Collider Physics - Chapter 5a
LHC – machine and detectors

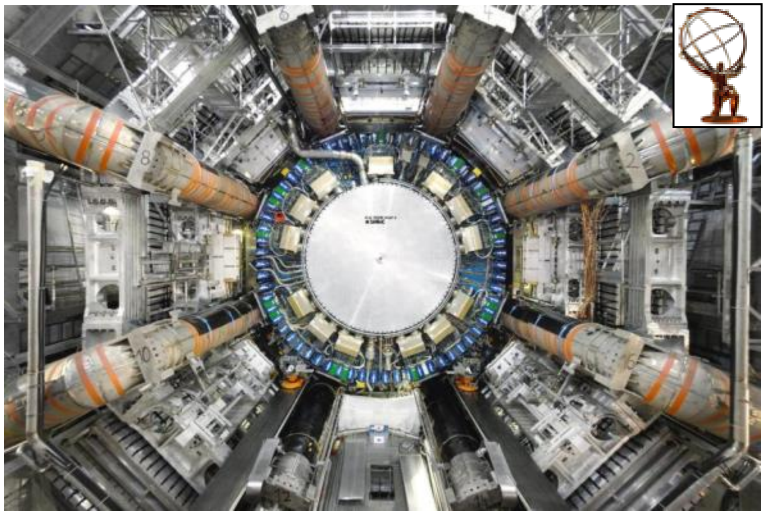
Paolo Bagnaia
SAPIENZA
UNIVERSITÀ DI ROMA

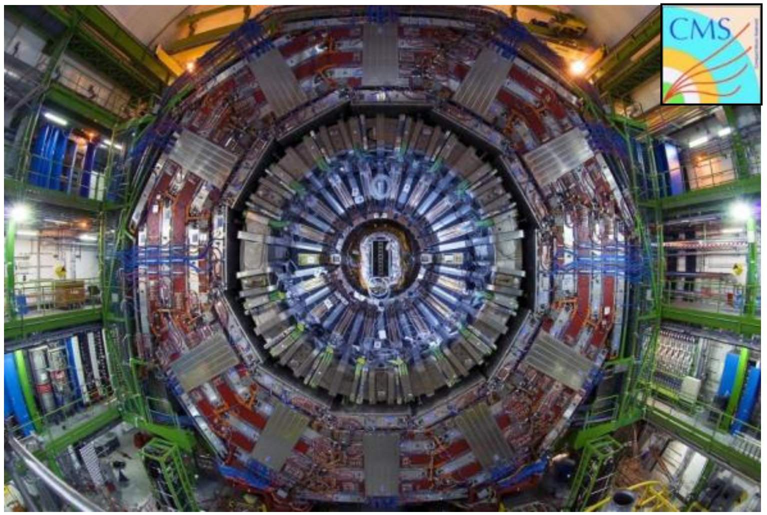
AA 21-22

last mod.
19-Nov-21

5 – LHC – machine and detectors

1. LHC physics
2. The LHC Collider
3. The luminosity
4. The ATLAS detector
5. The CMS detector
6. Detectors comparison
7. Detector performances
8. LHC events





LHC physics

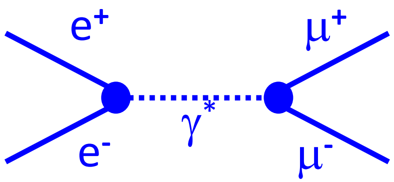
- the LHC physics programme still has a long story ahead;
- [the heavy ion programme is outside the scope of the lectures]
- until now, its results can be broadly divided into three categories :
    a. "bread and butter", i.e. quantitative improvements on soft & SM physics;
    b. the discovery of the Higgs boson [*still exploring the compatibility of the particle with the Higgs boson of the SM*];
    c. searches of physics beyond the SM;
- (a) contains beautiful and intelligent results, from soft physics to jets, from $W^{\pm}$ / Z to top;
- [*we all hope that*] (c) will be the most interesting part;
- it will be reviewed in the next chapter;
- this chapter includes three parts :
    1. a general discussion of the method of analysis of LHC, mainly the problems caused by the high $\mathscr{L}$;
    2. a report of some SM "not-Higgs" studies
    3. a report of the Higgs discovery [*noblesse oblige*], followed by a discussion of the present status of the Higgs analyses;
- the idea is to allow you to enter smoothly in the next section of the game, namely your Thesis and (hopefully) your **individual research activity**.

Enjoy it !

LHC physics: why 10^{34} cm^{-2} s^{-1}

Such a large $\mathcal{L}$ is a must or a luxury ?
Compute two toy processes :

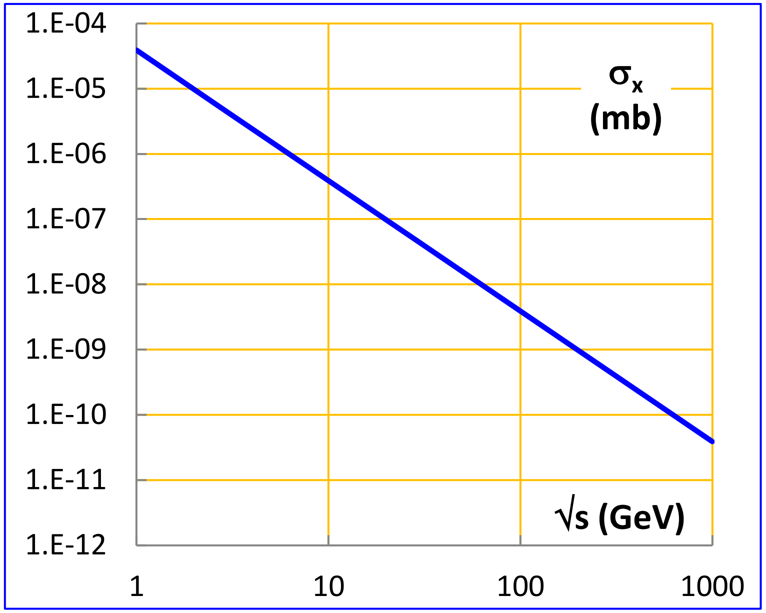
- cross section for a s-channel process :
  - ➢ $\sigma \approx K g^2 / s$;
    Ex. $\sigma[e^+e^- \to \gamma^* \to \mu^+\mu^-] = {}^4/_3\, \pi\, \alpha^2 / s$.
  - ❖ K : adimensional factor ~1 (e.g. $4\pi/3$);
  - ❖ g : coupling constant (e.g. α_{em}, α_s) (it depends on the dynamics);
  - ❖ s : $(\text{energy})^2$ in CM sys ($=4\, E^2_{beam}$ in e^+e^-, * $x_1 x_2$ for hadrons);

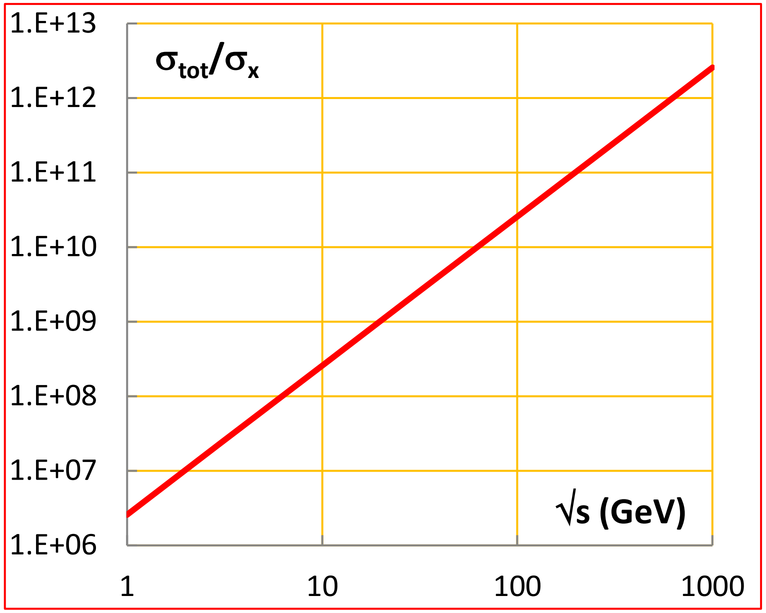


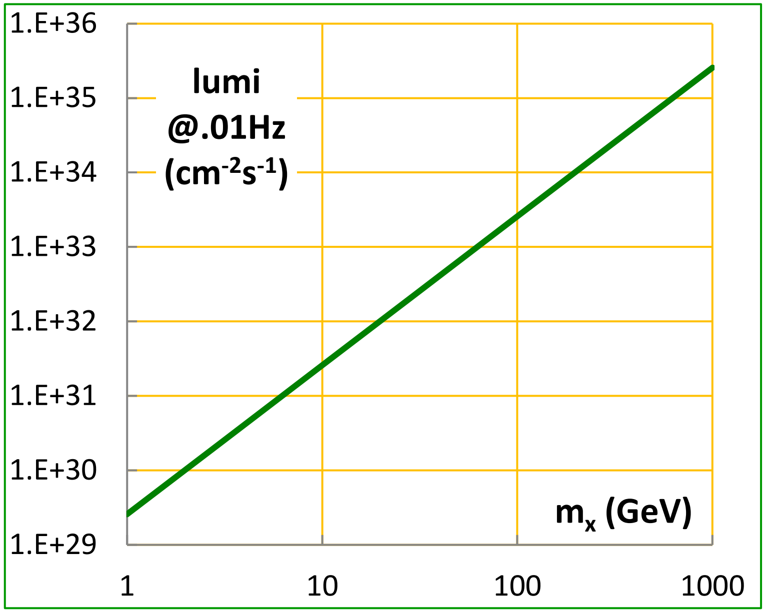
- formation of a resonance (s-channel) [e.g. $\sqrt{s} = m_x = 100$ GeV]:
  - ❖ $g \sim 10^{-2}$;
  - ❖ $m_x \sim 100$ GeV;
  - ➢ $\sigma \approx K g^2 / m_x^2 =$
    $= [0.389 \text{ GeV}^2 \text{ mb}] \times 10^{-4} / 10^4 \approx$
    $= 4 \times 10^{-36}$ cm^2;

[*of course, it is too simplistic : parton structure functions (pdf), decay BR, detector acceptance, analysis inefficiencies are neglected; but all these effects DECREASE the yield or the identification of the effects.*]

LHC physics: plots for 10^{34} cm^{-2} s^{-1}







these plots show the trend vs $\sqrt{s}$ of :

- σ_x : s-channel cross section just defined;
- σ_{tot}/σ_x : if $\sigma_{tot} \approx$ 100 mb, ratio between number of events and interesting ones;
- lumi@.01Hz : $\mathscr{L}$ to get a rate of .01 Hz for the m_x just defined;

∴ obvious, but concerning →

high $\mathscr{L}$ is a must.

LHC physics: events at 10^{34} cm^{-2} s^{-1}

How many (interesting) events? an estimate of the order of magnitude for pp at $\sqrt{s}$ = 14 TeV:

- "average year" ~ 10^7 s;
- $\mathcal{L}_{max} \approx 10^{34}$ cm^{-2} s^{-1};
- ➢ $\mathcal{L}_{int} \approx 10^{41}$ cm^{-2} = 100 fb^{-1};
- last column roughly includes the detection efficiencies;
- clearly, it is NOT possible to record all these events (→ act on trigger/selection).

Process	σ (pb)	rate (@ 10^{34} cm^{-2} s^{-1})	events / year
collisions (bc)	---	4×10^7	4×10^{14}
events	1×10^{11}	1×10^9	10^{16}
$W \to e\nu$	1.5×10^4	150	10^9
$Z \to e^+e^-$	1.5×10^3	15	10^8
$t\bar{t}$	800	8	10^8
$b\bar{b}$	5×10^8	5×10^6	10^{13}
$\tilde{g}\tilde{g}$ (SUSY) [m_g =1 TeV]	1	0.01	10^5
Higgs [m_H=125 GeV]	20	0.2	2×10^6
QCD jets [p_T>200 GeV]	10^5	1000	10^{10}

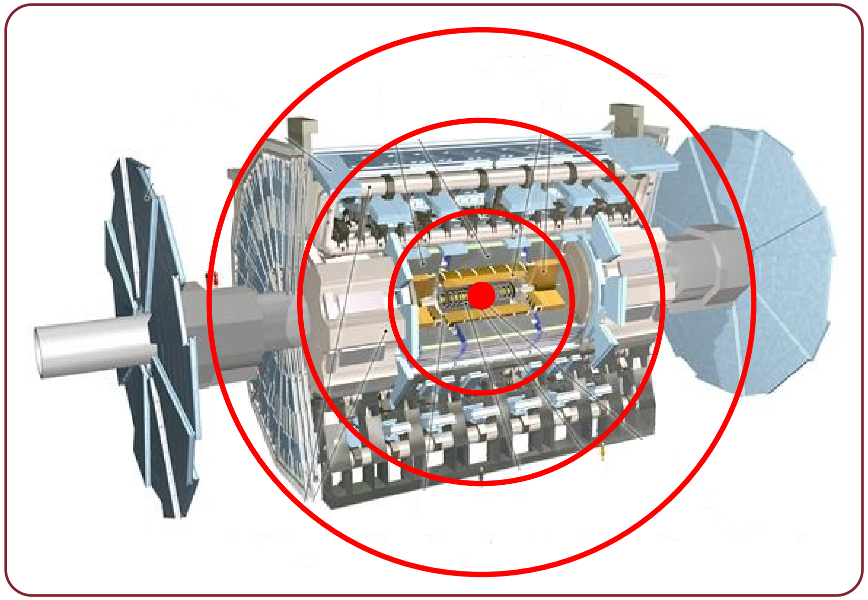
LHC physics: DAQ at 10^{34} cm^{-2} s^{-1}

[σ_{tot}(pp) is a fundamental parameter of the Nature; however, here we study it only as an obstacle to observe high-p_T collisions]

- $\mathcal{L} \approx 10^{34}$ $cm^{-2}s^{-1}$ (actually higher);
- τ_{bc} = 25 ns
- $f_{bc} = 1/\tau_{bc}$ = 40 MHz;
- $\sigma_{tot} \approx$ 100 mb (= 10^{-25} cm^2);
- therefore :
  - ➢ R_{int} ≈ 1 GHz;
  - ➢ $\mathcal{L}_{bc}$ = 2.5 ×10^{26} cm^{-2};
  - ➢ n_{bc} = 25 events / bc;
  - ➢ $n_{inelast}$ ≈ 20 events / bc;
  - ➢ $N^{\pm}_{partic.}$ ≈ 1000 / bc;
  - ➢ $dN^{\pm}/d\eta$ ≈ 100 / bc;
  - ➢ $W_{detect.}$ ≈ 3 kW;
  - ➢ Δs_{bc} = 25 ns × c = 7.5 m;

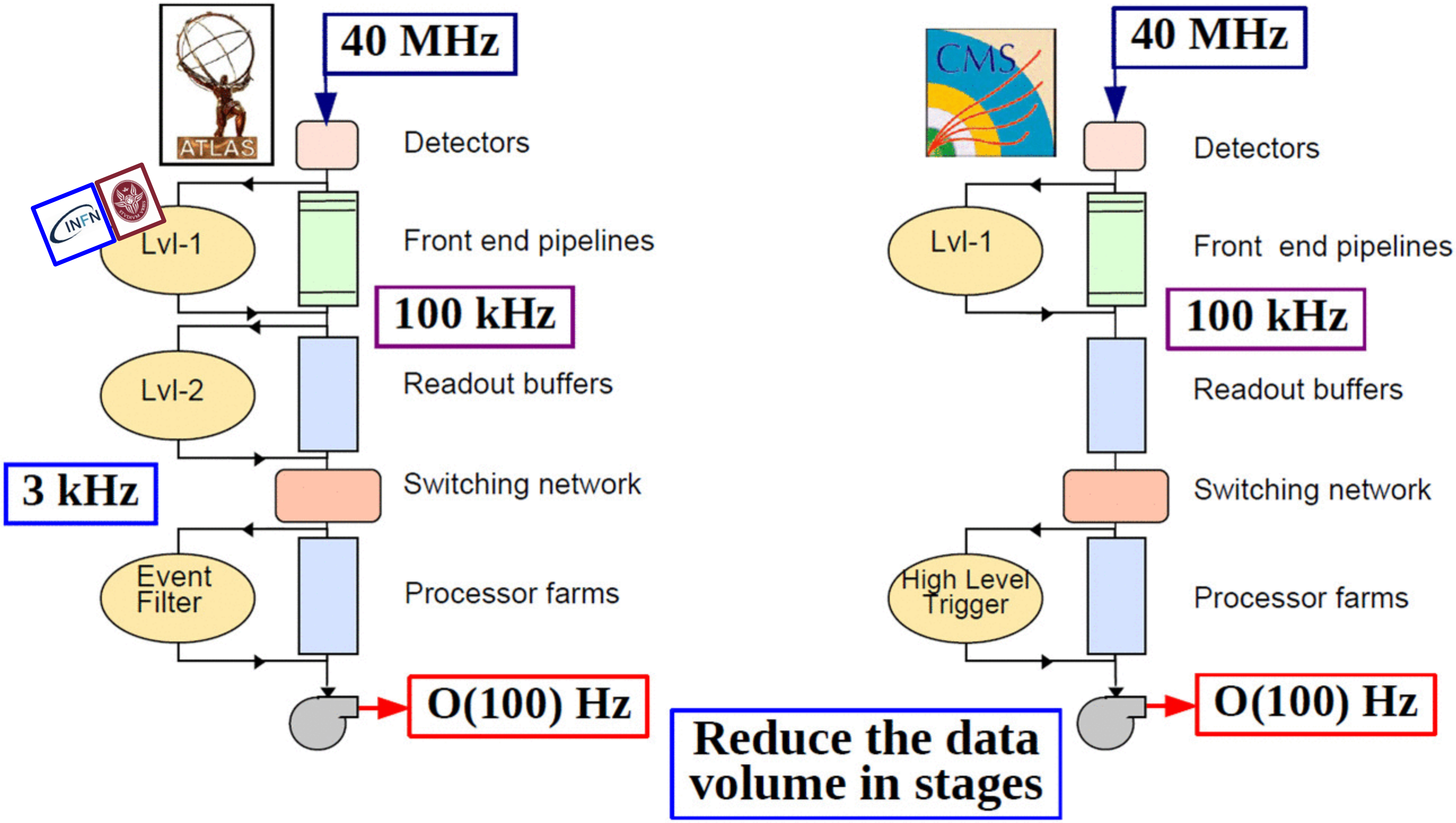
do you see the paradox ?

- i.e. there are "waves" of ~1000 $\pi^{\pm}$ (+ as many γ's) every 25 ns;
- the waves are on concentric spheres at 7.5 m each other (e.g. at the same time the muon chambers "see" previous bc's respect to the inner detector);
- the detectors must have an adequate bandwidth to cope with it (and the necessary radiation resistance !!!).



LHC physics: trigger at 10^{34} cm^{-2} s^{-1}

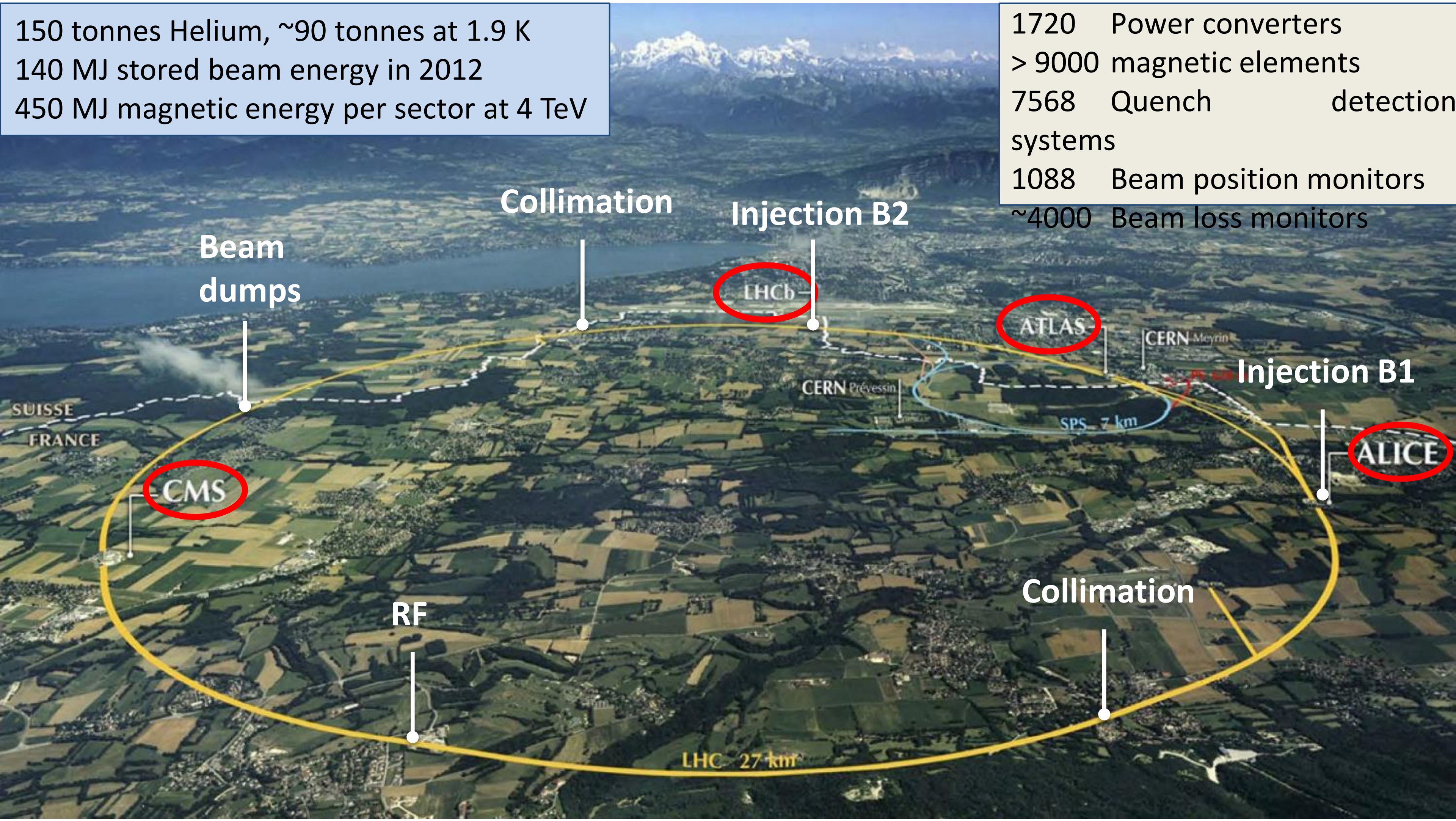
Trigger Setup



The LHC Collider

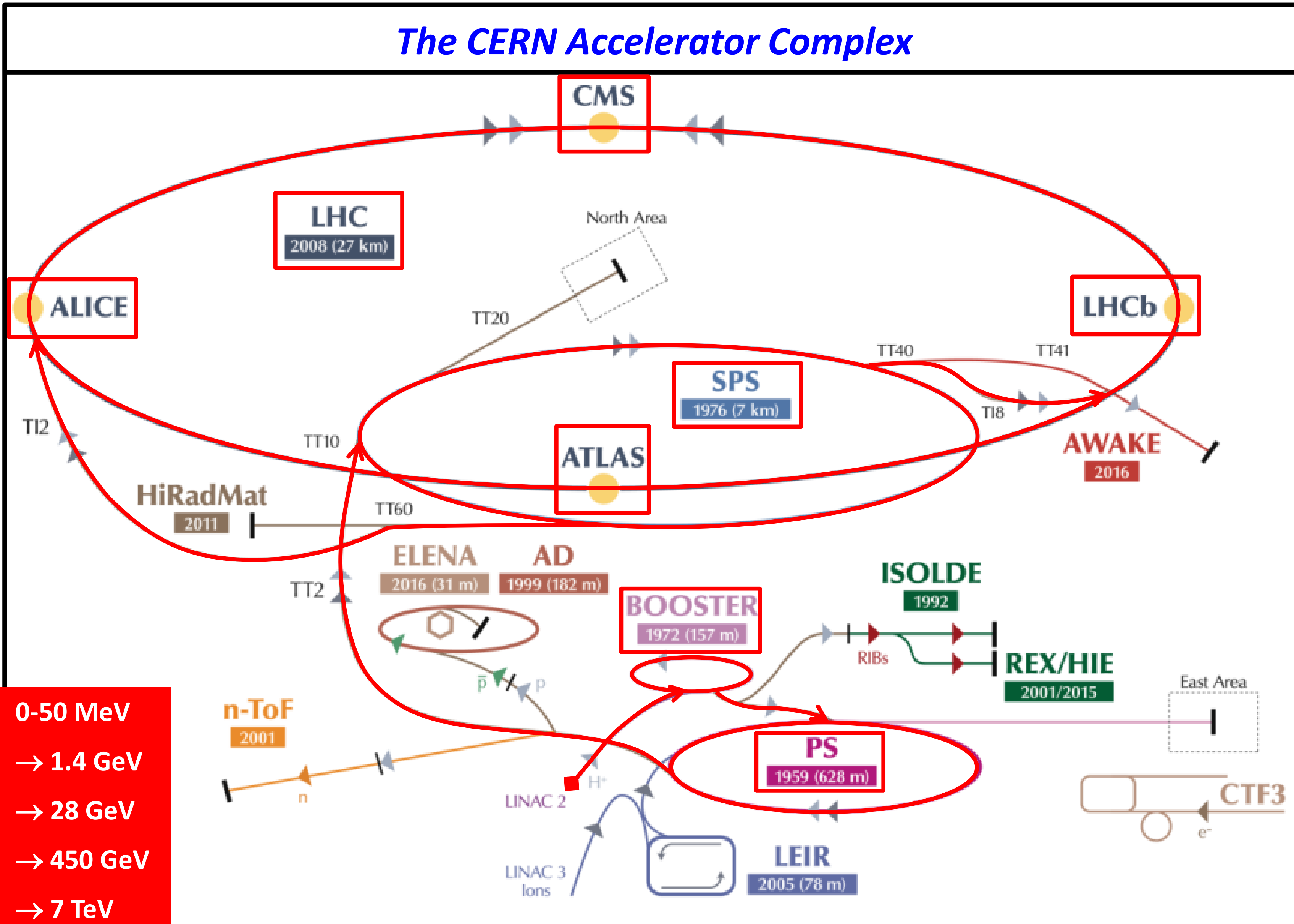
150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
450 MJ magnetic energy per sector at 4 TeV

1720	Power converters
> 9000	magnetic elements
7568	Quench detection systems
1088	Beam position monitors
~4000	Beam loss monitors



The LHC Collider: a view

The LHC Collider: the complex



Linac2	0-50 MeV
PSB	→ 1.4 GeV
PS	→ 28 GeV
SPS	→ 450 GeV
LHC	→ 7 TeV

The LHC Collider : parameters

Date	2009	2012	2015	nomin.
Maximum beam energy (TeV) ↑	3.5	4	6.5	7
Delivered integrated luminosity (fb^{-1}) ↑	up to 5.6	23.3	4	—
Luminosity $\mathscr{L}$ (10^{33} $cm^{-2}s^{-1}$) ↑	3.7	7.7	5.2	>10
Time between collisions τ_{bc} (ns) ↔	49.90	49.90	24.95	24.95
Full crossing angle (μ rad) ↔	240	≈ 300		≈ 300
Energy spread $\Delta E/E$ (units 10^{-3}) ↓	0.116	0.116		0.113
Bunch length (cm) ↔	9	9		7.5
Beam radius (10^{-6} m) ↓	26	20		16.6
Initial luminosity decay time, $-\mathscr{L}/(d\mathscr{L}/dt)$ (hr) ↑	8	8		14.9
Transverse emittance ($10^{-9}\pi$ rad-m) ↓	0.7	0.6		0.5
β^*, ampl. function @ i.p. (m) ↓	1	0.6	0.4	0.55
Beam-beam tune shift / crossing (10^{-4})	23	60		34
Particles per bunch (10^{10}) ↑	15	15		11.5
Bunches per ring per species ↑	1380	1380	2244	2808
Average beam current / species (mA) ↑	374	374		584

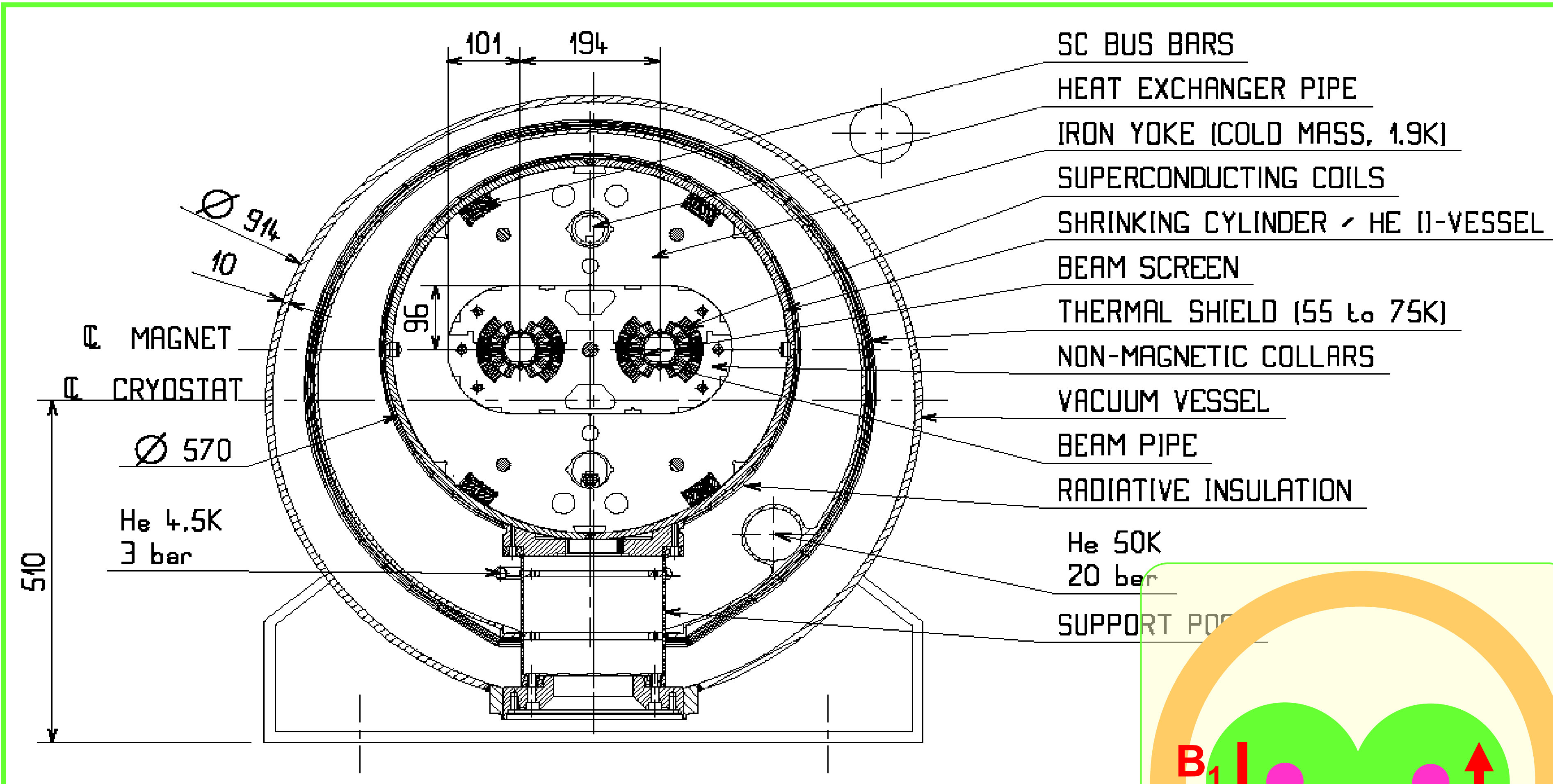
Parameter	Value
Circumference	26.659 km
Interaction regions	4 total, 2 high $\mathscr{L}$
Free space at interaction point	38 m
Magnetic length of dipole	14.3 m
Length of standard cell	106.9 m
Phase advance per cell	90°
Dipoles in ring	1232 main dipoles
Quadrupoles in ring	482 2-in-1 + 24 1-in-1
Magnet type	s.c. 2 in 1 cold iron
Peak magnetic field	8.3 T
Injection energy	450 GeV
RF frequency	400.8 MHz

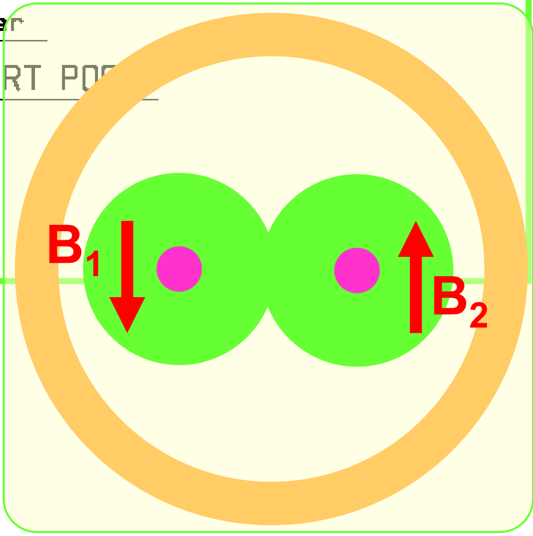
from [PDG]

The LHC Collider: dipoles

1000th Dipole Installed (sep 5, 2007)

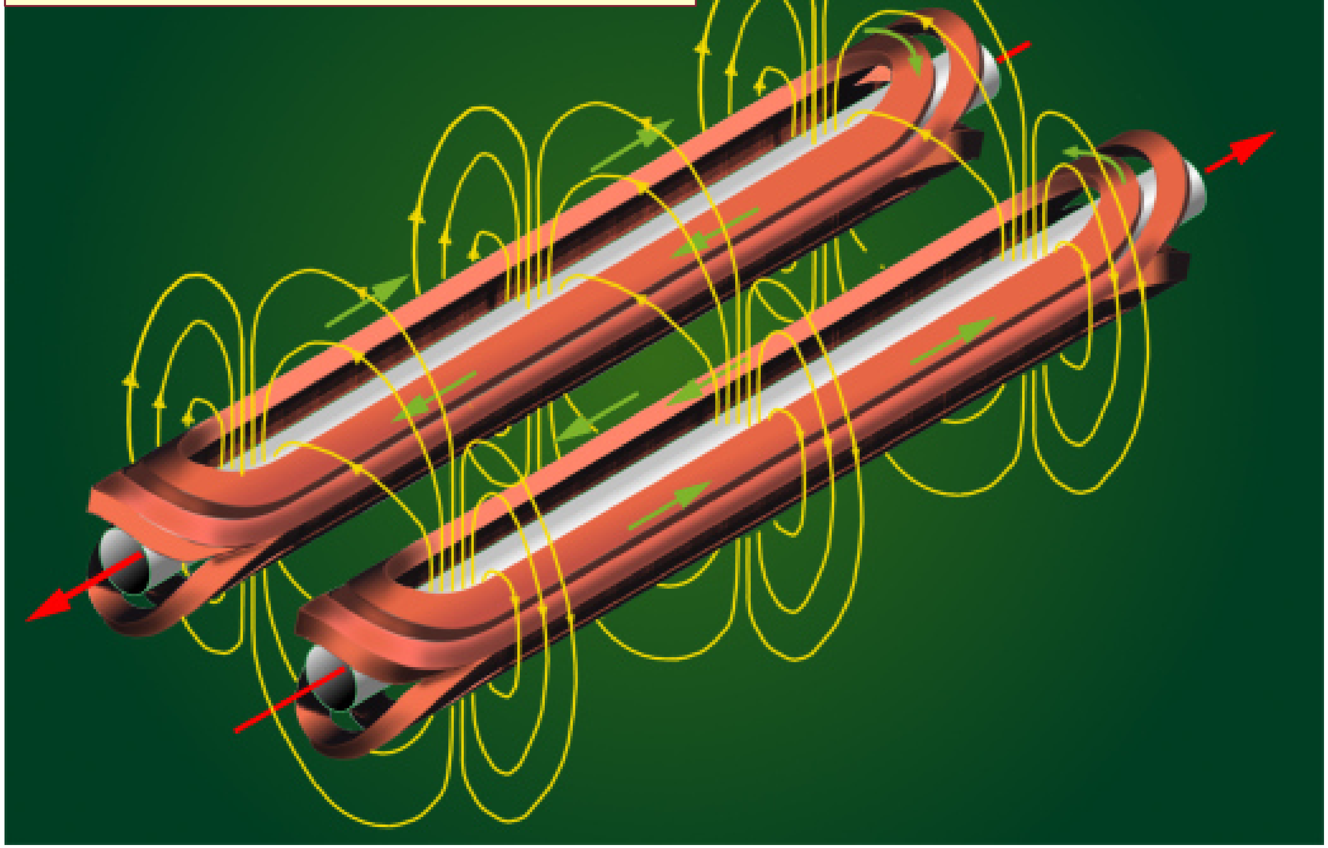
The LHC Collider: dipole structure





The LHC Collider: dipole operations

Mike Lamont – CERN academic training – sep 2013 (read it ! it's wonderful !!!)



Dipoles

- Number 1232
- Field (450 GeV) 0.535 T
- Field (7 TeV) 8.33 T
- Bending radius 2803.95 m
- Main Length 14.3 m

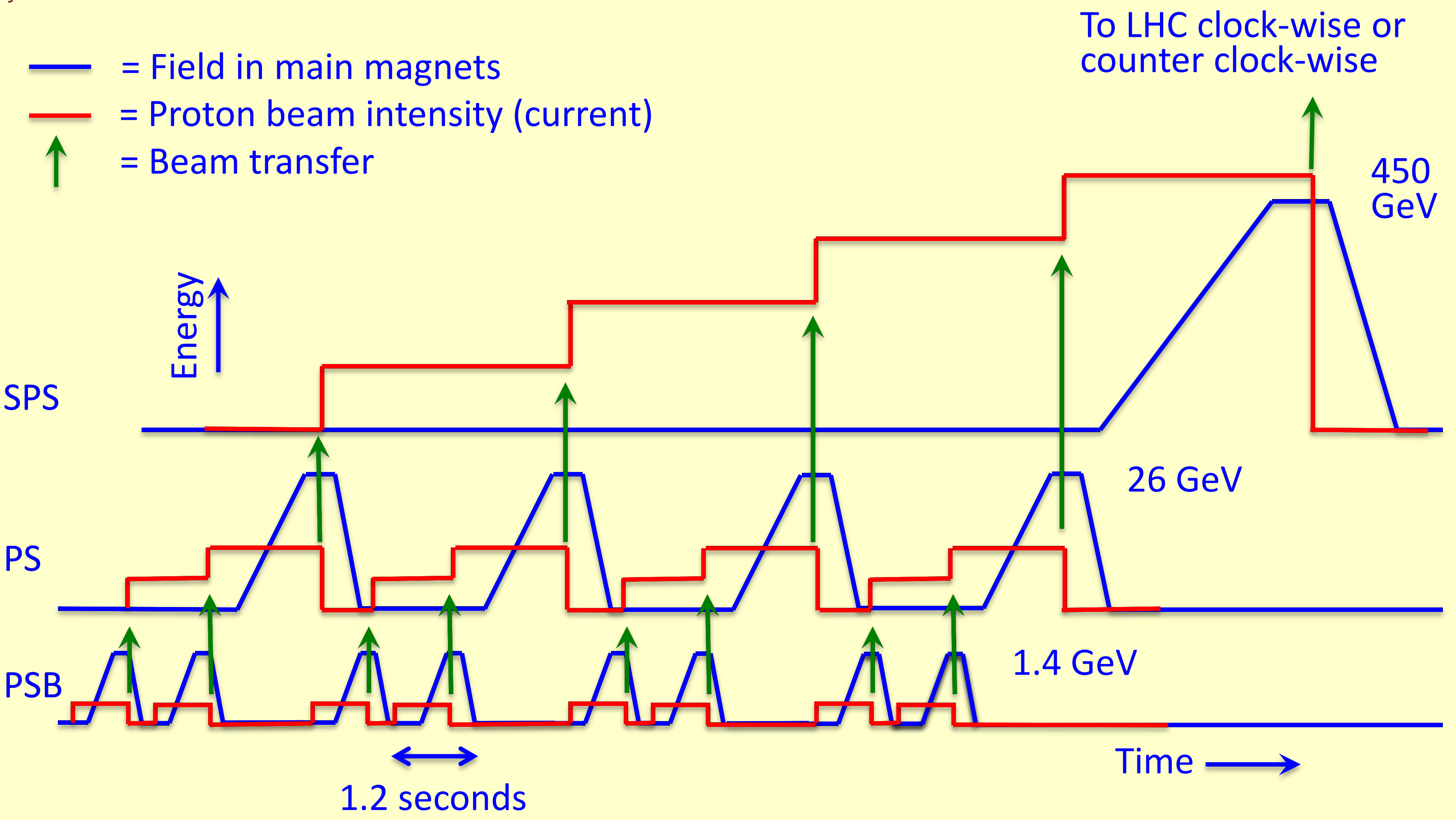
Horizontal force component per quadrant (nominal field) 1.7 MN/m.

Force tends to "open" the magnet, hence the Austenitic steel (YUS 130S) collars.

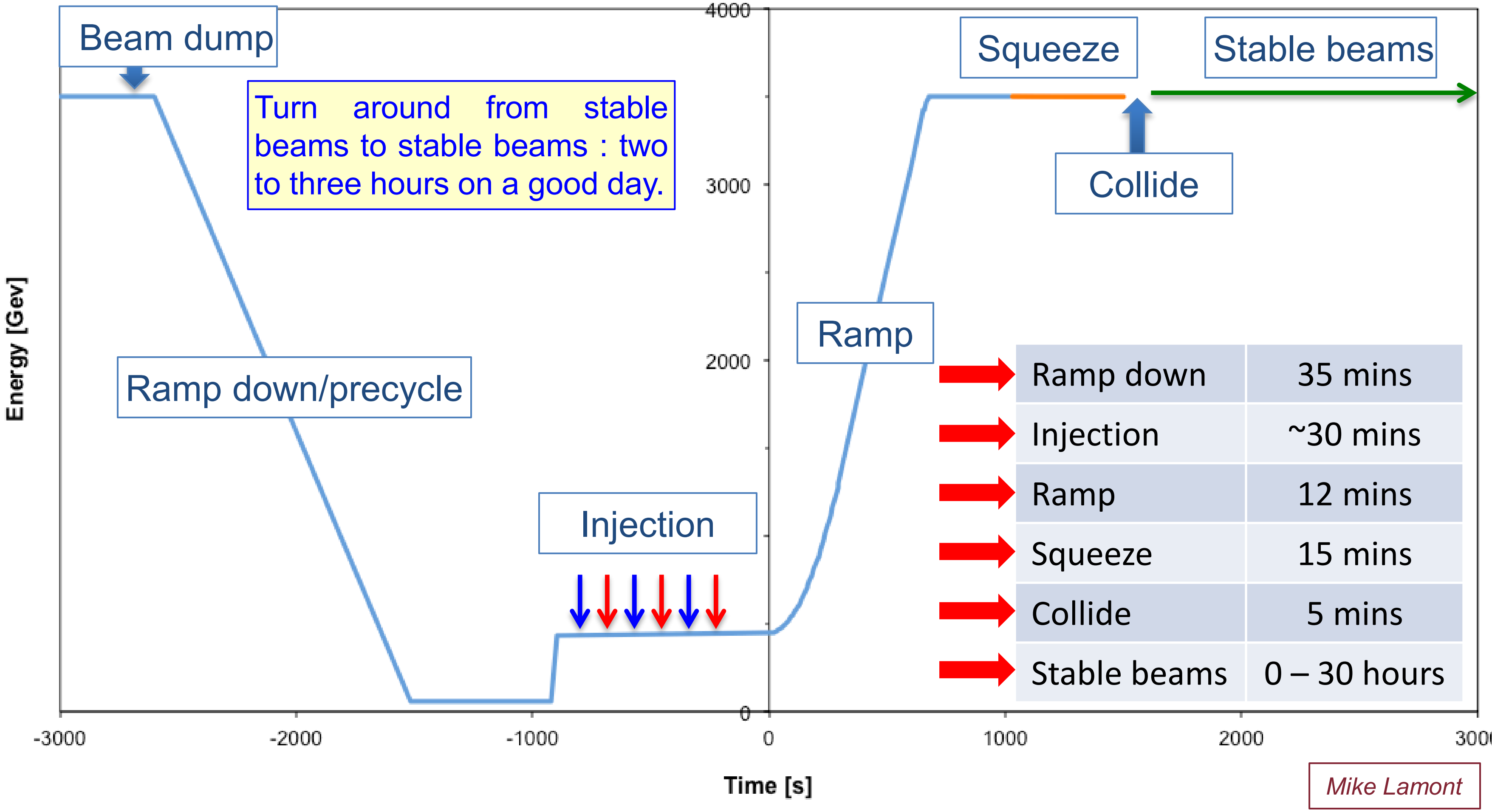
[more info : http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/]

The LHC Collider: injection cycle

from Mike Lamont



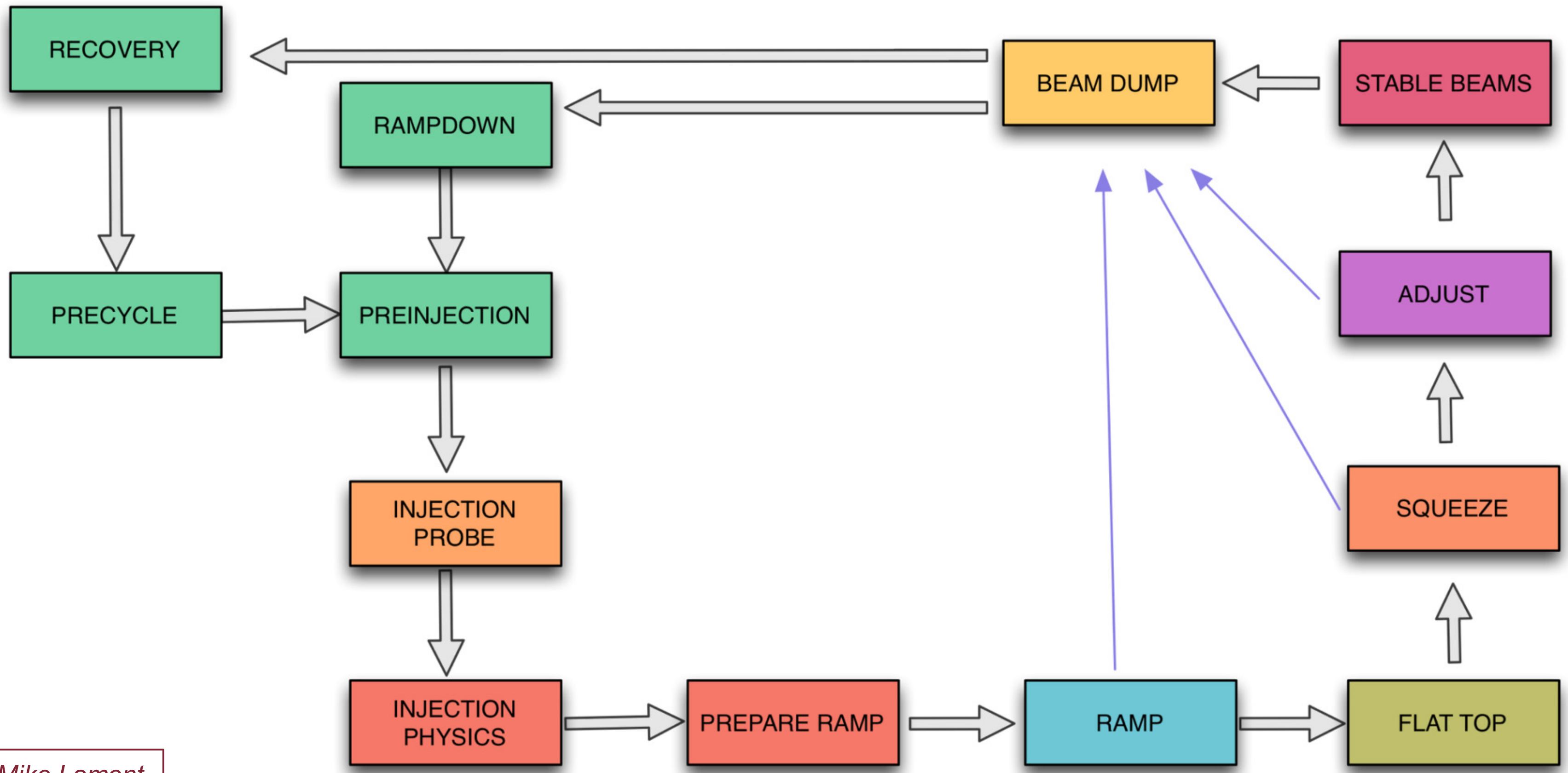
The LHC Collider: data-taking cycle



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

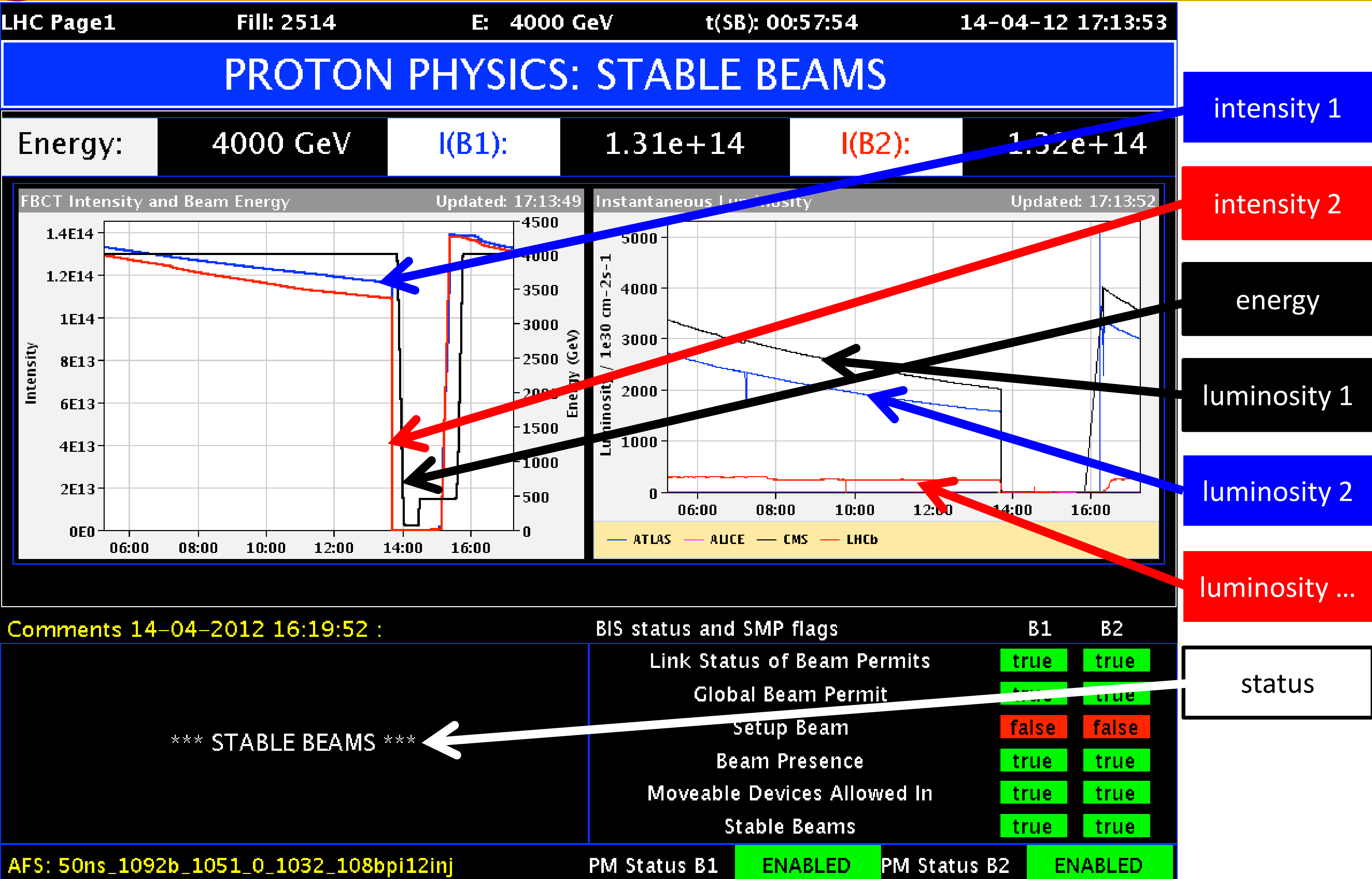
The LHC Collider: nominal cycle

Globally the machine state is fairly well described by machine mode/beam mode combination

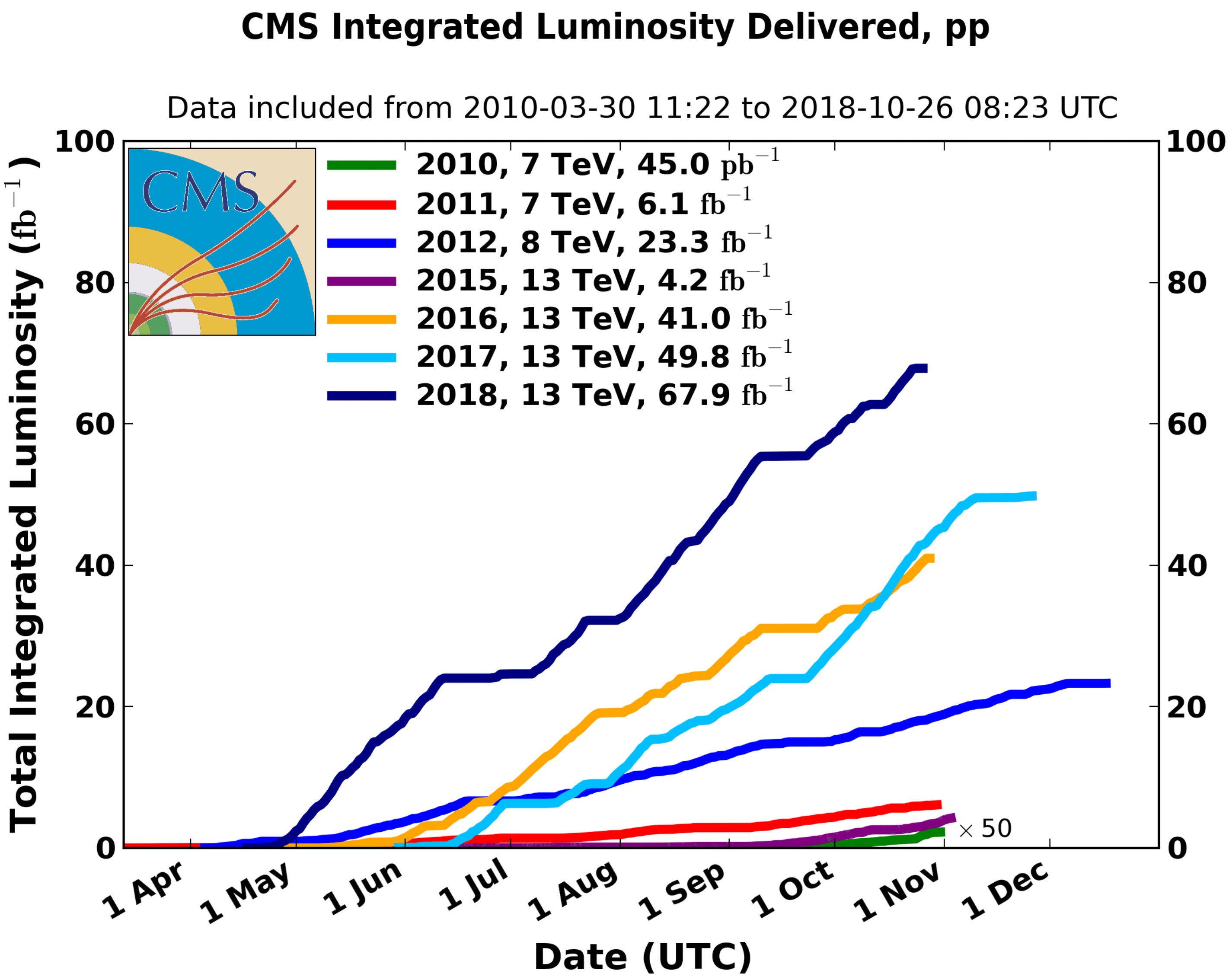


Mike Lamont

The LHC Collider: the user view

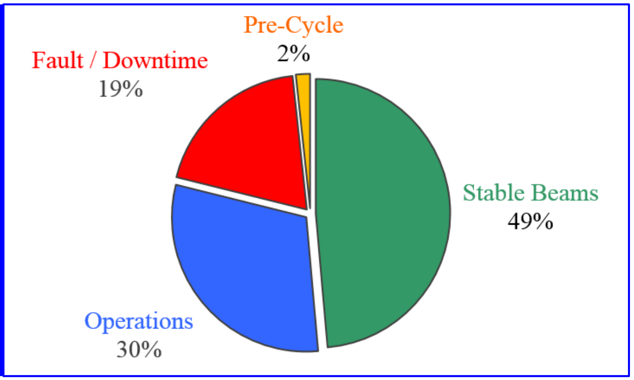


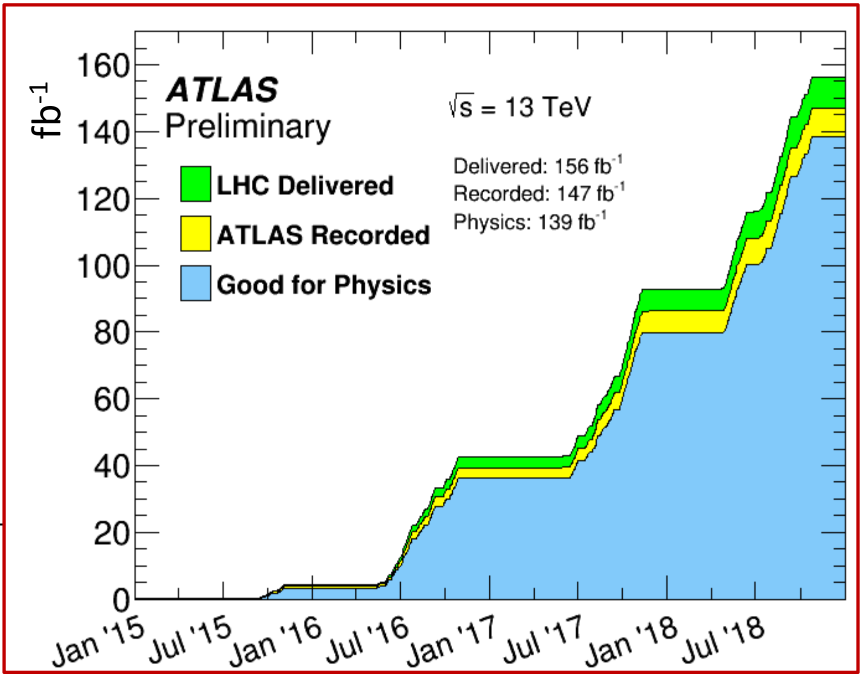
The luminosity: $\mathscr{L}_{int}$ vs time



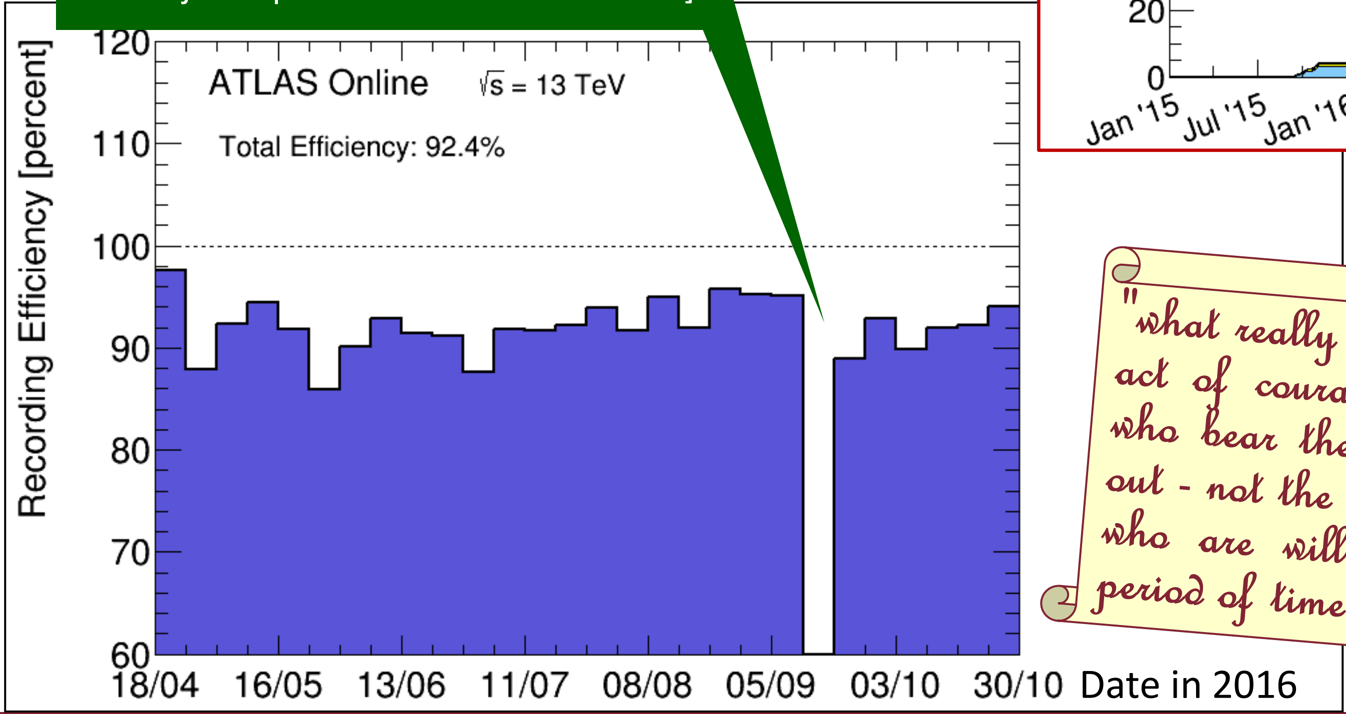
The luminosity: $\mathscr{L}_{int}$ vs time

LHC perfor-mances 2017





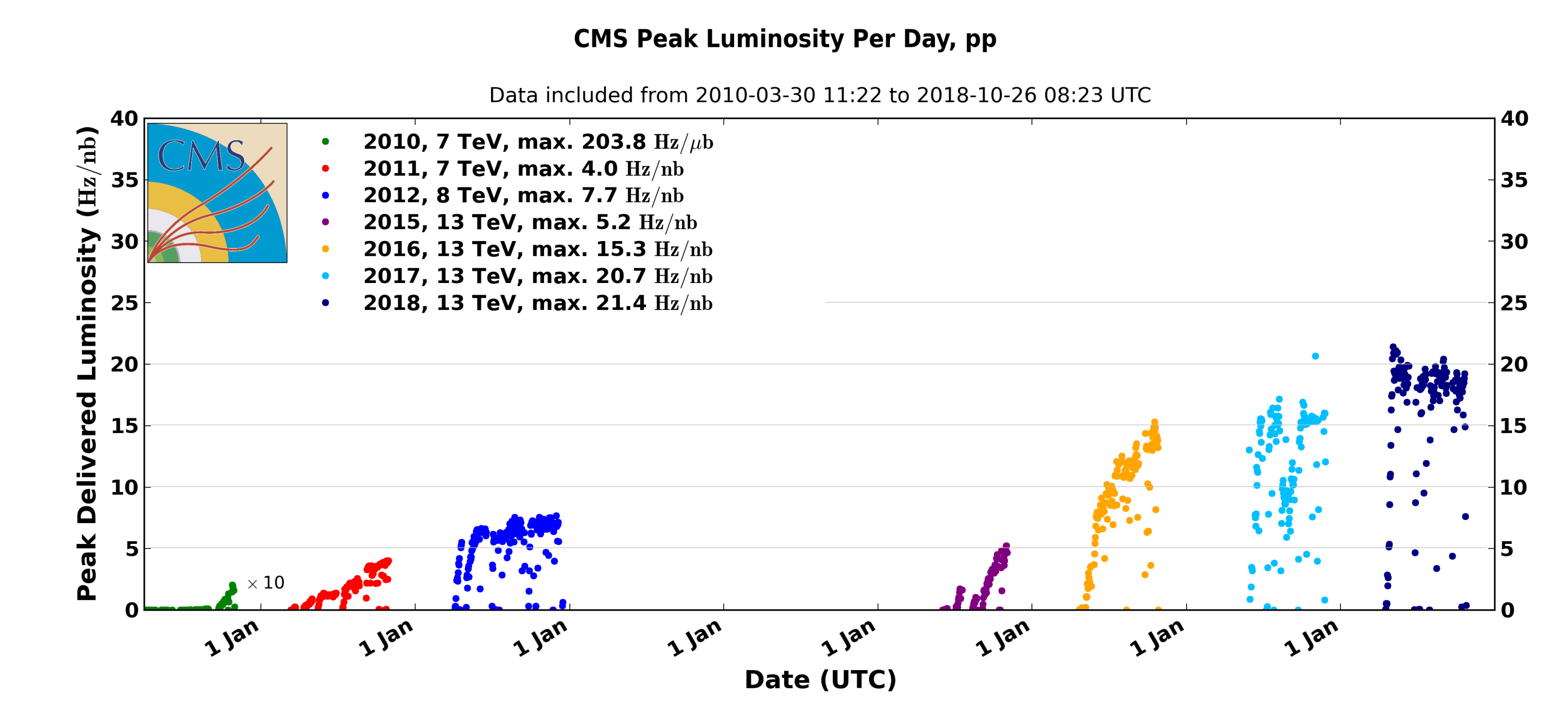
An almost impossible achievement: efficiency > 90% for many months [the hole is just a period of LHC maintenance].



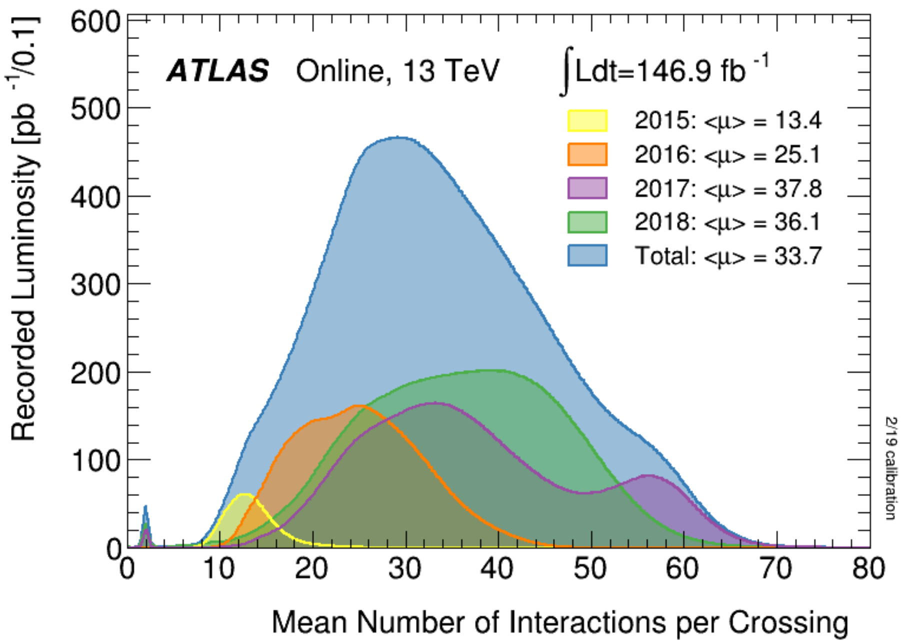
"what really counts is not the immediate act of courage or of valor, but those who bear the struggle day in and day out - not the sunshine patriots but those who are willing to stand for a long period of time", John F. Kennedy.

The luminosity: $\mathscr{L}_{peak}$

- In 2016 LHC has achieved the luminosity foreseen in the project, i.e. $\mathscr{L} = 10^{34}$ cm^{-2}s^{-1} …
- … and in 2017-18 it doubled it ($\mathscr{L} = 2\times10^{34}$ cm^{-2}s^{-1});
- for $\sqrt{s}$ = 14 TeV, wait another couple of years.
- [1 Hz/nb = 10^{33} cm^{-2}s^{-1}]



The luminosity : $\langle n_{int} \rangle$



$\mu = \langle n_{int} \rangle = \mathscr{L}\tau_{bc}\sigma_{inel}$ = [e.g. ≈]
$\approx (10^{+34})\times(25\times10^{-9})\times(8\times10^{-26}) \approx 20.$

see § 1

Pros and cons of the value of μ at LHC:

☺ for fixed τ_{bc}, <u>$\mu \propto \mathscr{L}$</u>, so large μ necessary for rare processes, like Higgs;

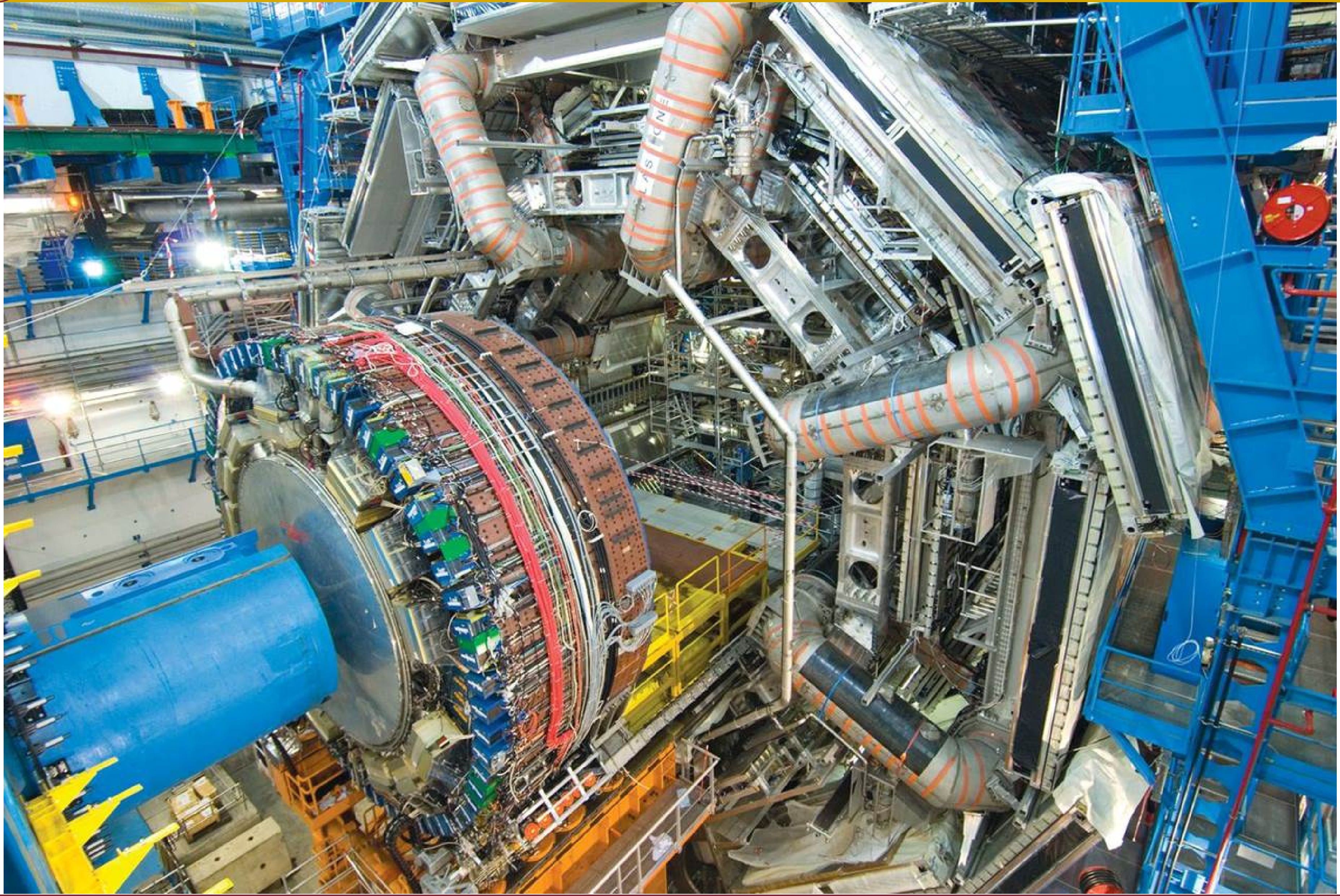
☺ for fixed $\mathscr{L}$, <u>$\mu \propto \tau_{bc}$</u>; so a decrease in μ is payed by a decrease in τ_{bc}, the processing time for the trigger and DAQ (now 25 ns, the bare minimum);

☹ large μ → many overlapping events
→ systematics in trigger thresholds;
→ systematics in vertex reconstruction;
→ systematics in calo calibrations and reconstruction;
→ mistakes in assignment of heavy flavors, jets, muons to event;
→ (… many other problems …)

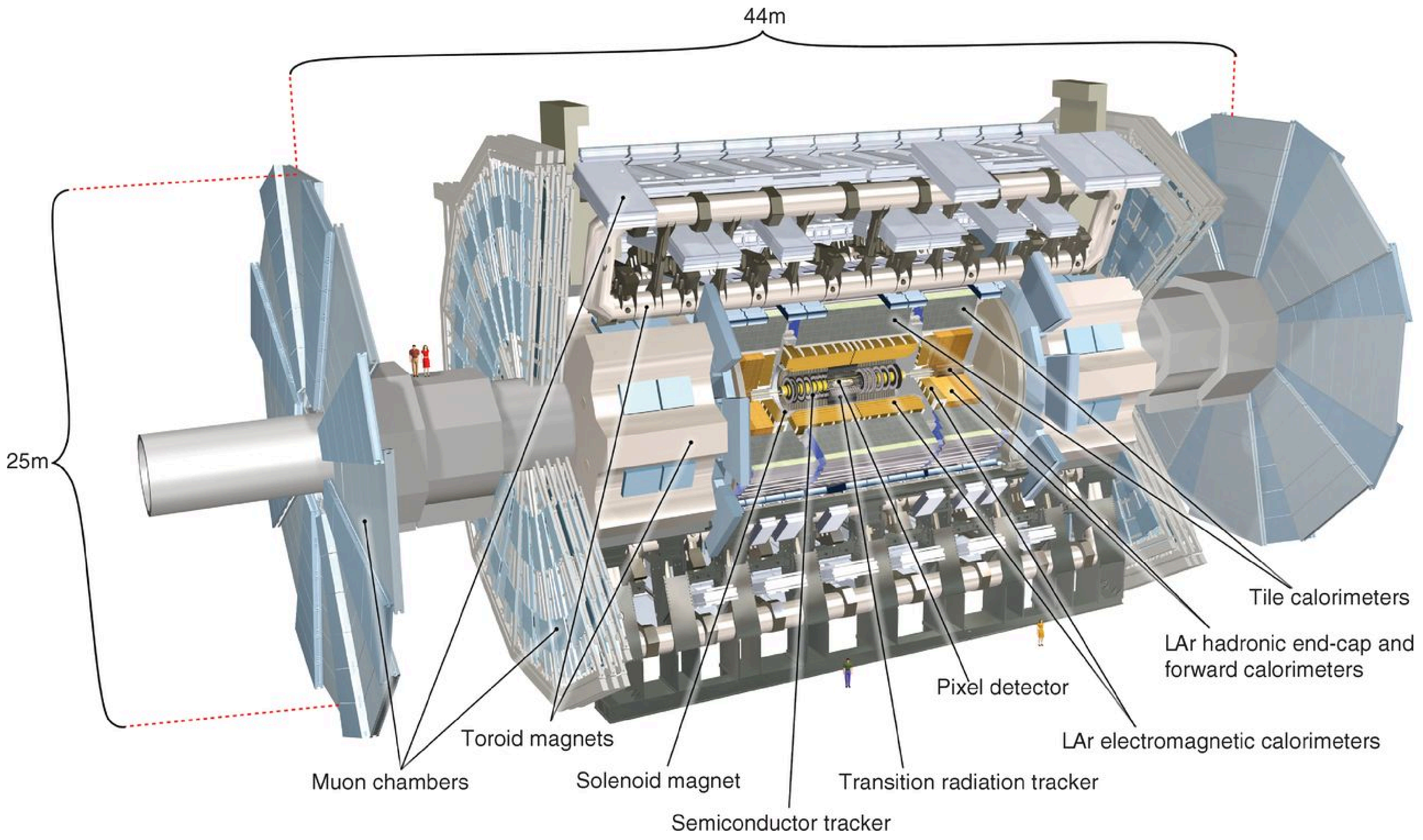
☺ some of the LHC data have been taken with a different τ_{bc} (50 ns instead of 25 ns); for the same $\mathscr{L}$, this fact doubles μ (→ 25 ns is better than 50 ns, but …)

☺ anyway, **<u>large μ is necessary</u>**, so you better learn to survive with it.

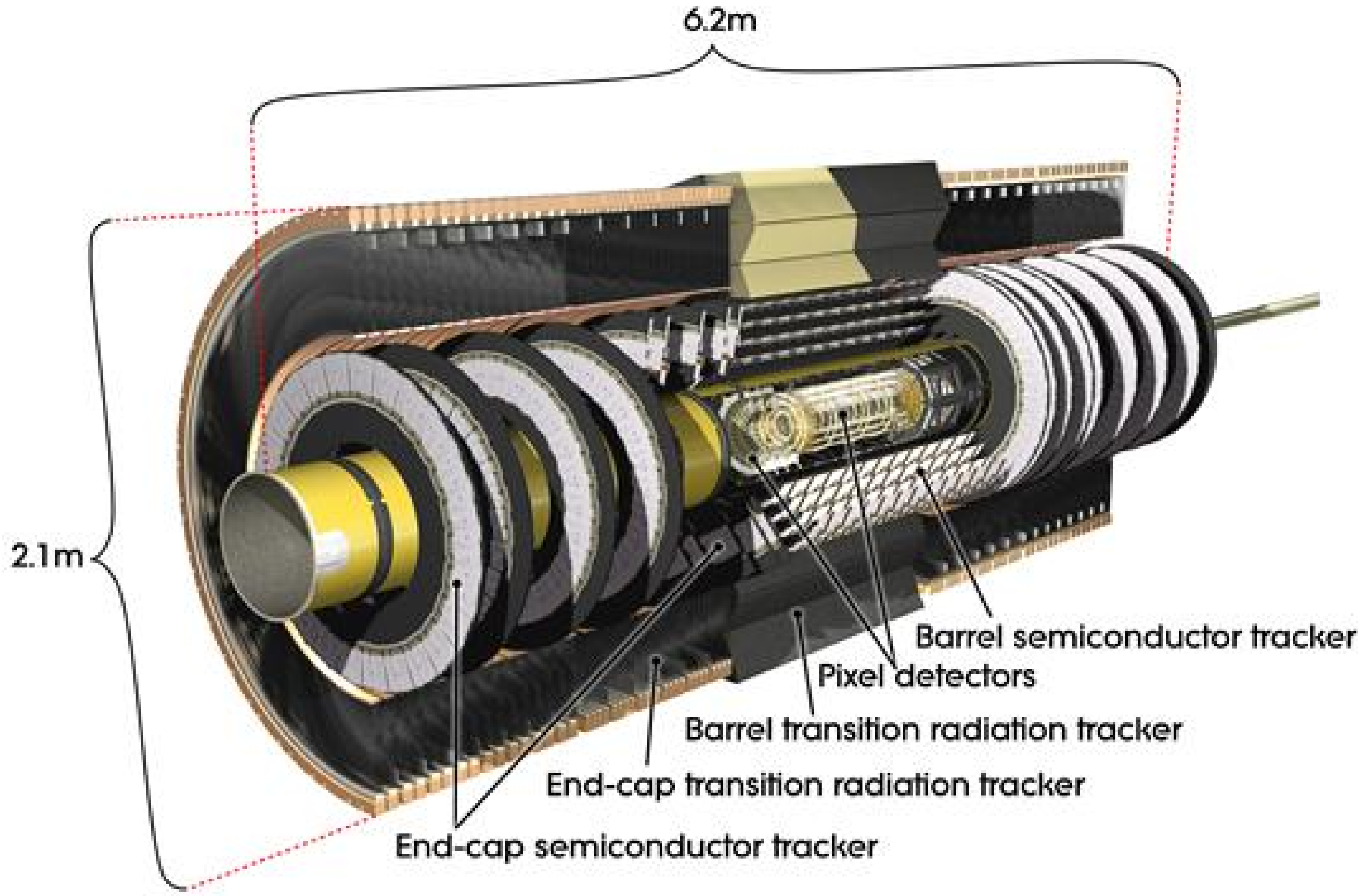
The ATLAS detector



The ATLAS detector: scheme



The ATLAS detector: inner tracker

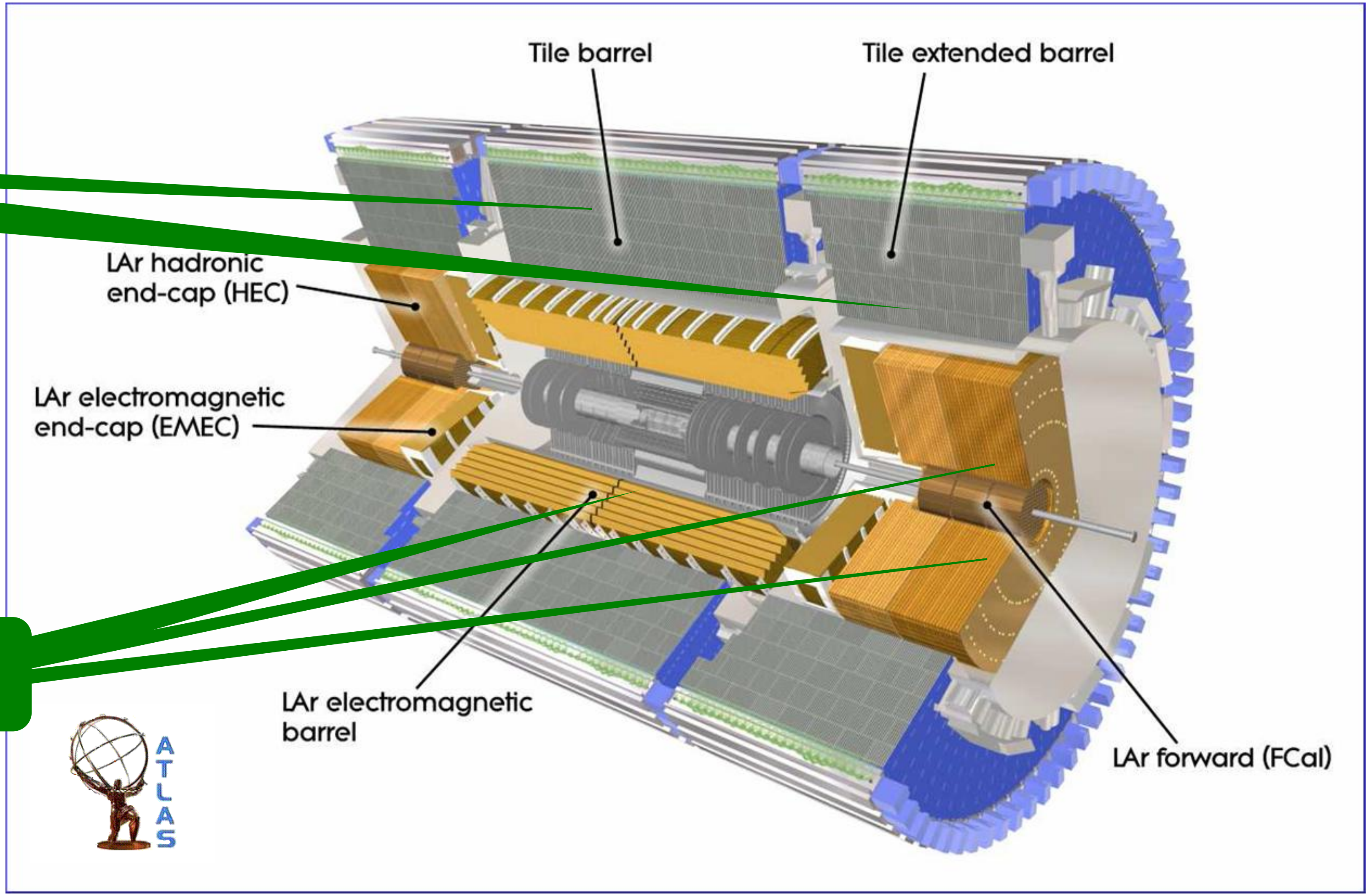


Pixel	SCT	TRT
3 cylindrical layers	4 cylindrical layers	73 straw planes
2×3 disks	2×9 disks	160 straw planes

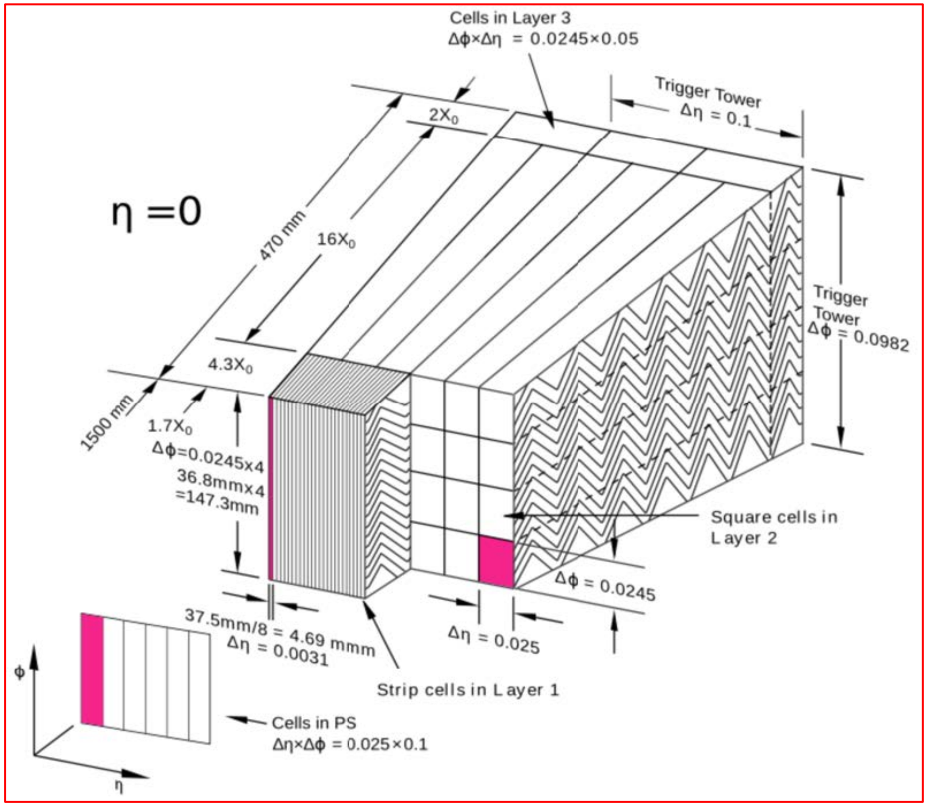
The ATLAS detector: calorimeters

sandwich
scint-Fe

"accordion"
LAr - Pb

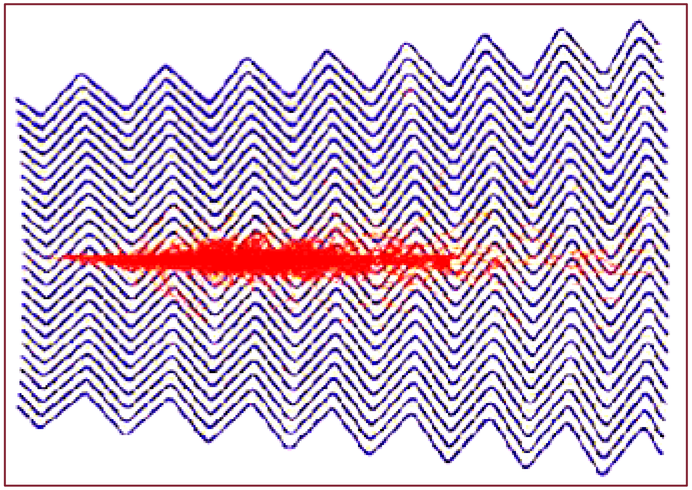


The ATLAS detector: e.m. calo

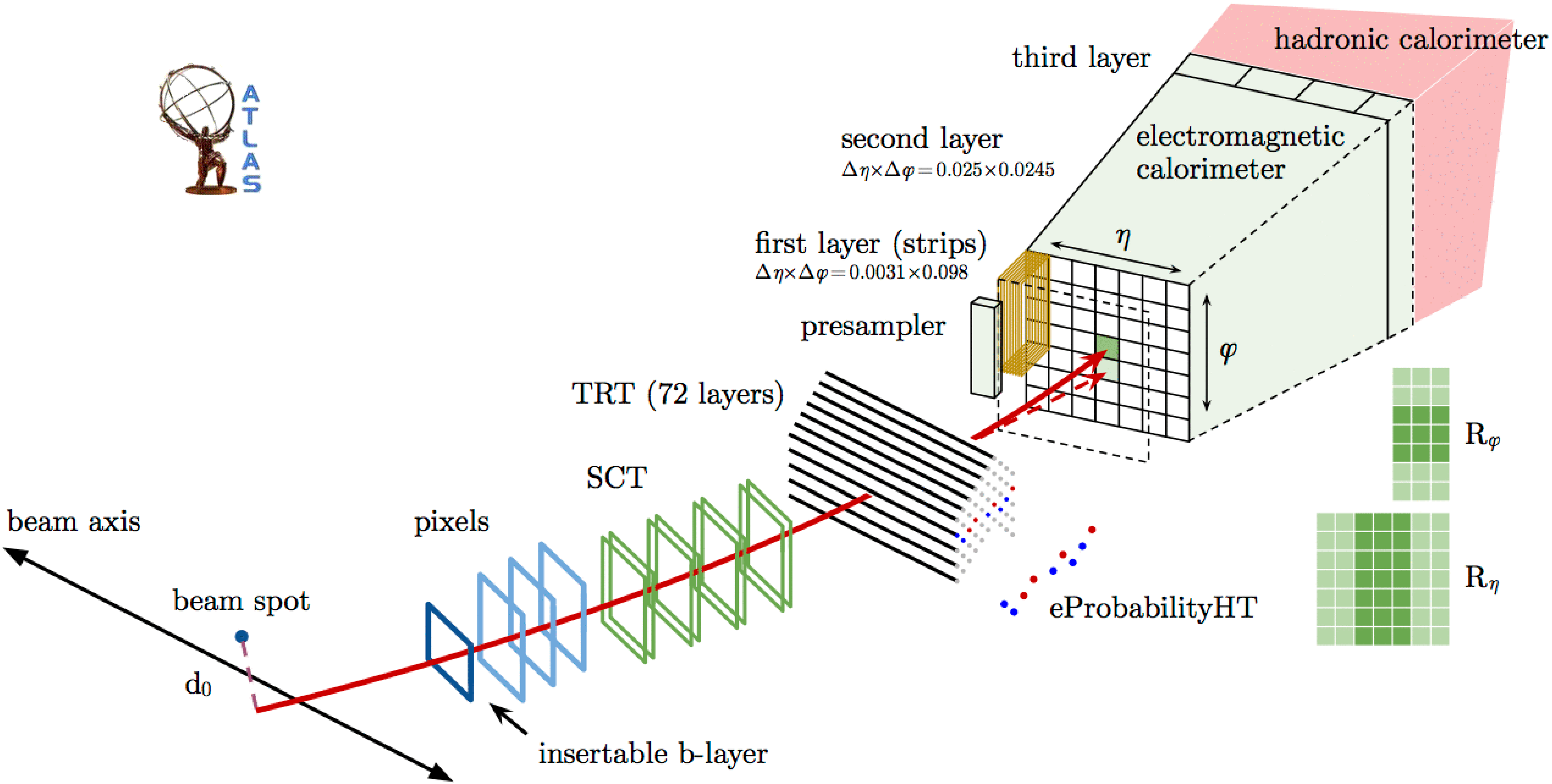


- "accordion" LAr – Pb
- cryogenic
- hermetic
- longitudinal + radial segmentation

e/γ

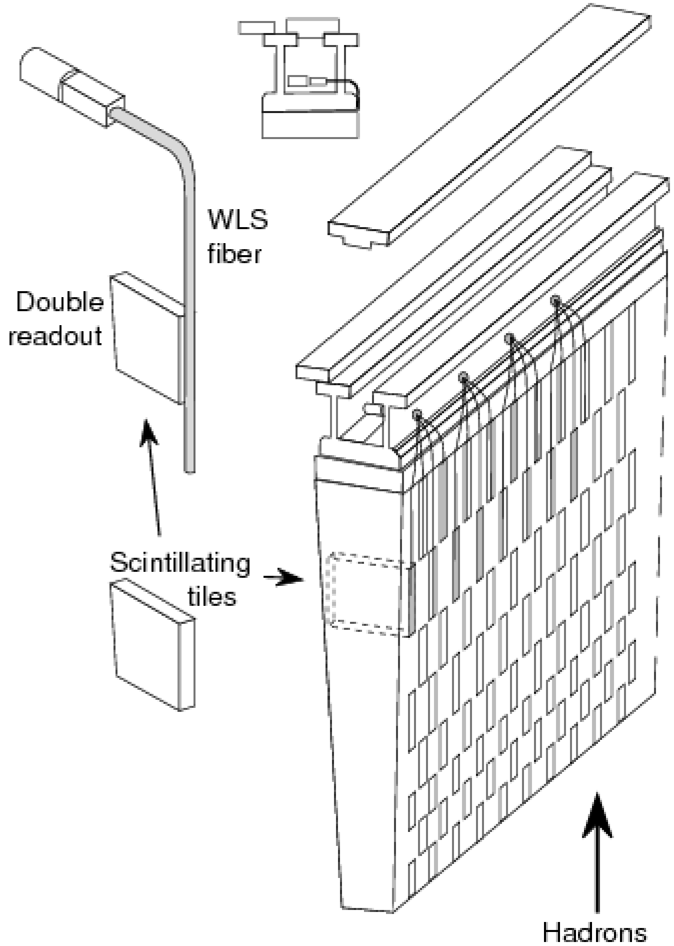


The ATLAS detector: $e^{\pm}$ id and measure



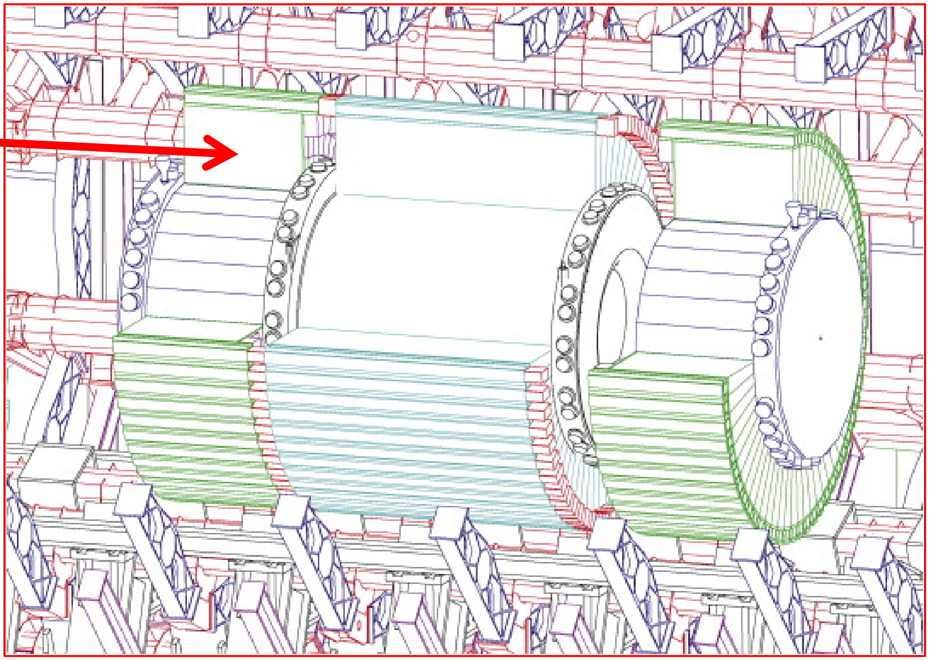
an electron is detected many (>> 100) times after the interaction point; even the non-detection in the had. calo is important (cfr a γ in the pixels/SCT/TRT).

The ATLAS detector: had. calo

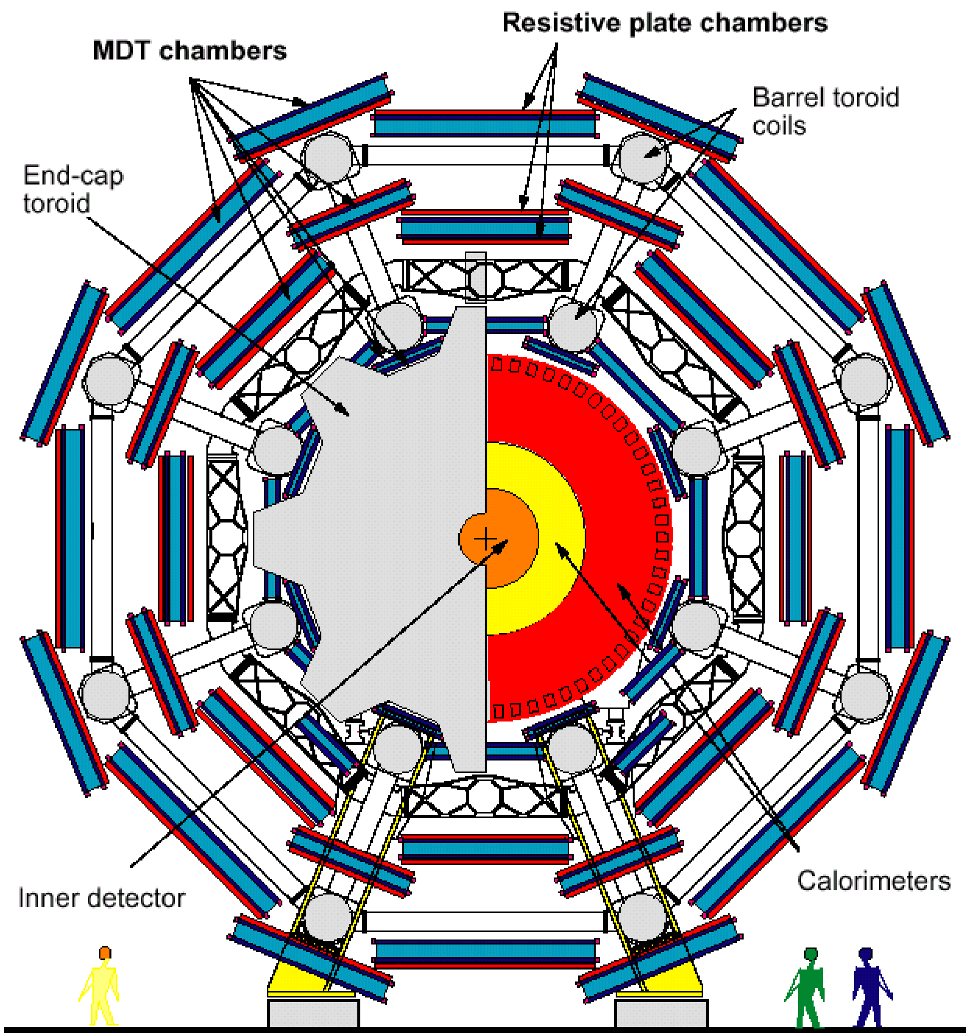


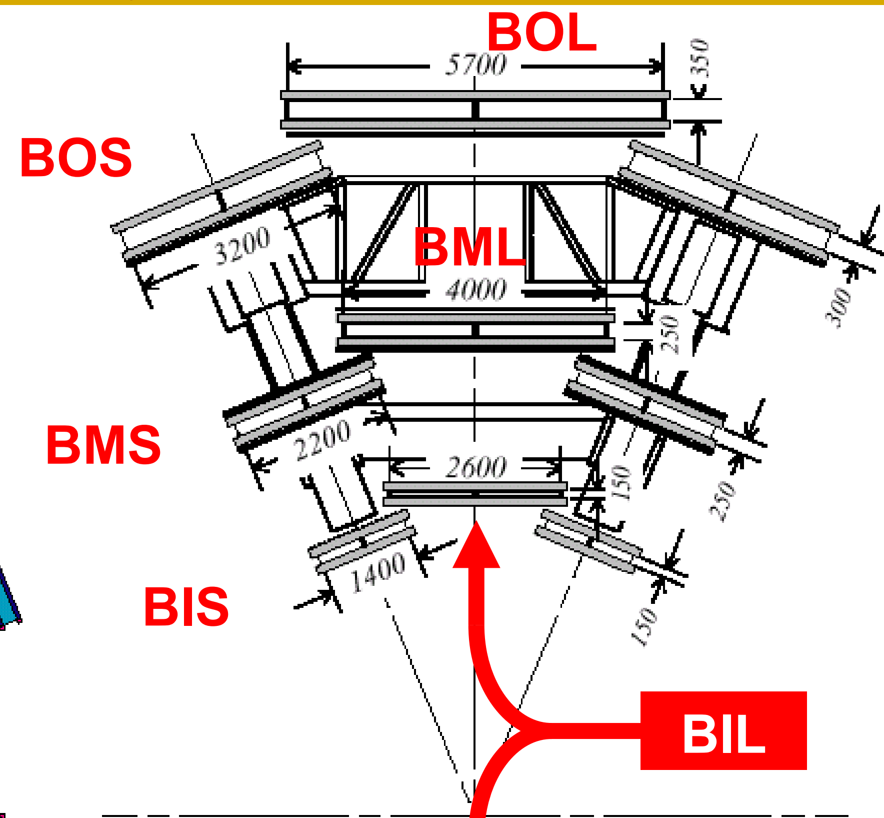
Interaction point ↓

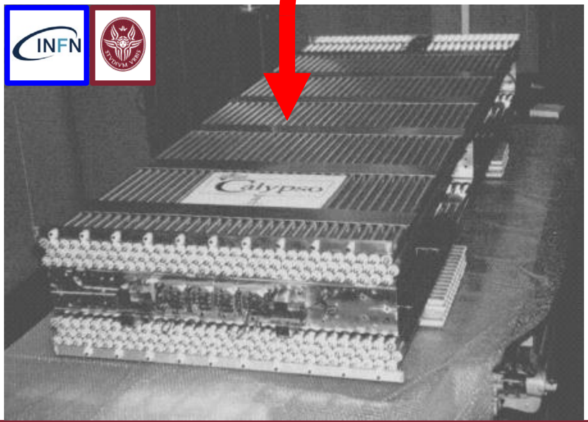
- "tiles" Fe – Scintillator
- WLS readout
- hermetic
- high segmentation



The ATLAS detector: μ spectrometer



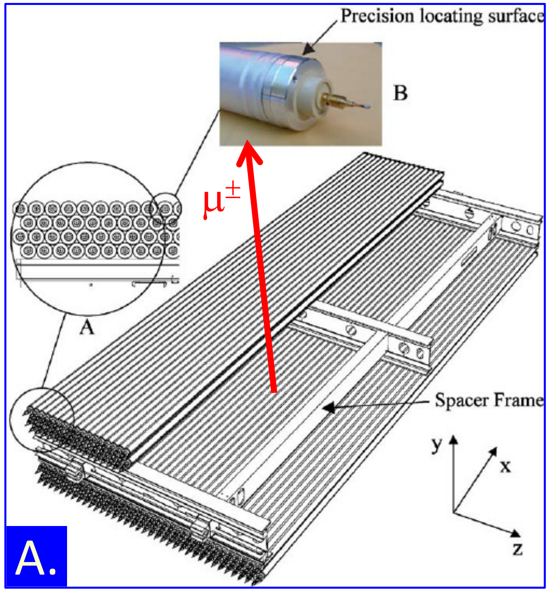


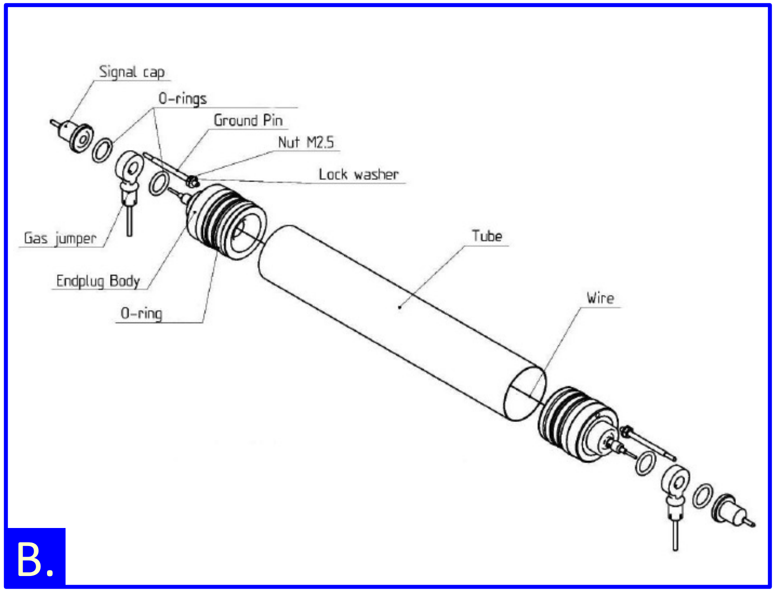


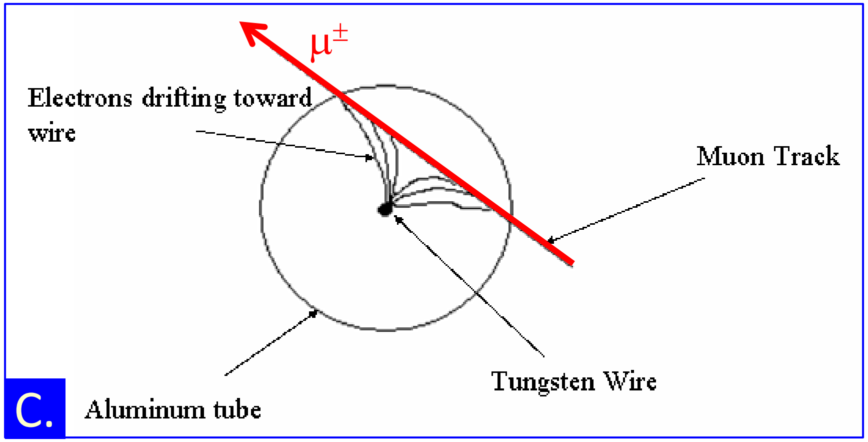
The ATLAS detector: μ chambers

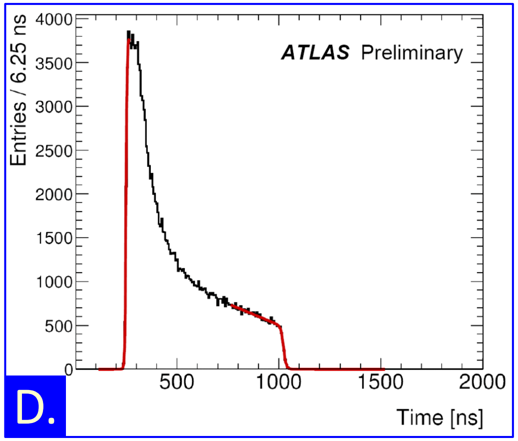
Schematic view of:

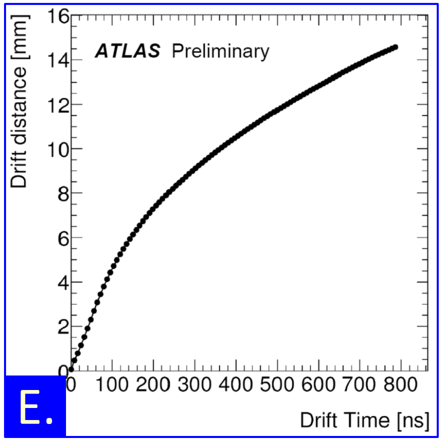
A. a chamber of drift tubes
B. a single tube
C. a muon hitting a tube
D. the hit time distribution
E. the r-t relation





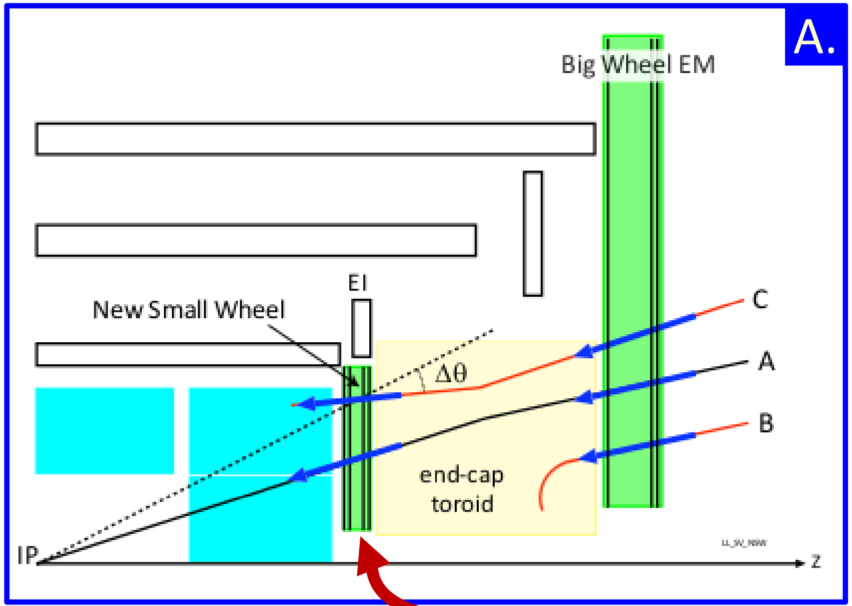




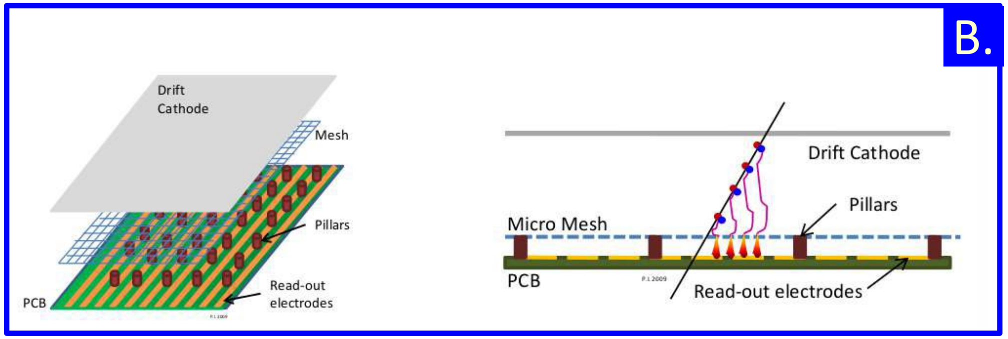


The ATLAS detector: New Small Wheel (NSW)

A.



B.



in > 2021 $\mathscr{L}$ much larger (see later):

- new detectors must be built;
- Roma builds the NSW:

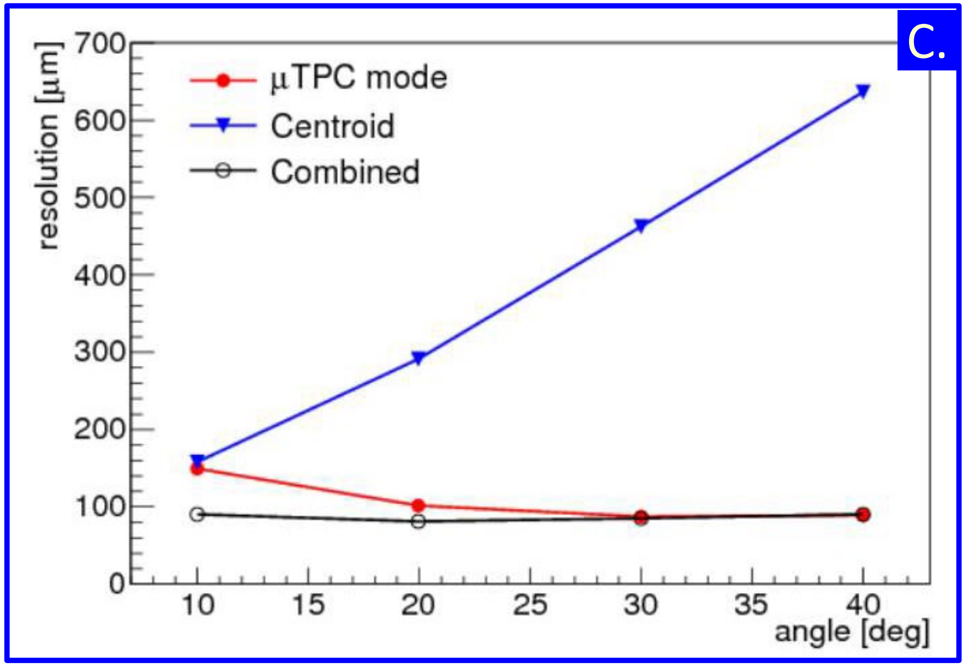
  A. layout;

  B. principle (e-drift in Ar-CO_2);

  C. test-beam performances

  (current real life not so good … working)

C.



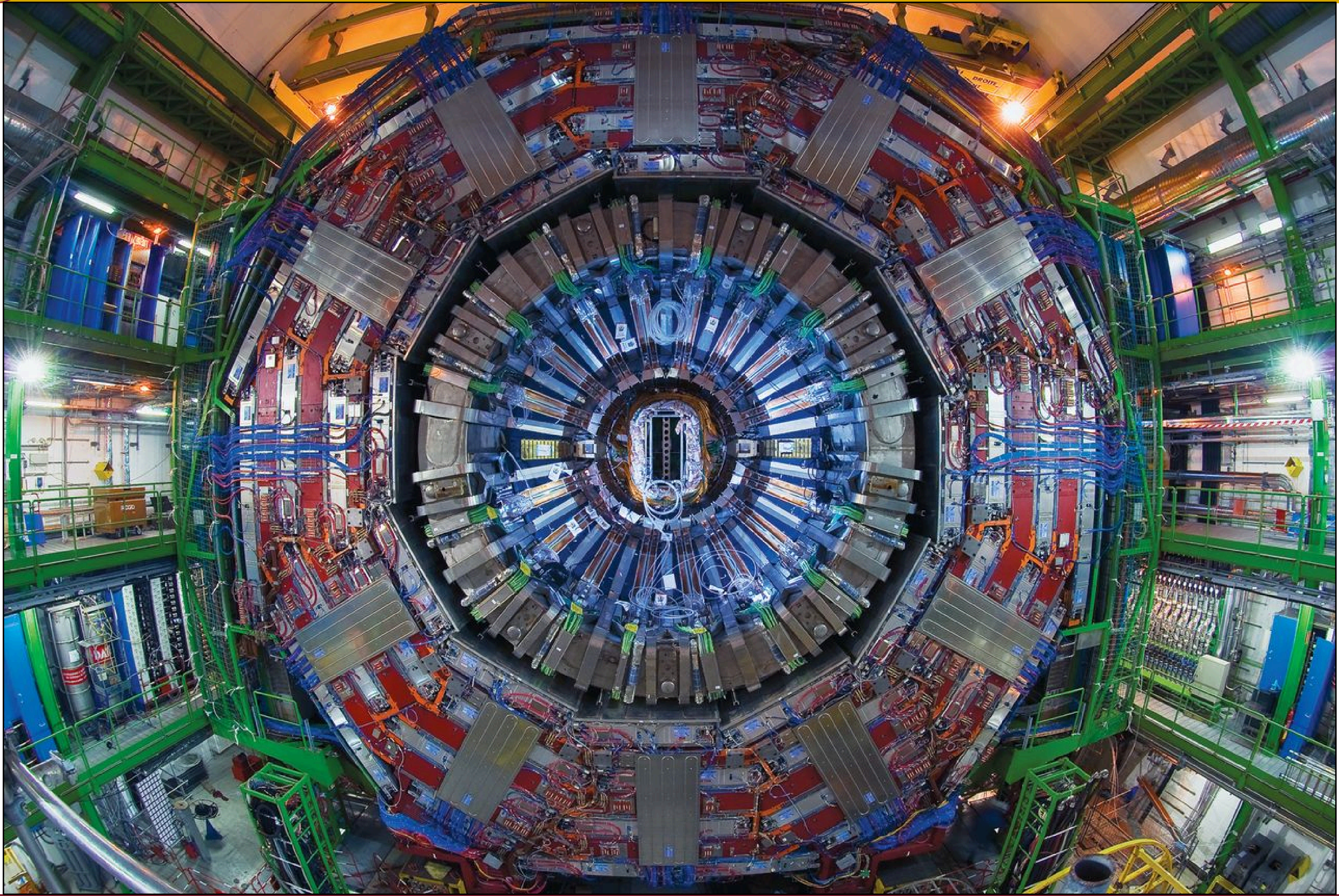
The ATLAS detector: NSW nice (?) photos

CERN oct '21
(by M.Kado)

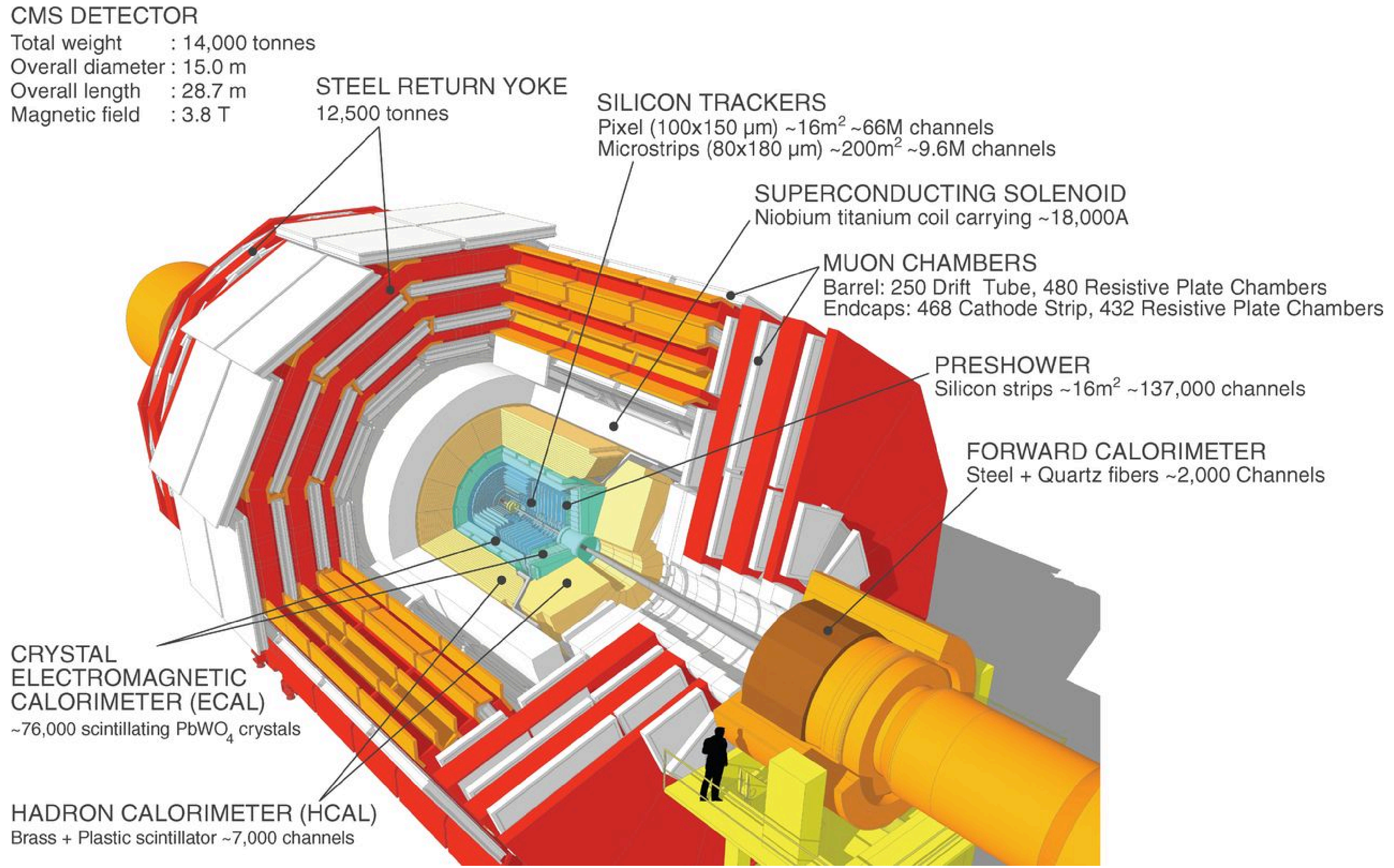
Roma 2018

CERN, oct '21

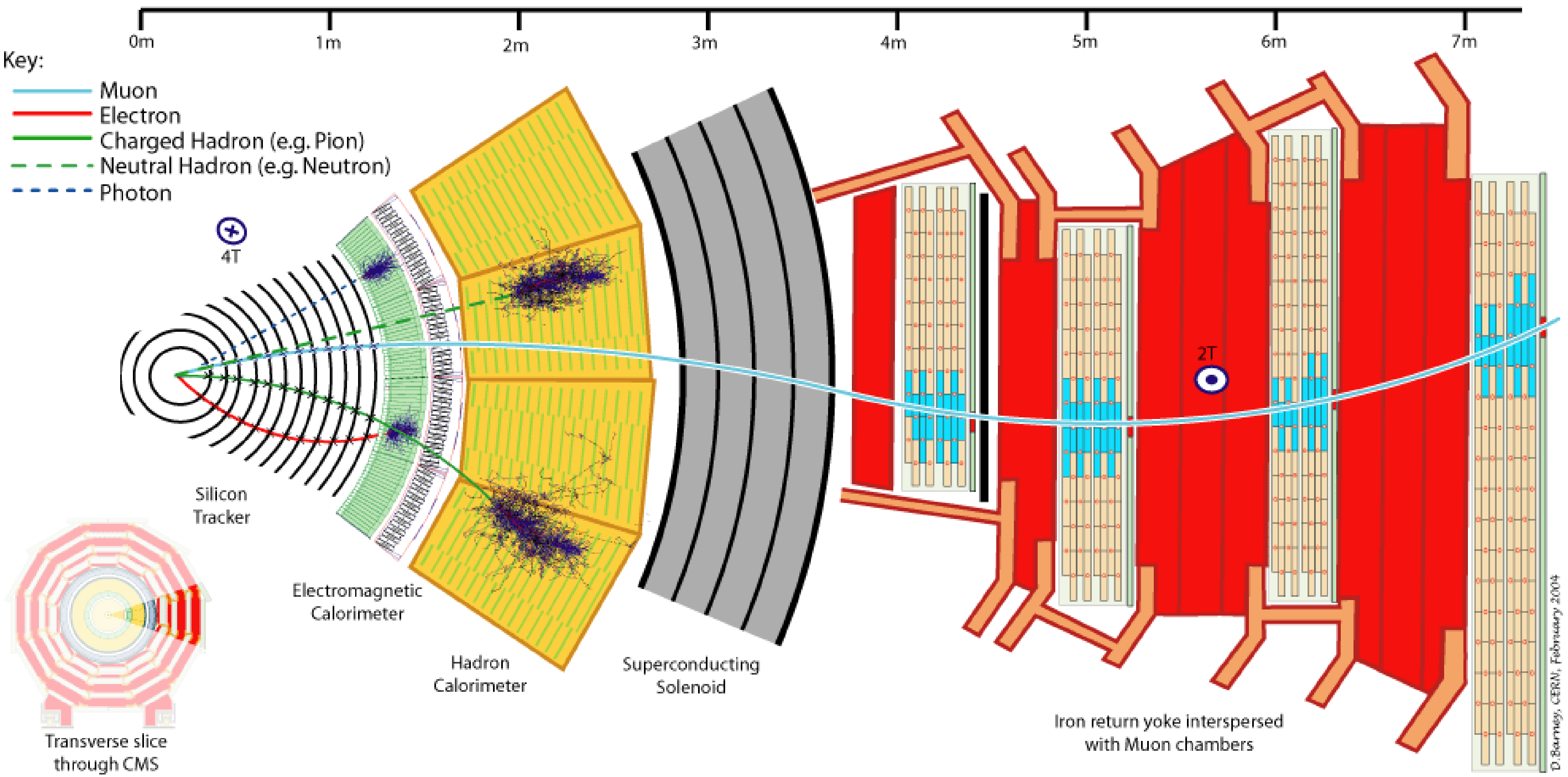
The CMS detector



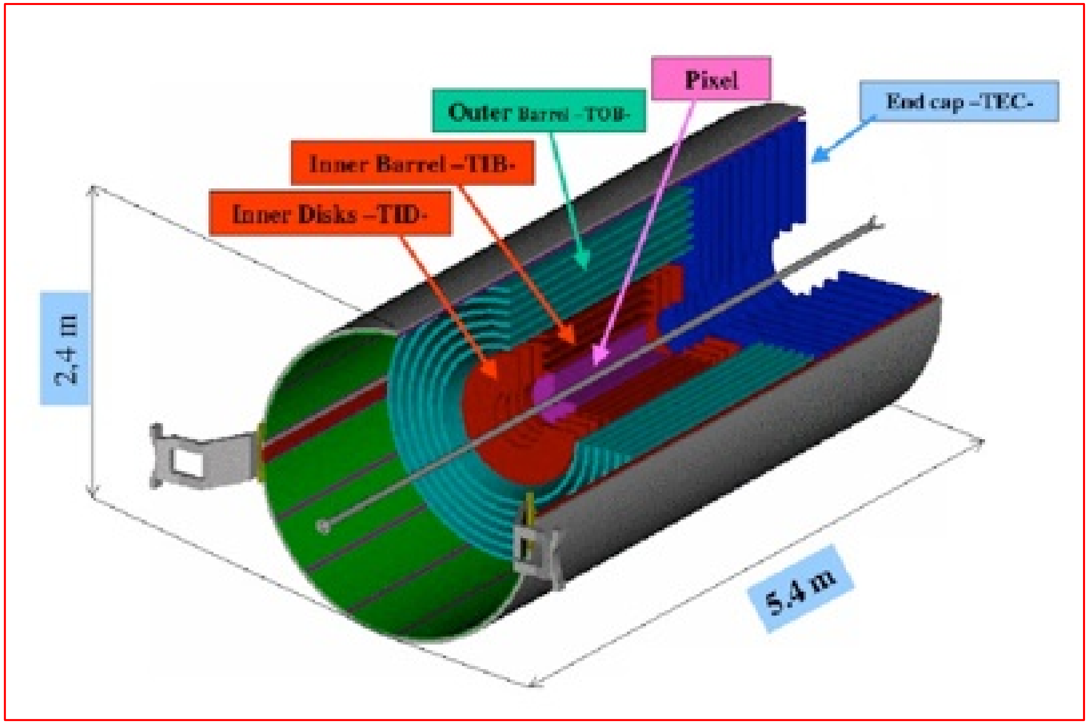
The CMS detector: view

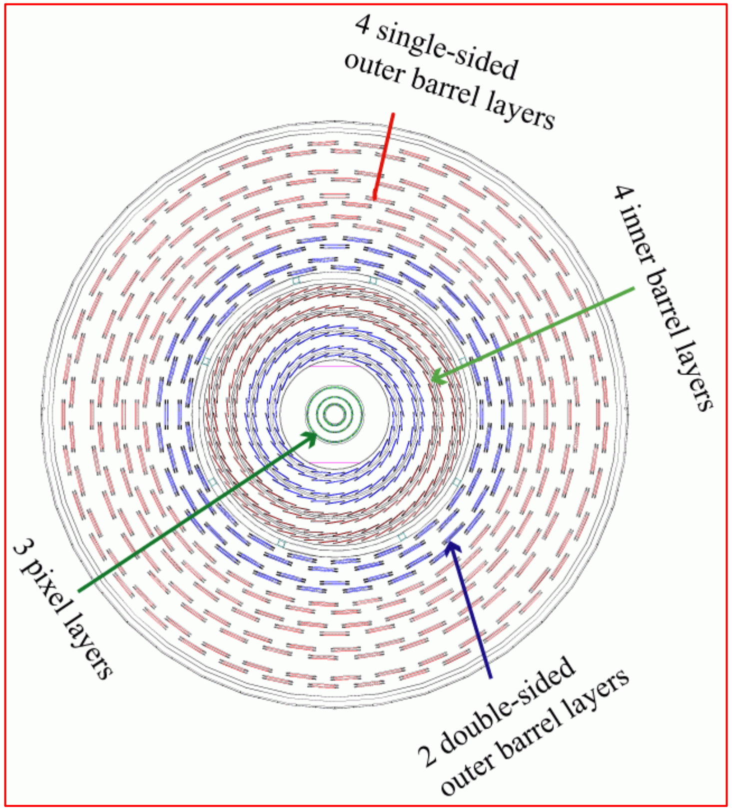


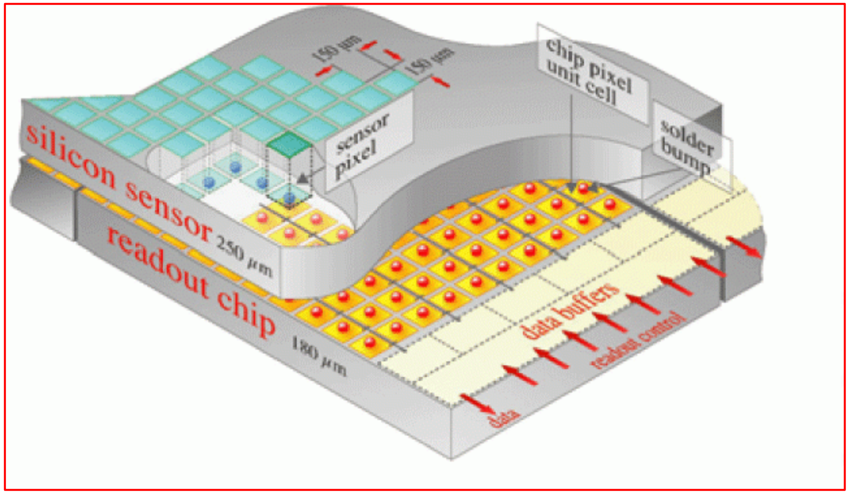
The CMS detector: scheme



The CMS detector: inner tracker

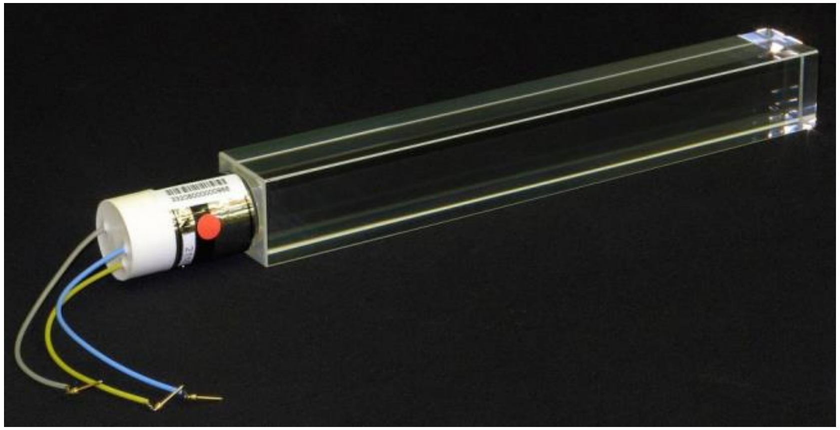


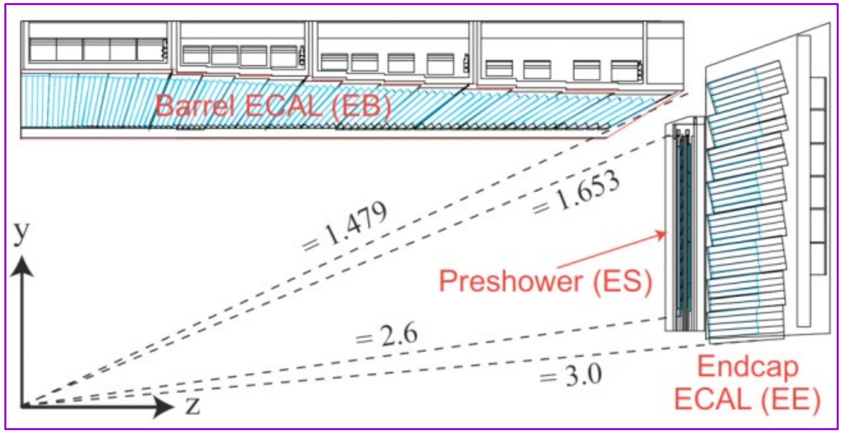


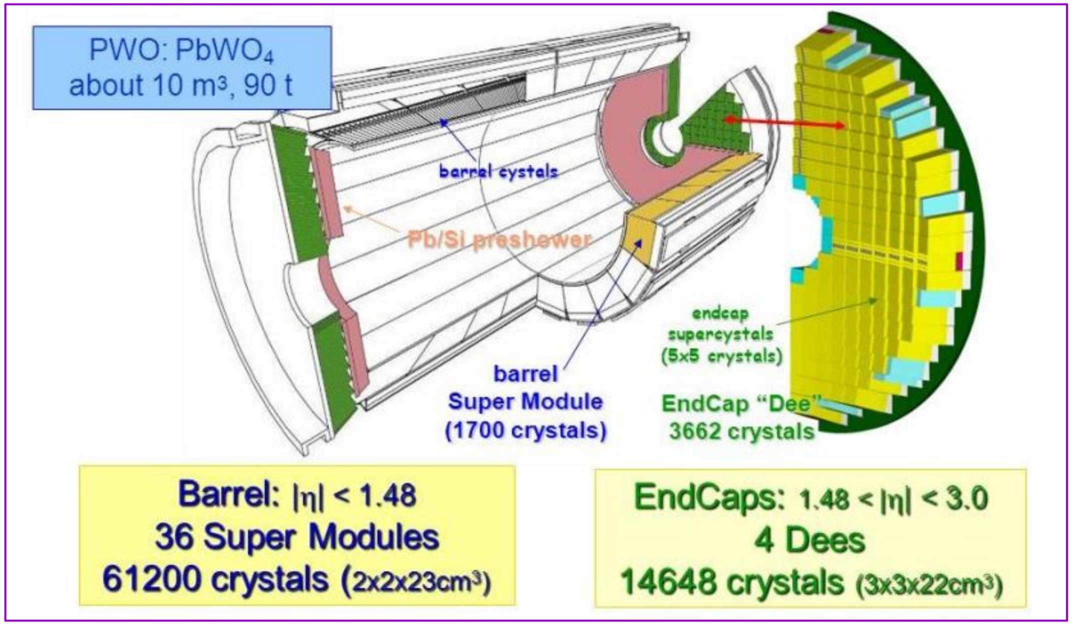


Si pixel + strip detector

The CMS detector: e.m. calo







e.m. calo:
$PbWO_4$ crystals

The CMS detector: had. calo

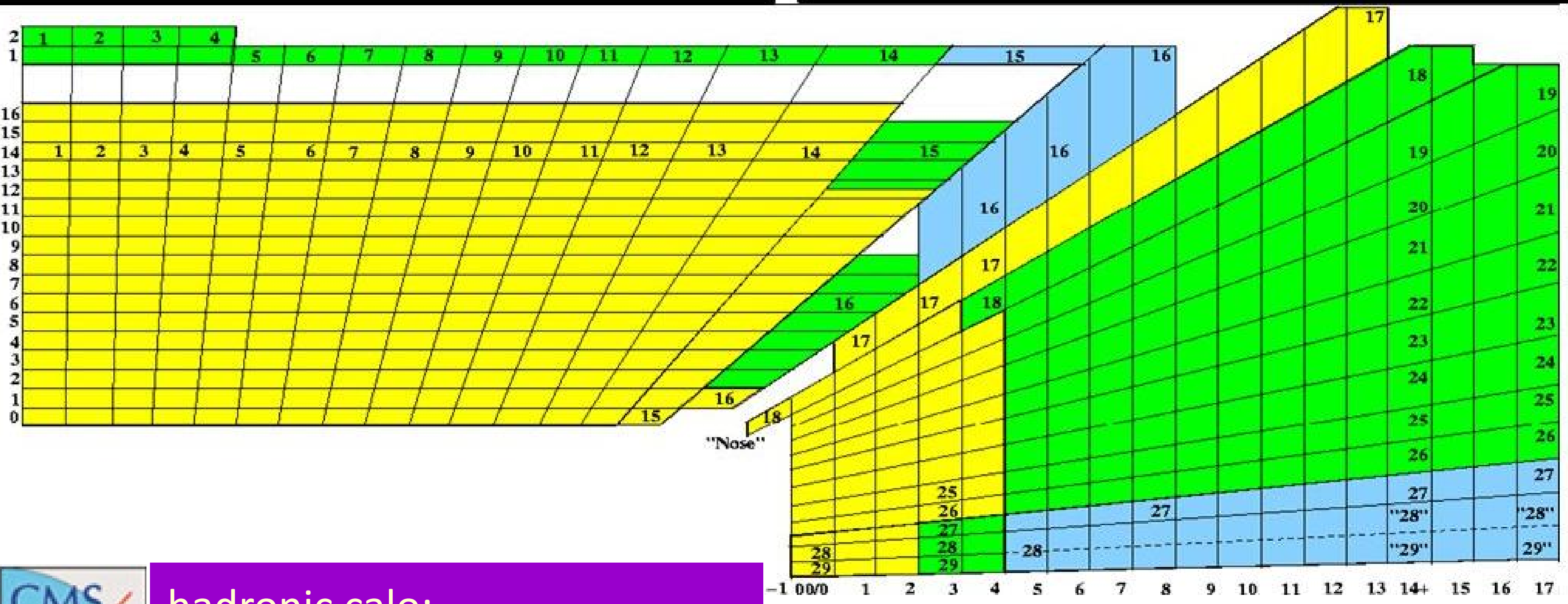
<u>HCAL (tower structure)</u>:
- Barrel (HB): $|\eta| < 1.4$, 2304 towers
- End caps (HE): $1.3 < |\eta| < 3.0$, „ towers
- Outside coil (HO): $|\eta| < 1.26$ (tail catcher)

→ 4608 towers (Plastic scintillator tiles, ≈ 10 λ_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)

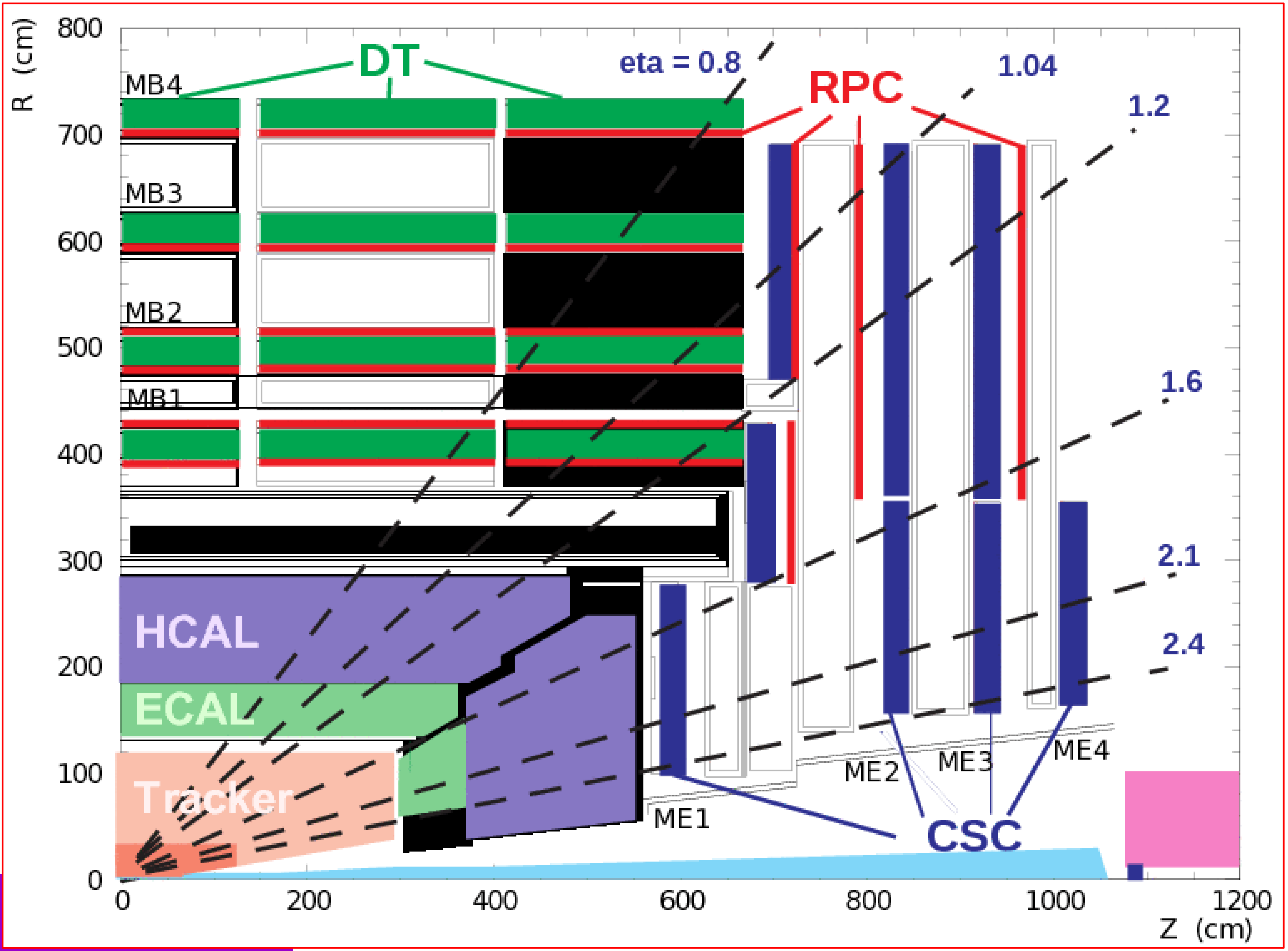
→ 2 x 900 towers (Quartz fibers, ≈ 10 λ_N)
→ $\Delta\eta \times \Delta\varphi \approx 0.111 \times 0.175 \rightarrow 0.302 \times 0.350$

<u>CASTOR calorimeter</u> (not shown):
- $5.1 < |\eta| < 6.5$, ≈ 22 X_0, ≈ 10 λ_N



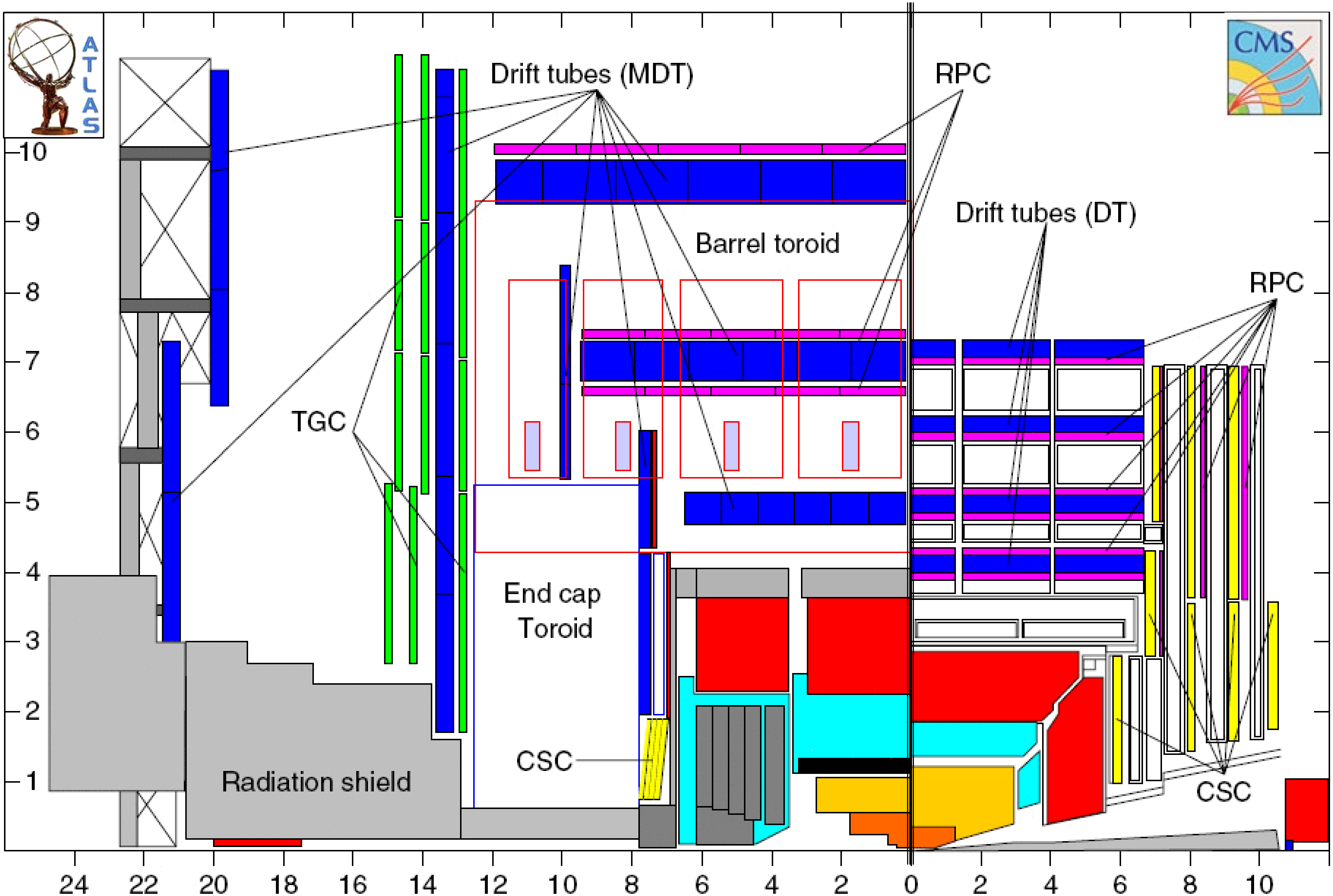
hadronic calo:
Brass/scintillator/wls readout

The CMS detector: μ system



muon system:
drift tube (DT) chambers

Detectors comparison : ATLAS vs CMS



Detectors comparison : structure

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

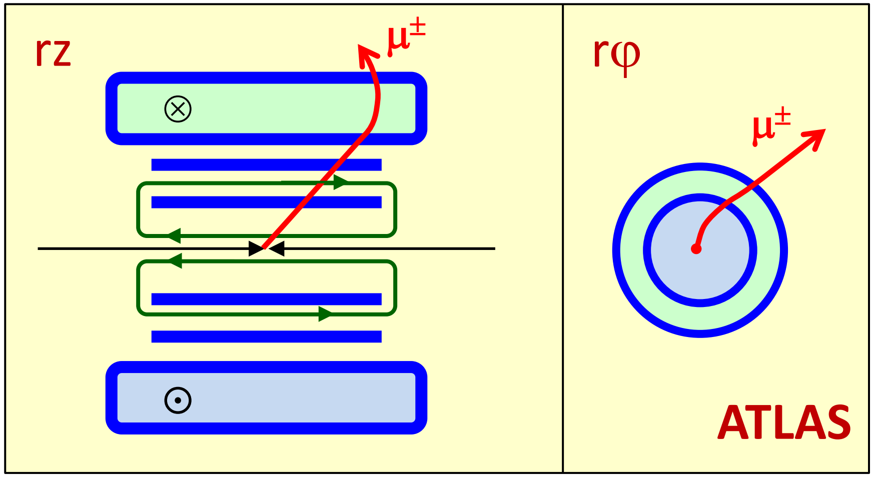
Detectors comparison : performances

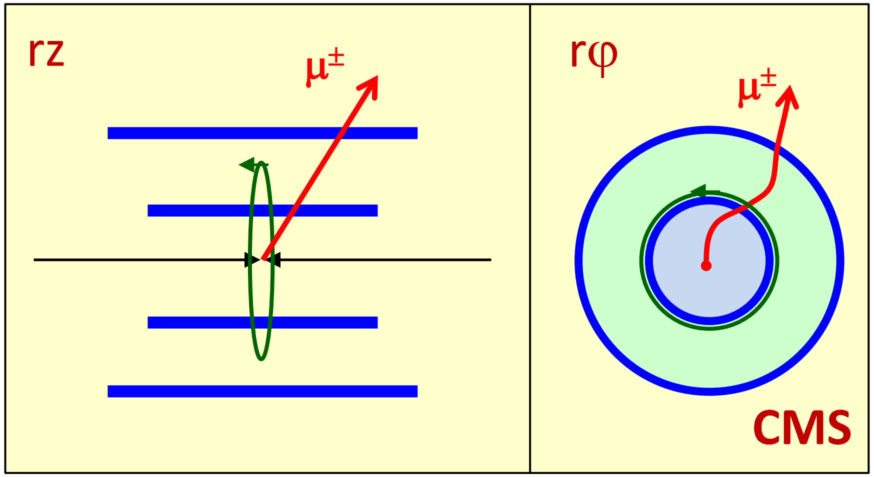
thanks to Anna Colaleo

	ATLAS	CMS
Tracker/ Inner Detector	TRD → particle identification $\sigma/p_T \approx 5 \times 10^{-4} p_T$ (GeV) $\oplus$ 0.01	No particle identification $\sigma/p_T \approx 1.5 \times 10^{-4} p_T$ (GeV) $\oplus$ 0.005
Electro-magnetic calorimeter	$\sigma/E \approx 10\%/\sqrt{E}$ (GeV) Longitudinal segmentation	$\sigma/E \approx (2 \div 5)\ \%/\sqrt{E}$ (GeV) No longitudinal segmentation
Hadronic calorimeter	$> 10\ \lambda$ $\sigma/E \approx 50\%/\sqrt{E}$ (GeV) $\oplus$ 0.03	$> 5.8\ \lambda$ + tail catcher $\sigma/E \approx 65\%/\sqrt{E}$ (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).

Detectors comparison : mag. spectrometers





ATLAS:

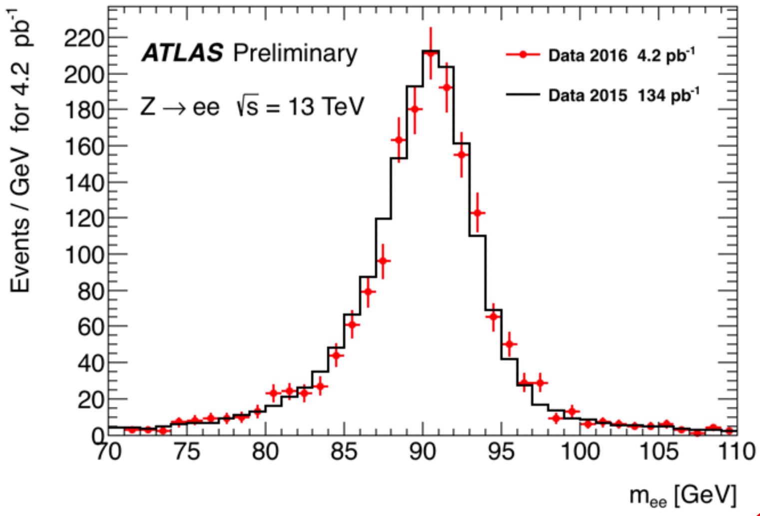
- main magnet: toroid B = 0.7 T;
- bending in (r,z);
- straight tracks in (r,φ);
- at small r, a solenoid B = 2 T → bending also in (r,φ);
- less precise in extrapolating to main vtx;
- μ-system in air → no multiple scatt. for μ's;
- larger bending for μ at large η → more precise.

CMS:

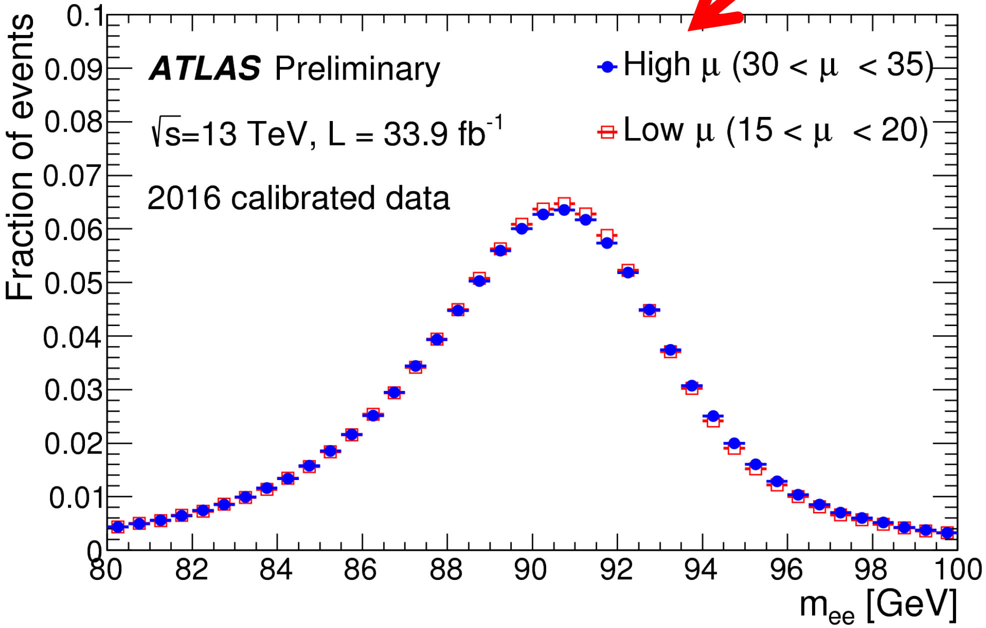
- main magnet: solenoid B = 4 T;
- bending in (r,φ);
- straight tracks in (r,z);
- more precise in extrapolating to main vtx;
- μ-system in Fe → large multiple scatt. for μ's;
- less bending for μ's at large η.

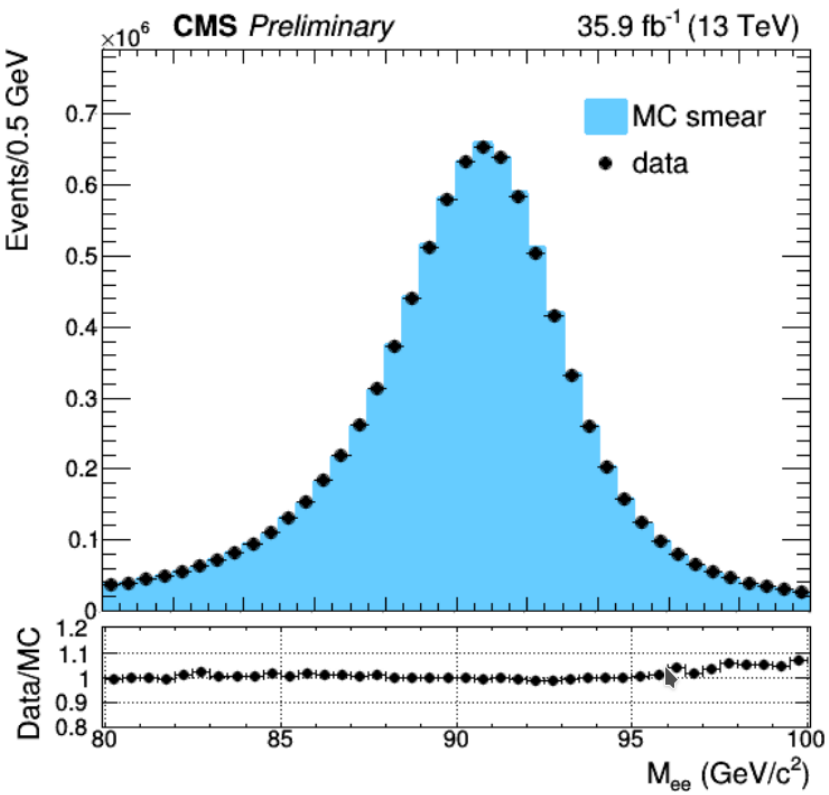
thanks to Anna Colaleo

Detector performances : $Z \to e^+e^-$

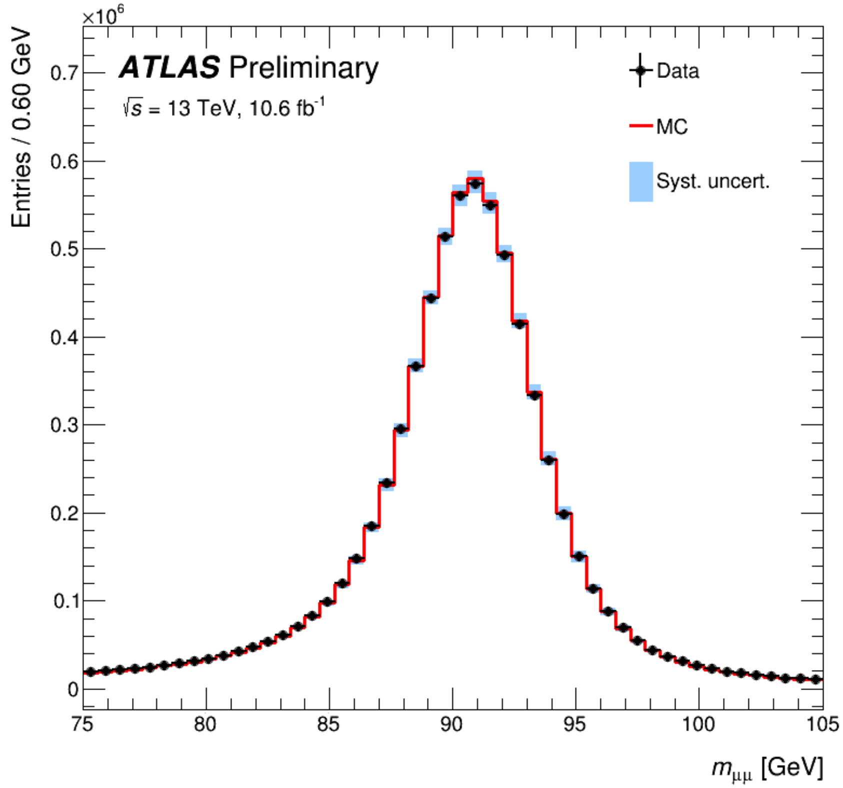


- the classic benchmark of tracker + e.m. calo.;
- no improvement wrt LEP, used only for detector debug/calibration (e.g. to show the independence from $\mathscr{L}$).

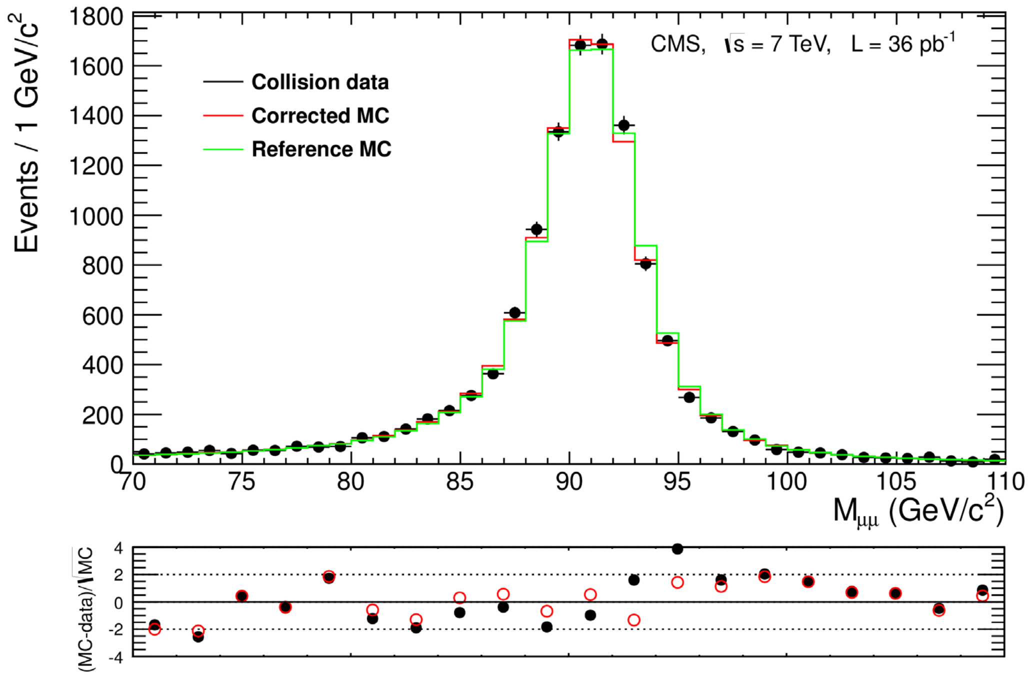




Detector performances : $Z \to \mu^+\mu^-$



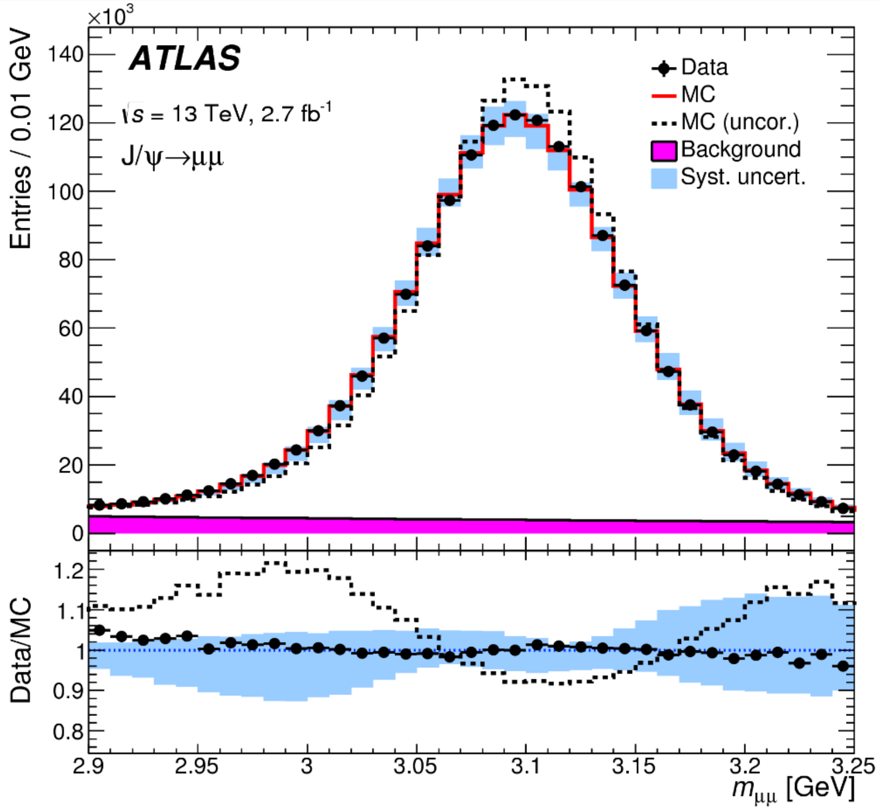
- the classic benchmark of tracker + muon chambers;
- [no way to improve wrt LEP, used only for detector debug/calibration.]



A famous joke:

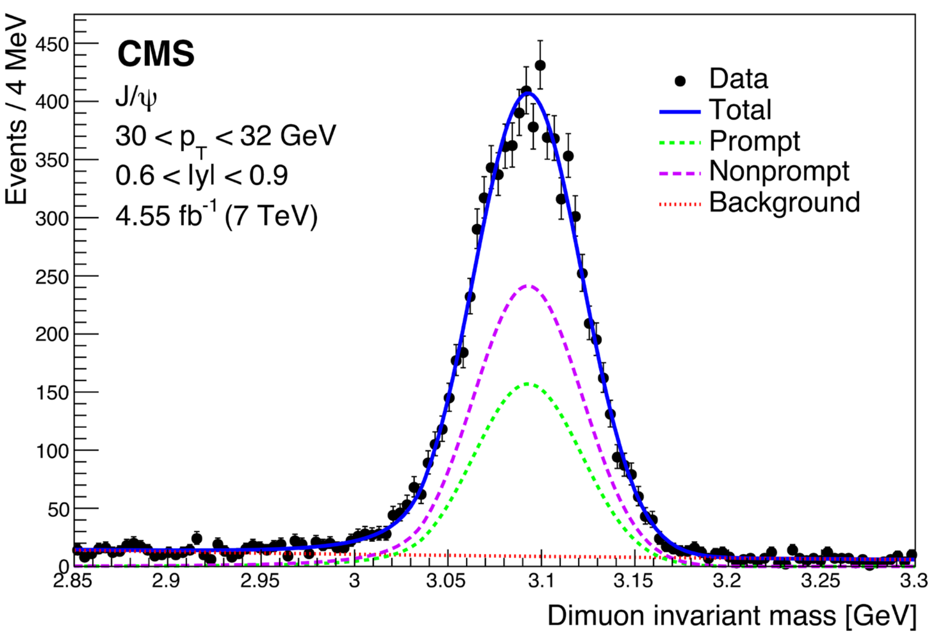
time evolution of physics processes: discovery → precision meas → detector study → background.

Detector performances : $J/\psi \to \mu^+\mu^-$

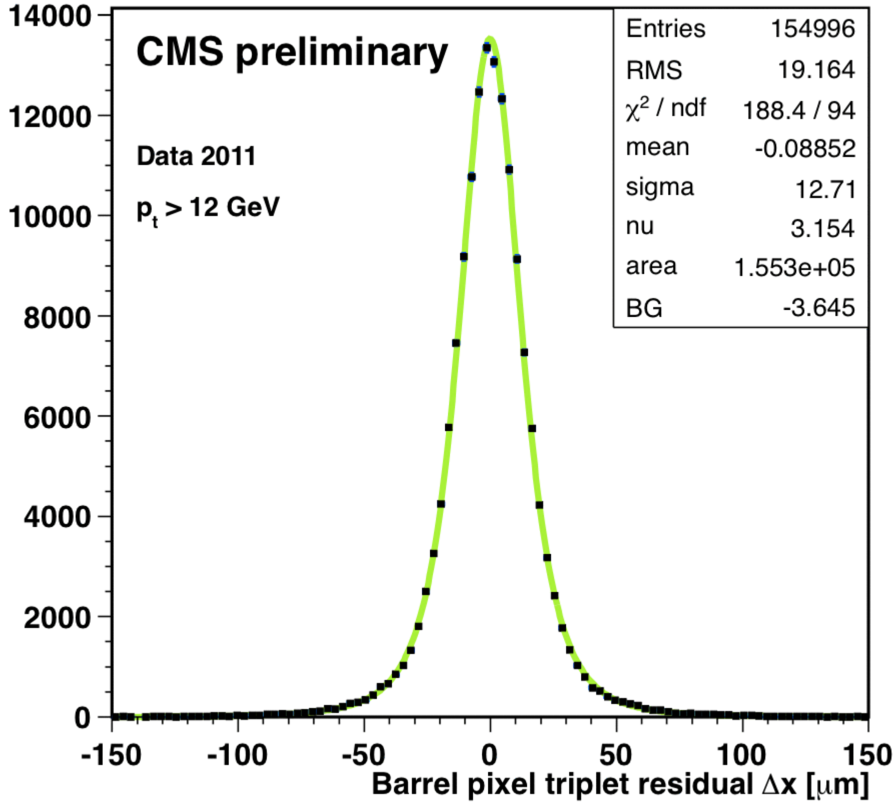


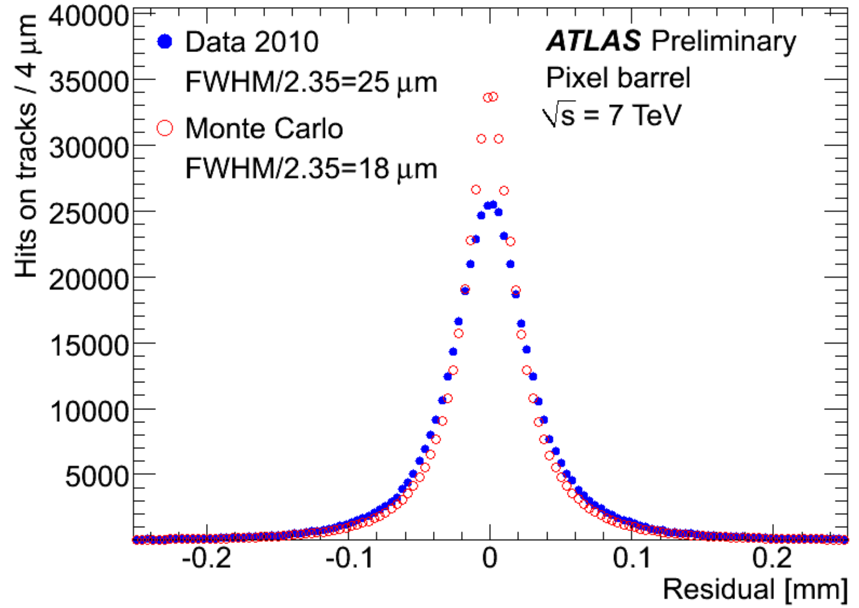
$Z \to \mu^+\mu^-$ and J/ψ $Z \to \mu^+\mu^-$ are ideal channels for μ studies :

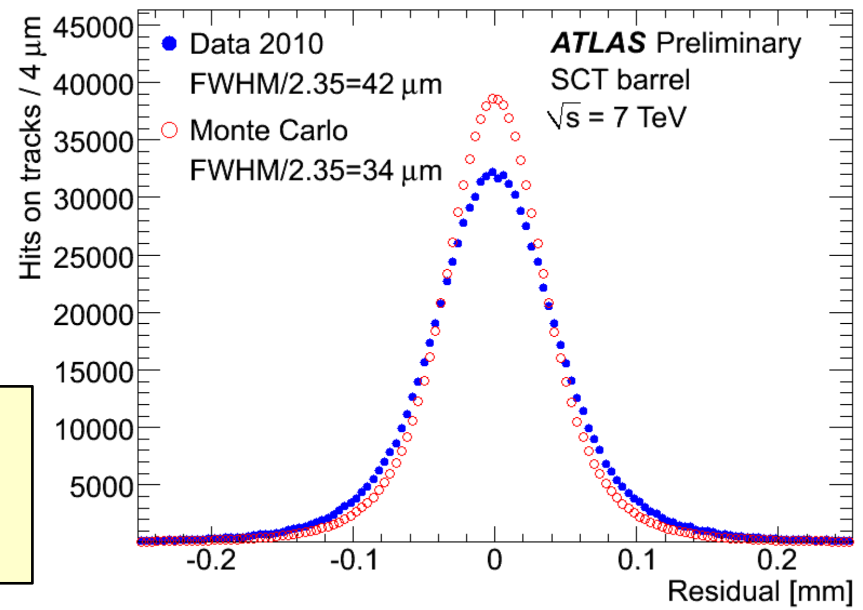
- inner detector + muon spectrometer;
- agreement (MC $\leftrightarrow$ data) $\to$ confidence in analysis (including errors !).



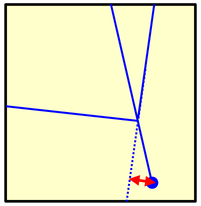
Detector performances : silicon trackers





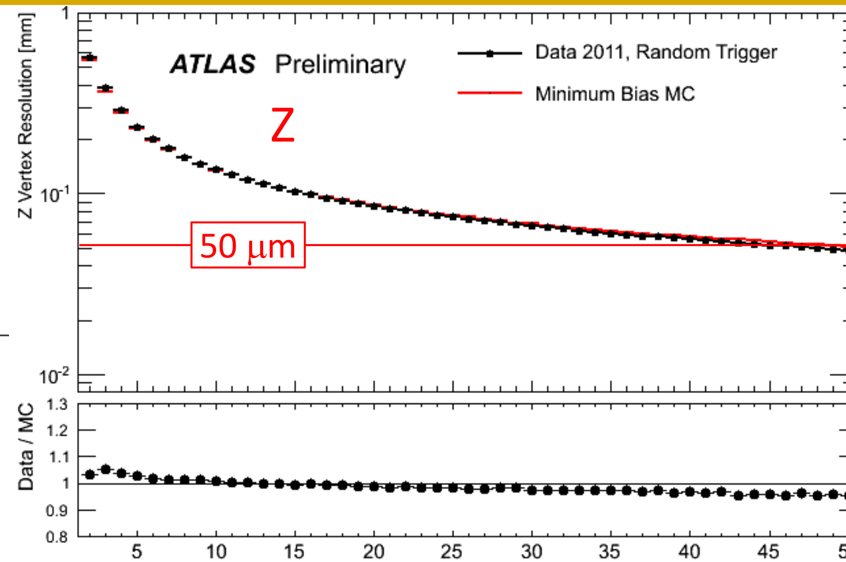


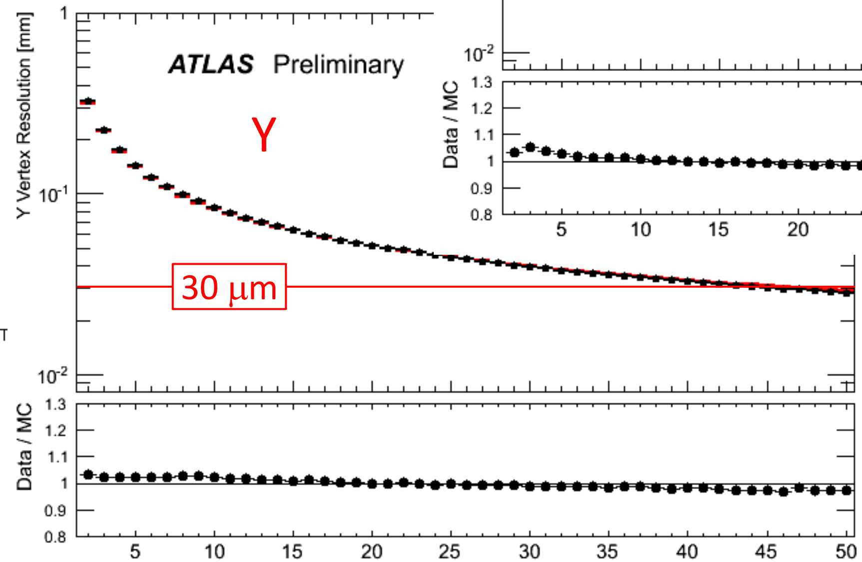
- resolution of few μm necessary for impact parameter → identification of secondary verteces → heavy flavors → higgs;
- agreement (MC ↔ data) → confidence in analysis (including errors !).

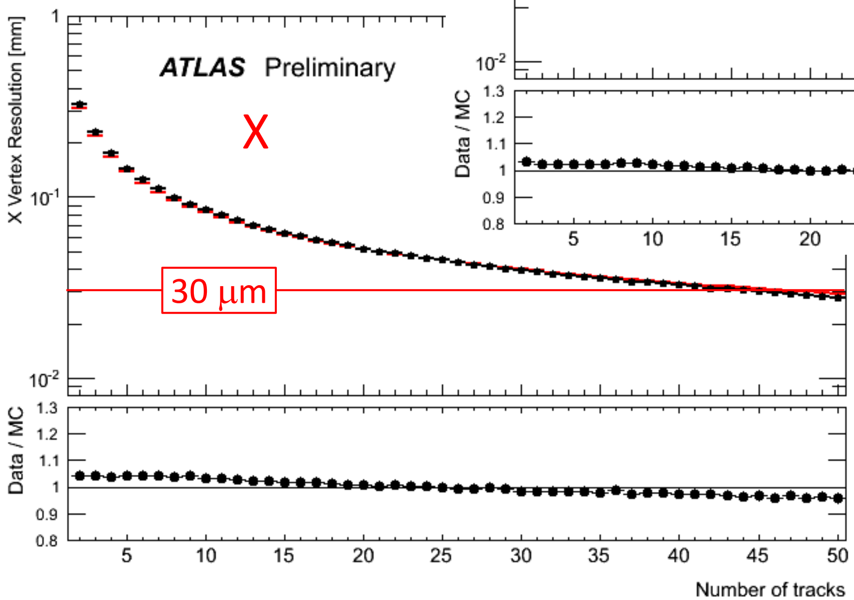


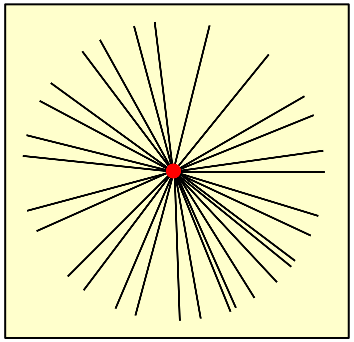
Detector performances : vertex resolution

- 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).

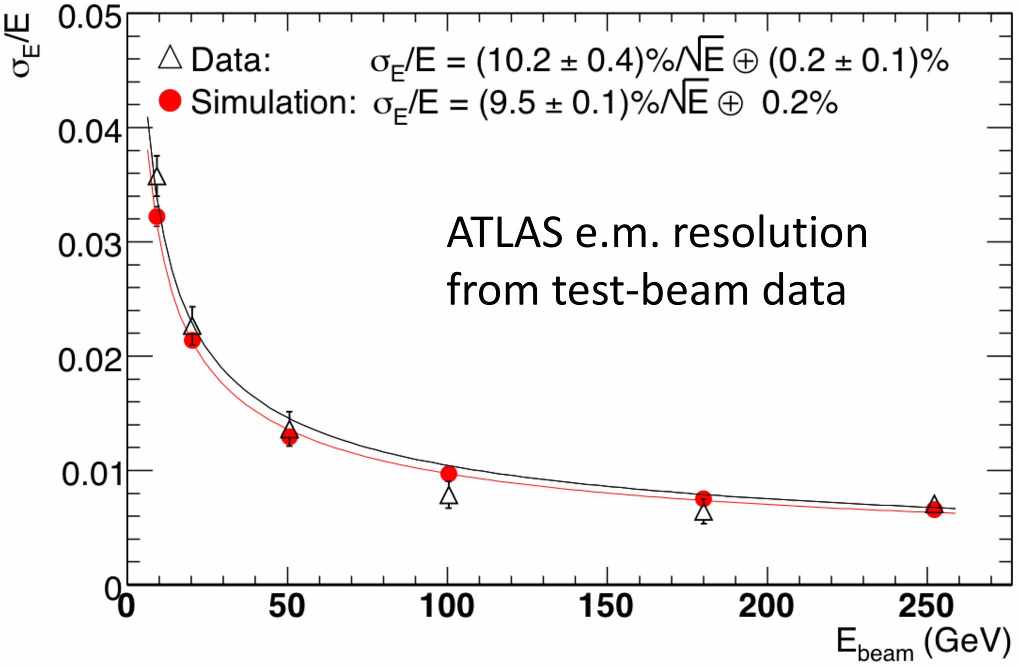








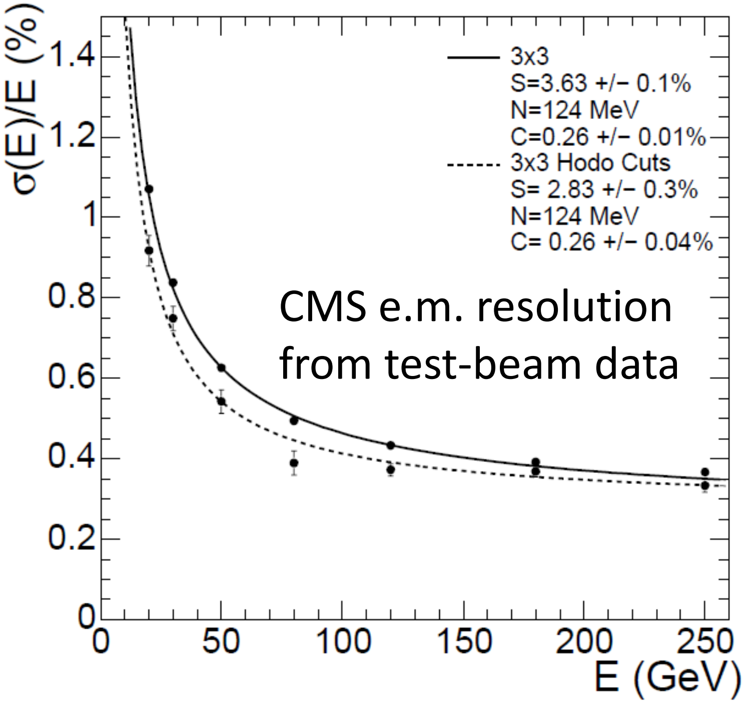
Detector performances : e.m. calo



ATLAS e.m. resolution from test-beam data

→ test these expectations with real particles:

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



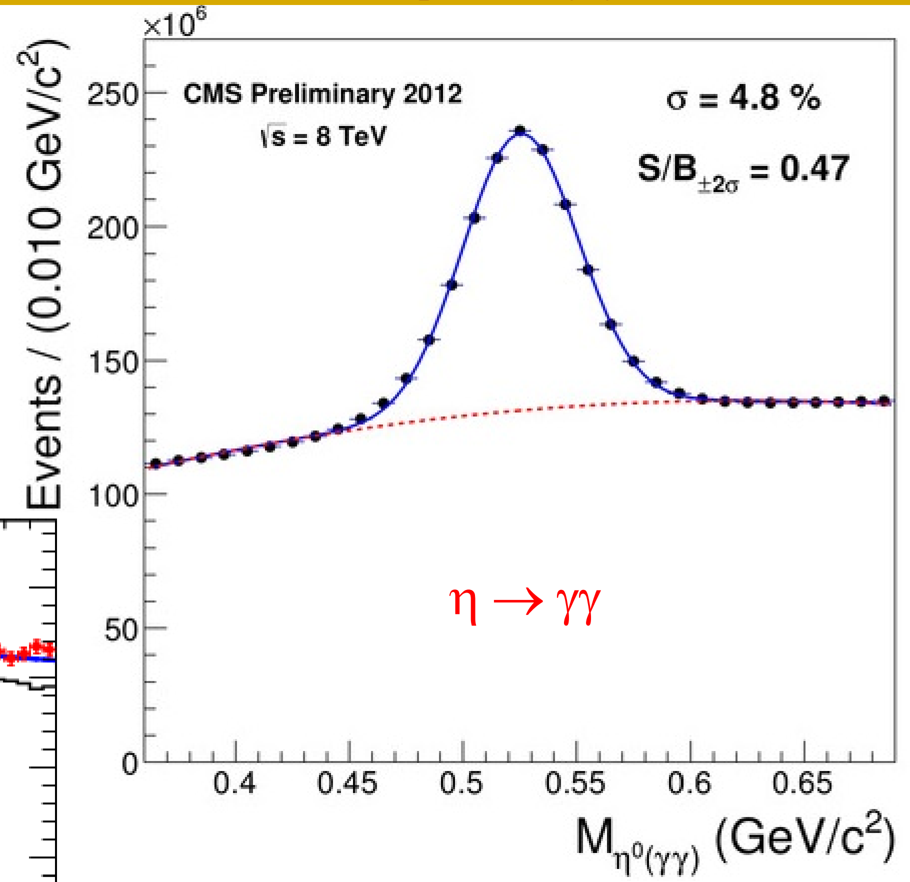
CMS e.m. resolution from test-beam data

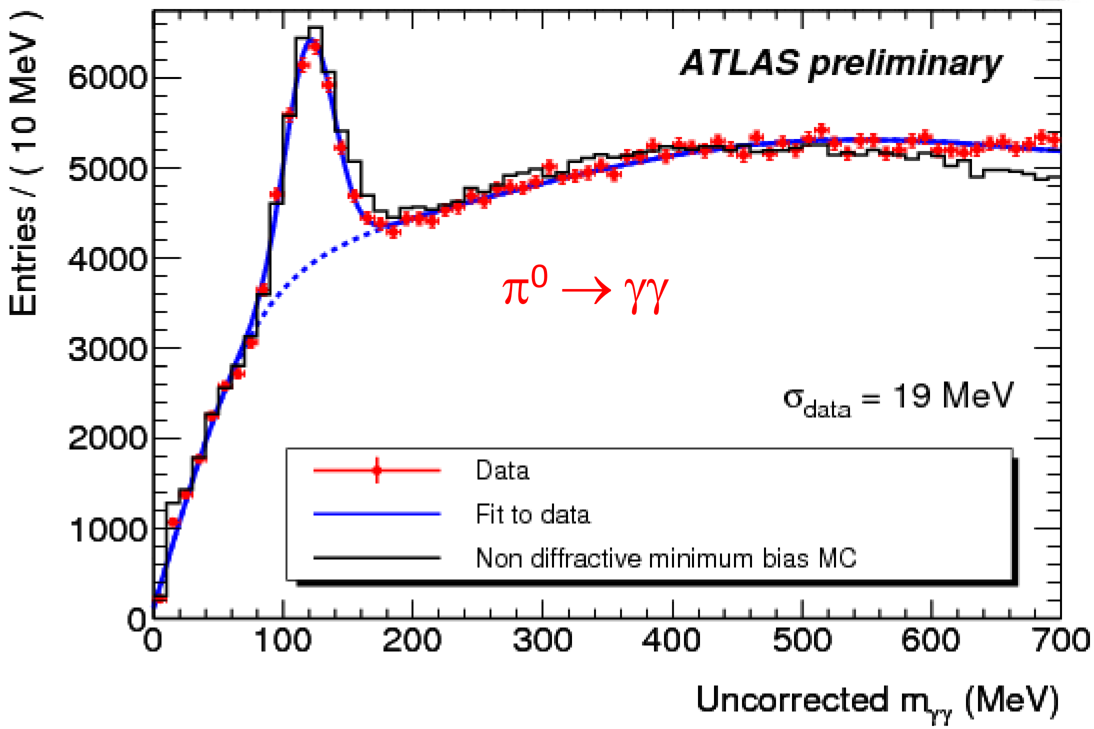
- although real life is somewhat different (sys from cell-to-cell calib, control of temperature, etc), test-beam results are impressive;
- expect $\sigma/E \approx \sigma_1/E \oplus \sigma_2 / \sqrt{E} \oplus \sigma_3$;
- σ_1 looks negligible, while σ_3 dominates at high E.

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

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.

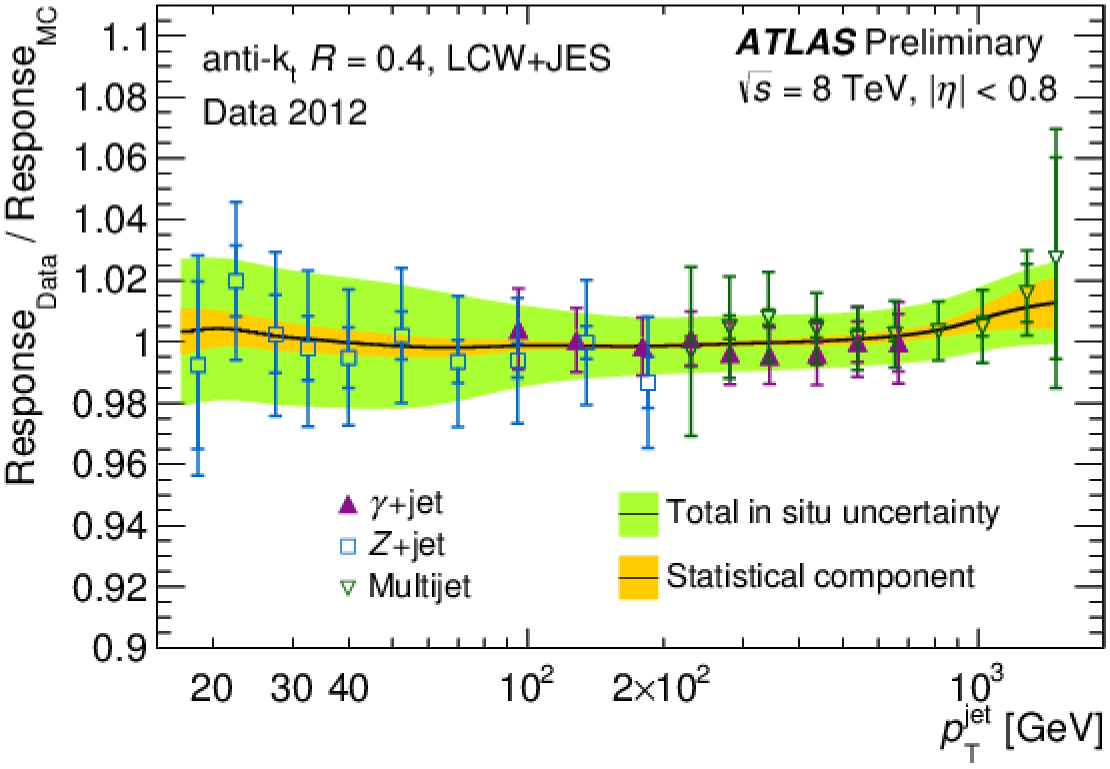




Detector performances : jet response

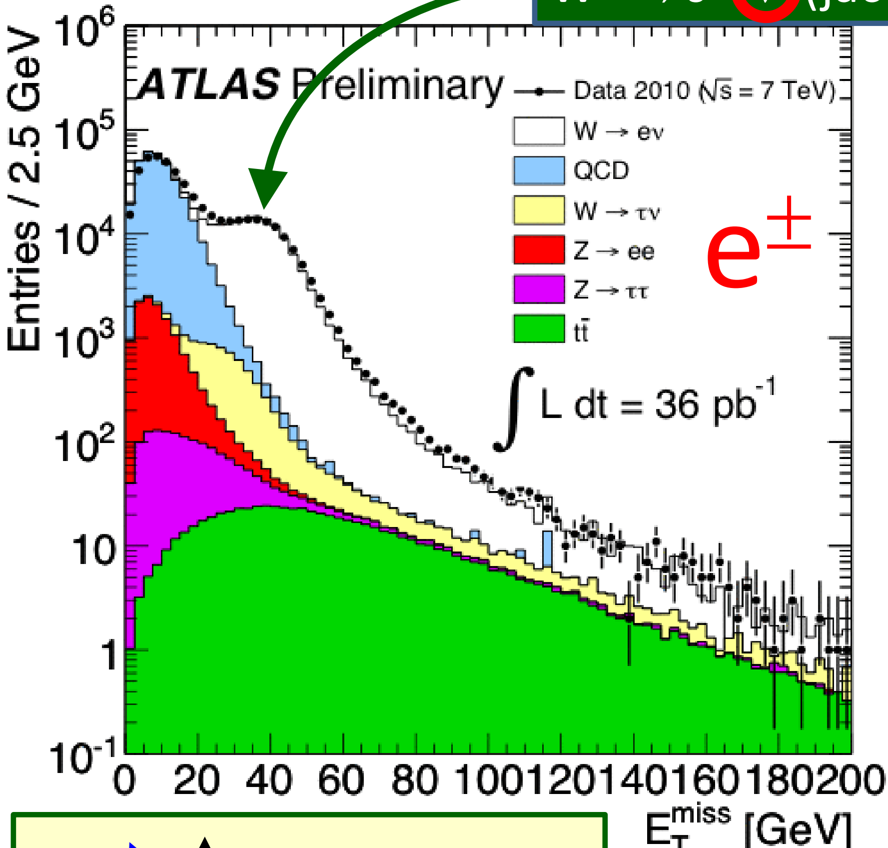
jet resolution as a function of p_T^{jet} :

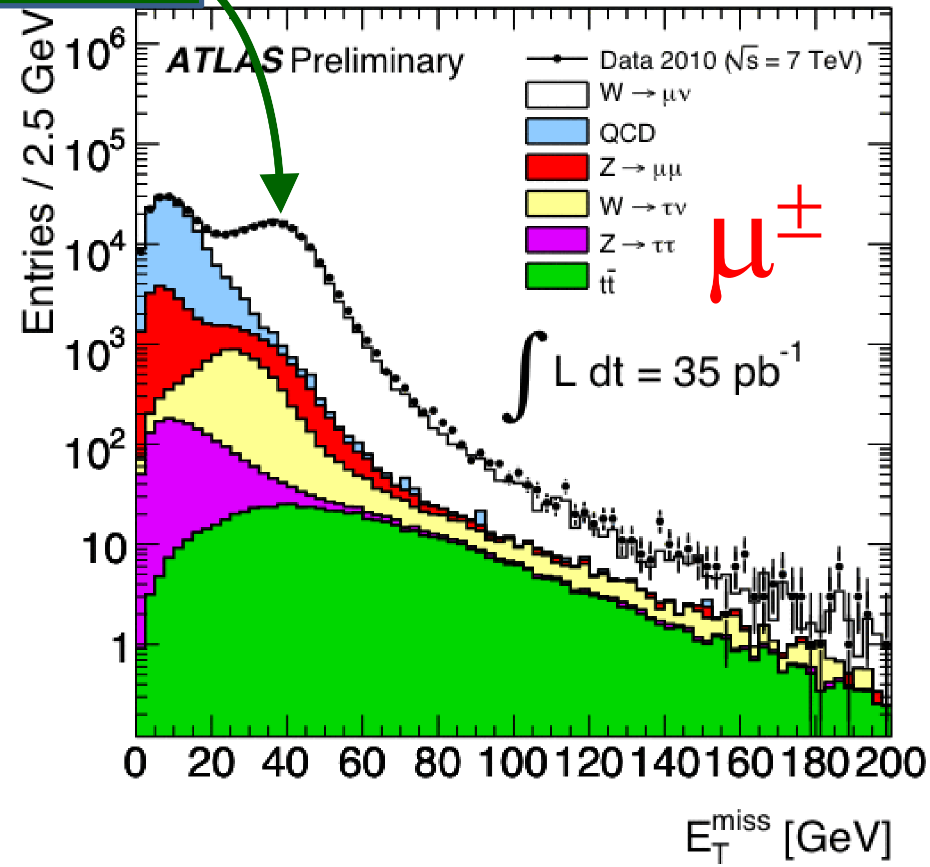
- measured for different event types;
- stat and (mainly) syst uncertainty 2%, almost independent on p_T.

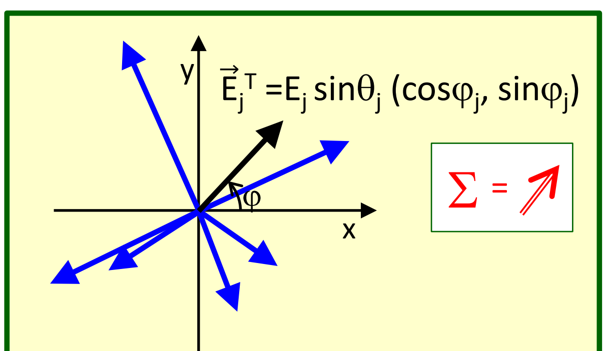


Detector performances : $\not{E}_T$

$W^\pm \to \ell^\pm \nu$ (jacobian peaks)







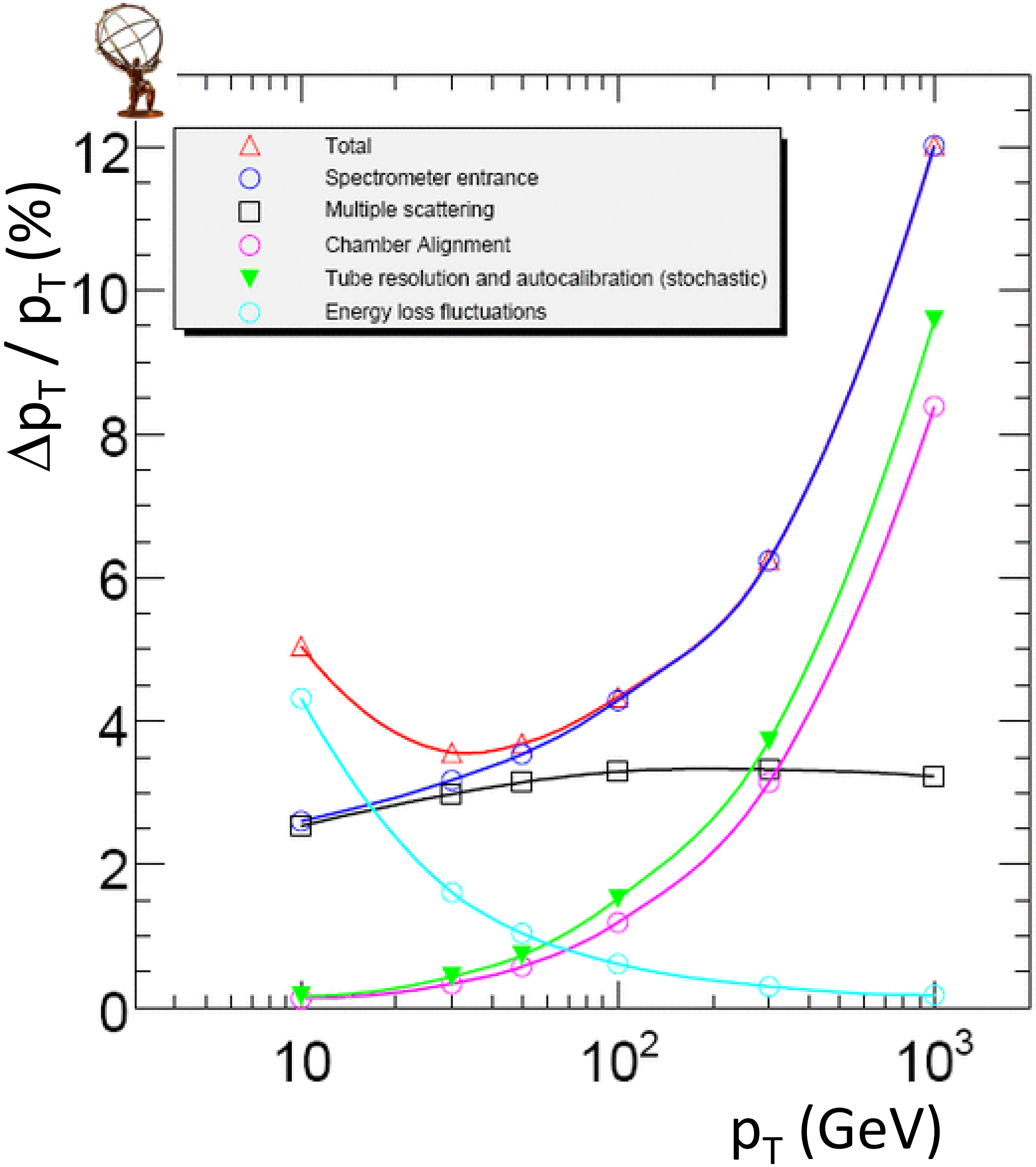
$\vec{E}_j^{\,T} = E_j \sin\theta_j \,(\cos\varphi_j, \sin\varphi_j)$

$\not{E}_T$ [= $|\sum \vec{E}_j^{\,T}|$] for events with $e^\pm$ or $\mu^\pm$ with p_T > 20 GeV :

- **great** agreement with predictions;

→ **reliable** measurement

Detector performances: ATLAS $\mu^{\pm}$

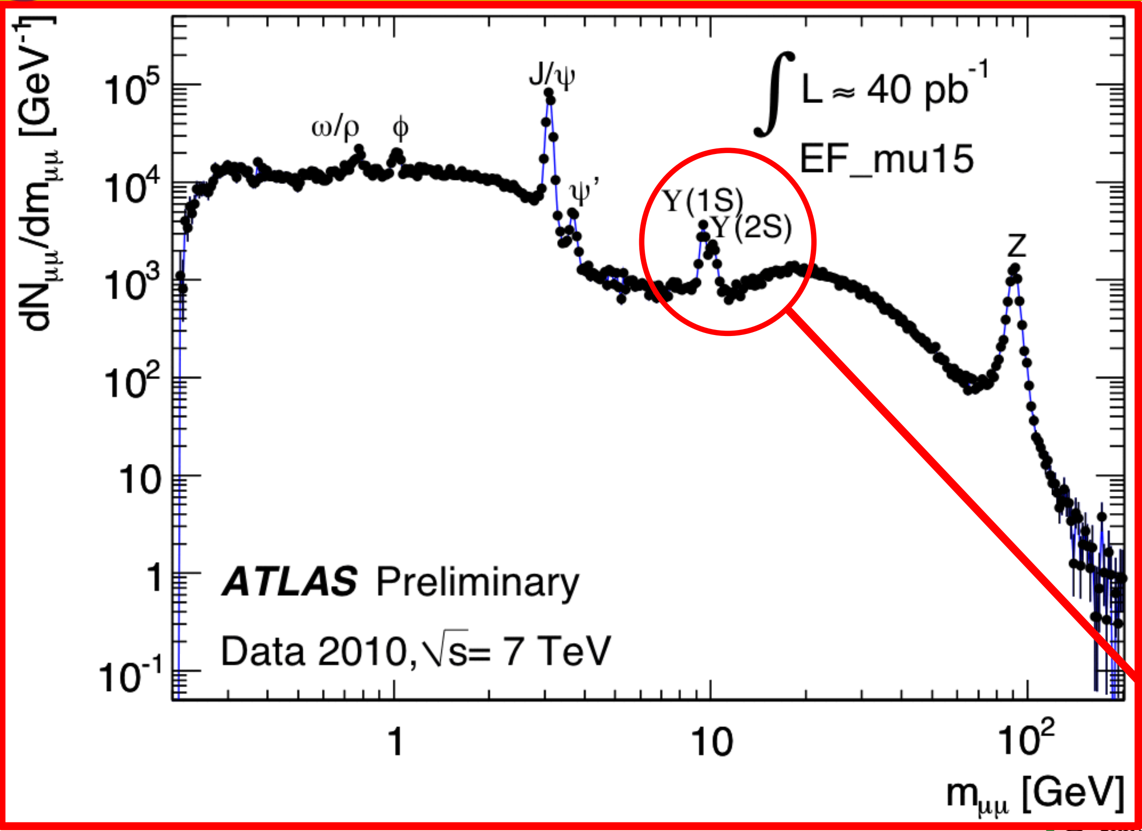


$\Delta p_T/p_T$ vs p_T [project, low η] :

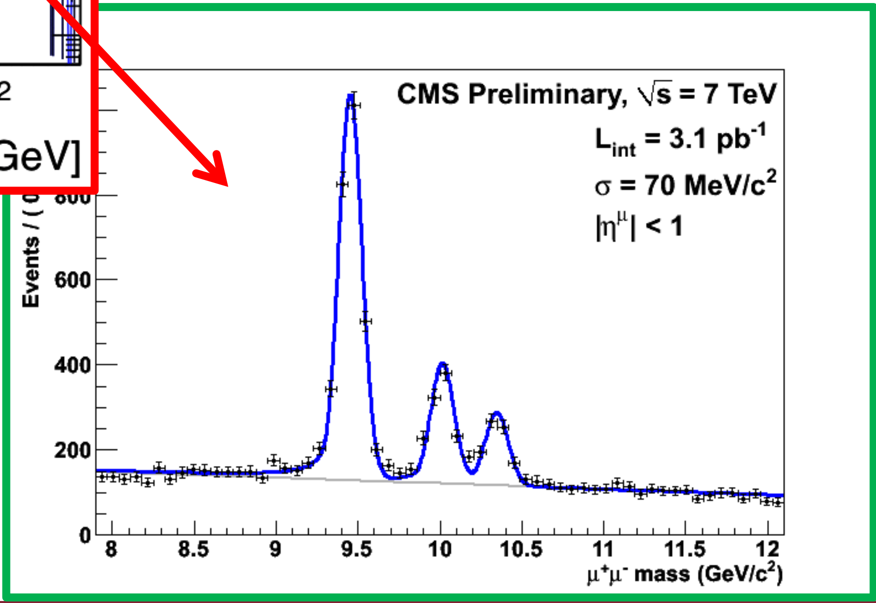
- ▼ meas. error + calib ($\propto p_T$);
- ○ chamber alignment ($\propto p_T$);
- □ multiple scattering ($\propto \approx$const);
- ○ ΔE_μ(calo) fluctuations (tail at high loss measurable from brem shower);
- ○ at spectrometer entrance (= ▼ ⊕ ○ ⊕ □);
- △ total at main vertex (= ○ ⊕ ○).

- 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.

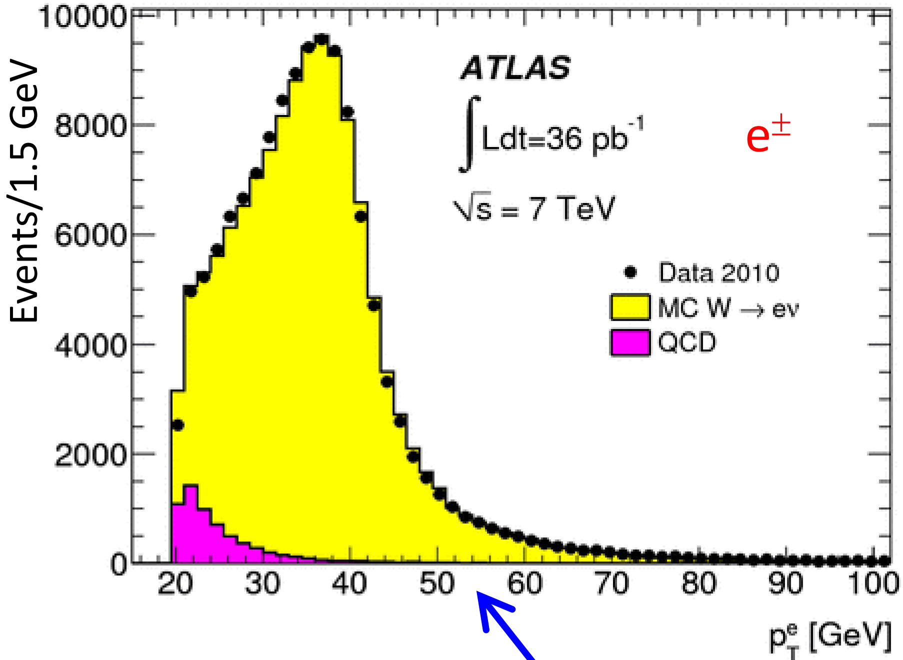
Detector performances : mass($\mu^+\mu^-$)

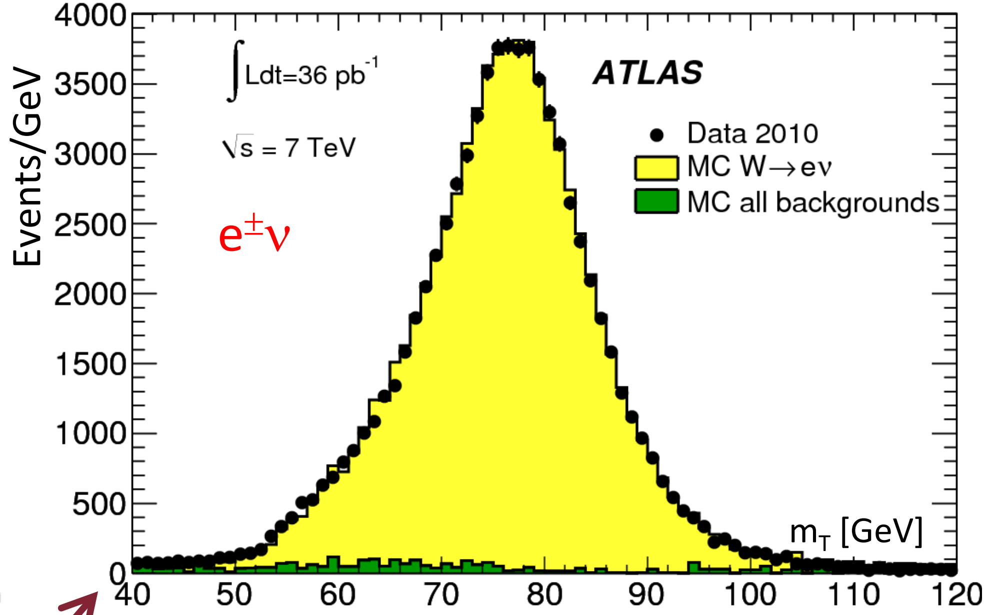


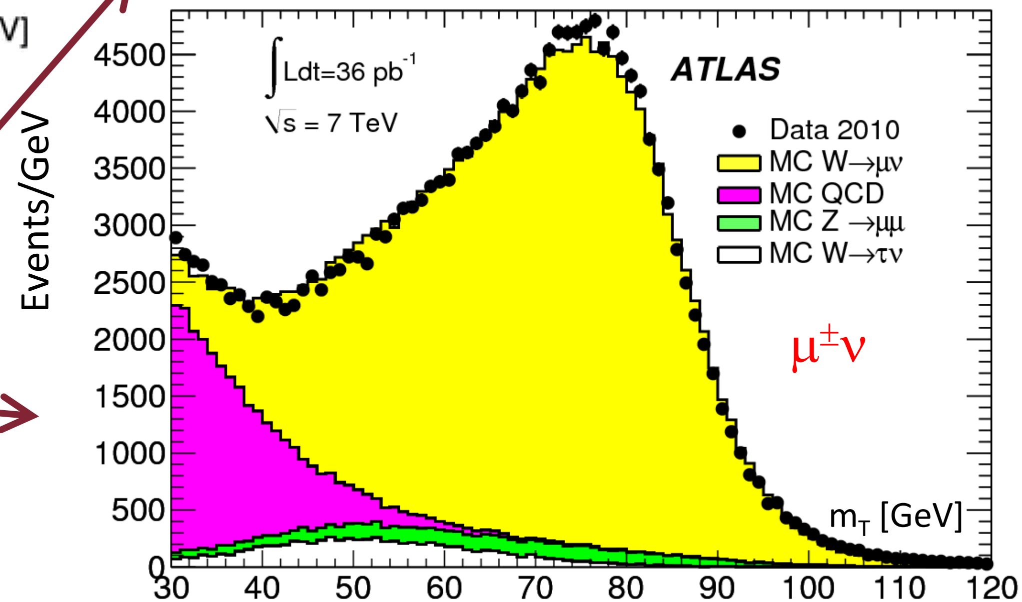
- at low $m_{\mu\mu}$, low trigger thresholds from low $\mathscr{L}$ runs;
- also a technical challenge.



Detector performances: $W^{\pm} \rightarrow \ell^{\pm}\nu$



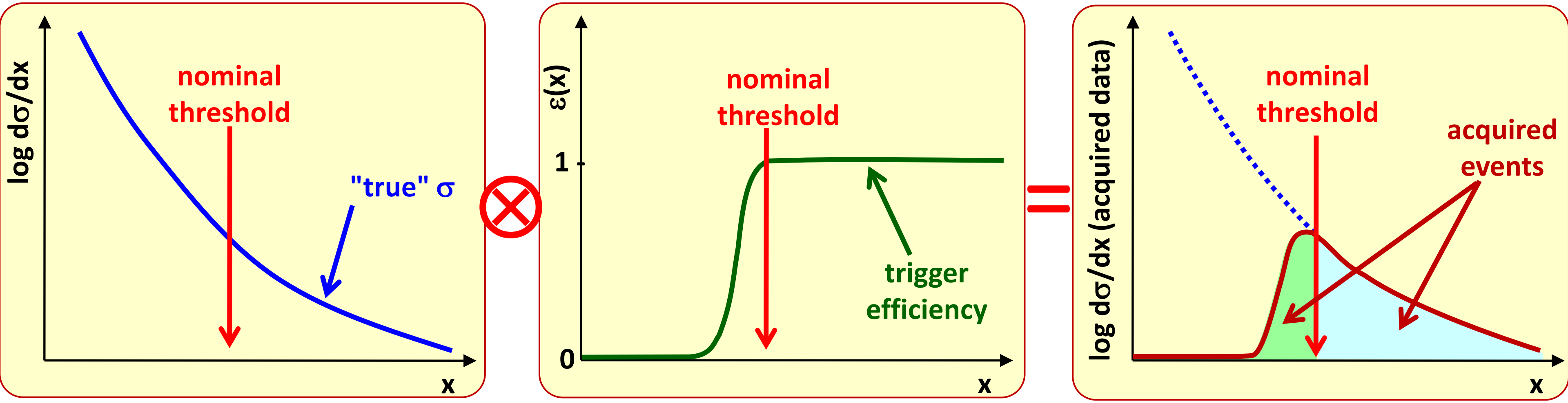




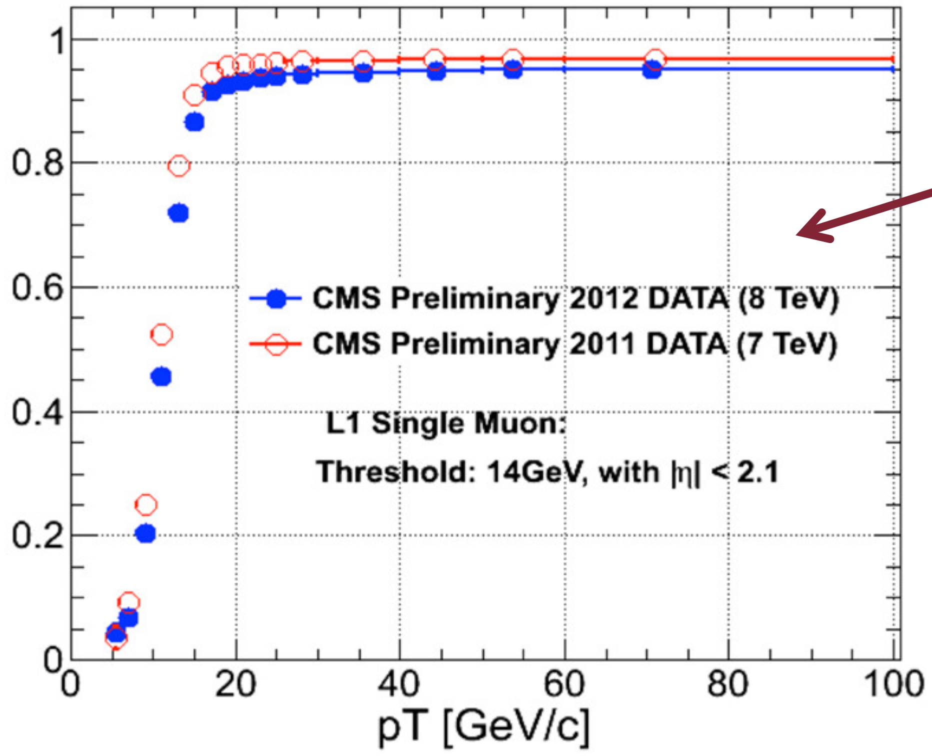
- the jacobian peak of the $e^{\pm}$;
- the transverse mass for $e^{\pm}\nu$ and $\mu^{\pm}\nu$.

Detector performances: trigger thresholds

- e^+e^- : small cross section → [R = $\mathscr{L}\sigma$ ≈ 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 = $\mathscr{L}\sigma$ ≈ 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.

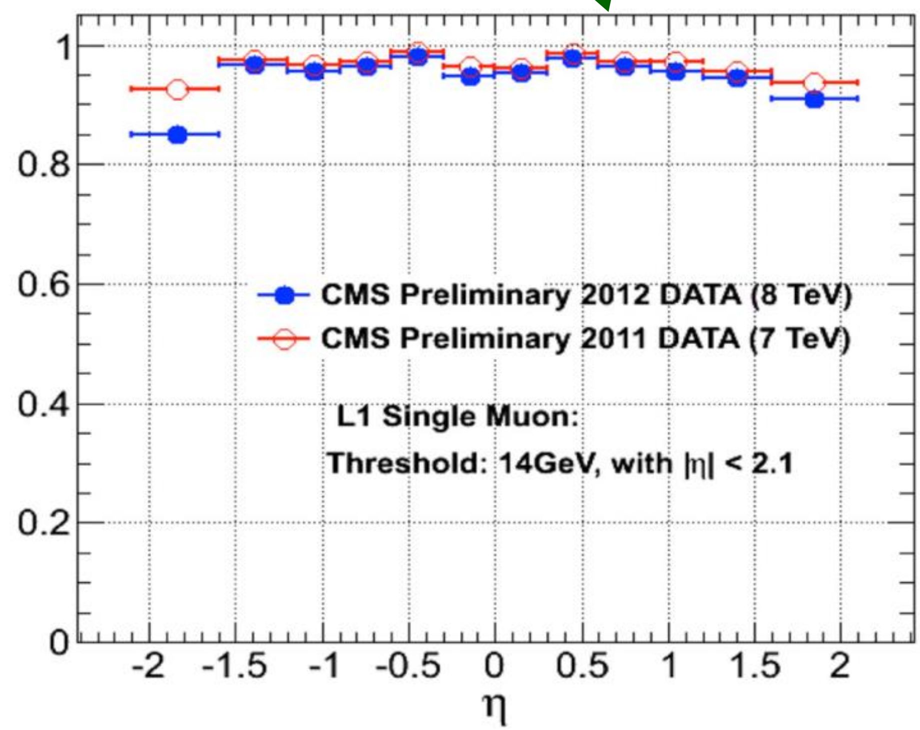


Detector performances: μ-trigger lvl-1



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.



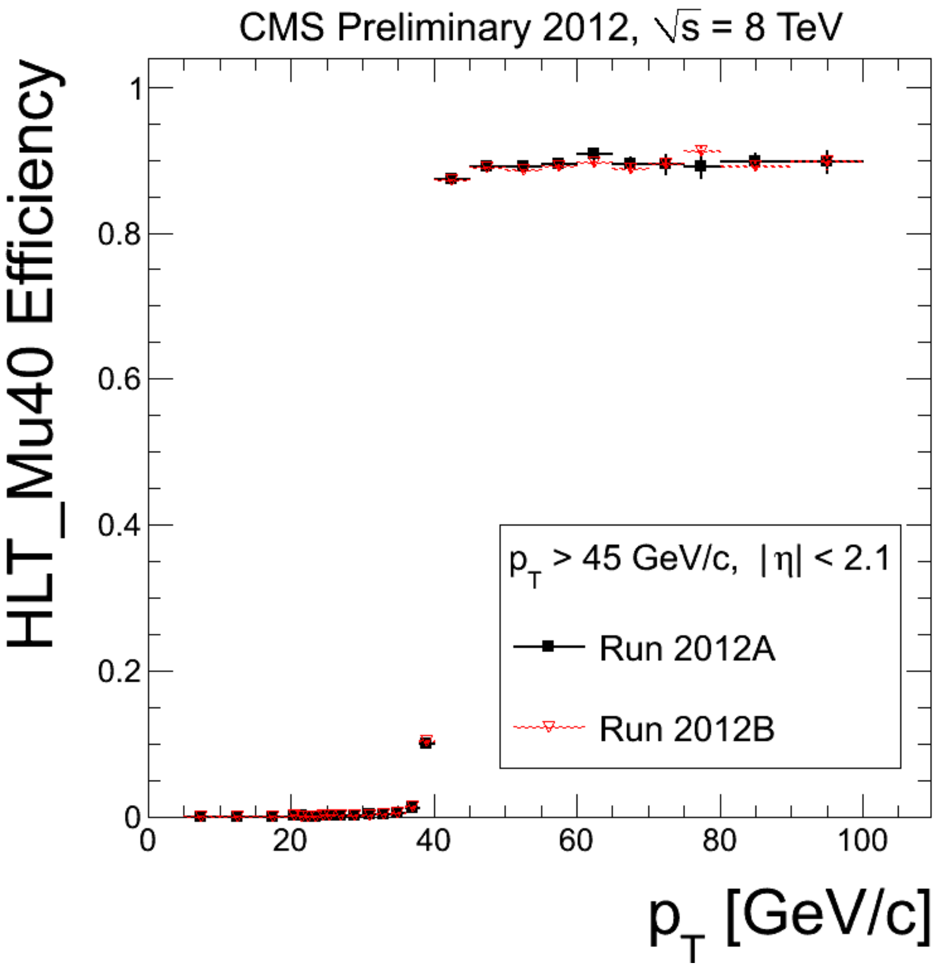
NB the effective yield $N_{obs} = N_{produced} * \varepsilon$:

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

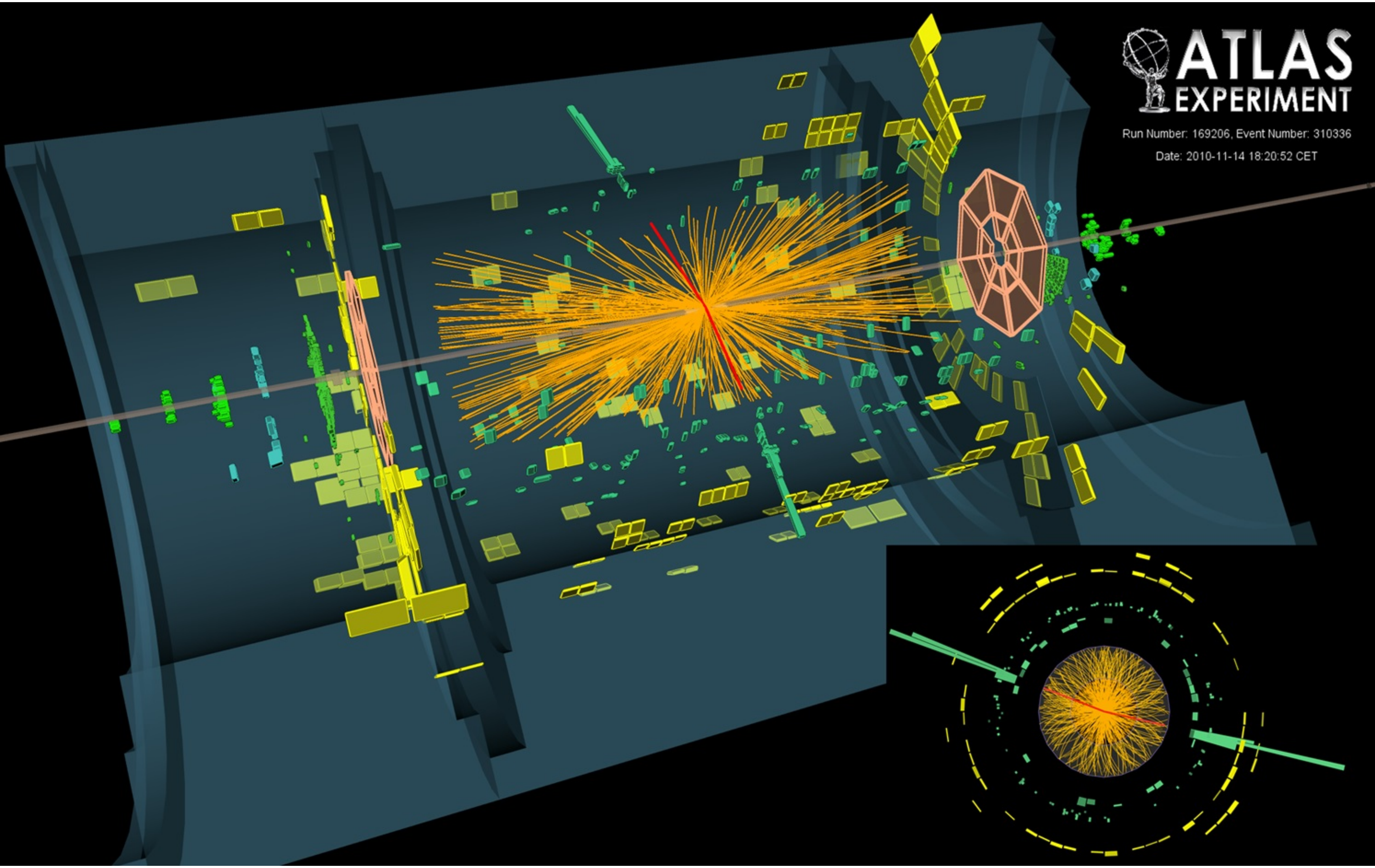
Detector performances: μ-trigger HLT

Efficiency ε vs p_T at the highest trigger level (HLT):

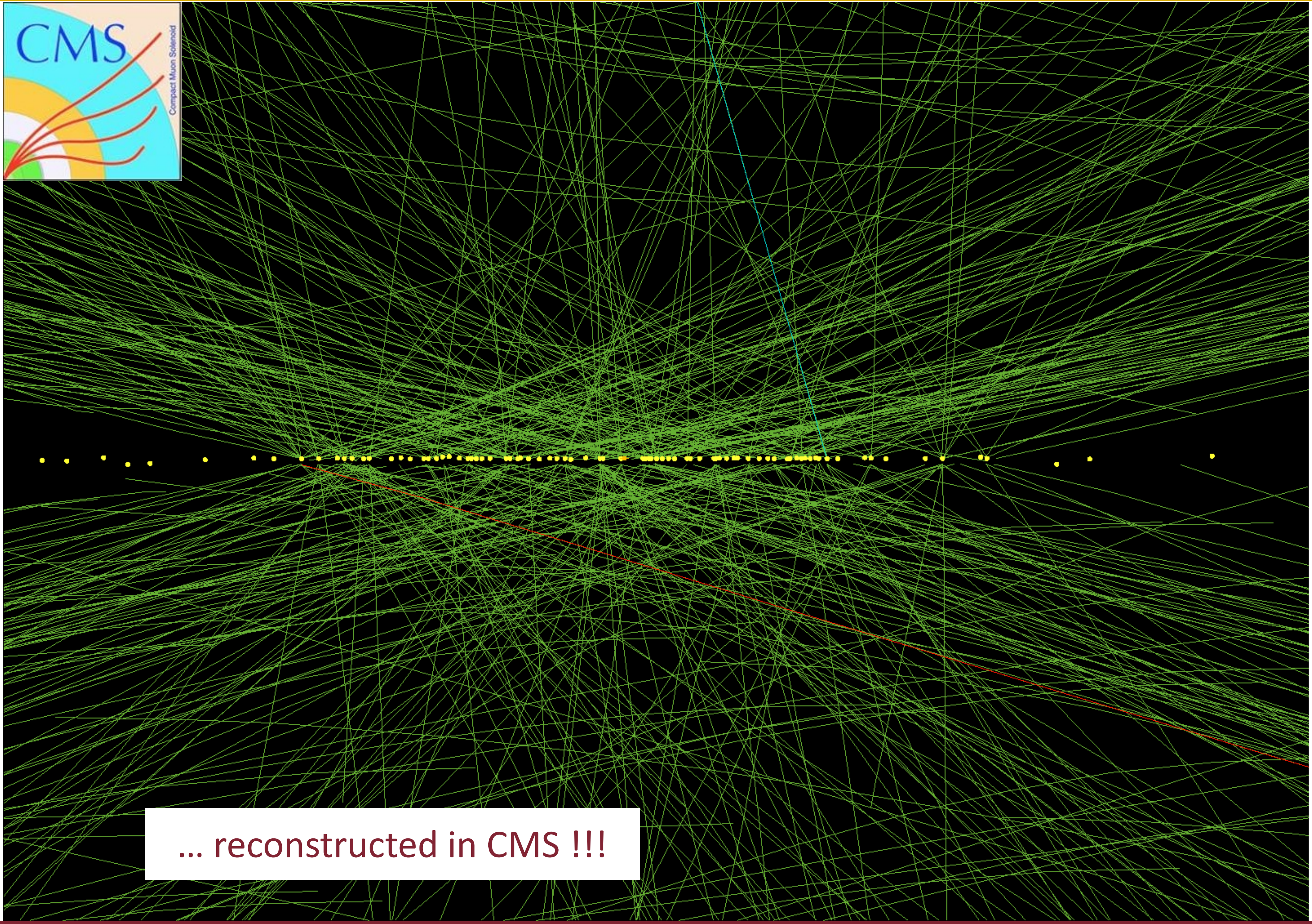
- notice the sharper "size" of the threshold (→ less useless data);
- … at the price of a much higher threshold (→ no recovery of events lost in lvl1);
- … with the advantage of (much) smaller rates :
  O(10 KHz) @ lvl-1 → O(10 Hz).



LHC events : Pb Pb $\to$ Z X $\to$ e^+e^- X

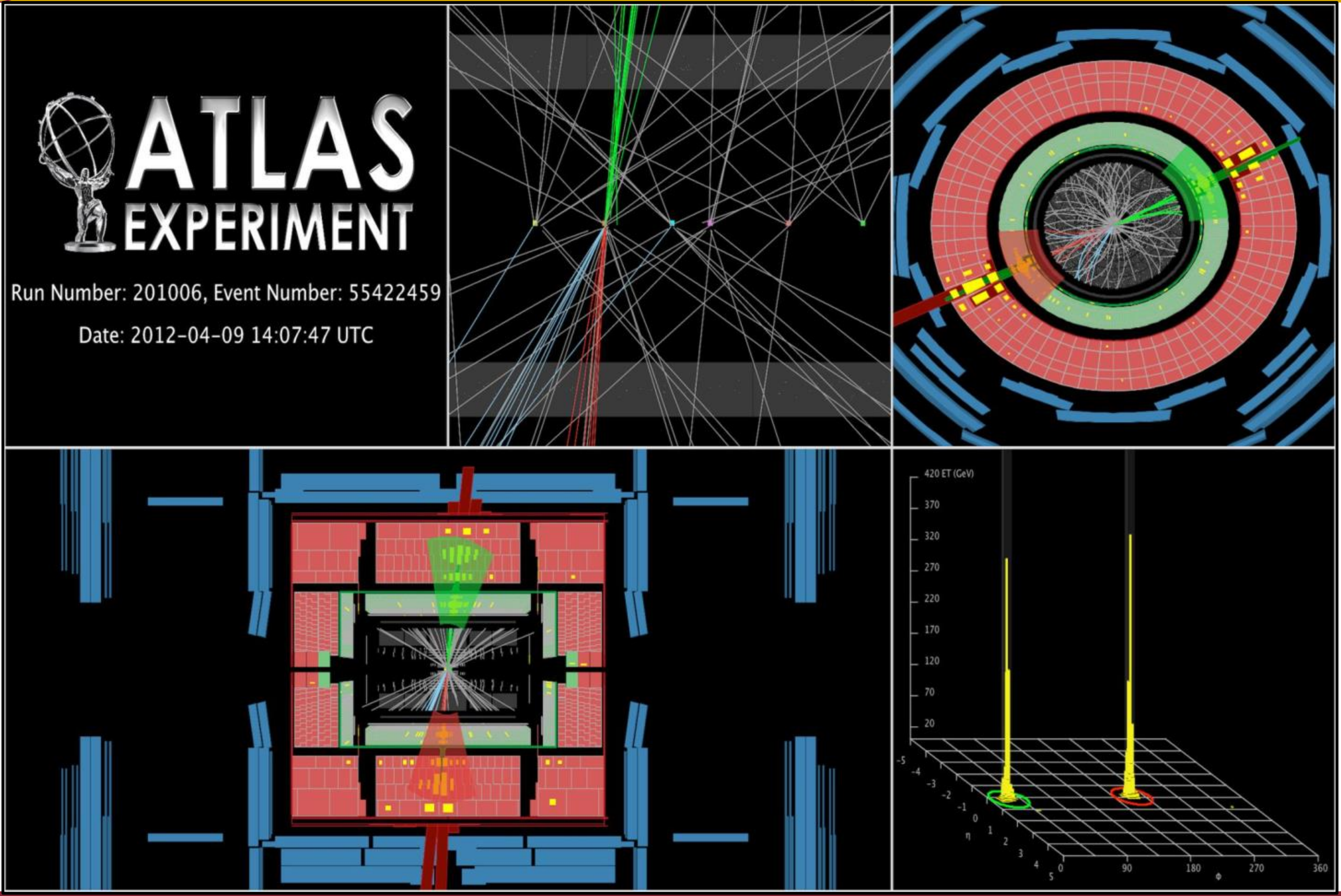


LHC events : 78 primary interactions

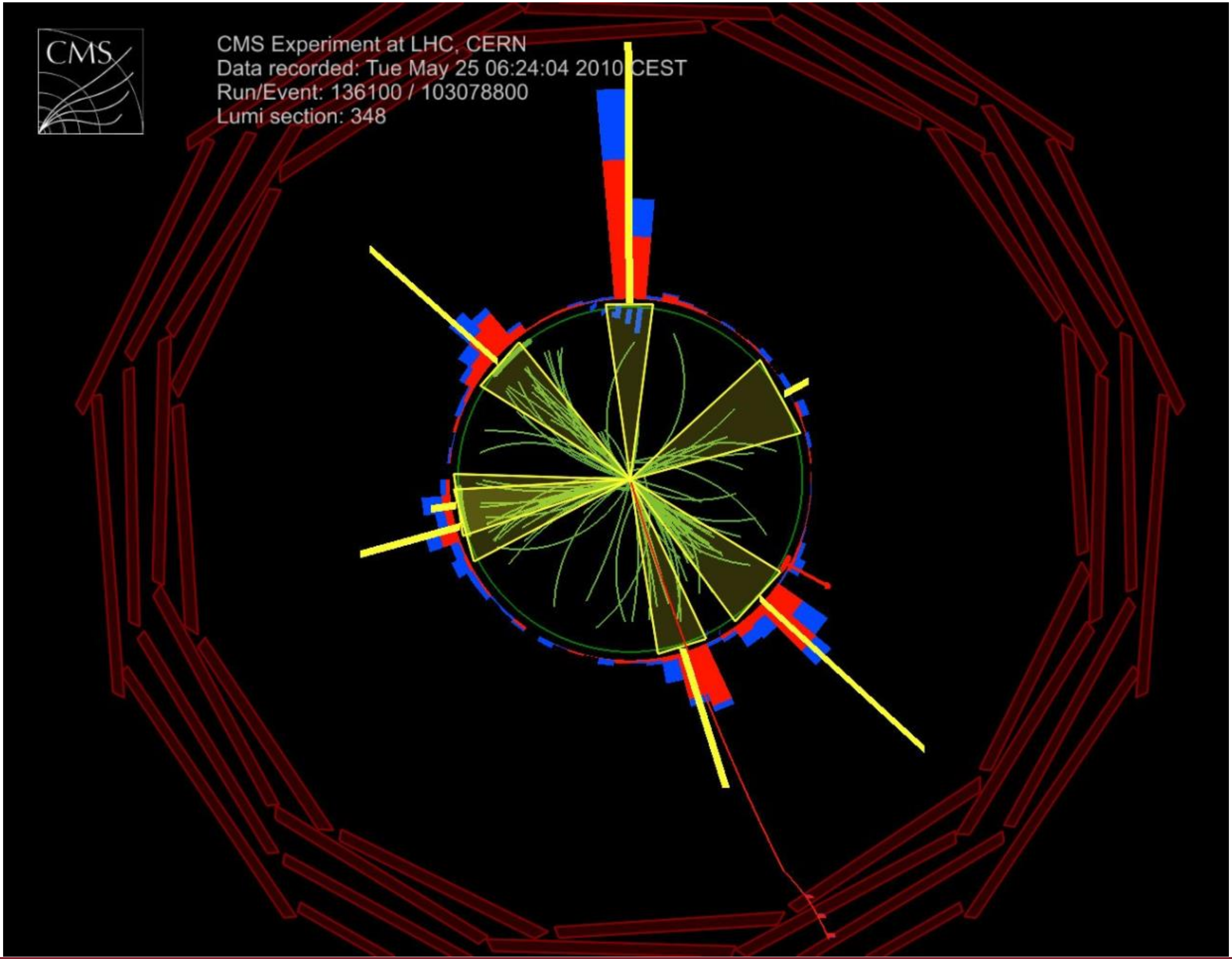


... reconstructed in CMS !!!

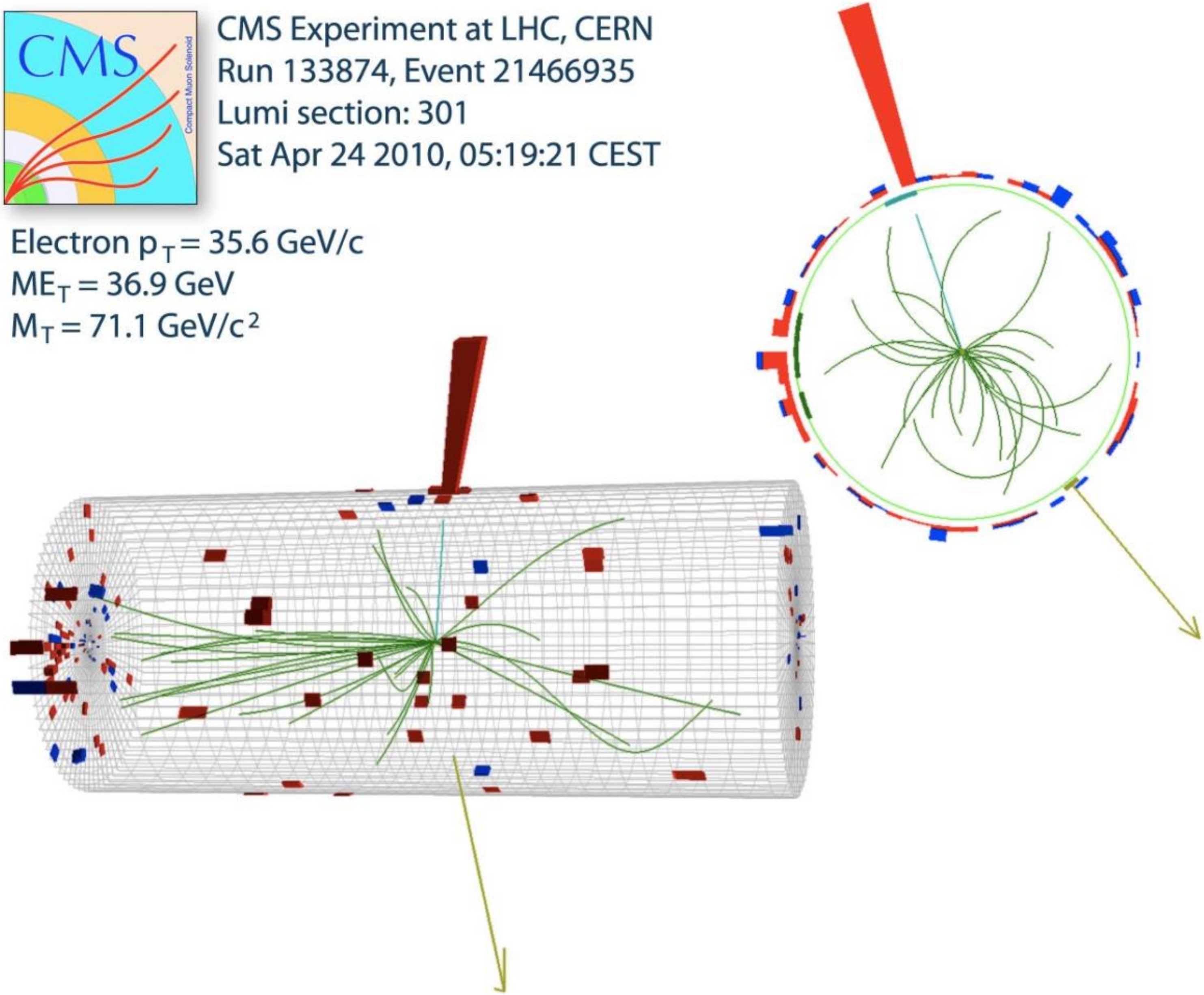
LHC events : 2 jets, $p_T \approx 2$ TeV



LHC events : a multijet event



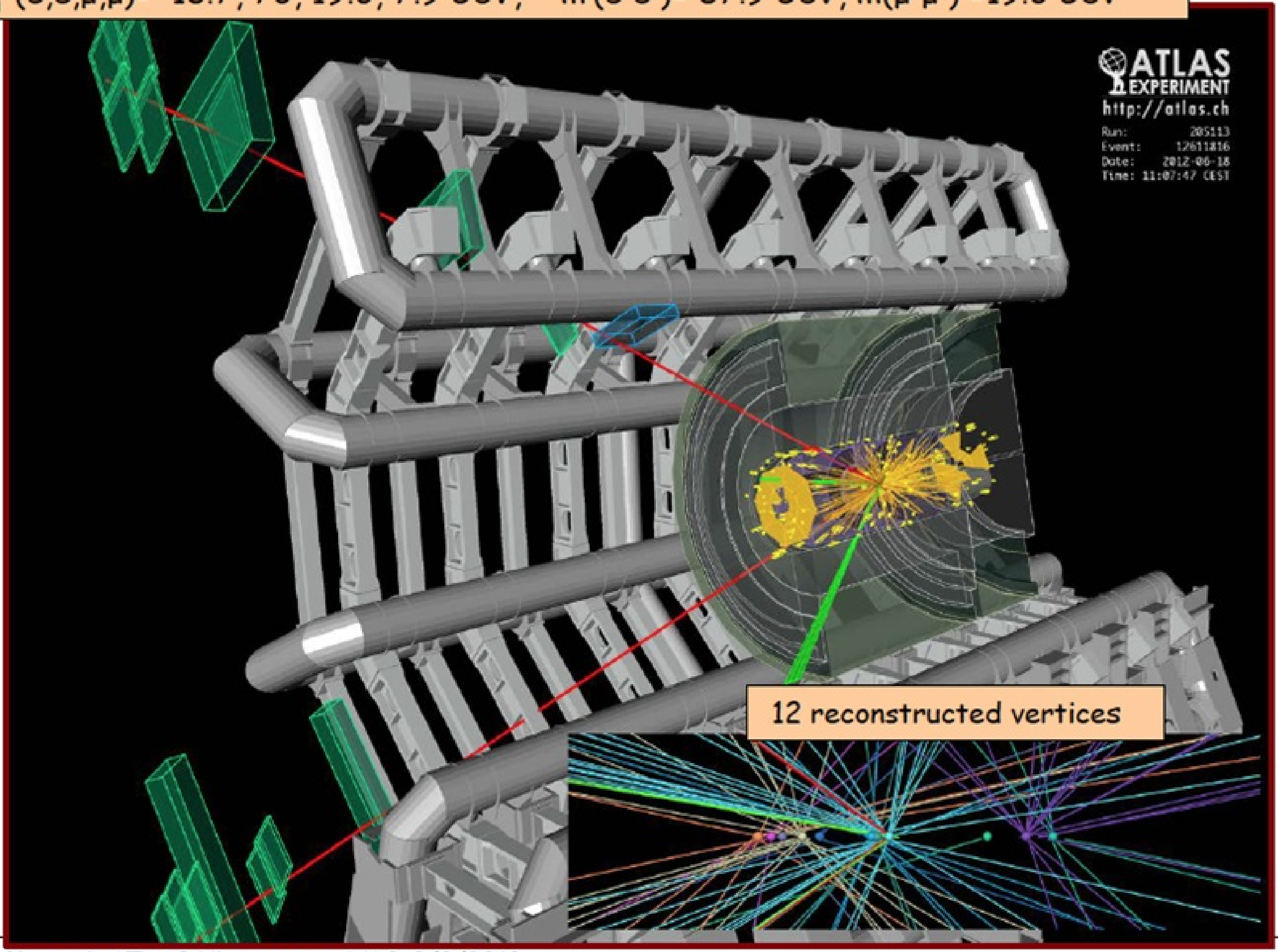
LHC events : W → eν



LHC events : $H \to ZZ^* \to (e^+e^-)(\mu^+\mu^-)^*$

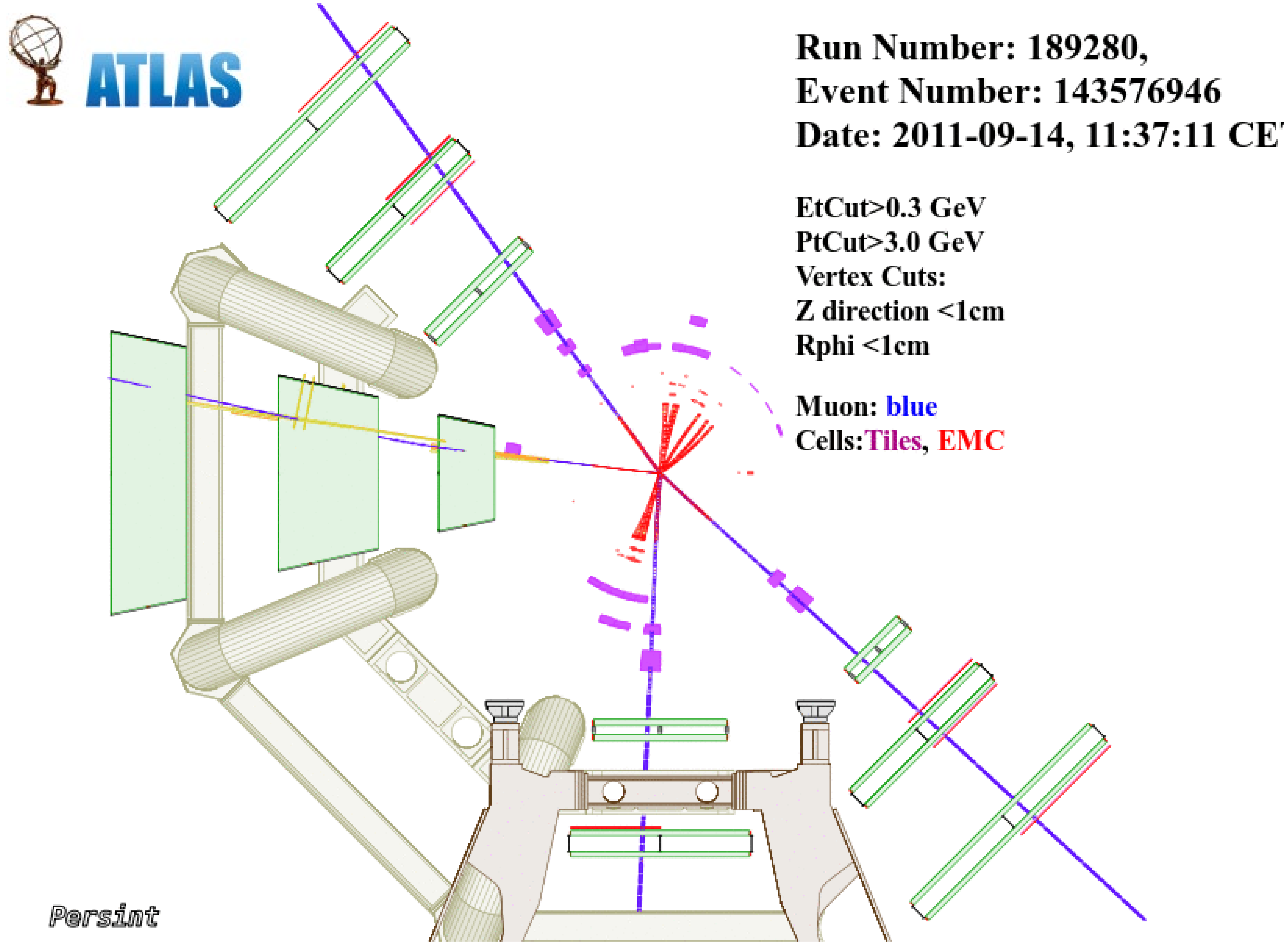
2e2μ candidate with $m_{2e2\mu}$= 123.9 GeV

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

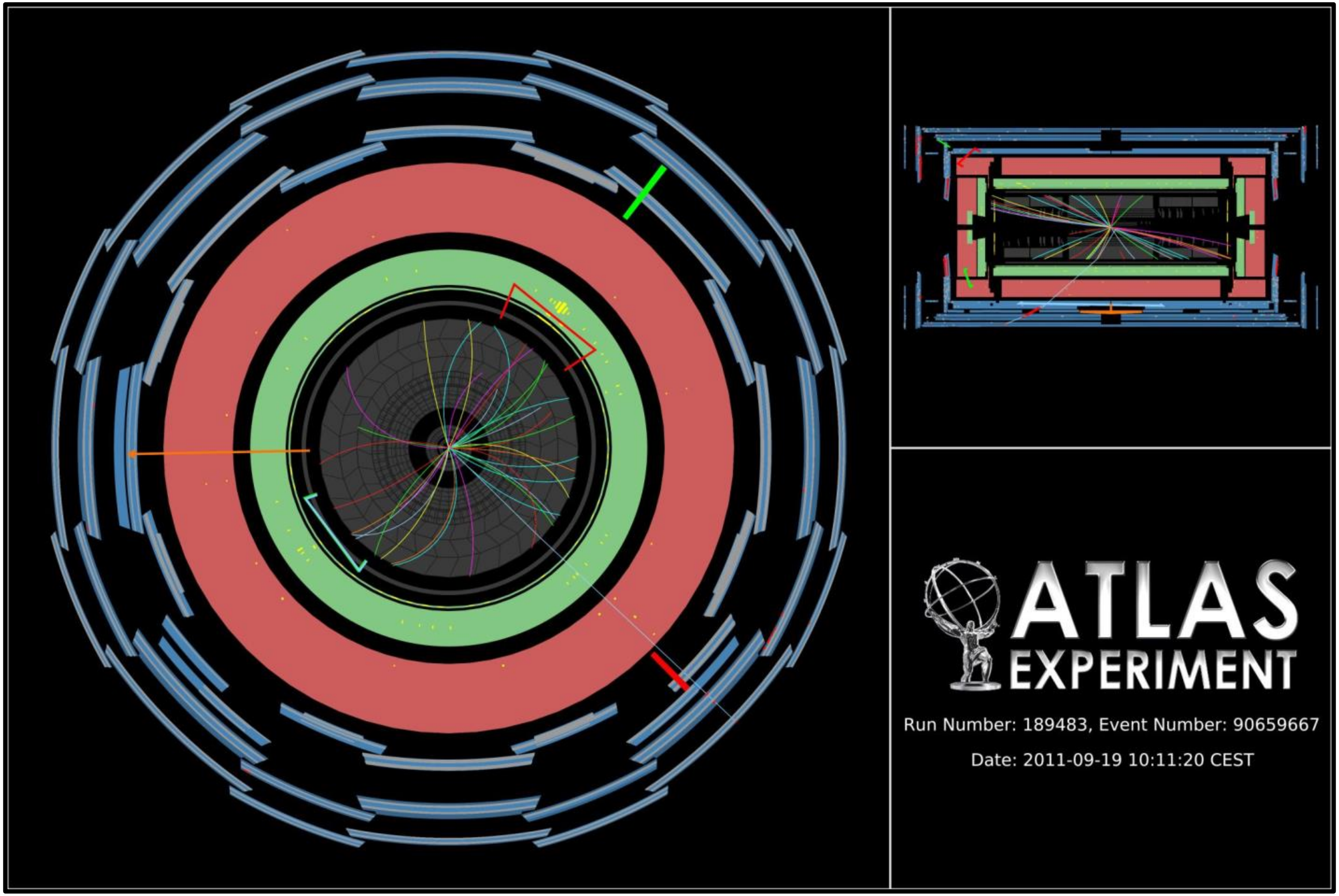


F. Gianotti, ATLAS Higgs paper, LMC, 8/8/2012

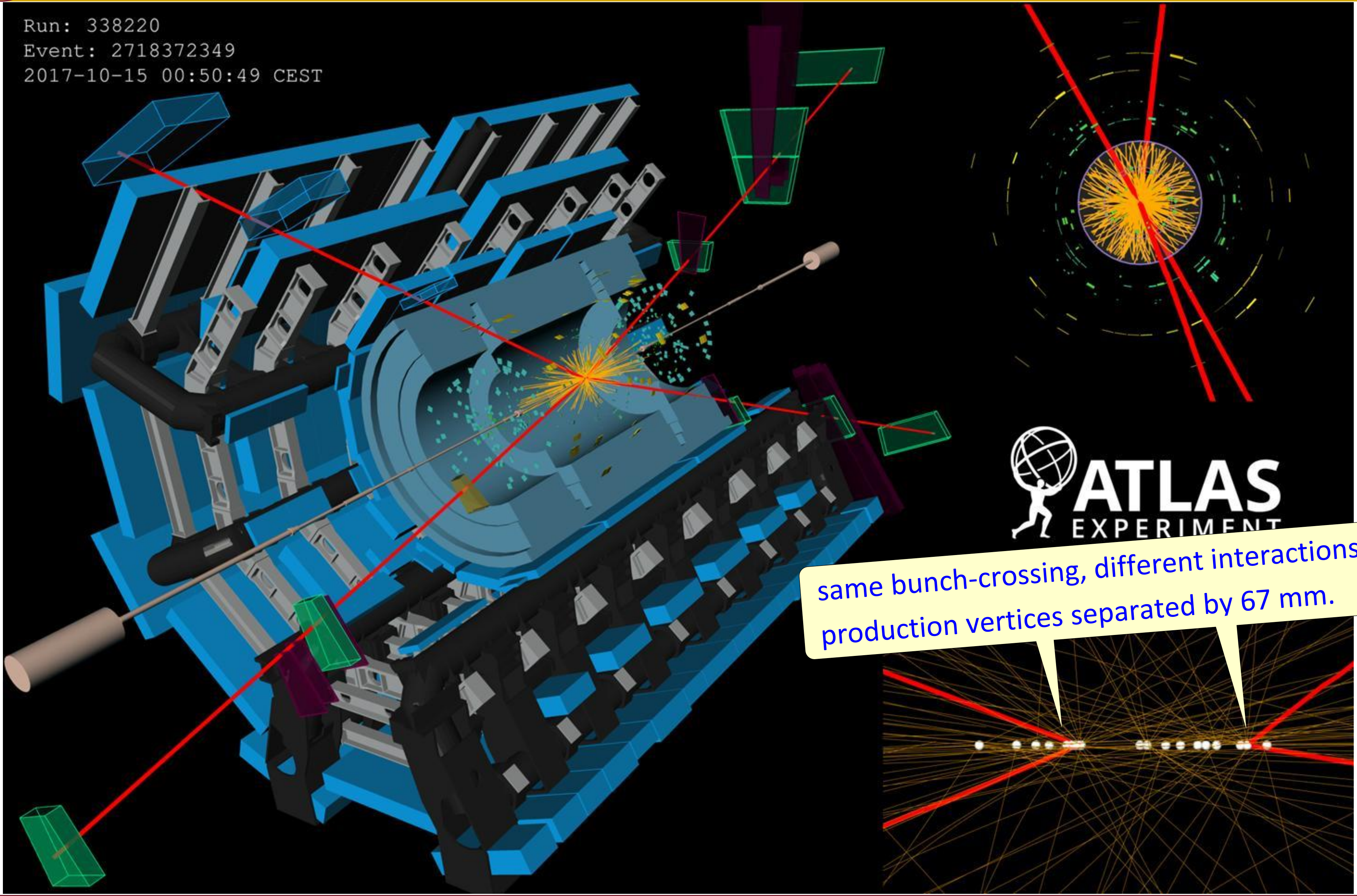
LHC events : $H \rightarrow ZZ^* \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)^*$



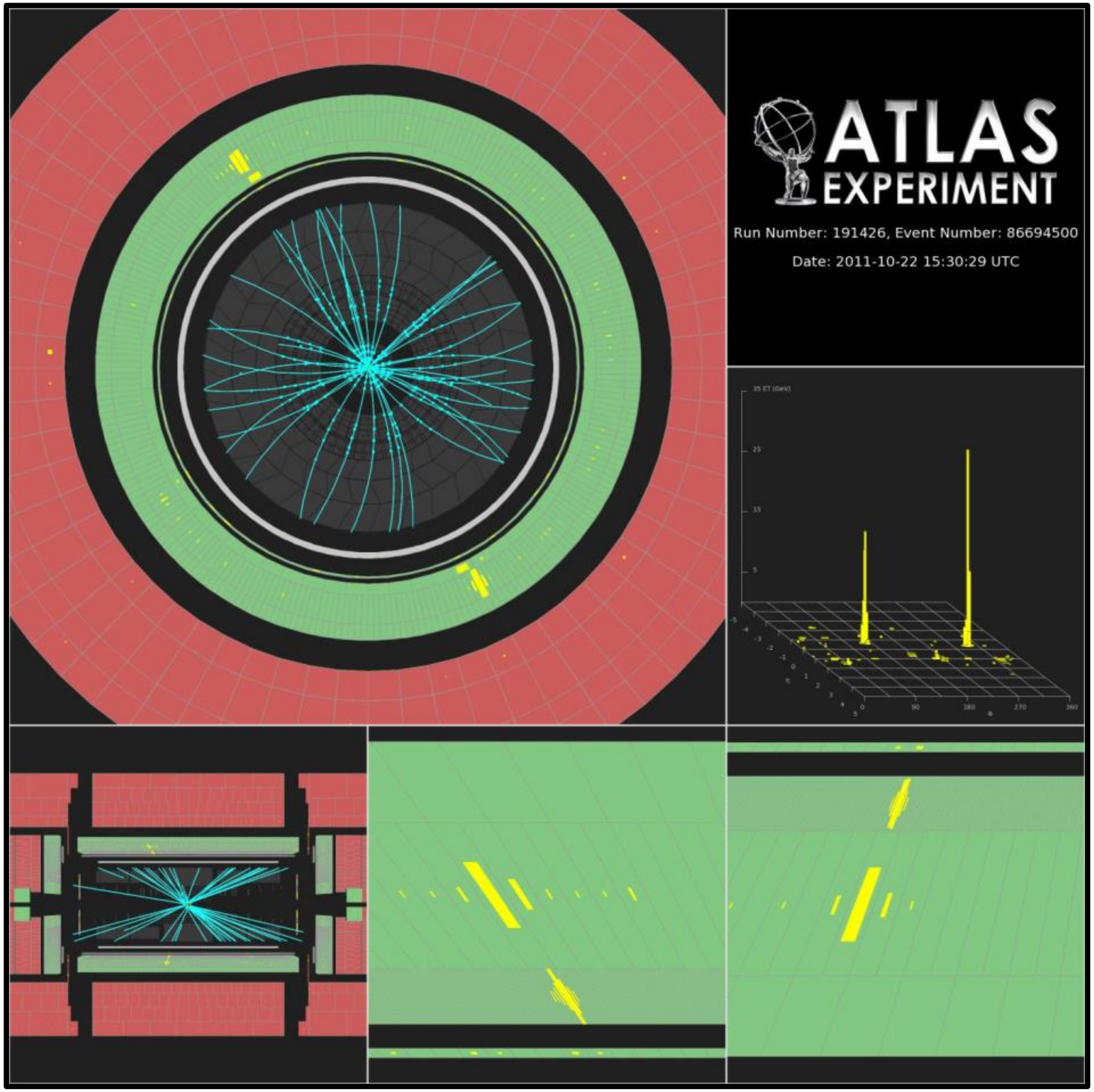
LHC events : $H \rightarrow W^+W^- \rightarrow e^+$□ $^-\bar{\nu}$



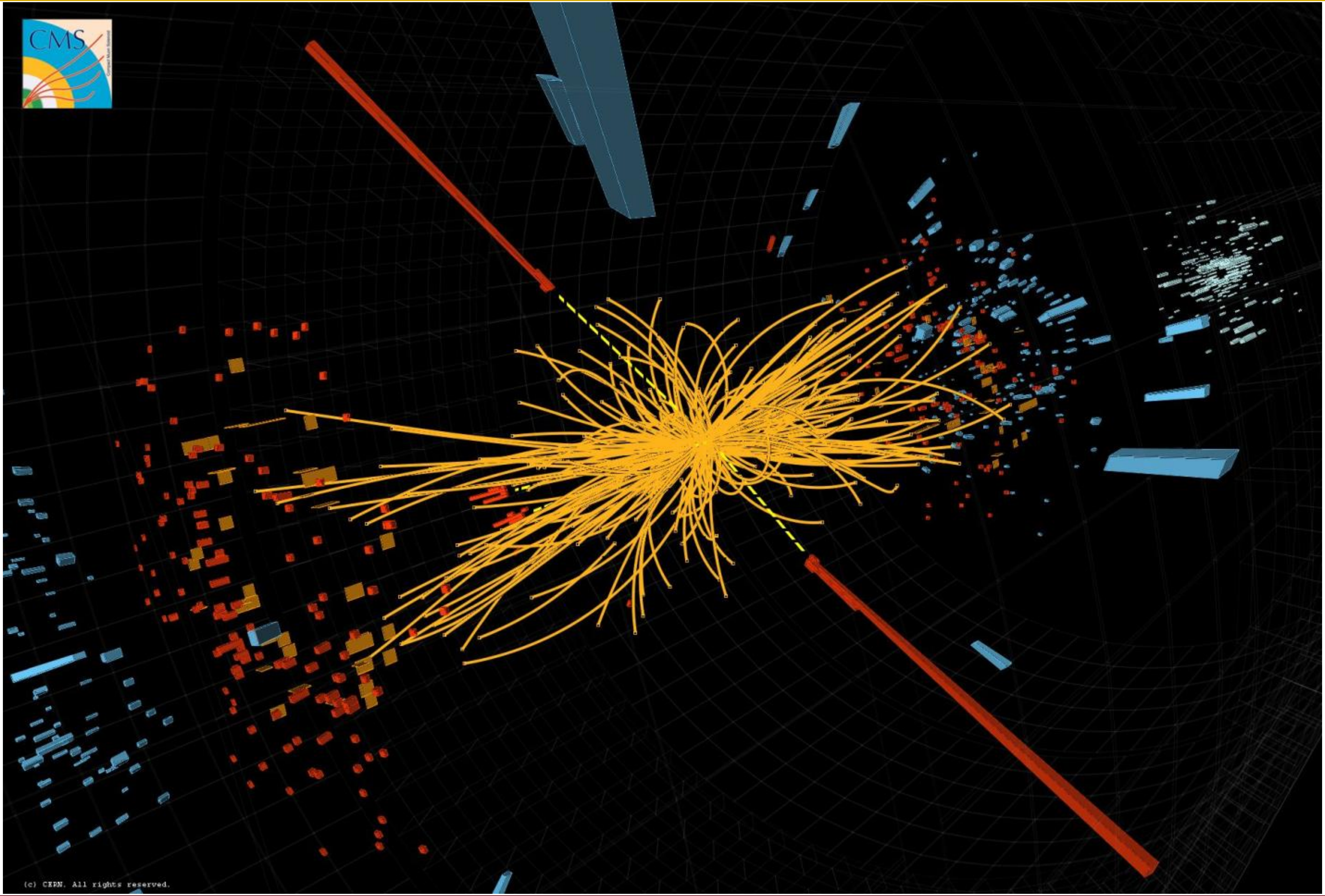
LHC events : $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow \mu^+\mu^-$



LHC events : H $\rightarrow \gamma\gamma$



LHC events : H $\rightarrow \gamma\gamma$



References: collider & experiments

1. LHC : JINST 3 (2008) S08001.
2. LHC : L.Evans, Ann. Rev. Nucl. Part. Sci. 2011. 61:435–66.
3. LHC (recent) : J. Wenninger, PoS (Charged 2018) 001.
4. ATLAS detector : JINST 3 (2008) S08003.
5. ATLAS events : https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayPublicResults/
6. CMS detector : JINST 3 (2008) S08004.
7. CMS events : https://cdsweb.cern.ch/
8. [*see also references on results*]

Jacopo Robusti (Tintoretto) - The Forge of Vulcan, ca. 1578
Palazzo Ducale - Venice

Sapienza
Università di Roma

End of chapter 5a