sPHENIX perspectives: from HIC to EIC

Special Edition frontline report from first week of full detector physics data taking

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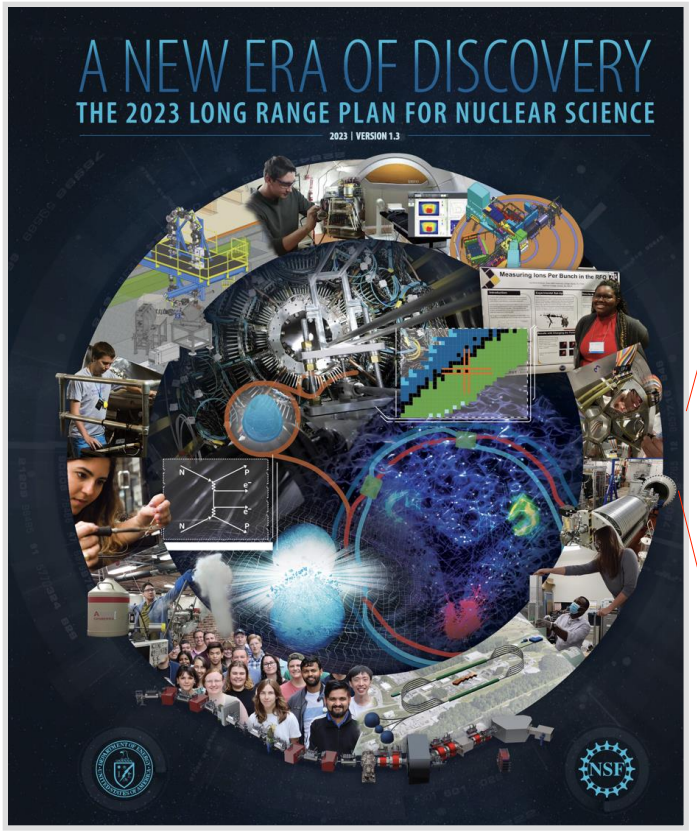
for sPHENIX Collaboration

Brookhaven National Laboratory

NSAC LRP 2023

→ completing the RHIC science program



1 | EXECUTIVE SUMMARY

- How do we use atomic nuclei to uncover physics beyond the Standard Model?

These questions are addressed by thousands of nuclear scientists working in experimental, theoretical, and computational investigations. Anchoring this world-leading program are the four national user facilities, each with unique capabilities for addressing our science questions: the Argonne Tandem Linac Accelerator System (ATLAS), CEBAF, FRIB, and the Relativistic Heavy Ion Collider (RHIC). A consortium of 13 university-based accelerator laboratories, known collectively as the Association for Research at University Nuclear Accelerators (ARUNA) laboratories, provide additional capability for cutting-edge experiments while training the next-generation scientists in the tools and techniques of nuclear science. Our work is done in small and large collaborations across the country, connecting theoretical and experimental researchers at universities and national laboratories in a dynamic and exciting enterprise that leads to scientific discovery. Our progress on these and other intriguing questions since the last Long Range Plan—and the many opportunities for the future—are covered in this plan. We describe some of the many technological and computational innovations that drive our field and lead to considerable benefits to society. Central to this work are the people: we highlight the process of training nuclear scientists and how they go on to contribute to our nation in many areas.

Our vision for the future builds on the ongoing, world-leading US program in nuclear science, which includes

- Unfolding the quark and gluon structure of visible matter and probing the Standard Model at the 12 GeV CEBAF facility.
- Exploring the nature of quark–gluon matter and the spin structure of the nucleon at the RHIC facility and through leadership across the heavy ion program at the Large Hadron Collider (LHC).
- Making breakthroughs in our understanding of nuclei and their role in the cosmos through research at the nation's low-energy user facilities, ATLAS, the newly constructed FRIB, the ARUNA laboratories, and key national laboratory facilities.
- Carrying out a targeted program of experiments, distributed across the United States, that reaches for physics beyond the Standard Model through rare process searches and precision measurements.
- Explaining how data gathered in these endeavors are connected and consistent through theory and computation. Nuclear theory motivates, interprets, and contextualizes experiments, opening up fresh research vistas.

Here are the recommendations of the 2023 Long Range Plan.

RECOMMENDATION 1
The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

This recommendation requires

- Increasing the research budget that advances the science program through support of theoretical and experimental research across the country, thereby expanding discovery potential, technological innovation, and workforce development to the benefit of society.
- Continuing effective operation of the national user facilities ATLAS, CEBAF, and FRIB, and completing the RHIC science program, pushing the frontiers of human knowledge.
- Raising the compensation of graduate researchers to levels commensurate with their cost of living—without contraction of the workforce—lowering barriers and expanding opportunities in STEM for all, and so boosting national competitiveness.
- Expanding policy and resources to ensure a safe and respectful environment for everyone, realizing the full potential of the US nuclear workforce.

Nuclear science is an ecosystem in which facility operations and research at laboratories and universities by senior investigators, technical staff, postdocs, and students work together to drive progress on the forefront science questions discussed above and throughout this Long Range Plan. A healthy workforce is central not only to these scientific goals but also to the nation's security, technological innovation, and prosperity.

Next, we reaffirm the exceptionally high priority of the following two investments in new capabilities for nuclear physics. The Electron–Ion Collider (EIC), to be built in the United States, will elucidate the origin of visible matter in the universe and significantly

3

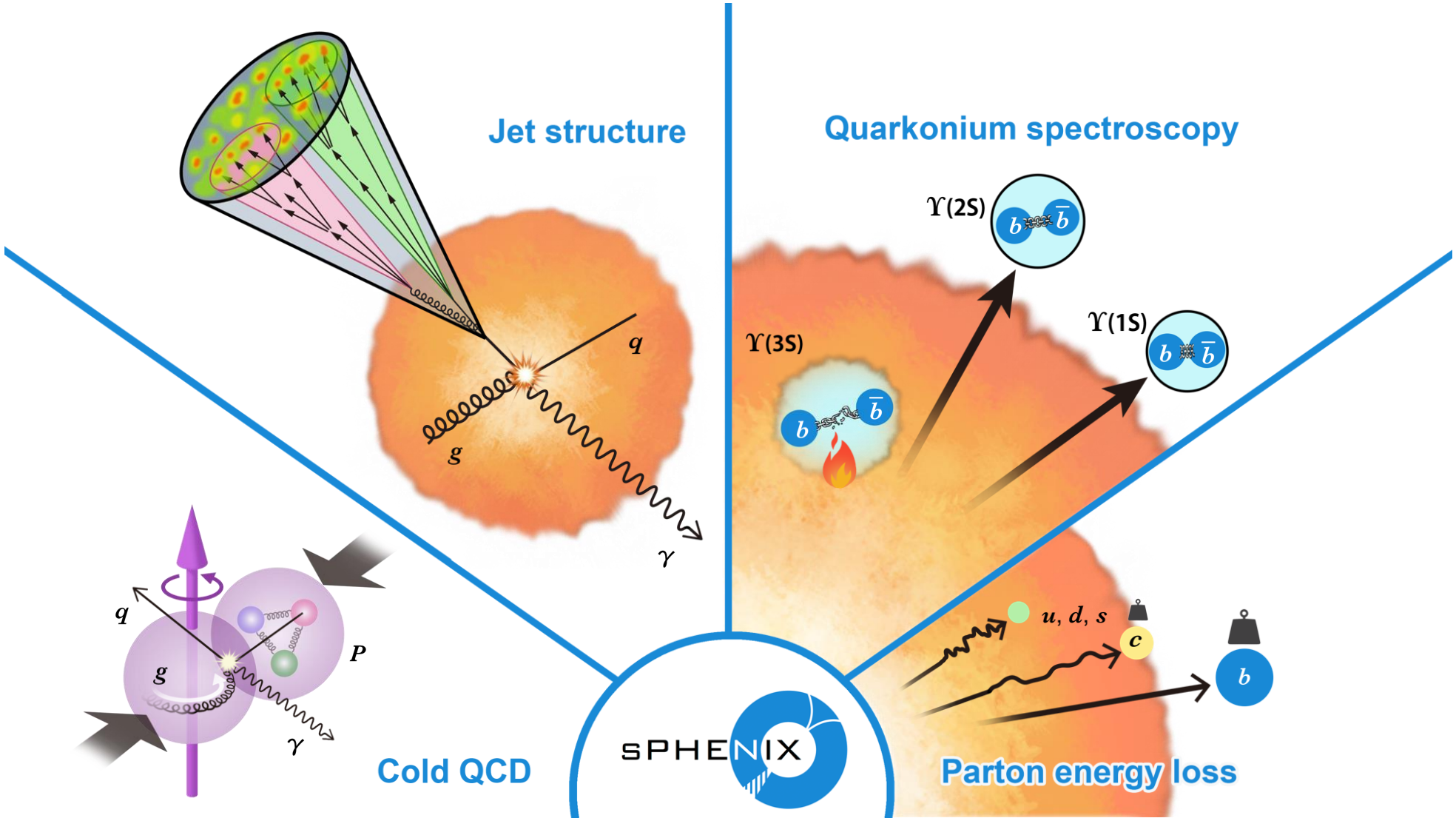
- Continuing effective operation of the national user facilities ATLAS, CEBAF, and FRIB, and completing the RHIC science program, pushing the frontiers of human knowledge.

RECOMMENDATION 3
We recommend the expeditious completion of the EIC as the highest priority for facility construction.

Brookhaven National Laboratory

Cornerstones of sPHENIX science program

Strong connection from HIC to EIC: from detector, analysis technique to physics



2010 sPHENIX proposed as upgrade / replacement of PHENIX

2012 Initial proposal

2014 Full proposal

2015 BaBar magnet arrives from SLAC

2016 Collaboration formed

2016 Final PHENIX run

2016 Test beam HCal, EMCal

2016 CD-0 (mission need)

2018 CD-1/3a (begin final design, place long lead-time procurements)

Sept 2019 PD2/3 (review complete)

March 2019 Approved CERN experiment

2018 Test beam EMCal

Begin construction…

Beam-use proposal

Aug 2020

RHIC 20 years

Oct 2020

Transition from MIE detector pre-production to production

Construction of detectors, infrastructure, software

End of construction

Dec 2021

RHIC incident Aug 2023
Transferred commission time to Run24

Installation

Dec 2022

Run 2023 Commis. & AuAu candles

Dec 2023

Run 2024 pp ref. & cold QCD

Dec 2024

Run 2025 AuAu high stat

Dec 2025

Data Campaign 2?

Dec 2027

Towards a potential relationship with the EIC

Data Campaign 1

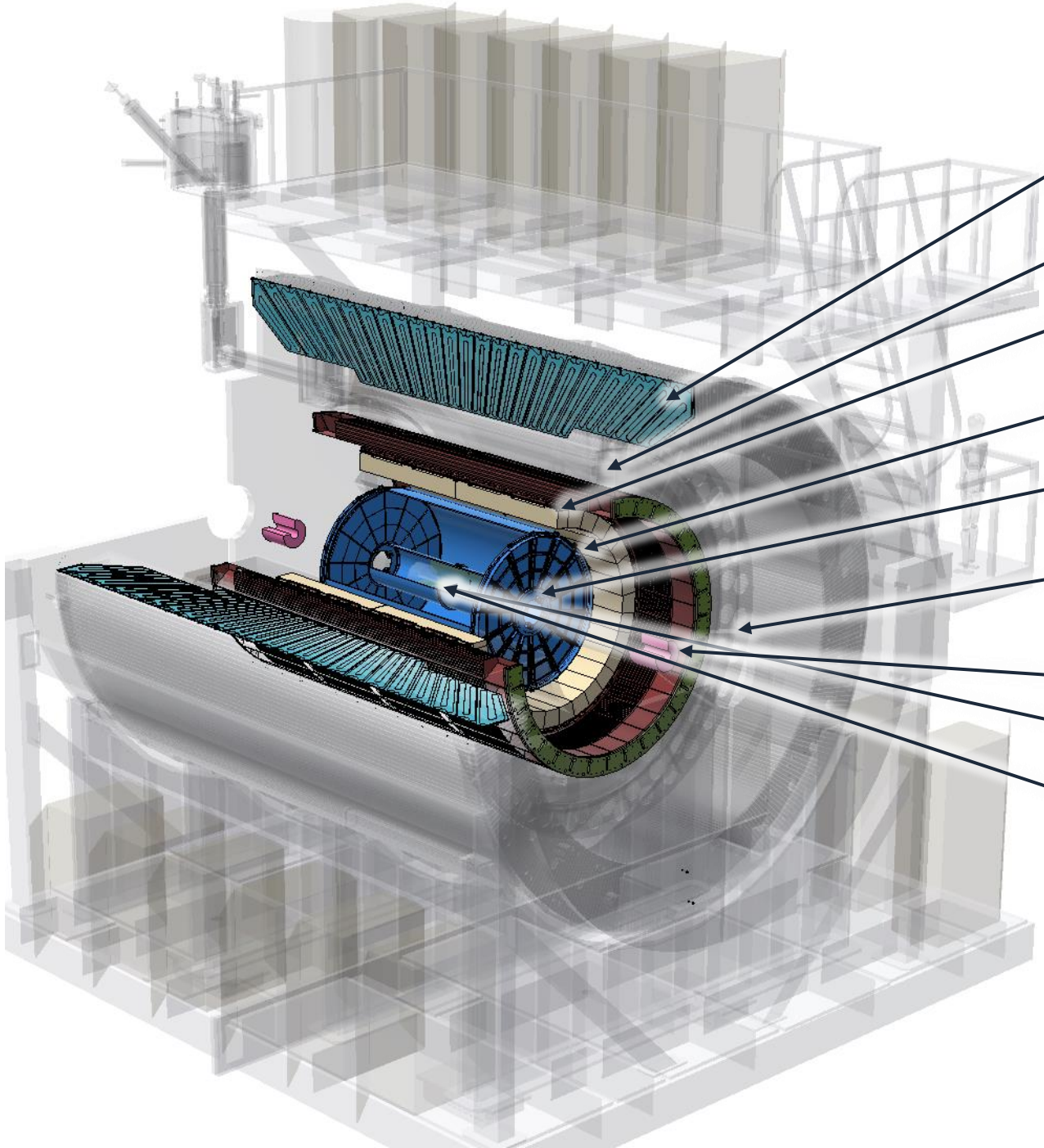
PD-4 date

INSTITUTE for NUCLEAR THEORY

Heavy Ion Physics in the EIC Era

All time info is in **Pacific Time (UTC -7)**; please convert accordingly. **This is an in-person program.**

Program talks will take place in room C421.



Hadronic Calorimeter(s)

1.4 T super conducting magnet

Electromagnetic Calorimeter

Micromegas Outer Tracker (TPOT)

Time Projection Chamber (TPC)

Event plane detector (EPD)

M.B. and Event Plane Detectors

Intermediate Tracker (INTT)

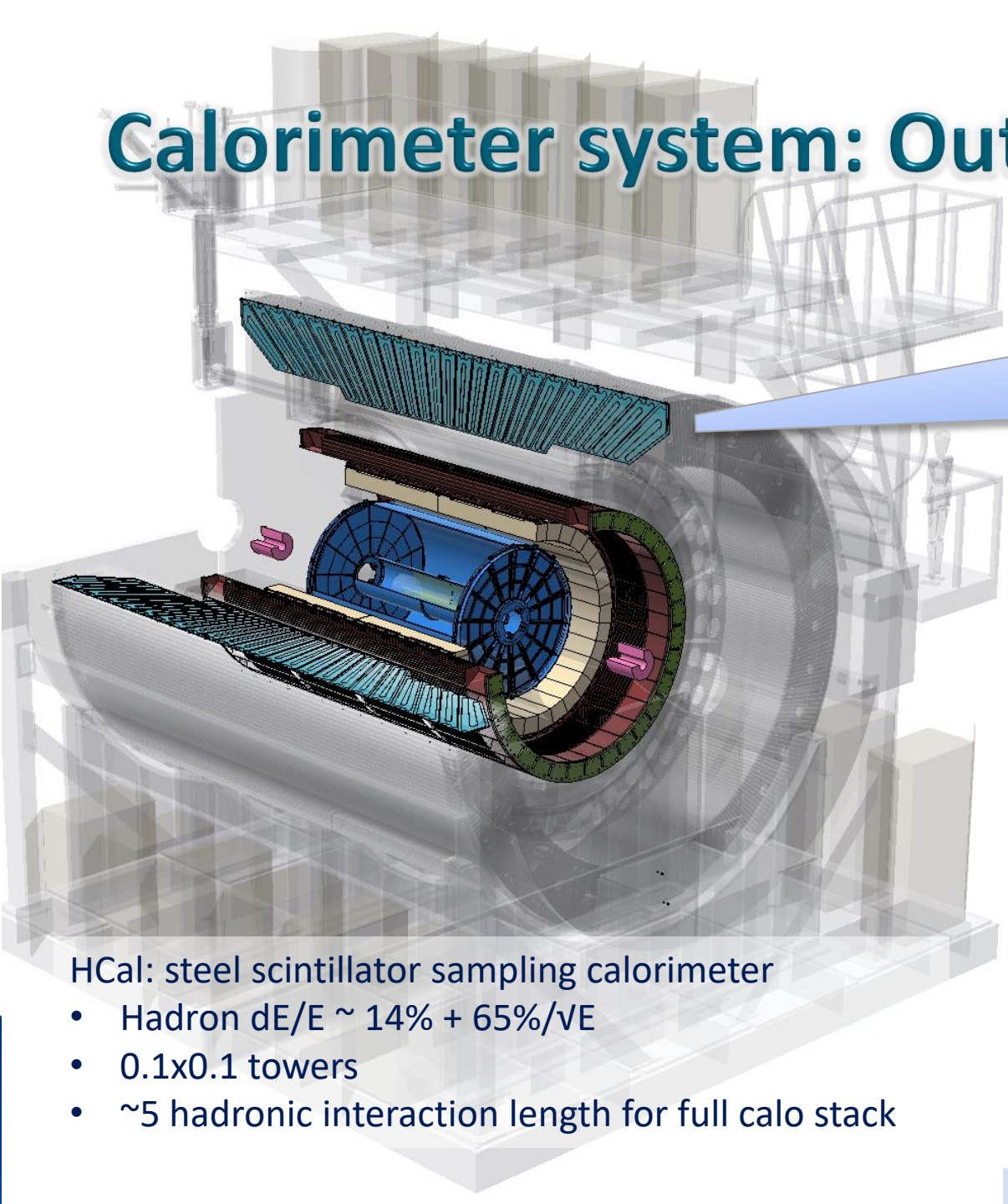
MicroVertex Detector (MVTX)

DAQ:

15 kHz calo trigger + 10% streaming

10 GB/s data logging

Calorimeter system: Outer HCal (Reuse in EIC)



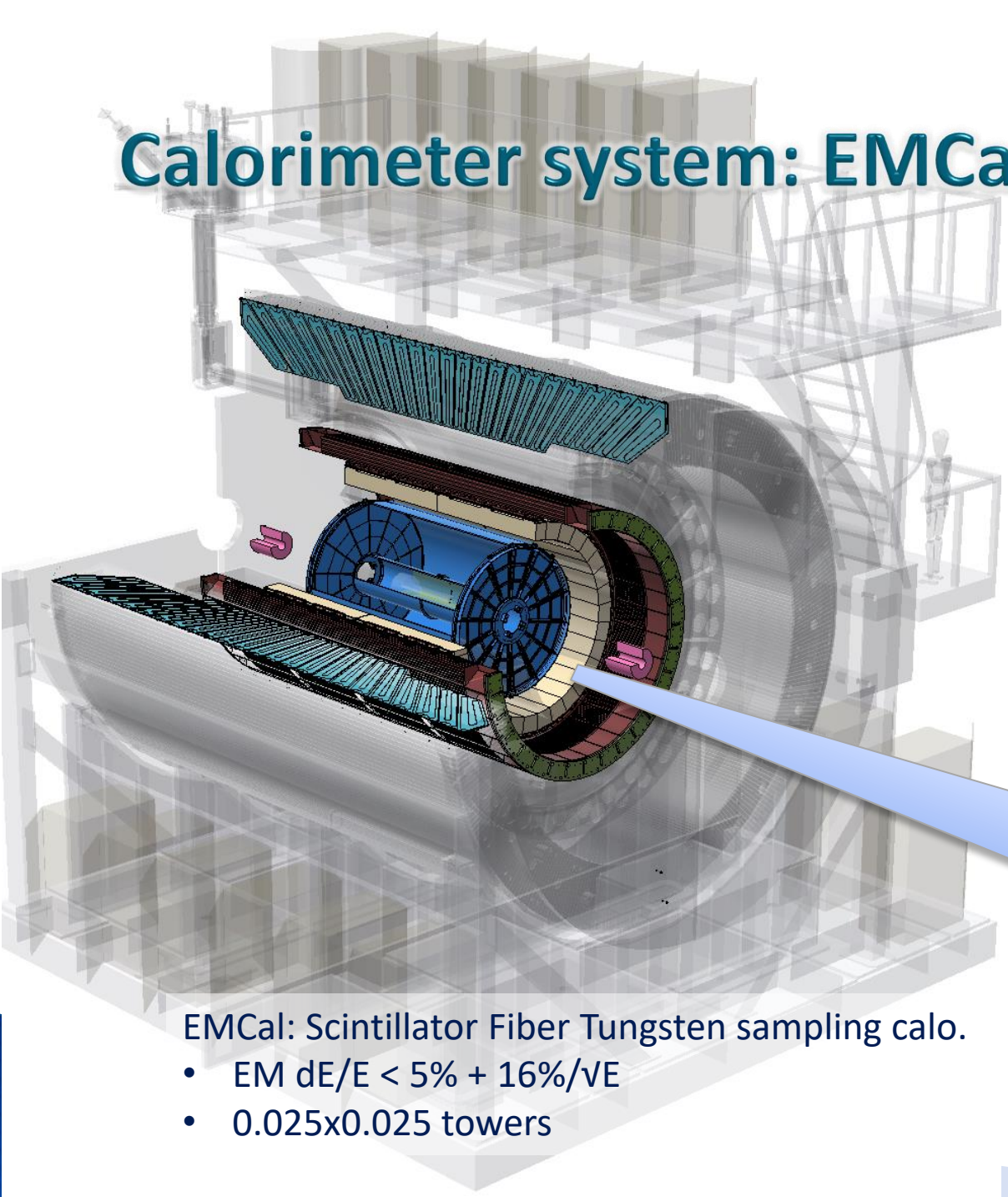
HCal: steel scintillator sampling calorimeter

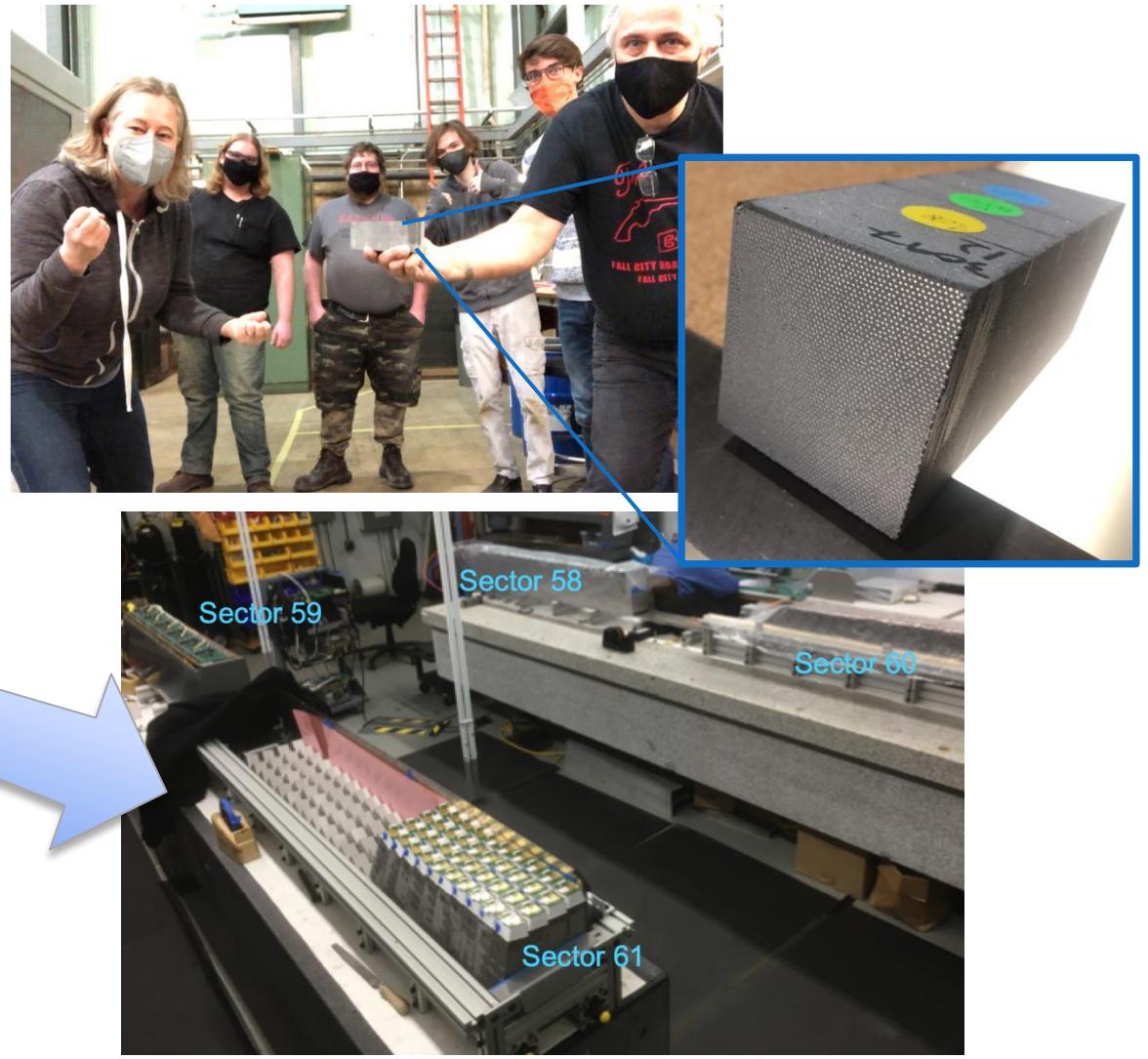
- Hadron dE/E ~ 14% + 65%/√E
- 0.1x0.1 towers
- ~5 hadronic interaction length for full calo stack

Calorimeter system: Inner HCal

Inner HCal: Al-scintillation tile sampling calorimeter
Mechanical support for EMCal + EM-shower tail catcher
+ constraint longitudinal position of hadronic shower

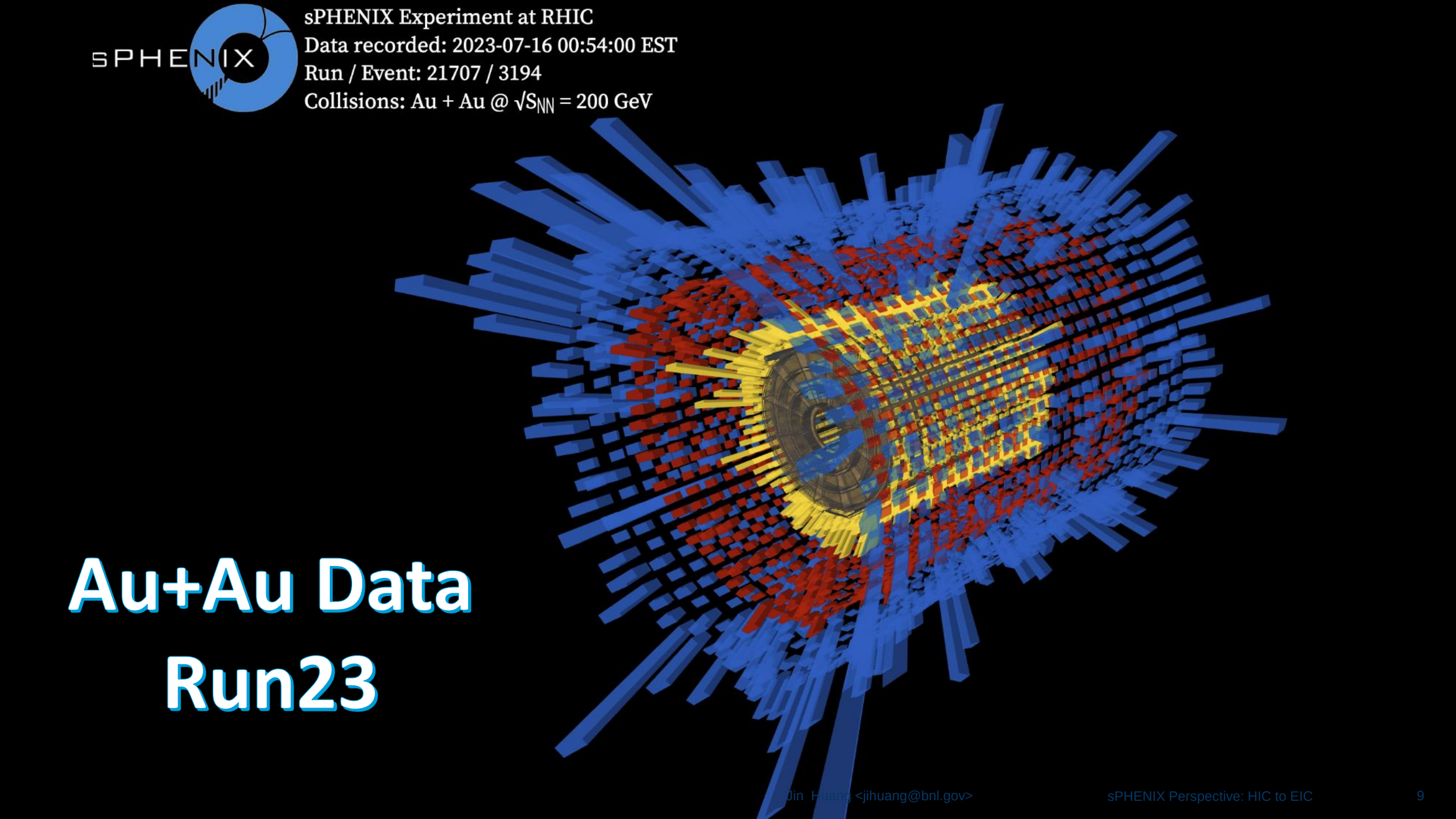
Calorimeter system: EMCal (same tech. as EIC fECal)





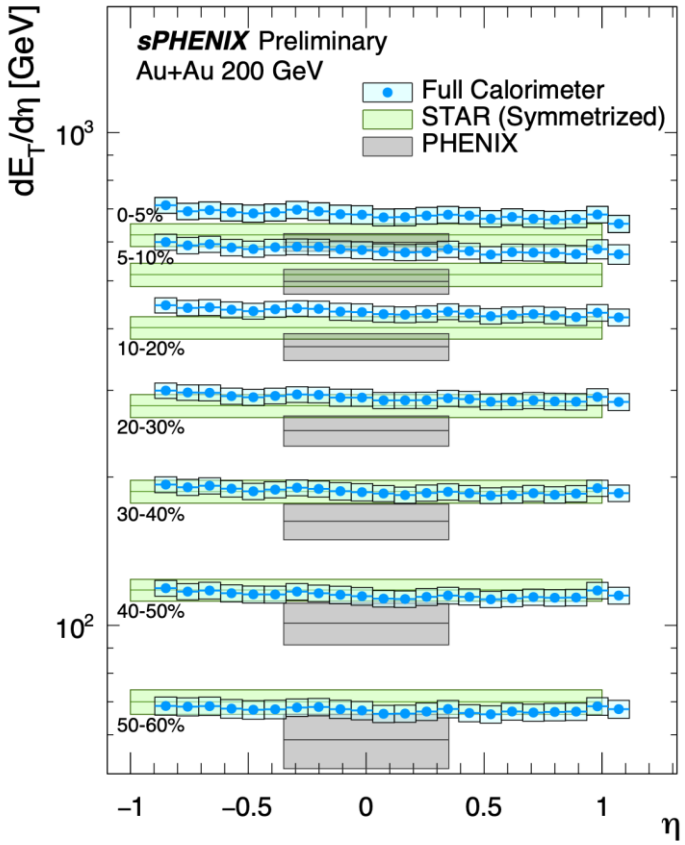
EMCal: Scintillator Fiber Tungsten sampling calo.

- EM dE/E < 5% + 16%/√E
- 0.025x0.025 towers

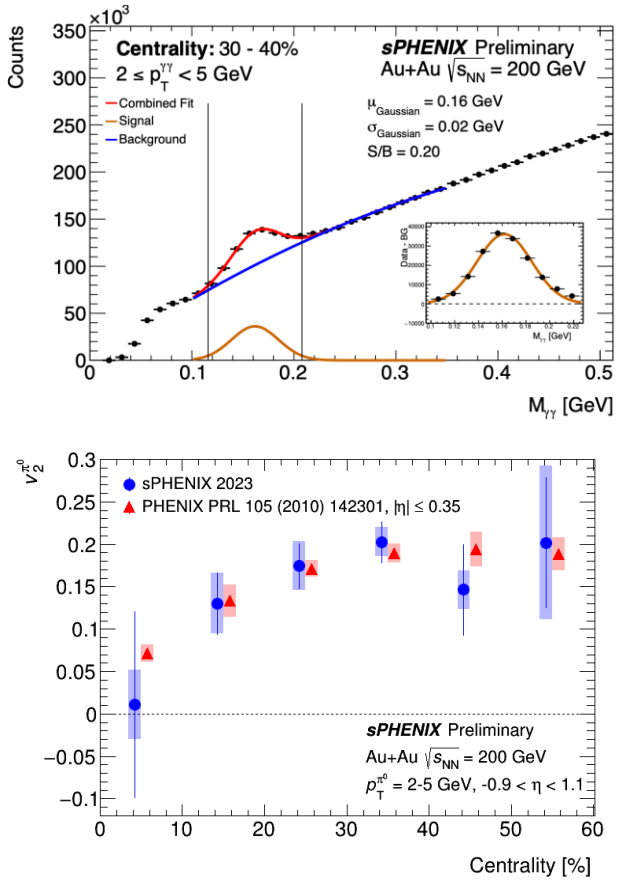


Au+Au Data Run23

Run23 commissioning: First “standard candle” analyses

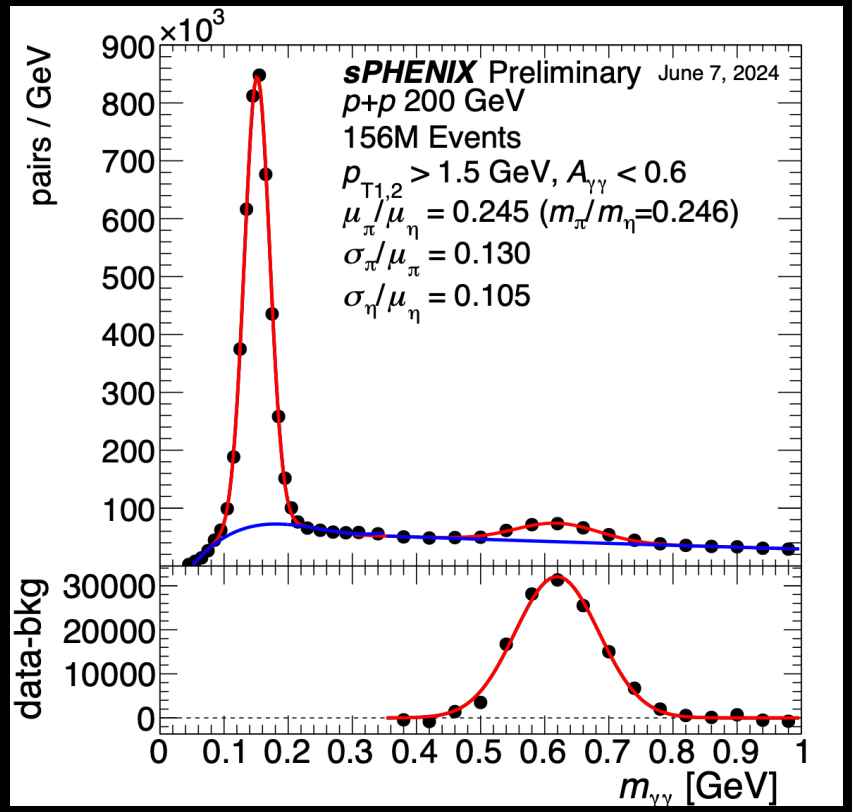


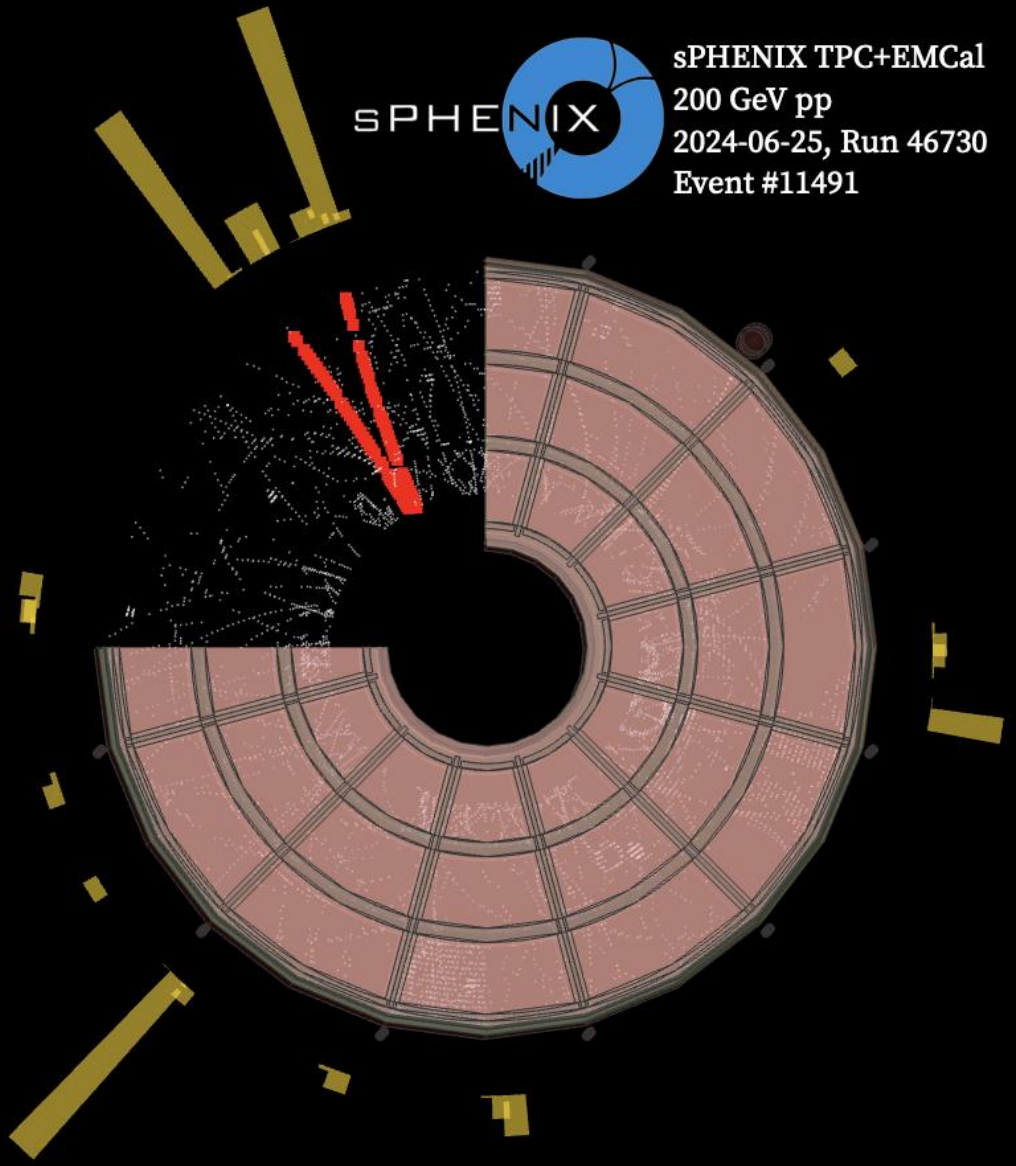
Fully corrected $dE_T/d\eta$ measurements using the sPHENIX calorimeter system. STAR and PHENIX measurements are included for comparison.



$v_2^{\pi 0}$ as a function of centrality, integrated over the range of $2 \geq p_T \geq 5$ GeV. sPHENIX data (blue) are shown in comparison to results from PHENIX (red)

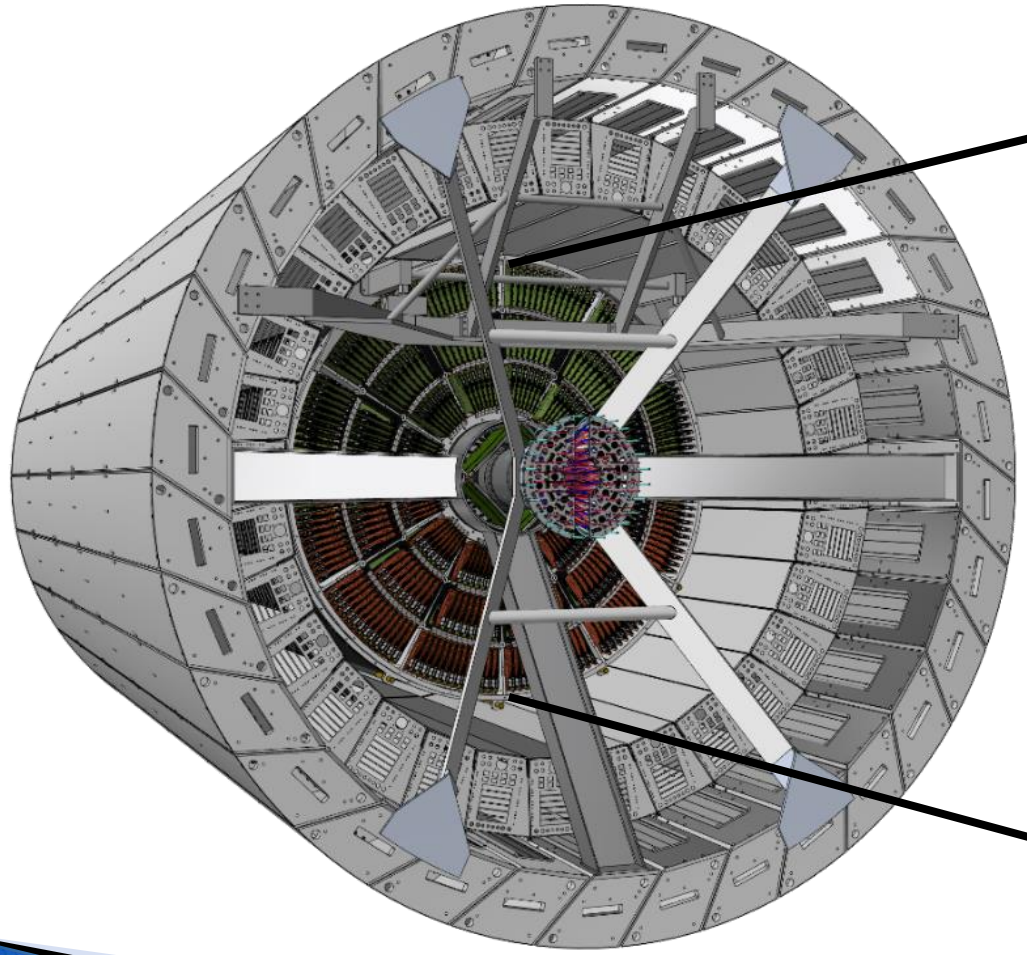
Analyses of Run 24 data are underway



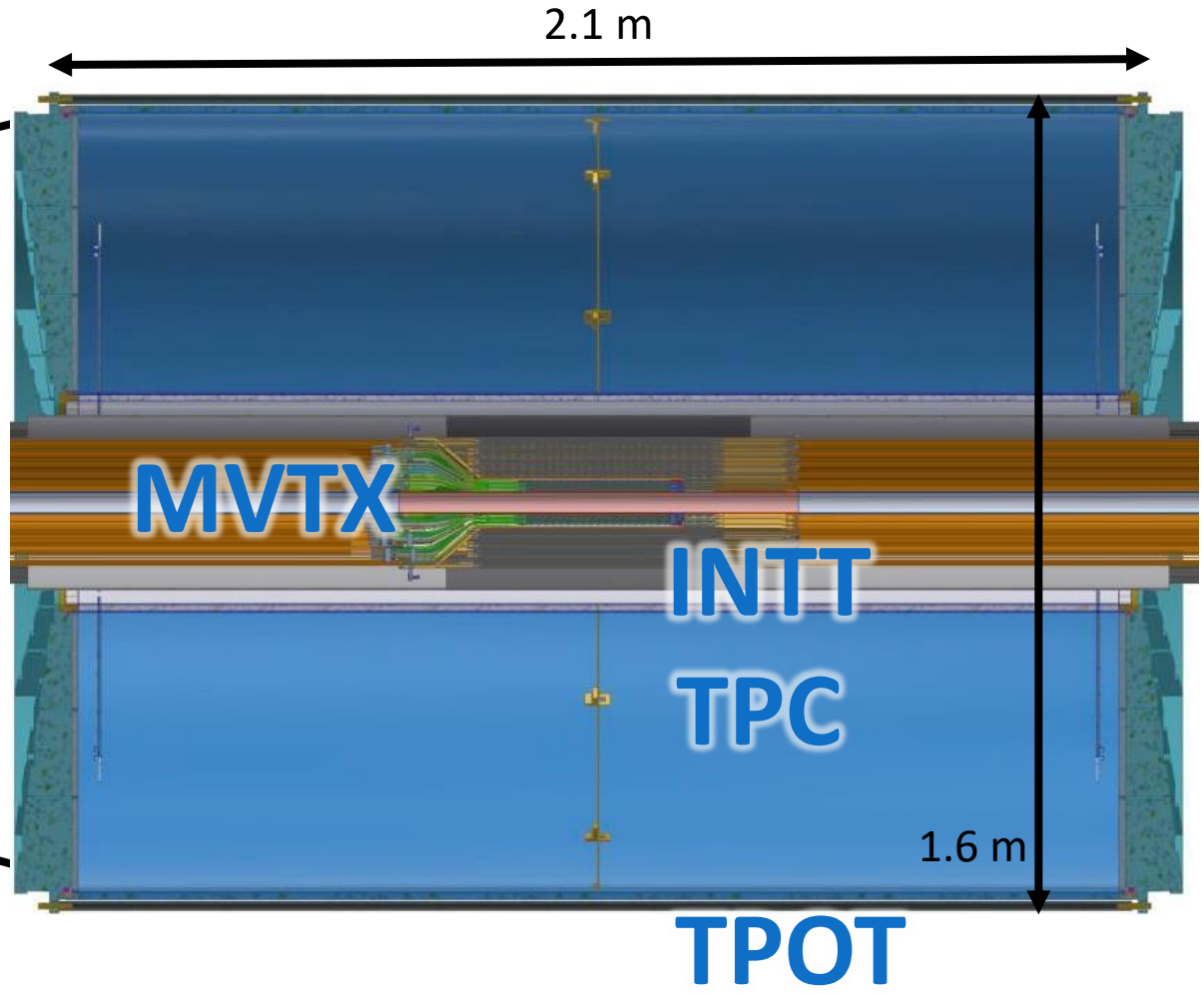


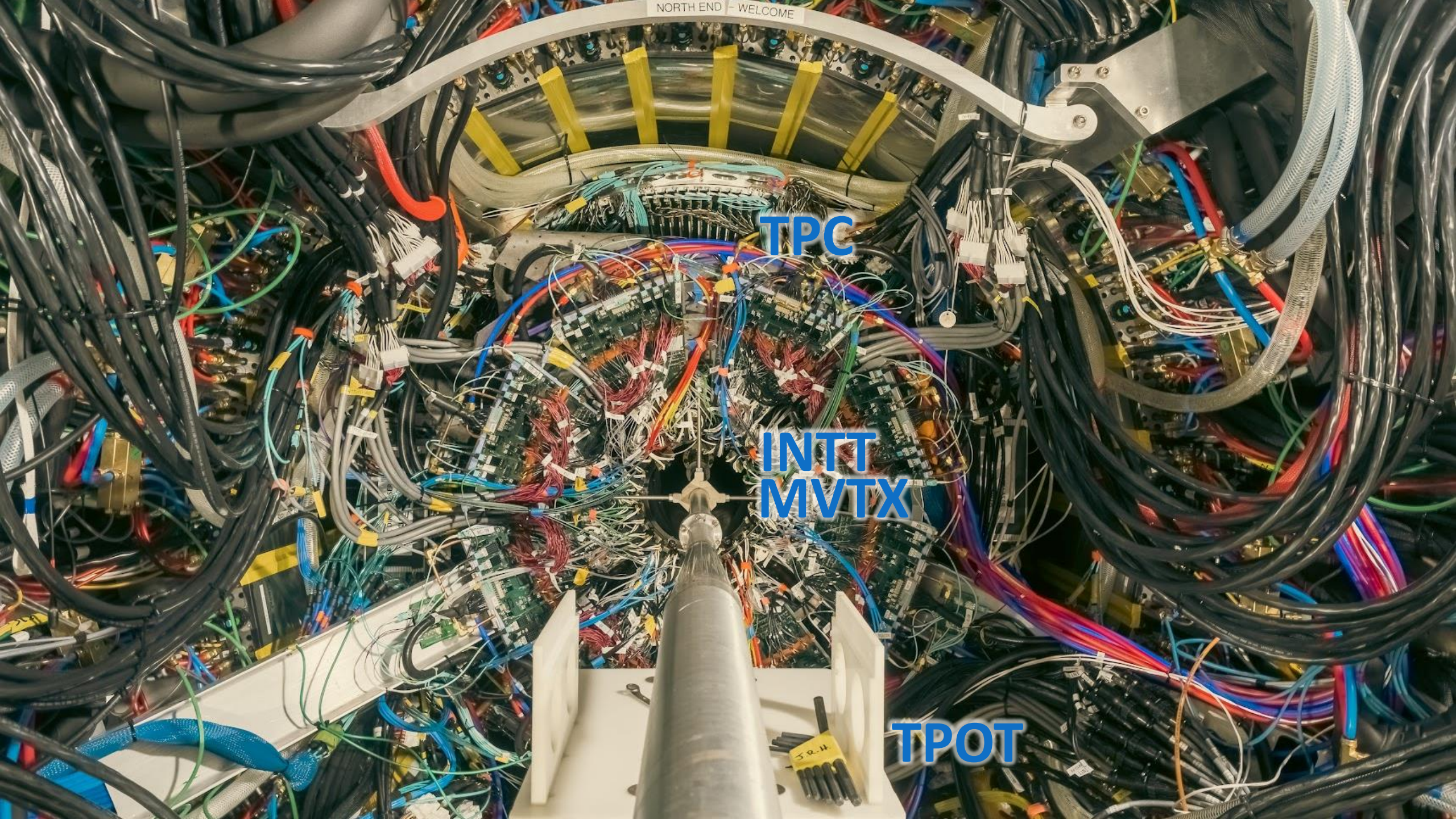
- π^0 and η invariant mass distributions
- 0.01% of collected data

sPHENIX Tracking Detectors

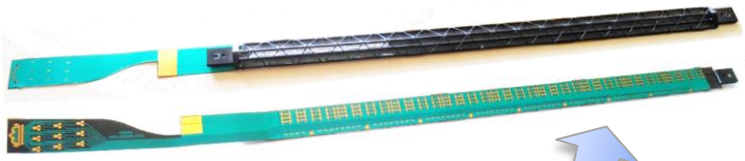


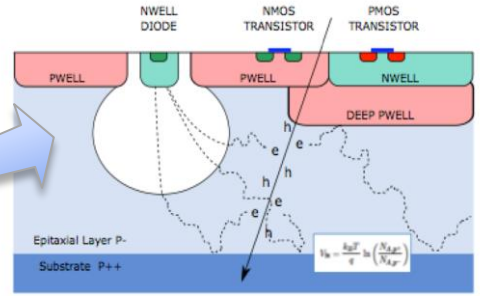
Detectors inside the magnet

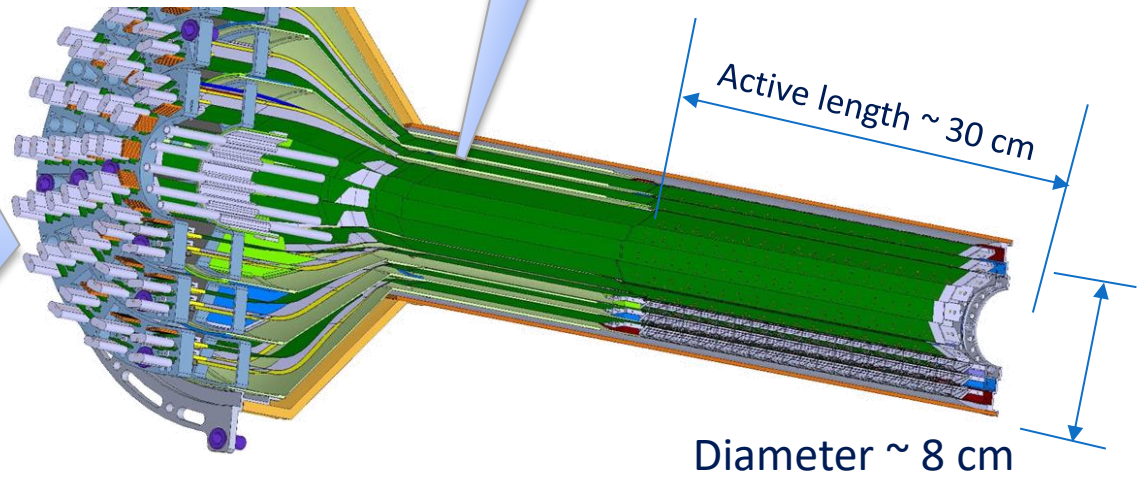



NORTH END - WELCOME
TPC
INTT
MVTX
TPOT

Precision vertex trackers

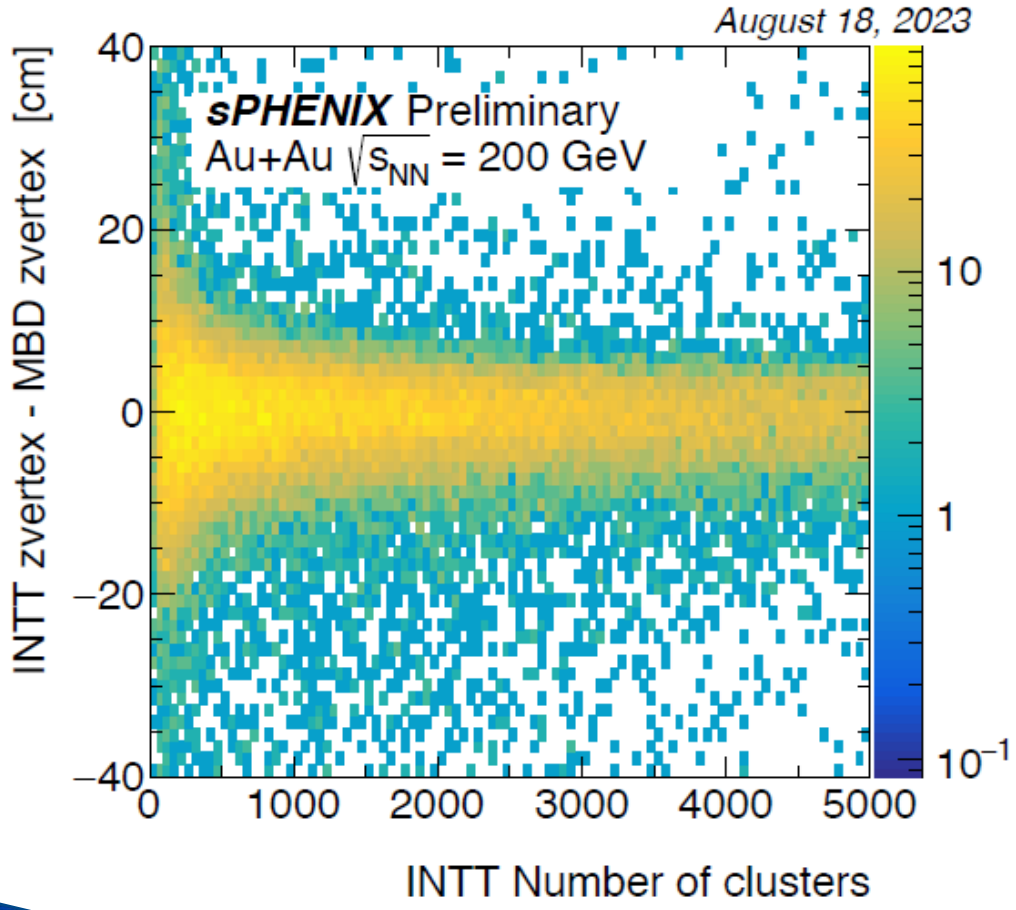


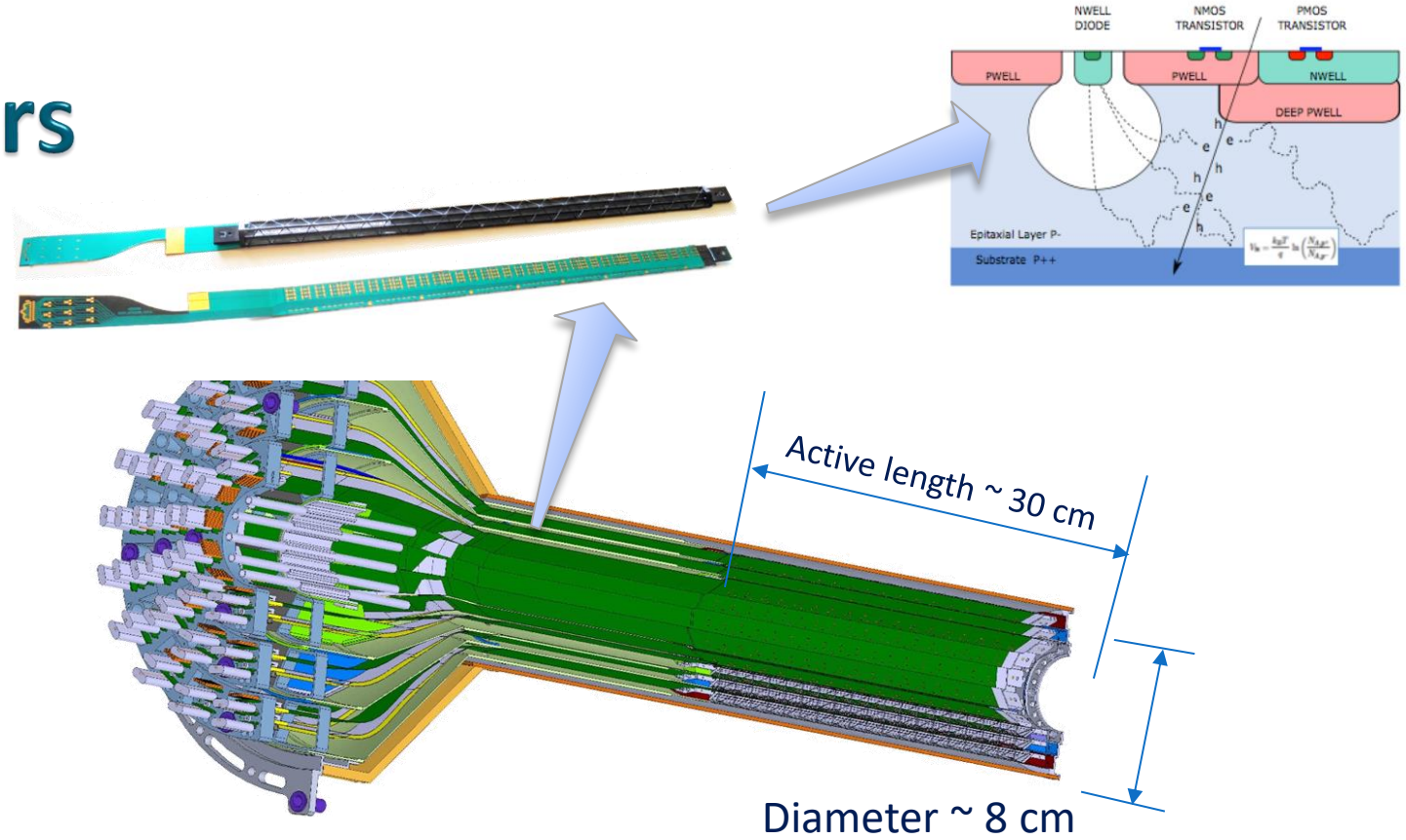




- **MVTX**: MAPS based vertex tracker, 3 layers
  - Using staves from ALICE ITS2 upgrade
  - ALPIDE chip, 30um pitch, Low mass (~0.3% X_0)
  - 5um position resolution, 5-10us integration time
  - Technology foundation to the EIC SVT main tracker
- **INTT**: silicon strip tracker, 2 layers
  - 78 um pitch, provides timing tag resolving bunch crossing

Precision vertex trackers





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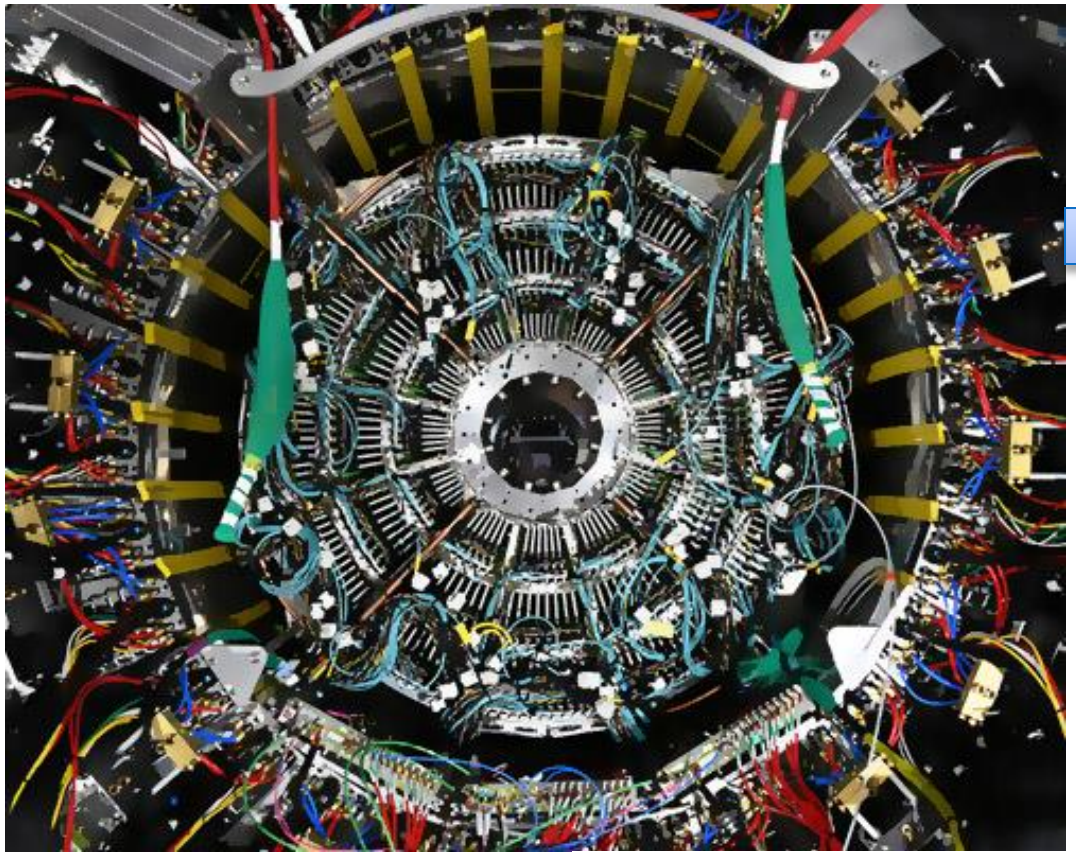
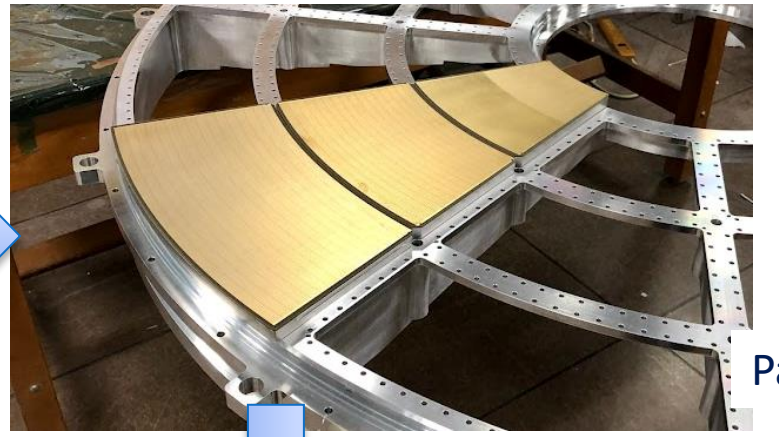
Main tracker: Time projection chamber (TPC)



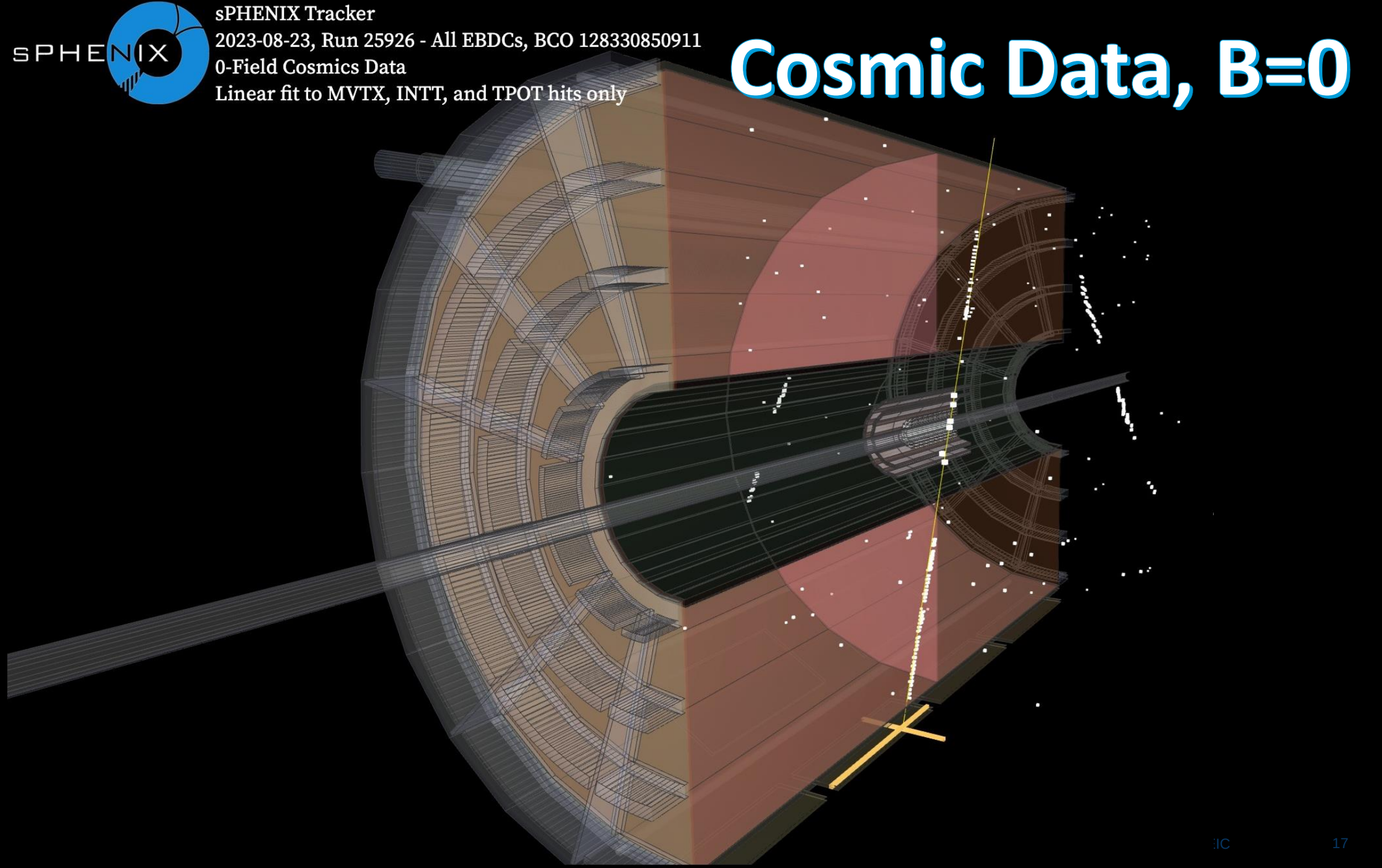
Installed TPC in sPHENIX



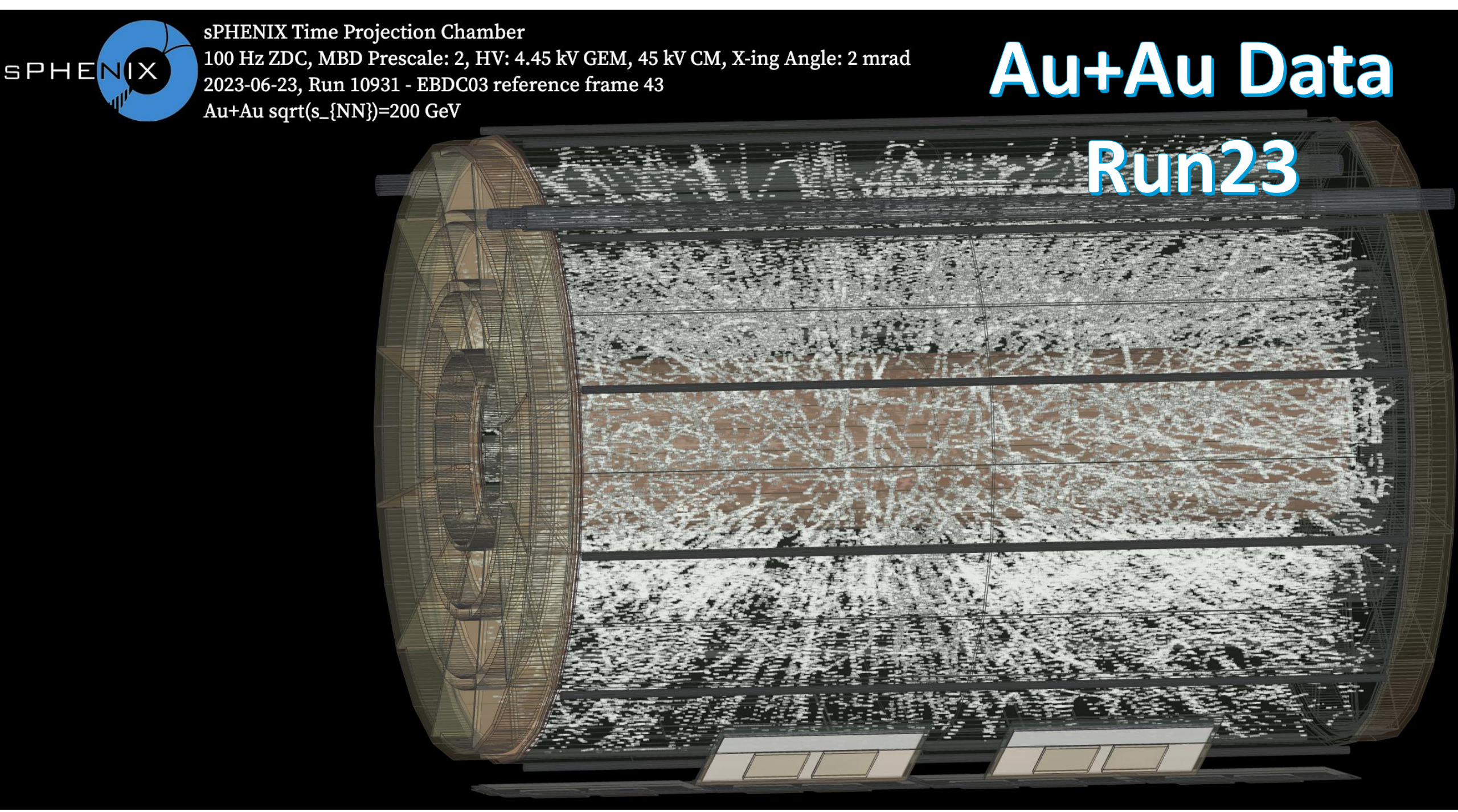
Pad Planes

TPC FEE

FELIX Readout card



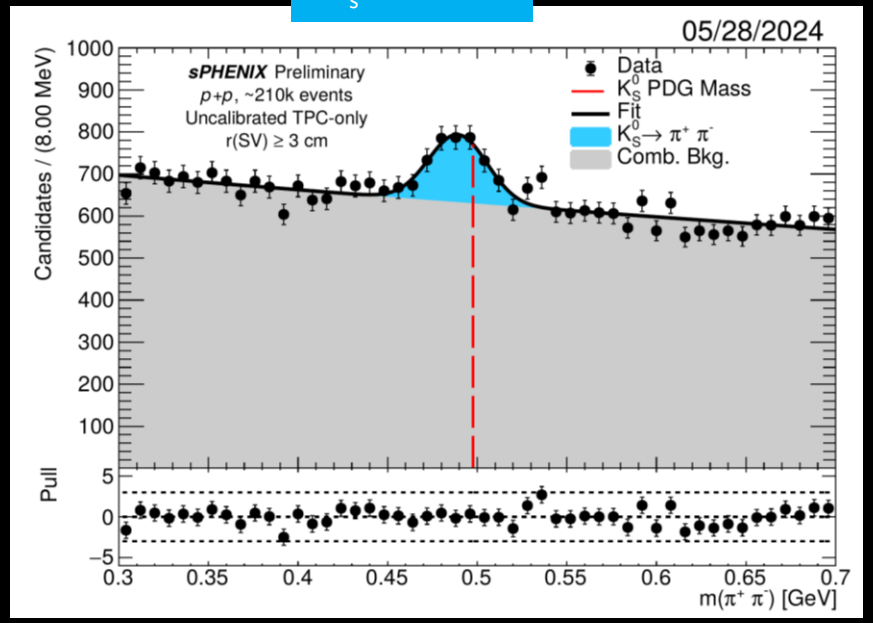
Cosmic Data, B=0


sPHENIX
sPHENIX Time Projection Chamber
100 Hz ZDC, MBD Prescale: 2, HV: 4.45 kV GEM, 45 kV CM, X-ing Angle: 2 mrad
2023-06-23, Run 10931 - EBDC03 reference frame 43
Au+Au sqrt(s_{NN})=200 GeV
Au+Au Data
Run23

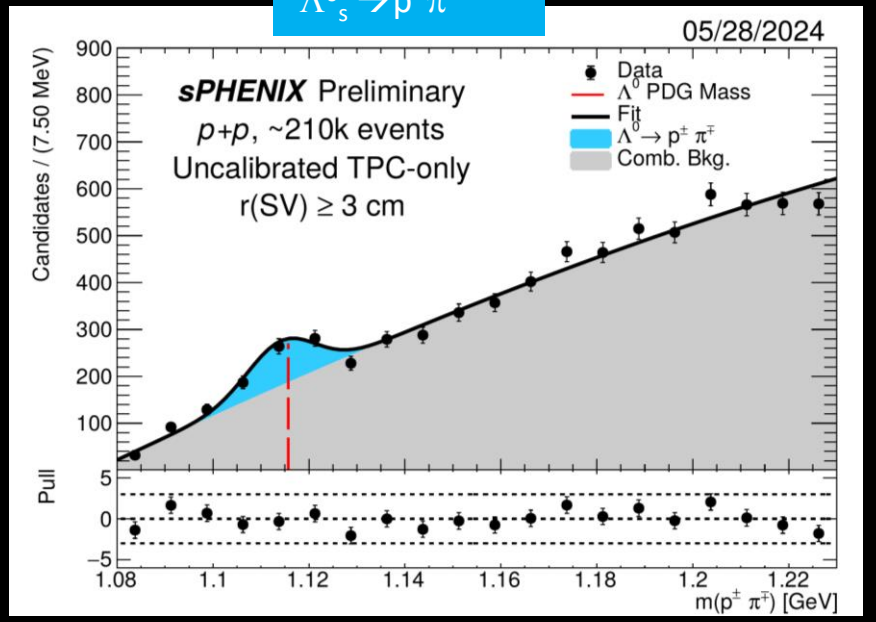
sPHENIX Tracking
No TPC distortion corrections
2024-6-12, Run 41989
BCO: 401966769578532
200 GeV p+p

p+p Data Run24

$K^0_s \rightarrow \pi^+\pi^-$

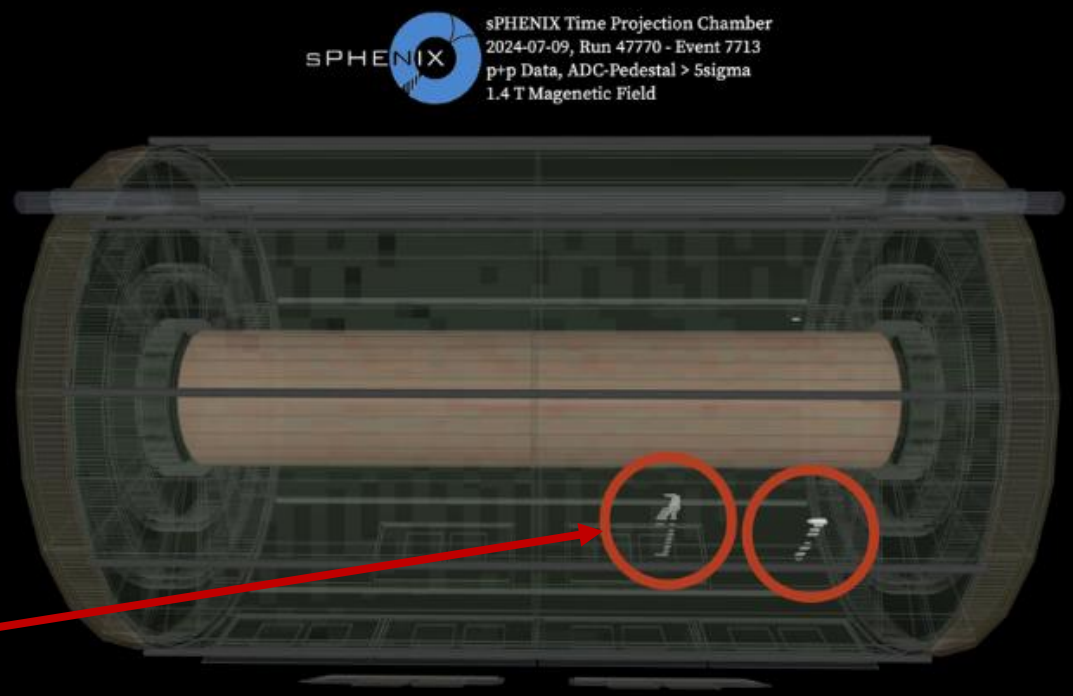


$\Lambda^0_s \rightarrow p^{\pm}\pi^{\pm}$



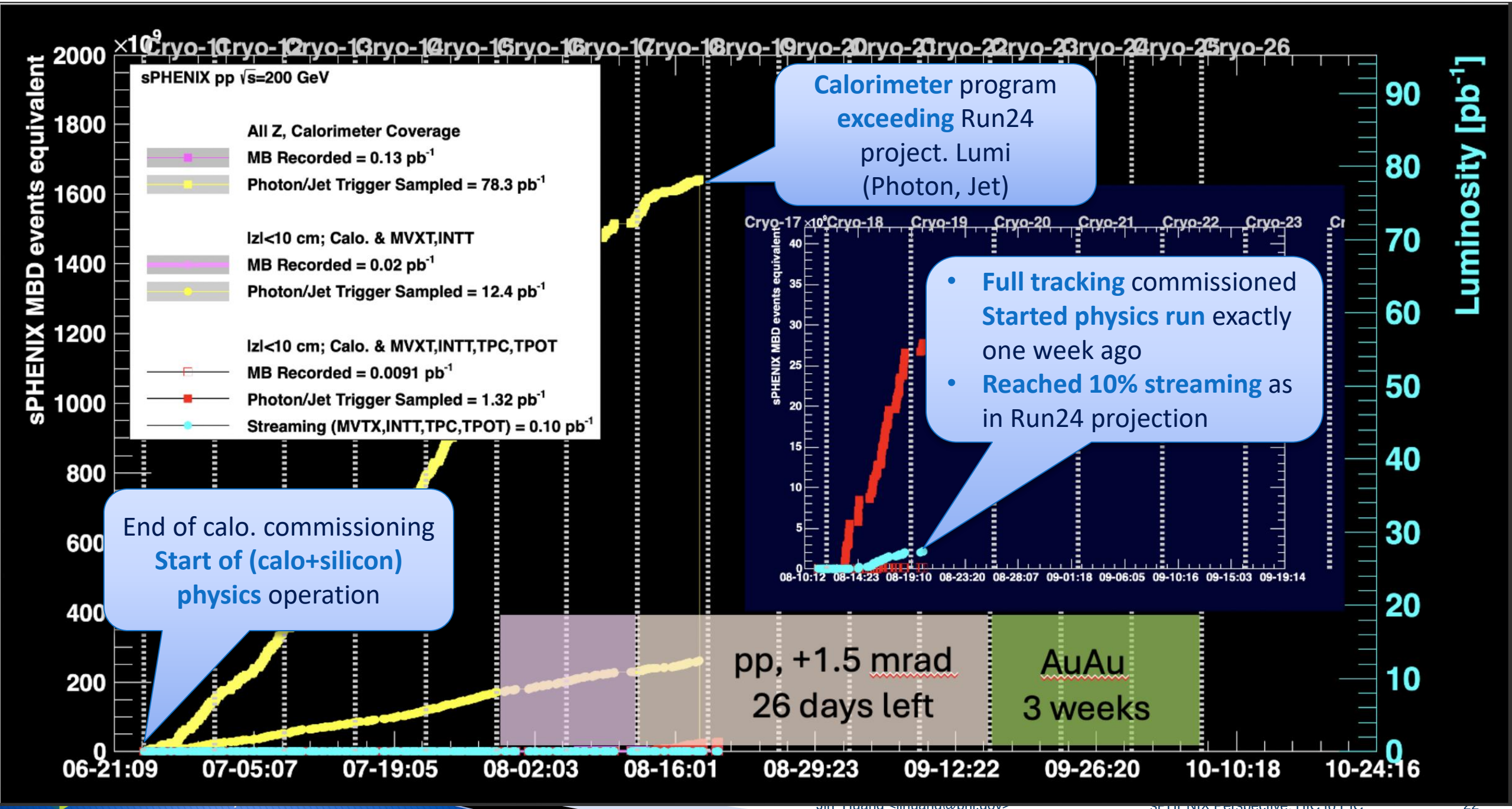
Commissioning challenges and solutions

- sPHENIX is a major new collider detectors, and naturally there are challenges. Collaboration/Lab came together resolving them expediently Prominent examples:
- Run23 AuAu commissioning was cut short due to RHIC magnet failure
  → moved 6-week commission time to Run24
- MAPS silicon tracker experience beam background that was distinct from ALICE run at LHC
  → Firmware and hardware protection, beam background feedback to RHIC
  - Quite Relevant experience for EIC
- TPC experience beam background that leads to frequent gigantic ionization (>1000MIP) that leads to GEM discharge and damage
  → Approval and installation of Isobutane-gas mixture. Physics operational last week!



Special run
Detecting >1000 MIP beam bgd hits
100% streaming data

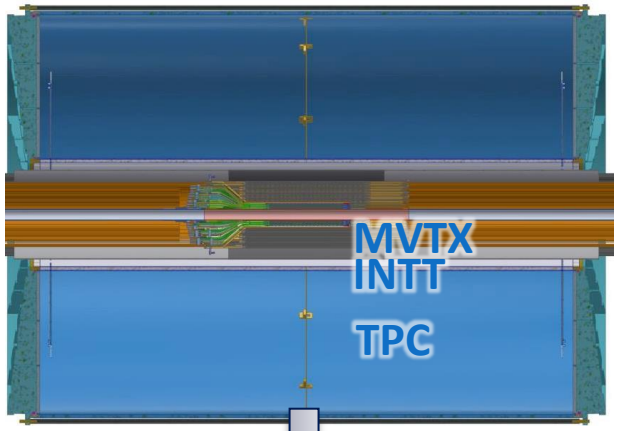
Taco party celebrating start of TPC physics run Yesterday!

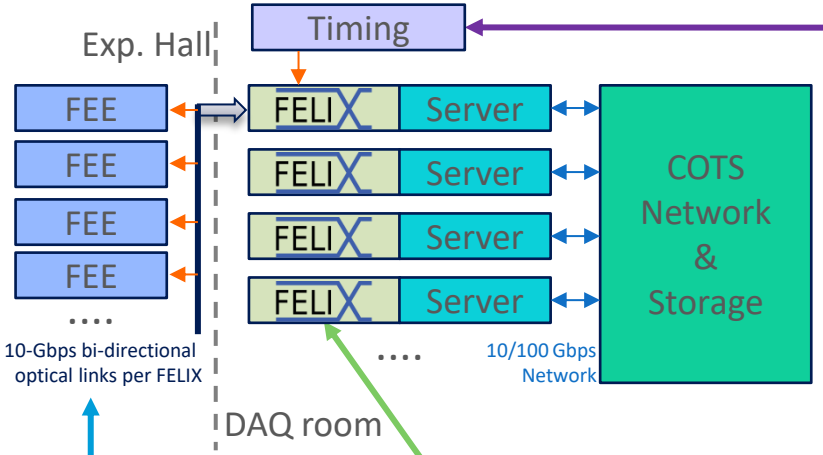

sPHENIX pp √s=200 GeV
All Z, Calorimeter Coverage
MB Recorded = 0.13 pb-1
Photon/Jet Trigger Sampled = 78.3 pb-1
|z|<10 cm; Calo. & MVXT,INTT
MB Recorded = 0.02 pb-1
Photon/Jet Trigger Sampled = 12.4 pb-1
|z|<10 cm; Calo. & MVXT,INTT,TPC,TPOT
MB Recorded = 0.0091 pb-1
Photon/Jet Trigger Sampled = 1.32 pb-1
Streaming (MVTX,INTT,TPC,TPOT) = 0.10 pb-1
sPHENIX MBD events equivalent
Luminosity [pb-1]
Calorimeter program exceeding Run24 project. Lumi (Photon, Jet)
Full tracking commissioned
Started physics run exactly one week ago
Reached 10% streaming as in Run24 projection
End of calo. commissioning
Start of (calo+silicon) physics operation
pp, +1.5 mrad
26 days left
AuAu
3 weeks
06-21:09
07-05:07
07-19:05
08-02:03
08-16:01
08-29:23
09-12:22
09-26:20
10-10:18
10-24:16

Streaming readout electronics

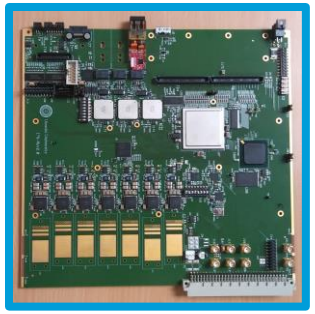
- sPHENIX plan to streaming rec. 10% p+p collisions in hybrid streaming DAQ (achieved last week!)
  → 2-3 orders of magnitude increase in soft-HF statistics
- EIC physics leads to the plan to use 100% streaming in EIC Detectors

sPHENIX streaming DAQ for tracker





Global Timing Module
(NSLS II/sPHENIX)
Receiving from RHIC RF low glitter clock source

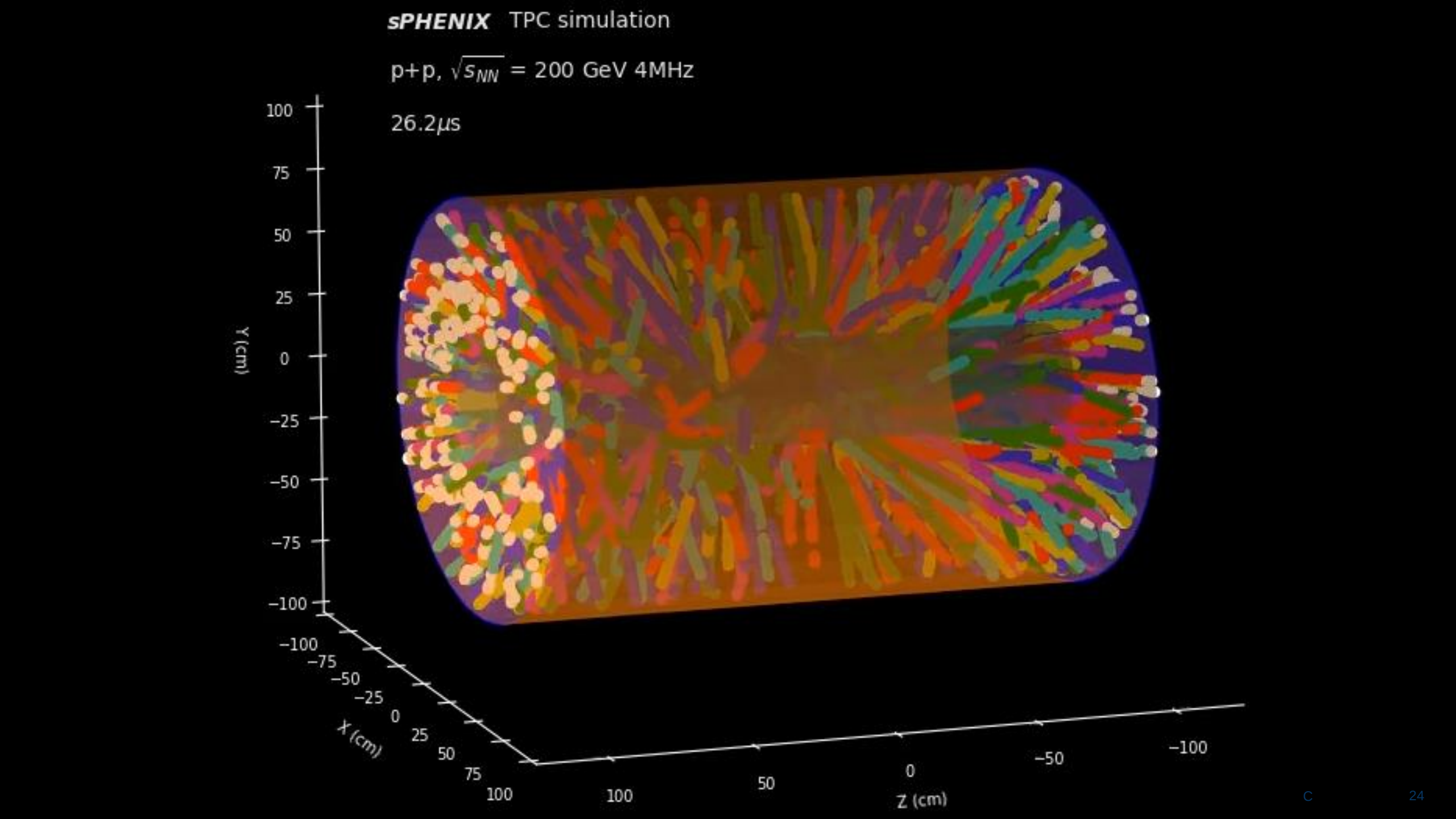


MVTX RU, 200M ch
ALPIDE (ALICE/sPHENIX), FPHX (PHENIX)

INTT ROC, 400k ch

TPC FEE, 160k ch
SAMPAv5 (ALICE/sPHENIX)

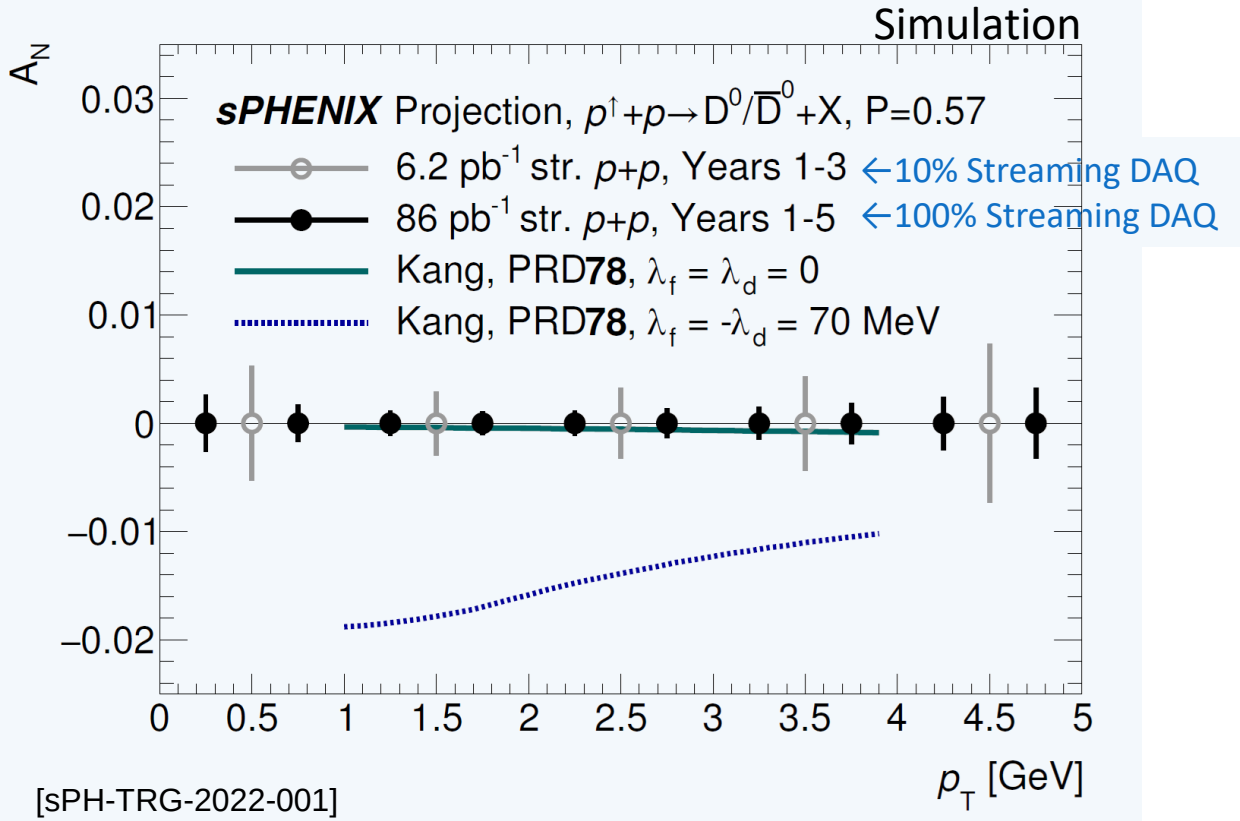
BNL-712 / FELIX v2 x38 (ATLAS/sPHENIX)
FELIX Ref: 10.1109/tim.2019.2947972


sPHENIX TPC simulation
p+p, $\sqrt{s_{NN}}$ = 200 GeV 4MHz
26.2μs
Y (cm)
X (cm)
Z (cm)

Streaming-DAQ enabled scientific connection: e.g. gluon dynamics via heavy flavor transverse spin asym.

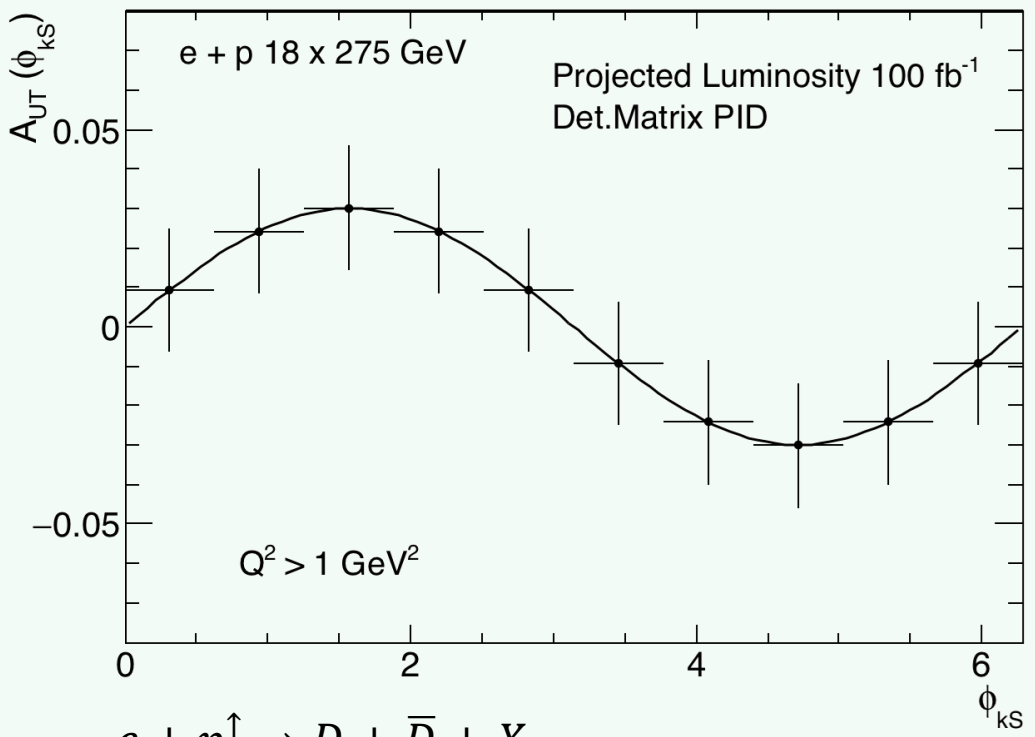
Universality test on gluon Sievers

sPHENIX D^0 trans. spin asymmetry, A_N → Gluon Sievers via tri-g cor.



[sPH-TRG-2022-001]
Model: 10.1103/PhysRevD.78.114013

EIC SIDIS D^0 transverse spin asymmetry → Gluon Sievers



$e + p^{\uparrow} \to D + \bar{D} + X$

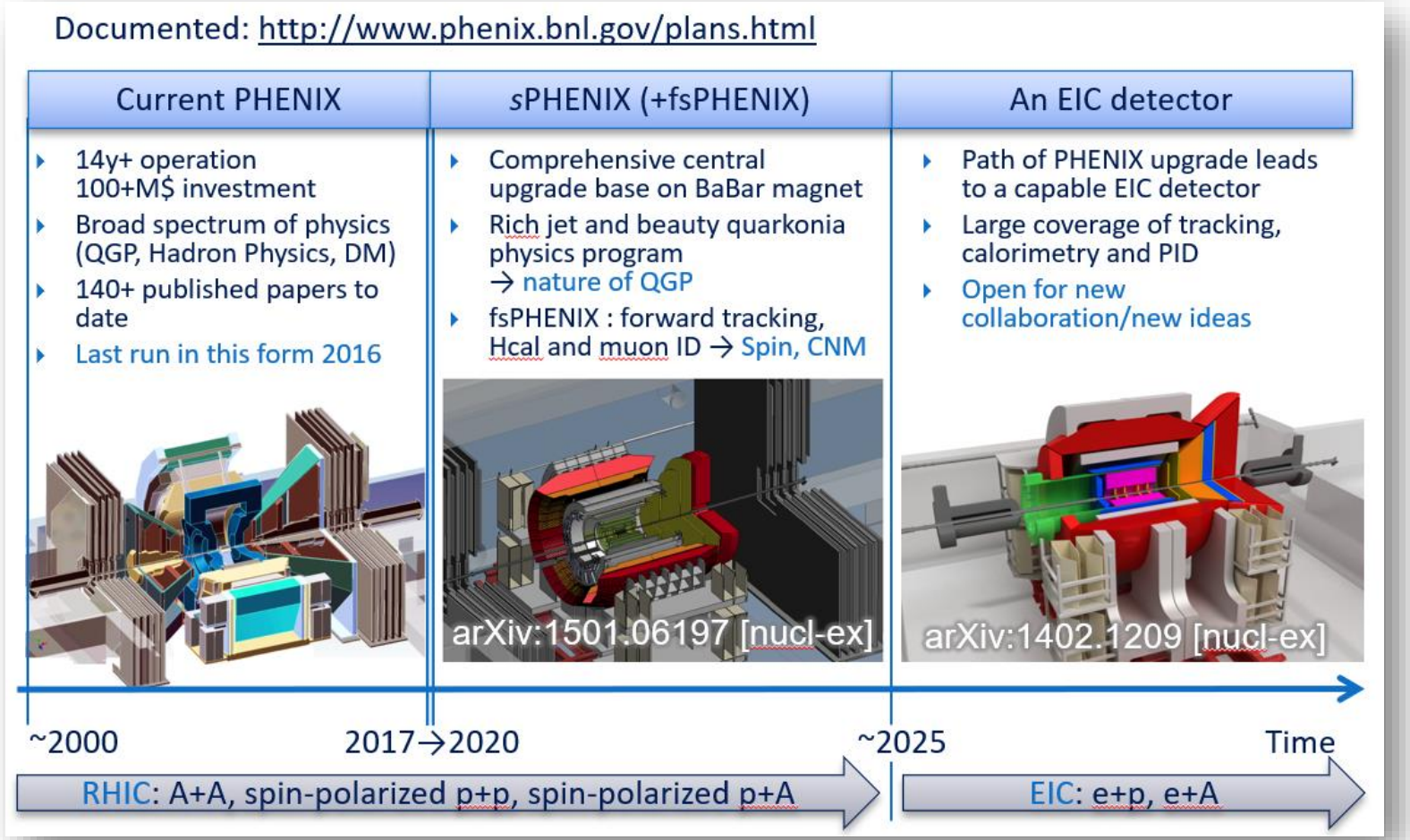
[CNFS HF@EIC workshop, Nov 4-6, 2020]

sPHENIX HIC to EIC: ePHENIX concept in 2014

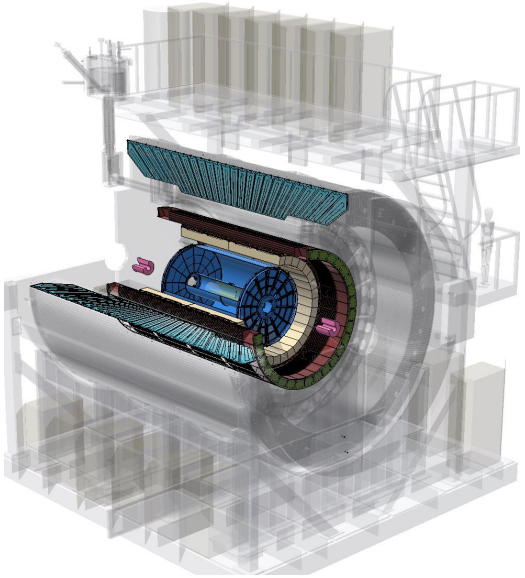
Seminar slides, ~1 decade ago

HIC to EIC was envisioned from the conceptual design stage of sPHENIX, a decade ago

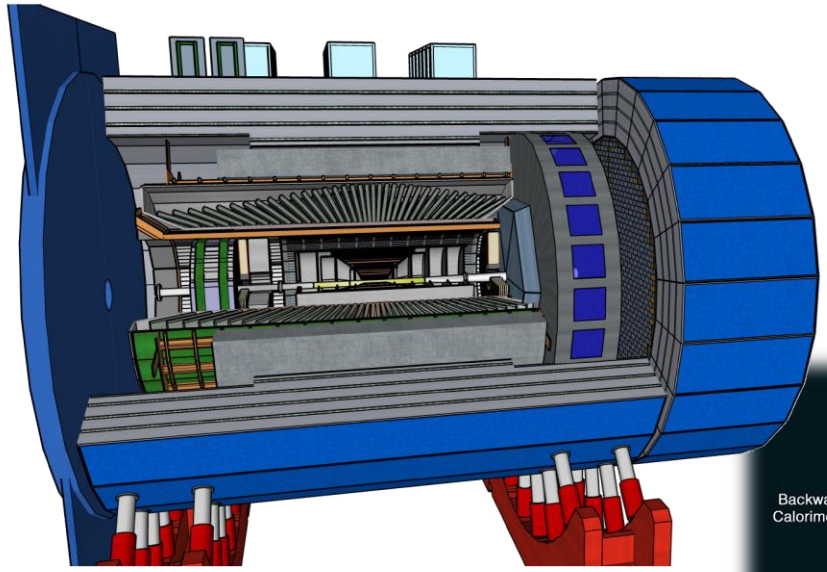
- Forward upgrade proposal arXiv:1501.06197
- EIC detector proposal arXiv:1402.1209



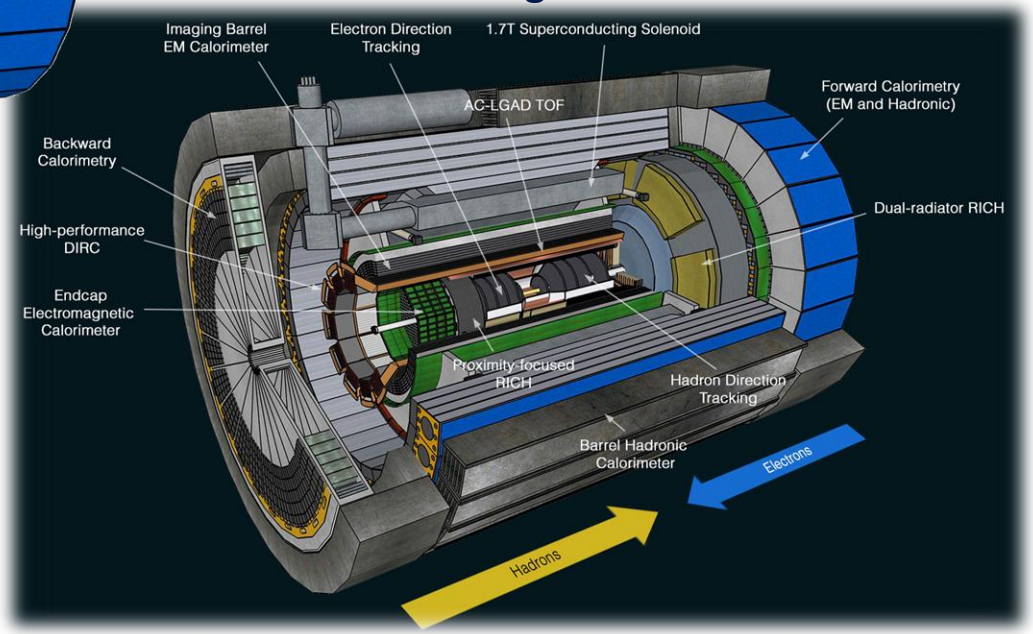
Evolution of EIC detectors: reusing some of sPHENIX



ECCE Detector proposal
arXiv:2209.02580

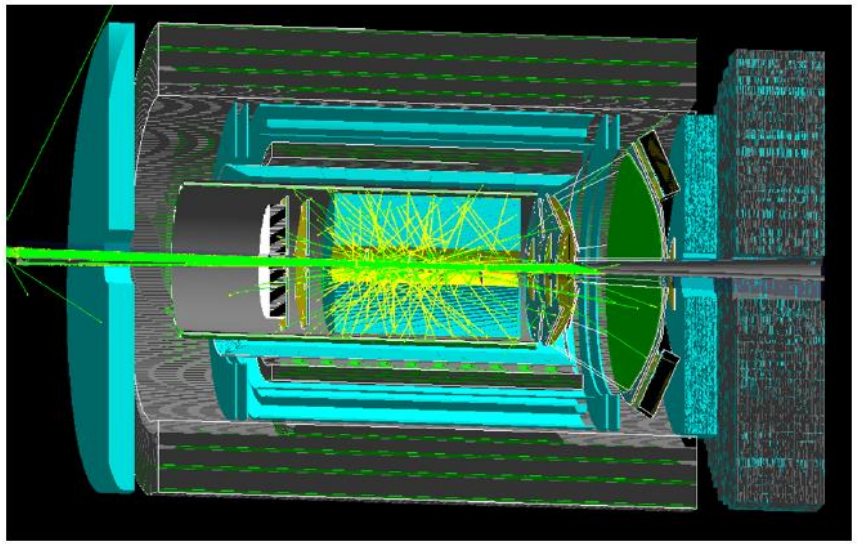


ePIC, the EIC project detector
https://www.bnl.gov/eic/epic.php
See talk: Olga Evdokimov



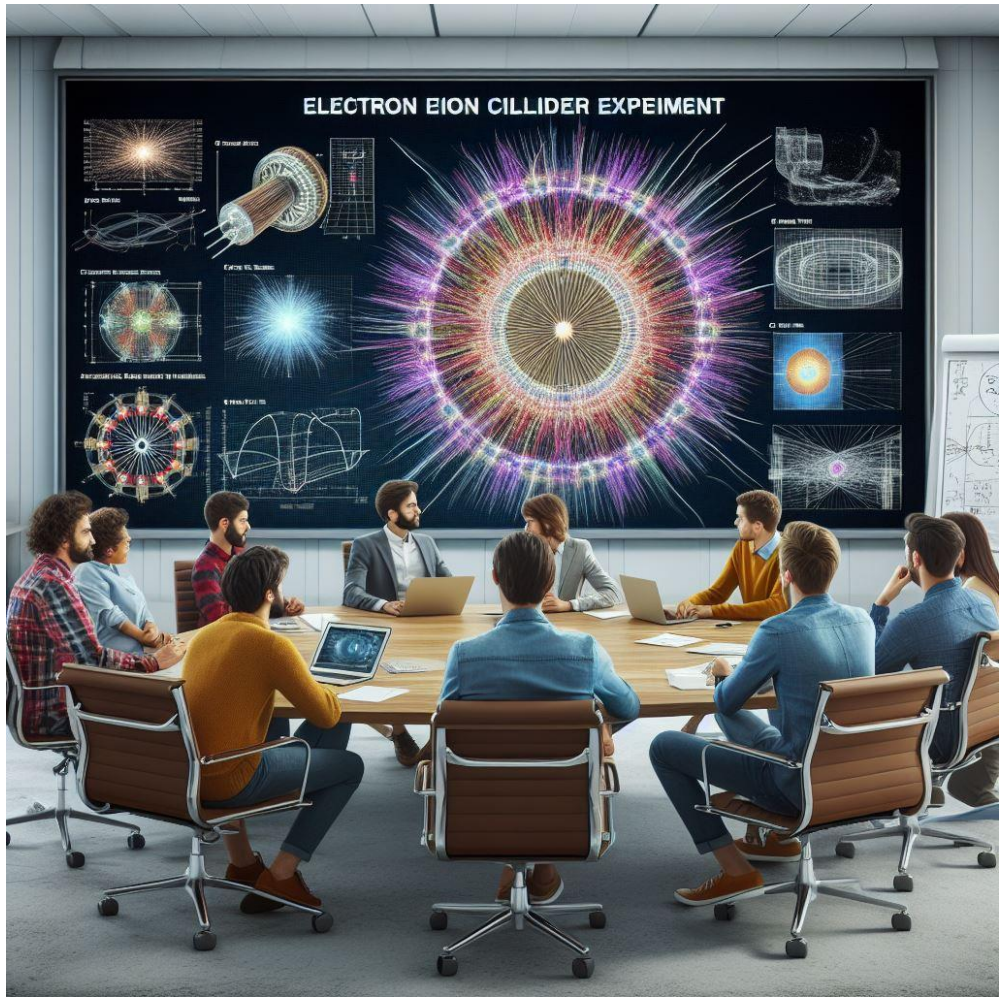
Bonus: generative AI for simulation and analysis

- EIC simulation involve generate billions background+noise time frames, then doing embedding into them
  - This is traditionally computationally expensive
- Generative AI has found success in scientific fast simulation: GAN, Diffusion, ..
- High fidelity is key to science application: notice the misspelling on the right



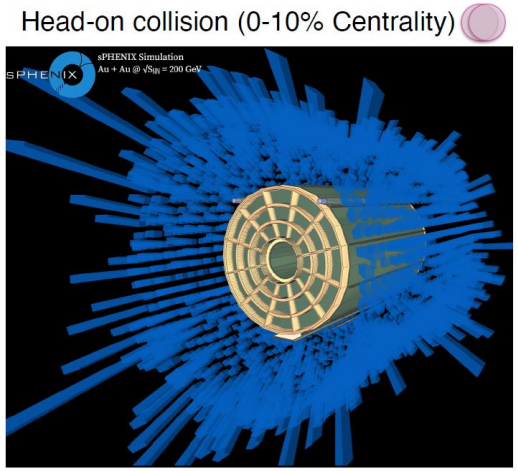
EIC CDR

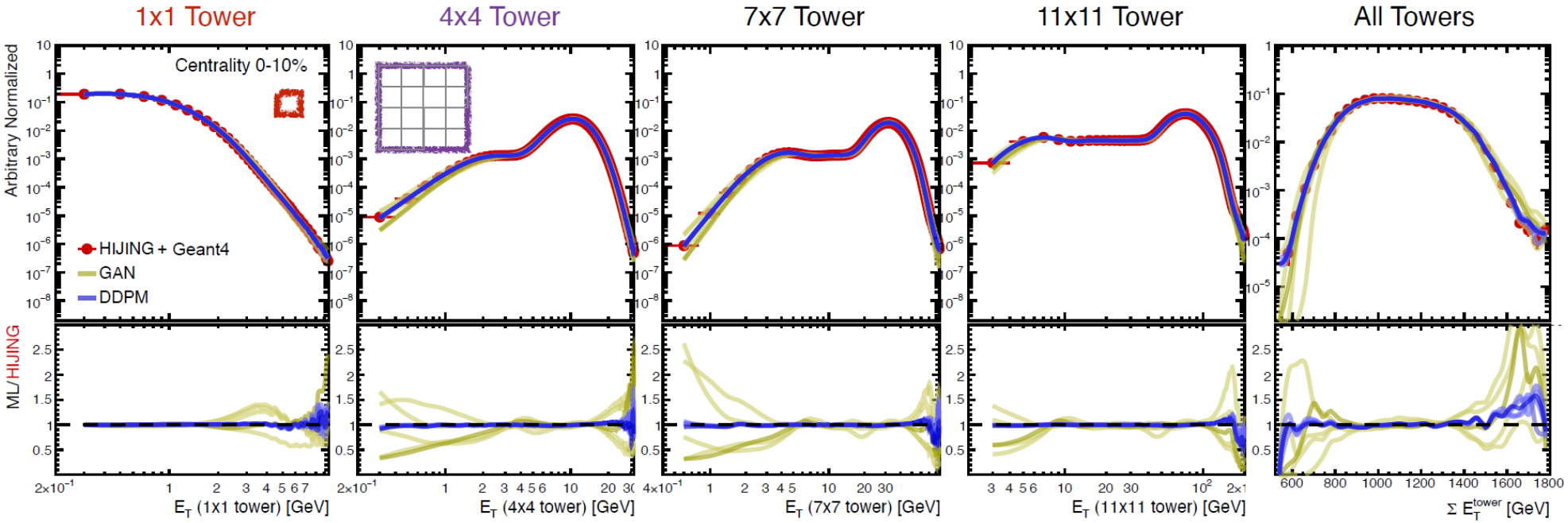
Diffusion model (DALL·E 3) hallucinating this very meeting…



Our approach: fast simulation with Denoising Diffusion Probabilistic Model (DDPM)

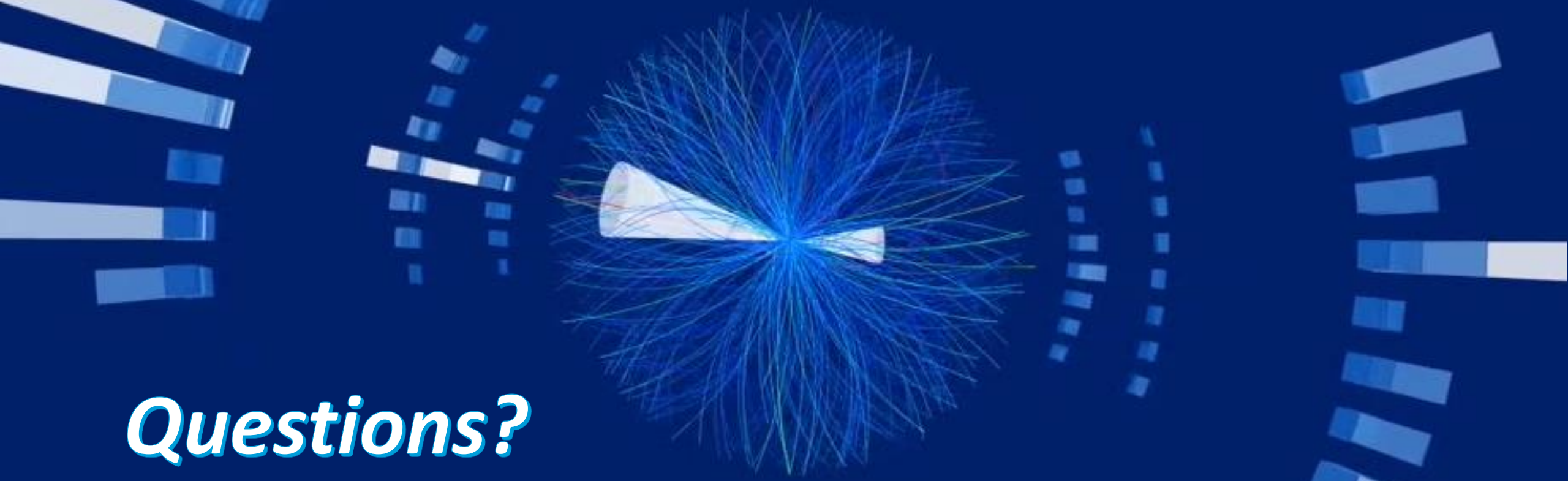
- Go, Torbunov et. al., arXiv:2406.01602 , PRC accepted (yesterday)
- x100 speed gain comparing to G4 (after scaling 32-core CPU for 1x GPU)
- Diffusion model produce much higher quality than GAN models





Summary

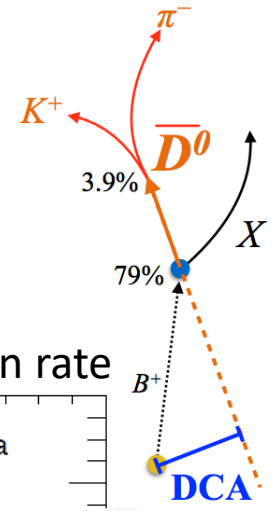
- sPHENIX completed (most) commissioning and started physics operation
- Natural connection to EIC: detector, analysis, physics
- Motivated collaborators who also contribute to ePHENIX, ECCE/ATHENA, ePIC (proj. detector)



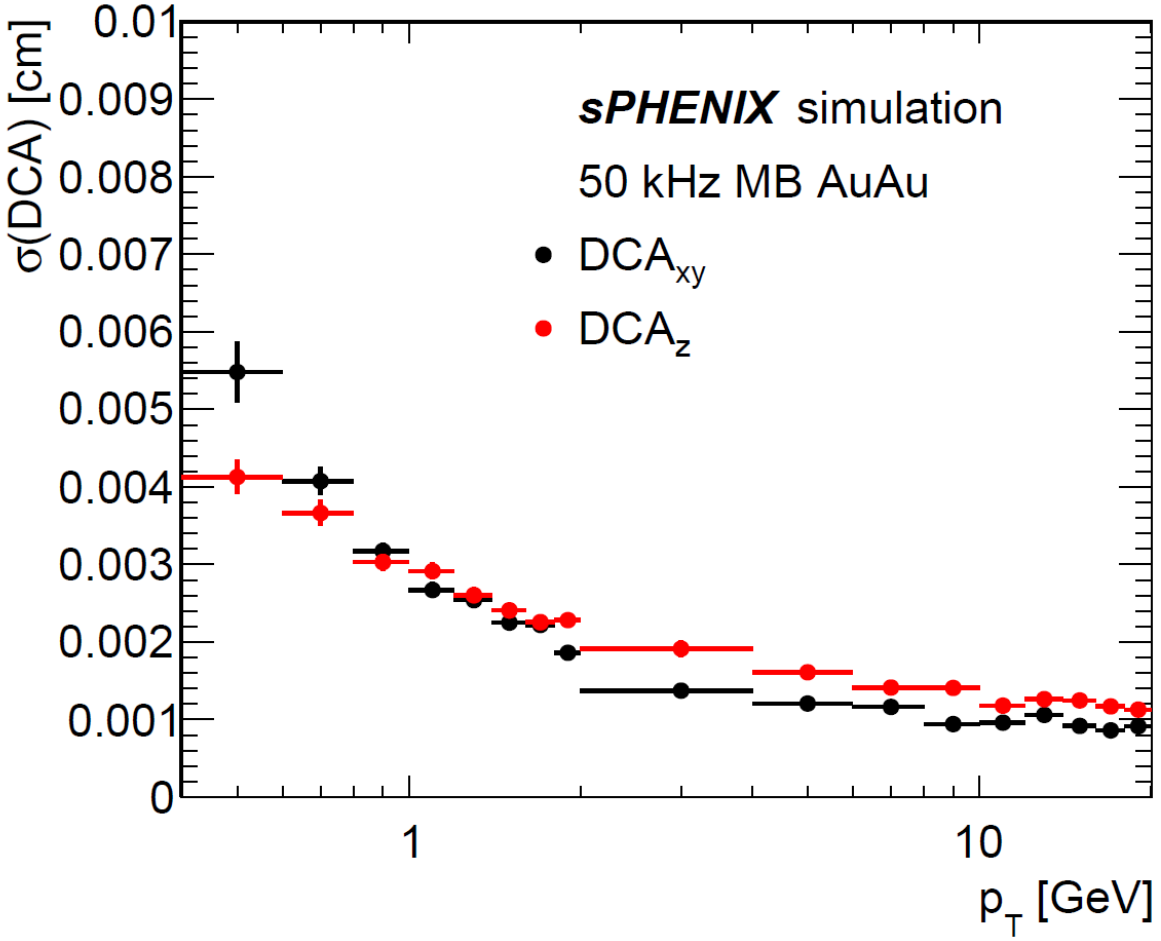
Questions?

Extra Information

Cleanly separate open bottom meson via DCA

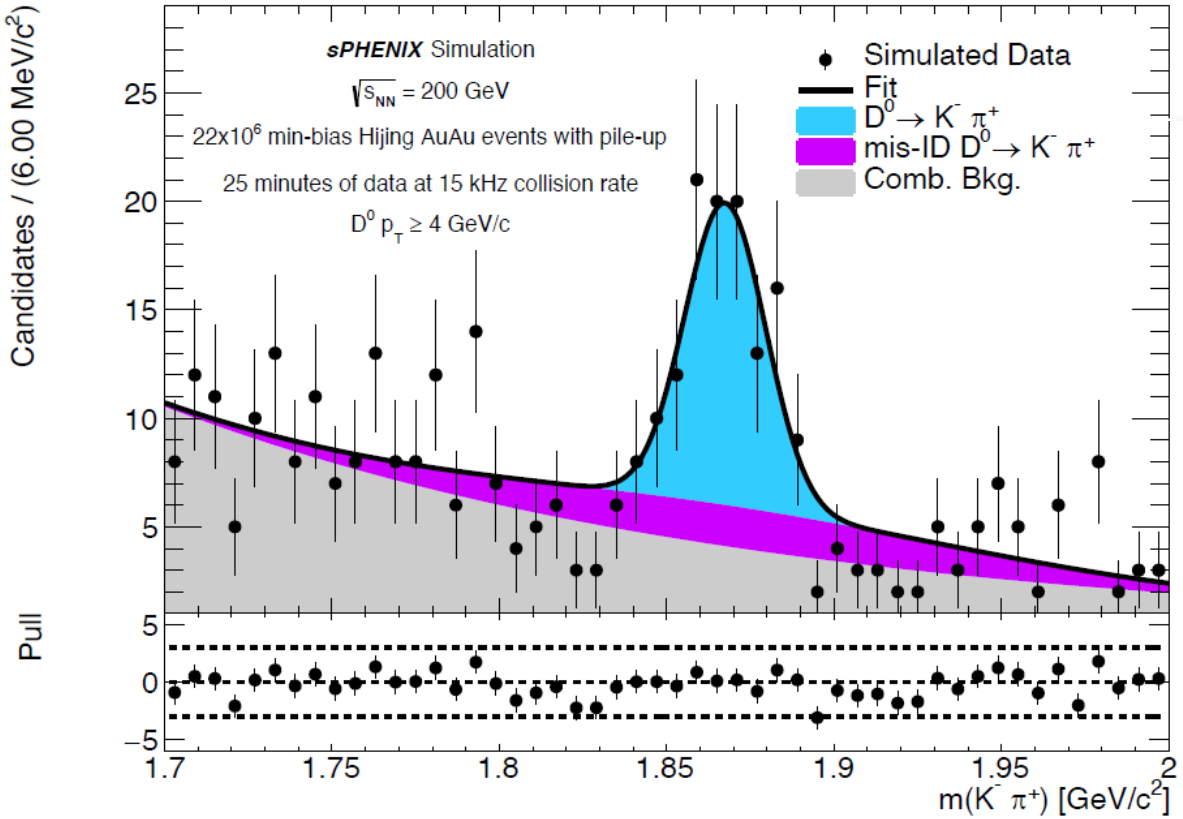


DCA resolution



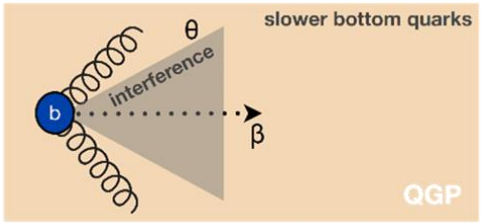
Precision vertex + fast DAQ → large HF sample

Simulation: 25 minutes of data at 15 kHz collision rate

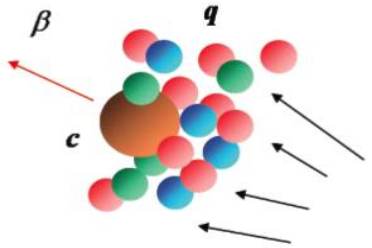


Access b-quark suppression/v2 via non-prompt D

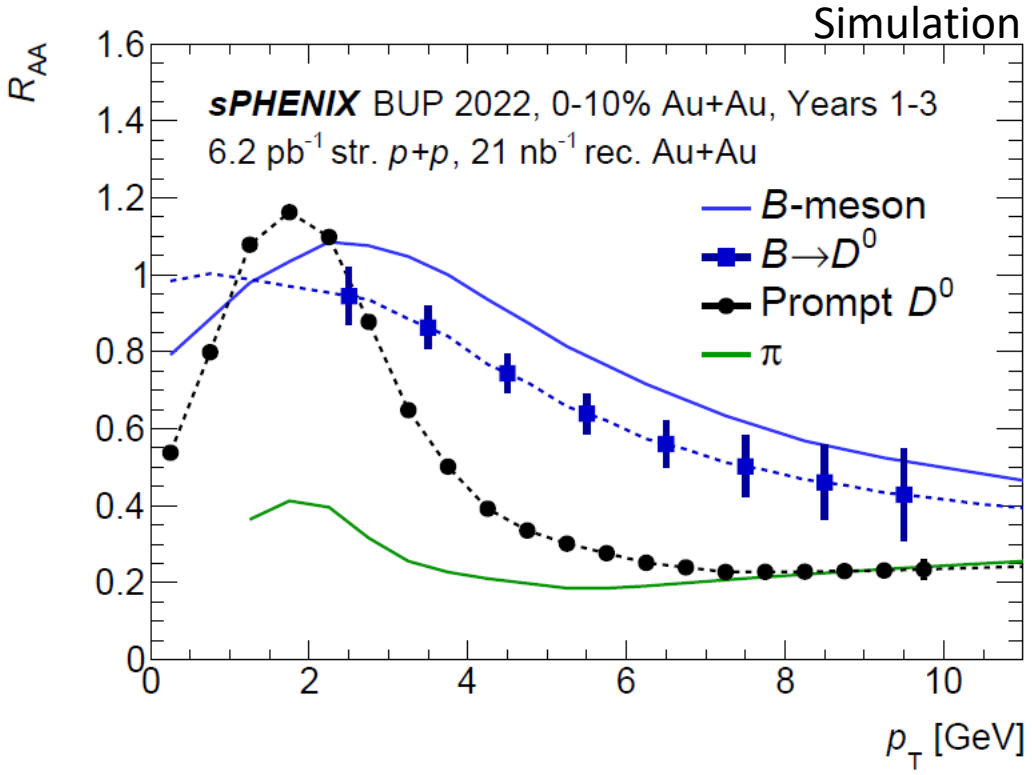
- Bringing high precision non-prompt-*D* suppression and flow to RHIC

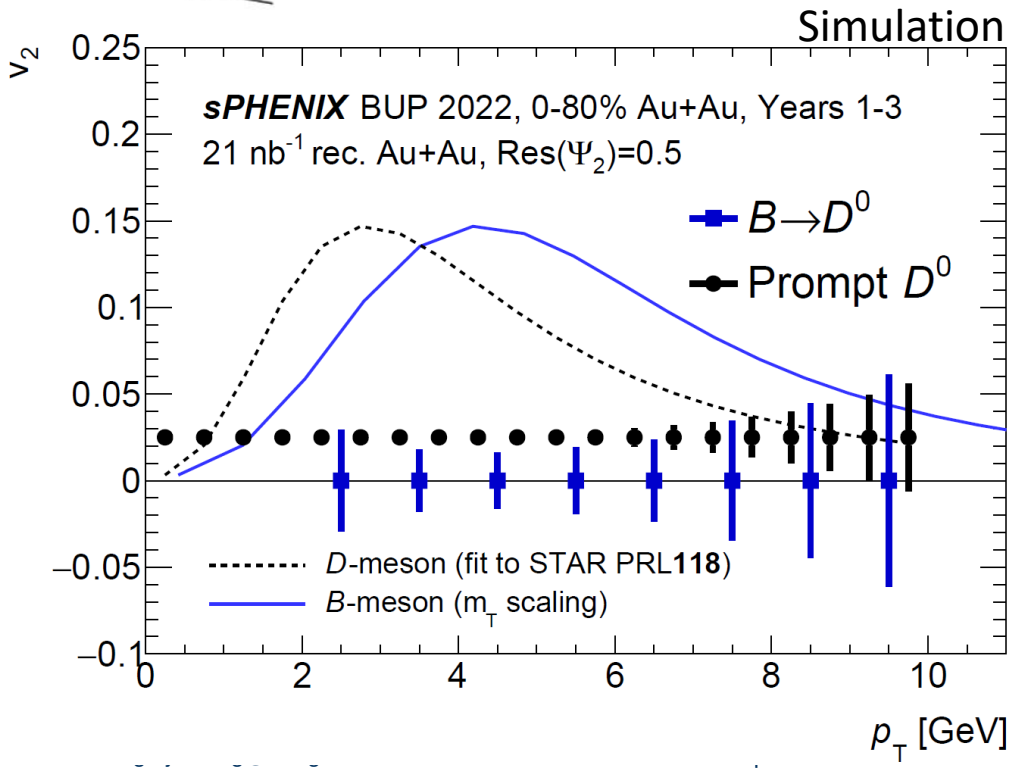


- Probe the mass dependence of quark energy loss in QGP, light → c → b
- Sensitive to pick up collision energy loss



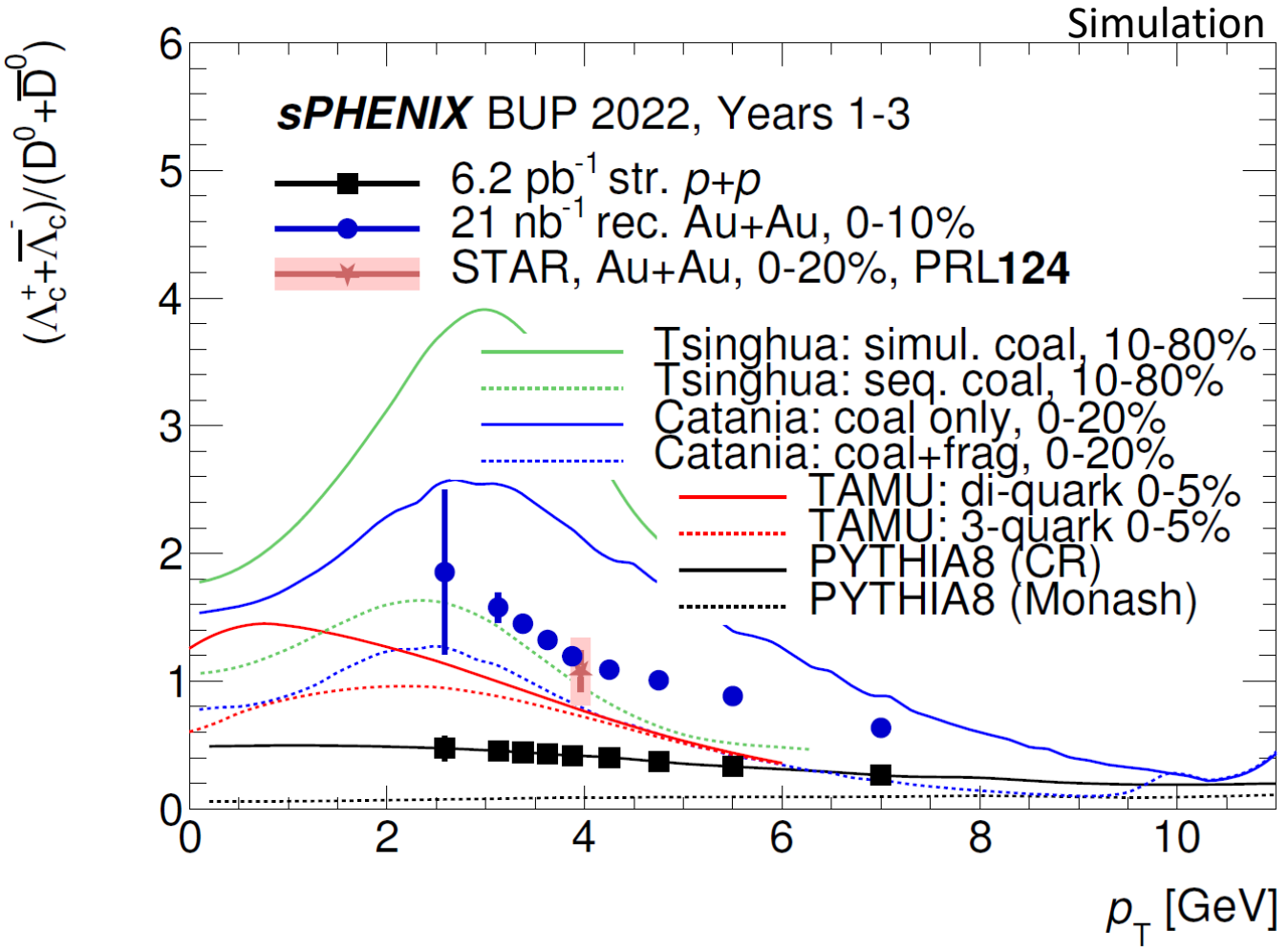
- Determine the bottom quark collectivity
- → clean access to D_{HQ} at RHIC energy





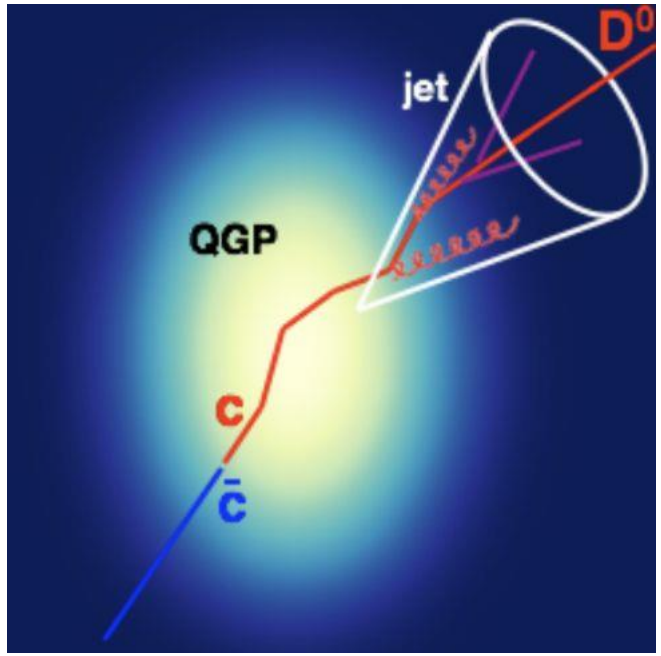
News from beam use proposal 2020 – hadronization

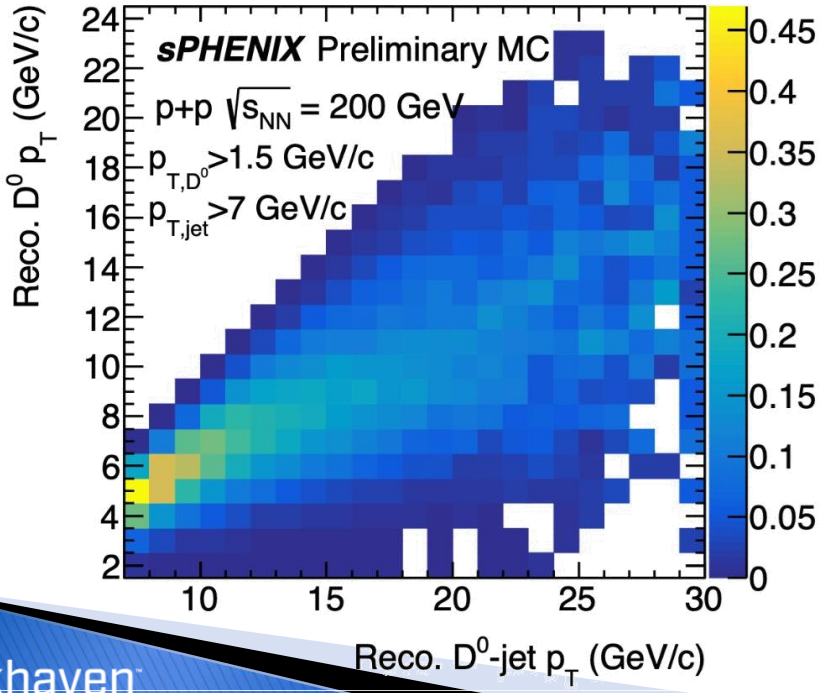
- STAR and ALICE collaboration reported enhanced charm baryon to meson ratio → challenging hadronization models
- sPHENIX streaming readout will deliver first $p + p$ measurement at RHIC
- sPHENIX will also map out the Λ_c/D ratio over momentum dependence

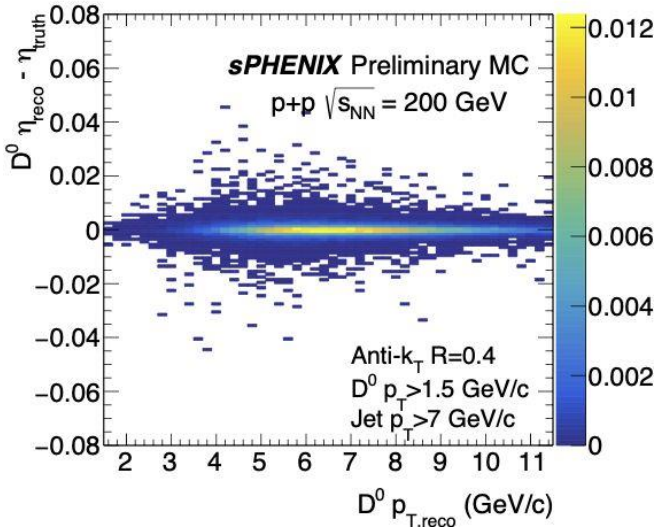


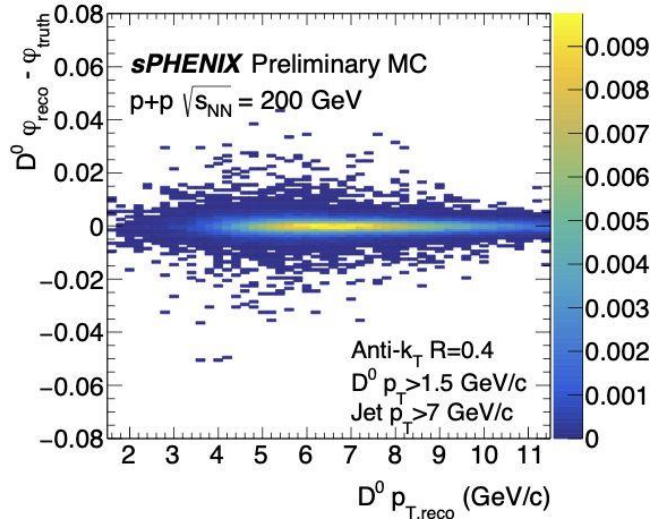
D-tagged jets

- Access charm jet and easy background rejection
- Study of heavy-quark initiated jet structure and parton shower
- Enabled by abundant D0 statistics + jet capability







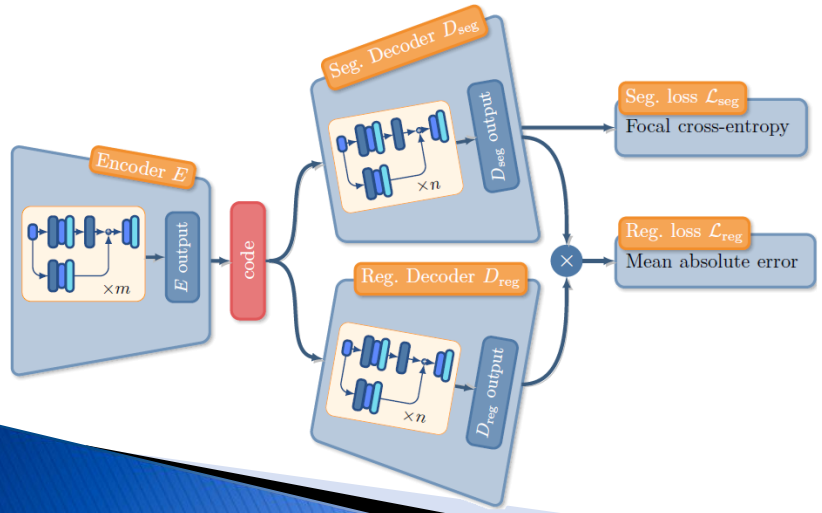


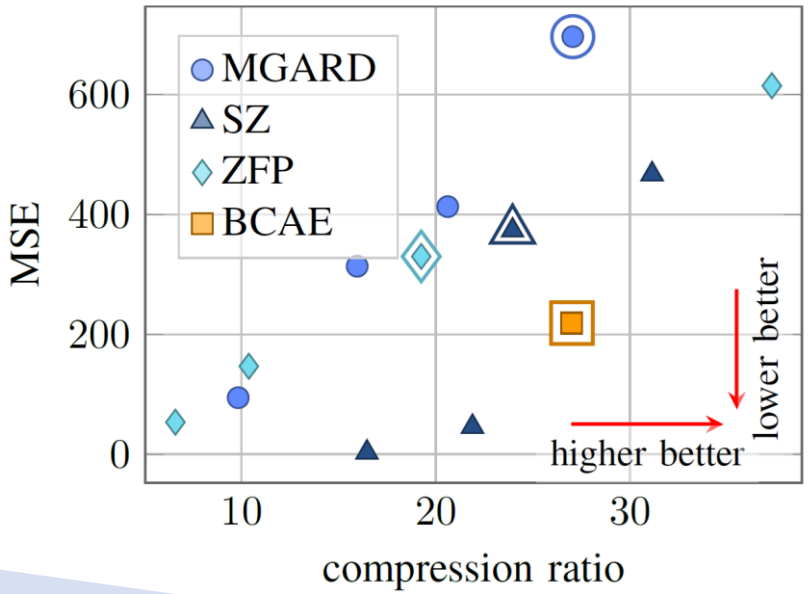
Our approach 1/2: Real-time AI algorithm

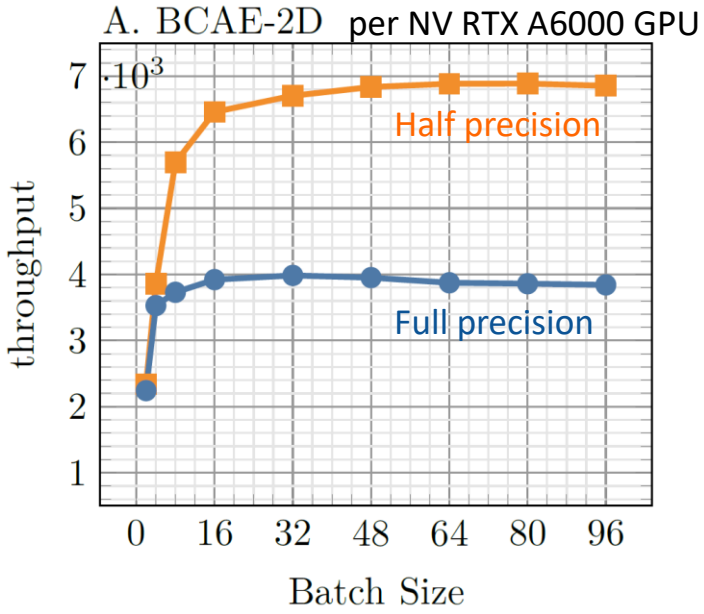
[Huang et al SC23, DOI: 10.1145/3624062.3625127 arXiv:2310.15026]

- Bicephalous Convolutional Auto-Encoder (BCAE) that perform data compression and noise filtering in one step
- Validating on (simulated) sPHENIX TPC 3D voxel data
- Paper award in Data Reduction Workshop in SC23

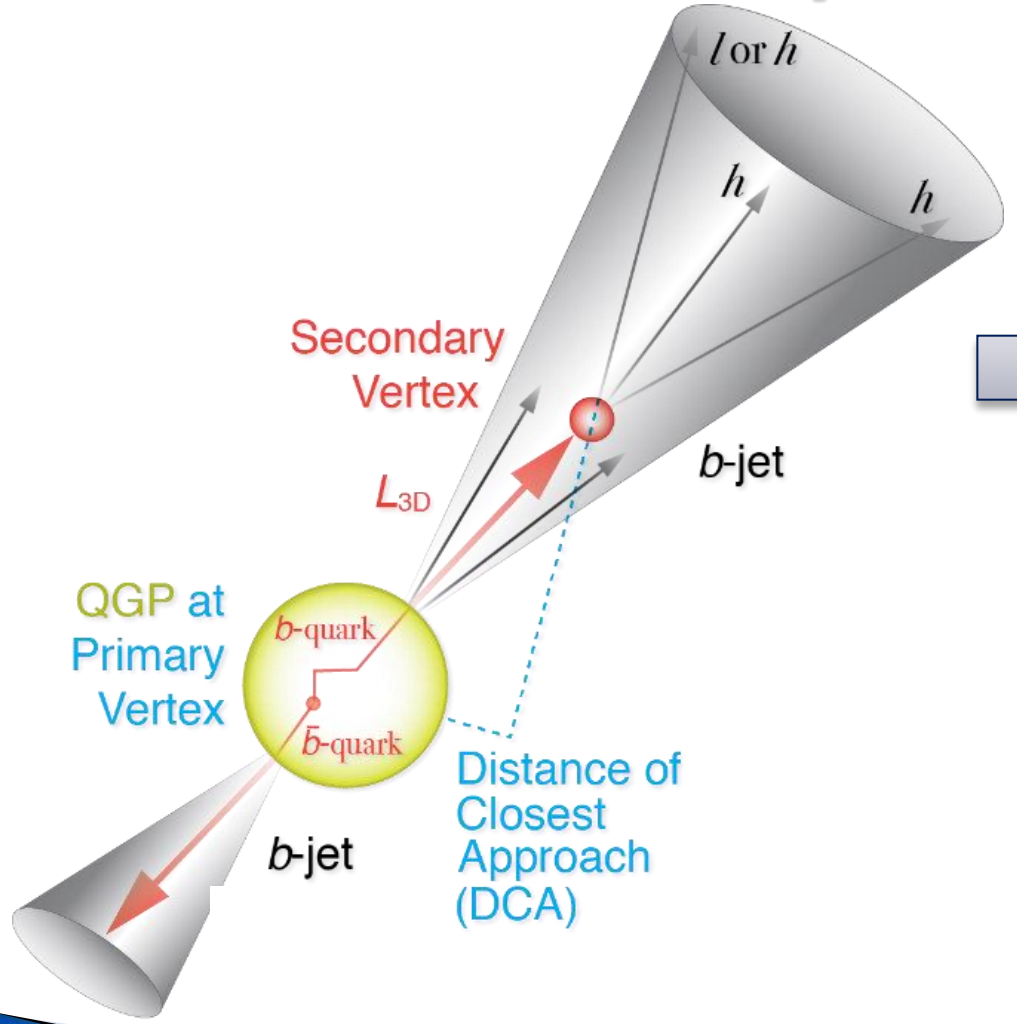
BCAE architecture

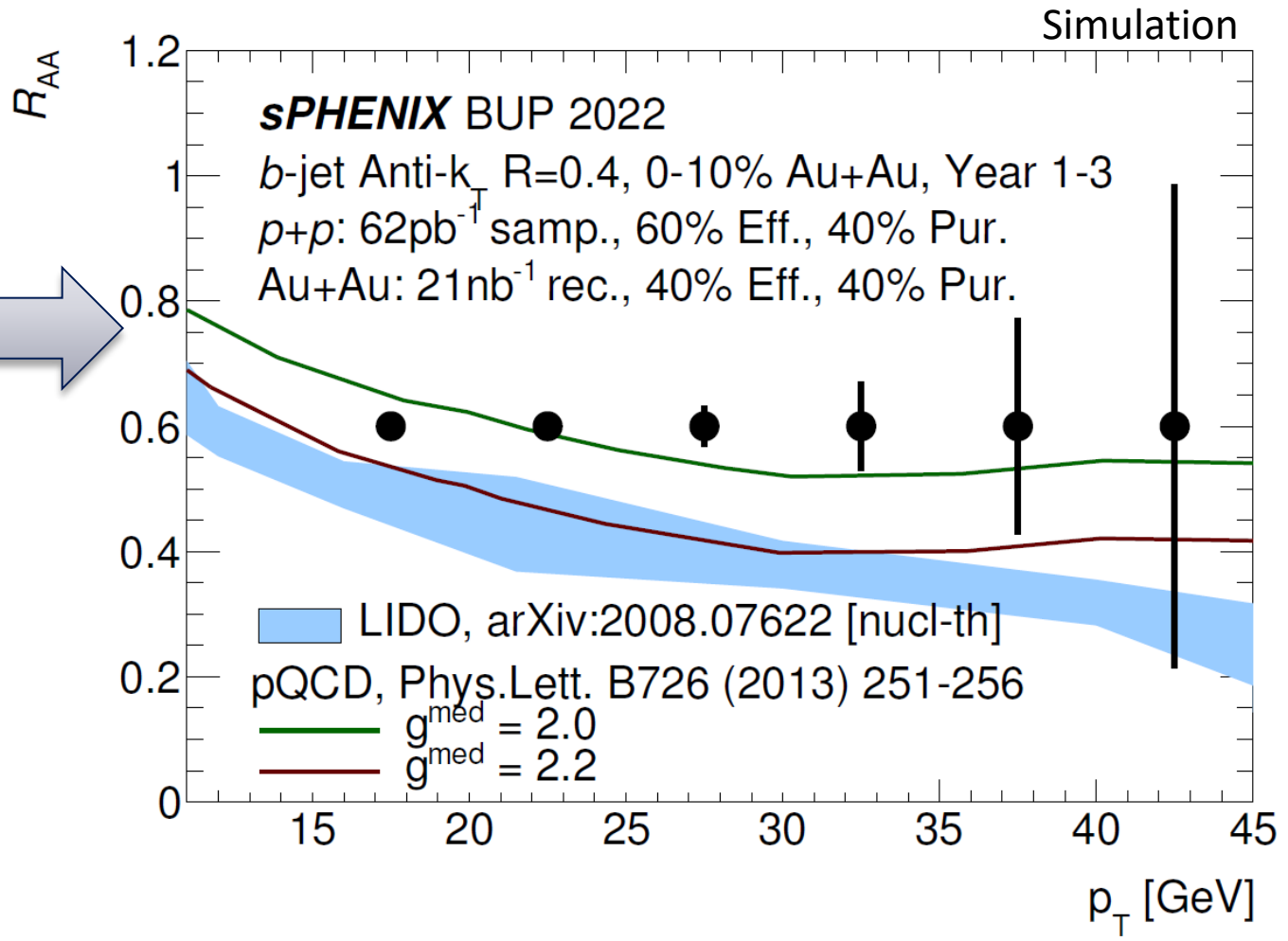




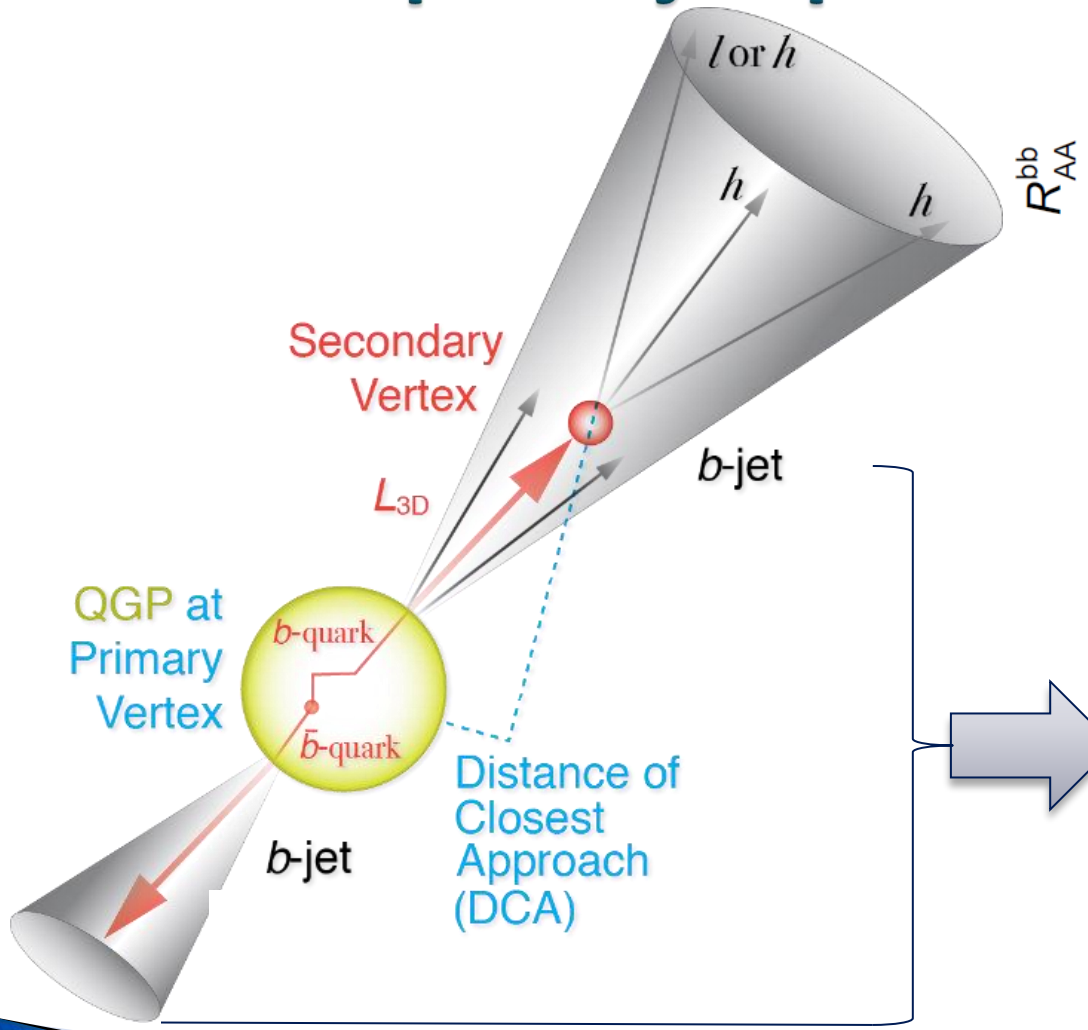


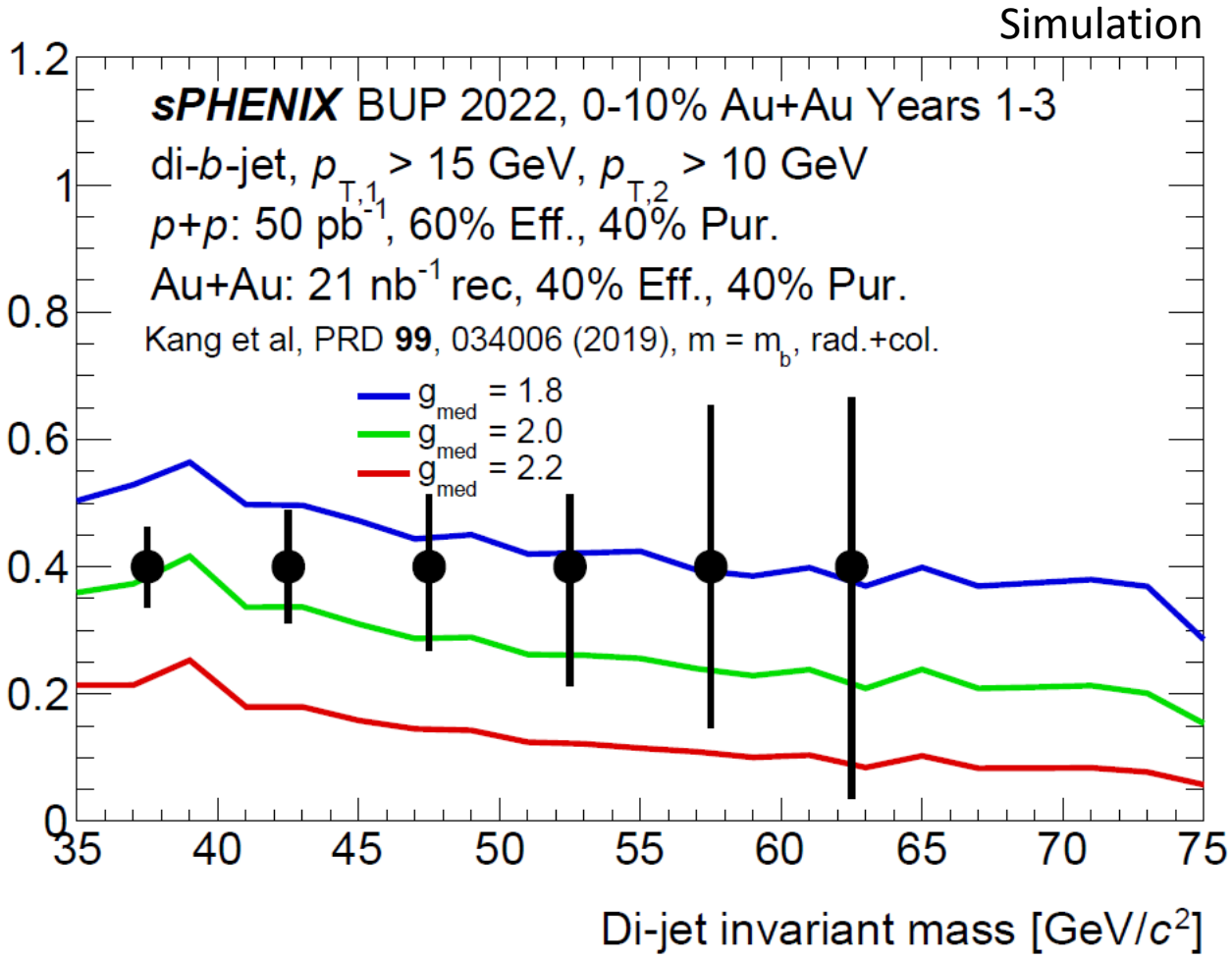
sPHENIX bottom quark jet





Bottom quark jet pairs → Enhanced sensitivity

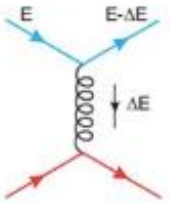




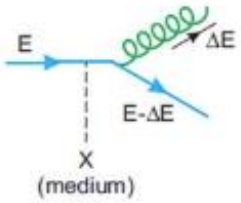
b-jet vs light jet → differentiating energy loss mech.

b/light ratio on RAA
Partial exp. systematic uncert. cancelation

Collisional energy loss

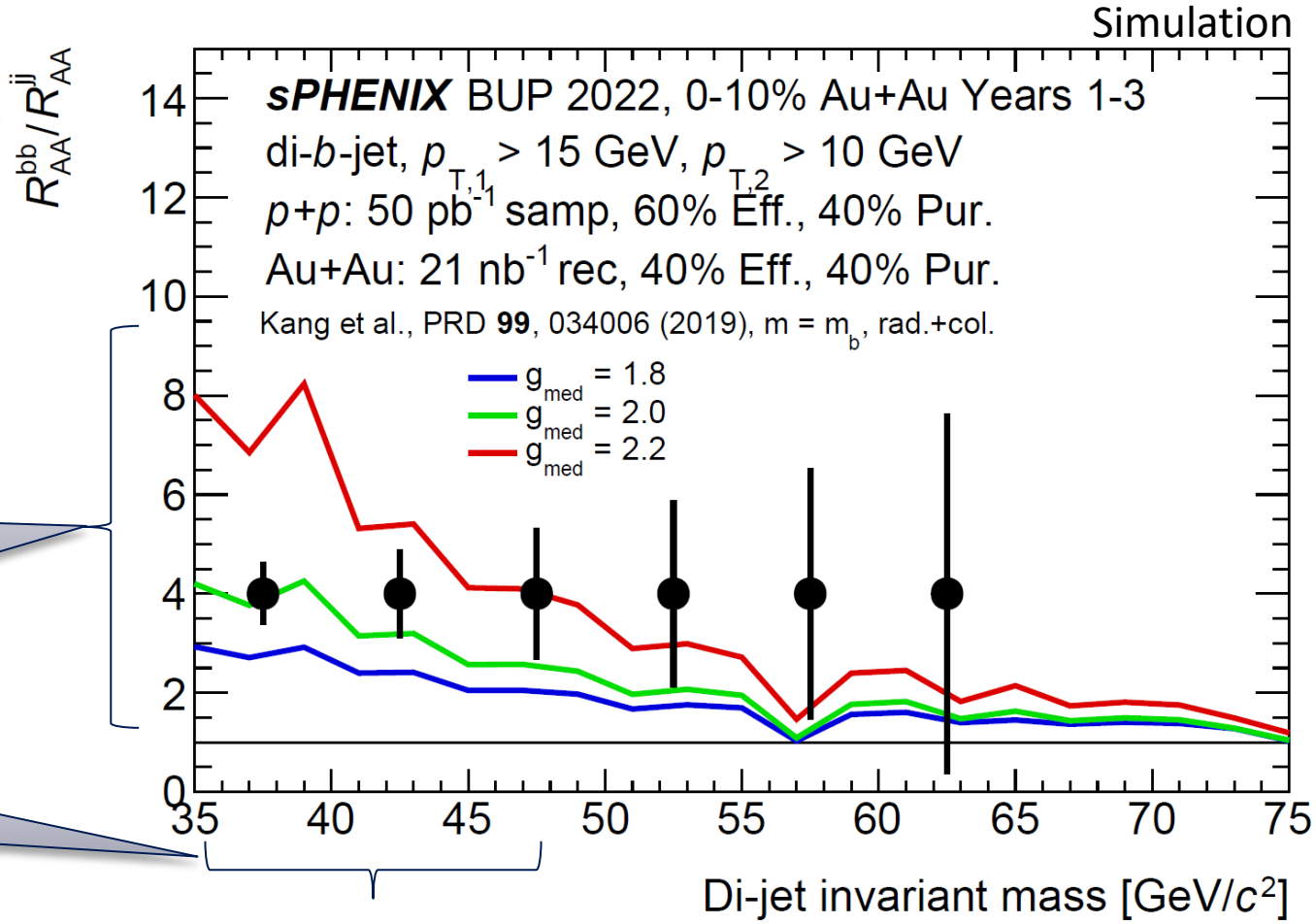


Radiative energy loss

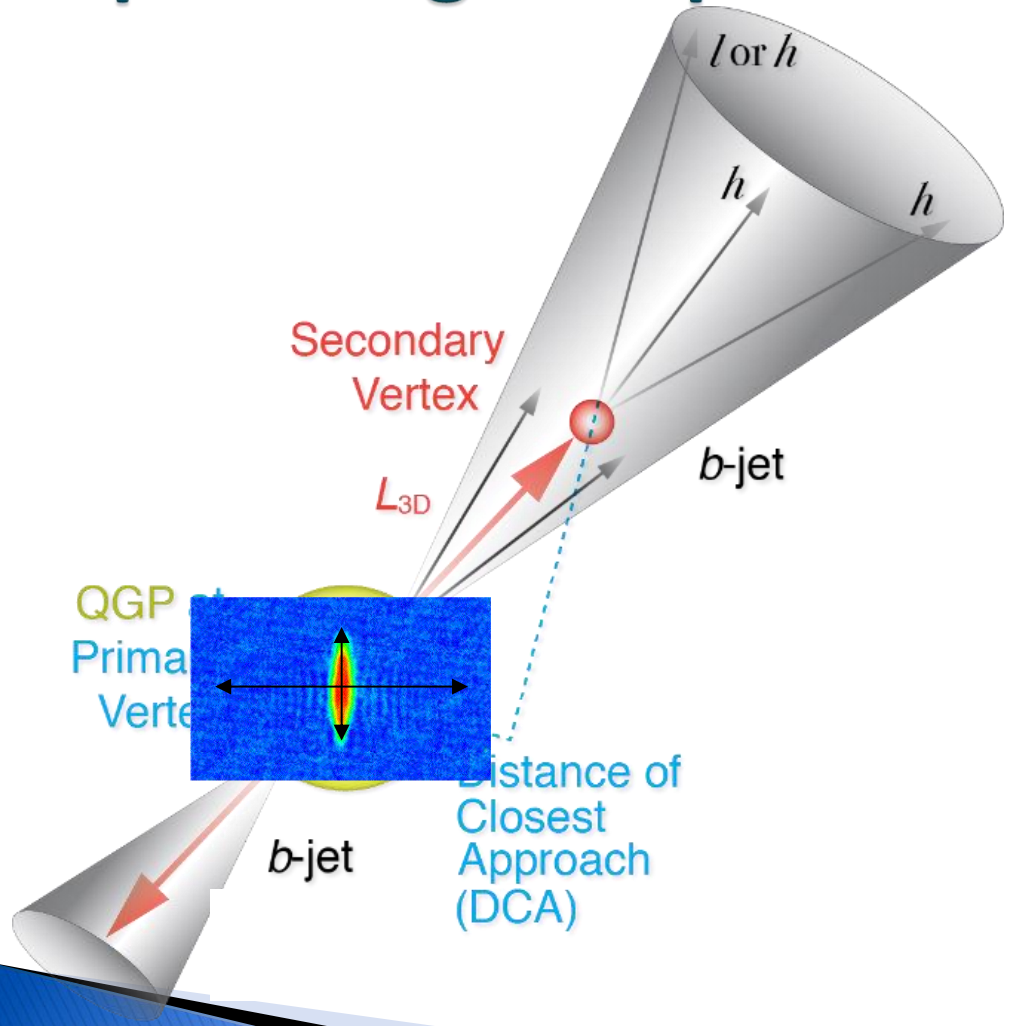


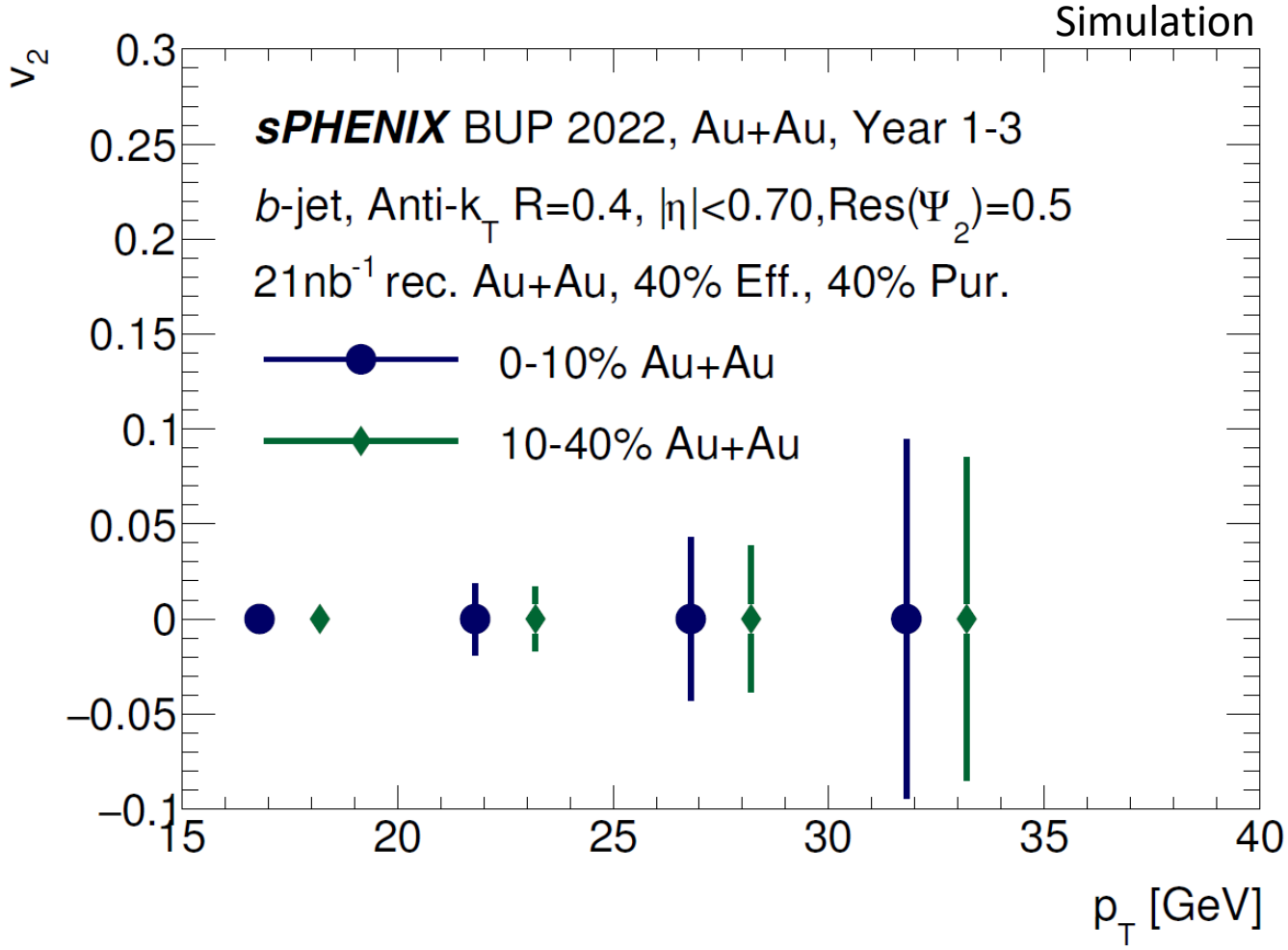
1-8 times mass effect!
x2 effect vs 10% variation on g_{med}!

Unique region in the RHIC kine.
@ max sensitivity to mass eff.



b-jet Flow signature
→ pathlength dependence energy loss

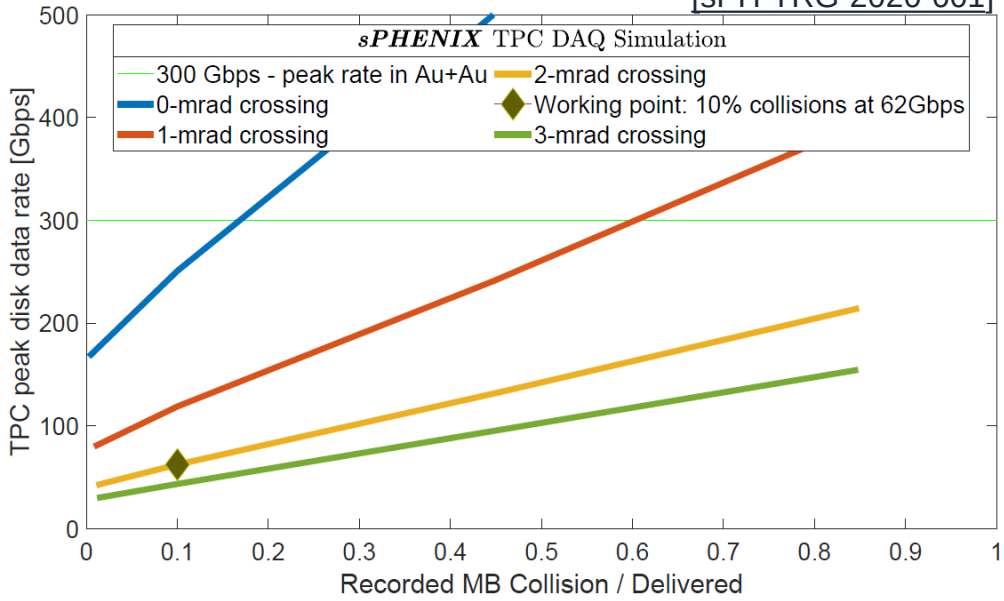




Streaming readout status at sPHENIX

- All three sPHENIX tracking detector uses streaming readout
- Developed plan to take 10% streaming data for heavy flavor physics program commended by RHIC PAC.

[sPH-TRG-2020-001]

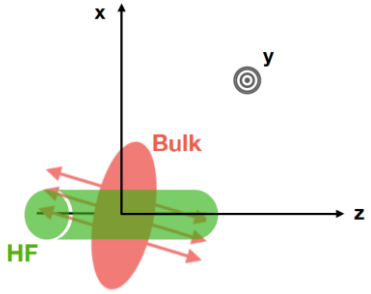


RHIC PAC 2020 report

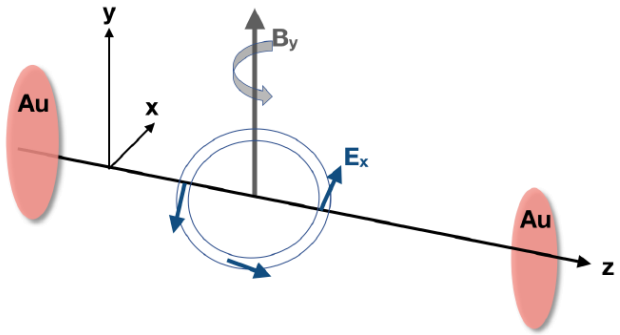
We commend sPHENIX for developing the continuous streaming readout option for the detector, which increases the amount of data that can be collected in Run-24 by orders of magnitude. In particular in the sector of open heavy flavor, this technique will give access to a set of qualitatively novel measurements that would otherwise not be accessible. Given the tight timeline for completing the RHIC physics program before construction of the EIC begins, this is a tremendous and highly welcome achievement.

Charm v_1 (via prompt D_0)→ initial geom. & *B*-field

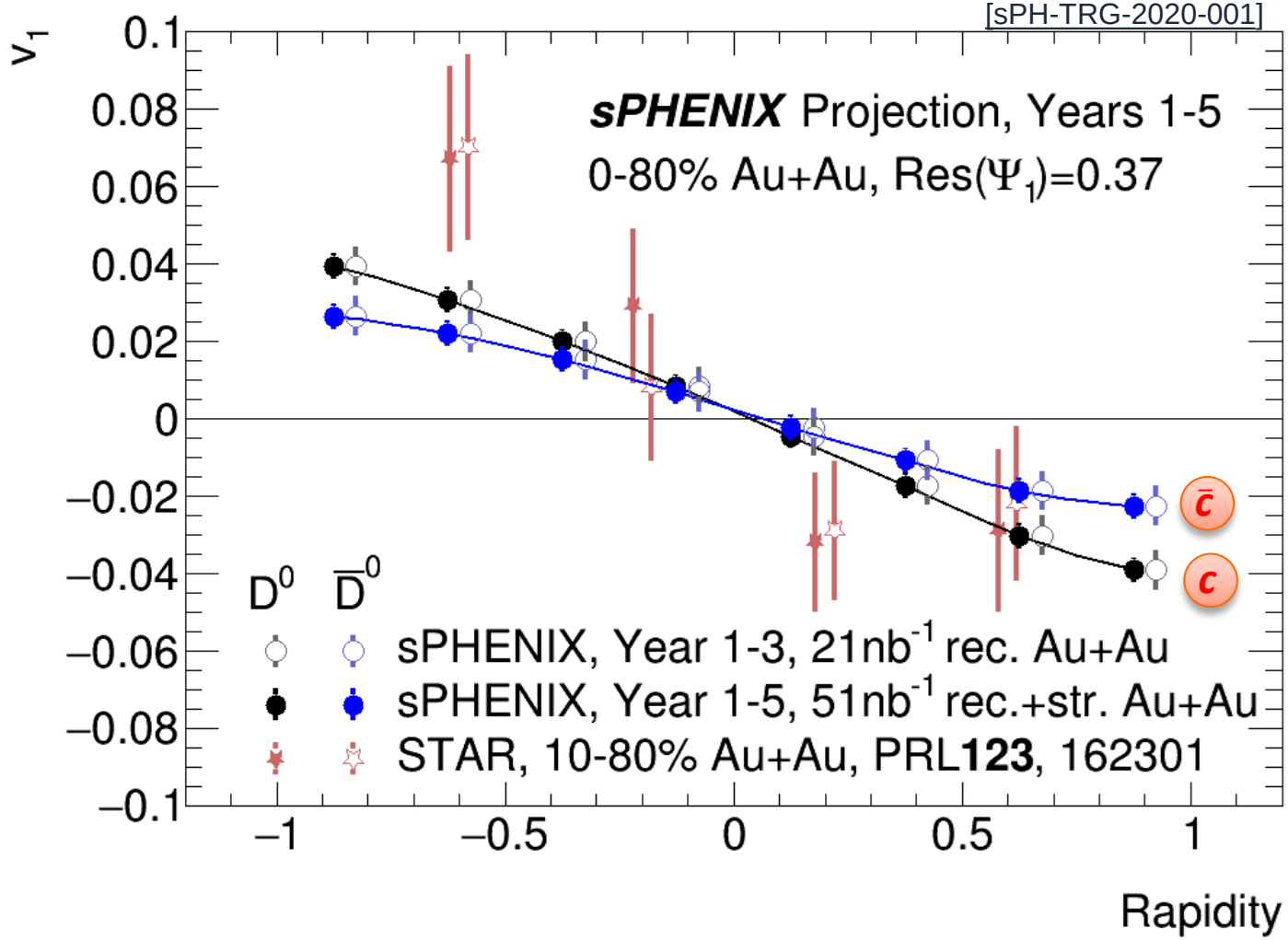
- v_1: Geometry tilt of QGP source



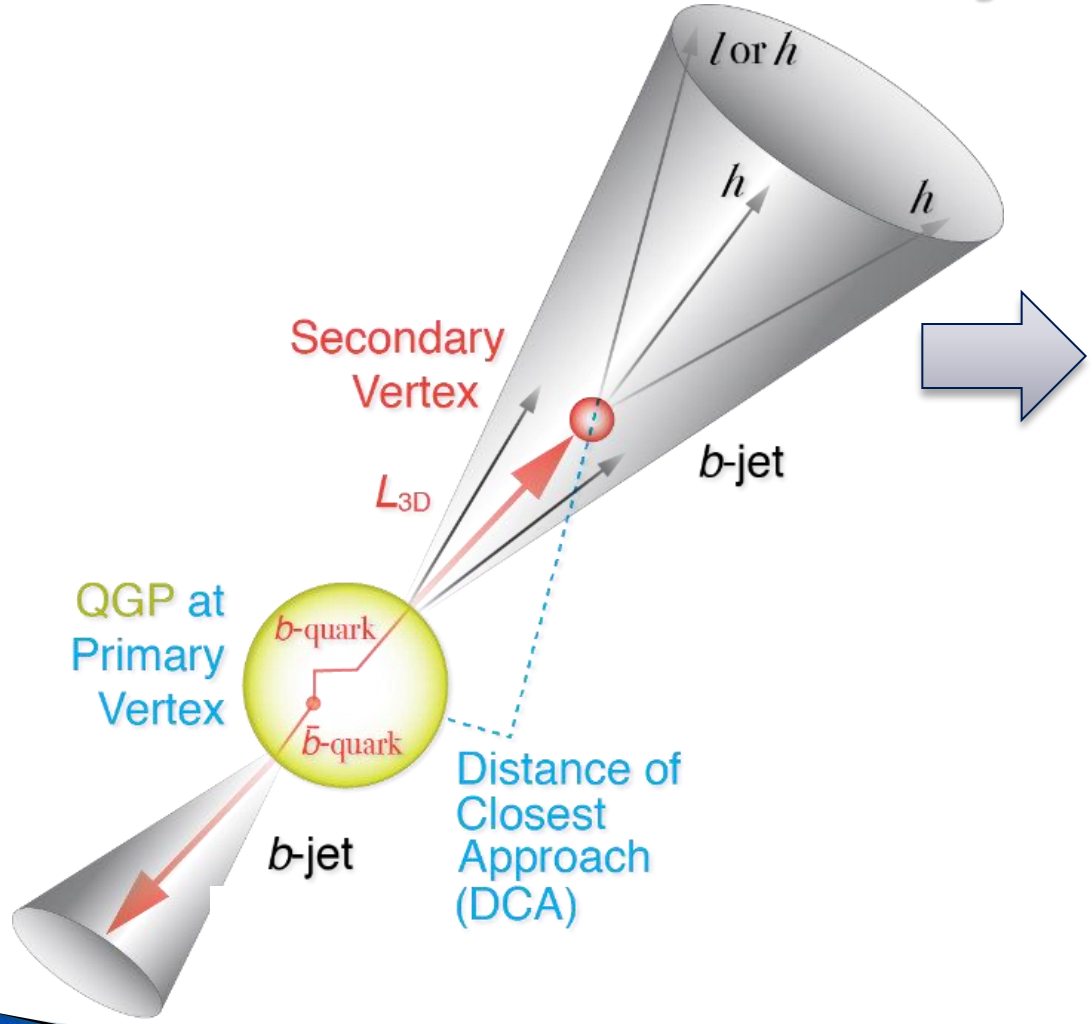
- Δv_1: Initial magnetic field

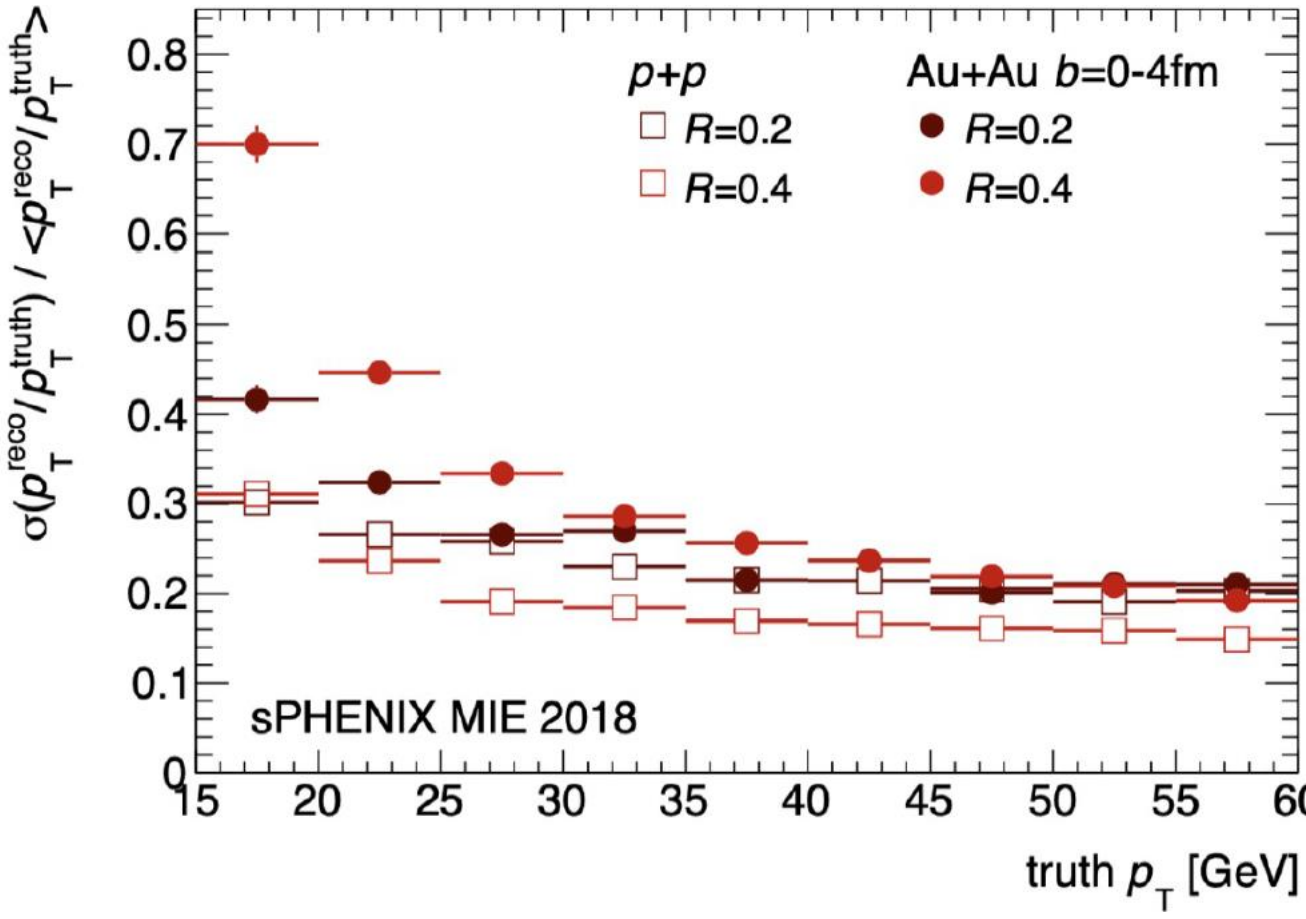


[sPH-TRG-2020-001]



sPHENIX calorimetric jets and b-jet tagging

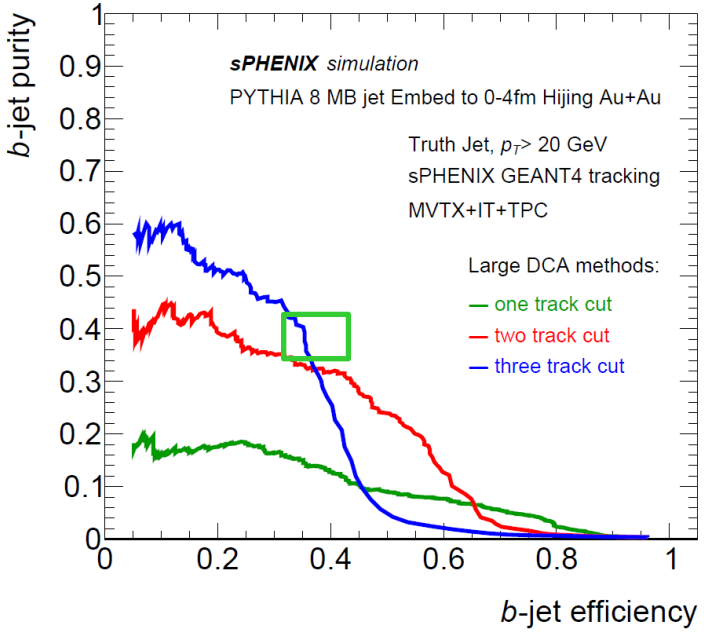




Combining calo.-jet and precision vertex: *b*-jet tagging

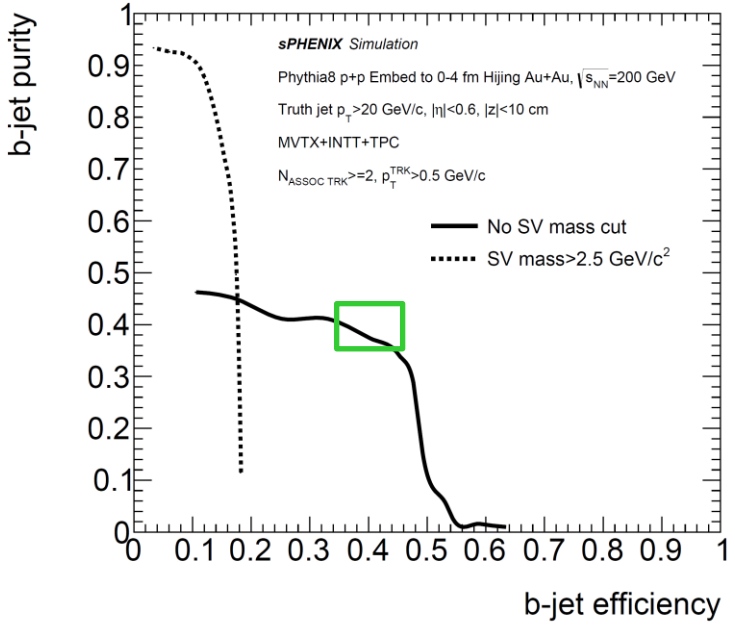
- Demonstrate b-jet capability: tagging algorithms evaluated using full detector HI simulation
- Reaching a promising working point in central Au+Au collisions

Track-counting tagger

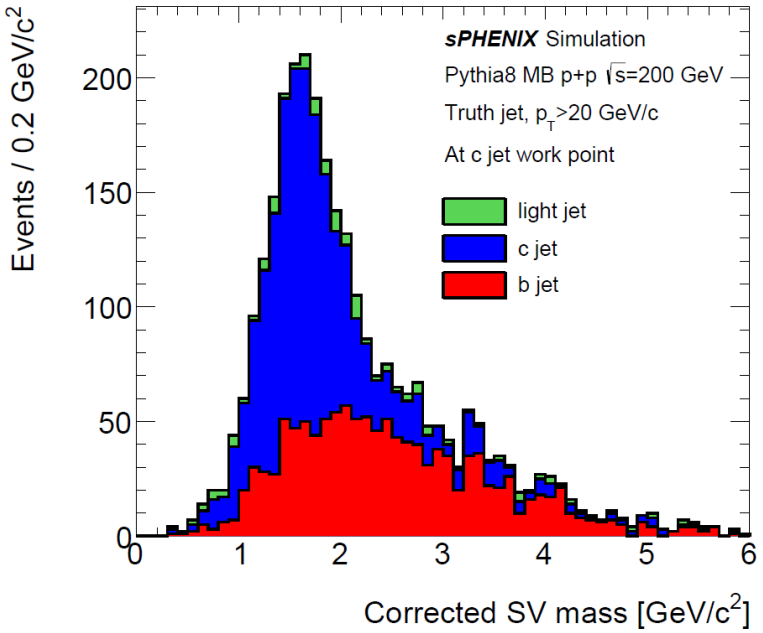


CMS work-point, Phys. Rev. Lett. 113, 132301 (2014)

Secondary-vertex tagger



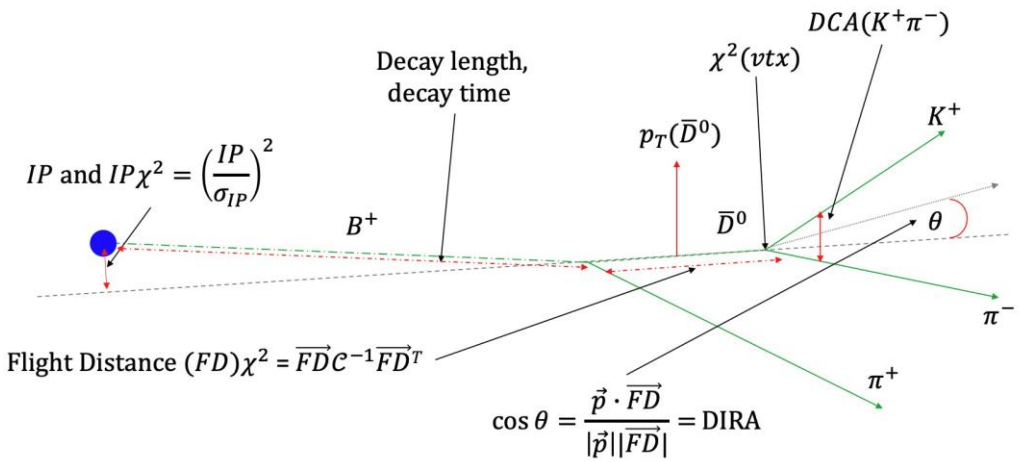
Secondary-vertex mass



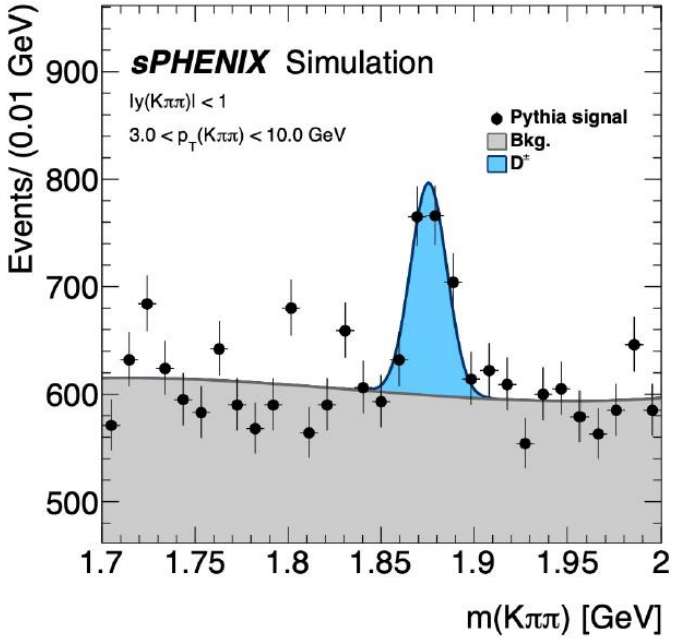
[sPH-HF-2018-001]

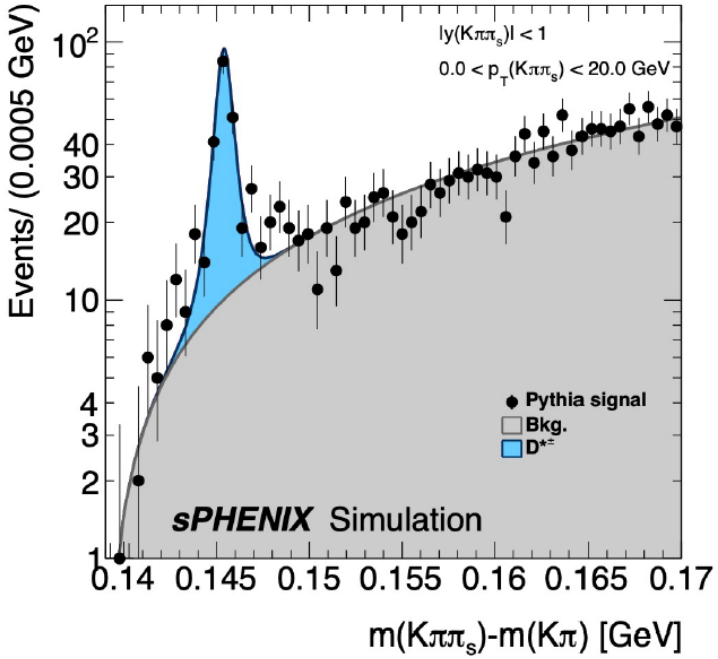
HF resonance reconstruction

- sPHENIX integration of KFParticle:
  - Generic resonance reco, also used in CBM, STAR , ALICE
- Used in mock data challenges → day-1 data

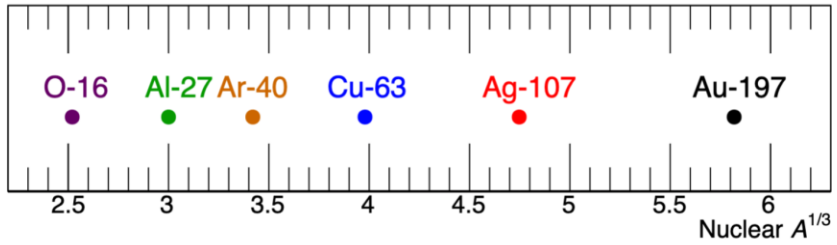


[sPH-HF-2021-001]

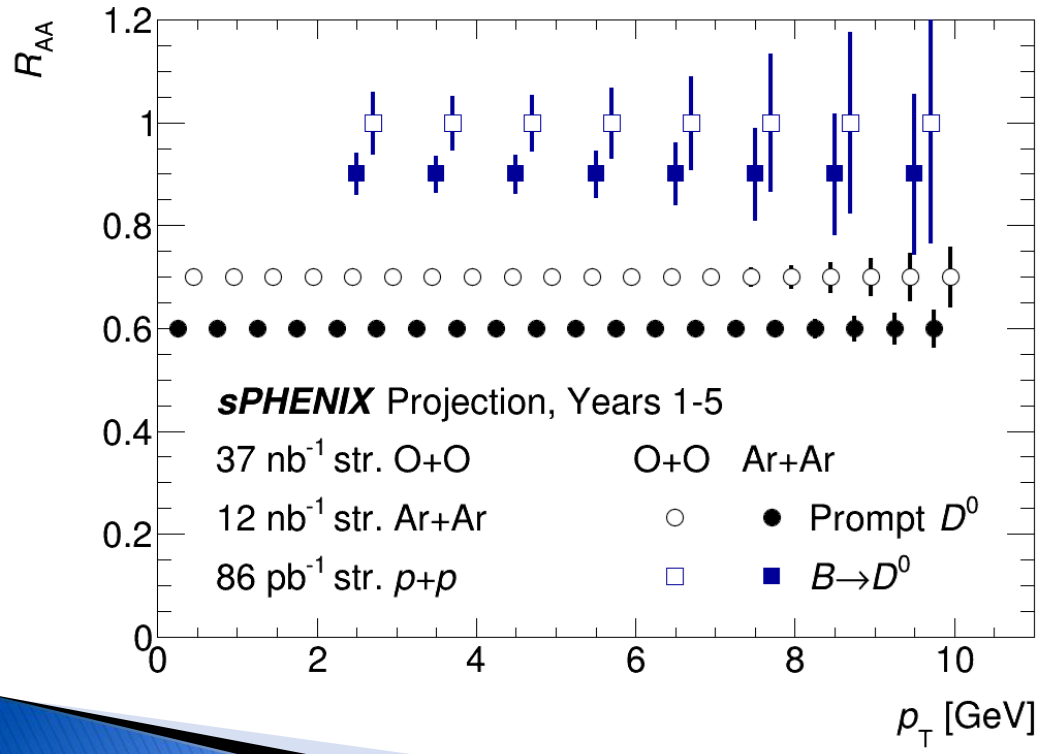




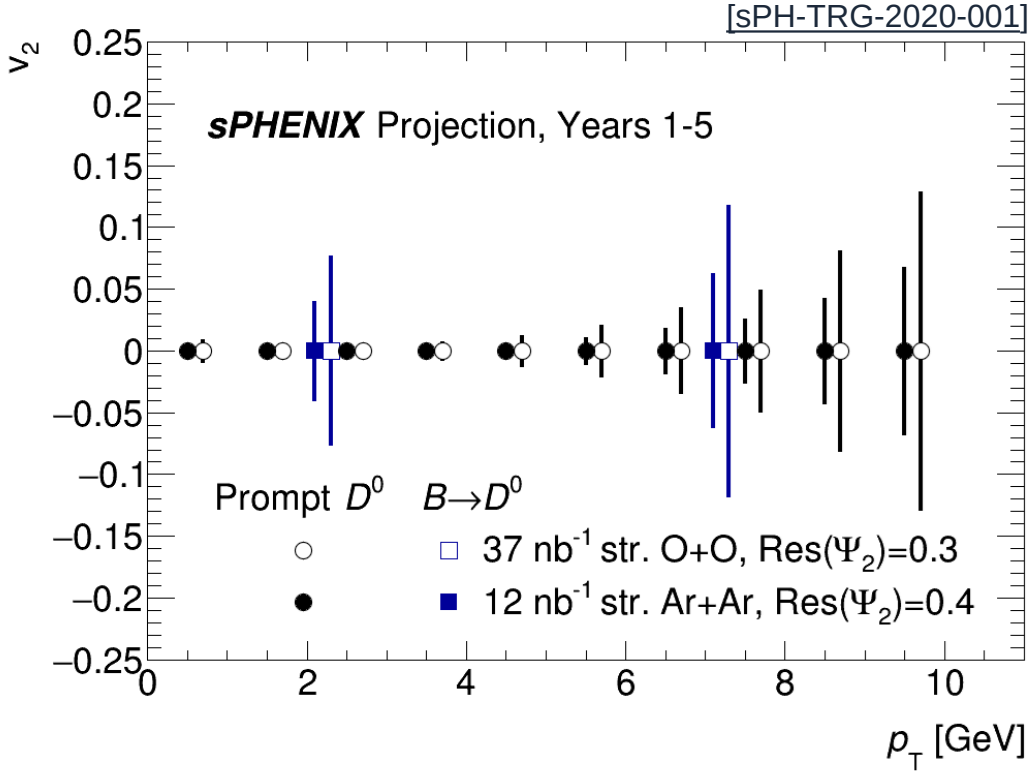
Possible runs beyond 2025 – Small collision system



- If opportunity arise in 2026-27, OO, ArAr runs
- pA: Mystery of non-zero HF v2 but lack of quenching. Small-A collision may bridge the gap from pA to large-AA



[sPH-TRG-2020-001]

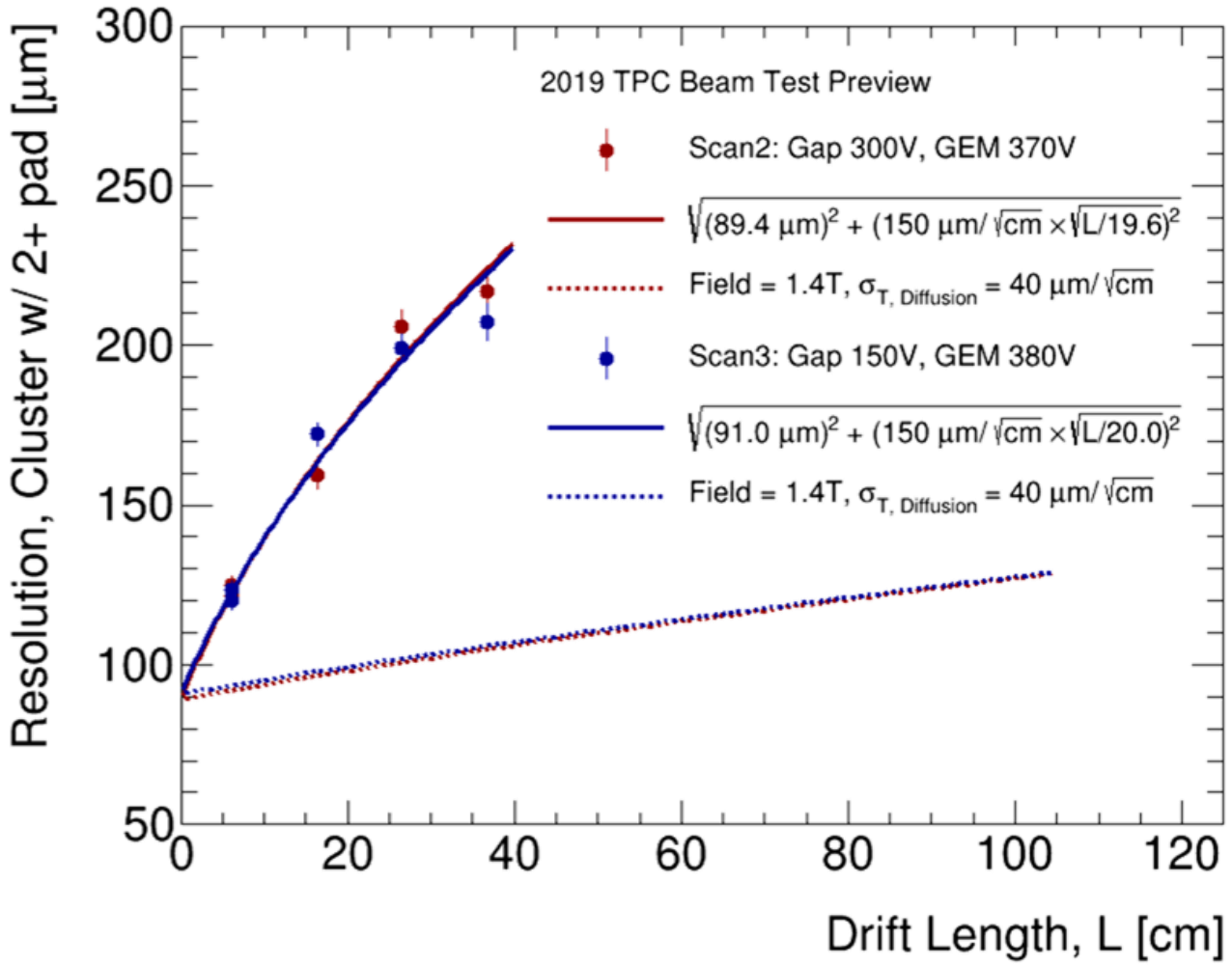


The tracking stack in the 2019 test beam

sPHENIX MVTX 2019 Beam Test
Using 180nm ITS2 ALPIDE MAPS sensor
MVTX Cluster hit Spatial Resolution < 5 um

Main tracker: Time projection chamber (TPC)

- Gateless and continues readout with GEM (similar to the ALICE TPC upgrade)
- Fast drift, low T diffusion, low ion backflow:
  50:50 Ne-CF4 gas, 13 us drift
- 48 layer of pad rows, zigzag pad
- SAMPA v5 ASIC with 80ns shaping time
- dp/p ~ 1% at 5GeV/c



Proposed run schedule, year 1-3

RHIC PAC-2021 Report:
"sPHENIX construction, installation and operation to accomplish its science goals is now the overarching priority for RHIC for the next 4 – 5 years."

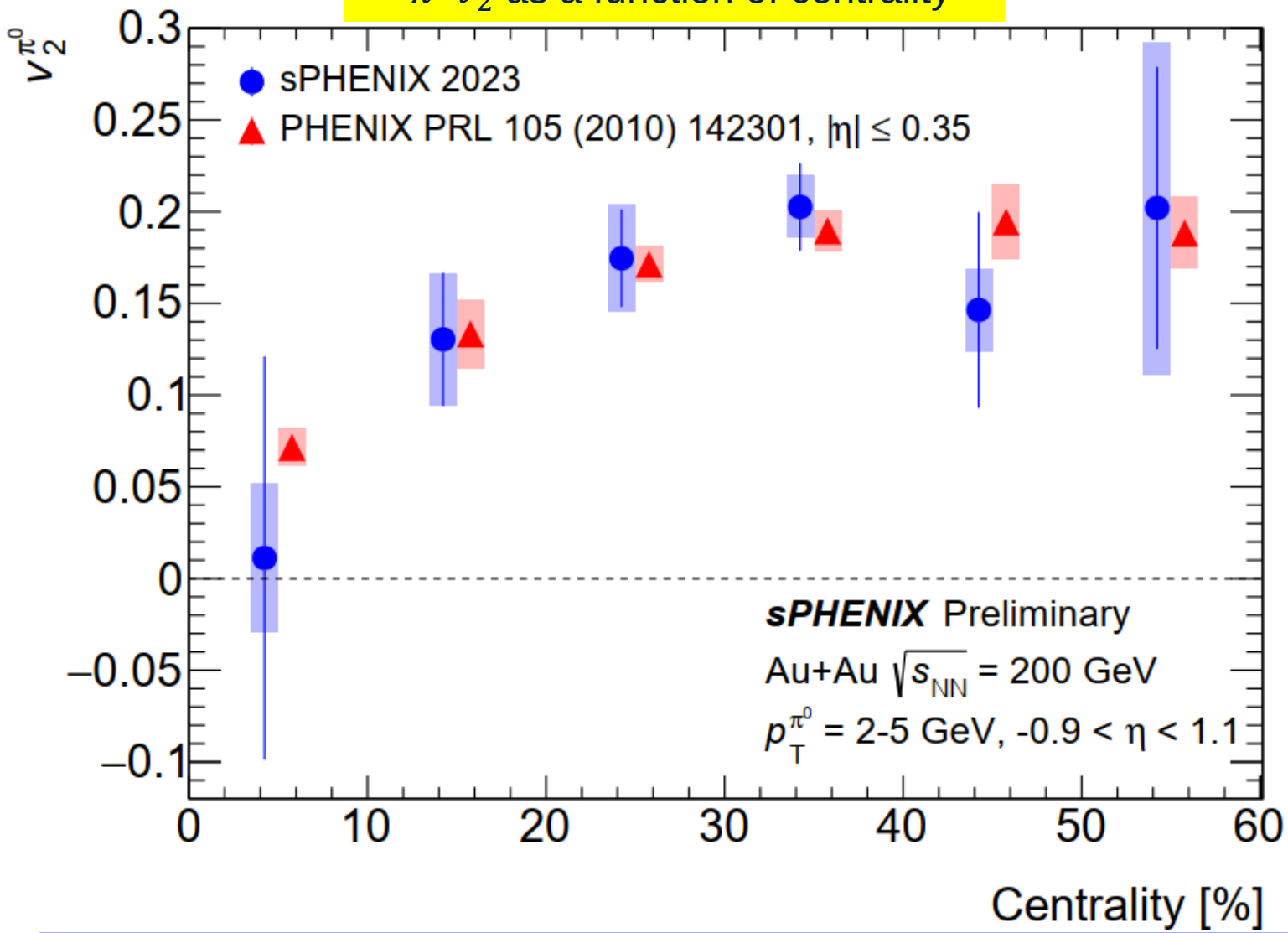
sPHENIX BUP2021 [sPH-TRG-2021-001], 24 (& 28) cryo-week scenarios

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) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 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}

First Physics Measurements in Au+Au: $\pi^0 v_2$ versus Centrality

Using commissioning data ~ 5 M events from Run 2023 with EMCal and MBD to measure $\pi^0 v_2$

$\pi^0 v_2$ as a function of centrality

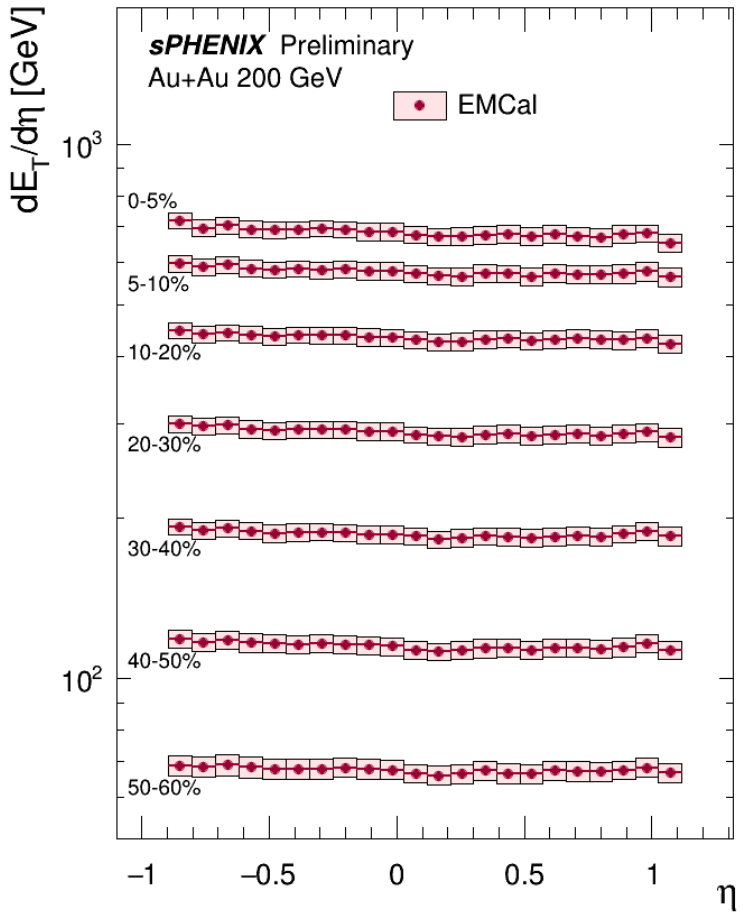


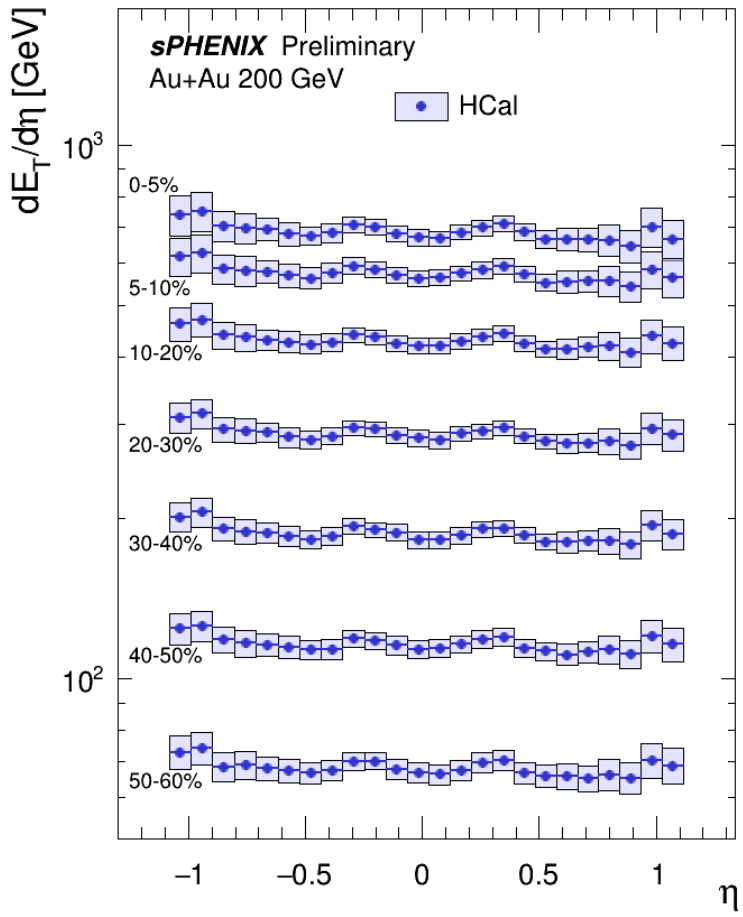
For more details/results see sPHENIX contributed talk by Emma McLaughlin on 6/7/24 at 4:30 pm

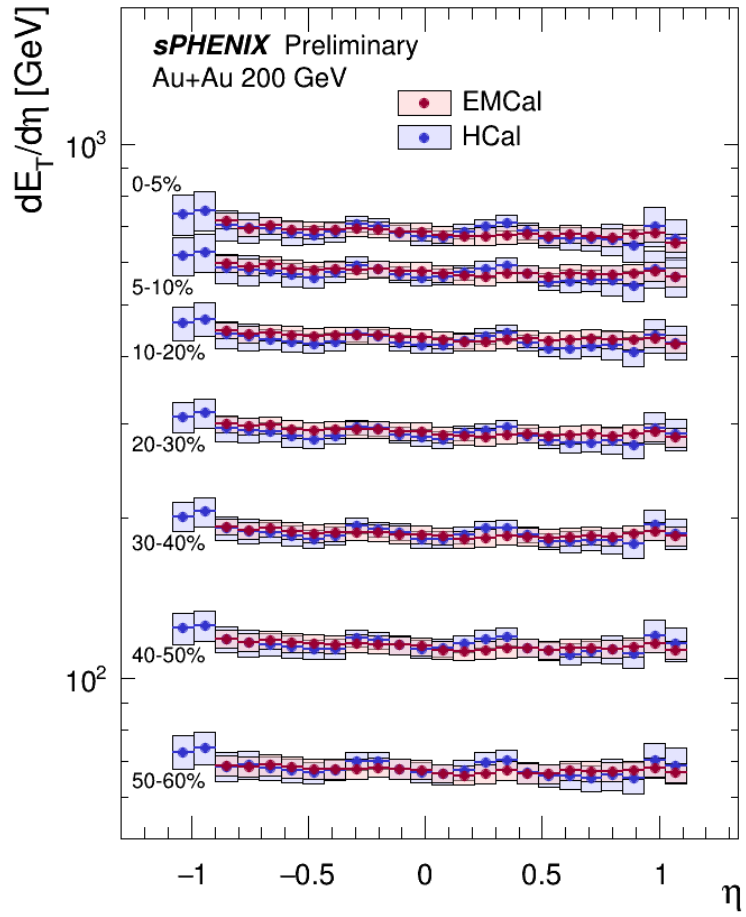
First Physics Measurements in Au+Au: $dE_T/d\eta$ versus Centrality

Using commissioning data ~ 249k events from Run 2023 with EMCal+IHCal+OHCal+MBD to measure $\frac{dE_T}{d\eta}$

$\frac{dE_T}{d\eta}$ distribution in each calorimeter subdetector





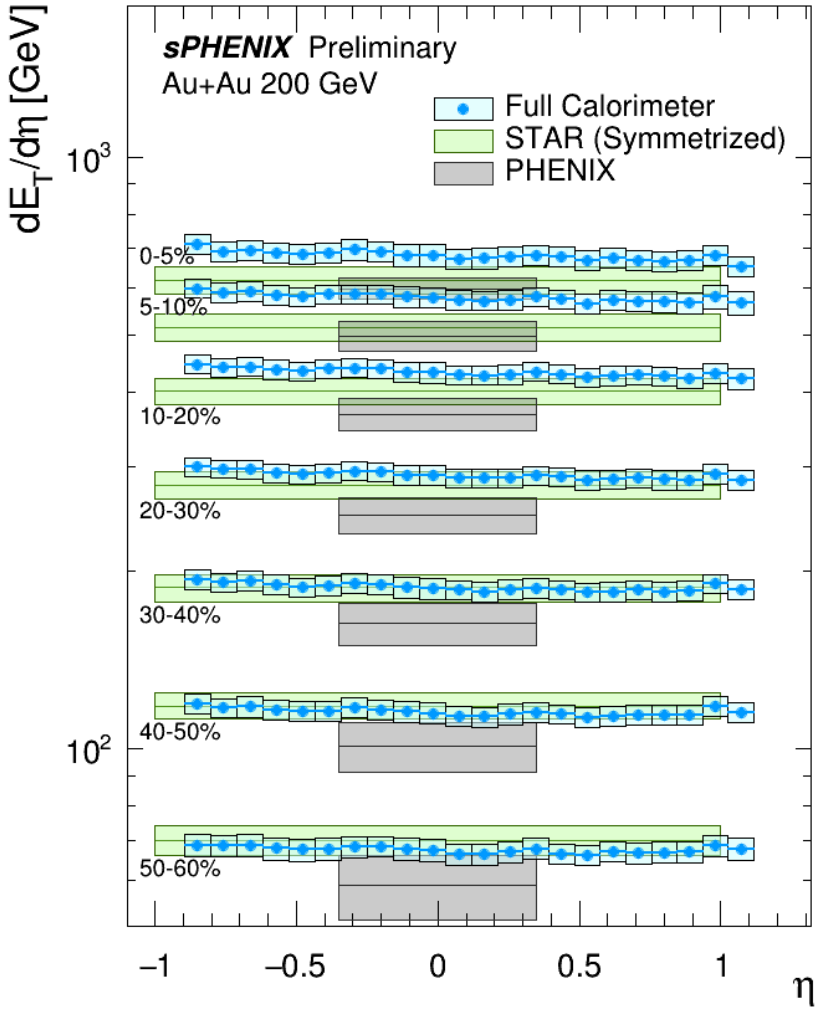


For more details/results see sPHENIX contributed talk by Emma McLaughlin on 6/7/24 at 4:30 pm

First Physics Measurements in Au+Au: $dE_T/d\eta$ Comparison

Using commissioning data ~ 249k events from Run 2023 with EMCal+IHCal+OHCal+MBD to measure $\frac{dE_T}{d\eta}$

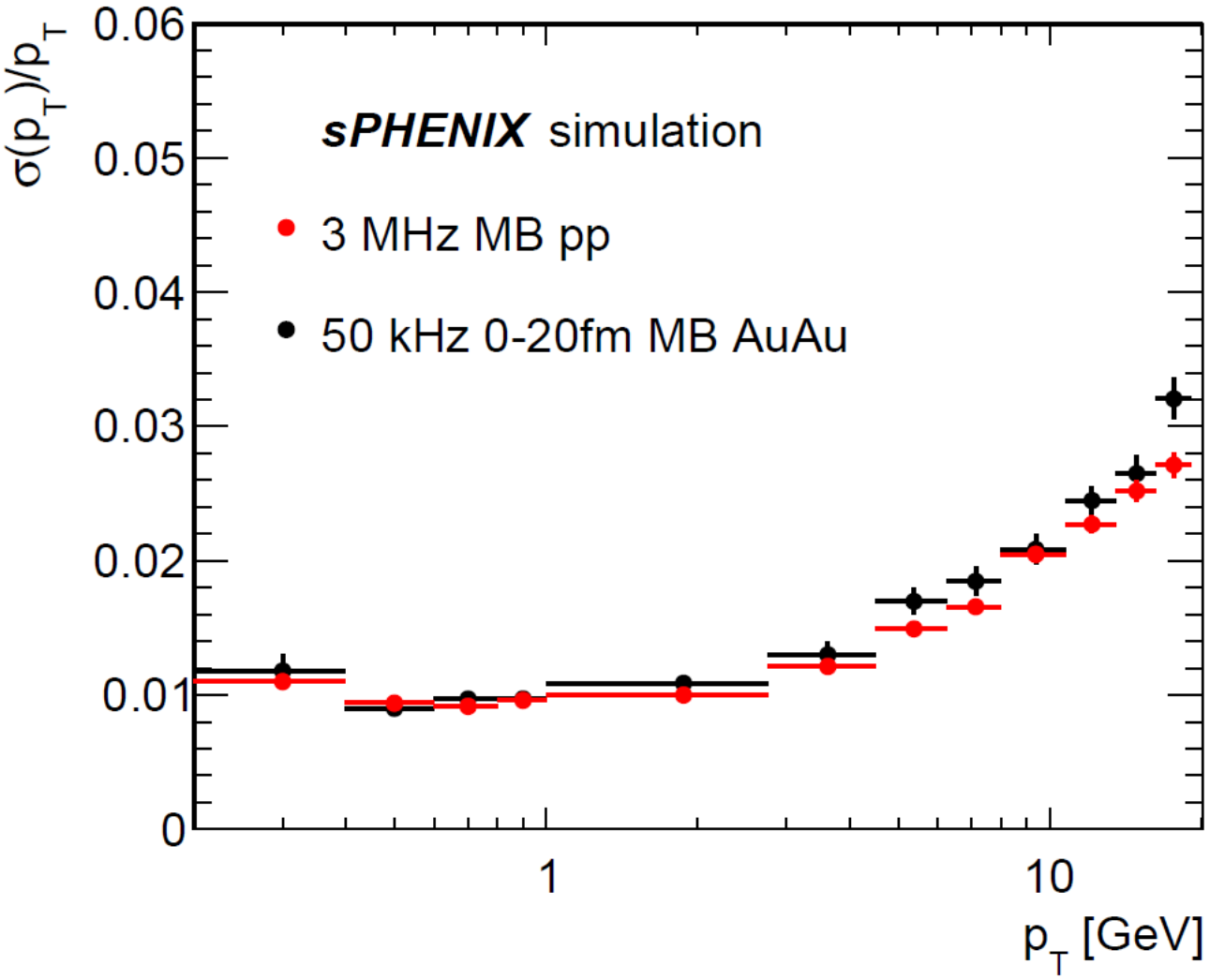
$\frac{dE_T}{d\eta}$ distribution, comparison to other experiments STAR and PHENIX

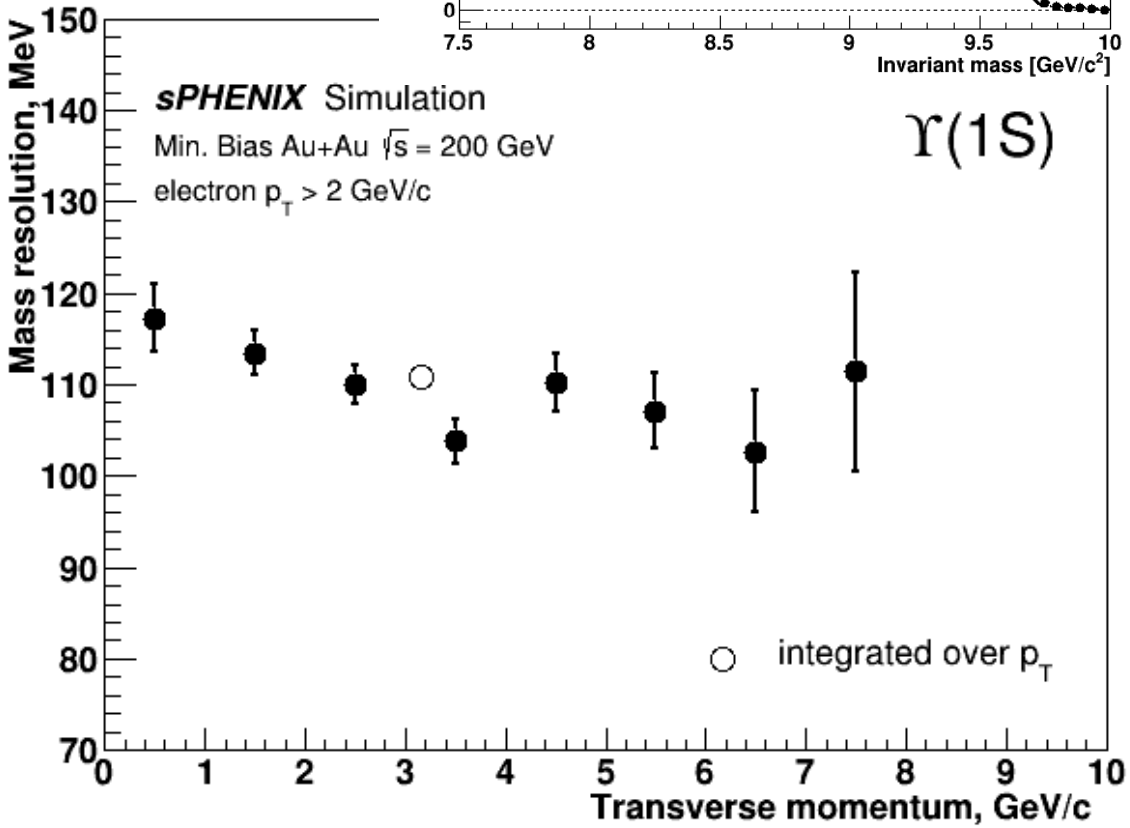


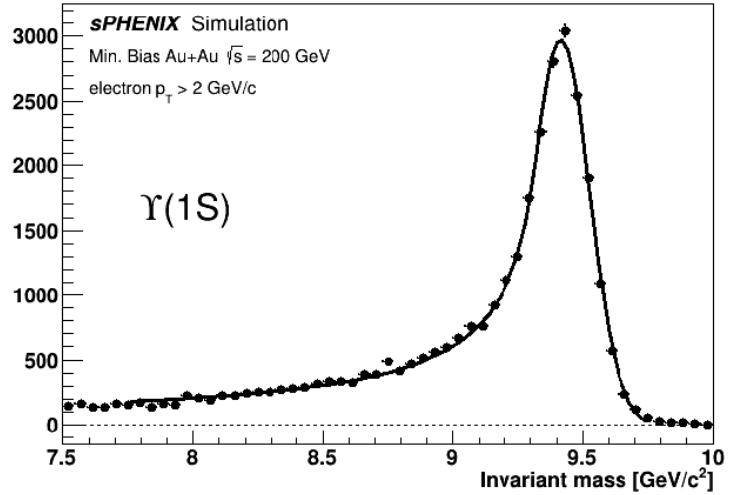
Presented are sPHENIX centrality intervals from preliminary centrality calculations which will be updated before finalizing centrality selections and reporting quantities like $\langle N_{part} \rangle$

For more details/results see sPHENIX contributed talk by Emma McLaughlin on 6/7/24 at 4:30 pm

Tracking performance

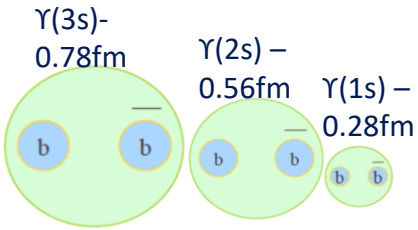




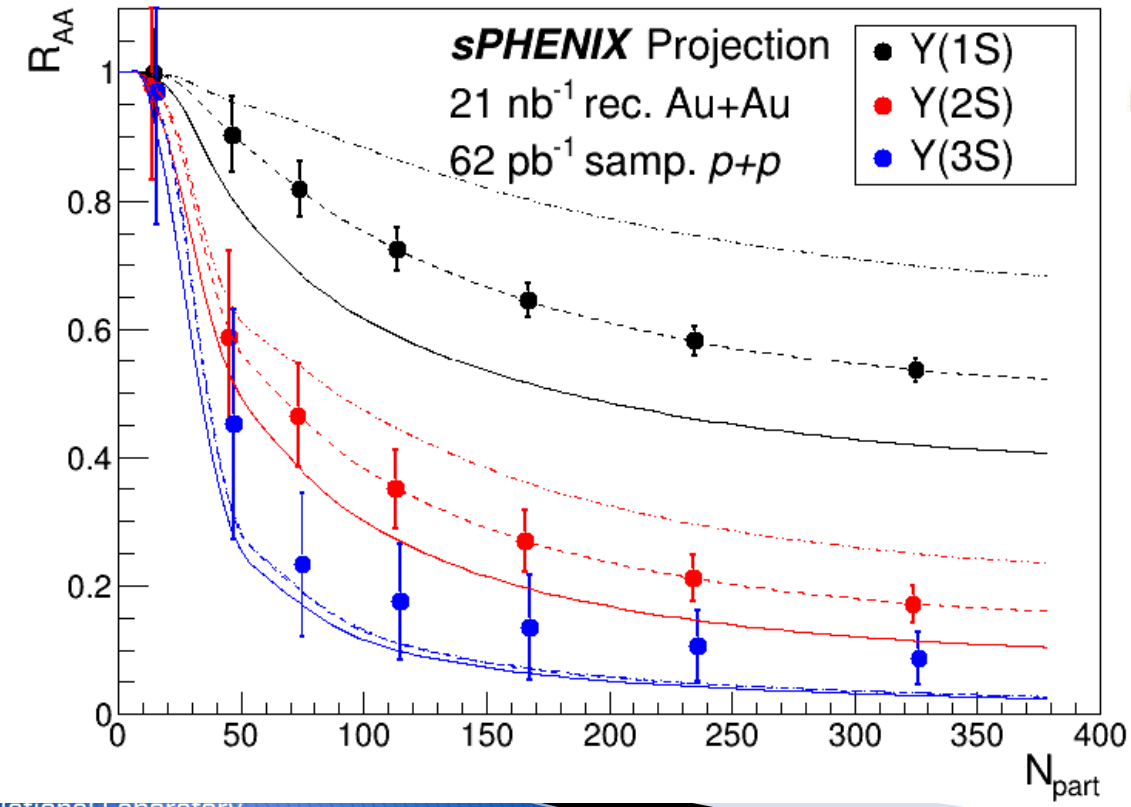


sPHENIX hidden heavy flavor

- Suppression with clear distinction of three Upsilon states
- Color dipoles probing the QGP at three length scales



Simulation



Simulation