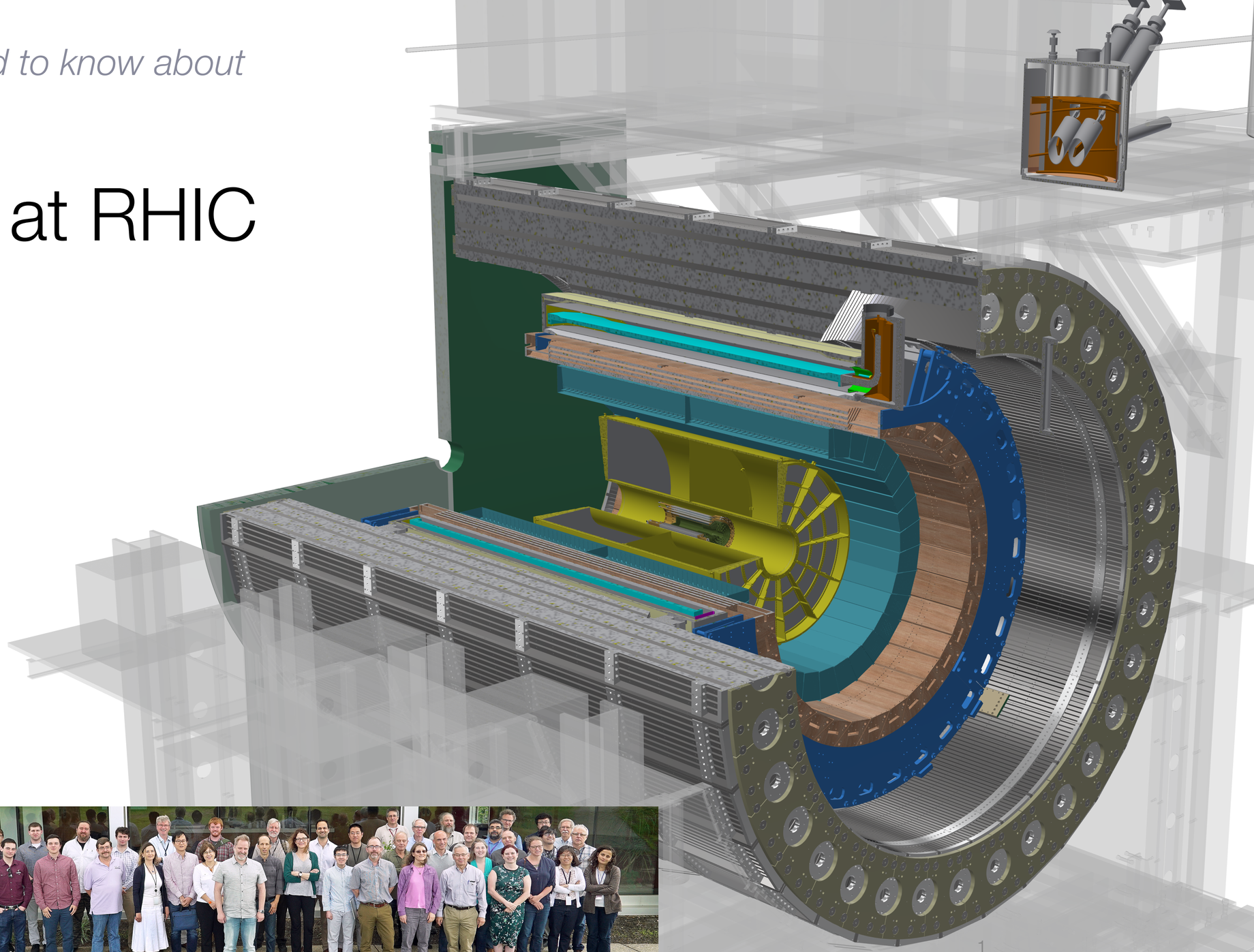
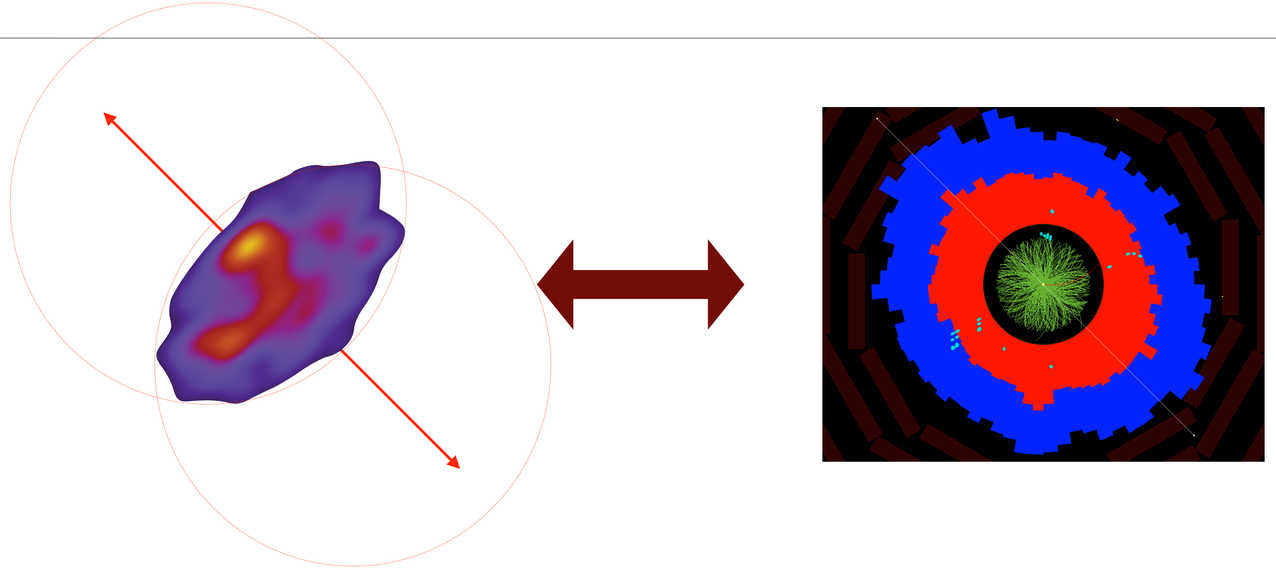
*Everything you always wanted to know about*

# sPHENIX at RHIC



Gunther Roland for the
**sPHENIX Collaboration**

# Two Decades of Hot QCD in a Nutshell

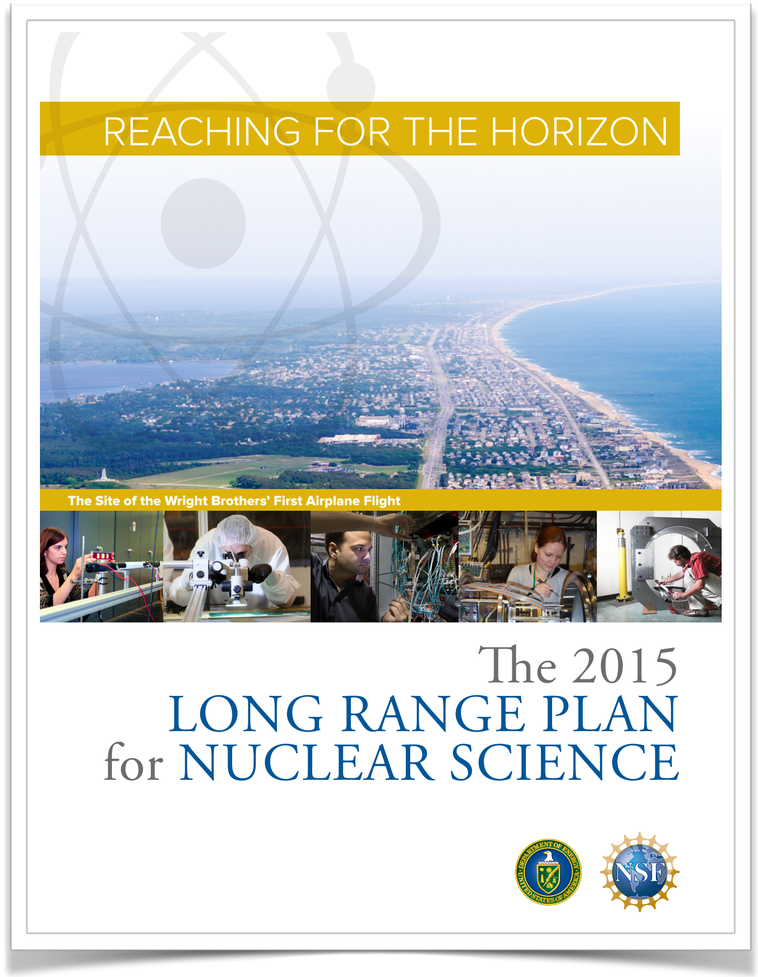


Studies at RHIC (2000-2005) demonstrated near perfect fluidity and extreme opacity for high momentum colored probes of Quark-Gluon Plasma produced in heavy ion collisions

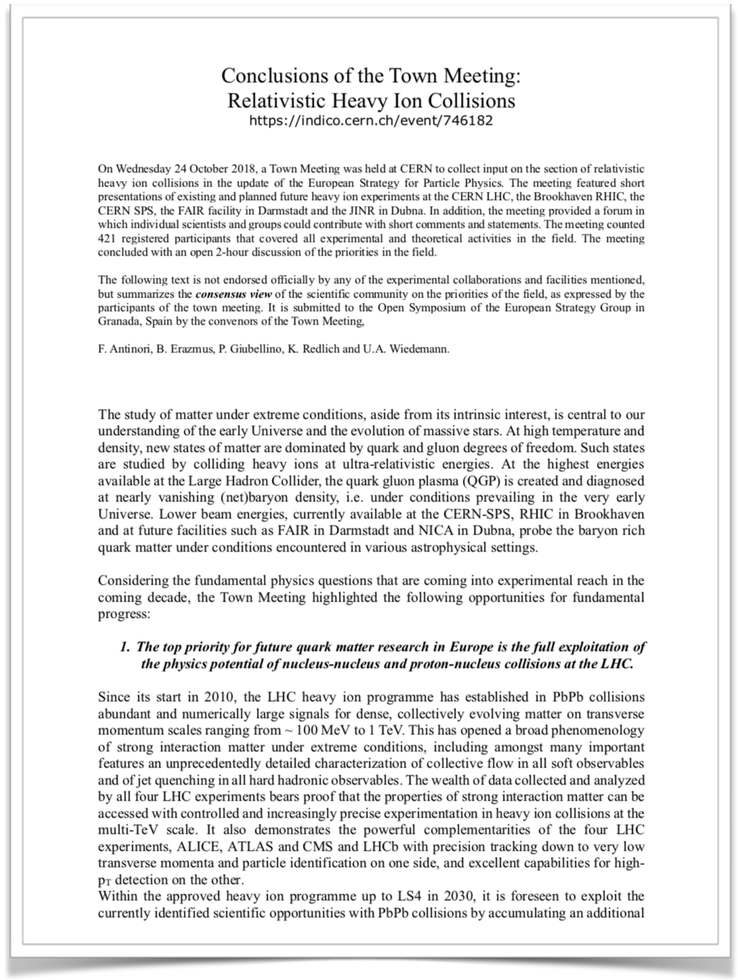
Precision studies at RHIC and LHC early this decade show that structure and fine structure of final state correlations can be understood; firmly establish hydrodynamics as effective theory of long-wavelength dynamics of QGP (at few x Tc)

Task for the next decade: **Use improved experiments at RHIC and LHC to understand how QGP properties arise from underlying (asymtpitically) weakly coupled interaction**

# Planning for the next decade - Parallelaktion(*)




2015 US NP LRP



Conclusions of the Town Meeting:
Relativistic Heavy Ion Collisions
https://indico.cern.ch/event/746182

On Wednesday 24 October 2018, a Town Meeting was held at CERN to collect input on the section of relativistic heavy ion collisions in the update of the European Strategy for Particle Physics. The meeting featured short presentations of existing and planned future heavy ion experiments at the CERN LHC, the Brookhaven RHIC, the CERN SPS, the FAIR facility in Darmstadt and the JINR in Dubna. In addition, the meeting provided a forum in which individual scientists and groups could contribute with short comments and statements. The meeting counted 421 registered participants that covered all experimental and theoretical activities in the field. The meeting concluded with an open 2-hour discussion of the priorities in the field.

The following text is not endorsed officially by any of the experimental collaborations and facilities mentioned, but summarizes the ***consensus view*** of the scientific community on the priorities of the field, as expressed by the participants of the town meeting. It is submitted to the Open Symposium of the European Strategy Group in Granada, Spain by the convenors of the Town Meeting,

F. Antinori, B. Erazmus, P. Giubellino, K. Redlich and U.A. Wiedemann.

The study of matter under extreme conditions, aside from its intrinsic interest, is central to our understanding of the early Universe and the evolution of massive stars. At high temperature and density, new states of matter are dominated by quark and gluon degrees of freedom. Such states are studied by colliding heavy ions at ultra-relativistic energies. At the highest energies available at the Large Hadron Collider, the quark gluon plasma (QGP) is created and diagnosed at nearly vanishing (net)baryon density, i.e. under conditions prevailing in the very early Universe. Lower beam energies, currently available at the CERN-SPS, RHIC in Brookhaven and at future facilities such as FAIR in Darmstadt and NICA in Dubna, probe the baryon rich quark matter under conditions encountered in various astrophysical settings.

Considering the fundamental physics questions that are coming into experimental reach in the coming decade, the Town Meeting highlighted the following opportunities for fundamental progress:

1. ***The top priority for future quark matter research in Europe is the full exploitation of the physics potential of nucleus-nucleus and proton-nucleus collisions at the LHC.***

Since its start in 2010, the LHC heavy ion programme has established in PbPb collisions abundant and numerically large signals for dense, collectively evolving matter on transverse momentum scales ranging from ~ 100 MeV to 1 TeV. This has opened a broad phenomenology of strong interaction matter under extreme conditions, including amongst many important features an unprecedentedly detailed characterization of collective flow in all soft observables and of jet quenching in all hard hadronic observables. The wealth of data collected and analyzed by all four LHC experiments bears proof that the properties of strong interaction matter can be accessed with controlled and increasingly precise experimentation in heavy ion collisions at the multi-TeV scale. It also demonstrates the powerful complementarities of the four LHC experiments, ALICE, ATLAS and CMS and LHCb with precision tracking down to very low transverse momenta and particle identification on one side, and excellent capabilities for high-$p_T$ detection on the other.
Within the approved heavy ion programme up to LS4 in 2030, it is foreseen to exploit the currently identified scientific opportunities with PbPb collisions by accumulating an additional

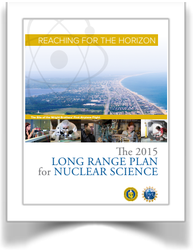
WG5 for 2019 ECFA document



(*) with apologies to Robert Musil

# Complementarity of LHC and sPHENIX for QGP studies

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.**




2015 US NP LRP

"This programme after LS2 includes precision studies of the **flow of heavy quarks and of open heavy flavor and quarkonia** production , the detailed analysis of fluctuations of conserved charges and of **quenched jet fragmentation via high statistics photon/Z-jet correlations,** and access to signals of electromagnetic radiation from the dense medium. This will enable to fully establish the long-wavelength matter properties of the plasma produced at the LHC, and to get **access to the partonic dynamics that underlies the observed surprisingly strong collective phenomena. "**

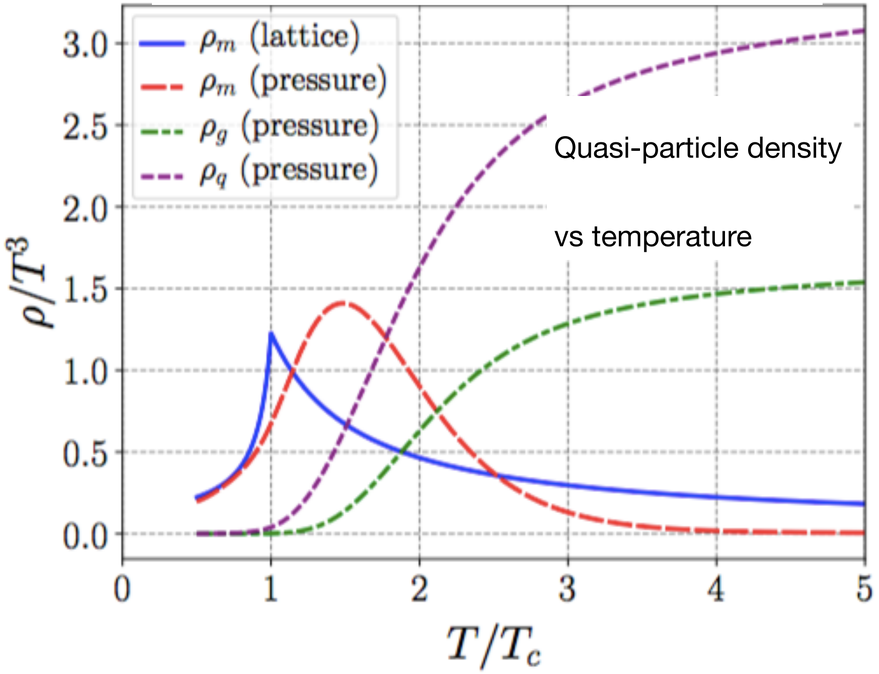
"As the **temperature dependence of transport properties** can be accessed experimentally by varying the center of mass energy over a logarithmically wide range, the **combined analysis of LHC data and future high precision data from RHIC** offers a qualitatively novel handle on the temperature dependence of properties of hot and dense matter. **The Town Meeting observes that the recently approved sPHENIX proposal targets these opportunities by bringing greatly extended capabilities to RHIC…**


Conclusions of the Town Meeting: Relativistic Heavy Ion Collisions

WG5 for 2019 ECFA document

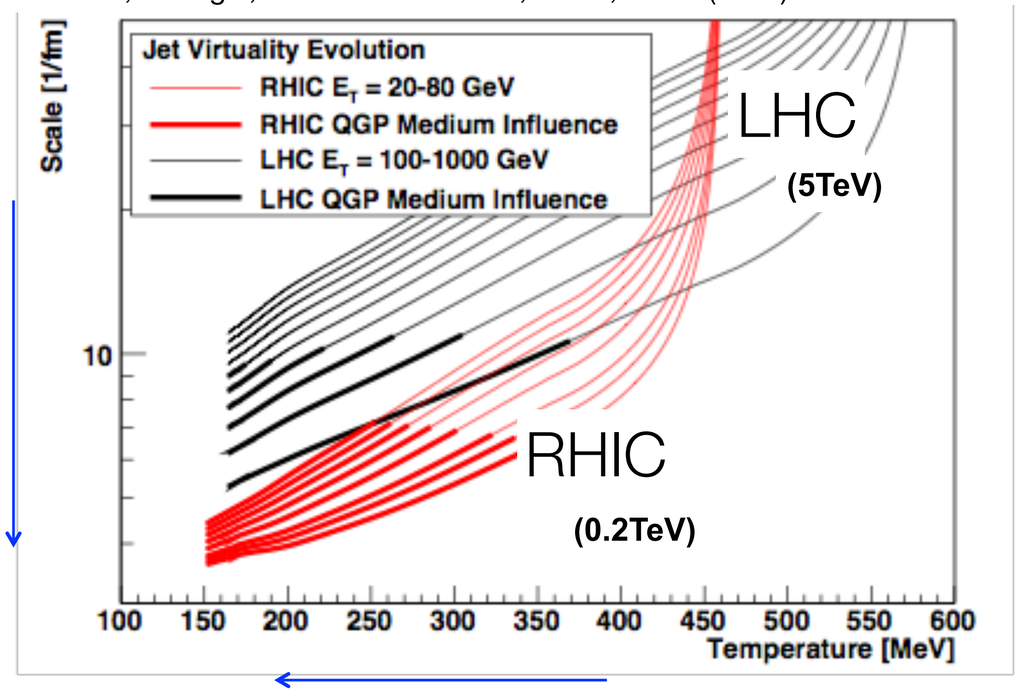
# Complementarity: Why RHIC *and* LHC?

A. Ramamurti, E. Shuryak,arXiv:1708.04254




Structure of QGP expected to depend on  temperature

M. Habich, J. Nagle, and P. Romatschke, EPJC, 75:15 (2015)

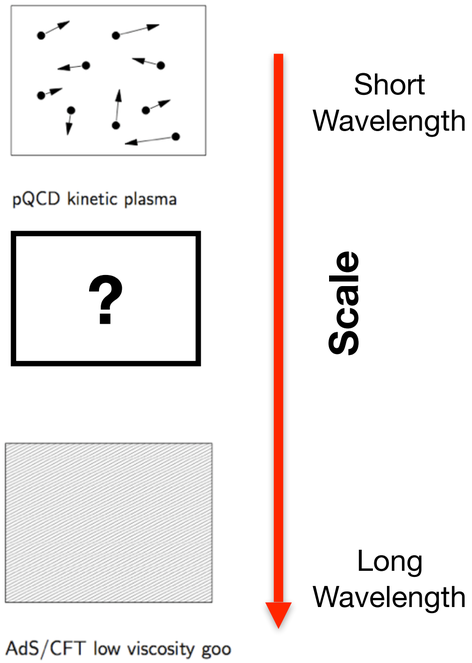



Initial QGP conditions and QGP evolution are different at RHIC vs LHC

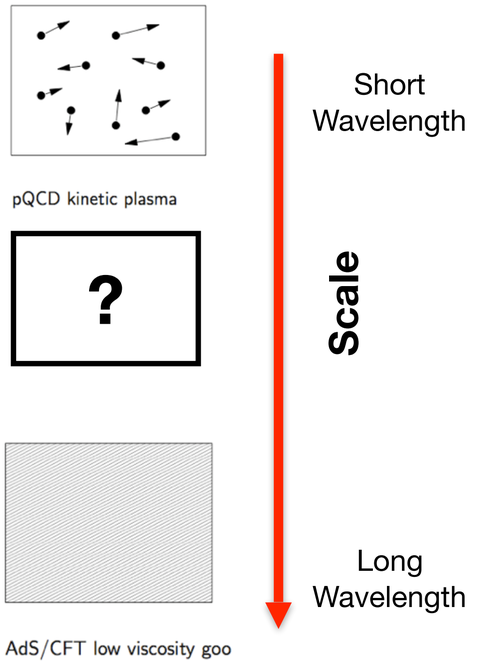
RHIC QGP spends more time near $T_C$

➥ Use **combined RHIC and LHC data** to extract T dependence

# Illustration: Scattering off QGP constituents

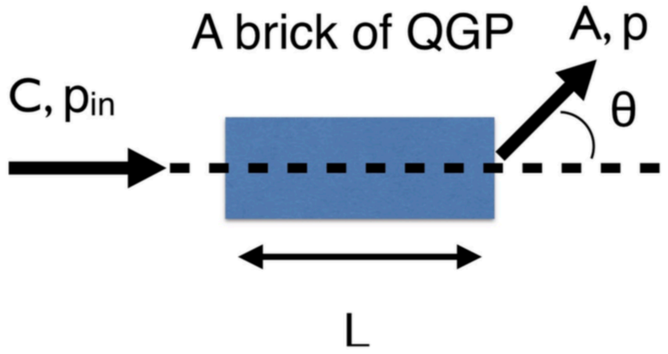


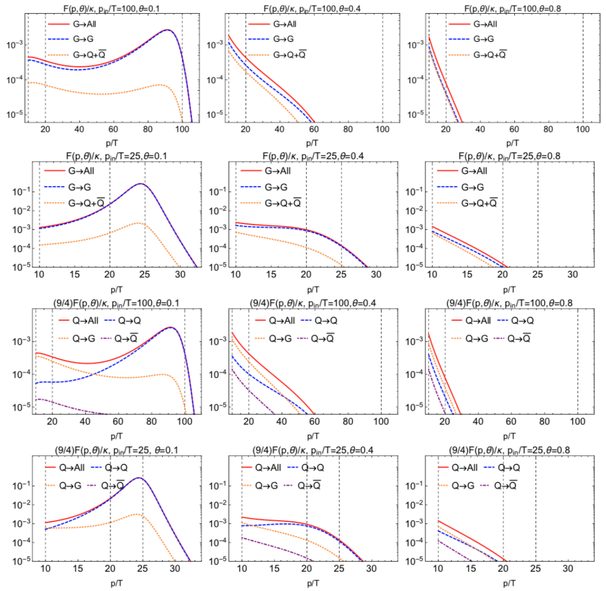
# Illustration: Scattering off QGP constituents




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

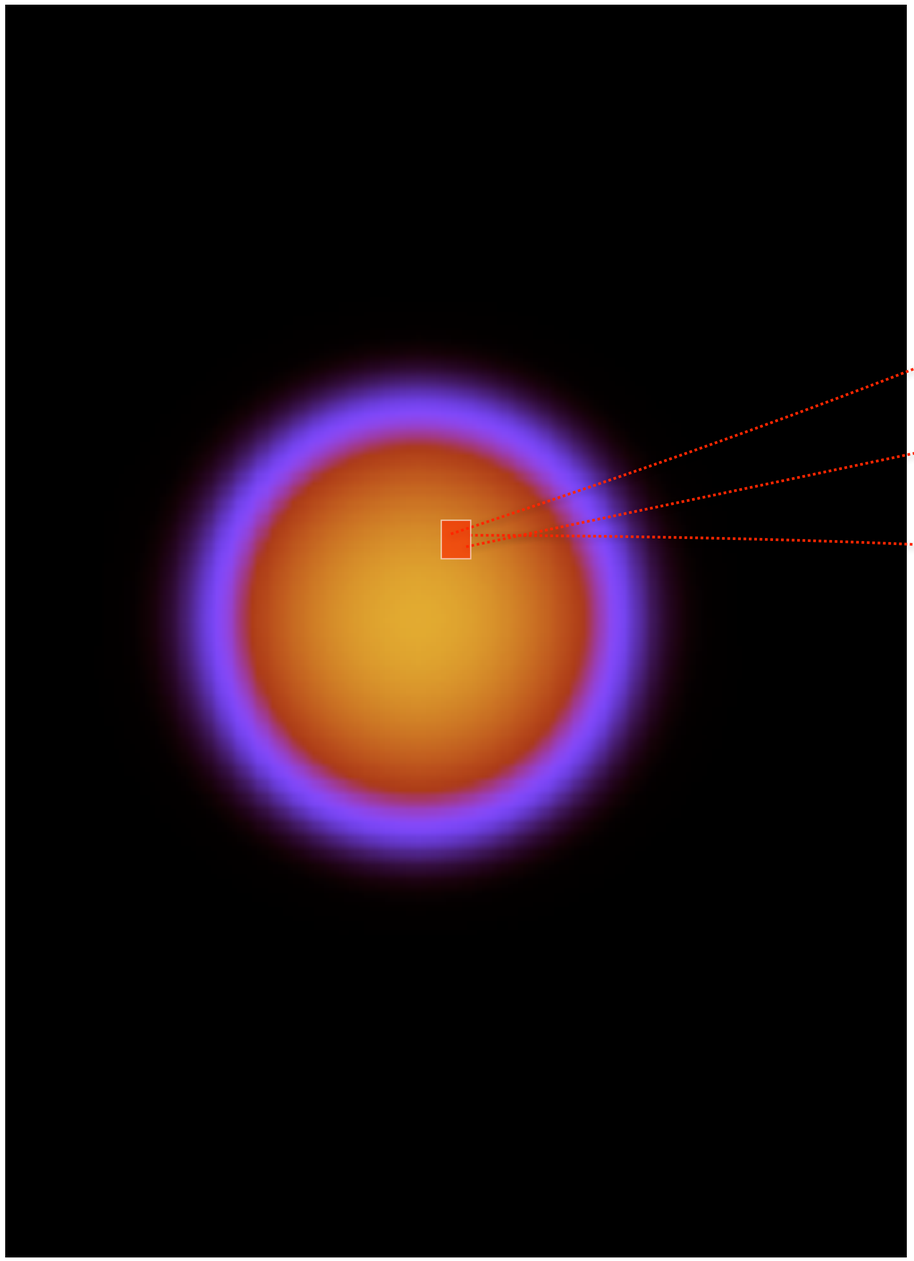
Francesco D'Eramo,[a,b] Krishna Rajagopal,[c] Yi Yin[c]

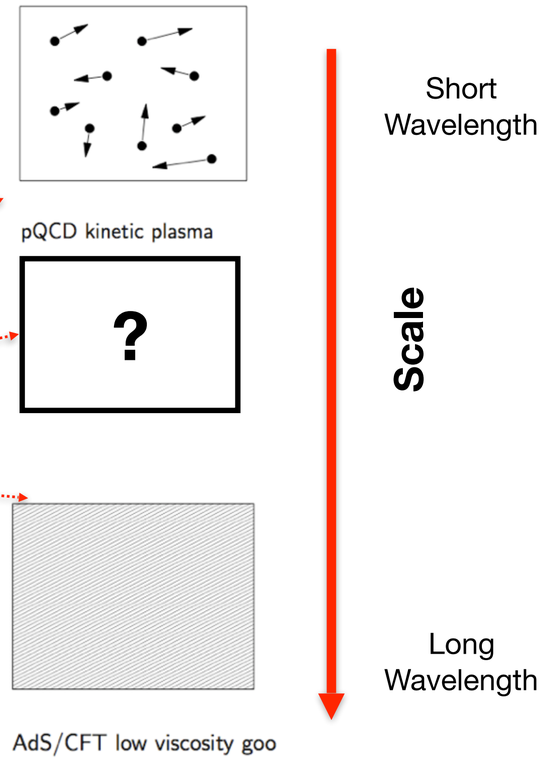


Need joint exp/theory effort over next decade to turn conceptual approach into well controlled observables

# Experimental approach





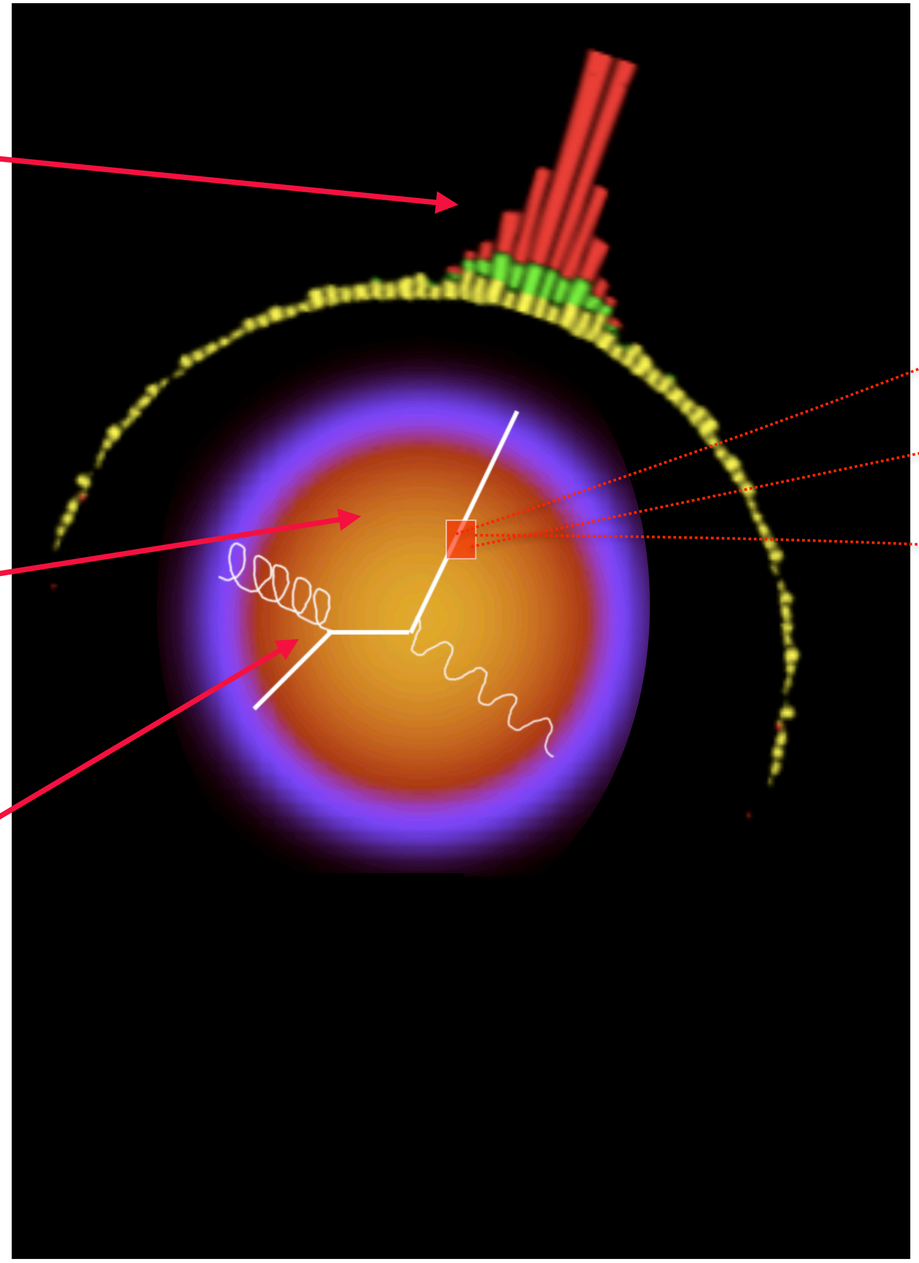

How does long-wavelength physics emerge from underlying gauge theory?

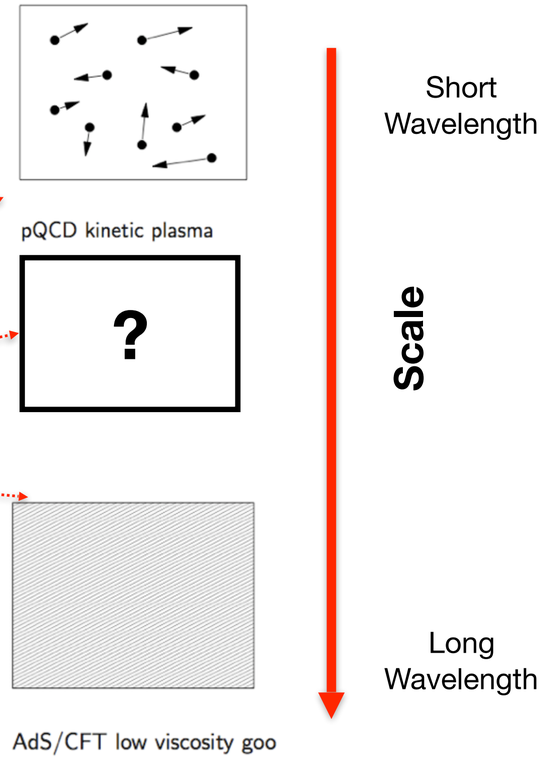
# Experimental approach

**Full** characterization of final state

**Different** QGP initial conditions and evolution at RHIC and LHC

**Same** hard process





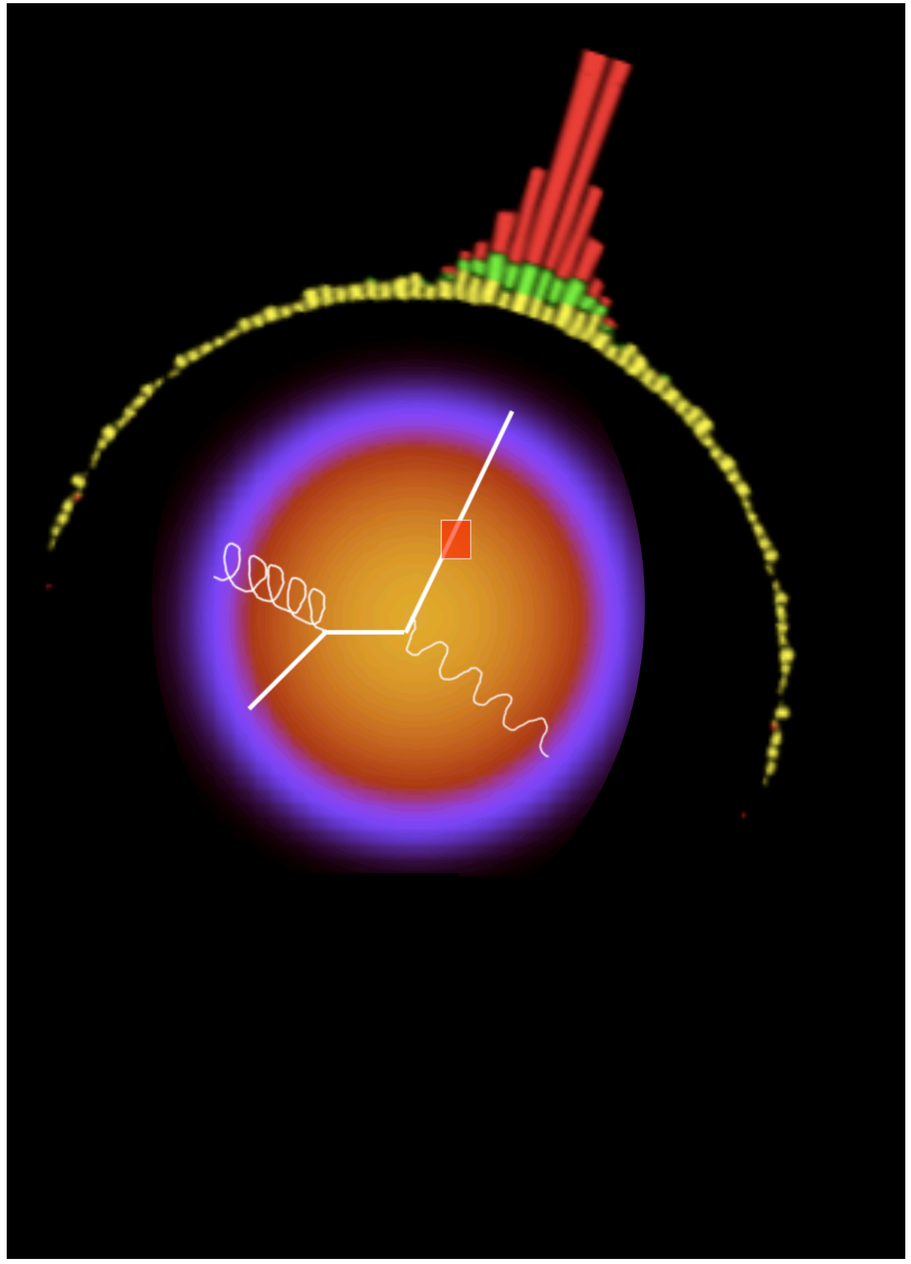

How does long-wavelength physics emerge from underlying gauge theory?

# Experimental approach

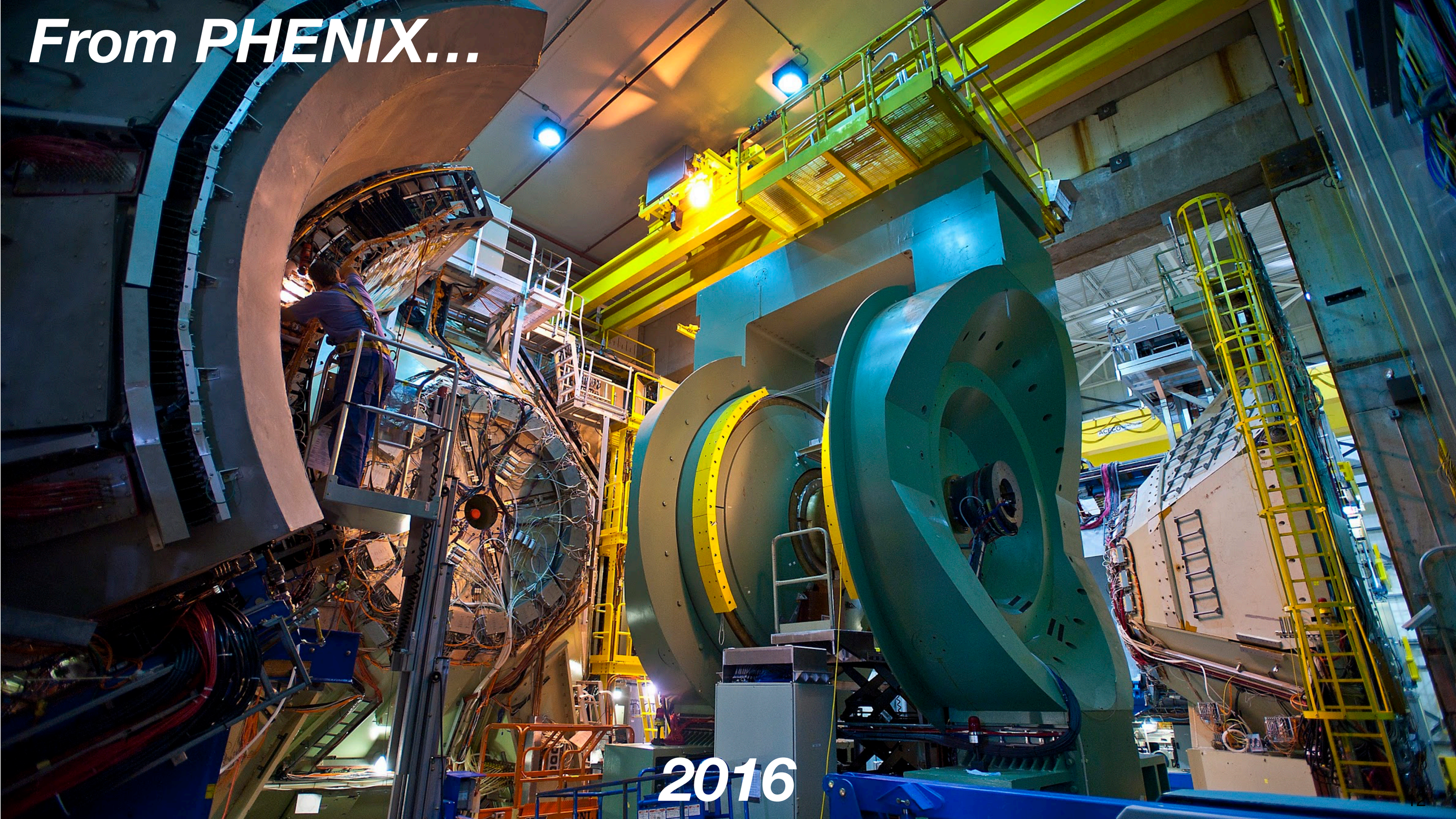
**Full** characterization of final state

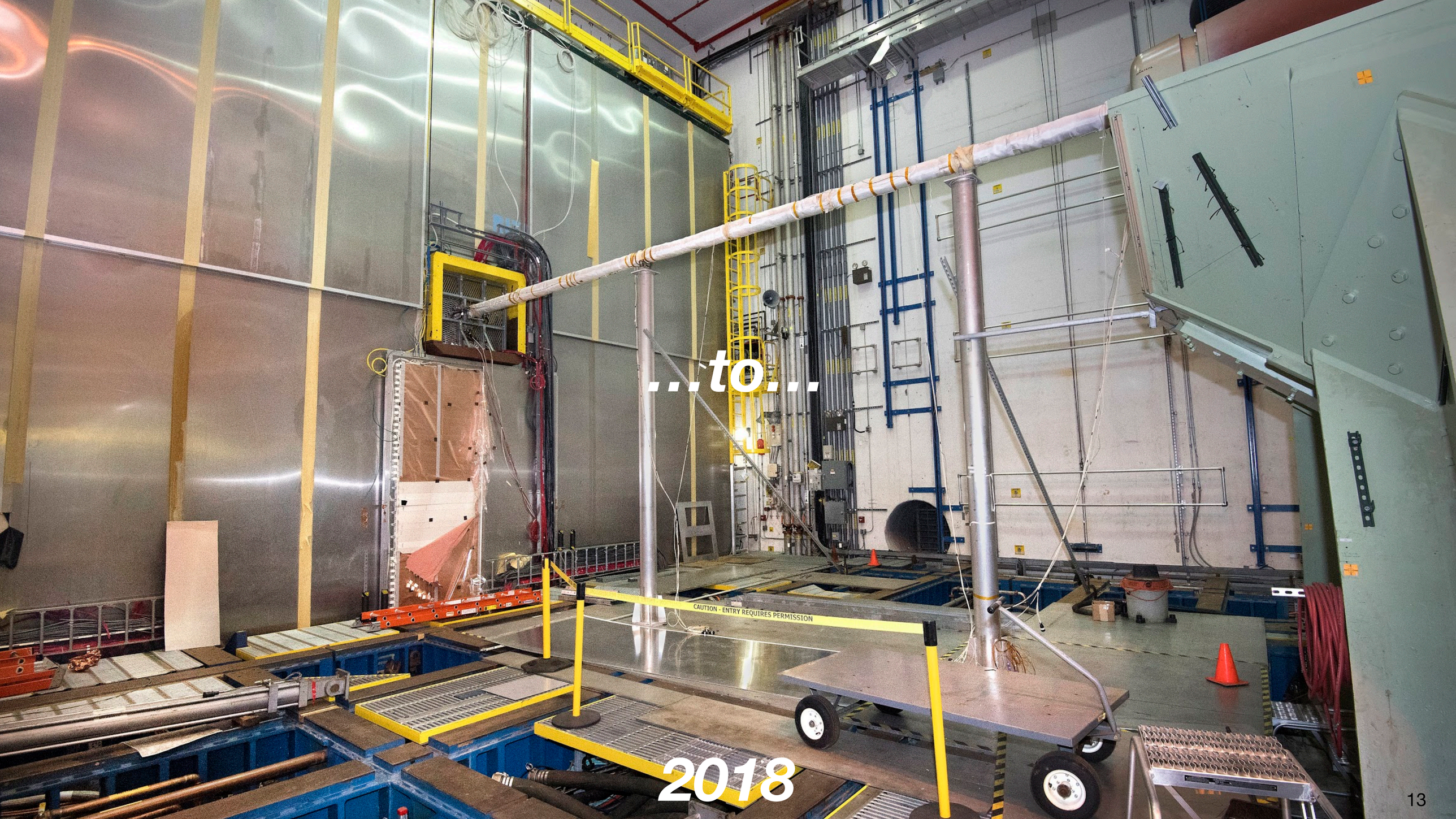
Ability to tag initial state and to fully characterize final state drives sPHENIX detector design

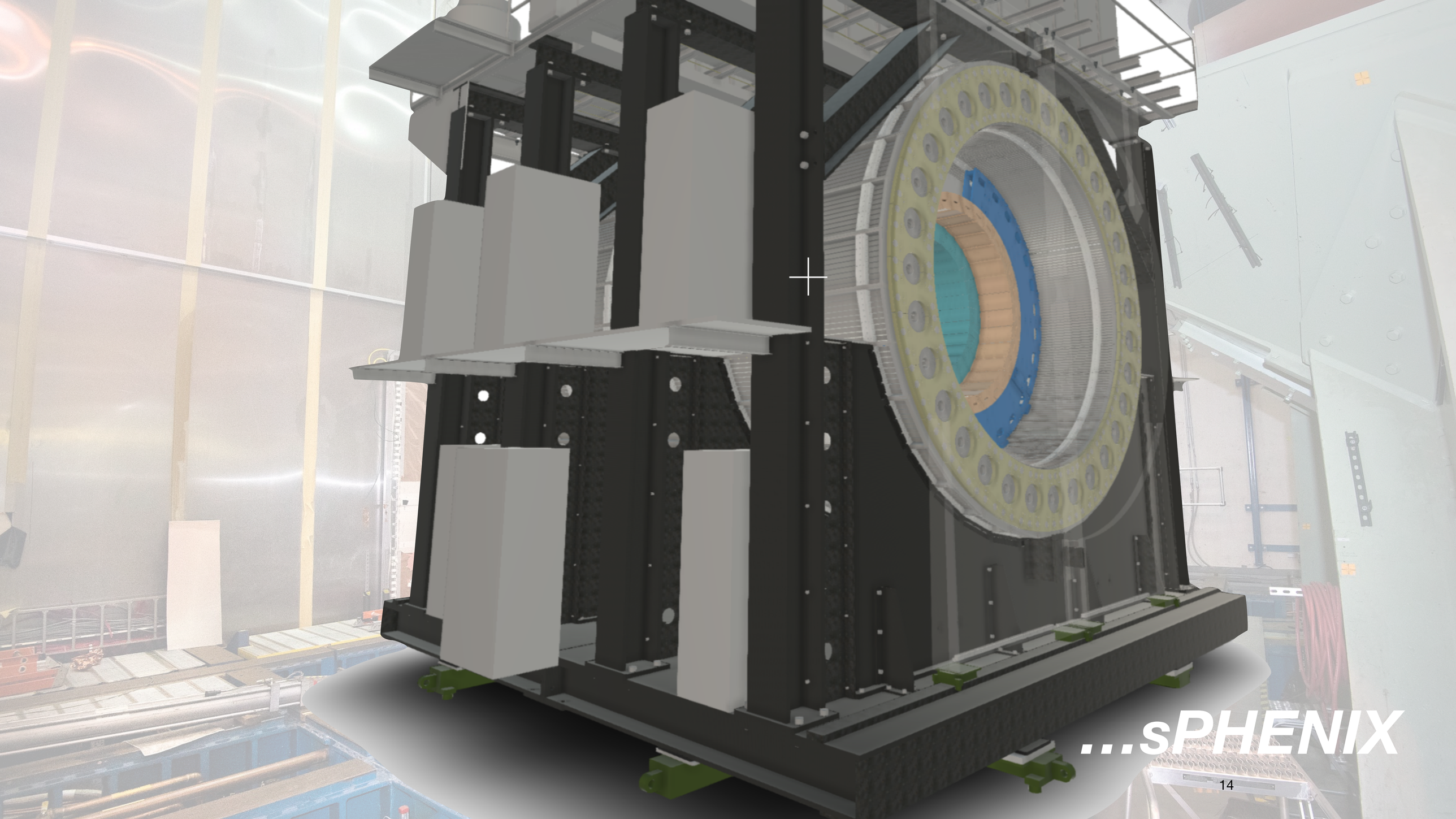
**Same** hard process



# How do we get from *PHENIX* to ***s****PHENIX*?

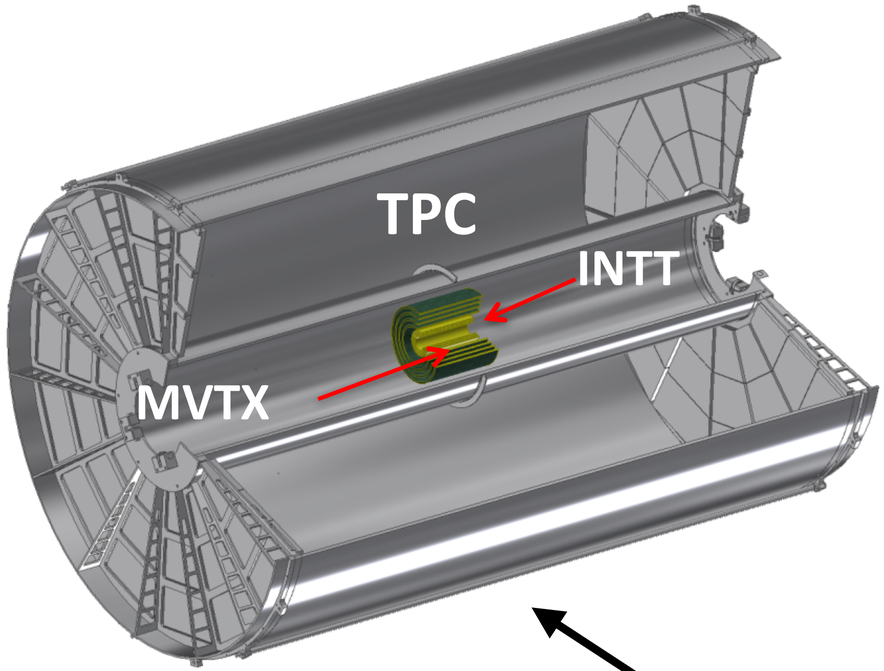

From PHENIX…
2016


...to...
2018
CAUTION - ENTRY REQUIRES PERMISSION


...sPHENIX

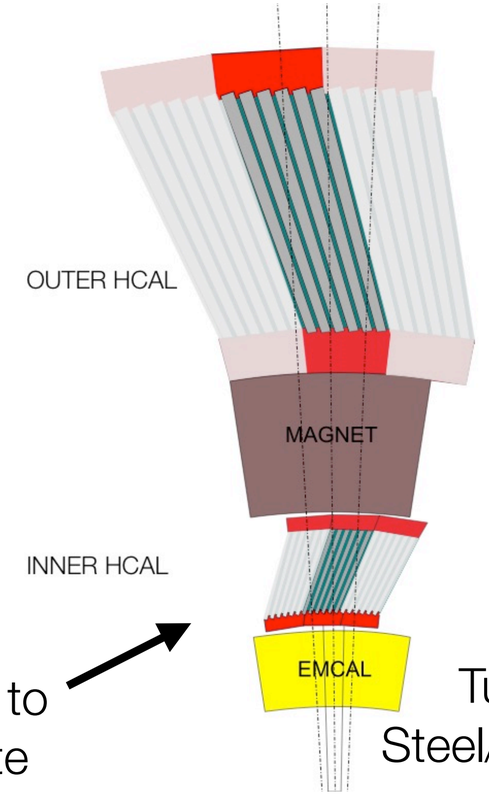
# sPHENIX Subsystems

## Tracker




Continuous readout TPC
Si strip intermediate tracker
3-layer MAPS-based μ vertex

## Calorimeter stack




15kHz readout in Au+Au to
match RHIC collision rate

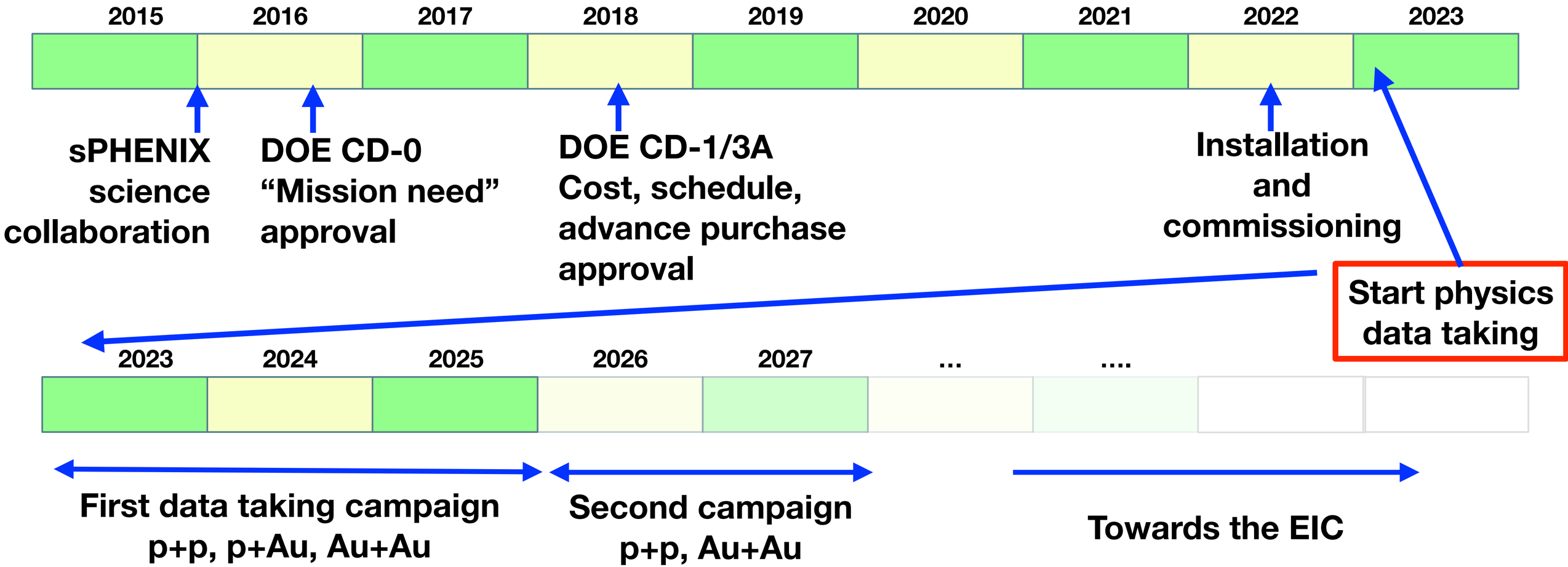
Tungsten/SciFi EMCal
Steel/plastic scintillator HCAL
SiPM readout

**Qualitative** improvement on 20 years of studies at RHIC through higher statistics ( x10+), full calorimetry and higher precision tracking



https://indico.bnl.gov/event/4640/attachments/18495/23200/sphenix-conceptual-design.pdf

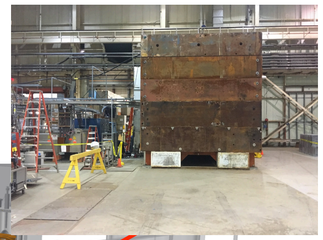
# When will sPHENIX take data?



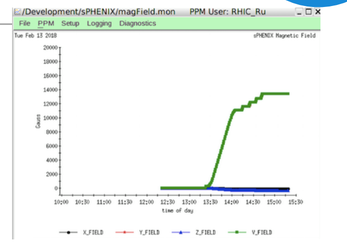

https://indico.bnl.gov/event/4788/attachments/19066/24594/sph-trg-000_06142018.pdf

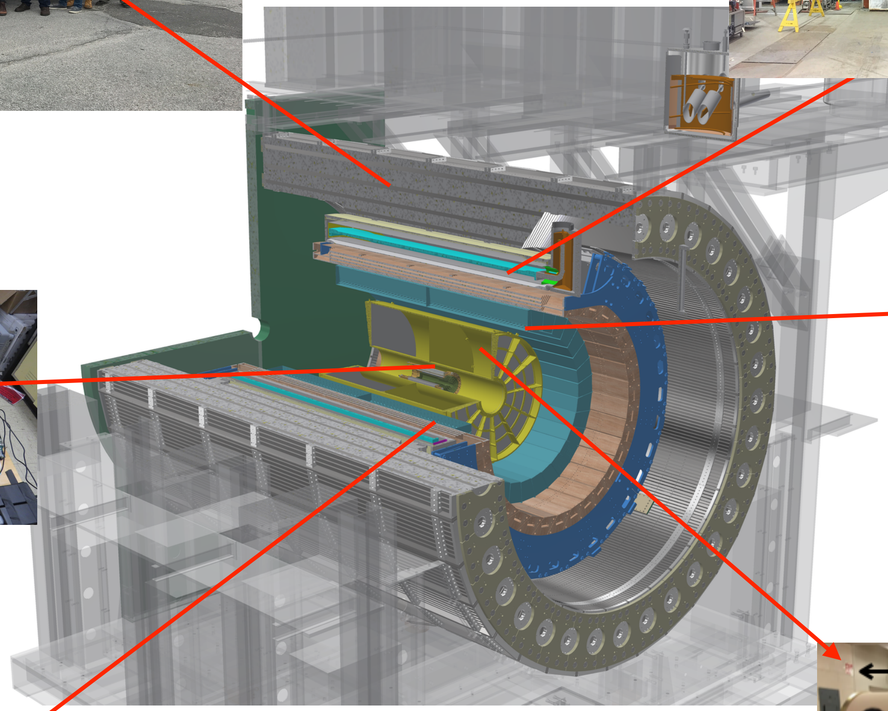
# sPHENIX *today*

Flux return/**oHCAL** absorber
First production sectors
**arrived September 19;**
**now at 10 out of 32;**
**rec'vd HCAL pre-prod tiles**

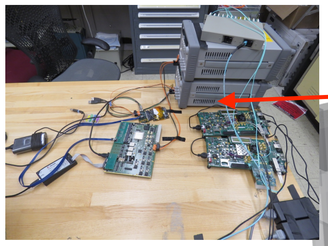


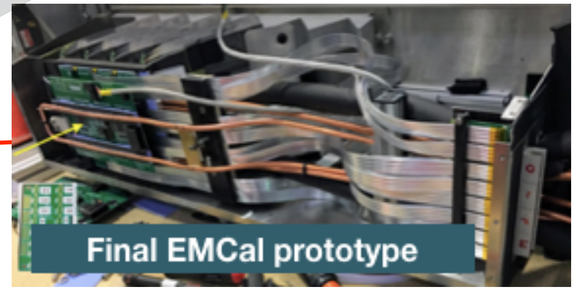
Full field **magnet** test
at 1.4T at BNL on
**2/13/2018**



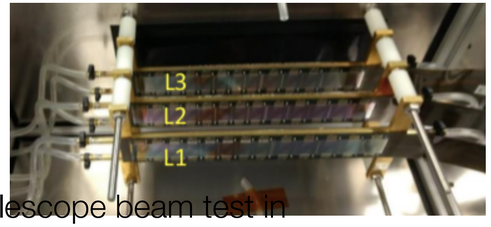



**MVTX** full chain test and beam
test in **Spring 2018**
**Order for staves and readout units submitted**

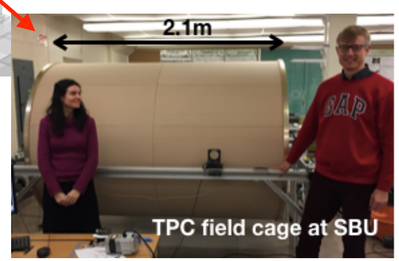





Approval of **EMCAL** materials
purchase received in **August '18**
**"Sector 0" production underway**




**INTT** telescope beam test in
**Spring 2018**
Detector will be delivered by Riken
**Finalized detector layout**
**(4 → 2 layers)**

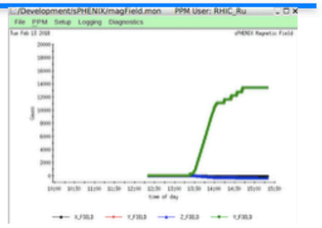


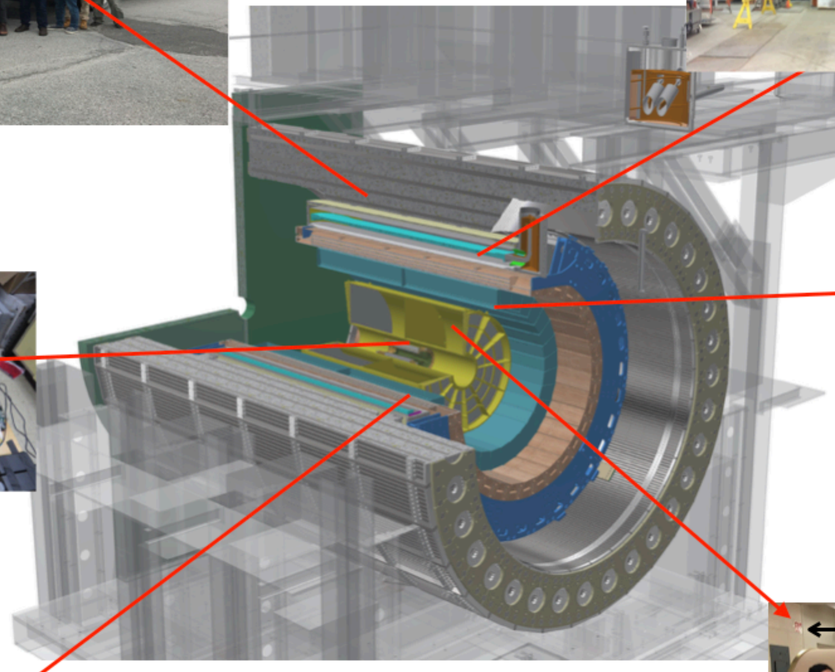

Beam test of **TPC** prototype in
**June 2018**
Ready for producing of full-size
field cage "prototype"
**Machining of assembly frame underway**
**Pre-production of modified SAMPA chip underway**

# sPHENIX *today*

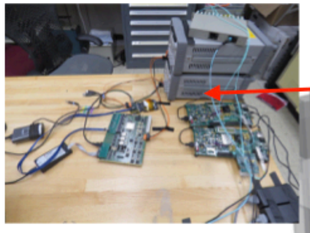
Flux return/**oHCAL** absorber
First production sectors
**arrived two weeks ago**

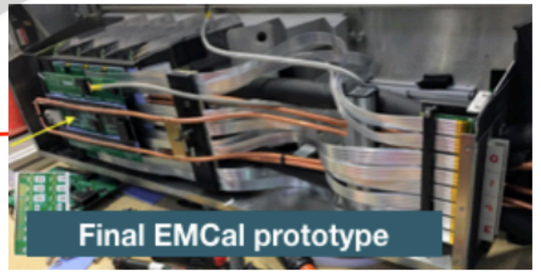
Full field **magnet** test
at 1.4T at BNL on
**2/13/2018**



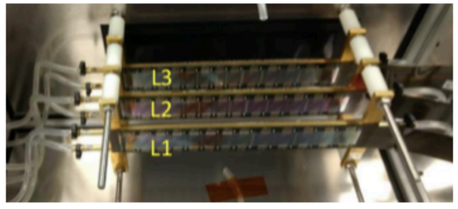


**MVTX** full chain test and beam test in **Spring 2018**
Expecting stave procurement in **late 2018**

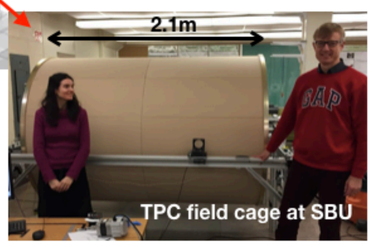





Approval of **EMCAL** materials purchase received in **August '18**
**"Sector 0" production starting 2018**




**INTT** telescope beam test in **Spring 2018**
Detector will be delivered by Riken

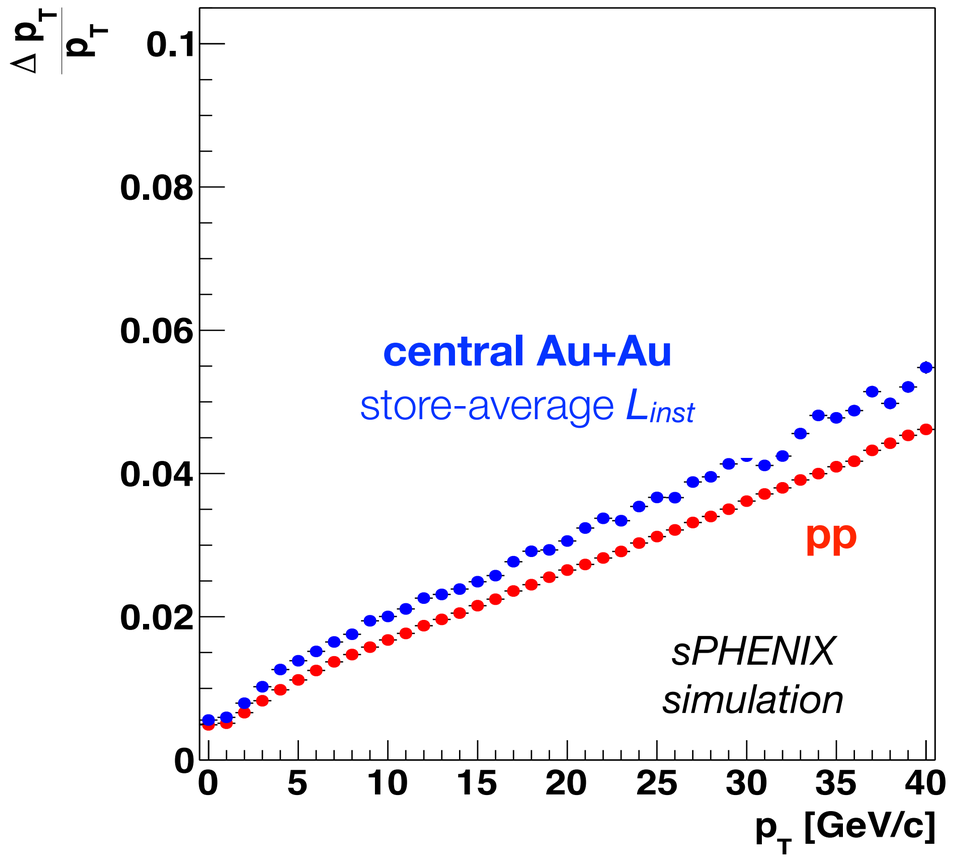



Beam test of **TPC** prototype in **June 2018**
Ready for producing of full-size field cage "prototype"

# What are key sPHENIX performance parameters?

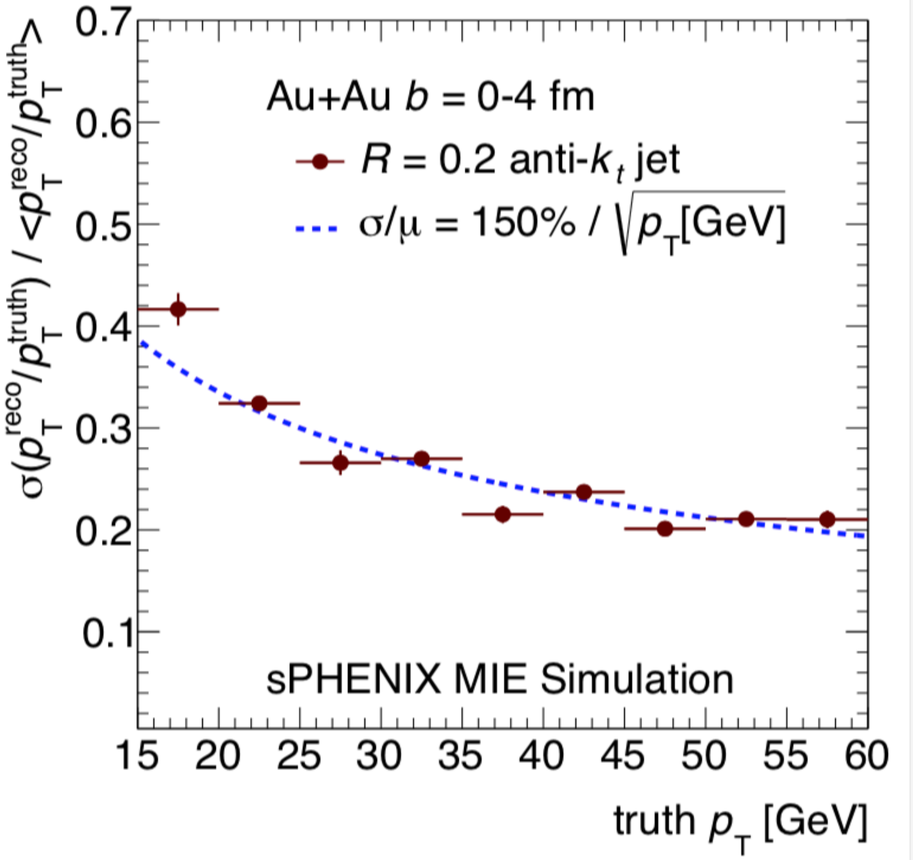
# Performance simulation: Track and jet resolution

**Track pT resolution (central Au+Au)**




High momentum resolution
Tracking efficiency > 90% in high pileup Au+Au environment

**Single jet resolution (central Au+Au)**

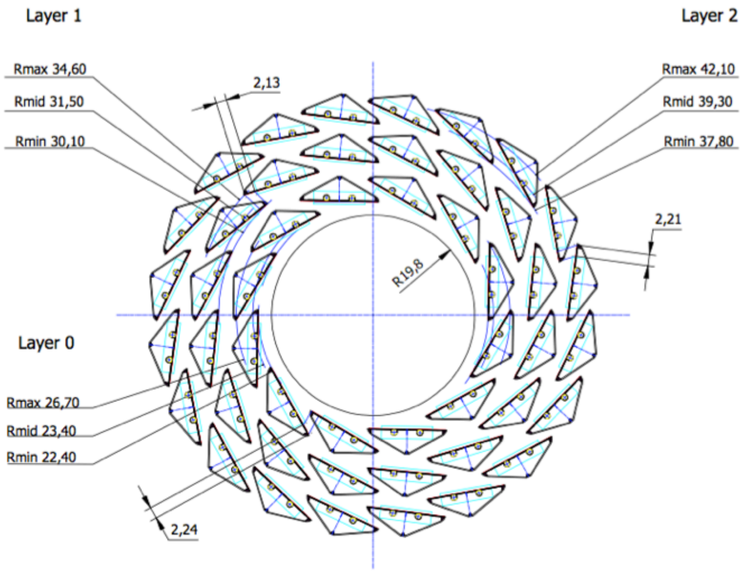



Calorimeter-related performance studied using GEANT simulations verified with **test beam data**

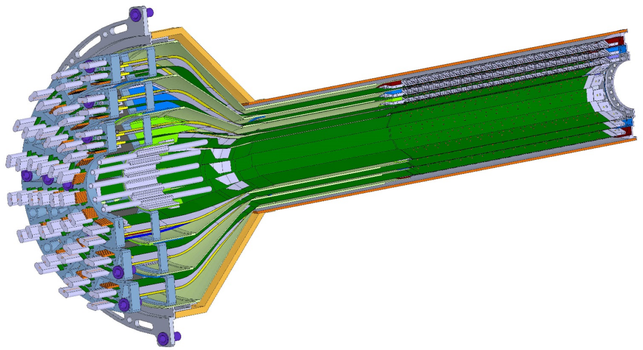
arXiv:1704.01461

# Microvertex tracker performance

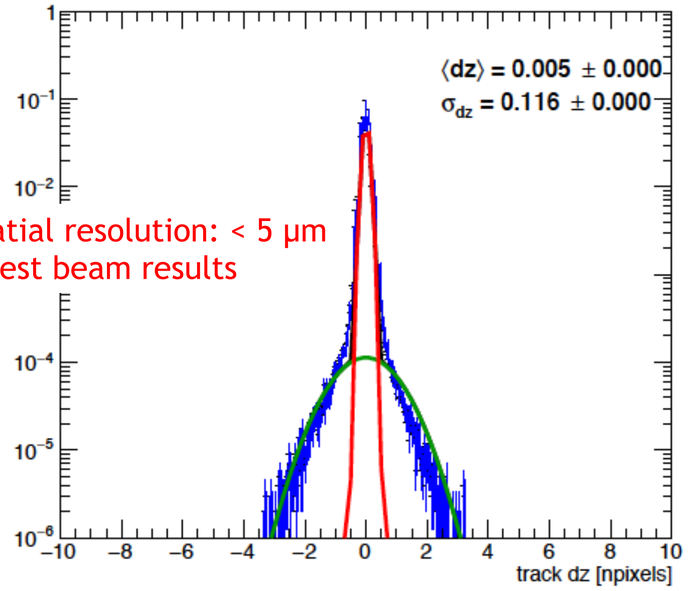
**Stave layout beam view**




MVTX based on copy of ALICE Inner Barrel staves



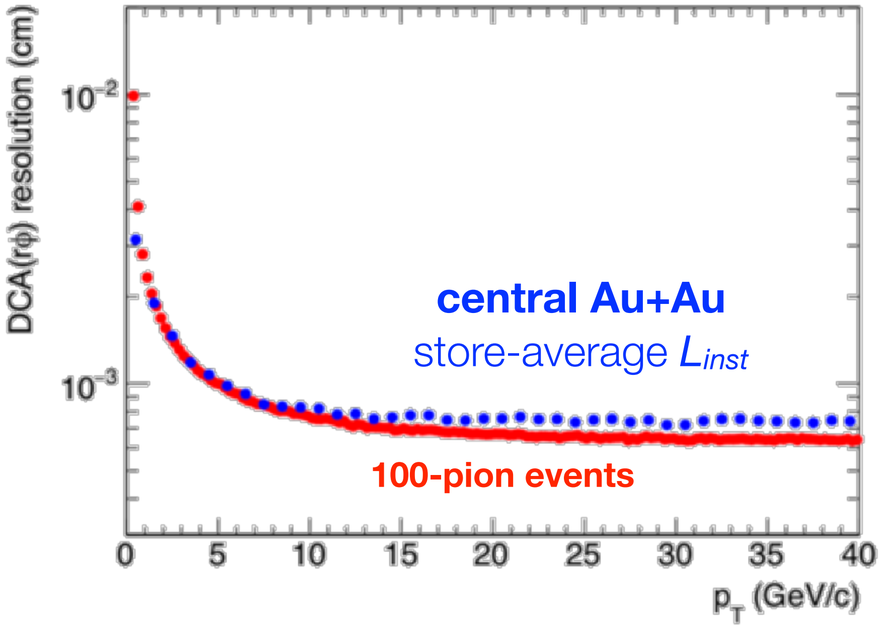
**MVTX spatial resolution**




Hit spatial resolution: < 5 μm
FNAL test beam results

Spatial resolution verified in full chain **test beam** at FNAL

**MVTX DCA resolution**



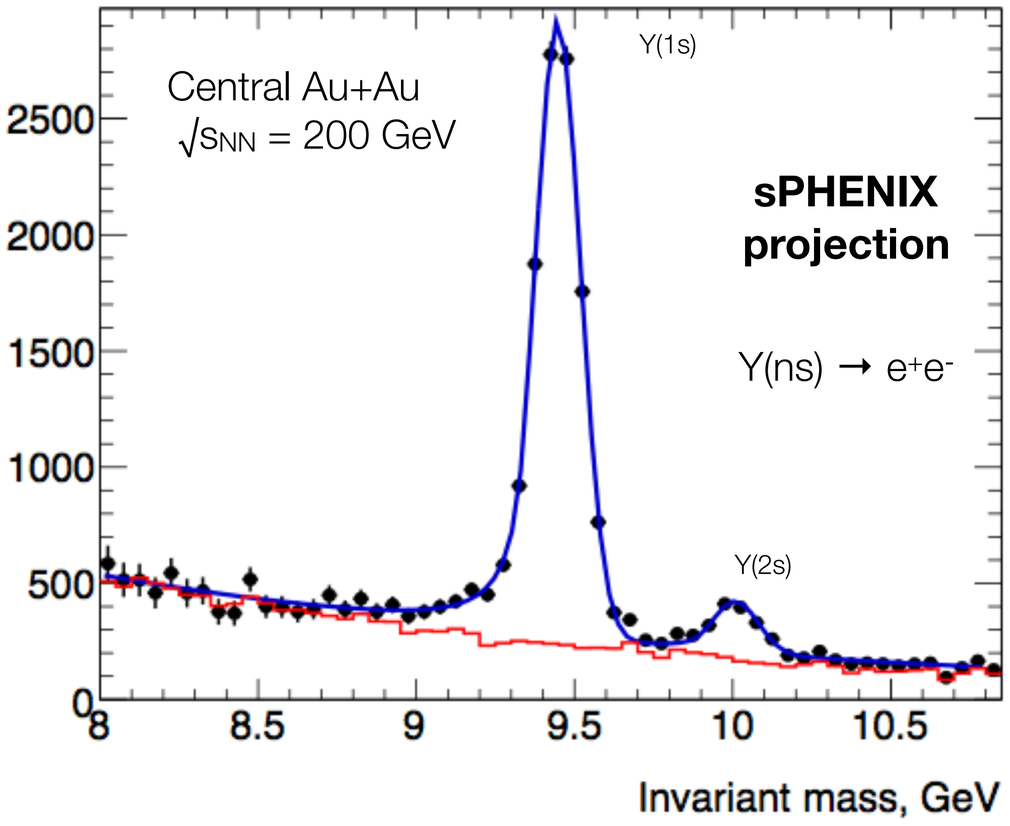

b-jet tagging and open HF hadrons through secondary vertexing

https://indico.bnl.gov/event/4072/attachments/11335/13816/sPH-HF-2018-001-final.pdf

# What are some key sPHENIX measurements?

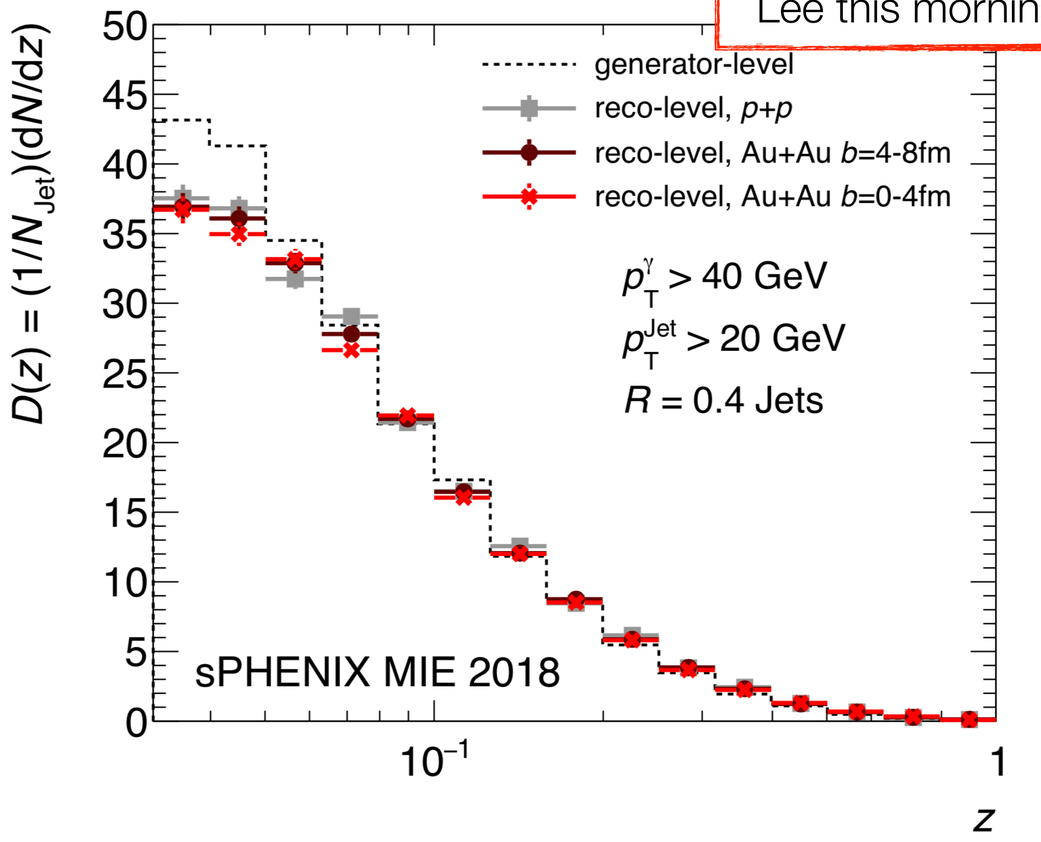
# Examples: Upsilons and γ + Jet

Talk by Songkyo Lee this morning




High resolution Y spectroscopy

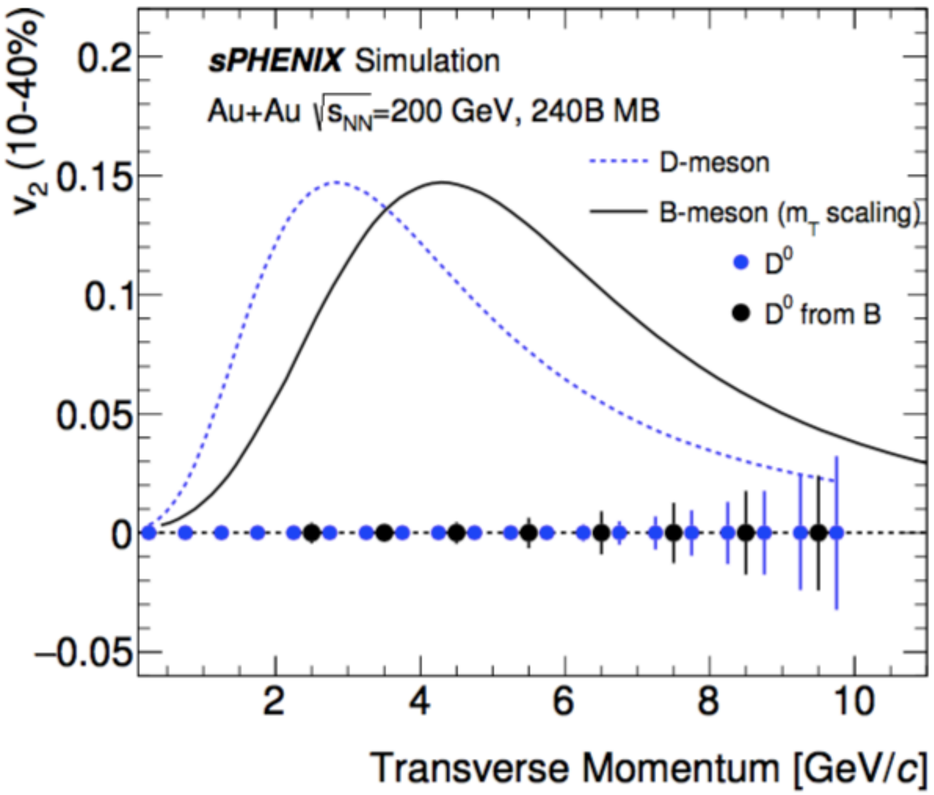
Sequential suppression of Y(nS) states




photon-jet Fragmentation Functions

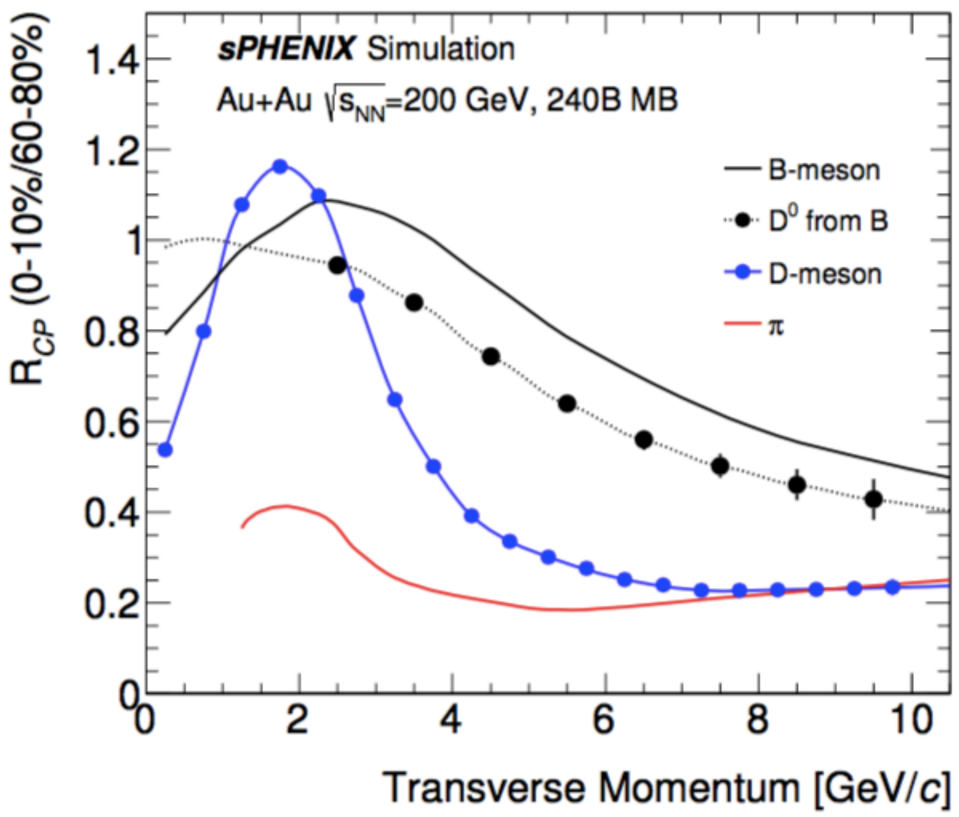
Modification of parton shower in QGP

# MVTX enables world-class HF science program




Prompt and secondary $D^0$ flow

c and b quark thermalization in medium




Open heavy flavor suppression

Flavor dependence of energy loss

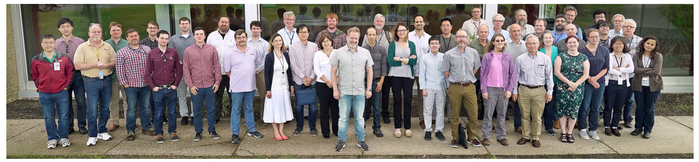
https://indico.bnl.gov/event/4072/attachments/11335/13816/sPH-HF-2018-001-final.pdf

# sPHENIX collaboration

# sPHENIX collaboration: 70 institutions and counting

Augustana University
Banaras Hindu University
Baruch College, CUNY
Brookhaven National Laboratory
China Institute for Atomic Energy
CEA Saclay
Central China Normal University
Chonbuk National University
Columbia University
Eötvös University
Florida State University
Fudan University
Georgia State University
Howard University
Hungarian sPHENIX Consortium
Insititut de physique nucléaire d'Orsay
Institute for High Energy Physics, Protvino
Institute of Nuclear Research, Russian Academy of Sciences, Moscow
Institute of Physics, University of Tsukuba
Institute of Modern Physics, China
Iowa State University
Japan Atomic Energy Agency
Joint Czech Group
Korea University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Lehigh University
Los Alamos National Laboratory
Massachusetts Institute of Technology
Muhlenberg College
Nara Women's University
National Research Centre "Kurchatov Institute"
National Research Nuclear University "MEPhI"
New Mexico State University
Oak Ridge National Laboratory
Ohio University
Peking University
Petersburg Nuclear Physics Institute
Purdue University
Rice University
RIKEN
RIKEN BNL Research Center
Rikkyo University
Rutgers University
Saint–Petersburg Polytechnic University
Shanghai Institute for Applied Physics
Stony Brook University
Sun Yat Sen University
Temple University
Tokyo Institute of Technology
Tsinghua University
Universidad Técnica Federico Santa María
University of California, Berkeley
University of California, Los Angeles
University of California, Riverside
University of Colorado, Boulder
University of Debrecen
University of Houston
University of Illinois, Urbana-Champaign
University of Jammu
University of Maryland
University of Michigan
University of New Mexico
University of Tennessee, Knoxville
University of Texas, Austin
University of Tokyo
University of Science and Technology, China
Vanderbilt University
Wayne State University
Weizmann Institute
Yale University
Yonsei University

BNL, June '18



Santa Fe, Dec '17

BNL, June '17

GSU (Atlanta), Dec '16


BNL, June '16

Rutgers, Dec'15

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Japan Atomic Energy Agency
Joint Czech Group
Korea University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Lehigh University
Los Alamos National Laboratory
Massachusetts Institute of Technology
Muhlenberg College
Nara Women's University
National Research Centre "Kurchatov Institute"
National Research Nuclear University "MEPhI"
New Mexico State University
Oak Ridge National Laboratory
Ohio University
Peking University
Petersburg Nuclear Physics Institute
Purdue University
Rice University
RIKEN
RIKEN BNL Research Center
Rikkyo University
Rutgers University
Saint–Petersburg Polytechnic University
Shanghai Institute for Applied Physics
Stony Brook University
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University of Colorado, Boulder
University of Debrecen
University of Houston
University of Illinois, Urbana-Champaign
University of Jammu
University of Maryland
University of Michigan
University of New Mexico
University of Tennessee, Knoxville
University of Texas, Austin
University of Tokyo
University of Science and Technology, China
Vanderbilt University
Wayne State University
Weizmann Institute
Yale University
Yonsei University

2016 2017 2018

# Onto 2019

- Construction will reach peak activity by this summer
- In parallel, next iteration of software development/physics studies
  - Preparing for “mock data challenges”
  - Jets and open HF will be the focus of these challenges
  - Opportunity for a massive JETSCAPE simulation and analysis exercise
  - Requires some work (STAT?)

Hi Gunther,

in principle we are able to read the Jetscape hepmc3 output. That code lives on a separate branch which is quite old (but if needed can be refreshed). We have installed jetscape (also needs to be refreshed but that's no problem) and are able to run their examples. Basically it needs someone who wants to run this.

The problem we face is that so far hepmc2 and hepmc3 mutually exclusive, you can't have them in parallel (identically named library and includes - big mistake). Hepmc3 is under heavy development and no clear standards which makes it a bit of a moving target when considering to upgrade all our writers from hepmc2 to hepmc3 (we also need to move to root6 beforehand which I am working on). The faster way if immediately needed would be to invest the time to downgrade jetscape to hepmc2.

So - yes we have been able to read jetscape output and with a small effort we can recover that capability. But really integrating it is a longer effort.

Chris

# Outlook

- sPHENIX will probe microscopic structure of strongly coupled QGP
- New state of the art detector at RHIC, complementing capabilities of LHC
  - Upsilon spectroscopy
  - Jet suppression and substructure
  - Open heavy flavor over full kinematic range
- Growing international collaboration
- **Approaching peak construction activity (2019-2021)**
- Upcoming simulation studies promising use-case for JETSCAPE
- Exciting physics program at RHIC starting in 2023

# Backup

# Multi-year run plan for sPHENIX

| Year | Species | Energy [GeV] | Phys. Wks | Rec. Lum. | Samp. Lum. | Samp. Lum. All-Z |
|---|---|---|---|---|---|---|
| Year-1 | Au+Au | 200 | 16.0 | 7 $nb^{-1}$ | 8.7 $nb^{-1}$ | 34 $nb^{-1}$ |
| Year-2 | p+p | 200 | 11.5 | — | 48 $pb^{-1}$ | 267 $pb^{-1}$ |
| Year-2 | p+Au | 200 | 11.5 | — | 0.33 $pb^{-1}$ | 1.46 $pb^{-1}$ |
| Year-3 | Au+Au | 200 | 23.5 | 14 $nb^{-1}$ | 26 $nb^{-1}$ | 88 $nb^{-1}$ |
| Year-4 | p+p | 200 | 23.5 | — | 149 $pb^{-1}$ | 783 $pb^{-1}$ |
| Year-5 | Au+Au | 200 | 23.5 | 14 $nb^{-1}$ | 48 $nb^{-1}$ | 92 $nb^{-1}$ |

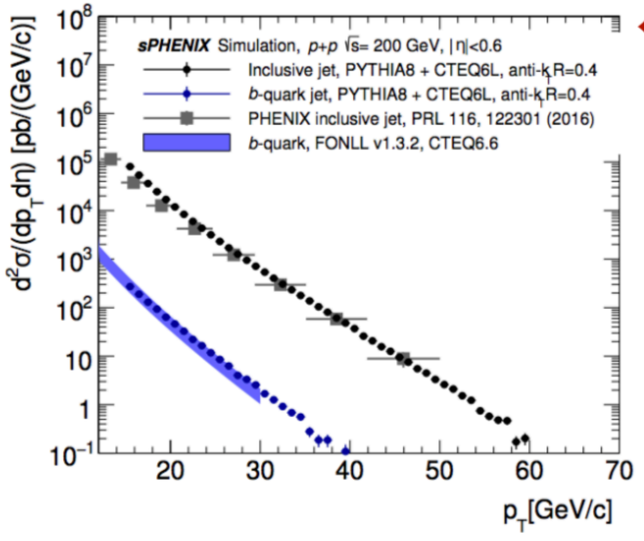
- Consistent with DOE CD-0 "mission need" document
- Incorporates BNL C-AD guidance on luminosity evolution
- Incorporates commissioning time in first year

**Minimum bias Au+Au at 15 kHz for |z| < 10 cm:**

**47 billion** (Year-1) + **96 billion** (Year-2) + **96 billion** (Year-3) = Total **239 billion events**

For topics with Level-1 selective trigger (e.g. high $p_T$ photons), one can sample within |z| < 10 cm a total of 550 billion events.

# b-jet tagging




**⇐ Need good efficiency & purity!**

- Methods developed & evaluated in full detector simulation
- Multiple methods provide complementarity & cross checks
- **Large DCA:**
  - Count tracks in jet above DCA cut threshold
- **Secondary vertex:**
  - Reconstruct secondary vertex within jet