sPHENIX

Chris Pinkenburg, BNL

322 days till first beam
The goals of heavy-ion experiments at RHIC and the LHC as a result of the 2015 Long Range Plan for Nuclear Science are two-fold:

1. To map the QCD phase diagram with experiments planned at RHIC
2. To probe the inner workings of quark-gluon plasma (QGP) by resolving its properties at shorter and shorter length scales
sPHENIX Collaboration

- Officially formed in 2016
- More than 320 members from 84 institutions in 14 countries as of 2021

*Members from around the world gathered around a common science goal*
Guided by the science mission, sPHENIX aims to probe the QGP in different ways:

- Vary probe’s momentum and angular scale.
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- Vary probe’s mass and
Guided by the science mission, sPHENIX aims to probe the QGP in different ways:

- Vary probe’s momentum and angular scale
- Vary probe’s mass and momentum
- Vary probe’s size
sPHENIX Detector Overview

Calorimetry
- Outer Hadronic Calorimeter (oHCAL)
- Inner Hadronic Calorimeter (iHCAL)
- Electromagnetic Calorimeter (EMCAL)

Magnet
- 1.4T superconducting solenoid used by the BaBar experiment

Tracking
- Time Projection Chamber (TPC)
- Intermediate Silicon Tracker (INTT)
- MAPS-based Vertex Tracker (MVTX)

Performance
- High data rate: read out rate of 15 kHz for all subdetectors
- Acceptance: hermetic coverage over full azimuth & pseudorapidity $|\eta| \leq 1.1$ for the tracking & calorimeter systems

Triggers:
Only lvl1 triggers – no high level triggers
→ No online Event building needed
sPHENIX Detector Overview

In a nutshell – designed to take a ton of minbias data in a very short period of time

**Calorimetry**
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sPHENIX Probes: Jets and Photons

- Jet measurements out to 70 GeV
  - overlap with LHC measurements

- High stats also for
  - photons ($\gamma$-jet measurements)
  - charged hadrons (fragmentation functions, substructure)

- Large luminosity Au+Au in first year
  - dijets, jet $v_2$

| Year | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $|z| < 10$ cm | Samp. Lum. $|z| < 10$ cm |
|------|---------|----------------|------------|---------------|-----------------|-----------------|
| 2023 | Au+Au   | 200            | 24 (28)    | 9 (15)        | 3.7 (5.7) nb$^{-1}$ | 4.5 (6.9) nb$^{-1}$ |
sPHENIX complements LHC expts

Particular strength at low pT

Larger QGP effects but difficult to trigger:
- low pT, highly quenched jets
- low pT charm and beauty

![Diagram showing R_AA and X+Jet at different pT values for various processes such as Hadrons, Jets, D Mesons, B Mesons, and b Jets.](image-url)
# sPHENIX 3-Year Run Plan

**sPHENIX Beam Use Proposal (BUP) sPH-TRG-2020-001, August 31, 2020.**

| Year   | Species       | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $|z| < 10$ cm | Samp. $|z| < 10$ cm |
|--------|---------------|------------------------|------------|---------------|-----------------|-----------------|
| 2023   | Au+Au         | 200                    | 24 (28)    | 9 (13)        | 3.7 (5.7) $nb^{-1}$ | 4.5 (6.9) $nb^{-1}$ |
| 2024   | $p^+p^+$      | 200                    | 24 (28)    | 12 (16)       | 0.3 (0.4) $pb^{-1}$ [5kHz] | 45 (62) $pb^{-1}$ |
|        |               |                        |            |               | 4.5 (6.2) $pb^{-1}$ [10%-str] |                  |
| 2024   | $p^++$Au      | 200                    | –          | 5             | 0.003 $pb^{-1}$ [5kHz] | 0.11 $pb^{-1}$ |
|        |               |                        |            |               | 0.02 $pb^{-1}$ [10%-str] |                  |
| 2025   | Au+Au         | 200                    | 24 (28)    | 20.5 (24.5)   | 13 (15) $nb^{-1}$ | 21 (25) $nb^{-1}$ |

### Year 1 (2023):
- Commissioning Au+Au
- Measurement of standard Au+Au candles at RHIC

### Year 2 (2024):
- Commissioning p+p
- $p^+p^+$, $p^++$Au: HI reference set and cold QCD

### Year 3 (2025):
- Very large Au+Au heavy-ion set for jet and heavy flavor physics
- 141 B events recorded in total
sPHENIX Progress

First Two IHCal sectors on IHCal Barrel

Magnet, outer hcal and rack platform at ip8

Inner Hcal barrel complete and ready to install EMC

The final EMC block

4/5/2022
• sPHENIX DAQ is rate limited to 15kHz
  – Same rate in p+p and Au+Au
• Beam Crossing Angle reduces rate of collisions outside |z|<10cm by
• The TPC will “see” the full rate – pileup and resulting space charge need to be dealt with
• RHIC has 20 years of experience – collider operations will reach their peak luminosity very quickly on day 1
The Buffer Boxes are the only components interfacing with the tape storage system.
We then read back the combined data file and the 60 originals into our analysis framework. Word by word we check that the packets in the combined file are the same as in the originals, and that they are all there and accounted for. 500 million events, 200 runs.

100% success rate! It shows that our framework is able to handle the combined stream, as well as 60 on-the-fly streams. Keep in mind that those files are generated by the real DAQ processes.
Two Classes of Front-end Hardware

The calorimeters, the INTT, and the MBD re-use the PHENIX “Data Collection Modules” (v2)

Triggered readout

The TPC and the MVTX are read out through the ATLAS “FELIX” card directly into a standard PC

Streaming readout
Streaming Readout + Triggered Events (concept)

FEE data input to DAM. Rate = 1550 Gbps @ 12000 kHz Collision, 15 kHz Trigger 13 us Drift

DAM data output: Throttled data rate = 133 Gbps, Triggered data rate = 140 Gbps

Chunks correlated with triggered events
... plus “opportunistic” streaming-only data

we extend the “stream time” and add tracking-only events without the calorimeters

We can “back-fill” our storage limit with those events
For p+p running, a partial triggerless DAQ?

What we write to disk, 40 Gbps 15kHz triggered events, 0.1% of all collisions

+ Streaming 10% of all collisions, 60Gbps 50% more data but × $O(100 - 1000) p + p$ events!

A treasure chest of truly unbiased p+p events
Event and Data Volume numbers

Numbers taken from the beam-use proposal

Significantly lower data volumes due to the introduction of a beam crossing angle, fewer useless off-vertex collisions (TPC)

Numbers include 30% uncertainty to the high side

Run 1: Au+Au: 13 weeks @ 60% RHIC uptime x 60% sPHENIX uptime → 43 billion events 72 PB 73Gbit/s
Run 2: p+p, p+A: 21 weeks @ 60% RHIC uptime x 60% sPHENIX uptime → 69 billion events 78 PB 49Gbit/s
Run 3: Au+Au: 24.5 weeks @ 60% RHIC uptime x 80% sPHENIX uptime → 107 billion events 180 PB 97Gbit/s

These are conservative uptime figures establishing minimum sampled luminosity goals. We can write up to 230PB/year if needed, so significantly higher uptimes are ok
Software

• Very small core group – use what you already have
  – PHENIX took data at 6kHz and was more complicated
  – Students will write most of the code – no fancy “look what I can do with C++”
• Do not re-invent the wheel, use existing modern tools
  – ACTS
  – KFParticle
  – Conditions DB
  – PanDA
• Very short commissioning, flexibility is key
• Get tons of help from other experiments: ALICE, ATLAS, STAR
  – Thank you
• Our events are time ordered which makes reconstruction, calibrations and synchronization of multiple streams a lot easier
Deployment

• Code in github
  – Pull requests trigger extensive CI (including q/a) run in sdcc
  – Addresses the “when did we lose 10% momentum resolution?”

• Singularity/Docker container with sdcc farm image

• Daily and tagged archival builds in cvmfs

• Daily builds with gcc, clang, insure, Coverity, scan-build
  – Keeps our software c++ compliant
Continuous processing chain

The processing is done by chaining up modules. At every step the state of the Node Tree can be saved and the analysis can pick up where it left.

Common reco for raw and simulated data

The diagram shows the processing chain with the following steps:

1. Fun4AllServer
2. Event generator (input file, single particle, pythia8)
3. PHG4Reco
4. Interface Detector 1
   - Construct() → Geometry
   - Stepping Action (Hit extraction)
5. Interface Detector 2
   - Construct() → Geometry
   - Stepping Action (Hit extraction)
6. Digitisation
7. Raw Data
8. RCdaq
9. Tracking, Clustering
10. Jet Finding, Upsilon, Photons...
11. Output Files

Geant4
- Modular: Each detector is its own entity providing the flexibility needed for complex setups
- Generic detectors like boxes, cylinders, cones exist and can be configured on a macro level
- No volume hierarchy, all detectors are put into world volume

Setup calls dataflow
Combining data reconstruction and simulations

Many simulation needs besides “full detector”
sPHENIX Tracking

Goal of 10sec/evt (both passes) and 4GB/job within reach

- Distortion correction scheme
  - Move clusters associated to tracks onto Acts surfaces based on a variety of correction schemes for static, beam induced, or event-by-event fluctuations

github.com/acts-project/acts

JDO et al., Computing and Software for Big Science 5, 23 (2021)
Tracking Performance

Meets our physics requirements
Multithreading

- Our memory is mostly consumed by heavy ion events, multi threading on event by event basis does not help
- Multi threading inside event loop does look promising
- But relies on the node having spare cycles to run those threads

Time per event versus nthreads

- Averaged over 50 events
- 24,576 channels evaluated per event

EMC pulse fitting

TPC Clustering

sPHENIX simulation

EMC Test
Beam data pulse fitting with ML
MDC2: Testing Testing Testing

1st pass: Full GEANT4 simulation
- HepMC from generator
- Only 1 AA generator?
- Details of Flow?
- Update all detectors and support structures
- Add missing detectors (ZDC, TPOT, EPD)
- Add mis-alignments
- Use 3D magnetic field map

2nd pass: Pileup Simulation
- G4Hits
- SC Distortions

3rd pass: TPC e-drift Simulation + clustering
- G4Hits TPC, MVTX, INTT
- G4Hits Calorimeters
- G4Hits BBC, EPD

4/5th pass: Seeding + Tracking
- Tracks + Vertex
- Distortion Correction

3rd pass: Calorimeter Reconstruction
- Calorimeter Towers + Clusters

Global Reco
- Define event objects

Low Res Vertex
- Centrality
- Reaction Plane

DST pass: Particle Flow, Jet Reco
- Define physics objects (e/gamma, jets, KFParticles, ParticleFlow....)

Clusters TPC, MVTX, INTT
- Add Calibrations/Alignments

SC Distortions

Real Data Reconstruction

• No more Truth Info used during reconstruction
• Truth Info can be correlated during analysis
Production Workflow

Get a head start by processing calorimeter files separately

75% data reduction

Calorimeter Clustering

1st pass tracking

2nd pass tracking

Particle Flow

75% data reduction

x40

Reduced data format likely ROOT → random access
All DST content in single file to enable analysis from tape

HPSS

Aggregation

Analysis

Get a head start by processing calorimeter files separately
Calibrations

- Two types of calibrations
  1. Distortion corrections (timescale 10ms)
  2. All others (timescale 5mins to years)

- 64 bit (BigInt) beam clock serves as Time stamp
  - event level granularity
  - Our events are time ordered – easy assignment of calibrations to raw data files (looking at first and last event)
  - Gaps in validity (beam off periods) but no overlapping validity ranges

- Distortion corrections
  - No plan to keep calibrations long term (huge data volume)
  - Output of Job A produces distortion calibration for Job C – easy 1:1 match (needs some initial accumulation but then is rolling average)
  - Reprocessing means redoing distortion corrections
  - No need for a conditions DB here – some naming convention will do (and filesystem which can handle this → MDC goal)

NEW: TPC distortions in Track Reco

NEW: EMCal Calibrations (details)
Space charge distortions

Diffuse Laser
- AI stripes on Central Membrane (CM)
- ~kHz diffuse UV laser releases e-
- stripes reco measures distortion at CM
- fast, interleaved with data => monitors fluctuations

Direct Laser
- 4x steerable lasers on each side of TPC
- ~all points can be reached by 2+ lasers
- creates straight-line tracks at ~Hz
- laser reco measures distortion in volume
- slow, not used during run => monitors static distortion

Additional Space point outside some areas of the TPC

Correction essential for required momentum resolution for Upsilon program

Last not least: Analysis of the direct currents (continuous readout of the tpc pads)

Diffuse Laser fires in coincidence with an event, e- arrive shortly after e- from event
Dataflow is the name of the game

- Our CPU estimate: 25sec/evt reco time
- Two reconstruction passes, near time during data taking and offline between RHIC Runs

  - 107B AuAu events in 24 weeks @ 25sec/evt: 184,290 cores
    - We cannot afford idling cores

- Speed of the reconstruction is not speed of the job
  - Just run a job and see how long it takes to start up
  - Can be mitigated by longer running jobs (consideration for 24h length)

- Cores idle during data copying
  - Everything needs to go through 10 Gb/s network
  - Need to work on pre-fetch and post processing copy schemes so cores always have data ready on local disk
sPHENIX Handy Remote Execution Koordinator

Jason Webb (NPPS)
+ PanDA team (NPPS)
+ Rucio team (SDCC)
In an ideal world... everything on local side will be
  - archived / reproducible (preferably "turn key")
  - may require "yet-another-workflow-definition"
  - may require "yet-another-job-submission-tool"

The user action on the left is a workflow... CWL
Summary

• Full “near time” reconstruction planned followed by second offline pass

• Envisioned processing time per event well within reach
  – Two orders of magnitude speed increase compared to 3 years ago (Thanks: ACTS)

• Tools from the wider community (PanDA, Rucio)
• DB from Belle 2

• Data flow the remaining big challenge
  – Ongoing Mock Data Challenge for testing

• Guinea pig for the EIC
YOU WENT TOO FAR
Each Front-End Card contributes what we call a “Packet” to the overall event structures.

A Packet ID uniquely identifies the detector component / front-end card where it comes from.

A hitformat field identifies the format of the data, and ultimately selects the decoding algorithm.

We can change/improve the binary format and assign a new hitformat for a packet at any time.

Insulation of offline software from changes in the online system.

About 180-240 such packets in a typical sPHENIX event.
That’s all there is to it, no backdoor communications – steered by ROOT macros.
MDC2: Testing Testing Testing

1st pass: Full GEANT4 simulation
- Update all detectors and support structures
- Add missing detectors (ZDC, TPOT, EPD)
- Add mis-alignments
- Use 3D magnetic field map

2nd pass: Pileup Simulation

3rd pass: TPC e-drift Simulation + clustering

HepMC from generator
- Only 1 AA generator?
- Details of Flow?

4/5th pass: Seeding + Tracking
- Distortion Correction

Tracks + Vertex

3rd pass: Calorimeter Reconstruction

Clustering TPC, MVTX, INTT
- Add Calibrations/Alignments

Calorimeter Towers + Clusters

Low Res Vertex
- Define event objects

Centrality

Reaction Plane

• No more Truth Info used during reconstruction
• Truth Info can be correlated during analysis

Global Reco

DST pass: Particle Flow, Jet Reco
- Define physics objects (e/gamma, jets, KFParticles, ParticleFlow,...)
Conditions DB coming online

Open ended calibrations (e.g. alignment)

<table>
<thead>
<tr>
<th>start</th>
<th>end</th>
<th>start</th>
<th>end</th>
<th>start</th>
<th>end</th>
<th>APPEND IOVs, IOV_END is not allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>t1</td>
<td>null</td>
<td>t2</td>
<td>null</td>
<td>t3</td>
<td>null</td>
<td></td>
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</tbody>
</table>

This is the original model, only start times are allowed, and only appending is allowed
\[ t_{insert} > t_{last} \]

The client will define this as \( \text{now}() + \text{DELTA} \), where \( \text{DELTA} \) needs to be defined to be big enough to account for latency etc. but small enough to be useful

Sensible would likely be “next run”, so some work to do on the client side

Thanks to Paul Laycock, Ruslan Mashinistov, Dmitri Smirnov (all NPPS)
Conditions DB

Run wise calibrations

start=t1  end=t2
start=t2  end=t3
start=t3  end=t4

OVERLAPPING IOVs ARE NOT ALLOWED!!

On writing, check that start time comes after the end time of the previous Payload_IOV, AND its end time comes before the start time of the next Payload_IOV - no over-writing so this is a safe operation.

Important constraints - the end time of one unit of data will be numerically distinct from the start time of the next unit of data.

The service will always return the closest PIOV object, it’s up to the client to decide whether to throw an ERROR because of the END of validity time.
Reprocessing preparation

Workflow - Clone the Prompt_GT, this creates an **unlocked** GT

You can do what you want with unlocked Global Tags :)

While editing, the service will take care of removing unnecessary PIOVs

Once editing is finished, lock the Repro_GT before use in production
### sPHENIX Construction Schedule:

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</thead>
<tbody>
<tr>
<td>Complete oHCAL Sector Installation</td>
<td>AH</td>
<td>12/16/21</td>
<td>3/1/22</td>
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<tr>
<td>Build the Carriage, Platforms, Pole Tip Doors</td>
<td>AH</td>
<td>3/7/22</td>
<td>7/15/22</td>
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<tr>
<td>Install the iHCAL Barrel</td>
<td>AH</td>
<td>6/14/22</td>
<td>7/15/22</td>
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<td>Remove the Shield Wall</td>
<td>AH/IR</td>
<td>4/4/22</td>
<td>4/29/22</td>
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<tr>
<td>On-carriage detector infrastructure AH installs</td>
<td>AH</td>
<td>3/7/22</td>
<td>7/15/22</td>
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<td>Magnet and Cryo Infrastructure in AH</td>
<td>AH</td>
<td>6/2/22</td>
<td>7/15/22</td>
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<td>Move sPHENIX To the IR</td>
<td>AH/IR</td>
<td>7/18/22</td>
<td>7/22/22</td>
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<td>Magnet Cryo, Power, Cool Down &amp; Testing in IR</td>
<td>IR</td>
<td>4/22/22</td>
<td>9/9/22</td>
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<tr>
<td>IR Detector Infrastructure</td>
<td>IR</td>
<td>5/2/22</td>
<td>Through end of project</td>
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<tr>
<td>EMCAL, TPC install structures, TPOT install in IR</td>
<td>IR</td>
<td>7/25/22</td>
<td>10/24/22</td>
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<td>Magnet Mapping</td>
<td>IR</td>
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Offline Event-Building from 60 streams

Use 15 SEBs/EBDCs = 15 streams

Configure 4 setups with different packet content that can be combined, mimicking the eventual data makeup

Run 4 “volleys” one after another to get 60 files, 240 packets combined, about the number of packets and event size we expect
sPHENIX Progress

IHCal Barrel Complete!

Outer Hcal fully installed
Rack platform done
sPHENIX Progress

Prepping for EMCal installation into the IHCal

UIUC EMCal Block factory

Final EMCal block

4/5/2022

Software & Computing Round Table
First MDC2 result (Help by Tejas Rao + Chris Hollowell)

![dCache RIP](image)

![Lustre](image)

4/5/2022

Software & Computing Round Table
Automatic Pull Request Checks

- Passed checks
- Report available
Automatic Pull Request Checks

Compilation with gcc 4.8, gcc 8.3 and clang

New warnings fail CI

Static code analysis with cppcheck, scan-build

New warnings fail CI

Runtime analysis with valgrind

Work in progress (new G4 version)

Full link to all warnings (legacy, false positives)

New link to warnings from this PR