Heavy Ion Physics
Lecture 2: Accelerators and Detectors

HUGS 2015

Bolek Wyslouch

History of the relativistic heavy ion physics

- Figures of merit:
  - CM energy per colliding nucleon pair
  - Atomic number of the colliding nuclei
- Accelerators with O(1 GeV) per nucleons beams started to operate in the 1970s
  - Berkeley, Brookhaven in the US
  - GSI in Germany
  - CERN in Switzerland/France
  - Dubna in Russia
- Physics driven by continuous improvements in both accelerator and detector technology!

Accelerators in Relativistic Heavy Ion Physics

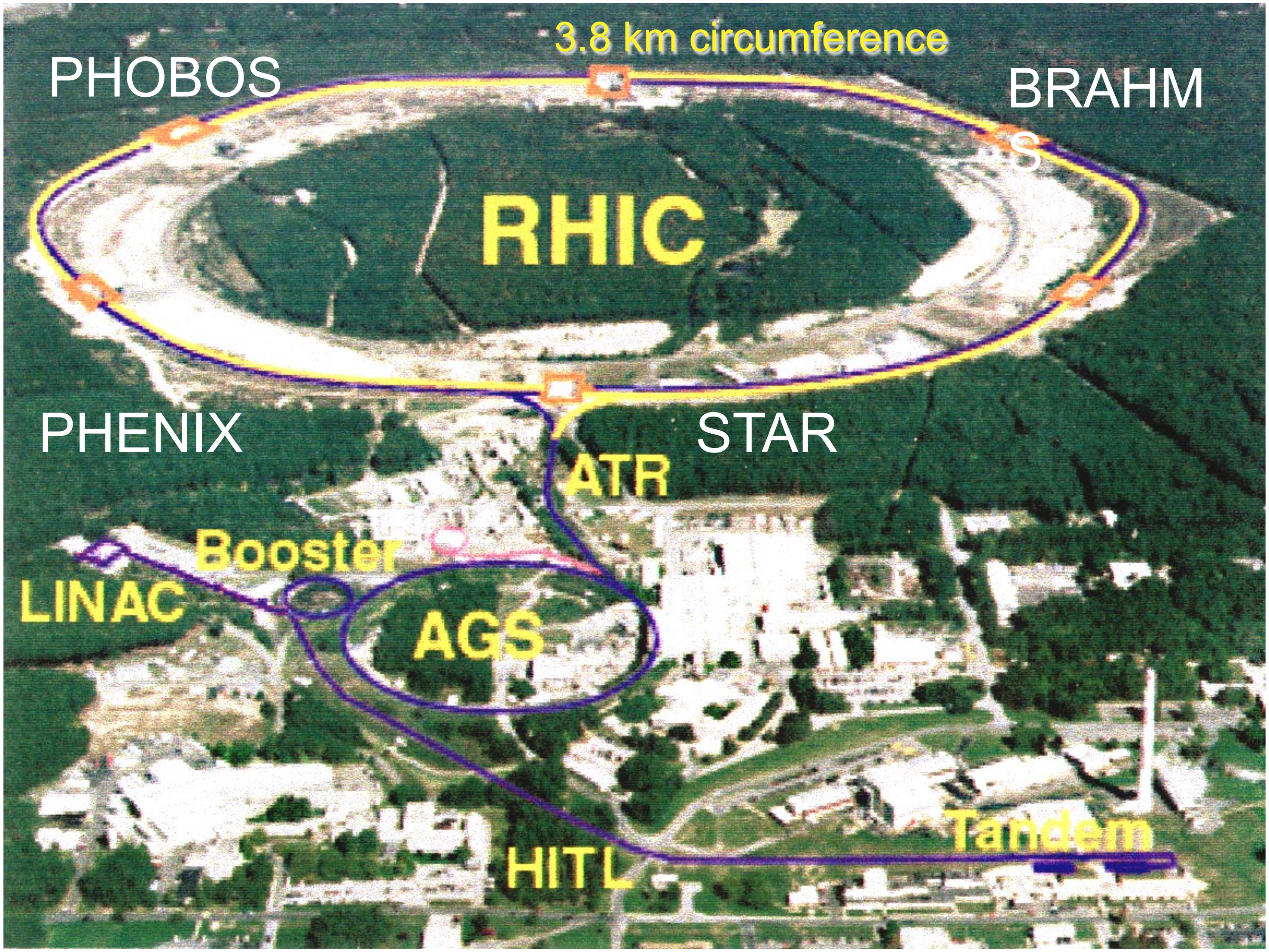
Accelerator	Place	HI-Periods	Max. Energy	Projectiles	Experiments
Bevalac	LBNL, Berkeley	1984 – 1993	< 2 *A*GeV	C, Ca, Nb, Ni, Au, ...	Plastic Ball, Streamer Chamber, EOS, DLS
Synchro-Phasotron	JINR, Dubna	1974 – 1985	> 100 *A*MeV		
AGS	BNL, Brookhaven	1986 – 1994	14.5/11.5 *A*GeV	Si, Au	E802, ..., E917
SPS	CERN, Geneva	1986 – 2002	200/158 *A*GeV	O, S, In, Pb	NA34,... , WA80,...
SIS	GSI, Darmstadt	1992 – today	2 *A*GeV	Kr, Au	FOPI, KAOS, HADES
RHIC	BNL, Brookhaven	2000 – today	$\sqrt{s_{NN}} = 200$ GeV	Cu,Au	STAR, PHENIX, BRAHMS, PHOBOS
LHC	CERN, Geneva	2010 →	$\sqrt{s_{NN}} = 5.5$ TeV	O, Ar, Pb	ALICE, CMS, ATLAS
FAIR	GSI, Darmstadt	?	30/45 *A*GeV	Multiple	
Nuklotron	JINR, Dubna	?	~5 *A*GeV		

Fixed Target vs. Colliding Beams

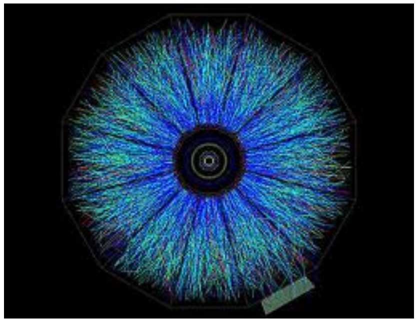
- Fixed target
  - CM energy limited by $E_{CM} = \sqrt{2(1GeV)E_{beam}}$. Best ever achieved was at CERN SPS with E_{beam} of about 160 GeV/nucleon (E_{CM}~ 20 GeV per nucleon pair)
  - Very high beam intensity/luminosity
- Colliding beams
  - Much higher CM energy $E_{CM} = 2E_{beam}$. Expect E_{CM}~ 5500 GeV per nucleon pair at LHC
  - Lower luminosity
- I will focus on results from colliding beam facilities:
  - RHIC at Brookhaven National Laboratory, since 2000
  - LHC at CERN, since 2010

The First Dedicated Heavy Ion Collider

Relativistic Heavy Ion Collider



Au+Au 7.7 - 200 GeV
d+Au
U+U
Cu+Cu
…

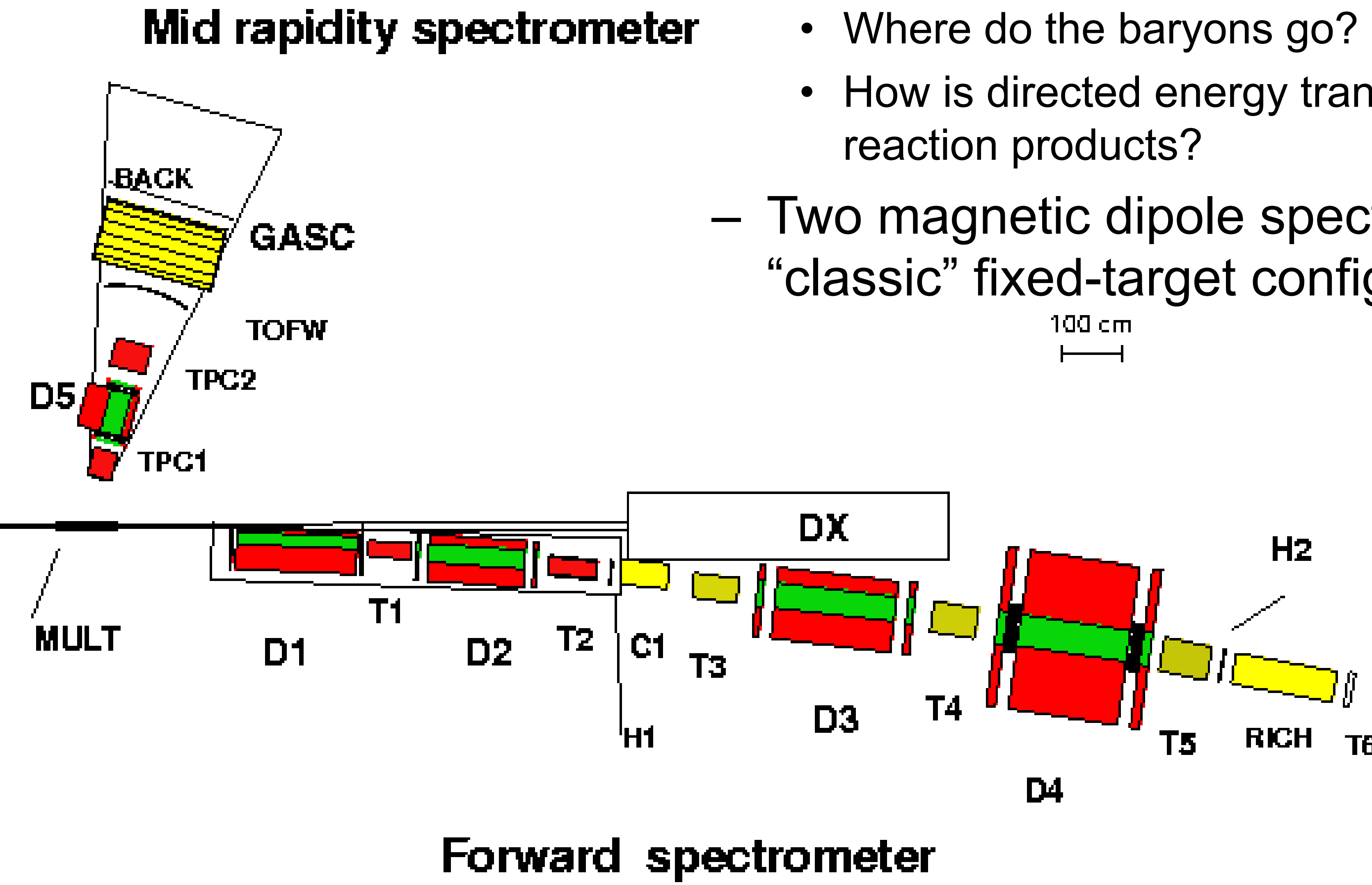


Since 2000~

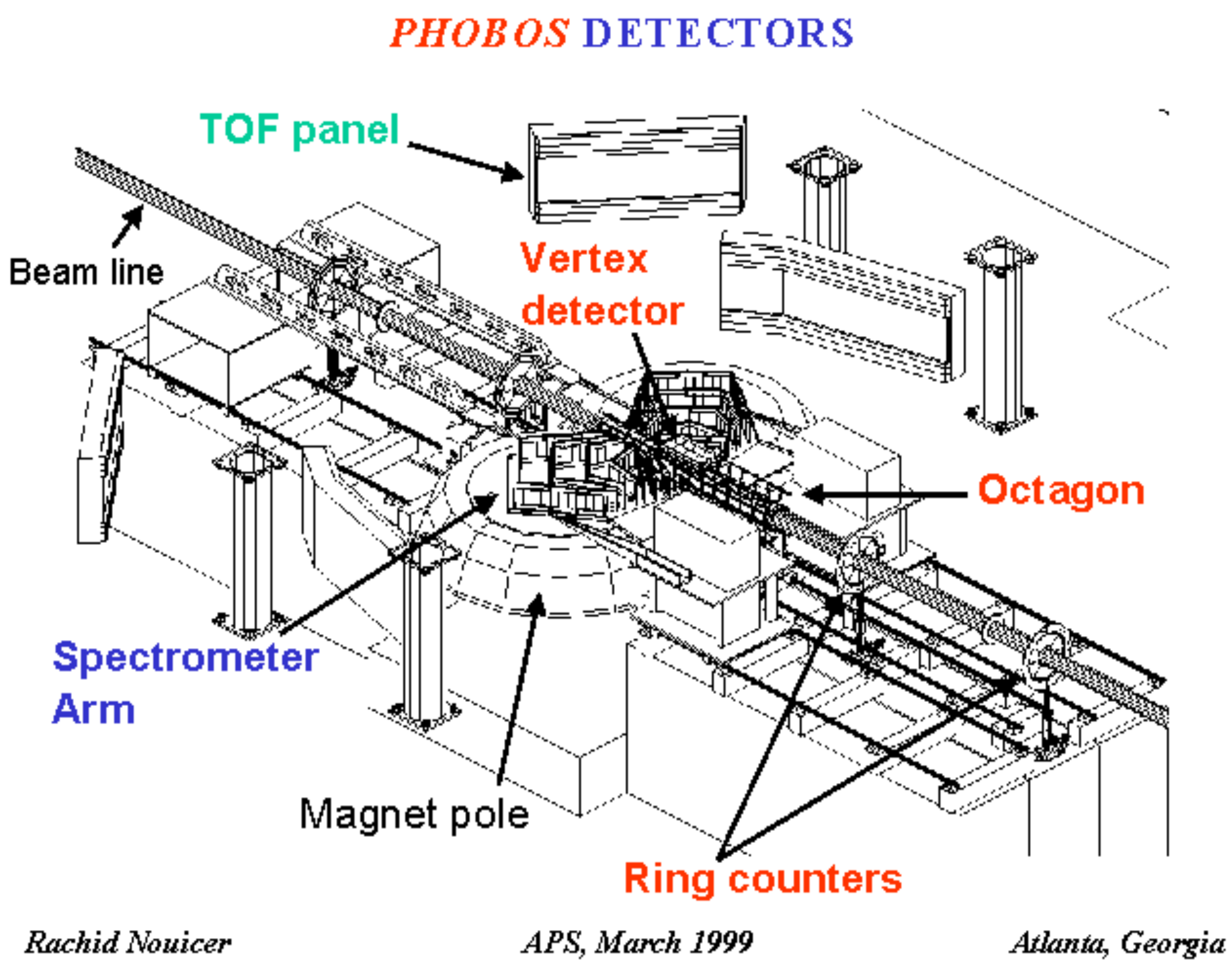
BRAHMS@RHIC

Specialized in:

- Quality PID spectra over a broad range of rapidity and p_T
- Special emphasis:
  - Where do the baryons go?
  - How is directed energy transferred to the reaction products?
- Two magnetic dipole spectrometers in "classic" fixed-target configuration



PHOBOS



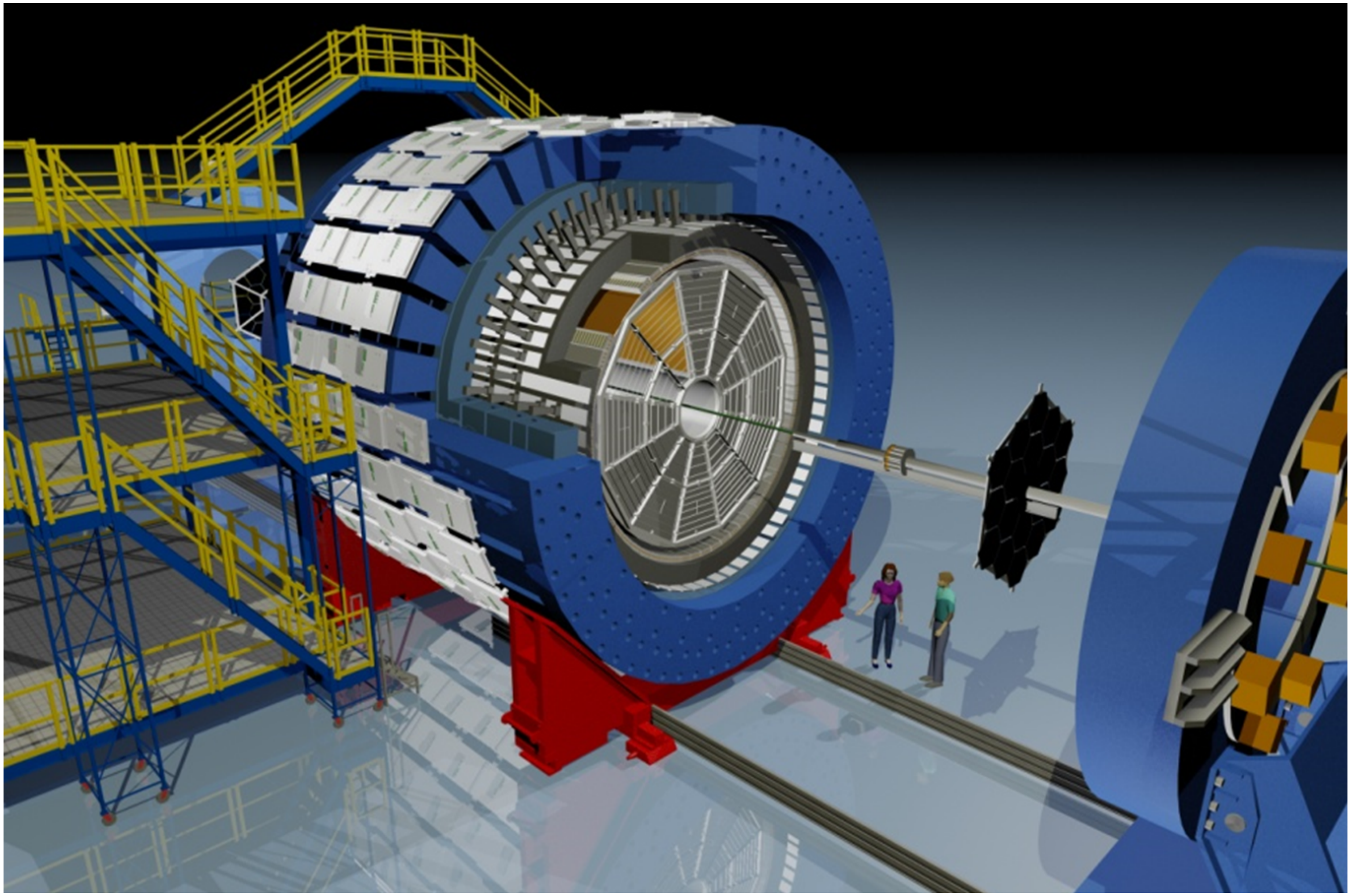
Large acceptance multiplicity detector

Small acceptance spectrometer with particle identification

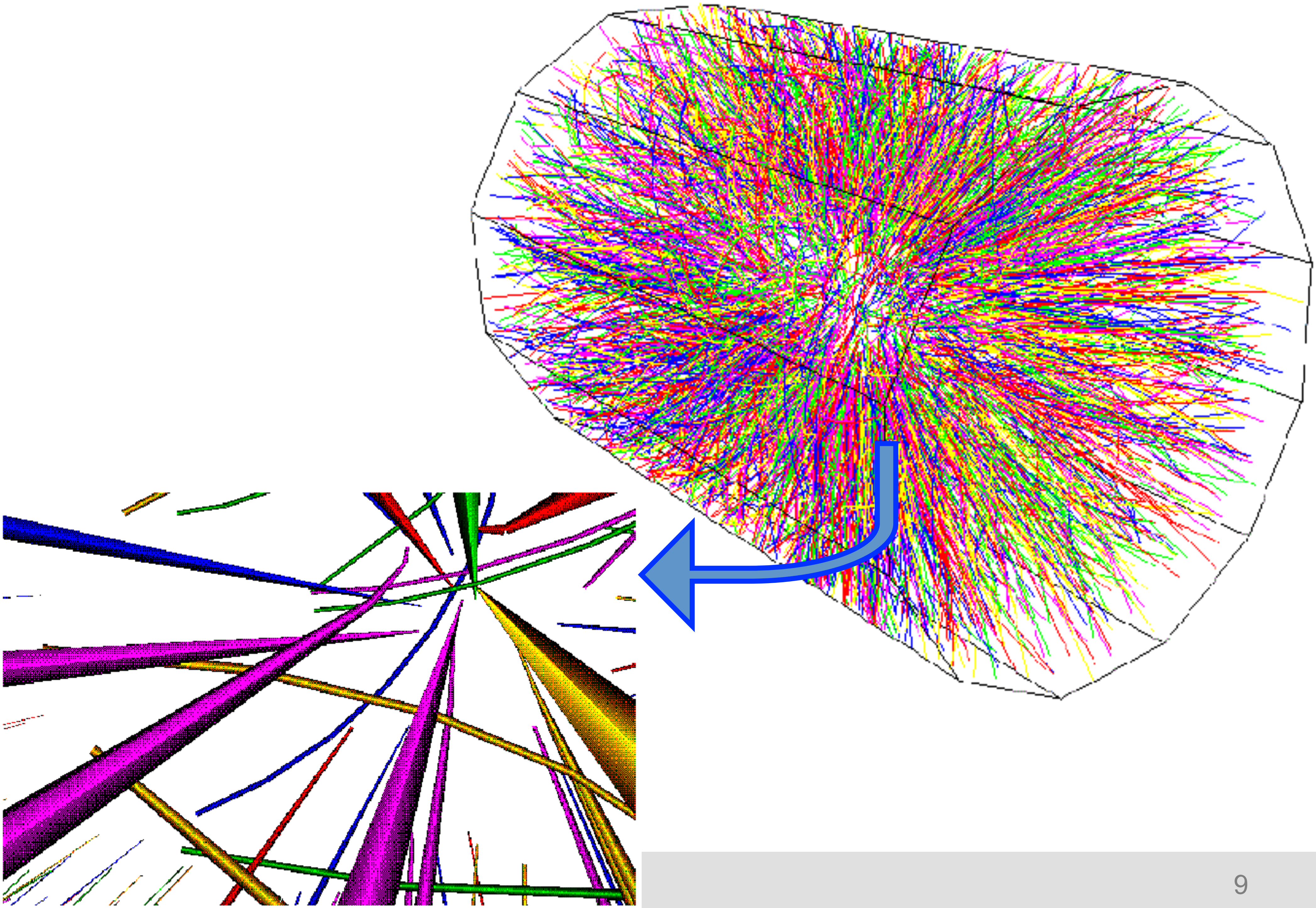
Collecting large quantity of minimum bias events

STAR

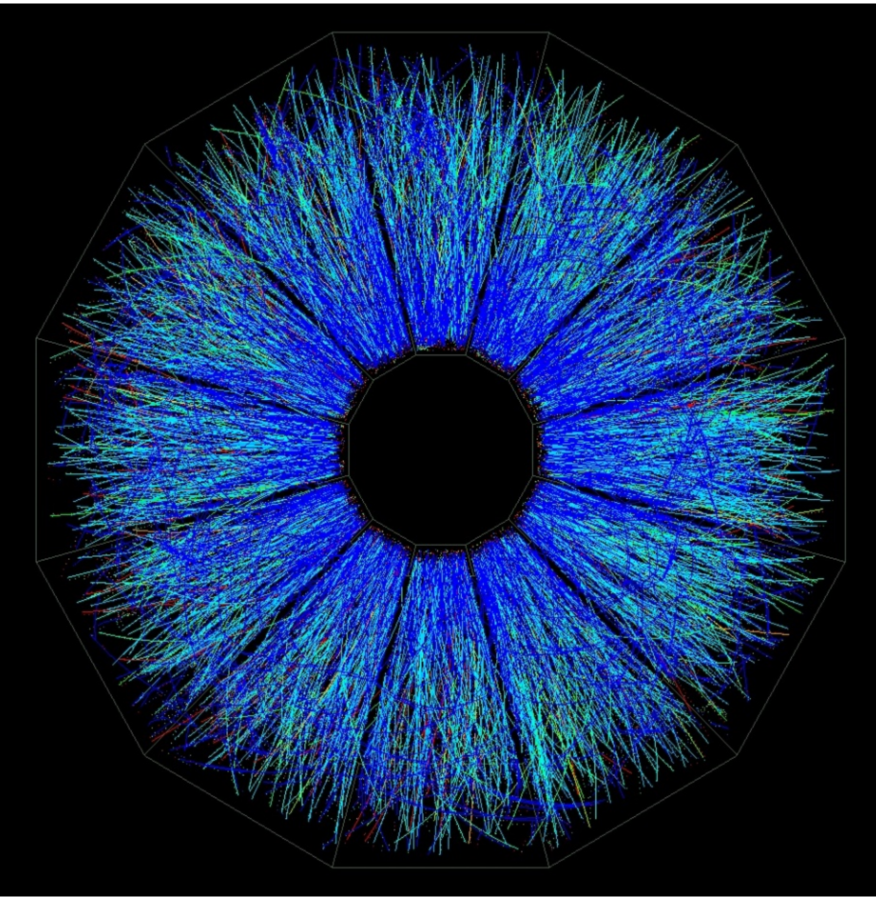
- An experiment with a challenge:
  - Track ~ 2000 charged particles in $|\eta| < 1$



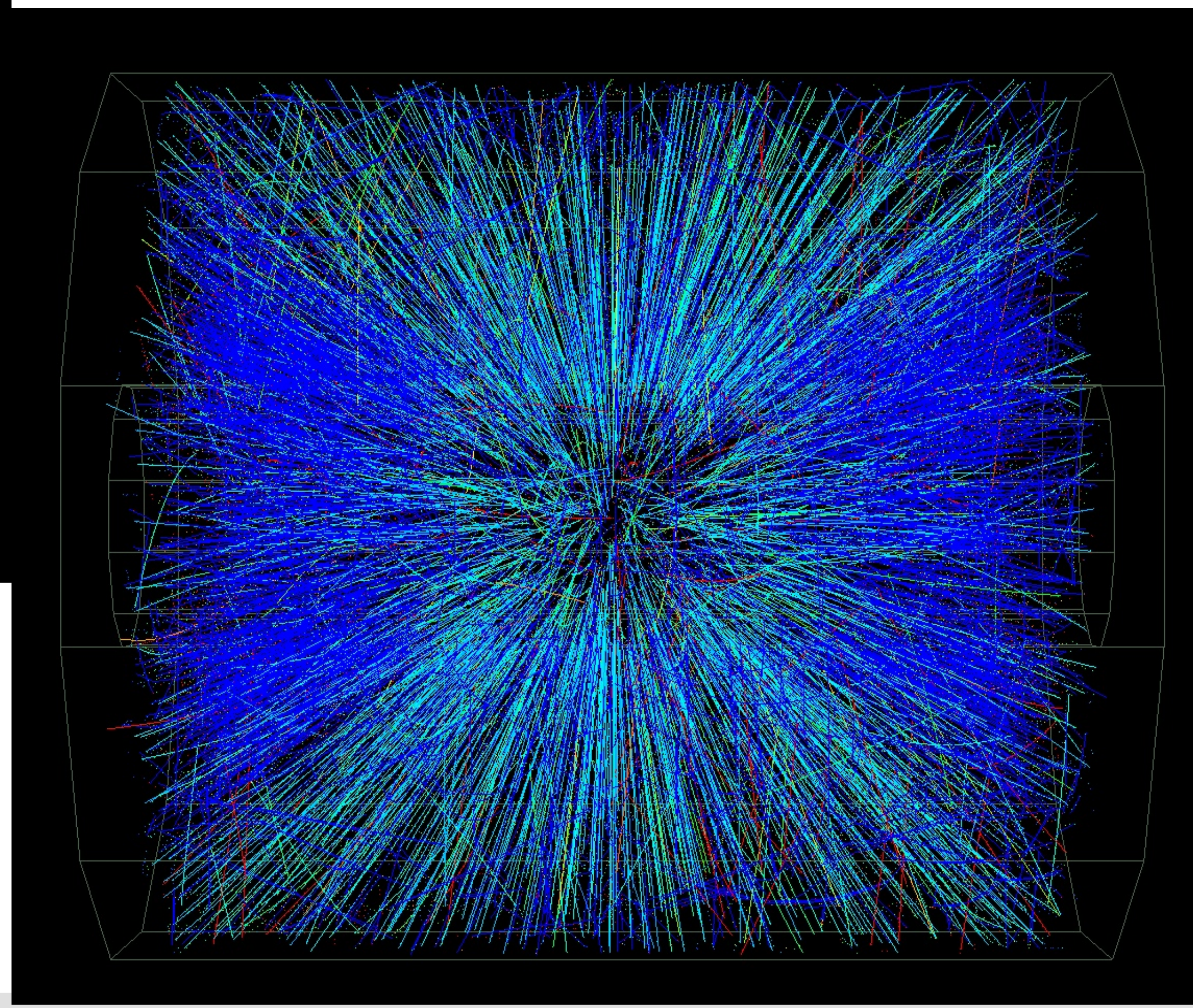
STAR Event



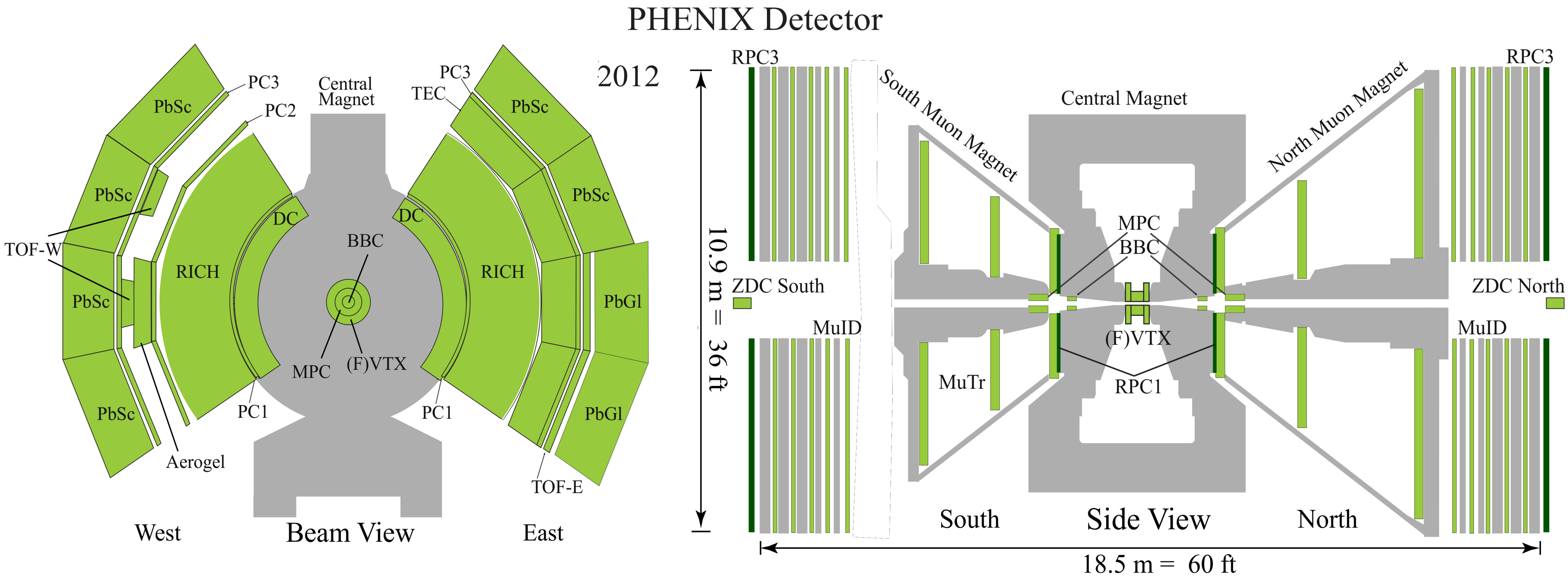
STAR Event



Data Taken June 25, 2000.
Pictures from Level 3 online display.



PHENIX

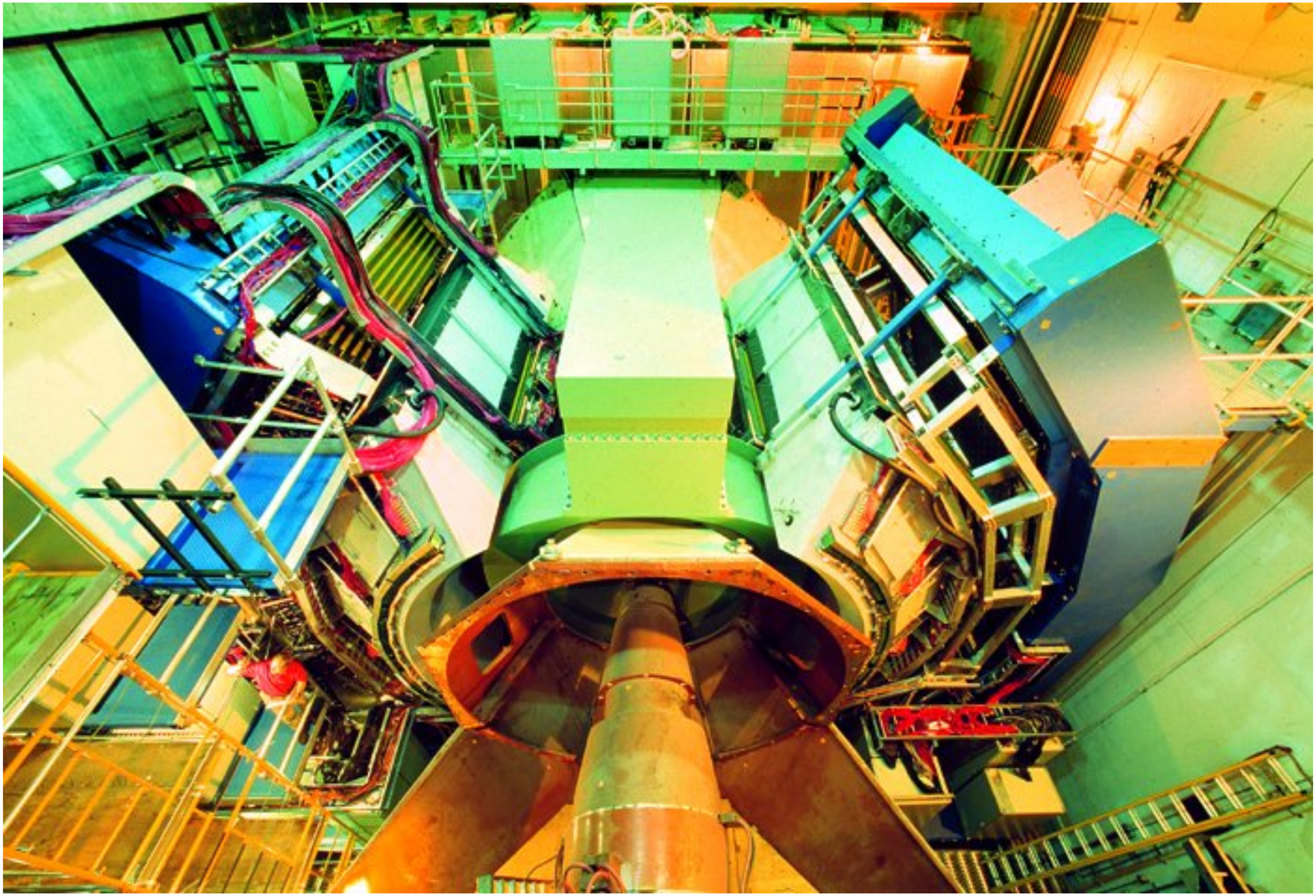


- An experiment with something for everybody
- A complex apparatus to measure
  - Hadrons; Muons; Electrons; Photons

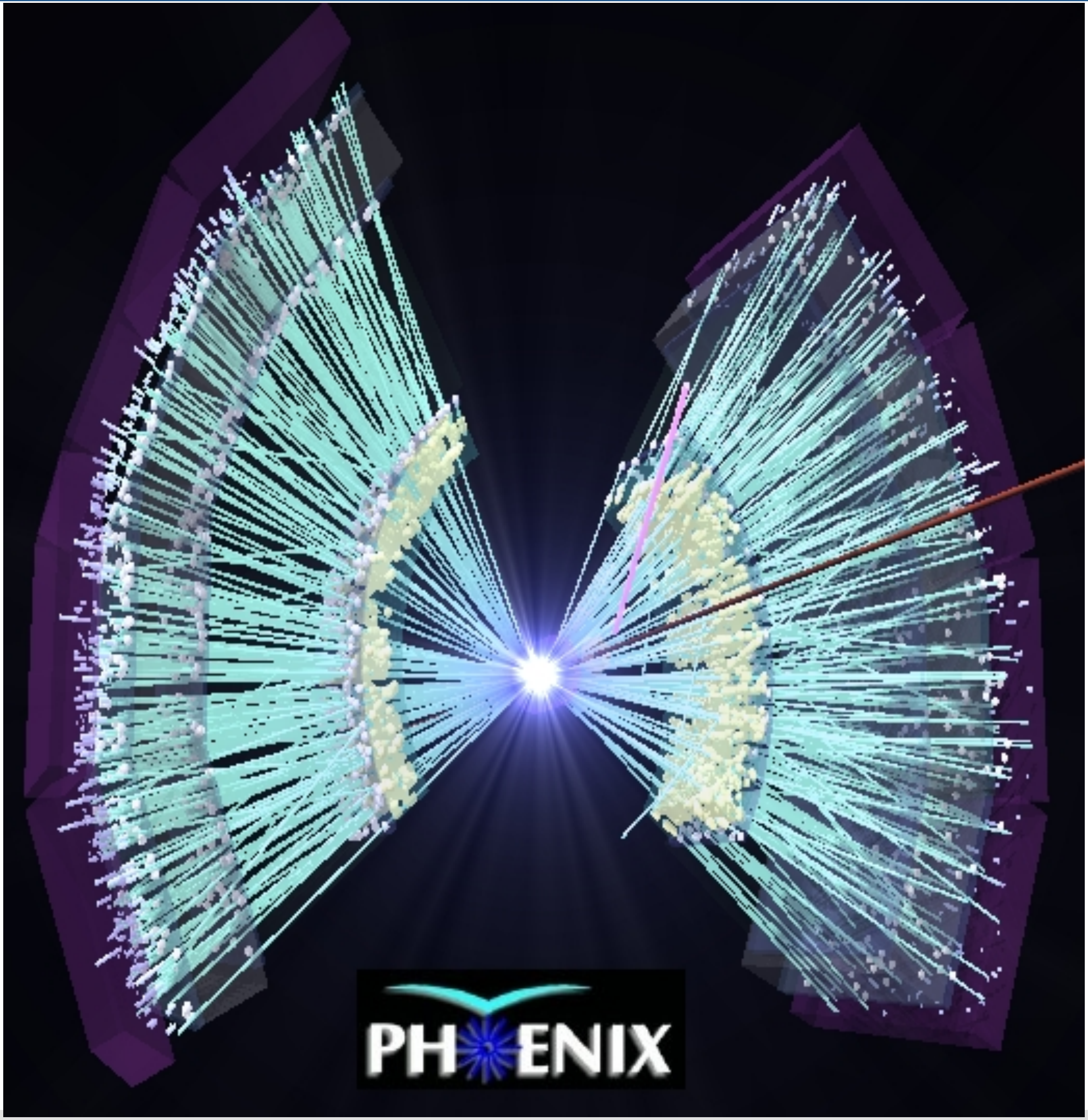
Executive summary:

- *__High__* resolution; *__High__* granularity

PHENIX Reality



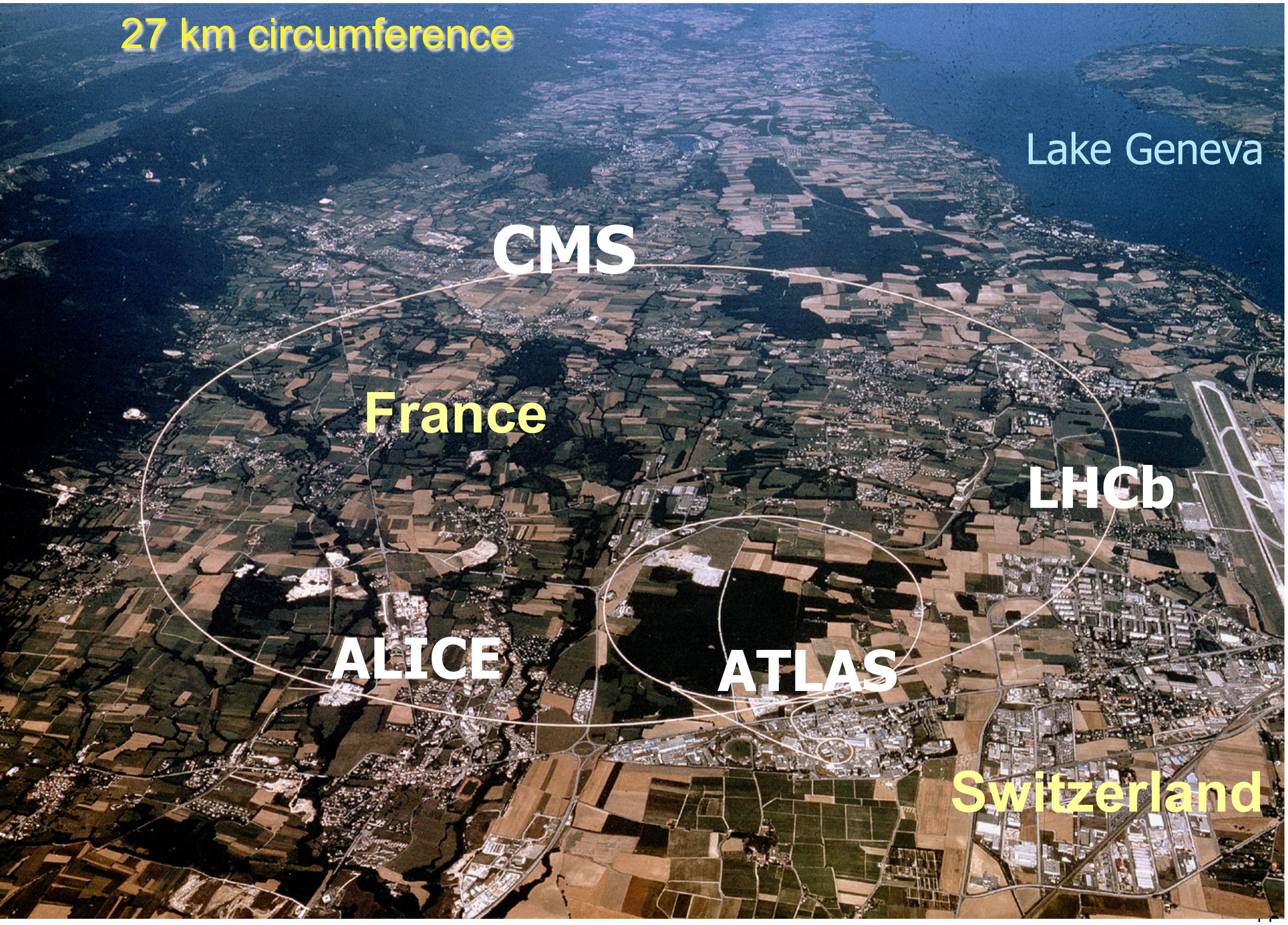
PHENIX Single Event



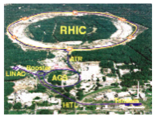
The New Frontier

Large Hadron Collider

p+p 7-8 TeV
Pb+Pb 2.76 TeV
p+Pb 5.02 TeV



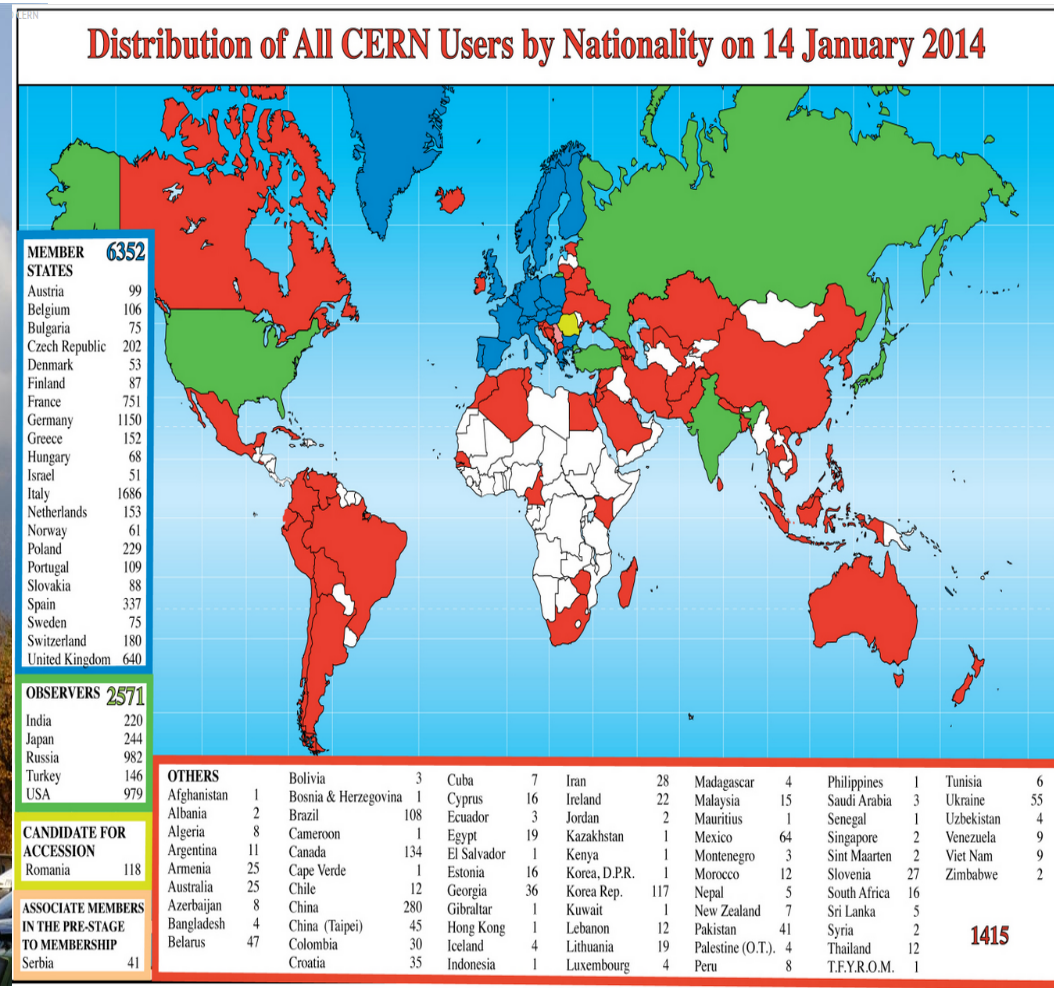
2015 and beyond:
p+p 13-14 TeV
Pb+Pb 5~5.5 TeV
P+Pb ~8 TeV



RHIC

Flags of CERN’s Member States

LHC: ~10,000 users



Construction Budget: ~12 billion USD (~50% LHC, ~50% detectors)

20 European Member States and around 60 additional countries collaborate in our scientific projects.

Speed of the accelerated protons and lead ions

Formula 1

100 m/s

Lockheed SR-71 Blackbird

980 m/s

LHC

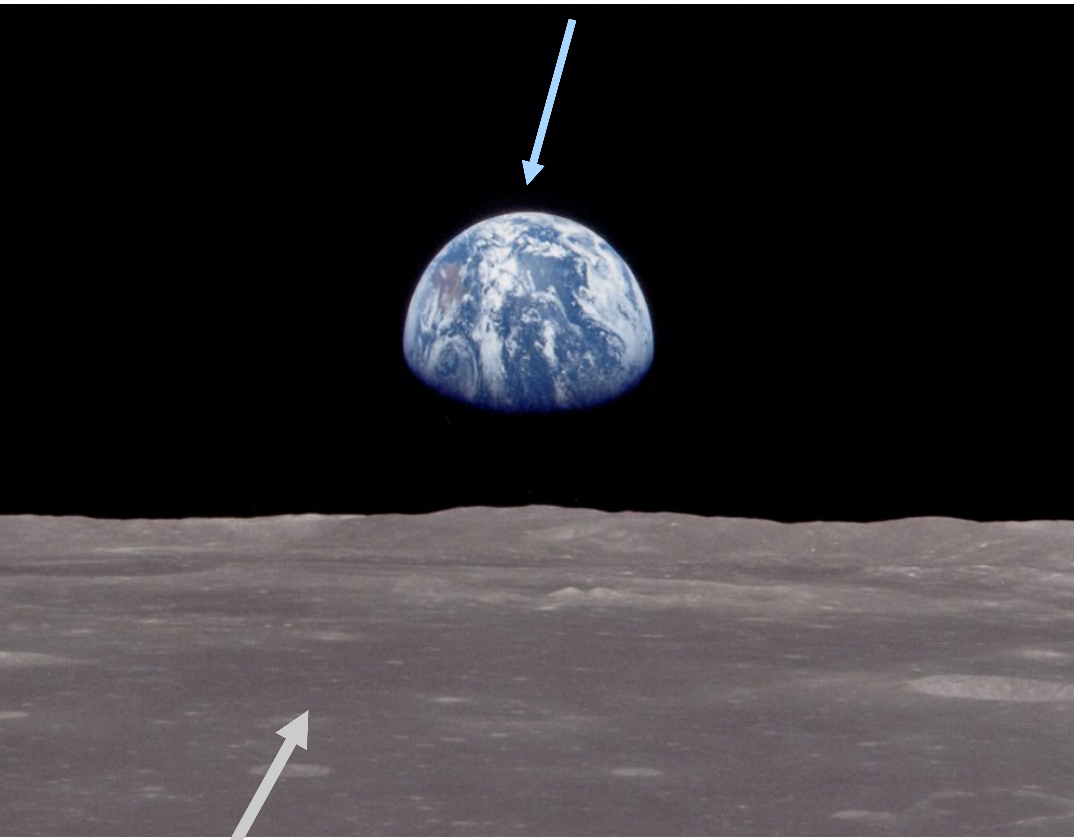
~c=300,000,000 m/s

Protons at 4 TeV: (1-3e-8)c
Ions at the same B field: (1-2e-7)c
Differ by 51 m/s

Difference: ~4.6 mm after 1 turn!

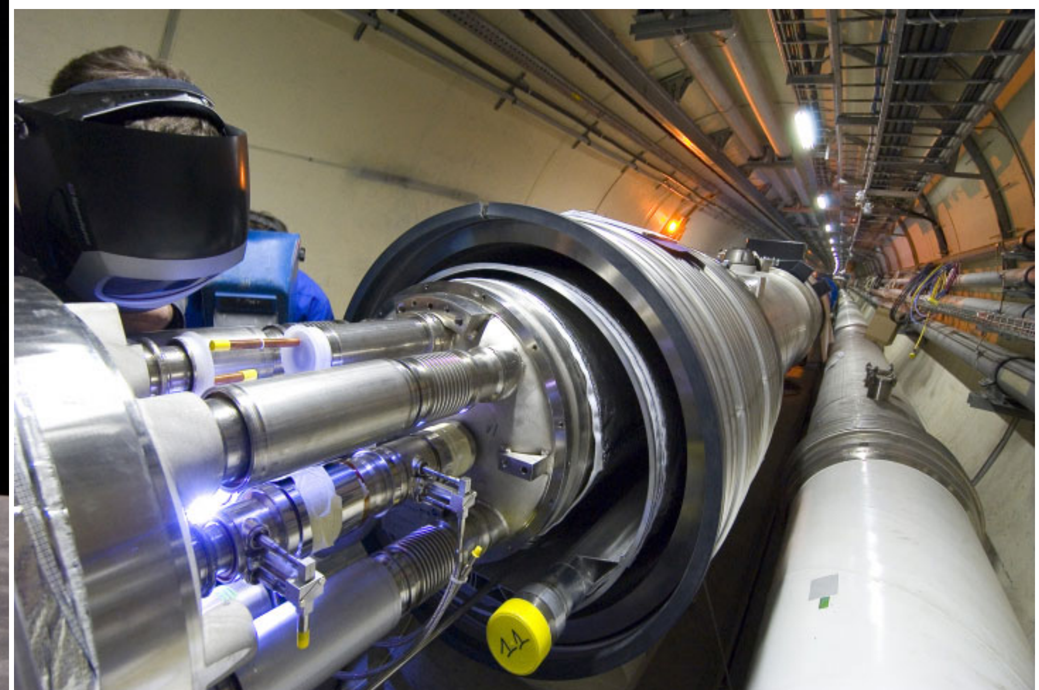
Inside the beam pipe

Earth~ 1 atm



Moon ~ 10^{-14} atm

LHC ~ 10^{-15} atm



Like pumping down a cathedral…

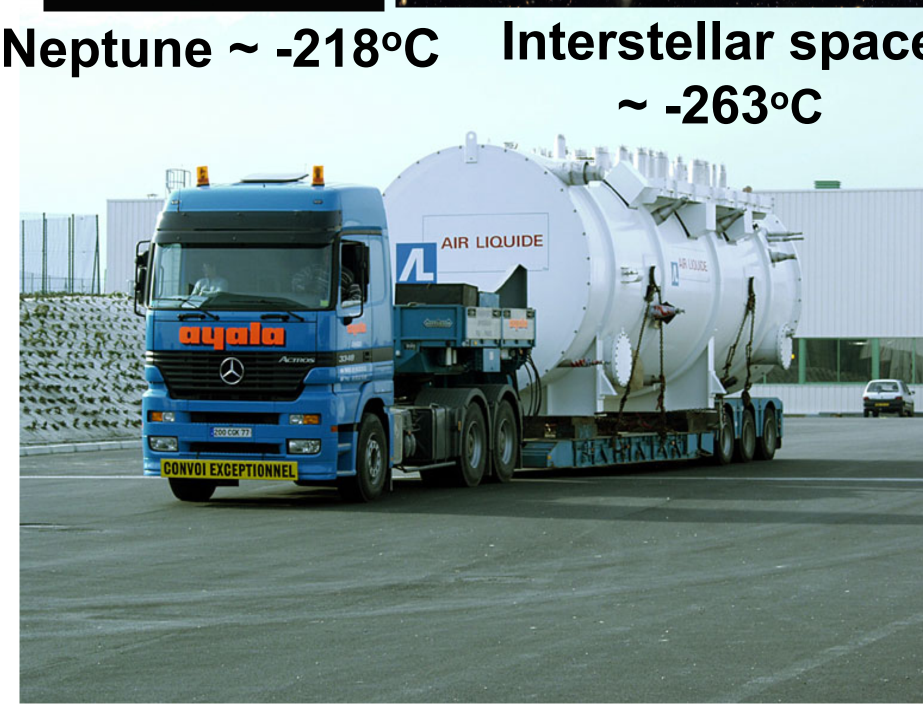
To accelerate protons to almost the speed of light, we need a vacuum similar to interplanetary space. The pressure in the beam-pipes of the LHC will be about 10 times lower than on the moon.

Superconducting Magnets

LHC ~ **-271°C**

Neptune ~ -218°C

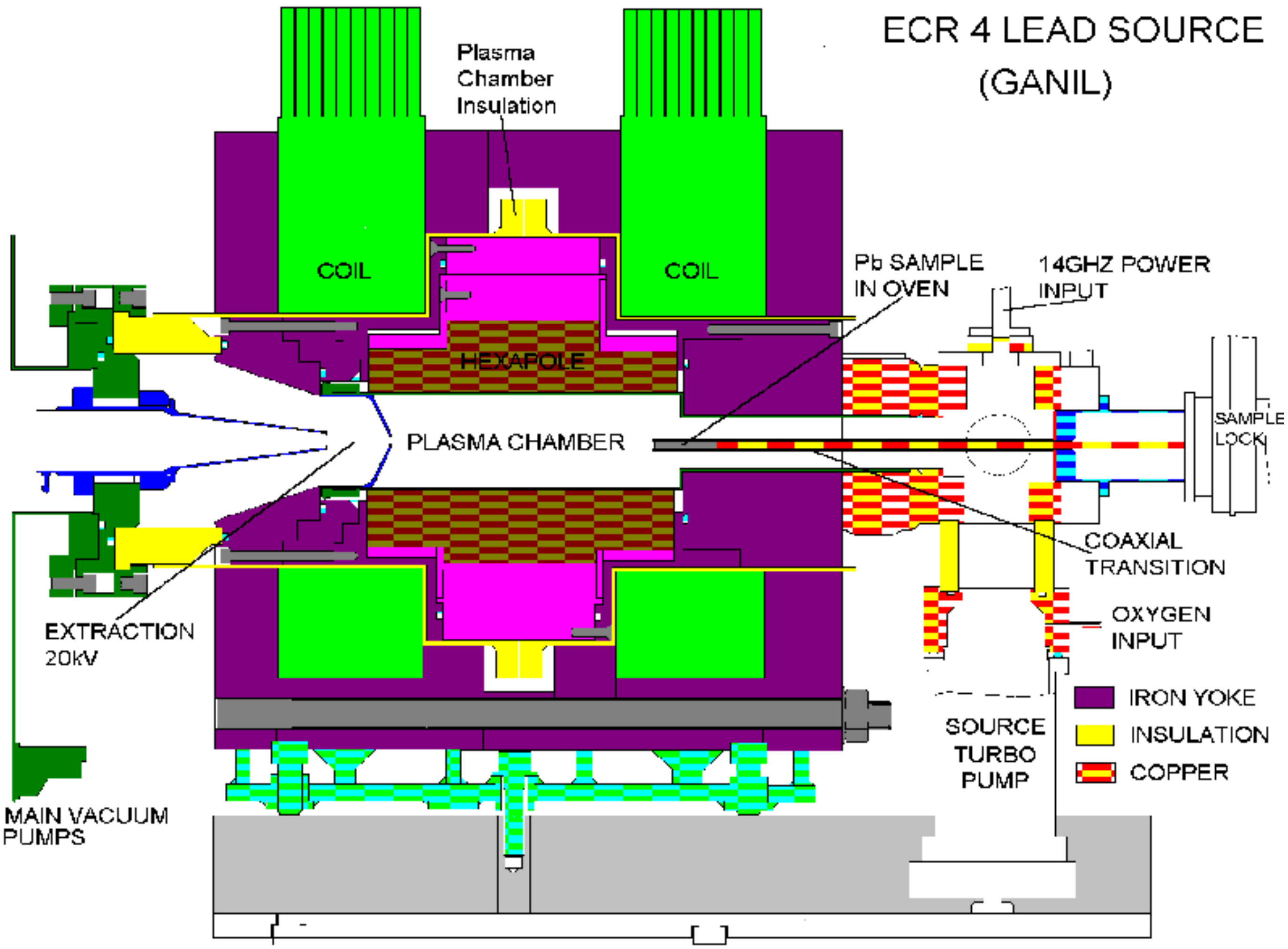
Interstellar space ~ -263°C



Magnetic field: 8.4 Tesla (~200,000 times of the field from Earth)

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

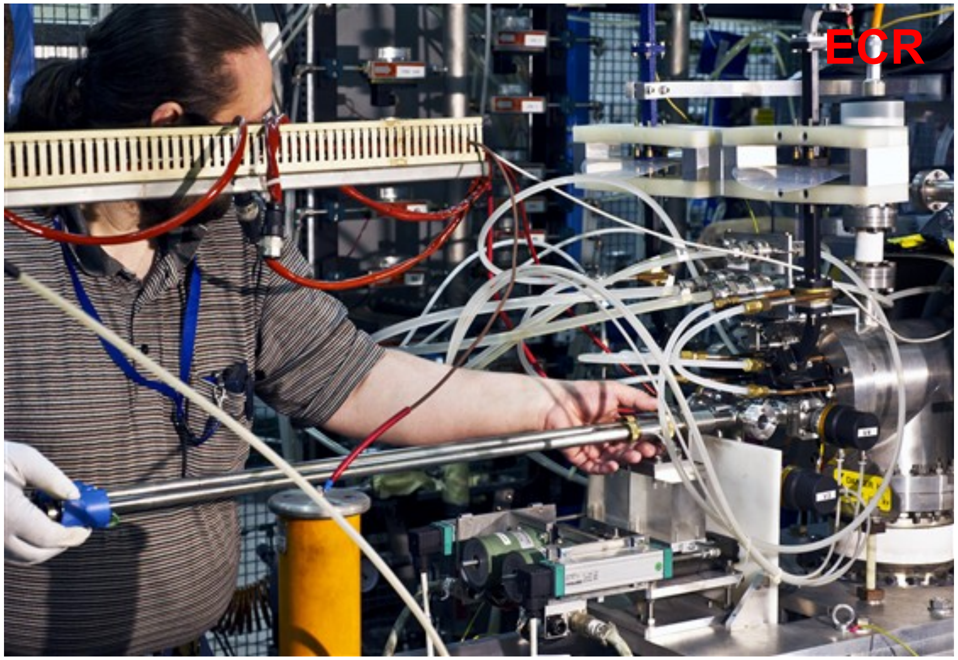
Lead Ions at LHC



- A cloud of ions is bombarded by energetic electrons circulating in magnetic field
- Electrons are energized by circularly polarized microwaves at cyclotron frequency
- CERN/LHC uses isotopically pure ^{208}Pb
- About 1300$/gram

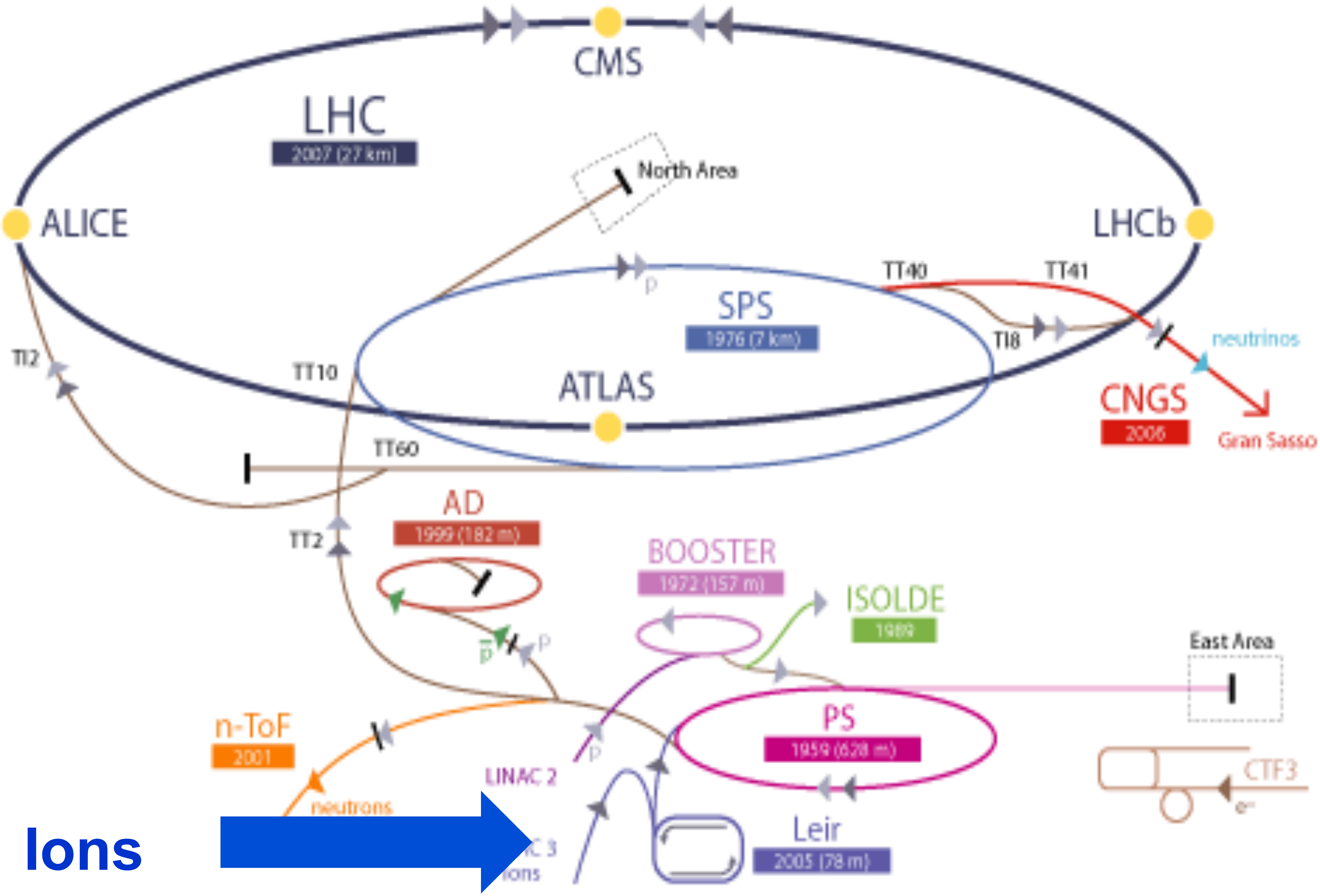
Lead Beams in LHC

- LHC is accelerating ions of ^{208}Pb, fully ionized, charge +82



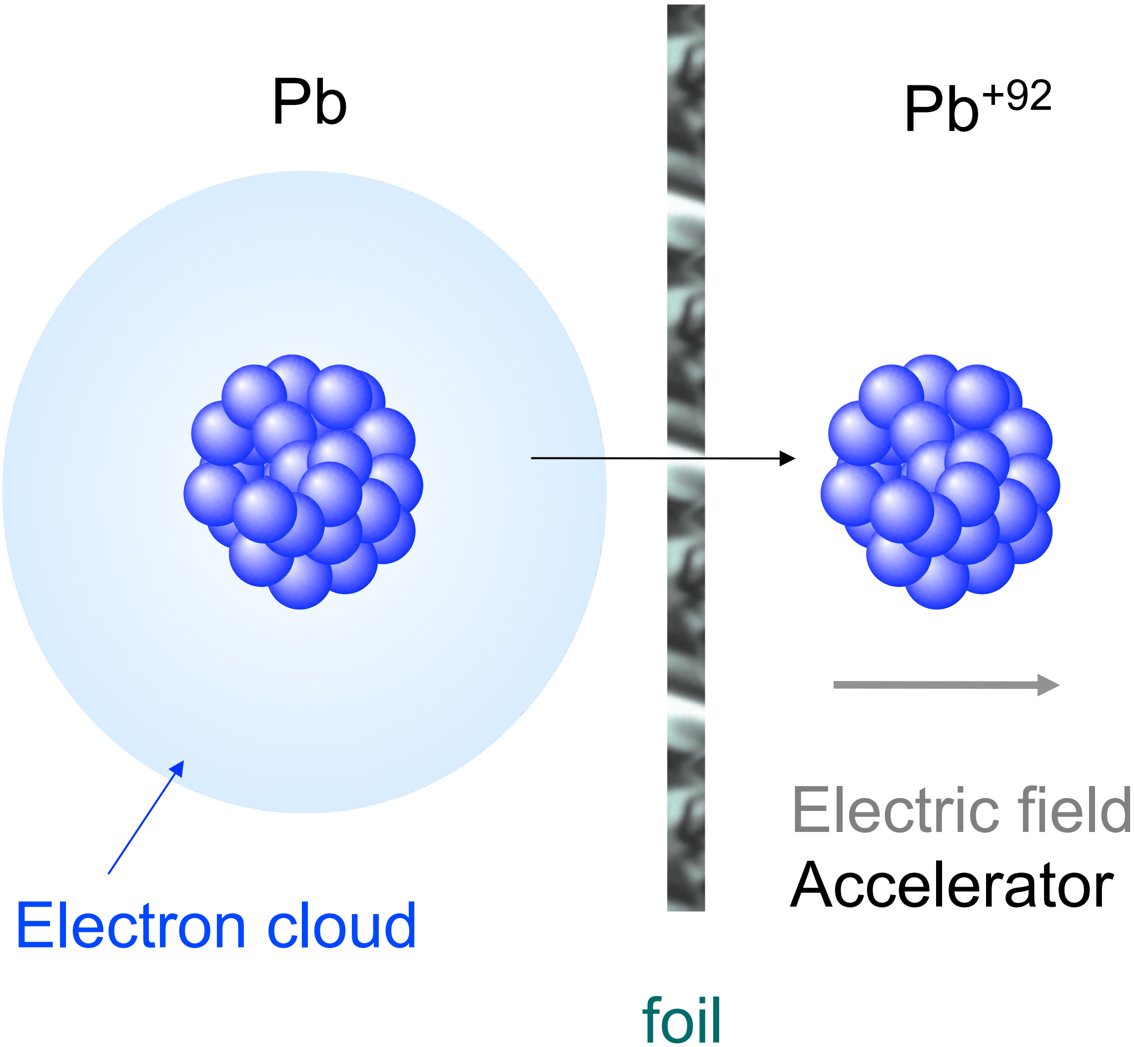
- Energy of 2.76 TeV/nucleon pair (82/208=0.4 times proton energy of 7 TeV)
- "Only" 7 10^7 ions per bunch, much less than typical proton bunch of 10^{11} Electrostatics!
- In 2010 LHC collided up to ~140 bunches per beam, about 1/40 of nominal luminosity, ~200 Hz of inelastic collisions
- In 2011 we got 20 times higher luminosity

CERN Accelerator Complex



Ions

Stripping all electrons



Each nucleon carry
~ Kinematic energy of 

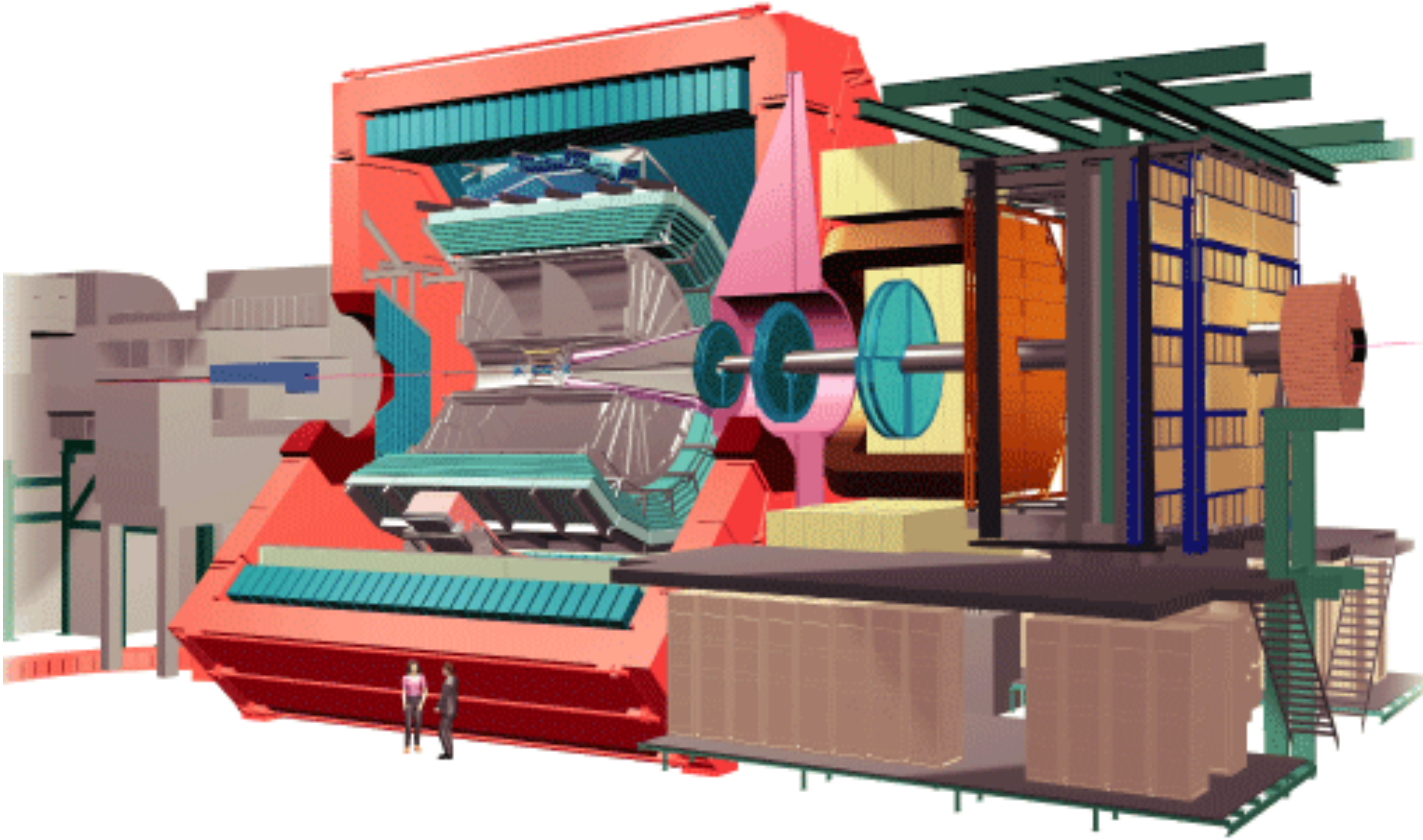
Pb^{+92}

1.38 TeV per nucleon

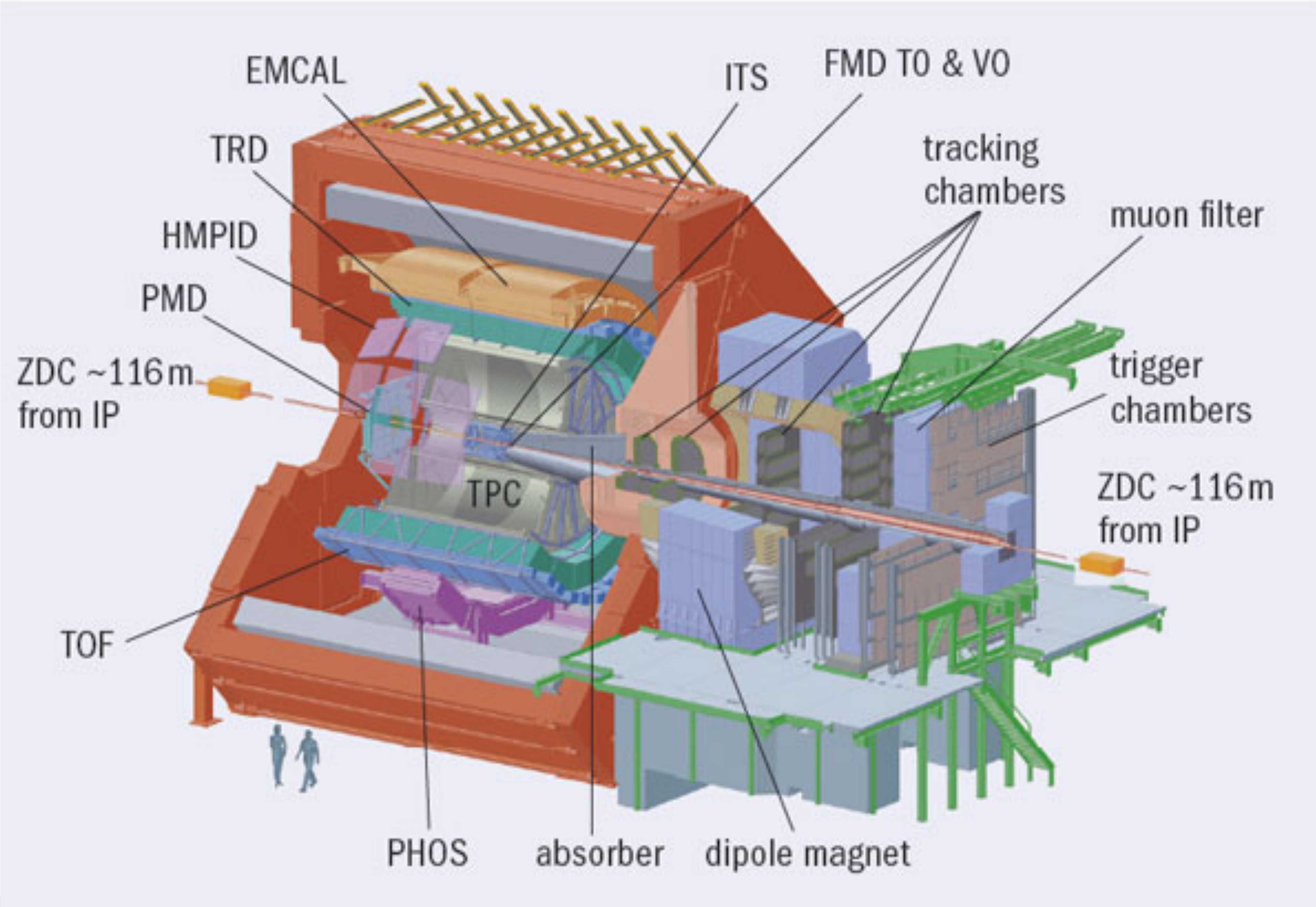
Each ion carry 1.38 TeV x 208 ~ 50 μJ

CERN Accelerator movie

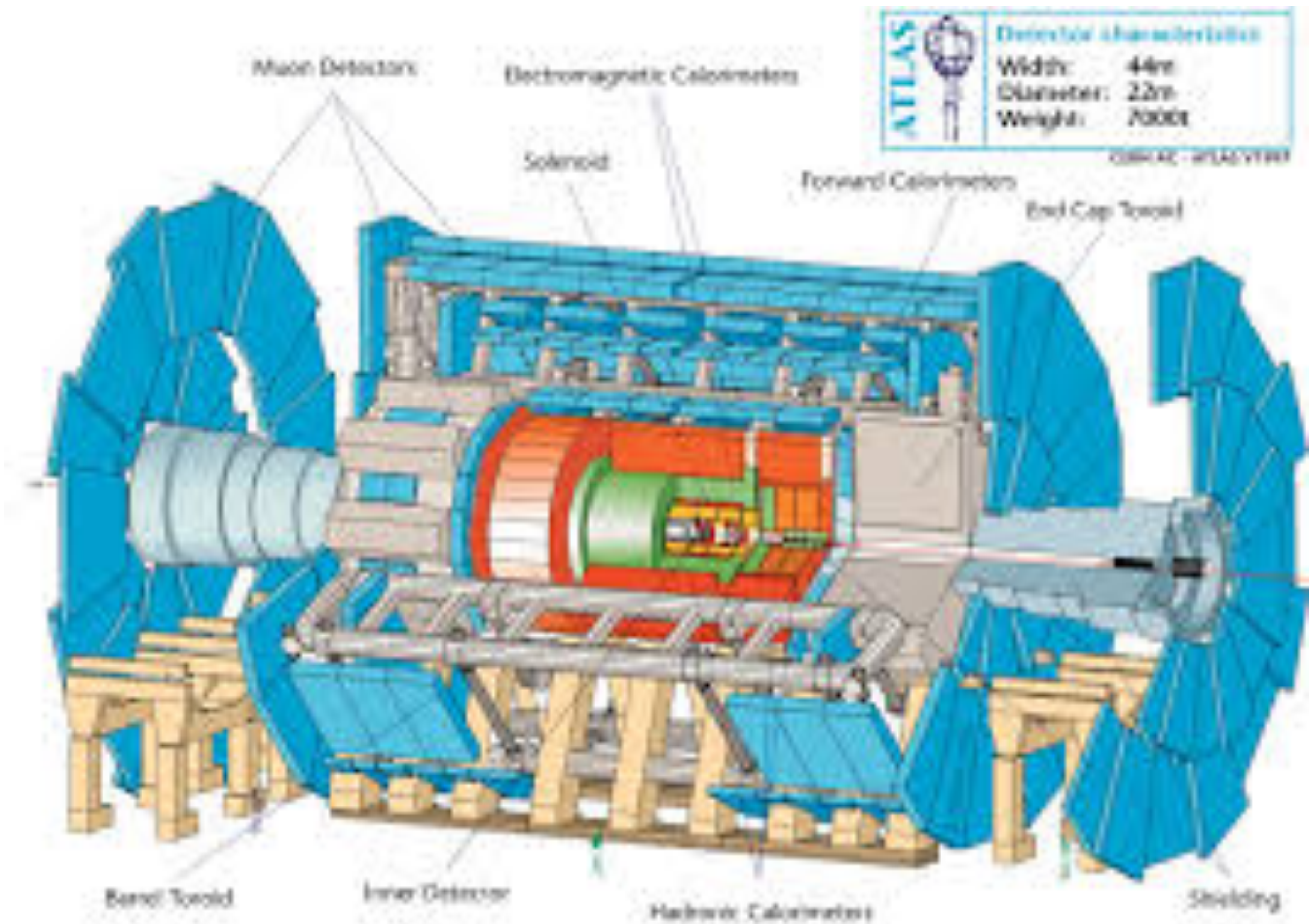
ALICE Detector



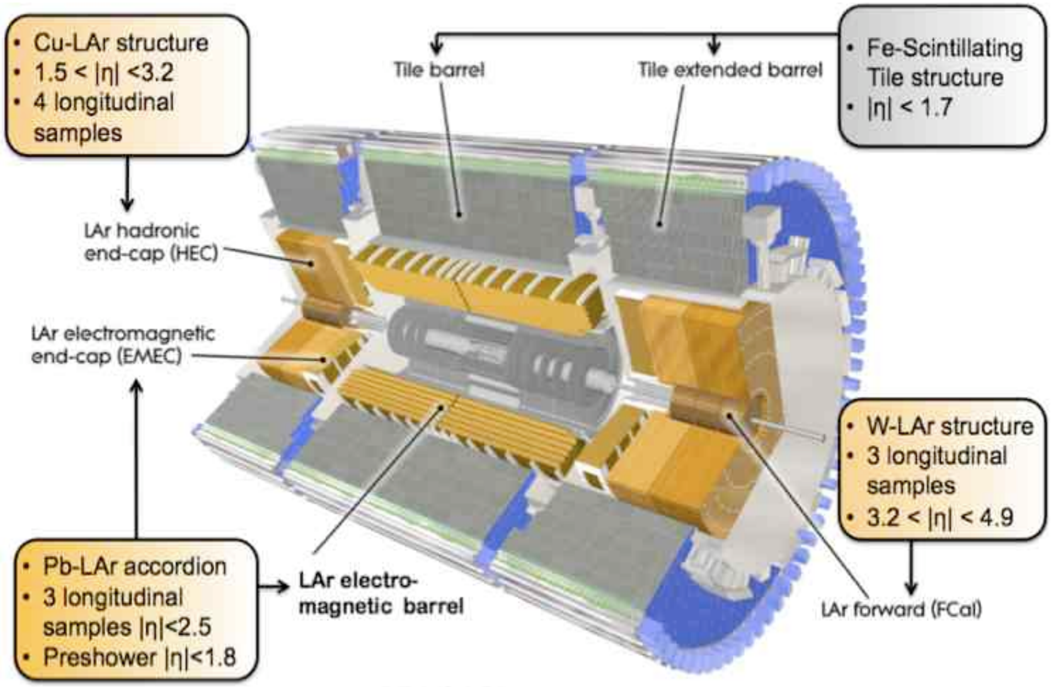
ALICE Detector Elements

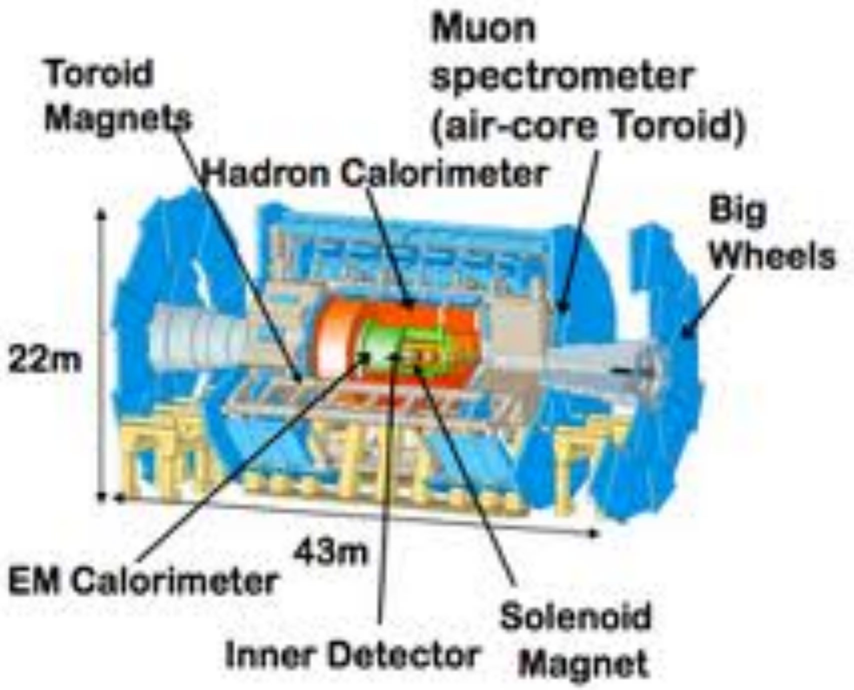


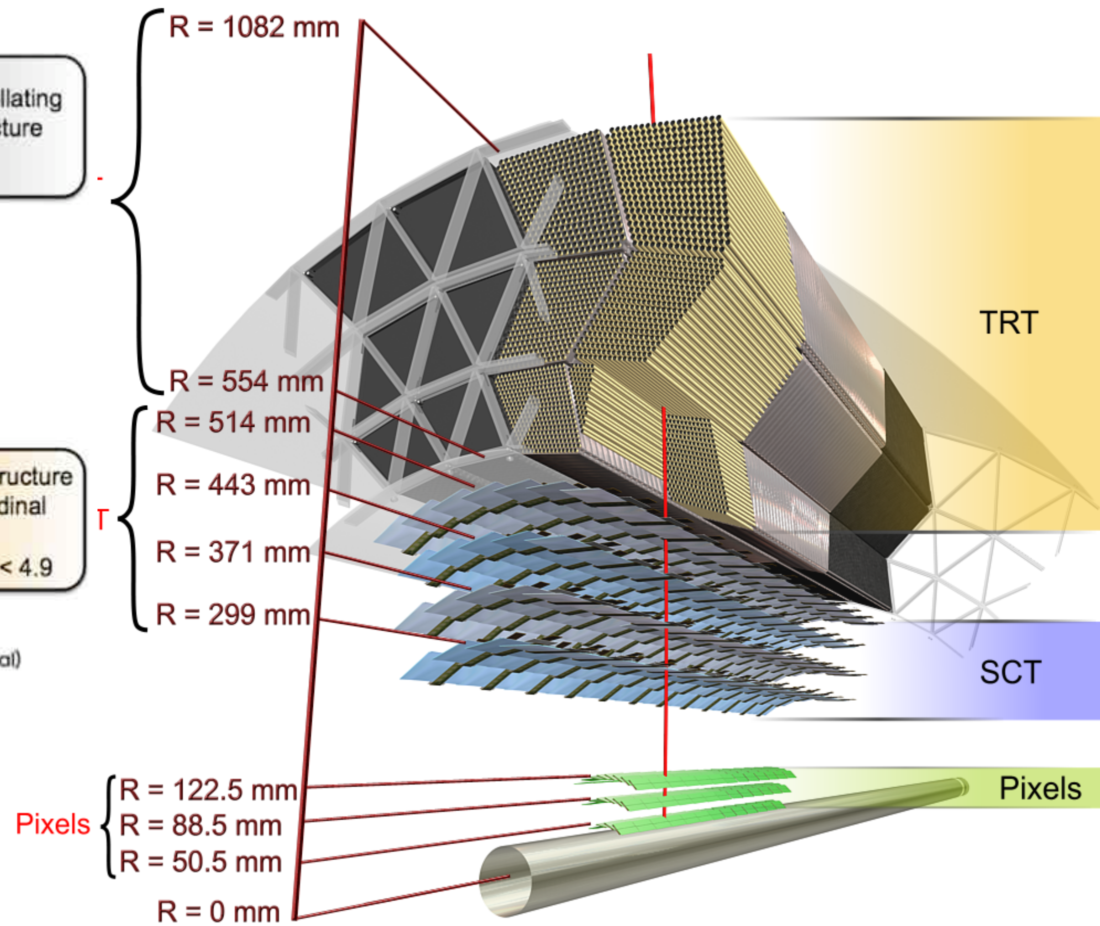
ATLAS Detector



ATLAS Detectors







CMS detector - construction (2000)

CMS design principles

- Use one single superconducting solenoid to provide uniform axial magnetic field
  - Largest coil that can be transported to CERN by road
  - Place tracking and calorimeters inside the coil
- Best possible electromagnetic calorimeter
  - Use $PbWO_4$ crystals
- Best possible tracking system
  - Based completely on silicon sensors
- Hermetic calorimetry
- Large and redundant muon system
- Construct large pieces on the surface and then lower them underground for final assembly
- Affordable?? (cost ~500 million US$)

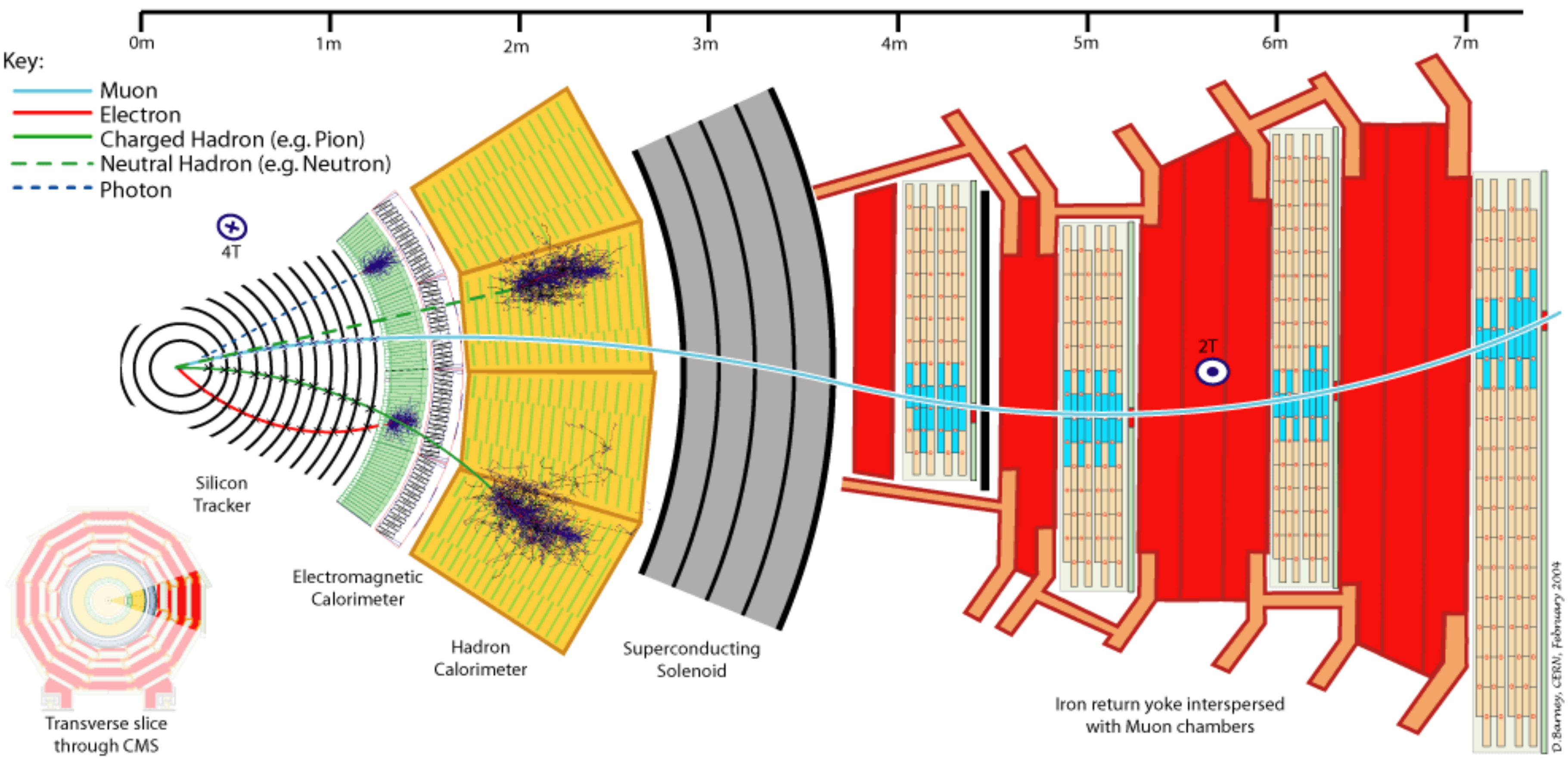
“Boundary conditions”

- LHC was designed to find Higgs and to extend the high energy frontier.
- BUT, Geneva region is small!, accelerator had to fit between the city and the mountains
  - “small” radius-> large magnetic field -> relatively low energy of 14 TeV
  - Some of us still remember SSC accelerator in Texas: 80 km circumference, 40 TeV
- LHC answer: high luminosity, ~25 (or more!) collisions every 25 ns
- All sub-detectors, trigger and DAQ need to be FAST

CMS as a detector for heavy ions

- Much lower luminosity, collision frequency was ~4kHz compared 1 GHz for pp
- But the multiplicity is higher, corresponds to 200-300 pp collisions at the same time
- % of fired channels in some detectors is relatively high, e.g. strip tracker or calorimeters
  - Requires some adjustments to electronics and software
- Specially designed triggers
- Adjustments to data acquisition system

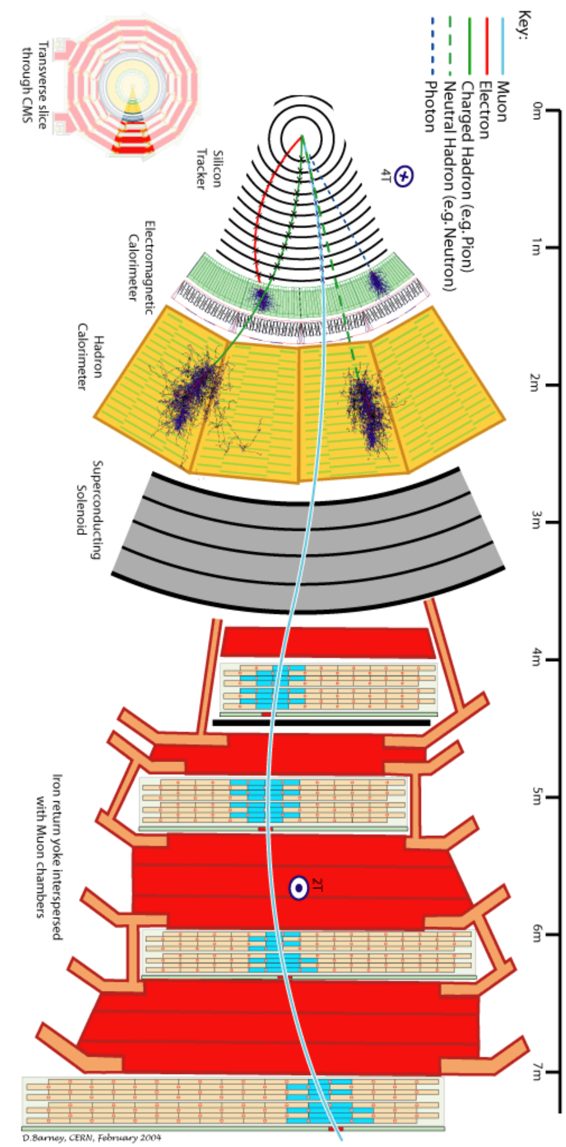
Particles in CMS



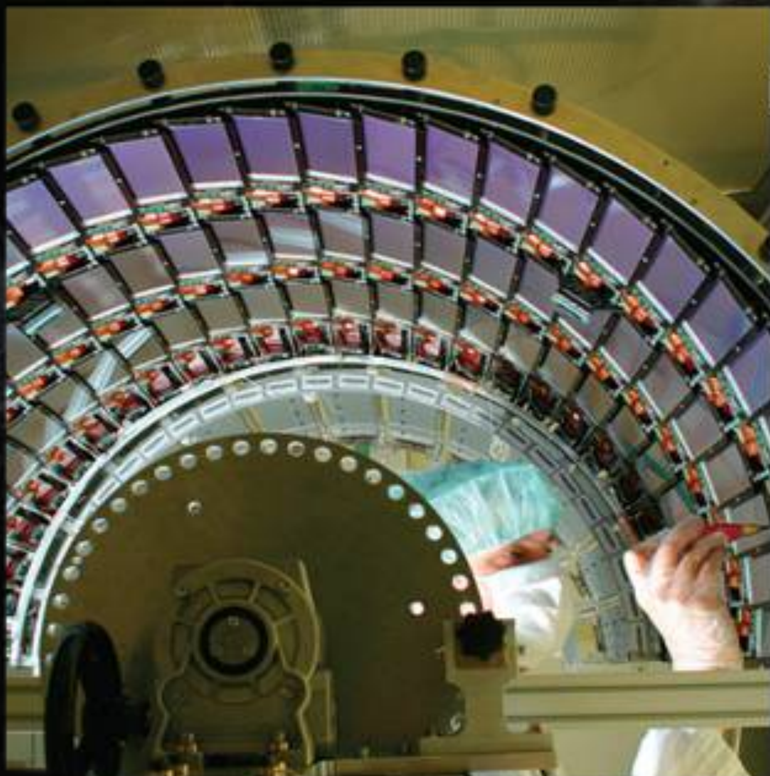
CMS Sub-detectors

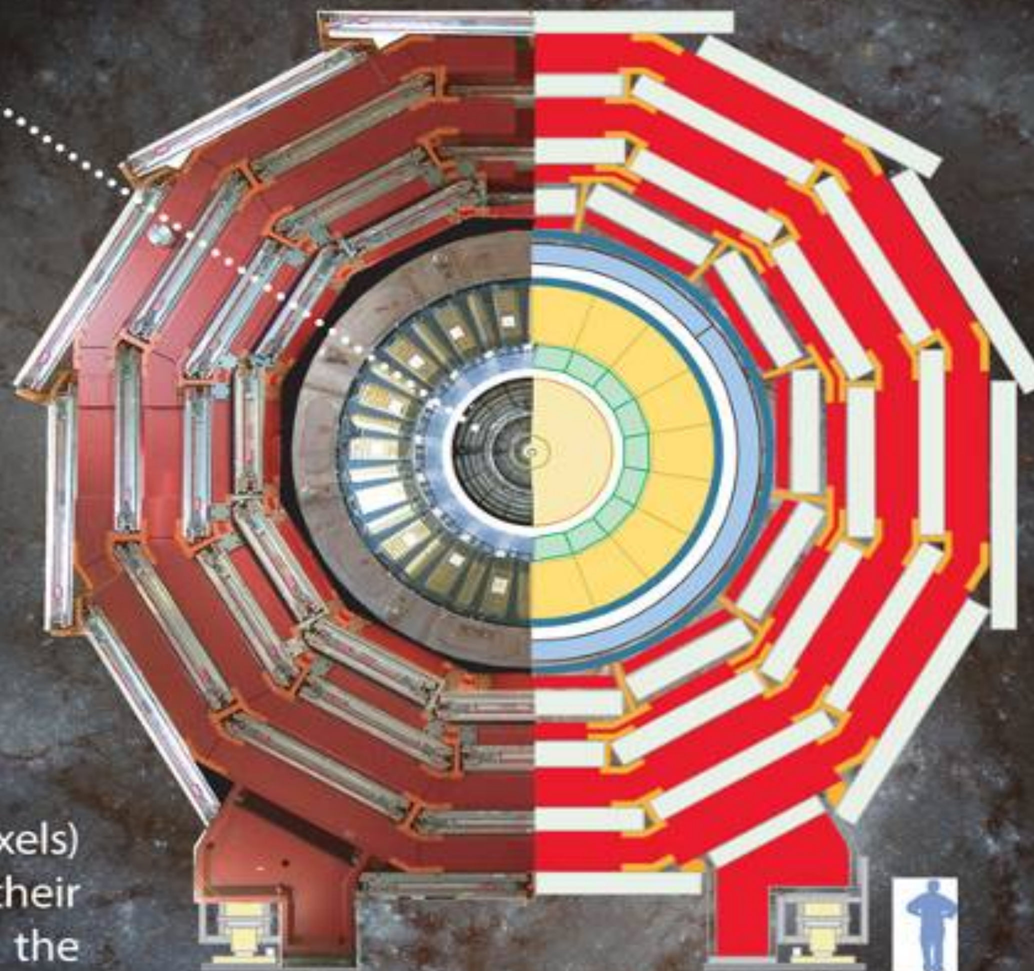
- Starting from the interaction point and going outwards
-
- Silicon Tracker
  - Pixels
  - Strips
- Electromagnetic Calorimeter (ECAL)
- Hadronic Calorimeter (HCAL)
- Solenoid Magnet

- Muon Detectors



CMS Sub-detectors: Tracker



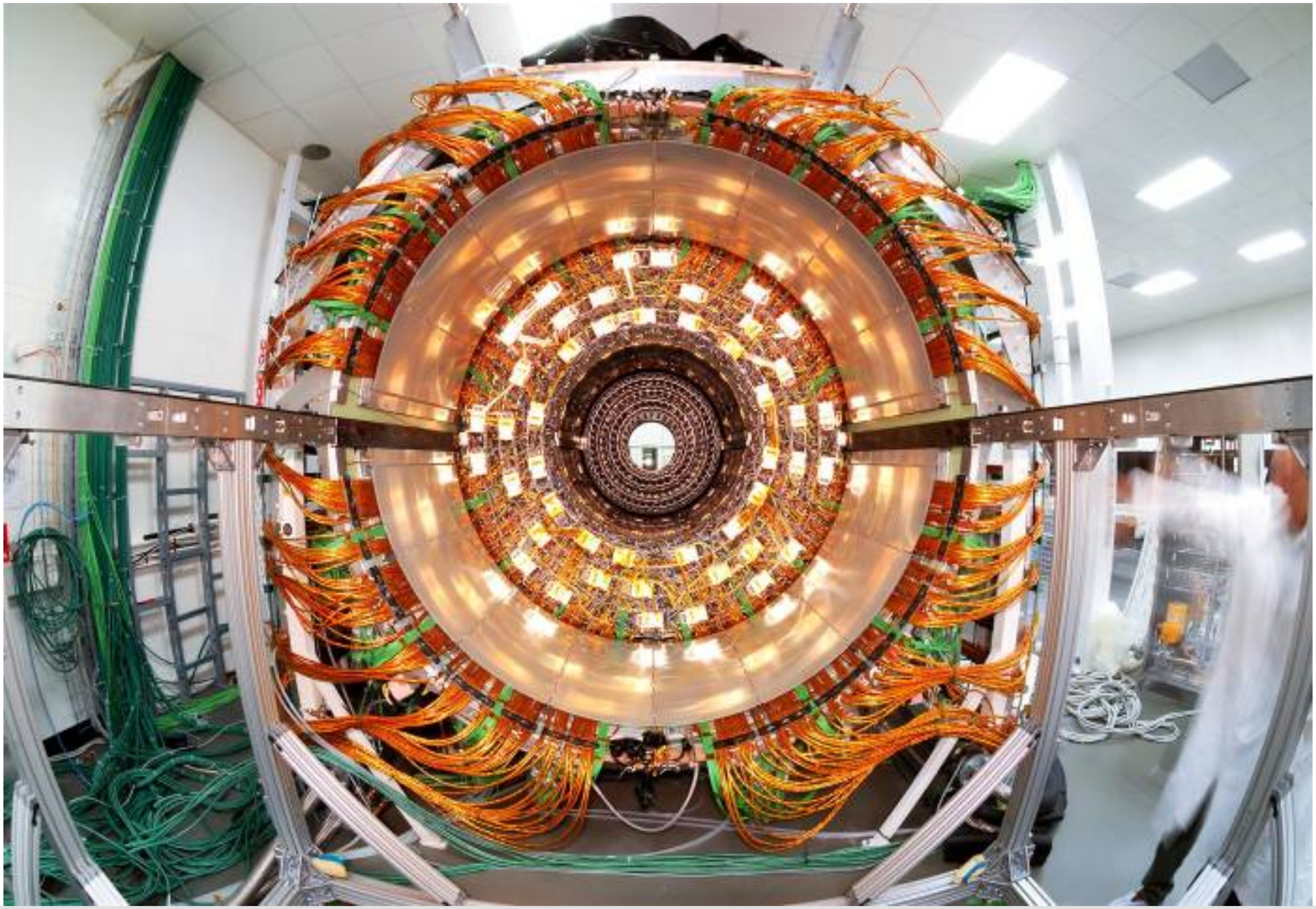


Tracker

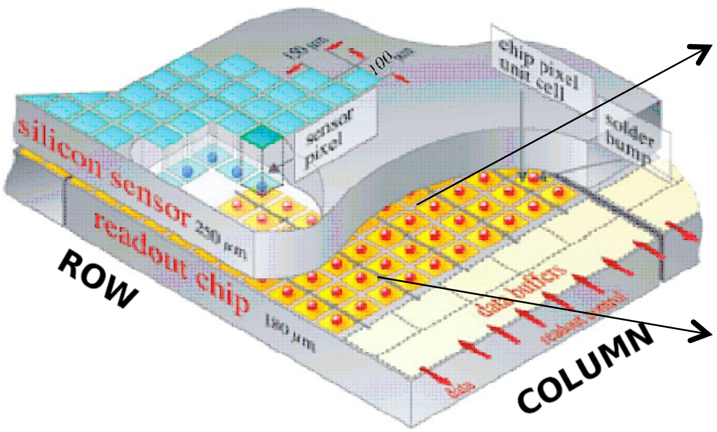
Finely segmented silicon sensors (strips and pixels) enable charged particles to be tracked and their momenta to be measured. They also reveal the positions at which long-lived unstable particles decay.

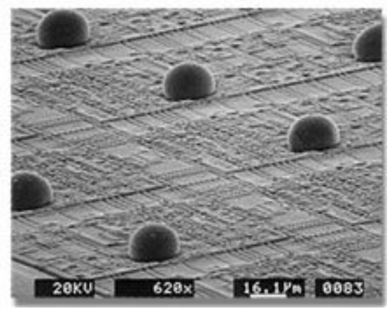
CMS Sub-detectors: Tracker

- Largest silicon-sensor system ever made
  - 6m long, ~2.2m diameter, will operate at -15^{o}C
  - More than 220m^2 of sensors (65M pixels and 10M strips)



Pixel ReadOut Chip



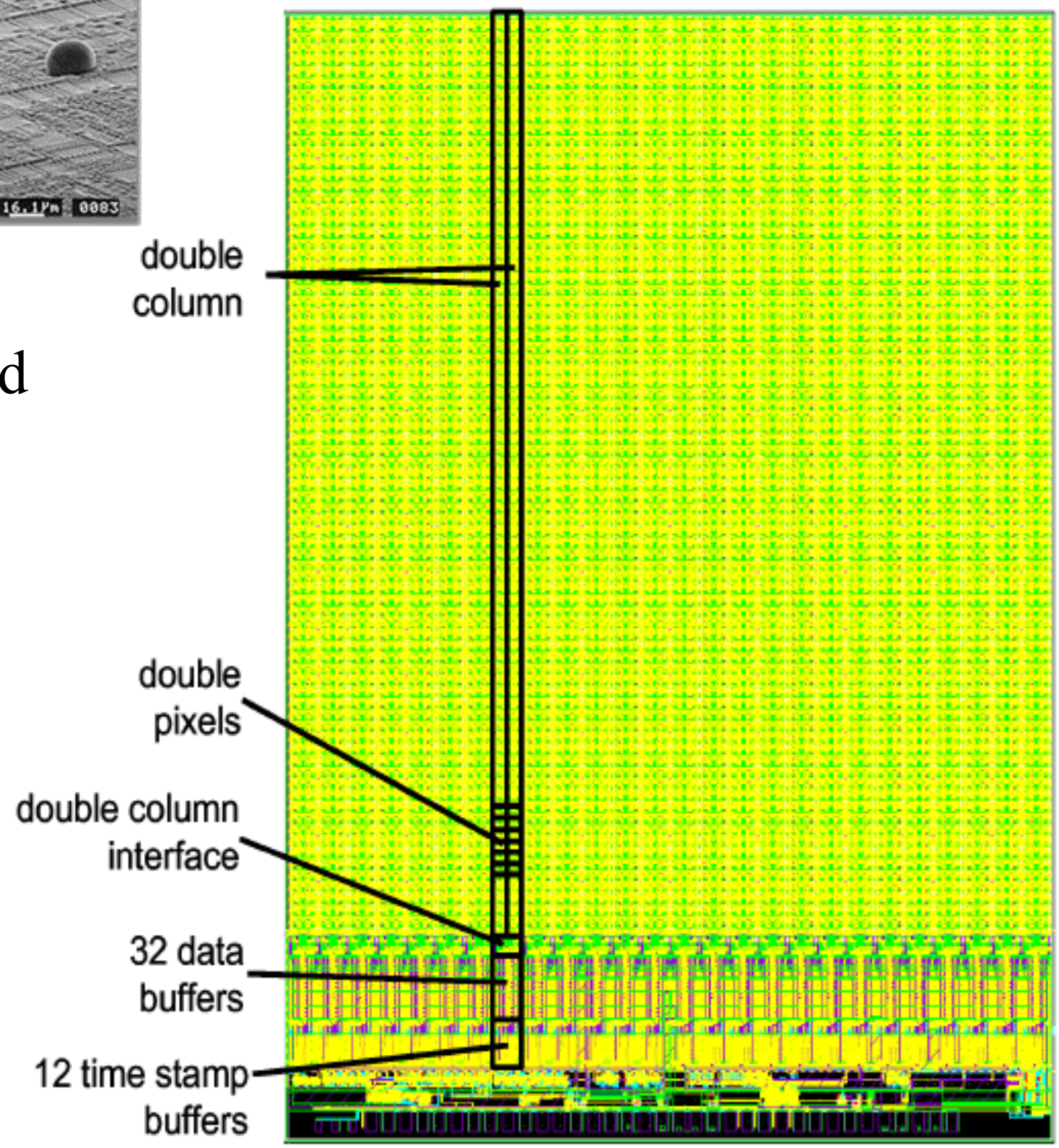


•ReadOut Chip (ROC) bump bonded sensor pixels.

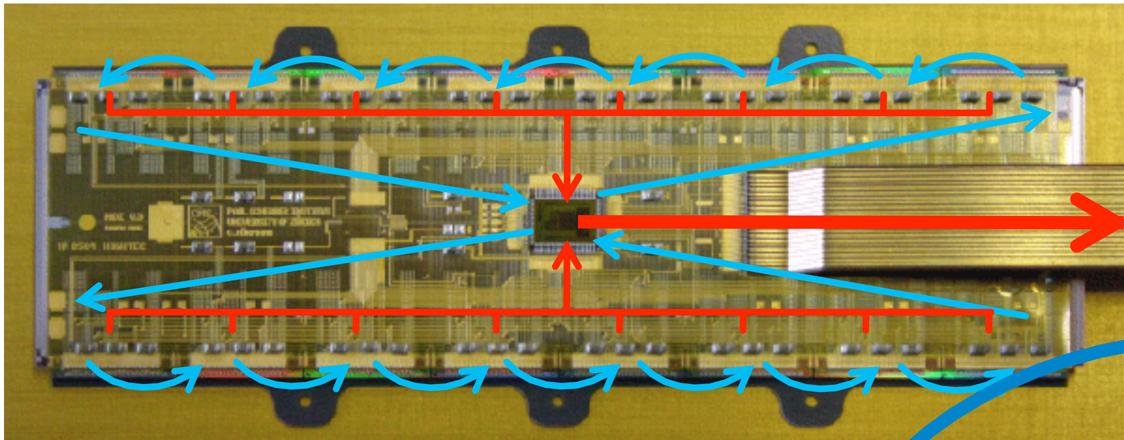
•52 × 80 = 4160 pixels per ROC
•15,840 ROCs
•66 million pixels

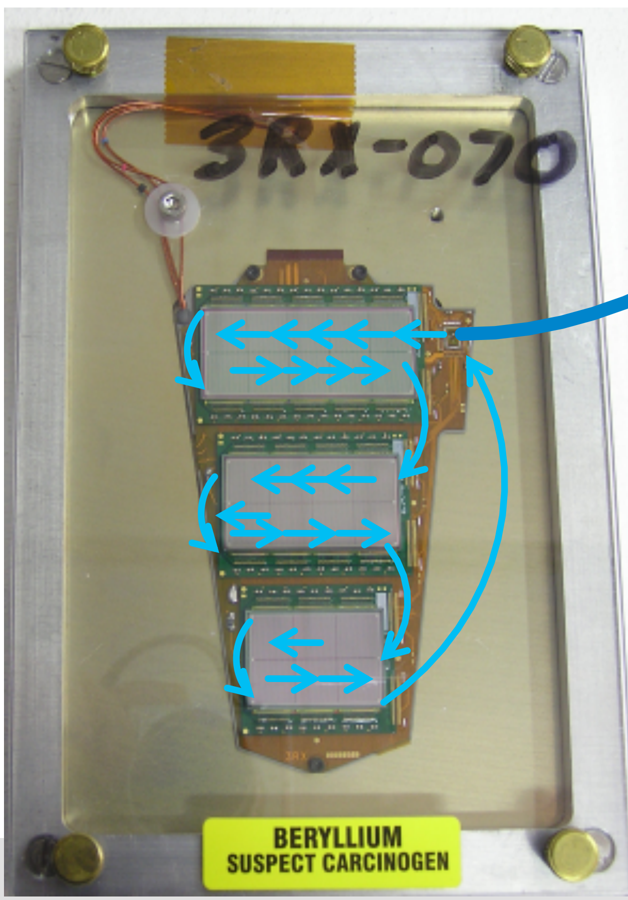
•Automatic zero-suppression

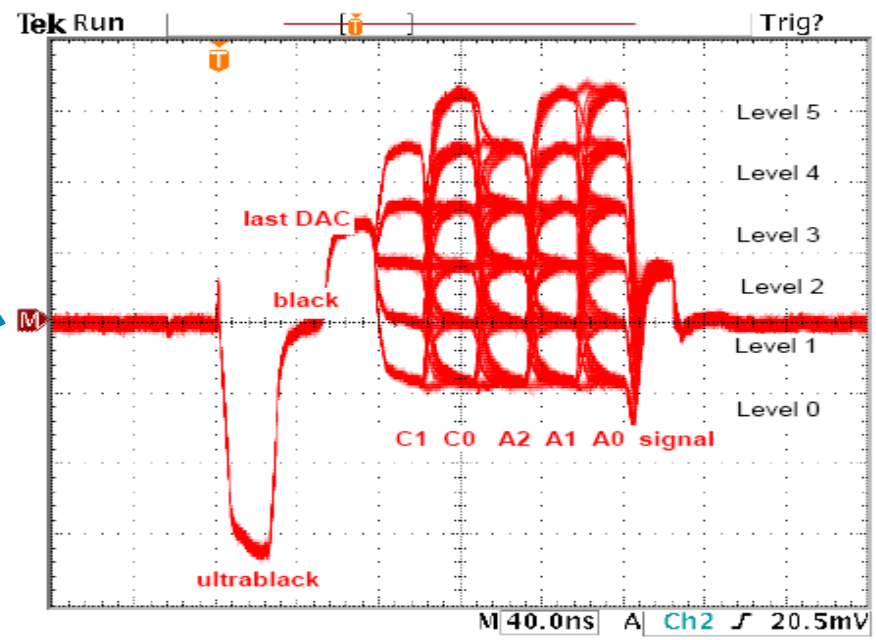
•Each pixel has a programmable threshold



Pixel Analog Readout







•On receiving a L1 trigger, the Token Bit Manager (TBM) initiates a sends "token bits" that instruct each ROC to send its hit data to the TBM

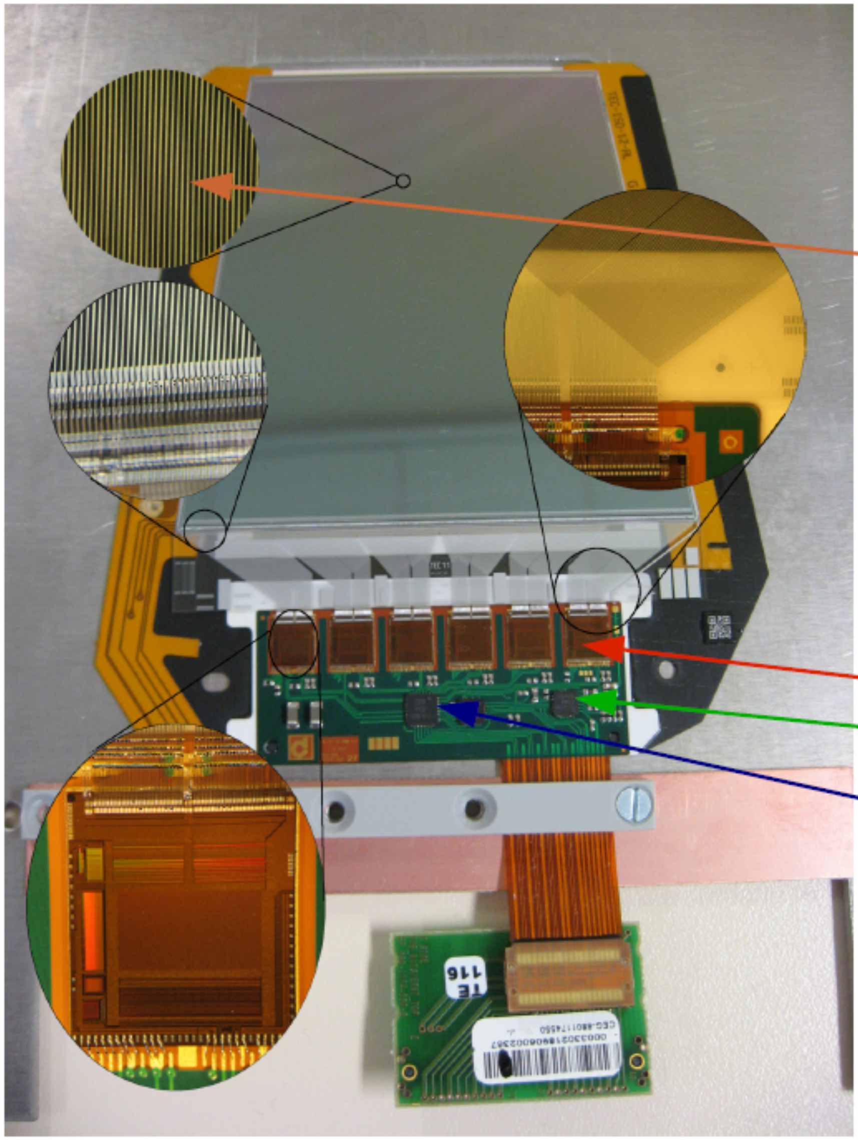
•The signal from the TBM is electrical and analog. It encodes the ROC #, row and column and charge deposit of each pixel hit

•The electrical signal from the TBM is converted to optical by the Analog-Optical Hybrid (AOH)

CMS Sub-detectors: Tracker

Assembling (left) and installation (below) of part of the Pixel detector

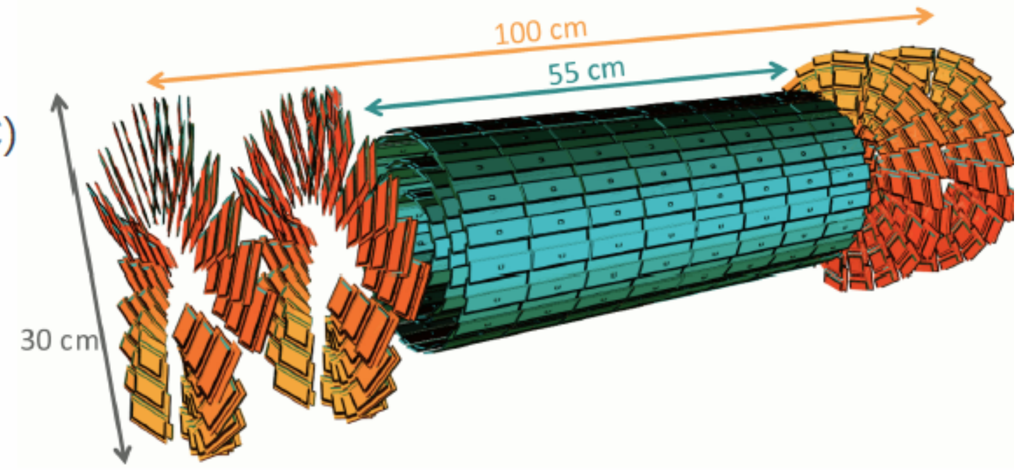
Tracker Sensor



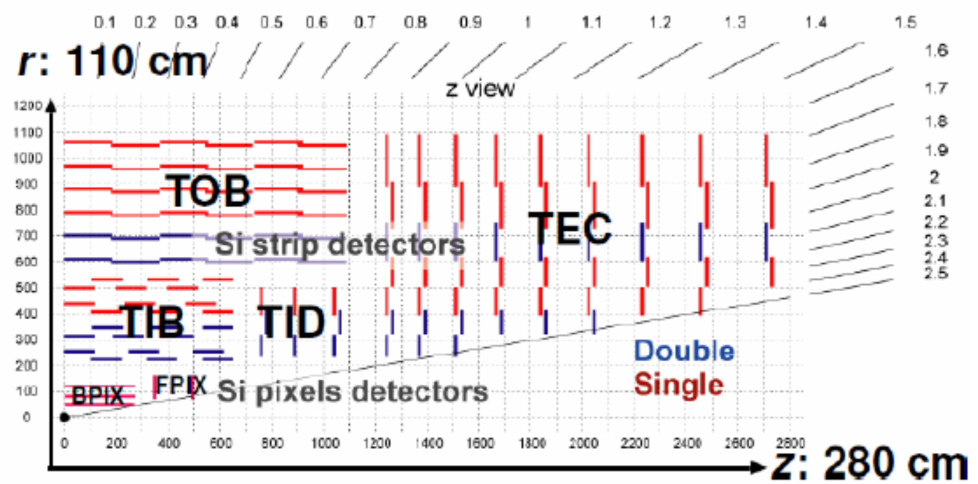
- Sensor
  - p^+ implant in n-type silicon bulk
  - 512 or 768 strips
  - strip pitch p=80-205 m.
  - w/p = 0:25 (w: p+ implant width).
  - AC-coupled readout.
- Electronics on Hybrid
  - 4 or 6 APV readout chips.
  - DCU: leakage current, temperature,.
  - Multiplexed on 2 or 3 readout lines by MUX.

Tracker detector

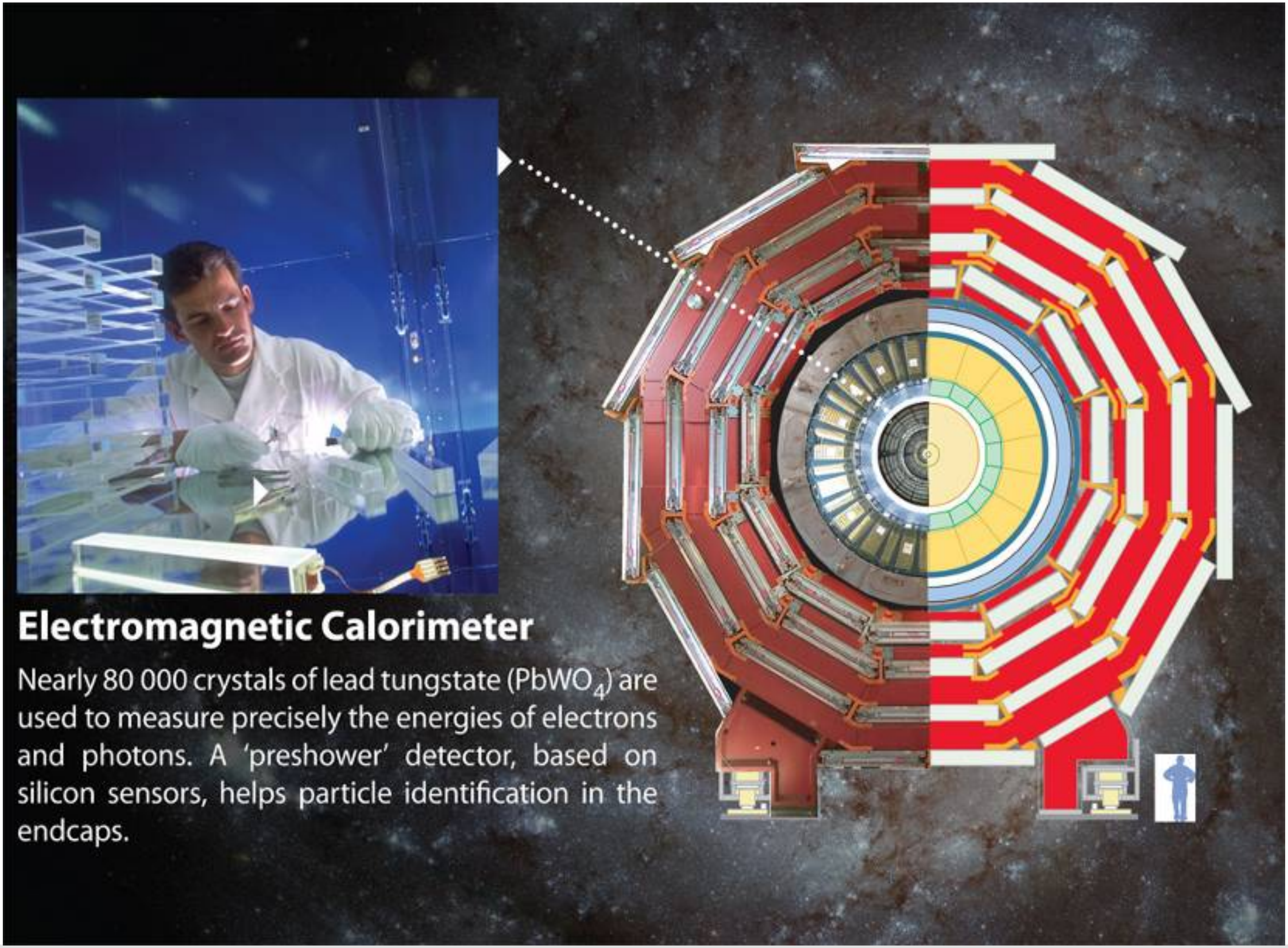
- Silicon pixel + Strip detector with optical analog readout
- **Pixel** :
  - N+ in n sensors :
    - 100 µm x 150 µm
    - 52x80 pixel read by one ReadOut Chip (ROC)
  - Barrel (Bpix):
    - 3 layers (56cm long) at r= 4.3,7.2, 11.0 cm
    - → 48M pixels, 11520 ROCs, 1120 RO links
  - Endcap (FPix) :
    - 4 disks inner (outer) radius=6 (15) cm at z= ±34.5, ±46.5 cm
    - → 18M pixels, 4320 ROCs, 192 RO links



- **Strip** :
  - 9.3M strips in 15148 modules :
    - Inner: 4 layers barrel (TIB), 3 disks (TID) cap
    - Outer:6 layers barrel (TOB), 9 disks (TEC)cap
  - 200m² silicon sensor (p-in-n) :
    - Pitch from 80 to 205 µm
    - 20<r<55 cm thin (d=320 µm)
    - r>55 cm thick (d=500 µm)
  - Generally measure rΦ direction
  - Some radii ('Stereo'): additional 2nd modules rotated by 100 mrad
    - → measurements for η(track)

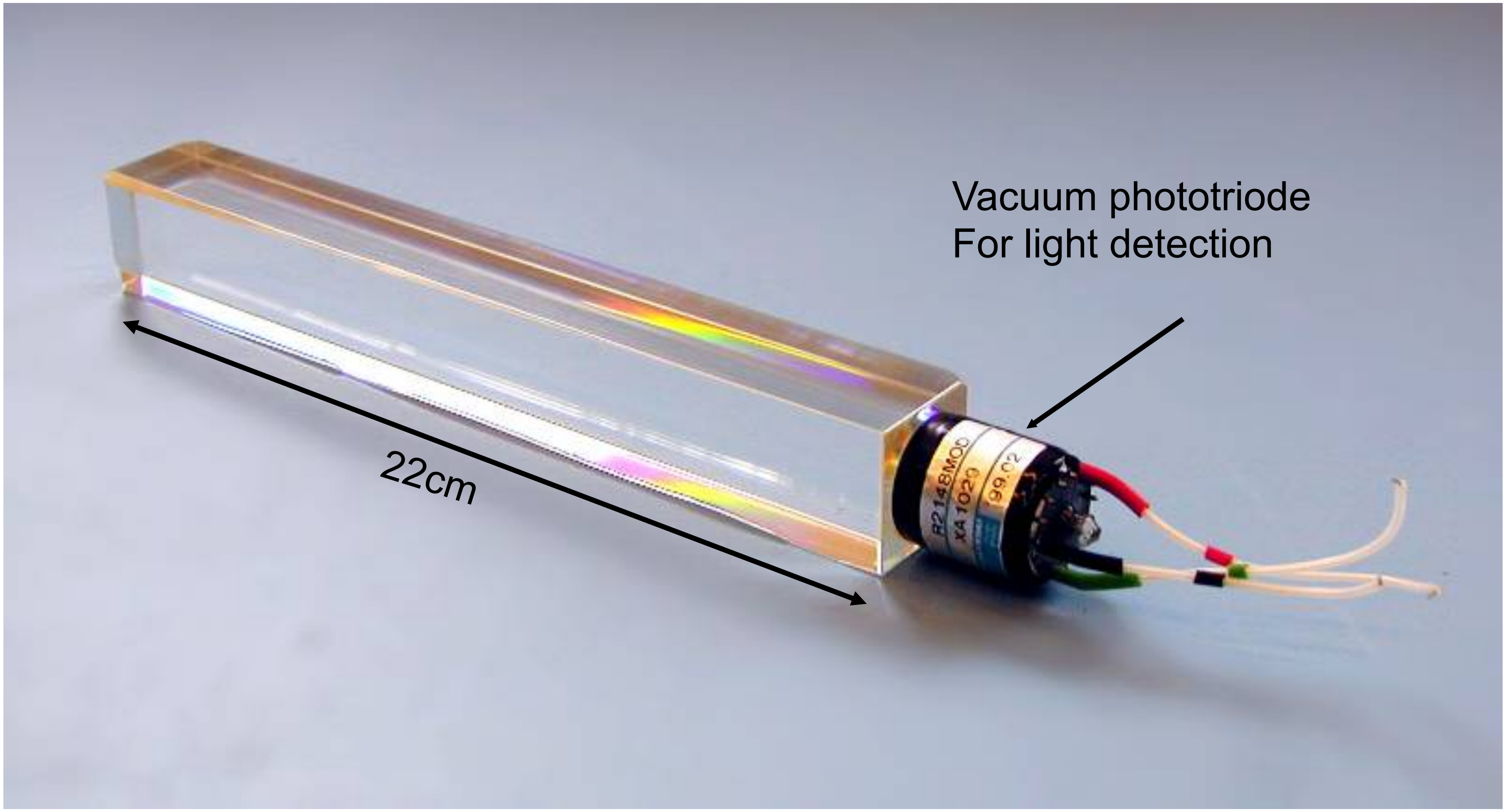


CMS sub-detectors: ECAL

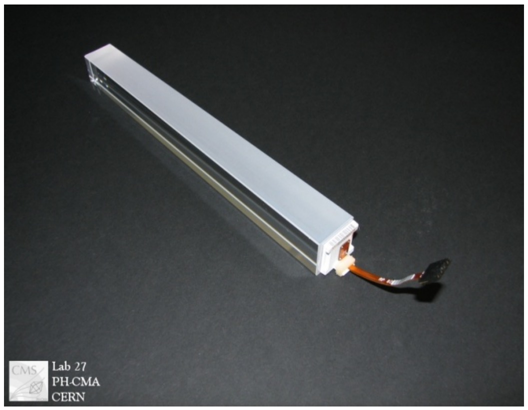


Calorimeters: Lead Tungstate Crystal

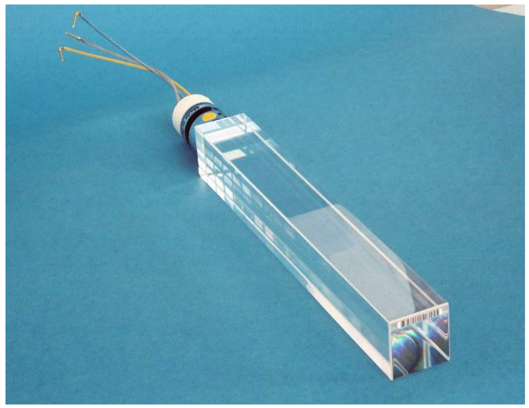
- One dense substance – $PbWO_4$ - produces the shower and scintillation light



Lead tungstate crystals ($PbWO_4$)



Barrel crystal,
tapered
34 types



Endcap crystal,
tapered
1 type

Reasons for choice:

- Homogeneous medium — 8.3 g/cm^3
- Fast light emission — ~ 80% in 25 ns
- Short radiation length — X_0 = 0.89 cm
- Small Molière radius — R_M = 2.20 cm
- Emission peak — 420 nm

Caveats:

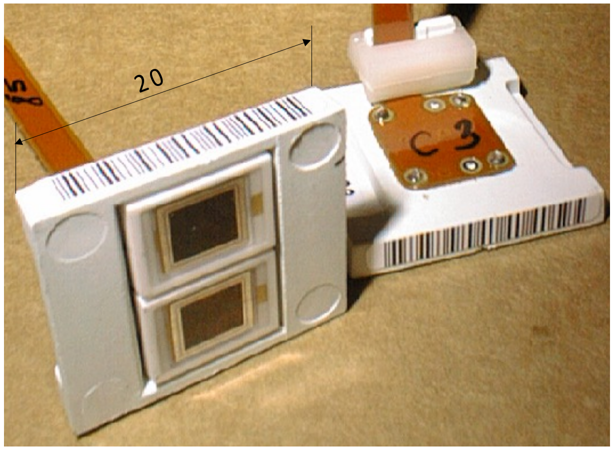
- LY temperature dependence ~-2.2%/^{O}C Need to stabilise to few 0.01^{O}C
- Formation/decay of colour centres under irradiation altering crystal transparency
  Need **precise monitoring system**
- Low light yield
  Need photodetectors with gain in magnetic field
- Light yield spread between crystals ~ 10%
  Need **intercalibration**

Photodetectors

Barrel: Avalanche photo-diodes (APD, Hamamatsu)

- Two 5x5 mm^2 APDs/crystal, ~ 4.5 p.e./MeV
- Gain 50
- QE ~ 75% at 420 nm
- **Temperature dependence $\Delta G/\Delta T$ = -2.4%/°C**
- **High-Voltage dependence $\Delta G/\Delta V$ = 3.1%/V**

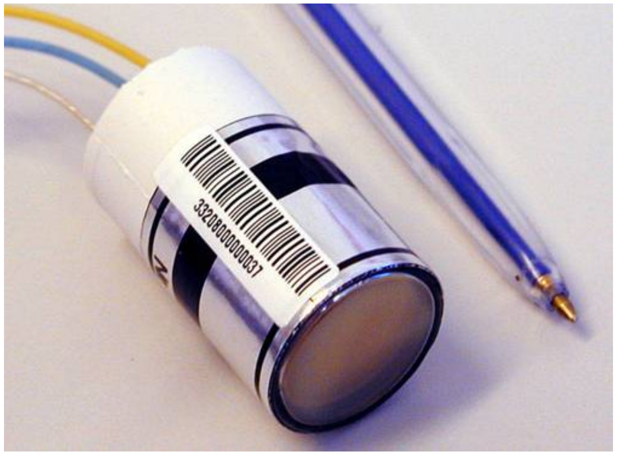
Need to stabilize T at few 0.01°C and HV at ~10mV



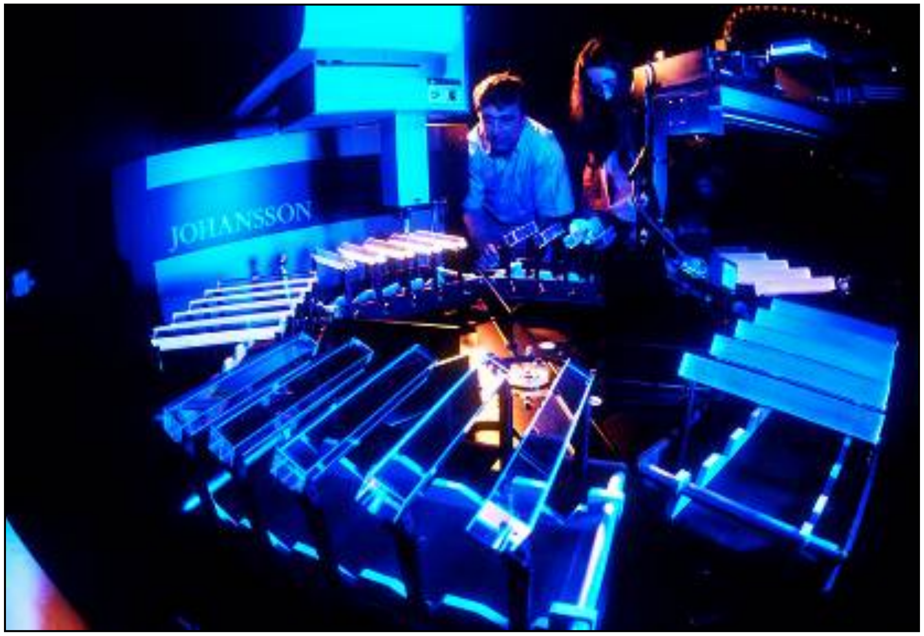
Endcaps: Vacuum photo-triodes (VPT, RIE)

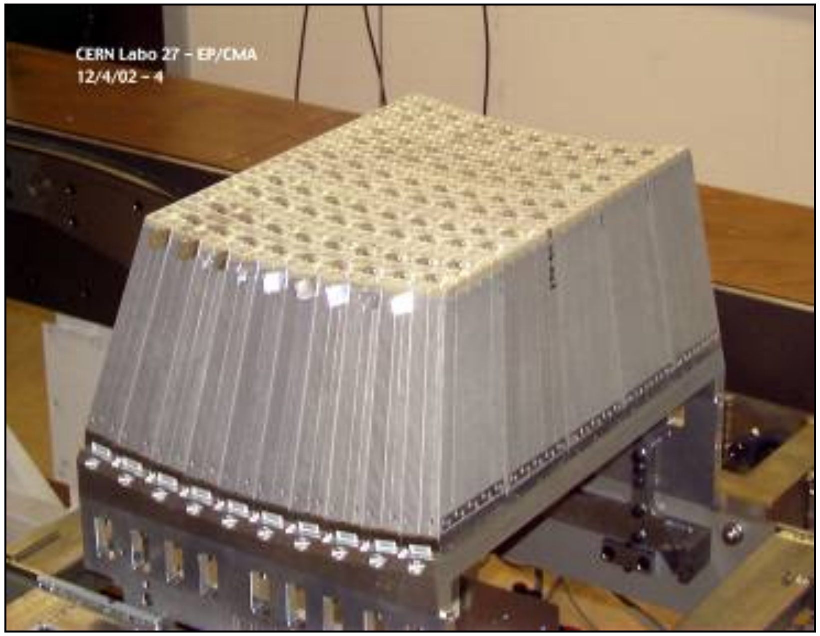
- More radiation resistant than Si diodes
- UV glass window
- Active area ~ 280 mm^2/crystal, ~ 4.5 p.e./MeV
- Gain 8 -10 (B=4T)
- Q.E. ~ 20% at 420 nm
- **Gain spread among VPTs ~ 25%**

Need intercalibration

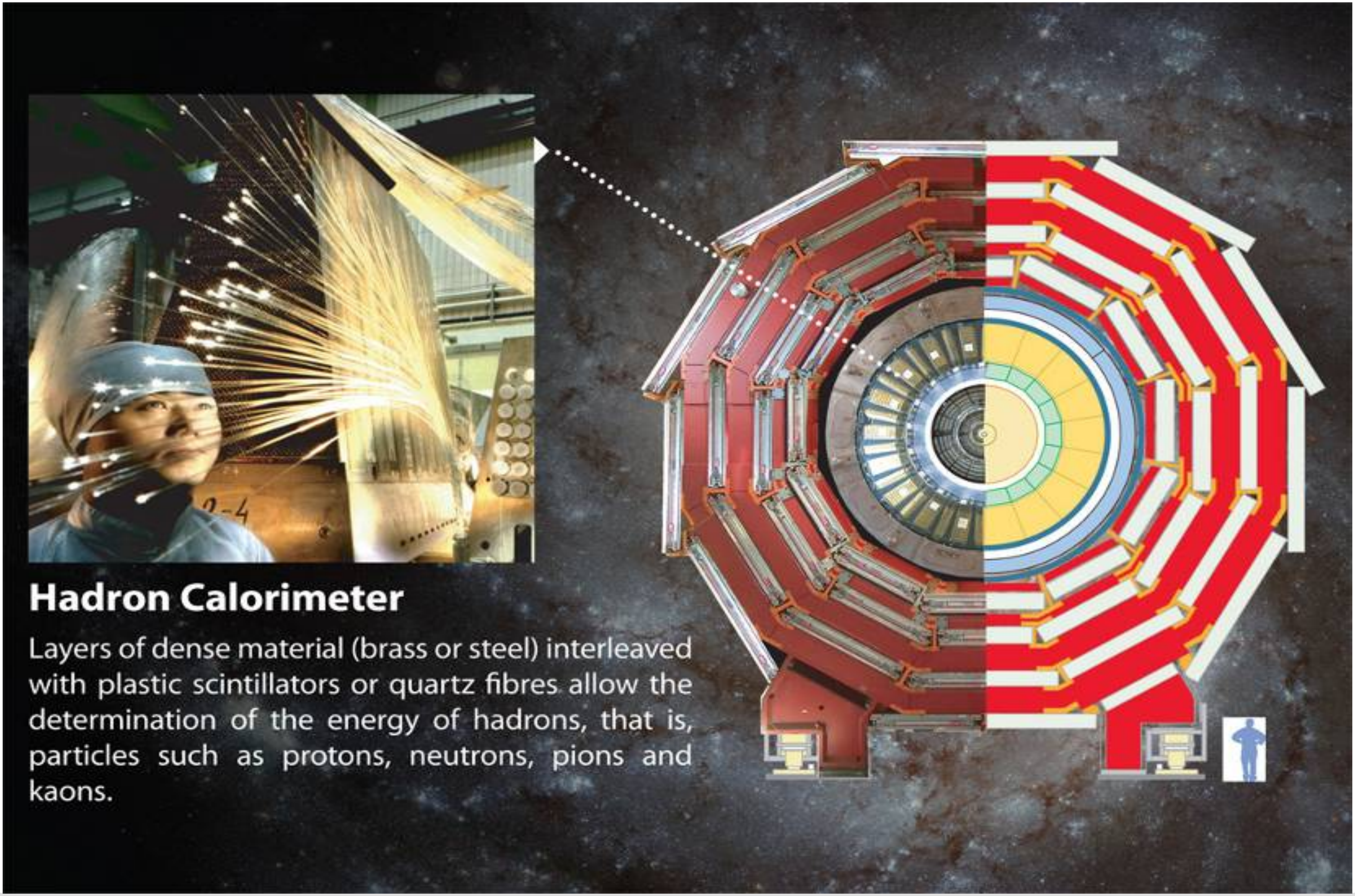


CMS Sub-detectors: ECAL

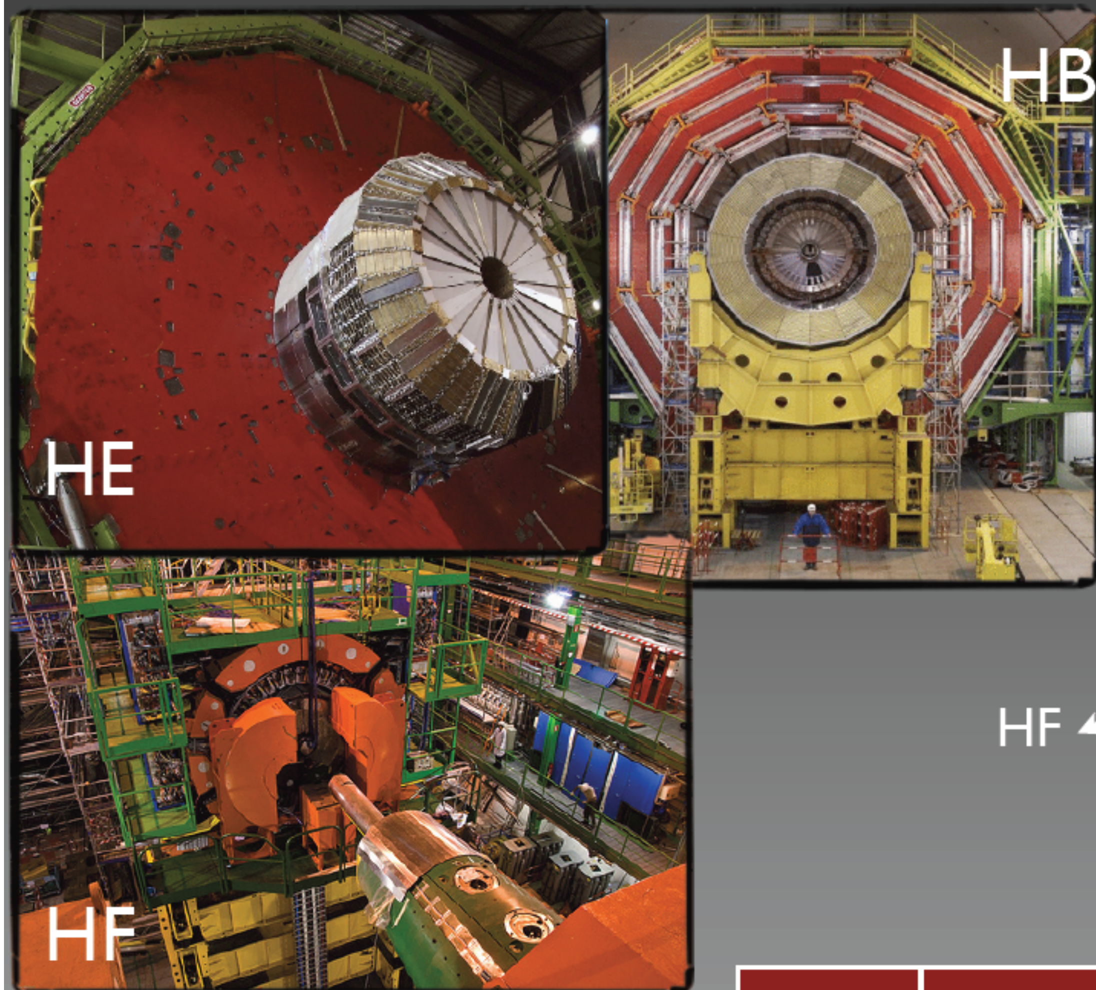


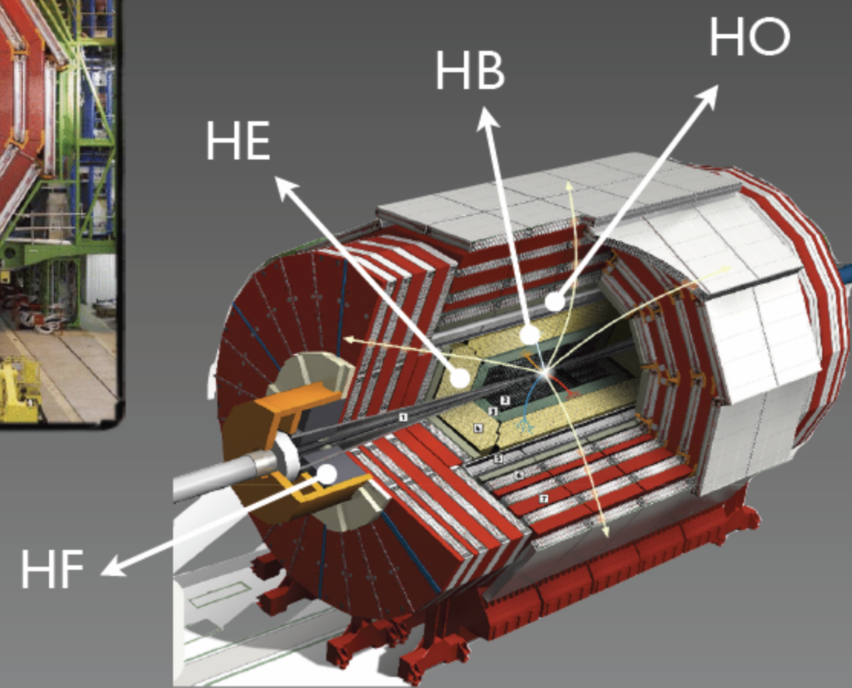


CMS Sub-detectors: HCAL



HCAL Structure





Detector	Active Material	Absorber	Readout	# Channels
HB/HE/HO	Scintillator Tile	Brass	Hybrid Photo-Diode (HPD)	2592/2592/2160
HF	Quartz Fiber	Steel	PMT	1728

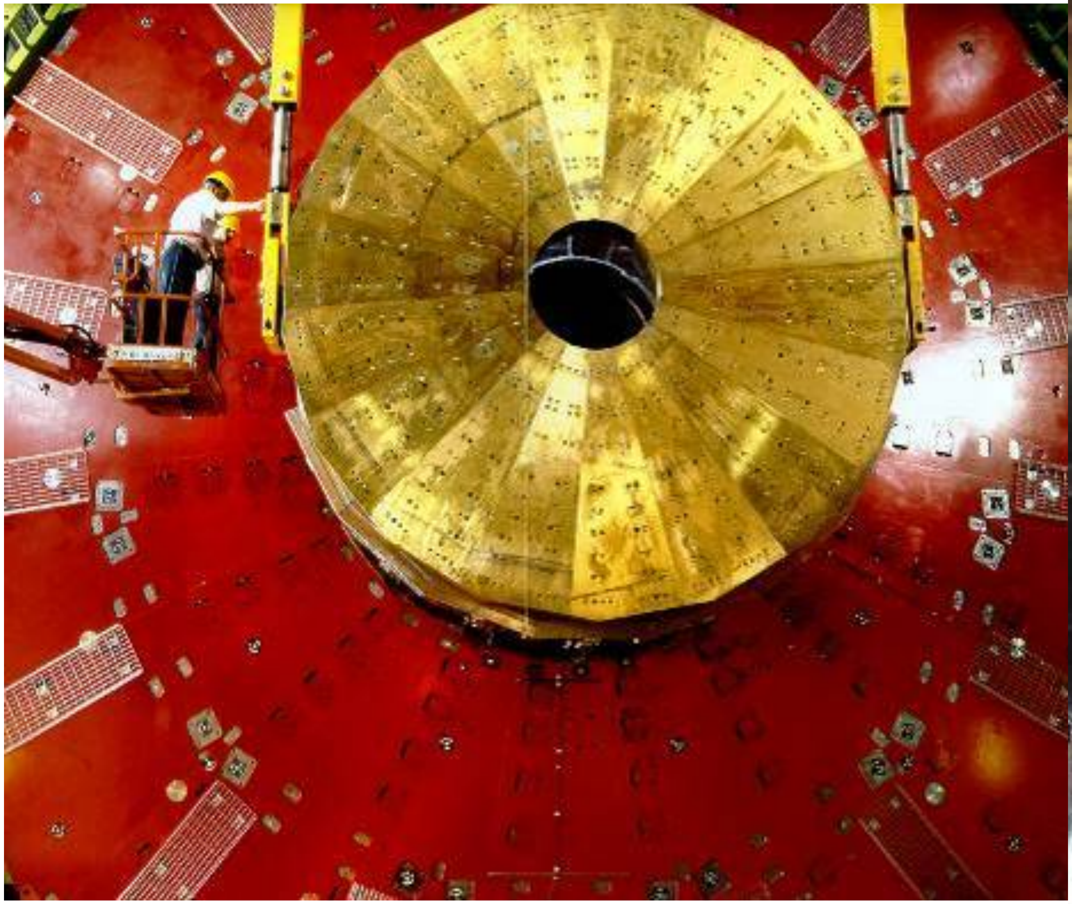
CMS Sub-detectors: HCAL

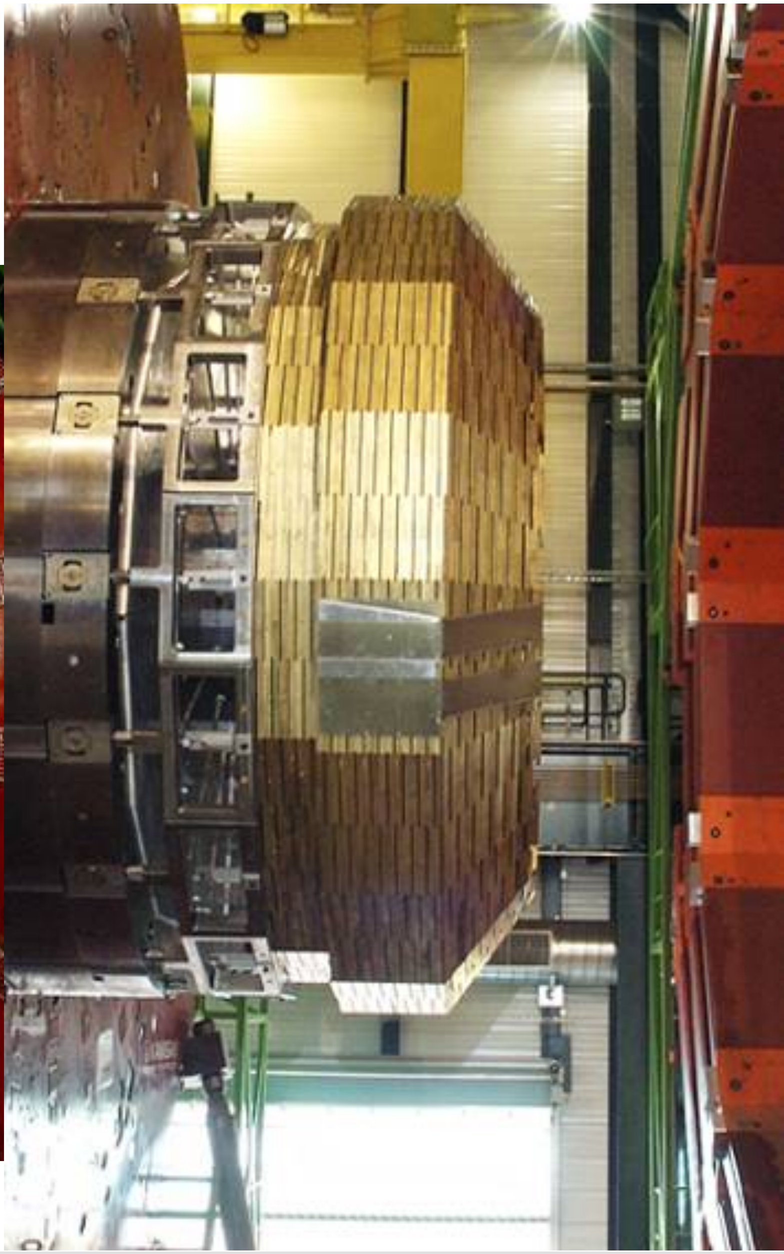
Weapons to ploughshares: Brass for HCAL recuperated from Russian warships!



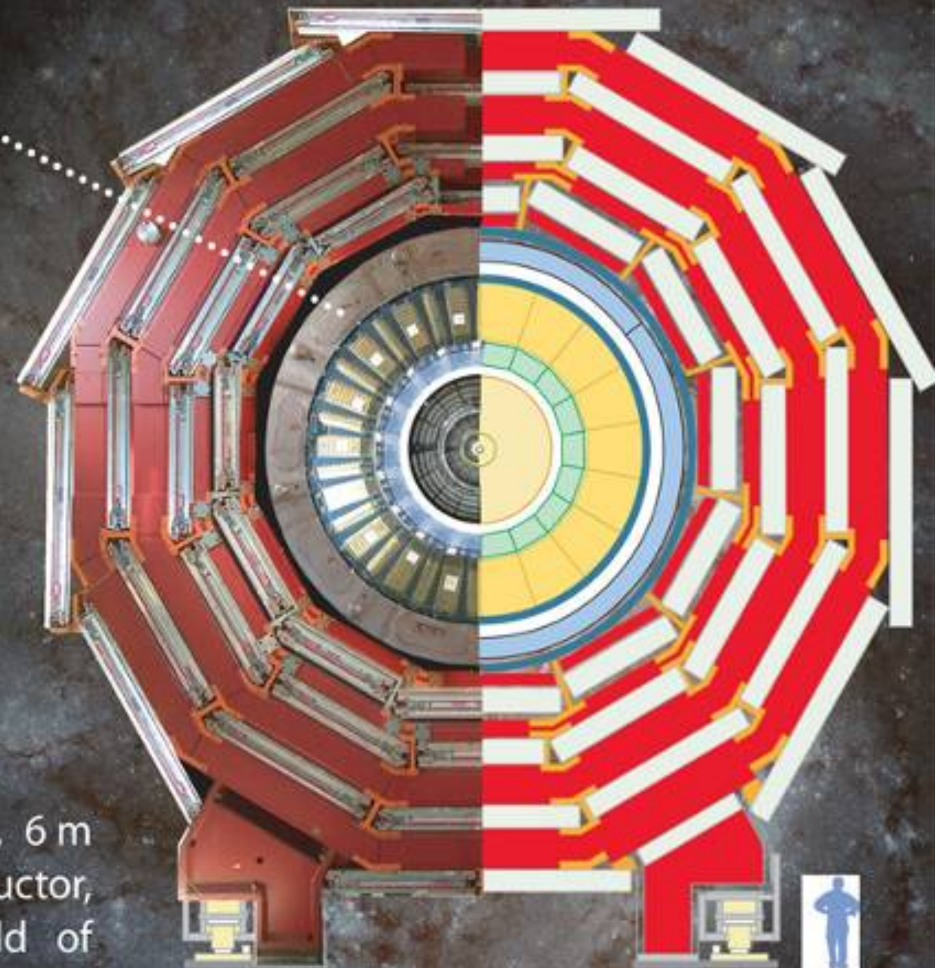

CMS Sub-detectors: HCAL

Installed Endcap HCAL





CMS Solenoid



Superconducting Solenoid

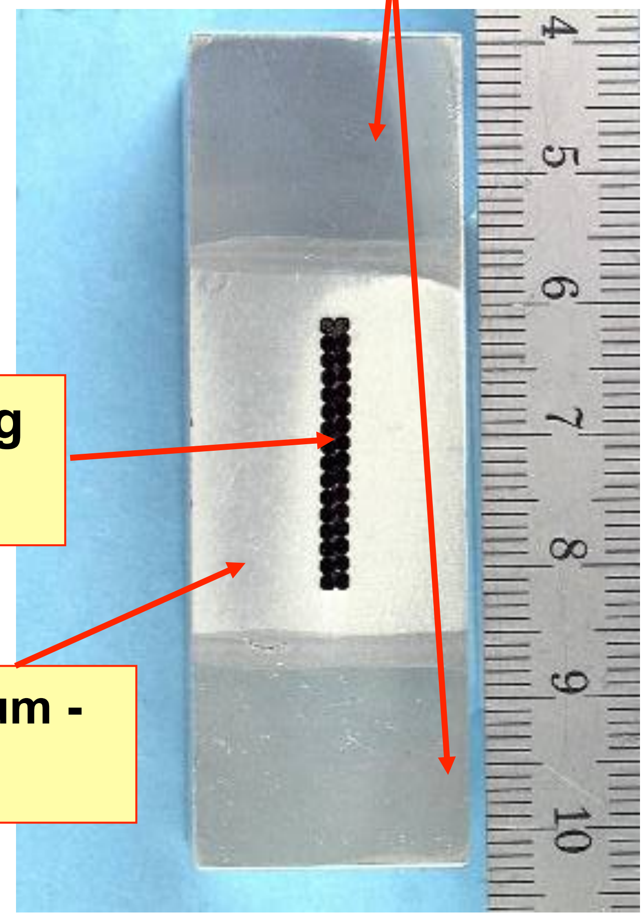
Passing 20 000 amperes through a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to –270°C, produces a magnetic field of 4 teslas (about 100 000 times stronger than that of the Earth). This field bends the trajectories of charged particles, allowing their separation and momenta measurements.

CMS Solenoid

Magnet cable

- B-field needs to be uniform and large (few teslas)
- Use superconductors

Aluminium alloy - mechanical stabilizer



Superconducting cable - NbTi

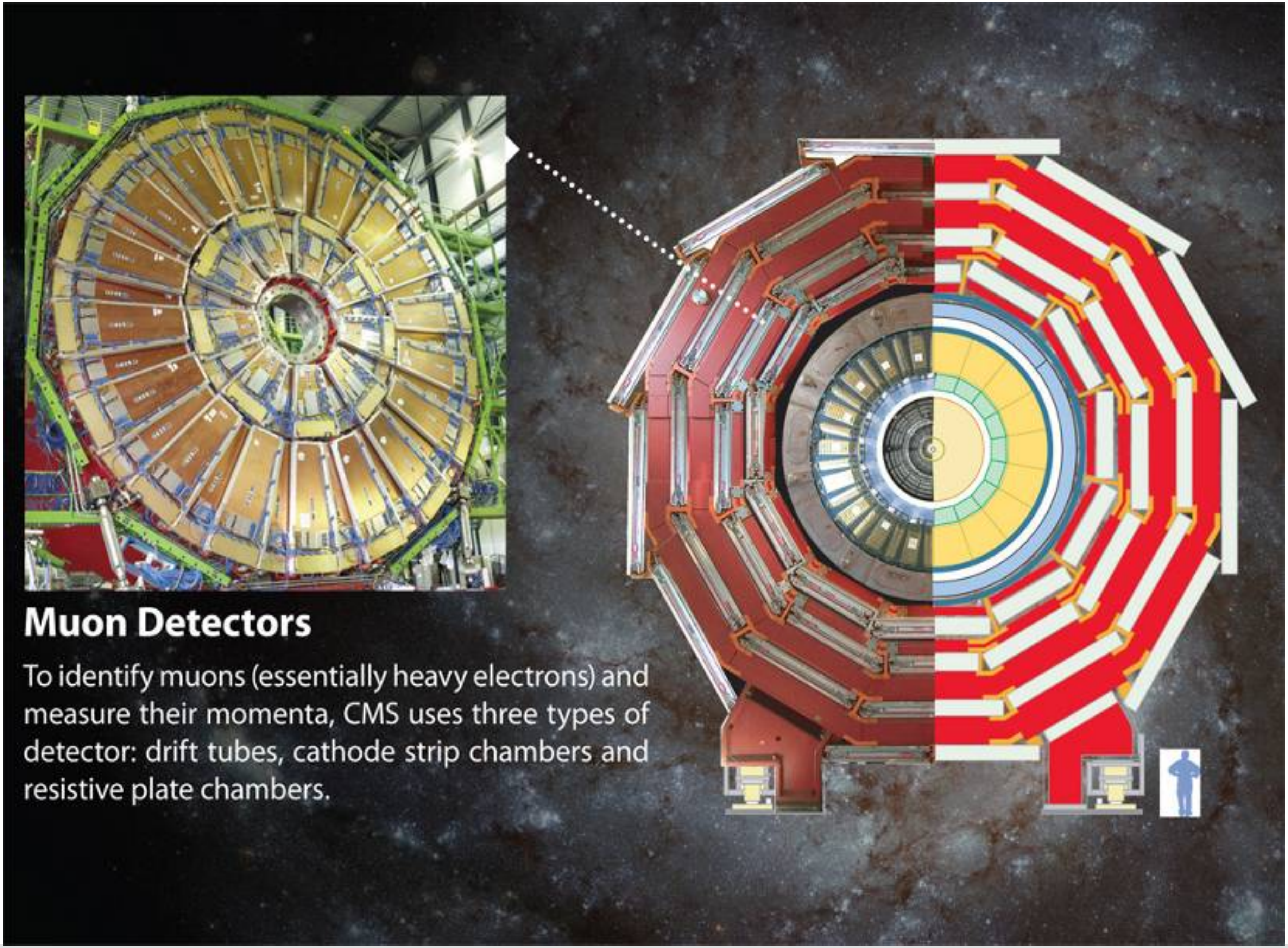
Ultra-pure Aluminium - magnetic stabilizer

CMS uses approx: 1 million km of NbTi filaments!

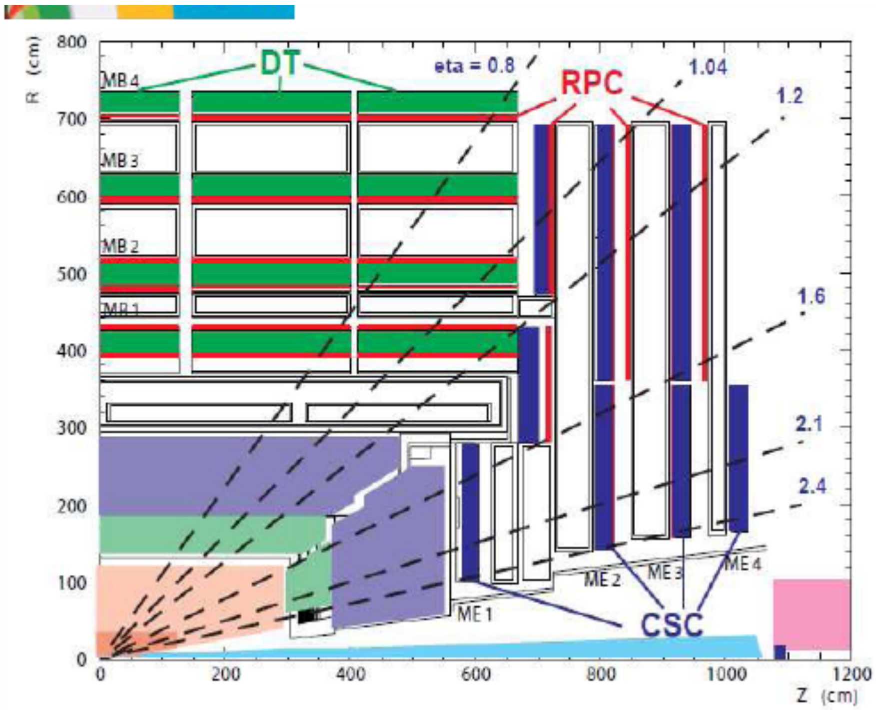
CMS Solenoid

Coil is constructed vertically but needs to be horizontal!

CMS sub-detectors: Muon Chambers



Muon system

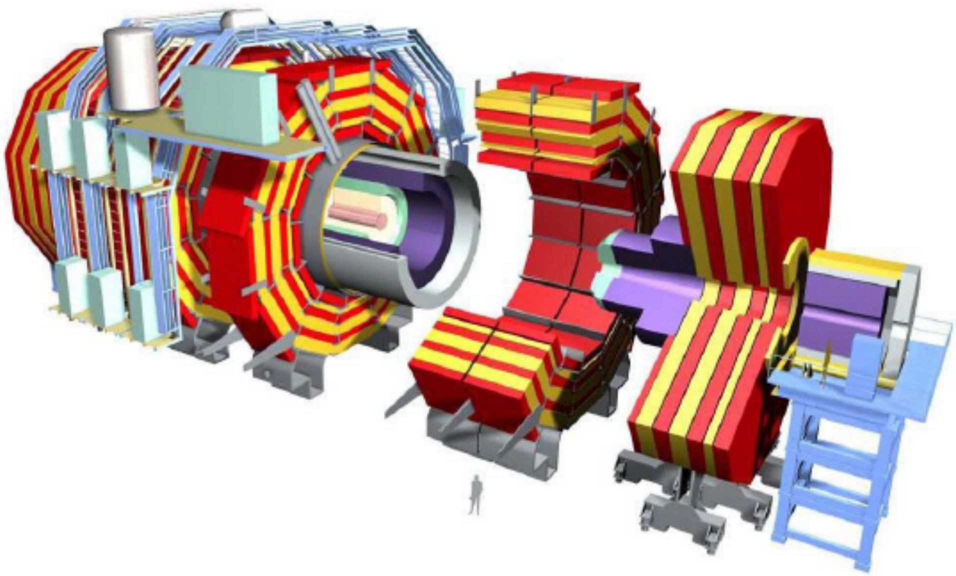


3 different technologies of gaseous detectors

Drift Tube (DT) in the barrel ($|\eta|<1.2$)
Cathode Strip Chambers (CSC) in the endcaps ($0.9 < |\eta| < 2.4$)
Resistive Plate Chambers (RPC) both in barrel and endcaps (up to $|\eta|=1.6$)

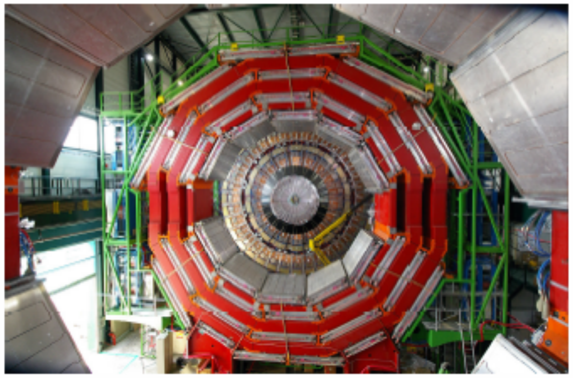
All detectors used both in triggering and reconstruction

Barrel: 5 Wheels
Endcap: 4 Disks per side

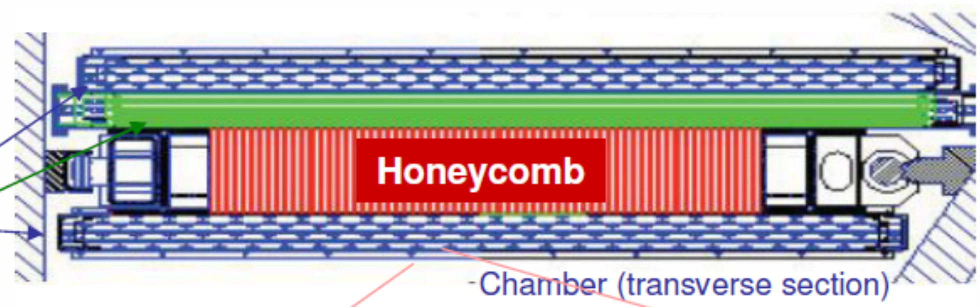


Total Weight: 14,500 tons
Overall diameter: 14.60 m
Overall length: 21.60 m
Magnetic Field: 3.8 T

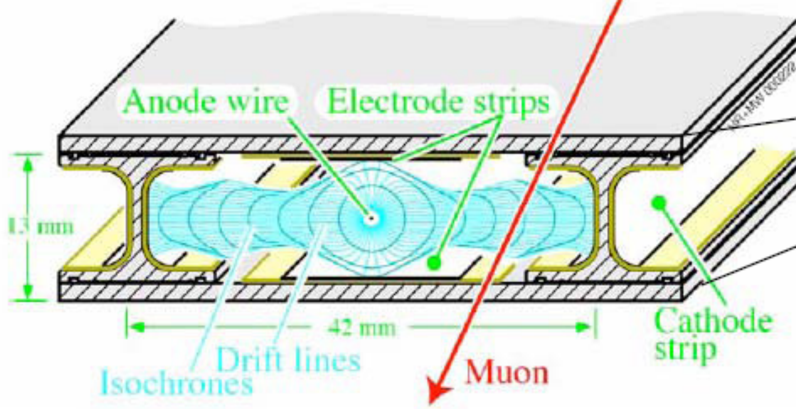
Drift Tubes

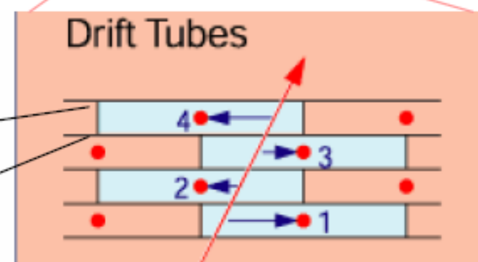


250 chambers (50 per wheel)
5 wheels / 12 sectors / 4 stations
Readout channels>170k



- (4+4) layers in the bending coordinate (Φ)
- 4 layers measuring z (Θ)
(except in outermost station)

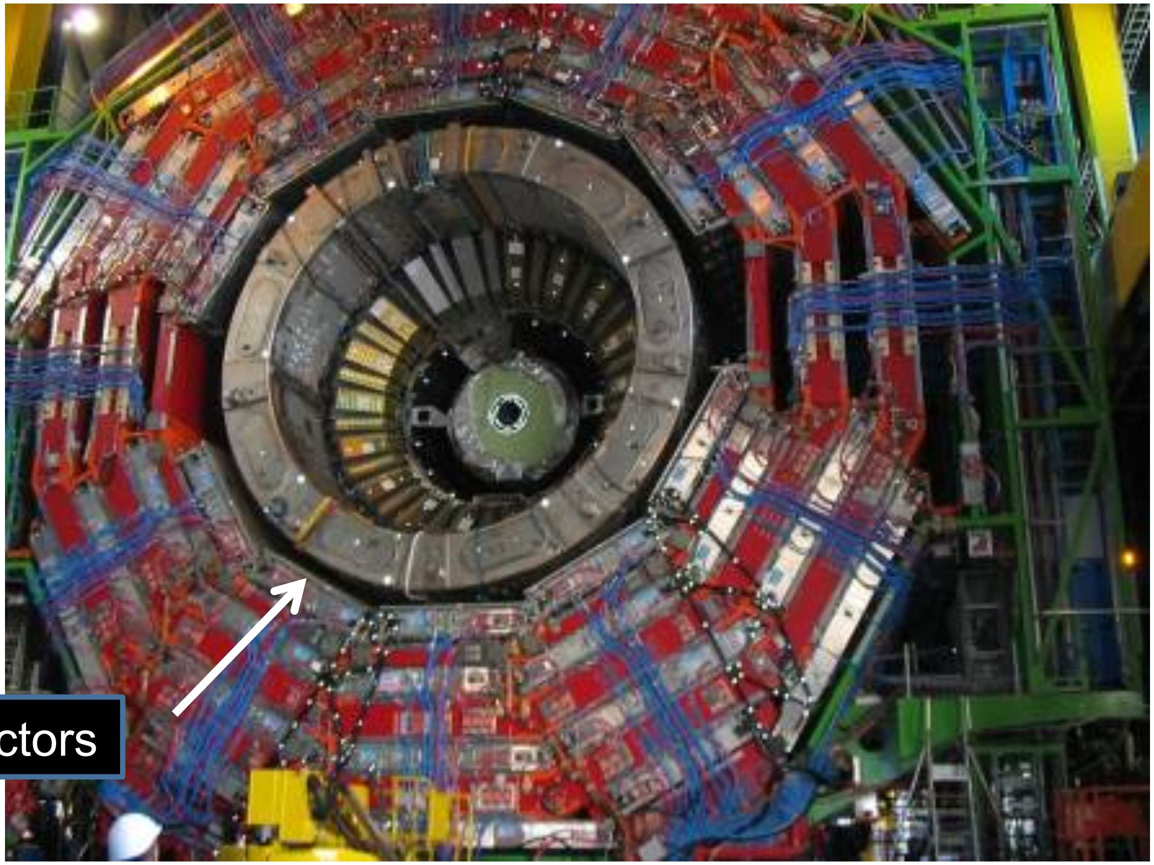




Gas mixture: Ar/CO_2 (85/15) %
Anode wire: 3.6 kV
Electrode strips: 1.8 kV
Cathode: -1.2 kV
Vdrift ~ 55 μm/ns → Max drift time ~380 ns
Single wire resolution ~ 200 μm
Local reconstruction (r-Φ) ~ 100 μm

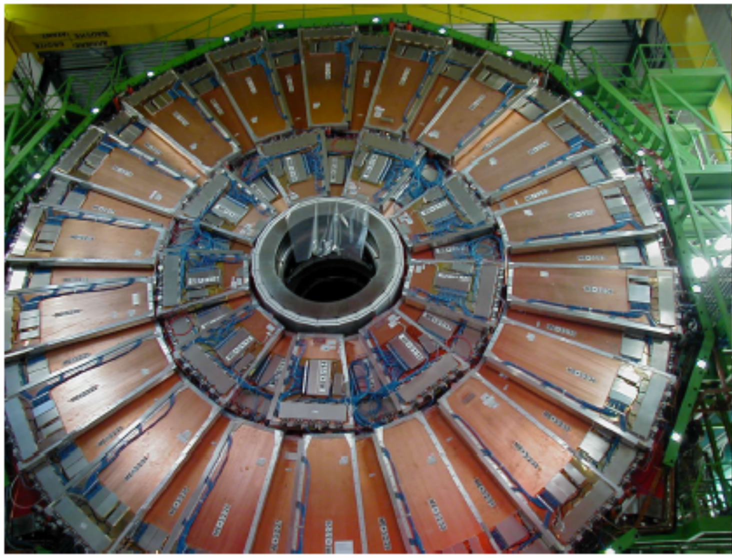
CMS sub-detectors: Muon Chambers

- Position measurement
  - Drift Tubes (DT) in barrel
  - Cathode Strip Chambers (CSC) in endcaps
- Trigger
  - Resistive Plate Chambers (RPCs) in barrel and endcaps



Muon detectors

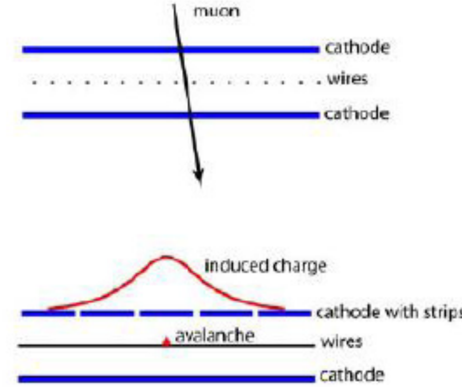
Cathode Strip Chambers

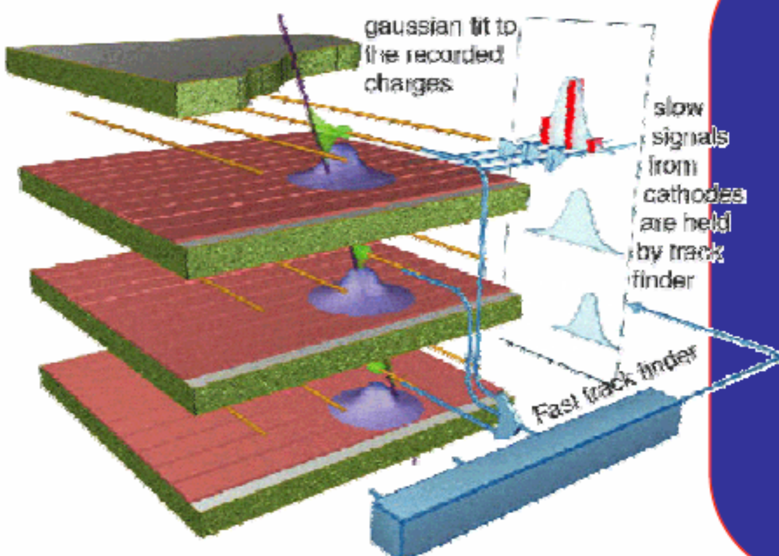


Tracking and triggering in the endcaps. CSCs used due to higher B field and rate

468 chambers, >400k channels.
- 4 disks/endcap,
- 1, 2 or 3 rings/disk
- 18 or 36 chambers/ring

2 million cathode strip chamber wires.





MWPC chambers with cathode strip readout

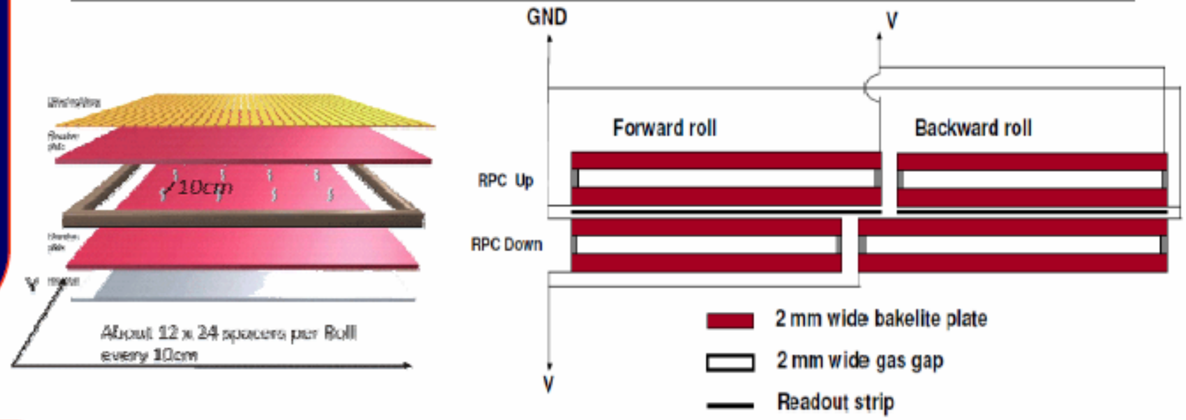
- 6 layers per chamber
  - 9.5 mm gap, $Ar/CO_2/CF_4$ (40/50/10)%
- Bending coordinate (Φ) measured by centroid on strips
  - Strip pitch 8.4-16 mm
- Fast response from wire group (r coordinate) for BX identification

- Design resolution
  - ~150 μm/chamber
  - 75 μm for the innermost chamber that operate in a critical region (less spaced, tilted wires; smaller strips; smaller gap)

Resistive Plate Chambers

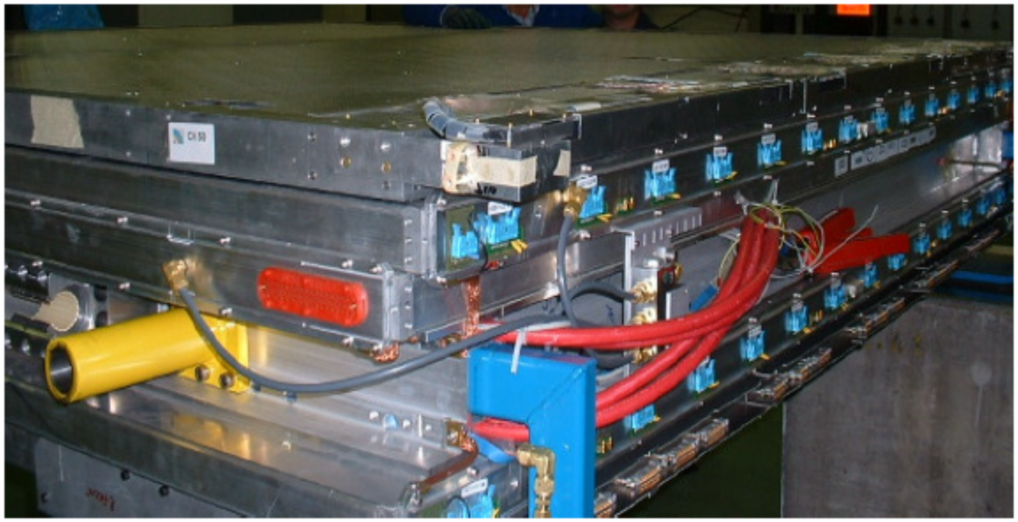
- Double-gap in avalanche mode to cope with hit rates up to ~1KHz/cm²
- $C_2H_2F_4$/iso-C_4H_{10}/SF_6 (96.2/3.5/0.3)%; closed loop
- Strips measure bending coordinate (Φ~1 cm resolution)
- Fast response; very good timing resolution (~2ns)

RPC used both in reconstruction and triggering in barrel and endcaps



BARREL
480 chambers (72 per wheel)
5 wheels / 12 sectors / 6 stations
Readout channels > 50k

ENDCAPS
432 chambers (72 per Disk)
6 Disks / 2 rings / 36 stations
Readout channels > 40k

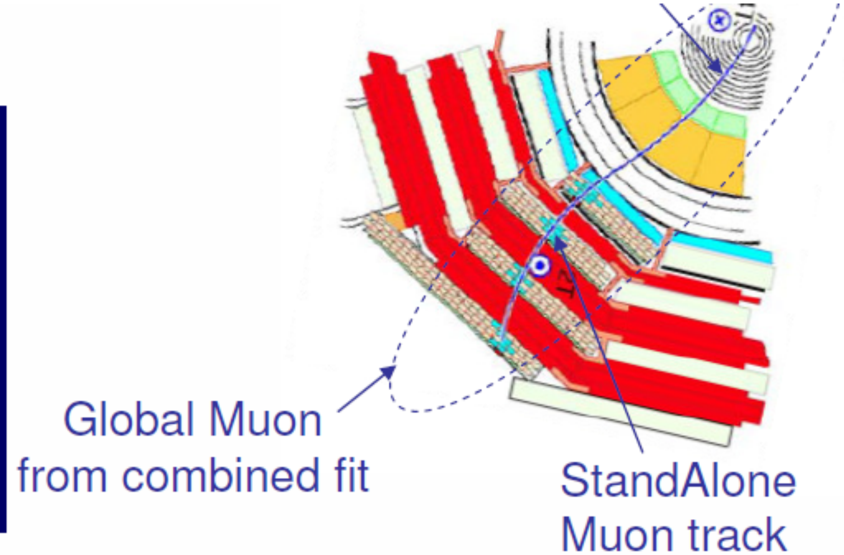


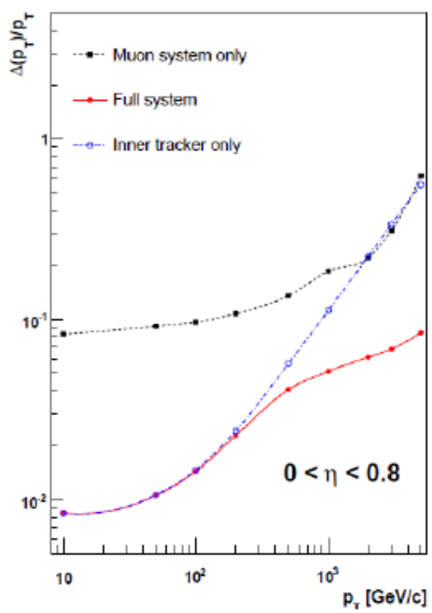
Muon reconstruction in CMS

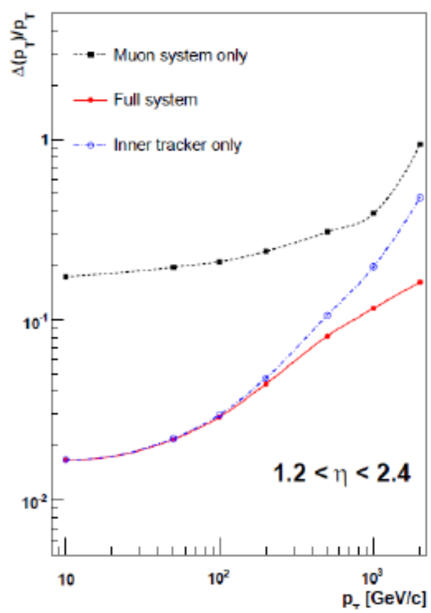
Muon reconstructed independently both in Tracker and in muon system

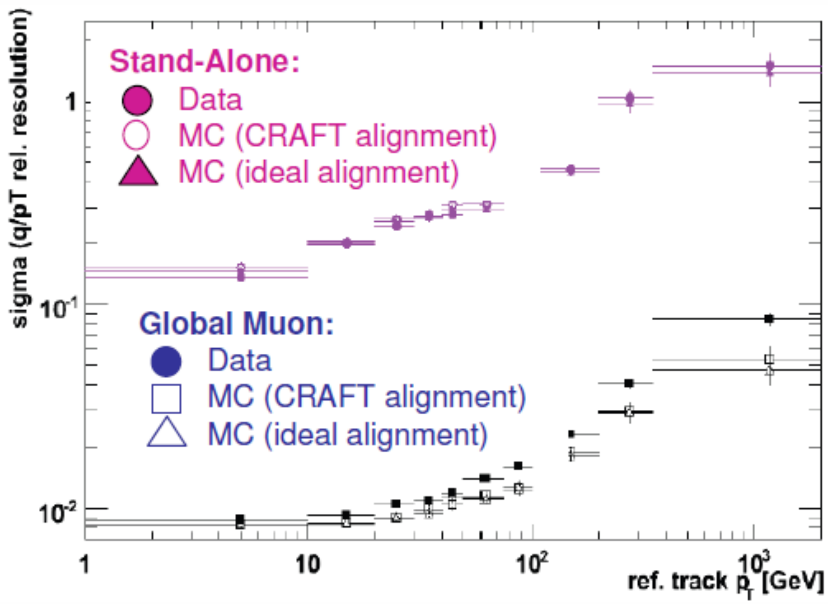
- Inner tracker dominates resolution up to 200 GeV/c due to multiple scattering in the iron
- Above 200 GeV/c, improvement from combined muon-tracker fit

Resolution measured by comparing bottom and top leg of the cosmic track

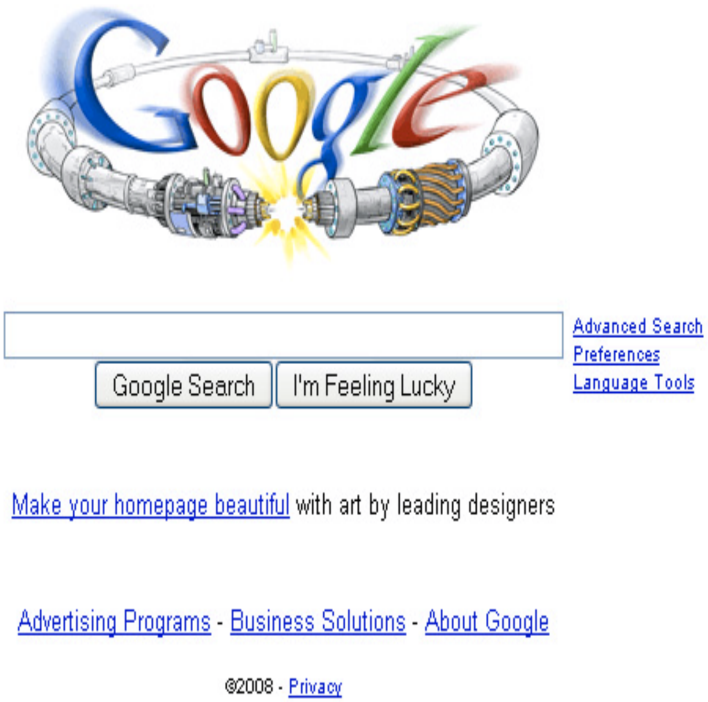




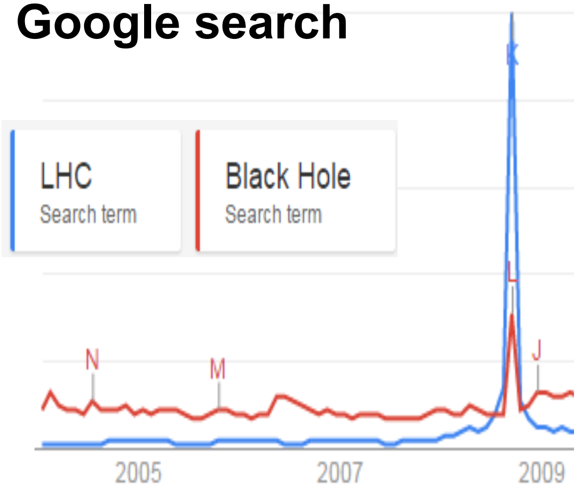




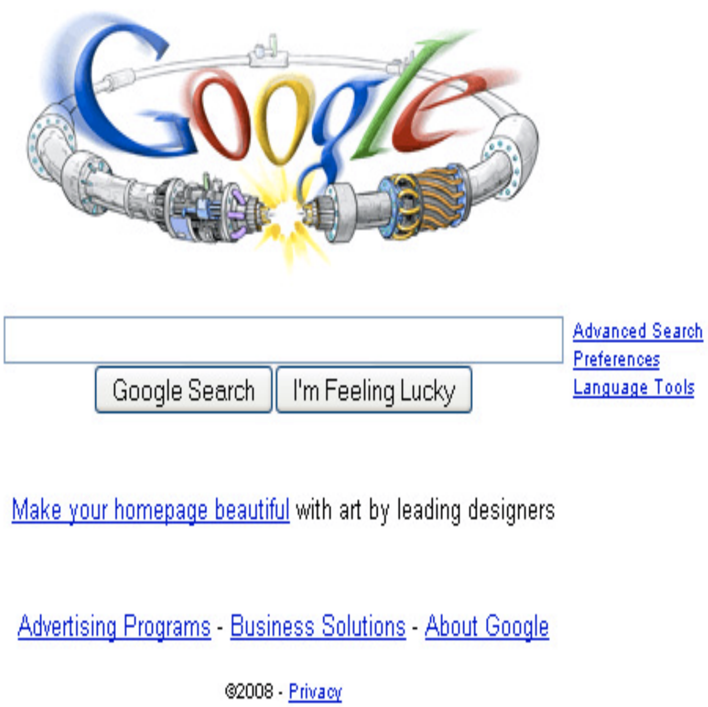
LHC startup (2008)



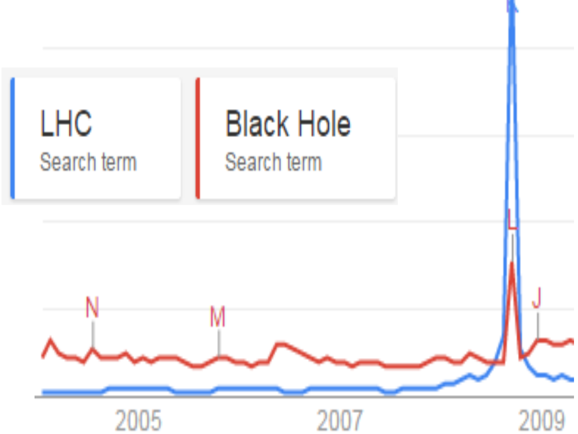
Google search

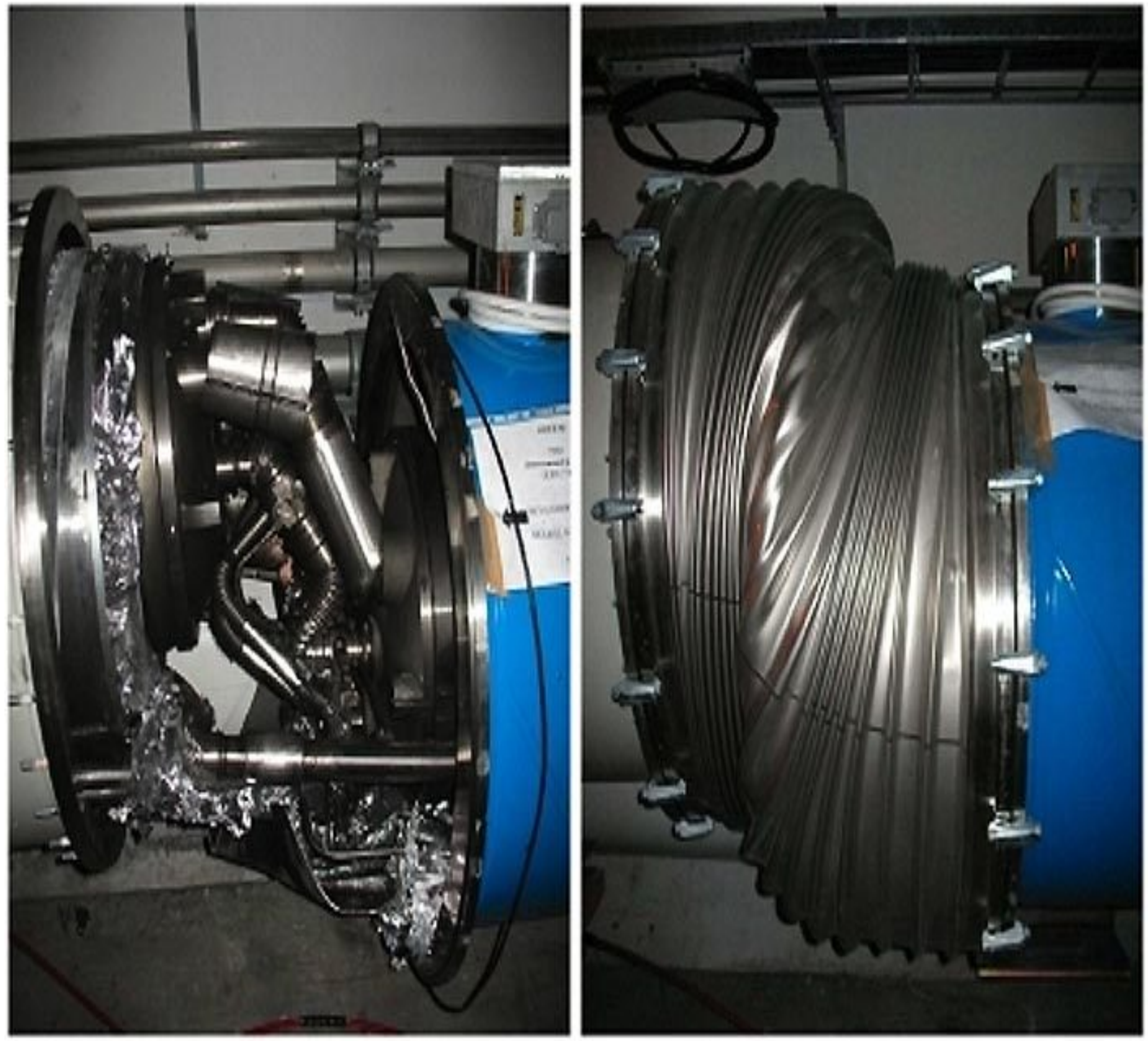


LHC startup (2008)



Google search

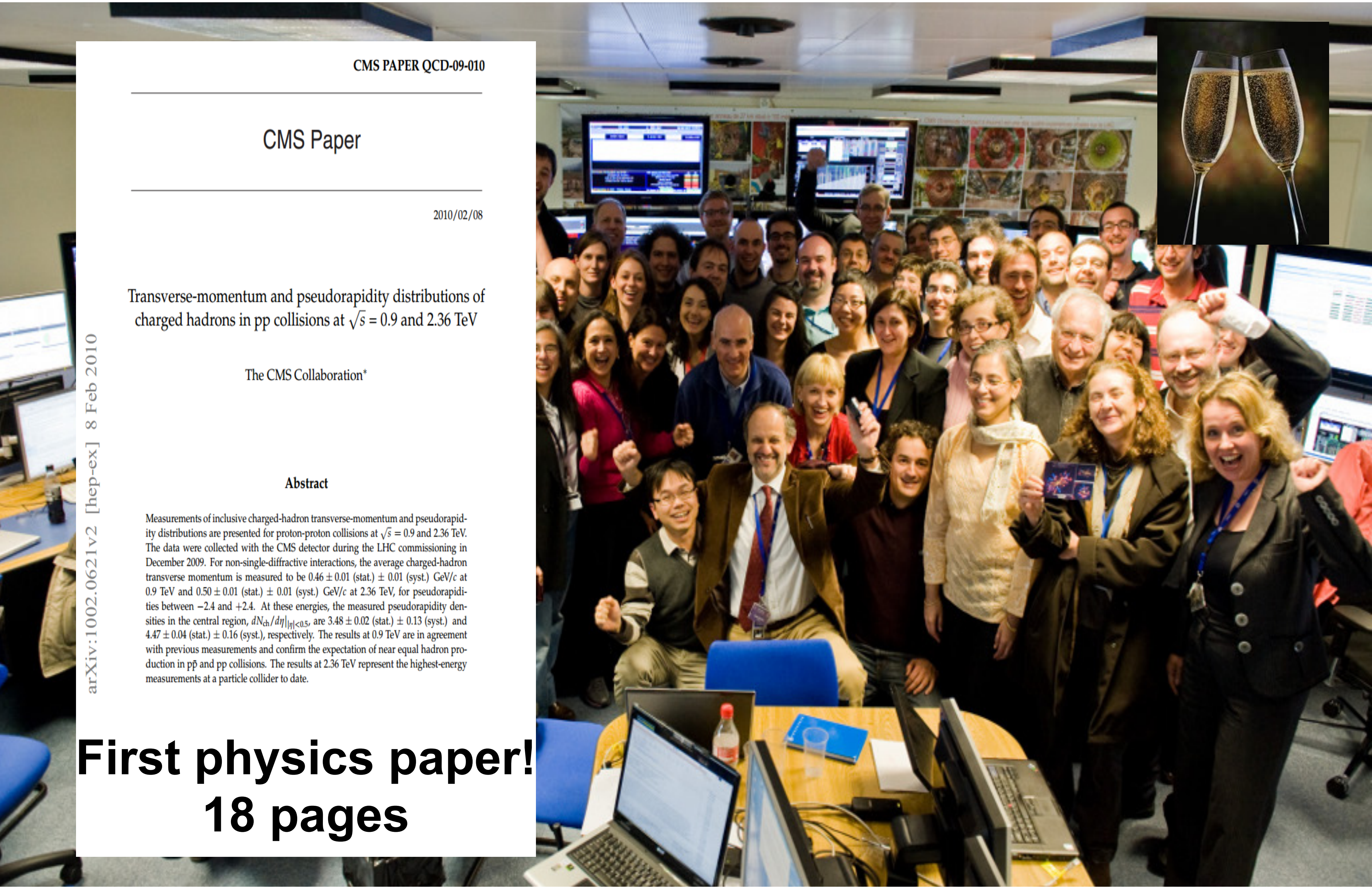




LHC magnet quench…
Leaking 2 tones of liquid helium

Finally: LHC Startup and CMS center (2010)

First CMS paper (2010)


CMS PAPER QCD-09-010

CMS Paper

2010/02/08

Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV

The CMS Collaboration*

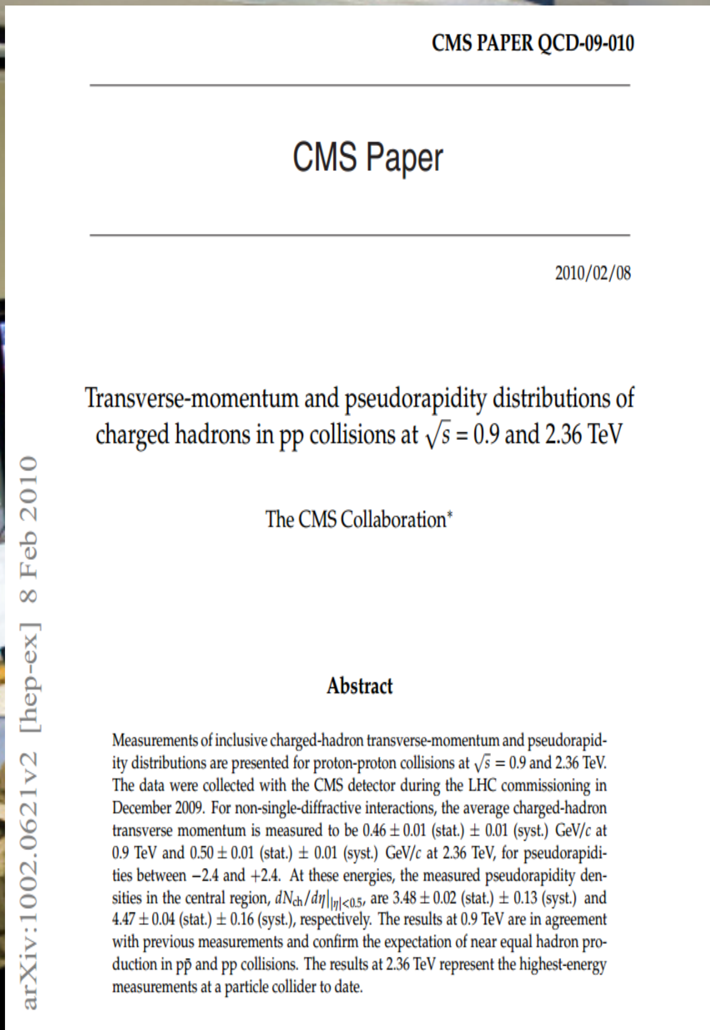
Abstract

Measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions are presented for proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The data were collected with the CMS detector during the LHC commissioning in December 2009. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be 0.46 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 0.9 TeV and 0.50 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 2.36 TeV, for pseudorapidities between -2.4 and $+2.4$. At these energies, the measured pseudorapidity densities in the central region, $dN_{ch}/d\eta|_{|\eta|<0.5}$, are 3.48 ± 0.02 (stat.) $\pm$ 0.13 (syst.) and 4.47 ± 0.04 (stat.) $\pm$ 0.16 (syst.), respectively. The results at 0.9 TeV are in agreement with previous measurements and confirm the expectation of near equal hadron production in $p\bar{p}$ and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

arXiv:1002.0621v2 [hep-ex] 8 Feb 2010

First physics paper!
18 pages

First CMS paper (2010)



CMS PAPER QCD-09-010

CMS Paper

2010/02/08

arXiv:1002.0621v2 [hep-ex] 8 Feb 2010

Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV

The CMS Collaboration*

Abstract

Measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions are presented for proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The data were collected with the CMS detector during the LHC commissioning in December 2009. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be 0.46 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 0.9 TeV and 0.50 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 2.36 TeV, for pseudorapidities between -2.4 and $+2.4$. At these energies, the measured pseudorapidity densities in the central region, $dN_{ch}/d\eta|_{|\eta|<0.5}$, are 3.48 ± 0.02 (stat.) $\pm$ 0.13 (syst.) and 4.47 ± 0.04 (stat.) $\pm$ 0.16 (syst.), respectively. The results at 0.9 TeV are in agreement with previous measurements and confirm the expectation of near equal hadron production in $p\bar{p}$ and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

First physics paper!
18 pages

100 pages of comments from 4000 collaborators