LHC detectors

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Course on Physics at the LHC
LIP, 14th March 2018
From collision remnants to physics
We hunt for new physics with exciting signatures
Discovery drives the LHC detectors concept

- Before discovery different signatures to be expected depending on the Higgs mass
- $4\pi$-hermetic general purpose detectors are needed covering: leptons, photons, jets, …
Proton-remnants underly the hard processes

- Single proton collisions produce high multiplicity events

![Graph showing proton-remnant behavior](image-url)
Proton-remnants underly the hard processes

- Single proton collisions produce high multiplicity events
- Distributions are approximately uniform in pseudo-rapidity

Average 15-20 charged particles per inelastic collision
Proton-remnants underly the hard processes

- Single proton collisions produce high multiplicity events
- Distributions are approximately uniform in pseudo-rapidity
- Most particles are pions with strong interactions preserve isospin

\[ N(\pi^0) \approx \frac{1}{2} N(\pi^\pm) \]

\[ \pi^+ = |ud\rangle \]
\[ \pi^- = |\bar{u}\bar{d}\rangle \]
\[ \pi^0 = \frac{1}{\sqrt{2}} (|u\bar{u}\rangle - |d\bar{d}\rangle) \]

**strong interactions preserve isospin**
Proton-remnants underly the hard processes

- Single proton collisions produce high multiplicity events
- Distributions are approximately uniform in pseudo-rapidity
- Most particles are pions with \( N(\pi^0) \approx \frac{1}{2} N(\pi^\pm) \)
- As \( \pi^0 \rightarrow \gamma \gamma \) dominates \( N(\gamma) \approx N(\pi^\pm) \) in the detector

![Diagram of proton collision with labels for electromagnetic energy deposits, charged particle tracks, a muon, and minimum bias trigger for physics.](image)
Beyond pions and photons

• Production of other particles suppressed by
  • content of the proton (PDFs)
  • mass ($m_s \sim 19m_d$)
  • interactions

Strange particles account for $O(10\%)$ of the multiplicities
What can we detect?

- Final states
  - secondary vertices from long-lived decays only in rare cases

- Must interact within detector volume
  - electromagnetic or strong interactions
  - electrons, muons, photons
  - neutral or charged hadrons

- Long-lived weakly interacting particles
  - indirectly detected
  - missing transverse energy
  - good resolution when balancing energy

maximum information needed to reconstruct the hard process
Particles and their interactions

- Detectors register the passage of particle through matter
- Combine absorbers (start interactions) with sensitive materials (convert to optical/voltage)
Main concepts behind general purpose detectors

**Magnetic field** "$F = qvB$"
- separate by charge
- measure p by curvature

**Calorimetry**
- measure E from deposits
- electromagnetic and hadronic

**Inner tracking**
- minimal interference with event
- points to measure curved tracks
- particle identification

**Outer tracking**
- muons (weakly interacting)
The two general purpose detectors

- Standalone measurement of $p(\mu)$
- Resolution is flat in $\eta$ and independent of pileup

- Two complementary $p(\mu)$ measurements
- Tracks point to primary vertex
Particles and their interactions
Material distribution in general purpose detectors

B field source

High-Z materials

Dense materials (e.g. Iron, Copper, Brass, Stainless Steel, Uranium)

Lightweight materials (Si, gaseous)

it's a challenge to fit it all within volume

trade-off between best energy resolution and particle identification
>60% of the energy of a jet may be reconstructed at the level of the tracker.
Example: a jet of 5 particles

- Reconstruction starts in the tracker (start from easy tracks, use remaining hits for others)
  - but that does 2/3 particles in this jet

\[ p_T = 35 \text{ GeV} \]
Example: a jet of 5 particles

- Coarse granularity in the hadronic calorimeter
- See local energy maxima, connect neighbours
- Determine energy sharing iteratively
Example: a jet of 5 particles

- The electromagnetic calorimeter sees things in coarser detail ($\Delta \phi, \Delta \eta \sim 0.02$)
- Use to refine entry point in calorimeter, link to tracks and balance energy
- Cluster energy unassociated to tracks: photons and neutral hadrons
Particle flow algorithm is a reconstruction paradigm

Cluster linked to track?

N

Photon (e.m. cluster)

Neutral hadron (had cluster)

Electron (track+e.m. cluster)

Charged pion (track+had cluster)

Muon (track)

Y

E_{\text{track}} \text{ compatible with } E_{\text{calo}}? 

Y

deficit

excess

Split cluster until balanced

it also shapes the re-design of the detectors for Phase II of the LHC
Particle flow algorithm is a reconstruction paradigm.
Connecting the dots with tracking
Why?

- **Identify the vertex** from the hard interaction

  …but also secondary vertices from long lived particles
Why?

• **Identify the vertex** from the hard interaction

  …but also secondary vertices from long lived particles

• **Measure particle trajectories**

  • momentum (p), energy loss (dE/dx), link to coarser calorimeters and muon chambers
With what?

- **Solid state detectors**
  - Ge, Si, Diamond, ...
  - pixels and strips
With what?

• Gaseous detectors

  • drift tubes, resistive plate chambers, cathod strip chambers, gas electron multipliers, ...

  • usually for outer tracking
How?

- While transversing a medium a **charged particle leaves an ionization trace**
  - create a depletion zone in between electrodes: gaseous, liquid or solid-state (semi-conductor)
  - ionization charges drift towards electrodes
  - amplify electric charge signal and deduce position from signals collected in individual strips

---

**ionization chamber** ≈ **Si strip detector**
Gaseous versus solid state

- In solid state detectors, ionization energy converts into e-h pairs.
  - 10 times smaller with respect to gaseous-based ionization.
  - Charge is increased → improved E resolution.

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Solid state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Atomic number (Z)</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Ionization energy (ε)</td>
<td>Moderate</td>
<td>30eV</td>
</tr>
<tr>
<td>Signal speed</td>
<td>Moderate</td>
<td>Fast</td>
</tr>
</tbody>
</table>

\[ n = \frac{E_{loss}}{E_{eh}} \rightarrow \frac{\sigma_{E}}{E} \propto \frac{1}{\sqrt{n}} \propto \sqrt{\frac{E_{eh}}{E_{loss}}} \]
Gaseous versus solid state

- Higher density materials are used in solid state detectors
  - charge collected is proportional to the thickness
  - most probable value for Silicon

\[
\frac{\Delta p}{x} \sim 0.74 \cdot 3.876 \text{ MeV/cm} \rightarrow N_{eh} \sim \frac{23 \cdot 10^3}{300 \ \mu m}
\]

- excellent spatial resolution: short range for secondary electrons
Inner tracking at the LHC

- CMS strips
- CMS pixels
- LHCb VELO
- ATLAS SCT
- ALICE pixels
- ATLAS pixels
- ALICE ITS
- ATLAS pixels (inner barrel layer)
- LHCb SciFi
- 2 x ~2.5 m
Outer ⟷ inner tracking
Coordinates for tracking

- The LHC experiments use a uniform B field along the beam line (z-axis)
  - trajectory of charged particles is an helix – radius R
  - use transverse (xy) and longitudinal (rz) projections
  - pseudo-rapidity: \( \eta = -\ln \tan \frac{\theta}{2} \)  
    transverse momentum: \( p_T = p \sin \theta = p / \cosh \eta \)
  - Impact parameter is defined from distance of closest approach to primary vertex
Resolution for the impact parameter

- Depends on radii+space point precisions
  - For two layers we expect
    \[ \sigma^2_{d0} = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{(r_2 - r_1)^2} \]
    - Improve with small \( r_1 \), large \( r_2 \)
    - Improves with better \( \sigma_i \)
Resolution for the impact parameter

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  - Improve with small \( r_1 \), large \( r_2 \)
  - Improves with better \( \sigma_i \)

- Precision is degraded by multiple scattering
  - Gaussian approximation is valid
  - Width given by
    \[ \theta_0 = \frac{13.6\text{MeV}}{\beta c p} z \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)] \]
    - extra degradation term for \( d_0 \)
    \[ \sigma_{d_0} \sim \theta_0 \]
Resolution for the impact parameter

- For a track with $\theta \neq 90^0$ we can write $r \rightarrow r / \sin \theta$ and $x \rightarrow x / \sin \theta$

- By substitution in the formulas of the previous slide we have:

$$\sigma_{d_0} \sim \sqrt{\frac{r^2 \sigma_1^2 + r^2 \sigma_2^2}{(r_2 - r_1)^2}} \left( \frac{r}{p \sin^{3/2} \theta} \right) \rightarrow a \oplus \frac{b}{p_T \sin^{1/2} \theta}$$

- Typical resolution expected/measured
  - 100 $\mu$m @ 1 GeV   20 $\mu$m @ 20 GeV

- Typical lifetimes (rest frame)
  - $B \sim 500 \mu$m   $D^0 \sim 120 \mu$m   $\tau \sim 87 \mu$m
Momentum measurement

- Circular motion under uniform B-field
  \[ R[m] = 0.3 \frac{B[T]}{p_T[GeV]} \]

- Typically measure the sagitta
  - deviation to straight line relates to R by
  \[ R = \frac{L^2}{2s} + \frac{s}{2} \approx \frac{L^2}{2s} \]

- Uncertainty in pT measurement improves with B, number of hits and path
  \[ \frac{\sigma_{pT}}{p_T} = \frac{8p_T}{0.3BL^2\sigma_s} \]

- Multiple scattering introduces, again extra degradation
  \[ \frac{\sigma_{pT}}{p_T} \sim a p_T \oplus \frac{b}{\sin^{1/2}\theta} \]
Momentum resolution

\[
\frac{\sigma_{p_T}}{p_T} \sim \alpha p_T \frac{b}{\sin^{1/2}\theta}
\]

\[
\sigma(\frac{\Delta p_T}{p_T}) [\%]
\]

\[
p_T [\text{GeV/c}]
\]

\[
\eta
\]

0 < \eta < 0.8
Si-based detectors
Usage of Si-based trackers for HEP

- Kemmer, 1979 transferred Si-technology for electrons to detector - NIM 169(1980)499

- NA11/32 spectrometer at CERN →
  - 6 planes Si-Strip, <2k channels
  - Resolution ~4.5 μm

- SLD vertex detector at SLAC →
  - 120-307 M pixels: 0.4%X0
  - Resolution <4 μm, d₀ ~ 11-9 μm

- ALEPH detector at LEP →
  - Enable precise measurements for B-physics (lifetime, b-tagging)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detectors</th>
<th>Channels ($10^3$)</th>
<th>Si area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aleph (LEP)</td>
<td>144</td>
<td>95</td>
<td>0.49</td>
</tr>
<tr>
<td>CDF II (TEV)</td>
<td>720</td>
<td>405</td>
<td>1.9</td>
</tr>
<tr>
<td>D0 II (TEV)</td>
<td>768</td>
<td>793</td>
<td>4.7</td>
</tr>
<tr>
<td>AMS II</td>
<td>2300</td>
<td>196</td>
<td>6.5</td>
</tr>
<tr>
<td>ATLAS (LHC)</td>
<td>4088</td>
<td>6300</td>
<td>61</td>
</tr>
<tr>
<td>CMS (LHC)</td>
<td>15148</td>
<td>10000</td>
<td>200</td>
</tr>
</tbody>
</table>
Ionization energy loss in the Si

Most probable value of the Landau distribution for energy loss defines the minimum ionizing particle.
Si properties

• Widely used in high energy physics and industry

• Low ionization energy
  • Band gap is 1.12 eV
  • Takes 3.6 eV to ionize atom → remaining yields phonon excitations
  • Long free mean path → good charge collection efficiency
  • High mobility → fast charge collection
  • Low Z → reduced multiple scattering

• Good electrical properties (SiO$_2$)

• Good mechanical properties
  • Easily patterned to small dimensions
  • Can be operated at room temperature
  • Crystalline → resilient against radiation
**Bond model of semi-conductors**

- Covalent bonds formed after sharing electrons in the outermost shell

- Thermal vibrations
  - break bonds and yield electron conduction (free e⁻)
  - remaining open bonds attract free e⁻ → holes change position → hole conduction
Energy bands structure compared

- In solids, the quantized energy levels merge
  - **Metals**: conduction and valence band overlap
  - **Insulators and semi-conductors**: conduction and valence band separated by energy (band) gap
  - If $\mu$ (band gap) sufficiently low: electrons fill conduction band according to Fermi-Dirac statistics
Intrinsic carrier concentration

- Energy state occupation probability follows Fermi statistics distribution
  \[ f(E) = \frac{1}{e^{(E-\mu)/kBT} + 1} \]

- Typical behaviour @ room temperature
  - excited electrons move to conduction band
  - electrons recombine with holes

- Excitation and recombination in thermal equilibrium

- Intrinsic carrier concentration given by
  \[ n_e = n_h = n_i = A \cdot T^{3/2} \cdot e^{-E_g/k_BT} \]

  with \( A = 3.1 \times 10^{16} \text{ K}^{3/2} \text{cm}^{-3} \) and \( E_g/2k_B = 7 \times 10^3 \text{K} \)

  \[ n_i \approx 1.45 \times 10^{10} \text{ cm}^{-3} \]

  \[ \Rightarrow 1/10^{12} \text{ Si atoms is ionized} \]
Intrinsic S/N in Si detectors
Intrinsic S/N in Si detectors

Example: Si detector with thickness $d=300\mu m$
For a 300μm thickness sensor

• Minimum ionizing particle (MIP) creates:

\[
\frac{1}{E_{eh}} \frac{dE}{dx} = \frac{3.87 \cdot 10^6 \text{eV/cm}}{3.63 \text{eV}} \cdot 0.03 \text{cm} = 3.2 \cdot 10^4 \text{eh pairs}
\]

• Intrinsic charge carriers (recall slide 43):

\[
n_i \cdot d = 1.45 \cdot 10^{10} \text{cm}^{-3} \cdot 0.03 \text{cm} = 4.35 \cdot 10^8 \text{eh pairs}
\]

Number of thermally-created e-h pairs exceeds mip signal by factor 10!
Si doping: n-dope bond model

- Doping with a group 5 atom (e.g. P, As, Sb)
  - Atom is an electron donor/donator
  - Weakly bound 5th valence electron
  - Positive ion is left after conduction electron is released
Si doping: n-dope bond model II

- Energy level of donor is below edge of conduction band
  - Most electrons enter conduction band at room temperature
  - Fermi level moves up with respect to pure Si
Si doping: p-dope bond model

- Doping with a group 3 atom (e.g. B, Al, Ga, In)
  - atom is an electron **acceptor**
  - open bond attracts electrons from neighbouring atoms
  - acceptor atom in the lattice becomes negatively charged
Si doping: p-dope bond model - II

- Energy level of acceptor is above edge of conduction band
  - Most levels are occupied by electrons $\rightarrow$ holes in the valence band
  - Fermi level moves down with respect to pure Si

![Energy band diagram](image.png)
p-n junctions

- Difference in Fermi levels at the interface of n-type or p-type
  - diffusion of excess of charge carriers until thermal equilibrium (or equal Fermi level)
  - remaining ions create a **depletion zone**: electric field prevents further the diffusion
p-n junctions

pn junction scheme

acceptor and donor concentration

space charge density

concentration of free charge carriers

electric field

electric potential

∅ ... acceptor  + ... empty hole
⊕ ... donator   − ... conduction electron
Biasing p-n junctions

**Forward-biased junction**
- Anode to p, cathode to n
- Depletion zone becomes narrower
- Smaller potential barrier facilitates diffusion
- Current across the junction tends to increase

**Reverse-biased junction**
- Anode to n, cathode to p
- e, h pulled out of the depletion zone
- Potential barrier is suppressed
- Only leakage current across junction
Depletion zone width and capacitance

• Characterize depletion zone from Poisson equation with charge conservation:

• Typically: \( N_a = 10^{15} \text{ cm}^{-3} \) (p+ region) \( \gg \) \( N_d = 10^{12} \text{ cm}^{-3} \) (n bulk)

• **Width of depletion zone** (n bulk):

\[
W \approx \sqrt{\frac{2\varepsilon V_{\text{bias}}}{q} \cdot \frac{1}{N_d}}
\]

<table>
<thead>
<tr>
<th>Reverse bias voltage (V)</th>
<th>( W_p ) (µm)</th>
<th>( W_n ) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.02</td>
<td>23</td>
</tr>
<tr>
<td>100</td>
<td>0.4</td>
<td>363</td>
</tr>
</tbody>
</table>

• **Device is similar to a parallel-plate capacitor**

\[
C = \frac{q}{V} = \frac{\varepsilon A}{d} = A \sqrt{\frac{\varepsilon q N_d}{2V_{\text{bias}}}}
\]

• Depletion voltage saturates the capacitance

• Typical curve obtained for CMS strip detector
Leakage current

- Thermal excitation generates eh pairs
- Reverse bias applied separates pairs
- eh pairs do not recombine and drift

⇒ leakage current

- Depends on purity, defects and temperature

\[ j_{\text{gen}} \propto T^{3/2} e^{\frac{1}{k_B T}} \]

⇒ usually require detector cooling for stable operation (-30°-10°C)

![Graph showing leakage current vs temperature](image)

Factor 2 every 8 °C
Charge collection

• eh pairs move under the electric field
  • larger biases smaller collection times
  • typically smaller than LHC bunch crossing

Simulation by Thomas Eichhorn (KIT)

Charge collection simulation for a 45° incident particle
• Segmentation of the implants determines precision in position reconstruction

• Typical configuration
  • p implants in strips
  • n-doped substrate ~300μm (2-10kΩcm)
  • depletion voltage <200 V
  • backside P implant establishes ohmic contact
  • Al metallisation

• Field is closest to the collecting electrodes (where most of the signal is)
Position resolution (AC coupled)

- AC coupling blocks leakage current from amplifier
- Deposit SiO$_2$ between p$^+$ and Al strip
  - Capacitance $\sim$32 pF/cm
  - Shorts through pinholes may be reduced with a second layer of Si$_3$N$_4$
- Use large poly silicon resistor ($R>1\,\text{M}\Omega$) connecting the bias voltages to the strips
CMS module

- silicon sensors
  ~20 cm strip length
- carbon fibre support
- pitch adapter
- hybrid front-end electronics with read-out chips
- kapton flat cables for power and data
Pixel sensors

- High track density better resolved with 2D position information
  - back-to-back strips for 2D position information \( \rightarrow \) yields “ghost” hits
- Hybrid pixel detectors with sensors and bump-bonded readout chips

one sensor, 16 front-end chips and 1 master controller chip
Hybrid Pixel Module for CMS

Sensor:
- Pixel Size: 150mm x 100mm
  - Resolution $\sigma_{r-\phi} \sim 15\mu m$
  - Resolution $\sigma_z \sim 20\mu m$
- n+-pixel on n-silicon design
  - Moderated p-spray $\rightarrow$ HV robustness

Readout Chip:
- Thinned to 175$\mu$m
- 250nm CMOS IBM Process
- 8” Wafer

Kapton signal cable
21 traces, 300$\mu$m pitch
Alu-power cable
6 x 250$\mu$m ribbon
High Density Print
3 Layers, 48$\mu$m thick
Silicon Sensor $t=285\mu$m
100$\mu$m x 150$\mu$m pixels
$\mu$-bump bonding
16 x Readout Chips (CMOS) 175$\mu$m thick
SiN base strips
250$\mu$m thick, screw holes

R. Horisberger
• **Signal** depends on the thickness of the depletion zone and on dE/dx of the particle

• **Noise** suffers contributions from:

  \[
  ENC = \sqrt{ENC_0^2 + ENC_i^2 + ENC_{R||}^2 + ENC_{R_{series}}^2}
  \]

  - capacitance
  - leakage current
  - parallel resistor
  - series resistor

• **Optimizing S/N**

  - \( N_{ADC} > \text{thr} \), given high granularity most channels are empty
  - decrease noise terms (see above)
  - minimize diffusion of charge cloud after thermal mot
  - (typically \( \sim 8 \mu m \) for \( 300 \mu m \) drift)
  - radiation damage severely affects S/N (next slide)
Influence of radiation

• Si is not fully robust against radiation
  • induced defects result in noise, inefficiency, leakage,…
  • need to increase depletion voltage at higher fluences
  • expected hit finding efficiency after 10 years of LHC operation: 95%
CMS tracker

- **Pixel detector**: \( \sim 1 \text{m}^2 \) area
  - 1.4k modules \( \Rightarrow \) 66M pixels
- **Strips**: \( \sim 200\text{m}^2 \) area
  - 24k single sensors, 15k modules
  - 9.6M strips = electronics channels
  - 75k readout chips
• In some regions can attain $1.8X_0$
  
  • often photons will convert, electrons will radiate :(
  
  • use for alignment and material budget estimation :) 

• Precise knowledge is crucial, e.g. for Higgs with $\gamma$ and electrons in the final state
• Use photon conversions ($\gamma \rightarrow e^+e^-$)
  • probability of interaction depends on the transversed material ($1-e^{-x/X_0}$)
  • 54% of the $H \rightarrow \gamma\gamma$ events have are expected to have at least one conversion
Electrons

They brem

Brem photons convert

Conversion tracks collect secondary electron clusters

Track momentum change followed by Gaussian Sum Filter

Brem clusters collected by « track tangents »
...to be continued
Summary

• Hunting for new physics: wide variety of final states vs underlying event/pileup
  • general purpose detectors attempt to cover all possible signatures while rejecting background
  • choice of technology: trade-off between particle identification, resolution and budget

• Particle flow as a paradigm
  • use the best out of the detectors for optimal performance
  • yields a close 1:1 physics reconstruction of the hard process final state

• Magnetic field and tracking play a crucial role and set the base
  • B field is at the heart of the experiment
  • tracking detectors are at the base of the reconstruction

*tomorrow: calorimetry, performance, and trigger*
Backup
The magnet is the heart of an experiment

- Goal: measure 1 TeV muons with $\delta p_T/p_T=10\%$ without charge error
  - $\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3Bl^2}\sigma_s$ this implies $\sim50\mu$m uncertainty in measuring $s$
  - either use “continuous tracking” or “extreme field”

- From Ampere’s theorem: $\int \vec{B} \cdot d\vec{s} = \mu_0I \Rightarrow B = \mu_0nI$.
  - $n = 2168$ (120) turns per coil in CMS (ATLAS)

- special design needed for superconducting cable in CMS
- size limited by magnetic pressure ($P\approx6.4$ MPa)
The magnet is the heart of an experiment II

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>0.6T</td>
<td>4T</td>
</tr>
<tr>
<td>(8 coils, 2x2x30 turns)</td>
<td>(1 coil, 2168 turns/m)</td>
<td></td>
</tr>
</tbody>
</table>

**Challenges**
- spatial/alignment precision over large surface
- 1.5GJ energy stored
- limited pointing capabilities
- non-trivial B
- additional solenoid (2T) needed for tracking
- space needed

**Drawbacks**
- design and winding of the cable
- 2.7GJ energy stored
- limits space available for calorimetry
- no photomultipliers for calorimeters
- multiple scattering in iron core
- poor bending at large angles
Radiation levels: a challenge for detectors and electronics

- Activation of materials, impurities, loss of transparency/response, spurious hits …

- Additional shielding/moderators needed to limit radiation impact in the detectors

Reminder: $1 \text{ Gy} = 1 \text{ J/kg} = 100 \text{ rad}$
Position resolution

- Affected by different factors
  - transverse drift of electrons to track
  - strip pitch to diffusion width relationship
  - statistical fluctuations on energy deposition

\[ \sigma_x \propto \frac{\Delta p}{S/N} \]

A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992