Particle Detectors

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History of Instrumentation ↔ History of Particle Physics

The ‘Real’ World of Particles

Interaction of Particles with Matter

Tracking Detectors, Calorimeters, Particle Identification

Detector Systems
Detectors based on Ionization

Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers
- Transport of Electrons and Ions in Gases

Solid State Detectors

- Transport of Electrons and Holes in Solids
- Si- Detectors
- Diamond Detectors
Gas Detectors

In gaseous detectors, a charged particle is liberating electrons from the atoms, which are freely bouncing between the gas atoms.

An applied electric field makes the electrons and ions move, which induces signals on the metal readout electrodes.

For individual gas atoms, the electron energy levels are discrete.

Solid State Detectors

In solids (crystals), the electron energy levels are in ‘bands’.

Inner shell electrons, in the lower energy bands, are closely bound to the individual atoms and always stay with ‘their’ atoms.

In a crystal there are however energy bands that are still bound states of the crystal, but they belong to the entire crystal. Electrons in these bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.
Conductor, Insulator, Semiconductor

In case the conduction band is filled the crystal is a conductor.

In case the conduction band is empty and ‘far away’ from the valence band, the crystal is an insulator.

In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.
Band Gap, e-h pair Energy
The energy gap between the last filled band – the valence band – and the conduction band is called band gap $E_g$.

The band gap of Diamond/Silicon/Germanium is 5.5, 1.12, 0.66 eV.

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.

Temperature, Charged Particle Detection
In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is left behind.

Such a process can be the passage of a charged particle, but also thermal excitation $\rightarrow$ probability is proportional $\text{Exp}(-E_g/kT)$.

The number of electrons in the conduction band is therefore increasing with temperature i.e. the conductivity of a semiconductor increases with temperature.
Electron, Hole Movement:
It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with an effective mass different from elementary electrons not embedded in the lattice.

This mass is furthermore dependent on other parameters such as the direction of movement with respect to the crystal axis. All this follows from the QM treatment of the crystal (solid state physics).

Cooling:
If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of a charged particle.

Diamond \( (E_g=5.5\text{eV}) \) can be used for particle detection at room temperature, Silicon \( (E_g=1.12\text{ eV}) \) and Germanium \( (E_g=0.66\text{eV}) \) must be cooled, or the free charge carriers must be eliminated by other tricks → doping → see later.
Primary ‘ionization’:
The average energy to produce an electron/hole pair is: Diamond (13eV), Silicon (3.6eV), Germanium (2.9eV)

Comparing to gas detectors, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce and electron/hole pair e.g. for Si is a factor 7 smaller than the energy to produce an electron-ion pair in Argon.

Solid State vs. Gas Detector:
The number of primary charges in a Si detector is therefore about $10^4$ times larger than the one in gas → while gas detectors need internal charge amplification, solid state detectors don’t need internal amplification.

While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar → very short signals.
Diamond Detector

Typical thickness – a few 100μm.
<1000 charge carriers/cm³ at room temperature due to large band gap.

Velocity:
μₑ=1800 cm²/Vs,  μₕ=1600 cm²/Vs
Velocity = μE, 10kV/cm → v=180 μm/ns → Very fast signals of only a few ns length!

A single e/h par produced in the center

T=2-3ns
However, charges are trapped along the track, only about 50% of produced primary charge is induced →
Velocity:
\( \mu_e = 1450 \text{ cm}^2/\text{Vs} \), \( \mu_h = 505 \text{ cm}^2/\text{Vs} \), 3.63eV per e-h pair.

\( \approx 33000 \) e/h pairs in 300\( \mu \text{m} \) of silicon.

However: Free charge carriers in Si:

\( T=300 \text{ K} \): \( e,h = 1.45 \times 10^{10} / \text{ cm}^3 \) but only 33000 e/h pairs in 300\( \mu \text{m} \) produced by a high energy particle.

Why can we use Si as a solid state detector ???
Doping of Silicon

In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes and n-type conductor (more electrons than holes).

Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

Bringing p and n in contact makes a diode.
Si-Diode used as a Particle Detector!

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.
Under-Depleted Silicon Detector

Zone without free charge carriers positively charged. Sensitive Detector Volume.

Zone with free electrons. Conductive. Insensitive to particles.

Electric Field
Fully-Depleted Silicon Detector

Zone without free charge carriers positively charged. Sensitive Detector Volume.
In contrast to the (un-doped) diamond detector where the bulk is neutral and the electric field is therefore constant, the sensitive volume of a doped silicon detector is charged (space charge region) and the field is therefore changing along the detector.

→ Velocity of electrons and holes is not constant along the detector.
Silicon Detector

N (e-h) = 11 000/100μm
Position Resolution down to ~ 5μm!
Silicon Detector

Every electrode is connected to an amplifier → Highly integrated readout electronics.

Two dimensional readout is possible.

CMS Outer Barrel Module
Large Silicon Systems

CMS tracker (~2007)
- 12000 modules
- ~ 445 m² silicon area
- ~ 24,328 silicon wafers
- ~ 60 M readout channels

CDF SVX IIa (2001-)
- ~ 11m² silicon area
- ~ 750 000 readout channels
CMS Tracker
Problem:
2-dimensional readout of strip detectors results in ‘Ghost Tracks’ at high particle multiplicities i.e. many particles at the same time.

Solution:
Si detectors with 2 dimensional ‘chessboard’ readout. Typical size 50 x 200 μm.

Problem:
Coupling of readout electronics to the detector

Solution:
Bump bonding for correcting a sensor to the readout electronics chip

Monolithic silicon sensors that incorporate the sensor and the electronics inside one substrate
**Pixel-Detectors**

- **ATLAS:** $10^8$ pixels
- **ALICE:** $10^{10}$ pixels

Bump bonding of pixels to readout electronics.

‘Hybrid Pixel Detectors’

Sensitive element and electronics on the same silicon wafer produced with ‘standard’ electronics fabrication process. ‘Monolithic Pixel Detectors’
Radiation Effects ‘Aging’

Increase in leakage current

Increase in depletion voltage

Decrease in charge collection efficiency due to under-depletion and charge trapping.
Summary on Solid State Detectors

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5um) for vertex measurement but also for momentum spectroscopy over large areas (CMS, ATLAS+CMS Phase-II).

Technology is improving rapidly due to rapid Silicon development for electronics industry.

Typical numbers where detectors start to strongly degrade are $10^{15}-10^{16}$ hadron/cm$^2$.

‘Clearly, monolithic solid state detectors are an ultimate goal.'
Calorimetry
Bremsstrahlung + Pair Production $\rightarrow$ EM Shower
Electro-Magnetic Shower of High Energy Electrons and Photons

\[ N(n) = 2^n \] .... Number of particles \((e^\pm, \gamma)\) after \(n X_0\)

\[ E(n) = \frac{E_0}{2^n} \] .... Average energy of particles after \(n X_0\)

- Shower stops if \(E(n) = E_{\text{critical}}\)

\[ n_{\text{max}} = \frac{1}{3n^2} \ln \frac{E_0}{E_0} \rightarrow \text{Shower length rises with } \ln E_0 \]

Number of \(e^\pm\) track segments (of length \(X_0\)) after \(n X_0\):

\[ N_{\text{tr}}(n) = 2^n \]

Total \(e^\pm\) track length (as \(n_{\text{max}} X_0\))

\[ L = \sum_{n=0}^{n_{\text{max}}} 2^n X_0 = (2 \frac{E_0}{E_c} - 1) X_0 \approx 2 \frac{E_0}{E_c} X_0 = c_4 \cdot E_0 \]

Total (charge) track length is proportional to the energy of the particle.

\[ \rightarrow \text{Calorimeter Principle} \]
Calorimetry: Energy Measurement by total Absorption of Particles

Only Electrons and High Energy Photons show EM cascades at current GeV-TeV level Energies.

Strongly interacting particles like Pions, Kaons, produce hadronic showers in a similar fashion to the EM cascade → Hadronic calorimetry

Momentum Spectrometer: $\Delta p/p \propto p$

Calorimeter: $\Delta E/E \propto 1/\sqrt{E}$

Energy measurement improves with higher particle energies – LHC!
Liquid Nobel Gases
(Nobel Liquids)

Scintillating Crystals,
Plastic Scintillators

Calorimetry: Energy Measurement by total Absorption of Particles
Calorimetry

Calorimeters can be classified into:

**Electromagnetic Calorimeters,**
to measure electrons and photons through their EM interactions.

**Hadron Calorimeters,**
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

**Homogeneous Calorimeters,**
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

**Sampling Calorimeters,**
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, No. 4, October 2003
Calorimeters are attractive in our field for various reasons:

In contrast with magnet spectrometers, in which the momentum resolution deteriorates linearly with the particle momentum, on most cases the calorimeter energy resolution improves as $1/\sqrt{E}$, where $E$ is the energy of the incident particle. Therefore calorimeters are very well suited for high-energy physics experiments.

In contrast to magnet spectrometers, calorimeters are sensitive to all types of particles, charged and neutral. They can even provide indirect detection of neutrinos and their energy through a measurement of the event missing energy.

Calorimeters are commonly used for trigger purposes since they can provide fast signals that are easy to process and interpret.

They are space and therefore cost effective. Because the shower length increases only logarithmically with energy, the detector thickness needs to increase only logarithmically with the energy of the particles. In contrast for a fixed momentum resolution, the bending power $BL^2$ of a magnetic spectrometer must increase linearly with the particle momentum.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, No. 4, October 2003
EM Calorimetry

Approximate longitudinal shower development

\[ N(n) = 2^n \quad \text{... Number of particles (e^+,\gamma) after } nX_0 \]
\[ E(n) = \frac{E_0}{2^n} \quad \text{... Average energy of particles after } nX_0 \]

Shower stops if \( E(n) = E_\text{limit} \)

\[ n_{\text{max}} = \frac{1}{\ln 2} \ln \left( \frac{E_0}{E_n} \right) \rightarrow \text{Shower length rises with } \ln E_0 \]

Radiation Length \( X_0 \) and Moliere Radius are two key parameters for choice of calorimeter materials

Approximate transverse shower development

The transverse shower dimension is mainly related to the multiple scattering of low energy electrons.

\[ \Theta_0 = \frac{2.4 \text{ [MeV]}}{13 \text{ [MeV]}} \sqrt{1 - \frac{1}{X_0}} \]

Electrons \( E_c \), \( E \leftrightarrow p_c \)

\[ \Theta_0 \approx \frac{2.4 \text{ [MeV]}}{13 E_c \text{ [MeV]}} \cdot \sqrt{\frac{1}{X_0}} \quad Z = 1/13 - 1 \]

\( E_c \approx \frac{640}{Z + 274} \text{ MeV} \approx \frac{640}{Z} \text{ MeV} \)

\[ \Theta_0 = 0.0344 \cdot Z \cdot \sqrt{\frac{1}{X_0}} \]

Moliere Radius \( g_m \) = Lateral Shower Radii after \( 1X_0 \):

\[ g_m \approx 0.0344 \cdot Z \cdot X_0 \]

35% of energy are in a cylinder of \( 2g_m \) Radius.
Crystals for Homogeneous EM Calorimetry

In crystals the light emission is related to the crystal structure of the material. Incident charged particles create electron-hole pairs and photons are emitted when electrons return to the valence band.

The incident electron or photon is completely absorbed and the produced amount of light, which is reflected through the transparent crystal, is measured by photomultipliers or solid state photon detectors.
## Crystals for Homogeneous EM Calorimetry

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BGO</th>
<th>PbWO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.67</td>
<td>4.53</td>
<td>4.53</td>
<td>7.13</td>
<td>8.28</td>
</tr>
<tr>
<td>$X_0$ (cm)</td>
<td>2.59</td>
<td>1.85</td>
<td>1.85</td>
<td>1.12</td>
<td>0.89</td>
</tr>
<tr>
<td>$R_M$ (cm)</td>
<td>4.5</td>
<td>3.8</td>
<td>3.8</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>250</td>
<td>1000</td>
<td>10</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>slow component</td>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td>15</td>
</tr>
<tr>
<td>Emission peak (nm)</td>
<td>410</td>
<td>565</td>
<td>305</td>
<td>410</td>
<td>440</td>
</tr>
<tr>
<td>slow component</td>
<td></td>
<td></td>
<td></td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Light yield γ/MeV</td>
<td>$4 \times 10^4$</td>
<td>$5 \times 10^4$</td>
<td>$4 \times 10^4$</td>
<td>$8 \times 10^3$</td>
<td>$1.5 \times 10^2$</td>
</tr>
<tr>
<td>Photoelectron yield</td>
<td>1</td>
<td>0.4</td>
<td>0.1</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>(relative to NaI)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rad. hardness (Gy)</td>
<td>1</td>
<td>10</td>
<td>$10^3$</td>
<td>1</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

- Barbar@PEPII, 10ms interaction rate, good light yield, good S/N
- KTeV@Tevatron, High rate, Good resolution
- L3@LEP, 25us bunch crossing, Low radiation dose
- CMS@LHC, 25ns bunch crossing, high radiation dose
Crystals for Homogeneous EM Calorimetry

Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.
When a charge particle traverses these materials, about half the lost energy is converted into ionization and half into scintillation.

The best energy resolution would obviously be obtained by collecting both the charge and light signal. This is however rarely done because of the technical difficulties to extract light and charge in the same instrument.

Krypton is preferred in homogeneous detectors due to small radiation length and therefore compact detectors. Liquid Argon is frequently used due to low cost and high purity in sampling calorimeters.

### Noble Liquids for Homogeneous EM Calorimetry

<table>
<thead>
<tr>
<th></th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z )</td>
<td>18</td>
<td>36</td>
<td>58</td>
</tr>
<tr>
<td>( A )</td>
<td>40</td>
<td>84</td>
<td>131</td>
</tr>
<tr>
<td>( X_0 ) (cm)</td>
<td>14</td>
<td>4.7</td>
<td>2.8</td>
</tr>
<tr>
<td>( R_M ) (cm)</td>
<td>7.2</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Density (g/cm(^3))</td>
<td>1.4</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Ionization energy (eV/pair)</td>
<td>23.3</td>
<td>20.5</td>
<td>15.6</td>
</tr>
<tr>
<td>Critical energy ( \epsilon ) (MeV)</td>
<td>41.7</td>
<td>21.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Drift velocity at saturation (mm/( \mu )s)</td>
<td>10</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>
Noble Liquids for Homogeneous EM Calorimetry

E.g. Liquid Argon, 5mm/μs at 1kV/cm, 5mm gap → 1 μs for all electrons to reach the electrode.

The ion velocity is $10^3$ to $10^5$ times smaller → doesn’t contribute to the signal for electronics of μs integration time.
Homogeneous EM Calorimeters, Examples

NA48/62 Liquid Krypton
2cmx2cm cells
$X_0 = 4.7\text{cm}$
125cm length (27$X_0$)
$\rho = 5.5\text{cm}$

KTeV CsI
5cmx5cm and
$X_0 = 1.85\text{cm}$
2.5cmx2.5cm crystals
50cm length (27$X_0$)
$\rho = 3.5\text{cm}$

NA48 Experiment at CERN and KTeV Experiment at Fermilab, both built for measurement of direct CP violation. Homogenous calorimeters with Liquid Krypton (NA48) and CsI (KTeV). Excellent and very similar resolution.
Energy resolution of sampling calorimeters is in general worse than that of homogeneous calorimeters, owing to the sampling fluctuations – the fluctuation of ratio of energy deposited in the active and passive material.

The resolution is typically in the range 5-20%/\sqrt{E(\text{GeV})} for EM calorimeters. On the other hand they are relatively easy to segment longitudinally and laterally and therefore they usually offer better space resolution and particle identification than homogeneous calorimeters.

The active medium can be scintillators (organic), solid state detectors, gas detectors or liquids.

Sampling Fraction = Energy deposited in Active/Energy deposited in passive material.
EM Calorimetry → Hadron Calorimetry

Similar process for Hadrons.

The equivalent to EM Bremsstrahlung is Pion radiation.

The equivalent to the radiation length is the nuclear interaction length.
Hadronic Calorimetry

Strong Interaction

Approximate Energy Distribution

\[
\begin{align*}
\pi^+ & \rightarrow \pi^+ \rightarrow \text{Strong Interaction} \\
\pi^- & \rightarrow \pi^- \rightarrow \text{Nuclear Excitation} \\
\pi^0 & \rightarrow \pi^0 \rightarrow \text{Slow Nucleons} \\
\eta & \rightarrow \eta \rightarrow \text{Hadron Kascade} \\
\eta & \rightarrow \gamma \rightarrow \text{Electromagnetic Component}
\end{align*}
\]

\[
\begin{align*}
\text{Energy Resolution:} & \\
\bullet & \text{A large fraction of the energy 'disappears' into} \\
\quad & \text{Binding energy of emitted nucleons} \\
\quad & \pi^0 \rightarrow \mu^+ \nu \text{ which are not absorbed} \\
\bullet & \pi^0 \text{'s decaying into } \gamma \gamma \text{ start an EM cascade} \\
\quad & (\gamma \rightarrow 10^{-14}) \\
\quad & \text{Energy resolution is worse than for EM calorimeters}
\end{align*}
\]

In a hadron cascade, the longitudinal shower is given by the Absorber Length \( l_a \approx e^{-\frac{2}{3}r_a} \).

In typical detector materials \( l_a \) is much longer than \( x_0 \):

\[
\begin{align*}
2 & \sim \frac{4}{3} \cdot 35 A_{\text{eff}}^2 \\
\text{Fe} & \quad 7.87 \quad 1.76 \text{cm} \quad \sim 17 \text{cm} \\
\text{Pb} & \quad 12.35 \quad 0.56 \text{cm} \quad \sim 17 \text{cm}
\end{align*}
\]
Hadron Calorimeters are Large because $\lambda$ is large

Hadron Calorimeters are large and heavy because the hadronic interaction length $\lambda$, the ‘strong interaction equivalent’ to the EM radiation length $X_0$, is large (5-10 times larger than $X_0$).

Because part of the energy is ‘invisible’ (nuclear excitation, slow nucleons), the resolution of hadron calorimeters is typically worse than in EM calorimeters 20-100%/√E(GeV).
The Standard Model of Particles Physics, a theory that was established in the early 1970ies, is in excellent agreement with experiments. Experiments at LEP/Tevatron/LHC/KEK etc. verified the theory to impressive precision.

The Higgs Particle, a necessary element of the standard model, was found at the LHC.

Although the standard model is perfectly fitting the experiment, we know/think that it cannot be the final answer:

CP violation and the other CKM matrix elements are put into the model explicitly and they are not derived from a theory.

The Matter- Antimatter asymmetry in the Universe cannot be explained by the level of standard model CP violation.

The masses of the particles are also unexplained.

The cosmological constant predicted by the standard model differs by many orders of magnitude from the observed one.

The Higgs mass renormalization requires fine tuning operations etc. etc.
A few Reasons why you want to become an Experimental Particle Physicist

Substantial theory efforts did not really advance on these questions and did not touch base with experiment.

It is very difficult to find out what is wrong with the theory if all experimental results are in agreement with the theory.

The next step in advancing our knowledge will most likely come from experiment. Maybe LHC or some telescope, or some astrophysics experiment or some other future accelerator …

We have to invent new technologies for future accelerators and experiments!
You

have to develop the tricks and technologies to advance on the most fundamental questions in Physics!
Detector Systems
CMS Detector
ALICE Particle ID

Alice uses ~ all known techniques!
MiniBooNE detector, Neutrinos

800 tons of mineral oil
1280 photomultipliers

*Interaction*  |  *track*  |  *Cherenkov*  |  *Candidate*
---|---|---|---
$\nu_\mu$ CCQE  |  Muon  |  |  
$\nu_\mu + n \rightarrow p + \mu^-$  |  |  
$\nu_e$ CCQE  |  Electron  |  |  
$\nu_e + n \rightarrow p + e^-$  |  |  
Neutral pion  |  |  |  
NC$\pi^0$  |  |  |  
$\nu + N \rightarrow \nu + N + \pi^0$  |  |  |  

MiniBooNE Detector
Super-Kamiokande, Neutrinos
Daya Bay, Neutrinos

20 tons of liquid scintillator
NEXT experiment, double $\beta$ decay
CERN Neutrino Gran Sasso
(CNGS)
If neutrinos have mass:

- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

Muon neutrinos produced at CERN. See if tau neutrinos arrive in Italy.
CNGS Project

CNGS (CERN Neutrino Gran Sasso)
- A long base-line neutrino beam facility (732km)
- send $\nu_\mu$ beam produced at CERN
- detect $\nu_\tau$ appearance in OPERA experiment at Gran Sasso

⇒ direct proof of $\nu_\mu$ - $\nu_\tau$ oscillation (appearance experiment)
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

- Excavated
- Concreted
- Decay tube (Qu4 contract)

SPS tunnel
LHC/TIB tunnel
LEP/LHC tunnel
Connection gallery to TIB/LHC
Hadron stop and first muon detector
Second muon detector

06/2003
CERN-AC-D1-MAM

CNGS
Radial Distribution of the $\nu_\mu$-Beam at GS

Flat top: 500m  
FWHM: 2800m

5 years CNGS operation, 1800 tons target:
- 30000 neutrino interactions
- $\sim 150 \nu_e$ interactions
- $\sim 15 \nu_\tau$ identified
- $< 1$ event of background

Typical size of a detector at Gran Sasso
Neutrinos at CNGS: Some Numbers

For 1 year of CNGS operation, we expect:

- protons on target: $2 \times 10^{19}$
- pions / kaons at entrance to decay tunnel: $3 \times 10^{19}$
- $\nu_\mu$ in direction of Gran Sasso: $10^{19}$
- $\nu_\mu$ in 100 m$^2$ at Gran Sasso: $3 \times 10^{14}$
- $\nu_\mu$ events per day in OPERA: $\approx 2500$
- $\nu_\tau$ events (from oscillation): $\approx 2$
Opera Experiment at Gran Sasso

Basic unit: brick
56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target
Emulsions: micrometric precision

Basic unit: brick
56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target
Emulsions: micrometric precision
31 target planes / supermodule

In total: 206336 bricks, 1766 tons

SM1

SM2

First observation of CNGS beam neutrinos: August 18th, 2006

 Targets

Magnetic Spectrometers
Scintillator planes 5900 m²
8064 7m long drift tubes

3050 m² Resistive Plate Counters
2000 tons of iron for the two magnets
The Brick Manipulator System (BMS) prototype:
a lot of fun for children and adults!

Tests with the prototype wall

"Carousel" brick dispensing
and storage system
First Tau Candidate!
AMS

**Alpha Magnetic Spectrometer**

Try to find Antimatter in the primary cosmic rays. Study cosmic ray composition etc. etc.
AMS

Installed on the space station.
AMS

USS: Unique Support Structure

Tracker Radiator

Wake Radiator & Electronics

TRD Gas Box

TRD: Transition Radiation Detector

TOF (s1,s2) Time of Flight

Tracker Radiator

Grapple Fixture

TOF (s3,s4) Ram Radiator

Time of Flight

RICH: Ring Image Cherenkov Counter

Lower USS

ECAL: Electromagnetic Calorimeter

USS Keel

PAS: Payload Attach System