The LHC machine-experiment interface (lecture 2)

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Academic Training

CERN,

April 19, 2005

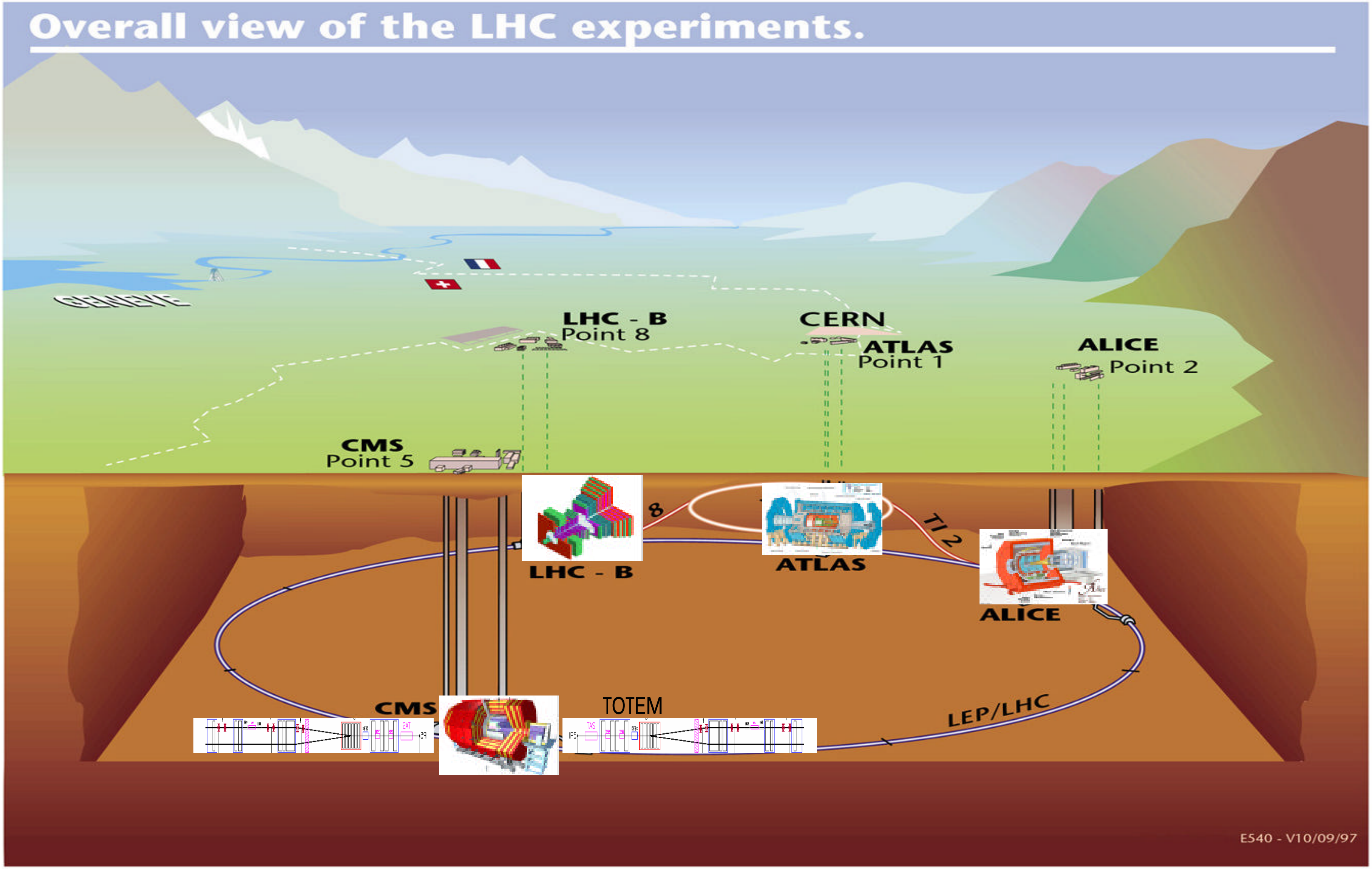
Recap from yesterday

- Successful development (and experimental verification) of Standard Model of particles physics
- Strong indirect evidence that new physics exists beyond SM
  - → And still need to find the missing piece (Higgs)
- LHC (and experiments): multi-purpose facility
  - → Extremely broad range in physics topics
- Experimental signatures categories
  - → High p_T objects
  - → Reconstruction of (low mass) objects decays
  - → Leading particles

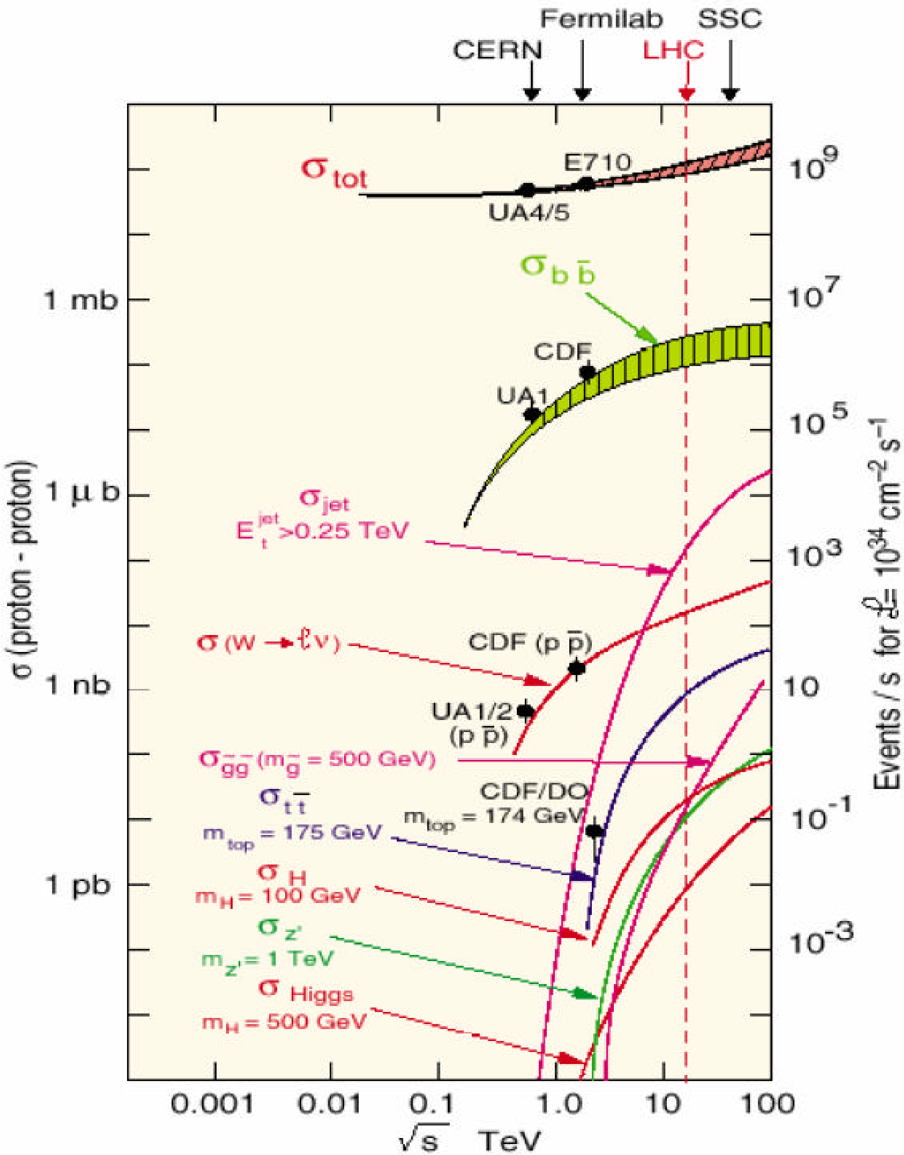
Contents

- LHC environment for experiments
- Description of the experiments
  - → ATLAS (A Toroidal LHC ApparatuS)
  - → CMS (Compact Muon Solenoid)
  - → ALICE (A Large Ion Collider Experiment)
  - → LHCb (Large Hadron Collider beauty experiment)
  - → TOTEM ((Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC))
- Issues in operational conditions
- Commissioning of the experiments
  - → Goals, needs and expectations
- Physics reach in first period
- Yet another challenge: trigger
  - → If time permits ...
- Summary

Recap: LHC and experiments



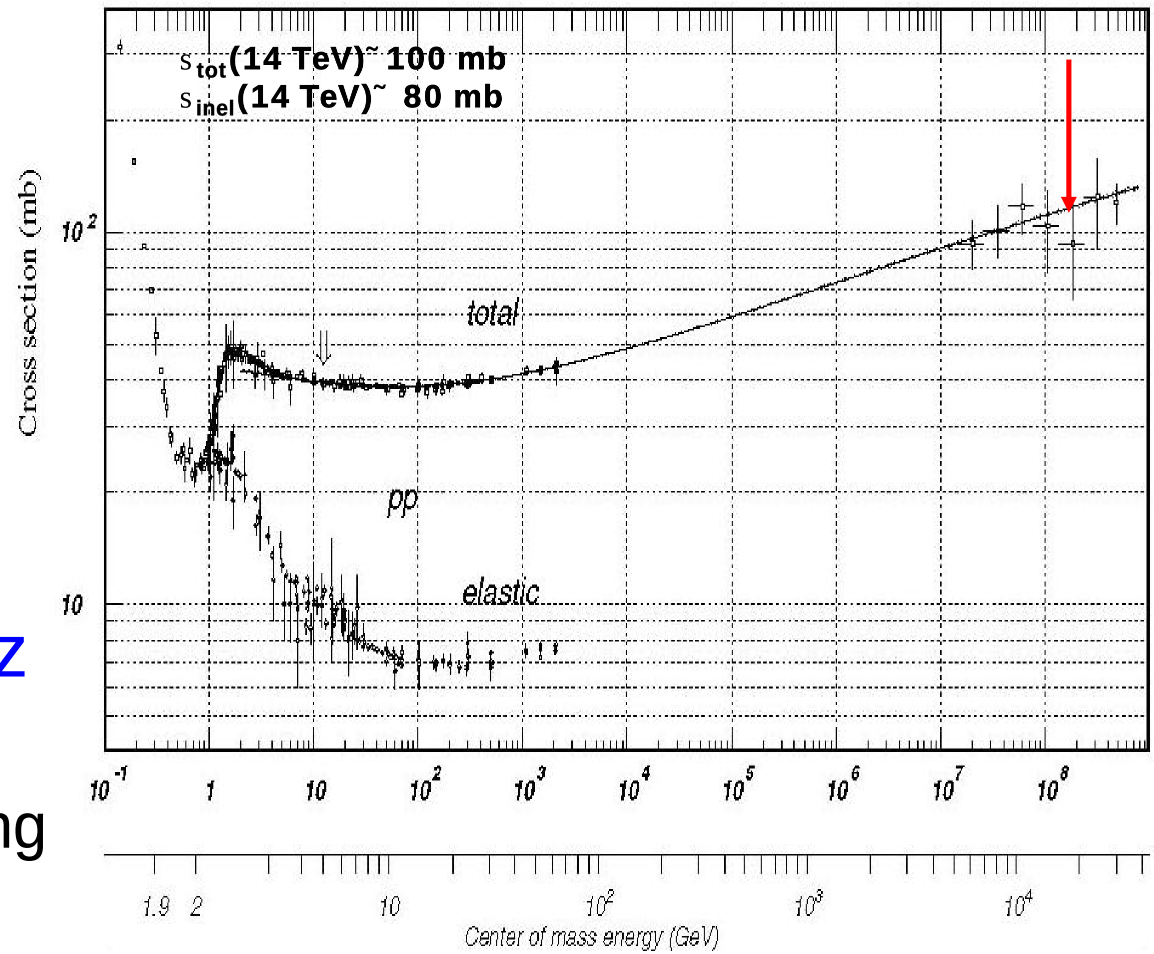
Cross-sections in pp collisions



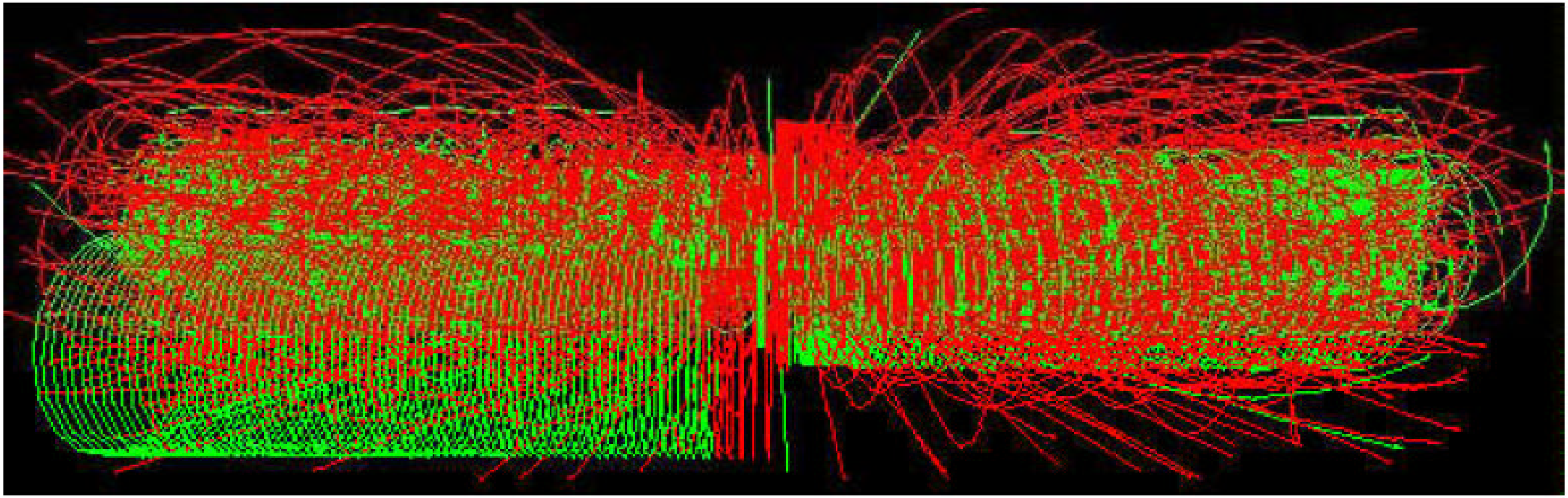
- One of the major challenges
  - → Identify (and keep) the interesting (and sometimes rare) events
  - → Example: H → $\gamma\gamma$ (m_H ~ 120 GeV)
  - → Occurs only in 1 out of 10^{13} pp collisions
- However other processes with large cross-section also of interest
  - → σ(bb) ~ 0.2 mb !

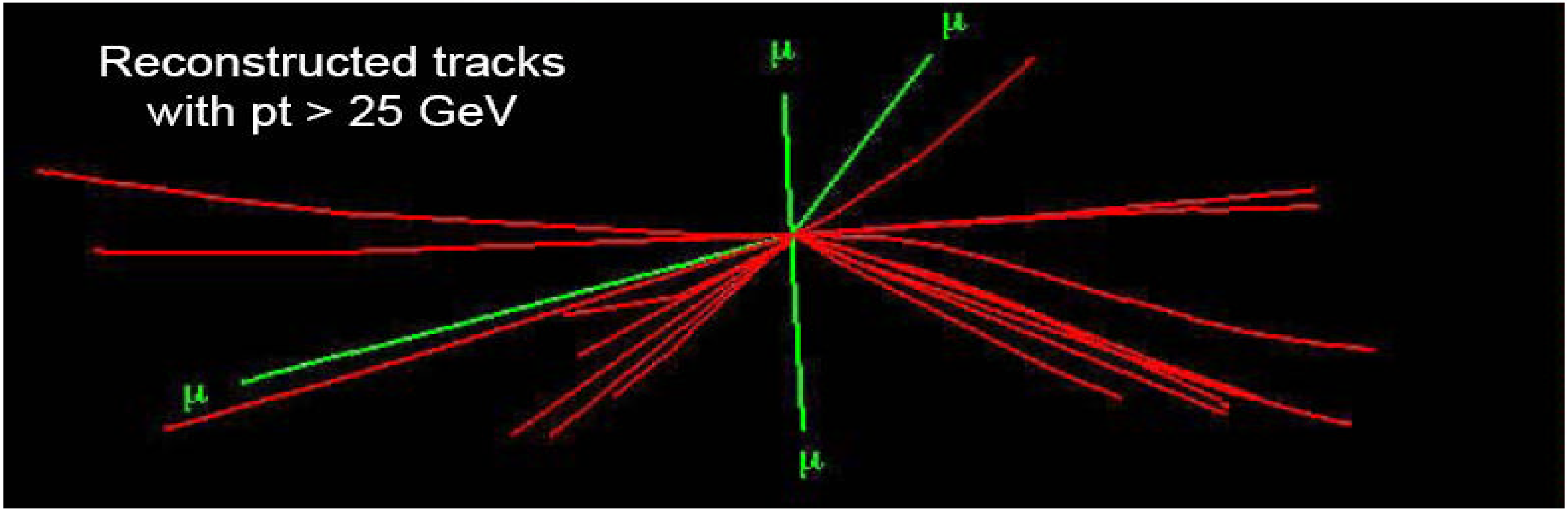
Interaction rate in pp collisions

- Interaction rate
  - → Luminosity
    $L = 10^{34}\ cm^{-2}s^{-1}$
    $= 10^{7}\ Hz/mb$
  - → $\sigma(pp)$ = 80 mb
  - → Rate 0.8 GHz
- Bunch crossing frequency 40 MHz
  - → 20 interactions per bunch crossing
- Filling of bunches
  - → Only 2836 out of 3564 possible one are filled
  - → Interaction/(filled crossing) ~ 25

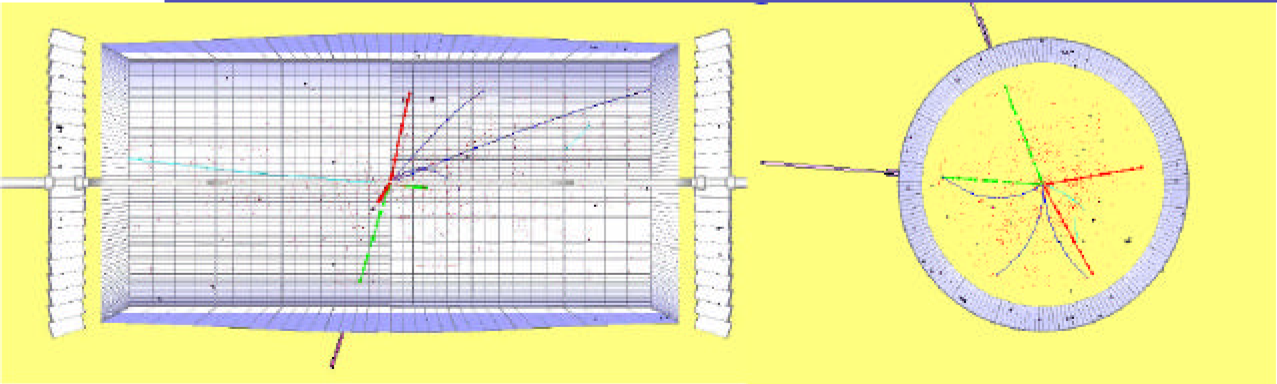


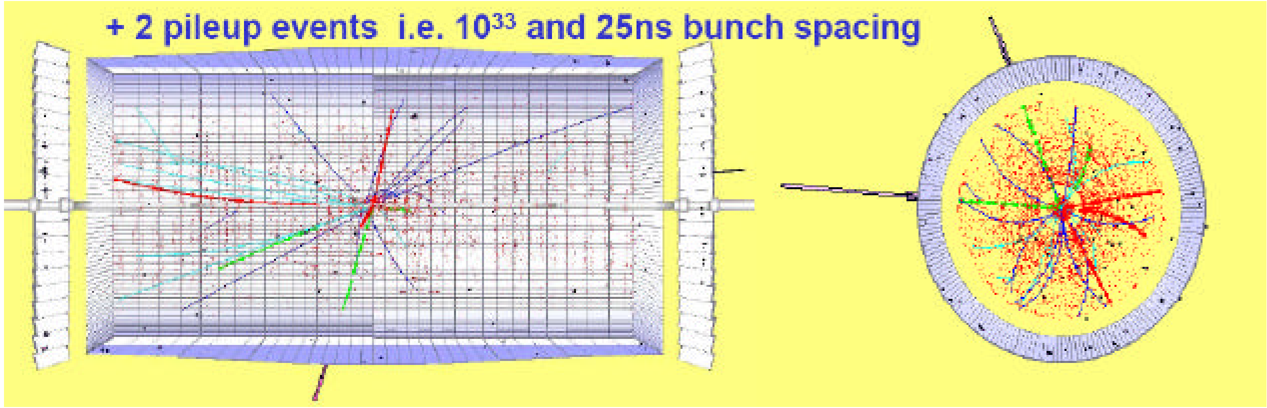
Challenge: Pile-Up Events

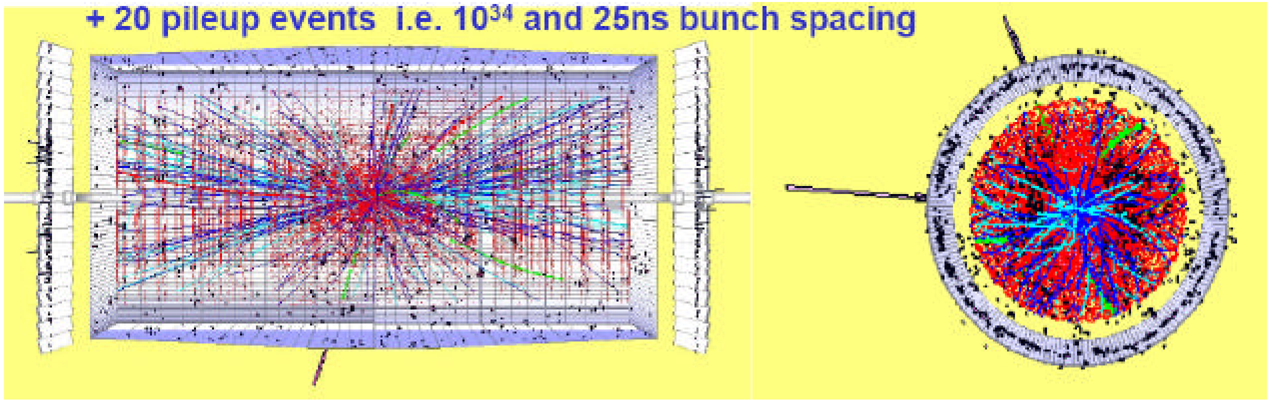




Challenge: Pile-Up Events







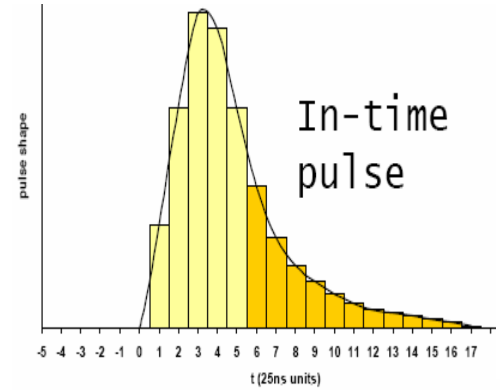
- Example of golden Higgs channel
  → H → ZZ
  → 2e 2μ
- Need to understand detector first before able to exploit design luminosity

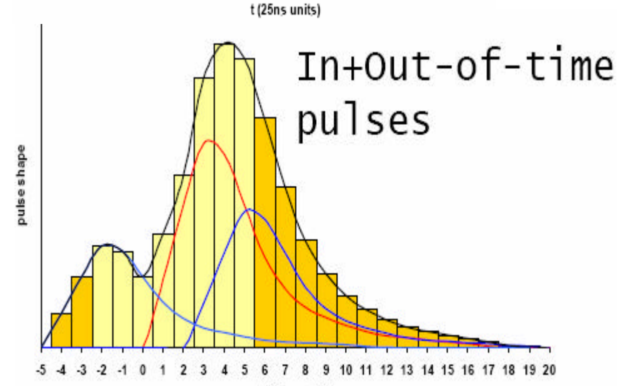
Experimental conditions: pp vs. PbPb

- Proton-proton collisions at $\sqrt{s}$ = 14 TeV
  - → Packets collide every 25 ns (40 MHz)
  - → Luminosity up to 10^{34} cm^{-2} s^{-1}
  - → Total pp cross-section ~100 mb
    - Total interaction rate 1 GHz
    - About 20 inelastic events per crossing
  - → One pp event: 5-10 charged particles/unit of rapidity
- Pb-Pb collisions $\sqrt{s}_{total}$ = 1150 TeV
  - → Packets collide every 100 ns
  - → Luminosity up to 10^{27} cm^{-2} s^{-1}
  - → Total Pb Pb cross-section: ~ 8 b
    - Total interaction rate: only 8 kHz
  - → One PbPb event: 2000-8000 charged particles/u.o.rap.

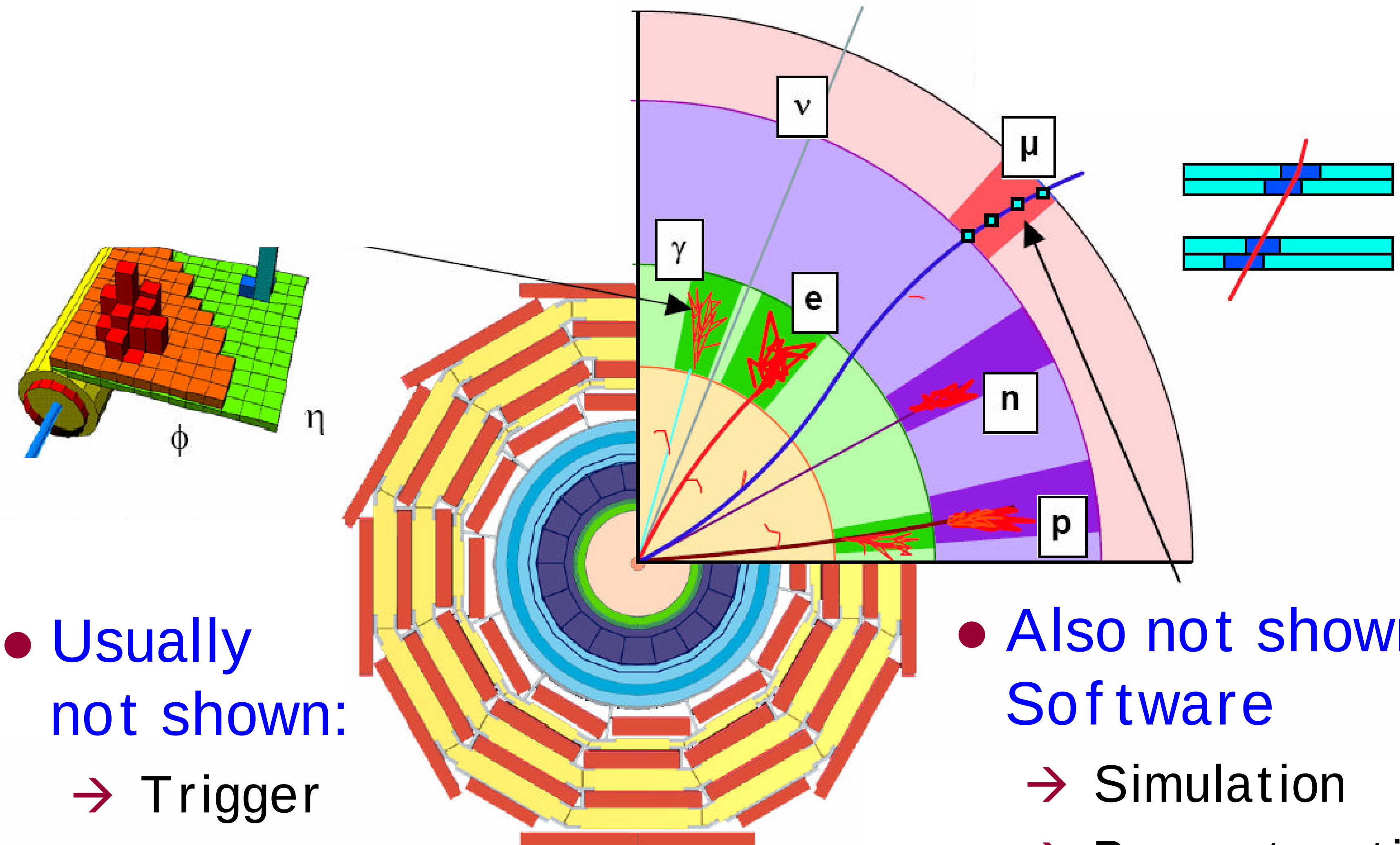
Detector design principles

- Fast response
  - → Reduce impact of pile-up events
  - → Identify crossing of interest
- High granularity
  - → Minimize probability to observe hit from pile-up event in detector segment (pp collisions)
  - → highest multiplicities (HI collisions)
- Radiation resistant (pp collisions)
  - → Collisions produce a huge flux of particles
  - → 10 years of LHC give up to 10^{17} n/cm^2 and up to 10^7 Gy
- Precise vertexing
- Particle identification





Generic (collider) detector layout

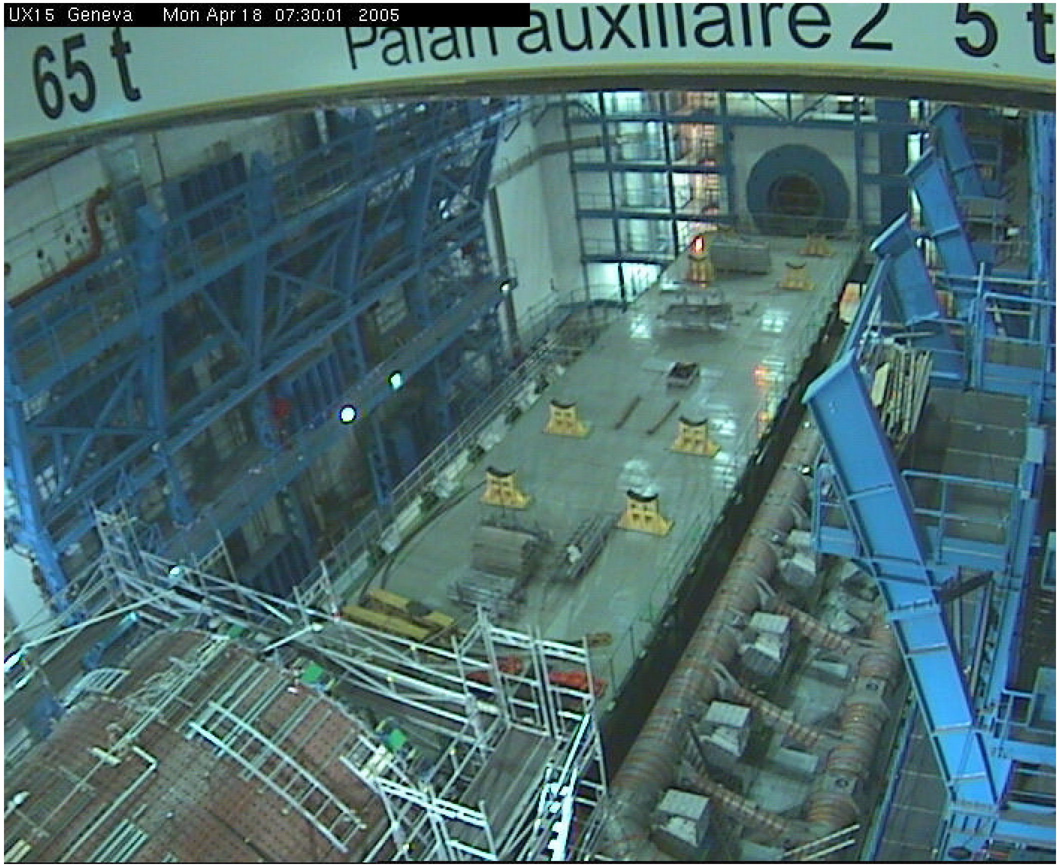


- Usually not shown:
  - → Trigger
  - → Data acquisition
- Also not shown: Software
  - → Simulation
  - → Reconstruction
  - → Operation/control

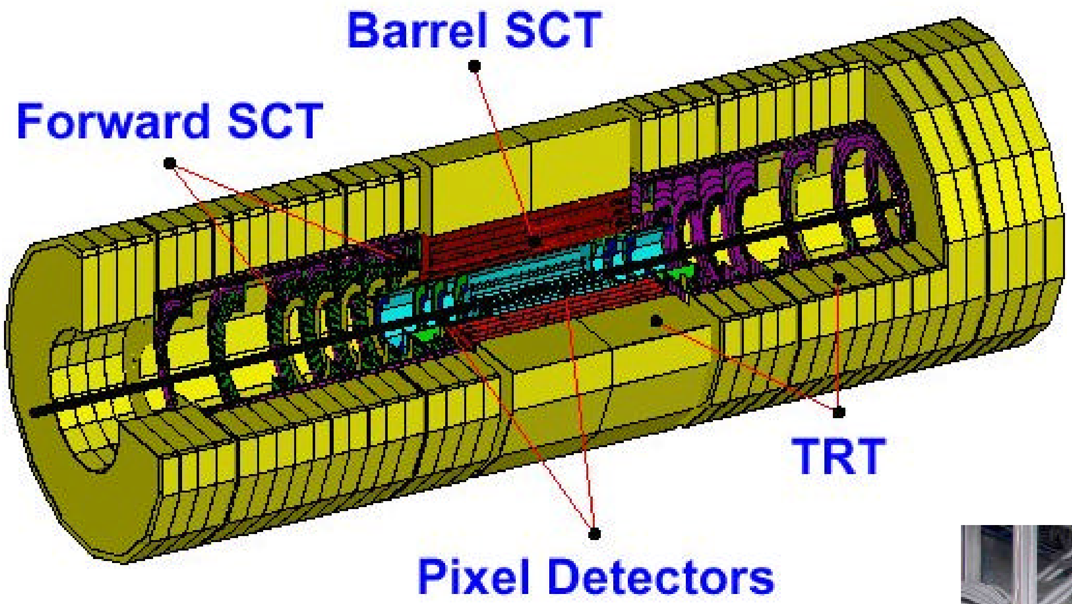
ATLAS experiment

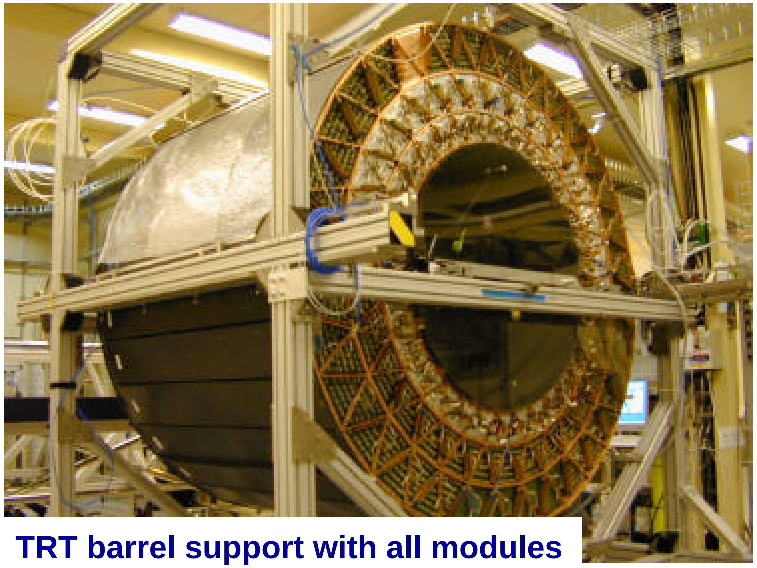
- Assembly has started last year in the cavern
  - http://atlaseye-webpub.web.cern.ch/atlaseye-webpub/web-sites/pages/UX15_webcams.htm

→ view as of yesterday

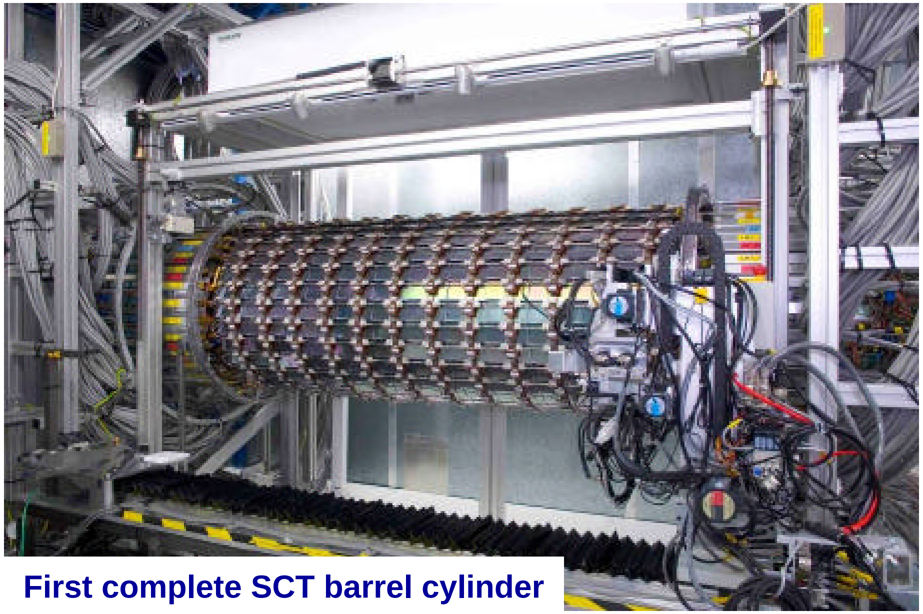


ATLAS experiment: tracking





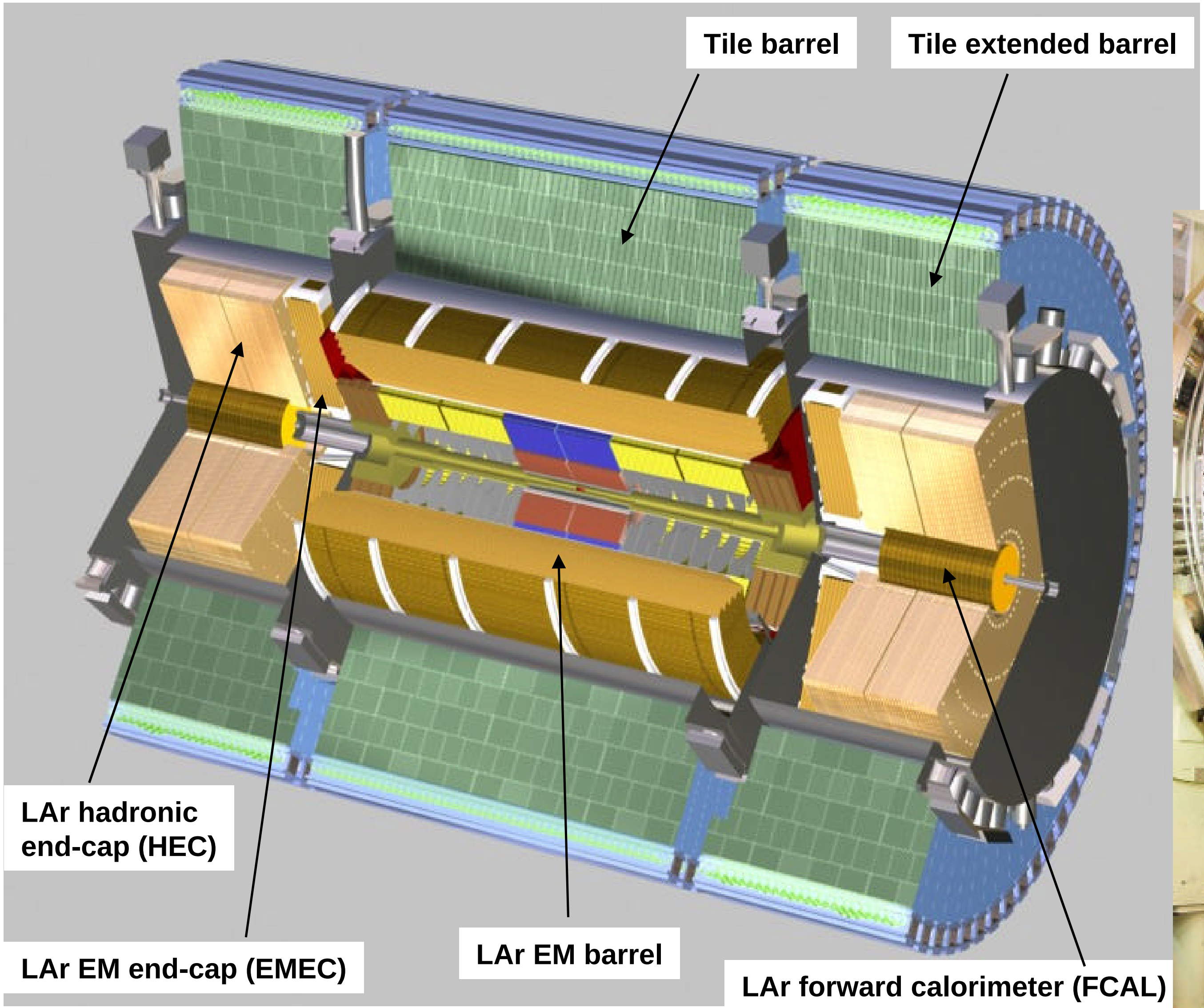
TRT barrel support with all modules

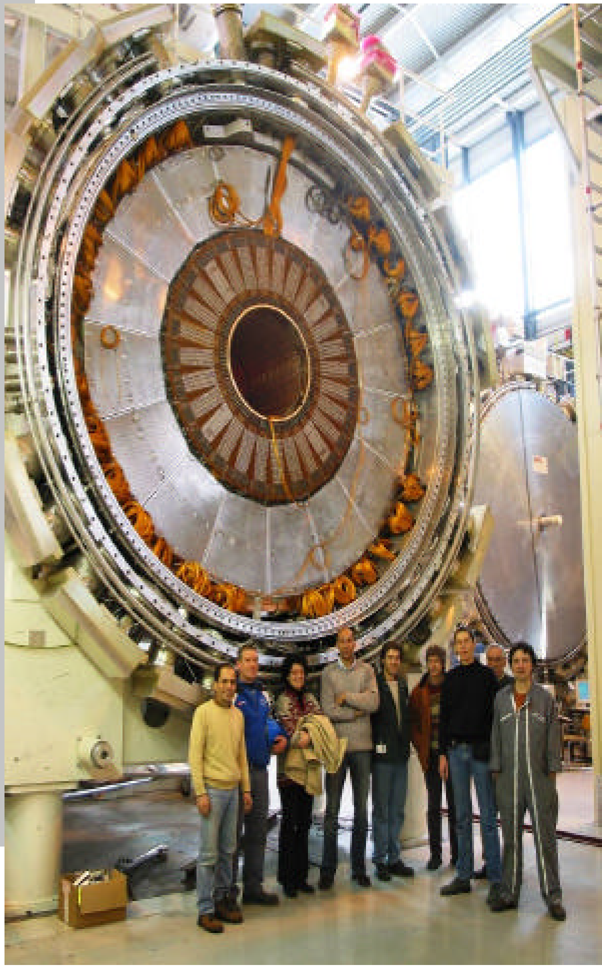


First complete SCT barrel cylinder

- Si pixels
  - → $0.8 * 10^8$ channels
- Si strips (SCT)
  - → $6 * 10^6$ channels
- Transition radiation tracker (TRT)
  - → $4 * 10^5$ channels

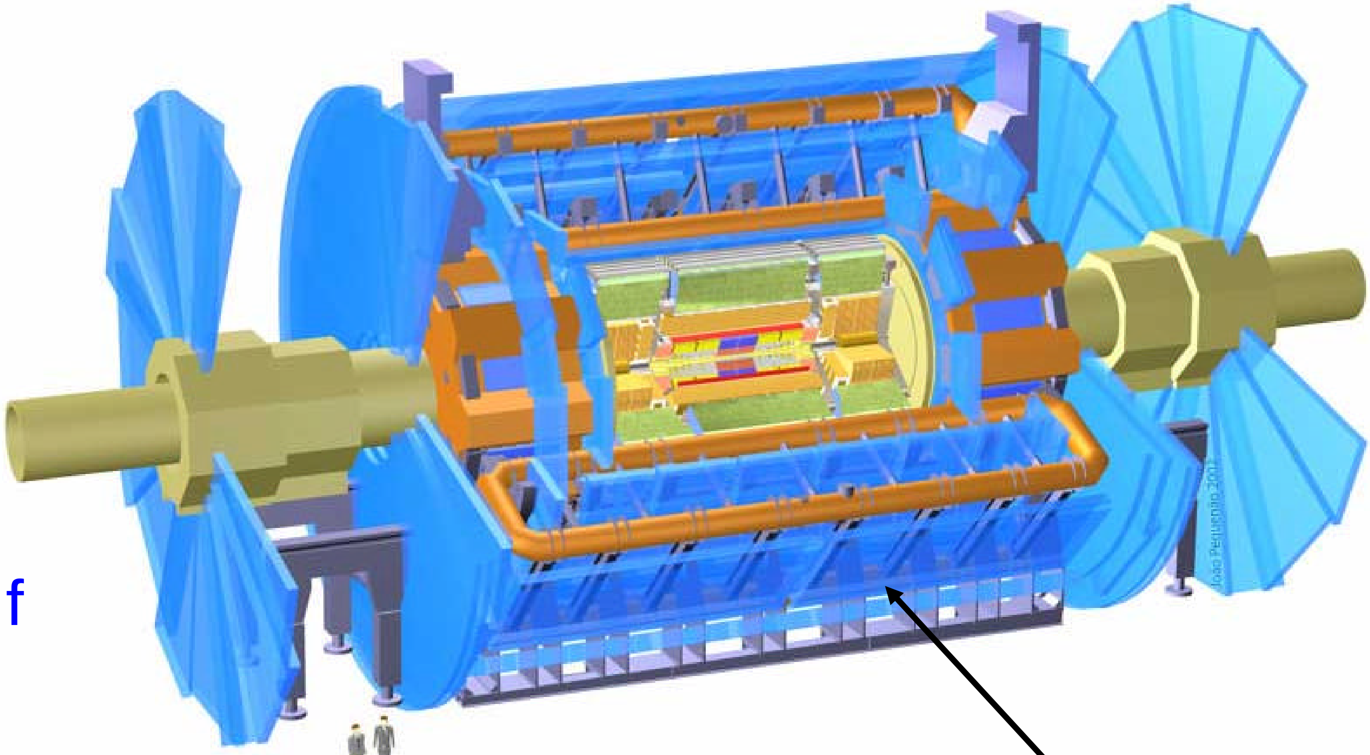
ATLAS experiment: calorimetry



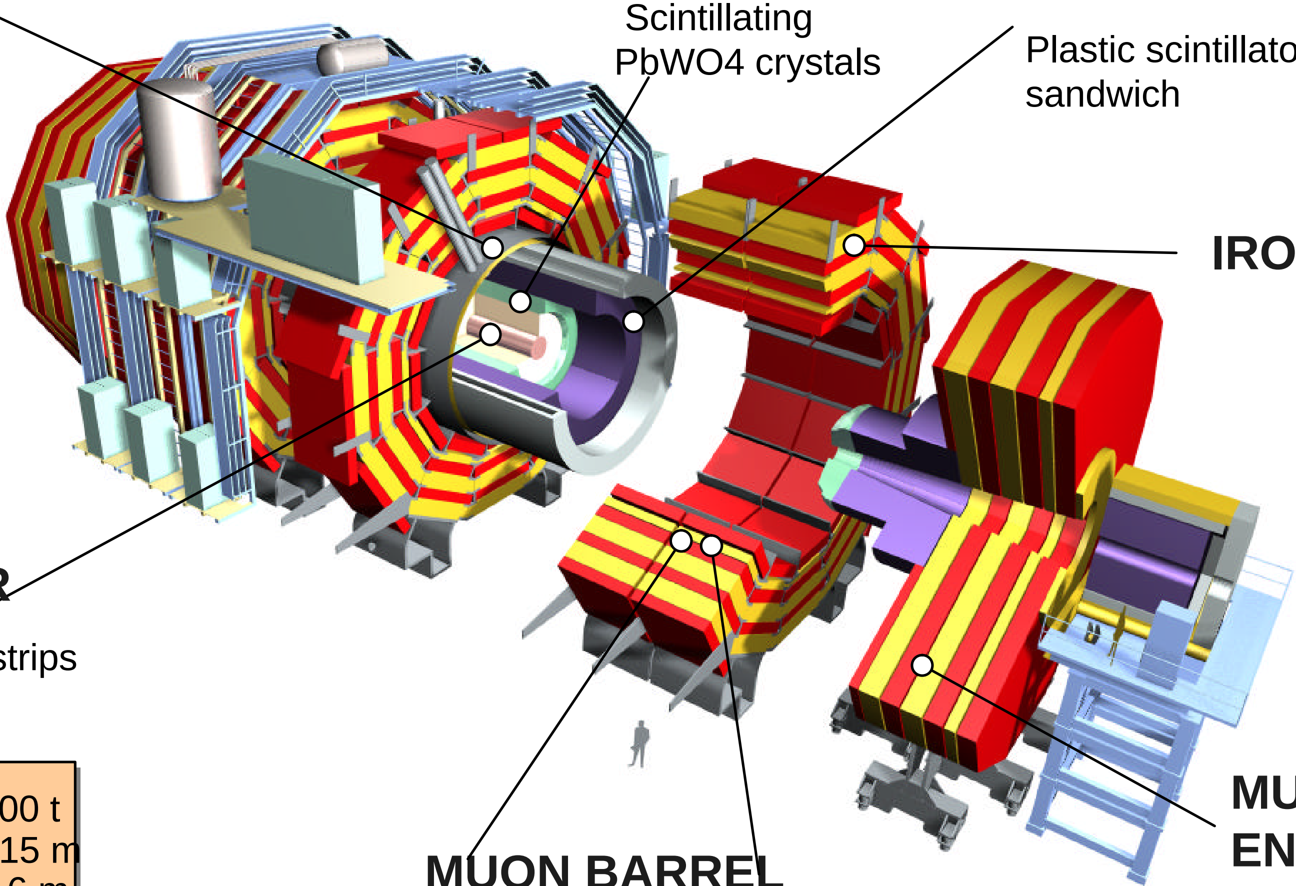


ATLAS experiment: muon system

- Dimensions
  - → Length 46 m
  - → Diameter 25 m
- Weight
  - → 7000 tons
- Total length of cables
  - → 3000 km
- Data volume per second
  - → 10000 Encyclopedia Britannica

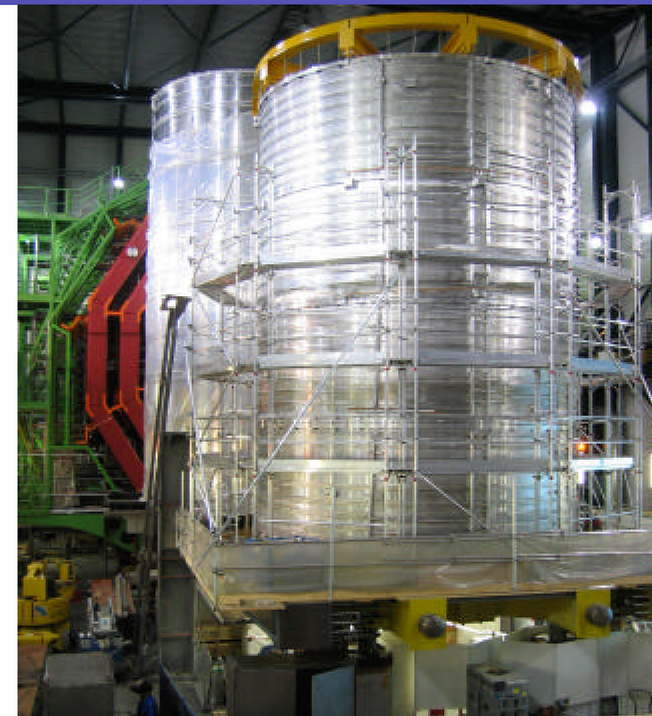


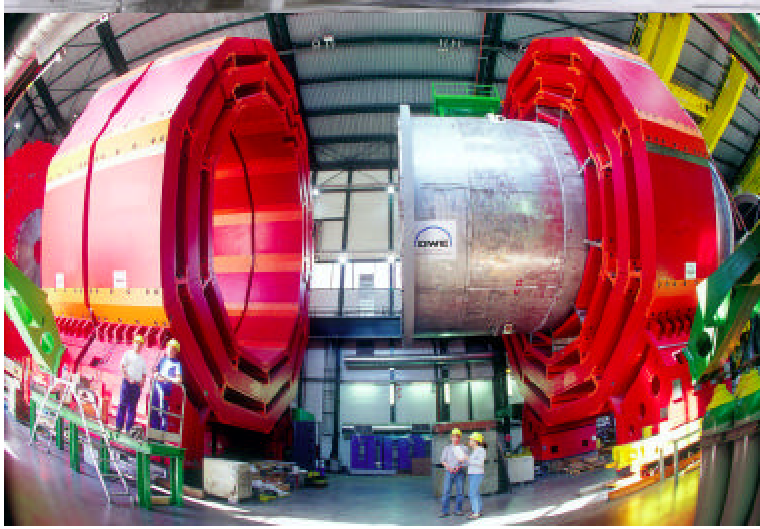
CMS experiment

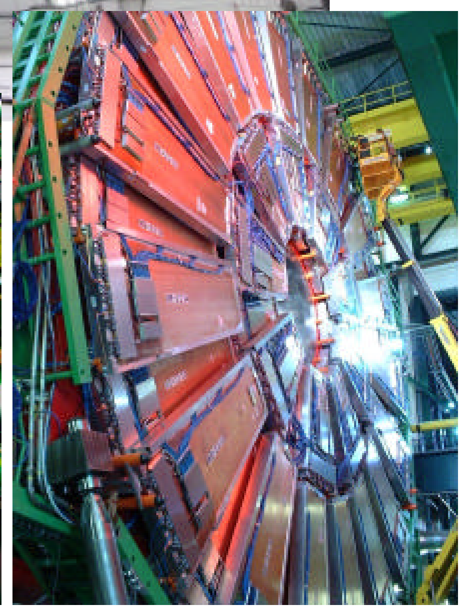


Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

CMS assembly and cavern



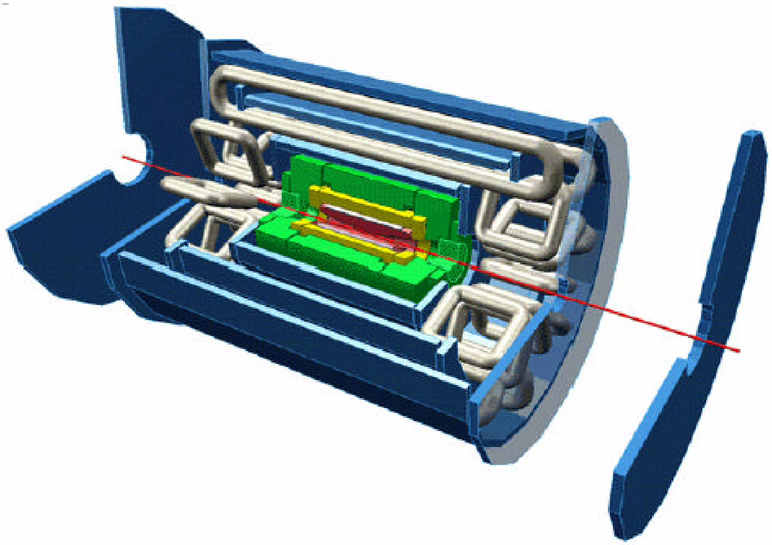


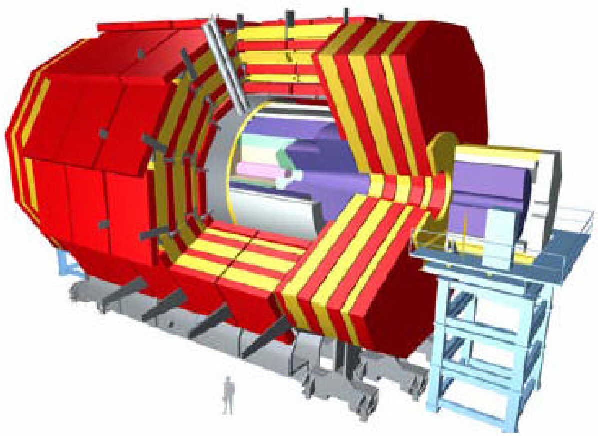


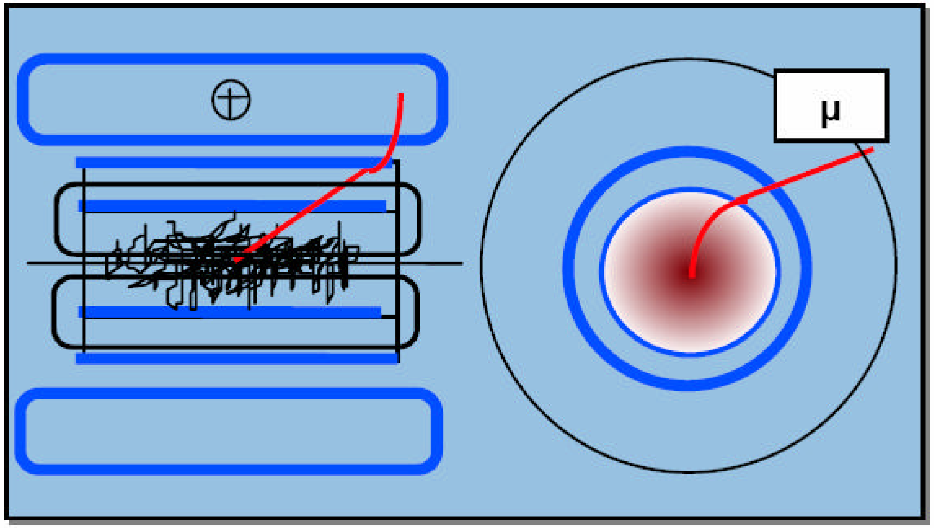
Magnet Architecture

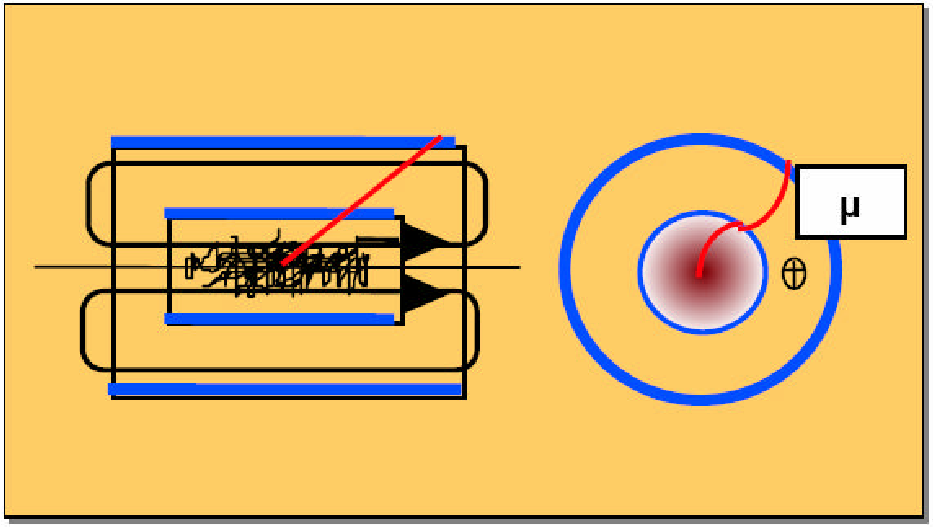
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid

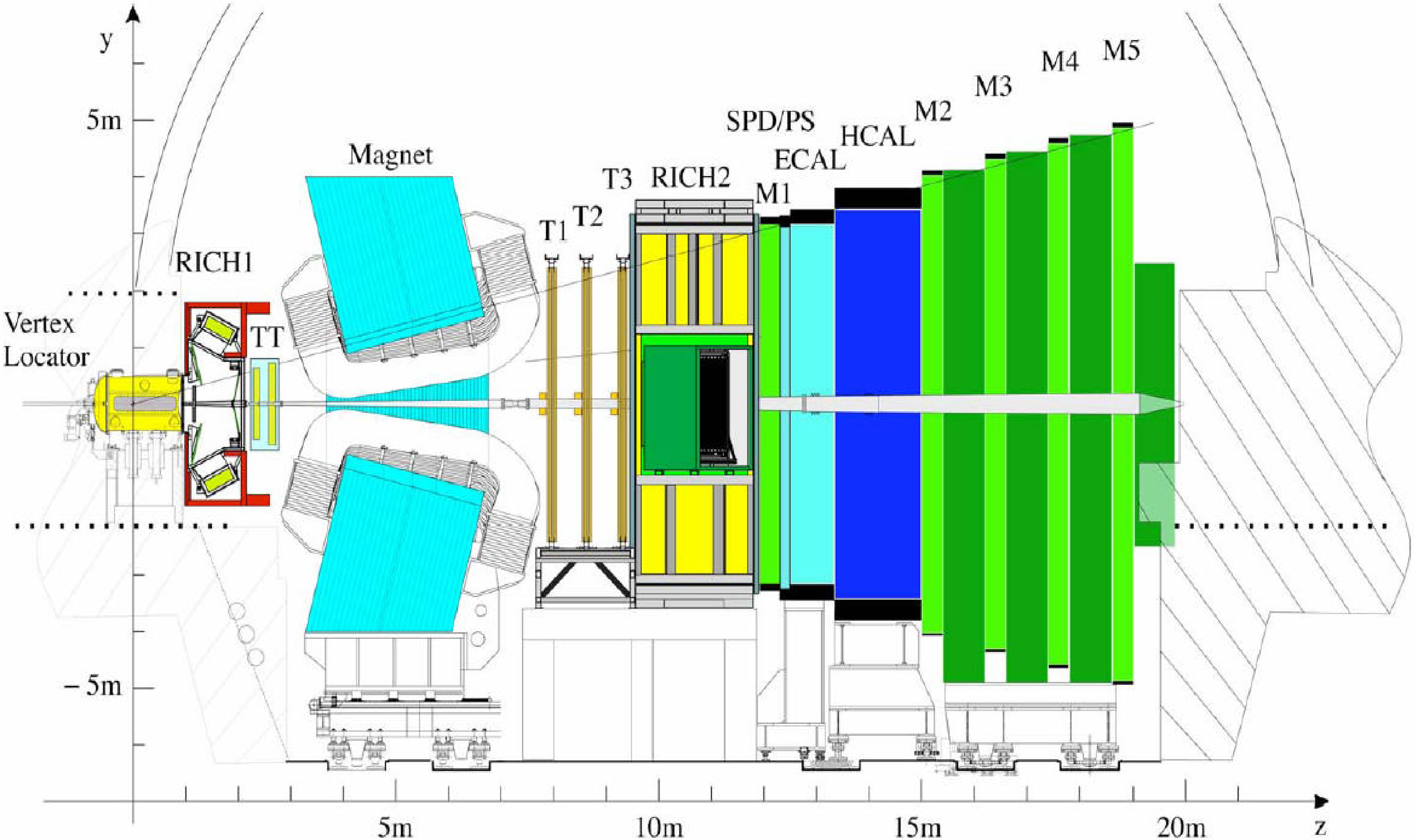






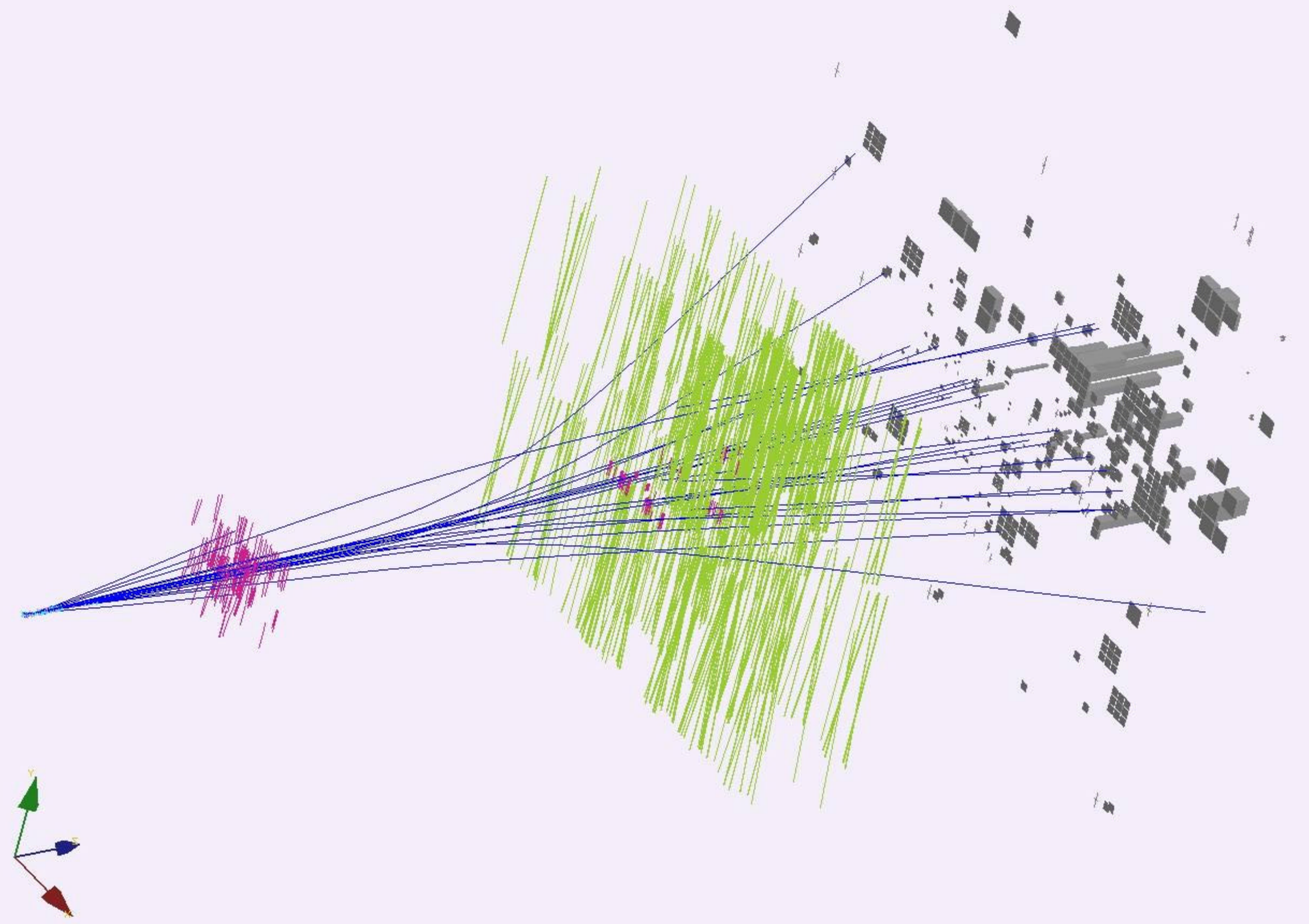


LHCb Layout

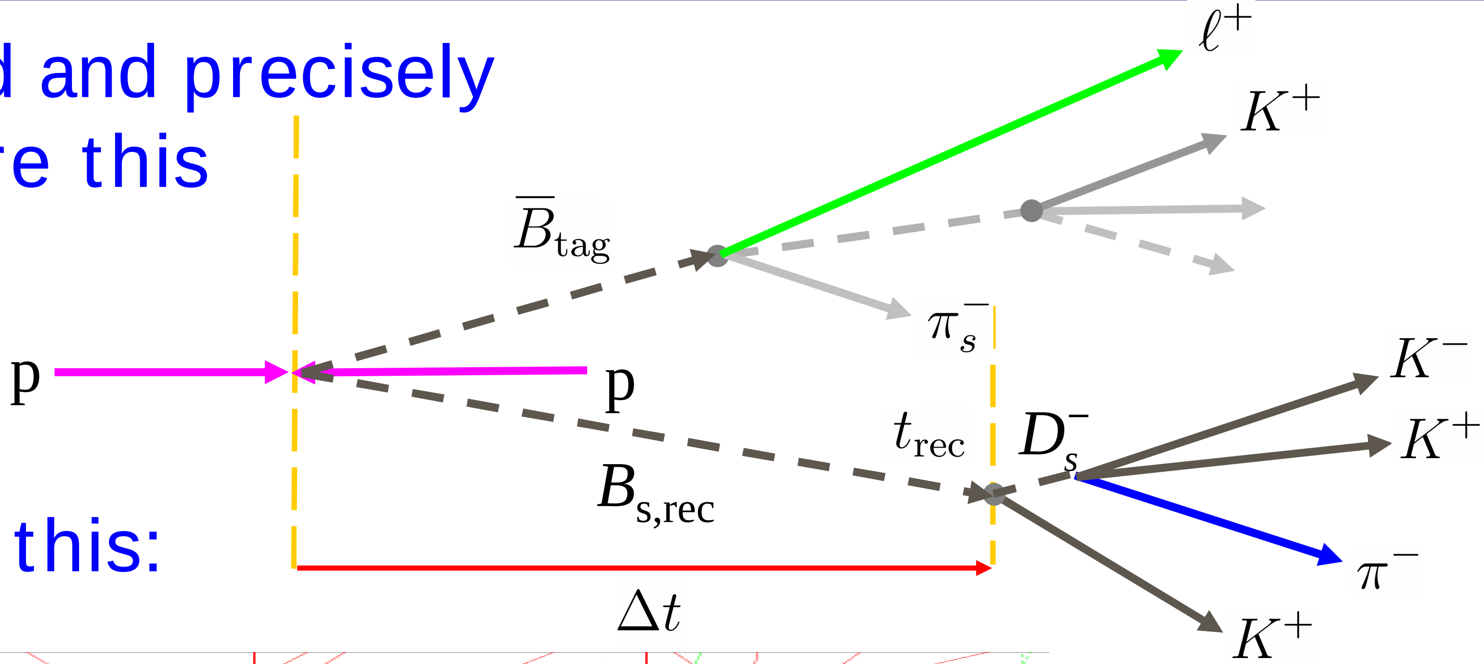


y
5m
- 5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

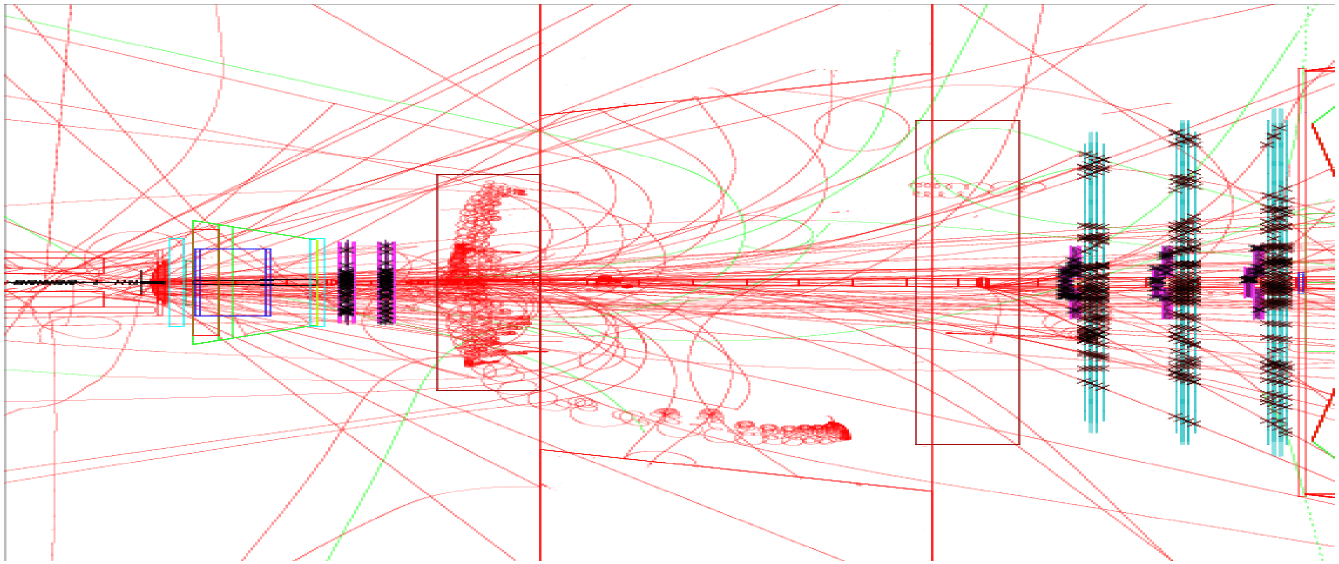
LHCb: simulated event



- To find and precisely measure this

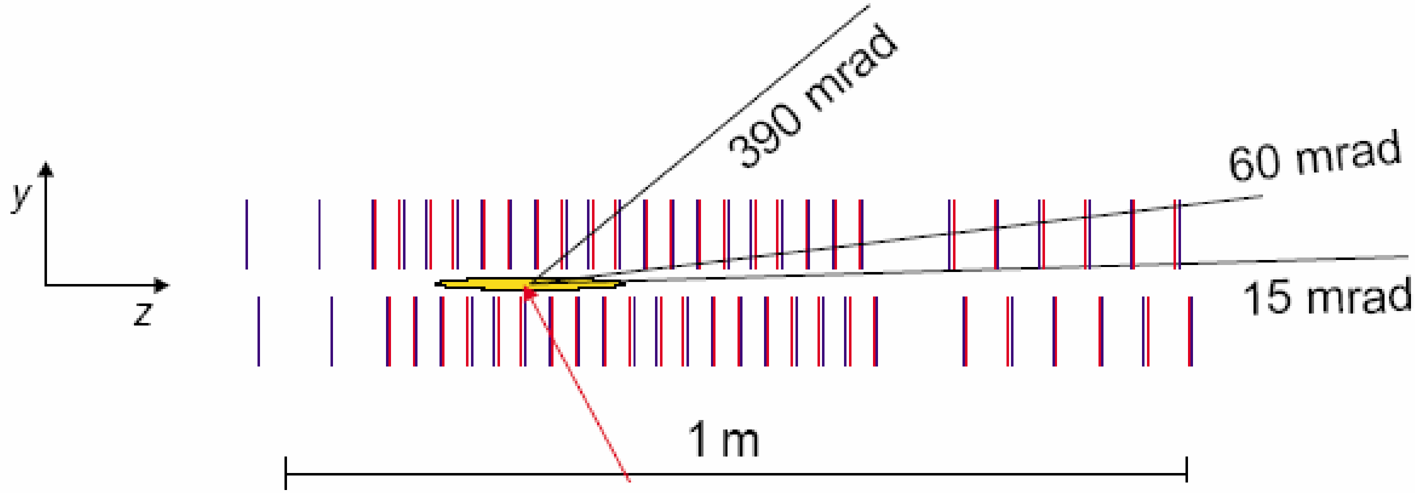


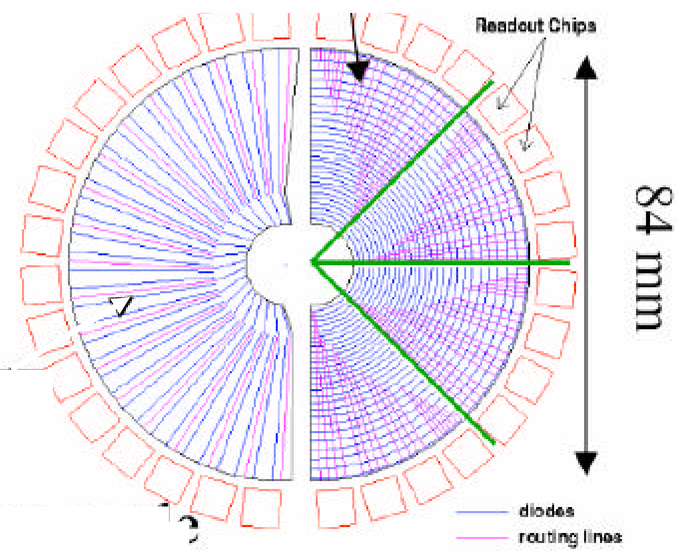
- Inside this:

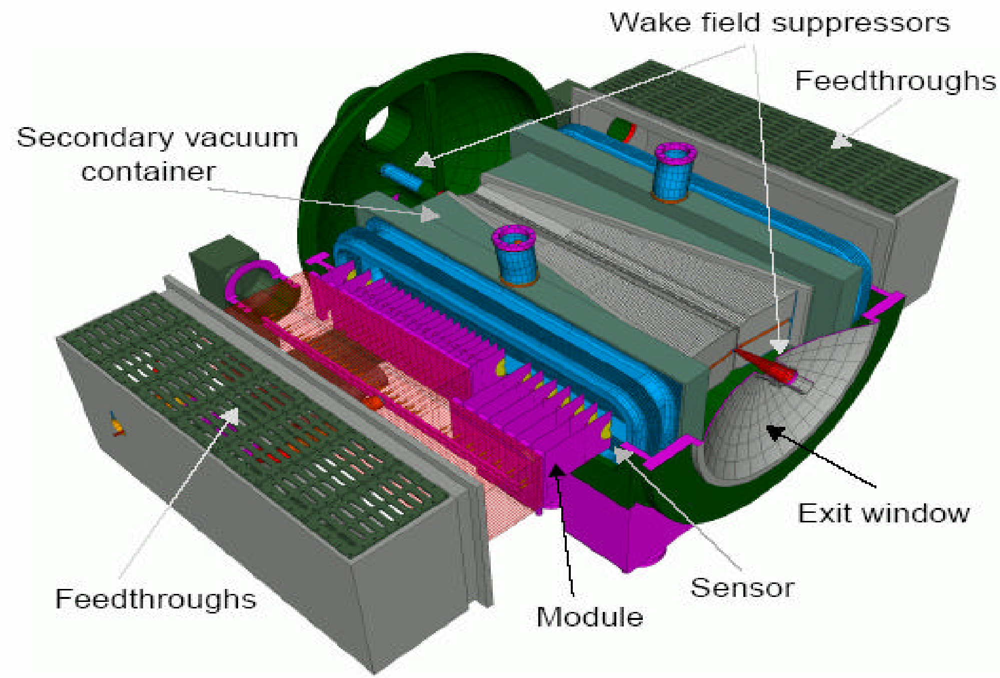


LHCb: VELO detector

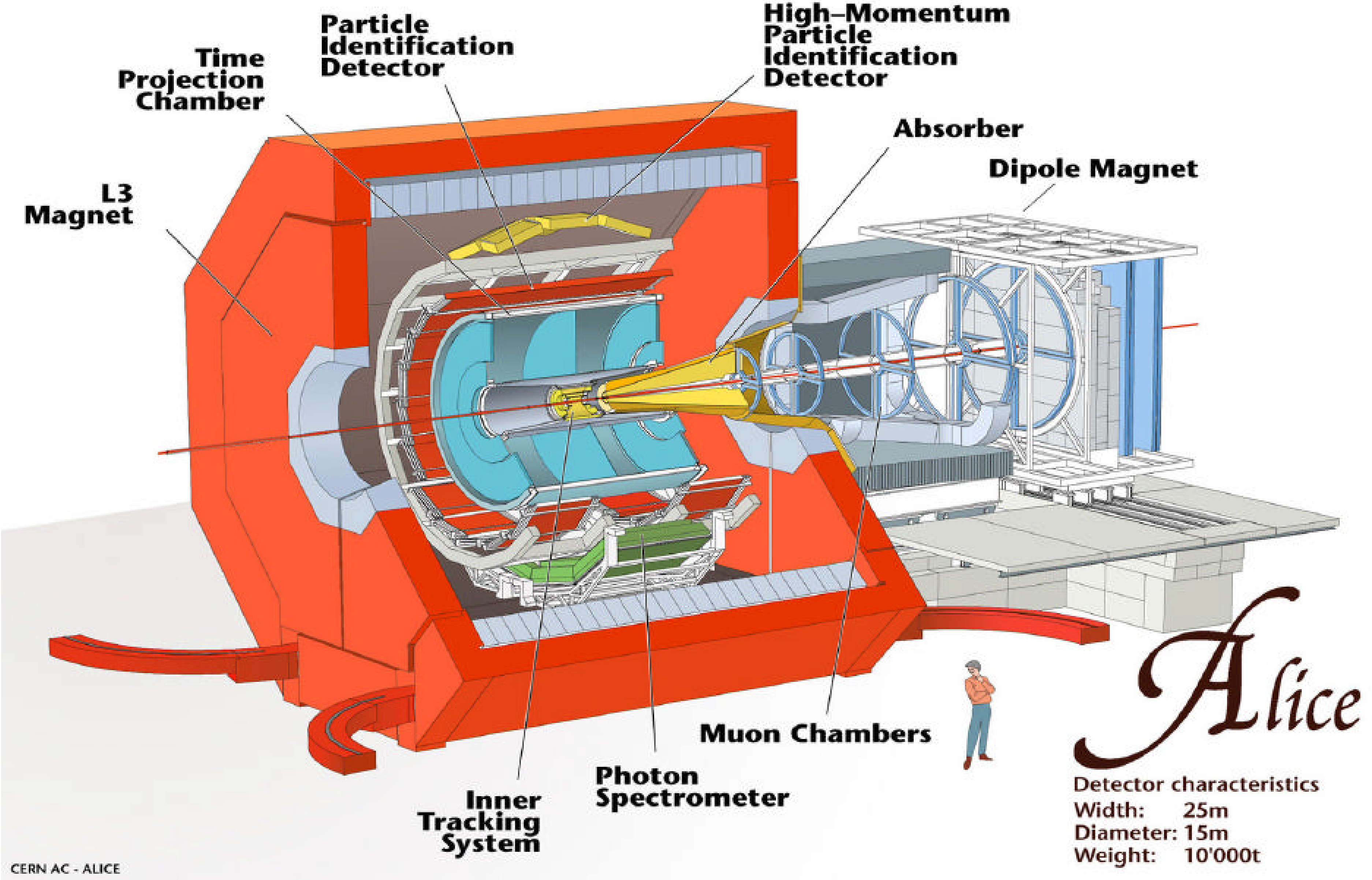
cross section at $x=0$:

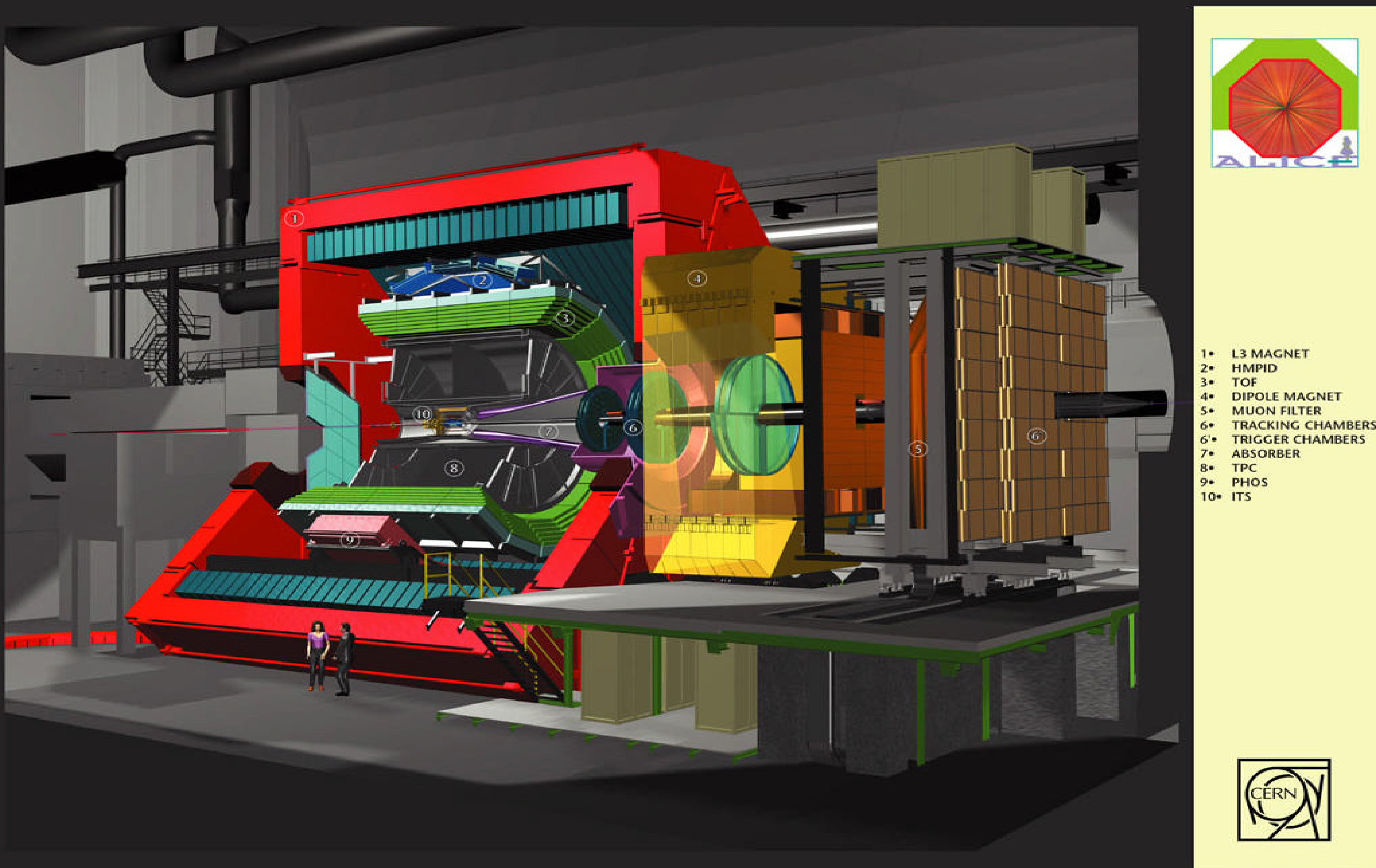




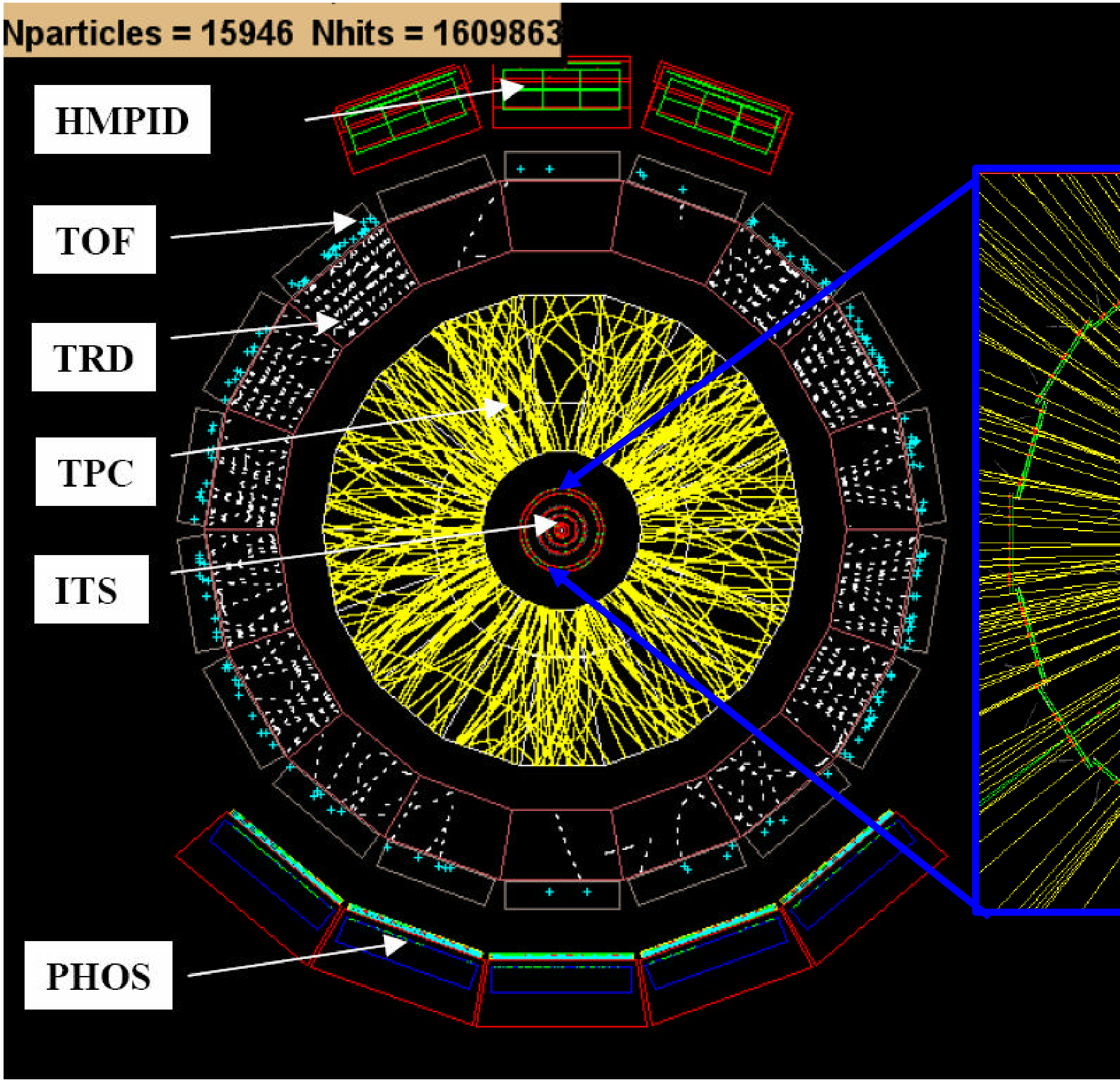


ALICE Layout

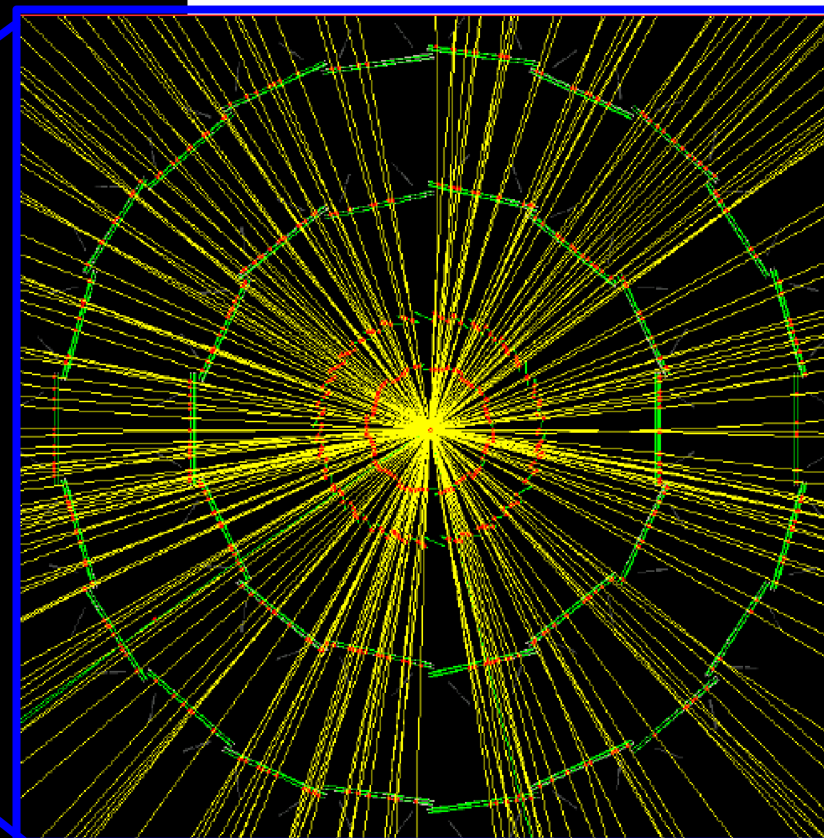



1 ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩
1• L3 MAGNET
2• HMPID
3• TOF
4• DIPOLE MAGNET
5• MUON FILTER
6• TRACKING CHAMBERS
6'• TRIGGER CHAMBERS
7• ABSORBER
8• TPC
9• PHOS
10• ITS
ALICE
CERN

Central PbPb collision in ALICE

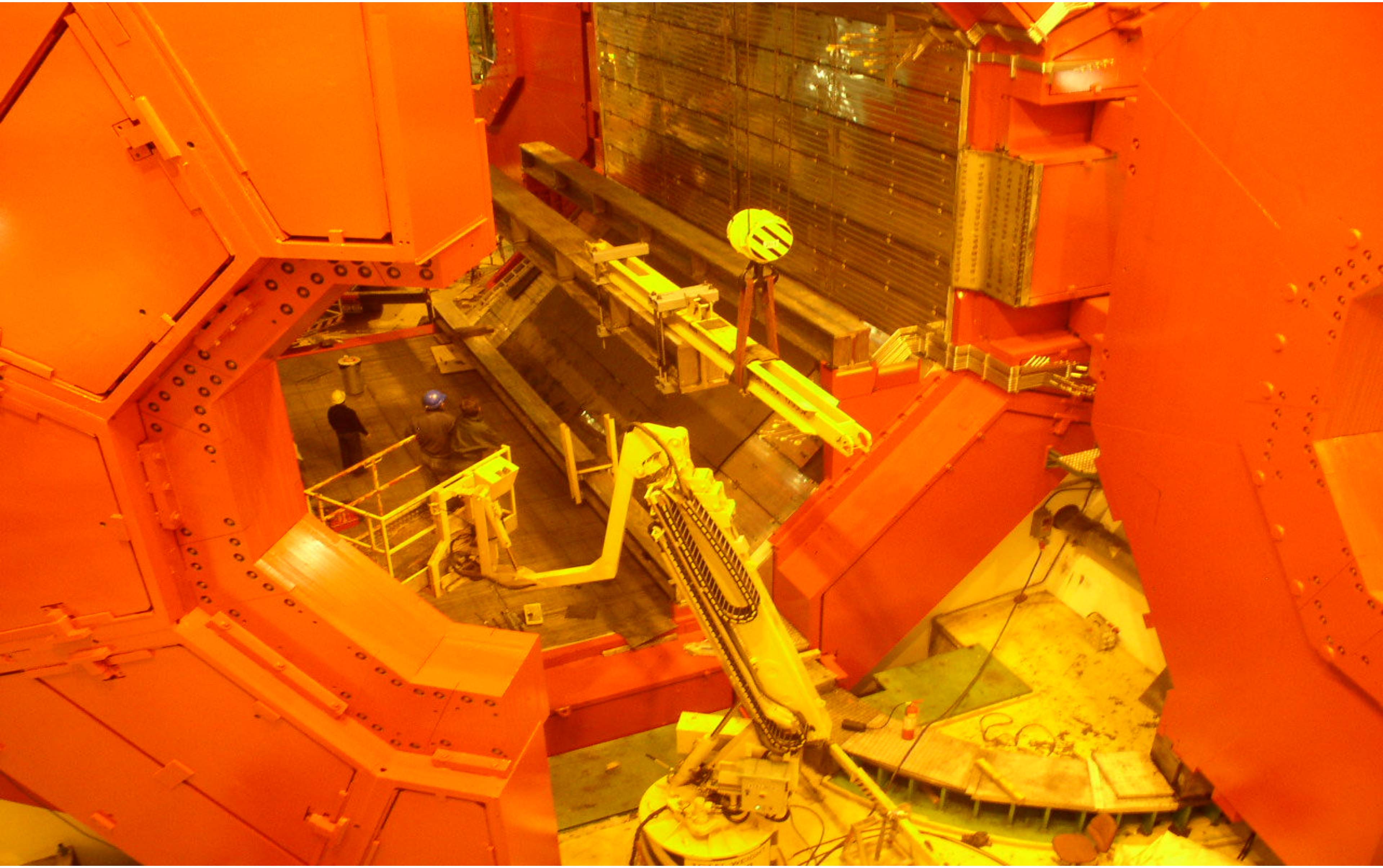


- >80000 particles produced

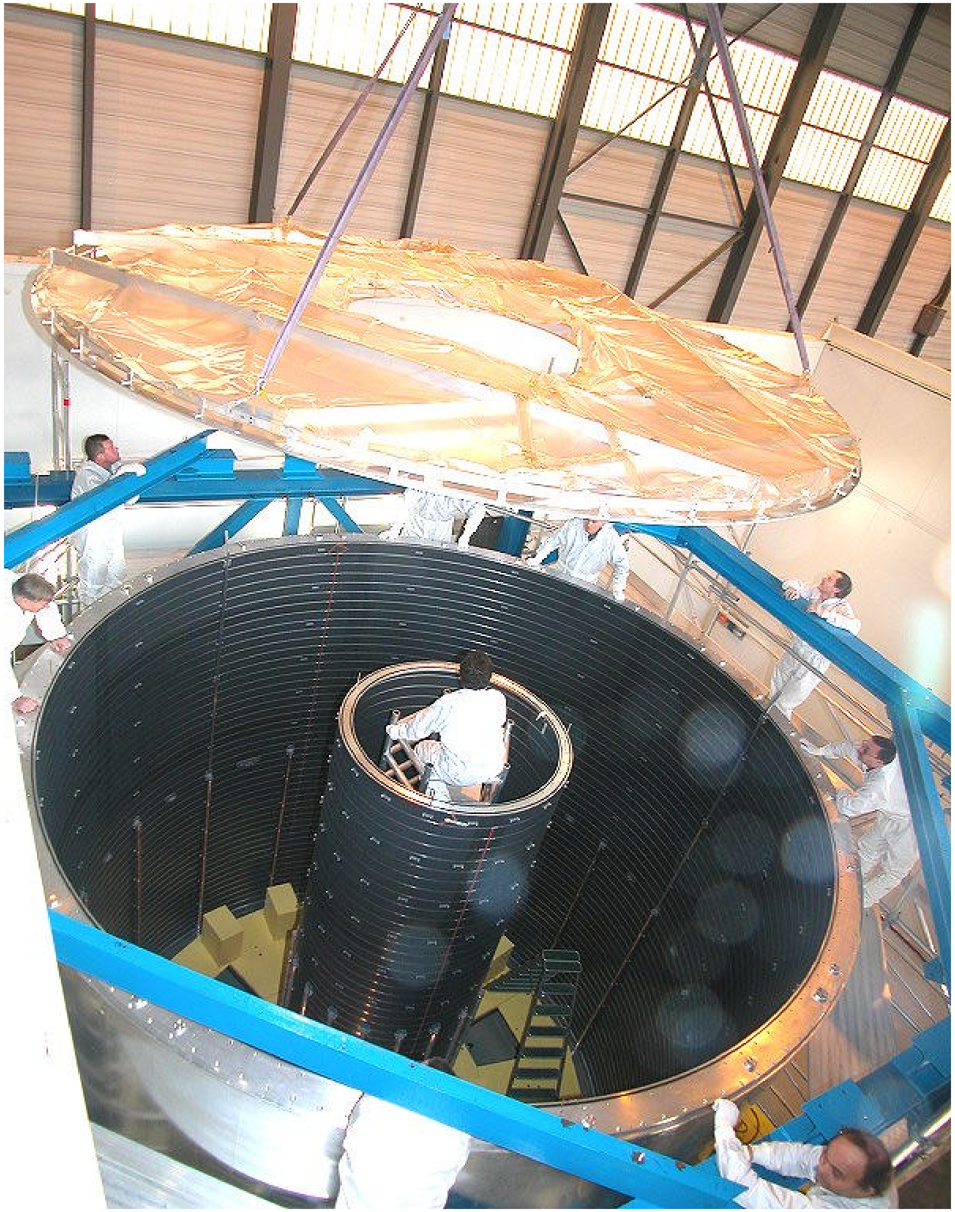


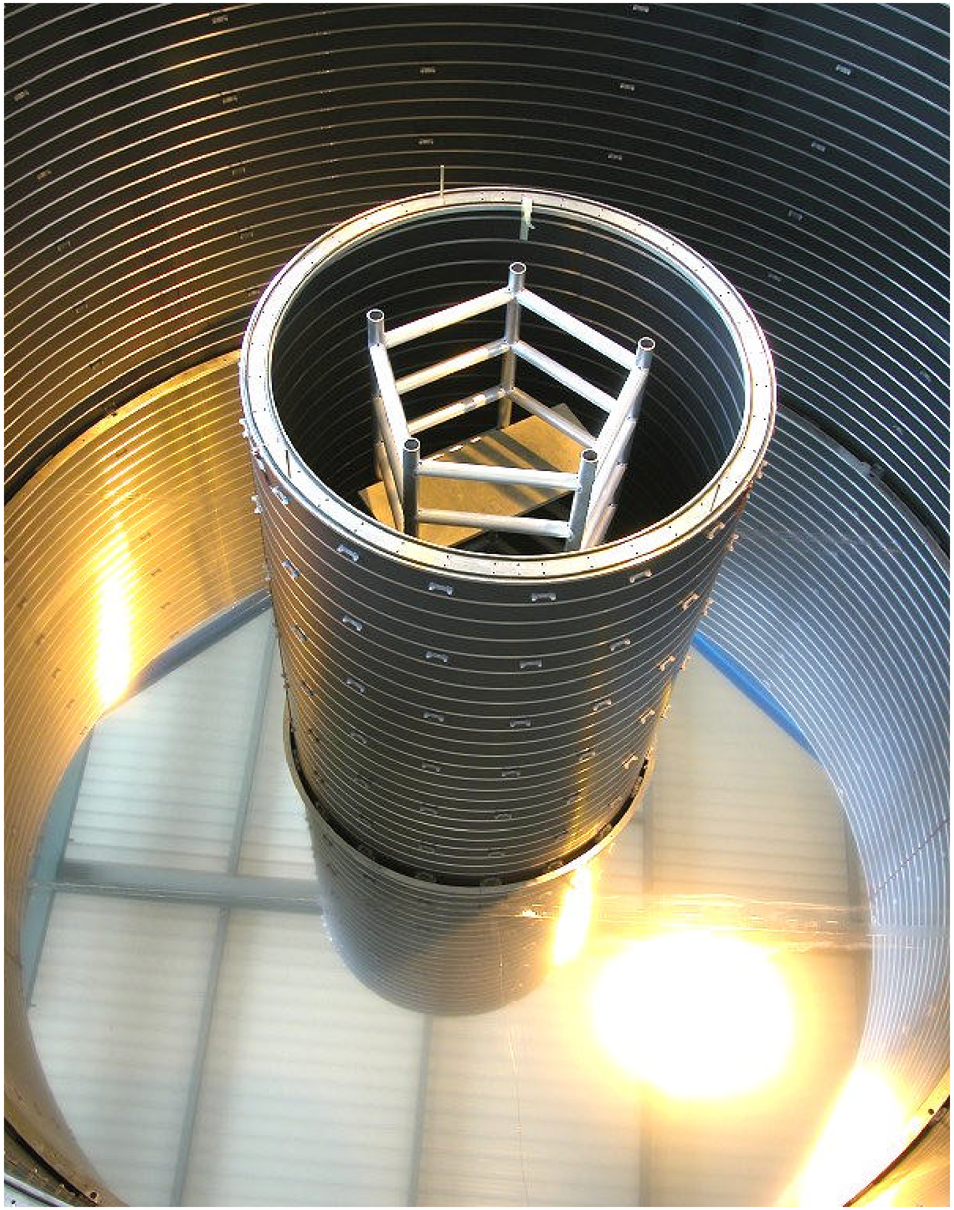
- >16000 particles inside ITS accep.

ALICE: former L3 magnet

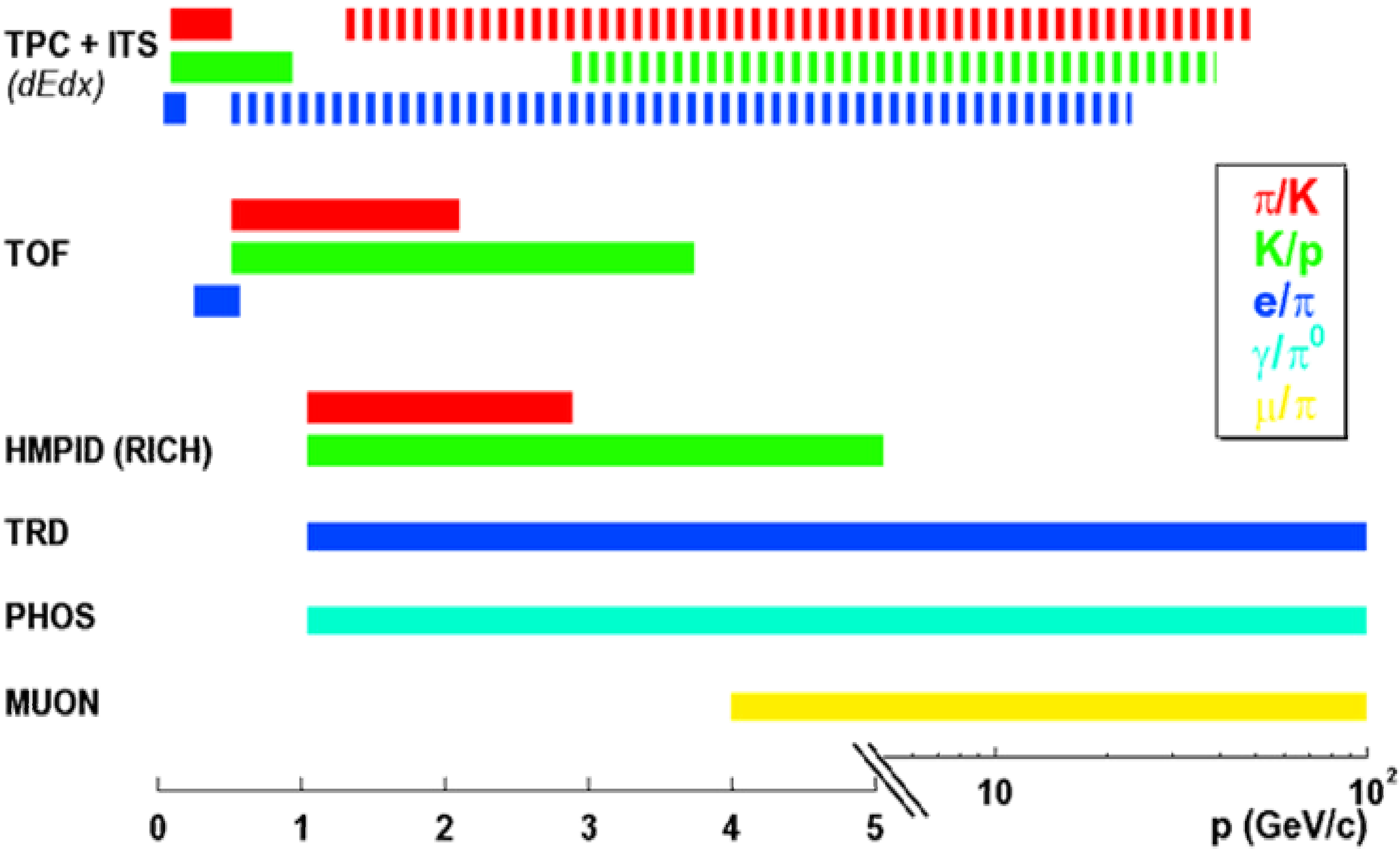


ALICE: Mounting TPC electrode

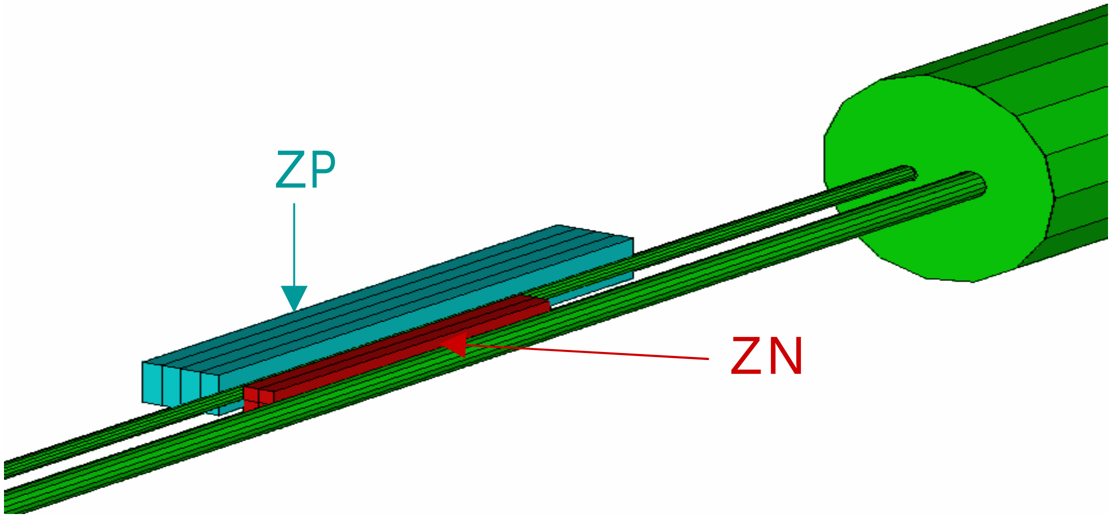




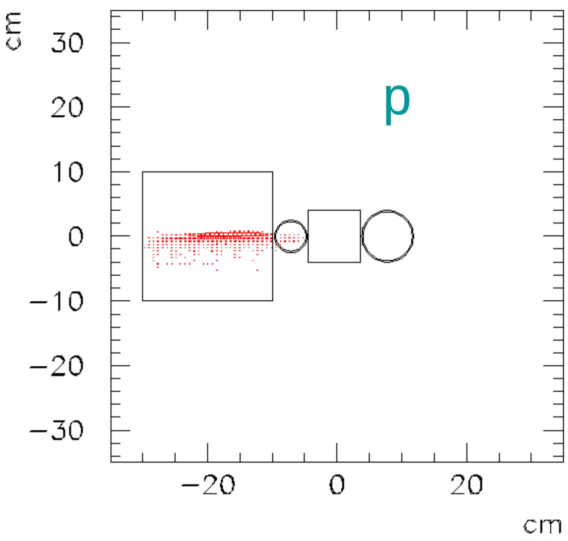
ALICE: particle identification

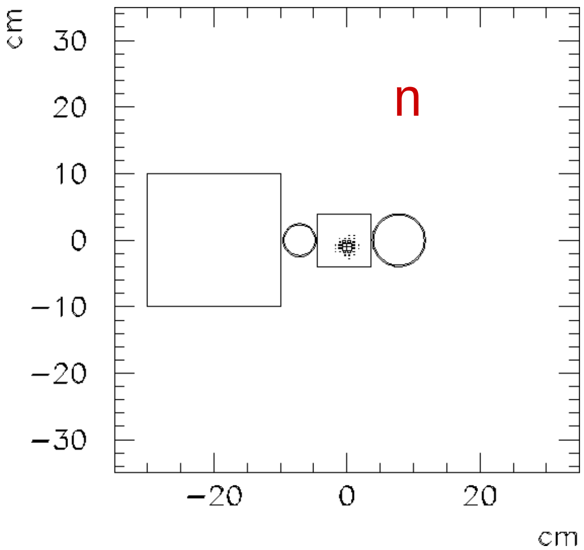


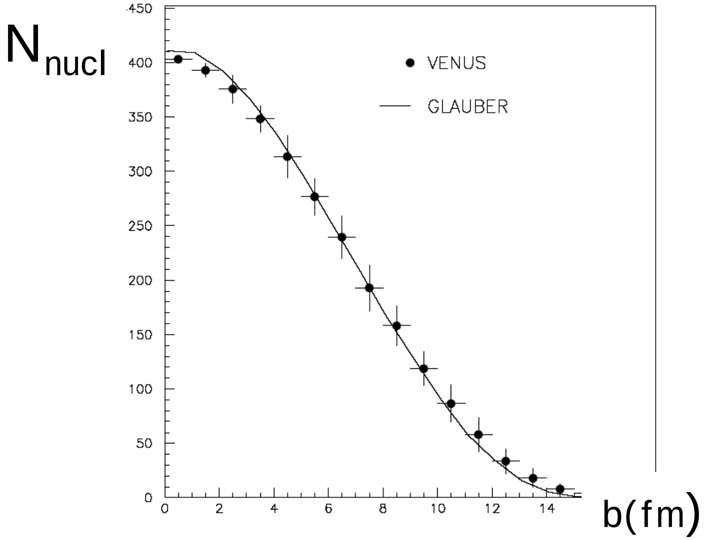
ALICE Zero-Degree Calorimeter



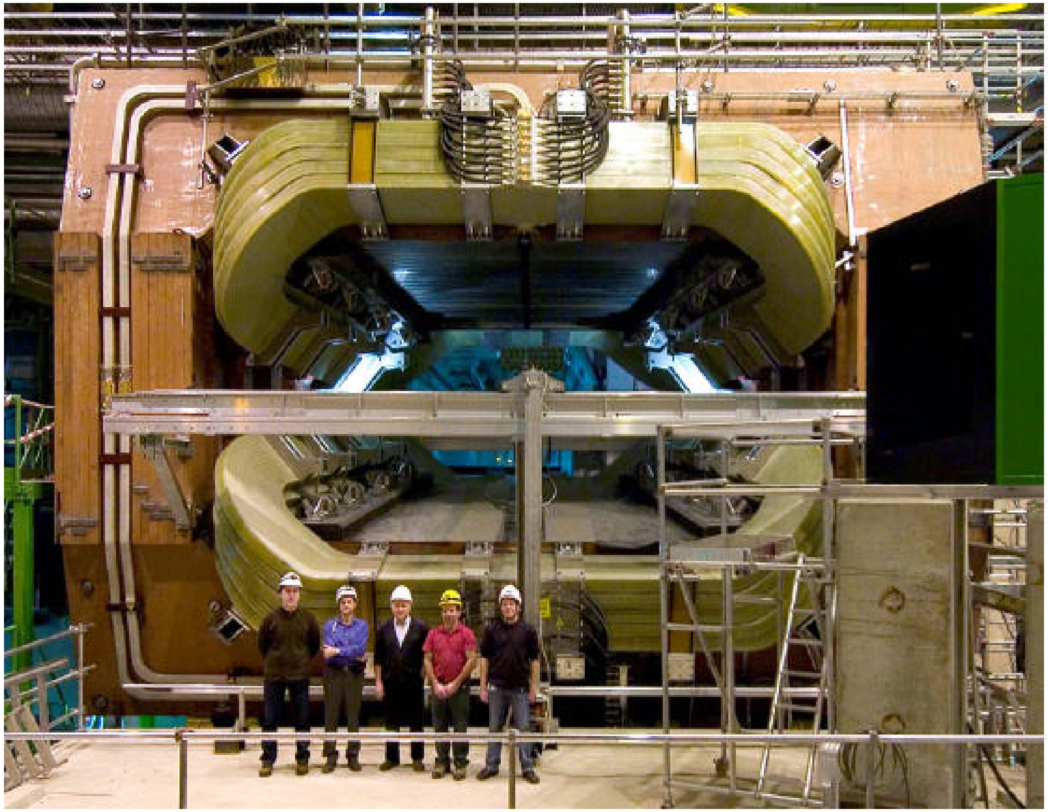
- Calorimeters at > 100 m from IP
  - → 2 parts: for n and p
- Measure number N_{nucl} of spectator nucleons
  - → determines collision geometry (impact parameter b)







ALICE / LHCb Magnets



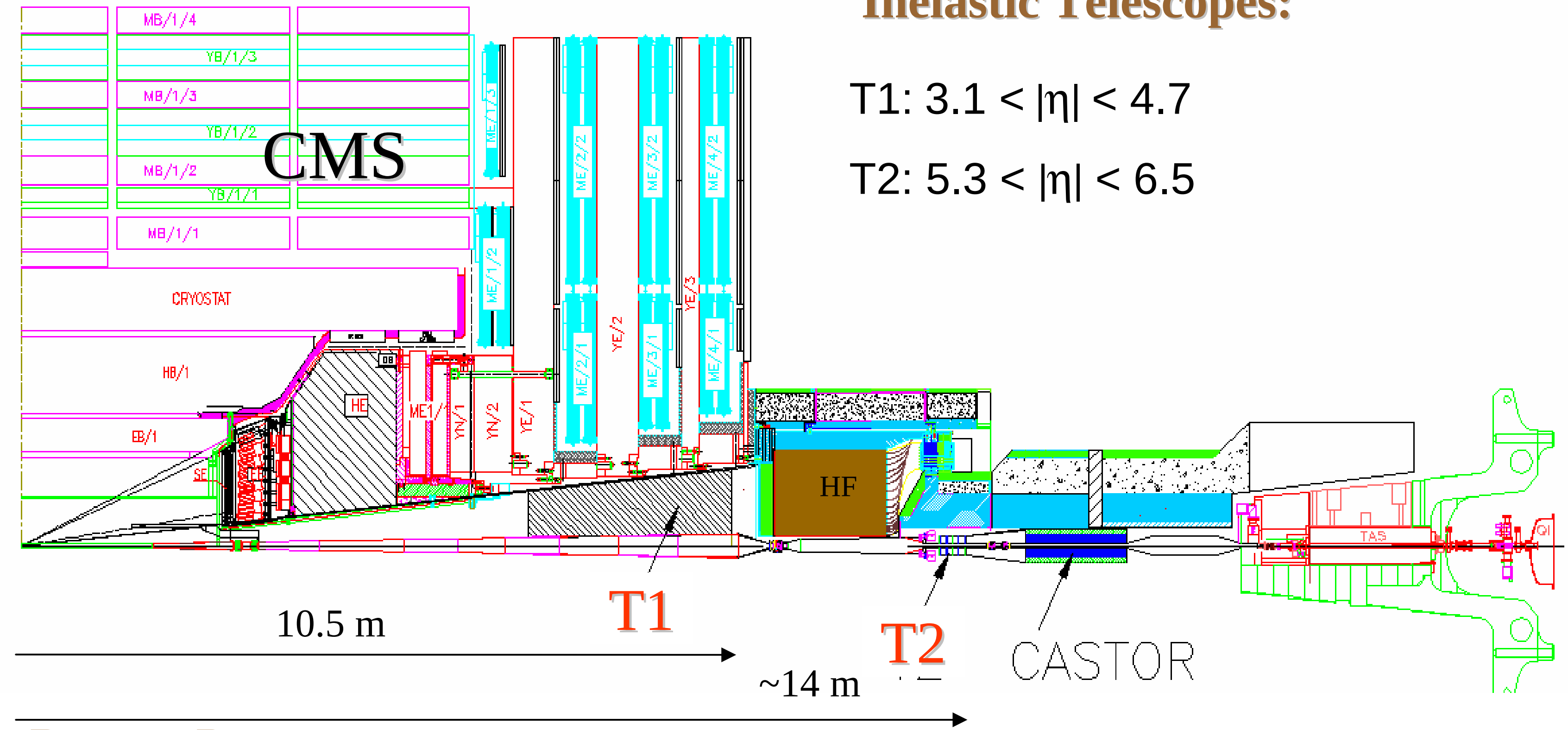
- ALICE
  - → Polarity to be reversed 1-4 times per year
- LHCb
  - → Polarity to be reversed at each fill (physics run)

TOTEM: experimental layout

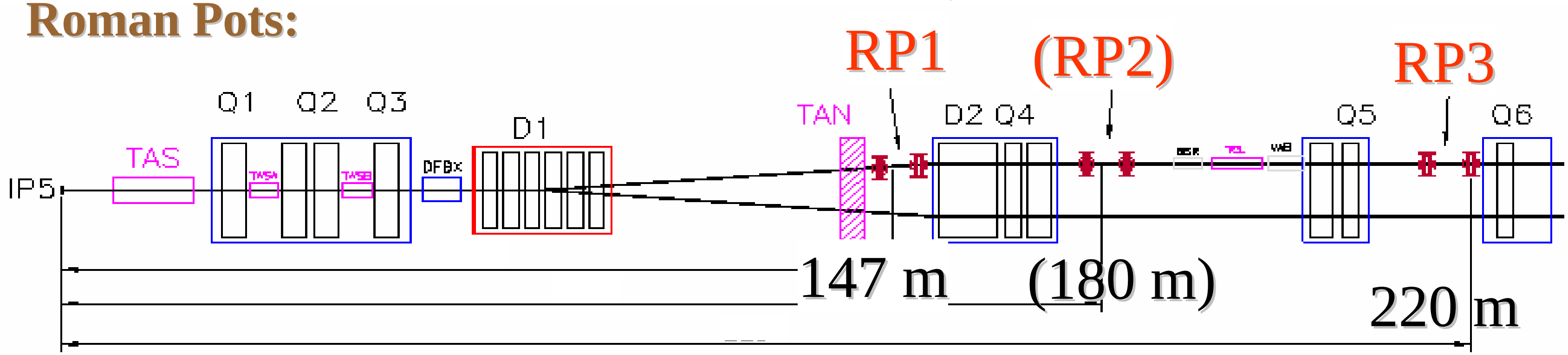
Inelastic Telescopes:

T1: $3.1 < |\eta| < 4.7$

T2: $5.3 < |\eta| < 6.5$

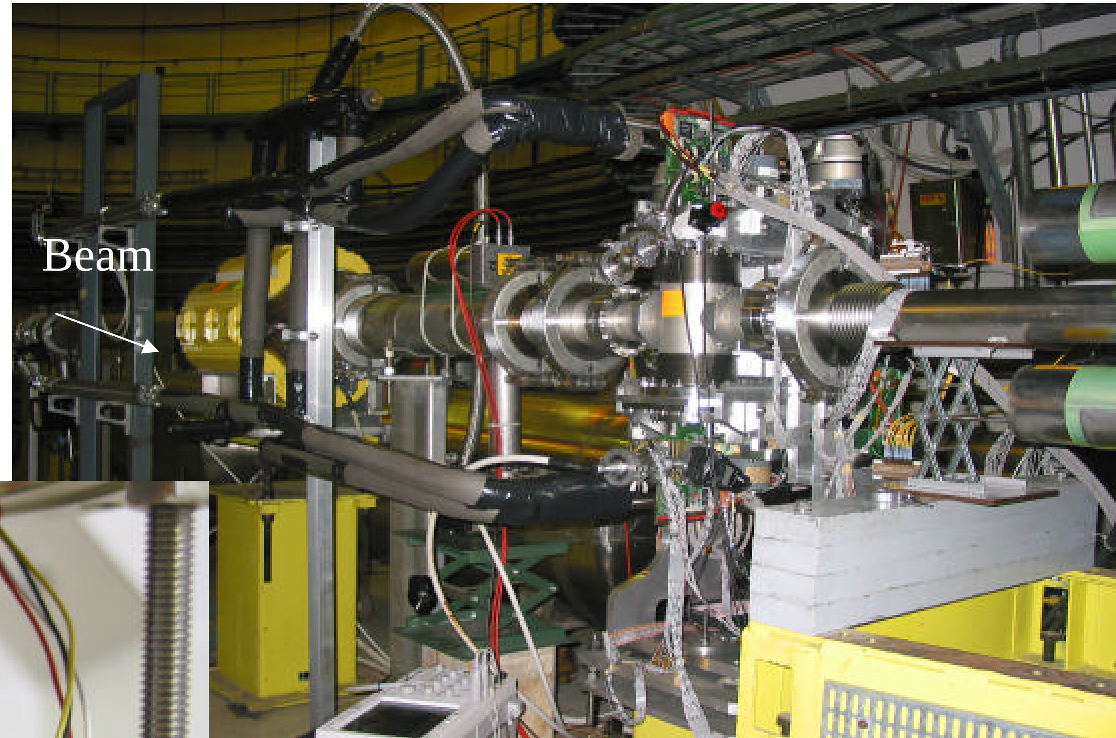


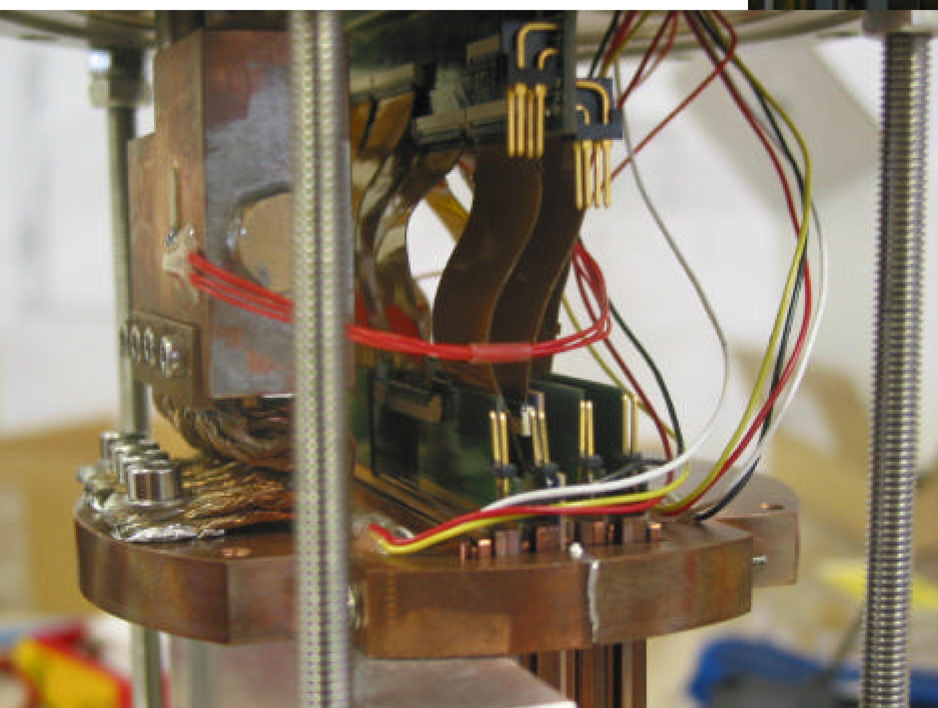
Roman Pots:



TOTEM experiment

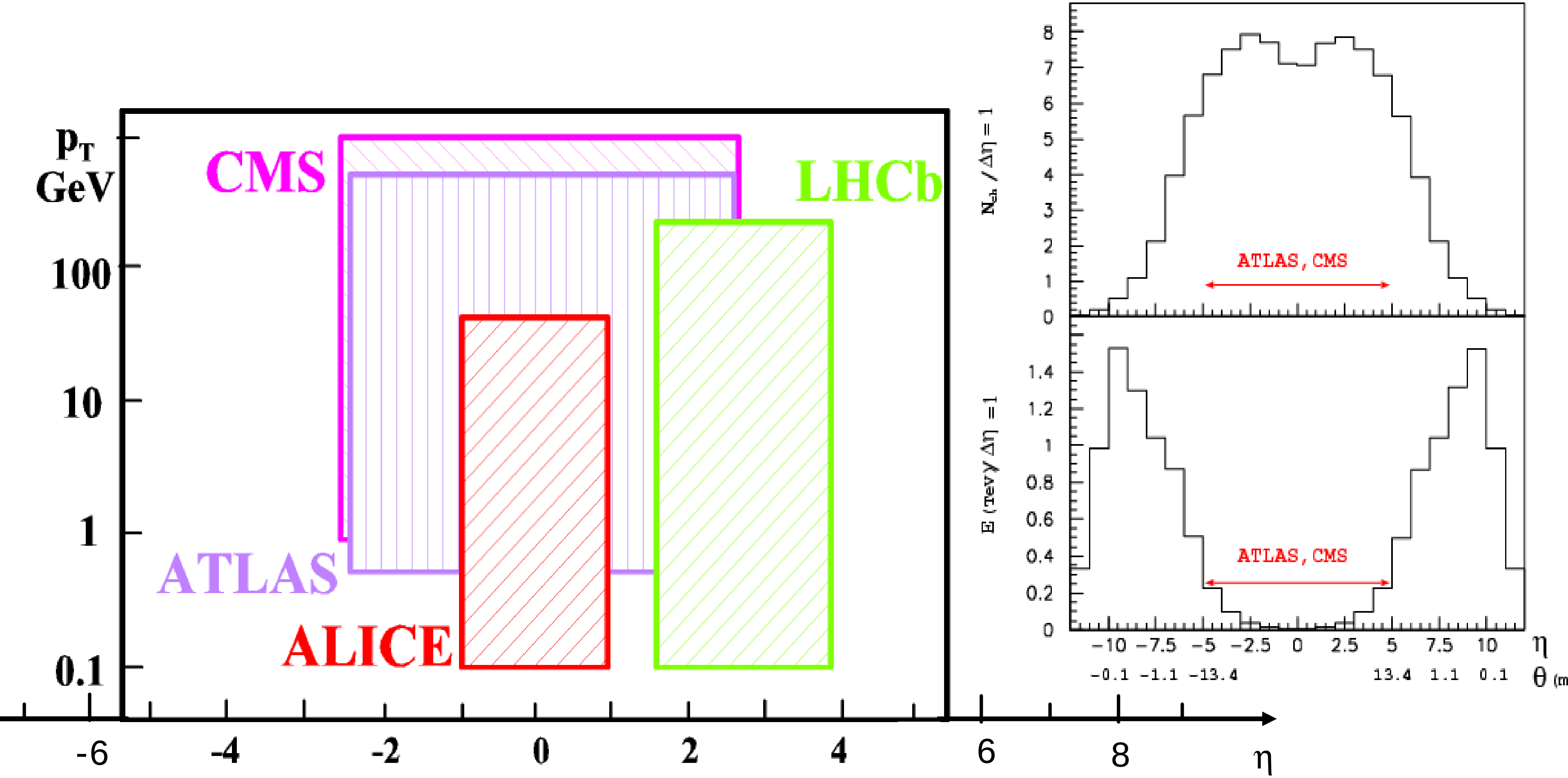
- Roman Pot prototype
  - → Successful test in SPS in 2004





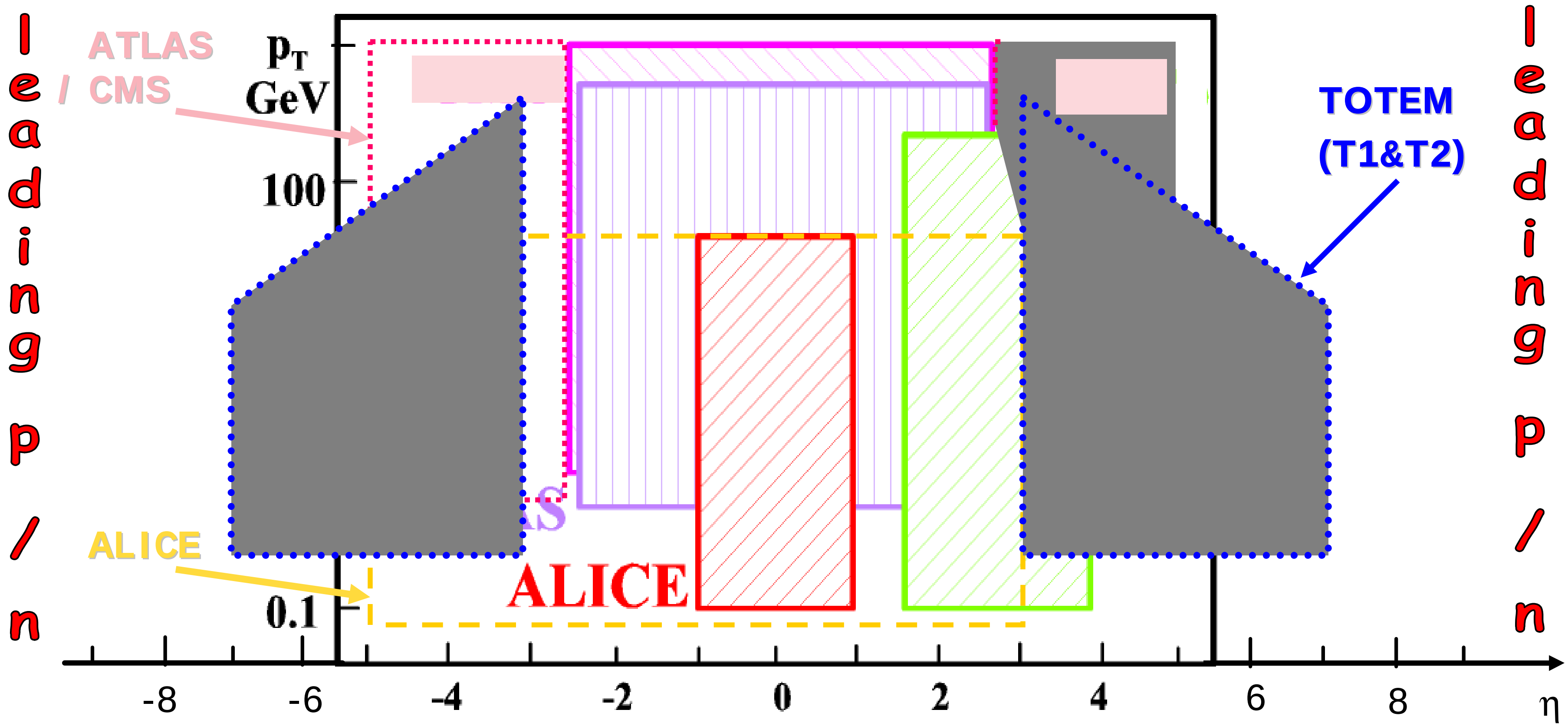
- Details on interface detector – machine
  - → Lecture by D. Macina on Friday

Baseline coverage



- (identified) particle measurements:
  - → $-2.5 \le \eta \le 4$ via ATLAS/CMS, LHCb and ALICE

Baseline coverage (cont'd)



- Charged particle multiplicities (energy flow)
  → |η| ≤ 7 via TOTEM/ALICE (|η| ≤ 5 via ATLAS/CMS)
- Leading particles
  → Protons via TOTEM (RP), neutrons via ALICE (ZDC)

LHC operational aspects

- LHC: facility with very broad physics programme
  - → Different physics goals → sometimes different running/operational conditions
  - → Global optimization needed
    - Similar to allocation of test beam time in fixed target
    - Contrast to Tevatron / LEP :
      - → Maximize integrated luminosity (and $\sqrt{s}$ for LEP as well)
- Some ‘dimensions’ of operational parameter space
  - → Particle species
  - → Number of bunches
  - → Beam energy
  - → Magnitude of focusing (β^* value)
  - → Luminosity
  - → Polarities etc. of experimental magnets

Naïve view of machine start-up

  - More discussion in R. Assmann's lecture tomorrow

- Several steps
  - → Single beam running
  - → Establish collisions and pilot (physics) run
    - Small number of bunches involved
  - → Regular physics runs (optimize for luminosity)
- All of the above are useful for the experiments
  - → Single beam run to be used for
    - Timing and synchronisation of experiments
    - Studies of backgrounds (vacuum quality, beam gas, ...)
    - Start to 'shake' detectors
- Clear wish to move towards stable, reproducable operation as soon as possible

Examples for experiments' wishes

- ATLAS/CMS
  - → Optimized for pp luminosities of 10^{34} cm^{-2} s^{-1}
  - → To exploit initial physics potential, aim for luminosities of $= 10^{33}$ cm^{-2} s^{-1} soon
    - And minimize number of pile-up events
  - → Initial lower luminosities useful to understand properties of minimum bias pp interactions
- LHCb
  - → Optimized for L = $2 \ast 10^{32}$ cm^{-2} s^{-1} and 25 ns spacing
    - On average 0.4 interactions per bunch crossing
  - → Want to achieve this luminosity also with lower initial currents (change focusing in IR8 – β^* ?)
- General comment: ALICE, LHCb
  - → Lower luminosities: more sensitive to machine related background
    - Often scales with beam current

Examples for experiments' wishes

- ALICE: pp running as reference measurement
  - → Limitations on luminosities
    - Possible radiation damage to detectors $L < 10^{32}$ cm^{-2} s^{-1}
    - Central detector to be operated $L < 10^{31}$ cm^{-2} s^{-1}
  - → Operational values
    - $L = 10^{29}$ cm^{-2} s^{-1} initially (only one event per TPC readout)
    - $L = 2\text{-}5 * 10^{30}$ cm^{-2} s^{-1} later (20-50 events per TPC readout)
  - → Tuning of luminosity via beam displacement or β^* ?
  - → Running at $\sqrt{s}$ = 5.5 TeV (direct comparison with PbPb)
- TOTEM
  - → Need special machine optics configuration for measurement of total cross-section ('large β^*')
    - Measure almost all scattered protons (produced under small angles)
  - → Running at $\sqrt{s}$ = 8 TeV (ρ parameter)
    and $\sqrt{s}$ = 1.8 TeV (comparison to Tevatron)

TOTEM running scenarios

Running scenarios	s_{tot}, low |t| elastic scattering, minimum bias	Diffractive physics large p_T phenomena	Large |t| elastics scattering
β*(m)	1540	1540	18
N_b	43	156	2808
Half crossing angle [μrad]	0	0	160
e_N[μrad rad]	1	1 (3.75)	3.75
I_b	0.3 10^{11}	0.6 10^{11}(1.15 10^{11})	1.15 10^{11}
L [cm^{-2} s^{-1}]	1.6 10^{28}	2.4 10^{29}	3.6 10^{32}

Operation in pp collision mode

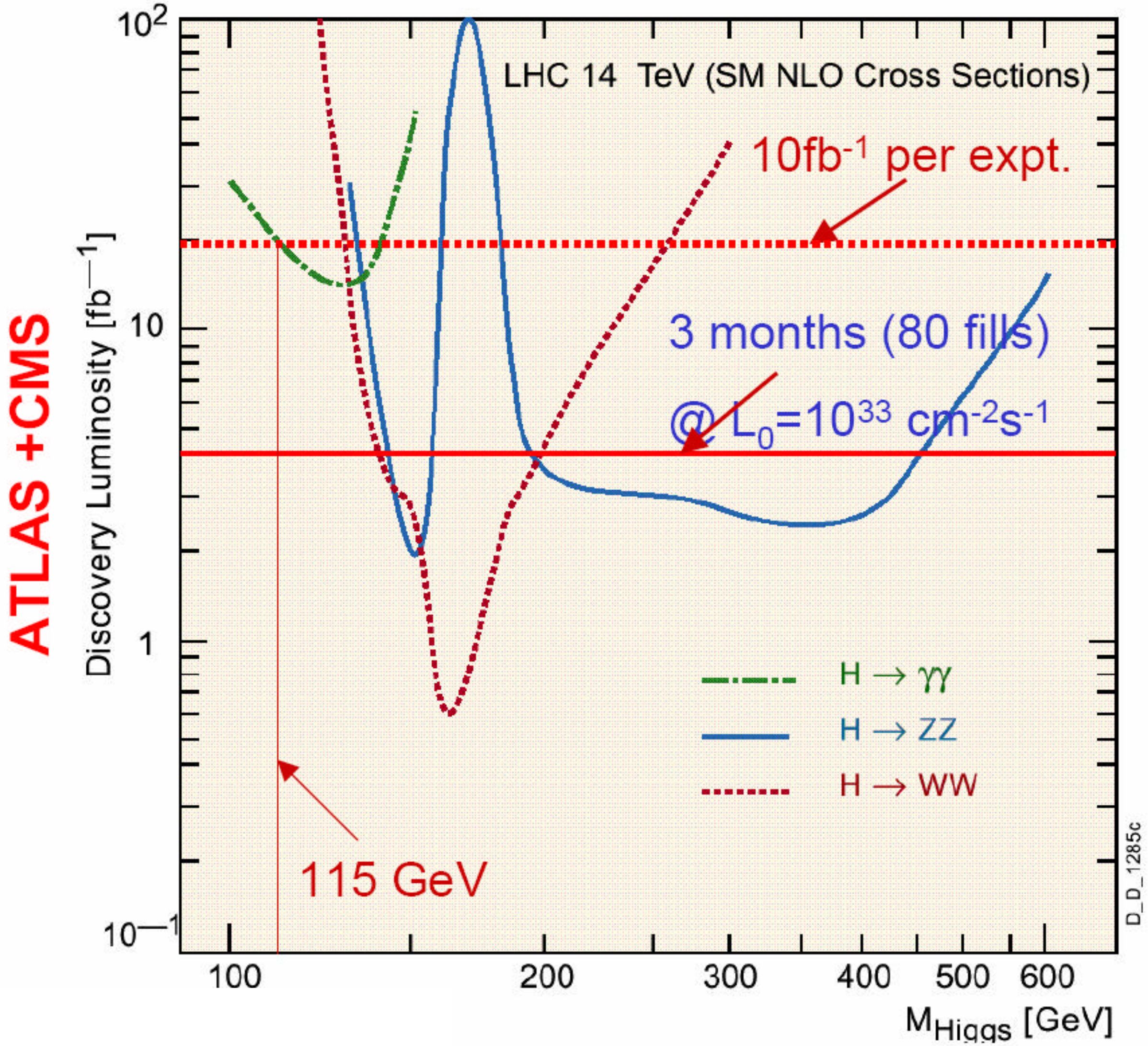
- Aim to get to stable luminosity running ($L_{peak} = 10^{33}$ cm^{-2} s^{-1}) soon
  - → Stability (integrated luminosity recorded) is what counts
  - → Go to design luminosity to exploit full phase space accessible and statistical precision
- Main message: due to larger $\sqrt{s}$ (compared to Tevatron) LHC has potential for early discoveries
  - → That's why the SSC (history now) had $\sqrt{s}$ = 40 TeV
- Bunch spacing: 25 ns vs. 75 ns
  - → For same L_{peak} factor of 3 more pile-up events @ 75 ns
    - i.e. at $L_{peak} = 3 * 10^{33}$ cm^{-2} s^{-1} same conditions as for design luminosity with spacing of 25 ns

Commissioning of experiments

- Commissioning of machine
  - → See R. Assmann's lecture
- Need to understand precisely the functioning of the experiments
  - → How to get from charges/voltages to the Higgs mass
- Learn to smoothly operate the detectors
- Identify and solve initial problematic issues
- Calibration/alignment at various levels (starts before collisions)
  - → Electronics chain stand-alone, mechanical aligment
  - → Charge/light injection to simulate particles
  - → Physics events
- Various ambitious goals
  - → Electromagnetic energy scale to 0.1% (or even better to 0.02%)

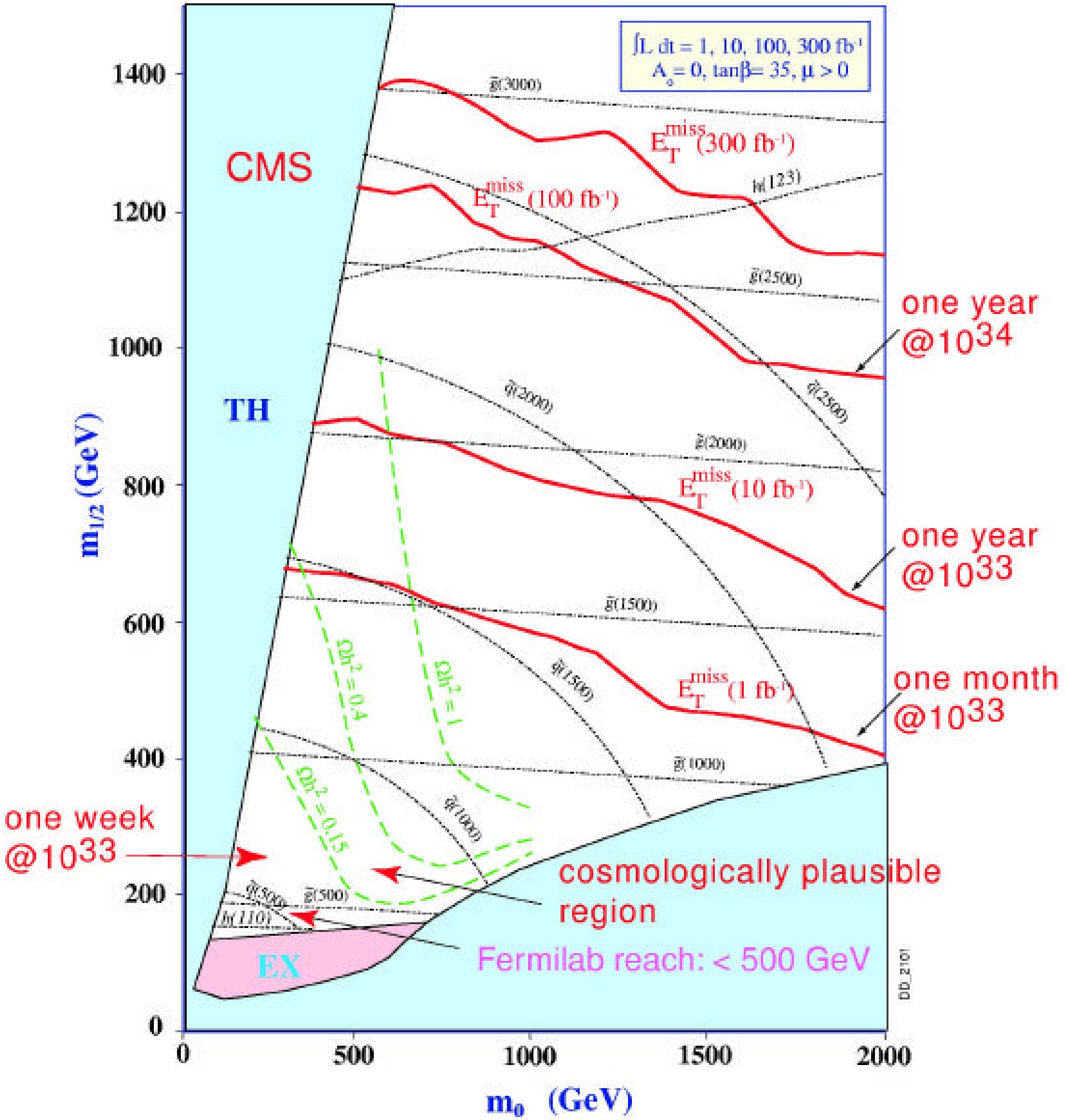
Initial physics reach: Higgs

Example Discovery Reach (5σ): ATLAS +CMS



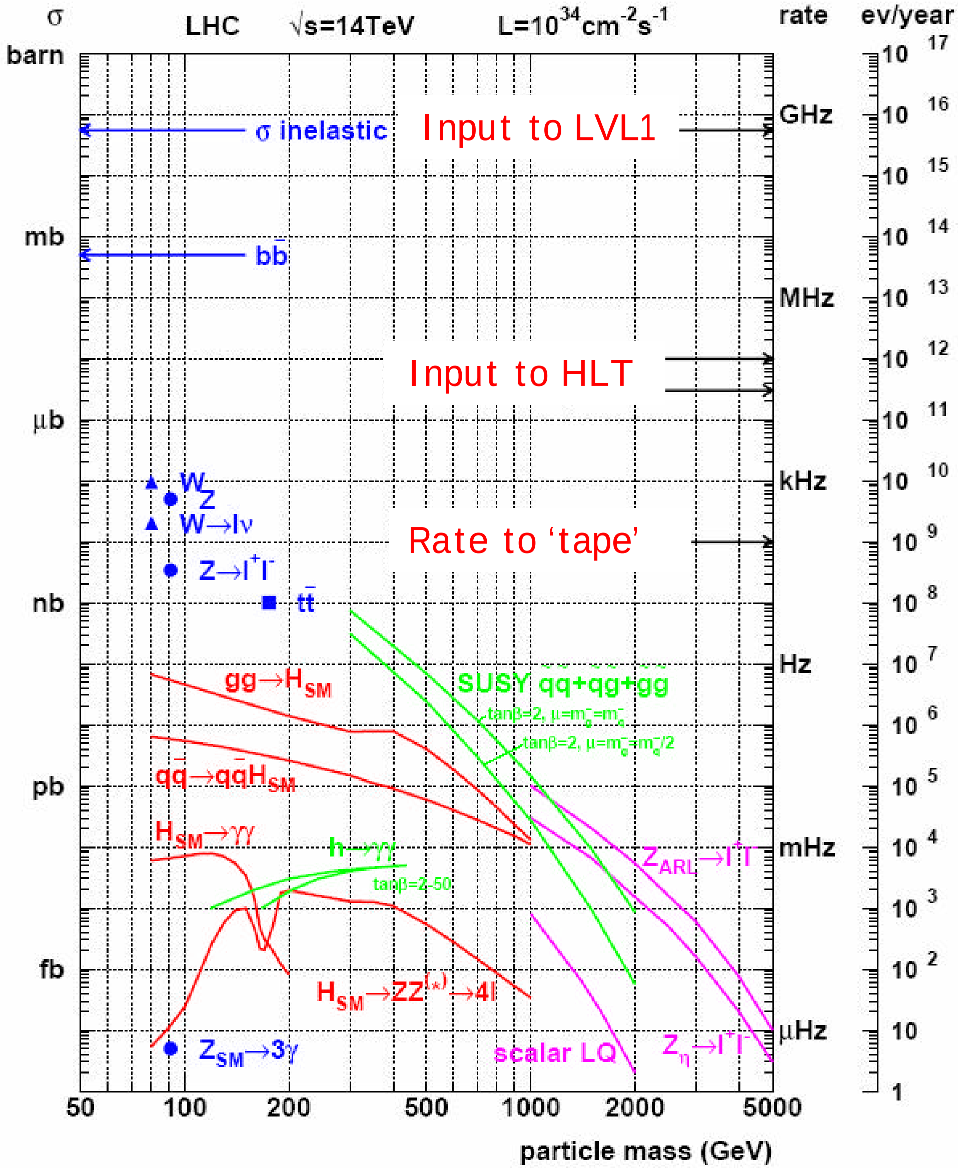
- Full mass range covered
  - → With 10 fb^{-1} per experiment
  - → And not all channels shown
- With good detector understanding
  - → Required luminosity for smaller masses not too large

Initial physics reach: SUSY



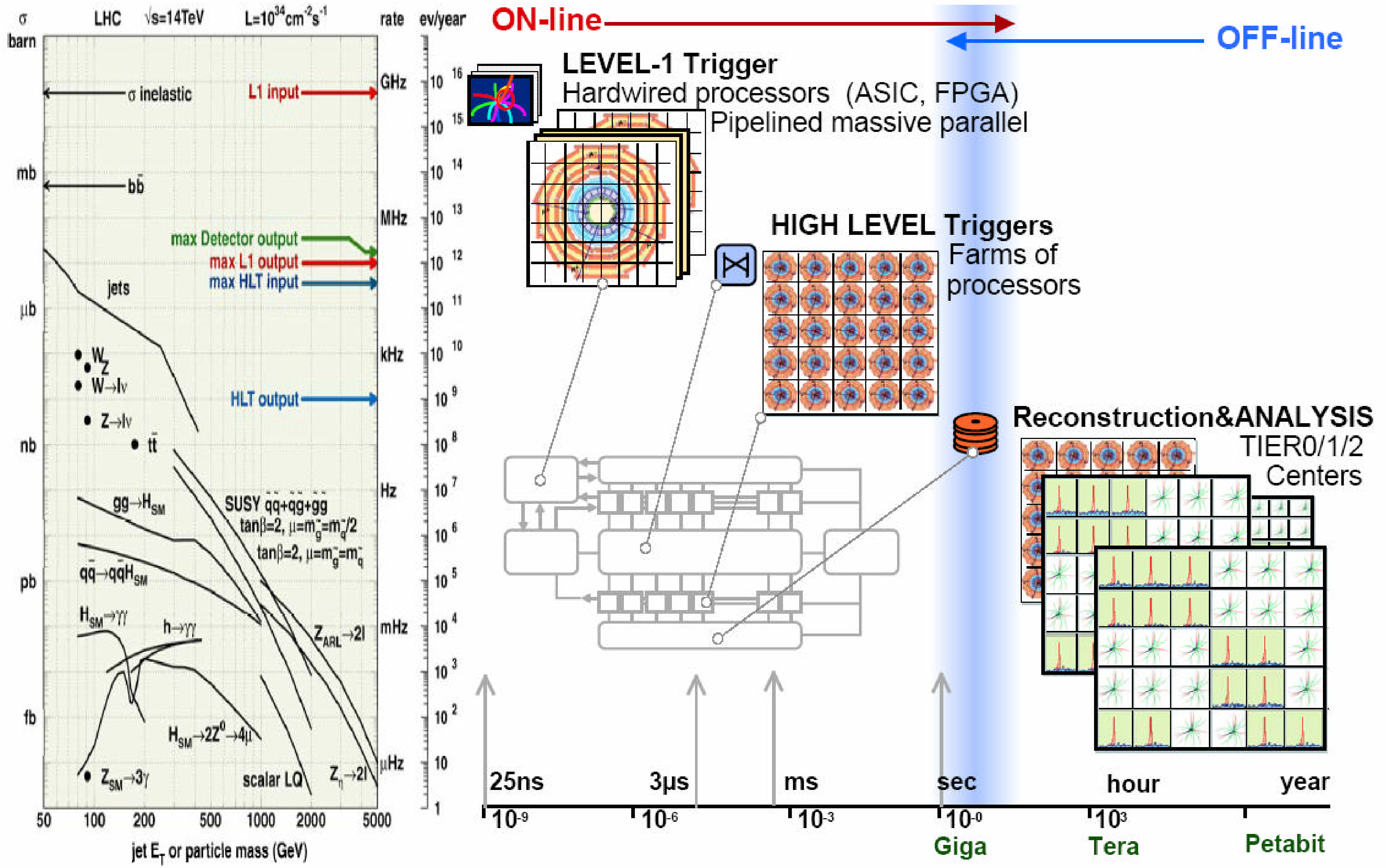
- Some discoveries could be made fast (i.e. early)
  - → With a few months of good quality data
- Need to under-stand detector properly
  - → Sources of fake missing transverse energy

Trigger (DAQ) challenge

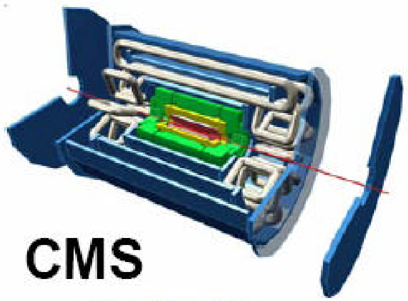
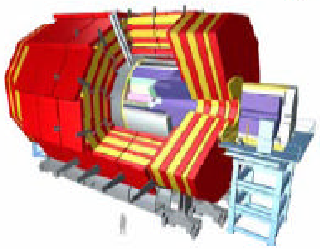
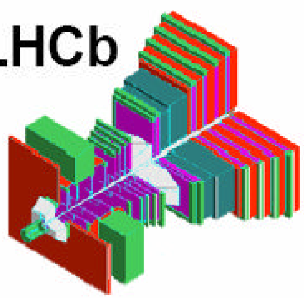
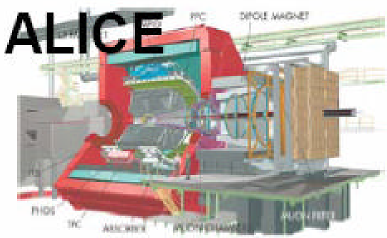


- Extremely wide range of cross-sections
  - → Total pp cross-section
  - → ...
  - → W/Z production
  - → ...
  - → Higgs production
- Very high selectivity needed 'on-line'
  - → To keep rate events of interest
  - → accept only 1 in every ~ 10^7 interactions

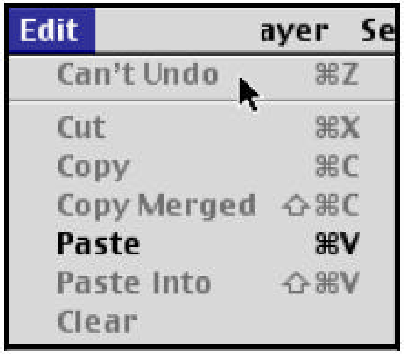
Trigger/DAQ system view

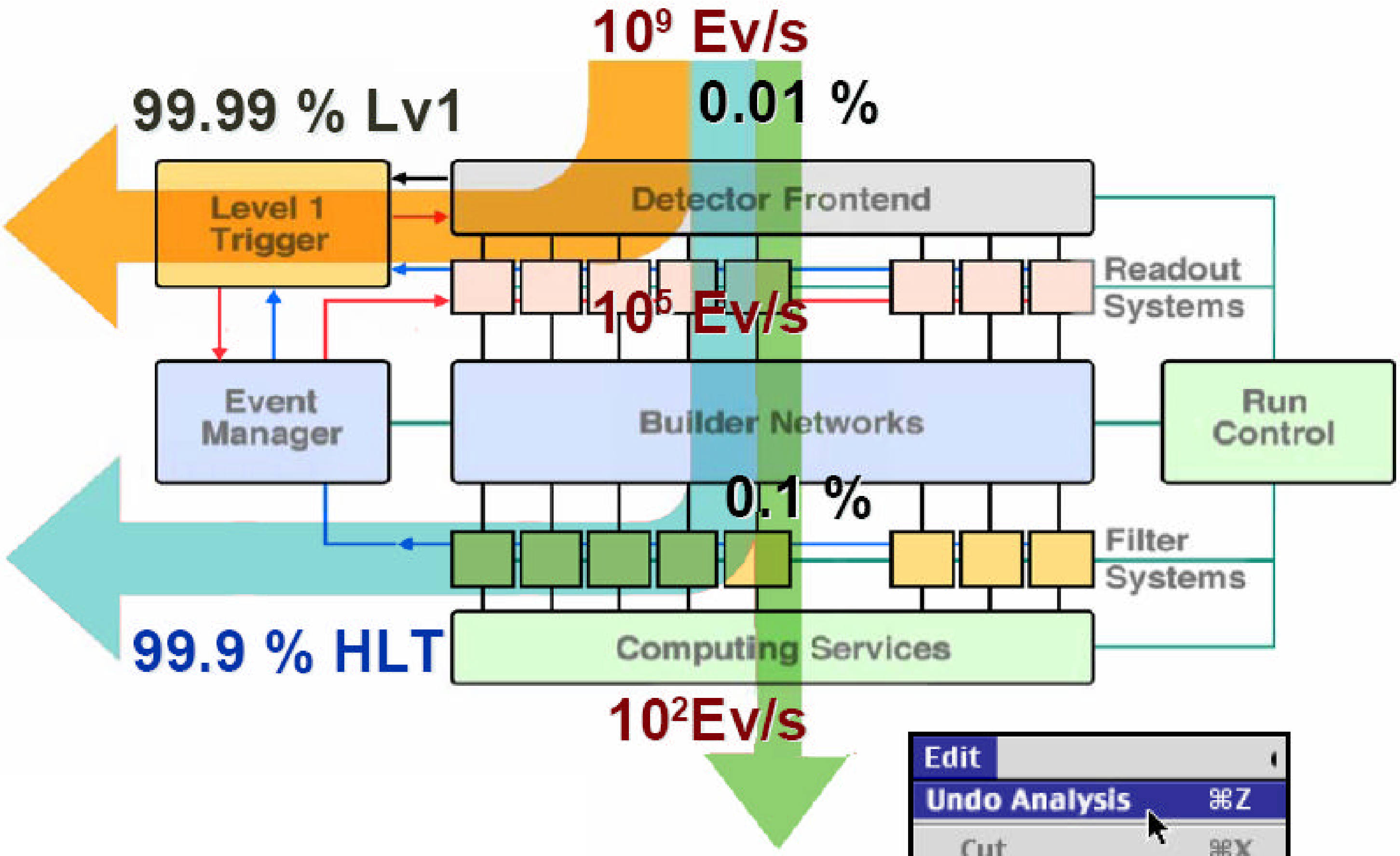


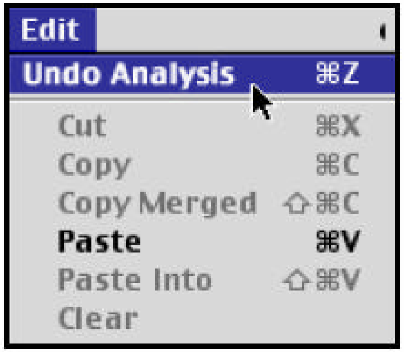
Overview T/DAQ parameters

	No.Levels Trigger	Level-1 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	Filter Out MB/s (Event/s)
ATLAS 	3	10^5 LV-2 10^3	10^6	10	100 (10^2)
CMS 	2	10^5	10^6	100	100 (10^2)
LHCb 	3	LV-0 10^6 LV-1 4 10^4	$2x10^5$	4	40 ($2x10^2$)
ALICE 	4	Pp-Pp 500 p-p 10^3	$5x10^7$ $2x10^6$	5	1250 (10^2) 200 (10^2)

Trigger: always remember this!







- Courtesy P. Sphicas

Summary of today

- LHC
  - → challenging conditions for (precision) measurements
    - High luminosity often need → pile-up events in pp
- Detectors
  - → optimized for various categories of signatures
    - → non-exclusive
  - → very complex systems
    - up to 10^8 electronic channels, huge size, ...
  - → Assembly in progress (construction often finished)
  - → Task ahead: commissioning
- Operation
  - → LHC is more like a facility
    - Like sharing of beam time in fixed target programme
  - → Optimisation between different running needs TBD

Summary of Monday and Tuesday

- Huge and very diverse LHC physics potential
  - → Impact on our knowledge about nature's secrets in the new century / millennium
- Need excellent machine and detectors to exploit this potential
  - → Machine and experiments are NOT independent
  - → Commissioning will take some time ...
- Now let's move on towards real interface issues
  - → Tomorrow: Ralph Assmann on the LHC machine
  - → Thursday: Emmanuel Tsesmelis on the experimental caverns
  - → Friday: Daniela Macina on interface