

# The CMS Silicon Tracker

Design, Construction, Status and Long-Term Performance



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Studentenseminar

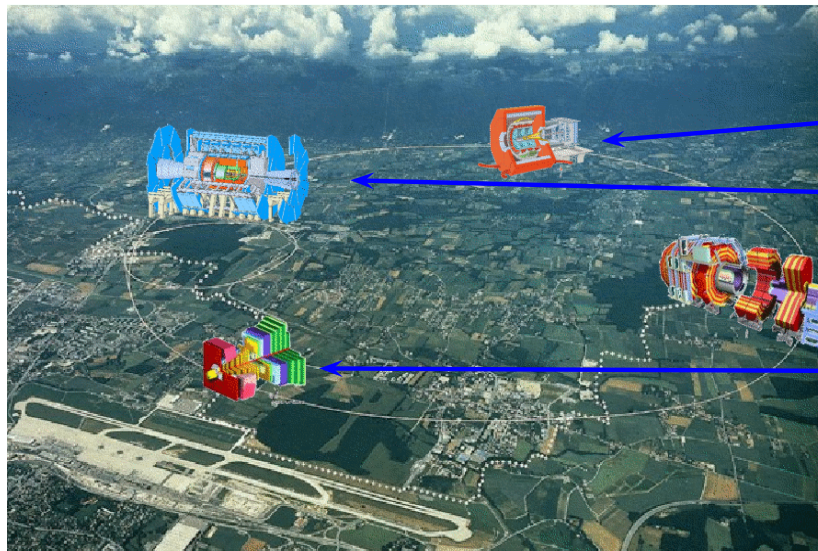
8.5.2008

- Introduction
- The CMS Silicon Tracker
  - Design
  - Construction
  - Long-term Performance
  - Alignment
- Summary/Outlook

# Introduction – The Large-Hadron-Collider (LHC)

## ● LHC:

- $pp$  collider at CERN in Geneva
- $\sqrt{s} = 14$  TeV
- Built in the former LEP Tunnel
- First Collisions in 2008  
(starting at 10 TeV)
- Physics luminosity from 2009



## ● Four Experiments:

- Alice (Heavy Ion)
- ATLAS (Multi-purpose)
- CMS (Multi-purpose)
- LHCb ( $b$ -physics)

# Introduction – The CMS Experiment

CMS: **C**ompact **M**uon **S**olenoid

**Compact:** Size:  $21 \times 15 \text{ m } \varnothing$  (Atlas  $44 \times 20$ ),

Weight: 12.500 t (Atlas  $\simeq$  7000 t)

**Muon:** Good muon system

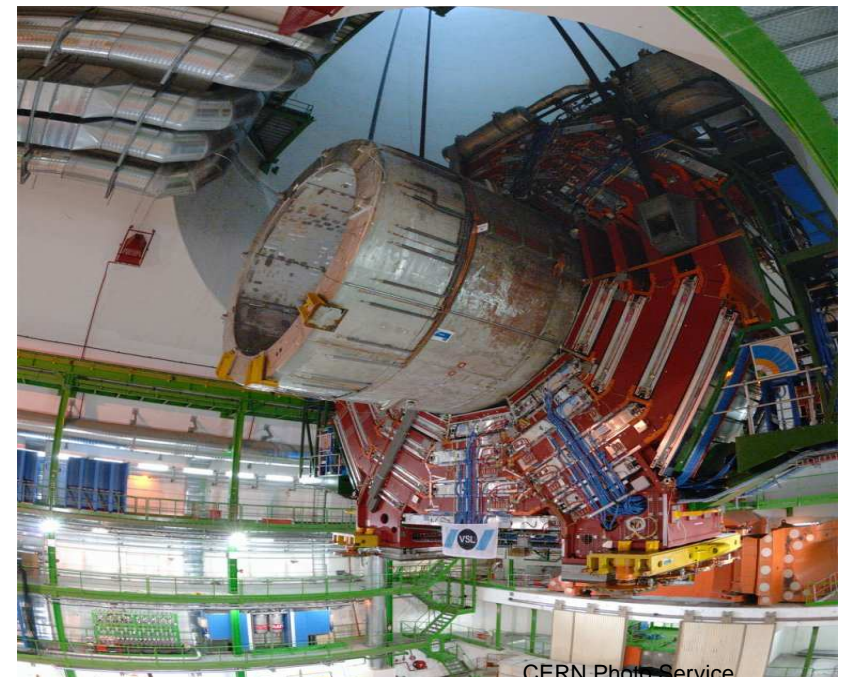
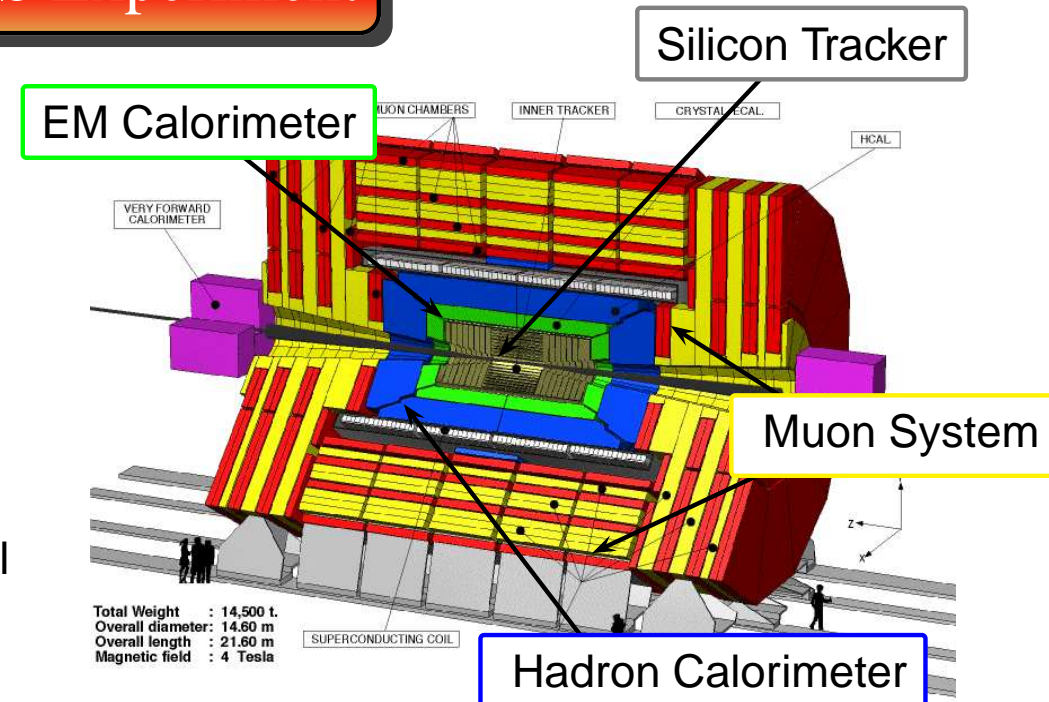
**Solenoid:** Magnetic field of 4 T over  $12 \text{ m} \times 6 \text{ m}$ ,  
stored energy 2.7 GJ, Calorimeters inside the Coil

## Furthermore:

- Very precise EM Calorimeter
- Very good Tracking System

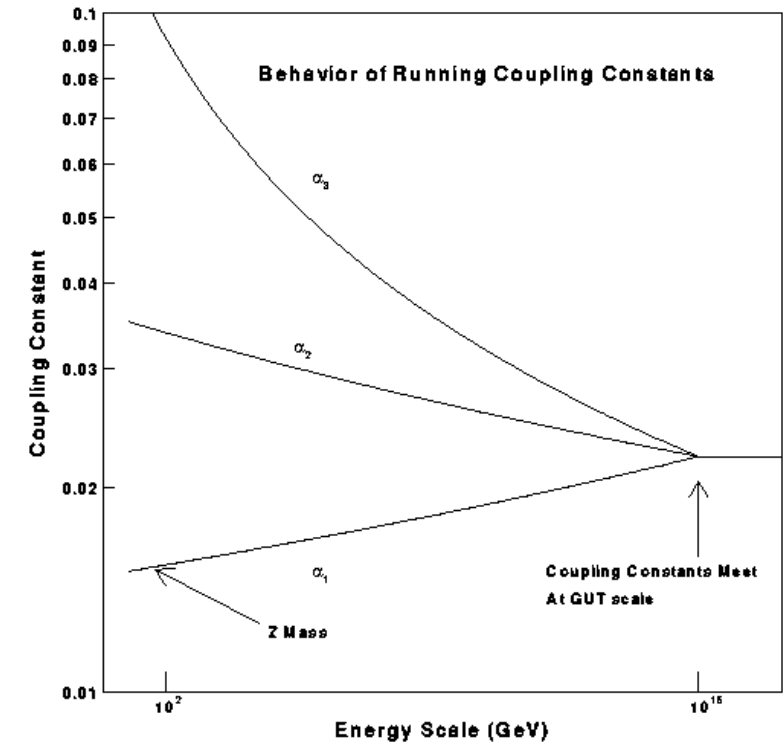
## (Very Short) Timeline:

- 28.2.2007: Solenoid lowered into cavern
- January 2008: All heavy elements lowered



# Physics at the LHC

- First collider reaching far into the TeV range.
- Things which can be expected (hoped for) at the LHC
  - shed light onto EWSB (discover the Higgs-Boson)
  - Find new Physics like
    - \* Supersymmetry or
    - \* Extra-dimension to
  - Solve prominent problems of the SM such as
    - \* Origin of Mass
    - \* Hierarchy problem ( $M_{\text{Higgs}} \ll M_{\text{GUT}}$ )
    - \* Dark Matter
    - \* ...



Do we have unified coupling strength at  $M_{\text{GUT}}$  ?

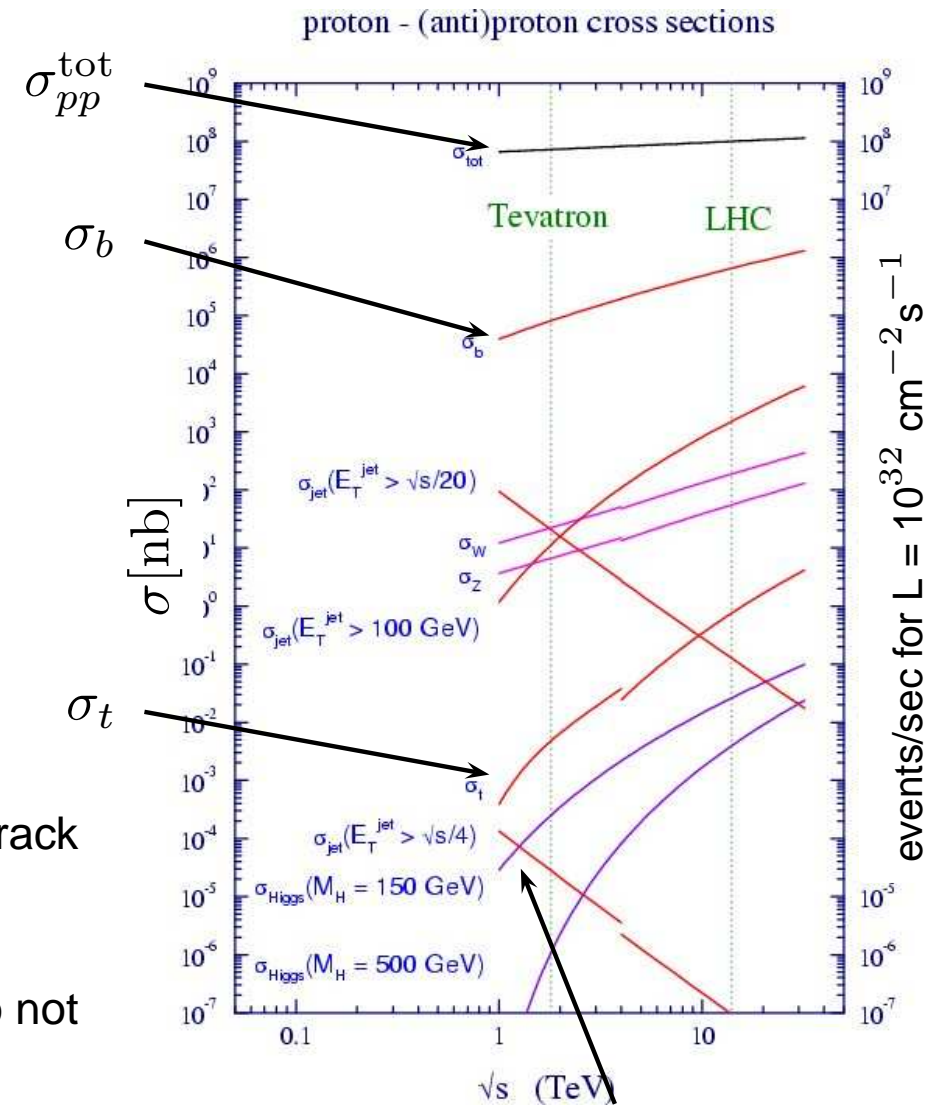
# LHC – As physics environment

To get the rare processes we need:

- Nominal Luminosity  $10^{34}/\text{cm}^2\text{s}$ ,
  - >2000 proton bunches, which leads to
  - 40 MHz collision rate with
  - up to 25 minimum-bias collisions overlaid which results in
  - 1000 charged tracks in every bunch crossing

From the tracking point of view we need

- fast detectors which can be read out every 25 ns
- precise detectors to measure a curvature in a TeV track ( $\mathcal{O}(1\text{mm})$  over 2 m)
- granular detectors such that 1000 tracks at the same time do not pose a problem for pattern recognition

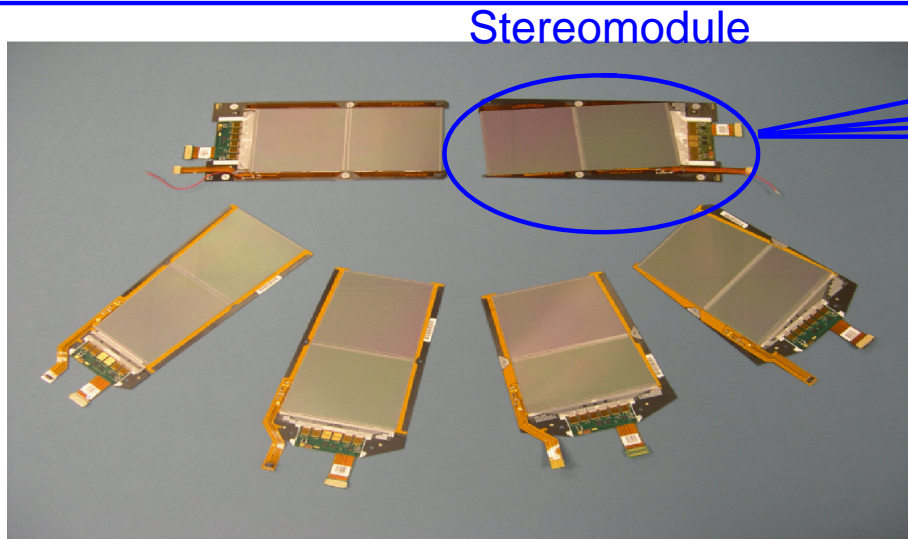
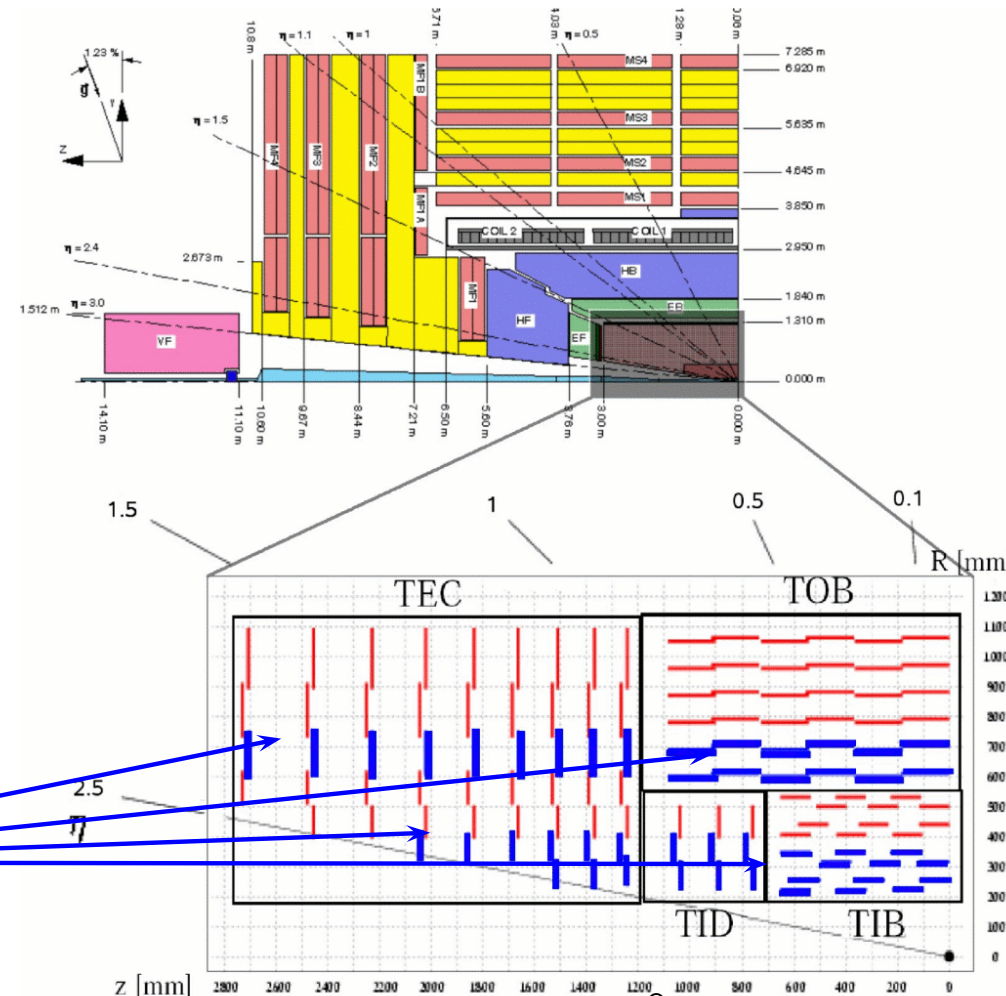


$\sigma_{\text{Higgs}150 \text{ GeV}}$

**What is the CMS Answer to this challenge?**

# Introduction – The CMS Silicon-Strip Detector

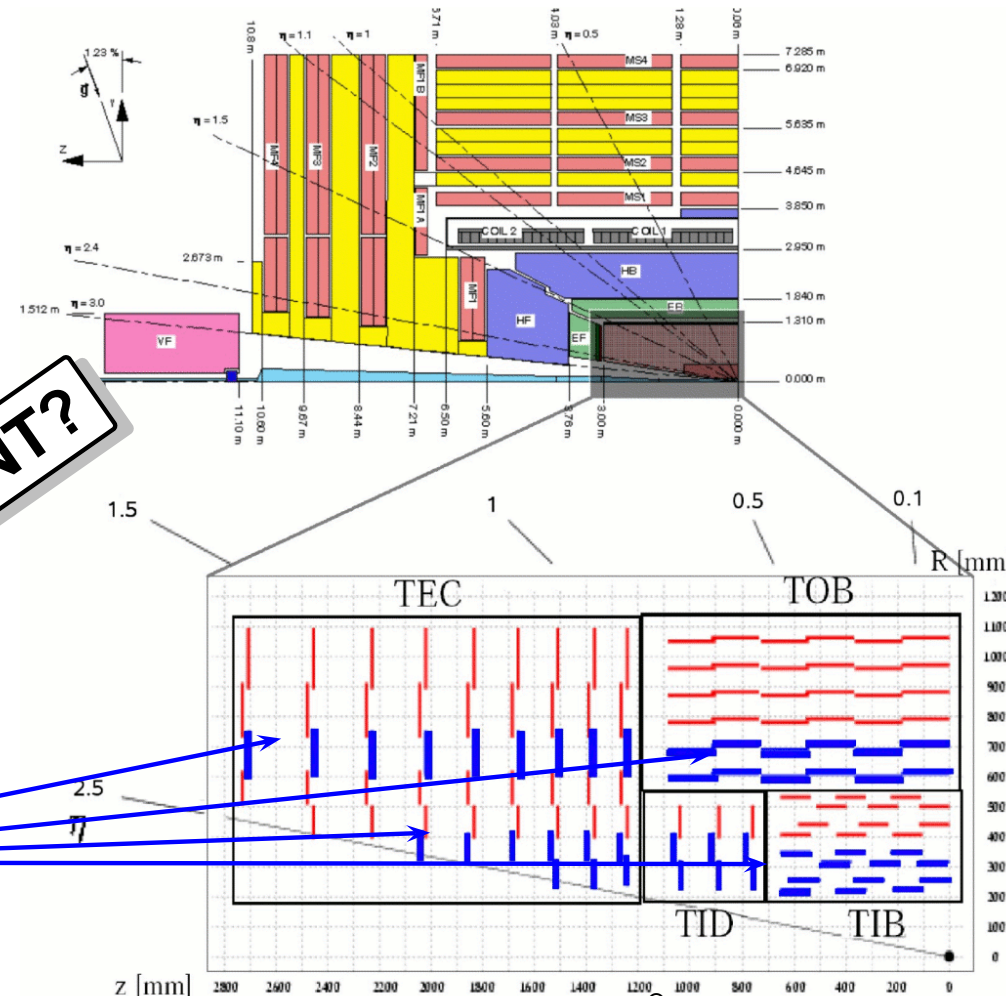
- Largest silicon tracker ever built (active area  $\sim 200 \text{ m}^2$ )
- Approx. 9.6 million electronic channels
  - 10 layers in barrel region (4 Inner Barrel (TIB), 6 Outer Barrel(TOB)) and 9 discs in the endcaps (up to 14 Hits per track)
- Goal:  $\frac{\delta p_T}{p_T} \sim 10\%$  for 1 TeV Muons
- Analog Read-Out for particle ID
- First “all-silicon” central tracker
- + Pixel detector ( $>60$  Mio channels (not covered here))



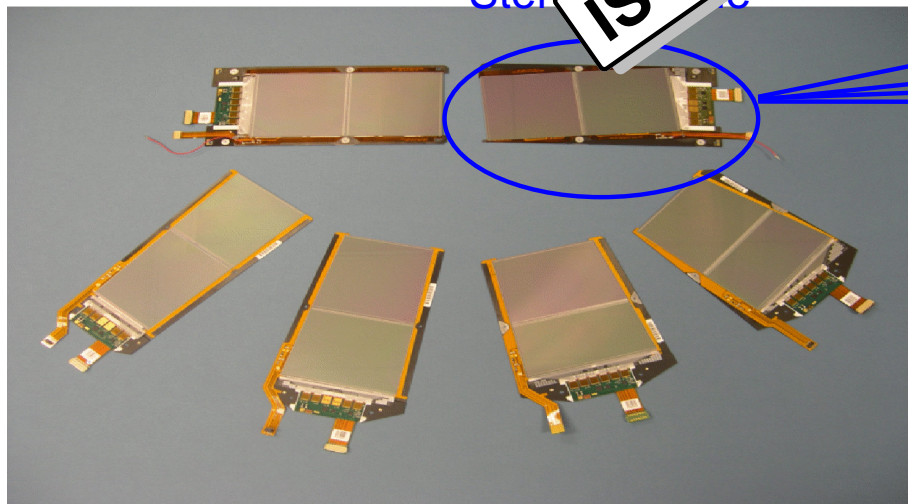
- Angular Coverage down to  $9^\circ$  to the beam-pipe ( $|\eta| < 2.5$ )
- 4 layers (3 rings) contain stereo modules for 2-D hitreconstruction

# Introduction – The CMS Silicon-Strip Detector

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**IS THIS SUFFICIENT?**

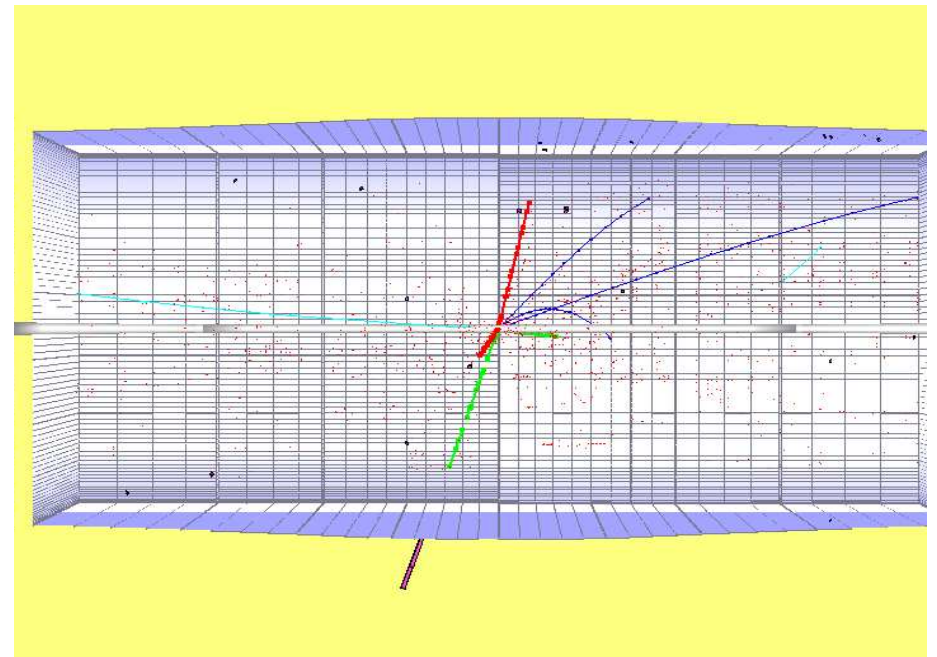
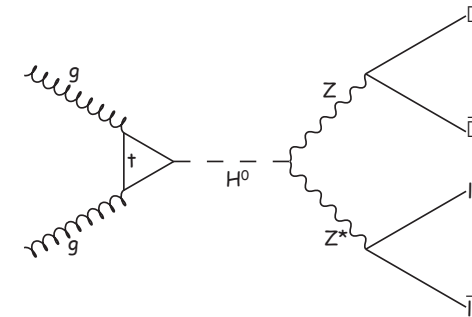


- Angular Coverage down to  $9^\circ$  to the beam-pipe ( $|\eta| < 2.5$ )
- 4 layers (3 rings) contain stereo modules for 2-D hitreconstruction

# Occupancy

Crude Estimate:

- Approximately 10 million channels
  - In every collision we have:
    - 1000 tracks  $\times$  10 hits
  - so in the strip tracker we have
    - 10 000 hits/10 000 000 channels
    - Occupancy  $\mathcal{O}(1 \text{ ‰})$

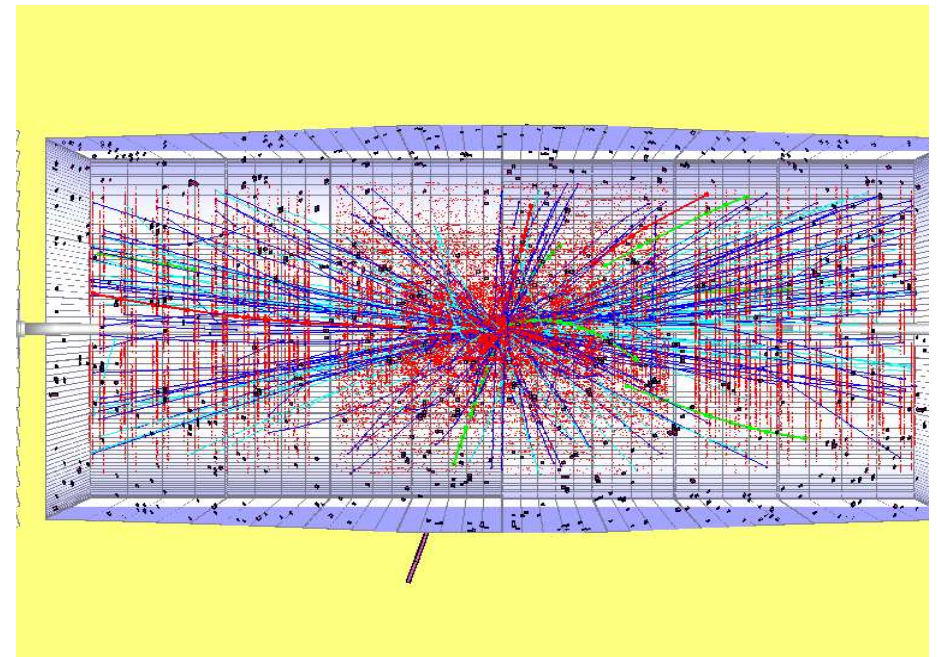
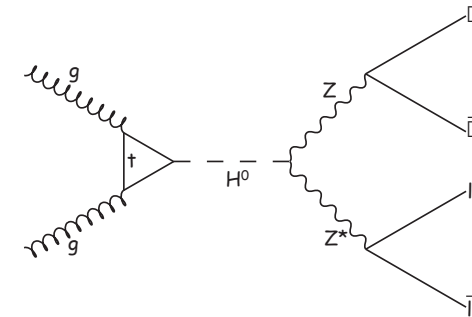


$$H \rightarrow 2\mu 2e$$

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$$H \rightarrow 2\mu 2e + 20 \text{ soft interactions}$$

At nominal luminosity pattern recognition non-trivial task (but still doable)

## Resolution – What do we need?

What is the Sagitta  $s$  for a  $q = 1$  TeV track?

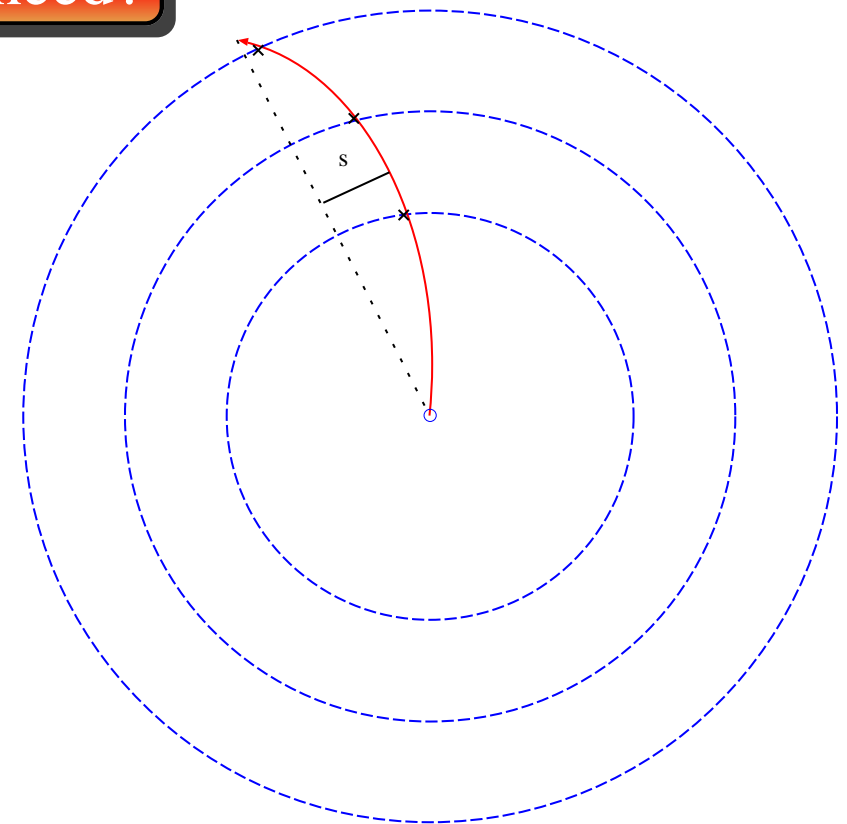
$$s = 0.3 \frac{BL^2}{q} = \frac{0.3 \cdot 4 \cdot (1.1)^2}{1000} = 1.4 \text{mm}$$

For moment resolution ( $N$ =number of tracking layers)

$$\frac{\Delta p_T}{p_T} = \frac{p_T \sigma_{\text{spatial}} \sqrt{720/(N+4)}}{0.3BL^2}$$

So to get a good momentum resolution we can increase

- improve the resolution ( $\sigma_{\text{spatial}} \downarrow$ )
- increase the number of tracking layer ( $N \uparrow$ )
- increase the magnetic field ( $B \uparrow$ )
- build a larger device ( $L \uparrow$ )



**CMS:**

- Large  $B$  field,
- large tracker,
- relatively few but precise tracking layers

## Resolution – What do we need?

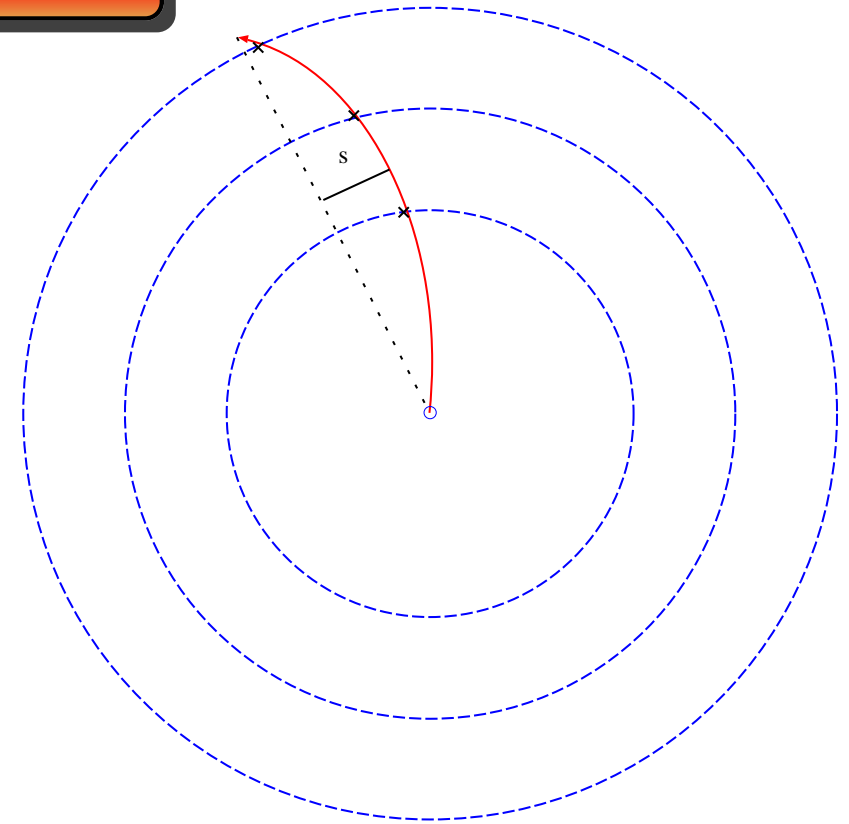
In slightly more detail:

$$\frac{\Delta p_T}{p_T} = \frac{p_T \sigma_{\text{spatial}} \sqrt{720/(N+4)}}{0.3BL^2}$$

$$\rightarrow 0.1 = \frac{1000 \text{ GeV} \sigma \sqrt{720/17}}{0.3 \cdot 4 \cdot (1.1\text{m})^2}$$

$$\rightarrow \sigma = \frac{0.1 \cdot 0.3 \cdot 4 \cdot 1.21}{6.5 \cdot 1000}$$

$$\sigma = 22\mu\text{m}$$



Spatial resolution in the real detector:

- Pixel (innermost 3 layers): 9 - 20  $\mu\text{m}$
- Strip (10 - 12 layers): 23 - 50  $\mu\text{m}$

→ should be sufficient (Detailed calculation a bit more elaborate)

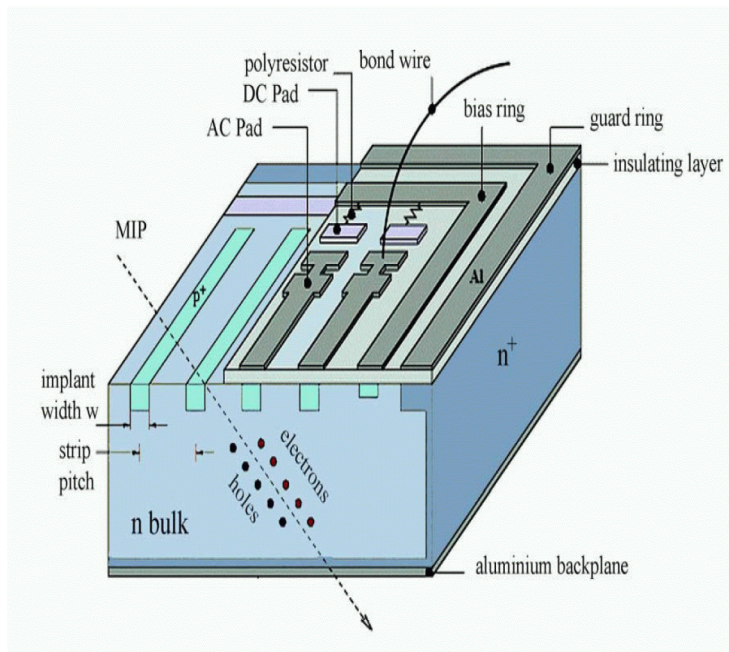
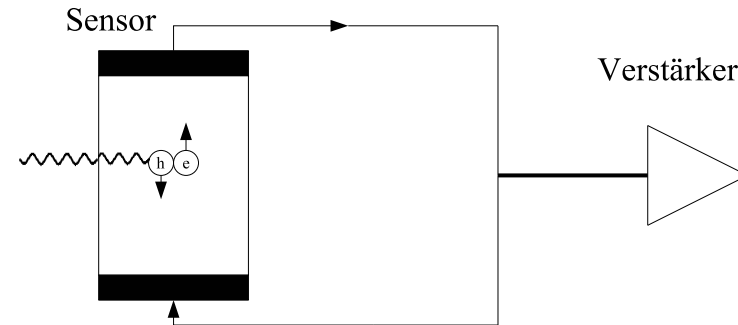
## LHC – As radiation environment

- $10^8$  charged particles per  $\text{cm}^2$  and second
- Integrated radiation dose of 840 kGy for the innermost layers (4cm radius)
- At 115 cm (end of tracking system) still 1.8 kGy

Need detectors which can withstand this harsh environment for  $\sim 10$  years

# Silicon Detectors

- Silicon Sensors are a diode operated under reverse bias
- A crossing particle creates electron-hole pair in the silicon volume ( $\sim 3 \times 10^4$  for MIP in  $300\mu\text{m Si}$ )
- The resulting current (by collection and induction) is measured



## Advantages of Silicon

- Good spatial resolution because of small dimension of the parts
- Charge collection quite fast
- Intrinsic radiation hardness
- Industrial production possible

→ All running HEP experiments have silicon vertex-detectors

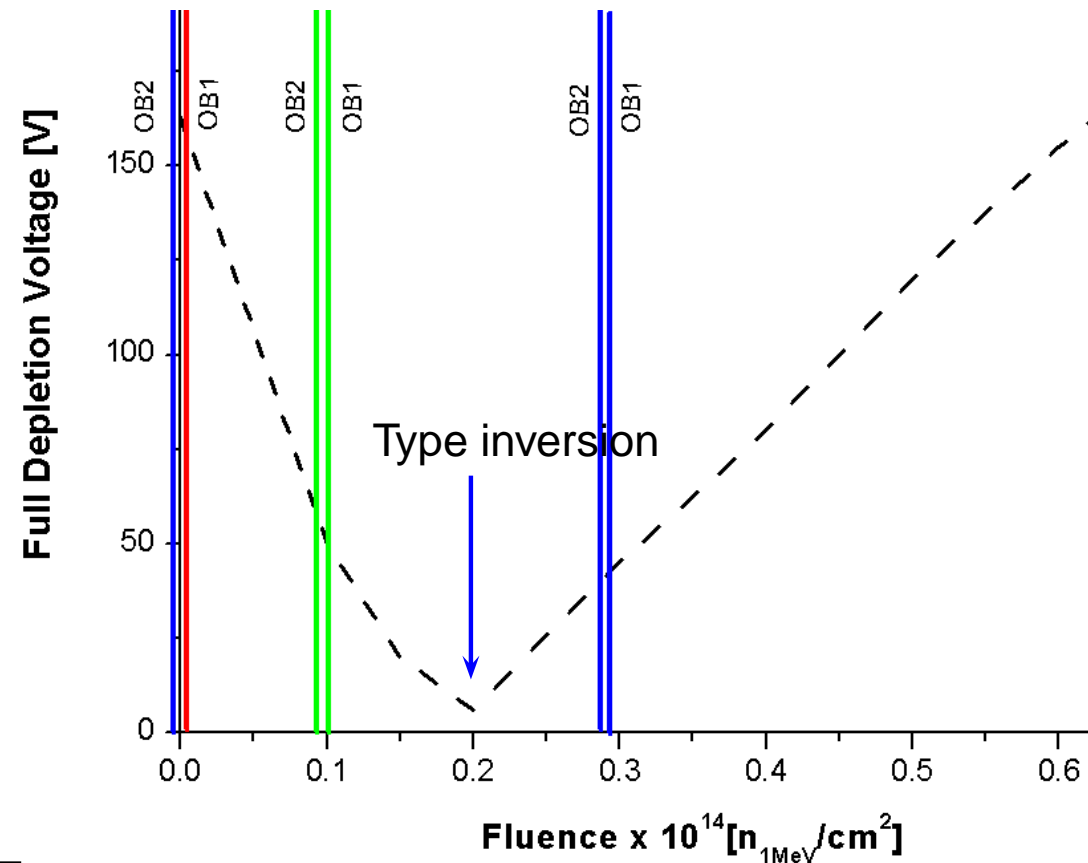
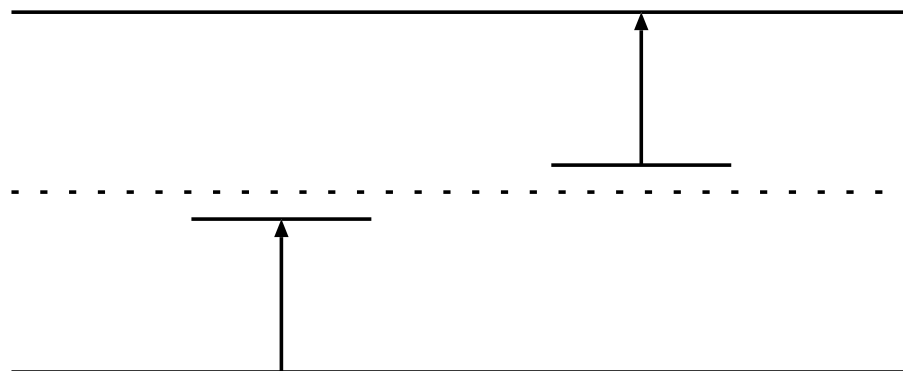
# Radiation Damage in Silicon

- Bulk damage
- Surface damage

Bulk damage leads to formation of point- and cluster defects within the silicon.

As a result it leads to

- Leakage currents (more noise)
- Increased bias voltage (may be underdepletion)
- charge trapping (reduced signal)



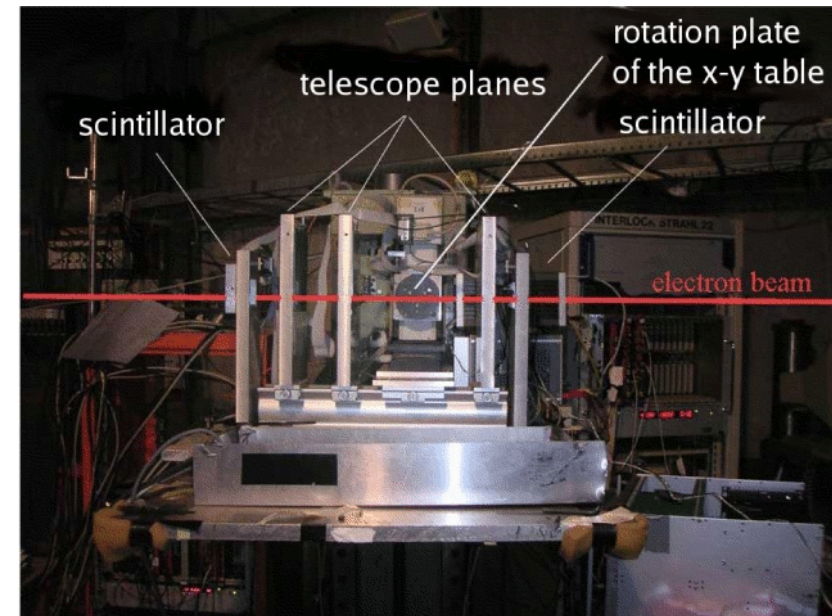
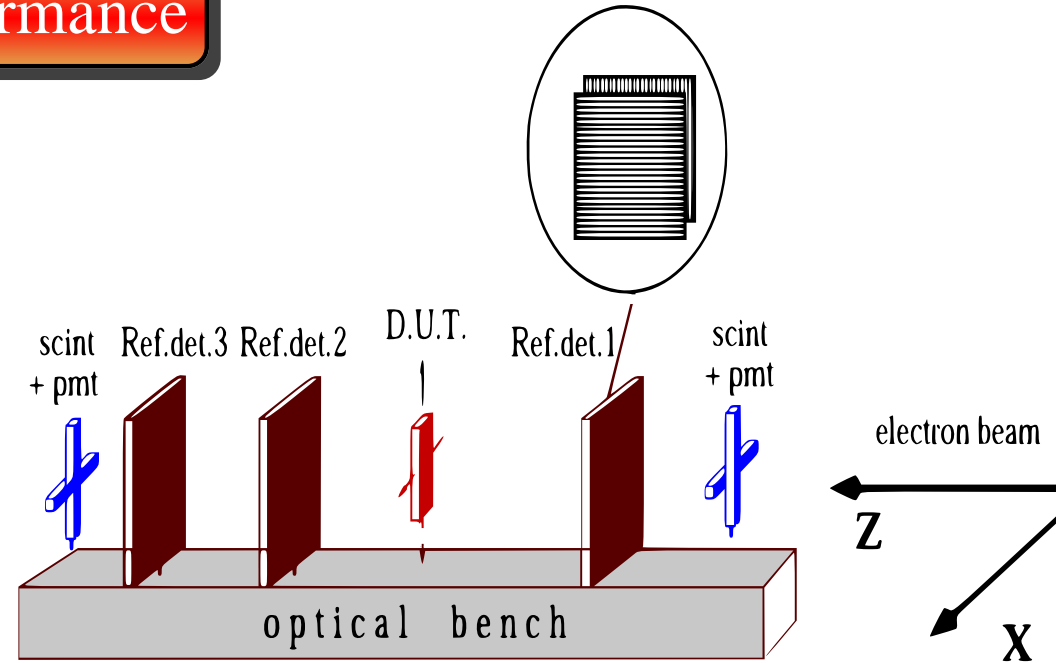
Microscopic defects have Macroscopic effects

# Long Term performance

How can we be sure that this whole thing still works in 10 years?

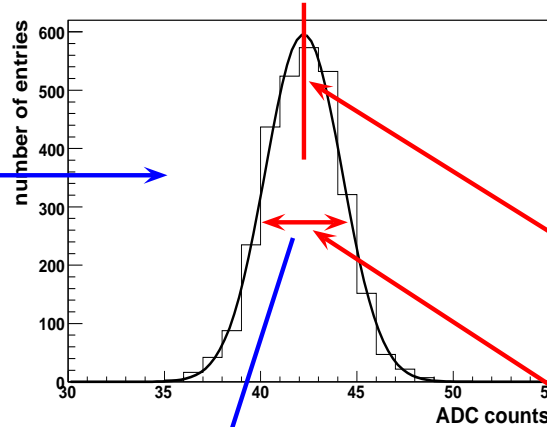
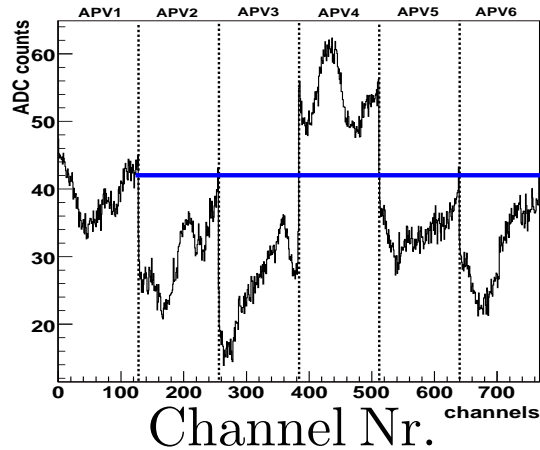
Strategy:

- Irradiate detectors with very high fluences
- Put into testbeam to check various parameters like
  - Signal-to-Noise (you still want to see a signal)
  - Resolution (you want to see a sharp signal)
  - Interstrip Coupling (you want to see it in the right place)



# Schematic Data Analysis

## Pedestal



- „Pedestal“ and „Noise“ Determination
- Subtract „Common Mode“

**Pedestal:** Mean for each channel for large number of events

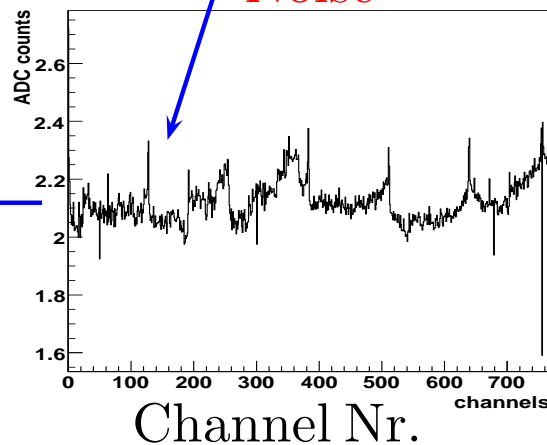
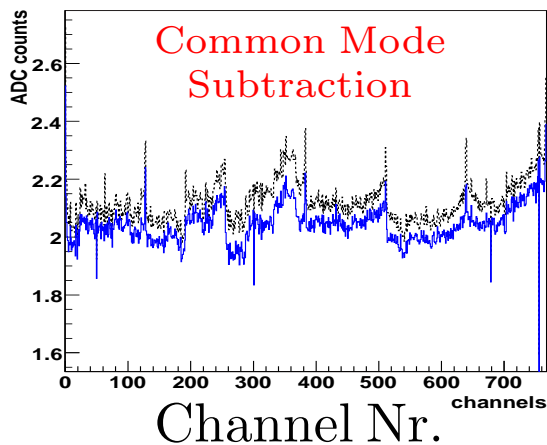
**Raw Noise:** RMS of Pedestal distribution

**Common Mode:** For each event, for

$N$  channels take

$$\frac{1}{N} \sum_{i=0}^N (\text{Raw}_i - \text{Pedestal}_i)$$

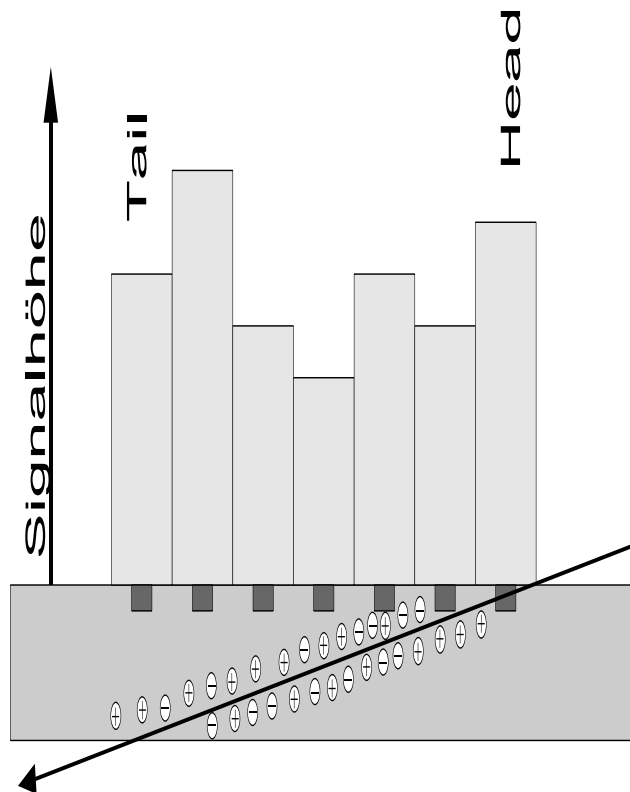
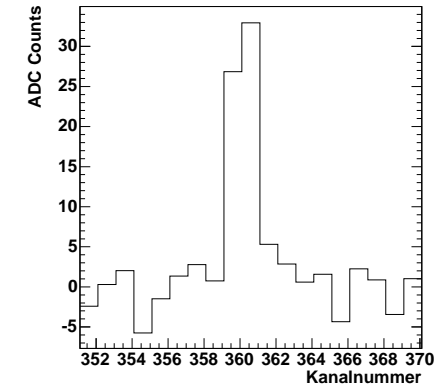
## Noise



Noise of 2 ADC counts  $\sim$  1000 electrons  $\rightarrow$  very good noise behaviour

# Data Analysis – Cluster Finding (Where did the particle cross our detector?)

- Goal: Reconstruct position of the particle hit as good as possible
- Naïve expectation: digital resolution (just take strip with highest signal  
→ strip position = hit position)
- May be improved due to charge sharing



- Clusters are reconstructed with different algorithms

**Standard weighted algorithm:** center-of-gravity, Cut on S/N of “seed” ( $4\sigma$ ), neighboring strip ( $3\sigma$ ) and the clusters ( $5\sigma$ )

**Head-Tail:** (first and last strip of the cluster are used as well as the average charge of the cluster (well suited for large angles))

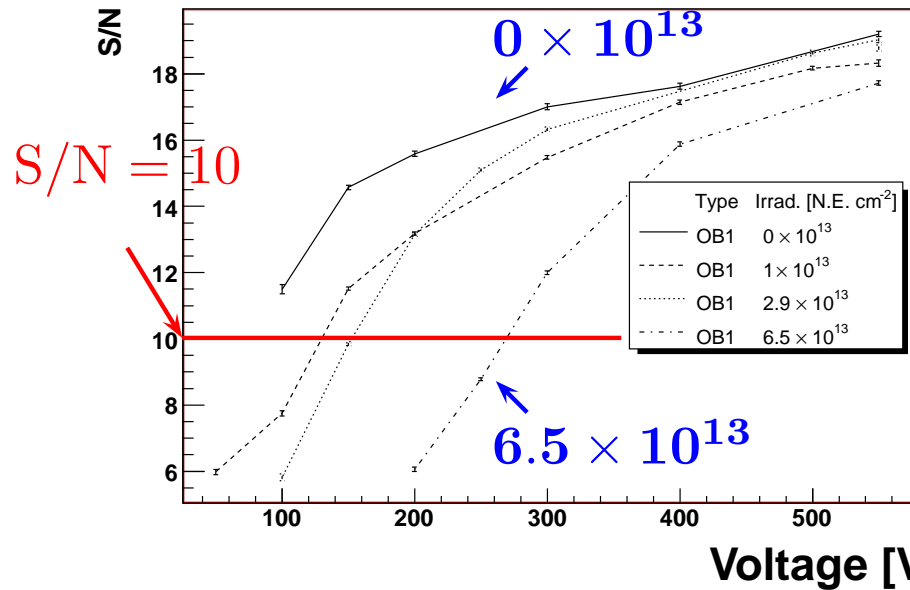
**Binary Readout:** Position of Seed = Position of Cluster

Standard weighted algorithm is used if not stated otherwise

But first: The signal-to-noise

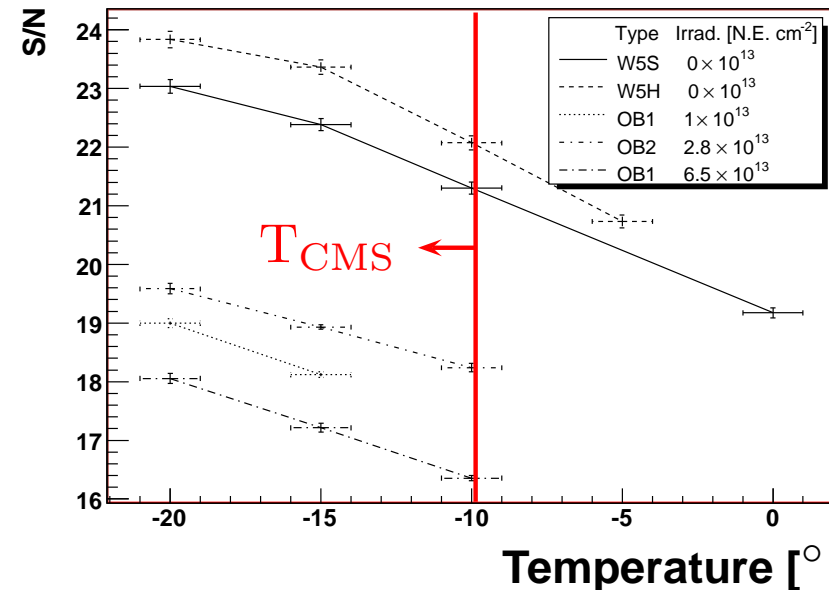
# Signal-to-Noise Analysis

Variation of Bias Voltage



Signal increasing strongly below depletion voltage

Variation of Sensor Temperature

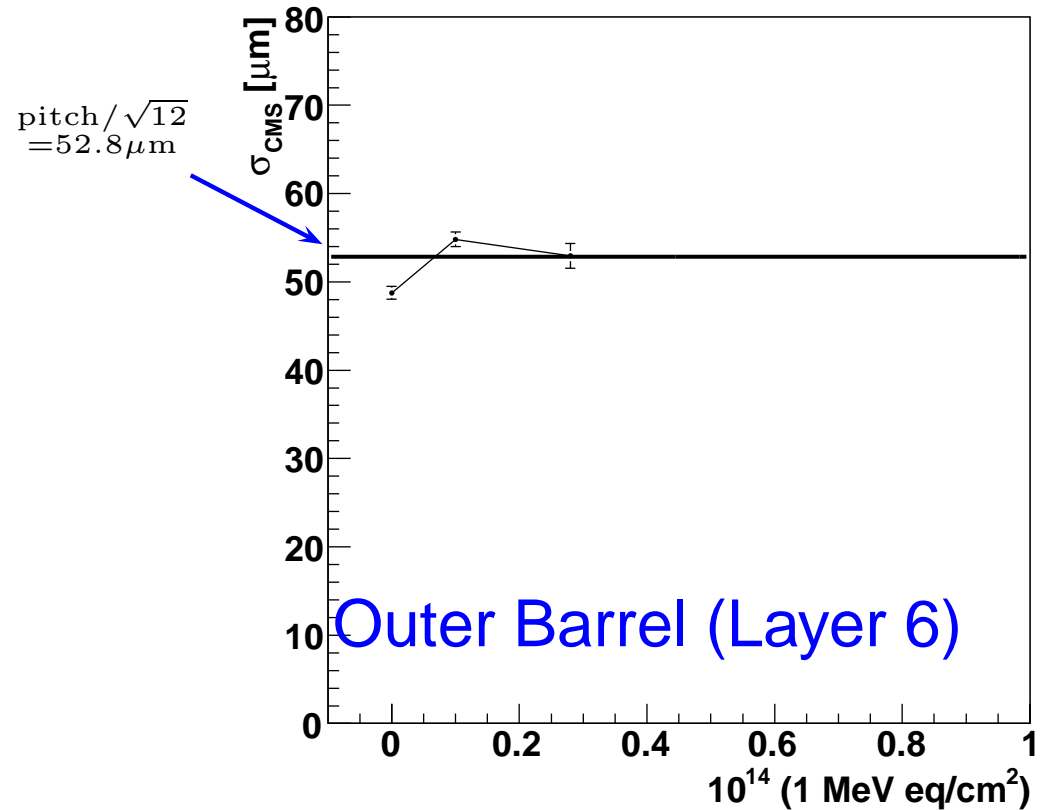
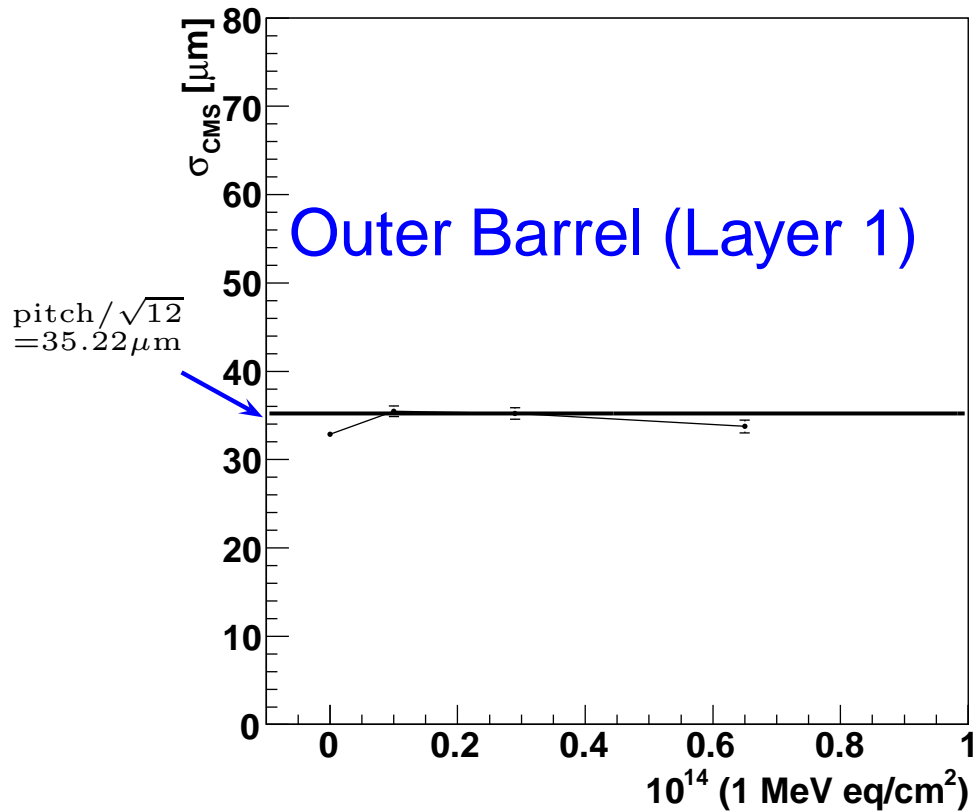


With increasing temperature, noise increases → SNR should become worse

S/N is stable and above the required specification also for highest irradiation level

# Spatial Resolution – Long-Term Performance

OB1

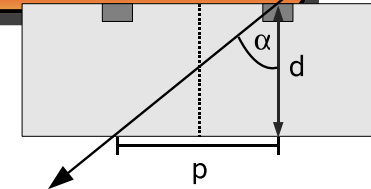


0° incident angle, 450 V bias voltage

No influence of irradiation on the module resolution

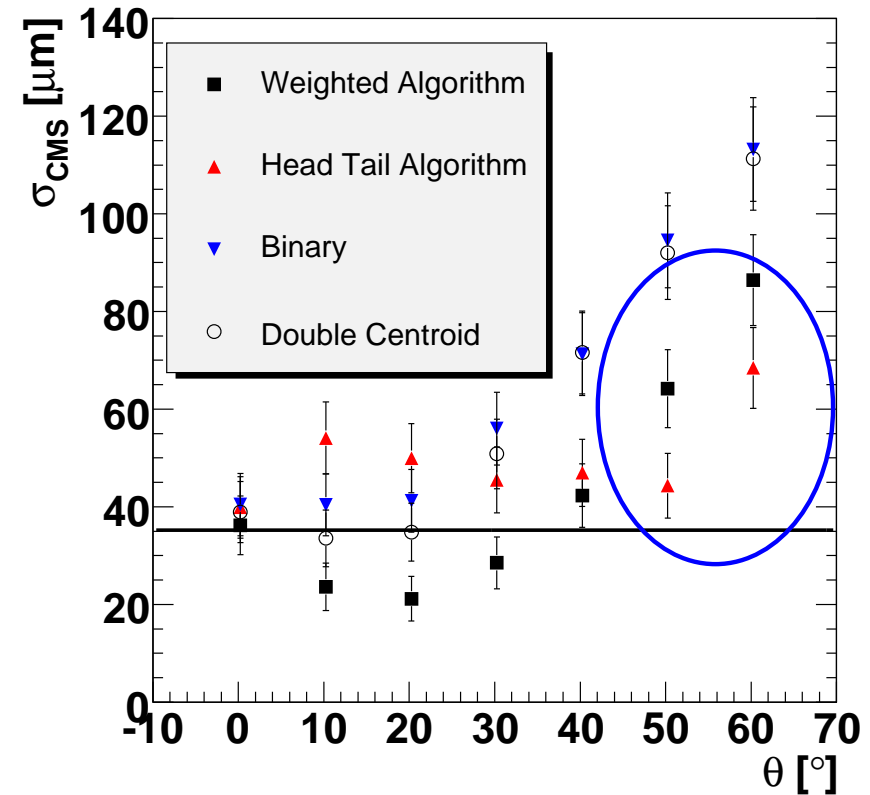
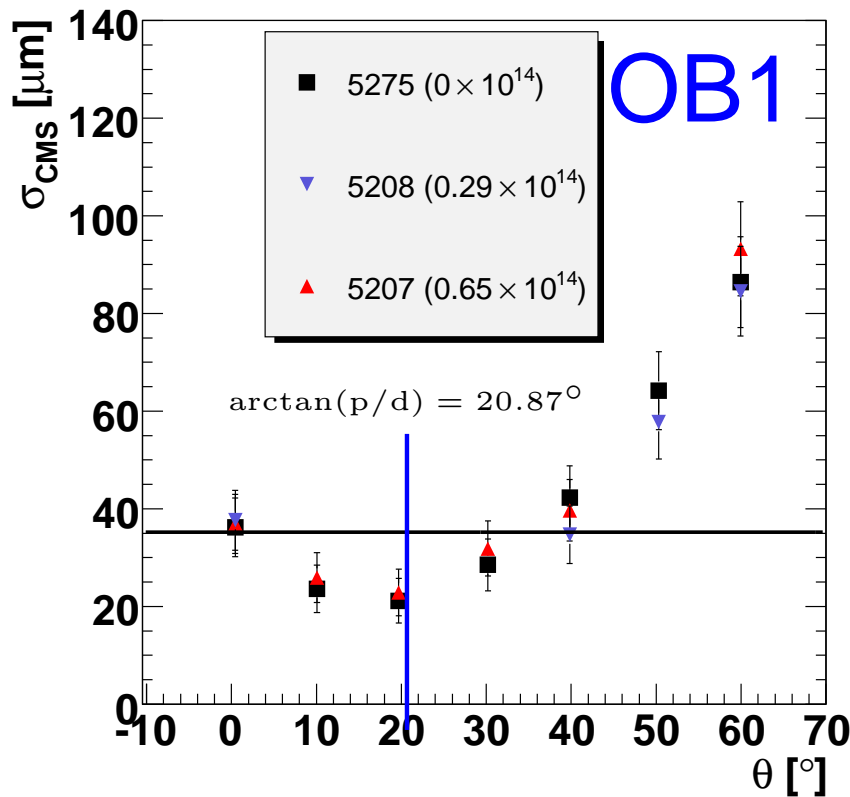
# Spatial Resolution Studies – Angular Scans and Cluster Algorithms

Resolution should improve due to charge sharing up to an angle of  $\arctan \frac{p}{d}$  ( $p$ =strippitch,  $d$ =sensor thickness)



Different Irradiation Level

Cluster Algorithms



Expected behavior, no influence of irradiation

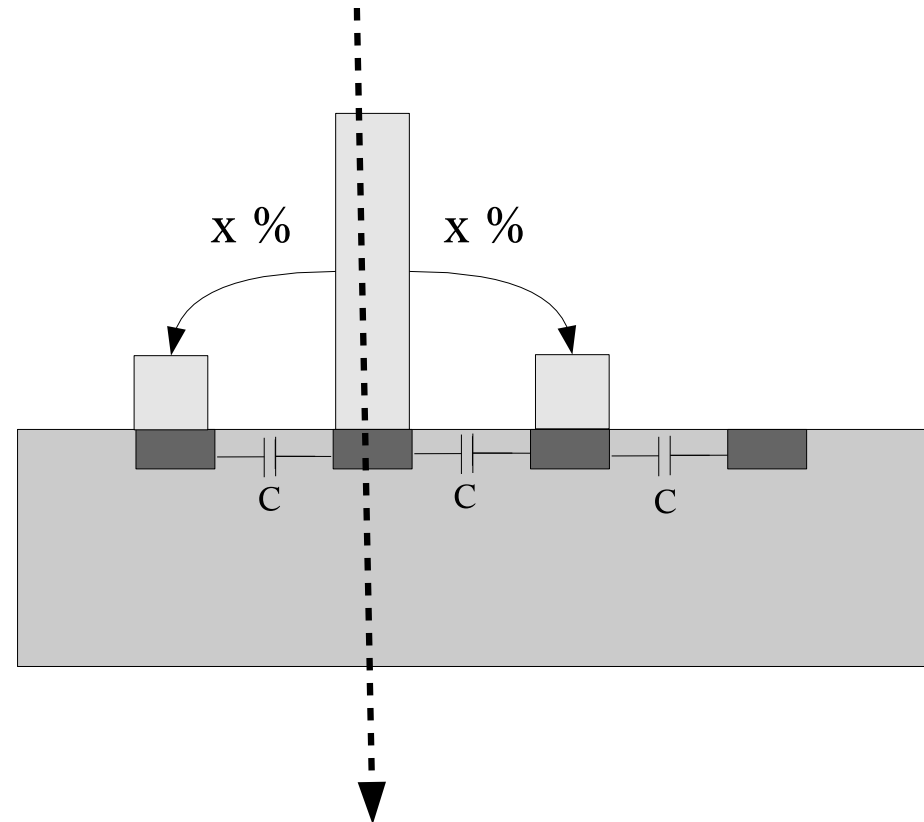
Weighted Algorithms performs best apart from very large angles (head-tail)

# Crosstalk

Apart from charge sharing also capacitive coupling can lead to charge being introduced on strips.

Consider perpendicular entry of a particle in the middle of strip:

- Charge is spread in narrow region within the sensor ( $\mu\text{m}$ )
- All charge is collected on this strip
- Due to capacitive coupling, charge is induced on neighboring strips



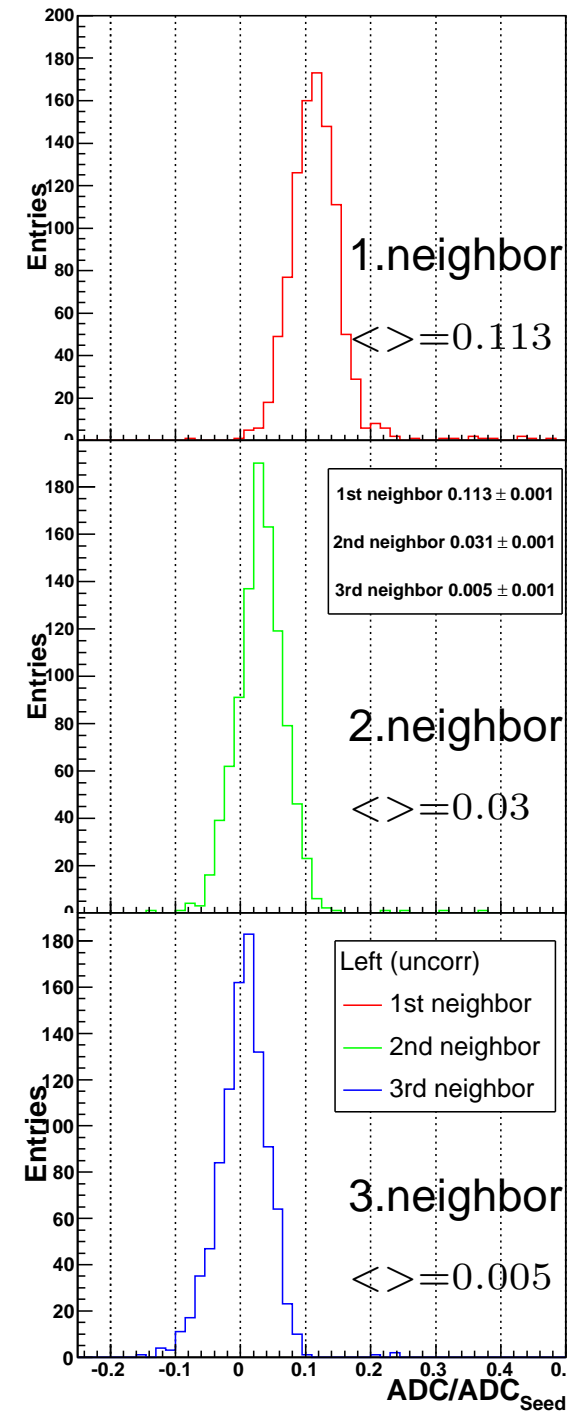
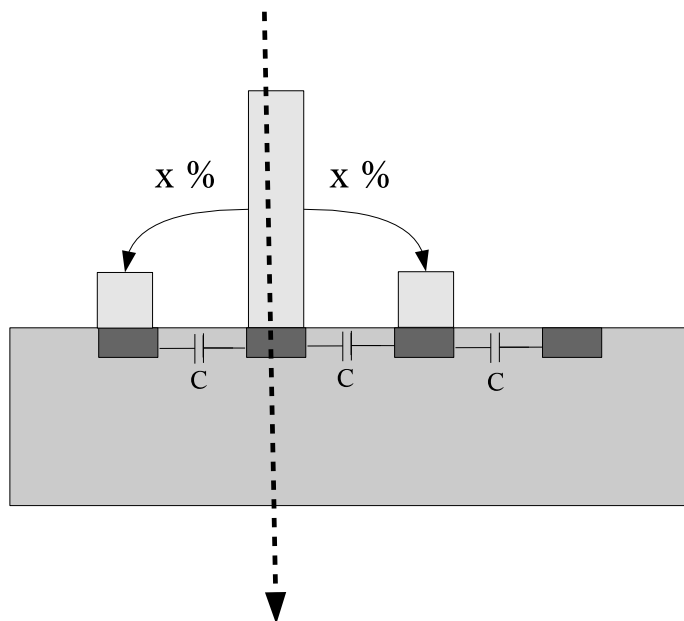
If this effect gets too large, reconstruction becomes more difficult

# Crosstalk Measurement

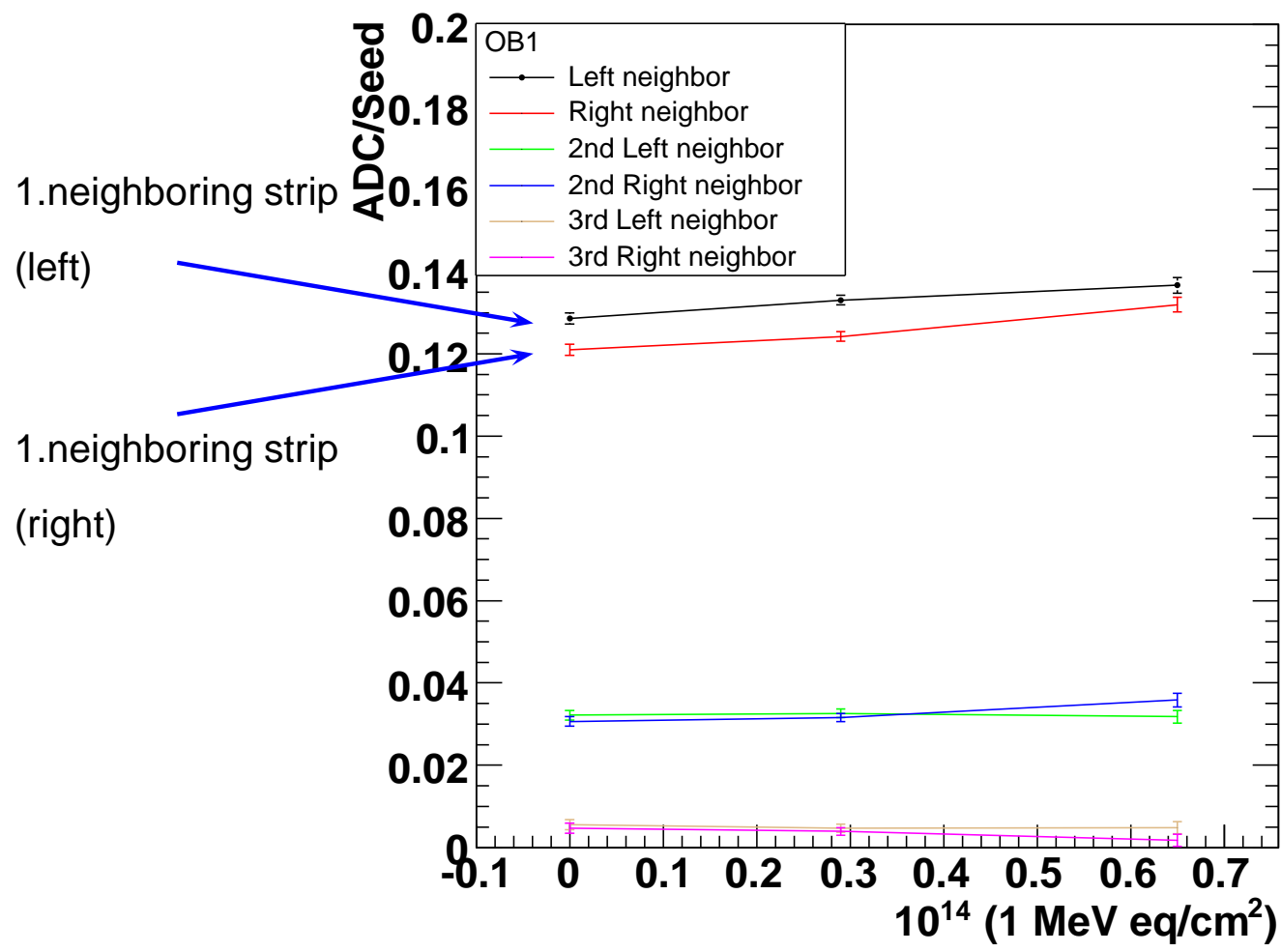
With the Testbeam Setup:

External track reconstruction enables direct measurement of crosstalk:

- Select events where center ( $\pm \frac{1}{4}$  strip) of strip has been hit
- Look for signal on neighboring strips



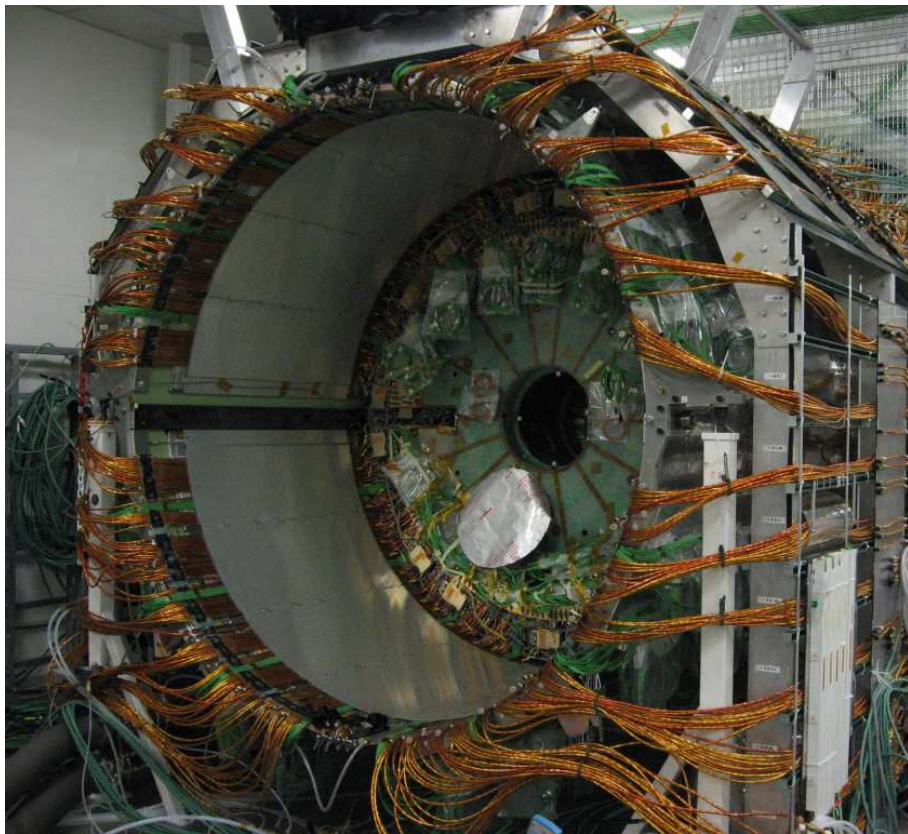
# Crosstalk vs. Irradiation Level



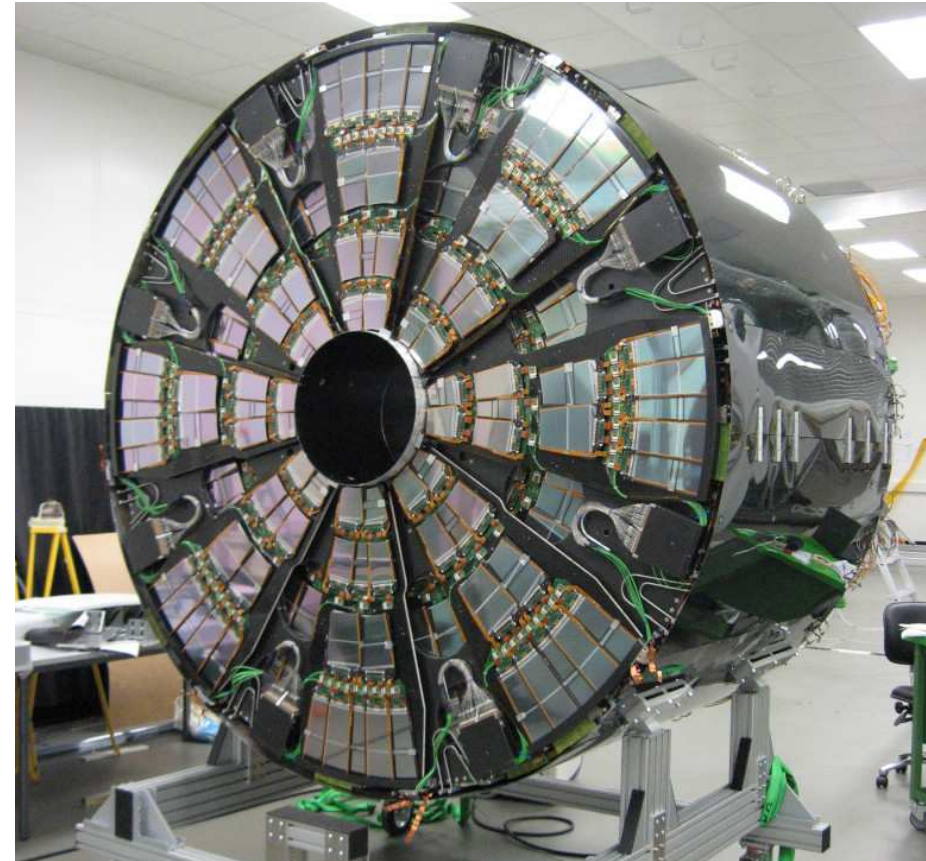
- Crosstalk slightly asymmetric
- Very moderate increase with irradiation

## The Real Thing

Ok, you convinced me that this might work, but how does the real detector look like?



Tracker Inner Barrel &  
Tracker Outer Barrel



Tracker End Cap

## Testing

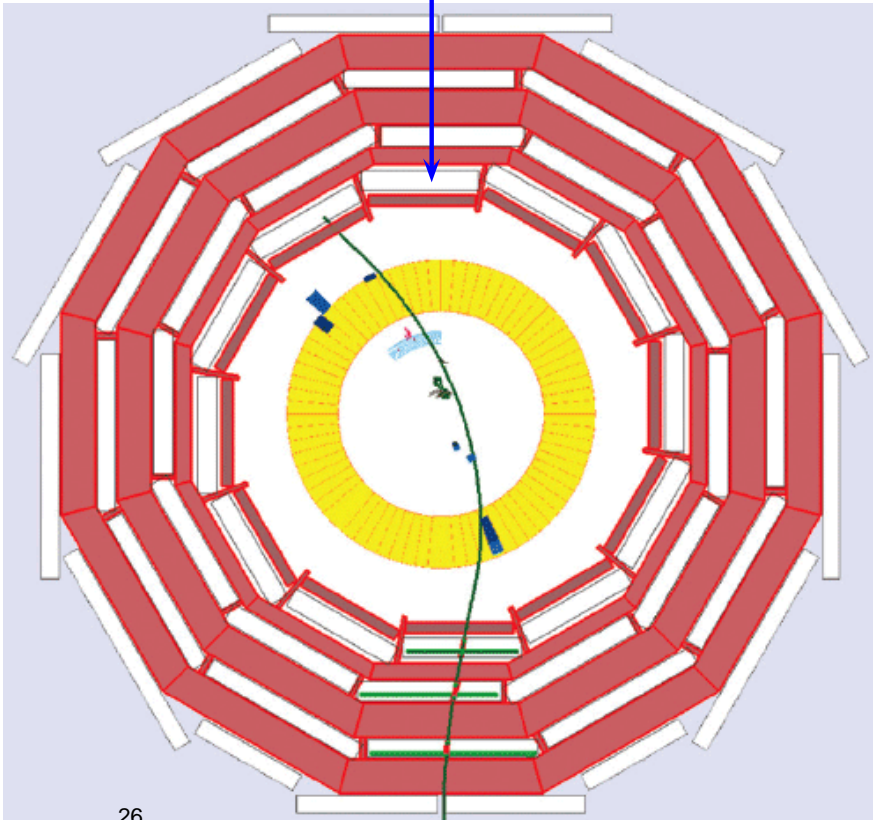
Great, we have a beautiful detector, but can we test it before inserting this  $\sim 100$  MCHF object forever?

- Magnet Test Cosmic Challenge (MTCC) (Summer 2006)
- Slice Test (Spring 2007)

# Magnet Test Cosmic Challenge – Summer 2006

Tested only very few modules, but:

- Transport of tracker support tube exercised ✓
- Insertion of structure into detector exercised ✓
- Operation in 4 T magnetic field ✓



## The CMS Silicon Tracker Slice Test

- Took place from March to July 2007 at CERN
- All parts of the silicon tracker were assembled and a large fraction of tracker was read out

### Goals of the Slice Test

- Stable data taking with all subdetectors
  - Common Commissioning of all Subdetectors
    - \* Determine possible interference between subdetectors (crosstalk)
    - \* Measure at different temperatures, determine thermal properties of the tracker
  - Record cosmic muons with all subdetectors
  - Establish and test the read-out and reconstruction chain (transfer data to Tier1 center and run reconstruction chain, etc...)

Total: >2100 Modules,  $\sim 25 \text{ m}^2$  of silicon (compare to  $6 \text{ m}^2$  for CDF SVX II)

## Slice Test: Schedule

**Since Beginning of March:** TIB/TOB/TEC read out together at room temperatur (chiller at  $+15^{\circ}\text{C}$ )

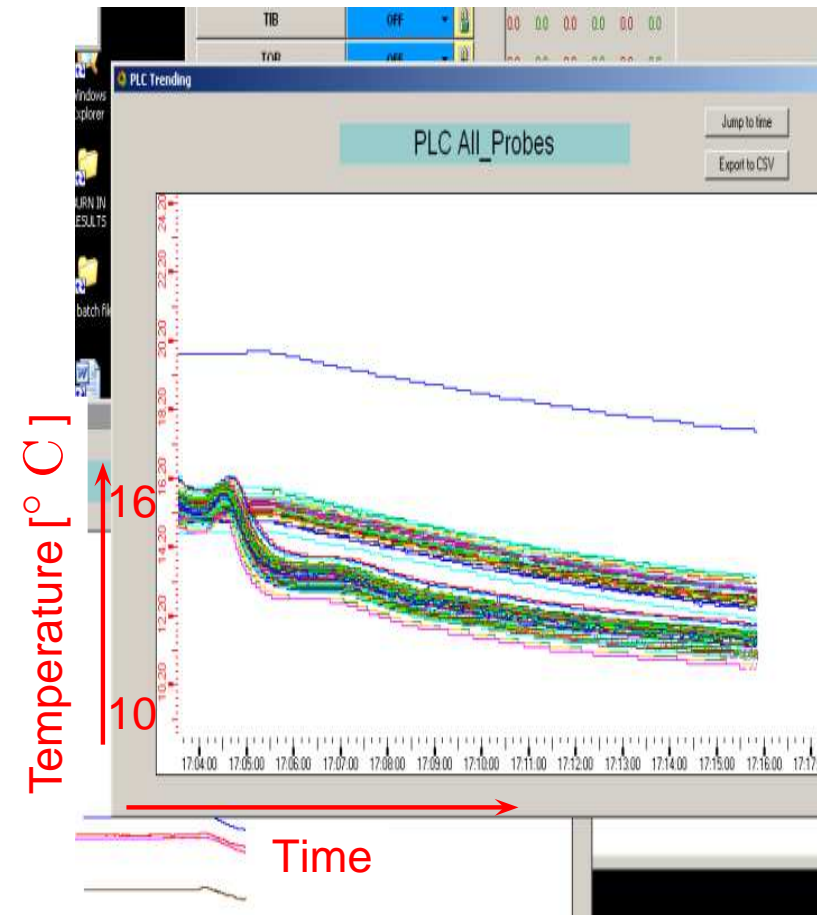
**May 25th:** Lowering chiller temperature to  $+10^{\circ}\text{C}$

**June 5th:** Lowering chiller temperatur to  $-0.5^{\circ}\text{C}$

**June 15th:** Lowering chiller temperatur to  $-10^{\circ}\text{C}$

**June 25th:** Lowering chiller temperatur to  $-15^{\circ}\text{C}$  (Reduced Slice)

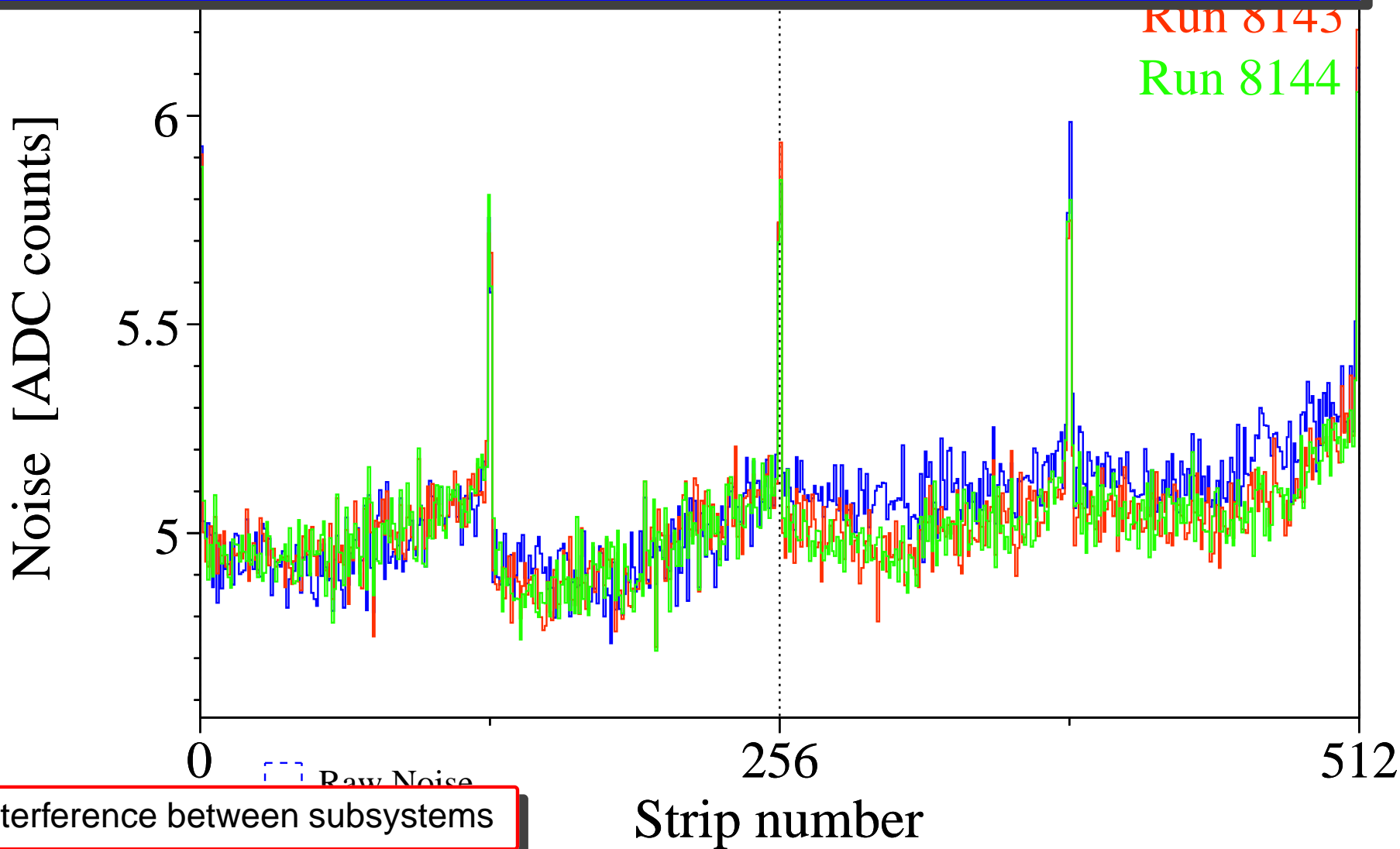
**Juli 1st:** Warming up to room temperature (Chiller  $+15^{\circ}\text{C}$ )



5 Steps in temperature, time at each step to check system and to take meaningful amount of cosmics

# Interference between Subsystems – Example from One Endcap

Other subsystems **off** , Other subsystem **powered**, Other subsystems **powered and read-out**



No interference between subsystems

## Defects/Troubles/Issues

- $\sim 0.7\%$  faulty channels in the two participating TEC sectors (800 modules)
- Most of these are not randomly distributed, but are located on faulty
  - APV read-out chips (128 channels)
  - Lasers ( $2 \times 128 = 256$  channels)
  - Modules (512 or 768 channels)

● = counted as dead  
● = more info to come

## Defects/Troubles/Issues

n.c. = not connected

Defect	+15C	+10C	0C	-10C	-15C
● S3 BP4 2.1/0 bad tick (known before slice test)	×	×	×	×	×
S3 BP1 5.3/0 low tick	×	×	×	×	×
● S3 BP5 7.3 two bad APVs (known since integration)	×	×	×	×	×
● S3 BP3 4.3 1 bad APV (known since integration)	1	1	2	2	2
● S2 FP3 1.4/0 laser with bad noise in dec. mode	×	3	4	×	n.c.
●● S2 BP6 2.1/2 laser with bad noise in peak and dec. mode	×	×	×	—	—
● S2 FP7 5.4 PLL not working	—	×	×	×	n.c.
S2 FP8 3.2/1 laser with high noise	4	×	—	—	n.c.
● S2 BP2 7.5/0 low noise & pedestal	—	—	—	—	×
S3 BP4 7.2/1 very high base tick is saturated	—	—	—	—	×

× = defect is present

— = defect is not present

1 = bad strips

2 = low noise

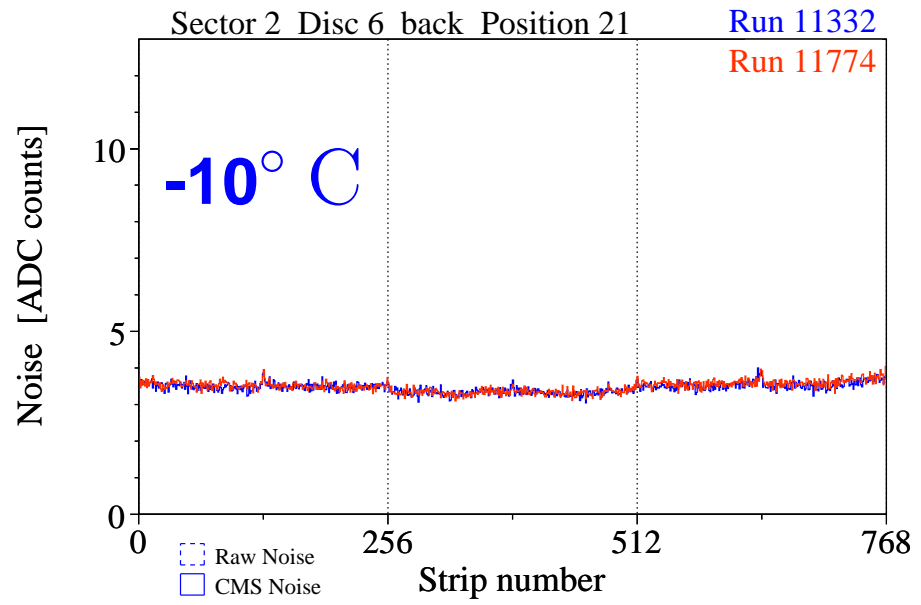
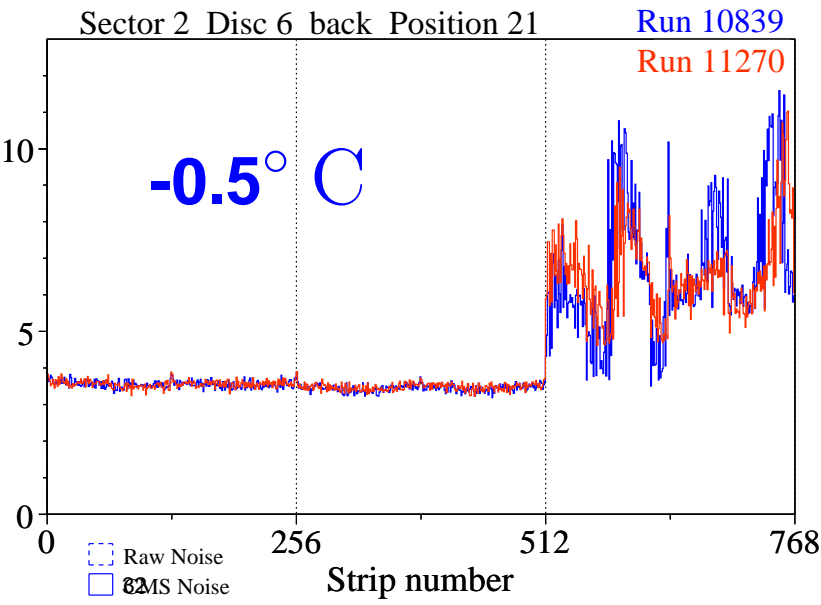
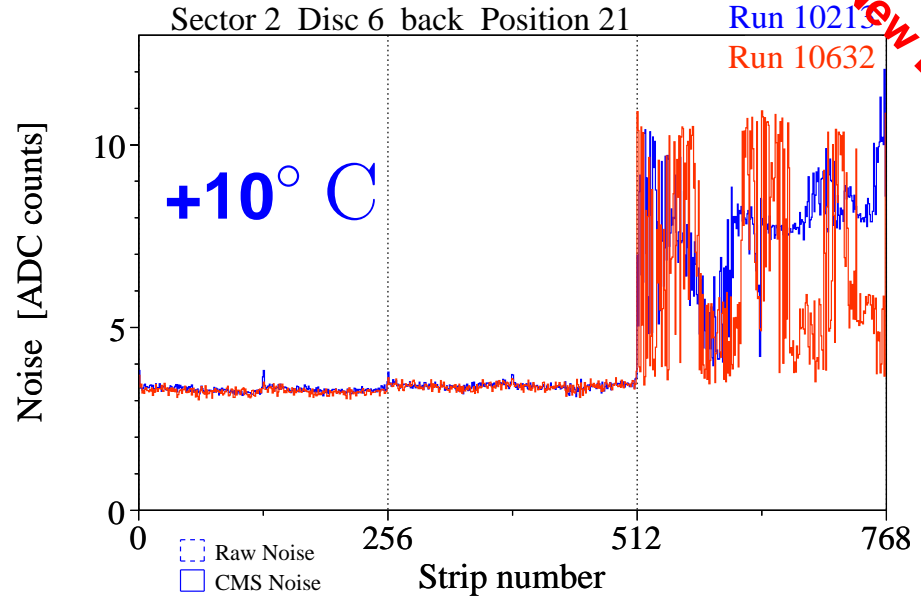
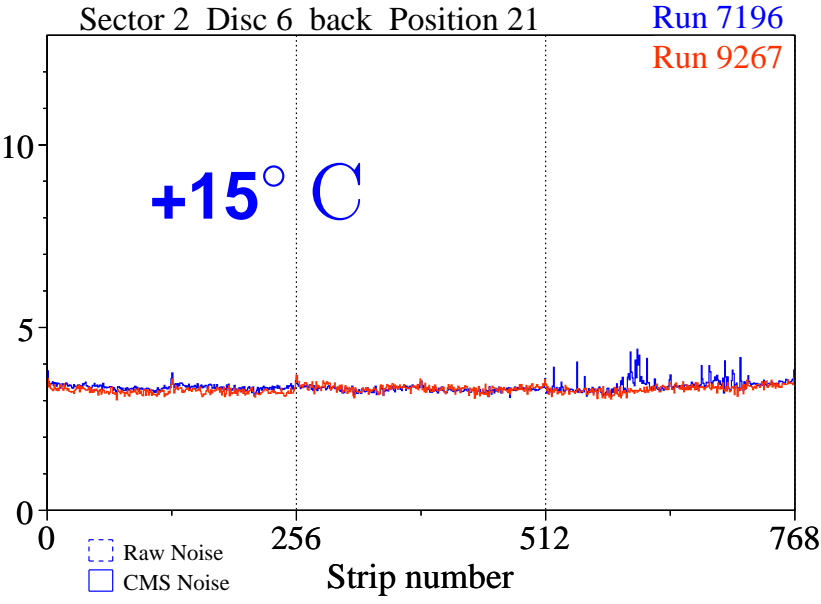
31

3 = no run in dec. mode av.

4 = not clear

Above defects affect  
**2944 channels** ( $\approx 0.6\%$ )  
some definitely lost, others may recover

# Defect Evolution with Temperature: S2 BP6 Pos 2.1 (Peak Mode)

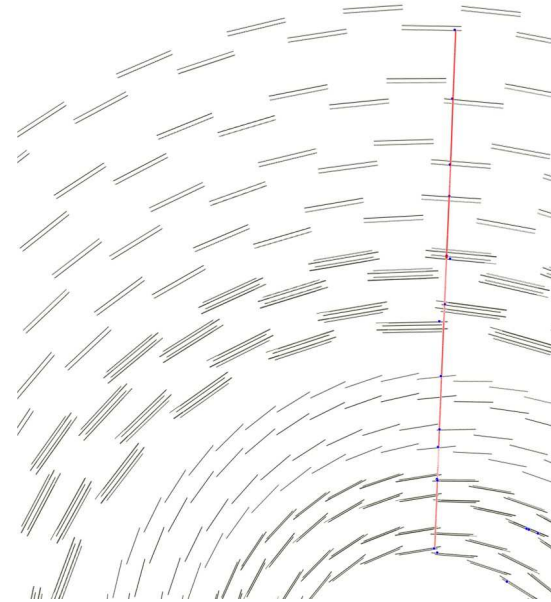


Behavior differs from run to run  
→ can generate many fake hits in physics runs

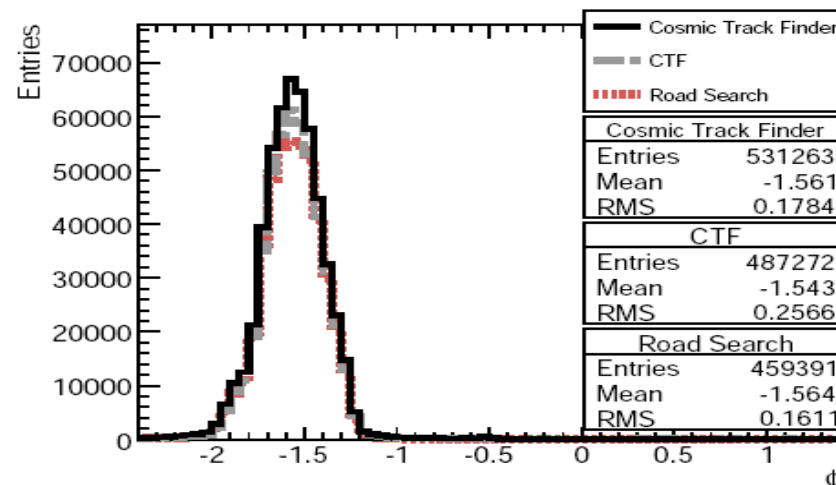
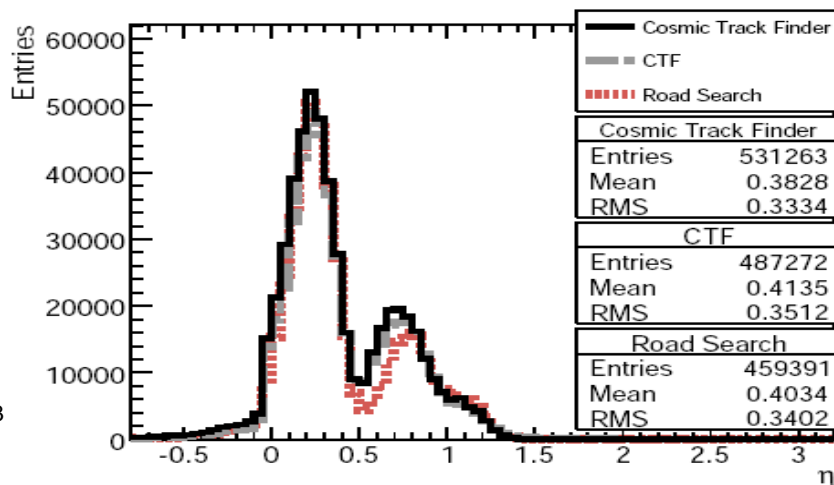
Runs from beginning and end of each temperature step

# Slice Test – Cosmic Data

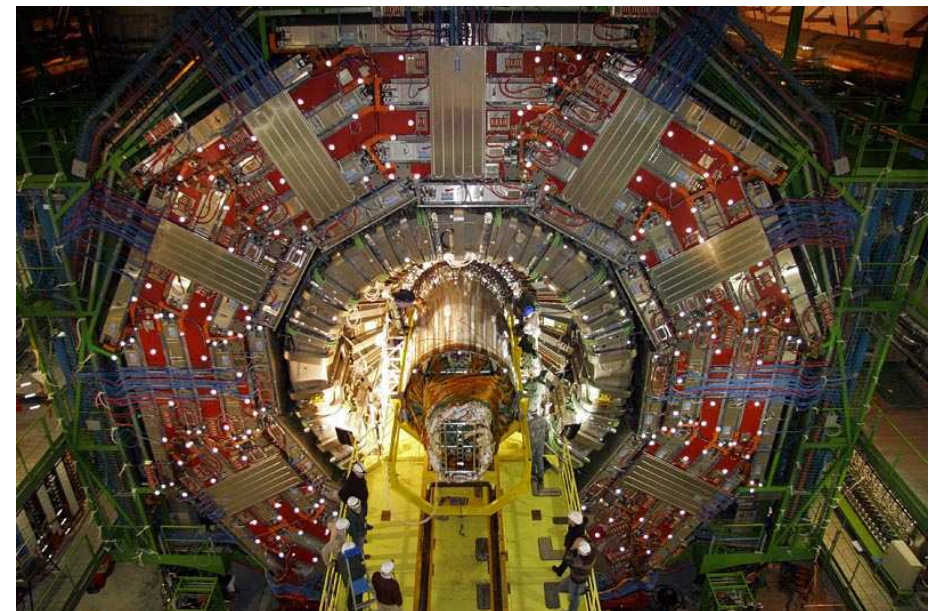
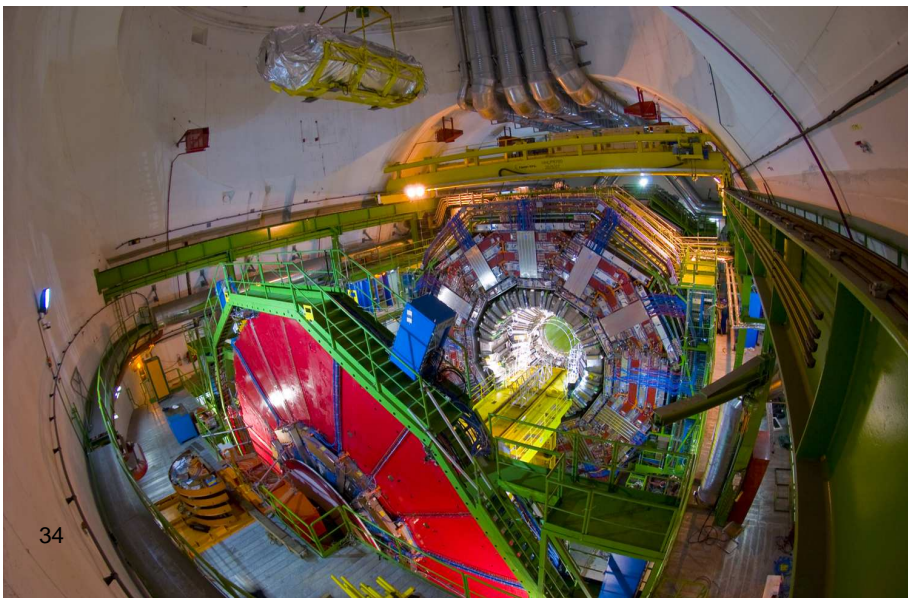
- More than 5 million cosmic triggers collected
- Approx. 1 million at every temperature step
- Reconstruction done via Grid on T1 centres (FNAL)



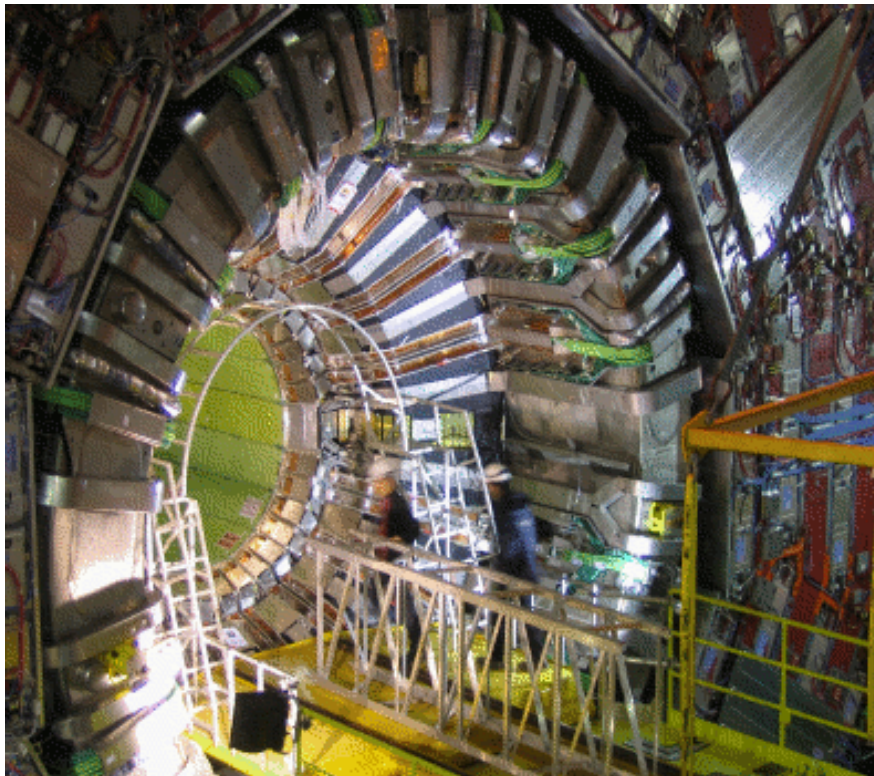
Cosmic track through Inner and Outer Barrel



# Tracker → P5 (13-14.12.2007)

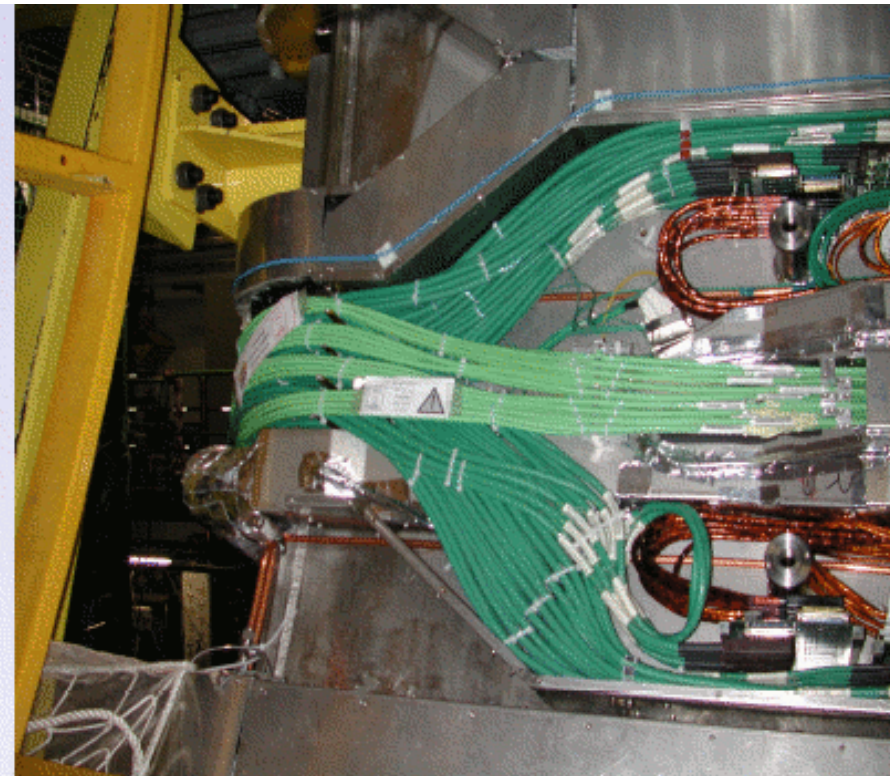


## Installation – Connecting the Tracker



What does this mean in numbers:

- 2520 electrical connections
- 452 pipes
- 495 multi-ribbon cables



This whole task was finished within 8 weeks

- 4.2.2008 Beginning of connection (started with piping)
- 1.4.2008 Both sides of the tracker finished

Check-out of the system is ongoing (not covered here)

# Tracker Alignment

Alignment is the adjustment of an object in relation with other objects, or a static orientation of some object or set of objects in relation to others.

## Problems of Misalignment

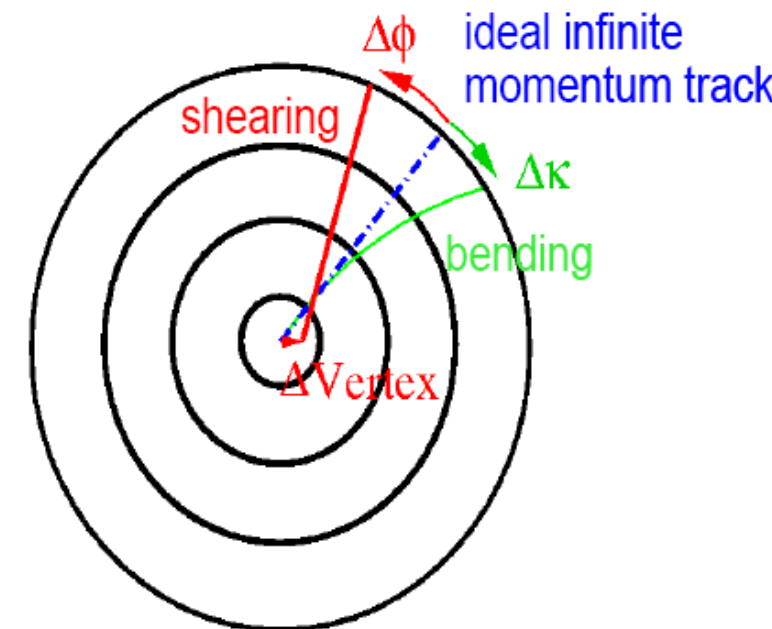
- Measurements get biased ( $p_T$  shift)
- Resolution worsens
- Efficiency may suffer
- ...

Aligning the CMS tracker is a huge task:

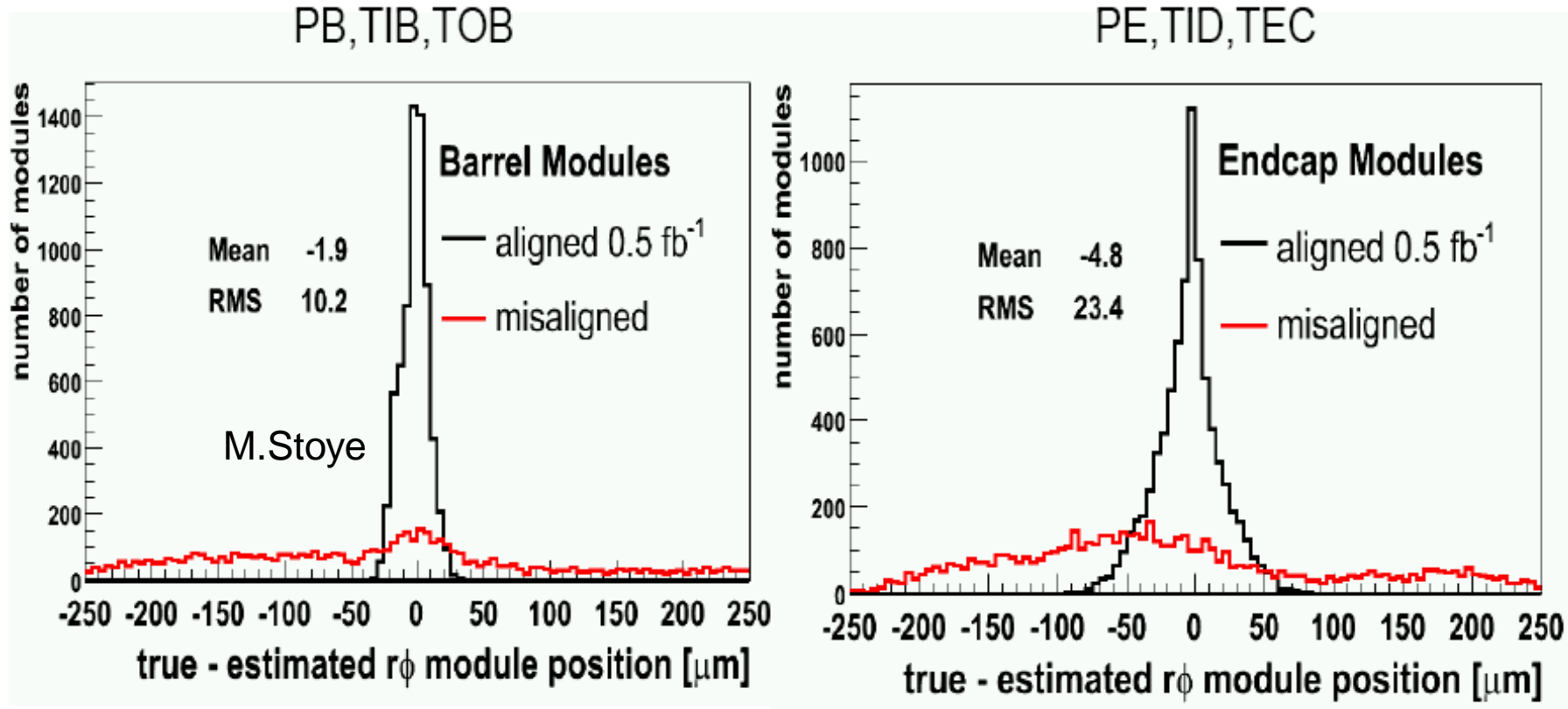
- $> 15.000$  silicon module, 6 degrees of freedom each
- $\rightarrow \sim 50.000$  alignment parameters

CMS uses

1. Information about mounting precision and a laser alignment system for the initial precision
2. track-based alignment for the final precision, i.e. for a large sample of tracks, the average  $\chi^2$  is minimized



# Full Scale (MC) Study

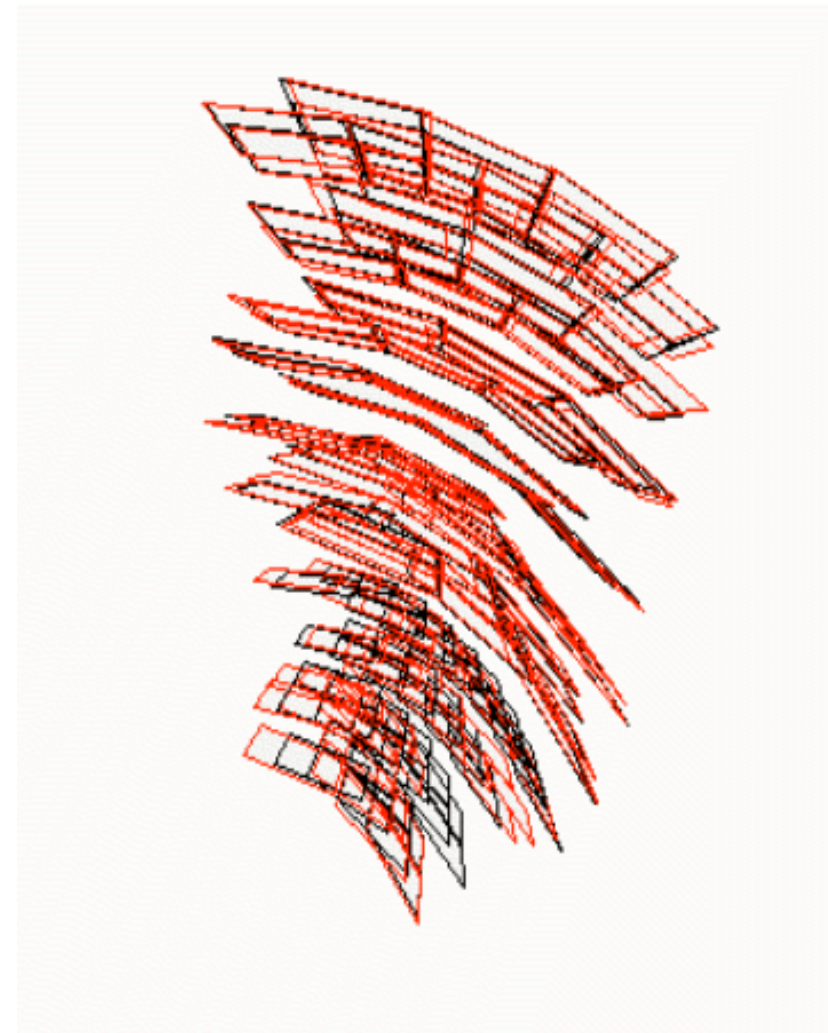
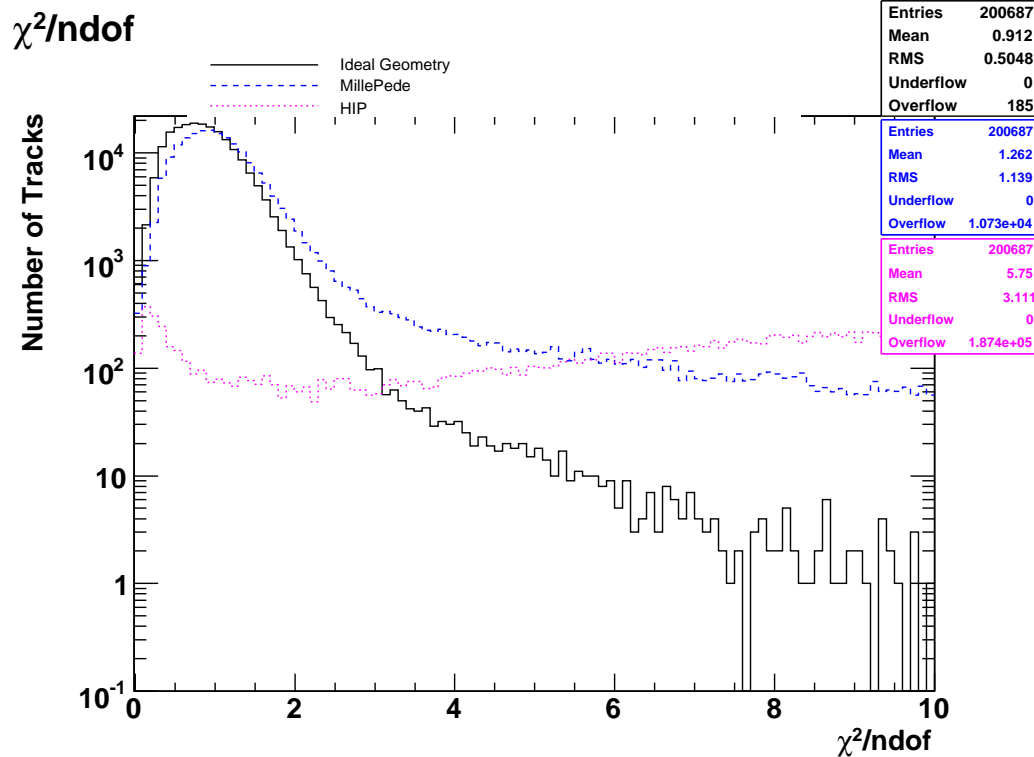


- Used a data set which corresponds to 0.5 fb<sup>-1</sup>
- Compared to true positions from MC
- Result: remaining deviation from ideal position often smaller than the resolution of the module  
→ no impact on resolution, e.g. for b-tagging expected

# Alignment Validation – Data Driven

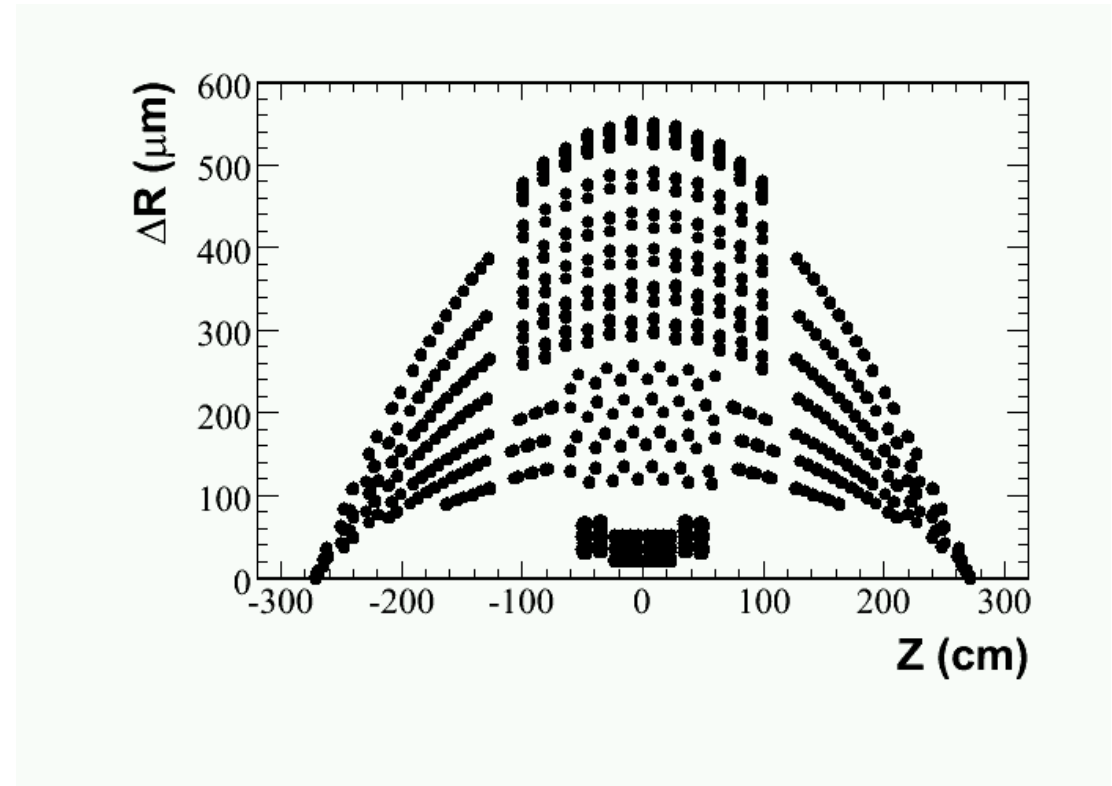
After the Alignment: Need to check that the obtained result is (close to) the optimal one

- Different 'figures of merit' can be thought of:
  - $\chi^2$ , Residuals, ...
- Furthermore: Check for 'weak modes' which do not/hardly change the  $\chi^2$



## Alignment Monitoring

- Also during running need to check the alignment continuously.
- checks similar to validation
- check validity of constants which may be altered due to
  - general sagging
  - thermal effects
  - magnetic effects (caused by CMS solenoid)
  - geological activity



(Systematic Misalignment study: Zijin Guo)

## Summary and Outlook

- The CMS silicon strip tracker has been successfully
  - assembled
  - tested
  - and inserted into CMS
- Connection is done and check-out of the system is ongoing
- Alignment of the CMS tracker will be an important task both during the start-up phase and later on
- The long term performance of the silicon modules with respect to irradiation damage seems to be under control

Exciting times and many challenges ahead of the tracker

## Summary and Outlook II

[...] because as we know, there are **known knowns**; there are things we know we know. We also know there are **known unknowns**; that is to say we know there are some things we do not know. But there are also **unknown unknowns** — the ones we don't know we don't know.  
(D. Rumsfeld, 2002)



Ulrich Husemann: Desy Seminar, 29.4.08

... so: Expect the unexpected

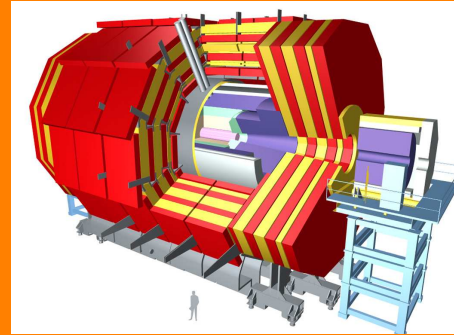
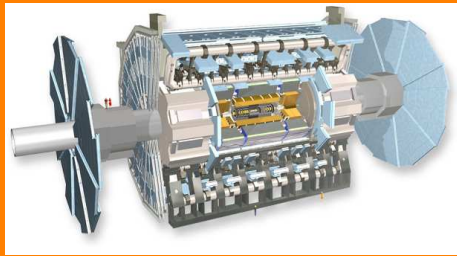


**The End**



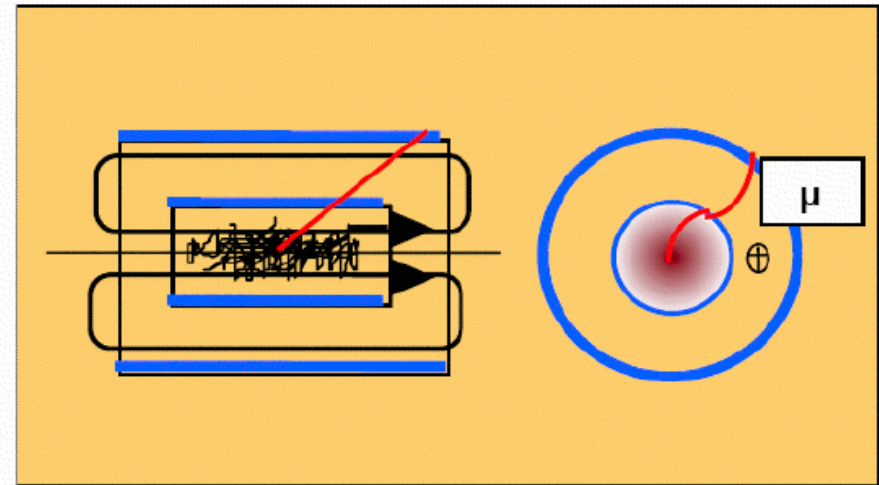
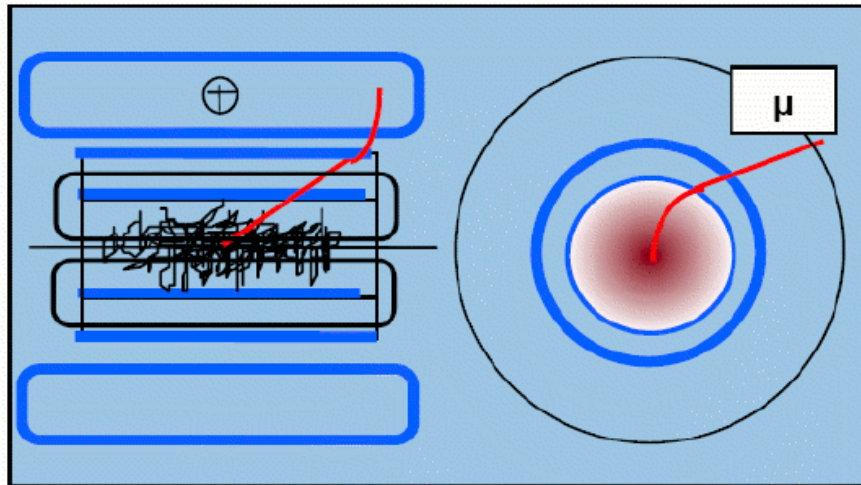
**Backup**

# CMS vs. ATLAS (in a nutshell)



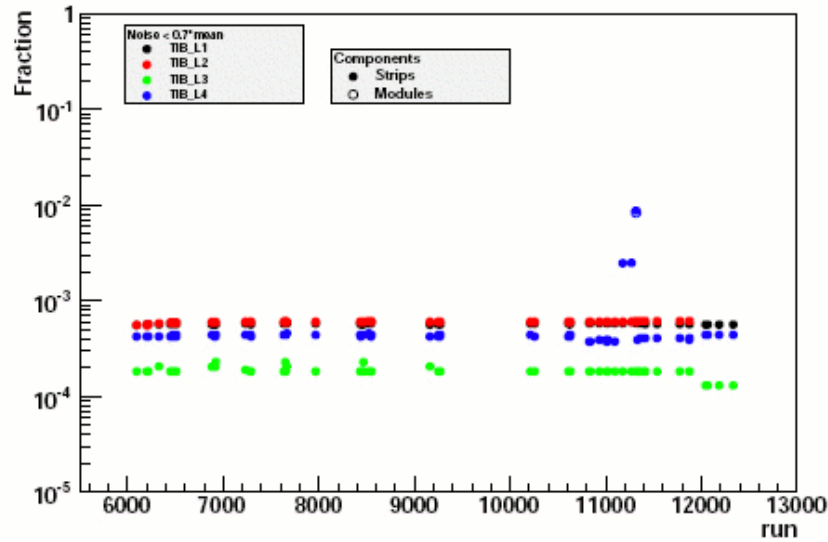
	Air core toroids+solenoid in inner cavity	solenoid
MAGNET(S)	Calorimeters outside field 4 magnets	Calorimeters inside field 1 magnet
TRACKER	Si pixel+strips TRD → particle identification $\sigma/p_T \sim 5 \times 10^{-4} p_T \otimes 0.01$	Si pixel + strips particle identification via analog readout $\sigma/p_T \sim 1.5 \times 10^4 p_T \otimes 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	PbWO4 crystals $\sigma/E \sim 34\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scintillator + Cu-Liquid argon (10λ) $\sigma/E \sim 50\%/\sqrt{E} \otimes 0.03$	Cu-scint. (> 5.8λ+catcher) $\sigma/E \sim 65\%/\sqrt{E} \otimes 0.05$
MUON	Air → $\sigma/E \sim 7\% @ 1 \text{ TeV}$ standalone	Fe → $\sigma/E \sim 5\% @ 1 \text{ TeV}$ combining with tracker

## CMS vs. ATLAS Magnetic Field Configurations

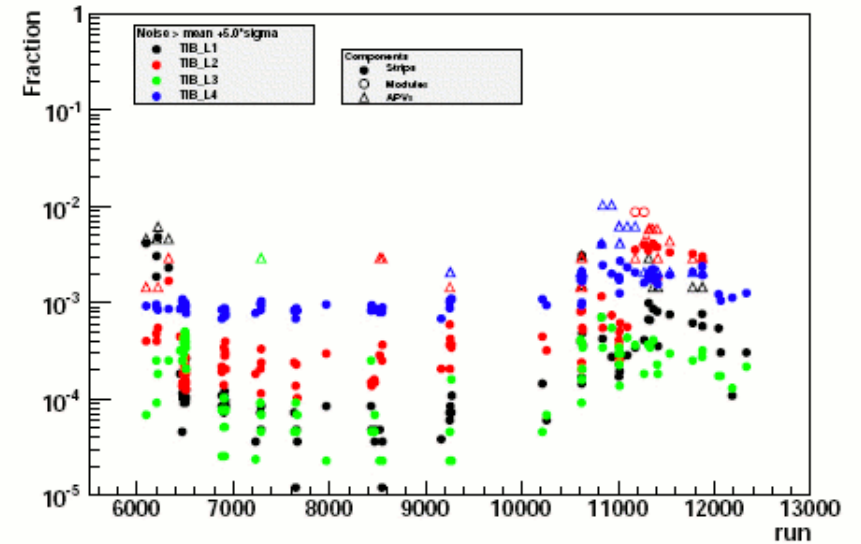


# Backup – Dead and Noisy Strips – TIB & TOB

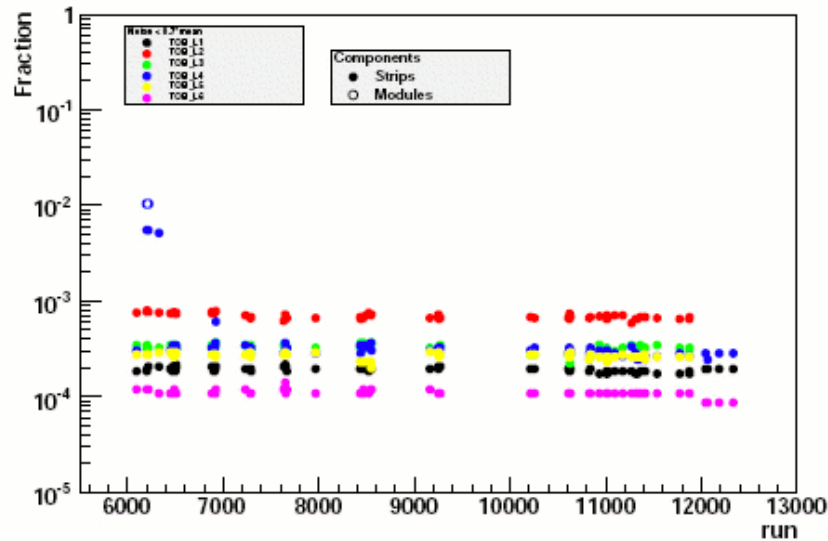
TIB Low noise components



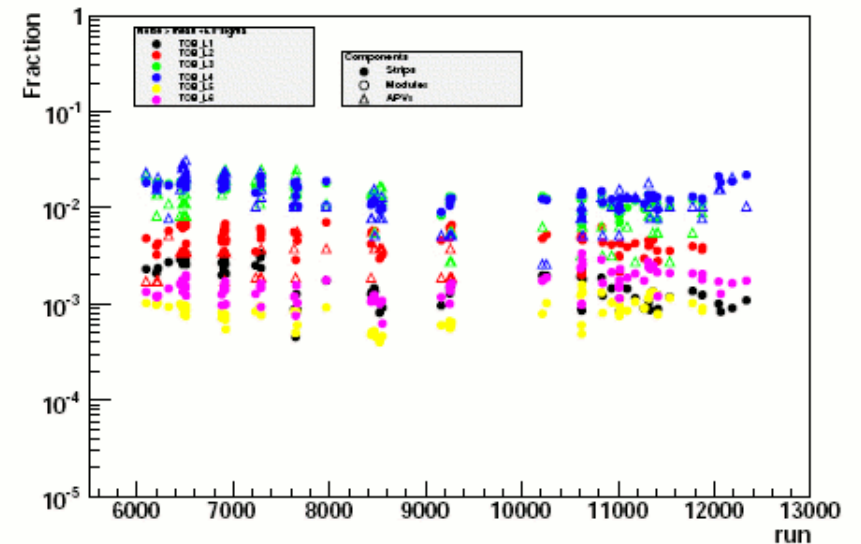
TIB High noise components



TOB Low noise components



TOB High noise components



## Backup – Digital Resolution

- Constant probability distribution

$$f(x) = \begin{cases} \frac{1}{d} & 0 \leq x \leq d \\ 0 & \text{else} \end{cases}$$

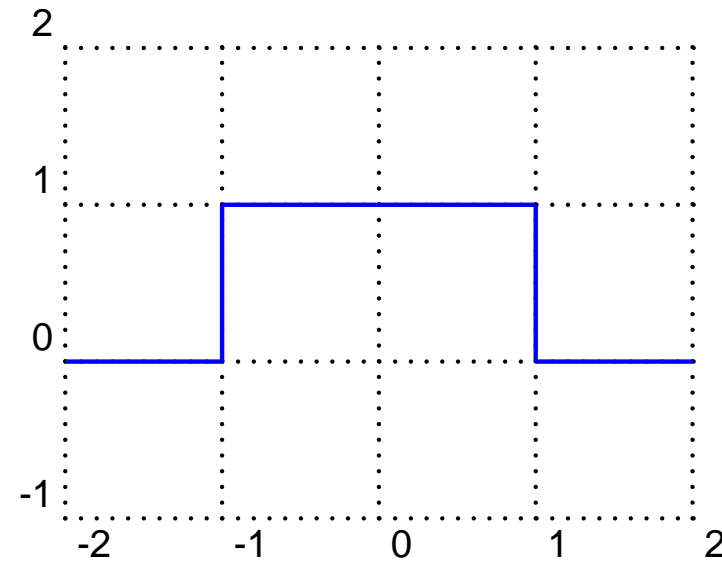
- Calculate variance and mean:

$$\langle x^2 \rangle = \frac{1}{d} \int_0^d x^2 dx = \frac{d^2}{3}$$

$$\langle x \rangle = \frac{1}{d} \int_0^d x dx = \frac{d}{2}$$

- Width:

$$\sigma_x = \sqrt{\langle x^2 \rangle - \langle x \rangle^2} = \sqrt{\frac{d^2}{3} - \frac{d^2}{4}} = \frac{d}{\sqrt{12}}$$



# Backup – Spatial Resolution of TEC Modules

Two modules were investigated one from STM and one Hamamatsu

