SoLID Project
Solinoidal **L**arge **I**ntensity **D**evice

The SoLID Collaboration

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1 Electromagnetic Calorimeter [Draft]

1.1 Overview

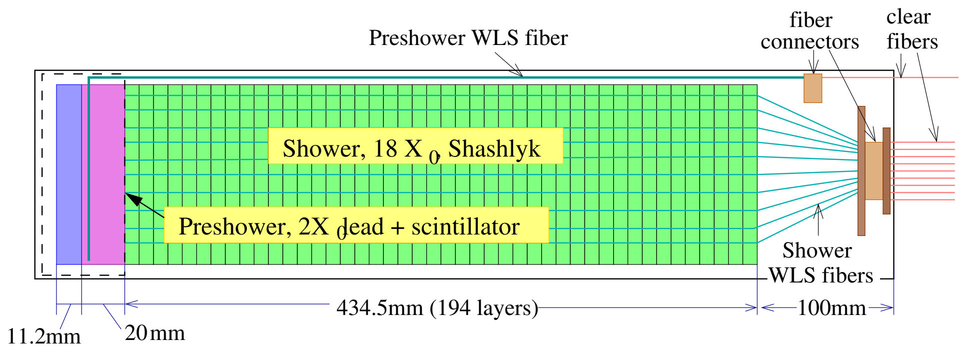
Electromagnetic calorimeters (EC) are used in both PVDIS and SIDIS experiments to measure the energy deposition of electrons and hadrons, and to provide particle identification (PID). The incidental hadron is dominated by pions at SoLID energy. There are three calorimeters for the SoLID experiments: the PVDIS experiment uses a forward angle calorimeter (FAEC), and the SIDIS experiments require coverages for both a forward angle calorimeter (FAEC) and a large angle calorimeter (LAEC). The required coverage are summarized in Tab. 1.

	PVDIS FAEC	SIDIS FAEC	SIDIS LAEC
z (cm)	(320, 380)	(405, 465)	(-65, -5)
Polar angle (degree)	(21,36)	(7.5,14.7)	(15.7, 24)
Azimuthal angle	Full coverage		
Radius (cm)	(118, 261)	(100, 220)	(80, 140)
Coverage area (m^2)	17	12	4.5

Table 1: Coverage for the SoLID electromagnetic calorimeters. The z direction is along the electron beam and the origin is at the solenoid center. The range of various dimensions are shown.

The SoLID EC's main characteristics are determined by both the physics goal and the designed running condition of the experiments, as shown in Tab. 2a. The design is challenging due to our unique constraints including high radiation background (˜500 kRad), strong magnetic field (1.5 T on LAEC) and the budget. These factors prevent the use of many traditional calorimeter technologies, including NaI (Tl), CSI, BGO and lead-glass because of their low radiation resistance, $PbWO_4$, LSO and PbF_2 because of their high cost, and lead/scintillator fiber calorimeter for the high cost and the large amount of light readout required. Two calorimeter technologies that were optimized for the SoLID experiments and met the experimental criteria, were chosen for the shower and the preshower detectors, respectively. As illustrated in Fig. 1a, the shower calorimeter modules are based on the Shashlyk design [1], and the preshower detector consists of a layer of passive radiator followed by scintillator pads [2, 3]. The overview for these designs are summarized in Tab. 2b and 2c.

A Shashlyk calorimeter is a sampling calorimeter constructed from alternating layers of scintillator and a heavy absorber such as lead. In the experiment, particles incident close to perpendicular to the scintillator-lead layers. Scintillation light is absorbed, re-emitted and transported to the photon detector by wave-length shifting



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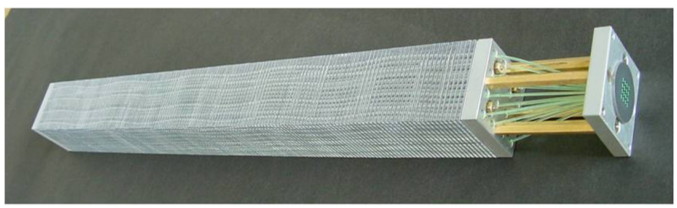

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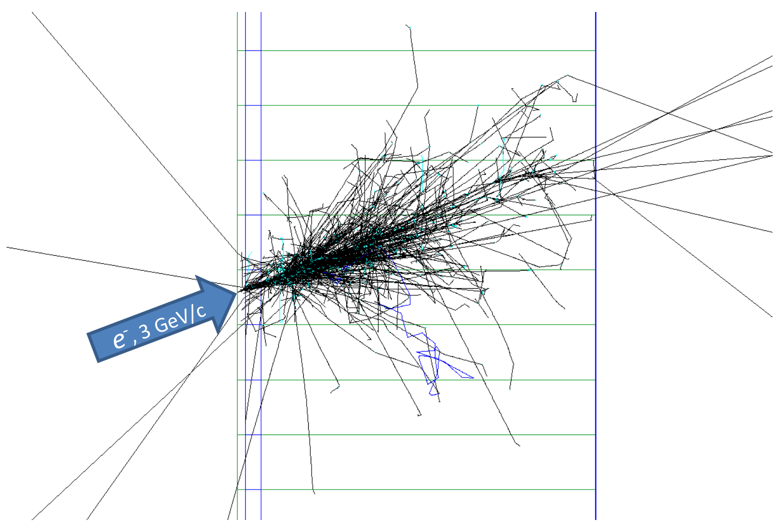


(c)

Figure 1: (a) Design diagram of the SoLID electromagnetic calorimeter module; (b) a photo of the COMPASS II Shashlyk calorimeter module; and (c) GEANT4 simulation of the shower generated by a 3-GeV electron incident on the PVDIS calorimeter. The black and green tracks are secondary photons and electrons respectively. The green horizontal lines are edges of calorimeter modules. The first two layers of materials are the preshower detector, consisting of $2X_0$ of lead and 2 cm thick of scintillator.

	Design specification	Desired performance
π^- rejection	[50-100:1]	$\gtrsim$[50:1] for above Cerenkov threshold
e^- efficiency	94%	$\gtrsim$95%
Energy resolution	$\sim 4\%/\sqrt{E}$	$< 10\%/\sqrt{E}$
Timing resolution	100 ps	<300 ps
Radiation resistance	500 kRad	$\gtrsim$400 kRad
Position resolution	1 cm	$\lesssim$1 cm
Longitudinal length	475 cm	-
Lateral granularity	10×10 cm^2, square	-

(a) Overview of the SoLID calorimeter design and desired performance

Type	passive radiator + sensitive layer
passive radiator	$2X_0$, Pb
Sensitive layer	2 cm, plastic scintillator tile
Light transportation	WLS fiber embedded in scintillator

(b) Preshower configuration

Type		Shashlyk sampling calorimeter
Each layer	Absorber	Pb, 0.5 mm
	Scintillator	STYRON 637 plastic scintillator, 1.5 mm
	Gap	Paper, 0.12 mm $\times$ 2 sheets per scintillator layer
	Radiation Length	$9.3\times10^{-2}X_0$
Overall	Radiation length (X_0)	24 cm
	Molire radius	5 cm
	Length	18 X_0, 43.4 cm
	Layer count	194
	Light transportation	WLS fiber, penetrating layers longitudinally

(c) Shower configuration

Table 2: Summary for the SoLID electromagnetic calorimeters.

(WLS) optical fibers penetrating through the calorimeter modules longitudinally along the impact particle direction. Since each 10×10 cm^2 module contains 100 1 mm WLS fibers, the total area required for light readout is reduced by a typical factor of 10^2 compared to the lateral area of the calorimeter.

The Institute for High Energy Physics (IHEP) of Russia has extensive experience in the R&D and mass production of Shashlyk type calorimeters. They have successfully developed the Shashlyk calorimeters for many experiments and have been working on building COMPASS calorimeters, as shown in Fig. 1b. Our

Shashlyk calorimeter module design is based on the COMPASS module. Geant4-based simulations, as illustrated in Fig. 1c, was used to study the key specifications with optimal physics results while minimizing the cost.

1.2 Shower Detector

1.2.1 Sampling Ratio of the Shower Detector

Each layer of the shower module consists of a 1.5 mm-thick scintillator plate and a 0.5-mm absorber plate made of lead. The thickness of the scintillator plate should be thin enough to ensure fine longitudinal sampling, while thick enough to reduce light attenuation on the lateral direction. A thickness of 1.5 mm was chosen following the experience of previous Shashlyk designs (for the KOPIO experiment [1, 4], the PANDA experiment [5] and the COMPASS-II experiment as in Fig. 1b). Each scintillator layer is sandwiched by two sheets of paper which reduce the loss of scintillation light. Each sheet introduces a gap of 120 μm between the lead and scintillator plates.

The Pb absorber thickness of 0.5 mm or less is favored to provide a fine sampling and therefore better energy resolution. With a configuration using 1.5 mm scintillator and 0.5 mm lead, an energy resolution of about $4\%/\sqrt{E}$ is achieved with an effective radiation length of 24 cm, as shown in Fig. 2.

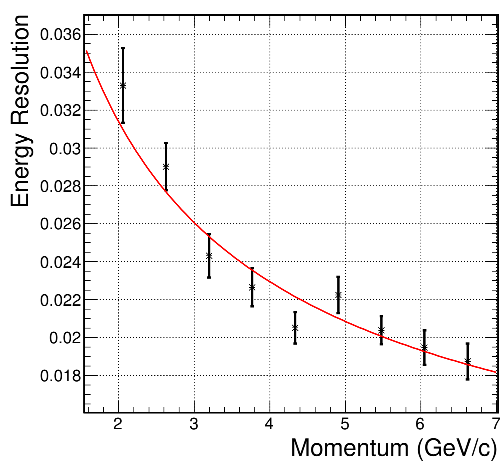


Figure 2: Energy resolution of the SoLID calorimeter (preshower + shower).

1.2.2 Total Length of the Calorimeter

The overall length of calorimeter should be long enough to enclose most of the electromagnetic shower and short enough to maximize the difference in energy deposition between electrons and pions. The ratio of energy leak out for electron showers, which were averaged inside the acceptance of the SIDIS-Forward calorimeter, was studied for different total lengths of calorimeter as shown in Fig. 3. A total length of 20 radiation length was found to be a good balance **[Support plot]**. Considering a 2 radiation lengths of preshower, this leads to a shower detector length of 18 radiation lengths or 43.4 cm.

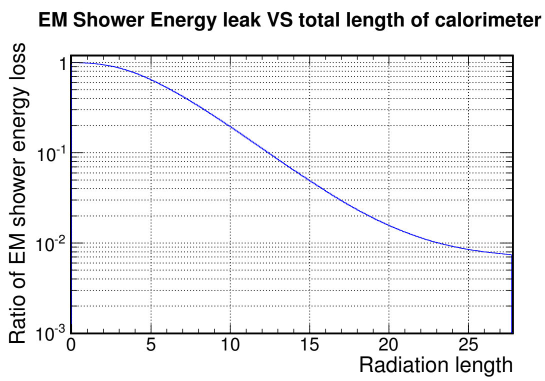


Figure 3: Ratios of energy leak out for an average SIDIS-Forward electron shower vs. different total length of the calorimeter.

1.2.3 Lateral Size of the Calorimeter Module

A smaller lateral size for calorimeter modules leads to a better position and lower background; however, this would also increase the total number of modules and channel counts, and therefore higher overall cost. The study shows that a lateral size of about $10 \times 10\ \text{cm}^2$ will provide a good balance between position resolution, background and the overall cost as shown in Fig. 4.

1.3 Preshower Detector

Segmenting the EC longitudinally into a preshower and a shower part is essential to reach the required pion rejection. Several design was considered for the preshower detector, including a full Shashlyk-type design that is optically isolated from the

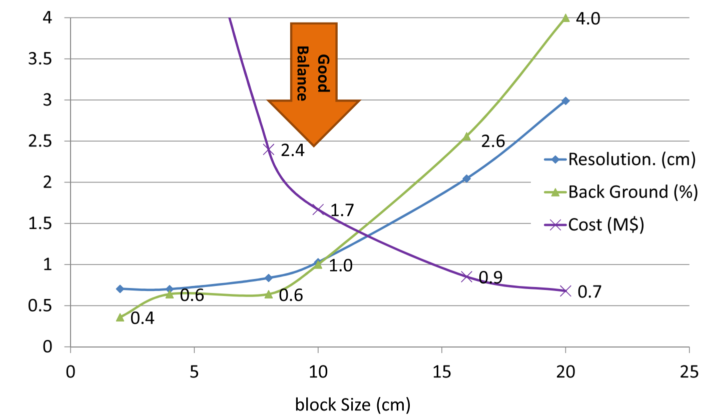


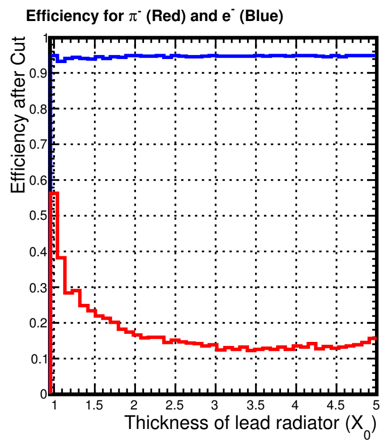
Figure 4: Position resolution and background level from simulation and the cost of the shower detector vs. lateral block size of the module.

shower detector, and a passive radiator/scintillator pad design as used in the HERMES [2] and LHCb [3] experiments. Comparing to a Shashlyk-type preshower, the passive radiator/scintillator pad design have several advantage, including increased radiation hardness, simplicity in construction and fewer WLS fibers to readout. For a passive radiator of $2X_0$, the impact to overall energy resolution is less than $0.5\%/\sqrt{E}$ for electrons with momentum larger than 2 GeV$/c$. Therefore, the passive radiator/scintillator pad design was adopted for the preshower detector.

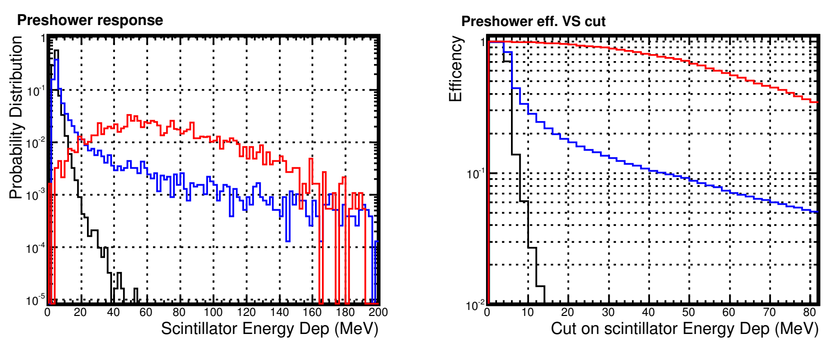
- The thickness of preshower radiator was determined by optimizing the overall pion rejection at the desired electron efficiency. As shown in Fig. 5a, the preshower-alone pion rejection improves as the radiator thickens up to $3.5X_0$ due to immediate development of the electromagnetic shower. However, the impact to the overall energy resolution degrades with a thicker absorber. A radiator thickness of $2X_0$ was found to be the best option for the SoLID application.

- The scintillator and readout design is similar to that of the LHCb experiment [3], as illustrated in Fig. 6. A single WLS fiber is embedded in a 2 cm-thick scintillator pad. It absorbs, re-emitted and conducts the photons for readouts.

With the above configuration, the relation between pion rejection and electron efficiency for preshower alone can be plotted as a function of scintillator energy cuts, as shown in Fig. 5b.



(a)



(b)

Figure 5: Simulated performance for the preshower detector. (a) $1/(\pi^-$ Rejection$)$ (red curve) at a 95% electron efficiency (blue curve) VS different thickness of the lead radiator. (b) for a preshower consisting of $2X_0$ of lead radiator and 2 cm thick of scintillator, left: spectrum for energy deposition in the scintillator; right: detector efficiency for different threshold cut. The color code is electron in red, π^- in blue and μ^- in black.

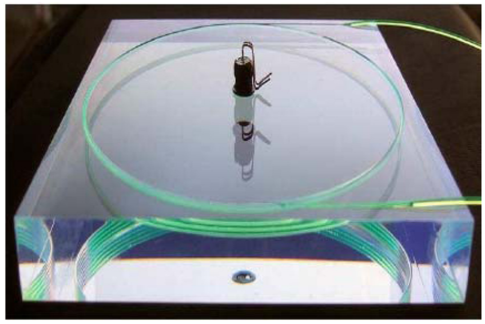


Figure 6: Reading out photons in the scintillator using a single wavelength shifting fiber as used in the LHCb experiment [3]. The WLS fiber is embedded in a circular grove cut by a diamond cutter.

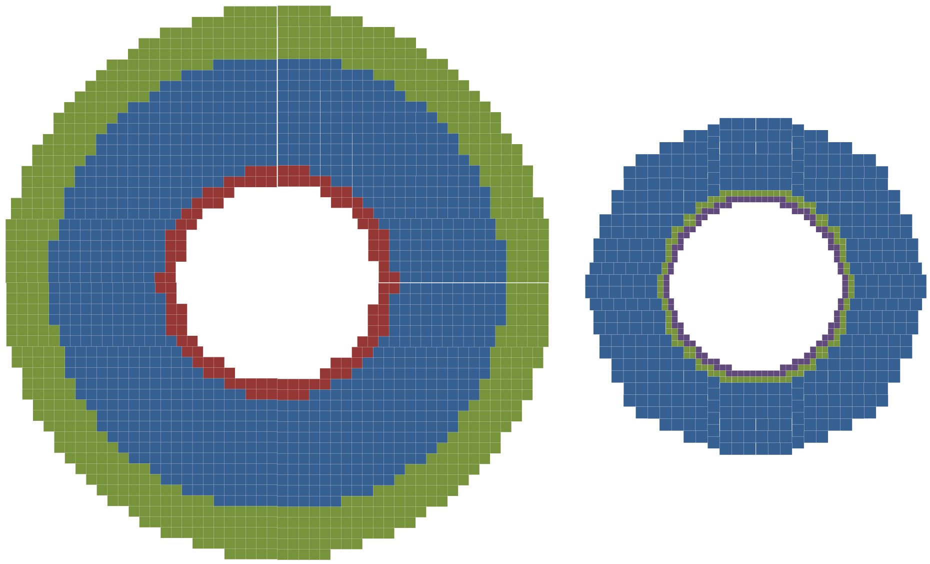
1.4 Layout and Acceptance

The total areas of PVDIS EC and SIDIS ECs coverages are almost the same. The modules will be re-arranged between the two configurations, where modules from PVDIS FAEC will be split and re-arranged into SIDIS FAEC and LAEC. The SIDIS EC layout must preserve the 2-fold rotation symmetry in the spectrometer. The design layout that meets these requirements is shown in Fig. 7.

As described earlier, the designed EC modules are about 60-cm long. However, the most inner radius of the SIDIS LAEC cannot use these regular modules because they would block particles and prevent them from reaching the SIDIS FAEC. Modules with a smaller lateral size of 5×5 cm^2 and two shorter lengths (41cm, 22cm) will be used for the inner side of the SIDIS LAEC. The layout for these smaller modules is shown in Fig. 7c.

1.5 Light Readout

The blue light from scintillators is converted into green light by WLS fibers and is carried out to the back of the calorimeters for readout. The Bicron BCF91a WLS fiber is chosen for this project as a balance between the required radiation hardness and the cost. The magnetic field reaches about 1.5 T behind SIDIS LAEC and a few hundred Gauss behind both PVDIS and SIDIS FAEC. Field-insensitve photon sensors are in general expensive and less radiation-hard compared to PMTs. Therefore, the default design is to use clear fibers to further guide the light out of the solenoid for readout by PMTs. The light coupling between WLS and clear fibers can be provided by bundle connectors similar to what LHCb used as shown in Fig. 8.



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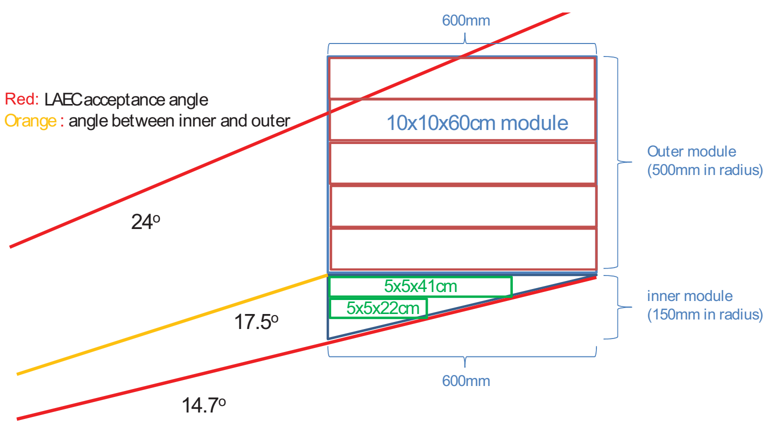


(c)

Figure 7: Layout for the SoLID electromagnetic calorimeters: (a) PVDIS FAEC module layout are in blue and green. SIDIS FAEC module layout are in blue and red. (b) SIDIS LAEC module layout with $10 \times 10 \times 60$ cm^3 modules in blue, $5 \times 5 \times 41$ cm^3 module in green and $5 \times 5 \times 22$ cm^3 module in purple. (c) Side view of SoLID LAEC.

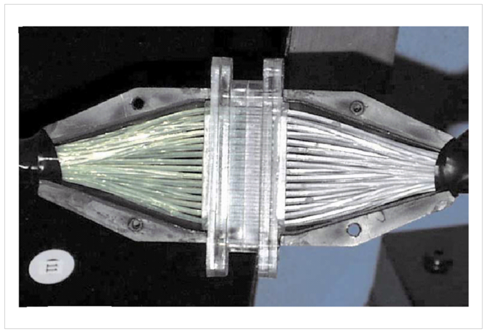


Figure 8: WLS and clear fiber bundle connectors used in the LHCb calorimeter.

There are field insensitive photon sensors that can be used for readout. SiPM has enough gain (10^6) for sampling calorimeters, but its dark rate is prone to neutron background. We are still evaluating the neutron background at the calorimeters and the choice of SiPM as direct readout without the need of fiber connectors and clear fibers.

1.6 Radiation Effect

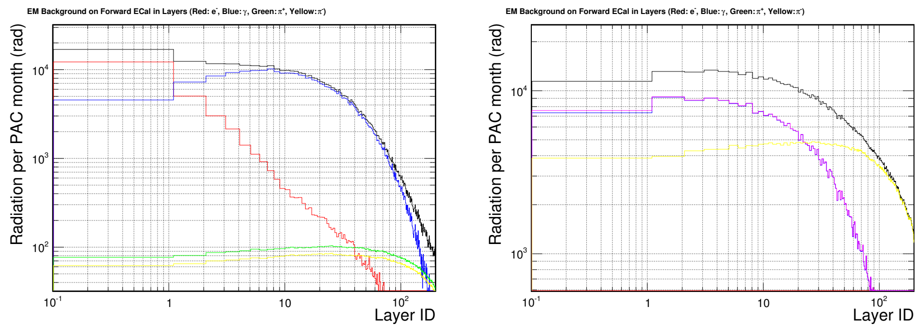
The expected luminosities and run time are 169 PAC-days in the PVDIS configuration at $10^{39} N \cdot \mathrm{cm}^{-2}\mathrm{s}^{-1}$, 245 PAC-days for the SIDIS experiments and 60 PAC-days[1] for the J/Ψ experiment at $10^{37} N \cdot \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The radiation level at EC reaches 60 kRad/PAC-year for PVDIS with the baffle and 400 kRad/PAC-year in the SIDIS and J/Ψ experiments, which leads to a total radiation dose of less than 400 kRad for all approved experiments. [TO BE Updated: The COMPASS module has been tested up to 500 kRad. By increasing the thickness of the first few lead layers and using more radiation resistant scintillator and fibers, the radiation hardness can be further improved].

1.7 Expected Performance

1.7.1 Electron-pion separation

With a multidimensional cut of the preshower and shower response (as shown in Sec. 1.9), the overall pion rejection averaged over the acceptance of each calorimeter is shown in Fig. 10. For the PVDIS configuration, particles observe longer effective length due to larger incident angles, causing the electromagnetic shower for higher momentum tracks to be contained better inside the calorimeter module.

[1] Proposed days, pending PAC beam time assignment.



(a) SIDIS calorimeter (forward) (b) PVDIS calorimeter

Figure 9: Radiation dose rate in each layer of the scintillator tiles in Shashlyk calorimeter, if there is no preshower. The preshower effectively block radiation equivalent to the first 20 layers. The color stands for different contributions of various incoming particles: electrons (red), photons (blue), EM total (magenta), π^+ (green), π^- (yellow) and black for total radiation rate.

The overall π^- rejection with respect to the track momentum P and polar angle θ can be described as

$$\frac{1}{\pi^{-}\text{rejection}} \approx 0.01 \left[\frac{3.5 + 0.3\,(\theta/\text{degree})}{P/\,(\text{GeV}/c)} + \frac{1.6 - 0.1\,(\theta/\text{degree})}{\sqrt{P/\,(\text{GeV}/c)}} \right].$$

1.7.2 Shower Position Measurement

The position resolution of the electromagnetic shower center was studied for different lateral sizes of the calorimeter modules, as shown in Fig. 11. The red curves are the position resolutions along the azimuthal direction, for which the tracks are perpendicular to the position measurement direction. The blue curves are for the radial direction for the most extreme incidental angle as in the PVDIS configuration. The dashed curves are for shower centers calculated using a simple energy-weighted geometrical center. The solid curves are further corrected with the distribution of energy deposition between neighboring calorimeter blocks, which flags the full position resolution for the calorimeter system. At the designed lateral granularity of 10×10 cm^2, the position resolution is better than 1 cm.

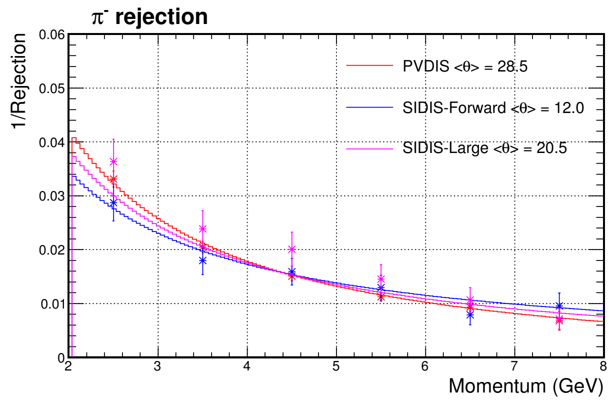


Figure 10: Overall π^- efficiency (1/rejection) at a constant 94% electron detector efficiency averaged within the acceptance of each calorimeter. For three calorimeter configurations, the track polar angle θ are different, which lead to slight differences in the pion rejection curves.

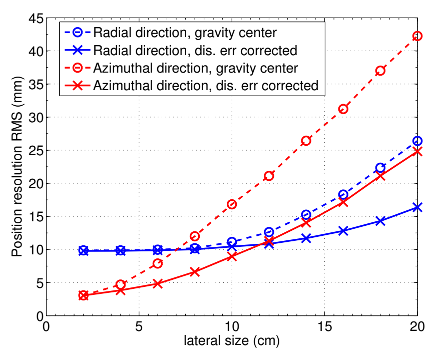


Figure 11: Position resolution for electrons showers vs. different lateral size of the calorimeter. See text for details.

1.8 Cost Estimation

The estimated cost for the SoLID calorimeters is summarized in Tab. 3. Cost for R&D and prototyping is estimated to be 0.3M$.

1.9 Appendix: PID Selection Cuts

A three dimensional PID cut was used to select the best electron samples with maximal π^- rejection as illustrated in Fig. 12. For each given momentum bin, the

	Per-module cost($)	All-module cost(M$)
Module material	700 (L)/250 (S)	1.26
Module production	800 (L)/500 (S)	1.49
Clear fibers	260 (L)/65 (S)	0.46
Fiber connectors	200	0.39
PMTs	600 x 2	2.34
Labor	5 tech years, 5 student years	0.75
Total	-	6.7
Total+ 30% contingency	-	8.7

Table 3: Cost estimation for the SoLID calorimeters. There are 1724 large modules (L), which measure $10 \times 10 \times 60$ cm^3, and 224 smaller modules (S) with two sizes, $5 \times 5 \times 41$ cm^3 and $5 \times 5 \times 22$ cm^3.

cut on E/P and preshower energy roughly follows the contour lines of the ratio of π^- efficiency to e^- efficiency, which is the theoretical best cut for the π^-/e^- separation. A momentum dependence is then introduced to the cut to maintain a constant 94% electron efficiency. Events passing the cut are highlighted in red in the plots.

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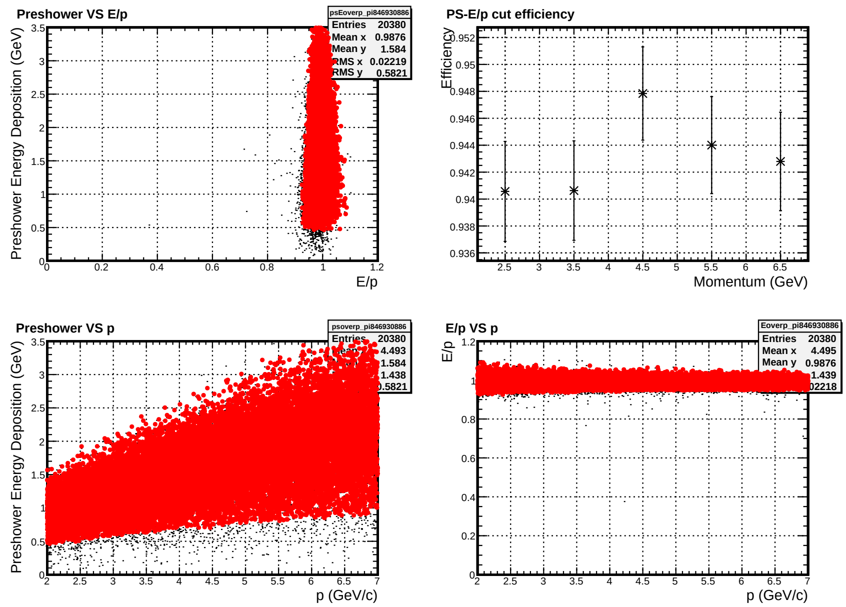

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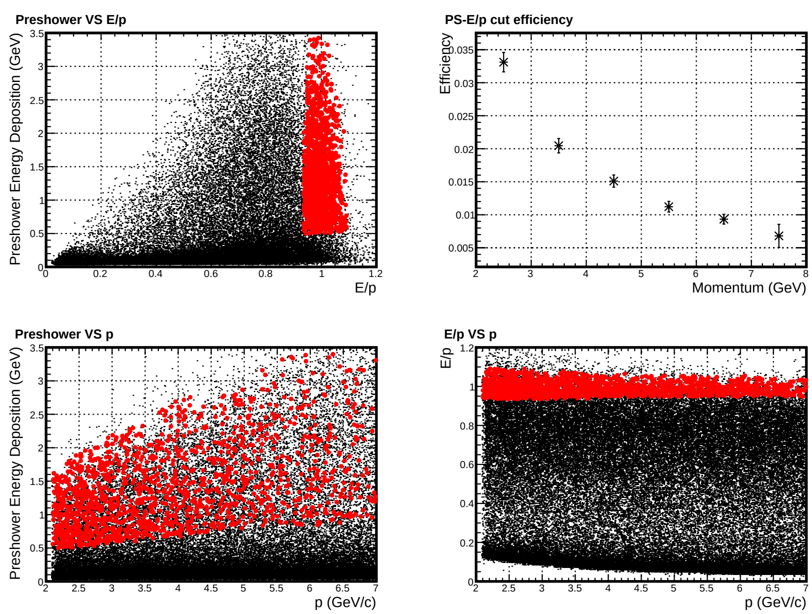

(b)

Figure 12: Illustration of electron sample cuts as highlighted in red dots, in comparison to simulated electron (a) and π^- (b) samples. See text for details.

A Hadron Blind Detectors

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References

[1] Sample citation