sPHENIX

Dave Morrison (BNL)  Gunther Roland (MIT)  Co-spokespersons
sPHENIX: A fantastic high-rate capable detector at RHIC IP8, built around the former BaBar 1.5 T superconducting solenoid, with full electromagnetic and hadronic calorimetry and precision tracking and vertexing, with a core physics program focused on light and heavy-flavor jets, direct photons, Upsilon and their correlations in p+p, p+A, and A+A to study the underlying dynamics of the QGP – physics delivered by 22 weeks of Au+Au, 10 weeks each of p+p and p+A (@ 200 GeV).

*full disclosure: co-spokespersons G. Roland, D. Morrison
sPHENIX in one plot

Initial hard scattered parton virtuality in units of 1/fm as a function of the local temperature of the QGP medium.

- **Jet Virtuality Evolution**
  - RHIC $E_T = 20-80$ GeV
  - RHIC QGP Medium Influence
  - LHC $E_T = 100-1000$ GeV
  - LHC QGP Medium Influence

Vacuum virtuality evolution initially, with medium influence becoming significant as virtuality of parton shower and medium become comparable.


Upsilon family 1S, 2S, 3S establish fixed locations in this space.
sPHENIX reach exploits RHIC luminosity

extended reach in p+Au

for measurements able to use full vertex range
– can sample 0.6 trillion events
RHIC luminosity: more differential measurements

direct photons, charged hadrons

γ-jet

hydro energy density profile

statistical uncertainties based on sPHENIX run plan
RHIC/LHC measurements in 2020s

Ensemble-based measurements and $x+$hadron correlations add low $p_T$ reach

$\frac{R_{AA}}{R_{AA}}$

- $R_{AA}$ (RHIC Today)
- $R_{AA}$ (RHIC Tomorrow)
- $R_{AA}$ (LHC Today)
- $R_{AA}$ (LHC Tomorrow)

$X+$Jet

- $X+$Jet (RHIC Today)
- $X+$Jet (RHIC Tomorrow)
- $X+$Jet (LHC Today)
- $X+$Jet (LHC Tomorrow)

- $R_{AA}$ (Hadrons)
- $R_{AA}$ (Jets)
- $R_{AA}$ (D Mesons)
- $R_{AA}$ (B Mesons)
- $R_{AA}$ (b Jets)

- $X+$Jet (Dijets ($p_T,1$))
- $X+$Jet ($\gamma+$Jets ($p_T,\gamma$))
- $X+$Jet ($Z^0+$Jets ($p_T,Z$))
- $X+$Jet (Double b-Tag ($p_T,1$))

$p_T$ [GeV/c]
RHIC / LHC Timeline

LHC

- 2015
  - End of Long Shutdown 1
  - Stochastic e-Cooling
  - LS2

- 2020
  - Installation
  - Shutdown 2021
  - sPHENIX

- >2025
  - Electron-Ion Collider (Notional BNL Plan)

RHIC

- 2014-2017
  - Heavy Flavor Probes of QGP
  - Origin of Proton Spin

- 2019-2020
  - Beam Energy Scan II

- 2022-2025
  - Precision jets and quarkonia
Many sPHENIX developments since last PAC

- DOE NP long-range plan
- sPHENIX Project
- sPHENIX Scientific Collaboration
RECOMMENDATION I
The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.
- Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.
- The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.
- The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.

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.

New instrumentation at RHIC in the form of a state-of-the-art jet detector (referred to as sPHENIX) is required to provide the highest statistics for imaging the QGP right in the region of strongest coupling (most perfect fluidity) while also extending the kinematic reach at RHIC (as illustrated in Figure 2.13) to overlap that for jets at LHC energies. Upgrades to the LHC luminosities and detector and measurement capabilities are keys to providing a complete picture, as are new experimental techniques being developed to compare how light quark jets, heavy quark jets, and gluon jets “see” QGP. In general, using common, well-calibrated, jet shape observables in suitably tagged fully reconstructed jets at RHIC and the LHC will be critical to using the leverage in resolution and temperature that the two facilities provide in concert (see Sidebar 2.5) to relate observed modifications of jets to the inner workings of QGP.

Figure 2.13: Future reach of four precision measurements via jets for probing the most strongly coupled liquid with sPHENIX, in color, compared to current measurements from RHIC where available, in grey.
Immediately before last year’s PAC meeting

John Harris as acting IB chair, institutions were asked to indicate their potential interest in the collaboration, leading to a first collaboration meeting at Rutgers in December 2015
Continues six-year history of development

sPHENIX Concept in the PHENIX Decadal Plan (charged by ALD Steve Vigdor): October 2010

(new superconducting solenoid & optional additional tracking)

BNL Review (chaired by Tom Ludlam) of sPHENIX proposal: October 2012

Updated sPHENIX proposal: October 2013

BNL Review (chaired by Sam Aronson) of “ePHENIX” LOI: January 2014


Updated proposal, submitted to DOE: June 2014 (incorporation of Babar magnet and tracking)

DOE Science Review: July 2014


DOE Science Review (chaired by Tim Hallman): April 2015 – successful science review with no tracked recommendations

sPHENIX pCDR: November 2015
Institutions by the time of the Rutgers meeting

57 institutions signed up: Abilene Christian, Augustana College, Banaras Hindu University (India), Baruch College, CUNY, BNL and BNL (PHENIX), UC-Davis, UCLA, UCR, Chonbuk National University (South Korea), Colorado, Columbia, Joint Czech Group (Charles University): Prague Czech Technical University, Prague Institute of Physics, Czech Academy of Sciences – Prague; University of Debrecen, Florida State, Georgia State, Howard University, Houston, sPHENIX (Hungary), Illinois – U.C., Institute of Nuclear Research, Russian Academy of Sciences, Moscow, Iowa State, University of Jammu (India), JAEA (Japan Atomic Energy Agency), Korea University, National Research Centre “Kurchatov Institute”, Lehigh, LLNL, LANL, Maryland, MIT, Michigan, National Research Nuclear University (Moscow Engineering Physics Institute), Muhlenberg College, Nara Women’s University (Japan), New Mexico State, University of New Mexico, ORNL, Ohio University, Insititut de Physique Nucléaire d’Orsay, Petersburg Nuclear Physics Institute (National Research Centre “Kurchatev Institute”), IHEP (Protvino), RIKEN/RBRC, Rikkyo University, Rutgers, Stony Brook, Saint-Petersburg Polytechnic University, Tennessee - Knoxville, Texas - Austin, Tokyo Institute of Technology (Tokyo Tech, TITech), University of Tokyo (Center for Nuclear Study), Institute of Physics - University of Tsukuba, Universidad Técnica Federico Santa María - Valparaíso (Chile), Vanderbilt, Wayne State, Weizmann Institute, Yale, Yonsei University (Korea).
Inaugural sPHENIX collaboration meeting
Inaugural sPHENIX collaboration meeting

Rosi Reed (Lehigh)  Sevil Salur (Rutgers)

Hosts
Food Options:

Thursday:
Lunch: On your own. Student Center & Busch Faculty Dining Hall.
Dinner: Reception would be in International Lounge.

Friday:
Lunch: Working Pizza Lunch would be provided.
Dinner: Lots of restaurants in New Brunswick Area.
Suggestions: YELP or ask one of us 😊

Rutgers Univ.
December 2015
Second sPHENIX collaboration meeting May 2016
Food and discussion
Structure of the scientific collaboration

• Co-spokespersons (Roland, Morrison)

• Institutional Board (58 institutions)

• Executive Council – elections, appointments complete by late April

• Topical groups – focus on specific observables to drive simulations
  • Jet structure (Dennis Perepelitsa (BNL), Rosi Reed (Lehigh))
  • Heavy-flavor tagged jets (Jin Huang (BNL), Mike McCumber (LANL))
  • Upsilon spectroscopy (Tony Frawley (Florida), Marzia Rosati (Iowa))
Executive Council

• Ed O’Brien (BNL) (ex officio)
• Megan Connors (GSU) (junior)
• Sarah Campbell (Columbia) (junior)
• Tom Hemmick (Stony Brook)
• John Lajoie (Iowa State)
• Anne Sickles (UIUC)
• Bill Zajc (Columbia)
• Joern Putschke (Wayne State)
• Jamie Nagle (Boulder)
• Huan Huang (UCLA)
• Itaru Nakagawa (RIKEN)
• Christine Aidala (Michigan)
Director’s Review of sPHENIX Cost and Schedule

- November 9-10, 2015, committee includes BNL and outside experts
- Based on information in the pCDR
  - HCal and EMCal unchanged
  - Reuse PHENIX silicon vertex pixel detector
  - Tracker assumed to come from outside funds
- Base cost estimate reasonable; increase overall project contingency to 40%; bring tracker into project with its own $5M contingency

There are many exciting challenges ahead for sPHENIX. A new collaboration is under development, with the first collaboration meeting planned for December 2015. We believe that a highly engaged and robust scientific collaboration is a vital component of the sPHENIX project and physics program, and that all effort should be made to develop this collaboration, and its integration with the sPHENIX project, as quickly as possible.
Extensive pre-conceptual R&D relevant to sPHENIX

• EIC R&D:
  
  • eRD1 (calorimetry consortium – W/Sci-Fi EMCal) BNL, Caltech, JLab, IU, UIUC, IPN Orsay, Penn. St., TAMU, UCLA, Yerevan PI
  
  • eRD6 (tracking consortium – TPC) BNL, FIT, Stony Brook University, UVA, Yale

• Current BNL program development funds targeted at tilted plate HCal

• Current BNL LDRD targeted at SiPMs, TPCs

• Anticipating news in July on LANL LDRD targeted at MAPS

• Supporting efforts to obtain other funding – e.g. JSPS tracking proposal
Focused “workfests” and other events

- Continues practice that was very productive in developing sPHENIX proposals
- Invite outside experts when appropriate – e.g., discussion with ALICE & STAR experts on space charge distortion in TPC
- Upcoming plans: two-day EMCal workfest in August, two-day test beam paper writing workshop, discussion with ALICE to gauge needs of sPHENIX TPC readout
SBU Machine Shop making parts for TPC

Walter  Jeff

Field Cage Mandrel Under Construction

Lilly

3/22/2016
scintillating fibers embedded in tungsten/epoxy matrix
MAPS for precision microvertexing

Following ALICE ITS upgrade developments closely, learning from real-world experience of STAR HFT – very useful discussions with Luciano Musa (CERN), Leo Greiner (LBNL), Flemming Videbaek (BNL).
Low-field test of sPHENIX (née BaBar) solenoid

Cooled to 4K, verified superconducting, 100 A = 260 G
Preparations underway for high-field test (4600A)
HCal

steel plates, tilted with respect to beam axis
polystyrene with embedded wavelength shifting fiber
SiPM readout
EMCal

- Fibers threaded through screens
- Filled with Tungsten powder and epoxy
- Attach light guide
- Moliere radius ~2.3 cm
- 1D and 2D Projective modules being explored
Calorimeter system test at FNAL

120 GeV/c proton
1-60 GeV secondary

Sean Stoll (BNL)
John Haggerty,
Craig Woody (BNL)
Ron Belmont (Colorado)
Jin Huang (BNL)
Early analysis of FNAL test beam results

Test beam momentum spread (3%) not yet unfolded in these results
Expect additional improvements as detailed tower-to-tower calibrations are finalized
Satisfies performance requirements
Simulation agrees well with early data results – enables refinement of design via simulation
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.
Baseline scope, cost, and schedule charge to Collaboration from ALD

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Process to address baseline scope charge

• Worked with Project Management to translate funding constraint in charge into something Collaboration could reason effectively about:

  • Reduce total project cost (TPC) by $6M to $75M
    • many elements in TPC – redirected BNL labor, contingency, overhead, escalation to AY$, and M&S (e.g., purchased items or non-BNL labor) – focus of charge is effectively M&S
    • equivalent to reducing $20M “discretionary” M&S by nearly $4M (FY16$, before contingency) – verified this understanding with ALD

• Engaged collaboration to identify the compelling physics addressable within this constraint scenario. Topical groups organized simulations of physics performance. Extensive discussion at 2nd sPHENIX Collaboration meeting May 2016.

• Project Management worked up cost estimates for response document.
Collaboration approach to baseline scope charge

- Focus on three main science drivers: jet structure, HF jets, Upsilon spectroscopy – established three corresponding Topical Groups

- Cost reductions are relative to the pCDR detector, but with further simulation of 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.

- Defined a reference configuration we believe would address physics in sPHENIX proposal (3-layer MAPS inner tracker, TPC, full calorimeter stack) to provide a performance target for buy-back discussion.

- Strong consensus to prioritize tracking; consider effects of calorimeter acceptance and granularity; consider risk to schedule; potential for buying back capability (e.g., possible use of contingency, LDRD, or non-DOE funds)
Collaboration used input from Topical Groups and Project Management to weigh pros and cons of many options and identify the “best worst-case” configuration.

- reducing the depth of the outer HCal by one \( \lambda_{\text{int}} \)
- reduce eta coverage of inner and outer HCal
- don’t build inner HCal
- larger EMCal towers
- gang together 2x2 towers of EMCal
- reduce eta coverage of EMCal
- reduce TPC readout channels
- reduce DAQ refresh
- reuse existing beam-beam counter
- don’t reuse VTX pixels
- introduce 1- or 2-layer MAPS vertex detector
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<table>
<thead>
<tr>
<th>Scenario A</th>
<th>Δ</th>
<th>Scenario B</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>two-layer MAPS inner barrel</td>
<td>+3.0</td>
<td>one-layer MAPS inner barrel</td>
<td>+2.1</td>
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<td>no reuse of VTX</td>
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<td>no reuse of VTX</td>
<td>-0.2</td>
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<td>reduce TPC readout</td>
<td>-0.5</td>
<td>reduce TPC readout</td>
<td>-0.5</td>
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<tr>
<td>reduce EMCal segmentation</td>
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<td>reduce EMCal segmentation</td>
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</tr>
<tr>
<td>reduce EMCal $\eta$ acceptance</td>
<td>-2.0</td>
<td>further reduce EMCal $\eta$ acceptance</td>
<td>-2.2</td>
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<tr>
<td>reduce DAQ refresh</td>
<td>-0.5</td>
<td>reduce DAQ refresh</td>
<td>-0.5</td>
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<tr>
<td>reuse beam-beam trigger counter</td>
<td>-0.5</td>
<td>reuse beam-beam trigger counter</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
| Total                                     | -2.5  | Total                                     | -3.6  | (in $M$)
Focus on tracking

comparative TPC radii

MAPS cf. VTX

ALICE: 60-250 cm
STAR: 50-200 cm
sPHENIX: 30-80 cm

higher efficiency (98% vs 70-94%)
longer staves (27cm vs 20cm)
10+ year old silicon
benefit by ALICE commissioning
reduced EMCal: $|\eta| < 0.6$
thin OHCal: thinner by one $\lambda_{\text{int}}$
each change shifts mean low appearance of low-side tail
effects become pronounced with both changes
LHC experience: dealing with jets that span substantial changes in detector material subject to large systematic uncertainties
Jet fragmentation bias

Figure B.1: (Left) Comparison of the jet response for three different HCal configurations: Nominal outer HCal (black markers), outer HCal thinned by 20 cm (red markers) and no inner HCal (blue markers). (Right) Comparison of the jet fragmentation bias for nominal (black markers) and thinned outer HCal (240 cm outer radius, red markers).

a small loss in total energy containment for the thinned outer HCal configuration relative to the nominal configuration, combined with a moderate increase in the number of jets for which less than 70% of the energy was reconstructed. Further studies showed that the change in the jet response only has a small effect on reconstructing unfolded jet spectra, even when using a Gaussian kernel that ignores the increased low-energy tail. Removing the inner HCal has a significantly larger effect on the mean and shape of the jet response.

Fragmentation function bias

One expects that the thinned HCal configuration leads to the biggest change in jet response for jets with high-z fragmentation products that are not contained in the calorimeter system. To study this effect, we plot the average jet energy response as a function of the momentum fraction $z$ carried by the highest $p_T$ charged fragment in Fig. B.1(right).

Even for the nominal HCal configuration, a dependence of the response on the hardness of the jet fragmentation is seen, with a change of about 0.08 in $h_{p_{\text{reco}}}/p_{\text{truth}}$ from softest to hardest fragmenting jets. For the thinned HCal configuration, this increases to 0.11-0.13. We expect that this additional bias would only lead to a moderate increase in the uncertainty of fragmentation function ratios for Au+Au/p+p, as the increase is only about 50% of the bias already seen in the nominal configuration, and present in both p+p and Au+Au events (i.e., only related to the single particle containment).

B.1.2 Outer HCal shortening

For the shortened outer HCal (reducing the pseudorapidity coverage from $|\eta|<1.1$ to $|\eta|<0.9$), all measured at the outer corner of the calorimeter) the expected impact is in the statistics of jet related probes. The reduction in coverage will predominantly affect lower $p_T$ jets, as jets at the highest $p_T$ have a narrow rapidity distribution that falls within the remaining acceptance. Figure B.2 shows the fraction of jets (left) and dijets (right) contained in the nominal calorimeter system as a function of jet $p_T$, obtained from generator level distributions. As expected, the fraction of fully contained jets is lowest for low $p_T$ jets (which have a wider rapidity distribution) than for high $p_T$ jets.
Effect of reduced segmentation in EMCal

Figure B.3: (Left) Jet response for the nominal calorimeter systems (black markers) and the calorimeter system with ganged EMCal readout (green markers) for high $p_T$ jets. (Right) Ratio of the hadron rejection factor as a function of electron efficiency between the ganged EMCal configuration and the nominal EMCal configuration, for central Au+Au collisions. The ratio is shown for two pseudorapidity regions and three particle momenta.

Effect on jet energy response

Figure B.3 shows the energy response in the calorimeter system for high $p_T$ jets for the nominal configuration (black markers) and the ganged EMCal configuration (green markers). Ganging has no visible effect on this distribution, as the change in granularity is small compared to the typical jet size and the total collected jet and background energies are unchanged.

Figure B.4: 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.

$\text{e}/\pi$ lower by ~2x in 2×2 ganged EMCal
Reduced Y acceptance with $|\eta| < 0.6$ EMCal

**Figure B.5:** (Left) Y to $e^+e^-$ acceptance as a function of rapidity for the nominal (blue markers) and $|\eta| < 0.6$ configurations, averaged over Y $p_T$. (Right) Y to $e^+e^-$ acceptance as a function of $p_T$ for the nominal (blue markers) and $|\eta| < 0.6$ configurations, averaged over $\eta$. 

We also investigated the loss in statistics when requiring jets and dijets to be fully contained in the (Fig. B.6, right). As expected, essentially no change is observed for the central rapidity region, the nominal configuration shown in Fig. B.2. One observes that for low reduced EMCal acceptance. The result is shown in Fig. B.7, to be compared with the acceptance for still tolerable increase in unfolding uncertainties for jet spectra.

The effect of reducing the EMCal acceptance to $0.6$, was studied for low $h/p_0.7$ a shift in the mean of several percent and the appearance of an enhanced low
Looking forward with the Project

Project Schedule and Budget based on Review committee recommendations:

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>Tracker review</td>
<td>Sept 2016</td>
</tr>
<tr>
<td>CD-0</td>
<td>Sept-Oct 2016</td>
</tr>
<tr>
<td>Director’s Cost and Schedule Review</td>
<td>Late Fall 2016</td>
</tr>
<tr>
<td>Test Beam at FNAL (2\textsuperscript{nd} round prototyping)</td>
<td>Jan 2017</td>
</tr>
<tr>
<td>OPA-CD-1/CD-3a Reviews</td>
<td>May-Jun 2017</td>
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<tr>
<td>CD-1/CD-3a authorization</td>
<td>Nov 2017</td>
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<tr>
<td>Preproduction R&amp;D and Design complete</td>
<td>May-Jun 2018</td>
</tr>
<tr>
<td>OPA-CD-2/CD-3b review</td>
<td>May-Jun 2018</td>
</tr>
<tr>
<td>CD-2/CD-3b authorization</td>
<td>Jul 2018</td>
</tr>
<tr>
<td>sPHENIX Installed, cabled, ready to commission</td>
<td>Apr 2021</td>
</tr>
<tr>
<td>First RHIC beam for sPHENIX</td>
<td>Jan 2022</td>
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Outlook

• sPHENIX scientific collaboration now exists officially – organizing efforts to provide guidance on physics questions – topical groups were instrumental in developing response to recent ALD charge

• Organizing a new “cold QCD” topical group to provide a target for current collaborators and potential new groups with interests in spin, forward and future EIC physics

• sPHENIX project continues excellent progress – pCDR, advanced prototypes, test beam, preparations for high-field magnet test, tracking review, updated cost and schedule review

• Collaboration is committed to building a world-class experiment with the capabilities needed to deliver the full suite of sPHENIX physics – the scientific questions remain extremely relevant