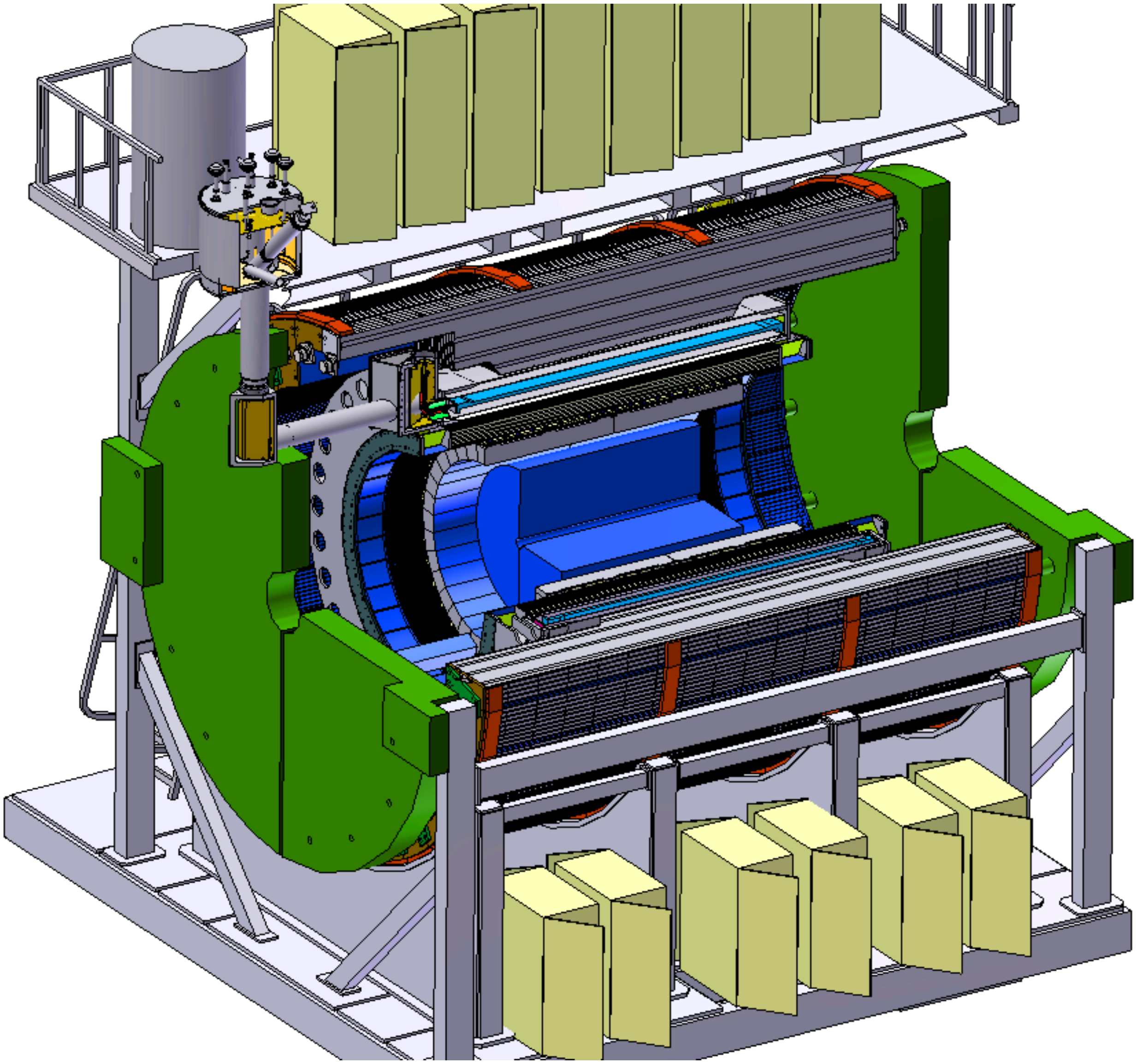

Answering the Baseline Scope Charge

The sPHENIX Collaboration
May 31, 2016

Executive Summary

In this document the sPHENIX collaboration answers a charge (see Appendix A.5.2) from BNL ALD Berndt Mueller to develop a baseline design scope that provides a compelling phsyics program within the constraints of possible DOE funding redirected from RHIC operations. The document describes a reference design aimed at a compelling program focussed on three science drivers: jet structure, heavy-flavor jet production and Υ spectroscopy. We then provide a comprehensive list of re-scoping options for each of the main subdetector systems, and describe the associated cost savings, the engineering and schedule impact and impact on key performane measures related to the three science drivers. Based on these criteria, we develop examples of rank-ordered lists of re-scoping options including the cumulative cost-savings and science impact.

Overview

0.1 Introduction

In this document the sPHENIX collaboration answers a charge (see Appendix A.5.2) from BNL ALD Berndt Mueller to develop a baseline design scope that provides a compelling phsyics program within the constraints of possible DOE funding redirected from RHIC operations. The document describes a reference design aimed at a compelling program focussed on three science drivers: jet structure, heavy-flavor jet production and Υ spectroscopy. We then provide a comprehensive list of re-scoping options relative to the reference design for each of the main subdetector systems, and describe the associated cost savings, the engineering and schedule impact and impact on key performane measures related to the three science drivers. Based on these criteria, we develop examples of rank-ordered lists of re-scoping options including the cumulative cost-savings and science impact.

The total amount of redirected DOE funds available is quoted as $75M in FY16 dollars. Based on discussions between ALD, project and collaboration, the charge can however more narrowly interpreted as aiming at a reduction in discretionary M&S costs by $4M in FY16 dollars compared to the detector design described in the 2015 directors cost and schedule review. In this document we will therefore exclusively focus on these M&S savings, excluding non-discretionary infrastructre items such as cryogenics, magnet, central pedestal and flux doors.

0.2 sPHENIX science drivers

sPHENIX is a next-generation RHIC experiment providing world-class capabilities for multi-scale studies of the microscopic nature of the strongly coupled quark gluon plasma. It uniquely provides measurements complementary to those being obtained at the LHC by working at a collision energy near T_c, where the medium coupling is believed to be strongest and the corresponding dynamical effects the most pronounced.

The physics aims of sPHENIX have been endorsed broadly and repeatedly. The top recommendation of the September 2014 Phases of QCD Matter Town Meeting at Temple University reads in part, "implementation of new capabilities of the RHIC facility (a state-of-the-art jet detector such as sPHENIX and luminosity upgrades for running at low energies) [is] needed to complete its scientific mission,". The top recommendation of "The Hot QCD White Paper: Exploring the Phases of QCD at RHIC and the LHC", includes the statement, "implementation of new capabilities of the RHIC facility needed to complete its scientific mission: a state-of-the-art jet detector such as sPHENIX and luminosity upgrades for running at low energies.” Both of these documents provided carefully considered community input for the development of the most recent NSAC Long Range Plan, “The 2015 Long Range Plan for Nuclear Science,” which was officially accepted by the DOE Office of Nuclear Phyics in October 2015, and reads in part:

> There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.

In addition to these community-wide endorsements of the aims of sPHENIX, the detailed science case presented in the sPHENIX proposal had a successful science review in April 2015 conducted by the DOE Office of Nuclear Physics.

For the physics studies presented in this document we considered three main science drivers. These were selected to represent the main known experimental approaches to the science case discussed in the NP LRP and to provide a comprehensive test of all aspects of the expected detector performance. They are:

1. **Jet structure:** Modifications of jet structure provide a unique test of the microscopic nature of the sQGP, as each jet itself represents a multi-scale object in angular and momentum space. Corresponding measurements depend sensitively on the performance on the acceptance and performance of the calorimeter system for jet finding and jet energy determination, the EMCal for measuring isolated photons as jet energy tags and on the tracking system to provide high resolution charged particle information to characterize the jet structure jet-by-jet.

2. **Heavy-flavor tagged jets:** Measurements of heavy-flavor hadrons and jets over a wide kinematic range are critical for studies of the flavor dependence of parton interactions with the mediumfor and for disentangling the effects of radiative vs. collisional energy loss processes. In addition to the general jet finding performance, these measurements depend critically on the performance of the inner tracking system for displaced tracks and vertices needed for high efficiency heavy-flavor tags.

3. **Upsilon spectroscopy:** Spectroscopy of the Υ family allows to study the effects of color-screening as a function of size and binding energy of the quarkonium probes and as a function of density and size of the medium for collisions of varying centrality. Separation of the three Υ states requires very good momentum resolution in the intermediate p_T range and electron/hadron separation, thereby testing the performance of the outer tracker and electromagnetic calorimetry.

Within the collaboration, we established three Topical Groups to work on the science, analysis and performance evaluation related to each of the three science drivers. The Topical Groups worked with the software and simulation team on one side and the subdetector project teams on the other side to establish the science impact of the individual re-scoping options.

0.3 Methodology and document structure

The discretionary M&S expenditures are linked to five major subsystems: Outer HCal, inner HCal, EMCal, outer tracker, inner tracker and DAQ/trigger, following the structure established by the sPHENIX project. For each of the five subsystems, we solicited input from the collaboration, the project leadership, the three topical groups and susbsystem epxerts to assemble a comprehensive list of re-scoping options aimed at reducing individual subsystem costs. For each identified option, cost savings and the engineering, design and schedule impact were estimated by project leadership in consultation with the engineering team and subsystem experts. The resulting cost, engineering and design impact, at the level of detailed achievable in the time allowed, is described in detail in Appendix A.

The large number of identified options precludes establishing simulation geometries for all possible combinations of subsystem configurations and running full GEANT simulations for these combined configurations. Rather, we studied the impact on key physics performance figures related to three science drivers for each option individually and for select combinations of options when they were individually found to have non-negligible impact on the same performance characteristics. For the various options, the performance studies were done at different levels of detail, ranging from generator level studies of loss of statistical precision, to single particle GEANT4 + reconstruction studies of resolution and bias effects to full central Au+Au HIJING GEANT4 + reconstruction studies. Where applicable, the physics impact of various changes was also evaluated based on experience with corresponding measurements at RHIC and LHC. In particular for the MAPS inner tracking option and the TPC outer tracker, we consulted with the project managers in the ALICE upgrade program, Luciano Musa (CERN, ALICE ITS upgrade manager) and Harald Appelshauser (Frankfurt, TPC project manager) and with experts from the STAR collaboration (Flemming Videbaek, HFT and iTPC project manager and Gene van Buren, STAR TPC expert). The resulting science impact evaluation for all proposed subsystem changes is described in Appendix B.

The following sections of the document are organized as follows: We briefly describe the reference design used to evaluate the relative performance impact of each subsystem option. Next we provide a concise summary of the cost, engineering, design and schedule impact and science impact of each option. This is followed by a rank-ordered table of options, from least to most undesirable, based on our evaluation of savings vs. engineering and science impact. Following a summary, we provide an extended discussion of the each option's impact in the Appendices A (cost, engineering, schedule) and B (physics performance).

0.4 Reference configuration

All cost changes are evaluated with respect to the detector configuration discussed in the 2015 Director's cost and schedule review, in which in particular included a TPC outer tracker and a 2-layer inner tracker based on reconfigured VTX pixel modules. However, based on more detailed simulations of the VTX pixel performance, including known dead areas, and the operational experience with the VTX detector in the 2016 RHIC run, this configuration is not expected to provide acceptable performance for the sPHENIX science program. This configuration would essentially preclude the heavy-flavor part of the science program, and not provide the highly desirable redundancy in tracking performance for the jet structure and Y spectroscopy science drivers, in terms of providing precise track stubs to match to the TPC outer tracker.

The evaluation of the science impact of the subsystem changes is therefore performed relative to a reference configuration for which our simulations show excellent physcis performance. The reference configuration uses the HCal, EMCal and TPC subsystems from the cost&schedule configuration unchanges, but replaces the inner tracker with a three-layer MAPS based tracker, using a module (“stave”) design copied from that of the ALICE ITS upgrade inner barrel (IB) detector. This option was extensively evaluated in a workshop organized by the LANL group in late March 2016, attended by ALICE ITS project management (Luciano Musa) and experts (Leo Greiner, LBNL). At the workshop, a detailed cost estimate for this option was prepared, corresponding to $4M FY16 direct M&S costs for the IB copy, including engineering costs for integration in the sPHENIX detector infrastructure. The full 3-layer IB copy therefore increases the cost of the reference configuration by $4M in M&S costs, and by $ FIXME in fully loaded costs compared to the cost&schedule review configuration. A significant part of the performance gain associated with the reference configuration could be realized with a 2-layer MAPS configuration, esimated in $3M in FY16 M&S cost.

0.5 Summary

Thinned Outer HCal

Cost delta: -$0.4M

We investigated reducing the thickness of the outer HCal (nominal depth of 82.5 cm) by 20 cm, or approxiately one nuclear interaction length. Several possible effects were investigated through full GEANT4 simulations of the calorimeter response. It should be noted that the calorimeter simulations have recently been compared to data from the FNAL test beam and ahve been found to reproduce the measured response quite well (put a number in here). We looked at the effect of thinning on the jet energy response, high-z fragmentation functions, and triggering in pp and pAu.

From a physics perspective, the effect of thinning the outer HCal by this amount seems to be moderate, and considered by itself, a thinner outer HCal would still enable the core elements of the sphenix physics program to be carried out.

From the perspective of the project, the effect of this modification would be extremely significant. The OHCal is the structural backbone of the sPHENIX structure. Reducing the radial thickness will significantly reduce the ability of the OHCal to support the detector. The finite element analysis would need to be redone. The tilt angle reanalyzed and likely changed. The prototyping and test beam would have to be redone. It would make no sense to build the full scale mechanical prototype now. The IHCal will still need some redesign due to the changes in the EMCal. Well want the ϕ segmentation to match between the two for mechanical reasons.

Sets the OHCal engineering back as much as twelve months and requires R&D be redone.

Considerations

In the nominal design, the 5.5λ total depth of the calorimeter stack (at $\eta = 0$) is distributed as 1λ (EMCal), 1λ (inner HCal), and 3.5λ. If the outer HCal is reduced to 2.5λ, one has to consider the effects if one or more of the other calorimeters in the stack is also modified. If the inner HCal is not installed, the depth of the calorimeter stack is reduced by an additional 1λ over the whole acceptance, falling to 2.5λ at midrapidity.

If the EMCal acceptance is cut to $|\eta| < 0.7$, the thickness of the calorimeter stack in the range $0.7 < \eta < 1.1$ becomes thinner by 1λ, but the effect in that range (aside from the lack of EMCal coverage) is moderated by the increasing thickness of the calorimeters along lines of constant η due to their rectangular profile.

Shortened HCal

Cost delta: –$0.7M

We investigated shortening the outer HCal (nominal length 631 cm) to 541 cm. For an HCal of the nominal length, the outer corner of the HCal lies along $\eta = 1.0$ while then inner corner of the HCal is at $\eta = 1.3$. For a reduced length calorimeter, the outer corner of the HCal lies along $\eta = 0.89$ while then inner corner of the HCal is at $\eta = 1.19$. This is a minimum length for the outer HCal, as supporting the weight of the calorimeter requires it to extend beyond the end of the solenoid cryostat.

The effect on sphenix physics stems directly from the reduced acceptance. The smaller acceptance catches fewer jets and high p_T hadrons and dijets, and it also reduces the acceptance for systematic studies of the response. The former issues can be determined in a straightforward manner; the effect of the latter issue is guided by relevant experience.

From the perspective of the project, save on not only mechanics but also scintillator tiles and electronics channels. The shorter OHCal will be easier to make, handle, transport and assemble. It will be more rigid. The detector cross section will be unchanged so engineering revisions will be minimal (the project estimates that it would take four weeks). The R&D done to this point will be valid. We can advance to the next step in prototype work. Restoring the acceptance with endcap calorimeters is conceivable, but would require immediate consideration in the engineering of the main part of the detector. In addition, the procurement process for the endcap steel would need to begin very soon, as it would have the similar long lead-time issues as the steel for the current design.

Considerations

Shortening the outer HCal steel also implies moving the flux doors at each end of the experiment inward by the same 45 cm. This is needed so that the strong magnetic field is well-contained and kept away from the electonics racks on the carriage, allowing personnel to get to those racks for routine or exceptional maintenance during the run without requiring the magnet to be deenergized. Moving the flux doors inward by this amount significantly reduces the space potentially available for instrumentation beween the end of the TPC and the flux door, as would be required for forward spin and cold QCD measurements. This would be seen particularly negatively by the members of the collaboration interesting in spin physics and by those intereseted in the use of sPHENIX as a day-1 EIC detector. ¡¡¡¡¡¡¡ HEAD

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Inner HCal

¿¿¿¿¿¿¿ origin/master

EMCal Ganged Towers

Cost delta: -$1.7M

We have studied the effect of ganging together the electronic outputs of groupings of four nominally-sized EMCal towers. This has several effects of this modification are a reduction in the e/π separation performance in Au+Au collisions

EMCal Coarsened Segmentation

Cost delta: $-\$1.8M$

We have investigated reducing the number EMCal towers from $256 \times 96 = 24576$ ($\Delta\eta \times \Delta\phi = 0.024 \times 0.024$) to $192 \times 80 = 15360$ ($\Delta\eta \times \Delta\phi = 0.033 \times 0.028$) a reduction of tower numbers by 37.5%.

TPC

Cost delta: -$0.5M

We have considered the effect of instrumenting only alternate rows of the TPC readout plane, reducing the cost of the electronics by approximately a factor of two.

Considerations

A number of people in the collaboration have expressed a very strong interest in maintaining the potential for π, K, p particle identification through a dE/dx measurement in the TPC. While we may already be driven to set the voltages on the TPC GEMs in a way that minimizes ion backflow at the expense of worsened dE/dx resolution, the additional worsening that comes from not reading out half the pad rows will be taken as a very negative statement about their physics interests.

MAPS

DAQ/Trigger

Cost delta: -$1.5M

The costs associated with the DAQ and Trigger are an area where significant reductions are achievable. Although we think the $0.5M trigger detector is a suitable target for a non-DOE, possibly non-US, contribution, for the purposes of answering this charge, we do not assume that that will happen. Each of the RHIC experiments has built trigger detectors that would suit the needs of sPHENIX, and some of these detectors, such as the trigger detector used by PHOBOS, are currently unused and available. We would repurpose one of these detectors for use in sPHENIX and reduce the M&S costs accordingly.

We would reuse the infrastructure currently in place in the PHENIX counting house, consisting of data collection modules (DCMIIs), subevent buffers (SEBs), assembly and trigger processors (ATPs), a high throughput networking switch and several racks of computers. Some amount of new equipment would be needed, such as new level-1 and global trigger boards. There is some risk associated with this approach, as it means, absent funds to renew th computing infrastructure, starting a new experiment with computing that will be by then several years old.

Appendix A

Physics performance studies

Below we describe the simulation studies performed to evaluate the impact of the re-scoping options we identified on the three science drivers. We first compare each change individually to the performance of the reference configuration, and then study a select set of changes in combination to evaluate their combined effect on the physics performance. For each option we describe the simulations employed, ranging from generator level evaluations of count rates to single particle and single jet GEANT4 simulations + reconstruction to full HIJING central Au+Au GEANT4 simulations and reconstruction. All studies were performed for 200 GeV Au+Au collisions.

A.1 Hadronic calorimeter changes

A.1.1 Outer HCAL thinning

The main impact on the science program from thinning the outer HCAL is expected in areas:

- Reduced jet energy containment leading the larger systematic uncertainties in the jet energy scale and larger fluctuations in the jet-by-jet energy measurement.
- Increased punch-through of high momentum particles leading to a fragmentation function bias

The impact was studied with full GEANT4 simulations and jet reconstruction using the anti-k_T algorithm for single jets for the reference configuration, the 20cm thinner oHCAL and the minimal outer HCAL.

A.1.2 Outer HCAL shortening

For the shortened outer HCAL (reducing the pseudorapidity coverage from $\|\eta\| <$ FIXME to $\|\eta\| <$ FIXME), all measured at the outer corner of the calorimeter) the expected impact is in the statistics of jet related probes. The 20% reduction in coverage will predominantly affect lower p_T jets ($p_T <$

FIXME), as jets at the highest p_T have a narrow rapidity distribution that falls within the remaining acceptance. From generator level studies, we expect the following loss of statistics: FIXME

Some of the physics impact can be recovered using tracker + EMCal reconstruction of jets, although reduced control over the jet energy scale and increased jet-by-jet fluctuations will limit the precision that can be achieved with such studies.

A.1.3 Removal of the inner HCAL

The impact on jet energy scale and fluctuations for this option is expected to be larger than for the outer HCAL thinning, with major impact on engineering of the inner detector mechanical design leading to expectations of minimal overall savings. We therefore did not perform detailed studies of this option.

A.2 EMCal

A.2.1 2×2 ganging of EMCal channels

The reduced EMCal segmentation from 2x2 ganging of readout channels is expected to affect three physics areas: jet finding and jet energy reconstruction, electron/hadron separation for the Υ to e^+e^- channel and photon identification. We performed full GEANT4 and reconstruction studies of the effect on the single jet response and full GEANT4 simulations for Au+Au HIJING events for electron identification. Studies of the effect on photon identification are ongoing.

A.2.2 Changing EMCal segmentation

The reduced EMCal segmentation from increasing the tower dimensions from $d\eta \times d\phi = 0.024 \times 0.024$ to 0.033×0.28 was not evaluated with full GEANT4 simulations, as time did not permit implementing the corresponding detector geometry. However, as the change increases the tower area by 60%, as compared to a factor of 4 for the 2x2 ganging, the expected impact can be well estimated based on the 2x2 ganging full simulations. For the jet response, the 2x2 ganging did not show any noticable effect, implying that the 60% increased tower size will also have no effect on jets. For e/h separation, the effect of the 2x2 ganging of about a factor of two suggests scaling with the $\sqrt{\text{area}}$, i.e., the fluctuations in the background energy. This implies a 26% change in e/p separation in central Au+Au collisions for the 60% increase in tower size, which is well within the projected safety margin for the measurement.

A.2.3 Reduced EMCal pseudorapidity coverage

Reducing the EMCal coverage will directly affect the expected statistics for Υ to e^+e^- and photon-based measurements. The corresponding loss in statistics is summarized in the table below, based on generator level studies. 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.

A.3 Outer tracker

For the outer tracker, the performance of a TPC tracker was evaluated using GEANT4 simulations of single particles, single Υ to e^+e^- decays, and full HIJING and GEANT4 simulations in a limited acceptance around mid-rapidity (due to timing limitations). Simulations were performed for an ideal TPC and two configurations with inner field cage boundary at $r = 20$ cm and $r = 30$ cm. For the latter configurations, effects of residual space charge distortions expected after corrections were included. We evaluated general performance characteristics (efficency, fake track rate, DCA and momentum resolution) and specifically the Υ mass resolutions for the different cases. The TPC simulations were performed in combination with the 3-layer MAPS configuration of the reference design, and include the effects of track reconstruction and kinematic fits. The effect of various inner tracker options on the tracking performance is evaluated separately in A.4.

A.3.1 Tracking performance evaluation

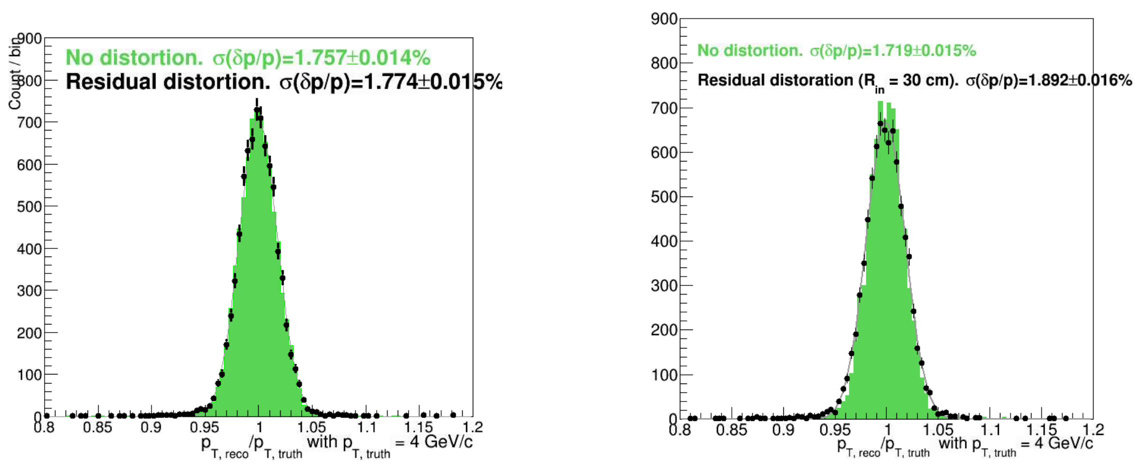

Figure A.1: Comparison of residual TPC distortions, after applying corrections, for the inner radius at (left) 20 cm and (right) 30 cm. Leaving 10 cm clear between the inner surface of the field cage and the beginning of the tracking volume results in significantly smaller residual distortions after correction.

Configuration	Υ mass resolution
3 maps layers and 60 TPC layers with no distortion due to space charge	66 MeV/c^2
3 maps layers and 30 TPC layers with no distortion due to space charge	76 MeV/c^2
3 maps layers and 60 TPC layers with distortions due to space charge	67.4 MeV/c^2
3 maps layers and 30 TPC layers with distortions due to space charge	77.2 MeV/c^2

Table A.1: Effects of corrected TPC space charge distortions and sparsified readout on the Υ mass resolution.

A.3.2 Υ mass resolution

A.4 Inner tracker

A.4.1 VTX pixel configuration

A.4.2 2-layer MAPS tracker

A.5 DAQ and trigger

A.5.1 Minimum bias trigger counter and vertex locator

A.5.2 Offline event building

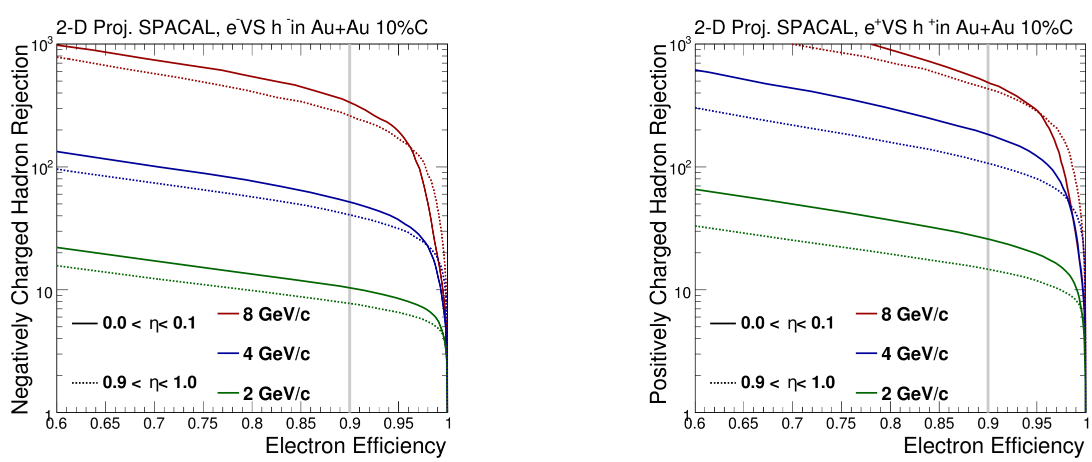

Figure A.2: For a 2×2 ganged EMCal (with inner HCal present) inclusive charged hadron rejection is plotted on the left (right) as function of electron ID efficiency, for negatively (positively) charged tracks of three choices of momentum and for middle and edge rapidity in 10% most central Au+Au events.

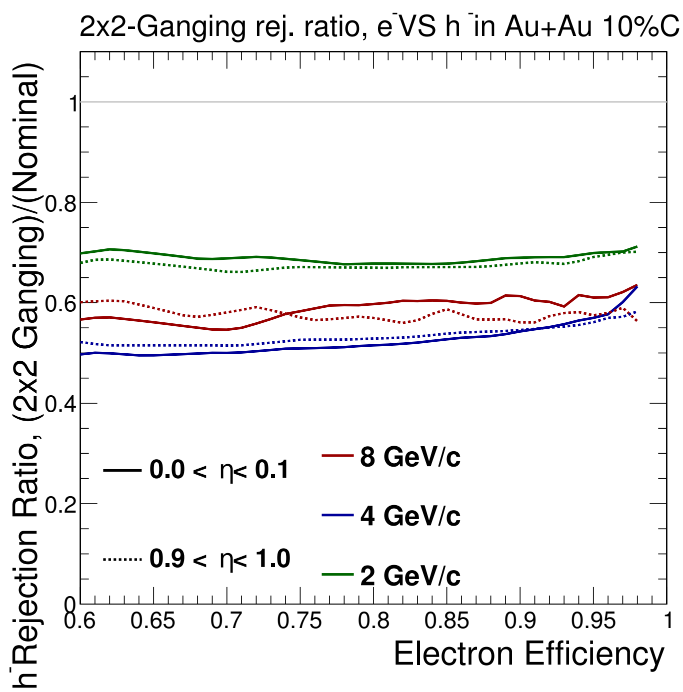

Figure A.3: Ratios of inclusive charged hadron rejection of 2×2 ganged EMCal to the reference design, as functions of electron ID efficiency. This is evaluated for negatively charged tracks of three choices of momentum and for middle and edge rapidity in 10% most central Au+Au events.

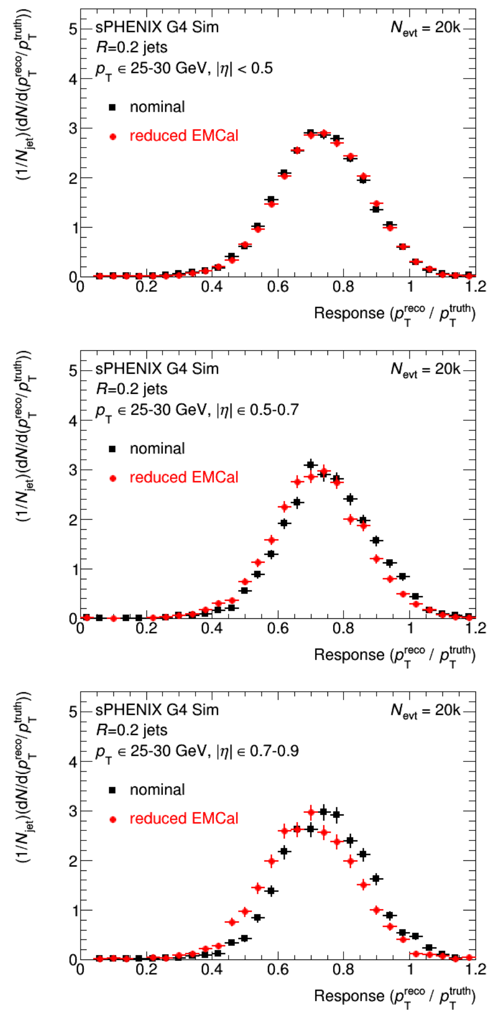

Figure A.4: The effect on the jet response on reducing the EMCal to an acceptance within —eta—¡0.6 was also examined with full GEANT4 simulations.

Charge

BROOKHAVEN
NATIONAL LABORATORY

Nuclear and Particle Physics Directorate

Building 510F
P.O. Box 5000
Upton, NY 11973-5000
Phone 631 344-5397
Fax 631 344-5820
bmueller@bnl.gov

Managed by Brookhaven Science Associates
for the U.S. Department of Energy

Memorandum

From: Berndt Mueller
To: David Morrison, Gunther Roland
Cc: Ed O'Brien, James Dunlop
Date: March 30, 2016

Dear Dave and Gunther:

In discussions since the November 2015 Cost and Schedule Review for sPHENIX, it has become clear that further work is needed to develop a plan for the construction of the sPHENIX detector within the constraints of possible DOE funding redirected from RHIC Operations.

I have therefore requested that sPHENIX Project Management, in close collaboration with the sPHENIX Collaboration, develops a credible plan encompassing an option of baseline design scope, cost, and schedule that will allow the detector to be completed on schedule for data taking in the FY2022 RHIC run within the presently foreseen DOE funding profile, and that the sPHENIX Project Management present this plan to BNL management no later than May 31, 2016. The plan should maintain the 40% contingency requested by the cost and schedule review. This plan should not assume the availability of additional funding from non-DOE sources, but may describe which elements would be added to the baseline scope of sPHENIX if additional funding became available.

I am aware that design scope choices will likely require making priority choices with respect to the scientific scope of the sPHENIX physics program. The sPHENIX collaboration and project management team should work closely in establishing these priority choices as needed. I trust that you understand that the sole purpose of my request is to ensure the success of sPHENIX and its future science program. I will be happy to answer any questions you may have at our bi-weekly sPHENIX spokespersons meetings.