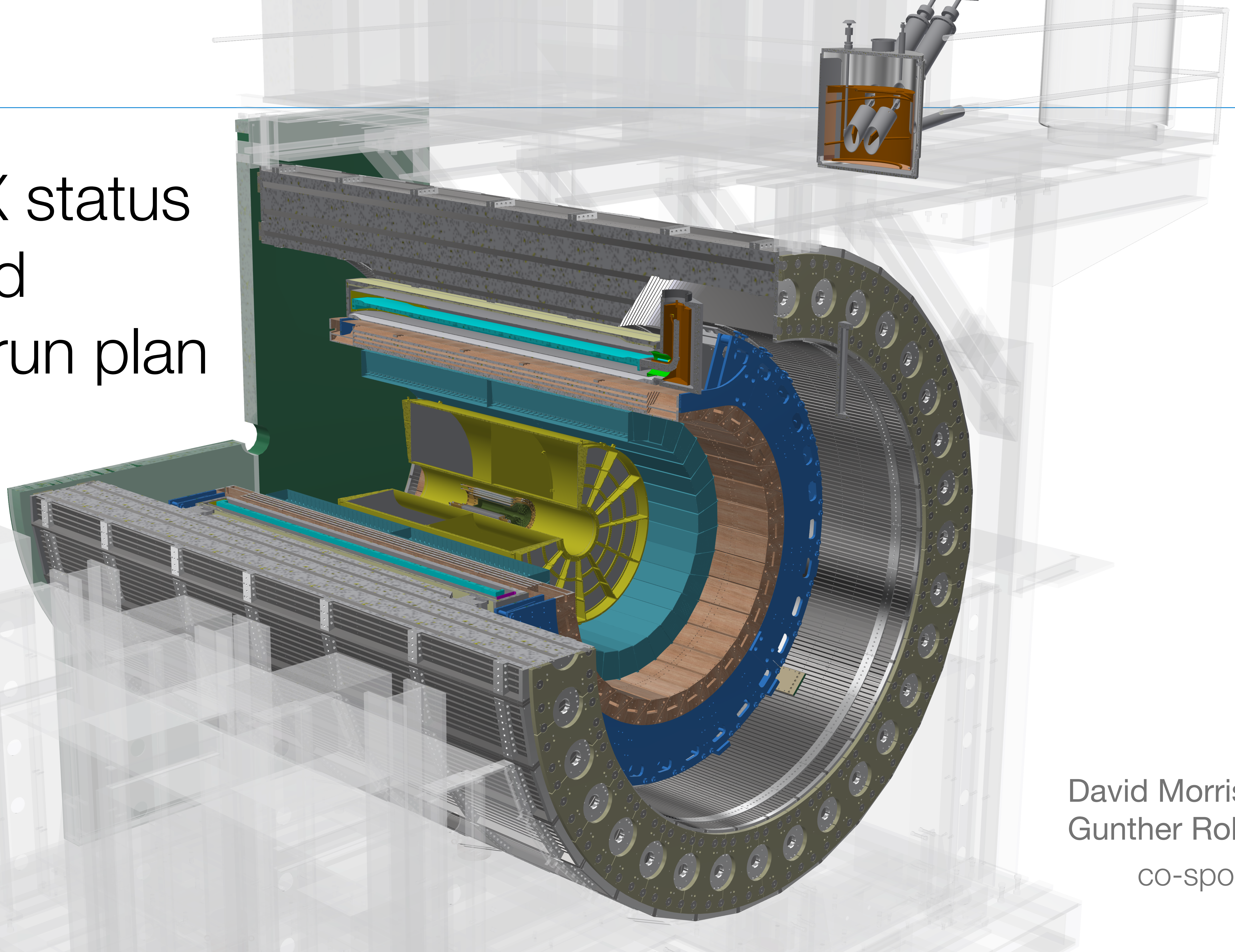
sPHENIX status and updated run plan

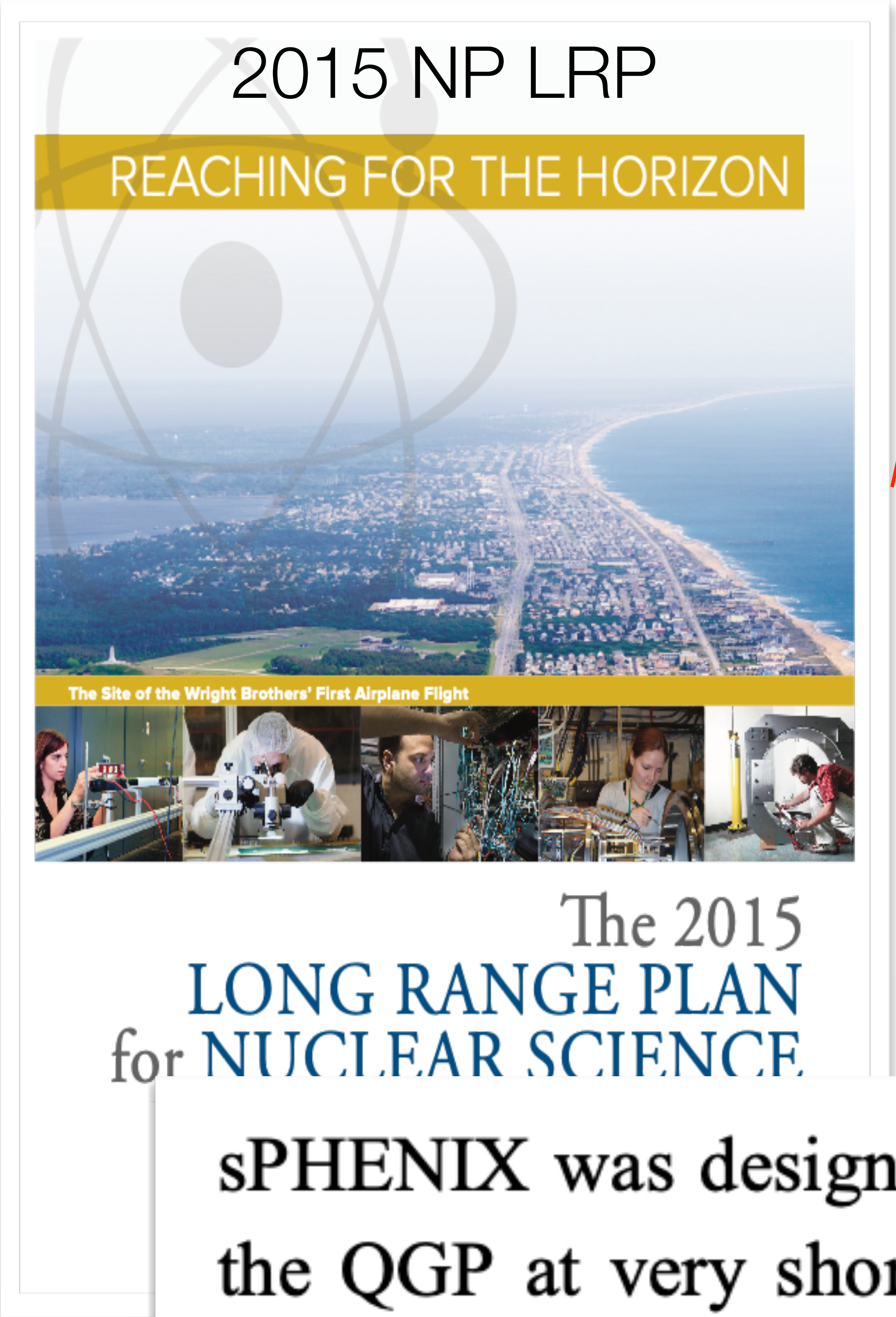


David Morrison (BNL)
Gunther Roland (MIT)
co-spokespersons

sPHENIX presentations at this meeting

1. Earlier today: sPHENIX project status (Ed O'Brien)
2. sPHENIX status and updated run plan (GR, DM)
   - Collaboration overview and recent progress
   - **Recall key considerations connecting sPHENIX science mission and design, commissioning and operations**
   - 2023-2025 beam use proposal
3. sPHENIX TPC Outer Tracker (Hugo Pereira da Costa)
   - Proposed upgrade to complement existing solutions for TPC distortion monitoring and corrections

sPHENIX Science mission



2. Quantum Chromodynamics: The Fundamental Description of the Heart of Visible Matter

describe quark and gluon interactions, the emergent phenomenon that a macroscopic volume of quarks and gluons at extreme temperatures would form a nearly perfect liquid came as a complete surprise and has led to an intriguing puzzle. A perfect liquid would not be expected to have particle excitations, yet QCD is definitive in predicting that a microscope with sufficiently high resolution would reveal quarks and gluons interacting *weakly* at the shortest distance scales within QGP. Nevertheless, the η/s of QGP is so small that there is no sign in its macroscopic motion of any microscopic particlelike constituents; all we can see is a liquid. To this day, nobody understands this dichotomy: how do quarks and gluons conspire to form strongly coupled, nearly perfect liquid QGP?

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.**

This section is organized in three parts: characterization of liquid QGP, mapping the phase diagram of QCD by doping QGP with an excess of quarks over antiquarks, and high-resolution microscopy of QGP to see how quarks and gluons conspire to make a liquid.

EMERGENCE OF NEAR-PERFECT FLUIDITY

The emergent hydrodynamic properties of QGP are not apparent from the underlying QCD theory and were, therefore, largely unanticipated before RHIC. They have been quantified with increasing precision via experiments at both RHIC and the LHC over the last several years. New theoretical tools, including LQCD calculations of the equation-of-state, fully relativistic viscous hydrodynamics, initial quantum fluctuation models, and model calculations done at strong coupling in gauge theories with a dual gravitational description, have allowed us to characterize the degree of fluidity. In the temperature regime created at RHIC, QGP is the most liquidlike liquid known, and comparative analyses of the wealth of bulk observables being measured hint that the hotter QGP created at the LHC has a somewhat larger viscosity. This temperature dependence will be more tightly constrained by upcoming measurements at RHIC and the LHC that will characterize the varying shapes of the sprays of debris produced in different collisions. Analyses to extract this information are analogous to techniques used to learn about the evolution of the universe from tiny fluctuations in the temperature of the cosmic microwave background associated with ripples in the matter density created a short time after the Big Bang (see Sidebar 2.3).

There are still key questions, just as in our universe, about how the rippling liquid is formed initially in a heavy-ion collision. In the short term, this will be addressed using well-understood modeling to run the clock backwards from the debris of the collisions observed in the detectors. Measurements of the gluon distribution and correlations in nuclei at a future EIC together with calculations being developed that relate these quantities to the initial ripples in the QGP will provide a complementary perspective. The key open question here is understanding how a hydrodynamic liquid can form from the matter present at the earliest moments in a nuclear collision as quickly as it does, within a few trillionths of a trillionth of a second.

Geometry and Small Droplets

Connected to the latter question is the question of how large a droplet of matter has to be in order for it to behave like a macroscopic liquid. What is the smallest possible droplet of QGP? Until recently, it was thought that protons or small projectiles impacting large nuclei would not deposit enough energy over a large enough volume to create a droplet of QGP. New measurements, however, have brought surprises about the onset of QGP liquid production.

Measurements in LHC proton-proton collisions, selecting the 0.001% of events that produce the highest particle multiplicity, reveal patterns reminiscent of QGP fluid flow patterns. Data from p+Pb collisions at the LHC give much stronger indications that single small droplets may be formed. The flexibility of RHIC, recently augmented by the EBIS source (a combined NASA and nuclear physics project), is allowing data to be taken for p+Au, d+Au, and ^{3}He+Au collisions, in which energy is deposited initially in one or two or three spots. As these individual droplets expand hydrodynamically, they connect and form interesting QGP geometries as shown in Figure 2.9. If, in fact, tiny liquid droplets are being formed and their geometry can be manipulated, they will provide

22

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.**

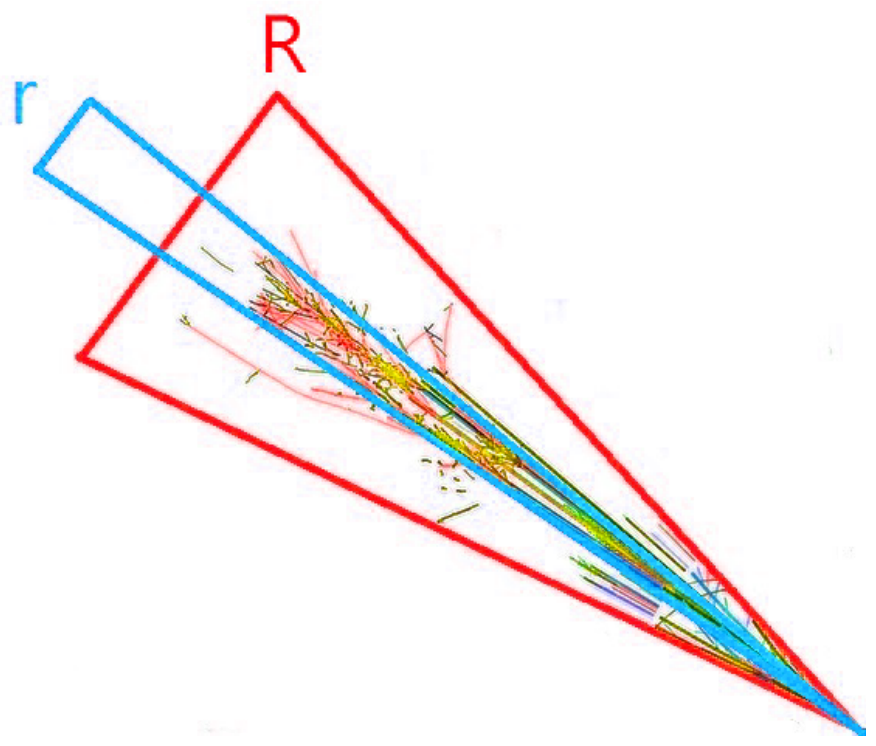
sPHENIX was designed as a state-of-the-art jet detector at RHIC to explore the properties of the QGP at very short scales, and its scientific program was endorsed by the 2015 NSAC Long Range Plan for Nuclear Science. The PAC considers the completion of the sPHENIX scientific program as the highest priority of the RHIC program after the completion of BES-II and before the transition to the EIC facility.

2020 RHIC PAC report p.10

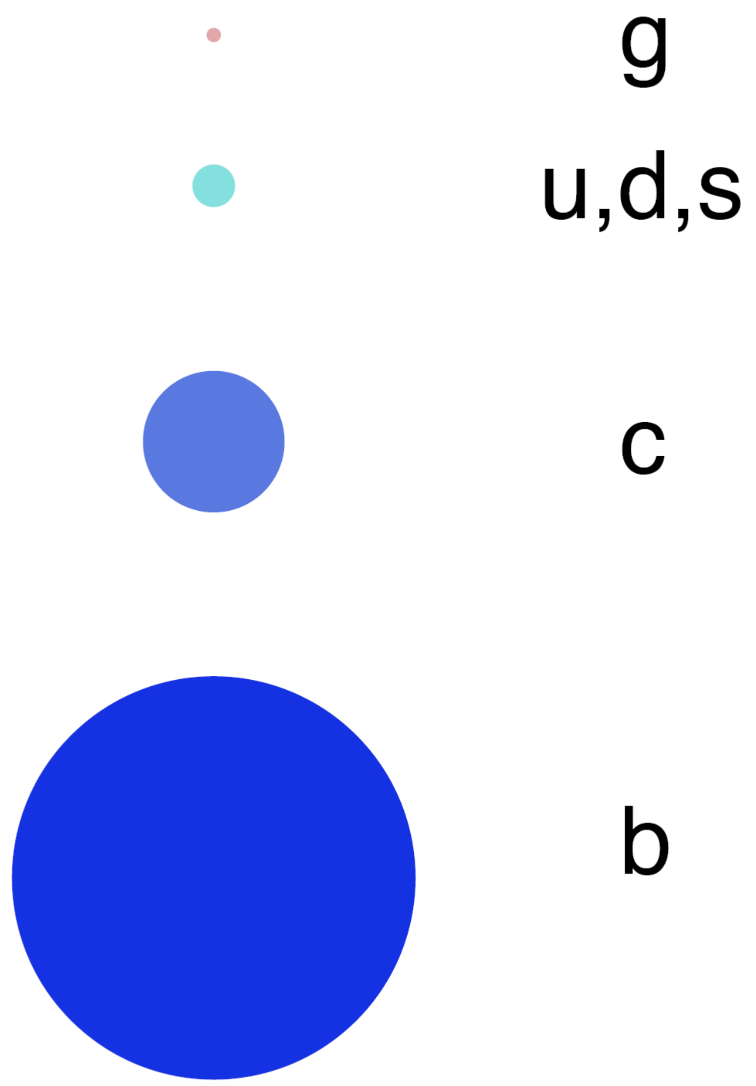
https:/

sPHENIX Science

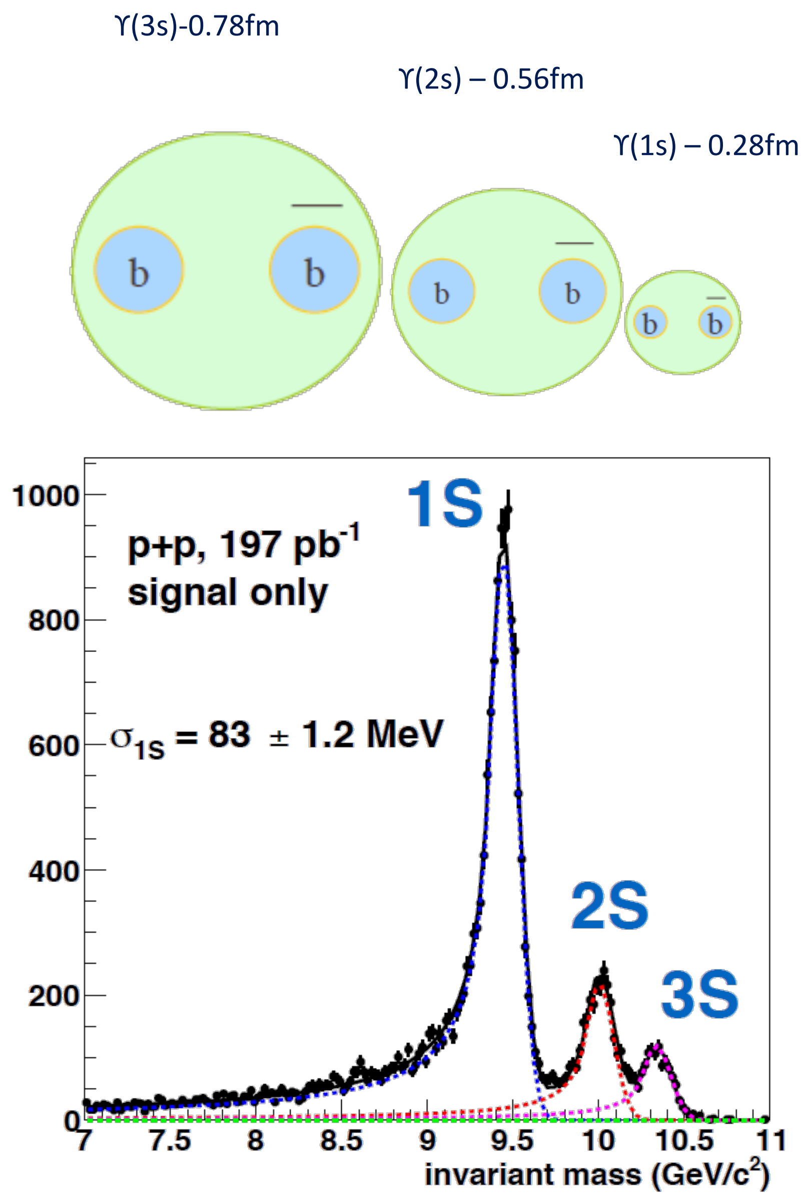
Jet cor. & substructure
Vary momentum/angular size of probe



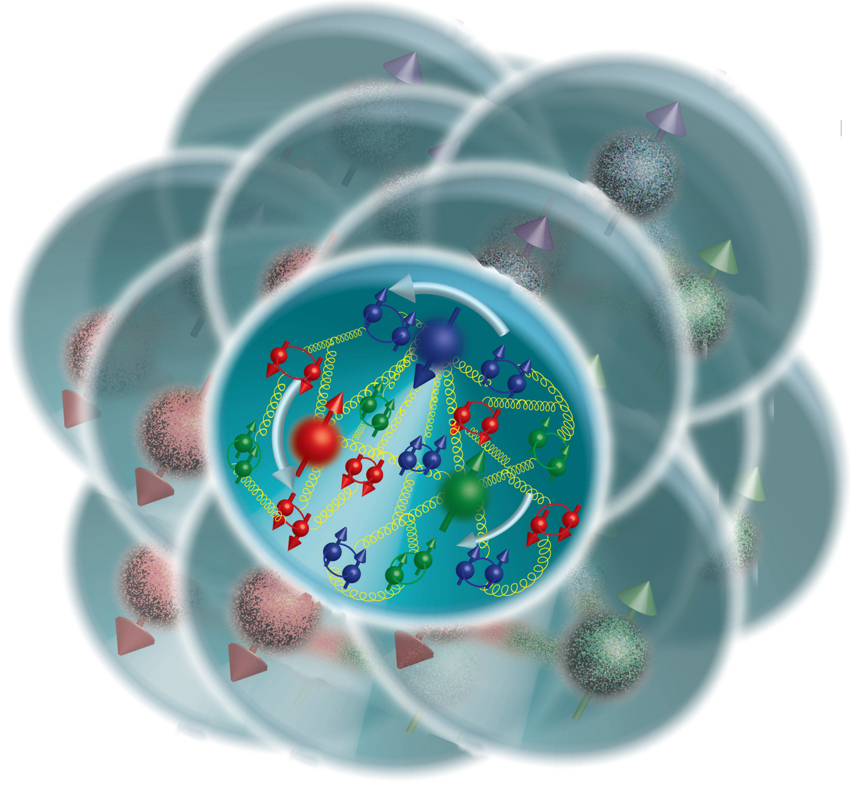
Parton energy loss
Vary mass/momentum of probe



Upsilon spectroscopy
Vary size of the probe



Cold QCD
Vary temperature of QCD matter



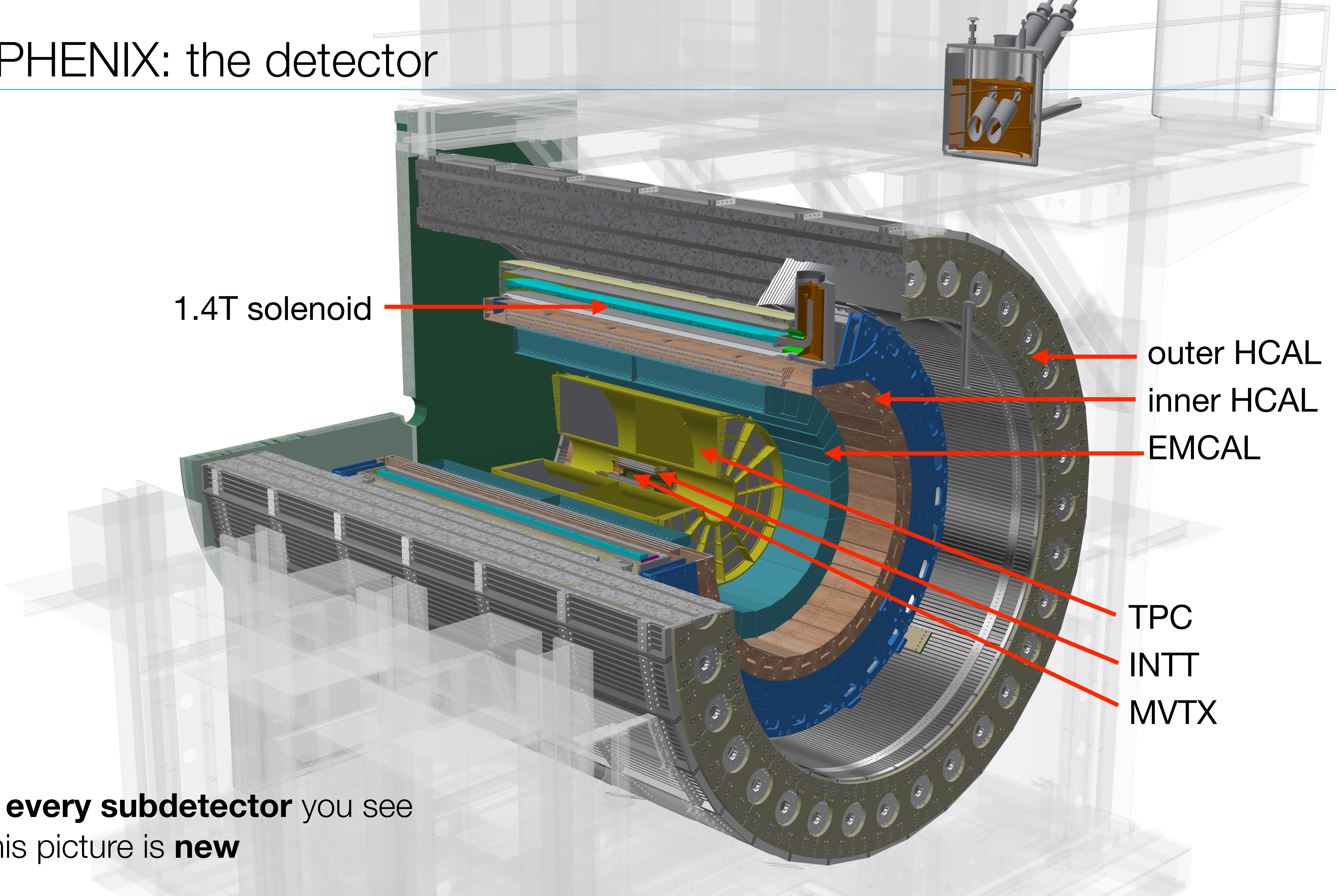
Mission: **Study QCD phenomena discovered at RHIC** with unprecedented precision

- Focus on **hard probes** (jets and heavy flavor)
- Kinematic reach and capabilities to allow **direct comparison with LHC**
- Affirmed by **Hot QCD white paper → LRP → sPHENIX CD-0 → ECFA → PAC**
- more than **100 (!) PRL/PLB** from RHIC, LHC on these topics since LRP (2015)

sPHENIX science mission and schedule

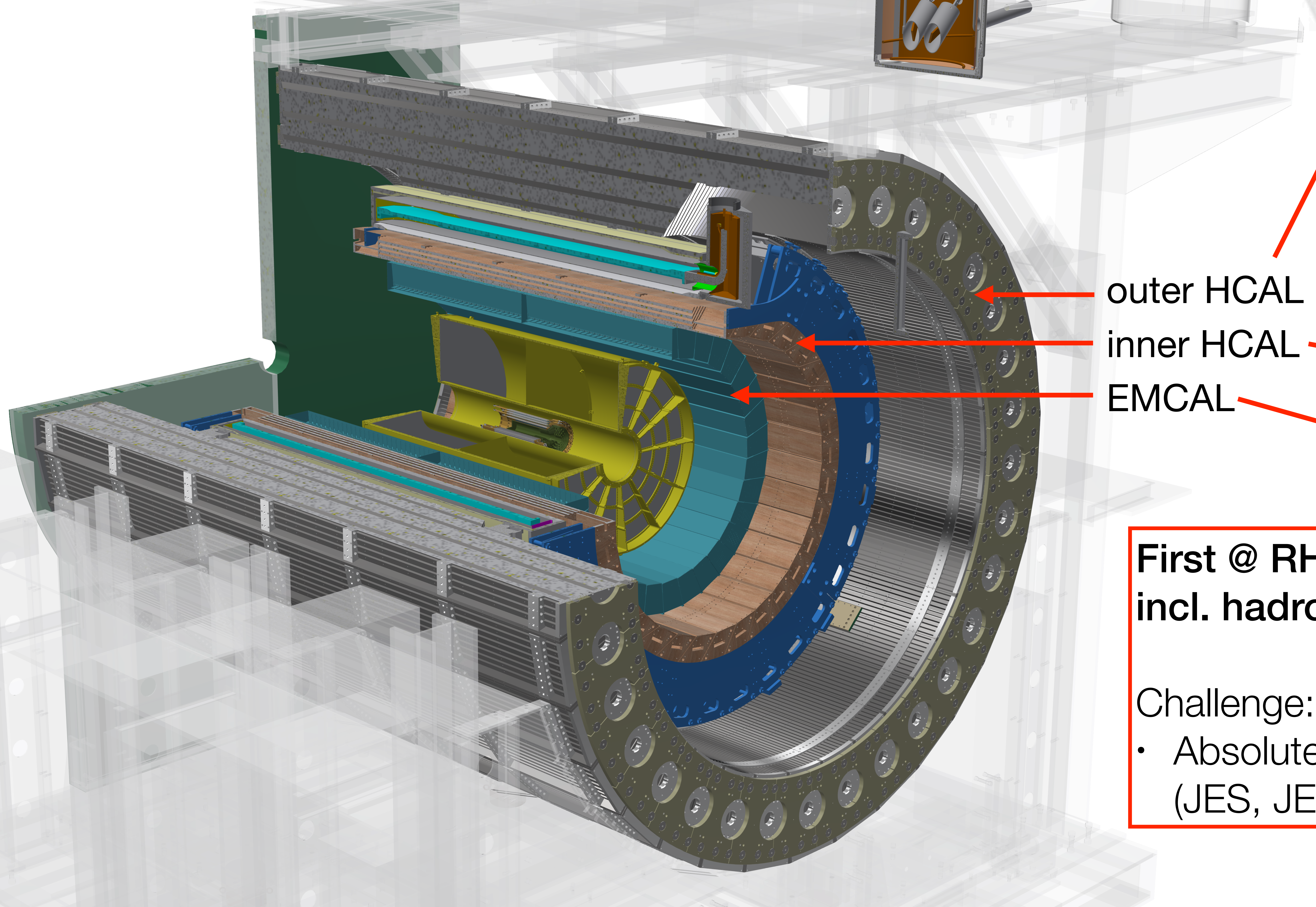
- **’15 LRP recommended installation of a new detector at existing collider**
  - this is unusual (vs LEP, Tevatron, LHC,…)
  - realized as upgrade to PHENIX
  - **needs to significantly advance HI physics vs prior 20 years of data taking**
- EIC @BNL reference schedule implies end of RHIC operations after 2025 run
  - this is unusual (vs prior colliders)
  - no opportunity for do-overs
- **Need to complete science mission on a 3-yr schedule guides construction, commissioning and running schedule and physics focus**

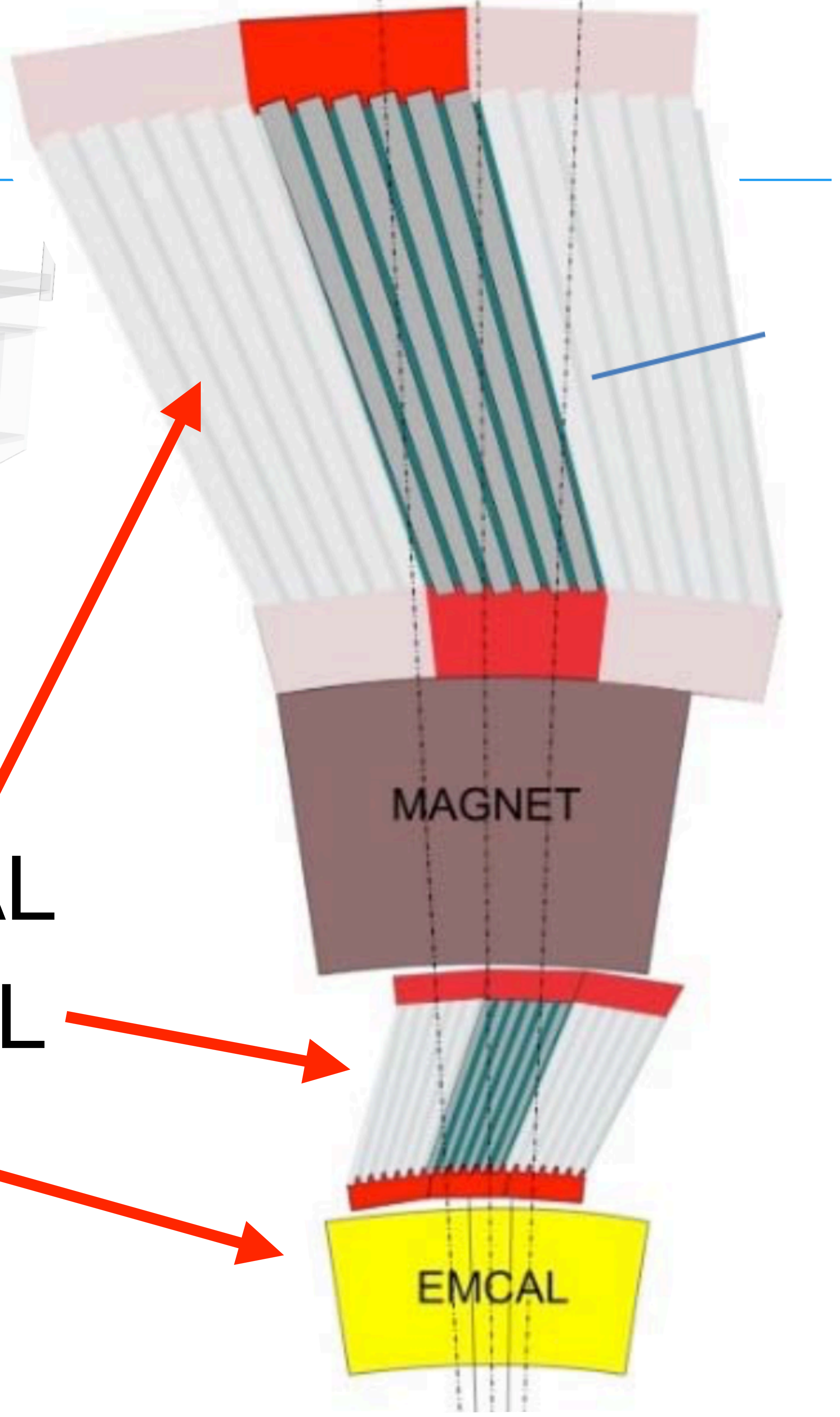
sPHENIX: the detector



n.b., **every subdetector** you see on this picture is **new**

sPHENIX calorimeters



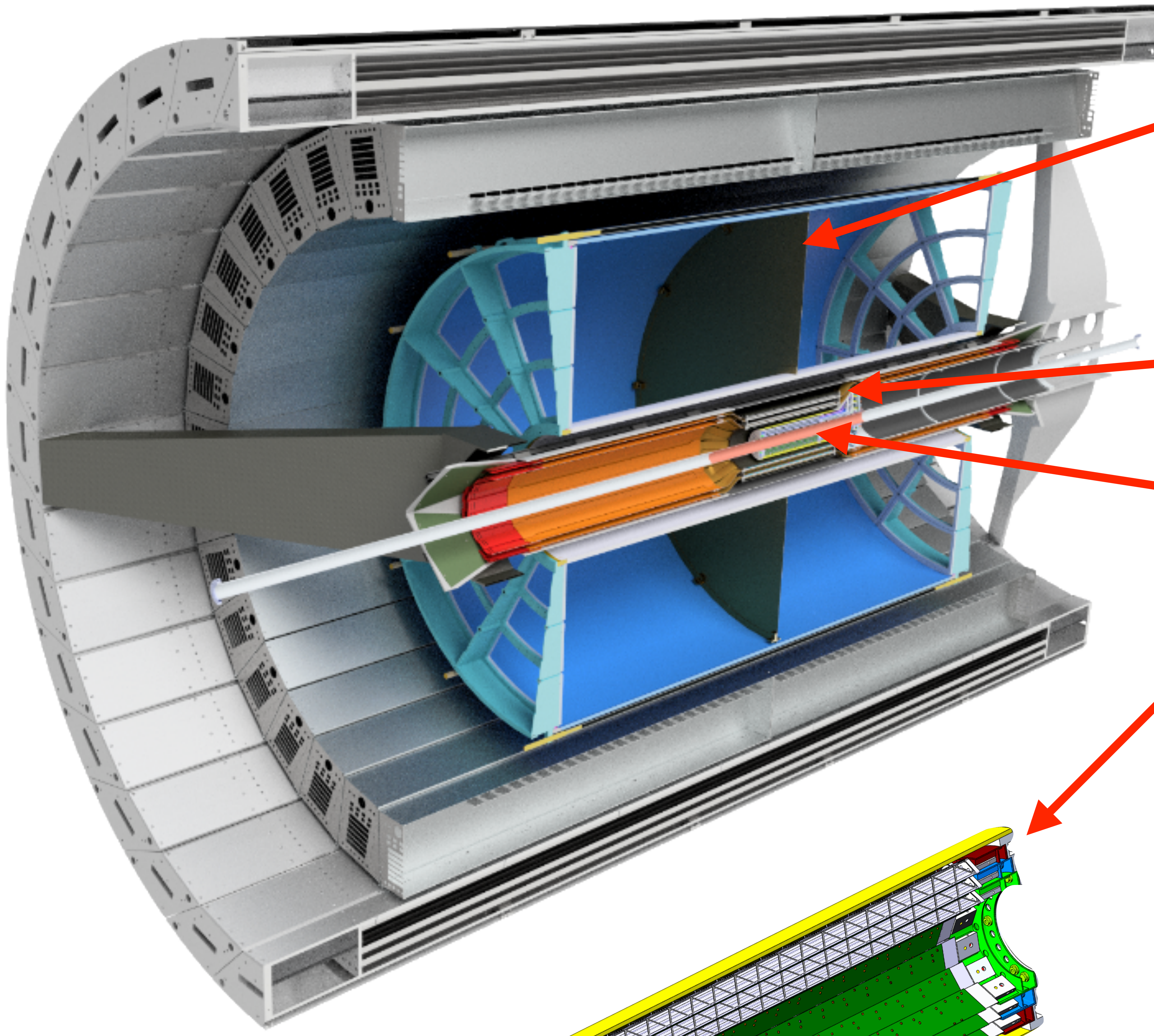


First @ RHIC: Full calorimeter stack incl. hadronic calo

Challenge:

- Absolute calibration of jet response (JES, JER)

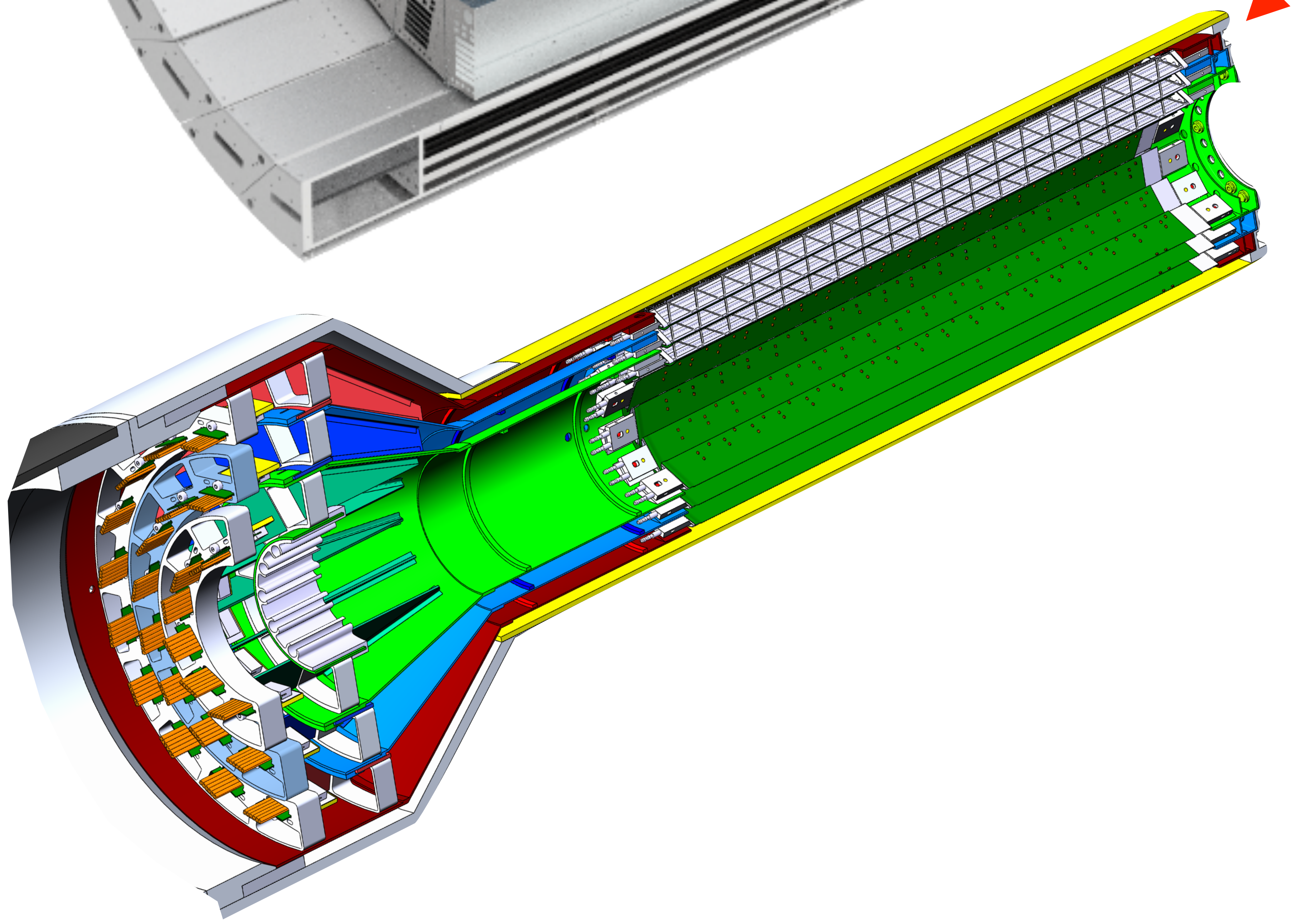
sPHENIX tracking



Continuous readout TPC (R = 20-78cm)
- shares many concepts with ALICE TPC upgrade

Si strip intermediate tracker (INTT, R = 7-11cm)

3 layer MVTX vertex tracker (R = 2.3, 3.1, 3.9cm)
- based on ALICE ITS IB detector

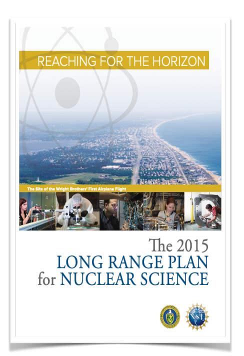


First @ RHIC: Large acceptance high-rate tracking

Challenges:
- Track reconstruction CPU time
- TPC distortion correction

sPHENIX schedule

2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023



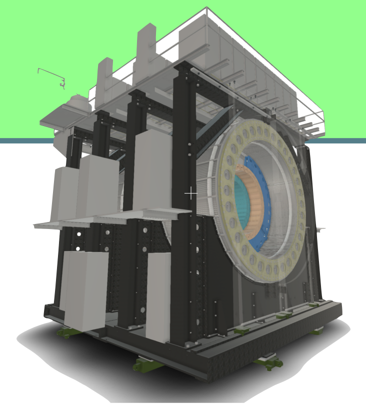
sPHENIX science collaboration

DOE CD-0
"Mission need" approval

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

BNL PD-2/3
: Final project design approval, authorization to execute

Installation & commissioning



The PAC supports the sPHENIX project management proposal to use the contingency funds to find ways to ensure meeting the construction schedule. The PAC considers the timely startup of sPHENIX physics data-taking as the highest priority of the RHIC program after completion of BES-II. The PAC recommends the sPHENIX and RHIC managements to work together to meet the schedule requirements of the sPHENIX project.

Collaboration and project are committed to sPHENIX being ready for data taking in early 2023
Possible b/c of extraordinary effort by project, collaboration and support by BNL/DOE

sPHENIX collaboration

- 82 institutions (22 new since CD-0)
  - world-class expertise in physics, silicon, TPCs, calorimetry, electronics, computing
  - about 25% non-US institutions
  - ≈ 330 participants (➔ 400-500 by 2023)
- Steady evolution of collaboration organization

2016

2017

2018

2019

U. Sao Paolo

NCU, Taiwan

Florida AMU

2020

2021

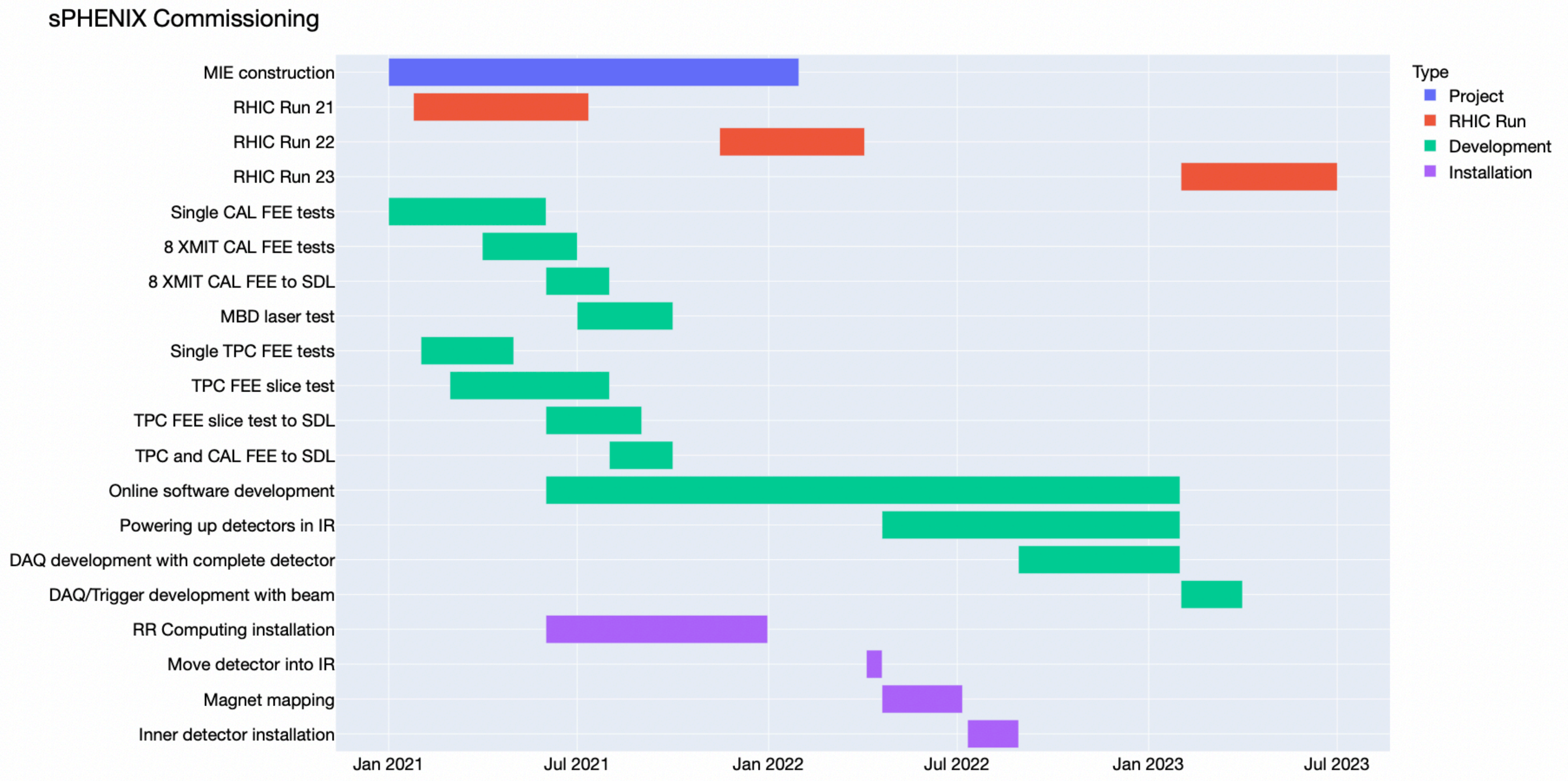
sPHENIX organization

Commissioning taskforce (est. 2021)

Led by Caroline Riedl (UIUC) and John Haggerty (BNL)

- Charge is to develop detector commissioning plan
- covers both ~now to beginning of data taking and commissioning with beam in 2023-2025 runs

Draft **beam commissioning plan informs run plan**



pre-beam commissioning

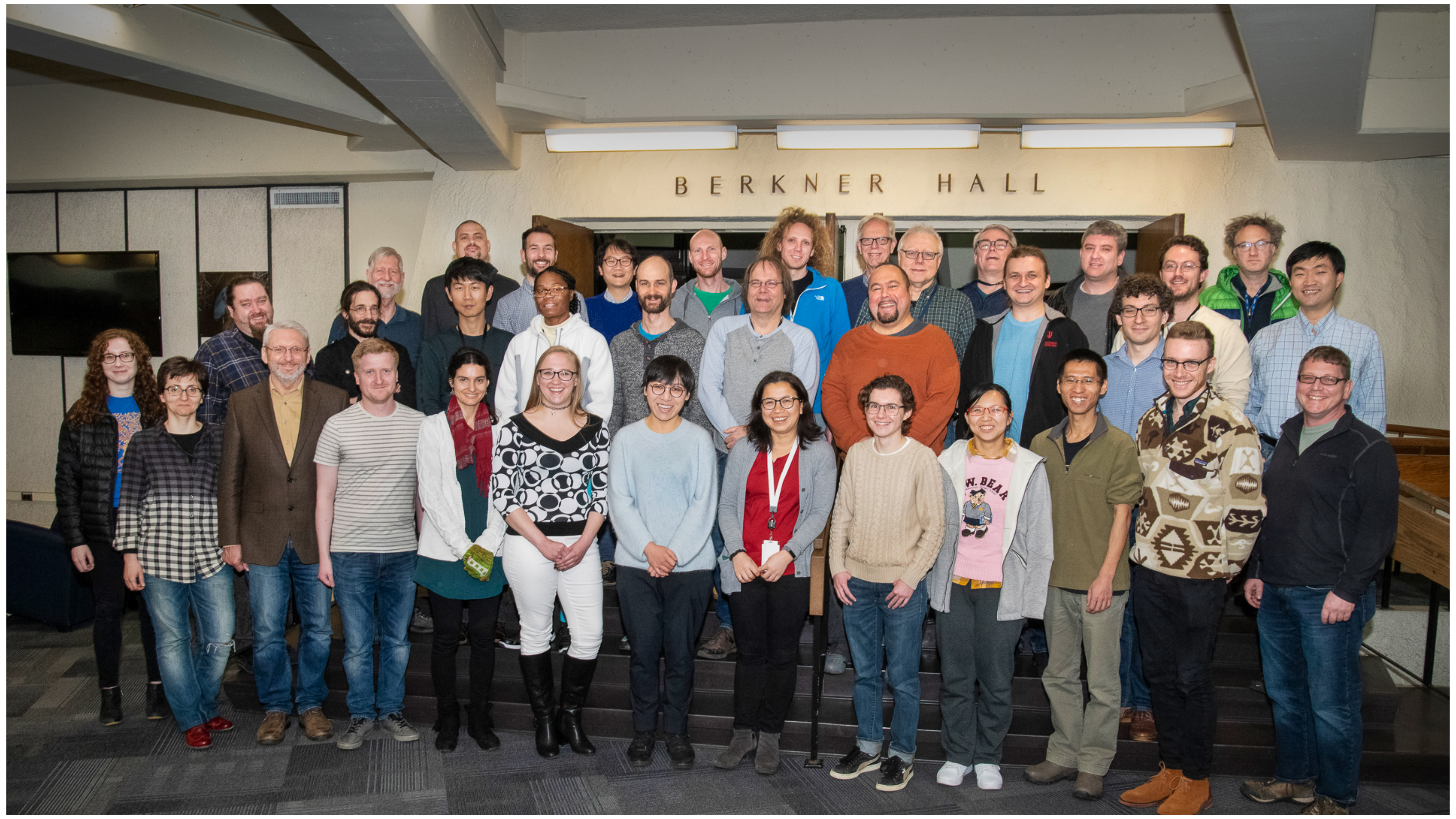
Weeks	Designation
0.5	Cool Down from 50 K to 4 K
2.0	Set-up mode 1 (Au+Au at 200 GeV)
0.5	Ramp-up mode 1 (8 h/night for experiments)
11.5	sPHENIX Initial Commission Time
9.0 (13.0)	Au+Au Data taking (Physics)
0.5	Controlled refrigeration turn-off
24.0 (28.0)	Total cryo-weeks

!

beam commissioning (Run 23)

Software/Computing

- **Key principle: Reconstruction with fixed, short latency**
  - Rapid diagnosis of rare failures
  - Timely completion of science program
  - → Reconstruction time budget of 5s/event
- **Challenges**
  - Reconstruction time performance
  - TPC distortion correction
  - Jet energy calibration
- **Collaboration on common software:**
  - Workfest w/ ALICE/STAR (July ’19)
  - Workfest w/ ALICE/STAR/CBM/ATLAS (Jan ’20)
  - ACTS tracking, CA seeding (ATLAS, ALICE, STAR
  - KFParticle 2ndary vertex reco (CBM)
  - TPC distortion correction (ALICE)
  - Particle flow jet reconstruction (CMS/ATLAS)



Mock Data Challenge (MDC-1)

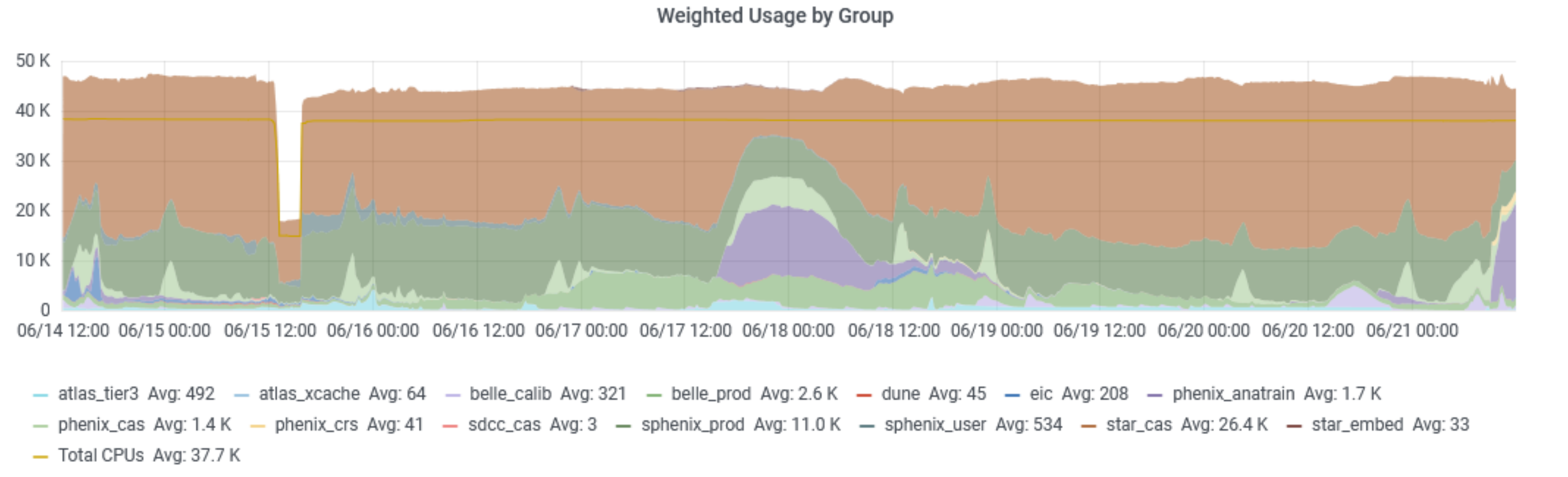
The PAC endorses the plans of the sPHENIX Collaboration to initiate a Mock Data Challenge (MDC). This is timely and it is important to have in place a software project with appropriate project structure, responsibility and review processes associated with a project. The goals and milestones of the MDC project should be defined to enable the collaboration to assess the software readiness for the start-up of the sPHENIX detector. The MDC project will be essential to shape up the sPHENIX software towards the commissioning of the detector in 2023.

2020 RHIC PAC report p.10-11

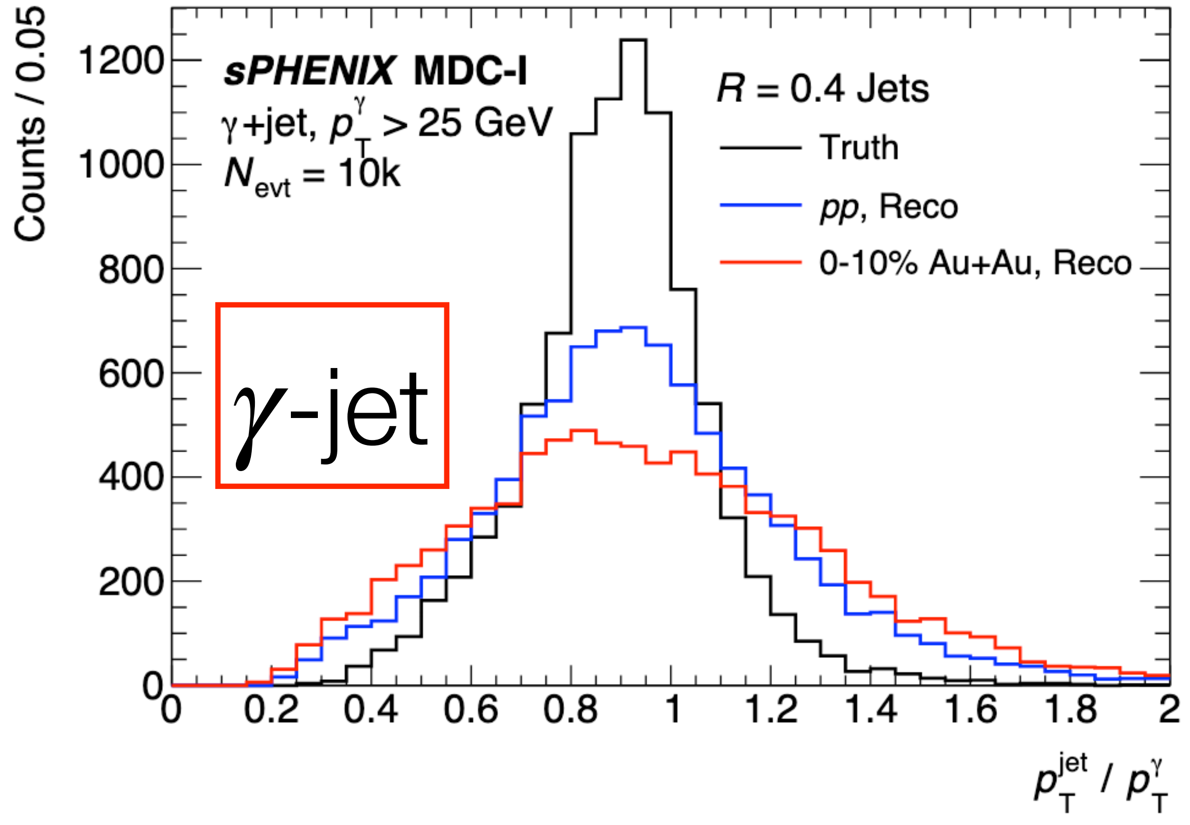
MDC-1 led by Camelia Mironov (MIT) and Chris Pinkenburg (BNL)

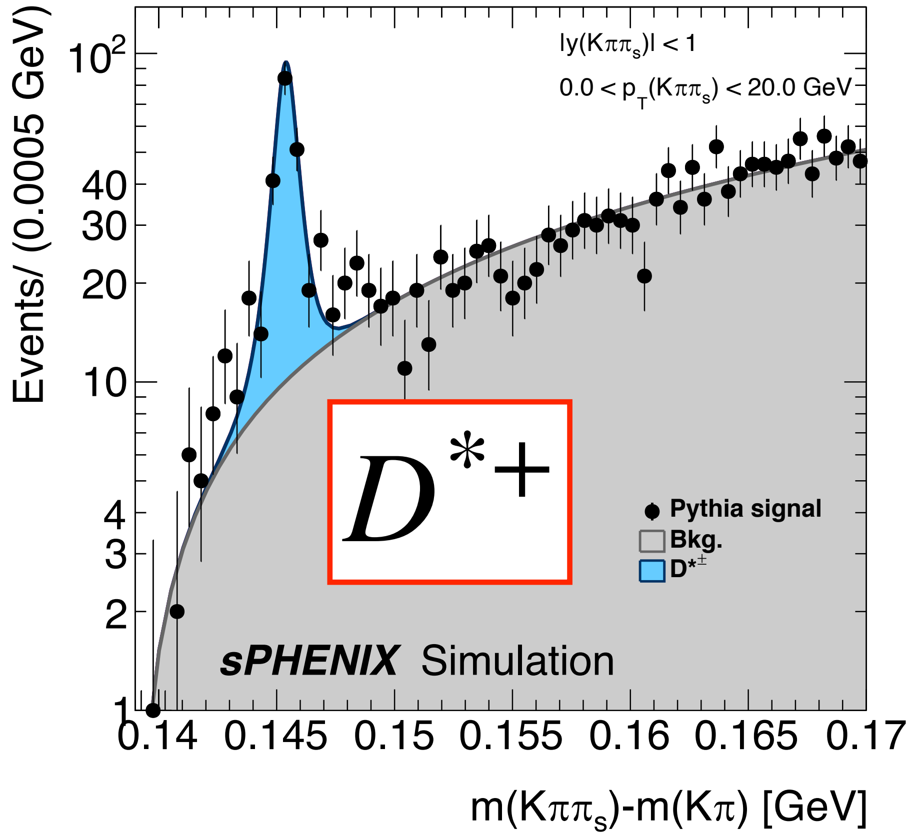
- **Exercise full chain** from large scale simulation, reconstruction in production environment to analysis of reconstructed data
- Effort involving **software teams and analysis groups** from Nov 2020 - March 2021
- Results reported at 2021 Software & Computing review (March 2021)
- Catalyzed **major progress in all areas** of sPHENIX computing effort

MDC-1 results



- Sustained MDC simulation and reconstruction effort
- Valuable lessons about interaction w/ scheduling system



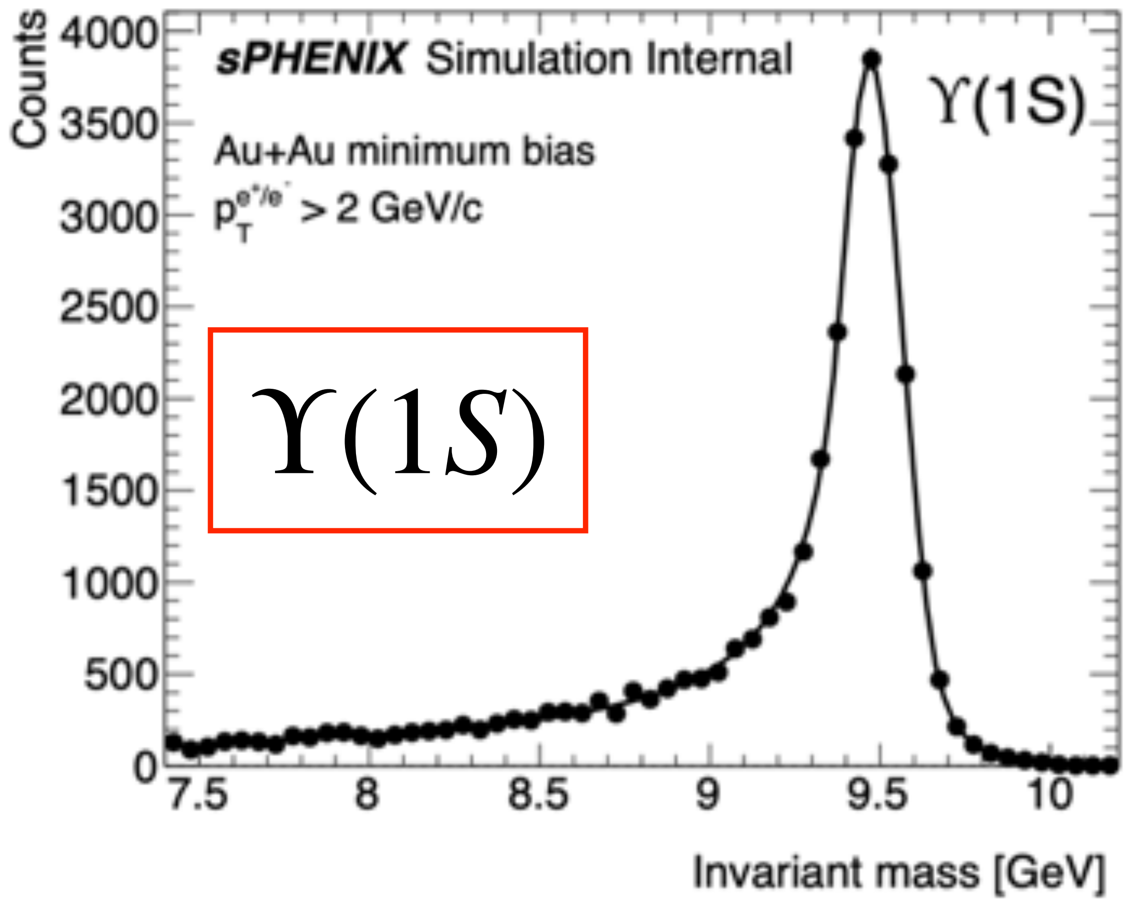


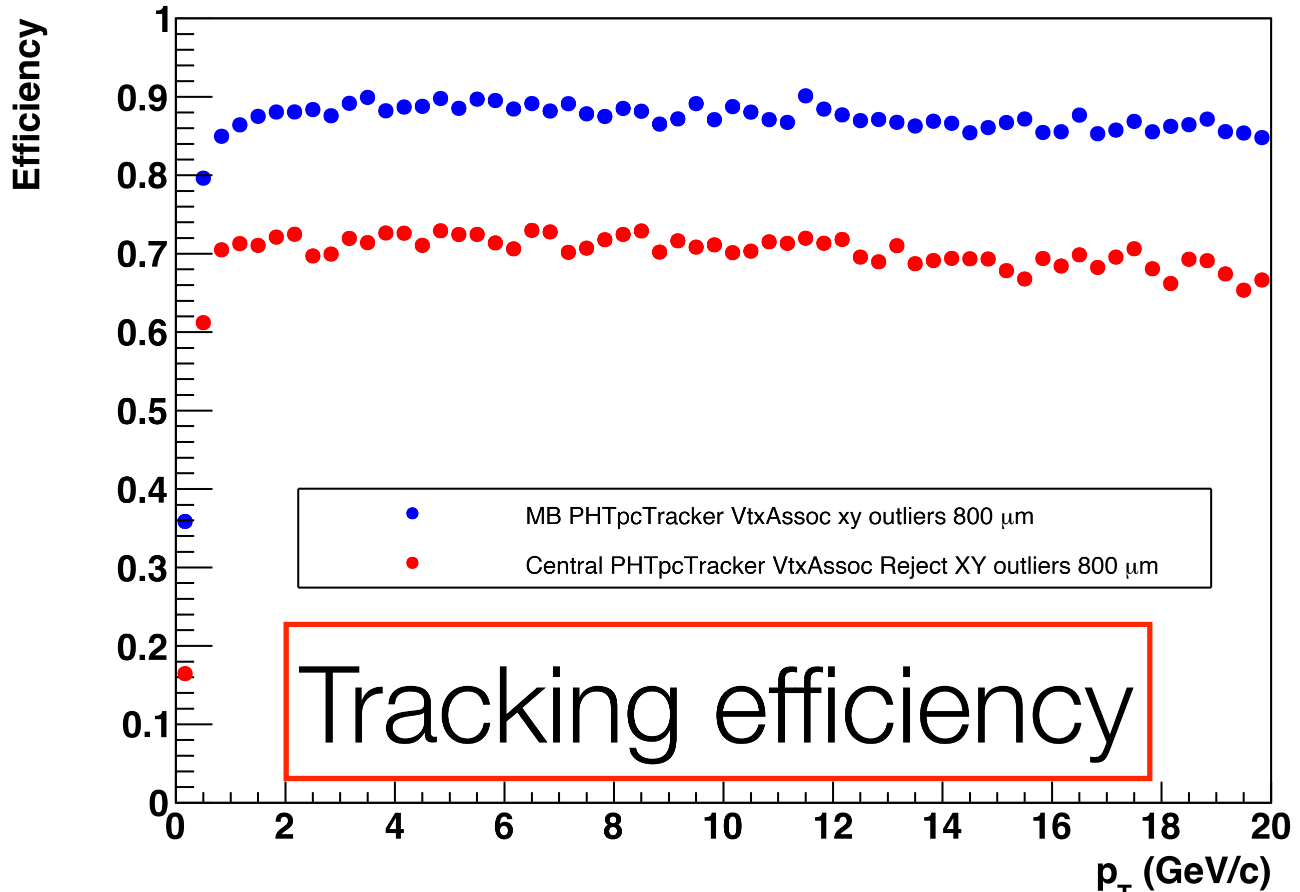
Mock data challenge, planning for convergence

2021 S&C review report

Findings

1. The experiment has successfully conducted the first simulation campaign organized as a Mock Data Challenge (MDC1). The data production/processing chain was executed. Full simulation was done.
2. Several new software tools, including job management PanDA as proof of concept and MC production tools, file catalog, parallel file reading and performance profiling (memory, time) were used or at least tested. Jenkins integration for Quality Assurance was in place during MDC1.
3. First full simulation using ACTS was carried out and reached the reconstruction performance goals.



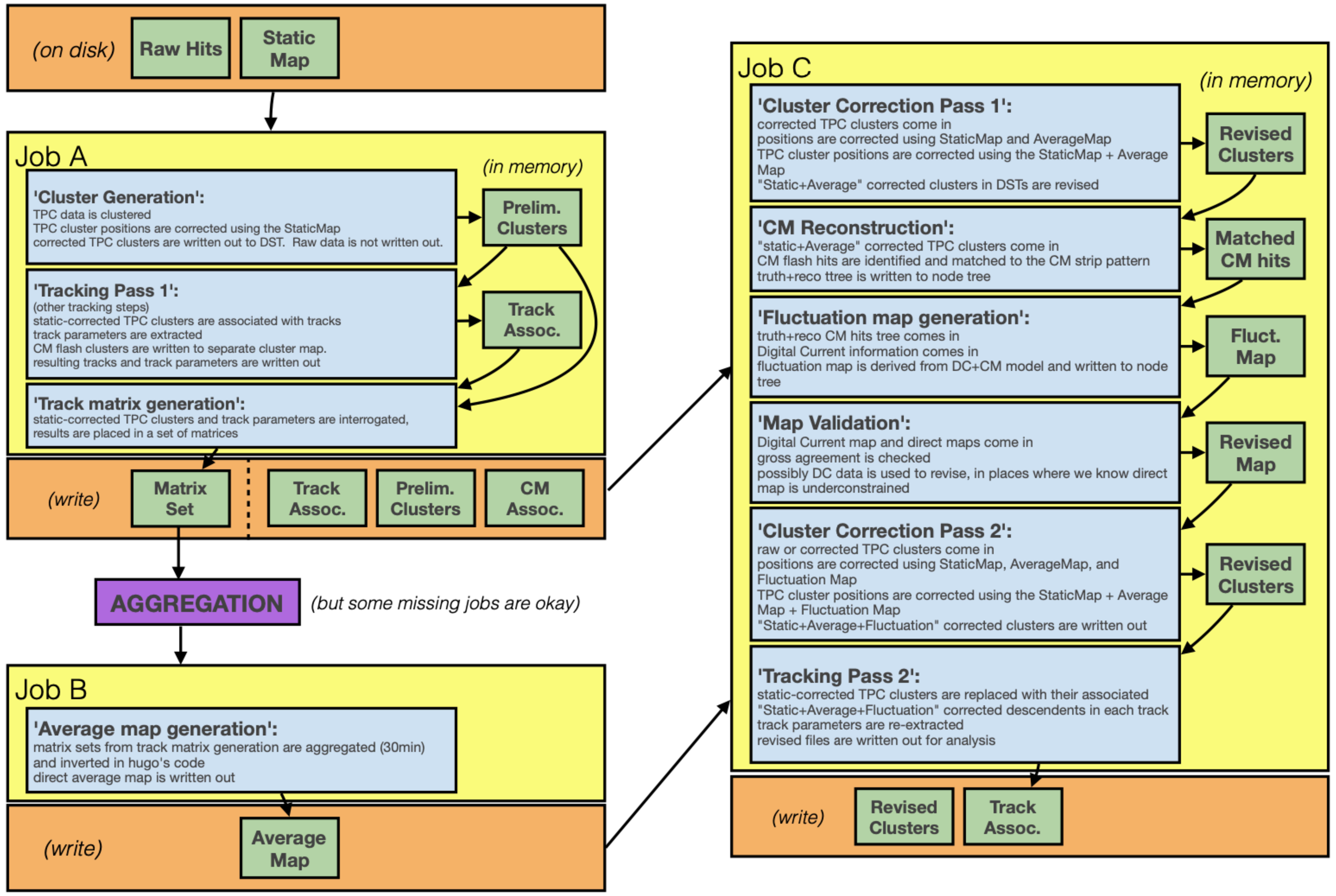


Flagship measurements performed on MDC-1 simulated/reco'd data

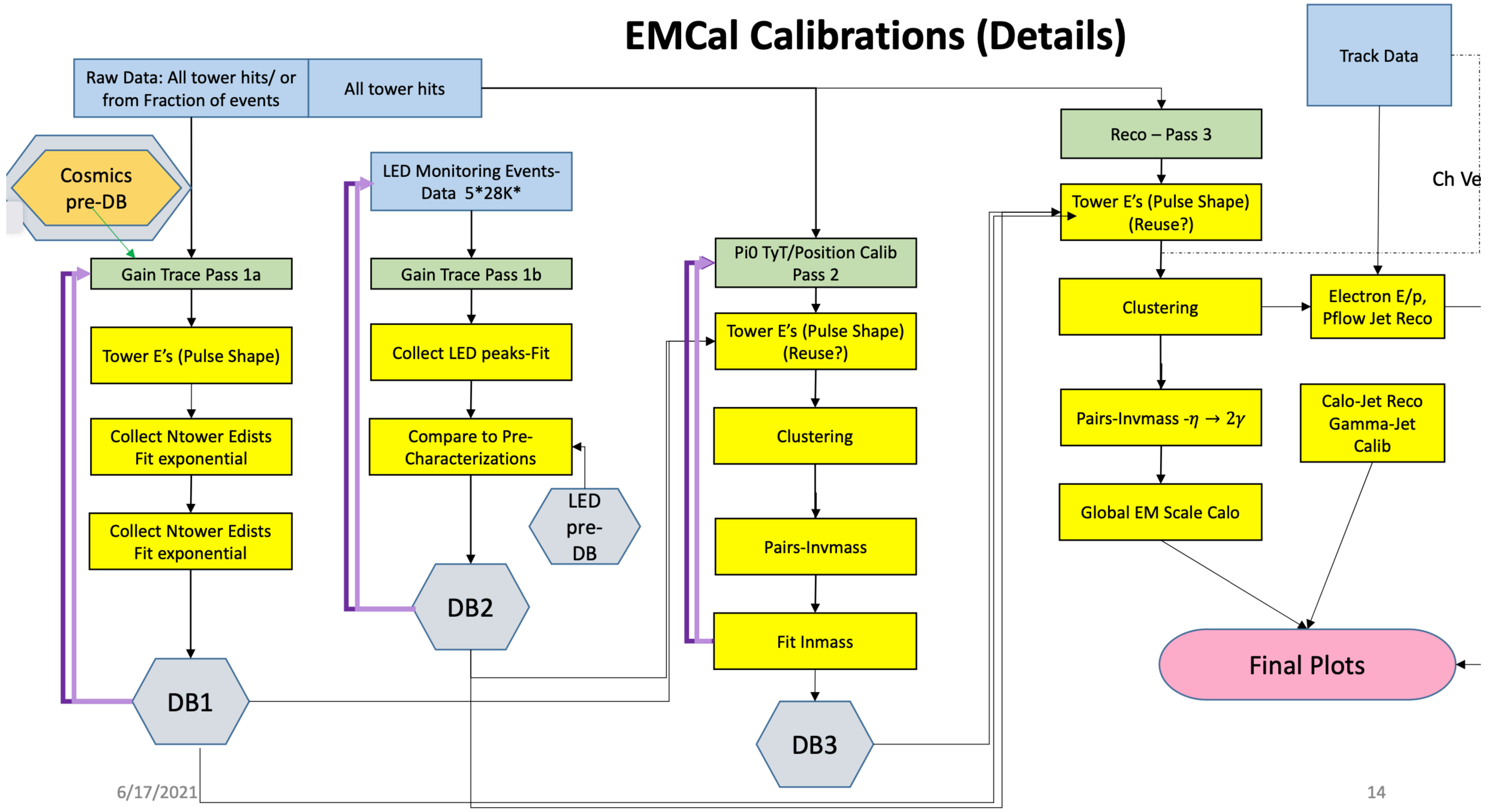
MDC-2

Preparing for MDC-2, starting in late 2021

- Include distortions and distortion correction as well as calo calibration workflows
- Production workflow management and database software (PanDa/Rucio, Belle-2 database)
  - Receiving strong support from NPPS and SDCC - most welcome!
- Exercise day physics analyses in “blind” mode (w/ truth information propagated separately)



TPC calibration workflow



EMCAL calibration workflow

2021 PAC charge and sPHENIX

BNL Nuclear Physics PAC 2021 Charge and Agenda
March 16, 2021

Charge
STAR: Beam Use Requests for Runs 22-25
sPHENIX: Beam Use Requests for Runs 23-25
CeC: Beam Use Requests
The Beam Use Requests should be submitted in written form to PAC by May 14, 2021
The BURs should be based on the following number of expected cryo-weeks.
First number is minimal expected RHIC run duration and second number is optimal duration:
2022: 18 (20)
2023: 20 (28)
2024: 20 (28)
2025: 20 (28)
Presentations:
STAR: Update on spin physics and isobar analyses
PHENIX: Update on ongoing analysis efforts and data archiving effort
sPHENIX: Installation status and schedule

sPHENIX run schedule

Each of run period has distinct, critical role for sPHENIX science mission

- 2023 - **commissioning** of detector, RHIC and data operations with Au+Au
- 2024 - **high statistics p+p** reference and **p+Au** cold QCD data
- 2025 - **high statistics Au+Au** data
- This is the **minimal "safe" schedule**
  - ensure safe combined operation of detector and collider
  - provide development time for calibration and reconstruction to ensure successful completion of science mission before transition to EIC
- For successful completion of sPHENIX science mission, **each of these runs needs to be successful**

Run plan for 28 week scenario

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}

Unchanged compared to 2020 BUP

- **Focus on core science** mission
- **Minimization of risk** guides ramp-up, commissioning and running conditions
- **Maximize science output** for investment
  - MIE, 1008 upgrade, research effort, RHIC ops, US HI research workforce

Run plan for 20 week scenario

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	20	5	$1.7\ \mathrm{nb}^{-1}$	$2.1\ \mathrm{nb}^{-1}$
2024	$p^{\uparrow}p^{\uparrow}$	200	20	16	$0.4\ \mathrm{pb}^{-1}$ [5 kHz] $6.2\ \mathrm{pb}^{-1}$ [10%-str]	$62\ \mathrm{pb}^{-1}$
~~2024~~	~~$p^{\uparrow}$+Au~~	~~200~~	~~–~~	~~0~~	~~0~~ ~~0~~	~~0~~
2025	Au+Au	200	20	16.5	$10\ \mathrm{nb}^{-1}$	$16\ \mathrm{nb}^{-1}$

Compared to 28 week scenario

- **Loss of p+Au** science program
- **Increased risk** to core science (e.g., commissioning, detector or machine delays)
- Significant **loss of science output** (precision!) for **minimal savings** on investment

Comparison of 28 vs 20 week scenarios

n.b., 28wk→ 20wk savings amount to **2%** of total investment

Comparison of 28 vs 20 week scenarios

20wk scenario for Run 24 does not allow p+Au run.

Shortening p+p run to ~8wks →unacceptable risk, loss of precision for core science program (p+p reference)

Comparison of 28 vs 20 week scenarios

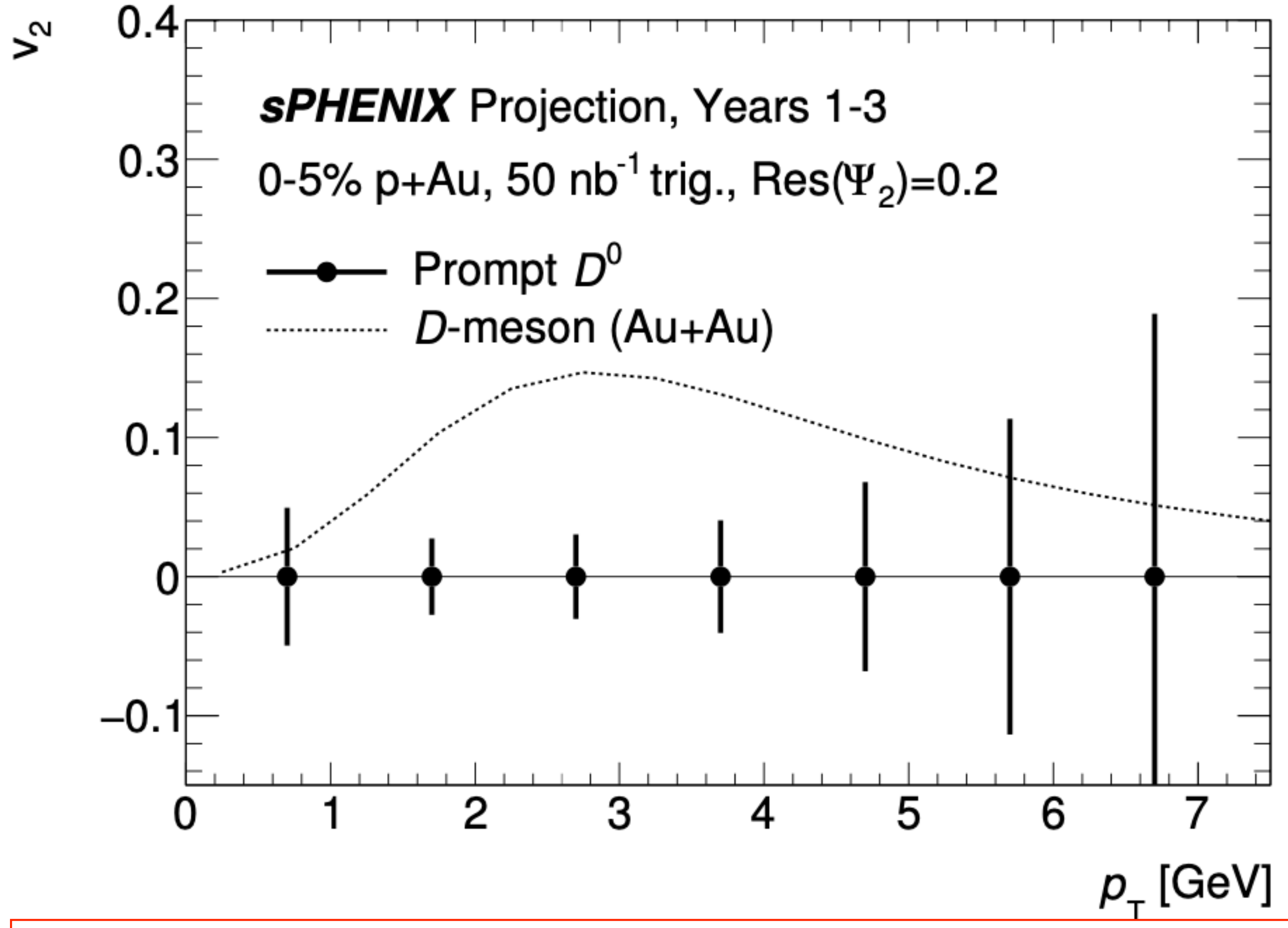
Commissioning a new detector from initial turn-on to physics operations in ~12 weeks is ambitious

- c.f., LHC schedule for Run 3
  - 2-week pilot beam in Fall 2021
  - 4wk machine set-up → 9wk commissioning w/ beam → physics ramp up
    - Expected lumi of 2022 LHC run is ~2/3 of run 2023 for same uptime

Weeks	Details
1.5	low rate, 6 bunches
2.0	low rate, 111 bunches, MBD L1 timing
1.0	low rate, crossing angle checks
1.0	low rate, calorimeter timing
4.0	medium rate, TPC timing, optimization
2.0	full rate, system test, DAQ throughput
11.5	**total**

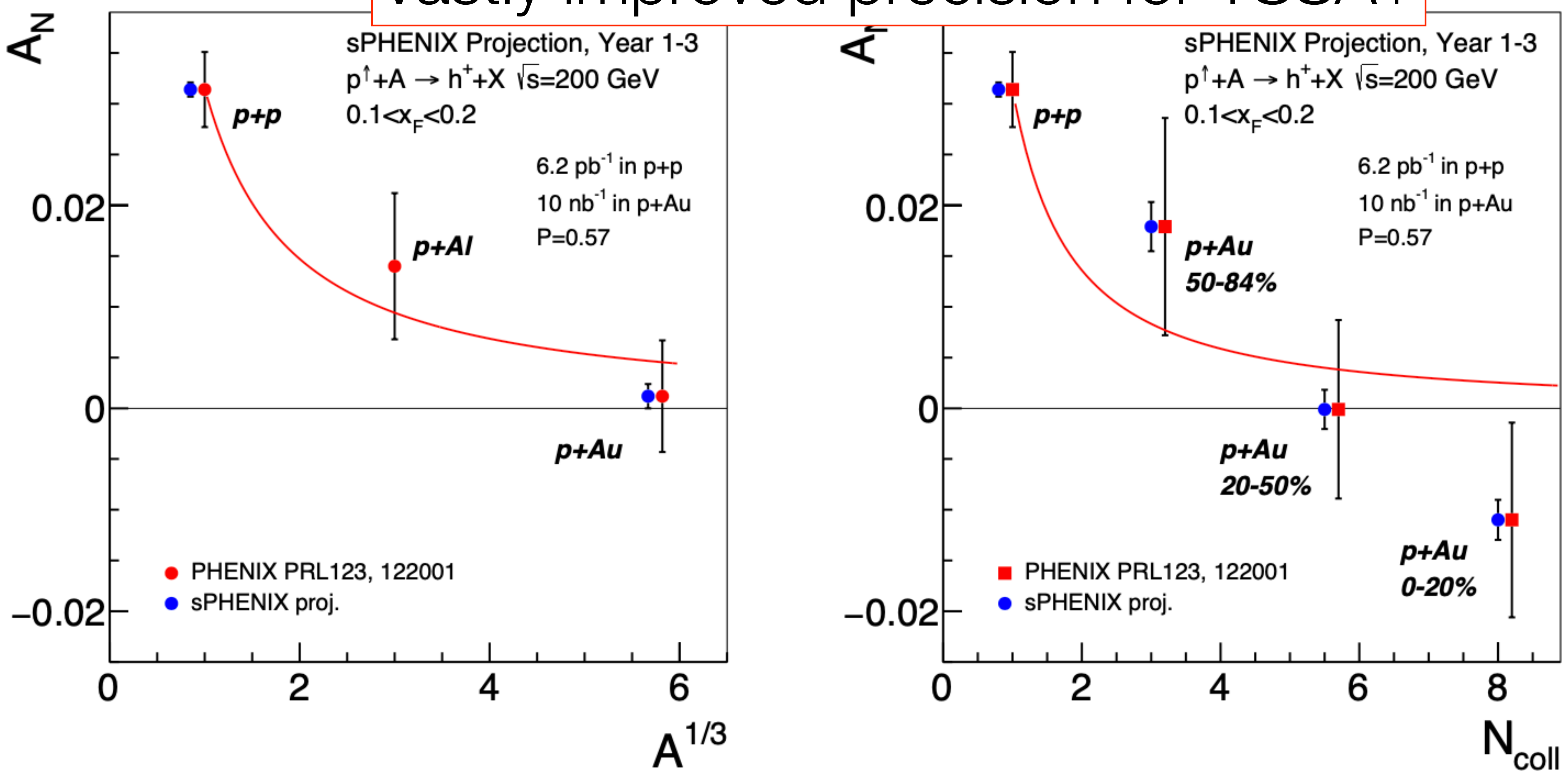
2023 beam commissioning plan

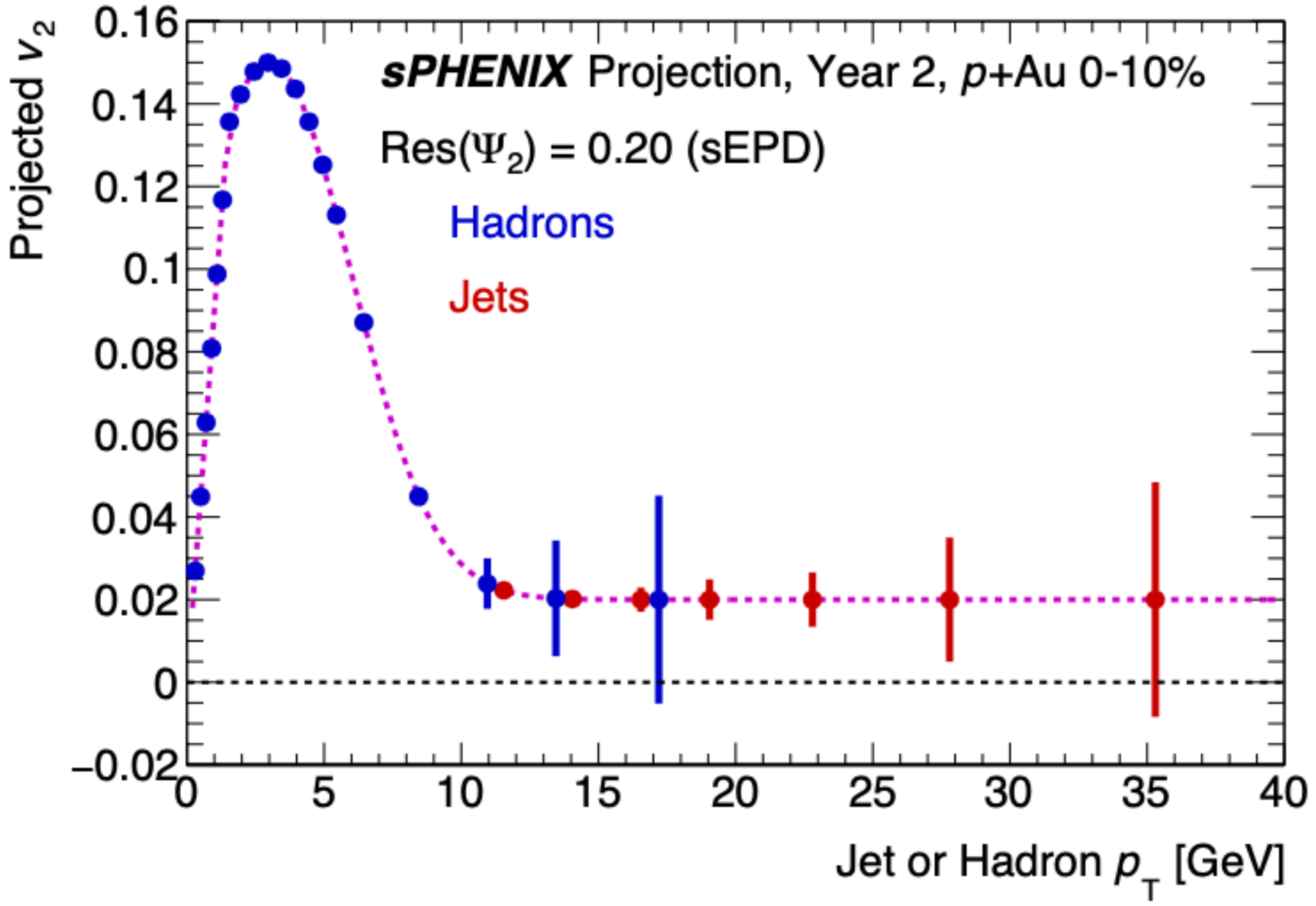
20wk scenario: Rich p+Au program lost



Collectivity and jet quenching in p+Au

Vastly improved precision for TSSA+





Over the last decade, many of the **highest impact discoveries** in the RHIC/LHC heavy ion program **from p+A**

- Collectivity and nuclear geometry, nuclear PDFs, system size dependence on quarkonia and strangeness
- Unique opportunities in polarized proton-nucleus

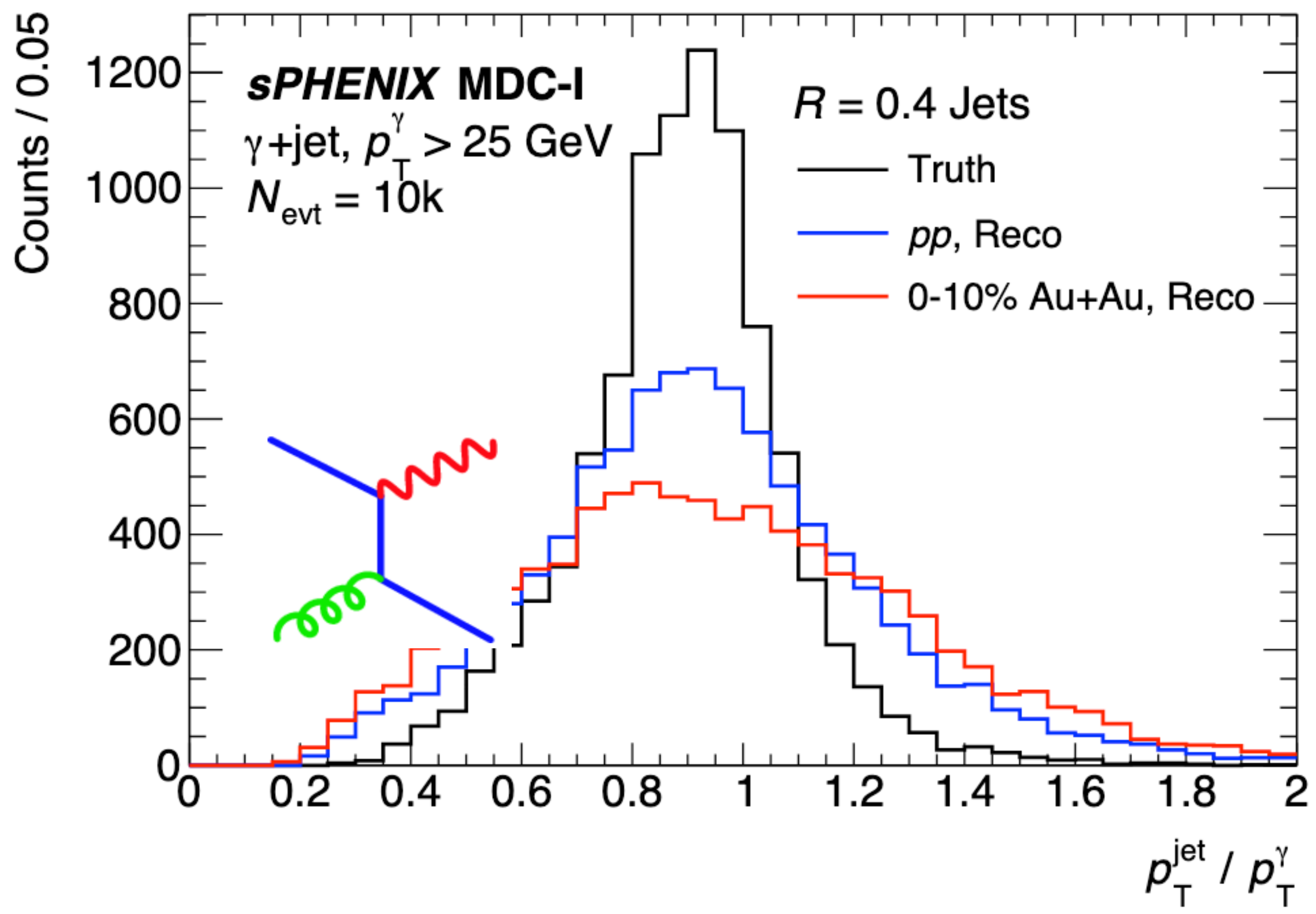
sPHENIX presents **unique capabilities for p+Au**

20wk scenario: Impact on Au+Au program

- 20wk vs 28wk scenario implies loss of **40-50% of Au+Au statistics**
  - Optimal performance typically achieved towards end of collider run
  - Affects both statistical uncertainty and systematic uncertainty based on data-driven calibration (a la LHC)
- sPHENIX science mission is predicated on **precision of hard probes measurements**, enabled by higher rate and improved instrumentation
- Scale of loss is set by **two conditions:**
  - Need **decisive improvement** compared to existing RHIC data (x10, not x2-3)
  - **Comparison to LHC** data ("complementarity" in LRP mission statement)
    - will be limited by sPHENIX for most observables in overlapping kinematic range
    - loss of sPHENIX precision directly leads to loss of discriminating power/ discovery potential

Illustration: photon-tagged jets at LHC and sPHENIX

Photon-tagged jets in sPHENIX

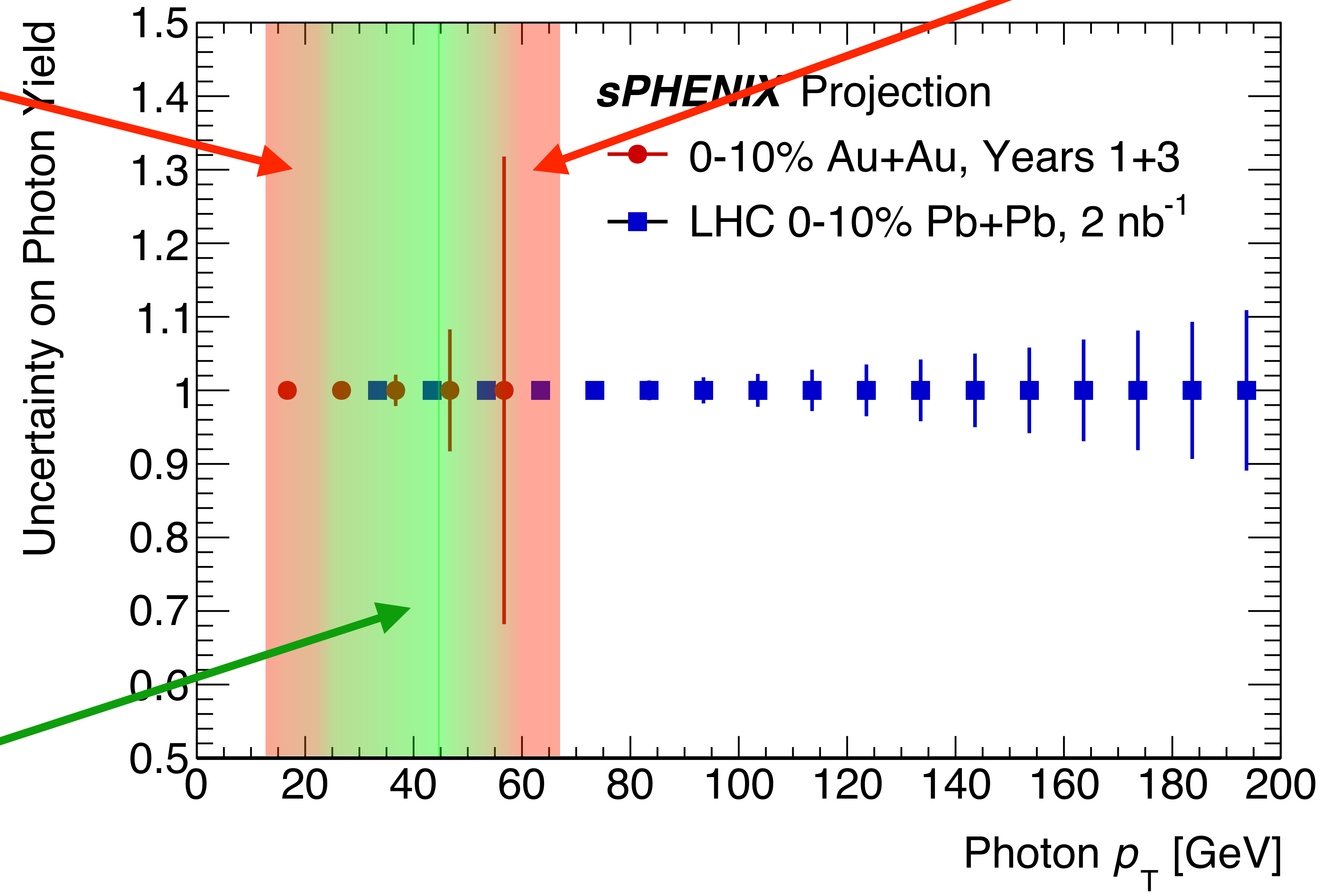


Direct comparison of **same probe** embedded in **different QGP** conditions

- LHC data has shown modifications of momentum balance, jet shapes and fragmentation functions
- sPHENIX tracking & calorimetry provide corresponding capability at RHIC

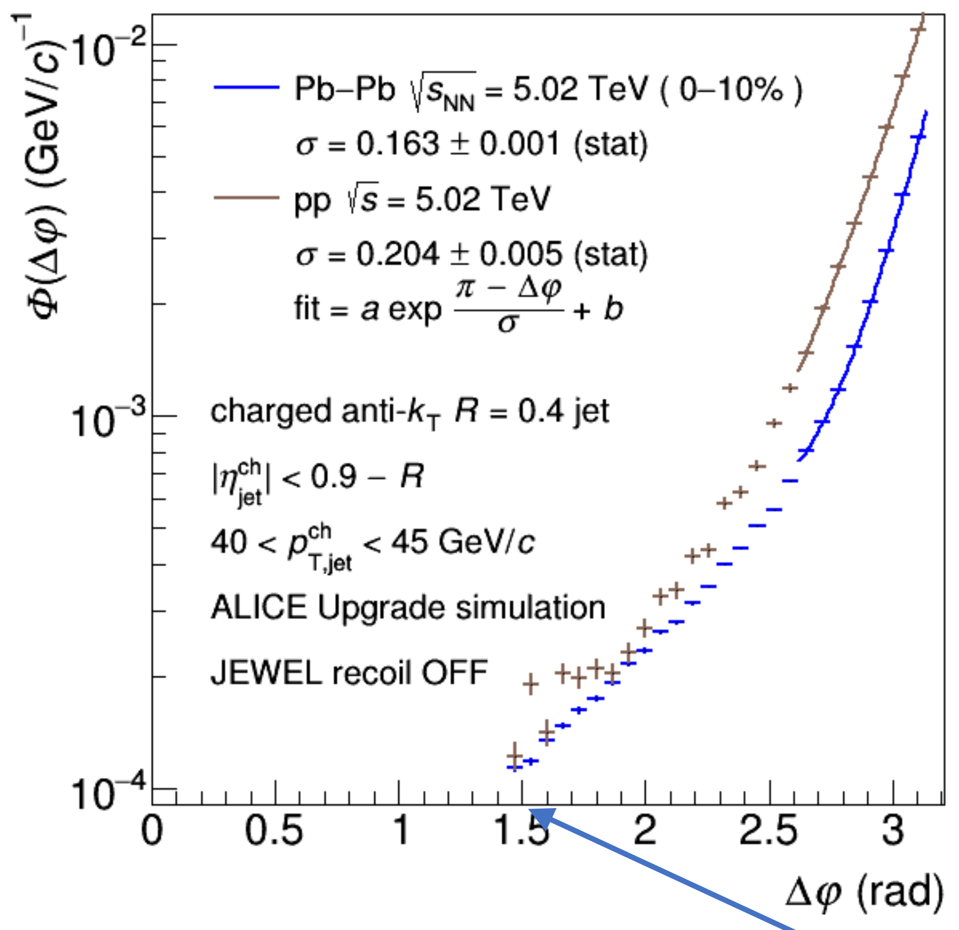
Low p_T: comparison limited by underlying event fluctuations at LHC

High p_T: Comparison limited by sPHENIX photon statistics



Need to **maximize precision in overlap** region: event statistics at sPHENIX!

Illustration: jet azimuthal correlations at LHC and sPHENIX

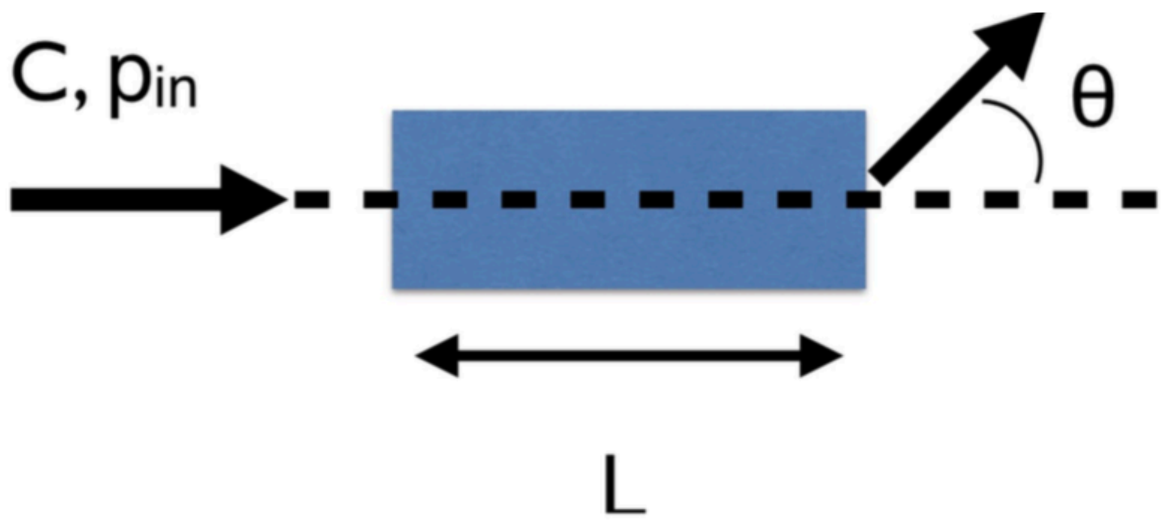


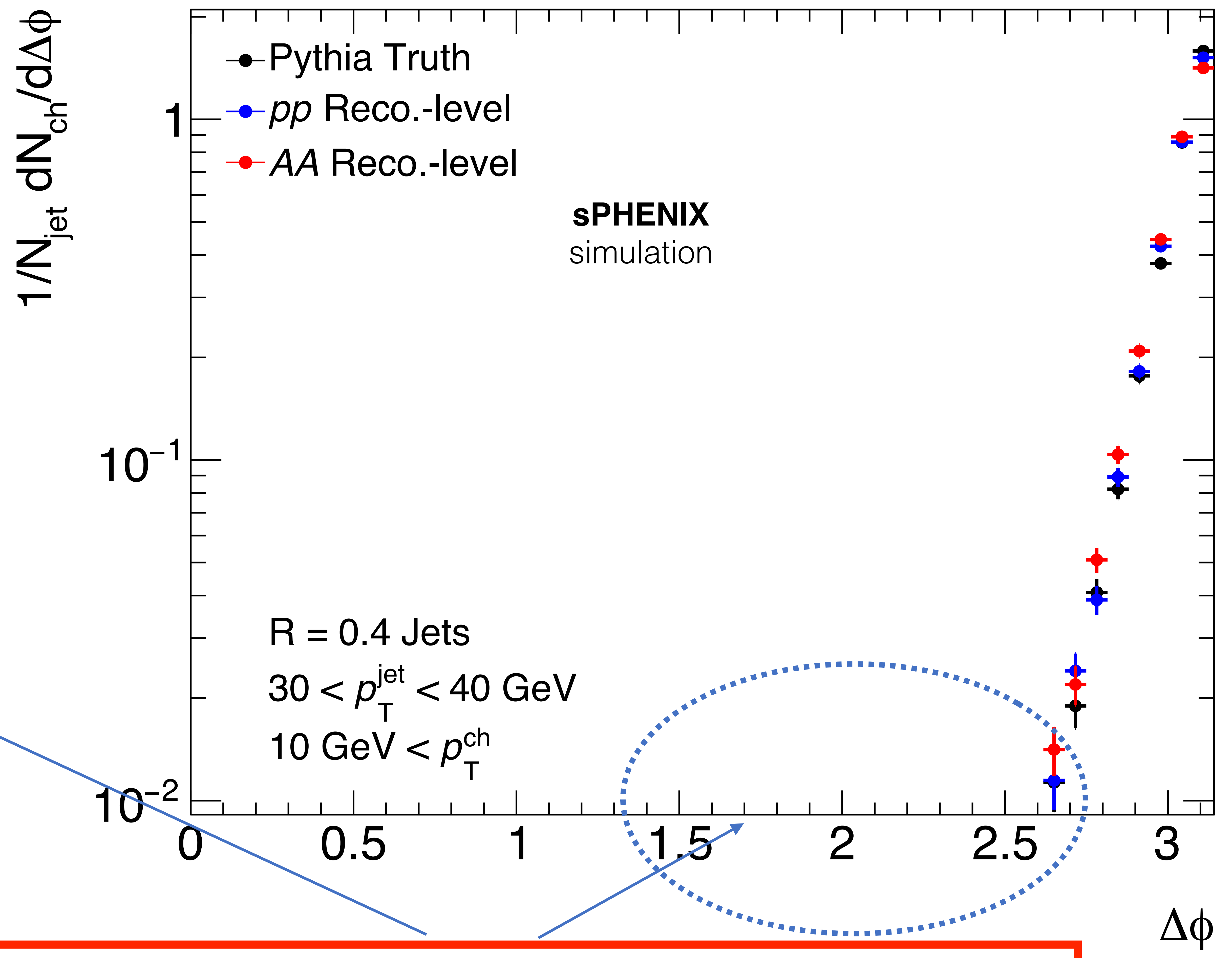
CERN Yellow Report projections for Runs 3, 4

Fig. 31: JEWEL simulation of the angular distribution of charged jet yield in the ALICE acceptance for $40 < p^{ch}_{T,jet} < 45$ GeV/c and $R = 0.4$ recoiling from a high-p_T reference hadron ($20 < p_{T,trig} < 50$ GeV/c), for central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with 10 nb^{-1} int. luminosity, and pp collisions at $\sqrt{s}$ = 5.02 TeV with 6 pb^{-1} int. luminosity. The recoil jet azimuthal angle $\Delta\varphi$ is defined with respect to the reference axis. The observable shown is $\Phi(\Delta\varphi)$ which incorporates statistical suppression of uncorrelated background. Figure from Ref. [1].

Molière Scattering in Quark-Gluon Plasma: Finding Point-Like Scatterers in a Liquid

Francesco D'Eramo,[a,b] Krishna Rajagopal,[c] Yi Yin[c]





At comparable jet energies, much smaller contribution from ISR/FSR at RHIC, as well as smaller smearing from UE fluctuations

Summary

- **sPHENIX collaboration and project continue on path towards scheduled start of data taking in early 2023**
  - Installation of full sPHENIX baseline detector now underway
  - Successfully completed first Mock Data Challenge
  - Preparations for MDC-2 underway
  - Expanding collaboration structure with emphasis on **commissioning, calibration and data operations**
- **sPHENIX presents major investment by nuclear physics community, BNL, DOE:**
  - MIE, 1008 upgrade, MVTX, iHCAL, SDCC, RHIC operations
  - Focus of a **majority of US HI research** groups
- **Key concern is increased risk, irrecoverable loss of physics and damage to science return on investment in 20 cryoweek scenario**