



Particle Identification in High Energy Physics

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Introduction

- The analysis of most High Energy Physics experiments requires a knowledge of the 4-momenta, (p, E) of the secondary particles
- 3-momenta, p, are usually obtained by measuring the deflection of the trajectory of each of the particles in a magnetic field
- Mass, energy or velocity, is needed to determine the fourth component of the 4-momentum, E, and fix a value for the mass M
- Since M uniquely (for particles) identifies the internal quantum numbers, this measurement is generally referred to as "particle identification"

Introduction

- The purpose of particle detectors
- The ideal particle detector in HEP
- Basic particle detection techniques
- Typical particle detector in HEP
- Particle signatures

What do we want to measure in HEP?

Of ALL particles produced in an interaction:

- Direction
- Energy
- Charge
- Particle identity

р

• Lifetime

p

The ideal detector

An apparatus that provides (for all types of particles):

- good particle identification
- precise measurement of energy/momentum
- precise measurement of trajectory (direction/origin)
- coverage of the full (4π) angular region

In addition (in some cases) it should be able to:

- take data at a high rate
- cope with a high particle densities
- survive high radiation doses
- survive 10+ years of operation (with little/no intervention)

A real detector will always be a compromise between the various requirements, existing technology and the availability of money, space, time etc...

Detecting particles

 Every effect of particles or radiation can be used as a working principle for a particle detector.

Claus Grupen



Particle detection techniques: the physics

Detect/measure properties of particles through their interaction with matter:

- Ionisation of atomic electrons
- Bremsstrahlung and photon conversions
- Inelastic nuclear interactions
- Cherenkov or transition radiation
- Emission of scintillation or fluorescence light

How can we "visualise" these processes?

- Photographic techniques
- By collection of induced charge (from ionisation)
- By detection of photons

Basic detection techniques: Photographic techniques

- Charged particles ionise atoms along their trajectory.
 - (I) Ions act as seeds for:
 - condensation in super saturated gas (Wilson chamber)
 - bubble-formation in super-heated liquid
 - electrical discharge or plasma formation -

All of these provide a visible trajectory that can be recorded photographically

(II) Ionisation can also be made visible chemically (photographic material)

• Photographic emulsion targets ·



- Basic detection techniques: Electrical
- We can also electrically collect the charge produced by the ionisation Particle causes ionisation in a material.
- Charge is separated/collected by an electric field.
- Requirement on material:
- no/few free charge carriers (non-conducting) $_{\rm V}$
- mechanism for transport of charge





Proportional chambers, Drift chambers, ...

Insulating gas/liquid between anode and cathode (transport through drift). Sometimes combined with very low conductivity solids.

Silicon strip detectors, CCDs, ..

Using a semi-conducting material: Mostly in the form of a reverse-biased pn-junction diode. 9

Basic detection techniques: Photo-detection

Charged particles can produce photons via scintillation, Cherenkov or transition-radiation etc. To detect these:



Photo-Multiplier Tube (PMT):

Electrons from photo-electric effect

"Electron multiplier" provides charge cascade

Very sensitive, but also bulky and expensive.





Particle signatures (first glance)



Electrons:

- leave a bent track (with a magnetic field)
- stopped in first layer of calorimeter(Calorimeter and tracking information)

Photons:

PHOTON

- no track
- stopped in first layer calorimeter

(Only calorimeter information!)

First layer of calorimeter: "Electro-magnetic calorimeter"

Particle signatures (first glance)



Charged hadrons:

- leave a bent track
- stopped deep in calorimeter
- (Calorimeter and tracking information)



Neutral hadrons:

- no track
- stopped deep in calorimeter

(Only calorimeter information!)

Second (+) layers of calorimeter: "Hadron calorimeter"

Particle signatures (first glance)



- not stopped in calorimeter
- track in muon detectors

(Calorimeter, tracking and muon-detector information)

Introduction to Particle Identification

- The identification of stable particles is achieved either by analyzing the way they interact, or by determining their mass.
- The difference in interaction is primarily used for lepton and photon identification.
- In order to unambiguously identify hadrons, their charge and mass has to be determined, which is achieved by simultaneous measurements of momentum and velocity.

Traditional detector setup



Components of a "traditional" particle physics experiment. Each particle type has its own signature in the detector. For example, if a particle is detected only in the electromagnetic calorimeter, it is fairly certain that it is a photon.

Tracking system

- The tracking system determines whether the particles are charged.
- In conjunction with a magnetic field, it measures the sign of the charge and the momentum of the particle.
- Photons may convert into an electron—positron pair and can in that case be detected in the tracking system.
- Charged kaon decays may be detected in a high-resolution tracking system through their characteristic "kink" topology: e.g. $K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ (64%) and $K^{\pm} \rightarrow \pi^{\pm} \pi^{0}$ (21%). The charged parent (kaon) decays into a neutral daughter (not detected) and a charged daughter with the same sign. Therefore, the kaon identification process reduces to the finding of kinks in the tracking system.

Calorimeters

- Calorimeters detect neutral particles, measure the energy of particles, and determine whether they have electromagnetic or hadronic interactions.
- PID in a calorimeter is a destructive measurement.
- All particles except muons and neutrinos deposit all their energy in the calorimeter system by production of electromagnetic or hadronic showers.



Calorimeters

- Photons, electrons and positrons deposit all their energy in the EM calorimeter.
- Their showers are indistinguishable, but an electron (and positron) can be identified by the existence of a track in the tracking system that is associated to the shower. (The energy deposit must match the momentum measured in the tracking system.)
- Hadrons on the other hand deposit most of their energy in the hadronic calorimeter (part of it is also deposited in the EM calorimeter).
- However, the individual members of the families of charged and neutral hadrons cannot be distinguished in a calorimeter.

Muon detection system

- The muon differs from the electron only by its mass; around a factor 200 larger.
- The critical energy E_c (the energy for which in a given material the rates of energy loss through ionization and bremsstrahlung are equal) is much larger for muons: it is around 400 GeV for muons on copper, while for electrons on copper it is only around 20 MeV.
- Therefore, muons do not in general produce electromagnetic showers and can thus be identified easily by their presence in the outermost detectors, as all other charged particles are absorbed in the calorimeter system.

Neutrinos do not in general interact in a particle detector as shown before, and therefore escape undetected. However, their presence can often be inferred by the momentum imbalance of the visible particles. In electron-positron colliders it is usually possible to reconstruct the neutrino momentum in all three dimensions and its energy.

PID by mass determination

- The three most important charged hadrons (pions, kaons and protons) and their antiparticles have identical interactions in an experimental setup as shown before (charge deposit in the tracking system and hadronic shower in the calorimeter).
- Mass determination is needed.
- PID is equally important in heavy-ion physics.
- To identify any stable charged particle, including charged hadrons, it is necessary to determine its charge **ze** and its mass **m**.
- The charge sign is obtained from the curvature of the particle's track.
- Since the mass cannot be measured directly, it has to be deduced from other variables.

Determination of mass

• The variables are in general momentum p and the velocity $\beta = v/c$, where one exploits the basic relationship

 $p = \gamma mv$ => m = p/ c $\beta \gamma$

Here c is the speed of light in vacuum and $\gamma = (1 - \beta^2)^{-1/2}$ is the relativistic Lorentz factor

• The resolution in the mass determination is

$$\left(\frac{\mathrm{d}m}{m}\right)^2 = \left(\frac{\mathrm{d}p}{p}\right)^2 + \left(\gamma^2 \frac{\mathrm{d}\beta}{\beta}\right)^2.$$

• Since in most cases $\gamma >>1$, the mass resolution is determined mainly by the accuracy of the velocity measurement, rather than the momentum determination.

Momentum and mass determination

- The momentum is obtained by measuring the curvature of the track in the magnetic field.
- The particle velocity is obtained by means of one of the following methods:
 - 1. Measurement of the energy deposit by ionization
 - 2. Time-of-flight (TOF) measurements
 - **3. Detection of Cherenkov radiation**
 - 4. Detection of transition radiation
- Each of these methods provide PID not only for charged hadrons, but also for charged leptons. The small obstacle of muons and pions not being well separated due to $m_{\mu} \approx m_{\pi}$ can luckily be handled, since muons can easily be identified by other means.

Energy loss (dE/dx)



The rate of energy loss for a relativistic particle is a weak function of the $\beta\gamma$ of the particle

$$\left(\beta\gamma = p/Mc = \frac{v!}{c}\left(1 - \frac{v^2}{c^2}\right)^{-1/2}\right)$$

- In the non-relativistic region ($\beta\gamma$ <4) the rate of energy loss falls to a minimum as $1/\beta^2$.
- Above $\beta \gamma \simeq 4$ the rate of energy loss rises again as $loq(\beta \gamma)$: this is the so-called relativistic rise
- At $\beta\gamma$ of a few hundred the rate of energy loss saturates (the "Fermi plateau")
- In solids and liquids the plateau is only a few percent above the minimum
- In high-Z noble gases at atmospheric pressure it reaches 50-70%.
- An accurate measurement of the energy loss in the relativistic rise region provides a measurement of $\beta\gamma$, and hence of M.

Cherenkov Radiation

- If a charged particle moves through a medium faster than the phase velocity of light in that medium, it will emit radiation at an angle determined by its velocity and the refractive index of the medium.
- Either the presence/absence of this radiation (in threshold Cherenkov counters), or a direct measurement of the Cherenkov angle (Differential or Ring-Image Cherenkov counters) can be used to give information on the particle velocity.
- Cherenkov emission is a weak effect and causes no significant energy loss (<1%)
- It takes place only if the track L of the particle in the radiating medium is longer than the wavelength λ of the radiated photons.
- Typically O(1-2 keV / cm) or O(100-200) visible photons / cm



Cherenkov radiation glowing in the core of a reactor

Transition Radiation

- When a highly relativistic particle (βγ ≥ 500) crosses the boundary between two dielectric media, X-ray photons are emitted.
- The energy of these photons is a function of βγ. Hence by measuring the transition radiation the mass of the particle may be obtained.

Selection of different methods

- The use of these methods is restricted to certain momentum ranges. For a given momentum range, **the separation power** can be used to quantify the usability of a technique.
- It defines the significance of the detector response R. If R_A and R_B are the mean values of such a quantity measured for particles of type A and B, respectively, and $\langle \sigma_{A,B} \rangle$ is the average of the standard deviations of the measured distributions, then the separation power n_{σ} is given by

$$n_{\sigma} = \frac{R_A - R_B}{\langle \sigma_{A,B} \rangle}$$

 Other criteria are: Luminosity and event rates, size and space requirements, accessibility, multiple scattering in the used materials, compatibility with other detector subsystems and geometrical coverage.

Examples in LHC experiments



ATLAS



LHC-B

A Toroidal Large AparatuS (ATLAS)



The dimensions are 25 m in height and 44 m in length, the overall weight of the detector is approximately 7000 t.

Compact Muon Solenoid (CMS)



The dimensions are 14.6 m in height and 21.6 m in length. The overall weight is approximately 12 500 t.

Requirements of ATLAS and CMS

The ATLAS and CMS detectors have been optimized to cover the whole spectrum of possible Higgs particle signatures. In summary, these are the requirements:

- Large acceptance in pseudo-rapidity and almost full coverage in azimuthal angle (the angle around the beam direction).
- Good identification capabilities for isolated high transverse momentum photons and electrons.
- Good muon ID and momentum resolution over a wide range of momenta and angles. At highest momenta (1 TeV) a transverse momentum resolution $\sigma_{\rm pT}/\rm p_T$ of the order 10% is required.

LHCb



Requirements of LHCb

LHCb is dedicated to heavy flavor physics. One particular aim is to look at evidence of new physics in CP violation and rare decays of beauty and charm hadrons. The level of CP violation in the SM cannot explain the absence of antimatter in our universe. A new source of CP violation is needed to understand this matter-antimatter asymmetry, implying new physics.

- geometrical acceptance in one forward region (1.9 < η < 4.9);
- good hadron ID;
- good momentum and vertex resolutions and
- an efficient and flexible trigger system.

A Large Ion Collider Experiment (ALICE)



The dimensions are 16 m in height and 26 m in length. The overall weight is approximately 10 000 t.



Central Detectors:

Inner Tracking System Time Projection Chamber Time-of-Flight Transition Radiation Detector **Spectrometers:**

High Momentum PID (RICH) Photon Multiplicity Forward Multiplicity Muon Spectrometer

Calorimeters:

EM Calorimeter Photon Spectrometer (PHOS) Zero Degree Calorimeter

Trigger:

Trigger Detectors pp High-Level-Trigger

Requirements of ALICE

The requirements for the ALICE experiment:

- reliable operation in an environment of very large charged track multiplicities;
- precision tracking capabilities at very low momenta (100 MeV/c), but also up to 100 GeV/c;
- low material budget;
- low magnetic field (0.2 ≤ B ≤ 0.5 T) in order to be able to track low momentum particles;
- good hadron ID for momenta up to a few GeV/c and electron ID up to 10 GeV/c in the central barrel;
- good muon ID (in the forward region).

ALICE PID Detectors

* ALICE has a unique capability on the particle identification



Central PID Detectors:

Inner Tracking System Time Projection Chamber Transition Radiation Detector Time-of-Flight High Momentum PID (RICH)

Particle identification techniques

- Particle identification by global signatures
- Muon detection
- d*E*/dx
- Time-of-Flight detectors
- Cherenkov detectors
- Transition radiation detectors

Particle identification from global signatures (recap.)



Electrons & photons:

- track if electron
- shallow E.M.-shower

Charged/neutral hadrons:

- track if charged track
- deep hadronic shower

At low *E* similar to $e/\gamma!$



The ALICE TPC **TPC:** main tracking device in ALICE CO₂ gap Outer field cage Ø5m Inner, outer readout chambers $\vec{\mathbf{E}} = 400 \text{ V/cm}$ (MWPCs) Central drift electrode (100kV) Endplate 5m

- * Was Ne-CO₂-N₂ before 2011
- ** **Requires high level data compression**

TPC main features:

 2° ~92 m³ active volume with gas mixture: Ne-CO₂ $(90-10)^*$ Low drift diffusion Maximum drift time 94 μs ✤ 72 (=18x2x2) MWPCs with pad

 Excellent performance on momentum reconstruction and dE/dx

✤ High readout rate capability:

1 kHz pp collisions

readout

Inner

field

cage

200 Hz central Pb-Pb collisions**

TPC Readout Chamber

ALICE TPC end plate



Wire arrangement in readout chambers



- In total 557,568 pads
- ✤ 3 different pad segments:
 - 63 rows with 4 x 7.5 mm² (IROCs)
 - 64 rows with 6 x 10 mm² (inner OROCs)
 - 32 rows with 6 x 15 mm² (outer OROCs)

dE/dx measurement in TPC

• Up to 159 samples in Ne-CO₂ gas mixture: $\sigma_{dE/dx} \approx 5\%$

 Very large dynamic range (up to 26x min. ionizing) allows to identify light nuclei and separate them by their charge

PID can be extended
 to higher momenta on
 the relativistic rise



Separation of π to K, p becomes constant at large p

ALICE upgrade after LS2



Physics program in RUN3

- Detailed characterization of QGP at the highest LHC energies
- Main physics topics:
 - Heavy flavors
 - Low-mass and low-pt di-leptons
 - Quarkonia (J/ψ, ψ',Y)
 - Jet quenching and fragmentation

Upgrade strategy

- Operate ALICE at high rate, record all MB events
 - goal: 50 kHz in Pb-Pb
- <u>Significant detector upgrades:</u>
 - Inner Tracking System (ITS)
 - improved vertexing and standalone tracking
 - increased readout speed and rate capability
 - Muon Forward Tracker
 - Electronics, Trigger, Readout systems
 - TPC with continuous readout.
 - high rate capability
 - preserve PID and tracking performance





- Designed for charged-particle tracking and dE/dx measurement in Pb-Pb collisions with dN_{ch}/dη=8000, σ(dE/dx)/(dE/dx)<10%

 - Employs gating grid to block backdrifting ions
 - Rate limitations: < 3.5 kHz (in p-p), ~500 Hz (in Pb-Pb)

GEM (Gas Electron Multiplier) F. Sauli (1996)



- Thin polyimide foil (Kapton[®]) $\sim 50 \ \mu m$
- Cu-clad on both sides ~5 µm
- Photolithography: ~10⁴ holes/cm²

Typical GEM geometry:

- Inner/Outer hole diameter: 50/70 µm
- **Pitch**: 140 µm
 - E_{hole} up to 100 kV/cm with

$$\Delta V_{GEM} = 500 V$$

 E_{below} > E_{above} electron extraction is improved





t <mark>electron</mark> signal (polarity!)

- "ion tail"
- "coupling to other electrods"
- s gain about a factor 3 lower than /PC
- $E_{T1} = 2000 \text{ V/Cm}$ $E_{T2} = 3000 \text{ V/Cm}$ $V_{G1} \ge \Delta V_{G2} \ge \Delta V_{G3} \le \Delta V_{G4}$ $E_{T3} = 1000 \text{ V/Cm}$ $E_{IND} = 4000 \text{ V/Cm}$ G = 2000



Electron microscope photograph of a GEI



• 2GEM + Micromegas

Time-of-Flight (TOF)



Combined measurement of Δt and p provides information on the mass!

• Only works in non-relativistic regime, $\beta < 1!$ (up to a few GeV/c)

For best mass determination we need:

- good time resolution (e.g. using scintillator detectors, multigap RPC etc.)
- long path length *L*

 t_1 : usually taken to be the collision time (from combined timing measurements)

 t_2 : detector typically installed after tracking detectors and before calorimeters. (longest possible L)

Time resolution and separation power

If two particles with masses m_A and m_B , respectively, carry the same momentum, their flight time difference can be calculated as

$$|t_A - t_B| = \frac{L}{c} \left| \sqrt{1 + \left(\frac{m_A c}{p}\right)^2} - \sqrt{1 + \left(\frac{m_B c}{p}\right)^2} \right|$$

with p>>mc the approximation $\sqrt{1 + (mc/p)^2} \approx 1 + (mc)^2/2p^2$

can be used, and the separation power becomes

$$n_{\sigma_{TOF}} = \frac{|t_A - t_B|}{\sigma_{TOF}} = \frac{Lc}{2p^2 \sigma_{TOF}} |m_A^2 - m_B^2| \qquad \qquad n_\sigma = \frac{1}{\langle \sigma_{A,B} \rangle}$$

Here σ_{TOF} is the resolution of the TOF measurement. Misidentification of particles occurs at higher momenta, where the time difference $|t_A-t_B|$ becomes comparable to σ_{TOF} .

Example: Assuming a time resolution of 100 ps (60 ps) and requiring a separation of $n_{\sigma TOF} = 3$, the upper limits for the momentum are 2.1 GeV/c (2.7 GeV/c) for K/ π separation and 3.5 GeV/c (4.5 GeV/c) for K/p separation.

 $R_A - R_B$



NA49 Time-of-flight detector

NA-49: fixed target experiment for heavy ion collisions

This allows for long path length:

*L≈*15m!

In addition big scintillator rods have excellent time resolution:

 $\sigma(\Delta t) \approx 60 \text{ ps!}$



Cherenkov radiation:

Photo emission by a charged particle travelling in a dielectric medium with a velocity greater than the velocity of light in that medium:

$$v_{\text{particle}} > \frac{c}{n} \quad \left(\beta_{\text{thr}} = \frac{1}{n}\right)$$



Huygens wavelets emitted all along the particles trajectory form a single wave front under an angle θ_c w.r.t. the particle direction:

$$\cos\theta_c = \frac{(c/n)\Delta t}{\beta c\Delta t} = \frac{1}{\beta n}$$

Medium	n-1	θ_{\max}	$\pi_{\text{thr}}(p) \; GeV/c$	$N_{\gamma}\left(eV^{\text{-1}}cm^{\text{-1}}\right)$	- Dath Q and Q (acmbined with	
Air	1.000283	1.36°	5.9	0.21	- Both ρ_{thr} and θ_c (combined with	
Isobutane	1.00217	3.77°	2.12	0.94	p) can be used for particle ID.	
Aerogel	1.0065	6,51°	1.23	4.7		
Aerogel	1.055	18.6°	0.42	37.1	<i>n</i> values can be chosen to get	
Water	1.33	41.2°	0.16	160.8	particle ID in a particular range of	
Quartz	1.46	46.7°	0.13	196.4	_ momenta! 51	

Cherenkov radiation

• The Cherenkov radiation propagates with a characteristic angle with respect to the particle track Θ_c , that depends on the particle velocity:

$$\cos(\Theta_C) = \frac{1}{\beta n}$$

- n is the refractive index of the material and n = n(E); E: photon energy
- Since $|\cos(\Theta_c)| \le 1$, Cherenkov radiation is only emitted above a threshold velocity $\beta_t = 1/n$ and $\gamma_t = 1/(1 \beta_t^2)^{1/2}$
- Cherenkov detectors contain two main elements: a radiator through which charged particles pass (a transparent dielectric medium) and a photon detector
- The number of photoelectrons detected in a given device

$$N_{p.e.} \approx N_0 z^2 L \sin^2(\Theta_C)$$

- L: the path length of the particles through the radiator; ze: the particle charge and N_0 : the quality factor or figure of merit.
- As Cherenkov radiation is a weak source of photons, the light transmission, collection and detection must be as efficient as possible. These parameters are contained in N₀, as well as the photon collection and detection efficiencies of the photon detector. Typical values of N₀ are between 30 and 180 cm⁻¹

Cherenkov radiators

Material	n-1	β _c	θ _c	photons/cm
solid natrium	3.22	0.24	76.3	462
Lead sulfite	2.91	0.26	75.2	457
Diamond	1.42	0.41	65.6	406
Zinc sulfite	1.37	0.42	65	402
silver chloride	1.07	0.48	61.1	376
Flint glass	0.92	0.52	58.6	357
Lead crystal	0.67	0.6	53.2	314
Plexiglass	0.48	0.66	47.5	261
Water	0.33	0.75	41.2	213
Aerogel	0.075	0.93	21.5	66
Pentan	1.70E-03	0.9983	6.7	7
Air	2.90E-03	0.9997	1.38	0.3
Не	3.30E-05	0.999971	0.46	0.03



Silica Aerogel



Types of Cherenkov counters

- Threshold counters measure the intensity of the Cherenkov radiation and are used to detect particles with velocities exceeding the threshold β_t . A rough estimate of the particle's velocity above the threshold is given by the pulse height measured in the photon detector.
- Differential counters focus only Cherenkov photons with a certain emission angle onto the detector and in this way detect particles in a narrow interval of velocities
- Imaging Cherenkov detectors make maximum use of the available information (Cherenkov angle and number of photons) and can be divided in two main categories: RICH (Ring Imaging CHerenkov) and DIRC (Detection of Internally Reflected Cherenkov light) devices

Cherenkov photon emission

The number of Cherenkov photons produced by unit path length by a charged particle of charge z is

 ^{dN}/_{dλ}
 ^{dN}/_{dλ}

$$\frac{d^2 N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2} \sin^2 \theta_c$$

$$\frac{v}{\lambda}$$

- Note the wavelength dependence ~ $1/\lambda^2$
- The index of refraction n is a function of photon energy E=hv, as is the sensitivity of the transducer used to detect the light.
- Therefore to get the number of photon we must integrate over the sensitivity range:

$$\frac{d N}{dx} = \int_{350 nm}^{550 nm} d\lambda \frac{dN}{d\lambda dx} = 475 z^2 \sin \theta_c \quad \text{photons/cm}$$

Transition radiation

- Transition radiation occurs if a relativistic particle (large γ) passes the boundary between two media with different refraction indices (n1≠n2) [predicted by Ginzburg and Frank 1946; experimental confirmation 70ies]
- Effect can be explained by re-arrangement of electric field
- A charged particle approaching a boundary creates a dipole with its mirror charge





The time-dependent dipole field causes the emission of electromagnetic radiation

$$S = \frac{1}{3}\alpha z^2 \gamma \hbar \omega_P \quad (\hbar \omega_P \approx 28.8 \sqrt{\frac{Z\rho}{A}} eV)$$

Useful documentation

General:

- Christian Lippmann: Nuclear Instruments and Methods in Physics Research A 666 (2012) 148–172.
- Joost Vossebeld: Post-graduate lecture series, University of Liverpool.
- Konrad Kleinknecht: Detectors for Particle Radiation, 2nd ed.
- T Ferbel (ed.) "Experimental Techniques in High Energy Physics", Frontiers in Physics.
- D. Bortoletto: Detectors for Particle Physics, Interaction with Matter, Purdue University.

Gaseous tracking detectors:

• F Sauli: http://documents.cern.ch/archive/cernrep/1977/77-09/Chapter01.pdf

Assignment

- All students may send me at least one question on the presentation/topic by mail to <u>saikat.ino@gmail.com</u> by tomorrow 2 p.m.
- I will try to answer and compile it and send to all students.
- If you have any comment/feedback, please write to me.

Thank you