FINAL REPORT

Study towards the design of a small angle spectrometer at LHC

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Introduction

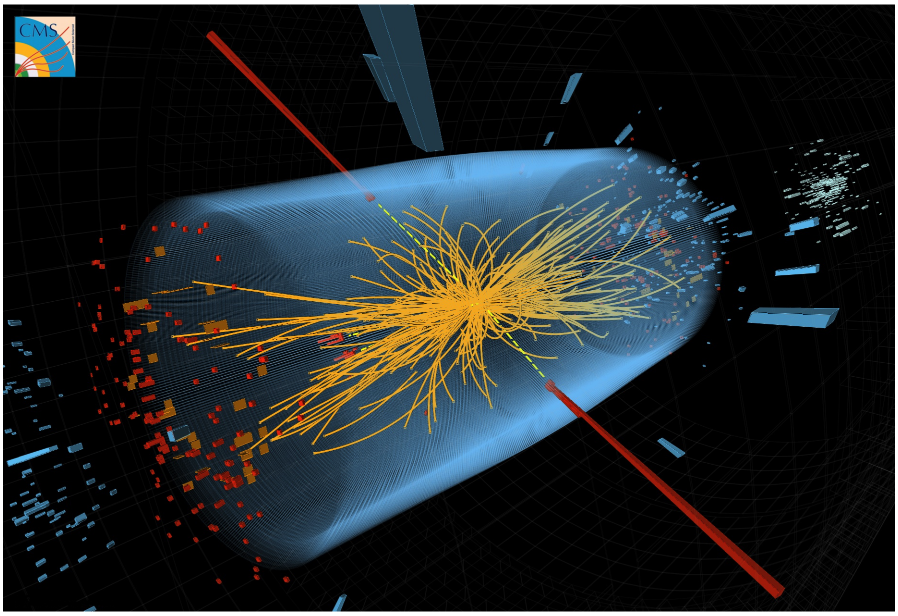


Figure 1: 7x7 pp collision at CMS

The main projects which are currently developing all the way around LHC involve what happens at very short distances from the interaction points: CMS, for instance, is 22m long, which means that the detector is able to collect particles having a transverse momentum P_T big enough to make them exit the pipe whithin this distance.
In a three-dimensional frame in which the two proton beams are travelling along the z-axis,

$$P_L = P_z$$
$$P_T = \sqrt{P_x^2 + P_y^2}$$
$$P = \sqrt{P_x^2 + P_y^2 + P_z^2}$$

therefore, when P_T is big, P_L is small: these experiments are focusing on less energetic particles.

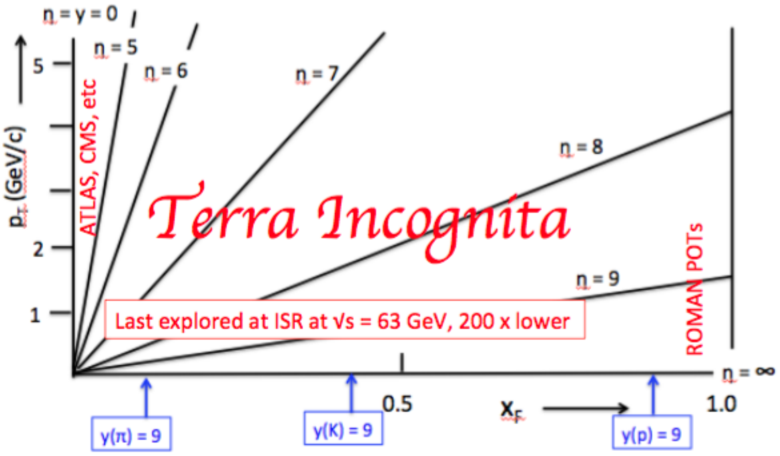


Figure 2: Schematic overview of η's values major experiments are interested in.

What we are interested in is to reveal particles going along the beam pipe at longer distances:

- from 84m to 140m
- $\eta \sim 9$ and even higher
- $0 < x_F \lesssim 0.5$.

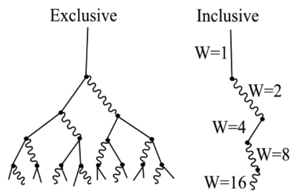
Spectra of these particles have been measured only at ISR (Intersecting Storage Rings) but at a 200 times lower energy; but they are of interest in studying, for example, cosmic ray showers.
One plausible solution seems to be to use a bent crystals to deviate particles towards the edge of the pipe; this tecnique is called *channeling*.
The working principle of channeling rather simple: in fact, since crystals are characterized by an ordered structure of charged ions, positive charged particles in between two ion planes feel the repulsive Coulomb force and get collimated (i.e. channeled). Moreover, if the crystal is slitghly bent, the beam deflects. Nevertheless, the actual realization of the channeling is extremely hard, because of a microradian-scale angular acceptance, due to the plane distance, $\sim \AA$.

Simulations

Settings

None of the experiments at LHC equip any kind of detector able to face this new level of study, then, first of all, we had the necessity to carry out Monte Carlo (MC) simulations.

What we use is the MARS CODE, which has been developed from the first 70's by Nikolai Mokhov here at Fermilab.
MARS is a set of MC simulations which simulate the passage of particles through matter; it comes from Feynman's ideas about what is called an *inclusive approach* to multiparticle reactions. Main features of this approach are that, at an interaction vertex, a particle cascade tree is constructed using a fixed number of representative particles; each one of these particles carry a statistical weight which is equal, in the simplest case, to the partial mean multiplicity for the particular interaction[1].
The one below is a graphical useful visualization of the difference between the *inclusive* and the *exclusive* approach:



As it clearly shows, more than one particles at the same level of the cascade is represented by a statistical weight larger than W=1: this feature has the evident benefit of a much shorter computing time.
The price to pay here is that energy and momentum are conserved only on the average over a certain number of collisions, but not at any single vertex, as quantum field theory would require.

MARS uses DPMJET as event generator and simulations have the following parameters:

- $\sim 10^6$ pp collisions

[1]This weight is W=1 when we have a real particle

- $\sqrt{s} = 13$ TeV
- $P_L \geq 0.5TeV$
- $\pm 142.5\mu$rad horizontal crossing
- $\sigma = 5.6cm$
- 3 virtual detectors revealing tracks passing through them placed at:
  - 84.3m from the interaction point;
  - 107.2m from the interaction point;
  - 131.2m from the interaction point.

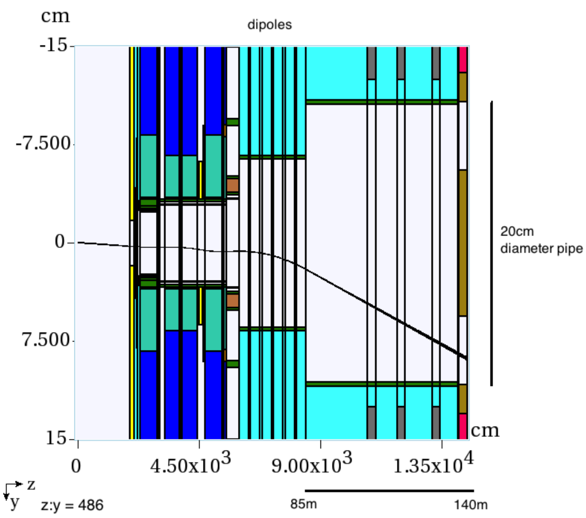


Figure 3: Primary beam, as it is shown on MARS GUI.

Within this parameter settings, DPMJET predictions are the following:

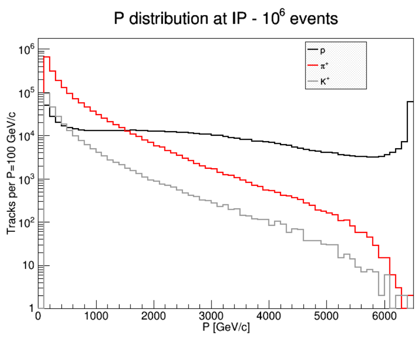


Figure 4: Positive particles

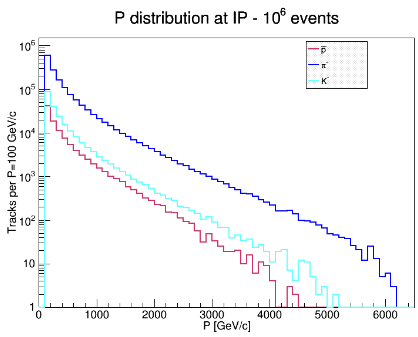


Figure 5: Negative particles

Results

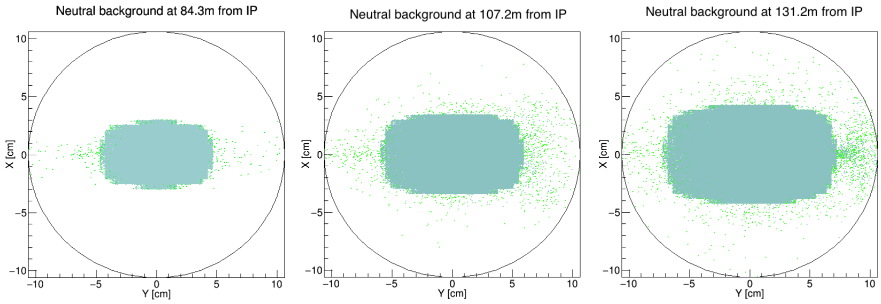
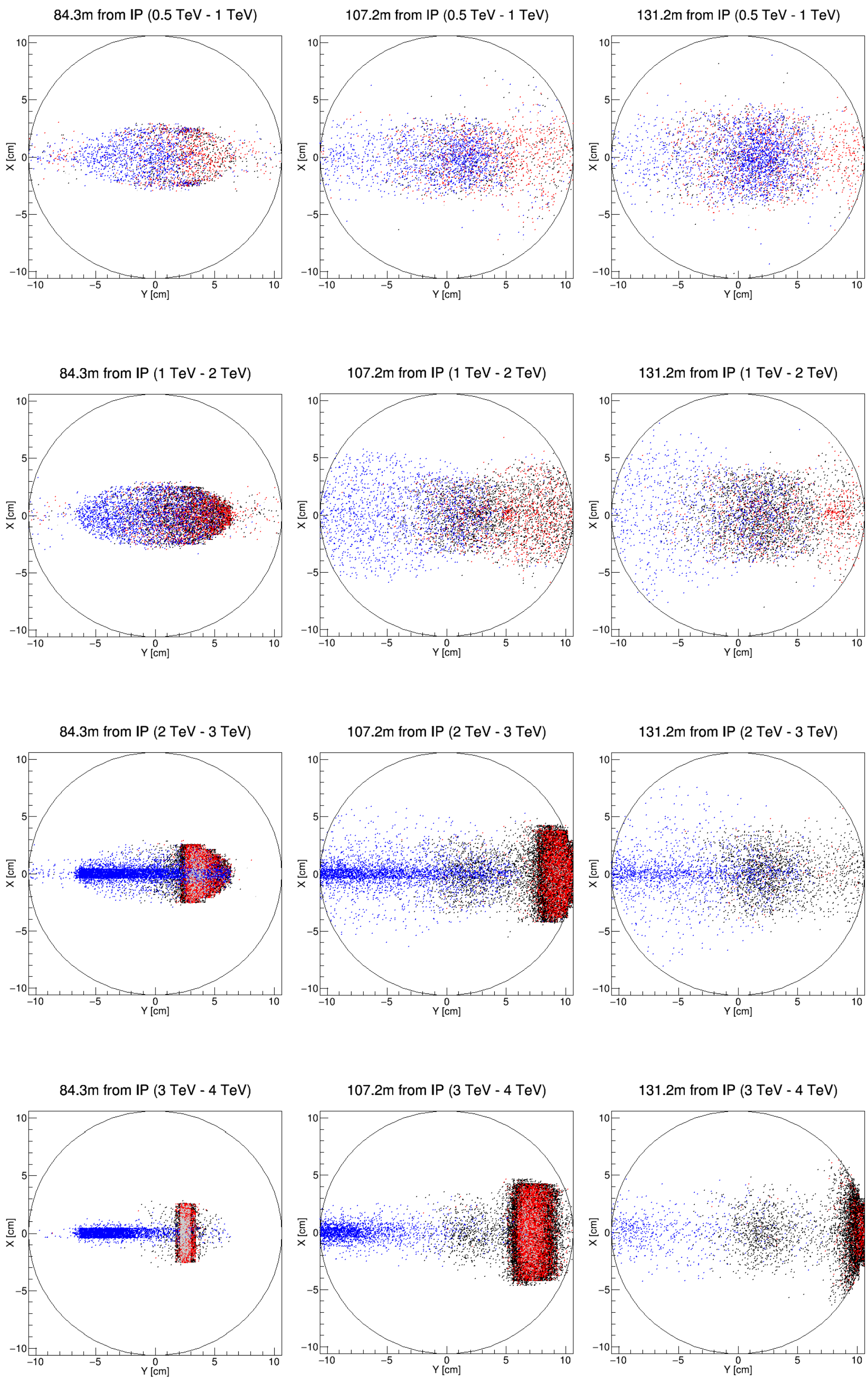


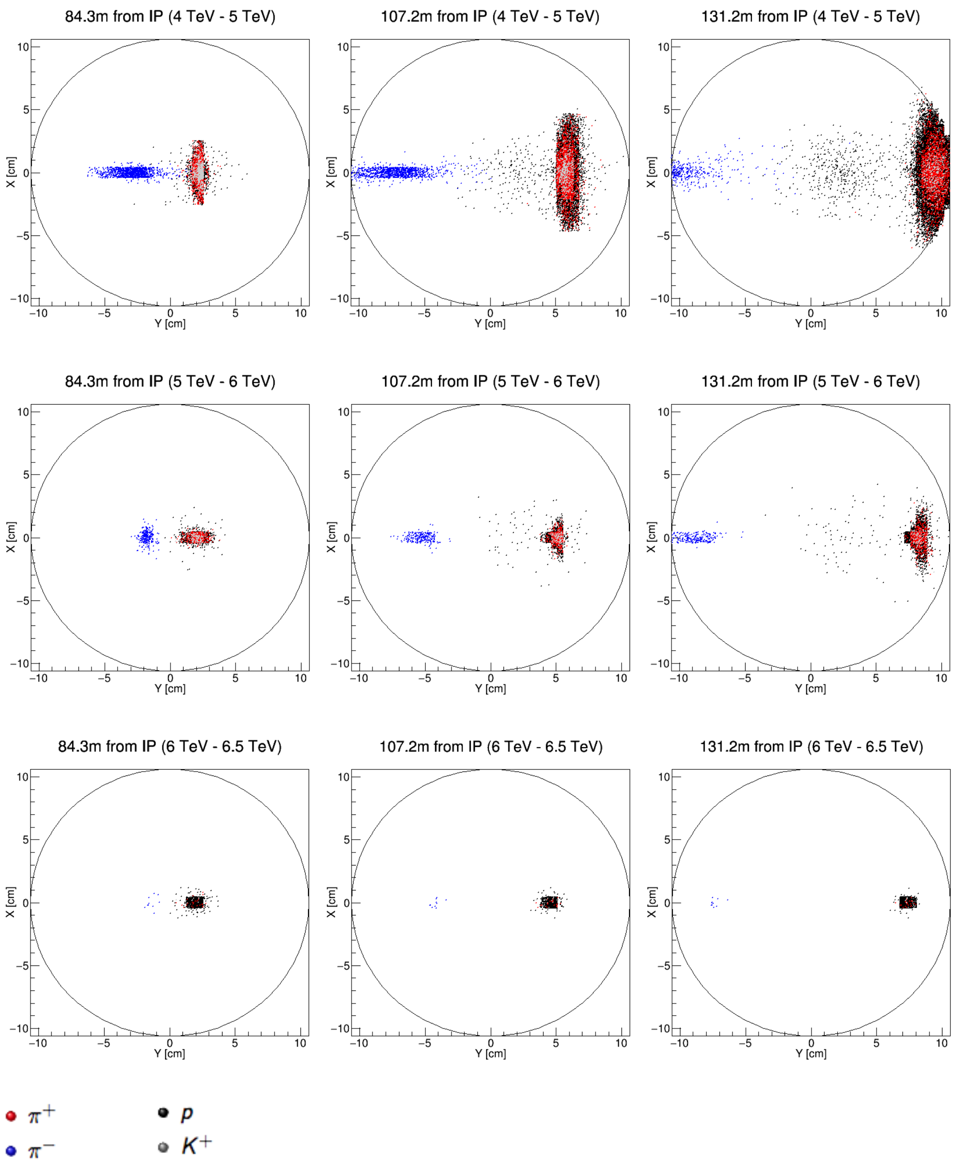
Figure 6: neutrons and γ at the 3 detectors.

It immediately shows a massive source of neutral background, which is one of the main responsible of crystal damaging.
But, as expected, neutral particles are not affected by fields in the quads and dipoles, then they appear only in the central area of the pipe; that is why we decided to analyze what happens closer to the edges and split the project in two phases:

- analysis of spectra without any crystal
- use a crystal to deviate particle trajectories, required only for highest-momenta particles.

Within this study I only focused on the first one.
With this purpose in mind, it is useful to visualize where the tracks appear in the three detectors. In order to do so, I produced several scatter plots of charged particles, out of data generated by DPMJET; I sorted them by slices of energy, because the distance they are able to walk depends of course on their energy.


84.3m from IP (0.5 TeV - 1 TeV)
107.2m from IP (0.5 TeV - 1 TeV)
131.2m from IP (0.5 TeV - 1 TeV)
84.3m from IP (1 TeV - 2 TeV)
107.2m from IP (1 TeV - 2 TeV)
131.2m from IP (1 TeV - 2 TeV)
84.3m from IP (2 TeV - 3 TeV)
107.2m from IP (2 TeV - 3 TeV)
131.2m from IP (2 TeV - 3 TeV)
84.3m from IP (3 TeV - 4 TeV)
107.2m from IP (3 TeV - 4 TeV)
131.2m from IP (3 TeV - 4 TeV)
X [cm]
Y [cm]



- Lower-energy ranges,

$$0.5TeV - 1TeV$$
$$1TeV - 2TeV$$

particles are spread out all the way in the horizontal plane, very few hitting the pipe.

- Higher-energy ranges,

$$5TeV - 6TeV$$
$$6TeV - 6.5TeV$$

they go down the pipe even more, making us not able to detect them, unless with a bent crystal.

- Middle-energy ranges,

$$2TeV - 3TeV$$
$$3TeV - 4TeV$$
$$4TeV - 5TeV$$

trajectories are at the edge of the pipe at 107.2m and they completely disappear at 131.2m, which means that in this region all of them are able to hit it.

Then it comes up the possibility to open window-detectors in the pipe with the following sizes along the vertical axis (x-axis):

LEFT SIDE $d_{x,L} = \pm 2cm$ **RIGHT SIDE** $d_{x,R} = \pm 5cm$

The following sketch is a suggestion on what our SAS should look like:

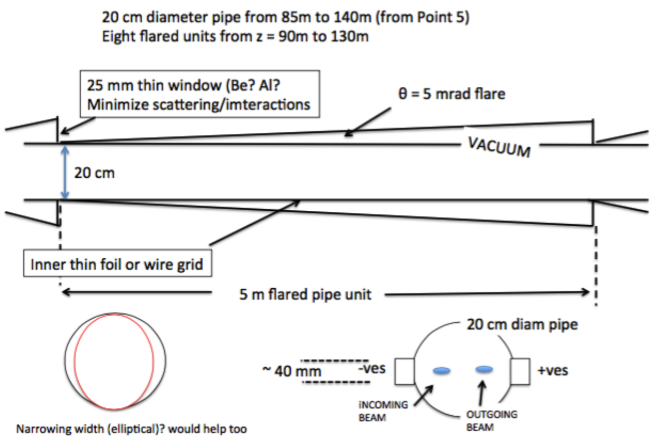


Figure 7: Beam pipe design for small angle spectrometer (very schematic)

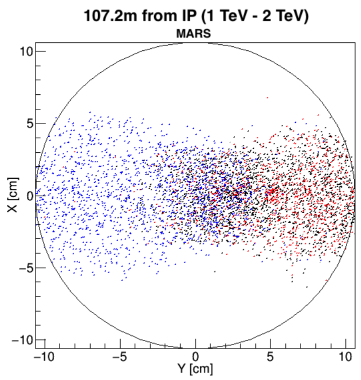
Particles should walk through the long paths placed around the pipe and be detected at the end of them.

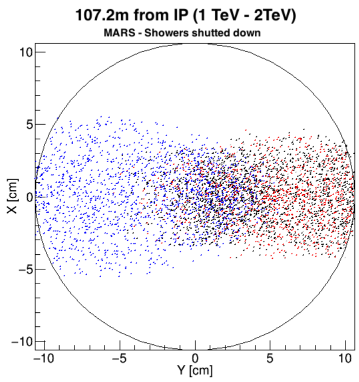
Background

MARS takes into account all physics processes also in the region of interest, including:

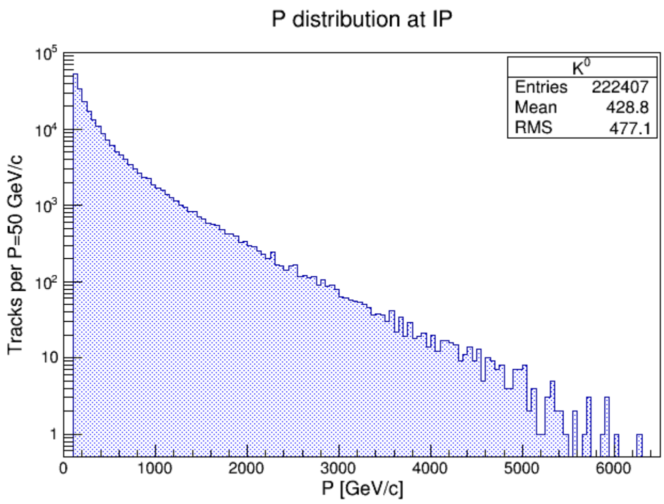
- **Scattering**
- **Decay**
- **Production of showers** from particles hitting the pipe

Scattering can only occur before the first detector, since there are no fields after this and particles just make straigh lines.
Production of showers can actually occur even in free-field region, but its contribution is very small; in fact we generated same simulations as before, but declaring all the materials as black holes, so that showers produced could not leave the materials.
Comparing the scatter plots created with these two approaches:





they are nearly the same, so showers are not a significant source of background.
Decay is, as the matter of fact, the most important cause of background particles. Let us take as an instance the decay of the K^0, a mixed eigenstate of K^0_S and K^0_L:



- $< P > \simeq 430 GeV$
- $c\tau = \begin{cases} 2.68cm & K_S^0 \\ 15.34m & K_L^0 \end{cases}$
- $\gamma \approx 10^3$
- $\lambda_D = \gamma c\tau \quad \Rightarrow \quad \begin{cases} \lambda_{D,K_S^0} \simeq 26.8m \\ \cancel{\lambda_{D,K_L^0} \simeq 15.3km} \quad \longleftarrow \quad \text{too long for our interests} \end{cases}$

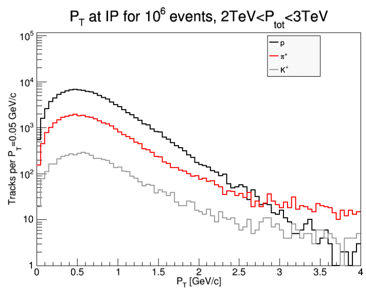
The most common decay channel for K^0 is

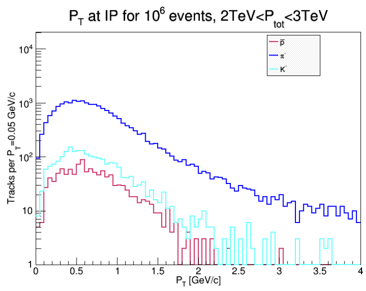
$$K_S^0 \to \pi^+\pi^- \qquad 68,20\%$$

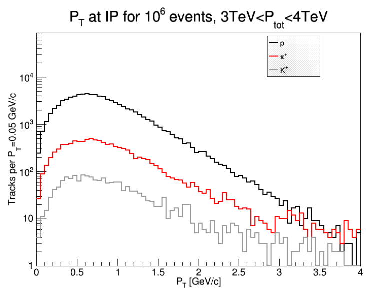
so this should explain the large amount of pions we have in the central area of the scatter plots.
However, since each pion takes half momentum from the kaon, on average, we would detect pions at $P_{\pi^\pm} = 215GeV$, which MARS is not set to see, because of the cuoff energy at $500GeV$.
Nevertheless, considering the huge flux of K^0 with P above the mean value, our assumption is absolutely consistent.

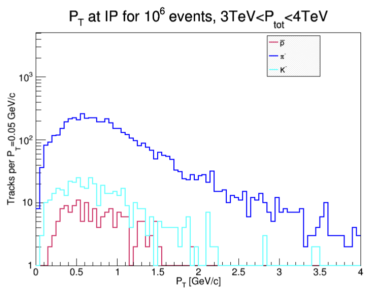
Conclusions

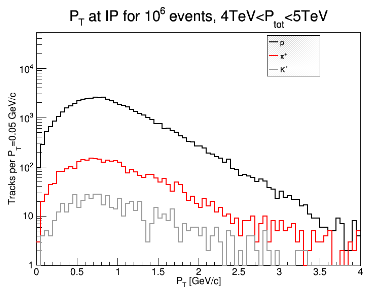
Of course, we are interested in measuring only spectra of the primary particles, therefore tracks reconstruction will be necessary.
As for now, what it is interesting for a quantitative analysis is to look at the P_T distribution at the Collision Point within the energy ranges useful for our purpose:

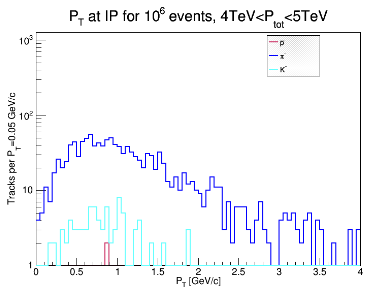












This is consistent with what we said so far, since a pick is clearly visible at low P_T in all the plots.

In conclusion, without a bent crystal only some slices of the spectra can be measured, and even for them, a lot of experimental work is required in order to reconstruct whether the tracks are coming from the origin or not. Nevertheless, this one seems to be a very promising study.