The sPHENIX Experiment at RHIC
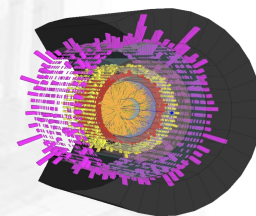
Weihu Ma
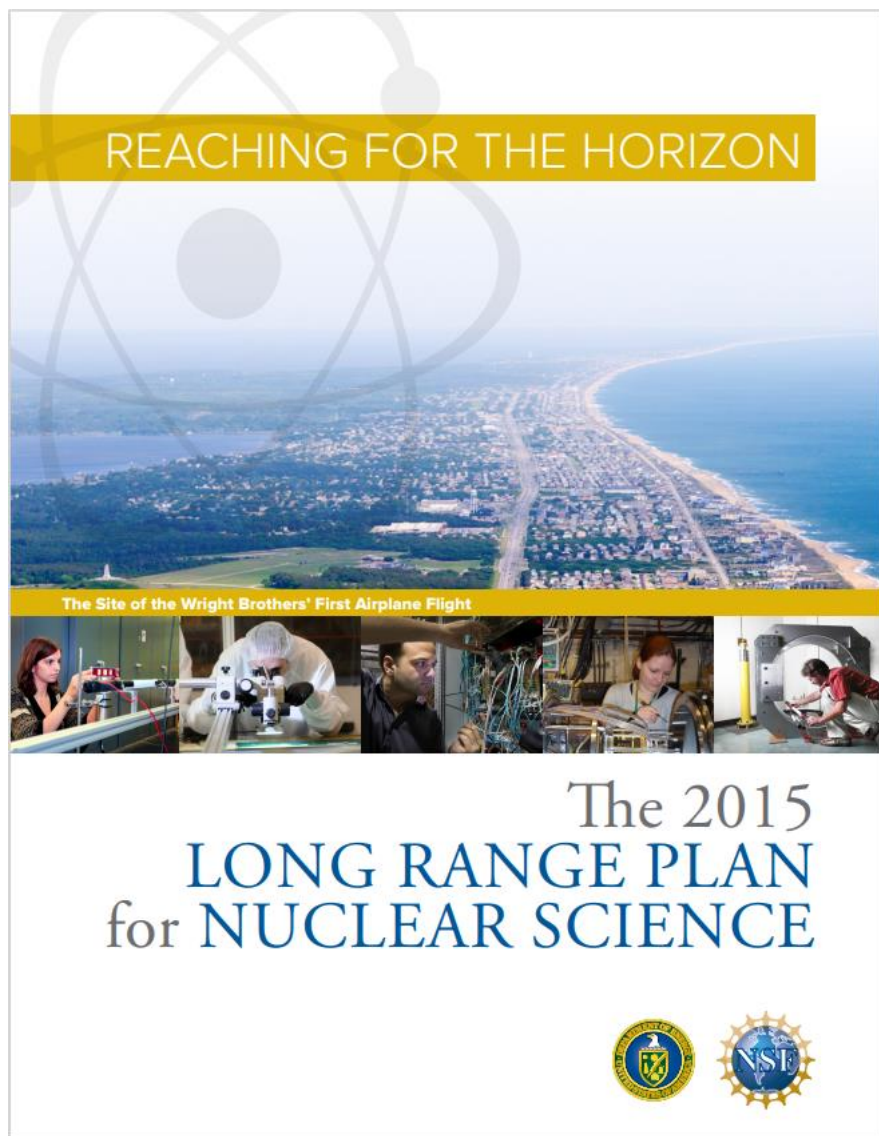
for the sPHENIX Collabration

Fudan University
Apr. 13, 2023

sPHENIX Science Mission

REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for **NUCLEAR SCIENCE**

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.** (2) Map the phase diagram of QCD with experiments planned at RHIC.

- ✓ sPHENIX will be the first new collider detector at RHIC in over twenty years;

- ✓ performing very high precision studies of jet production, jet substructure and open and hidden heavy flavor over an unprecedented kinematic range at RHIC;

- ✓ distinguished by high rate capability and large acceptance, combined with high precision tracking and electromagnetic and hadronic calorimetry.

sPHENIX Collaboration
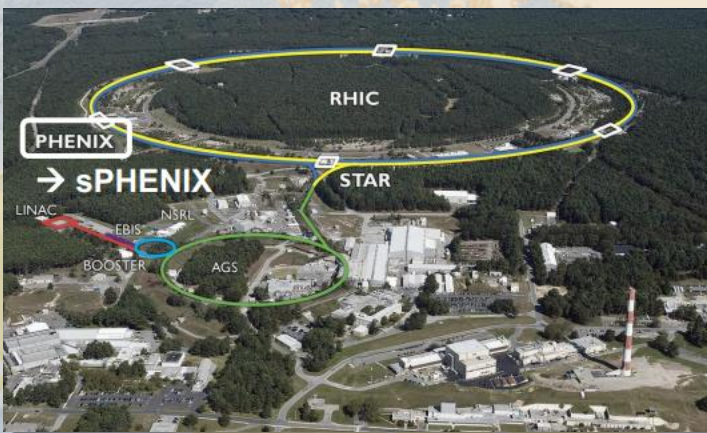
Encouraging diversity is a priority for our collaboration.
- **Diversity, Equity, & Inclusion training will be a requirement for being an sPHENIX author.**

✓ Replacement/upgrade of PHENIX. Proposed in 2010; collaboration formed in 2016.

✓ More than **360** members from **83** institutions in **14** countries as of 2022.

✓ Benefit from world-class expertise in physics, silicon, TPCs, calorimetry, electronics, computing, …

* shown here are institutions joined after CD-0

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sPHENIX Detector

◎ High data rates: 15 kHz for all subdetectors

◎ Trigger capability also with streaming readout

◎ 1.4T Solenoid from BaBar

◎ Hermetic coverage: $|\eta|<1.1$, 2π in φ

◎ Precision tracking

◎ Large-acceptance EM+H calorimeters: brings first full jet reconstruction & b-jet tagging at RHIC!!
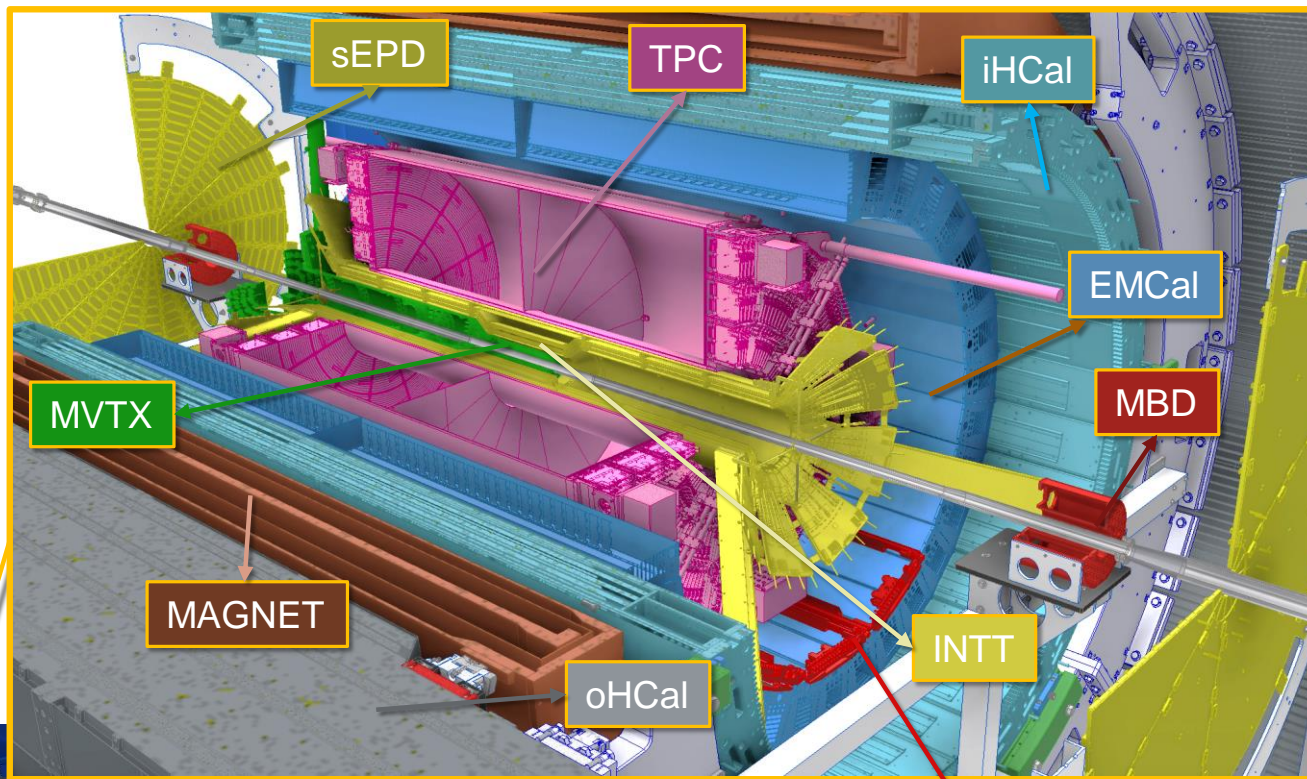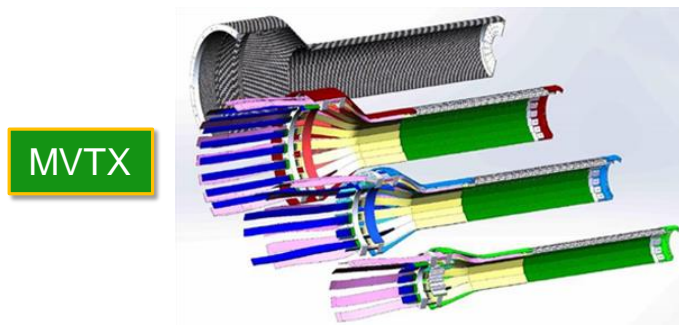

Calorimeter system

Tracking system

support carriage

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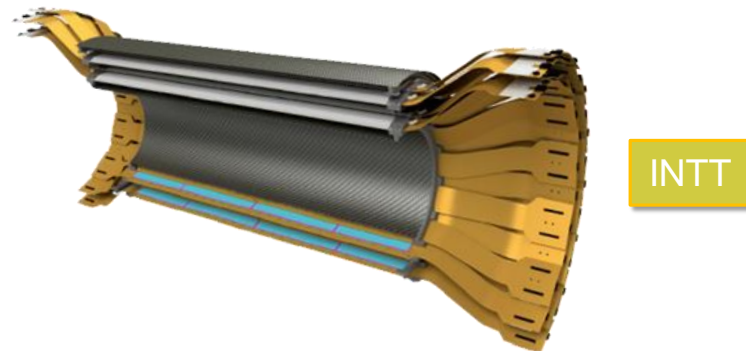GHP2023
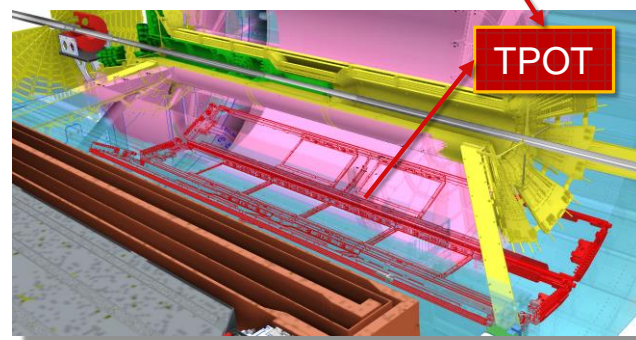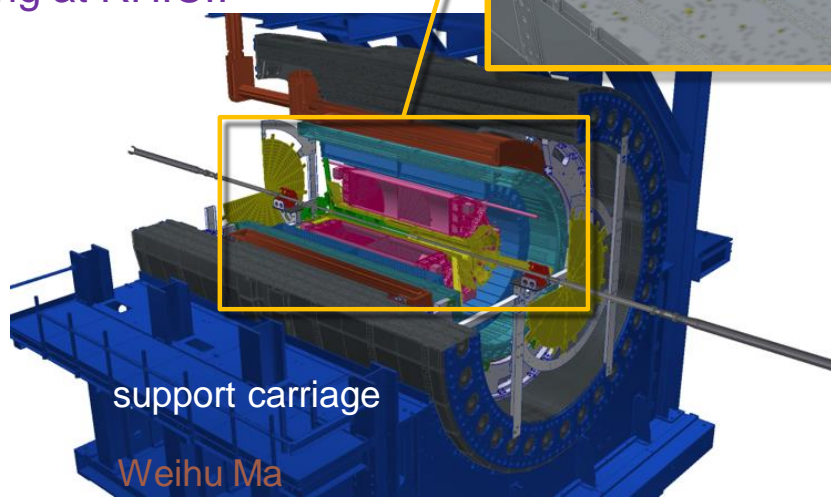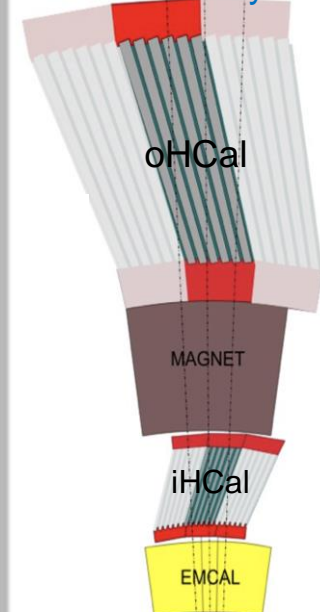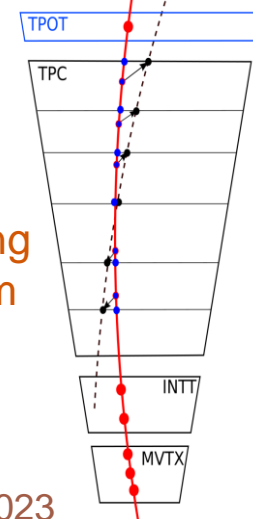
Tracking System

MAPS-based micro-VerTeX detector (MVTX)

- ✓ Based on ALICE ITS
- ✓ 3-layer Monolithic Active Pixel Sensors (MAPS).
- ✓ Excellent 2-D DCA resolution, < 10 μm for p_T > 2 GeV/c
- ✓ Installation complete!

## Intermediate Silicon Tracker (INTT)

- ✓ Two Barrels (four Layers) silicon strips
- ✓ Fast O(100 ns) integration time; can resolve one beam crossing
- ✓ Installation complete!

MVTX

INTT

TPC Outer Tracker (TPOT)

- ✓ 8 modules of Micromegas inserted between TPC and EMCal
- ✓ Calibration of beam-induced space charge distortions in the TPC
- ✓ TPOT module under test
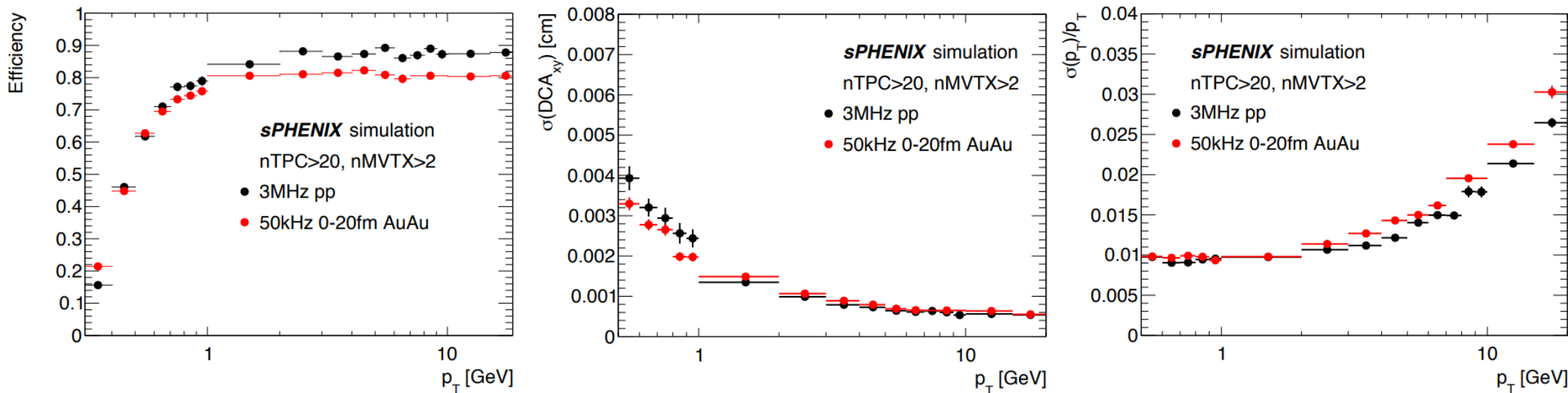- ✓ Installation complete!

TPC
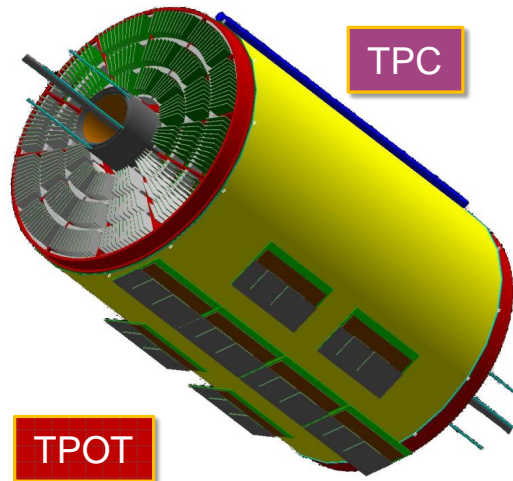
Time Projection Chamber (TPC)

- ✓ Compact
- ✓ Δp/p~1% at 5 GeV/c
- ✓ 48 layers (20-78 cm radius)
- ✓ Gateless, continuous readout
- ✓ Quad-GEM electron multiplier + chevron readout pads
- ✓ Installation complete!

TPOT

Tracking Performance

sPHENIX tracking performance

✓ Eff.~90% for pp at p_T>1 GeV. → promising to measure rare processes: e.g. Y(nS).

✓ DCA resolutions in r-ϕ, z < 40μm at p_T>0.5 GeV. → crucial for open heavy-flavor.

✓ p_T resolution < 2% for p_T < 10 GeV. → meets δM < 125 MeV for Y(nS) separation.
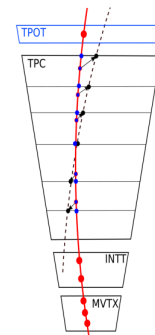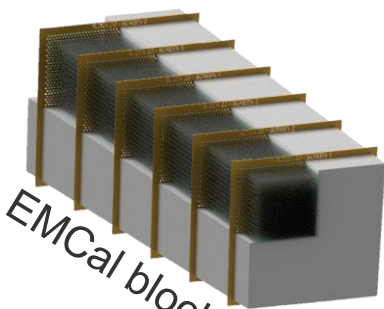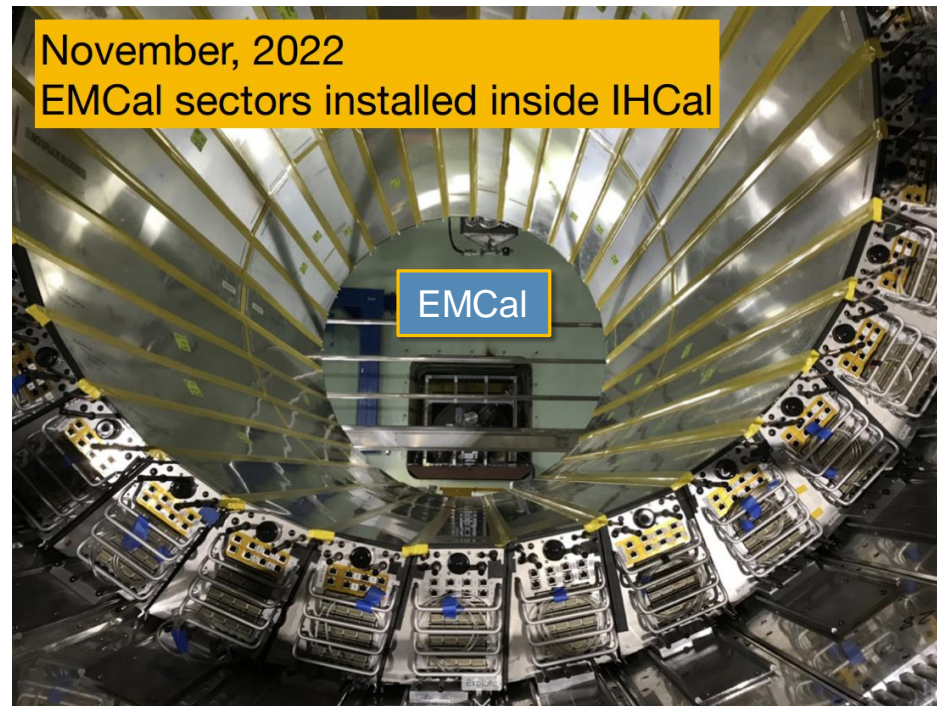
Electromagnetic Calorimeter (EMCal)

Calorimeter System(EMCal+iHCal+ oHCal)
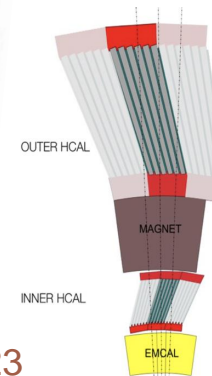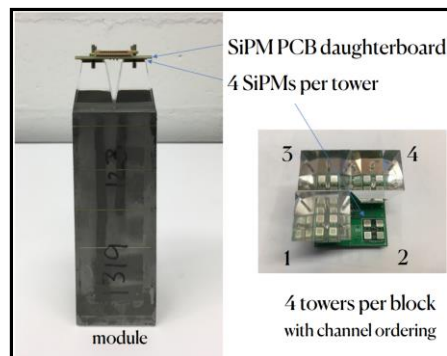
- ✓ Compact, coverage |η| <1.1, 2π in φ
- ✓ SiPM readout for both EMCal and HCal
- ✓ Less-biased jet measurement
- ✓ All Calorimeter electronics complete!

Electromagnetic Calorimeter (EMCal)

- ✓ Tungsten/scintillating fiber SPACAL
- ✓ ~7mm radiation length
- ✓ high granularity Δη x Δφ = 0.025 x 0.025
- ✓ Good energy resolution $\sigma_E/E \leq 16\%/\sqrt{E}$
- ✓ Installation complete!

November, 2022
EMCal sectors installed inside IHCal

EMCal

EMCal block

SiPM PCB daughterboard
4 SiPMs per tower

module

4 towers per block
with channel ordering

EMCal sector
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

OUTER HCAL

MAGNET

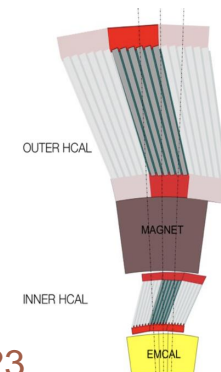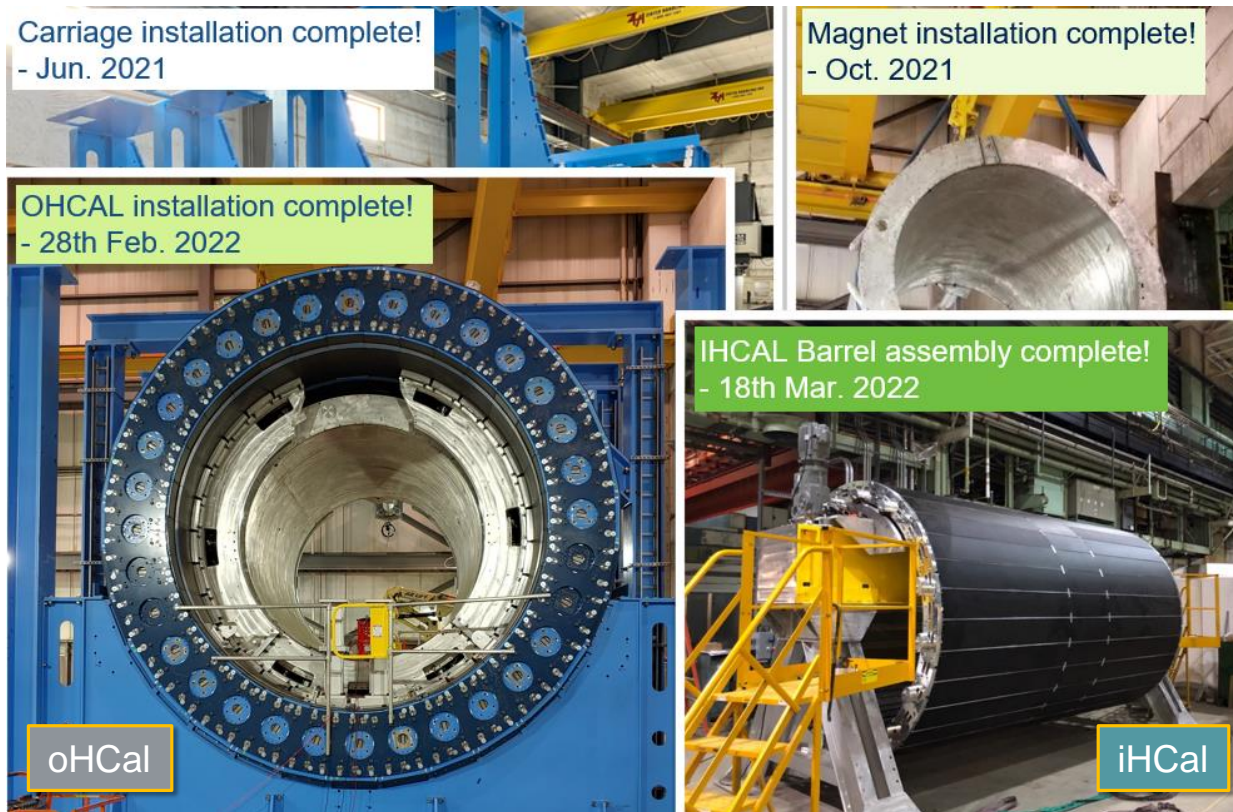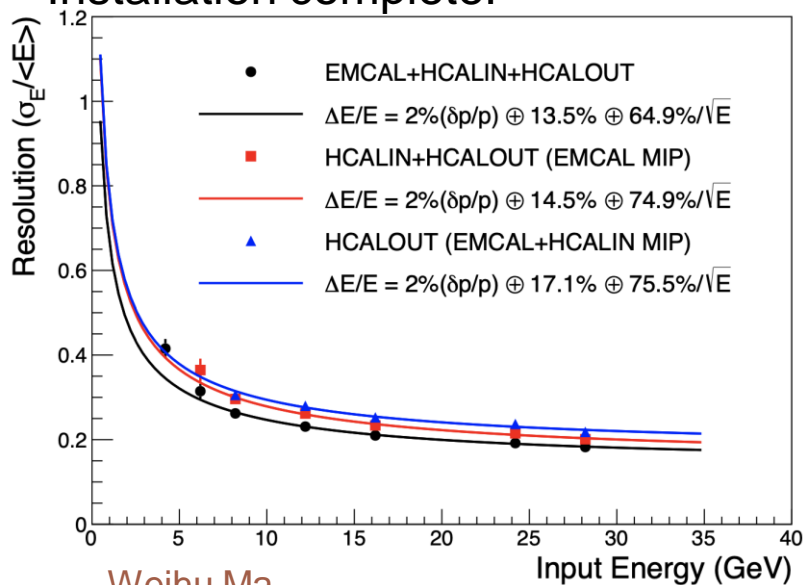INNER HCAL

EMCAL

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Hadronic Calorimeter (HCal)

Inner Hadronic Calorimeter (iHCal)

- ✓ Aluminum-scintillating tiles with embedded WLS fibers
- ✓ EM-shower tail catcher
- ✓ Installation complete!

Outer Hadronic Calorimeter (oHCal)

- ✓ Tilted steel plates/scintillator tiles with embedded WLS fibers
- ✓ $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ towers
- ✓ Installation complete!

Carriage installation complete!
- Jun. 2021

Magnet installation complete!
- Oct. 2021

OHCAL installation complete!
- 28th Feb. 2022

IHCAL Barrel assembly complete!
- 18th Mar. 2022

oHCal

iHCal

- EMCAL+HCALIN+HCALOUT
- $\Delta E/E = 2\%(\delta p/p) \oplus 13.5\% \oplus 64.9\%/\sqrt{E}$
- HCALIN+HCALOUT (EMCAL MIP)
- $\Delta E/E = 2\%(\delta p/p) \oplus 14.5\% \oplus 74.9\%/\sqrt{E}$
- HCALOUT (EMCAL+HCALIN MIP)
- $\Delta E/E = 2\%(\delta p/p) \oplus 17.1\% \oplus 75.5\%/\sqrt{E}$

HCal sector

OUTER HCAL

MAGNET

INNER HCAL

EMCAL

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sEPD and MBD

sPHENIX Event Plane Detector (sEPD)

- ✓ Measure event plane and centrality outside of mid-rapidity
- ✓ 1.2-cm-thick scintillator with embedded WLS fibers
- ✓ 2 Wheels of 12 sectors with 31 optically-isolated tiles
- ✓ $2.0 < |\eta| < 4.9$
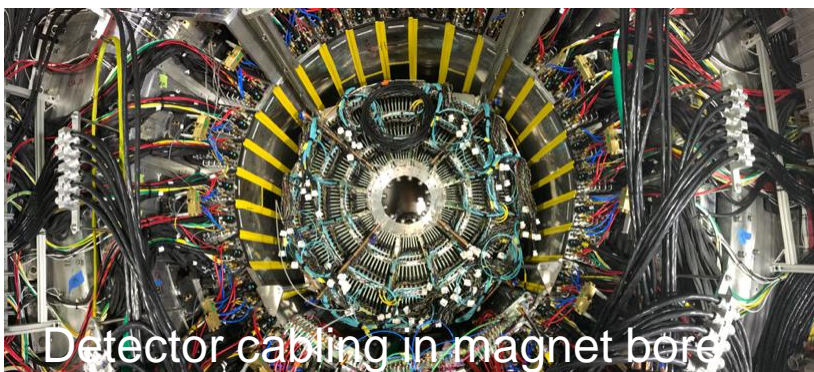- ✓ Detector complete!

Minimum bias detector (MBD)

- ✓ Provide minimum-bias trigger with high efficiency for heavy ion collisions (>90%)
- ✓ Contributes to centrality, reaction plane, start time, and interaction vertex
- ✓ Reuse of the PHENIX BBC(Beam-Beam counter)
- ✓ 2x64 channels of 3 cm thick quartz radiator on mesh dynode PMT
- ✓ $3.51 < |\eta| < 4.61$
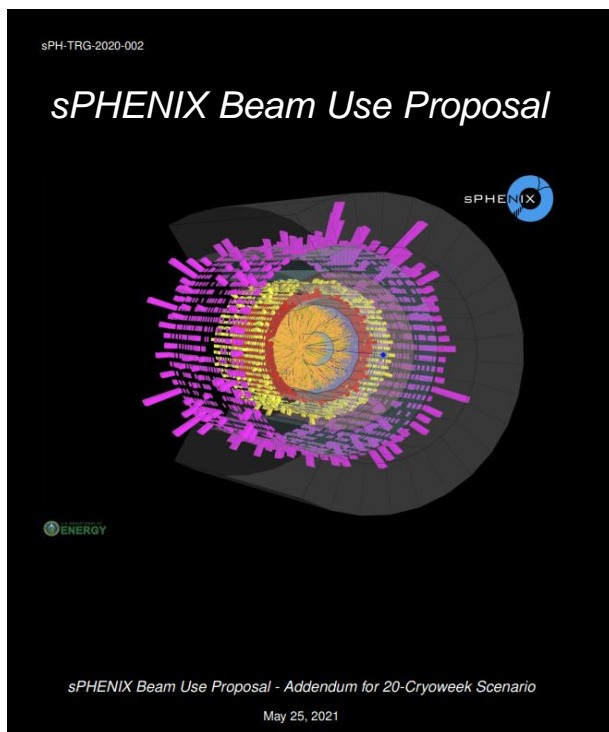- ✓ 120 ps timing resolution
- ✓ Detector complete!

sEPD sector

MBD

sEPD

MBD
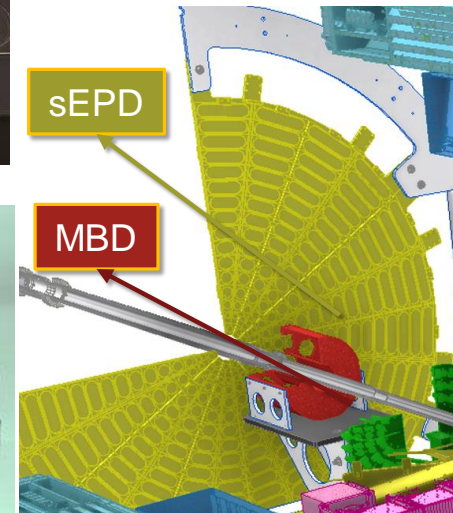
Detector Installation

- ✓ Magnet, OHCal, IHCal, EMCal, TPOT, TPC installed cabled and plumbed.
- ✓ Beampipe installed.
- ✓ Magnet ready for cool down.
- ✓ Gas and water systems to OHCal, IHCal, EMCal, TPOT, TPC ready to operate.
- ✓ Electronics racks ready to operate.
- ✓ Safety systems operational.

Detector cabling in magnet bore

sPHENIX electronics racks

Run plan of sPHENIX

2015 ▶ 2016 ▶ 2017 ▶ 2018 ▶ 2019 ▶ 2020 ▶ 2021 ▶ 2022 ▶ **2023**

sPHENIX science collaboration

DOE CD-0 "Mission need" approval

DOE CD-1/3A Cost, schedule, advance purchase approval

Today Installation and commissioning

Start first data taking!

sPH-TRG-2020-002

sPHENIX Beam Use Proposal

sPHENIX

sPHENIX Beam Use Proposal - Addendum for 20-Cryoweek Scenario

May 25, 2021

Summary of sPHENIX Beam Use Proposal for the years 2023–2025

| 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} [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}

● Year-1 (Au+Au): Commissioning, calibration, collection of a Au+Au data set.

● Year-2 (p+p & p+Au): Commissioning and p+p reference data & p+Au cold QCD Measurements.

● Year-3 (Au+Au): very large statistics data collection for jets and heavy flavor observables.
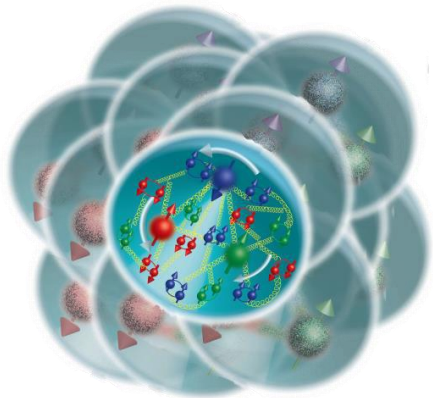
4 Core Physics Programs @ sPHENIX
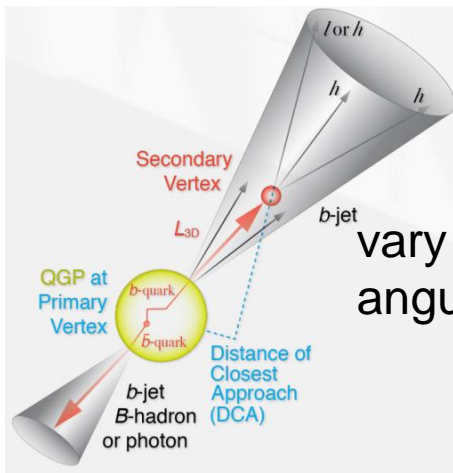
vary momentum & angular scale of probe

Jet physics

vary size of probe

Y(3s) 0.78fm Y(2s) 0.56fm Y(1s) 0.28fm
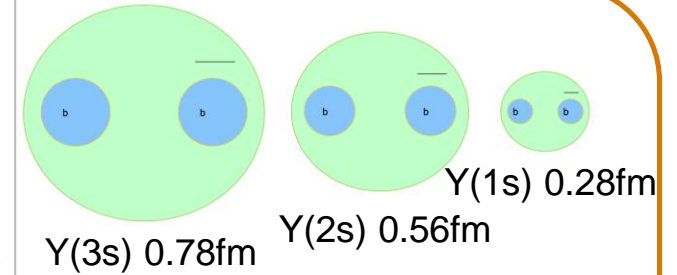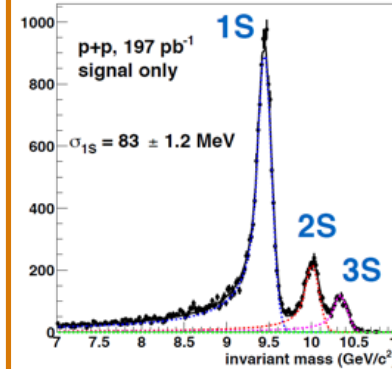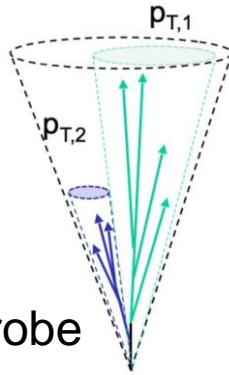
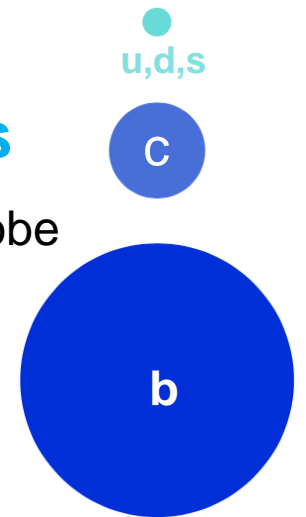## Quarkonium spectroscopy

Cold QCD

vary temperature of QCD matter

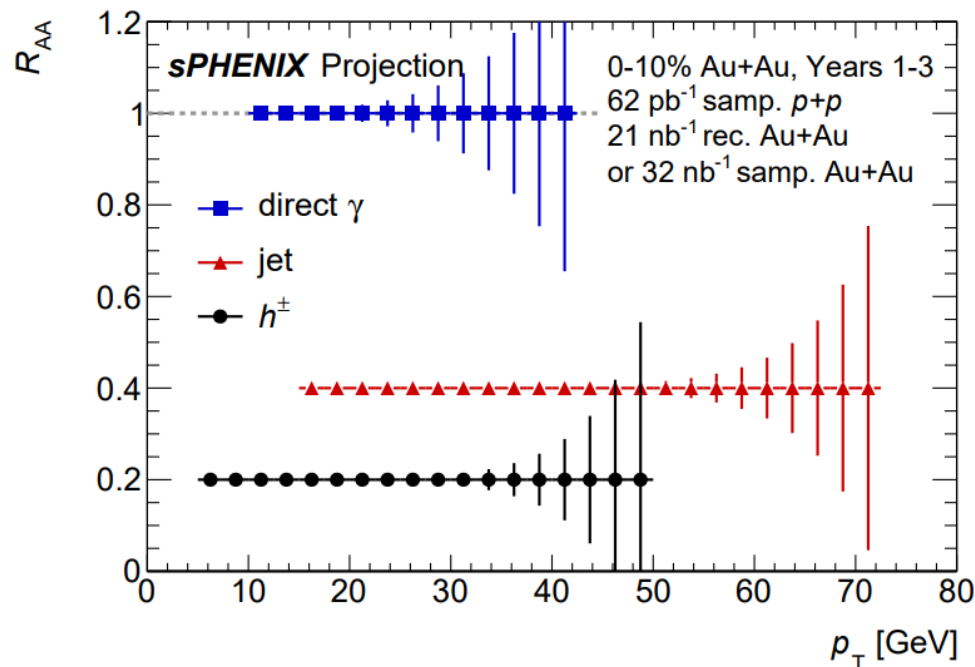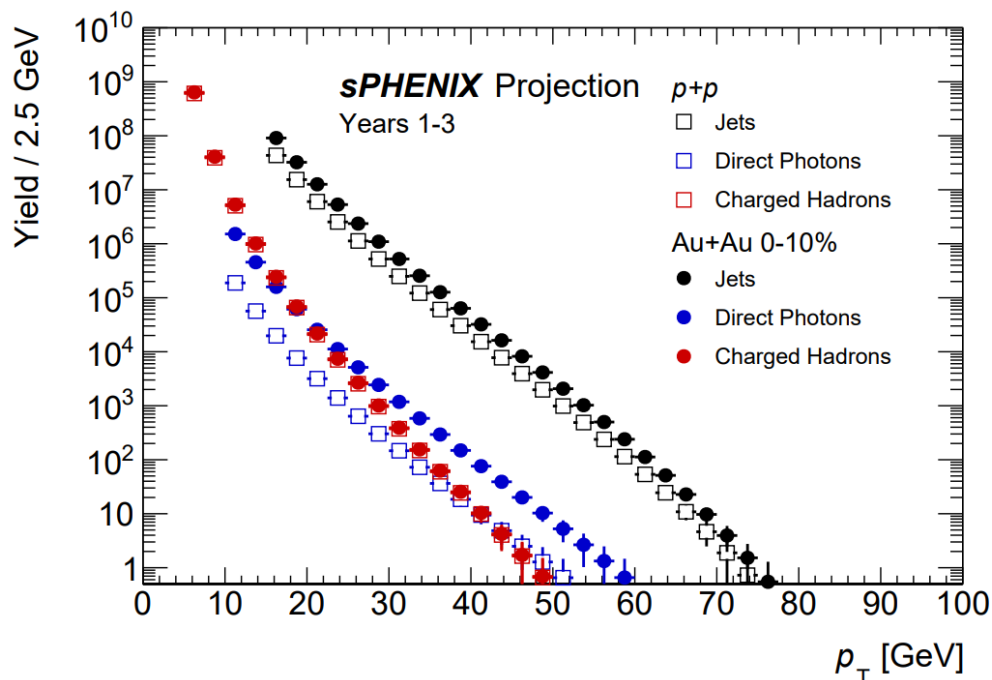study proton spin, transverse-momentum, and cold nuclear effects

Parton energy loss

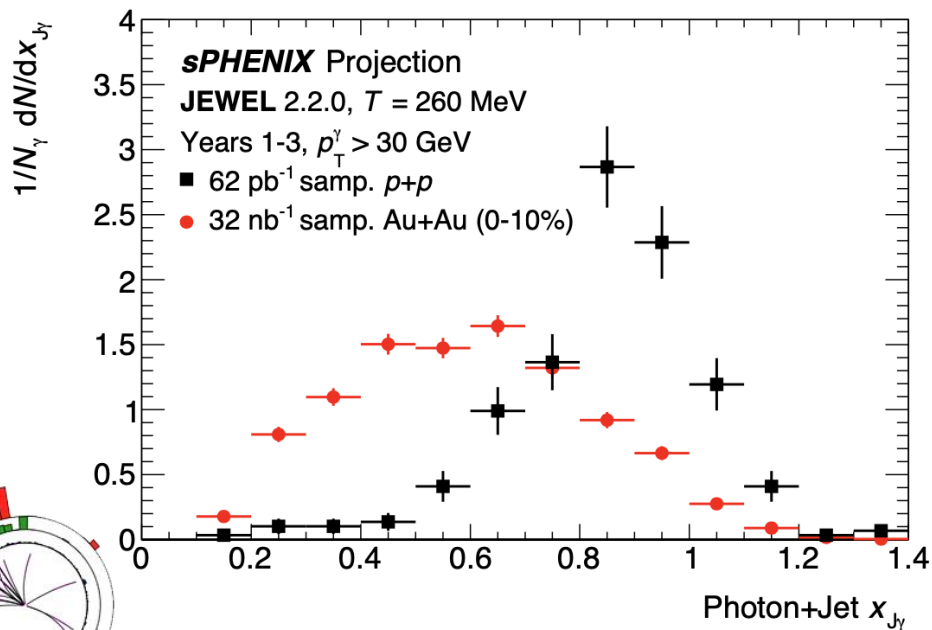vary mass & momentum of probe

photon
gluon

u,d,s

c

b

High-p$_T$ Probes

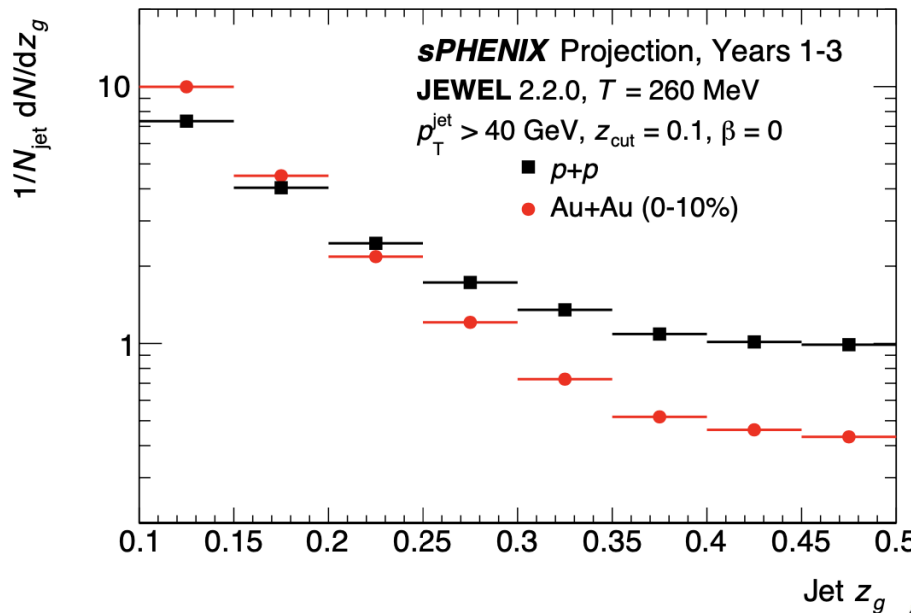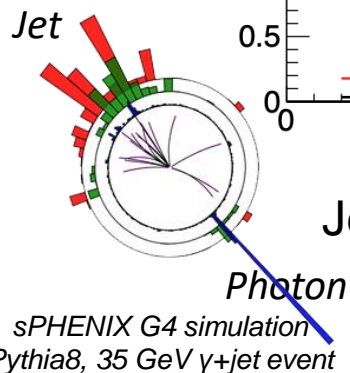Probing the QGP with precise jet, direct photon, and hadron measurements

✓High data rates & hermetic EMCal+HCal offer wide p$_T$ range for jet reconstruction.

✓sPHENIX can precisely measure the low p$_T$ region, which is challenging at the LHC.

✓sPHENIX will have kinematic reach out to ~ 70 GeV for jets, kinematic overlap with the LHC.
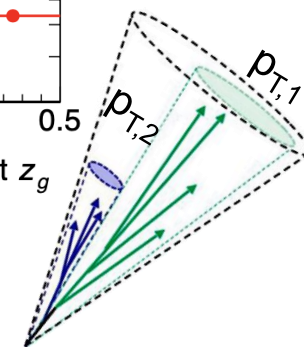
Jet Physics

sPHENIX Projection
JEWEL 2.2.0, $T = 260$ MeV
Years 1-3, $p_T^\gamma > 30$ GeV
■ 62 pb^{-1} samp. $p+p$
● 32 nb^{-1} samp. Au+Au (0-10%)

Photon+Jet $x_{J\gamma}$

Jet

Photon

*sPHENIX G4 simulation
Pythia8, 35 GeV γ+jet event*

Jet-to-photon momentum balance

$$X_{J\gamma} = p_T^{jet}/p_T^{\gamma}$$

sPHENIX Projection, Years 1-3
JEWEL 2.2.0, $T = 260$ MeV
$p_T^{jet} > 40$ GeV, $z_{cut} = 0.1$, $\beta = 0$
■ $p+p$
● Au+Au (0-10%)
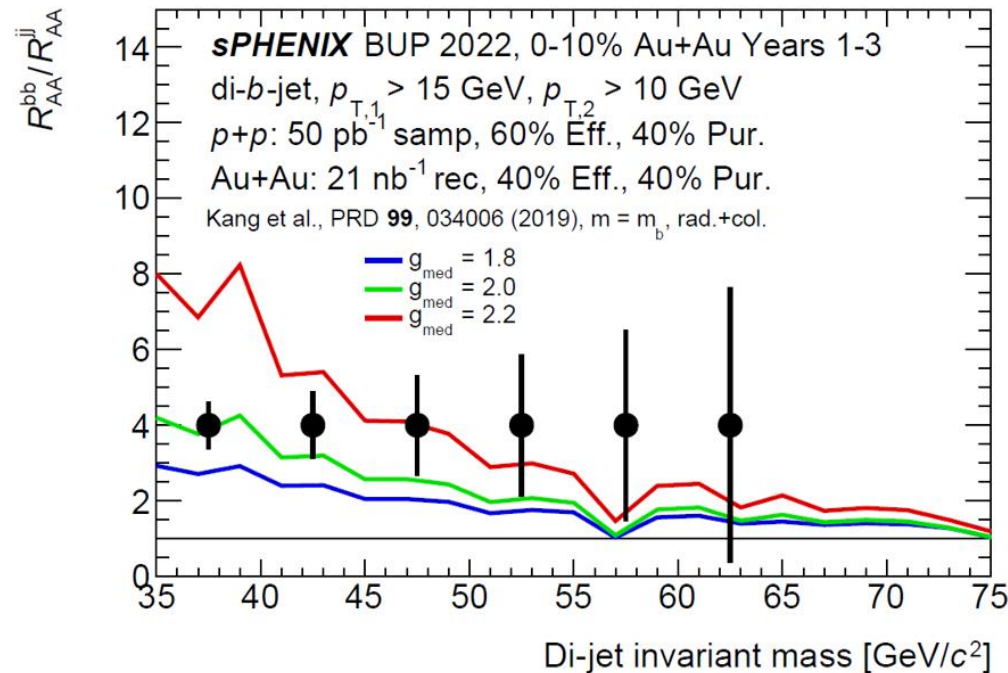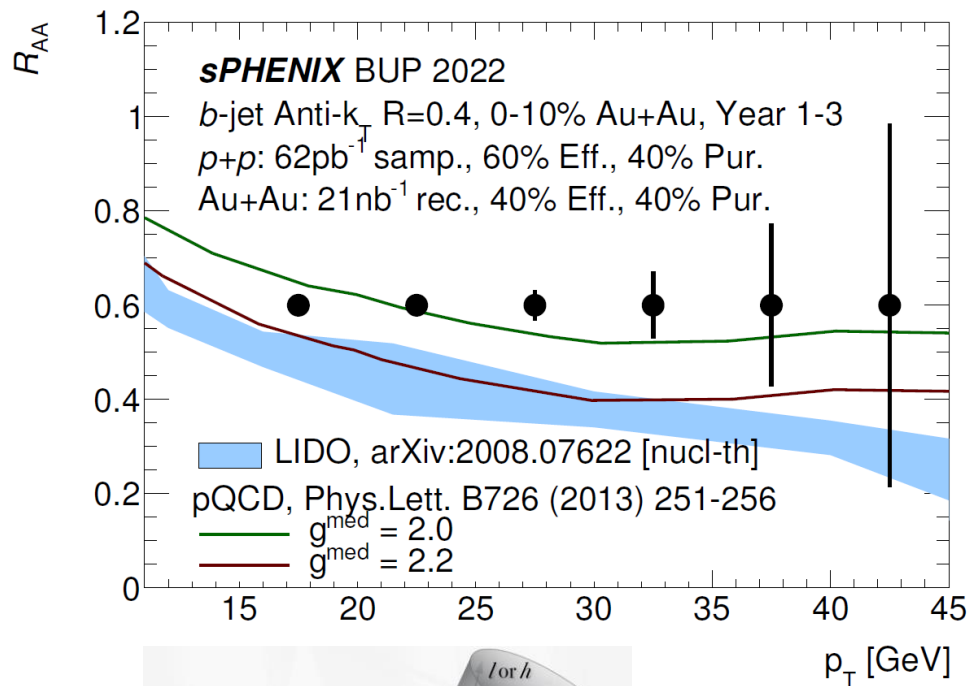
Jet z_g

$p_{T,1}$

$p_{T,2}$

Groomed momentum fraction

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$$

✓ A "flagship" measurement.
✓ Photon+jet measurements with high statistics.
✓ A direct measure of the jet energy loss.

✓ Jet substructure measurements thanks to the fine segmentation of calorimeter + good tracking resolution.
✓ Providing a glimpse into fundamental splittings at parton level.
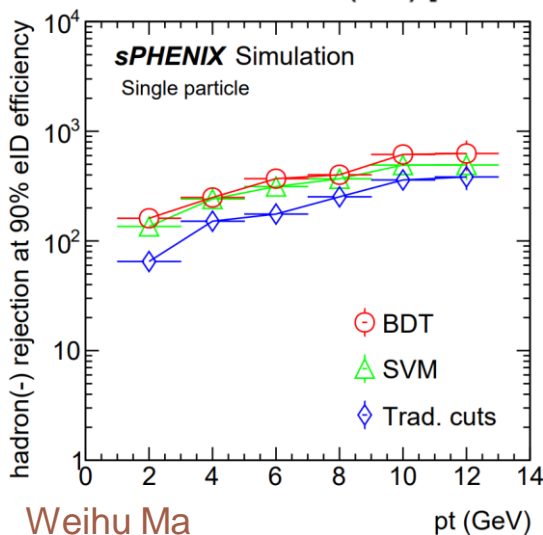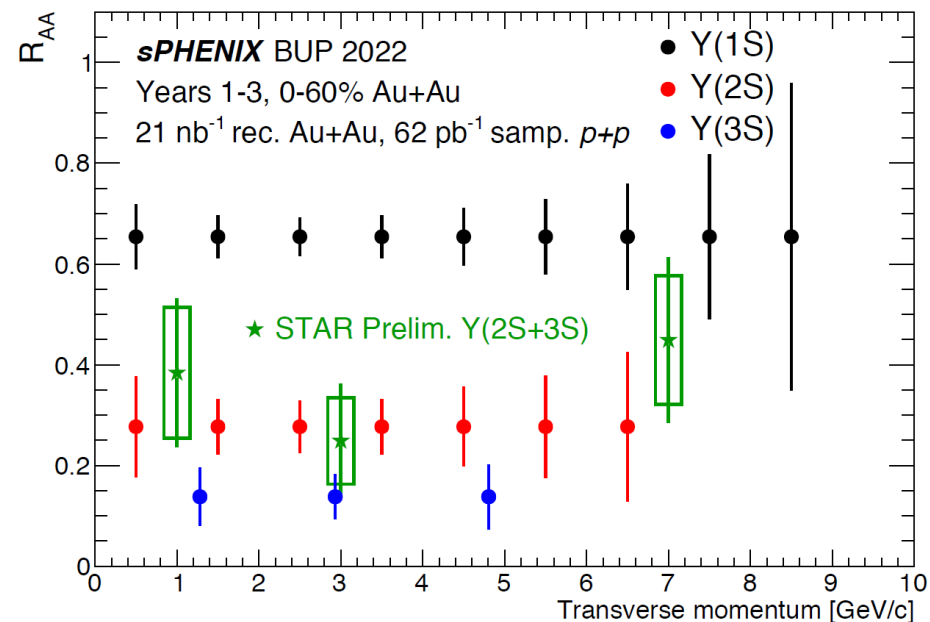
b-Jet Physics

sPHENIX BUP 2022
b-jet Anti-k_T R=0.4, 0-10% Au+Au, Year 1-3
$p+p$: 62pb^{-1} samp., 60% Eff., 40% Pur.
Au+Au: 21nb^{-1} rec., 40% Eff., 40% Pur.

LIDO, arXiv:2008.07622 [nucl-th]
pQCD, Phys.Lett. B726 (2013) 251-256
g^{med} = 2.0
g^{med} = 2.2

sPHENIX BUP 2022, 0-10% Au+Au Years 1-3
di-b-jet, $p_{T,1}$ > 15 GeV, $p_{T,2}$ > 10 GeV
$p+p$: 50 pb^{-1} samp, 60% Eff., 40% Pur.
Au+Au: 21 nb^{-1} rec, 40% Eff., 40% Pur.
Kang et al., PRD **99**, 034006 (2019), m = m$_b$, rad.+col.
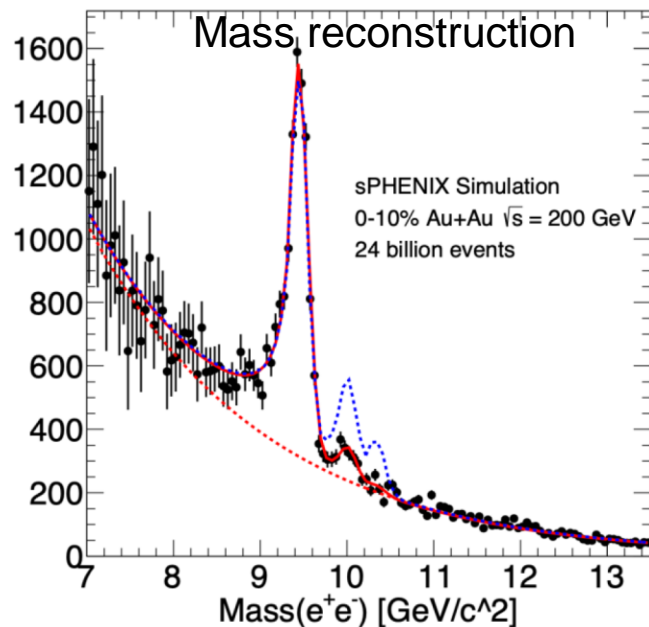
g_{med} = 1.8
g_{med} = 2.0
g_{med} = 2.2
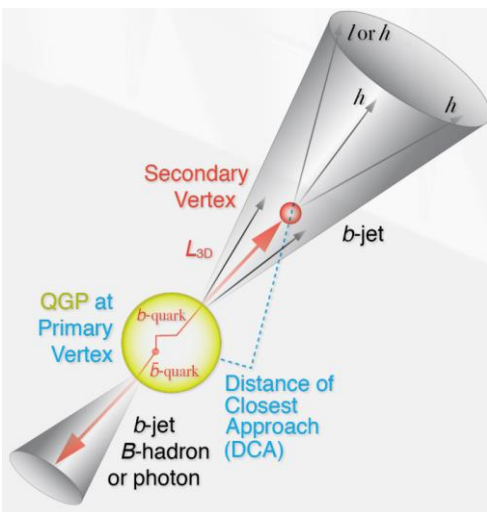
✓ First b-jet tagging at RHIC using precision-DCA track and secondary vertices tagger.
✓ sPHENIX data will place stringent constraints on the b-quark coupling to the QGP.
✓ Back-to-back heavy-flavor jet pairs studying the propagation of quarks in the QGP.

Open Heavy Flavor
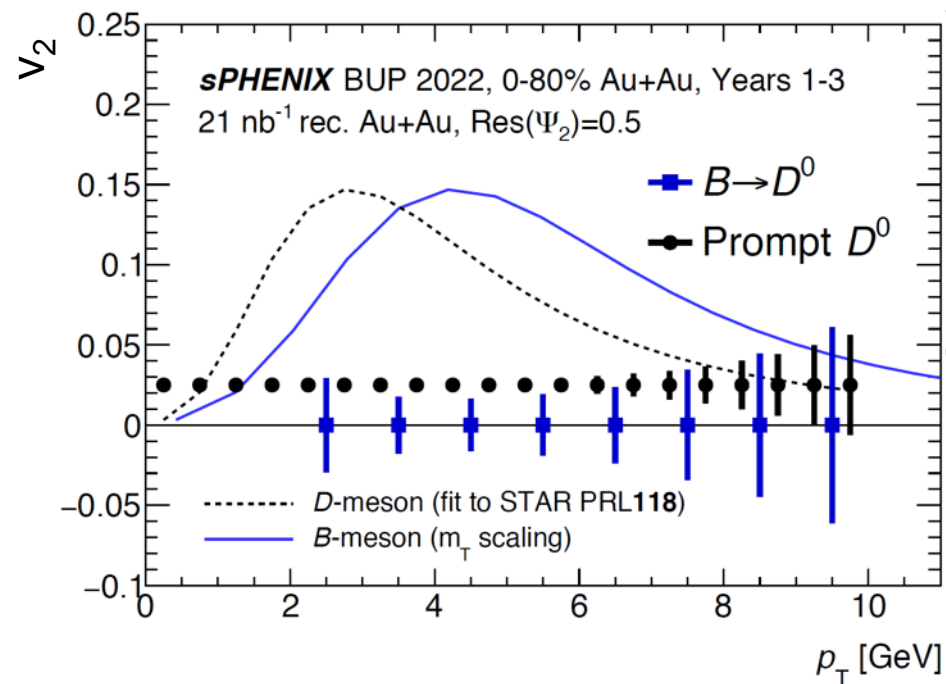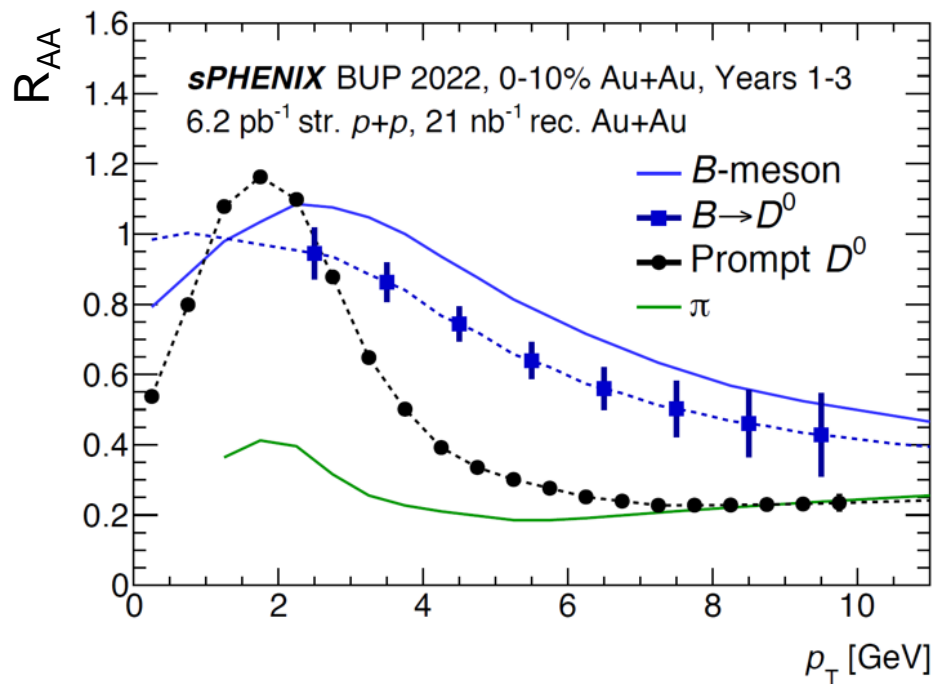
- ✓ Cleanly separate open bottom via DCA.
- ✓ Study mass dependence of energy loss and collectivity.
- ✓ Bottom quarks and light quarks are expected to be different for R_{AA} and v_2 for $p_T \lesssim 15$ GeV.

Upsilon R$_{AA}$

Mass reconstruction

sPHENIX Simulation
0-10% Au+Au √s = 200 GeV
24 billion events

sPHENIX BUP 2022
Years 1-3, 0-60% Au+Au
21 nb^{-1} rec. Au+Au, 62 pb^{-1} samp. p+p

- Y(1S)
- Y(2S)
- Y(3S)

★ STAR Prelim. Y(2S+3S)

sPHENIX Simulation
Single particle

⊙ BDT
△ SVM
◇ Trad. cuts

✓ Suppression with clear distinction of three Upsilon states. Color dipoles probing the QGP at three length scales.
✓ The centrality dependence and particularly the p$_T$ dependence are critical measurements for comparison between RHIC and the LHC.
✓ Signal enhancement with ML tools (BDT) is expected.

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Cold QCD

Hard probes in p+Au

TSSA for direct photon
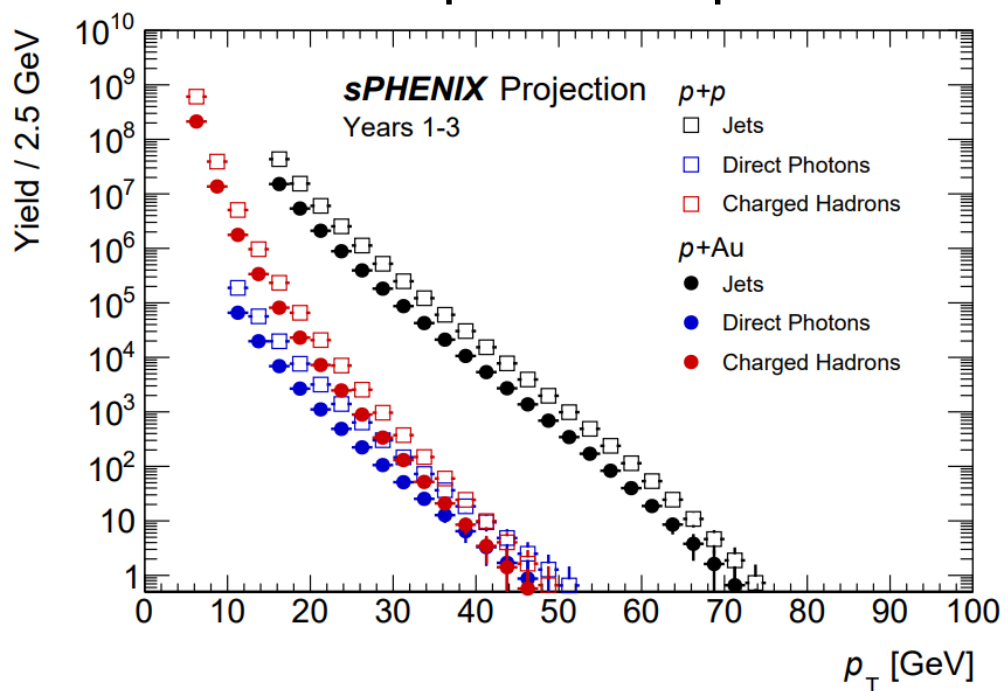
- ✓ Study of nuclear modifications using unpolarized p+Au measurements.
- ✓ Provide information on the nuclear modification of hadronization processes.
- ✓ Sensitive to the CNM effects.
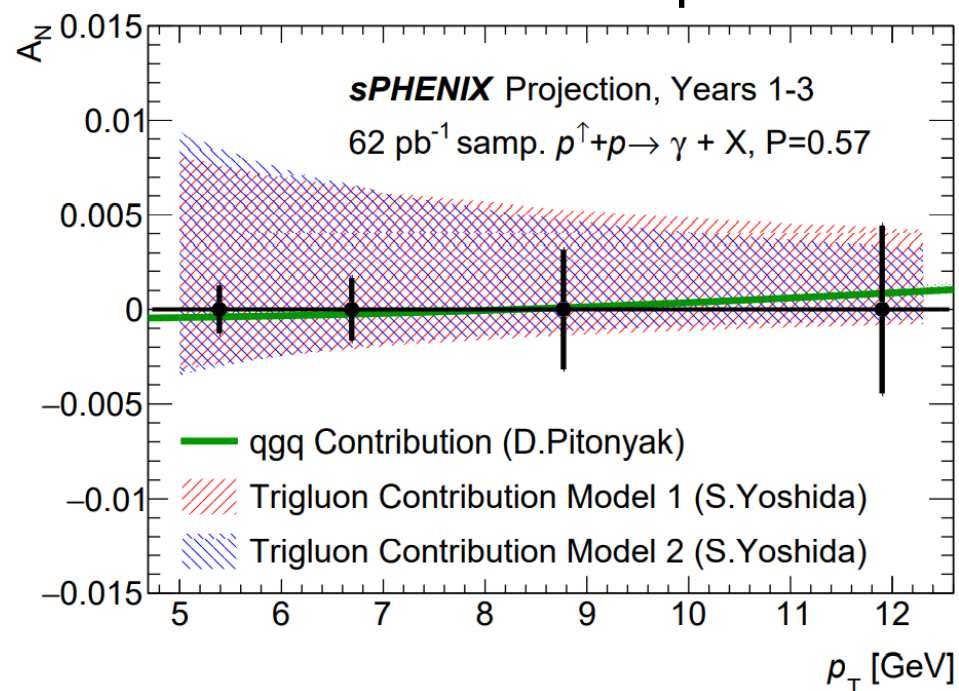
- ✓ Spin measurements such as transverse single spin asymmetry (TSSA) can be achieved using the beam polarization.
- ✓ Study the nucleon spin structure and parton dynamics.

Summary

- ✓ sPHENIX is the first new detector at RHIC in >20 years.

- ✓ sPHENIX enable new measurements of the microscopic nature of QGP.

- ✓ Large and hermetic electromagnetic and hadronic calorimetry.

- ✓ Highly precise tracking.

- ✓ High DAQ and trigger rate.

- ✓ Detector has been moved into data-taking position

- ✓ sPHENIX provides unique opportunities in low energy & offer kinematic overlap with the LHC.

- ✓ Wide range of physics covered in sPHENIX: jet correlations & substructure, Upsilon spectroscopy, open heavy flavor & cold QCD.

- ✓ Detector construction & data taking preparation on schedule!

- ✓ Preparing for the first data taking starting!
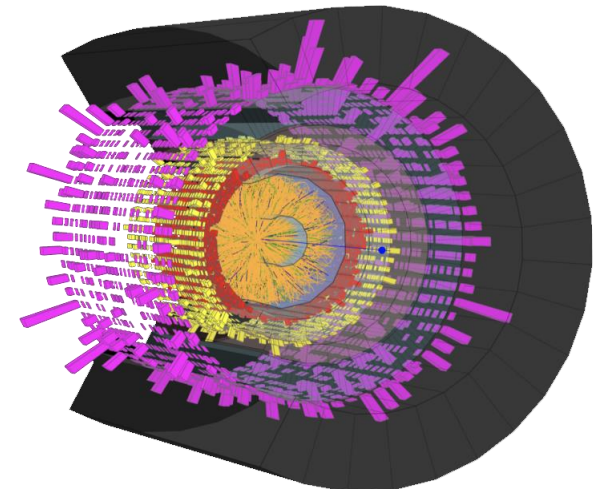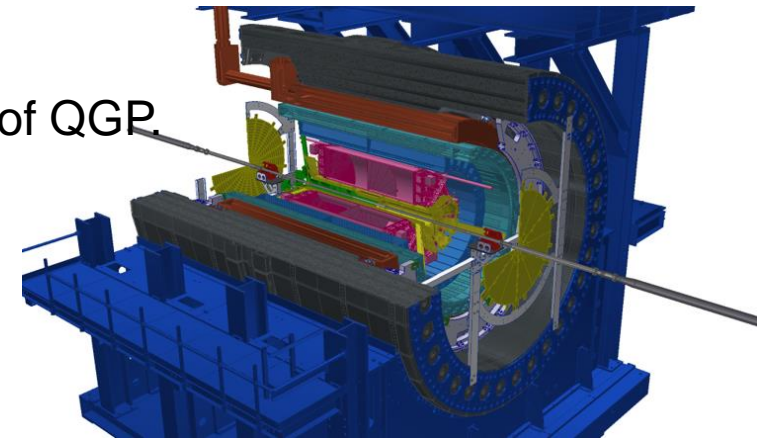
Thanks !

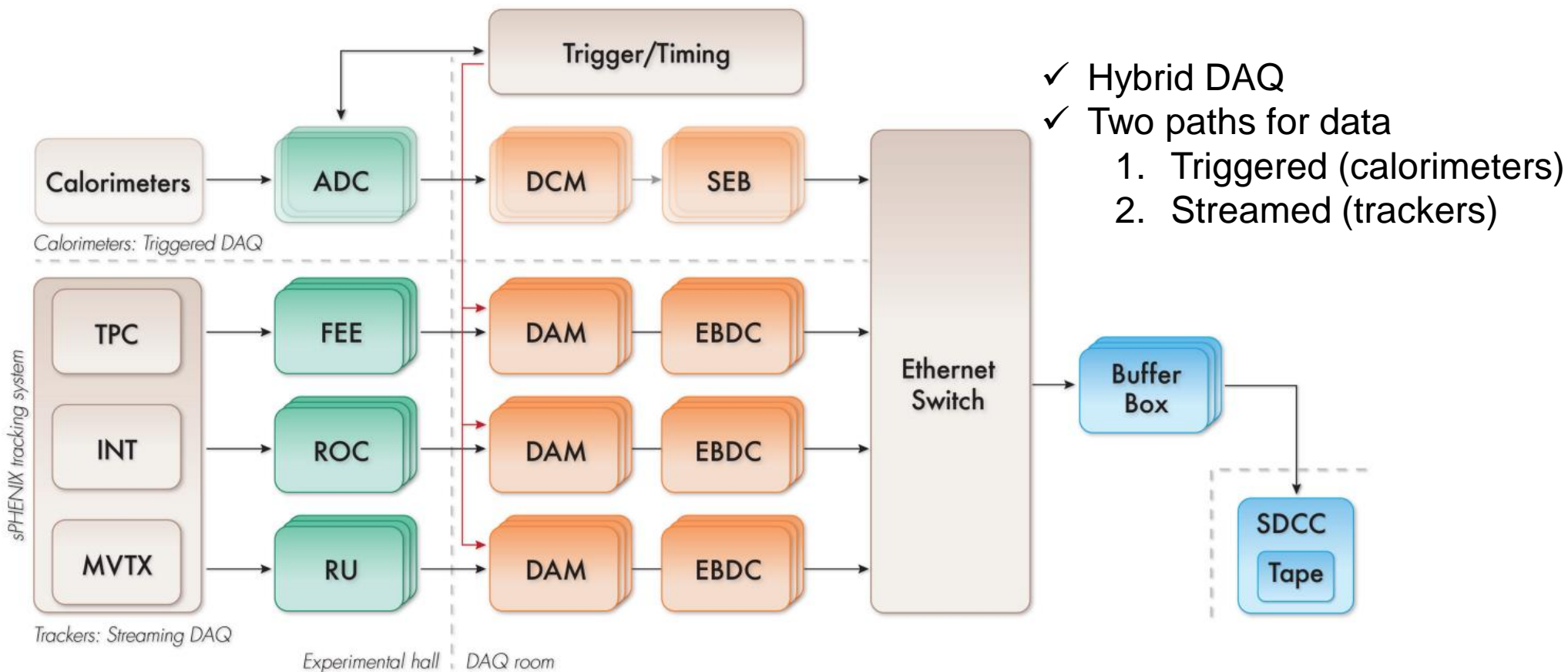10th workshop of the APS Topical Group on Hadronic Physics (GHP2023)
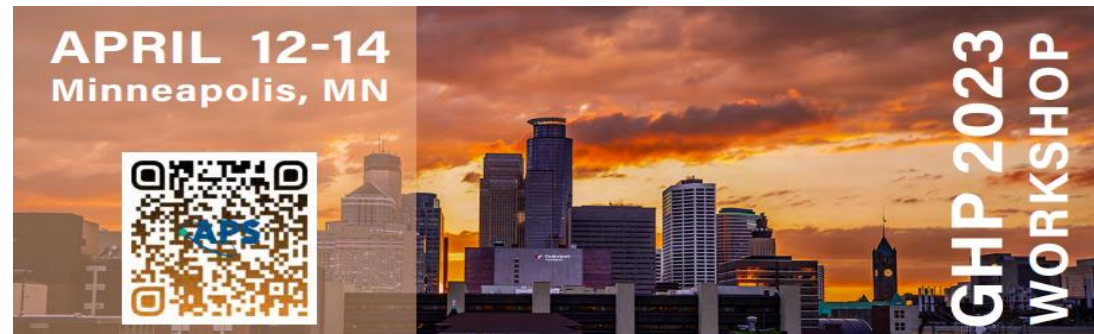
RHIC & LHC Complementarity

Different initial conditions and evolution for QGP between RHIC and LHC, allows study of scale and temperature dependence.

✓ Same hard probes at RHIC overlap with LHC kinematic range
✓ Opportunity for new probes at RHIC at the lower energy scale
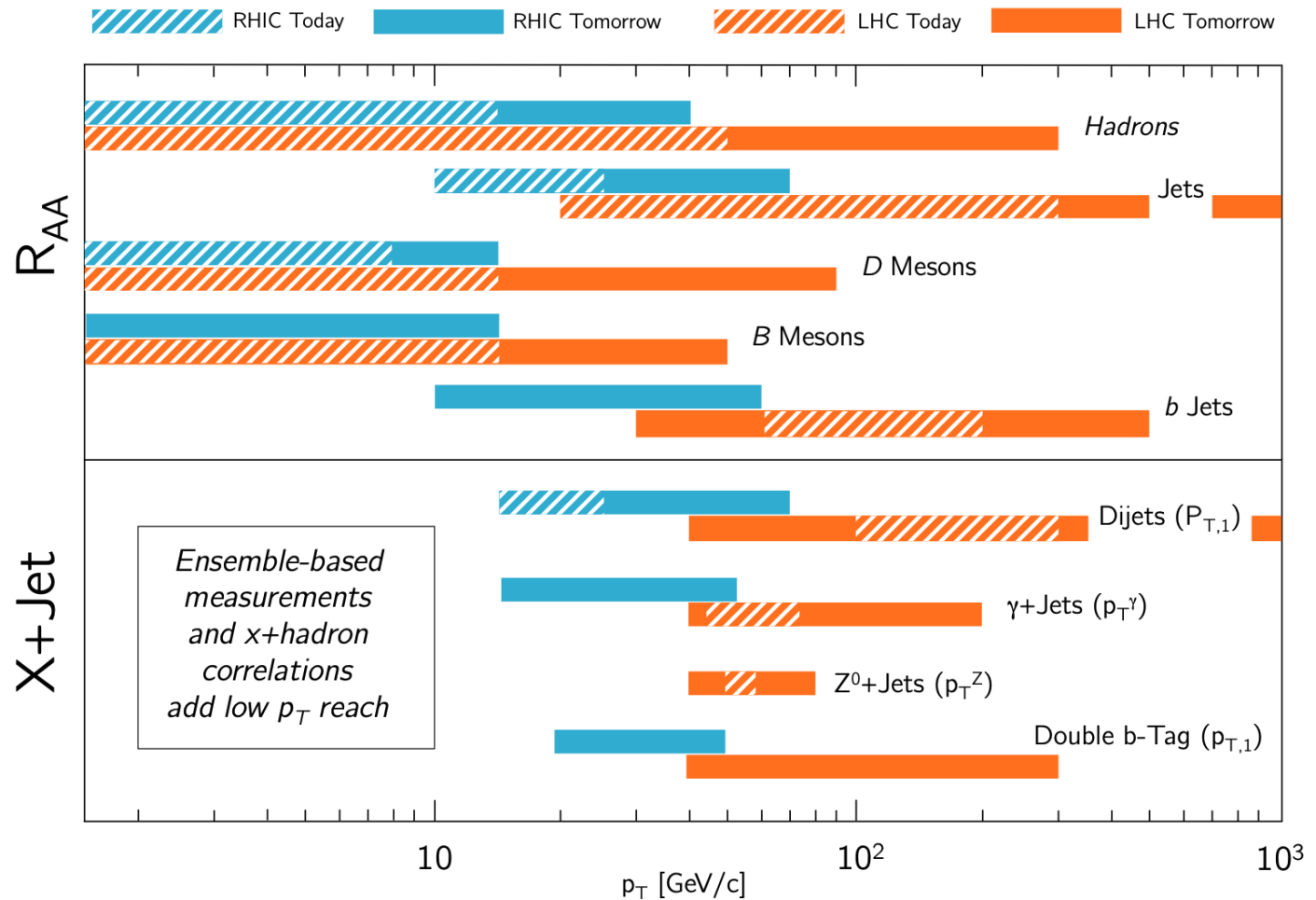
sPHENIX Readout

- ✓ Hybrid DAQ
- ✓ Two paths for data
 1. Triggered (calorimeters)
  2. Streamed (trackers)

Streamed trigger:
- ✓ Records ~10% of all collisions
- ✓ Significantly increases p+p data collected
- ✓ Crucial for open heavy flavor physics as well as cold QCD measurements
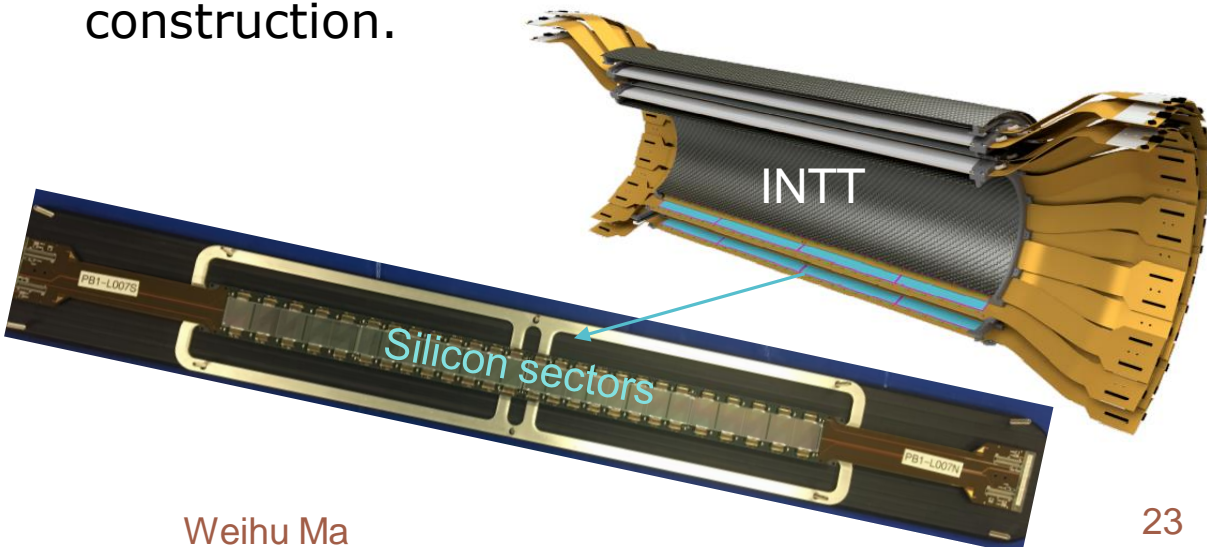
Precision Vertex Trackers

MAPS-based micro-VerTeX detector (MVTX)

- ✓ Nearest the collision point
- ✓ Based on ALICE ITS
- ✓ Covering 2.3<r<3.9 cm radius.
- ✓ 3-layer Monolithic Active Pixel Sensors (MAPS).
- ✓ Excellent 2-D DCA resolution, < 10 μm for p_T > 2GeV/c
- ✓ Both half-detectors assembled at LBNL!

MVTX

MVTX

Half-detector-1   Half-detector-2
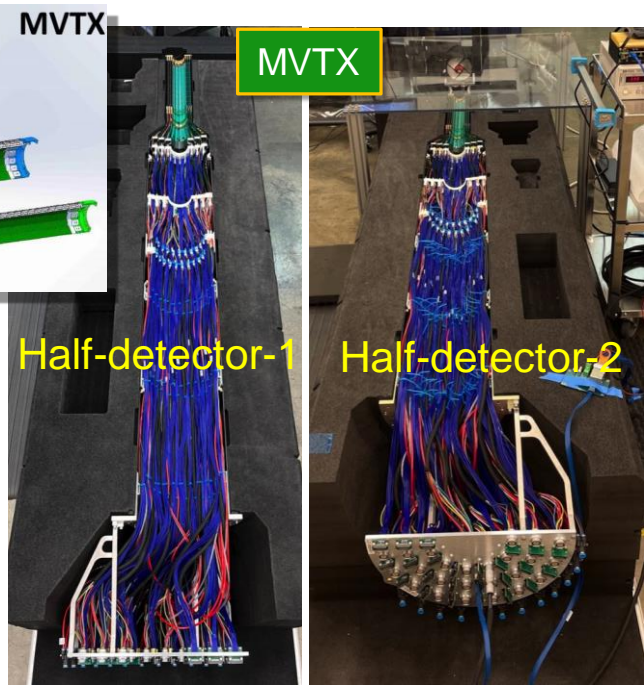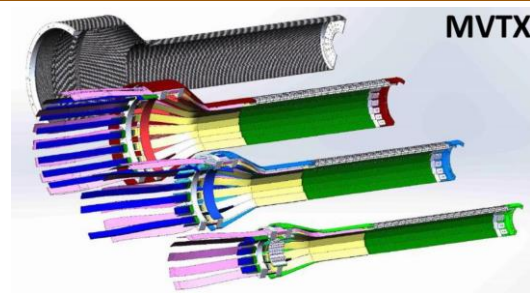
Intermediate Silicon Tracker (INTT)

- ✓ 2 layer (7-10 cm radius) silicon strip detector
- ✓ Fast O(100 ns) integration time; can resolve one beam crossing
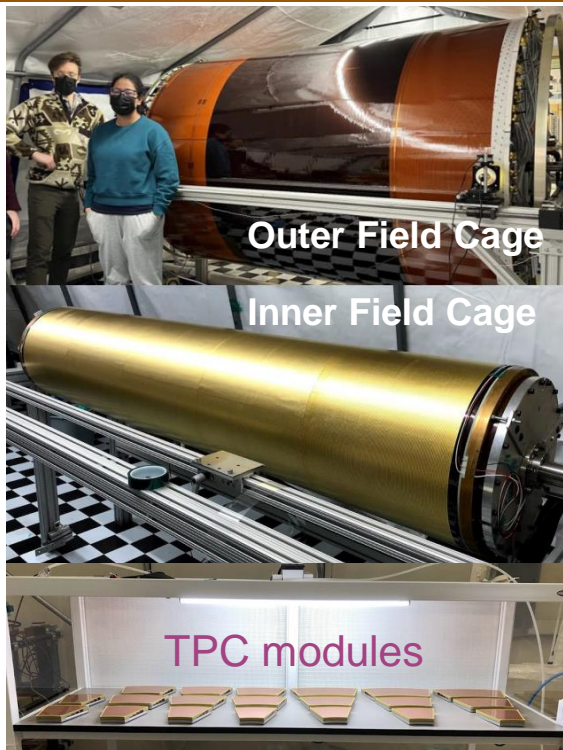- ✓ All ladders are produced, detector is under final construction.

INTT

Silicon sectors

INTT

3/4 of the INTT barrels are assembled, tested, and surveyed

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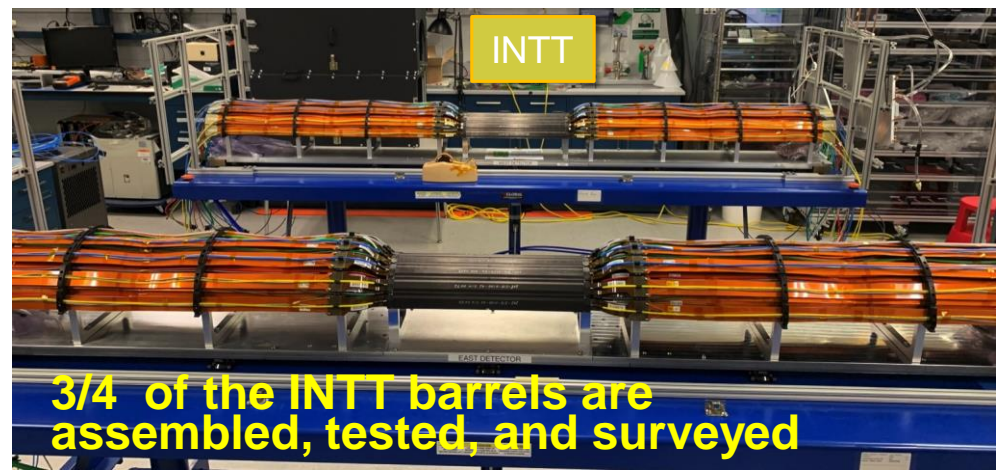
Time Projection Chamber (TPC)

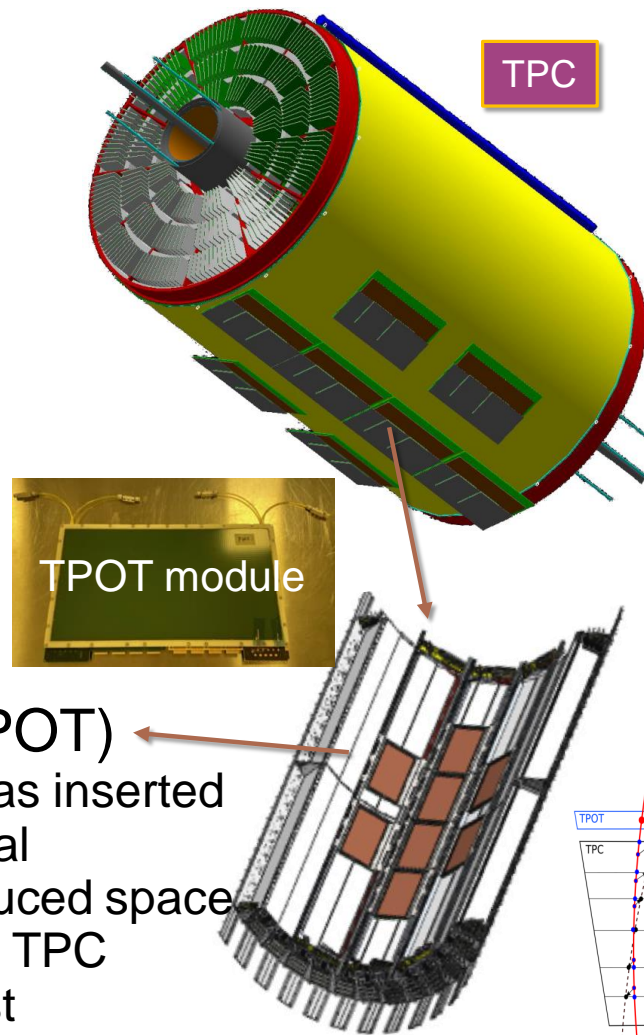## Time Projection Chamber (TPC)

- ✓ Compact (1/3 volume of ALICE TPC)
- ✓ Gateless, continuous readout
- ✓ Quad GEM electron multiplier + chevron readout pads
- ✓ $\Delta p/p \sim 1\%$ at 5 GeV/c
- ✓ Effective hit resolution: ~250 μm
- ✓ 48 layers (20-78 cm radius)
- ✓ Detector installation: middle of November

Outer Field Cage

Inner Field Cage

TPC modules
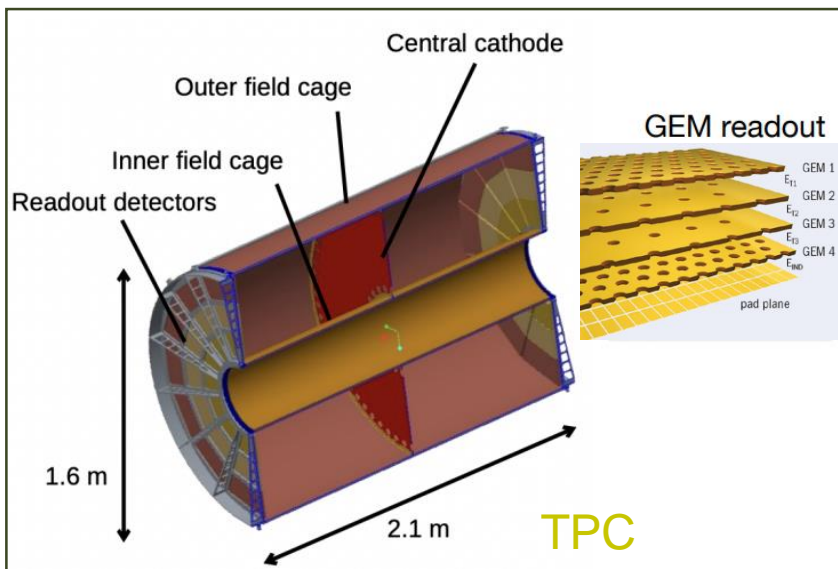
TPOT module

Geant4 view of sPHENIX TPC and TPOT

TPC

Central cathode

Outer field cage

Inner field cage

Readout detectors

GEM readout

GEM 1
GEM 2
GEM 3
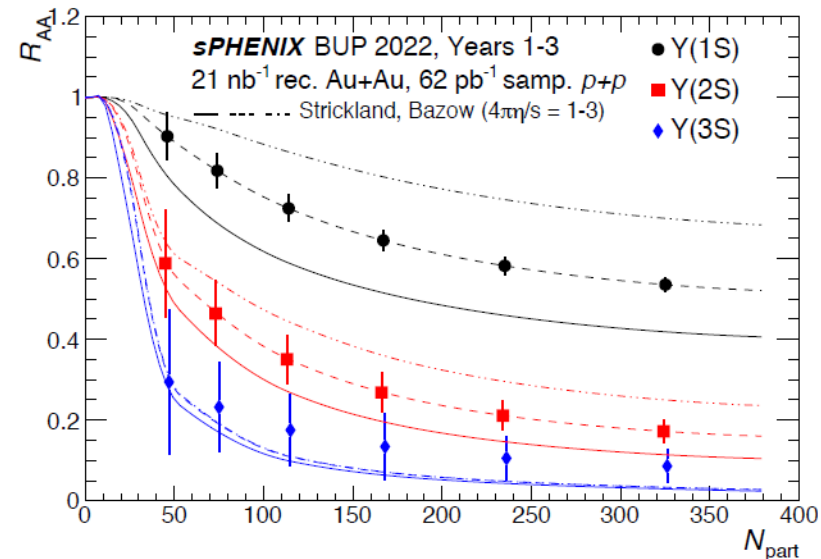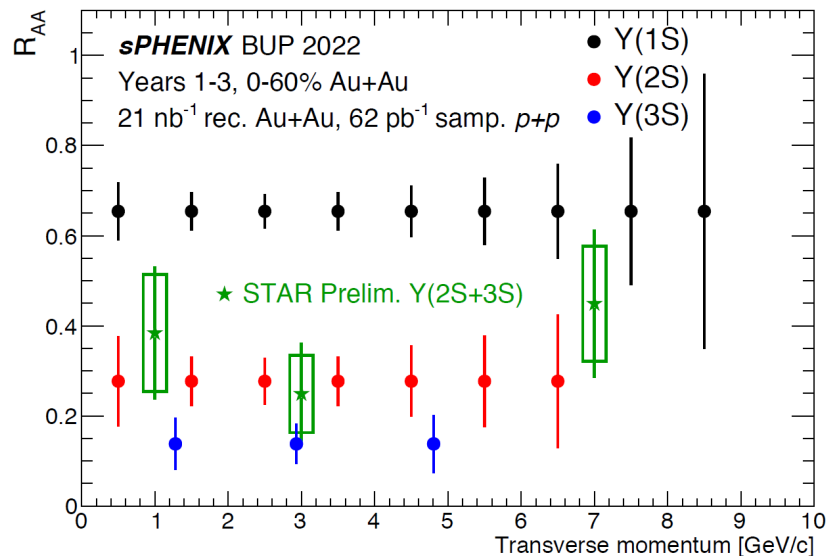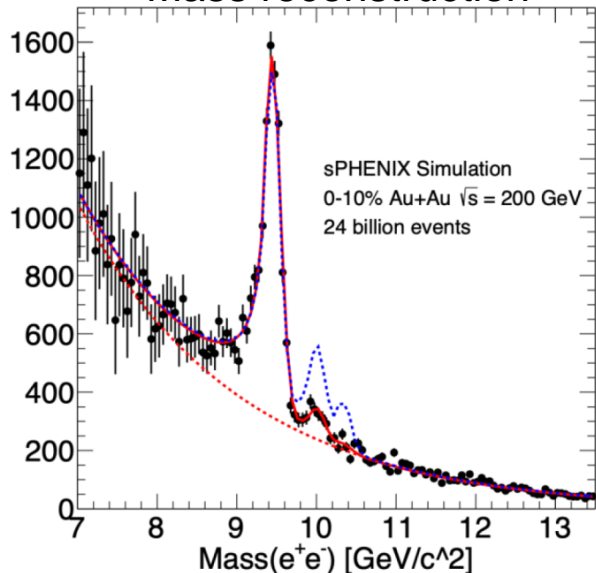GEM 4
pad plane

1.6 m

2.1 m

TPC

TPC Outer Tracker (TPOT)

- ✓ 8 modules of Micromegas inserted between TPC and EMCal
- ✓ Calibration of beam-induced space charge distortions in the TPC
- ✓ TPOT module under test
- ✓ Installation in Oct.

TPOT
TPC
INTT
MVTX

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GHP2023
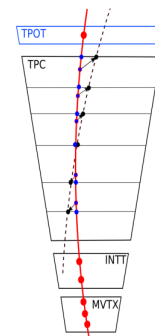
Upsilon R_{AA}
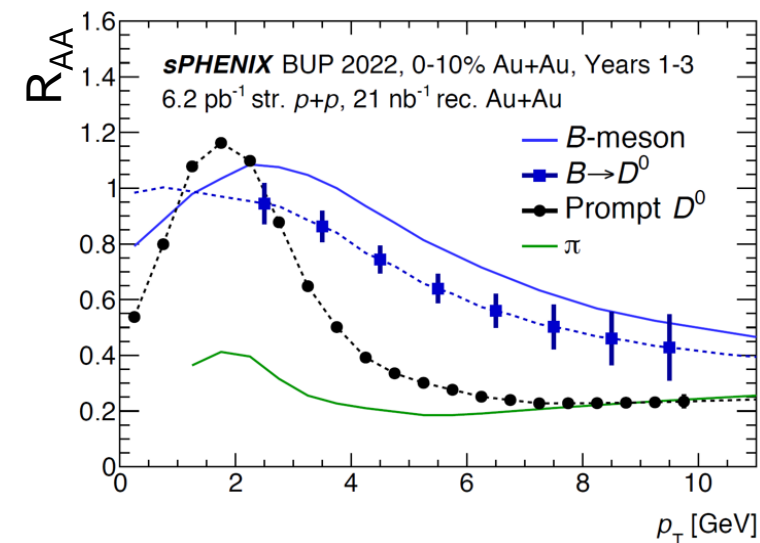
Mass reconstruction
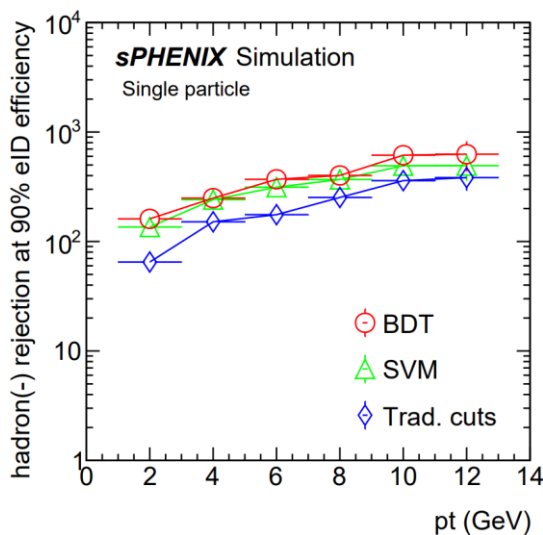
- ✓ Suppression with clear distinction of three Upsilon states. Color dipoles probing the QGP at three length scales.

- ✓ The centrality dependence and particularly the p_T dependence are critical measurements for comparison between RHIC and the LHC.

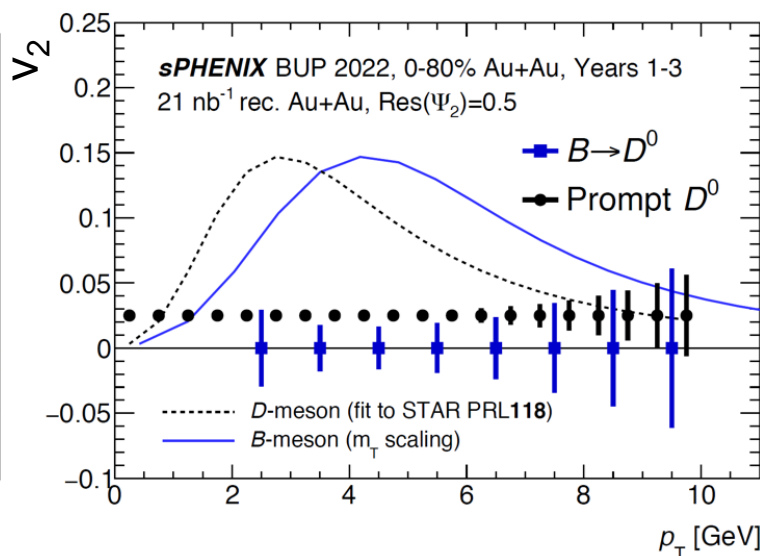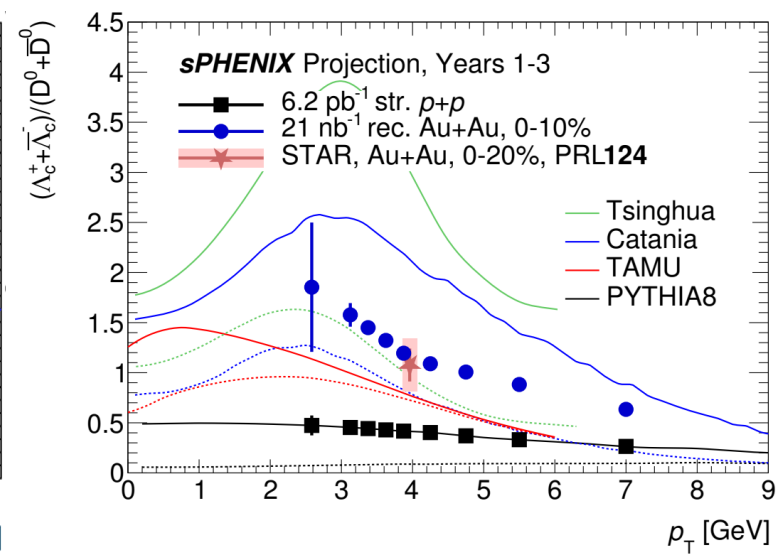- ✓ sPHENIX is developing ML algorithms to reject hadronic bkg.

Open Heavy Flavor
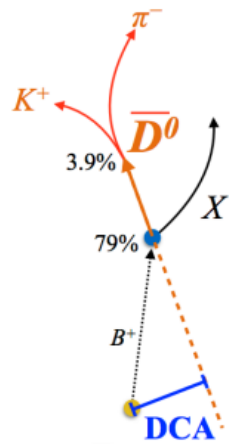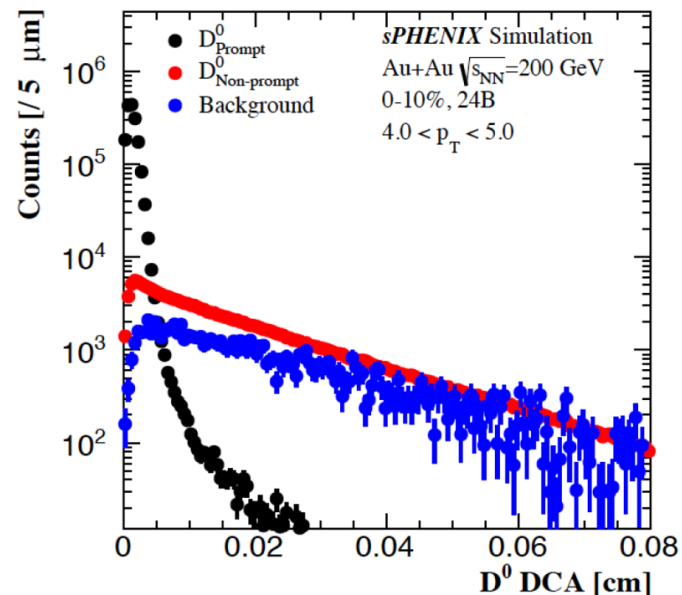
- ✓ Cleanly separate open bottom via DCA.
- ✓ Bottom quarks and light quarks are expected to be different for R_{AA} and v_2 for $p_T \lesssim 15$ GeV.
- ✓ Study mass dependence of energy loss and collectivity.
- ➢ sPHENIX will enable the precision measurement of the Λ_c/D at RHIC for understanding charm hadronization.

Event Display