Collider Particle Physics
- Chapter 10 -

LHC: accelerator and detectors

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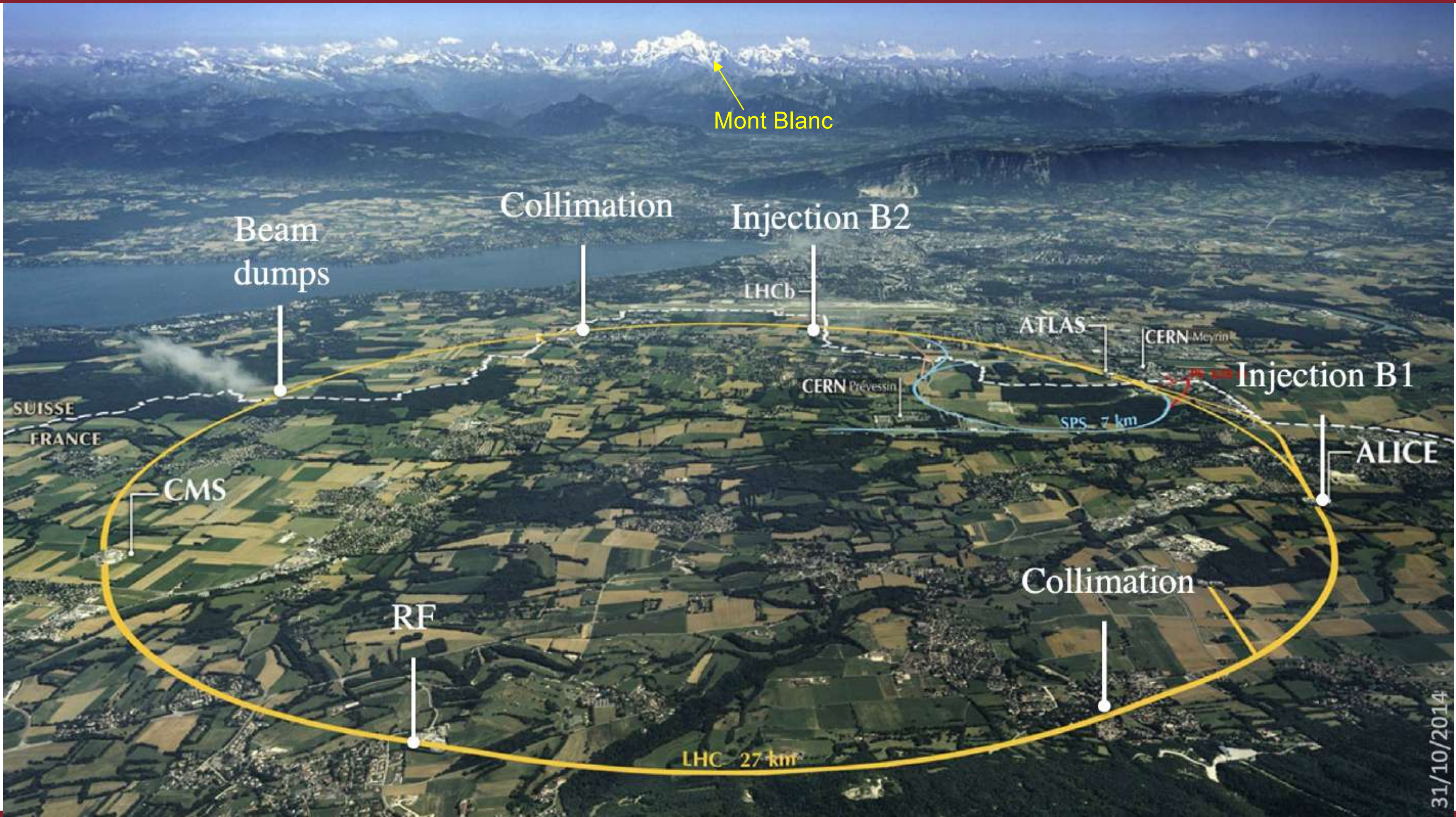
Chapter Summary

- LHC collider overview
- LHC performances
- LHC detectors
- ATLAS and CMS performances
- ATLAS/CMS trigger system
- Event display

LHC


Mont Blanc
Collimation
Injection B2
Beam
dumps
LHCb
ATLAS
CERN Meyrin
Injection B1
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
Collimation
RF
LHC 27 km
31/10/2014

LHC accelerator complex

Few interesting facts

9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.

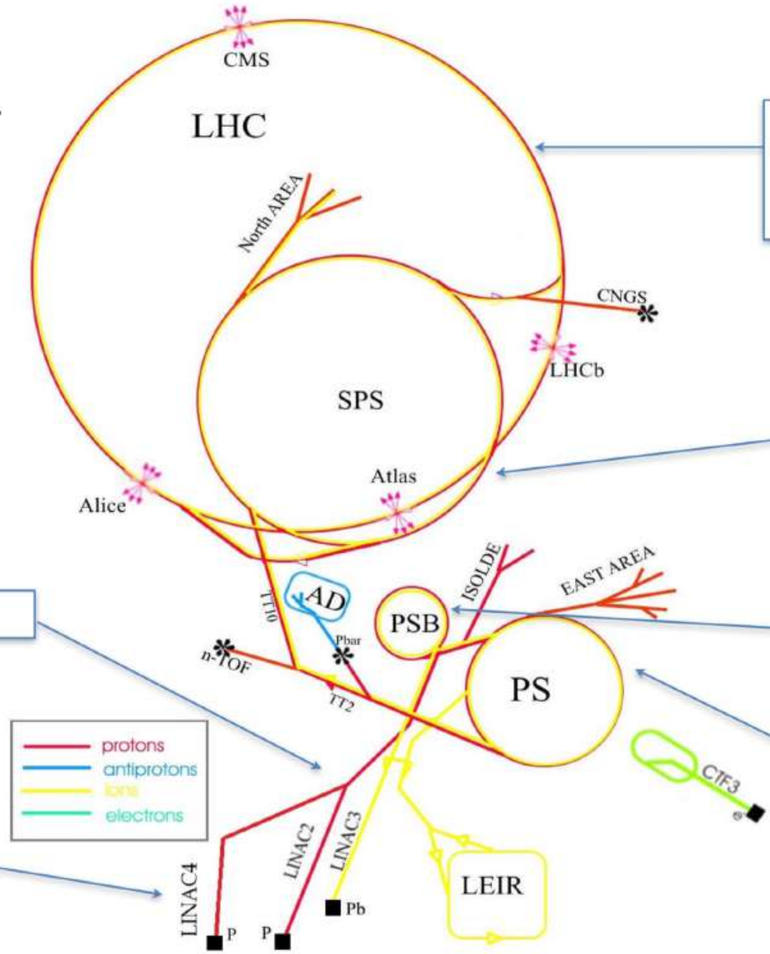
Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 Billion protons. Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.

Accelerated at 50 MeV in a LINAC

Hydrogen (gas) is ionized in a duoplasmotron.

First accelerated with a RF quadrupole at 750 keV.



Ramped to 7.5 TeV in the LHC
The maximum number of bunches (2808) not reached at Run 2 is limited by the injection kickers (~1 μs) and by the beam dump extraction (~3 μs)

SPS accelerates protons to 450 GeV, bunches before injection in the LHC.

The booster accelerates protons at 1.4 GeV.

PS brings them to 26 GeV, it is in the PS that bunches are formed with a 25ns spacing.

LHC Collider: the tunnel

LHC parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per direction
Energy, protons*	6.5 TeV (6.8 TeV in 2022)
Energy, ions	2.56 TeV/u (**) (record: 6.8 TeV/u in 2022)
Peak magnetic dipole field	7.74 T
Distance between bunches	~7.5 m
Luminosity (protons)	Peak Luminosity: ~ 1.2×10^{34} cm^{-2} s^{-1} (record: 2.6×10^{34} in 2022)
No. of bunches per proton beam (design value)	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11 245
Number of collisions per second	1 billion

(*) Design value: 7 TeV
(**) Energy per nucleon

Large Hadron Collider timeline

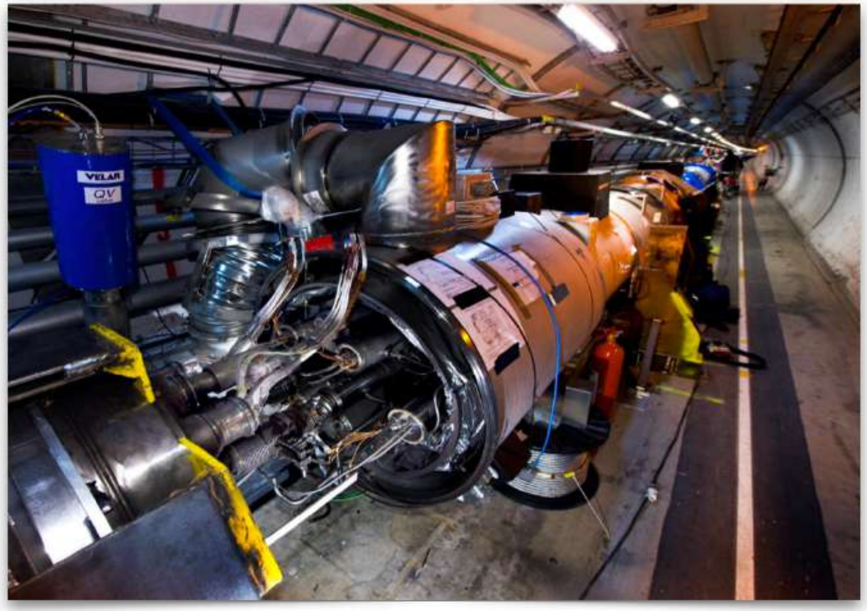
LHC time table:

- **Early 1980's:** first ideas about a multi-TeV proton collider at CERN
- **Oct 1990:** ECFA workshop on LHC in Aachen
- **16 Dec 1994:** CERN council approves the LHC
- **Feb 1996:** approval of ATLAS and CMS
- **Apr 1998:** start civil engineering
- **7 Mar 2005:** first dipole magnet installed
- **26 Apr 2007:** last dipole installed
- **10 Sep 2008:** first circulating beams
- **Oct 2009:** first pp-collisions

Not precisely the expected start …

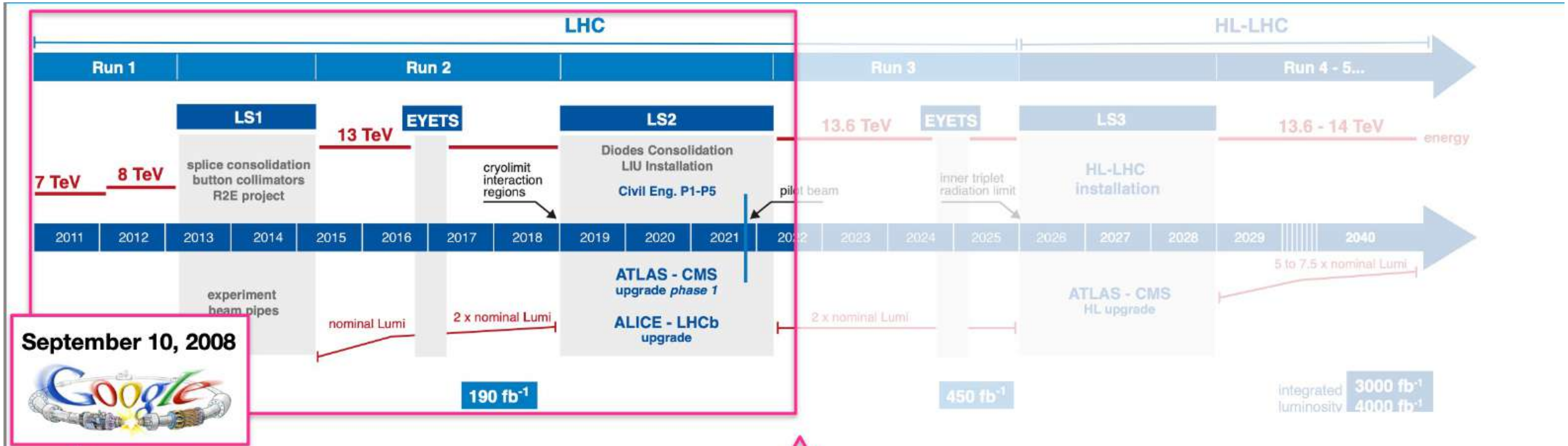
The Sun 1 September 2008

19 September 2008



… not the end of the world, but 700 m damaged area with 39 dipoles and 14 quadrupoles and beam vacuum affected over 2.7 km, 1 year repair and LS1 to consolidate interconnections!

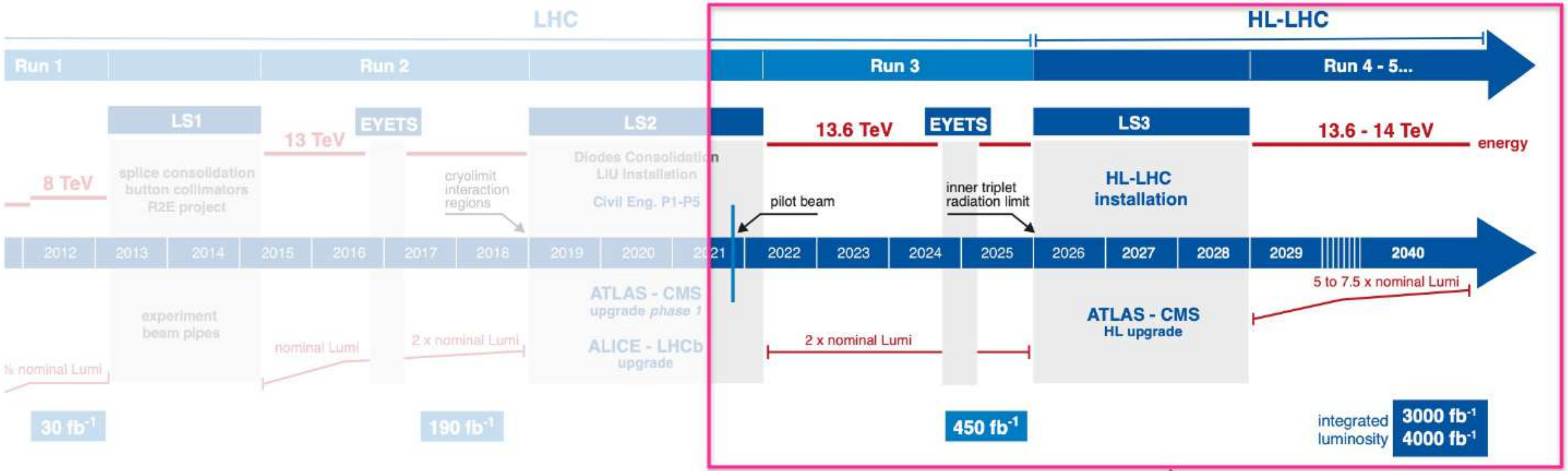
10 years of LHC

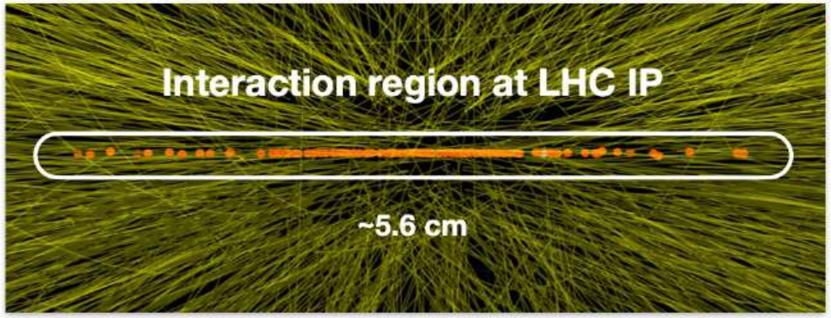


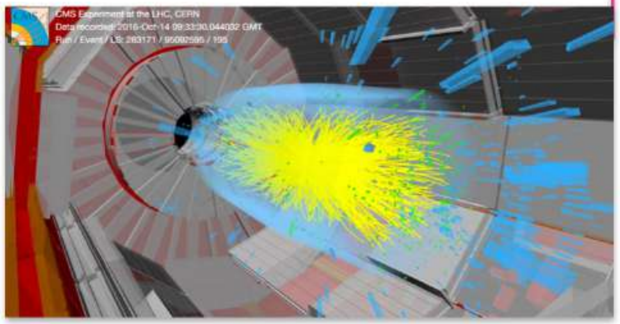
We are here!!

The day the world switched on to particle physics

The next 20 years of LHC: towards HL-LHC







Higher intensity comes at a cost:

At Run 2 average inelastic collisions per bunch crossings (Pile Up) was approximately 40.

Expected PU at HL-LHC **140-200**

Start of Run3: July 5th 2022

Run 3 started at 13.6 TeV !!

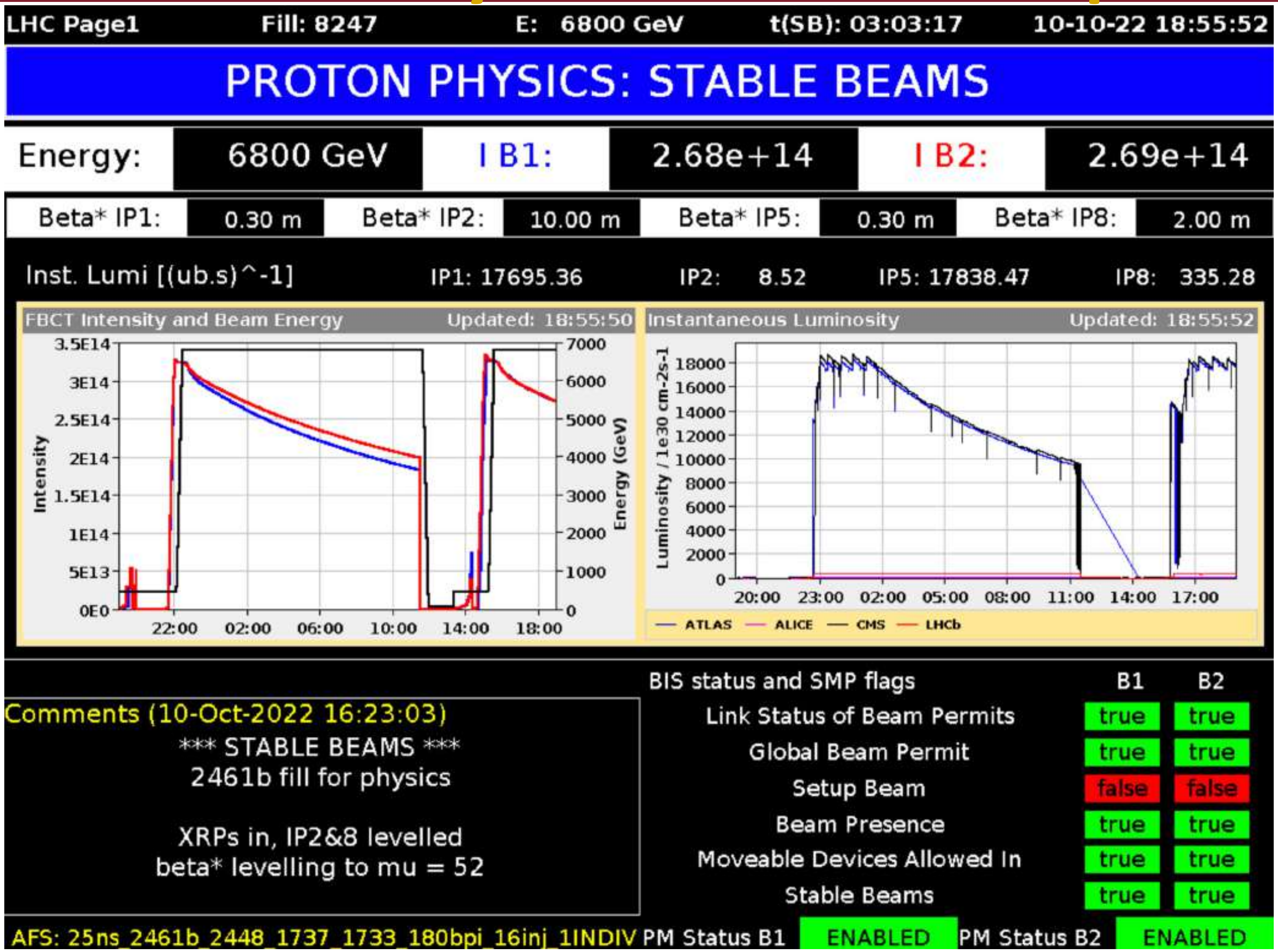
News and pictures from yesterday at CERN

The third run of the Large Hadron Collider has successfully started

A round of applause broke out in the CERN Control Centre on 5 July at 4.47 p.m. CEST when the Large Hadron Collider (LHC) detectors started recording high-energy collisions at the unprecedented energy of 13.6 TeV

LHC performances

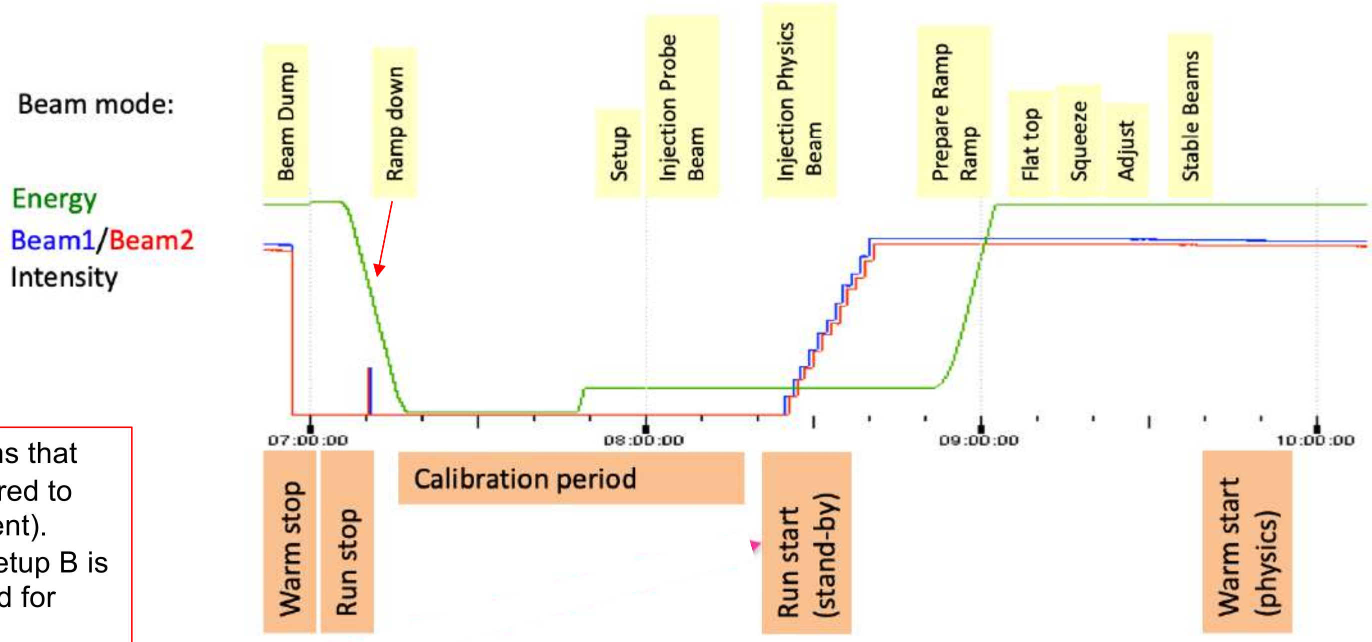
LHC cycle in 2022: example



LHC page 1

This what you can see in several screens around CERN …
and in the control rooms of course

LHC cycle: details



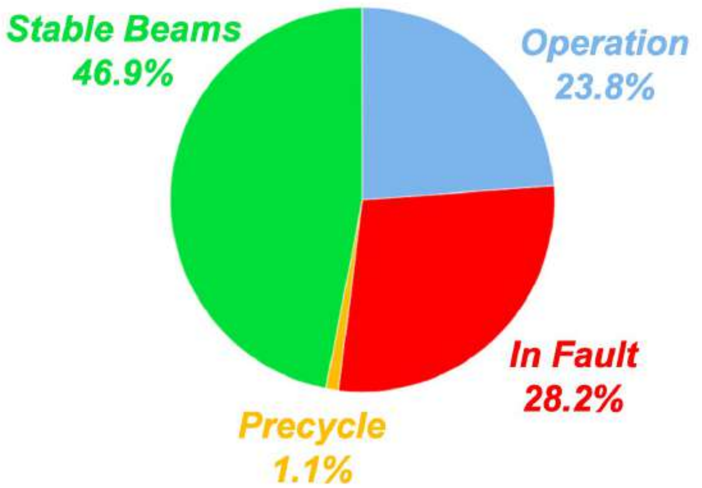
Ramp down means that the B-Field is lowered to reach 0 T (no current). Then, during the setup B is set to value needed for 450 protons.

Time estimates for 2017/2018 (based on Fill 6343, to be updated for Run 3)	
Injection Physics Beam to Prepare Ramp	~40 min
Ramping	~20 min
Squeeze	~15 min
Adjust (plus levelling to target Lumi)	~10-20 min
Running with levelled Lumi	~ 3 hours
Dump to Stable Beams (fastest turn-around in 2017)	**> 2 hours**
Precycle	~30 min

LHC performance in 2022

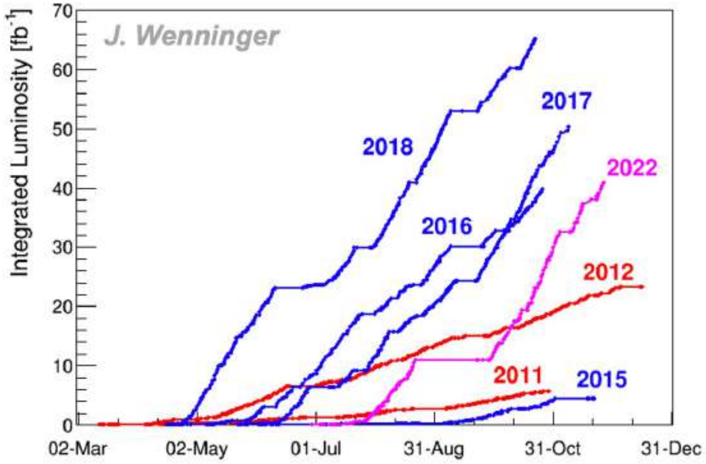
Target achieved!

Statistics from 20th September (w/o MD):

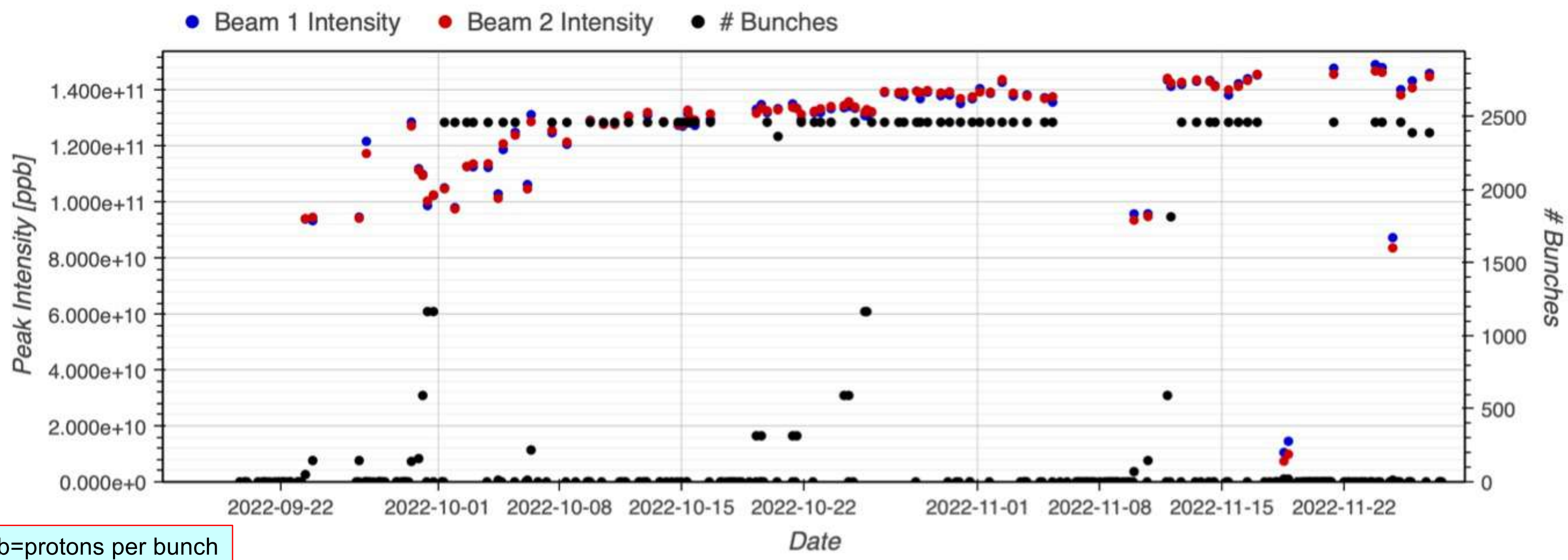


Machine availability: 72.8%

Remarkable performance for first year after Long Shutdown with > 40fb^{-1} delivered!



LHC 2022 parameters: # of bunches and ppb



ppb=protons per bunch

$$\mathcal{L} = \frac{k \cdot N^2 \cdot f}{4\pi \cdot \beta^* \cdot \epsilon} \cdot F$$

N = *No. particles per bunch*

K = *No. bunches*

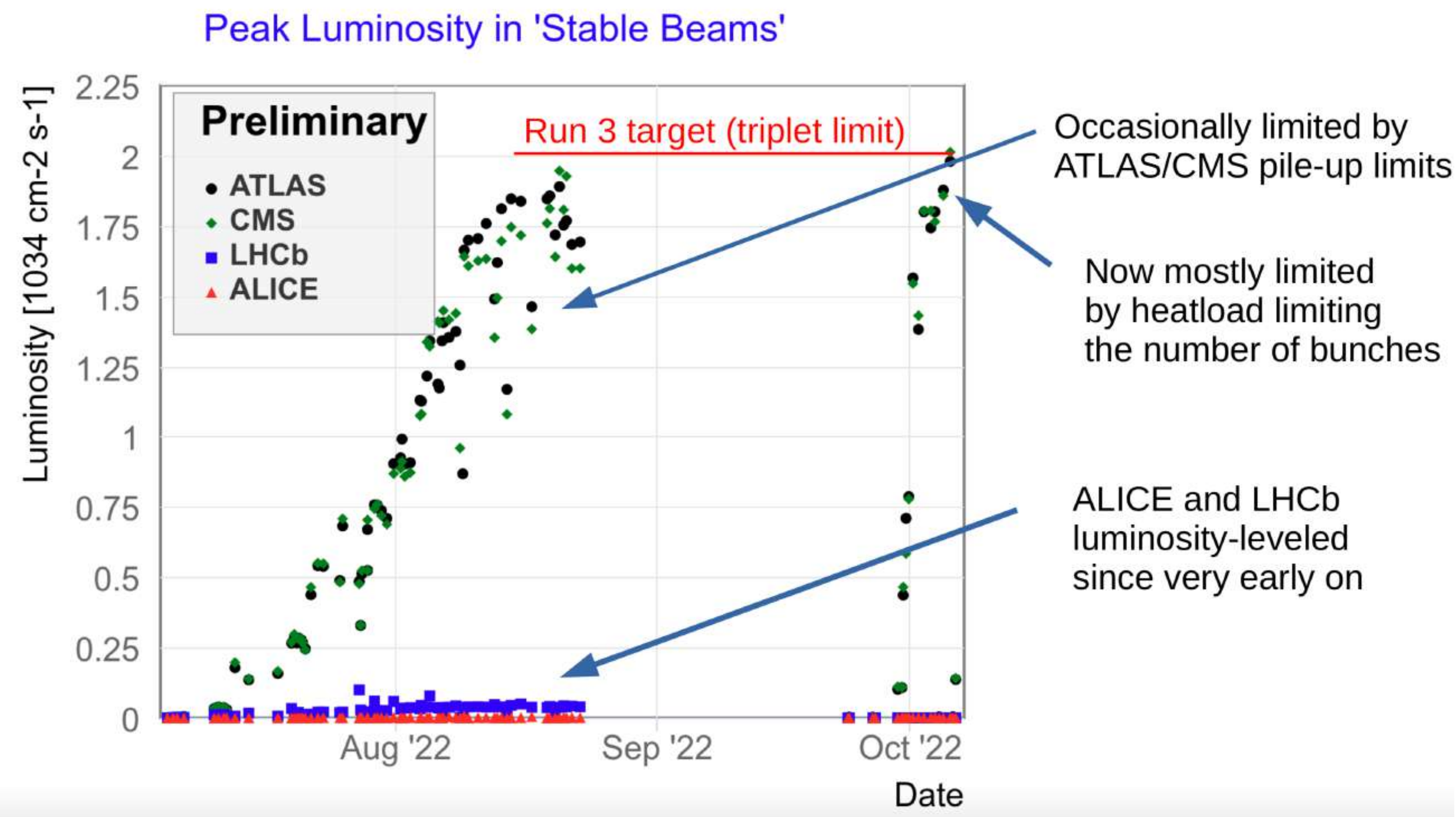
β^* = *beta-function at IPs*

ε = *transverse emittance*

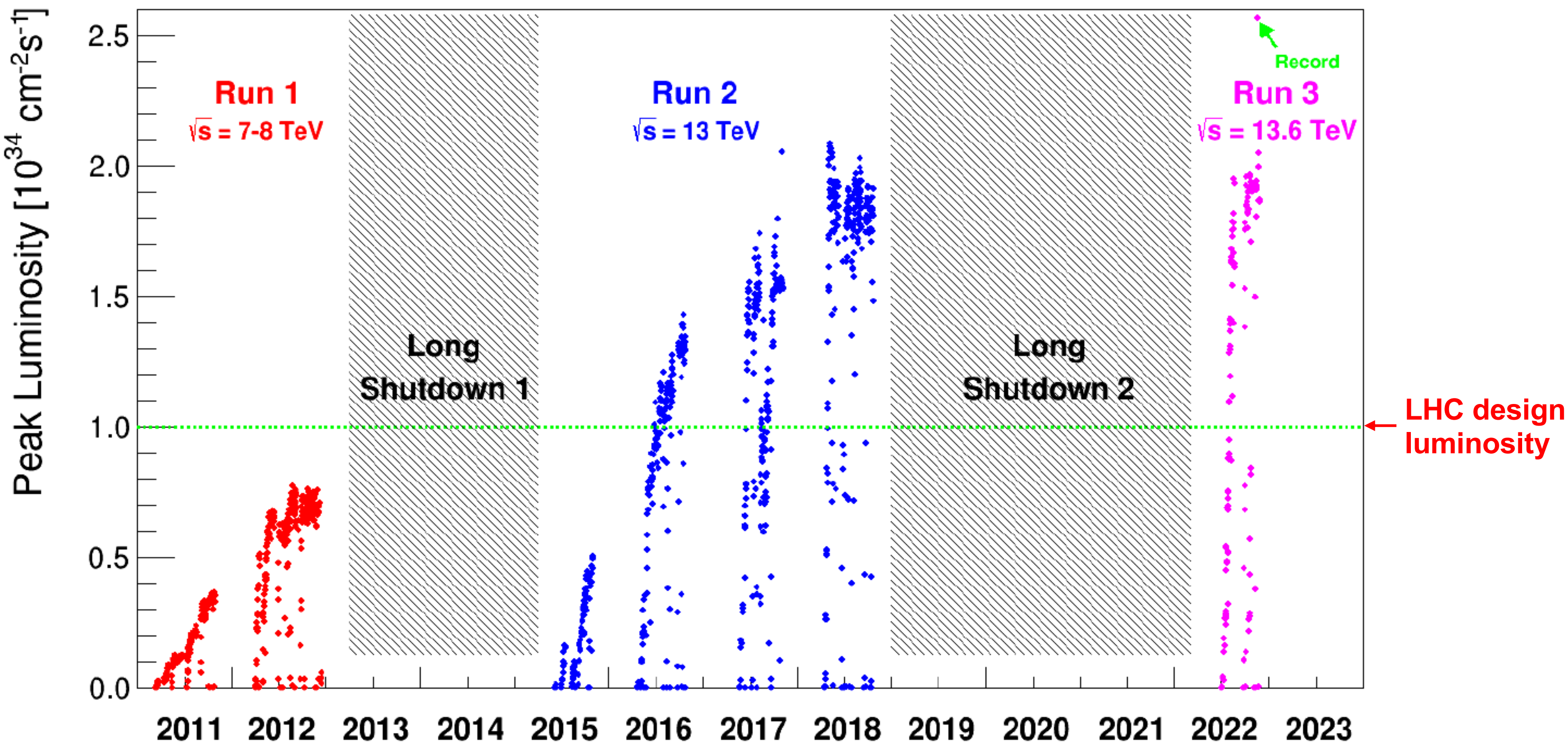
f = *revolution frequency*

F = [0 …1] *depends on the crossing angle*

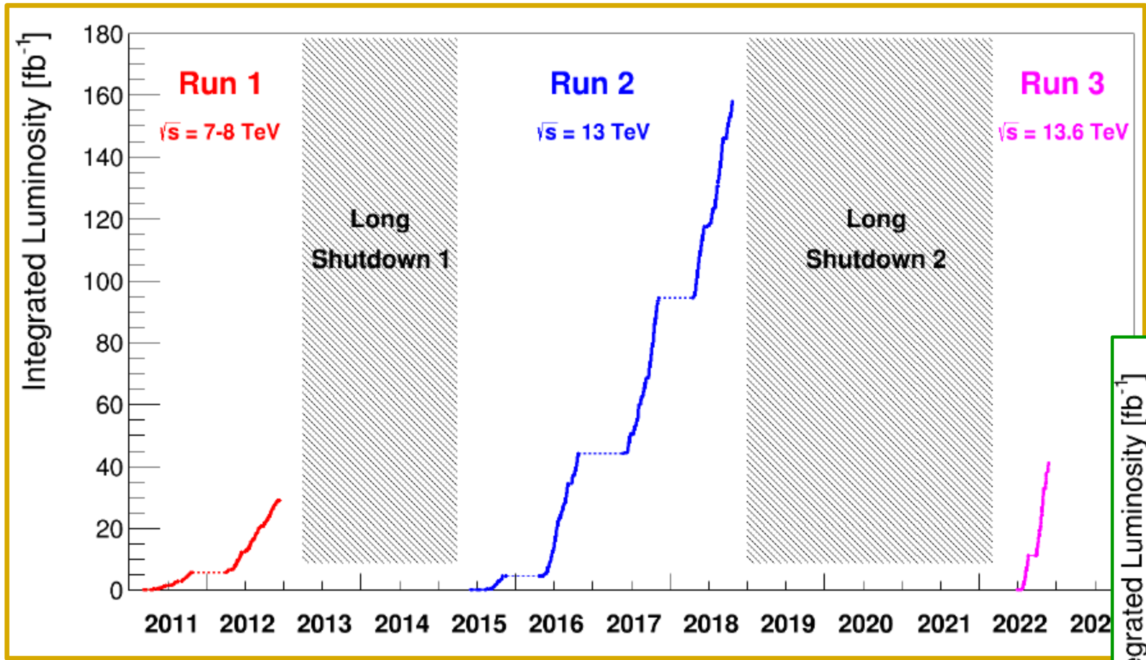
Luminosity ramp-up



LHC: peak luminosity along the years

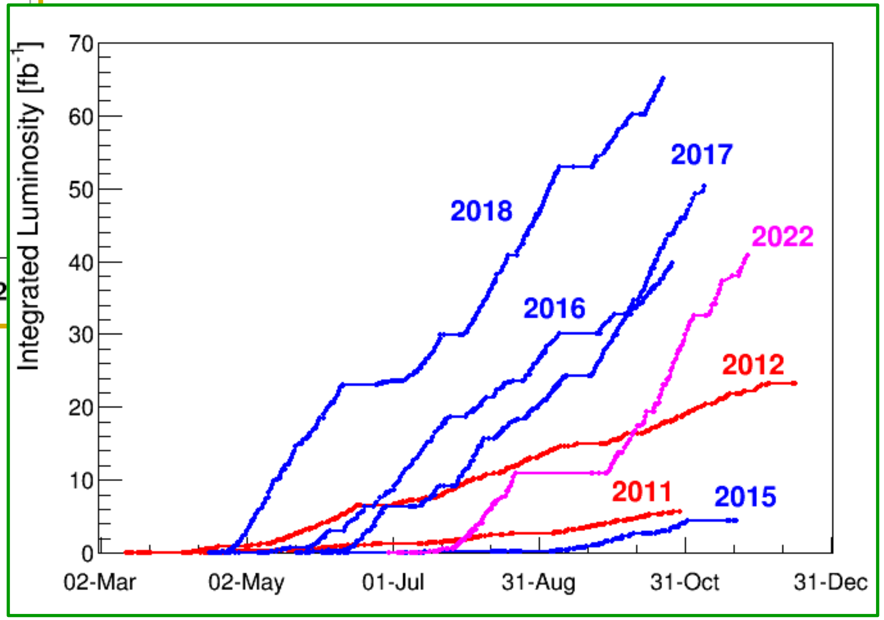


LHC: integrated luminosity along the years

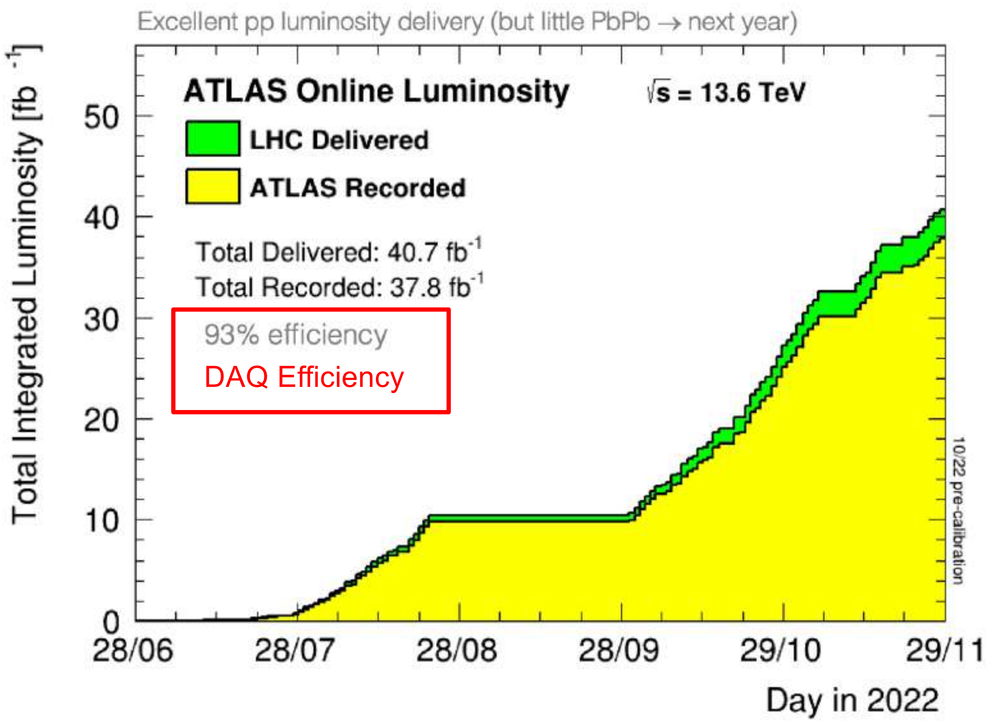


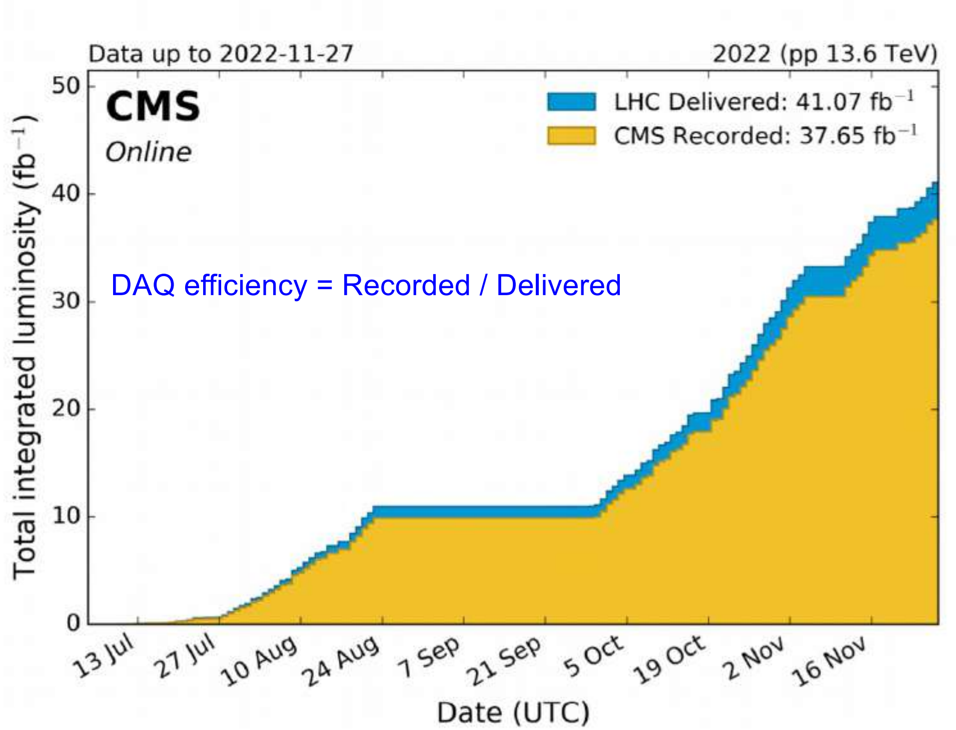
July 5th
Start of Run 3 physics

November 28th
End of 2022 run



ATLAS and CMS luminosity in 2022

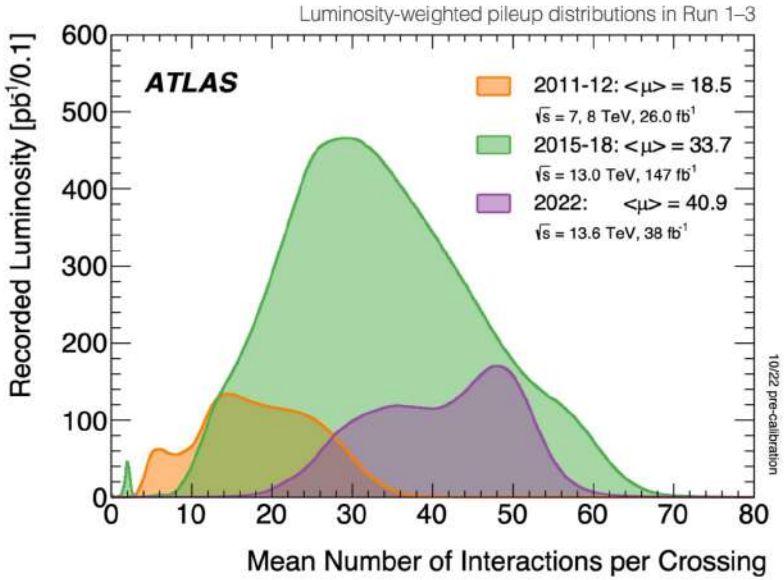


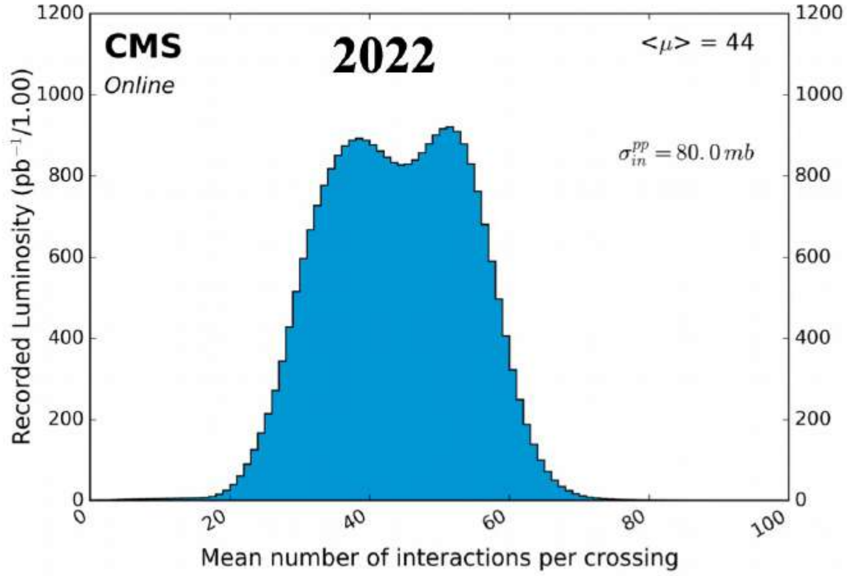


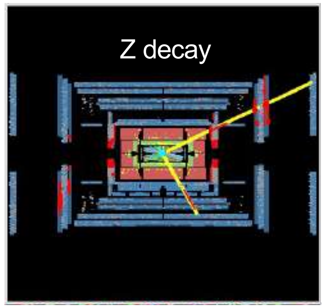
DAQ efficiency: it takes into account DAQ deadtime, automatic resynchronisations of some part of the detector and all kind of problems (hardware and/or software) that prevent the experiment to take data.

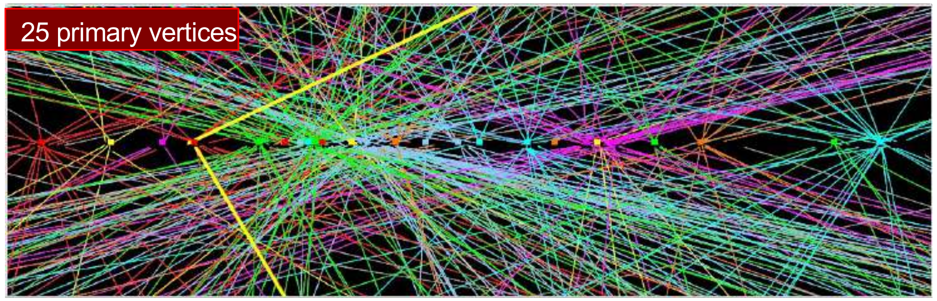
ATLAS and CMS pile-up

Pile-up = mean number of proton interactions per crossing









$$PU = \mathcal{L} \cdot \sigma \cdot \tau =$$

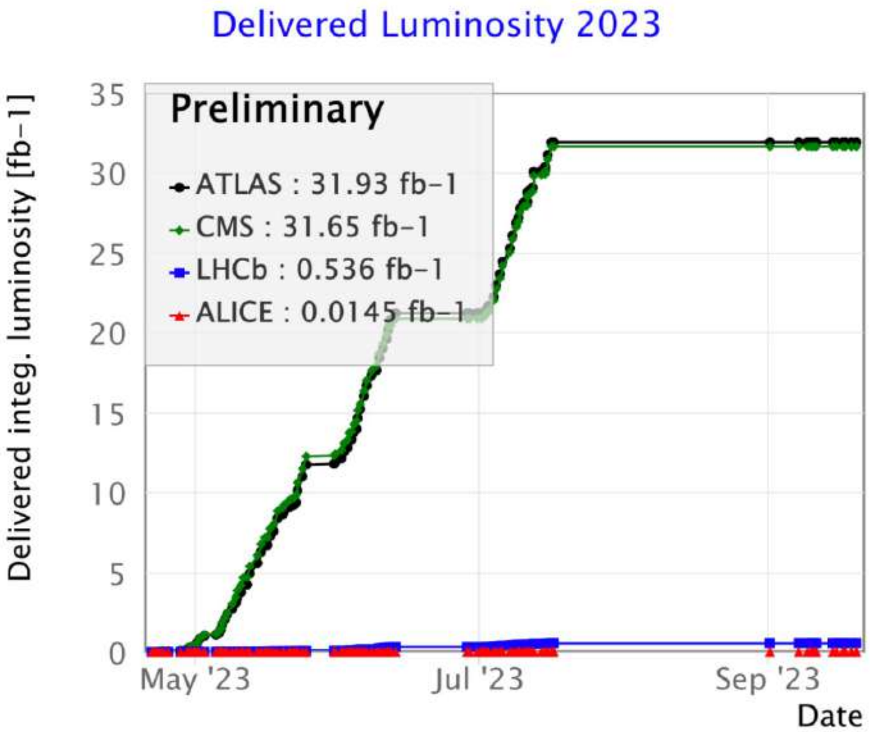
$$2 \cdot 10^{34} \times 80 \cdot 10^{-27} \times 25 \cdot 10^{-9} = \mathbf{40}$$

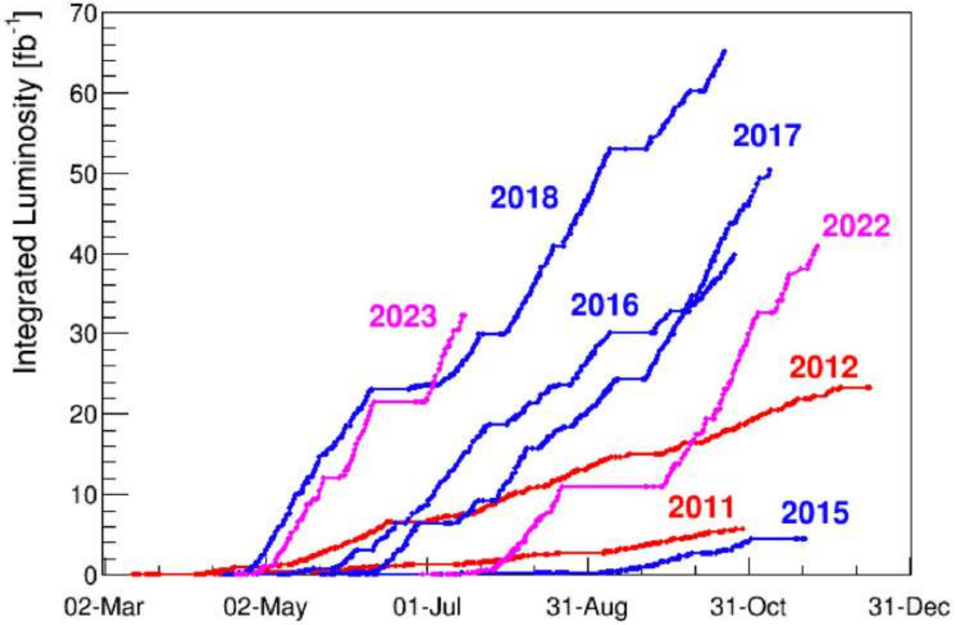
[*actually, the pile up depends on the number of protons per bunch*]

Let’s open a parenthesis

WHAT ABOUT 2023?

LHC: integrated luminosity in 2023





2023: very good slope until the IR8 triplet incident

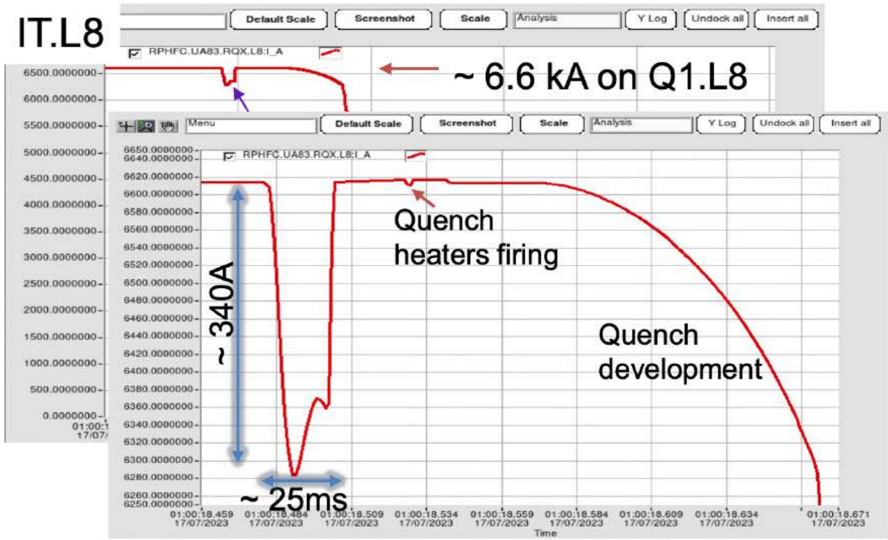
LHC had an incident on July 17th. It took until end of August to fix it and then the rest of the year was dedicated to high-beta run and lead-lead (Heavy Ions) collisions.

July 17th: electrical glitch

Monday, 17 July, 1 a.m.: ROOT CAUSE

The reason for the electrical glitch that caused the safety systems in the LHC to dump the beam and several magnets to quench was found: a tree on the Swiss side (about 55 km from CERN in the Canton of Vaud) fell on the power lines and disrupted the power system.

1 am : At stable beam in the LHC since 9 min, an electrical glitch occurred on the RF and magnet circuits, dumping the beam and triggering the protection system of a few LHC circuits, which IT.L8.



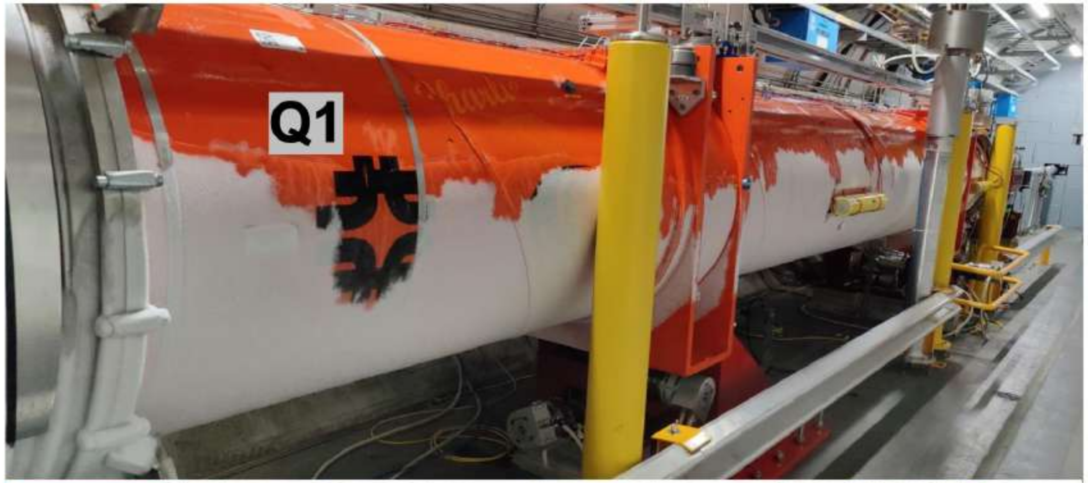
Signals measured by the quench detection system (QDS) are similar for a large current variation or a symmetrical quench (quench development in two adjacent coils). For the magnet protection, the quench heaters are triggered.

Similar event occurred in Aug 22, without damage.

Quenching is the process whereby there is a rise in temperature in the magnet coil windings. Therefore the magnet is no longer superconducting.

IT.L8 is the Inner Triplet (special quadrupoles to squeeze the beam at an interaction point) at point 8 (LHCb)

17th July event: electrical glitch and consequence



30s after the quench, a significant leak appears in the vacuum vessels of IT.L8 assembly.

8 hours after the quench, the pressure in the vacuum vessels is at 1bar and the average temperature of the cold masses is 150K

Leak location

Confirmed in the cold masses volume, the helium leak must be localised over the 40m of the triplet assembly.

Microphones and accelerometers were installed below the interconnection bellows.

With the pressurisation of the cold masses, accelerometers in Q1-Q2 interconnection measured significant vibration, indicating a possible position of the leak

Other investigation : X-ray of bellows

LHC criogenic scenarios

As the leak is in the IT cold mass volume, it possible to isolate it from the QRL. →

The LHC cryogenic systems are divided into 8 equivalent cryoplants around the LHC ring and each of them supply helium to superconducting magnets over 3.3 km via a cryogenic distribution line (called **QRL**) installed underground in parallel to magnets.

#	Opening what ?	How long ? *(from 24/07)*	Cryo status and consequences	Risks *(if no sector warm-up)*
A	W bellow only	< 3 days	ARC @ 20 K→30 K QRL @ 20 K→ 100 K	Helium circuit pollution + IT/QRL vac barrier condensation
B	IT cold mass interconnect bellows	< 10 days *(ARC cooldown before 20 days)*	ARC @ 20 K → 60 K QRL @ 20 K → 250 K → Reconditioning of the IT + D1 needed (without QRL)	+ QRL mechanical damage during unexpected transients (bellows) **Retained scenario**
C	IT cold mass interconnect bellows	> 10 days *(ARC cooldown after +20 days)*	ARC TTmax > 80 K QRL > 250 K → Reconditioning of the IT + D1 needed (without QRL)	+ Magnet interconnect mechanical damage due to thermal dilation (PIMS, bellows, shields, etc.). → **Risky situation, sector warmup* highly recommended**
D	QRL lines or magnet removal	People safety and magnet integrity cannot be guaranteed → **Sector warm-up* mandatory** (baseline)		

**Sector warm-up = 4 weeks . Sector cool-down = 5 weeks*

← It meant no more collisions in 2023

Helium at 4.5 K flowing through the QRL joins the LHC magnets at the many connection points over the line's 27 km.

LHC variation length with temperature

Let's suppose that no special materials were used in the LHC machine. We **can calculate the hypothetical changes in the lengths due to the low temperatures.**
We will take, on average, as a thermal dilatation coefficient : $\alpha \approx 10^{-5}\ K^{-1}$. The dipole length is 14,343 m at 300 K, so when temperatures reach 1,9 K we will get,

$$\Delta L = L_0 \cdot \alpha \cdot \Delta T \quad \Rightarrow \quad \Delta L = 14{,}343 \cdot 10^{-5} \cdot (1{,}9 - 300) \quad \Rightarrow \quad \Delta L \approx -0{,}043\ m$$

So, **the contraction is more than 4 cm**, and taking into account that there are 1232 dipoles,

$$\Delta L_T \approx 1232 \cdot (-0{,}043) \approx -53\ m\ (!)$$

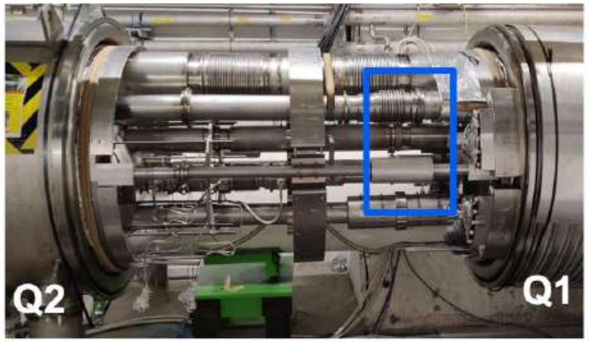
But taking into account all the magnetic multipoles, **the total contraction over the ring as a whole is close to 80 m**, and special devices (bellows and expansion loops) in the interconnections between the magnets compensate for this.

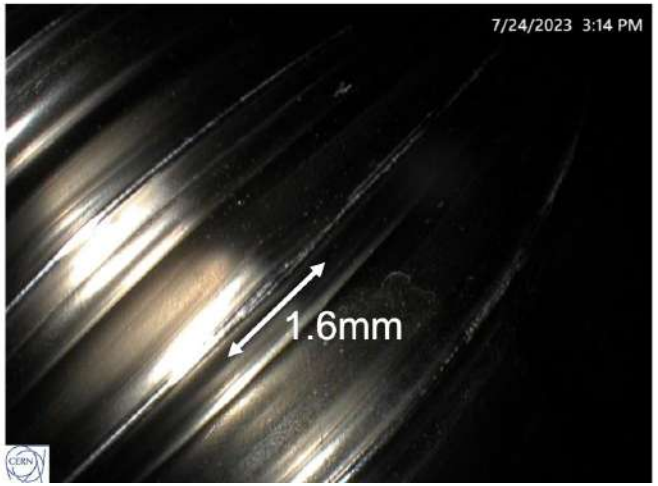
Obviously, the materials used in LHC must have a very controlled behaviour at low temperatures in order to avoid misfunctions and errors. However, it's imposible to avoid thermal contractions completely, so engineers have to take it into account during the assembly of the different pieces which form the structure of the machines.

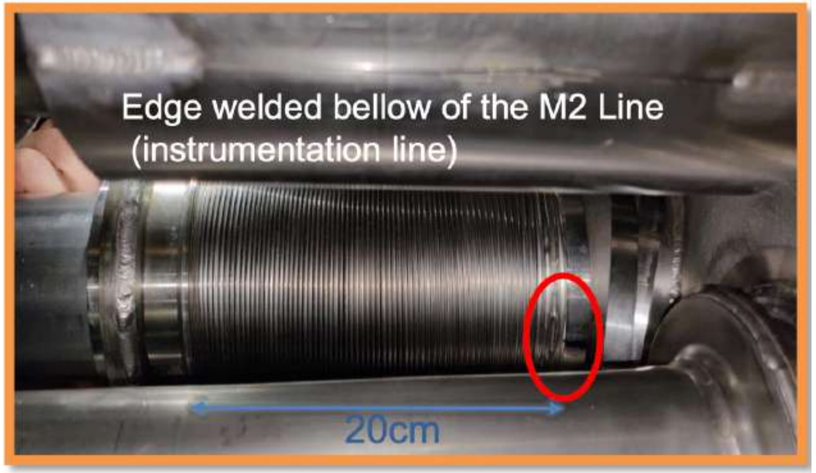
24th July: start of countdown

- Complete warm-up of the IT magnets ✓
- Electrical lock out ✓
- Depressurisation of all cryogenics lines ✓
- Injection of dry air in the interconnections ✓

→ Green light to open the IC







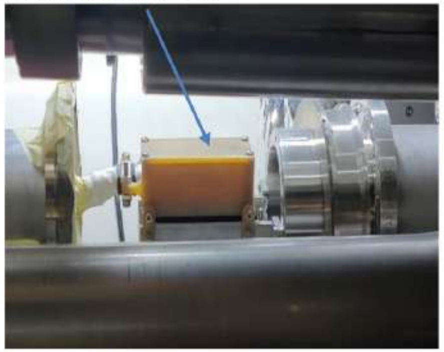
Intervention ongoing

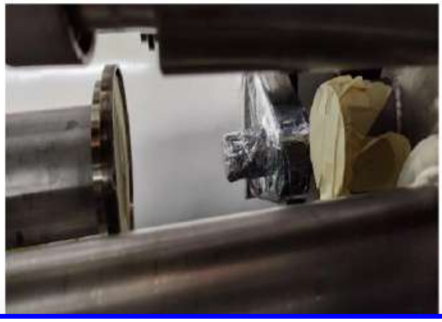
Bellow removal

Tuesday 25th

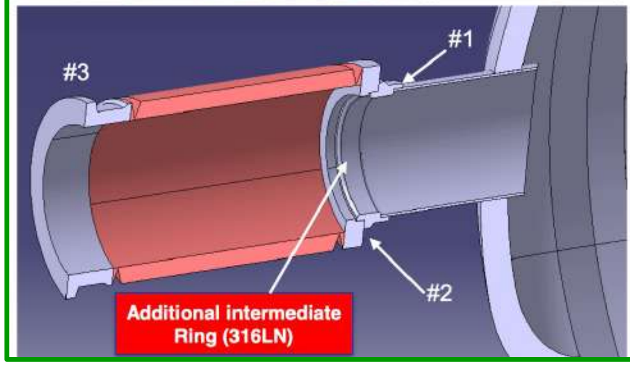
In IT.L8, the M2 bellow is removed.

Connection box
of instrumentation





Spare bellows welding



Wednesday 26th & Thursday 27th

The M2 bellows is an integral component of the as-delivered Q1 cold mass. In-situ replacement of the bellows requires a new strategy of welding at the interconnection.

First approach for weld execution was to insert a close-fitting ring into M2 tube inner diameter to avoid the installation of a gas inerting system (impossible to remove afterwards). However, irregularities in the M2 pipe geometry wrt the ring resulted in a root porosity appearing in the new weld – hence invalid for a pressure vessel. The new bellows and its weld to the M2 line had to be removed.

A new weld strategy was proposed with an intermediate ring first welded on the M2 tube allowing easy installation and removal of an inerting gas system.

#1 weld at intermediate ring was validated (endoscopy & leak test) before 2nd spare bellows installation.

#2 weld joins the new bellows to the intermediate ring

#3 weld joins the new bellows to the Q2 flange

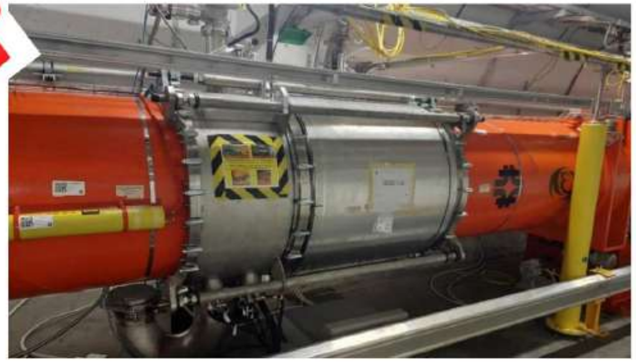
28th July: end of countdown

End of countdown

On Friday 28th, the Q1-Q2 interconnection is closed

→ Start of Insulation vacuum pumping & tightness checks

→ Start of cold mass purging



B	IT cold mass interconnect bellows	< 10 days *(ARC cooldown before 20 days)*	ARC @ 20 K → 60 K QRL @ 20 K → 250 K → Reconditioning of the IT + D1 needed (without QRL)	+ QRL mechanical damage during unexpected transients (bellows) ✓

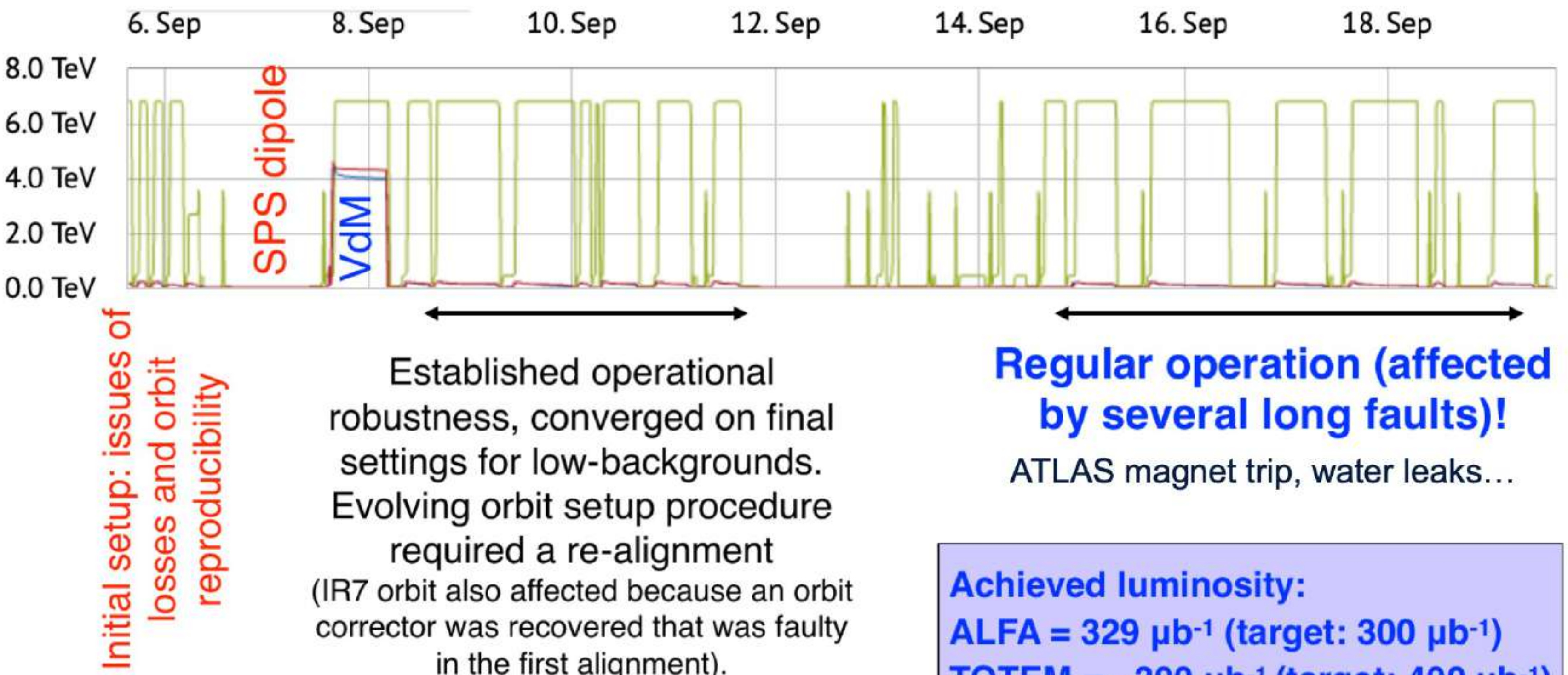
In total :

- IT magnet warm-up : 1 week
- Leak repair : 1 week
- Cool-down and reconditioning : 3.5 weeks
- ElQA and Powering : 0.5 weeks

➡ In total, 1 ½ month without beam in the LHC

Integrated Luminosity of High-beta run

Results of high-β run



Established operational robustness, converged on final settings for low-backgrounds. Evolving orbit setup procedure required a re-alignment (IR7 orbit also affected because an orbit corrector was recovered that was faulty in the first alignment).

Regular operation (affected by several long faults)!

ATLAS magnet trip, water leaks…

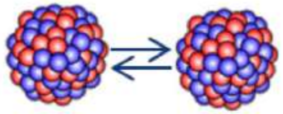
From LMC talk S. Redaelli

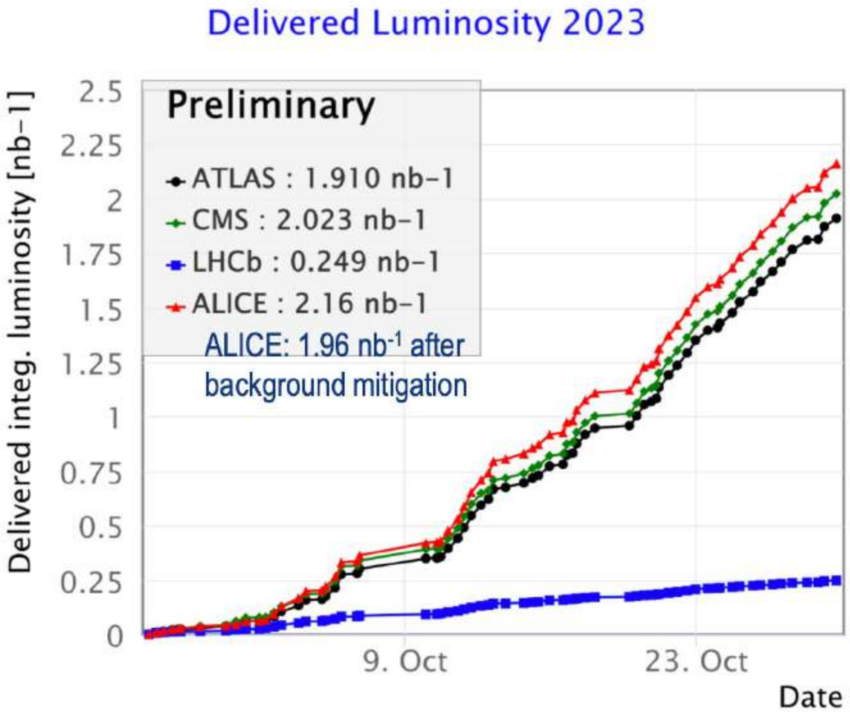
Achieved luminosity:
ALFA = 329 μb^{-1} (target: 300 μb^{-1})
TOTEM = ~300 μb^{-1} (target: 400 μb^{-1})

"soft physics" (total cross-section, etc …). ALFA detector is going to be dismounted, no more high-beta run in Run3

Heavy Ions integrated luminosity

Summary of 2023 luminosity production, Pb-Pb





- **Integrated luminosity below initial targets**
  - Suffered from several problems (beam losses, faults), and lower beam brightness than hoped for
- **In spite of problems, pending luminosity calibration, all experiments collected more data than in 2018**
  - ALICE got more data than in Run 1 + Run 2 combined

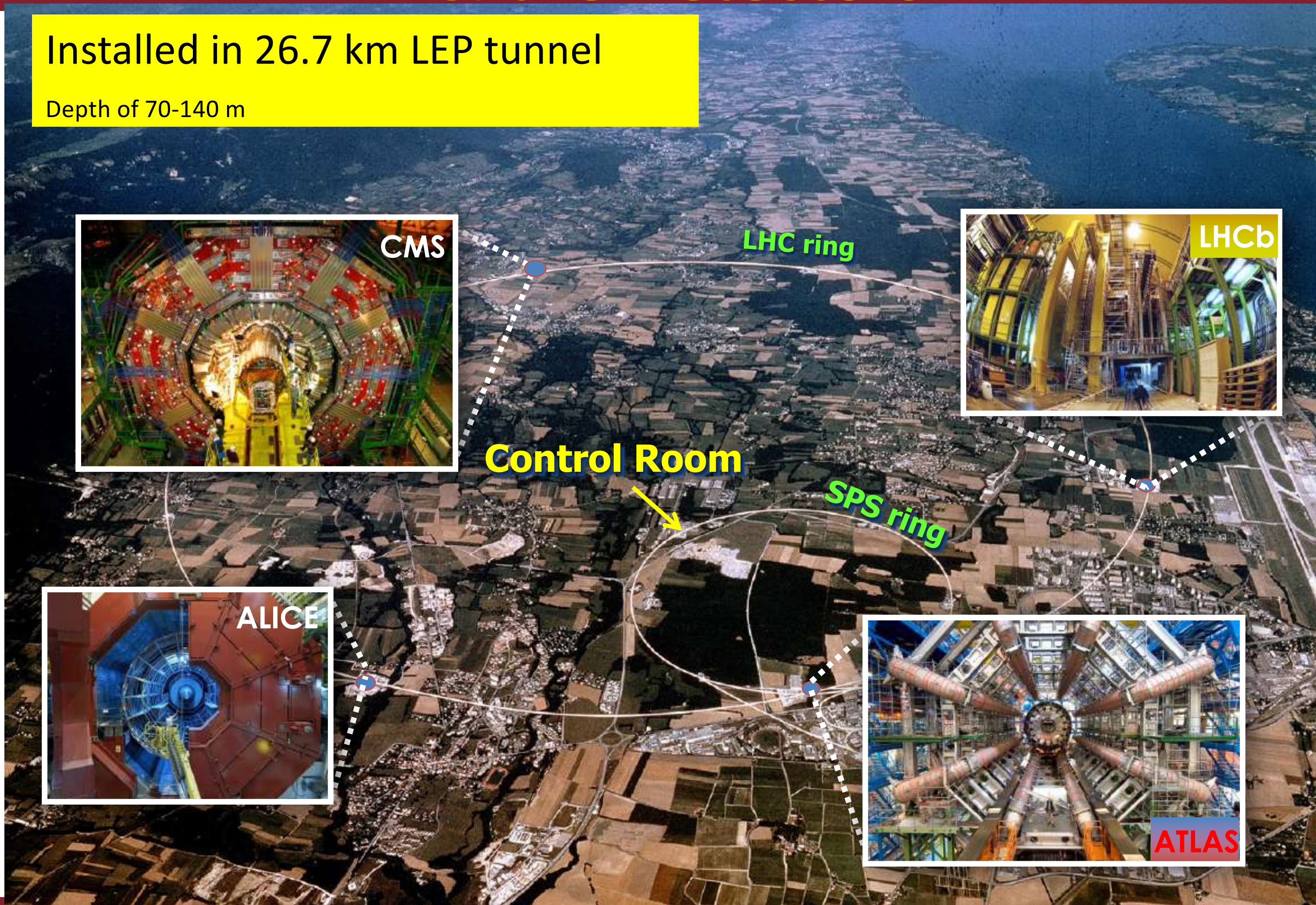
Comparison 2018:

ATLAS: 1.797 nb^{-1}
CMS: 1.802 nb^{-1}
LHCb: 0.235 nb^{-1}
ALICE: 0.905 nb^{-1}

Let's close the parenthesis }

LHC detectors

LHC: the Detectors

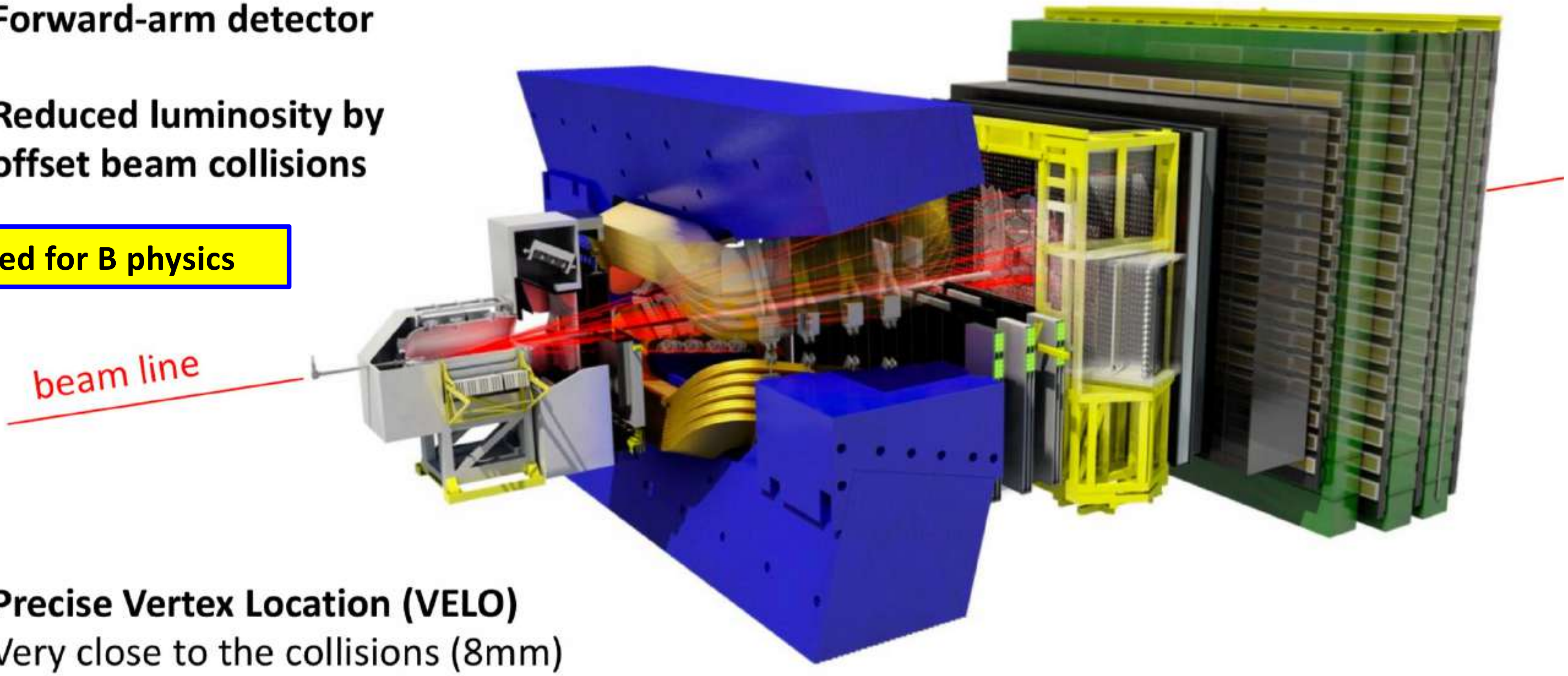


LHCb detector

Forward-arm detector

Reduced luminosity by offset beam collisions

❑ **it is specialized for B physics**



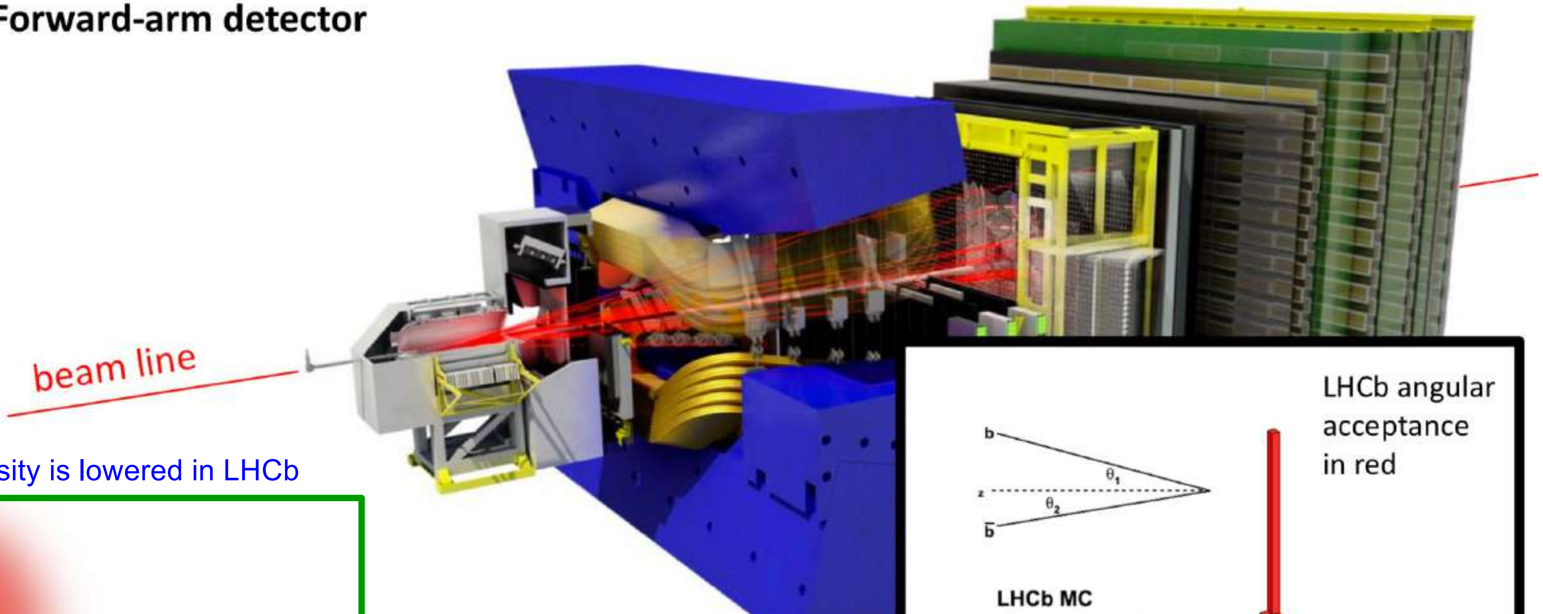
Precise Vertex Location (VELO)
Very close to the collisions (8mm)
→ must be moved away for safety every time beam is injected (!)

Excellent particle identification using Cherenkov radiation to measure particle speed

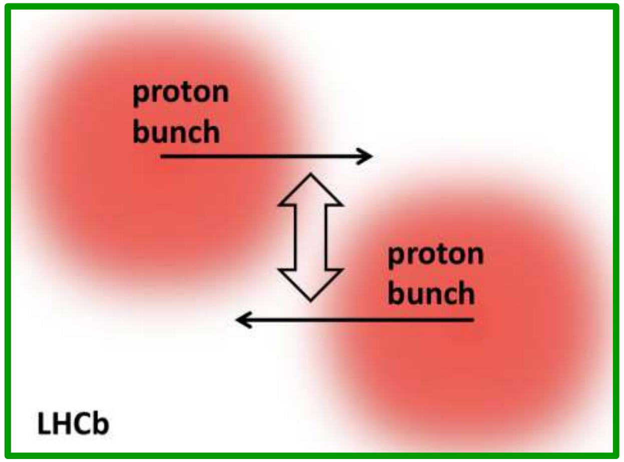
Powerful software-based trigger – make decisions using full event reconstruction

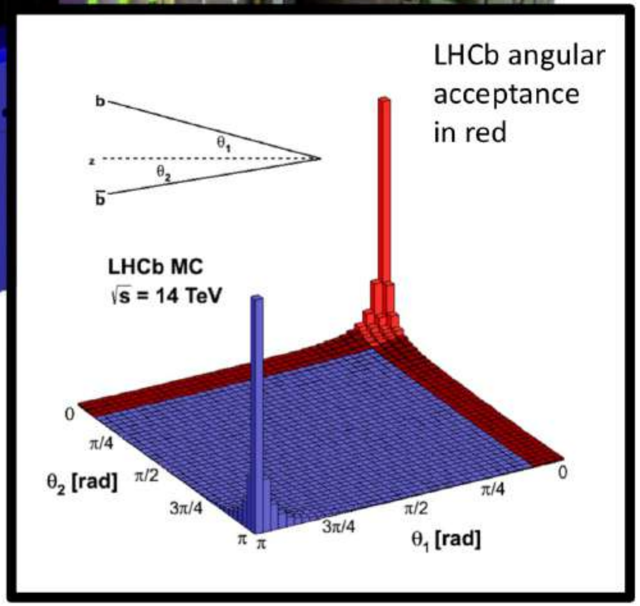
LHCb detector

Forward-arm detector



How lumininosity is lowered in LHCb

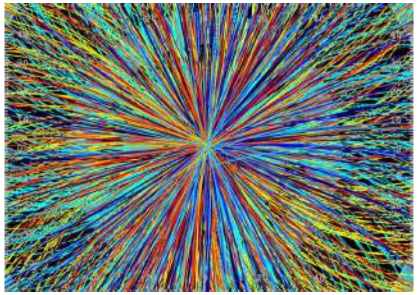




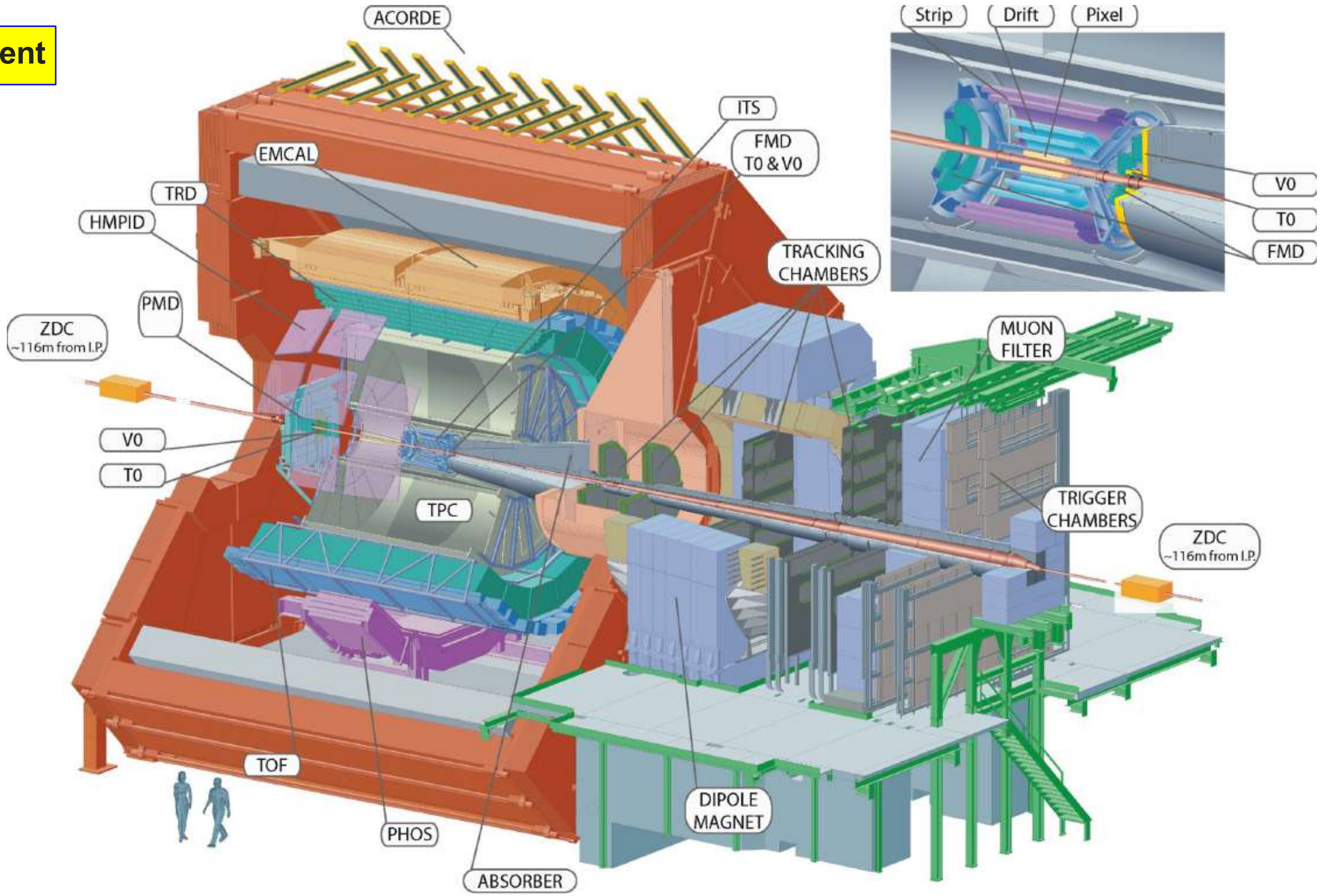
ALICE Detector

A Large Ion Collider Experiment

It is specialised for heavy ion collisions



A Pb-Pb collision in Alice.

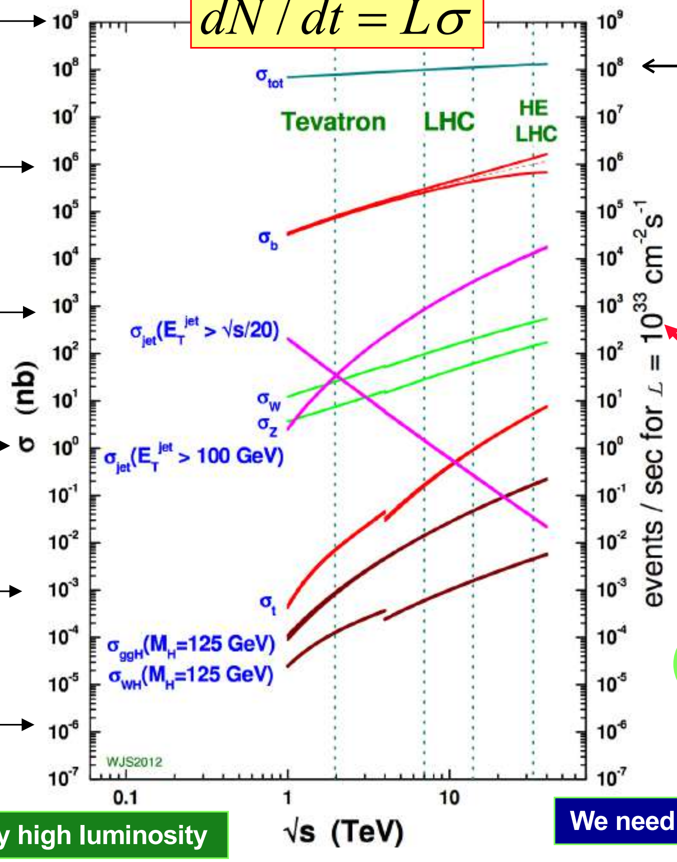


Production cross-section at LHC

proton - (anti-)proton cross sections

$$dN/dt = L\sigma$$

1 b=10^{-24} cm^2



- 1 mb ⟷ 10^6
- 1 μb ⟷ 10^3
- 1 nb ⟷ 10^0
- 1 pb ⟷ 10^{-3}
- 1 fb ⟷ 10^{-6}

⟷ total cross section: 10^8 evts/s (dominated by strong interaction)

Background is around here

(QCD bg)

⟷ max. read-out: ~ 10^3 evts/sec

$\mathcal{L}$(2016)=10^{34} cm^{-2}s^{-1} ➔ x 10 the ev/s

⟷ O(1) top-event/sec

⟷ O(1) Higgs/min

Rare events/interesting events are around here

We need a very high luminosity

We need a very high background rejection capability

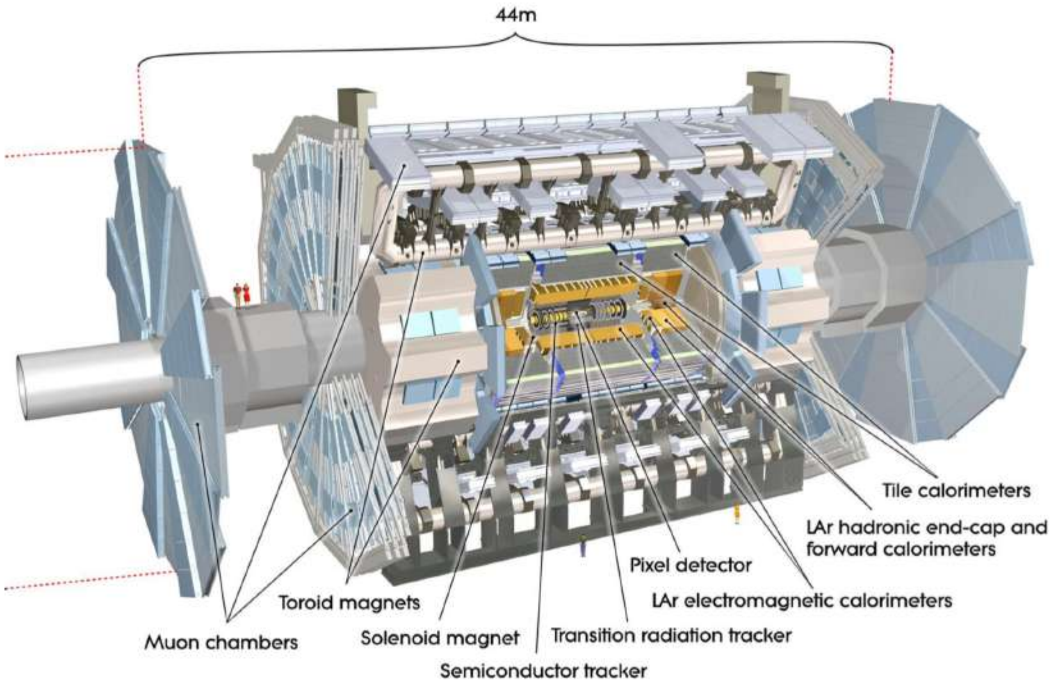
General Purpose Detectors: ATLAS and CMS

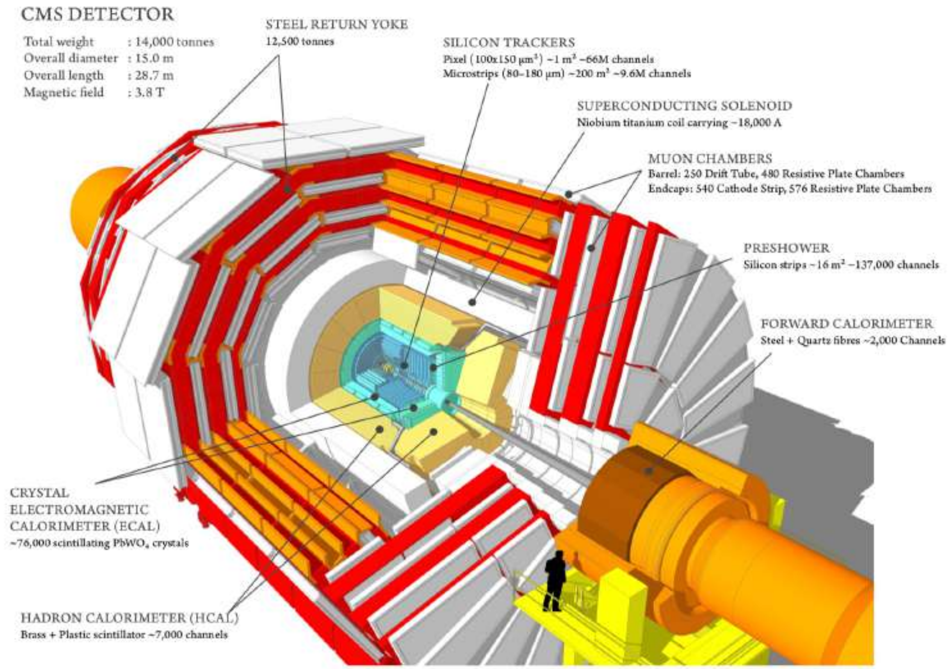
ATLAS nano fact sheet

- 25m Diameter and 44m length
- Over 7000 tons
- O(100) Million readout channels

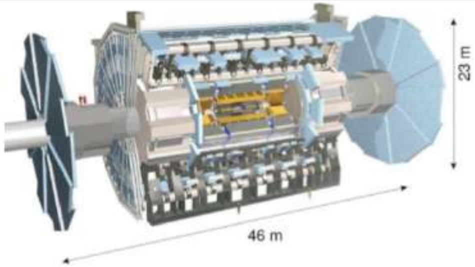
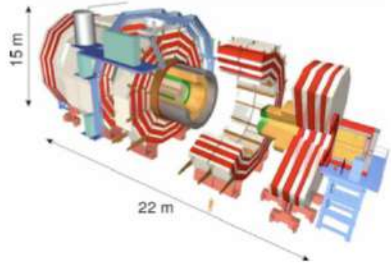
CMS nano fact sheet

- 15m Diameter and 21m length
- 14000 tons
- O(75) Million readout channels



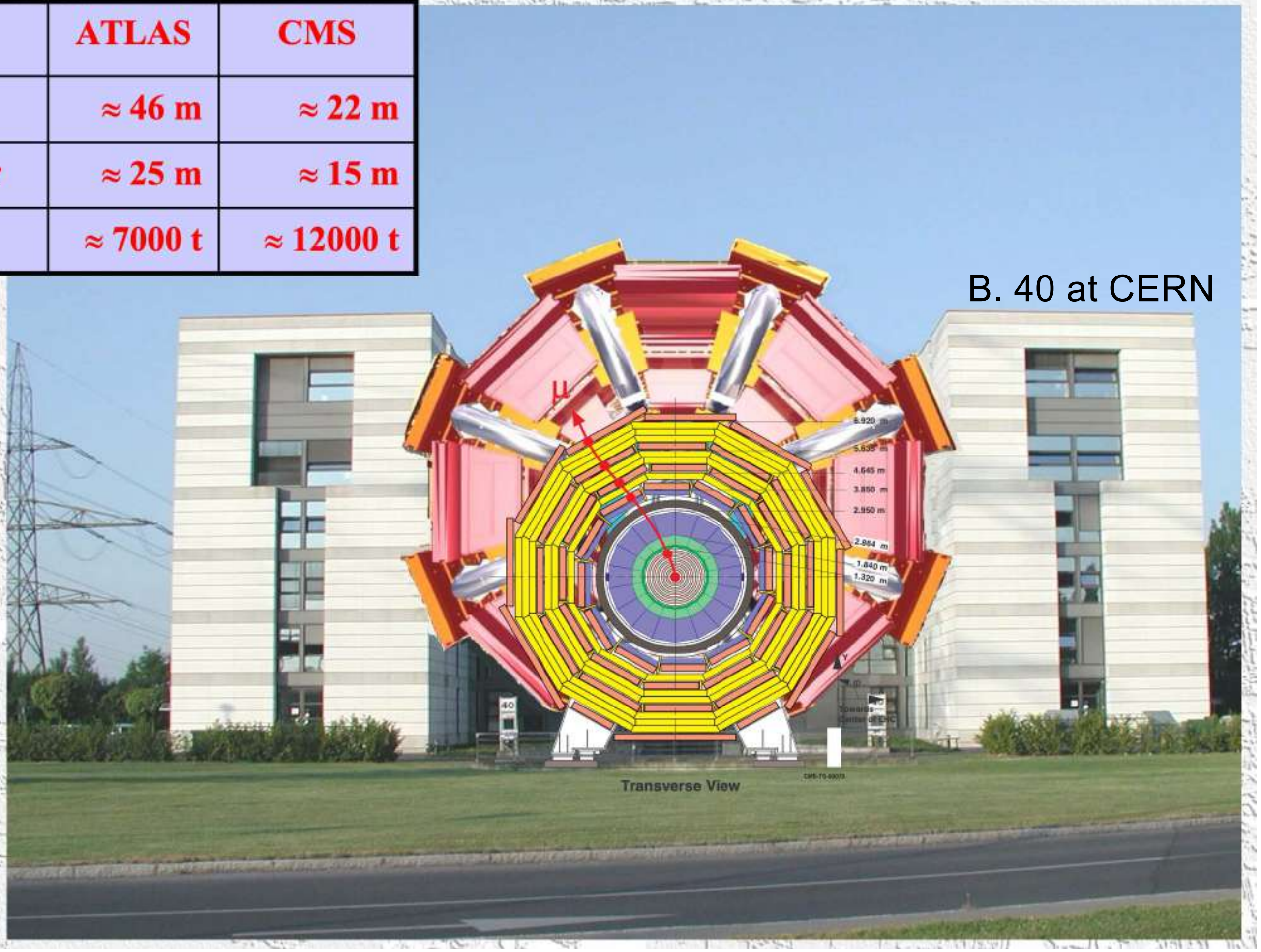


ATLAS and CMS: comparison

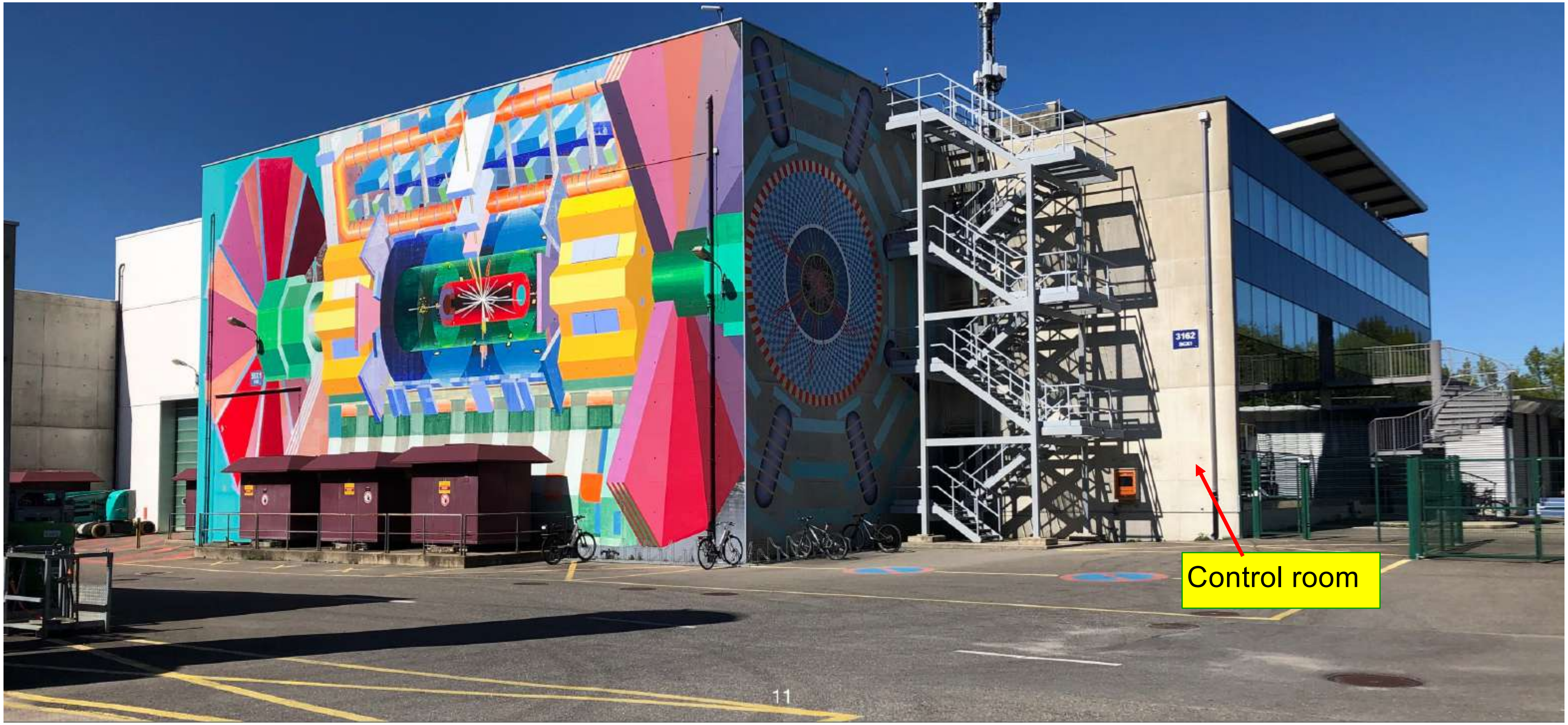
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\%$ (at 50 GeV) $\sim 11\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Comparison of Atlas and CMS

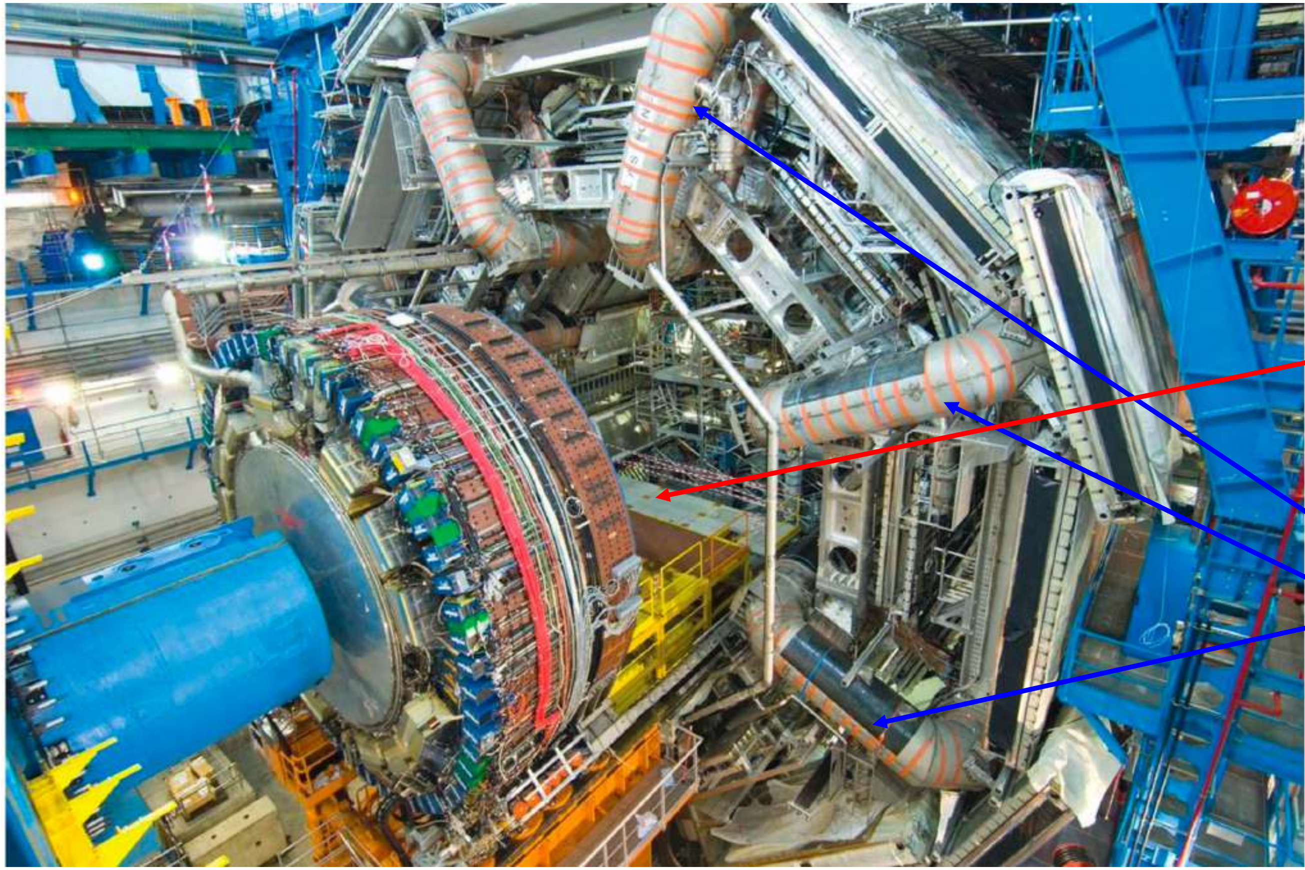
	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t



On the ATLAS control room wall



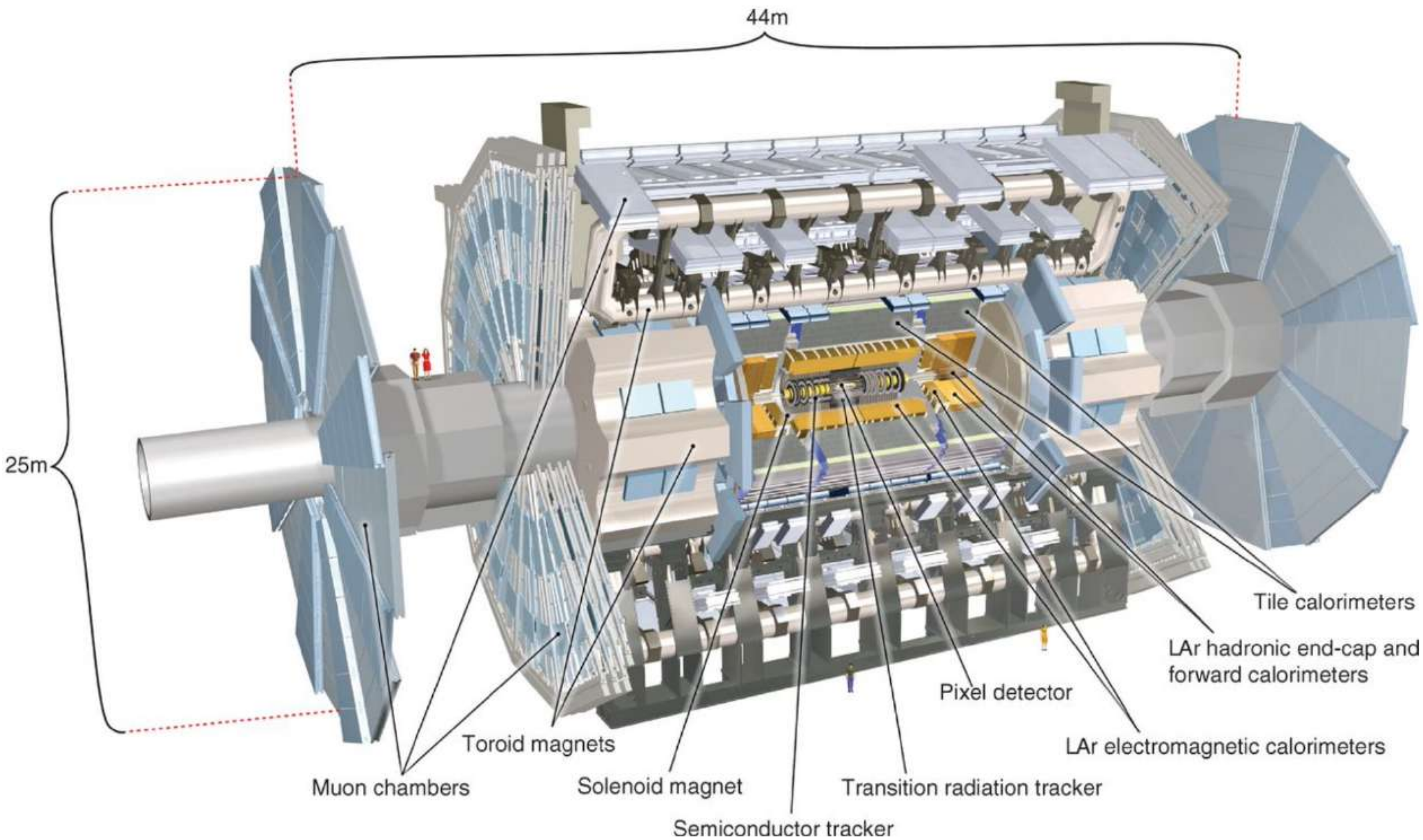
The ATLAS detector



View of the endcap calorimeter before insertion

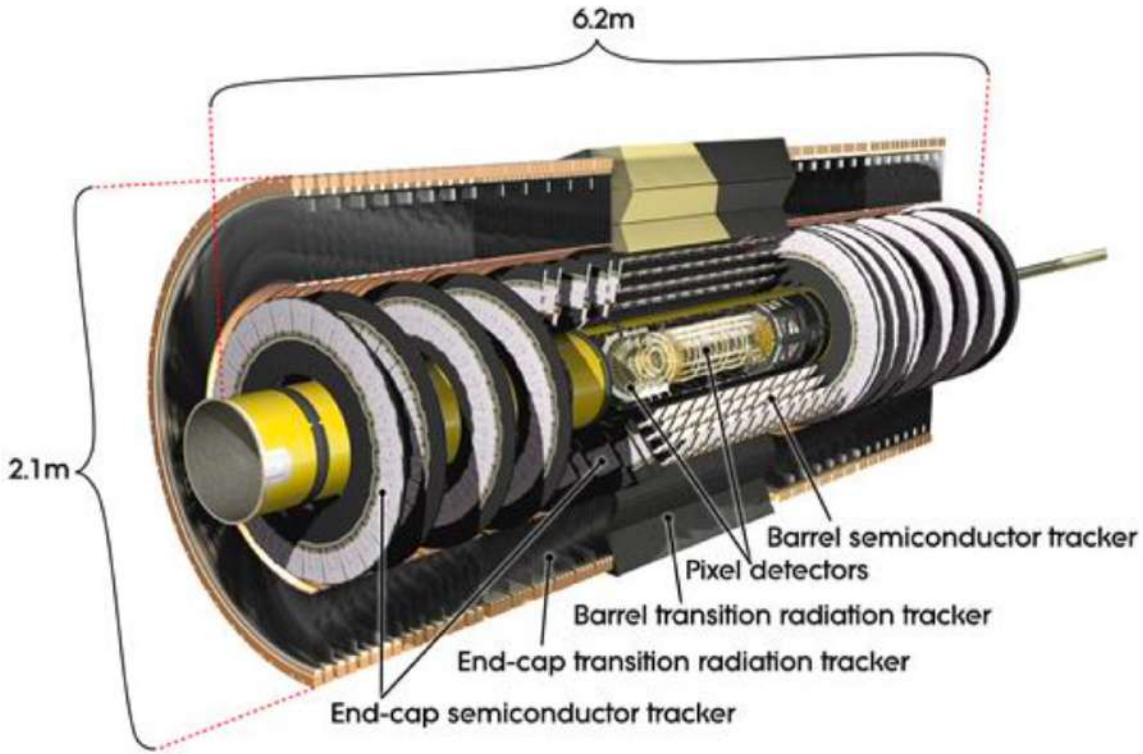
Barrel toroid superconducting coils

The Atlas detector: scheme



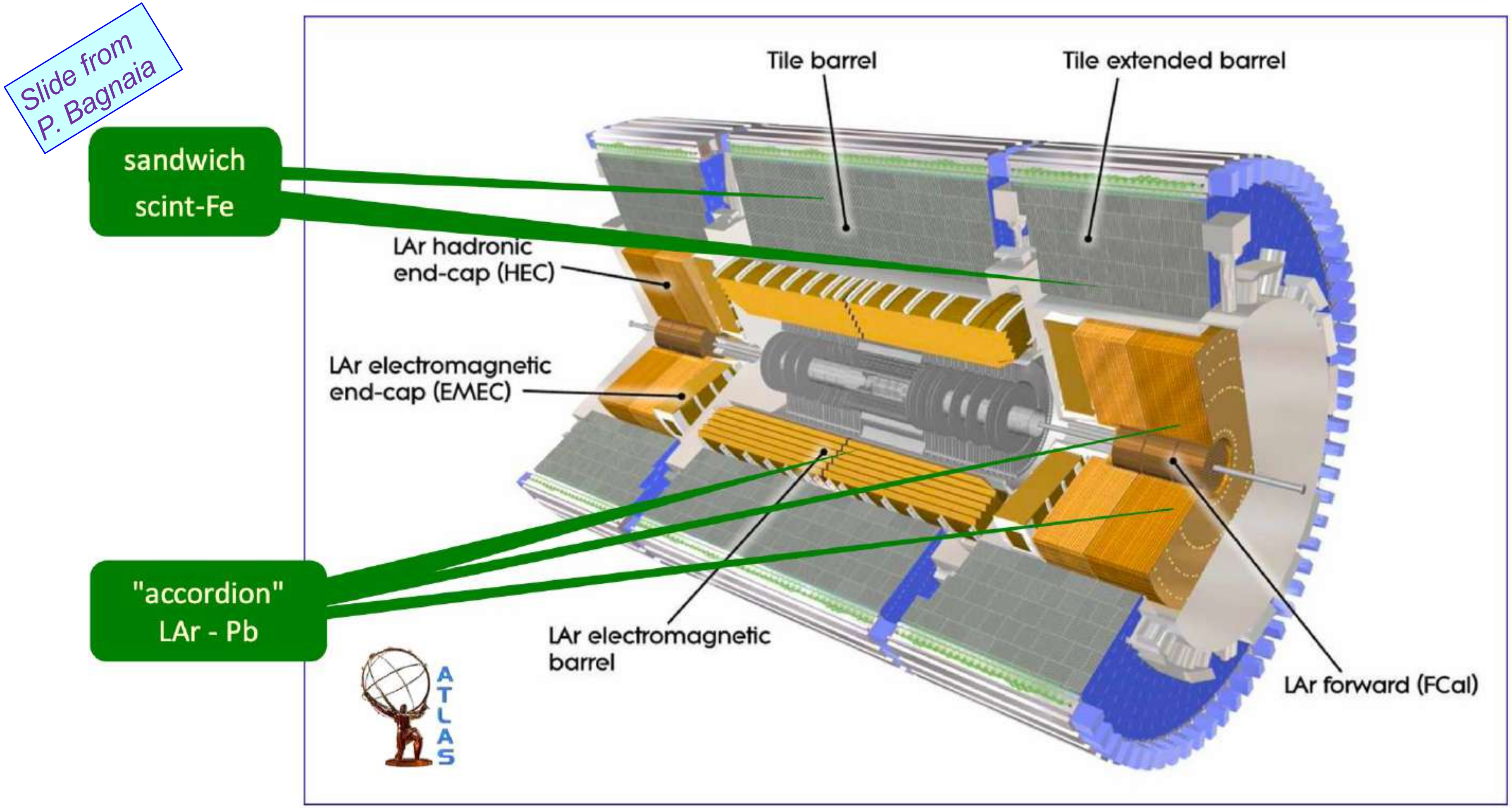
The Atlas detector: inner tracker

Slide from P. Bagnaia



Pixel	SCT	TRT
3 cylindrical layers	4 cylindrical layers	73 straw planes
2×3 disks	2×9 disks	160 straw planes

The Atlas detector: calorimeters



The Atlas detector: ecal

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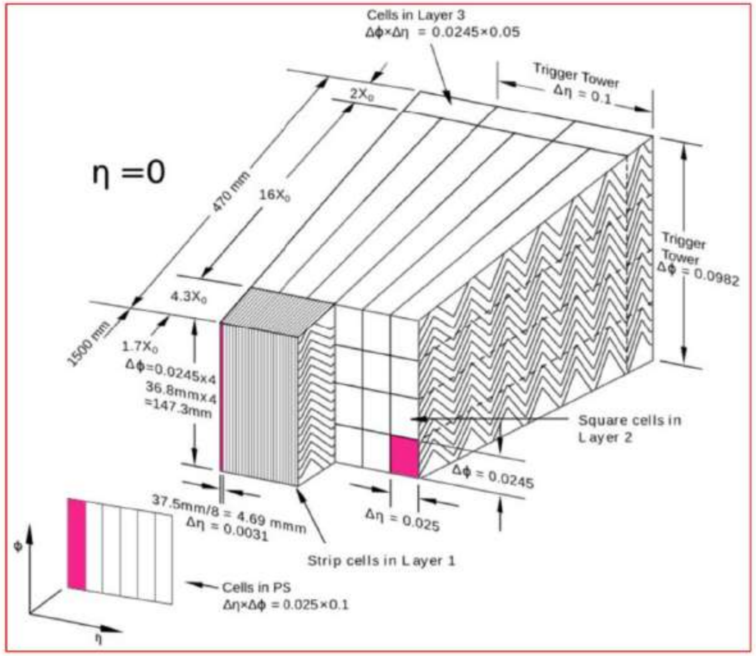
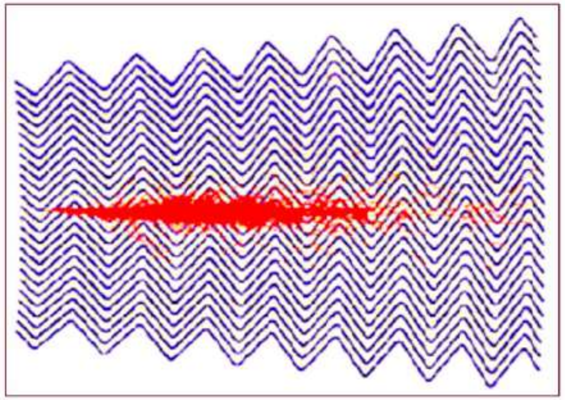
P. Bagnaia



e/γ



- "accordion" LAr – Pb
- cryogenic
- hermetic
- longitudinal + radial segmentation

The Atlas detector: e id and measurement

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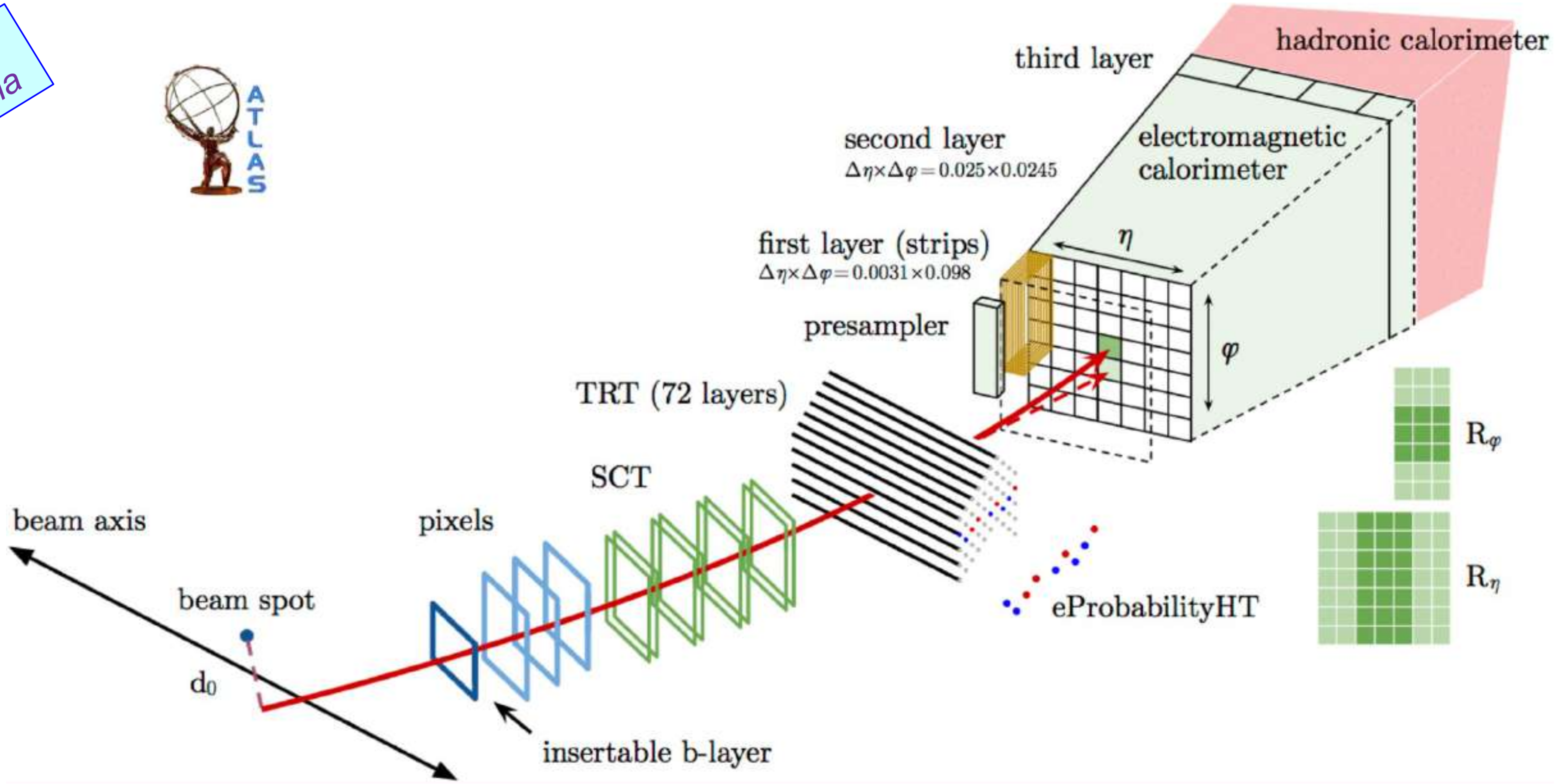

an electron is detected many (>> 100) times after the interaction point; even the non-detection in the had. calo is important (cfr a γ in the pixels/SCT/TRT).

The Atlas detector: hcal

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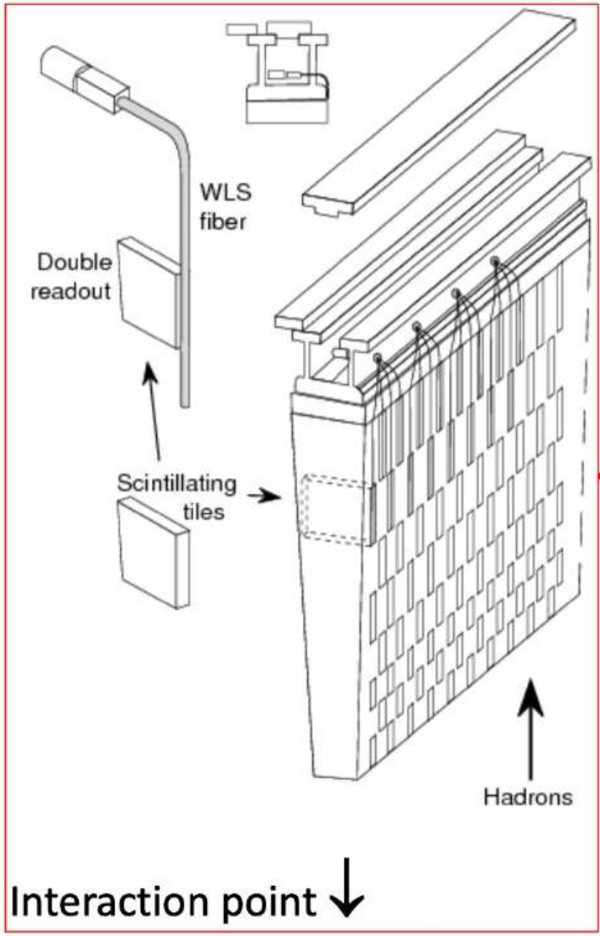
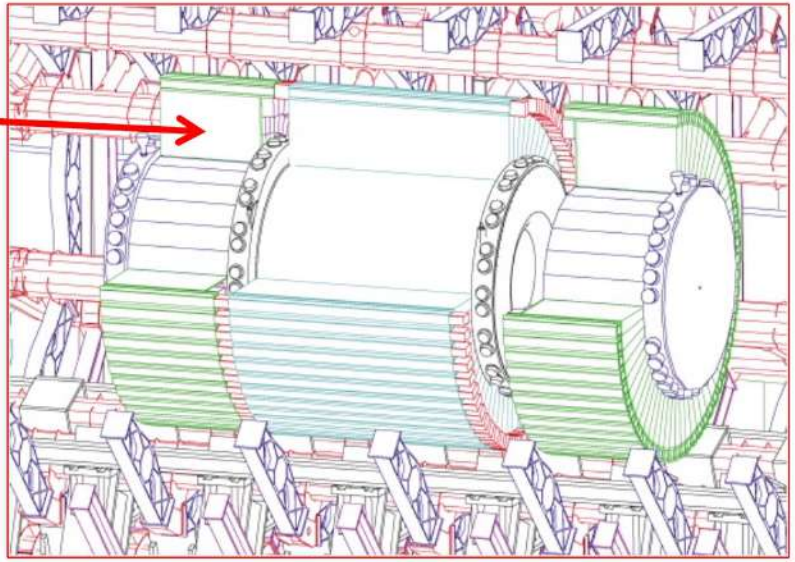
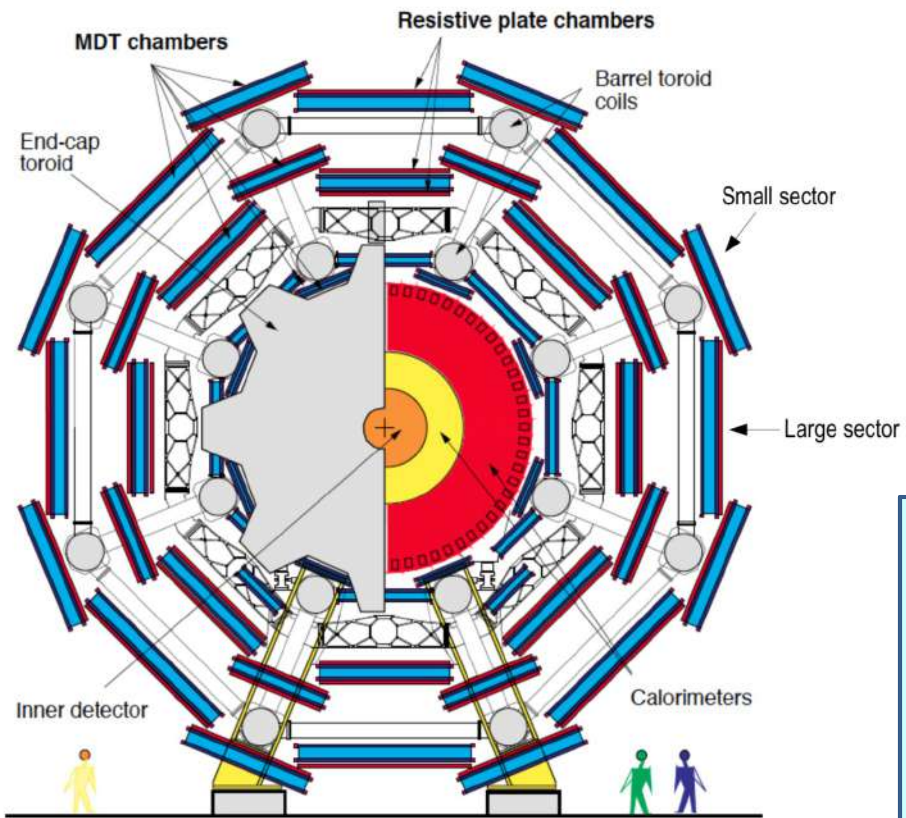
P. Bagnaia

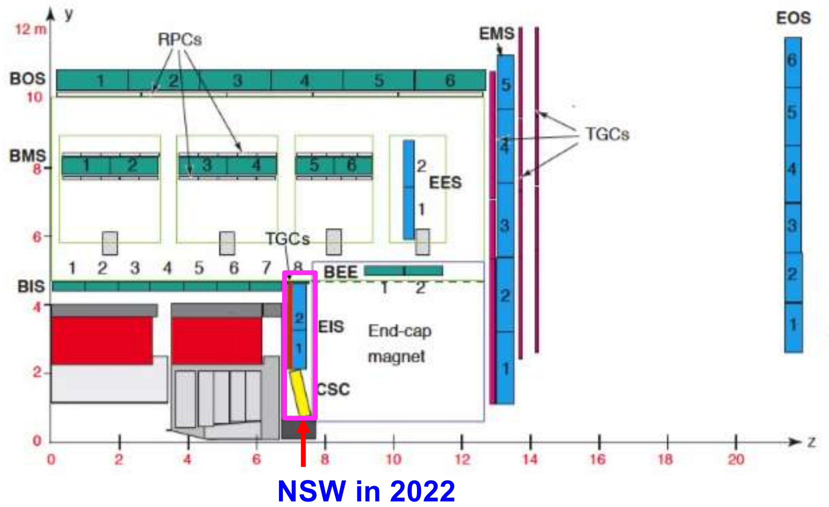


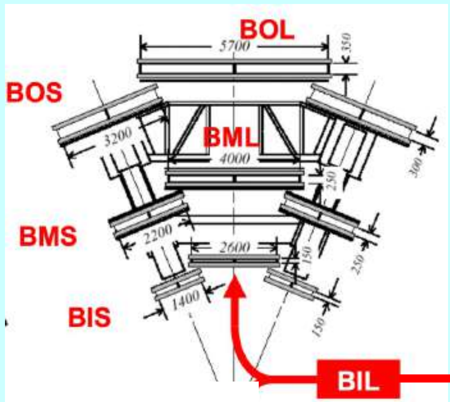
- "tiles" Fe – Scintillator
- WLS readout
- hermetic
- high segmentation

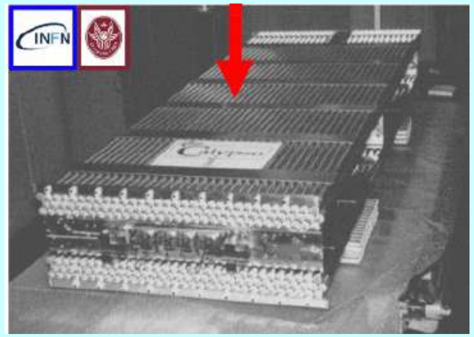


The Atlas detector: muon spectrometer





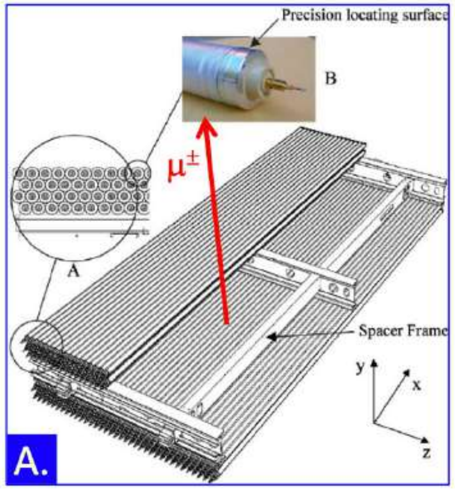


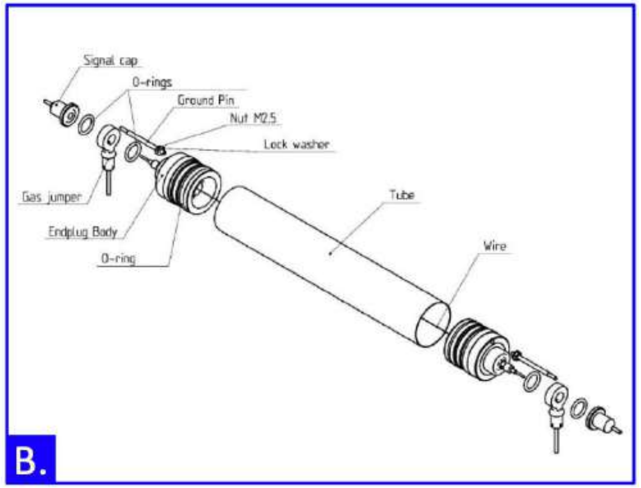


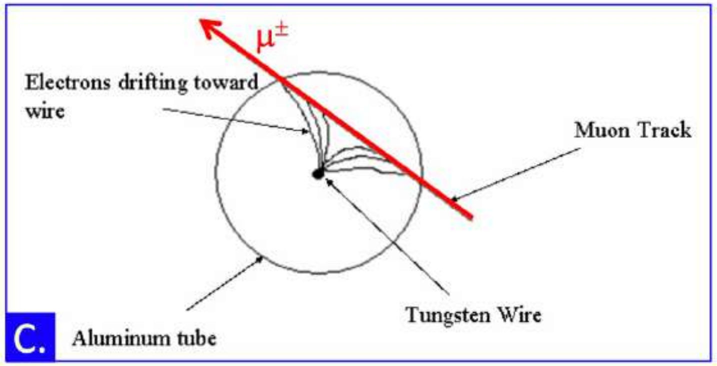
The Atlas detector: MDT chamber

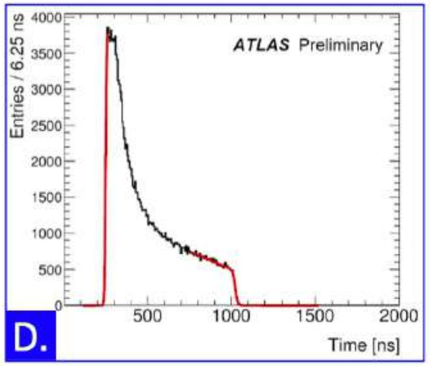
Slide from P. Bagnaia

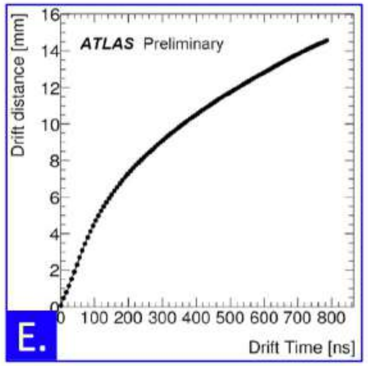
Schematic view of:
A. a chamber of drift tubes
B. a single tube
C. a muon hitting a tube
D. the hit time distribution
E. the r-t relation





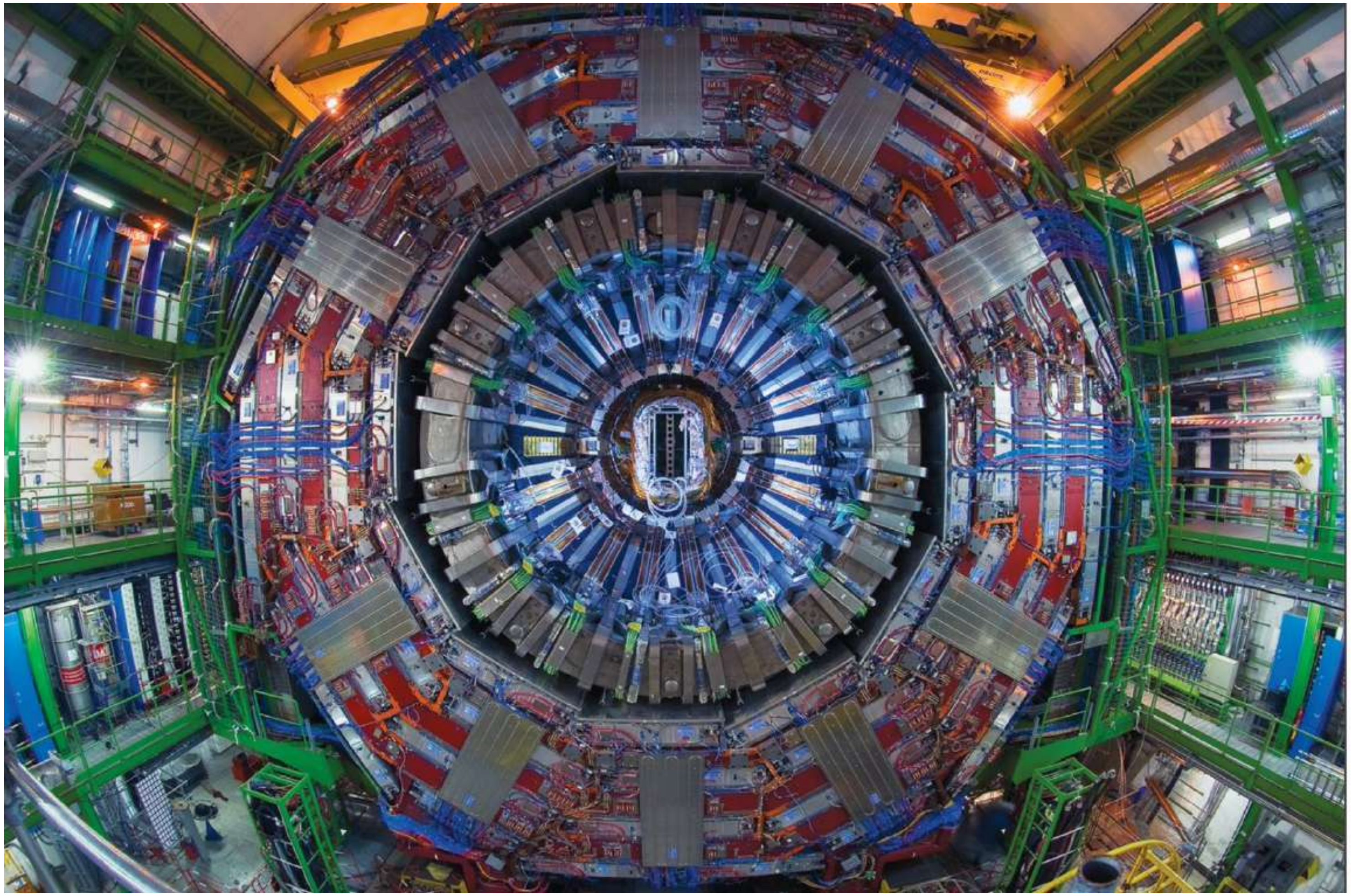




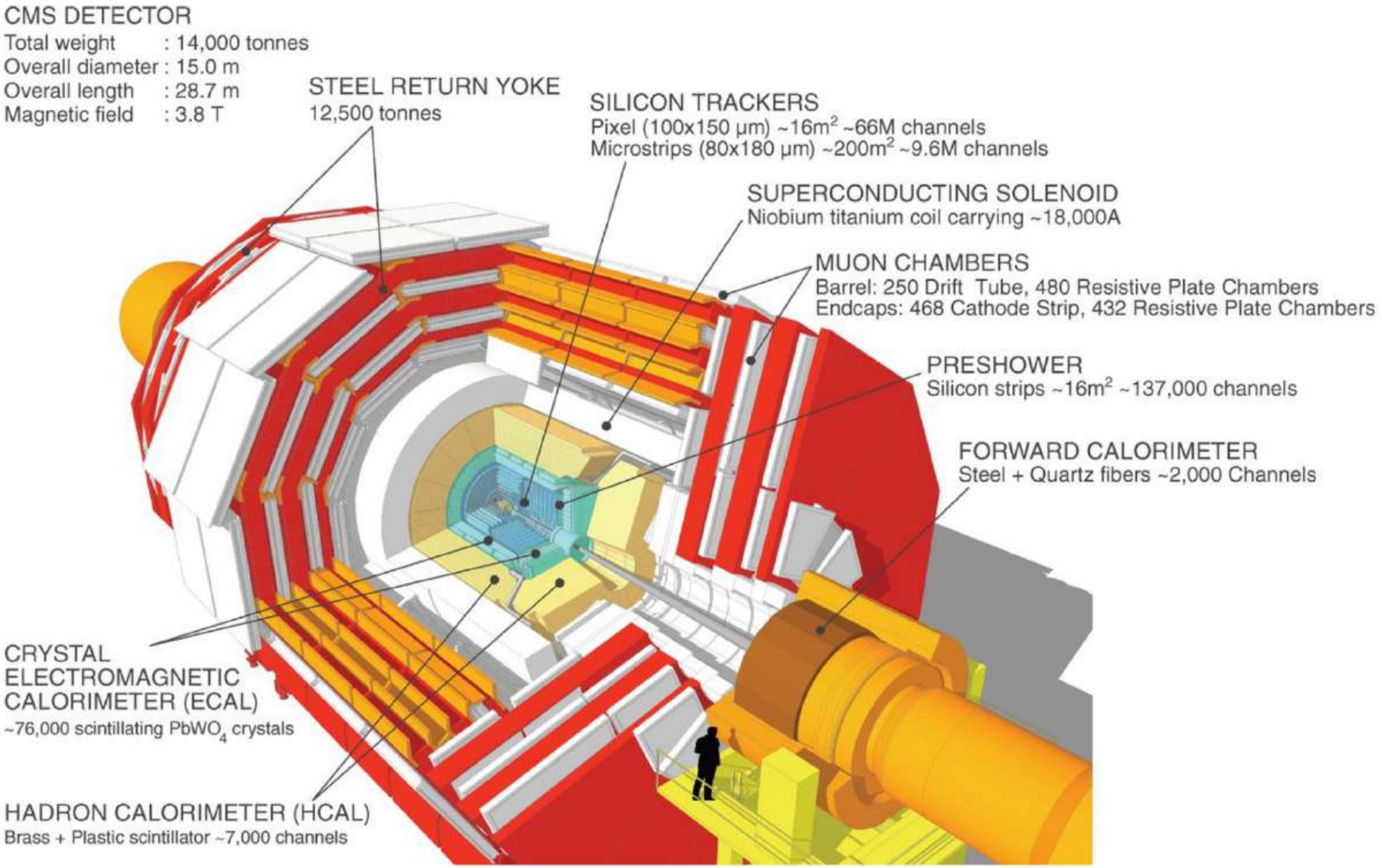


The CMS detector

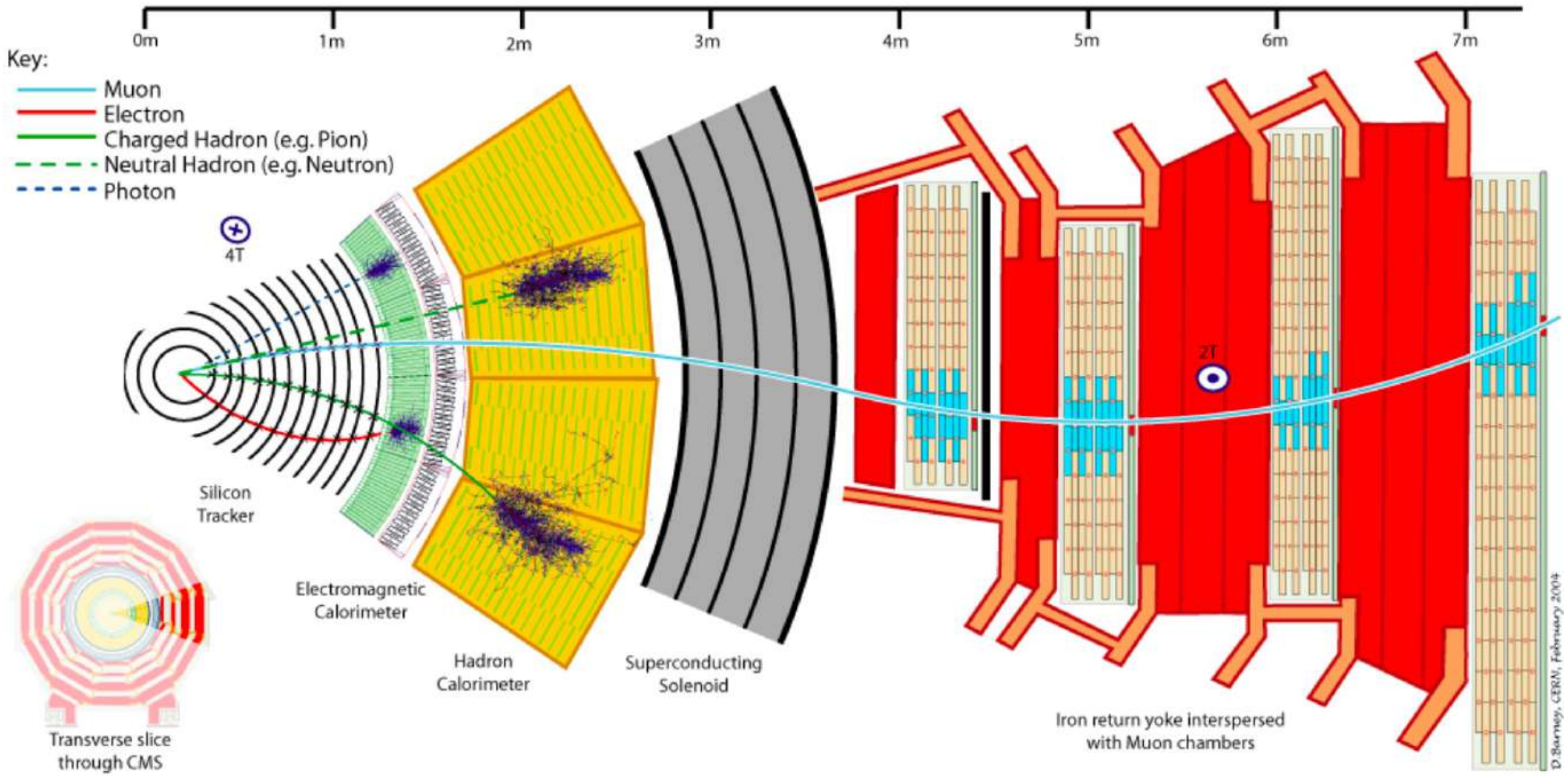
Slide from P. Bagnaia



The CMS detector: view

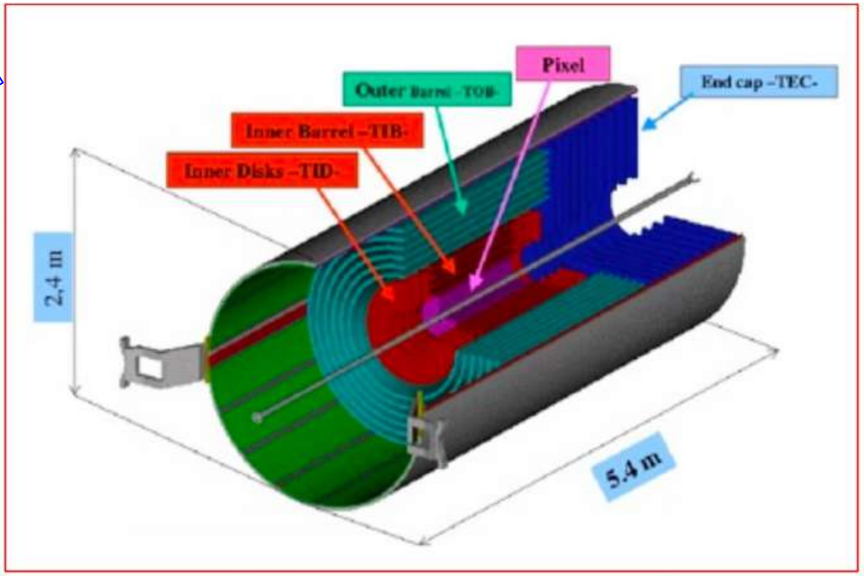


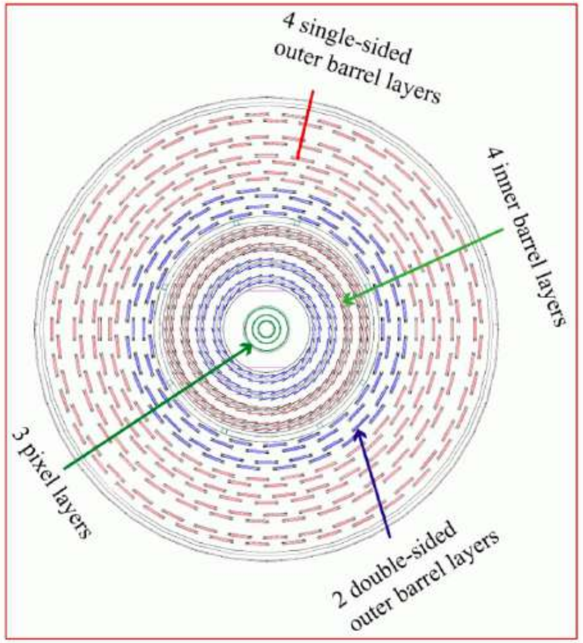
The CMS detector: scheme

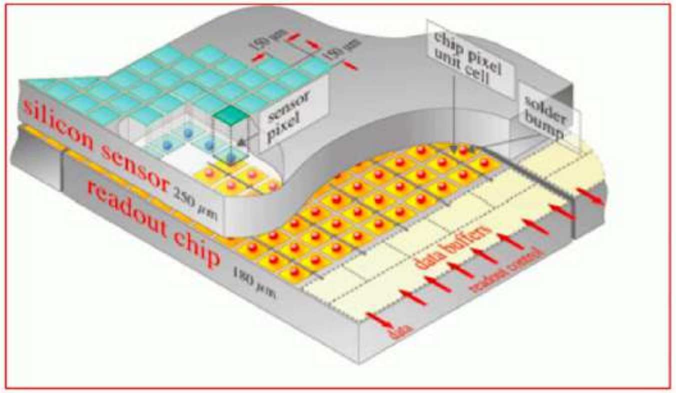


The CMS detector: inner tracker

Slide from P. Bagnaia







Si pixel + strip detector

The CMS detector: ecal

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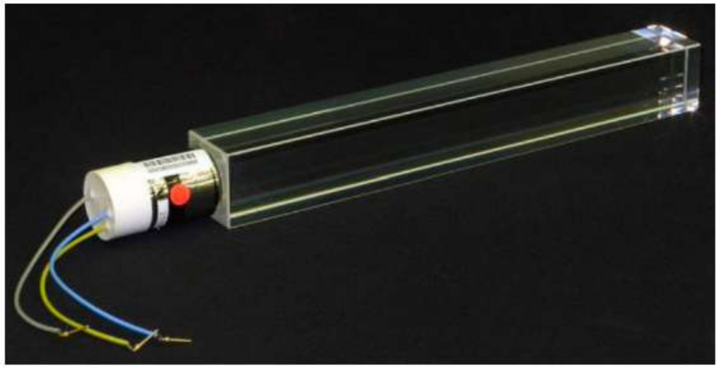
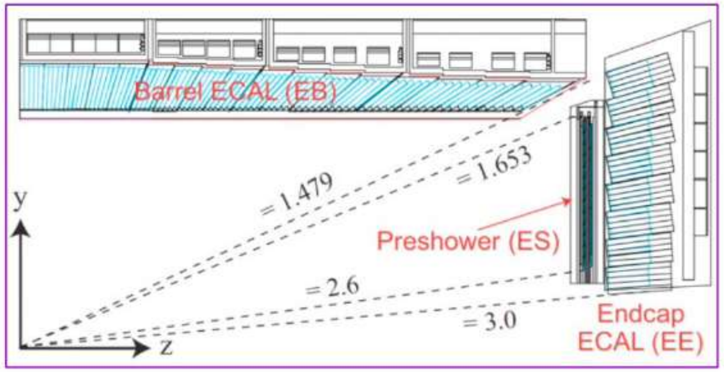
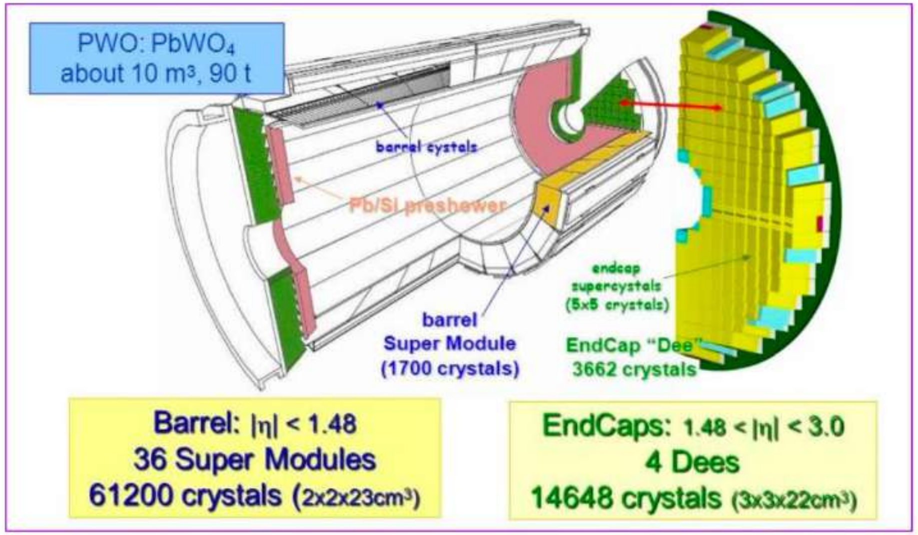
P. Bagnaia







e.m. calo:
$PbWO_4$ crystals

The CMS detector: hcal

Slide from P. Bagnaia

HCAL (tower structure):
- Barrel (HB): $|\eta| < 1.4$, 2304 towers
- End caps (HE): $1.3 < |\eta| < 3.0$, „ towers
- Outside coil (HO): $|\eta| < 1.26$ (tail catcher)

→ 4608 towers (Plastic scintillator tiles, $\approx 10\ \lambda_N$)

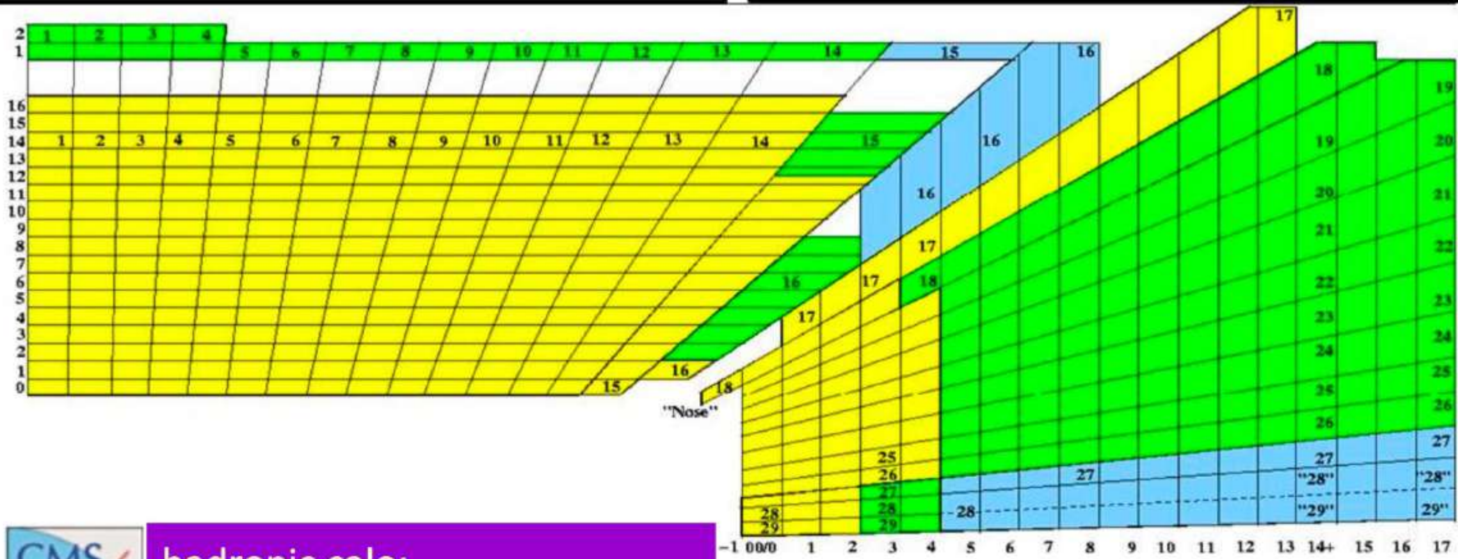
→ $\Delta\eta \times \Delta\varphi \approx 0.087 \times 0.087 \rightarrow 0.350 \times 0.175$

- Forward (HF): $2.9 < |\eta| < 5.0$ (not shown)

→ 2 x 900 towers (Quartz fibers, $\approx 10\ \lambda_N$)

→ $\Delta\eta \times \Delta\varphi \approx 0.111 \times 0.175 \rightarrow 0.302 \times 0.350$

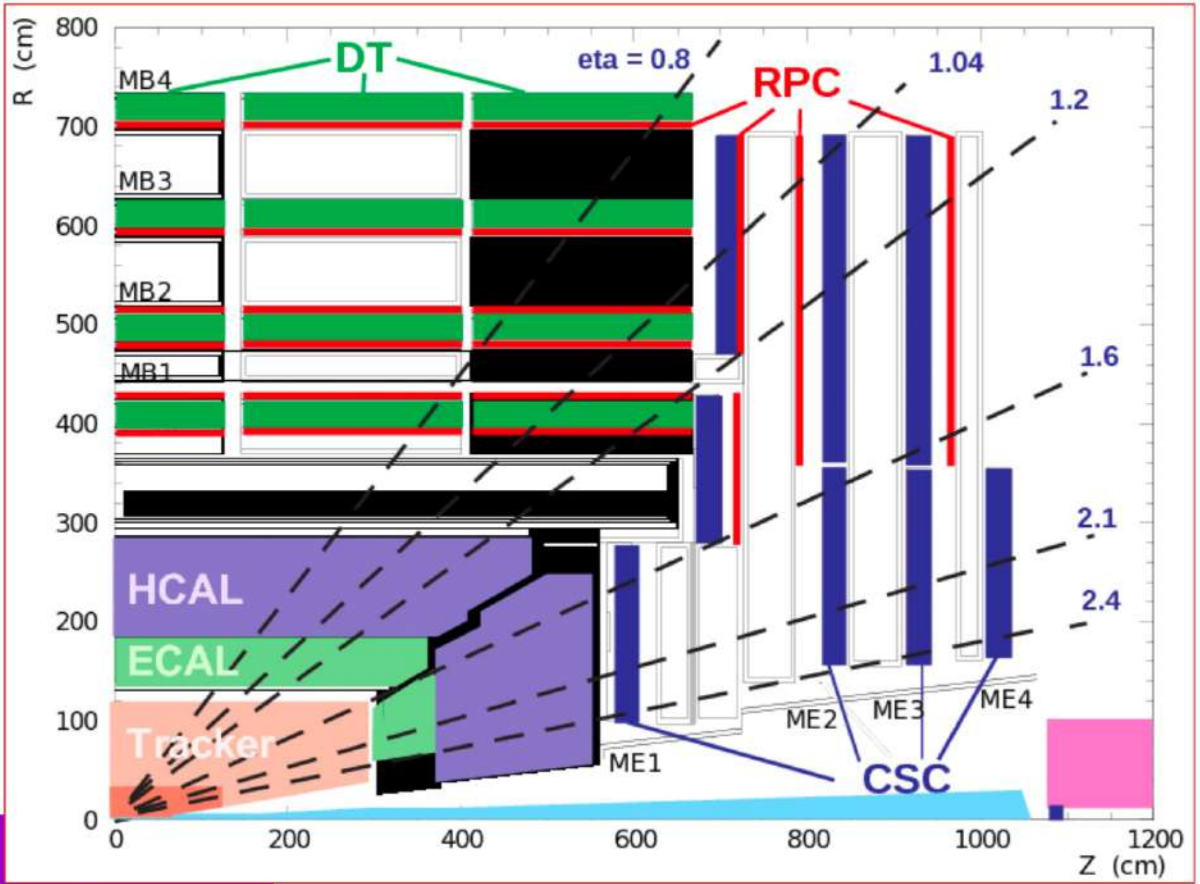
CASTOR calorimeter (not shown):
- $5.1 < |\eta| < 6.5$, $\approx 22\ X_0$, $\approx 10\ \lambda_N$



hadronic calo:
Brass/scintillator/wls readout

The CMS detector: muon spectrometer

Slide from P. Bagnaia



muon system:
drift tube (DT) chambers

Detector comparison: structure

Slide from P. Bagnaia

thanks to Anna Colaleo

	ATLAS	CMS
Magnet(s)	Air-core toroids + Solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
Tracker/ Inner Detector	Silicon pixels, Silicon strips, Transition Radiation Tracker. 2T magnetic field	Silicon pixels, Silicon strips. 4 T magnetic field
Electro-magnetic calorimeter	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate (PbW04) crystals both absorb and respond by scintillation
Hadronic calorimeter	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon detector	Large air-core toroid magnets with muon chamber form outer part of the whole ATLAS	Muons measured already in the central field, further muon chambers inserted in the magnet return yoke

Detector comparison: resolutions

Slide from P. Bagnaia

thanks to Anna Colaleo

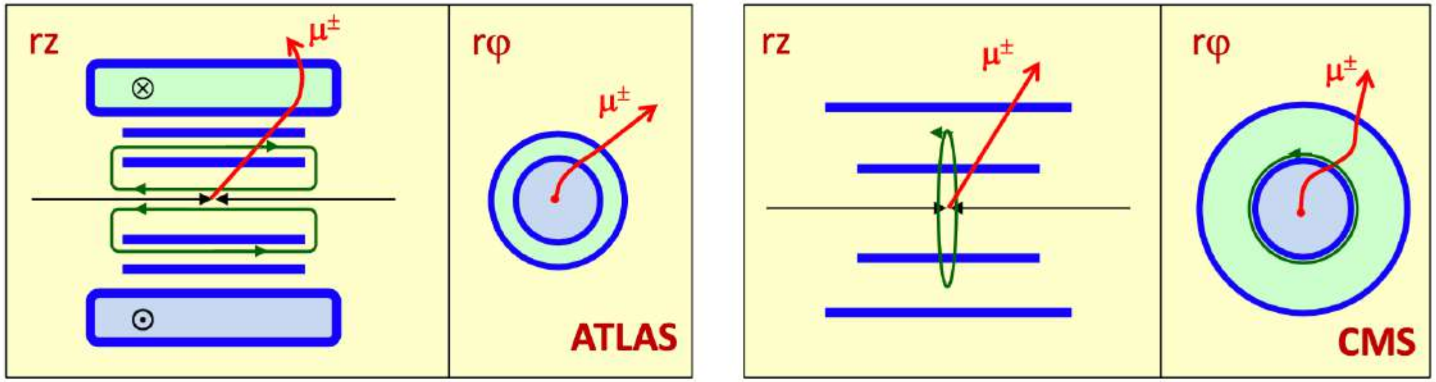
	ATLAS	CMS
Tracker/ Inner Detector	TRD → particle identification $\sigma/p_T \approx 5 \times 10^{-4} p_T\,(\text{GeV}) \oplus 0.01$	No particle identification $\sigma/p_T \approx 1.5 \times 10^{-4} p_T\,(\text{GeV}) \oplus 0.005$
Electro-magnetic calorimeter	$\sigma/E \approx 10\%/\sqrt{E}\,(\text{GeV})$ Longitudinal segmentation	$\sigma/E \approx (2 \div 5)\,\%/\sqrt{E}\,(\text{GeV})$ No longitudinal segmentation
Hadronic calorimeter	$> 10\ \lambda$ $\sigma/E \approx 50\%/\sqrt{E}\,(\text{GeV}) \oplus 0.03$	$> 5.8\ \lambda$ + tail catcher $\sigma/E \approx 65\%/\sqrt{E}\,(\text{GeV}) \oplus 0.05$
Muon detector	air $\sigma/p_T \approx 7\%$ @ 1 TeV (spectrometer alone)	Fe $\sigma/p_T \approx 5\%$ @ 1 TeV (combining spectrometer + tracker)

imho (*common, but not unanimous*):

- two complementary strategies almost everywhere;
- … with different optimizations (e.g. resolution vs robustness);
- a textbook example of "guided" detector design;
- … to guarantee optimal results (→ not miss major discoveries).

Detector comparison: magnetic spectrometers

Slide from P. Bagnaia



ATLAS:

- main magnet: toroid B = 0.7 T;
- bending in (r,z);
- straight tracks in (r,φ);
- at small r, a solenoid B = 2 T → bending also in (r,φ);
- less precise in extrapolating to main vtx;
- μ-system in air → no multiple scatt. for μ's;
- larger bending for μ at large η → more precise.

CMS:

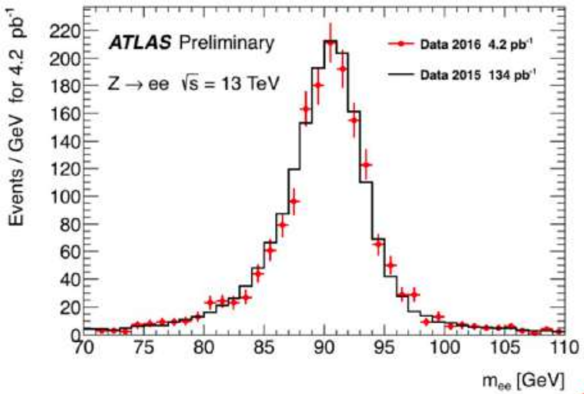
- main magnet: solenoid B = 4 T;
- bending in (r,φ);
- straight tracks in (r,z);
- more precise in extrapolating to main vtx;
- μ-system in Fe → large multiple scatt. for μ's;
- less bending for μ's at large η.

thanks to Anna Colaleo

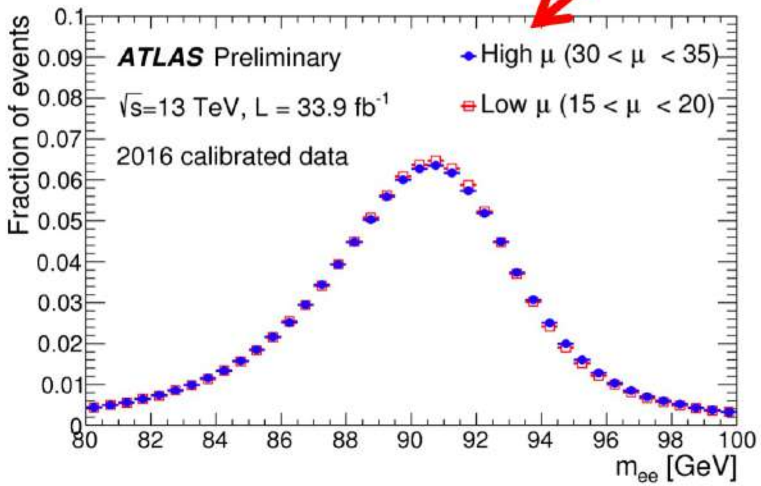
ATLAS and CMS performances

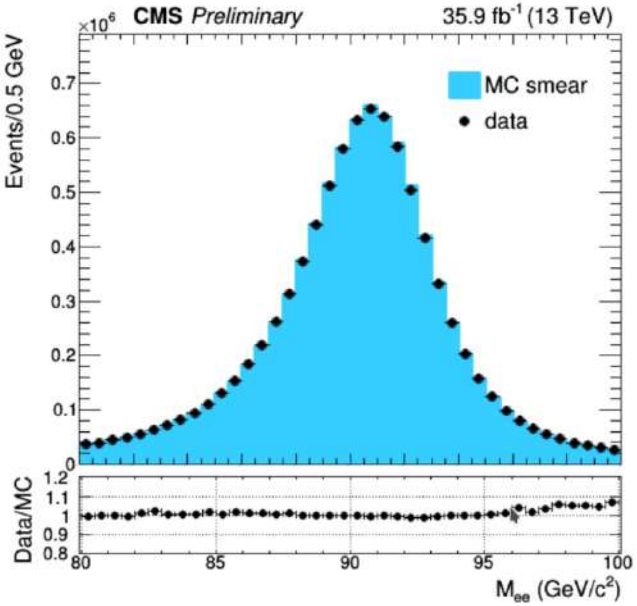
Detector performances: Z → e^+e^-

Slide from
P. Bagnaia



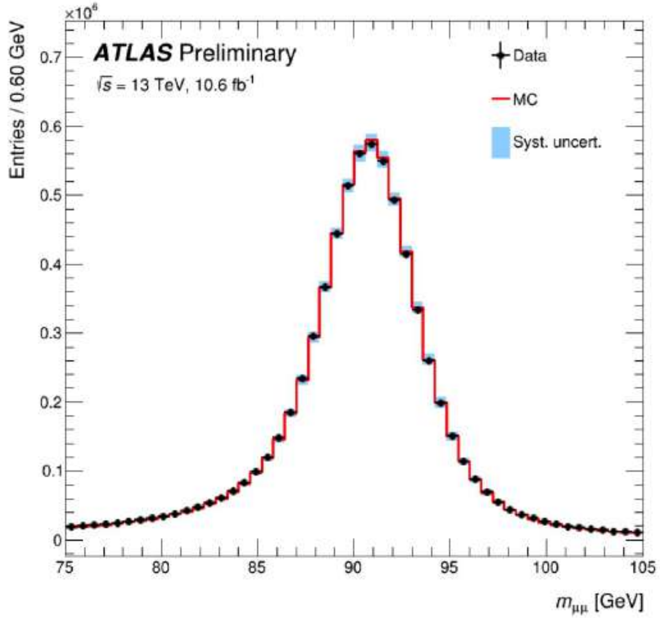
- the classic benchmark of tracker + e.m. calo.;
- no improvement wrt LEP, used only for detector debug/calibration (e.g. to show the independence from $\mathfrak{L}$).



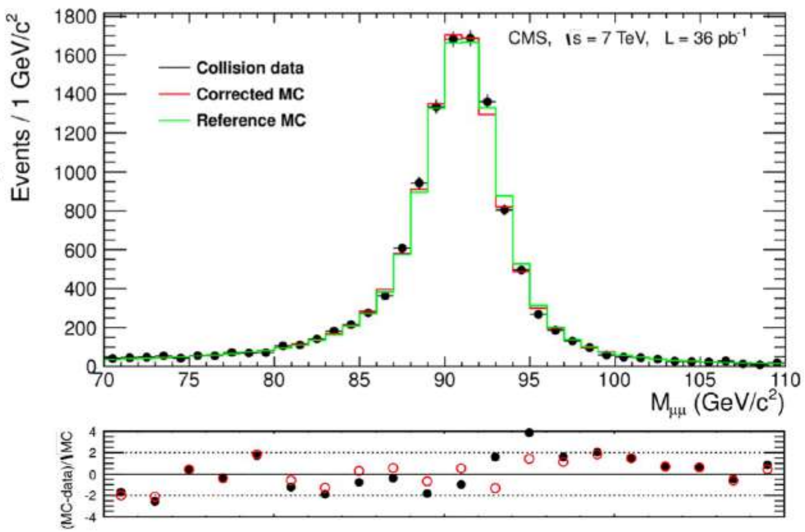


Detector performances: Z → $\mu^+\mu^-$

Slide from P. Bagnaia



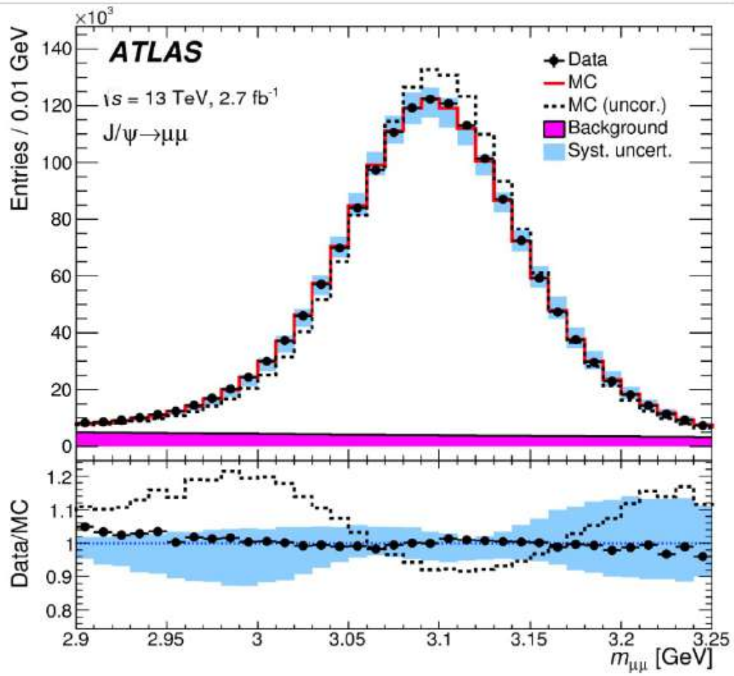
- the classic benchmark of tracker + muon chambers;
- [no way to improve wrt LEP, used only for detector debug/calibration.]



A famous joke:
time evolution of physics processes:
discovery → precision meas → detector study → background.

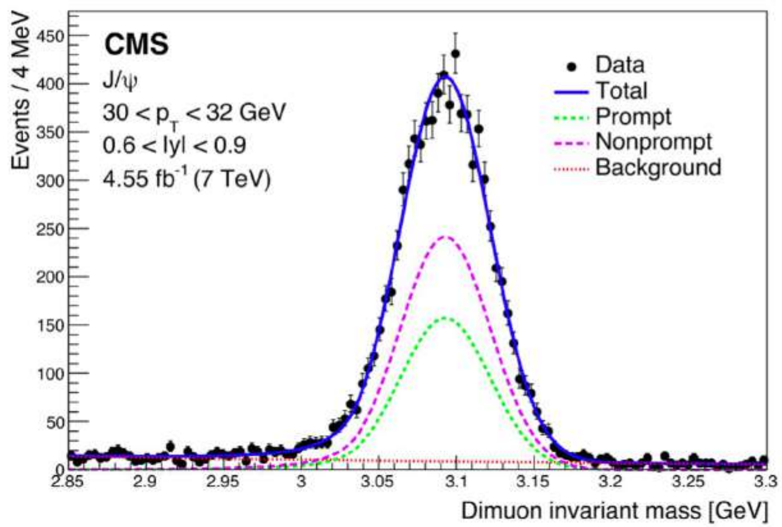
Detector performances: $J/\Psi \rightarrow \mu^+\mu^-$

Slide from P. Bagnaia



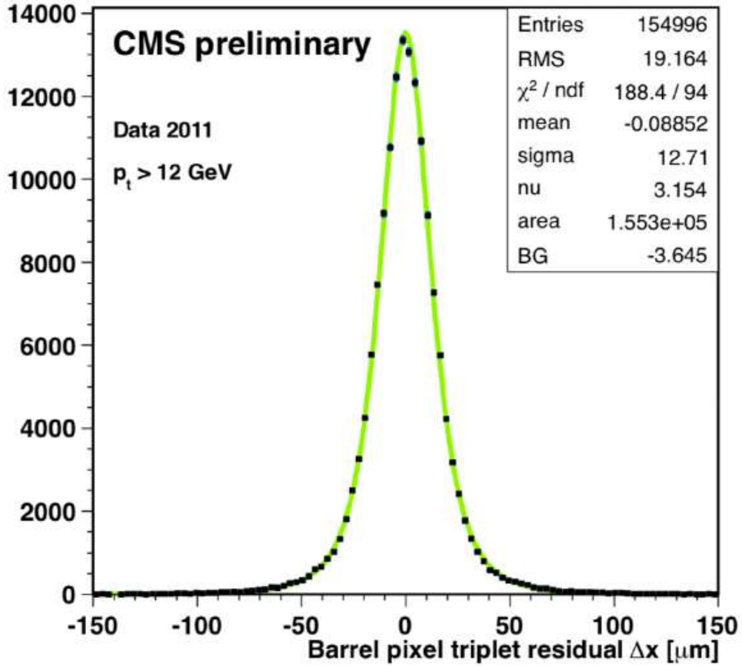
$Z \rightarrow \mu^+\mu^-$ and J/ψ $Z \rightarrow \mu^+\mu^-$ are ideal channels for μ studies :

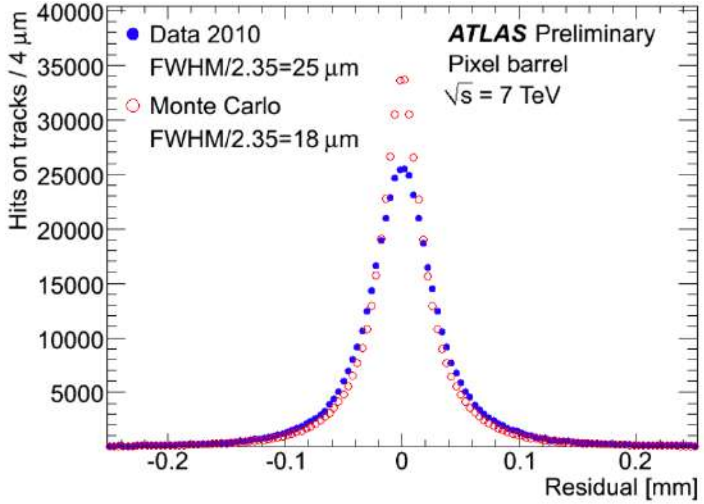
- inner detector + muon spectrometer;
- agreement (MC $\leftrightarrow$ data) $\rightarrow$ confidence in analysis (including errors !).

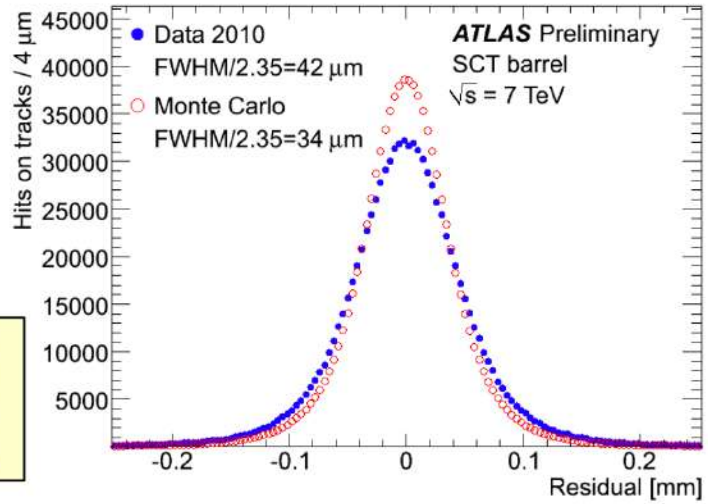


Detector performances: silicon trackers

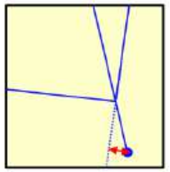
Slide from P. Bagnaia







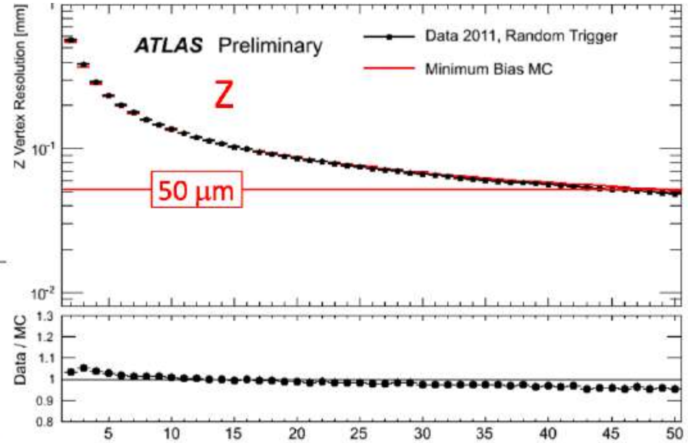
- resolution of few μm necessary for impact parameter → identification of secondary verteces → heavy flavors → higgs;
- agreement (MC ↔ data) → confidence in analysis (including errors !).

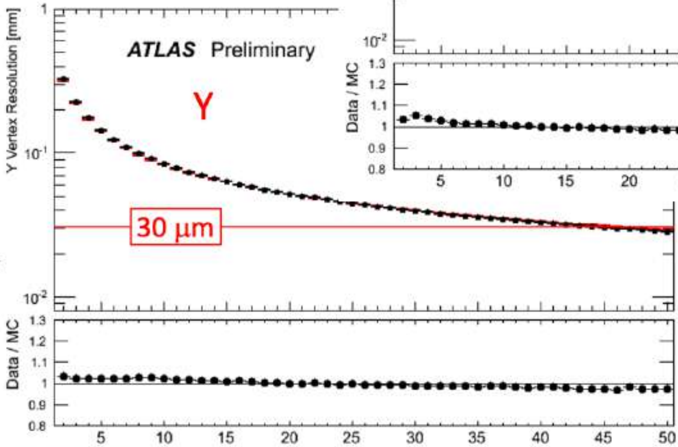


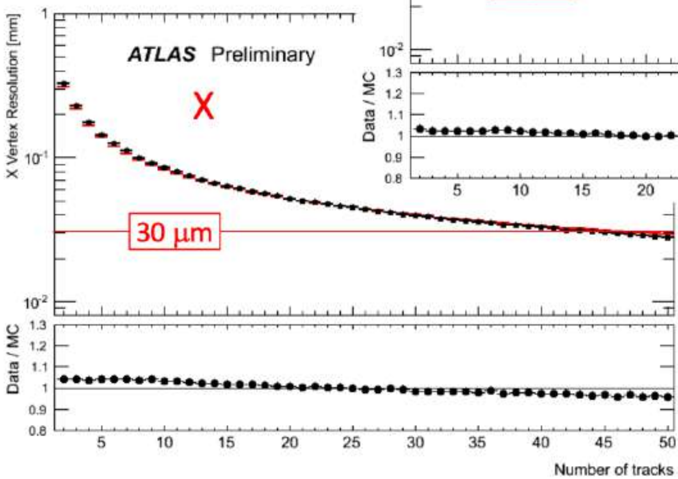
Detector performances: vertex resolution

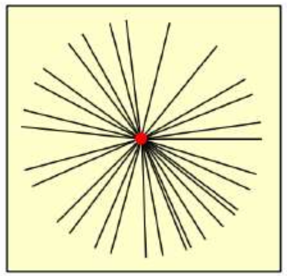
Slide from
P. Bagnaia

- Vertex resolution as a function of its track multiplicity.
- Expect $\sigma \approx \sigma_0/\sqrt{N} \oplus \sigma_1$;
- σ_0 and σ_1 constants, different for xy (transverse) and z (beam axis).



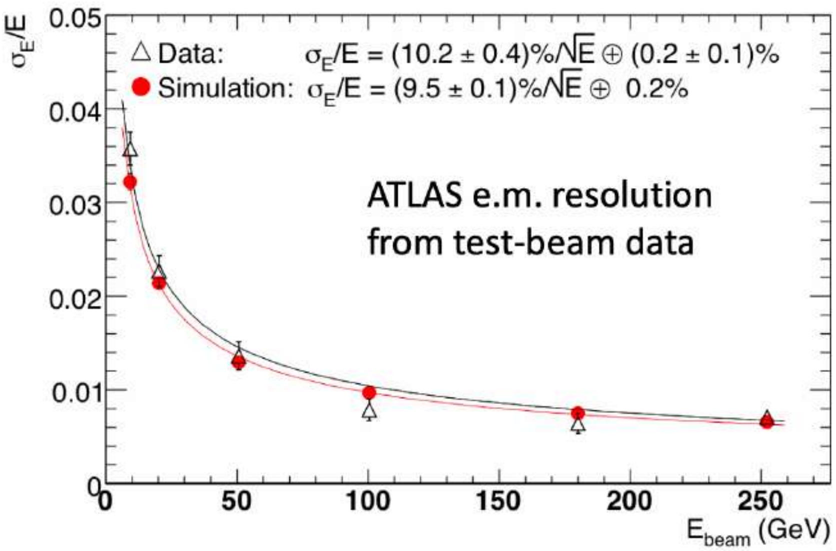






Detector performances: ecal

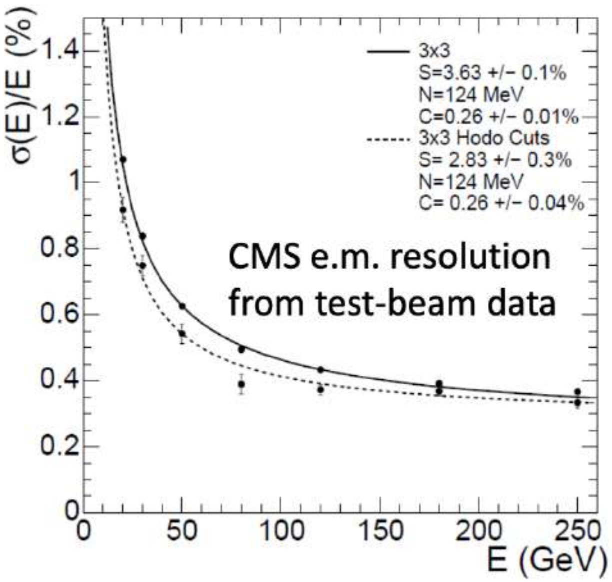
Slide from P. Bagnaia



- although real life is somewhat different (sys from cell-to-cell calib, control of temperature, etc), test-beam results are impressive;
- expect $\sigma/E \approx \sigma_1/E \oplus \sigma_2 / \sqrt{E} \oplus \sigma_3$;
- σ_1 looks negligible, while σ_3 dominates at high E.

→ test these expectations with real particles:

- Z (previous slides);
- π^0, η, … (next slides)

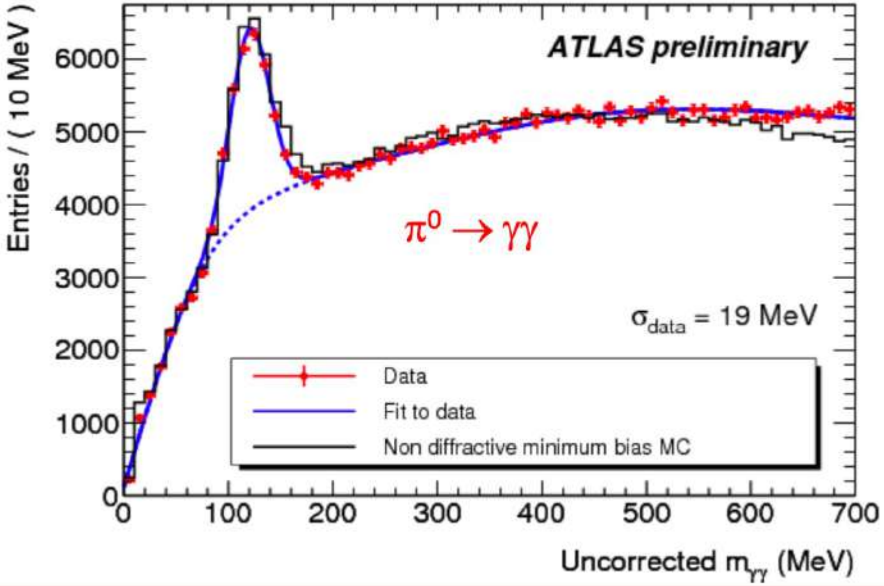


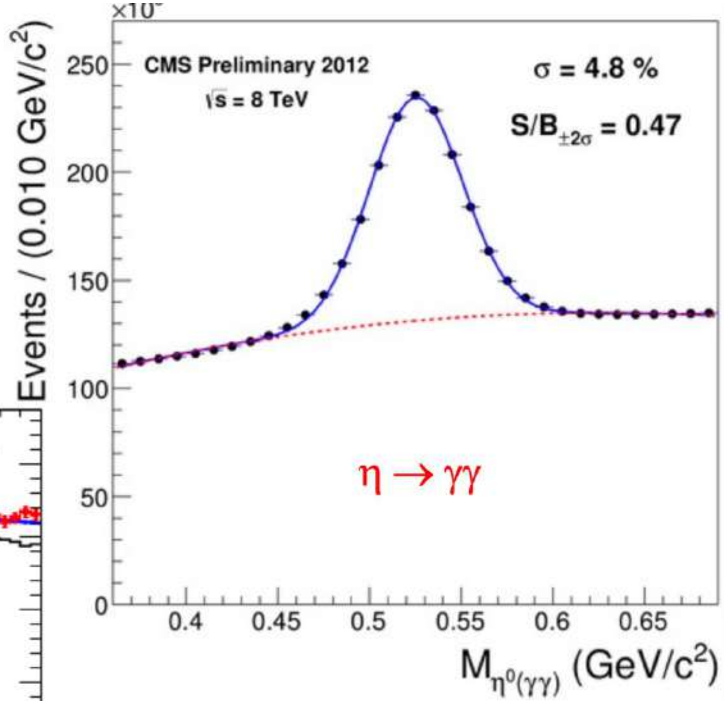
Detector performances: π^0, $\eta \rightarrow \gamma\gamma$

Slide from P. Bagnaia

The π^0 and η widths are a measurement of the electro calo resolution in a difficult environment (inside jets or in high multiplicity events).

Notice the good (almost perfect) agreement with MC predictions.



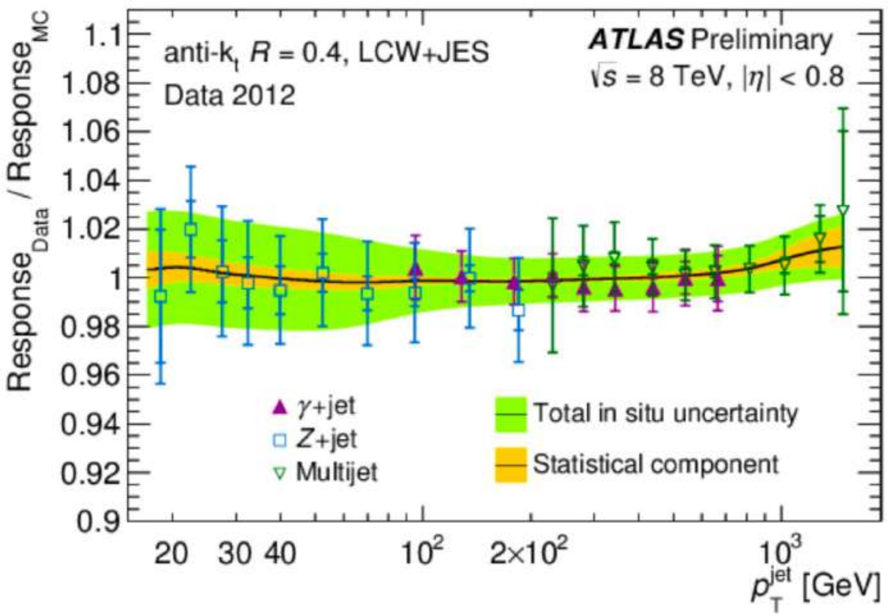


Detector performances: jet resolution

Slide from P. Bagnaia

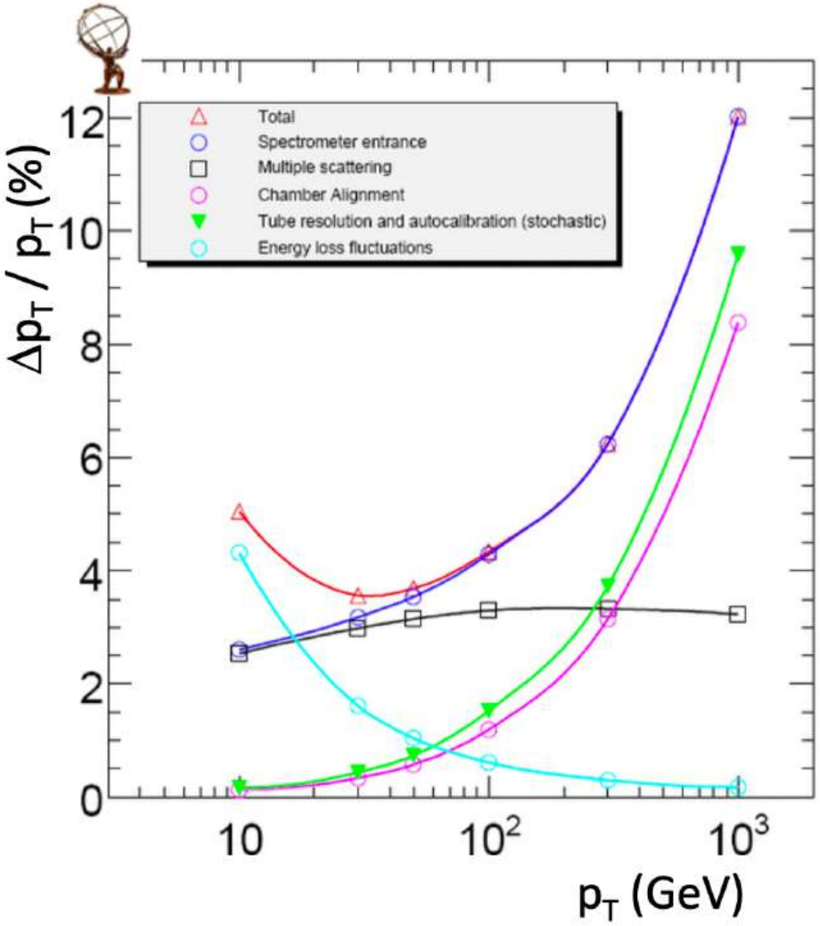
jet resolution as a function of p_T^{jet} :

- measured for different event types;
- stat and (mainly) syst uncertainty 2%, almost independent on p_T.



Detector performances: Atlas muon spectrometer

Slide from P. Bagnaia

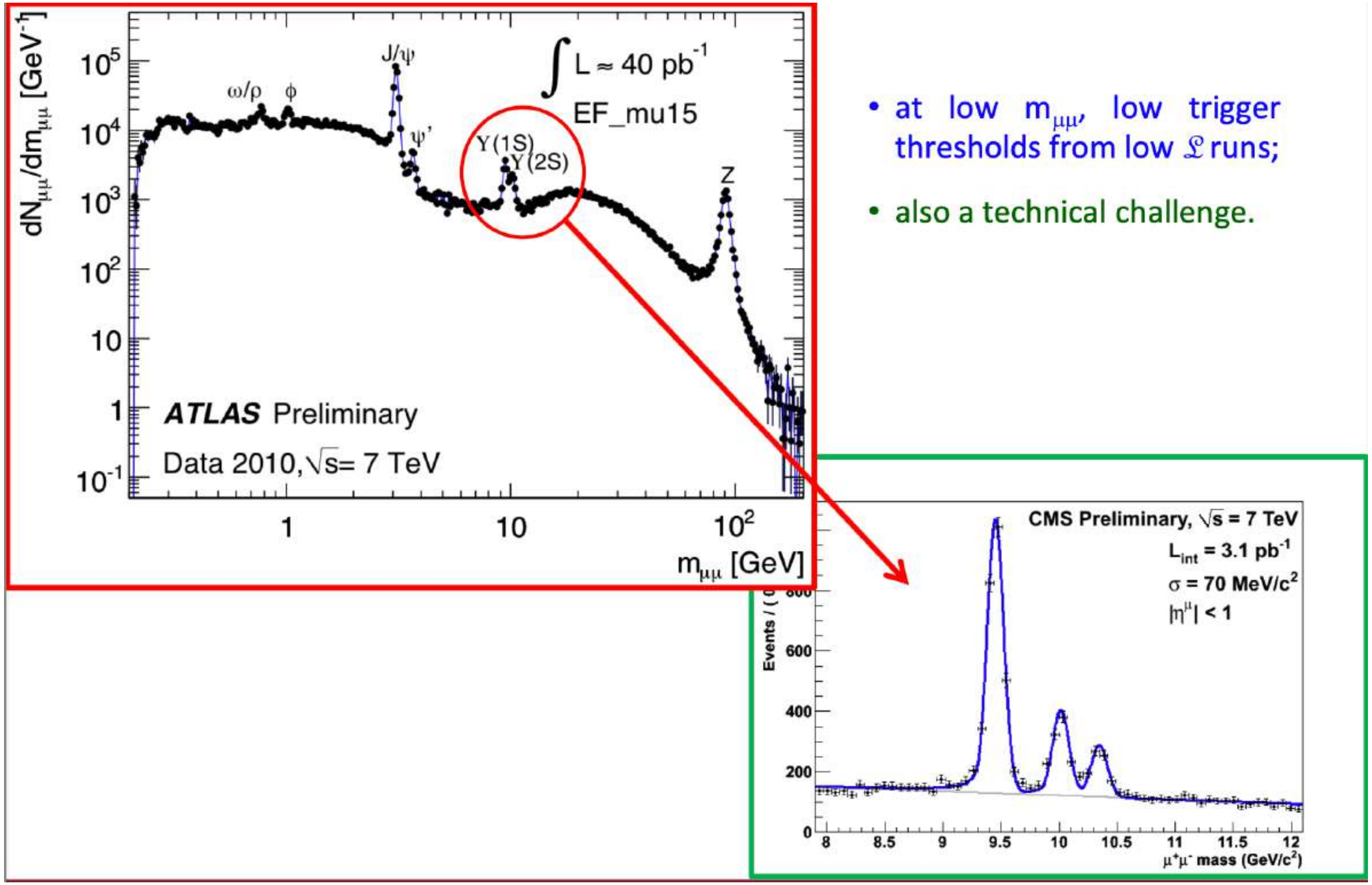


$\Delta p_T/p_T$ vs p_T [project, low η] :

- ▼ meas. error + calib ($\propto p_T$);
- ○ chamber alignment ($\propto p_T$);
- □ multiple scattering ($\propto \approx$const);
- ○ ΔE_μ(calo) fluctuations (tail at high loss measurable from brem shower);
- ○ at spectrometer entrance (= ▼ ⊕ ○ ⊕ □);
- △ total at main vertex (= ○ ⊕ ○).

- at low p_T (p_T < 200 GeV) vtx extrapolation (○) and scattering (□) give the main contributions;
- at high p_T the accuracy of the spectrometer (▼⊕○) dominates;
- at fixed p_T and high η (not shown), Δp_T gets worse.

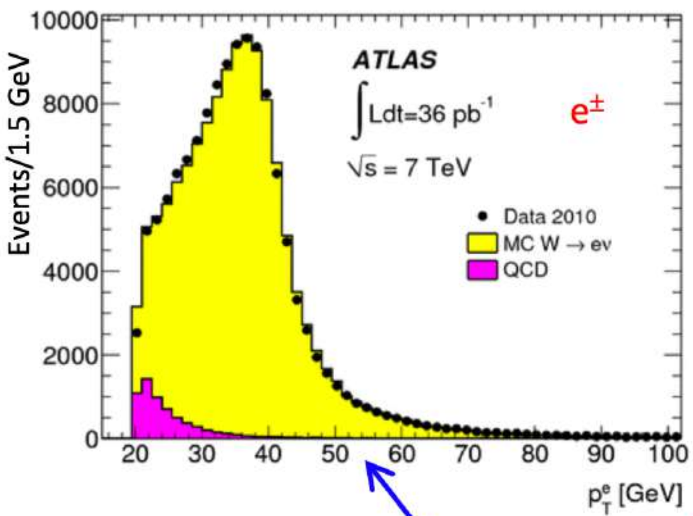
Slide from P. Bagnaia

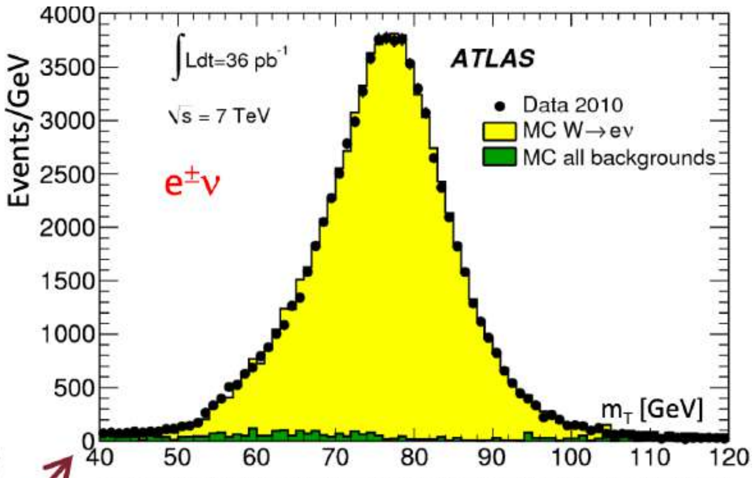


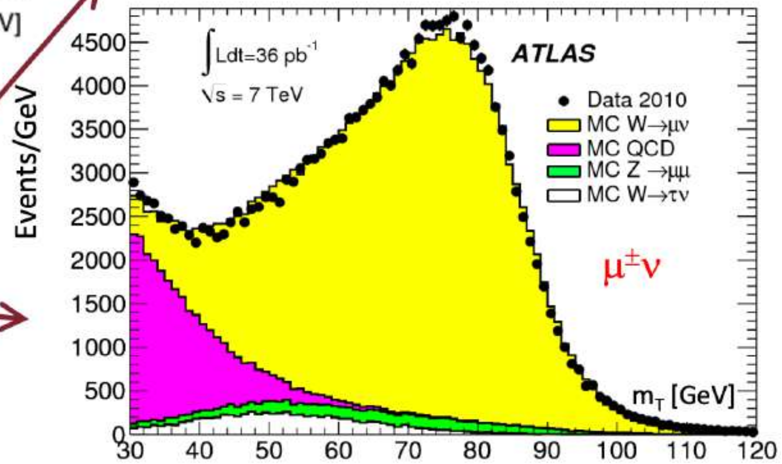
- at low $m_{\mu\mu}$, low trigger thresholds from low $\mathcal{L}$ runs;
- also a technical challenge.

Detector performances: W → ℓ ν

Slide from P. Bagnaia







- the jacobian peak of the $e^\pm$;
- the transverse mass for $e^\pm\nu$ and $\mu^\pm\nu$.

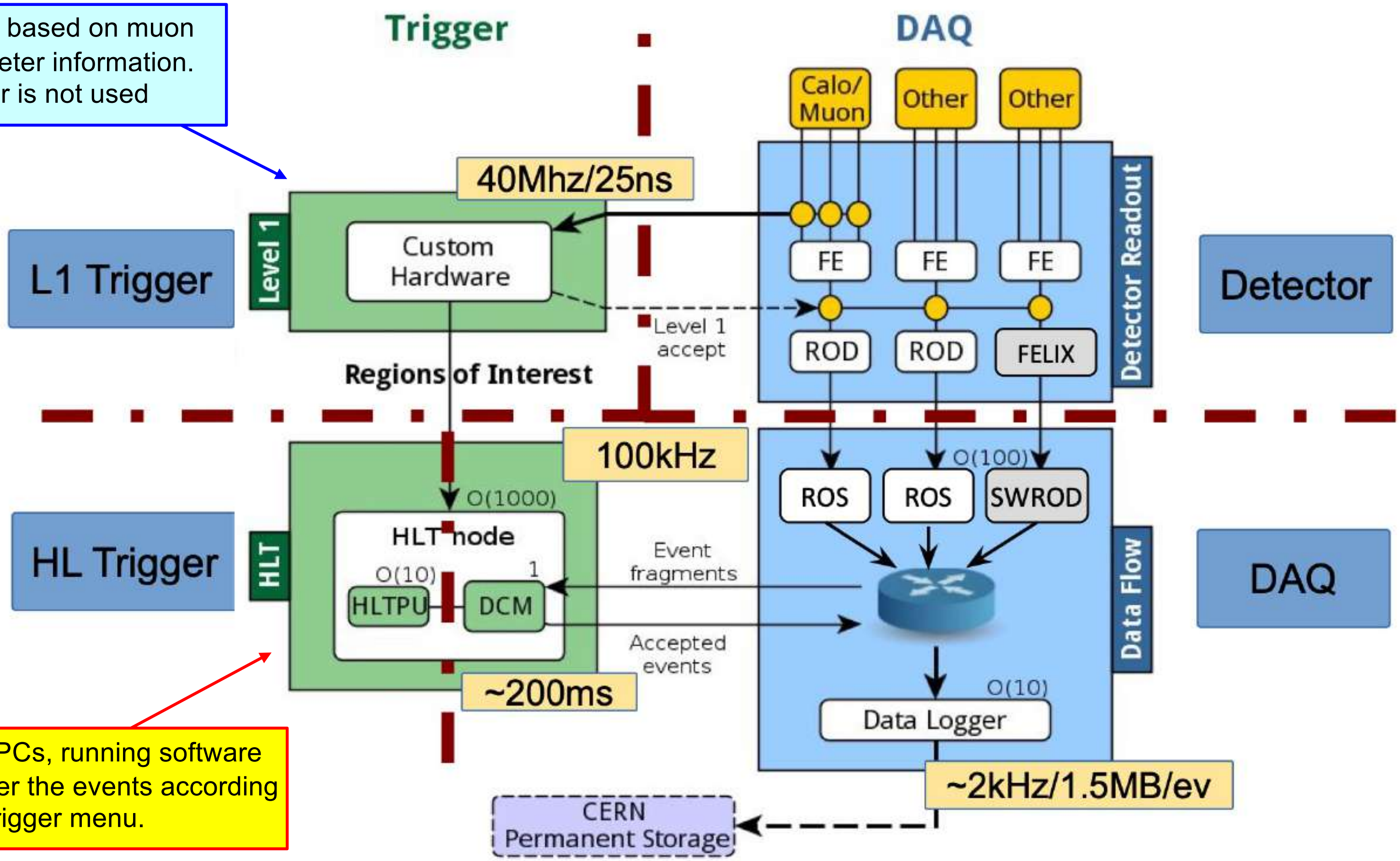
Trigger system

Trigger Concept

- Trigger of interesting events at the LHC is much more complicated than at e+e- machines.
  - At any crossing of the two beams we have proton-proton collision, therefore the interaction rate is 40 MHz
  - At any crossing we have more than one proton-proton collision --> pile up around 50 or more at Run3
- The maximum recording rate depends on the computing I/O technology.
  - currently with event size about 1-2 MB we can record event at a rate of 1-2 kHz (it was 100 Hz in Run1).
  - Therefore the trigger system has to reduce the rate from 40 MHz down to 1-2 kHz: a reduction factor of ~10^4.
- Trigger will cut “physics events”. The challenge is to select the “good” one with the hope/design not to cut the unknown/new events, for instance long living particles decaying in the middle of the detector.
- The time between collisions is 25 ns … too short to have a synchronous L1 trigger.
  - The L1 latency is about a few μs, including time needed for signal transmission. Trigger/DAQ electronics could be as far as 100 m from the the Front End electronics, corresponding to about 0.5 μs of transmission time.
  - A series of pipelines/buffer have been introduced to allow enough time for having a trigger decision. With a latency of 2.5 μs at L1, a buffer with a depth of at least 2500/25=100 is needed to contain events relative to 100 bunch crossing.
- Trigger detectors/electronics must have the capability to identify the bunch crossing that actually gave the trigger → fast detector (like RPC with a resolution time of 2-3 ns) or electronics tricks in other cases.
- Usually the trigger system has been implemented as a two stage trigger.

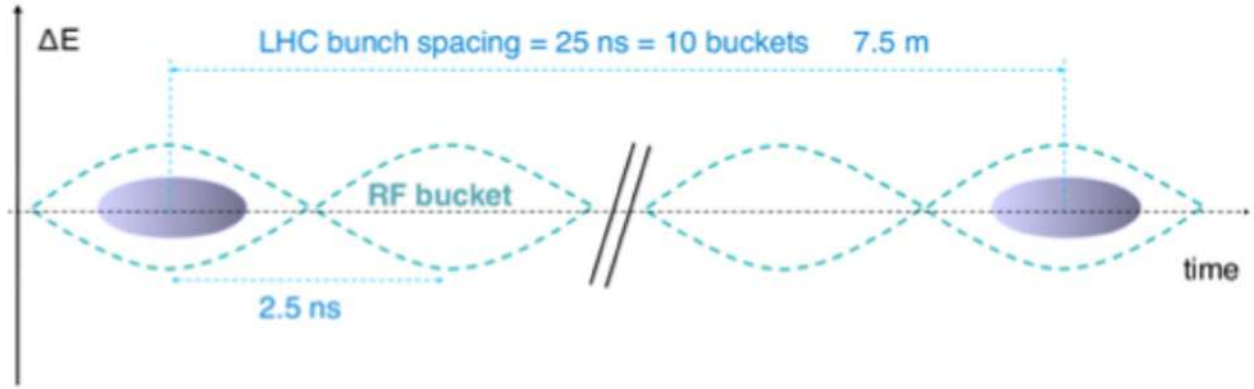
Example: ATLAS DAQ/Trigger overview

L1 trigger is based on muon and calorimeter information. Inner tracker is not used



Farm of many PCs, running software algorithm to filter the events according to predefined trigger menu.

LHC bunch structure



The trigger must know in which BCID should expect a collision.

- LHC bunch spacing of 25 ns corresponds to 10 buckets (7.5 m, 2.5 ns RF buckets)
- 3564 possible bunches in LHC identified by Bunch Crossing Identifier (BCID)
  - → BCID = 0,…., 3563
- A bunch can be filled or empty
  - 2 crossing bunches can be
    - "paired": both beams with protons
    - "unpaired": only one beam with protons
    - "empty": neither beam with protons
  - ATLAS defines additional crossings for special purposes
- A Bunch Group (BG) is a list of BCIDs

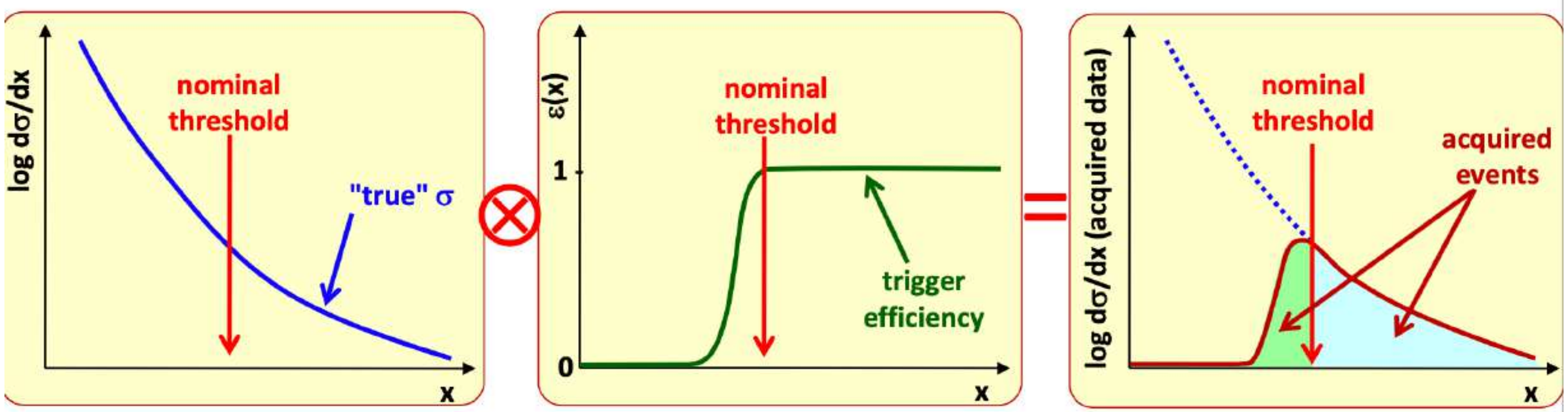
Maximum number of bunches in LHC: 2800; in 2022: ~ 2400 bunches

Bunch structure is defined in the PS

Detector performances: trigger thresholds

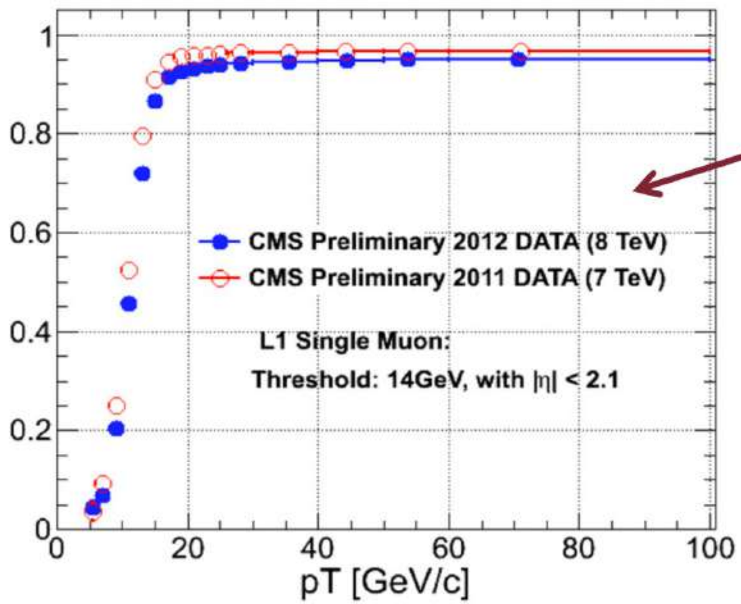
Slide from P. Bagnaia

- e^+e^- : small cross section → [R = $\mathcal{L}\sigma$ ≈ few Hz] → event trigger, i.e. trigger on single bunch crossing, if it contains an event candidate; @ LEP, 1□ ≈ 10^{-3}, negligible dead time;
- $pp(\bar{p}p)$: high hadronic total cross section → [R = $\mathcal{L}\sigma$ ≈ 10^6 - 10^9 Hz] → rates too big (and uninteresting events) → physics trigger, i.e. select a (tiny) fraction of events, which exhibit peculiar characteristics (i.e. high-p_T, multileptons, high $\not{E}_T$ ...); use cuts (i.e. thresholds), user defined in kinematical variables;
- the thresholds are applied on a kinematical variable "x" (e.g. p_T^{lepton}), measured in a rough and fast way by the trigger detector(s); therefore the experimenters have to compromise among rejection, efficiency, dead time, bandwidth ... and physics.



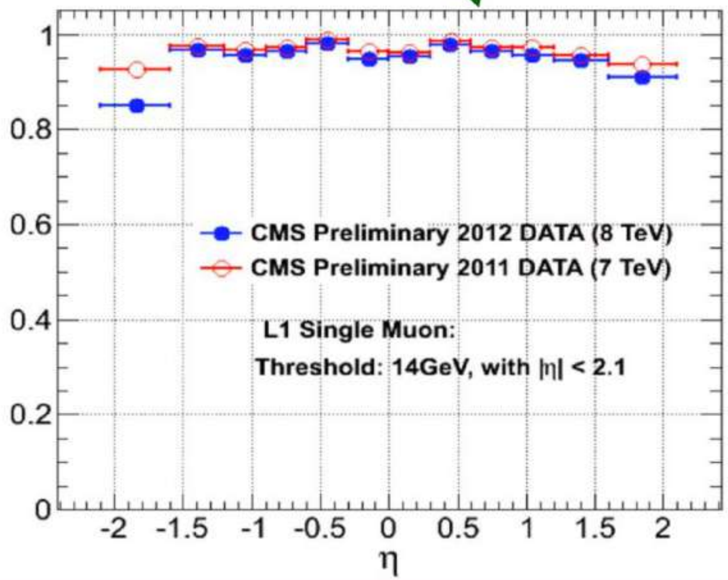
Detector performances: muon trigger level-1

Slide from P. Bagnaia



Efficiency ε at level 1 :

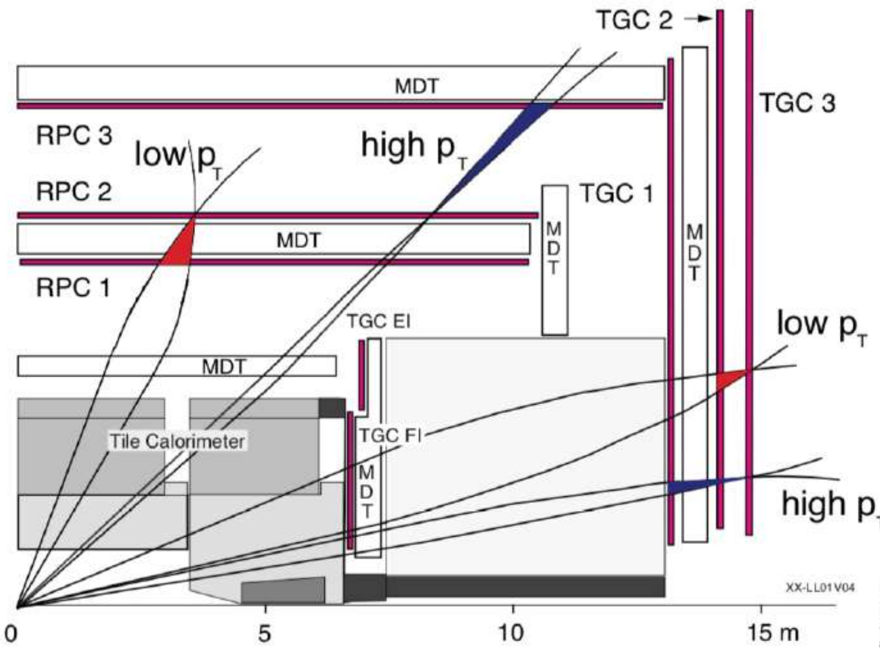
- vs p_T : notice the "size" of the threshold;
- vs η, integrated for p_T > 14 GeV : notice the flatness.



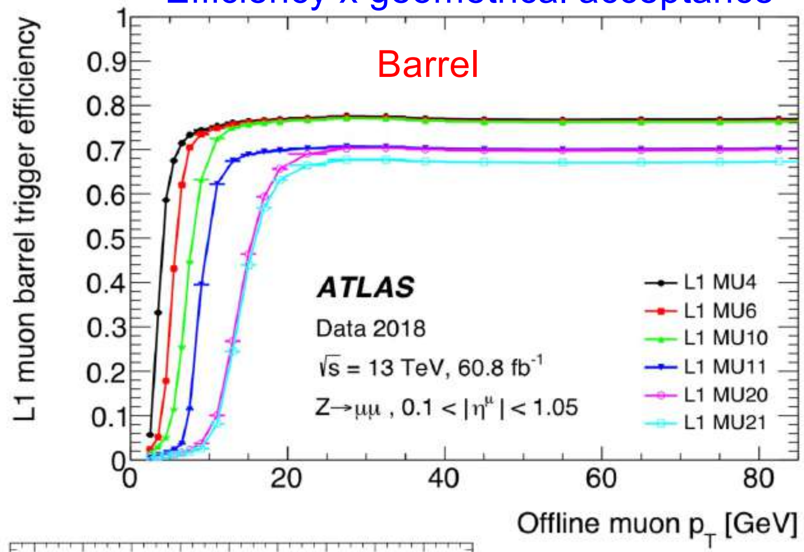
NB the effective yield $N_{obs} = N_{produced} * \varepsilon$:

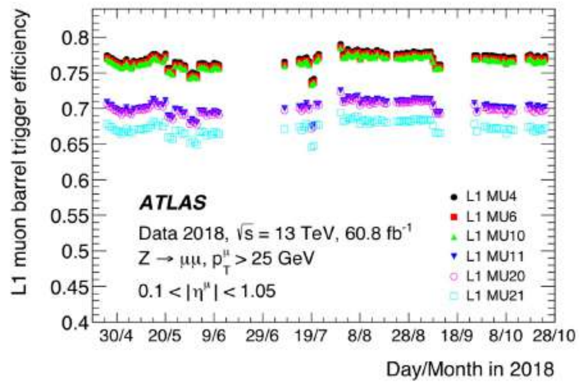
- the bulk of the data is near p_T threshold
- ... where ε is varying;
- ... and the physics less interesting.

ATLAS: L1 Muon Trigger



Efficiency x geometrical acceptance

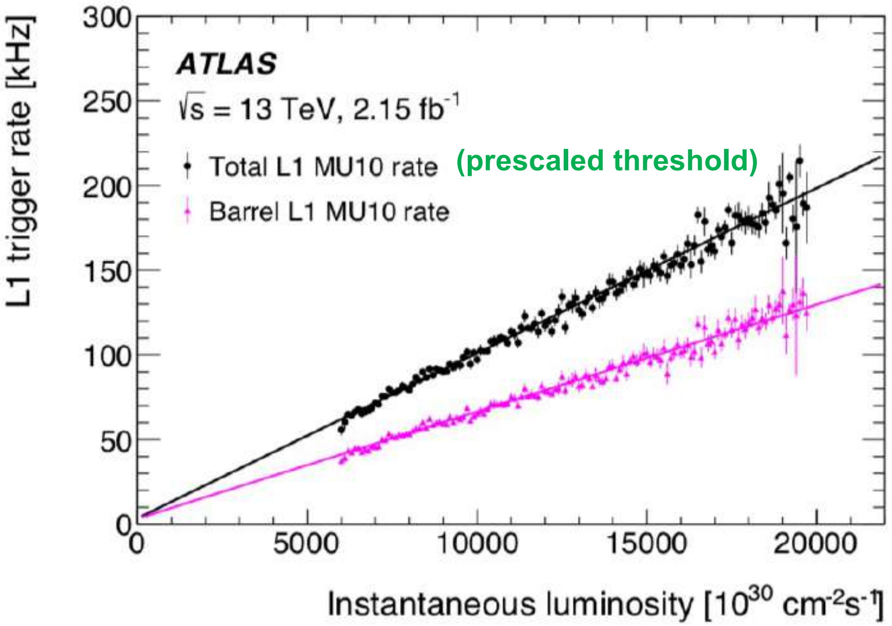


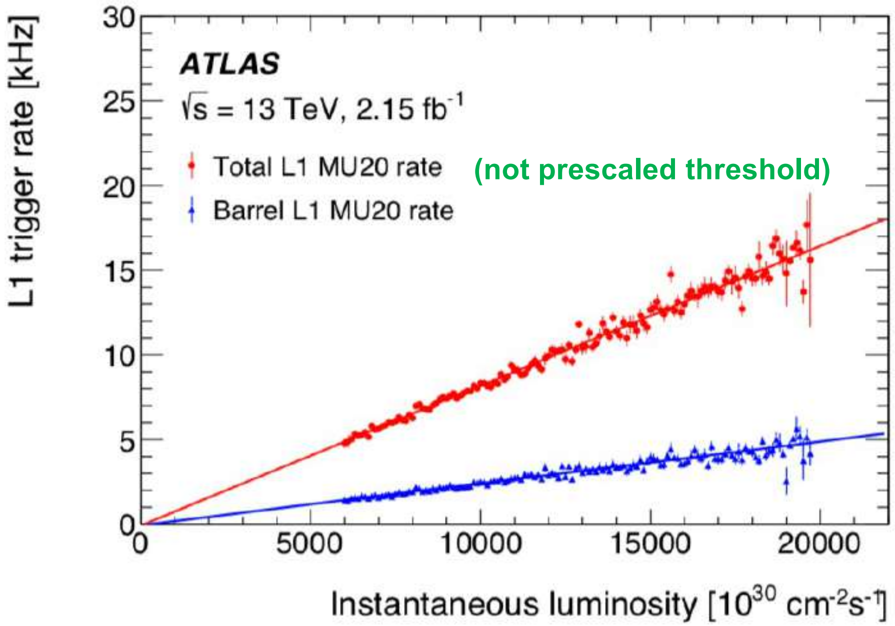


Trigger efficiency as a function of time

ATLAS: L1 Muon Trigger rate (an example)

- A trigger has to be as efficient as possible down to the lowest possible threshold
- On the other hand the trigger rate as to be kept under controll → that implies higher trigger thresholds



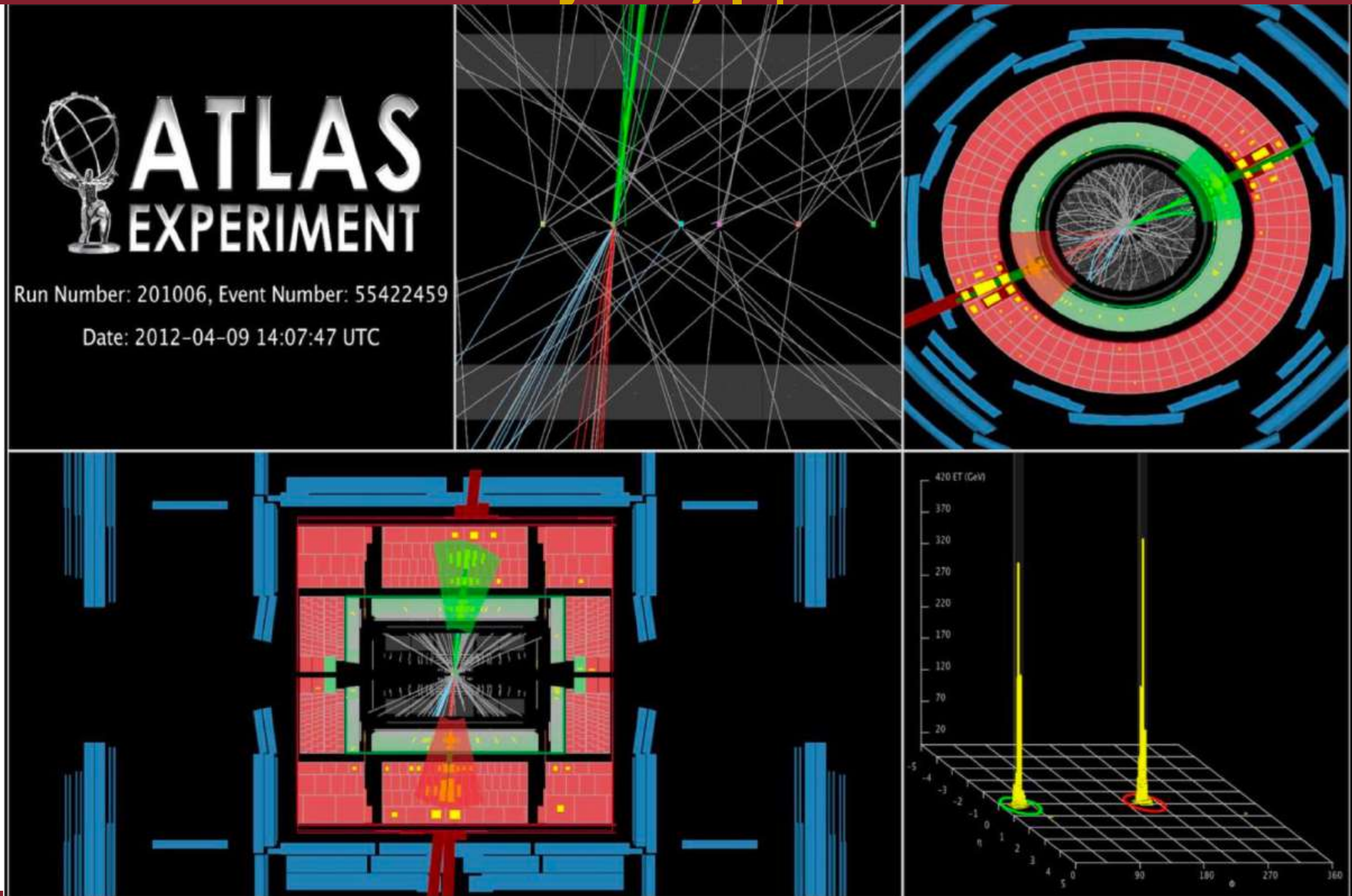


- A compromise between these two conflicting requirements has to be found.
- The trigger menu is changed online (adjusting prescaling factor) as a function of the LHC instantaneous luminosity.
- In any case, for HL-LHC, all trigger electronics will be changed in order to accommodate a L1 rate of ~ 1 MHz.

Event display

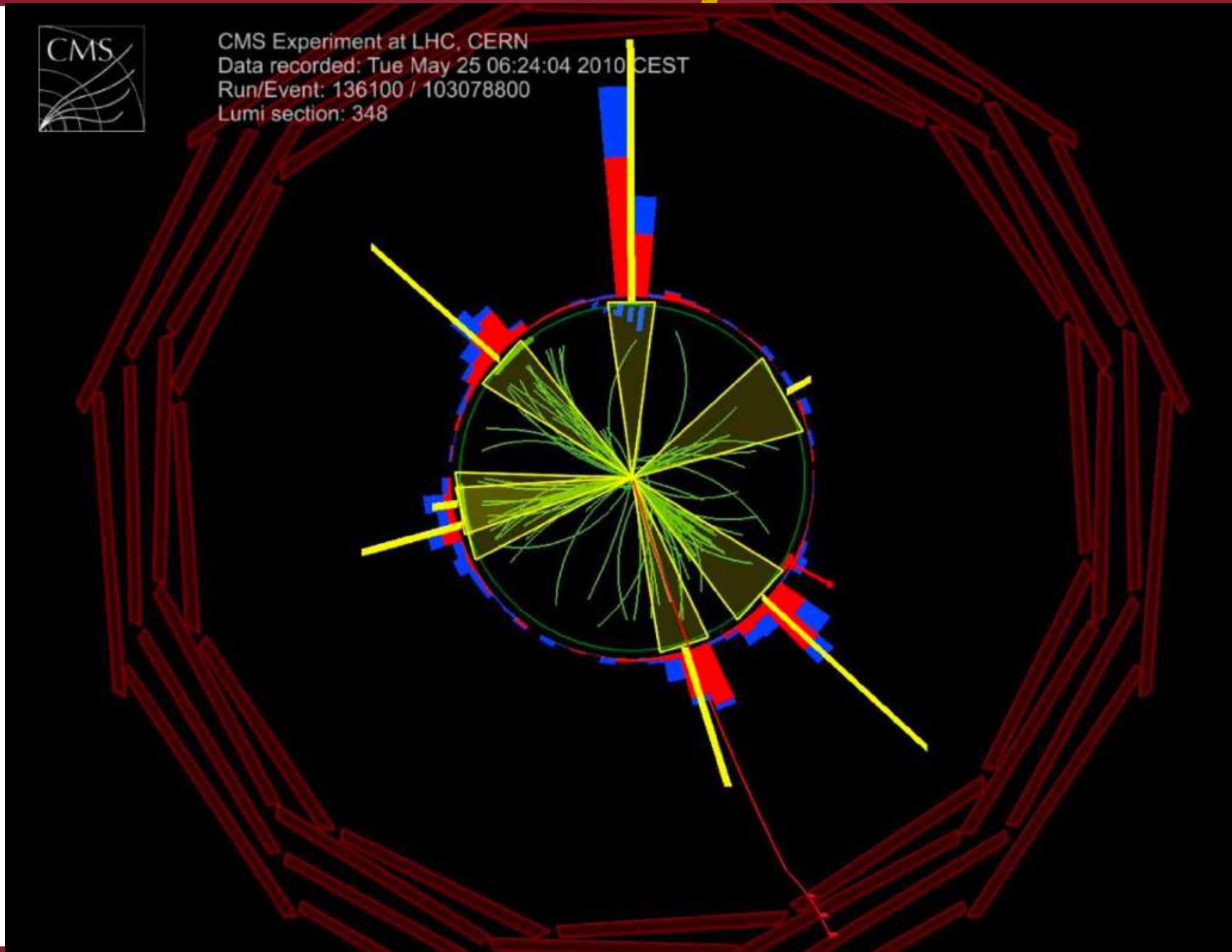
ATLAS: 2 jets ; $p_T \approx 2$ TeV

Slide from P. Bagnaia



CMS: multijet event

Slide from P. Bagnaia



CMS: W → eν

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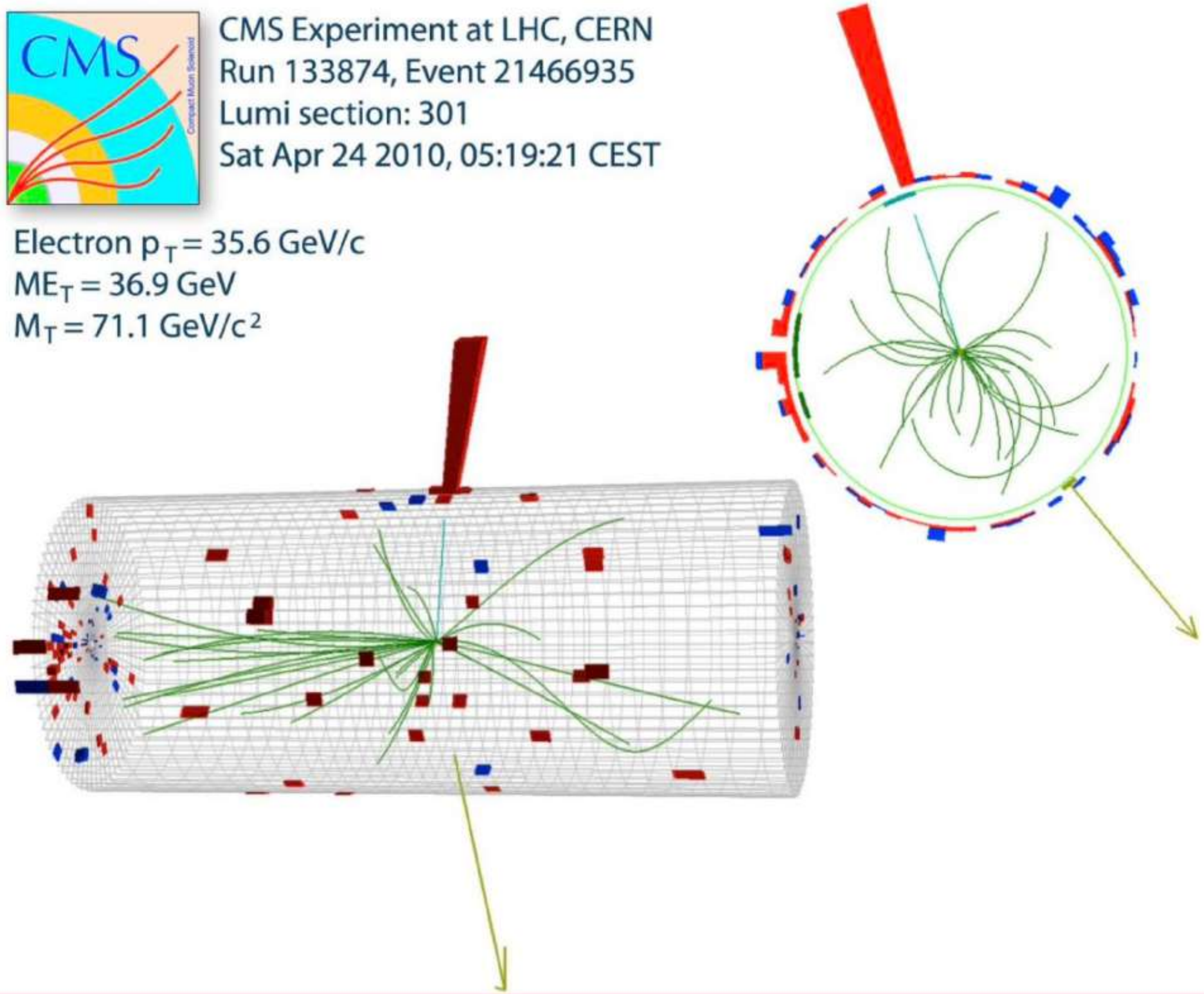
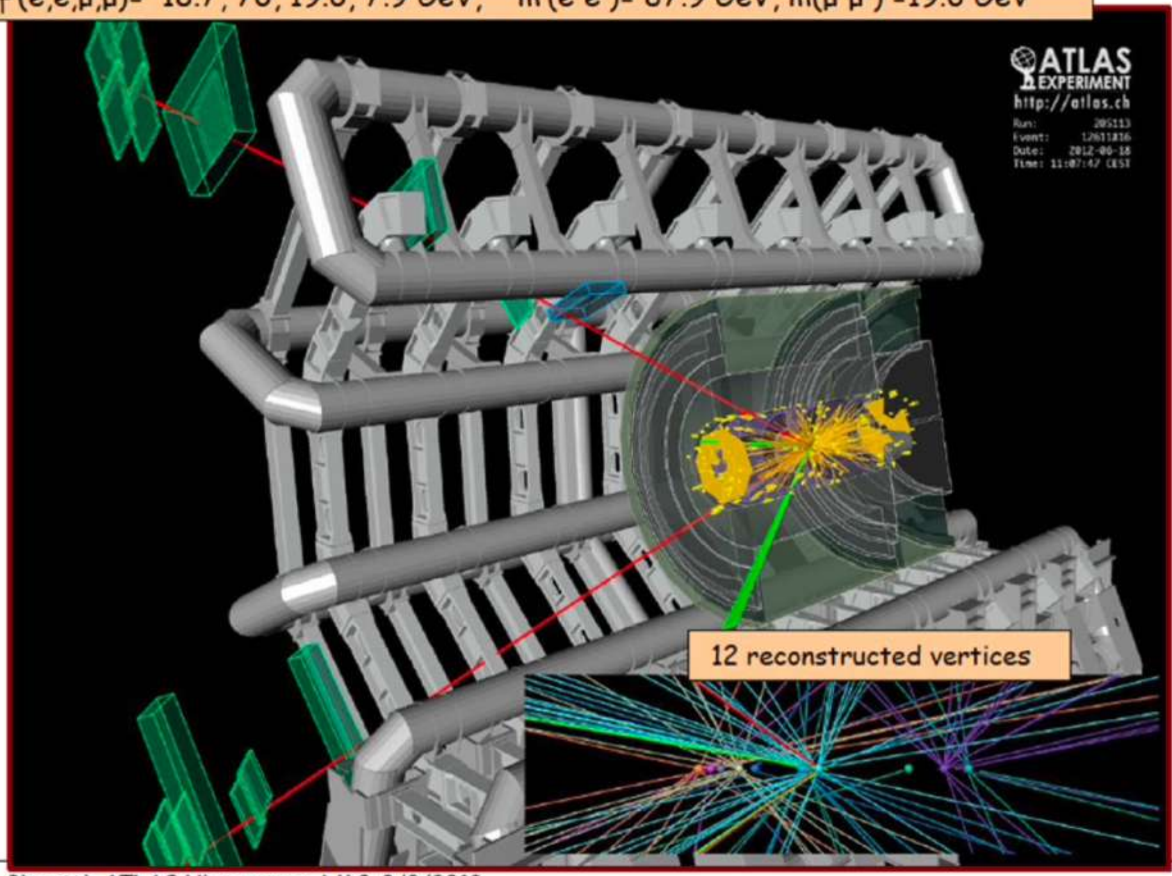


ATLAS: $H \rightarrow ZZ^* \rightarrow (e^+e^-)(\mu^+\mu^-)^*$

Slide from P. Bagnaia

2e2μ candidate with $m_{2e2\mu}$= 123.9 GeV

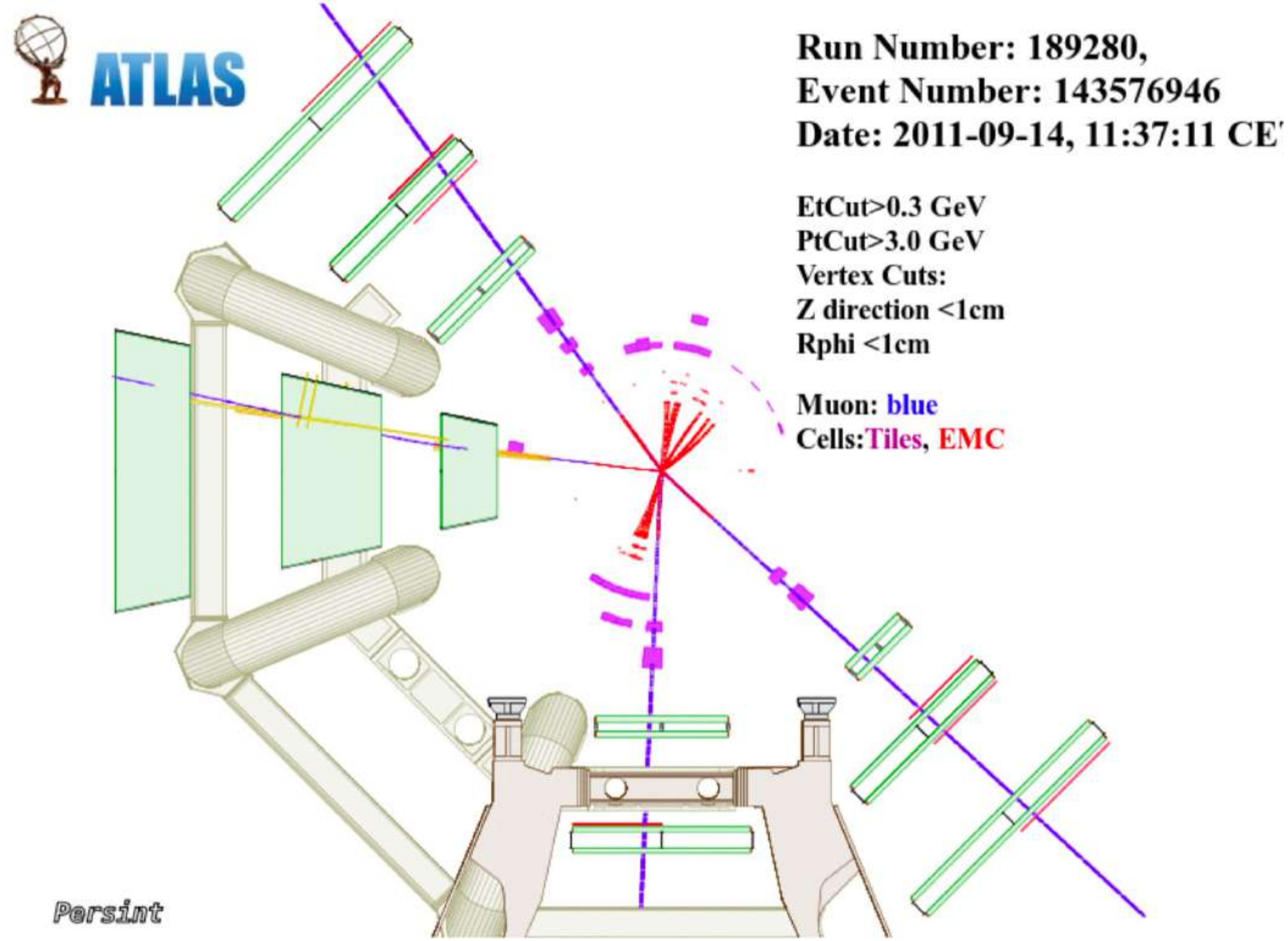
p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV



F. Gianotti, ATLAS Higgs paper, LMC, 8/8/2012

ATLAS: $H \rightarrow ZZ^* \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)^*$

Slide from
P. Bagnaia



ATLAS: H → W^+W^- → $e^+ \nu$, $\mu^- \bar{\nu}$

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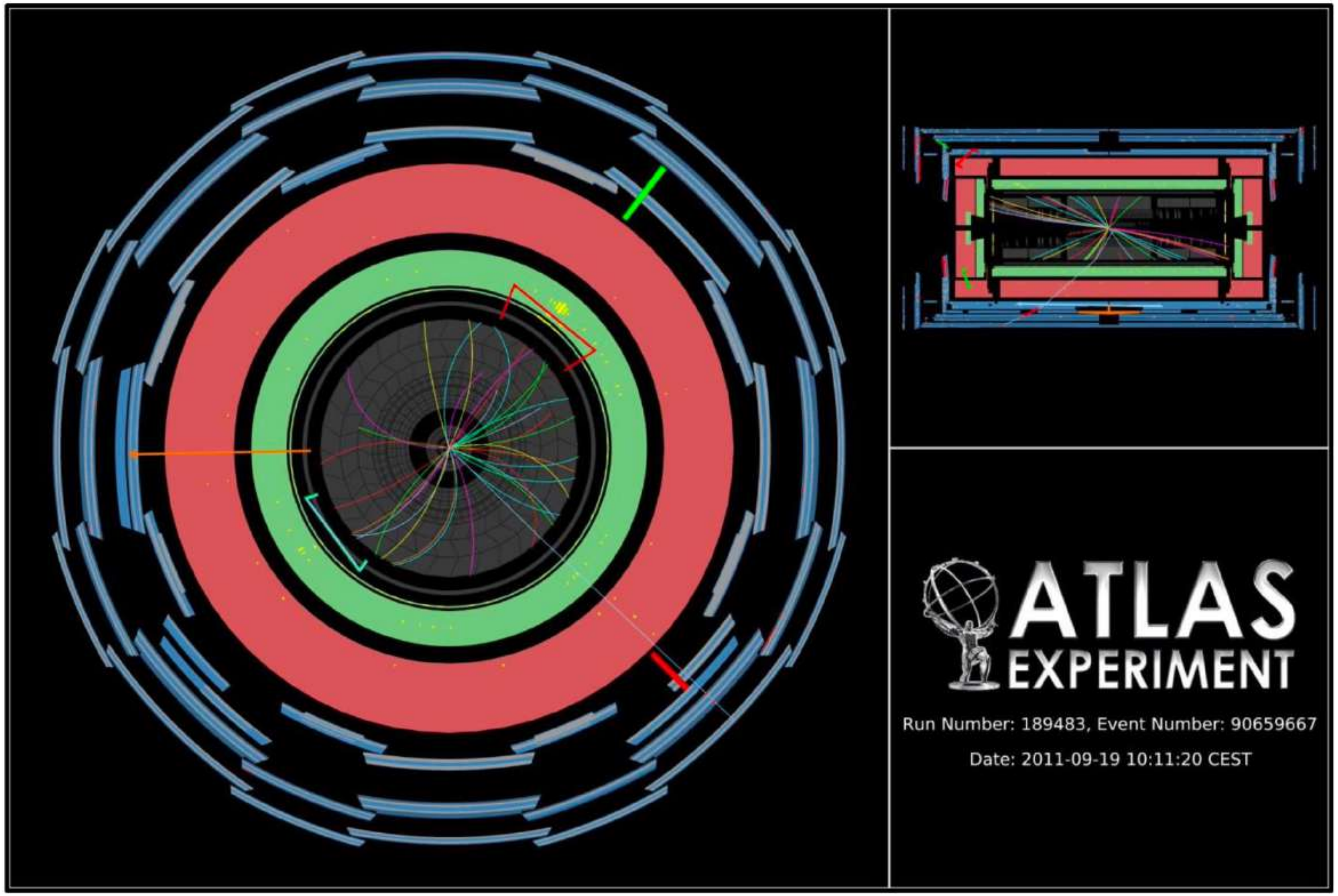

ATLAS: $Z \to \mu^+\mu^-, Z \to \mu^+\mu^-$

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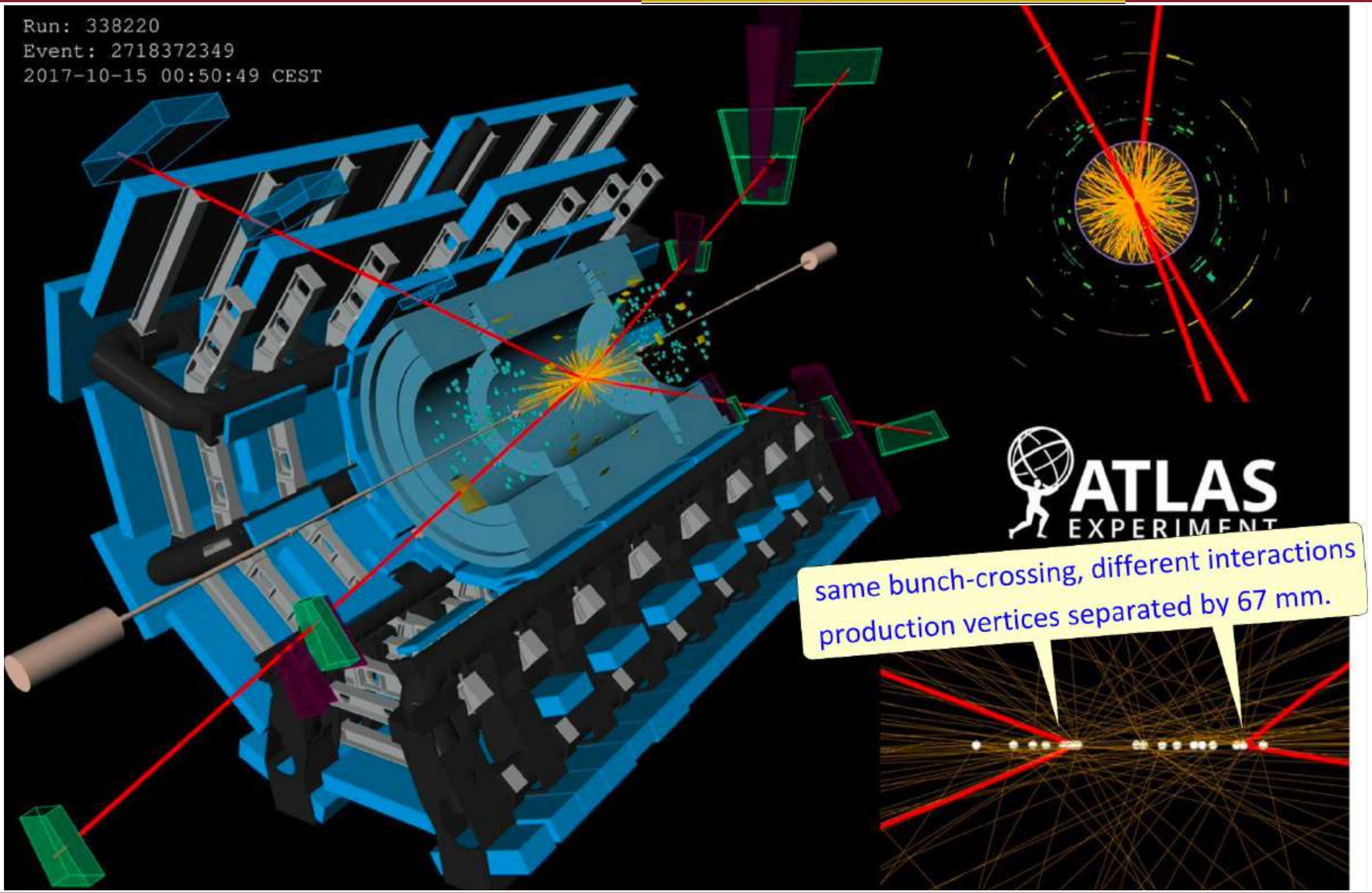

ATLAS: $H \to \gamma\gamma$

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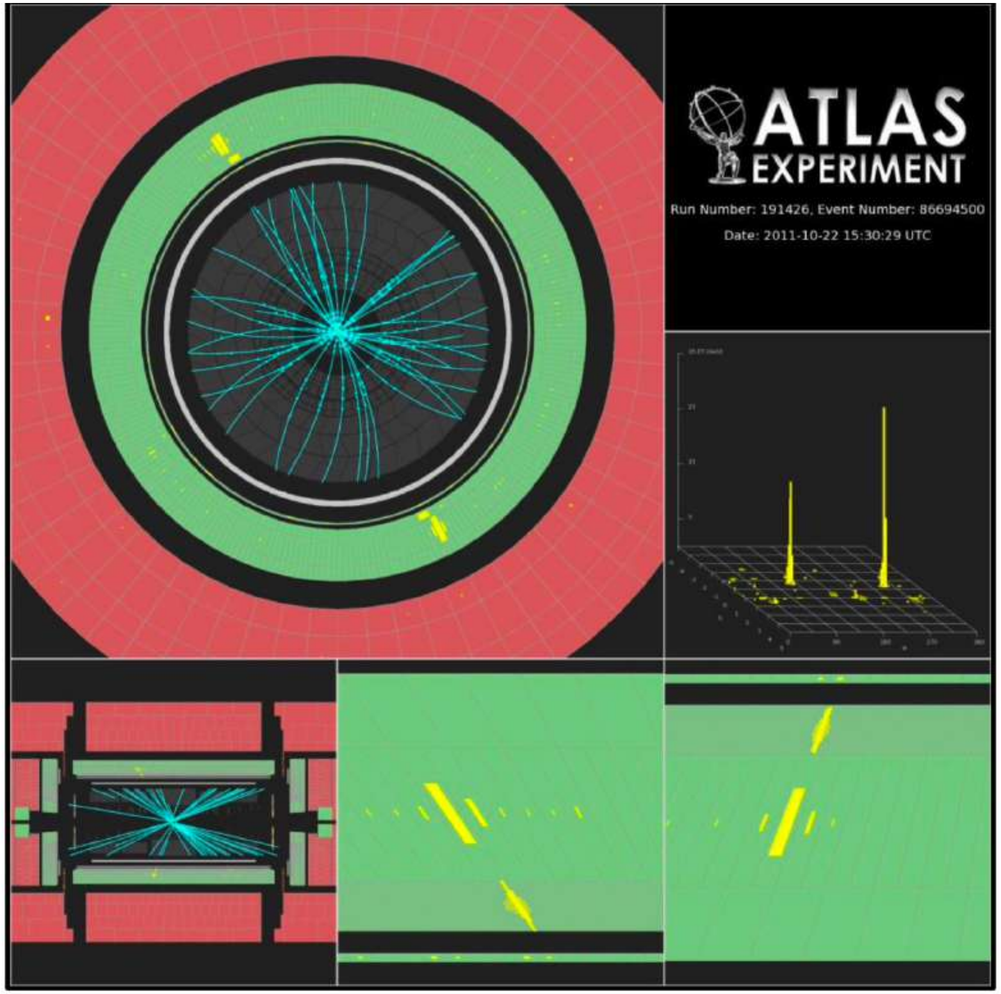
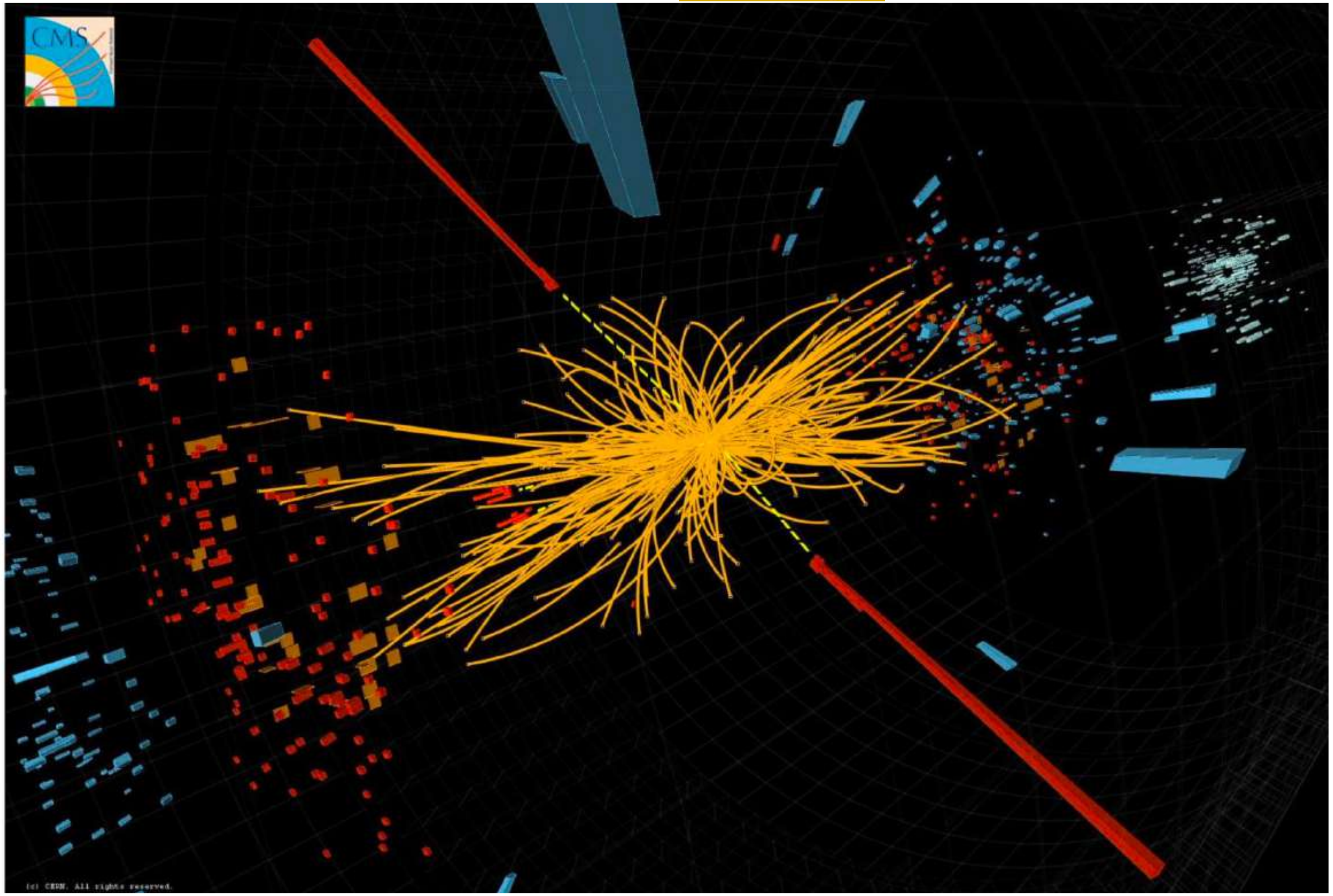
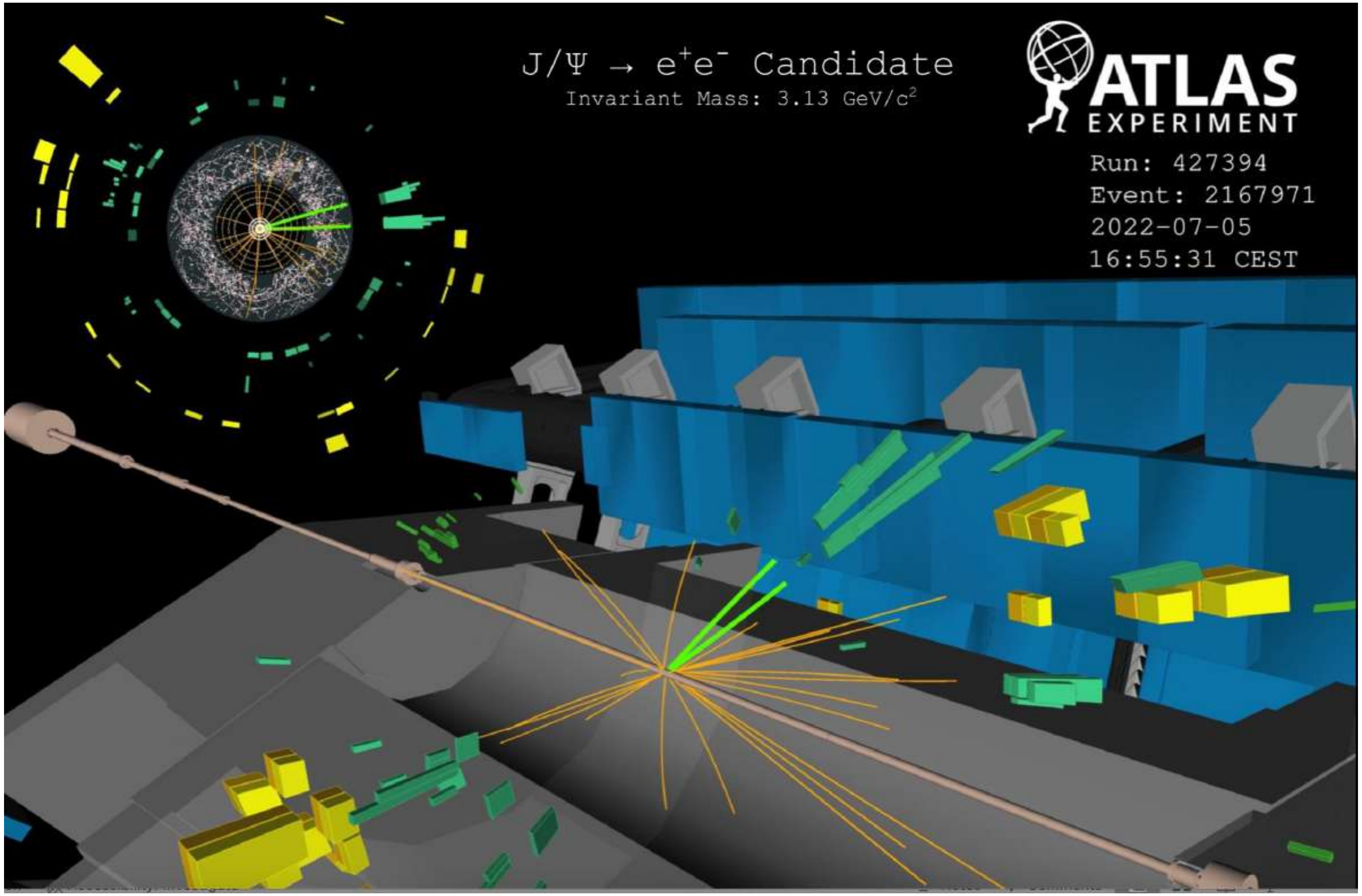


CMS: $H \to \gamma\gamma$

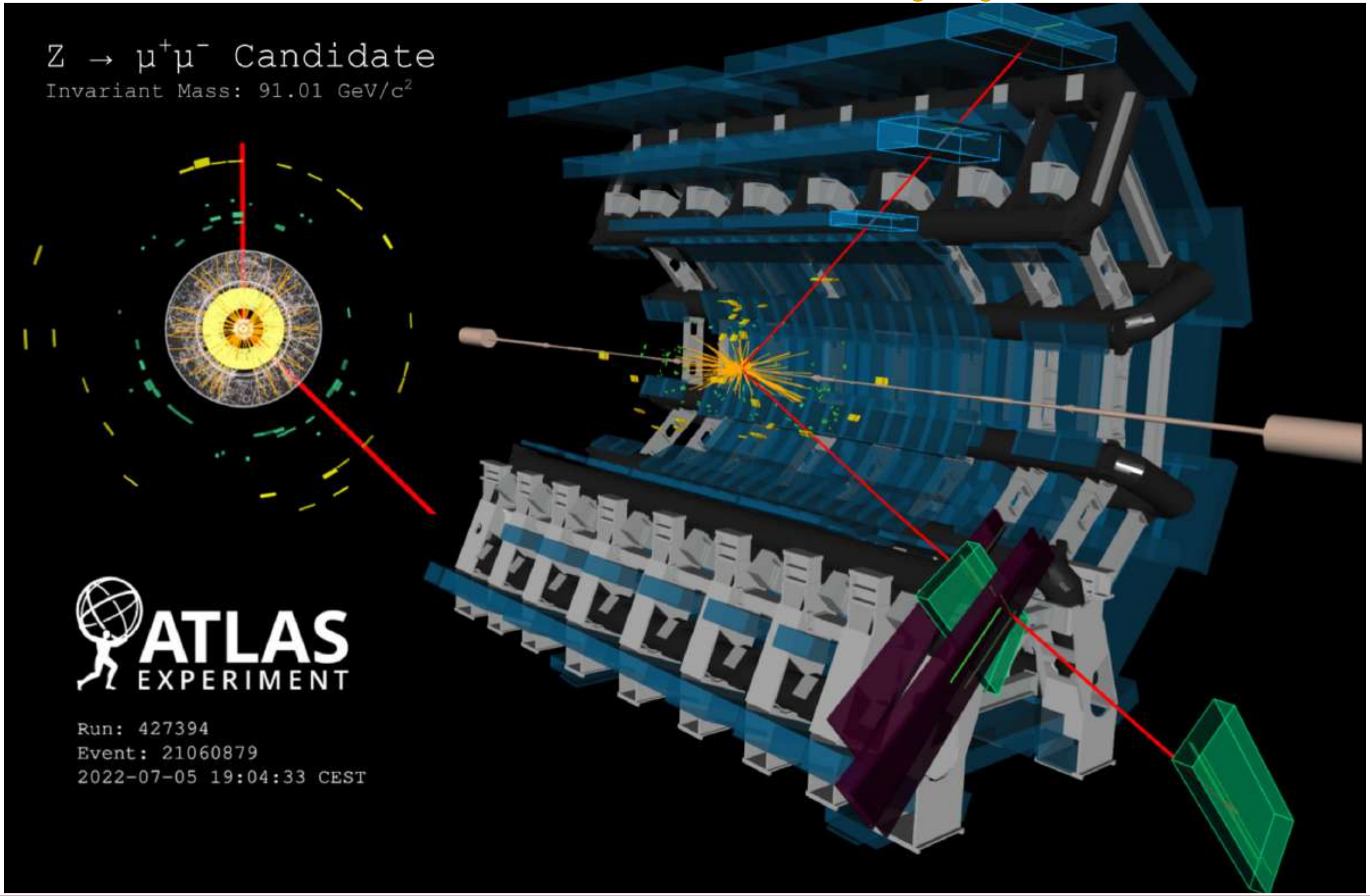
Slide from P. Bagnaia



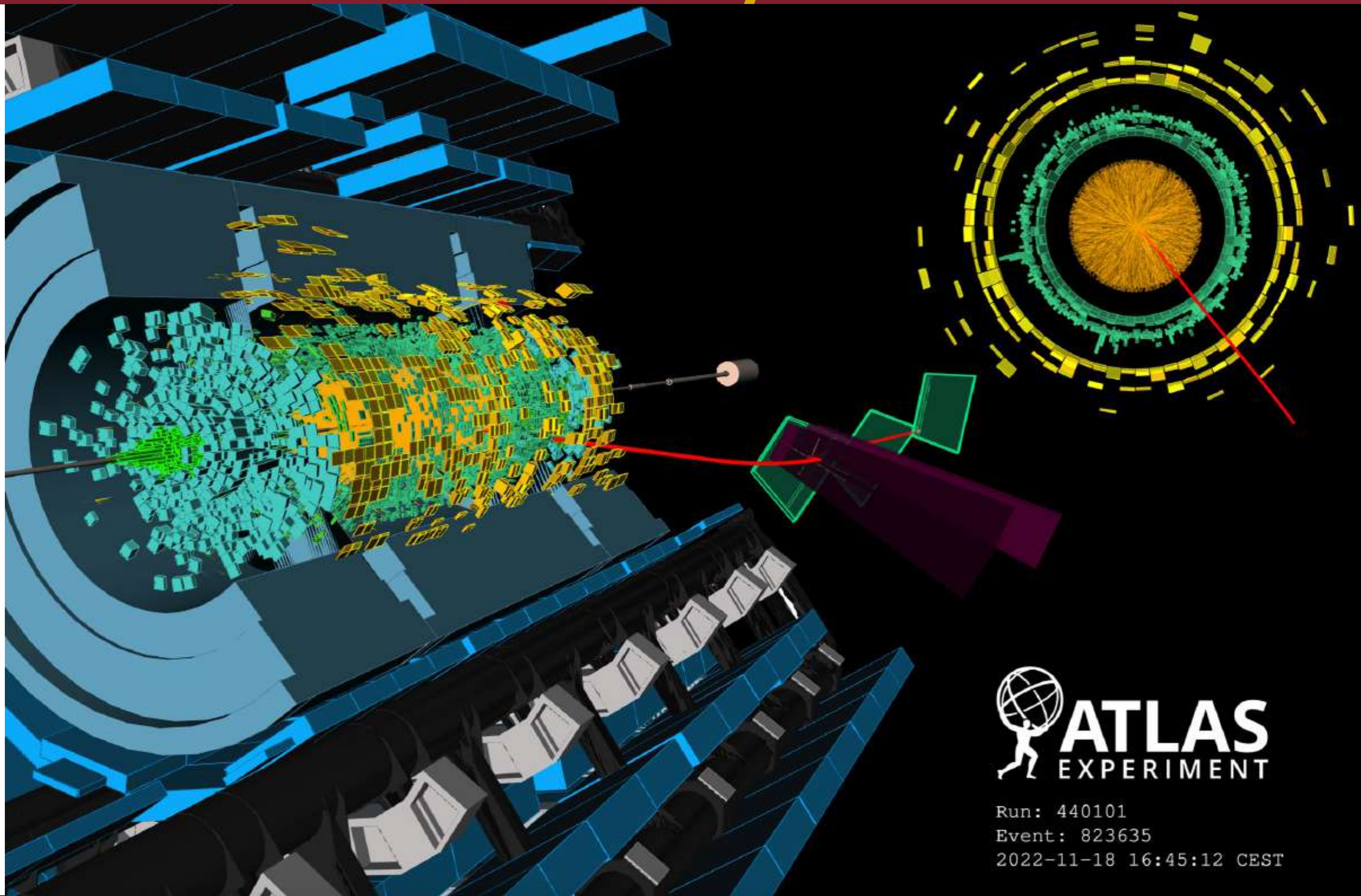
ATLAS Run-3: J/Ψ → e+e-



ATLAS Run3: Z → $\mu^+\mu^-$



ATLAS Run3: heavy ion collision



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End of chapter 10