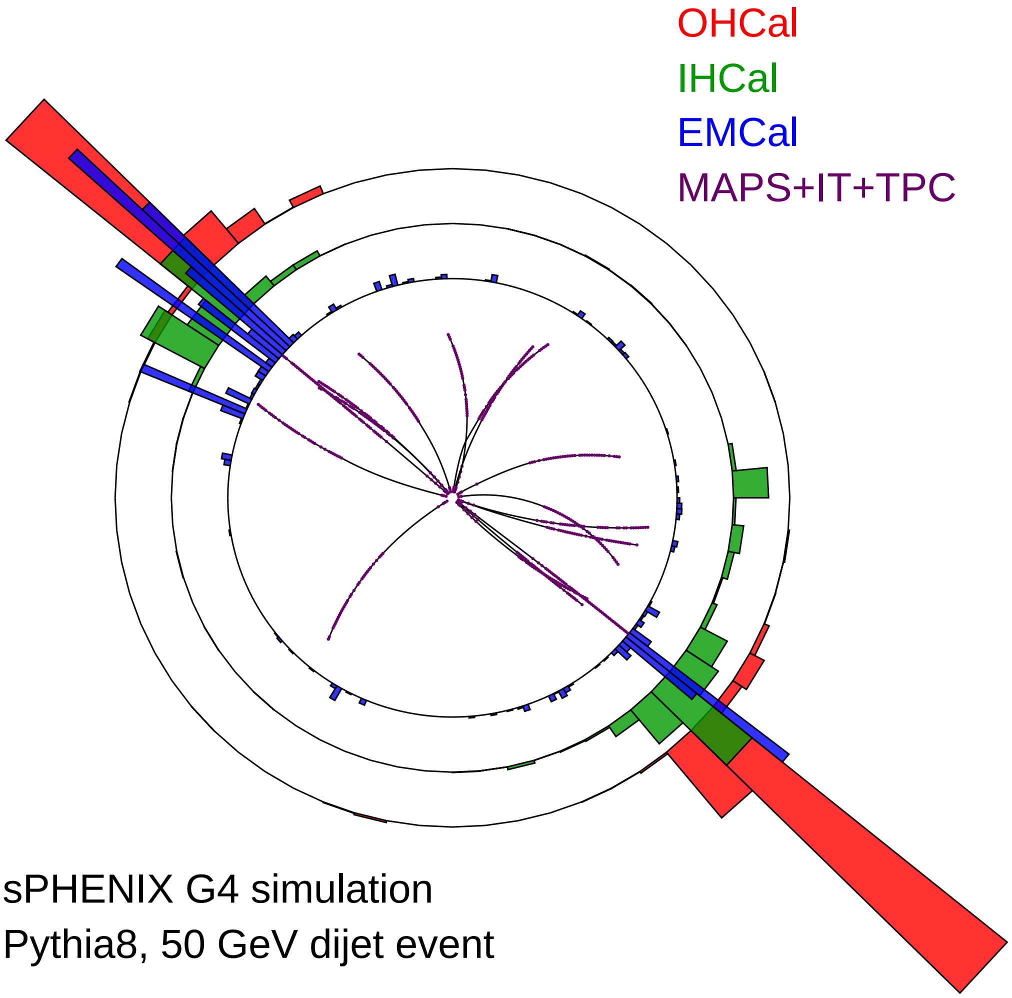
sPH-GEN-2017-002

sPHENIX MIE Cost Range and sPHENIX Scope

The sPHENIX Collaboration
November 3, 2017



Executive Summary

In this document the sPHENIX collaboration addresses a recommendation from the August 2017 sPHENIX Directors review, informed by consultation with BNL ALD Berndt Mueller, to document a baseline scope for the sPHENIX detector that conforms to a \$32M cost cap, while minimizing the impact on detector performance with respect to the main science drivers of the sPHENIX program: jet structure, heavy-flavor jet and hadron production and Υ spectroscopy, while also having minimal impact on jet and dijet observables for the cold QCD program. The charge is specifically in reference to the \$38M baseline as shown in the August Director's review and asks the collaboration to present a re-scoped baseline of \$32M. The system by system costs of the re-scoped sPHENIX detector are detailed in Table 1.

To accommodate the \$32M cap, cost savings of about \$6M need to be achieved through elimination, acceptance reduction or redesign of sPHENIX detector subsystems. The magnitude of required savings, in combination with the fact that the only tracking detector in the baseline scope, the TPC, was already redesigned during the 2016 baseline scope studies, leaves changes to the calorimeter system as the only viable options (we did not consider changes to non-discretionary infrastructure items such as cryogenics, magnet, central pedestal and flux doors).

Table 1: Revised sPHENIX cost estimate, with project scope as described in text to accommodate ALD guidance (in k\$).

WBS	System	Baseline	Contingency	Total
1.1	Project Management	1850	550	2400
1.2	TPC	2600	800	3400
1.3	EMCal	5300	1600	6900
1.4	HCal	9750	2900	12650
1.5	Calorimeter Electronics	4000	1200	5200
1.6	DAQ & Trigger	1200	350	1550
1.7	Min Bias Trigger Det	150	50	200
MIE Totals		24850	7450	32300

As changes to the outer hadronic calorimeter (oHCal) face the most severe schedule and engineering constraints, and the 2016 studies indicated that substantial savings could only be reached with a severe reduction in oHCal thickness, we focused our investigation on redesign or elimination of the inner hadronic calorimeter (iHCal) and a reduction of electromagnetic calorimeter (EMCal) acceptance. New studies of the physics impact concentrated on the jet finding performance of the modified calorimeter stack, combined with information on the loss of statistics due to the EMCal acceptance modification.

We estimate that the required savings can be achieved by replacing the stainless steel iHCal with a non-instrumented support structure (either a new design fabricated of stainless steel or a copy of the existing iHCal design fabricated from aluminum rather than stainless steel), combined with a reduction in EMCal acceptance from $|\eta| < 1.1$ to $|\eta| < 0.85$.

These changes largely preserve the unique sPHENIX capabilities for hard probe physics at RHIC. However, the truncated acceptance of the EMCAL reduces the statistical reach quite significantly. Furthermore, understanding quantitatively how the non-uniformity of the redesigned calorimeter stack and reduced interaction lengths influence state-of-the-art jet substructure observables will require additional studies. These proposed changes do not preclude restoring the full acceptance and nearly the full jet performance if additional resources, e.g. through foreign contributions, can be identified in a timely manner. One should note it will not be possible to restore the EMCal acceptance once the EMCal sector construction begins. The consequences of the descoping options are quite serious and the collaboration plans to revisit the the specific balance of cuts needed to address cost constraints prior to an OPA CD-2 review at which the official baseline scope of the project is established.

Contents

Chapter 1

Estimated cost savings

We have pursued a two-pronged approach to accommodating the $32M cost cap of the ALD charge. The first prong was to scrub the current cost estimates to look for savings. The second was to consider the effects of various alterations to the detector to reduce costs. The details of these efforts are described in the following sections. The descoping was done relative to the detector configuration and associated costs as prepared for the August 2017 Director′s review and shown in Table 1.1.

Table 1.1: sPHENIX cost estimate, as shown during August 2017 Director′s review (in k$).

WBS	System	Baseline	Contingency	Total
1.1	Project Management	1850	550	2400
1.2	TPC	2600	800	3400
1.3	EMCal	6700	2000	8700
1.4	HCal	11800	3500	15300
1.5	Calorimeter Electronics	5200	1600	6800
1.6	DAQ & Trigger	1200	350	1550
1.7	Min Bias Trigger Det	150	50	200
MIE Totals		29500	8850	38350

1.1 Cost scrubbing

sPHENIX project management led an exercise involving the L2 managers to examine the estimates shown during the August Director′s Review to see if there were any opportunities to reduce the nominal baseline costs. This reexamination of baseline costs yielded slightly over $0.1M in direct costs savings.The savings from the scrubbing exercise have been applied to the costs in Table 1.1.

1.2 Reduced EMCal pseudorapidity coverage

Cost delta: -$1.8M

The pseudorapidity coverage of the EMCal can be reduced to find cost savings. This is done relative to the 2017 MIE baseline EMCal design, which includes 24576 towers for a pseudorapidity coverage of $|\eta| < 1.1$. For a moderate acceptance reduction, the cost savings is approximately proportional to the change in acceptance once the fixed costs are subtracted. By reducing the acceptance of the EMCal detector from $|\eta| < 1.1$ to $|\eta| < 0.85$, a total savings of $1.8M can be achieved. The quoted savings includes a modest amount saved in the aforementioned scrubbing exercise. The savings from not building the associated calorimeter electronics in the descoped EMCal is described in the Calorimeter Electronics section of this chapter.

1.3 Non-instrumented iHCal replacement

Cost delta: -$2.65M

The total estimated cost for the iHCal, as part of the total HCAL cost shown in Table 1.1, including overhead and contingency, but without electronics is just under $4M. By instead building a structure that can support the EMCal, but eliminate the active detector components, a total savings of $2.65M can be realized. The savings comes from not building the iHCal scintillating tiles, no paid detector factory labor for assembling and testing the iHCal, and simplifying the iHCal support structure. The quoted savings includes a modest amount saved in the aforementioned scrubbing exercise. Two possible options for the simplified structure/frame are: A) a copy of the current iHCal mechanical design, but fabricated in aluminum instead of stainless steel; and B) an as-yet-to-be engineered stainless steel support frame. Both options are expected to present about 0.25 to 0.3 interaction lengths of dead material, yielding very similar effects on jet performance figures. While option B is expected to yield lower materials and fabrication costs, additional engineering will be required to produce an appropriate design for the structure. Option A preserves the possibility of instrumenting the iHCal region, resulting in jet-related performance parameters close to the current iHCal design. In Section 2 we present results for the current iHCal design in comparison to option A and an instrumented version of option A, with the understanding that option B and option A yield a similar degradation of jet performance, as verified in simulation. The savings from not building the associated calorimeter electronics in the descoped iHCal is described in the Calorimeter Electronics section of this chapter.

1.4 Reduced Calorimeter Electronics

Cost delta: -$1.6M

By reducing the amount of SiPMs purchased, calorimeter preamps and digitizers fabricated, as well as reducing specific electronics support equipment to match the reduction in the EMCal and iHCal scope, one saves $1.6M including contingency. The quoted savings includes a modest amount saved in the aforementioned scrubbing exercise.

Chapter 2

Performance impact

Here we present studies of the performance impact of the cost-savings options discussed above, i.e., replacement of the iHCal by an uninstrumented structure and reduction of the EMCal acceptance to $|\eta| < 0.85$. For comparison, we will refer to the "nominal" configuration, including the instrumented stainless steel iHCal and $|\eta| < 1.1$ EMCal. Our studies present a mix of full GEANT4 simulations, generator-level simulations and extrapolations based on studies for the 2016 baseline scope document.

2.1 Removal of iHCal

For our 2016 studies a fast evaluation of a no-iHCal configuration showed that compared to the expected savings the loss in physics performance made this option unattractive, leading us to focus on changes to the EMCal acceptance. Since then, the expected iHCal share of the total detector cost increased (partially necessitating the current cost savings studies) and we have developed a better understanding of the relative calibration of the elements of the calorimeter stack, as well as improved simulations. This has shifted the balance of physics performance loss vs. cost savings, where now a combination of an uninstrumented iHCal replacement and slightly reduced EMCal acceptance is the optimal compromise, in particular when considering potential scope recovery. Below we discuss studies related to the impact of iHCal changes on key jet performance parameters.

We have considered a number of options for replacing the nominal iHCal design. The matrix of options is defined by several choices: instrumented (scintillator tiles and electronics) vs. uninstrumented structure, material (stainless steel vs. aluminum) and mechanical design (a structure than can be instrumented vs. a frame that just provides the necessary support for EMCal installation).

The number of hadronic radiations lengths as a function of azimuth for different iHCal structures is shown in Fig. 2.1. The figure shows a change of about 0.3–0.35 interaction lengths going from the nominal design to a aluminum structure or stainless steel support frame. For reference, the total nominal calorimeter stack has a depth of approximately 5.5 interaction lengths.

Studies of jet energy scale (JES) and jet energy response (JER), i.e., mean and fluctuations of the observed jet energy in simulations compared to the truth information at the particle level, show

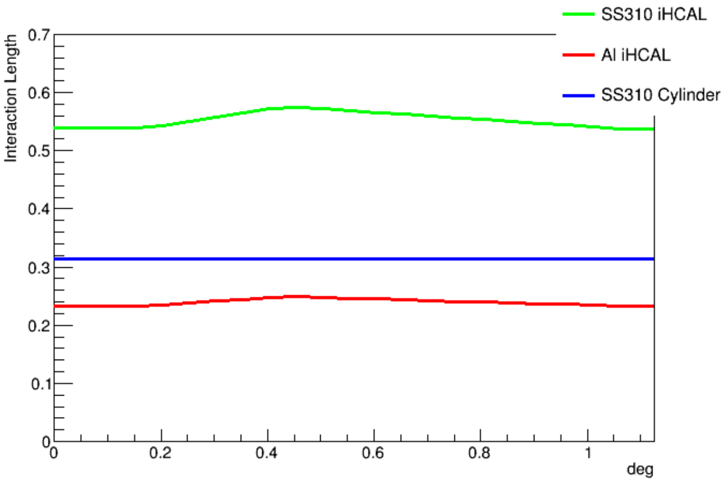


Figure 2.1: Hadronic interaction lengths provided by the iHCal options studied, as a function of azimuth. The physical structure of the calorimeter has a period of 1.25 degrees in azimuth.

that the thickness (measured in hadronic interaction lengths) of uninstrumented regions in the calorimeter stack should be minimized and that of instrumented regions maximized to achieve optimal performance.

As the uninstrumented aluminum structure and a stainless steel frame (for which further engineering studies are needed to minimize the material budget) represent a similar change in interaction lengths to the nominal design, we will limit the following discussion to three representative options: 1) the nominal iHCal design, 2) an uninstrumented aluminum structure of the same mechanical design (which is a fair representative of all uninstrumented structures/frames) and 3) an instrumented aluminum structure following the stainless steel iHCal design, which represents a possible recovery option.

We performed full GEANT4 studies for a sample of 50 GeV jets to evaluate the impact of changing from the nominal iHCal design to these alternative designs, i.e., an uninstrumented and instrumented aluminum structure. In addition to JES and JER we evaluated the jet finding efficiency for jets with high-z fragments, which could be affected due to increased punch-through in the "thinned" configurations.

A comparison of the reconstructed jet energy for the three options, in comparison to the nominal configuration is shown in Fig. 2.2. Relative to the nominal design, one observes a progressive change in JES and JER going to an instrumented aluminum structure and an uninstrumented structure. While changes in the JES can be addressed through calibrations, an increase in the JER reflects a irrecoverable worsening of the detector performance. In our studies, the JER grows from 0.104 to 0.114 and 0.136, respectively, in this progression of options. All figures carry a ±0.002 statistical uncertainty.

Future studies utilizing an optimal combination of calorimeter and track based information follow, e.g. the particle flow algorithms used in CMS and ILC jet reconstruction, may recover (or even improve) the calorimeter-only jet performance in the nominal configuration. This avenue is particularly important to pursue as removing a longitudinal segment of the calorimeter reduces

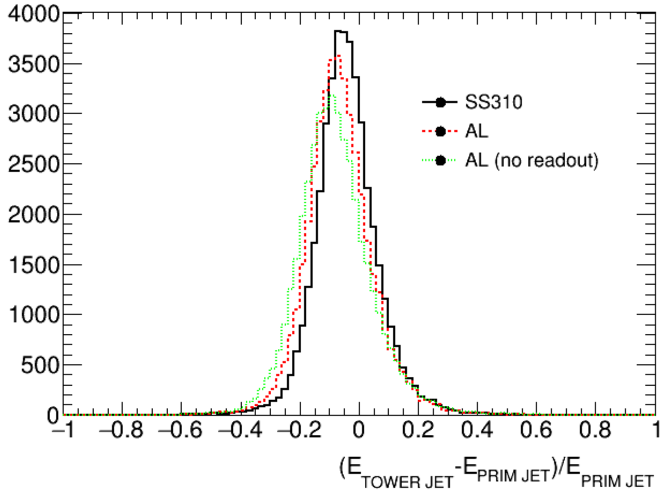


Figure 2.2: Normalized jet energy response for 50 GeV jets for nominal iHCal design (solid black line), instrumented aluminum structure (dashed red line) and uninstrumented aluminum structure (dotted green line).

key cross checks such as a jet response as a function of longitudinal center-of-gravity of the shower.

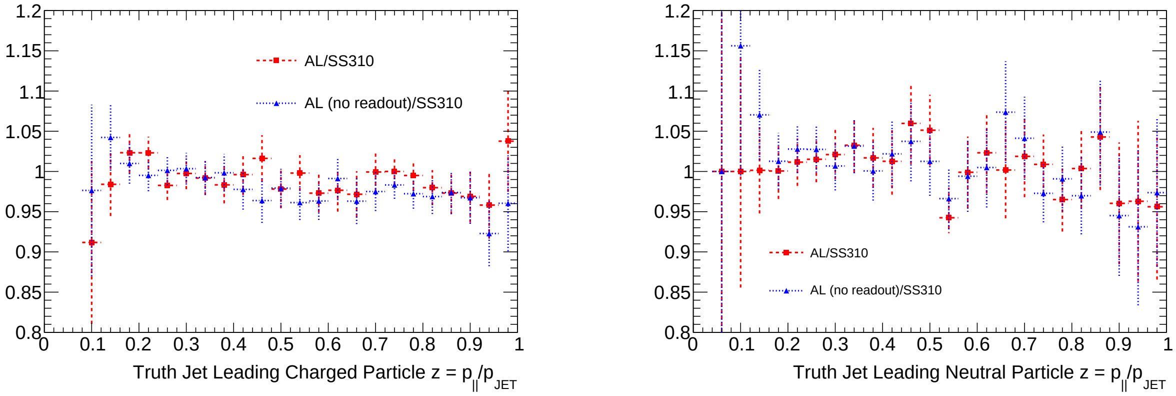


Figure 2.3: (Left) Ratio of jet reconstruction efficiencies as a function of $z = p_{||}/p_{jet}$ of the highest-z charged fragment, comparing instrumented and uninstrumented aluminum structures to the nominal iHCal design. (Right) Same, as a function of highest neutral particle z.

A possible consequence of reducing the effective thickness of the calorimeter stack is increased punch-through for hard-fragmenting jets, i.e., those with high-z charged or neutral fragments (with $z = p_{||}/p_{jet}$). In Fig. 2.3 (left) we show the ratio of jet finding efficiencies as a function of z of the highest z charged fragment between the two alternative aluminum structures and the nominal iHCal design. No strong z-dependence is observed. A similar result was observed for as a function of z for neutral particles, shown in Fig. 2.3 (right). It should be noted that the systematic uncertainty resulting from possible punch-through is expected to vary for different observables. While measurements of single jet spectra or dijet correlations should be insensitive to the small observed change in z-dependent efficiency ratios, studies for possibly more sensitive jet substructure related observables are ongoing.

Overall, the changes to the iHCal lead to modest (instrumented aluminum structure) to moderate (non-instrumented structure) changes in basic jet performance parameters. These in turn imply a manageable decrease in systematic precision for common jet observables such as nuclear modification factors, p_T imbalance and heavy-flavor jet fractions, which can be recovered through more advanced algorithms. A remaining concern is the effect on more complex novel jet observables such as jet substructure measurements through groomed jet reconstruction. Evaluating the full impact on such measurements through full simulations and analyses is the subject of ongoing studies.

2.2 Reduced EMCal pseudorapidity coverage

Reducing the EMCal coverage to $|\eta| < 0.85$ will directly affect the expected statistics for reconstruction of $\Upsilon \leftarrow e^+e^-$ decays and photon-based measurements. For jet-based measurements, the resulting non-uniformity of the jet response at the EMCal boundary will lead to increased systematic uncertainties, and may reduce the overall jet acceptance by $|\Delta\eta| \approx 0.25$ for more complex observables (e.g., jet substructure related measurements). Below we discuss the loss of acceptance and statistical reach for several channels.

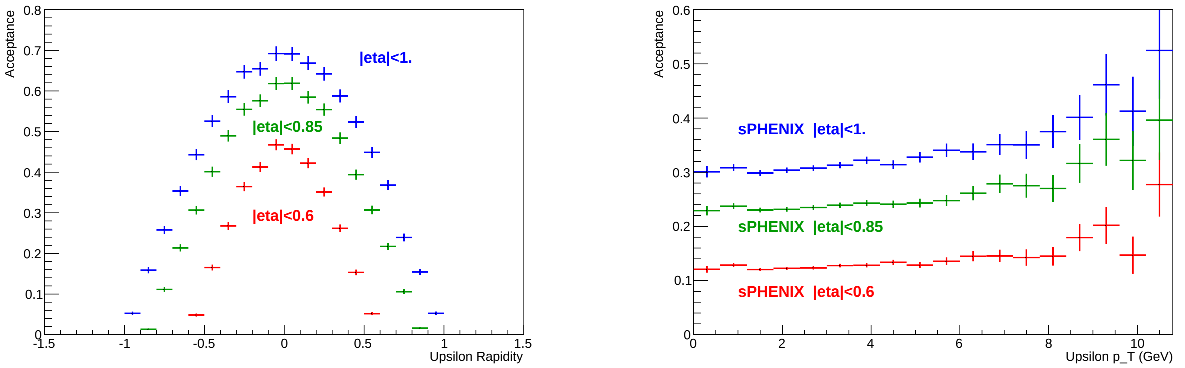


Figure 2.4: (Left) Υ to e^+e^- acceptance as a function of rapidity for the nominal (blue markers), $|\eta| < 0.85$ (green markers) and $|\eta| < 0.6$ (red markers) configurations, averaged over Υ p_T. (Right) Υ to e^+e^- acceptance as a function of p_T for the nominal (blue markers), acceptance as a function of rapidity for the nominal (blue markers), $|\eta| < 0.85$ (green markers) and $|\eta| < 0.6$ (red markers) configurations, averaged over η.

Loss of Υ acceptance and statistics Figure 2.4 shows the acceptance for Υ to e^+e^- decays for the nominal and reduced $|\eta| < 0.85$ and $|\eta| < 0.6$ EMCal configurations as a function of rapidity (left) and p_T (right). Based on these generator level studies, a loss in Υ statistics by about 25% is expected for the $|\eta| < 0.85$ configuration, compared to the nominal configuration, with a slightly smaller effect at high p_T. In Υ rapidity, about 0.25 units in rapidity reach are lost when requiring equal Υ statistics for the nominal and reduced η configuration. One should note that within the proposed five-year sPHENIX run plan a 25% loss is comparable to the statistics collected in a full RHIC year of data taking.

Impact on jet response and statistics For jet measurements, the reduced coverage leads to a change in jet response across the EMCal boundary. This effect was evaluated by full GEANT4 simulations and reconstruction of the single jet response in different regions of pseudorapidity and jet p_T.

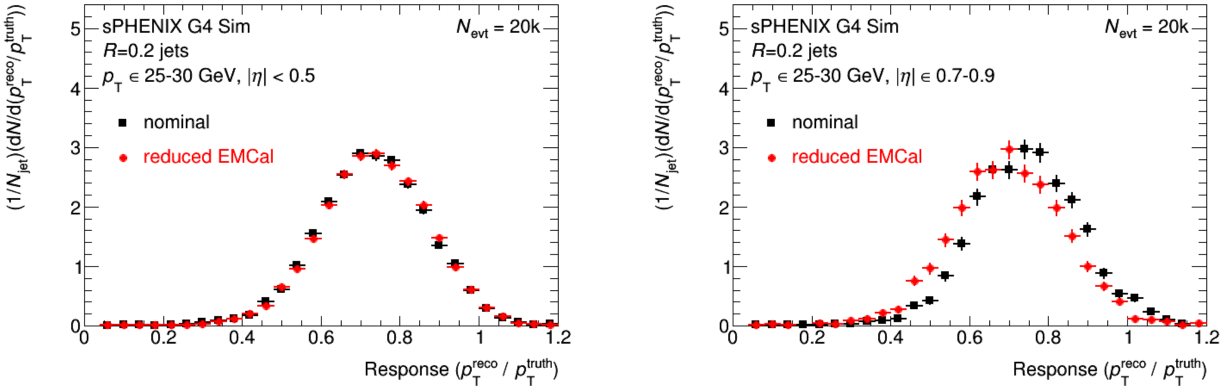


Figure 2.5: (Left) Comparison of jet response for $|\eta| < 0.5$ jets for nominal (black markers) and reduced acceptance (red markers) EMCal configuration. (Right) Comparison of jet response for $0.7 < |\eta| < 0.9$ jets for nominal (black markers) and reduced acceptance (red markers) EMCal configuration.

For our 2016 studies, the effect of reducing the EMCal acceptance to $|\eta| < 0.6$ on the jet energy response, p_T^{reco}/p_T^{truth}, was studied for low p_T jets, where we expect the largest effect, for three regions of jet pseudorapidity, $|\eta| < 0.5$ (Fig.2.5, left), $0.5 < |\eta| < 0.7$ (not shown) and $|\eta| > 0.7$ (Fig. 2.5, right). As expected, essentially no change is observed for jets in the rapidity region covered by the EMCAl, while for jets partially or completely outside of the EMCal acceptance a shift in the mean of several percent and the appearance of an enhanced low response tail are apparent.

The change in jet response seen for jets falling (partially) outside of the EMCal acceptance is of a similar order as that seen in the comparison of an instrumented iHCal-replacement with the nominal iHCal. Combining these two changes will lead to significantly increased systematic uncertainties on measurements including jets straddling the EMCal boundary and will likely reduce the usable acceptance for many jet-related measurements and in particular jet substructure measurements by 0.25 units in pseudorapidity compared to the nominal configuration.

We have investigated the loss in statistics when requiring jets and dijets to be fully contained in the reduced EMCal acceptance. The results for single inclusive jets are shown in Fig. 2.6 (left). We estimate a loss in acceptance for fully contained low p_T single jets of 20% to 30%, depending on the jet radius parameter R. For fully contained dijets with a leading jet p_T of 25 GeV and a subleading jet of $p_T > 5$ GeV, we estimate a 35% to 50% loss of statistics, depending on the radius parameter.

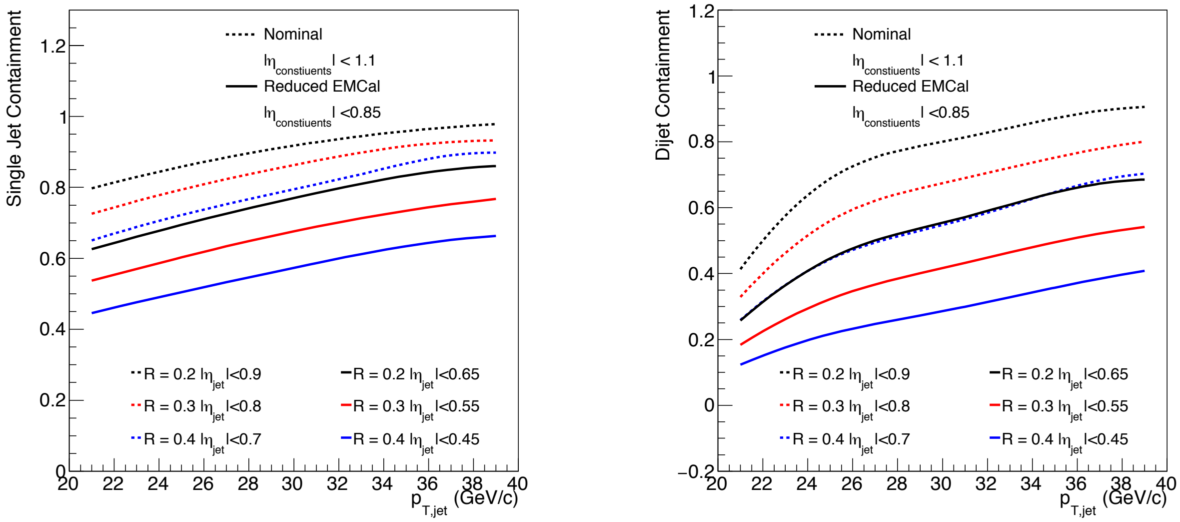


Figure 2.6: (Left) Fraction of inclusive single jets fully contained within the acceptance of the nominal ($|\eta| < 1.1$) and reduced ($|\eta| < 0.85$) EMCal configurations as a function of jet p_T and anti-k_T jet radius parameter. (Right) Fraction of dijets fully contained within the acceptance of the nominal ($|\eta| < 1.1$) and reduced ($|\eta| < 0.85$) EMCal configurations as a function of jet p_T and anti-k_T jet radius parameter.

Chapter 3

Summary

In this document the sPHENIX collaboration has outlined a modified baseline detector design that conforms closely to the \$32M cap on M&S costs set by BNL ALD Berndt Mueller. Savings are mostly achieved by replacing the instrumented stainless steel iHCal structure with an uninstrumented aluminum structure or by a stainless steel frame and by reducing the EMCal acceptance from $|\eta| < 1.1$ to $|\eta| < 0.85$.

The impact of these changes on the main sPHENIX science drivers, jet structure, heavy-flavor jet production and Υ spectroscopy production and Υ spectroscopy, as well as on cold-QCD-related jet and dijet observables, has been evaluated using generator-level studies to estimate the expected loss in statistics and full GEANT4 simulations to study the impact on jet reconstruction performance.

For single inclusive jet and heavy-flavor jet production, a loss in statistics of jets fully contained within the EMCal acceptance of about 35% – 50% is expected, depending on radius parameter. Similarly, the rapidity reach for Υ reconstruction will shrink by 0.25 units in rapidity, along with a 25% reduction in overall reconstructed Υ statistics.

For jet reconstruction, the main effect is related to the introduction of dead material in the current iHCal volume, in the form of an (potentially) uninstrumented Al structure or steel/Al frame. For the $p_T = 50$ GeV jet sample studied, this increases the jet energy resolution relative to the particle-level true jet energy from about 10% to about 14%. Experience from measurements at CERN suggests that this will lead to a noticeable, but still manageable, increase of overall systematic uncertainties. Our studies also show that this effect can be mitigated for a wide range of measurements (but not all) by including track-based information, e.g., through particle-flow type algorithms. Instrumenting an Al-based structure would allow nearly full recovery of the iHCal performance.

In addition to its role for jet reconstruction, the iHCal can play an important role for Drell-Yan and direct photon cold QCD measurements by improving hadron rejection by an approximate factor of two. More detailed studies of the full impact on these measurements of replacing the iHCal with an uninstrumented structure are ongoing. Similarly, the effect of the proposed changes on state-of-the-art jet substructure observables will require additional studies.

In conclusion, we have studied the physics performance of an sPHENIX baseline configuration that conforms with the \$32M cost cap in the ALD's charge through replacement of the iHCal and reduction in the EMCal acceptance. These changes largely preserve the unique sPHENIX capabilities for hard probe physics at RHIC, although there is a significant impact on statistical reach and jet reconstruction. If additional resources, e.g. through foreign contributions, can be identified in a timely manner the proposed changes do not preclude restoring the full acceptance and nearly the full jet performance. Finally, the collaboration plans to revisit the the specific balance of cuts needed to address cost constraints prior to an OPA CD-2 review at which the official baseline scope of the project is established.