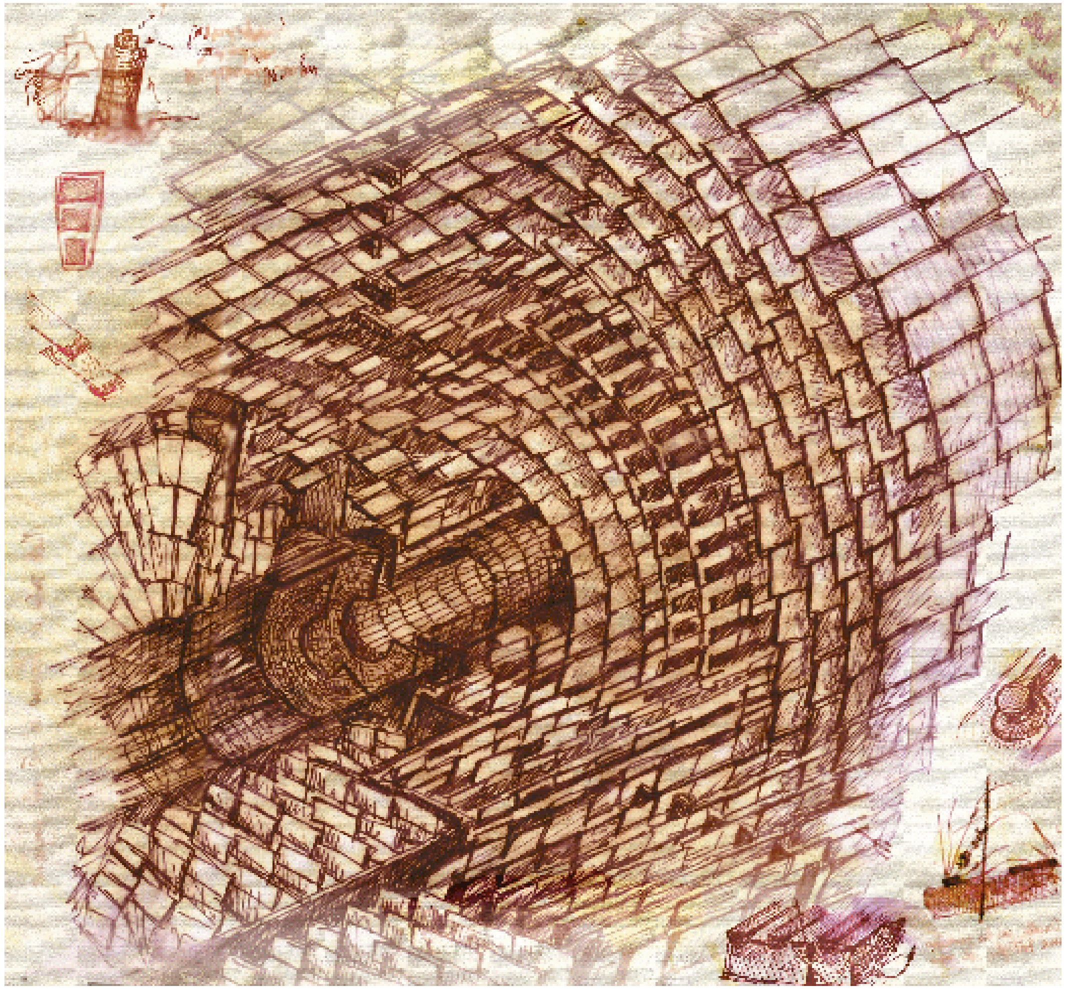
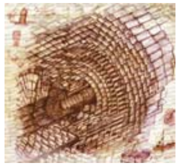
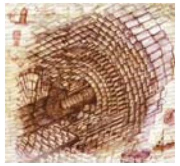
Tracking at the LHC: The CMS Example





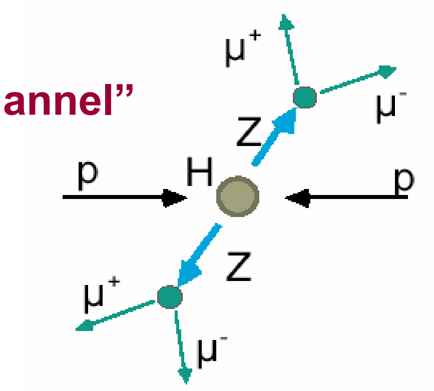
Outline

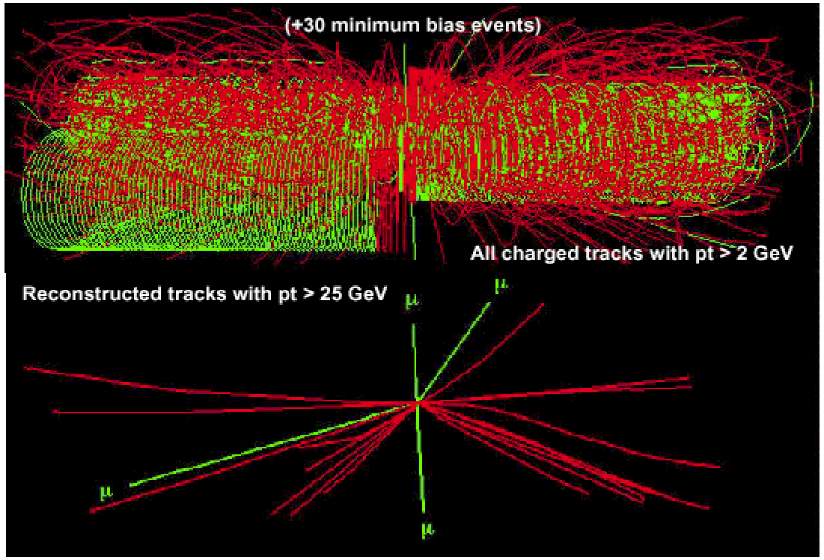
- The challenge
- The CMS Tracker concept
- Putting it in perspective
- Selected highlights:
  - The silicon sensors
  - Module components production & assembly
  - Shells, Rods and Petals
  - Alignment
  - Track reconstruction
  - The Tracker at HLT
- Tracking at the SLHC
- Summary and Conclusions



The Challenge

“Golden Channel”





Tracker Requirements:

Efficient & robust Pattern Recognition

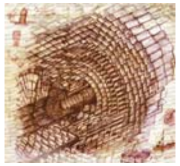
⇒ Fine granularity, to resolve nearby tracks
⇒ High speed, to resolve bunch crossings

Reconstruct narrow heavy objects

⇒ 1~2% Pt resolution at ~ 100GeV

Tag b/τ through secondary vertex

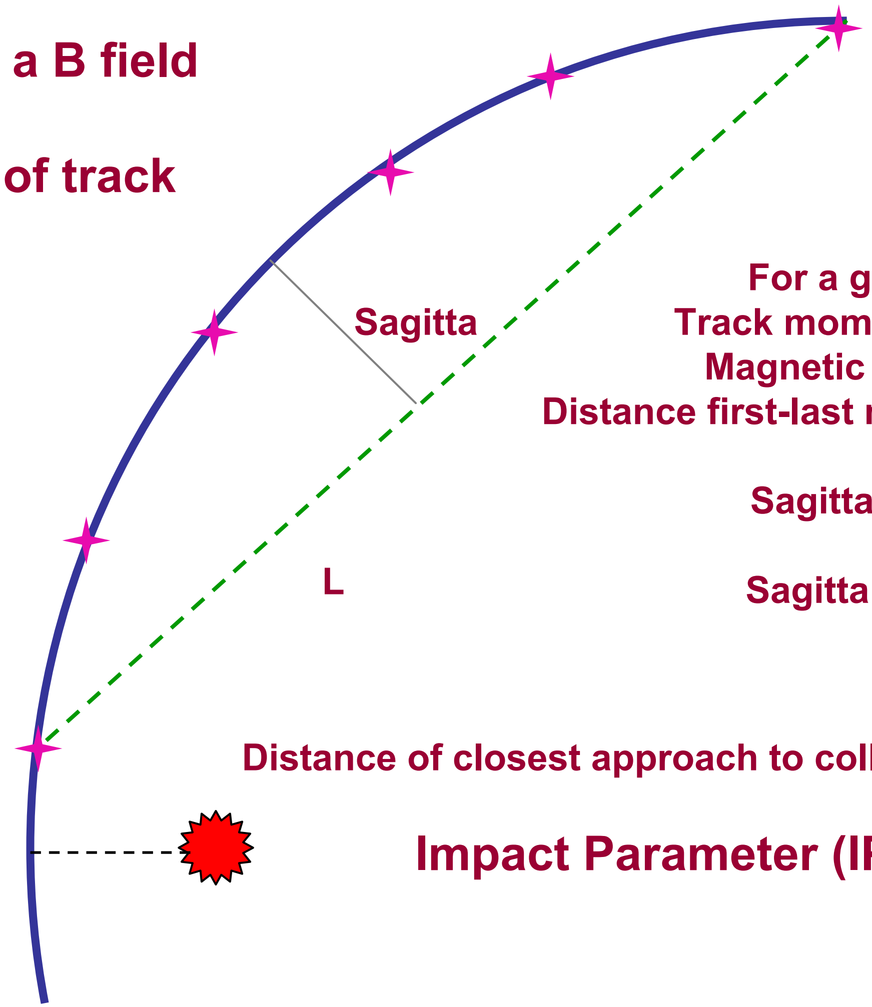
⇒ Good impact parameter resolution



The Challenge

For a charged particle in a B field

P ~ radius of curvature of track
~ 1 / Sagitta



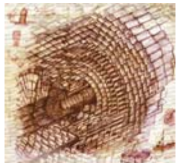
For a given
Track momentum P
Magnetic field B
Distance first-last measurement L:

Sagitta ~ B

Sagitta ~ L^2

Distance of closest approach to collision point:

Impact Parameter (IP)



The Challenge

To set the scale for the momentum measurement, recall that:

The CMS B Field = 4T and the TK Radius ~ 110 cm result in 1.90mm sagitta for 100 GeV Pt track (=> 20um ~ 40um resolution)

To set the scale for speed and granularity, recall that:
At high luminosity there will be 20~30 min. bias events every 25ns

Even assuming 25ns time resolution, these will result in a very high charged particle flux (modified the B field)

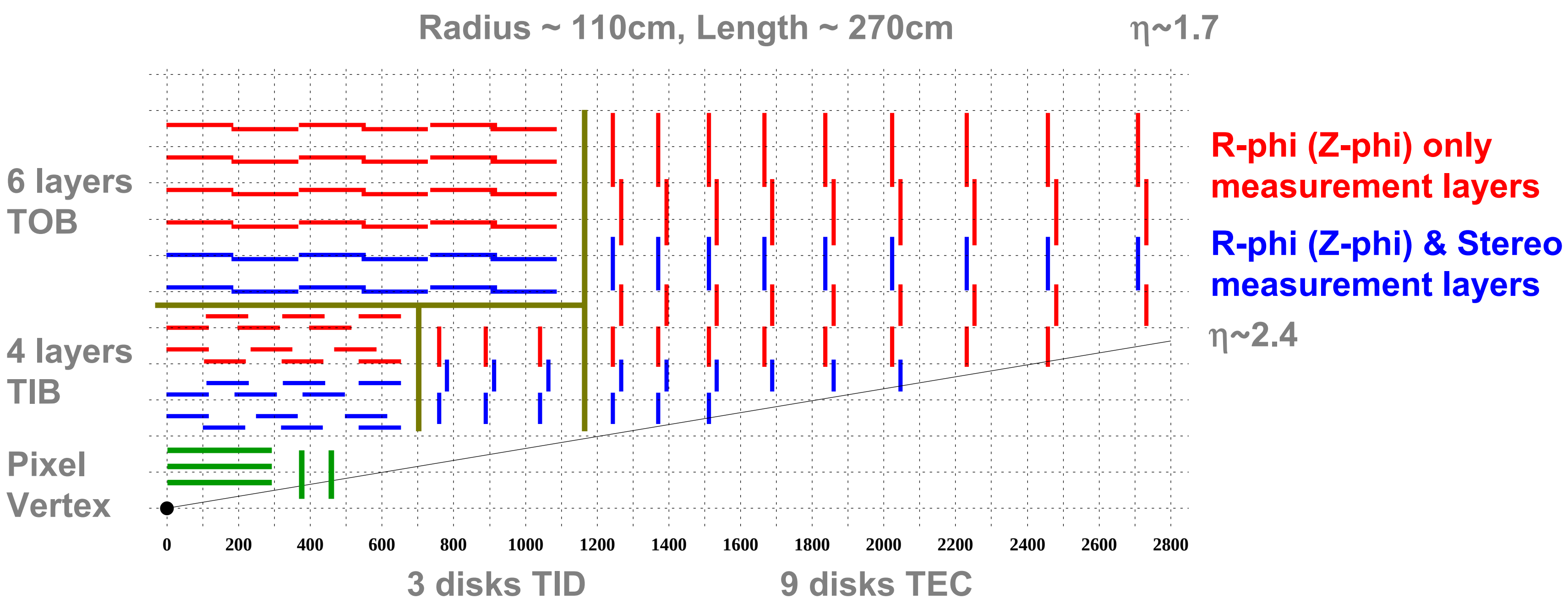
R	=	10cm	25cm	60cm
$N_{ch}/(cm^2*25ns)$	=	1.0	0.10	0.01

Impact parameter resolution should be “as good as possible”

The Concept

Rely on “few” measurement layers, each able to provide robust (clean) and precise coordinate determination

2 to 3 Silicon Pixel, and 10 to 14 Silicon Strip Measurement Layers

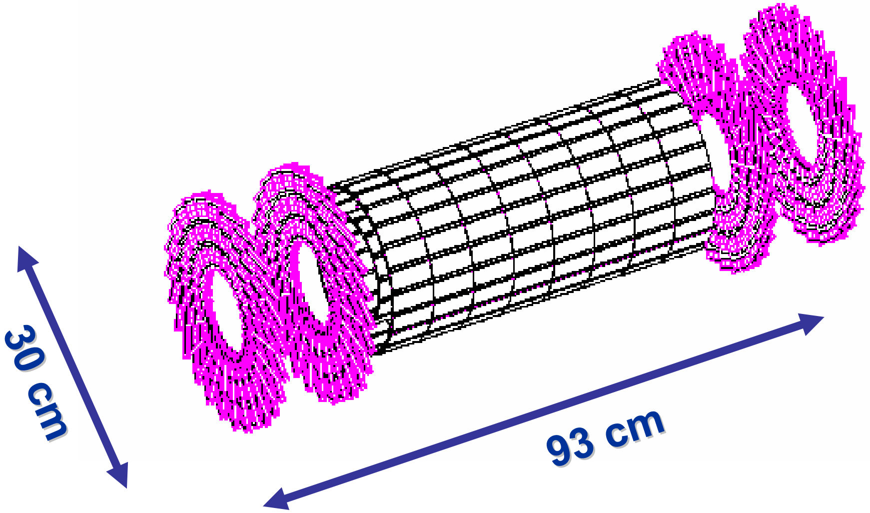


The Concept
Silicon Pixel vertex detector

The region below 20cm is instrumented
with Silicon Pixel Vertex systems
(First layer at R ~ 4cm)

$4\ 10^7$ pixels

Shaping time ~ 25ns



The Pixel area is driven by FE chip
The shape is optimized for resolution

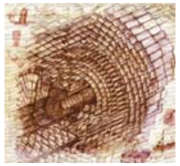
CMS pixel ~ $100\mu m * 150\mu m$

With this cell size, and exploiting
the large Lorentz angle

We obtain $IP_{trans.}$ resolution ~ $20\ \mu m$
for tracks with $P_t \sim 10GeV$

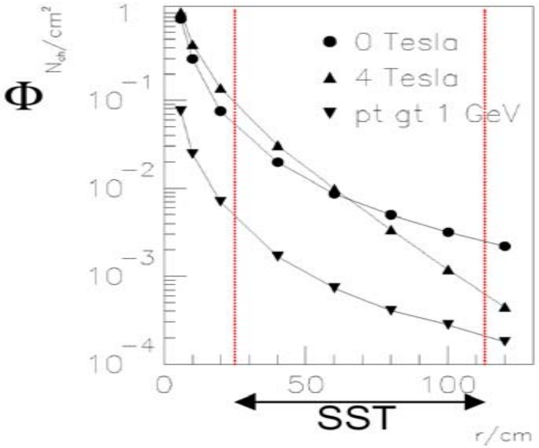
With this cell size occupancy is ~ 10^{-4}

This makes Pixel seeding the fastest
Starting point for track reconstruction
Despite the extremely high track density



The Concept
Silicon micro-strip Tracker

Efficient & clean reconstruction with few hits is ensured provided occupancy below few %



At small radii need cell size << 1cm^2 and fast (~25ns) shaping time
This condition is relaxed at large radii

$\Delta P_t / P_t \sim 0.1 * P_t$ (P_t in TeV) allows to reconstruct Z to $\mu^+\mu^-$ with $\Delta m_Z < 2$GeV up to $P_t \sim 500$GeV

Twelve layers with (pitch/ √ 12) spatial resolution and 110cm radius give momentum resolution

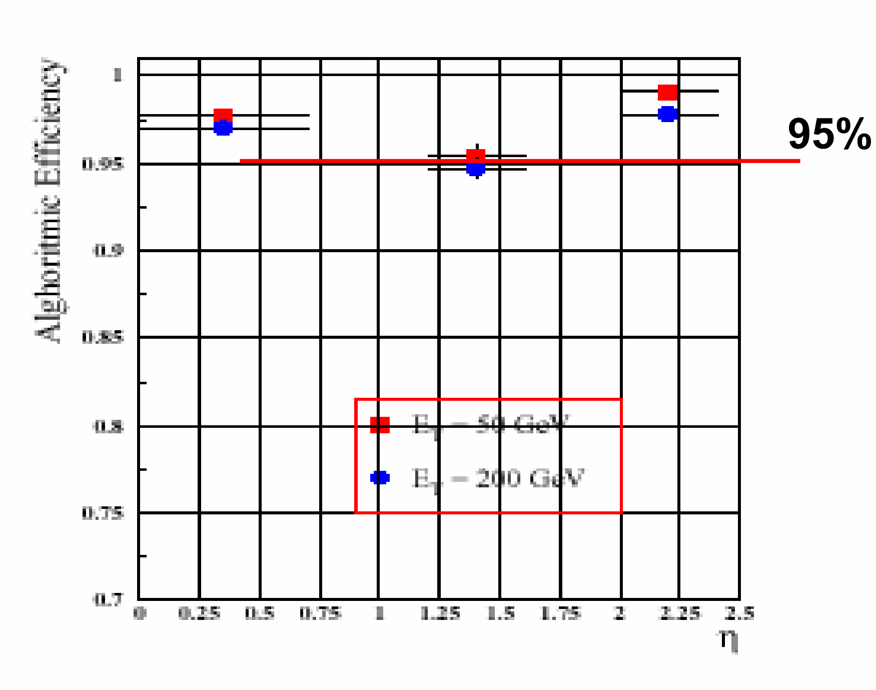
$$\frac{\Delta p}{p} \approx 0.12\left(\frac{pitch}{100\mu m}\right)^1\left(\frac{1.1m}{L}\right)^2\left(\frac{4T}{B}\right)^1\left(\frac{p}{1Tev}\right)$$

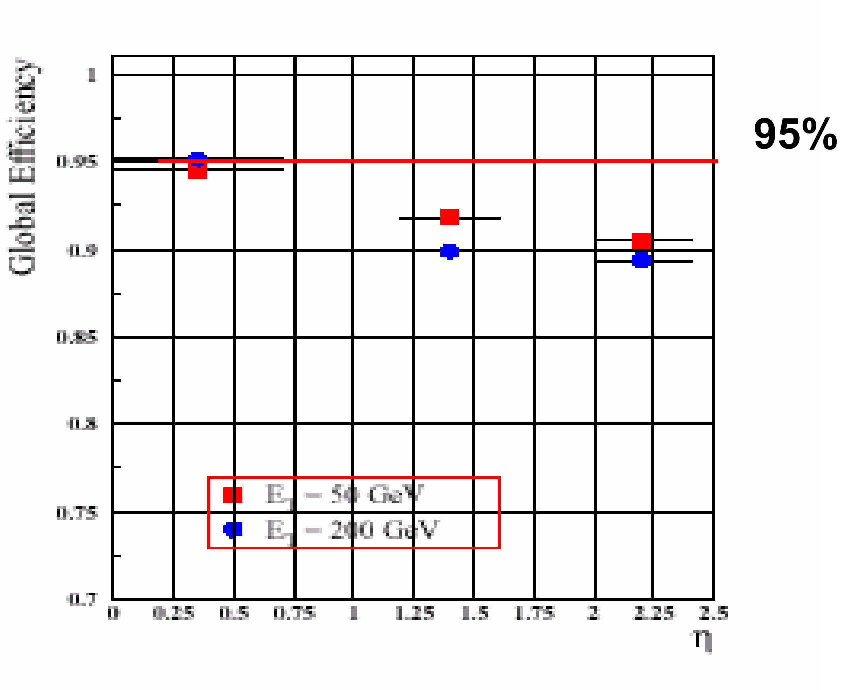
A typical pitch of order 100µm is required in the phi coordinate
To achieve the required resolution

Strip length ranges from 10cm in the inner layers to 20cm in the outer layers*

Pitch ranges from 80µm in the inner layers to near 200µm in the outer layers

The Concept
expected performance

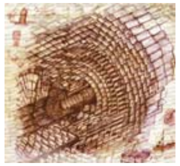




Efficiency for particles in a cone around jet axis:

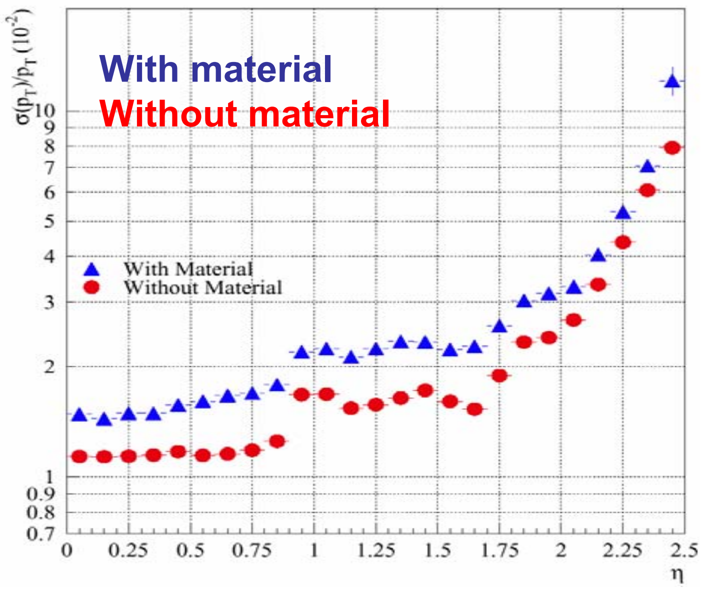
No significant degradation compared to single pions

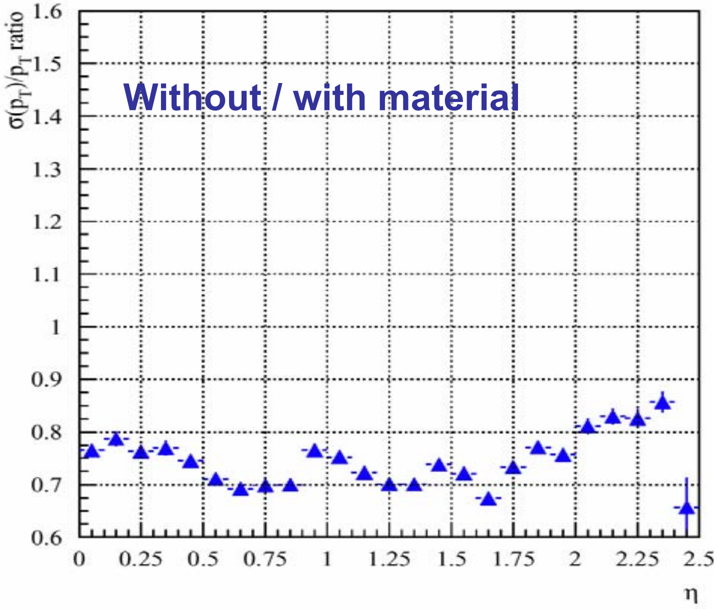
Loss of efficiency dominated by hadronic interactions in Tracker material



The Concept
expected performance

The CMS Tracker provides ~ 1% Pt resolution over ~ 0.9 units of η, and 2% Pt resolution up to η ~ 1.75, beyond which the lever arm is reduced

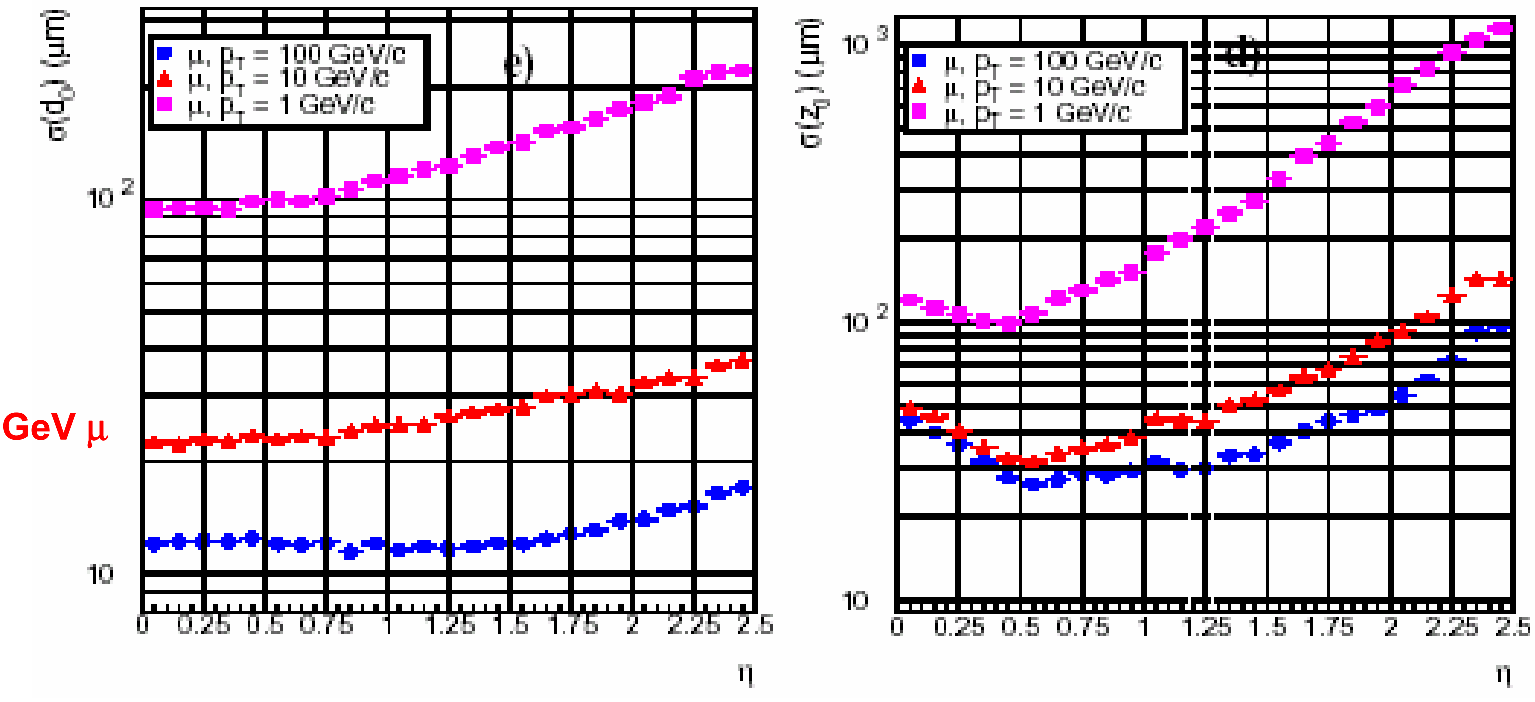




Even at 100 GeV muons are significantly affected by multiple scattering:
a finer pitch, and higher channel count
Would therefore yield only diminishing returns in improving the Pt resolution

The Concept
expected performance

For 10 GeV Pt tracks, σ(d_0) < 30μ for η < 1.5; degrading to ~ 40μ for η = 2.4

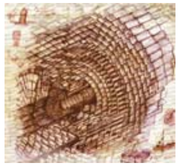


10GeV μ

10GeV μ

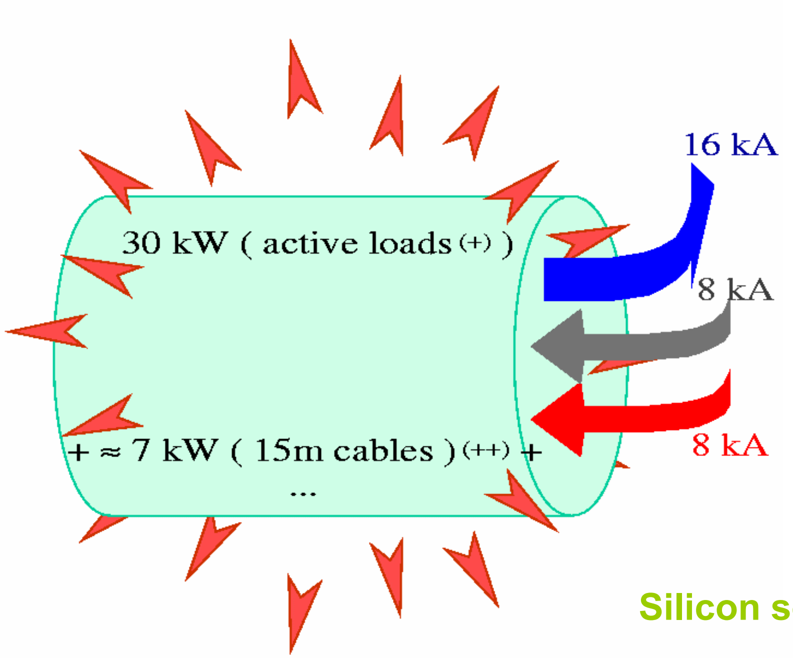
For 10 GeV Pt tracks, σ(Z_0) < 50μ for η < 1.5; degrading to ~ 150μ for η = 2.4

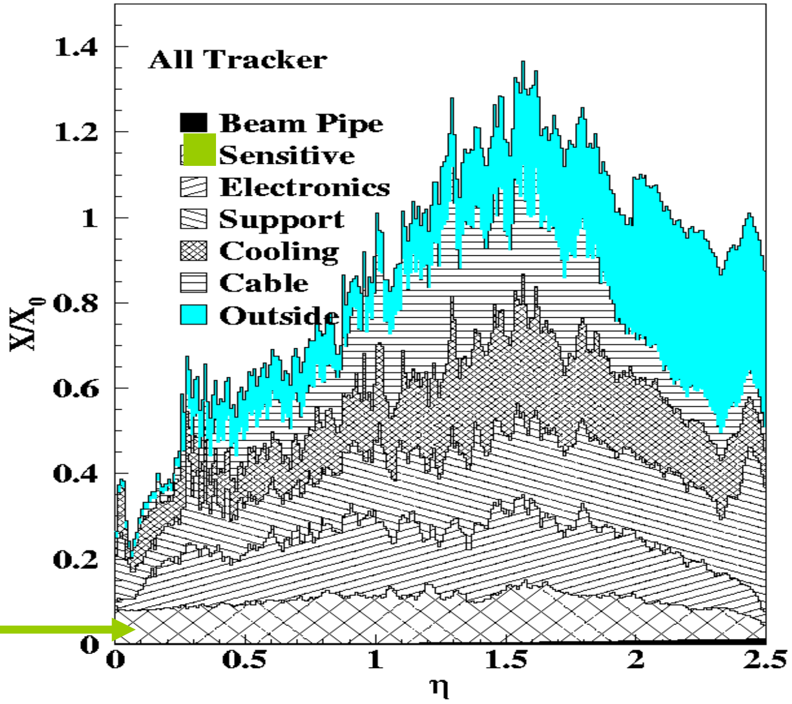
Dominated by Pixel geometry and multiple scattering



The dark side
Material in the Tracker volume

Cables required to bring 16KA in and out of active volume
Cooling required to absorb ~ 40kW dissipated in active volume
Mechanics to support all this, and ensure accurate & stable sensor placement





Silicon sensors

Putting it in perspective
from micro-strip to pixel vertex detectors

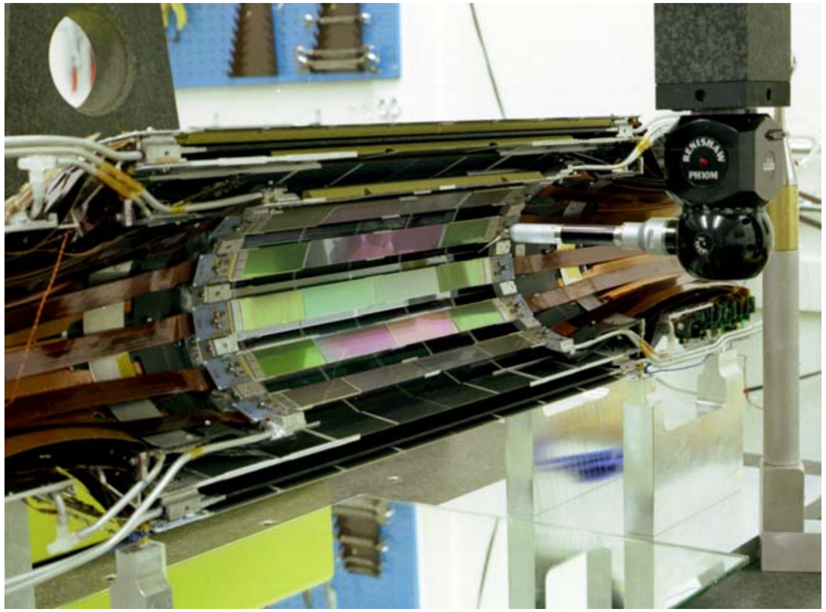
The 4 LEP experiments all installed
Silicon Micro-Strip Vertex Detectors
within a couple of years of LEP startup

Upgraded to become better & better
(from single to double sided)
Bigger & bigger

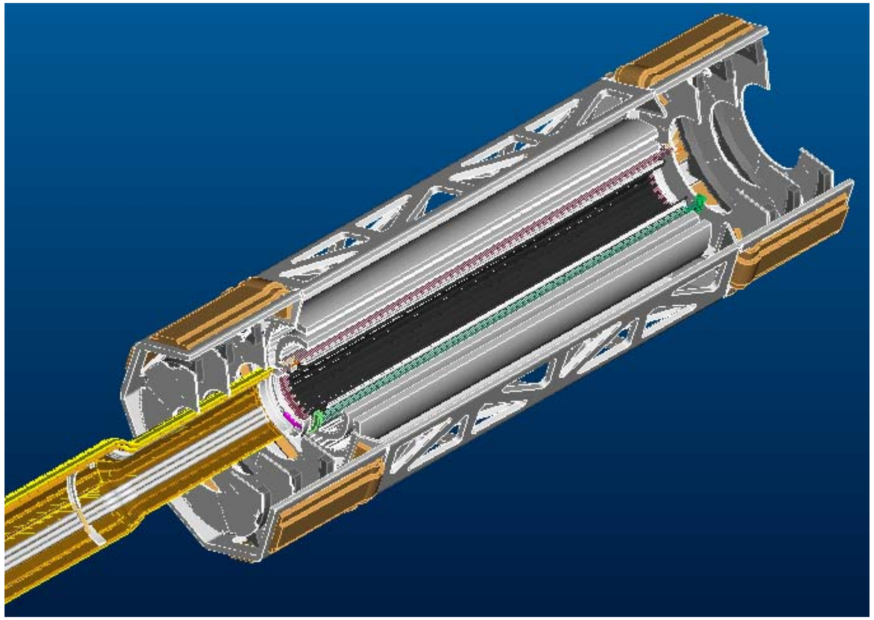
Both ATLAS and CMS will use
Silicon Pixel Vertex detectors
Of similar size as the LEP vertex detectors,
But far more complex

From ~few*10^5 to ~several*10^7 channels

Delphi micro-strip vertex detector 1998



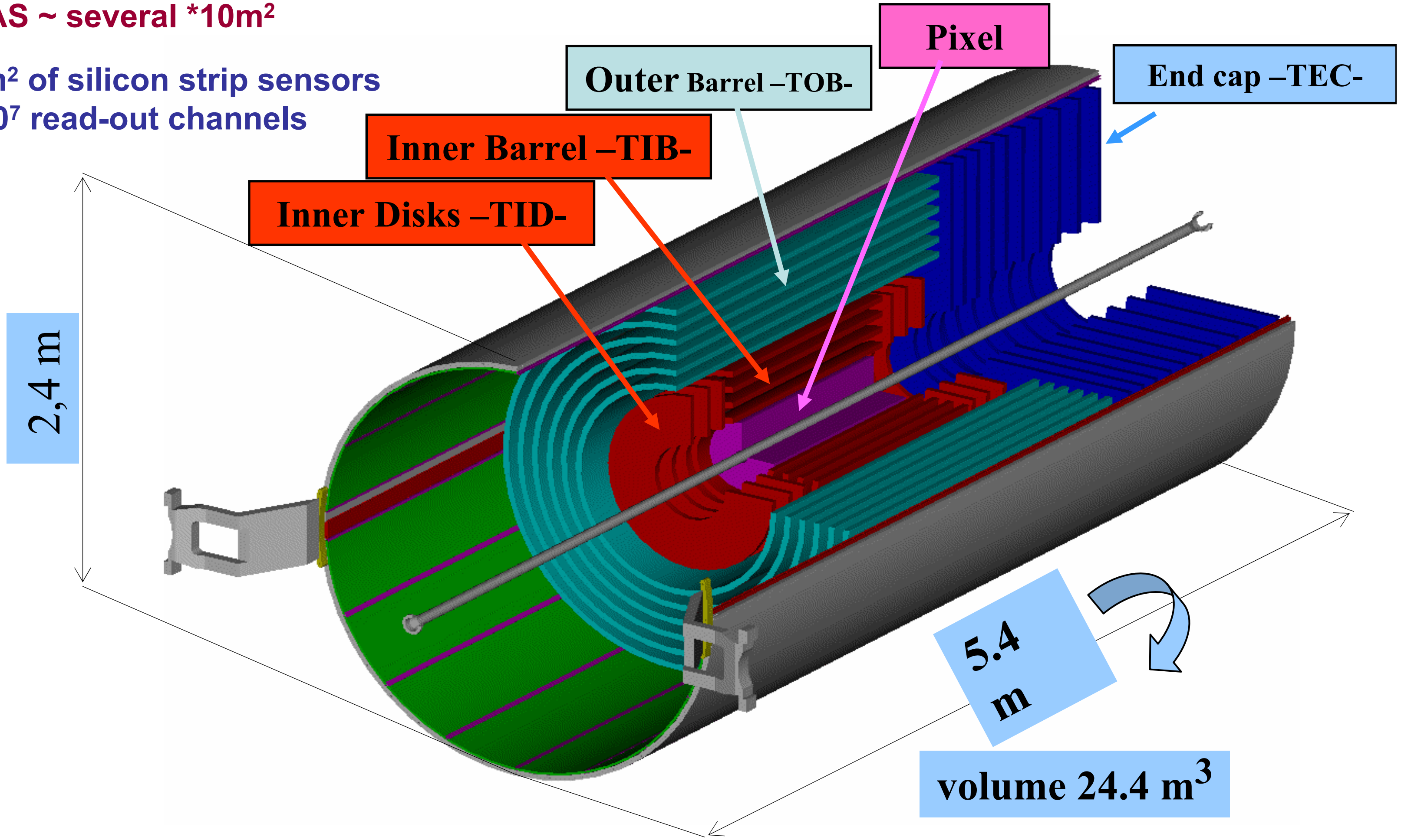
Atlas pixel vertex detector 2007



Putting it in perspective
from ~ few m² to ~ 210m² in ~ 24m³ volume

CDF & D0 ~ few m²
ATLAS ~ several *10m²

CMS ~ 210m² of silicon strip sensors
$10^7 + 10^7$ read-out channels



Pixel

Outer Barrel –TOB-

End cap –TEC-

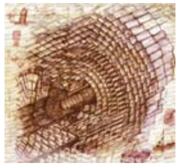
Inner Barrel –TIB-

Inner Disks –TID-

2,4 m

5.4 m

volume 24.4 m³

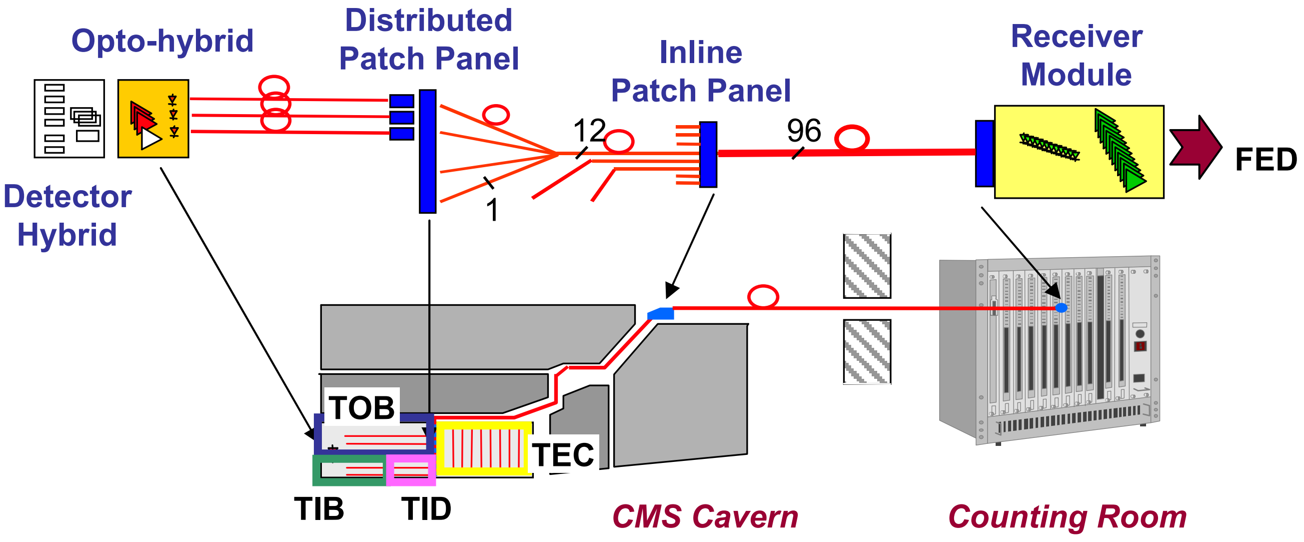


Putting it in perspective
Tracker read-out dominates CMS data volume

CMS Silicon Strip Tracker has no 0 suppression: CMM noise subtraction
(Pixels have local 0 suppression => intrinsic noise immunity crucial)

Analogue information from all 10^7 strips/event read-out at 100KHz event rate
Use analogue optical link: developed for Tracker now used throughout CMS

After digitization and 0 suppression in the FED, Tracker data volume ~ / event
=> Drives requirements of DAQ



Opto-hybrid

Distributed
Patch Panel

Inline
Patch Panel

Receiver
Module

Detector
Hybrid

CMS Cavern

Counting Room

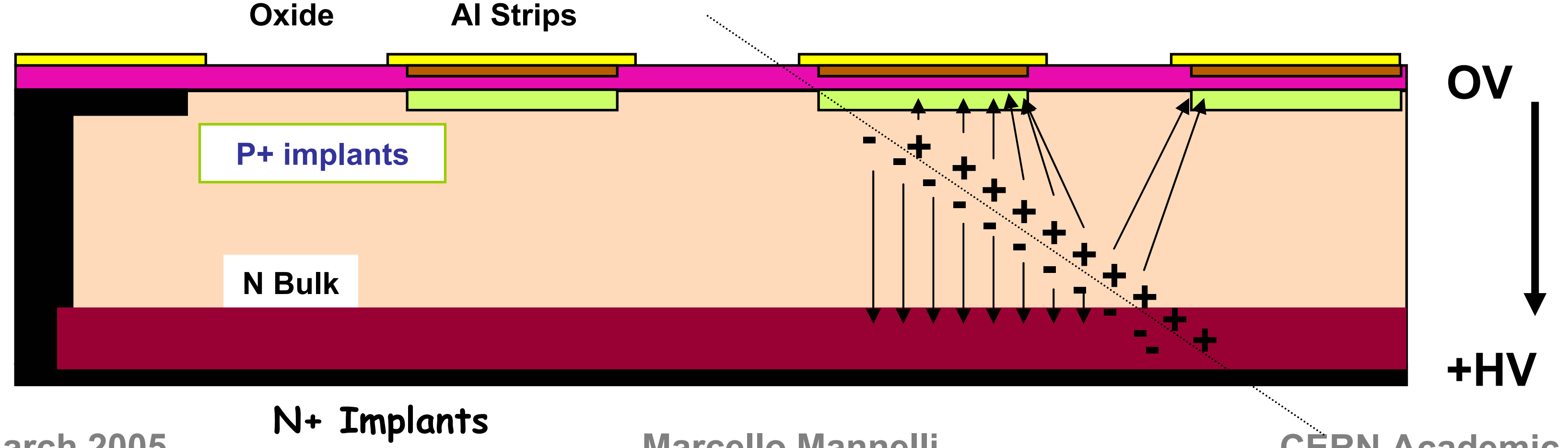
The Silicon Sensors
The reverse biased p-on-n diode

Bulk depletes from P+ implants, “front-side“ to N+ implant, “back-side”

Electron-hole pairs generated in the depleted region drift to the N+ and P+ electrodes respectively and generate a signal ~ to the depleted sensor thickness

Electron-hole pairs generated in the (conductive) un-depleted region recombine locally, and generate no signal

Even in a partially depleted sensor, the signal on the “front-side” is localized



The Silicon Sensors
Electrical characteristics of strip detectors

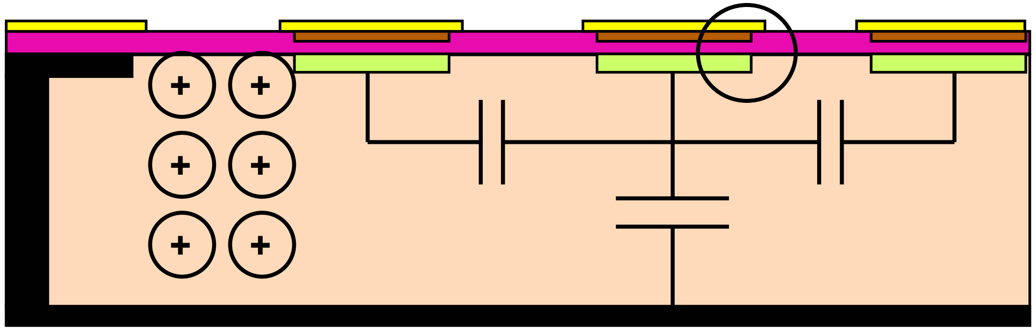
Sensor thickness & bulk resistivity: determines depletion voltage ($V_{depletion}$ ~ Neff * $Thickness^2$)

Strip Pitch / Width ratio: determines strip capacitive couplings & electronic noise

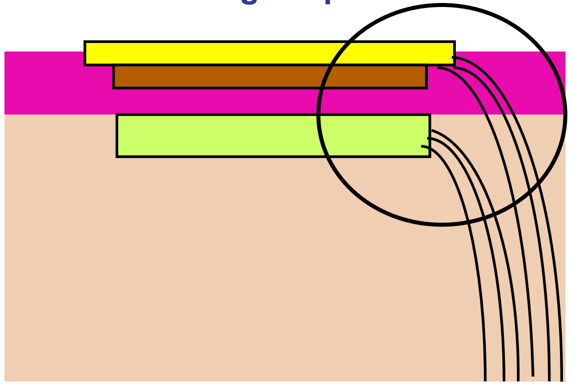
Strip Pitch & Width; Width of metal vs. implant: determine Electric field geometry, in particular high field region at strip edges & sensor breakdown characteristics

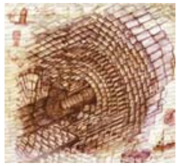
Nb. Breakdown voltage in Silicon Oxide ~ 30 * breakdown voltage in Silicon bulk

Single-Sided Lithographic Processing (AC, Poly-Si biasing)



Metal overhangs implant



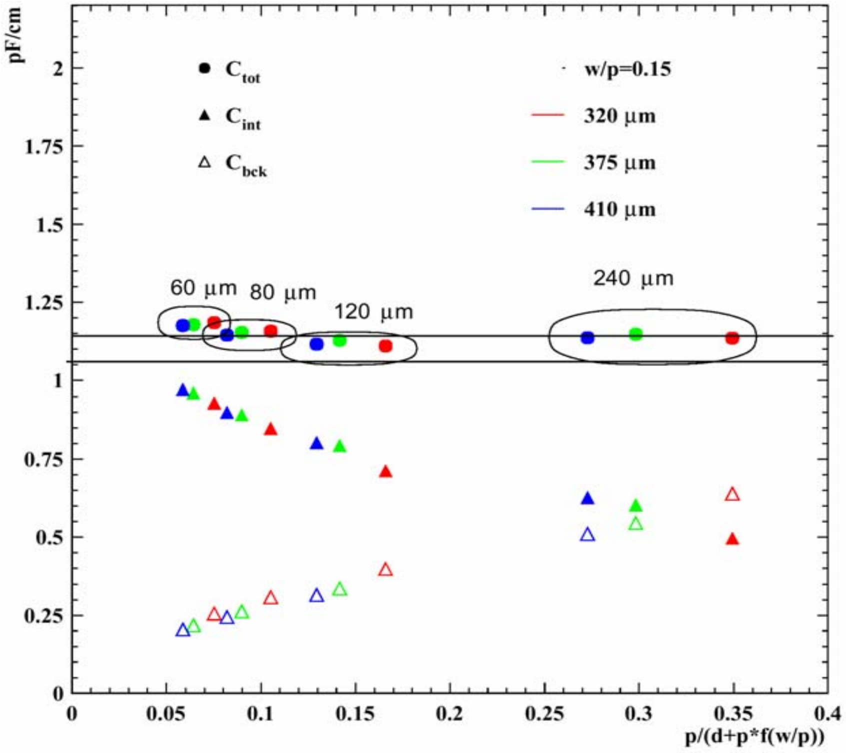


The Silicon Sensors
Electrical characteristics of strip detectors

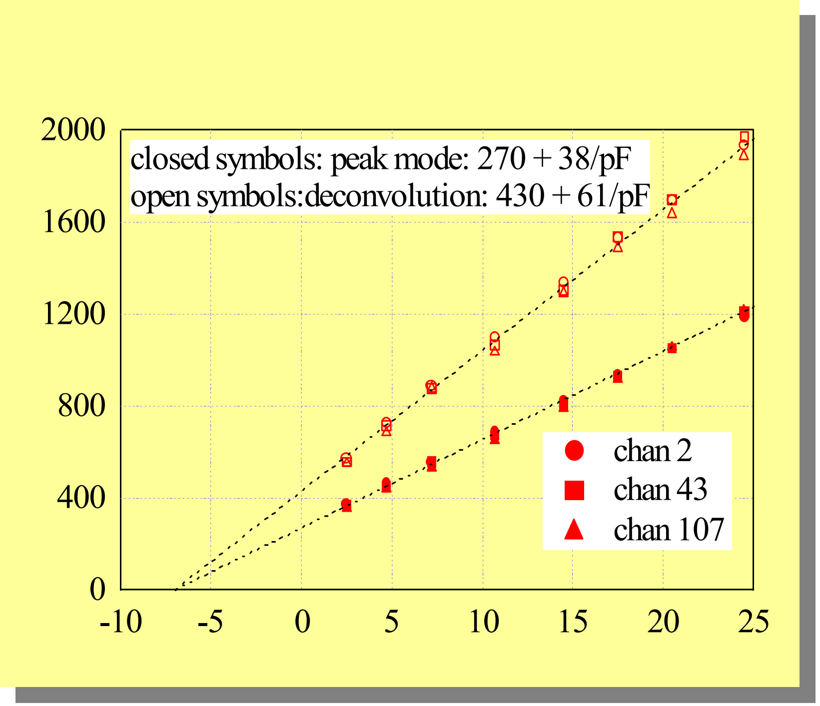
Total Strip capacitance is the main contribution to electronic noise

It is a function of w/p only, Independent of pitch and thickness

Ctot ~ 1.2pF/cm for w/p = 0.25



Noise ~ 430e- + 75e- * strip length cm



The Silicon Sensors
Radiation damaged reverse biased p-on-n diode

Radiation damage eventually results in “type inversion”

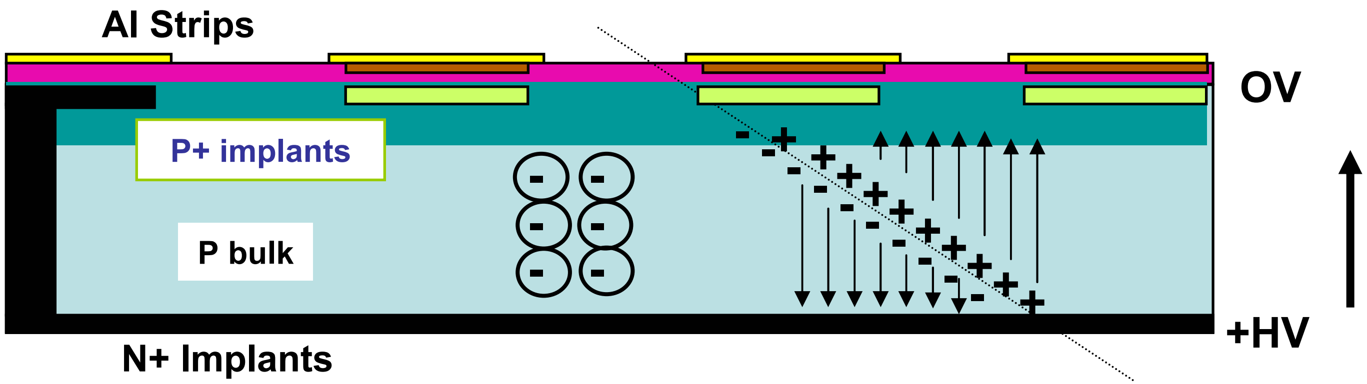
- The initially N bulk undergoes “type inversion” and becomes P
- The depletion voltage decreases and then increases again with higher fluence
- The effectively P bulk depletes from N+ implants, “back-side”, to P+ implant, “front-side”

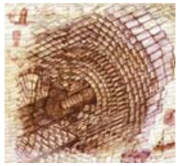
Electron-hole pairs generated in the depleted region drift to the N+ and P+ electrodes respectively and generate a signal ~ to the depleted sensor thickness

Radiation induced defects trap charge, leading to a loss of signal unless high fields

In the partially depleted sensor, the signal on the “front-side” is no longer localized

Sensor leakage current increases linearly with fluence (by ~ 3 orders of magnitude)





The Silicon Sensors
The radiation hard P-on-N strip detector

Radiation hardness “recipe”

P-on-N sensors work after bulk type inversion, Provided they are biased well above depletion

At room temperature and above, radiation induced defects diffuse and some eventually form clusters which further increase the sensor depletion voltage “reverse annealing”

Defect mobility below ~ 0C is sufficient low that reverse annealing is effectively frozen out

> Maintain radiation damaged silicon below ~0C (constantly)

Sensor leakage current depends ~ exponentially on temperature: it doubles for every ~7C temperature increase

Insufficient cooling efficiency will result in an exponential “thermal run-away” of the irradiated sensor

> Operate sensors below ~ -10C, to reduce required cooling efficiency & material

The Silicon Sensors
The radiation hard P-on-N strip detector

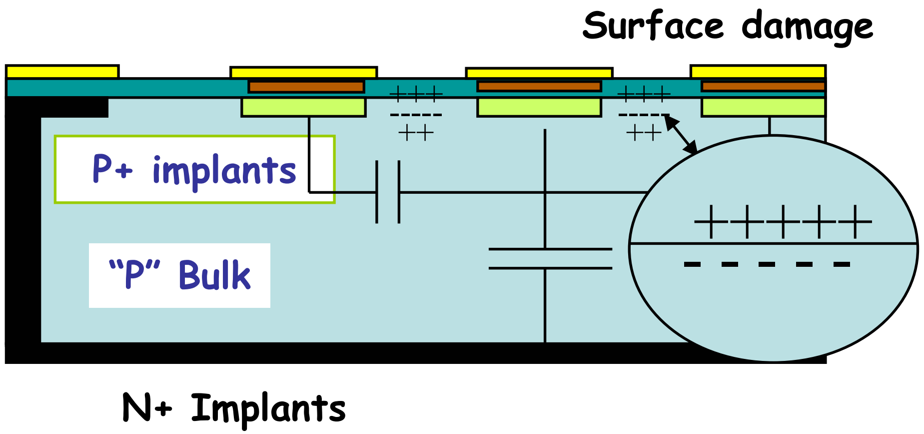
Radiation hardness "recipe"

P-on-N sensors work after bulk type inversion, Provided they are biased well above depletion

Optimize design for high voltage stability, as well as low capacitance

Use Al layer as field plate to remove high field at strip edges from Si bulk to Oxide
(much higher Vbreak)

Strip width/pitch ~ 0.25: reduce Ctot while maintaining stable high bias voltage operation
(avoid strip pitch > 200μm to ensure stable high voltage operation)



Surface radiation damage can increase strip capacitance & noise, and degrade high voltage stability

Use <100> crystal instead of <111>

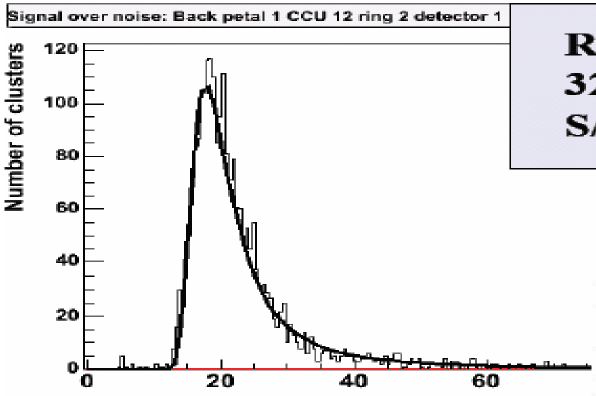
Take care with process: implants, oxides…

The Silicon Sensors
The radiation hard P-on-N strip detector

Radiation hardness “recipe”

P-on-N sensors work after bulk type inversion, Provided they are biased well above depletion

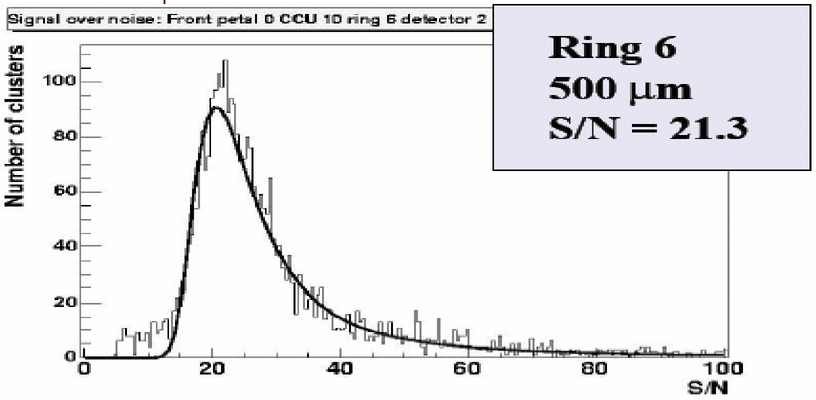
Match sensor thickness (& resistivity) to fluence (Vdep) to optimize S/N over the full life-time:



Ring 2
320 µm
S/N = 18.2

Use 320µm thickness for R < 60cm,
Strip ~ 10cm => S/N ~ 18 (14)

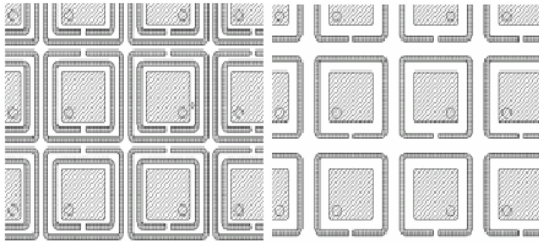
Use 500µm thickness for R > 60cm,
Strip ~ 20cm => S/N ~ 21 (16)

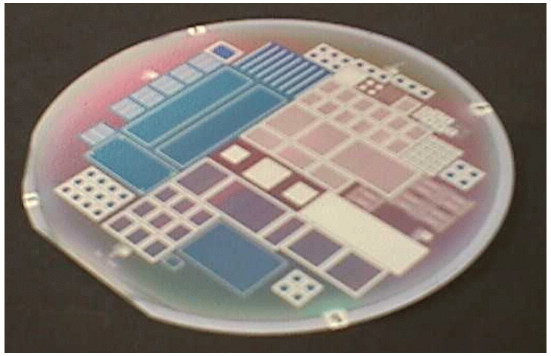


Ring 6
500 µm
S/N = 21.3

The Silicon Sensors
The radiation hard N-on-N pixel detector

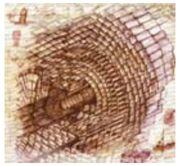
Highest radiation environment:





- Full depletion no longer possible
- Partial depletion, despite High Vbias
- Specific program of sensor R&D
  - The "back-side" of a double-sided sensor
  - n-on-n technology
  - Specific issues:
    - P-stop design to ensure pixel biasing & isolation
    - Open p-stop, "p spray" …
- Oxygenated bulk may allow lower bias voltage operation, especially for charged hadron induced damage (dominant)

Read-out chip architecture, and connection to pixels are major challenges, not covered here



Module components production & assembly
The numbers

6,136 Thin + 18,192 Thick sensors

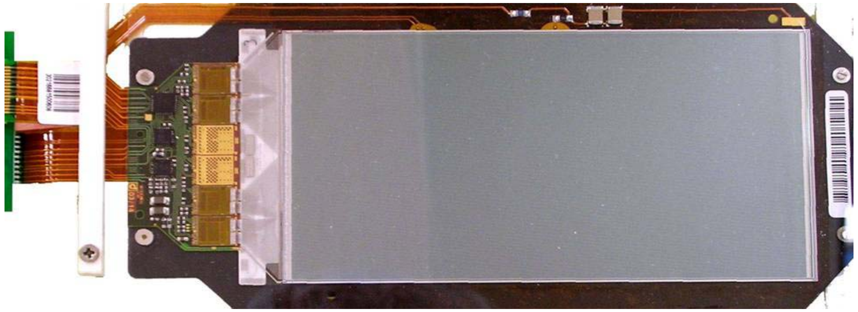
440 m2 of silicon wafers
210 m2 of silicon sensors

Large scale industrial sensor production

9,648,128 strips ≡ channels

75,376 APV chips

Reliable, High Yield Industrial IC process



Hybrids
Pitch adapters
Frames

6,136 Thin sensor modules (1 sensor / module)
9,096 Thick sensor modules (2 sensors / module)

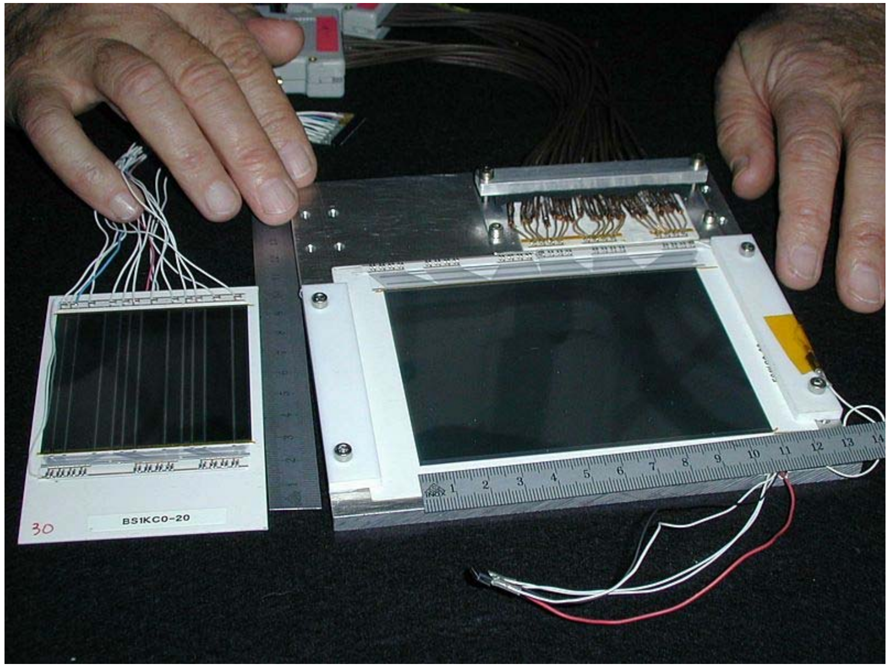
Automated module assembly

25,000,000 wire bonds

State of the art bonding machines

Module components production & assembly
6” silicon sensor production

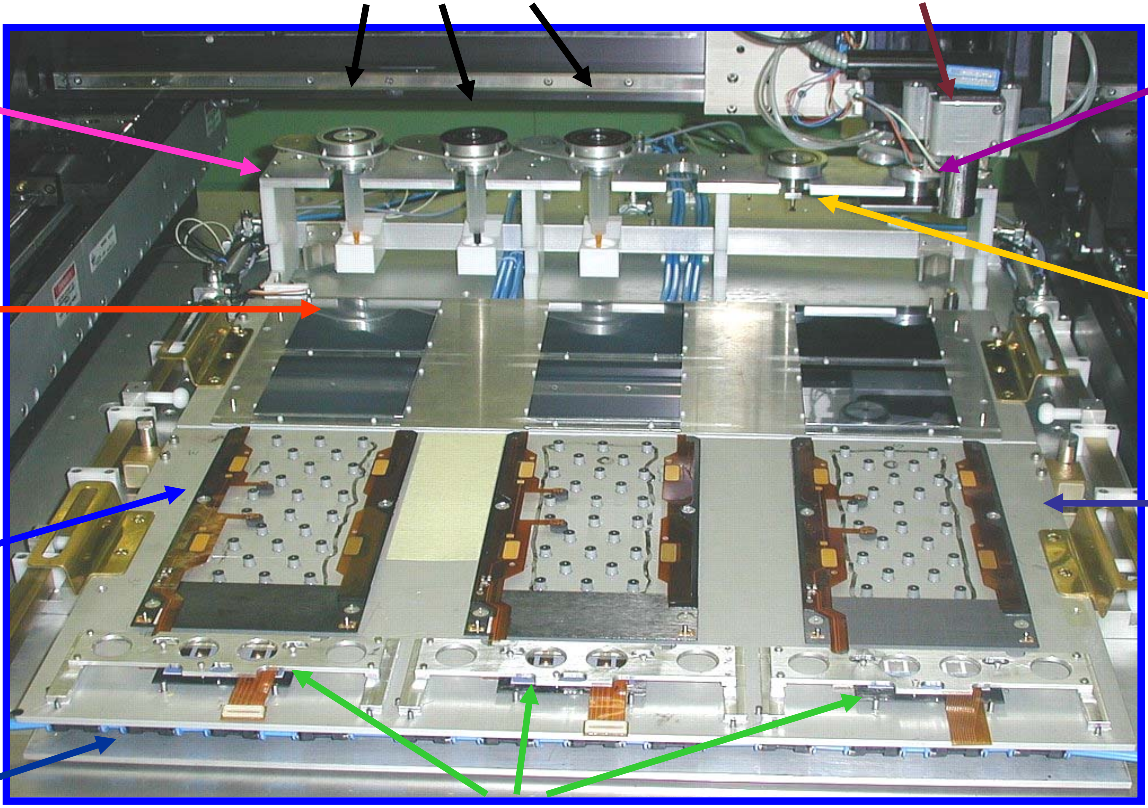
A 4” R&D sensor, next to a 6” production sensor



- 6’136 Thin sensors
- 18’192 Thick sensors
- 440 m^2 of silicon wafers
- 210 m^2 of silicon sensors
- Strip sensor production on an unprecedented scale for HEP

Relies on modern 6” commercial lines, and in particular on synergies with specialized industrial production of silicon sensors for I.R. cameras, medical, automotive etc

Module components production & assembly
Automated module assembly



Module components production & assembly
Automated module assembly

“Gantry see, Gantry do”

The gantry system localizes automatically the components to be assembled by searching for a Marker with a camera

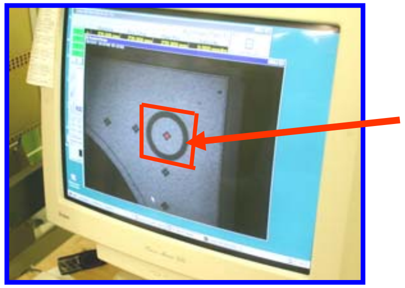
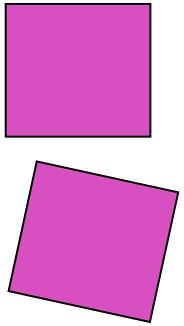
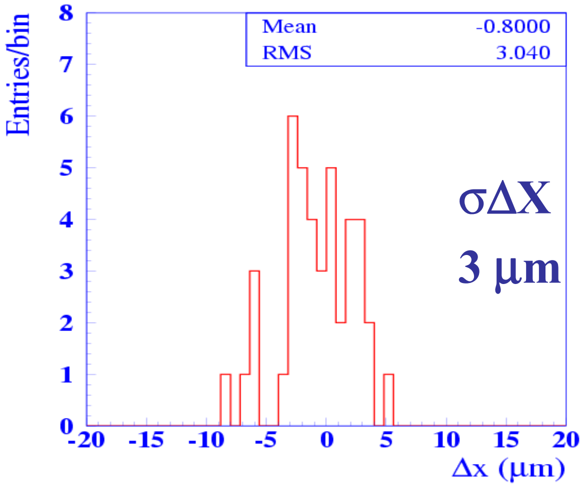


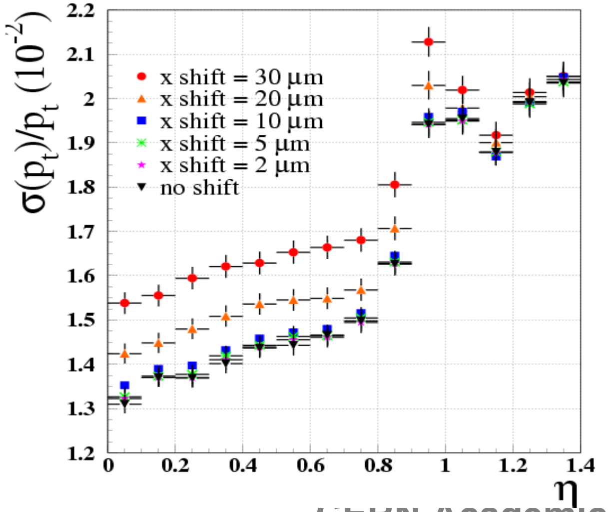
Image found: place Sensor pair precisely

Sensors within a module are placed to better than 5µ and 2µr Relative to each other

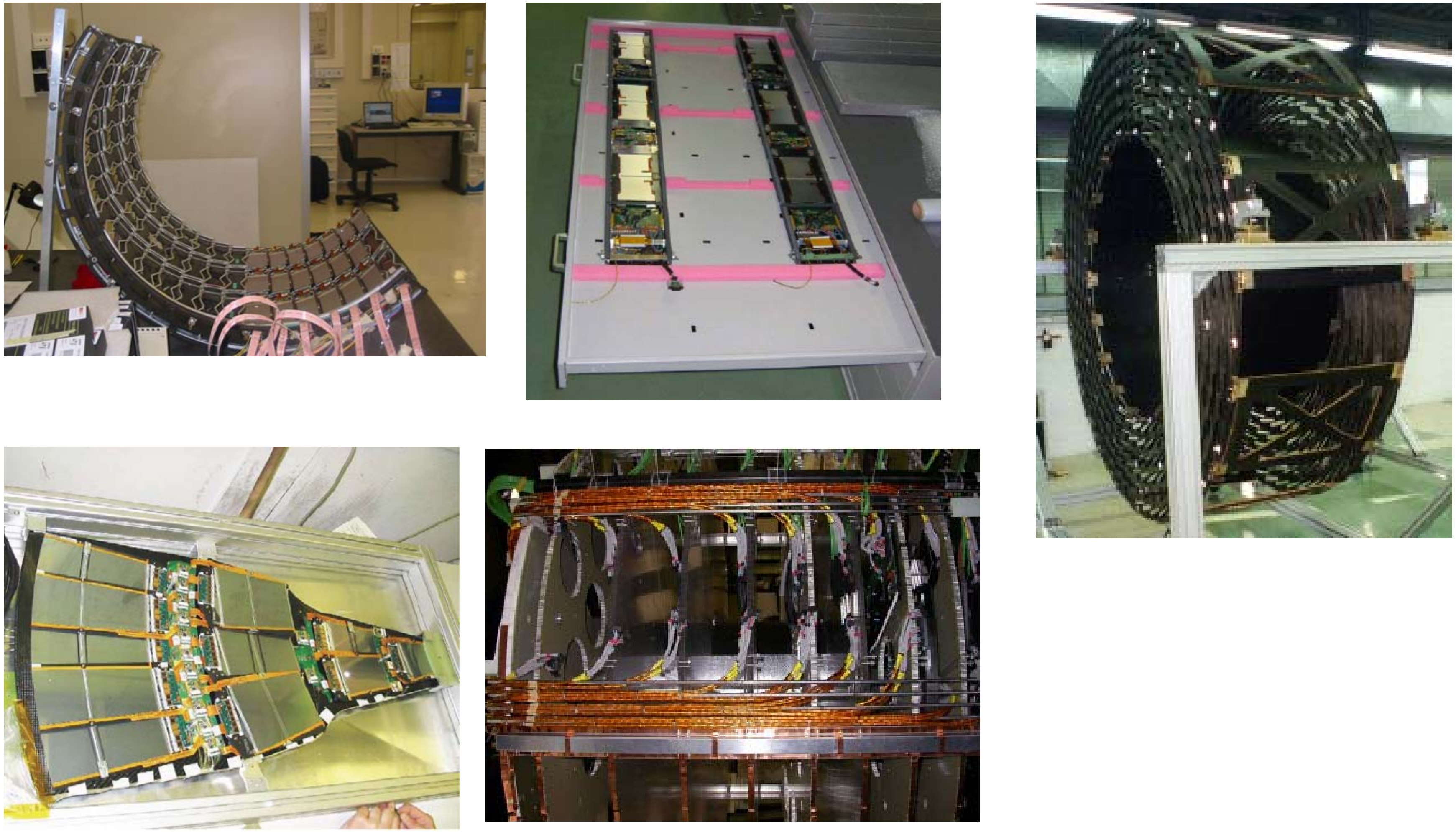
Miss-placements of up to 10µ do not significantly degrade the Ultimate muon Pt resolution even if not corrected for

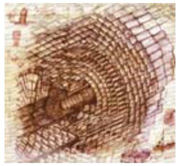




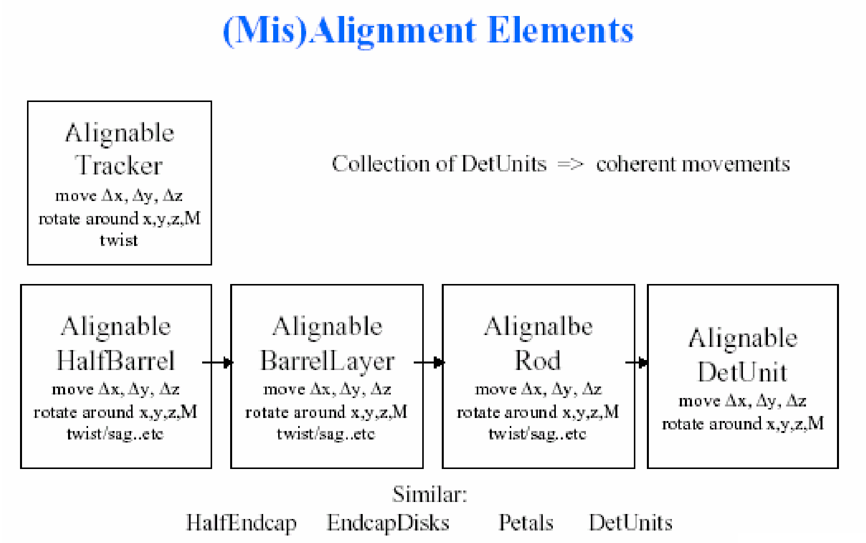


Shells, Rods and Petals





Alignment
Importance of initial accuracy



(Mis)Alignment Elements

Alignable Tracker
move Δx, Δy, Δz
rotate around x,y,z,M
twist

Collection of DetUnits => coherent movements

Alignable HalfBarrel
move Δx, Δy, Δz
rotate around x,y,z,M
twist/sag..etc

→ Alignable BarrelLayer
move Δx, Δy, Δz
rotate around x,y,z,M
twist/sag..etc

→ Alignalbe Rod
move Δx, Δy, Δz
rotate around x,y,z,M
twist/sag..etc

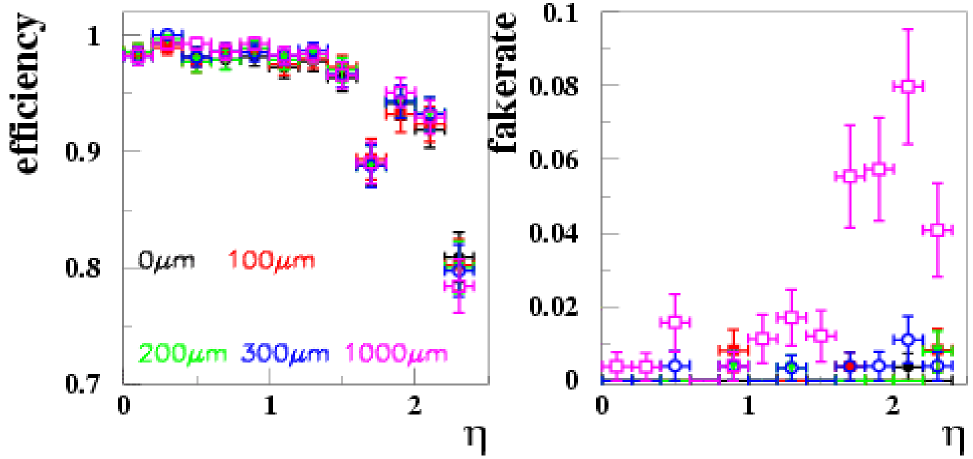
→ Alignable DetUnit
move Δx, Δy, Δz
rotate around x,y,z,M

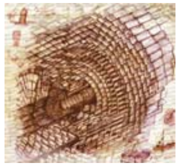
Similar:
HalfEndcap EndcapDisks Petals DetUnits

Software tools implemented to introduce, and account for, misalignments following the hierarchical organization of the mechanical degrees of freedom inherent in the support structures

Efficient & clean pattern recognition with misalignments of up to 1mm, for W->$\mu\nu$ events at $2*10^{33}$

This is the essential starting point for alignment with tracks & sets scale for initial accuracy required





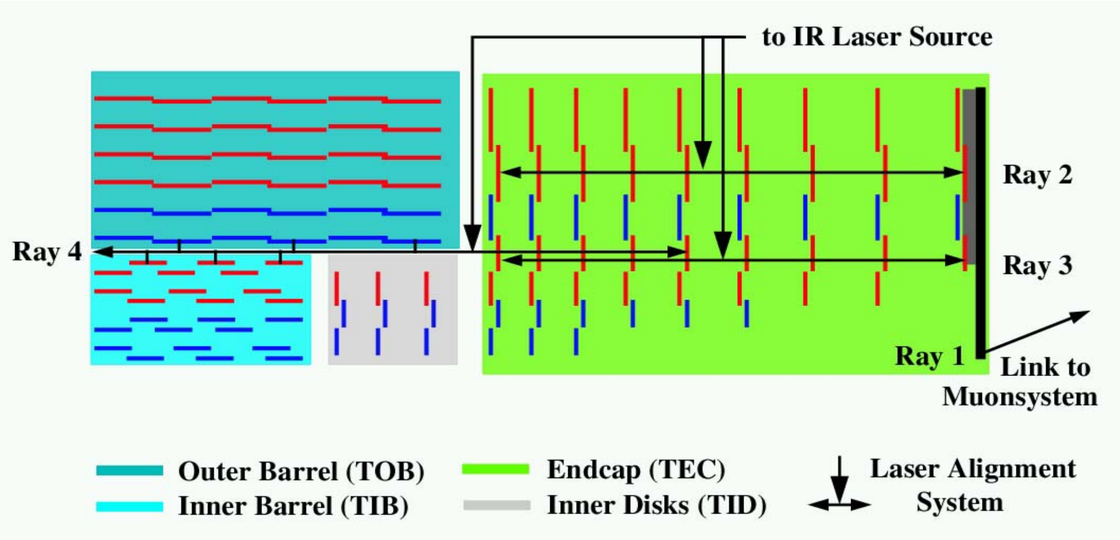
Alignment
Importance of initial accuracy

Mechanical Constraints & Metrology:

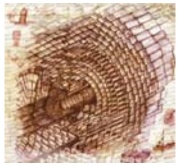
Sensors on Modules ~ 10μm
Modules within Sub-Structures 0.1~ 0.5 mm
Sub-Structures within Support Tube ~ few mm

Laser Alignment System:

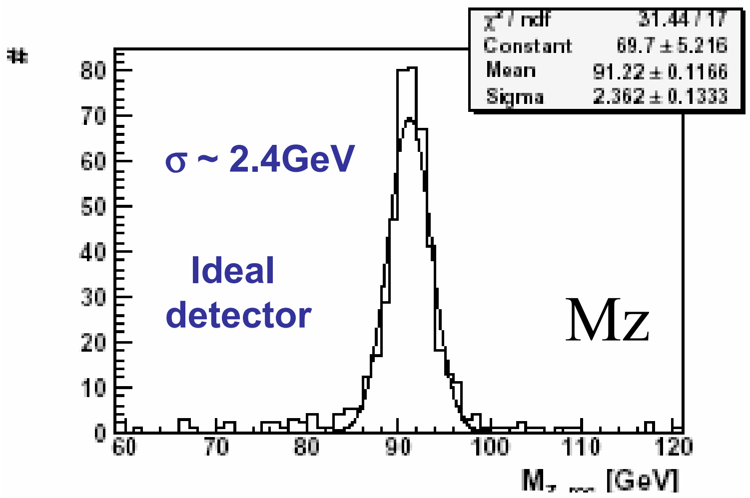
Aligns Sub-Structures
& monitors relative movements
at the level of ~ 10μm



Expect to ensure ~ few 100μm alignment uncertainties
Sufficient for a first efficient pattern recognition

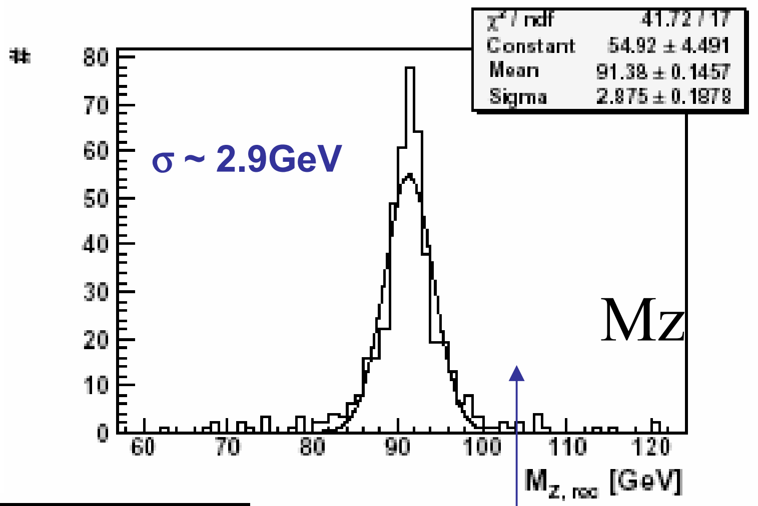


Impact of alignment on Physics
Use Z→μμ to illustrate

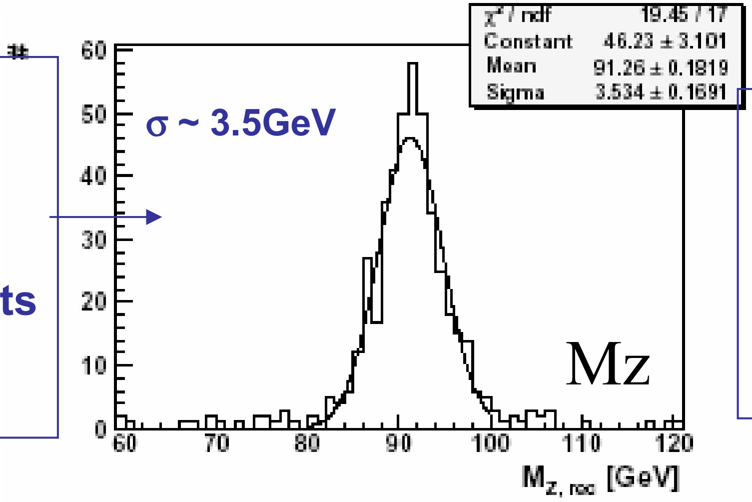


σ ~ 2.4GeV

Ideal detector



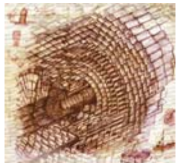
σ ~ 2.9GeV



σ ~ 3.5GeV

First Data Taking
<1fb^{-1}
Laser Alignment
⊗
Mechanical Constraints
⇒≈100μm alignment uncertainties

First Data Taking:
≈1fb^{-1}
First results of Alignment with tracks
⇒≈20μm alignment uncertainties

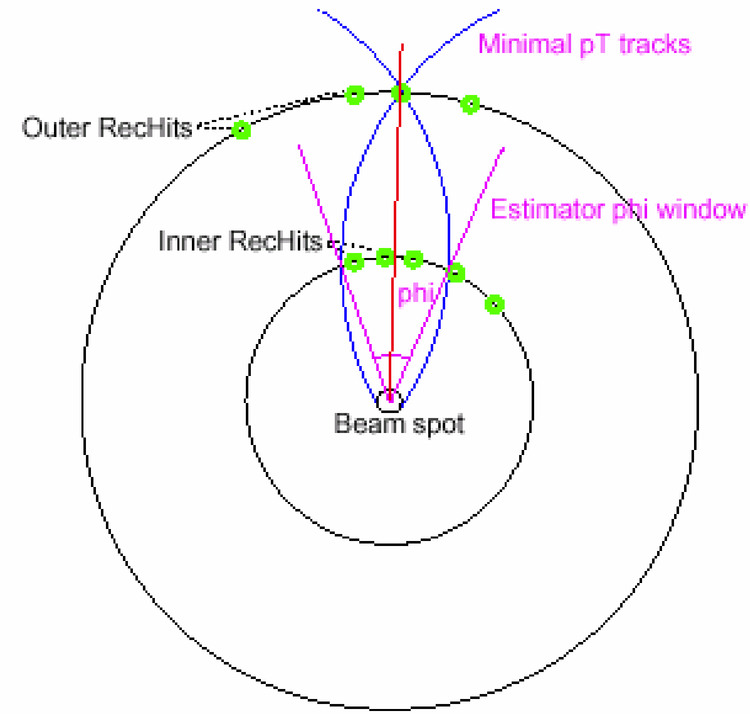


Track reconstruction
The basic components

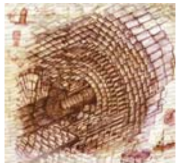
- **Generation of seeds (Seed Generator)**
- **Construction of trajectories for a given seed (Trajectory Builder)**
- **Ambiguity resolution (Trajectory Cleaner)**
- **Final fit of trajectories (Trajectory Smoother)**

Track reconstruction
Seed Generation

Use Pixel layers for seeding:
Lowest occupancy (despite highest track density)
Full 3-dimensional coordinate determination
Beam spot constraint



- **Fix a pair of "seed layers"**
- **Get all RecHits from the outer layer**
- **For each outer RecHit get all RecHits in the inner, compatible with a beam spot of a given size, and a minimum Pt cut**
- **Seed cleaning to avoid redundancy**

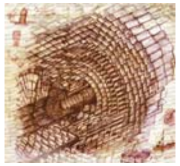


Track Reconstruction
Robust pattern recognition

The three Pixel layers, with the beam spot constraint, play a crucial role in ensuring a manageable track ambiguity level at the seed generation stage:

Requiring 2/3 pixel hits for a seed, and with relatively loose beam spot constraints, 1/15 (1/35) pixel seeds is reconstructed as a track at low (high) luminosity respectively

(This ratio is substantially higher for seeds with 3 pixel hits, but imposing This requirement would lead to significant inefficiencies)



Track Reconstruction
(Kalman filter) Trajectory Building

Combinatorial Trajectory Builder:

Starting from the seed:

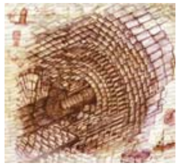
- The initial trajectory is propagated to the next layer, accounting for multiple scattering and energy loss

- On the new layer, new trajectory candidates are constructed, with updated parameters (and errors) for:
    - Each compatible hit in the layer
    - An “empty” hit to account for the possibility that the track did not leave a hit in the layer

- Start again with these new trajectory candidates for the next layer

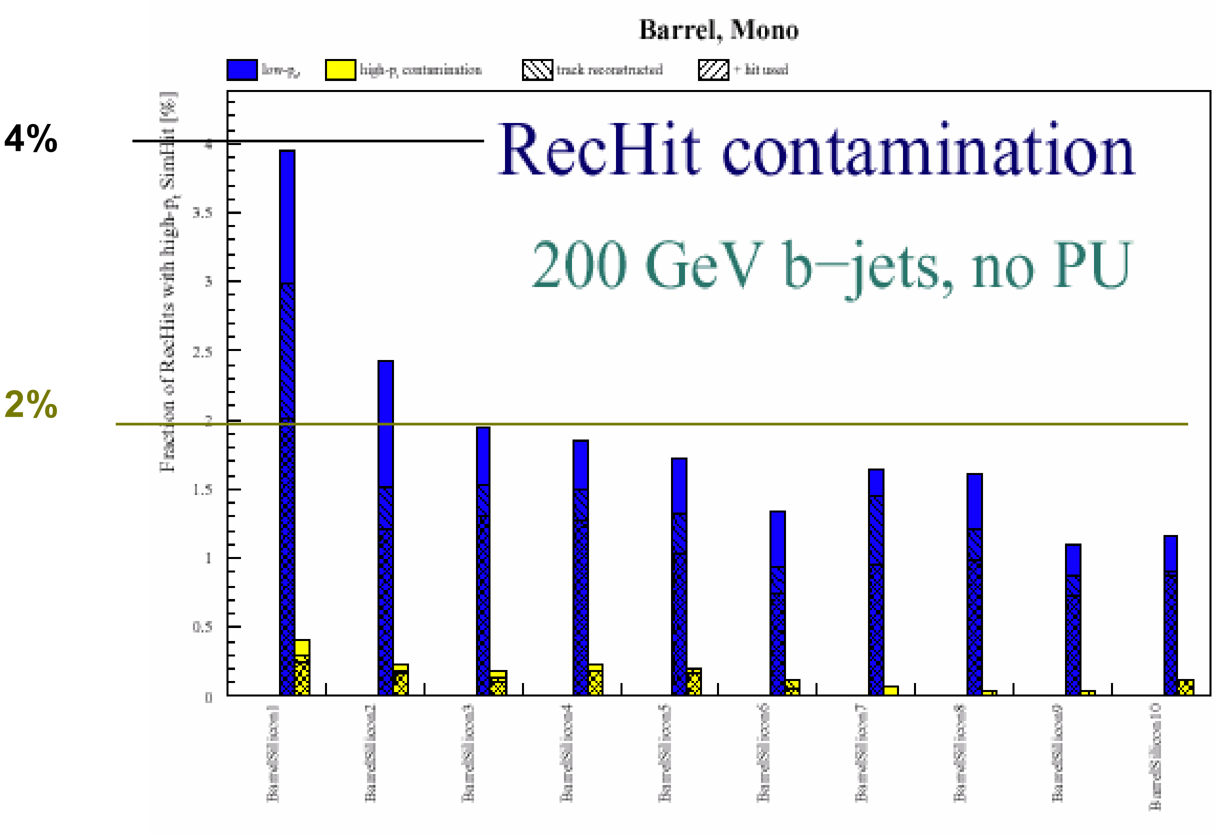
- All trajectories are grown to the next layer in parallel to avoid bias

- The number of trajectories to grow is limited according to their χ^2 and the number of invalid hits



Track Reconstruction
Robust and clean hits

Hit contamination at high luminosity is ~ 4% in the first Silicon Strip layer and less than ~ 2% elsewhere



RecHit contamination

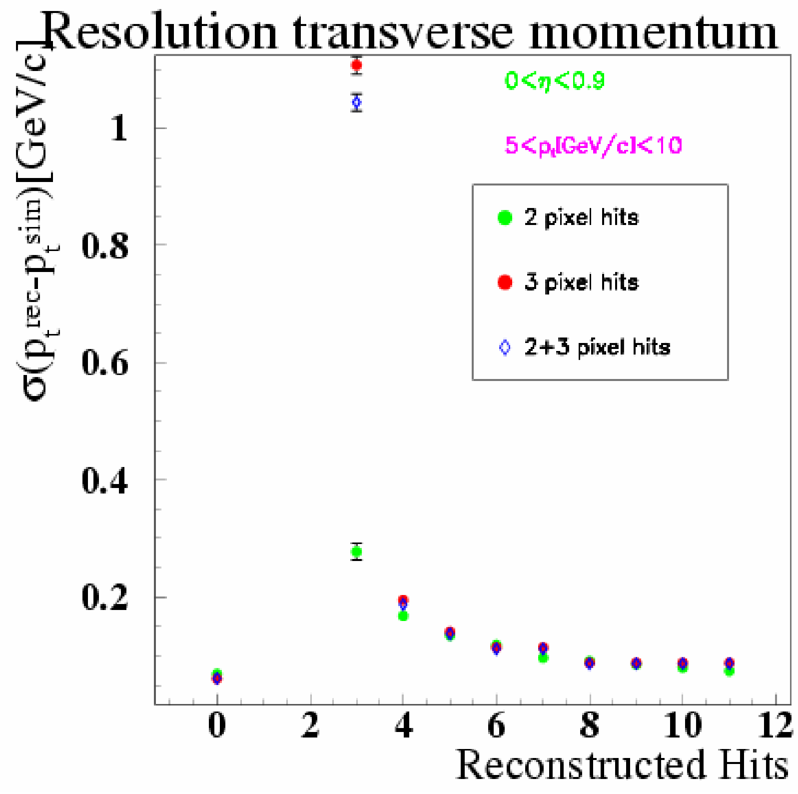
200 GeV b–jets, no PU

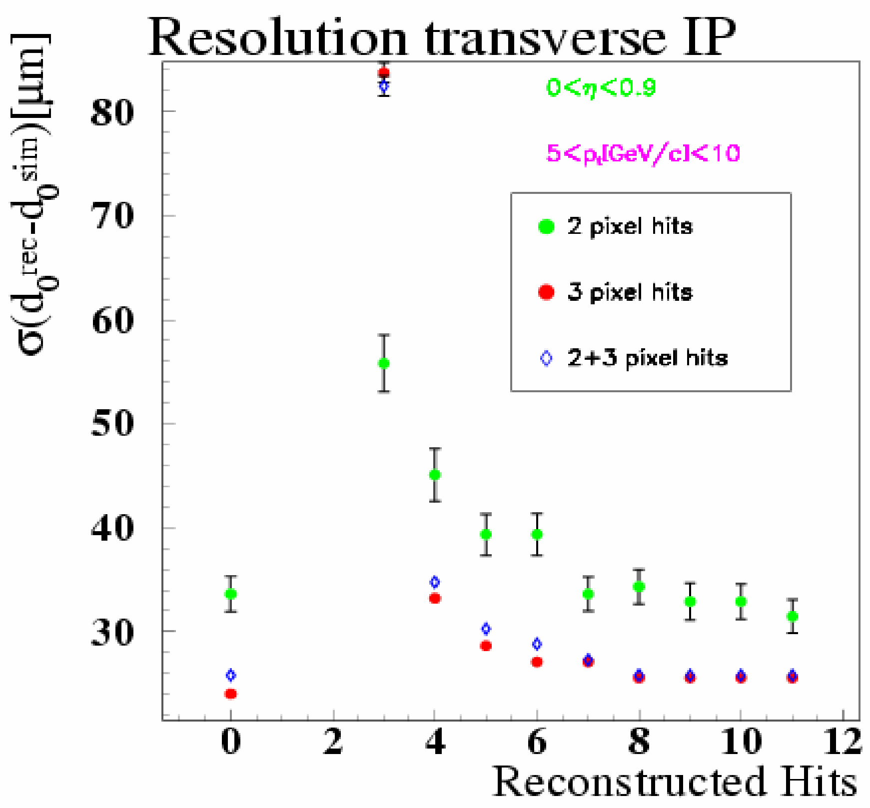
Hatching:

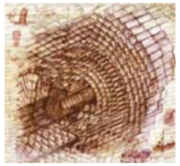
- SimTrack was reconstructed
- RecHit in that layer was used in the RecTrack

Track Reconstruction
Track parameter resolution vs. # of hits

Good track parameter resolution already with 4 or more hits







Track Reconstruction
Robust pattern recognition

Well defined track parameters with 4 or more hits result in small uncertainties on the predicted track state

In the r-phi view:

extrapolation error from Pixel Layer 3 to Silicon Layer 1 ~ 1mm

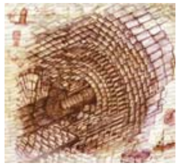
Once track includes hit on Silicon Layer 1 Pt is well determined so that:

extrapolation error from Silicon Layer 1 to Silicon Layer 2 ~ 200µm

(and for most tracks stays ~ constant beyond that, since dominated by multiple scattering in the Tracker material)

In the r-Z view:

Extrapolation error ~ 400µm already from Pixel Layer 3 to Silicon Layer 1, since it is independent of Pt determination and therefore does not require much lever arm

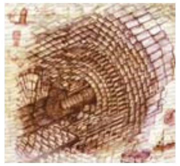


Track Reconstruction
Robust pattern recognition

The 200μm extrapolation error in r-phi from Silicon Layer 1 onwards means that even in the most difficult cases, such as very dense b and τ Jets and at full LHC luminosity

Track extrapolation from Silicon Layer 1 to Silicon Layer 2 is compatible with a spurious hit in < 5% of cases, despite the ~ 10cm strip length

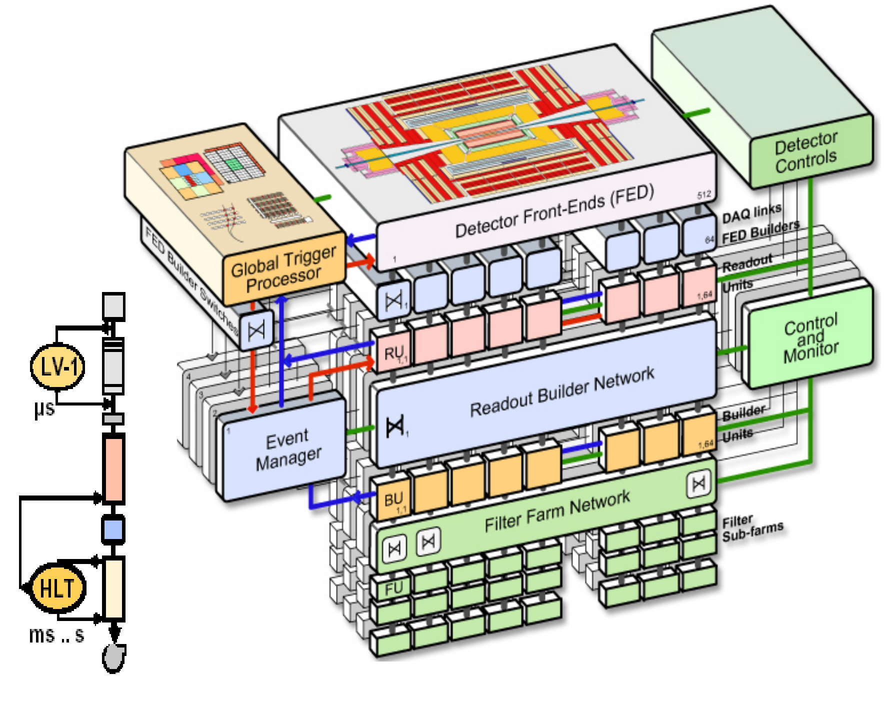
So that the resulting level of track ambiguities is low, and the pattern recognition problem is essentially solved by then (“join the dots”)



The Tracker at HLT
CMS L1 Trigger and HLT farm filter

Lvl-1 = “crude”
granularity and Pt resolution:
Rate dominated by
miss-measured jets & leptons

HLT task: reduce rate by ~ 1000
Exploit much better
Granularity and Pt resolution
to correctly tag and retain
only interesting physics events



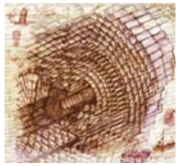
40 MHZ

50 KHz

100 Hz

On average ~300ms available for HLT
Decision on any given event
(Normalized to a 1GHz Pentium)

4 DAQ slices in 2007
=> 50 KHZ into HLT, 100 Hz out



The Tracker at HLT
for example t lepton tagging

Regional Tracking: Look only in

Jet-track matching cone

Conditional Tracking: Stop track as soon as

If Pt<1 GeV with high C.L.

Reject event if no “leading track found”
(jet is not charged)

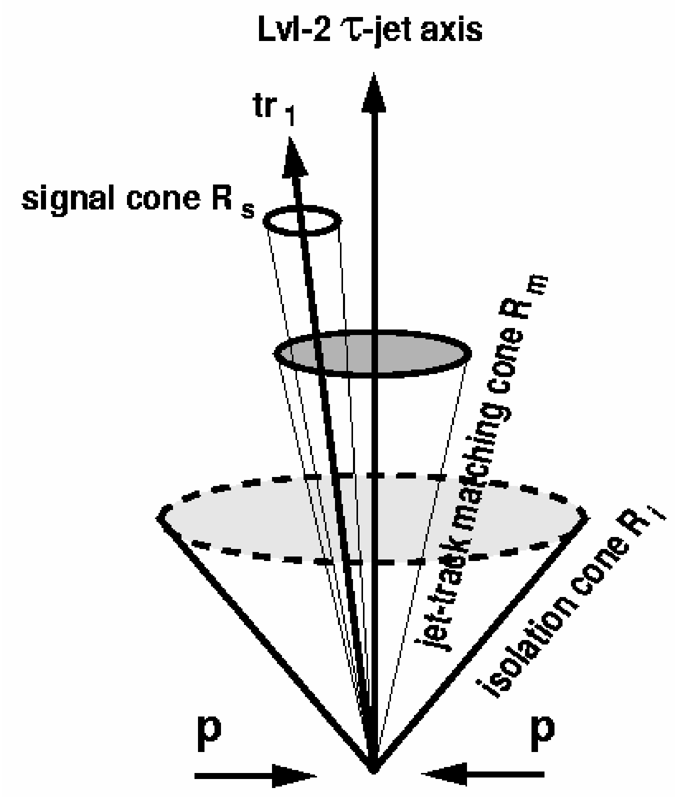
Regional Tracking: Look only inside

Isolation cone

Conditional Tracking: Stop track as soon as

If Pt<1 GeV with high C.L.

Reject event as soon as additional track
found (jet is not isolated)



Fast enough at low luminosity for full L1 rate; at high luminosity may need a moderate Calorimeter pre-selection factor to reduce rate

The Tracker at HLT
b tagging efficiency vs. rejection

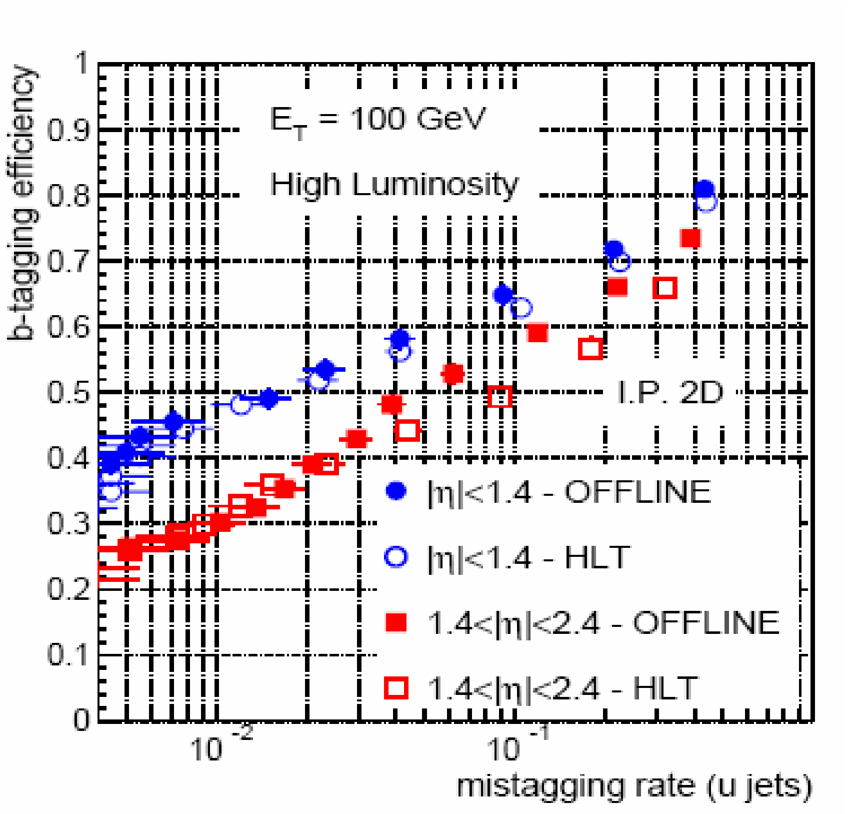
High quality Impact parameter based b tagging is also fast enough to be used in the HLT

Shown here is the b-tagging efficiency versus mis-tagging rate for u jets, for a typical impact parameter based tagging algorithm

Using conditional tracking (HLT)
Using full track reconstruction

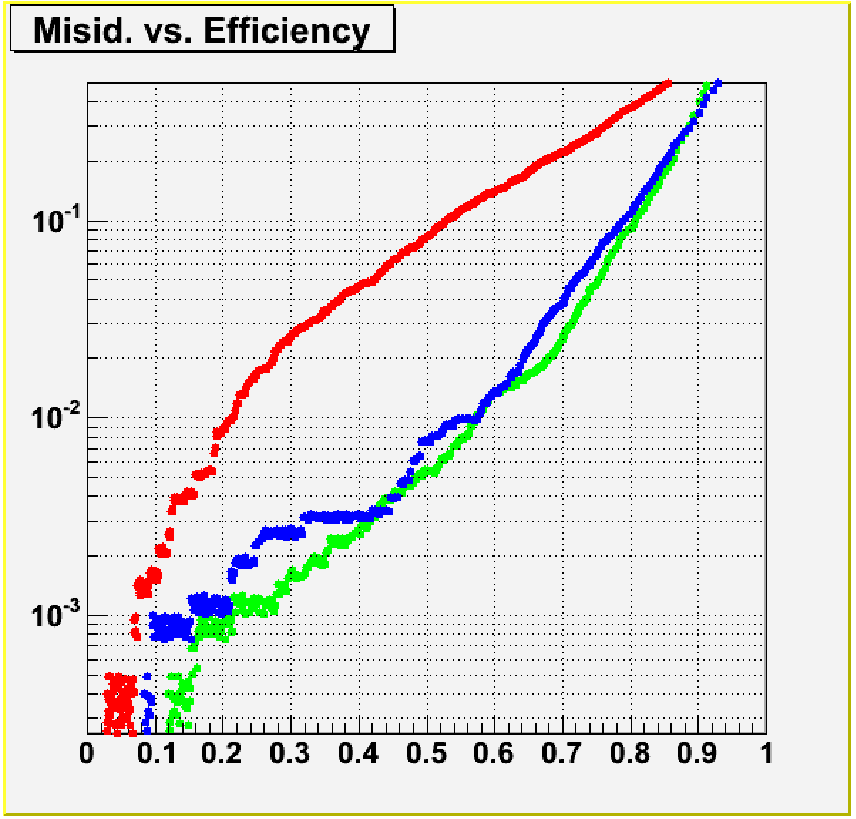
The performance is substantially the same in both cases

60% b tag => ~ 6% u jet mis-tag
1% u jet mis-tag => ~ 45% b jet tag



The Tracker at HLT
b tagging efficiency vs. rejection

Given more time (off-line) one can do better…
Below is an example multi-variate b tagging algorithm



u jet rejection

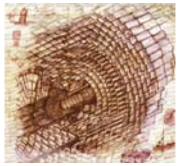
limited by vertex detector quality
60% b tag => ~ 1% u jet mis-tag

c jet rejection

limited by c lifetime

g jet rejection

limited by g splitting
to bb (4%) or cc (6%)



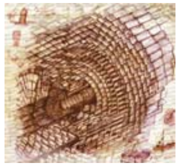
Tracking at the SHLC
A Look Ahead

- The Tracking systems of both ATLAS and CMS will have to re-built to cope with the ten-fold luminosity increased envisaged for the SLHC upgrade

- This will probably require a ~ ten-fold decrease in cell size, with a corresponding ~ ten-fold increase in total number of channels eg

– Inner region	~100μm*100μm	full 3-d
– intermediate region	~100μm*1mm	excellent r-phi, good r-Z
– Outer region	~100μm*1cm	excellent r-phi, poor r-Z

- Challenges include
  - a ten-fold improvement in radiation hardness
  - at least a ten-fold decrease in power consumption/channel
    - to maintain total power dissipation equal to or below current level
  - different approach to connecting read-out electronics & active sensor cell
    - For pixel length <1mm, may go for monolithic active pixel technology,
    - for longer pixels hybrid approach may still be competitive



Summary and Conclusions

The CMS Silicon Tracker has robust performance in a difficult environment

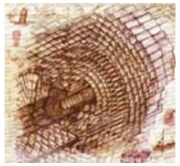
The pixel vertex detector allows fast & efficient track seed generation, as well as excellent 3-D secondary vertex identification

The fine granularity of the pixel and strip sensors, together with the analyzing power of the CMS 4T magnet provide robust pattern recognition, and a ~ 2% or better Pt resolution for 100GeV muons over about 1.7 units of rapidity

This allows for very precise and sophisticated event analysis

A good determination of track parameters with only a few hits (4~6) allows fast & clean pattern recognition

This makes possible the extensive use of track information already at HLT level for essentially the full L1 stream at both high and low luminosity



Summary and Conclusions

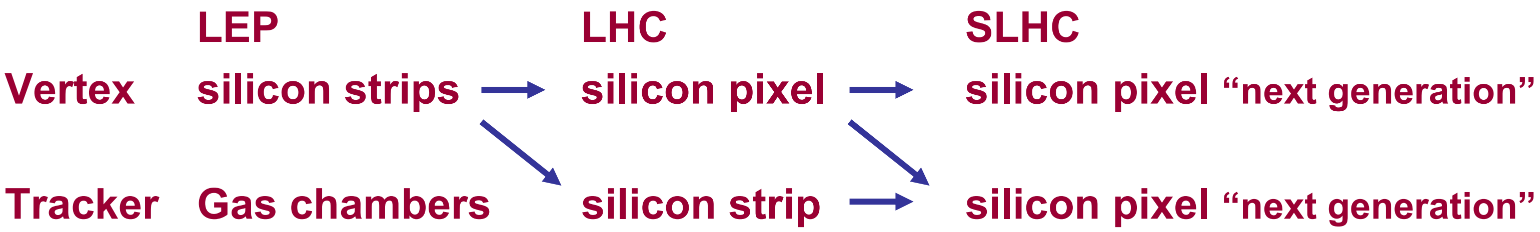
The scope of the CMS Silicon Tracker is made possible by the use of:

Commercial technologies and high quality, high volume, production lines (silicon strip sensors, FE chips, hybrids, lasers etc.)

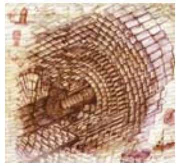
Modern high throughput machines for wire-bonding, wafer testing etc.

And the development of automated module assembly techniques

New Trackers for the SLHC will require major further steps in each of these areas



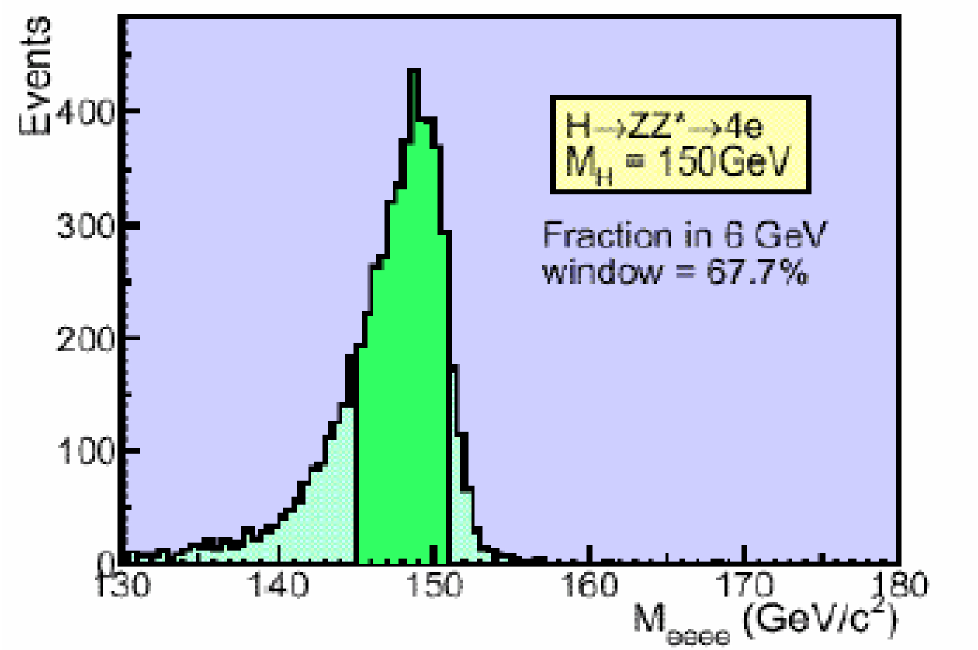
	LEP		LHC		SLHC
Vertex	silicon strips	→	silicon pixel	→	silicon pixel "next generation"
		↘		↘	
Tracker	Gas chambers		silicon strip	→	silicon pixel "next generation"



Reserve slides

Material inside the Tracking volume "The Dark Side…"

Degrades tracking performance, due to multiple scattering, Bremsstrahlung and nuclear interactions (see 100GeV μ Pt resolution and p reconstruction efficiency)



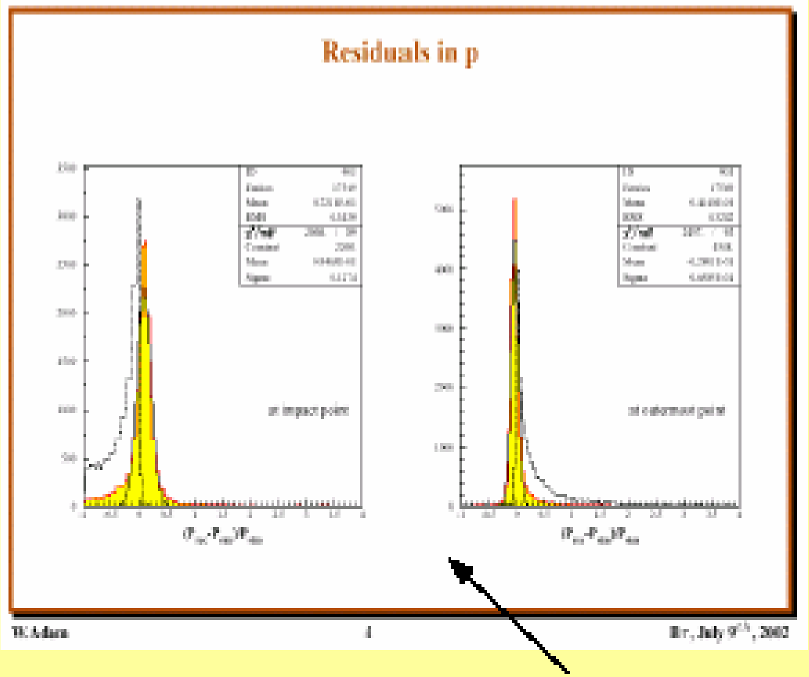
Dominates energy resolution for electrons

Reduces (somewhat) efficiency for usefully reconstructing H → $\gamma\gamma$

Material Budget minimization has been one of the driving principles in the design of the CMS Tracker
But so has ensuring that this will be a functional device…

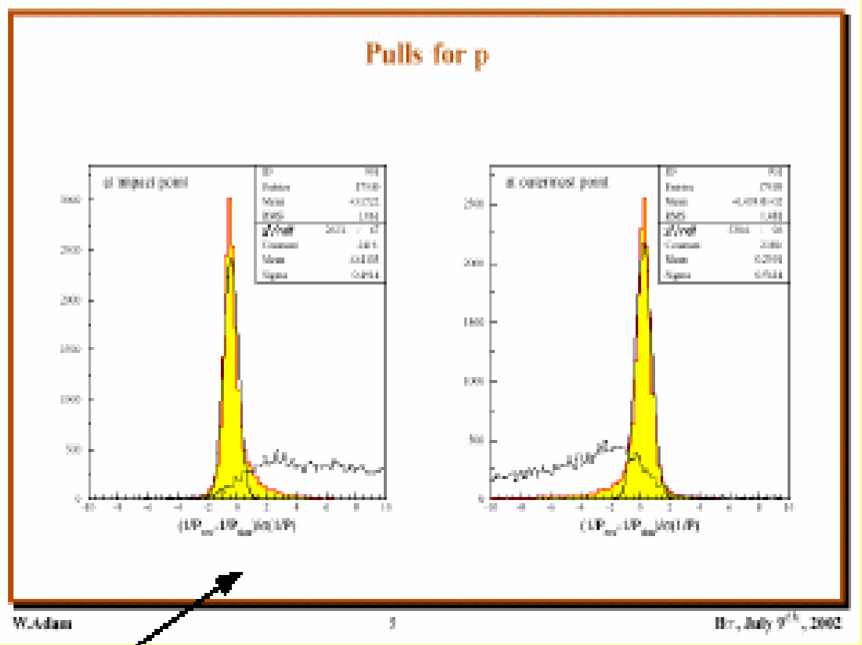
Electron reconstruction with the CMS Tracker

How to make the best of it, also for electrons?



Residuals in p

W.Adam 4 Br., July 9th, 2002



Pulls for p

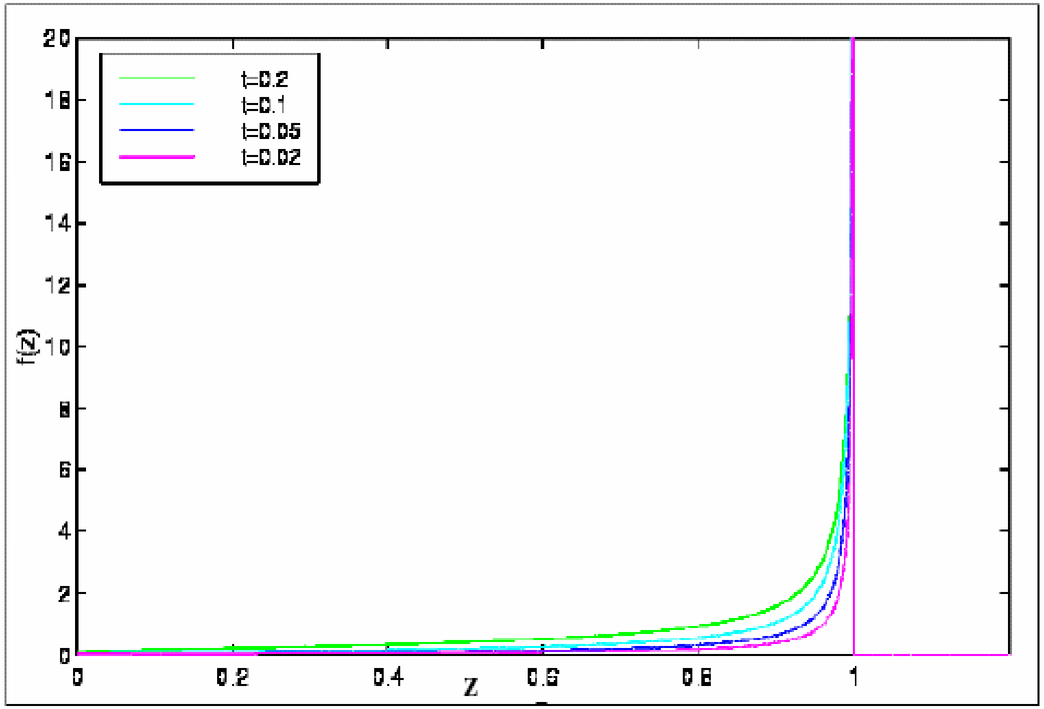
W.Adam 5 Br., July 9th, 2002

For electrons, using Bethe and Heitler formula for energy loss (Yellow distribution) works better than treating them as muons… (White distribution)

Can one do better?

Electron reconstruction with the CMS Tracker

In the standard treatment, a single Gaussian is used to approximate the underlying probability distribution



The energy loss of electrons in material is manifestly not well described by this

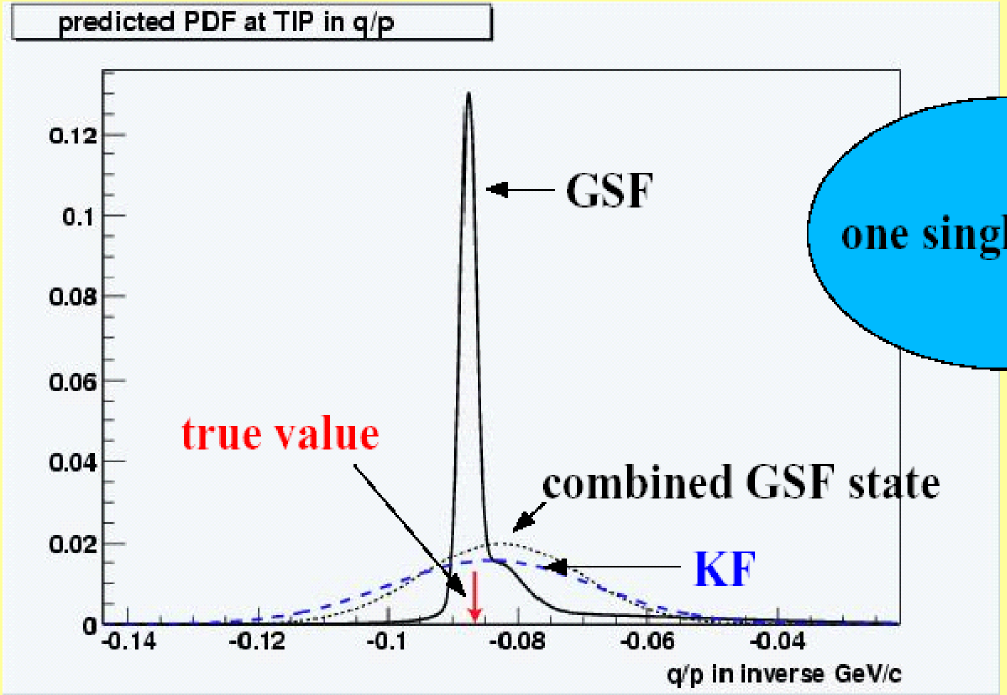
Electron reconstruction with the CMS Tracker

Gaussian Sum Filter (GSF)

Approximate Bethe & Heitler with multiple Gaussians

At each material layer create and test new track hypotheses corresponding to each of these Gaussians

Retain only “the best ones” (combinatorial reduction) and continue



one single track!

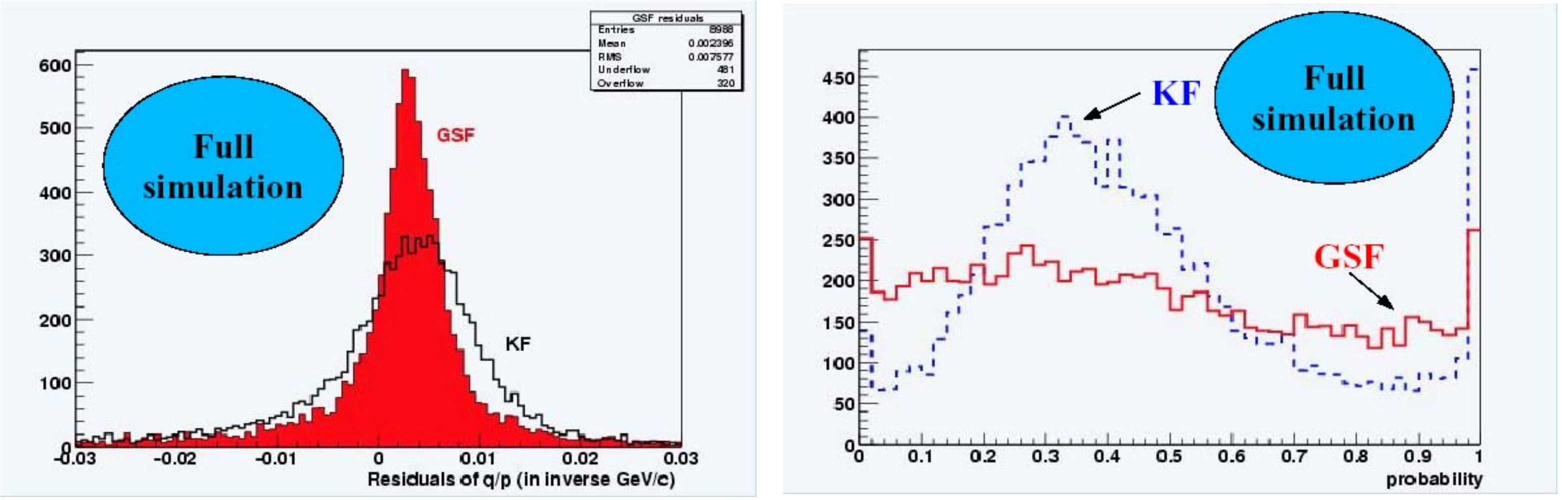
Single 10GeV electron
In barrel
(simplified geometry)

Electron reconstruction with the CMS Tracker

Gaussian Sum Filter (GSF)

Approximate Bethe & Heitler with multiple Gaussians
At each material layer create and test new track hypotheses
corresponding to each of these Gaussians
Retain only "the best ones" (combinatorial reduction) and continue

Residual and probability distributions for a sample of 10 GeV electrons in the barrel

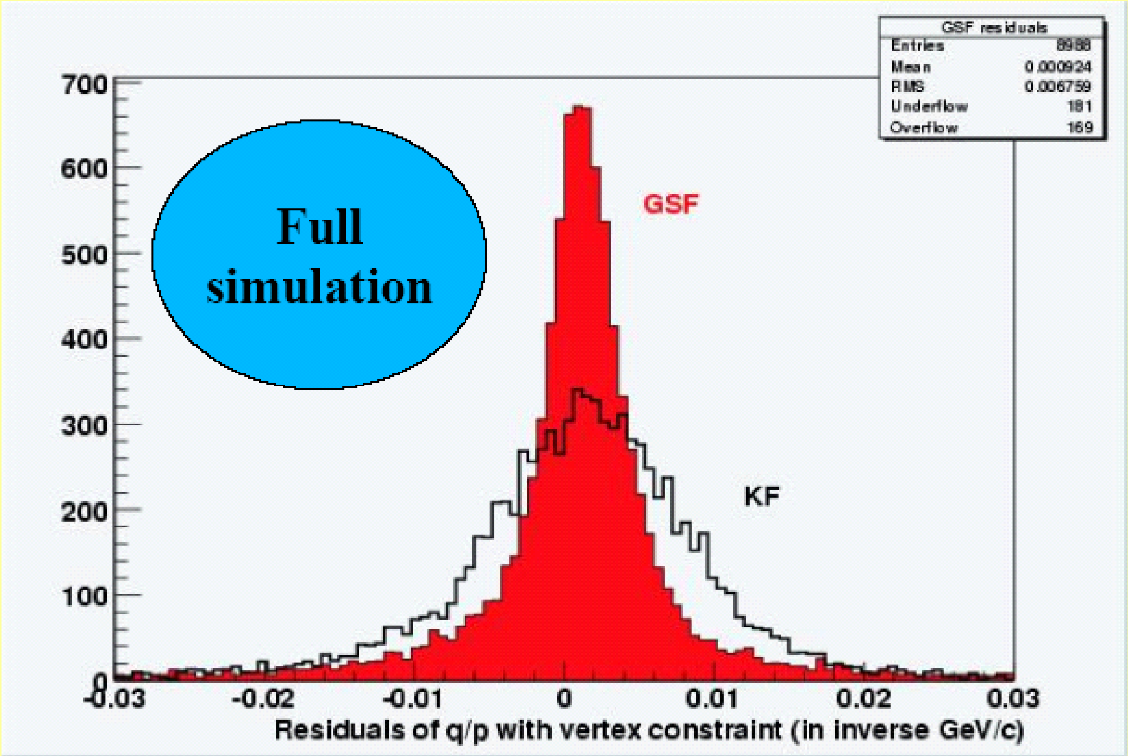


GSF significantly improves the resolution: FWHM is reduced by ~ factor of 2
And provides a better estimate of the errors

Electron reconstruction with the CMS Tracker

- **Can do even better if consider Transverse Vertex constraint:**

Residuals at TIP, including vertex constraint



Vertex constraint allows to measure momentum in innermost layers.

Distribution less skew, mode closer to zero and reduced amount of tracks in the tails.

The Construction
Front-End chip (APV25)

Use standard 0.25μm IBM technology

- Large volume high yield 8” wafer process
- Also used for Pixel read-out chip

Automatic wafer probing

- Allows systematic monitoring of yield
  - Crucial to provide feed-back to foundry on process quality to ensure adequate yield is maintained

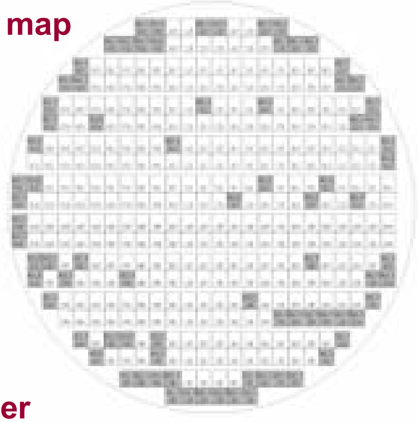
Test time < 2mins/chip

- 1 8inch wafer per probe station per day
- can complete testing in ~1-2 years

Irradiation results

- x-ray, pion & neutron - all excellent
- tests with heavy ions and pions
  - 8 chips x 10 LHC years
  - low SEU rate, no permanent damage or latch up

“Typical” tested wafer map
Note excellent yield



Automated wafer tester