Summer students lecture
CERN, August 9th, 2013

LHC, ATLAS, CMS etc. past, present and some perspectives

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CEN Saclay/IRFU/SPP and CERN

How it all started….
UA1/2, LHC, CMS, ATLAS, LHCb, ALICE
some significant results
what next

How it all started….(th ~1964 - ~1971, exp ~1973)

- From the W_1, W_2, W_3 and B mass-less gauge vector fields of SU(2) and U(1) through the mechanism of spontaneous symmetry breaking you get the massive W^+, W^- and Z and the mass-less A (γ) □□□□d□ related by□

$$Z = W_3 \cos\theta_{□} - B \sin\theta_{□}$$
$$A = W_3 \sin\theta_{□} + B \cos\theta_{□}$$

with three out of the four scalar fields of the theory disappearing in the masses of the W and Z, whilst the fourth survives - the SM Higgs boson!

- First measurements (in 70's) of charged and neutral current neutrino interactions interpreted in this unified electroweak scheme were giving: $\sin^2\theta_w \sim 0.3 - 0.5$
with:

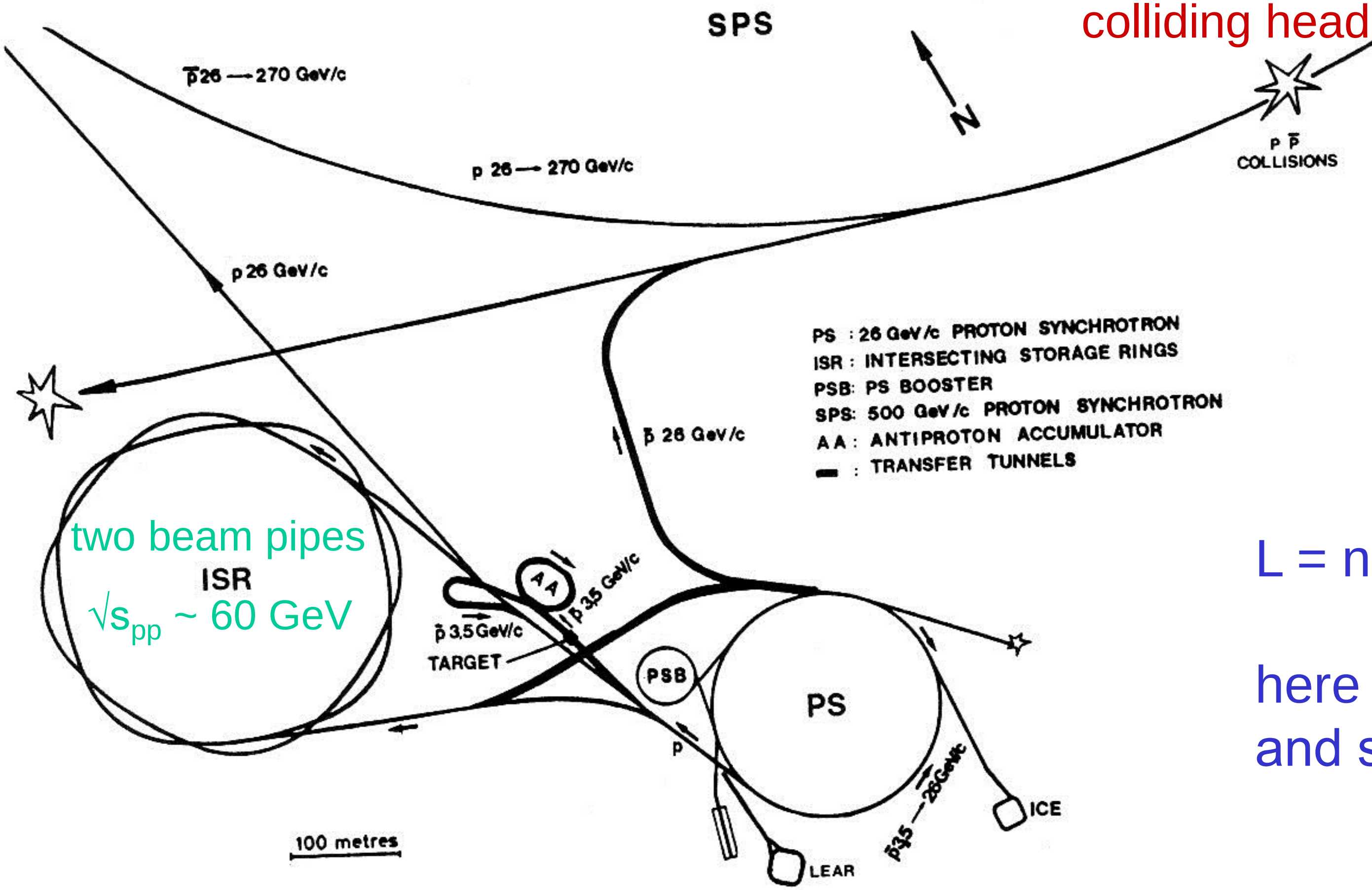
$$m_W = [\pi\alpha_{em}/(\sqrt{2}G_F)]^{1/2}/\sin\theta_w = 37.4 \text{ GeV}/\sin\theta_w \qquad m_Z = m_W/\cos\theta_W$$

this meant that: $m_{W,Z} \sim 50 - 100$ GeV

but existing machines, for ex. ISR or the CERN SPS in a fixed target mode, could not give more than $\sqrt{s} \sim 30 - 40$ GeV !! …….and the LEP was still far in the future, at least ten years here came the suggestion of Cline, McIntyre, Rubbia to convert an existing proton synchrotron into an antiproton-proton collider!

The CERN antiproton-proton collider complex (1980-90)

protons and antiprotons counter-rotating in same beam pipe - as in an e+e- machine! colliding head-on at √s ~ 500 - 600 GeV



two beam pipes

$\sqrt{s_{pp}} \sim 60$ GeV

colliding head-on at √s ~ 500 - 600 GeV is equivalent to ~ 150 TeV beam energy

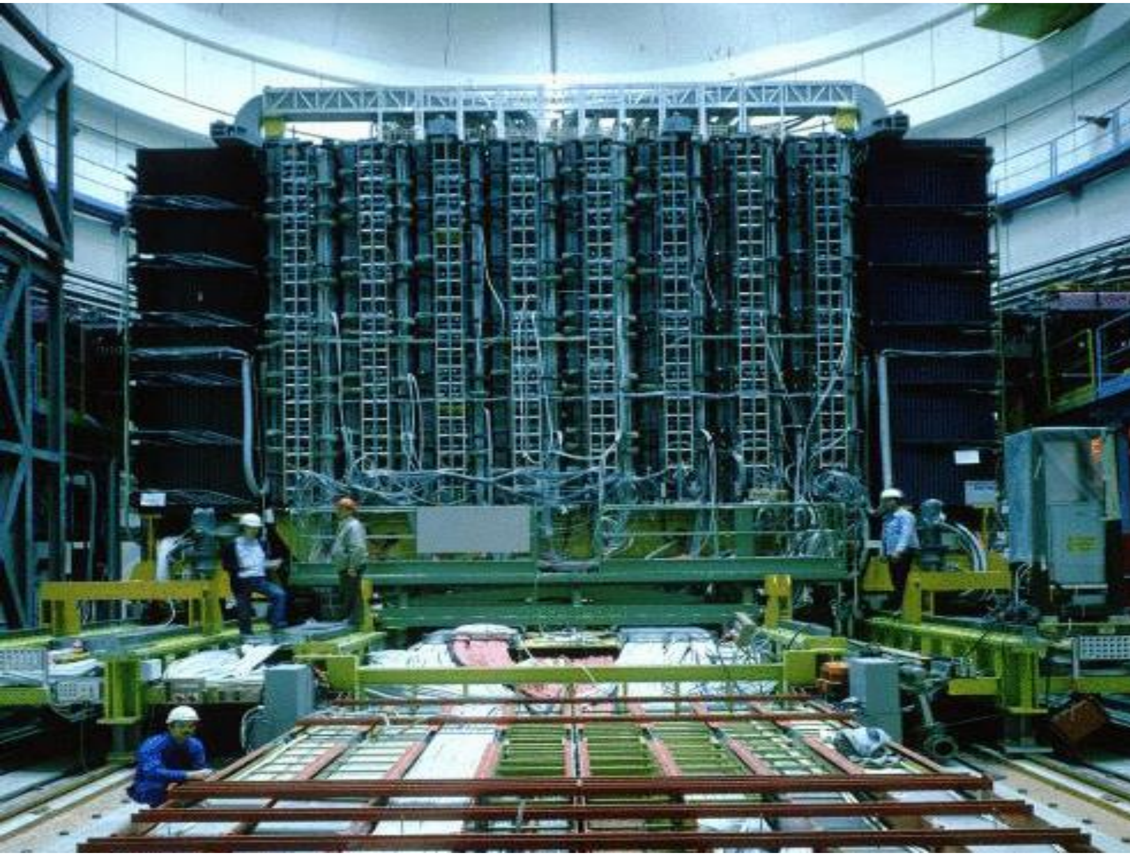
Luminosity:

$L = n(p)n(\text{anti-}p)f/(4\pi\rho^2)$

here comes S. Van der Meer and stochastic cooling….

➡ The transformation of the SPS into a collider at C. Rubbia's initiative was accomplished by the summer of 1981 - in ~ < 3 years!

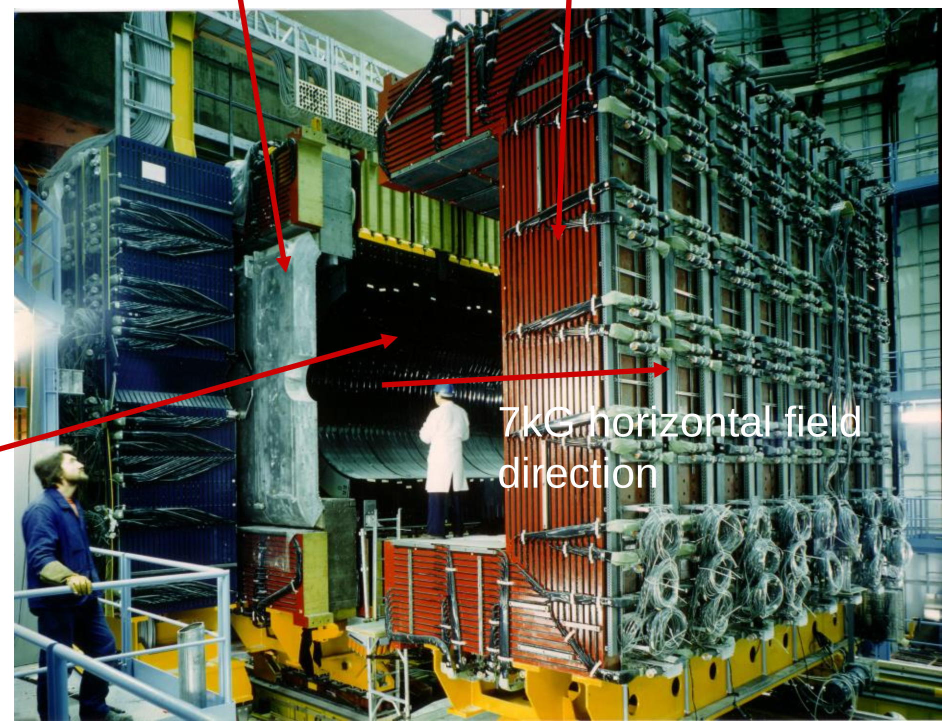
UA1 detector under construction (1979/81!!!)



UA1 detector: ~10 x 6 x 6 m^3,
~ 2000 tons ~130 physicists
calorimetric coverage $|\eta|$< 5.0
tracker coverage $|\eta|$< 3.0
muon system coverage $|\eta|$< 2.3

warm Al coil,
7kG horizontal field,

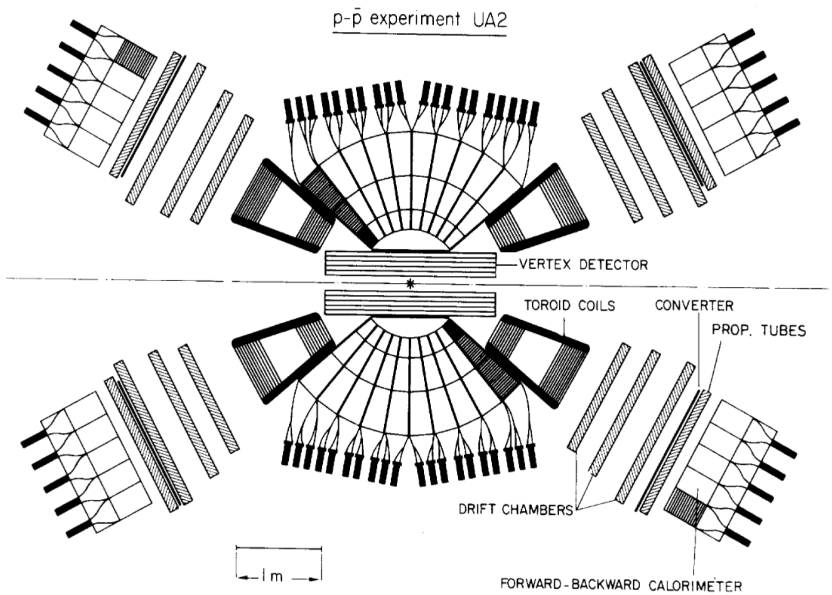
HCAL
5cm iron/1cmScint.
3.5 λ_{int} deep



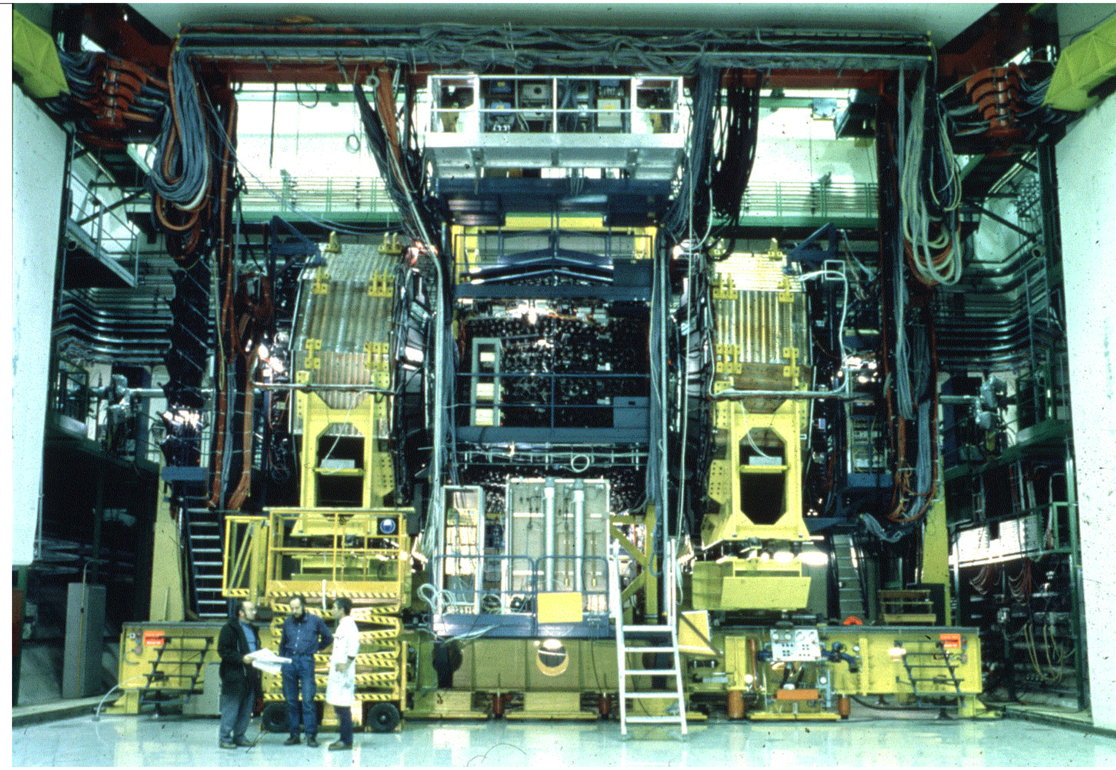
UA1 designed and built in < 3 years!!

ECAL (2x24 gondolas) Scint.-Pb sandwich
1.2 mm Pb/1.5 mm Sci $\Delta\phi\Delta\eta$= 180^o x 0.14
27X_0 deep, four segments in depth + 2x32 radial sectors in end-caps acceptance $|\eta|$ < 3.0

The UA2 detector



The UA2 detector in its initial configuration (1980-85).



The UA2 experiment in its final configuration for the runs of 1986 to 1990. Full calorimetry down to ~5° thus improved measurement of missing p_T

Central region: tracking detector, “pre-shower” electromag. and hadronic calorimeters;
ECAL: Sci+Pb sandwich, HCAL: Fe+Sci sandwich
$\Delta\theta\ \Delta\phi \sim 10^o x 15^o$, 4.5 λ_{int} no magnetic field
In 20° – 40° regions : toroidal magnetic field; tracking detectors;
“pre-shower” + electromagnetic calo.

The first major success: first observation of hadronic jets at the antiproton-proton collider - summer 1982

Not totally sure that jets would be seen in hadron collisions (NA35)

….

- but already seen in e+e- however!

Remember:

NA(35), ISR/AFS

(correlation/trigger bias….)

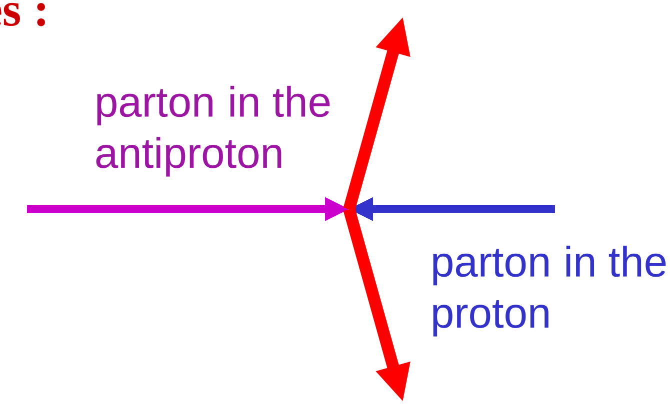
G. Preparata

(Fire Sousage model….)

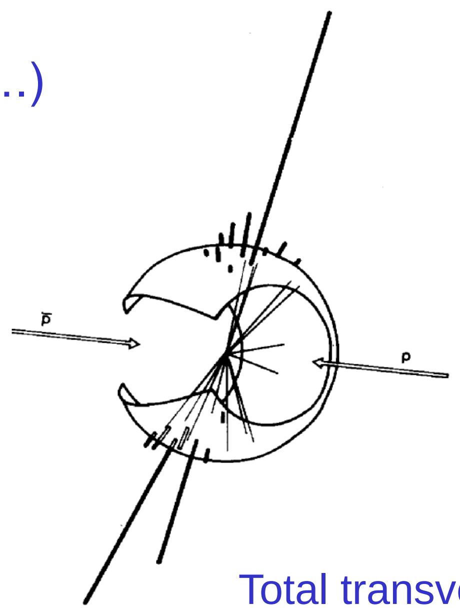
Odorico….

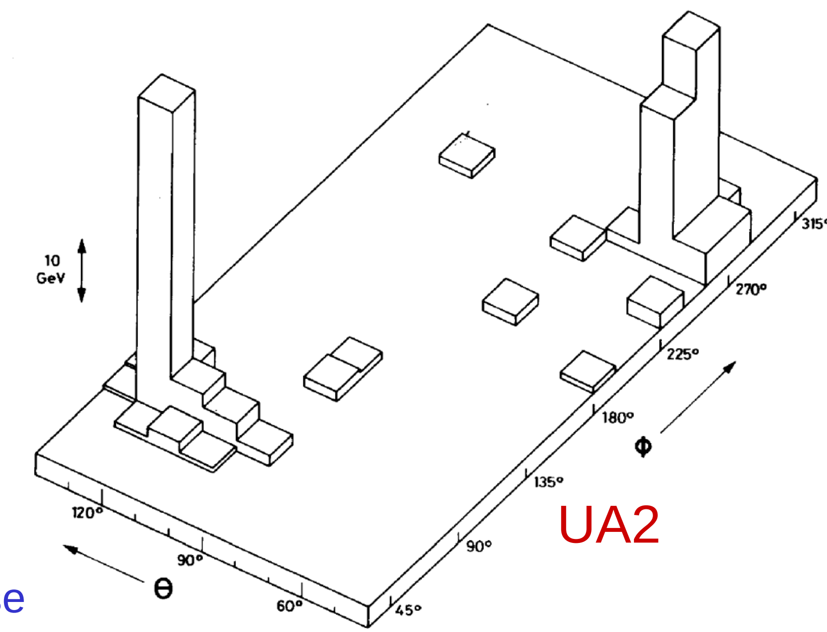
Elementary processes :

$$\bar{q} + q \to \bar{q} + q$$
$$\bar{q} + g \to \bar{q} + g$$
$$g + q \to g + q$$
$$g + g \to g + g$$
$$\bar{q} + q \to g + g$$
$$g + g \to \bar{q} + q$$



First evidence for jets in hadron colliders, December 1981 run, spectacular UA2 early jet event in calorimeters, Paris conf. summer 1982



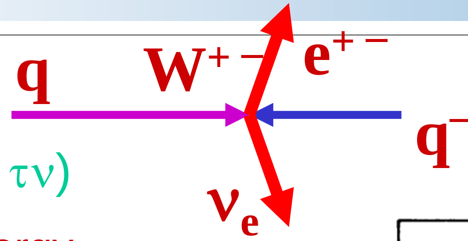


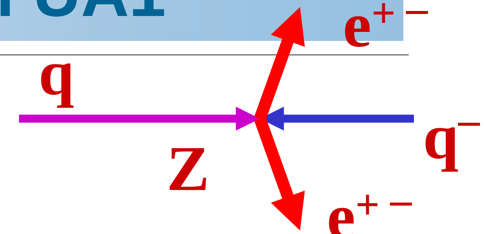
UA2

Total transverse energy ~ 140 GeV

Run of winter 1982, W discovery, followed by run of spring 1983 and Z discovery in UA1

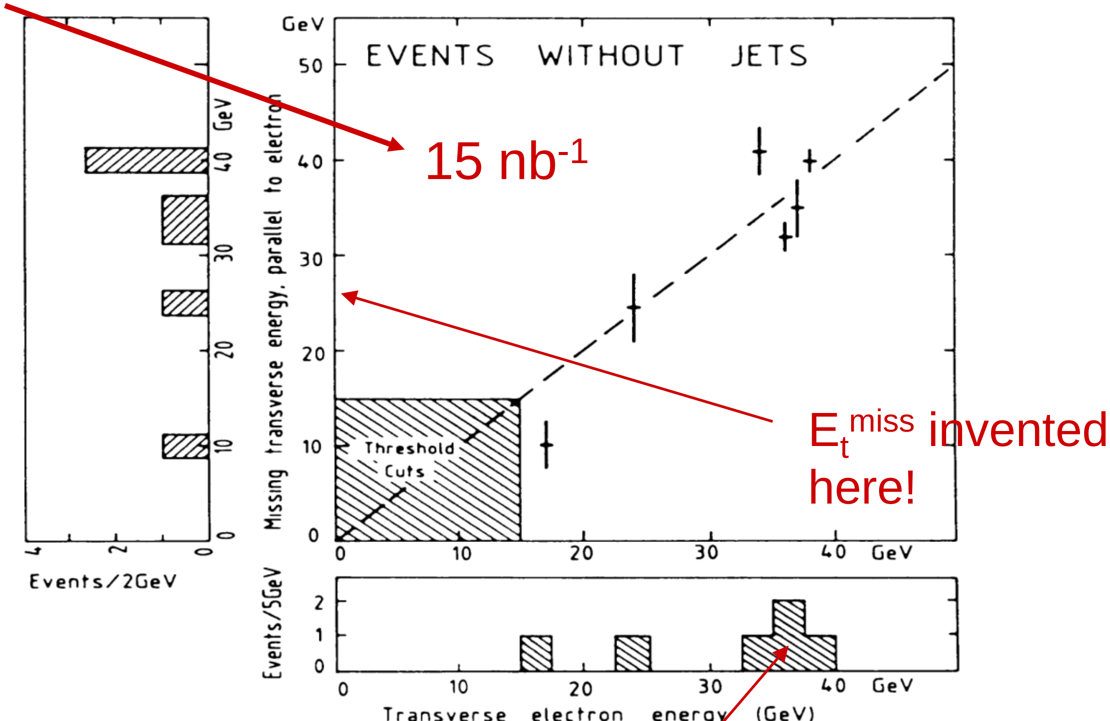
Search for leptonic decays:

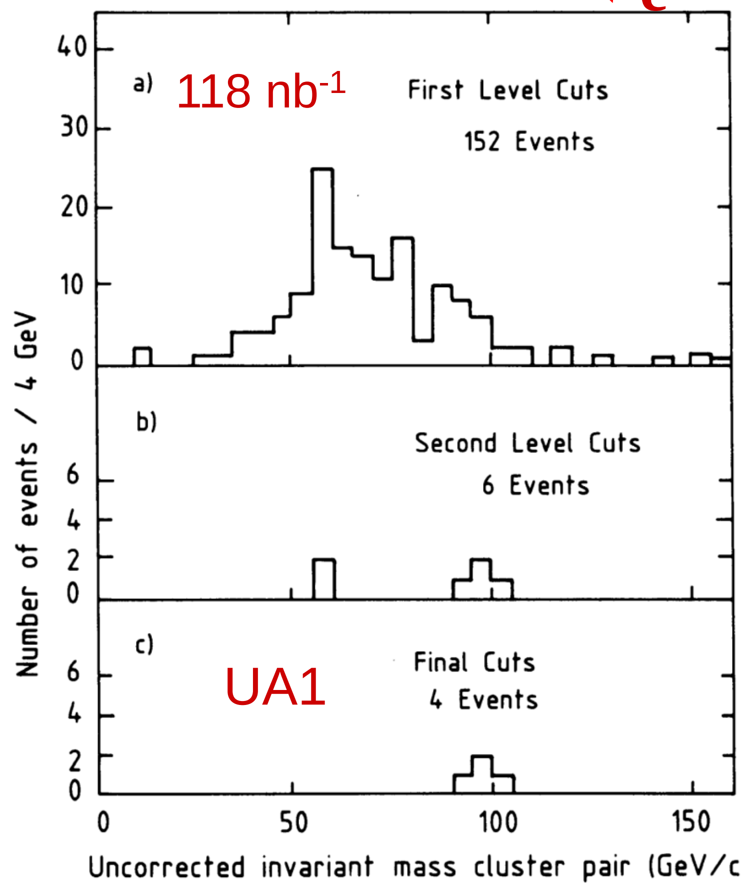




➡ 6 events selected (5 $W \to e\nu$ + 1 $W \to \tau\nu$)

Correlation between missing transverse energy and e^{+-} transverse energy for the first W events





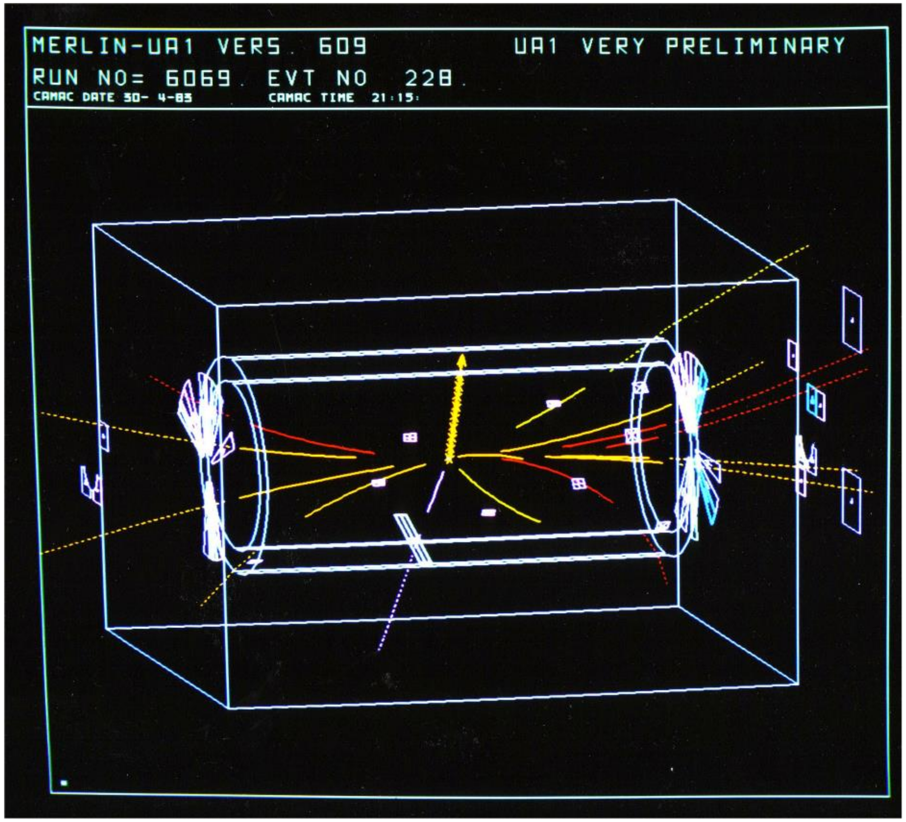
➡ $m_W = 81 \pm 5$ GeV (UA1)

from first "Jacobian peak"

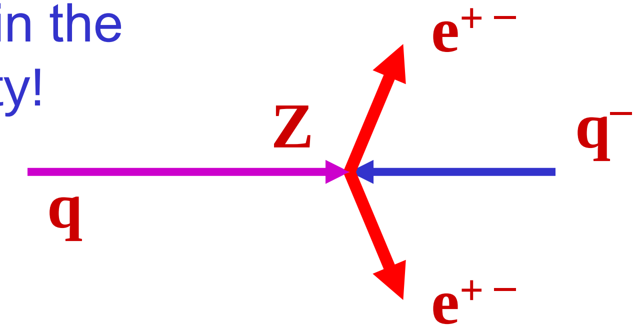
➡ $m_Z = 95.5 \pm 2.5 \pm (3.0)$ GeV (UA1

$\sigma_Z BR(Z \to ll) = 41 \pm 21\ (\pm 7)$ pb

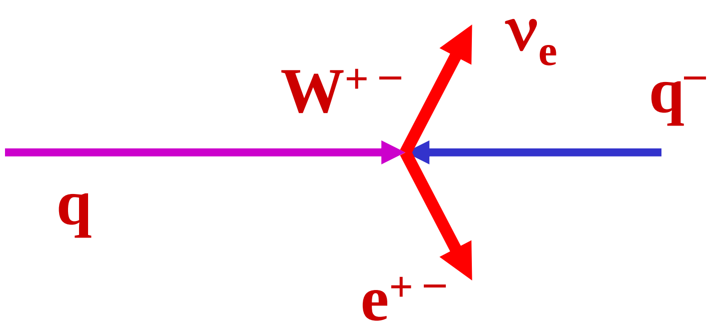
First W → eν events in UA1 (Dec.1982, Jan.1983) and first Z → e⁺e⁻ events in UA1 (May 1983)

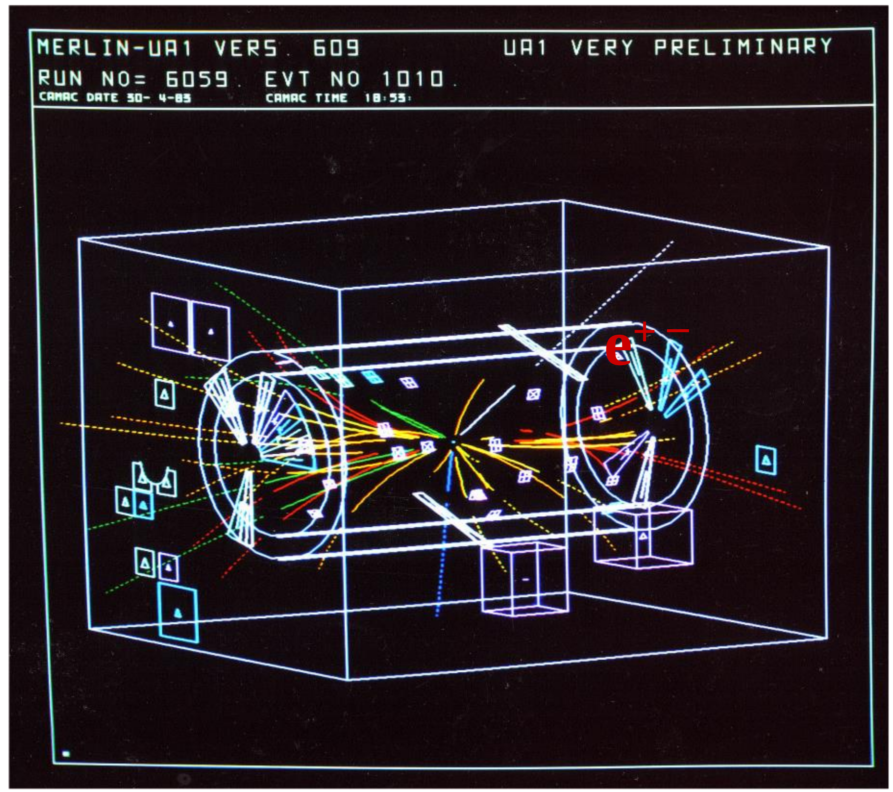


First W's and Z's in the history of humanity!

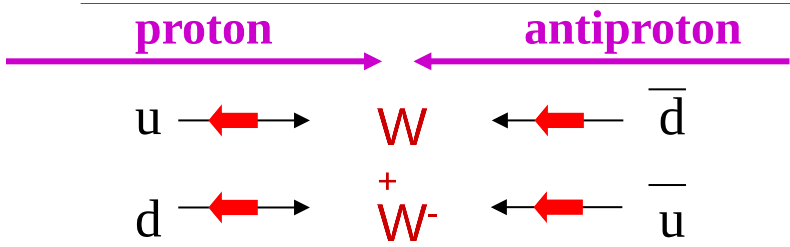


Megatek interactive graphic displays



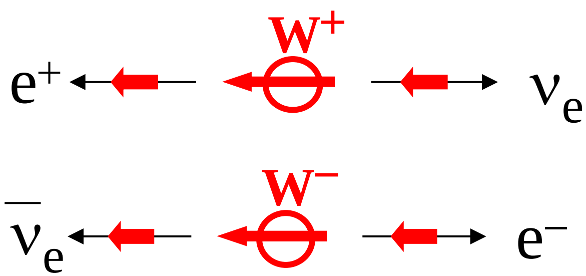


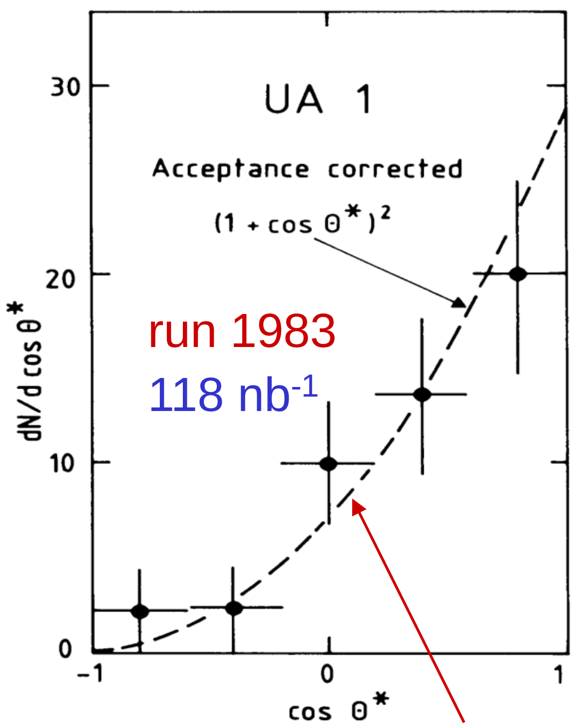
W confirmation, V-A asymmetry in UA1, spring 1983

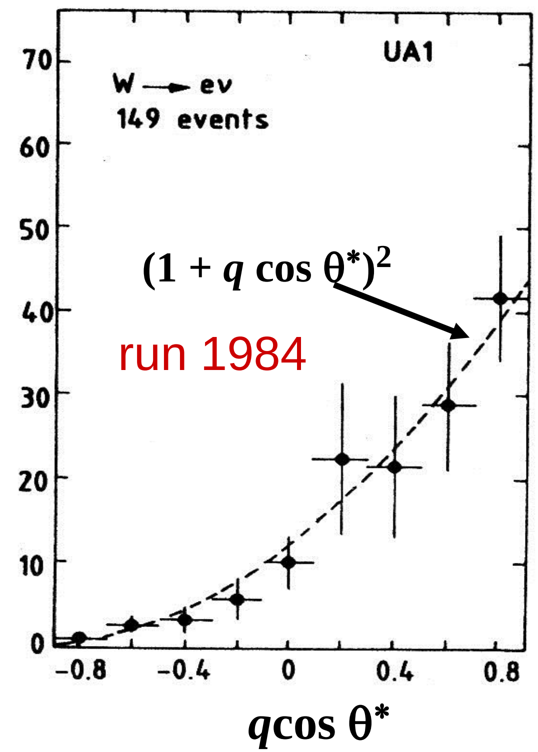


The almost complete W$^\pm$ polarization along antiproton direction was a consequence of V–A coupling - and of the collider cm energy ~ 500 - 600 GeV guarantying valence quark fusion into W (x_q, x_{anti-q} ~ m_W / $\sqrt{s}$ ~ 0.2), combined with V-A in decay results in leptonic ang. asymmetry!

In the W rest frame:







Electron (positron) angular distribution:

$$\frac{dn}{d\cos\theta^*} \propto \left(1 + q\cos\theta^*\right)^2$$

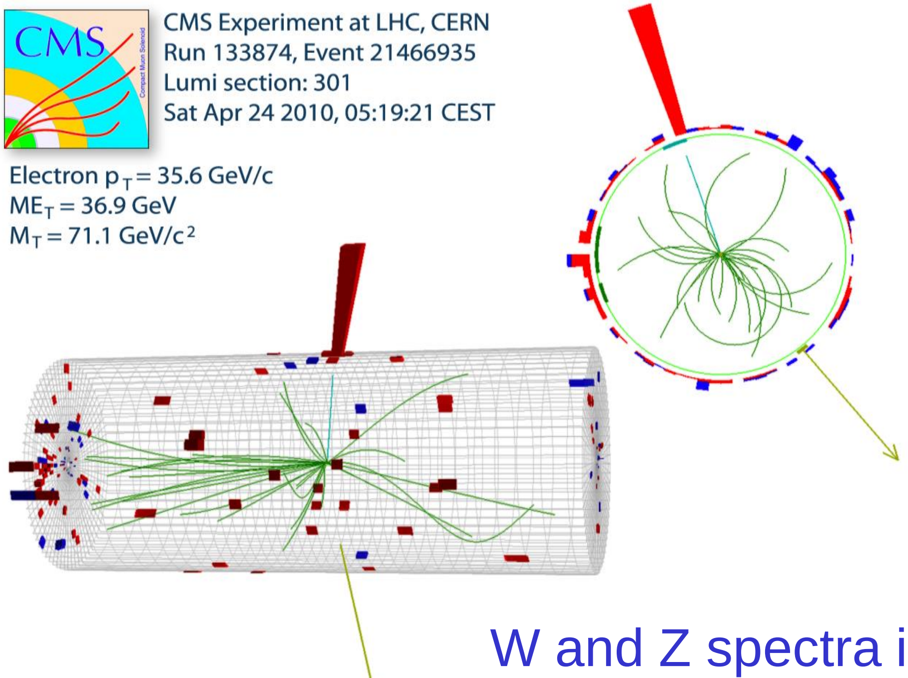
q = +1 for positrons; q = -1 for electrons

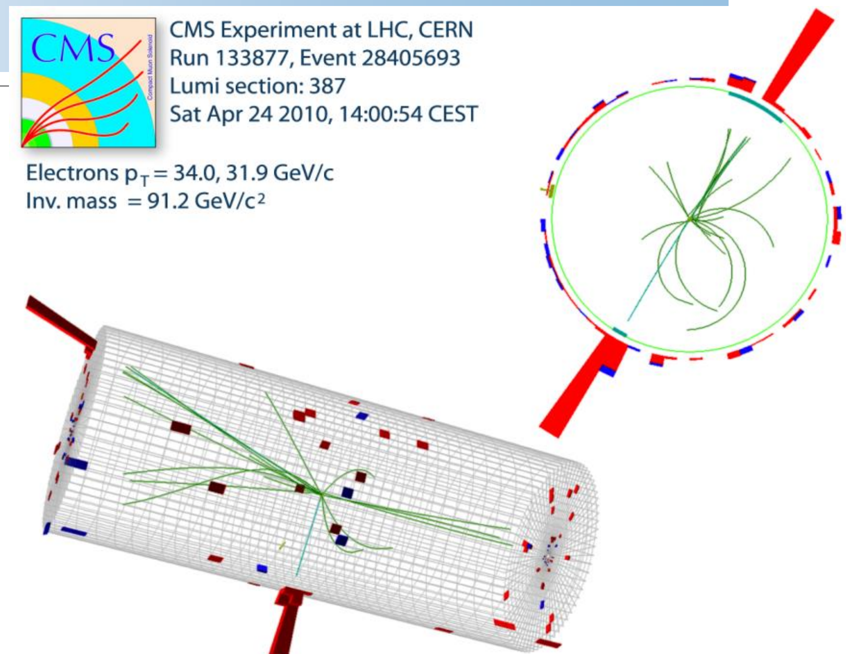
θ^* = 0 along antiproton direction

magnetic field of UA1 crucial for this!

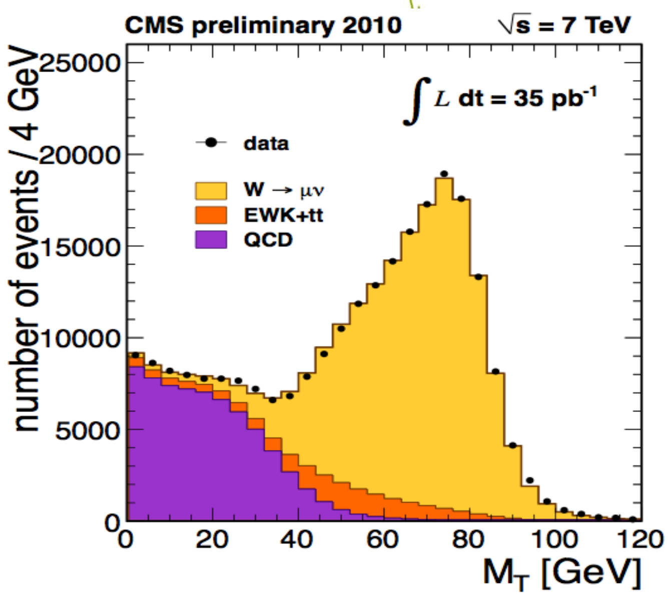
it is really THE W (spin =1, max. parity violation)!

First W → eν and Z → e⁺e⁻ events in CMS, April 2010

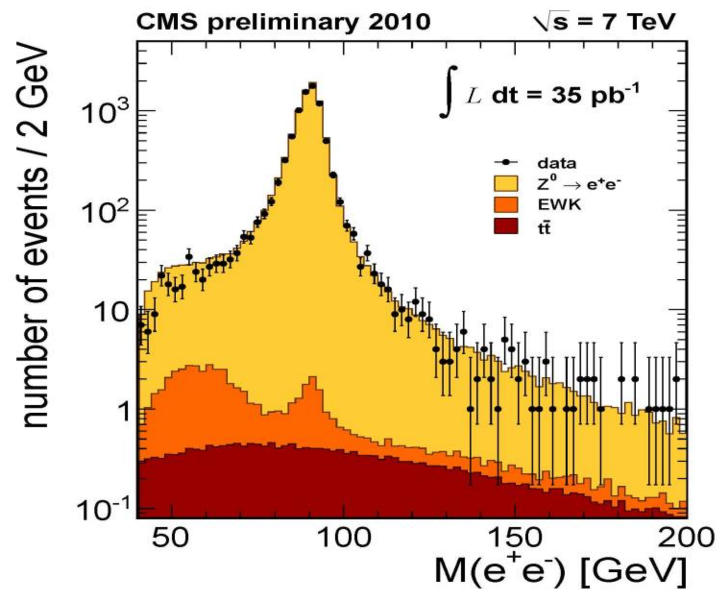




W and Z spectra in CMS, Nov. 2010



By end 2012 we had ~150.000.000 W and ~15.000.000 Z decaying leptonically



Few words about the LHC,
how this adventure began

LHC, how it all started…. 1989-90

Precursor: Lausanne meeting 1984…

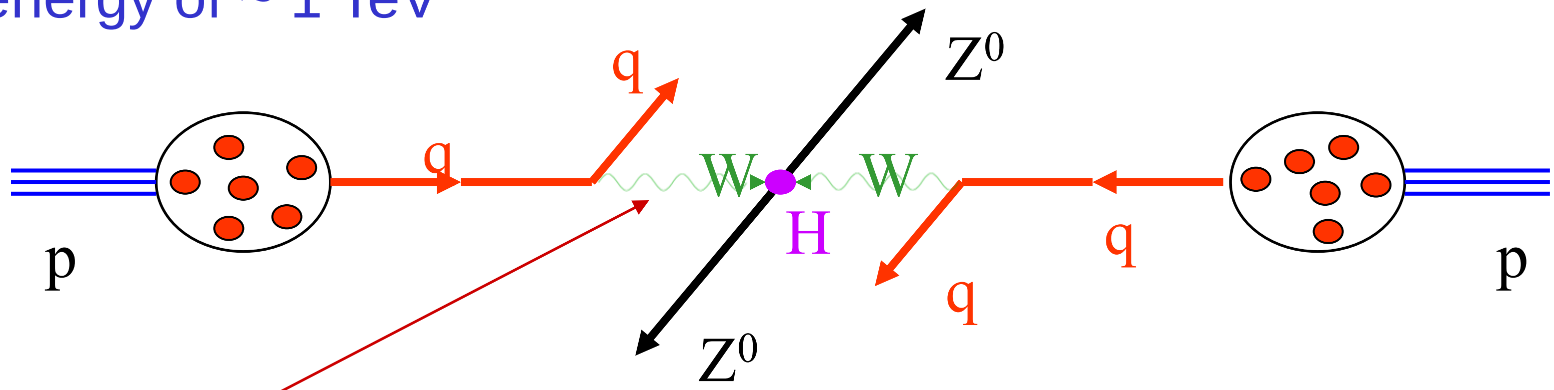
QuickTime™ and a decompressor are needed to see this picture.

In September 1989 the new DG, C. Rubbia asked (Altarelli, Pauss, Denegri) to organize a year's long study (with ~250 participants) whether and how a 17 TeV pp collider in the existing LEP tunnel could compete with the SSC - then in construction - in the search for the Higgs, top, SUSY etc - assuming 10 Tesla dipoles could be produced.

The outcome was the ECFA Aachen Workshop in October 1990; the main result was that an LHC luminosity ~ ten times larger was required to compensate the factor of ~ 2 inferior energy vs the SSC i.e. $10^{34} cm^{-2} s^{-1}$!!!

The LHC: required energy and luminosity

- To solve ew symmetry breaking need to study W_L-W_L scattering at a centre of mass energy of ~ 1 TeV



E_W ~ 500 GeV

➡ E_{quark} ~ 1 TeV

➡ E_{proton} ~ 6 TeV ➡ required LHC energy: pp collisions at ~ 6 + 6 TeV

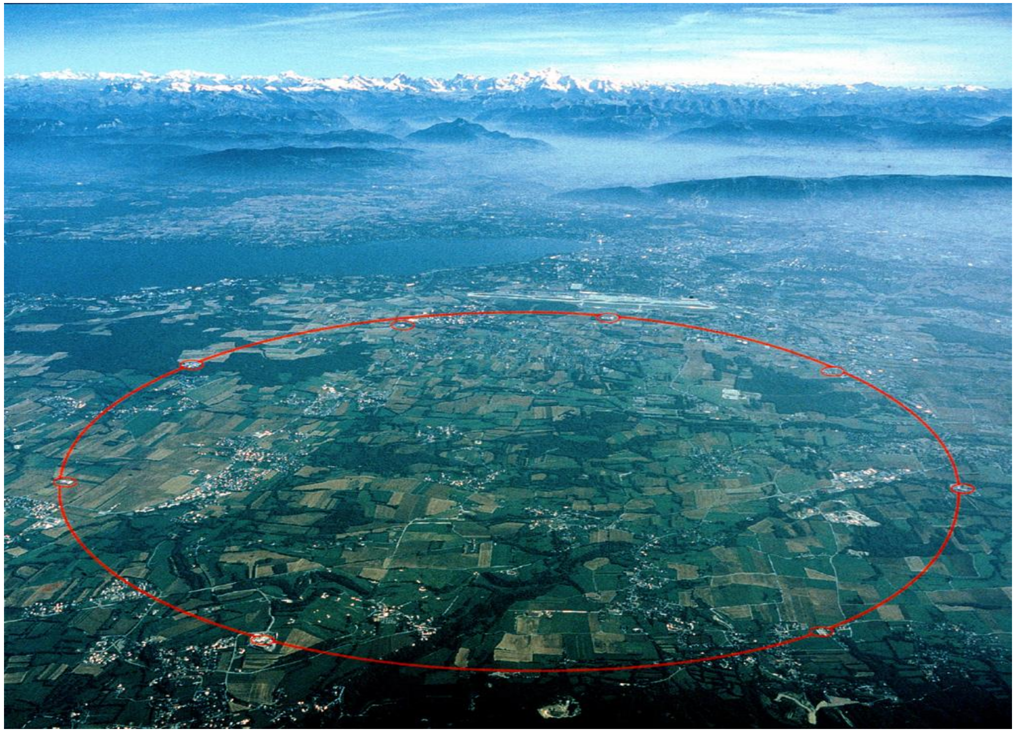
- Event Rate = Luminosity x Cross-section x Branching Ratio = L x σ x BR

e.g. H(1TeV) → ZZ → 2e+2μ or 4e or 4μ

For 10 events/year = 10^{34}x10^{7}x10^{-37}x10^{-3} !! ➡ required L ~ 10^{34} cm^{-2} s^{-1}

Luminosity, measured in $cm^{-2}s^{-1}$, gives the number of proton-proton collisions taking place per sec. For L = $10^{34}cm^{-2}s^{-1}$ and σ(pp) ~ 100 mb ➡ rate = 10^{9}/sec

The Large Hadron Collider (LHC) - the genesis



The LHC project started at the initiative (and with the daring!!) of C. Rubbia

and the Conference in Aachen, Oct. 90, marked the real start-up, since then work on the collider and magnets, the various detector designs and understanding physics went on without let-up

Scientifico-diplomatic trips in 1990/91/92 to Japan, India, Russia, USA, Canada etc

LHC vs SSC: Rubbia's arguments: savings!

- existing LEP tunnel ~1 GCHF
- existing infrastructure at CERN (PS. SPS, etc) ~ 1 GCHF
- "two-in-one" scheme for dipoles saves ~ half the cost of magnet ~ 0.7 to 1 GCHF

thus overall LHC cost ~ 3 GCHF

- will be ready by 1998 - 2000 !!

Intersecting Storage Rings -

a prototype of a hadron (pp) collider, CERN 1970's

QuickTime™ and a
decompressor
are needed to see this picture.

Two independent beams, pipes, sets of magnets etc……ISR. ISABELLE, SSC
were all constructed/conceived this way

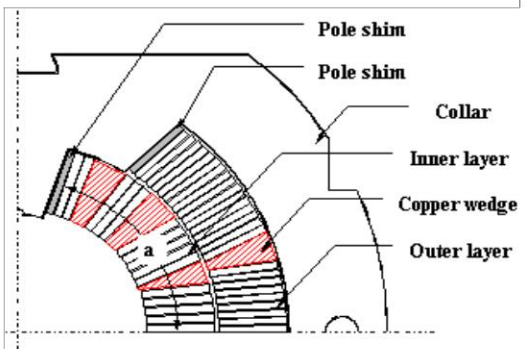
The LHC tunnel - a single set of magnets
thanks to the "two-in-one" magnet scheme

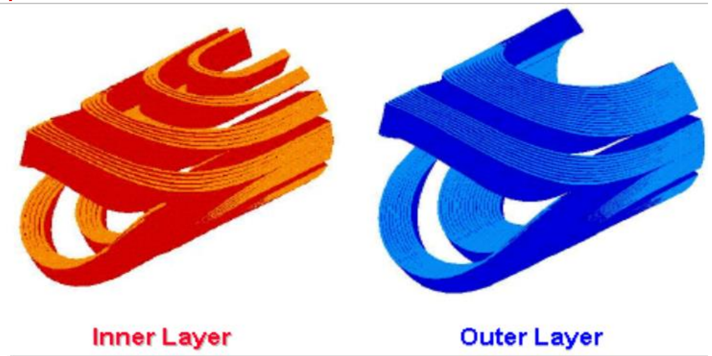
QuickTime™ and a
decompressor
are needed to see this picture.

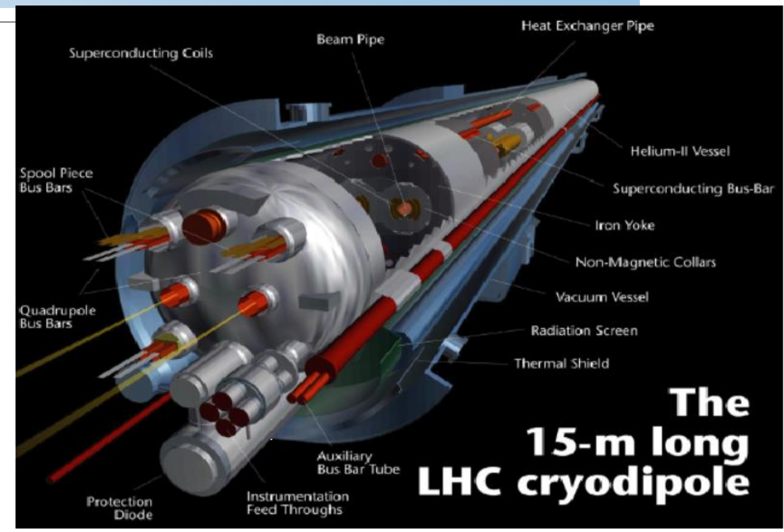
No space for two independent sets of magnets, plus cryogenics etc

The key elements: LHC dipoles
coil structure for the two-in-one scheme
(suggested by R. Palmer in 1984)

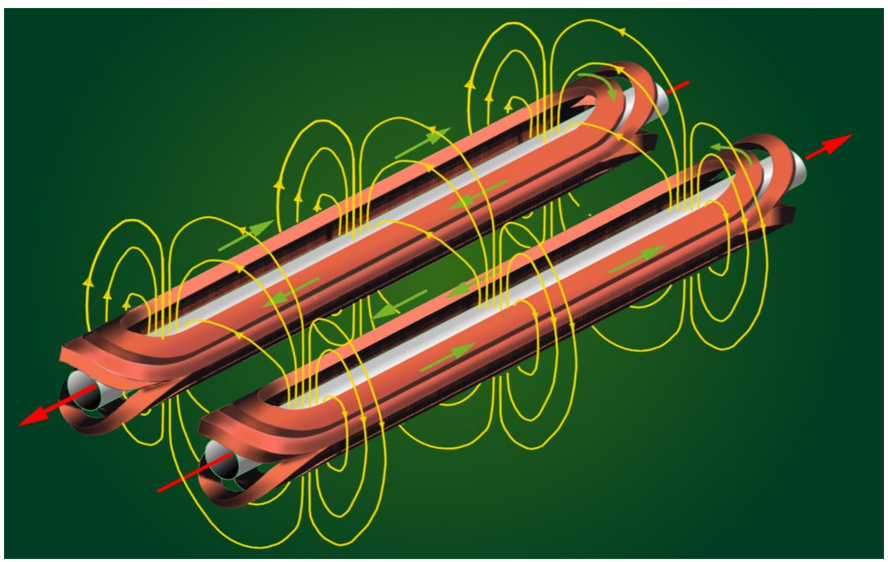
LHC dipole coil design, 6-block coil structure



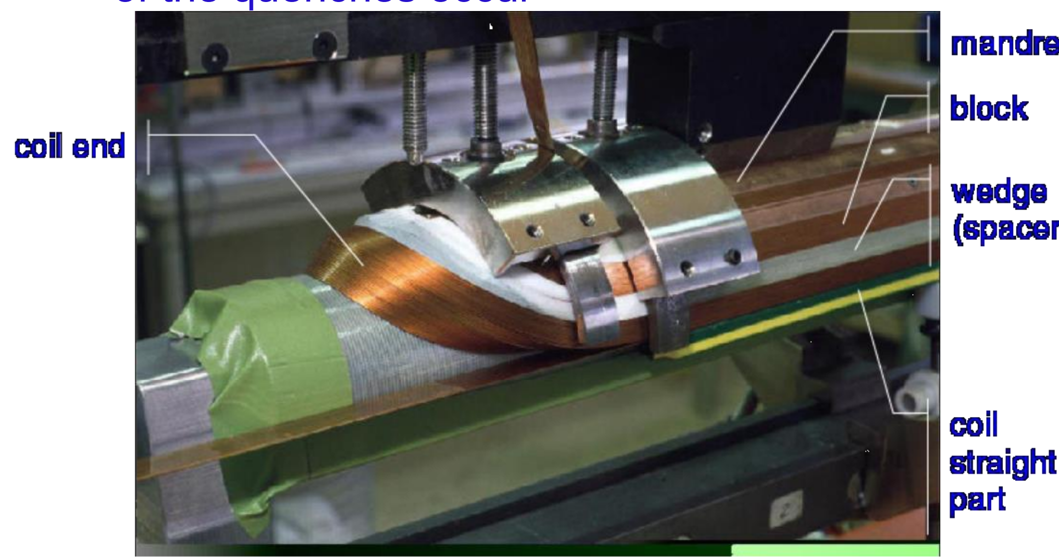




Field lines in the two-in-one dipole
(two beam-lines in a single magnetic enclosure)



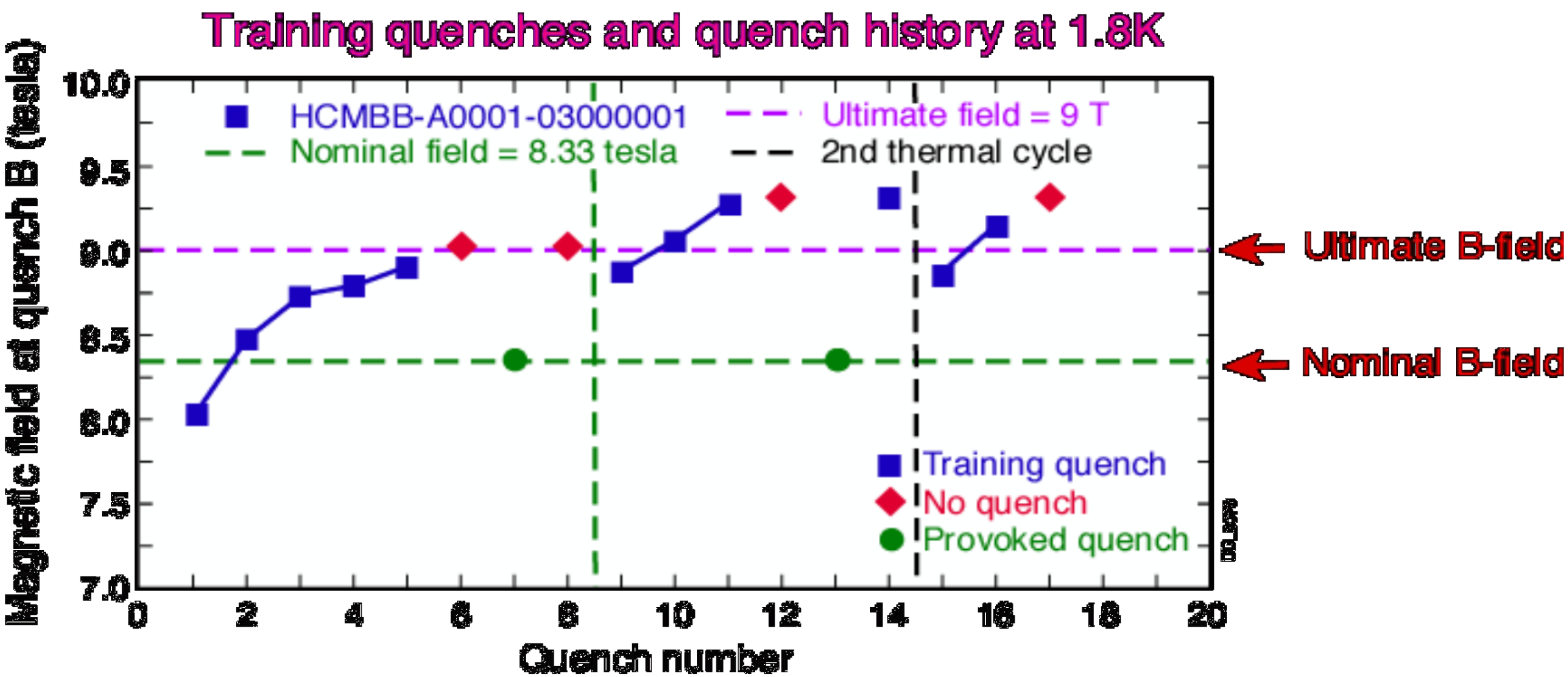
Most delicate is the coil end - this is where most of the quenches occur



LHC dipoles (pre-series) - training

10 years of R&D were necessary with three generations of prototypes to develope the dipoles

Quench performance of the last tested pre-series dipole

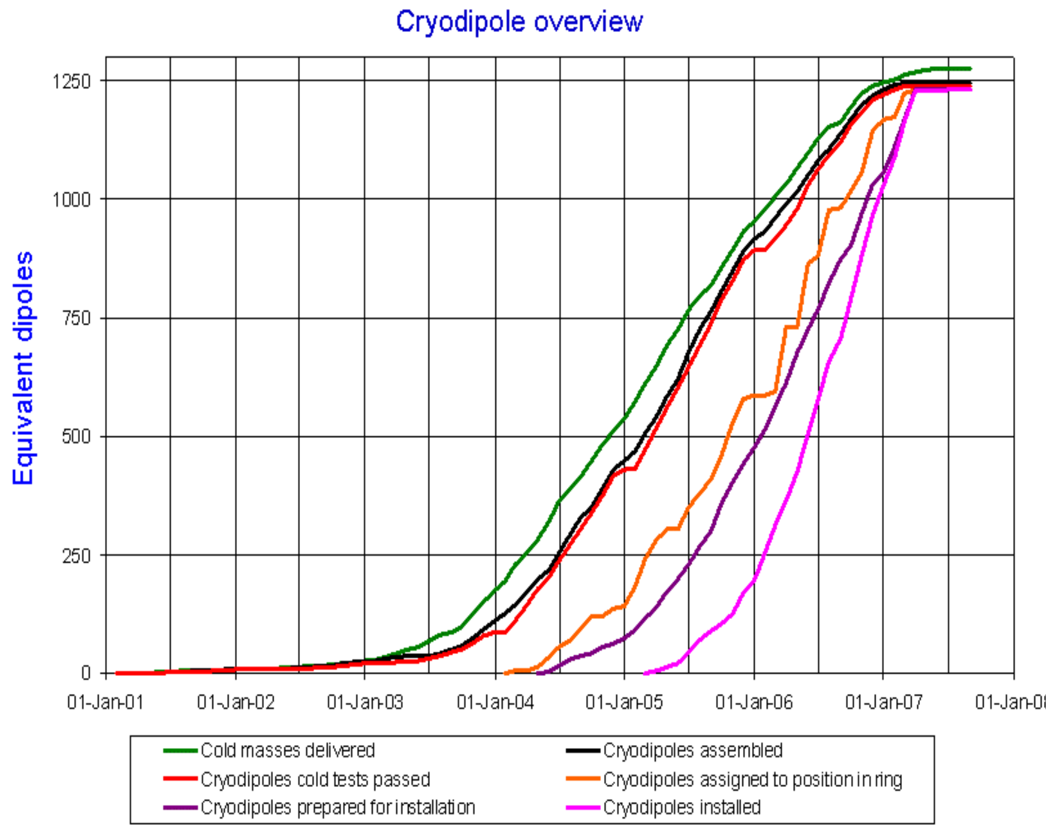


- MBPSN01 dipole reached nominal field after one quench
- Ultimate field of 9T reached after 5 training quenches
- during the following 2 test campaigns magnet never quenched below 8.8T

➡ Last modifications to the dipole coil configuration done in 2001

LHC dipoles production, testing, installation, 2002-07

Hall at CERN for final assembly and testing of dipoles -2005/2006

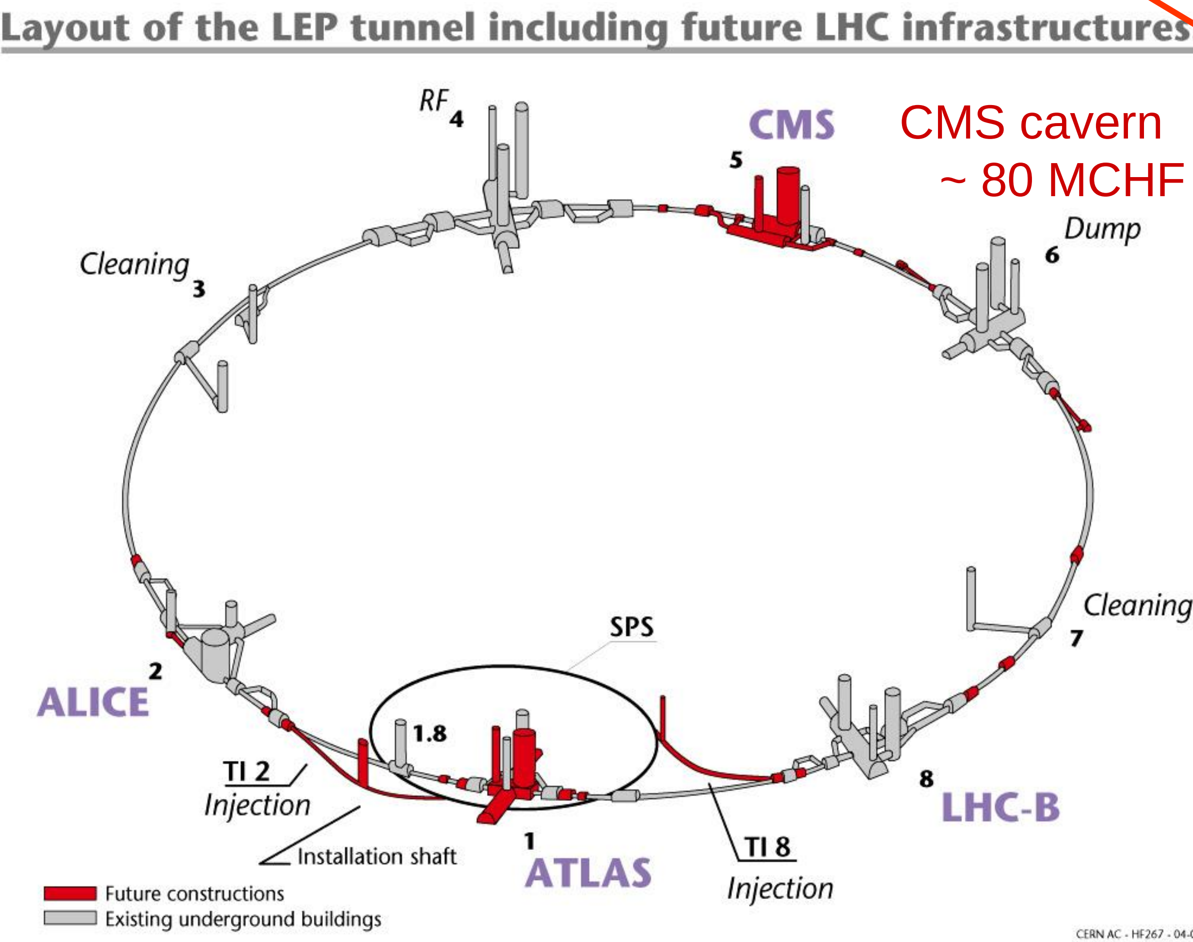


Updated 31 August 2007 Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

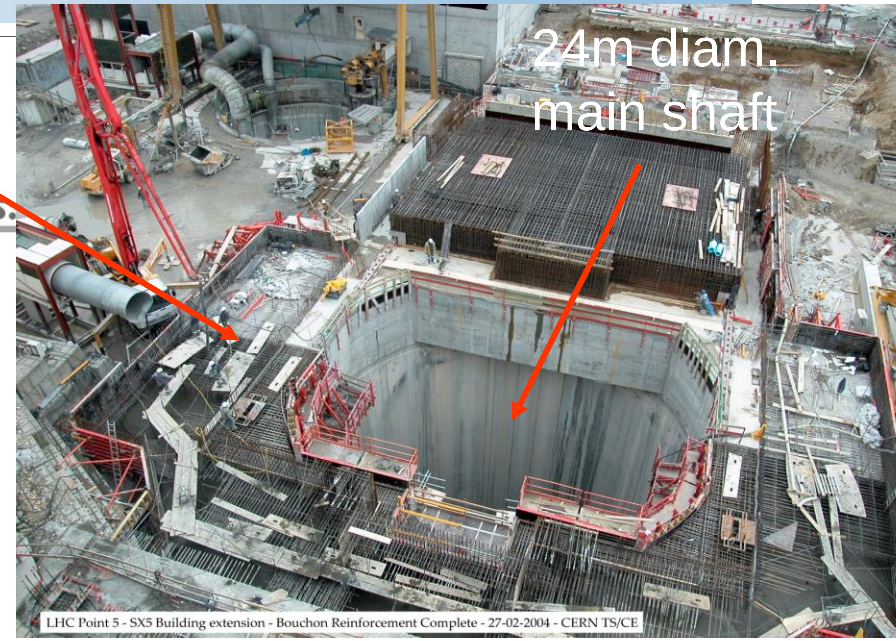
Magnets constructed between 2002 and 2007, by Jan. 2007 ~ 1200 dipoles and ~ 400 quads installed in the tunnel, they have to be aligned with 100μm precision

LHC infrastructures - a very major undertaking

Freeze-out of soil to
-70°C before concreeting



CMS cavern
~ 80 MCHF



ATLAS cavern finished in May 2003
cost ~ 100 MCHF

Conceiving the detectors for the LHC

Few words about the detectors, the design difficulties…..
ATLAS, CMS in particular

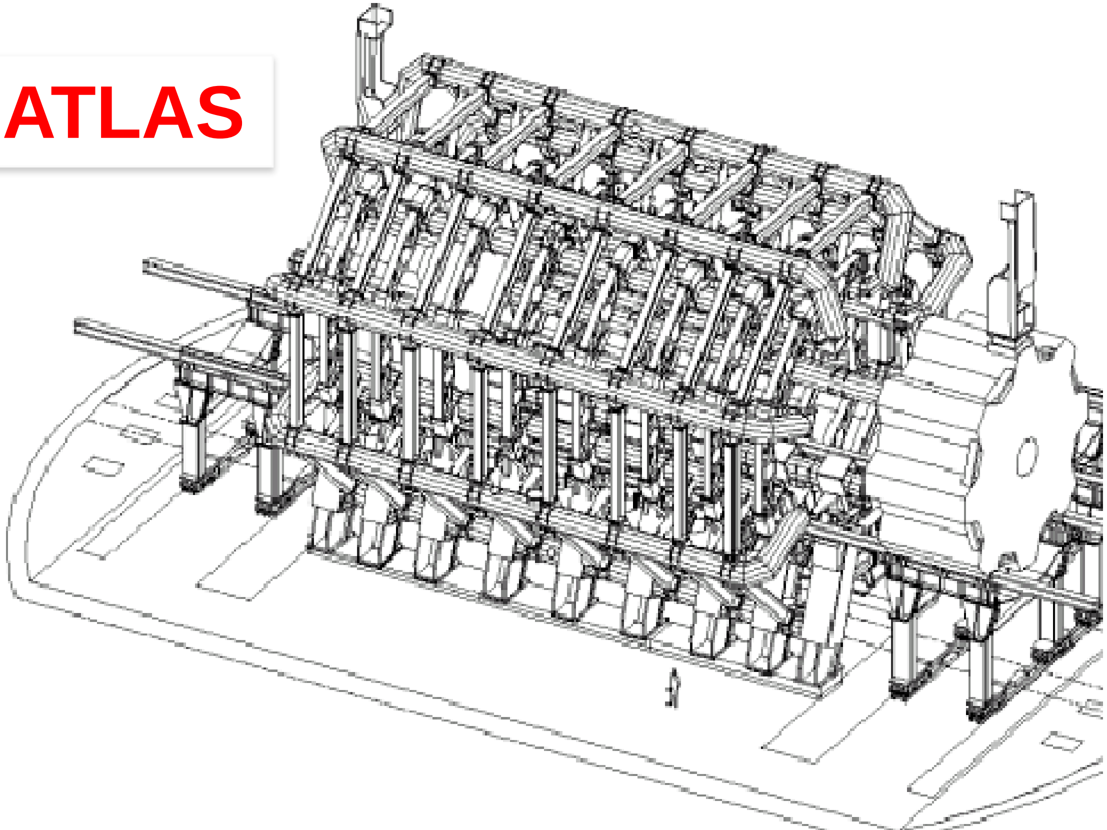
- we were just emerging from the p-pbar collider where max. luminosity was $10^{30}cm^{-2}s^{-1}$ - 4 orders of magnitude smaller than needed/desired for LHC!!!………and the Tevatron was just approaching $10^{30}cm^{-2}s^{-1}$

- the backbone of the detector is the magnet (solenoid vs toroid)
  - but what tracking possible/feasible at $10^{34}cm^{-2}s^{-1}$, with ~ 30 pile-ups - a frightening perspective!?
  - what ECAL granularity feasible/acceptable/useful at $10^{34}cm^{-2}s^{-1}$?? questions of granularity, rapidity of response, radiation hardness…
  - trigger, DAQ (S. Cittolin!) with 10^9 pp collisions/sec etc.

The magnets, backbones of ATLAS and CMS

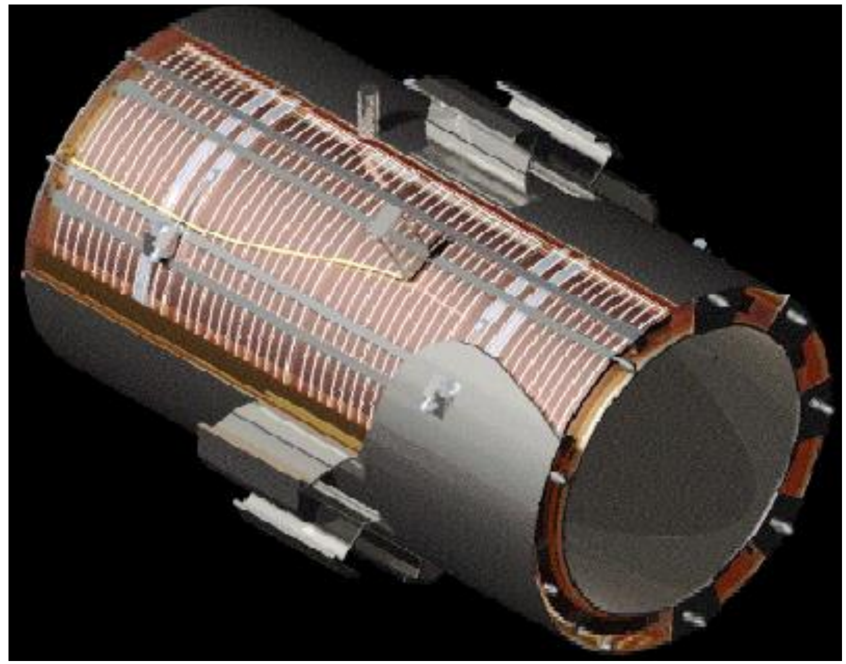
The designs of ATLAS and CMS were largely determined by the choice of the magnetic field configuration for measurement of muons. Complementary designs for the two experiments

ATLAS



Superconducting air-core toroids
26m x 5m, B ~ 0.5T

CMS



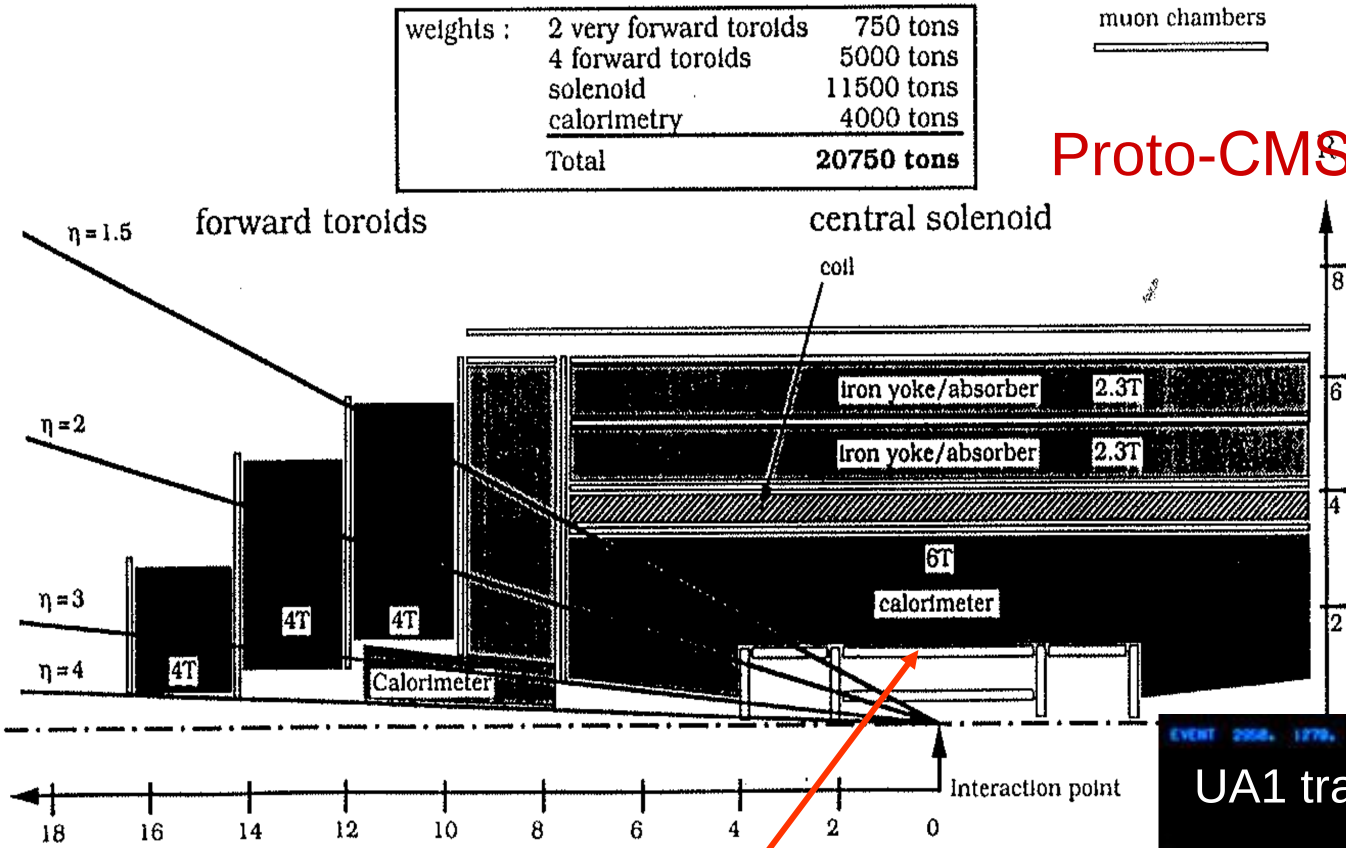
Superconducting solenoid
ϕ ~ 6m, L = 13m, B = 4T

How it all started…. for CMS!

Compact Muon Solenoid (CMS)

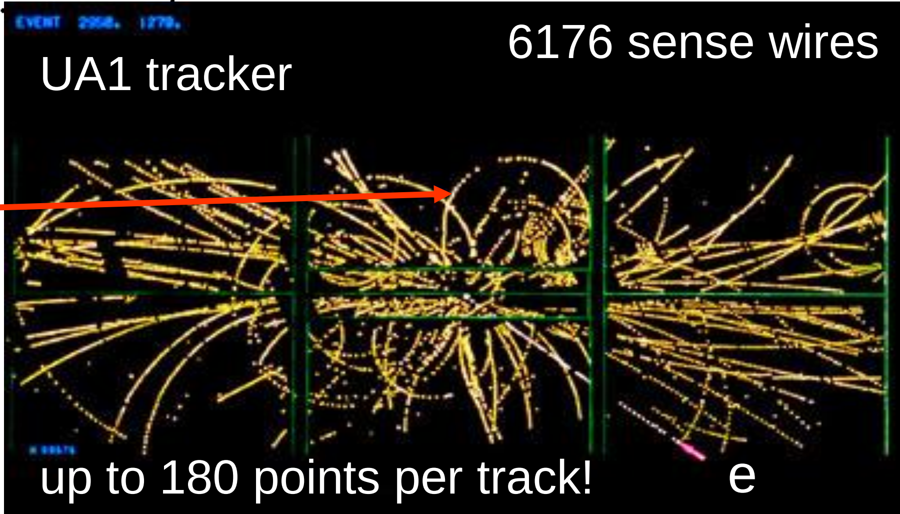
weights :		
	2 very forward toroids	750 tons
	4 forward toroids	5000 tons
	solenoid	11500 tons
	calorimetry	4000 tons
	Total	**20750 tons**

Proto-CMS in 1990…..



The UA1 tracker was by far the most sophisticated in its days, but the p-pbar collider did not exceed $10^{30}cm^{-2}s^{-1}$ and now for the LHC we need $10^{34}cm^{-2}s^{-1}$!! The answer: granularity and fast detector response

- Tracking? …maybe in outermost regions…



- Our test beam and MC studies in 1991/92 led to rapid progress in the detector design.

Before ATLAS: EAGLE and ASCOT

QuickTime™ and a
decompressor
are needed to see this picture.

EAGLE
Warm iron toroid
+ smaller inner
superconducting
solenoid

Evian conference
Situation in October 1992:
ASCOT,EAGLE,CMS,L3P
ALICE and 3 B-phys
proposals!

ASCOT

QuickTime™ and a
decompressor
are needed to see this picture.

ASCOT
Superconducting
air core toroid

Evolution of CMS, LOI in October 1992, organization of proto-collaborations 1991-1994

October 1992

By mid-1992 the design of CMS has much evolved and “stabilized”, stayed remarkably the same since the LOI (October 1992), only changes in subdetector technology

For CMS, the key points in the design were:

- robust large-acceptance muon system with a strong solenoidal field - driven by H $\rightarrow$ 4 muons
- excellent electromagnetic calo. - driven by H $\rightarrow \gamma\gamma$
- excellent tracking, of highest granularity affordable
- overall calorimetry hermetic - driven by SUSY (E_t^{miss}) requirements
- of reasonable overall cost:

  initial ceiling imposed by LHCC: 450 MCHF

Marriages in 1992/94:
ASCOT + EAGLE into ATLAS
CMS + L3P into CMS

Technical proposals of ATLAS and CMS, Dec. 1994

QuickTime™ and a decompressor are needed to see this picture.

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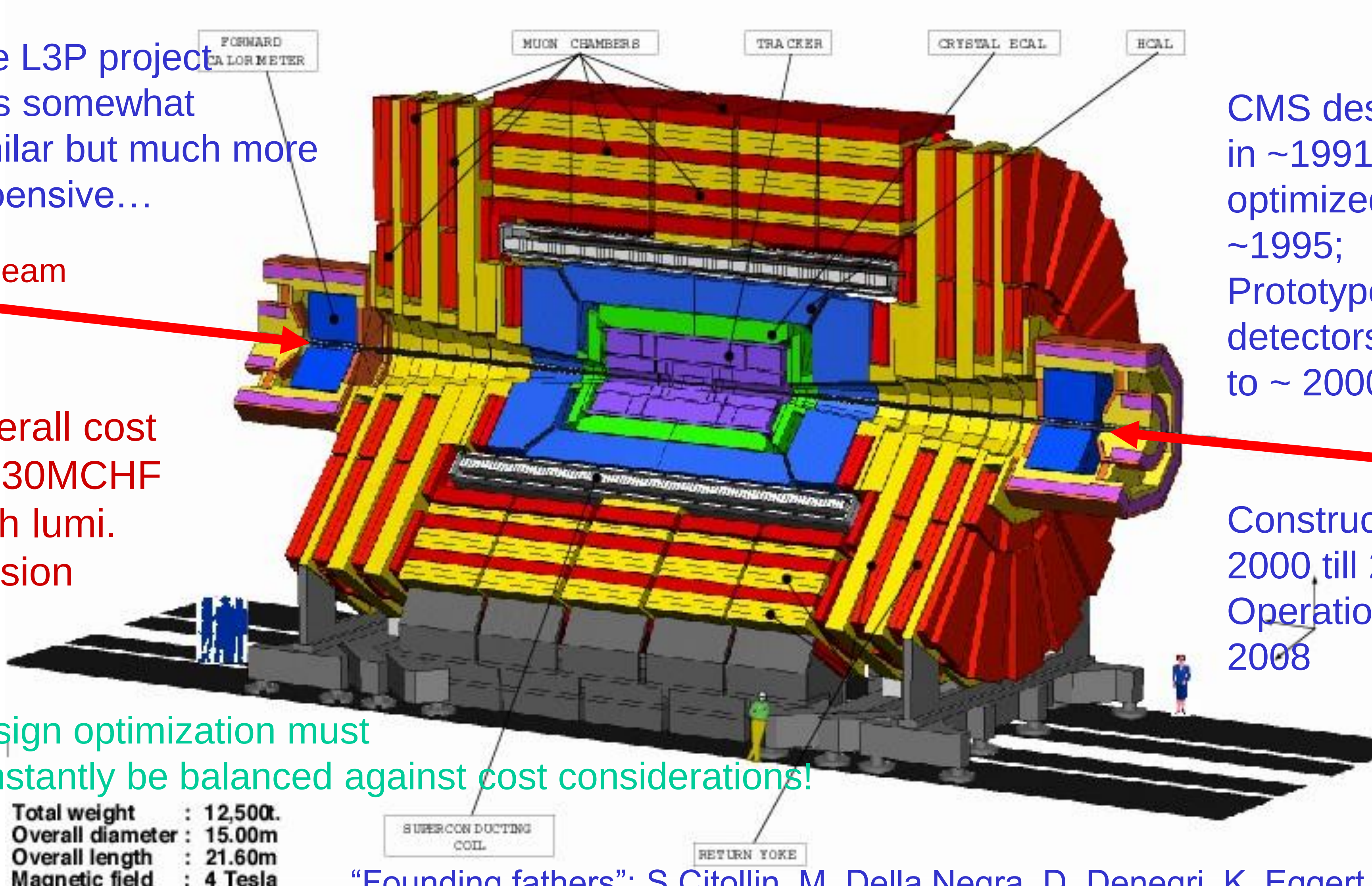
CMS changes in subdetector technology since LOI:

- for the ECAL: shashlik (Pb+Sci sandwich) to PbWO4 crystals in Sept. 94 - for reasons of resolution and space (L_{rad}, R_{Mol}) ie granularity and depth
- for the tracker: MSGC to Si microstrips in 1995/96 - as Si became affordable
- in 1995 adjunction of a Si-pixel microvertex detector to the tracker design

The CMS (Compact Muon Solenoid) detector

The L3P project was somewhat similar but much more expensive…



CMS designed in ~1991/92, design optimized up to ~1995;
Prototypes for sub-detectors tested up to ~ 2000;

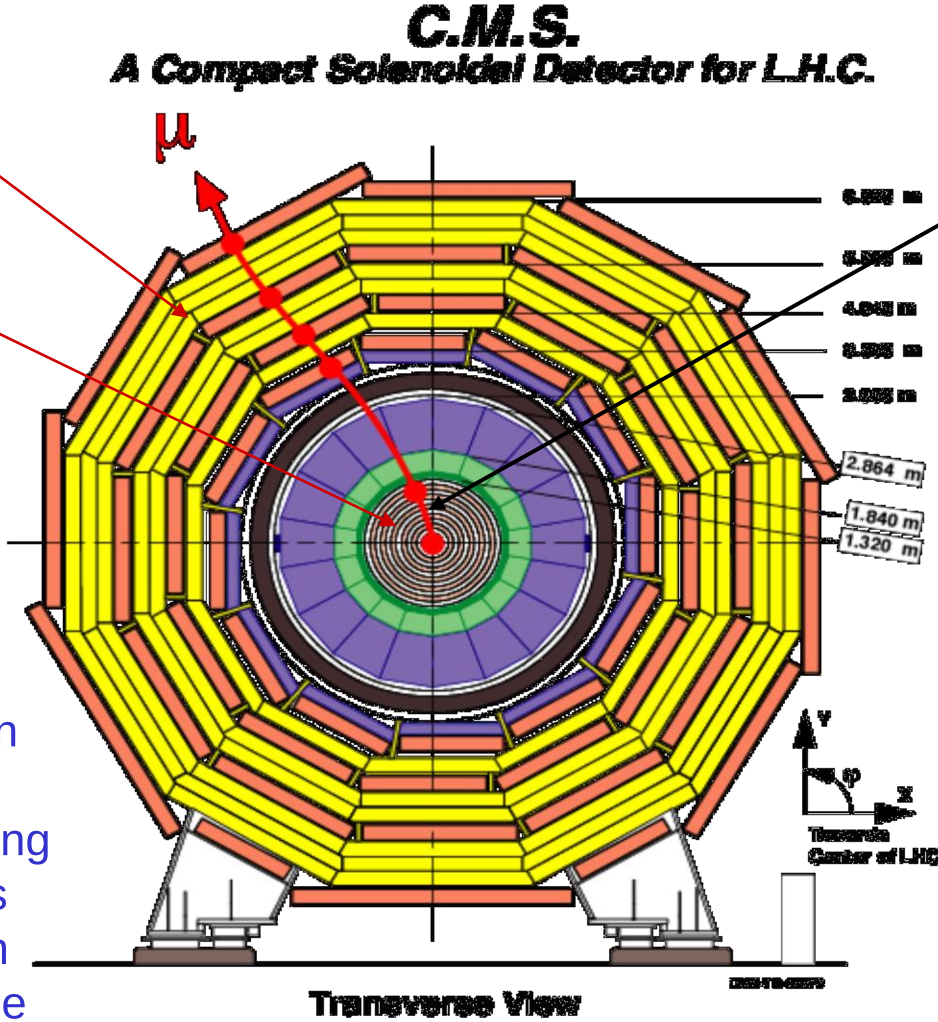
Overall cost ~ 630MCHF high lumi. version

Construction from ~ 2000 till 2008
Operational in Sept 2008

Design optimization must constantly be balanced against cost considerations!

"Founding fathers": S.Citollin, M. Della Negra, D. Denegri, K. Eggert, E. Radermacher, and T. Virdee,
subsequently key contributions from A.Herve, P.Sphicas…

CMS in transverse view - basic design



B ~ 2 Tesla

B = 4 Tesla

p = reB

Total bending power on a muon ~ 16Tm

momentum resolution from curvature:

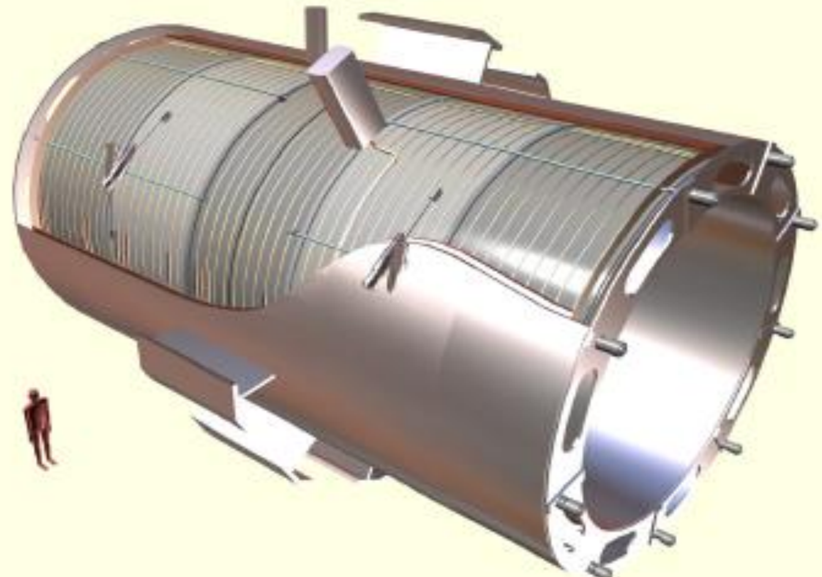
$$(1/p)\Delta p/p \sim \varepsilon \sqrt{n} / (B\, l^2)$$

ε= resolution on point measurement
n = number of points measured per track
l = useful track length
B = magnetic field

In the design of CMS care was taken to have good efficiency for detecting ~4.5 - 5 GeV muons (penetration through calos,coil!) to be able to observe Υ

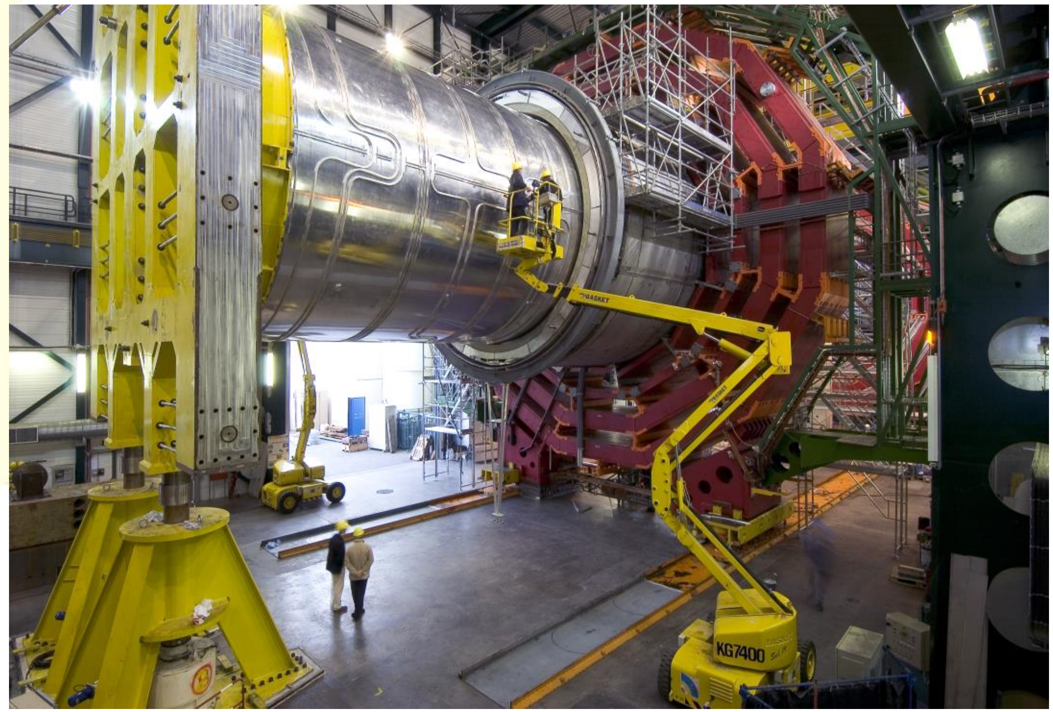
The goal is to identify and measure all particles produced at the interaction point…..

CMS solenoid - largest in the world (3GJ stored energy!)
cable and coil modules production/assembly



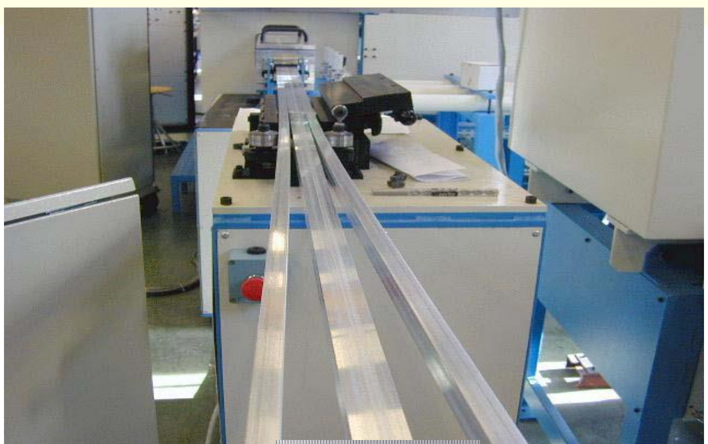
Design: H.Desportes. J.C.Lotin (Saclay)

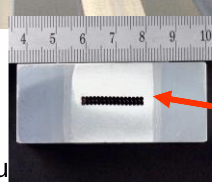
all 5 coil modules finished in 2004
assembly in CMS hall, Jan. 2005



Insertion of coil in vacuum tank in September 2005

Cost of coil and return yoke: 125 MCHF



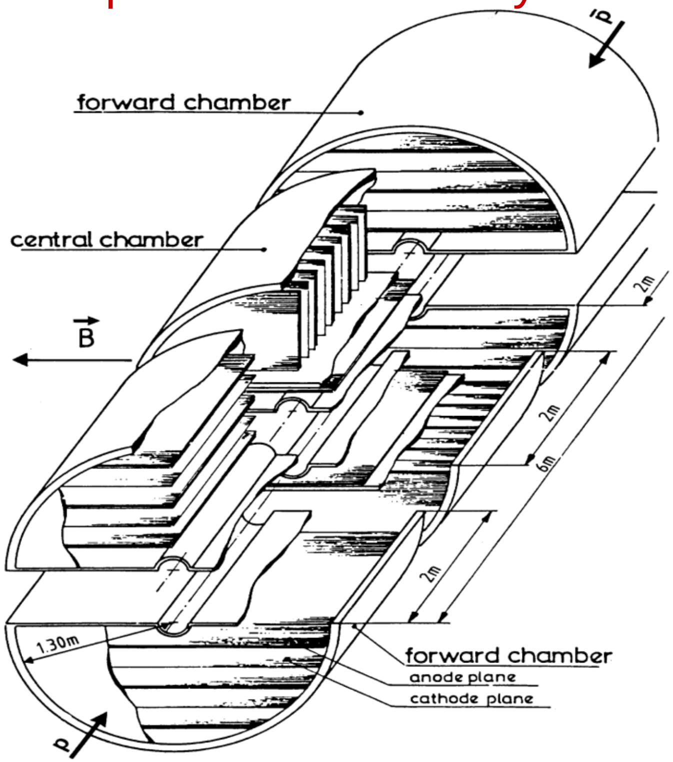


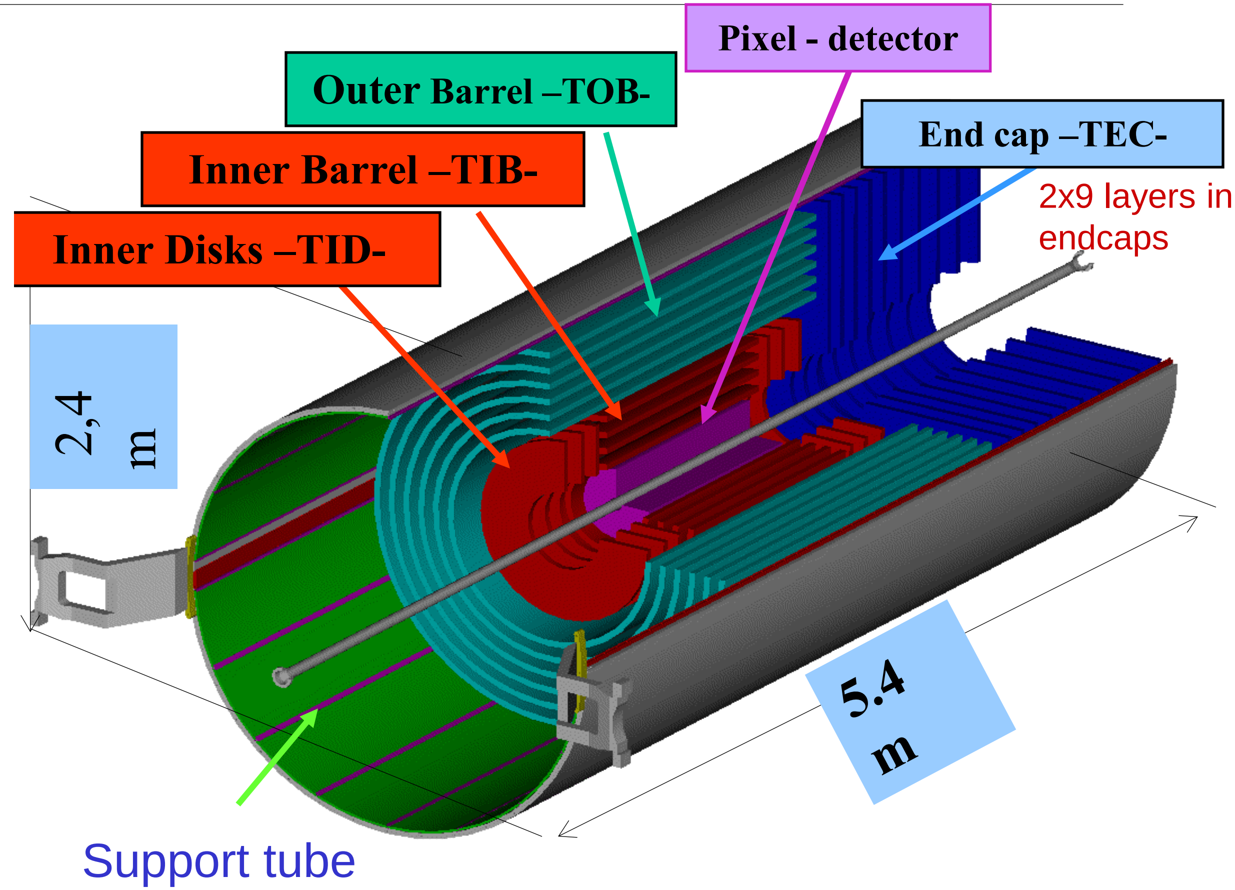
s.c cable: all 21 lengths (53 km) finished in 2003
(electron-beam welding)

Insert with super conductor

The UA1 tracker and the all-Silicon CMS tracker

The UA1 tracker was by far the most sophisticated in its days !!





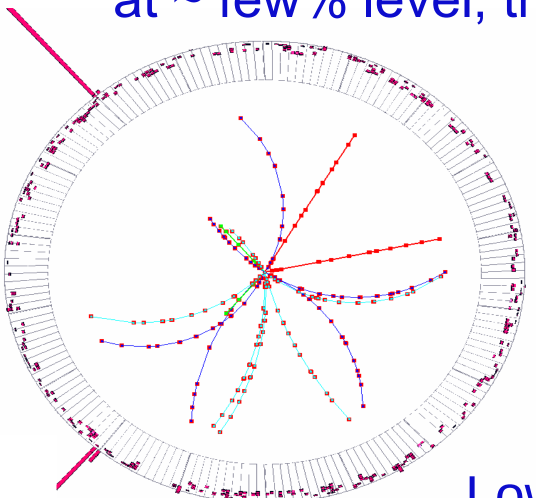
UA1 tracker: Imaging drift chamber,
6m long, 2.3m in diameter, 6176 sense wires, up to 180 hits per track,
maximum drift distance 18cm
i.e. 4μsec drift time,
Acceptance $|\eta| < 3.0$

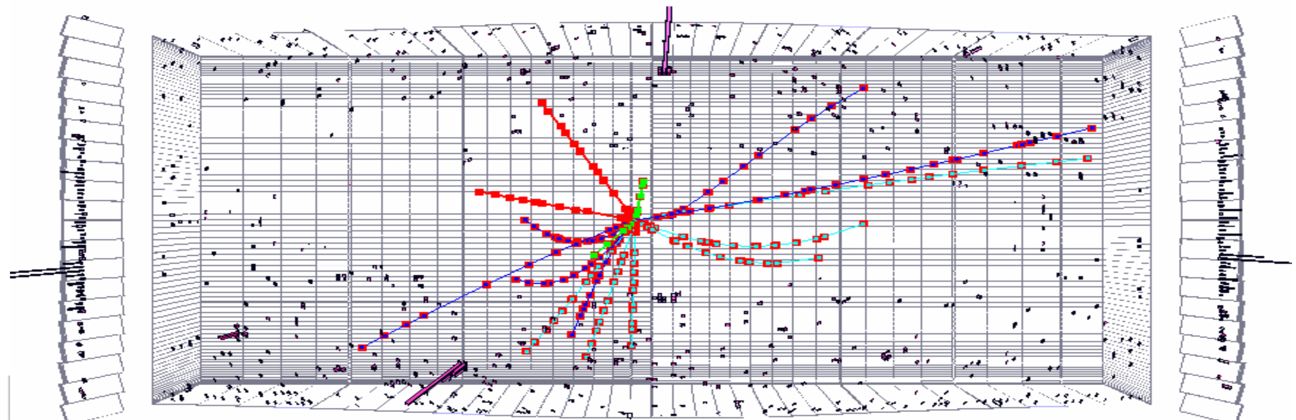
Factor ~10^4 in granularity!

210 m^2 of silicon sensors
~ 6,000 thin detectors (1 sensor)
~ 9,000 thick detectors (2 sensors)
10 million microstrips and
70 Million pixels

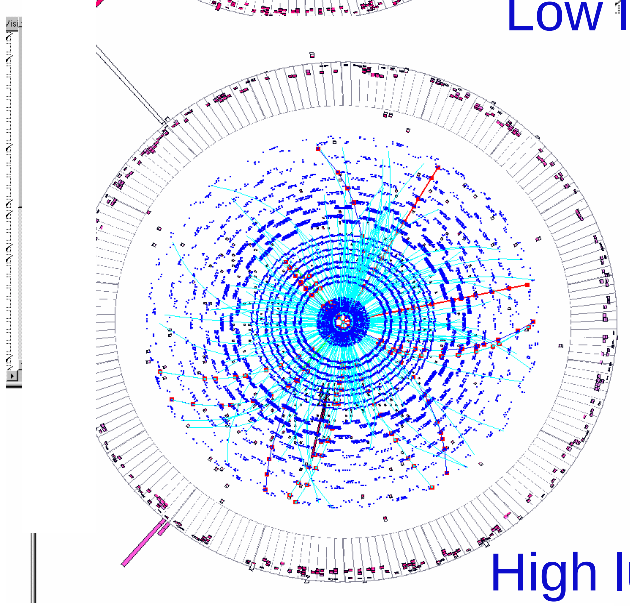
Need for granularity in a tracker at LHC - for pattern recognition

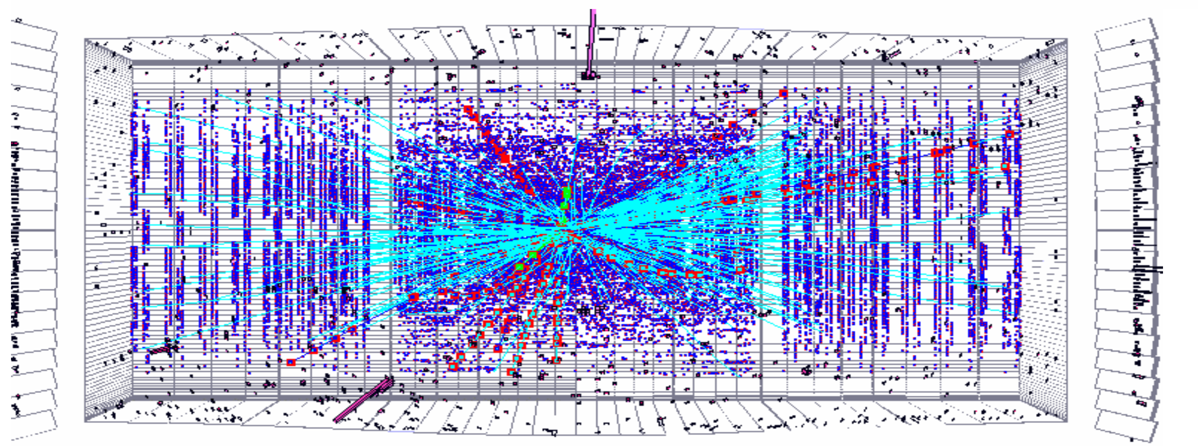
Good pattern recognition requires low occupancy of individual detectors, at ~ few% level, thus large number of small size detector channels, and fast….





Low lumi, $10^{32} cm^{-2} s^{-1}$





High lumi, $10^{34} cm^{-2} s^{-1}$ ← we MUST function in this regime!

Calorimeters in CMS - ECAL for e/γ HCAL essential for jets and E_t^{miss} measurements

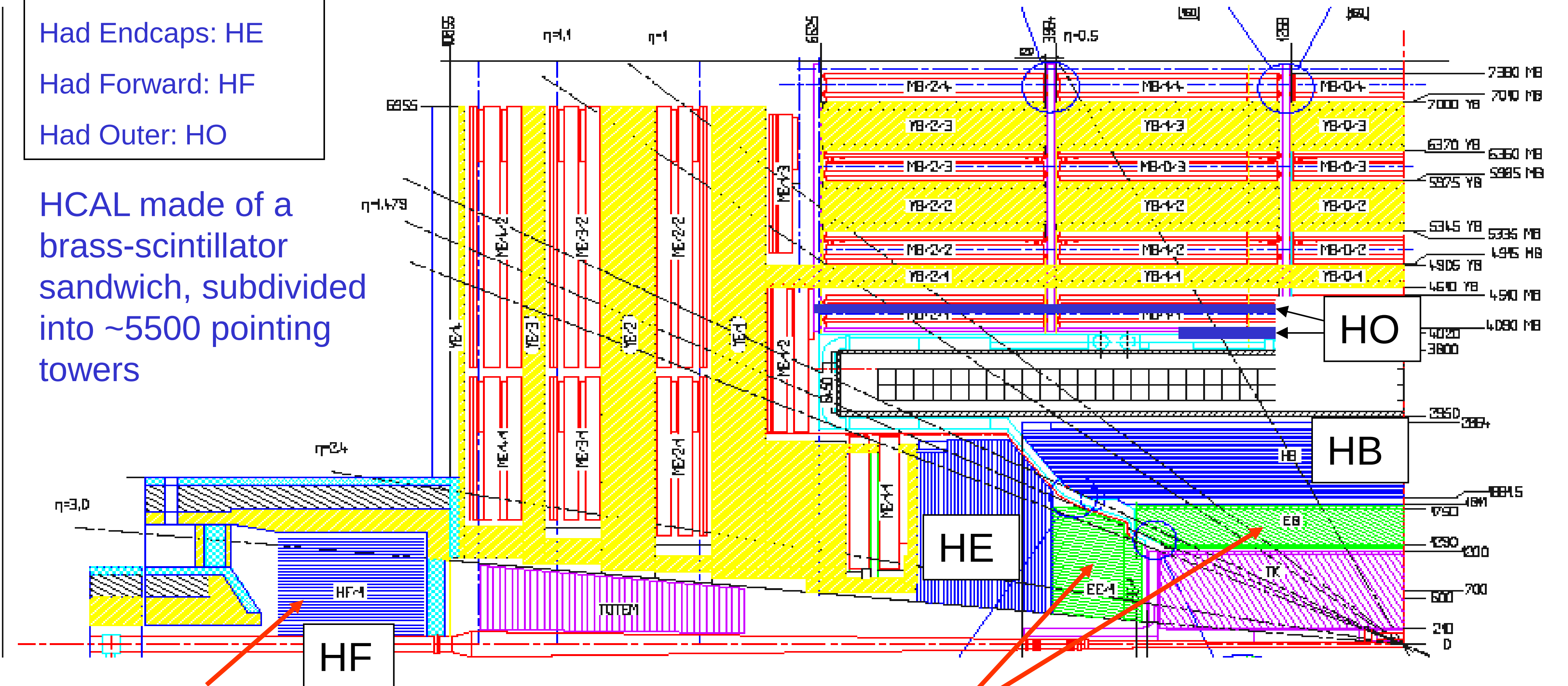
Had Barrel: HB

Had Endcaps: HE

Had Forward: HF

Had Outer: HO

HCAL made of a brass-scintillator sandwich, subdivided into ~5500 pointing towers

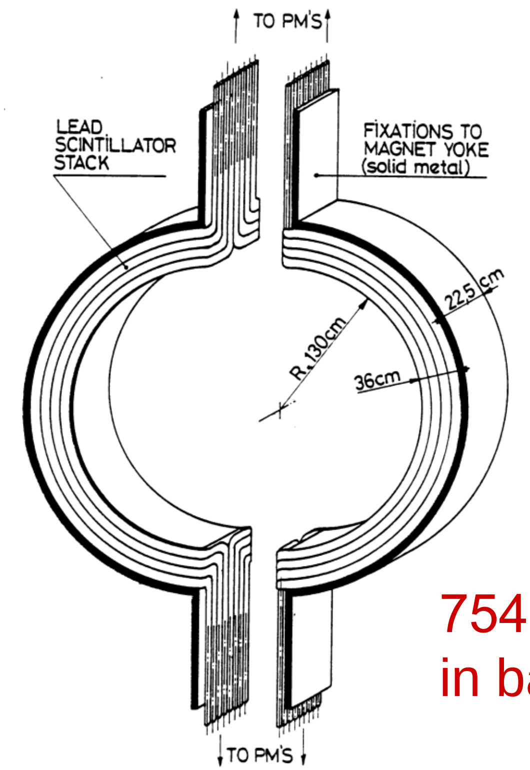


HF made of a quartz fibers in Fe (Cerenkov calo)

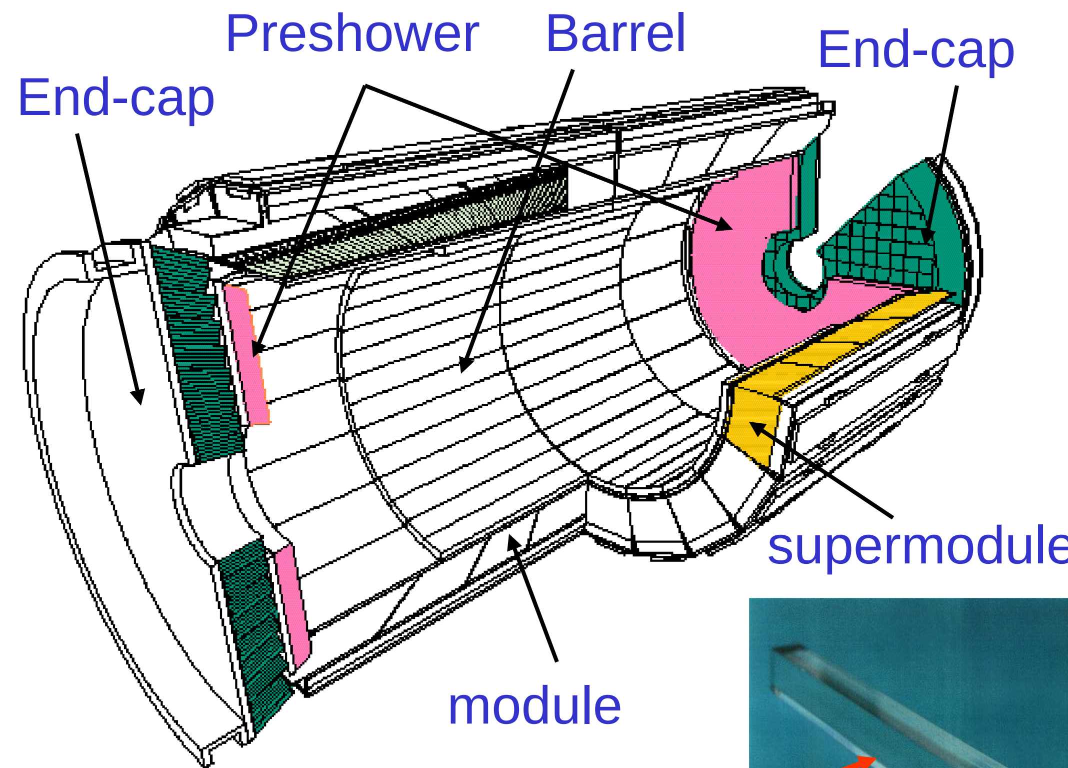
ECAL ultimately made of 76.000 pointing scintillating crystals

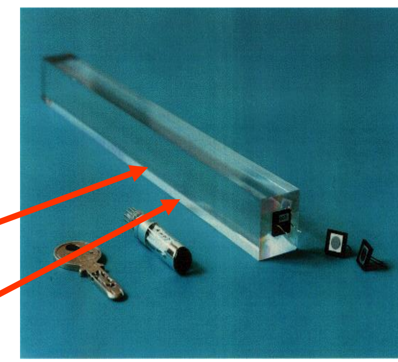
ECAL initial design with Pb-scint sandwich “Shashlik”-type, may reappear in ~ 2018 endcap!

From the UA1 electromagnetic calorimeter to the crystal ($PbWO_4$) calorimeter of CMS



754 PM's in barrel





A TeV em shower contained in a crystal of $24x2x2cm^3$

ECAL (2x24 gondolas)
Scint.-Pb sandwich, 1.2mmPb/1.5mmSci
$\Delta\phi\Delta\eta$= 180º x 0.14; $27X_0$ deep, four segments in depth + 2x32 radial sectors in end-caps
ECAL acceptance: $|\eta| < 3.0$
Resolution for electrons/photons:
$\Delta E/E \approx 14\%/\sqrt{E} + 3\%$(sust)

Factor $\sim 10^2$ in granularity!

74.000 crystals
L_{rad} = 9mm, R_{mol} = 2cm ($\Delta\eta$ = 0.014)
~10nsec response read out with avalanche photo-diodes in barrel and VPT's in the end-caps

Cartridges from Soviet Black-Sea Navy 75/150mm guns for CMS HCAL brass-scintillator calorimeter!

~ 800 tons recoverd this way!

QuickTime™ and a
decompressor
are needed to see this picture.

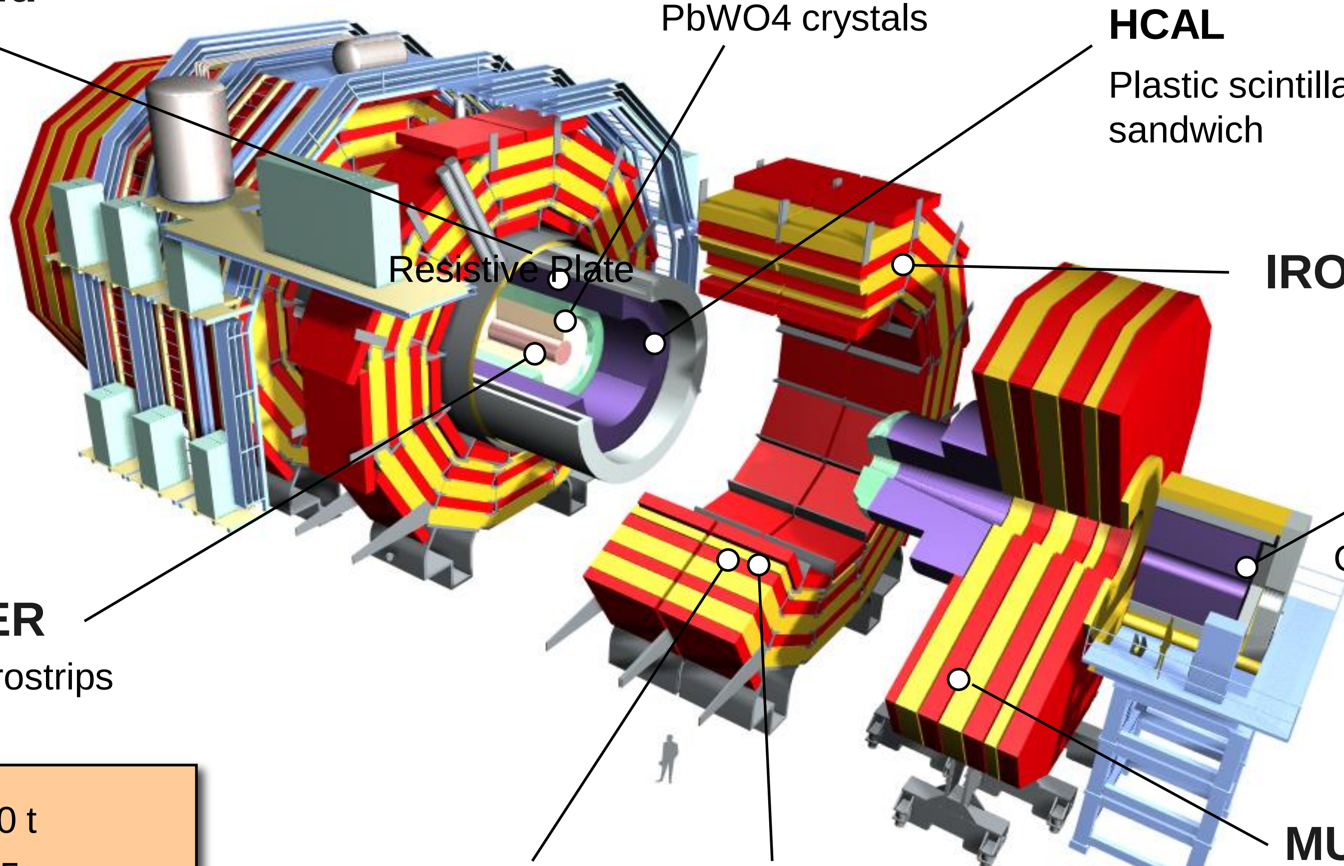
In UA1 there were 220 HCAL towers,
in CMS 5500 towers, 25 times more….

Half HCAL in CMS surface assembly hall

Brass from Russia, melted in Bulgaria, cut and shaped in a Spanish shipyard in El Ferrol according to USA/Fermilab design/specifications; scintillator from Ukraina, Belarus and USA, readout elements (HPD's) from Holland, calibration/monotoring system from USA……

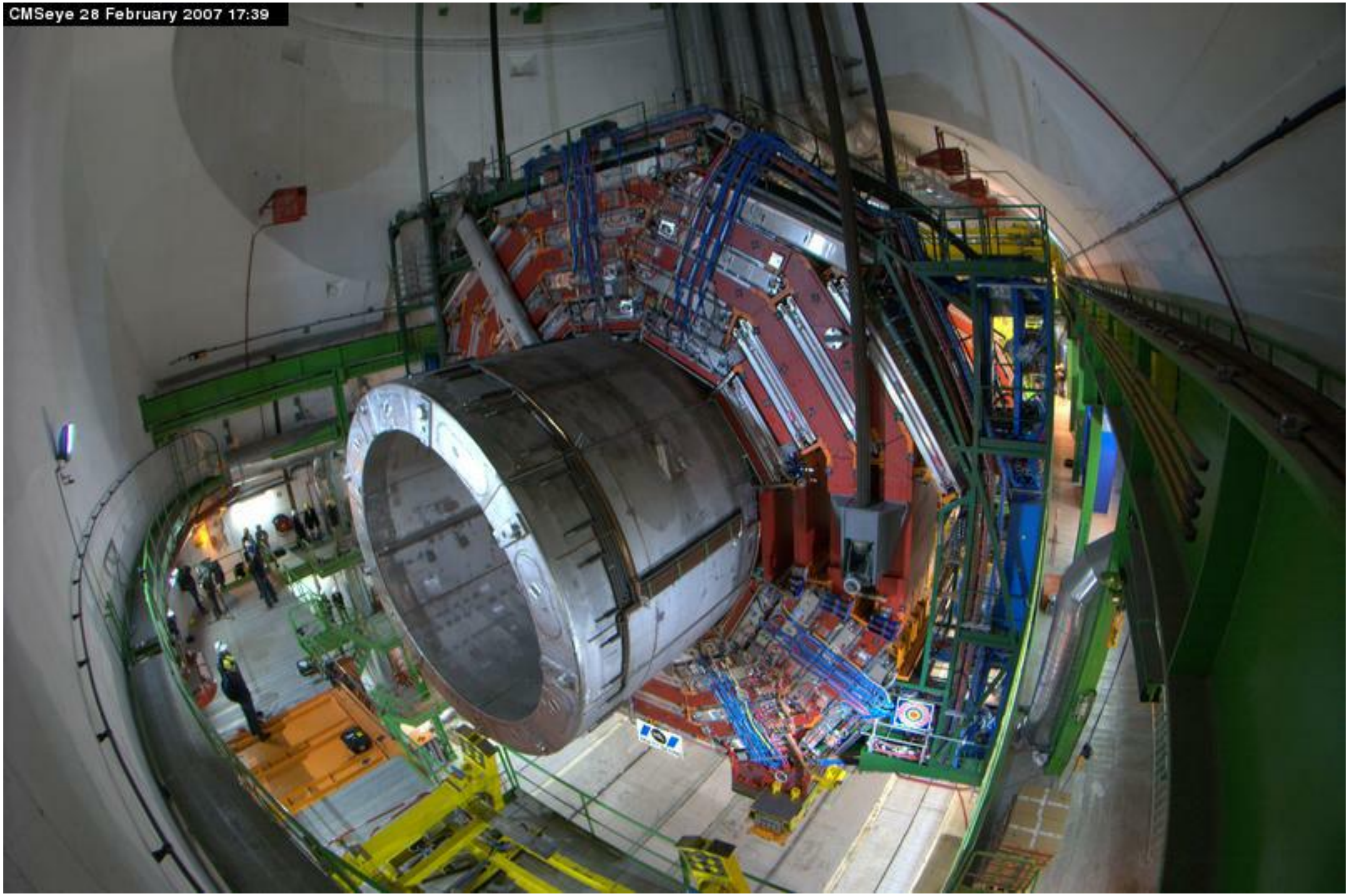
The CMS detector, modular design - major components - assembled on surface then lowered

modular design: A. Herve



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

From the construction phase of CMS: a delicate operation, YB0 emerging from the shaft into the underground experimental cavern, Feb. 28-th 2007



The central piece of CMS, of 2500 tons on four cables after a trip of 100 meters in 10 hours! Clearance of ~20 cm in the shaft!

Title CMS in all its splendor

QuickTime™ and a
decompressor
are needed to see this picture.

ATLAS: A Toroidal LHC ApparatuS
largest particle physics detector ever built

outer air-core
~0.5Tesla toroids

length: 45m
height: 25m

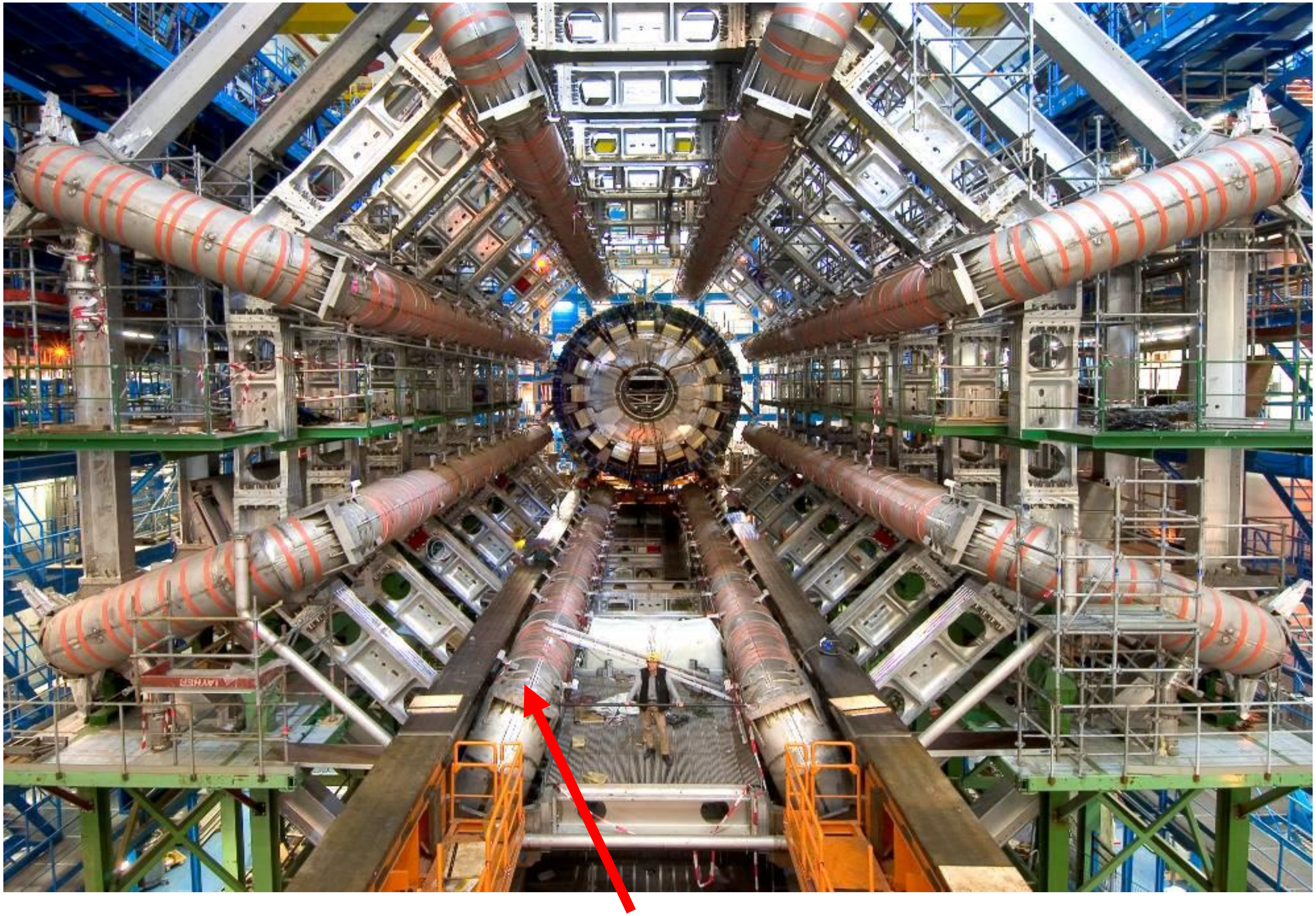
26m x 5m

QuickTime™ and a
decompressor
are needed to see this picture.

inner 2Tesla
solenoid

“Founding fathers”: D. Fournier, D. Froidevaux, P. Jenni,. F. Dydak, M. Virchaux…….

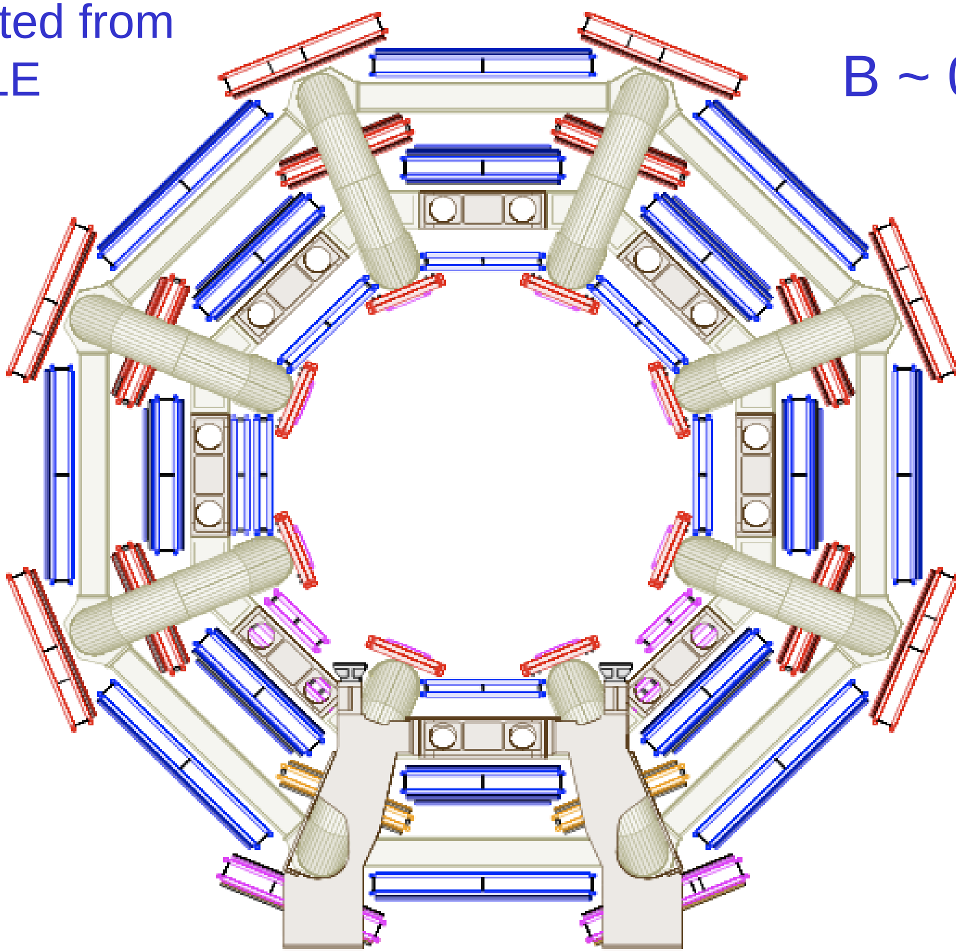
ATLAS - during construction phase
assembled directly in the underground exp. cavern



Superconducting air-core toroids   26m x 5m, 20kA, B ~ 0.5T

ATLAS barrel toroid - field shape

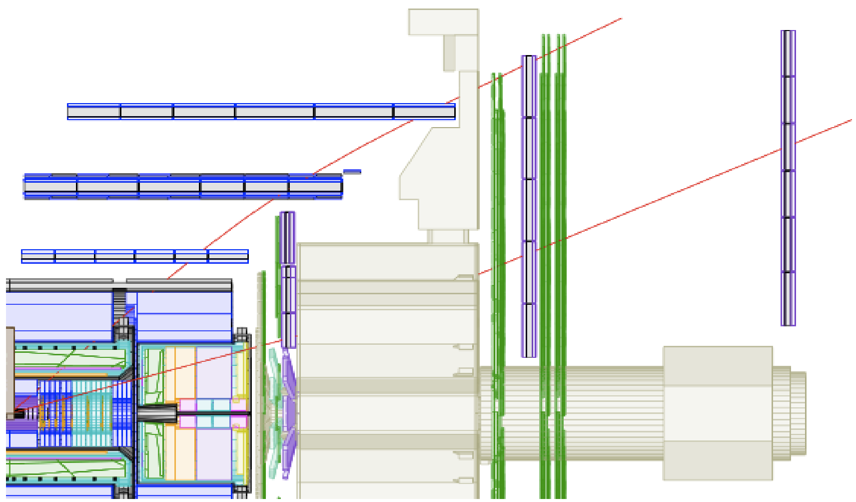
inherited from
EAGLE



B ~ 0.5T

QuickTime™ and a decompressor are needed to see this picture.

Design of toroids: H. Desportes, J.C. Lotin (Saclay) and H. Baynam (Rutherford)



Superconducting air-core toroids
20 kAmpers current; cost ~150 MCHF

ATLAS - calorimetry, ECAL, HCAL

ATLAS calo inherited
from EAGLE

HCAL: steel &
scintillator tiles

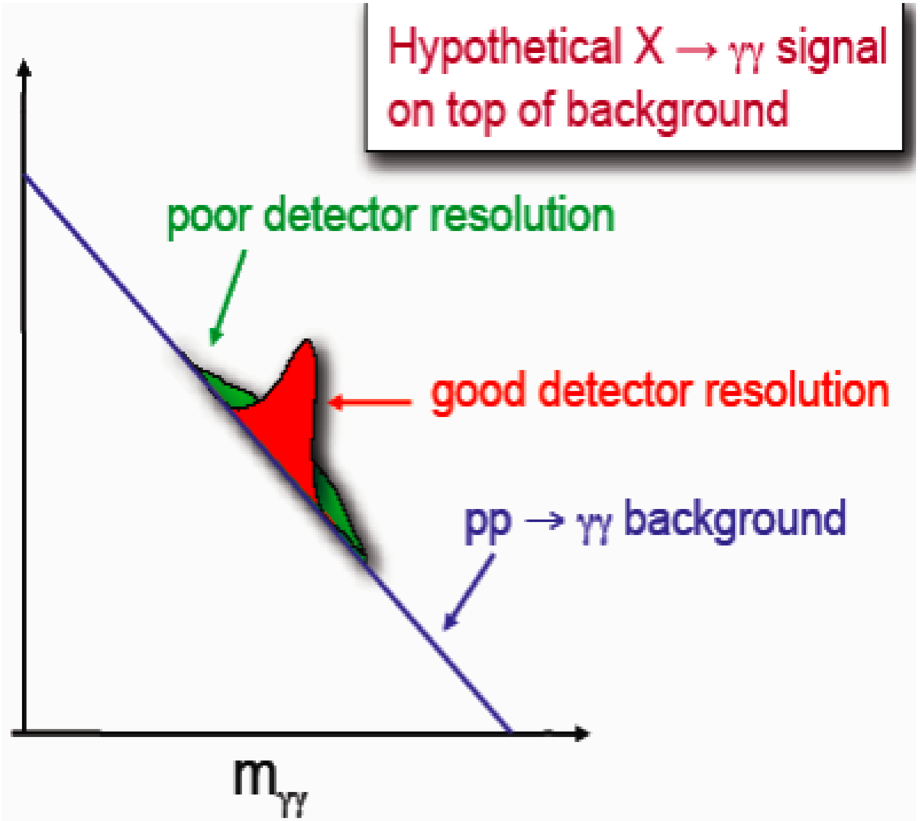
QuickTime™ and a
decompressor
are needed to see this picture.

thin 2Tesla
solenoid just
in front of ECAL
used as a
presampler
converter

The design of the LAr cryo-ECAL is particularly original

LAr chosen for its radiation hardness and uniformity of response

Higgs decay to 2 photons influenced choice of ECAL in both ATLAS and CMS, aiming at ~1% resolution at ~100 GeV



$$M^2 = 2E_1E_2(1-\cos\theta)$$

$$dM/M \propto d\cos\theta/\cos\theta$$

$$dM/M \propto dE/E$$

QuickTime™ and a decompressor are needed to see this picture.

this is what we had in mind…..

γ_1= 86 GeV

QuickTime™ and a decompressor are needed to see this picture.

γ_2= 56 GeV

Higgs signal vs background S/B ~ 1/15, with ~1GeV ie ~1% mass resolution

ATLAS - LAr “accordeon geometry”ECAL

ECAL module

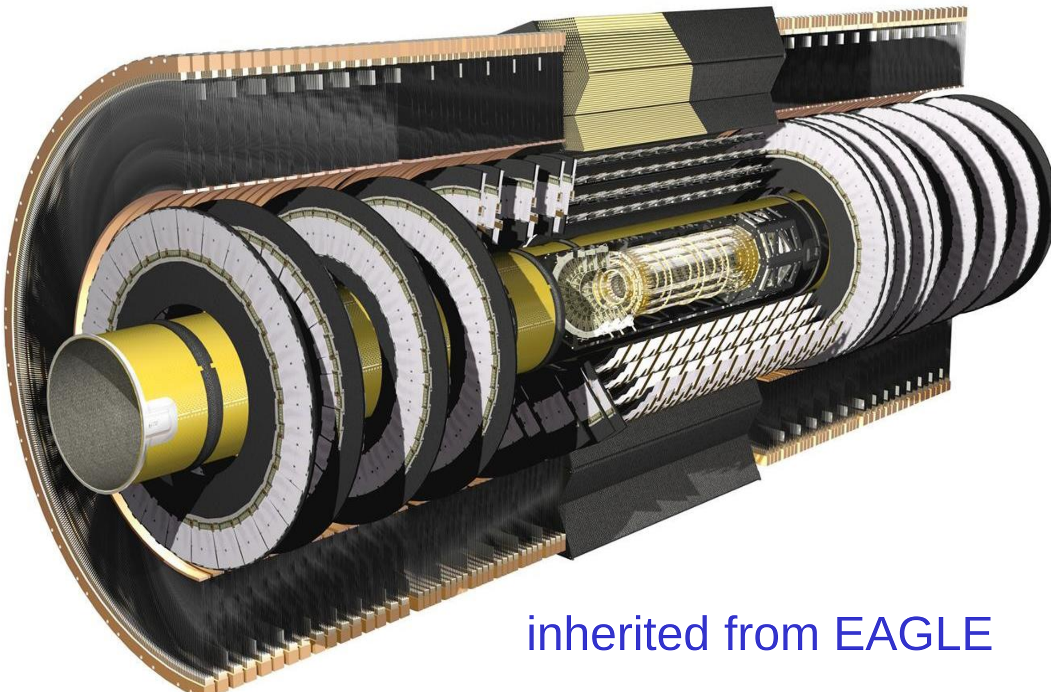
QuickTime™ and a
decompressor
are needed to see this picture.

Simulation of an electromagnetic shower development in the ATLAS LAr ECAL

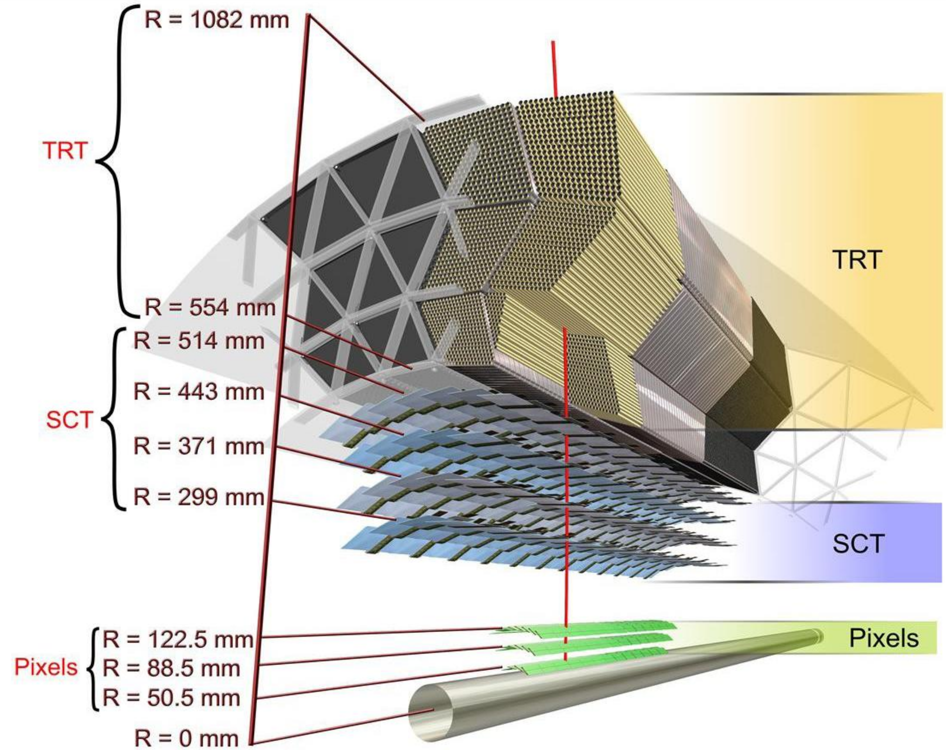
QuickTime™ and a
decompressor
are needed to see this picture.

this geometry (Pb + electrodes) allows fast signal extraction (~30nsec), mandatory with 25nsec bunch crossings at the LHC

ATLAS tracker



inherited from EAGLE



Inner detector:

3 pixel layers followed by 4 microstrip layers followed by 4mm diameter straw-tube layers - with tracking and TRD functions

- Si-pixel detector 10^8 channels,15 μm resolution
- 50000 straws in barrel, ~300000 in endcaps

~ 30 to 40 points per track, ~120 μm resolution

Tracker of different concept than the CMS one: numerous lower resolution points vs fewer high precision points; one of the motivations was study of CP violation in $B^0_d \rightarrow K^0_s \psi \rightarrow \pi^+\pi^- \mu\mu/ee$……..

straw-tubes for pattern rec. TRD functions

LHC operation in 2012: pile-up, up to ~ 30 (50 nsec bunch spacing)

- a major challenge for the trackers

QuickTime™ and a
decompressor
are needed to see this picture.

$Z \rightarrow \mu\mu$ event from 2012 data in ATLAS with 25 reconstructed vertices

In 2015 we wish to have 25 nsec bunch crossing time to reduce pile-up the aim is ultimately (by ~2020) to reach $5x10^{34}cm^{-2}s^{-1}$ implying ~200 pile-ups! New trackers altogether will be required for both ATLAS and CMS with improved performance and radiation hardness

ATLAS - installation phase,
insertion of the endcap HCAL in the toroid

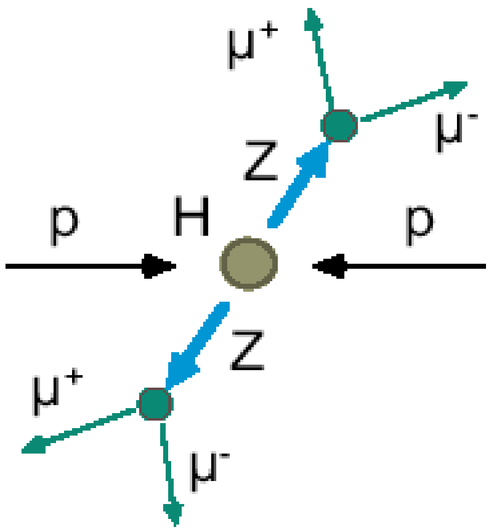
Muon chambers

QuickTime™ and a
decompressor
are needed to see this picture.

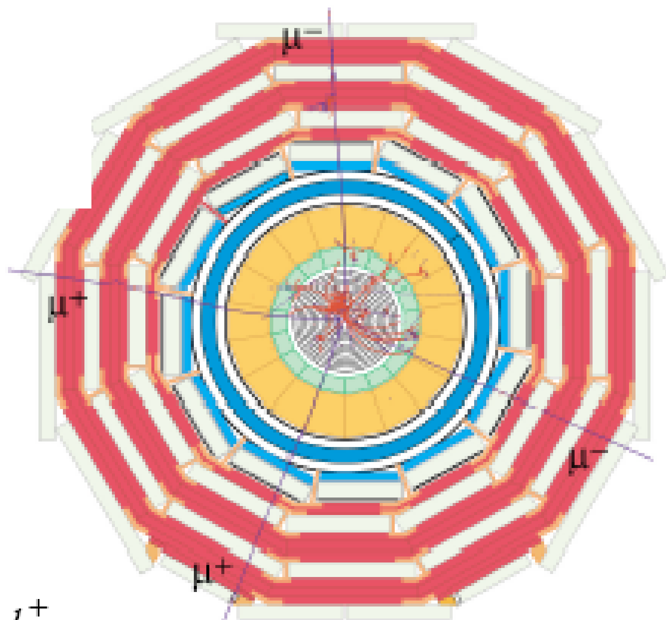
Very demanding alignment system with ~30μm precision over tens of meters!

Production and detection of the Higgs in CMS - if m_H ~ 150 GeV ($H \longrightarrow ZZ/ZZ^* \longrightarrow$ 4 leptons)

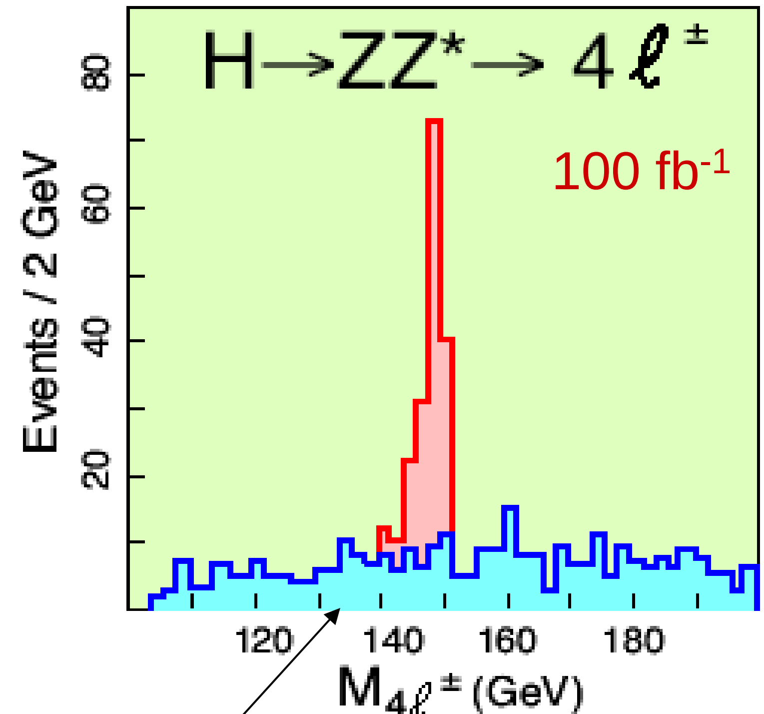
- as expected in 1992/93!!



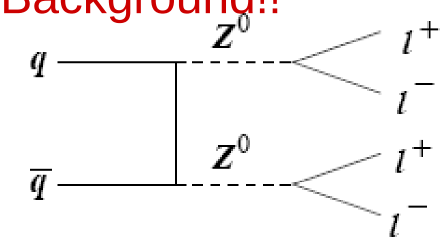
Expectations for signal and background if the Higgs has a mass ~ 150 GeV
Similar situation in the mass range ~ 130 - ~ 400 GeV



M_{Higgs} = 150 GeV



Electroweak ZZ Background!!



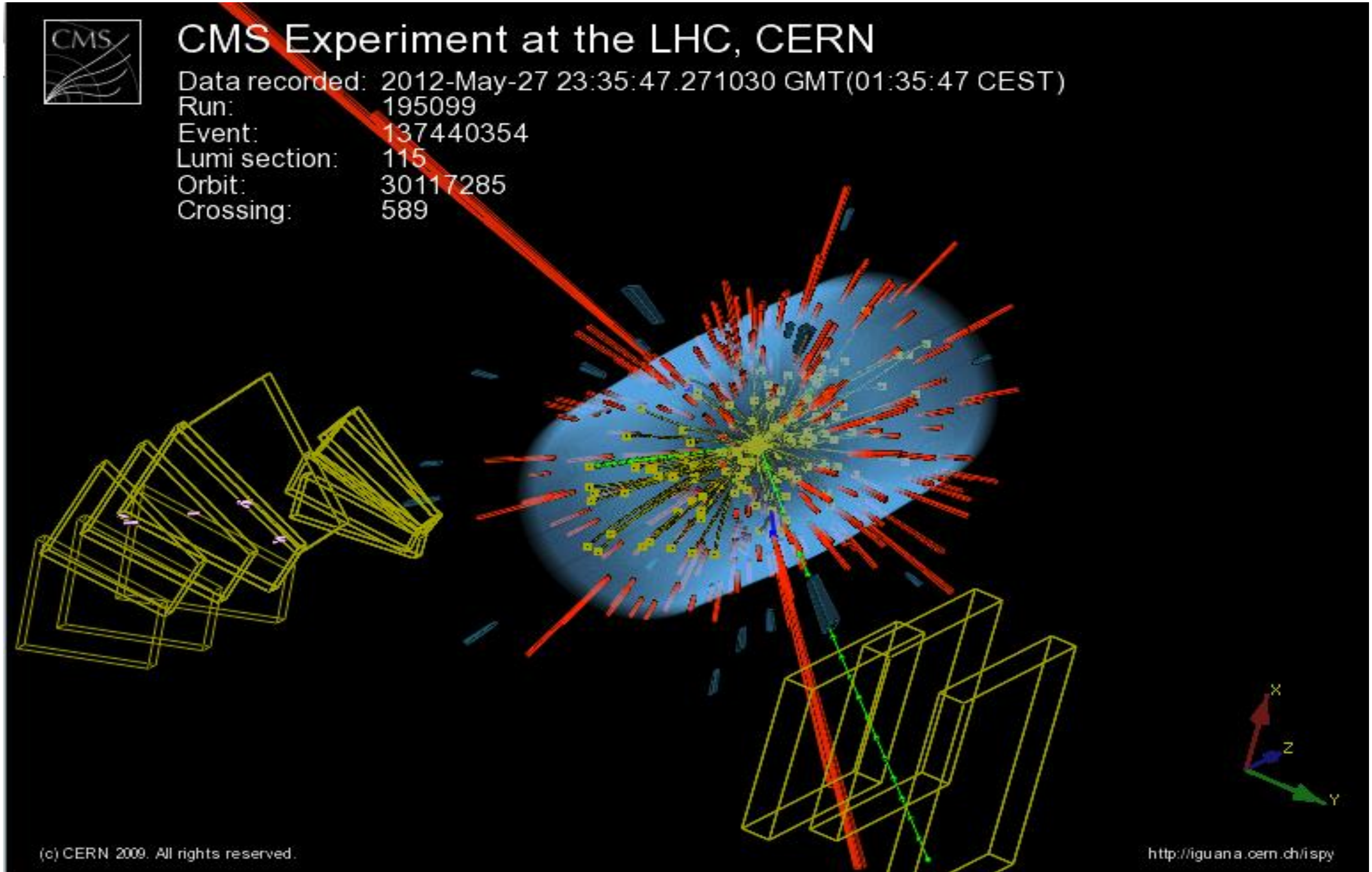
Electroweak ZZ background

$H \rightarrow \mu\mu\mu\mu$ candidate in ATLAS, $\sqrt{s}$ = 8TeV, with $m(4\mu)$ = 125.1GeV, May 2012

QuickTime™ and a
decompressor
are needed to see this picture.

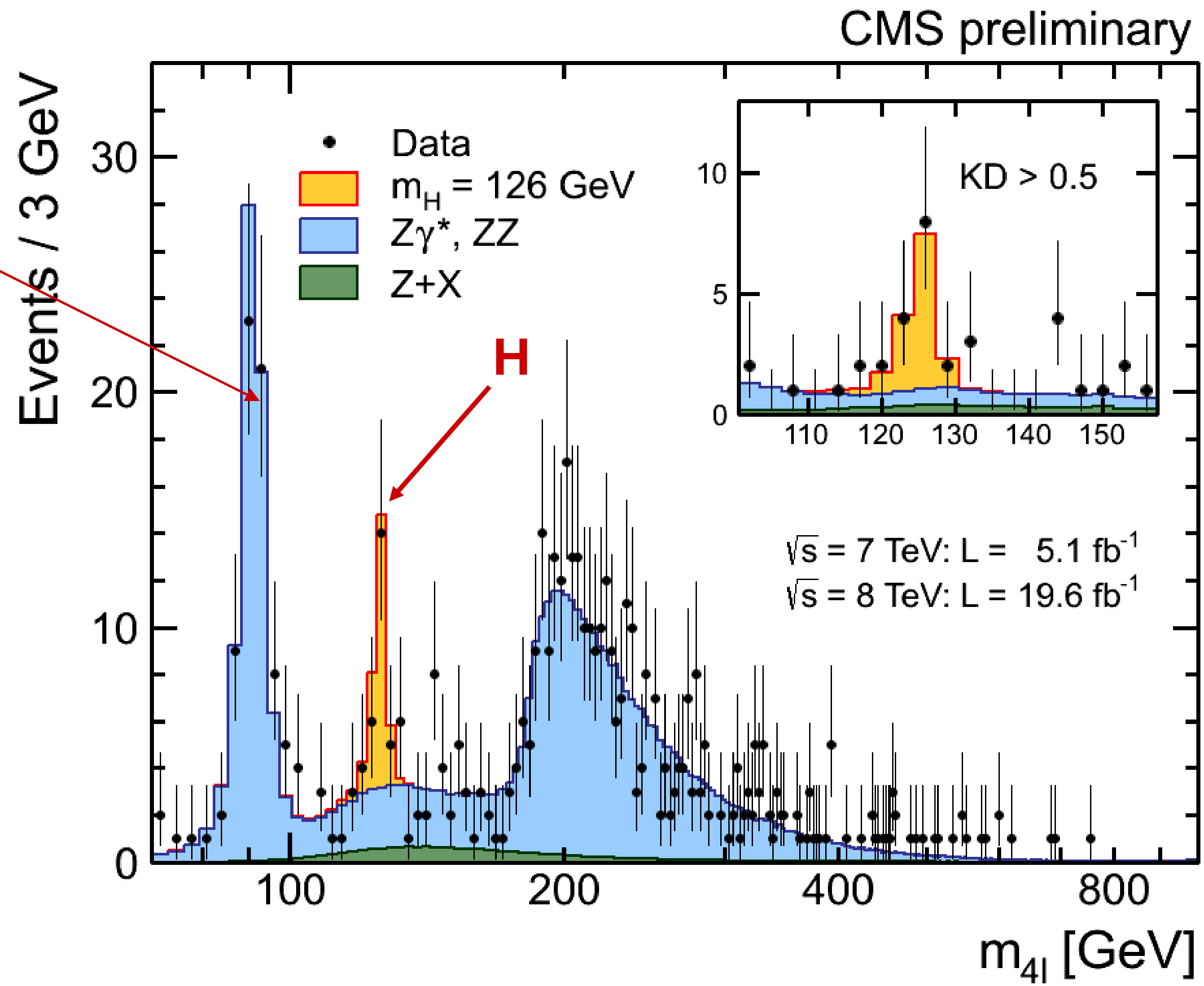
p_T (muons)= 36.1, 47.5, 26.4, 71 .7 GeV, m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices

H → ZZ → eeμμ candidate event in CMS, √s = 8 TeV, data of June 2012



Higgs → 4 leptons, CMS, full statistics, Feb. 2013, full mass range

QuickTime™ and a
decompressor
are needed to see this picture.



QuickTime™ and a
decompressor
are needed to see this picture.

$H \rightarrow \gamma\gamma$ candidate in CMS

QuickTime™ and a
decompressor
are needed to see this picture.

$$m^2_{\gamma\gamma} = 2\ E_1 E_2\ (1 - \cos\theta_{12})$$

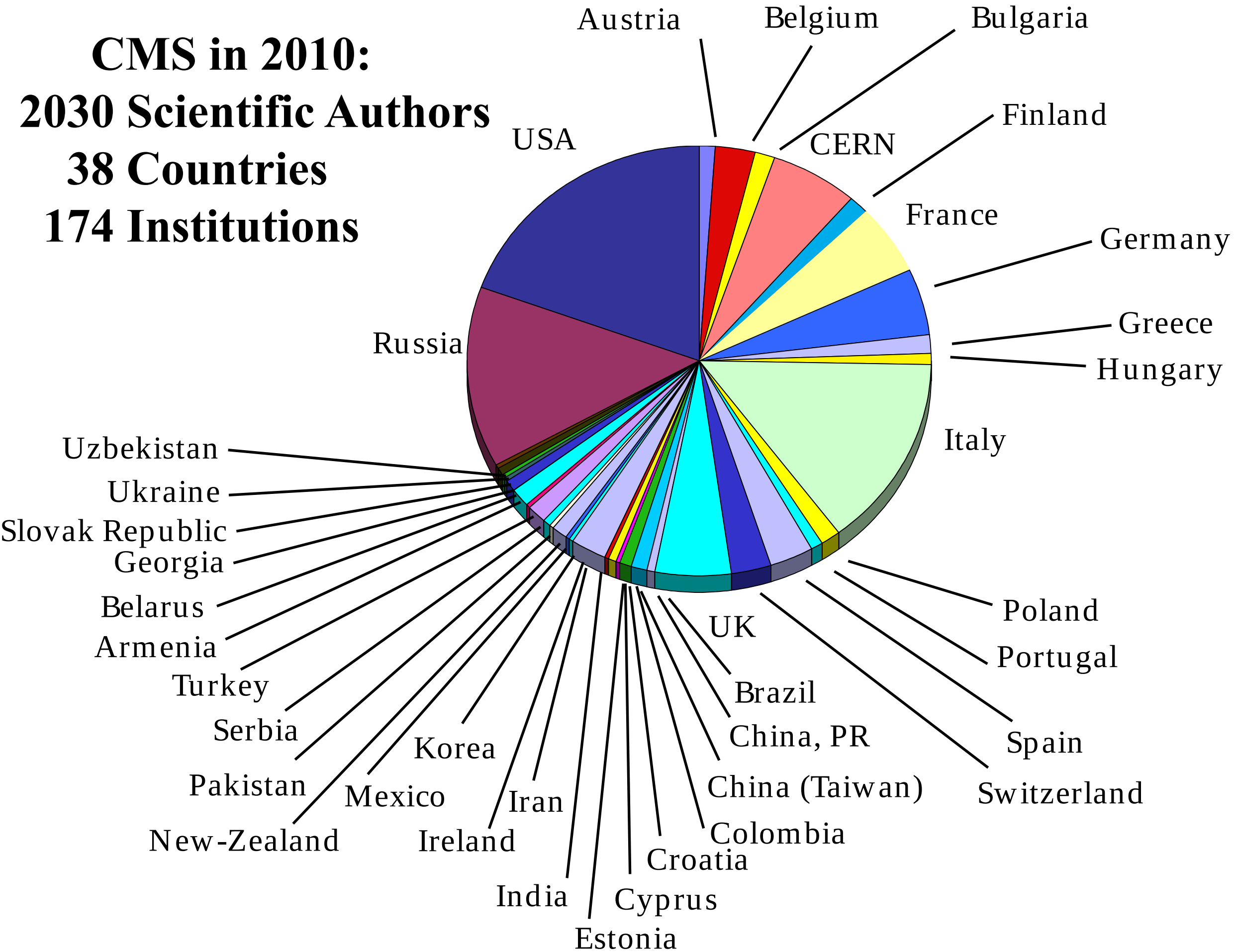
H → γγ, ATLAS, full statistics 2011+ 2012, mid-2013

~450 events in the signal region

QuickTime™ and a
decompressor
are needed to see this picture.

If these totally globalized experiments did not stall as Babel's Tower did, was due to…….

CMS in 2010:
2030 Scientific Authors
38 Countries
174 Institutions



QuickTime™ and a decompressor are needed to see this picture.

…….everybody using the metric system (no inches, feet, yards, pounds, imperial gallons etc)……..and the use of english!

LHC experiments are really international endeavors! CMS for example:

QuickTime™ and a
decompressor
are needed to see this picture.

Flux return yoke
Germany,Russia,Chekia,Japan

Hadron calorimeter
USA,Russia,Ukraina,Turkey,Iran,
India,Hungary

Solenoid magnet
France,Italy,Switzerland,Finland,
Croatia,UK,Japan,CERN

Tracking system
Germany,Italy,France,Belgium,USA
Finland,Switzerland,CERN…..

Electromagnetic calorimeter
Russia,China, France,Italy,Japan,
UK,Switzerland,Greece,Taiwan

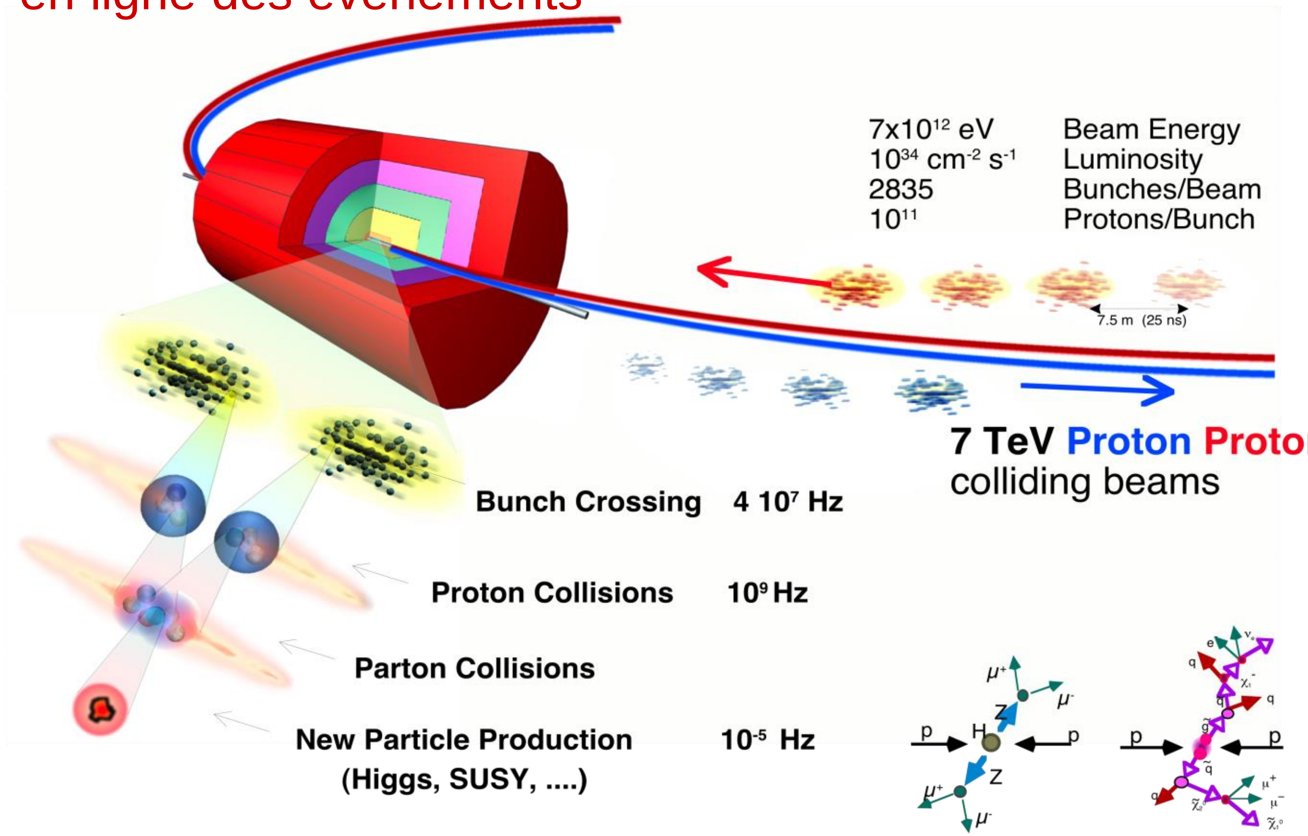
Support tube
Support tube

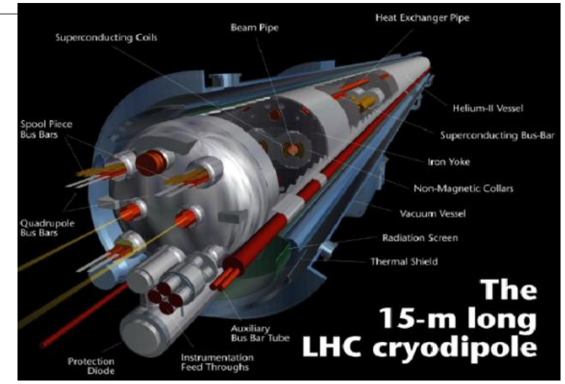
Muon system
Italy,Germany,Spain,USA,Russia,
Bulgaria,Korea,Pakistan,CERN

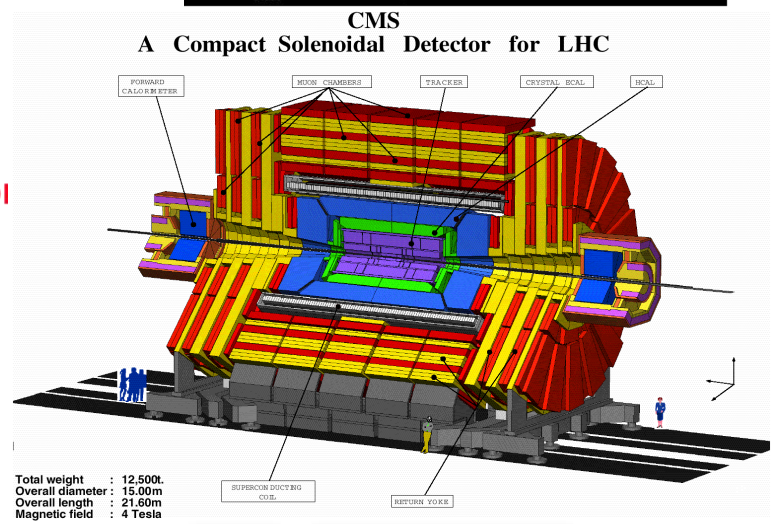
Support system
China,Pakistan,USA

Le système accélérateur - détecteur - informatique de sélection des données

nécessité d'un système de déclenchement et de présélection en ligne des événements

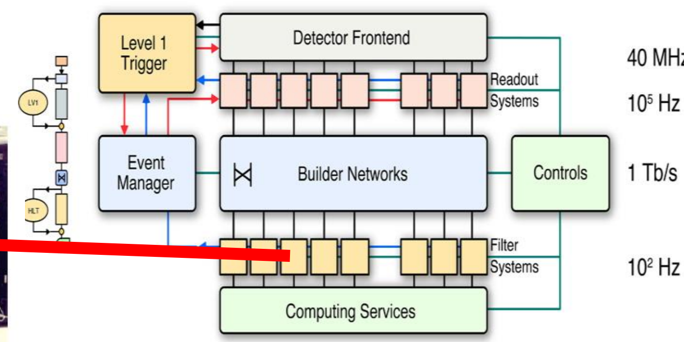






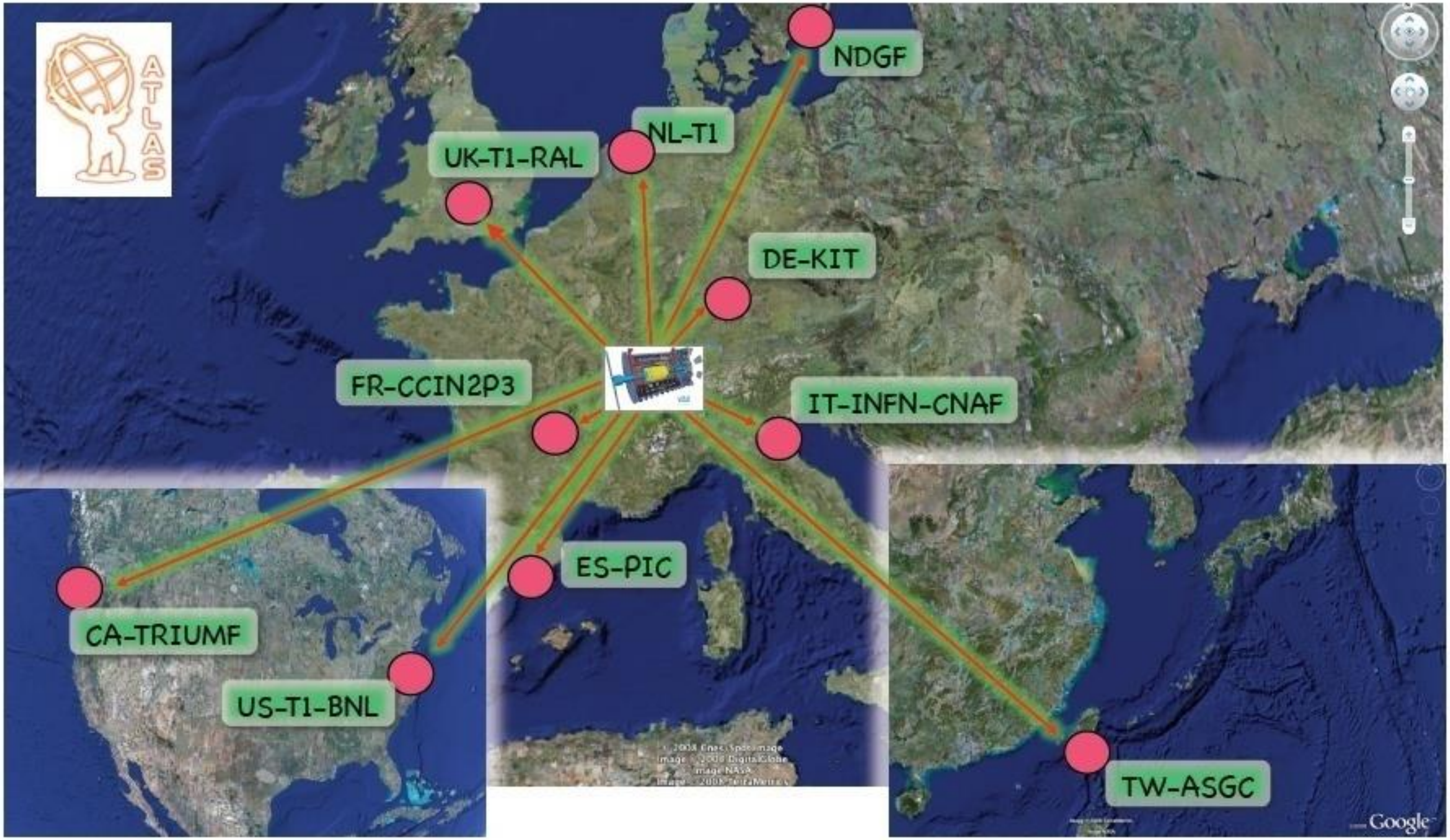
Selection of 1 event in 10,000,000,000,000

5000 processors



D. Denegri; Summer students program, CERN, August 2013

wLCG Grid: Tier-0 and the 10 ATLAS Tier-1s



The experiments produce ~15 Millions of Gigabytes of data/Year (~20 millions of CDs!) The analysis of LHC data require ~100,000 today fastest PC.

The LHCb experiment -
dedicated to c-and b-physics studies, CP violation in B^0_s in particular

Collider mode detector - thus taking advantage of full cms collision energy and b-production cross section of` ~350 μb, but of a "fixed target experiment " configuration, to take advantage of predominantly forward b production

particle identification

Early "fixed target" versions (σ ~1μb) by:
L. Camilleri (gas jet)
G Carboni (bent crystal)

Interaction point

Beam

QuickTime™ and a decompressor are needed to see this picture.

Beam

Vertex detector

Tracking, magnet

Calo Muon

Founding fathers: T. Nakada, P. Schlein, ….

Fully instrumented within 1.9 < η < 4.9; excellent vertex resolution and tracking, particle identification; trigger: p_μ > 3 GeV/c, $p_{T\mu}$ > 0.5 GeV/c, $M_{\mu\mu}$ > 2.5 GeV/c2

LHCb reconstruction of vertices, primary, secondary, tertiary

Excellent track and impact parameter resolution of ~10 microns allows efficient secondary and tertiary vertex reconstruction

β

QuickTime™ and a decompressor are needed to see this picture.

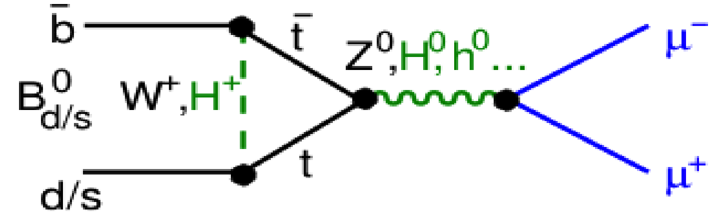
Reconstruction of all tracks in the event

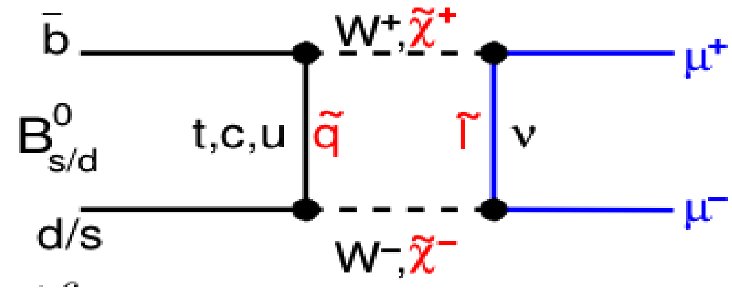
Reconstruction only of tracks associated with B production and subsequent B and charm decays

LHCb has particle identification over broad momentum range with Ring Imaging Cherekov detectors (essential K/π separation) needed for ex. in $B^0_s \rightarrow \phi\psi \rightarrow K^+K^-\mu\mu$, $B \rightarrow D_sK^{+-}$, $B^0_d \rightarrow \pi\pi, \pi K, KK$ etc.

Simulation of a rare decay $B^0_s \to \mu^+ \mu^-$ event in LHCb

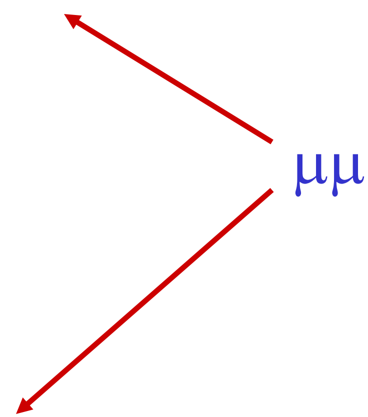
Search for rare modes, such as $B^0_{s,d} \to \mu\mu$ can reveal new physics present as virtual particles, in quantum corrections, before it could be produced kinematically as real particles





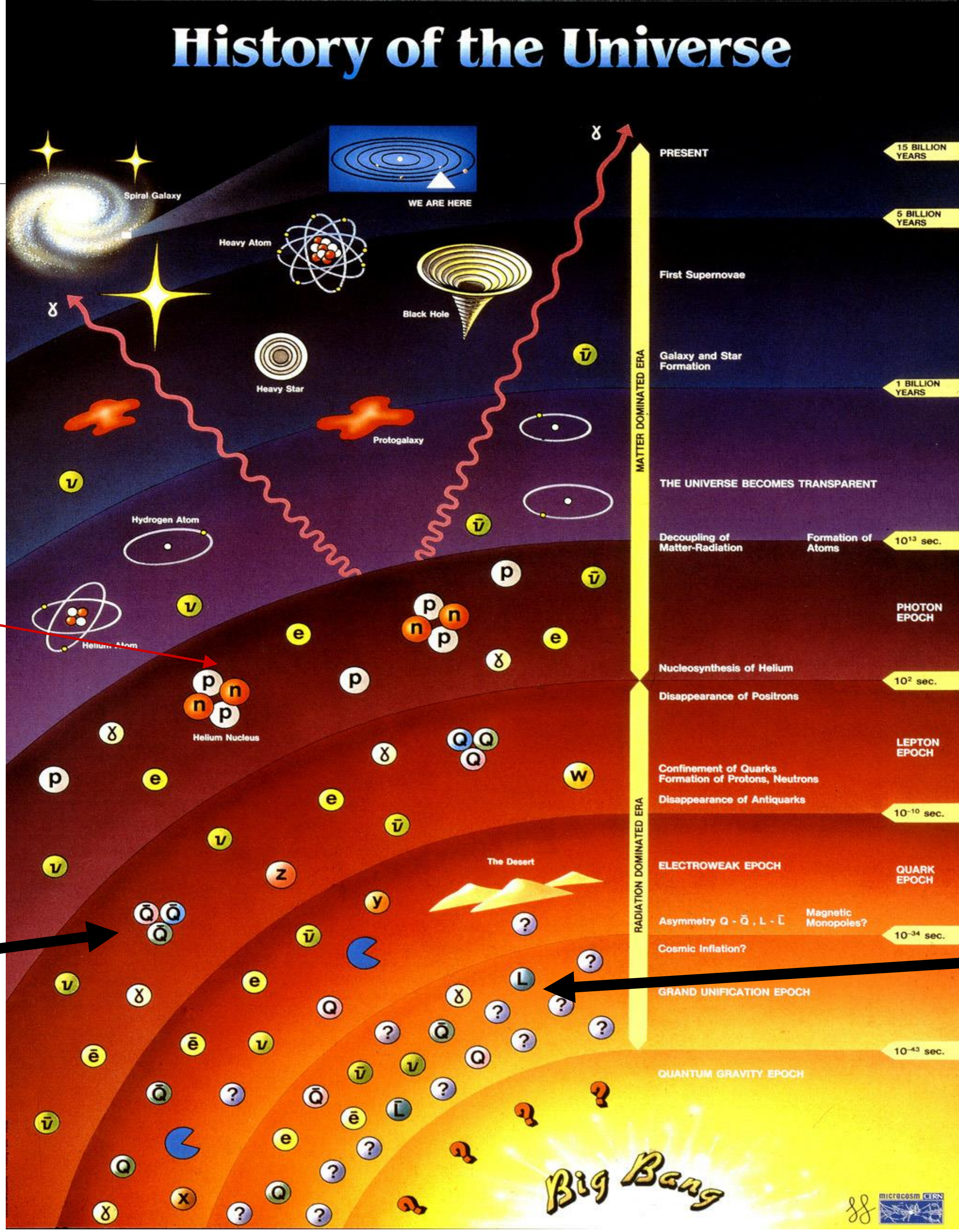
Expected SM $BR(B^0_s \to \mu\mu) = 3.2 \times 10^{-9}$

QuickTime™ and a decompressor are needed to see this picture.



Heavy ion collisions at the LHC

Evolution of structures



History of the Universe within the Big-Bang Model and connection with particle physics

minutes after Big Bang nucleo-synthesis era

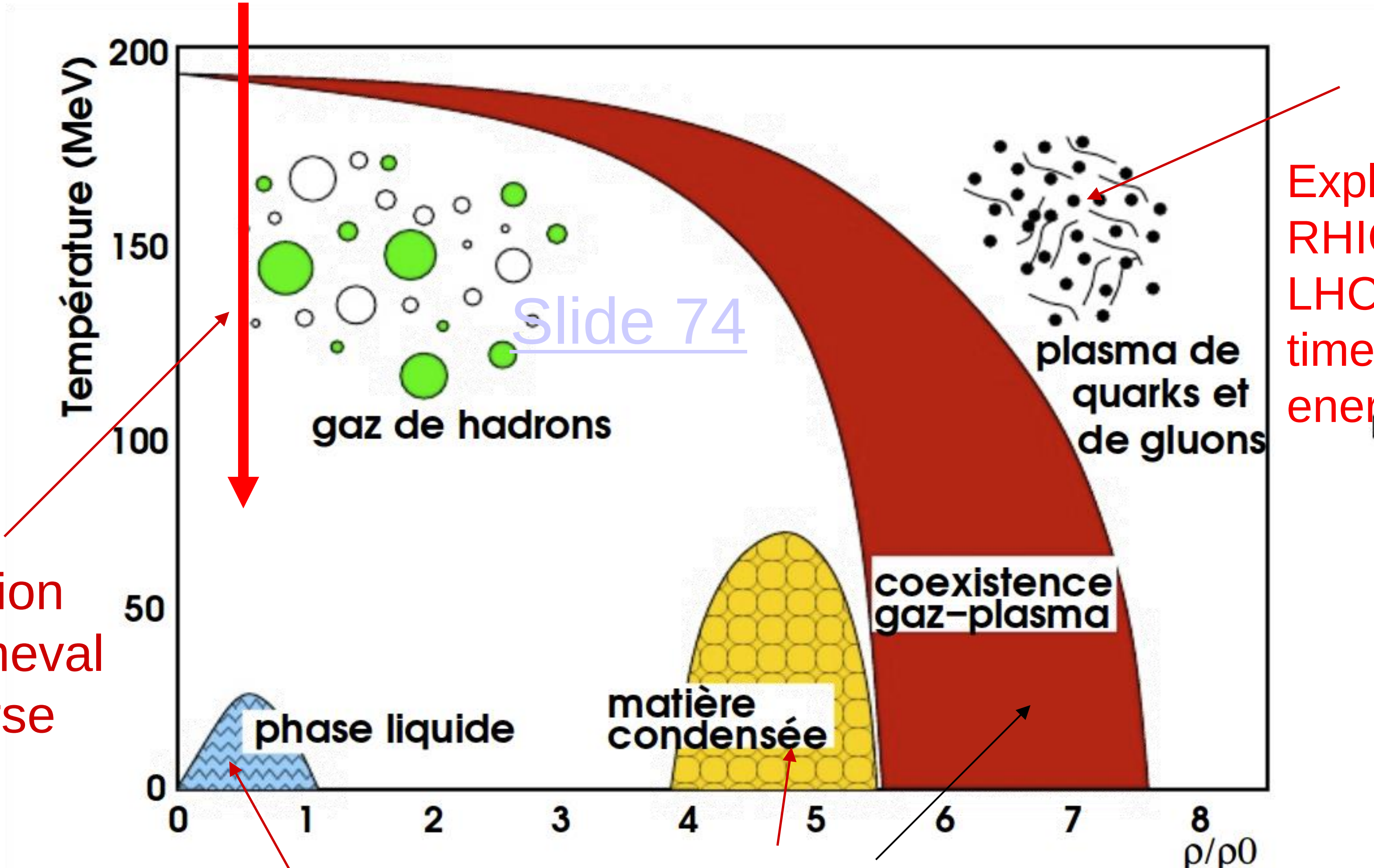
10^{-6}sec after Big Bang (hadronization era)

Heavy ions regime at LHC ALICE, CMS,ATLAS

At the beginning there were only elementary particles!

LHC -pp- probes the era at ~ 10^{-12-15} sec after the Big Bang (Electroweak era) CMS, ATLAS

Phases of strongly interacting matter - connection with LHC



QGP

Explored at RHIC and now LHC, with ~ 30 times greater energy density

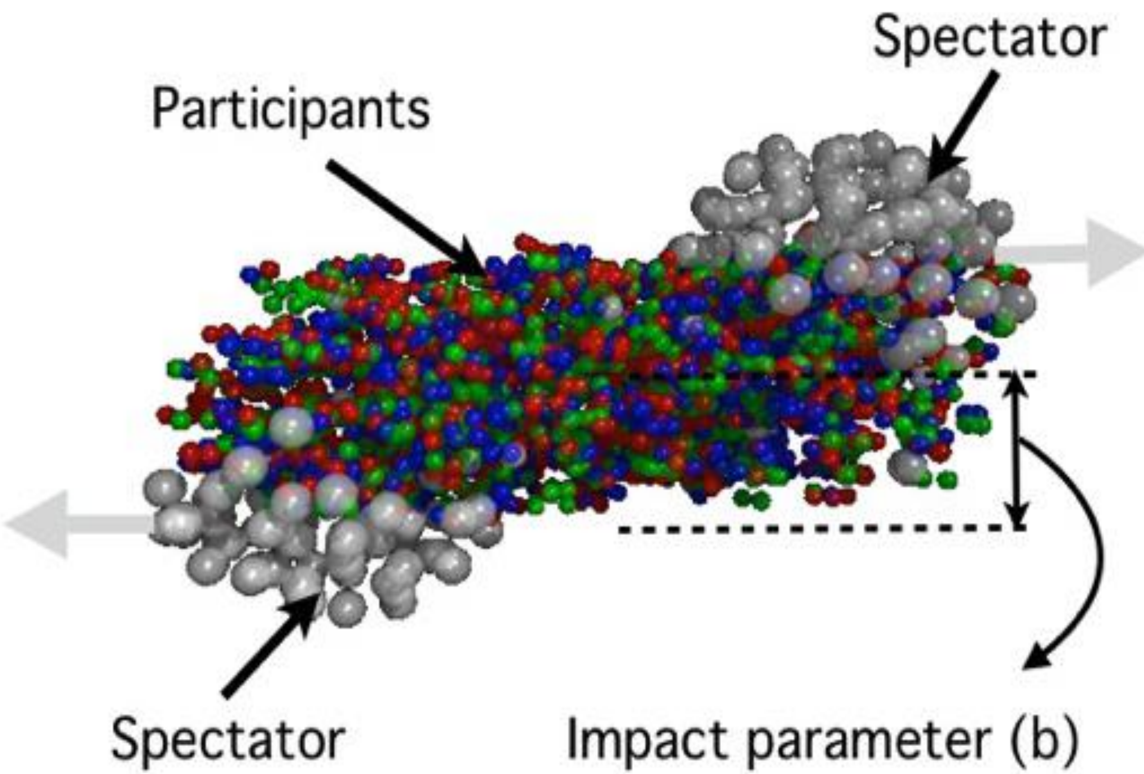
Evolution of primeval Universe

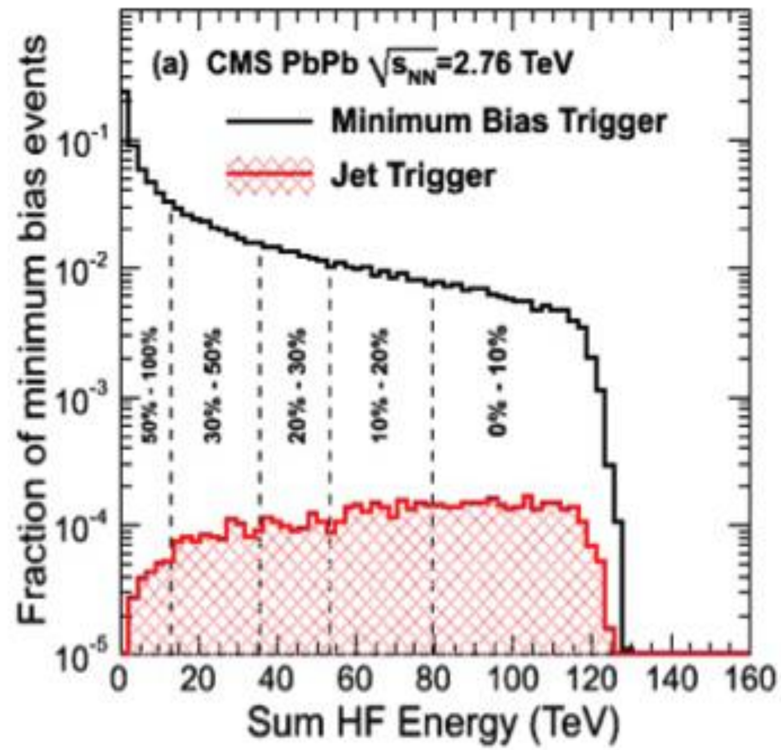
nuclei

neutron stars? quasi-cristaline structure

density relative to nuclear density

Heavy ion collisions - classification of events according to centrality of collision

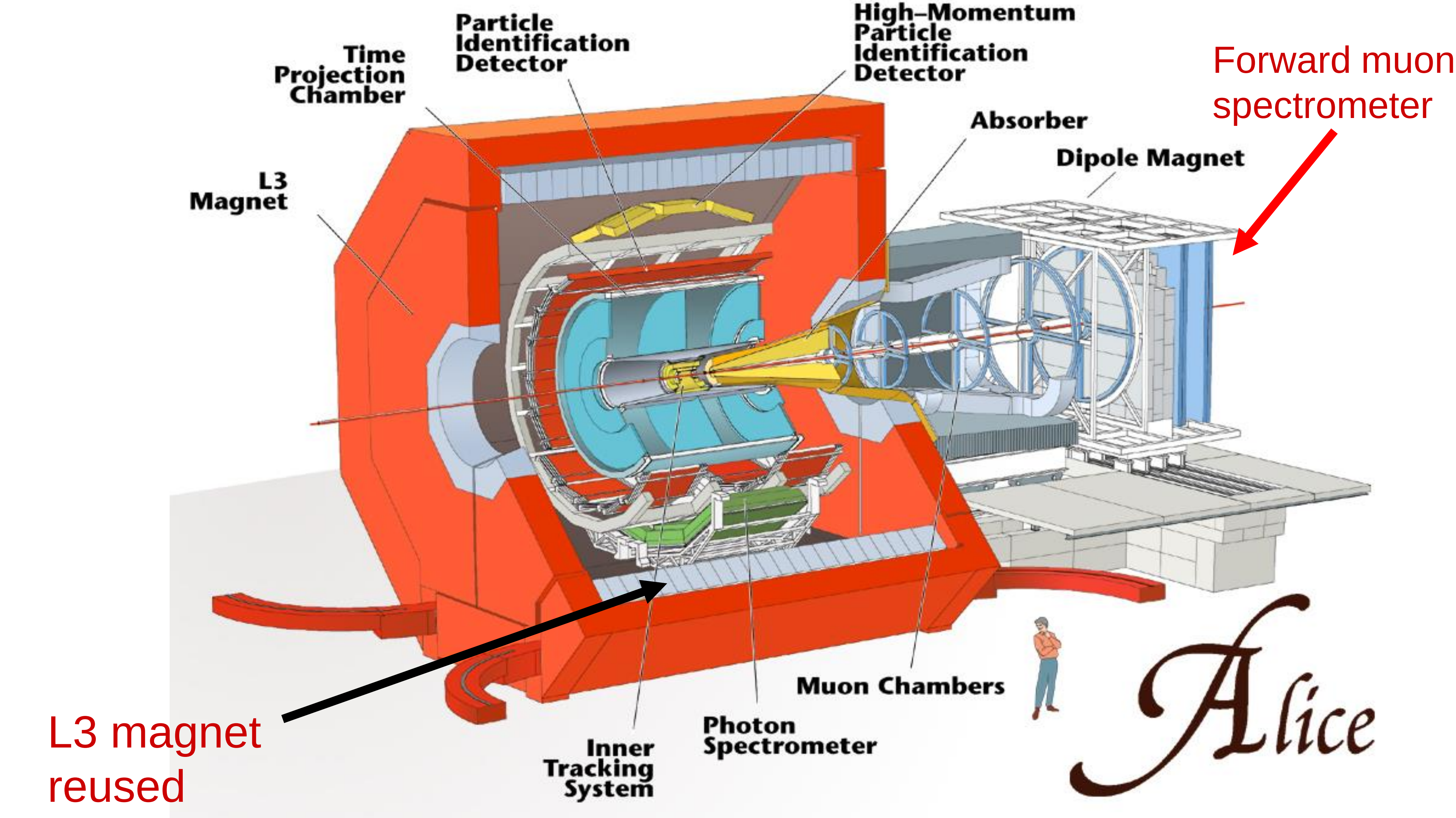




Events are classified by 0-5,5-10,10-30,30-50,50-90% in this measurement

ALICE - optimized for Heavy Ion collision studies

in low to medium p_t range, particle identification



Tracking in ALICE - optimized for large particle densities and particle identification

initially (~1990/95) theoretical expectations were for up to 8000 charged particles per unit of rapidity ($dn_{ch}/d\eta$)! This was a major worry in CMS…..

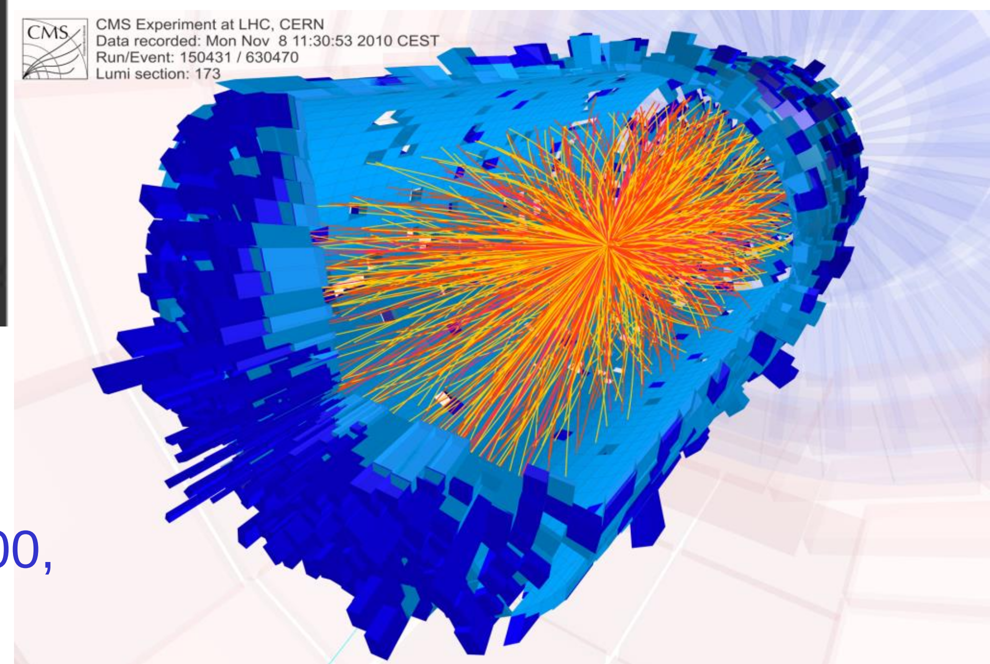
QuickTime™ and a
decompressor
are needed to see this picture.

ALICE TPC

First Pb-Pb collisions in ALICE, Nov. 8th 2010

RHIC at BNL, started in 2000,
It showed that (extrapolated) $dn_{ch}/d\eta$ will be much less than initially feared….

Pb-Pb collision in CMS



CMS tracker could sustain up to ~ 5000 particles per unit of rapidity!
It turned out that in reality there were ~1800, thus very successful HI program possible

QGP properties - ALICE
thermal photon emission from the QGP

Production cross-section of photons in central Pb-Pb collisions

QuickTime™ and a decompressor are needed to see this picture.

Photons shining from the plasma (thermal emission) - from the $PbWO_4$ ECAL of ALICE

QCD

The LHC Quark-Gluon Plasma is the hottest man-made matter

Operational efficiency of all these detectors is exceptional; example of CMS operation in 2011!

ATLAS and CMS including trigger/DAQ - are of unprecedented complexity!

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decompressor
are needed to see this picture.

enough of history and the past,
some recent results, issues and perspectives…..

$B^0_s \rightarrow \mu^+ \mu^-$ - first observation in LHCb in March 2013 followed by CMS in July 2013

LHCb March 2013

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are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

a hotly contested issue!!

CMS July 2013

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decompressor
are needed to see this picture.

Signals observed in 2013 by both LHCb and CMS entirely compatible with the SM expectation for a BR of ~ 3.2 x10^{-9}
(CMS: $3.0^{+1.0}_{-0.9}$ x 10^{-9} significance: ~4.8σ)

…….thus no signs (yet) from this type of study of physics beyond the SM,
next episode will be the search for B^0_d in 2015/16

$Z' \rightarrow l^+l^-$ searches in ATLAS and CMS, $\sqrt{s}$ = 8 TeV

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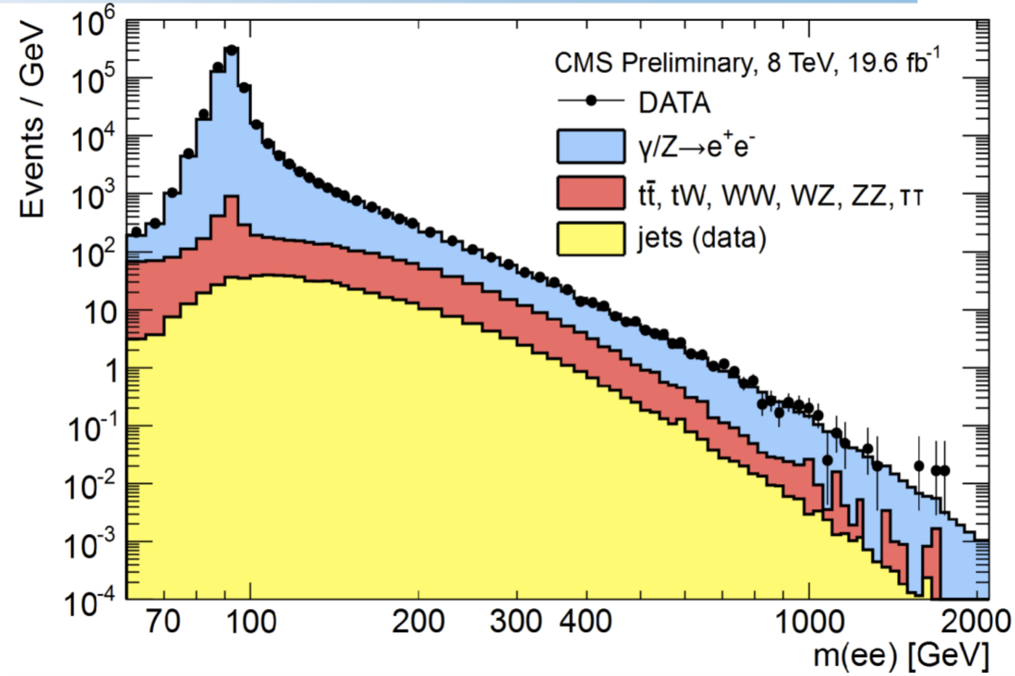

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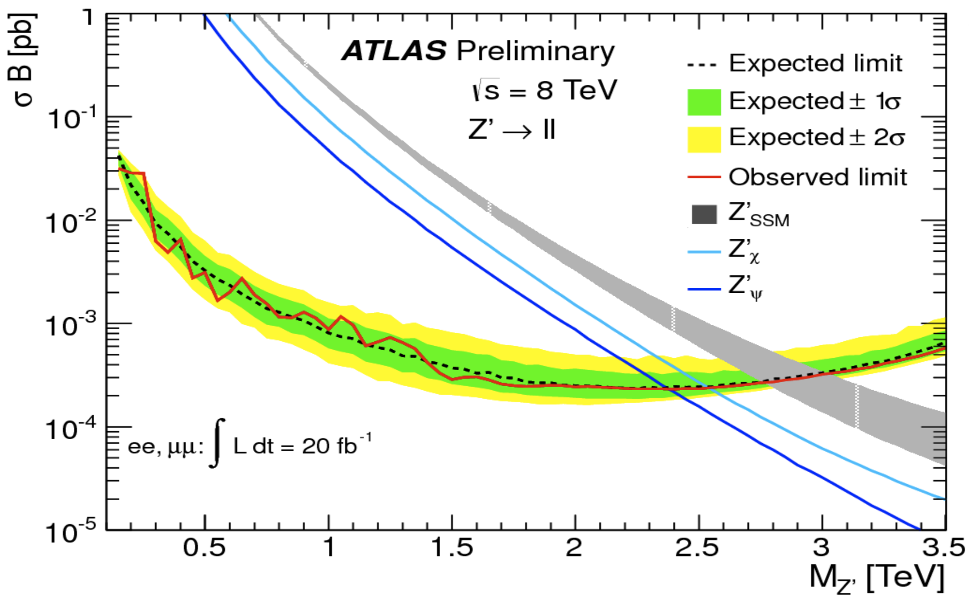

$M(Z'_{SSM}) > 2.8$ TeV @ 95CL

similarly $M(W'_{SSM}) > 2.8$ TeV @ 95 CL

In 2015/16 these searches will be extended into the ~ 5 TeV range….and beyond with the HL-LHC and HE-LHC!

Heavy Ions, 2012 data, quarkonia suppression

Sequential suppression of Y(nS) states compared with pp collisions at same nucleon-nucleon cm energy

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pp

PbPb

Full statistics

In the design of CMS care was taken to have very good efficiency for detecting ~ 4.5 - 5 GeV muons (penetration through calos, coil!) to be able to observe the Y and this effect (predicted by H. Satz)
It turned out to be very useful for Higgs searches too, the Higgs being so light!

the Higgs….

(Brout-Englert-Higgs particle)

Higgs → 4 leptons, CMS and H → γγ, ATLAS, full statistics, 2011+ 2012, status in mid-2013

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decompressor
are needed to see this picture.

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decompressor
are needed to see this picture.

Higgs mass, full statistics, CMS, mid-2013

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decompressor
are needed to see this picture.

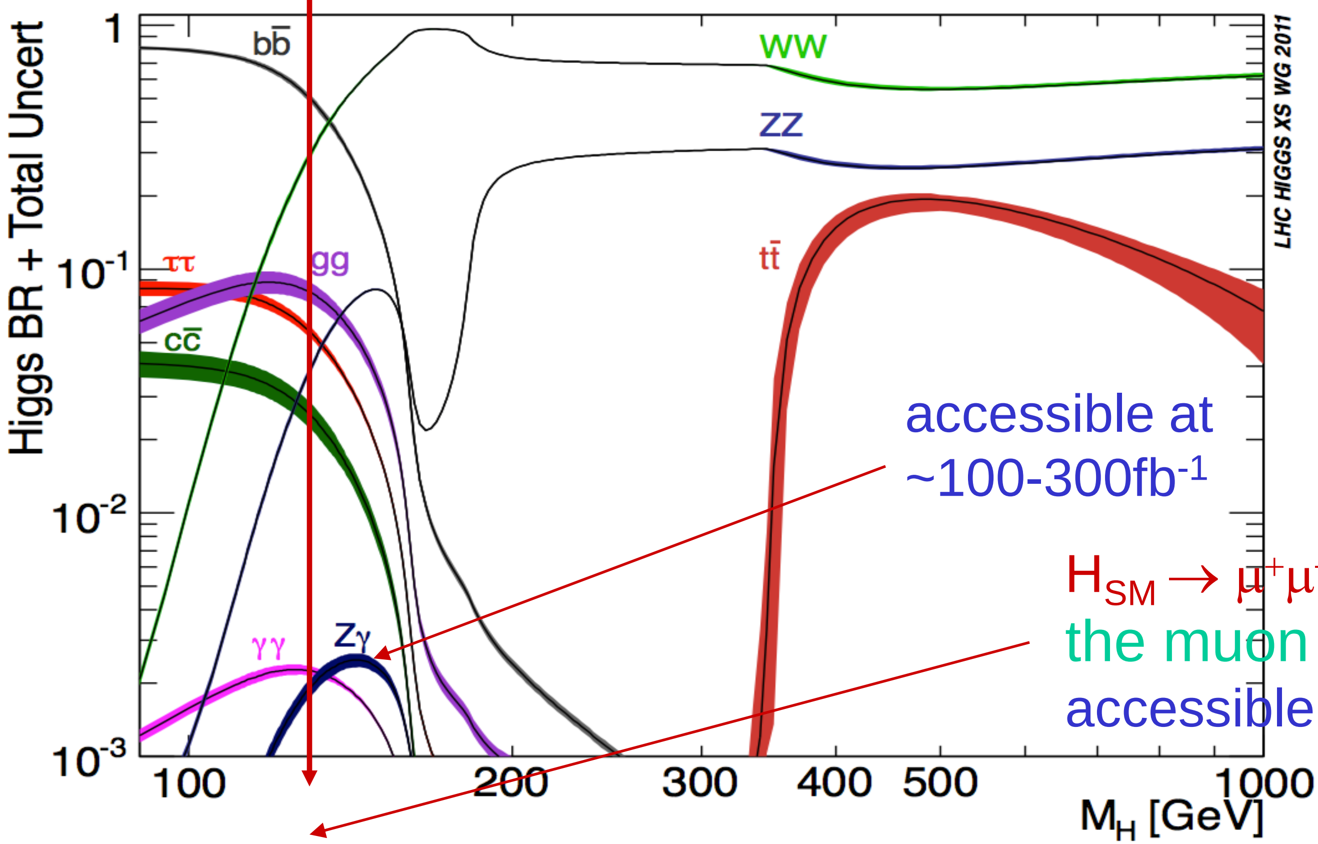
mass established
to 0.5% precision
by ATLAS and CMS,
better than for top!

Mass calculated with ZZ and γγ decay modes:

$m_H = 125.7 \pm 0.3$ (stat) $\pm$ 0.3 (syst) GeV

Looking for other decay modes:
a Higgs at ~ 125 GeV is a particularly favorable case!

A Higgs boson with a mass of 125 GeV is “well located” i.e. in a mass range in which a max. number of decay modes is accessible, bosonic and fermionic.



$H_{SM} \to \mu^+\mu^-$ (BR ~ 10^{-4})
the muon collider mode!
accessible at ~ 300fb^{-1}

The main task in the coming years will be to determine as precisely as possible branching ratios - from production cross sections and decays in the various modes - to clarify the exact nature of the object seen…..SM, SUSY, composite….

Higgs couplings, the key prediction of the theory, present situation and expectations for LHC 2020

present situation
2013

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Possibly in ~2020

Higgs couplings ∝ particle masses

We need precise measurements of properties looking for small deviations to clarify/understand the exact nature of the observed Higgs boson; for ex. in the decoupling limit of the MSSM the h is very much SM-like!

Prospects, future aims

medium term prospects

after LTS-1 (2013/14) we should be getting > ~ 50 fb^{-1}/year,

after LTS-2 (2017/18) > ~100 fb^{-1}/year

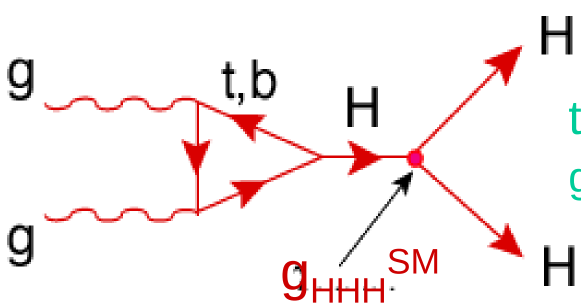
the obvious questions now: is the object seen THE Higgs?

- mass, J^P, more BR's, more precisely
- is it the SM, the SUSY lightest, a composite Higgs etc??

with > ~ 100 - 300 fb^{-1} look for new modes

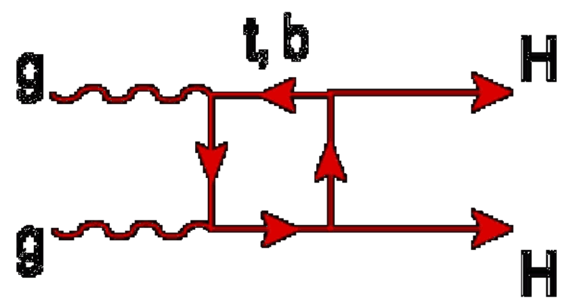
$H_{SM} \rightarrow Z\gamma$, $H_{SM} \rightarrow \mu^+\mu^-$ at known Higgs mass - the muon collider mode!!

with > ~1000 fb^{-1} look for HHH couplings:



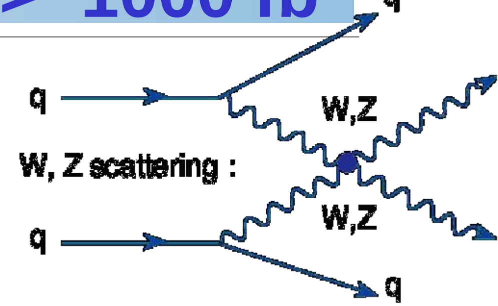
triple H coupling:
$g_{HHH}^{SM} = 3m_H^2/v$

Bkgd:



A more recent preliminary study shows that with $HH \rightarrow bb\tau\tau$ there is some hope…

H and the unitarity constraint, need to detect and select on forward jets, and requires >~1000 fb^{-1}



Scattering of longitudinal W's: $W_L W_L \rightarrow W_L W_L$ at ~1TeV :

QuickTime™ and a
decompressor
are needed to see this picture.

➡ violation of unitarity

Adding a contribution of a scalar with coupling proportional to mass:

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decompressor
are needed to see this picture.

➡

Compensation of terms with bad energy behavior provided: $g_{WWH} = g\, M_W = 2m_W^2/v$

At the very limit of observability with HL-LHC, a HE-LHC would be much more appropriate…….

Longer term upgrades: importance of forward jet tagging with increasing luminosity - towards 10^{35} cm^{-2} s^{-1} - cross sections are small!

A key instrumental issue in ~ 5-8 years, needed to improve S/B in VB fusion/scattering processes pp → qqH, qqVV …., investigating unitarity constraint, if elementary H or not….? The problem is pile-up!

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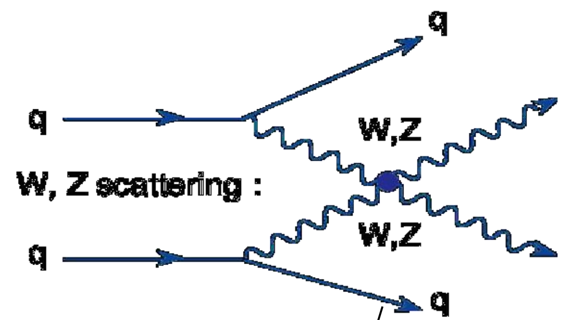
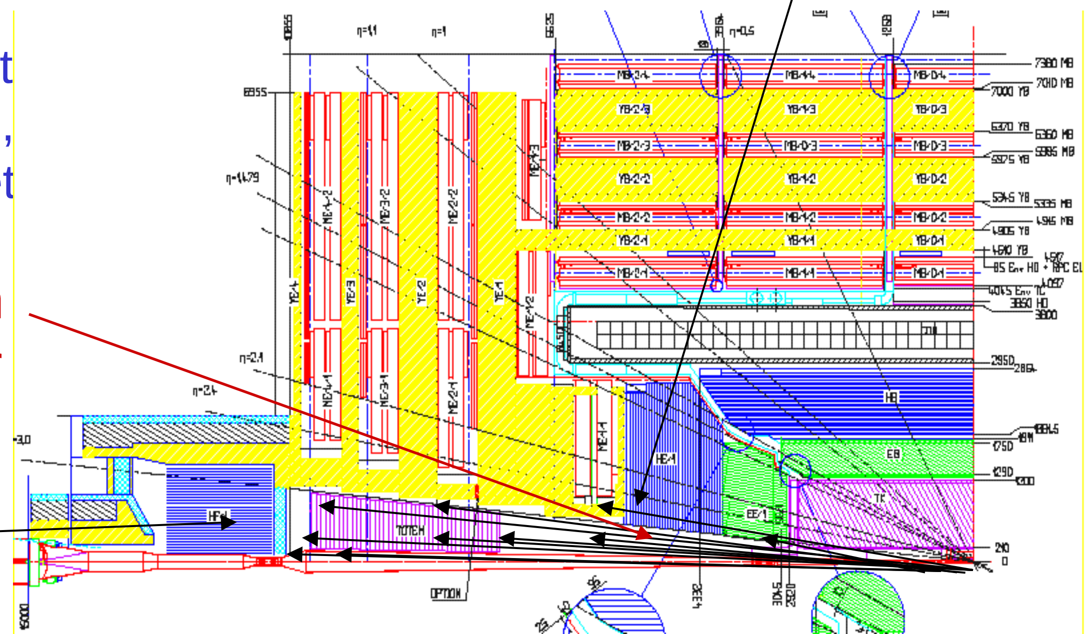


Methods: - increase forward calo granularit
reduce jet reconstruction cone 0.4 to ~ 0.2,
optimise jet algorithms to minimize false jet

introduce some tracking beyond 2.5 in rapidity with resolution δz ~ 2-3mm, or δt ~ 20-40 psec, and/or a device to count impacts/density on front face of VFCAL



THE Big Question for the (near) future,
where the LHC could play a decisive role:

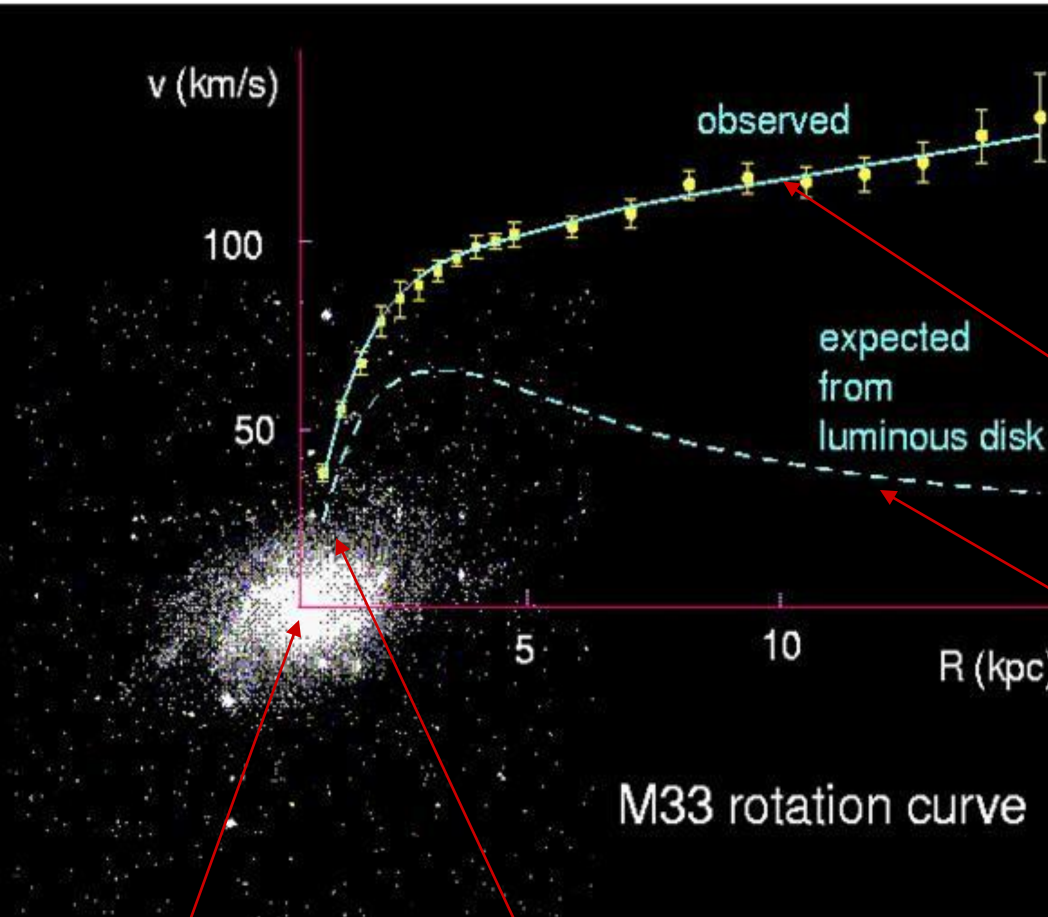
DARK MATTER

Extra dimensions

Higgs, inflaton, quintessence

Galaxy rotation curves - evidence for Dark Matter at galactic level (Vera Rubin ~1980 -1990)

Rotation curve for M33



The study of rotation curves for spiral galaxies shows that the galactic mass

$$M_{total} \sim 10 \times M_{luminous\ matter}$$

Possible explanations:
- baryonic Dark Matter in the galactic halo
- massive compact objects (machos)
- non-baryonic Dark Matter such as the SUSY LSP…in the halo

$$\lambda' = \lambda \sqrt{((1+v/c)/(1-v/c))}$$

From Newtonian mechanics:

$M(< r) \sim r^3 \Rightarrow v \sim r$ $\quad m_{star}v^2/r = G_N m_{star} M(< r)/r^2 \Rightarrow v \sim 1/\sqrt{r}$

Galactic Dark Matter halo - could the LHC bring the solution?

What is this halo made of?….no known SM particle to solve the problem!
the neutralino-1/SUSY-LSP - a plausible DM candidate

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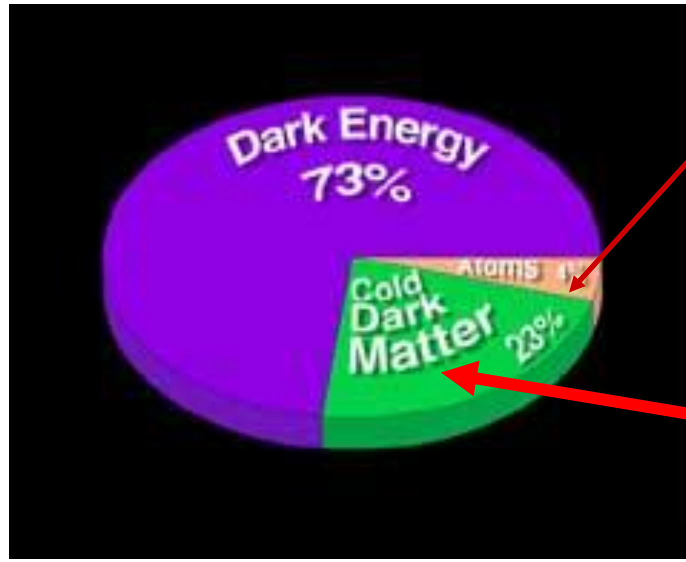
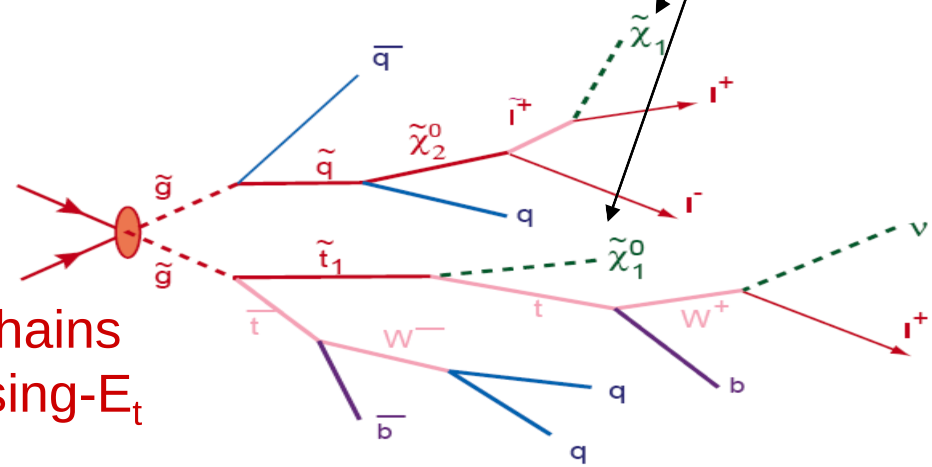


usual matter, atoms, nuclei, baryonic matter ~4% only!

not a small problem! ?!

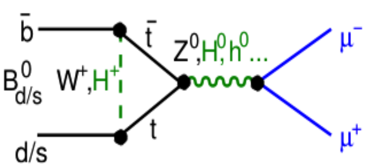


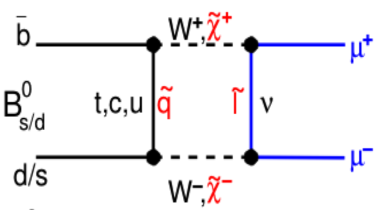
If this is the case the LHC is the appropriate machine to discover it! - the LSP would be produced as the end product of SUSY decay chains and manifest itself experimentally through missing-E_t

Supersymmetry - a typical mass spectrum

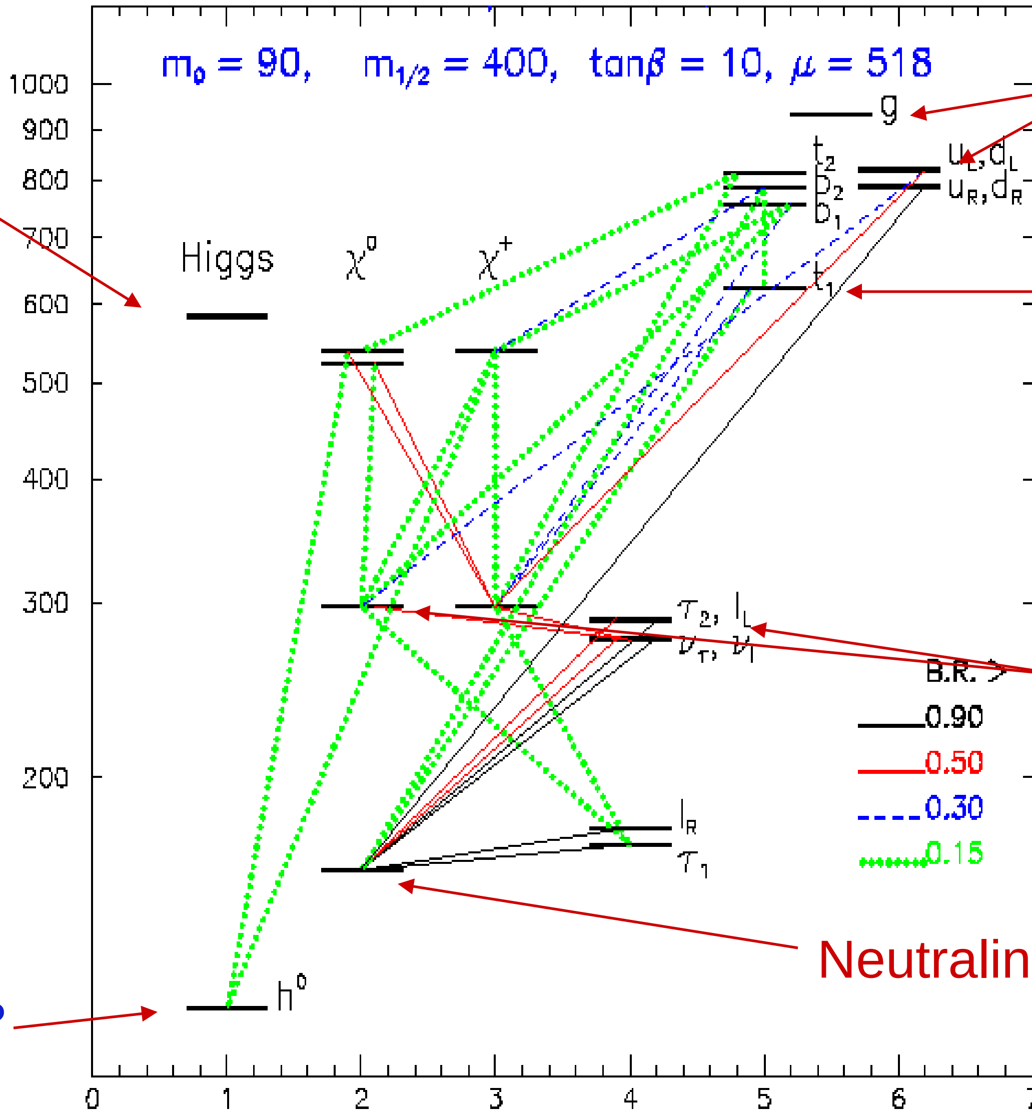
four are here
A,H,H^+H^-
direct searches
give no sign yet

indirect searches
give no sign;





the 125 GeV one?
possibly….



produced by strong interactions
direct searches give no sign yet, might be > 2TeV

Stop - produced by strong interactions
could be much lighter than all others sis (>~ 500 GeV)
no sign yet

produced also by ew interactions, no sign yet

Neutralino-1, LSP - DM candidate

$$\tilde{\chi}_1^0$$

…l'objet de toutes nos pensées

Stop perspectives….14 TeV LHC, 300 fb^{-1}

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decompressor
are needed to see this picture.

presently
excluded
domain

If the 125 GeV Higgs is in fact the h from MSSM, then stop is likely in the ~0.5 -1 TeV range (other squarks being ~ >`2-3 TeV)

With 14 TeV, stop could be discovered up to ~950 GeV with 300 fb^{-1}

Looking at the future

- We are doing much better than expected!, not only ~20 years ago when the LHC adventure started, but even few years ago (Physics TDRs time)!

- With half the energy (7-8 TeV) and almost the design inst. luminosity at twice the pile-up (50 vs 25 nsec), but ~1/3 the integrated luminosity thought to be needed, we have the Higgs!

- Performances on physics objects (eff., purity, isolation - for electrons, taus, b-jets etc resolution on Etmiss, taus …) as well as full physics channel analyses are much better - due to Tevatron-induced more sophisticated software/analysis tools (BDT, MVA etc) - than we thought they will be,

- and we are coping much better with pile-up than initially feared.

Thus we can look with confidence at $\sqrt{s}$ = 13-14 TeV, 2 - 4 x10^{34}cm^{-2}s^{-1} (25 ns) and getting ~50 -100 fb^{-1}/year looks very promising!

CMS: Pixels and HCAL, upgrades in 2013 - 1016

- New Pixels Design
– 4 barrel layers and
  3 endcap disks at each end.
  smaller inner radius
–– Reduced mass

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decompressor
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- Installation date
– Ready by late-2016,

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- New HCAL Design
– HF new PMT
– Replace HPDs with SiPMs in HB and HE
- longitudinal segmentation

- Installation date
- HF full PMT in LS1
- HBHE slice after LS1
- HB and HE in LS2

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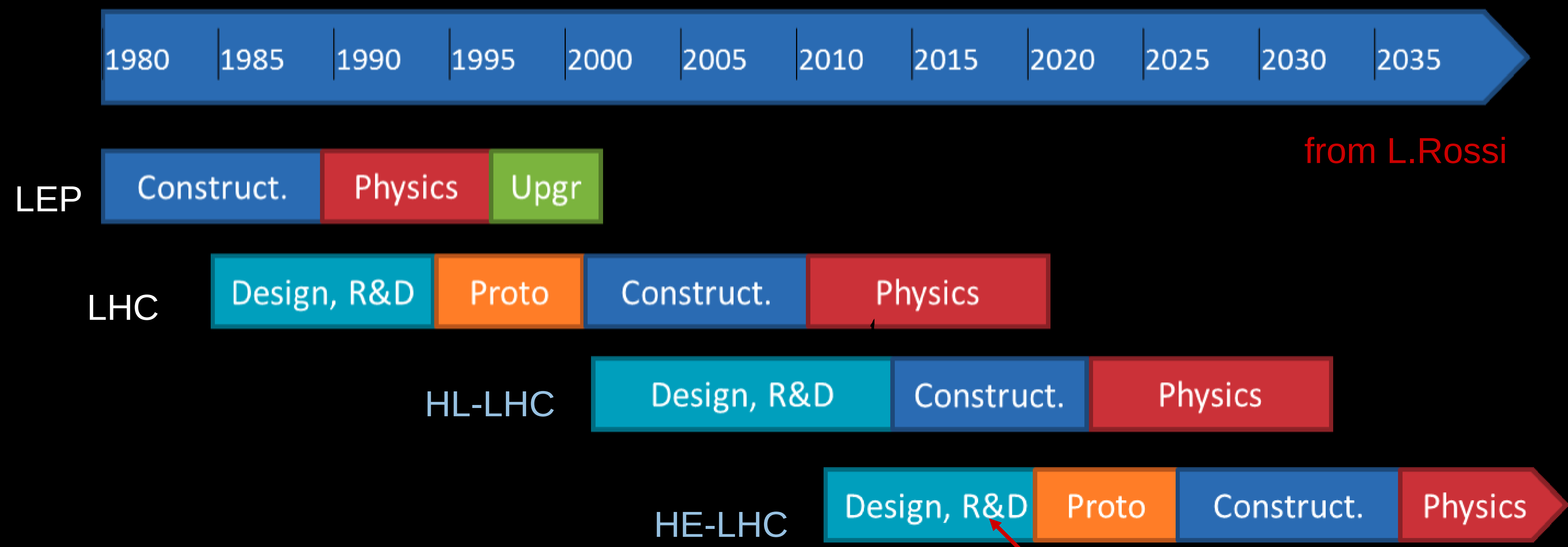
Possible long term exploitation of the LHC complex, tunnel, infrastructure etc.



2000 large magnets of 15-20 T
1500 tons of HEP grade Nb3Sn
500 tons of HTS for magnets
100 tons of SC for Sc links

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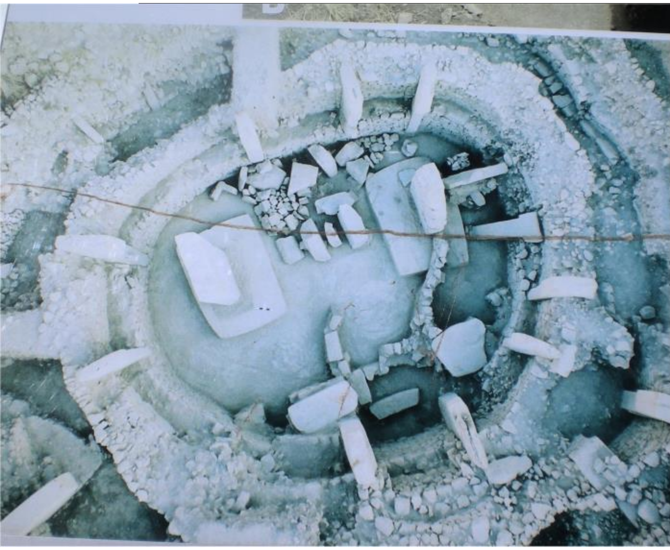
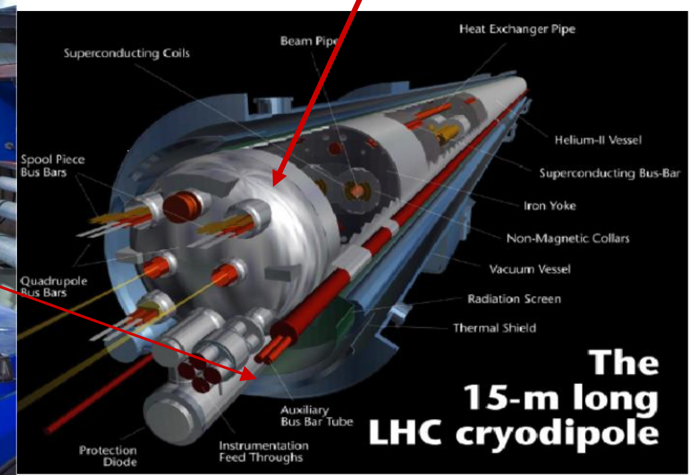
Homo sapiens-sapiens has a propensity to build circular structures - and made some progress over past 11.000 years!



Goebekli-Tepe, ~ 9000 BC, Sanli-Urfa/Turkish-Syrian border, 2012

Result of activities of homo sapiens sapiens scientificus, Geneva, French-Swiss border,~ AD 2000

key elements



T-LEP - a potential longer-term future for CERN

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~ 90 km circumference tunnel with a E_{cm}~ 350 GeV e^+e^- collider capable of producing ~ 80000 Higgs bosons/year; tunnel eventually reusable for a hadron collider at ~100 TeV proton-proton cm energy

Conclusions

The LHC is an incredible technological and scientific endeavor - on a world-wide scale

The LHC started operation in November of 2009; between March and November 2010 the luminosity increased by a factor ~ 100000; in 2012 LHC at 8 TeV approached 7 x 10^{33} cm^{-2} s^{-1} - almost the design value!

The four major experiments ATLAS, CMS, ALICE and LHCb are all operating very successfully and with very high efficiencies. ATLAS and CMS are experiments of unprecedented complexity. The physics harvest up to now is extraordinary, the Higgs, B^0_s decay to $\mu\mu$ observed, jet quenching studied, Y suppression established, beautiful and detailed studies in EWK and QCD physics etc

The LHC will go to ~13 TeV in 2014/15 and feed the world particle physics community for the next ~ 20 years; many technical challenges are ahead of us - and many physics opportunities, clarification of the Higgs (i.e. is it THE Higgs boson or a A Higgs from an extentionn of the SM), looking for SUSY etc

Spares, additional plots

CMS - of quasi-celestial harmony and perfection!

La rosace de Notre Dame de Paris

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Higgs couplings, the key prediction of the theory, present situation

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Higgs couplings to elementary particles as predicted by Higgs mechanism

$g_{HVV} = 2m_V^2/v$ $g_{Hff} = m_f/v$ $g_{HHH} = 3m_H^2/v$

$g_{HWW} = g\, m_W$

Higgs couplings ∝ particle masses

$m_H = v\sqrt{\lambda}$

$m_W = gv/2$ $m_Z = m_W/\cos\vartheta_W$ $v \approx 250$GeV

v being known, m_H or equivalently λ is the only free parameter of the SM

Masses of the Higgs and top, and ewk vacuum stability

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decompressor
are needed to see this picture.

G. Giudice

arXiv:1112.3022

Higgs: Spin-Parity, $H \rightarrow 4$ leptons, CMS, 0^+ vs 0^-
$H \rightarrow \gamma\gamma$, ATLAS, polar angular distribution, 0^+ vs 2^+

full statistics

0^+ vs 0^-
3.3σ

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decompressor
are needed to see this picture.

0^+ vs 2^+

QuickTime™ and a
decompressor
are needed to see this picture.

4-lepton final state allows also explicit rejection of J^P 1^+ and 1^-
at present with ~3.5 σ

Stop searches - for ex. summary from ATLAS at 7 TeV

Variety of methods and strategies used; absence of significant excess gives these 95% CL's.

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Overview of - up to now unsuccessful - SUSY searches

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