Institut Matériaux Microélectronique Nanosciences de Provence

master Physique Subatomique Astroparticules

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Master 2 Internship Defense

Design of a new experimental technique to measure the fundamental properties of neutrinos

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Under the supervision of Mathieu Perrin-Terrin and Antoine Roueff
21/06/2023

Outline

I. **Context and introduction to the Neutrino Tagging method**

II. **Internship goals**

III. **Track reconstruction algorithm**

IV. **Results**
   - Track reconstruction performances
   - Optimization of the experimental setup

Neutrino Tagging : Context

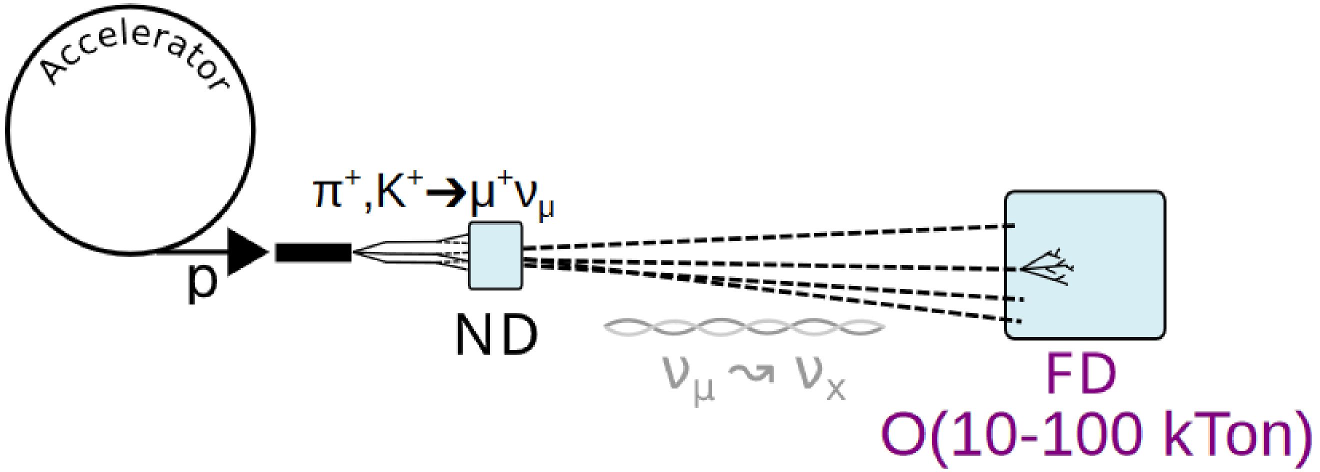
Context

- Study of neutrino oscillation

→ Measurement of CP violation phase δ_{CP}

State of the art accelerator based neutrino experiment (Long Baseline)

- 2 detectors (ND and FD) to compare the flavors
- Neutrinos interact very weakly
  - High intensity beam (10^{18} part./sec)
  - Large-scale detectors (10-100 kTon)



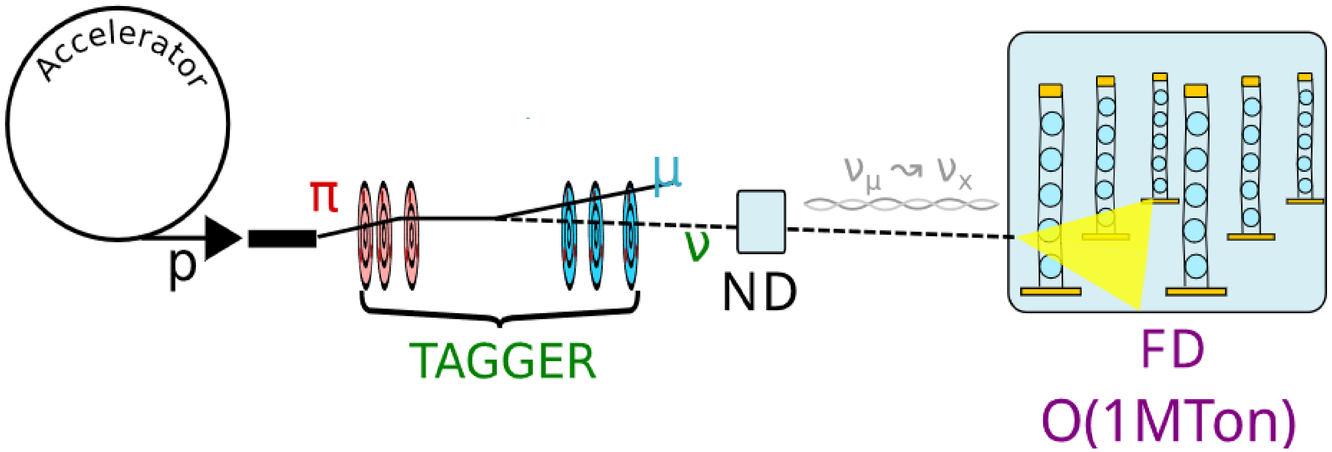
Challenge for ongoing experiments

- Enhance measurement accuracy
  - Significant statistics
  - Low systematics

Neutrino Tagging : Principle and motivation

Principle : follow particle by particle

- Kinematic reconstruction of neutrino properties: $\pi^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu}$
- Association of detected ν_x with tagged ν_μ



Motivations

- **Composition of the beam**
  - Energy
  - Flavor
  - Chirality (neutrino/antineutrino)
- **Energy resolution**
  - 20% for more conventional experiments vs. <1% for neutrino tagging

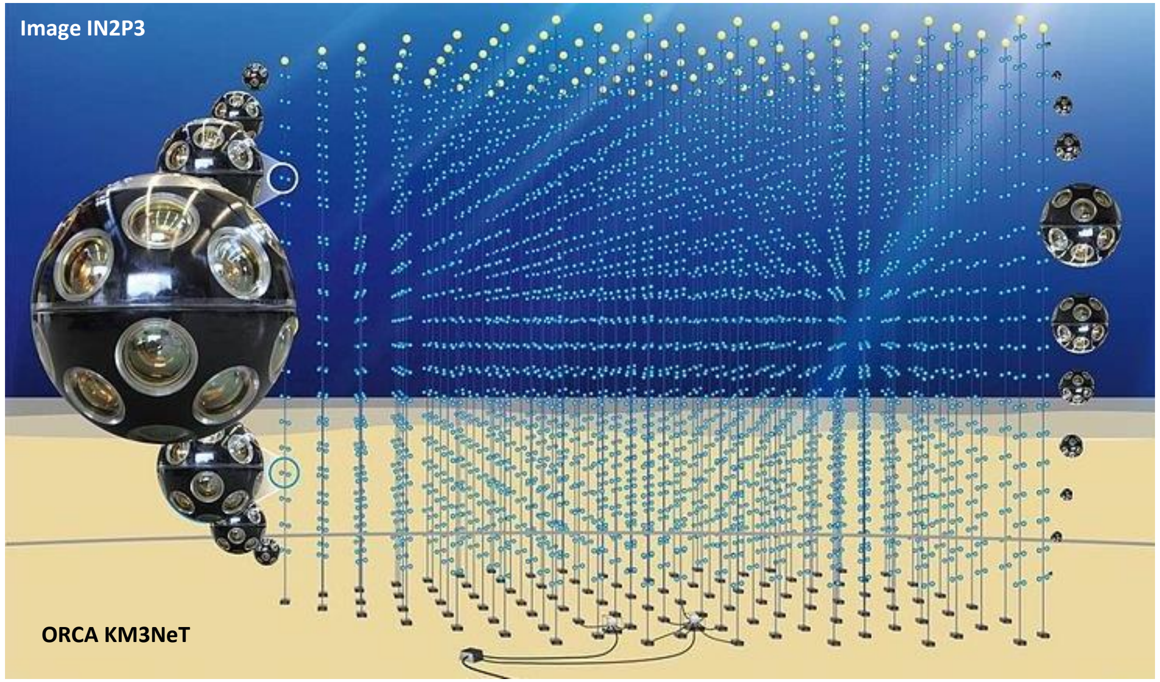
Neutrino Tagging : Technological challenge

Technological challenge

- High intensity beam

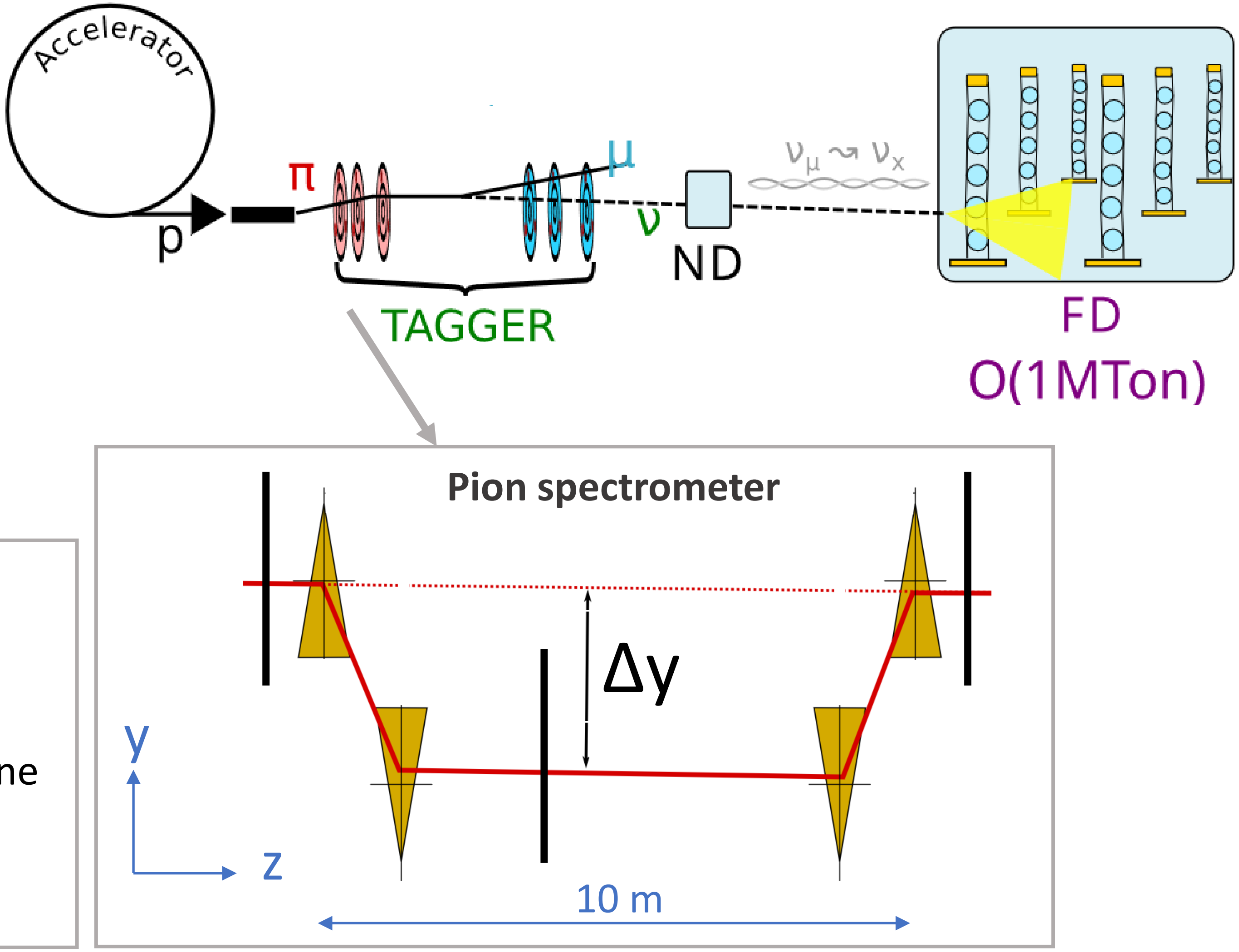
→ Design an adapted beamline to reduce particle rate

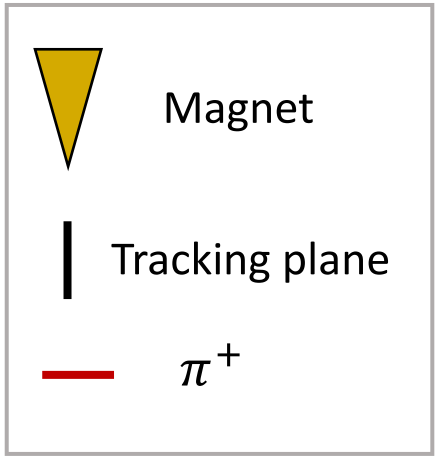
→ Natural water Cherenkov detector
(MTon vs. kTon to detect a particle flux of 10^{12} part./s)



O(1MTon)

Neutrino Tagging : Experimental setup



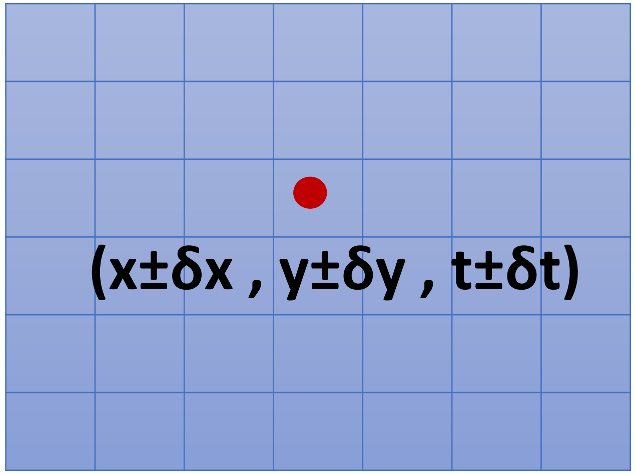


$$p\ \alpha\ \frac{1}{\Delta y}$$

Neutrino Tagging : Tracking planes

Time resolved sillicon pixel detectors

- Measurement of the time and position of the particles

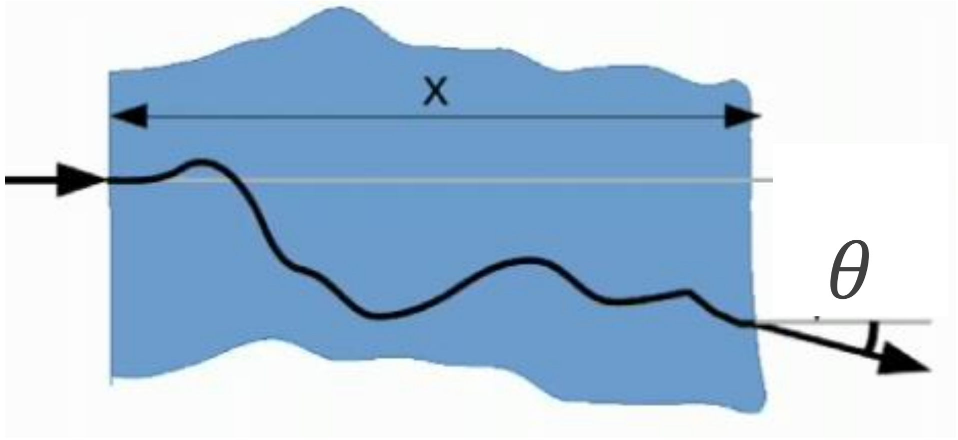


Detector caracteristics

- Pixel size ~50 µm
- Time resolution (20 - 50 ps)
- Thickness <1mm : induce Multiple Coulomb Scattering (~80 µrad for 0.5mm of Silicon)

$$\theta = \frac{13.6\text{MeV}}{c_0 p}\sqrt{\frac{x}{X_0}}$$

Thickness of the scattering medium in terms of radiation wavelengths



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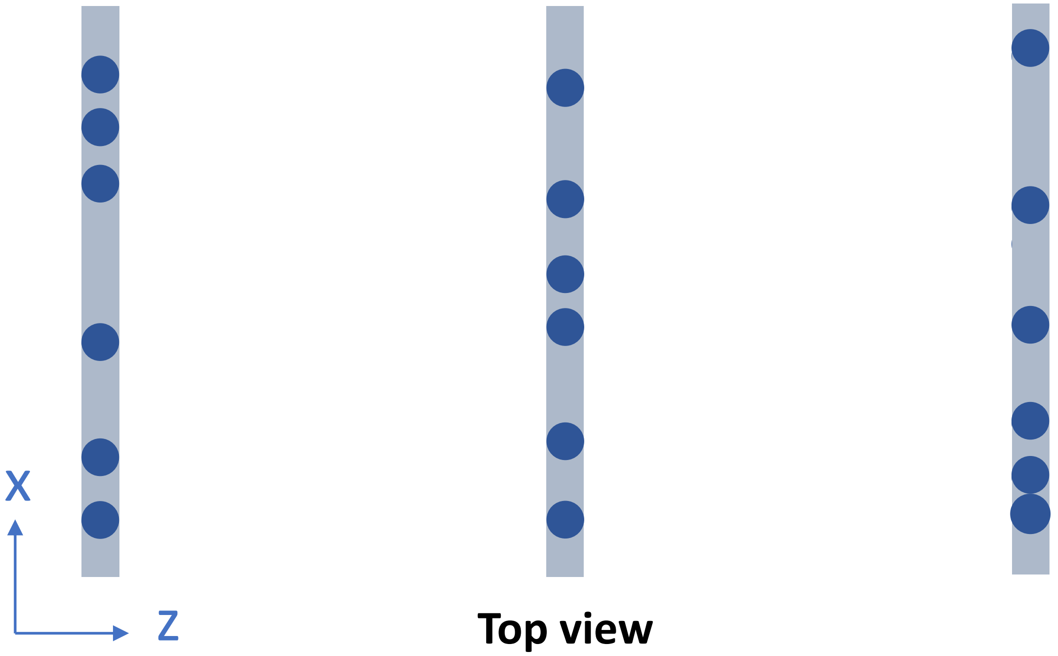
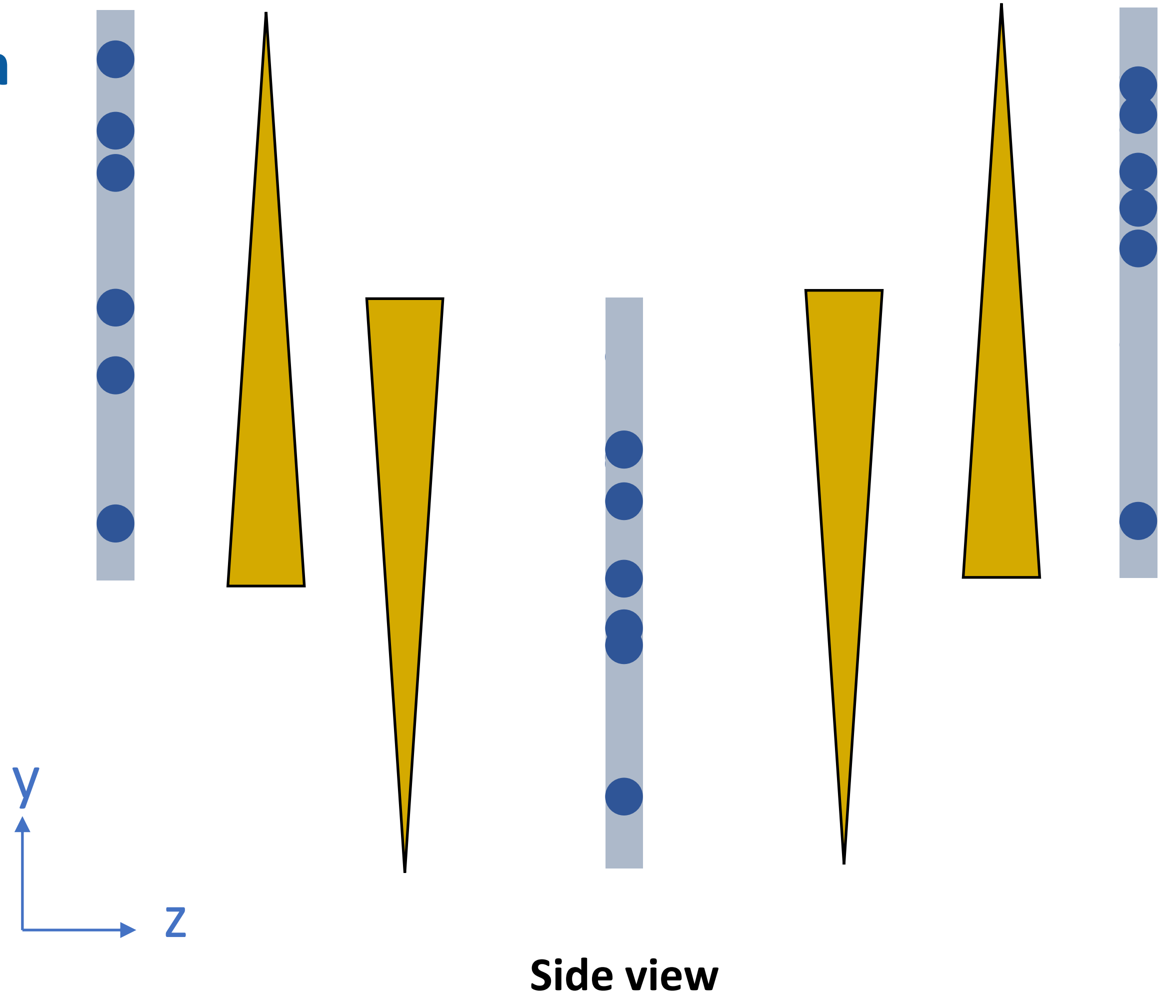
Goals of the internship

1 **Implement track reconstruction algorithm**

- Hits/particles association
- Estimation of the kinematics quantities





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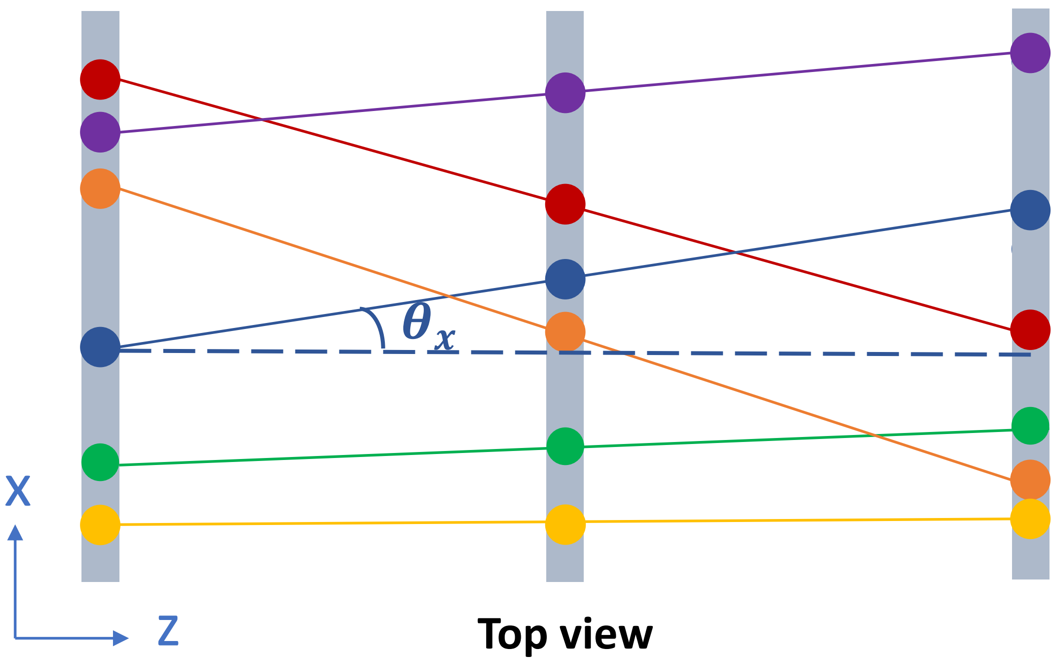
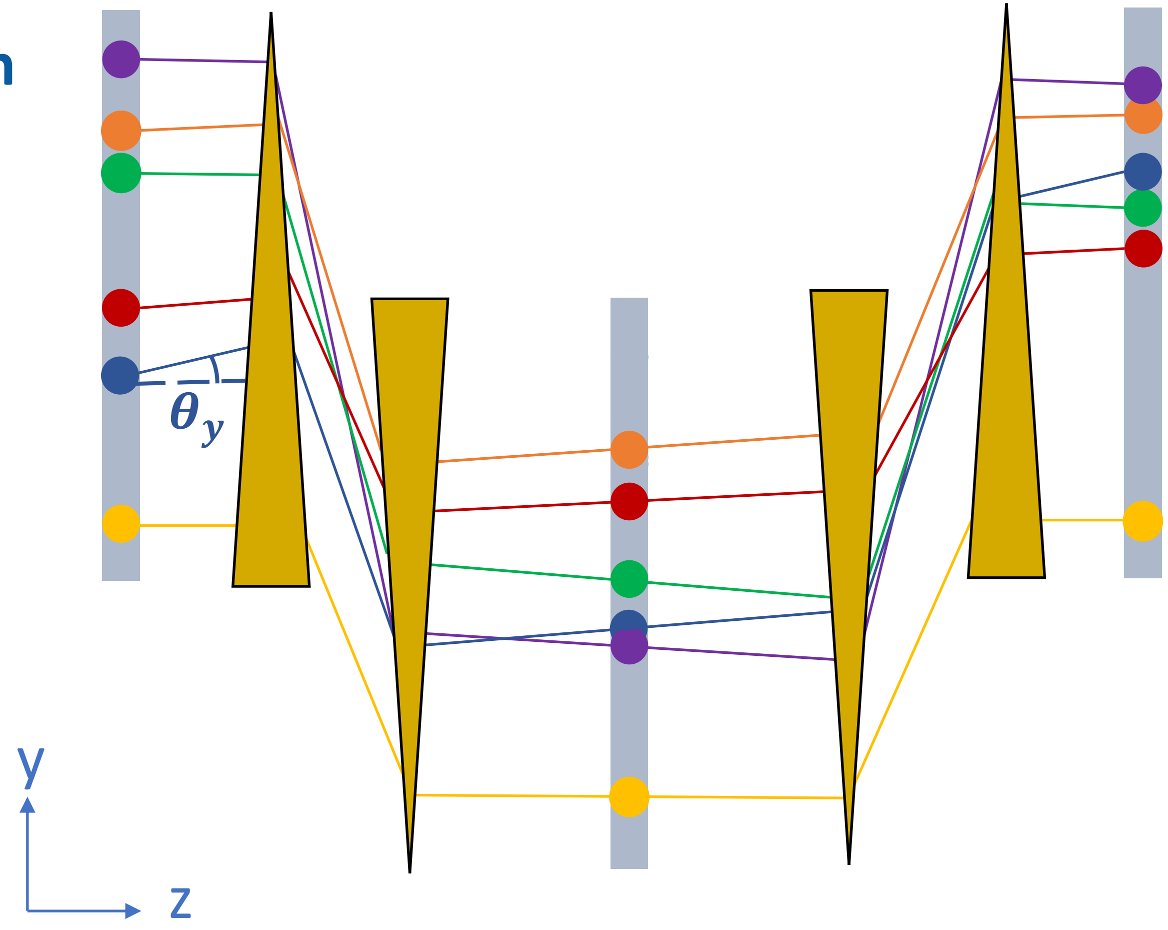


Top view



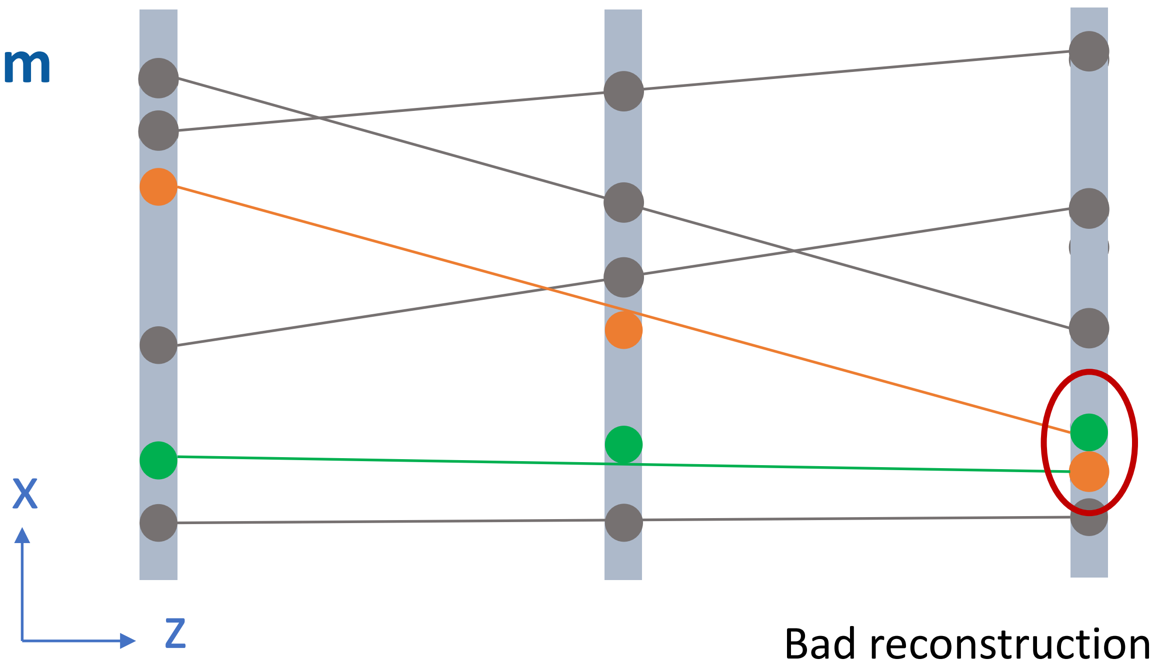
Side view

Goals of the internship

1 **Implement rack reconstruction algorithm**

- Hits/particles association
- Estimation of the kinematics quantities

Top view



Bad reconstruction due to measurement resolution

Goals of the internship

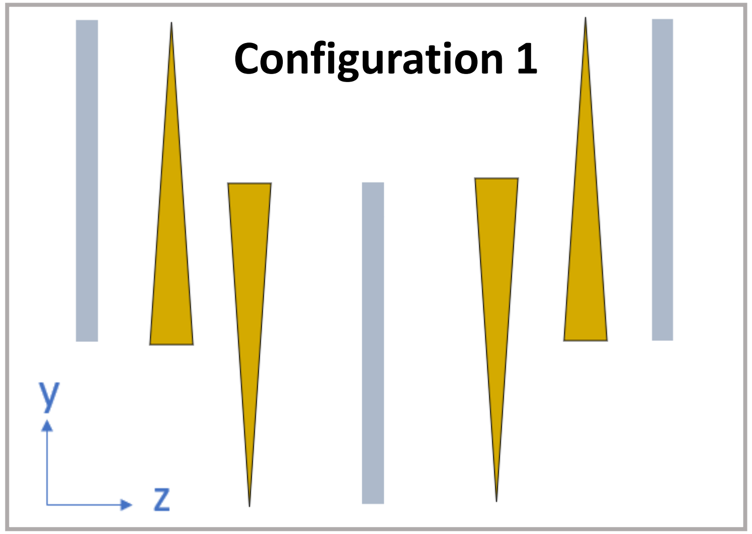
2 Optimization of the experimental setup

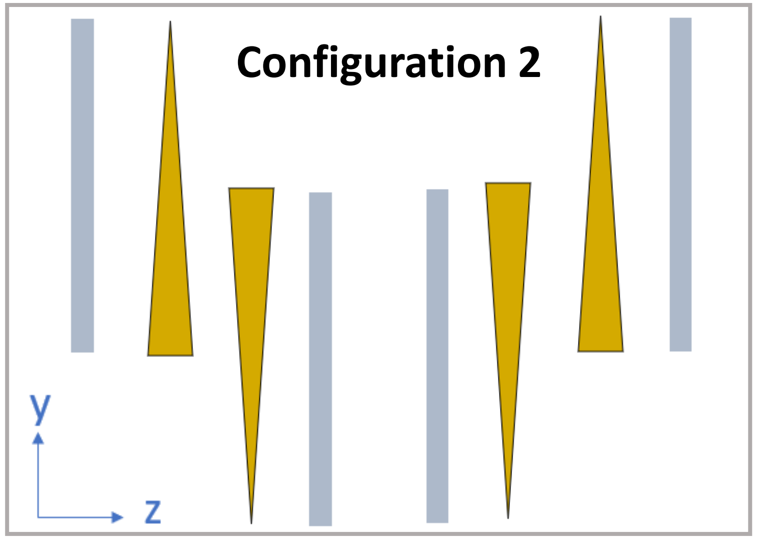
Detection plane

- Time resolution (20 - 50 ps)
- Spatial resolution (40 - 200 µm)
- Thickness (0,4 – 1,5 mm)

Configuration of the π spectrometer

- Number of planes (3 and 4)





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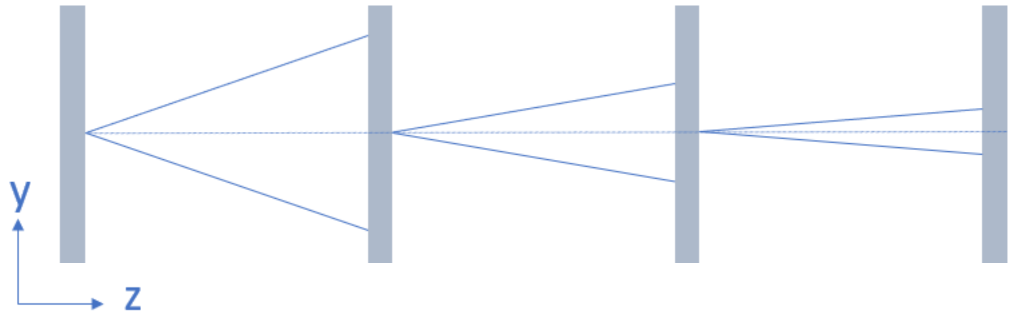
Track reconstruction : Method

Challenge

- Large number of particles (10^{12} part./s)

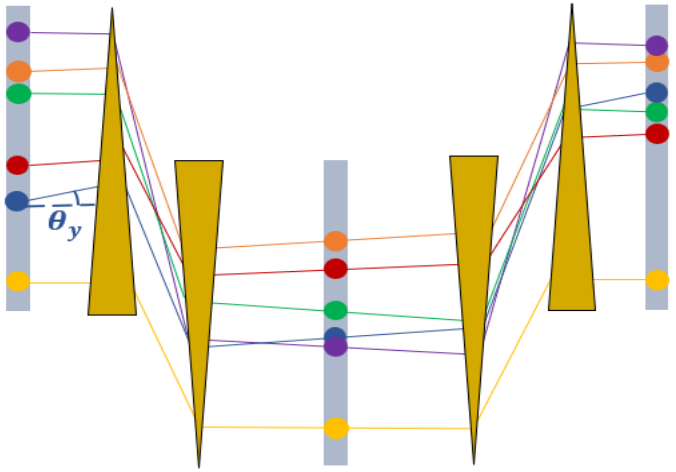
Algorithm implemented in C ++/ROOT



Association algorithm

- Kalman filter propagation through detection planes

  → compute the Chi2 of each possible track



- Search of the set of hits associations that minimizes the chi2 sum of all tracks

- As the exhaustive search impossible
  → suboptimal optimisation of the chi2 sum

Outline

Results : Simulation

Particles generation

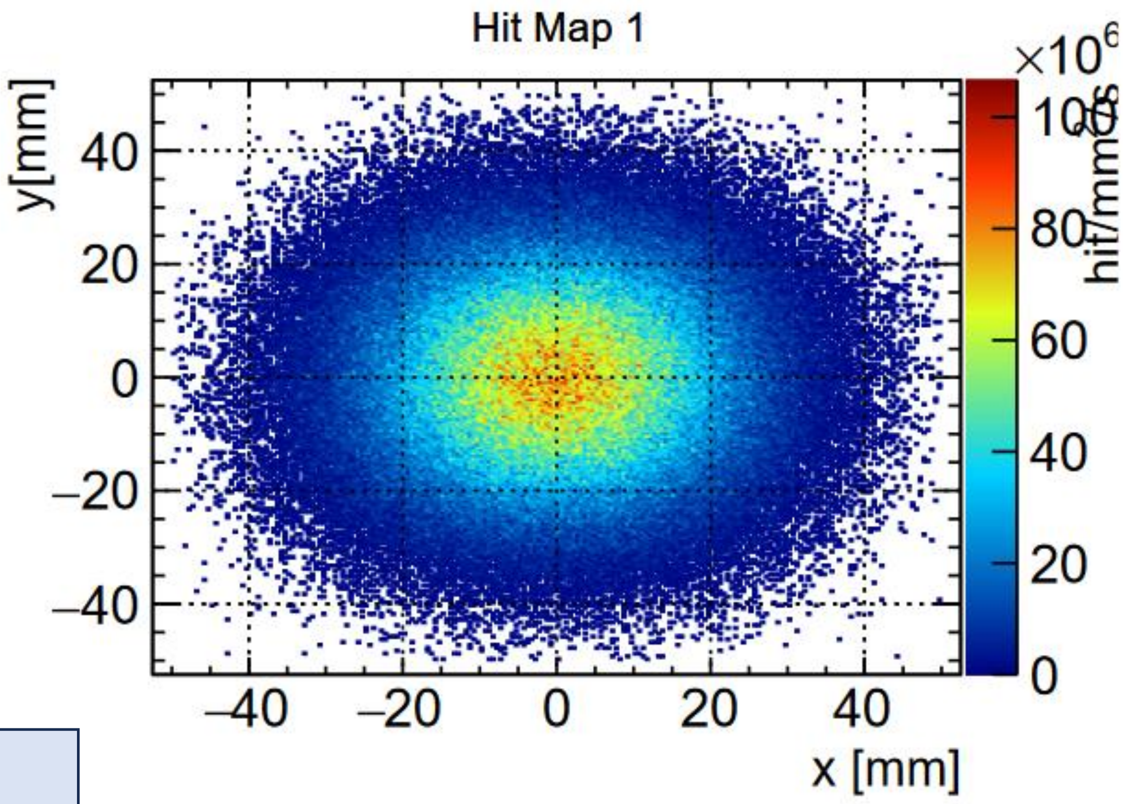
- Experimental conditions : 100 MHz/mm^2 peak flux

  → 1 event = 30 particles within 300 ps spreaded on 5x5 cm planes

- Evaluate association performances on 10 000 events

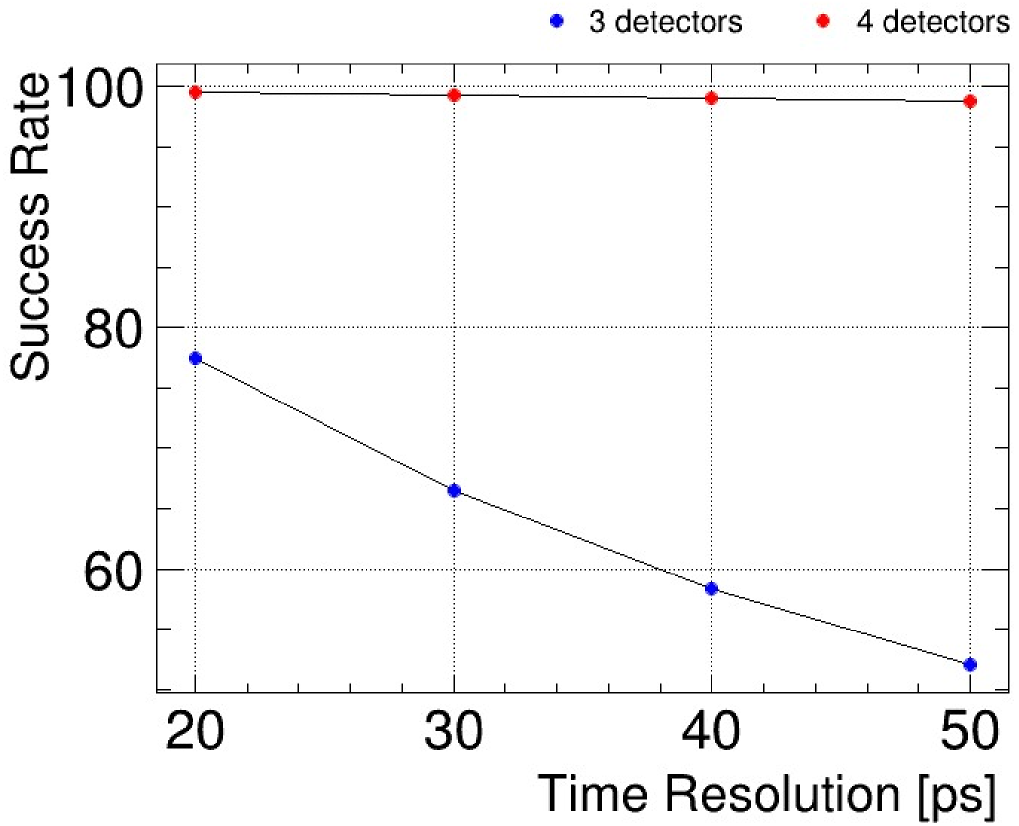
- $P_\pi = 12\ GeV \rightarrow p_\nu = (1 - m_\mu^2/m_\pi^2)E_\pi = 0.43E_\pi = 5GeV$

First maximal oscillation at 1600 km

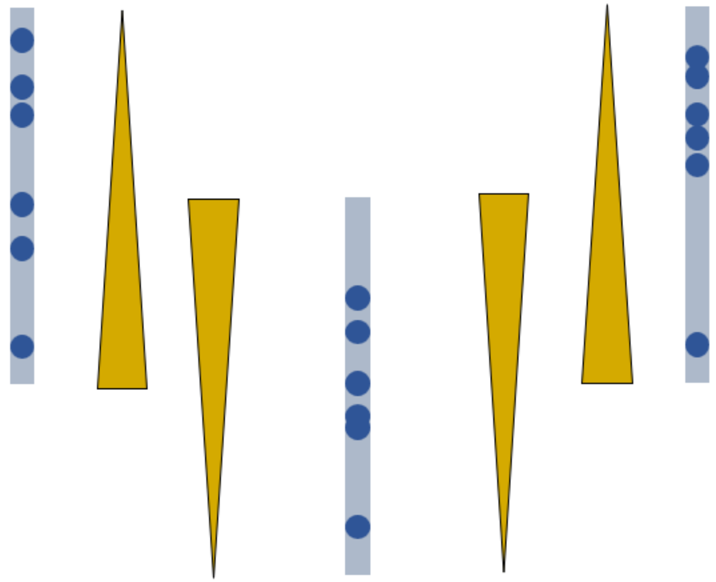


Results : Track reconstruction

Success rate : Proportion of correctly reconstructed tracks among all tracks (30 part. x 10 000 events)



In the y-plane, any triplet of hits is a physically valid track



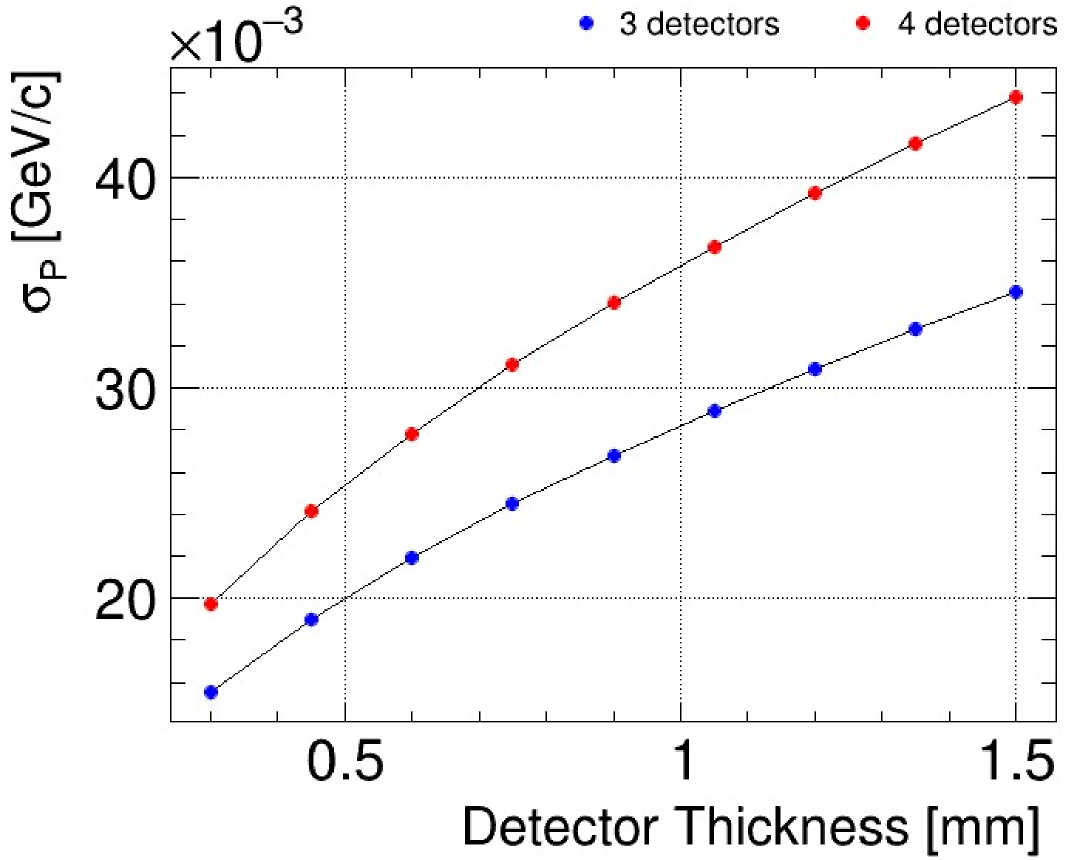
→ Time resolution essential to reconstruction (constraint)

Results : Momentum resolution

Number of planes

4 planes configuration degrades momentum resolution by ~20%
(will be reflected on σ_{p_ν} and σ_{E_ν} as $p_\nu = 0.43 E_\pi$)

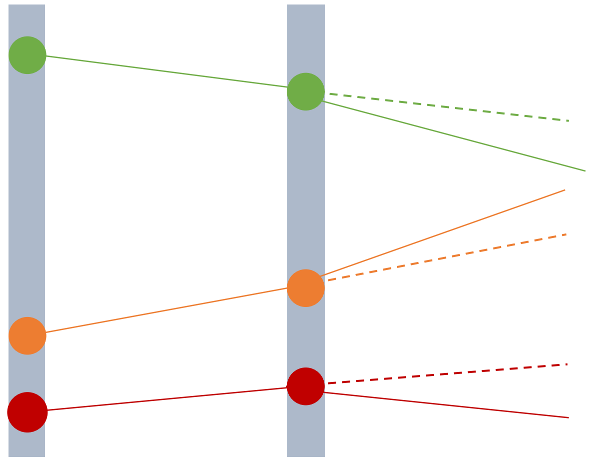
Requires to study the best trade off by studying the complete setup

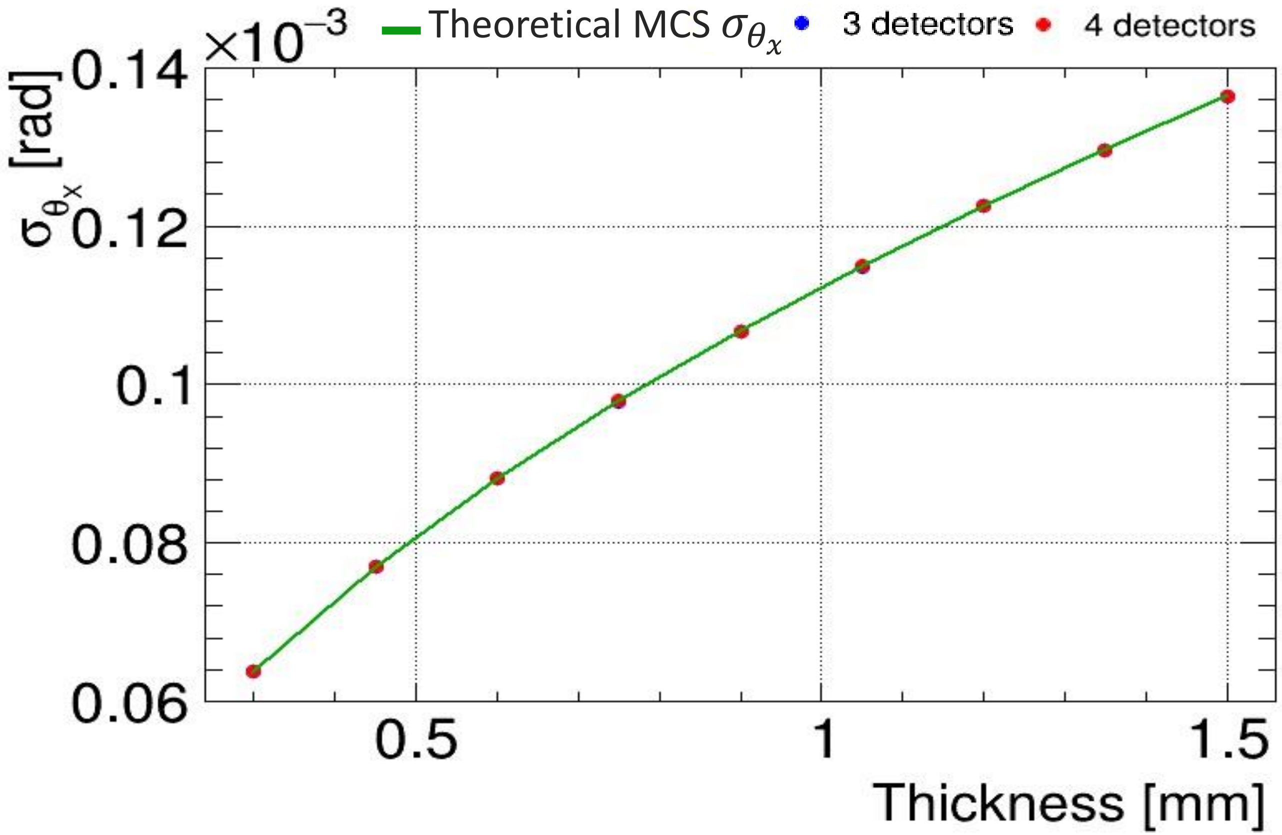


Results : Angular resolution

Importance of multiple coulomb scattering

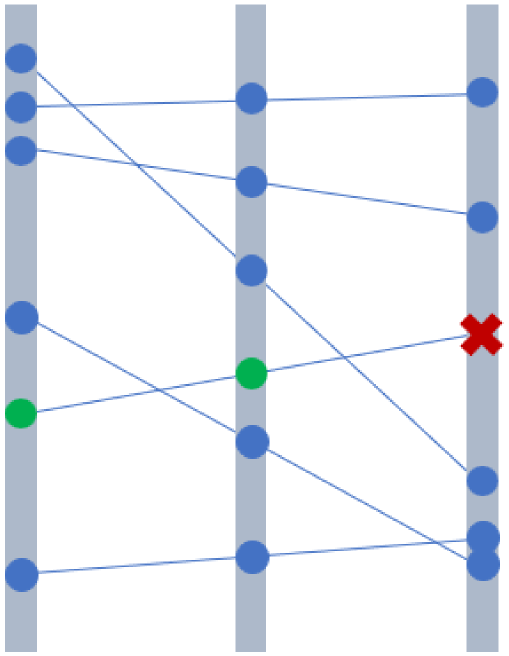
- Resolution on particle direction dominated by **multiple coulomb scattering (MCS)** in the last plane of detection

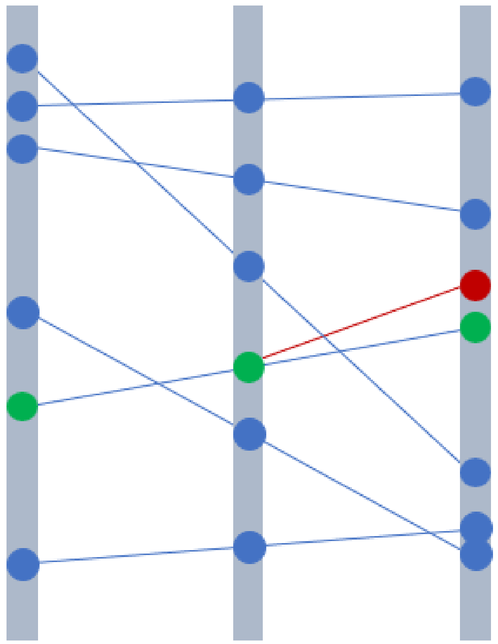




Next steps …

- **Missing hits, false detection and pixel clusters**





Conclusions

- Promising results : ability to reconstruct tracks, despite the very high rate

- Identification of the most relevant detector characteristics
  - Time resolution
  - Number of planes
  - Thickness

- Perspective : Implement the decay reconstruction and include realistic detection effects

Thank you for your attention

Backup : CP violation (oscillations)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric **Reactor** **Solar**

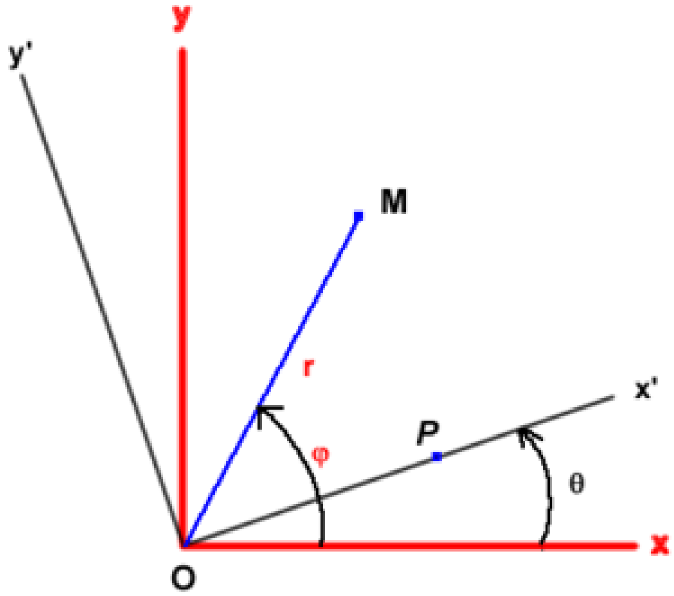
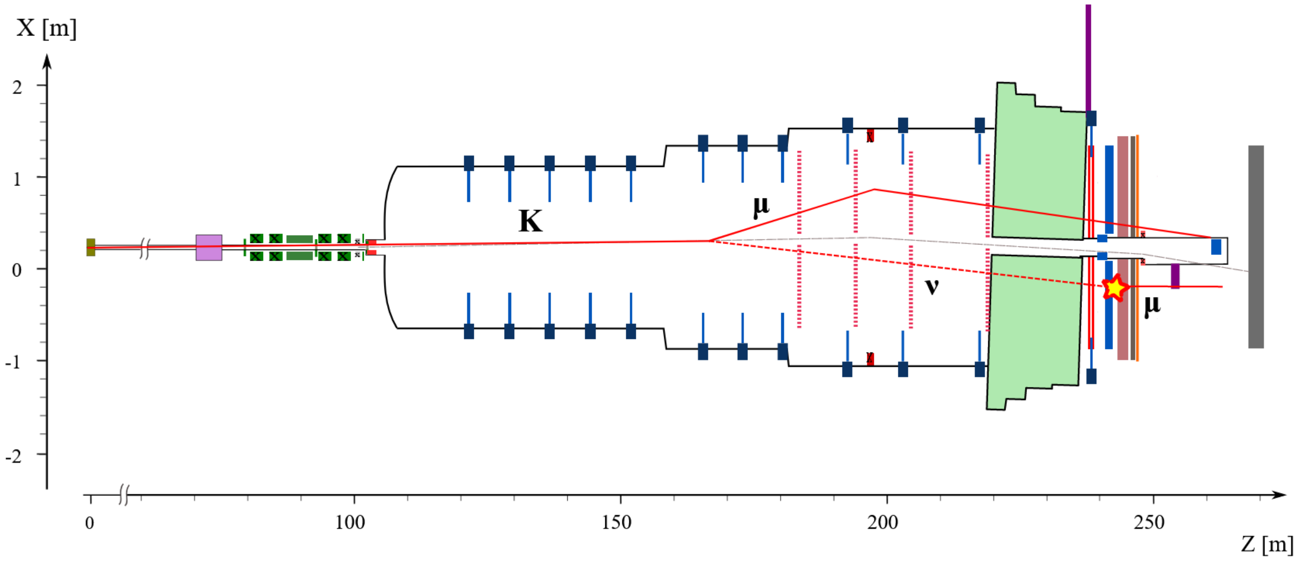


Image Wikipédia

Backup : Neutrino Tagging perspectives

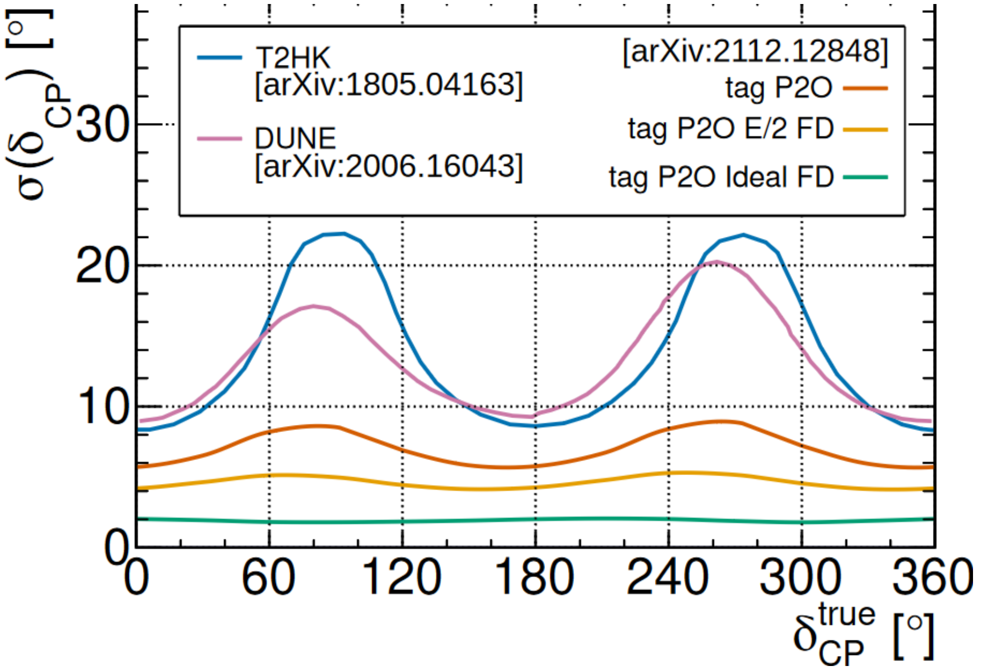
- **Short term : proof of concept NA62/GigaTracKer**



- **Long term : KM3NeT/ORCA**

Baseline 1600 km

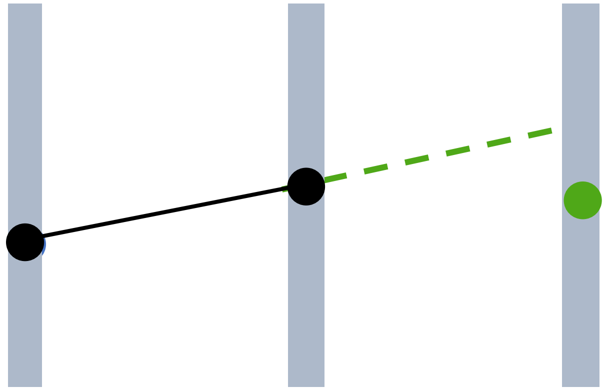
Coupled with Cherenkov detector



Eur. Phys. J. C (2022) 82:465
Mathieu Perrin-Terrin

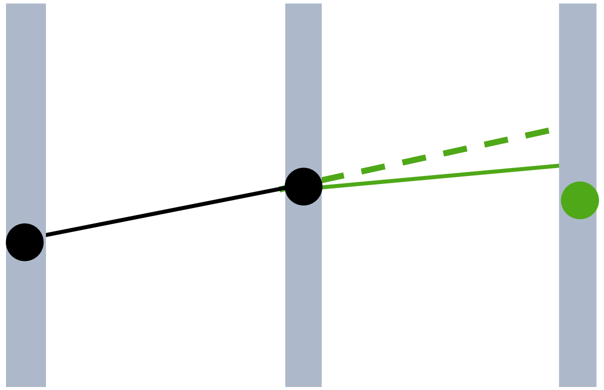
Backup : Kalman filter

Estimation of kinematics quantities (Track fitting) : Kalman Filter



Step 1 : Prediction of the $\boldsymbol{X}_k$

$$\boldsymbol{X}_k = \begin{pmatrix} x_k & y_k & \delta t_k & \theta_{x,k} & \theta_{y,k} & 1/p \end{pmatrix}^\top$$



Step 2 : Estimation of the $\boldsymbol{X}_k$

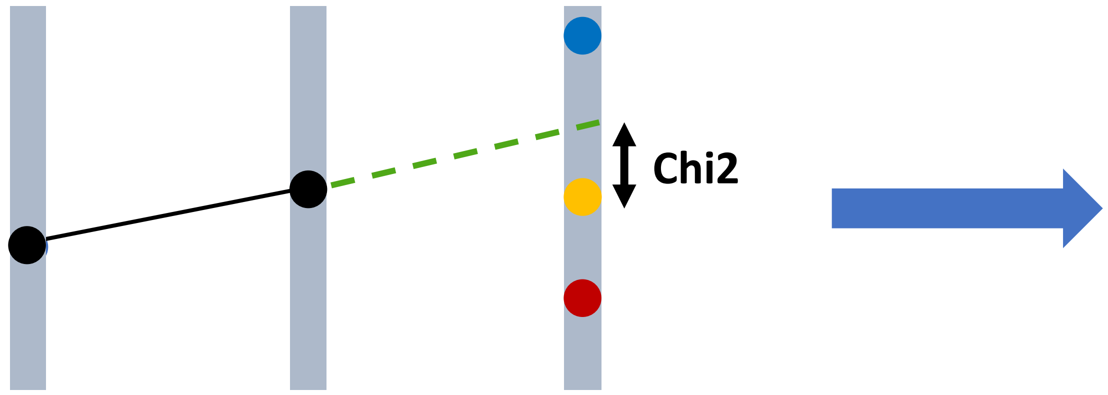
(Update with the measurement $\boldsymbol{Y}_k$)

$$\boldsymbol{Y}_k = \begin{pmatrix} x_k & y_k & \delta t_k \end{pmatrix}^\top$$

+ Estimation of associated **uncertainties**

Backup : Kalman filter

Reconstruction of the tracks (Track finding)



Step 1 : Prediction of the $\boldsymbol{X}_k$

$$\boldsymbol{X}_k = \begin{pmatrix} x_k & y_k & \delta t_k & \theta_{x,k} & \theta_{y,k} & 1/p \end{pmatrix}^\top$$

- If Chi2 < threshold, add to a list of potential good tracks
- Algorithm that selects the best association of tracks with no hits in common

Backup : Kalman filter

$$\boldsymbol{X}_k = \boldsymbol{F}_k \boldsymbol{X}_{k-1} + \boldsymbol{V}_k$$

$$\boldsymbol{V}_k \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{Q}_k)$$

State equation

$$\boldsymbol{Y}_k = \boldsymbol{H}_k \boldsymbol{X}_k + \boldsymbol{W}_k$$

$$\boldsymbol{W}_k \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{R}_k)$$

Measurement equation

Prediction

$$\boldsymbol{m}_{k|k-1} = \boldsymbol{F}_k \boldsymbol{m}_{k-1|k-1}$$
$$\boldsymbol{P}_{k|k-1} = \boldsymbol{F}_k \boldsymbol{P}_{k-1|k-1} \boldsymbol{F}_k^T + \boldsymbol{Q}_k$$

Gain calculation

$$\boldsymbol{S}_k = \boldsymbol{H}_k \boldsymbol{P}_{k|k-1} \boldsymbol{H}_k^T + \boldsymbol{R}_k$$
$$\boldsymbol{K}_k = \boldsymbol{P}_{k|k-1} \boldsymbol{H}_k^T \boldsymbol{S}_k^{-1}$$

Update

$$\boldsymbol{m}_{k|k} = \boldsymbol{m}_{k|k-1} + \boldsymbol{K}_k \left(\boldsymbol{y}_k - \boldsymbol{H}_k \boldsymbol{m}_{k|k-1}\right)$$
$$\boldsymbol{P}_{k|k} = \boldsymbol{P}_{k|k-1} - \boldsymbol{K}_k \boldsymbol{H}_k \boldsymbol{P}_{k|k-1}$$

Optimal Bayesian estimation of state vector

Backup : Kalman filter

$$\boldsymbol{F}_k = \begin{pmatrix} 1 & 0 & 0 & d_k & 0 & 0 \\ 0 & 1 & 0 & 0 & d_k & \beta'_k \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \text{and} \quad \boldsymbol{Q}_k = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma'^2_{\theta_y} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma'^2_{\theta_y} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} .$$

Backup : Tracks reconstruction

Likelihood

$$-2\log \mathbb{P}(\underline{\boldsymbol{Y}}|\underline{\boldsymbol{A}}) = \sum_{i=1}^{n}\sum_{k=1}^{K} \log\det\left(2\pi \boldsymbol{S}_k\right) + \underbrace{\left(\boldsymbol{y}_k^{A_k^i} - \boldsymbol{H}_k \boldsymbol{m}_{k|k-1}^{m}\right)^T \boldsymbol{S}_k^{-1} \left(\boldsymbol{y}_k^{A_K^i} - \boldsymbol{H}_k \boldsymbol{m}_{k|k-1}^{m}\right)}_{\text{Chi2}}$$

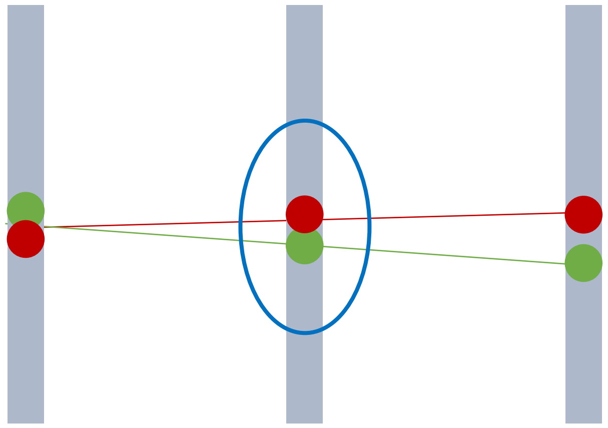
➔ Minimize the **Chi2** : $\widehat{\underline{\boldsymbol{A}}} = \arg\min_{\underline{\boldsymbol{A}}} -2\log \mathbb{P}(\underline{\boldsymbol{Y}}|\underline{\boldsymbol{A}})$

Backup : Permutations

Add of permutation function

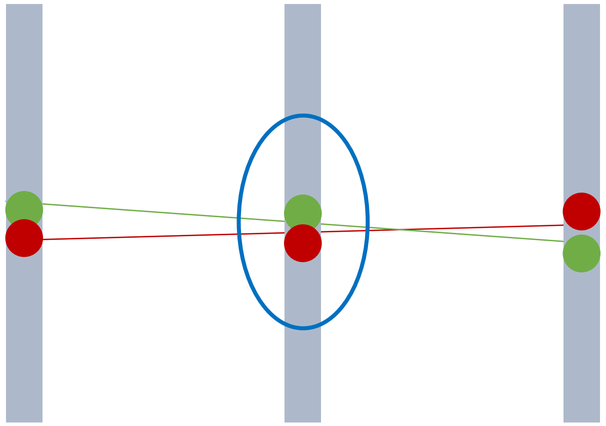
Issue

The majority of bad track finding is due to close tracks that had exchange their hits

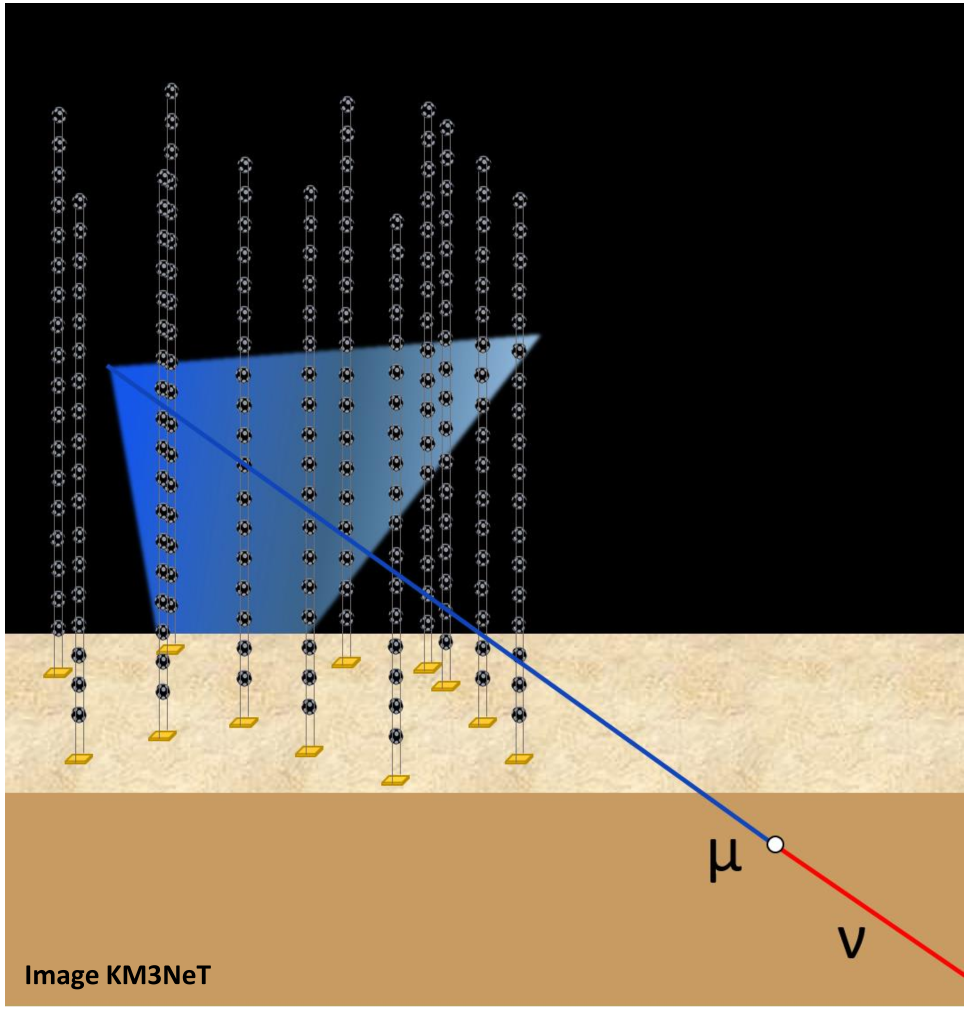


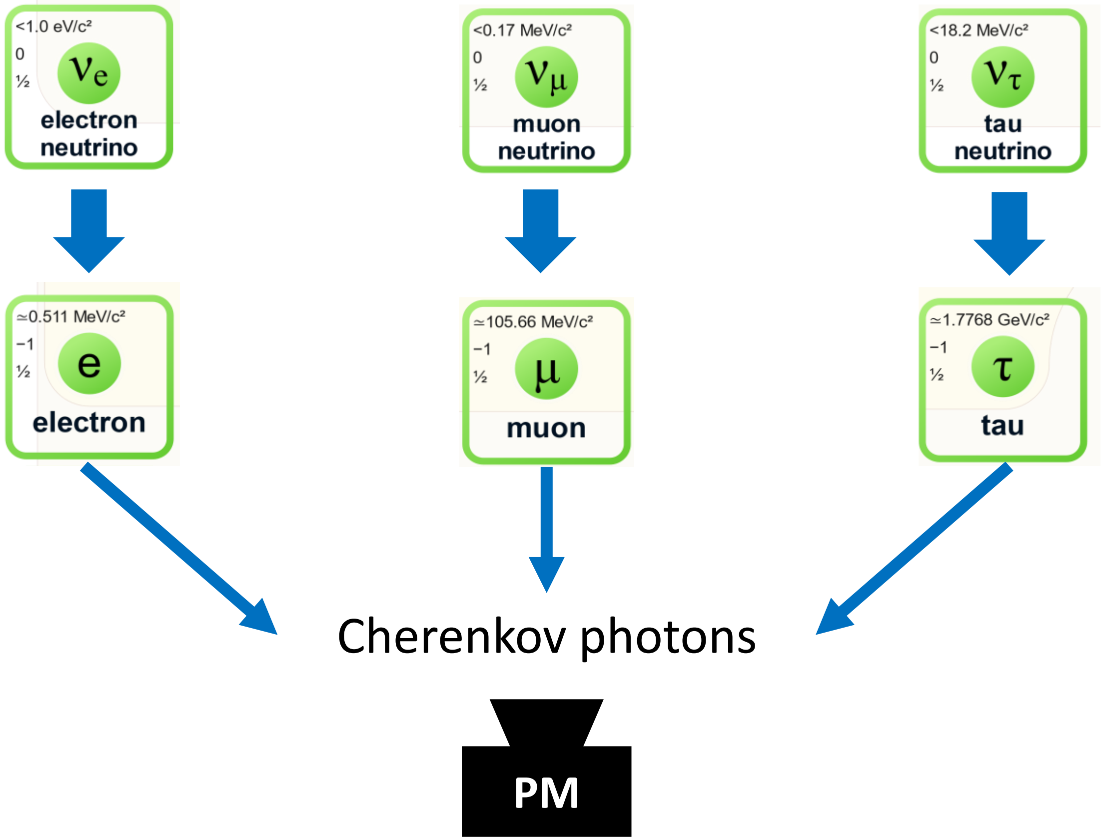
Solution

Permute the hits of the close track and compute the chi2
→ If the permutation decreases the chi2, the permutation is validate



Backup : Cherenkov detector





Information on energy, flavour and direction of neutrinos

Backup : possible baselines

- Cern → Pillos (Grèce) : 1700 km
- Cern → ARCA (Italie) : 1300 km
- Protvino → ORCA (France) : 2600 km

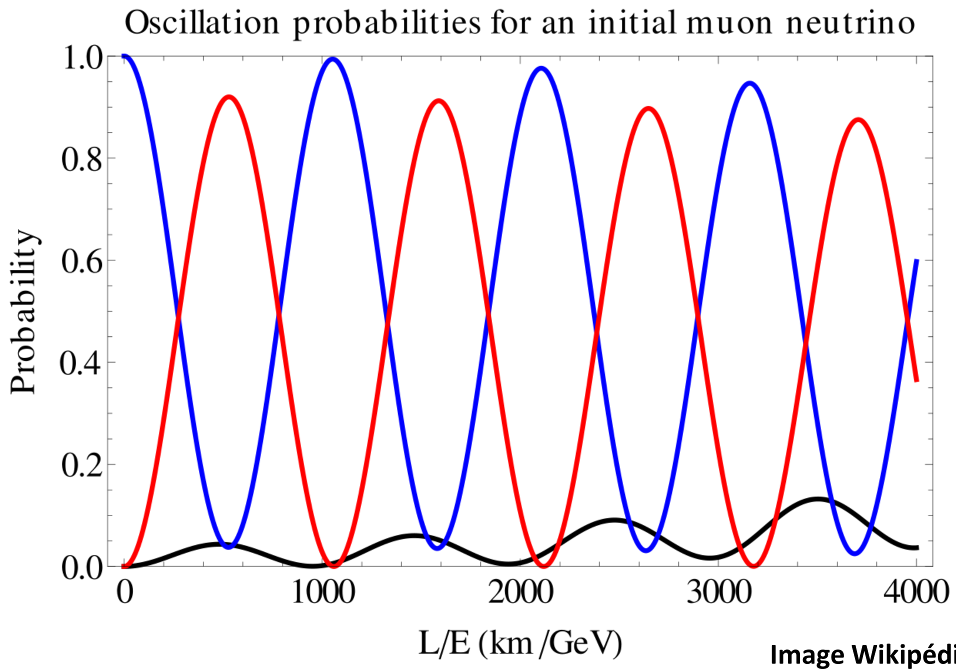
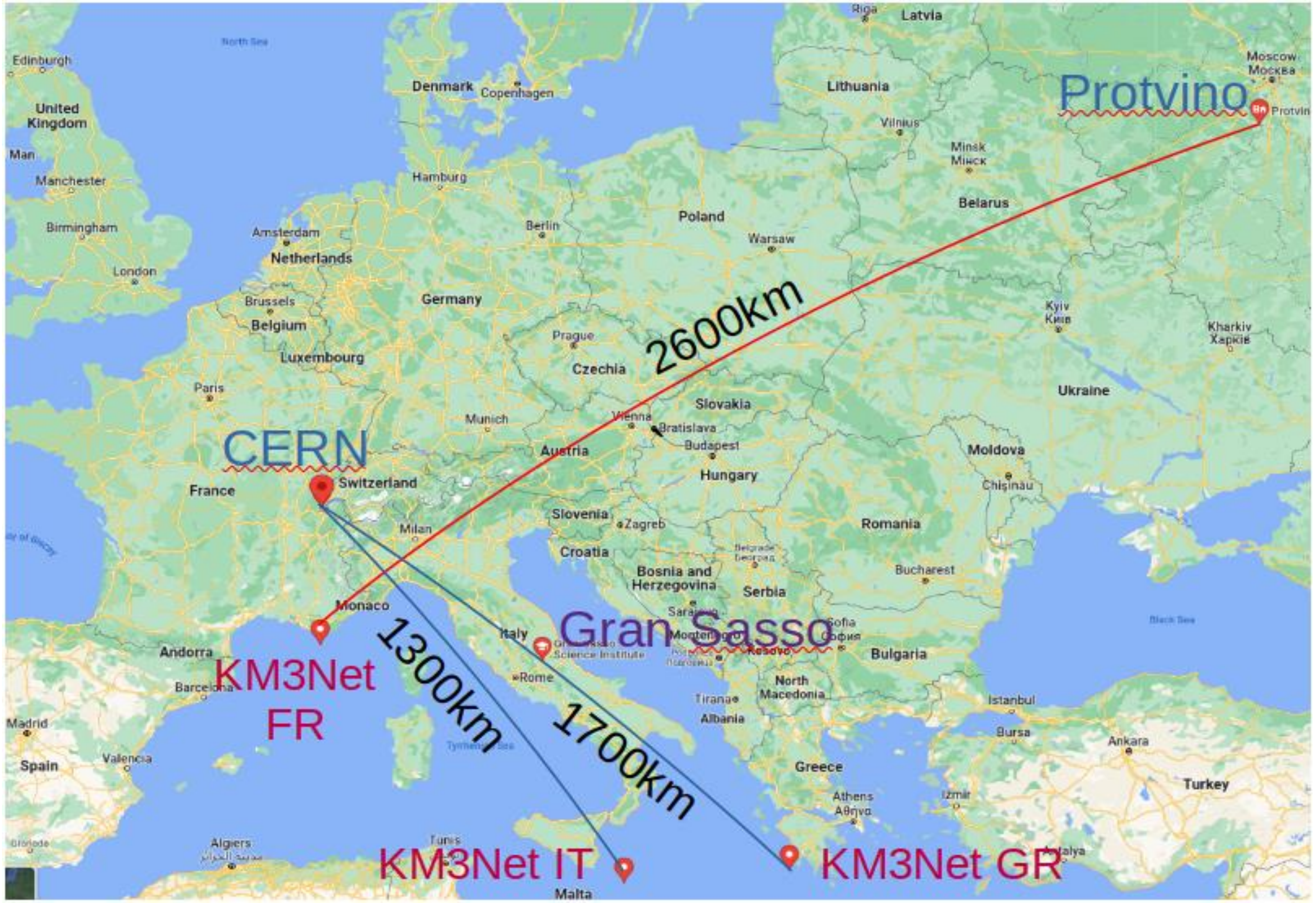


Image Wikipédia



Backup : Neutrino production

Neutrino production

1. Proton acceleration
2. Proton collision with a target
3. Generation of pions
4. Decay of pions into neutrinos + muons