1997–1998 ACADEMIC TRAINING PROGRAMME
LECTURE SERIES ON LHC DETECTORS

PLACE: AUDITORIUM
DATE: 10 February 1998

SPEAKER: F. PAUSS / ETH, Zürich, CH
TITLE: Requirements and Design Criteria for CMS
TIME: from 10.15 to 11.00 hrs

The Compact Muon Solenoid (CMS) experiment is a general-purpose detector designed to exploit the physics of pp-collisions at a centre-of-mass energy of 14 TeV over the full range of luminosities expected at the LHC. Physics requirements and design considerations which led to the CMS detectors will be reviewed.

SPEAKER: L. ROSSI / EP
TITLE: Tracking at LHC
TIME: from 11.15 to 12.00 hrs

The role of tracking and vertexing for the LHC experiments will be described. The characteristics of the various tracking detectors will be illustrated and the motivations for the solutions adopted will be commented upon. Some system aspects will be covered together with recent R&D advances.
REQUIREMENTS AND DESIGN CRITERIA FOR CMS

CERN Academic Training Lectures
February 10, 1998

Felicitas Pauss
ETH Zürich
OUTLINE OF TALK

• Introduction
• The Experimental Challenge at LHC
• The CMS Design Objectives
• Subdetector Requirements
  – technological choices
  – performance figures
• Conclusion
FUNDAMENTAL QUESTIONS

○ Mass Problem
Mechanism to give particle masses:
electroweak symmetry breaking $\rightarrow$ HIGGS sector
  – Standard Model: one scalar Higgs
  – Supersymmetry: at least five Higgs particles
  – Alternative symmetry breaking: no Higgs

○ Unification of Forces: Supersymmetry
  – stabilize Higgs mass
  – natural explanation of weak scale
  – mass-scale of SUSY particles: $O(1\text{TeV})$

○ Matter-Antimatter Asymmetry
  – CP-violation

CMS at LHC can answer or shed considerable light on these questions
**EXPERIMENTAL CHALLENGE**

**LHC:** pp collisions at $E_{cm} = 14$ TeV

$L_{\text{Design}} = 10^{34} \text{cm}^{-2}\text{s}^{-1}$, bunch crossing every 25ns

- **High Interaction Rate**
  - 40 MHz collision rate must be reduced to $\sim 100$ Hz
  - 1st level trigger decision will take $\approx 2$-3 $\mu$s

  $\Rightarrow$ pipelining

- **Large Particle Multiplicity**
  - $\sim 20$ superimposed min.bias events at $L_{\text{Design}}$
  - $\sim 1000$ tracks every 25ns ($|\eta| < 3$)
    $\rightarrow$ highly granular detectors
    $\rightarrow$ good time resolution

  $\Rightarrow$ large number of detector channels

- **Severe Radiation Environment**
  - high radiation levels
  - large flux of low energy n’s in experimental hall
  - activation: limited access to some detectors

  $\Rightarrow$ radiation hard detectors and electronics
PARTICLE MULTIPLICITIES

Min. bias $\langle n_{ch} \rangle$ per 2x2 cm$^2$ cell at $L_{Design}$ every 25 ns:
(no detector material)

<table>
<thead>
<tr>
<th>$B = 0T$</th>
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<tbody>
<tr>
<td>$\eta=0$ (r)</td>
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<tr>
<td>No $p_T$ cut</td>
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<tr>
<td>$\eta=2$ (z)</td>
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<tr>
<td>No $p_T$ cut</td>
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<tr>
<td>$\eta=2$ (z)</td>
</tr>
<tr>
<td>No $p_T$ cut</td>
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</tbody>
</table>
Radiation Levels in CMS Area

ECAL-TDR Data, November 1997 (5 x 10^5 pb^{-1})

Absorbed Dose (Gy)

E > 100 keV Neutron Fluence (n/cm^2)
A general purpose pp detector designed to operate at the highest LHC luminosity also well adapted for studies at the initial lower luminosities in order to fully exploit the discovery potential offered by LHC

◇ high field solenoid (4T)
◇ very good muon identification and momentum measurement
◇ high resolution em calorimeter (crystals)
◇ powerful inner tracking system
◇ cost effective detector
CMS HISTORY

- **LHC Workshop, Aachen 1990**
  Concept of compact detector based on a 4 Tesla superconducting solenoid

- **Expression of Interest, Evian 1992**
  Conceptual design

- **Letter of Intent, Oct 1992**
  CERN/LHCC 92-3

- **Technical Proposal, Dec 1994**
  CERN/LHCC 94-38

- **Technical Design Reports:**
  - Magnet: May 1997
  - Hadron Calorimeter: June 1997
  - Electromagnetic Calorimeter: Dec 1997
  - Muon System: Dec 1997
  - Tracker: April 1998
CHOICE OF MAGNET

At high luminosities the environment is the cleanest for muons → need magnetic field

CHOICE OF THE FIELD CONFIGURATION STRONGLY INFLUENCES THE REST OF THE DETECTOR DESIGN

• **SOLENOID**
  - bending in the transverse plane
    beam spot in transverse plane (20μm) for free
  - worsening of $p$ resolution in forward direction
    → have to keep aspect ratio high

• **TOROID**
  - constant $p_T$ resolution over wide $\eta$ range
  - no magnetic field for inner tracker
    → additional solenoid is needed
C.M.S.
A Compact Solenoidal Detector for L.H.C.

Very Forward Calorimeter
Superconducting Coil
Central Support Plate
Return Yoke
Muon Chambers
Inner Tracker
E.M. Crystal Cal.
Hadron Cal.

Total Weight: 12,000 t.
Overall Diameter: 14.00 m
Overall Length: 20.00 m
Magnetic Field: 4 Tesla
CMS
A Compact Solenoidal Detector for LHC

weight: 12,500t.
diameter: 15.00m
length: 21.60m
magnetic field: 4 Tesla

CMS-PARA-001-11/07/97 JLB.PP
CMS collaboration
(151 institutions with about 1600 scientists)
Subdetector Requirements
Technological Choices
and
Performance Figures


**Physics Examples**

- $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$ (SM, SUSY)
- $h, A, H \rightarrow \mu^+\mu^-$ (SUSY)
- $\tilde{g}, \tilde{q} \rightarrow \text{multi-}\mu + \text{jets} + E_T^{\text{miss}}$ (cascade decays)
- $Z' \rightarrow \mu^+\mu^-$, $W' \rightarrow \mu\nu$
- rare decays: $B_s^0 \rightarrow \mu^+\mu^-$
- CP violation: $B_d^0 \rightarrow J/\Psi \rightarrow \mu\mu, K_s^0 + \mu_{\text{tag}}$

**Benefits**

- $\mu$ can be identified inside jets
  - $\rightarrow$ b-tag: $b \rightarrow \mu + X$
  - $\rightarrow$ determine efficiency of isolation cuts
- can trigger on and identify $\mu$'s down to low $p_T$
  - $\rightarrow$ acceptance for $H \rightarrow ZZ^* \rightarrow 4\mu$
  - $\rightarrow$ CP violation
  - $\rightarrow$ Heavy Ions

**Design Requirements: 3 Basic Tasks**

- identification
- momentum measurement
- trigger: challenging in hadron collider experiments
$H(150\text{GeV}) \rightarrow Z^0 Z^{0*} \rightarrow 4\mu \text{ (event 8)}$
CMS Muon System

- Field parallel to beam: vertex with $\pm 20 \, \mu m$
- Bending in transverse plane
- Easy trigger: track pointing to vertex
- 3 independent momentum measurements
  - in air, before absorber: low momentum \( \mu \)'s
  - after coil
  - after return yoke

Favourable aspect ratio allows good muon momentum resolution up to \( |\eta| = 2.5 \) with a single magnet
MUON SYSTEM

PERFORMANCE DETERMINED BY

- **Pattern Recognition**
  Hits can be spoilt by
  - correlated bgd: δ's, em showers, punchthrough
  - uncorrelated bgd: neutrons and associated γ's

- **Momentum Resolution**
  - at high momenta: large $\int Bdl$
    * good resolution:
      per station: 100μm (MB1), 75μm (ME1)
      per layer: $\sim$250μm (MB1), $\sim$150μm (ME1)
    * μ and tracker alignment: $< 20μrad$ (RΦ)
  - at low momenta: inner tracking better

- **1st Level Trigger**
  - genuine μ-rate (b,c → μX) very high
  - flexible threshold
  - large geometrical acceptance: $|\eta| > 2.0$
Muon Induced Secondaries

1 TeV muon with a "catastrophic" energy loss of 22 GeV
CMS momentum resolution

$\Delta p/p$

$\eta=0.1$

- full system
- last 4 tracker points
- muon system only
- inner tracker only

$p [\text{GeV/c}]$
The rate is dominated by $\pi, K$ decays up to 4 GeV and by $b-, c$-quark decays from 4 to 25 GeV.

The trigger rate can be adjusted by moving the threshold in a wide range of $p_t$ without loosing much efficiency for heavier objects.

Two muon event rates are 2 orders of magnitude lower.
CMS Muon System

4 Muon Stations in Barrel and Endcaps

Barrel: $0 \leq |\eta| \leq 1.3$
Drift Tubes (12 Layers: 8 in $R\phi$, 4 in $z$)

Endcaps: $0.9 \leq |\eta| \leq 2.4$
Cathode Strip Chambers (6 Layers)

RPC: $0 \leq |\eta| \leq 2.1$ (2 Layers)
$H \rightarrow ZZ / ZZ^* \rightarrow 4 \ell^\pm$

$\Gamma_H, \sigma_{4\ell}$

$\sigma^{\text{exp}}_{4e^\pm}$

$\sigma^{\text{exp}}_{4\mu^\pm}$

$\Gamma_{\text{SM}}^H$

$\Gamma_{\text{SUSY}}^H, \tan \beta = 3$

$4e^\pm$, window algorithm
5 % / $\sqrt{E} \oplus 0.5 %$
50 MeV noise/crystal

$4e^\pm$, cluster algorithm
2 % / $\sqrt{E} \oplus 0.5 %$
25 MeV noise / crystal

$m_H$ (GeV)
**Physics Examples**

- Heavy Higgs: $H \rightarrow ZZ(WW) \rightarrow lljj (l\nu jj)$
- SUSY Higgs: $h,A,H \rightarrow \tau^+\tau^-, t \rightarrow H^\pm b \rightarrow \tau^\pm \nu b$
- SUSY particles: $\tilde{g},\tilde{q} \rightarrow$ jets + $E_T^{\text{miss}}$ (cascade decays)
- $Z' \rightarrow jj$, $W' \rightarrow jj$
- Compositeness: search via $pp \rightarrow$ jets
- Top mass measurement: $t \rightarrow Wb \rightarrow 3j$

**Figure of Merit**

- jet-jet mass resolution
  * low $p_T$ jets: $W,Z \rightarrow \text{jet+jet}$
  * high $p_T$ jets: boosted $W$s, $Z$s and $W'$, $Z'$
- missing transverse energy resolution
  * all signatures involving non-interacting particles ($\nu$, LSP=$\tilde{\chi}_1^0$, ...)
$+20 \text{ min bias}$

$H \rightarrow ee \text{ jet jet, } m_H = 800 \text{ GeV}$
PERFORMANCE DETERMINED BY

- **Jet Energy Resolution**
  limited by jet algorithm, fragmentation, magnetic field effects and energy pile-up at high luminosity

- **Mass Resolution**
  effect of cone-size and granularity:
  mass resolution for $W \rightarrow jj$ from $H \rightarrow WW \rightarrow l\nu jj$
  for $m_H=1\text{TeV}$ (boosted $W$s)

| W mass resolution in GeV (no pileup) |
|-----|-----------------|-----------------|------------|-----|
| $\Delta R$ | all $E_T >1\text{GeV}$ | $\Delta \eta \Delta \phi$ | $\sigma_M$ | $\varepsilon\%$ |
| 0.4 | 5.0 | 6.1 | 0.05x0.05 | 6.1 | 66 |
| 0.5 | 4.7 | 5.4 | 0.10x0.10 | 8.9 | 52 |
| 0.6 | 4.8 | 5.0 | 0.15x0.15 | 12.6 | 26 |
| 0.7 | 4.8 | 5.5 | 0.20x0.20 | 15.9 | 13 |

$\rightarrow$ granularity: $\Delta \eta \Delta \phi \approx 0.1x0.1$ sufficient

- **$E_T^{miss}$ Resolution**
  - forward calorimeter coverage up to $|\eta|=5$
  - hermeticity: minimize cracks and dead areas
  - absence of tails in the energy distribution is more important than a low value for the stochastic term
Hadron Calorimeter

Central Calorimeter: $0 \leq |\eta| \leq 3$
Forward Calorimeter: $3 \leq |\eta| \leq 5$

CMS event pile-up background in bunch crossing at $10^{34}$ cm$^{-2}$ s$^{-1}$

No VFCAL:
$$\sigma (E_t^{\text{miss}}) = 1.0 \sqrt{\Sigma E_t}$$

With VFCAL:
$$\sigma (E_t^{\text{miss}}) = 0.69 \sqrt{\Sigma E_t}$$
HCAL Barrel / endcap designs
Hadron Calorimeter

Total Thickness of calorimeter system

Effect of tail catcher planes on reduction of tails in hadron response
**HCAL PARAMETERS**

- **Barrel and Endcaps inside 4T Field**
  - non-magnetic material: copper/plastic-scintillator
  - 6 cm Cu sampling (8cm in HE)
  - 3 depth segments (17 sampling plates)
  - granularity: $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$
  - $\eta$-coverage: HB: $0 \leq |\eta| \leq 1.3$, HE: $1.3 \leq |\eta| \leq 3.0$
  - resolution: $\Delta \ E/E \sim 100\%/\sqrt{E} \oplus 4\%$

- **Forward Calorimeter**
  - high radiation environment: iron/quartz fibre
  - absorbed dose $\sim$ MGy/year
  - neutron flux $\sim 10^9 cm^{-2} s^{-1}$
    - activation: need shielding
  - $\eta$-coverage: $3.0 \leq |\eta| \leq 5.0$
  - granularity: $\Delta \eta \times \Delta \phi = 0.175 \times 0.175$
  - fibres almost parallel to incident particles
    - sensitive to $\bar{C}$-light from $\pi^0$
      - very localized response to hadron shower
      - very fast signal ($< 10$ns)
  - hadronic energy resolution: $\sigma/E = 0.52 - 0.06 \ln E$
Jet-Jet Mass Resolution

\[ t \to Wb \quad \text{with} \quad W \to \text{jet} + \text{jet} \]

Reconstructed dijet mass distribution
\[ \Delta R = 0.4 \]

No pile-up: \[ \sigma_M \sim 8 \text{ GeV} \]
With pile-up: \[ \sigma_M \sim 12 \text{ GeV} \]

Similar results for \( H \to WW \to l\nu jj \)
**Physics Examples**

- $H \rightarrow \gamma \gamma$ (SM, SUSY)
- $H \rightarrow ZZ^{(*)} \rightarrow 4e$ (SM, SUSY)
- $\tilde{g}, \tilde{q}$ cascade decays:
  - $\tilde{g}, \tilde{q} \rightarrow$ multi-electrons + jets + $E_{T}^{\text{miss}}$
  - $\tilde{\chi}_{2}^{0} \rightarrow ee\tilde{\chi}_{1}^{0}$: shape of $m_{e^+e^-}$
- $Z' \rightarrow e^+e^-, W' \rightarrow e\nu$

**Measure performance using the benchmark reaction** $H \rightarrow \gamma \gamma$

*for $m_{H} = 100$ GeV, $\Gamma_{H} \sim \text{few} \ MeV$!*

- mass resolution:
  - energy resolution: stochastic, systematics, noise
  - angle of emission of photons
- background rejection ($\pi^0$)

**CMS Design Goal**

high resolution electromagnetic calorimeter

$\rightarrow$ fully active (homogeneous) calorimeter:

$\rightarrow$ **Crystals**
$H ightarrow \gamma \gamma', M_H = 100 \text{ GeV}$
## Crystal Calorimeters

### Characteristics of some typical shower media

<table>
<thead>
<tr>
<th>Material</th>
<th>$X_0$ (cm)</th>
<th>$R_M$ (cm)</th>
<th>Relative light output</th>
<th>peak $\lambda$ (nm)</th>
<th>$\tau$(ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI</td>
<td>2.59</td>
<td>4.8</td>
<td>1.0</td>
<td>410</td>
<td>230</td>
</tr>
<tr>
<td>BGO</td>
<td>1.12</td>
<td>2.3</td>
<td>0.18</td>
<td>480</td>
<td>300</td>
</tr>
<tr>
<td>CsI</td>
<td>1.85</td>
<td>3.5</td>
<td>0.20</td>
<td>315</td>
<td>16</td>
</tr>
<tr>
<td>CeF$_3$</td>
<td>1.68</td>
<td>2.6</td>
<td>0.08</td>
<td>340</td>
<td>25</td>
</tr>
<tr>
<td>PbWO$_4$</td>
<td>0.89</td>
<td>2.2</td>
<td>0.01</td>
<td>440</td>
<td>5-15</td>
</tr>
</tbody>
</table>

EM shower in PbWO$_4$ crystals - ‘light’ seen by PD’s not shown
### CMS ECAL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barrel</th>
<th>Endcaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta ) coverage</td>
<td>(</td>
<td>\eta</td>
</tr>
<tr>
<td>( r ) inner, ( r ) outer [mm]</td>
<td>1238, 1750</td>
<td>316, 1711</td>
</tr>
<tr>
<td>( z ) inner, ( z ) outer [mm]</td>
<td>0, ( \pm 3045 )</td>
<td>( \pm 3170, \pm 3900 )</td>
</tr>
<tr>
<td>( \Delta \eta \times \Delta \phi )</td>
<td>0.0175 x 0.0175</td>
<td>0.0175 x 0.0175 to 0.05 x 0.05</td>
</tr>
<tr>
<td>Crystal dim. [mm^3]</td>
<td>21.8 x 21.8 x 230</td>
<td>24.7 x 24.7 x 220</td>
</tr>
<tr>
<td>Depth in X0</td>
<td>25.8</td>
<td>24.7</td>
</tr>
<tr>
<td>Off-pointing</td>
<td>3 deg.</td>
<td>( \approx 3 ) deg.</td>
</tr>
<tr>
<td>No. of crystals</td>
<td>61 200</td>
<td>21 523</td>
</tr>
<tr>
<td>Volume [m^3]</td>
<td>8.14</td>
<td>3.04</td>
</tr>
<tr>
<td>Crystal weight [t]</td>
<td>67.4</td>
<td>25.2</td>
</tr>
<tr>
<td>Modularity crystals</td>
<td>36 supermodules</td>
<td>4 Dees</td>
</tr>
<tr>
<td></td>
<td>1700 per SM</td>
<td>5382 per Dee</td>
</tr>
<tr>
<td></td>
<td>(20 in ( \phi ), 85 in ( \eta ))</td>
<td></td>
</tr>
</tbody>
</table>
CRYSTAL CALORIMETER

• Merit of Crystal Calorimeter
  intrinsic energy resolution $\sim 2\%/\sqrt{E}$ (E in GeV)
  $\rightarrow$ control of systematics for constant term ($\sim 0.5\%$)

• LHC Challenge
  – high precision
  – wide dynamic range ($\sim 16$ bits): 30MeV-2TeV
  – 40MHz collision frequency
  – hostile radiation environment: at shower max
    4kGy (barrel), 90kGy ($|\eta|=2.6$) for $5\cdot10^5$pb$^{-1}$
    corresponding to
    0.2Gy/hour (barrel), 6.5Gy/hour ($|\eta|=2.6$) at $L_{Design}$

• Performance Determined By
  – preamplifier and pile-up noise ($L$-dependent)
  – constant term: intercalibration error, crystal
    non-uniformity, shower leakage
  – voids between modules
  – material in front of ECAL
  – $\gamma/\pi^0$ rejection
  – radiation hardness of crystals, photodetectors
    and readout electronics
PbWO$_4$ energy resolution

- Input to shower MC:
  - Photostatistics contribution 2.3%/\sqrt{E}
  - Electronics noise:
    \[ E_T = 30 \text{ MeV/channel (barrel — APD)} \]
    \[ E = 150 \text{ MeV/channel (endcap — VPT)} \]
    + APD leakage current:
    \[ 6 \text{ MeV/channel (low luminosity)} \]
    \[ 22 \text{ MeV/channel (1st year at high luminosity)} \]
  - Constant term 0.5%
    - 0.3% from longitudinal non-uniformity
    - 0.4% from intercalibration error

- Basic reconstruction algorithm is 5x5 crystals
  Resolution given in table for no edge effects and no conversions

<table>
<thead>
<tr>
<th></th>
<th>Barrel ($\eta = 0$)</th>
<th>Endcap ($\eta = 2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stochastic term</td>
<td>2.7%/\sqrt{E}</td>
<td>5.7%/\sqrt{E}</td>
</tr>
<tr>
<td>Constant term</td>
<td>0.55%</td>
<td>0.55%</td>
</tr>
<tr>
<td>$E_T$ noise ($10^{33}$)</td>
<td>155 MeV</td>
<td>205 MeV</td>
</tr>
<tr>
<td>$E_T$ noise ($10^{34}$)</td>
<td>210 MeV</td>
<td>245 MeV</td>
</tr>
</tbody>
</table>
Photon conversions

Material in front of ECAL

- Beam Pipe
- Pixel detector system
- Silicon detector system
- MSGC detector system
- Air

<table>
<thead>
<tr>
<th></th>
<th>Unconverted</th>
<th>Converted (invisible)</th>
<th>Converted (visible)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endcap</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ENDCAP PRESHOWER

Main function: $\pi^0\gamma$ separation
$\eta$ coverage 1.65 to 2.61
two lead converter: 2 $X_0$ and 1 $X_0$

Schematic section

Variation of $\pi^0$ rejection in endcaps
Higgs mass resolution

Low luminosity
Constant $10^{33} \text{ cm}^{-2}\text{s}^{-1}$

High luminosity
$10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at injection
### Higgs signal significance

#### Table:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Stochastic term</th>
<th>Constant term</th>
<th>Noise</th>
<th>Other effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>270 MeV</td>
<td>390 MeV</td>
<td>265 MeV</td>
<td>355 MeV</td>
</tr>
</tbody>
</table>

#### Graph:

- **Fiducial area cuts within $|y| < 2.5$**
- **Unrecoverable conversions**
- **Isolation cuts ($10^{24}$ cm$^{-2}$s$^{-1}$)**
- **$\pi^0$ rejection algorithms**

#### Parameters:

- **30 fb$^{-1}$ (low luminosity)**
- **100 fb$^{-1}$ (high luminosity)**

#### Luminosity:

- **0.010**
- **0.120**
- **0.130**
- **0.140**
- **0.150 (GeV)**
INNER TRACKING

• **Physics Examples**
  - $H \rightarrow 4\ell$: isolated $e, \mu$ (SM, SUSY)
  - $b$-jet tag: $H \rightarrow b\bar{b}$; $\tilde{g}, \tilde{q}$ - decays; $t \rightarrow Wb$
  - CP violation: $B^0_d \rightarrow J/\Psi_{\mu\mu} K^0_s \rightarrow \mu^+\mu^-\pi^+\pi^-$

• **Benefits**
  - topological information
  - precise momentum measurement
  - $e$ and $\tau$ identification
  - isolation using charged tracks
  - secondary vertex and impact parameter measurement
  - ECAL calibration using $p/E$ matching

• **Design Goals**
  - for isolated leptons: $\Delta p_T/p_T \sim 0.1 p_T$ (TeV)
  - $\sim 12$ precision hits per high $p_T$ track
    $\rightarrow$ use microstrip technology (silicon and MSGCs)
  - high $p_T$ track reconstruction efficiency:
    isolated: $\varepsilon > 95\%$, within jets: $\varepsilon > 90\%$
    ghost tracks $< 1\%$ for isolated tracks
  - impact parameter resolution: at high $p_T$
    $\sim 20\mu m$ ($r\phi$), $\sim 100\mu m$ ($z$)
30 minimum bias events + H \rightarrow ZZ \rightarrow 4\mu

all charged particles with $|\eta| < 2.5$

reconstructed tracks with $p_t > 2.0$ GeV
INNER TRACKING

PERFORMANCE DETERMINED BY

• *Pattern Recognition*
  - high charged particle flux
  - 4T causes high particles density at *small* radius
    → high detector granularity

• *Momentum Resolution*
  - spatial resolution:
    * pixel: $\sigma_{r\phi}, \sigma_z \sim 15\mu m$
    * silicon strip: $\sigma_{r\phi} \sim 15\mu m$
    * MSGC: $\sigma_{r\phi} \sim 50\mu m$
  - conversion and bremsstrahlung effects:
    need low material budget
    also to maintain ECAL performance

• *Radiation Levels*
  - charged particles from pp interaction
  - neutrons from ECAL
    → radiation hard detectors and electronics
### Tracker Layout

<table>
<thead>
<tr>
<th>Detector</th>
<th># layers</th>
<th>$\eta$ acceptance</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel Pixel</td>
<td>2</td>
<td>&lt; 2.17</td>
<td>80 M</td>
</tr>
<tr>
<td>Fwd Pixel</td>
<td>3</td>
<td>1.69 - 2.9</td>
<td>3.6 M</td>
</tr>
<tr>
<td>Barrel Silicon Strips</td>
<td>4</td>
<td>&lt; 2.23</td>
<td>7.8 M</td>
</tr>
<tr>
<td>Fwd Silicon Strips</td>
<td>11</td>
<td>1.38 - 2.6</td>
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Gomel, 8-17 August '97
Rui Ribeiro - CERN-PPE
The CMS Tracker (V3) LO 1
Full CMS momentum resolution

\( \Delta p_t / p_t \) vs. \( \eta \)

- \( p = 1000 \text{ GeV} \)
- \( p = 100 \text{ GeV} \)
- \( p = 10 \text{ GeV} \)
Impact parameter resolutions of CMS tracker versus $p_T$

In transverse plane

- $\eta = 2.25$
- $\eta = 1.3$
- $\eta = 0$

In z-coordinate

- $\eta = 2.25$
- $\eta = 1.3$
- $\eta = 0$
CONCLUSIONS

- CMS is characterized by the excellent energy resolution provided by the crystal calorimeter and the excellent momentum resolution provided by the 4T field, the pixels and the microstrip detectors of the inner tracking system.

- The performance of the sub-detectors as described in the Technical Design Reports is being demonstrated with close to final prototypes.

- Preproduction of the various sub-detectors has started/will start this year (after approval of TDRs).

- The detector will be ready for data taking in 2005.
# Construction Schedule

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- Black square: Civil Engineering
- Striped square: Design and Prototype
- Hollow square: Construction and Assembly
- Circle with stroke: Installation
- Grey square: Magnet Assembly
- Grey circle: Magnet test

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Version 26 - A.H. / E.R.

CMS-TS-95.0026
Rev. 98 02 04