Quarkonium Detection and Physics with sPHENIX

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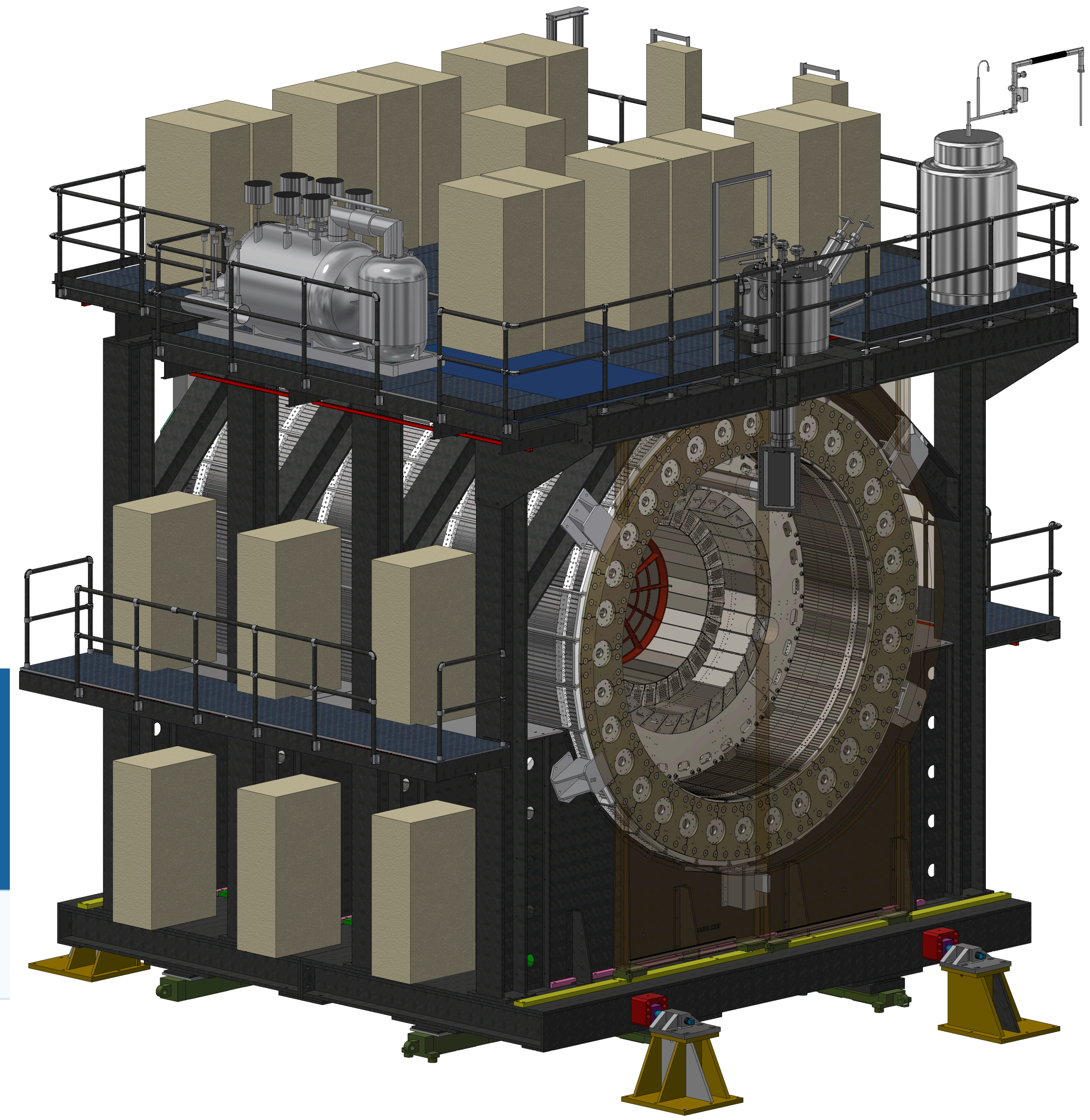
For the sPHENIX Collaboration



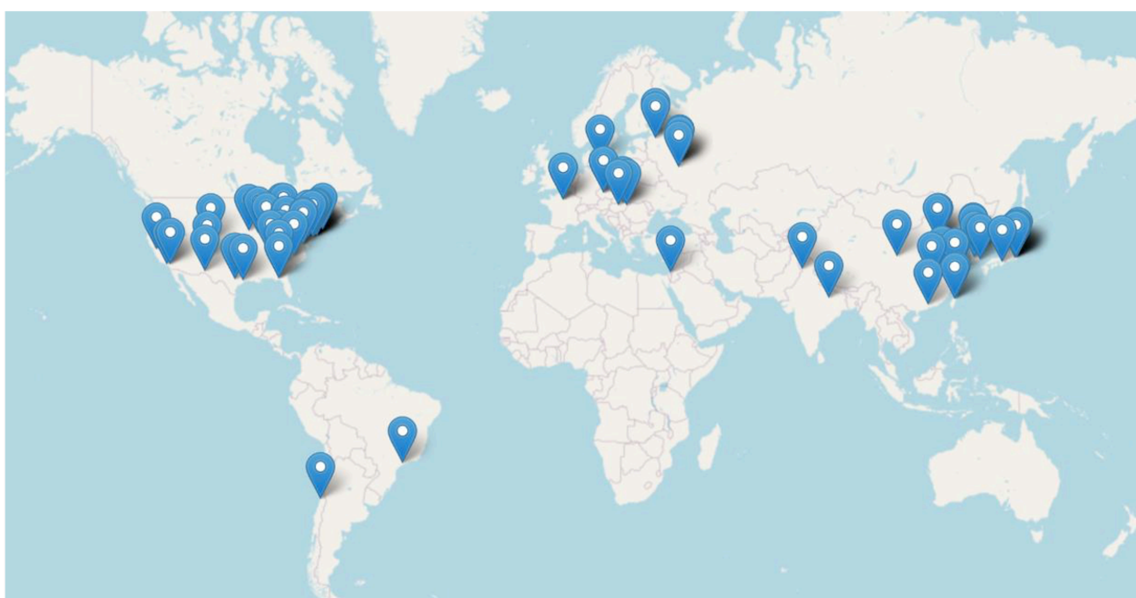
Center for Frontiers in Nuclear Science
Workshop series

Physics Opportunities with Heavy Quarkonia at the EIC

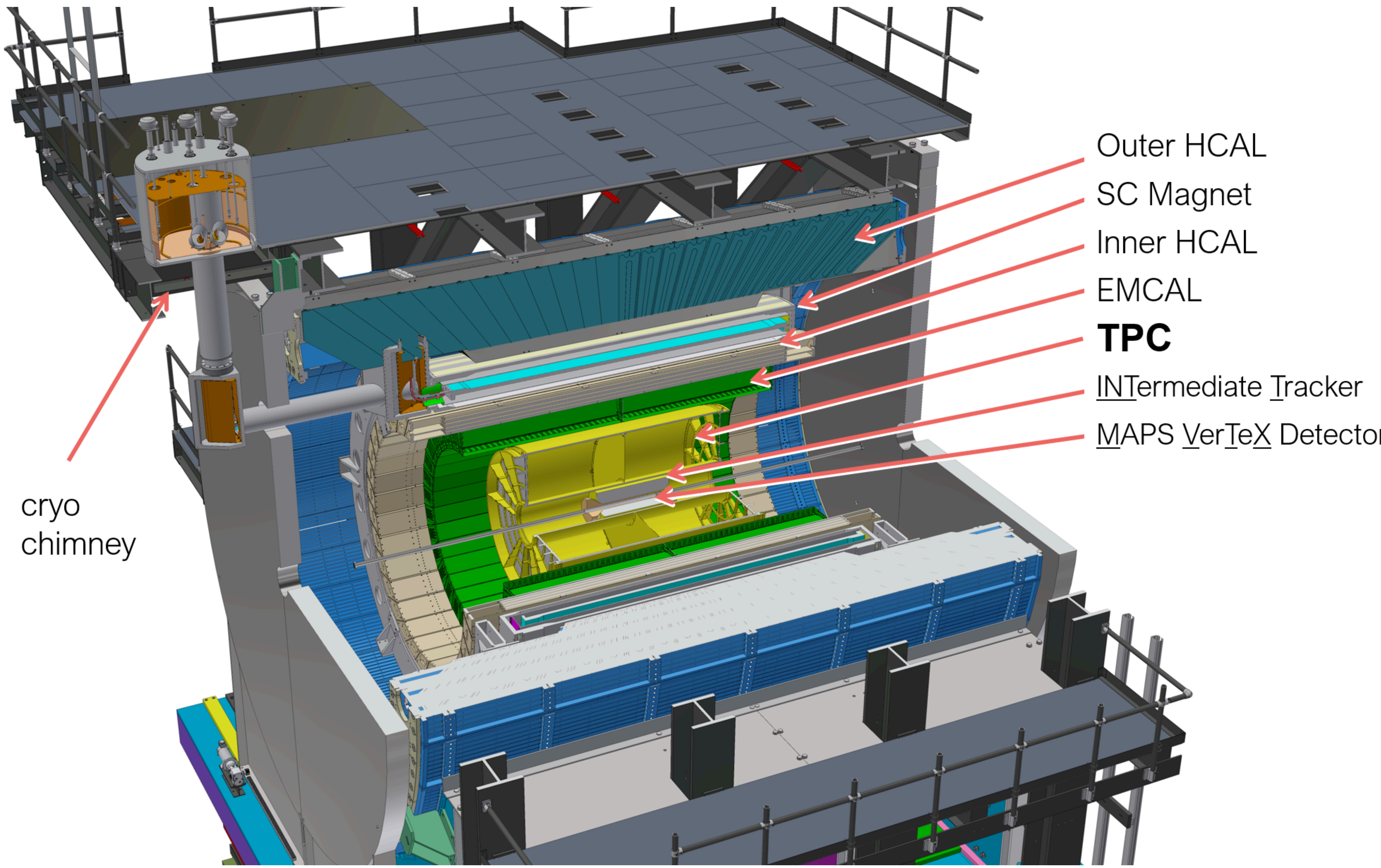
25-27 October 2021
Online
US/Eastern timezone

The sPHENIX Collaboration

More than 320 members from 84 institutions in 14 countries as of 2021



The sPHENIX Detector



-1.1 < η < 1.1
2π azimuthal coverage

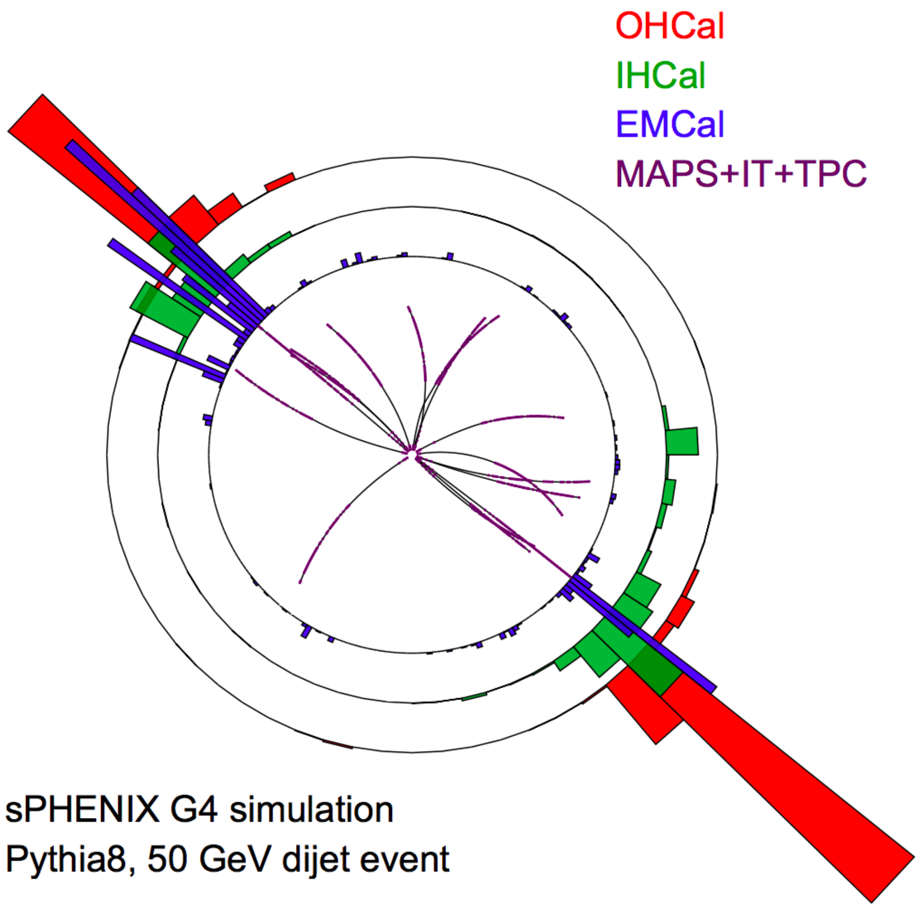
15 kHz MB trigger

Solenoidal magnetic field
B = 1.4 T

The sPHENIX Physics Program

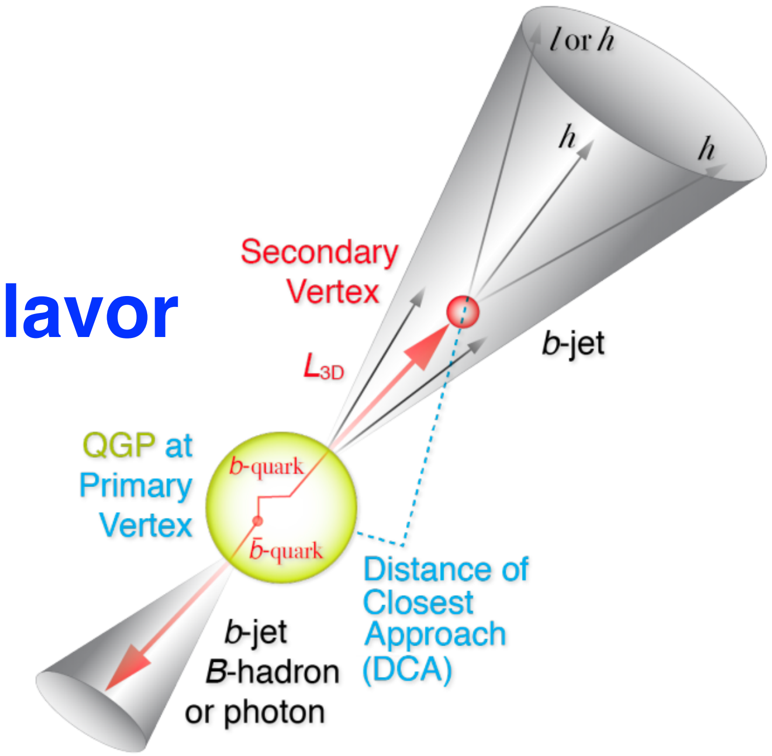
The major legs of the sPHENIX physics program

Jets

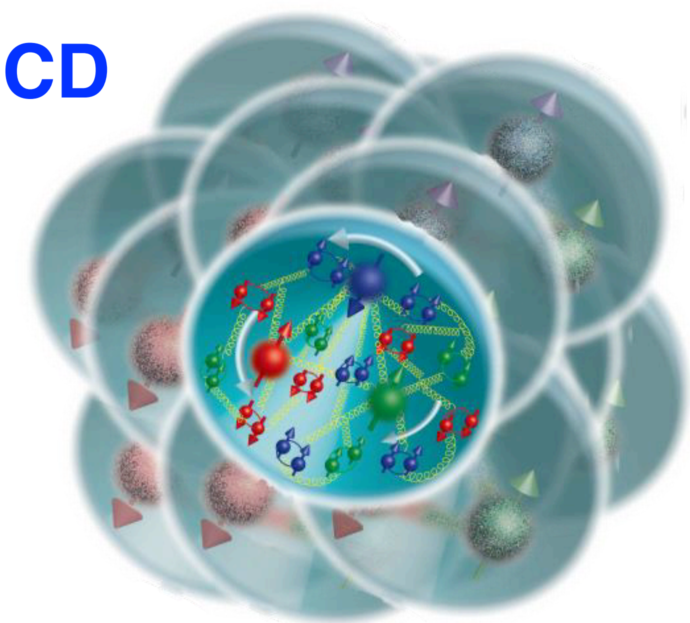


sPHENIX G4 simulation
Pythia8, 50 GeV dijet event

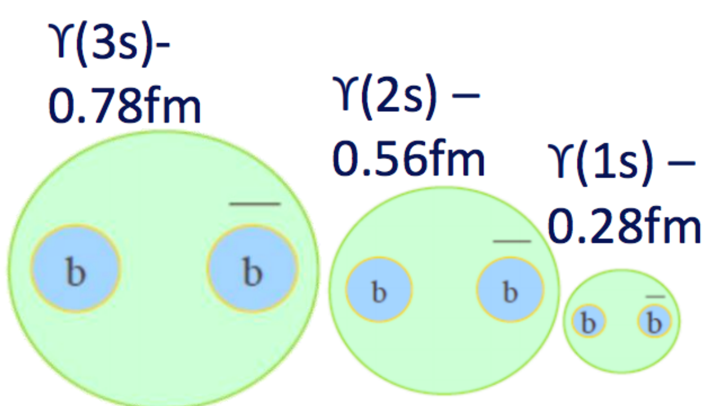
Heavy flavor



Cold QCD



Upsilons

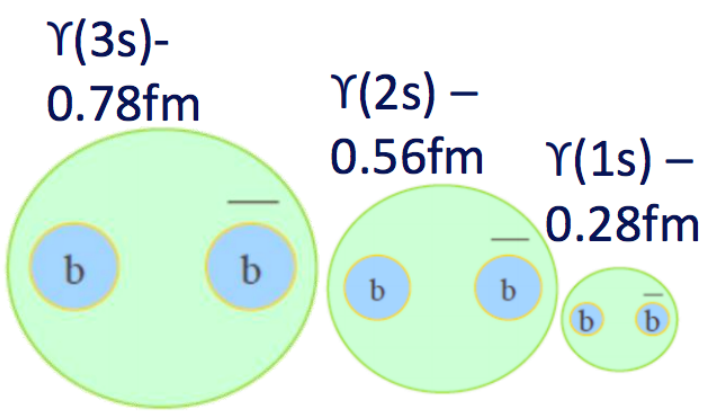


with the goal of studying these in $p^{\uparrow}$+ $p^{\uparrow}$, $p^{\uparrow}$+ Au and Au+Au collisions

Upsilon Physics Motivation

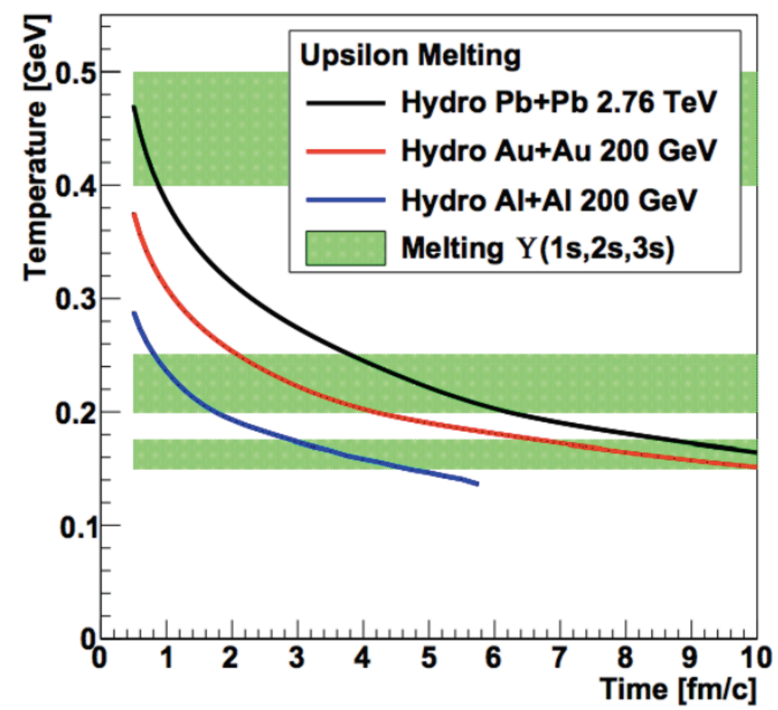
Three states with very different binding energy and radii

- All with experimentally observable dilepton decay yields
- Different sensitivity to QGP conditions



Complementary to LHC:

- Samples QGP in different temperature region
- Underlying b+b yield is very different
  - ~ 0.05 / Au+Au event at RHIC
  - ~ 5 / Pb+Pb event at LHC
- Minimal coalescence at hadronization at RHIC



See the talk by Rongrong Ma on Tuesday for a detailed review of the quarkonia physics story.

Key issues for the measurement

Resolving the Υ states drives the required tracking performance.

Our goal in Au+Au running (the worst case occupancy) is:

- A di-electron mass resolution of < 100 MeV/c^2 at a mass of 10 GeV/c^2.
- A track reconstruction efficiency of > 90%.
    - We currently achieve those in full Au+Au simulations.

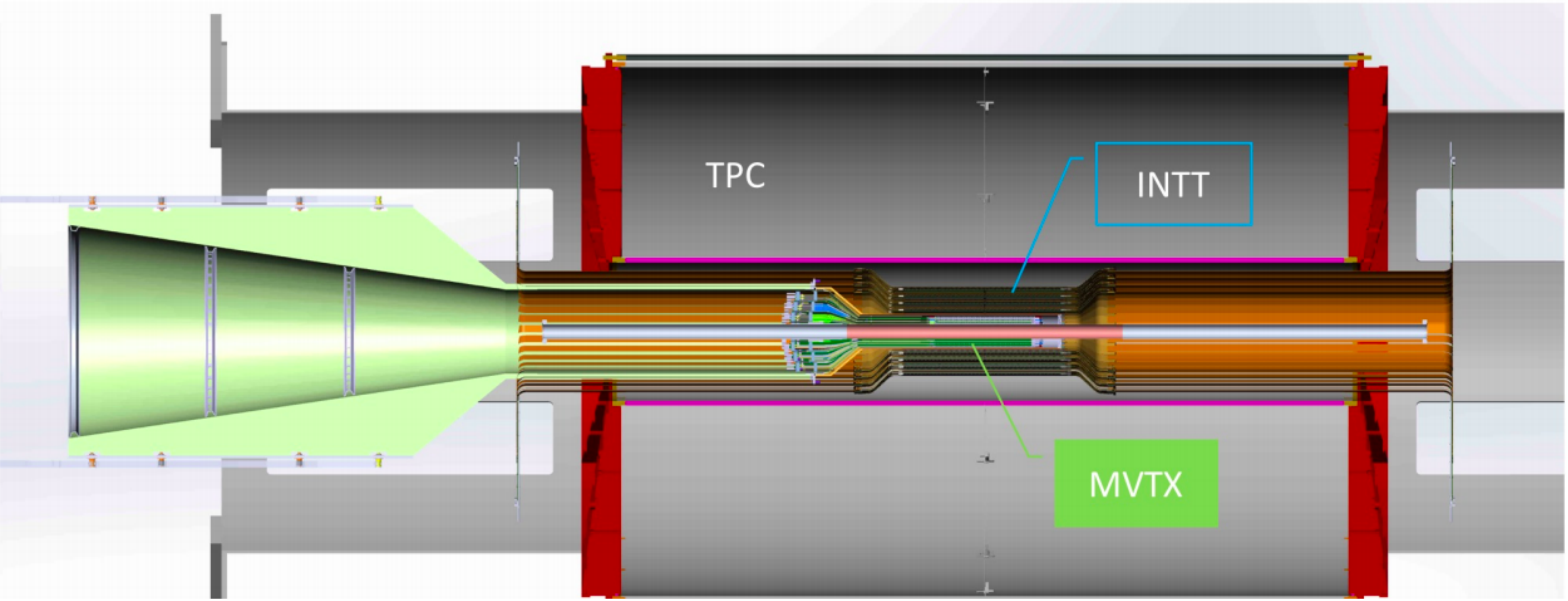
sPHENIX measures Quarkonia decays via di-electron detection.

- Radiative tails in mass spectra are significant.
- Minimizing the tracking detector thickness is important.

No particle ID detectors in sPHENIX aside from calorimeters.

- TPC is run in a mode that makes dE/dx resolution poor.
    - This is to minimize space charge distortions due to ion backflow.
- Electron ID relies on track matching to calorimeters.

The Tracking detectors

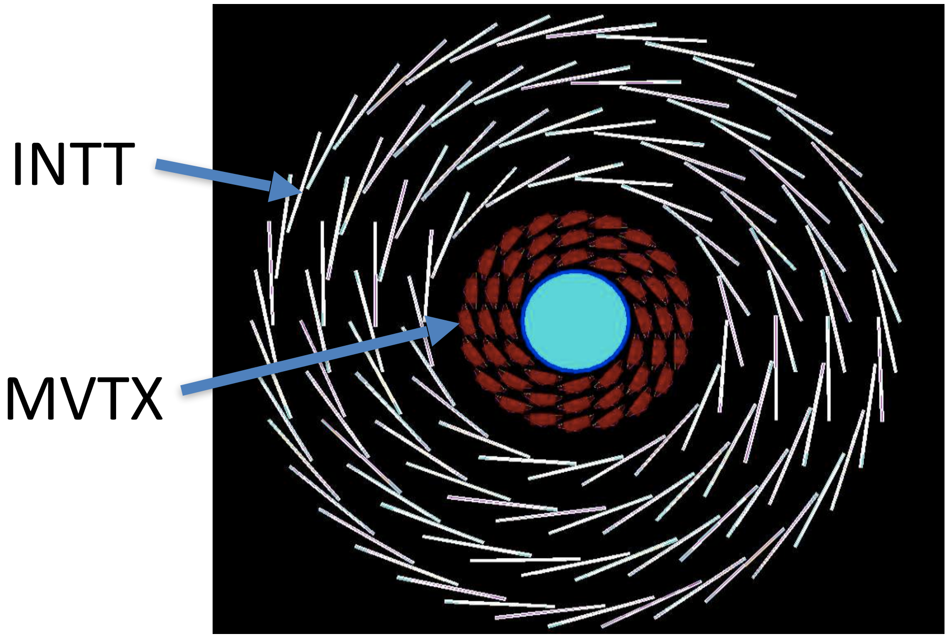


Functions:

TPC - momentum measurement

MVTX - precise track vertex

INTT - timing & pattern recognition



The Tracking detectors

TPC - Gateless, continuous readout

- 90:10 Ne-CF4 gas - low diffusion + high ion mobility
- Electron drift velocity 8 cm/μs - 13.2 μs maximum drift time
- Quad GEM electron multiplier + chevron readout pads
- 48 layer readout covering 30 - 78 cm radius
- R-ϕ resolution ~ 150 μm
- Δp/p ~ 1% at 5 GeV/c

INTT - Silicon strips with 80 μm pitch

- 4 layers 6 < R < 12 cm
- Pitch 78 μm
- Fast - can resolve one beam crossing

MVTX - 30 μm pitch MAPS pixels

- 3 layers 2.3 < R < 3.9 cm
- ~ 5 μm space point precision each

Calorimeters

EMCal

Tungsten-scintillating fiber sampling calorimeter

18 X_0, 1 λ

$\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

Read out by silicon photomultipliers

2D projective geometry

Small Moliere Radius, short radiation length

Energy resolution $\leq 16\%/\sqrt{E}$ @ 5%

HCal

Sampling calorimeter

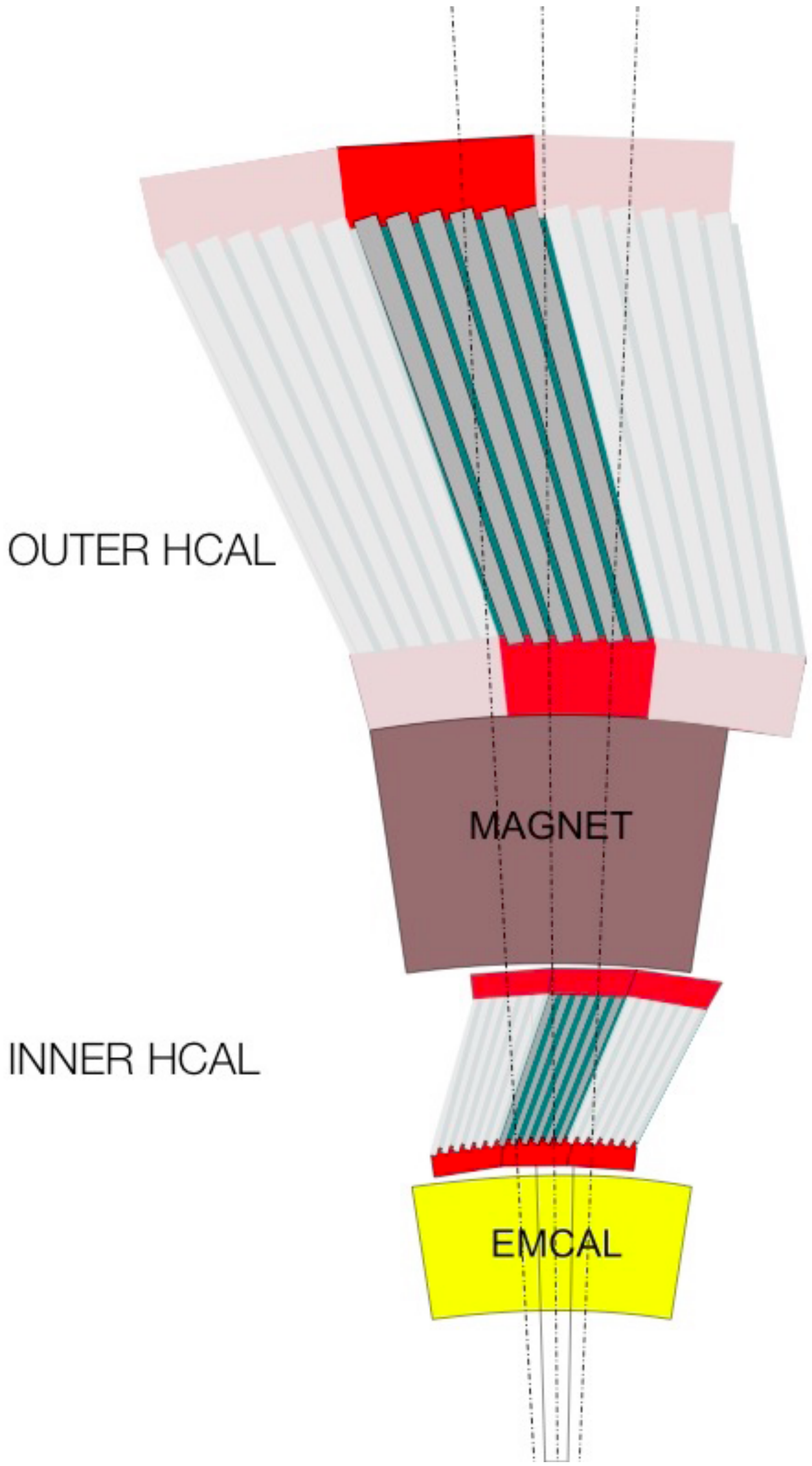
Magnet steel plates / scintillator tiles

3.8 λ

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

Read out by silicon photomultipliers

Doubles as the flux return for the solenoid



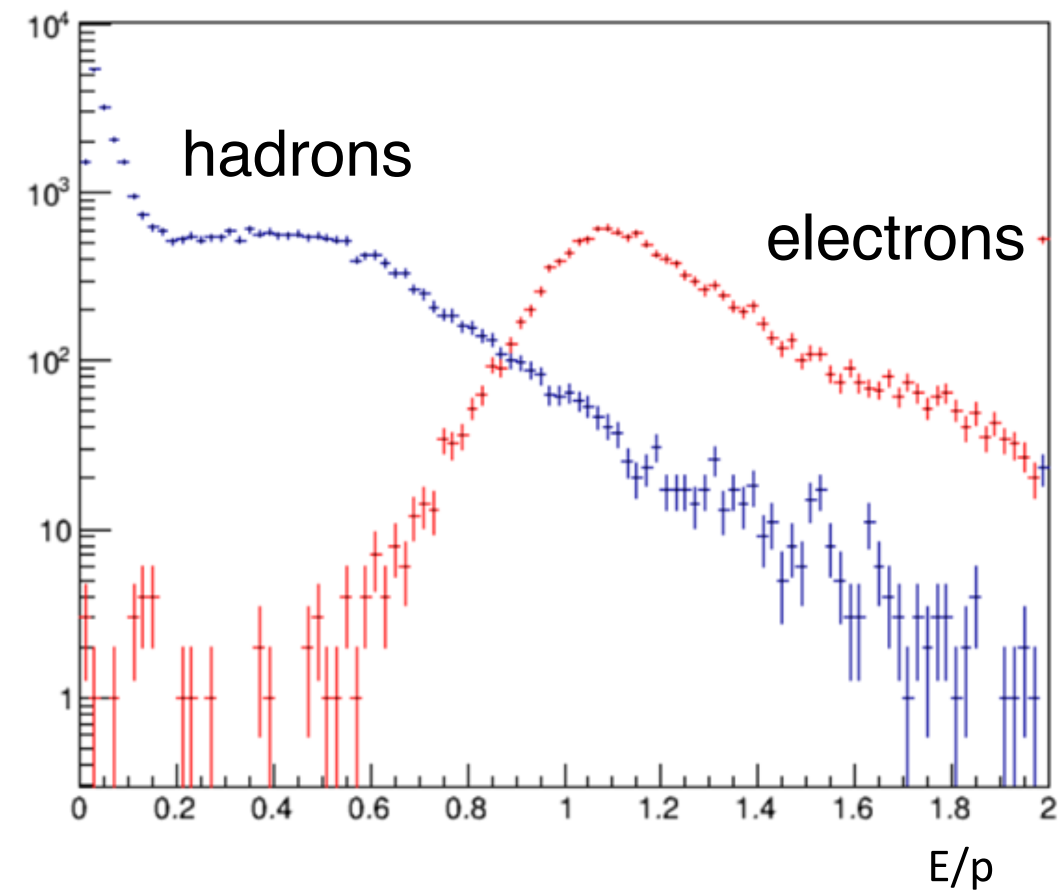
Hadron rejection

Our goal is to achieve a hadron rejection factor of ~100 with electron efficiency of ~90%, in the momentum range of the Upsilon decay electrons.

To be accomplished by analyzing tracks matched to the EMCal and HCal.

- Optimized and fully calibrated E/p cuts
- Shower shape analysis
- Vertex cuts to reduce background, eliminate conversions.

Optimizing this is a major focus of our Quarkonium topical group, now that our tracking code has stabilized.



Event pileup

High occupancy in the TPC is unavoidable.

- Minimize collisions **outside the silicon acceptance** with 2 mr beam crossing angle.
  - Limits Au+Au rate to 50 KHz max, p+p rate to 2 MHz max
- 13.2 μs electron collection time => event pileup in the TPC.
  - ~ 2 events in Au+Au at 50 KHz
  - ~ 26 events in p+p at 2 MHz

The MVTX readout latency also leads to event pileup in p+p collisions.

- But the MVTX gets the position right.
- MVTX occupancy not a big problem.

Only the INTT can resolve a beam crossing.

Integration windows / events:

	Window	**Au+Au**	**p+p**
	μs	50 kHz	2 MHz
TPC	± 13.2	1.5	52
MVTX	± 5	1	20
INTT	-.02 +.08	1	1

This event "pileup" is properly included in all simulations

The INTT's main function is to resolve ambiguities due to pileup

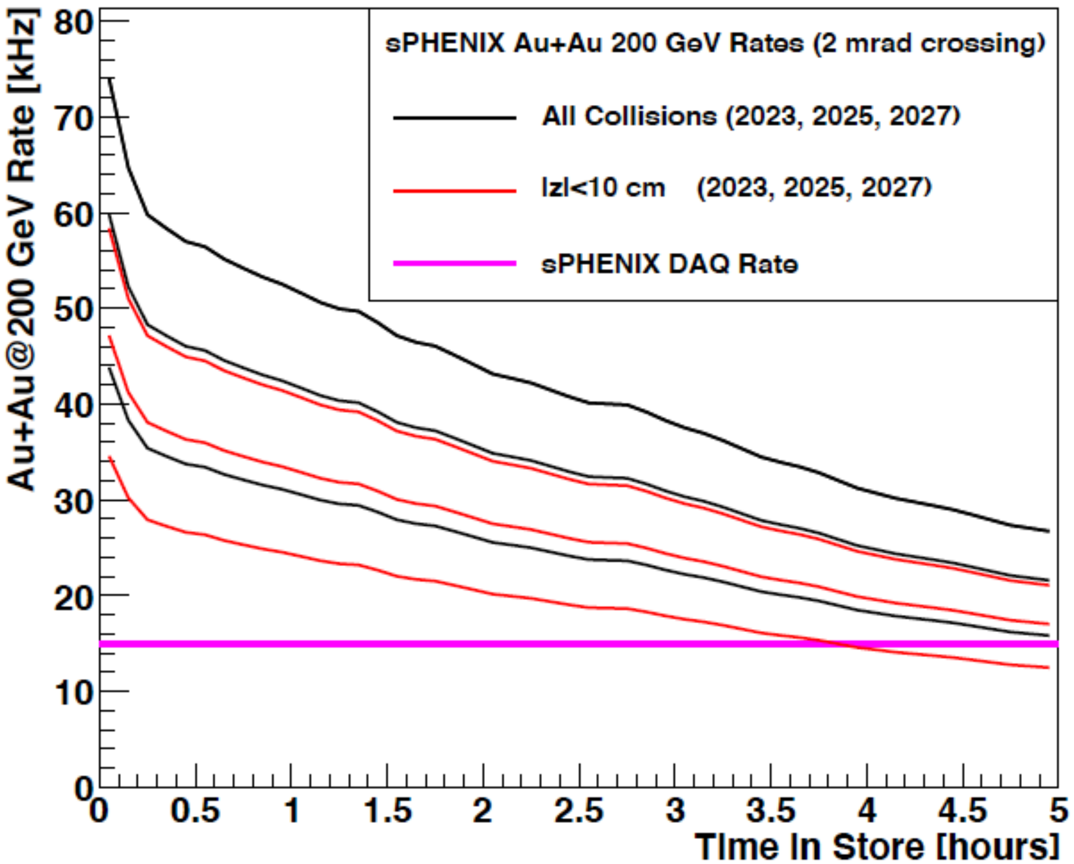
Trigger strategy

The sPHENIX DAQ will record data at 15 KHZ.

- Au+Au data will be recorded using minimum bias triggers.
  - Provides all physics with large integrated luminosity.
- p+p and p+Au data will be recorded using level 1 triggers.
  - The Y trigger will be an EMCal trigger based on the combined energy (and possibly invariant mass) of the dielectron pair.

Au+Au interaction rate vs time-in-store for a 2 mr beam crossing angle.

- Only collisions inside the MVTX acceptance (|z| < 10 cm) will be recorded.
- The magenta line is the DAQ rate.



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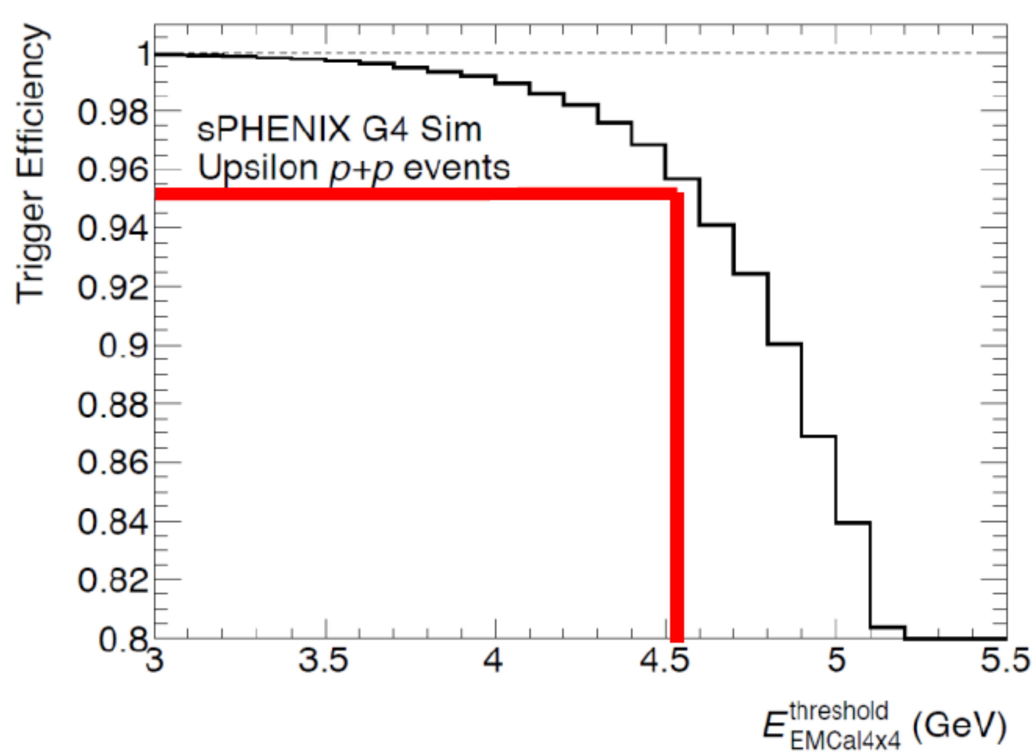
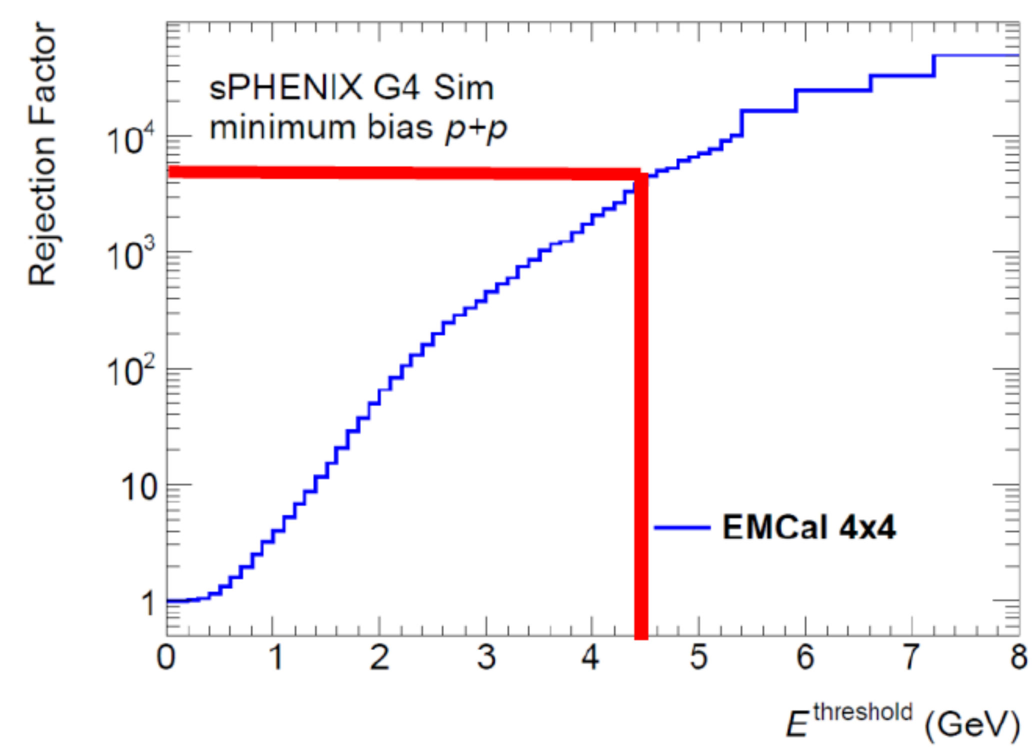
Upsilon trigger efficiency and rejection in p+p simulations.

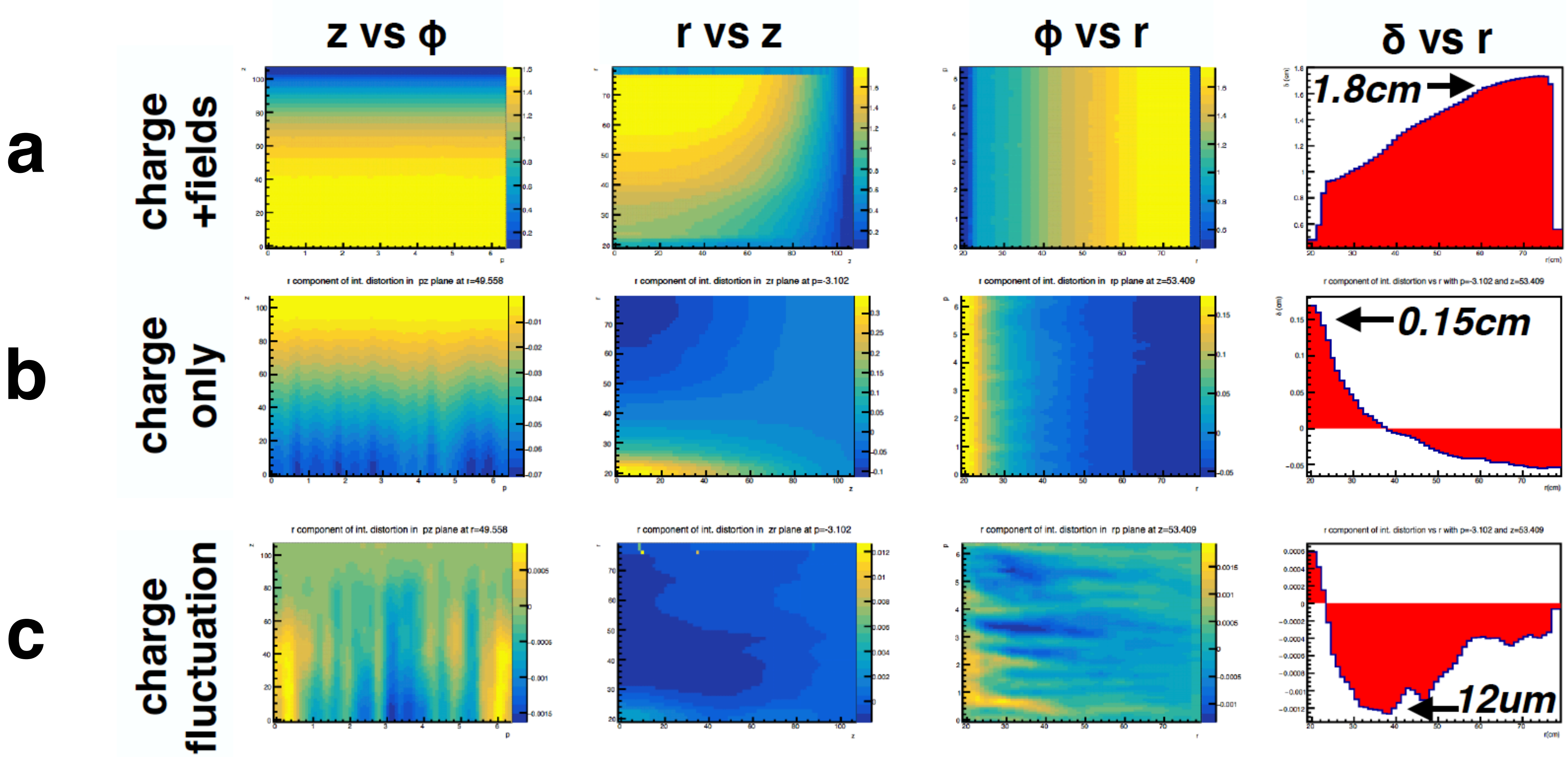




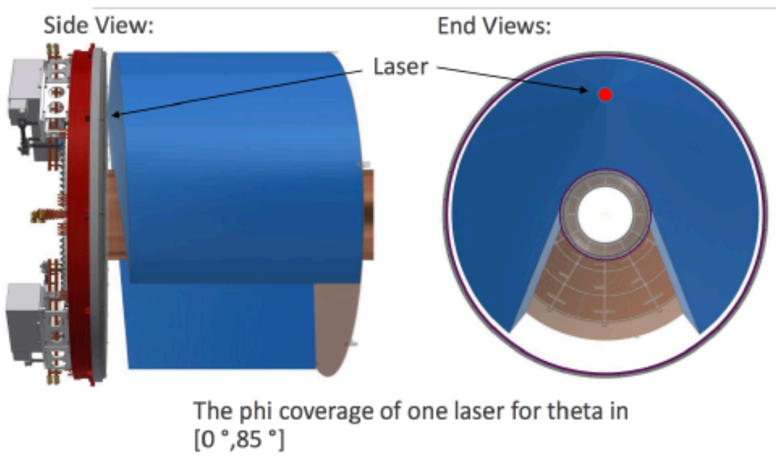
Position distortions in the TPC

Distortion of cluster positions occurs on three position scales:

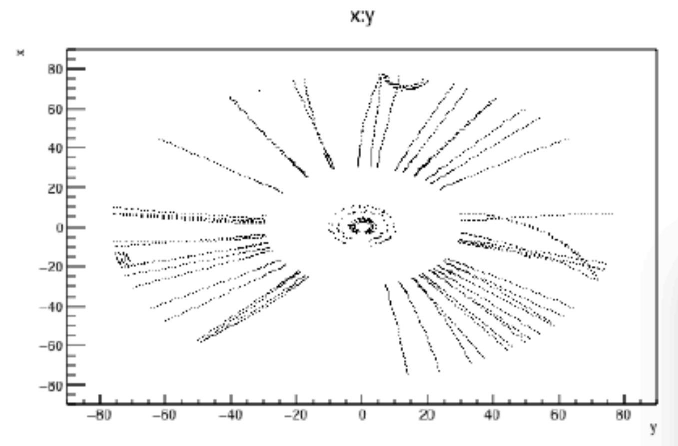
- a) Static ExB distortions
  - calibrate without beam and done.
- b) Average space charge distortions due to buildup of ion charge
  - calibrate using time averaged tracks.
- c) Fluctuations in space charge distortions
  - calibrate at KHz rate (next slide)



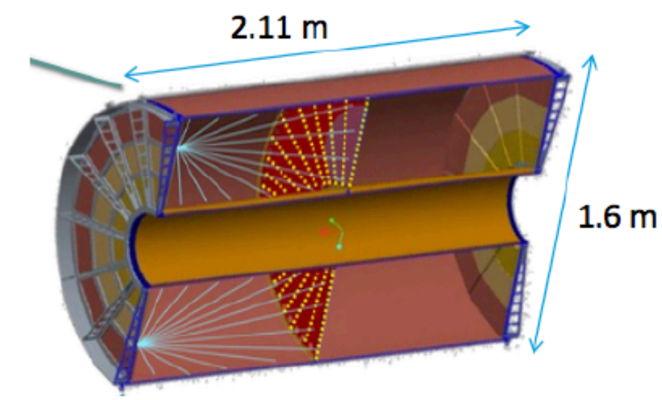
Distortion calibration / monitoring



Static Distortions mapped (full 3D) by **line laser**. Magnetic field also mapped directly.

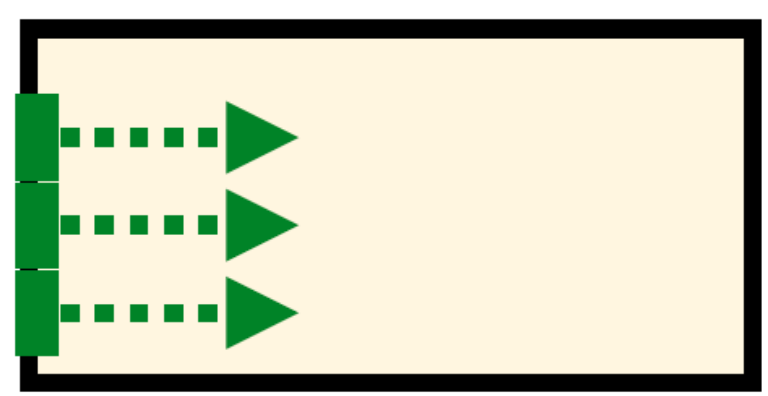


Average distortions monitored (full 3D) by **tracks** after statics removed.



Distortion fluctuations monitored (2D) by **CM pattern/diffuse laser** after averages removed.

Digital current infers IBF from readout. Provides orthogonal, but indirect, measure of SC distortion



Tracking reconstruction

The reconstruction software goal: reconstruct Au+Au event in 10 seconds per event. Includes making, applying, all calibrations. This is challenging ….

- We have adopted the ACTS tracking package for final track fitting.
- Implemented over the last ~ 1.5 years.
- Extremely fast, experiment-agnostic package.
- Osborn, J.D. *et al*. Implementation of ACTS into sPHENIX Track Reconstruction. *Comput Softw Big Sci* **5,** 23 (2021).

Track finding in the TPC and silicon detectors is done separately.

- Track stubs are matched in η, ϕ, position at the beam-line.
- Multiple matches are resolved later, using fit quality

Silicon track seeding: uses the ACTS tracking package.
TPC track seeding: cellular automaton seeding and Kalman filter developed for sPHENIX, based on the algorithm developed for the ALICE TPC.

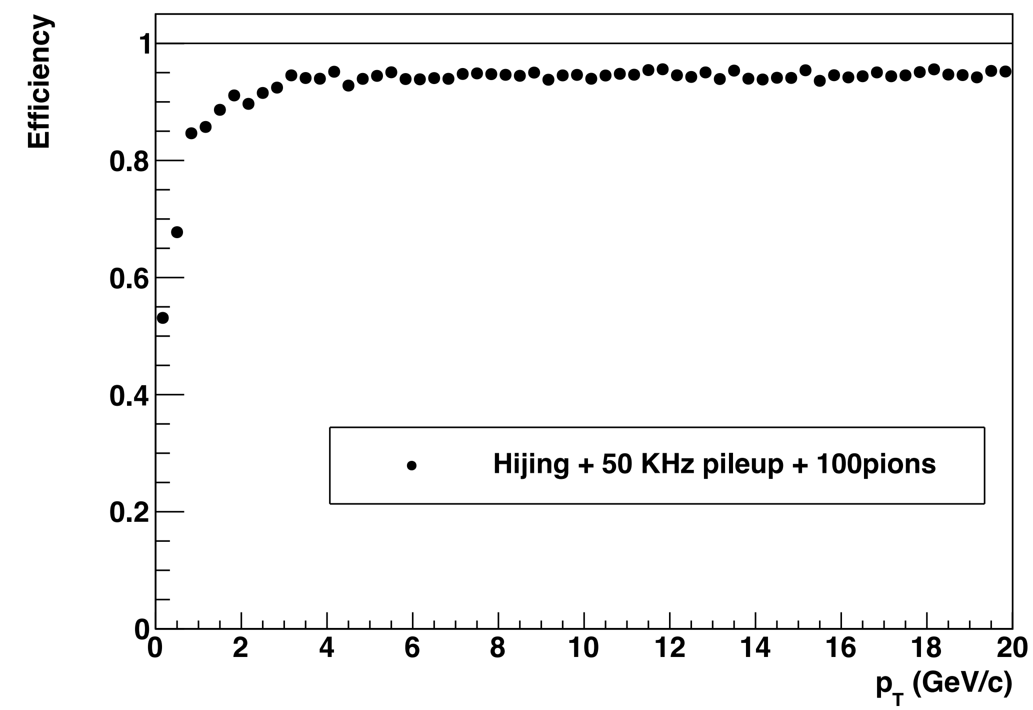
Final track fitting with the ACTS Kalman Filter

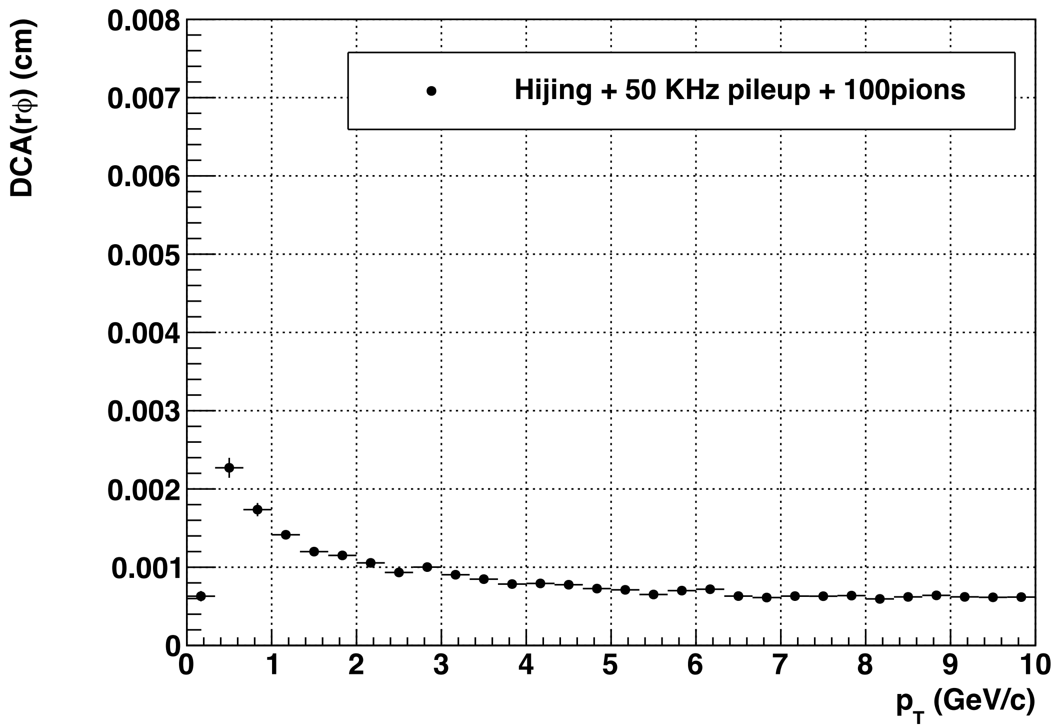
Tracking performance

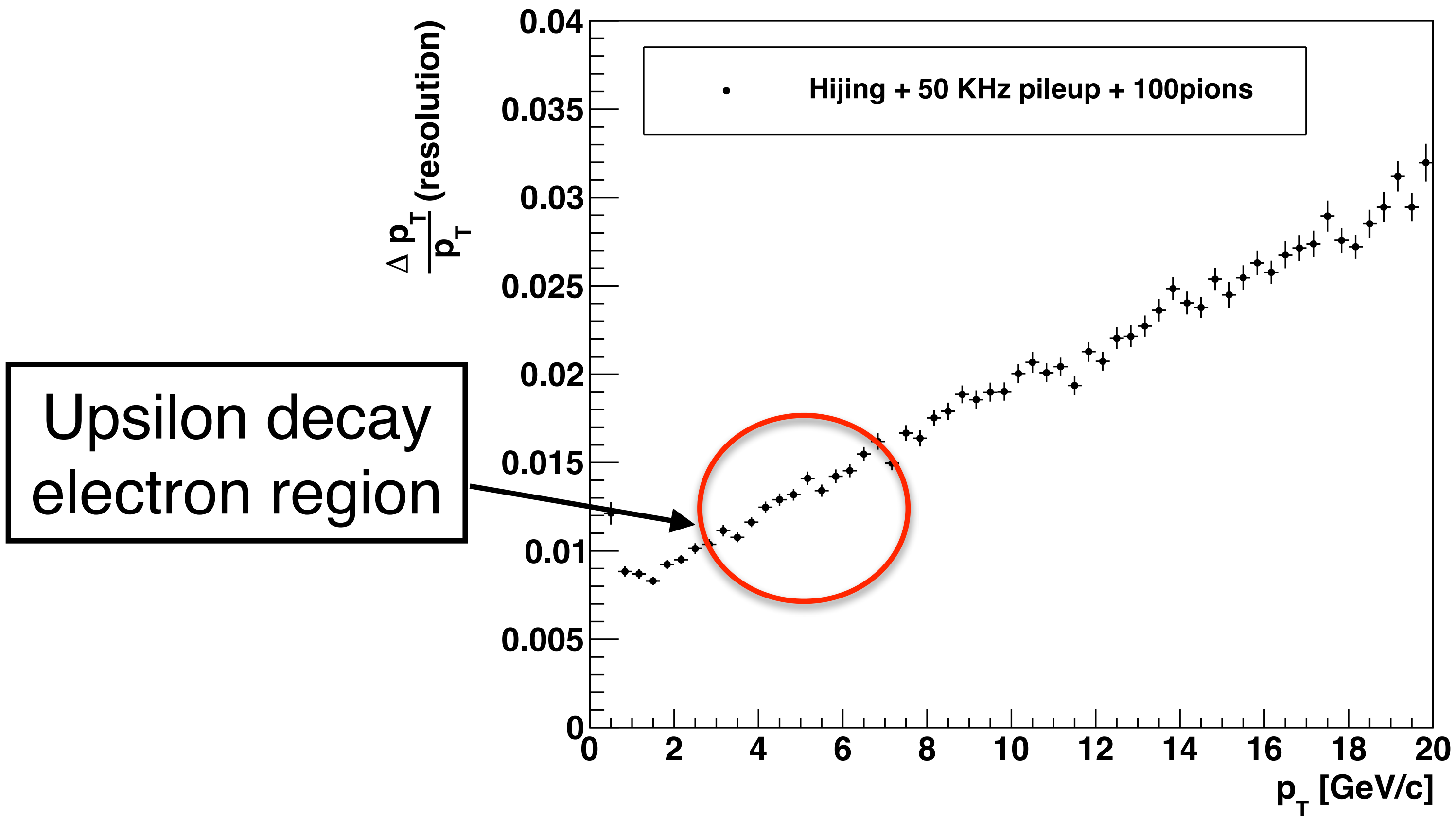
Simulated performance for minimum bias Hijing events with 50 KHz pileup rate + embedded 100 pions.

Have not yet implemented TPC clustering that is designed to handle overlaps.

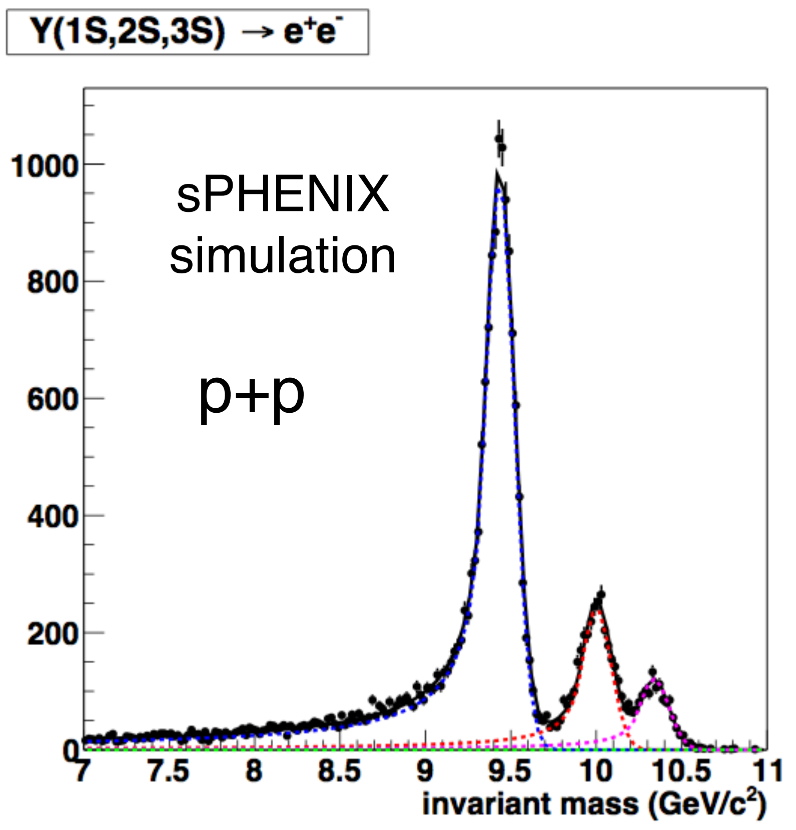
- Should improve efficiency, p_T resolution.





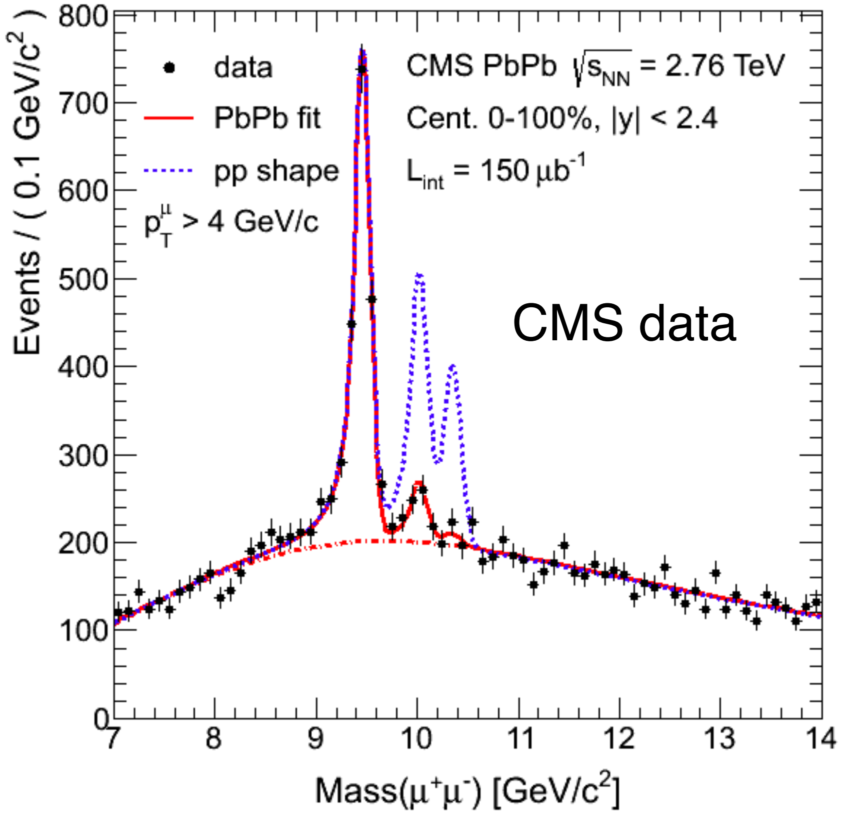


Upsilon Reconstruction Simulations



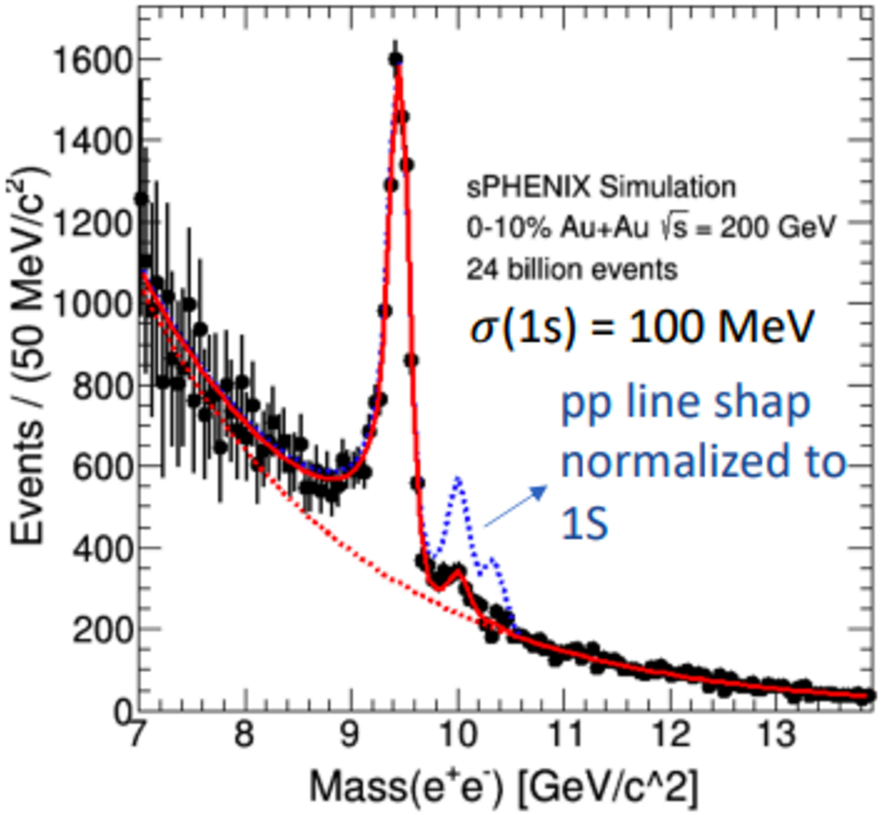
Simulated mass spectrum in p+p collisions (signal only) (left).

CMS data for p+p, Pb+Pb (right).



Simulated mass spectrum in 0-10% central Au+Au collisions.

- Before like-sign background subtraction.
- Suppression taken from Strickland & Bazow.



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

2023: Commissioning high multiplicity Au+Au run
Measurement of standard Au+Au candles at RHIC

2024: Commissioning p+p
p↑+p↑, p↑+Au : HI reference set and cold QCD

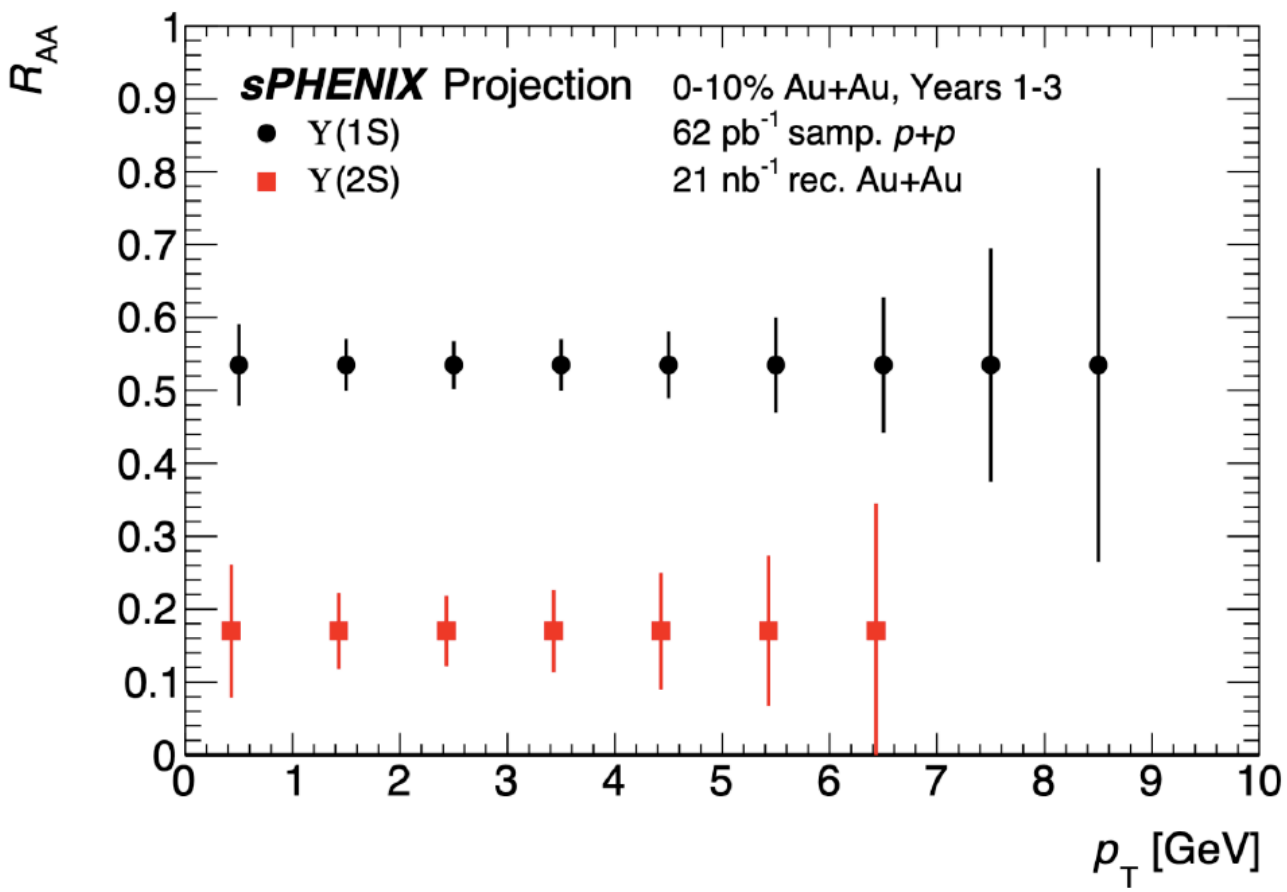
2025: Very large Au+Au heavy-ion set for jet and heavy flavor physics
141 B events recorded in total

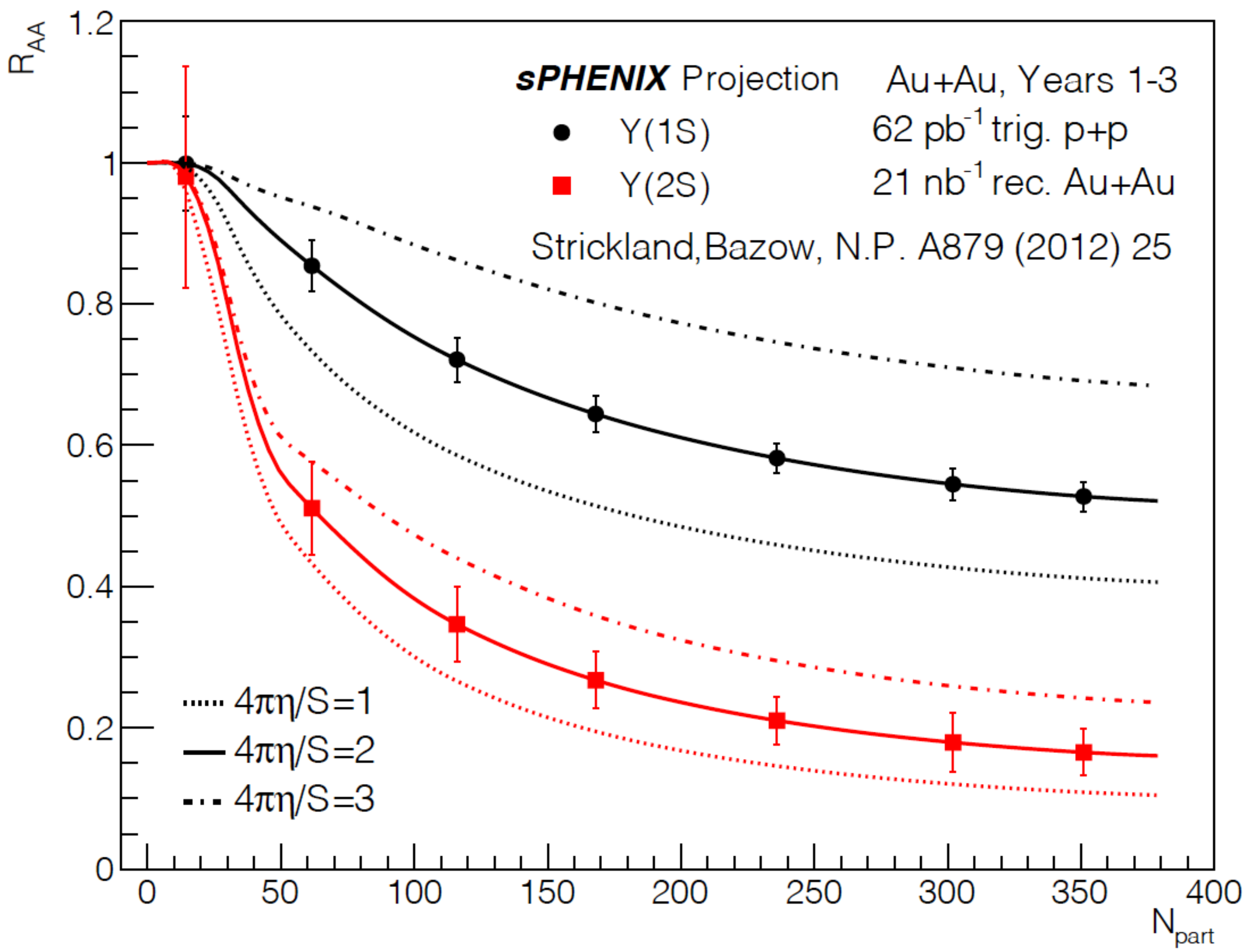
Upsilon Measurement Projections

Au+Au nuclear modification.

Uses expected luminosity from Au+Au run in 2025 and p+p run in 2024.

The Υ(3S) state is so heavily suppressed that it is weaker than the estimated Drell Yan background.





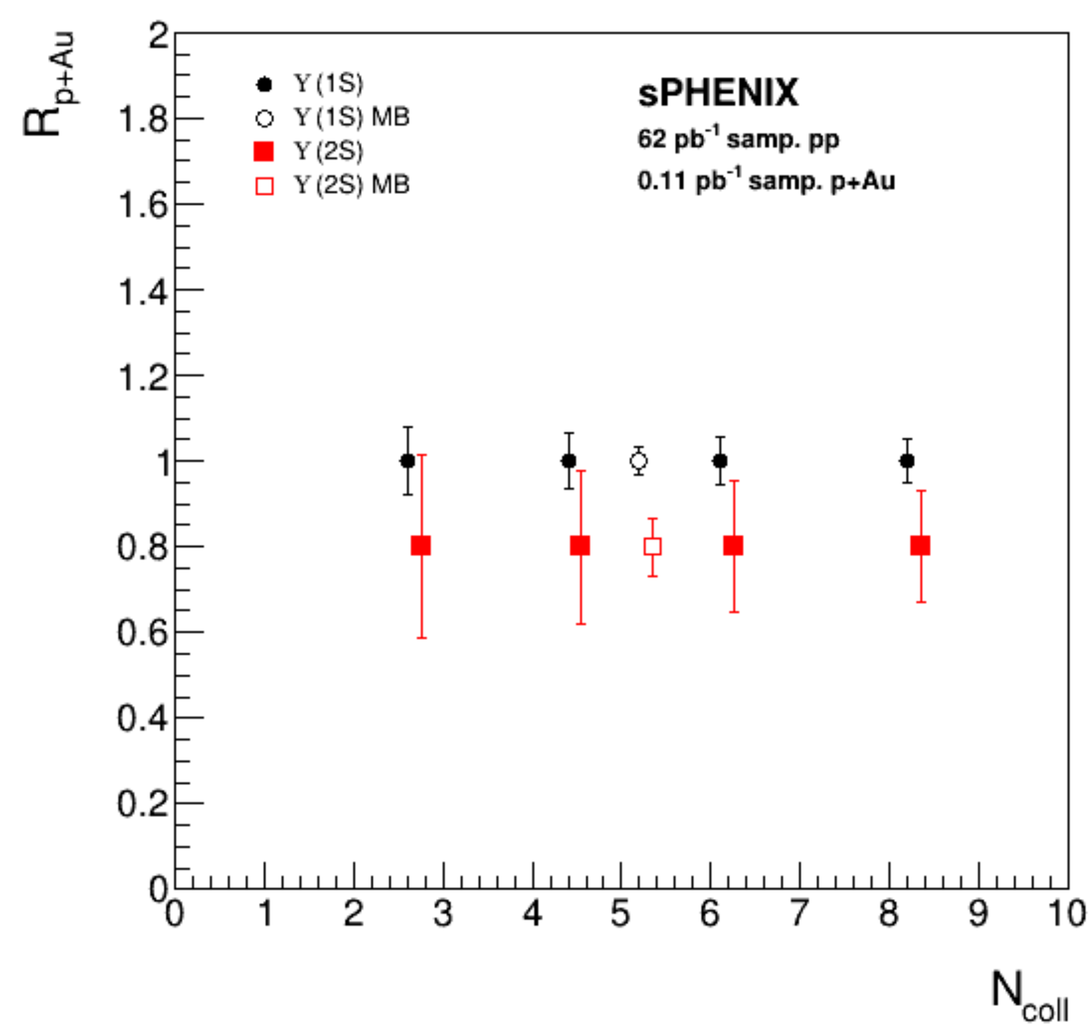
Υ measurements in p+Au collisions

This measurement serves as a baseline for the Au+Au measurement.

It is also interesting in its own right.

The modification of the Υ yields in p+Au collisions is a measure of cold nuclear matter effects.

- Effects that modify the production of Υ states in a nuclear target.
- Generally, any modification not due to energy produced in the collision.
  - Gluon shadowing (nPDF's), CGC.
  - Initial state parton energy loss
  - Nuclear "absorption"
    - i.e. collisions with target nucleons.



Theoretically not well constrained.

Startup timeline

sPHENIX commissioning starts November 2022.

Beginning of RHIC run FY23 in January 2023.

The Babar SC magnet installed in the sPHENIX carriage.

Summary

The goal is for sPHENIX to provide precise measurements of the Υ(1S) and Υ(2S) invariant yields in Au+Au, p+Au and p+p collisions.

These measurements will be complementary to measurements by the LHC experiments at higher collision energies.

- Different initial temperatures.
- Different underlying bottom production cross sections.

Tracking performance is key to this program. The challenges in getting the required performance from the TPC in the RHIC environment have been outlined.

We are in the process of optimizing the reconstruction and analysis tools needed for this analysis. First beam in a little over a year!