Highly parallel algorithm for high $p_T$ physics at FAIR-CBM

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Abstract.
The limitations of presently available data on $p_T$ range are discussed and planned future upgrades are outlined. Special attention is given to the FAIR-CBM experiment as a unique high luminosity facility for future continuation of the measurements at very high $p_T$ with emphasis on the so-called mosaic trigger system to use the highly parallel online algorithm.

1. Introduction

One of the most striking features observed at BNL-RHIC is the suppression of high $p_T$ production in central $A+A$ collisions relative to peripheral $A+A$ or $p+A$ or $p+p$ collisions, whose ratios are denoted by $R_{CP}$, $R_{A+A/p+p}$ and $R_{A+A/p+p}$, respectively. This is generally interpreted as a sign of parton energy loss in hot and dense strongly interacting matter created at the early stage of nucleus-nucleus collisions. This interpretation implies that the suppression should decrease towards lower energies where the initial energy and parton density are expected to be much smaller.

Numerous results on the energy dependence of hadron yields and spectra indicate that the onset of deconfinement is located at lower SPS energies [1, 2]. Existing data on central and peripheral Pb+Pb collision at 158 GeV/nucleon from the NA49 experiment allow measurement of the ratio $R_{CP}$ up to about 3.5 GeV/c in transverse momentum [3, 4]. A slight suppression is seen in this range, but the interpretation of this result is hindered by the poorly known interference with the Cronin effect [5]. The nuclear modification factors $R_{A+A/p+p}$ and $R_{A+A/p+p}$ would give a clearer picture: the first one is expected to contain a certain amount of Cronin effect and a possible suppression, while in the second quantity the Cronin effect approximately cancels. Therefore, the NA49 experiment extracted the modification factors $R_{Pb+Pb/p+p}$, $R_{p+Pb/p+p}$ and $R_{Pb+Pb/p+Pb}$ from the existing $p+p$ [6], $p+Pb$ and $Pb+Pb$ data at top ion-SPS energy. The modification factor $R_{Pb+Pb/p+Pb}$ (which does not contain the Cronin effect to first order) tends to confirm the previous expectations concerning $R_{CP}$. 

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The NA49 experiment, however, has only limited statistics on p+p and p+Pb collision data at top ion-SPS energy as it is visible in Fig.1. Therefore, future data runs are planned. The proposed FAIR-CBM high luminosity experiment has also a great potential in this field, as it will be able to populate the momentum space up to the kinematic limit.

One should emphasize the lack of existing p+p reference data in the energy range between 24 GeV and 200 GeV [7].

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{\(p_T\) range for \(\pi^\pm\) in p+p, p+Pb and Pb+Pb at 158 GeV/nucleon at midrapidity.}
\end{figure}

2. Future plans

As the current p+p and p+Pb statistics are limited to \(p_T \leq 2.5\) GeV/c, the future plan is to record more p+p and p+Pb reference data in the SHINE/NA61 experiment which is in preparation at the CERN-SPS to increase this range up to 4 GeV/c. Due to the limitation of this upgraded experiment and the development possibilities of the detector there is no hope in the foreseeable future to reach higher luminosity than 1000 interactions per second at CERN. There is, however, a unique opportunity at the FAIR accelerator in GSI, Darmstadt which will be ready around 2014, where the planned CBM detector [8] will be able to tolerate an interaction rate up to \(10^9\). This represents an improvement by a factor of about a million relative to the available SPS setup.

Though the proton beam energy at the FAIR accelerator will be limited to 90 GeV this will not decrease the physics interest. The main issues in p+p and p+A processes are even more exciting at high \(p_T\) at this lab energy, due to the fact that there is little information on either the Cronin effect or high \(p_T\) suppression in this range. As seen from Table 1, one can profit from the increased luminosity despite the small estimated cross-sections. Even with 45 GeV beam energy one expects significant statistics above 4 GeV/c.

Referring to the white region in between 24 and 100 GeV beam energy, the CBM experiment will study uncharted territory where the interesting change of the \(p_T\) spectra from convex to concave is happening. According to the usual argument this phenomenon is regarded as a simple phase-space limitation effect, but one should be aware that at 90 GeV beam energy the
### Table 1. Rate estimates and comparisons for high $p_T$ at low energies.

| Events | Energy [GeV] | $>3$ GeV/c | $>4$ GeV/c | $>5$ GeV/c |
|--------|--------------|------------|------------|------------|
| $2 \cdot 10^6$ | 158 | 100 | 1 | 0.01 |

Estimates with the assumption $10^{11}$ proton/sec $10^9$ interaction/sec

| 1 day $= 10^{14}$ | 158 | $5 \cdot 10^6$ | $5 \cdot 10^7$ | $5 \cdot 10^8$ |

| CBM Perspectives | Suppression | $158 \rightarrow 90$ | $10^{-1}$ | $10^{-2}$ | $10^{-3}$ |
|------------------|-------------|---------------------|----------|----------|----------|
| $1$ day $= 10^{14}$ | $90$ | $5 \cdot 10^8$ | $5 \cdot 10^5$ | 500 |
| $20$ day $= 2 \cdot 10^{15}$ | $90$ | $10^{10}$ | $10^7$ | $10^4$ |
| Suppression | $90 \rightarrow 45$ | $10^{-3}$ | $10^{-6}$ | $10^{-10}$ |
| $20$ day $= 2 \cdot 10^{15}$ | $45$ | $10^7$ | 10 | 0 |

3.5 GeV/c transverse momentum represents only about 0.5 in $x_T$, which is still rather far from the kinematic boundary. There may be some deeper physical effect, because the deviation from the simple exponential spectrum already starts around 1 GeV/c. This was a big surprise at CERN-ISR in the beginning of the seventies and due to lack of systematic measurements the real cause of this effect was not elucidated since then.

The CBM experiment at FAIR/GSI is being designed to measure hadronic, leptonic and photonic observables at the interaction rates up to 10 MHz in AA and 1 GHz in pp, pA collisions.

The acceptance should cover a large part of the phase space and be approximately uniform. The high interaction rates require unprecedented performances in terms of speed and radiation hardness, as well as a fast and efficient online event selection. The current layout comprises a high-resolution silicon tracking system (STS) placed in the 1 Teslameter field of a superconducting dipole magnet. This system should provide a momentum determination better than 1% and reconstruction of secondary vertices with a precision of 50 microns. Other parts of the detector are described in ref [8].

In case of 1 GHz collision rates one expects pileups on the level of few hundreds which induces a search for efficient triggering schemes to find the extremely rare events.

### 3. High $p_T$ particles in the STS

The basic idea of the filtering algorithm is that one can define rather narrow corridors for the high $p_T$ tracks because they are almost straight. Due to the relatively small number of hits in these narrow corridors one can perform extremely fast and exhaustive searches even in case of 500-fold pileup. In order to ensure full efficiency the corresponding regions of a given silicon surface (=mosaics) can be used in a number of corridors, therefore a so-called *multi-tasking MOSAIC-trigger network* is proposed.

In a fixed target experiment the Lorentz-boost transforms the small momenta in centre-of-mass system to large longitudinal momenta in lab system. It is known that all forward going particles with identical $p_T$ will have higher longitudinal momenta than the mid-rapidity particles. The Lorentz gamma-factor even at 25 GeV beam energy will provide a factor of 3.5 increase in energy that is a $p_T = 1$ GeV/c mid-rapidity pion would be equivalent to more than 3.5 GeV/c longitudinal momentum particle in the lab system.

#### 3.1. Curvature of the Trajectory

Due to the fact that the magnetic field is relatively modest in the CBM experiment, such particles will follow practically straight line in the STS part of CBM.
Inside the 1 meter long magnet one expects approximately homogenous magnetic field, thus one gets in \( xz \)-projection circular trajectories and almost exactly straight lines in \( yz \) projection. During this study we assume that there are 9 silicon detector planes which are located at positions with \( z \)-coordinates:

- PIXEL planes: \( z_1 = 5 \text{cm} \), \( z_2 = 10 \text{cm} \), \( z_3 = 18 \text{cm} \), \( z_4 = 20 \text{cm} \);
- STRIP planes: \( z_5 = 40 \text{cm} \), \( z_6 = 60 \text{cm} \), \( z_7 = 80 \text{cm} \), \( z_8 = 90 \text{cm} \), \( z_9 = 100 \text{cm} \), which have double-sided \( x \) and \( y \) readout.

In principle 3 points are enough to define a circle in the \( xz \)-plane. The track candidates are defined by using information from planes \( z_2 \), \( z_4 \) and \( z_6 \). From the pixel planes \( z_2 \) and \( z_4 \) one can get two space points \((x_2, y_2, z_2)\) and \((x_4, y_4, z_4)\) which give in a very good approximation the direction vector of the emerging particle.

Using this direction vector, one can calculate the \( x \) and \( y \) coordinate at position \( z_i \) assuming infinite momentum particle:

\[
x_i = m_x \ast (z_i - z_4) + x_4, \quad \text{where} \quad m_x = (x_4 - x_2)/(z_4 - z_2)
\]
\[
y_i = m_y \ast (z_i - z_4) + y_4, \quad \text{where} \quad m_y = (y_4 - y_2)/(z_4 - z_2)
\]

The \( y_i \) values are correct predictions, therefore one should check whether is there any particle hit within the measurement error.

One can get an estimate on the perpendicular momentum \( p_{xz} \) if one calculates

\[
\delta x_6 = x_6 - m_x \ast (z_i - z_4) + x_4,
\]

which gives the measure of deviation from the straight line and can be used to estimate by a parabolic curve the \( x \) value at \( z_i \):

\[
x_i^{\text{pred}} = A \ast z_i \ast z_i + B \ast z_i + C,
\]

where constants \( A \), \( B \) and \( C \) are determined from the previous 3 points.

4. Global High \( p_T \) Trigger for pp, pA interactions at FAIR CBM detector

In typical experiments the high \( p_T \) trigger is generally based on local detector elements (calorimetric cells or specialized few planes trackers) covering only some limited phase space. This arrangement assures reasonable parallelism and simple selection algorithms.

![Figure 2](image2.png)  **Figure 2.** Point source: singlecone corridors.

![Figure 3](image3.png)  **Figure 3.** Extended source: doublecone corridors.
The proposed mozaic trigger method is based on the information obtained by the standard large phase space tracking detector (in the concrete case the CBM-STS silicon detector) containing a relatively large (8-10) number of planes. By this global access scheme and a high parallelism one can achieve better performance than in the traditional local scheme. This relies on a data-driven algorithm based on strategically subdivided memory partitions (mozaics) reducing the calculations to the read-out of Content Addressable Memories (CAMs).

4.1. Algorithm
In reality the algorithm uses local detector elements, but they are virtual and created by data-driven online software.

Due to the extended beam-spot size there is no point source of particles (Fig.2). Instead of the singlecone track classification one proposes to use a doublecone approach based on the principal plane as it shown in Fig. 3., where plane #4 was selected because this was the last pixel plane.

4.2. Super parallelism definition:
If one takes the \((x_4, y_4)\) point of a high \(p_T\) track, then the search should be restricted only to the doublecone region, the opening angle of the cone is given by the beam spot size and the Coulomb-scattering. One needs as many parallel processors as the number detected points in the principal plane, in this ideal case the system is called super-parallel. One speaks about virtual super parallelism, if it is realized by less number of processors, where a broker provides in batch mode the processors and memory partitions necessary for the track candidates passing through the point \((x_4, y_4)\).

4.3. Practical parallelism
For each measured point the pixel coordinates \((x, y, z)\) or strip coordinates \((x, z)\) or \((y, z)\) are stored in a 1-bit CAM which are called mozaics. We assume

- Strip mozaic (CAM1) contains 64 - 256 bits
- Pixel mozaic (CAM2) contains 1 - 4 kbits,
where the optimal selection is depending on the pitch and the beam spot size. Assuming 50 microns pitch on sensor of 5cm*5cm size one needs 250 - 1000 pixel mozaics/sensor or 4 - 16 single-side strip mozaics/ sensor. The total number of mozaics is expected to be few tenthousands, which includes about 10 Mbit memory cells. This is a low number, but requires special content addressing memories realized in the readout FPGAs.

![HitCAM1](image)

**Figure 4.** HitCAM1.

![HitCAM2](image)

**Figure 5.** HitCAM2.
There will be used 2 types of CAMs:

HitCAM (Fig. 4. and Fig. 5.) will provide the nearest hit as reply for a given query which asks for a hit in a given domain. For HitCAM1 the domain is given as a range $[\text{min}, \text{max}]$, for HitCAM2 one needs to define 2-dimensional domain $[\text{minx}, \text{maxx}] [\text{miny}, \text{maxy}]$.

ListCAM (Fig. 6. and Fig. 7.) will provide a list of all hits within the domain defined by the query.

4.4. Programming scheme

The 3 phase programming scheme is shown in Fig. 10.

4.4.1. PHASE-I: Proximity tracklets

The proposed high $p_T$ selection method is starting on the principal plane #4. The required number of processors is equal to the number of mozaics in the principal plane. For each mozaic in plane #4 the list of mozaics in #3 plane is predetermined and in one single-step content addressing readout cycle one gets all the $[(x_3, y_3); (x_4, y_4)]$ tracklets which are potentially passing through the target. At the end of PHASE I each tracklet initiates a thread in its multi-core CPU. This procedure is very effective because $z_3$ is so close (proximity plane) to $z_4$, that generally there is only 1 tracklet candidate per plane #4 mozaic even in case of high pileups. Important remark: mozaics of #3 and #4 planes are ListCAM2 type. This assures exhaustive search for all tracks originating from the target.

4.4.2. PHASE-II: Linear tracking in pixel planes

The total $z$-difference between plane #1 and plane #4 is only 15 cm, therefore all the tracks are almost exactly linear in $xz$-plane too. Mozaics belonging to planes #1 and #2 are HitCAM1 type, providing the nearest hit for the query. All the threads are executing the same programming steps:

From planes #3 and #4 one predicts the $(x, y)$ domain in plane #2 if there is no hit found the thread dies, otherwise $(x_2, y_2)$ stored.

For surviving tracklets the procedure is repeated with prediction for plane #1. Due to the fact that very high momentum tracks frequently miss the first plane one does not kill tracklets with missing first point, but a flag stored instead of $(x_1, y_1)$.

4.4.3. PHASE-III: Parabolic tracking in strip planes

For parabolic tracking one need some curvature measurement. This is accomplished in plane#6, which again has ListCAM type mozaics but only in the $xz$-projection. This assures the exhaustive search in case of momentum calculations. All the other $x$ and $y$ strip planes have HitCAM1 type mozaics.
Combining each linear tracklet from the previous phase with all the candidates from \(x\)-plane\#6 list, one redefines the new set of active threads.

The successive planes are searched for the corresponding hits using the parabolic approximation from the previous 3 planes.

The simplified computing network is shown in Fig. 8.

CAM mosaics belonging to different doublecones can overlap as it is shown in Fig. 9., where for simplicity the plane \#5 between the principal and momentum planes are not shown.

During the parallel searches along the actual doublecones the same mosaic in plane \(z_i\) can be queried simultaneously from different threads therefore one needs multi-port CAMs (Fig. 11.) or physically more copies of them in order to avoid queing at the memories.

4.4.4. Trigger PHASE At the end of the tracking one can calculate an approximate value of the transverse momentum, \(p_{REC}^{T}\) from the \(p_{xy}^{REC}\) component determined from the \(\delta m_x\) deflection in the magnetic field as the angular difference

\[
p_{xy}^{REC} = C(B_{field})/\delta m_x, \quad \text{where} \quad \delta m_x = m_{xx} - m_x,
\]

\(m_x\) stands as above and

\[
m_{xx} = (x_9 - x_7)/z_9 - z_7
\]
Parabolic tracking

Figure 10. The 3-phase programming.

Linear tracking

Figure 11. Multi-port CAM.

and apply the TRIGGER threshold:

\[ p_T^{REC} > p_T^{LIMIT} \]

5. Mozaic trigger simulation for CBM-STS

The algorithm was tested on proton-Carbon interactions generated by the CBM Geant simulation program. 90 GeV beam energy was used at the event generation. At the simulation all the particle transport effects were included. For simplicity, it was assumed that the detector efficiency is equal to 100%. Particle hits were represented by single bit value, without using the analogue dE/dx information.

The recorded particle tracks were distorted by the passage through the detector materials, therefore the accuracy of momentum reconstruction is varying from track to track. Some
particles suffered more serious scattering effects, which caused that their trajectory became so distorted that it was not fitted anymore into the prescribed doublecone corridors. Table 2 shows the results on the reconstruction efficiency as a function of the $p_T$ threshold. It can be seen that at lower $p_T$ the probability of serious track distortion is higher, the pattern recognition efficiency increases from 58% at 0.5 to 88% at 2.5 GeV/c.

In some cases, though the pattern recognition was correct, the trigger was not realized, because the reconstructed value of $p_T$ was lower than the trigger limit due to the measurement error. This measurement error is increasing with $p_T$ from 5% to 15% because smaller angular differences are measured with the same accuracy.

Table 3 shows the case where complete single events were reconstructed. It coincides with Table 2 except the effect that one can not only lose tracks by measurement errors but also can gain. Due to the distortion effects a correctly reconstructed lower $p_T$ track can pass the trigger threshold due to this error. These fake triggers are unavoidable, this effect is not a failure of the triggering algorithm, caused by the exponentially falling spectrum above 1 GeV/c. It is steeply increasing with $p_T$ from 1% to 48%.

The triggering efficiency is depending on the threshold value and the intensity of beam. The pileup effects were studied under the following assumptions:

a) In the STRIP detectors one can have more precise timing information. In the simulations presented in Table 4 it was assumed that at most 25-fold pileup was occurring, because if there was larger time difference between the hits they were not accepted as part of the same candidate.

b) One allowed much higher pileups in the PIXEL detectors assuming much slower readouts.

The results are very encouraging because in case of lower $p_T$ thresholds the number of bad triggers (i.e. wrongly reconstructed tracks) is rather limited but even at 2.5 GeV/c it is acceptable that one produces by this first level trigger a sample of better than 20% purity (out of 232 triggers 54 good and 178 bad tracks) even in case of 500-fold pileup in the pixel detectors which produces the 3.30 bad/good ratio. The final cleaning of this sample is performed by the additional information from RICH, TRD, TOF and ECAL detectors of CBM.

6. Further work
In the future one can further refine the algorithm. One should optimize the number and position of the detector planes. One should carefully study on large simulated sample the selection criteria within the doublecone mosaic corridors.

### Table 2. Tracking efficiency due to loss caused by scattering in detector.

| $p_T > 0.5$ GeV/c | $p_T > 1.5$ GeV/c | $p_T > 2.5$ GeV/c |
|-------------------|-------------------|-------------------|
| 930               | 217               | 59                |
| 542               | 169               | 52                |
| 58                | 0.78              | 0.88              |
| 26                | 15                | 8                 |
| 0.05              | 0.09              | 0.15              |

### Table 3. Correct tracking with wrongly reconstructed $p_T$ value above $p_T^{LIMIT}$

| $p_T > 0.5$ GeV/c | $p_T > 1.5$ GeV/c | $p_T > 2.5$ GeV/c |
|-------------------|-------------------|-------------------|
| 930               | 217               | 59                |
| 542               | 169               | 52                |
| 26                | 15                | 8                 |
| 7                 | 35                | 25                |
| 0.01              | 0.21              | 0.48              |
Table 4. Trigger efficiency versus pileup and $p_T^{\text{LIMIT}}$

| Pileup | $p_T^{\text{LIMIT}}$ (GeV/c) | all   | good  | $p_T^{\text{REC}} < p_T^{\text{LIMIT}}$ | bad   | bad/good |
|--------|------------------------------|-------|-------|----------------------------------------|-------|----------|
| 100/25 | 0.5                          | 930   | 552   | 30                                     | 1     | 0.002    |
|        | 1.5                          | 217   | 173   | 17                                     | 6     | 0.035    |
|        | 2.5                          | 59    | 54    | 10                                     | 43    | 0.80     |
| 200/25 | 0.5                          | 930   | 552   | 30                                     | 1     | 0.002    |
|        | 1.5                          | 217   | 174   | 19                                     | 10    | 0.057    |
|        | 2.5                          | 59    | 54    | 10                                     | 60    | 1.11     |
| 500/25 | 0.5                          | 930   | 552   | 30                                     | 10    | 0.018    |
|        | 1.5                          | 217   | 174   | 22                                     | 77    | 0.44     |
|        | 2.5                          | 59    | 54    | 10                                     | 178   | 3.30     |

On the technical side one should work out the HitCAM and ListCAM units and the total computing network.

Development work was executed in the framework of the FUTURE-DAQ project as part of the EU FP6 contract nr. 506078 (HadronPhysics) and supported by OTKA 68506, 71989 grants.

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