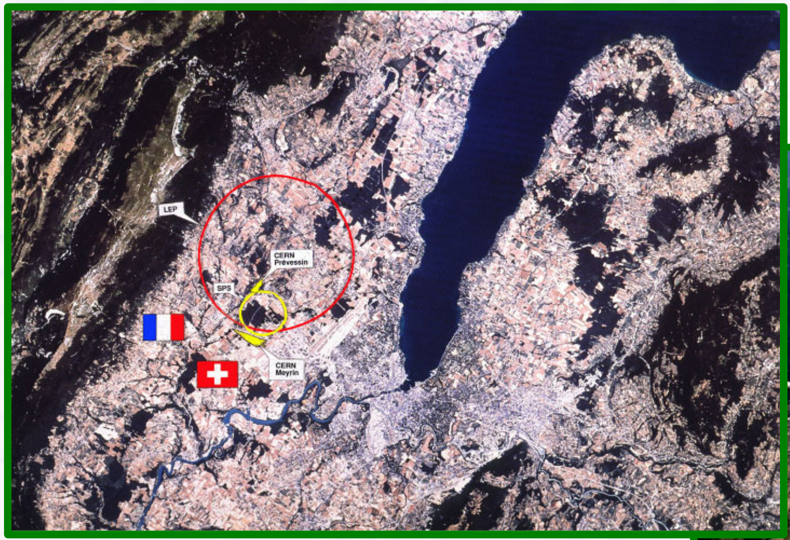
The LHC Project

(The Large Hadron Collider)

History – Physics – Accelerator – Detectors – Status



The High Energy Frontier

- **Accelerator projects on the market** (in very different states of development)
  - LHC
    - LHC (nominal) with 2 x 7 TeV and $L = 10^{34}\ cm^{-2}s^{-1}$
    - Super-LHC (SLHC) with 2 x 7 TeV and $L = 10^{35}\ cm^{-2}s^{-1}$
      - needs major detector upgrades and R&D on radiation hardness
    - Double-LHC (DLHC) with 2 x 14 TeV and $L = 10^{34}\ cm^{-2}s^{-1}$(?)
      - needs new superconducting magnets with B ~ 15 T, no R&D yet
  - e^+e^- Linear Colliders
    - ILC with $\sqrt{s}$ = 500 GeV and $L = 2 \times 10^{34}\ cm^{-2}s^{-1}$, upgradable to 1 TeV
      - Global Design Effort (GDE) under way to prepare Technical Design Report until 2010/12
    - CLIC with $\sqrt{s}$ = 3 TeV and $L = 6 \times 10^{34}\ cm^{-2}s^{-1}$
      - feasibility study under way, hope for positive results until 2010
  - $\mu^+\mu^-$ Collider
    - multi-TeV with $L = 10^{31}\ cm^{-2}s^{-1}$(?)
  - LHeC
    - LHC + 70 GeV e^- ring, $\sqrt{s}$ = 1.4 TeV (4.5x HERA), $L = 10^{33}\ cm^{-2}s^{-1}$ (20x HERA)

the only approved big project in high energy physics at present, under construction

The LHC: 24 years... and counting...

1984: Glimmerings of LHC (2x5..9 TeV)
and SSC (2x20 TeV),
LEP tunnel construction starts

1988: SSC approved (Waxahachie, Texas)

1989: First collisions in LEP and SLC,
R&D for LHC detectors begins

1993: SSC construction cancelled!!!

1994: LHC approved (start in 2005)

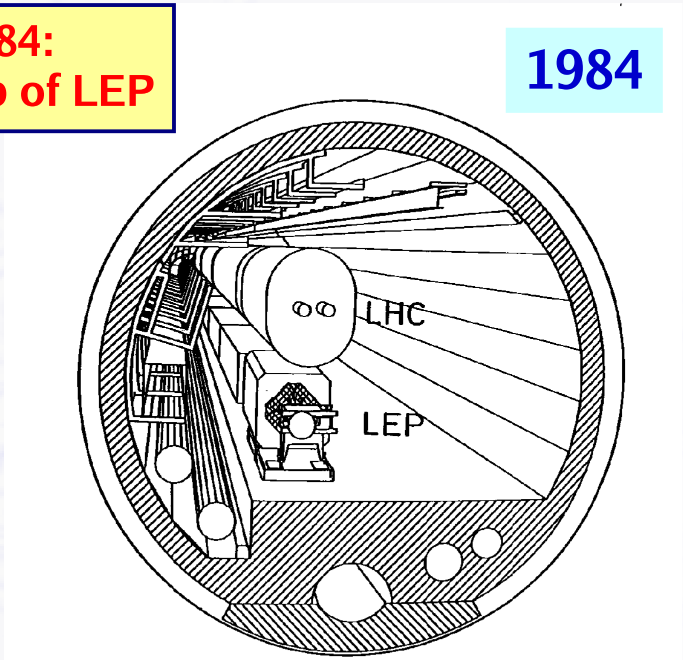
1995: Discovery of the top quark at Fermilab
by CDF (and D0),
ATLAS and CMS approved

1998: Start of LHC construction

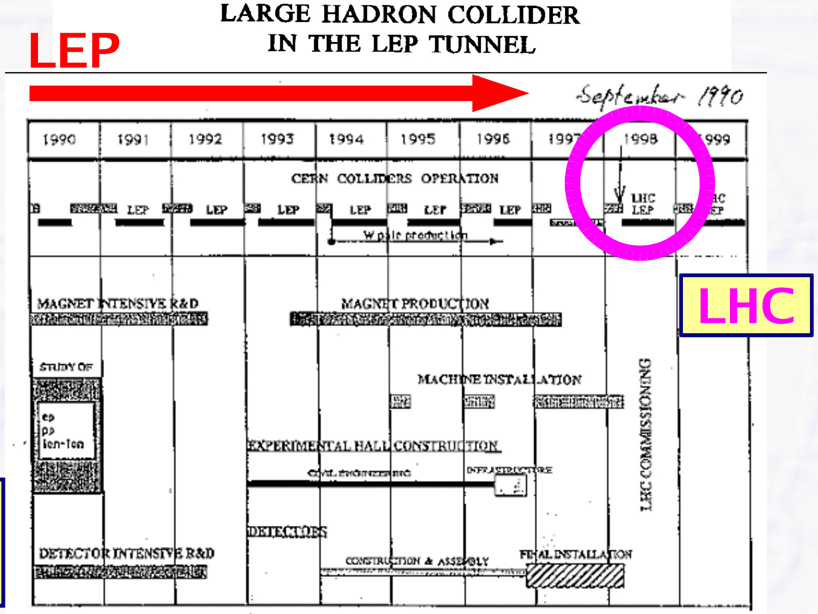
2000: End of LEP running,
no Higgs yet...

2008: LHC start

Idea in 1984:
put LHC on top of LEP



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

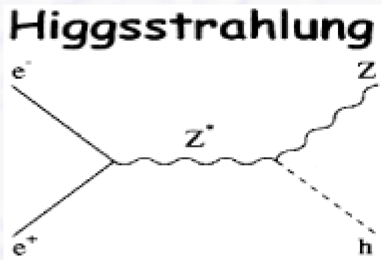


TIME SCALE FOR THE CONSTRUCTION OF THE LHC IN THE LEP TUNNEL

Schedule in 1990:
LHC start in 1998...

LEP Higgs Hunting

- **Main Higgs production at LEP via "Higgsstrahlung"**



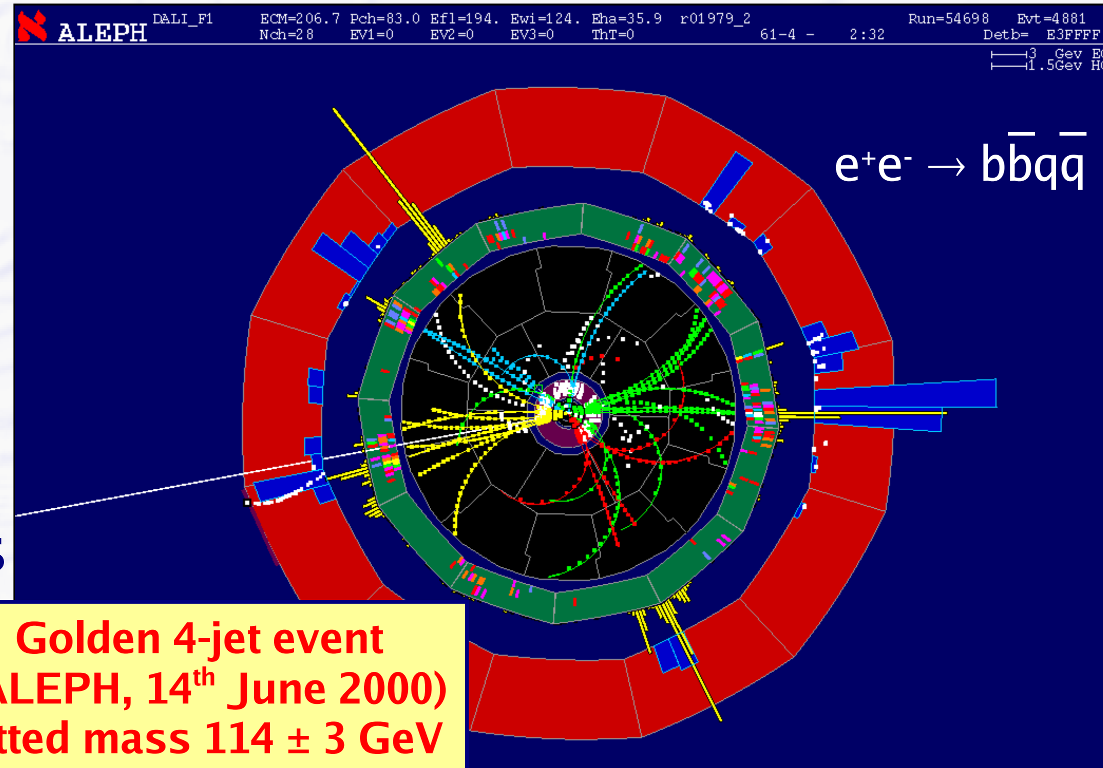
- **+ fast decay of Z and Higgs**

  $Z \rightarrow q\bar{q}$ (2 quark-jets)

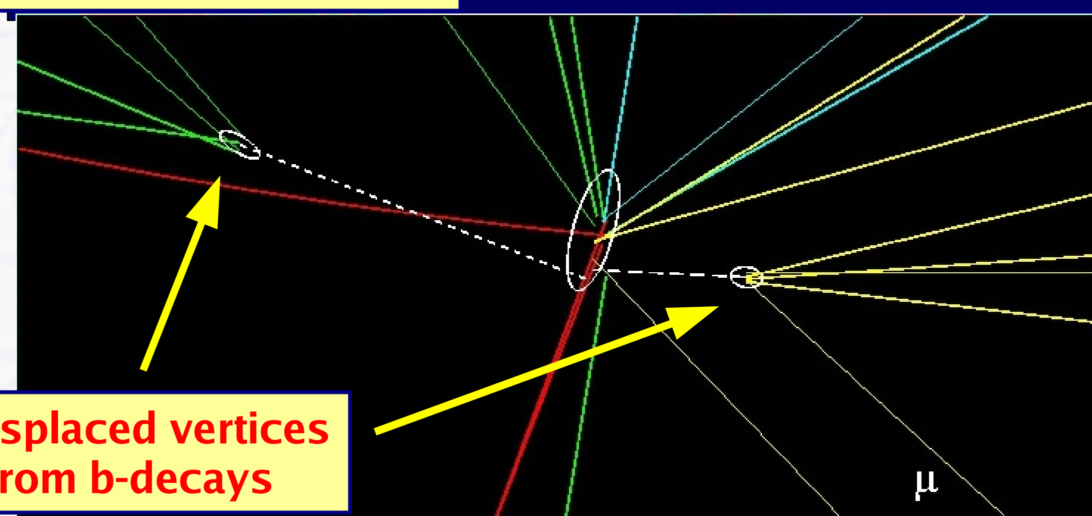
  $H \rightarrow b\bar{b}$ (2 b-quark jets)

  → b-particles have long lifetime
    - move away from interaction point before they decay

  → unique possibility to detect them via displaced vertices



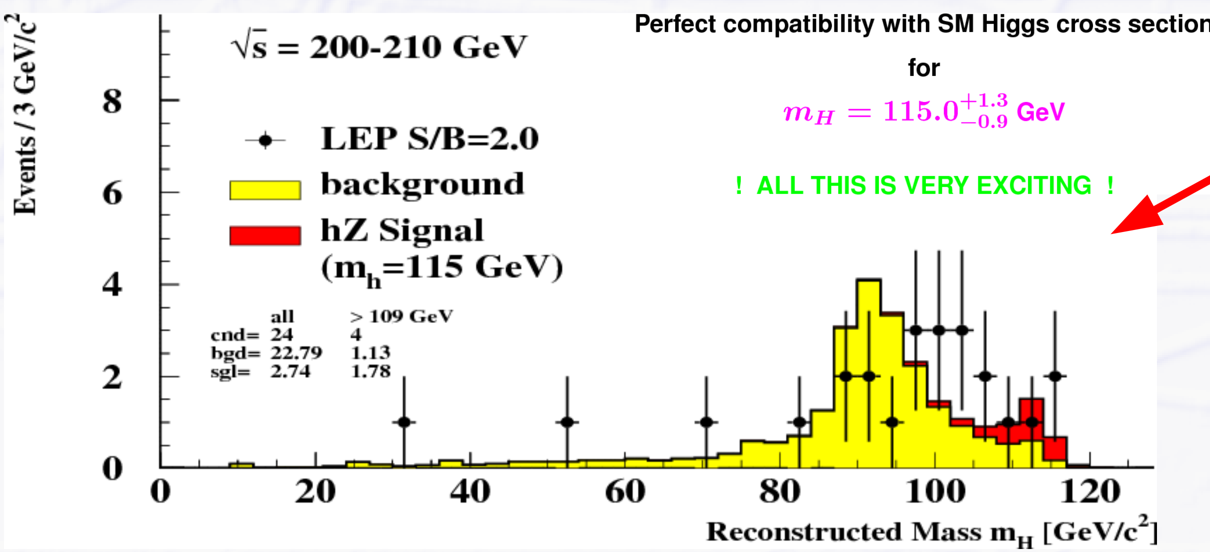
Golden 4-jet event
(ALEPH, 14th June 2000)
fitted mass 114 ± 3 GeV



2 displaced vertices
from b-decays

LEP Higgs Excitement

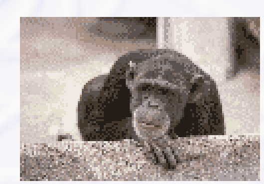
- At the end of LEP (November 2000)
  - hints of a Higgs signal, a few events at $M_{Higgs} \sim 114$ GeV, 2-3 sigma excess over the expected background... very exciting!!!
    - > 3 sigma: “evidence for...” (check flights to Stockholm)
    - > 4 sigma: “strong evidence for...” (book flight to Stockholm)
    - > 5 sigma: “discovery of...” (take flight to Stockholm)
  - loooong debate in committees + CERN management
    whether to continue LEP running for one more year... (impact on LHC?)



LEP Higgs Working Group
at LEPC seminar on 3rd November 2000,
one(!) day after LEP was turned off
(Peter Igo-Kemenes)

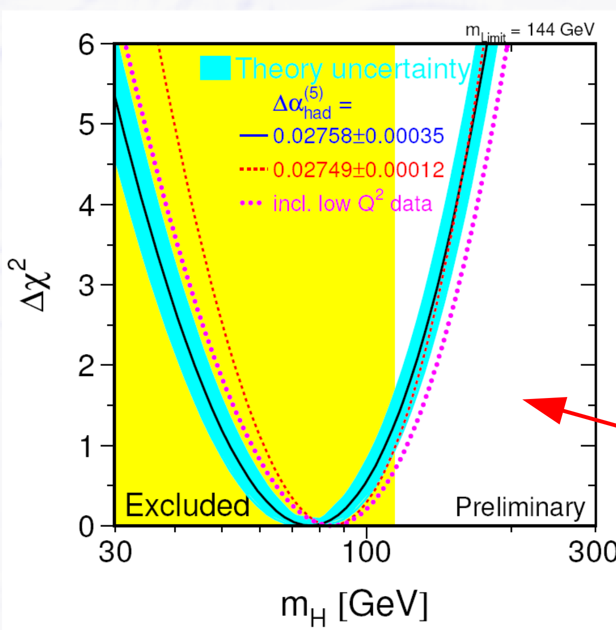
...but the final answer
by the CERN Council was...

NO



LEP Higgs Limits (July 2007)

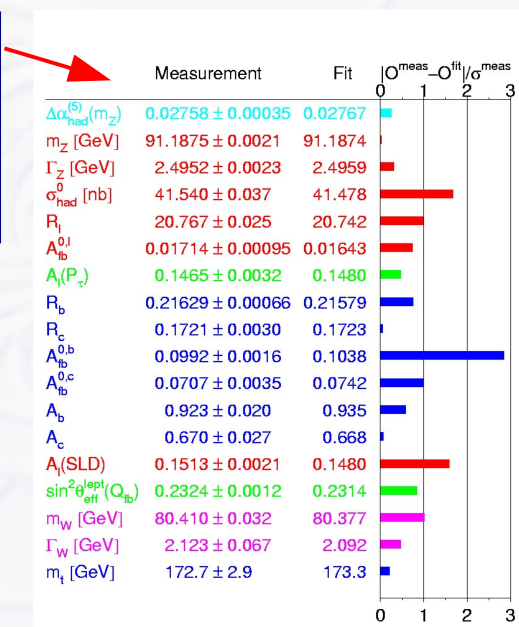
- **Higgs needed in Standard Model to generate particle masses**
  - without Higgs all SM particles would have mass = 0
  - no Higgs mass prediction from theory, except M_{Higgs} < ~1000 GeV
- **Limits from measurements**
  - M_{Higgs} > 114.4 GeV (direct search limit from LEP)
  - M_{Higgs} < 144 GeV (indirect limit from precision measurements)



deviations of best fit to many SM precision measurements (e.g. cross sections) with M_{Higgs} as free parameter

χ^2 – probability of M_{Higgs}

"blue-band plot"

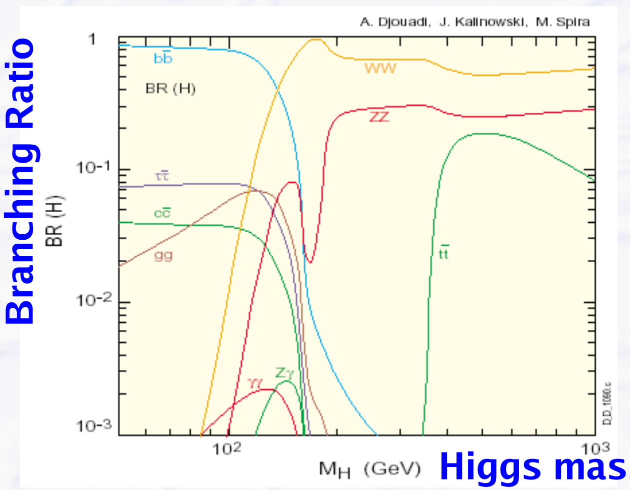


Higgs: Would LHC find it?

(yes, but it may take some time)

- **Higgs particle too heavy for present colliders + fast decaying**
  - **need high(er) energy colliders + detect decay products**
  - **favoured production and decay modes depend on (unknown) mass**

Branching Ratio



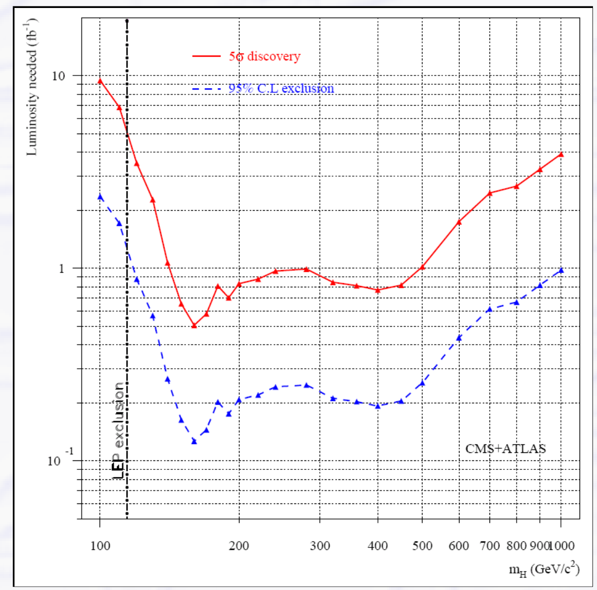
Higgs mass

Two best channels to detect:

$H \rightarrow ZZ \rightarrow$ 4 leptons (e,μ,τ)
$H \rightarrow$ 2 photons

= detector needs to have good photon, electron + muon energy and momentum measurement

Luminosity



Higgs mass

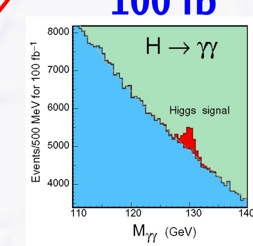
"discovery plot"

for 5 sigma discovery needed
(per experiment, ATLAS+CMS combined):

~ 5 fb^{-1} for M_{Higgs} = 115 GeV
~ 0.7 fb^{-1} for M_{Higgs} = 144 GeV

~full year in early LHC running

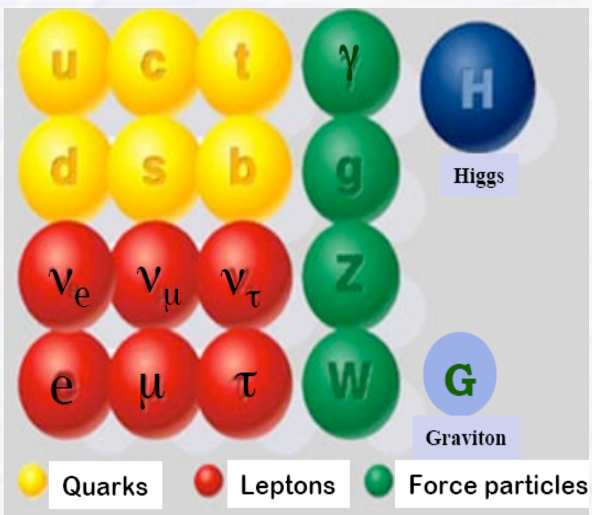
100 fb^{-1}



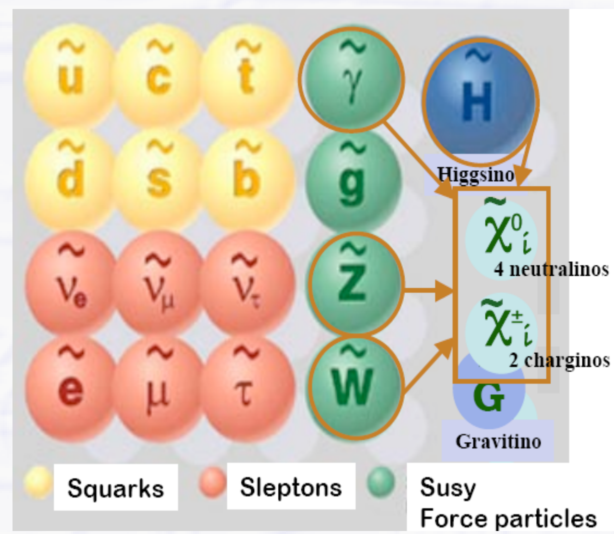
Beyond the Standard Model

- **In SM: matter particles = fermions, force carriers = bosons**
  - why this asymmetry?
  - extend standard model by new symmetry: ***Supersymmetry (SUSY)***
  - SUSY matter particles = bosons, SUSY forces carriers = fermions

Standard Model particles



SUSY particles



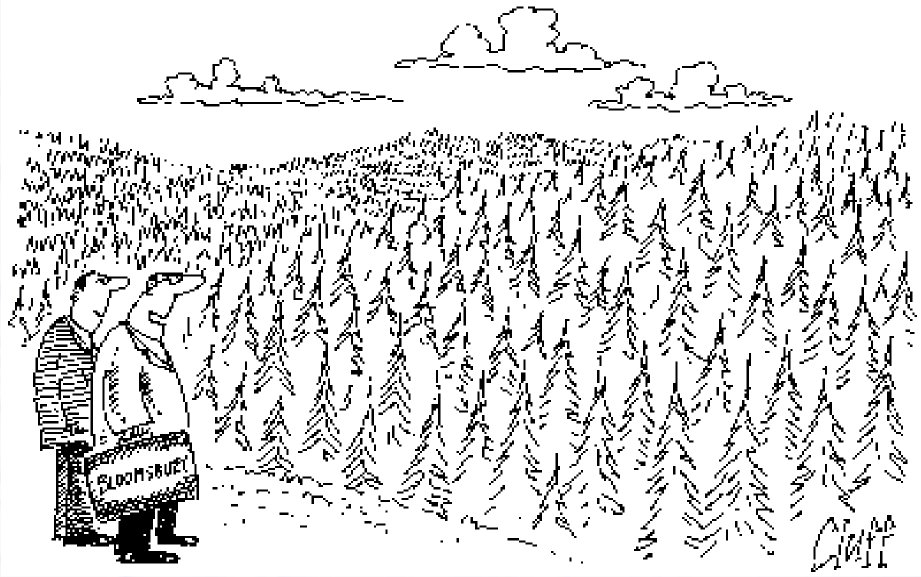
New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

If R-parity is conserved: Lightest SUSY particle (LSP) must be STABLE(!!!)

Supersymmetry and Dark Matter

- ...a very popular scenario for new physics

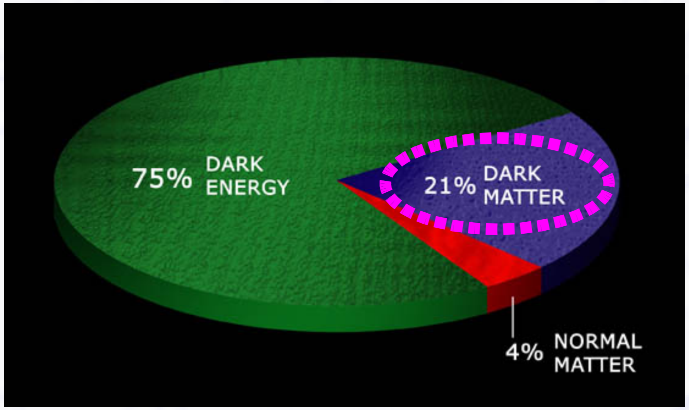
More than 7000 papers since 1990



"One day, all of these will be supersymmetric phenomenology papers."

Lightest SUSY particle (LSP) is a good candidate for *dark matter*

composition of the universe



matter

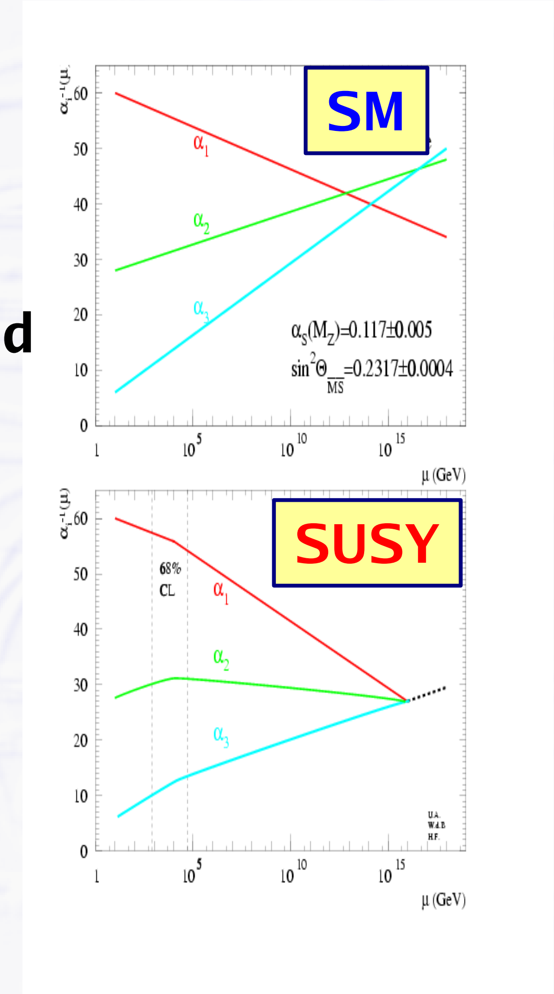
dark matter

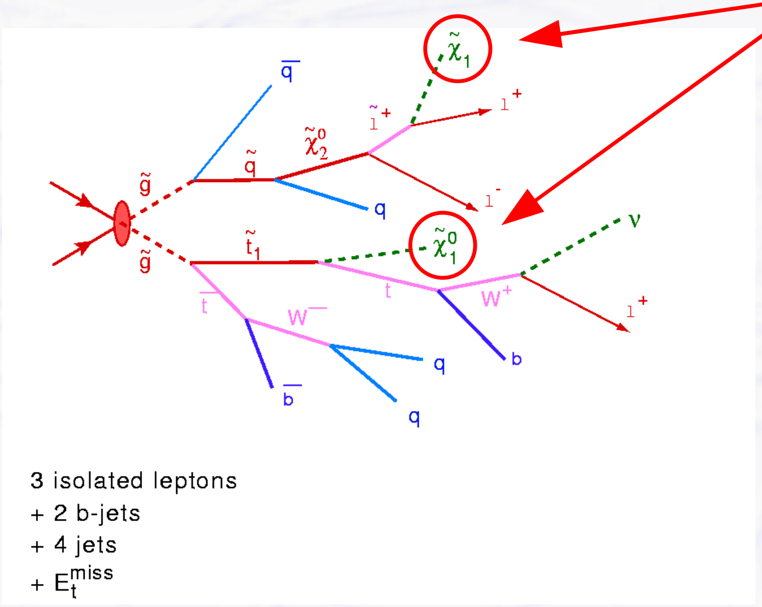
Darth Vader

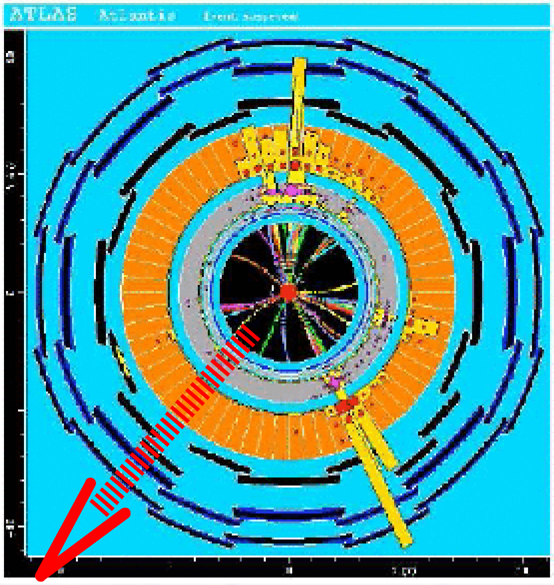
© Rocky Kolb

More on Supersymmetry

- Strength of el.-magn., weak and strong interactions (coupling "constants") are "running" with energy (= not constant)
  - SM: not converging at high energies
  - SUSY: converging at ~10^{16} GeV
- How to detect SUSY
  - cascade of SUSY particles, LSPs escape undetected







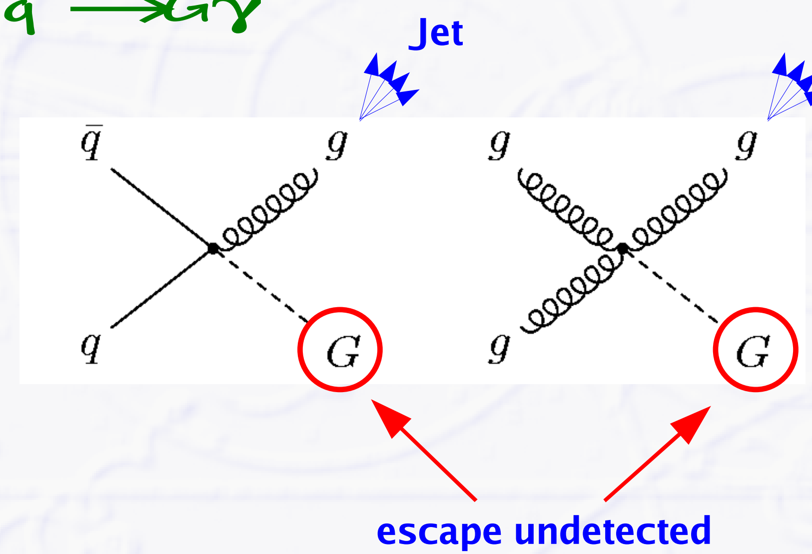
Missing (unbalanced) momentum and energy transverse to beam direction

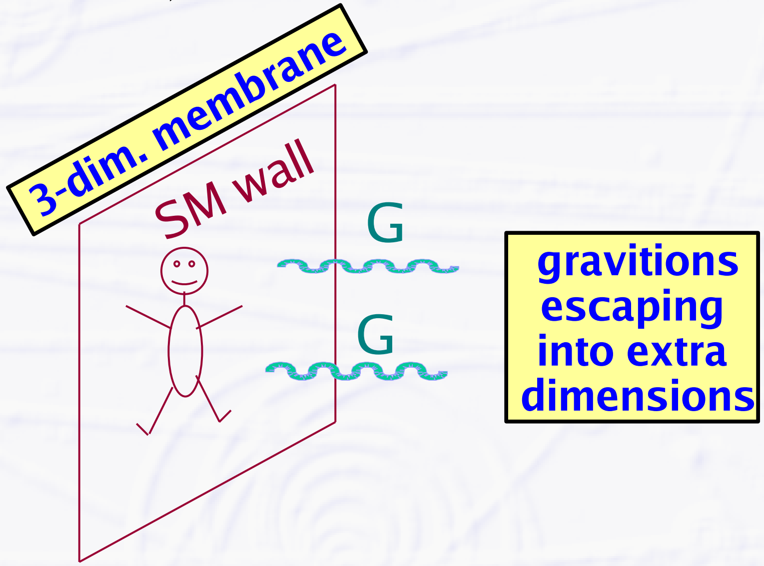
Exotics: (Large) Extra Dimensions

- **Why gravity is so weak compared to other interactions?**
  - hierarchy problem!
  - ➔ gravitons (force carriers of gravity) might disappear into large extra dimensions (ADD model: Arkani-Hamed, Dimopoulos, Dvali 1998)
- **LHC might be able to produce gravitons G via gluon-gluon gg or quark-quark $q\bar{q}$ fusion**

$gg \rightarrow gG,\; qg \rightarrow qG,\; q\bar{q} \rightarrow Gg$

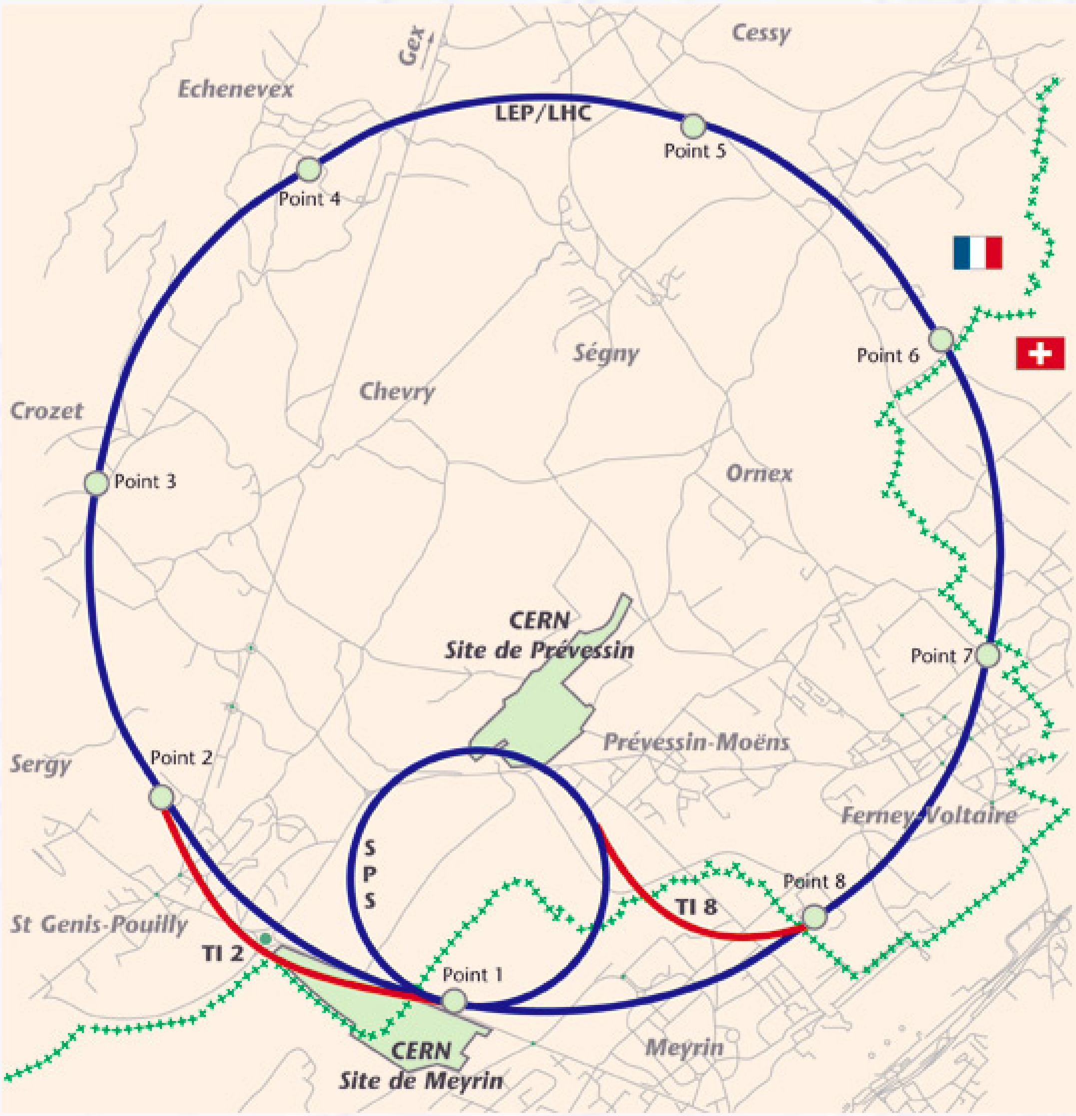
$q\bar{q} \rightarrow G\gamma$

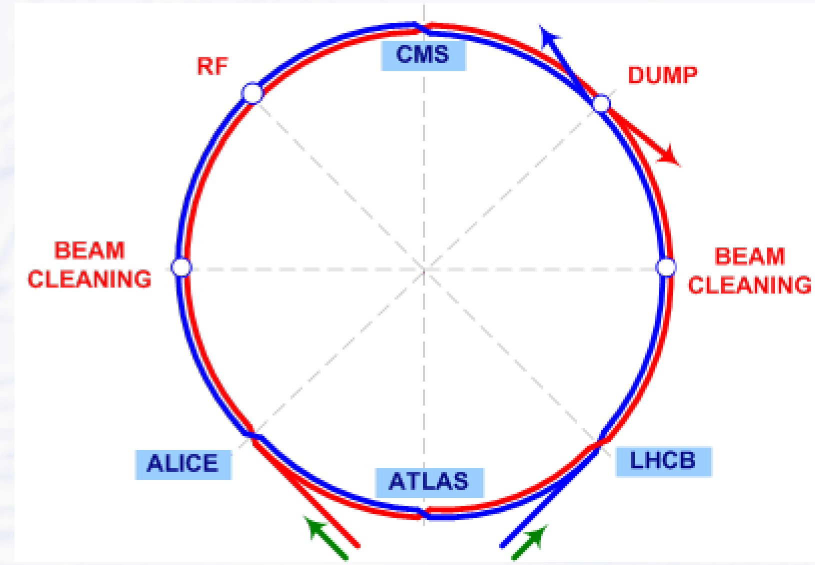




Event topology similar to SUSY: particle jets (from gluons) or photons with large missing (transverse) energy

The LHC



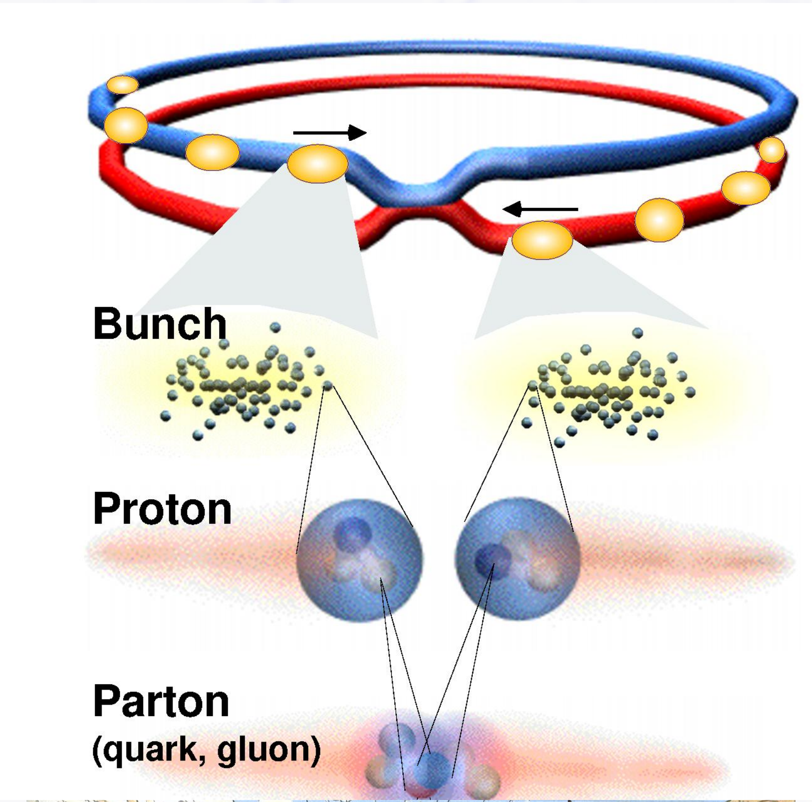


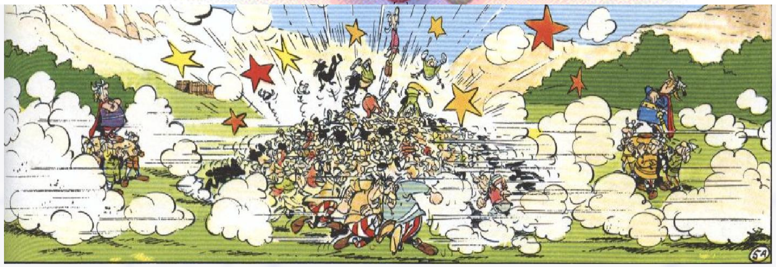
8 sectors (arcs) +

Point 1: ATLAS
Point 2: ALICE, injection
Point 3: Momentum cleaning
Point 4: RF
Point 5: CMS
Point 6: Beam Dumps
Point 7: Betatron cleaning
Point 8: LHCb, injection

Proton – Proton Collisions(*) in the LHC

- (*)LHC is also able to accelerate and collide heavy Pb ions
  - ➔ dedicated heavy ion experiment: ALICE





Proton – Proton:

2808 x 2808 bunches
bunch separation: 7.5 m (25 ns)
10^{11} protons/bunch

~10^{9} pp collisions/s
superposition of ~20 pp-interactions per bunch crossing: pile-up

~1600 charged particles in the detector per bunch crossing

CERN Accelerator Complex

7 TeV

5 LHC

450 GeV

4 SPS

26 GeV

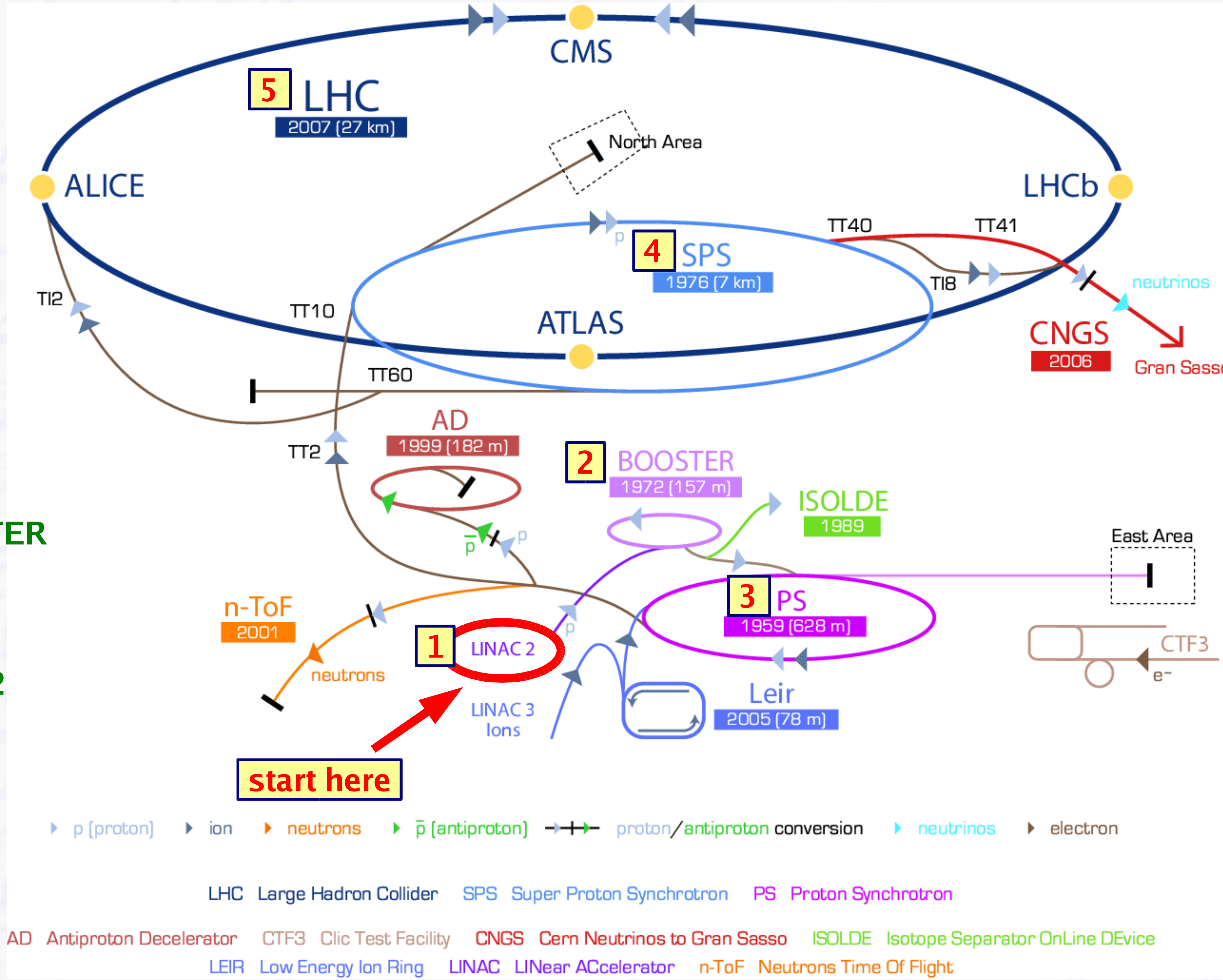
3 PS

1.4 GeV

2 BOOSTER

50 MeV

1 LINAC2



LHC Parameters

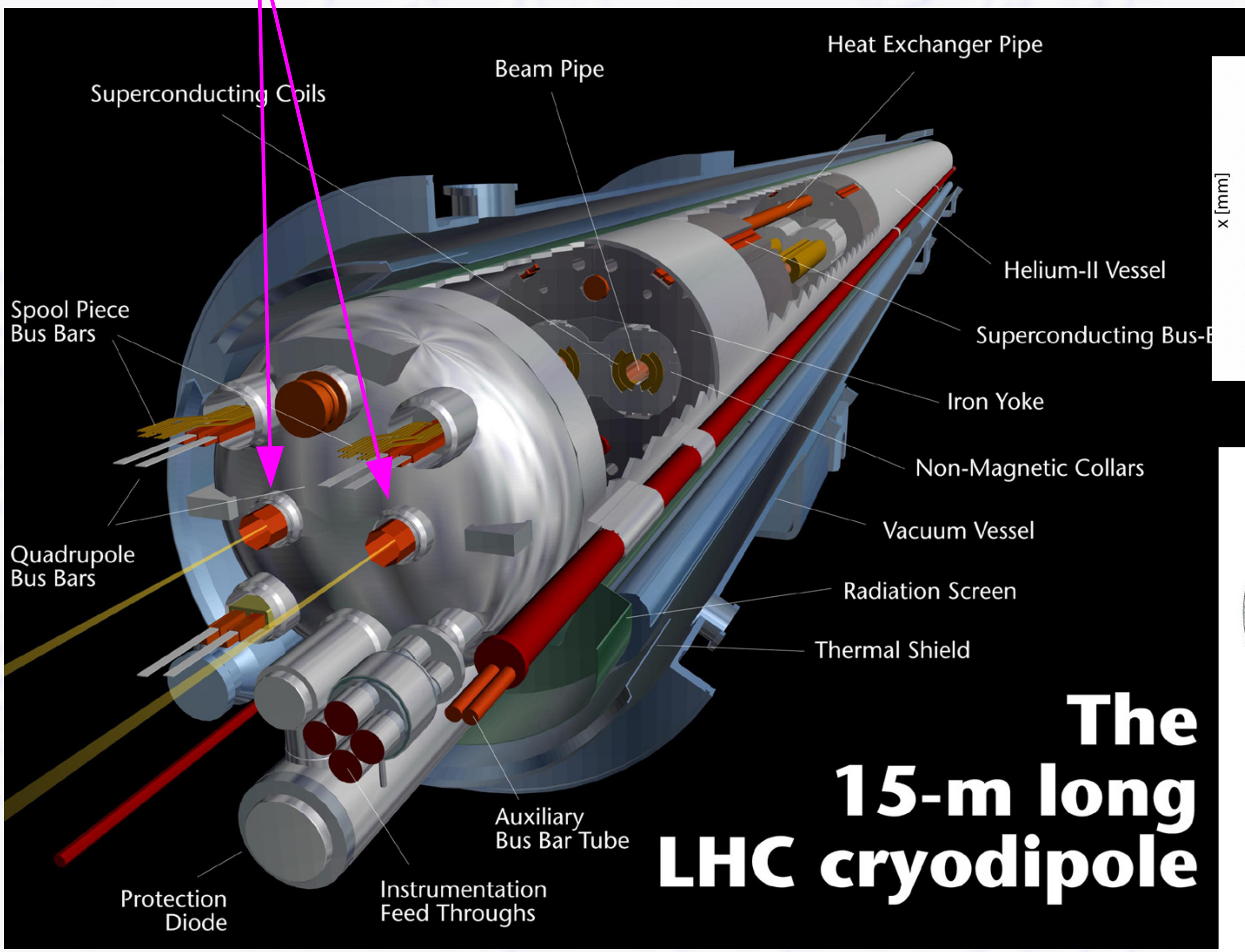
- Energy = 7 x Tevatron, luminosity = ~ 50 - 100 x Tevatron

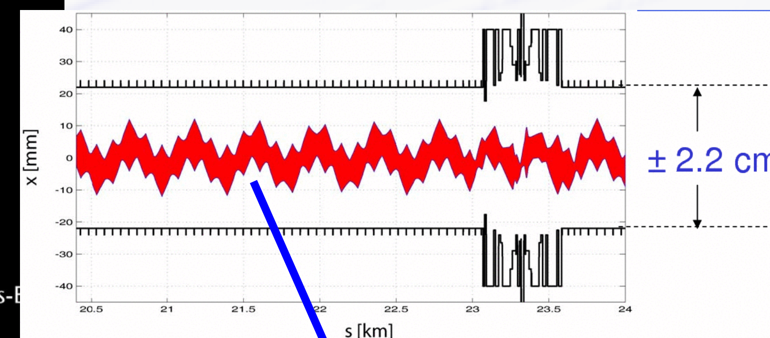
	LHC (2008)	Tevatron (1987)	SppS (1981)
max. Energy (TeV)	7	1	0.450
circumference (km)	26.7	6.3	6.9
luminosity ($10^{30}cm^{-2}s^{-2}$)	10000	210	6
time between collisions (μs)	0.025	0.396	3.8
crossing angle (μrad)	300	0	0
p/bunch (10^{10})	11	27/7.5	15/8
number of bunches	2808	36	6
beam size (μm)	16	34/29	36/27
filling time (min)	7.5	30	0.5
acceleration (s)	1200	86	10

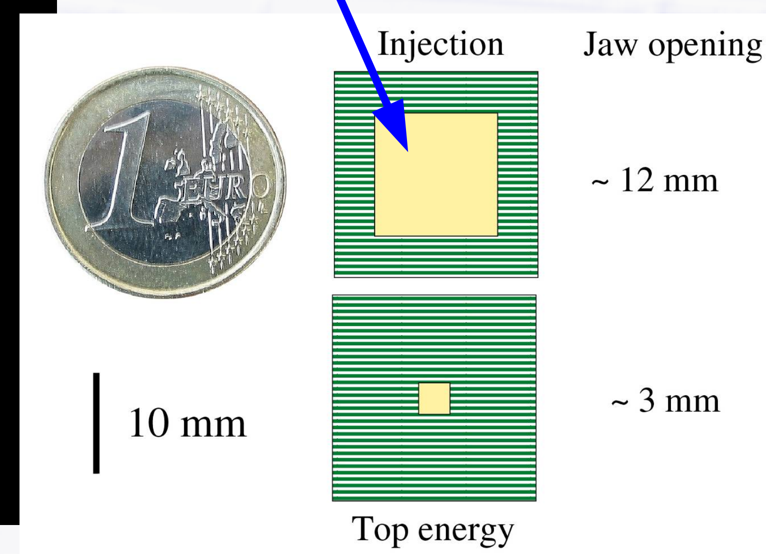
The LHC Dipoles

- 2 small beams in one magnet

size of vacuum chamber and beam envelope





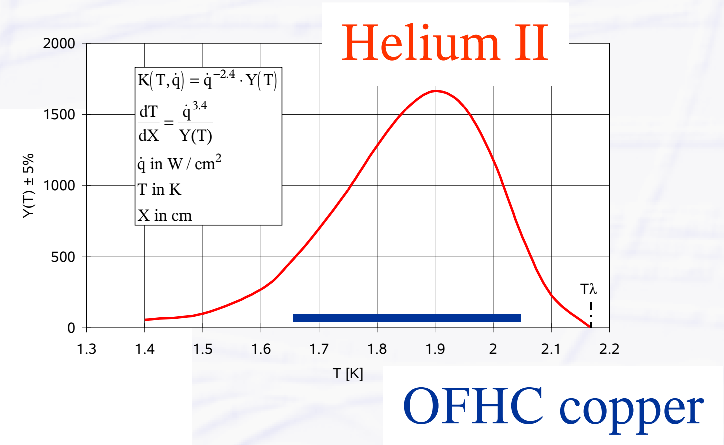


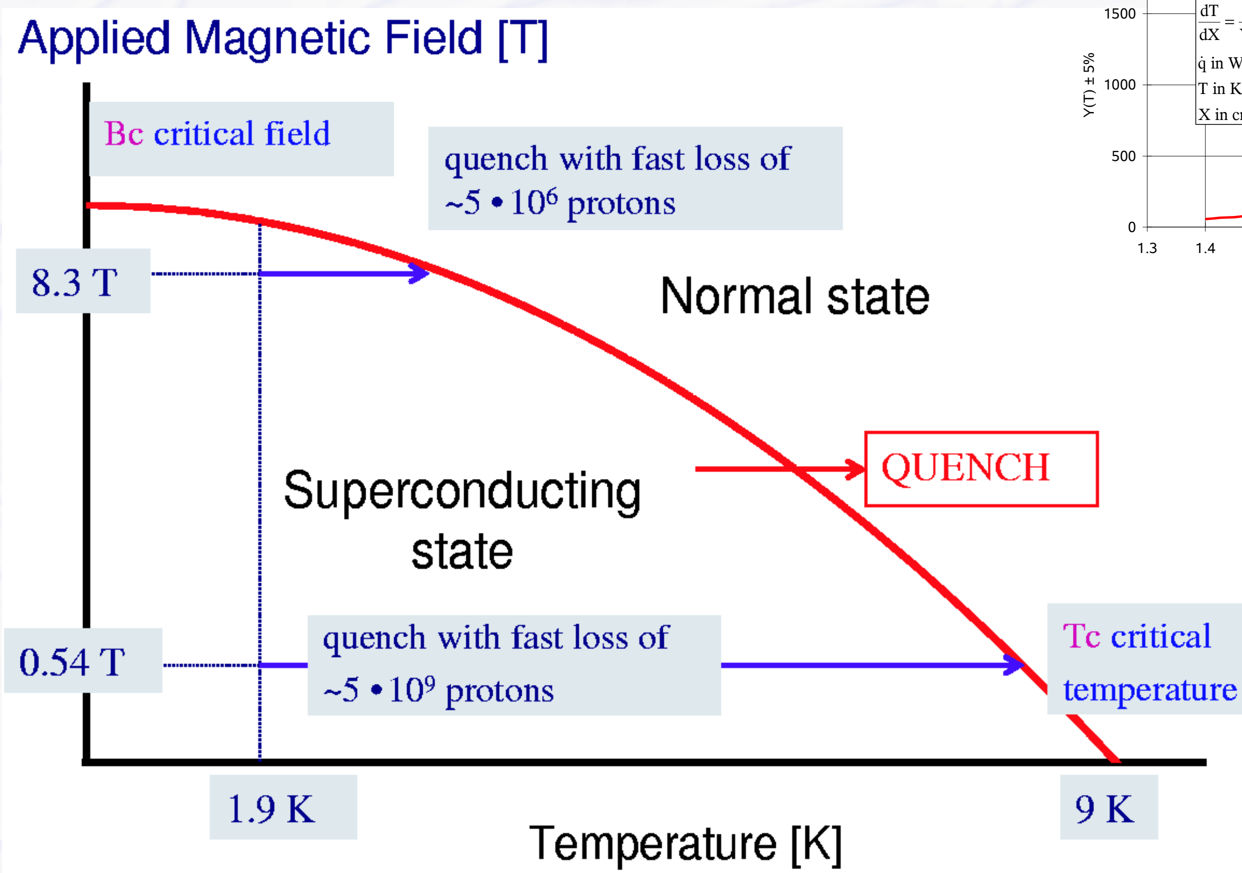
very small aperture (small vacuum chamber) = compact magnet = reduced cold mass

Cooling with Superfluid Helium (He II)

- LHC magnets (NbTi wires) work with superfluid Helium (1.9 K)
  - improved cooling capabilities
    - superfluid Helium also looses any friction
  - higher field possible

equivalent thermal conductivity peaks at 1.9 K





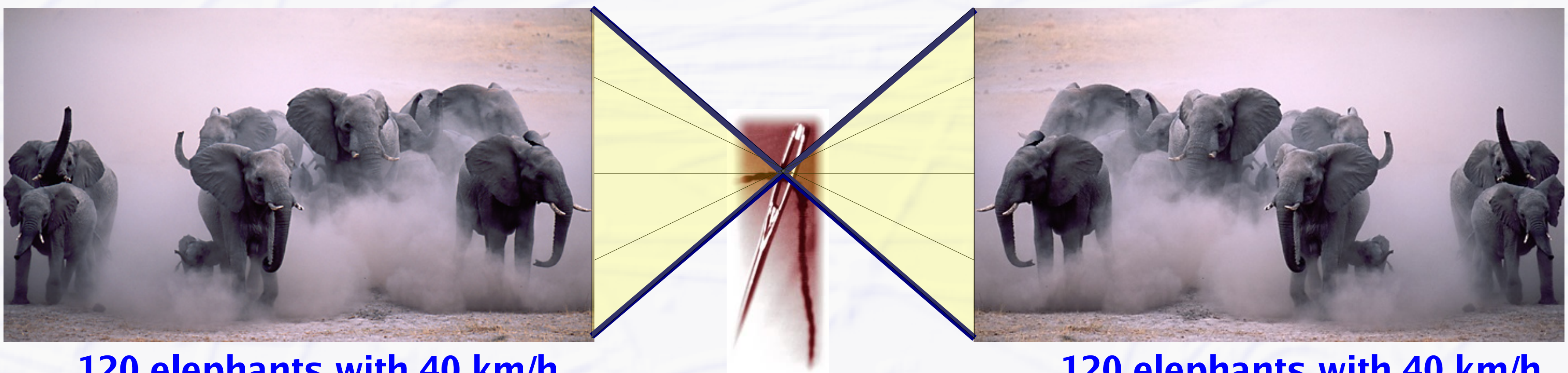
LHC in (popular) Numbers

- 1232 dipoles, 8.33 Tesla @ 7 TeV, 11850 A current
  - + 392 quadrupoles
  - + 3700 multipole corrector magnets + other 2500 corrector magnets
  - 1200 tons of NbTi superconducting cable with 7600 km length
  - stored energy in magnetic field 10 GJ
- total cold mass: 40'000 tons
  - 120 tons of superfluid Helium (1.9 K) for cooling
  - energy needed for quench:
    0.5 - 20 mJ/cm^3 = loss of < 10^7 protons at 7 TeV
- number of joints in between magnets
  - 10'000 superconducting splices (induction welding)
  - 50'000 splices for corrector circuits (ultrasonic welding)
- vacuum: 10^{-10} Torr = 3 million molecules per cm^3

LHC Beam Stored Energy

- 2808 bunches, 1.1 x 10^{11} protons/bunch @ 7 TeV
- 350 MJ stored energy per proton beam

Same as colliding 2 x 120 elephants...



120 elephants with 40 km/h

120 elephants with 40 km/h

The energy of a single 7 TeV proton is equivalent to a flying mosquito (1 µJ)

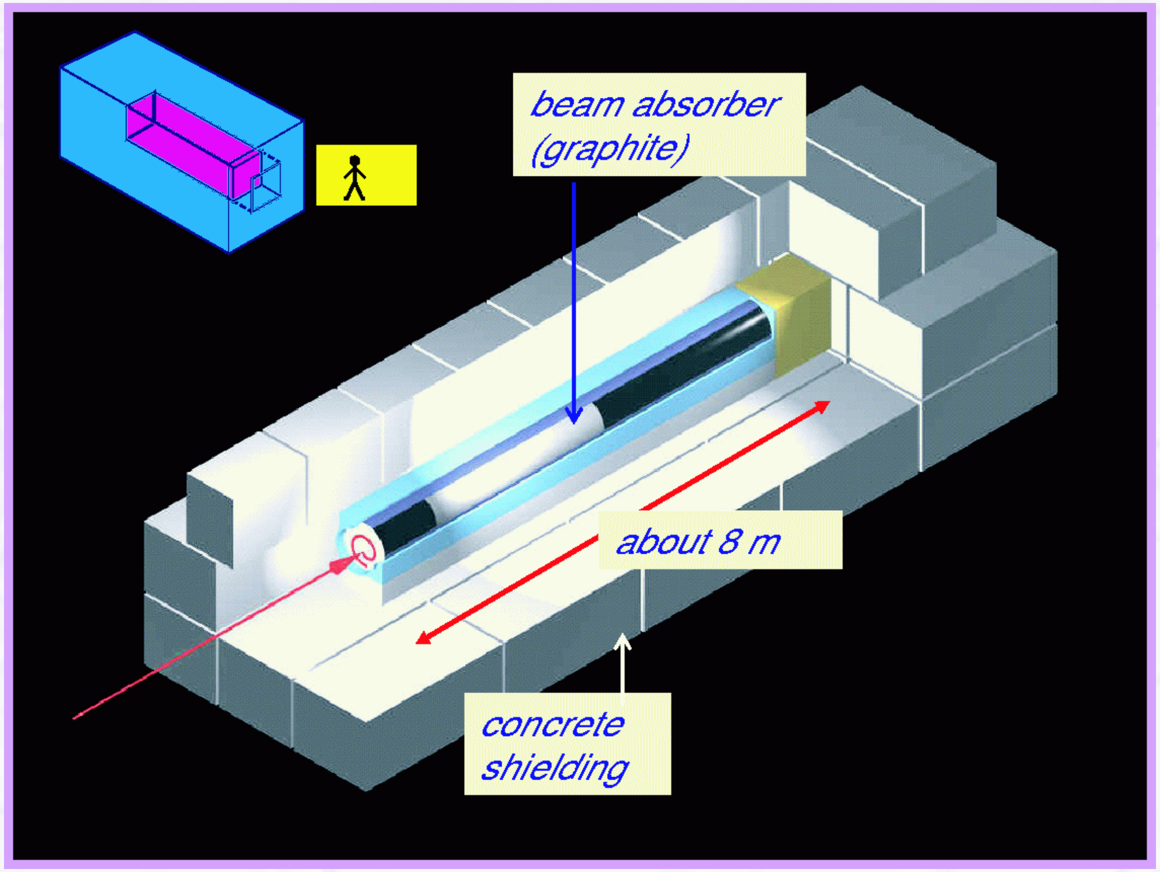
eye of a needle:
0.3 mm diameter

proton beams at interaction point are 10x smaller:
0.03 mm diameter

main problem at LHC is to control the stored energy and to avoid any damages

The LHC Beam Dump

- How to absorb 350 MJ of beam energy in 88 μs (one turn around LHC)
  - instantaneous beam power on dump = 4 TW
- Need graphite beam absorber
  - melting point ~ 3700 °C
  - heated up to ~1500 °C
- Also needed
  - "dilution kicker"
  - beam hits dump in a spiral

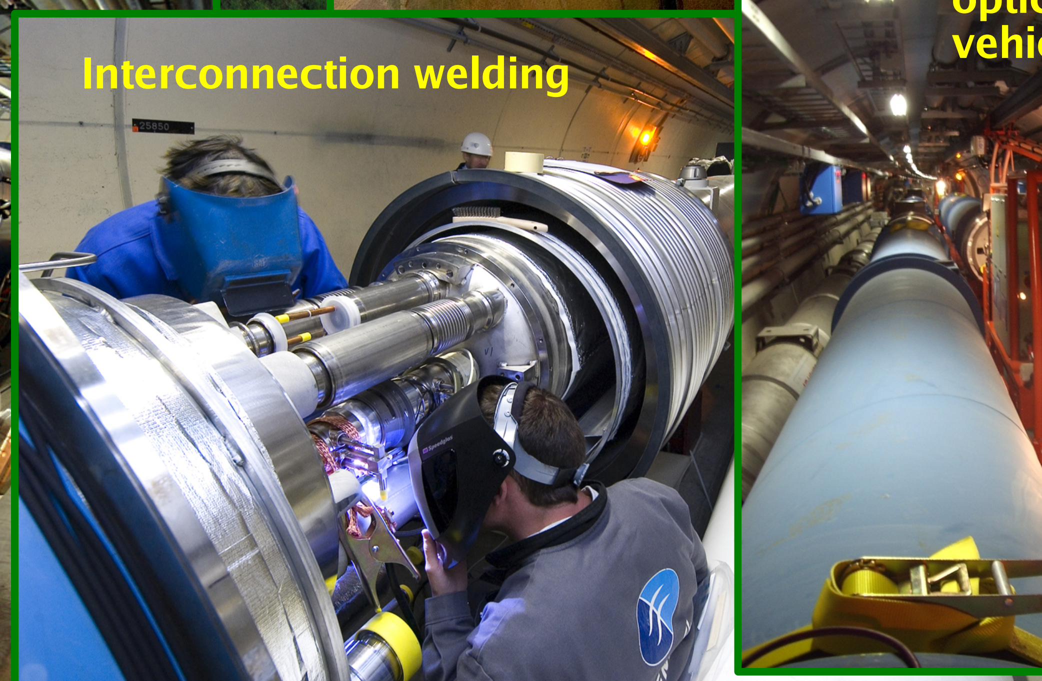


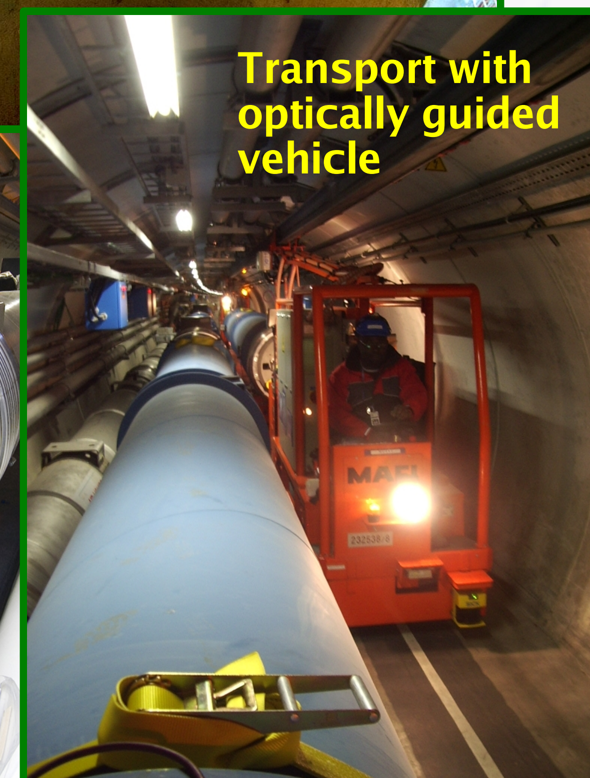
LHC Magnet Installation


Storage on car-parks all over CERN


Lowering through an elliptical shaft

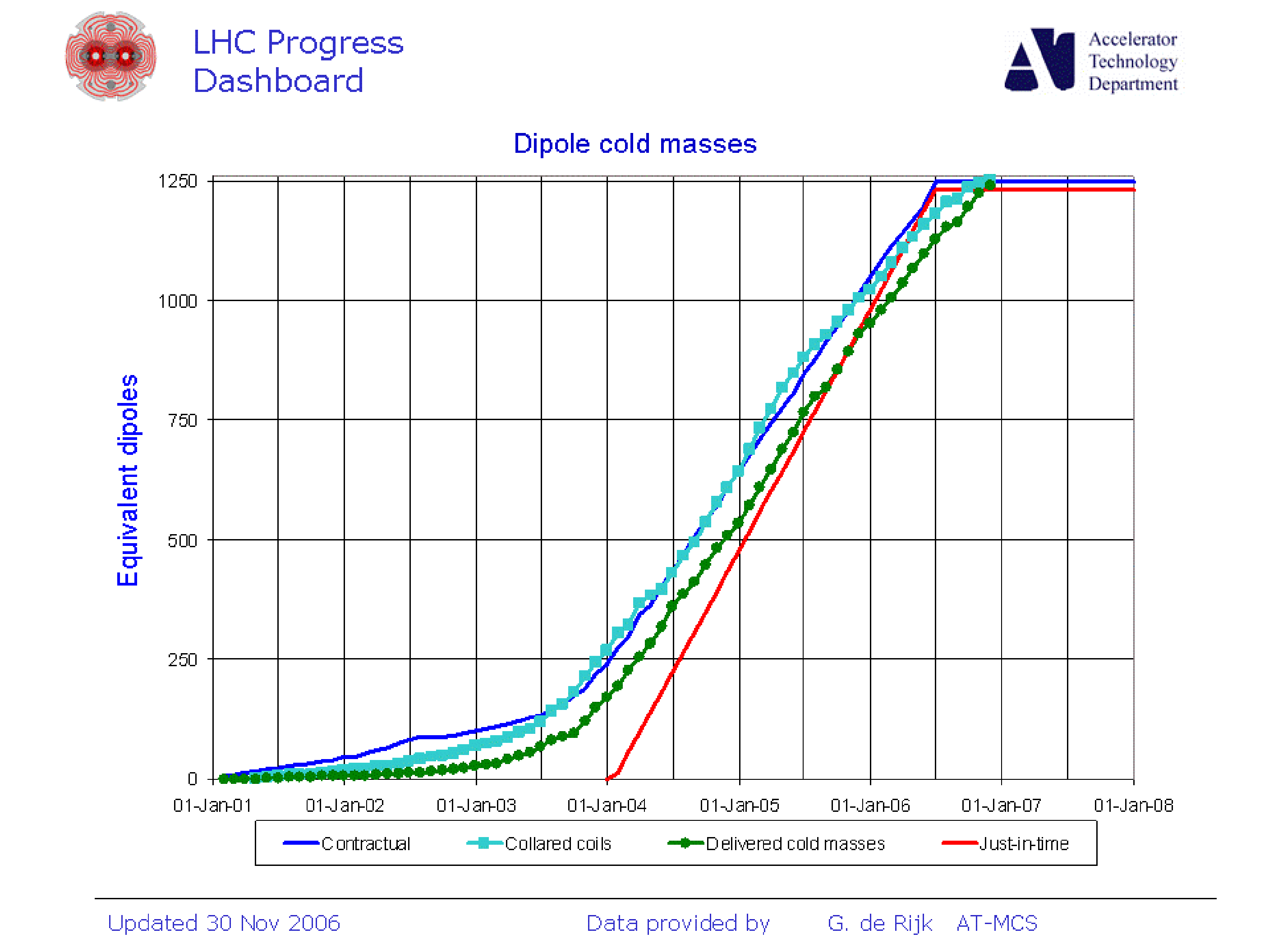

Quality Control


Interconnection welding


Transport with optically guided vehicle

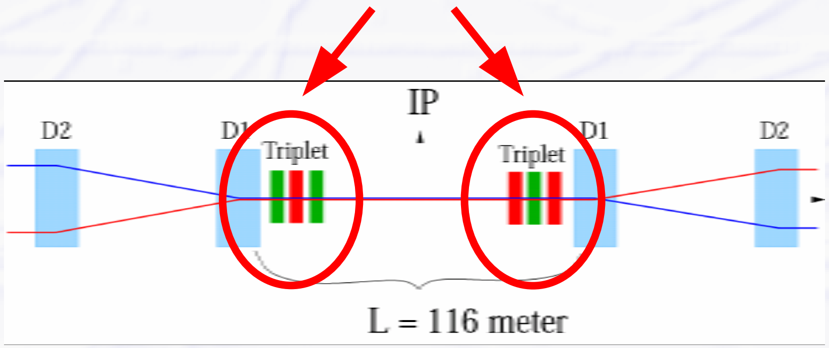
LHC Dipole Production 2001 - 2006

- **Magnet production was followed over many years by "dashboard" on CERN public homepage**

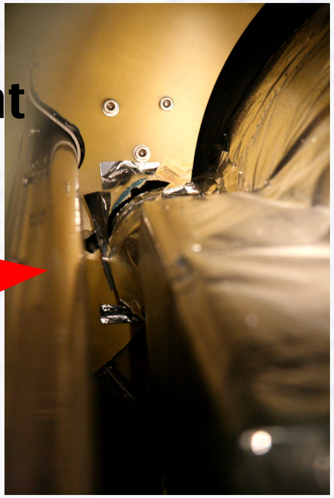


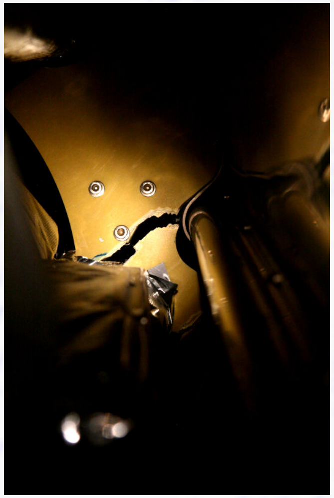
LHC Inner Tripletts...

- **High-pressure test of Inner Tripletts end of March 2007 failed**
  - Inner Tripletts = 3 very strong focussing quadrupoles in series on both sides of the interaction points



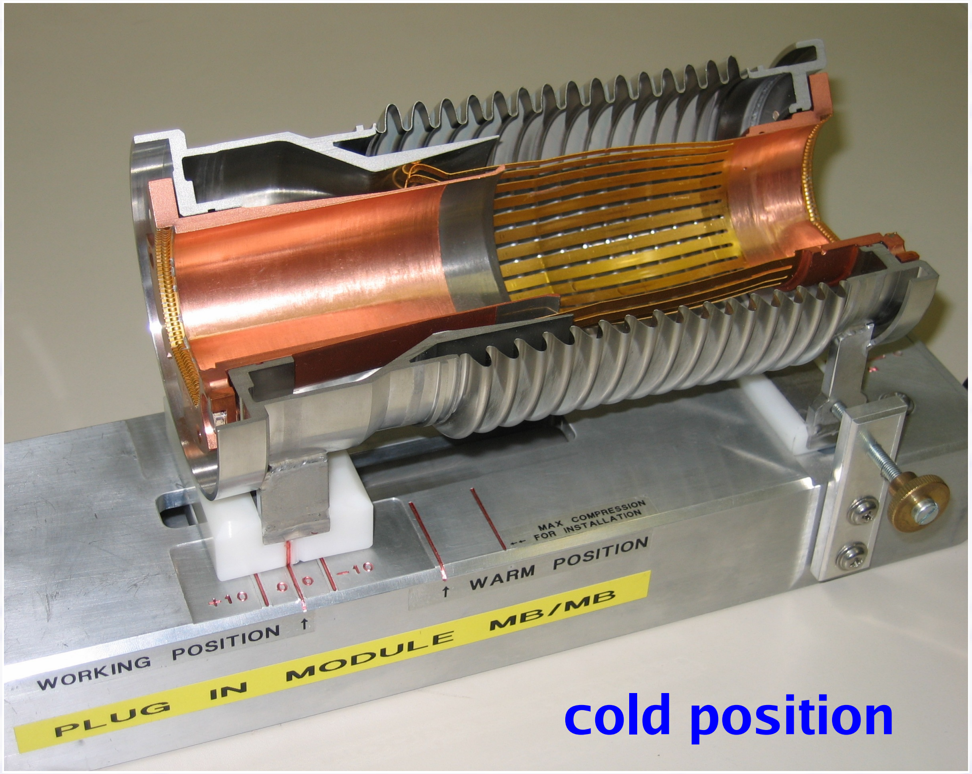
- **Mechanical support of pipes, tubes etc. broken**
  - strong longitudinal forces due to a quench of one of the magnets not taken into account





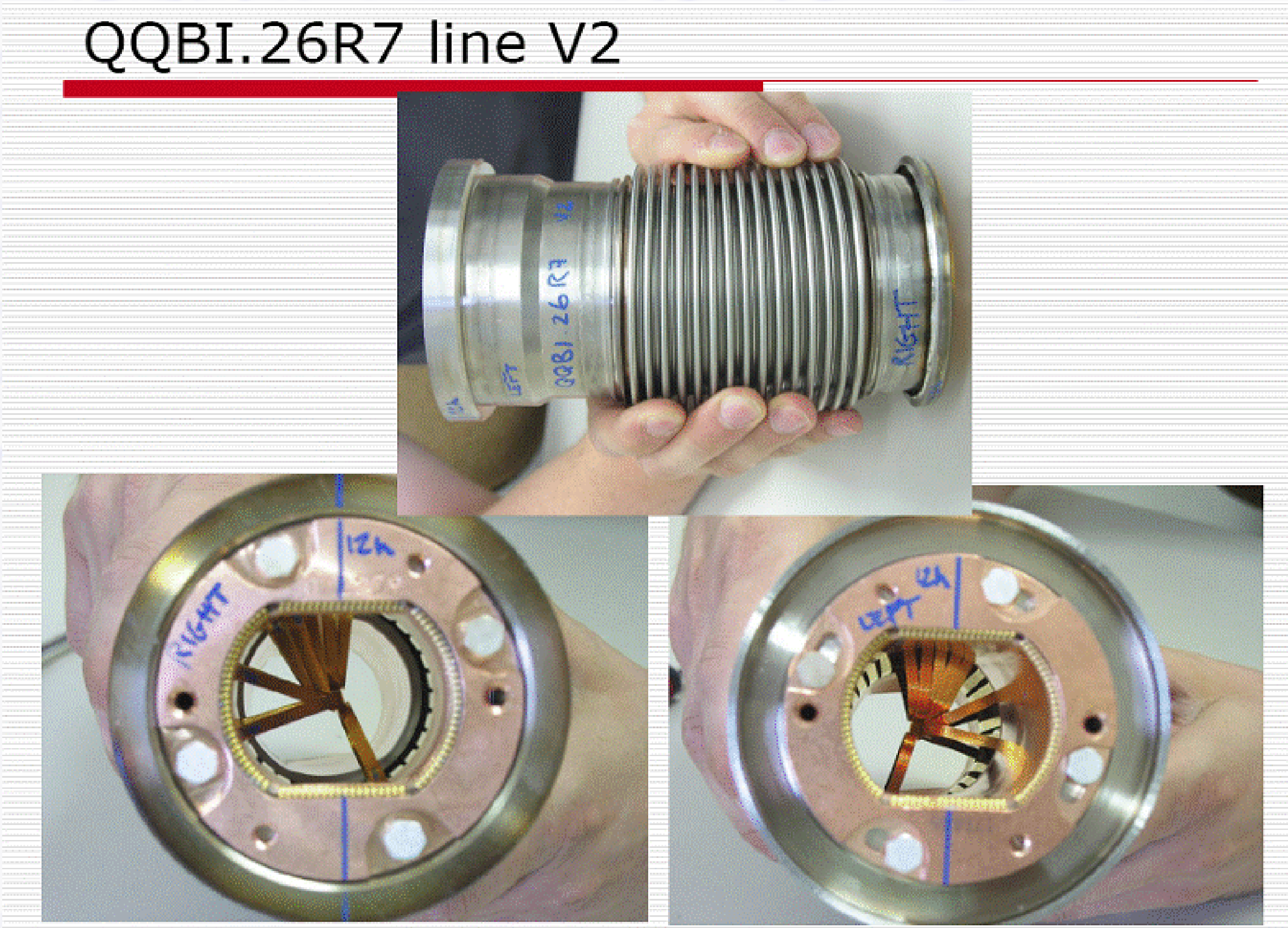
Beam Pipe Interconnection

- **Beam pipe between magnet needs to be flexible**
  - 18 m long dipoles shrink during cool-down by several cm
  - need bellows to follow elongation, but bellows bad for beam
    - large transverse impedance, beam disturbance
- **Need sliding RF-"fingers"**



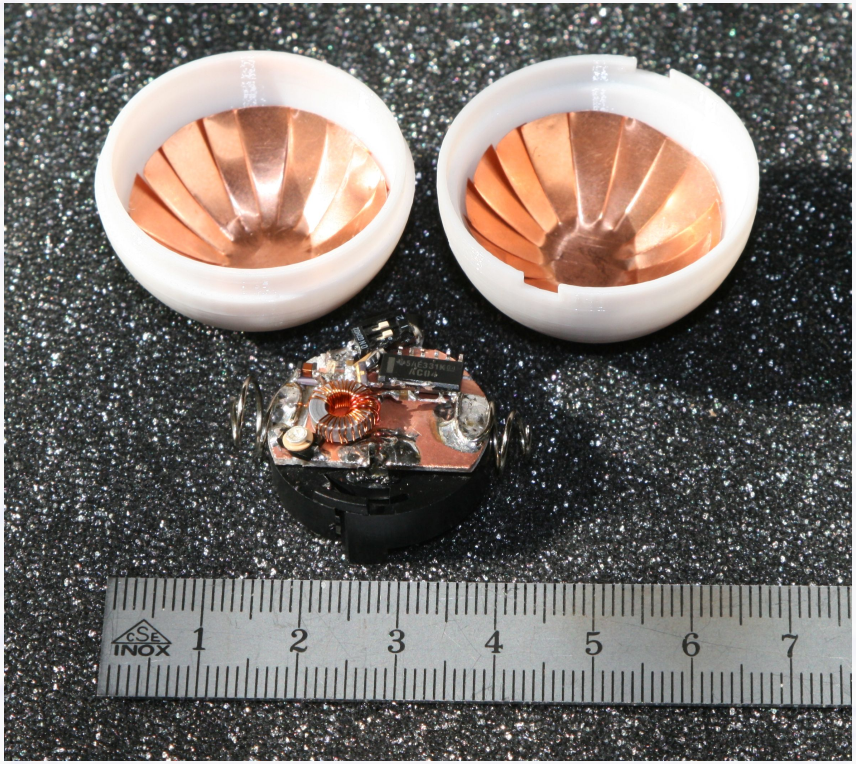
Interconnect Problem

- **After cool-down and warm-up (for repair work) of first sector some RF-fingers went stuck and extended into the beam path**



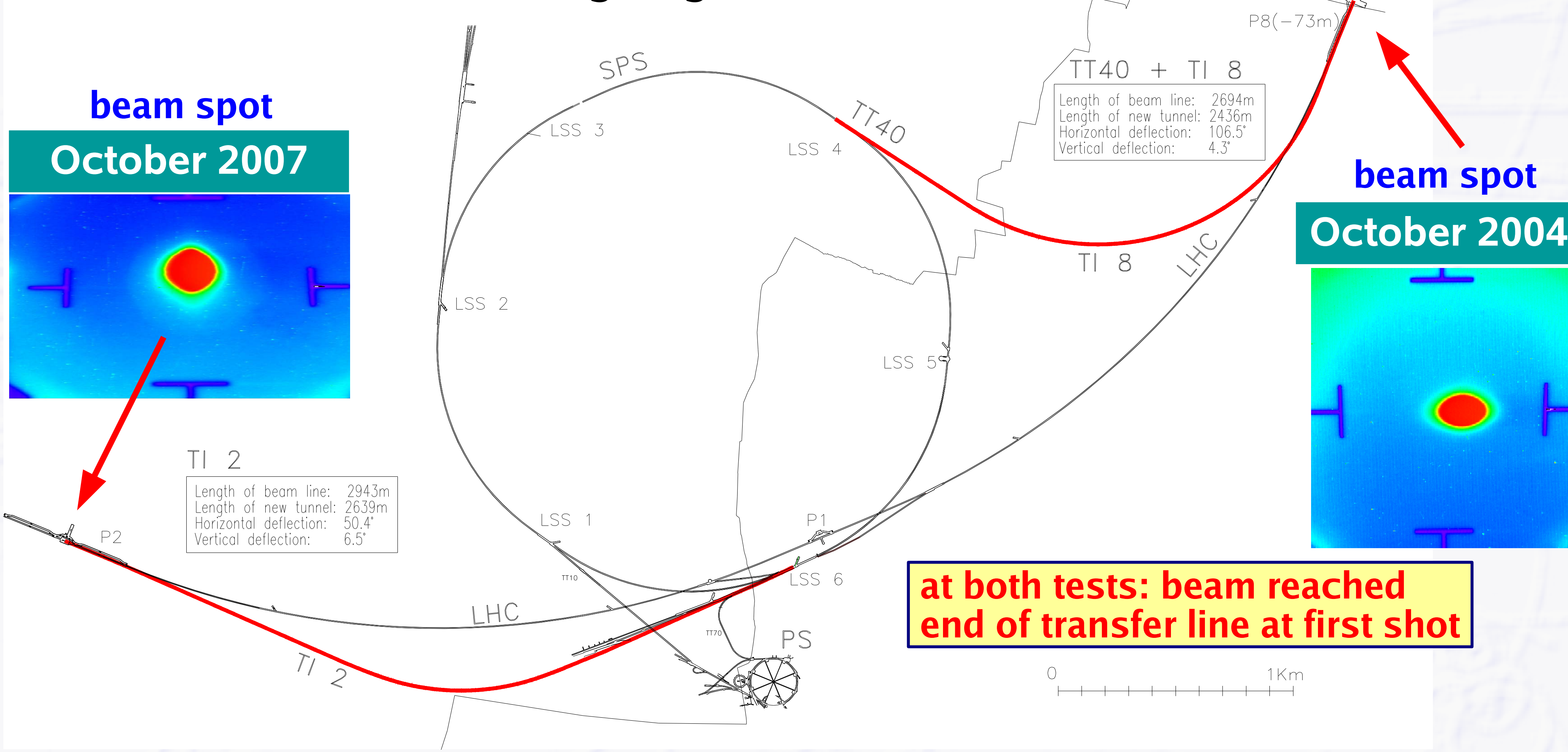
Solution: the RF-”Mole”

- Little “ping-pong” ball with 40 MHz RF-transmitter
  - 40 MHz signal seen by beam position monitoring system (bunch freq.)
- RF-mole pushed through beam pipe with compressed air
  - if stuck, beam position monitors detect position
  - beam pipe will be opened, obstacle removed (bad RF-finger)
- Alternative methods
  - X-ray the suspious interconnect
    - slower, needs more effort
  - Send RF-pulse through beam pipe
    - reflected from obstacles, time gives distance (“RADAR”)



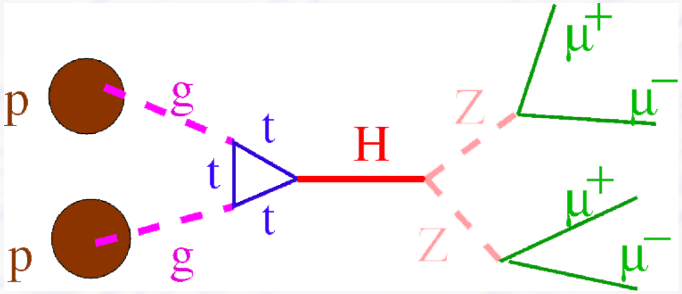
First Beam Tests of Transfer Lines

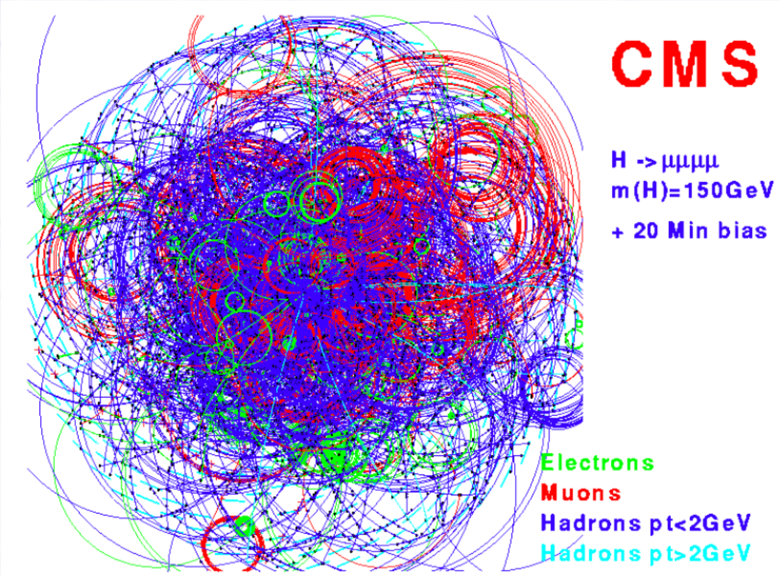
- 5.6 km total length of transfer lines SPS -> LHC
  - = ¾ of full SPS ring
  - >700 normal conducting magnets



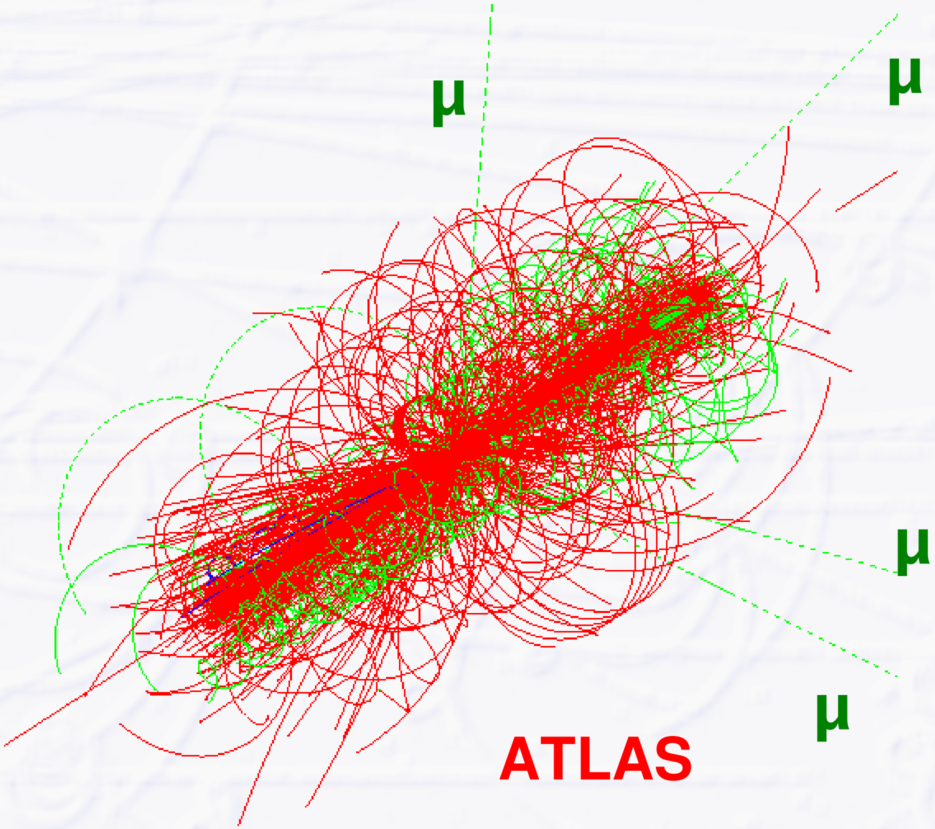
What we have to expect at LHC

- **One bunch crossing every 25 ns with ~20 interactions**
  - 1000 tracks per bunch crossing = 4 * 10^{10} tracks per second...
  - ...and very often you're interested in a few tracks only...





$pp \rightarrow H \rightarrow ZZ \rightarrow 4\mu$



Detector Challenges at LHC

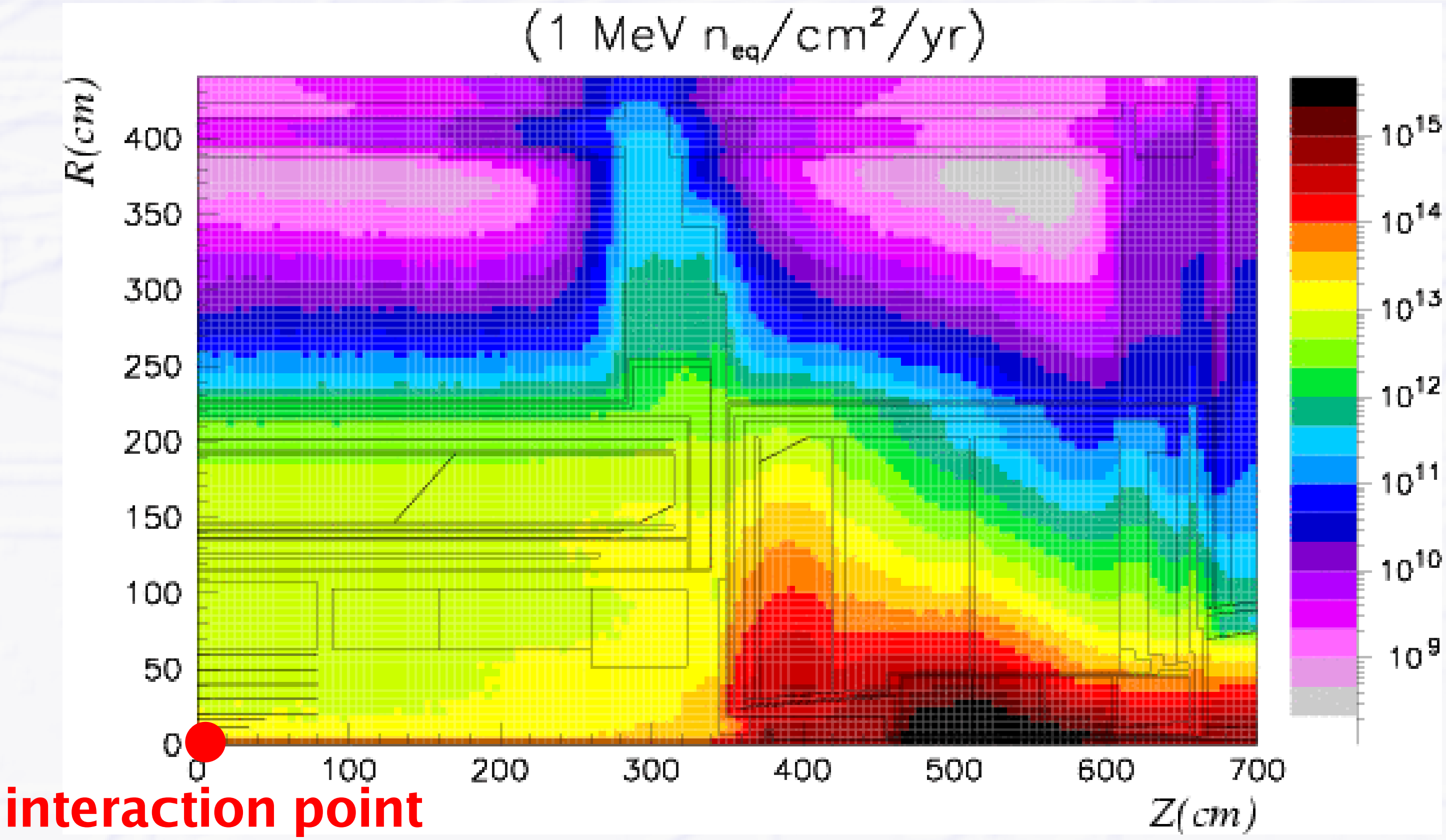
- **High energy collisions**
  - ➔ sufficiently high momentum resolution up to TeV scale
- **High luminosity (high interaction rate)**
  - ➔ high rate capabilities, fast detectors (25ns bunch crossing rate)
- **High particle density**
  - ➔ high granularity, sufficiently small detector cells to resolve particles
- **High radiation (lots of stongly interacting particles)**
  - radiation mainly due to particles emerging from collisions, not machine background
  - ➔ radiation-hard detectors and electronics (have to survive ~10 years)

- **LARGE collaborations!!!**
  - ➔ ~O(2000) physicists for ATLAS and CMS each
  - ➔ communication, sociological aspects
    - exponential raise of meetings, phone + video conferences...

Radiation Doses

200 MRad

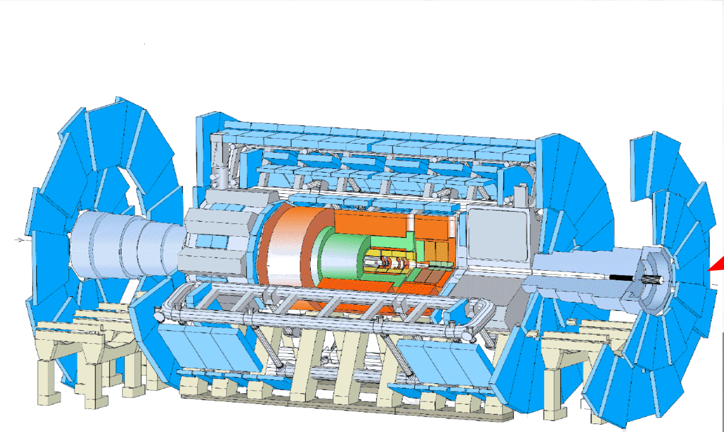
- ~ 2 x 10^6 Gray / r_T^2 / year at LHC design luminosity
  - where r_T [cm] = transverse distance to the beam
- Lots of R&D over >10 years to develop rad.-hard silicon detectors, gaseous detectors and electronics



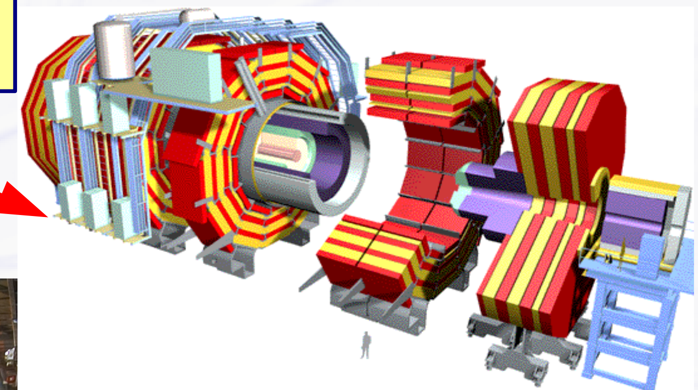
ATLAS neutron fluences

LHC Detectors

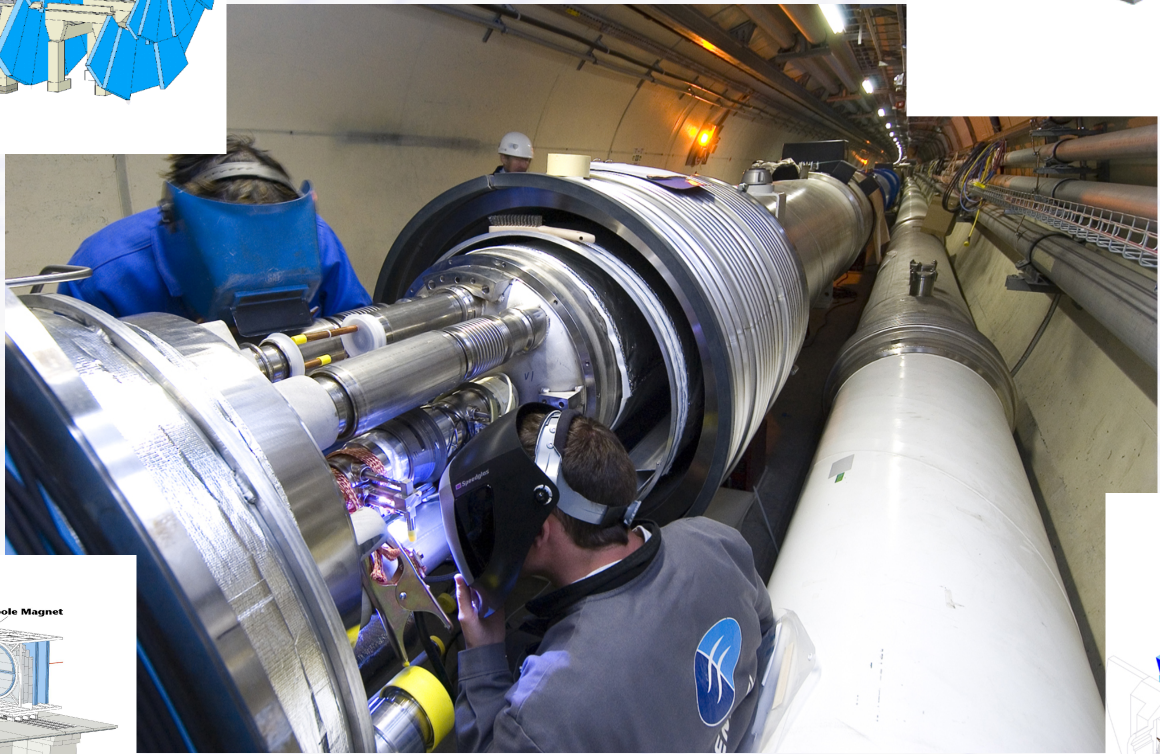
General purpose detectors
(good for everything...)



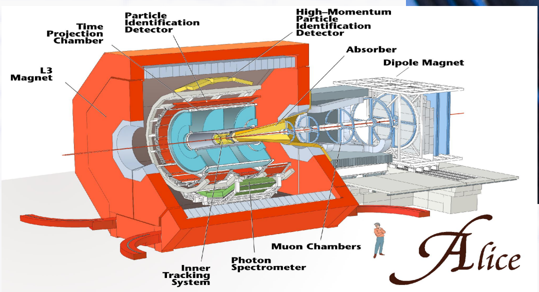
ATLAS



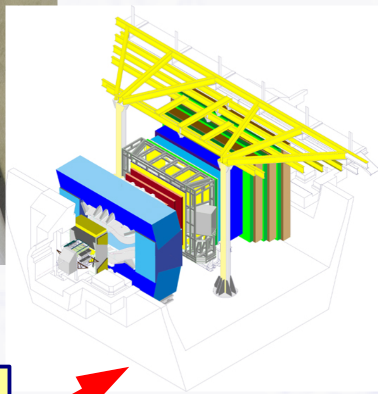
CMS



ALICE



LHCb



dedicated for
Heavy Ion collisions

dedicated for
b-physics

The Perfect Detector...

- ...should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get 4-momenta)
  = measure momentum + energy of all particles

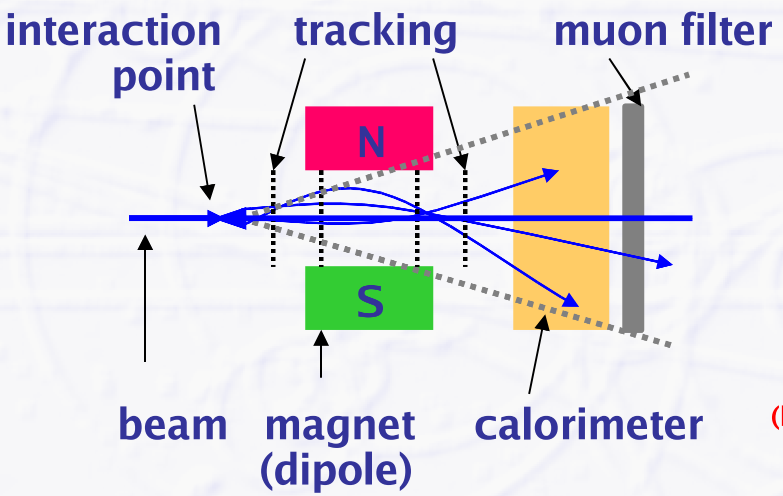
  → but limited efficiency, momentum and energy resolutions at real detector

  - not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas
    (holes, cracks for e.g. water cooling and gas pipes, cables, electronics, mechanics)

Fixed target geometry

"Magnet spectrometer"

LHCb



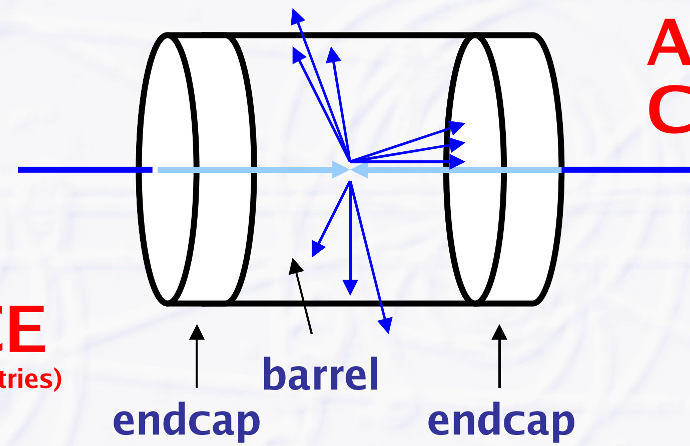
- Limited solid angle $d\Omega$ coverage
- rel. easy access (cables, maintenance)

ALICE
(both geometries)

Collider geometry

"4π multi purpose detector"

ATLAS
CMS



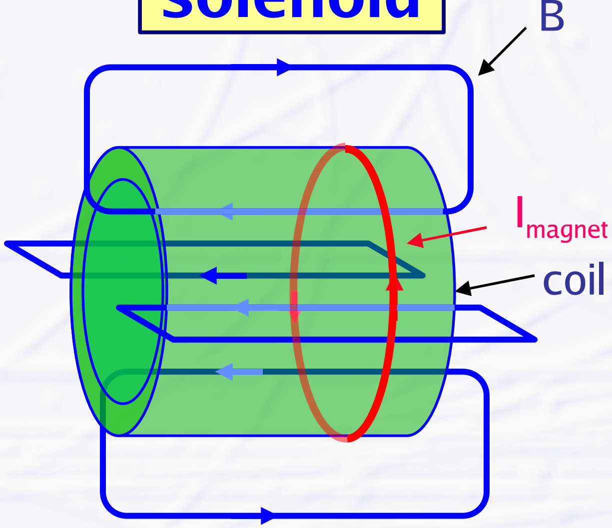
- "full" $d\Omega$ coverage
- very restricted access

High Energy Collider Detectors

- **Tracking Detector (or Tracker)** = momentum measurement
  - closest to interaction point: vertex detector (silicon pixels)
    - measures primary interaction vertex and secondary vertices from decay particles
  - main or central tracking detector
    - measures momentum by curvature in magnetic field
    - solid state detectors, Si strips (CMS, ATLAS) or gaseous detectors (ALICE, ATLAS)
- **Calorimeters** = energy measurement
  - electro-magnetic calorimeters
    - measures energy of light EM particles (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production
    - two concepts: homogeneous (CMS) or sampling (ATLAS)
  - hadron calorimeters
    - measures energy of heavy (hadronic) particles (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions
- **Muon Detectors** = momentum measurement for muons (more precise)
  - outermost detector layer, basically a tracking detector

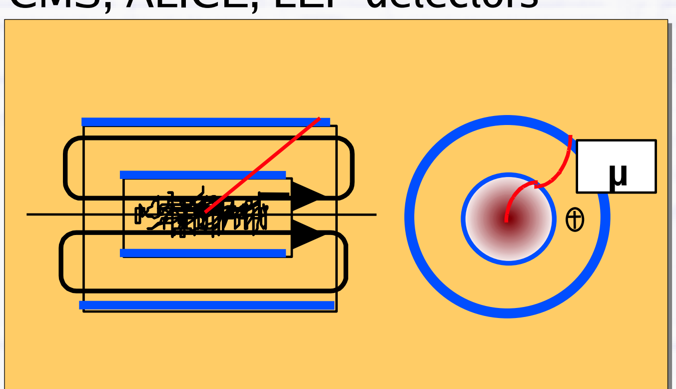
Magnet Concepts of LHC experiments

solenoid

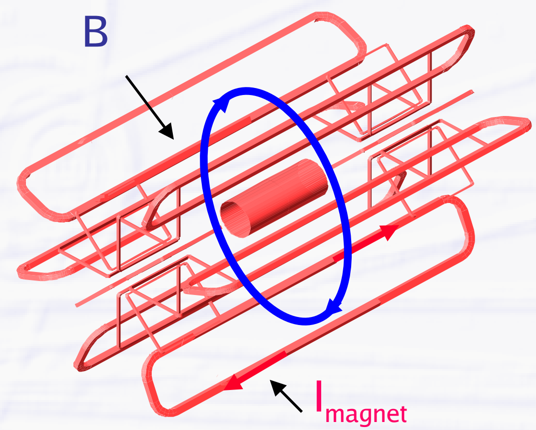


- \+ large homogenous field inside coil
- \- needs iron return yoke (magnetic shortcut)
- \- limited size (cost)
- \- coil thickness (radiation lengths)

CMS, ALICE, LEP detectors

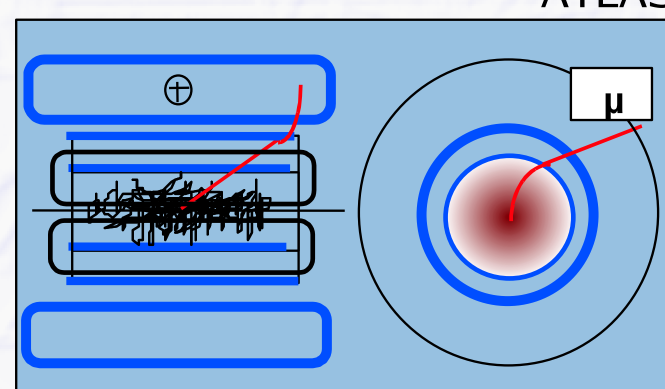


(air-core) toroid

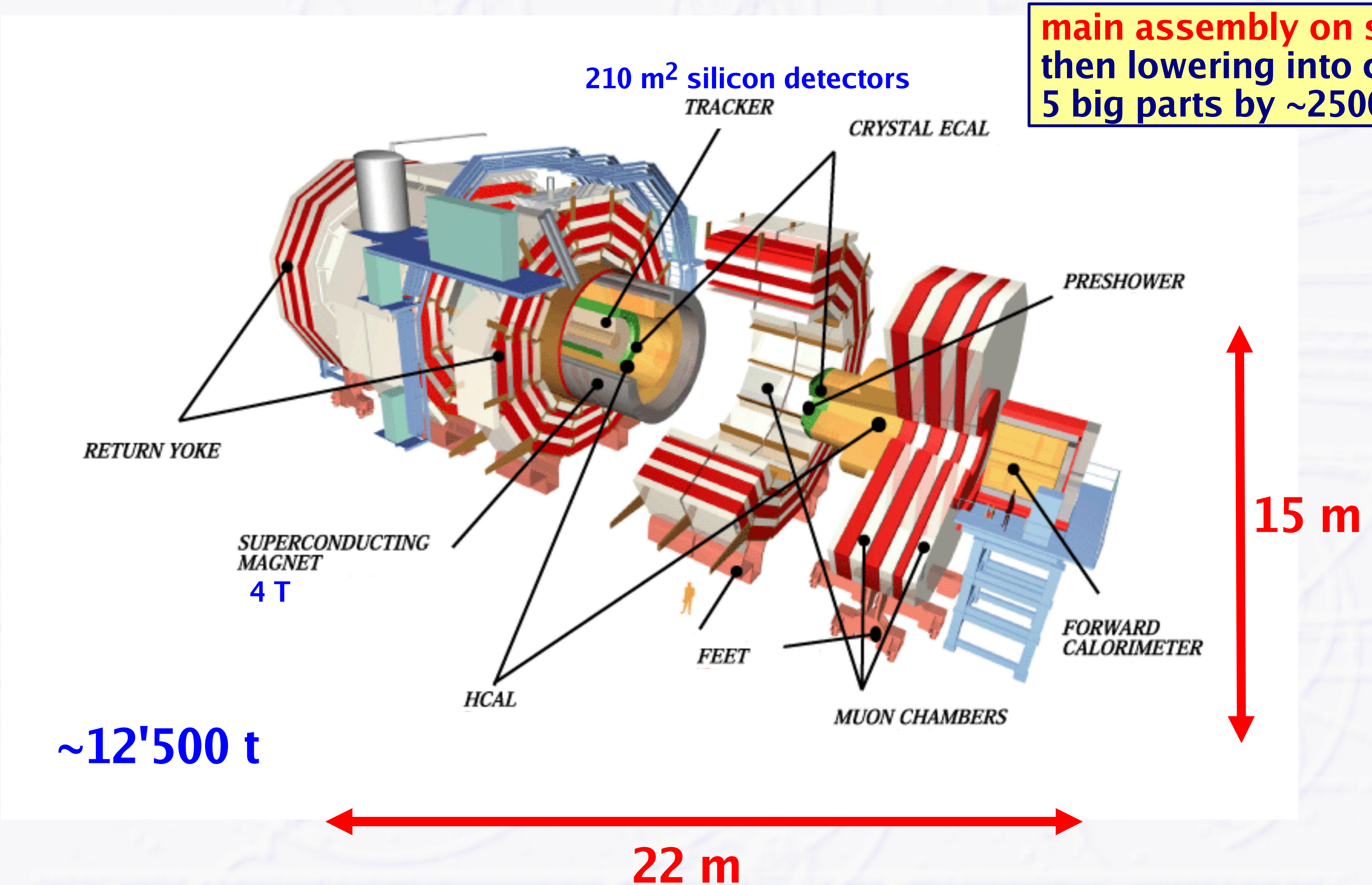


- \+ can cover large volume
- \+ air core, no iron, less material
- \- needs extra small solenoid for general tracking
- \- non-uniform field
- \- complex structure

ATLAS



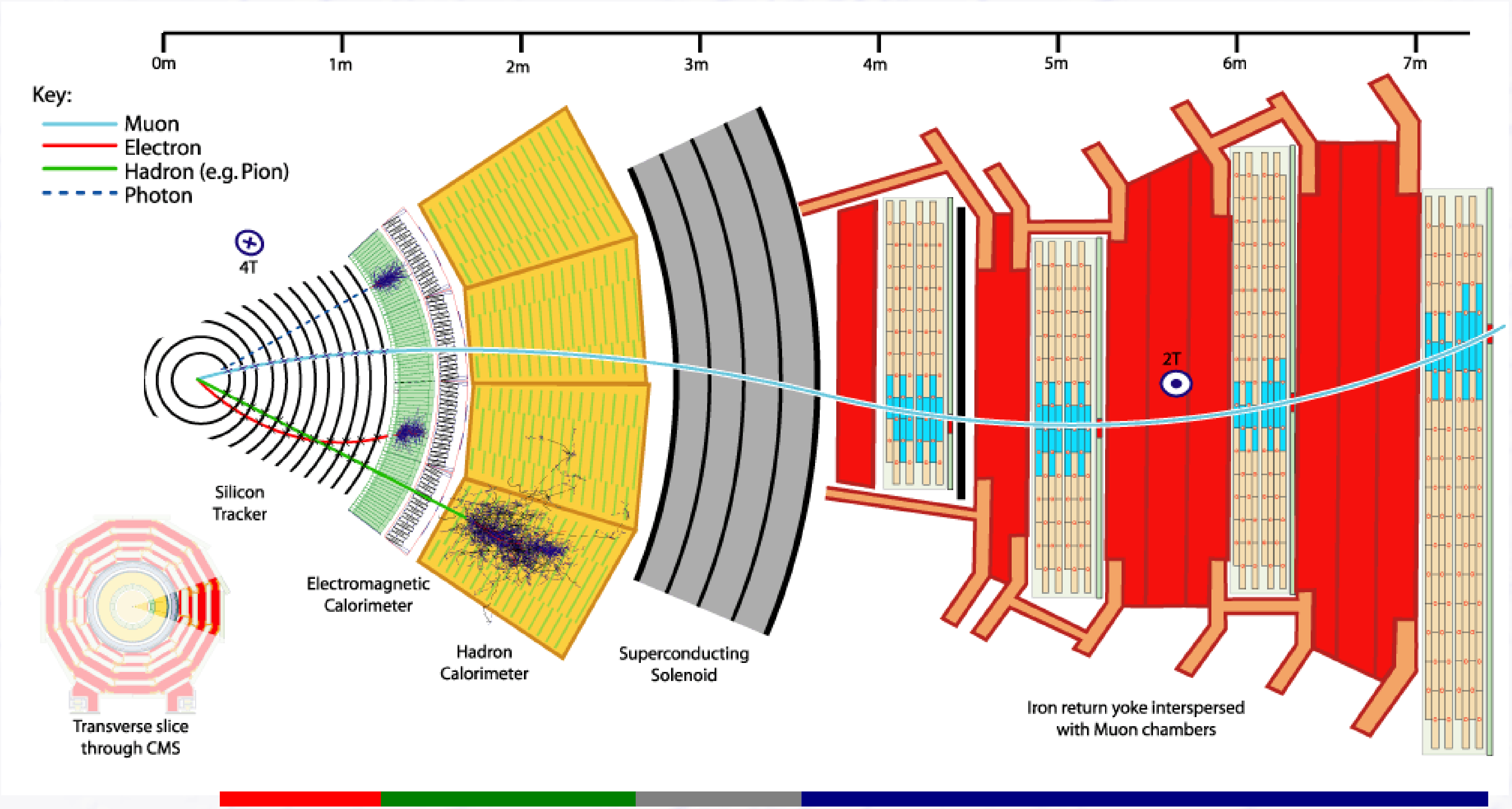
CMS (Compact Muon Spectrometer)



main assembly on surface, then lowering into cavern in 5 big parts by ~2500 t crane

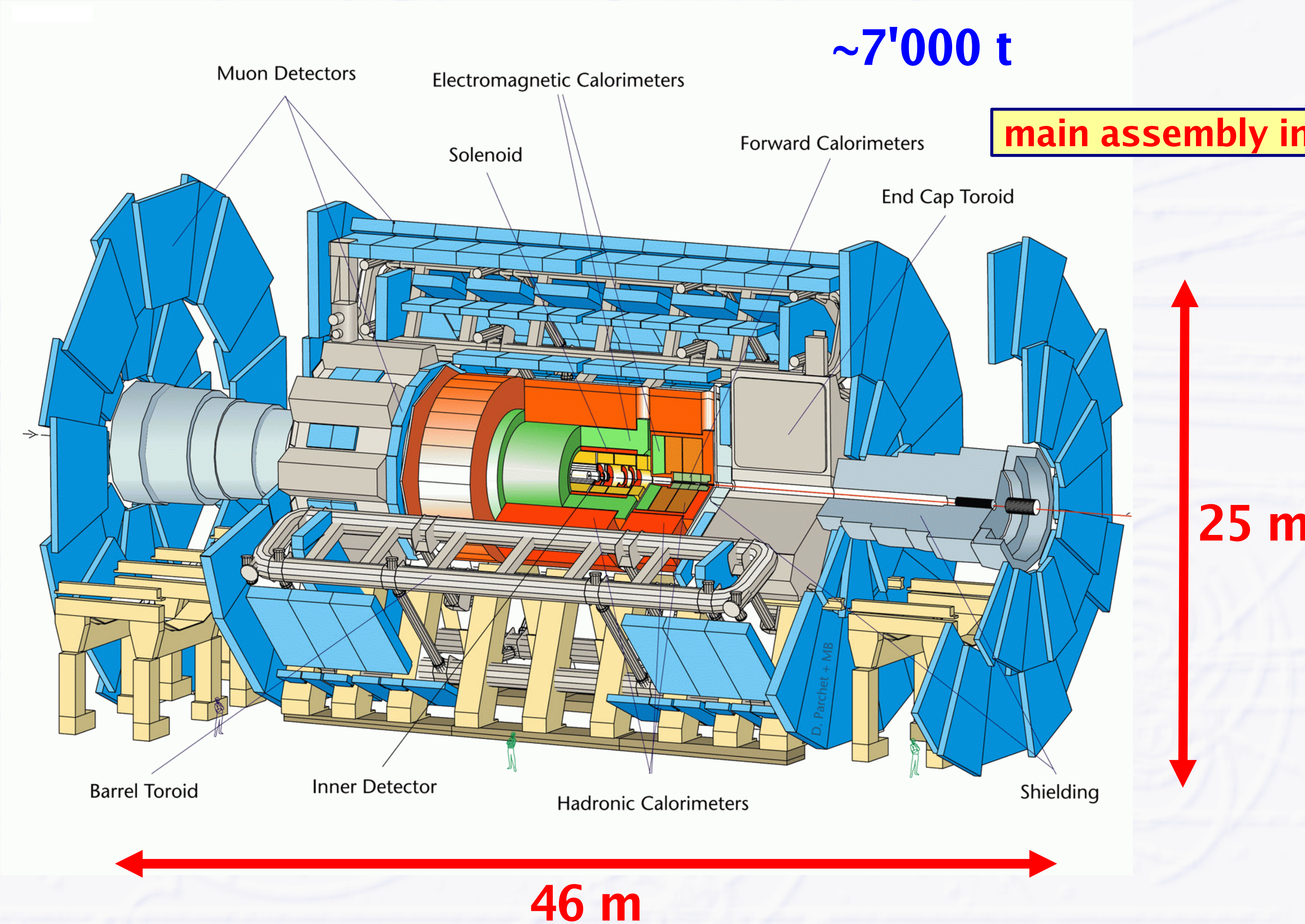
A typical Particle Detector

- Cut-away view of CMS

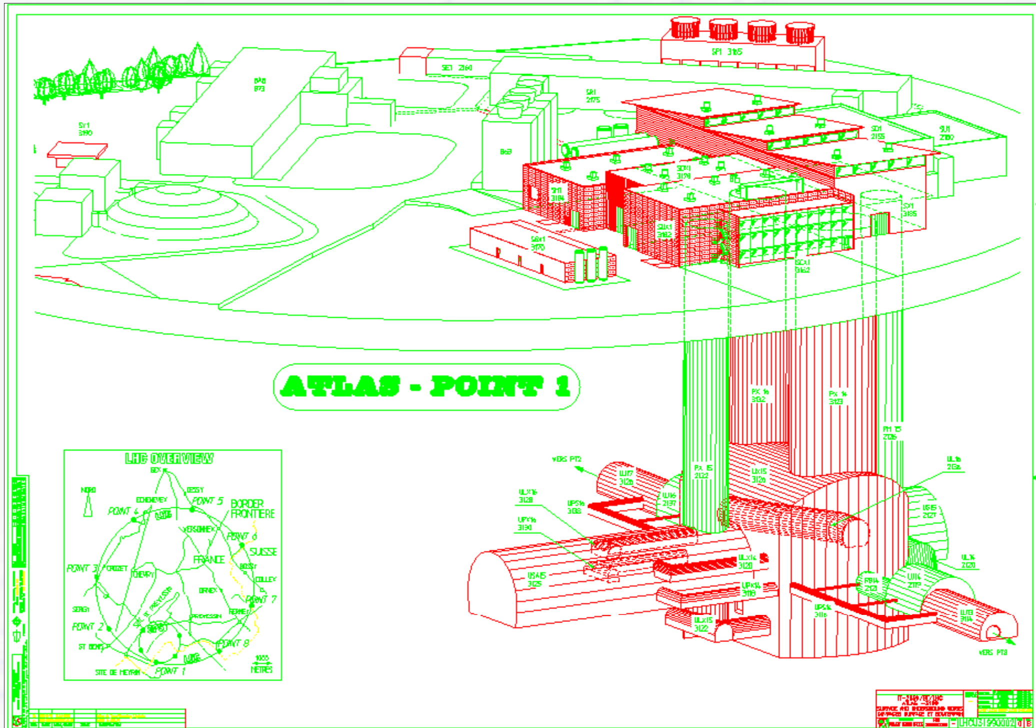


Tracker | Calorimeter | Coil | Muon Detector and iron return yoke

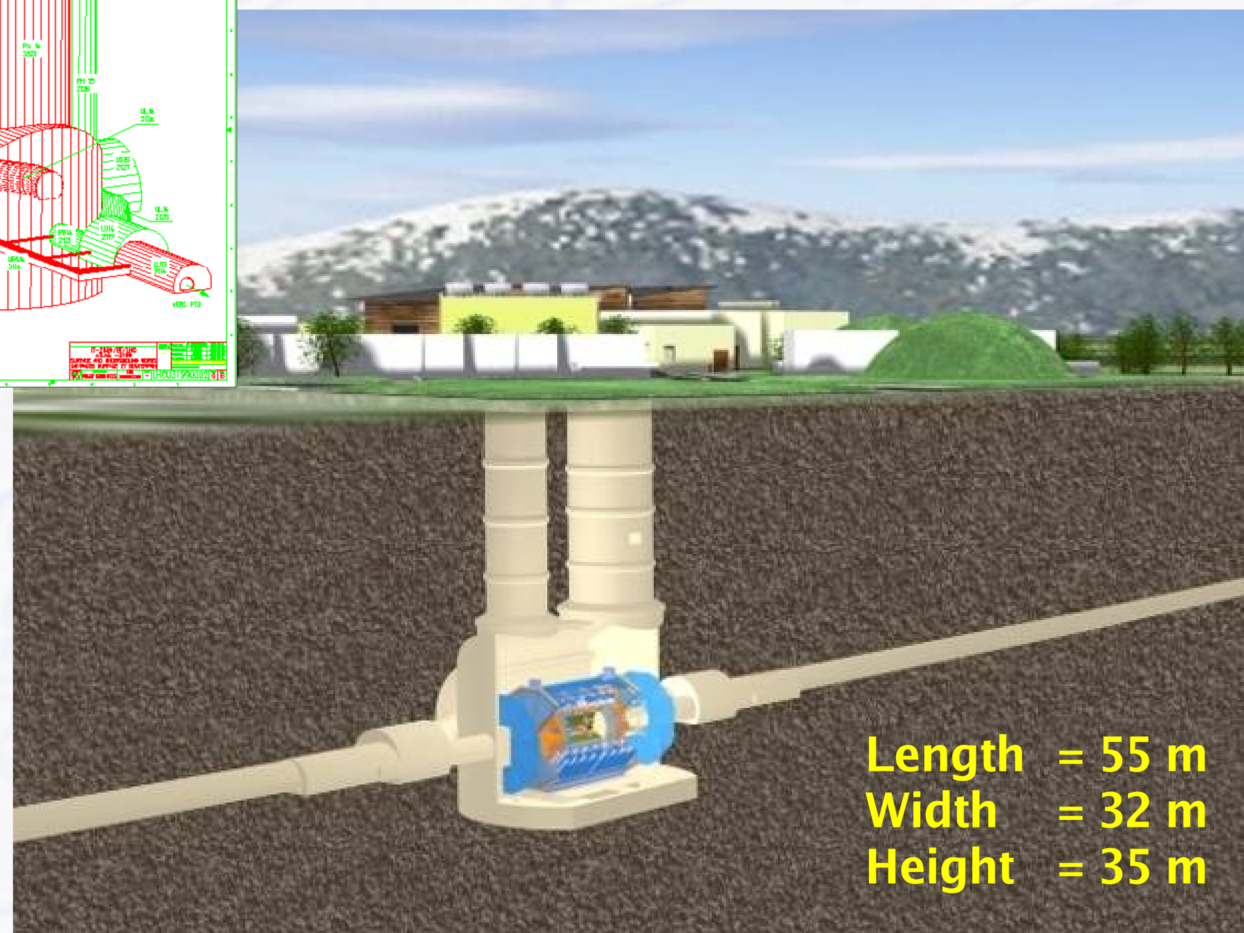
ATLAS (A Toroidal LHC ApparatuS)



ATLAS Underground Cavern

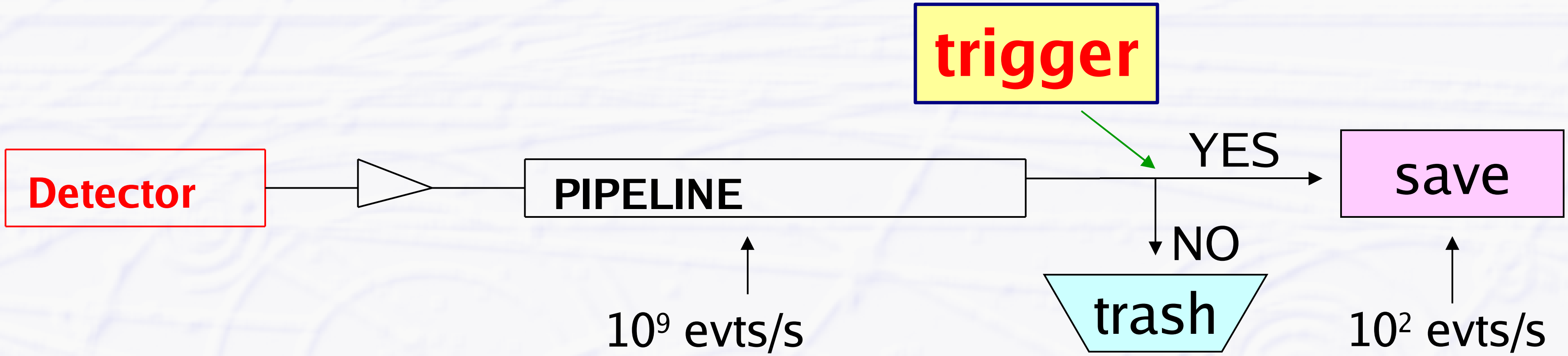


Huge cavern + surface buildings,
2 access shafts 18m + 12m Ø,
2 small shafts for elevators + stairs



How to Select Interesting Events?

- **Bunch crossing rate: 40 MHz, ~20 interactions per BX** (10^9 evts/s)
  - can only record ~200 event/s (1.5 MB each), still 300 MB/s data rate
- **Need highly efficient and highly selective TRIGGER**
  - raw event data (70 TB/s) are stored in pipeline until trigger decision

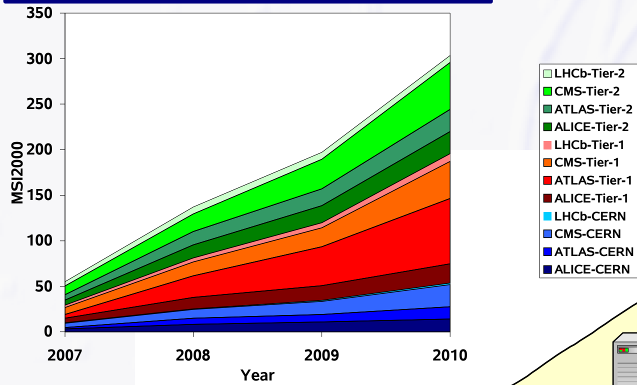


- **ATLAS trigger has 3 levels (CMS similar with 2 levels)**
  - Level-1: hardware, ~3 μs decision time, 40 MHz → 100 kHz
  - Level-2: software, ~40 ms decision time, 100 kHz → 2 kHz
  - Level-3: software, ~4 s decision time, 2 kHz → 200 Hz

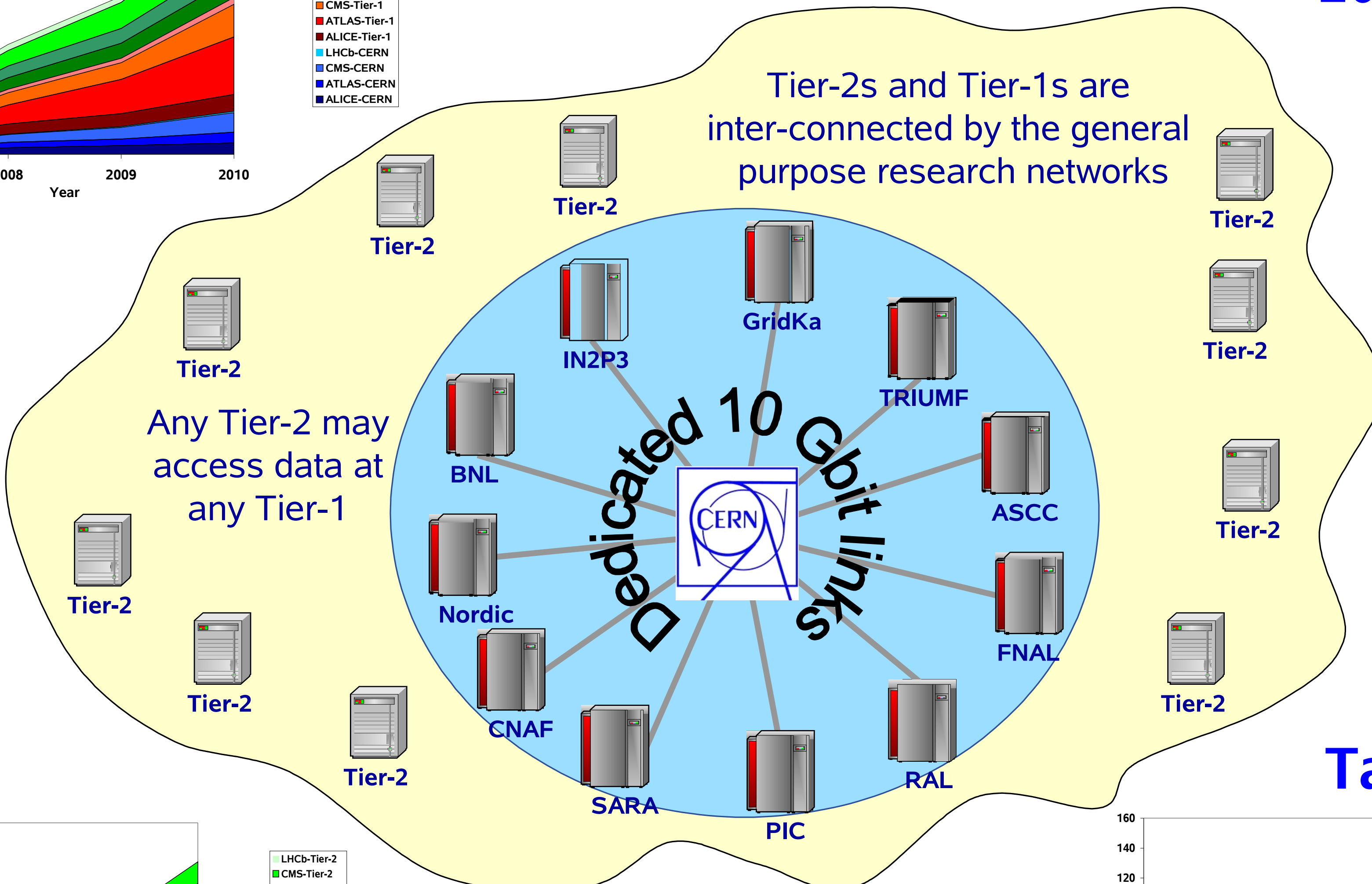
The Grid

raise by ~100 MSI2k/year
~10'000 Intel Core 2 Duo / year

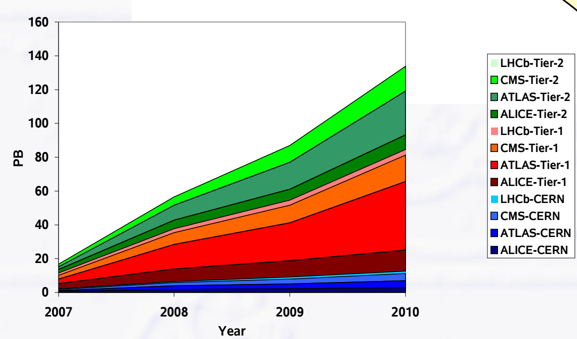
1 Tier-0
10 Tier-1
~100 Tier-2



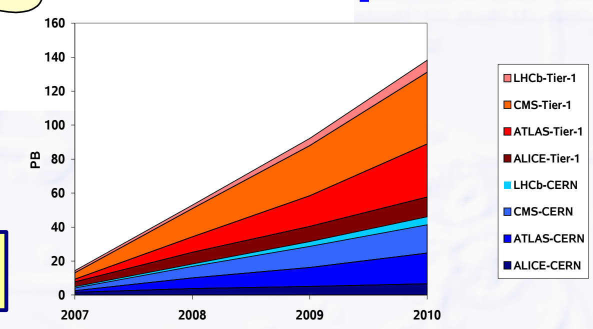
CPU



Disk



Tape



~15 PB/year disk + tape space

Start of Digging in 1998

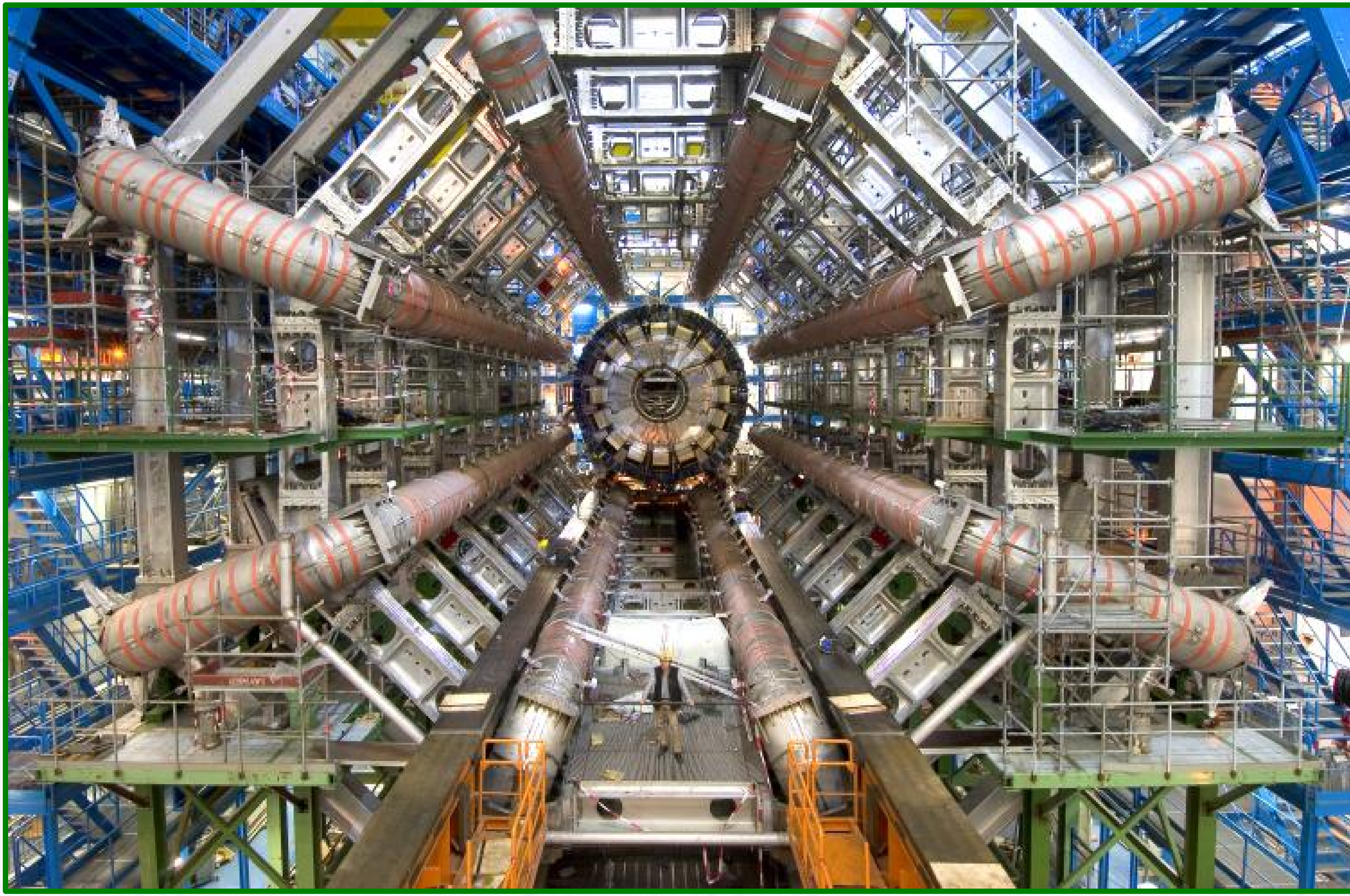
Gallo-roman remains
on future CMS site

ATLAS cavern
September 2000

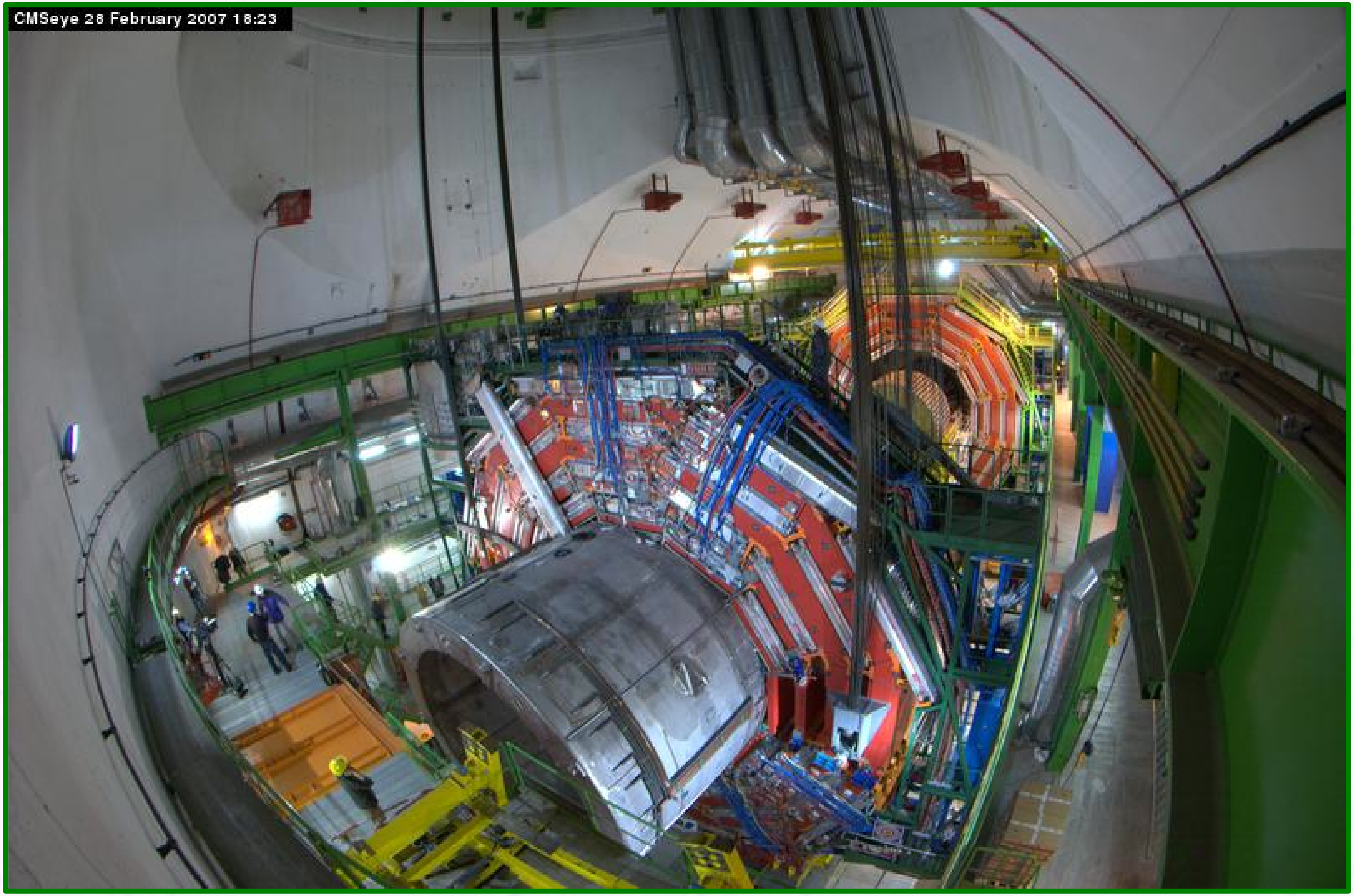
Start of ATLAS Construction

Transport and lowering of first superconducting Barrel Toroid coil

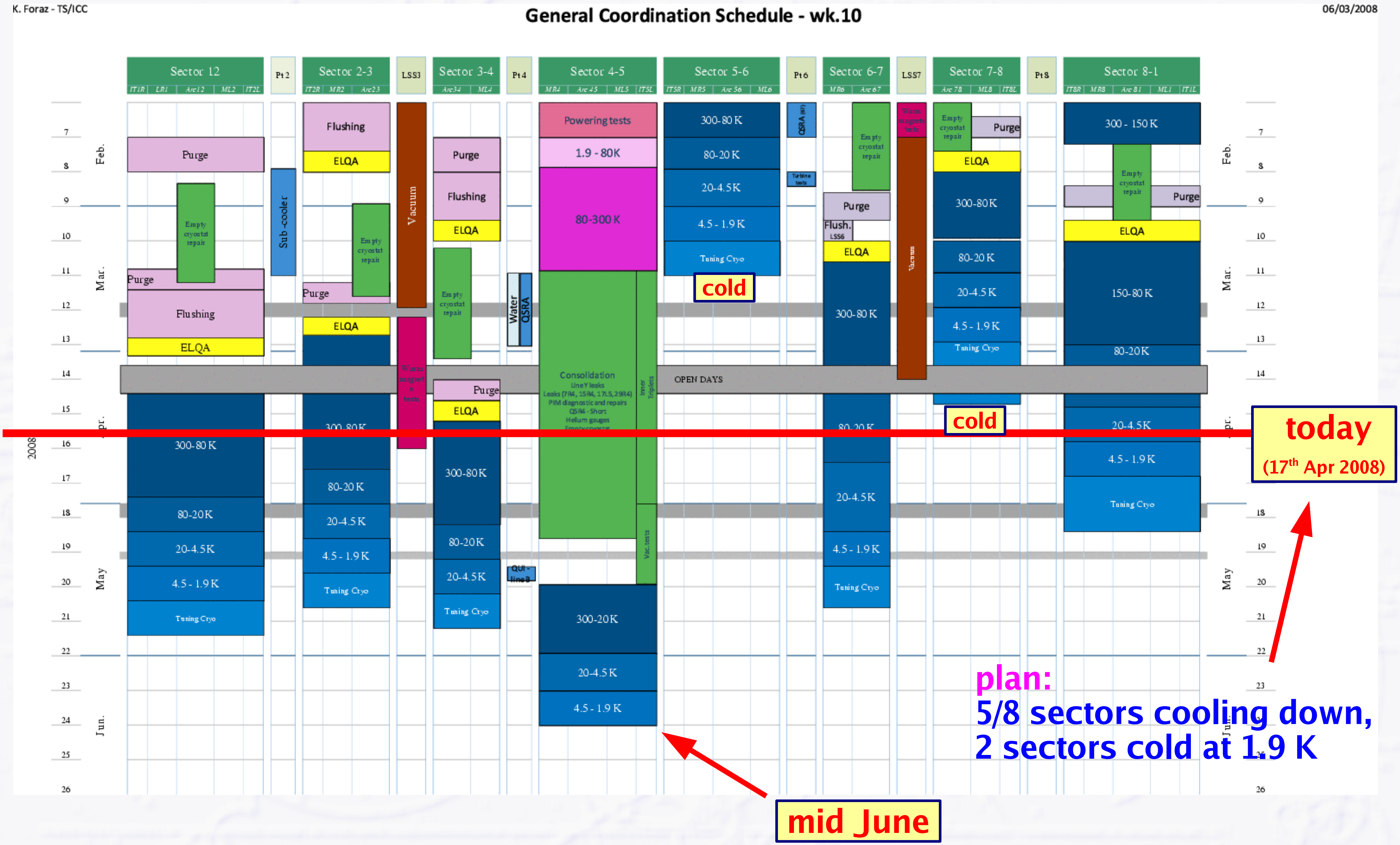
ATLAS Barrel Toroid Complete *(Nov 2005)*



CMS Lowering of 2000 t Central Part



LHC Cooldown Schedule



Cooldown Status *(as of 17th Apr 2008, 2pm)*

only ~1 week delay w.r.t. to cooldown schedule

sector 12: warm

sector 23: 140-240 K

sector 34: warm

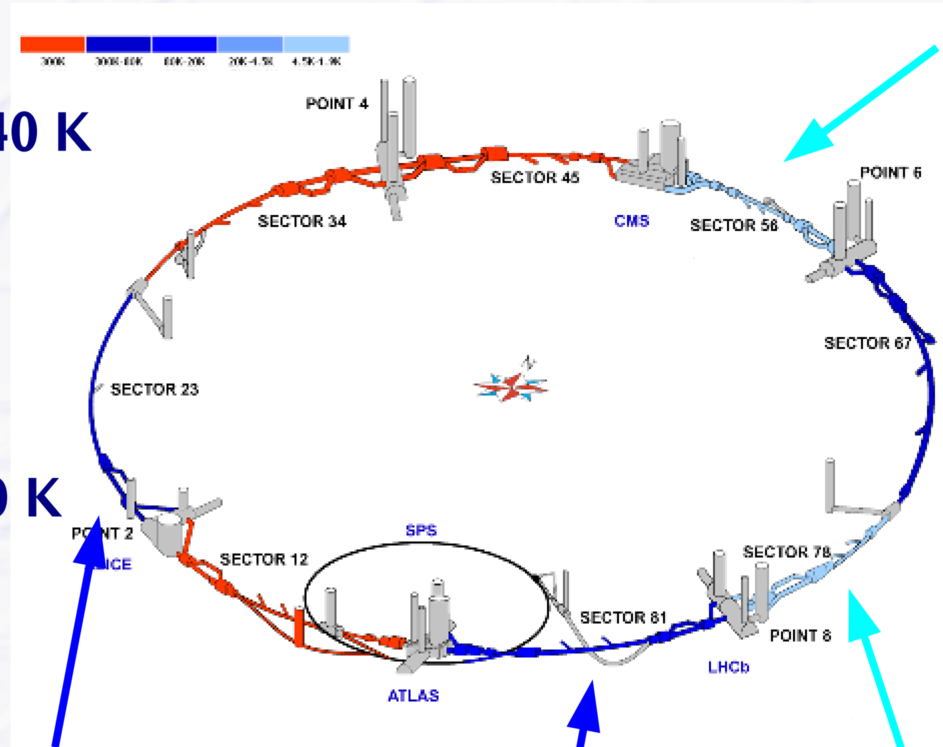
sector 45: warm

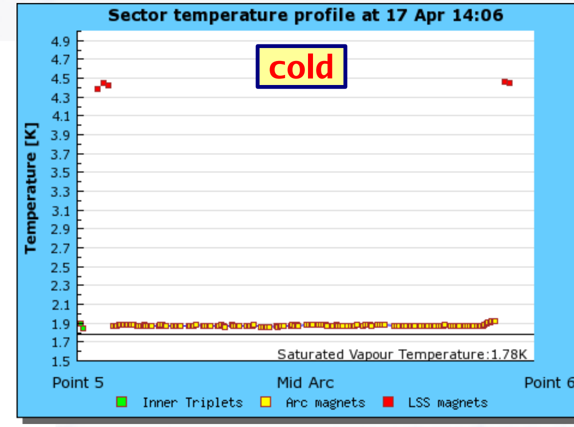
sector 56: 1.9 K

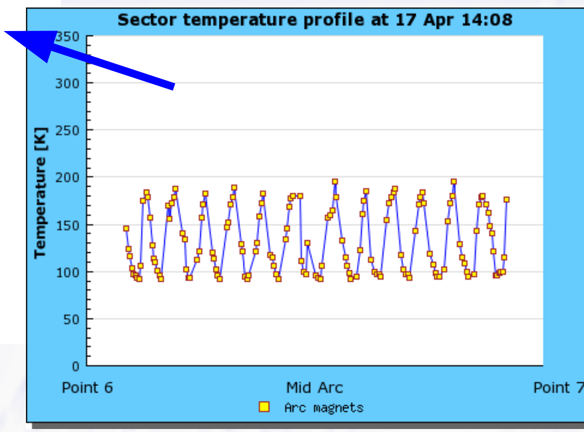
sector 67: 90-190 K

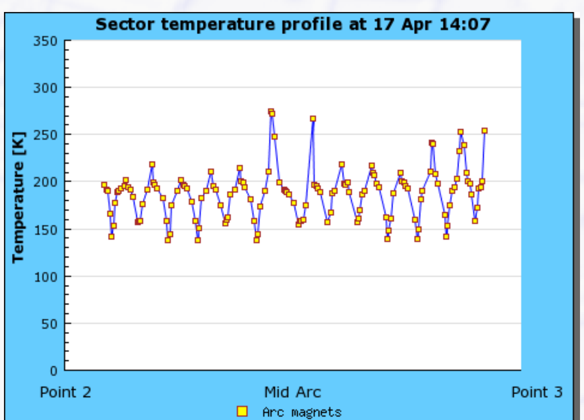
sector 78: 1.9 K

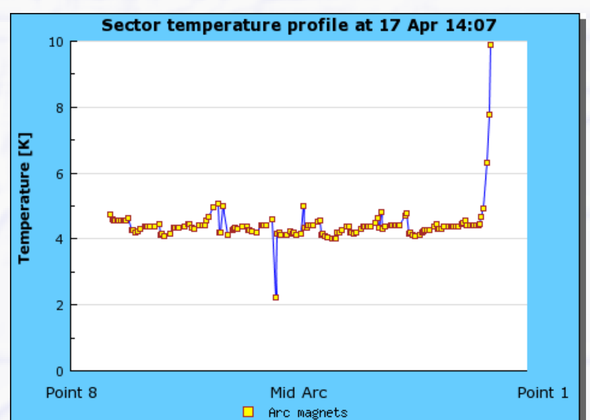
sector 81: 4.5 K

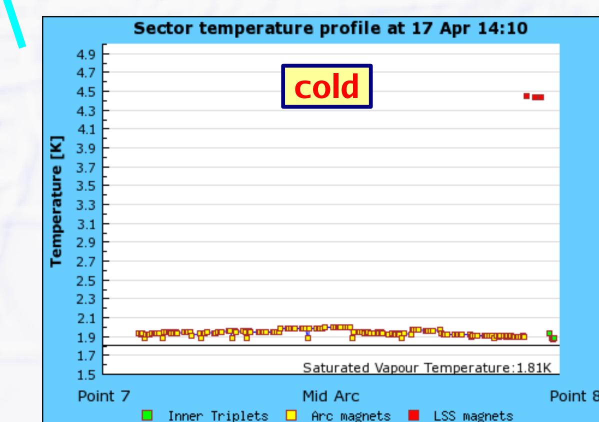












Powering Tests

- **Need 6 – 8 weeks after cooldown for powering tests**
  - ramp up magnets to full field/current
  - expect more and more quenches at higher and higher field
    - quench recovery ~ 1 day = need to wait ~1 day before next attempt
  - 7 TeV might require 40 – 50 “training quenches” = a long time...
- **First powering tests made in February (sector 45)**
  - ok up to 5.3 TeV then more frequent quenches between 5.3 and 6 TeV
  - test stopped at 6 TeV
- **Most likely scenario (to be confirmed this week)**
  - start with 2 x 5 TeV and keep it throughout 2008
    - experiments need to know energy early enough for sufficient Monte Carlo production
  - do magnet training 5 -> 7 TeV in 2008/2009 shutdown
  - not yet clear if first beam can be injected already after first initial powering tests or if one needs to wait until they are completed

LHC Beam Commissioning

		beam time [days]
1	Injection and first turn	4
2	Circulating beam	3
3	450 GeV - initial	4
4	450 GeV - detailed	5
5	450 GeV - two beams	1
6	Snapback - single beam	3
7	Ramp - single beam	6
8	Ramp - both beams	2
9	7 TeV - setup for physics	2
10	Physics un-squeezed	-
	TOTAL to first collisions	30
11	Commission squeeze	6
12	Increase Intensity	6
13	Set-up physics - partially squeezed.	2
14	Pilot physics run	30

30 days beam time(!) from first injection to first 2 x 7 TeV collisions

with typically 50% LHC operations efficiency:

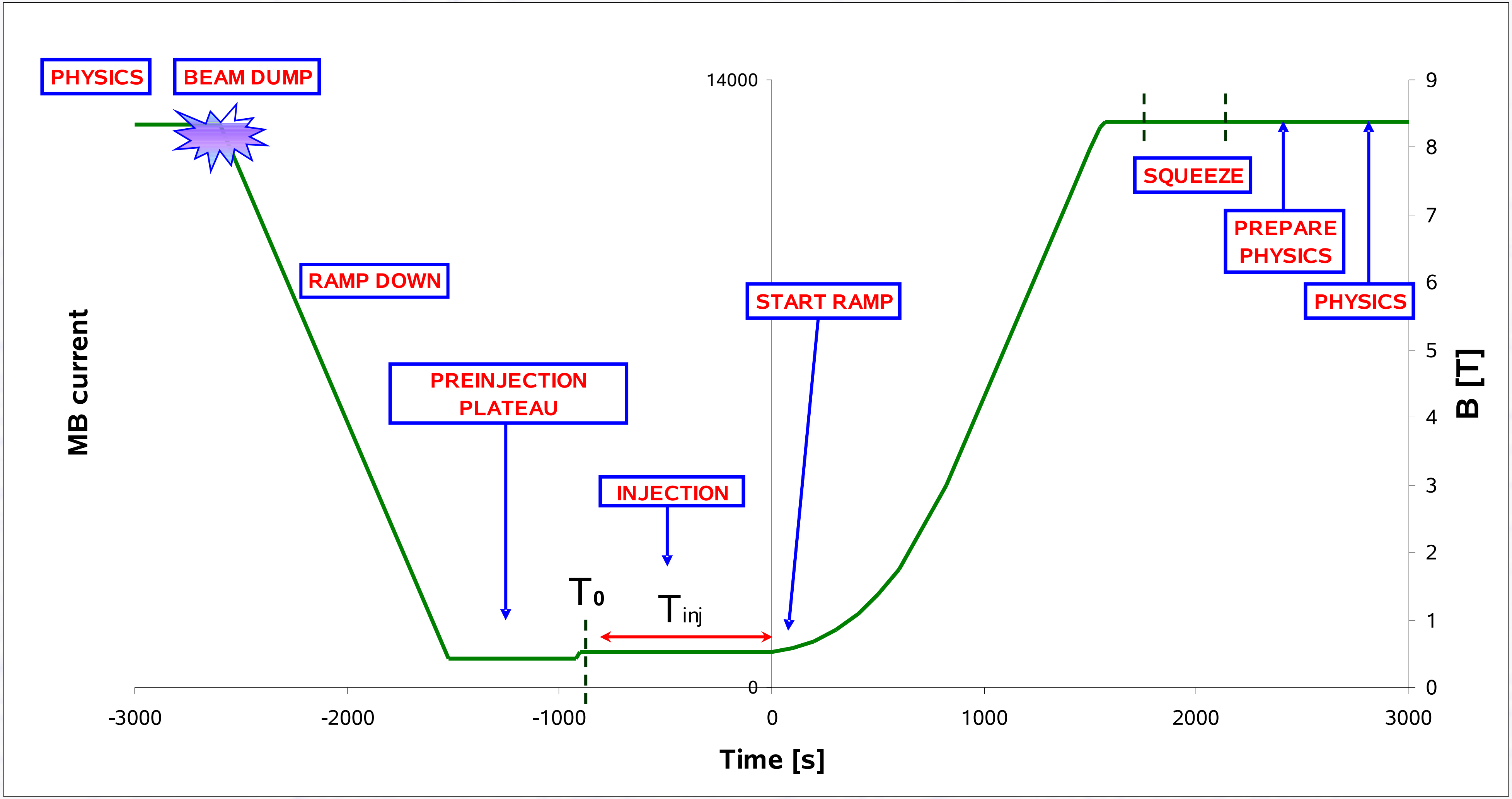
need ~60 days elapsed time until first collisions

commissioning at RHIC (2000): 70 days from first injection to first collision

$L = 1.2 \times 10^{31}\ cm^{-2}s^{-1}$
= 0.12% design luminosity at the end of pilot run

~ 3 pb^{-1} integrated L

LHC Operational Cycle



minimum time from end of physics to start of physics: 1.5 hours

- then physics run for ~10 hours(?)

LHC Schedule – The First Years

	April
Hardware commissioning	May
	June
Machine checkout	July
	August
Beam commissioning	September
	October
Pilot proton run	November
	December
Shutdown	January
	February
Machine checkout	March
75ns commissioning	April
First ION run	May
	June
75ns run	July
	August
Low intensity 25ns run	September
	October
	November
Shutdown	December
	January
	February
Machine checkout	March
Startup and scrubbing	April
	May
Half intensity 25ns run	June
	July
	August
	September
	October
Shutdown	November
	December
	January
	February
Machine checkout	March
Startup and scrubbing	April
	May
	June
Push to nominal 25ns	July
	August
	September
	October
	November
Shutdown	December
	January
	February
Machine checkout	March
Startup and scrubbing	April
	May
	June
Nominal 25ns	July
	August
	September
	October
	November
	December

disclaimer: this is a (somewhat) out-of-date scenario, = by far not official LHC schedule!

year 0

year 1

$L = 1 \times 10^{32} \Rightarrow 4 \times 10^{32}\ cm^{-2}s^{-1}$

= 1 – 4% design luminosity

year 2

$L = 7 \times 10^{32} \Rightarrow 2 \times 10^{33}\ cm^{-2}s^{-1}$

= 7 – 20% design luminosity

← longer shutdown to insert collimators for design luminosity

year 3

$L = 2 \times 10^{33} \Rightarrow 1 \times 10^{34}\ cm^{-2}s^{-1}$

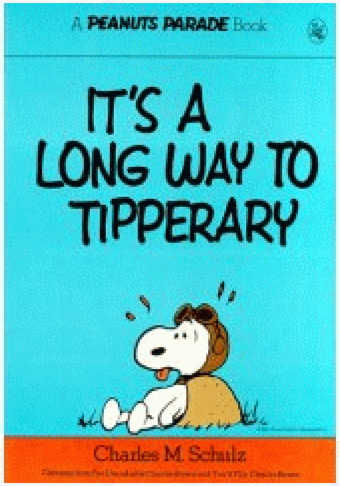
= 20 – 100% design luminosity

year 4

$L = 1 \times 10^{34}\ cm^{-2}s^{-1}$

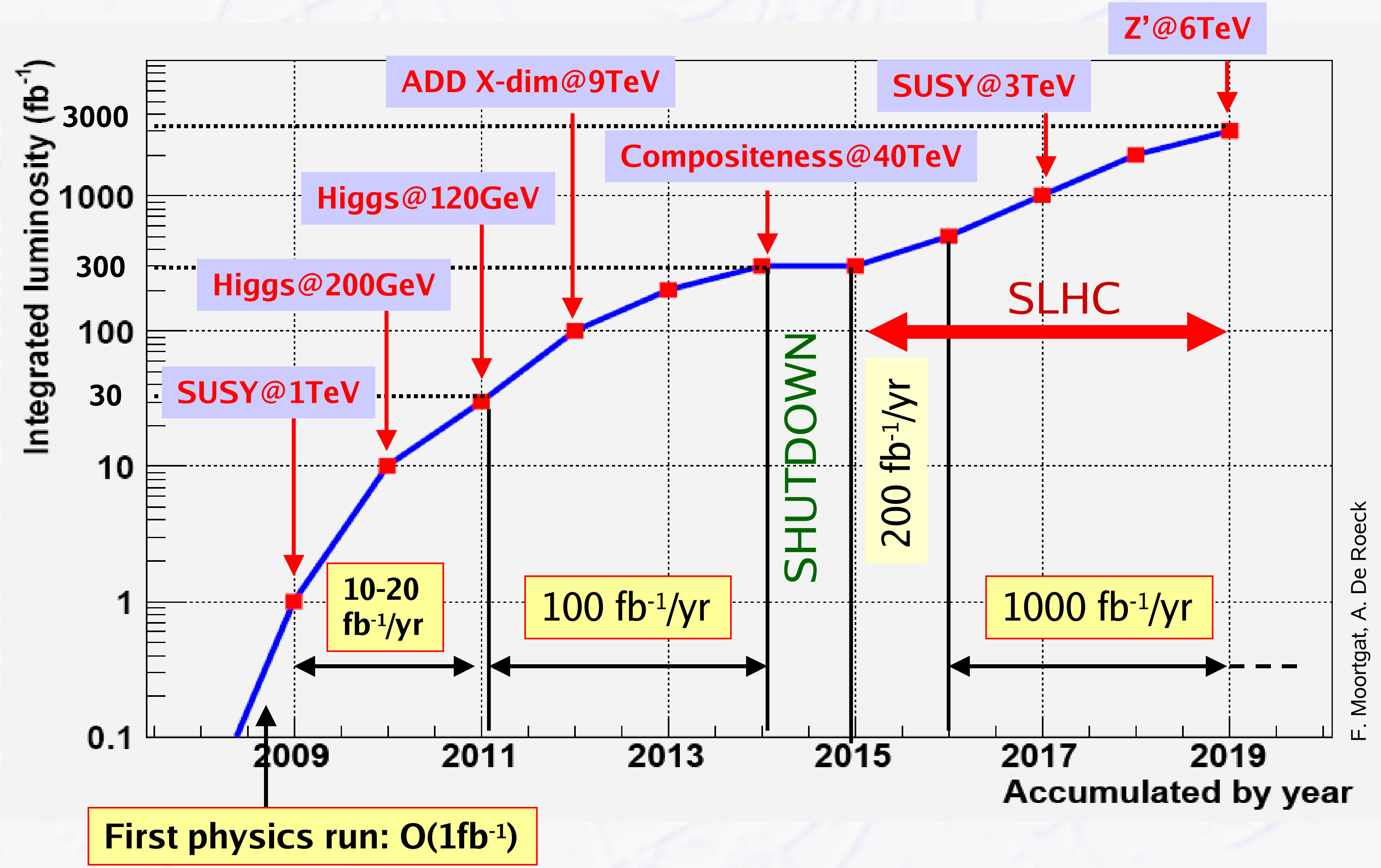
= 100% design luminosity

~ 80 fb^{-1} per year (6 month running) . . .



LHC luminosity/sensitivity evolution?

- "Roadmap to discovery" (somewhat optimistic luminosity assumptions...)



The first Higgs at LHC (4th April 2008)

LHC Inauguration: 21 October 2008

...there hopefully will be circulating protons by then...