# Heavy flavor physics at the sPHENIX experiment

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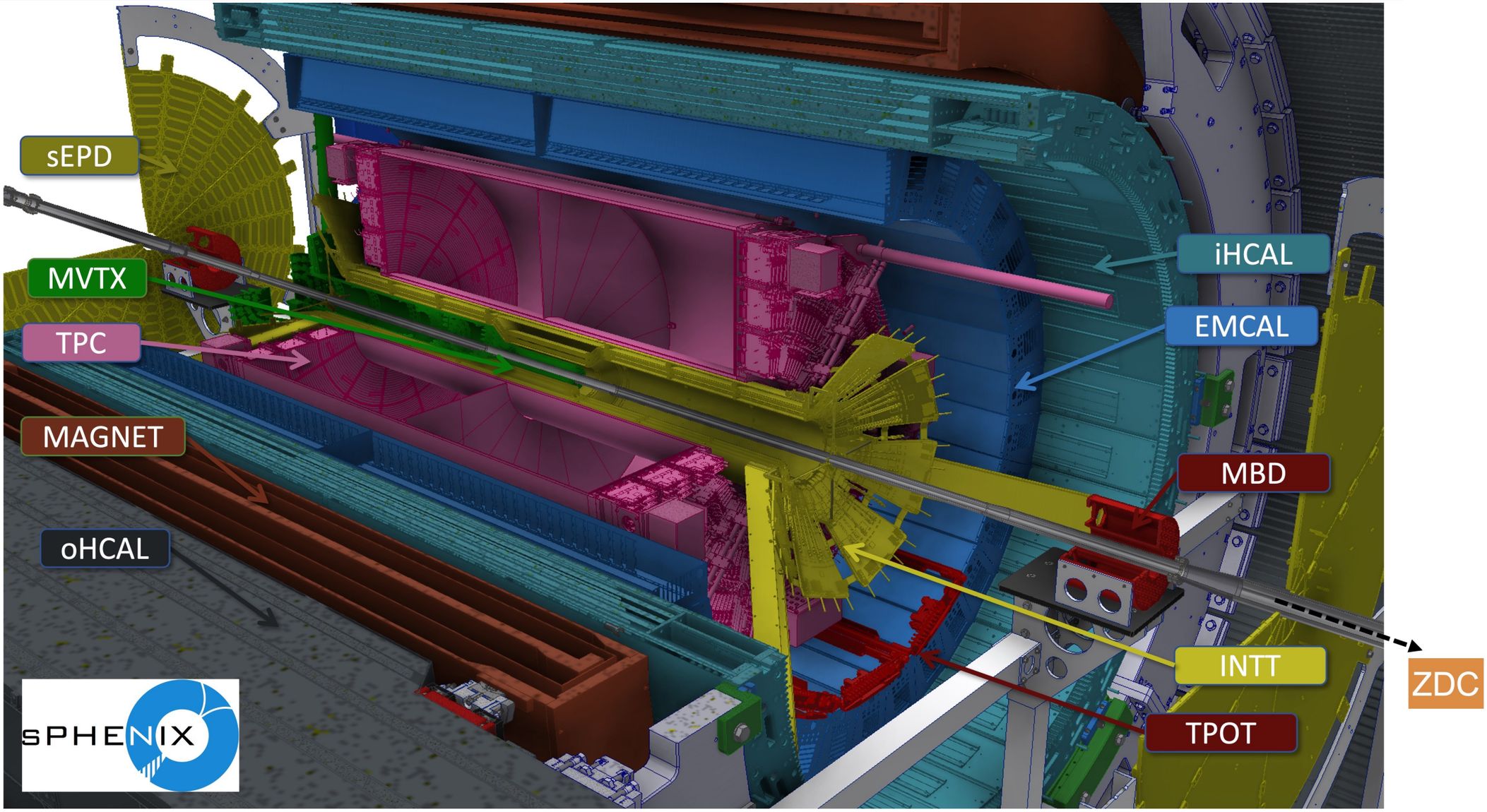
**ISMD 2023 - 52nd International Symposium on Multiparticle Dynamics**

21 – 26 August 2023, Gyöngyös, Hungary

Los Alamos NATIONAL LABORATORY

sPHENIX

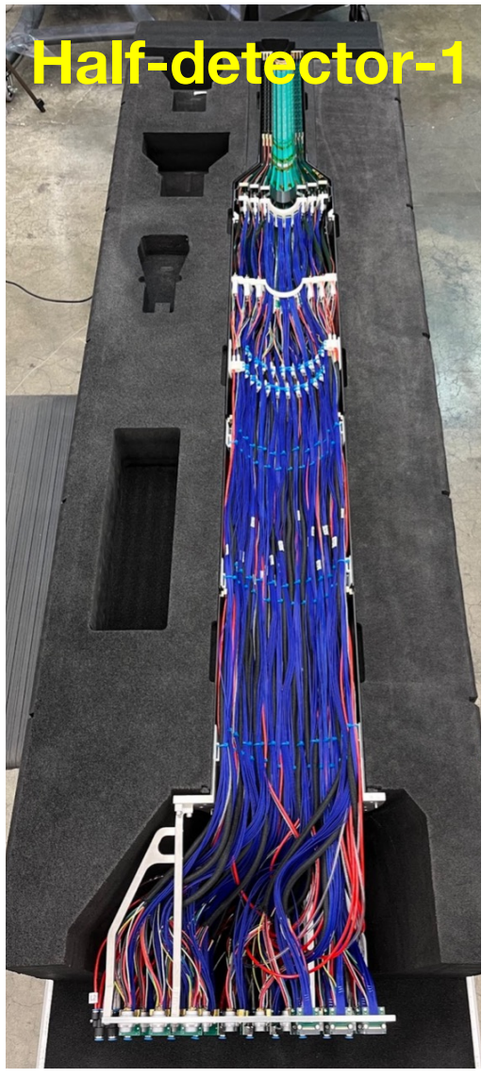
# The sPHENIX Experiment at RHIC

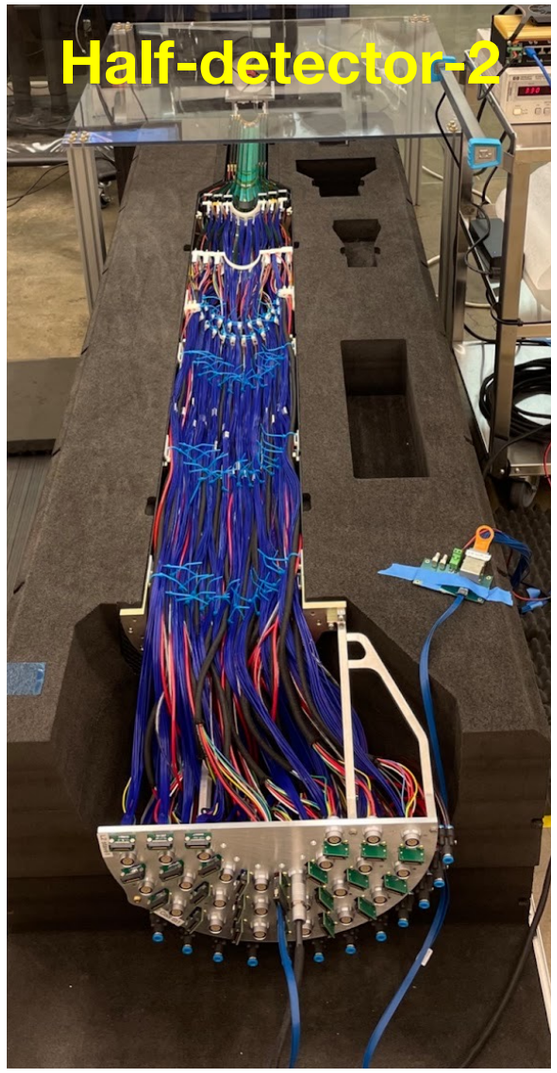


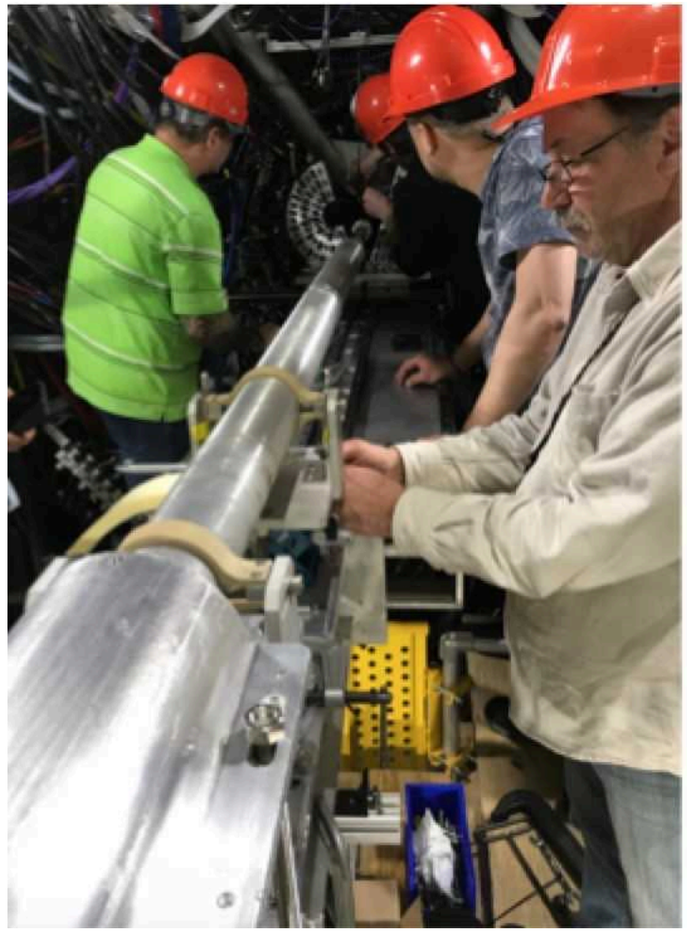

**New Heavy-Ion Collision Experiment in the Past 20 Years at RHIC: sPHENIX**

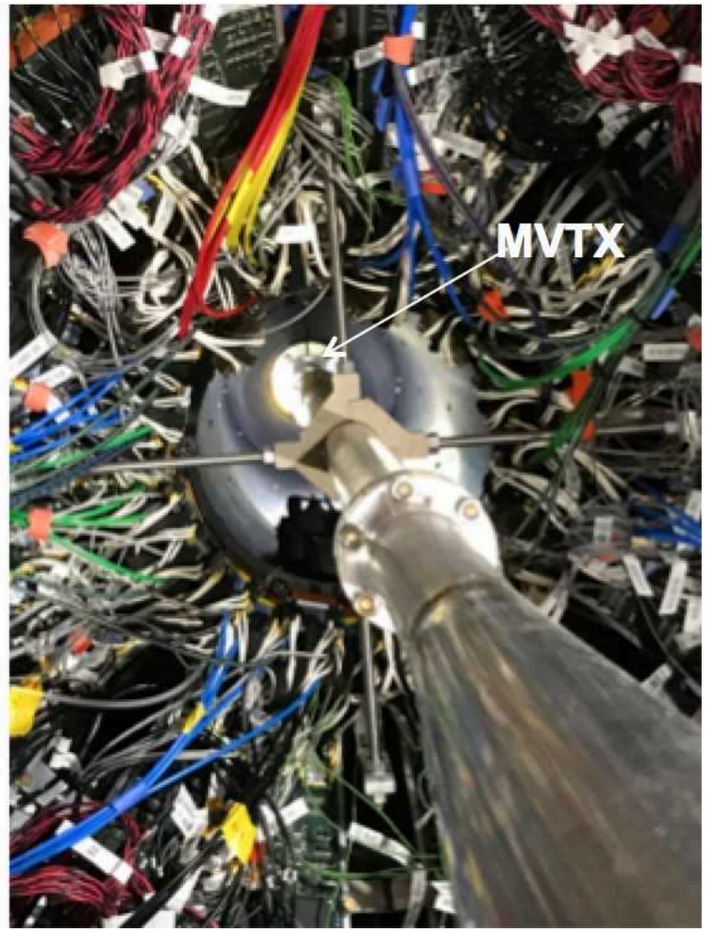
- Tracking system: MVTX, INTT, TPC, and TPOT
  - Excellent vertexing performance with streaming readout capability
- Calorimeter system: EMCAL and HCAL
  - First barrel hadronic calorimeter at RHIC
- Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales
- Complementary to LHC experiments

# MVTX Detector



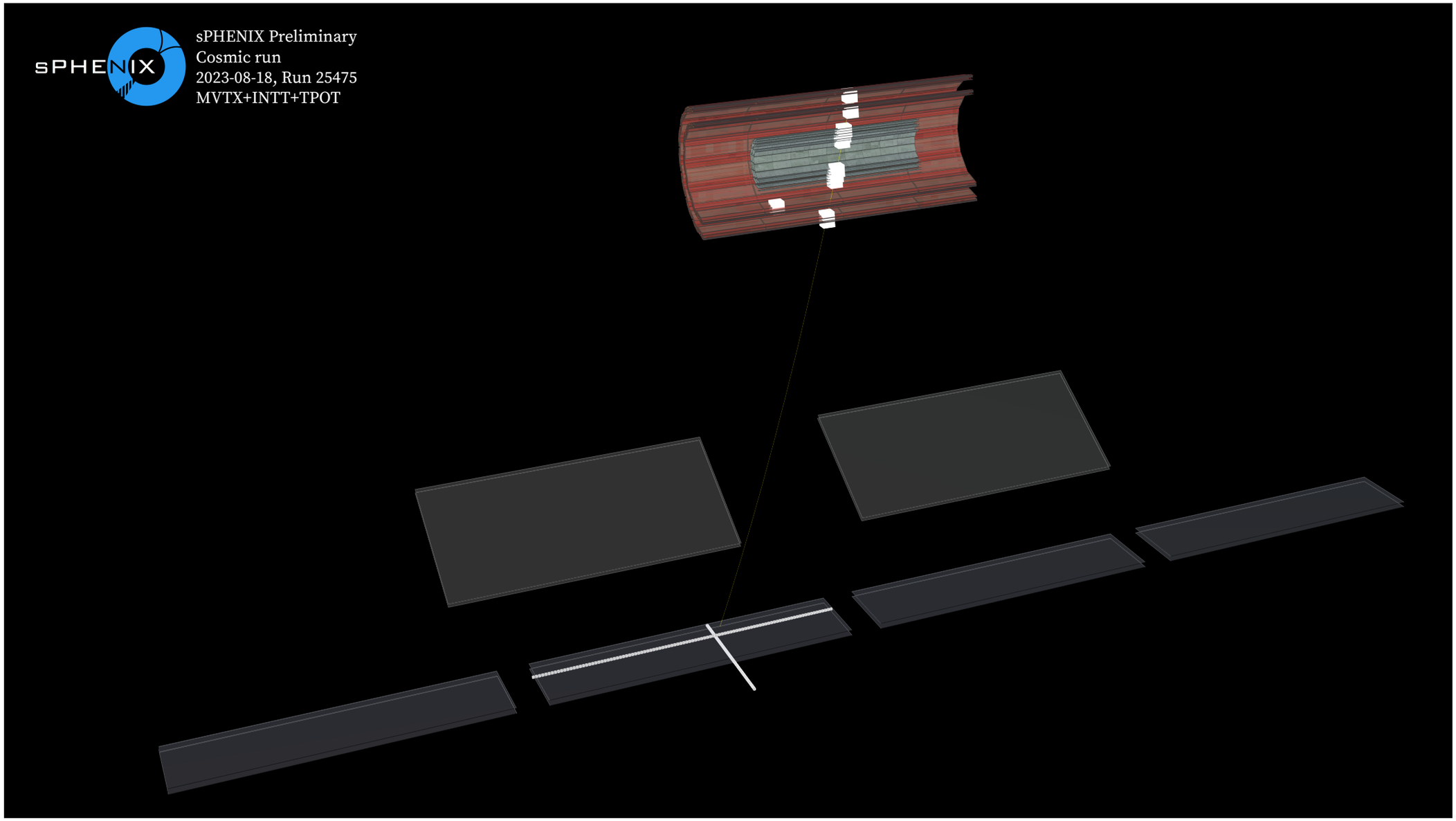





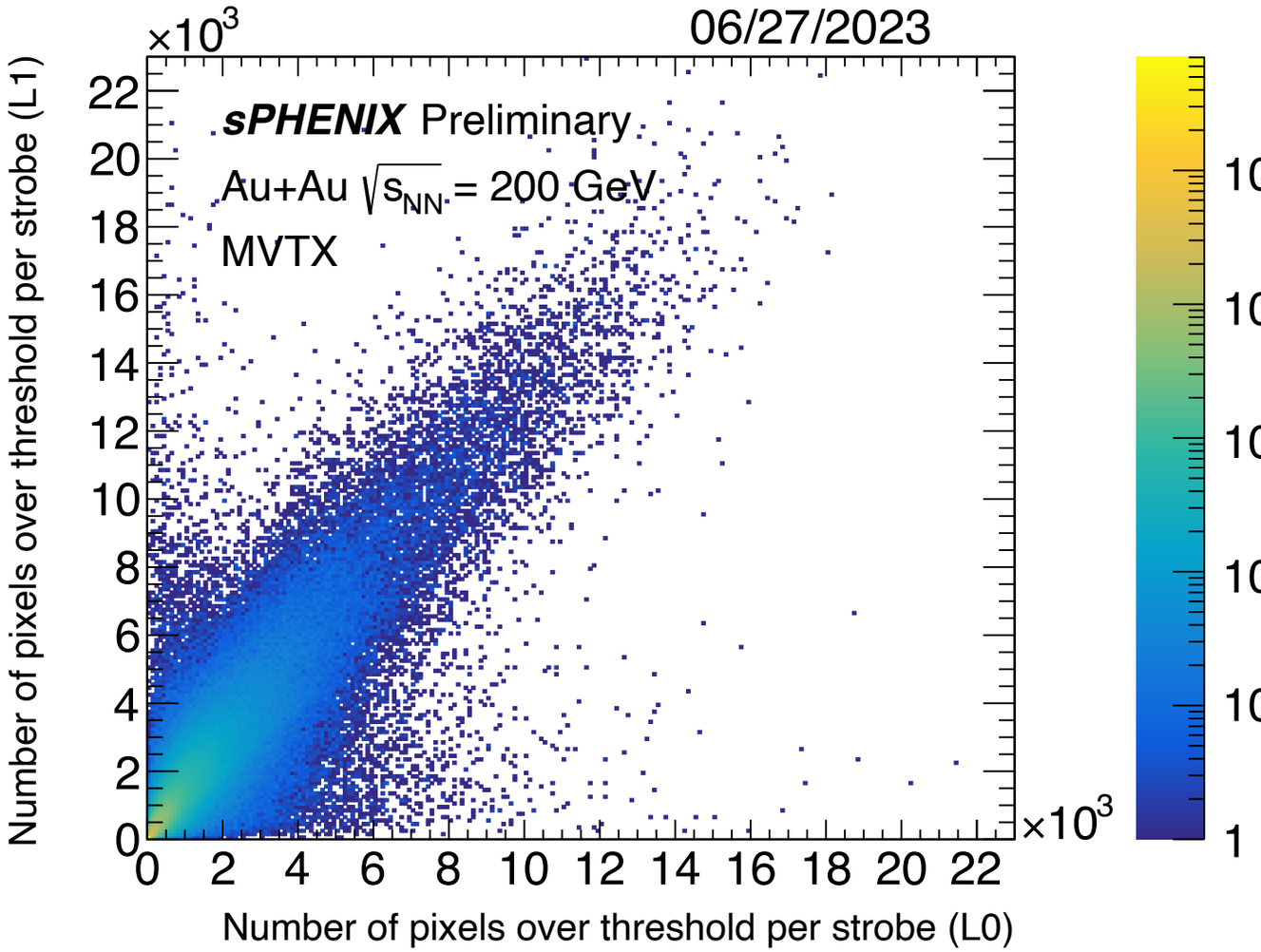

- Monolithic-Active-Pixel-Sensor-based Vertex (MVTX) Detector
  - 3 layers of silicon pixel detector with excellent position resolution of ~5 $\mu m$
  - Capable of operating with continuous streaming readout mode to maximize data taking
  - Crucial for heavy flavor physics measurements
- On 03/31/2023, MVTX detector installed to the sPHENIX detector
  - Tested and readout data properly
- Data taking with beam and cosmic events during Run 23
  - Offline data analysis ongoing

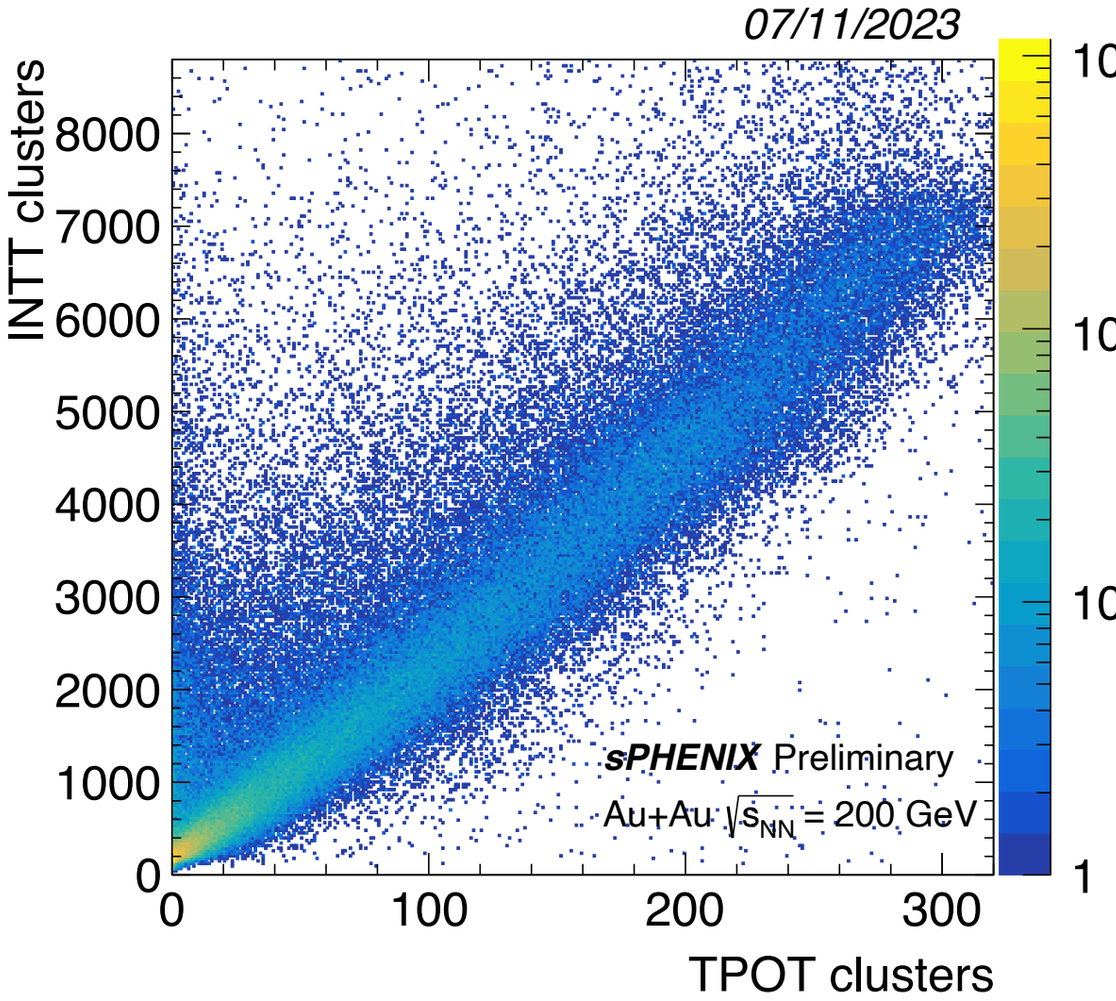
# MVTX+INTT+TPOT Cosmic Event Display



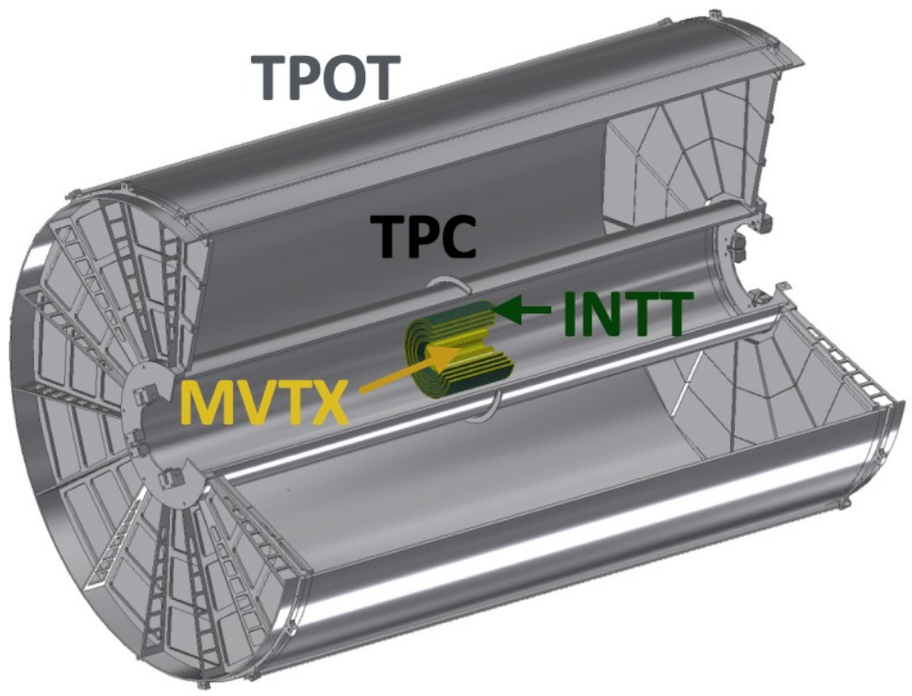

- Synchronized MVTX + INTT + TPOT event display for tracking commissioning with cosmic data
  - Coincident signal matching required to trigger cosmic events with outer HCAL sectors
  - Uniform B field on pointing in the +z direction
- MVTX: low noise level after noisy pixel masking and streaming readout mode continuous streaming readout only save hits with cluster size of at least 2
- Tracking: clusters line up from the cosmic muon track

# Correlation of Tracking Detectors

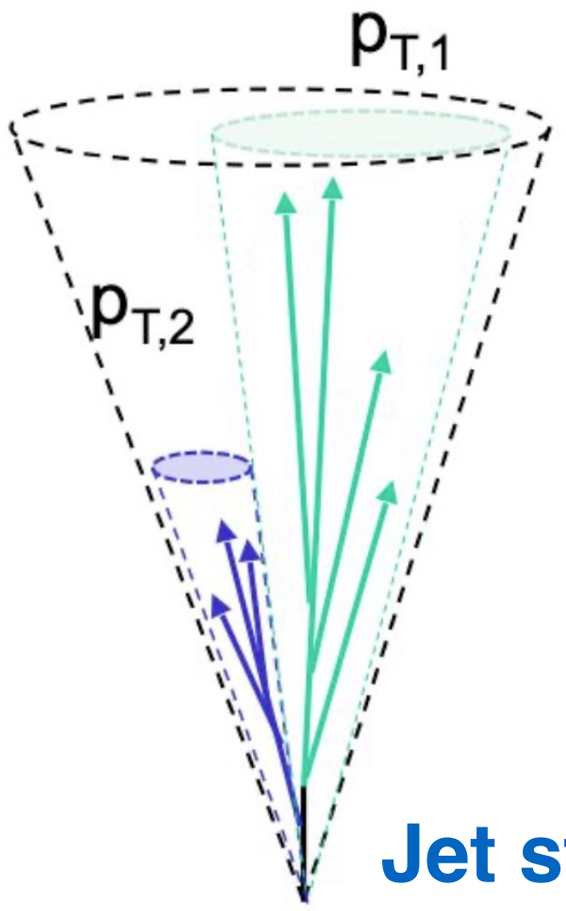



- Strong correlation observed in MVTX, INTT, TPOT, and MBD with beam collisions
- TPC event display shown Itaru's talk on Tuesday 08/22
- Overall good functionality and data taking capabilities of the tracking detectors

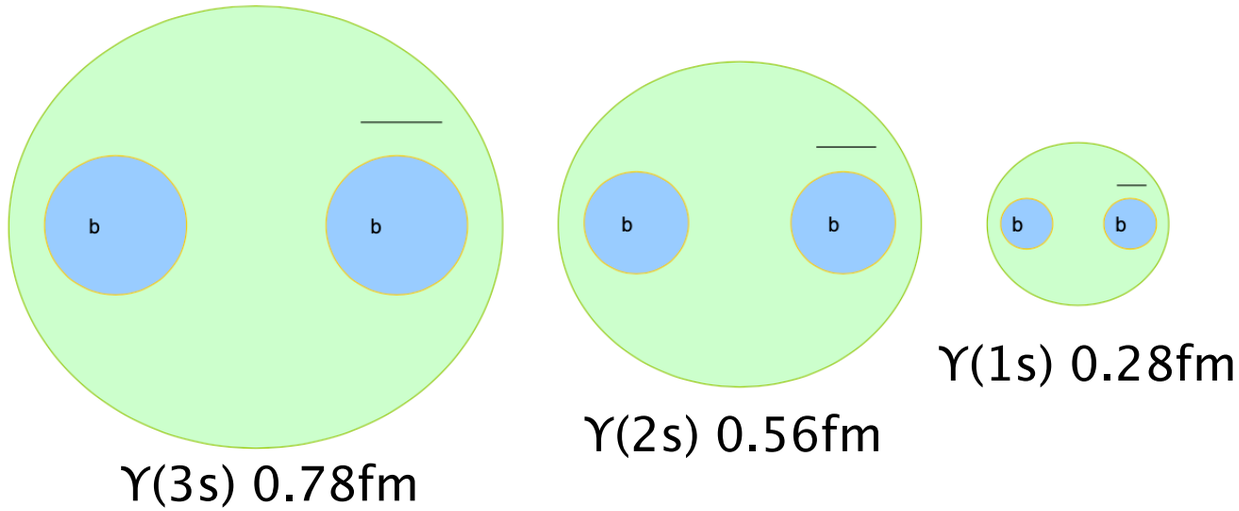


# The sPHENIX Physics Program



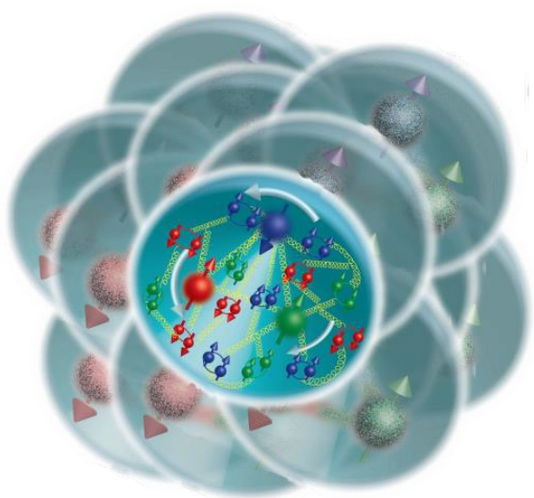

## Jet structure

vary momentum/angular scale of probe




## Quarkonium spectroscopy

vary size of probe

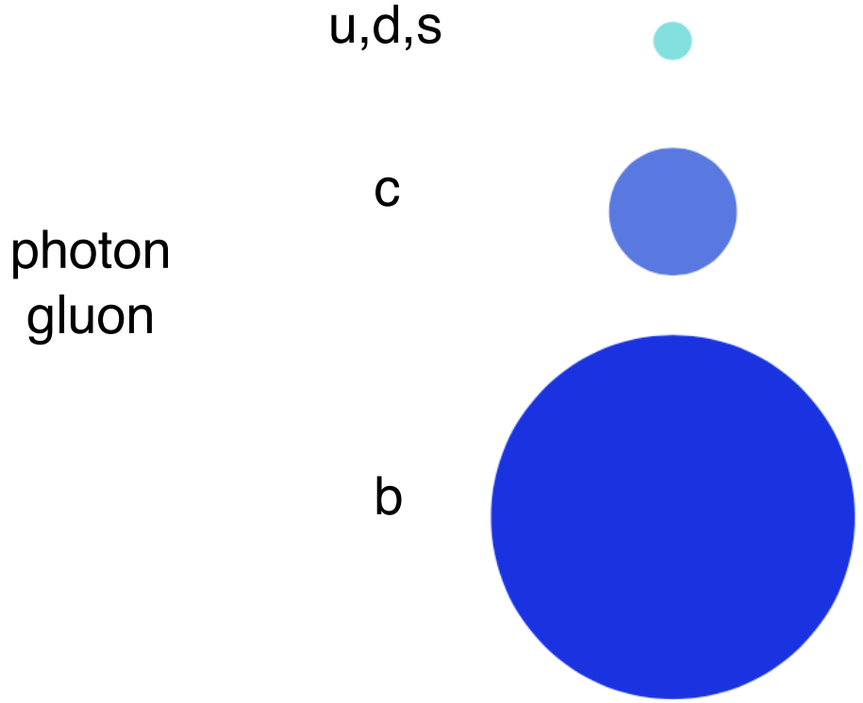


## Cold QCD

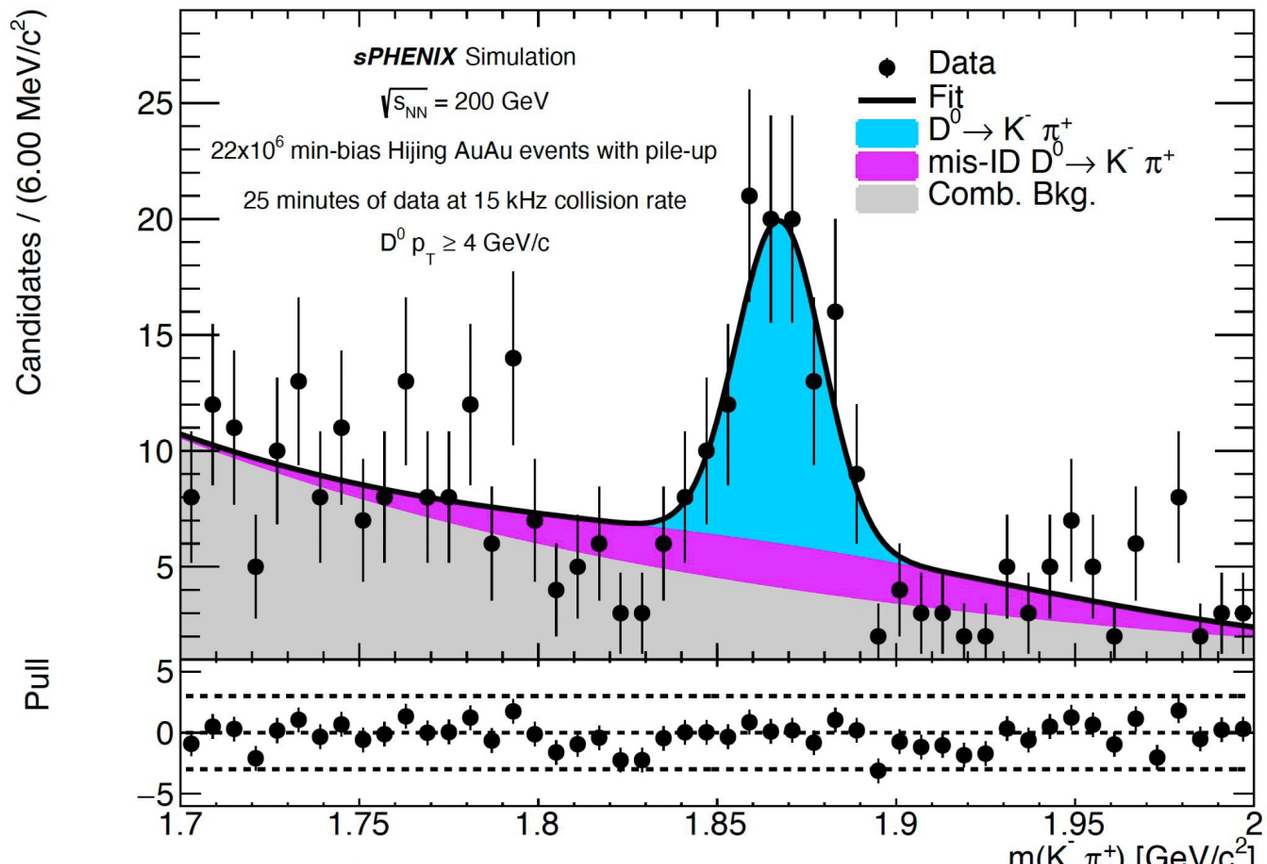
study proton spin, transverse-momentum, and cold nuclear effects

## Parton energy loss

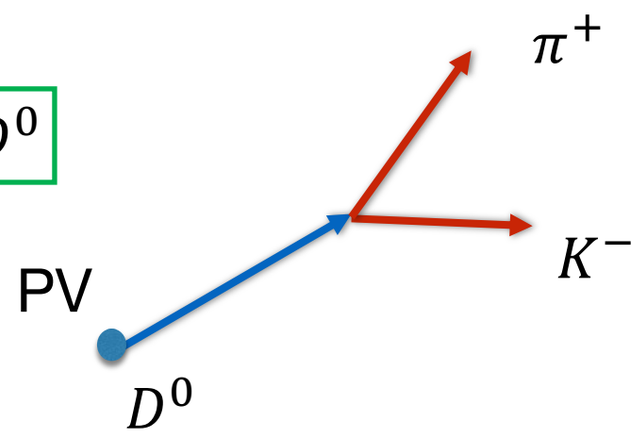
vary mass/momentum of probe



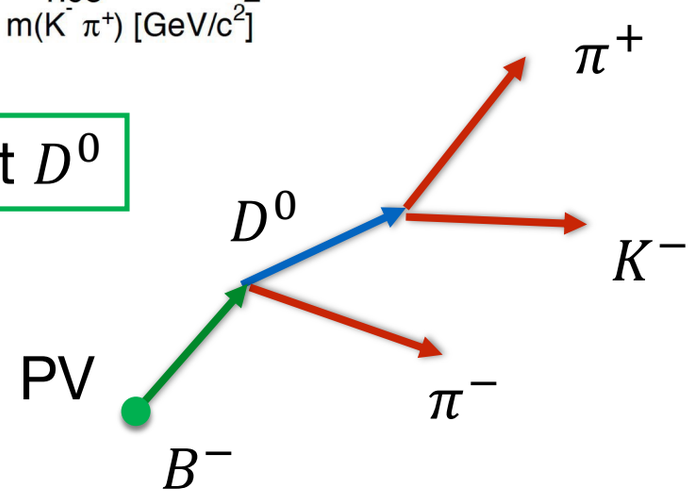
# $D^0$ Performance with Simulations




Prompt $D^0$

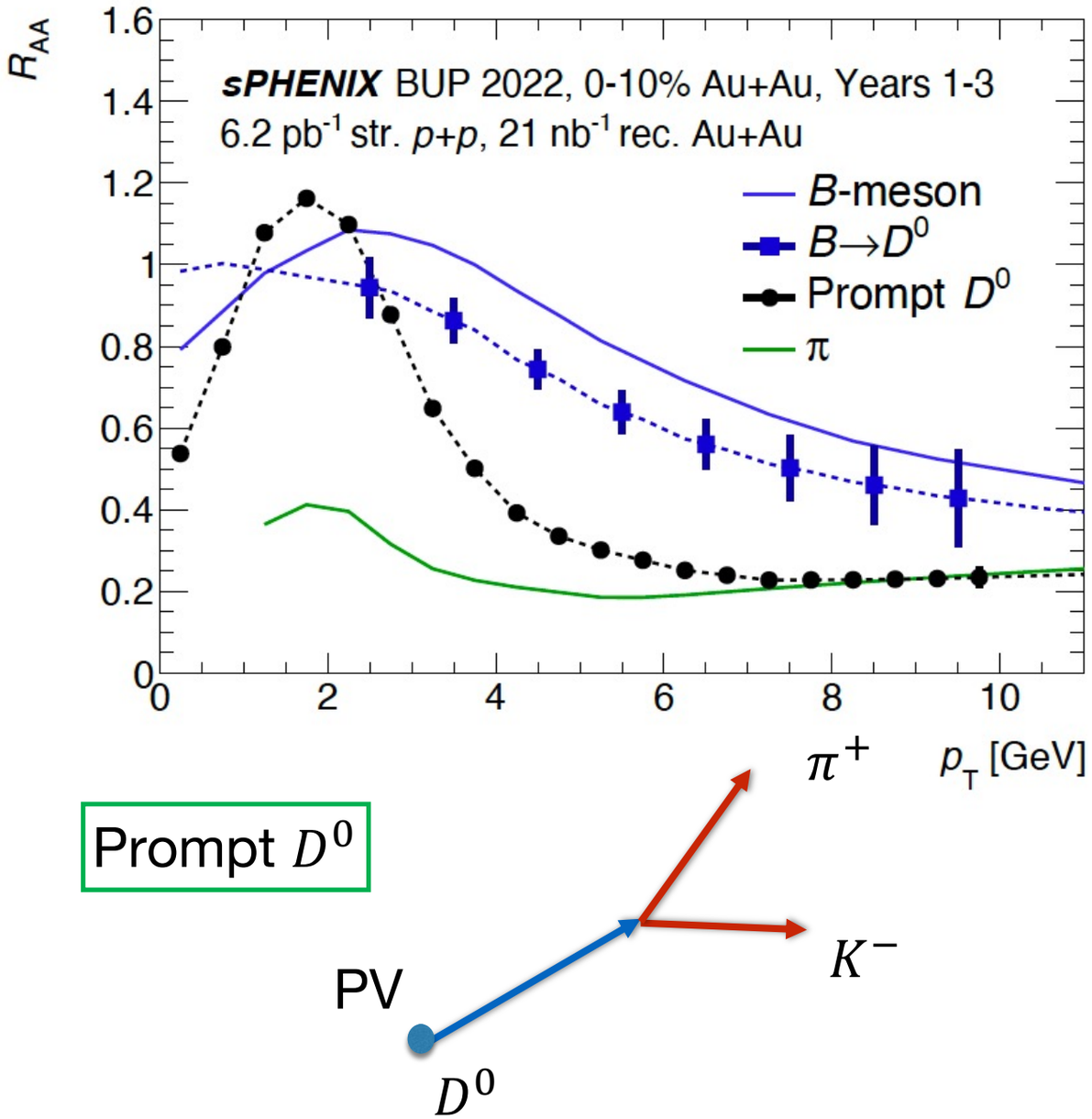


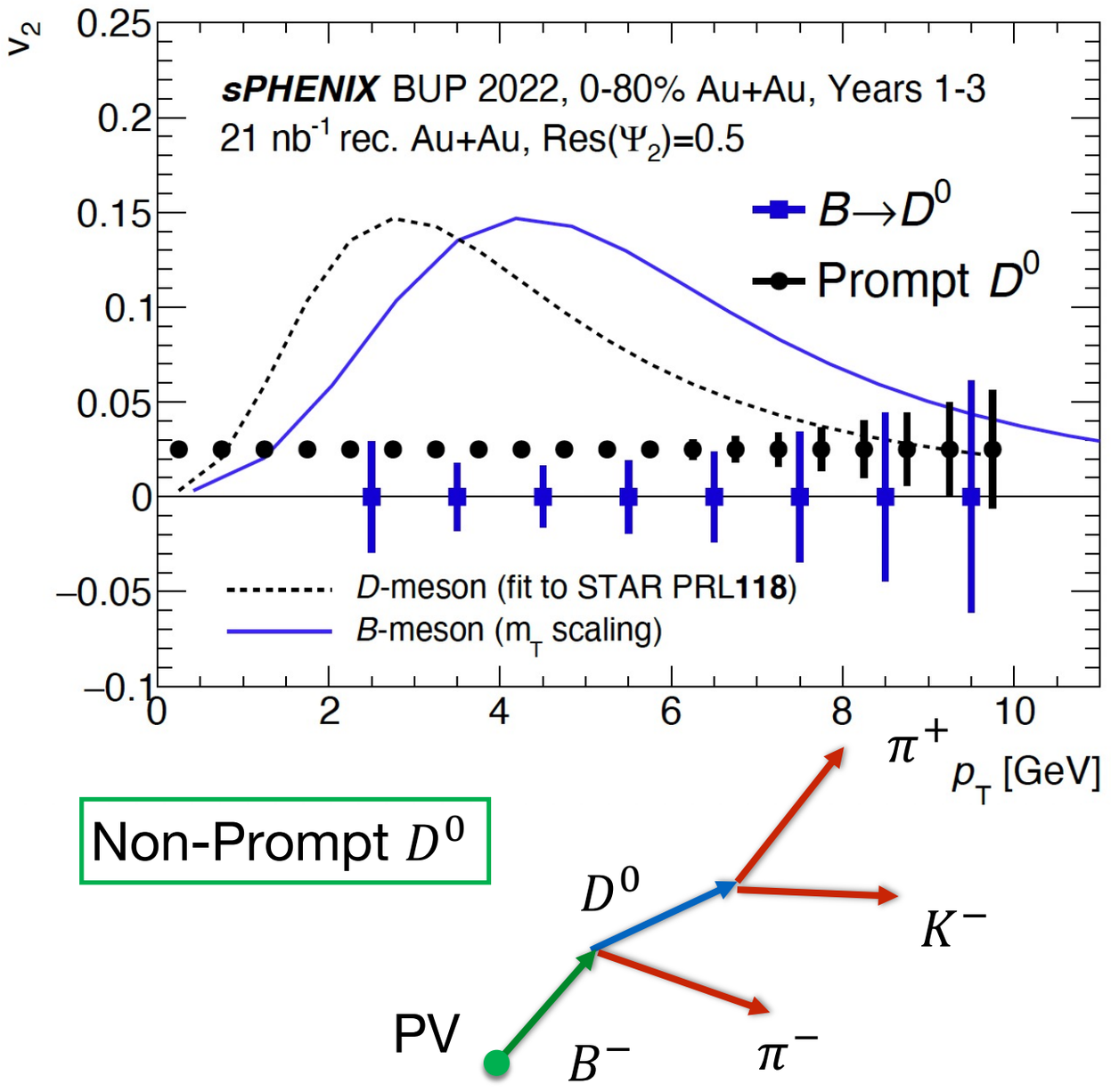

Non-Prompt $D^0$




- Simulation with HIJING Au + Au events with pile up with sPHENIX detector in GEANT 4
  - Apply KFParticle package to fully reconstruct $D^0 \rightarrow K^-\pi^+$ without hadronic PID
  - Clear $D^0$ observed with 25 minutes from simulation above assuming a 15 kHz DAQ rate
- Excellent statistics for heavy flavor physics measurement

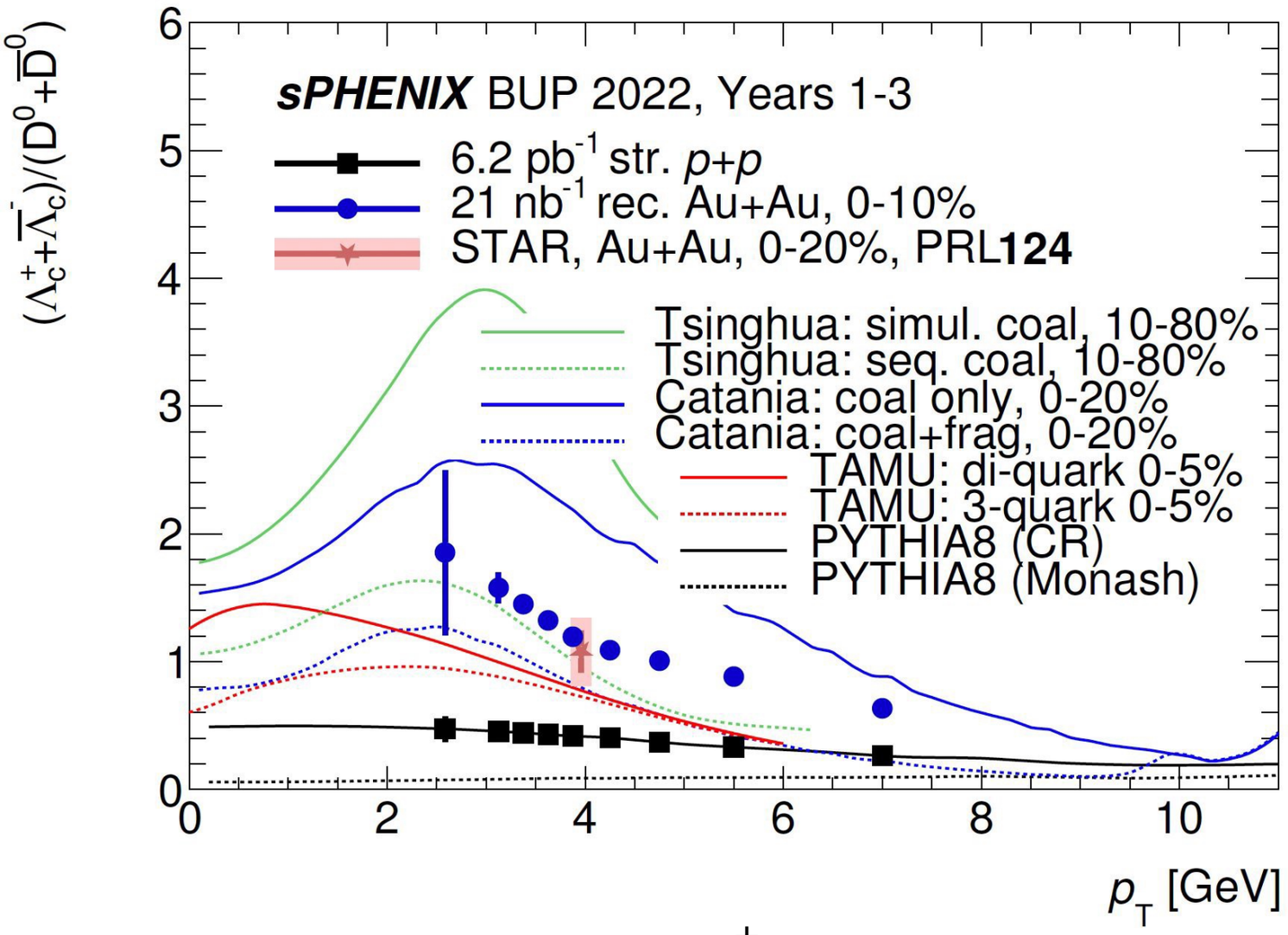
# $D^0$ $R_{AA}$ and $v_2$ Simulation Performance



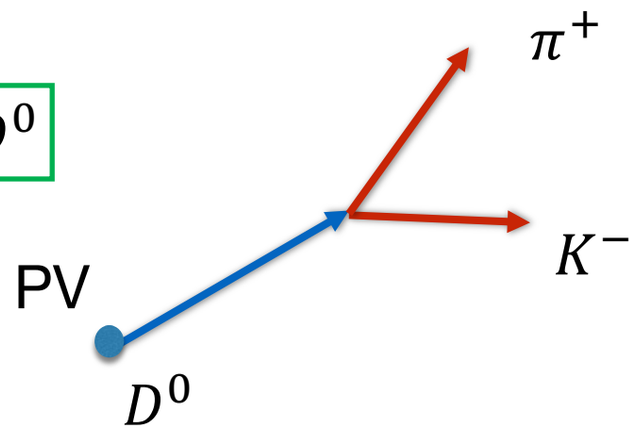

- High precision D-meson measurements thanks to large minimal bias p + p and Au + Au datasets and excellent tracking
- Data-driven method: separation of prompt and non-prompt $D^0$ via $B \rightarrow D^0$ decay with DCA
  - Constrain beauty quark diffusion coefficient in QGP medium
  - Flavor dependence of energy loss
  - Investigate charm quarks thermalization

# $\Lambda_c^+/D^0$ Simulation: Charm Hadronization

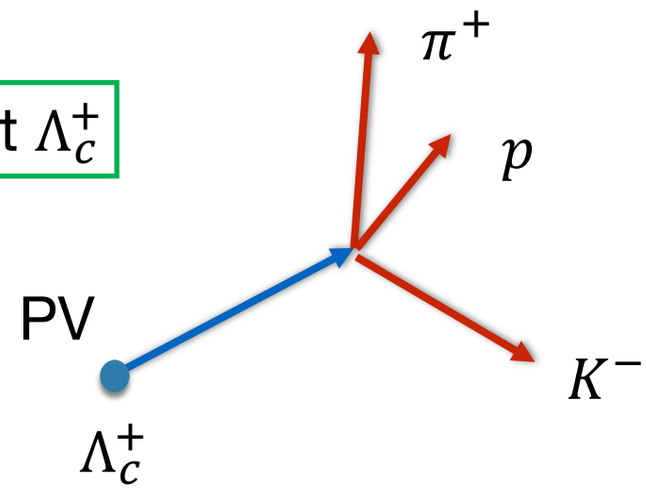



## Hadronization Through Quark Coalescence

Prompt $D^0$

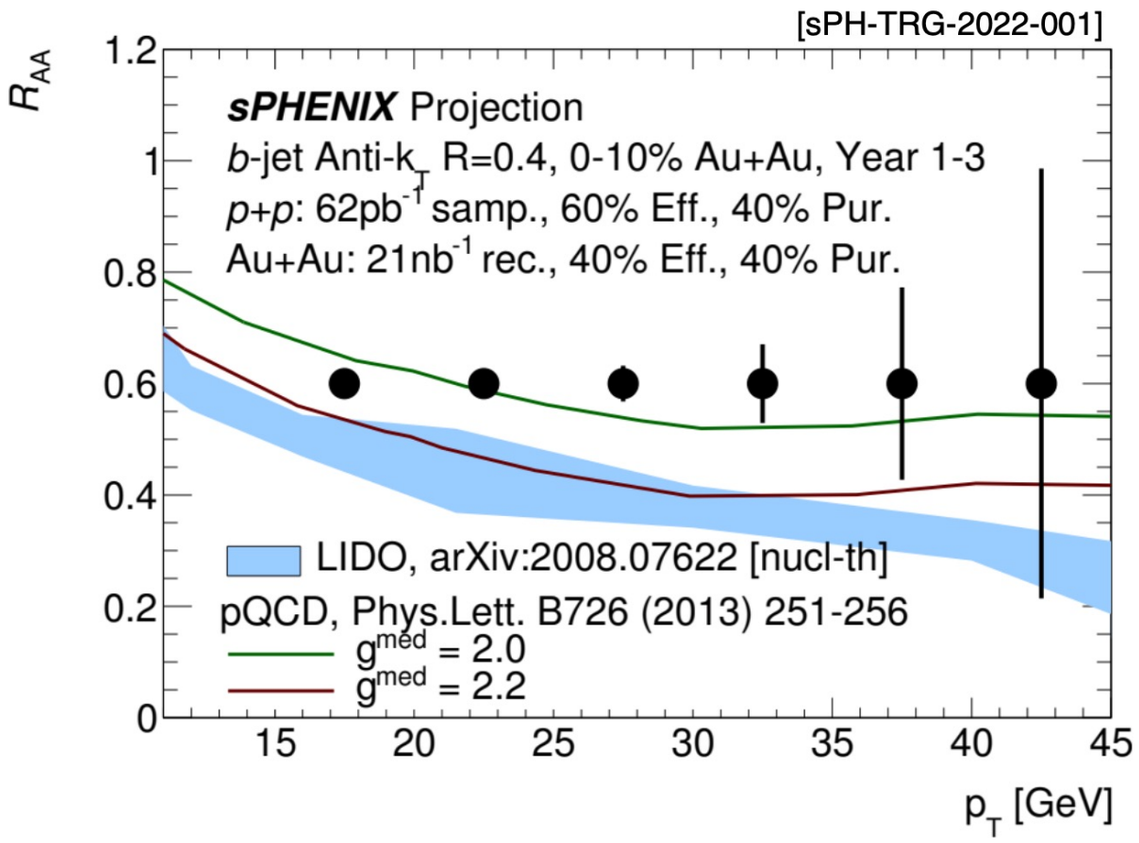


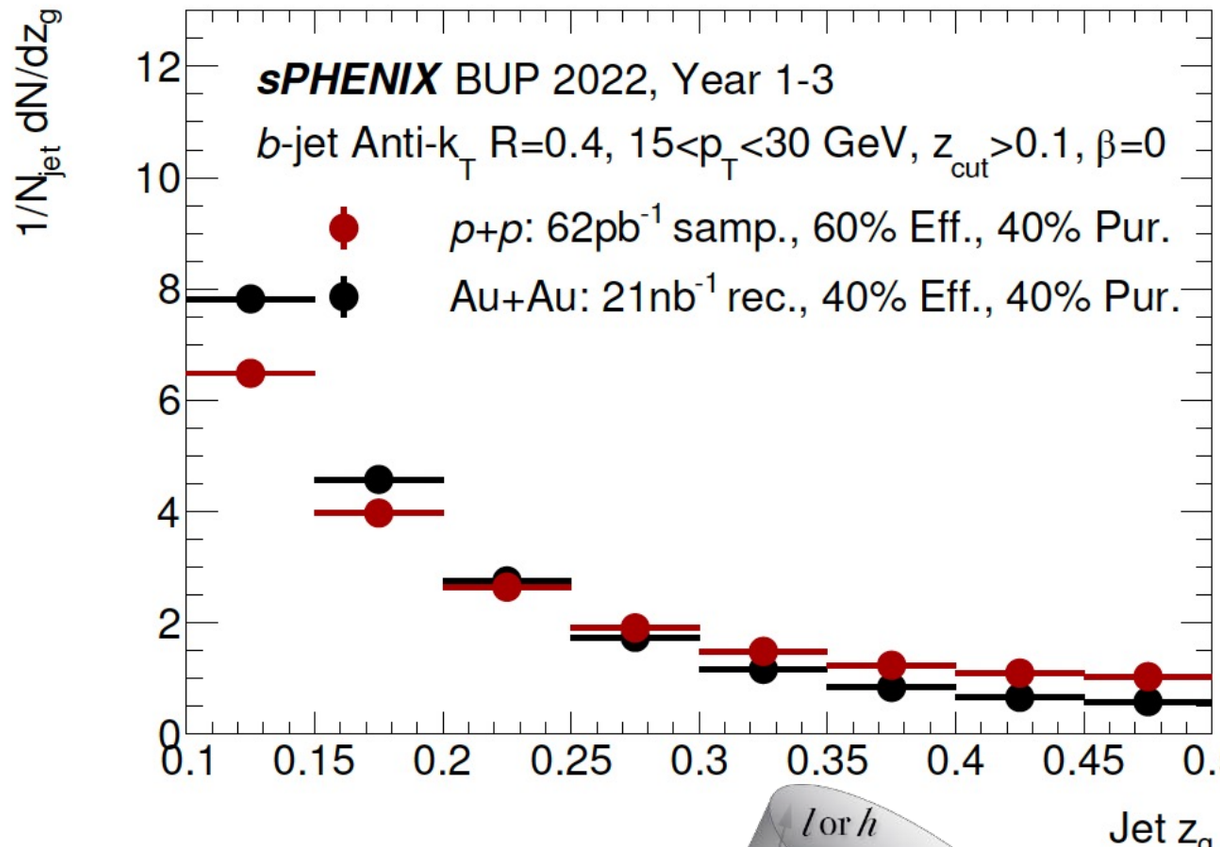

Prompt $\Lambda_c^+$



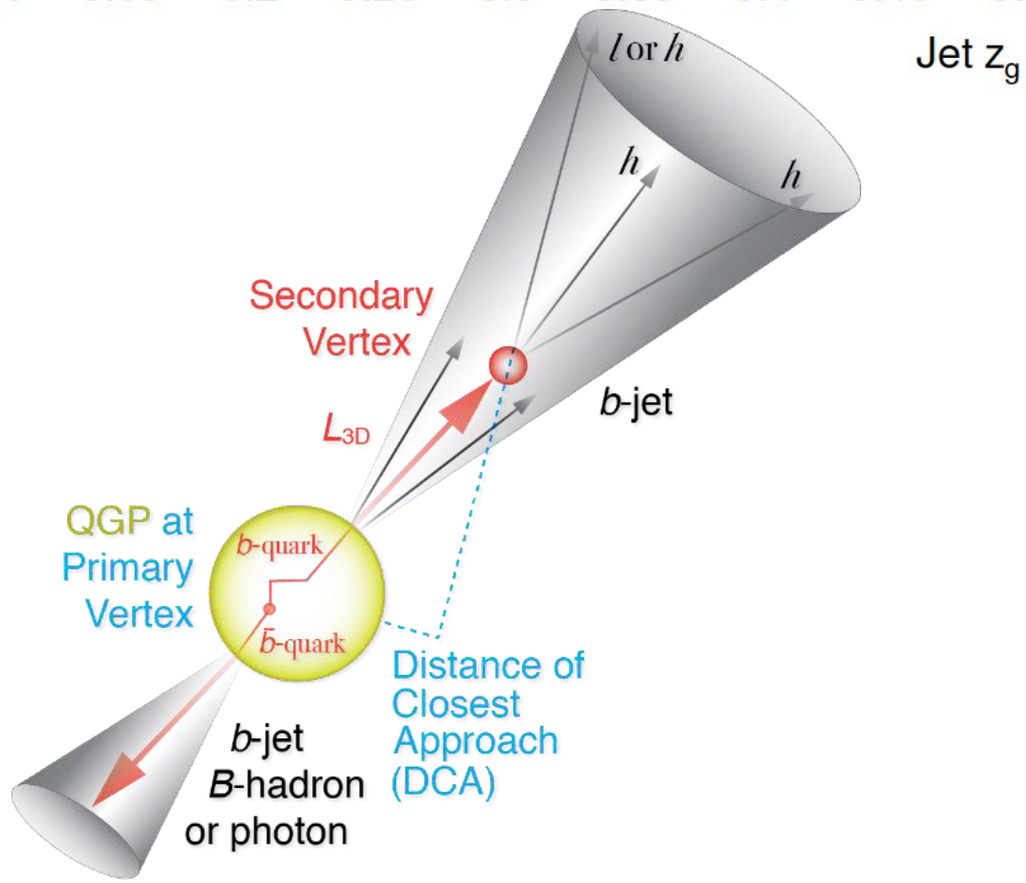

- Study charm hadronization from vacuum to QGP via the measurements of $\Lambda_c^+/D^0$ as a function of $p_T$ and event multiplicity from p + p to Au + Au

# b-jet $R_{AA}$ and Substructure Performance

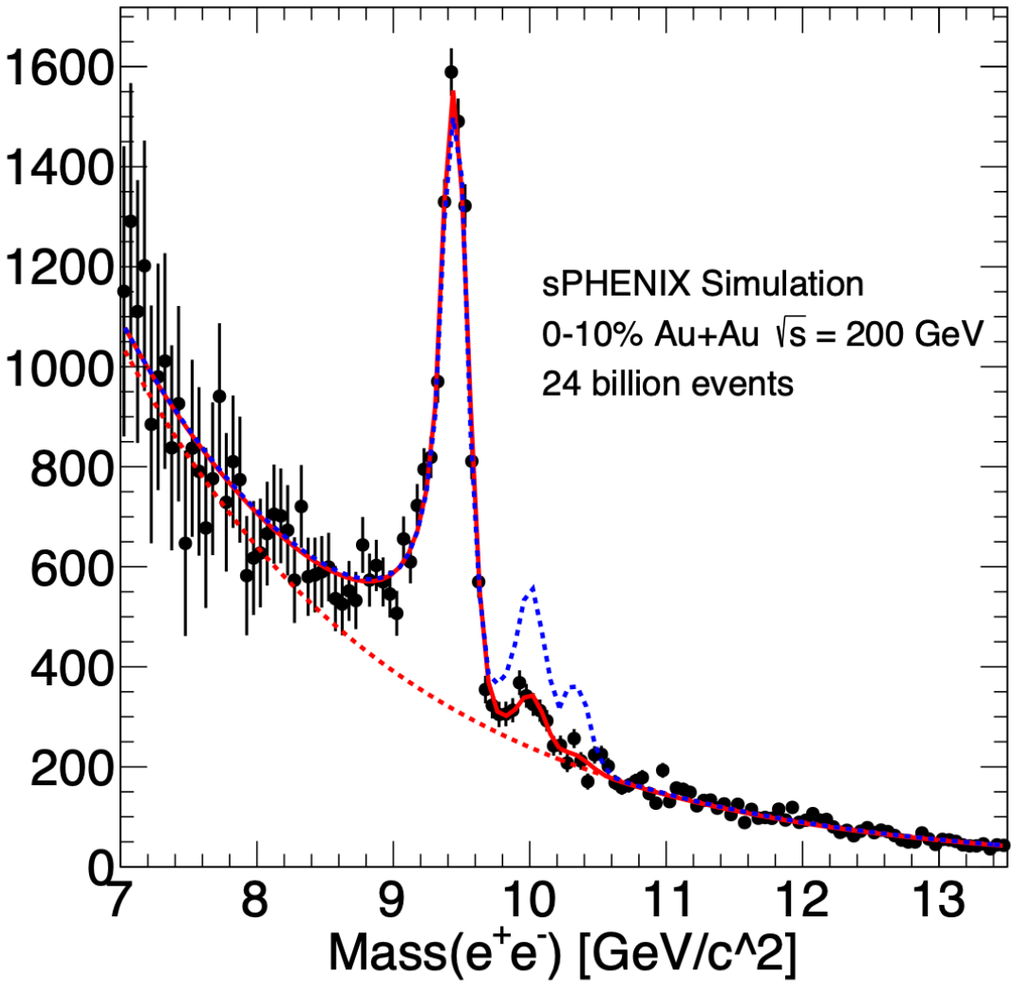


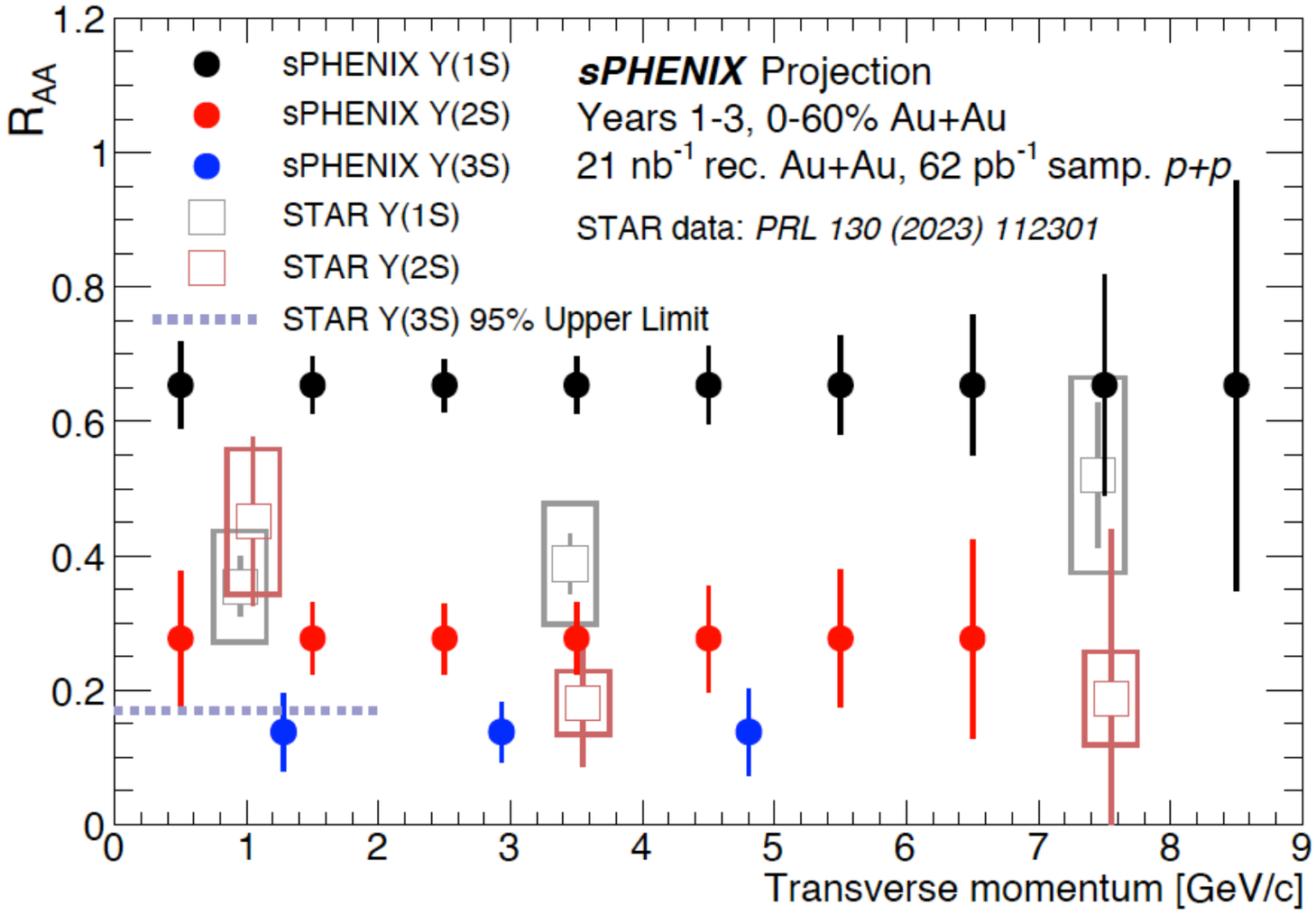




- First b-jet measurement at RHIC
- Excellent b-jet reconstruction and tagging capability thanks to the calorimeters and MVTX
- Differential subjet splitting function measurements with good precision at low $p_T$
- Test pQCD model calculations in $p + p$ collisions
- Quantify the medium modification of b-jets in the unique sPHENIX kinematic region
- Complementary to LHC jet substructure measurements

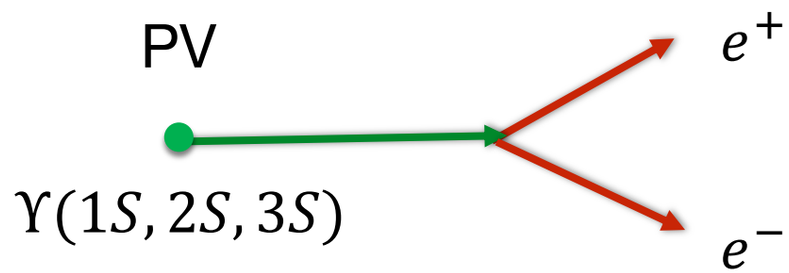


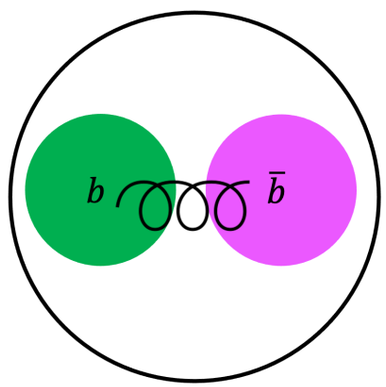
# Upsilon Spectroscopy

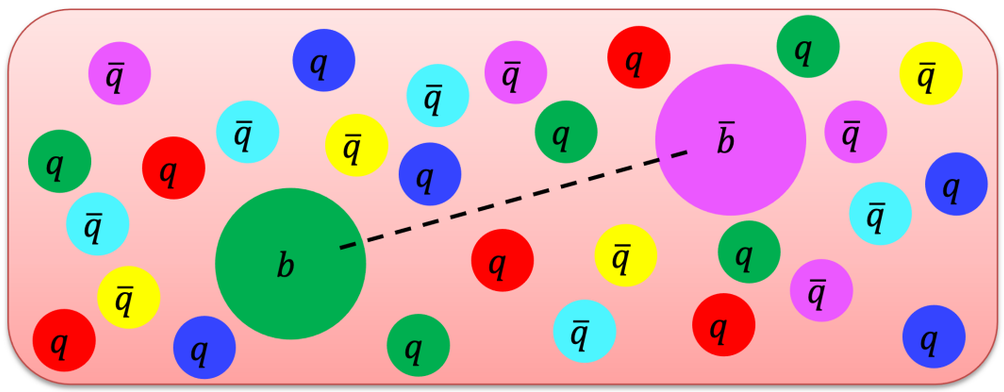



- Measuring QGP temperature via color screening effect
- Excellent mass resolution in the dielectronic decay channel
- $R_{AA}$ measurement with high precision
- Clearly separate $\Upsilon(3S)$ at RHIC, complementary with CMS $\Upsilon(3S)$ measurement at the LHC



# Summary

## The sPHENIX Experiment at RHIC

- Physics program: jets, **open heavy flavor**, **quarkonia**, cold QCD
- Demonstration of detector functionality and readiness for offline data analysis
  - Verify the functionality of the subdetectors through correlation studies
  - Event displays of the tracking systems
  - Beam collisions data taking complete. Currently taking cosmic data for calibration

## Projected Physics Measurements

- High statistics charm and bottom hadron measurements
  - Heavy quark diffusion
  - Heavy quark energy loss
  - Heavy quark hadronization
- First inclusive b-jet measurements at RHIC
  - High precision at low $p_T$
  - Complementary to LHC experiments
- Upsilon spectroscopy
  - Precision Measurement of QGP temperature at RHIC
  - Clearly separate $\Upsilon(3S)$ state

**Exciting physics results from sPHENIX are forthcoming!**

# Thank You



- This work is supported by the United States Department of Energy Office of Science and Los Alamos National Laboratory Laboratory Directed Research & Development (LDRD)


- **Thank you very much for your attention!**

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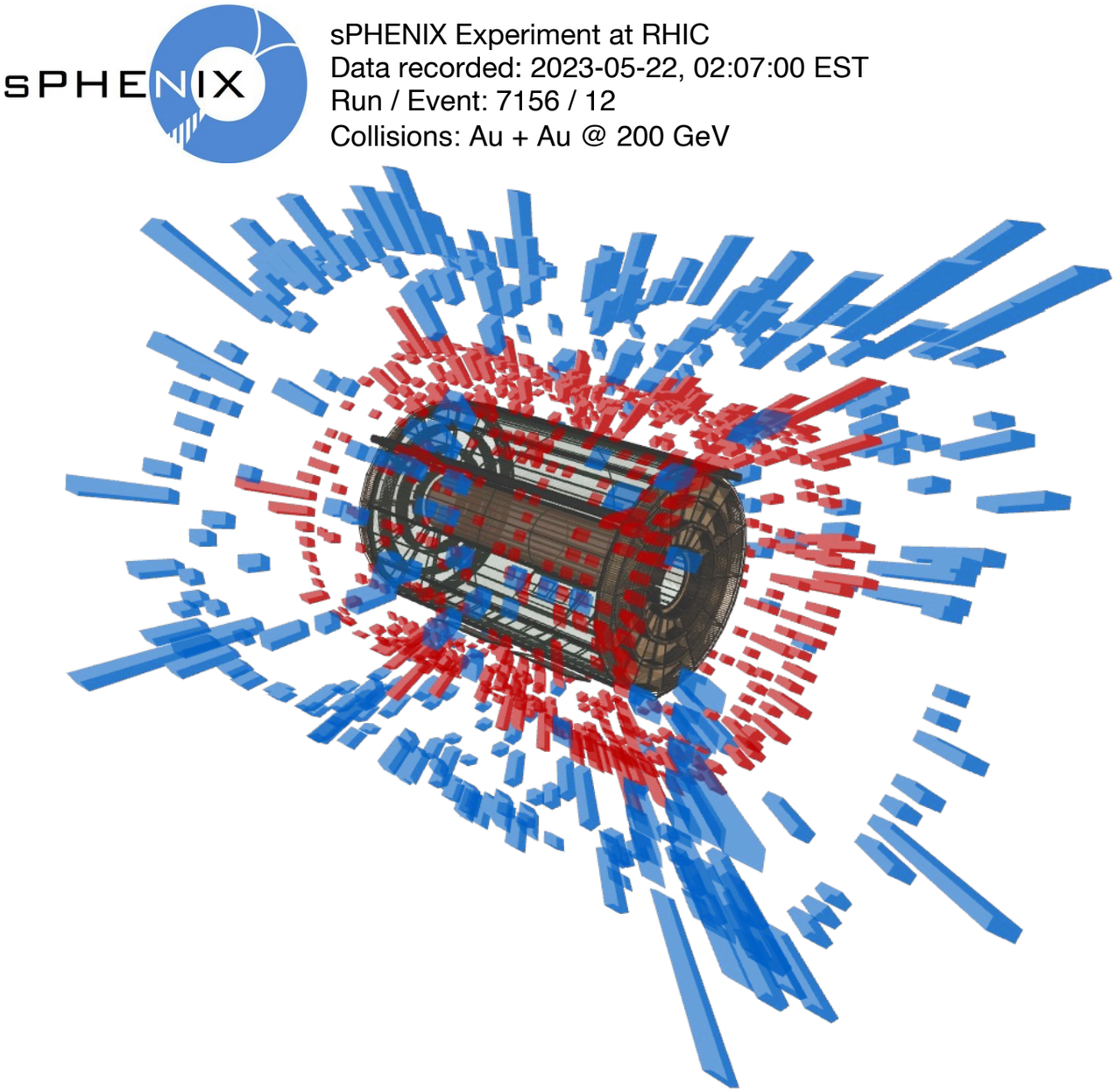
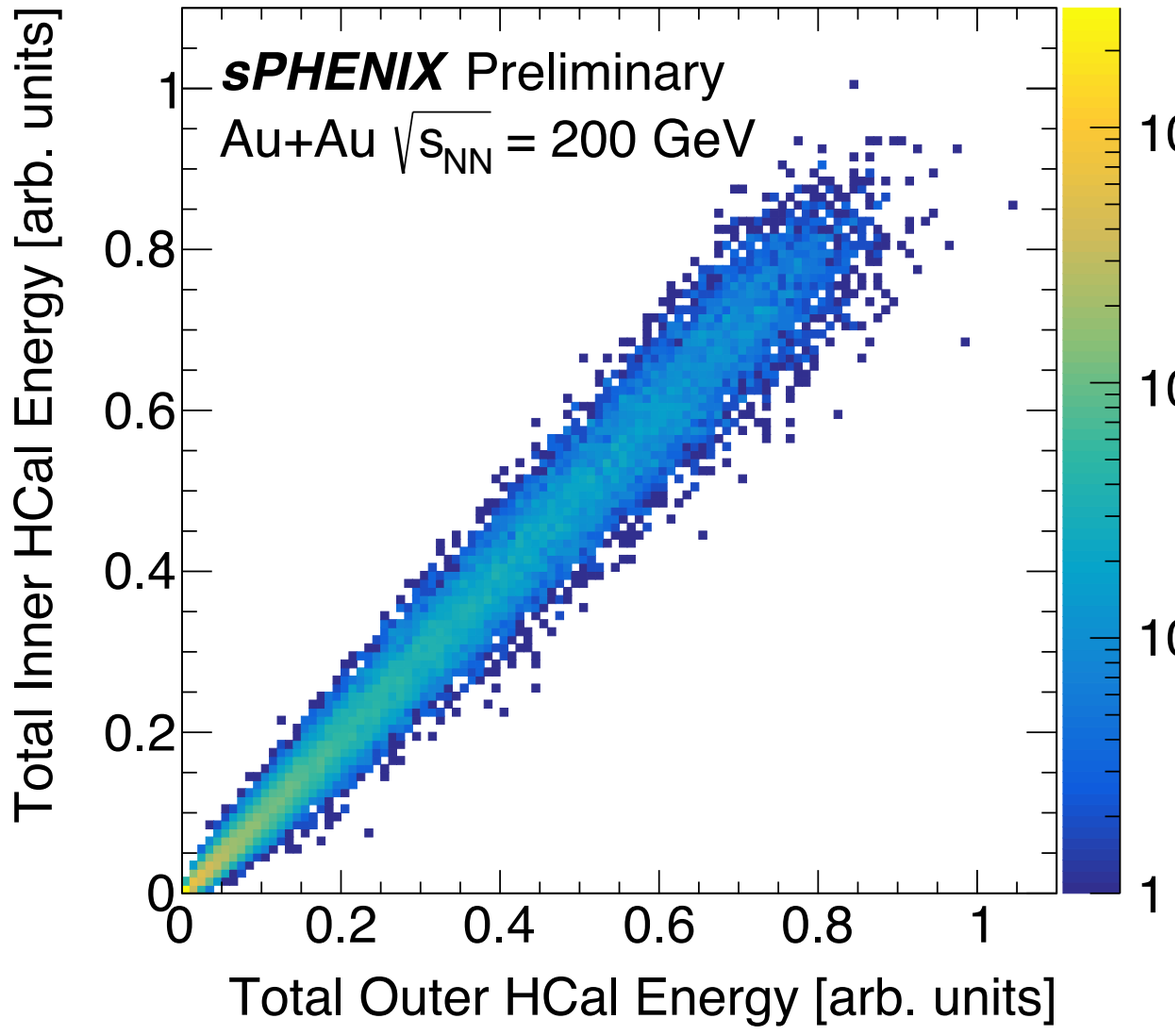
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

# Back Up

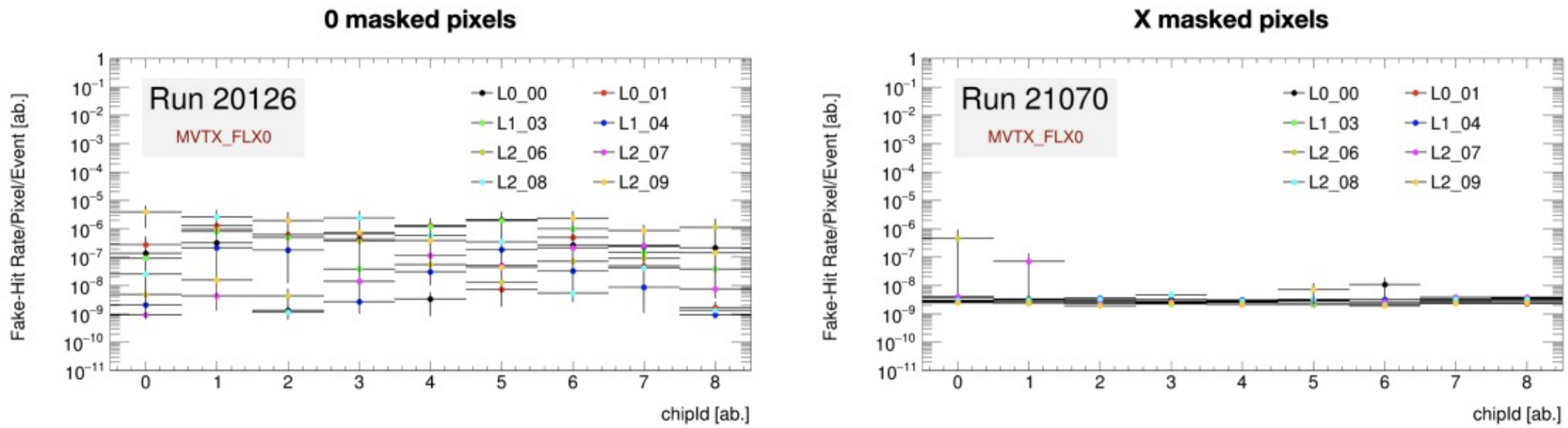
# The Calorimeters System



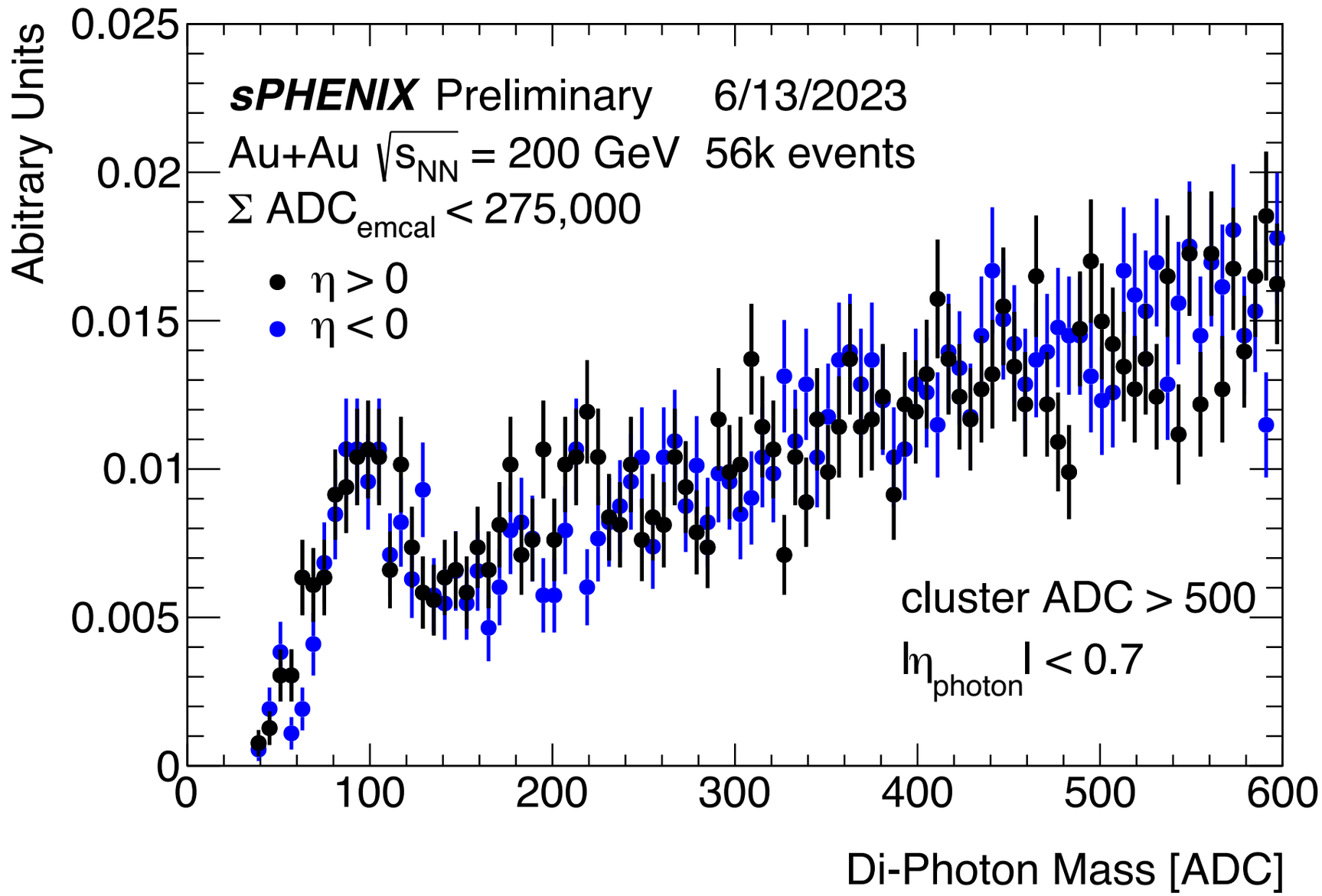

- A Au + Au collision event recorded and displayed by the calorimeter system: EMCAL + HCAL
- Strong correlation between inner and outer HCAL, again indication of the HCAL system is working
- Collect good Au + Au collision data for jet physics studies

# MVTX Noise Level




- Significant noise level suppression down to $10^{-8}$ level after noisy pixel masking within a heartbeat frame for each stave
- Low noise level for MVTX operation and data taking

# $\pi^0$ Reconstruction with EMCAL




- Clear $\pi^0$ to diphoton in both forward and backward rapidities reconstructed with EMCAL data readout in Au + Au collisions
- EMCAL functions with good performance, pending further calibration for physics measurements

# sPHENIX Beam Use Proposal

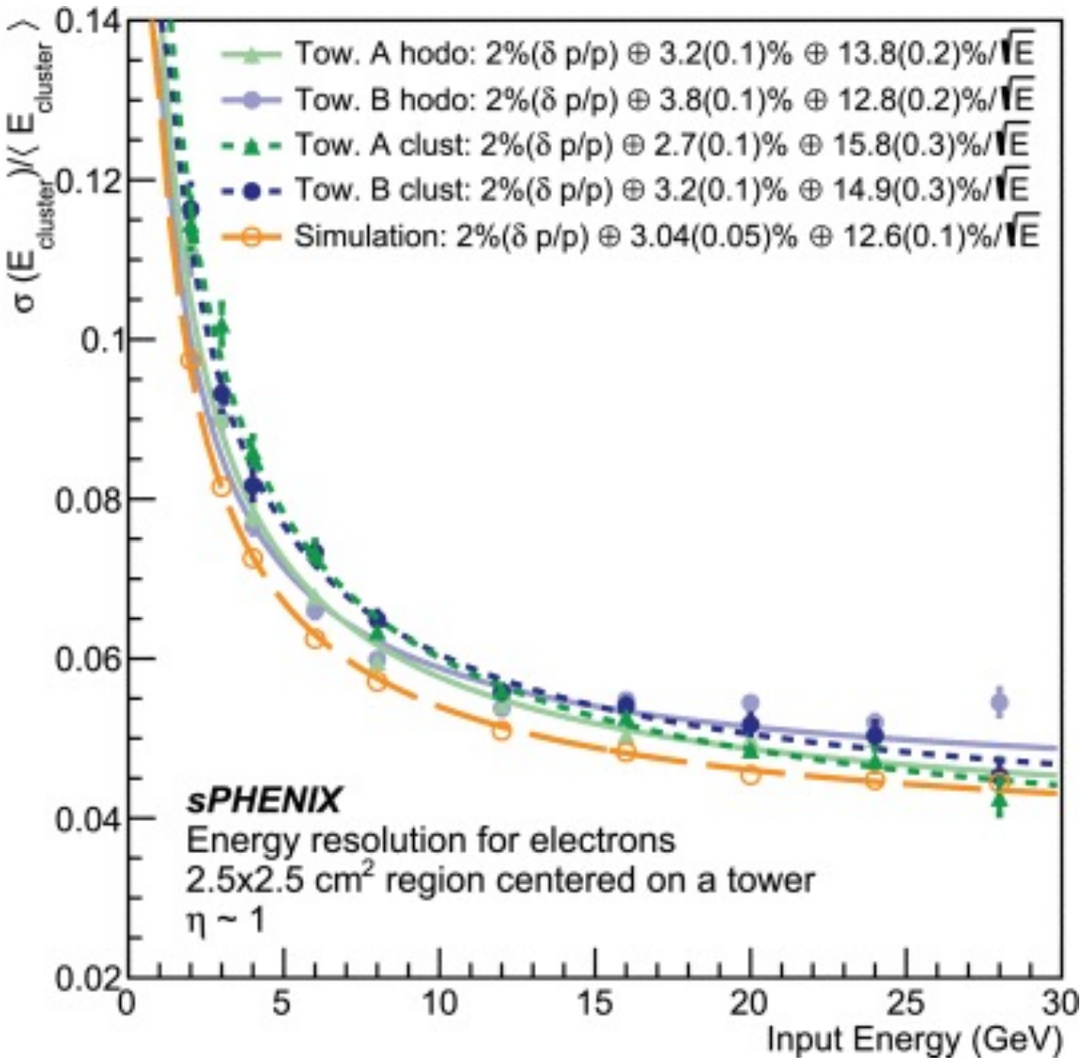
| Year | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $\lvert z\rvert$ <10 cm | Samp. Lum. $\lvert z\rvert$ <10 cm |
|---|---|---|---|---|---|---|
| 2023 | Au+Au | 200 | 24 (28) | 9 (13) | 3.7 (5.7) $\text{nb}^{-1}$ | 4.5 (6.9) $\text{nb}^{-1}$ |
| 2024 | $p^{\uparrow}p^{\uparrow}$ | 200 | 24 (28) | 12 (16) | 0.3 (0.4) $\text{pb}^{-1}$ [5 kHz]<br>4.5 (6.2) $\text{pb}^{-1}$ [10%-*str*] | 45 (62) $\text{pb}^{-1}$ |
| 2024 | $p^{\uparrow}$+Au | 200 | – | 5 | 0.003 $\text{pb}^{-1}$ [5 kHz]<br>0.01 $\text{pb}^{-1}$ [10%-*str*] | 0.11 $\text{pb}^{-1}$ |
| 2025 | Au+Au | 200 | 24 (28) | 20.5 (24.5) | 13 (15) $\text{nb}^{-1}$ | 21 (25) $\text{nb}^{-1}$ |

sPHENIX Beam Use Proposal endorsed by the BNL NPP (Nuclear and Particle Physics) PAC (Physics Advisory Committee)

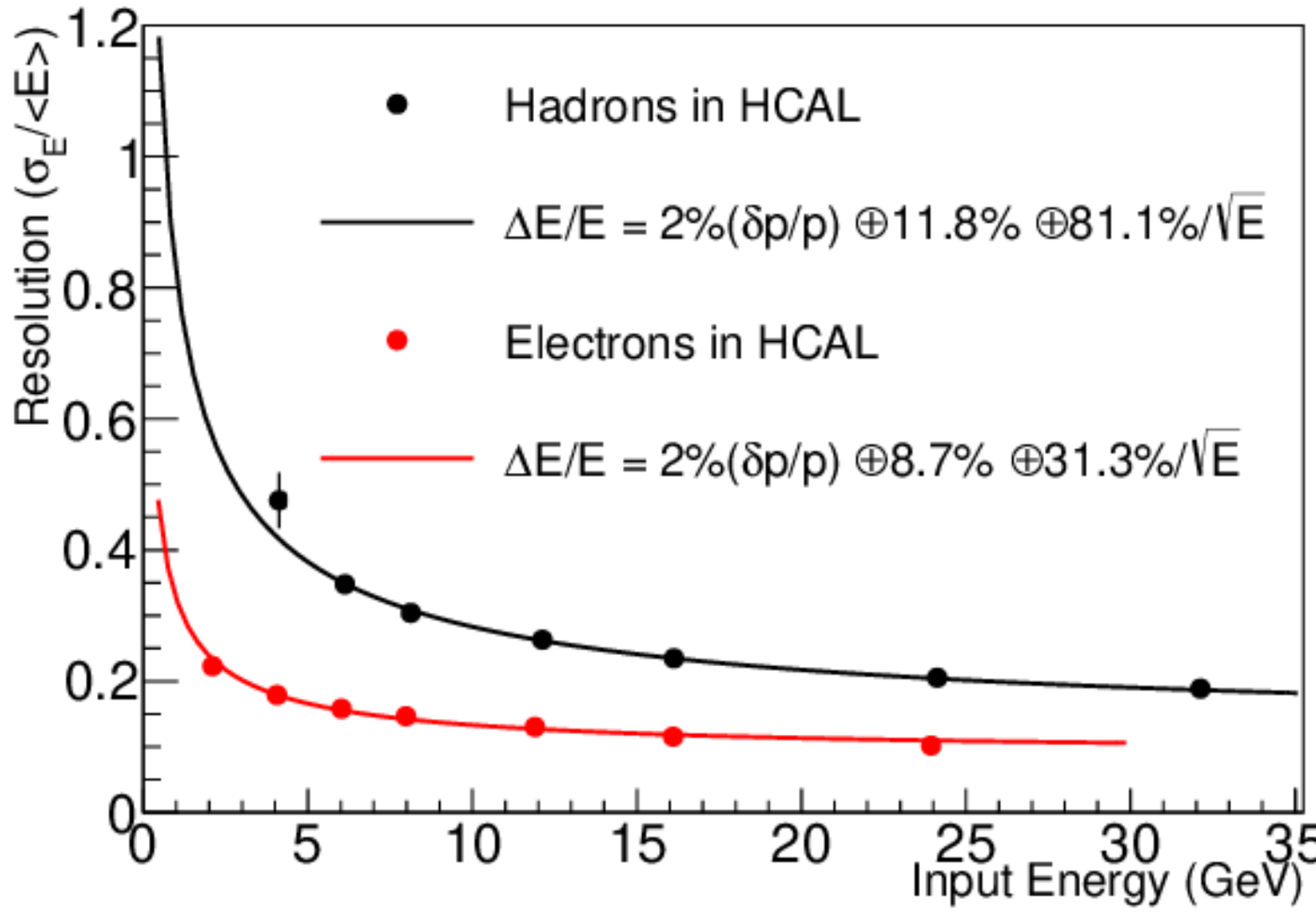
- Extensive **3-year** data taking starting in around 6 months
  - **Year-1**: commissioning and first physics in Au+Au
  - **Year-2**: p+p and p+Au runs for heavy-ion reference and cold QCD physics
  - **Year-3**: very large Au+Au dataset (141B events in total)
- We Just finish taking year-1 data early and moving on to year 2

# Calorimeter System Performance

## EMCAL



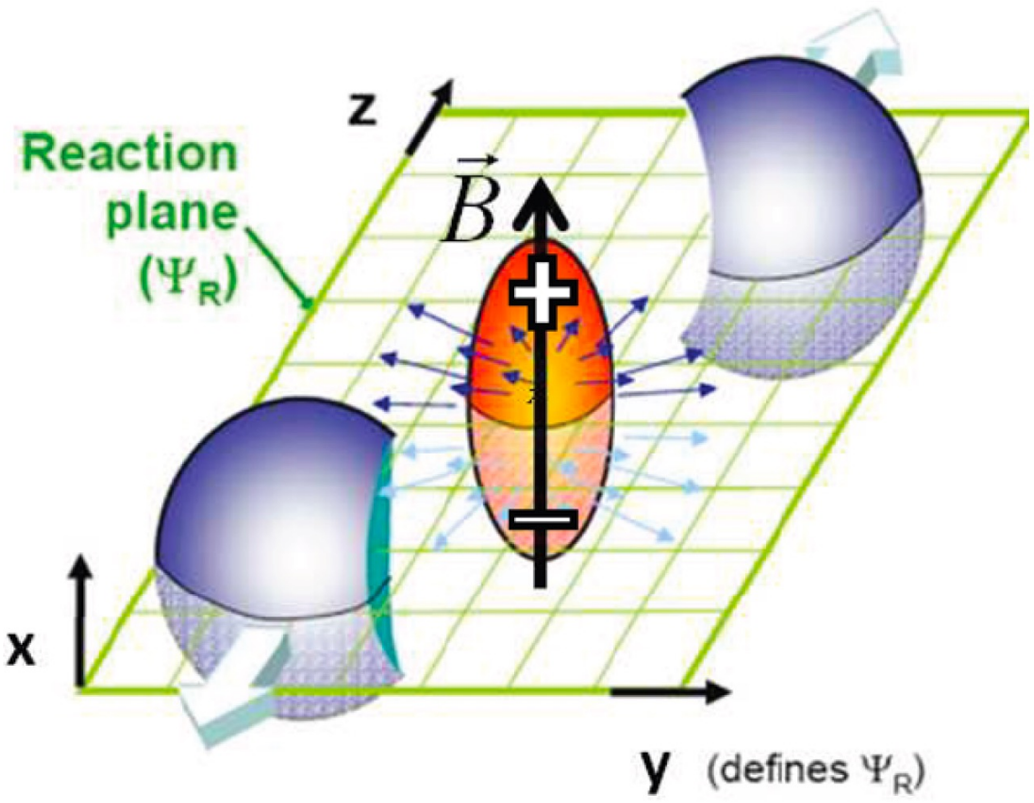

## HCAL

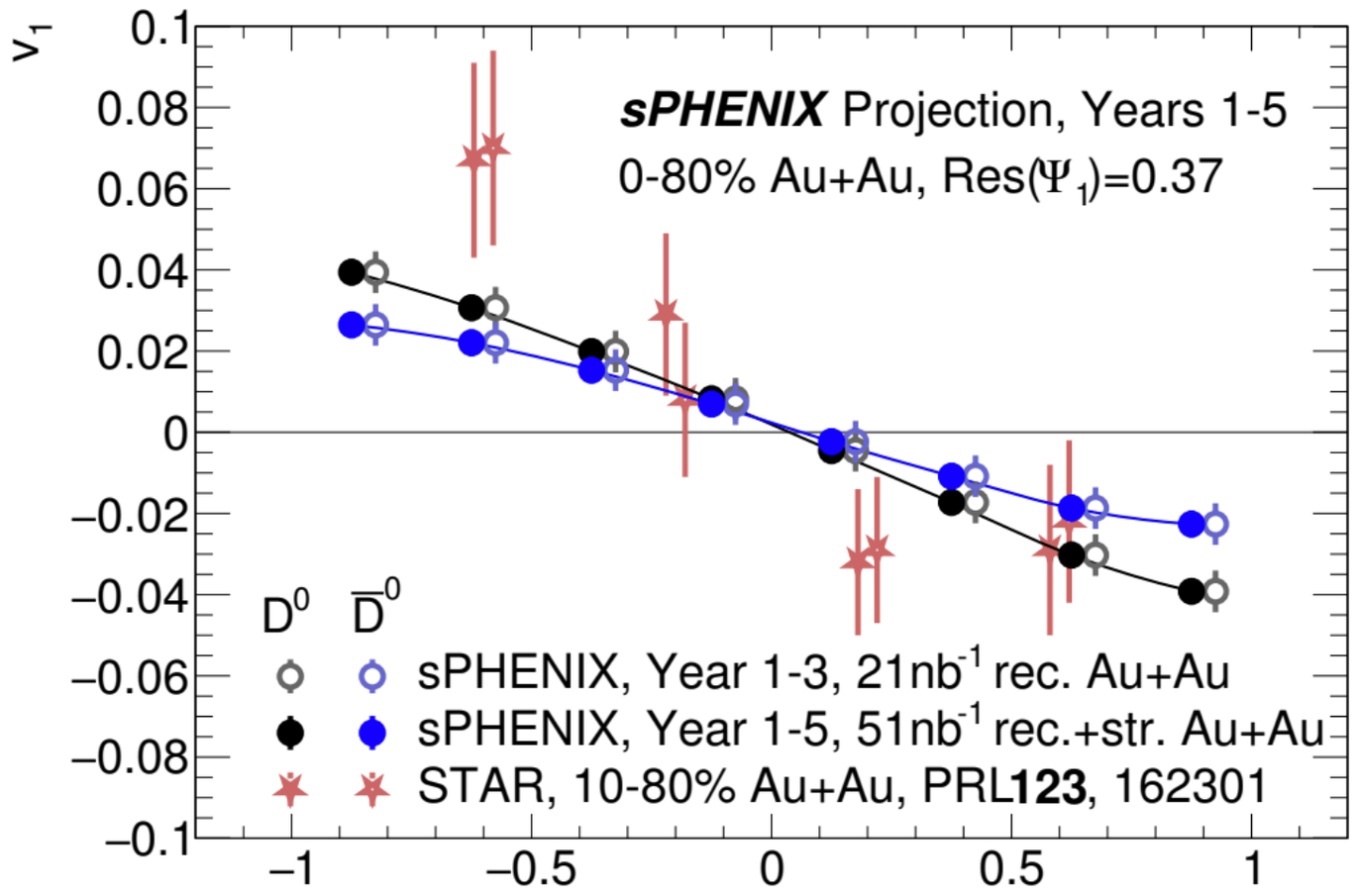



(b)

- High $p_T$ trigger implemented to the calorimeter system dedicated for jet physics studies
- Advanced 3D topological jet clustering algorithm
- Capable of performing precision calorimetric jet measurements
- First mid-rapidity calorimetric jet measurements at RHIC

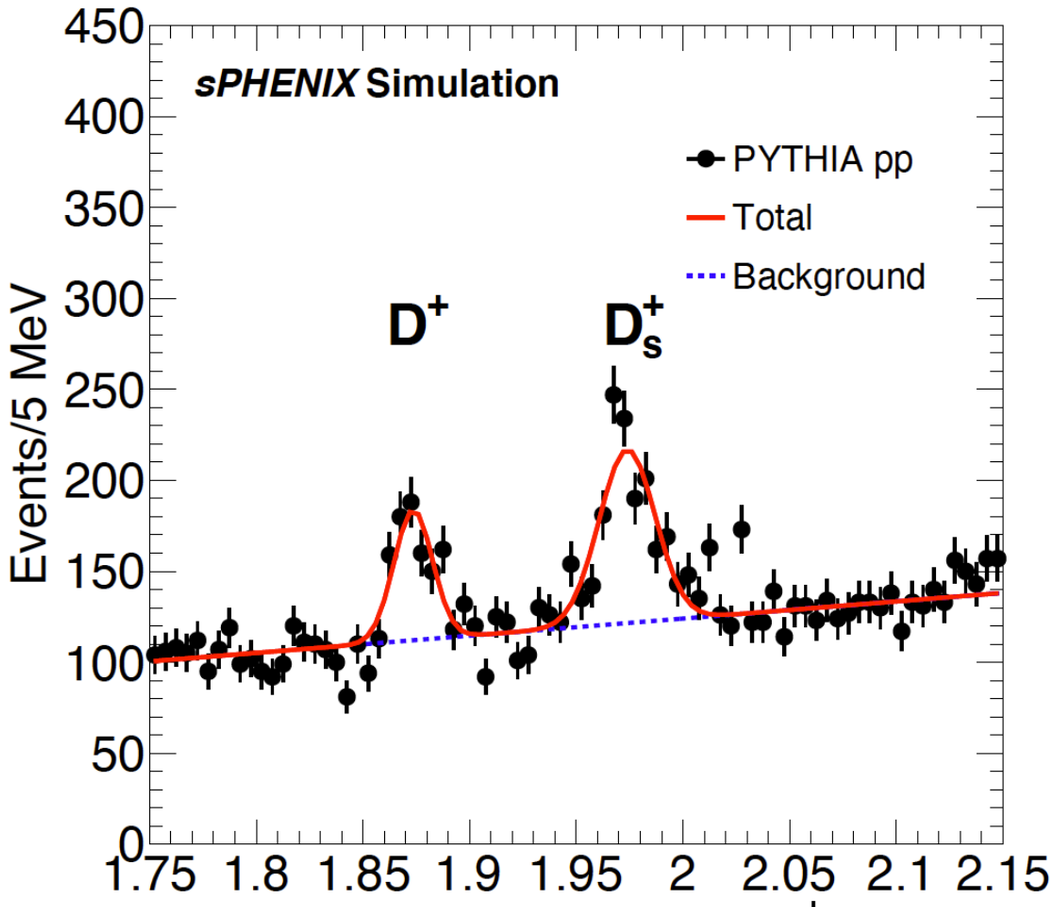
# D-meson Directed Flow $v_1$

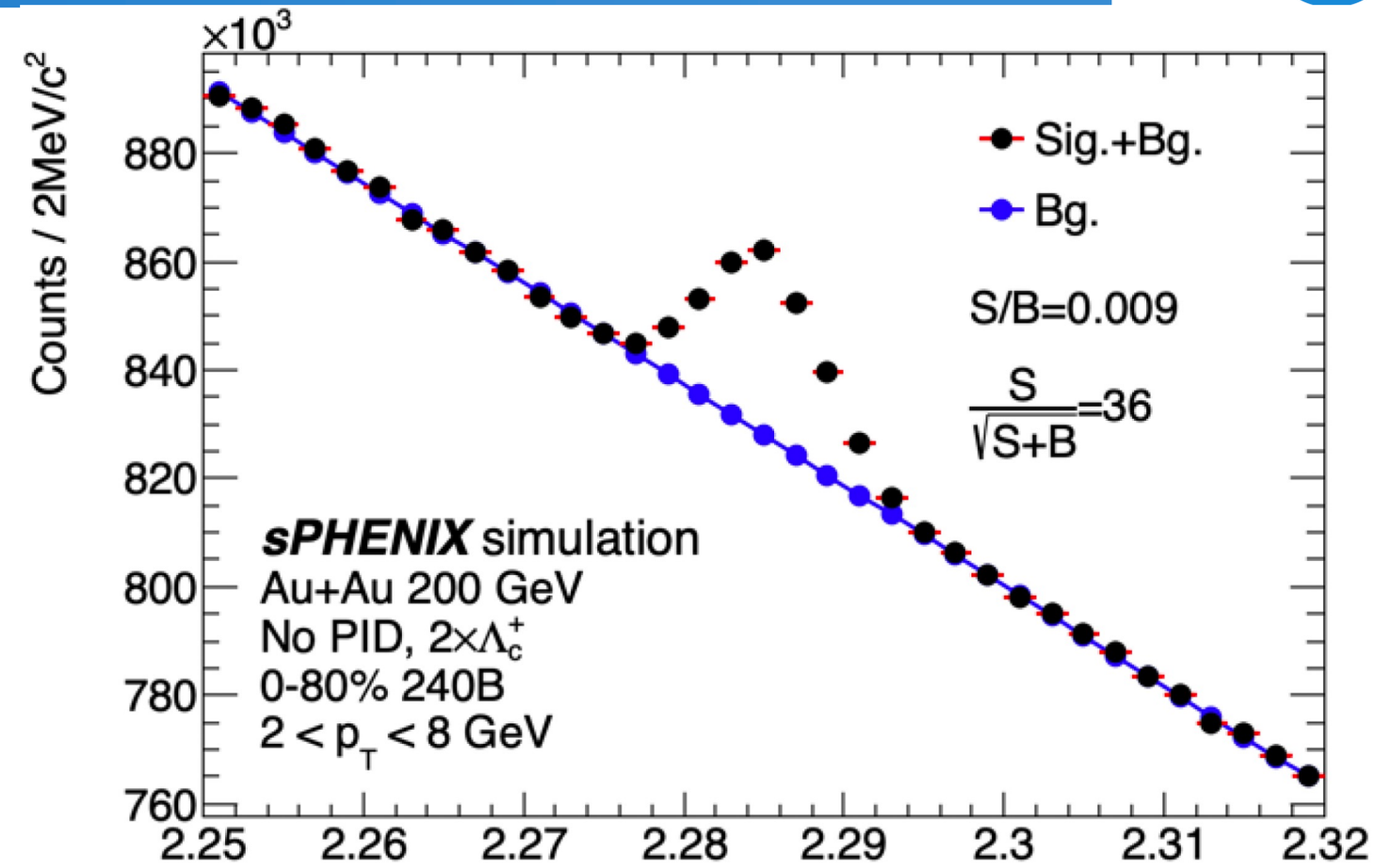


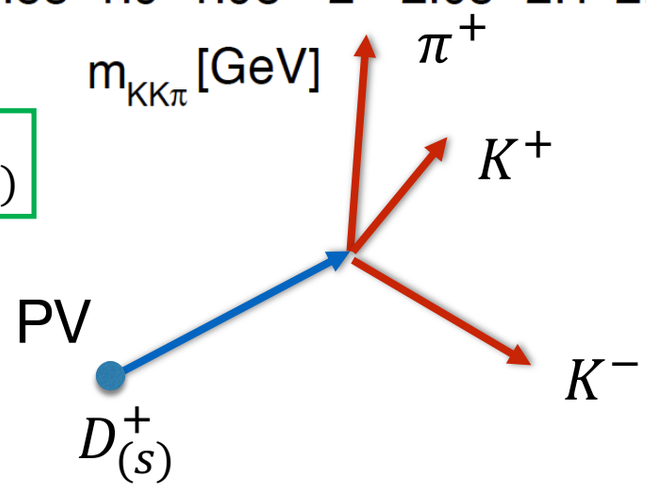

- Directed flow $v_1$: first order Fourier coefficient of particle emission in the azimuthal direction with respect to the reaction plane in heavy-ion collisions
- Relatively large mass of charm quark
  - Predominantly produced in early hard scattering processes
  - Long thermal relaxation time
  - Induce larger $v_1$ due to the Lorentz force
- D-meson $v_1$ sensitive the initial tilt and pressure asymmetry due to non-equilibrium effects in the initial stage of heavy ion collisions
  - Novel probe of the spacetime evolution of the initial magnetic field in heavy-ion collisions

# Prompt $D^+$, $D_s^+$, and $\Lambda_c^+$ Reconstruction

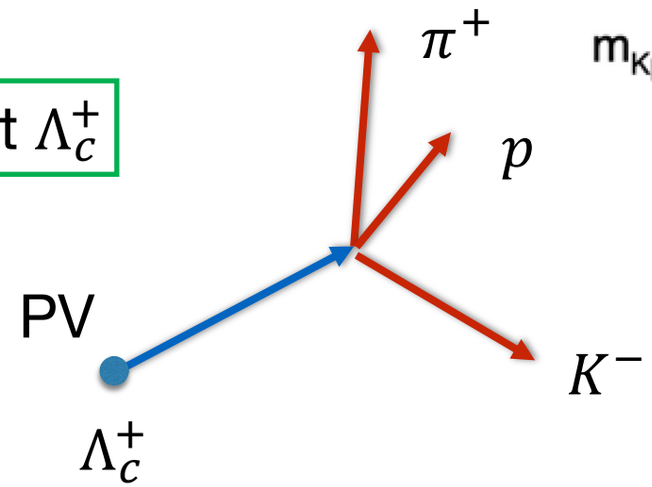



Prompt $D_{(s)}^+$

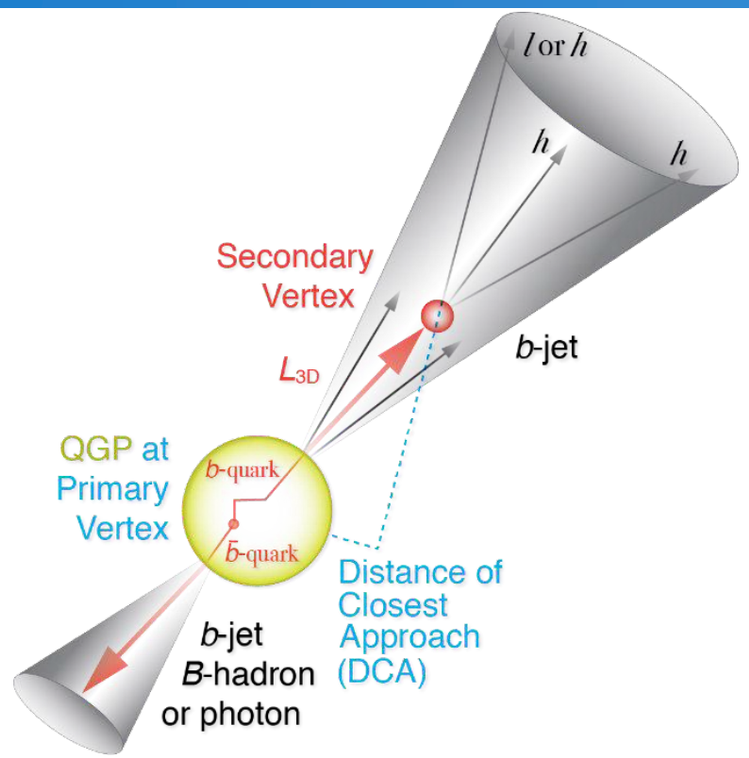


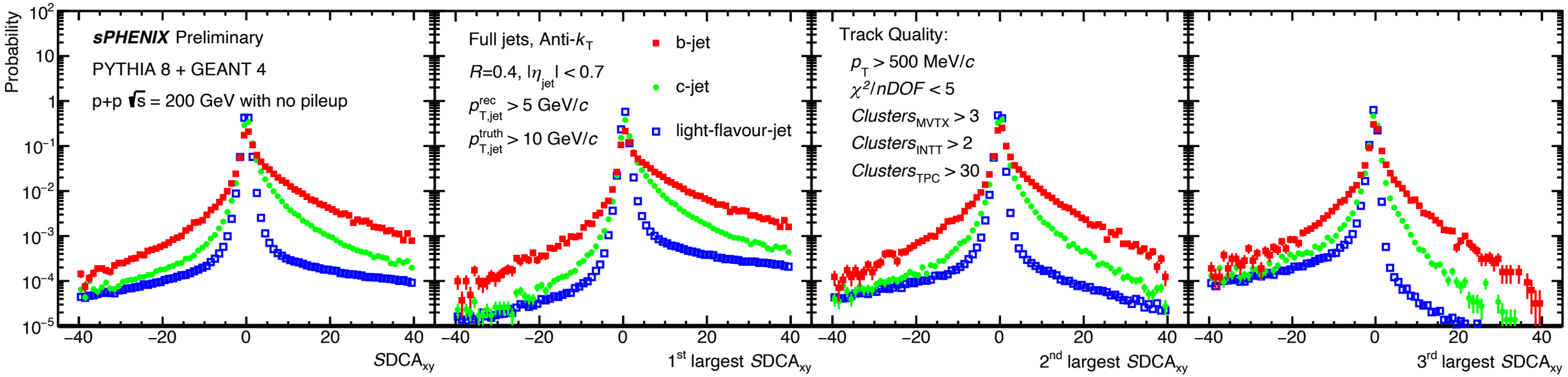

Prompt $\Lambda_c^+$




- More complex 3-prong decays
- High precision measurement thanks to streaming readout data taking and tracking
- Study charm hadronization from vacuum to QGP via the measurements of $D_s^+/D^+$ and $\Lambda_c^+/D^0$ as a function of event multiplicity

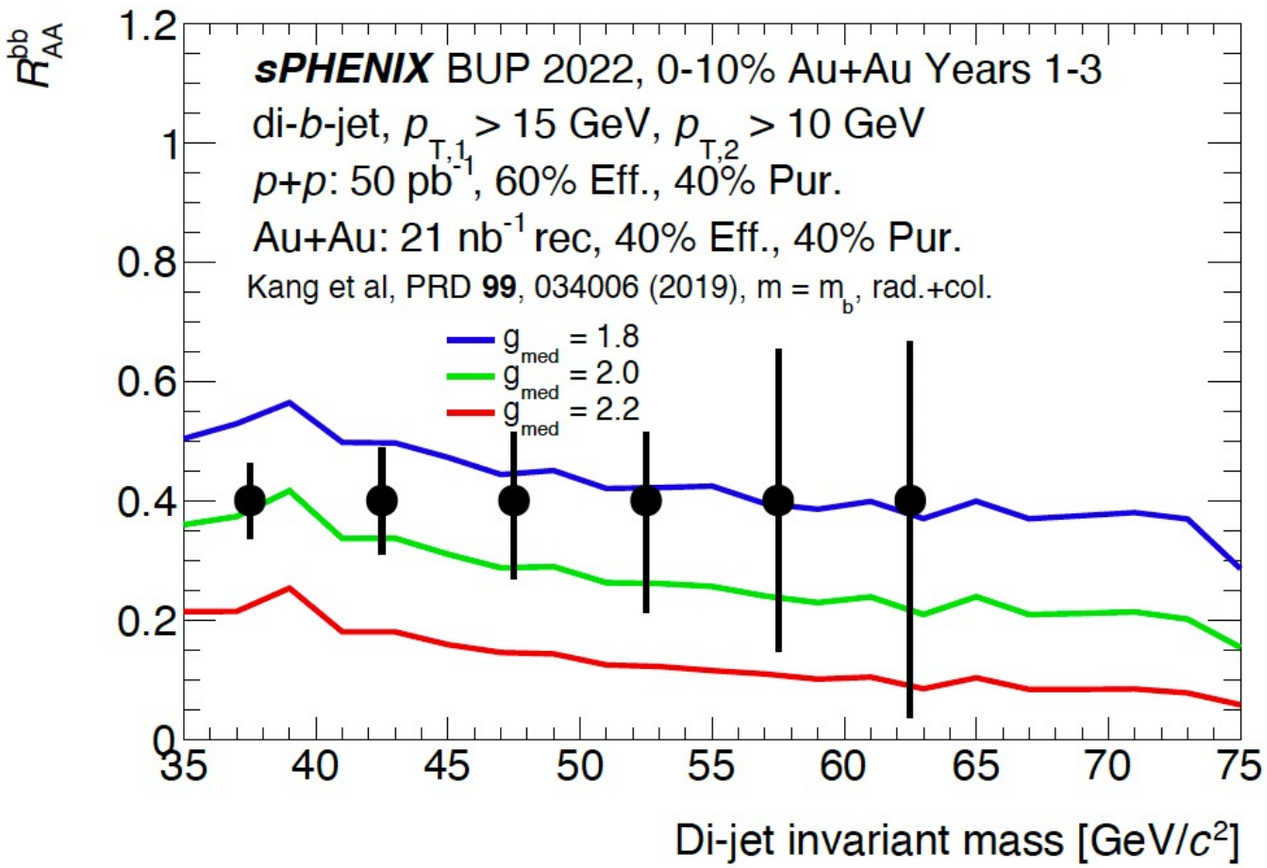
# b-jet Performance

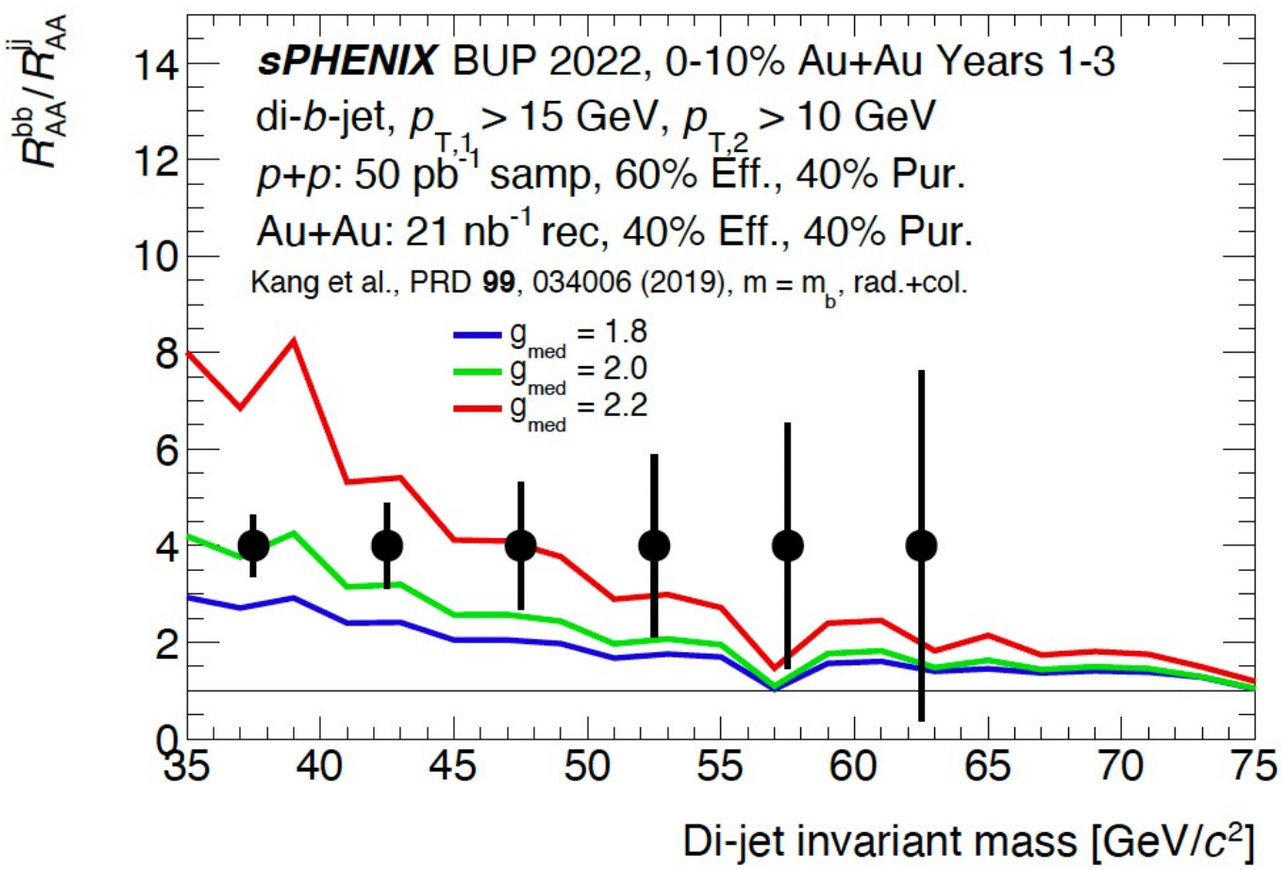



- Latest sPHENIX software for simulation with anti-$k_T$ algorithm for jet reconstruction
- Selection of c-jet and b-jet from inclusive jets with displaced vertices through DCA
- Excellent performance for b-jet physics measurements
- Ready to analyze data with fully built event with particle flow to study b-jet physics

# Di-b-jet Invariant Mass

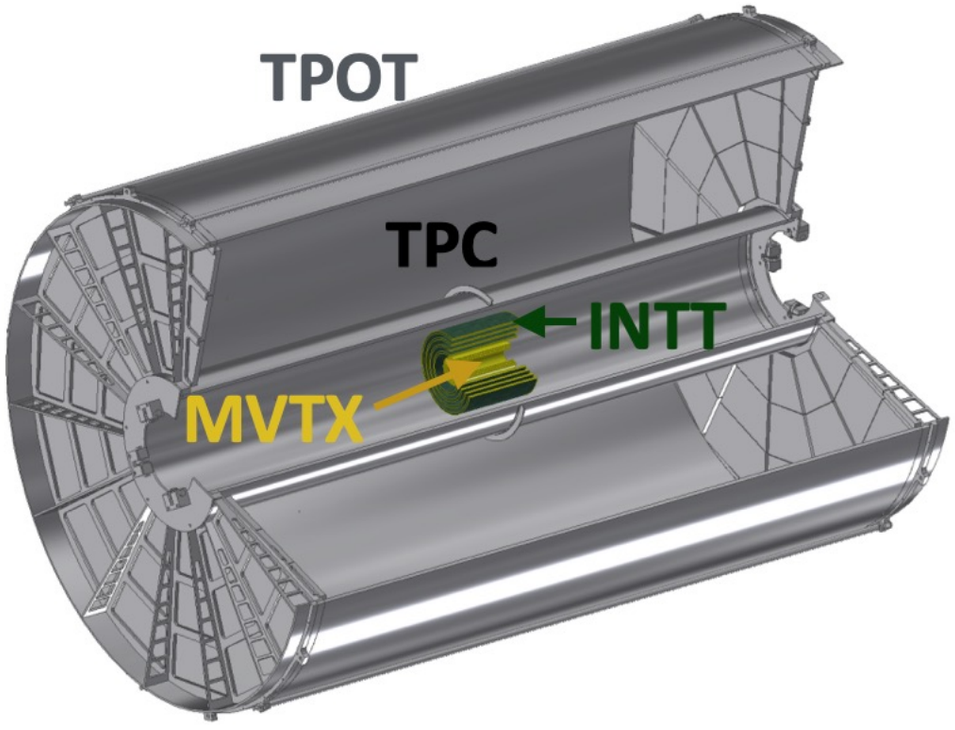


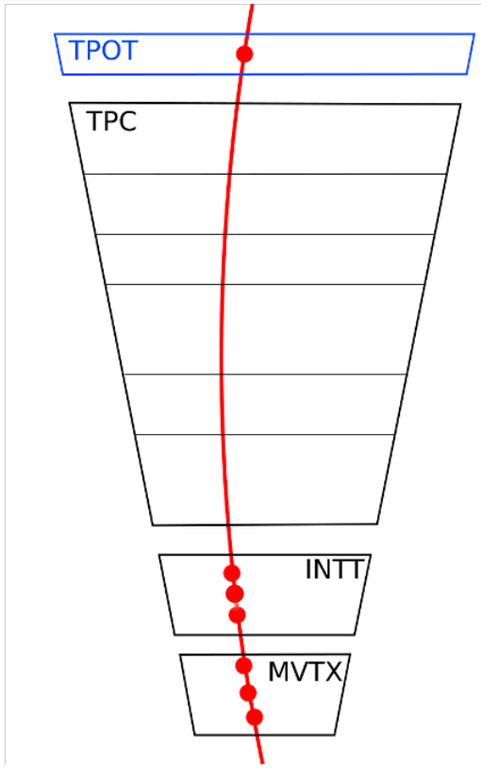



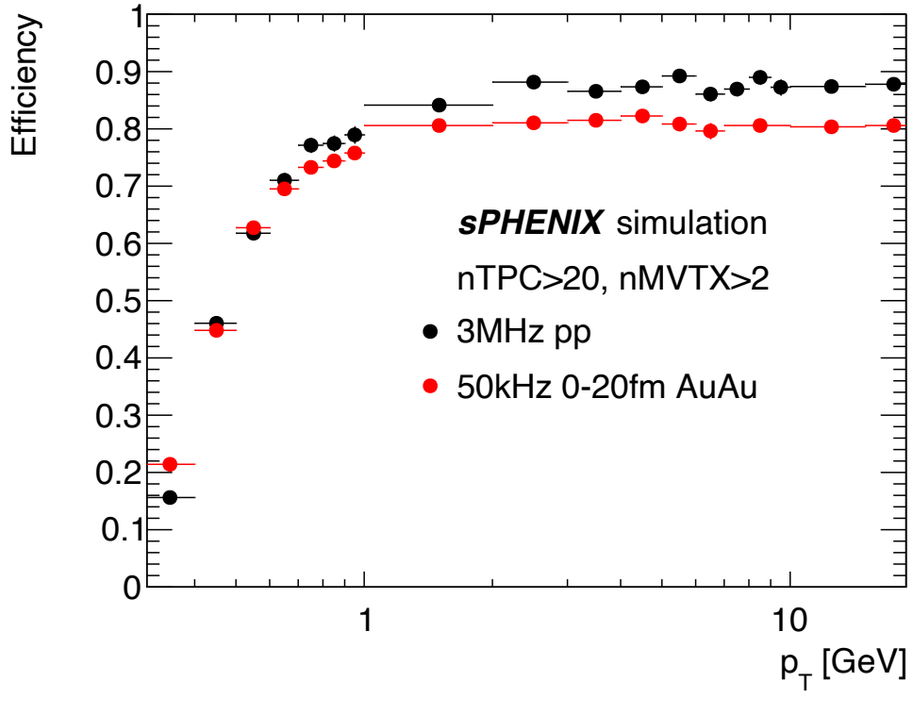

- Back-to-back b-jet pairs studies enabled by the large detector acceptance and multi-observable capabilities

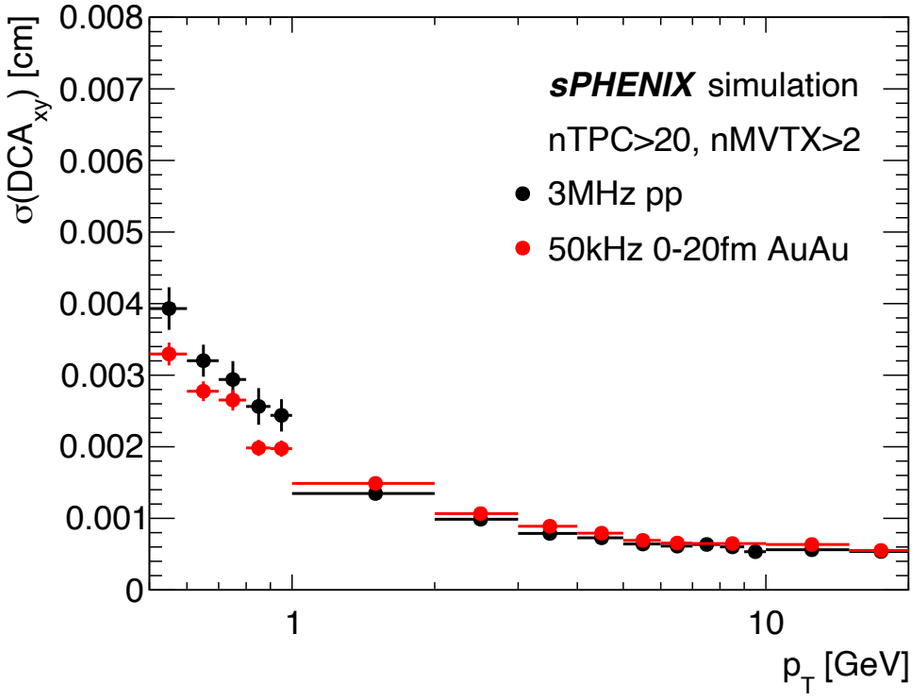
  Precision di-b-jet $R_{AA}$ as a function of di-jet invariant mass measurement
- Pinpoint the propagation of beauty quarks in the QGP
- Extract beauty quark coupling parameter to the medium
- Complementary to LHC di-b-jet balance measurements

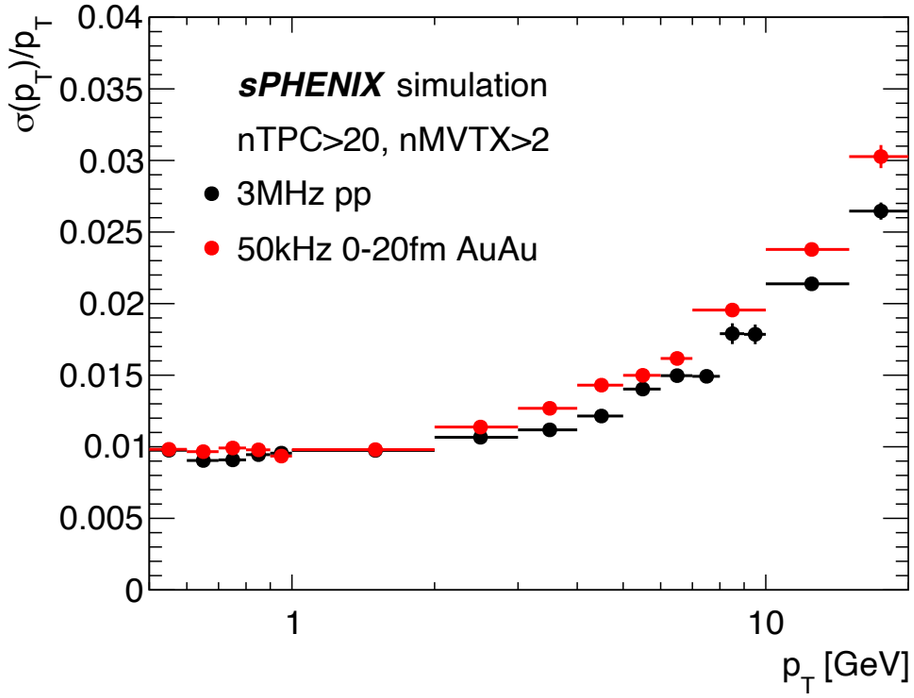
# Tracking System and Performance




- MVTX and INTT operating in continuous streaming readout mode with advanced electronics
- TPC + TPOT as the outer tracking device for momentum determination
- Excellent tracking reconstruction and vertexing performance for HF physics studies