Particle interaction and detectors

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discovery of Neutral Currents by Gargamelle (1973)
Contents

• Particle, interactions, and detectors
• Calorimetry and energy
today

• Trackers and momentum
• Trigger and data acquisition
Particles can be “seen” as the result of an interaction with matter (detector)

In the end, everything is converted to:

- optical pictures
- voltage/current signals

\[ -\left(\frac{dE}{dx}\right)_{\text{tot}} = -\left(\frac{dE}{dx}\right)_{\text{coll}} - \left(\frac{dE}{dx}\right)_{\text{rad}} - \left(\frac{dE}{dx}\right)_{\text{pair}} - \left(\frac{dE}{dx}\right)_{\text{photonucl}} - \left(\frac{dE}{dx}\right)_{\text{photoeff}} - \left(\frac{dE}{dx}\right)_{\text{compton}} - \left(\frac{dE}{dx}\right)_{\text{hadron}} \]
What can we detect?

• Directly observable particles must:
  – Undergo strong or EM interactions
  – Be sufficiently long-lived to pass the detectors

• We can **directly** observe:
  – Electrons, muons, photons
  – Neutral or charged hadrons
  – Pions, protons, kaons, neutrons,…
  – analyses treat jets from quark hadronization collectively as single objects
  – Use displaced secondary vertices to identify jets originating from b-quarks

• We can **indirectly** observe long lived weakly interacting particles (e.g. neutrinos) through **missing transverse energy**
• Short-lived particles decay to long-lived ones

• We can only ‘see’ the end products of the reaction, but not the reaction itself

• In order to reconstruct the production/decay mechanism and the properties of the involved particles, we want the maximum information
Which properties do we want to measure?

- Energy (calorimeter)
- Momentum (tracking)
- Charge (tracking)
  - Direction, bending in magnetic field
- Life-time (tracking)
- Mass:

\[
E^2 = m^2 \cdot c^4 + \vec{p}^2 c^2 \Rightarrow m = \frac{\sqrt{E^2 - \vec{p}^2 c^2}}{c^2}
\]

\[
F = q \cdot \vec{v} \cdot \vec{B} = m \cdot \frac{v^2}{R}
\Rightarrow q \cdot \vec{B} \cdot R = m \cdot v = |\vec{p}|
\]
Passage of particles

- “Onion”-like structure
- Each layer measures $E$ and/or $p$ of particles
- Redundancy of measurements

Energy measurement
total absorption of showers

- Momentum measurement (curvature in magnetic field)
- Muon detection measure momentum

Missing ET undetected neutrinos...
Fixed target vs Collider

\[ \sqrt{s} = E_{cm} = \left[ m_1^2 + m_2^2 + 2E_1 m_2 \right]^{\frac{1}{2}} \]

\[ E_{cm} = 2E \]
Detector layers

- **Inner tracking**
  - Measure charged particle (momentum)

- **Magnetic field:**
  - Measure momentum

- **Calorimeters**
  - Measure energy of all particles

- **Outer tracking**
  - Measure muons
Top quarks: example
From Picture to Reconstruction
It gets more complicated
Particle detection

- In order to detect a particle
  - It must interact with the material of the detector
  - Transfer energy

- i.e. detection of particles happens through energy loss in the material it traverses

- Particle interaction:
  - Charged particles: Ionization, Bremsstrahlung, Cherenkov
  - Hadrons: Nuclear interactions
  - Photons: Photo/Compton effect, pair production
  - Neutrinos: Weak interactions

*Energy loss by multiple reactions*
Particle interaction

Ionization:

Pair production:

Compton scattering:
Calorimetry

• Incident particle creates a shower inside the material of detector
  – Shower can be either electromagnetic or hadronic

• Energy is deposited in material through ionization/excitation

• Measure energy deposited in material
  – Electrons, photons and hadrons (including neutral hadrons)

• Deposited energy is proportional to incident energy
• Calorimeters are used to measure energy of neutral and charged particles
  – cannot measure momentum of neutral particles
  – electrons can be measured with better precision, and identified with a calorimeter
• As energy increases:
  – momentum measurement is less precise: $\sigma_p \sim p$
  – energy measurements become more precise: $\sigma_E/E \sim 1/\sqrt{E}$
Purpose/principle of a calorimeter

• Measurement of energy via *total* absorption (destructive measurement)

• Detector response $\sim E$ for:
  – Charged particles (electrons/positrons and hadrons)
  – Neutral particles (neutrons, $\gamma$)

• Principle of measurement:
  – Electromagnetic shower
  – Hadronic shower

• Conversion due to ionization or excitation of the detector material $\Rightarrow$ current, voltage
Calorimeters are subdivided into electromagnetic and hadronic sub-detectors

- EM: electrons and photons
- Had: hadrons

Electromagnetic interactions develop over shorter distances than hadronic interactions

Fundamental processes of signal generation differ, calling on different optimization
How to measure the energy?

The energy is proportional to light & penetration depth of the shower

The eye is not able to quantify this; have to measure the amount of light and penetration path electronically
Evolution of calorimeters

• Nuclear Physics
  – Advances of solid state detector in the ’50s push technique of total absorption and energy measurement of nuclear radiation

• Cosmic Rays (1958)
  – Construction of first sampling calorimeter

• Particle Physics
  – First electromagnetic calorimeters, eventually hadronic calorimeters become essential components

• Uranium/compensation
  – In an effort to advance energy resolution, introduce uranium calorimeters (~1975) to “compensate” for lost energy in nuclear collisions

• High precision (EM) calorimetry
  – Crystals continued to advance
  – Other techniques (liquid Argon, scintillating fibers, etc.)
Today, widespread in particle physics

- $4\pi$ coverage at colliders
  - Energy measurements
  - Particle identification
  - Triggers
- Neutrinos detectors at accelerators
- Underground detectors
- Space-based detectors (GLAST, AMS)
- ...
Discovery of the W

- Calorimeters are important in the discoveries
- High transverse energy electron measured, and recoiling neutrino deduced (to balance the electron)

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Discovery of the Higgs

- di-photon invariant mass
Ideal calorimeter

- Excellent energy/position resolution
- Stable calibration
- Large dynamic range
- Excellent shower containment with multi-shower separation
- Compact
- Fast (high-rate capability)
- Operating in magnetic field
- Inexpensive
- Robust (radiation, etc)
Calorimeter detectors

- Favor shower development
- Collect deposited energy
- Alternate passive and active material
  - Lead (iron) interspersed with scintillator
- Sampling (vs. homogeneous)
  - Scintillator (sensitive material) emits light with passage of ionizing particle
  - Collect light deposited in sensitive material
  - WLS, PMTs convert light into electric signal
- “Projective” tower geometry
  - Each tower has EM followed by Had calorimeter
- (almost) “full” coverage
  - central, forward, etc
EM and HADronic showers

• Electromagnetic
  – Multiplication through pair production and bremsstrahlung
  – Mean free path $X_0$ (radiation length)
  – No invisible energy

• Hadronic
  – Multiplication through multi-particle production in nuclear interactions
  – Mean free path $\sim \lambda$ (interaction length)
  – Nuclear binding energy, and neutrinos invisible
EM showers

- Created by incident electron or photon
  - Electrons emit bremsstrahlung
  - Photons undergo pair production
- Length of shower expressed in terms of $X_0$ (radiation length)
  - $X_0$ depends on material
  - 95% containment requires typically 20 $X_0$
Hadronic shower

• Created by incident charged pion, kaon, proton, etc.

• Typical composition
  – 50% EM (e.g. $\pi^0 \rightarrow \gamma\gamma$)
  – 25% visible non EM-energy
  – 25% invisible energy (nuclear breakups)

• Requires longer containment (expressed in $\lambda$, interaction length)
Electromagnetic showers

• In matter, high energy **electrons and photons** interact **primarily** through EM interactions with the nucleus (and at lower energies with the atomic electrons)

• **Electrons**
  – Bremsstrahlung (nuclear)

• **Photons**
  – Compton scattering (atomic electrons)
  – Pair production (nuclear)
  – Photoelectric effect (atomic electrons)
EM showers: electrons

- Electron energy loss
- At high energy, the energy loss of an electron from bremsstrahlung dominates over ionization loss
- At low energy, ionization loss becomes important
- The energy at which ionization loss equals bremsstrahlung loss is the critical energy $E_C$
  - $E_C \approx 7$ MeV for lead

$E_C \approx \frac{1}{m^2}$
EM showers: photons

- Compton scattering
- Pair production
- Photoelectric effect

Dominant:
EM shower: model

- EM shower can be understood by a simple model
  - after one radiation length $X_0$ a photon produces an $e^+e^-$ pair
  - the electron and positron each emit one bremsstrahlung photon after another radiation length

- It leads to a cascading number of particles: $N(t)=2^t$ (for $t$ steps)

- each particle has an energy: $E(t)= E_0/2^t$
Electromagnetic shower: size

• Longitudinal development depends on material thickness:
  \[ X_0 = 180 \frac{A}{Z^2} \text{ g/cm}^2 \] (higher Z materials have shorter radiation lengths)

\[ Z \text{ is the atomic number} \]

• Transverse dimension scales with the Moliere radius:
  \[ R_M = 21 \text{ MeV} \frac{X_0}{E_C} \] where \( E_C = 580 \text{ MeV/Z} \)
EM calorimeters

• Homogeneous Calorimeter
  – shower is "observed" throughout the detector
  – electrons and photons stop in calorimeter
  – scintillation proportional to energy of electron
  – advantage: excellent energy resolution
  – limited spatial resolution

• Sampling Calorimeter
  – shower is sampled by an "active" readout medium alternated with denser radiator material
  – one material to induce showering (high Z)
  – another to detect particles (by counting number of charged tracks)
  – many layers sandwiched together
  – advantages: segmentation gives detailed shower shape information; good spatial resolution
EM showers: Fluctuations

- Energy measurement is limited in precision by fluctuations in the EM shower and in the measurement process.
- The shape of an EM shower fluctuates only modestly, and resolution of an EM calorimeter is usually limited by other effects (assuming full containment has been achieved).
- Dominant fluctuation in the shower is the depth of the first pair conversion.
EM showers: Energy resolution

\[
\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]

- **1\text{st}: Stochastic (or “sampling”) term**
  - Accounts for statistical fluctuations of the number of primaries
- **2\text{nd}: Noise term:**
  - Electronic noise, pedestal fluctuations, etc.
  - Pileup (other energy entering the measurement region)
- **3\text{rd}: Constant term**
  - Non-uniformities, calibration uncertainties
  - Incomplete shower containment (leakage), other fluctuations proportional to energy

Constant term dominated by longitudinal non-uniformity of light collection
EM calorimeter types

• “Lead-scintillator” calorimeter

\[ \Delta E/E \sim 20\%/\sqrt{E} \]

• Exotic crystals (BGO, PbW, ..)

\[ \Delta E/E \sim 1\%/\sqrt{E} \]

• Liquid argon calorimeter
  – Slow collection time (~1µsec)

\[ \Delta E/E \sim 18\%/\sqrt{E} \]
Crystal calorimeter example

- CMS EM Calorimeter:
  - 83,000 crystals (PbWO$_4$, lead tungstate)
  - Very dense, fast, radiation hard
  - Scintillation light yield not significantly damaged by radiation
  - 1% resolution at 30 GeV
Energy resolution

Relative and absolute energy calibration:

• Several steps before, during, after data-taking
  – test beam pre-calibration
  – monitoring during data-taking
  – inter-calibration by physics with specialized data streams
Hadron Calorimetry

- Hadron Calorimeters, as EM calorimeters, measure the energy of the incident particle(s) by fully absorbing the energy of the particle(s) and providing a measurement of the absorbed energy.

- Hadronic Showers are more complicated than EM showers, significantly reducing the optimal precision.
Had and EM showers

- Had shower: the **longitudinal development is characterized by the nuclear interaction length**
**Hadronic showers**

- **Hadronic cascades** develop analogously to EM showers
  - Strong interaction controls overall development
- As a strongly interacting particle (hadron) passes through matter, it initiates a nuclear interaction, and starts a nuclear shower
- **Energy deposited by:**
  - Electromagnetic component (i.e. as for EM showers)
  - Charged pions or protons
  - Low energy neutrons
  - Energy lost in breaking nuclei (nuclear binding energy \(\sim 8\) MeV/nucleon)
Hadronic showers

- Hadronic showers are:
  - broader and more penetrating
  - subject to larger fluctuations

- Electrons, photons
  \[ \pi^0 \rightarrow 2\gamma \]
  \(~50\%~

- Charged hadrons (20%)
- Nuclear fragments, p (25%)
- Neutrons, soft \(\gamma\)'s (15%)
- Breakup of nuclei (40%)
  \(~50\%~

Either not detected or often too slow to be within detector time window
\(e/h > 1\)

= Invisible energy

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Hadronic showers: fluctuations

Sources of fluctuations:
• EM vs. non-EM components
• nuclear binding energy losses
• sampling
• leakage of ionizing particles
• leakage of non-ionizing particles
• detector response: saturation or non-linear
• noise
• non-uniformities of the detector
• time dependence of various components
Hadronic showers

- Individual hadronic showers are quite dissimilar

red – EM component
blue – charged hadrons
Hadronic showers: compensation

• A dominant factor in the resolution of a hadron calorimeter is the unequal response to EM energy deposition and hadronic energy deposition
• Recover part of the “invisible energy”
• one can reduce this fluctuation by equalizing the EM and hadronic response: $e/h=1$
  – Amplify the nuclear signal (amplify the nuclear energy itself or favor the nuclear signal in sampling)
  – Attenuate the EM signal
  – Measure the hadronic/EM ratio in each event and correct
• Offline compensation:
  – Weighting methods
  – Multiple shower measurements (2+ active media, select EM, etc.)
EM calorimeters: summary

- EM showers are well understood theoretically
- Electromagnetic calorimeters are continuing to advance
- Optimization is trade-off between competing constraints
- EM calorimeters have good energy resolution (typically 2-10%/E^{1/2})
- EM showers develop through brems and pair production
- Characteristic length is radiation length X_0
Hadronic showers are more complex than EM showers
Hadronic calorimeters have worse energy resolution than EM cal. (typically 40%/E^{1/2} to 100%/E^{1/2})

- Hadrons also lose energy through a showering process
- However, instead of brems, the fundamental process is nuclear interaction
- Characteristic length is called the hadronic interaction length $\lambda$ ($\lambda \approx 35 \text{ gm/cm}^2 \text{ A}^{1/3}$)
Calorimeters

- CMS EM hom. calorimeter
- CMS PbWO₄ crystal
- ATLAS sampling calorimeter
- Light guides and PMT

Sampling calorimeter: scintillator alternated with detector material

CMS Hadronic Calorimeter

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The CDF Calorimeters

All scintillator-based sampling calorimeters

| $|\eta|$ Range       | $\Delta \phi$ | $\Delta \eta$ |
|------------------|--------------|--------------|
| 0. - 1.1 (1.2 h) | 15°          | ~ 0.1        |
| 1.1 (1.2 h) - 1.8| 7.5°         | ~ 0.1        |
| 1.8 - 2.1        | 7.5°         | ~ 0.16       |
| 2.1 - 3.64       | 15°          | 0.2 - 0.6    |

Table 1.2: CDF II Calorimeter Segmentation
CDF calorimeters at the Tevatron

- EM calorimeter in front; Hadron in the back
- Lead for EM; steel for hadron in sandwich
- Scintillator to detector shower
### CDF EM Calorimeter

**Central Electromagnetic Calorimeter (CEM)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>$18X_0$, 1l</td>
</tr>
<tr>
<td>Abs. (pb) layer</td>
<td>$1/8''$ (4.2 mm, 0.6 $X_0$)</td>
</tr>
<tr>
<td>Scint. layer</td>
<td>5 mm, polystyrene (SCSN-38)</td>
</tr>
<tr>
<td>w.l.s.</td>
<td>3 mm Y7 acrylic sheet</td>
</tr>
<tr>
<td>PMT</td>
<td>Ham. R580 (1.5'')</td>
</tr>
<tr>
<td>light yield</td>
<td>$&gt;100$ p.e./GeV/pmt</td>
</tr>
<tr>
<td>resolution</td>
<td>$13.5 / \sqrt{E_T}$</td>
</tr>
</tbody>
</table>

**Shower Max Detector (Gas Strip Chamber)**

At EM Shower Max

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**Fig. 1.** Prototype strip chamber cross section.
HCAL: ATLAS tile calorimeter

Fe/Scint with WLS fiber Readout via PMT
CMS calorimeters

Ring 0  Ring 1  Ring 2

Iron

MAGNET CRYOSTAT and COIL

5.8λ  

HCAL-HB

1.1λ  

ECAL-EB

Tracker

4T

PS

ECAL EE

HCAL HE
CMS ECAL calorimeter

**ECAL pre-shower (ES):**
- $1.65 < |\eta| < 2.60$
- Pb/Si (~3$X_0$)

**Barrel super-module (SM):**
- 1700 crystals

**ECAL endcap (EE):**
- $1.48 < |\eta| < 3.00$
- 14648 PbWO$_4$ crystals
- $3 \times 3 \times 22 \text{ cm}^3$ (~25$X_0$)

**ECAL barrel (EB):**
- $|\eta| < 1.48$
- 61200 PbWO$_4$ crystals
- $2.2 \times 2.2 \times 23 \text{ cm}^3$ (~26$X_0$)

**PbWO$_4$:**
- High density (8.3 g/cm$^3$)
- Small Molière radius (2.2 cm)
- Short rad. length (0.89 cm)
- Fast (80% of scintillation in 25 ns)
- Radiation hard

**ECAL barrel:** homogeneous, compact, hermetic, fine grain PbWO$_4$ crystal calorimeter
- Emphasis on e/γ energy resolution
- No longitudinal segmentation
HCAL: CMS sampling calorimeter

CMS HCAL barrel

2593 towers
$\Delta \eta \times \Delta \phi = 0.017 \times 0.017$

pixel HybridPhotoDiode
Jets

- A “jet” is a narrow cone of hadrons and other particles produced by the **hadronization** of a quark or gluon.
- Processes creating jets are complicated – parton fragmentation, with EM or Had showering.
- Jet reconstruction is difficult.
- Jet energy scale and reconstruction is a large source of uncertainty.

- Measure energy in a “cone”
Jets: calibration

Before experiment starts

• Test beam
  – take one calorimeter “wedge”, send beam of particles with known energy
  – obtain correspondence “detector response → energy” in GeV

When the experiment is built/running

• Hardware calibration
  – Use radioactive sources with well defined decay energy (between runs)
  – Sources can move and “illuminate” all towers
  – Check uniformity
  – Laser calibration (connected to individual PMTs)
  – Measure uniform response over time
  – Cosmic rays (muons)
When the experiment is running

- **Relative and absolute** en. calibration
- **Collider data**
  - Measure of known physics process (i.e. Z+jets, γ-jet, jet-jet balancing)
  - Energy measured in tracker (redundancy)
- **Measure jets at high energy colliders**
When the experiment is running

- *Relative* and *absolute* en. calibration
- Collider data
  - Measure of known physics process (i.e. Z+jets, $\gamma$-jet, jet-jet balancing)
  - Energy measured in tracker (redundancy)
- Measure jets at high energy colliders

**EM shower energy calibration**
Invariant mass of neutral mesons

Remarkable performance at few hundreds of MeV

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ECAL: homogeneous

HCAL: sampling
Magnetic coil

ATLAS: toroid coils

CMS magnet

CMS Solenoïde
Assembly of iron yoke
Experimental cavern

2003

2004
Lowering of the detectors
Lowering: Endcap disks

YE+3
30.11.2006

YE+2
12.12.2006

YE+1
9.1.2007
The barrel was lowered to the collision hall in Feb. 2007
Cables, pipes, optical fibers

November 2007
CMS tracker

next lecture, only this picture today