THE CMS “*ALL-SILICON*” TRACKER

Lessons learned

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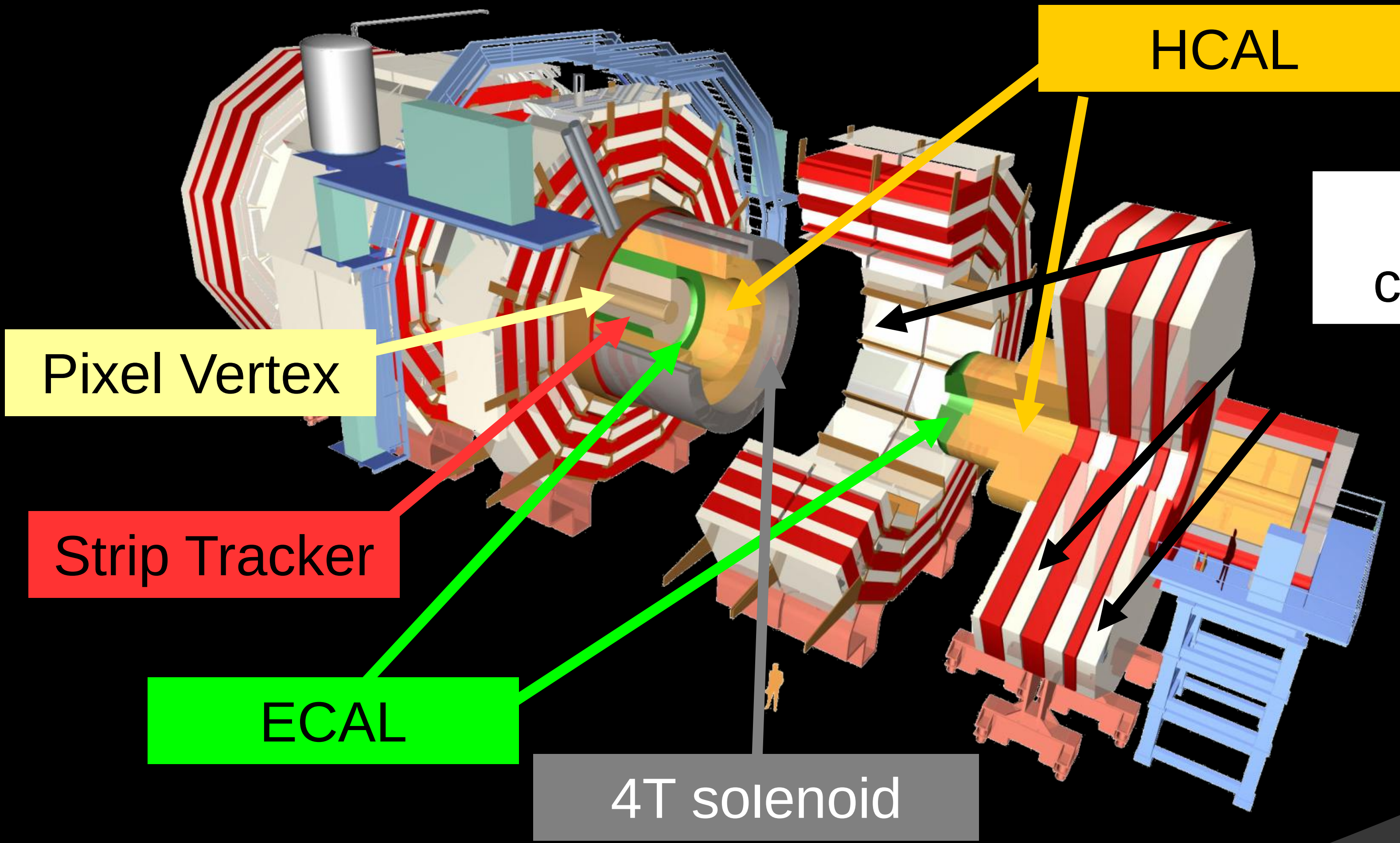
Outline

- The detector
- The story (focus on Si strip)
  - Construction
  - Commissioning
  - Operation
  - Performance
- Lessons learned
  - Thinking of upgrade

CMS: the Compact Muon Solenoid

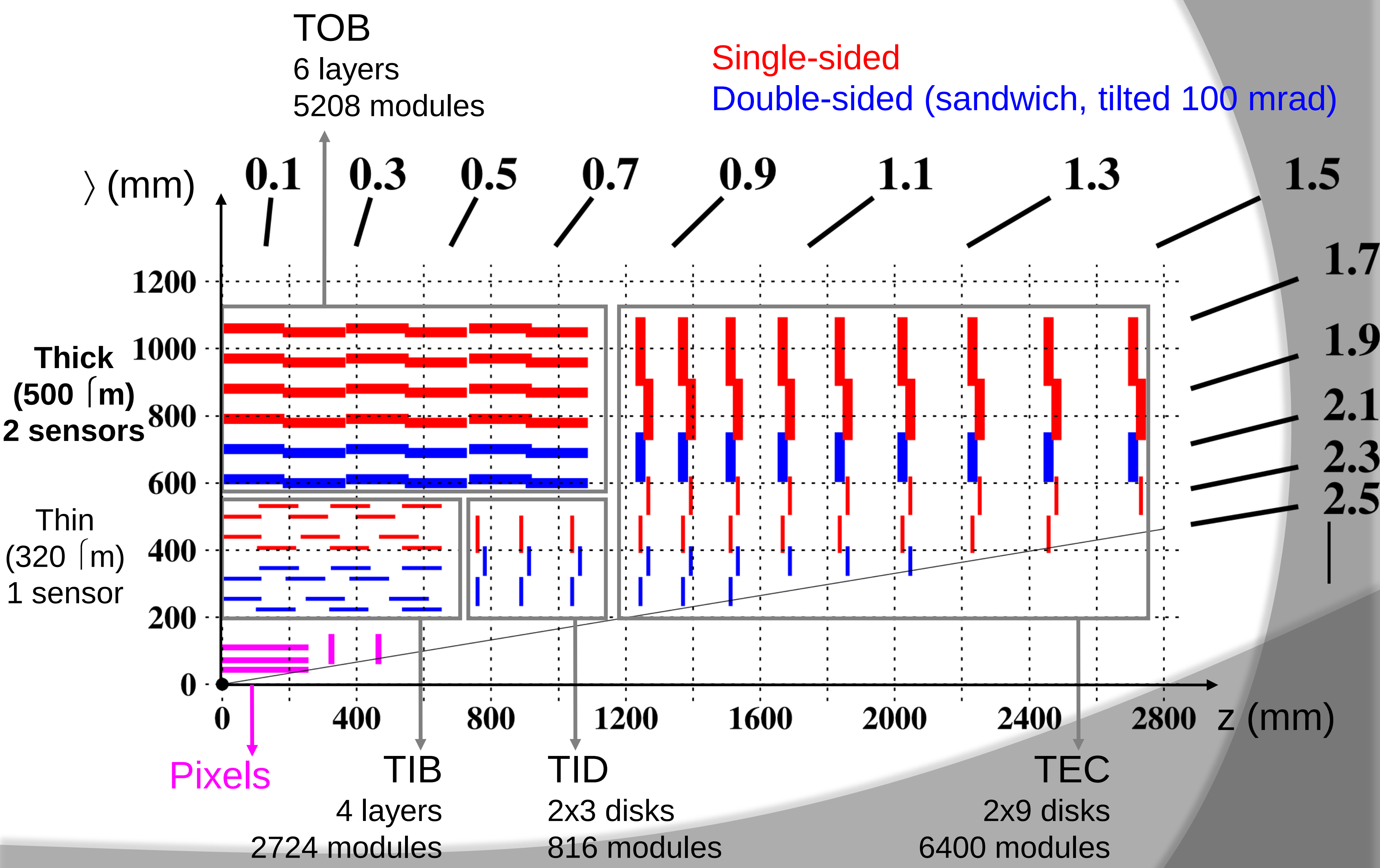


- Total weight: 12500 t
- Overall diameter 15 m
- Overall length: 21.6 m
- Magnetic field: 3.8 T

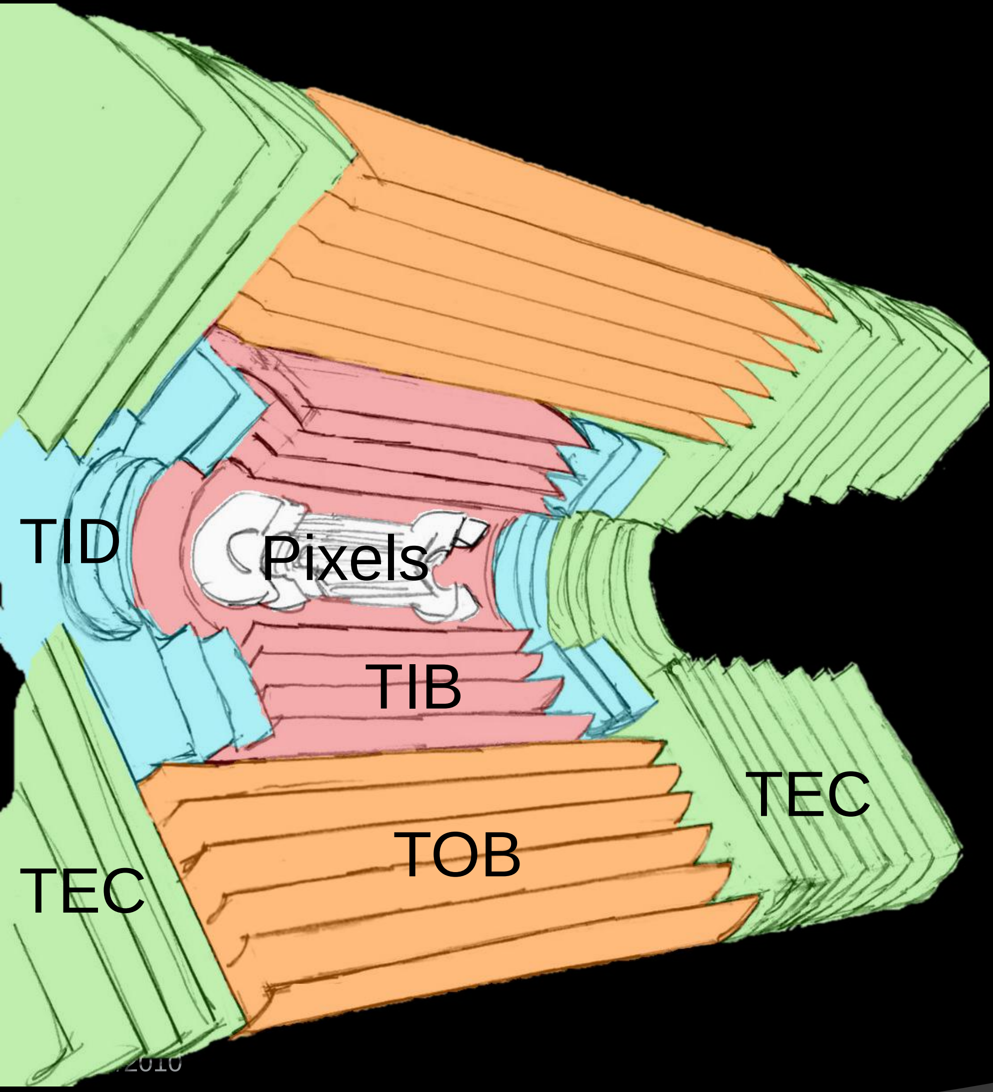
Environment, goals, requirements

- The LHC environment
  - 40 MHz bunch crossing (BX) frequency
  - Up to 30 pp collisions per BX (original design figure)
  - High-radiation environment
    - Up to 10^{14} n_{1MeV}/cm^2 for strips, ~ 3 x 10^{15} n_{1MeV}/cm^2 for pixels
- Physics goals
  - Precision tracking: @ 100 GeV $\sigma(p_T)$ ~ 2%, $\sigma(d_0)$ ~ 10 μm, $\sigma(z_0)$ ~ 30 μm
  - High efficiency (> 95%)
  - Low fake rate (< 10^{-3})
- Requirements (and design choices)
  - Rad hard silicon sensors, efficient low-temperature cooling
  - High granularity, fast electronics (resolve 1 BX)
  - Long lifetime (> 10 years)
    - Pixel: easy maintenance
    - Strips: high robustness and redundancy (~ no maintenance possible)
  - Stable mechanical structures (few μm)
  - Minimal amount of material

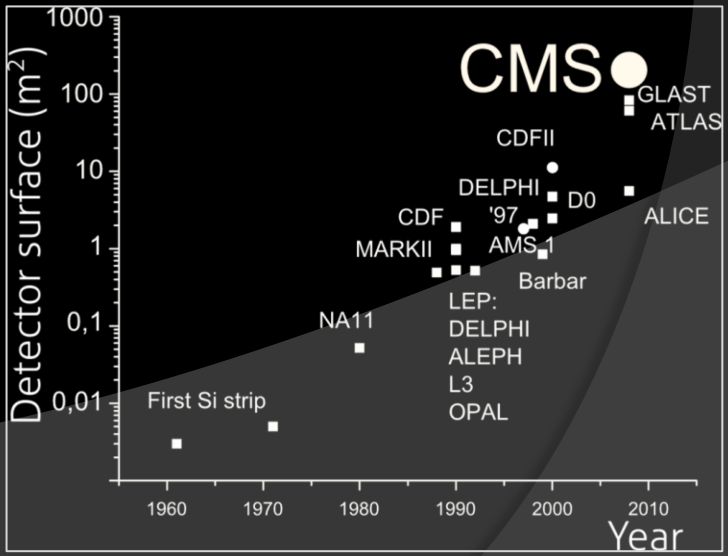
The Tracker Layout



A few numbers…



- **Overall**
  - Volume: 23 m^3
  - Operating Temperature: -10°C
  - Power dissipation: 35 kW
- **Strips**
  - Active area: 200 m^2
  - Modules: 15 k
  - Front-end chips: 73 k
  - Read-out channels: 9.3 M
  - Bonds: 24 M
  - Optical channels: 36 k
- **Pixels**
  - Active area: ~ 1 m^3
  - Front-end chips: 16 k
  - Readout channels: 66 M
  - Optical channels: 2 k

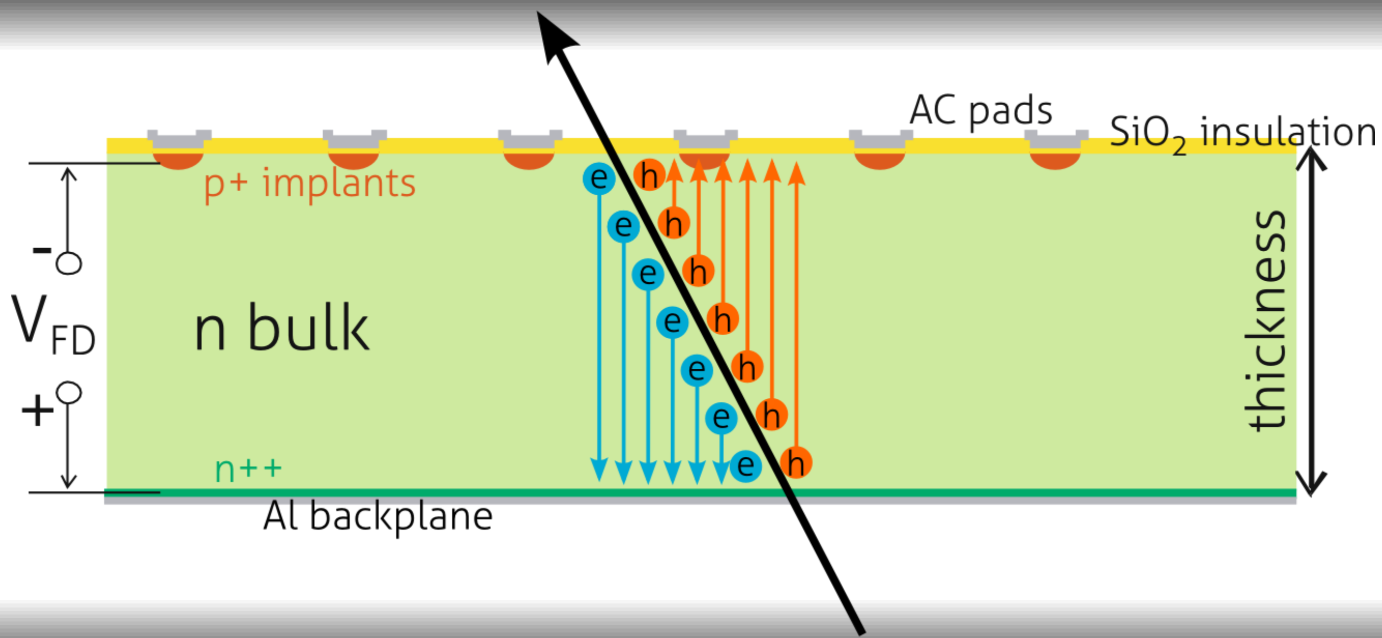


Construction timeline

Strip Tracker

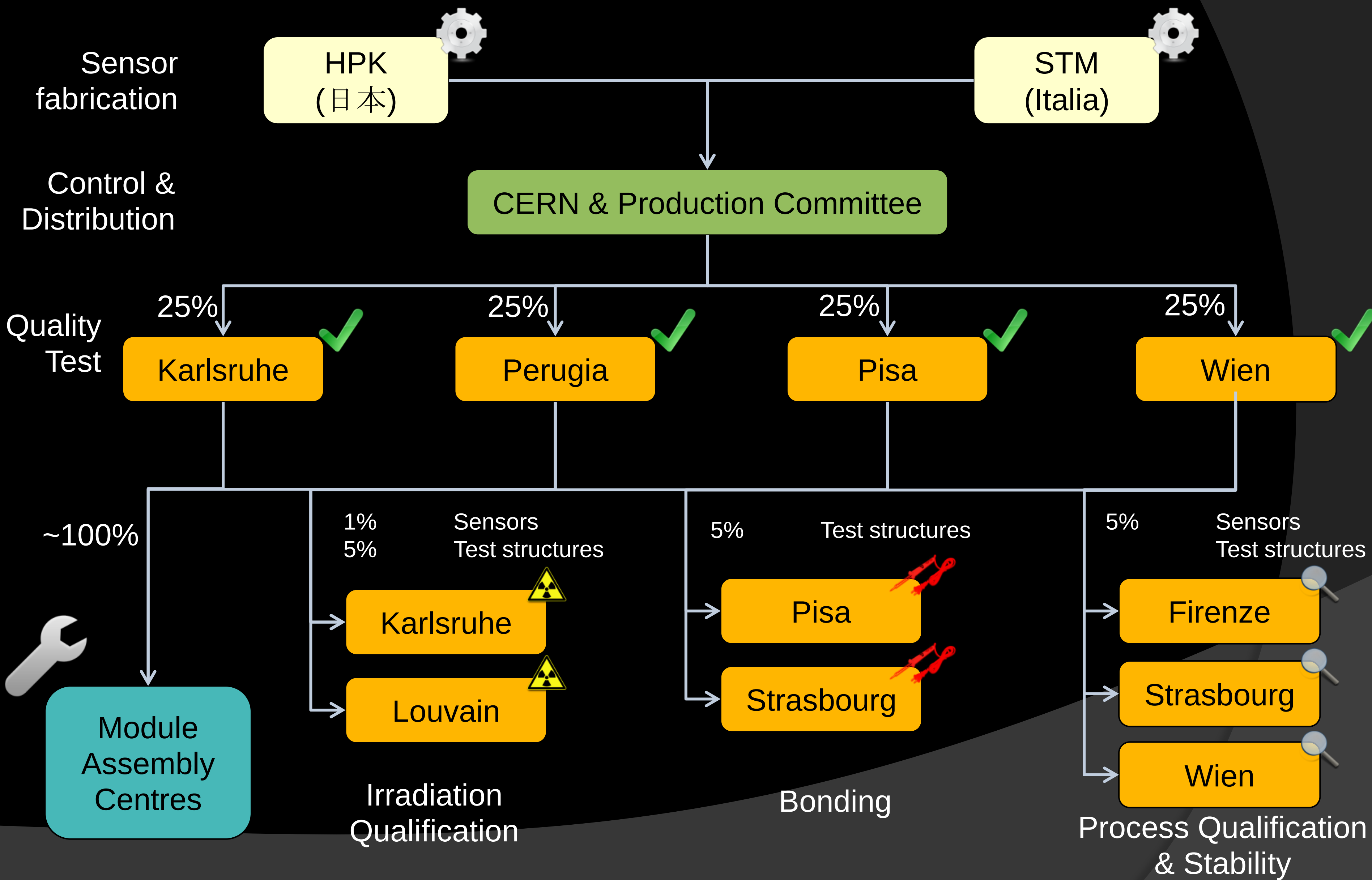
Aachen workshop	1990	
Letter of Intent	1992	
Technical proposal	1994	
Technical Design Report	1998 Apr	
Switch to all silicon	1999 Dec	
Layout defined	2000 Apr	(all basic components defined)
Module production started	2003	
Integration started	2005	
Installation	2007 Dec	→ 2008 Jul
Detector commissioned	2008 Aug	
Latest full commissioning	2009 Jul	
First collisions	2009 Nov	
Operational until upgrade	2020 ??	

Silicon sensor



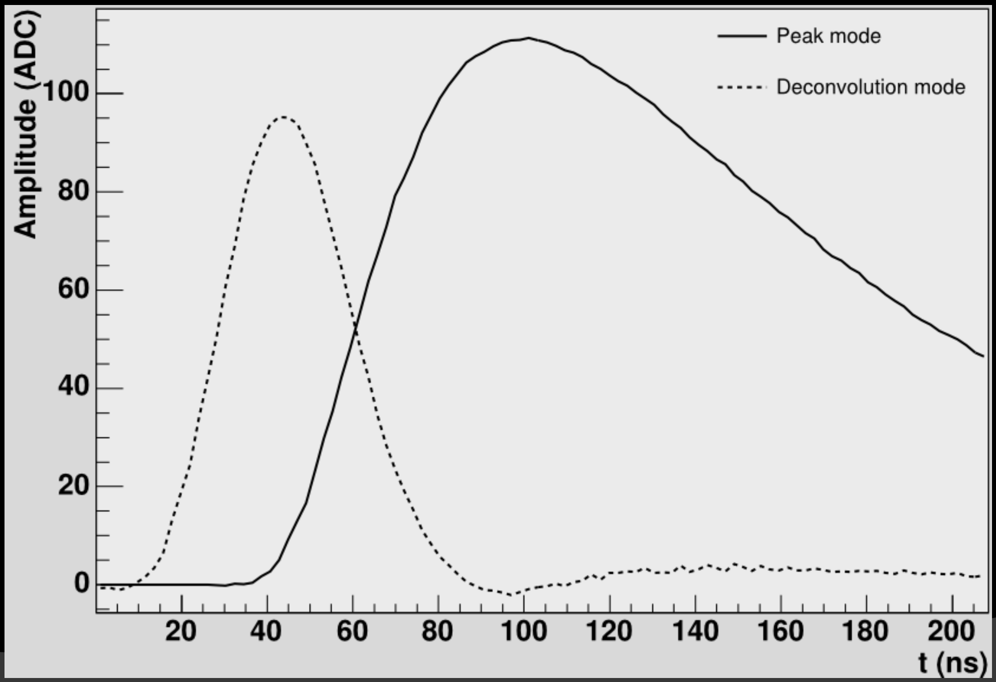
- Single-sided, AC coupled
- Float-zone, n bulk, p+ strip implant (Type inversion)
- Thickness: 320 and 500 µm (S/N, rad-hard)
- Resistivity: 1.25-3.25 and 2.5-7.5 kΩ (VFD)
- Pitch: 80 – 200 µm (Resolution, occupancy)
- <100> crystal orientation (Charge accumulation)

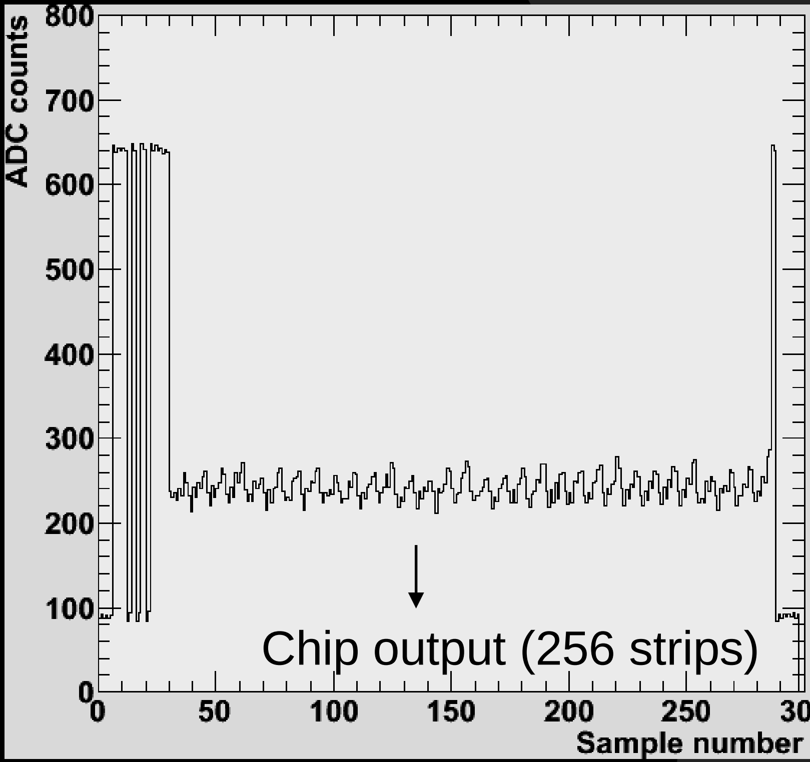
Sensor production



The APV25 front-end chip

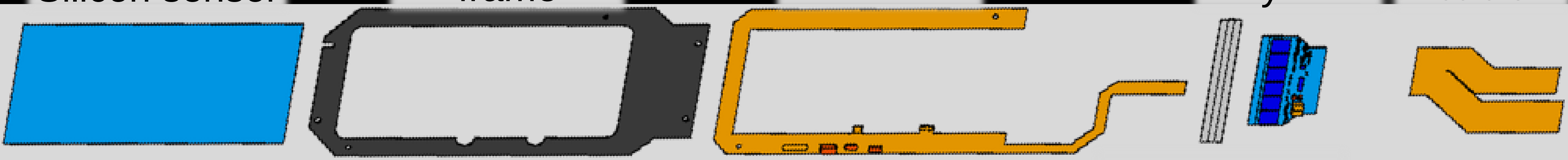
- 0.25 μm IBM technology
- 128 channels in parallel
  - Amplified
  - Shaped
  - Buffered in a pipeline
    - 192 bunch crossing
    - 4.8 μs maximum trigger latency
- Multiplexed upon trigger

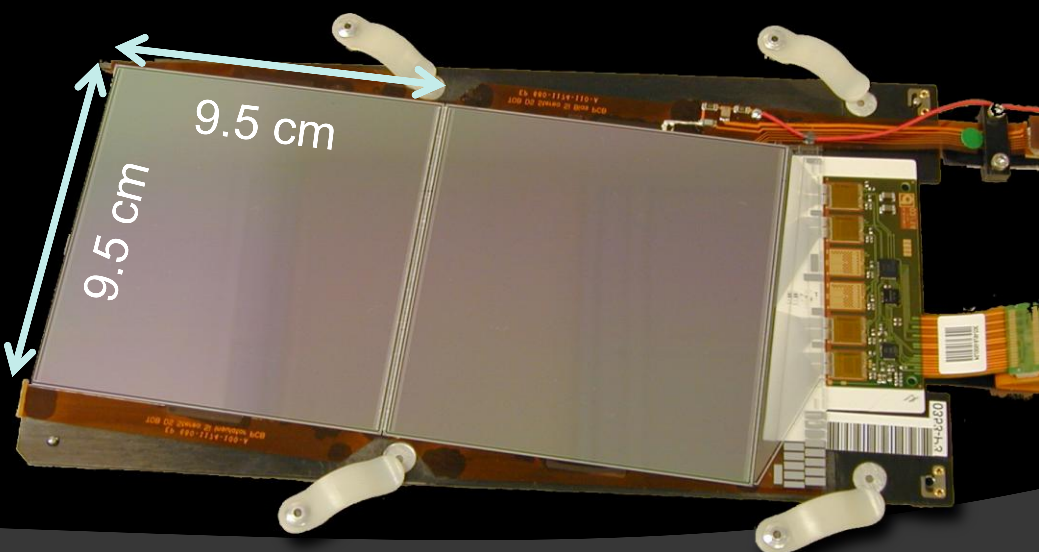




- Analogue output
  - Peak mode
    - Early operation
  - Deconvolution mode
    - Nominal operation
    - 3 samples combined
    - Faster, but higher noise

Module components

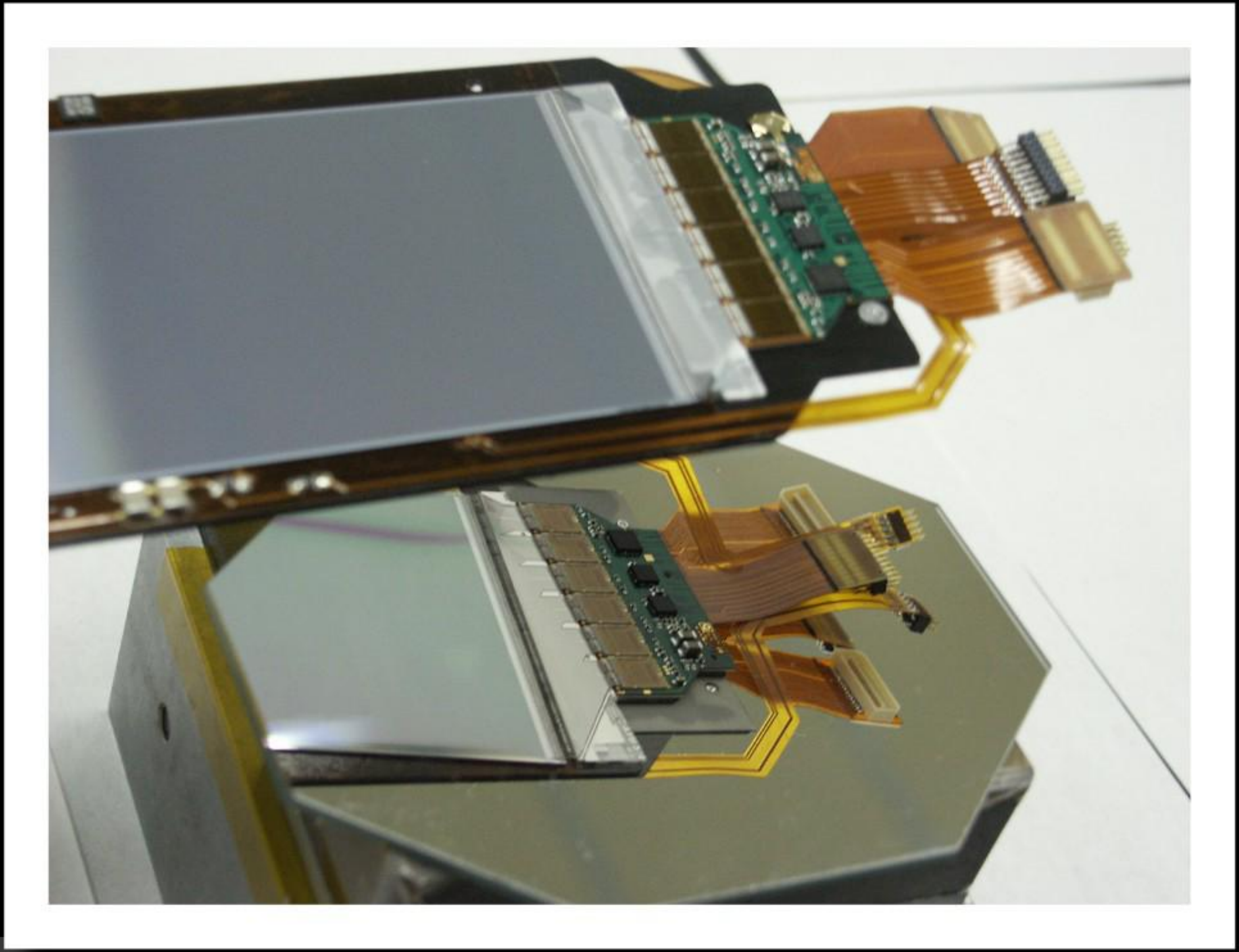




- All single-sided
- 15 sensor geometries
- Assembled with gantry: 10 μm precision
- APV25: ¼ μm technology, maximum dose of ~ 70 kGy
- DCU: local multi-purpose probe with unique ID

Double-sided module

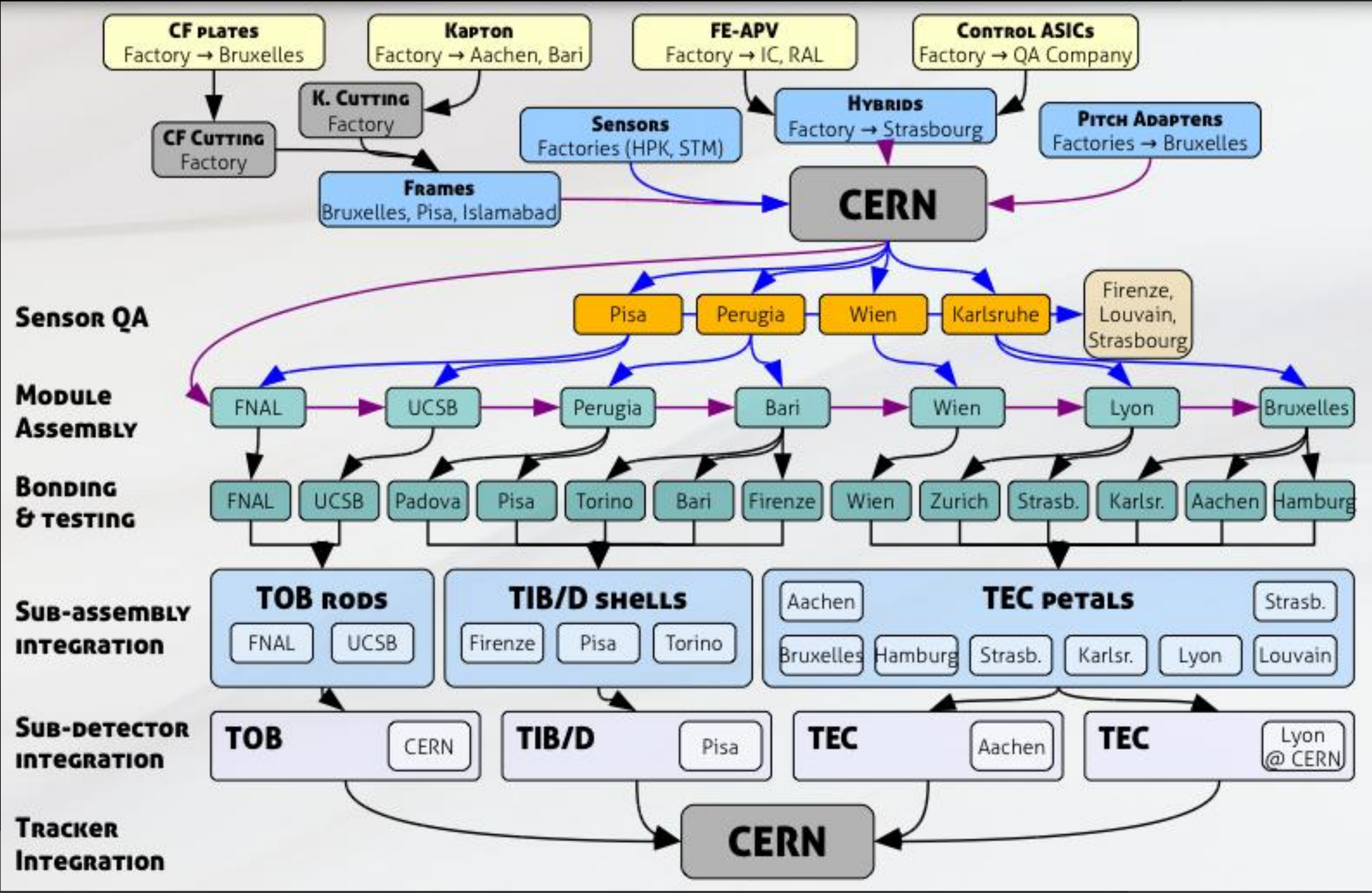
- Made of two back-to-back detectors (100 mrad tilt angle)



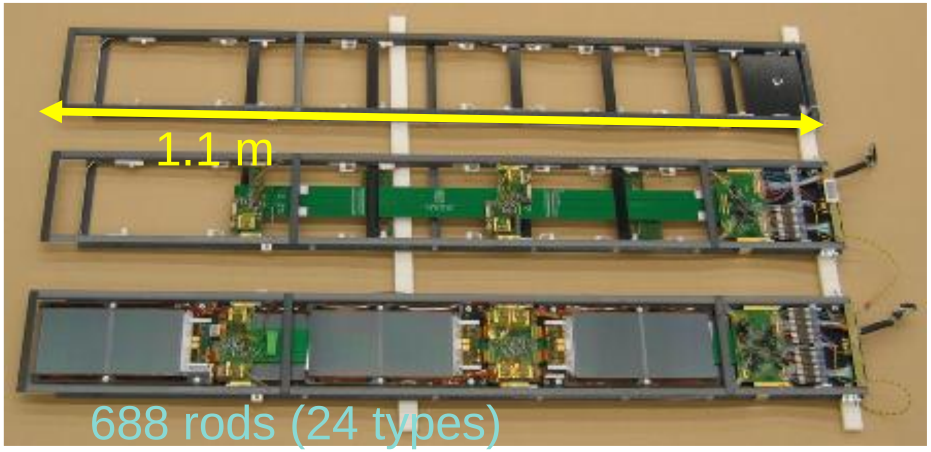
Module production sites

…spread all over the North hemisphere…

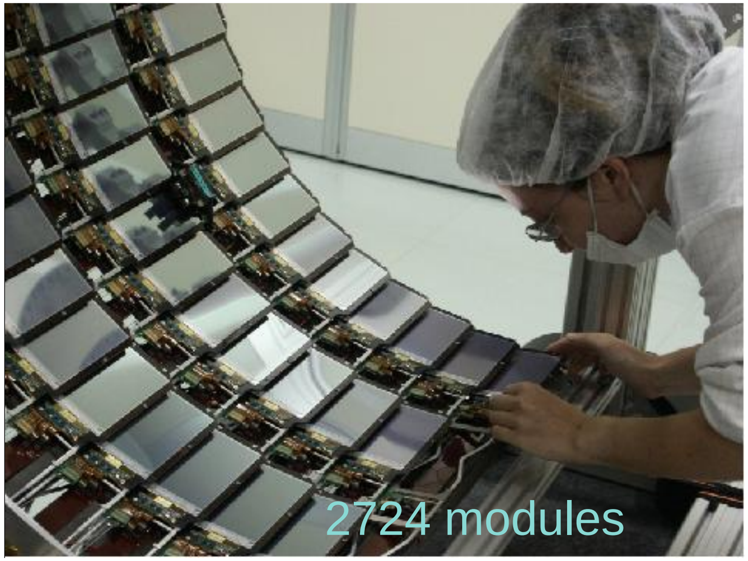
The tracker construction flow-chart

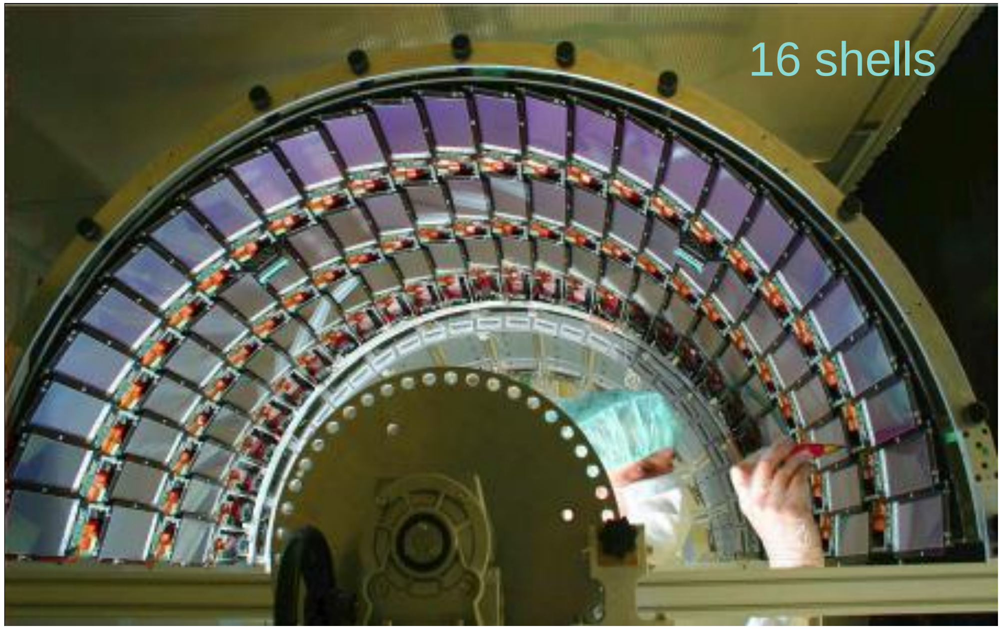


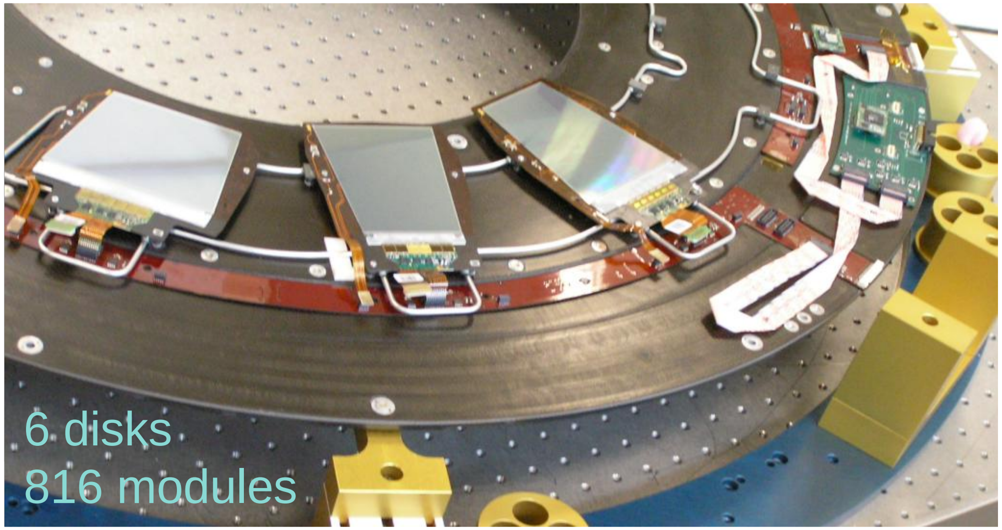
TOB: US + CERN



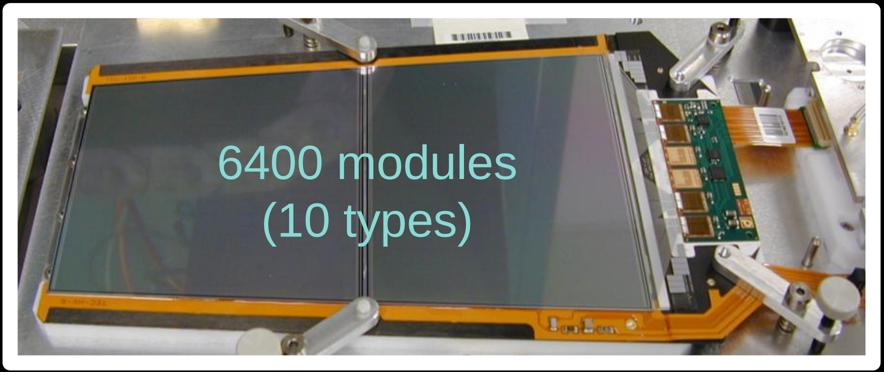
TIB/TID: Italy

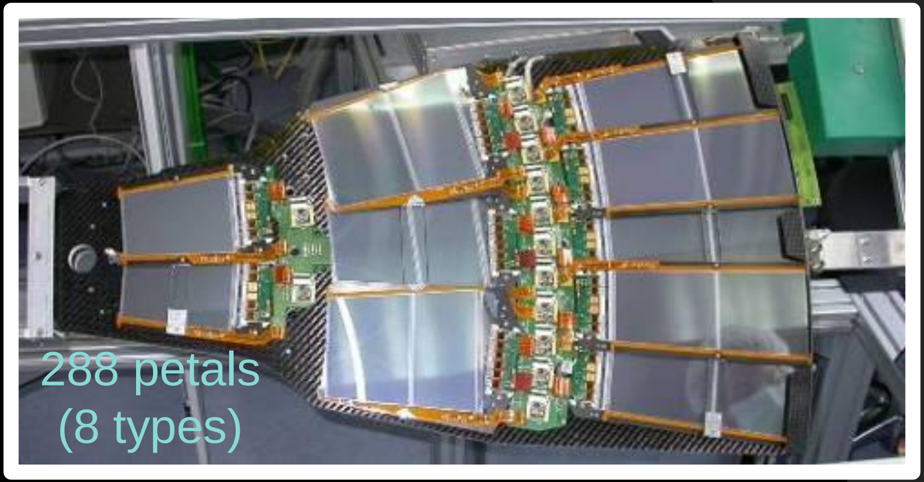


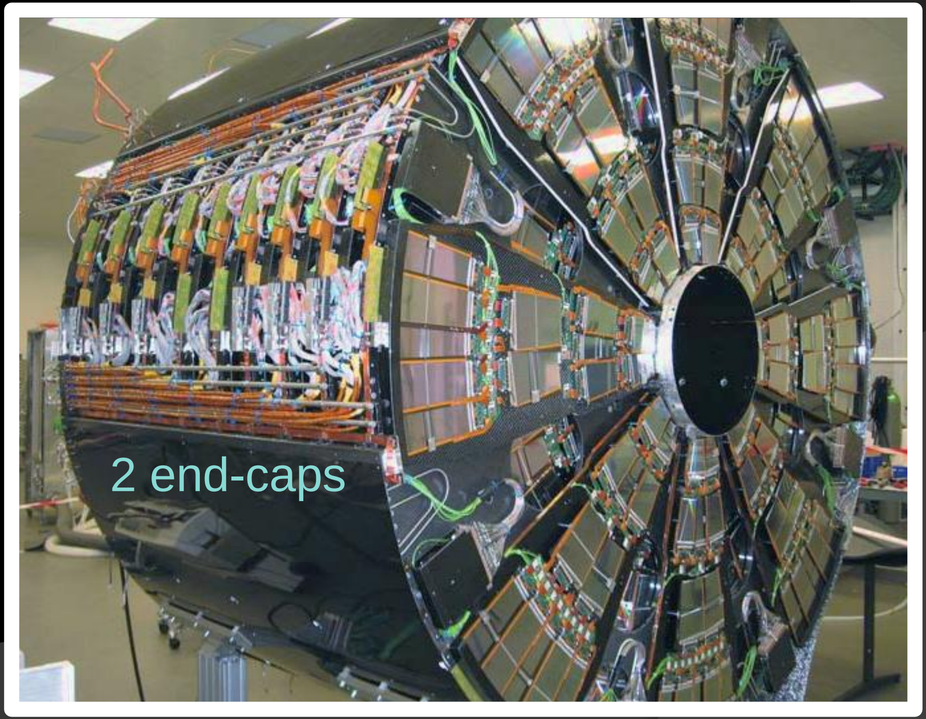




TEC: Central Europe

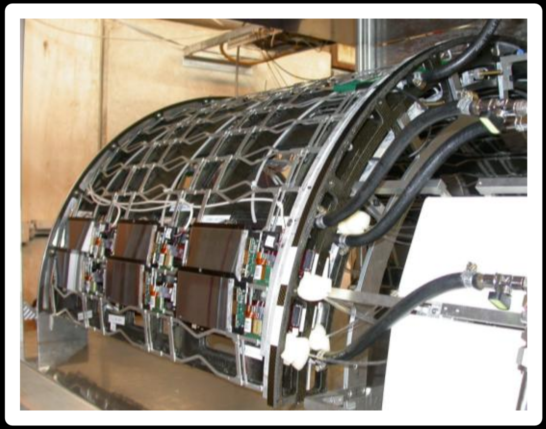


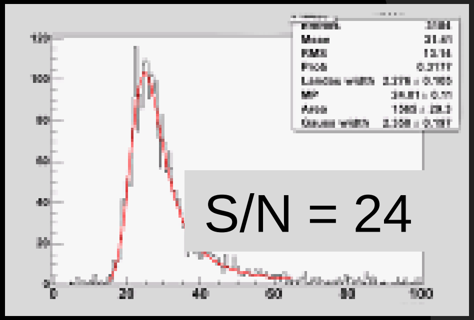


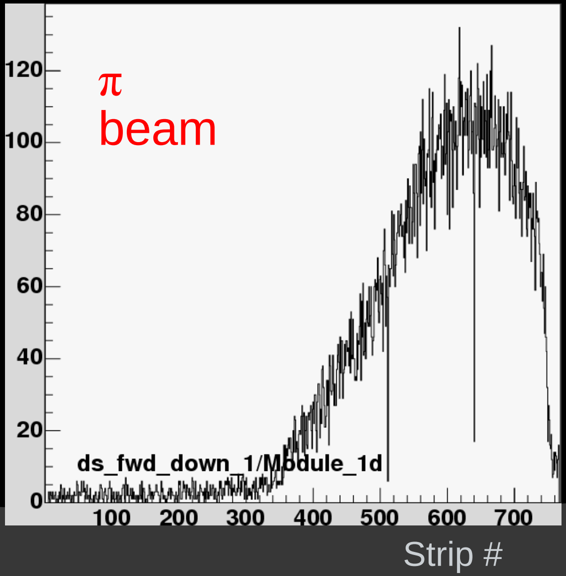


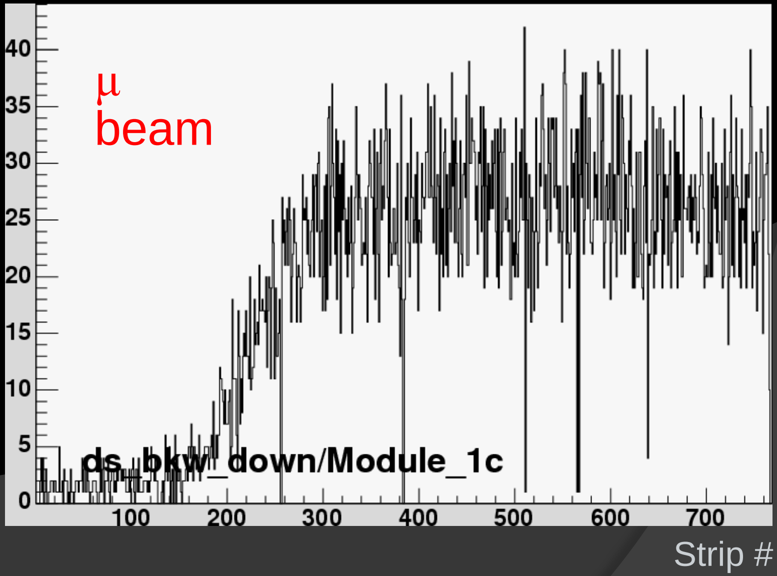
Many system tests

- Test beams: 1‰ (up to 2005)





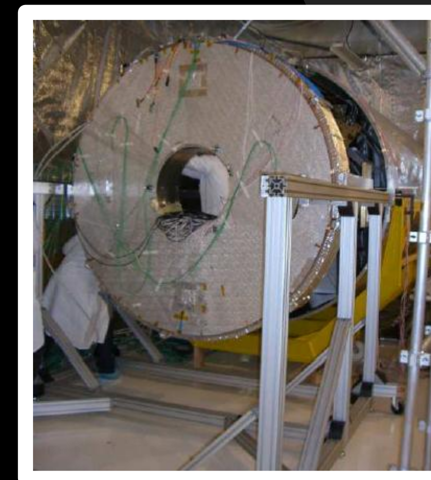


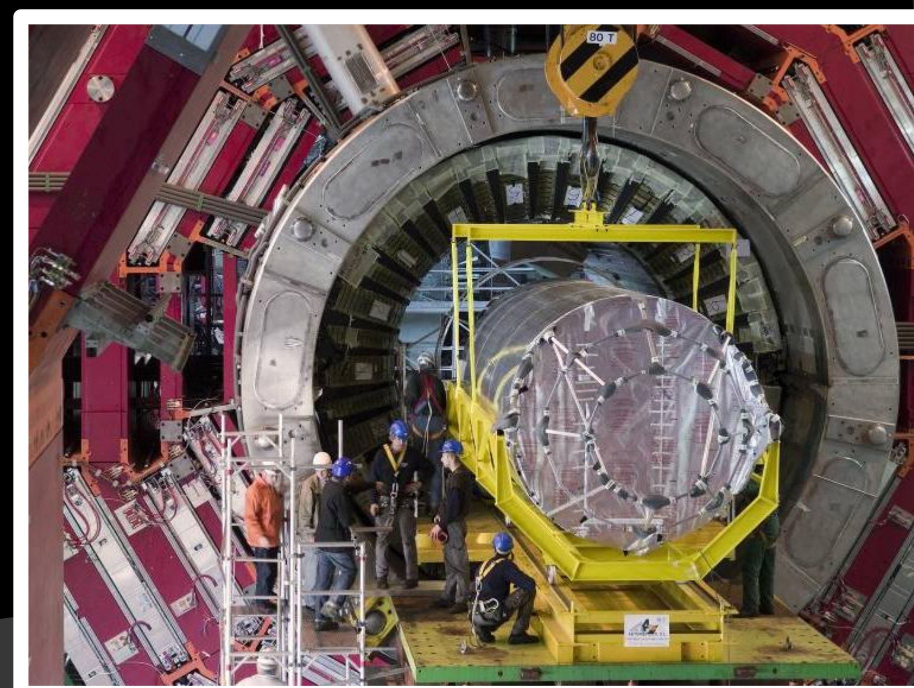


Many system tests

CMS milestone in summer 2006:

- Magnet test – cosmic challenge:
  - Test and commission the Magnet
  - Map the magnetic field
  - Check closure tolerances
  - Check noise and inter-operability
  - Trigger and record comic rays
- The Tracker participated with 1%
  - Validation of the transport
  - Exercise of tracker cabling
  - Measure performance
  - Exercise commissioning
  - “Global” data taking





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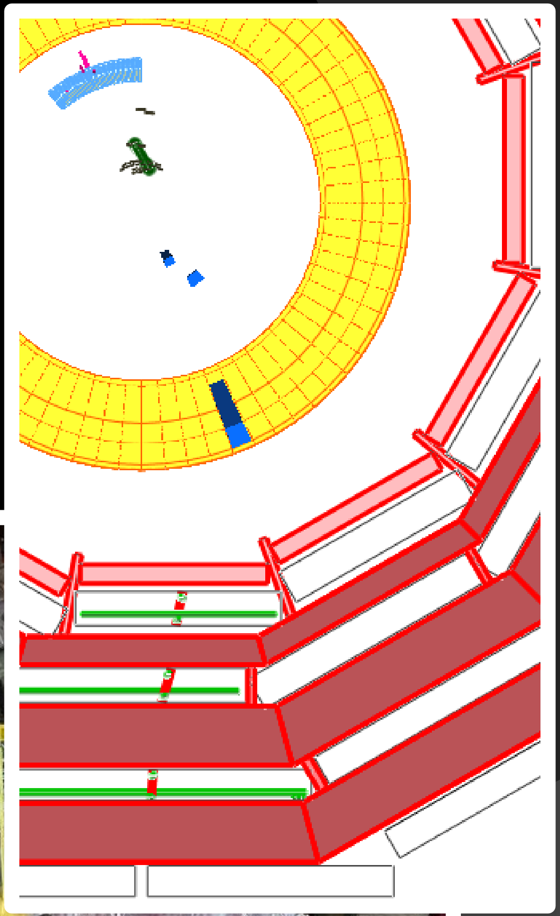
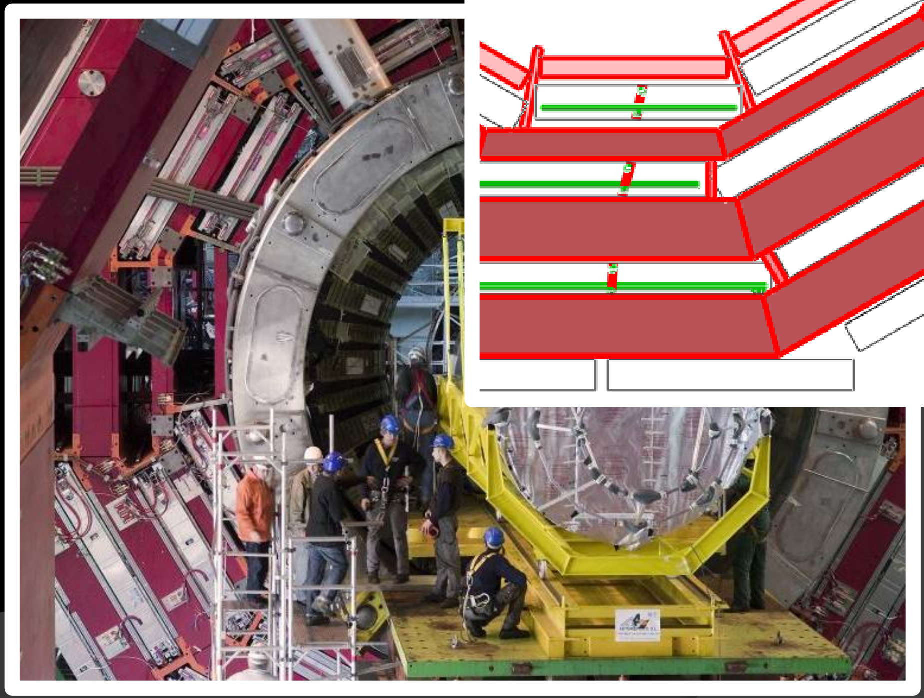
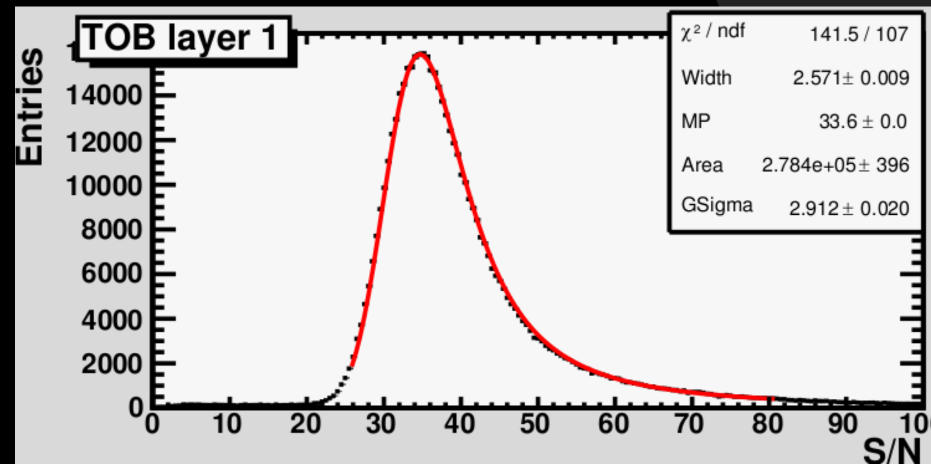
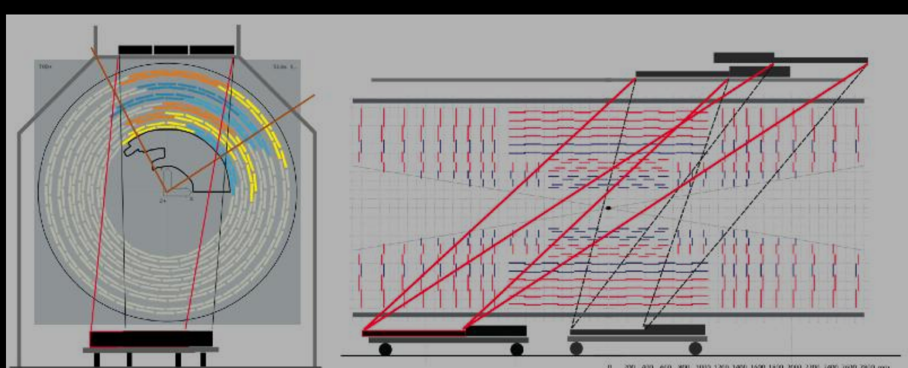
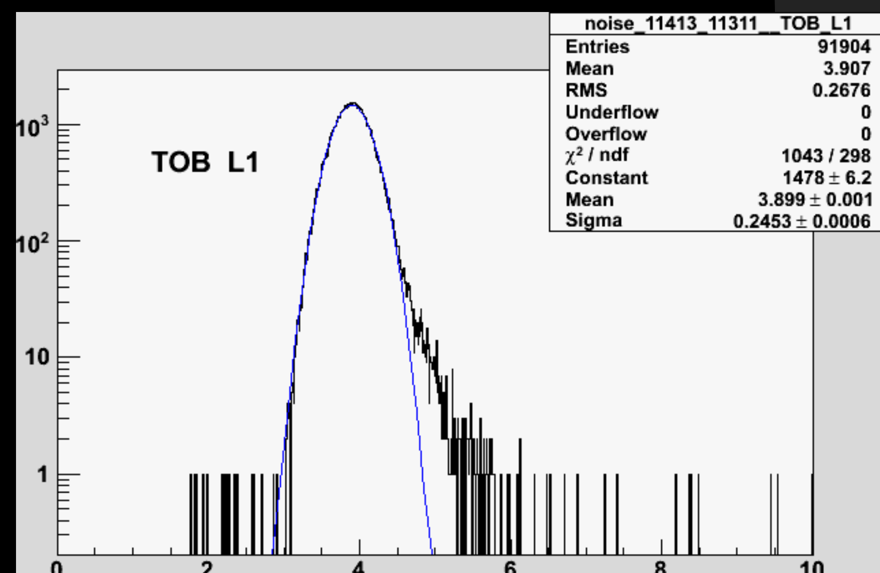



Many system tests

- Tracker integration (2007)
  - ~ 12% test of
    - Cooling
    - Power
    - Readout
  - Operation of safety, monitoring, DAQ systems
  - Commissioning procedures
  - Noise, tracking efficiency, alignment, resolution

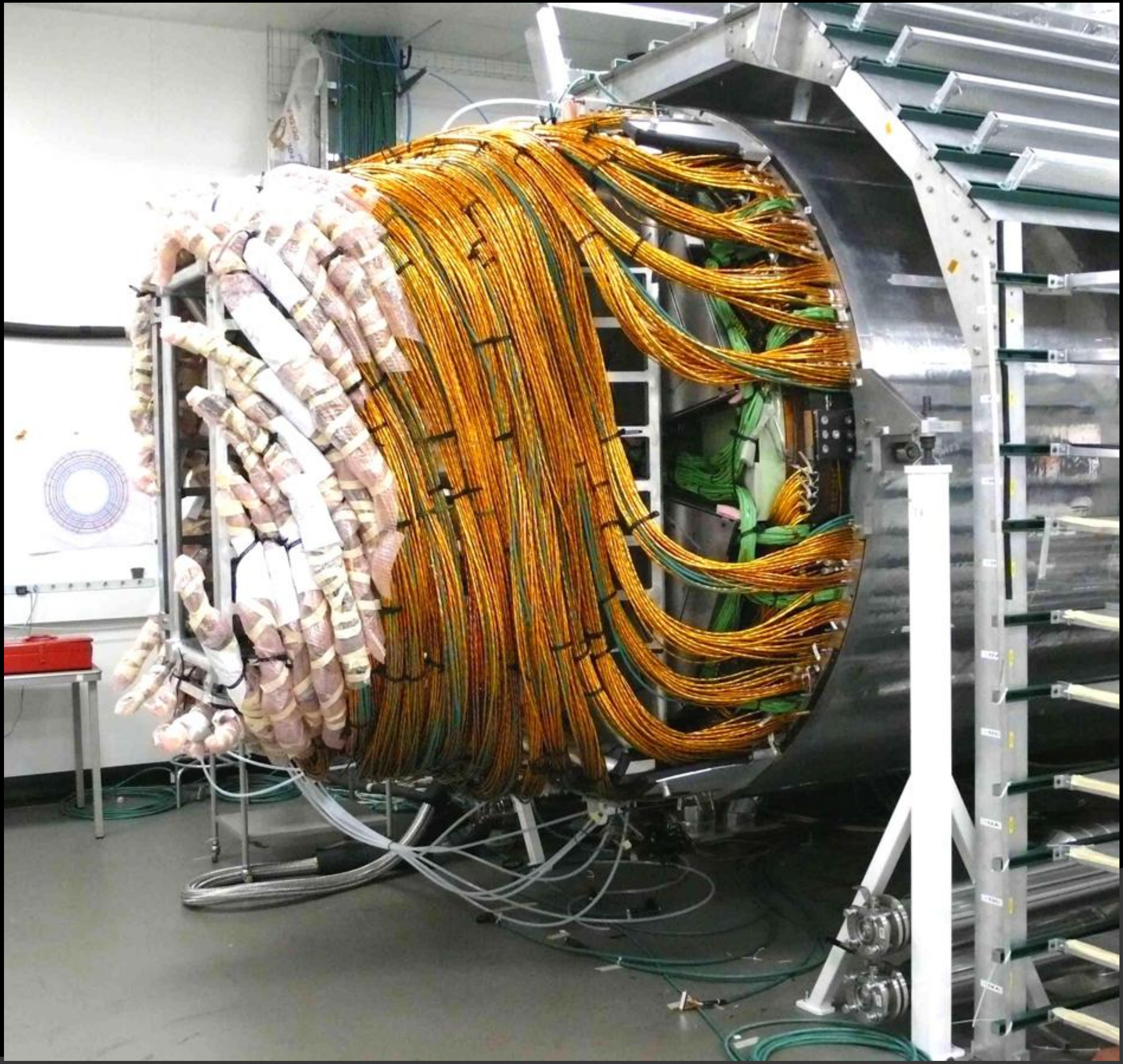






Noise (ADC)

Ready to go…



The Tracker goes to P5

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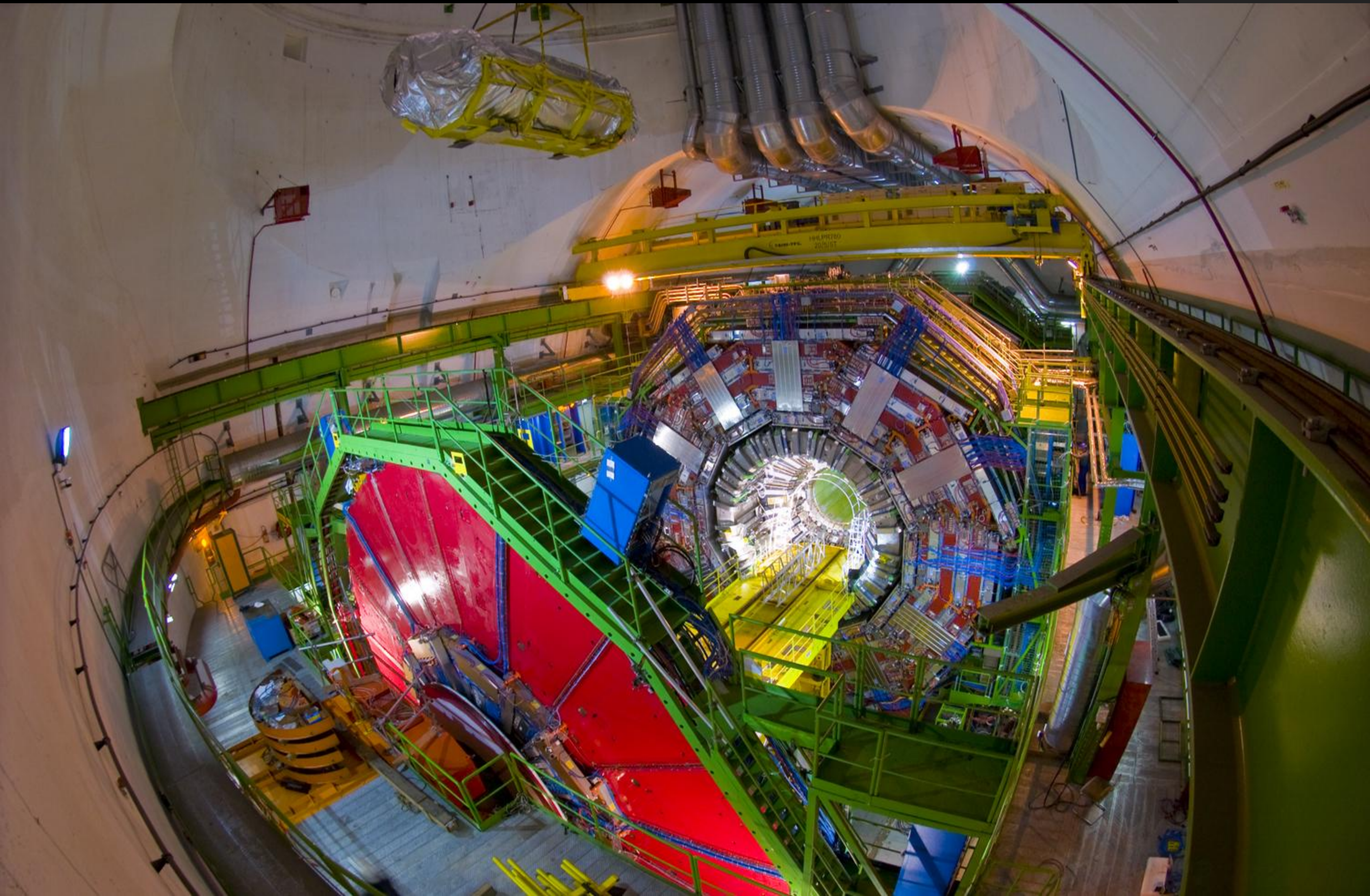
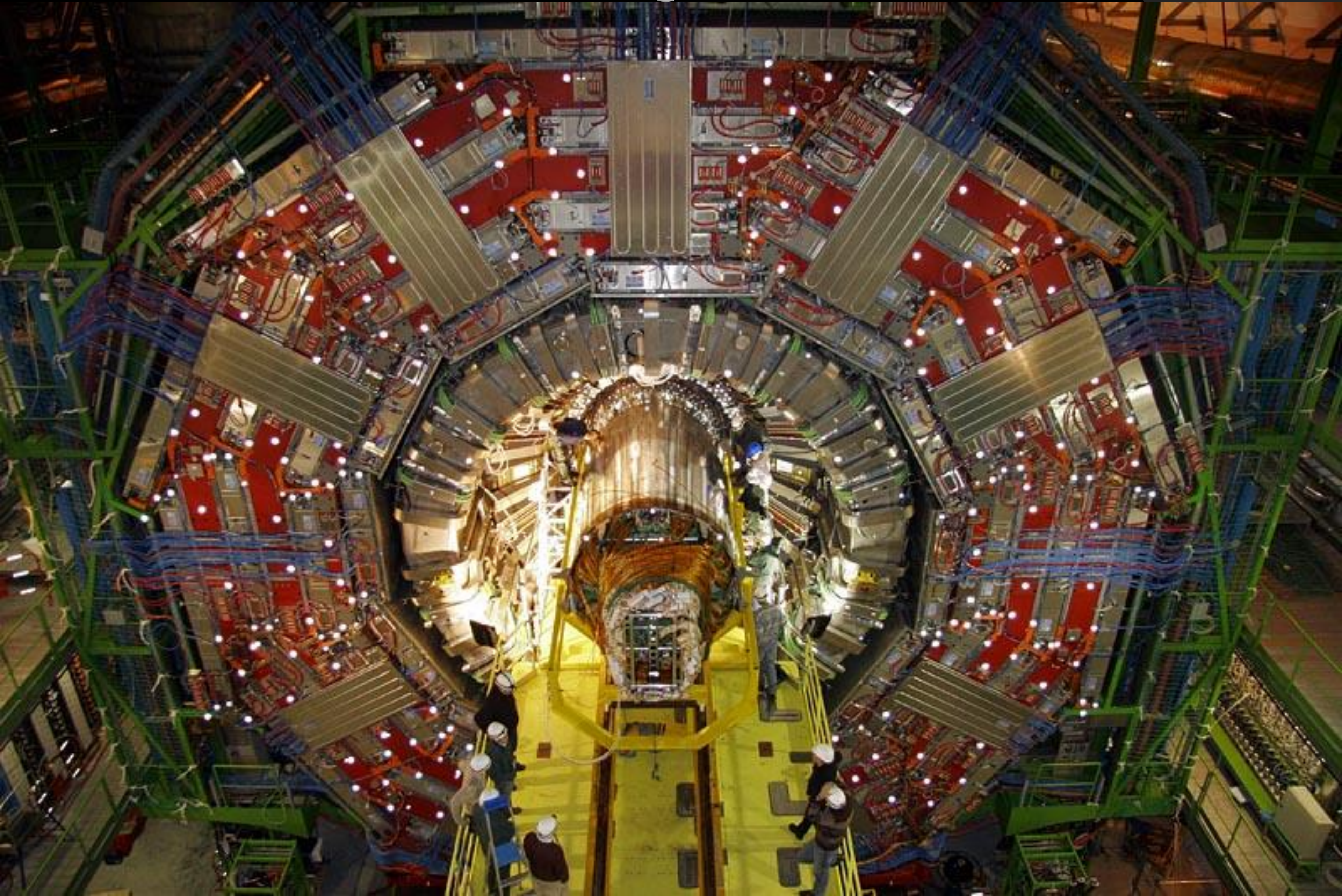


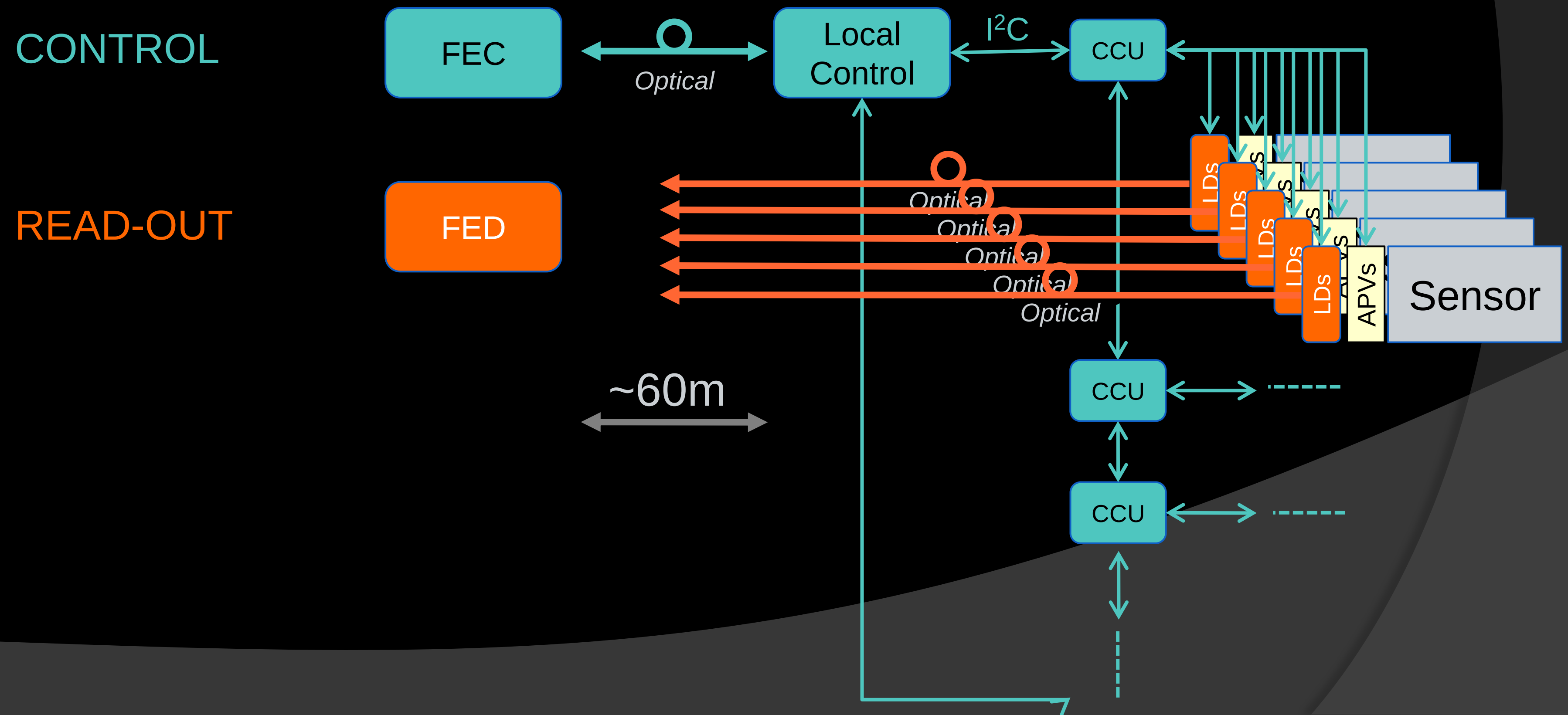
The Tracker goes into CMS



Control and readout architecture

- **Read-out system**
  - Based on the FE chip APV25 and Front-End Driver (FED)
    - APV25: analogue signal amplified, shaped and buffered in a pipeline
      - Sent via analogue optical link
    - FED: signal processing:
      - ADC + Data reduction (pedestal and noise subtraction, cluster finding)

- **Control system**
  - Based on FE chip CCU and Front-End Controller (FEC)
    - Token ring bidirectional digital flow (via optical link)
    - Slow control commands
    - Clock and trigger signal
    - Monitor the front-end electronics

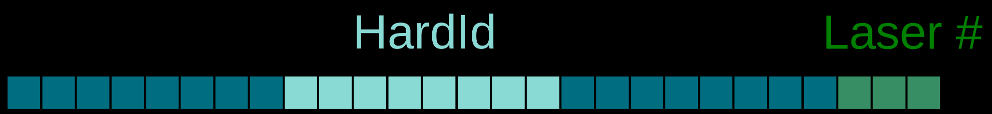


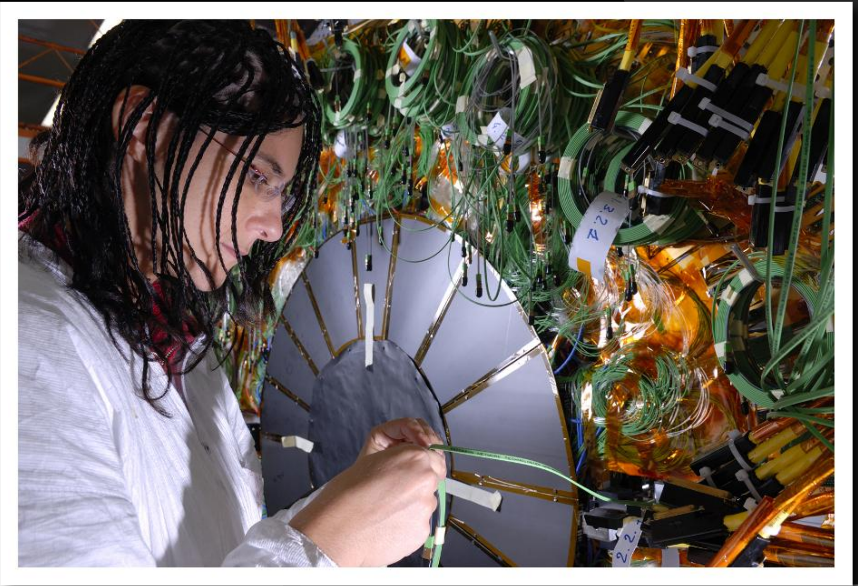
Commissioning tasks

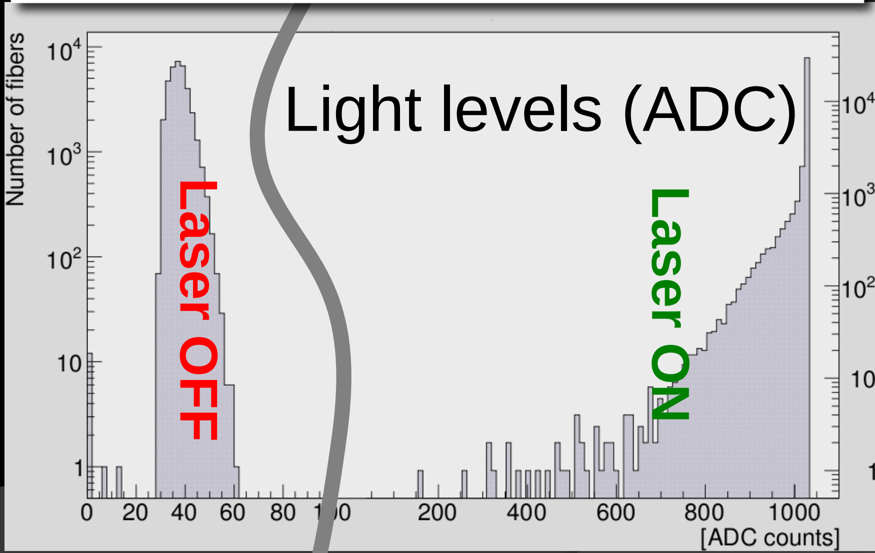
- Check of connection
  - Power supply cabling
  - Optical cabling
- Internal timing
  - Synchronization of all channels to include different fibre length
- Chip parameter tuning
  - Optical gain
  - Analogue baseline
  - Pulse shape
- Pedestal & noise
  - for FED on-line data reduction
- Timing adjust
  - Coarse (BX) synchronization of with CMS trigger
  - Fine tuning of pulse shape sampling (tune to 1ns level)

Example: optical cabling check

- Which channel is connected where???
  - Each module:
    - 3-byte code hard-wired (HardId)
    - 3 possible analogue out
    - Effective 27-bit id for each channel





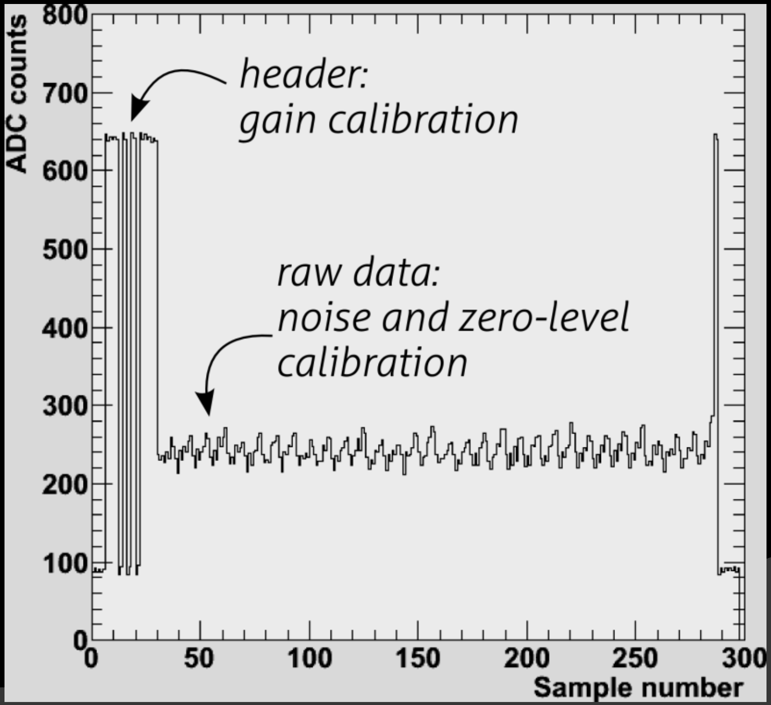


  - All lasers ON/OFF according to the n-th bit
  - Quick identification of the module connected to each readout channel
- 99.2% of channels identified!

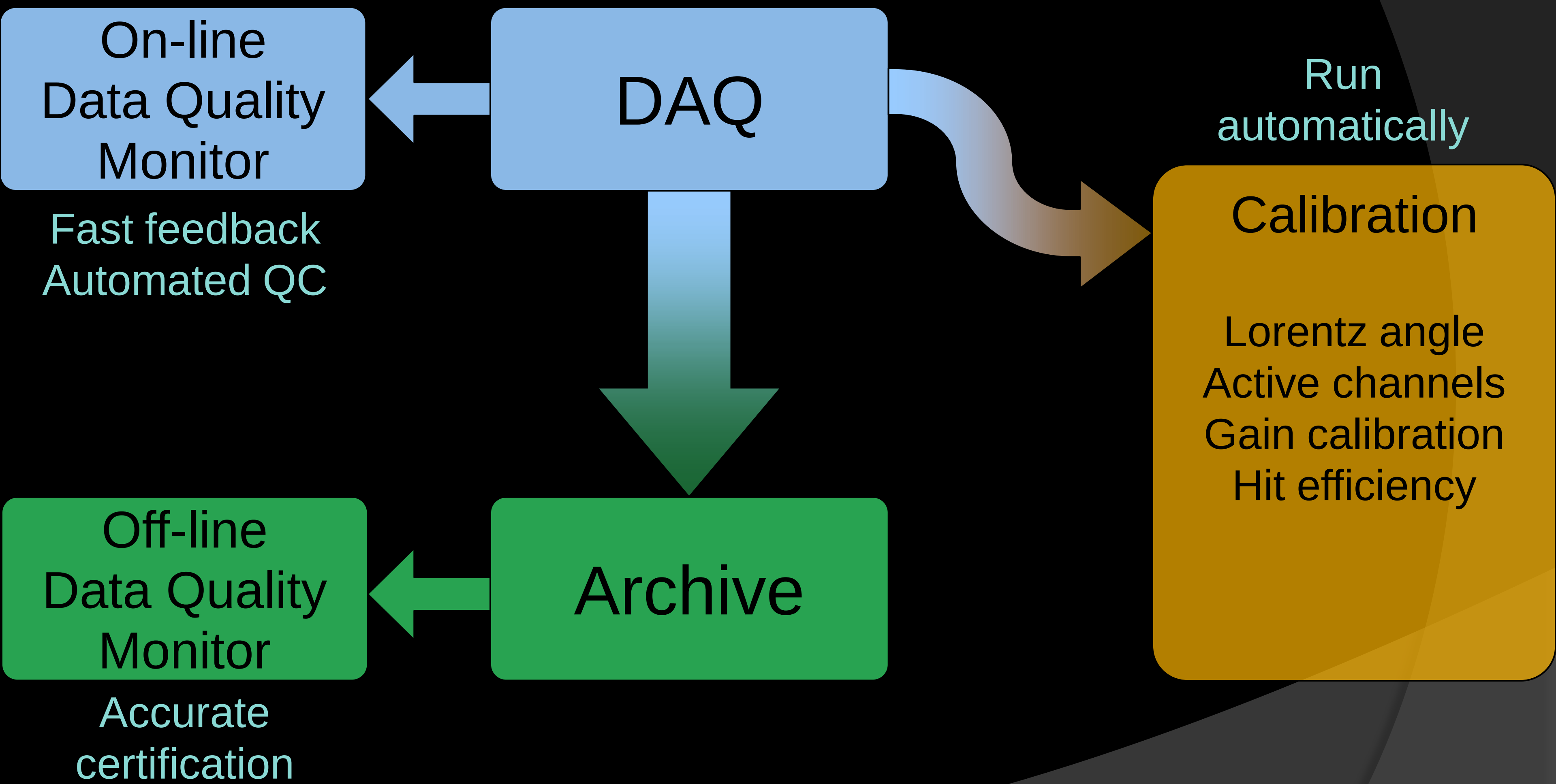
Spy channel

- Provides direct access to the front-end raw data stream for a fraction of events during normal data taking (physics runs)
- Snapshots of events at ~ 0.3 Hz
- Full information available: raw data from all 9 M channels
- Used to monitor calibration under real conditions

◉ "Goldmine of possibilities for monitoring and debugging"



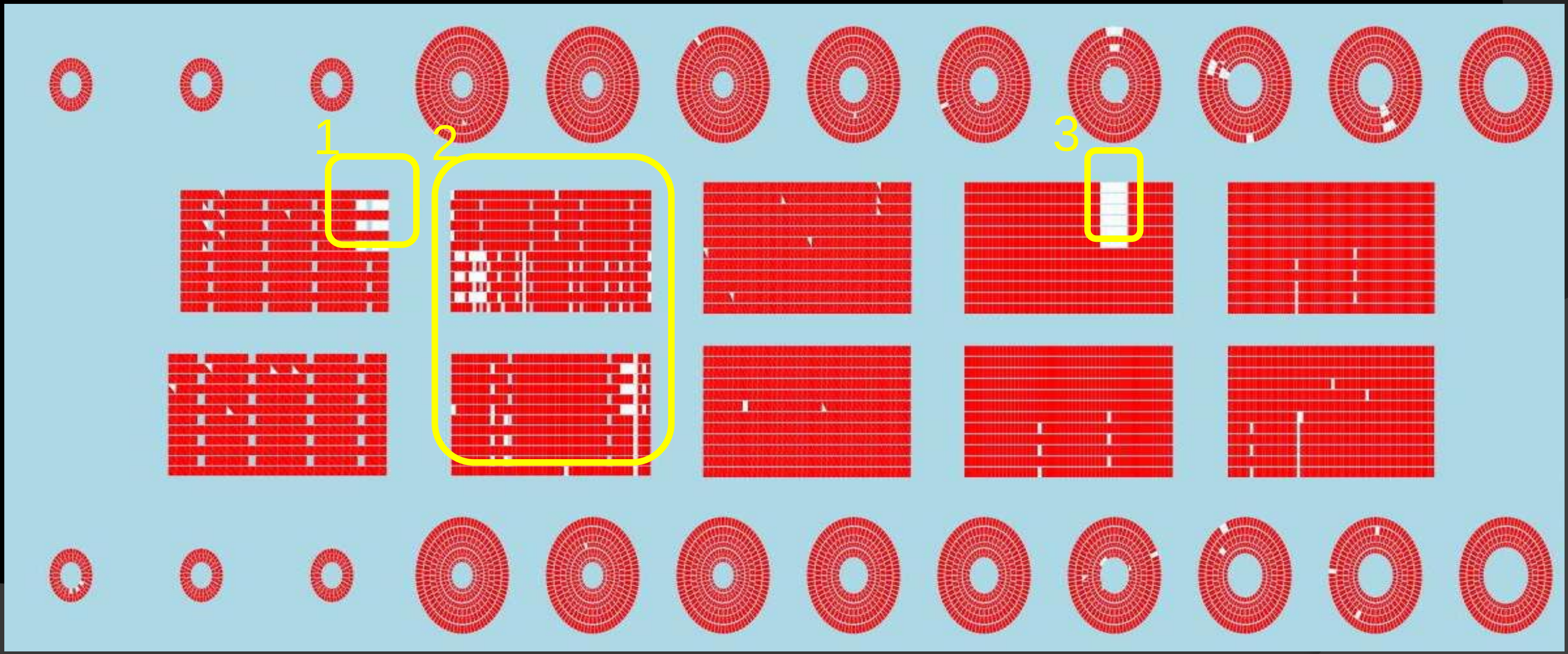
Operation


On-line
Data Quality
Monitor
DAQ
Run
automatically
Fast feedback
Automated QC
Calibration
Lorentz angle
Active channels
Gain calibration
Hit efficiency
Off-line
Data Quality
Monitor
Archive
Accurate
certification

Active channels

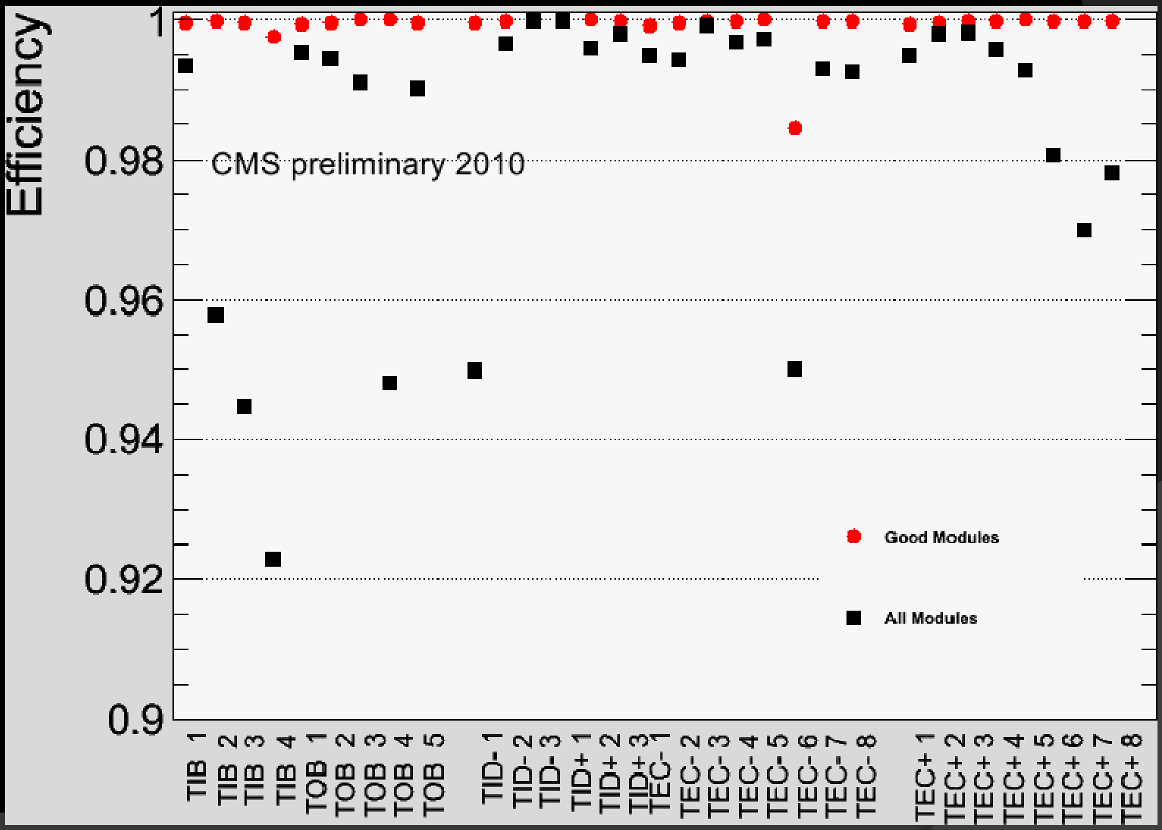
	Percentage	Total Modules
TIB/TID	96.25	3540
TOB	98.33	5208
TEC-	99.13	3200
TEC+	98.81	3200
Tracker	**98.1**	**15148**

- Missing channels mostly due to:
  - Shorted Power group
    - Electrical connections…
  - Some HV lines shorted
    - Electrical connections…
  - Control ring failure
    - Electrical connections…



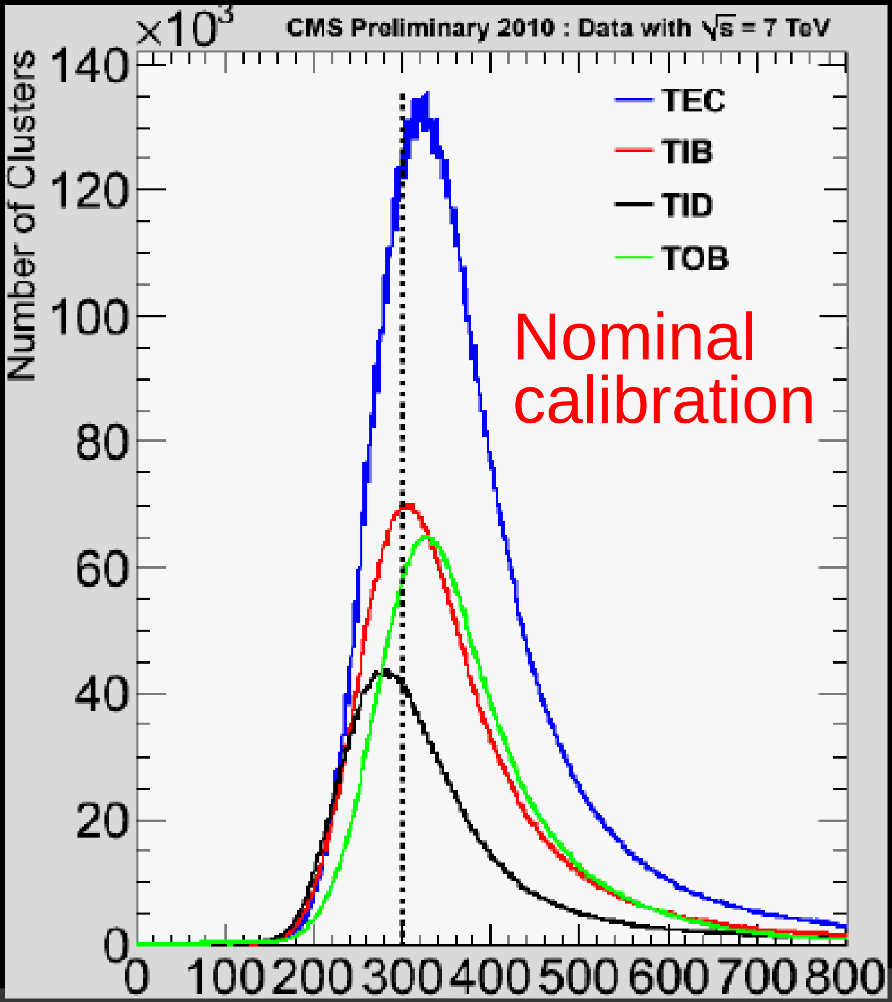
Single hit efficiency

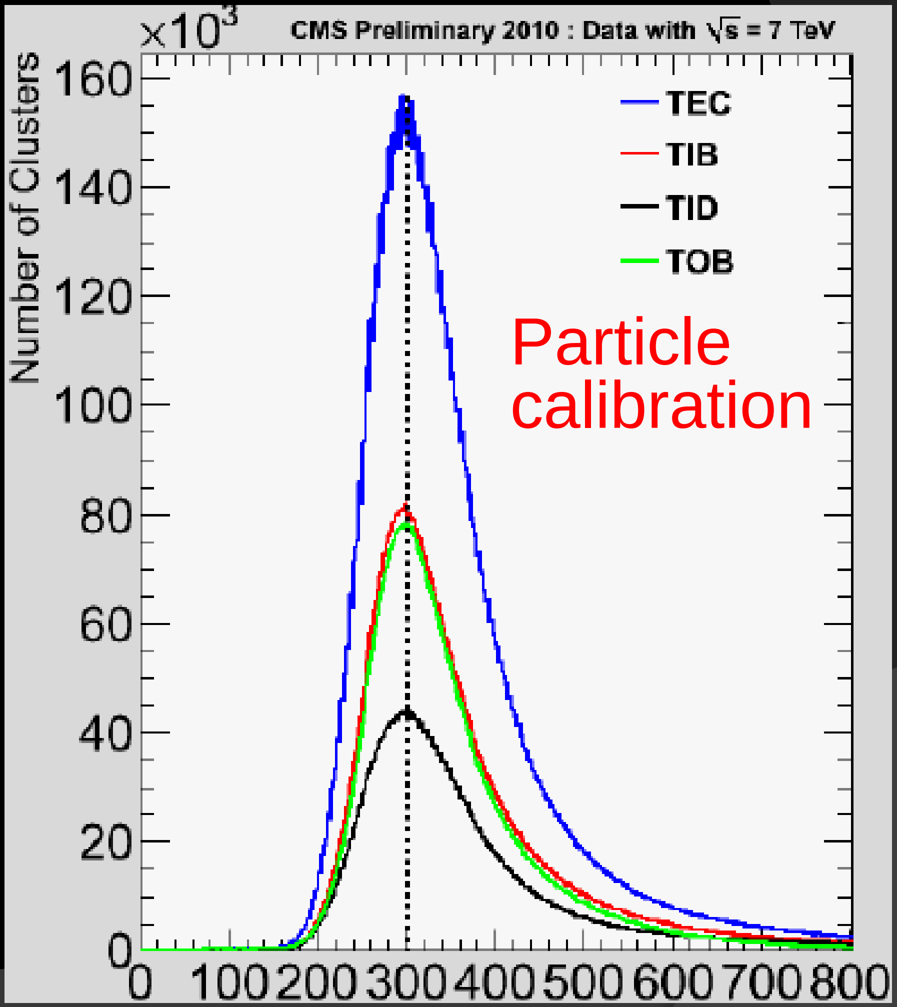
- Monitoring tool to find inactive modules
- Search for hits in modules where it is expected
- ε ≈ 100% in good modules



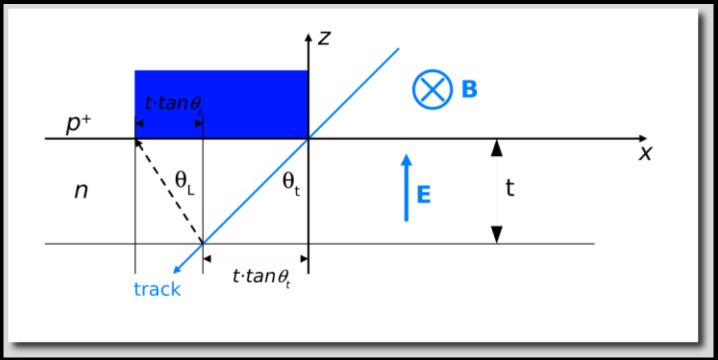
Calibration with particles

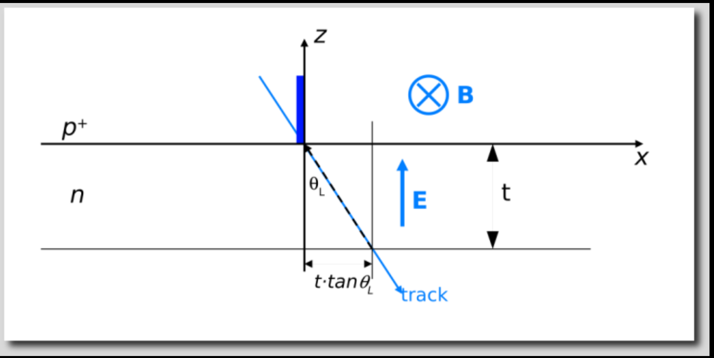
- Each module: signal MPV equalized



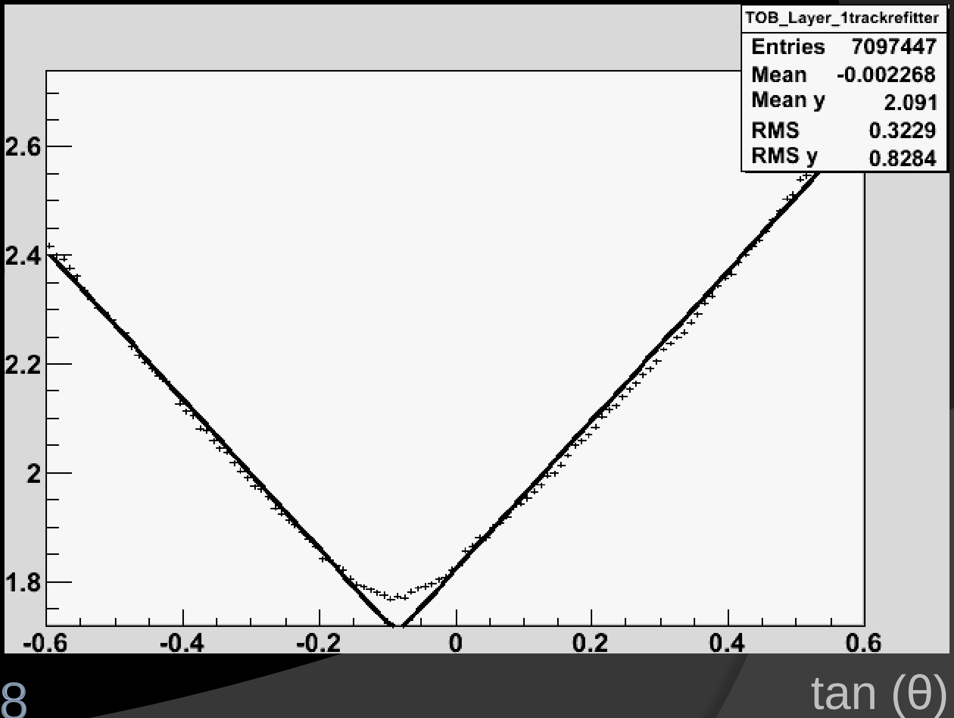


Lorentz angle





- Cluster width minimal for θ=θL
- tan(θL) = μH × B
- μH depends on temperature

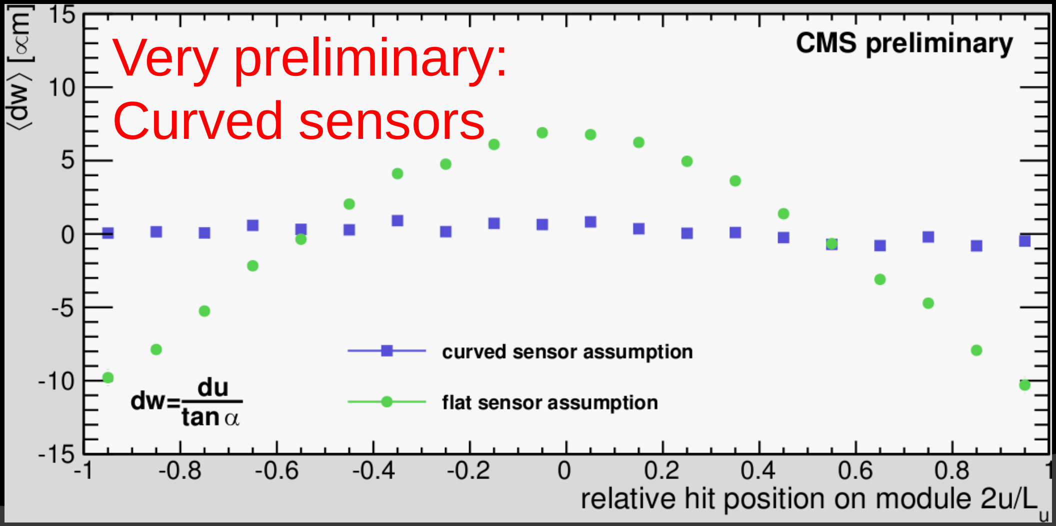


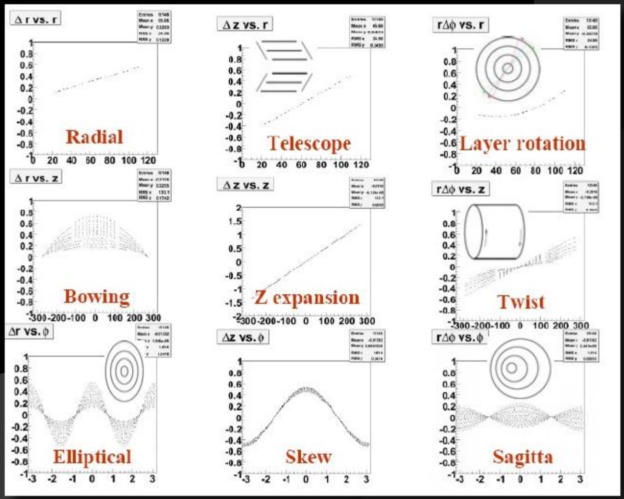
- Measured by layer
- Average values
  - μH (TIB 320 μm sensors) = 0.018
  - μH (TOB 500 μm sensors) = 0.025

The alignment puzzle

- 100'000 d.o.f.
- Hierarchy approach
  - Modules
  - Substructures
  - Macro-structures
- Aligned since first collisions
- Good resolution

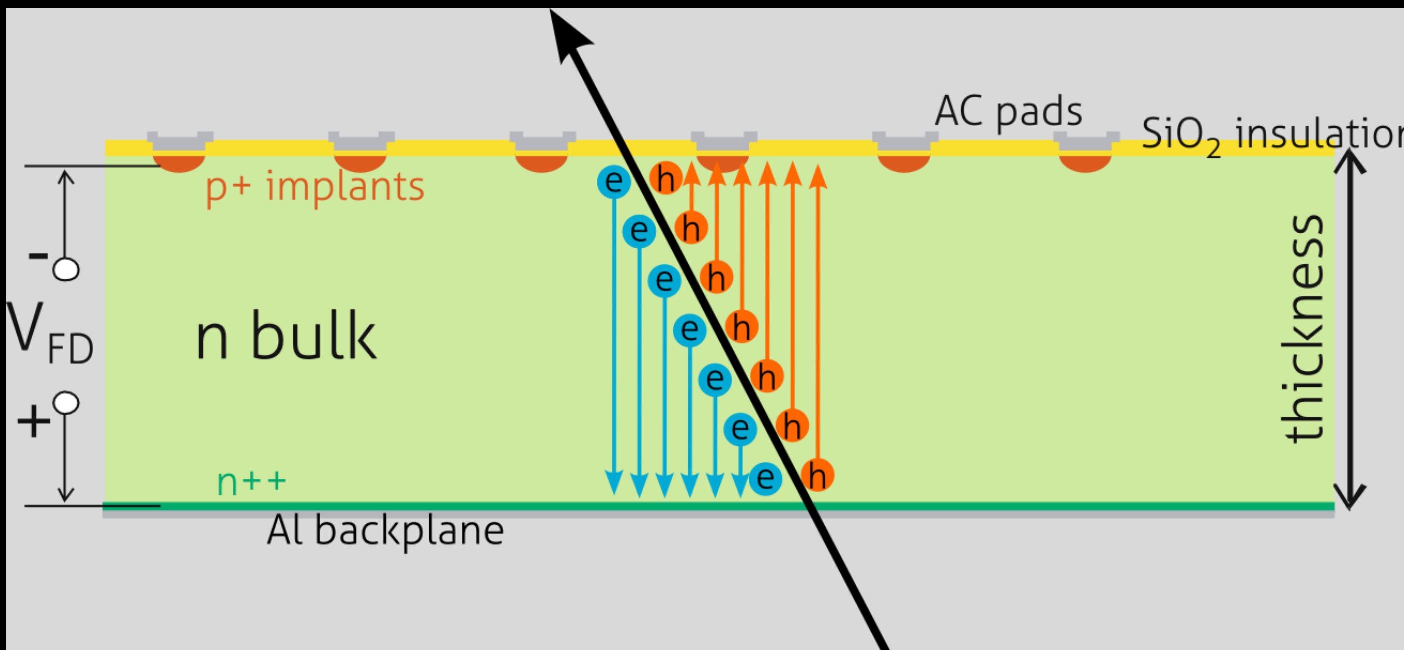
	Collision [μm]	MC startup [μm]	Ideal [μm]
TIB	**5.1**	10.1	3.2
TOB	**7.5**	11.1	7.5
TID	**4.3**	10.4	2.4





Unexpected shift

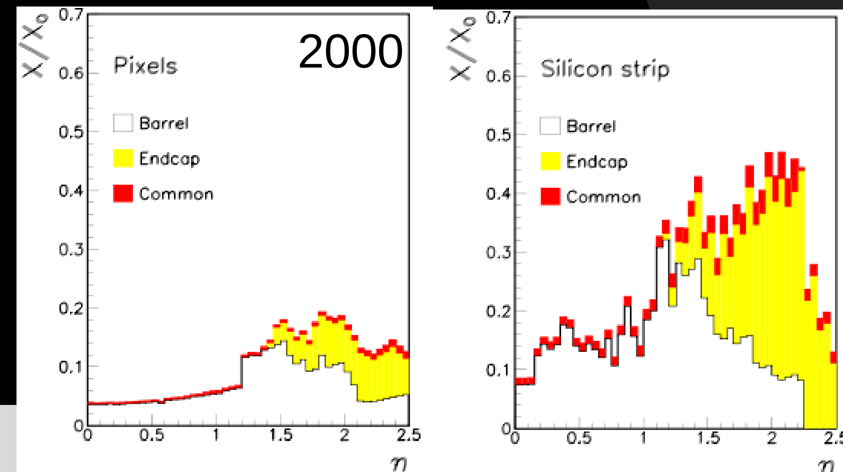
- Mode change: peak → deconvolution
- Alignment constants changed (!)
- Also visible in Lorentz angle analysis

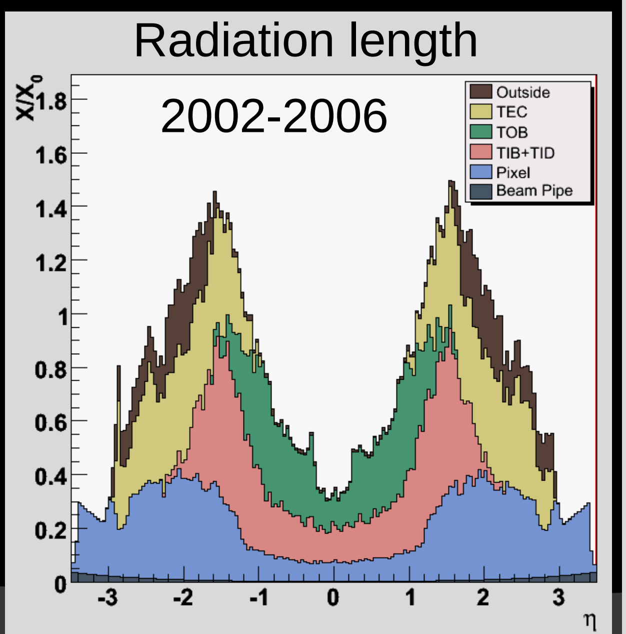


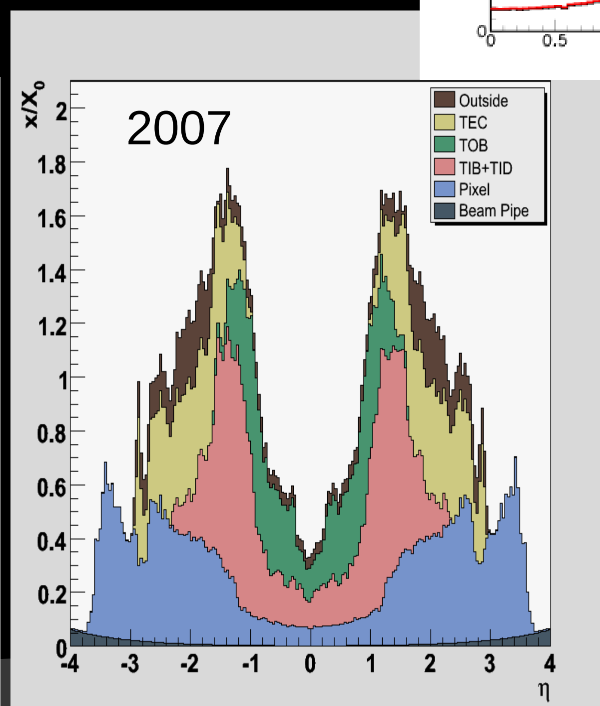
- Electrons signal unchanged
- Holes only partially contribute to signal, due to slow drift
- Effect unforeseen at design time

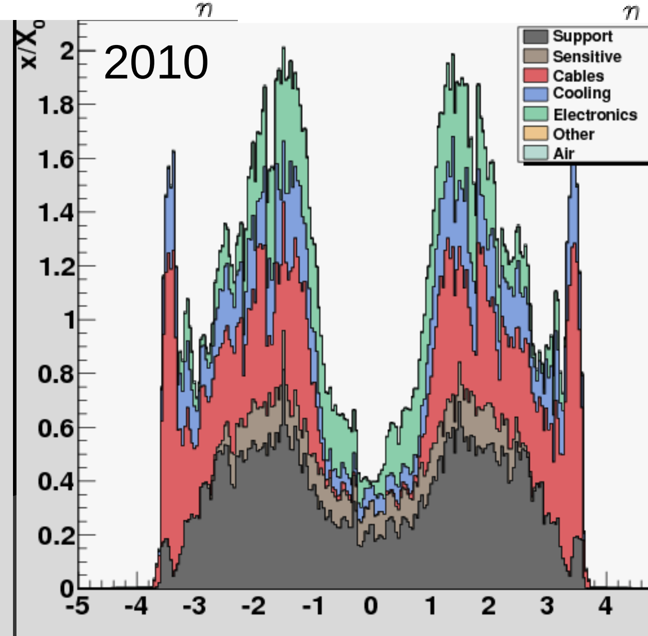
Material distribution

- Estimate of material amount increased with time
  - Optimistic assumptions
  - Simplified parameterizations
  - Missing elements
  - Items added to solve problems found along the way
- Today: correctly reproduced
- Testing on collision data



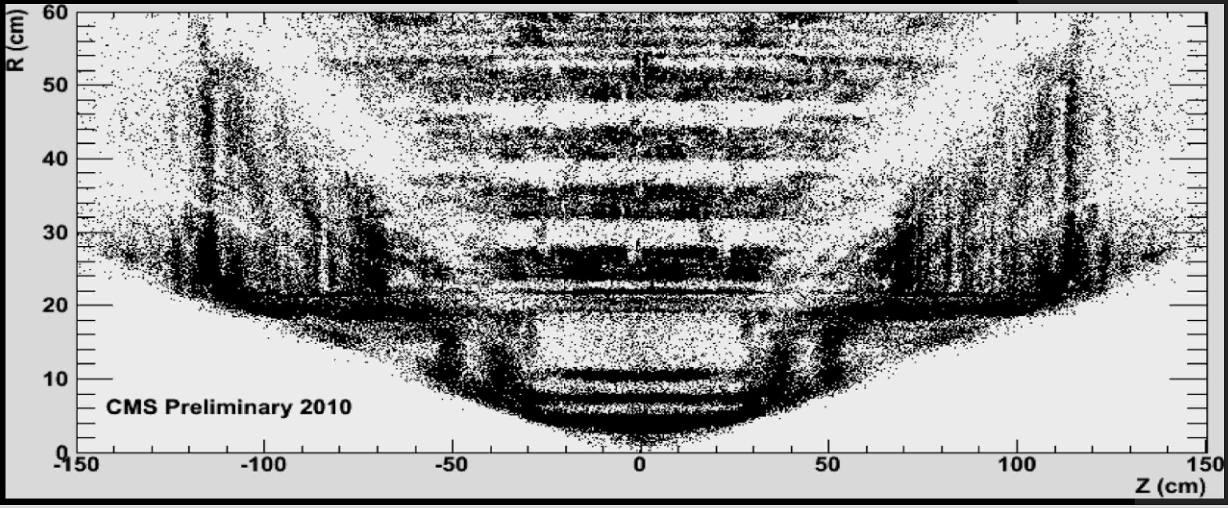


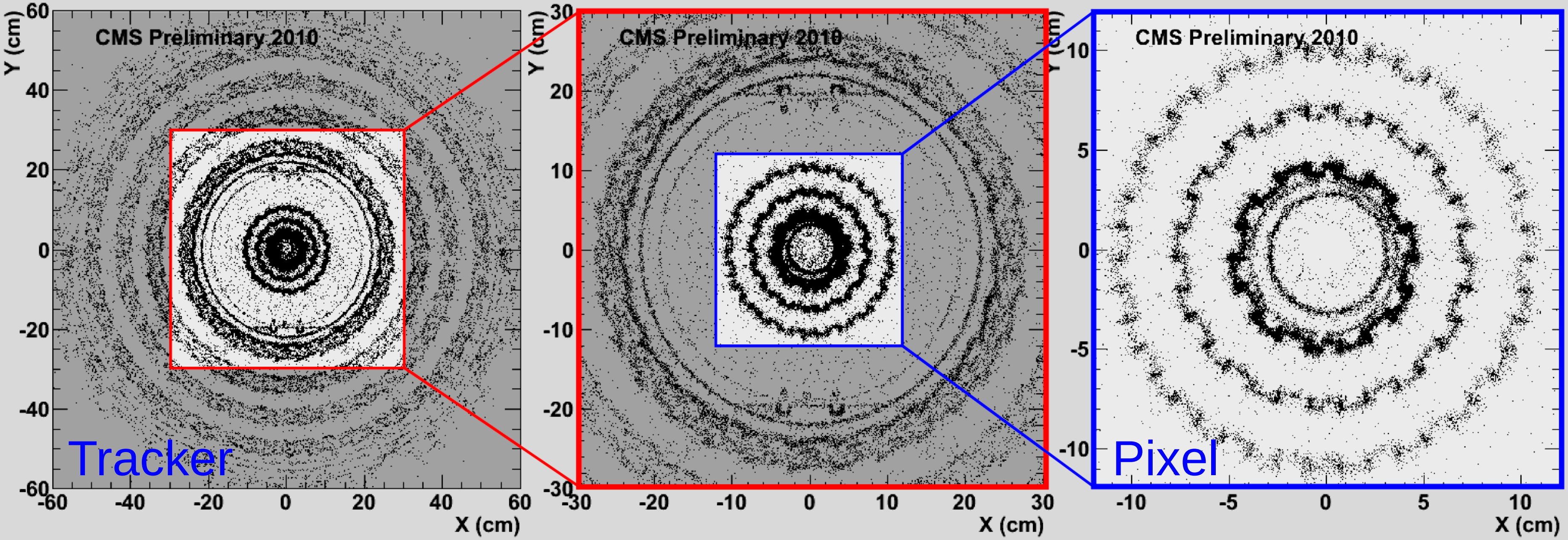




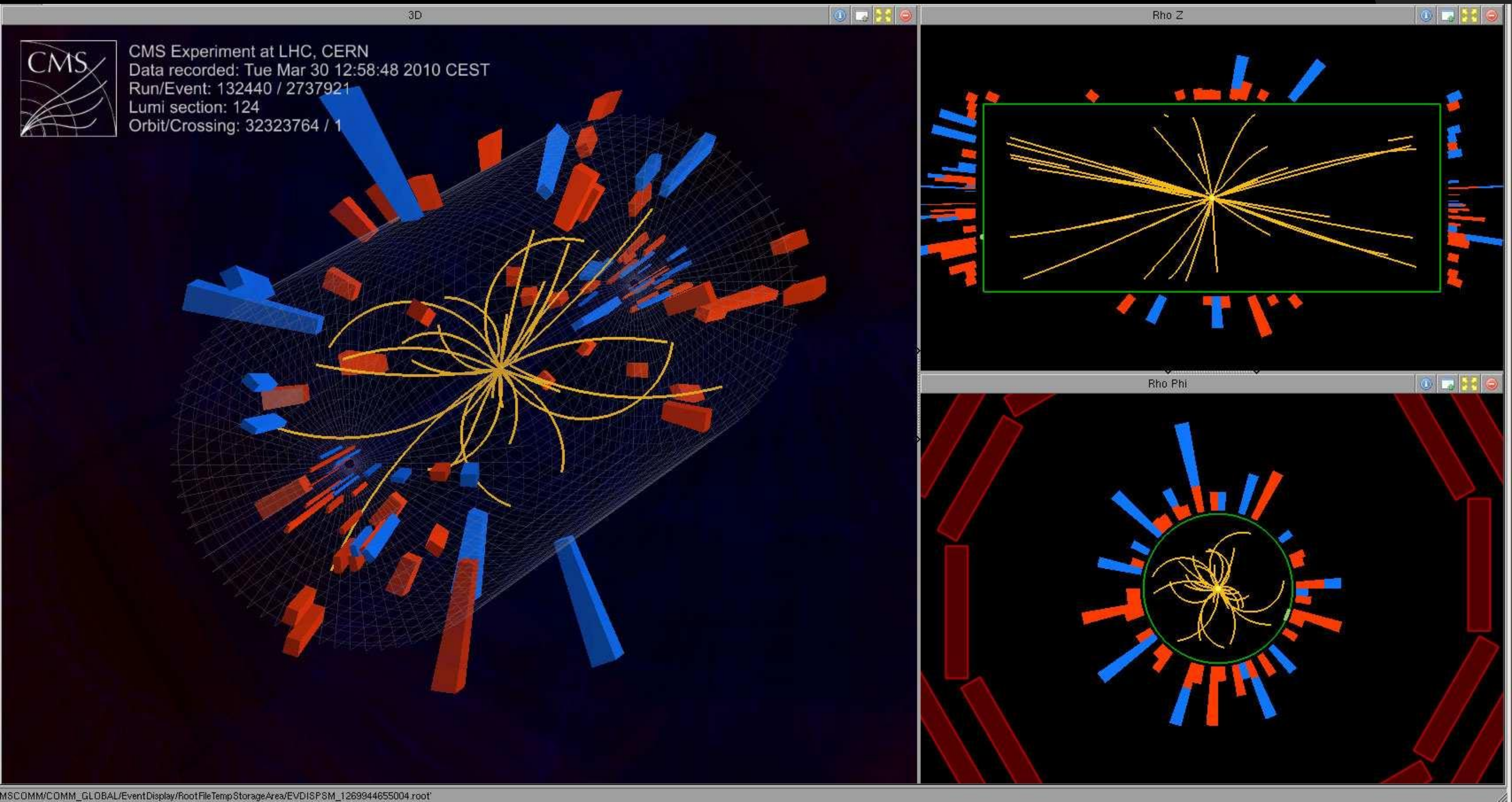
Material distribution

- From photon conversion





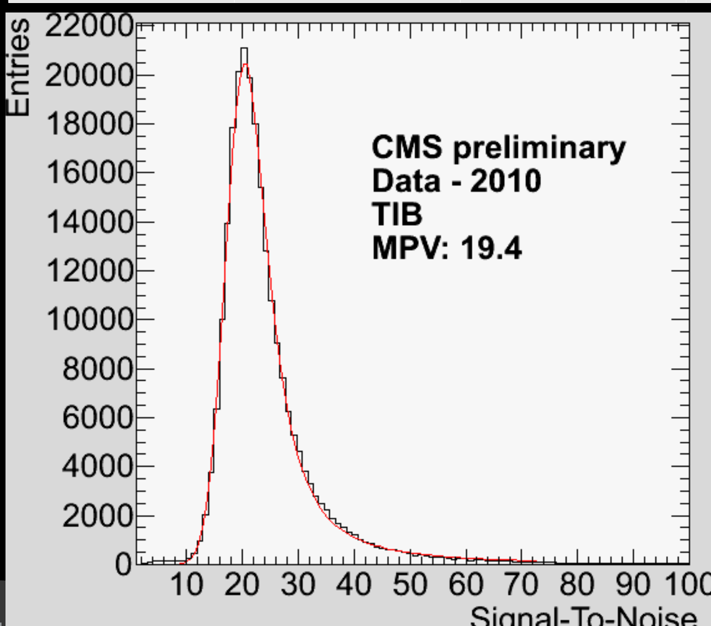
Performance

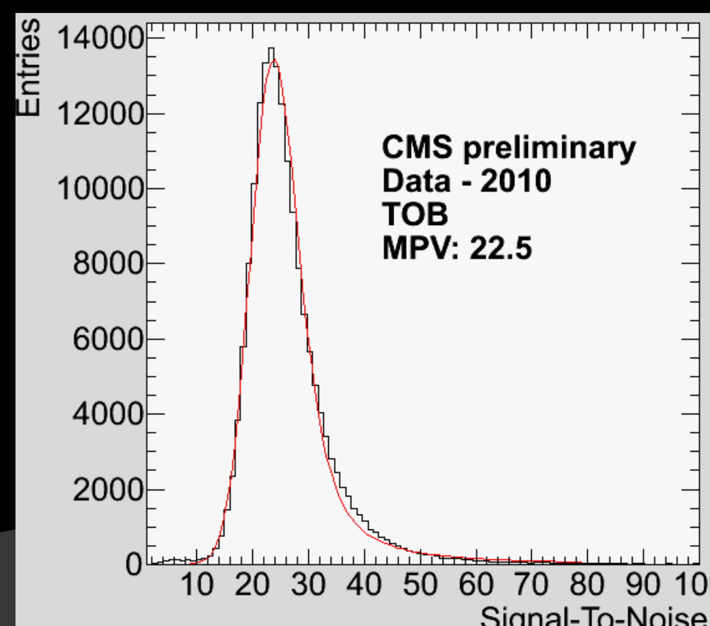


Signal/Noise

- Nominal in the deconvolution mode
- MPV of Landau distribution

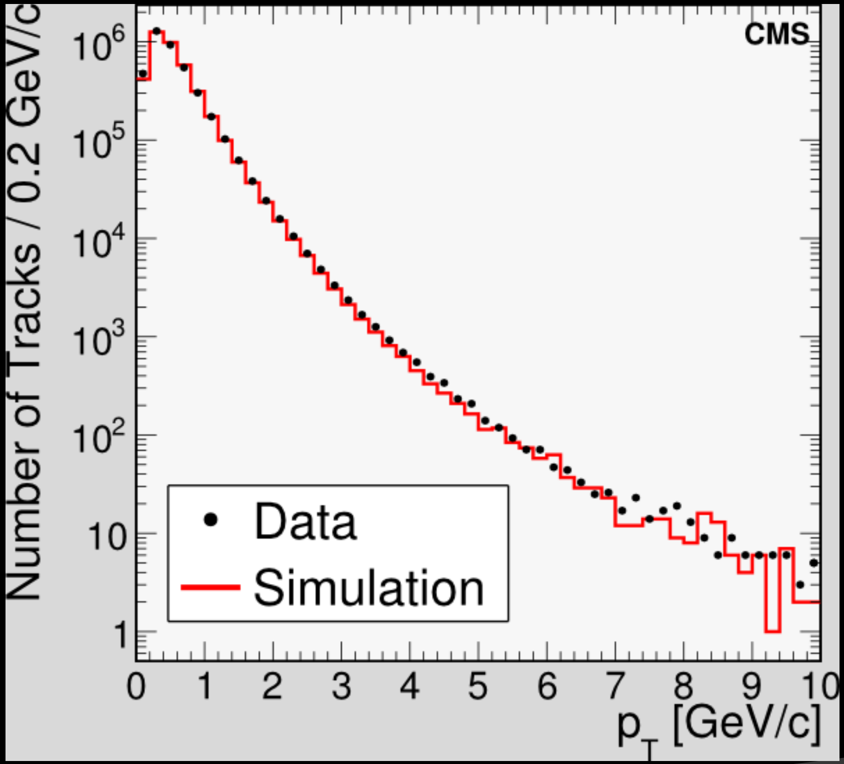
Thin (320 µm) 1 sensor				Thick (500 µm) 2 sensors		
TIB	TID	TEC+	TEC-	TOB	TEC+	TEC-
19.4	18.5	19.1	19.4	22.5	23.4	23.9

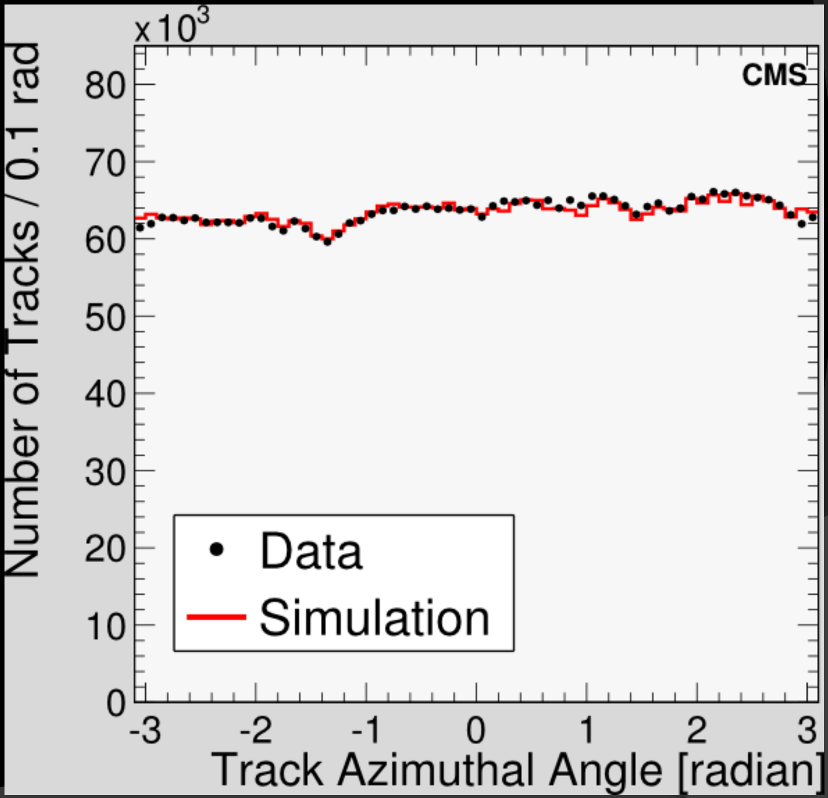




Track reconstruction

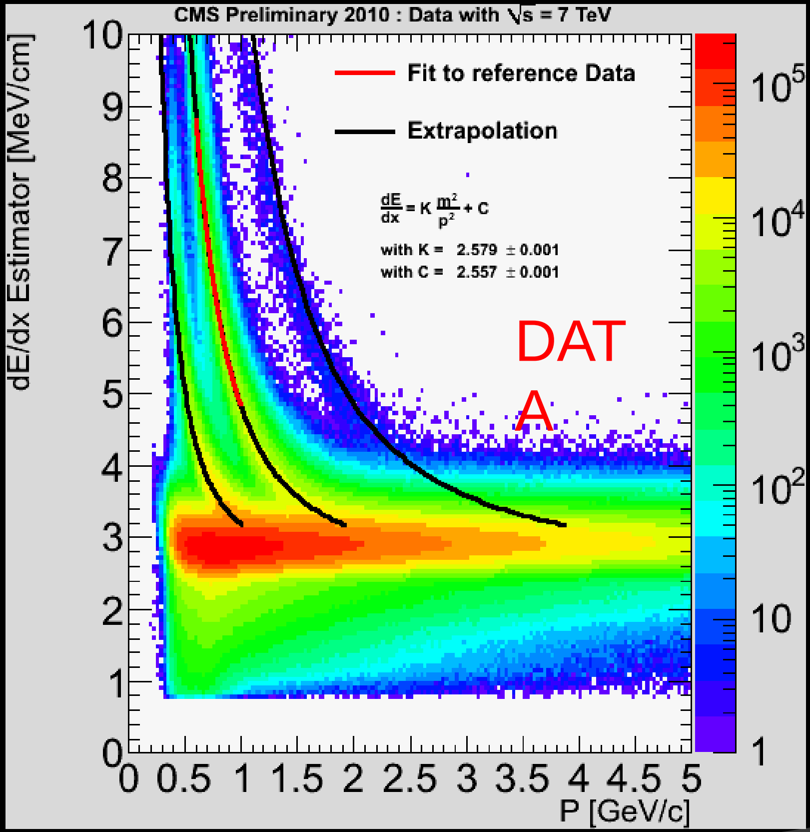
- Many track parameters measured
- Distributions well reproduced by simulation

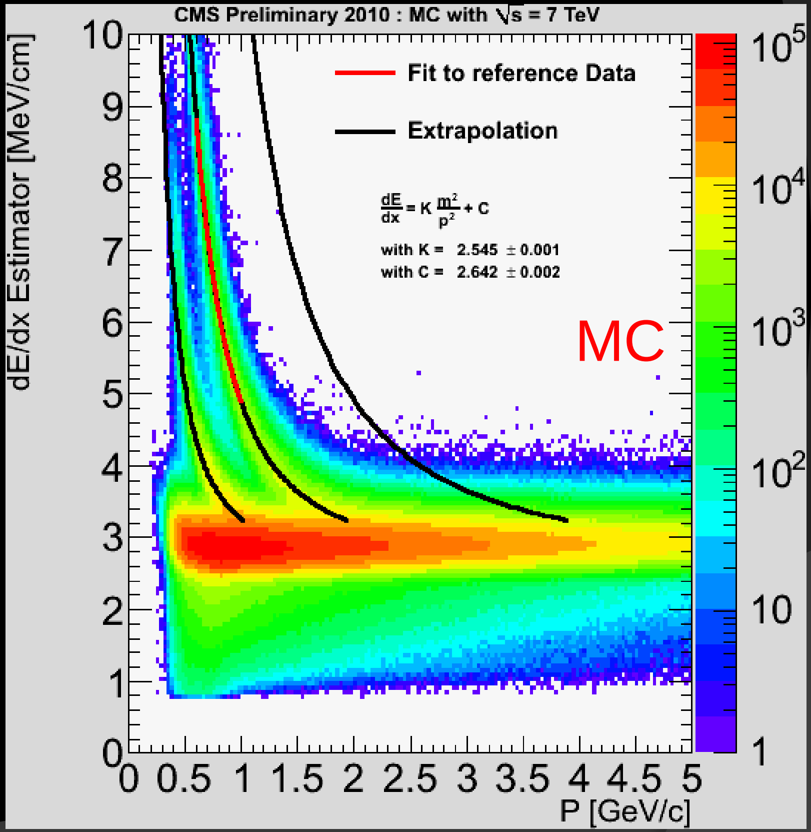




Energy loss

- Analogue readout fully exploited
- Pulse height proportional to energy loss in silicon
- π, K, p, d clearly identified

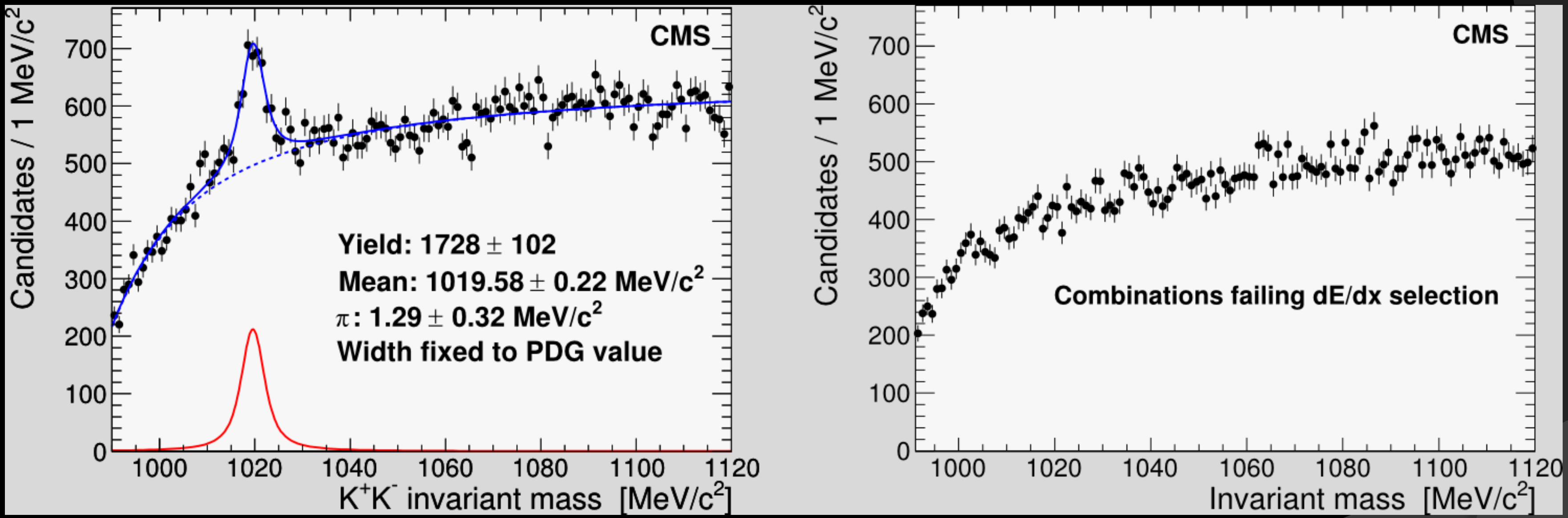




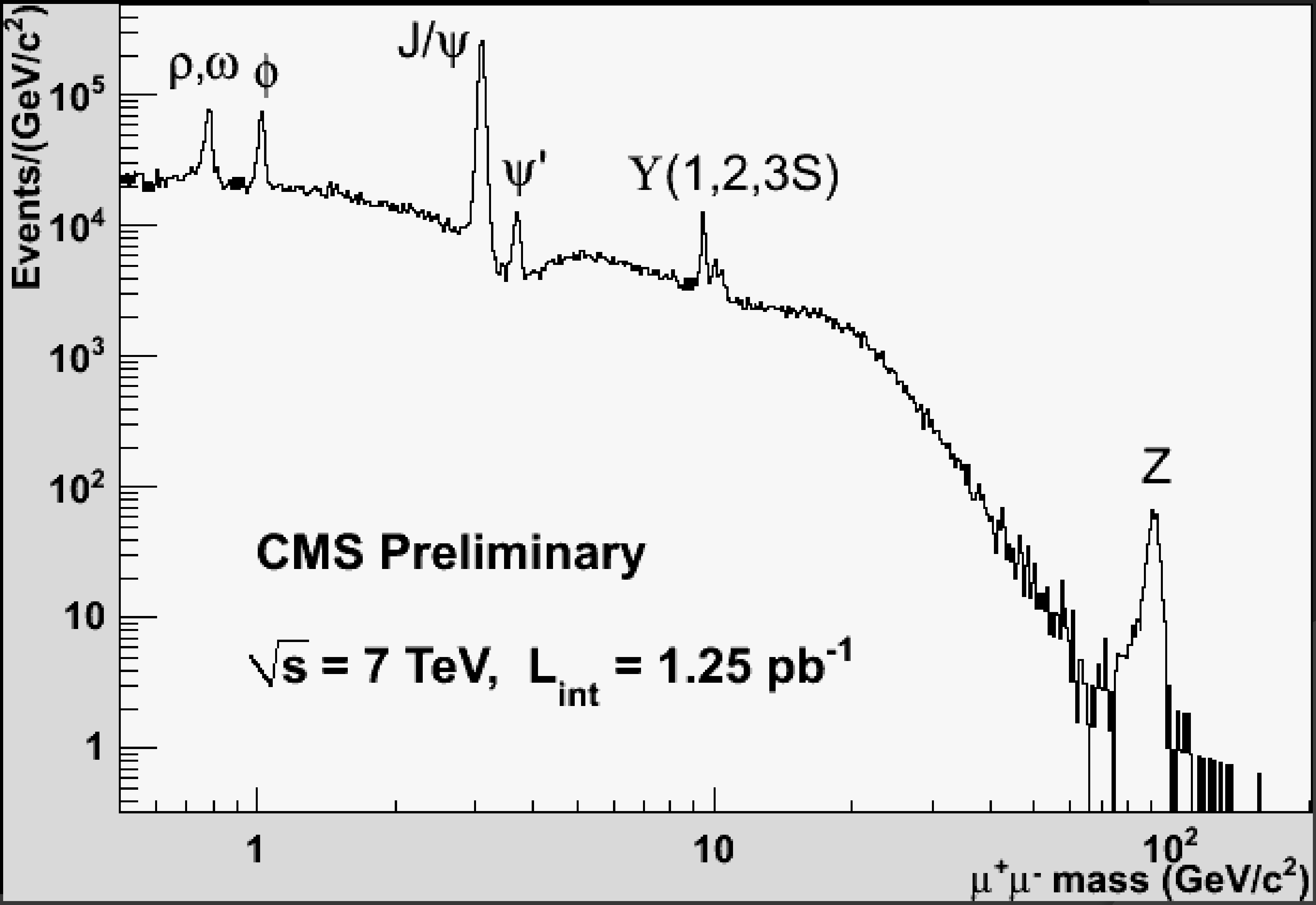
Analysis using energy loss

$\Phi \rightarrow K^+K^-$

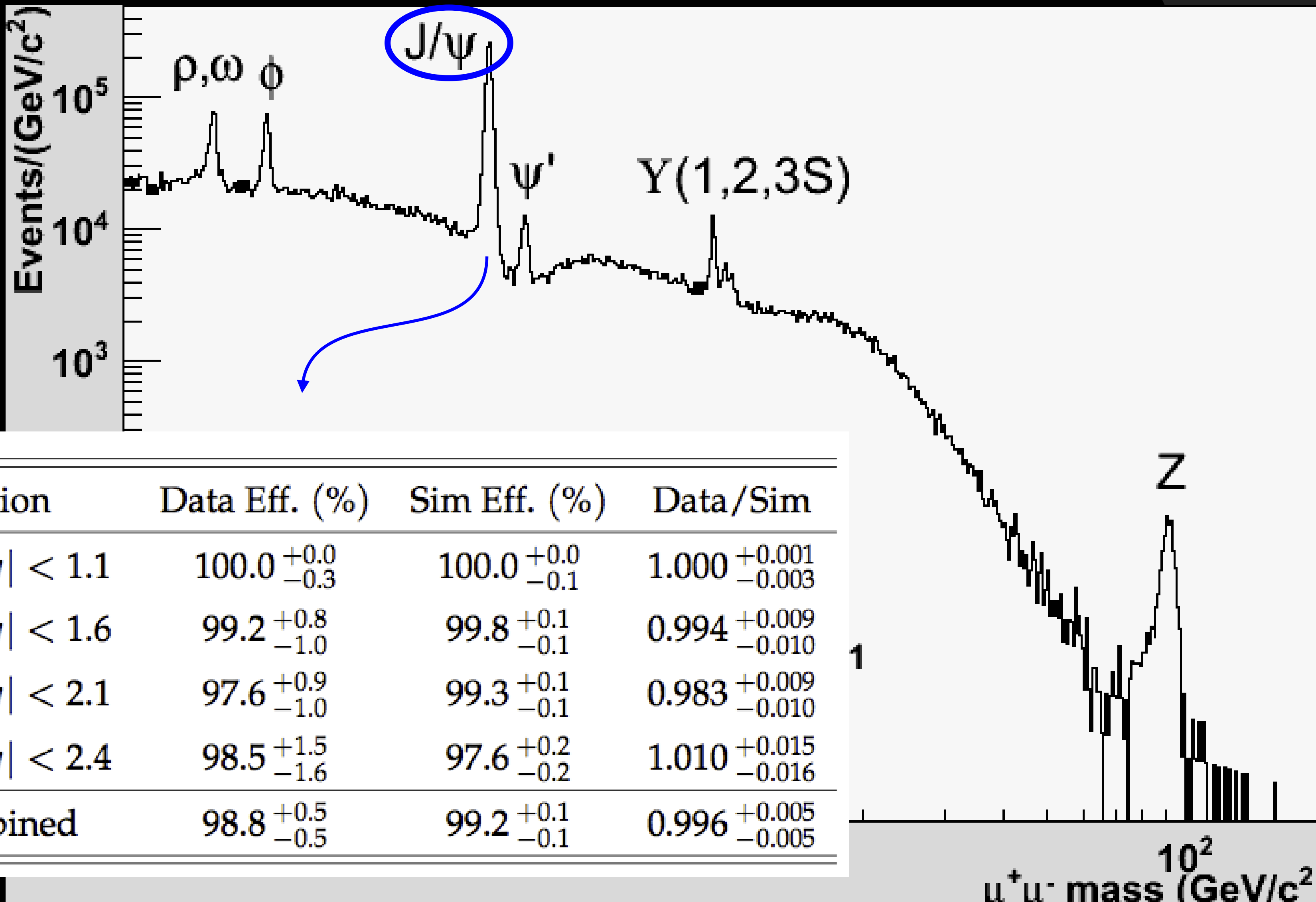
Both tracks fall into energy loss constrain



Di-muon invariant mass

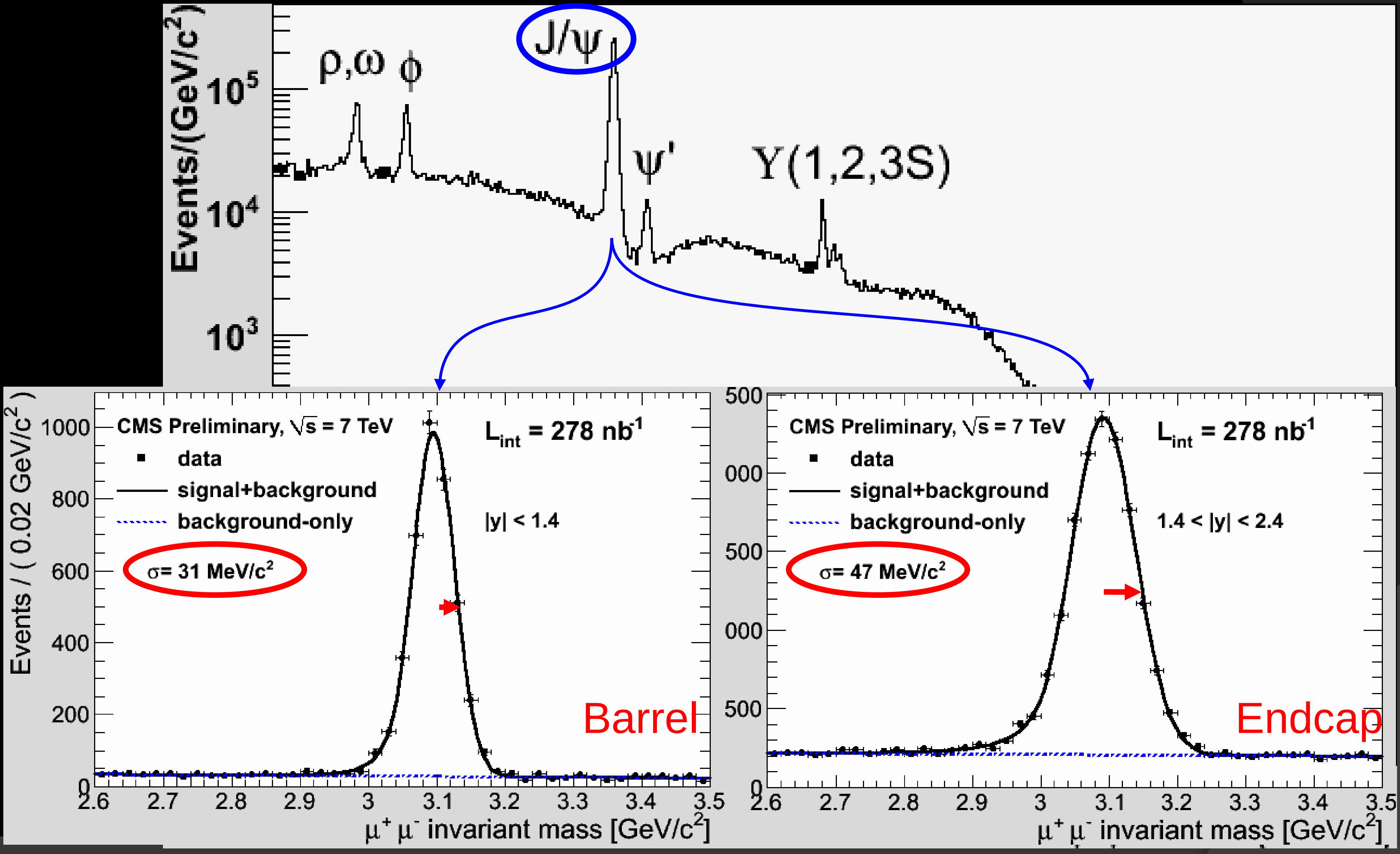


Track finding efficiency

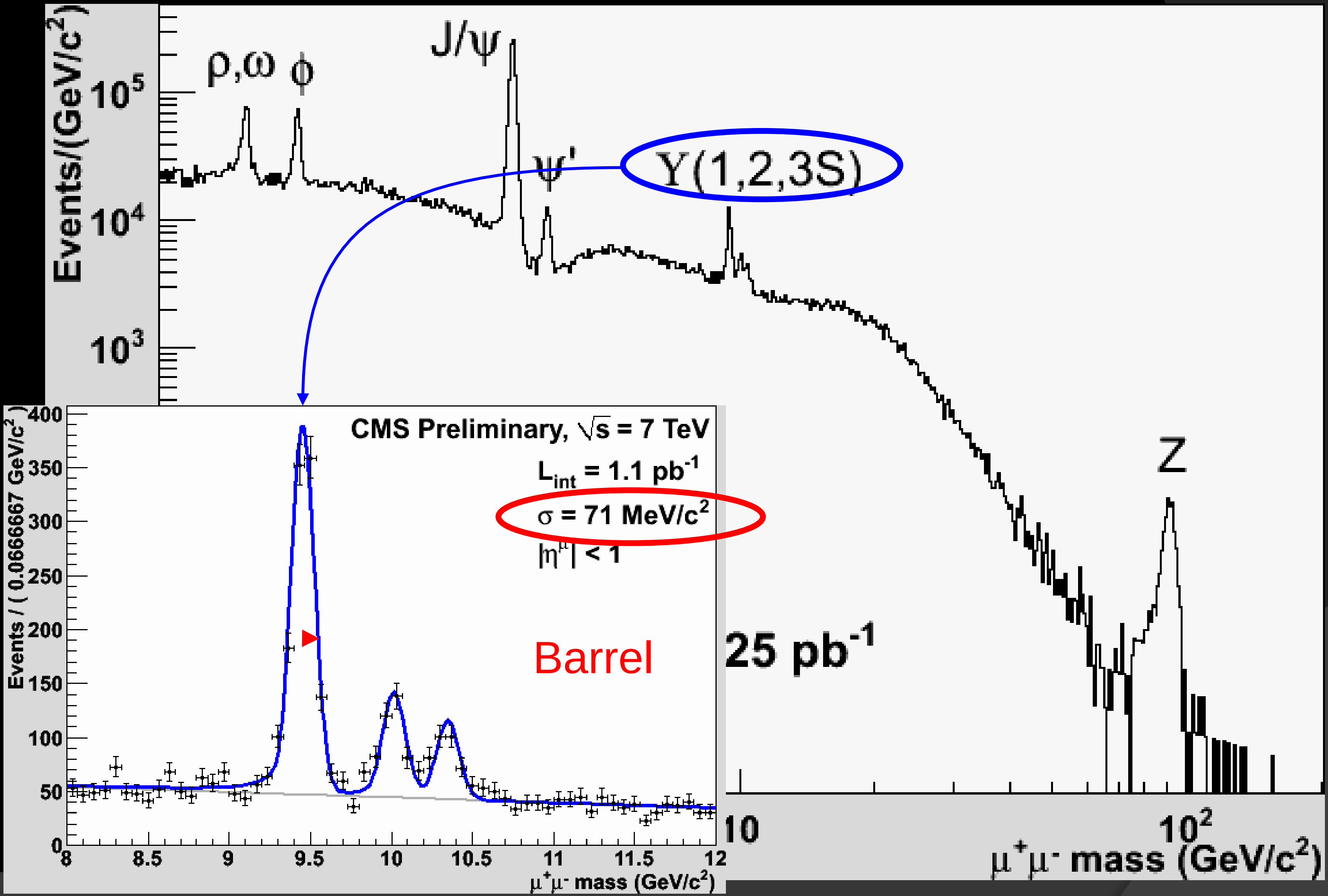


Region	Data Eff. (%)	Sim Eff. (%)	Data/Sim
$0.0 \leq \lvert\eta\rvert < 1.1$	$100.0^{+0.0}_{-0.3}$	$100.0^{+0.0}_{-0.1}$	$1.000^{+0.001}_{-0.003}$
$1.1 \leq \lvert\eta\rvert < 1.6$	$99.2^{+0.8}_{-1.0}$	$99.8^{+0.1}_{-0.1}$	$0.994^{+0.009}_{-0.010}$
$1.6 \leq \lvert\eta\rvert < 2.1$	$97.6^{+0.9}_{-1.0}$	$99.3^{+0.1}_{-0.1}$	$0.983^{+0.009}_{-0.010}$
$2.1 \leq \lvert\eta\rvert < 2.4$	$98.5^{+1.5}_{-1.6}$	$97.6^{+0.2}_{-0.2}$	$1.010^{+0.015}_{-0.016}$
Combined	$98.8^{+0.5}_{-0.5}$	$99.2^{+0.1}_{-0.1}$	$0.996^{+0.005}_{-0.005}$

Di-muon invariant mass

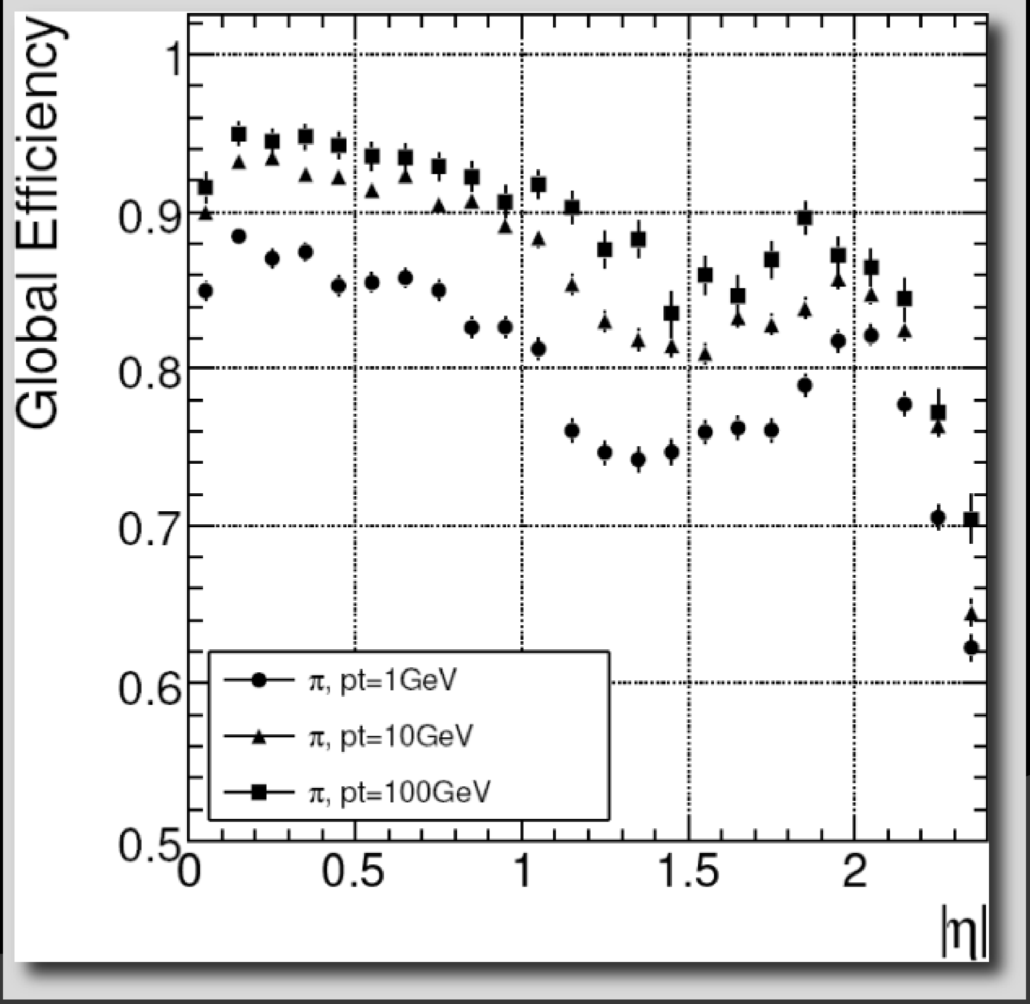


Di-muon invariant mass



Pion tracking efficiency

- Four tons is not transparent…



Detector maintenance

- Pixel system removable/installable in few days
- Removal foreseen for
  - Bakeout of beam pipe
  - Fix problems
  - Eventual upgrade
- FPIX successfully removed, maintained, in the 2008/2009 technical stop

- Strip Tracker maintenance is essentially not possible!

Lessons learned

- Very many… possibly some of them already forgotten!
- Difficult to figure out which ones are the most relevant for you (if any…)
- Will concentrate on those related to detector design
  - Rather then production/integration/commissioning
- A personal view
  - Would not expect that all my colleagues would agree with me…

Beware of low-tech stuff

- High-tech stuff (silicon sensors, microelectronics, optoelectronics…) is appealing and receives a lot of attention
- A lot of problems come from low-tech stuff
  - For the CMS TK:
    - Problems during production of FE hybrids and several PCBs
    - Most of missing channels come from
      - Faulty electrical connections
      - Leaking cooling pipes
- Anything that goes into the detector requires a high level of attention
  - Design, evaluation of components, even R&D
  - Strict quality control during production

Connectivity vs integration

- Connectivity is the devil
  - Connections are by far the major source of lost channels
  - A functional test is in most cases not enough
    - And it is in most cases all what can be done…
    - Expect to loose channels later
- Connectivity in a complex architecture is a bigger devil
  - E.g. the ring architecture of our controls
    - Despite the “redundancy” (option to skip a faulty node)
  - No more “rings” in the upgrade
    - Ring architecture abandoned for controls
    - DC-DC converters preferred over serial powering
- A more integrated design can be the cure
  - But much less flexibility to implement solutions late in the game
  - More emphasis on early “system testing”
    - Need to freeze the system design earlier
    - Reduce opportunities to profit from late developments

Old solutions, novel solutions, good solutions

- Novel solutions are appealing, but good solutions are what you need
  - E.g. best (lightweight, efficient, reproducible) cooling contacts in the TK are obtained with screws/washers/Alu contacts…!
  - Study carefully the problem, before falling in love with a sexy solution
- In a large system, the only good solutions are those that are simple and easily reproducible!
- Good engineering is always the key
- You cannot afford artist work in a large system

Detector maintenance

- Make up your mind about detector maintenance
  - Easy or impossible. Half-way is not a good choice (my opinion).
  - Clear choice at design level.
    - Easy maintenance: implications for mechanics, services, inactive volumes.
      - Implications can be severe for a large system with a lot of services
    - "Space experiment": high-level of redundancy, robust design, extreme quality control in all procurements/assembly steps

Requirements, technology and design choices

- Performance in operation is not the only requirement
- Consider quality assurance, testing at all assembly steps, detector commissioning and early operation
  - Good examples for CMS TK: DCU ID, “peak mode” of the readout chip, spy channel.
  - Less good: cooling pipes leak test, warm temperature operation.
    - Even more important in future with two-phase cooling
- To be considered in the design choices (requirements, evaluation of technological options and components)
- In principle all systems should be designed having well understood all testing/integration/commissioning steps
  - Looking ahead: some electronics technologies may be disfavoured because testing is more difficult (yield??)
- Environmental monitoring is of paramount importance
  - As well as monitoring of voltage/currents in all supply lines
  - O(10^5) parameters monitored in the TK… and we’ll add more probes!
  - Several R&D lines ongoing to develop better environmental sensors (notably dew point) for the upgrade

It takes longer than you think!

- In 2000 we had 2005 as target delivery date
- We were late by two years!
  - Schedule re-adjusted according to LHC schedule
    - But being ready on time would not have been feasible
- Parallel activities help, but are also a overhead
- As you proceed with integration, parallel work becomes progressively more limited
- More integrated design and more industrial assembly?
  - May speed up production, but requires more time for system-testing

How to estimate the material (…and get it completely wrong…)

- Start from an empty file
- Add the elements that you know
  - With optimistic assumptions
- Use theoretical values for services
  - E.g. X section of Cu per unit power etc…
- Ignore everything that you don't know how to estimate
  - Connectors, PCBs, cables supports etc…
- Don't add any contingency for elements to be added along the way
  - Additional shields, protections, mechanical reinforcements, tape, glue…

A different approach

that we are trying to promote for the upgrade

- Start from an existing detector
  - In our case, the CMS Tracker
- Remove/reduce material only where justified by a reasonably understood ongoing development
  - E.g. DC-DC converters, thinner sensors, more advanced electronics, CO_2 cooling
- Aspects not yet “reviewed” should serve as contingency for the uncertainties on the new developments
  - An approach similar to what we do to make schedules, or budget forecasts
    - But of course, not everybody agrees…
- Invest a lot in modelling studies

- Keep in mind: detectors that are not built tend to be lighter than detectors that are built!

That’s all I wanted to say
It was certainly not exhaustive
I don’t know if it was useful
I hope at least it was not too boring

Thank you for your attention