

# The sPHENIX Open and Close Heavy Flavor Program

Zhaozhong Shi

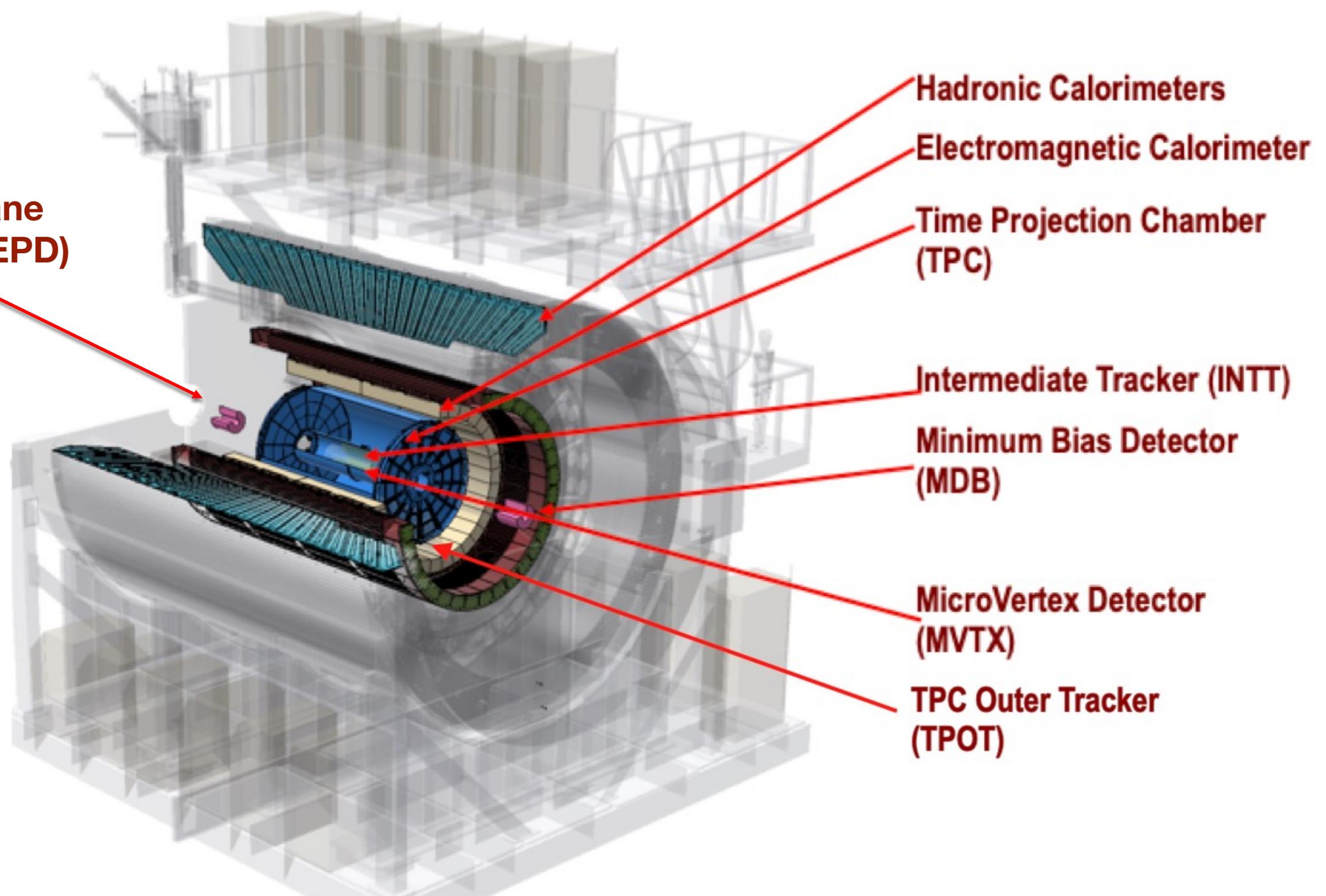
on behalf of the sPHENIX collaboration

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**QNP2022 - The 9th International Conference on Quarks  
and Nuclear Physics**

5-9 September 2022, Tallahassee, Florida, USA (Virtual)

# The sPHENIX Experiment at RHIC



## 2015 NSAC Long Range Plan for Nuclear Science: sPHENIX Experiment at RHIC

- Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales
- Complementary to LHC experiments

# sPHENIX Recent Schedule and Milestones



Year 2022

Jan      Feb      Mar      Apr      May      Jun      Jul      Aug



MCD II Starts:  
Software  
Milestone

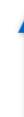
Outer HCAL  
Installation  
Complete

Inner HCAL  
Installation  
Complete

RBBC  
Workshop

Year 2023

Sep      Oct      Nov      Dec      Jan      Feb      Mar      Apr



Today

Babar  
Magnet  
Mapping  
Begins

EMCAL  
Installation  
Complete

INTT  
Installation

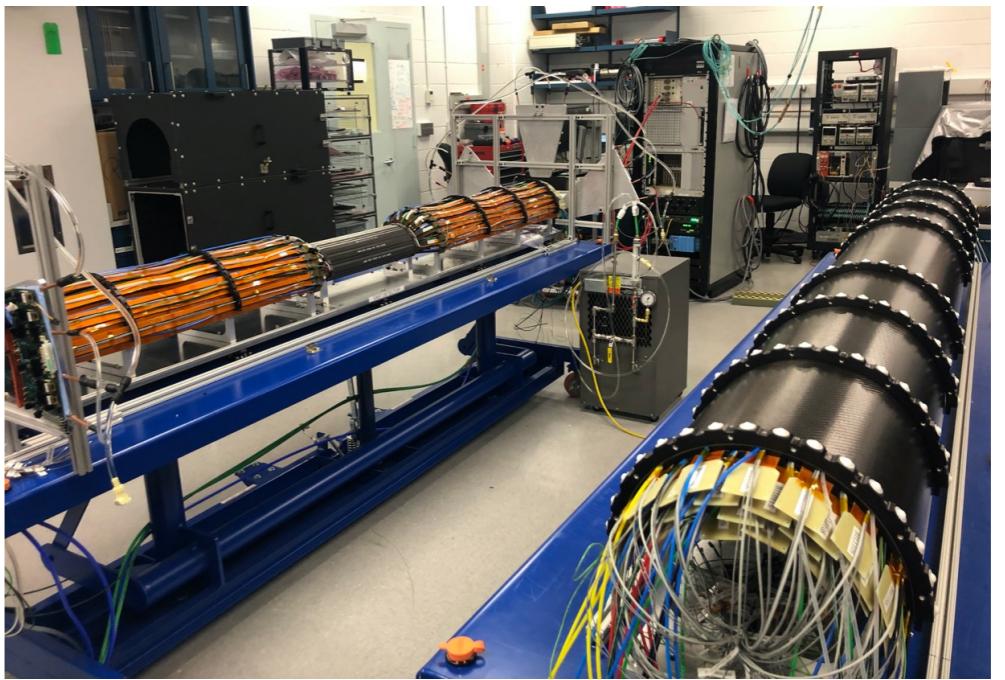
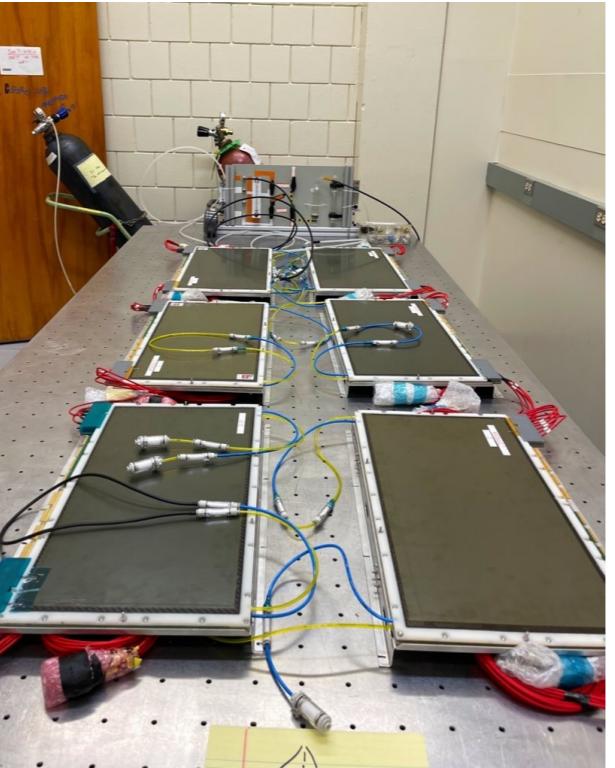
MVTX/EPD  
Installation

Entire  
sPHENIX  
Detector  
Testing

**Start first  
data taking!  
(~ 6 months)**

- Collective efforts of international collaboration from 85 institutions in 14 countries
- Intense preparation schedule to ensure timely and high-quality data taking in 2023

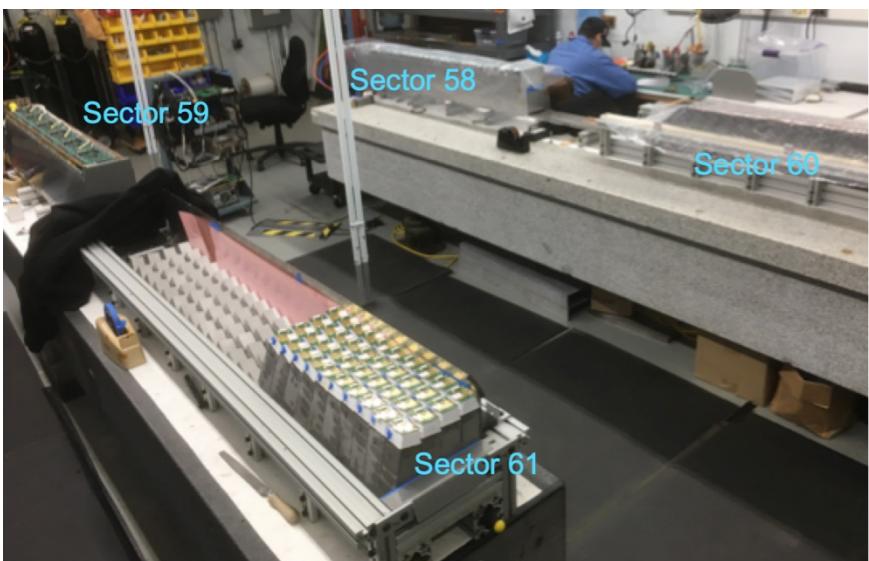
# sPHENIX Detector Commissioning



INTT half barrels completed and tested

TPC construction at Stony Brook University

TPOT effort by LANL/Stony Brook



EMCAL assembly at BNL



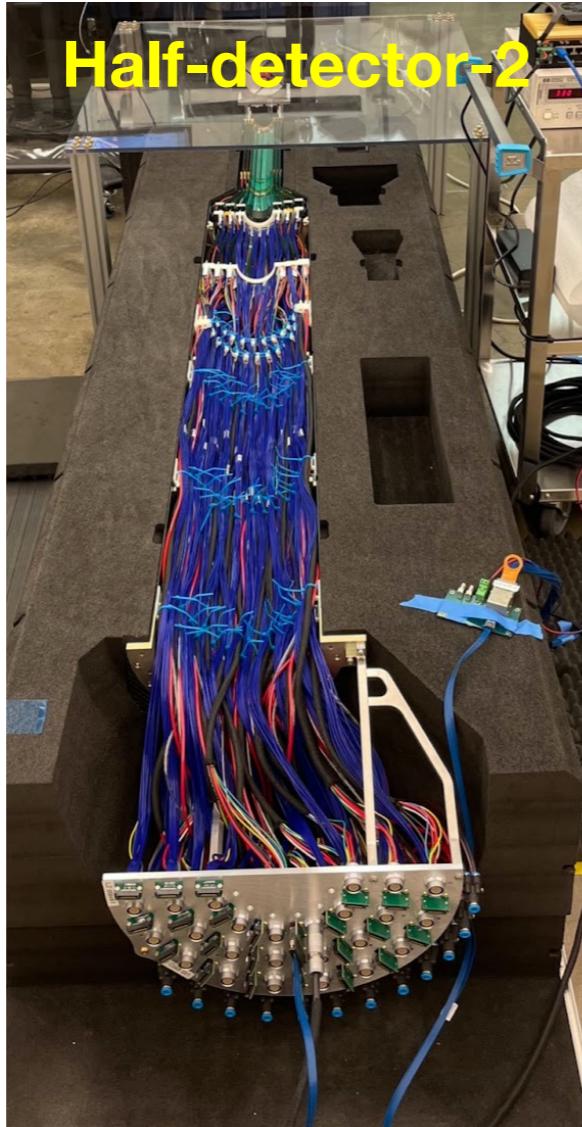
Commissioning task force



sPHENIX detector with HCAL in sPHENIX IP

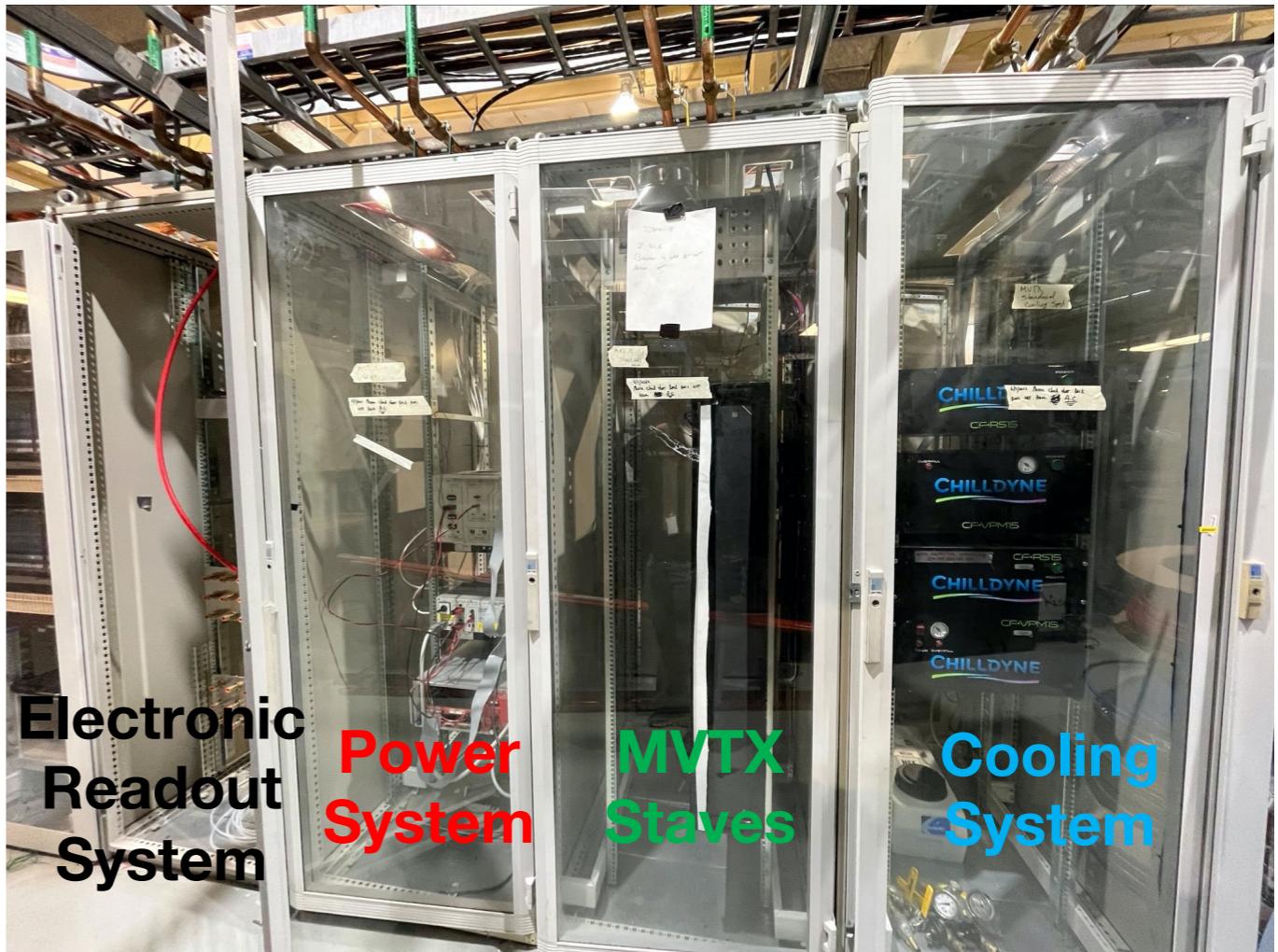
- Lots of construction activities of detectors ongoing in many places
- Collaborative and diverse workforce of students, postdocs, staff, and faculty
- Install the sPHENIX detector from outermost to innermost in sPHENIX IP at BNL

# MVTX Commissioning Status



## BNL Commissioning

- Clean tent setup  
MOSAIC system to test the staves performance
- Entire MVTX system testing  
Readout chain test  
Detector alignment with cosmic ray data and machine learning  
Online monitoring and slow control system  
Ensure MVTX functionality for data taking



## LBNL MVTX Detector Assembling

- Precision placement of staves at around  $50 \mu m$  obtained by CMM
- Stave gluing to carbon structure
- Power system and cabling preparation
- Readout mechanical structure
- Half detector fully assembled

# sPHENIX Beam Use Proposal



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

- Extensive **3-year** data taking starting in around 6 months

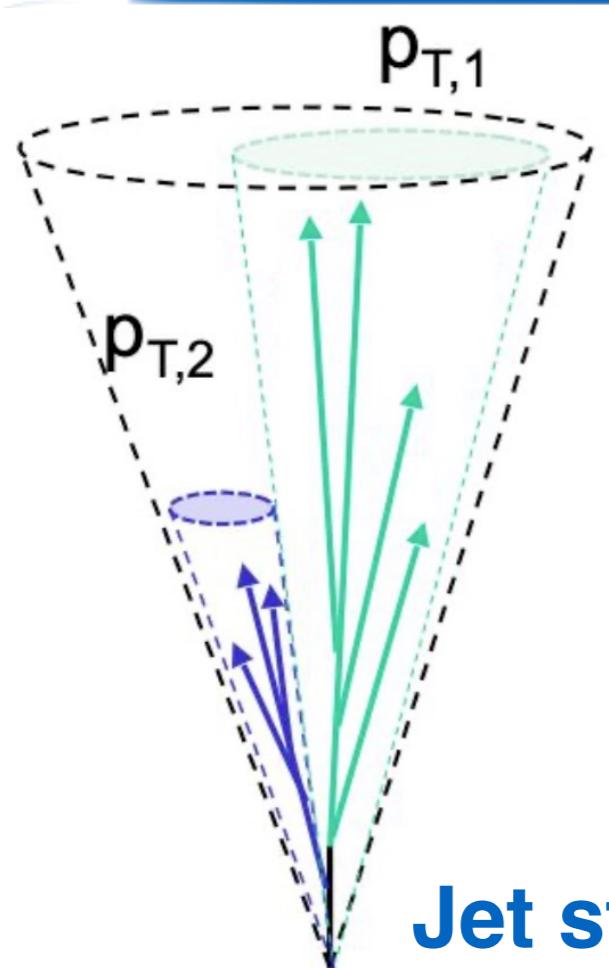
**Year-1:** commissioning and first physics in Au+Au

**Year-2:** p+p and p+Au runs for heavy-ion reference and cold QCD physics

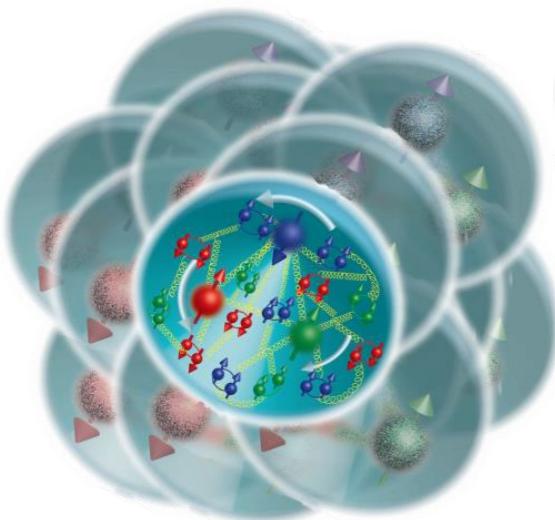
**Year-3:** very large Au+Au dataset (141B events in total)

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

# The sPHENIX Physics Program



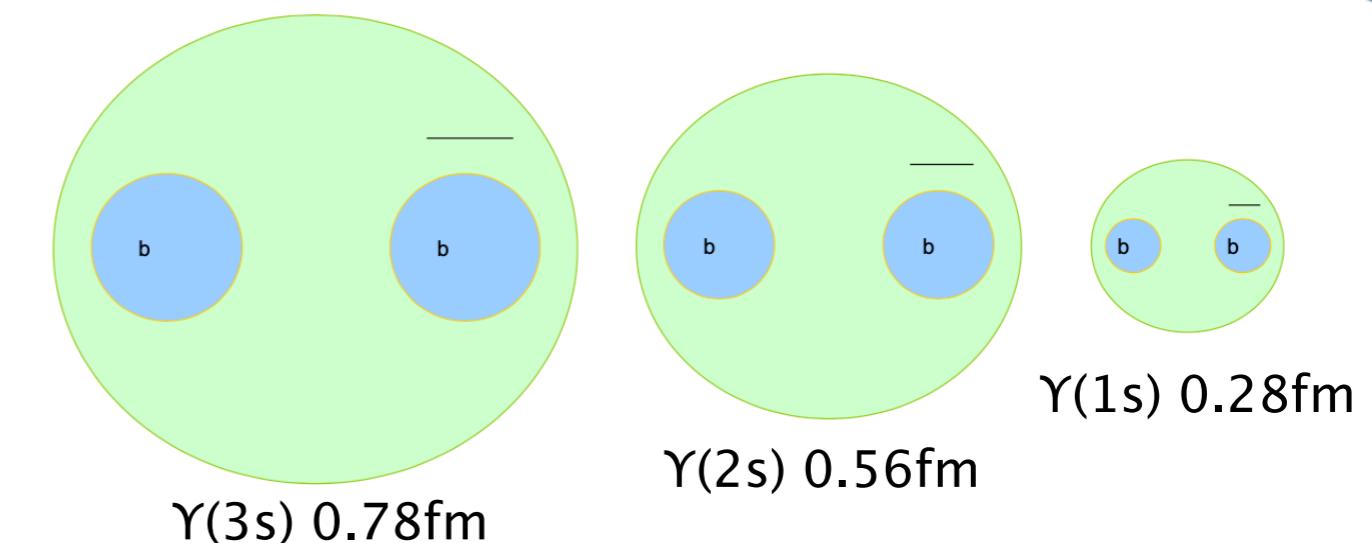
**Jet structure**  
vary momentum/angular scale of probe



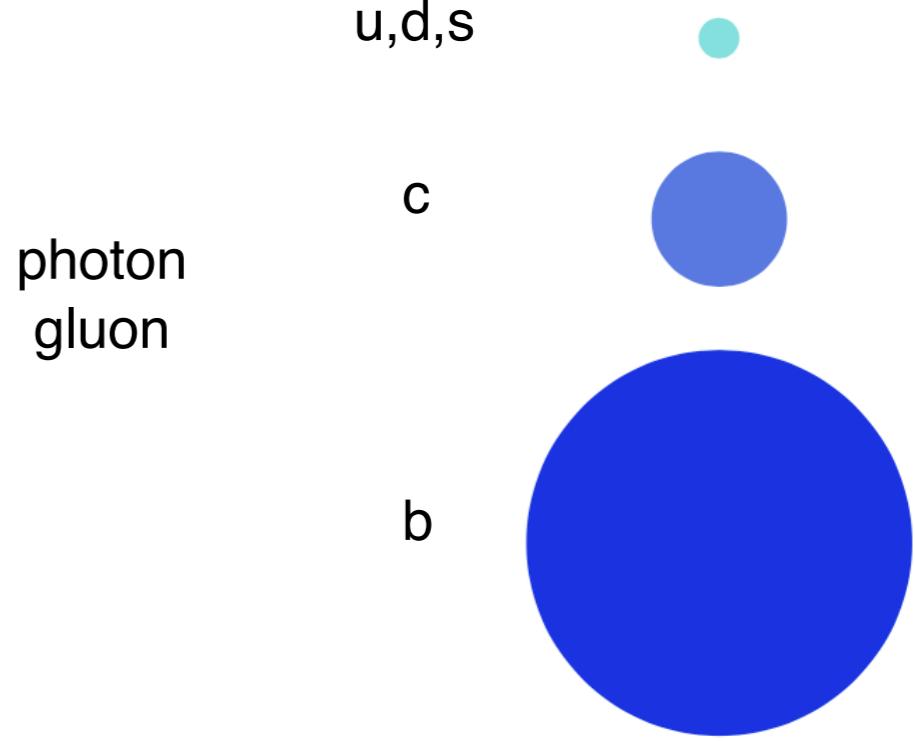
**Cold QCD**  
study proton spin,  
transverse-momentum,  
and cold nuclear effects



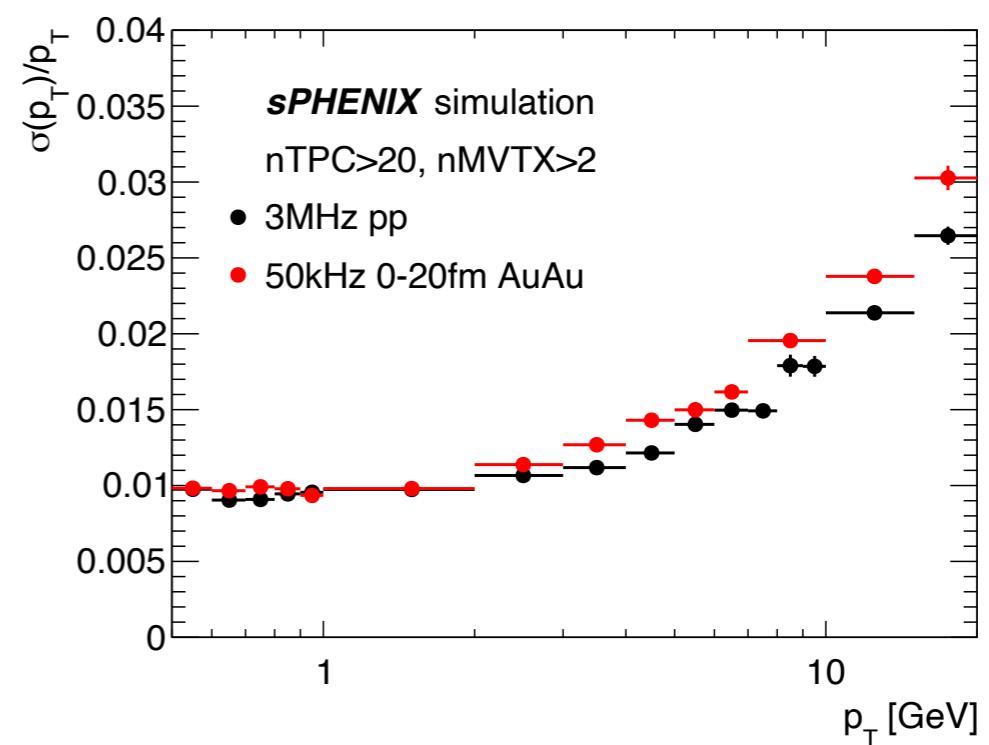
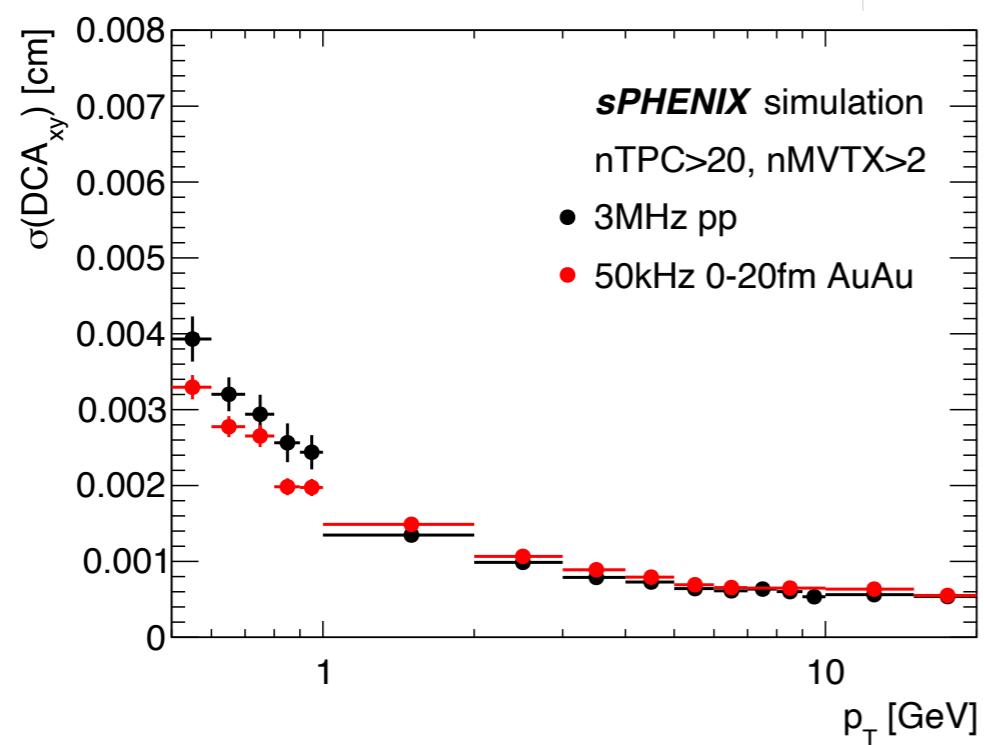
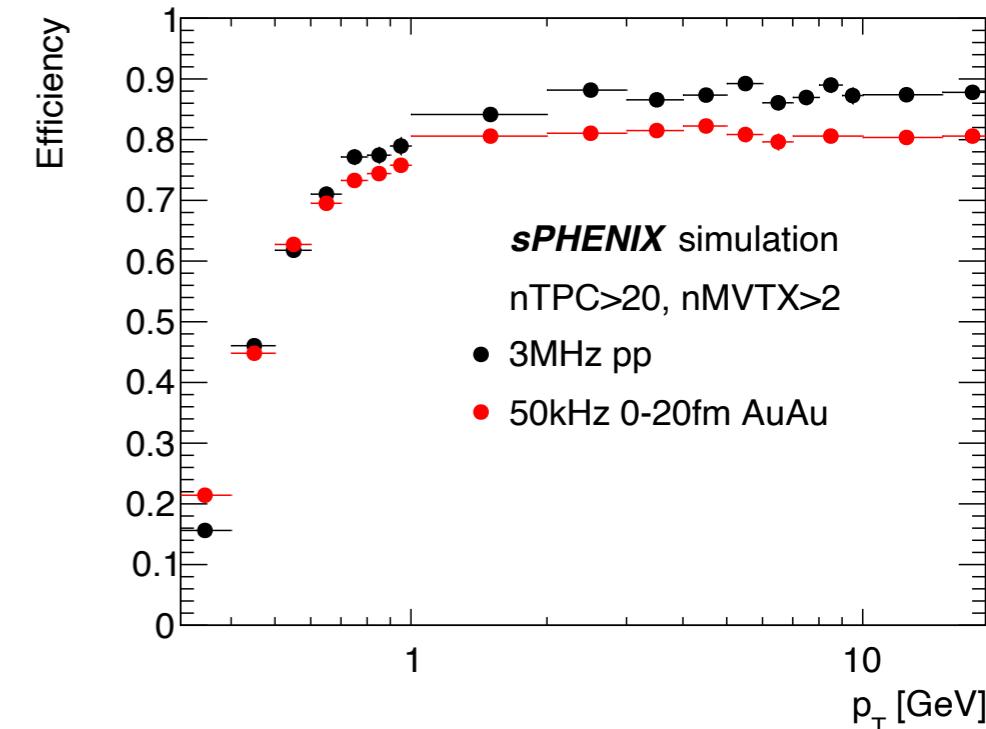
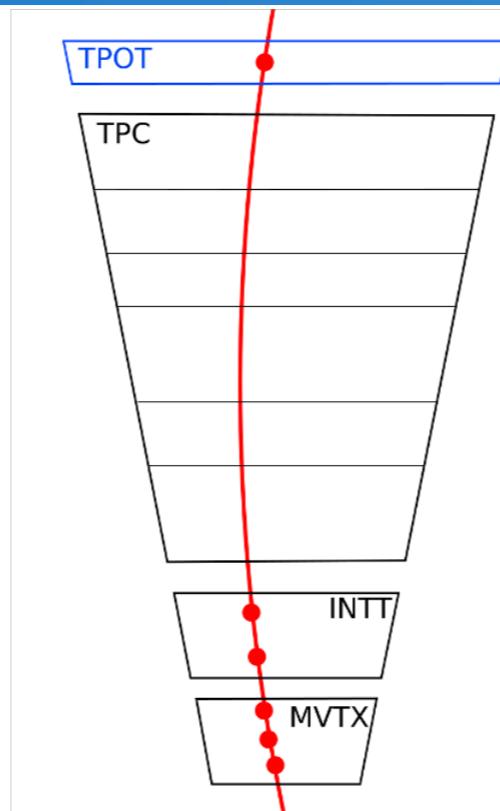
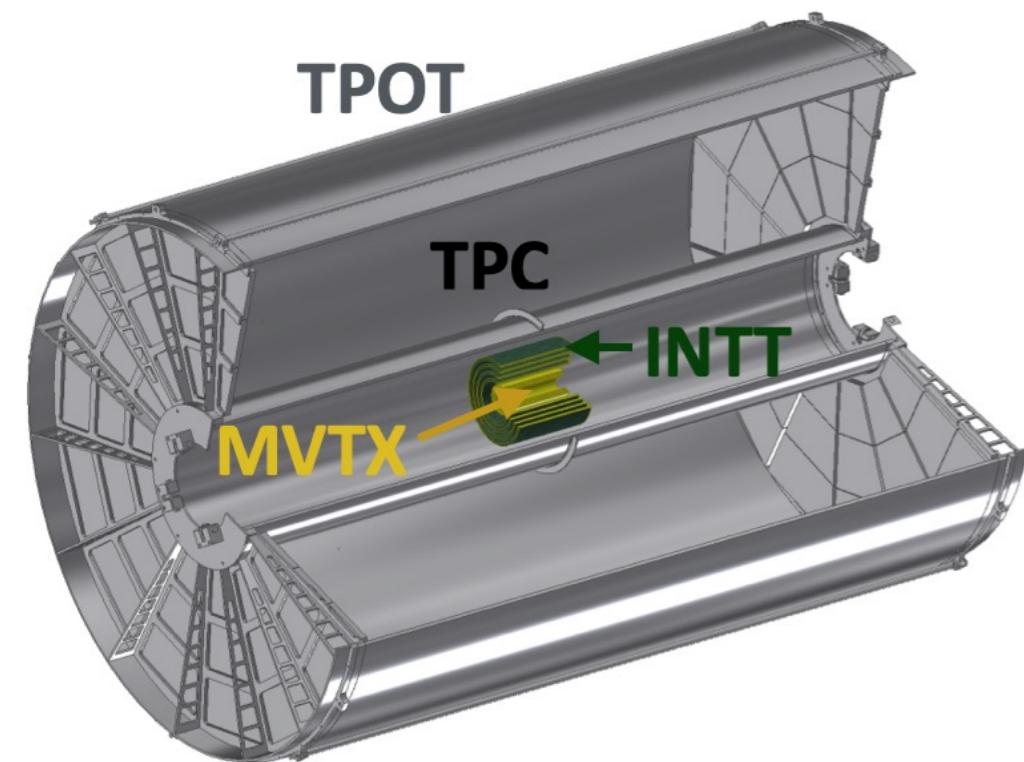
**Quarkonium spectroscopy**  
vary size of probe



**Parton energy loss**  
vary mass/momentum of probe  
u,d,s

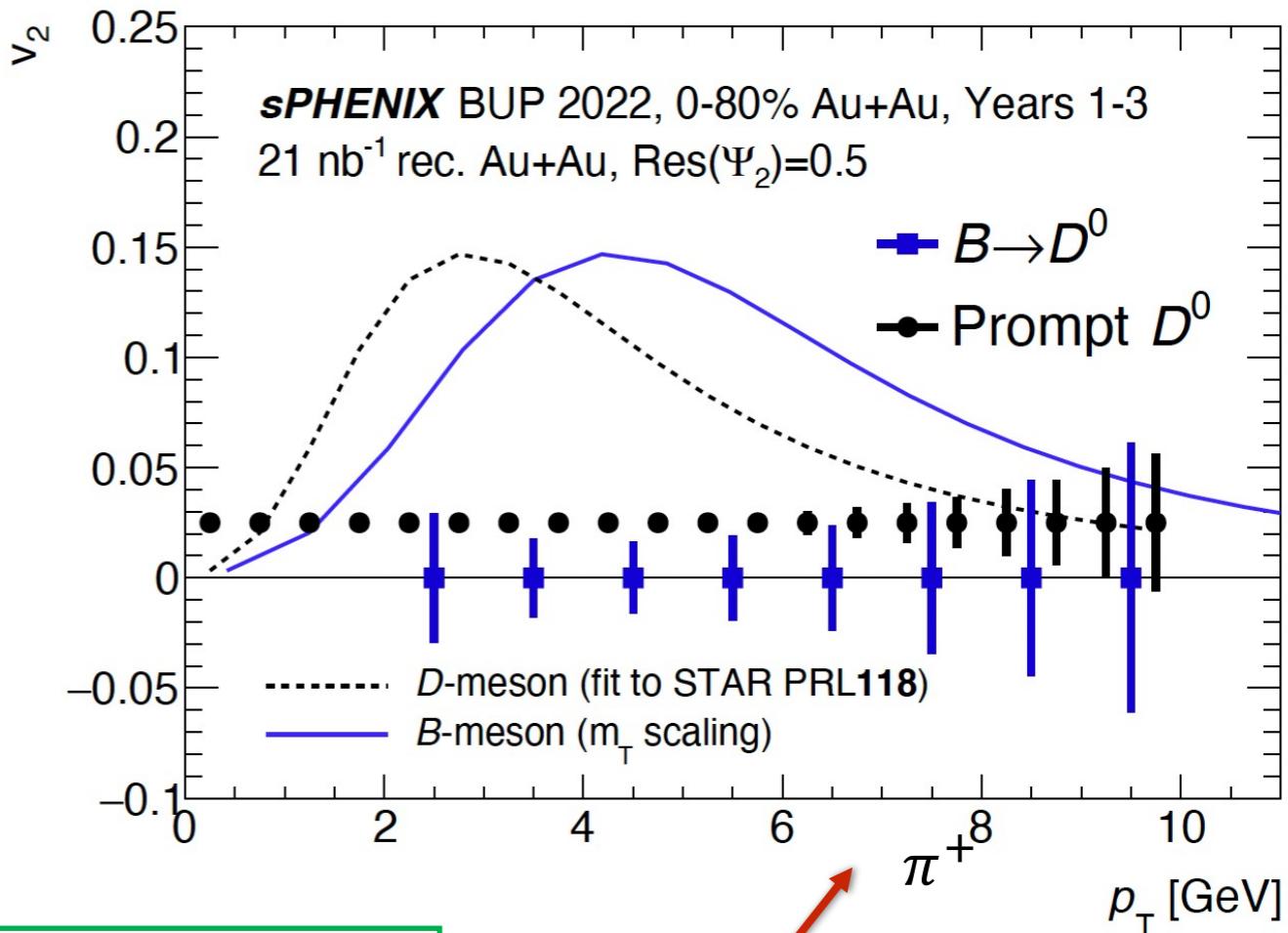
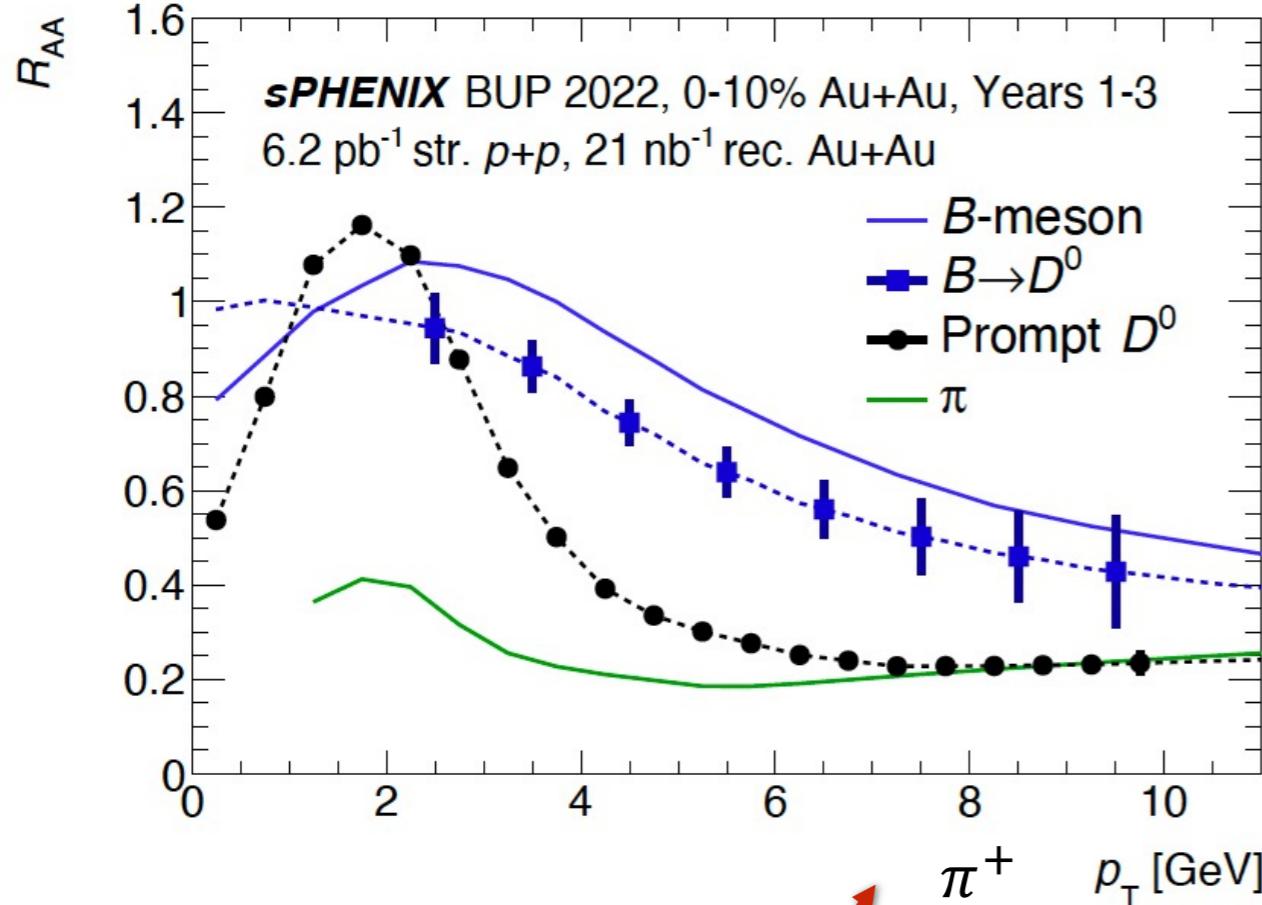


# Tracking System and Performance

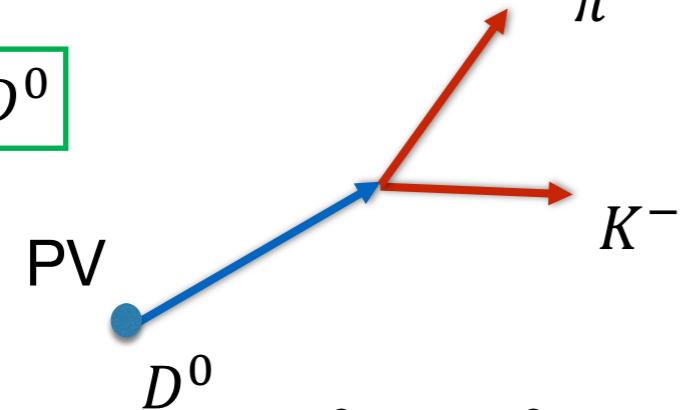


- MVTX and INTT operating in continuous streaming readout mode with advanced electronics
- TPC + TPOT as the outer tracking device for momentum determination
- Excellent tracking reconstruction and vertexing performance for HF physics studies

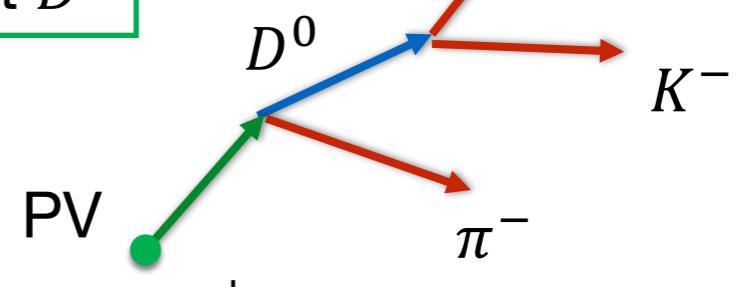
# Fully Reconstructed $D^0$ $R_{AA}$ and $v_2$



Prompt  $D^0$

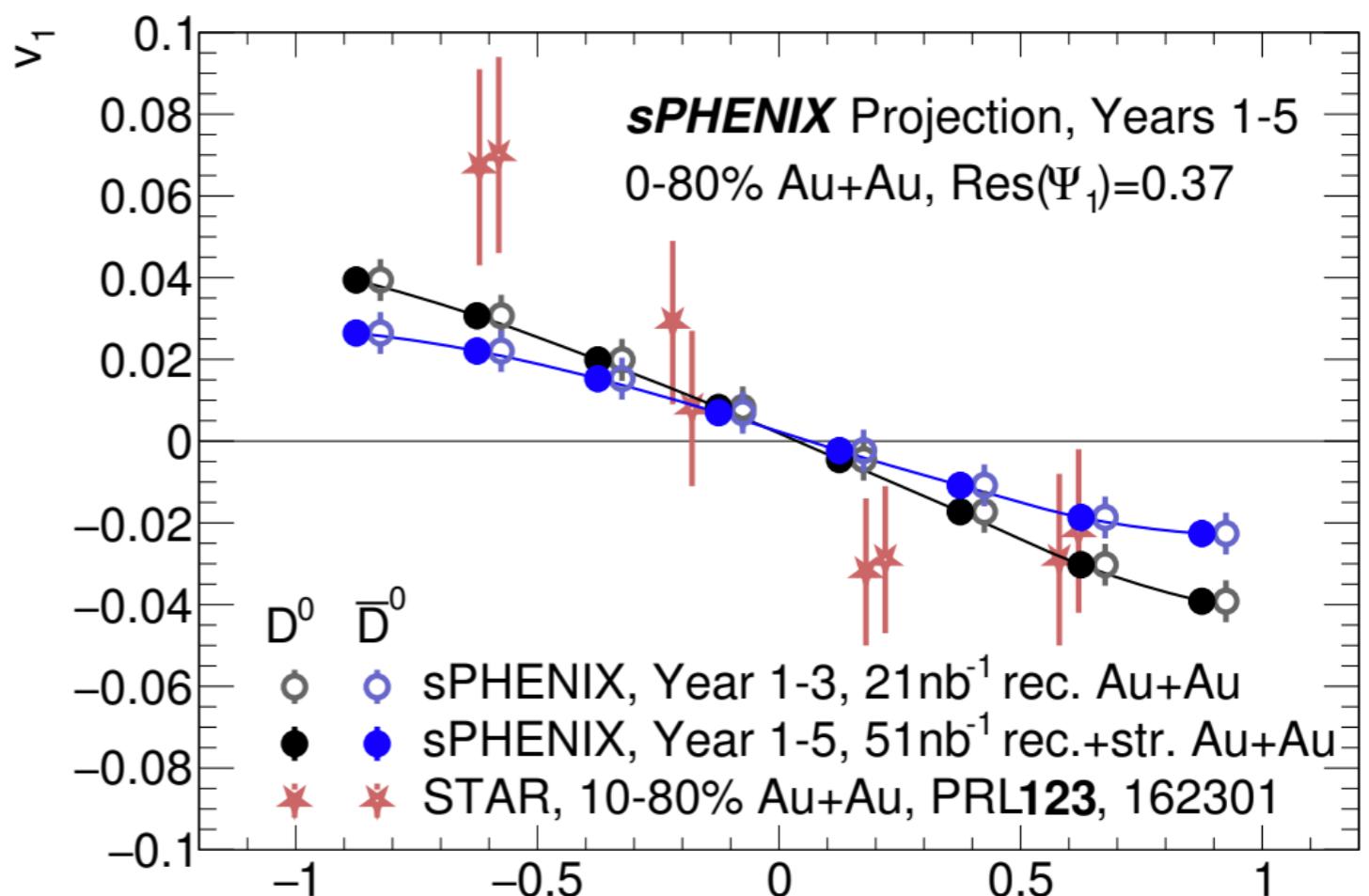
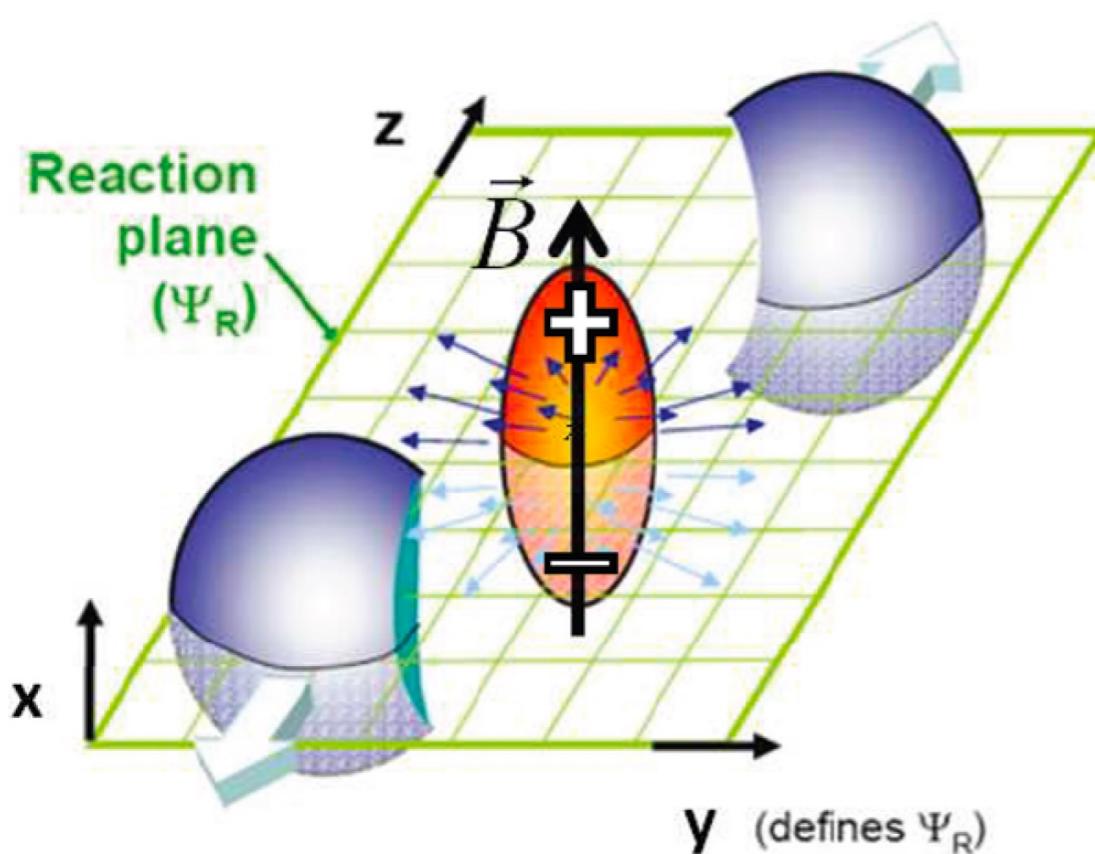


Non-Prompt  $D^0$



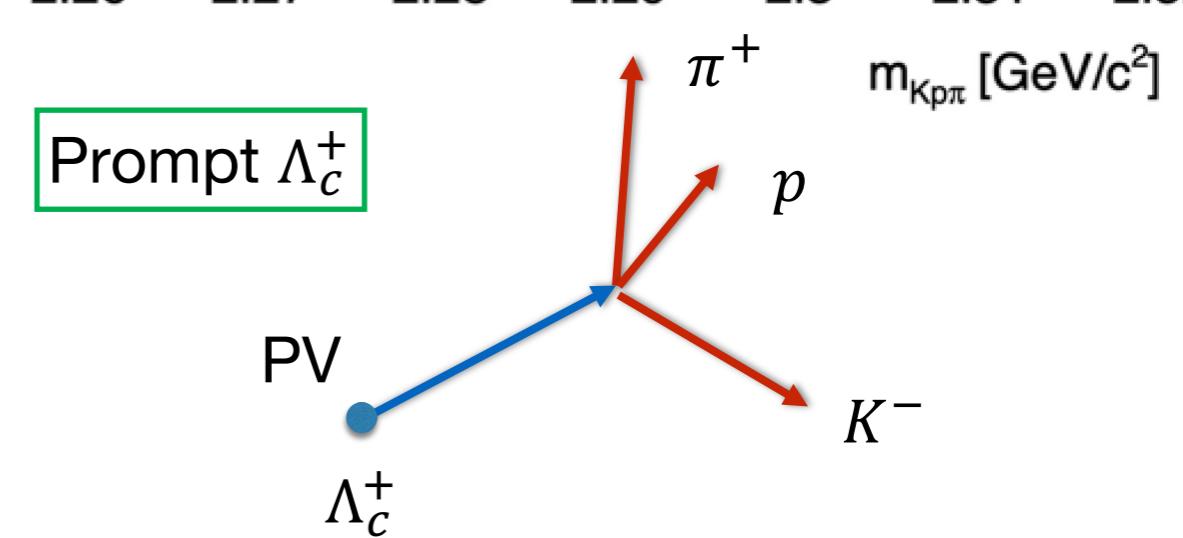
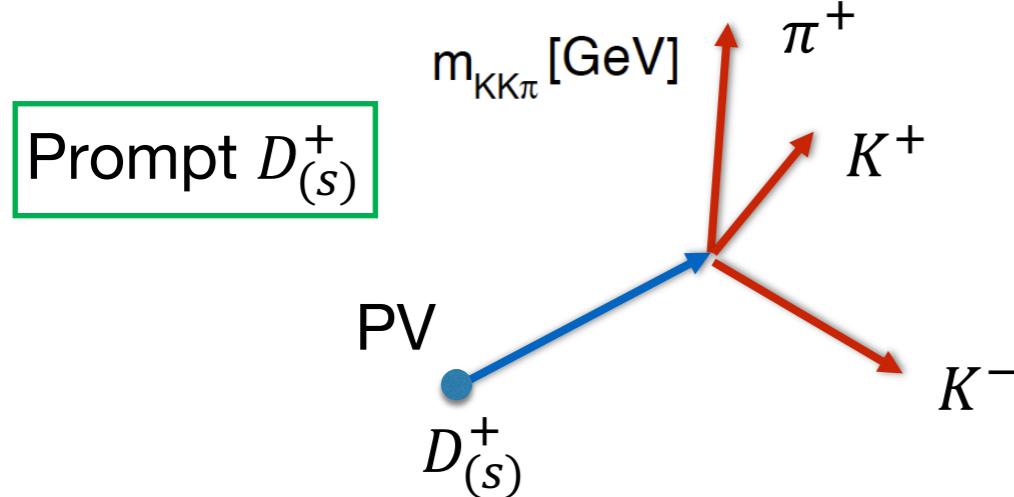
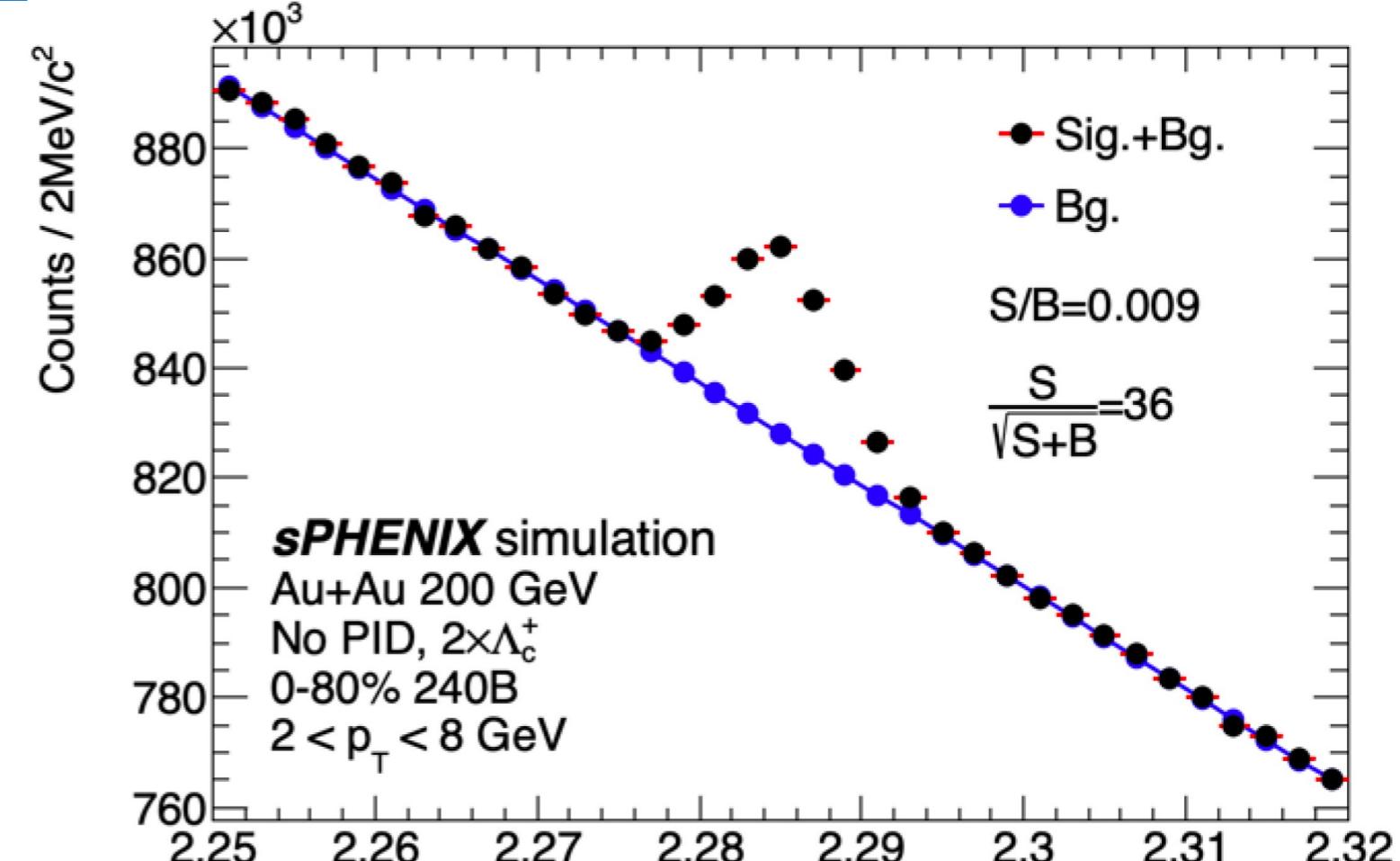
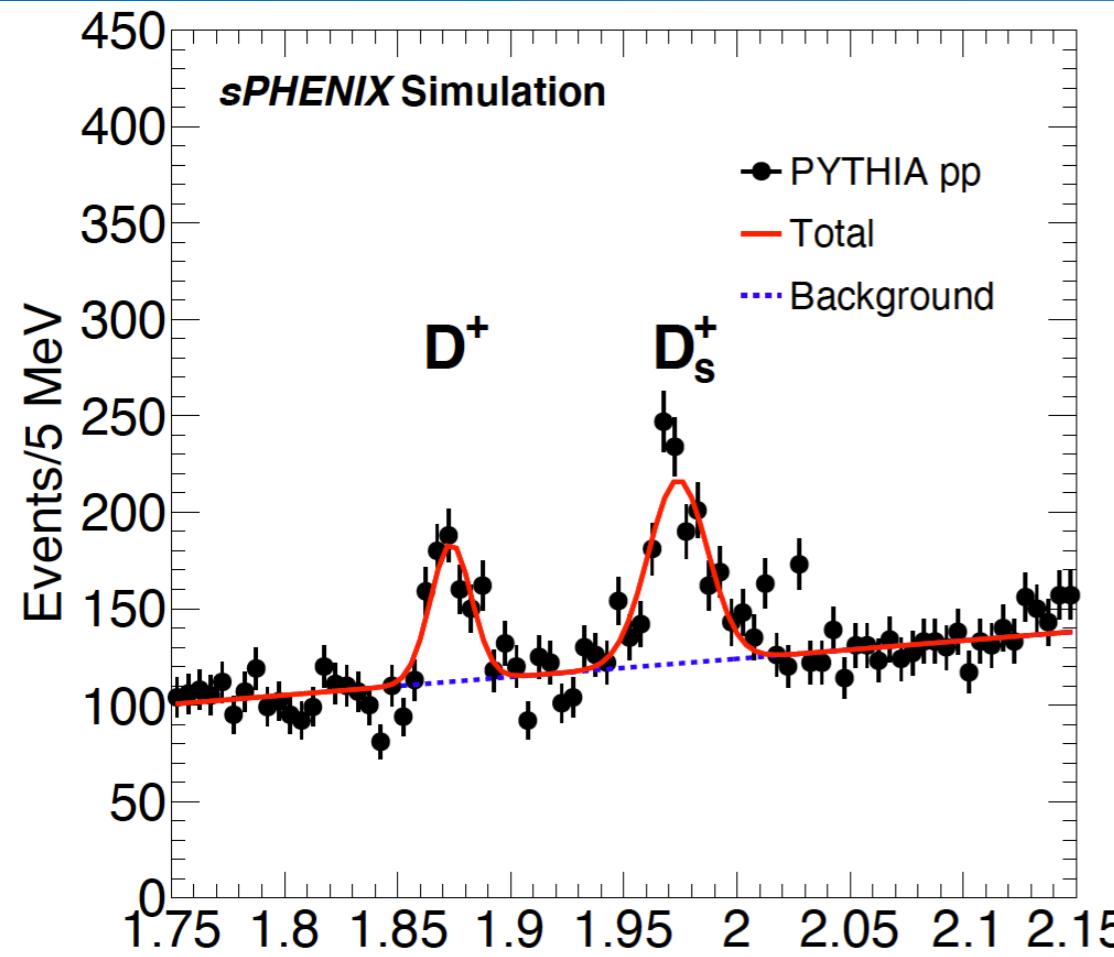
- Fully reconstructed  $D^0$  via  $D^0 \rightarrow K^-\pi^+$  without hadronic PID
- High precision D-meson thanks to dataset size and tracking system
- Data-driven method: separation of prompt and non-prompt  $D^0$  via  $B \rightarrow D^0$  decay with DCA
  - Constrain beauty quark diffusion coefficient in QGP medium
  - Flavor dependence of energy loss
  - Investigate charm quarks thermalization

# 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

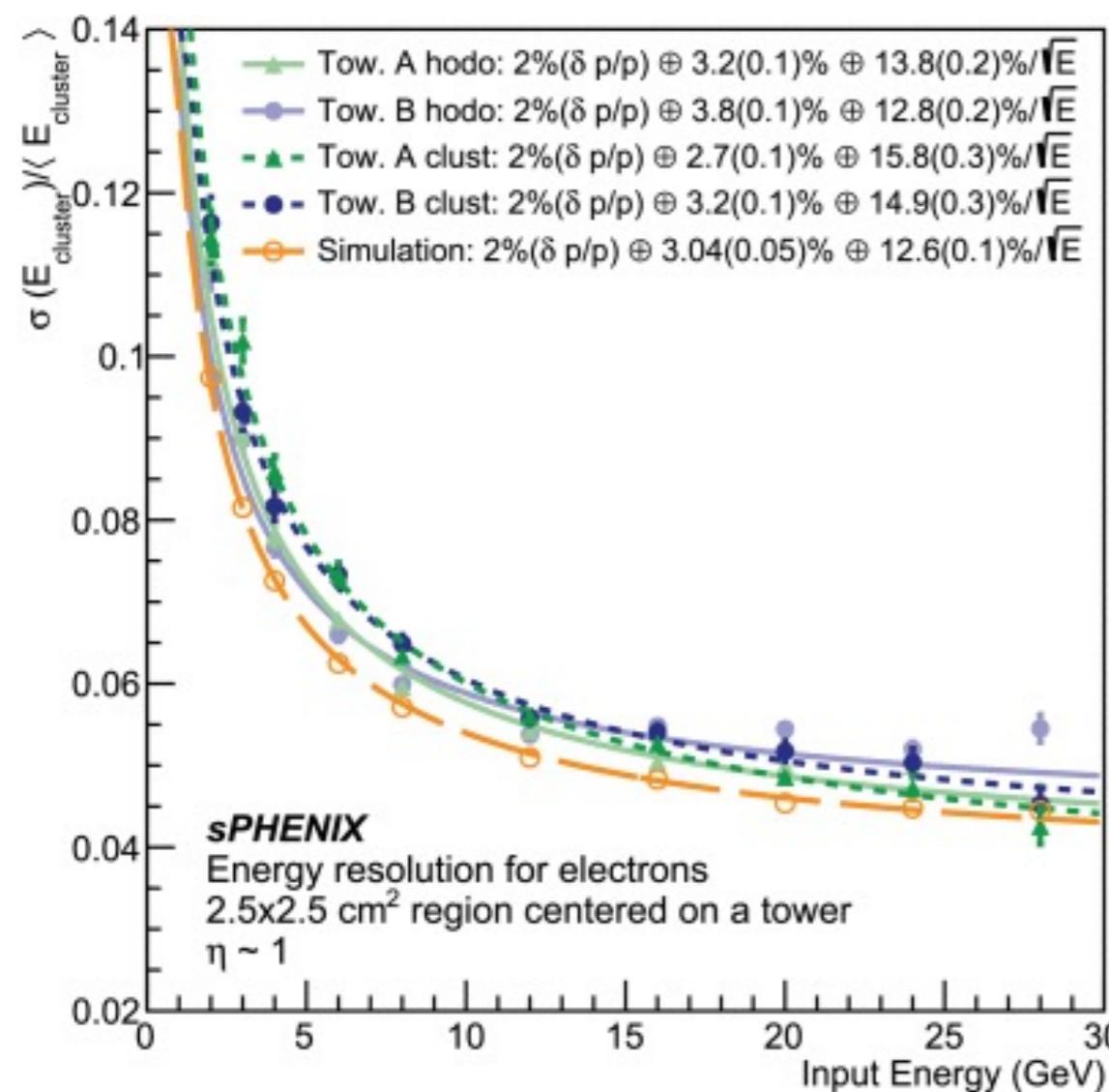
# $D_s^+/D^+$ and $\Lambda_c^+/D^0$ Ratios



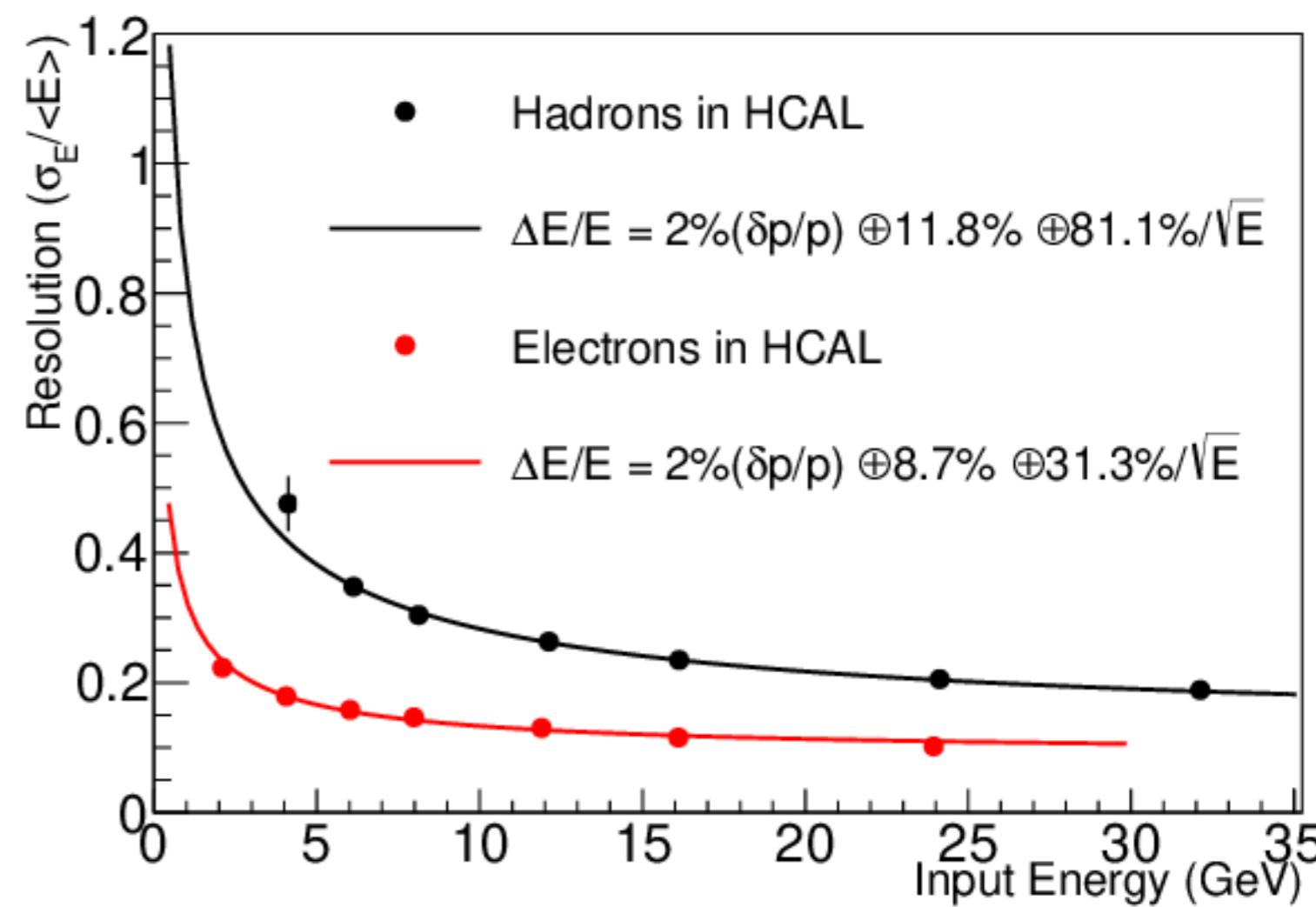
- More complex 3-prong decays
- High precision measurement thanks to streaming readout data taking and tracking
- Study charm hadronization from vacuum to QGP via the measurements of  $D_s^+/D^+$  and  $\Lambda_c^+/D^0$  as a function of event multiplicity

# Calorimeter System Performance

## EMCAL



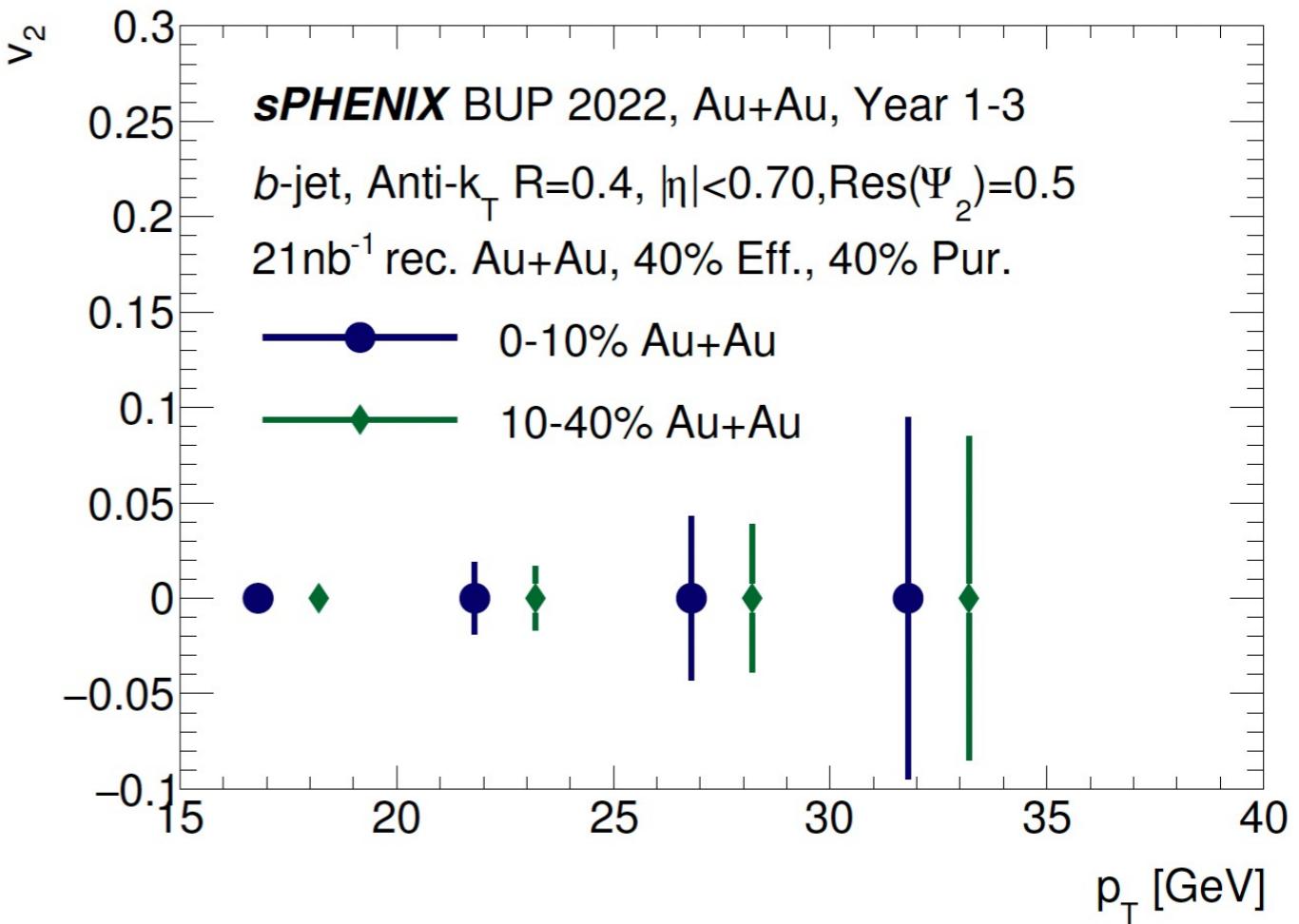
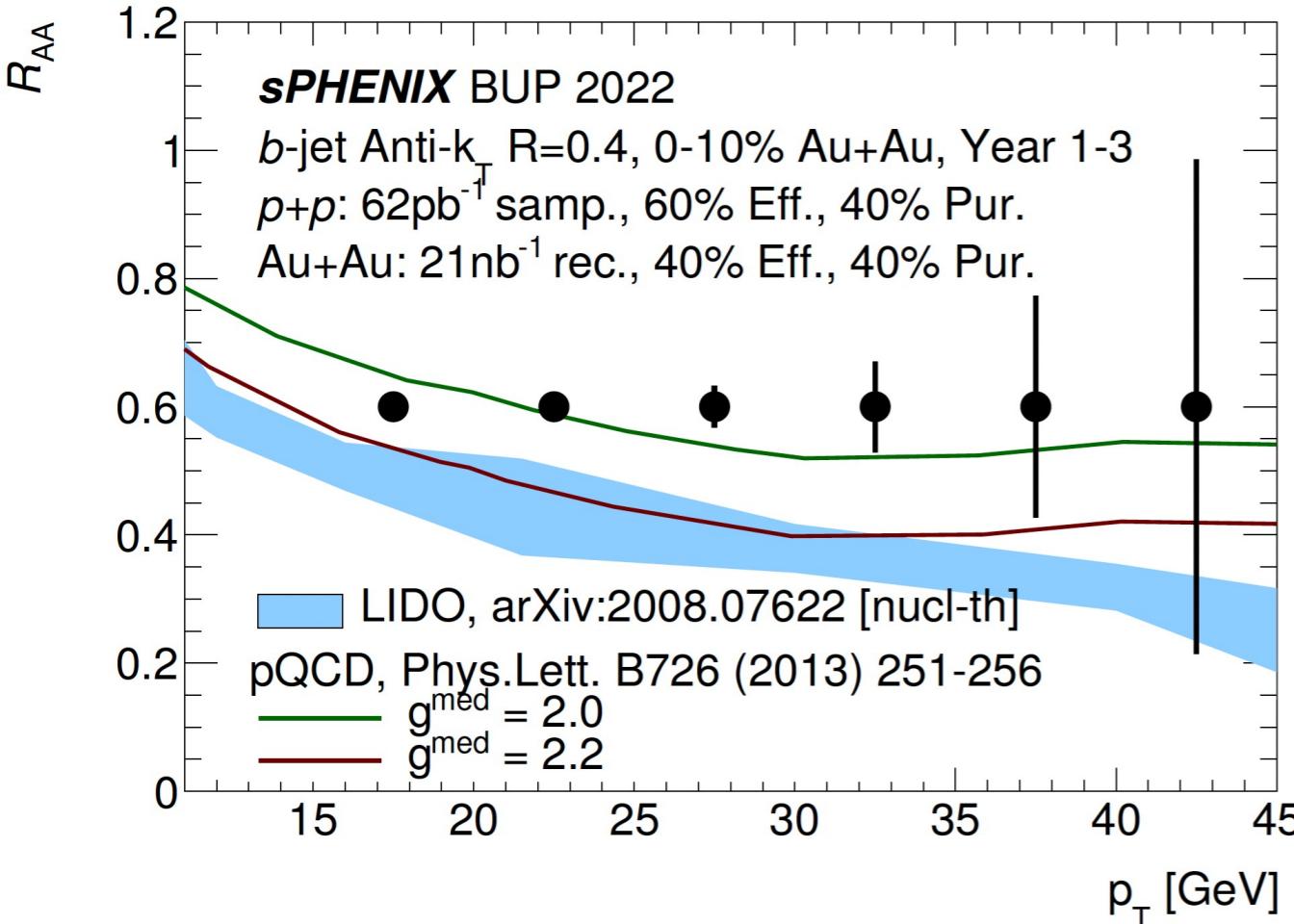
## HCAL



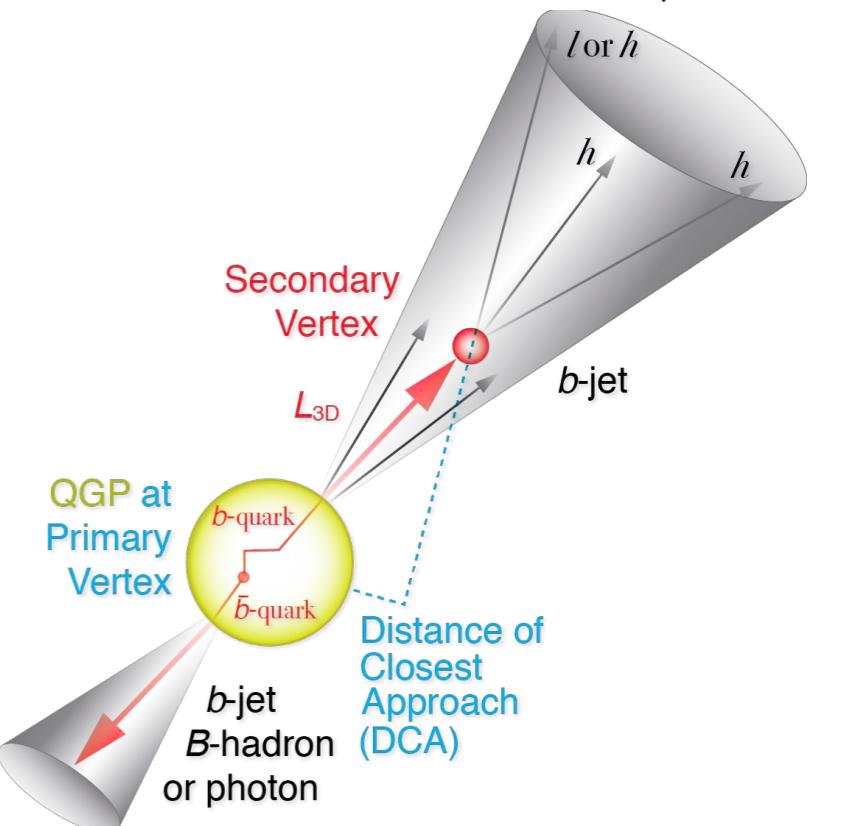
(b)

- 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

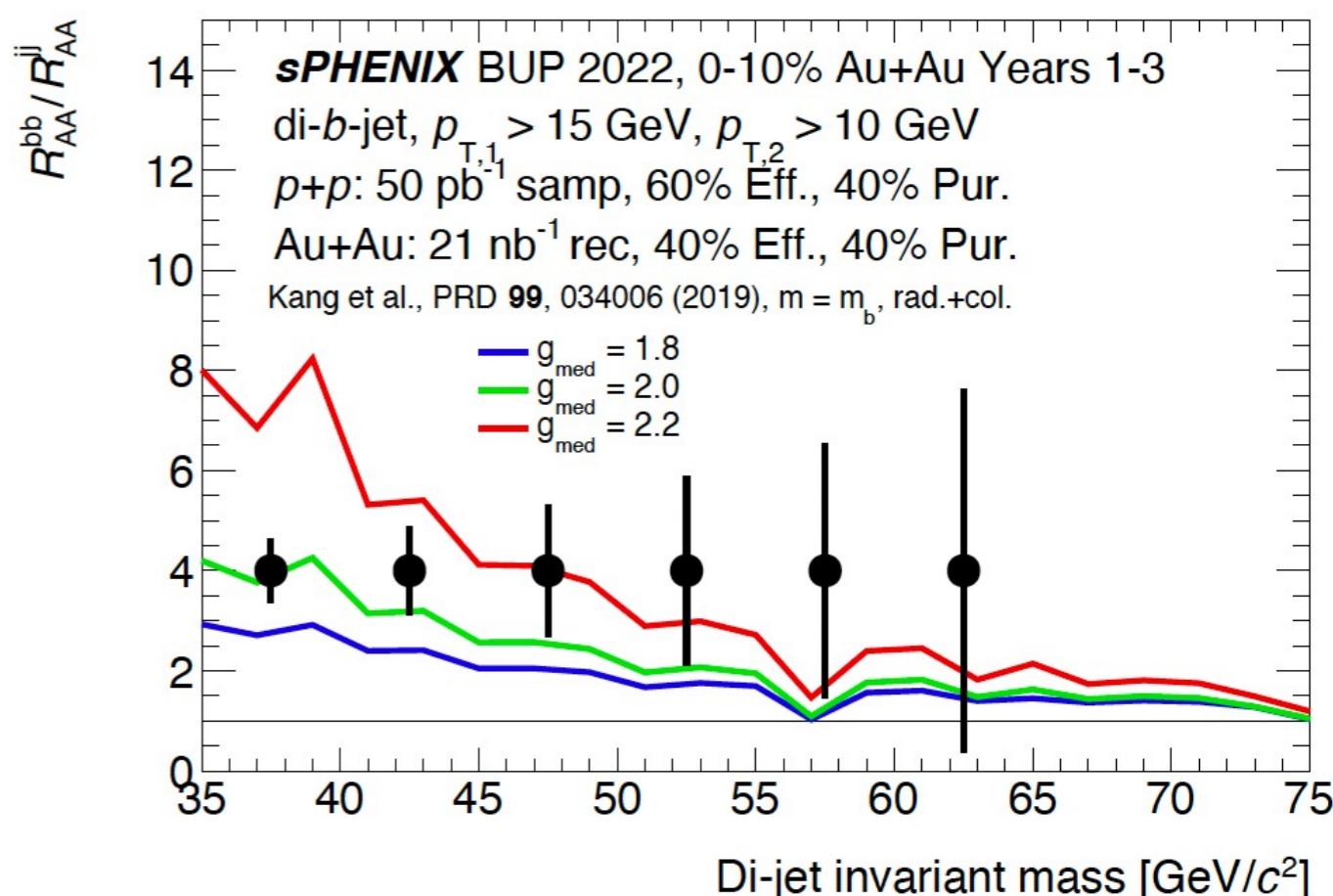
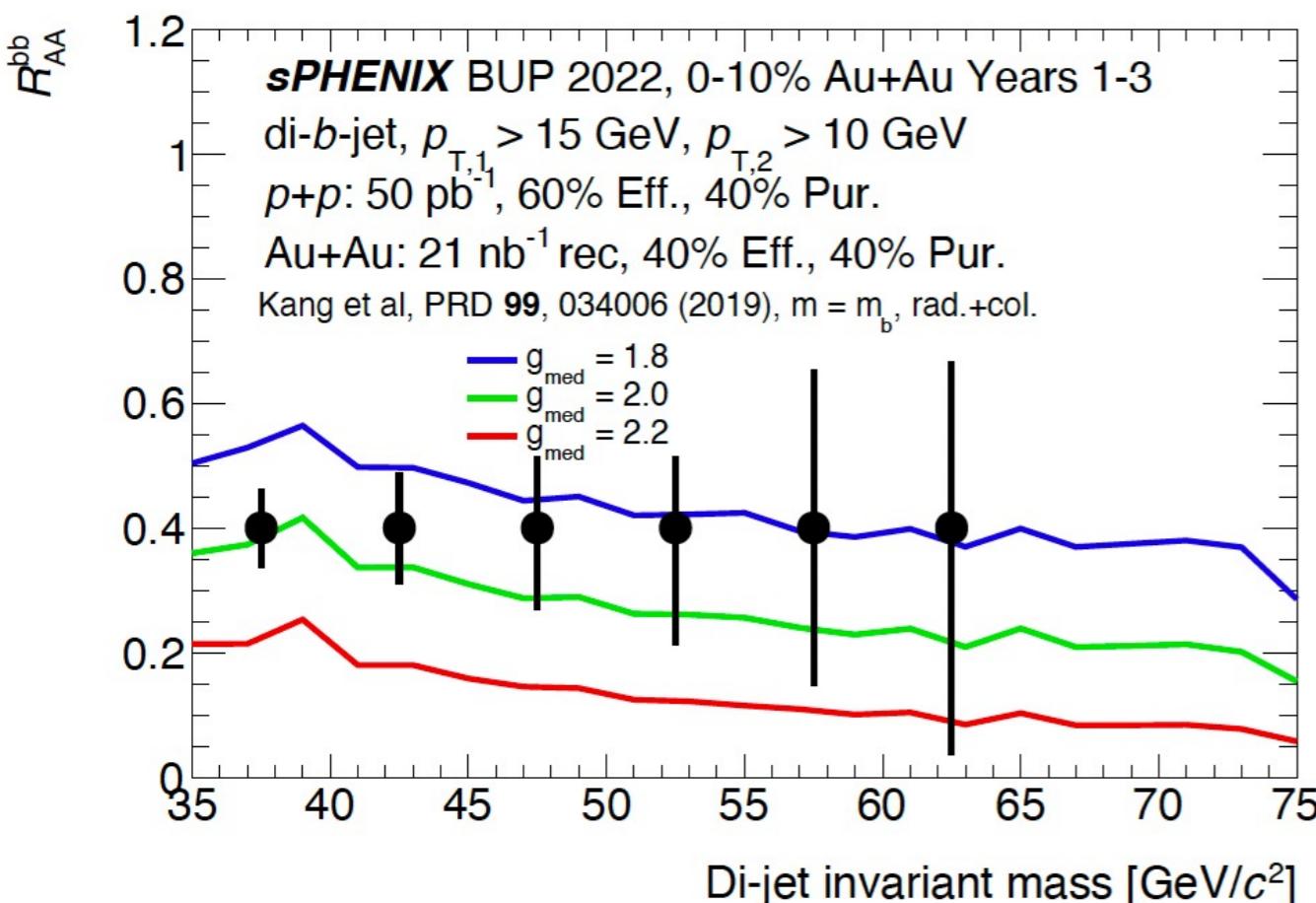
# b-jet $R_{AA}$ and $v_2$



- Utilization of MVTX to reconstruct secondary vertex within the jet cone
  - Identify jets with displaced vertices to tag the b quarks
  - Inclusive measurement with better statistics
- First b-jet measurement at RHIC
- Sensitive to heavy-quark collisional and radiative in-medium energy loss
- Pathlength dependence of beauty energy loss in the QGP
- Complementary to LHC with better precision at lower  $p_T$

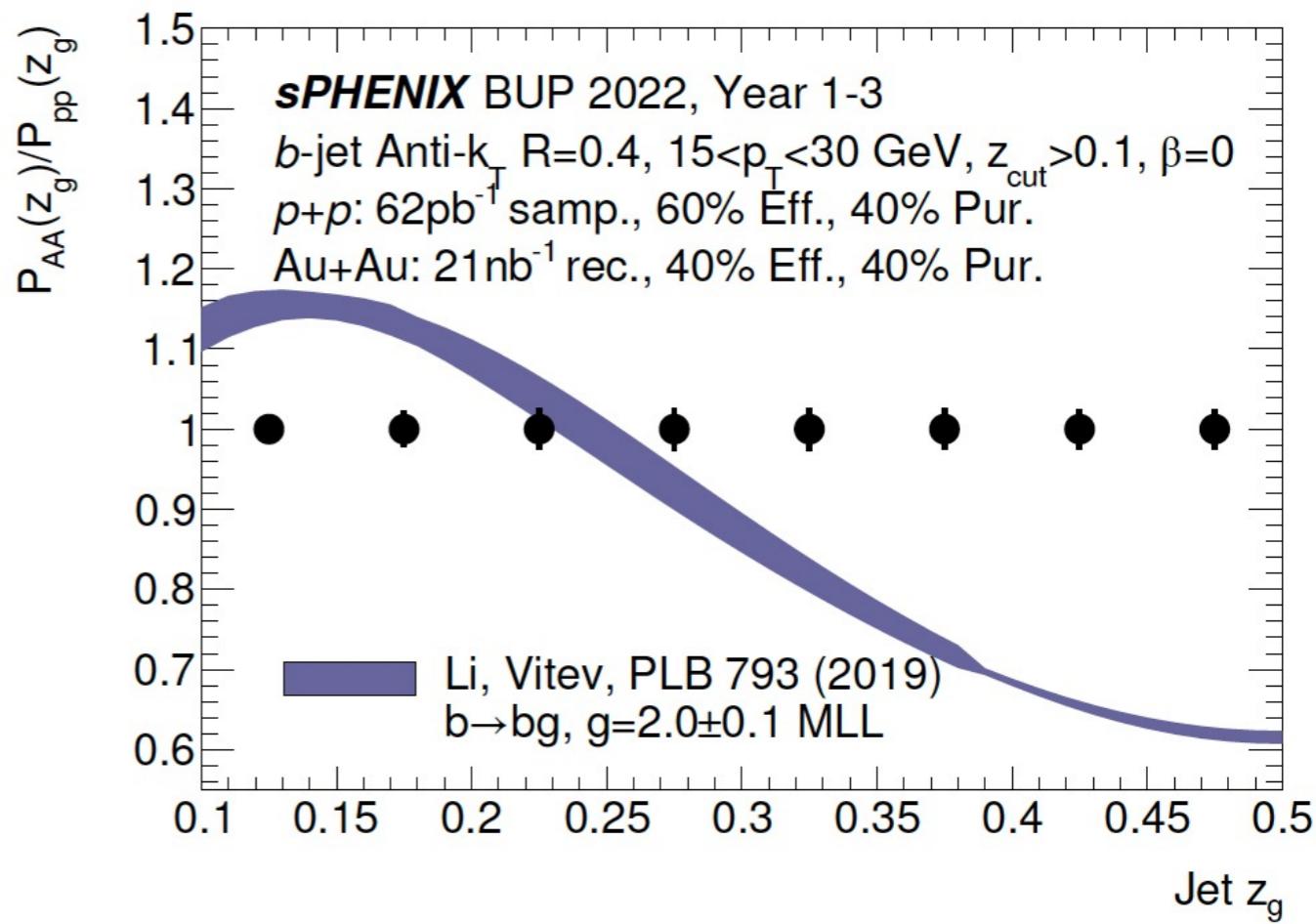
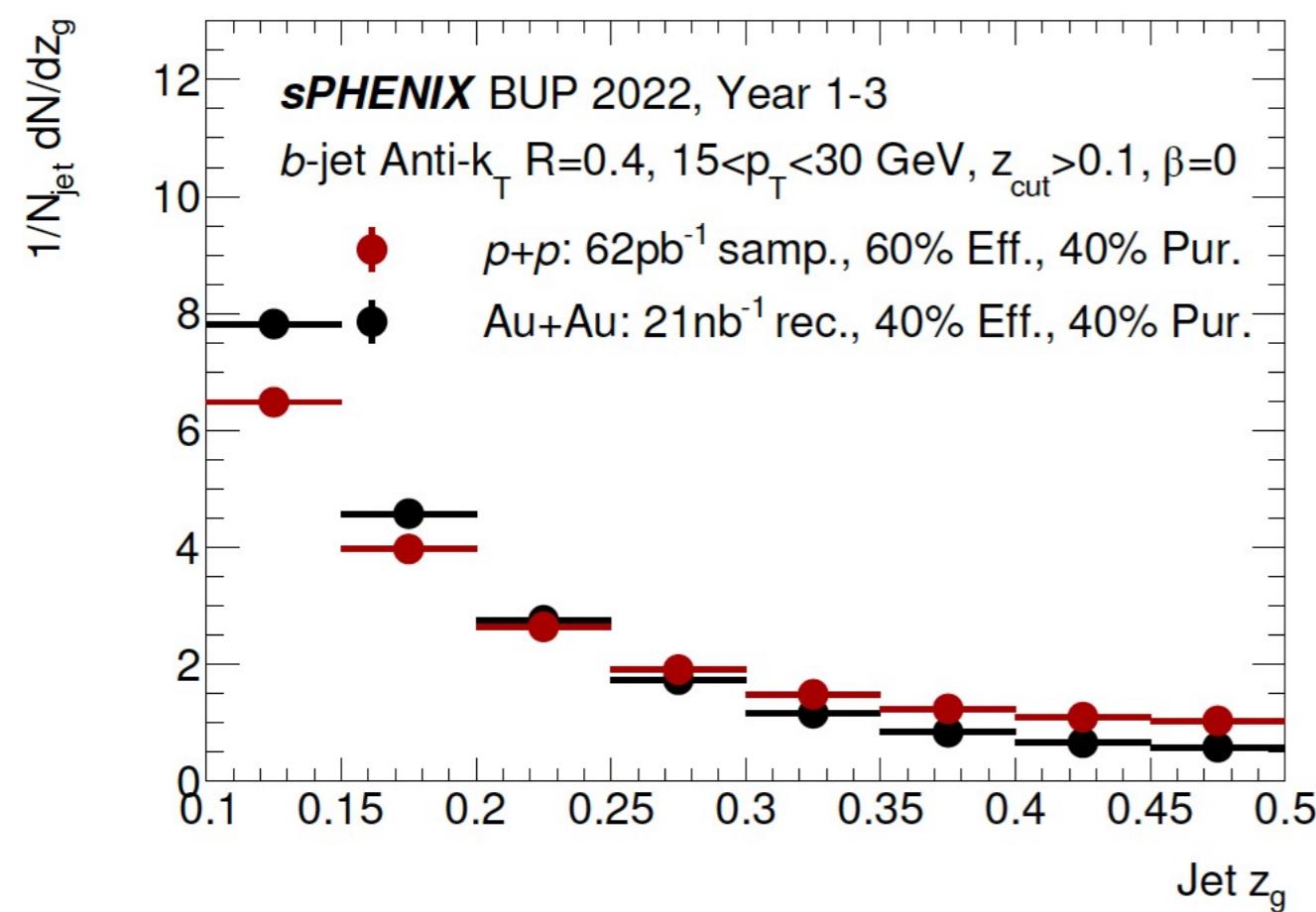


# Di-b-jet Invariant Mass



- 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

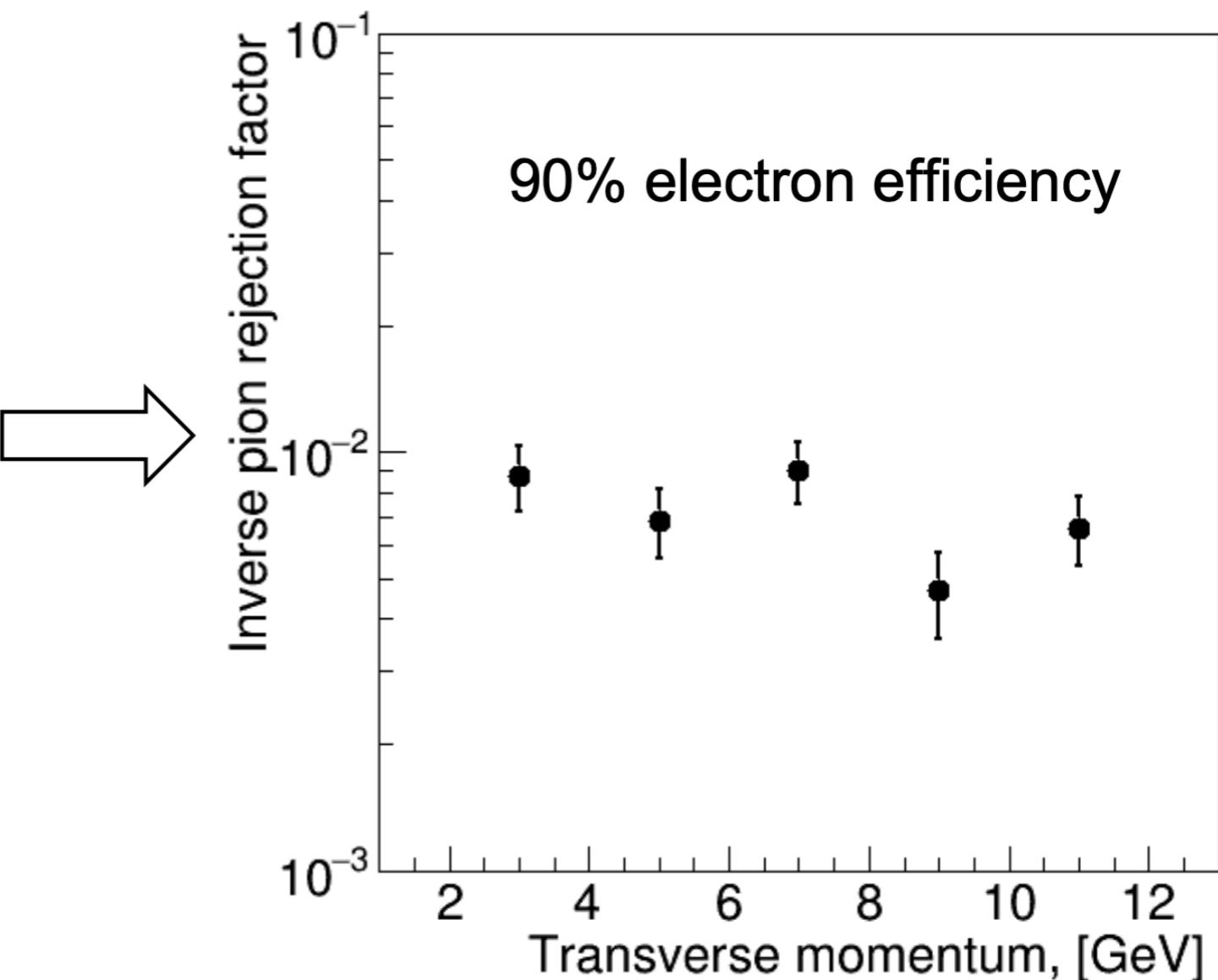
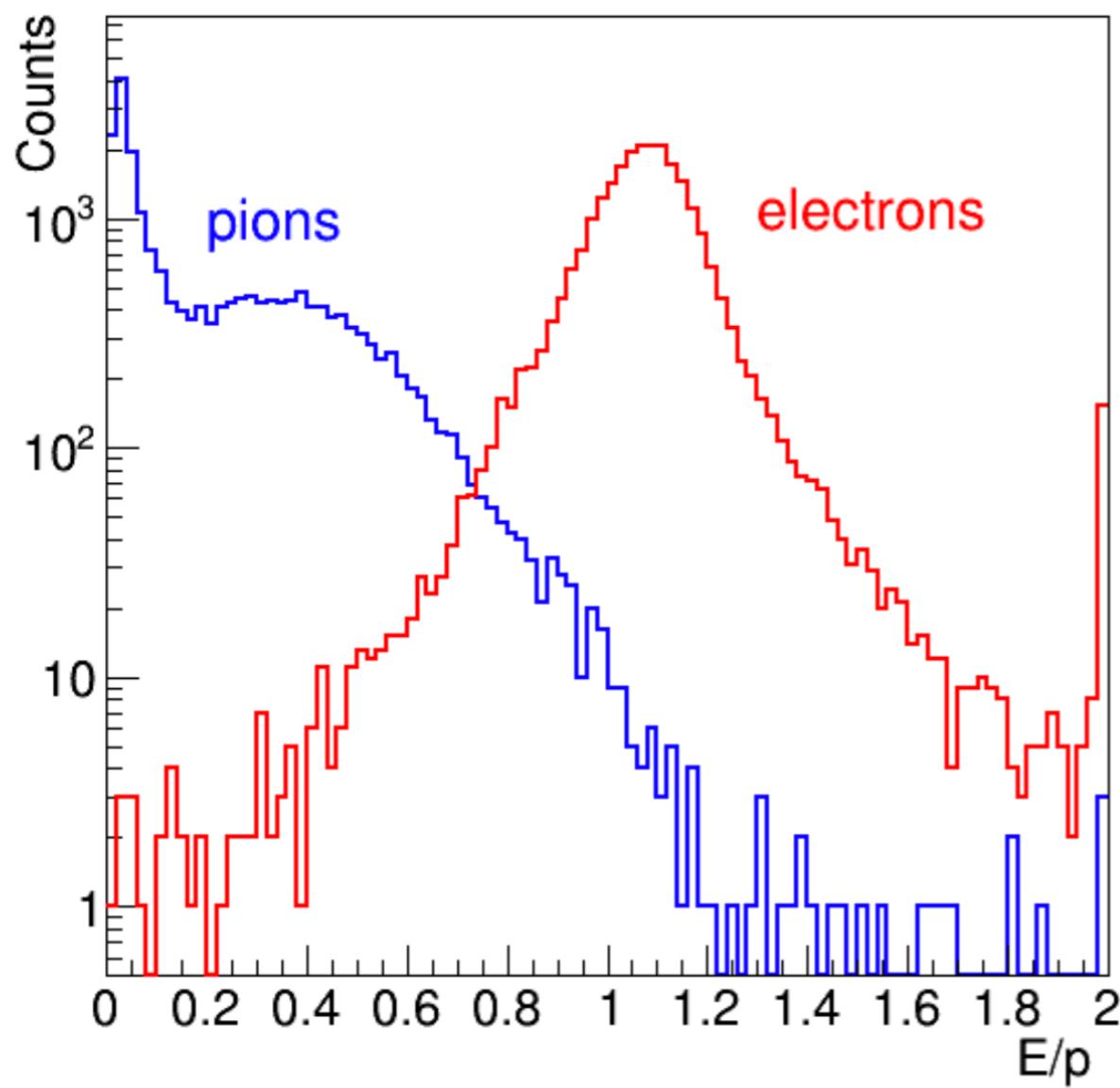
# b-jet Splitting Function $z_g$



- Differential subjet splitting function measurements thanks to the large dataset statistics
- Test pQCD model calculations in  $p + p$  collisions
- Quantify the medium modification of b-jets in the sPHENIX kinematic region
- Complementary to LHC jet substructure measurements

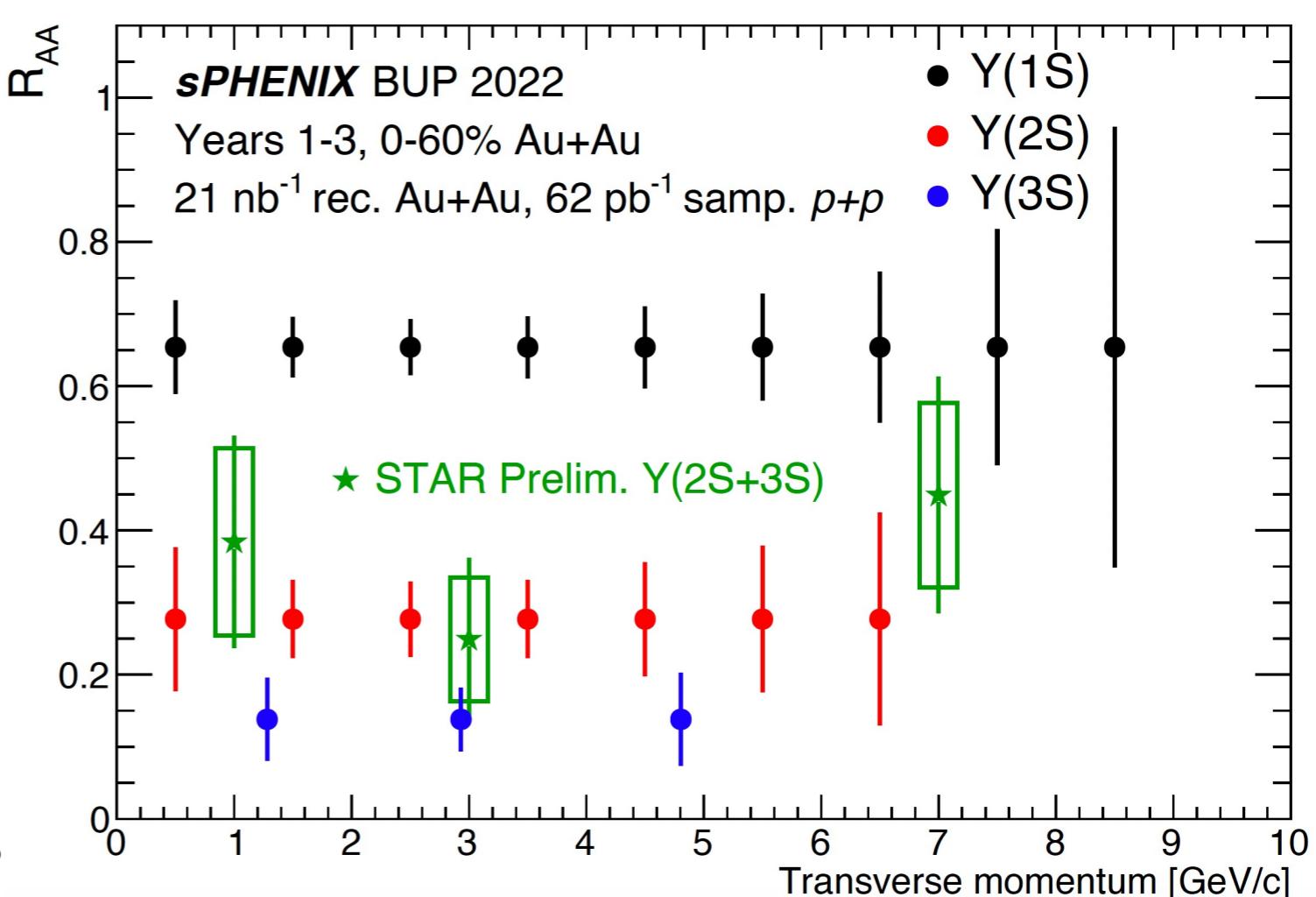
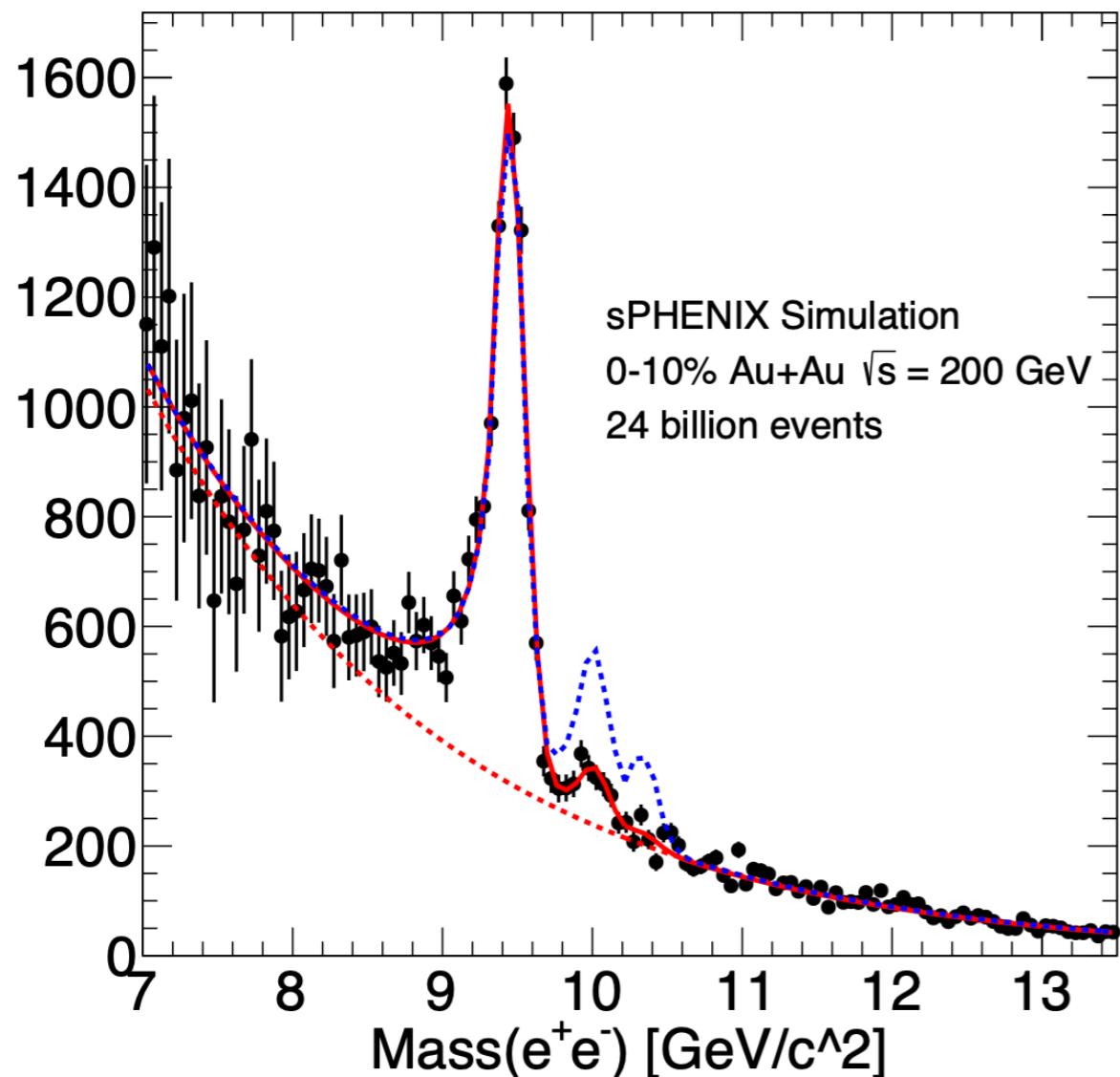
# Electron Identification Capabilities

Minimum Bias  $\sqrt{s} = 200 \text{ GeV}$  Au + Au Events

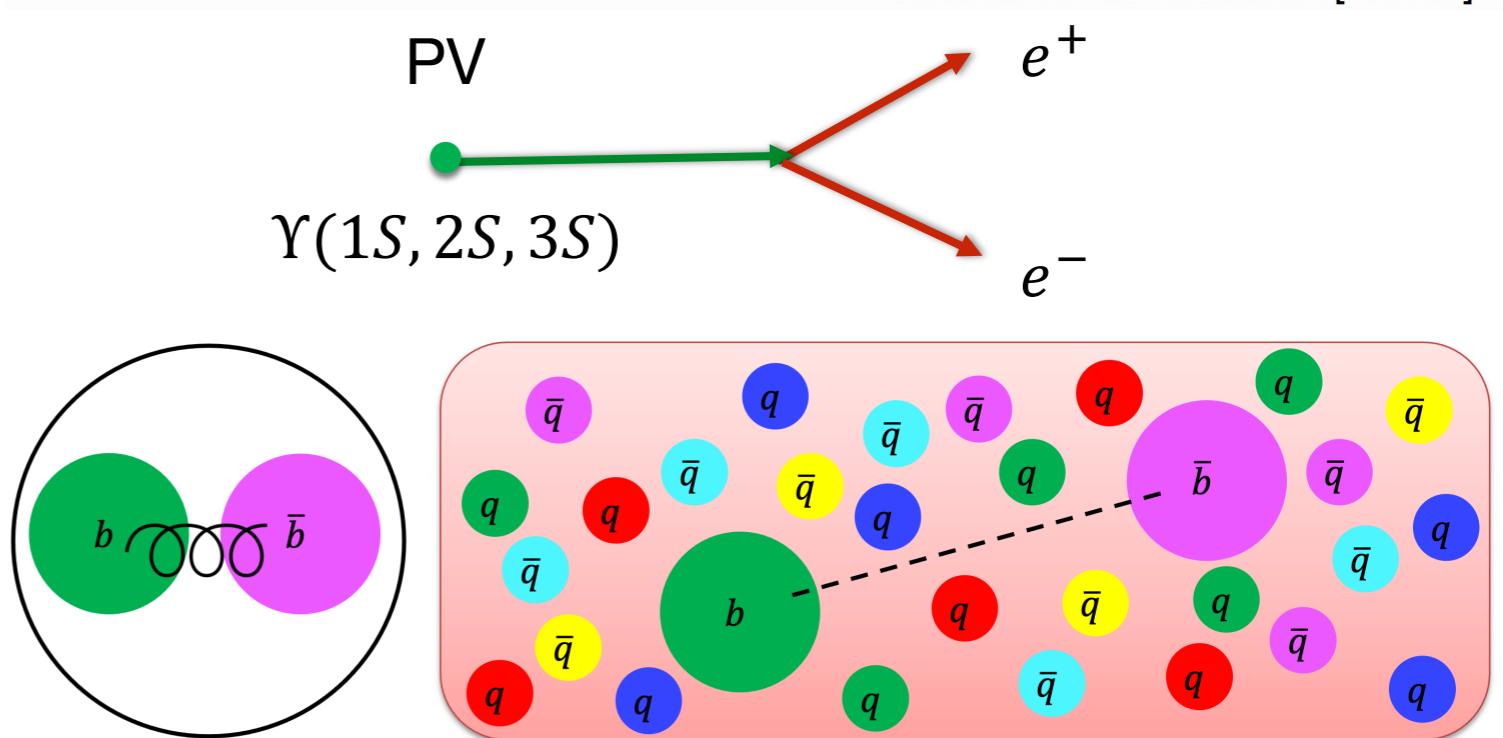


- Use shower core energy information from central EMCAL and HCAL for e/h separation
- Working point: EMCAL/ $p > 0.9$  and iHCAL/EMCAL  $< 0.2$  to maintain 90% electron efficiency
- Excellent electron identification capabilities for quarkonia background rejection
- Improvement with machine learning techniques currently in development
- Ongoing muons identification studies with machine learning techniques

# Upsilon Spectroscopy



- Measuring QGP temperature via color screening effect
- Excellent mass resolution in the dielectronic decay channel
- $R_{AA}$  measurement with high precision
- Potential observation of  $\Upsilon(3S)$  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
- Detector installation in interaction region in progress

## Detector Performance

- Excellent tracking and vertexing capabilities for heavy flavor physics measurements
- Outstanding calorimetric jet performance for heavy flavor jet studies
- Good electron identification performance for quarkonia background rejection

## Open Heavy Flavor Physics Program

- Fully reconstructed charm 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



## Hidden Heavy Flavor Physics Program

- Upsilon Spectroscopy
  - Thermometer of QGP
  - Potential observation of  $\Upsilon(3S)$  at RHIC

 **First data taking starts in around 03/2023: STAY TUNED!**



- 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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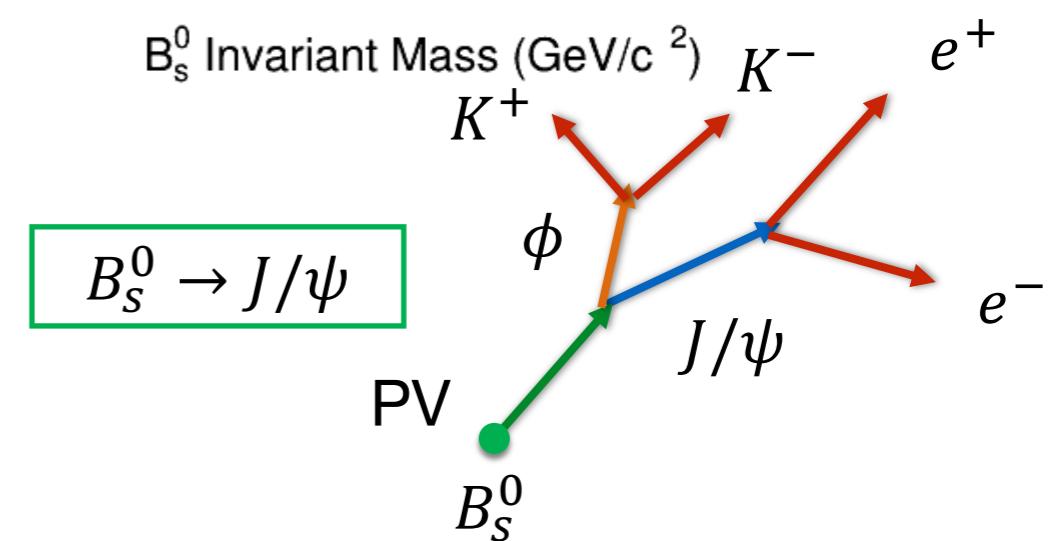
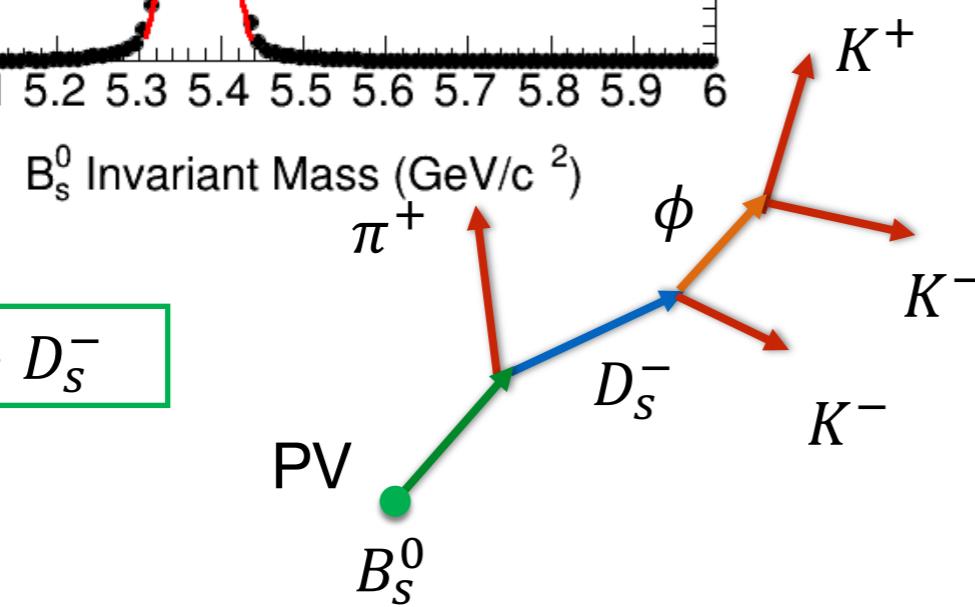
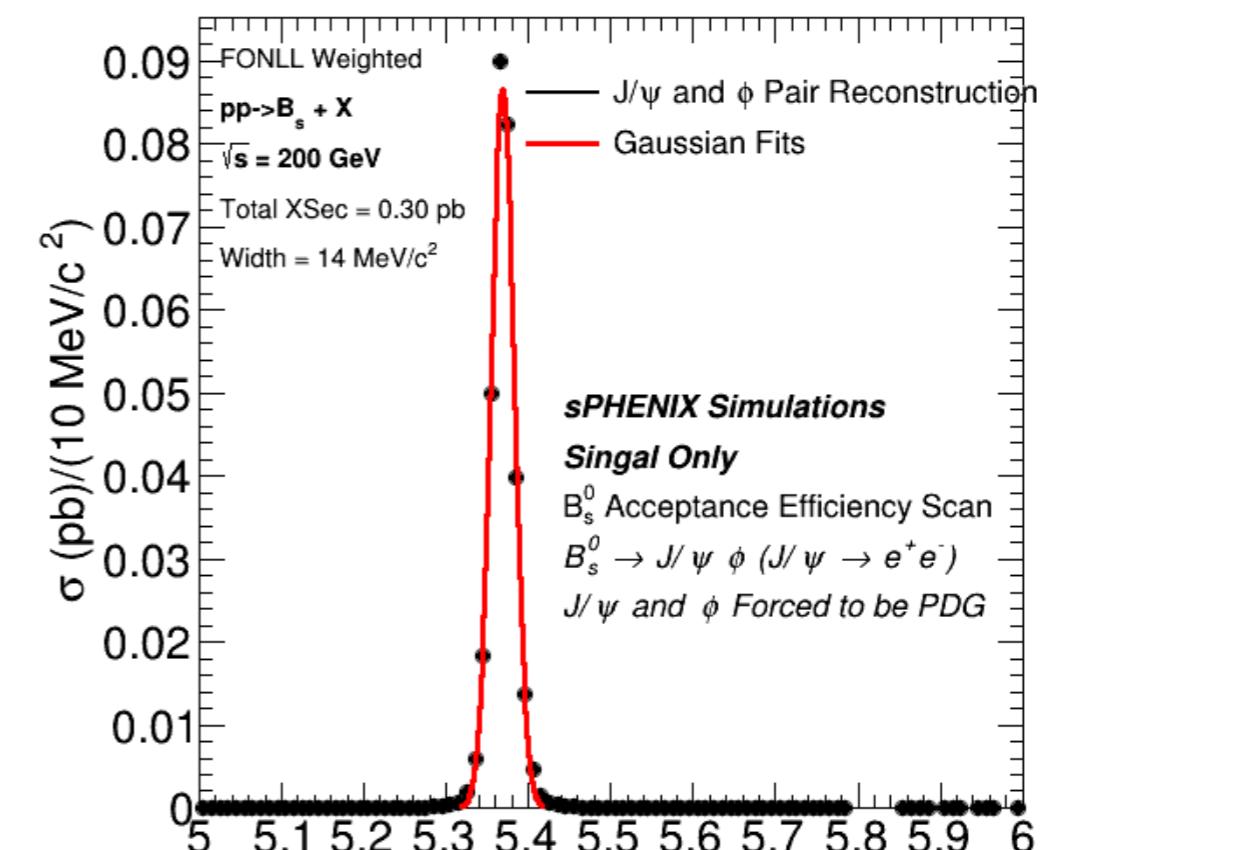
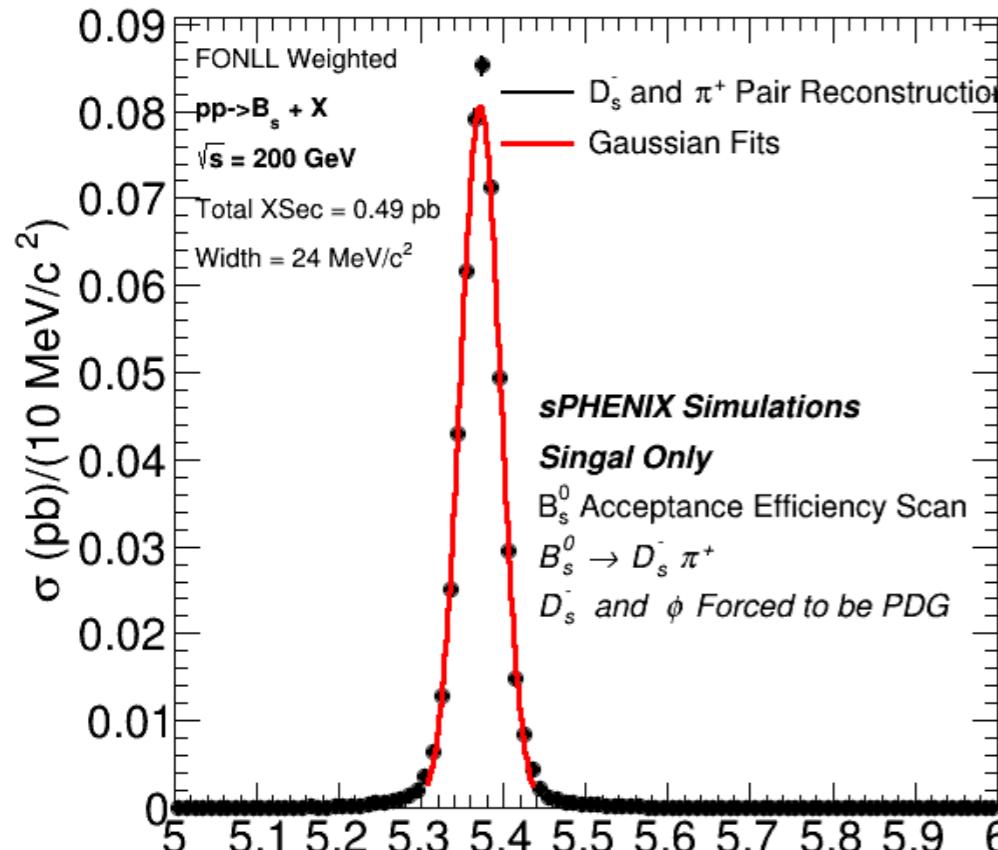


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LABORATORY DIRECTED  
RESEARCH & DEVELOPMENT

# Backup

# Fully Reconstructed $B_s^0$ Meson



- Exotic-hadron like complex 4-prong decays
- FONLL weighted  $B_s^0$  in GEANT simulation for signal only prediction
- First observation of fully reconstructed B-meson in nuclear collisions at RHIC
- Study beauty quark hadronization mechanism with  $B_s^0/B^+$  ratio
- Test QCD factorization theorem at RHIC energy in the beauty sector