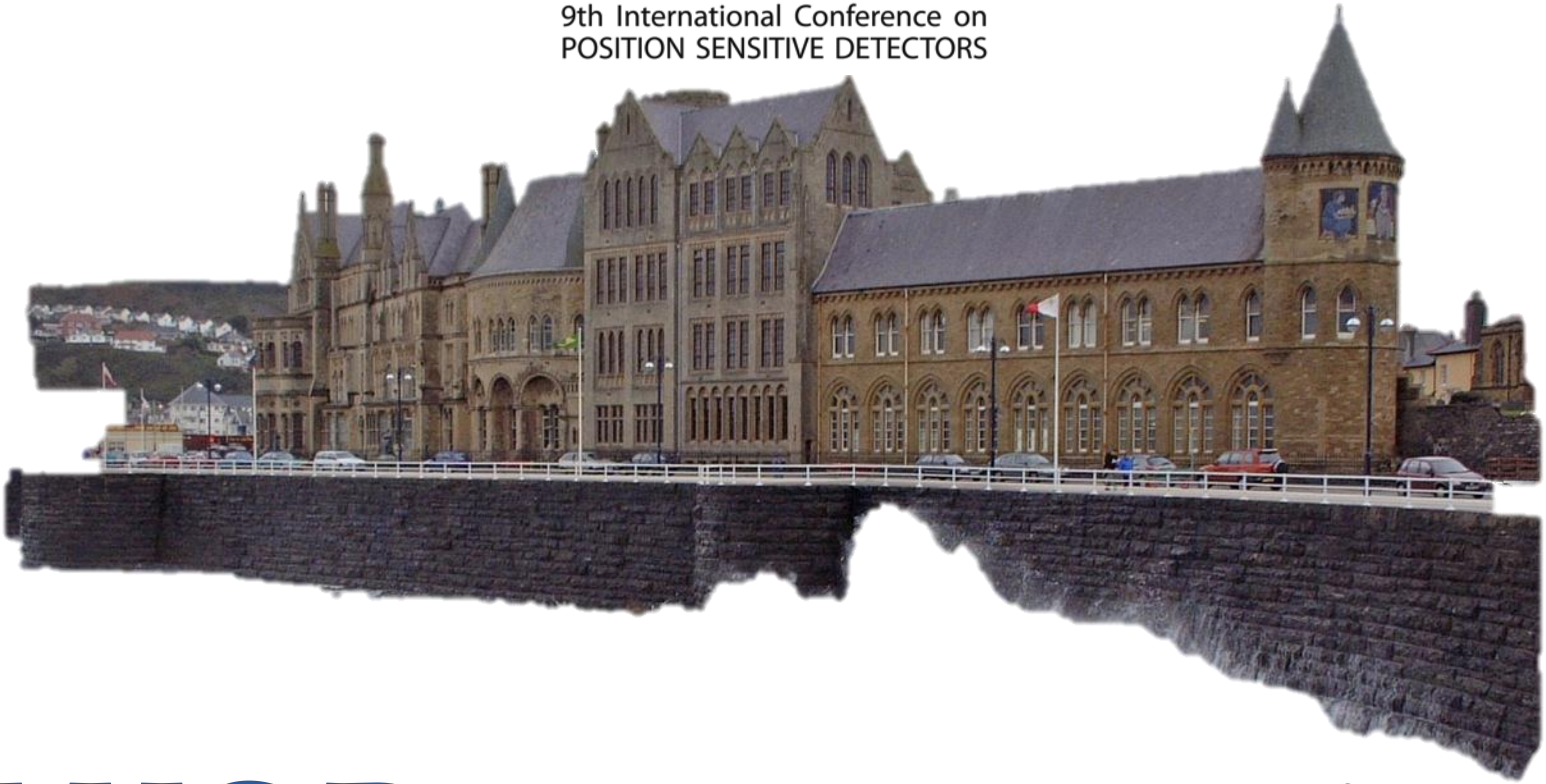
PSD9

9th International Conference on POSITION SENSITIVE DETECTORS



LHC Detectors overview

Emphasis on ATLAS

Beniamino Di Girolamo
CERN

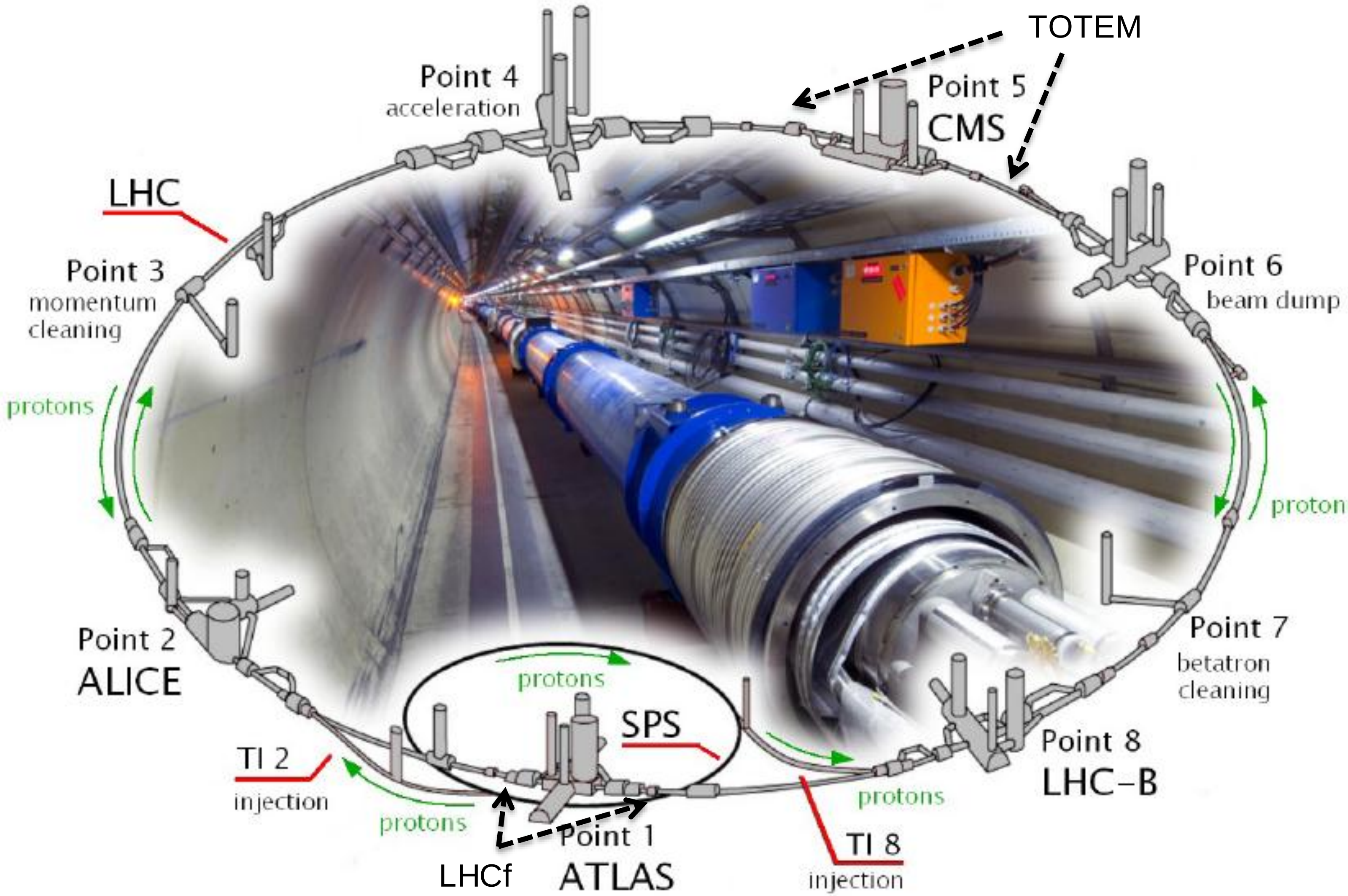
Outline

- The LHC experiments and their sub-detectors
- The details: I had to make a choice
  - Emphasis on vertex detectors and intermediate trackers
  - Little on data acquisition and trigger, computing
    - Extensive bonus material to cover some of these extremely important aspects
  - Trying to show intriguing aspects. More classical performance in many talks in this conference
- Chose to show a few physics results to illustrate how well the detectors are functioning
- Few words on future upgrades
- Conclusions
- What did not fit here you can be found in the Bonus Material

A variety of technologies

- The aim of this talk is to give a feeling of the LHC detector performance, but…
- …also show you how many different solutions have been found using a variety of technologies for Position Sensitive Detectors and more
- LHC instruments could easily fit all detectors described in instrumentation books
- At the end we will also see what is foreseen in future and no surprise: exploiting even more techniques
    - And even more acronyms

The LHC experiments




ATLAS

Requirements

- ATLAS and CMS to be as "general purpose" as possible and as hermetic as possible
  - All possible physics channels from known to unknown
  - The dream of measuring everything with a surrounding sphere
- ALICE measuring on a MeV to GeV dynamic range
  - Heavy ions focus
  - Paying attention to material budget
- LHCb dedicated to b physics
  - A forward detector
- TOTEM and the ATLAS forward detectors
  - Looking at luminosity, diffractive physics
- LHCf looking at π^0 to calibrate high energy cosmic rays experiments
  - A nice example of variety of technology: two almost identical detectors

General purpose detectors

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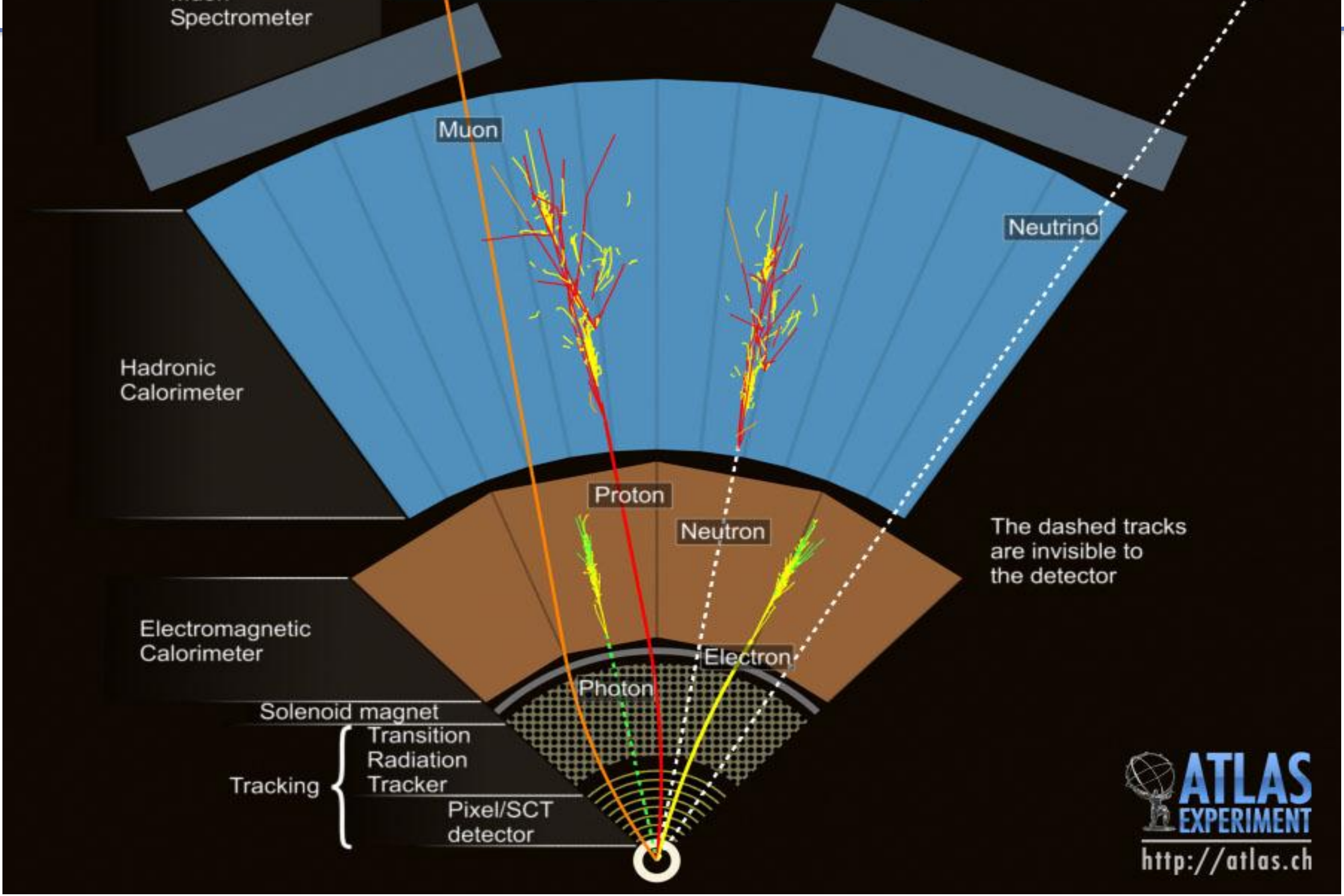
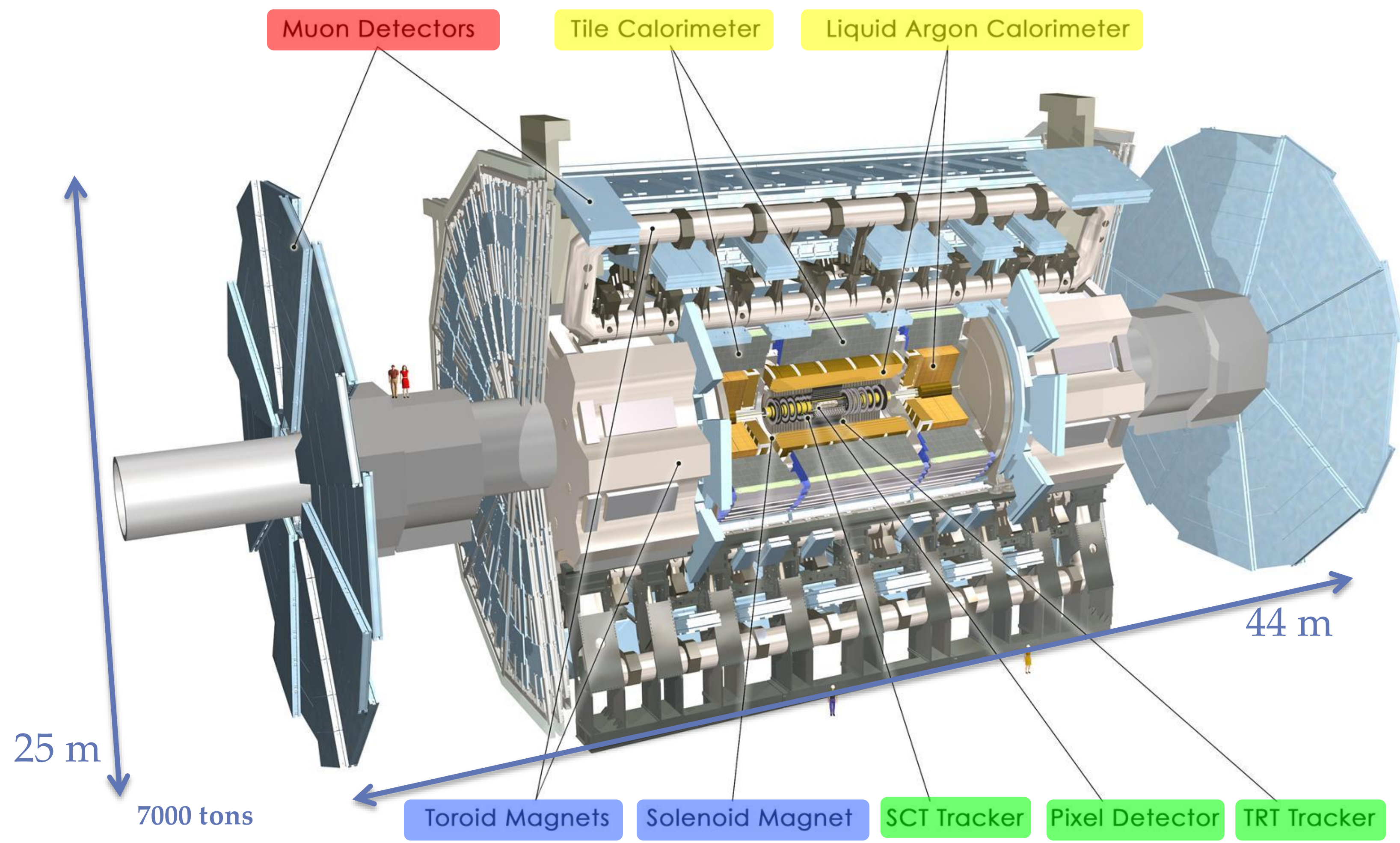
A closer look

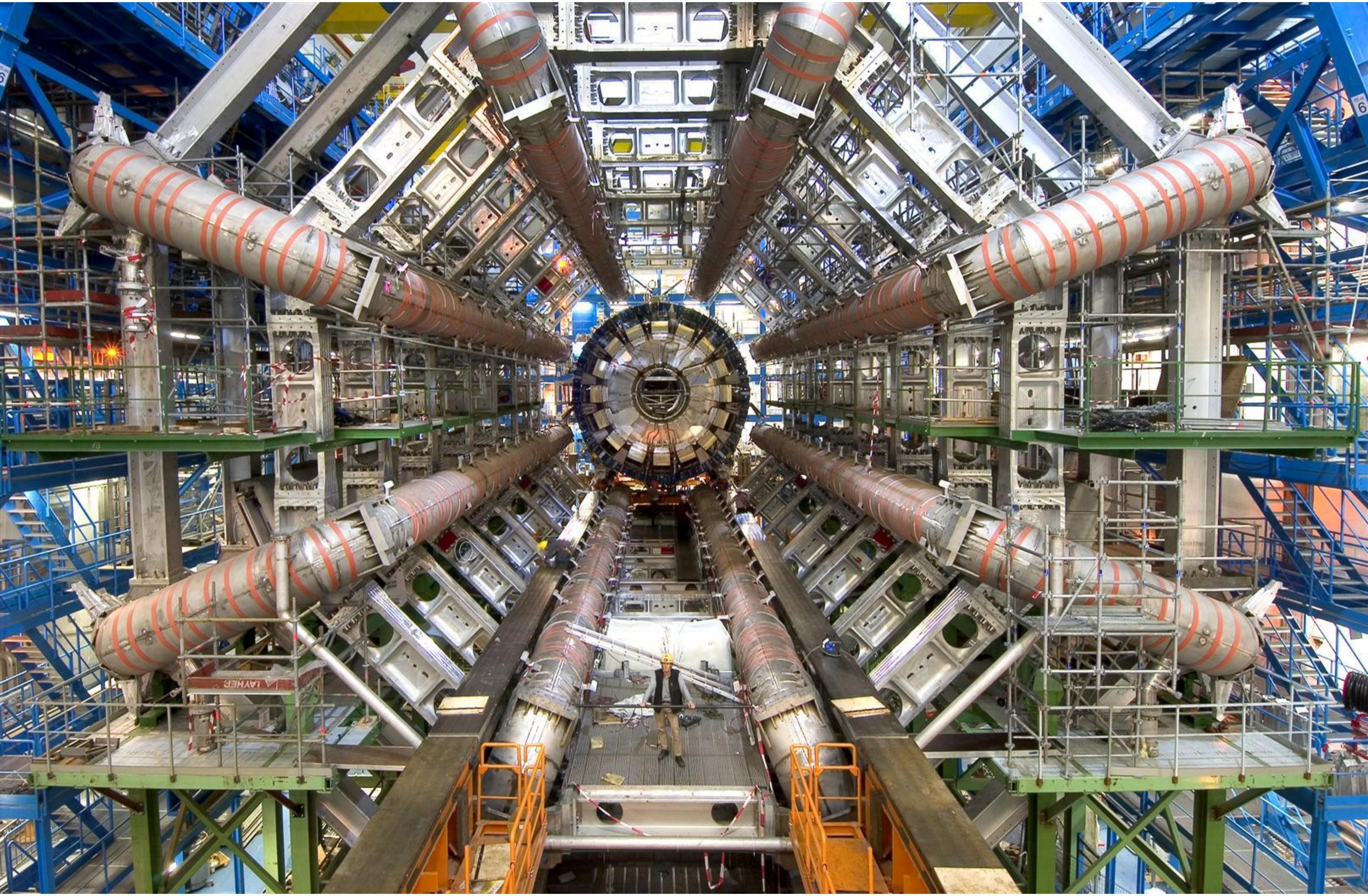
The dream of full coverage



ATLAS

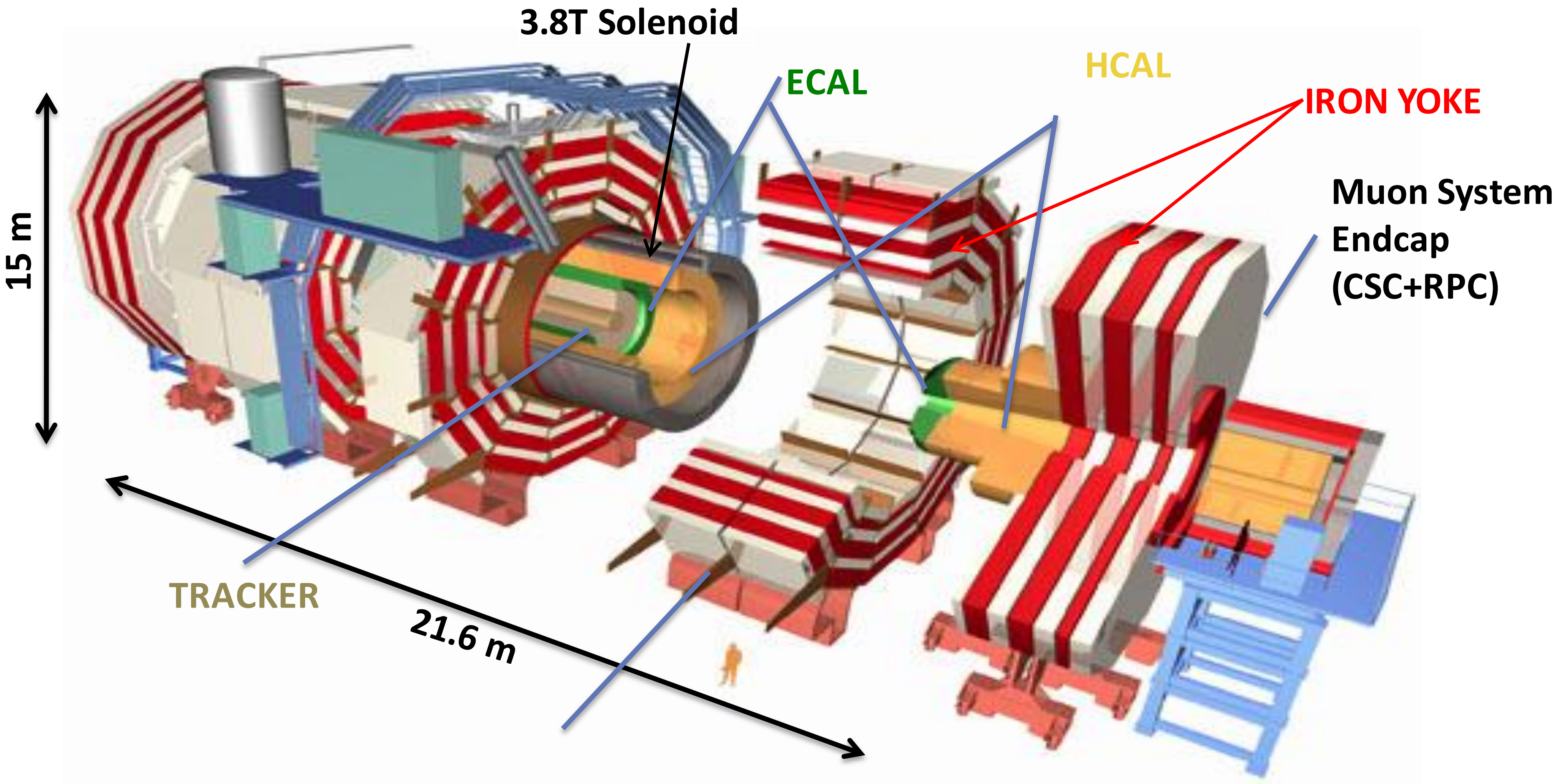


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
25 m
44 m
7000 tons
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker




friderici
special s.a.

CMS



12500 tons

Specialized detectors

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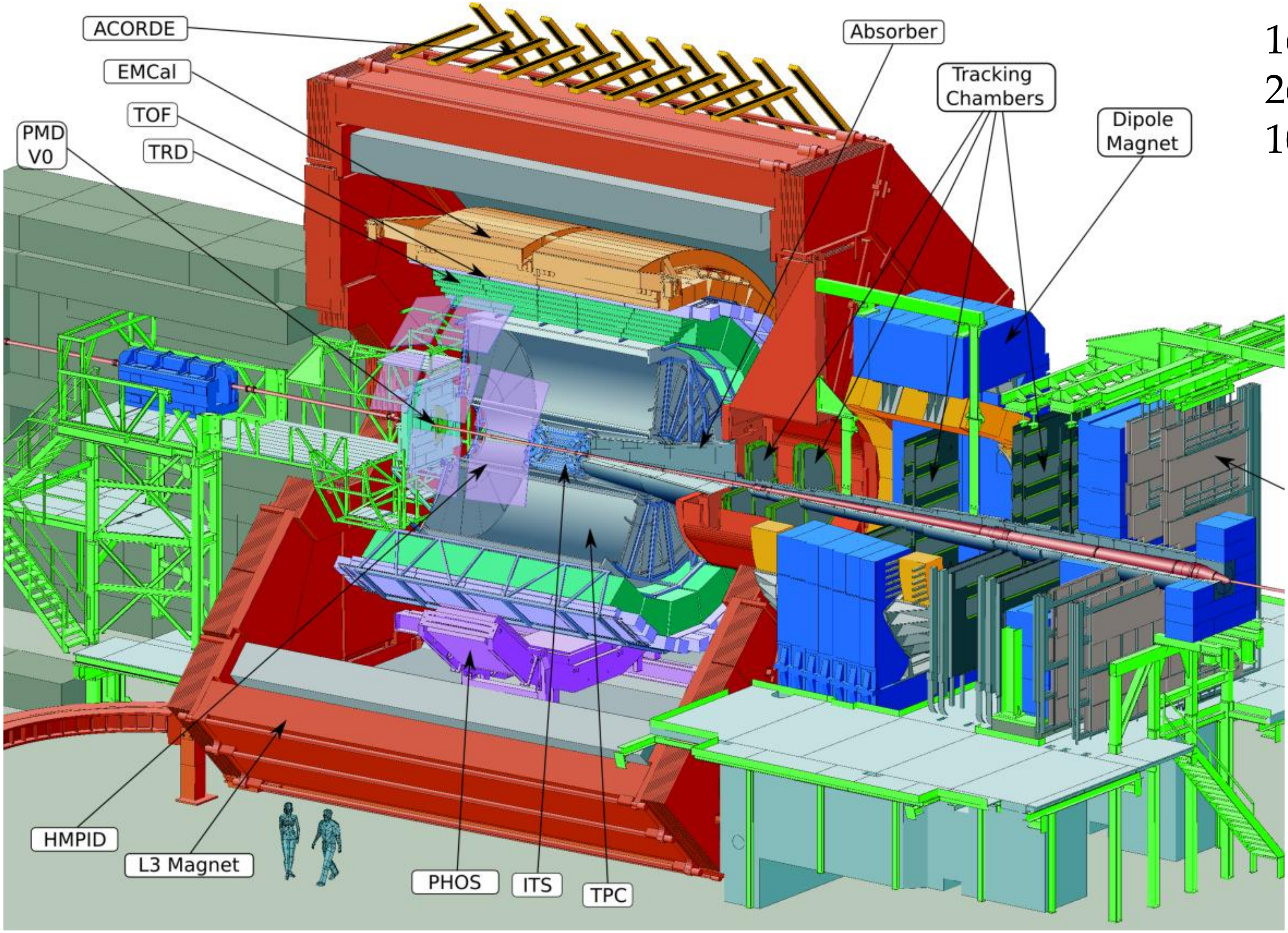
A closer look

ALICE

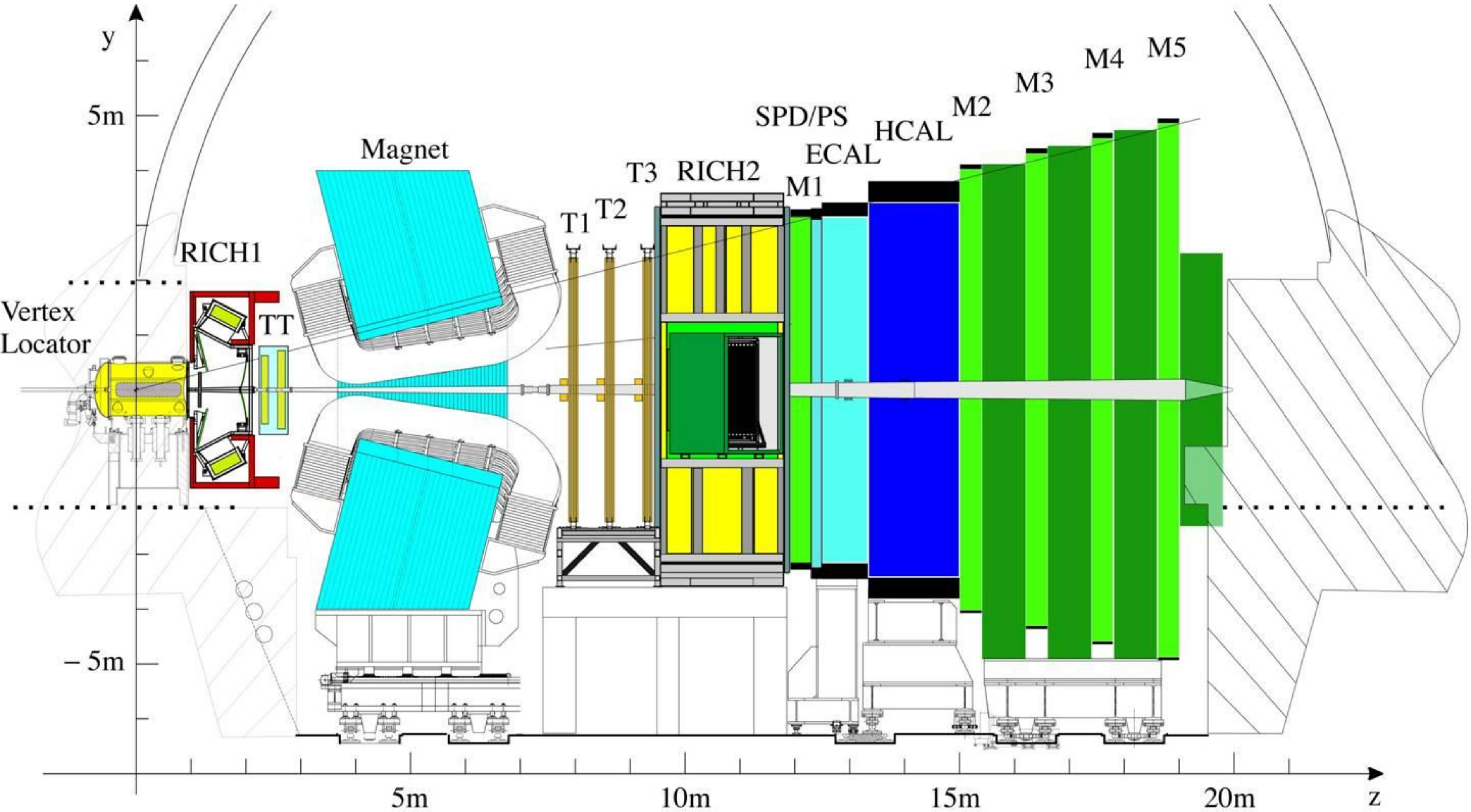


16 m wide
26 m long
10000 t

Main facts about ALICE

- Many sub-detectors!
- Design evolved with time and knowledge from running HI physics detectors
- Measurements from MeV to GeV
    - Low material budget!
- Need of particle identification
- Need of muon tracking with a fancy absorber
- Extremely light supporting structure for the detectors inside the 0.5 T magnet

LHCb

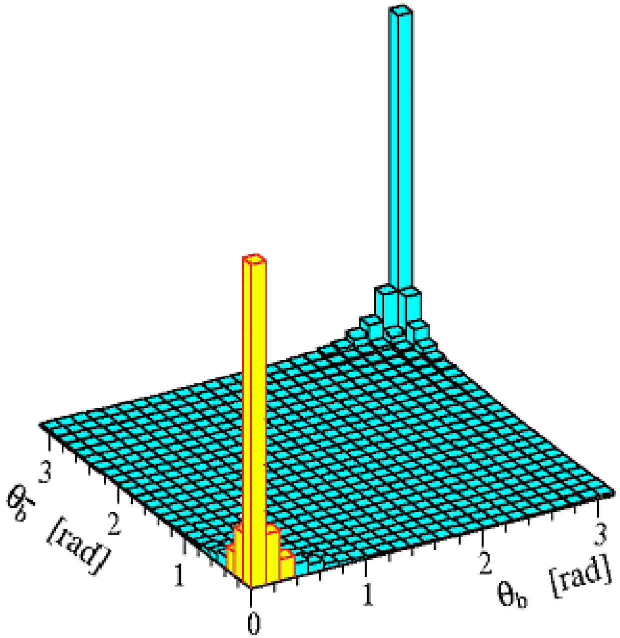


y
5m
– 5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

Main facts about LHCb

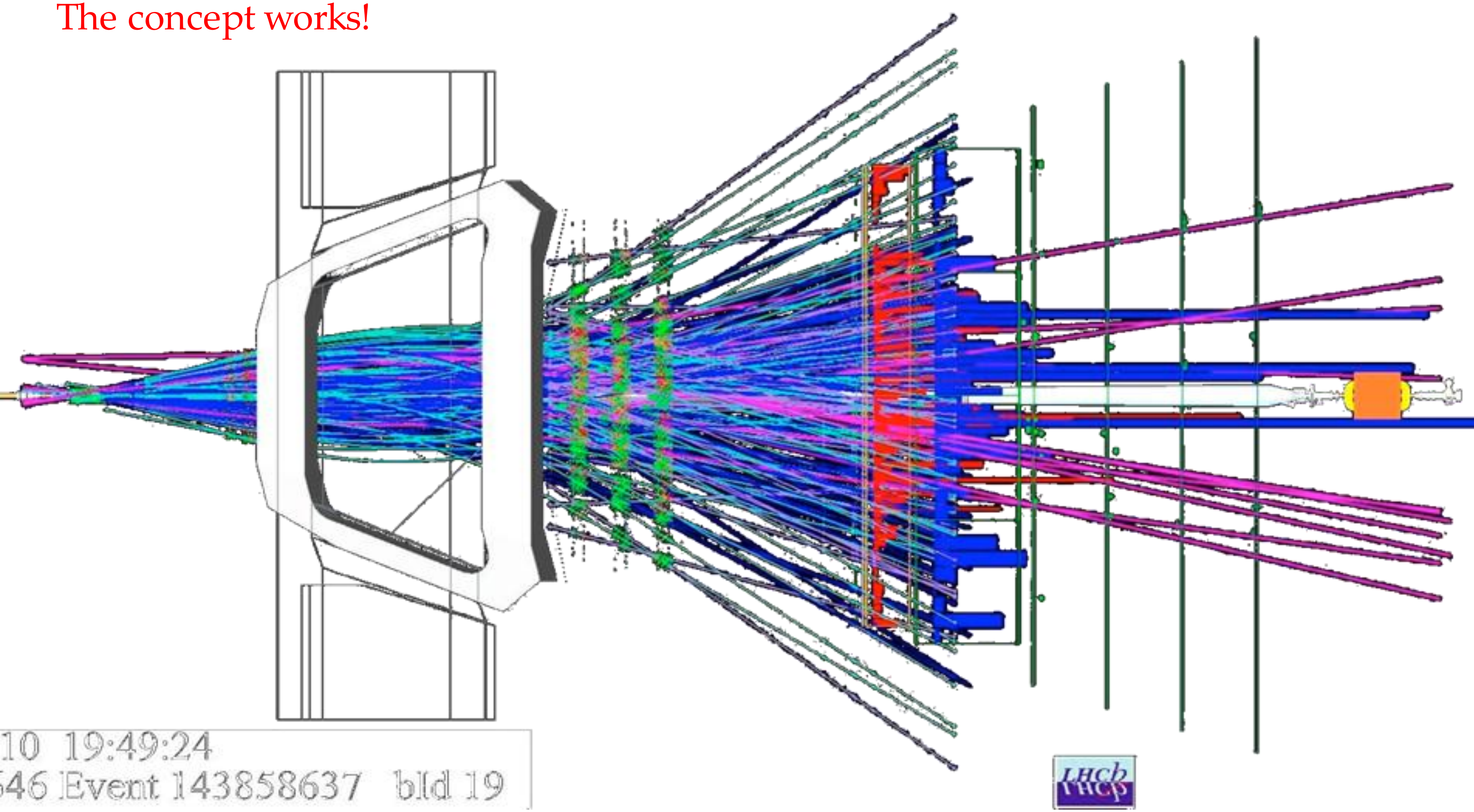
- B and D physics at the LHC are forward/backward
  - The interacting partons have different x
  - The produced $b\bar{b}$ pair are boosted forward or backward, together
    - The detector can look only at one side, and get both b, very useful as we have both the signal b and the tagging b in the acceptance

- Single arm spectrometer
  - Very good vertex detector
  - Dipole magnet for accurate momentum measurement
  - Good particle ID over a large momentum range
  - Should fit in an existing LEP cavern...



A typical LHCb event

The concept works!



Forward detectors

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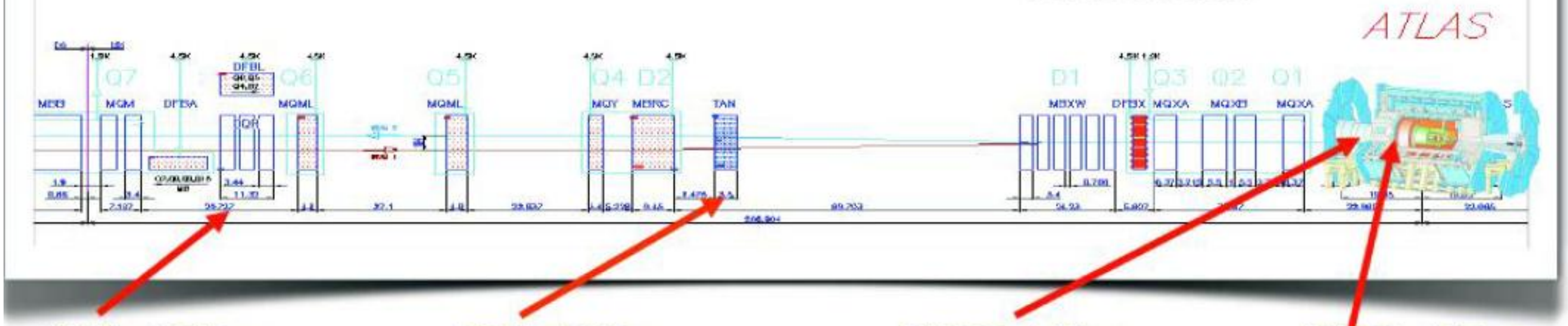
A closer look

ATLAS Forward

on both side



ALFA at 240 m

ZDC at 140 m

LUCID at 17 m

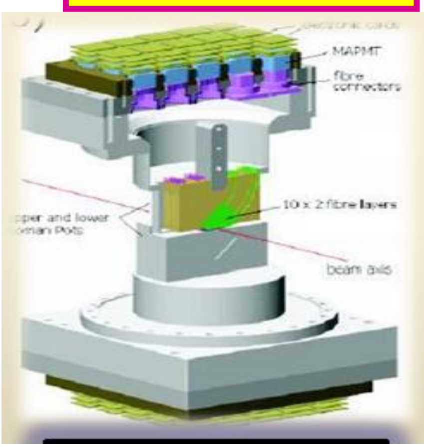
MBTS at 3.6 m

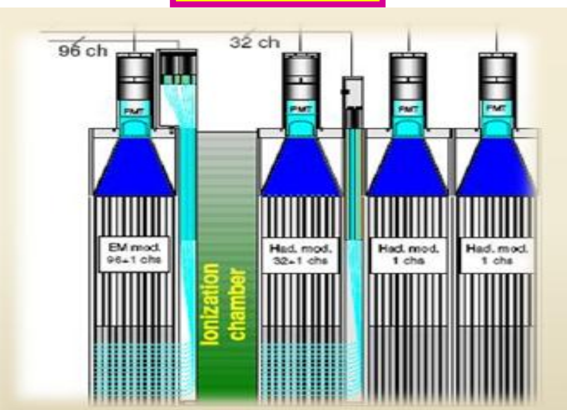
$10.6 < |\eta| < 13.5$

$|\eta| > 8.3$

$5.6 < |\eta| < 5.9$

$2.1 < |\eta| < 3.8$





SciFi tracker

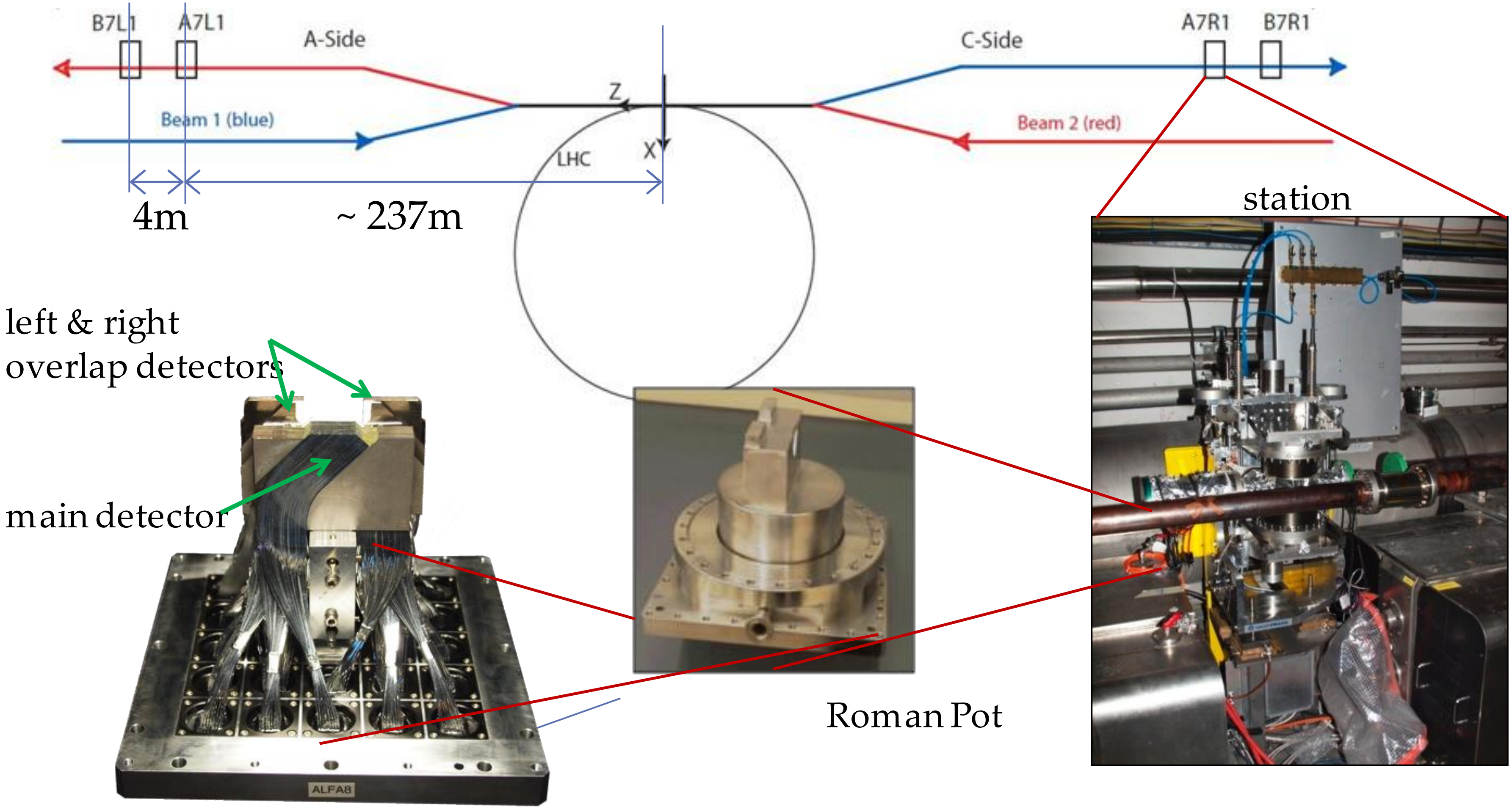
W+quartz rods calorimetry

Cherenkov rad.

Scintillators

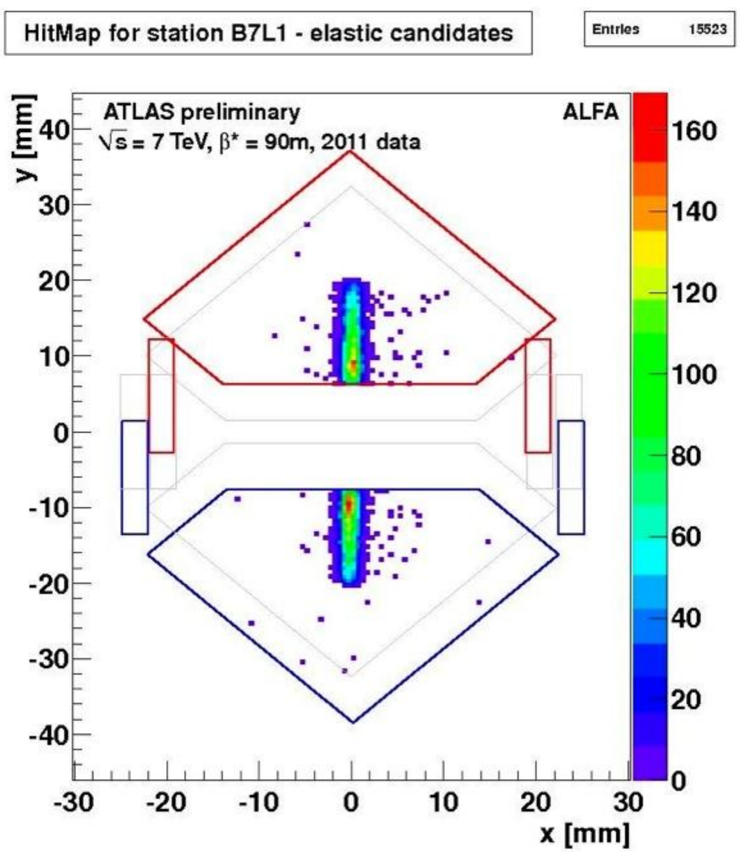
ATLAS: ALFA detector

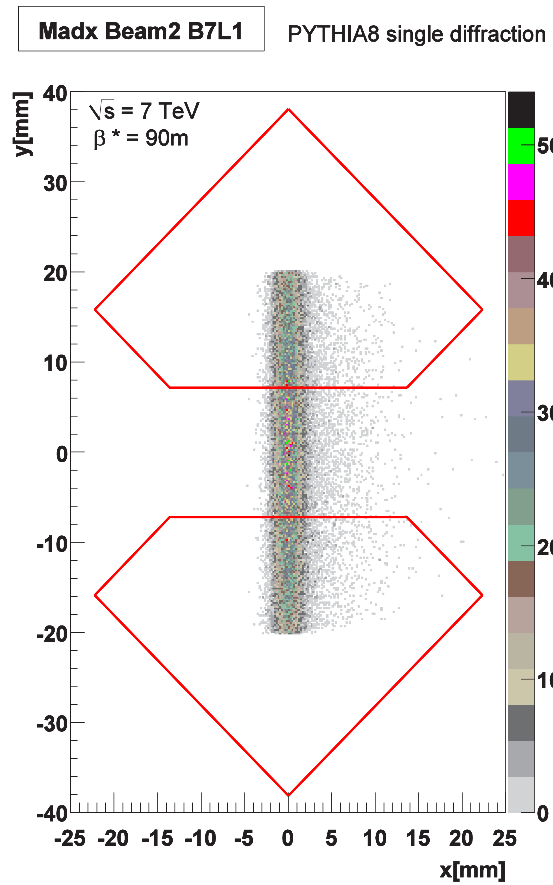
- system – 4 stations, 2 (A-side) + 2 (C-side)
- each station – 2 Roman Pots approaching the beam vertically – from below and above
- 1 main detector and 2 overlap detectors in each Roman Pot; tracker-type detectors



ATLAS: ALFA results

- Results from data taking at $\beta^* = 90$ m optics, detectors at 10 σ from the beam (~ 7 mm)





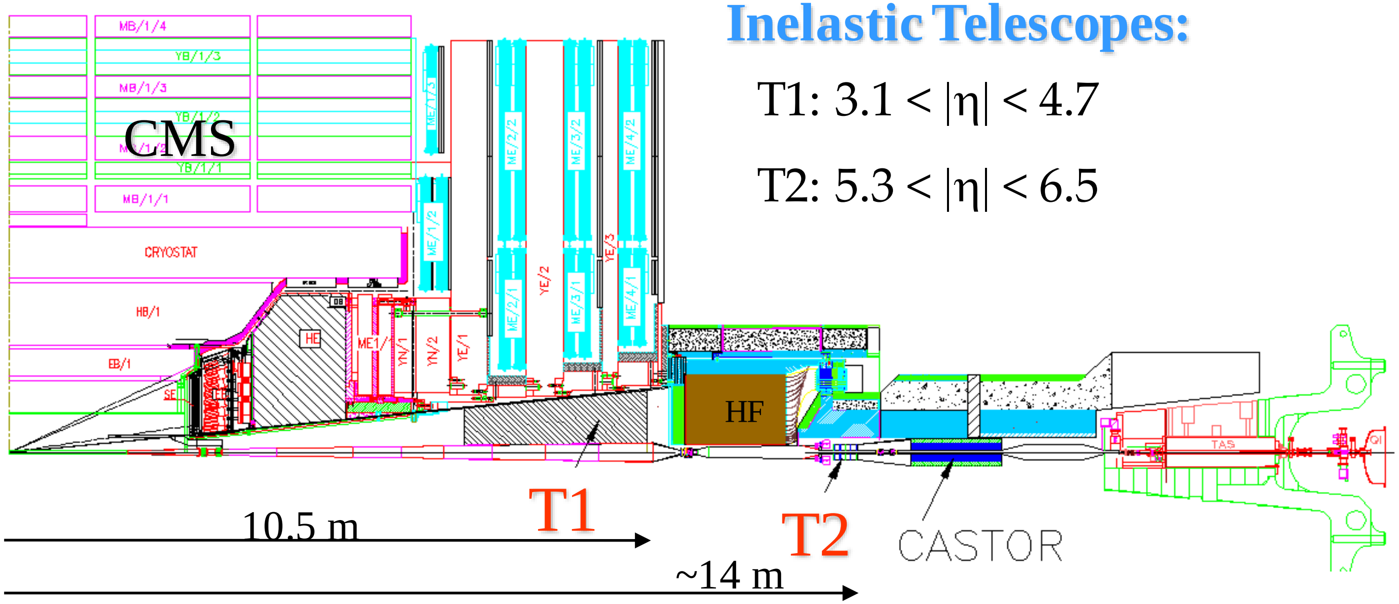
TOTEM

Inelastic Telescopes:

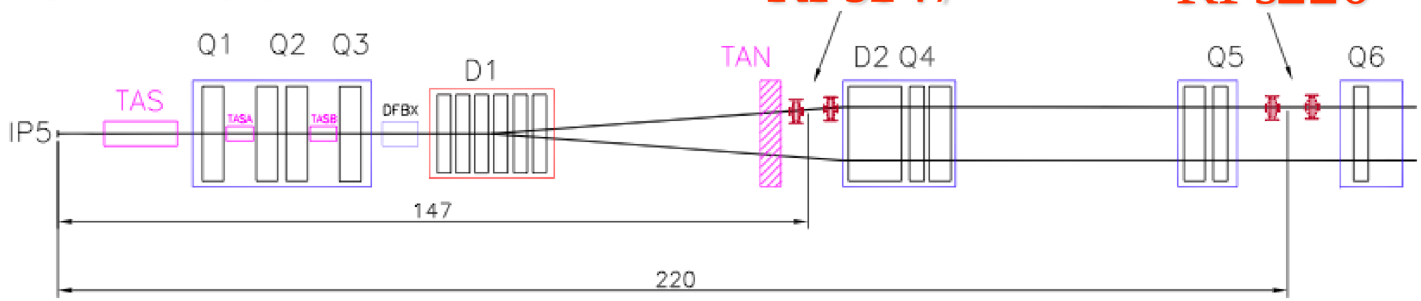
T1: $3.1 < |\eta| < 4.7$

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

T1: CSCs
T2: GEMs



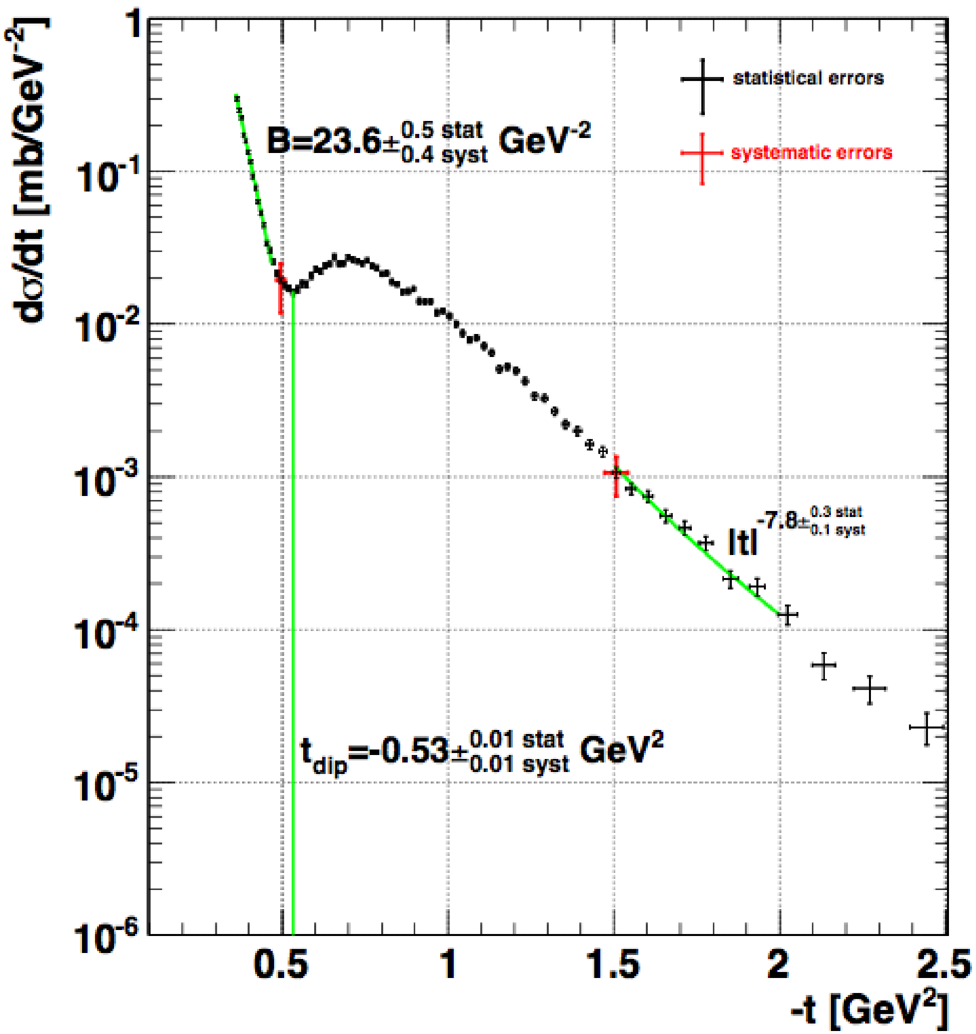
Roman Pots:



Si strips

Same scheme on both sides of IP5

TOTEM: Elastic pp scattering

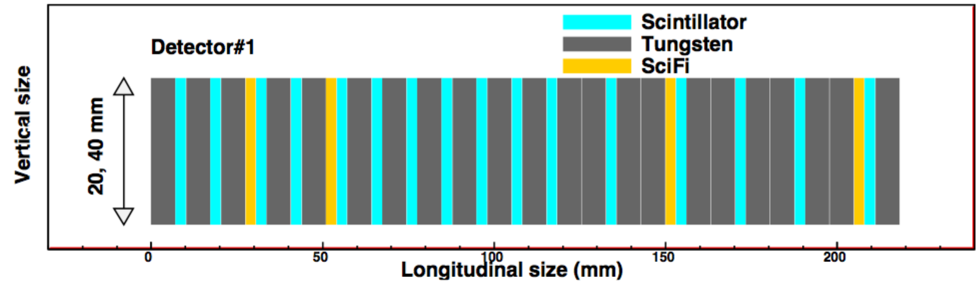


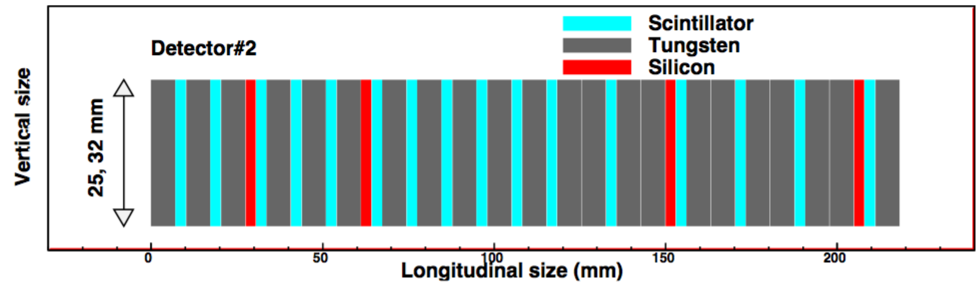
- Differential cross section for pp scattering
- Confirmed the move of the diffractive dip at increasing √s
  - First look at pp since ISR time
  - B increases in exp(-B|t|)
  - Power law confirmed for higher t
- Higher the t: deeper the look inside the proton
- It differs from models
  - Getting really interesting

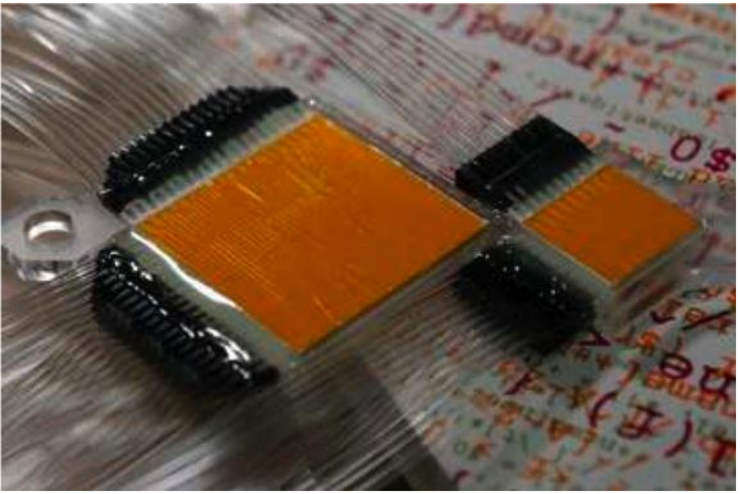
TOTEM Note: CERN-PH-EP-2011-101

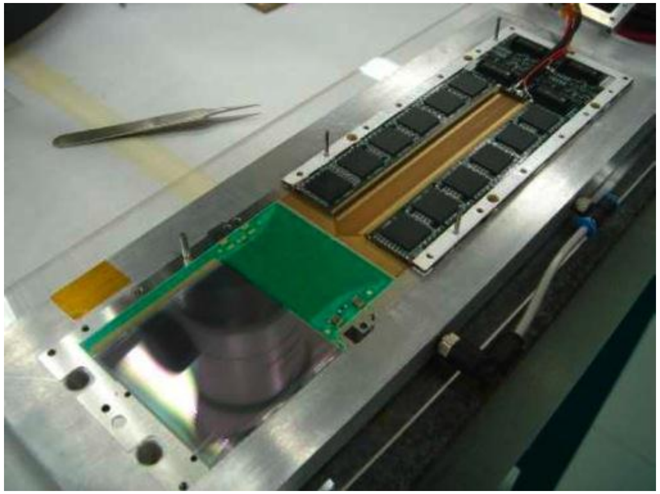
LHCf

- W sampling shower calorimeters (44 X_0 and 1.7 λ)
- At ± 140 m from IP1 in TAN absorbers, only neutral particles
- Tungsten and scintillator layers
- Position sensitive layers
    - Scintillating fibers with MAPMT readout on one side and Si sensors on the other









Vertex detectors

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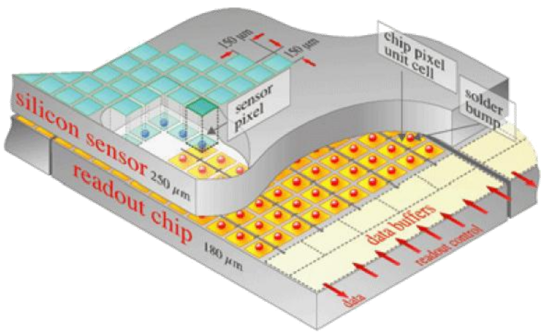
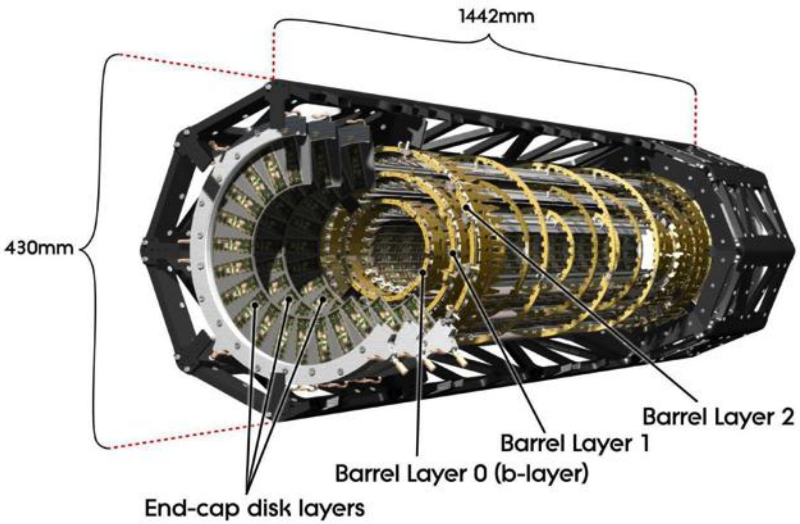
A lot of Silicon

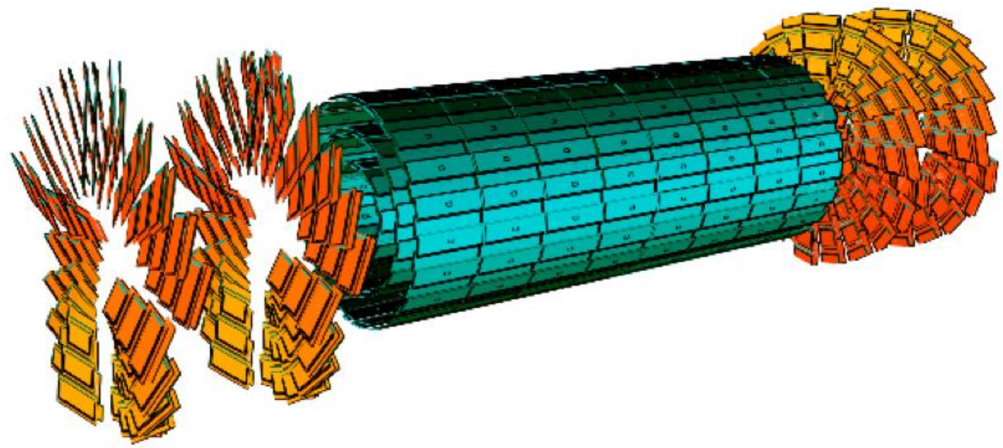
Vertex detectors

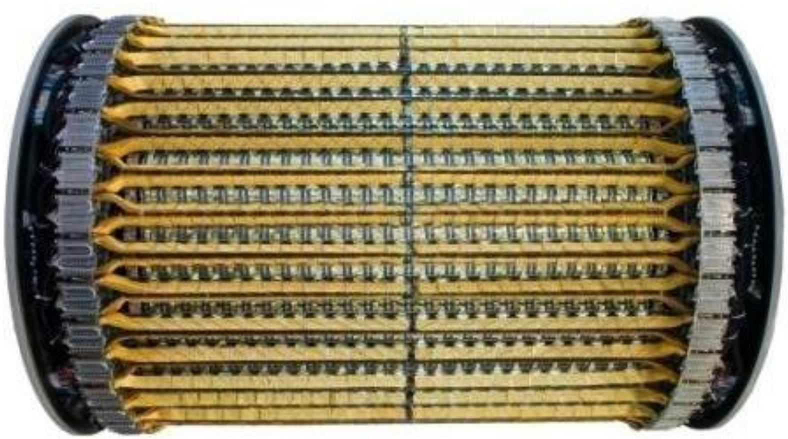
- Silicon has been the choice of the experiments
- Large pixel detectors are used in ALICE, ATLAS, CMS
- A strip detector is used by LHCb: the Vertex LOcator
- Silicon strip layers are deployed at larger radii
  - ATLAS uses a straw-tubes tracker as intermediate tracker before calorimetry
- Concentrating on Pixel: hybrid pixels for all
- Requirements:
  - Radius for the innermost layer and radii of the rest
  - Number of layers
  - Readout electronics
  - Granularity
  - Radiation tolerance
  - Material budget (for all, but ALICE has special needs)

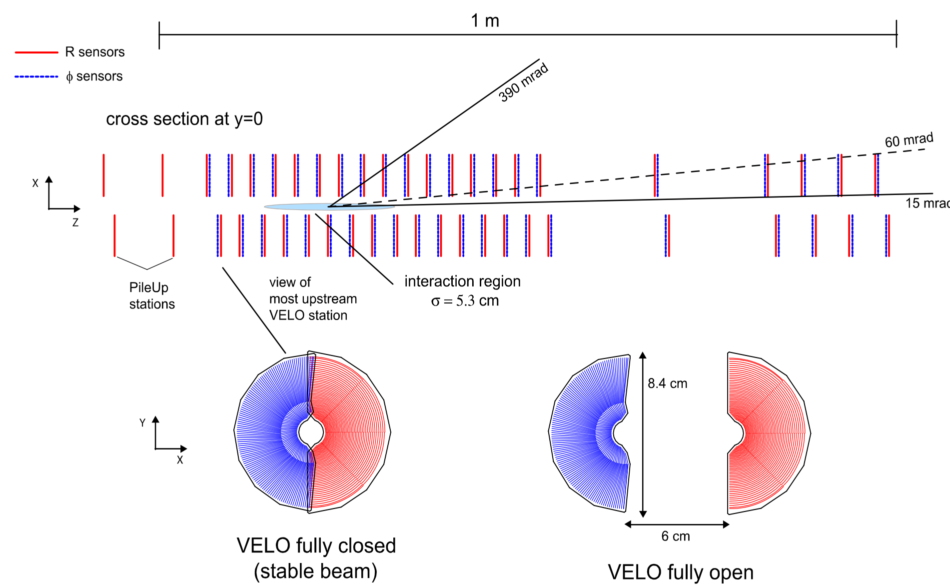


The Pixel + VELO detectors









The Pixel master table

	Pixel size		Sensor Thickness (X_0)	ASIC Thickness (X_0)	Layers		beam-pipe inner radius	spatial resolution
	z [μm]	rϕ [μm]	[μm] (%)	[μm] (%)	[#]	radii [mm]	[mm]	[μm]
ALICE	425	50	200 (0.21)	150 (0.16)	2	39-76	29	100 (z) 12 (rϕ)
ATLAS	400	50	250 (0.27)	180 (0.19)	3	50.5-88.5-122.5	29	115 (z) 10 (rϕ)
IBL	250	50	200 (0.21)*	100 (0.11)	1	33.25	23.5	79 (z) 10 (rϕ)
CMS	150	100	285 (0.30)	180 (0.19)	3	44-73-102	29	~ 15

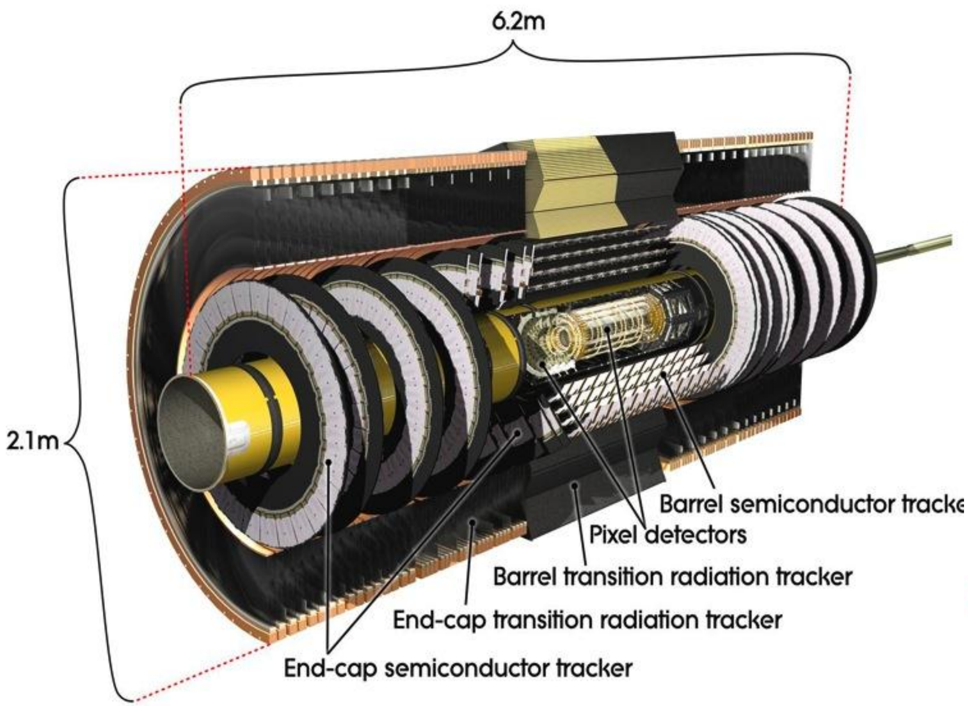
* IBL: decided to aim at using two technologies: planar sensors (200 μm) and 3D sensors (230 μm)

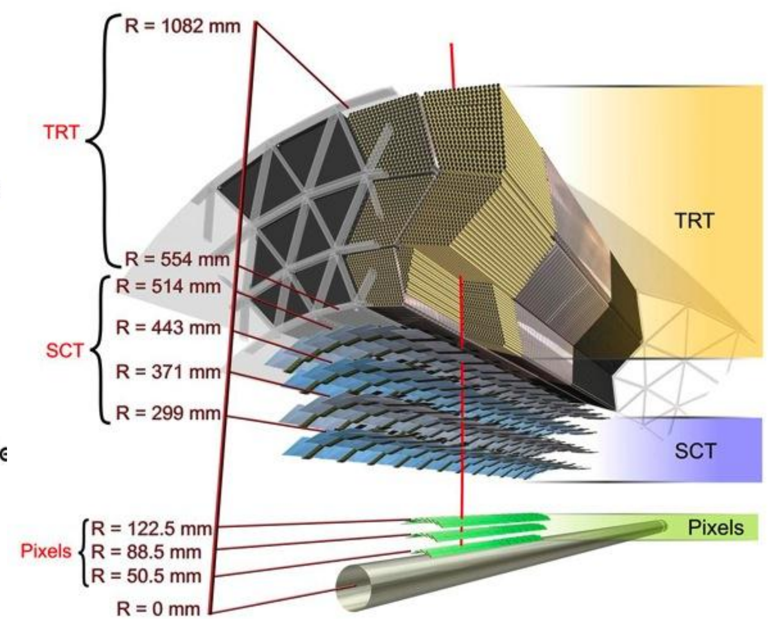
- Even though it seems IBL would have less material than ALICE Pixel, in reality ALICE has done an enormous effort to reduce material on services. ALICE has 13 X_0 up to the end of the TPC!
- The type of sensors differ, p-in-n for ALICE, n-in-n for ATLAS and CMS and LHCb VELO (with one n-in-p module installed)
- All using 250 nm CMOS ASICs
- The operating temperatures (^{0}C) are +25 (ALICE), -20 (ATLAS), +18 (CMS), -5 (VELO)

The outer layers

- CMS has a full silicon inner detector: 2 tons!
- ATLAS decided to invest in particle identification with straw tubes and radiators for transition radiation measurement
  - Advantage of inclusive isolated electron measurement, powerful tool for electron and photon studies in conjunction with e.m. calorimetry
- ALICE added silicon drift detectors between pixel and strips: need of extend 2-dim measure in radius
- Overall the biggest Inner Detectors ever built

ATLAS Inner Detector

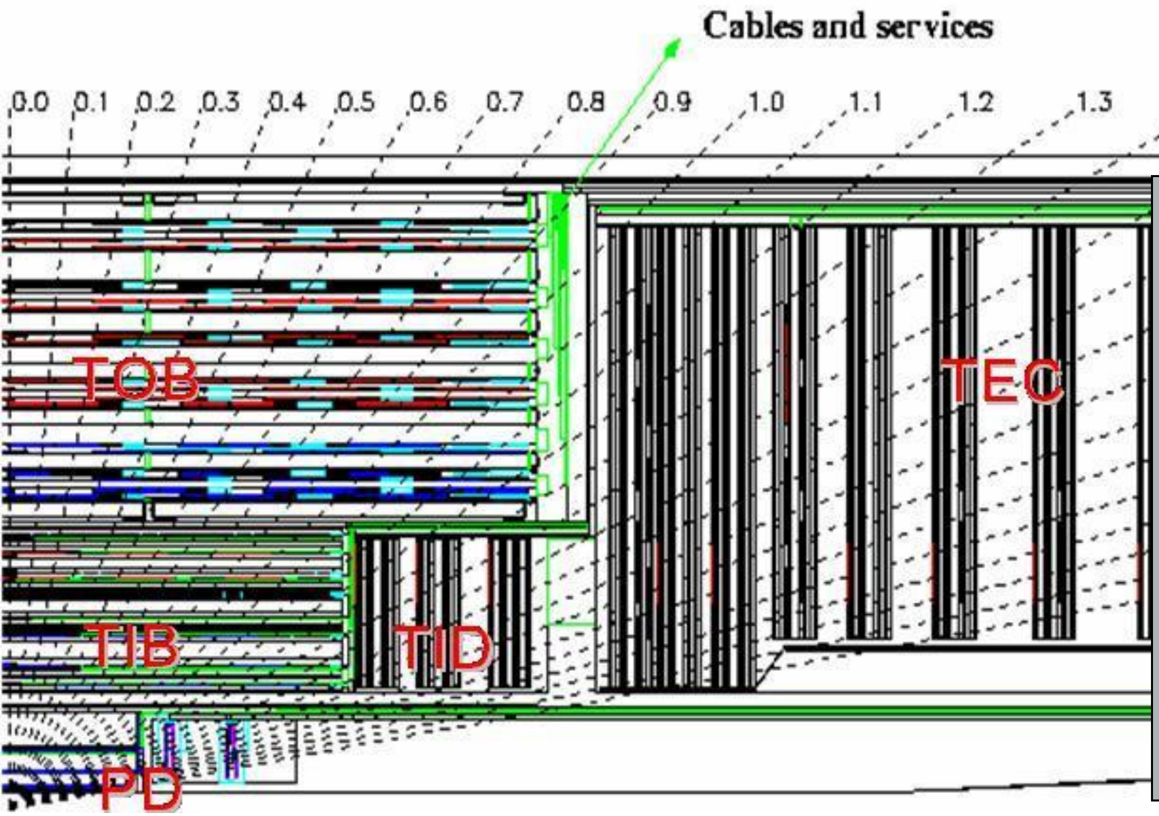




- 2 T solenoidal magnetic field
- Acceptance $|\eta|<2.5$
  (transition radiation tracker $|\eta|<2$)

- Momentum resolution
  $\sigma(p_T)/p_T = 0.05\%\ p_T\,[GeV/c] \oplus 1\%$
- Impact parameter resolution (0.25<|η|<0.5)
  $\sigma(d_0) = 10\ \mu m \oplus 140\ \mu m\ /\ p_T\ [GeV/c]$

CMS Strip tracker



Modules:

- 3112 + 3024 Thin modules (ss +ds)
- 5496 + 3600 Thick modules (ss +ds)

Silicon:

- 6,136 Thin sensors = $48m^2$
- 18,192 Thick sensors = $162m^2$

210 m^2 of silicon microstrip sensors

FE Electronics:

75,376 APV chips

9,648,128 strips ≡ electr. Channels

Tracker Inner Barrel (TIB): **4 layers:** 2 Rϕ (2D), 2 Rϕ-Stereo (3D)

Tracker Outer Barrel (TOB): **6 layers, :** 4 Rϕ (2D), 2 Rϕ-Stereo (3D)

Tracker Inner Disks (TID): **3*2 disks, :** 1 Rz (2D), 2 Rz-Stereo(3D)

Tracker EndCap (TEC): **9*2 disks, :** 4 Rz (2D), 3 Rz-Stereo(3D)

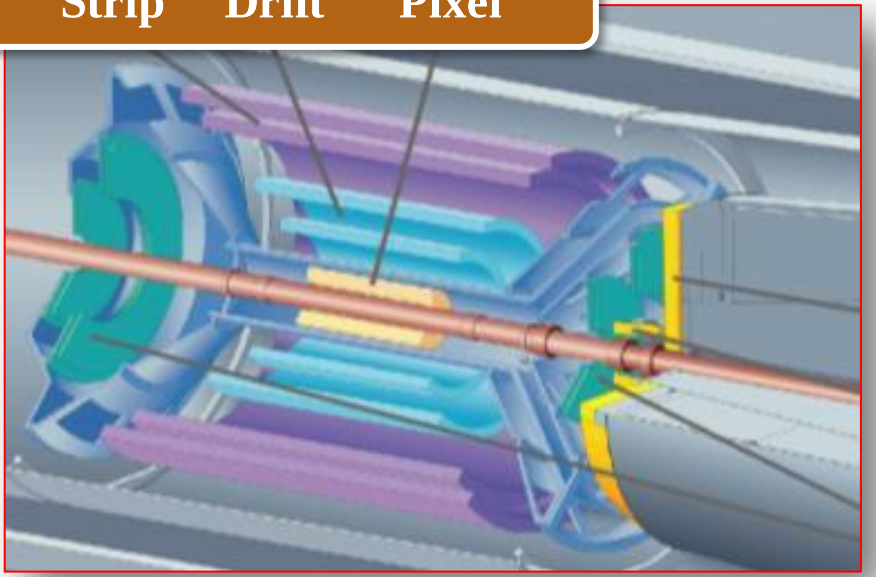
Each Track has at least
10 high precision measurements
for Pt and 4 in Θ

Coverage: | η | < 2.5

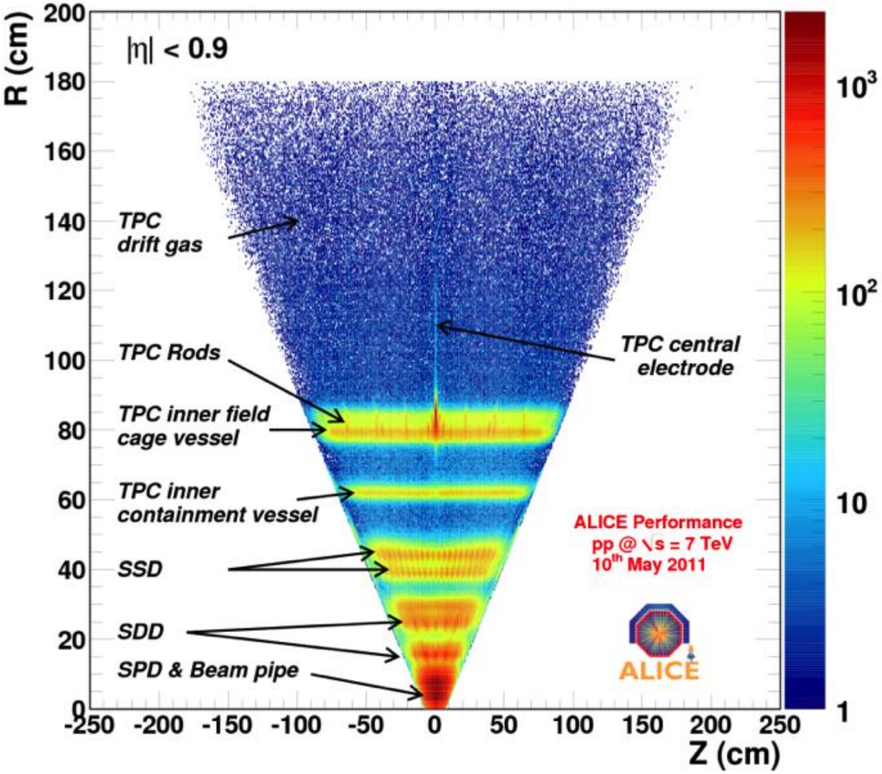
ALICE ITS

ITS: 3 different silicon detector technologies

Strip Drift Pixel



Material budget measured with γ conversions



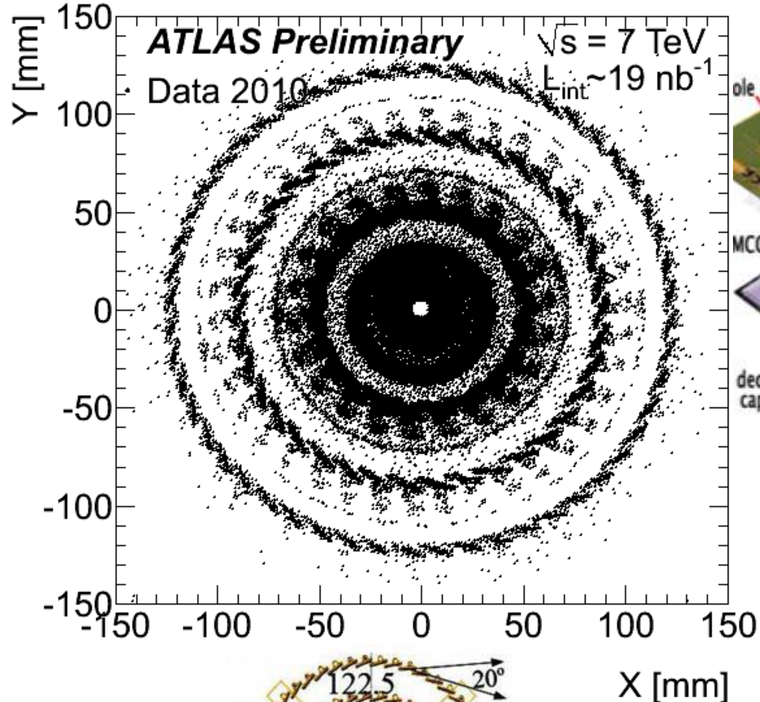
The silicon detectors master tables

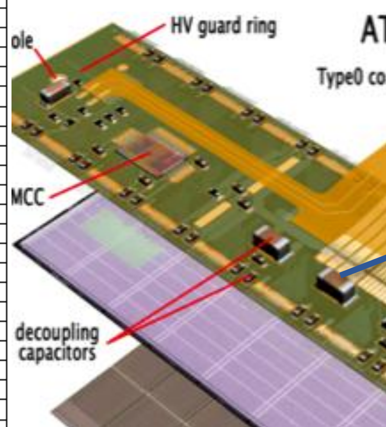
	Strips	Layers		spatial resolution
	pitch [μm]	[#]	radii [mm]	[μm]
ALICE	95	2	380-430	830 (z) 20 (rϕ)
ATLAS	80	4	299 to 514	580 (z) 17 (rϕ)
CMS	80-183	3	255 to 1080	23-52 (rϕ)

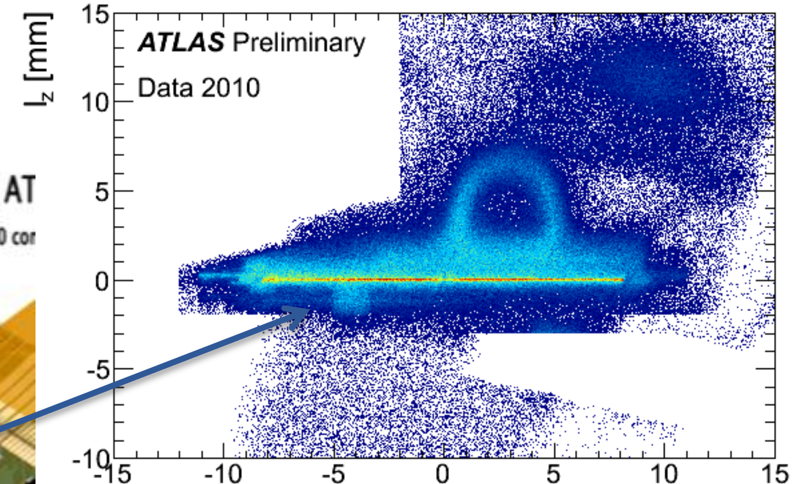
	Pixel	Drift	Strips	Pixel	Drift	Strips
	Area [m^2]			# channels [x 10^6]		
ALICE	0.2	1.3	5	9.8	0.13	2.6
ATLAS	1.8		61	80.4		6.3
CMS	1		198	66		9.3
VELO			0.2			0.17

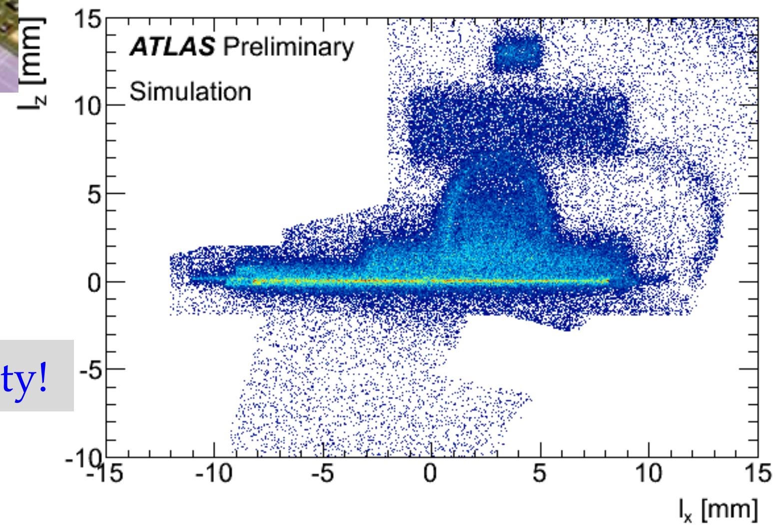
ATLAS Pixel having fun with tracks

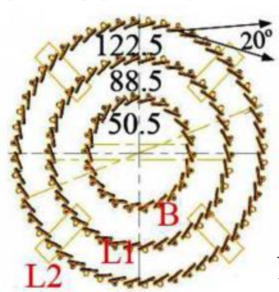
- Secondary vertices map for hadronic interactions
  - Imaging of the detector







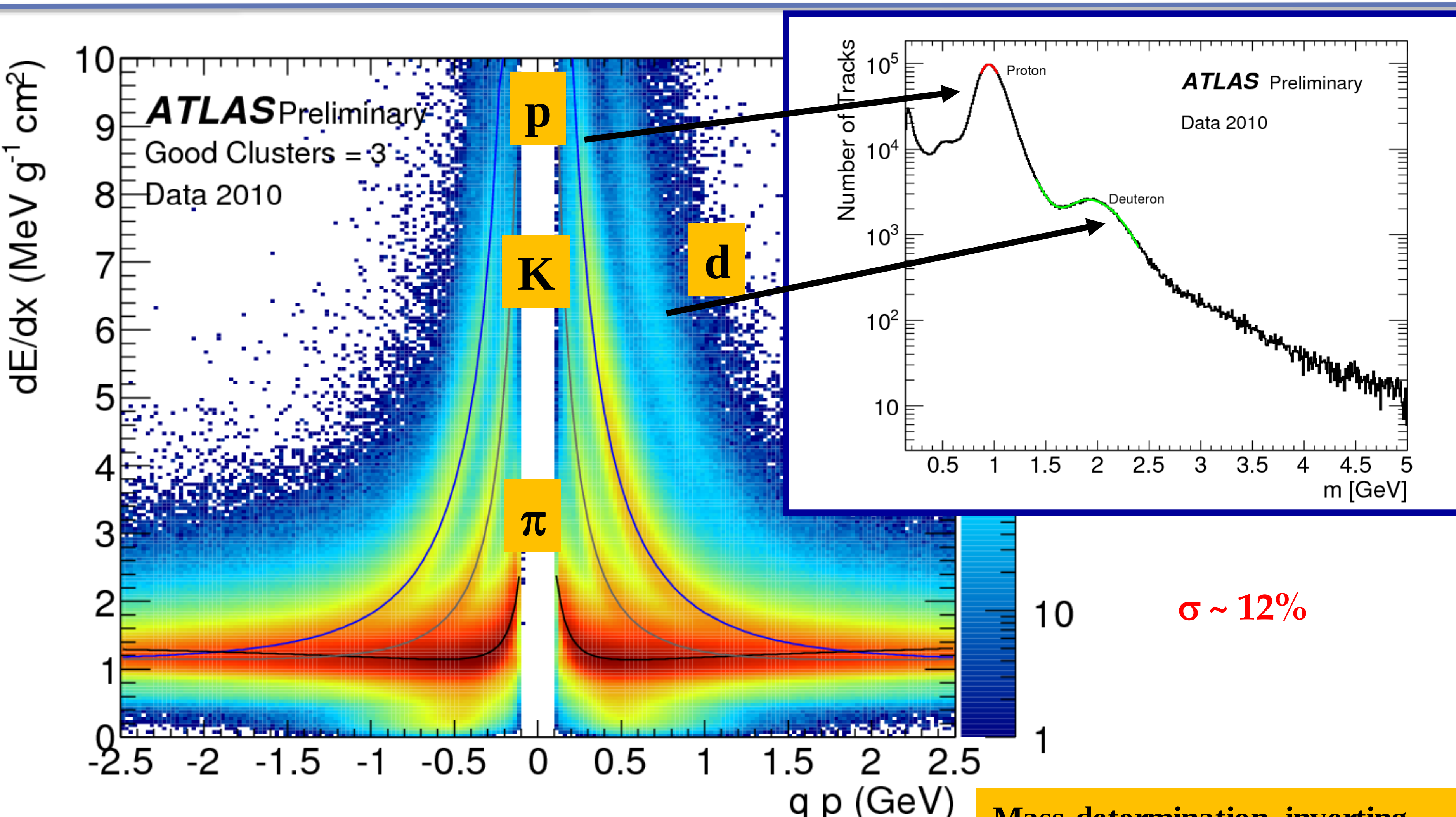




Detector drawing

How data describes the reality!

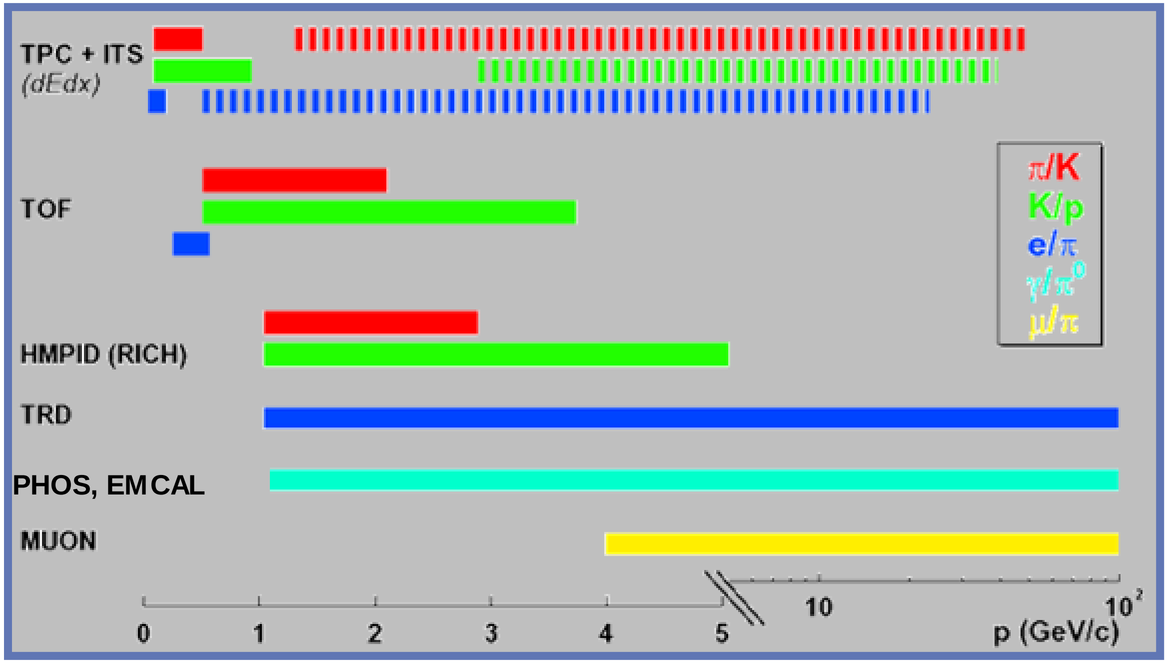
dE/dx in Silicon: ATLAS Pixels



σ ~ 12%

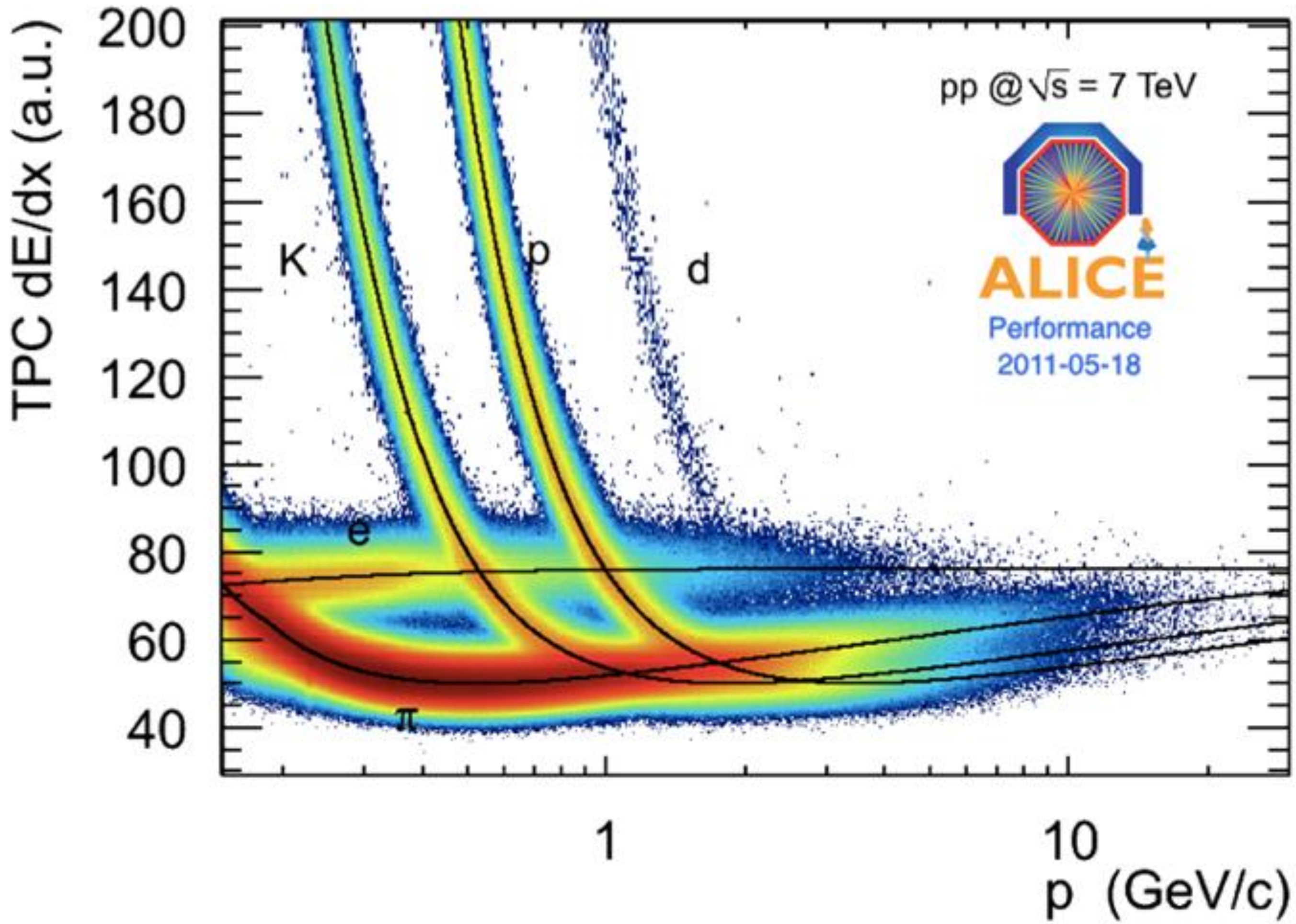
Mass determination inverting Bethe-Bloch energy loss relation

PID in ALICE



- 'stable' hadrons (π, K, p): 100 MeV < p < 5 GeV (several 10 GeV)
  - dE/dx in silicon (ITS) and gas (TPC) + time-of-flight (TOF) + Cherenkov (HMPID)
- decay topologies (K, Λ, ϕ, Ω, D)
  - K and Λ decays beyond 10 GeV
- leptons (e, μ), photons η,π^0
  - electrons TRD: p > 1 GeV, muons: p > 5 GeV, π^0 in PHOS, EMCAL: 1 < p < 80 GeV

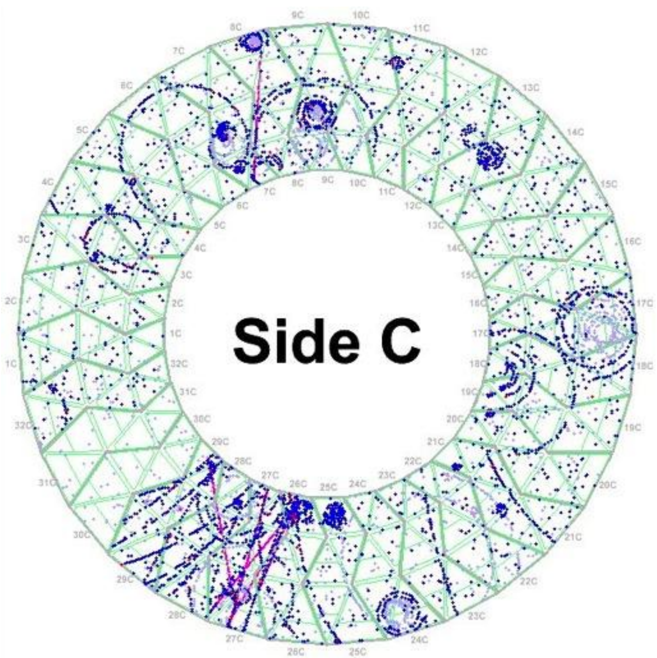
ALICE TPC: dE/dx

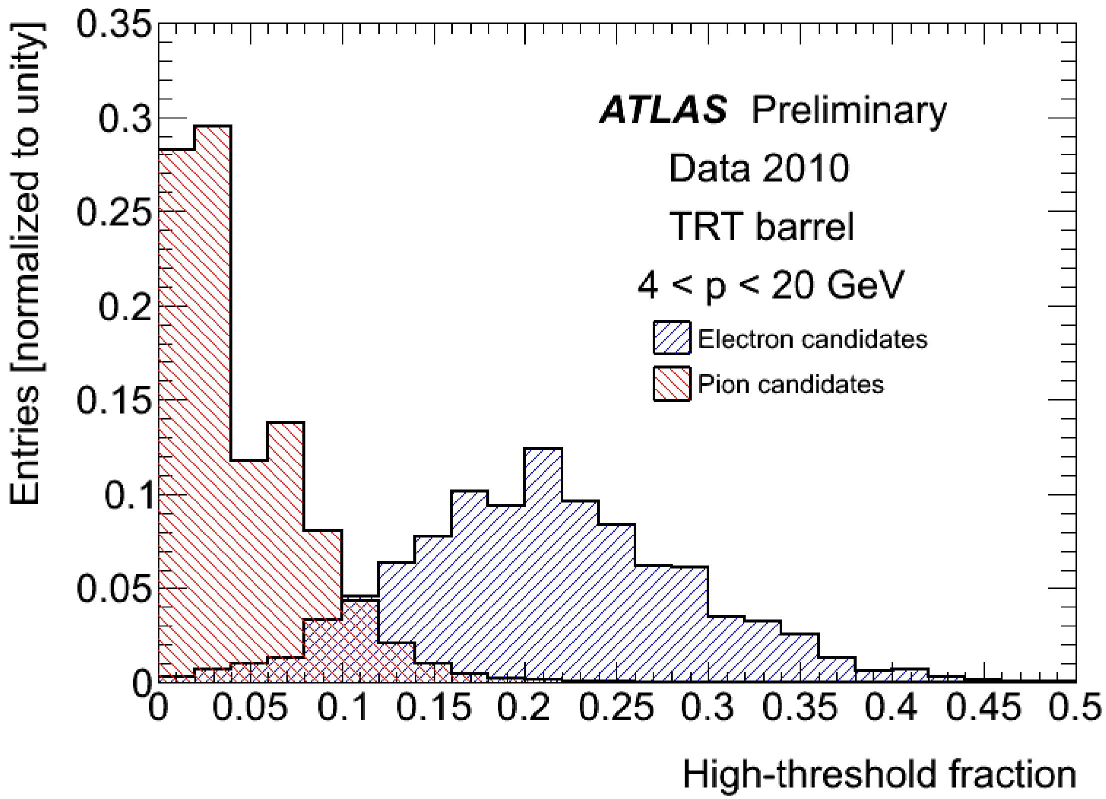


10 bit ADC: Dynamic range up to 26×MIP. σ ~ 5%

ATLAS TRT: transition radiaton at work

- Barrel shown here, same for endcaps
- ALICE has equally nice results





A quick look at results

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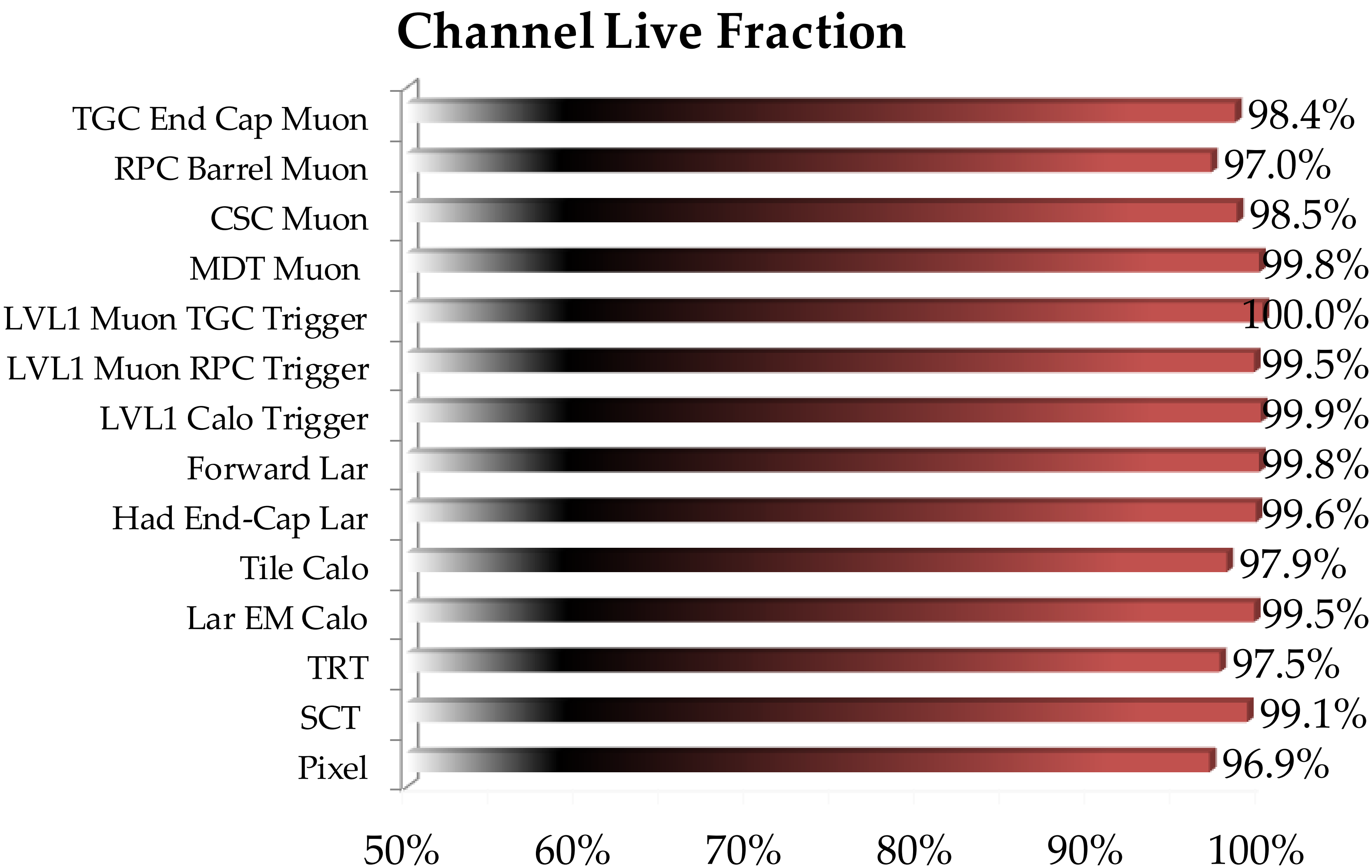
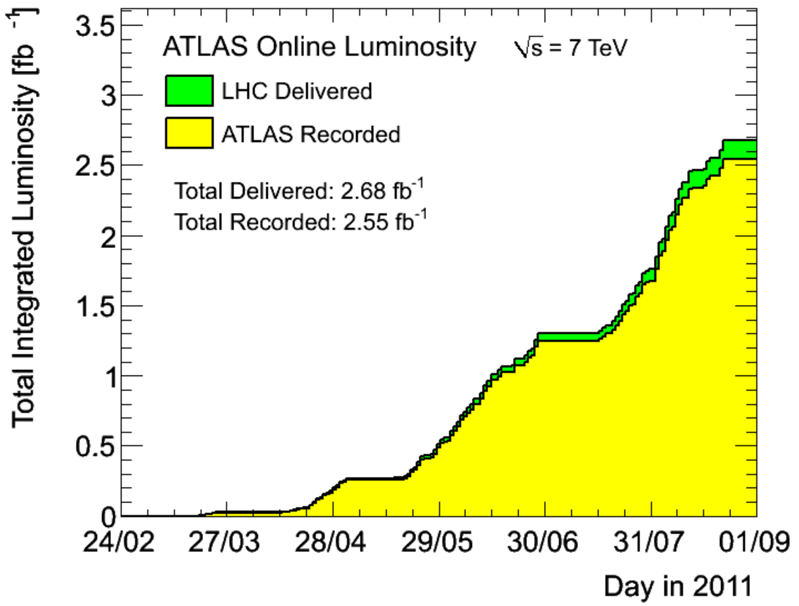
"It will be hard to make everything work quickly"

ATLAS status



Number of Channels
320 K
370 K
31 K
350 K
320 K
370 K
7 K
3.5 K
5.6 K
9.8 K
170 K
350 K
6.3 M
80 M

ATLAS data taking efficiency



Max inst lumi. : 2.37×10^{33} cm^{-2} s^{-1}

Delivered luminosity: 2.68 fb^{-1}

ATLAS ready recorded: 2.55 fb^{-1}

Preliminary uncertainty on 2011 luminosity 4.5%

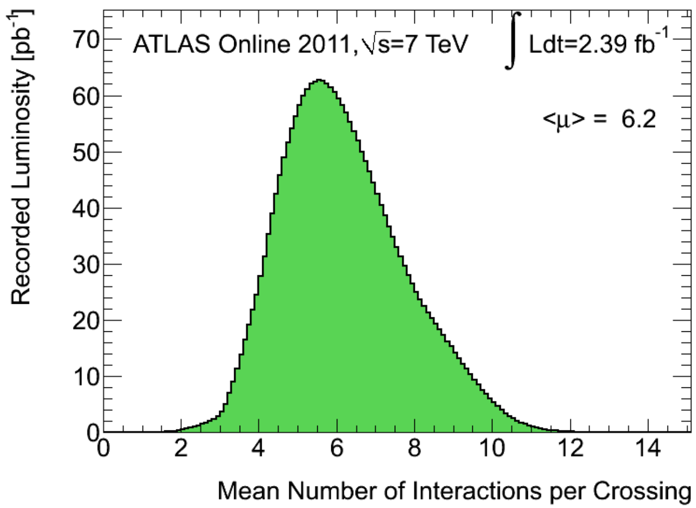
Data taking efficiency: ~95%

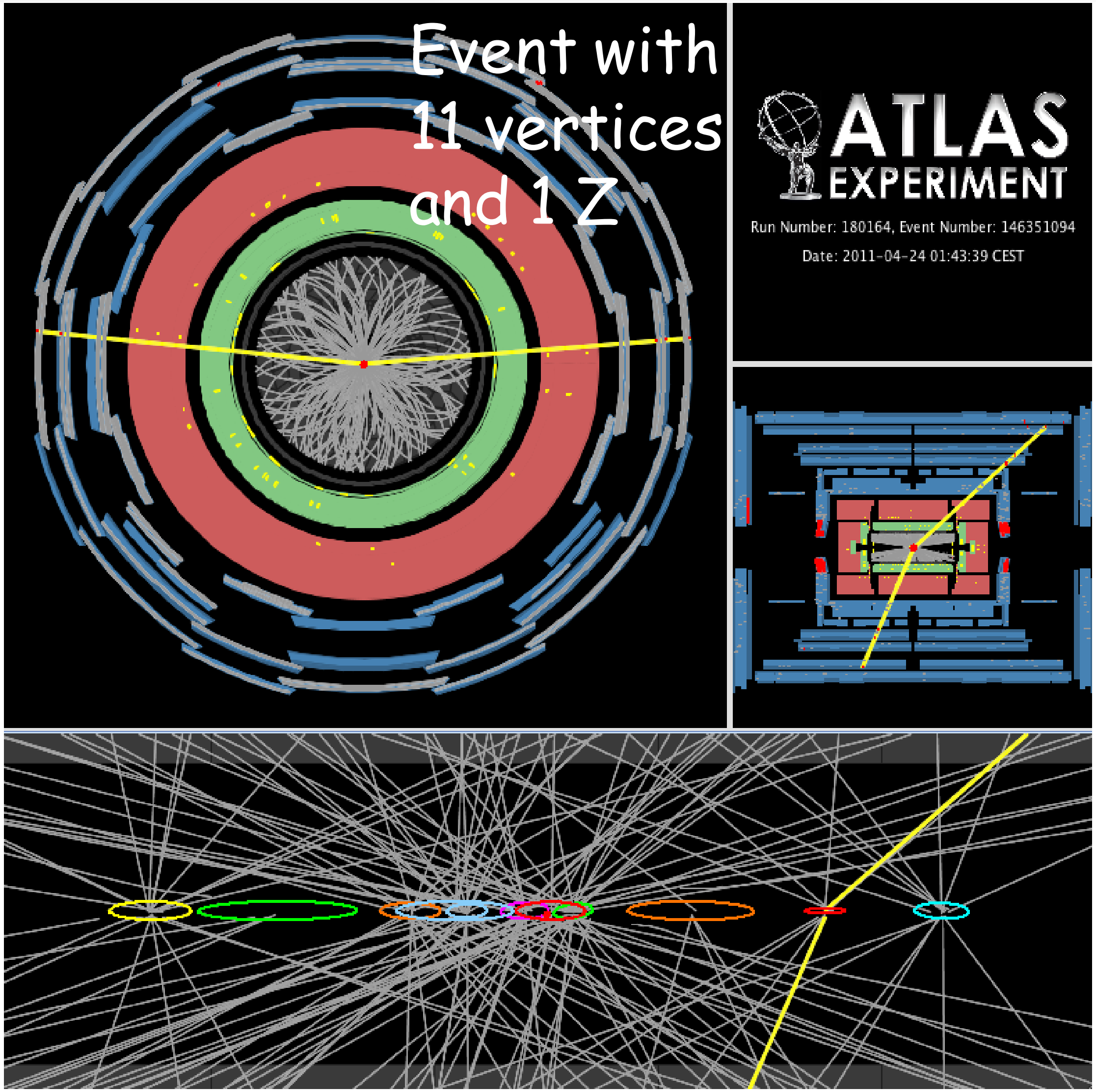
Fraction of good quality data per detector

Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.9	100	90.0	91.3	94.8	98.2	99.5	99.7	99.9	99.6	99.6	99.4

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and August 13th (in %). The inefficiencies in the LAr calorimeter will largely be recovered in the future.

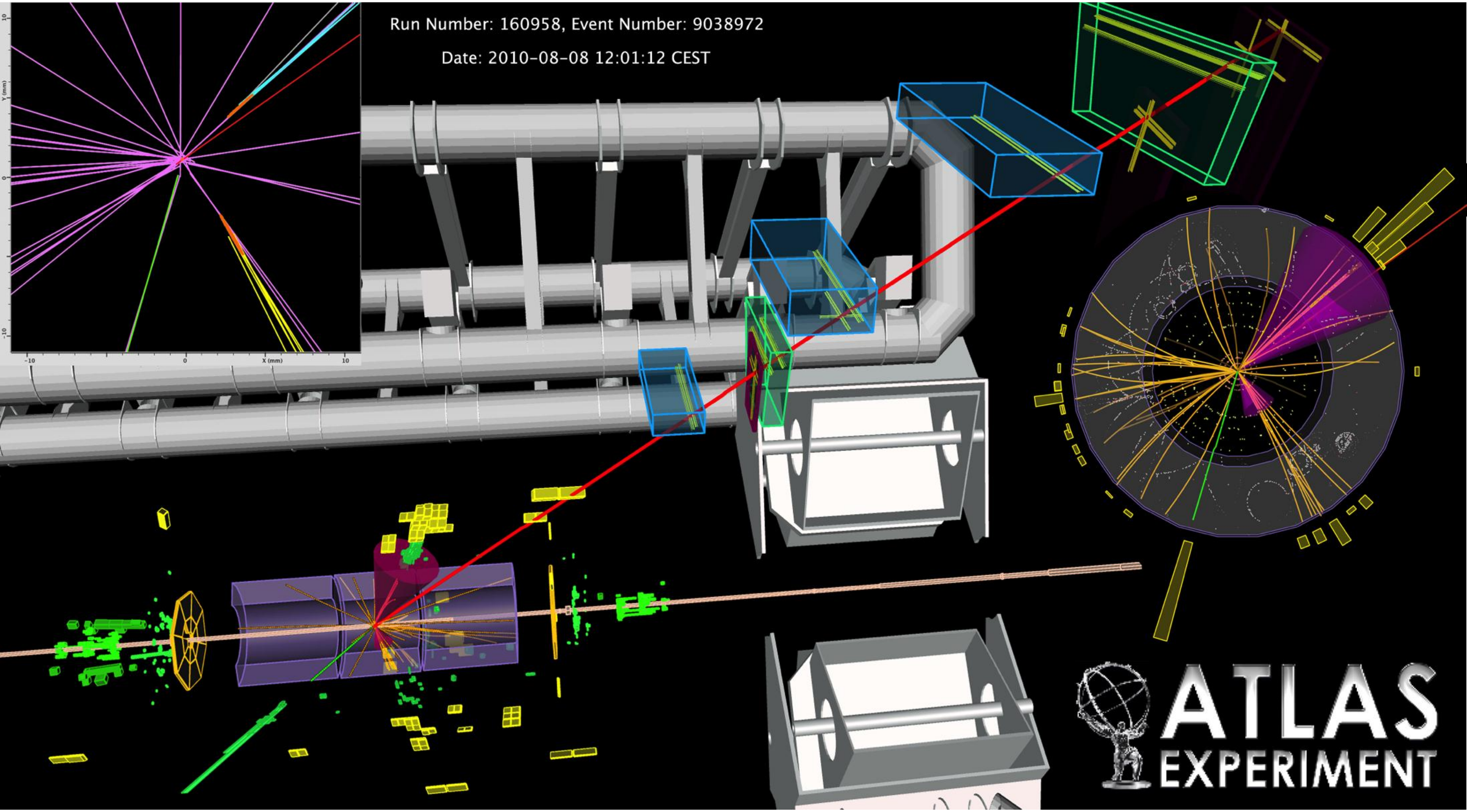
ATLAS pile-up





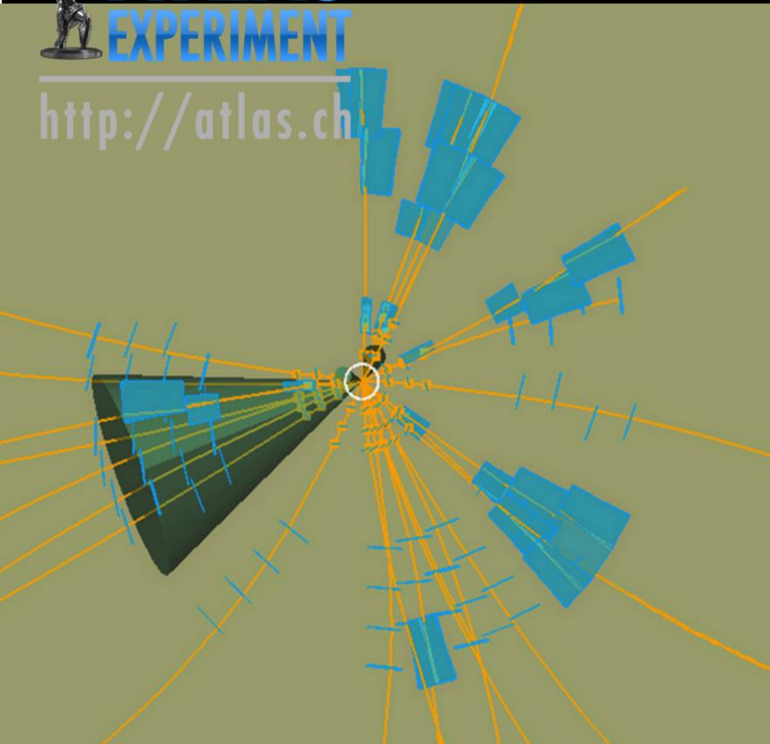
- Average Pile Up in 2011 : 6.0 Coll/BC
- Max Pile Up : 10-12 Collisions/BC
- Issue for:
  - Missing energy
  - Lepton Isolation (mainly calorimetric)
  - Jet Energy Scale and resolution
  - Vertexing
  - CPU time and event size

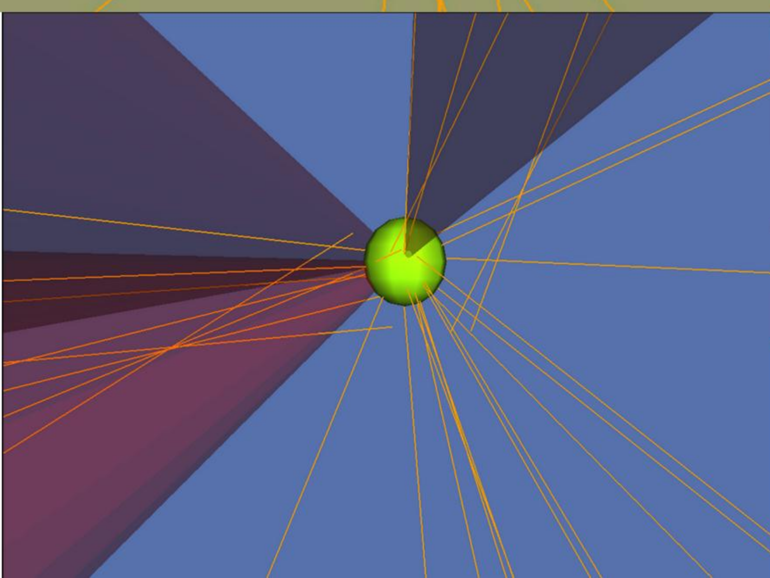
Few event displays

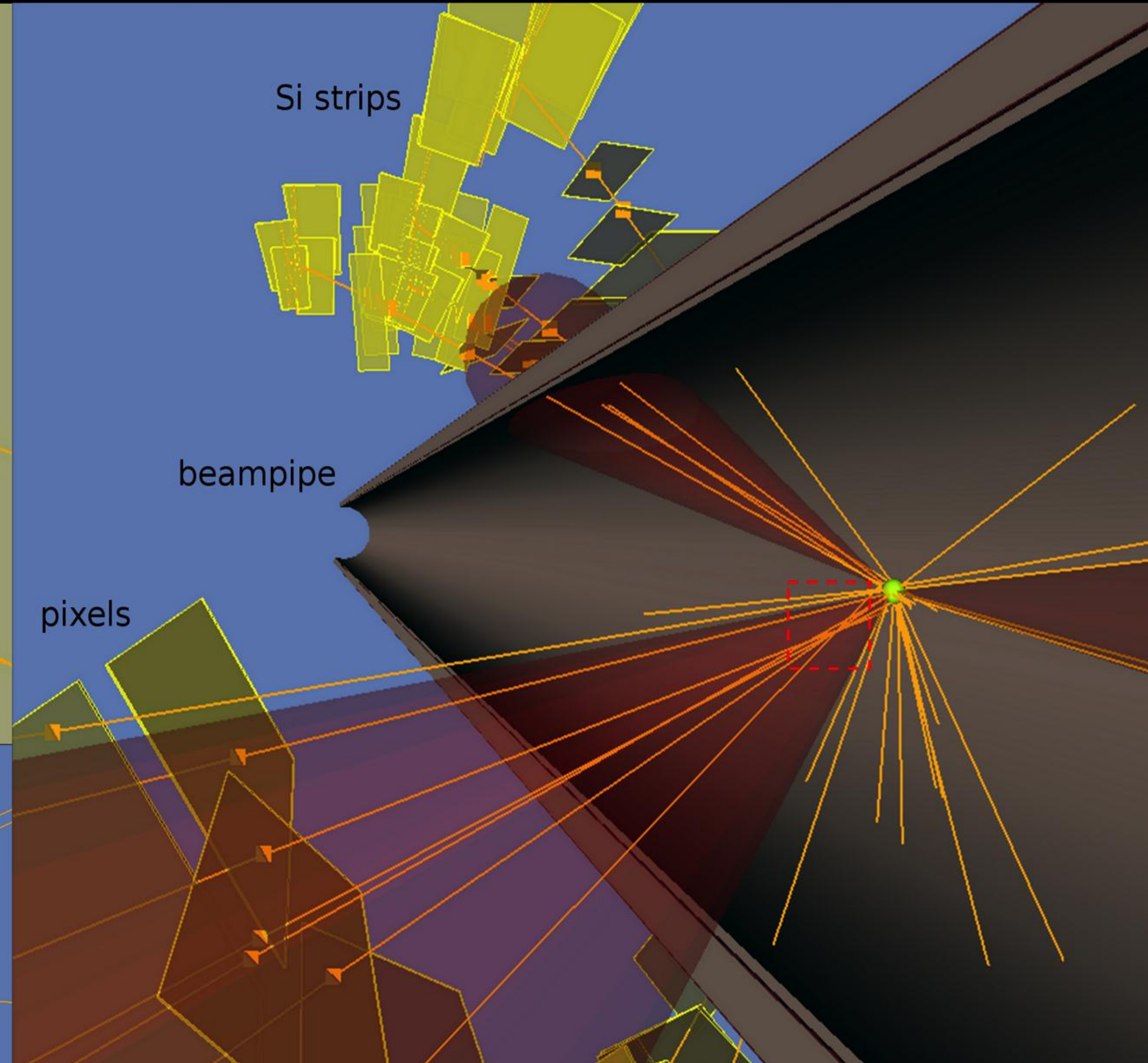


Run 152166
Event 817271

b-tagged jet in 7 TeV collisions





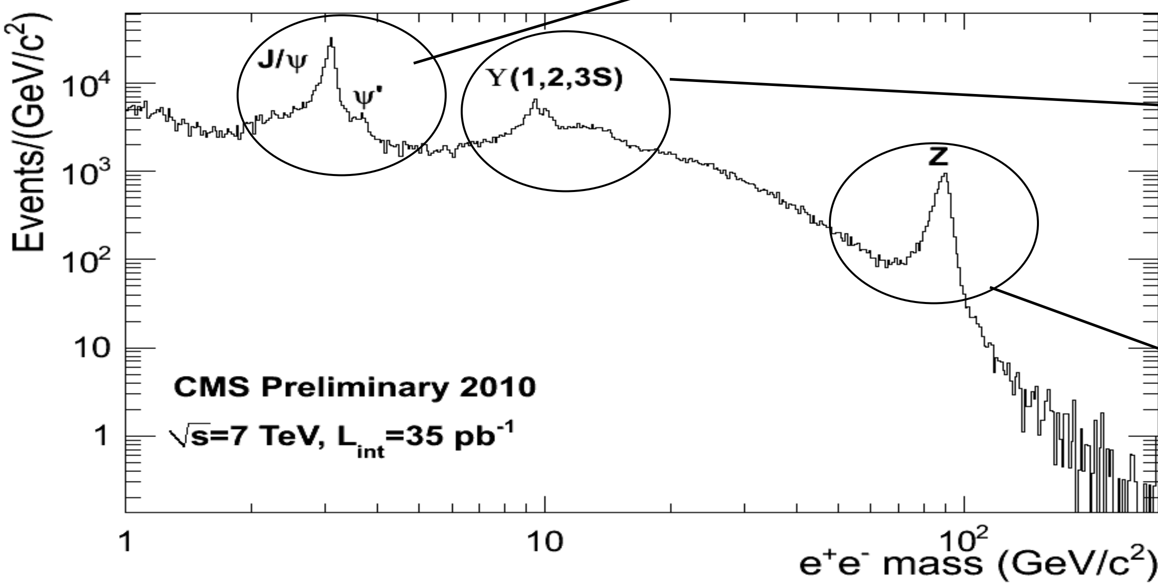


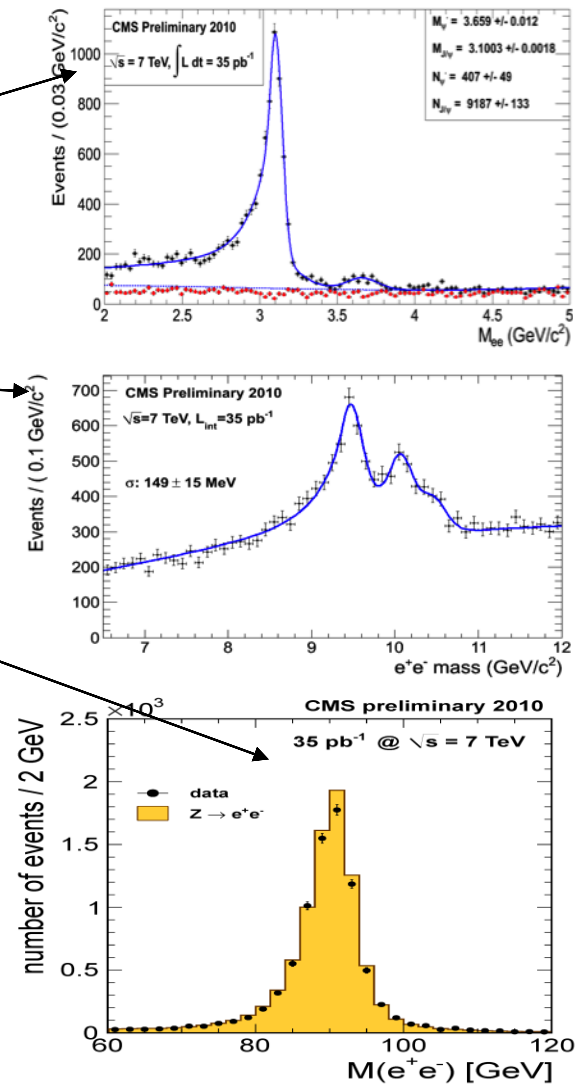
p_T^{jet}=19 GeV (measured at electromagnetic scale)

4 b-tagging quality tracks in the jet

CMS ECAL, photon and electron performance

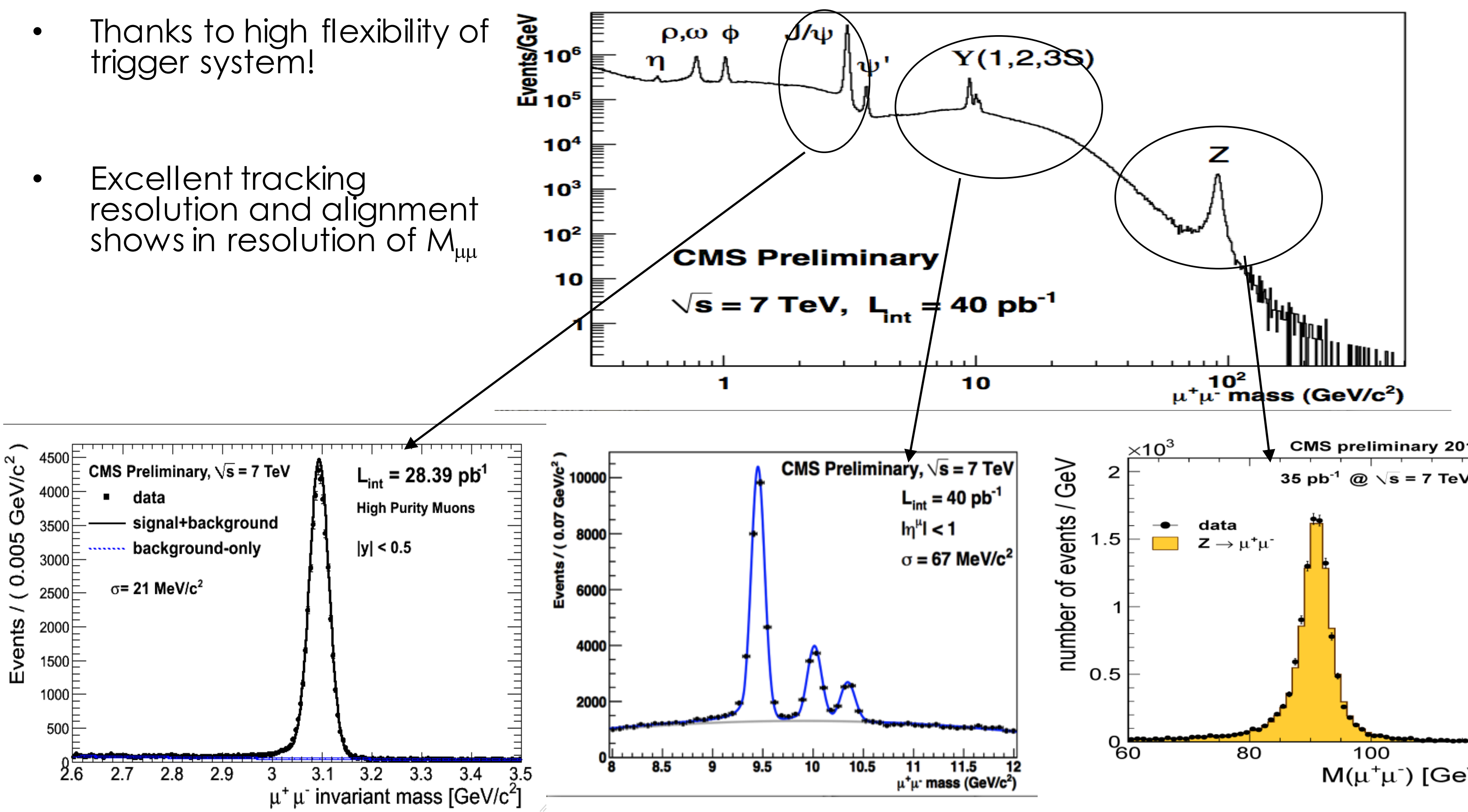
- Di-electron mass spectrum



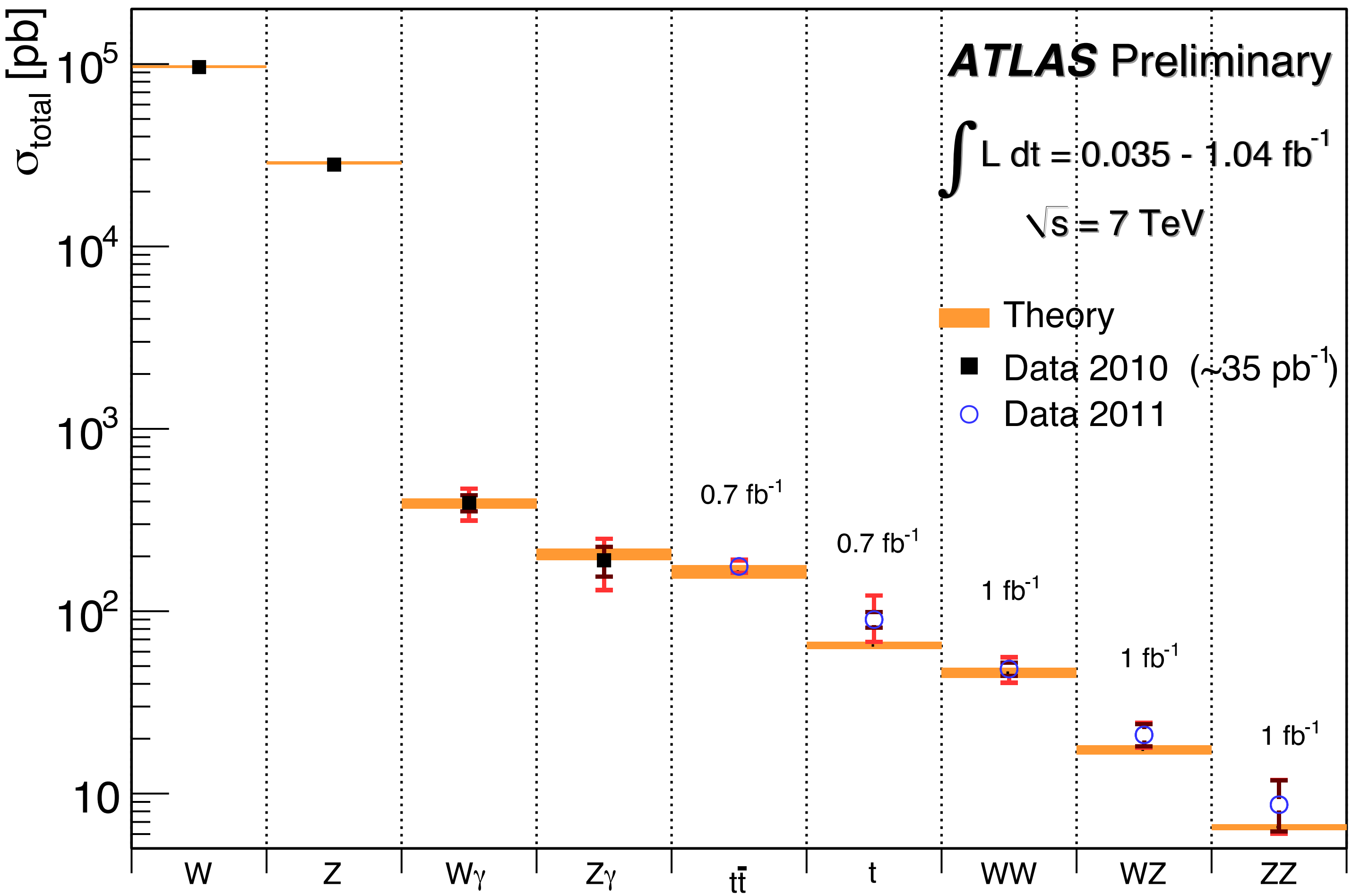


CMS tracking and muon performance

- Thanks to high flexibility of trigger system!
- Excellent tracking resolution and alignment shows in resolution of $M_{\mu\mu}$

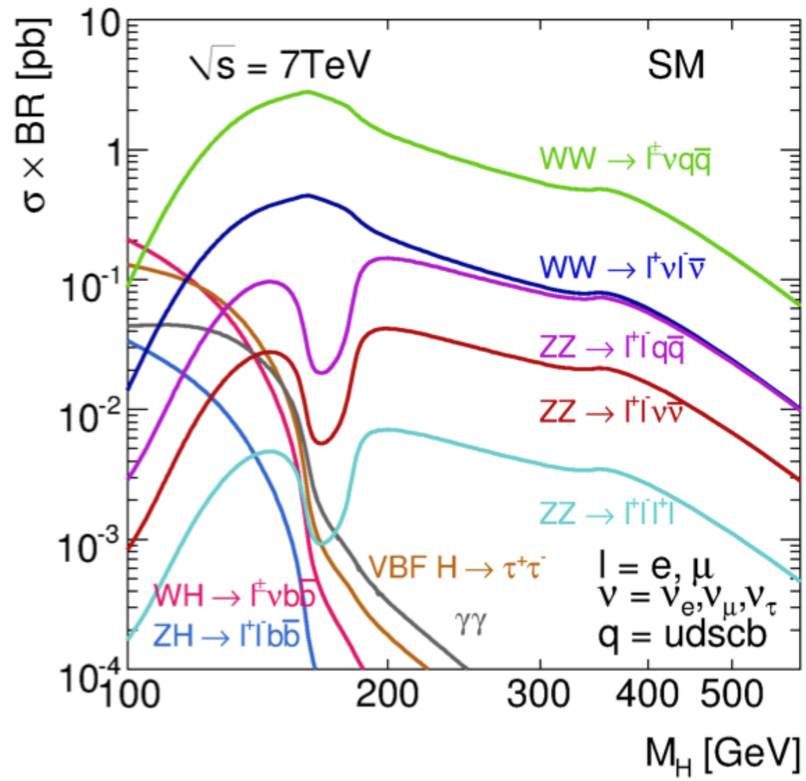


ATLAS: SM cross-sections



ATLAS Higgs cross-sections

- **H→γγ**: rare channel, but the best for low mass — *L=1.08 fb^{-1}*
- **H→WW$^{(*)}$**:
  - →lνlν: very important in the intermediate mass range — *L=1.70 fb^{-1}*
  - → lνqq: highest rate, important at high mass — *L=1.04 fb^{-1}*
- **H→ZZ$^{(*)}$**:
  - → 4l: golden channel — *L ~ 2.2 fb^{-1}*
  - → llνν: good for high mass — *L=1.04 fb^{-1}*
  - → llbb: also high mass — *L=1.04 fb^{-1}*
- **H→ττ**: good signal/ background, important at low mass, rare — *L=1.06 fb^{-1}*
- Associated prod. **H→ bb-bar** — *L=1.04 fb^{-1}*
  - ttH, WH, ZH
  - It is useful for the discovery
  - It is very important for Higgs property studies if SM Higgs is discovered

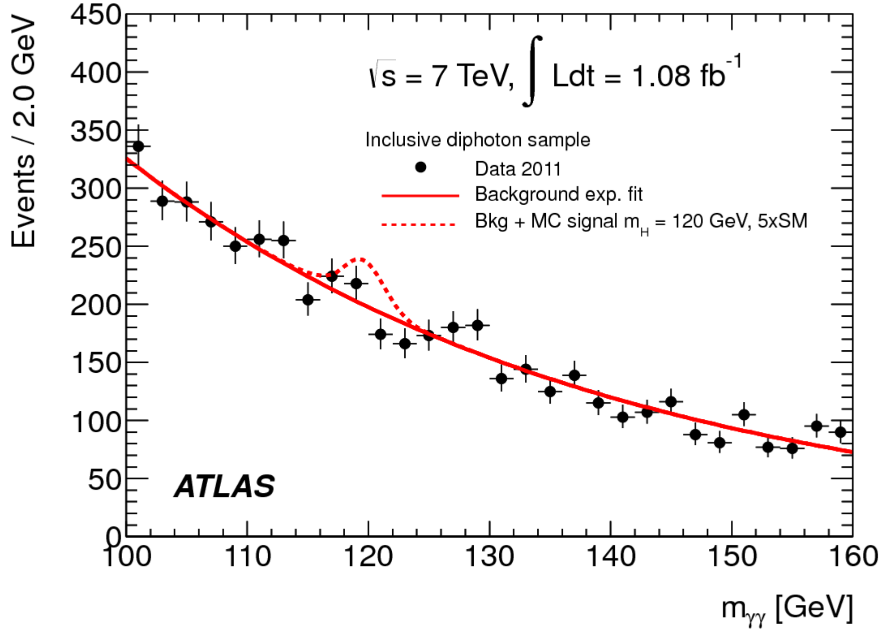


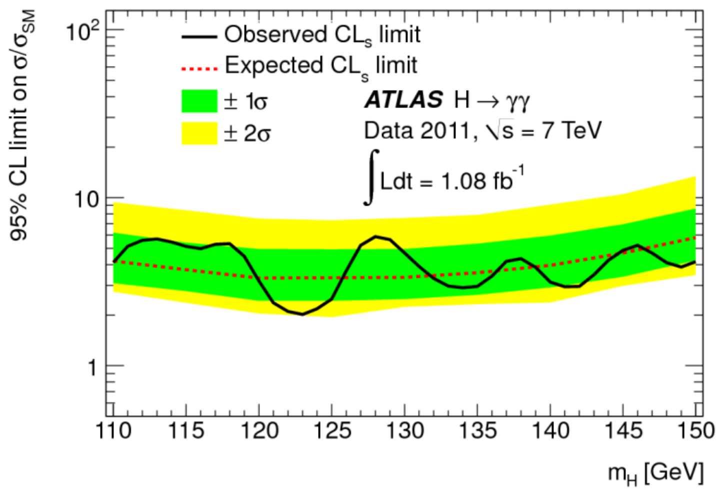
Events expected to be produced with L=1 fb^{-1}

m_H, GeV	WW→lνlν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

ATLAS: H->γγ

- Cleanest channels for very low Mass Higgs and simple signature
- Needs:
  - Good di-photon mass resolution
  - Determination of primary vertex
  - Good Photon Id.
  - γ/Jet, γ/π^0 discrimination
- Need to understand backgrounds with high precision with Data Driven techniques
  - QCD $\gamma\gamma$ production
  - γ-Jet and Jet-Jet production

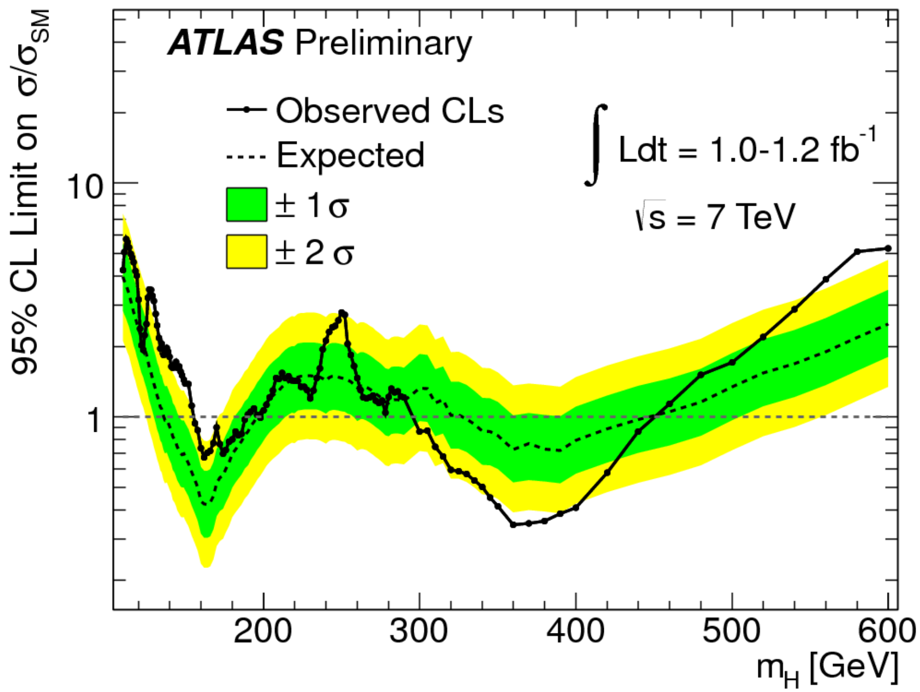




No indication of significant excess, therefore limits on SM Higgs production cross-section

ATLAS Higgs combination

- The combined upper limit on the SM Higgs boson σ divided by the SM expectation vs. m_H indicated by the black solid line



SM m_H excluded at 95% C.L.:

146 < m_H < 232 GeV
256 < m_H < 282 GeV
296 < m_H < 466 GeV

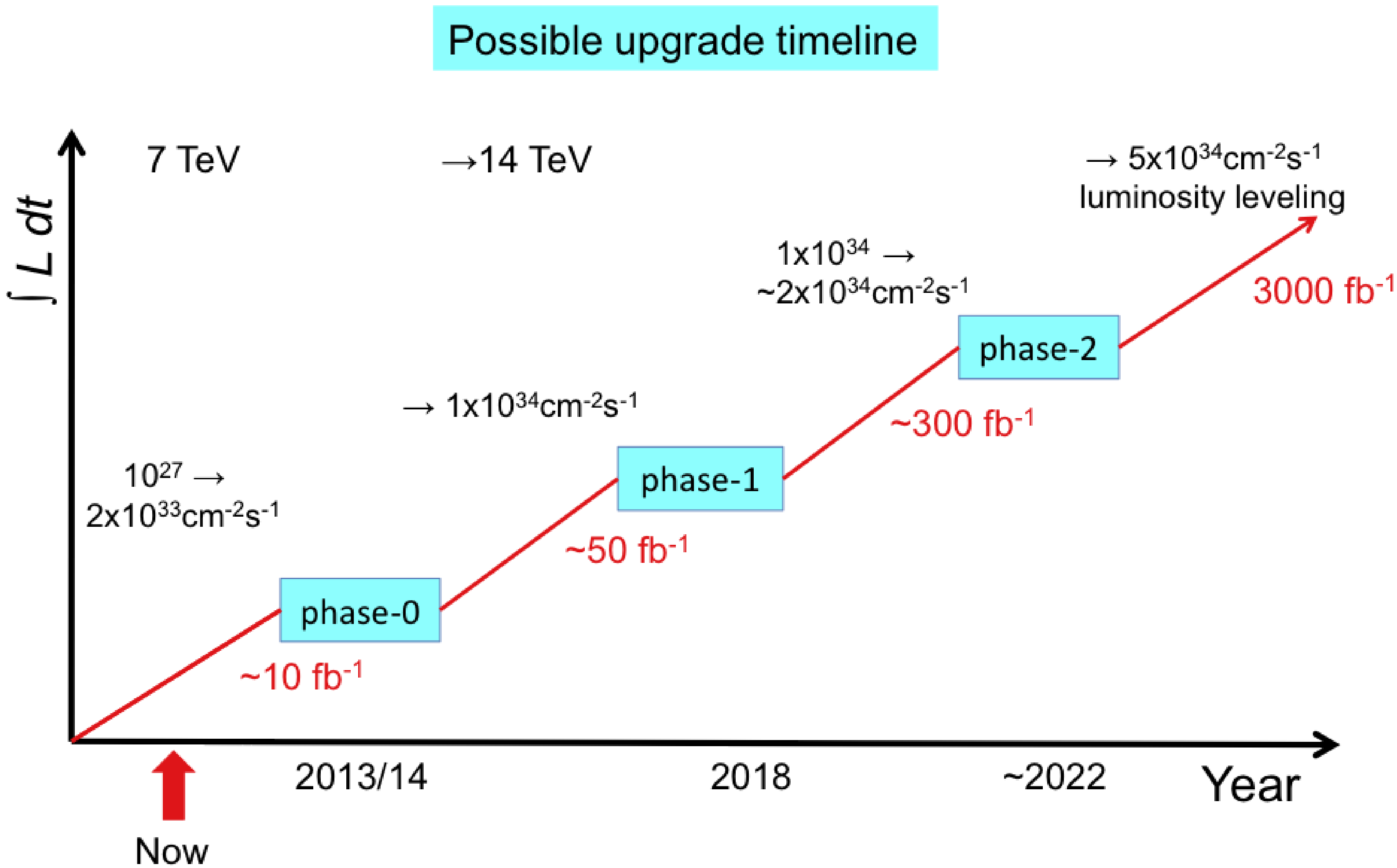
Fun just starting!

Thinking about the future

• • •

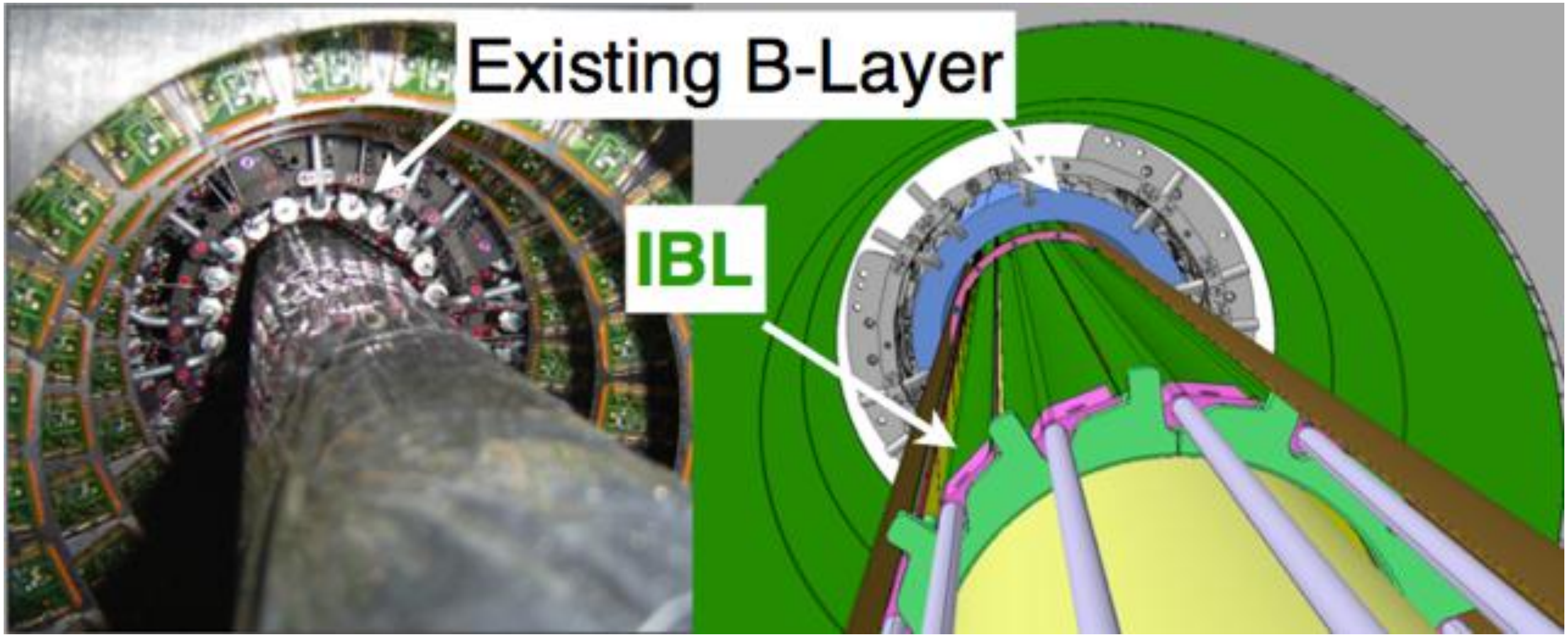
Yes, already

LHC upgrades and how detectors follow



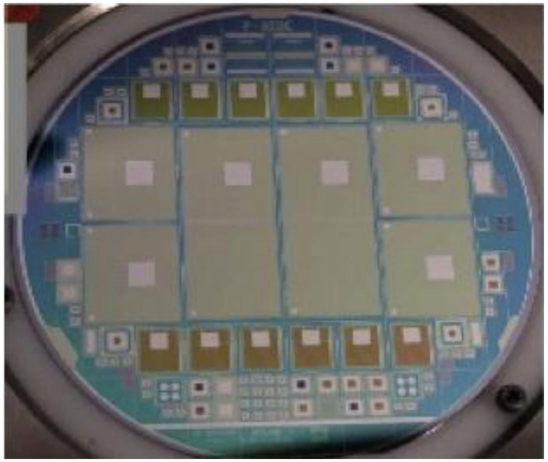
ATLAS: IBL in Phase0

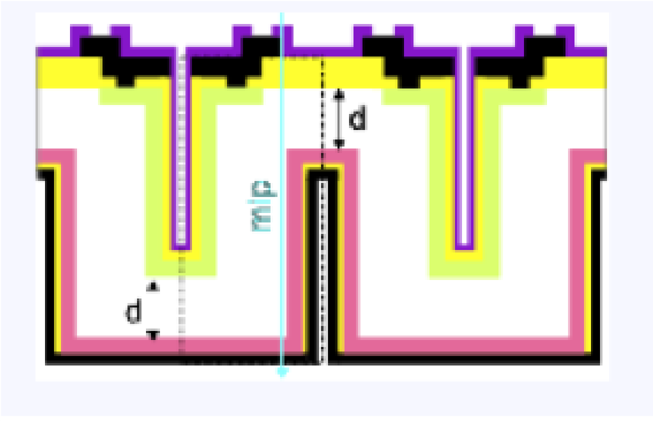
- The major project of Phase0
  - Installation of a reduced diameter beam pipe (47 mm) and the innermost Pixel layer: the Insertable B-Layer
- Improvement of b-tagging capabilities and redundancy to cope with future occupancies and radiation damage

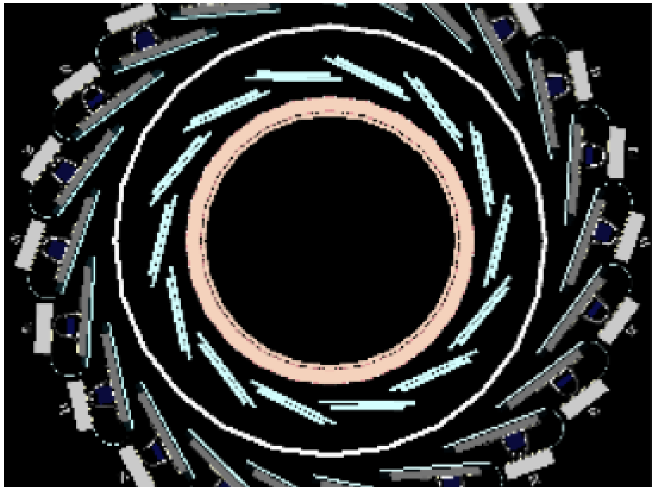


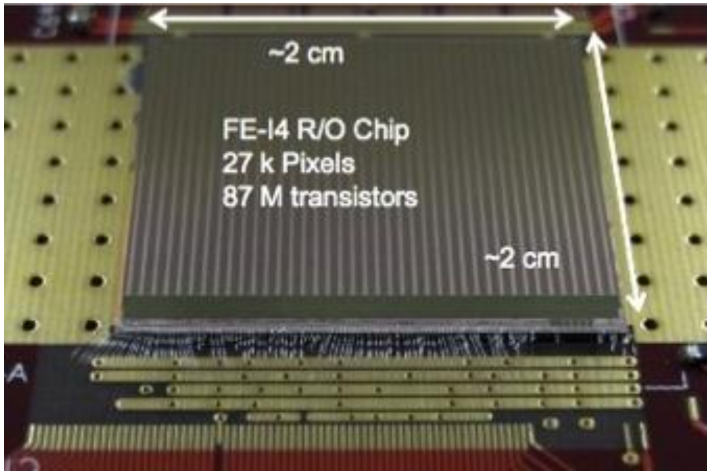
ATLAS IBL

- Innovative
  - Reduced thickness for sensor and ASIC
  - Planar and 3D silicon sensors









Upgrades in Phase 1 and 2

- ATLAS and CMS: increase in interaction rates and keeping an eye on physics results
  - Phase 1
    - ATLAS: Muon system, L1&2 trigger, Calorimetry
    - CMS: Pixel, trigger, DAQ, beam instrumentation and luminosity, infr.
  - Phase 2
    - ATLAS: Trigger, some Muon chambers, endcap and forward calorimetry, calorimeter readout for trigger, new Inner Detector
    - CMS: new Inner Detector, readout of Muon system, calorimetry readout, trigger electronics
- ALICE and LHCb: enlarge measuring capabilities
  - ALICE: Inner Tracker, Muon Forward Tracker, new forward calorimetry, particle identification improvement, TPC readout upgrade, trigger and DAQ
  - LHCb: move to 40 MHz readout, new VELOPIX, new Si tracker, PID improvements at low momenta, calorimeter readout
  - Both aiming at Phase 1

When being puzzled is good

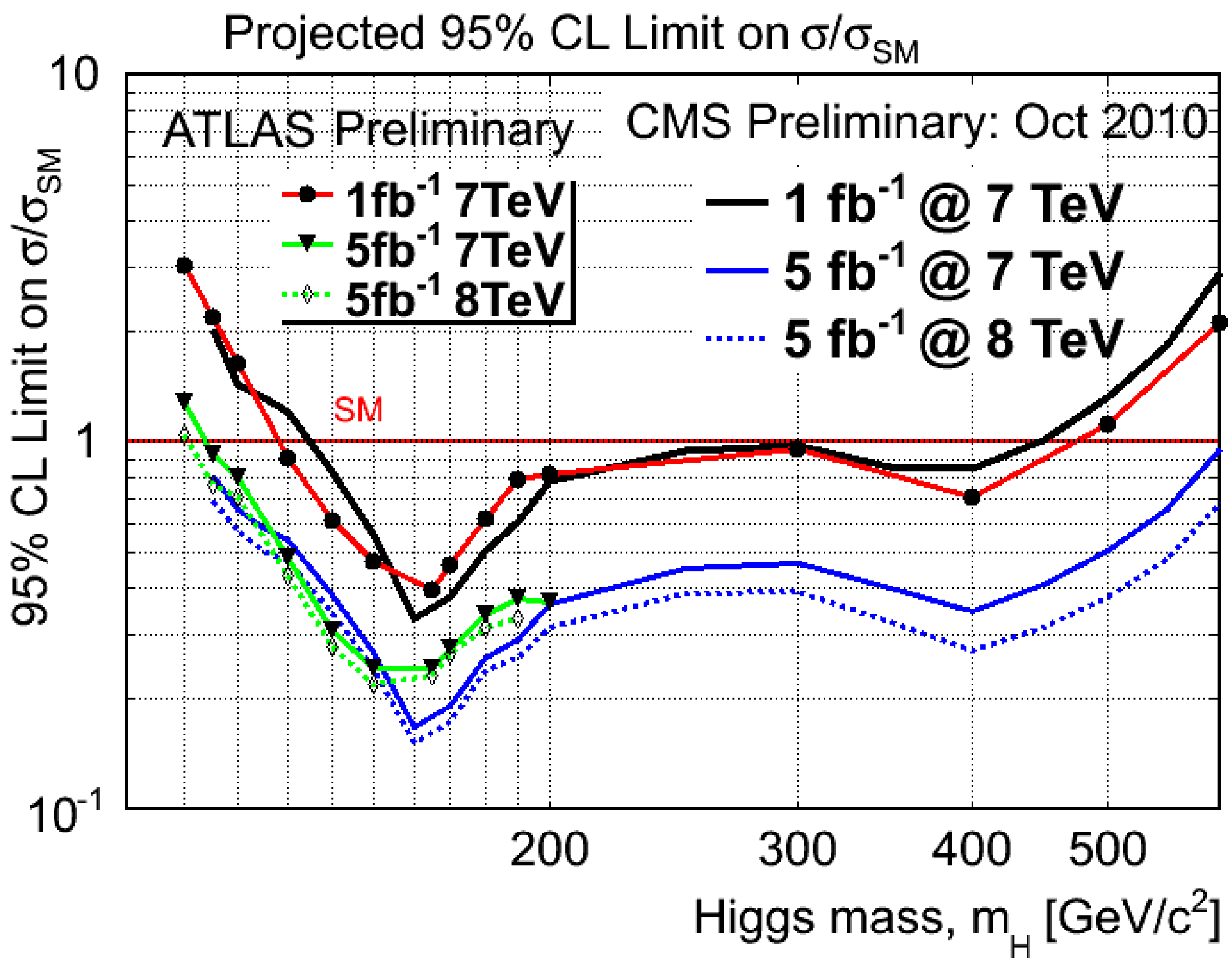
- 6 December 2009
- Switching on 80M Pixel for the first time, √s = 0.9 TeV
- Is that so simple?
- I looked clearly worried to see beam effects
- ATLAS channels increased by one order of magnitude

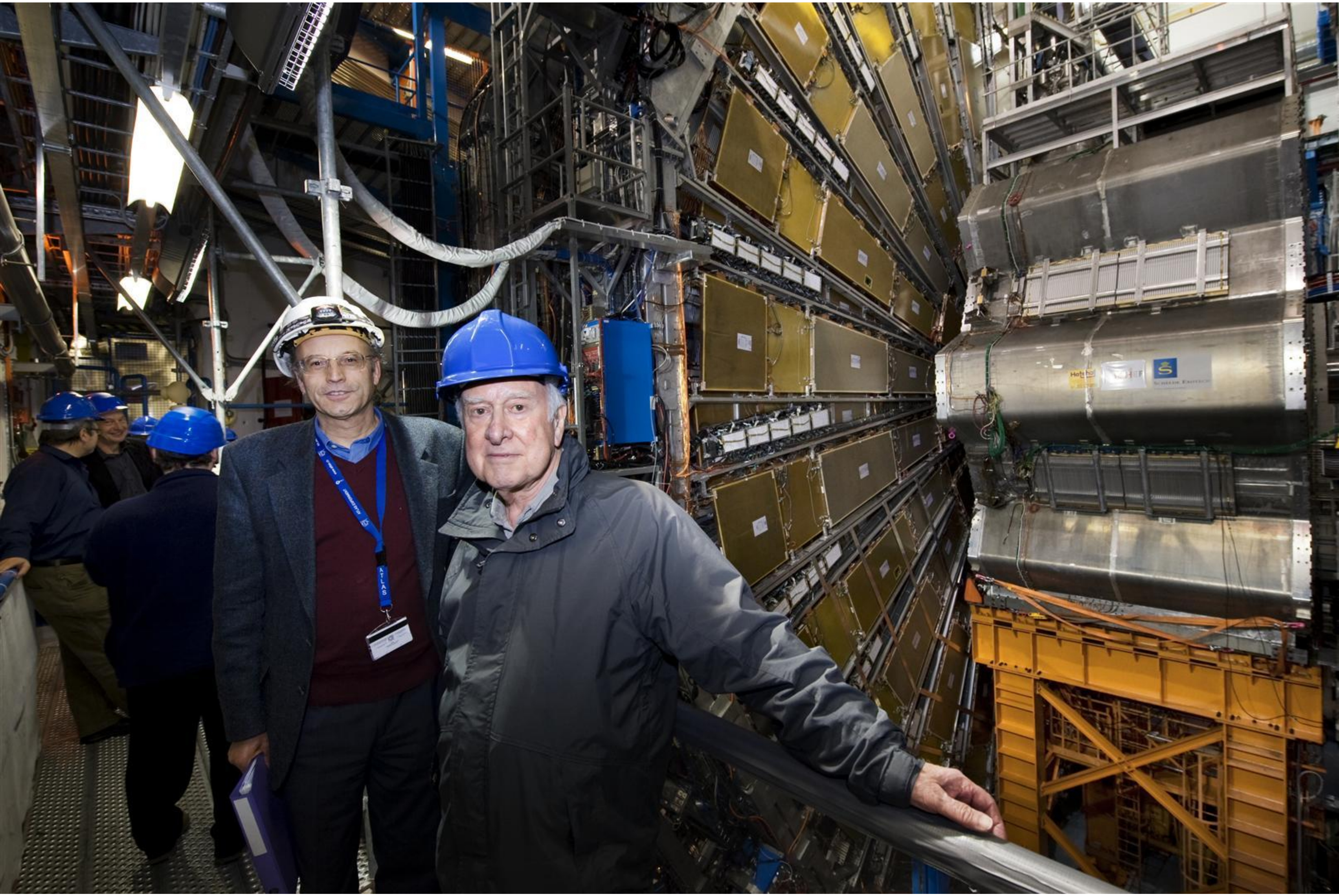
- 30 March 2010
- We did again, √s = 7 TeV
- I thought we we're getting used to it
- I was worrying for few moments then all went fine

Conclusions

- I'm greatly indebted to the Organizing Committee
  - Preparing such a talk is very challenging, but extremely interesting
- I'm greatly indebted to all LHC experiment colleagues
  - Many provided tons of material, impossible to mention all (already too many slides)
- Lessons learned: we were too worried that between switching on and getting results too much time was needed
  - It went much smoother
  - We're getting lots of results
- LHC performed really well and our DAQ, Trigger and Computing have been following well the challenge
- Now: waiting for even more results!

ATLAS&CMS looking forward





Higgs in ATLAS

Higgs in CMS