Simulation study for Forward Calorimeter in LHC-ALICE experiment

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Simulation study for Forward Calorimeter in LHC-ALICE experiment

Y.Hori, H.Hamagaki, T.Gunji
Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
E-mail: yhori@cns.s.u-tokyo.ac.jp

Abstract. We propose Forward Calorimeter (FOCAL) as an upgrade plan of ALICE detector at LHC. FOCAL will contribute to small-x physics in p+Pb collisions and Quark Gluon Plasma (QGP) physics in Pb+Pb collisions. Our conceptual design of FOCAL consists of SiW sandwich-type calorimeter and Si Strip layers to measure prompt $\gamma$ and $\pi^0 \rightarrow \gamma + \gamma$ up to 200 GeV energy, which corresponds to $< 20 (10)$ GeV/$c$ transverse momentum at $\eta = 3 (4)$.

1. Introduction
The physics goal of FOCAL is the understanding of the parton structure inside the proton and nuclei at small-x, especially, the gluon saturation effect like Color Glass Condensate (CGC). For this purpose, FOCAL measures prompt $\gamma$ and neutral mesons at the forward rapidity region in p+p and p+Pb collisions. FOCAL will also make an unique contribution for QGP physics by measuring inclusive $\gamma$, high $p_T \pi^0$ and jets at the forward rapidity region in Pb+Pb collisions.

Parton Distribution Functions (PDF) of the proton were precisely measured by the experiment at HERA and the rapid growth of the small-x gluon density was observed. The growth of the gluon density inside the hadron with decreasing $x$ is ultimately expected to be balanced by the gluon-gluon fusion process. These nonlinear effects lead to the gluon saturation at the small-x region [1]. This phenomenon is expected to occur when the area occupied by the gluons becomes equal to the area of transverse size of the hadron $\pi R^2$. This situation is expressed by the saturation momentum $Q_s$ as $\Lambda^2_{QCD} \ll Q^2 < Q^2_s(x) \sim \alpha_s x G(x, Q^2) / \pi R^2 \propto A^{1/3} x^{-0.3}$. It is expected that $Q^2_s$ reaches $\sim 10$ GeV$^2$ at LHC. The situation $\Lambda^2_{QCD} \ll Q^2_s$ will be realized in extremely high energy collisions at LHC.

2. Prompt $\gamma$ measurements at the forward rapidity region
Experimentally, saturation effects on small-x gluons are expected to be revealed in measurements of forward particle production. For a $2 \rightarrow 2$ parton scattering, the minimum $x$ probed in a process with a particle momentum $p_T$ and its pseudo-rapidity $\eta$ is given as

$$x^2_{\min} = \frac{x_T e^{-\eta}}{(2 - x_T e^{\eta})}, \quad x^1_{\min} = \frac{x_2 x_T e^{-\eta}}{(2 x_2 - x_T e^{\eta})}$$

(1)

where $x_T = 2p_T / \sqrt{s}$. Thus, $x^2_{\min}$ decreases by a factor of $\sim 10$ every 2 units of rapidity [2].

The production of prompt $\gamma$ at forward rapidity is sensitive to the small-x gluon distribution.
The dominated production processes at LO level are Compton scattering and annihilation process. Compton process is in particular interesting because small-$x$ gluon and large-$x$ (valence) quark are relevant if prompt $\gamma$ is produced at the forward rapidity region. Figure 1 shows the accessible $x$ range of the partons by the prompt $\gamma$ measurement at $\eta = 3 \sim 3.5$ in 8.8 TeV collisions calculated by PYTHIA simulation. The $x$ range that can be probed by prompt $\gamma$ is $10^{-3} \sim 10^{-5}$, which has hardly been probed even for the proton. The left graph of Figure 2 shows accessible range of $x$ and $Q^2$ by FOCAL at LHC and the other experiments.

The center and right graphs of Figure 2 show the cross section and annual yield of prompt 

\[ \begin{align*}
\text{Figure 1.} & \quad \text{Left and Center: } p_T \text{ and } x_1(x_2) \text{ range of relevant partons of } \gamma \text{ production at } \eta = 3 \sim 3.5, \text{ Right: Projection to the } x\text{-axis of the 2 left plots} \\
\text{Figure 2.} & \quad \text{Left: Accessible range of } x \text{ and } Q^2 \text{ by FOCAL at LHC, Center: } p_T \text{ spectrum at } \eta = 3 \sim 4 \text{ in 8.8 TeV } p+p \text{ collisions (blue - } \pi^0, \text{ pink - } \gamma \text{ from } \pi^0, \text{ black - prompt } \gamma), \text{ Right: Annual yield of prompt } \gamma \text{ at } \eta = 3 \sim 4 \text{ in } p+p \text{ (blue) and } p+Pb \text{ (red) collisions for a standard year of running at LHC, which does not include any nuclear effects} \\
\end{align*} \]

$\gamma$ at $\eta = 3 \sim 4$ in 8.8 TeV $p+p$ collisions. A width of $p_T$ binning is 0.5 GeV/c and error bars are from simulation statistics. These graphs show that yields of prompt $\gamma$ and $\pi^0$ are enough to be measured, but the ratio of prompt $\gamma$ to $\gamma$ from neutral mesons is quite small.

3. Conceptual design of Forward Calorimeter and Basic performance

Considering the physics requirements and the detector performance, the $\eta$ coverage of FOCAL should be $3 \sim 4$ and the distance from interaction point should be about 4.5 m, where is between
ALICE L3 magnet wall and TPC. The layout of FOCAL is summarized in Table 1.

In order to measure $\gamma$ and neutral mesons at the forward rapidity regions, FOCAL must have a large dynamic range ($\gamma$ energy $< 200$ GeV, which corresponds to $p_T < 20$ (10) GeV/$c$ at $\eta = 3$ (4)) and highly granularity (multiplicity $\sim 1$ particle/cm$^2$ at $\eta = 4$ according to the HIJING simulation). FOCAL also has to have good separation ability of $2 \gamma$ from high energy $\pi^0$ decays. A minimum distance of $2 \gamma$ from 100 (200) GeV $\pi^0$ is $\sim 10$ (6) mm.

These requirements can be fulfilled by a hybrid use of SiW sandwich-type calorimeter and Si Strip layers as shown in Figure 3 [3]. The thickness of each Si Pad detector is 0.5 mm and that of W absorber is 3.5 mm. It has 21X$_0$ depth and has 3 longitudinal segments. Each segment has 7 layers of Si Pad detector and W absorber. The Si Pad detector is laterally segmentized by 1 cm x 1 cm. A few layers of the Si Strip detector is used to separate $2 \gamma$ from high energy $\pi^0$. The thickness of Si Strip layer is 0.3 mm and the strip pitch is 0.5-1 mm.

Figure 4 shows the longitudinal shower shapes and sampling fraction at each segment calculated by GEANT 4 simulation. A shower maximum depth is about 5 $\sim$ 9 X$_0$ and total sampling fraction is almost constant up to 200 GeV $\gamma$. Figure 5 shows $\chi^2$ distributions of longitudinal deposited energy of $\gamma$ and $\pi^+$. $\gamma$ shower is effectively identified by a cut for $\chi^2$ distribution. Other basic performances are listed in Table 2.

| Distance from IP | 4.5 m | $\eta$ coverage | 3 $\sim$ 4 |
|-----------------|-------|-----------------|------------|
| Outer Radius    | 45 cm | $\phi$ coverage | $2\pi$     |
| Inner Radius    | 15 cm | Area            | $\sim 0.6$ m$^2$ |

**Table 1. Layout of FOCAL**
Figure 4. Left and Center: Longitudinal shape of γ shower with various energy, Right: Sampling fraction at each segment for γ shower.

Figure 5. $\chi^2$ distribution of γ and π⁺ shower shape with various energy.

| Parameter                        | Value         |
|----------------------------------|---------------|
| Cell occupancy in p-Pb collisions| < 10%         |
| Detection efficiency             | > 95%         |
| Linearity                        | < 1%          |
| Sampling fraction                | 1.4%          |
| Energy resolution                | $18/\sqrt{E}$%|
| Position resolution at 10 GeV γ  | 1.5 mm        |
| Charged Hadron rejection factor  | 250 at $\gamma$ eff.90% |

Table 2. Basic performance of Si Pad Detector
4. $\pi^0$ measurement

$\pi^0$ with $7 \sim 70$ GeV energy can be efficiently reconstructed by the invariant mass method using Si Pad detector and detection efficiency is $> 60\%$ as shown in the left graph of Figure 6. The efficiency decreases above 60 GeV $\pi^0$ because 2 $\gamma$ from $\pi^0$ are merged into same pad. The merging probabilities of 2$\gamma$ from $\pi^0$ are shown in the right graph of Figure 6.

Figure 7 shows the invariant mass spectra at various $p_T$ in $\eta = 3.0 \sim 3.5$ in 8.8 TeV p+Pb collisions calculated by HIJING event simulator. Energy and hit position are smeared according to the corresponding resolution listed in Table 2. Clear $\pi^0$ peak can be recognized.

![Figure 6](image1)

**Figure 6.** Left: Reconstruction efficiency of $\pi^0$ with invariant mass method (red - without the energy asymmetry cut, blue - with the energy asymmetry cut $< 0.8$), Right: 2 $\gamma$ merging probability ( red - 2 $\gamma$ hit same pad, blue- 2 $\gamma$ hit neighbor pad)

![Figure 7](image2)

**Figure 7.** $\gamma\gamma$ invariant mass spectra in $\eta = 3.0 \sim 3.5$ in 8.8 TeV p+Pb collisions, Red line is estimated combinatorial background by event mixing method

By one layer of the Si Strip detector with 0.5 mm pitch strip, 100 $\sim$ 200 GeV $\pi^0$ can be detected and its efficiency is $\sim 50\%$ with misidentification probability $< 1\%$ as shown in Figure 8. The performance of the Si Strip detector with 1 mm pitch strip is not so different from that of 0.5 mm pitch strip. The position of the Si Strip detector should be the depth of 5 $\sim 7X_0$ or
deeper, which corresponds to the shower maximum depth. It is also found that the use of multi Si Strip layers does not change the $\pi^0$ reconstruction efficiency drastically.

![Graph of Efficiency vs. the position of the Si Strip layer and Efficiency vs. $\pi^0$ energy](image)

**Figure 8.** Left: Efficiency vs. the position of the Si Strip layer (red solid line - 200 GeV $\pi^0$, blue dot line - 100 GeV $\pi^0$). Right: Efficiency vs. $\pi^0$ energy (red solid line - 0.5 mm pitch strip, blue dot line - 1 mm pitch strip)

The annual yield of $\pi^0$ with $19.5 < p_T < 20$ GeV/c at $\eta = 3 \sim 4$ is $\sim 5 \times 10^4$ according to Figure 2. The acceptance for $\pi^0$ with $p_T$ 20 GeV/c is almost 100% and the reconstruction efficiency by the Si Strip detector is $\sim 50\%$. Therefore, the annual count of $\pi^0$ with $19.5 < p_T < 20$ GeV/c at $\eta = 3 \sim 4$ is $\sim 2.5 \times 10^4$.

5. **Summary and future plan**

We performed a dedicated simulation study for FOCAL in LHC-ALICE experiment. As a next step, we have to do full simulation and construct prototype of FOACL module including a readout electronics.

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