Reconstruction methods in high energy physics experiments

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Tata Institute of Fundamental Research

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Outline of the Talk

1. Detection principles in HEP-Ex
   - Importance of observation in science
   - Rutherford's gold foil experiment
   - Historical development of detectors
   - Design of a modern HEP-Ex detector
2. What is reconstruction?
3. Reconstruction techniques
   - Pattern recognition & track finding.
   - Fitting and/or calibration.

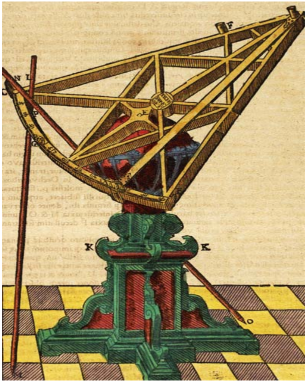
If you see it, it's there

- Check what you believe
- Reporoducability

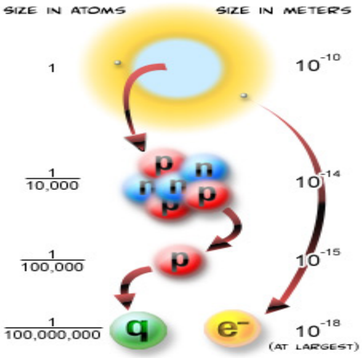
Theory reflects reality

- World as we see it: celestial bodies to microscopic objects
- Build up a theory to understand physical world
- How do we know a theory is correct?
- Test the theory with experiment

An example



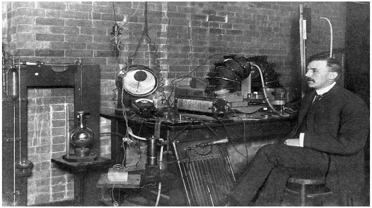
On a smaller scale



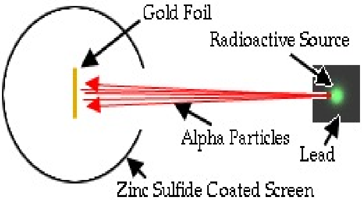
(a)

Figure : (a) Quest for fundamental particles

Break the indivisible



(a)



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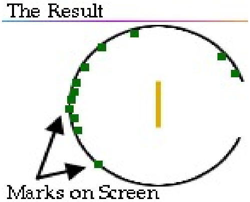

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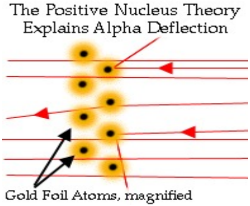
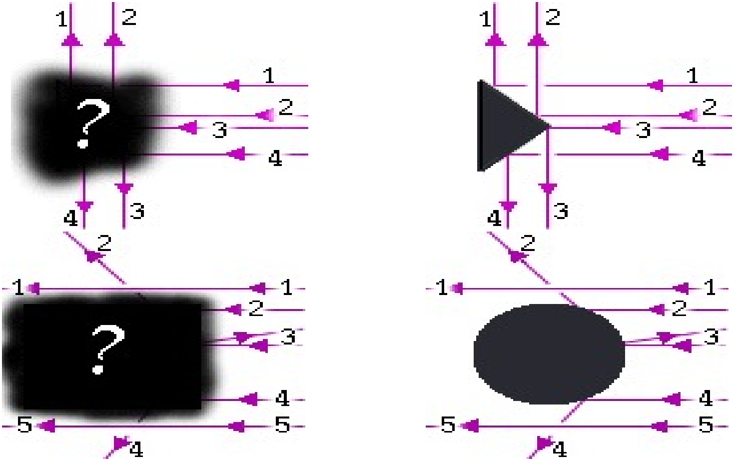
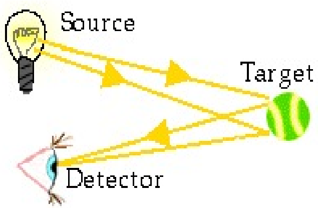


(d)

Analysis principle



Analysis principle

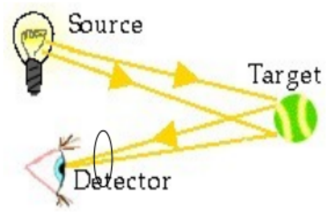


Beam

target

detector

Betterment of detector

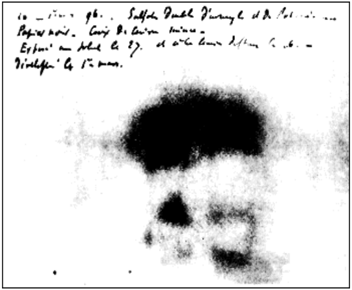


Beam

target

detector

α, β, γ, X-rays



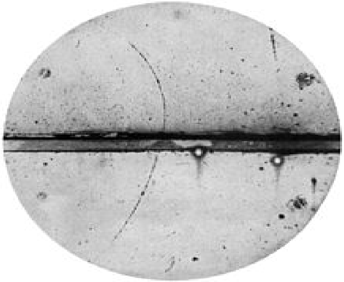
(a)

(b)

Figure : (a) Becquerel's photographic plate, fogged by exposure to radiation from a uranium salt; (b) X-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January 1896.

Cloud Chamber

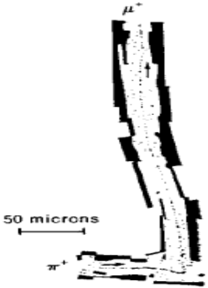
(a)



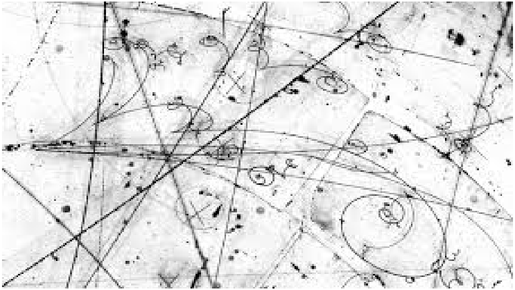
(b)

Figure : (a) Trails of particles in a cloud chamber; (b) Discovery of e^+ by Anderson

Nuclear emulsion and Bubble chamber



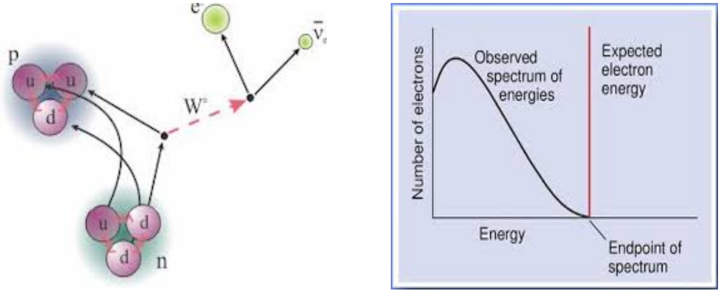
(a)



(b)

Figure : (a) Muon discovery via nuclear emulsion technique; (b) Bubble chamber

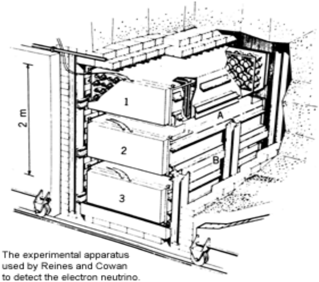
Importance of energy measurement



(a) (b)

Figure : (a) β decay and (b) energy spectrum of emitted electrons

Neutrinos

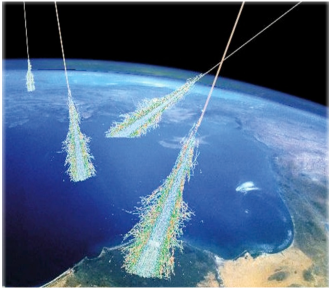


The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

(a)

Figure : (a) Discovery of neutrinos

Importance of angle measurement

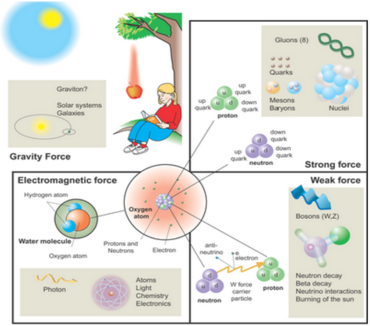


(a)

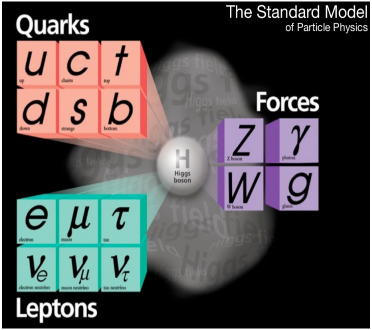
(b)

Figure : (a) Cosmic rays bombarding the upper atmosphere of the earth and (b) TIFR-based HAGAR telescope at Hanle, Ladakh

What did all these do for us?



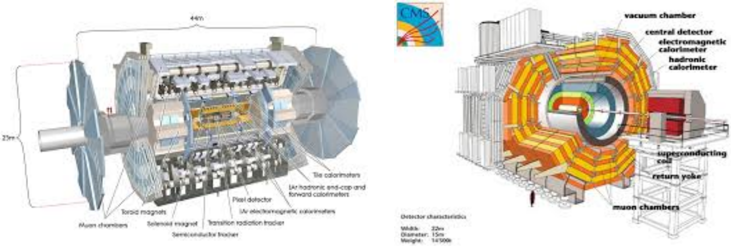
(a)



(b)

Figure : (a) four basic forces and (b) Fundamental building blocks of nature

Modern day detectors



(a) (b)

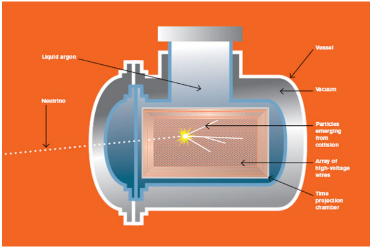
Figure : Modern day complex detectors (a) ATLAS and (b) CMS

INO RPC lab

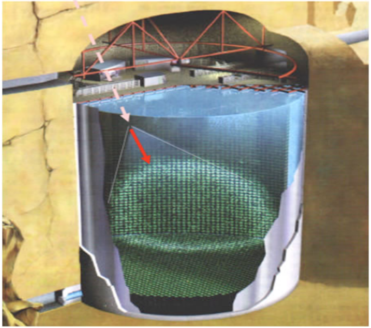
Design of a detector

- Need to know energy, direction, charge etc.
- Detector comprises:
  - Passive element (ex. Pb, Fe, LAr, H_2O etc.)
  - Active element (ex. Scintillating material + PMT, RPC etc.)

Examples of passive material



(a)



(b)

Figure : (a) a Liquid Argon TPC detector and (b) Neutrino event at Super Kamiokande

Examples of active material

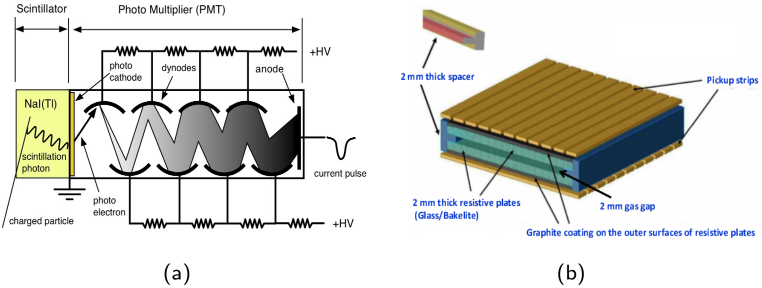


Figure : (a) Scintillating material+PMT and (b) an RPC detector

Examples of active material

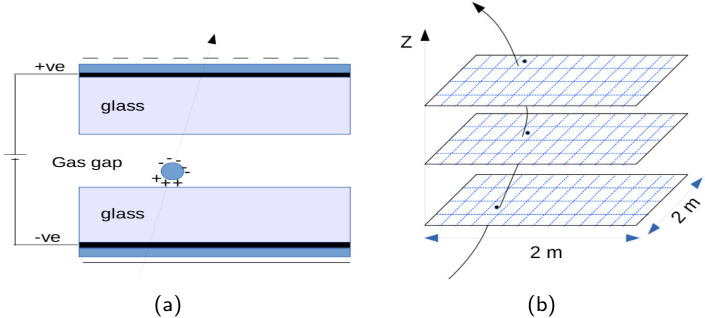


Figure : (a) and (b) (x,y) signal formation in RPC detector

How to build a detector

- In order to measure the properties of a particle
  - it must interact in the passive material and lose some energy.
  - transfer energy to the active material in some recognizable fashion.
- examples:
  - Charged particles: ionization, Bremsstrahlung, Cherenkov.
  - Photons: photo-electric/Compton effect, pair production

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From electronic signal to physics

- Whatever exotic physics we search for, the experimental data always come in the form of electronic signals.
- Measure the properties: charge, momenta, directions etc. from these signals.
- The physics depends on *how well* these measurements are.
- Issues: need to deal with background noise (process related and measurement related).

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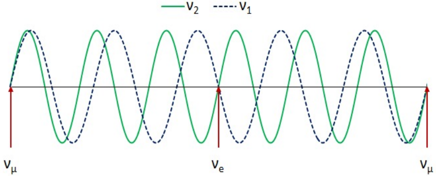
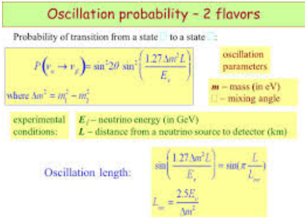
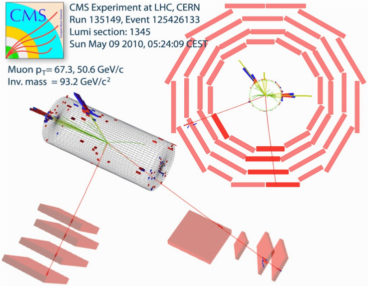
Neutrino oscillation

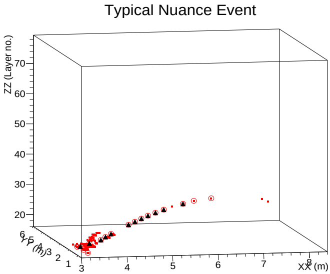


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$





(a)



(b)

Figure : (a) Typical event in CMS and (b) a neutrino event in ICAL

Typical challenges

- Pattern recognition
- Track fitting

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- Track fitting

Standard method I

- Electronic signals at the active detector planes are used to form 'hits'
- Consider all hits in all active planes: form clusters.

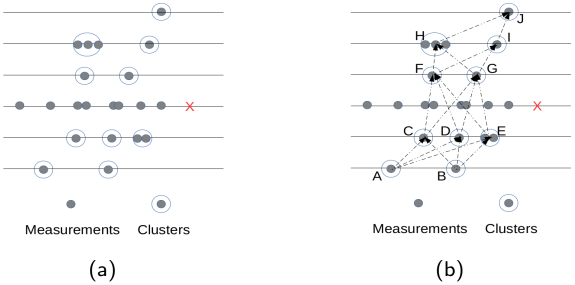


Figure : (a) Formation of clusters from hits and (b) formation of triplets from clusters

Standard method II

- Form triplets from clusters
- Form chain of triplets (segments)

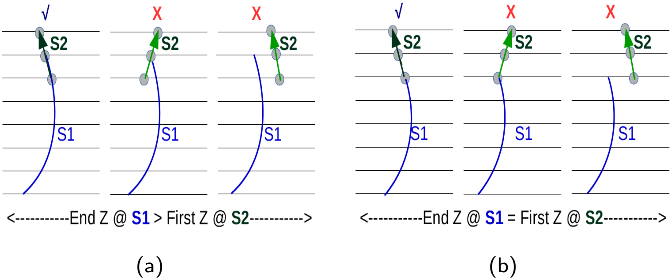
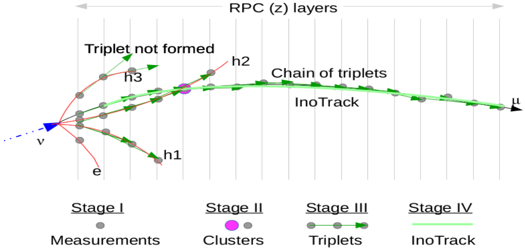


Figure : (a) and (b) Incrementing the length of track segments by appending new triplets

Standard method III



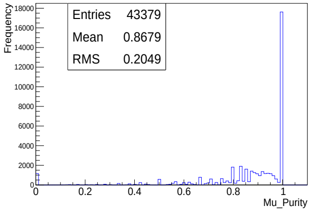
- Can work for any shape of tracking detector (barrel, planes etc.)
- Huge amount of combinations to try. Typically an event with 1000 hits/layer might take up to 100 sec

Performance in ICAL

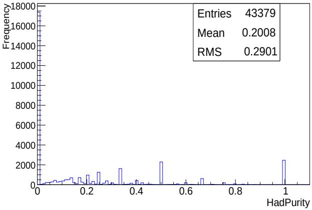
Table : NUANCE level Muon reconstruction performance

Program	Parameter Performance	
Finder	Directionality (up/down)	$\sim 96\%$
Finder	Correct identification of μ hits	$\sim 86\%$
,,	Correct identification of hadron hits	$\sim 80\%$
,,	Background rate of NC events	$\sim 1.7\%$

μ-hadron separation performance



(a) Degree of correct identification of muon hits

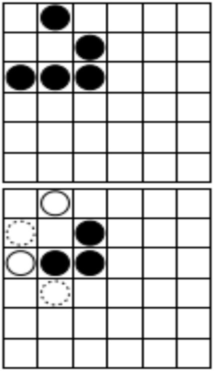


(b) Rate of inclusion of muon hits into hadron shower

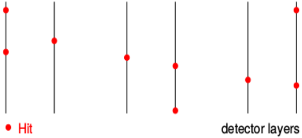
Figure : (a) Genuine μ fraction in hits tagged as ‘muon hits’ (b) genuine μ contamination in hits tagged as ‘hadron hits’

Cellular automaton I

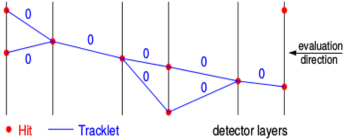
- Cell (*dead* or *alive*)
- Neighborhood
- Rule of evolution
- Discrete time step
- State of a cell depends on the state of its neighbors in the previous step
- Parallel track reconstruction in CMS, HERA-B using CA



Cellular automaton II



(a)



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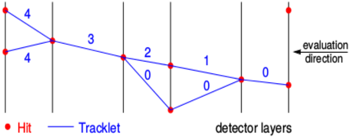

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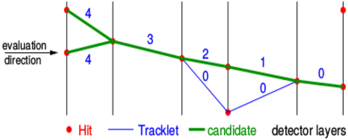


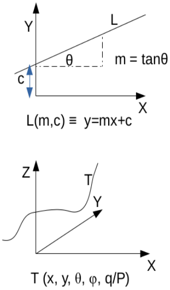
(d)

Typical challenges

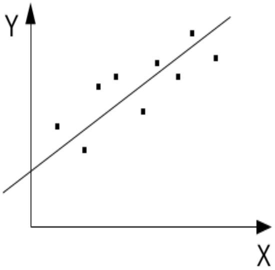
- Pattern recognition
- Track fitting

The problem

- Fit the tracks of selected track candidates
- Parameters of these tracks are q, P, positions and angles
- The state of the track evolves
- Use quadratic fit (Gluckstern), Kalman fit etc.



For straight line

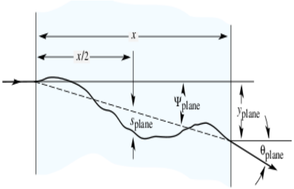


$$R^2 = \sum [y_i - f(a_1, a_2, ..., a_n)^2]$$

$$\frac{\partial}{\partial a_i} \left(R^2\right) = 0$$

Use of Kalman filter

- Prediction
- $\vec{F} = q\vec{v} \times \vec{B} + \hat{u}\frac{dE}{ds}$
- $m\frac{d\vec{v}}{dt} = \vec{F}$
- Solve for $(x, y, t_x, t_y, q/p)$
- Account for the random multiple scattering



- **Measurement**
  - Hits in a track
  - Detector resolution, electronic noise and alignment errors

Use of Kalman filter

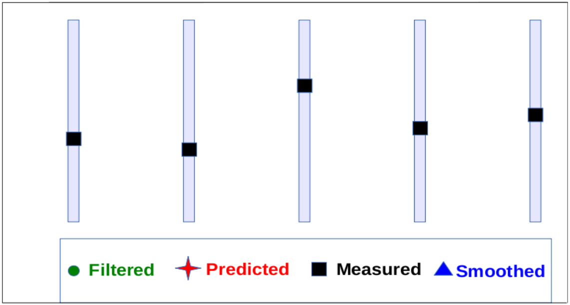


Figure : Kalman filtering and smoothing

- Start with a seed value of the state vector $\mathbf{x} = (x, y, t_x, t_y, q/p)$.
- Next plane is predicted.
- The measurement is considered.
- Hence, the state is filtered.
- Smooth the filtered states.

Least square minimization

- Filtered estimate is a weighted average of measurement and prediction:

$$x_f = \frac{\frac{1}{\sigma_p^2}x_p + \frac{1}{\sigma_m^2}x_m}{\frac{1}{\sigma_p^2} + \frac{1}{\sigma_m^2}}$$
$$= \frac{\sigma_m^2}{\sigma_p^2 + \sigma_m^2}x_p + \frac{\sigma_p^2}{\sigma_p^2 + \sigma_m^2}x_m$$

- $\sigma_p \to \infty$ implies $x_f \to x_m$
- $\sigma_m \to \infty$ implies $x_f \to x_p$

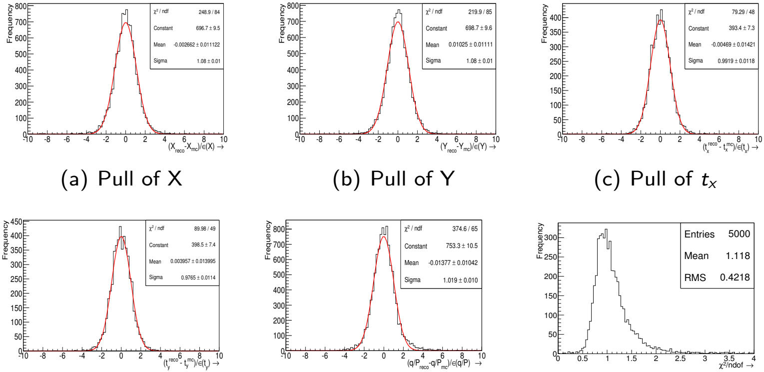
- Filtered error is given by:

$$\frac{1}{\sigma_f^2} = \frac{1}{\sigma_m^2} + \frac{1}{\sigma_p^2}$$

- $\sigma_f^2 \leq min(\sigma_m^2, \sigma_p^2)$. Filtering shrinks down the error.
- It can be written as:

$$\sigma_f^2 = (1 - \frac{\sigma_p^2}{\sigma_m^2 + \sigma_p^2})\sigma_p^2$$
$$= (1 - K)\sigma_p^2$$

Pull parameters

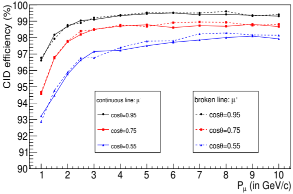


(a) Pull of X (b) Pull of Y (c) Pull of t_x

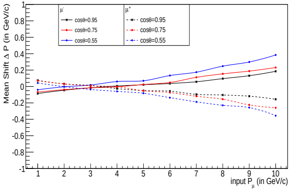
(d) Pull of t_y (e) Pull of q/P (f) Reduced χ^2

Figure : GoF plots for GEANT4 MC events $P_\mu^{Gen} = 6$ GeV/c at $\cos\theta_\mu^{Gen} = 0.95$

Performance



(a) Charge id. efficeincy

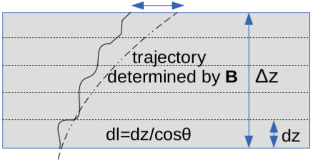


(b) Momentum mean shift

Current projects

- Generalising extrapolation formulae for (x, y, t_x, t_y) at low tracking momenta.
- $\frac{\partial(\frac{q}{p})_{l+dl}}{\partial(\frac{q}{p})_l} = \left(1 - \frac{2}{\beta P}\left\langle\frac{dE}{ds}\right\rangle dl\right) + O(B_i^{(2)})$
- $Q(l+dl) = Q(l) + Q'(l)dl = F(Ddl)Q(l)F(Ddl)^T + \delta Q dl$, Mankel[1]

$$\begin{pmatrix} c(t_x t_x)\frac{\ell^3}{3} & c(t_x t_y)\frac{\ell^3}{3} & c(t_x t_x)\frac{\ell^2}{2}D & c(t_x t_y)\frac{\ell^2}{2}D \\ \dots & c(t_y t_y)\frac{\ell^3}{3} & c(t_x t_y)\frac{\ell^2}{2}D & c(t_y t_y)\frac{\ell^2}{2}D \\ \dots & \dots & c(t_x t_x)\ell & c(t_x t_y)\ell \\ \dots & \dots & \dots & c(t_y t_y)\ell \end{pmatrix}$$



$$c(t_x, t_x) = (1 + t_x^2)(1 + t_x^2 + t_y^2)\langle\theta_0^2\rangle$$

$$\langle\theta_0^2\rangle = \left(\frac{0.0136}{\beta p}\right)^2 \left(\frac{l}{l_{rad}}\right)\left[1 + 0.038 ln\left(\frac{l}{l_{rad}}\right)\right]$$

[2] *Ranger*, A pattern recognition algorithm (Hera-B), R Mankel

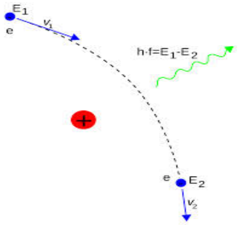
Concluding remarks

- Methods are optimal but never fullproof
- Search for new methods are always on
- In ICAL, the standard approches have been applied
- Other groups are attempting newer algorithms...
- Hope to have a better track reconstruction which will lead to better sensitivity of HEP experiments.

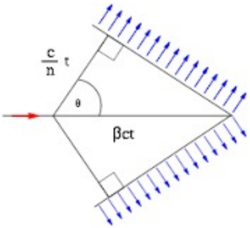
- I would like to thank the INO-ICAL collaboration for granting me the opportunity to spend time with the development of the reconstruction code for ICAL. The ample supports from Prof. N K Mondal and Dr. Wittek are appreciated.

Thank You

Bremsstrahlung and Cherenkov radiation



(a)



(b)

Figure : (a) Bremsstrahlung (b) Cherenkov radiation

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