LHC Detectors
From Design to Performance
or
“lessons learned”

PicoSEC-MCNet System Integration Training
Hamburg, 26. May 2014

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Disclaimer

It is fair to say that this was the first time most of the physicists and engineers involved in the LHC experiments construction faced a challenge of this scope and size.

➡ this talk: only a glimpse, main focus on CMS and ATLAS;

- examples of experiences, lesson (not) learned;

➡ many more details at e.g.

- D. Froidevaux and P. Sphicas, General Purpose Detectors for the Large Hadron Collider, Annu. Rev. Nucl. Part. Sci. 2006;
- T.S. Virdee, Physics requirements for the design of the ATLAS and CMS experiments at the Large Hadron Collider, Phil. Trans. R. Soc. A 2012 370, 2012;
- P. Jenni and P. Grannis, The evolution of hadron-collider experiments, Phys. Today 66(6) 38 (2012);
- S. Stapnes, Detector Challenges at the LHC, Nature, Vol 448|19 July 2007.

One sentence summarises it all...

We present updated results on SM Higgs searches based on the data recorded in 2011 at $\sqrt{s}$=7 TeV (~4.9 fb^{-1}) and 2012 at $\sqrt{s}$=8 TeV (~5.9 fb^{-1})

Results are preliminary:
- ❑ 2012 data recorded until 2 weeks ago
- ❑ harsher conditions in 2012 due to x2 larger event pile-up
- ❑ new, improved analyses deployed for the first time

H → γγ and H→ 4l: high-sensitivity at low-m_H; high mass-resolution; pile-up robust
- ❑ analyses improved to increase sensitivity → new results from 2011 data
- ❑ all the data recorded so far in 2012 have been analyzed
- → results are presented here for the first time

Other low-mass channels: H→ WW$^{(*)}$→ lνlν, H→ ττ, W/ZH
- ❑ E_T^{miss} in final state → less robust to pile-up
- ❑ worse mass resolution, no signal "peak" in some cases
- ❑ complex mixture of backgrounds
- → understanding of the detector performance and backgr advanced, but results not yet mature enough to be pres
- → 2011 results used here for these channels for the overa

ATLAS: Status of SM Higgs searches, 4/7/2012

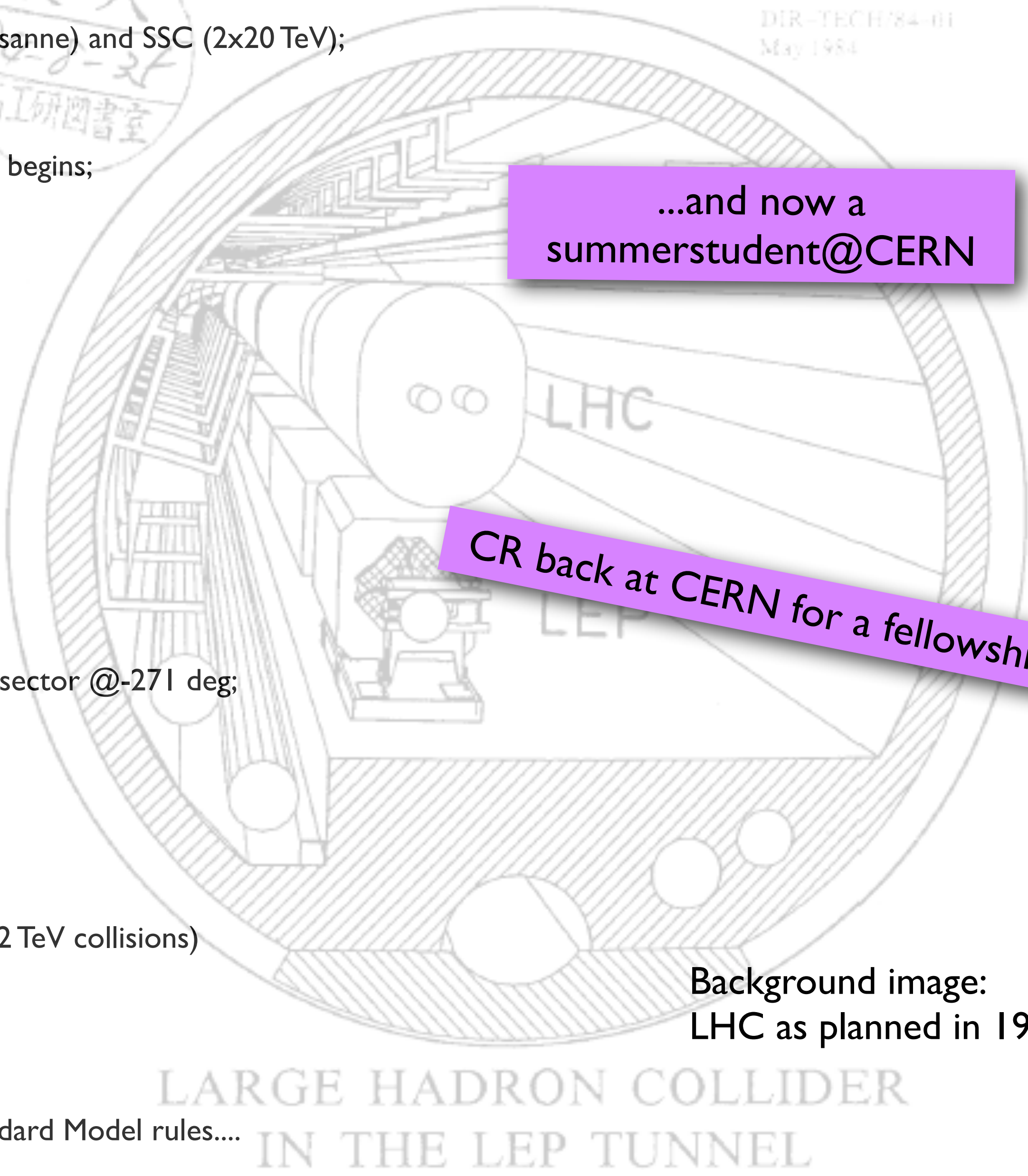
LHC history

- 1980: LEP not yet built, but physicists think about the possibility to re-use the tunnel for a hadron collider;
- 1984: Glimmerings of the LHC (2x5...9 TeV, symposium in Lausanne) and SSC (2x20 TeV);
- 1988: SSC approved (Waxahachie, Texas);
- 1989: First collisions in LEP and SLC, R&D for LHC detectors begins;
- 1993: SSC construction cancelled;
- 1994: LHC approved (start in 2005)
- 1995: Discovery of the top quark at Fermilab;
- 1996: ATLAS and CMS approved. 1997: ALICE, 1998 LHCb;
- 2000: end of LEP running, no Higgs yet;
- 2005: first cosmic seen in the ATLAS pit;
- 2006: new CERN accelerator control centre ready;
- 2007, June: the last dipole magnet lowered to the tunnel, first sector @-271 deg;
- 2008: LHC start;
- 2008, 10. September - 10:28: first full turn of a proton bunch
- 2008, 19. September - failure during powering tests
- 2009, 23. November: protons collide again! (30. November: 1.2 TeV collisions)
- 2010, 30. March: first high energy proton collision (3.5 TeV)
- 2012, 4. July: Higgs-like particle seen!
- 2012, 8. November: First observation of $B_s^0 \to \mu^+\mu^-$; the Standard Model rules....

CR still at school...

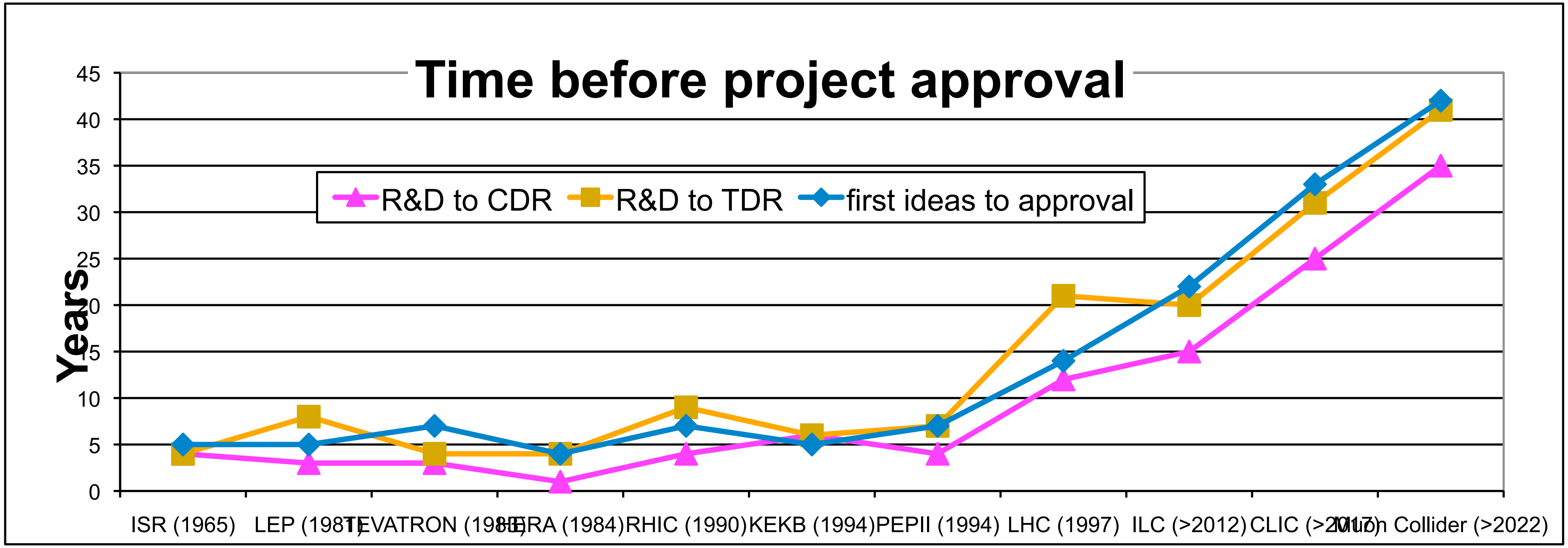
...and now a summerstudent@CERN

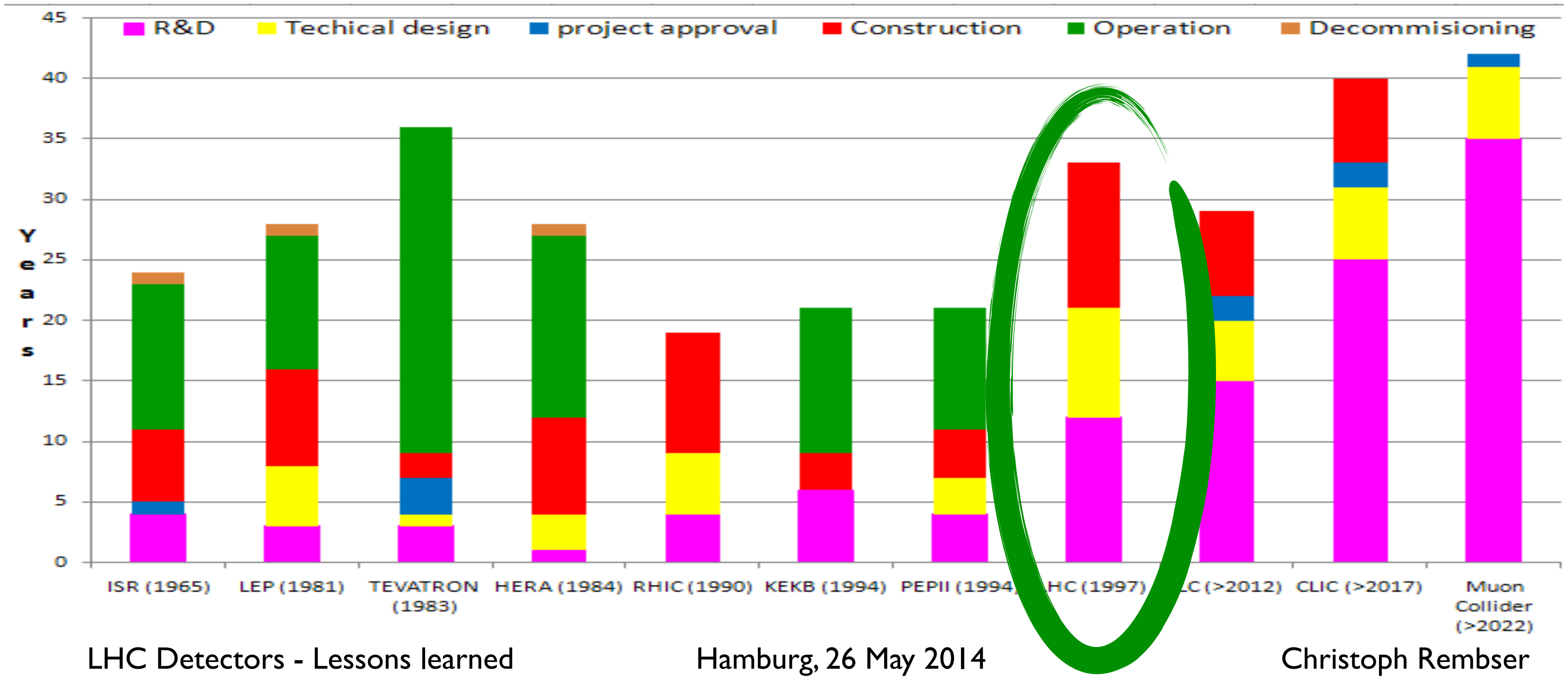
CR back at CERN for a fellowship



Background image:
LHC as planned in 1984

Accelerator projects take longer and longer...

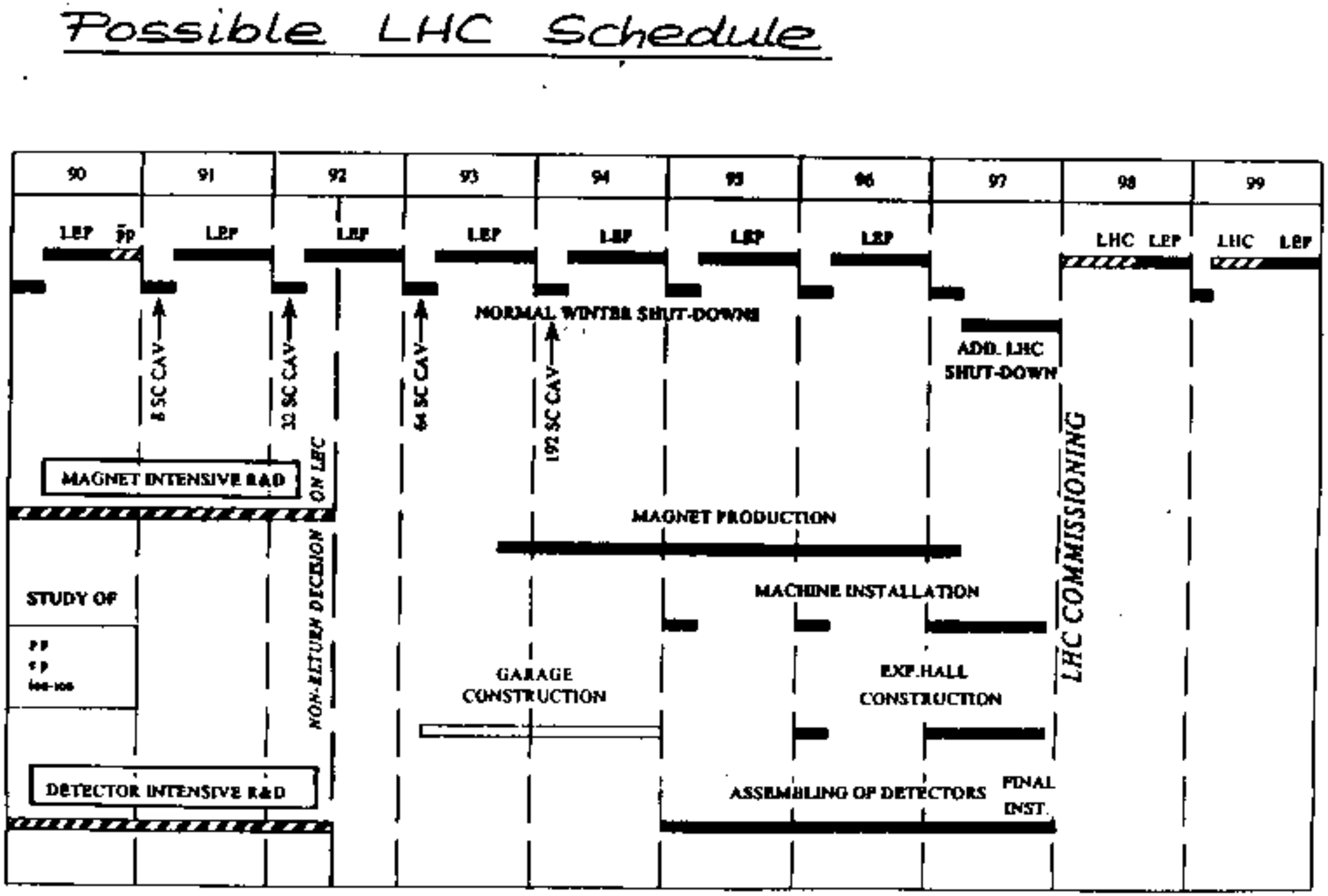




Figures from Jean Pierre Delahaye, ICHEP 2010

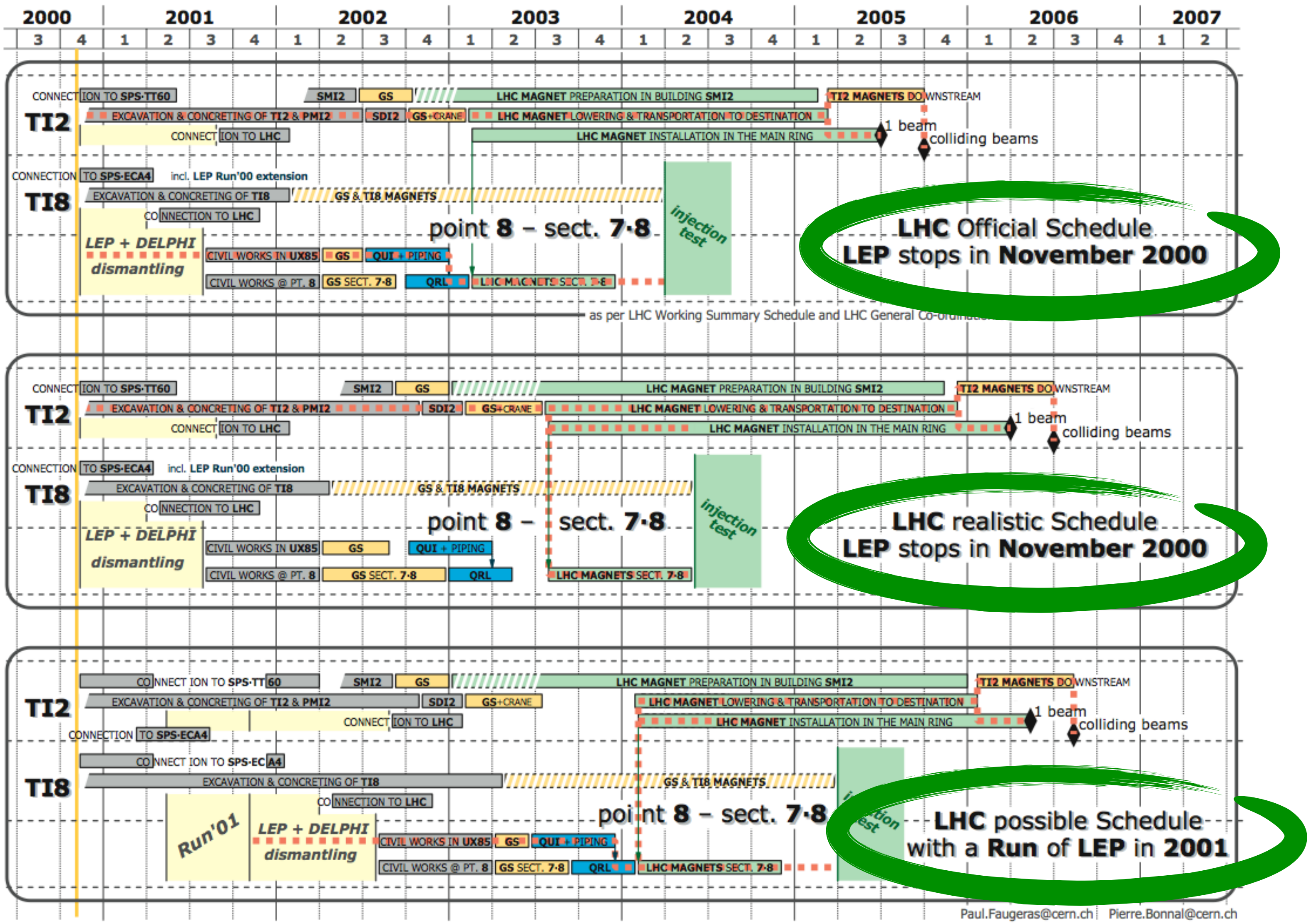
Time scales, project phases and schedule delays

LHC Schedule in 1990



Time scales, project phases and schedule delays

LHC Schedule in 2000



Time scales, project phases and schedule delays

ATLAS/CMS main construction milestones (delivery to CERN), status 2006

	ATLAS		CMS	
Detector system	**TDR**	**Actual**	**TDR**	**Actual**
Pixels	06/03	03/07	03/05	12/07
Silicon microstrips (barrel)	12/02	07/05	03/04	10/06
Silicon microstrips (end caps)	12/02	06/06	03/04	10/06
Transition radiation tracker	03/04	12/05		
Electromagnetic calorimeter (barrel)	06/03	07/04	12/03	03/07
Electromagnetic calorimeter (end caps)	01/04	09/05	06/04	03/08
Hadronic calorimeter	12/02	02/04	12/03	12/04
Muon chambers	12/04	12/05	12/03	06/06
Solenoid magnet	01/02	09/01	03/03	12/05
Barrel toroid magnet	06/02	06/05		
End-cap toroid magnet	12/03	11/06		

Shown are the milestone dates for the delivery of major components to CERN, as planned in the Technical Design Reports (TDR), and the actual or future planned delivery of milestones.

From Daniel Froidevaux and Paris Sphicas, General Purpose Detectors for the Large Hadron Collider, Annu. Rev. Nucl. Part. Sci. 2006

If there has been one lesson learned: research and development phase of projects this complex is impossible to plan!

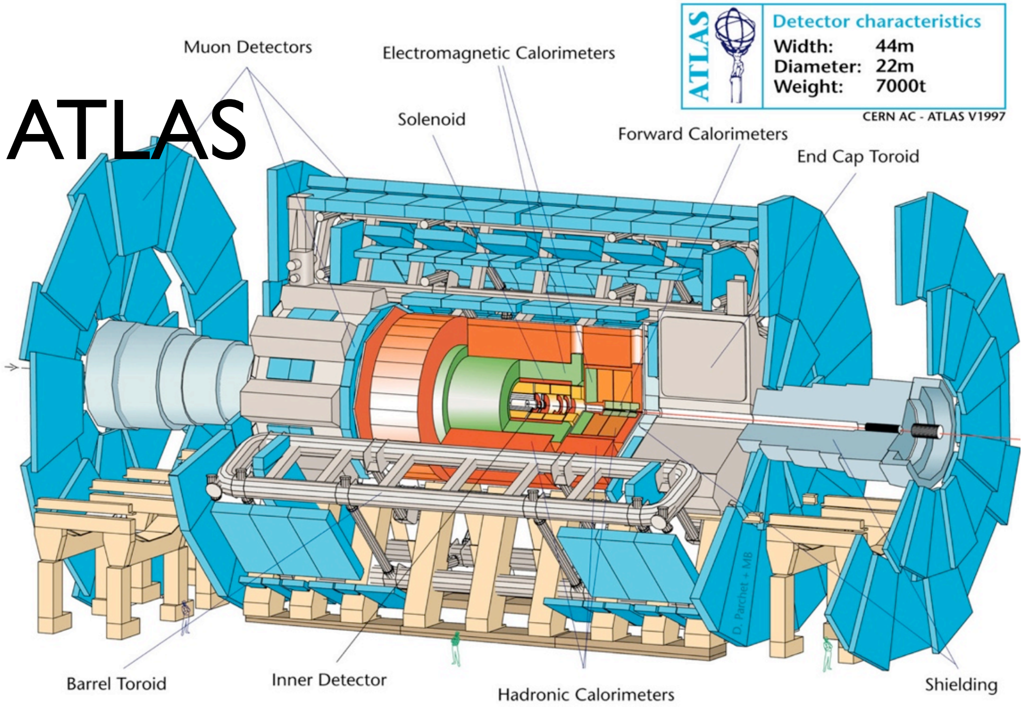
→ vigilant monitoring and flexibility mandatory!

Detector Concepts

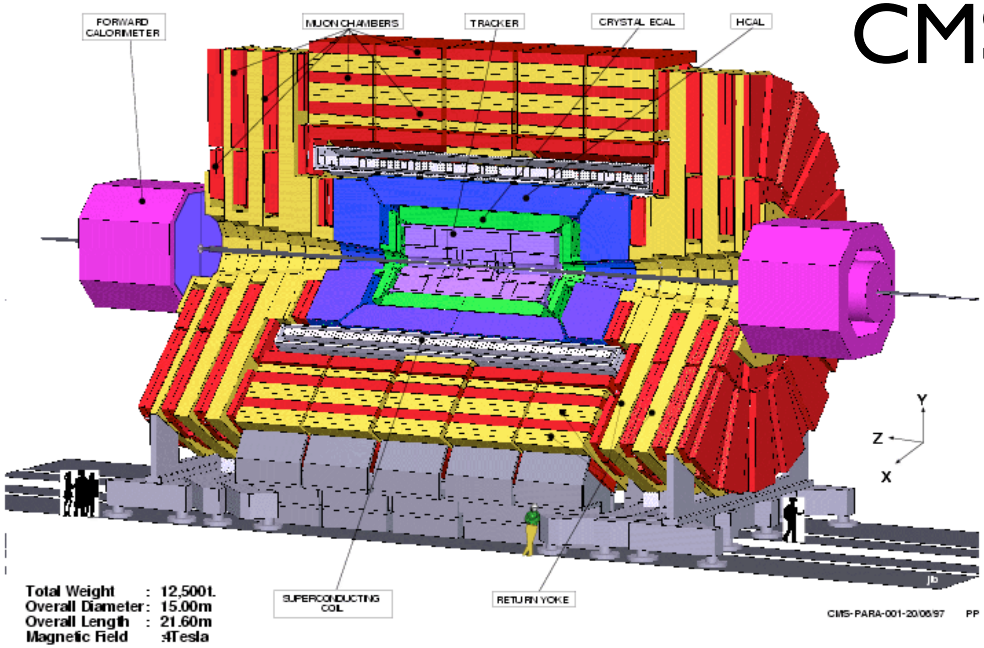
The ATLAS and CMS experiments are designed somewhat as cylindrical onions consisting of

1. an innermost layer devoted to the inner trackers, bathed in a solenoidal magnetic field and measuring the directions and momenta of all possible charged particles emerging from the interaction vertex;
2. an intermediate layer of EM and hadronic calorimeters absorbing and measuring the energies of electrons, photons, and hadrons; and
3. an outer layer dedicated to the measurement of the directions and momenta of high-energy muons escaping from the calorimeters.

ATLAS



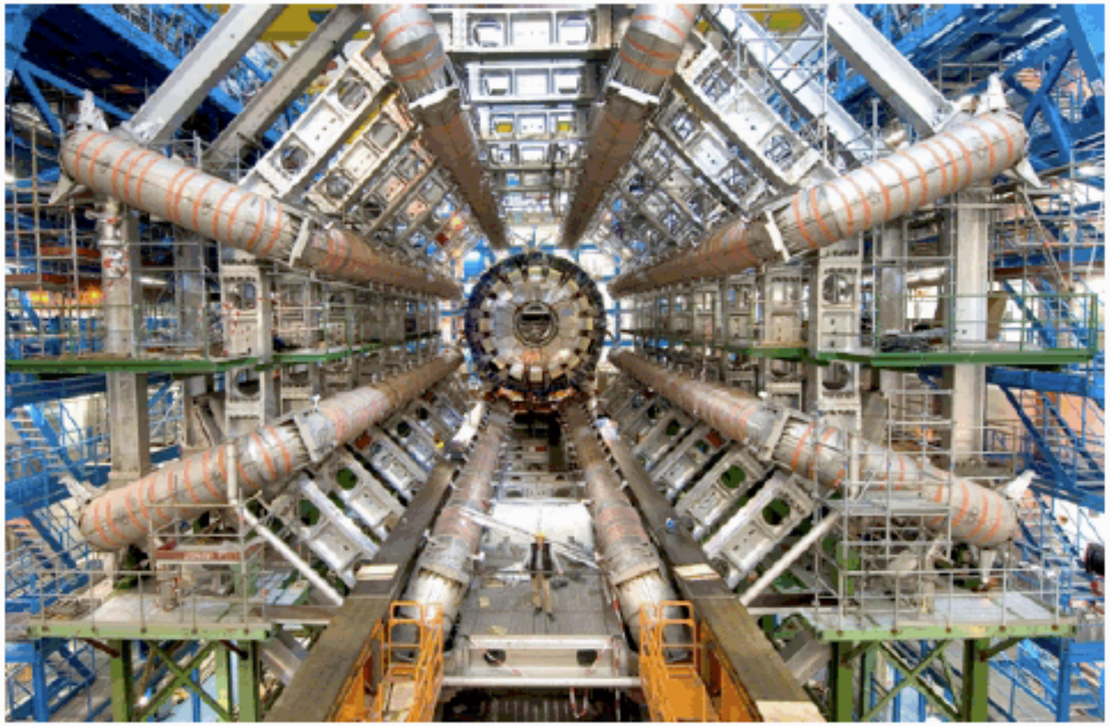
CMS

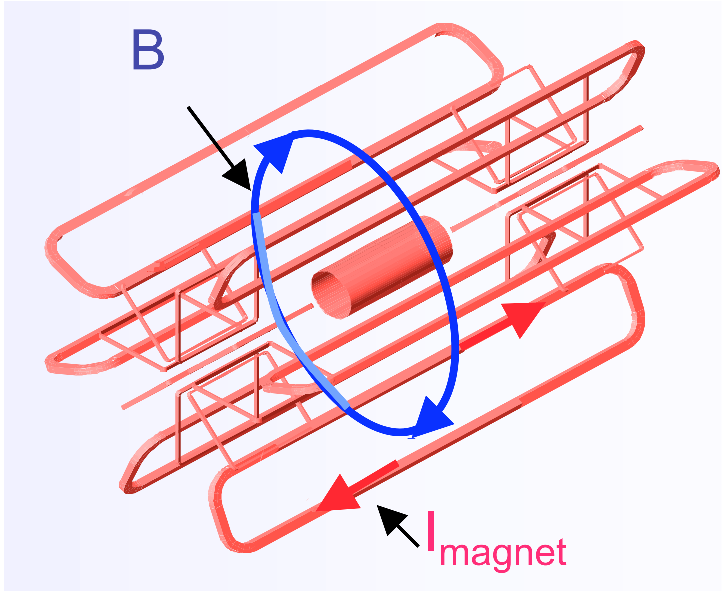


Don't forget: multi purpose detectors are difficult to build!

- A HEP detector: very much like an "eierlegende Wollmilchsau"

Magnet concept: ATLAS ➡ toroid

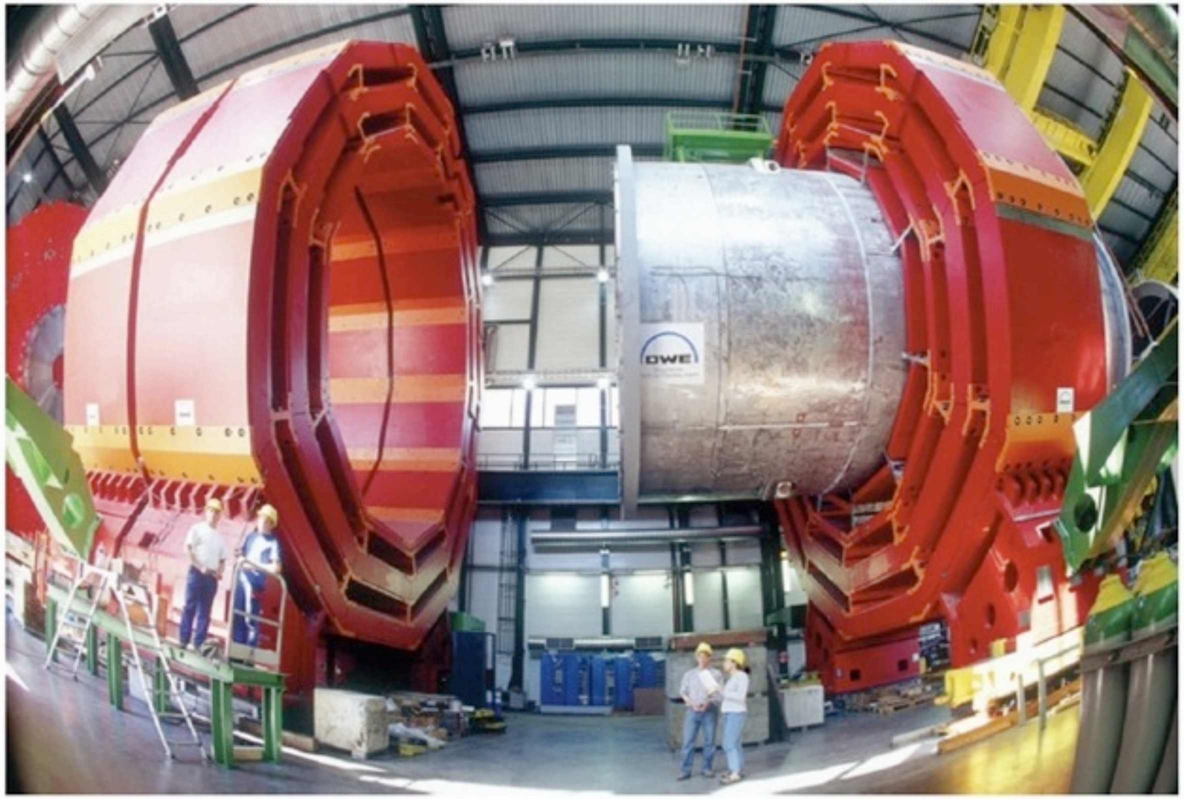


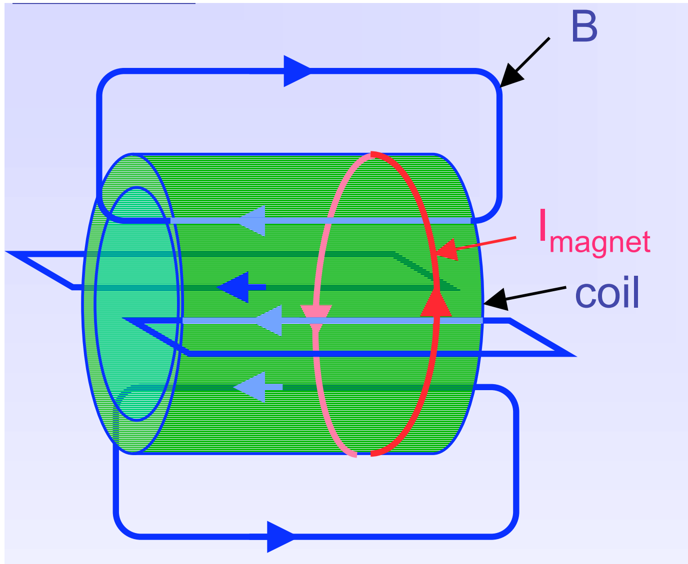


- Central Toroid field within Muon-System: 4 T
  - Closed field, no yoke
  - Complex field
- 2 T Solenoid-field for trackers

+ field always perpendicular to p_T
+ relative large field over large volume
- non uniform field
- complex structure

Magnet concept: CMS ➡ one solenoid

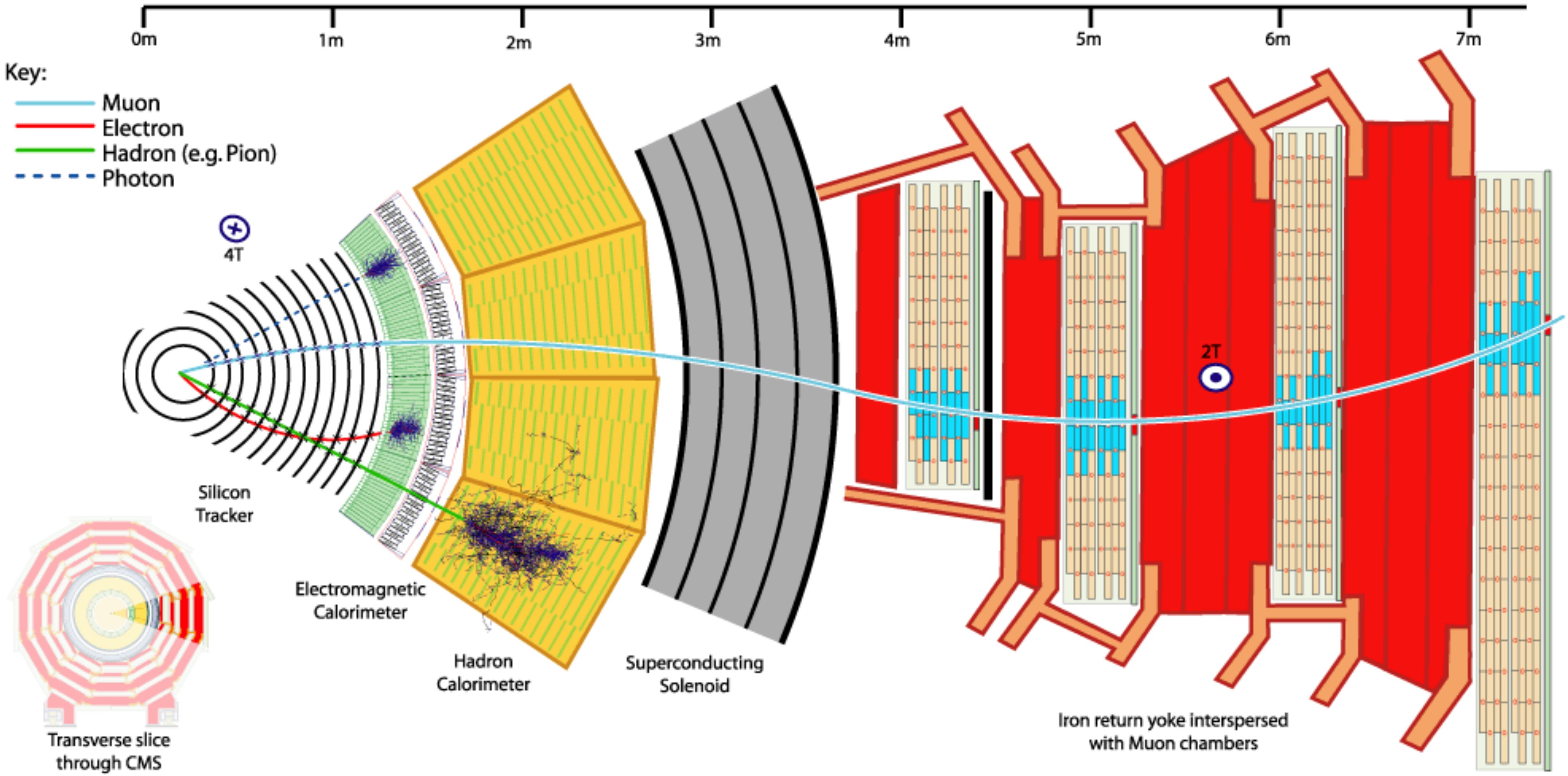




- Largest Solenoid in the world:
  - superconducting, 4 T field
  - encloses trackers and calorimeter
  - 13 m long, inner radius 5.9 m, I = 20 kA, weight of coil: 220 t

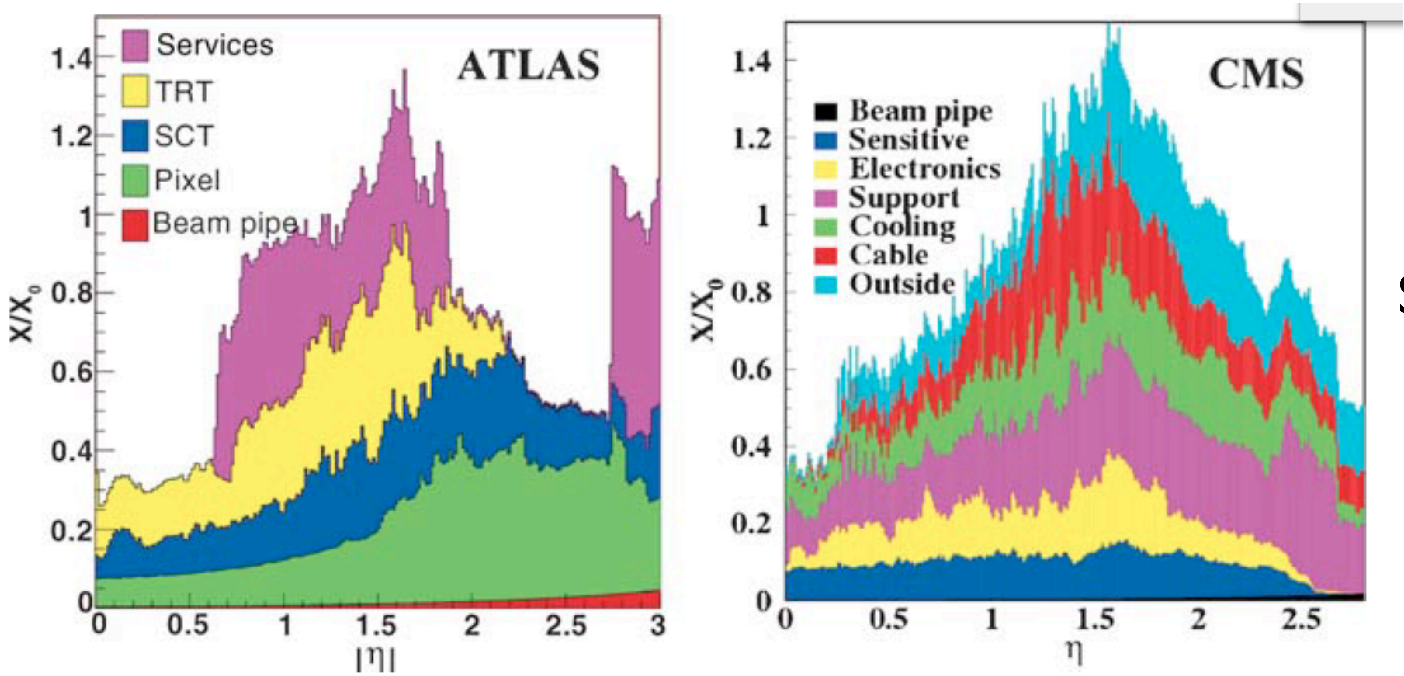
+ large homogeneous field inside coil
+ weak opposite field in return yoke
- size limited (cost)
- relative high material budget

CMS - an overview



Material distribution

Distribution of amount of material in the volume of the ATLAS (left) and CMS (right) trackers, expressed as fractional radiation length X/X0 versus pseudorapidity.



Status 2006

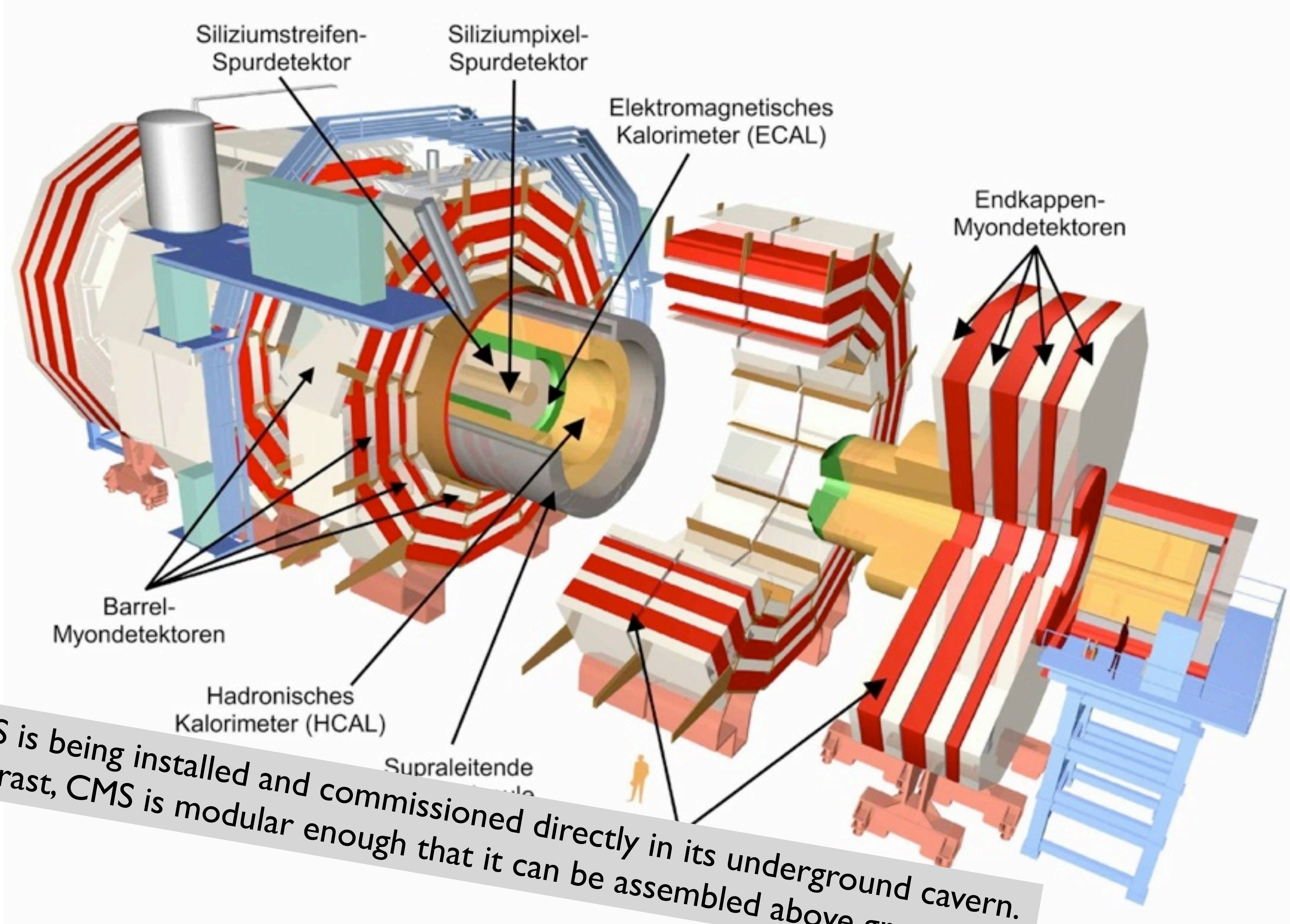
Date	ATLAS $\eta \approx 0$	ATLAS $\eta \approx 1.7$	CMS $\eta \approx 0$	CMS $\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50

Evolution of the amount of material expected

From Daniel Froidevaux and Paris Sphicas, General Purpose Detectors for the Large Hadron Collider, Annu. Rev. Nucl. Part. Sci. 2006

Excellent description of material is mandatory!
→ record position/weight/material of every part during construction!

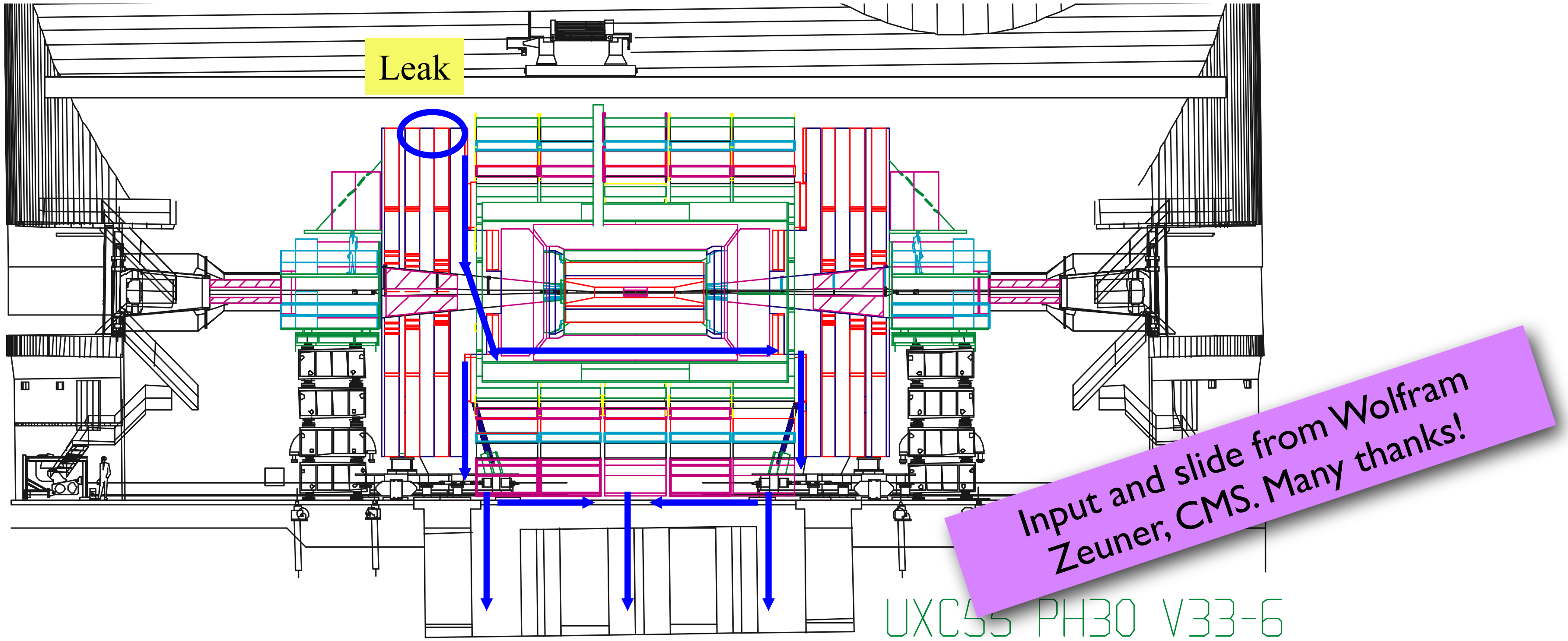
CMS - a few pieces only...



ATLAS is being installed and commissioned directly in its underground cavern.
In contrast, CMS is modular enough that it can be assembled above ground.

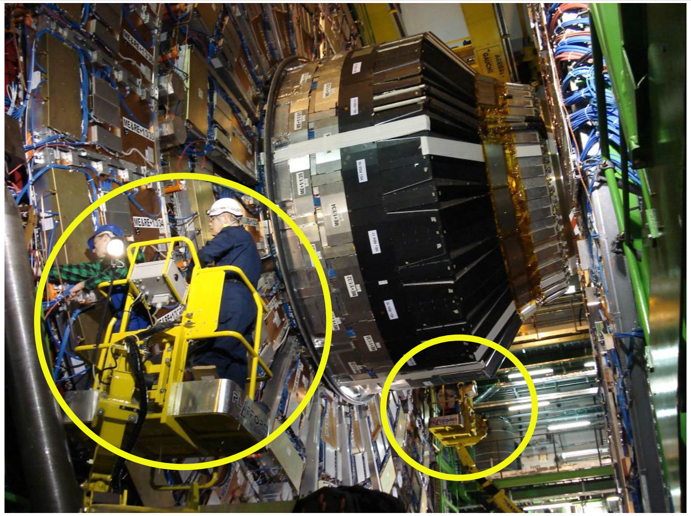
CMS: advantage of having fast access

- Incident 9 October 2009
- A flow restrictor bushing of a muon endcap cooling circuit broke causing severe flooding of CMS;
- About 400 of these bushings were used in CMS endcaps, 2/3 of them not accessible from outside;
- Strong indication that others could fail as well - stress corrosion;
- Repair required opening all endcap disks;
- After 4 days of dry-out, CMS continued running until December.

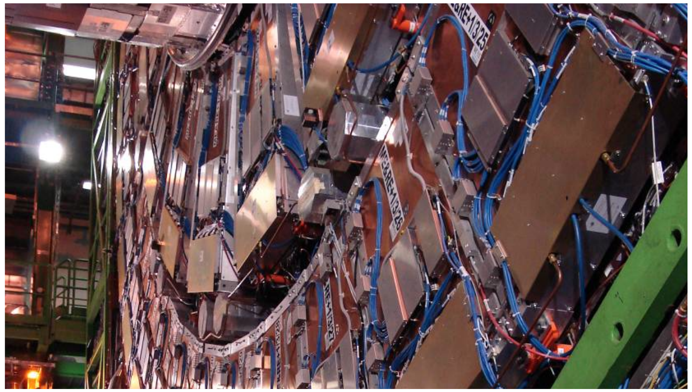


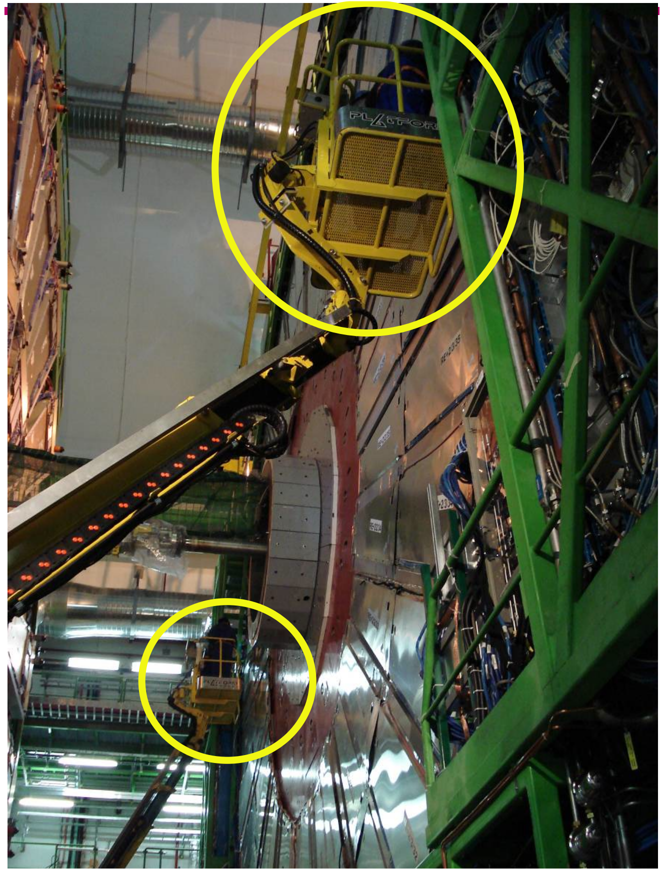
Expected Substantial Collateral Damage – Very Little Found!

High speed repair 5. Dec. 2009 - 22. Feb. 2010



- All endcap discs opened;
- 396 bushings exchanged;
- All circuits tested;
- Detector closed...
- ...and everything worked!



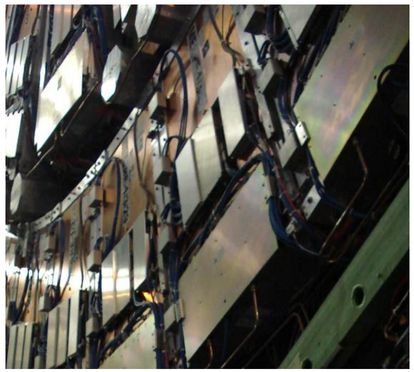


LHCC refs Feb 2010 AB

Approximate Milestones (Dec 16)

Input and slide from Wolfram Zeuner, CMS. Many thanks!

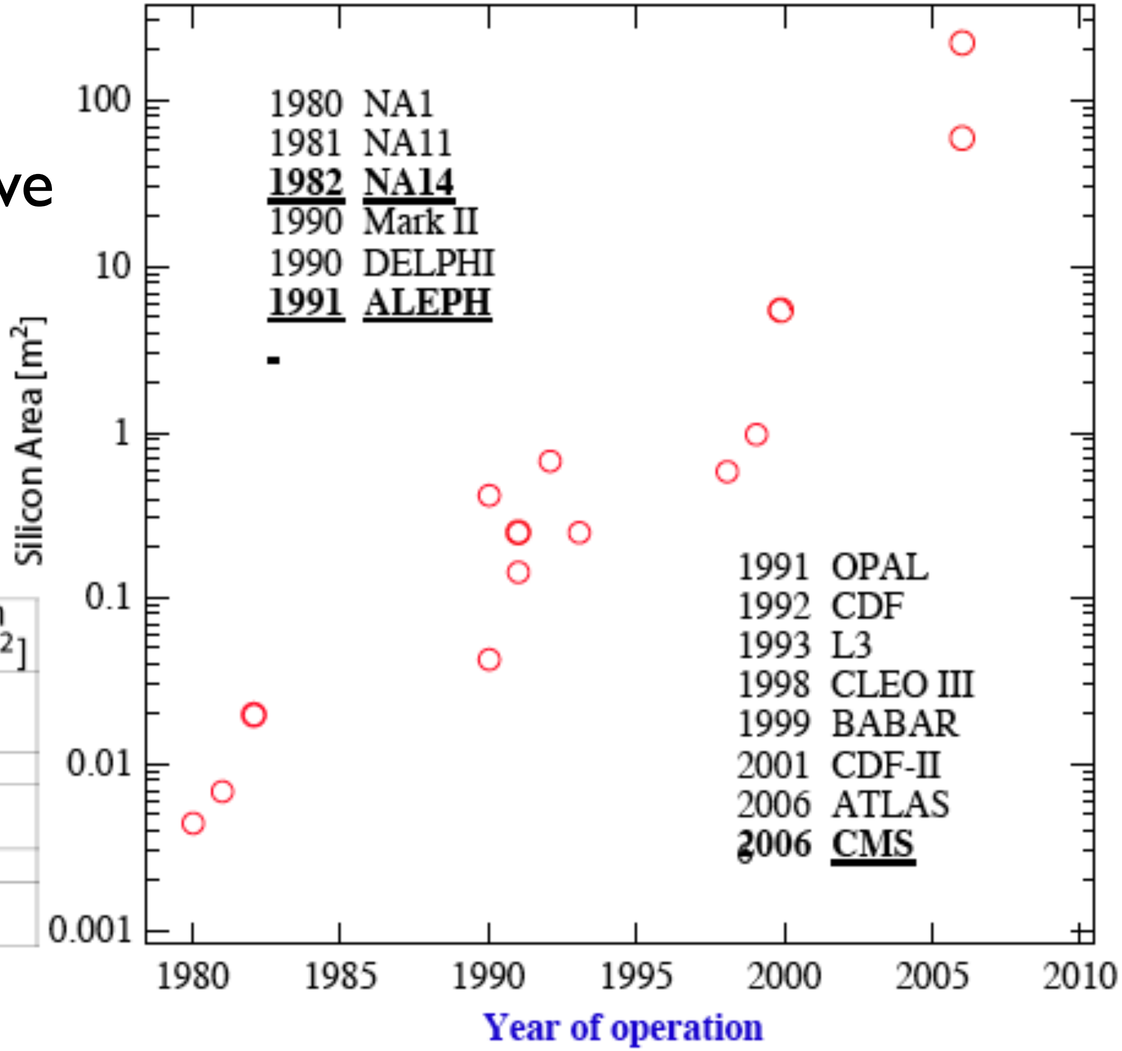
done 4 Jan	06 Jan: both HF's in garage, -z (5-6) endcap opening in prog
done 8 Jan	13 Jan: YE-1 repair underway
done 18 Jan	20 Jan: YE-1 repair complete
done 22 Jan	27 Jan: -z (5-6) endcap closed, YE+1 repair complete
done 29 Jan	03 Feb: HF- at beam height, +z (4-5) endcap closed
done 05 Feb	10 Feb: -z shielding closed, + end HF+ at beam height
started 06 Feb	15 Feb : beampipe pumpdown underway
	22 Feb: ready for beam! Estimate 22 Feb



Trackers...

In 1987, even the physicists thought that only a muon spectrometer behind an iron dump was guaranteed to survive the irradiation and that most tracking technologies were doomed at the highest luminosities of the LHC!

experiment	nb. of detectors	nb. of channels	silicon area [m^2]
CMS	15.95 k	10×10^6	223
ATLAS	16.0/2 k	6.15×10^6	60
AMS 2	2.3 k	196 k	6.5
DO 2		793 k	4.7
CDF SVX II	720	405 k	1.9
Babar		140 k	0.95
Aleph	144	95 k	0.49
L3	96	86 k	0.23



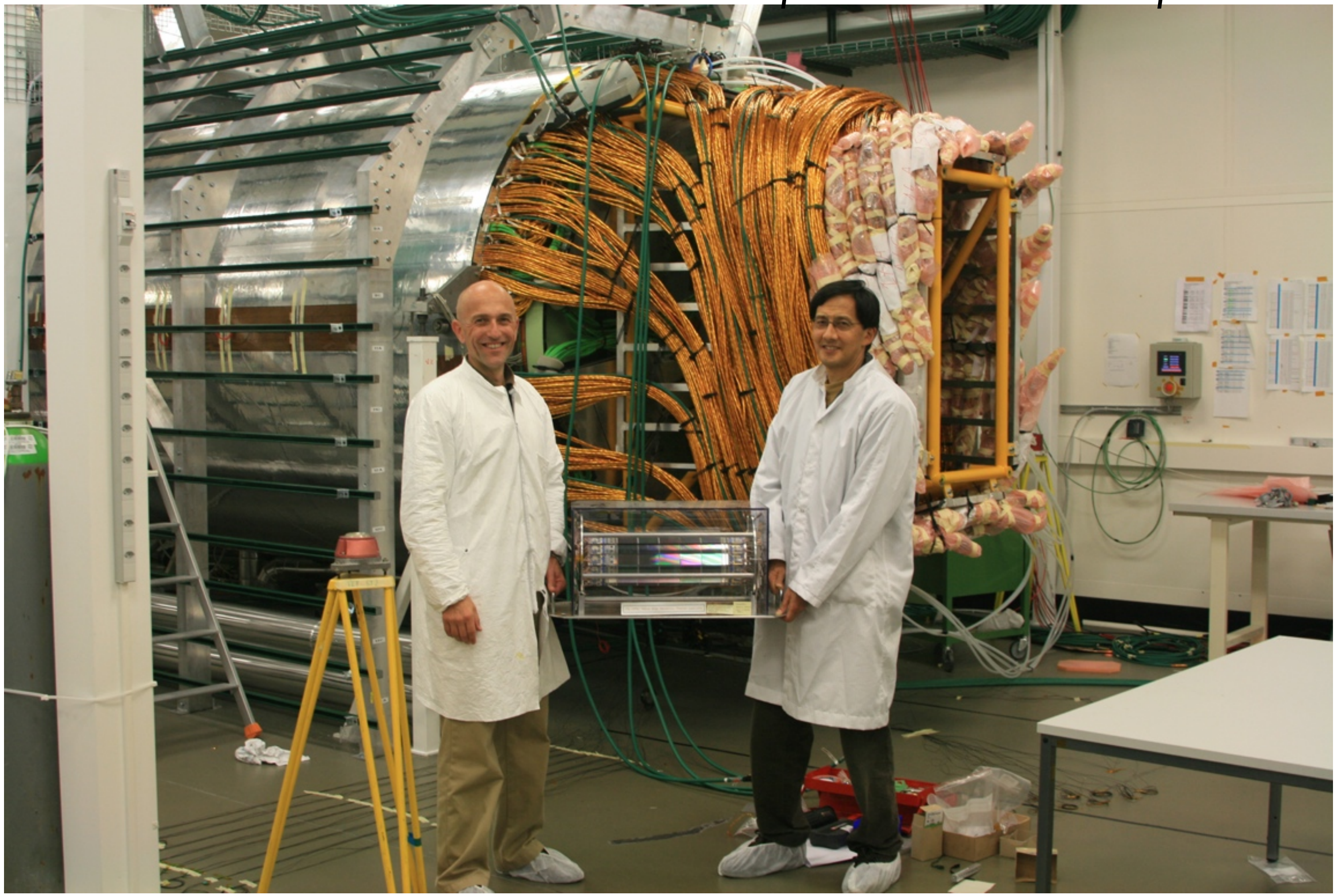
Choice: semiconductor detectors

CMS: Building > 15’000 SI strip modules with high precision, in short time scale and tight budget!

- CMS outer tracker: difficult choice between strips and MSGCs;
- decision was finally based on
  - ➡ drop in price per unit area of silicon sensors (progress in industry) and
  - ➡ robotic module assembly system **“The Gantry”** → order magnitude increase in number of produced modules.

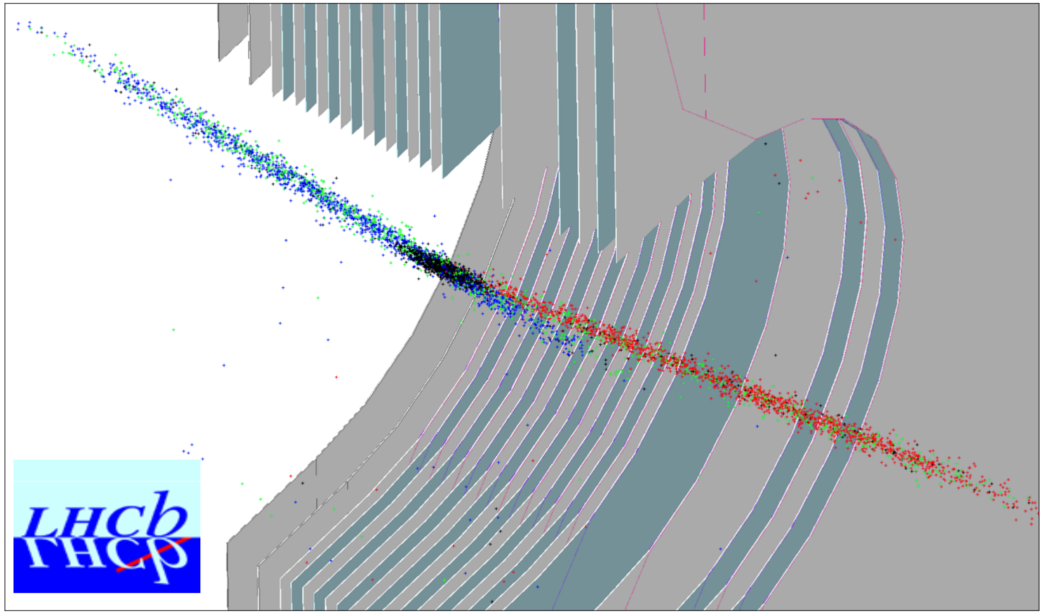
A personal highlight (and miracle of the LHC)
from Alan Honma, CMS.
Many thanks!

OPAL silicon strip detector vs. CMS strip detector



LHCb Velo - measuring the LHC luminosity

Massimiliano Ferro-Luzzi (LHCb, LHC Programme Coordinator up to 2011):
"It was very gratifying to see the beam-gas imaging method being realized in stages (first with pure residual gas in the VELO, then with ion pumps turned off ... i.e. a bit more gas, then with a gas injection system), and showing its full potential in 2012."



Many thanks to the LHCb Collaboration and Colin Barschel

LHCb event display:
Beam-gas interaction vertices.
The vertex colors green, blue, red and black denote interaction vertices in empty, beam 1, beam 2 and beam-beam crossing types.
(The longitudinal z-axis along the nominal beam-line is compressed by a factor 100 for a better visualization.
The sensors of the vertex detector are visible in alternating colors. Only the one half of the detector is shown.)

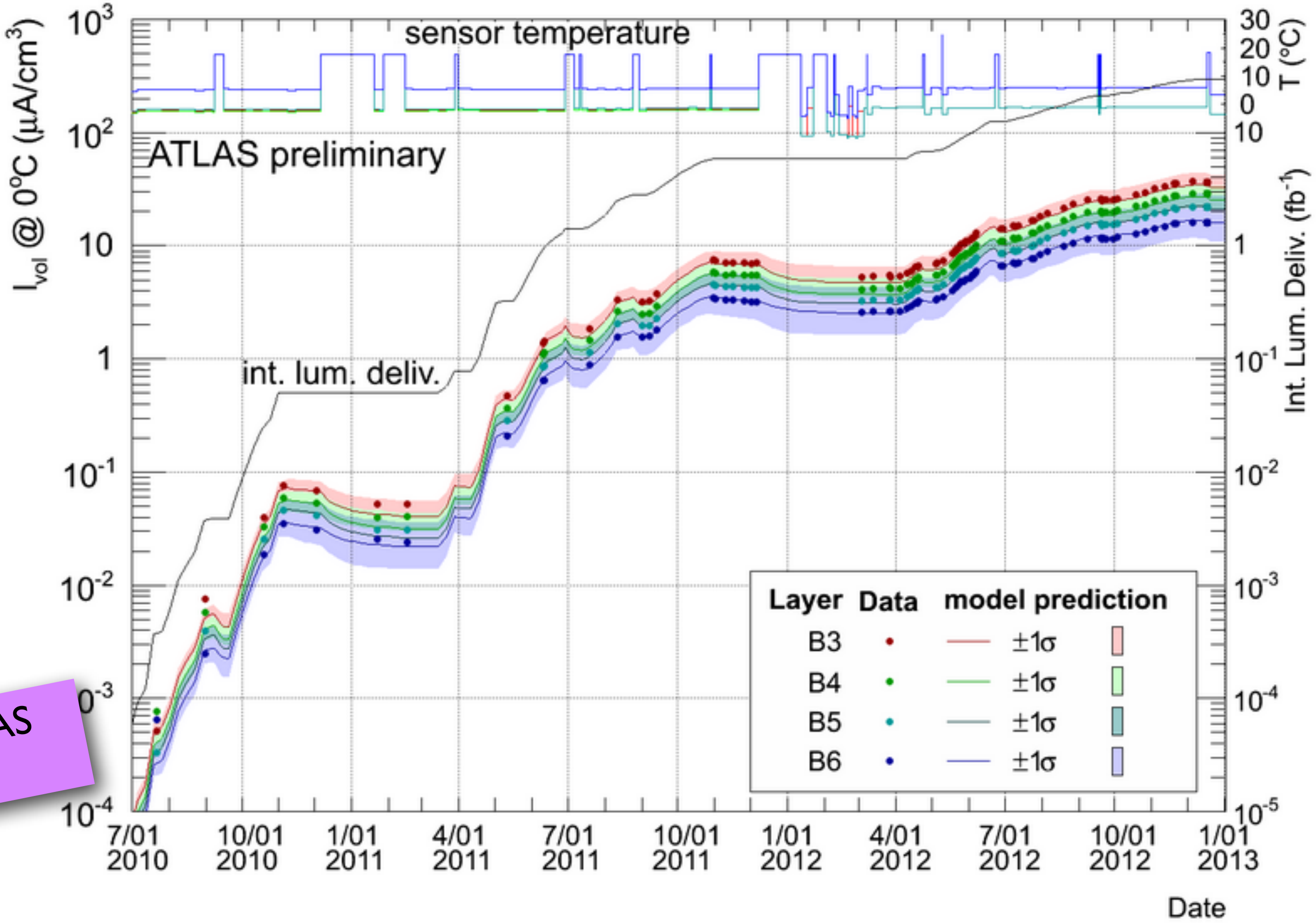
Input from Massimiliano Ferro-Luzzi, LHCb. Many thanks!

LHCb: integrated luminosity uncertainty of 3.5%, based on 2010 data;
improvements on resolution measurements and larger number of interactions gained with gas injection will allow to reach an absolute uncertainty of about 2% with the beam-gas method alone with 2012 data.

The ATLAS Inner Detector - Wow things

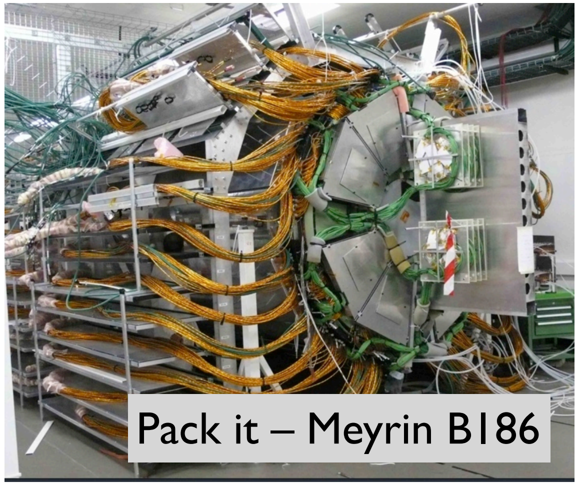
- The fact that we had the triple combination of: high detector up time (>99%), large fraction of the detector operational (>95% in all cases) and that the detectors all behaved in ways that we expected!

Example: increase in leakage current due to radiation over the 3 year period of from 2010 to 2013.
dots = measurements
line = prediction.
The different lines are for measurements made at different radii.



Slide from Steve McMahon, ATLAS
Many thanks!

Transport and installation of the CMS Tracker - as smooth as a dream!



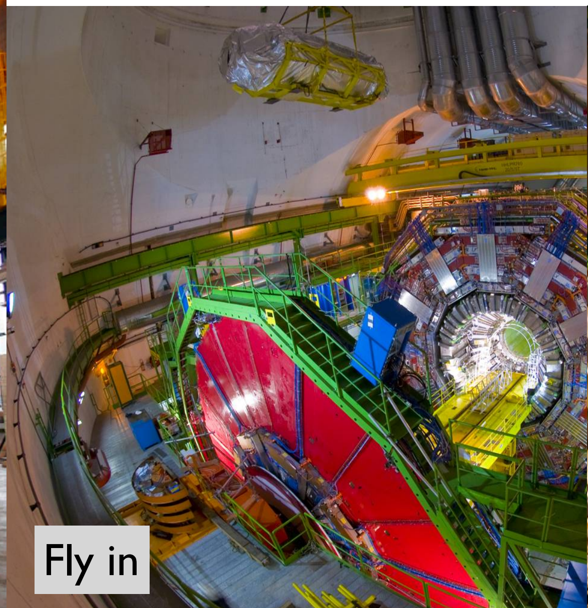
Pack it – Meyrin B186

Bag it

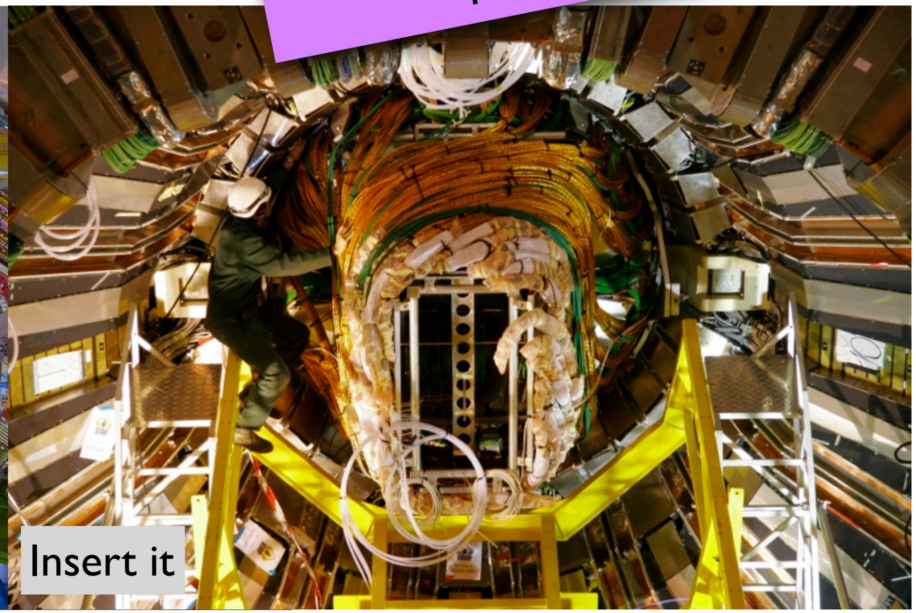
Move it

Slide from Frank Hartmann, CMS
Many thanks!

Down



Fly in



Insert it

Carefulness has been rewarded!

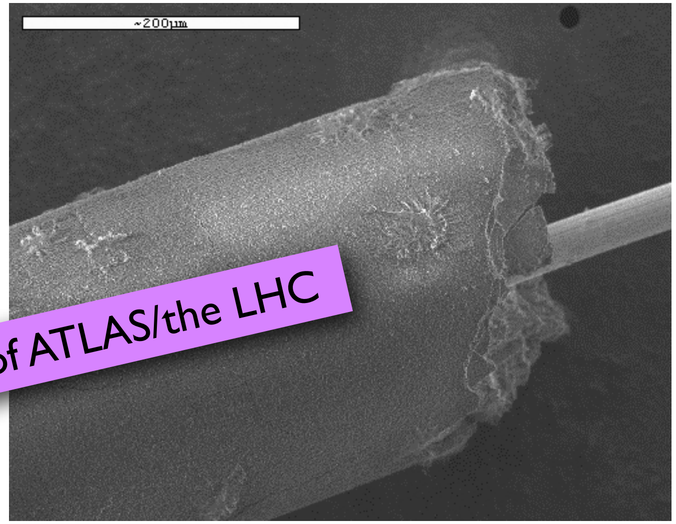
Tracker/ID: Things that went wrong

- **Steve McMahon (ATLAS):**
  The various failures of the **evaporative cooling system**
  - ➡ Burn out of bearing on compressors for evaporative system. We lost months as the system was dismantled, cleaned and rebuilt.
  - ➡ Failures of the heaters of the evaporative system where we lost 1 year in installation while we worked to understand the failures, find a fix an rebuilt.
- **Frank Hartmann (CMS):**
  … It's always the low tech: **Cooling and insulation**
  - ➡ CMS Tracker operated at higher temperatures as designed for in the first years
  - ➡ We exchange brine solution with C6F14 in the primary circuit to be robust against leaks in heat exchanger
    - Since we had a break in the heat exchanger in the early days
    - Reduce cooling capacity initially – improvement done early LS1
  - ➡ Vapour barrier at interfaces not optimal thus humidity higher than expected preventing TK from going cold
    - Only the interface – the RH in the detector is perfectly low
  - ➡ Ongoing campaign during LS1 to fix it and run at design temperature or lower after LS1.
    (In the end not critical since we did not accumulate enough radiation damage to be affected by reverse annealing; rad. induced leakage current even decreased)

"Plumbing" is a problem for many detector systems at the LHC!!

ATLAS TRT: bad surprise during assembly

- Original TRT gas mixture (70% Xe, 20% **CF_4**, 10% CO_2) was destroying the detector (2002)
  - ➡ glass wire joints of barrel TRT “melting” with radiation 0.3-04 C/cm, less than 1 year nominal LHC operation
  - ➡ Reason: hydrofluoric acid HF



One of CRs personal nightmares of ATLAS/the LHC

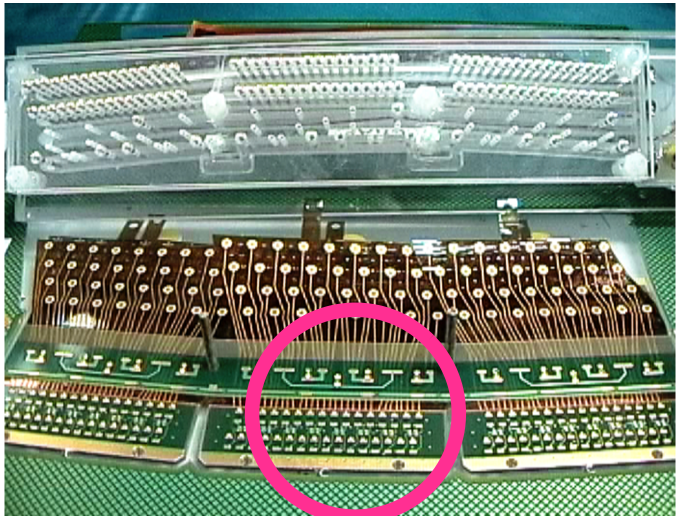
- Within one year, a new mixture was developed 70% Xe, 27% CO_2, 3% **O_2**
  - ➡ O_2 very unusual, strong quencher (“eats” electrons)
  - ➡ only works for TRT as straws have small diameter (we are very lucky!)

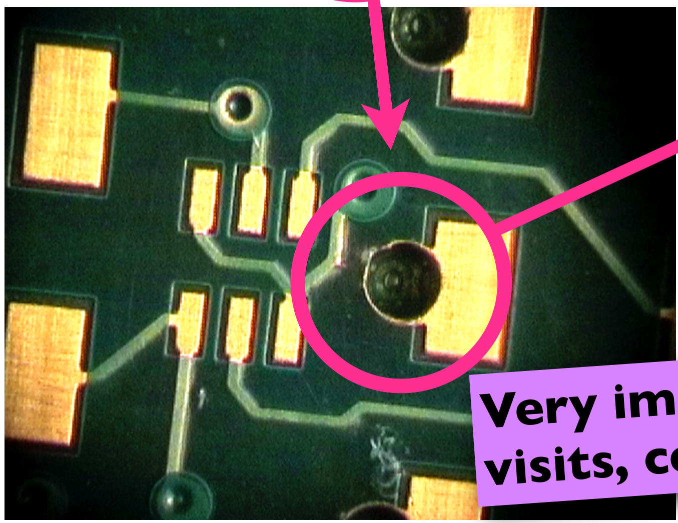
Wheel end-cap boards (WEBs)

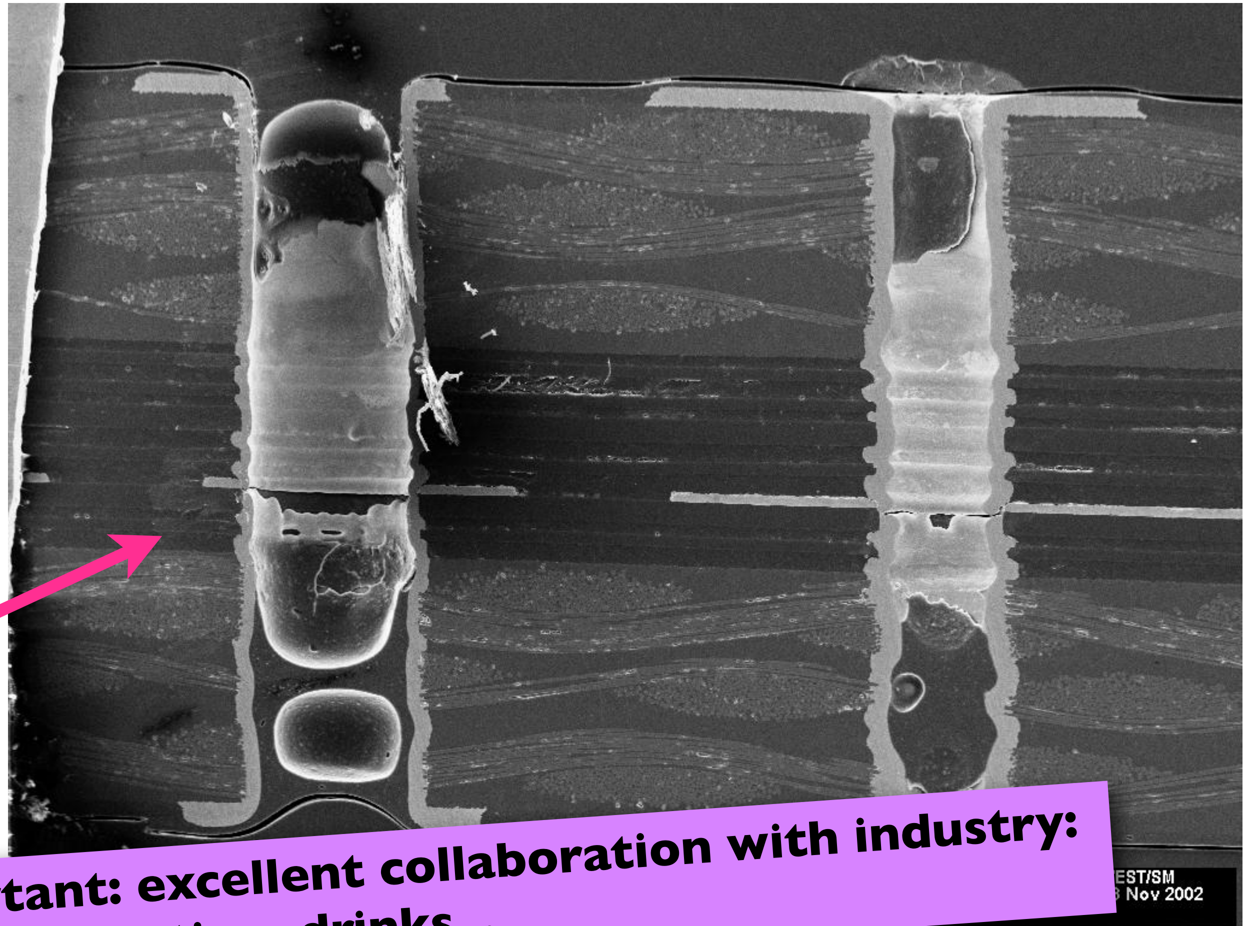
WEBs: connecting straws to HV, read-out and main mechanical structure of end-caps

My very personal fight…

- E.g. broken vias in printed circuit boards (diameter 150μm)



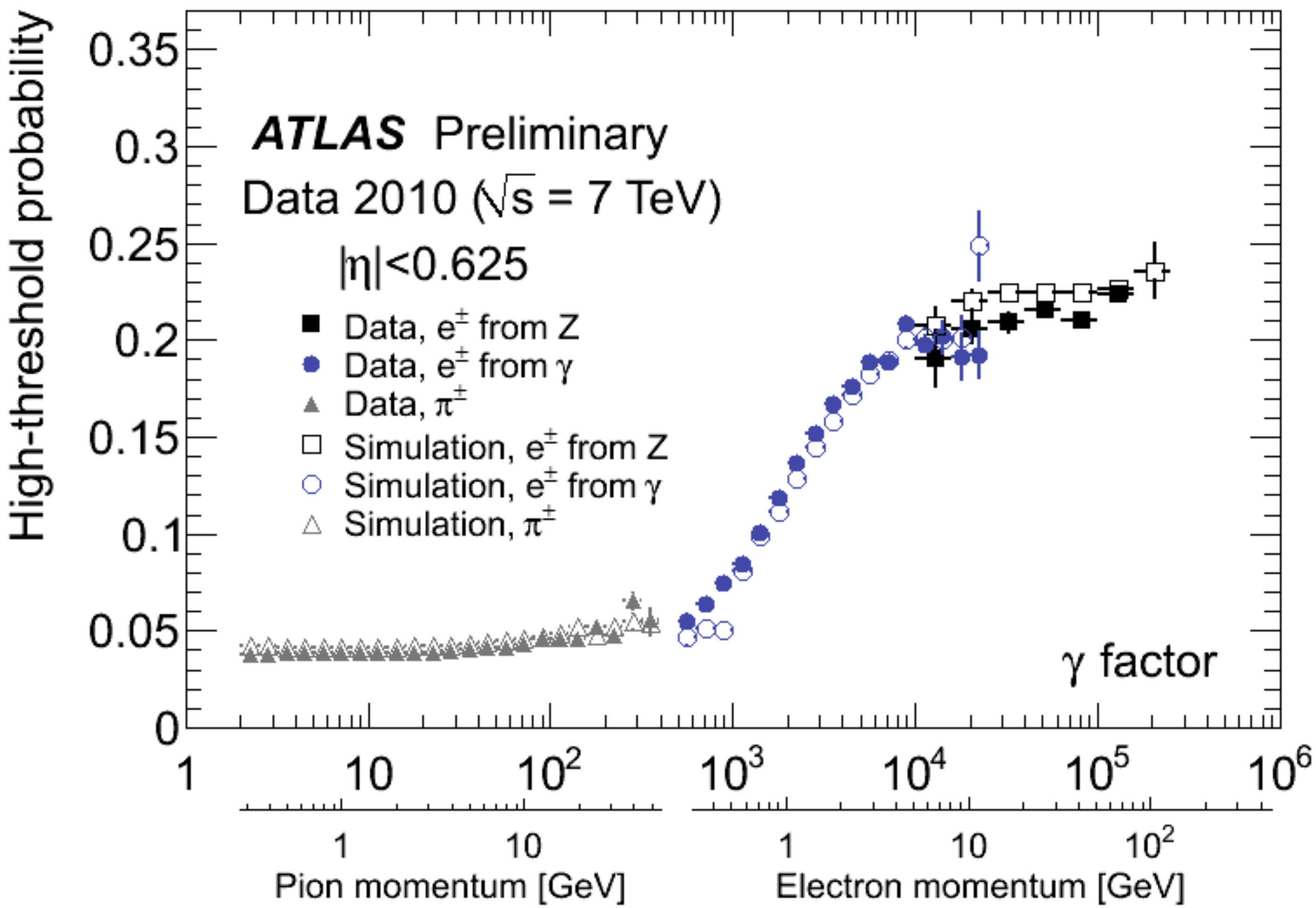




Very important: excellent collaboration with industry: visits, communication, drinks...

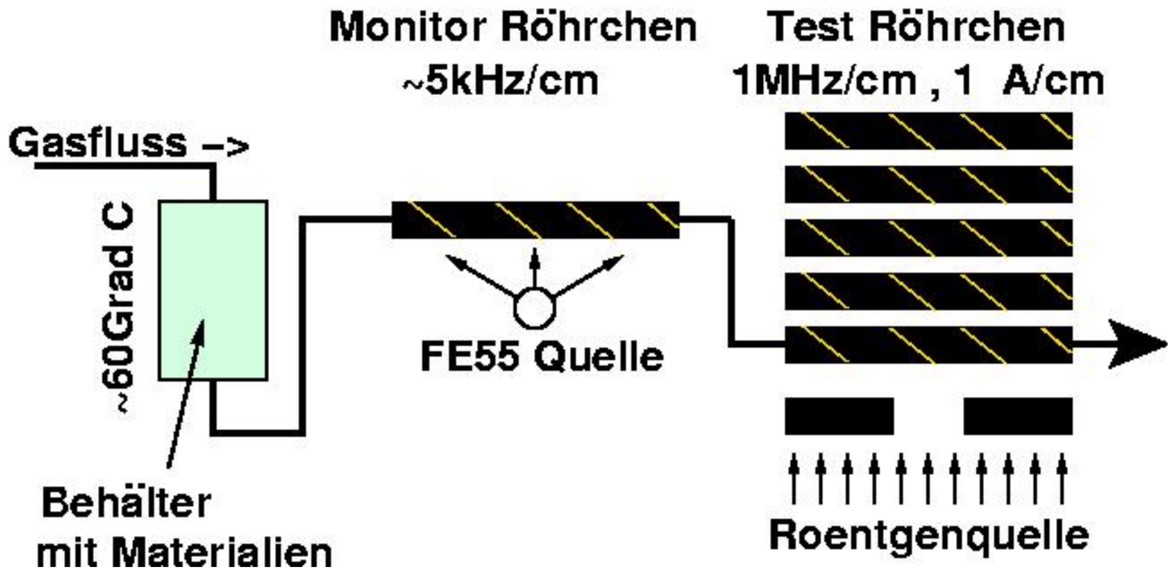
ATLAS TRT: happily operating...

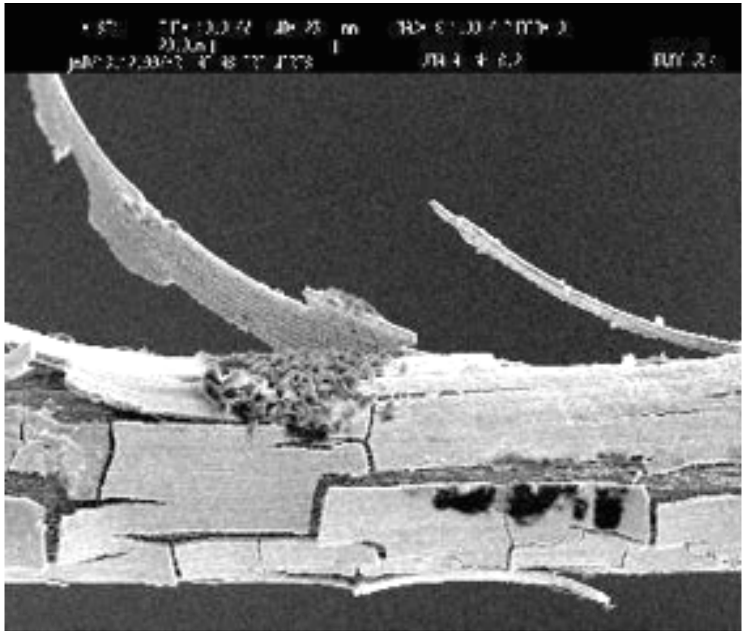
- Excellent performance in environment with high particle densities (>30% of all electronics channels have a hit per bunch crossing);
- Predicted resolution reached (even surpasses design values, reaching <100µm in barrel regions with 120µm design);
- Particle identification works;



Example: turn-on of transition radiation

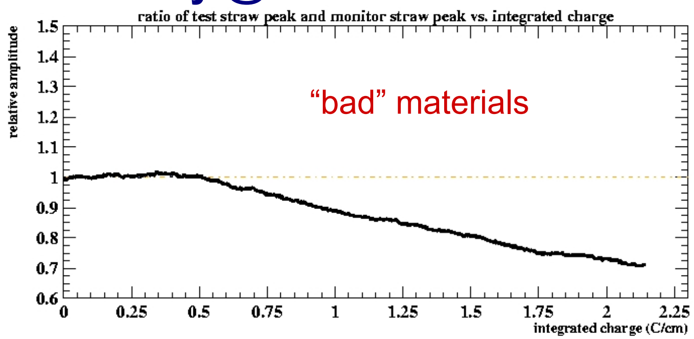
Don’t forget: do systematic tests of all materials used…

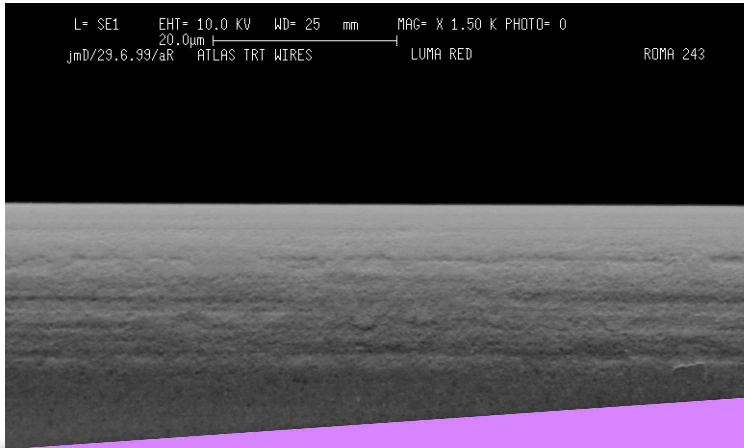


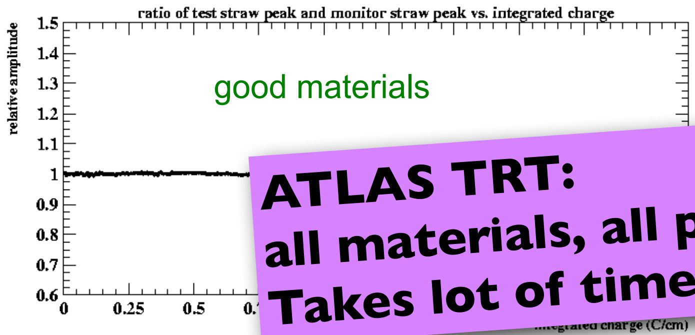


E.g.: signal wires, tested for 10y @ LHC

Comparison of monitor and test straw:







ATLAS TRT:
all materials, all parts, all equipment is validated!
Takes lot of time… and for sure you miss something…

Don't forget: do systematic tests of all materials used…

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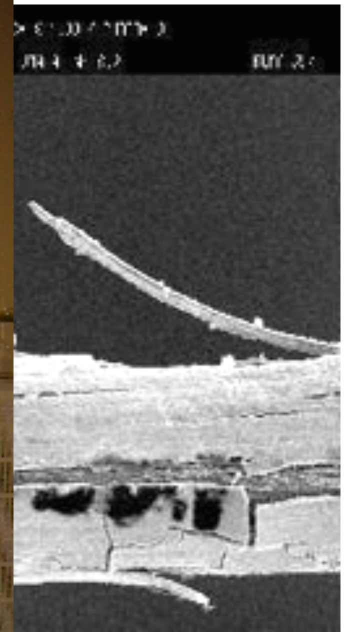
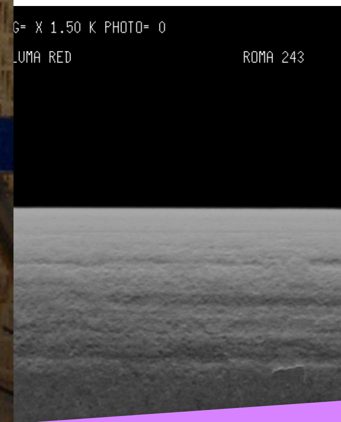
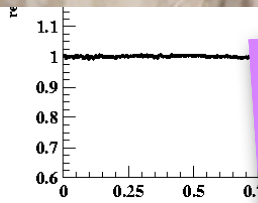


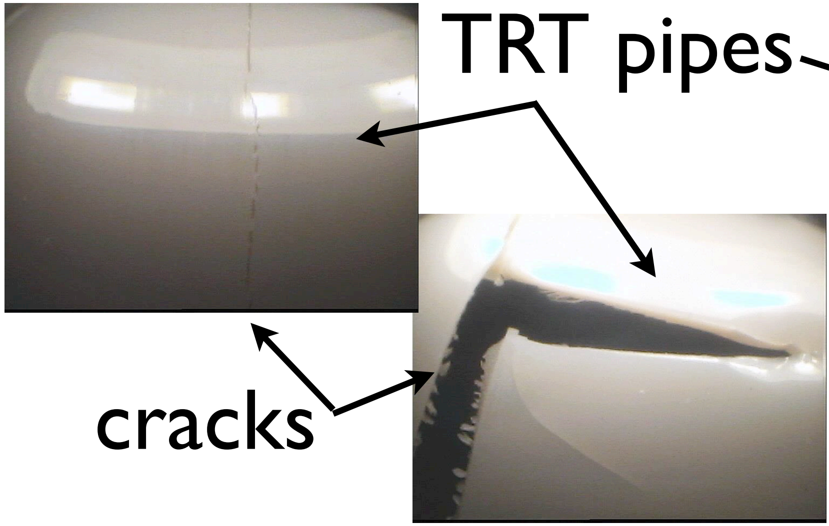




ATLAS TRT:
all materials, all parts, all equipment is validated!
Takes lot of time... and for sure you miss something...

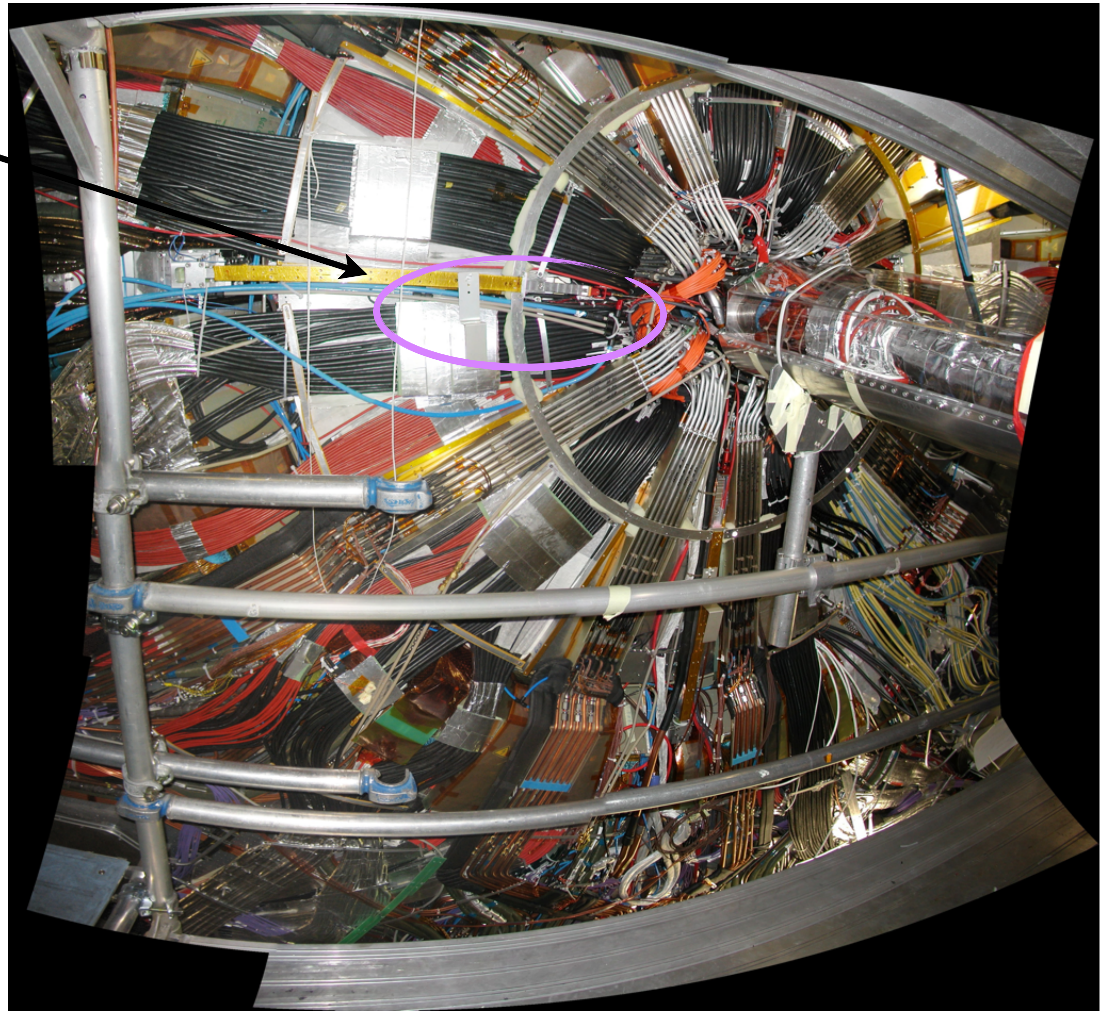
BUT...

- Cracks in outlet pipes of active gas developed in 2012
  - ➡ gas losses: 150l/day instead of <0.5l/day up to 2011;
  - ➡ reason: aggressive ozone produced when active gas mixture is radiated, ozone attacks plastic gas pipes (although plastic material has been validated - but material seem to have changed properties when being heated and bent....)
  - ➡ hope to fix leaks during LS1...



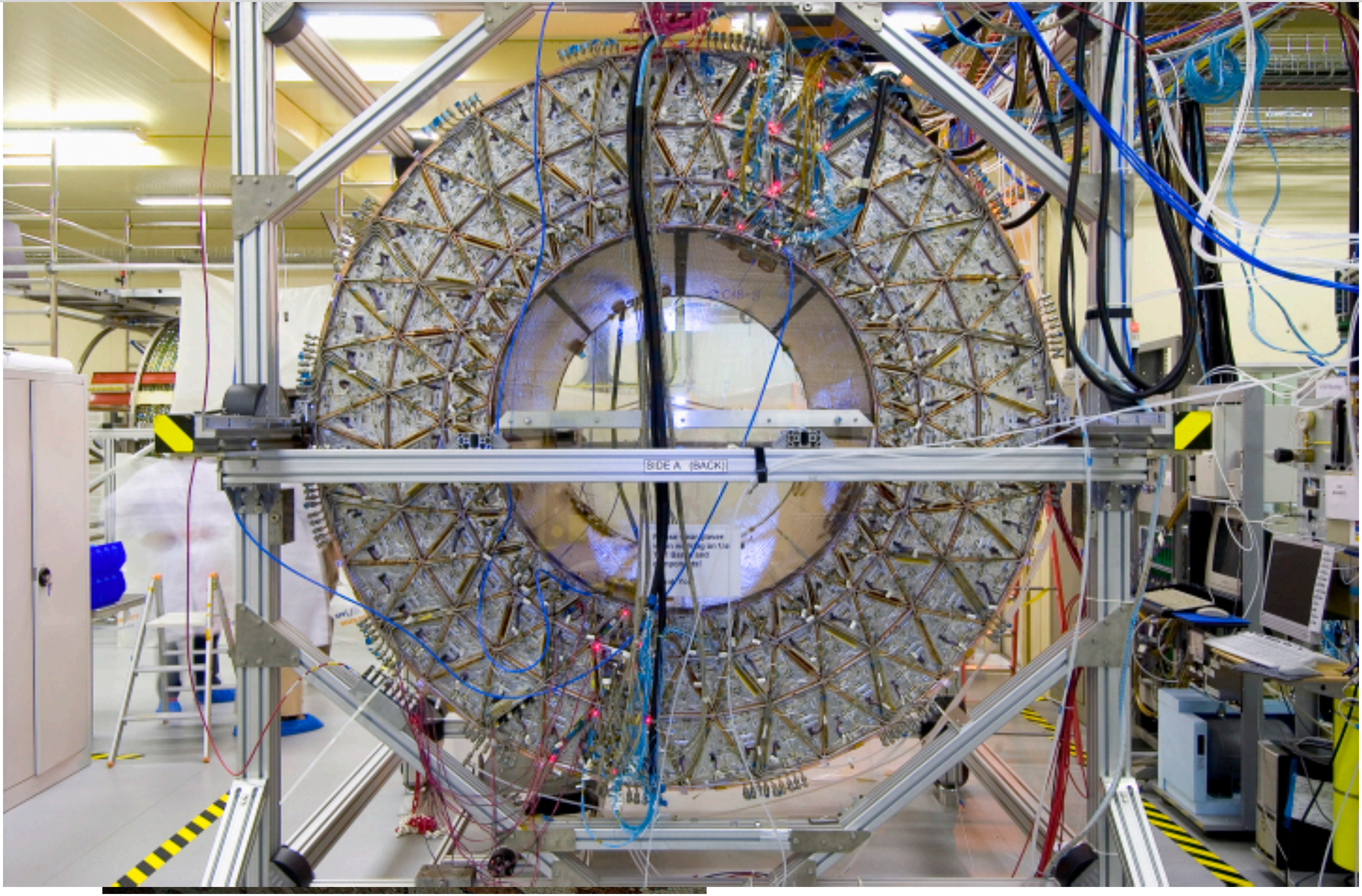
TRT pipes

cracks



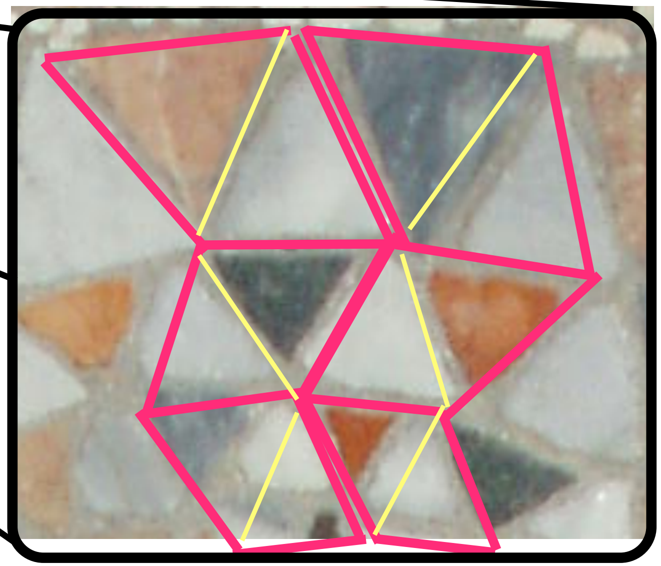
Difficult to access!!!
Might be necessary to switch to cheaper Ar based gas mixture in the future.

The ATLAS TRT: inspired by a historical design?



The ATLAS TRT: inspired by a historical design?

- ATLAS - a 12th century mosaic in the Otranto cathedral in Italy



N.B.: "Original" TRT design has foreseen 4 layers but no silicon detectors;

The ATLAS LAr Calorimeter

The Liquid Argon Calorimeter is built from Lead/Copper/Tungsten immersed in Liquid Argon at -183 degrees Celsius.

It comprises 182468 channels.

It measures the energy, the position and the time of arrival of the impinging particles with a precision of 1%, 500µm and 100 picosecond.

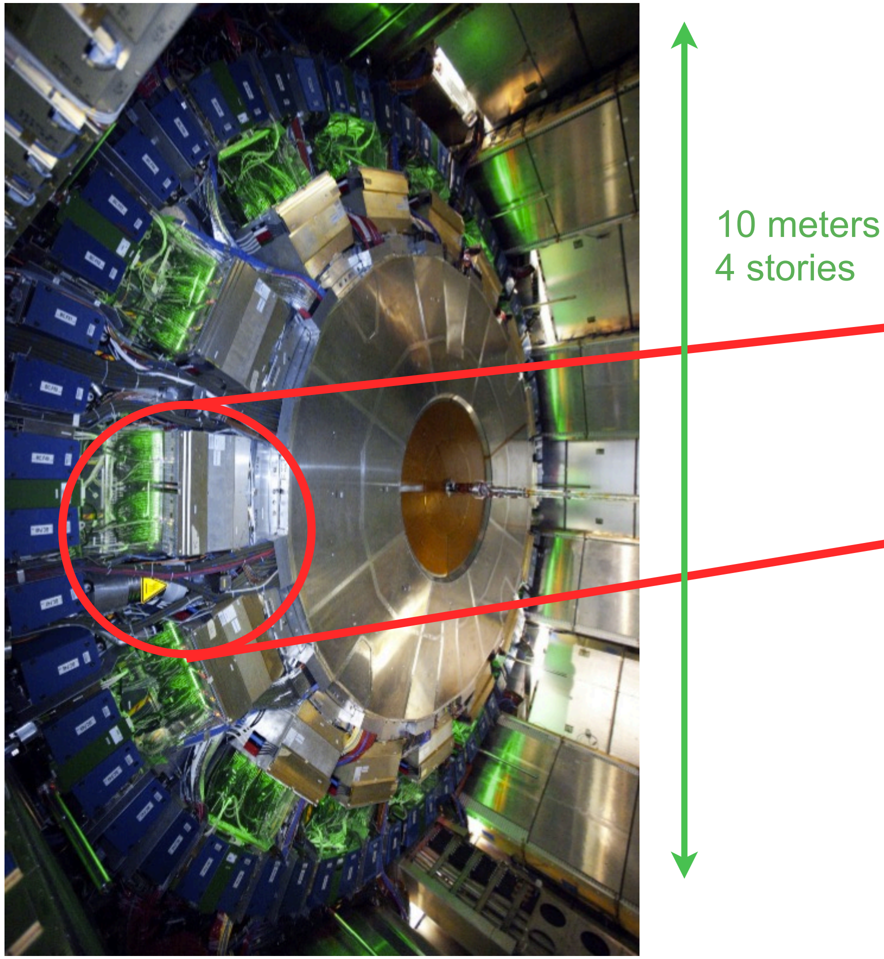
Three hundred physicists, engineers and technicians built it.

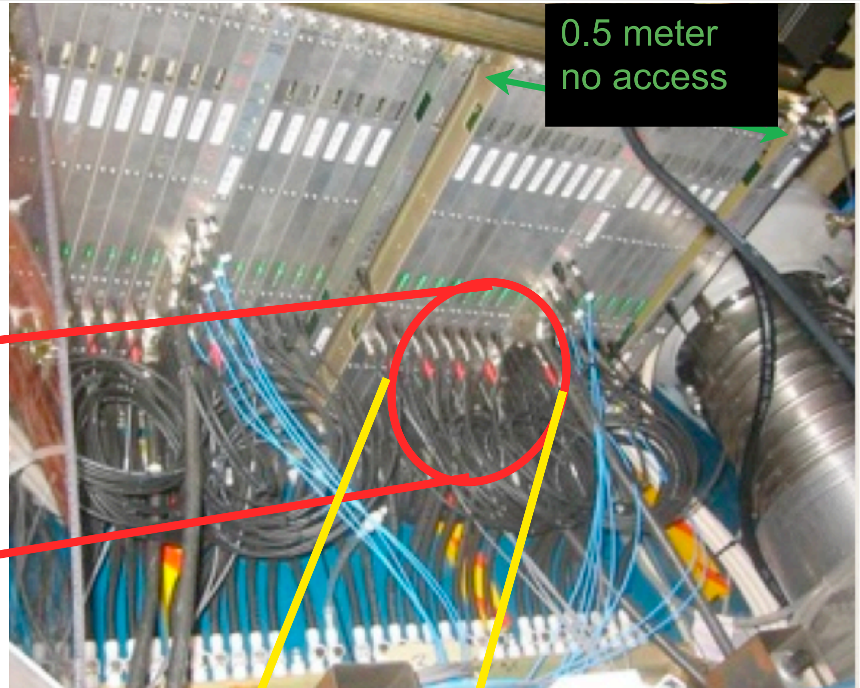
It is perfectly functioning with 99.94% of channels operational (106/182468 are not responding).

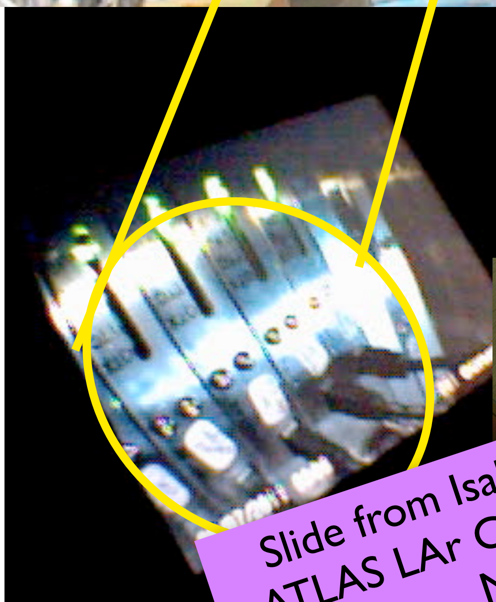
It is marvellous!

Slide from Isabelle Wingerter-Seez, ATLAS LAr Calorimeter - obviously. Many thanks!

Access to the LAr electronics





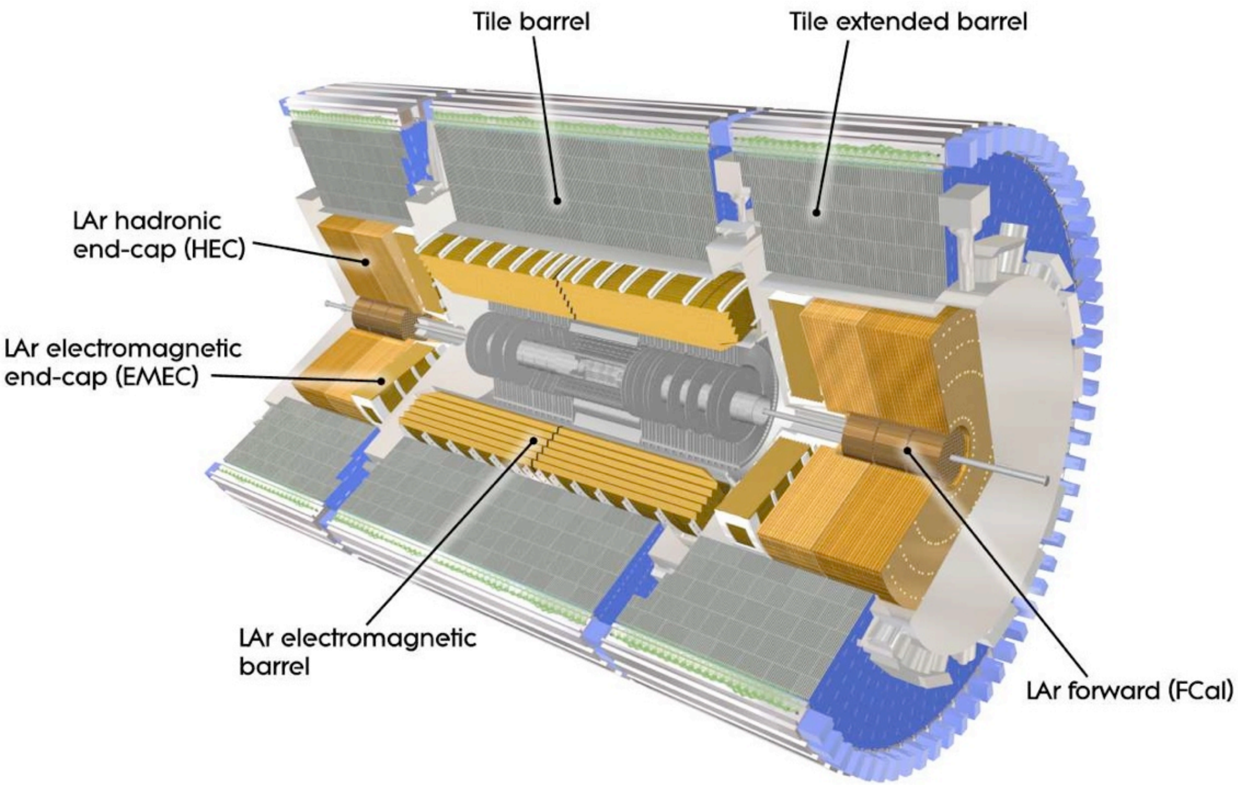


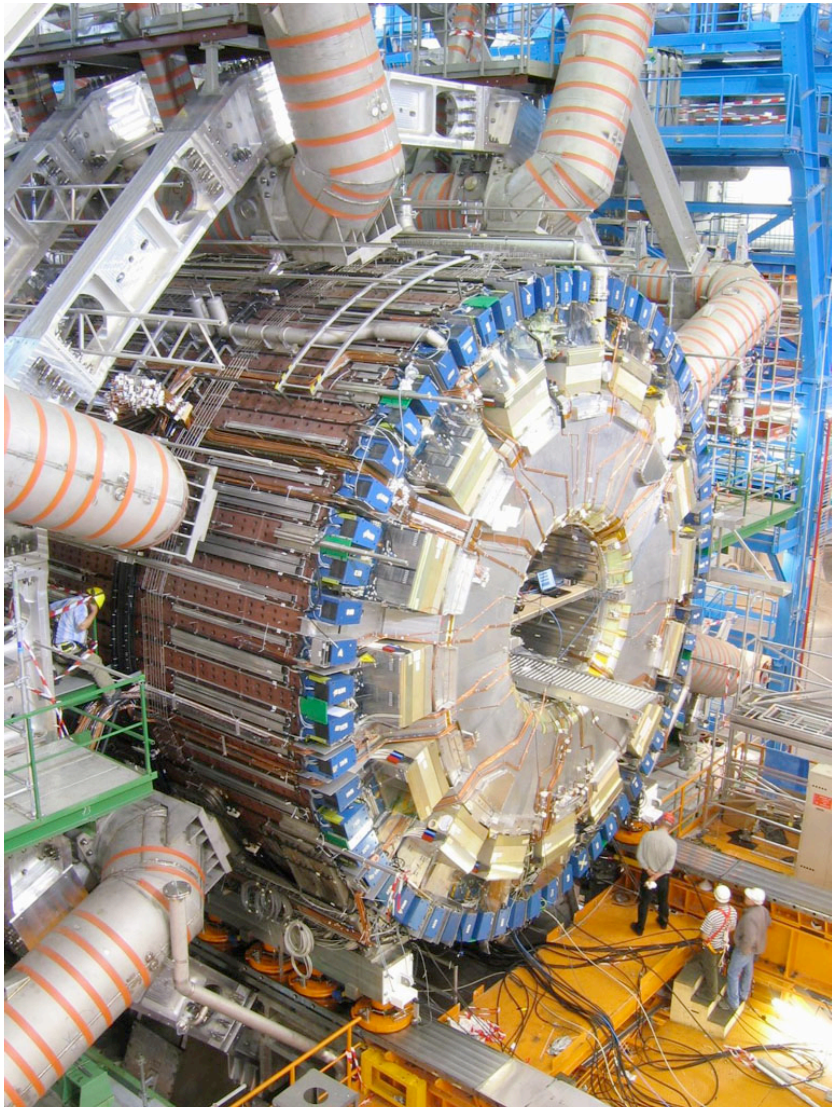
After one electronic board failed, need to unplug cables, plug new cables in, using an endoscope and a fishing rod from 2 meters away.

Slide from Isabelle Wingerter-Seez, ATLAS LAr Calorimeter - obviously. Many thanks!

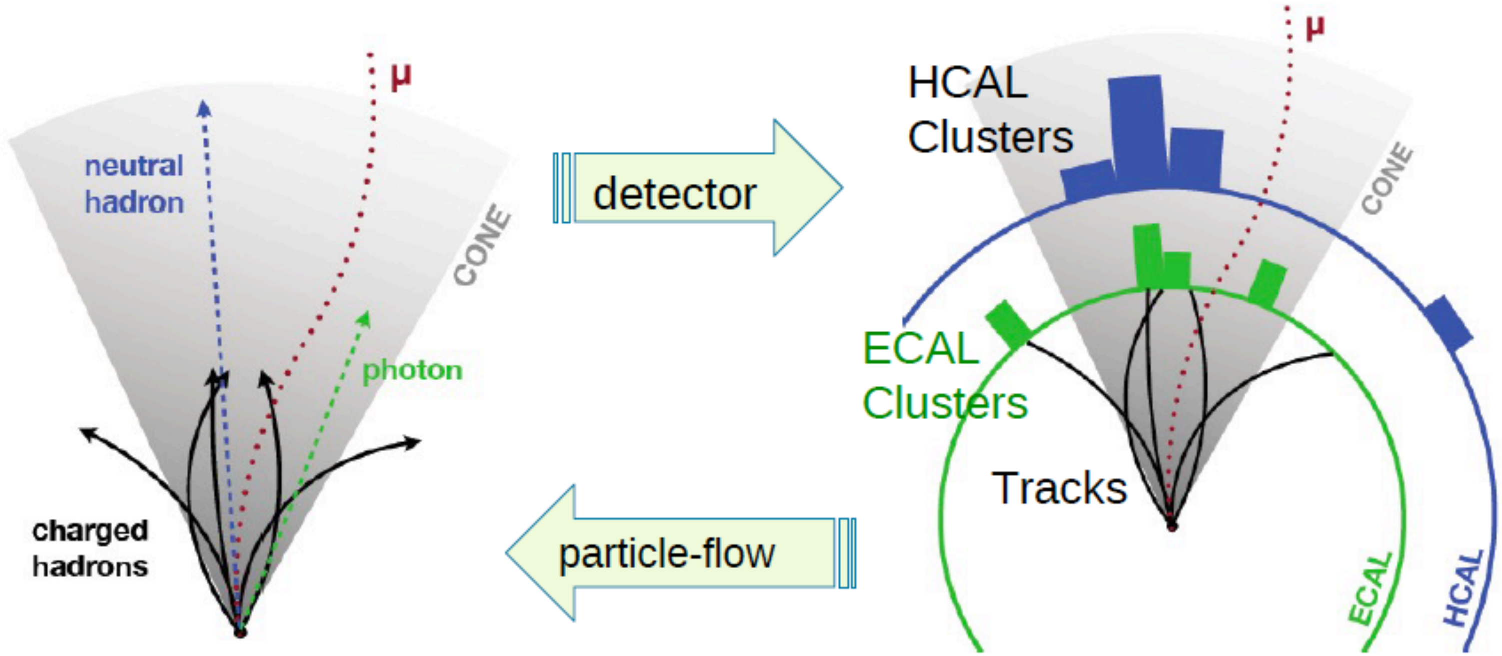
By the way....

- ....where is the ATLAS solenoids return yoke?



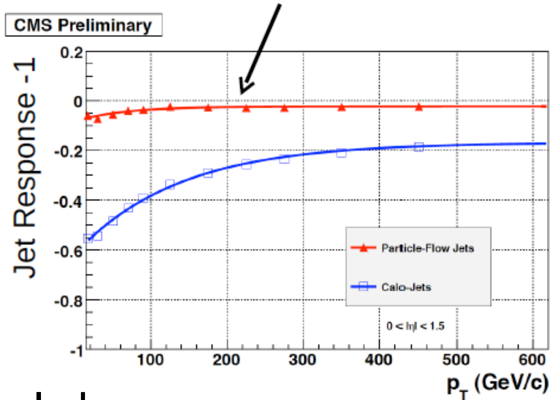


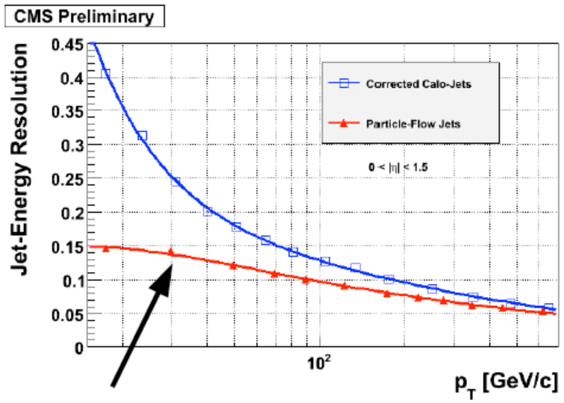
Particle flow - helping the calorimeter



The list of individual particles is used to build jets, to determine the missing transverse energy, to reconstruct and identify taus from their decay products, to tag b jets …

95-97% of the p_T reconstructed, over the whole range





Improved experimental methods help that detector performance surpasses expectations!

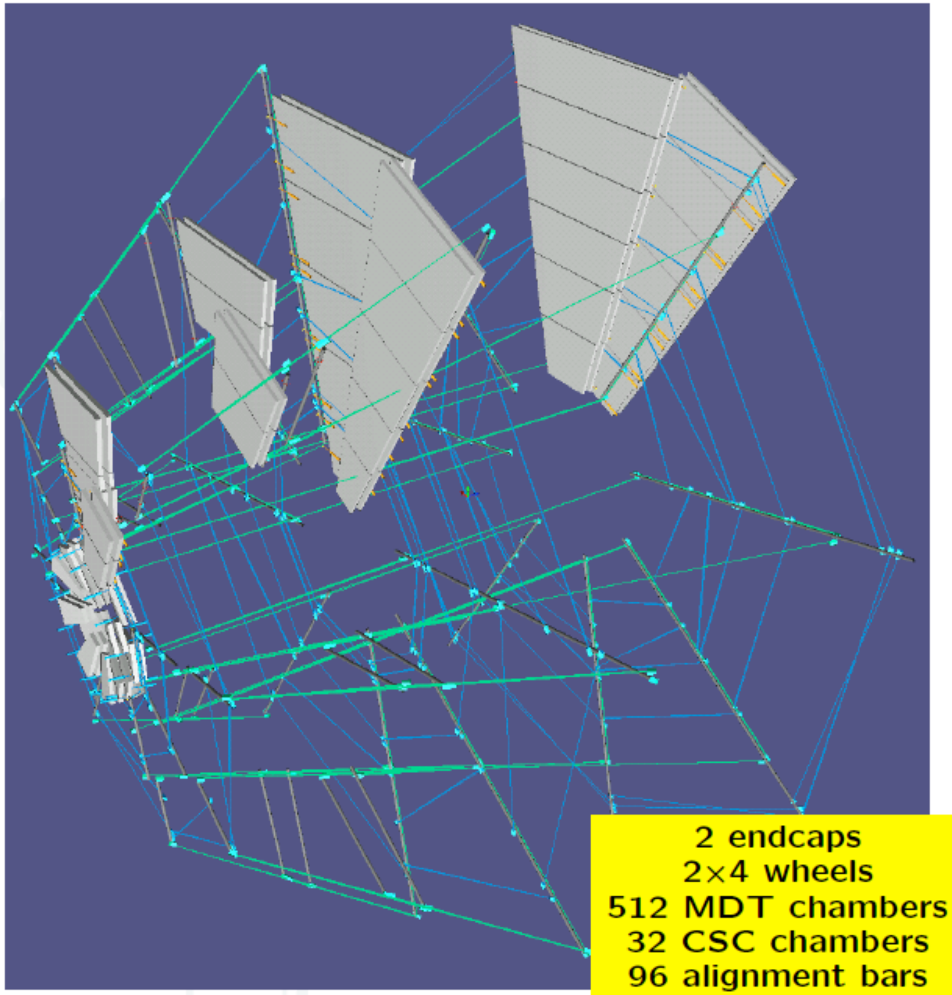
Example here: simulated QCD-multijets events in barrel: $|\eta| < 1.5$

Very large improvement at low pT, thanks to the tracks

from F. Beaudette, Performance of the particle flow algorithm in CMS, ICHEP 2010

Spot on: the ATLAS Muon alignment system

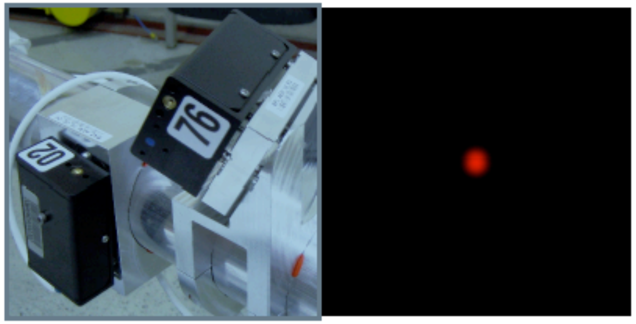
Christoph Amelung, ATLAS on the question about personal highlight at the LHC:
“Da hatten wir zum ersten Mal ein endcap-wheel zusammengesetzt mit allen Alignment-Sensoren, und alles hat funktioniert bzw wir haben alles zum Funktionieren gebracht: ein temporäres readout-system angeschlossen, alle (oder genügend viele) Sensoren die ihre Targets sehen. Und wenn man dann den Alignment-Fit laufen lässt kommt ein brauchbares chi2/ndf von 1.4 heraus! (Zwei Monate später, mit ein paar Verbesserungen implementiert war das chi2/ndf dann 1.0)”



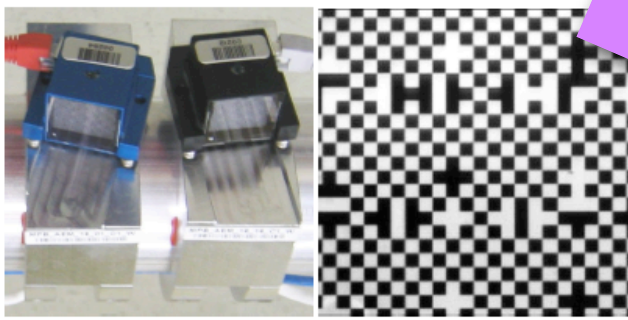
2 endcaps
2×4 wheels
512 MDT chambers
32 CSC chambers
96 alignment bars
≈ 6000 sensors

- **Optical sensors:**

  BCAM: camera looks at 1–4 laser diodes, measures bearing angles



RASNIK: camera looks at coded chessboard mask, measures displacements

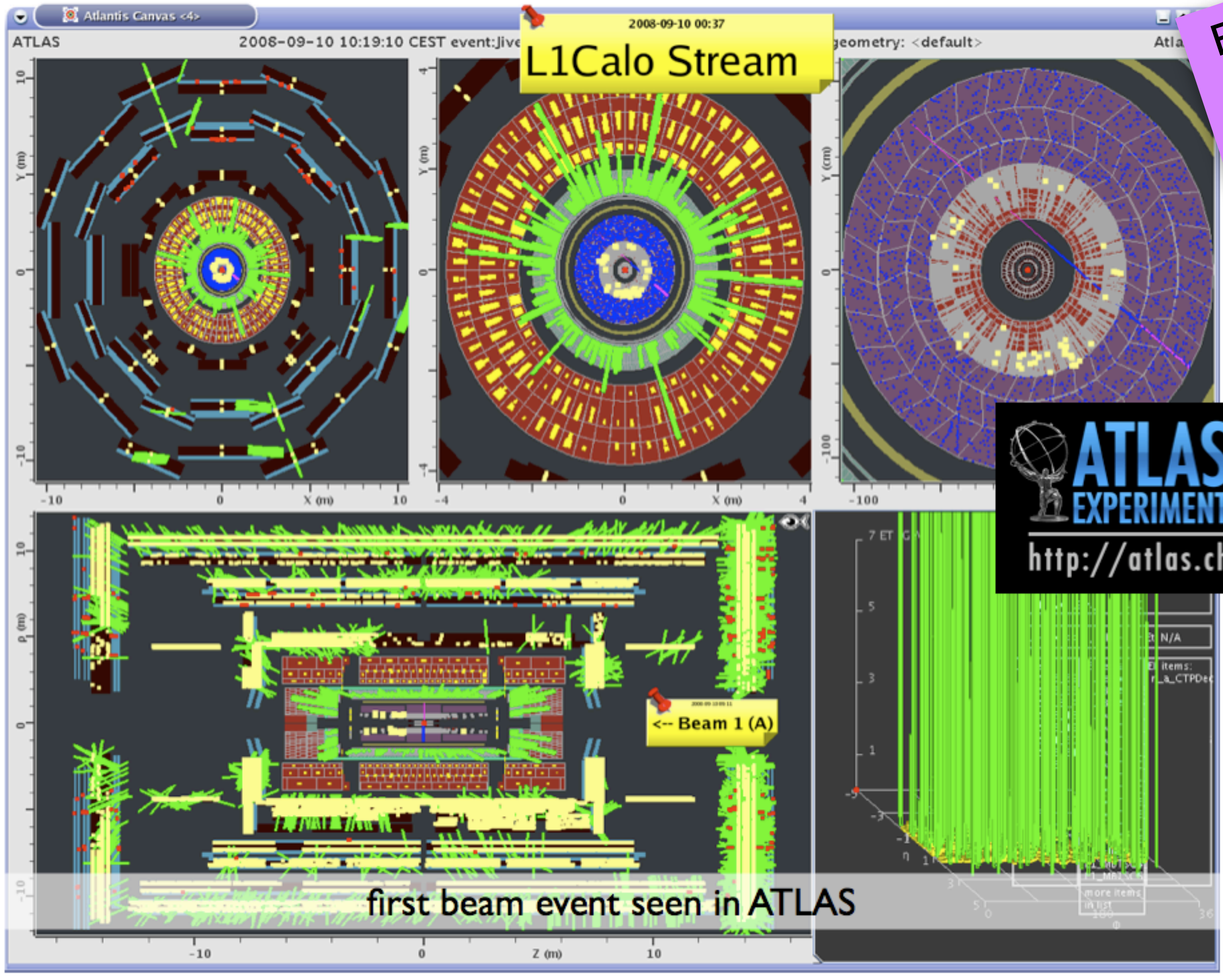


Input and slide from Christoph Amelung, ATLAS
Many thanks!

Beam “Splashes” were important!

- 2008: Single beam in LHC was steered onto collimator close to experiment
  ➝ spray of secondary/tertiary particles made that almost all electronic channels fired
  ➡ important to understand/calibrate detectors

First beam day 10 September 2008 was for many colleagues their LHC highlight!

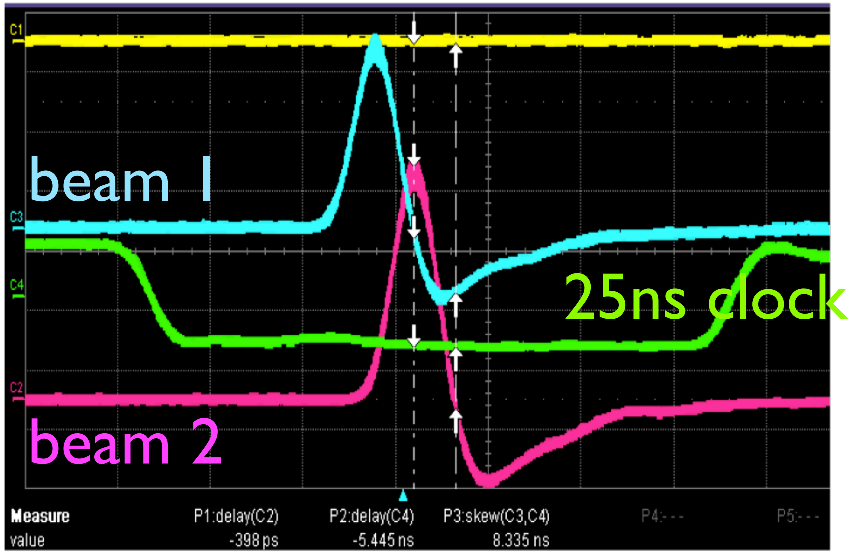


Thanks to experiences with single beam, low energy collisions, the break in 2009 to repair the LHC machine was not “lost” at all!

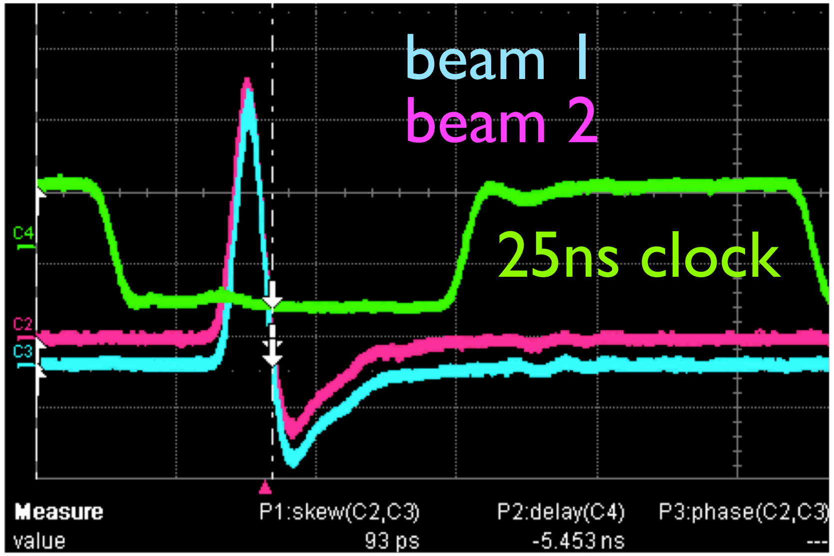
Be brave! Switch on your detector!

First collisions @ 450 GeV

Thilo Pauly: Einer der bewegensten Momente am LHC war fuer mich der 23 November 2009, als das erste Mal 2 Strahlen im LHC stabil zirkulierten, bei der Injektionsenergie von 450 GeV und sehr niedrigen Intensitaeten von ein paar 1e9 (Milliarden) Protonen pro Teilchenpaket. ...Wir haben versucht, das Timing der Strahlen so zu veraendern, dass sie sich exakt in der Mitte des ATLAS-Detektors treffen. ... Als dieser Mittelwert dann Richtung 0 wanderte, als der LHC das Timing auf 0 korrigierte, war fuer mich der Beweis erbracht, dass wir tatsaechlich die ersten Kollisionen gesehen haben und dass das Timing gut war. Das war ein tolles Gefuehl!



Scope traces of the beam pickup system (BPTX) 23.11.2009, **before** the phase adjustment of the LHC RF. The phase difference between the two beams in ATLAS is the peak-to-peak time difference, 900 ps. This corresponds to a vertex shift in z of 13.5 cm.



Scope traces of the beam pickup system (BPTX) 23.11.2009, just after the phase adjustment of the LHC RF. The effect of the cogging can be clearly seen, the peaks lie on top of each other, beams are crossing at the centre of ATLAS. The mean track z0 position was consistently found to have moved as well in the z direction, by 12 cm, as expected

Input from Thilo Pauly, ATLAS
Many thanks!

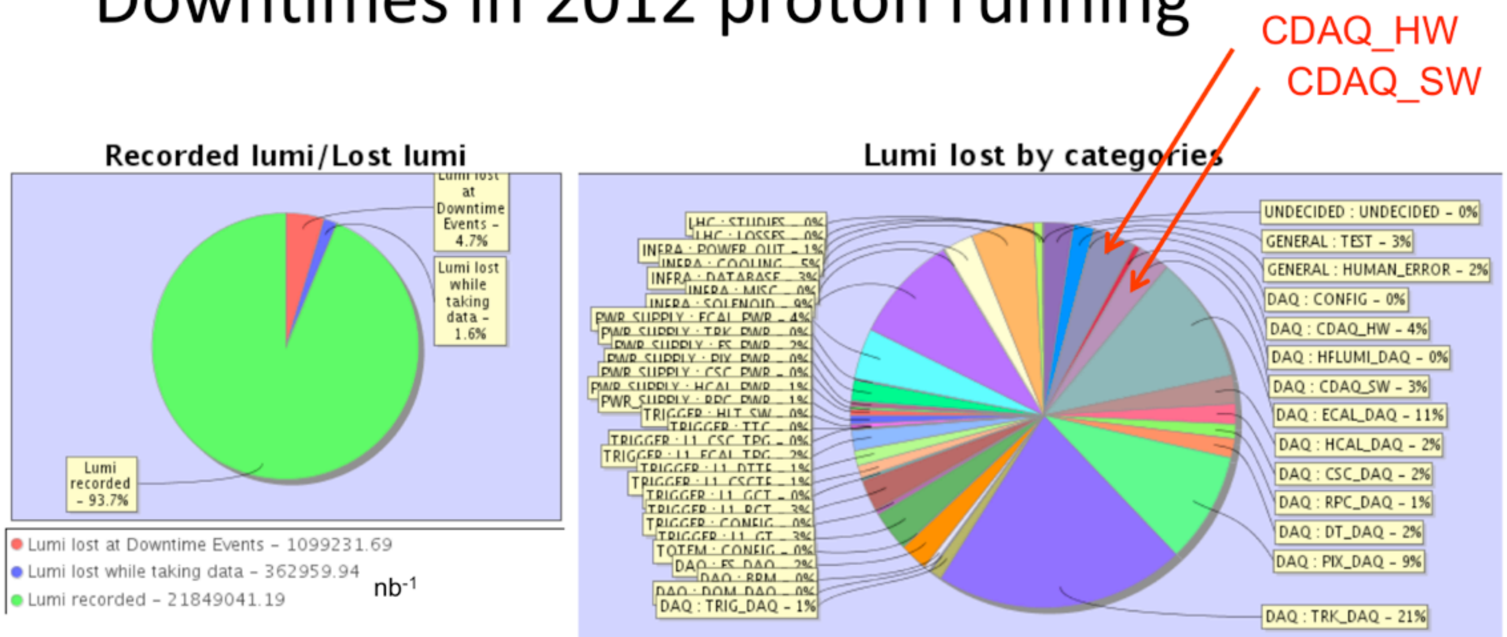
Perfect DAQ Systems

DAQ systems with more than 1000 PCs and tens of thousands of optical and electronic network links at the LHC were working reliably from day one onwards.

Example: the DAQ efficiency for 2013 (100% - luminosity lost because of hardware/software problems of the central CMS DAQ/delivered luminosity) was 99.7%, a remarkable number!

CDAQ operations & plans, CMS Run Coordination Workshop, Torino, 13th Feb 2013 11 H. Sakulin

Downtimes in 2012 proton running



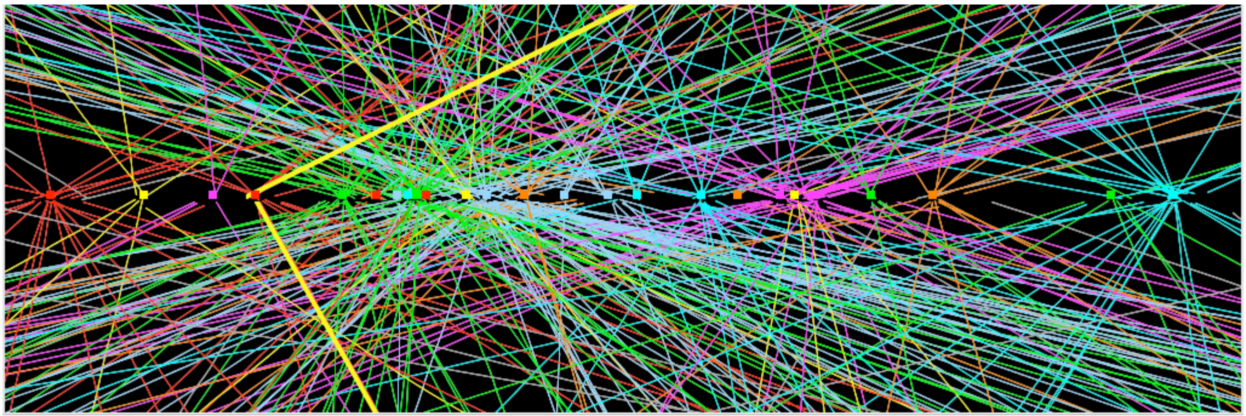
Experienced DAQ teams and excellent preparation of detectors in many test beams, cosmic challenges, dry runs.

- CDAQ_HW: 2h06, 39.5 / pb lost (0.17 % of total l
- CDAQ_SW: 2h16, 30.0 / pb lost (0.13 % of to
- All down time 94h06 (out of 1726) – 5%, 1462 / pb lost (4.7 % of tota lumi)

Input from Christoph Schwick, CMS. Many thanks!

Challenged by the LHC machine

- LHC up to now operated with bunch spacing of 50ns (25ns design) but high bunch currents to achieve luminosity;
- average number of interactions per bunch crossing about twice the design (24 interactions per b.c.)
  - ➡ challenge for tracking and vertexing, trigger, lepton isolation, jet energy scale/ resolution, missing transverse energy reconstruction, reconstruction CPU time...



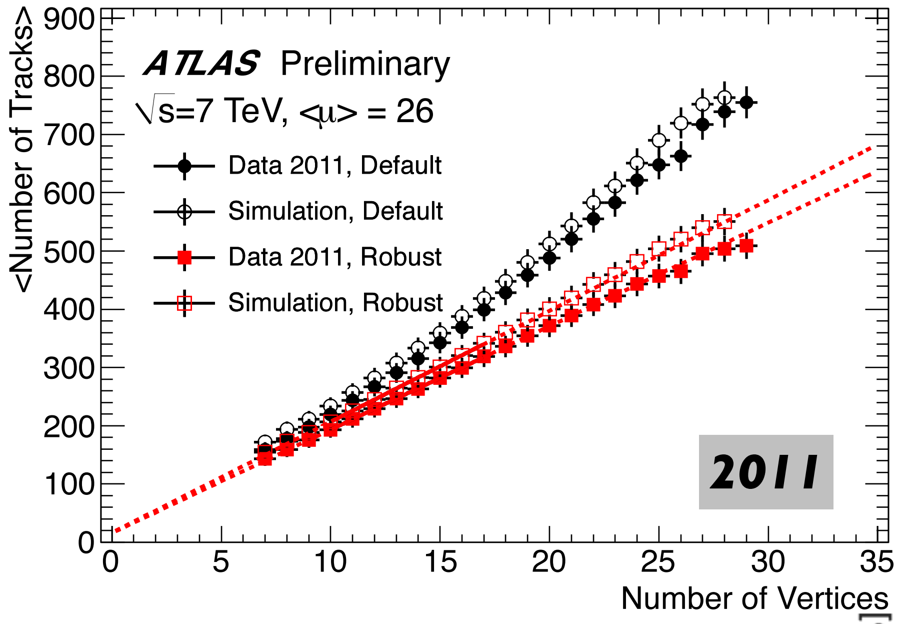
ATLAS, $Z \rightarrow \mu\mu$, pile-up 25

Impressive to see how detector teams solved this problem!

One of the miracles of the LHC...

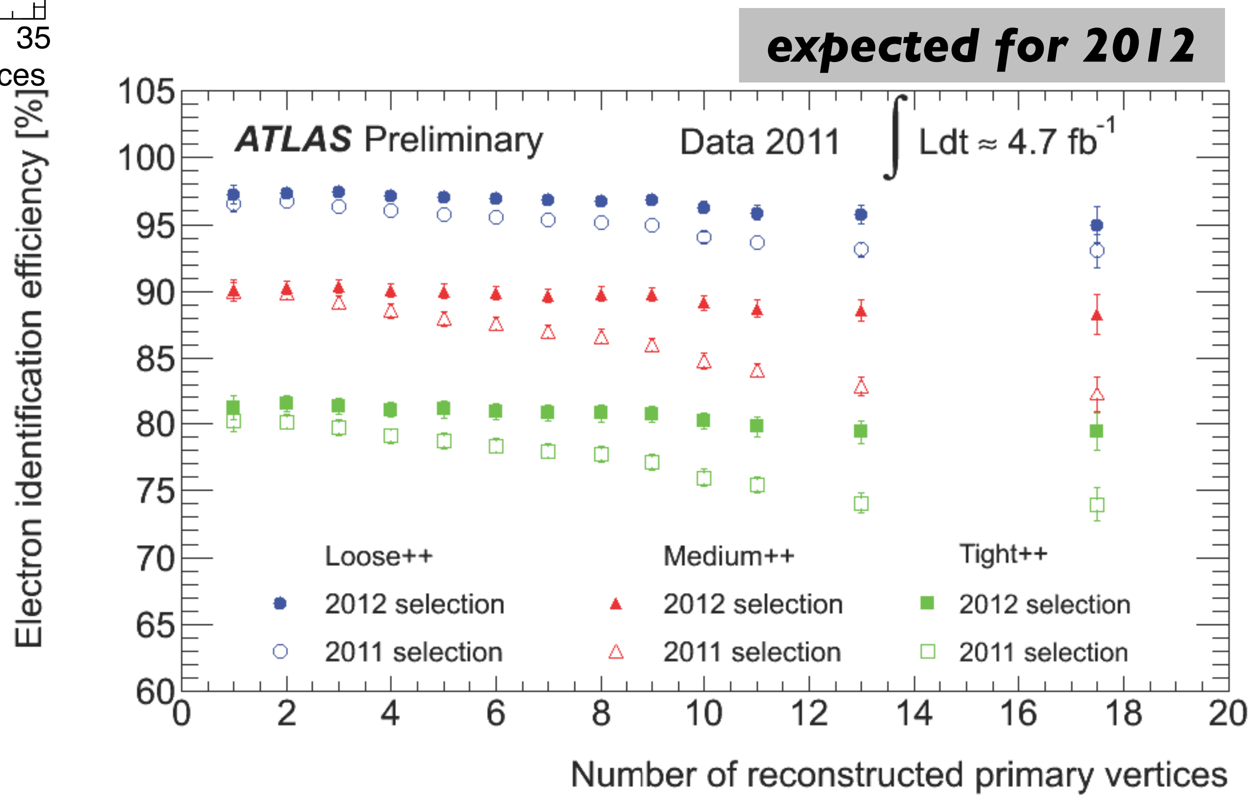
Massimiliano Ferro-Luzzi (LHCb, LHC Programme Coordinator up to 2011):
"I (and many others) had been more or less brainwashed for years that 50ns was not possible, because it would not be possible to satisfy the requests of all experiments... .
... LHCb had to suffer a bit, due to the higher pile-up, but they magnificiently coped with it,operating at 4 or 5 times the pile-up which the experiment was designed for another example of the great creativity and adaptability of physicists!"

Example: ATLAS Tracking tuning for 2012

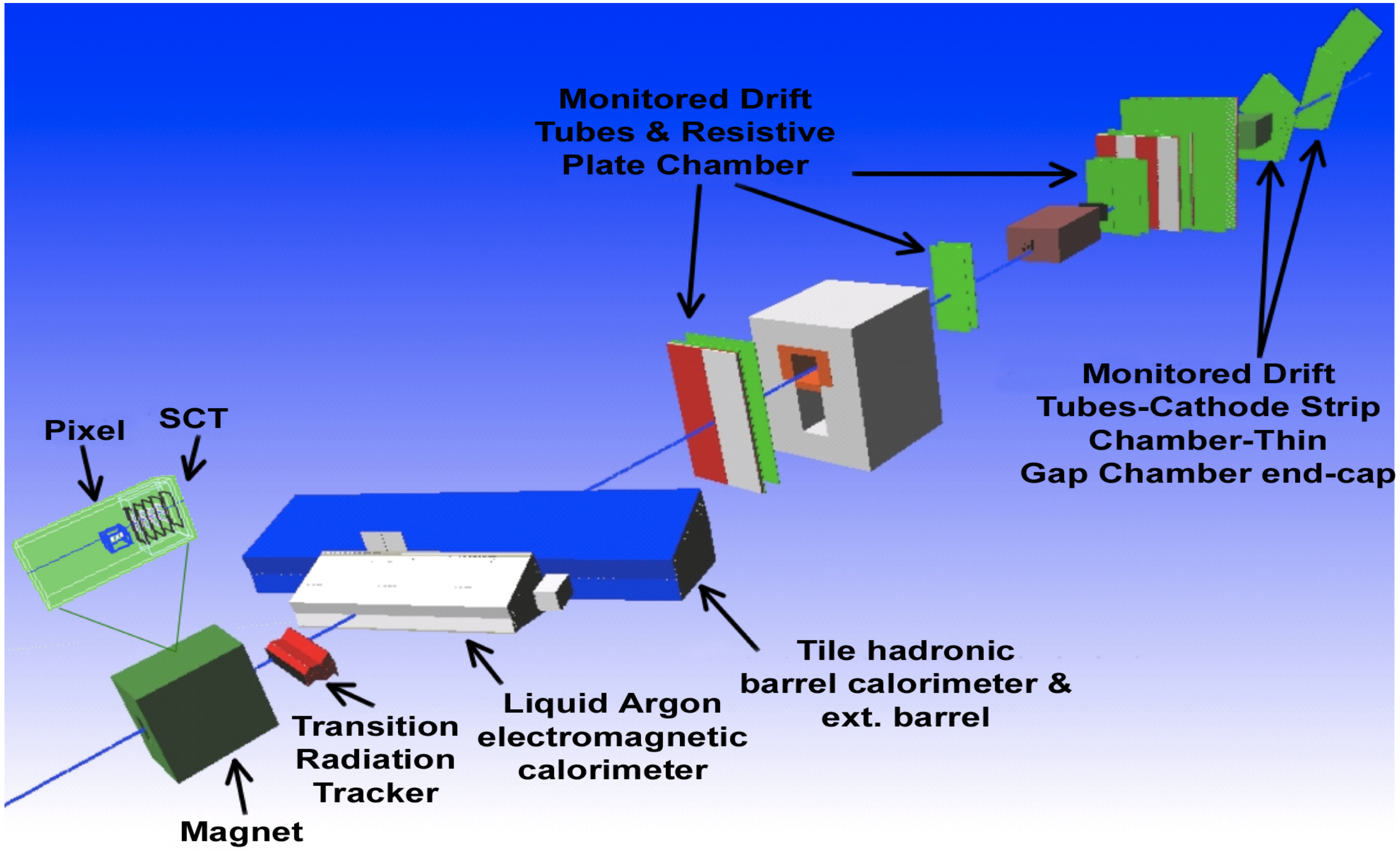


- Strong reduction of combinatorial "fake" tracks caused by pile-up by applying "robust" cuts (only small efficiency loss)...

... leads to improved electron identification efficiency almost independent of the number of vertices.



Test-beams are vital!

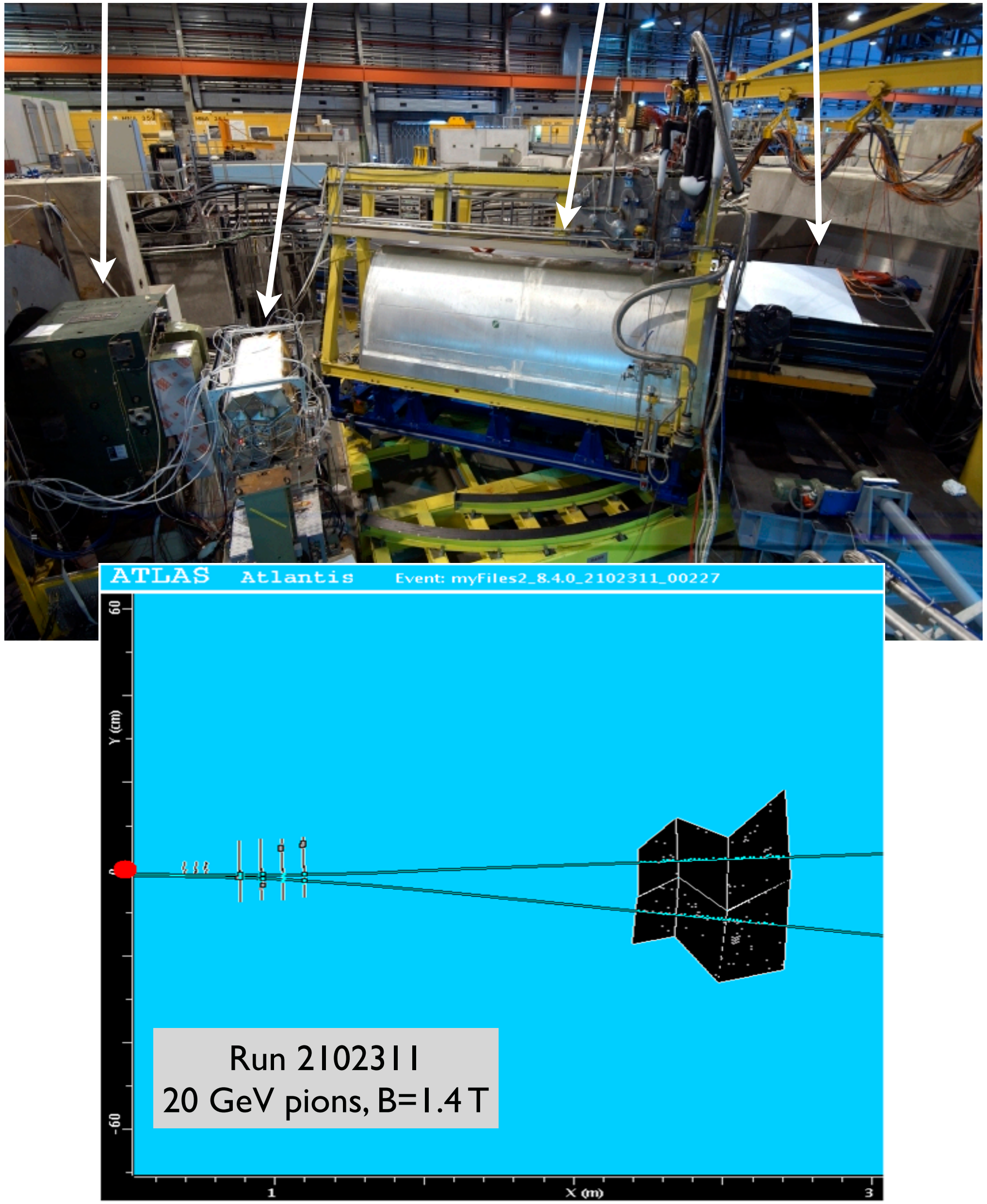


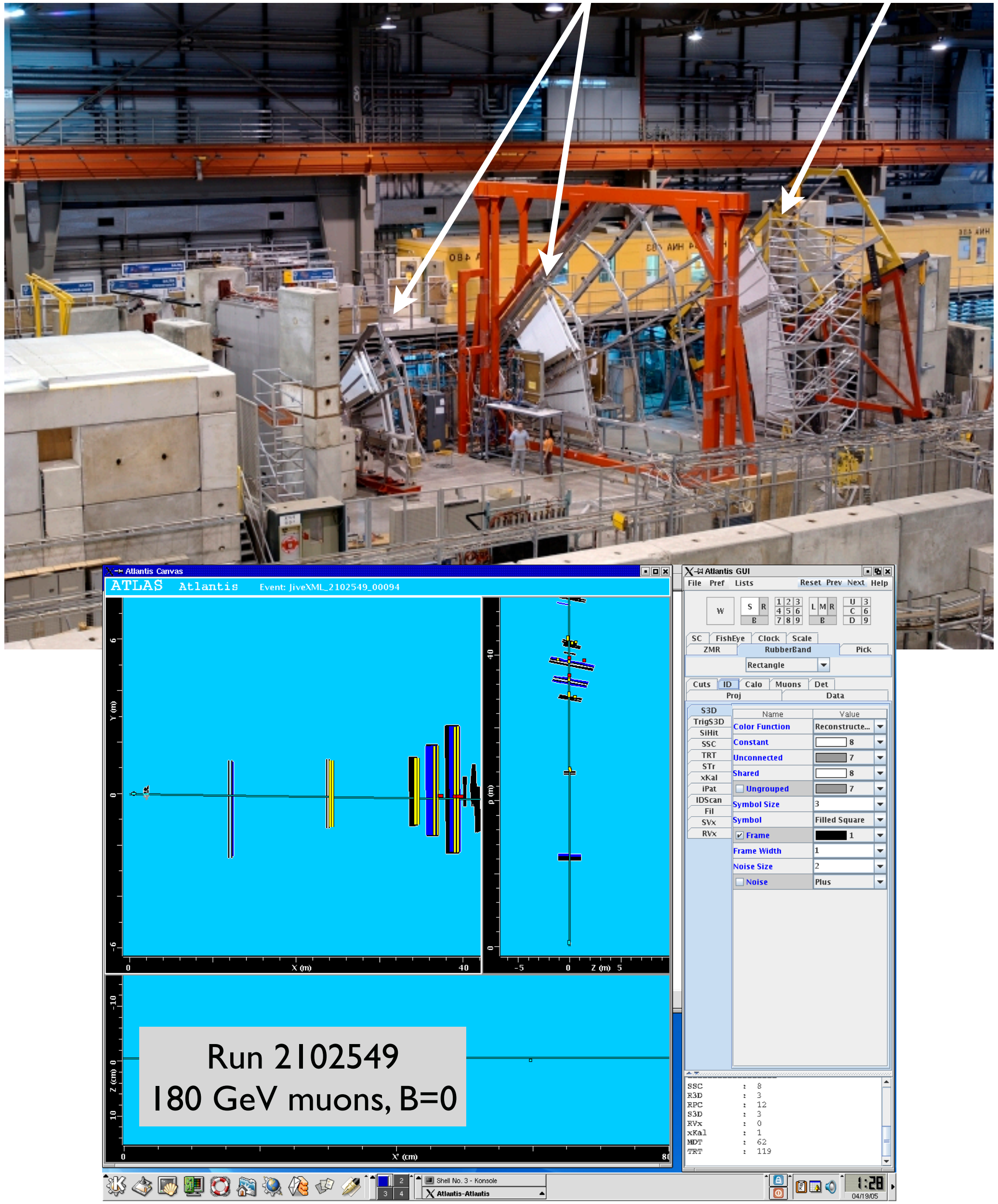
- Test beams at CERN's PS and SPS were important for many reasons!
  ➙ technology and system tests, calibration & validation - not only for detectors but also for electronics and software!
  ➙ teams were given goals & milestones (i.e. progress of projects could be monitored);
  ➙ shifts/work in the test beam are great to meet colleagues from other subsystems!

- Big campaigns
  ➙ ATLAS Combined test beam in 2004;
  ➙ CMS Cosmic challenge (2007) with CMS detector in CMS cavern.

ATLAS in North Area (H8), 2004

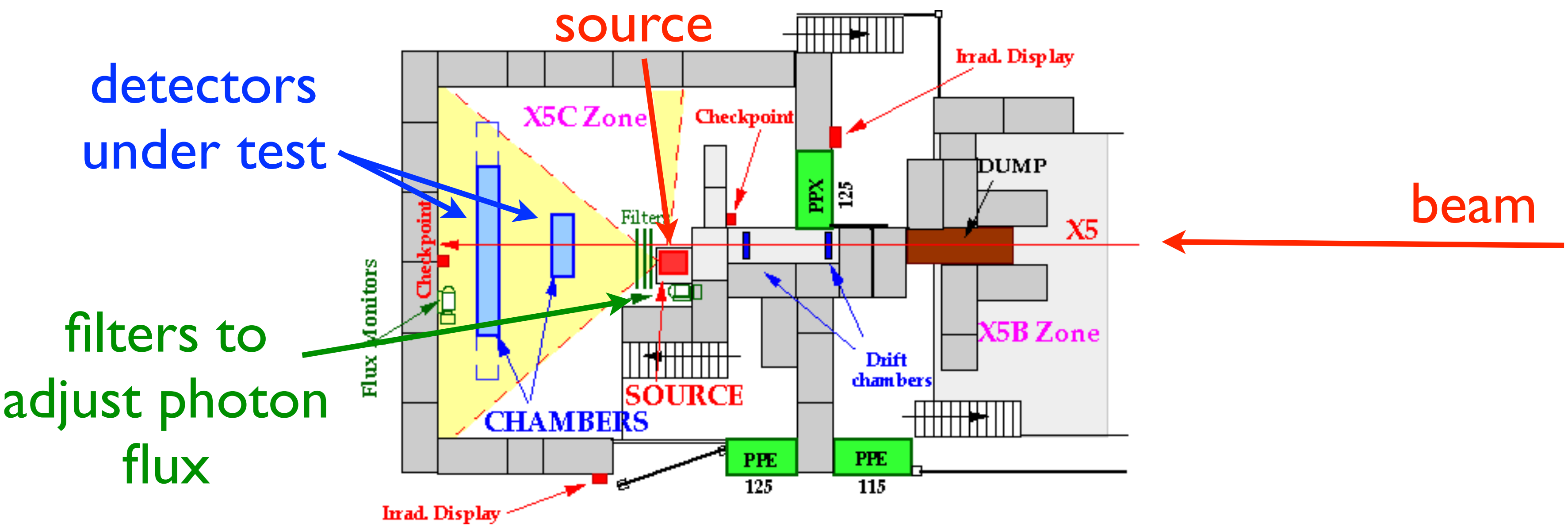
Pixels, SCT and TRT   Liquid Argon & Tile Calorimeters   Muon detectors, trigger cambers and drift tubes





Special and mandatory for LHC: the Gamma Irradiation Facility GIF

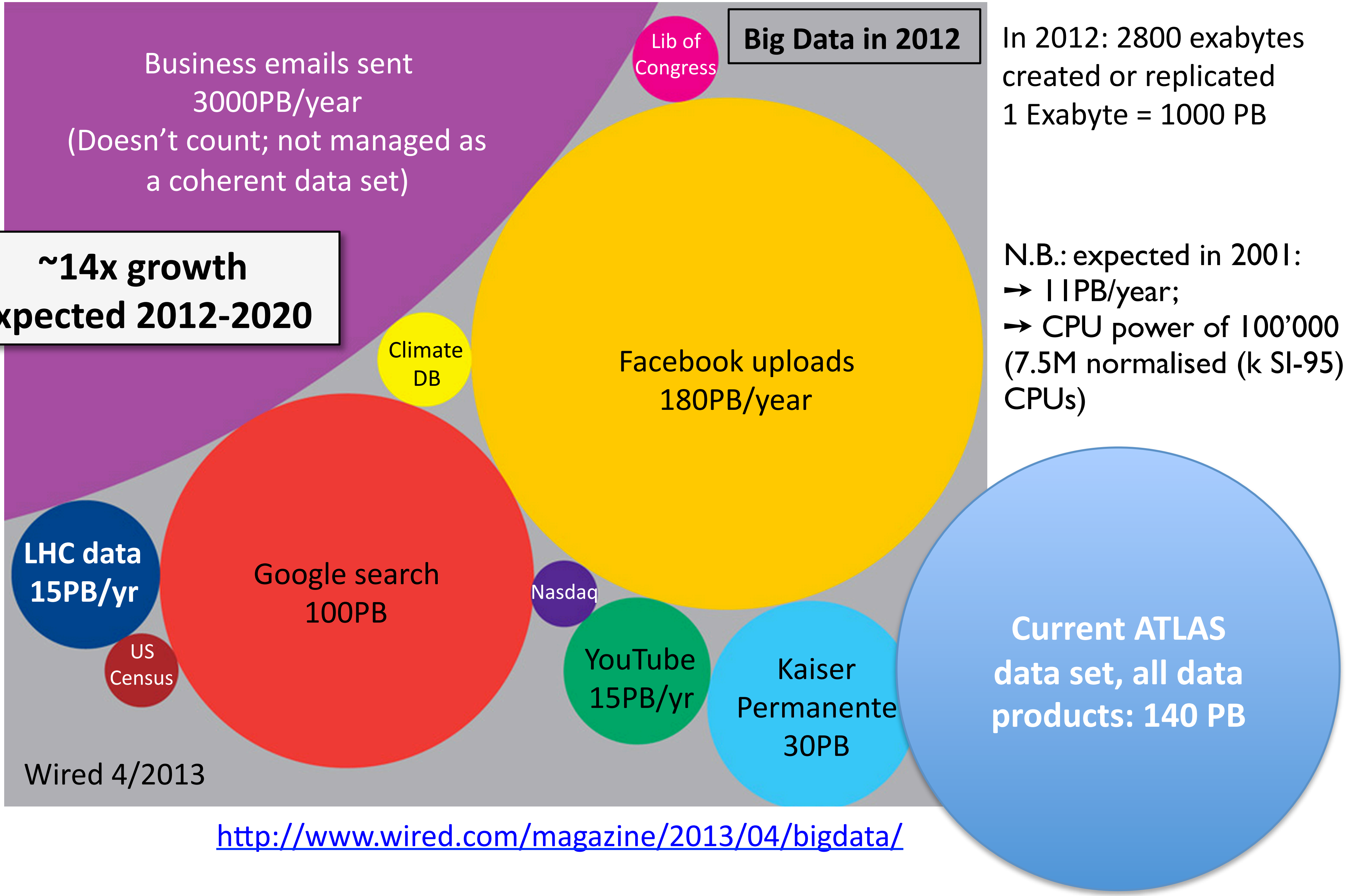
- Gamma source CS[137] 740 GBq (1997) with 662 keV photons plus parasitic muon beams O(100 GeV) from SPS in West Area
  - ➡ West Area closed and beams stopped in 2004
- Feature & idea: test **operation** and **aging** of large area detectors (RPCs, TGCs, drift tubes...) **at high rates (kHz/cm^2)**
  - ➡ photons from source provide background - beam particles are the signal;



- Main users: LHC experiments
  - ➡ fully booked over last 16 years, many publications an notes (e.g. search in NIMA: >200 articles);
- Still in operation today to help with aging problems;
- New GIF (GIF++) under construction in SPS North Area, ready for beam in 2015.

Data Management - where is the LHC in terms of Big Data?

~14x growth expected 2012-2020

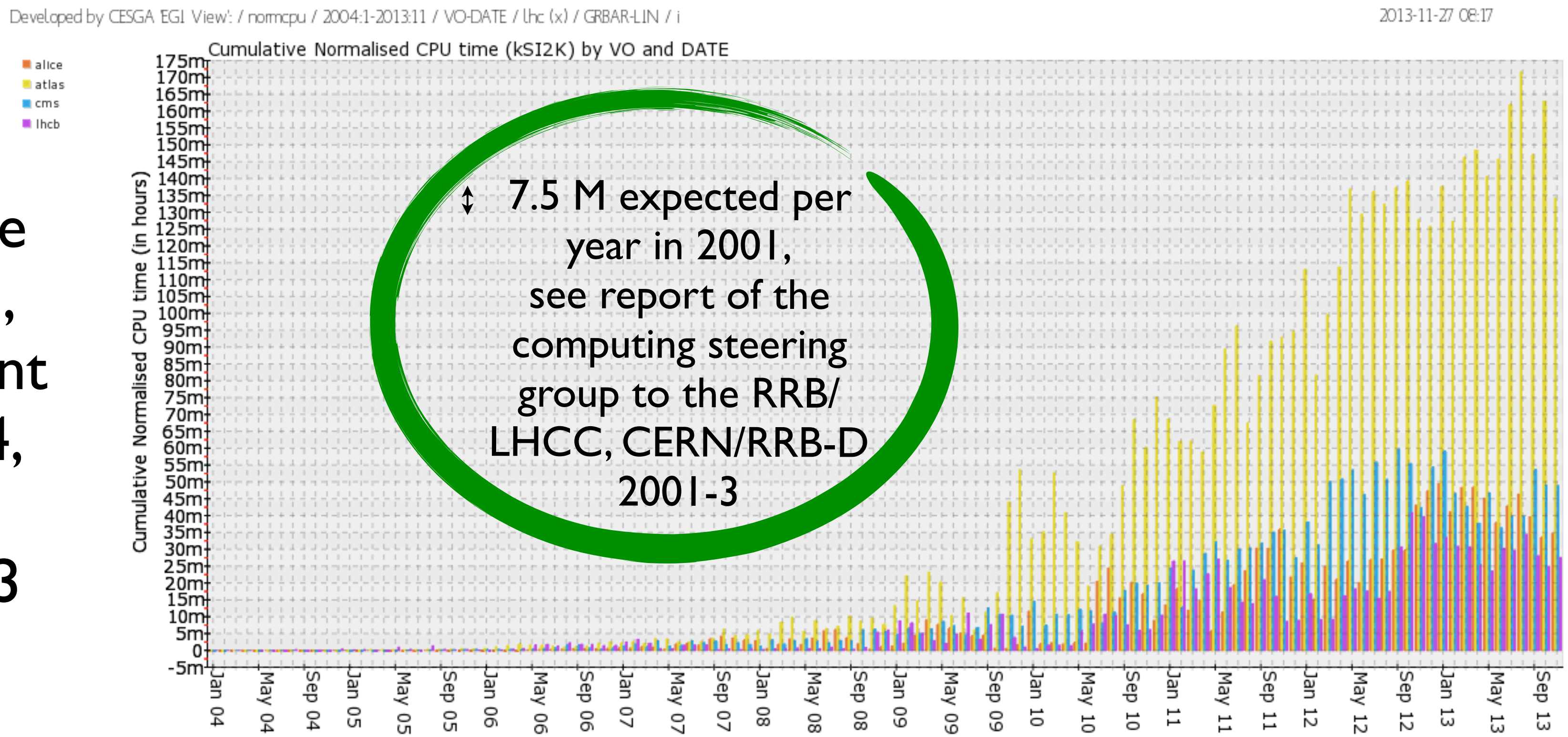


In 2012: 2800 exabytes created or replicated
1 Exabyte = 1000 PB

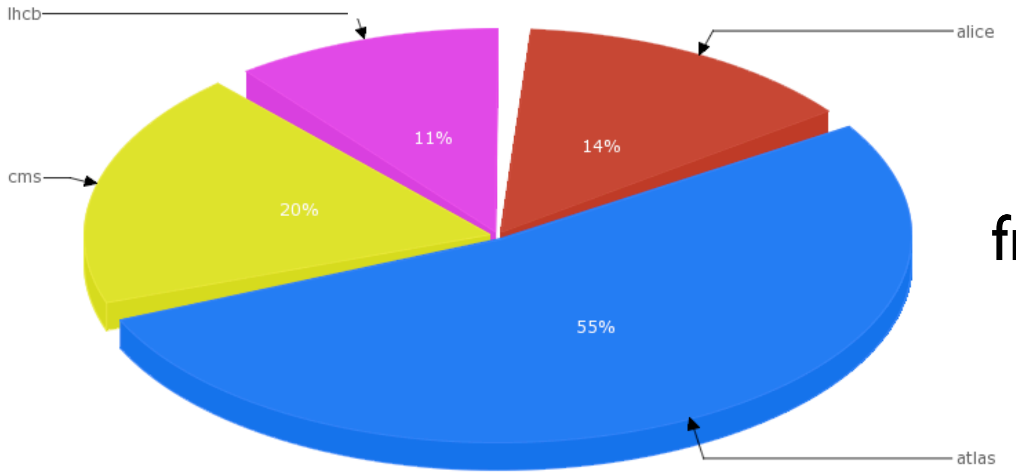
N.B.: expected in 2001:
→ 11PB/year;
→ CPU power of 100’000 PCs (7.5M normalised (k SI-95) CPUs)

http://www.wired.com/magazine/2013/04/bigdata/

LHC = Big Data



Cumulative CPU time, development since 2004, status 27.11.2013



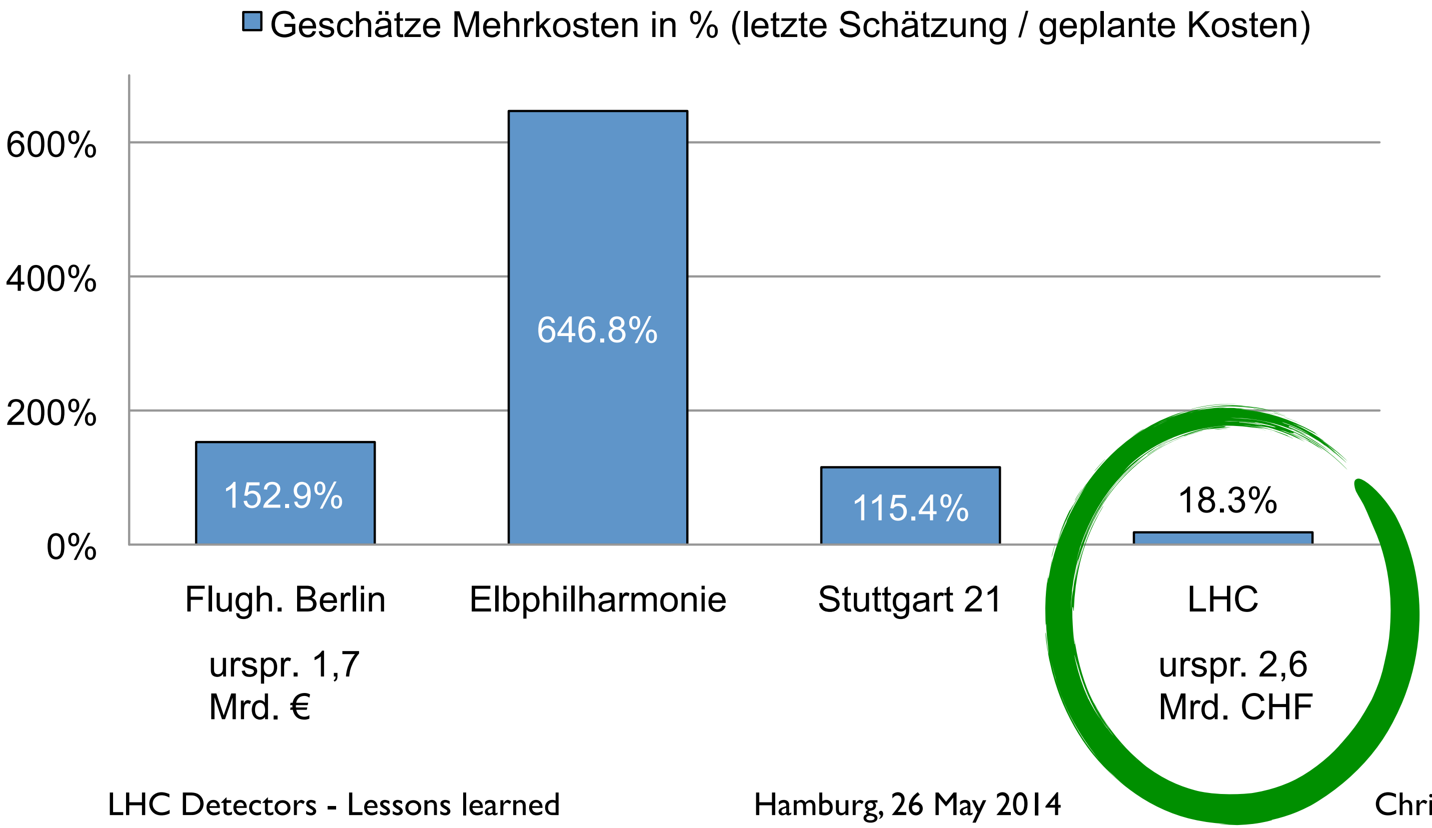
Normalised CPU time, fraction of each experiment, status 27.11.2013

Input from Markus Schulz (CERN IT)
Many thanks!

View of a person from a funding agency

- Conditions to support the LHC, from the BMBF point of view:
- *klarer Zweck (physics case)*
- *technische Machbarkeit*
- *reliable Kostenschätzung*
- *Finanzierungskonzept*
- Needed also: clear project structure
- *Organisation auf Projekt einstellen*
- *Personal (Projektleiter)*
- *Controllingstruktur*

Input from Hermann Schunck (BMBF), German Council Delegate during LHC design phase. Many thanks!



Kostenpunkt	in 1.000 CHF
Maschinen und Experimentierhallen	
Material	3.685
Personal	1.150
Injektor	153
Summe Maschine	**4.988**
Grid Computing	179
Detektor (CERN)	1.372
Detektor (Kollaborationen, nur Material)	903
Gesamtkosten LHC	**7.874**

Monitoring the LHC project

The "Little Helper for Committee Commentaries"

New in the world of really big science? Feeling helpless in front of a 6,234,588 piece mega-puzzle ? Need to comment quickly on the content of 1833 slides? No problem!

Follow these easy 3-step instructions to prepare your 1.5 h committee talk - and with a few mouse clicks you will look competent and useful.

Step 1 - ***Select appropriate slides from the presentations of the experiments***

- Download all slides into your talk. Add your name and date on the front page.
- Eliminate about 20% of slides at random. **End of step 1.**

(note that importance of topic scales with inverse square of number of slides about it)

Step 2 - ***Integrate your specific comments*** **(they all work fine; choose any and cross out as appropriate)**

- This is a matter of concern.
- This is (a / one of the most/ the most) critical item they should concentrate on.
- This item is (on/not on) the critical path.
- They have (realized/tackled/solved) the problem.
- They have (talked/negotiated) with the company.
- They have (re-organized the team/created a task force/"reassigned responsibilities").

Almost done. Now you have to show your quick grasp of this difficult matter by adding some specific, intelligent and useful recommendations. This will conclude your work on a great committee talk.

Step 3 - ***Make well prepared, intelligent and useful recommendations***

- The cabling/installation/commissioning takes much more time than expected
- This is a (aggressive / very/ very very / extremely) tight schedule [re-use often]
- The installation plan (has zero contingency / is a delta-function)
- They are (thinking about /working on /have shown) the new schedule (e.g. version 659.6a)

Always finish with this:

- They must speed up (installation/commissioning/cabling/testing).
- They need more resources.

The LHC Committee (LHCC) plays an important role in monitoring the progress of the LHC project and provides significant help if needed.

Text of the "Little Helper for Committee Comentaries:
RL & CR during LHCC sessions in 2006

A special THANK YOU! to my colleagues

Christoph Amelung, Massimiliano Ferro-Luzzi, Daniel Froidevaux, Frank Hartmann, Kerstin Höpfner, Alan Honma, Peter Jenni, Steve McMahon, Markus Nordberg, Thilo Pauly, Petra Riedler, Christof Roland, Markus Schulz, Hermann Schunck, Christoph Schwick, Isabelle Wingerter and Wolfram Zeuner

for their help, suggestions and personal highlights!

Conclusions

- HEP detectors are unique!
- ...but you can profit from other colleagues experience!
  - ➡ always communicate well, learn about new things, play around, share knowledge, give help (In HEP you always meet twice - at least!),
  - ➡ communicate also (especially!) the mistakes!
    From mistakes you and others can learn a lot;
- do tests, tests, tests
  (or as Ingrid says: life is a test beam!);
- work hard,
- document what you do...
- **...and enjoy what you do!!!!**

Spare slides (if any)

Als ich 2001 als Fellow zum ALICE Pixel Detektor kam, war das Projekt noch ganz am Anfang. Die ersten Chips waren bereits designt, aber die Wafer kamen nur ein paar Wochen vor mir an. Ich war von Anfang an beim Projekt dabei und durfte mich im ersten Jahr eingehend mit dem Chip und seiner Funktionsweise auseinandersetzen. In dieser Zeit habe ich sehr intensiv mit den Designern und den Leuten die das Readout-System entwickelten zusammengearbeitet um das Testen der Chips aufzubauen. Ich fand das persönlich sehr spannend, da ich zum ersten Mal etwas mehr Einblick in CMOS design und in das Entwickeln von Readout System bekommen habe. Der ALICE Pixel chip hat 42 DACs die interne Parameter verstellen. Wir haben also zuerst versucht die Arbeitsparameter festzulegen. Ich fand die 42 DACs immer eine schöne Referenz zum Hitchhiker's Guide to the Galaxy - die ultimative Antwort ;) (ich glaube aber nicht, dass die Designer das wirklich im Sinn hatten). Im Lauf der Jahre habe ich andere Aufgaben übernommen und war letztendlich für die Integrationstests des Detektors verantwortlich. Einer der aufregendsten Momente war als wir auf den ersten LHC beam gewartet haben und mit dem Pixel Detektor und seinem trigger die ersten tracks gesehen haben. Anbei ein Plot der auch im CERN courrier war.