The sPHENIX Detector:
Detector Development and Future Opportunities

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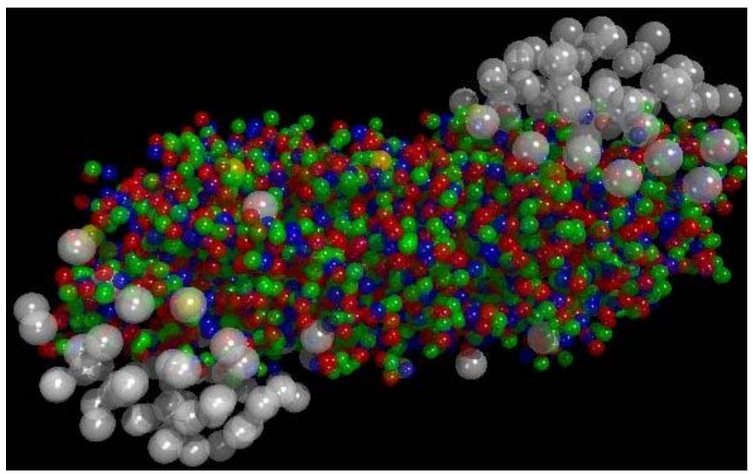
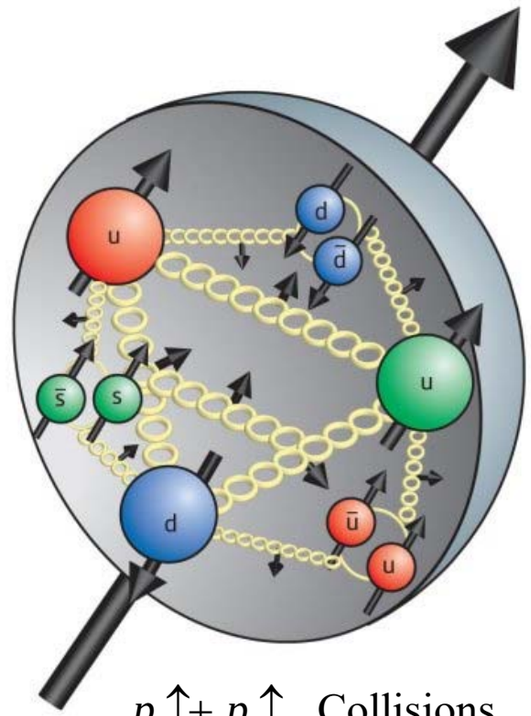
Iowa State University

for the sPHENIX Collaboration

The Big Picture at RHIC (and the EIC…)

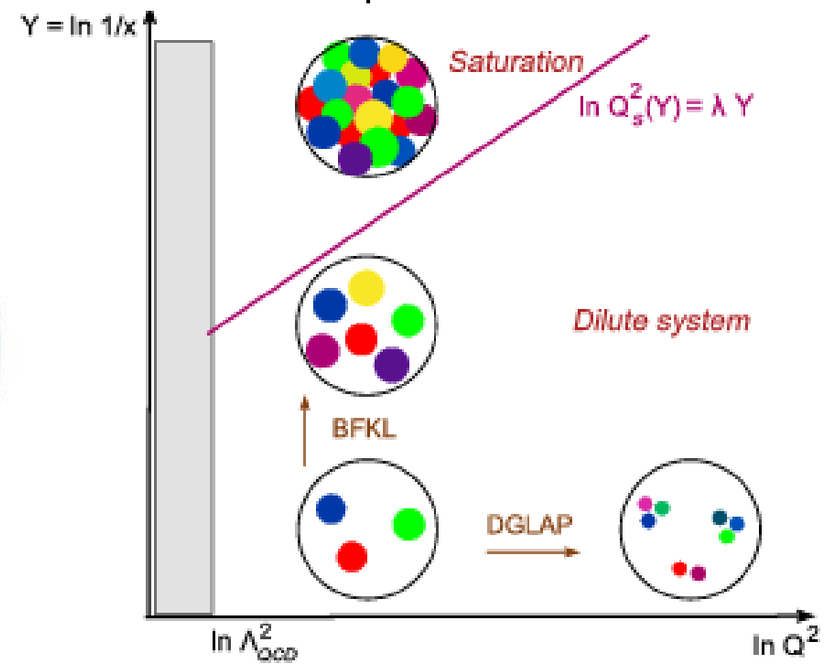
A+A Collisions





$p\uparrow + p\uparrow$ Collisions

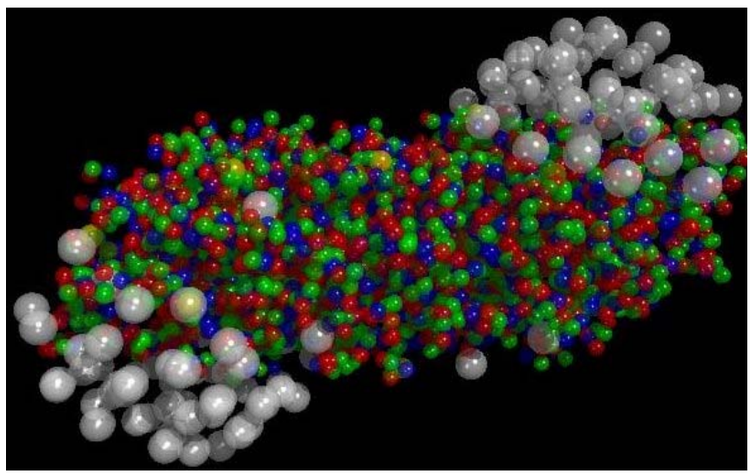
p+A Collisions

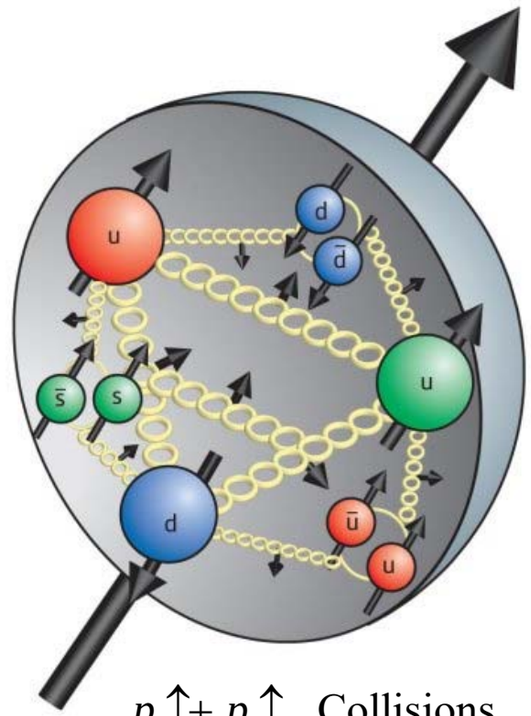


The Big Picture at RHIC (and the EIC…)

How do collective, many-body phenomena arise from first-principles QCD?

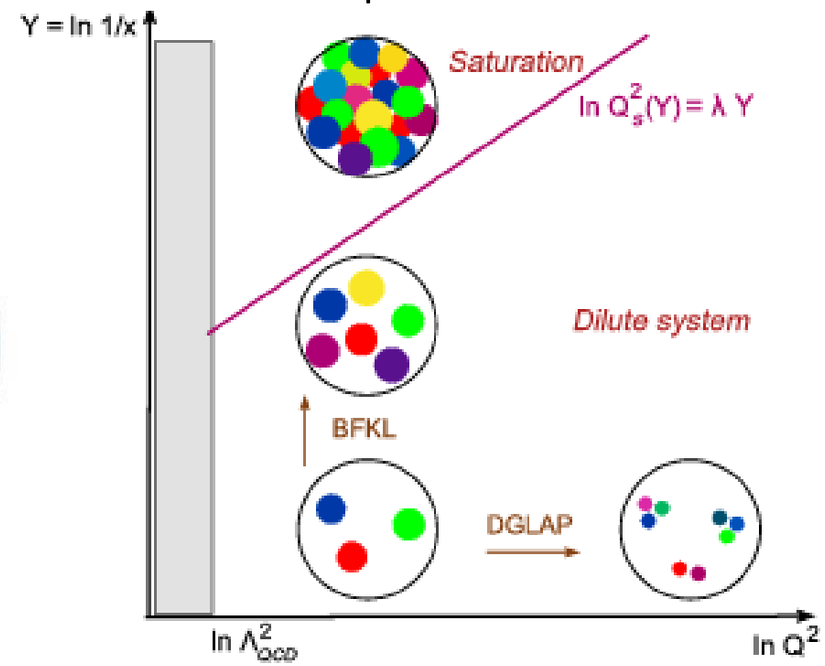
A+A Collisions





$p\uparrow + p\uparrow$ Collisions

p+A Collisions

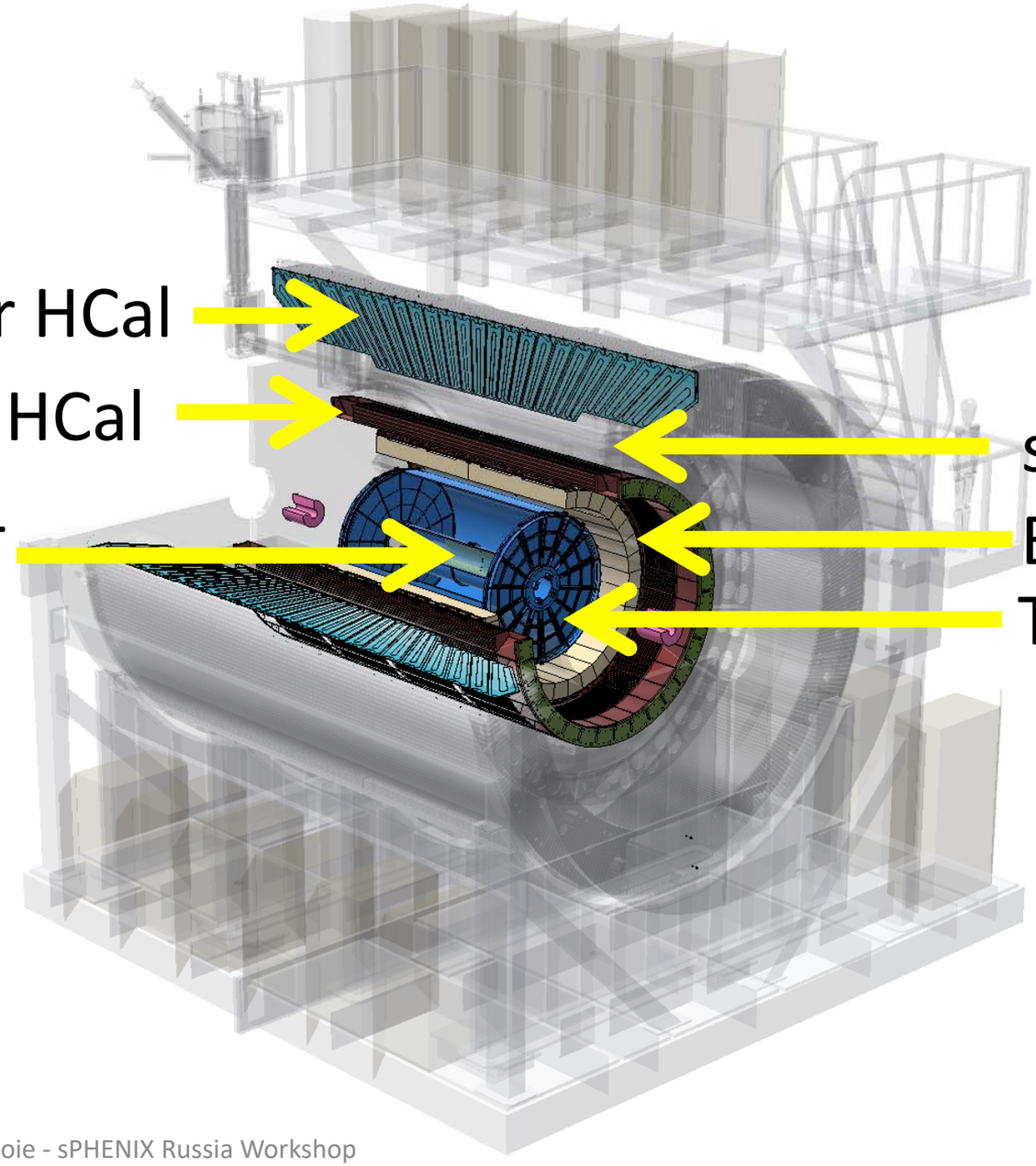


State of the art detector for:

Jets

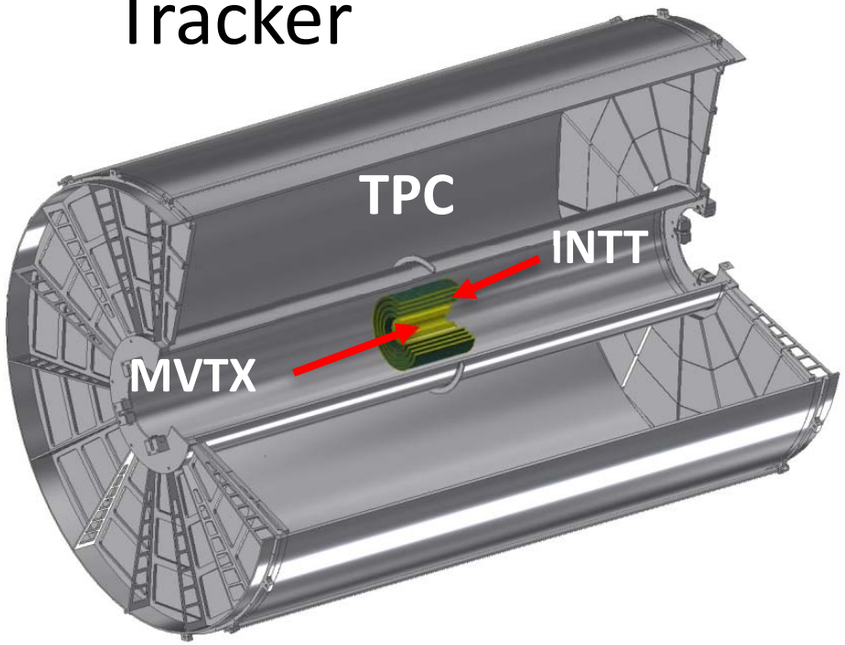
Upsilons

Open heavy flavor

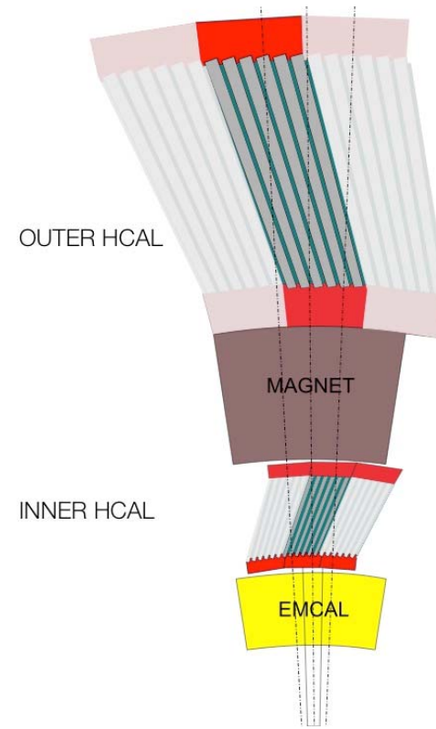


SPHENIX Subdetectors

Tracker



Calorimeter stack



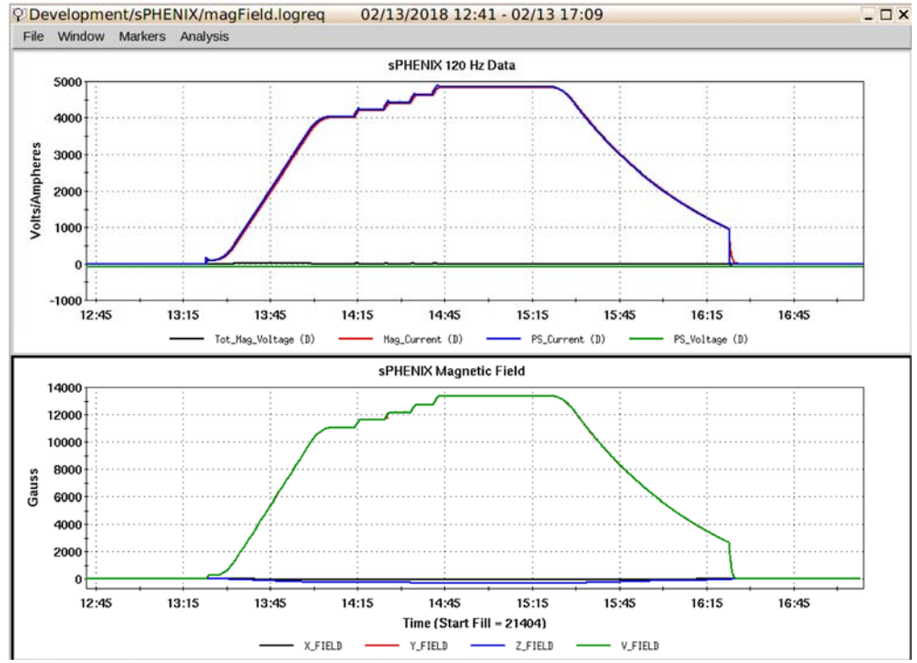
Continuous readout TPC
Si strip intermediate tracker
3-layer MAPS-based μ vertex

Tungsten/SciFi EMCal
Steel/plastic scintillator HCAL
SiPM readout

15kHz readout in Au+Au to match expected collision rate in |z| < 10cm

sPHENIX Solenoid

February 2015 leaving SLAC



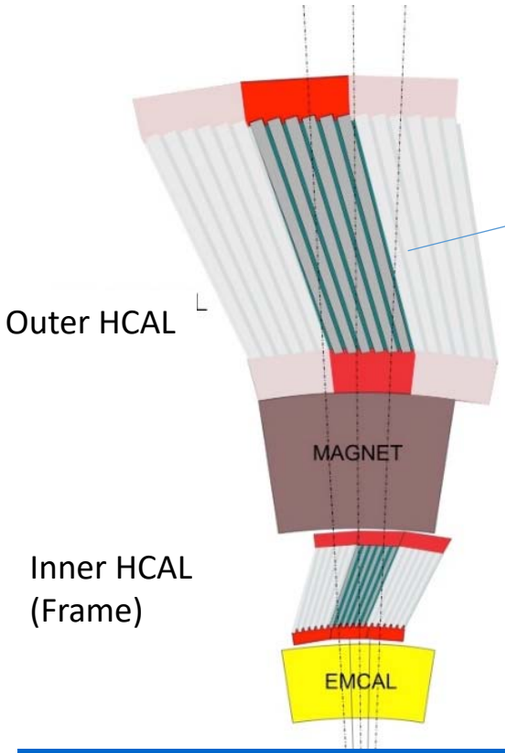
February 2018 full field test

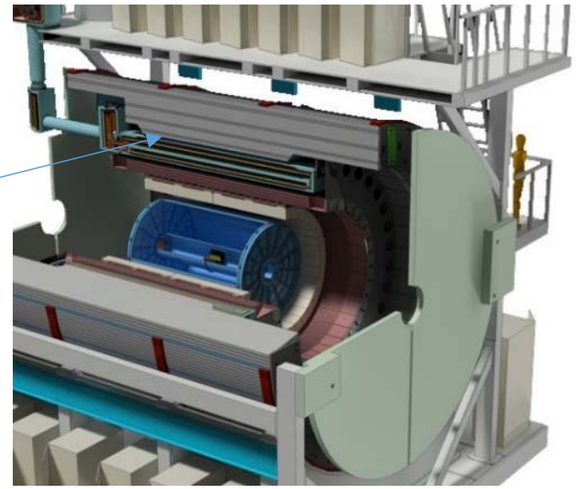
TM and © Laurent de Brunhoff

Former BaBar magnet provides a platform for high resolution tracking

- 1.5 T
- 2.8 m bore
- 3.8 m long

sPHENIX Hadronic Calorimeter





- HCAL steel and scintillating tiles with wavelength shifting fiber
  - **Outer HCal (outside the solenoid)**
  - **$\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$**
  - **1,536 readout channels**
- SiPM Readout

- Outer HCAL $\approx 3.5\lambda_I$
- Magnet $\approx 1.4X_0$
- Frame $\approx 0.25\lambda_I$
- EMCAL $\approx 18X_0 \approx 0.7\lambda_I$

HCAL performance requirements driven by jet physics in HI collisions

- Uniform fiducial acceptance $-1<\eta<1$ and $0<\phi<2\pi$
  - Extended coverage $-1.1<\eta<1.1$ to account for jet cone
- Absorb >95% of energy from a 30 GeV jet
  - Requires ~4.9 nuclear interaction length depth
- Hadronic energy resolution of *combined* calorimetry:
  - UPP: $\frac{\sigma}{E} < \frac{150\%}{\sqrt{E}}$
  - Gaussian response (limited tails)
- HCAL created by instrumenting barrel magnetic flux return

HCAL Details

Outer HCAL Sectors Assembly:

DELIVERABLE:
32 assembled and tested sectors - 1.9m inner radius, 2.6m outer radius

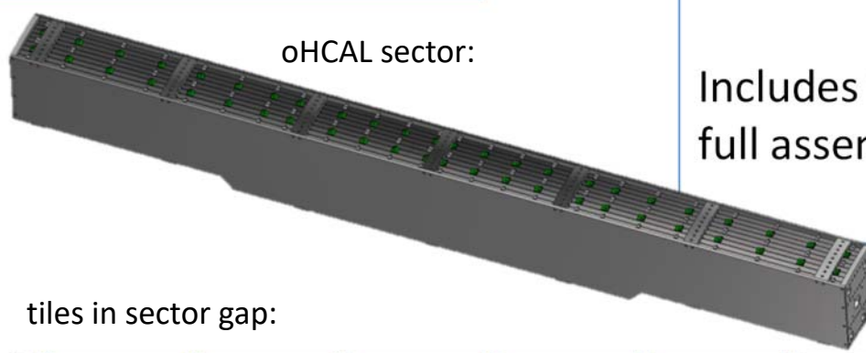
10 rows of 7mm scint. tiles (24 tiles per row), 12° tilt angle

Tapered 1020 steel plates ~26.1mm - ~42.4mm

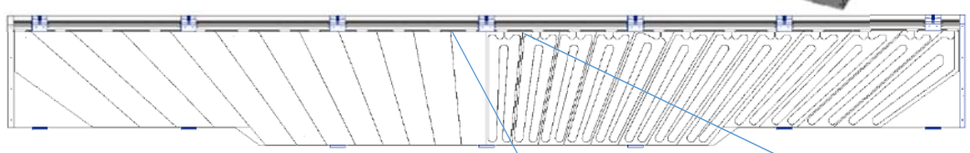
Completed sector is 6.3m long, 13.5 tons

Assembly Detail:
5 scintillators/tower
48 towers per sector
32 sectors;
1536 channels (7680 SiPMs)

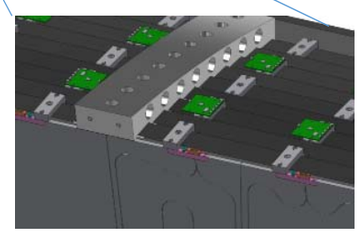
oHCAL sector:



tiles in sector gap:



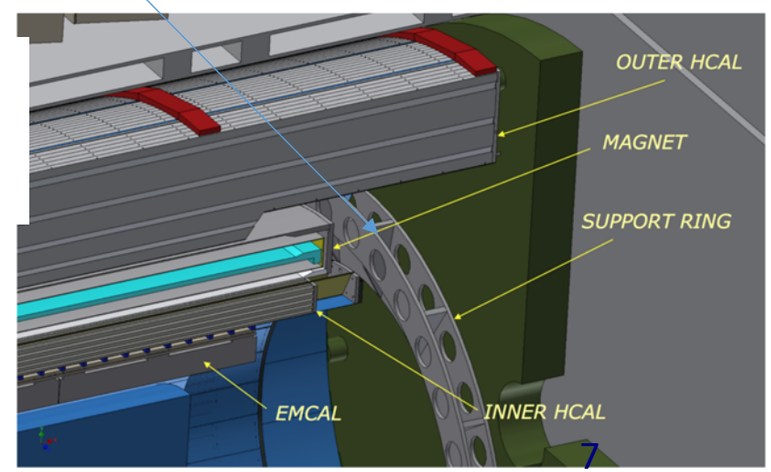
electronics/cable routing:



"Inner HCAL" Frame and Supports

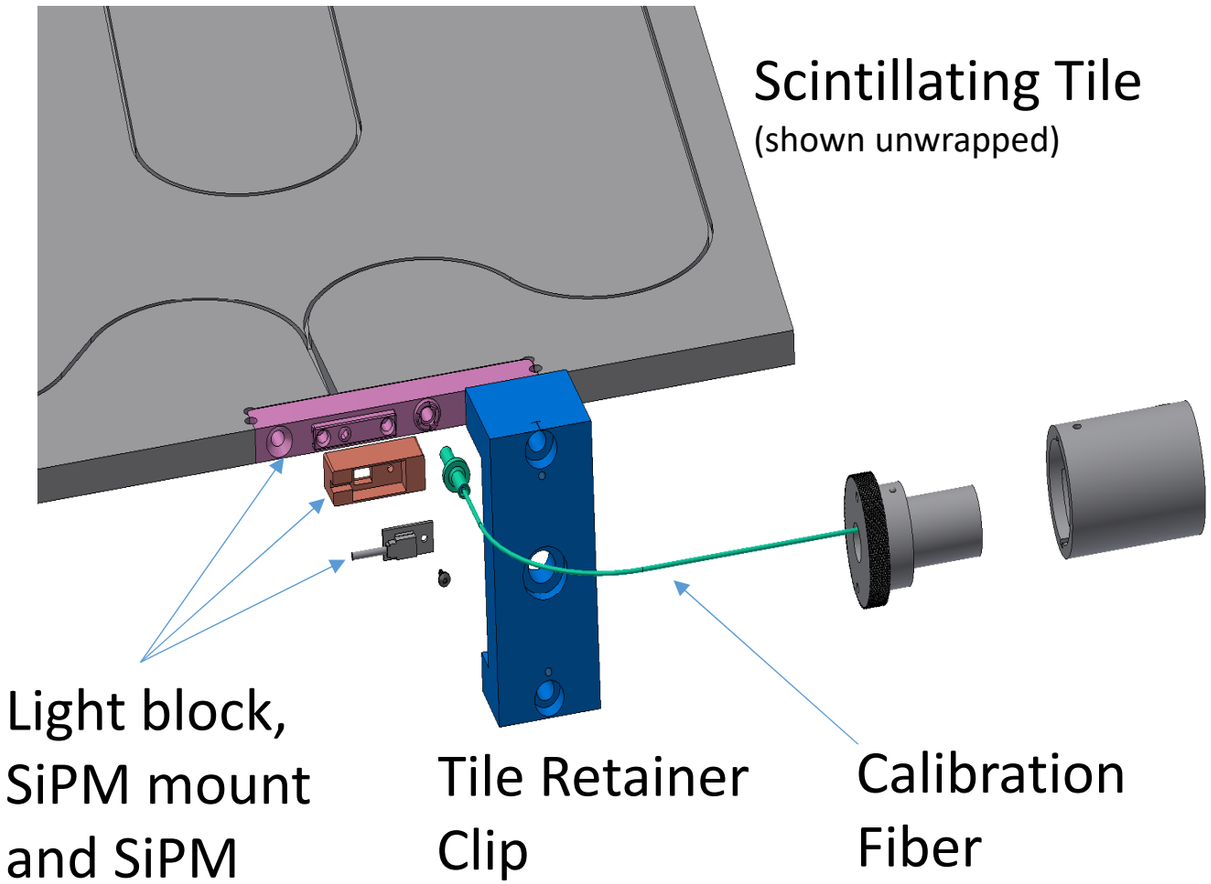
DELIVERABLE:
Al frame spanning 32 sectors - 1.16m inner radius, 1.37m outer radius

Includes "Support Rings" for full assembly.



Barrel Flux Return serves as HCAL absorber

Scintillating Tile Advanced R&D



- All aspects of the scintillating tile design are highly advanced
- Currently working on Advanced R&D contract (OPC funds):
  - 5th prototyping round (pre-production)
    - ~20% of production total (1560 tiles)
    - Includes tiles, clips, light blockers, SiPM mount, fiber bundles
  - Exercise vendor production capabilities
- Advanced R&D plan involves instrumenting six HCAL sectors with pre-production tiles and electronics

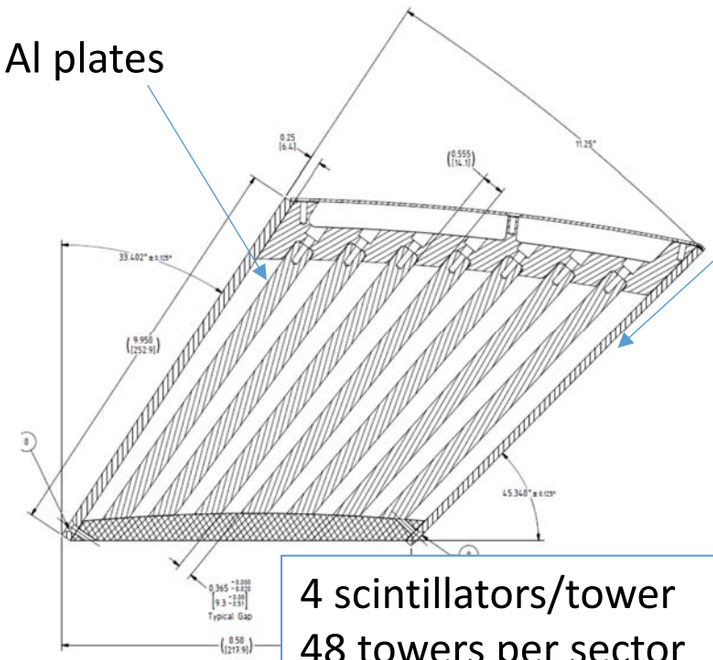
The Inner HCAL

DELIVERABLE:
32 sectors - 1.16m inner radius, 1.37m outer radius
8 rows of 7mm scintillator tiles (24 tiles per row)
32° tilt angle, flat stainless steel plates ~10.2mm - ~14.7mm

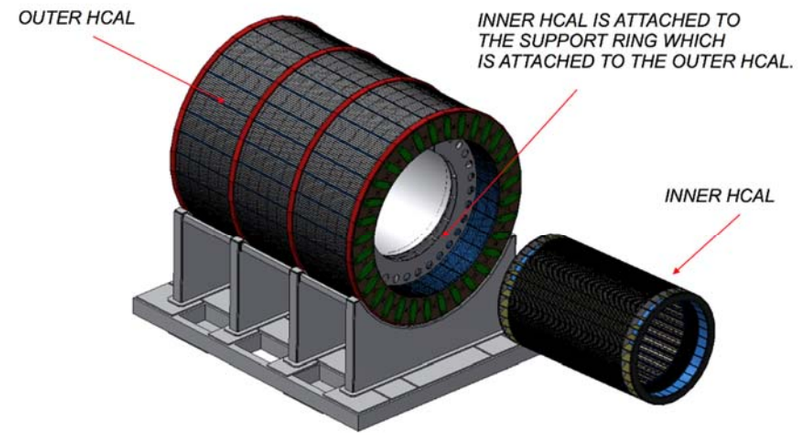
Completed sector is 4.3m long, weighs ~ 1 ton

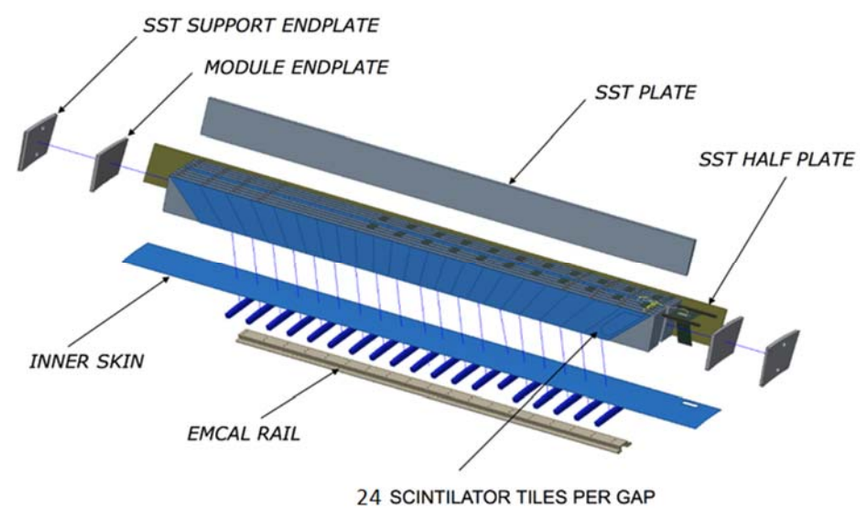
Flat Al plates

Half plates on sides

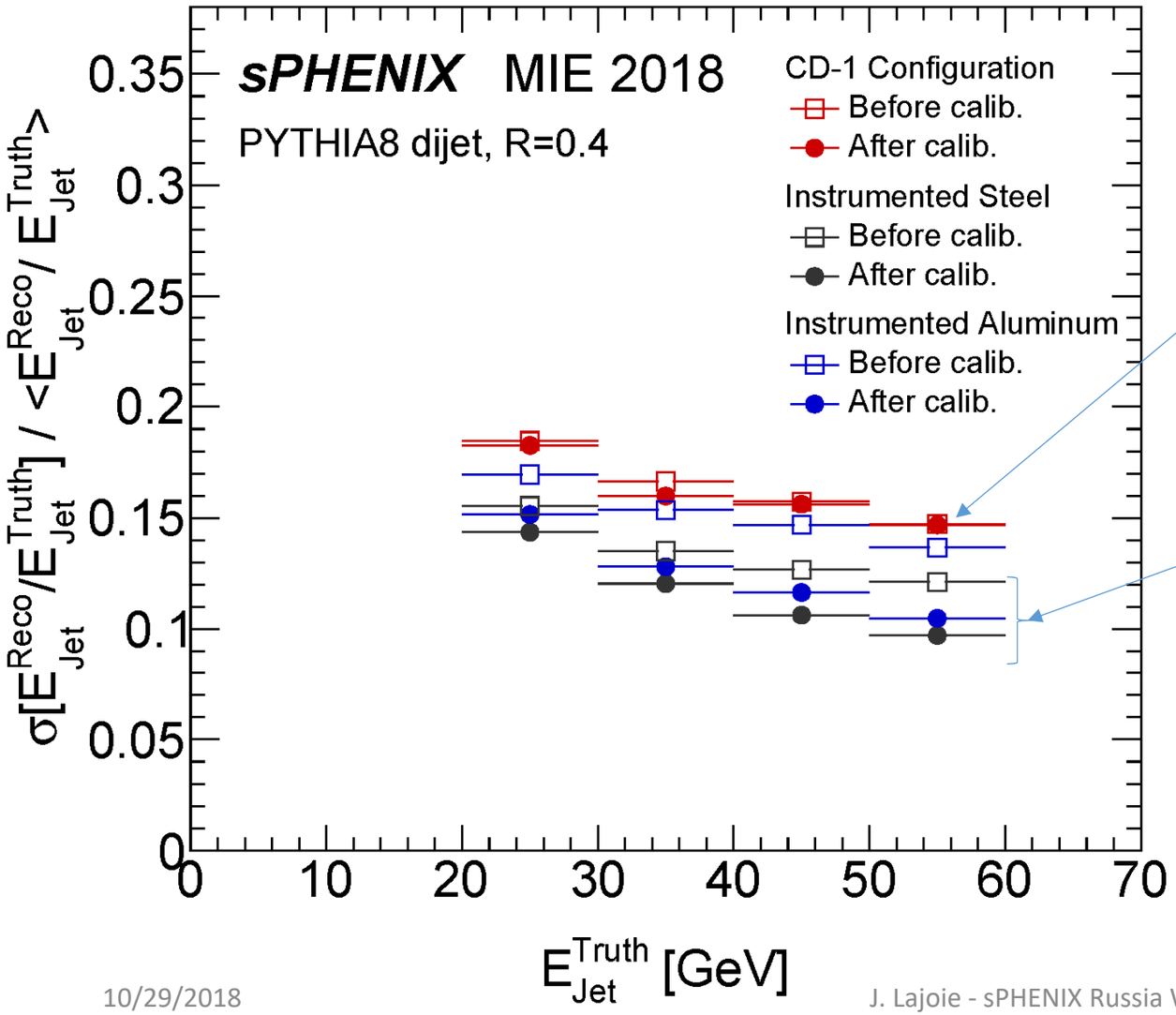


4 scintillators/tower
48 towers per sector
32 sector; 1536 channels (6144 SiPMs)





Improvement with iHCAL



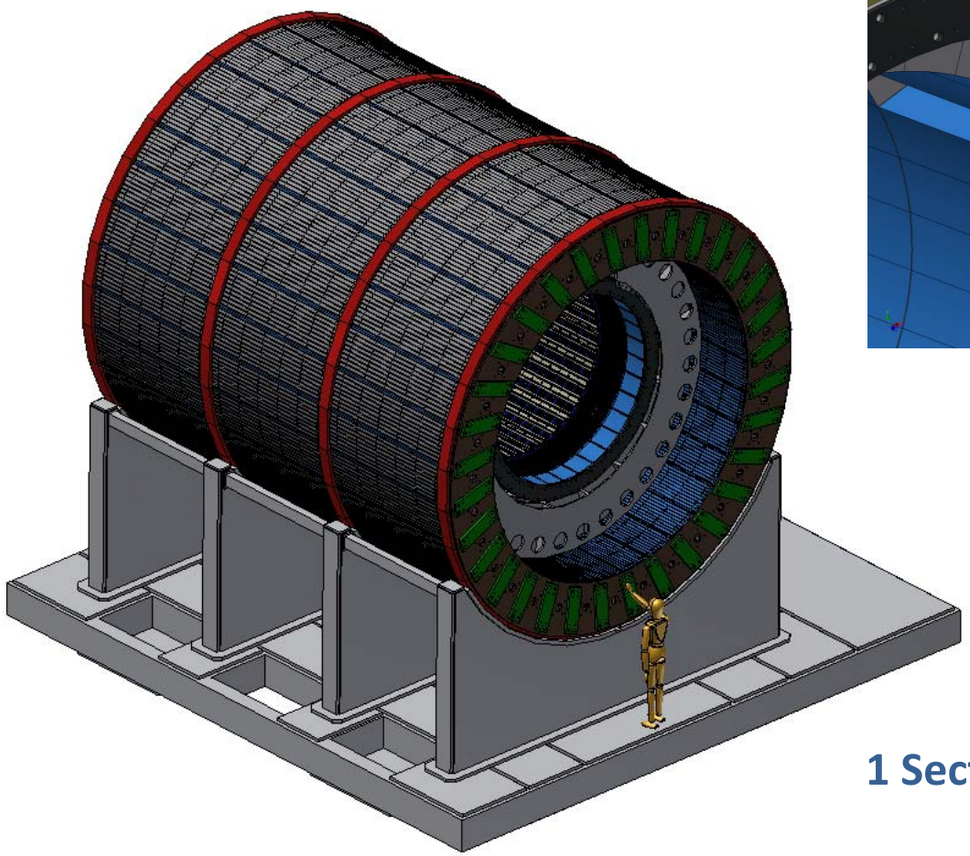
No resolution improvement after gamma+jet calibration with uninstrumented Al frame.

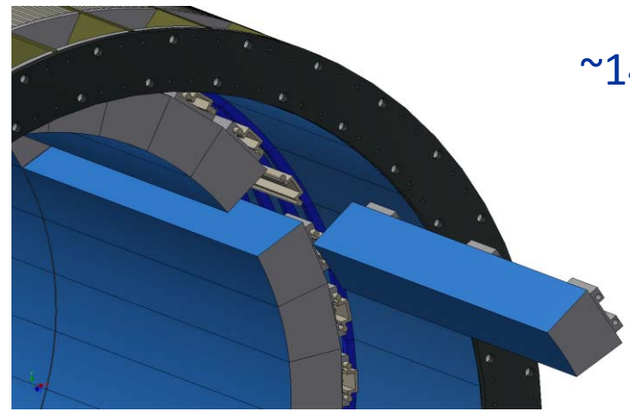
By instrumenting the Al frame we can recover most of the resolution with the SS310 iHCAL after gamma+jet calibration

EMCAL Subsystem

Electromagnetic calorimeter covering ± 0.85 in η and 2π in ϕ

$2(\pm\eta) \times 32\ (\phi) = 64$ Sectors





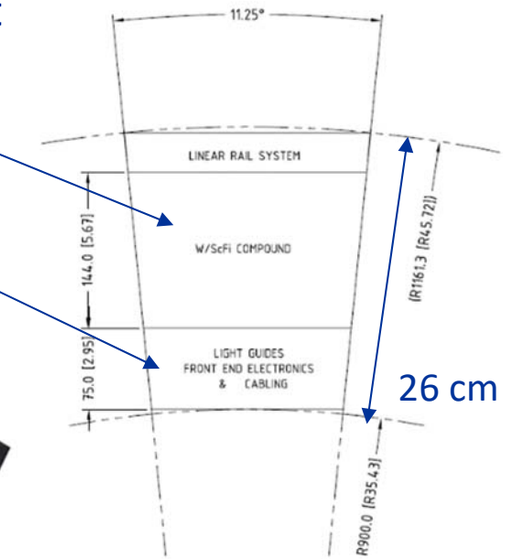
EMCAL Sector

Designed to be compact to fit inside the BaBar magnet

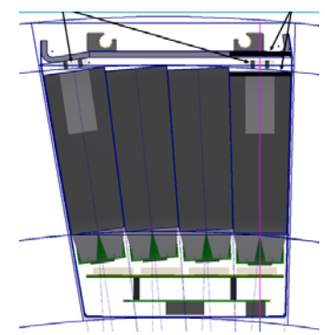
~14 cm absorber (η=0)

7.5 cm readout

26 cm



Approximately projective back to vertex in η and ϕ



Modules consist of four 2x2 tower blocks

1 Sector = 18 modules
= 72 Blocks
= 288 towers

EMCal Technical Overview

EMCAL Design Specs:

- Coverage: ± 0.85 in η (± 1.0 in η with Chinese support), 2π in ϕ
- Segmentation: $\Delta\eta \times \Delta\phi \approx 0.025 \times 0.025$
- Readout channels (towers): 72x256 = 18432
- Energy Resolution: $\sigma_E/E < 16\%/\sqrt{E} \oplus 5\%$
- Provide an e/h separation > 100:1
- Approximately projective in η and ϕ
- Compact, works inside 1.4T magnetic field and reduces cost of HCAL

Design technologies

- W/SciFi SPACAL
  Matrix of W powder and epoxy with embedded scintillating fibers
- SiPM readout
  Total number of SiPMs: 73,728

EMCAL Absorber Blocks

Design driver:

Must be compact to fit inside Babar magnet & minimize cost of HCAL

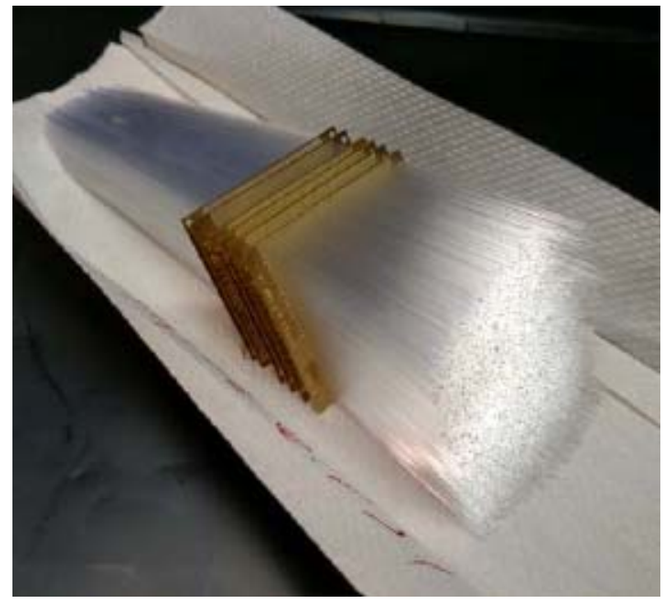
⇒ **W/SciFi SPACAL**

Absorber

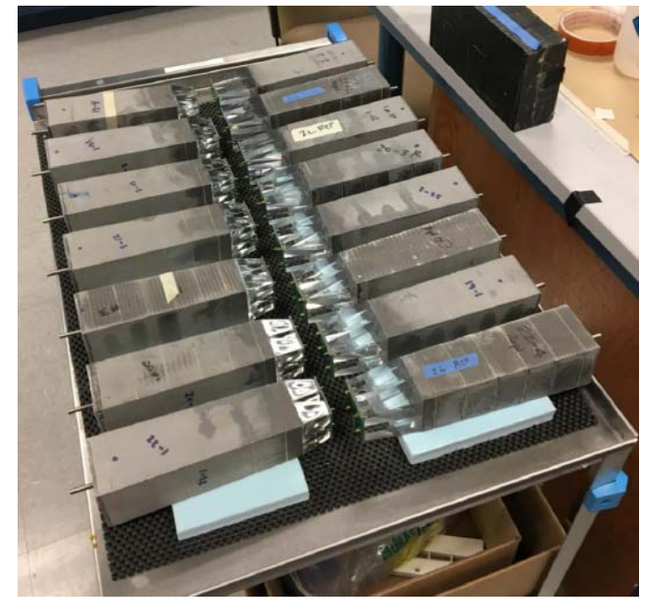
- Matrix of tungsten powder and epoxy with embedded scintillating fibers
- Density ~ 9-10 g/cm^3
- X_0 ~ 7 mm (18 X_0 total), R_M ~ 2.3 cm

Scintillating fibers

- Diameter: 0.47 mm, Spacing: 1 mm
- Sampling Fraction ~ 2 %



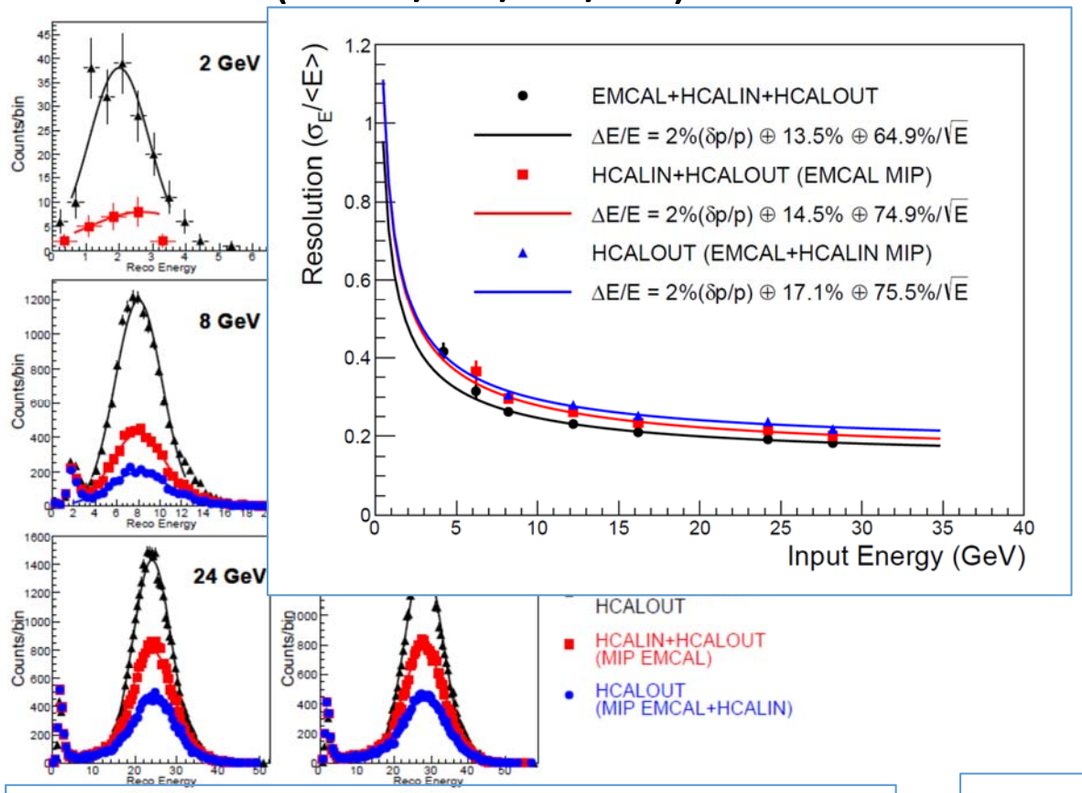
Fibers are held in position with metal meshes spaced along the module



Modules are formed by pouring tungsten powder into a mold containing an array of scintillating fibers and infusing with epoxy

Calorimetry Test Beams

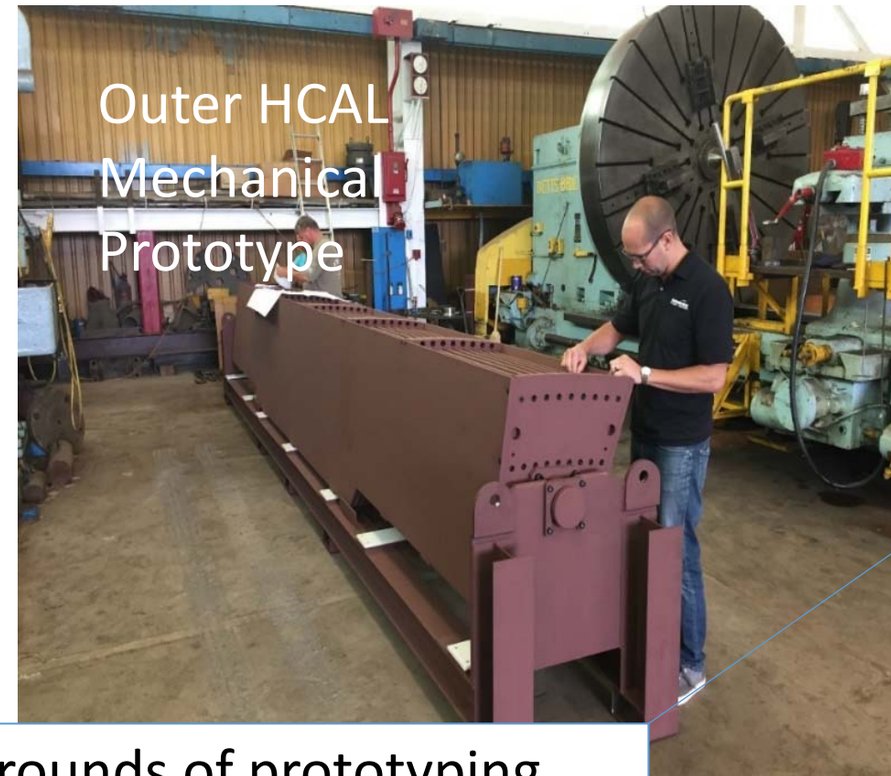
Test beams (2014/16/17/18):



In all cases, the combined system meets the sPHENIX spec!

https://arxiv.org/abs/1704.01461
(submitted to IEEE TNS)

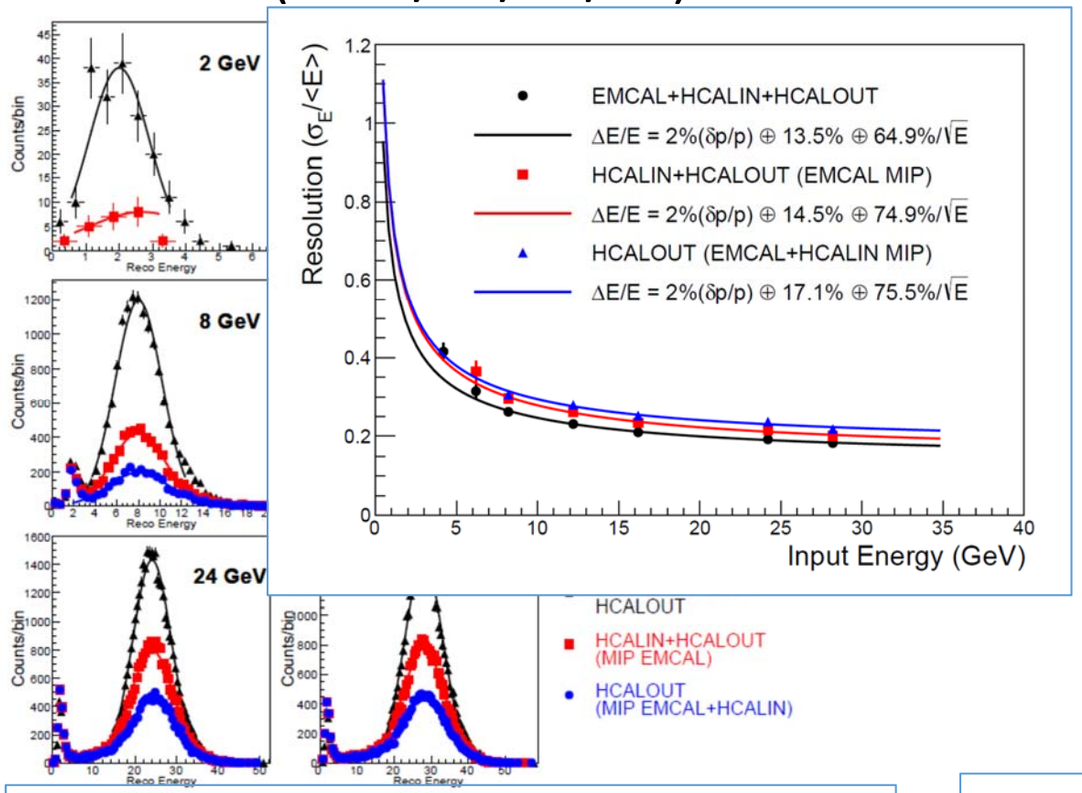
Full scale mechanical prototypes manufactured



Four rounds of prototyping with Uniplast – scintillating tile design very advanced.

Calorimetry Test Beams

Test beams (2014/16/17/18):



In all cases, the combined system meets the sPHENIX spec!

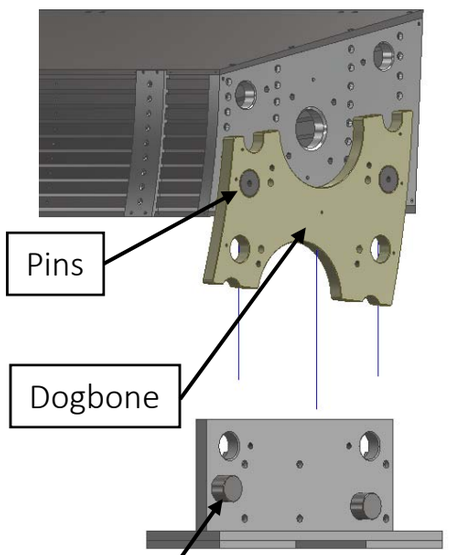
https://arxiv.org/abs/1704.01461
(submitted to IEEE TNS)

Full scale mechanical prototypes manufactured

Four round
with Unipla
tile design

Outer HCAL/Flux Return Assembly

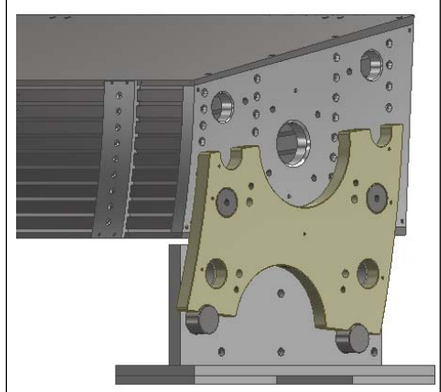
- Cradle has long pucks installed
- Incoming sector has dogbone attached w/ pins and bolts. One side is loose.
- Shims are placed onto middle upright



Long Pucks

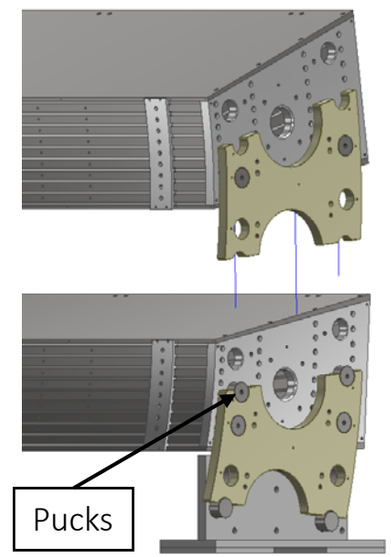
1 (are specific for this go/no go cradle and are not used in installation)

- Lower sector so that dogbone captures the cradle
- Tighten dogbone to the face of the sector
- Lower dogbone onto pucks
- Put in lower pins and bolts



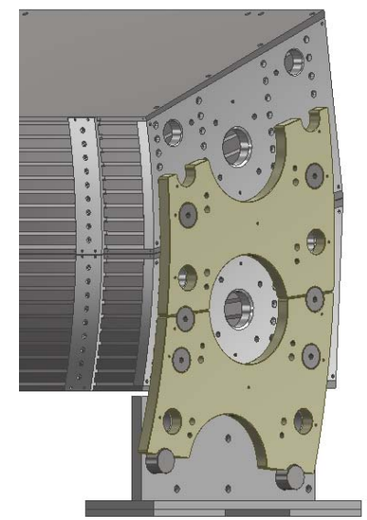
2

- Place pucks into upper part of installed dogbone
- Lower sector so that it captures previous sector
- Tighten dogbone to the face of the sector



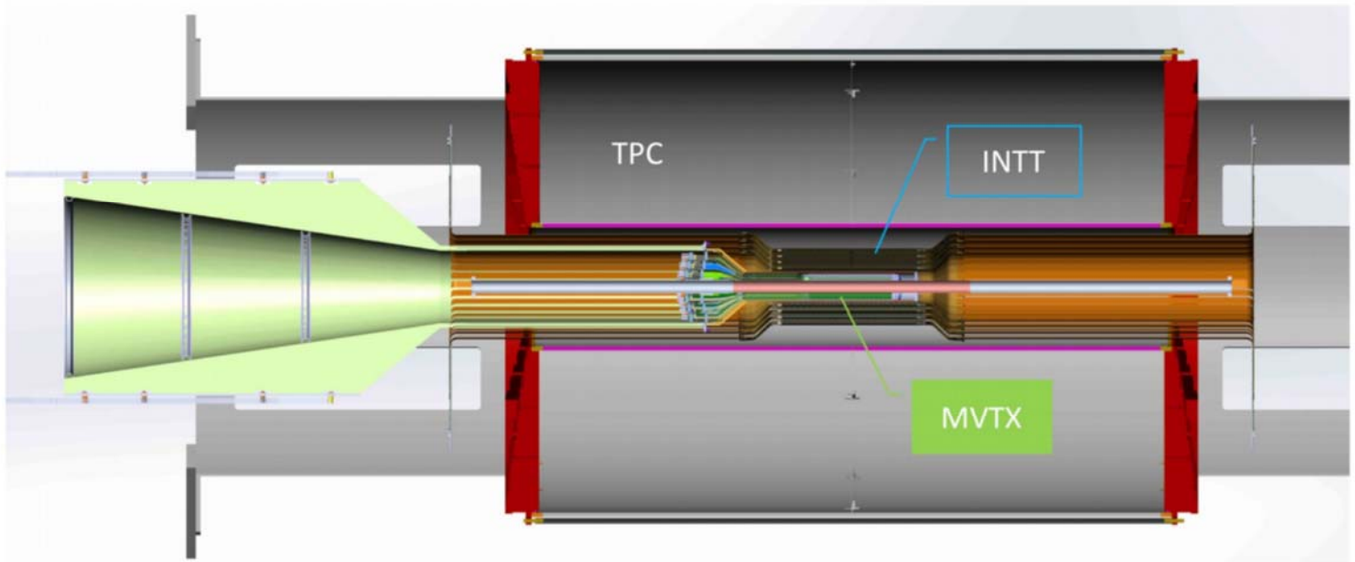
3

- Lower dogbone onto pucks
- Put in lower pins and bolts



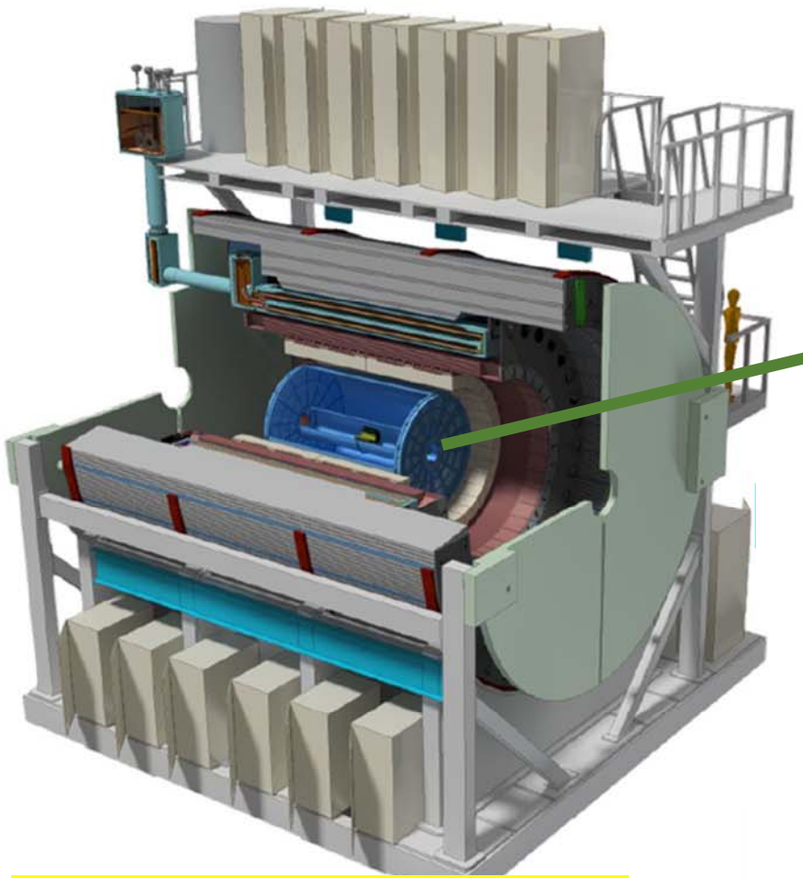
4

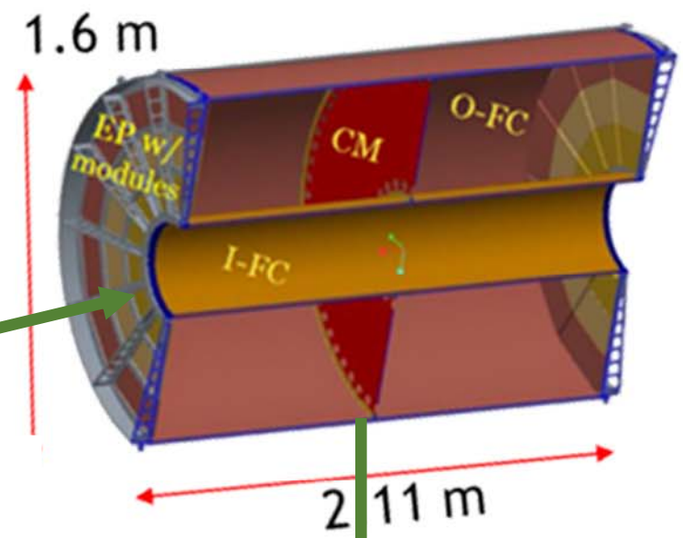
sPHENIX Tracking

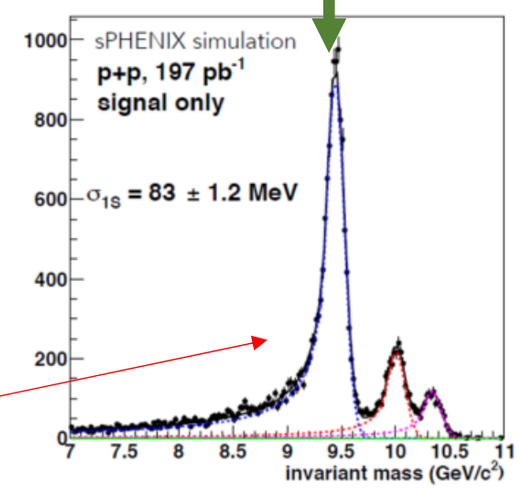


1. **Time Projection Chamber (TPC)**
   - 40 layer readout (30 < R < 78 cm)
   - Main tracking detector
2. **INtermediate silicon sTrip Tracker (INTT)**
   - 4 layers (6 < R < 12 cm)
   - Fast timing -> disambiguate pileup
3. **MAPS-based vertex detector (MVTX)**
   - 3 layers (2.3 < R < 3.9 cm)
   - Precision tracking and vertexing

The sPHENIX TPC





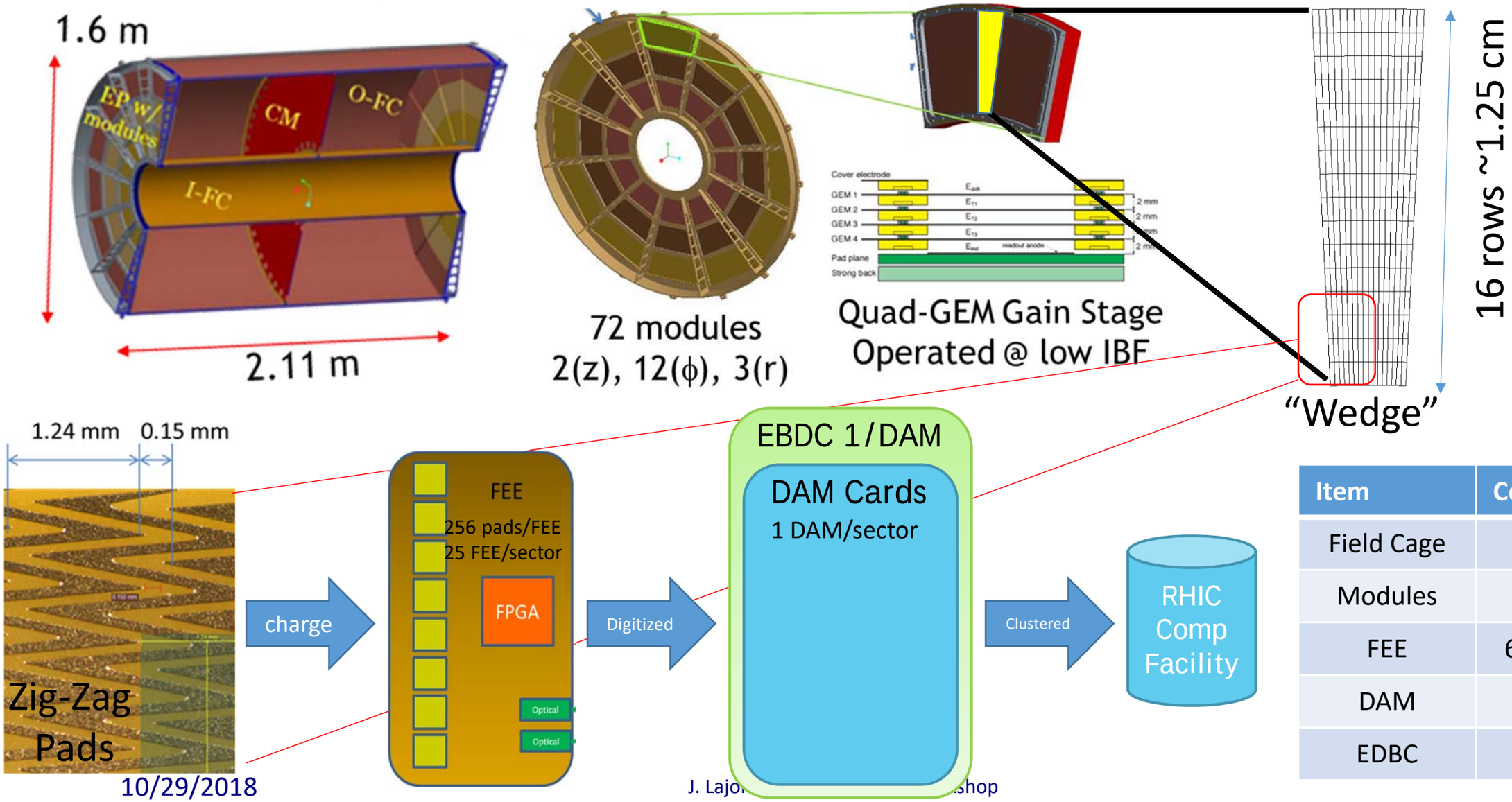


Charged Tracking in sPHENIX:

- MVTX provides vertexing
- TPC provides p-resolution
- INTT provides matching

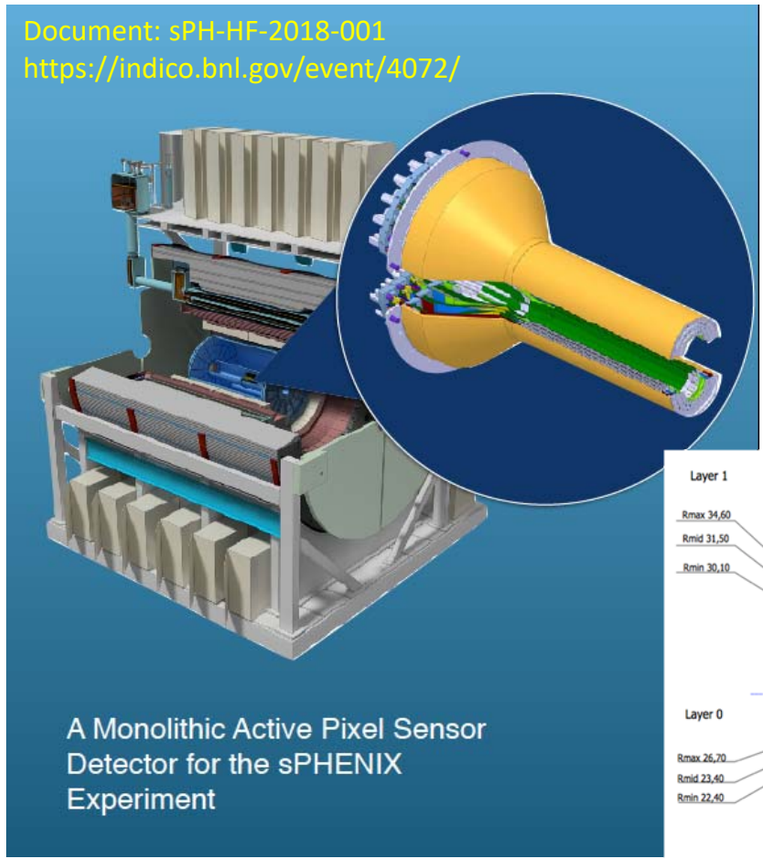
- A next-generation TPC operated in continuous readout mode using GEM Avalanche for low Ion Back Flow (IBF).
- Front End Electronics (FEE) uses SAMPA chip (developed by ALICE).
- Data Aggregation Module (DAM) uses the FELIX board (developed by ATLAS)

TPC Technical Overview

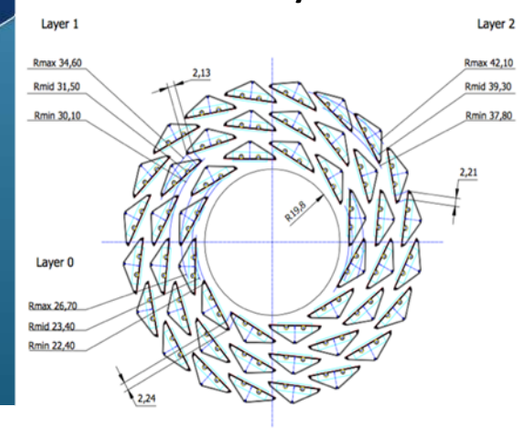


Item	Count
Field Cage	1
Modules	72+spare
FEE	624+spare
DAM	24+spare
EDBC	24+spare

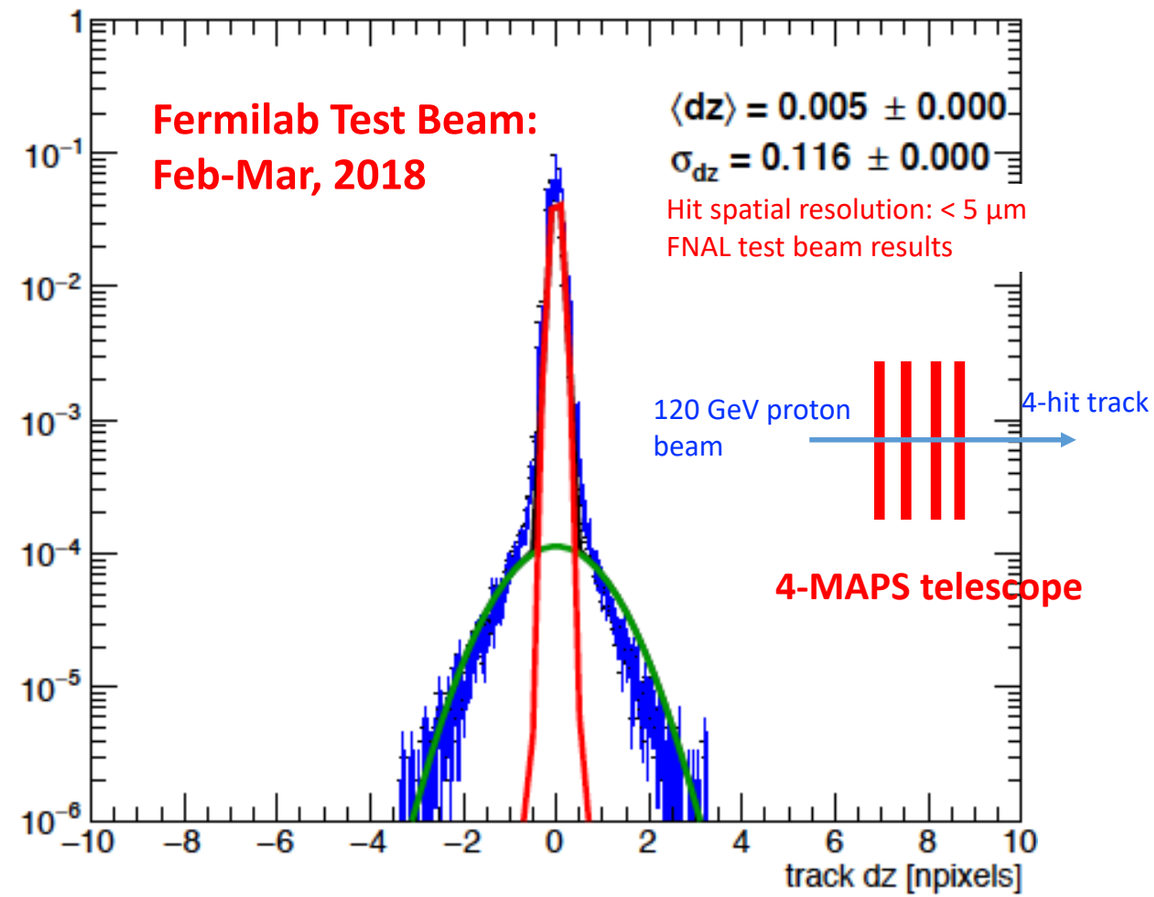
MVTX enables world-class HF science program



Stave layout beam view



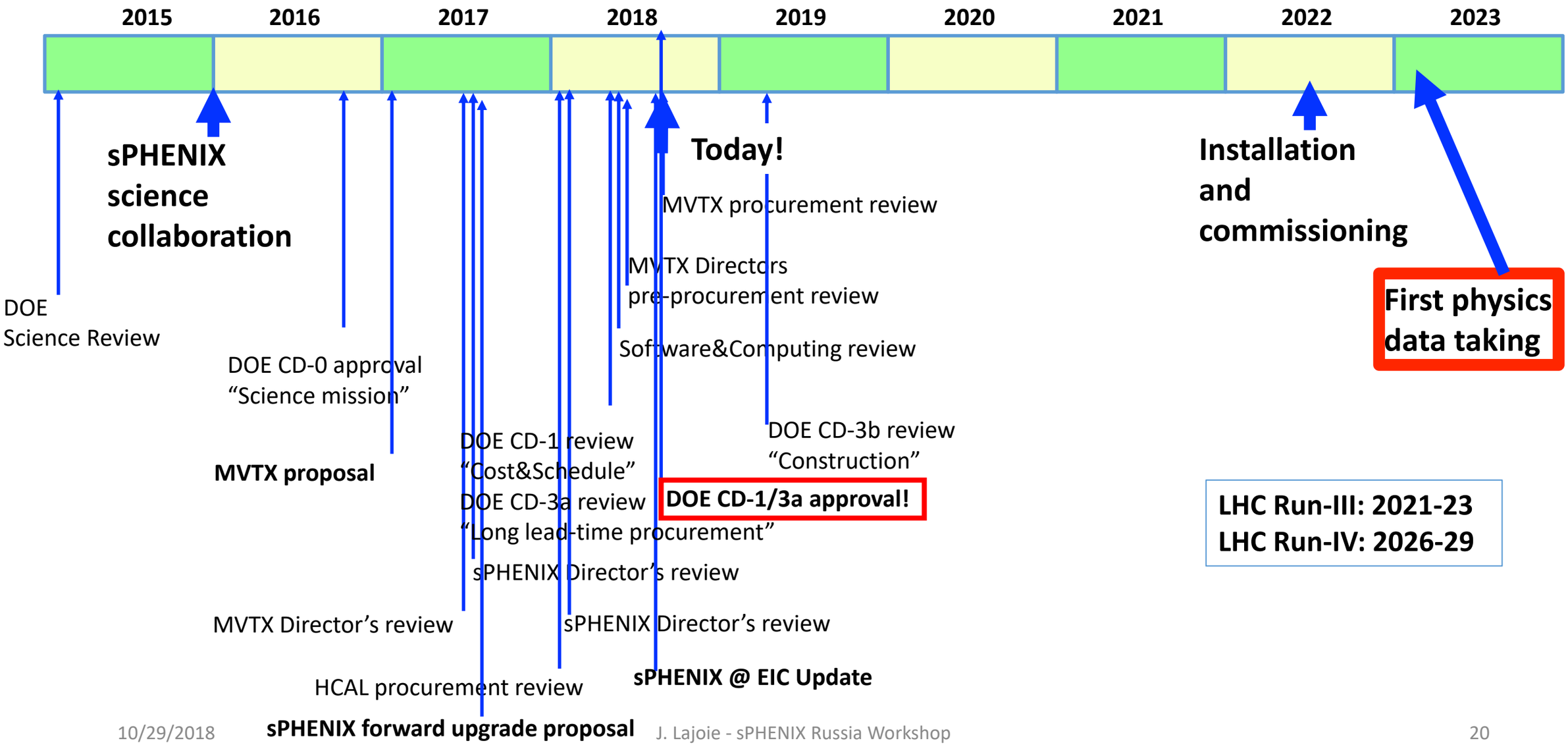
MVTX spatial resolution



Pixel Size: 28µm

MVTX based on copy of ALICE staves with support structure modified for sPHENIX

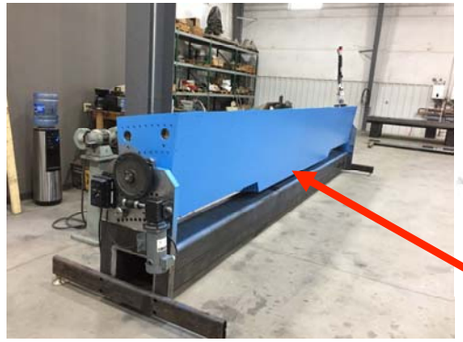
Realizing sPHENIX



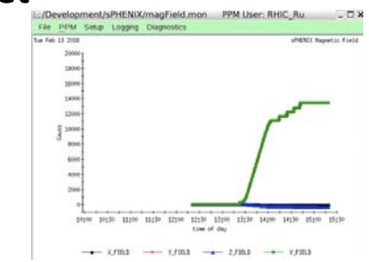
LHC Run-III: 2021-23
LHC Run-IV: 2026-29

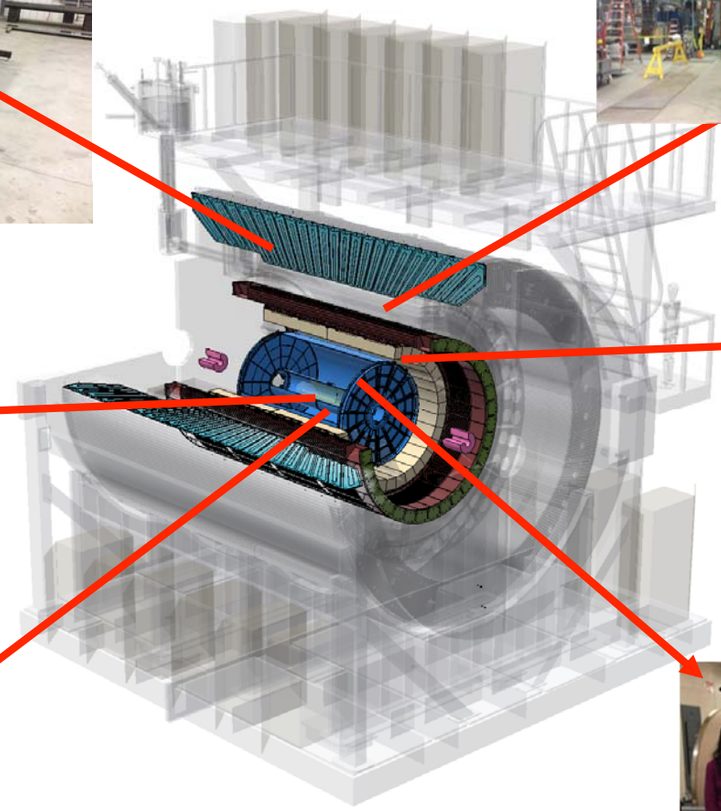
Realizing sPHENIX

Flux return/**oHCAL** absorber
Production sectors started arriving September ’18

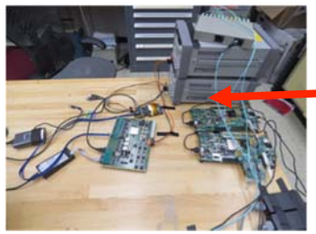


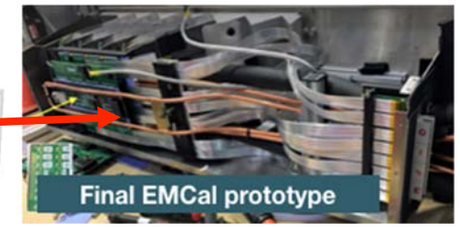
Full field **magnet** test at 1.4T at BNL on 2/13/2018



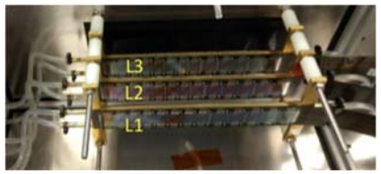


MVTX full chain test and beam test in Spring 2018
Expecting stave procurement in late 2018

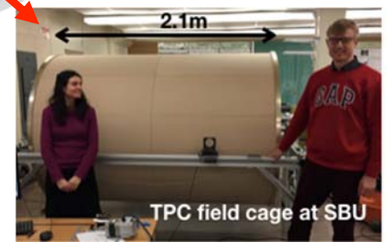




EMCAL materials purchase underway;
“Sector 0” production starting 2018

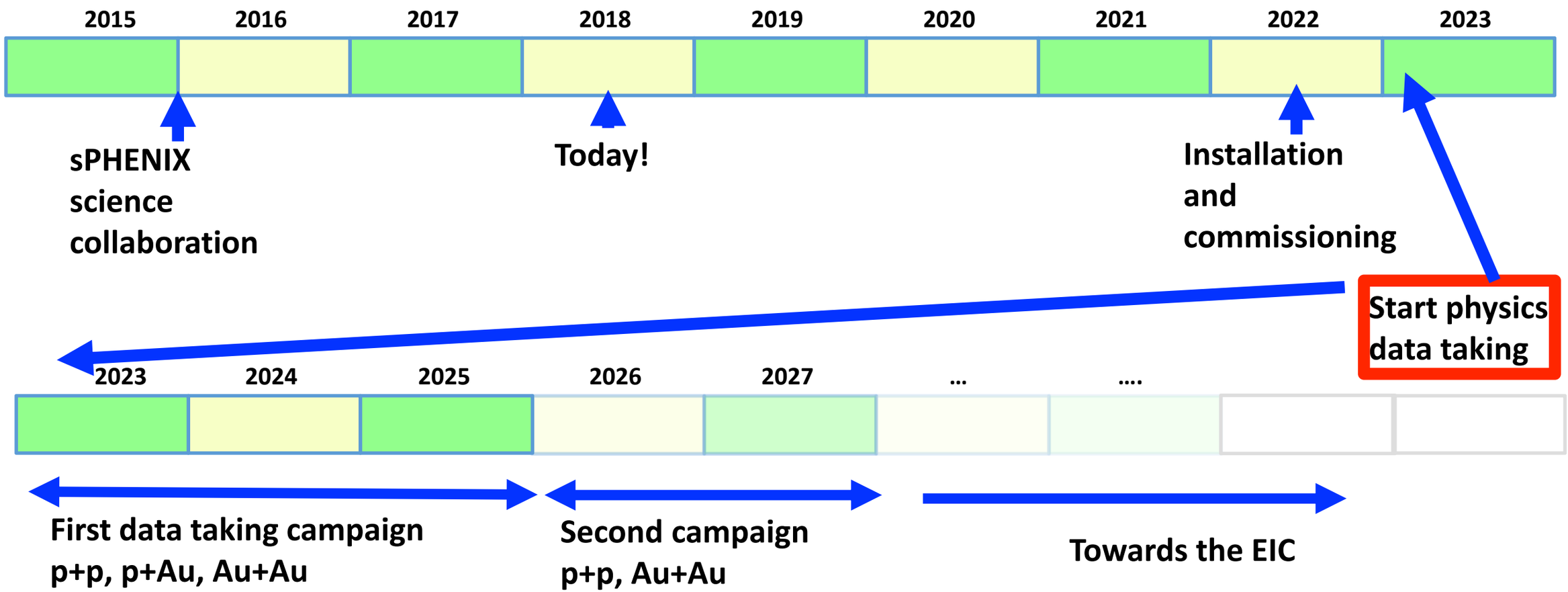


INTT telescope beam test in Spring 2018
Detector will be delivered by Riken

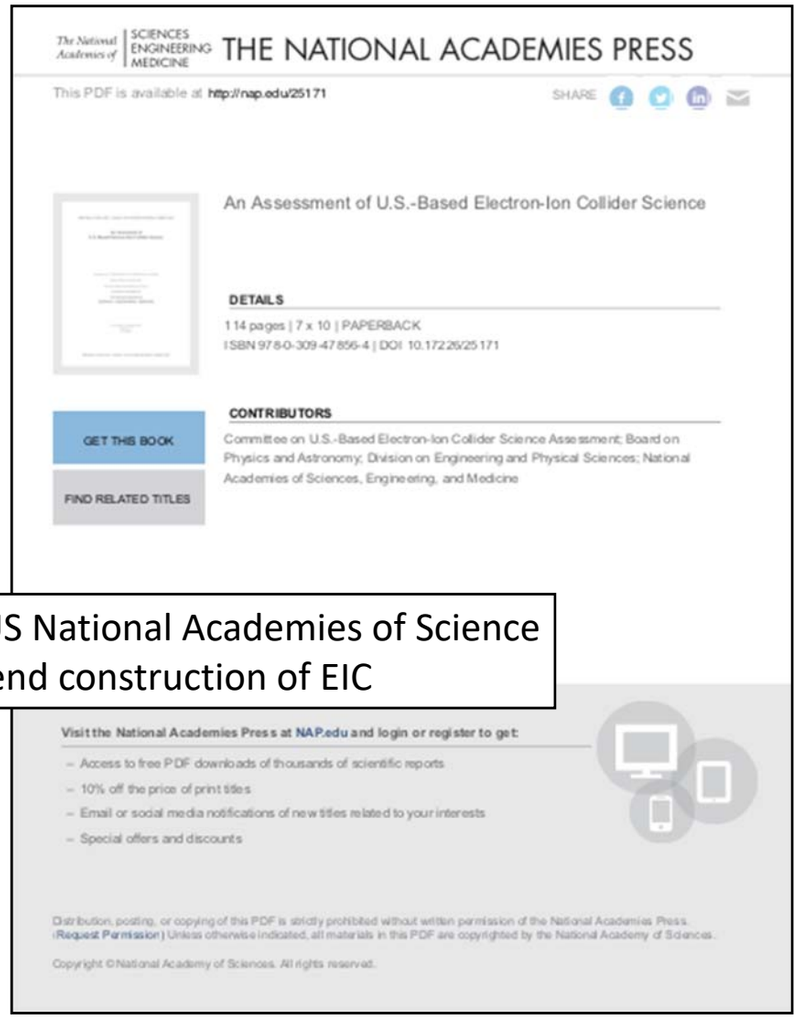


Beam test of **TPC** prototype in June 2018
Ready for producing of full-size field cage “prototype”

Realizing and Running sPHENIX



sPHENIX @ EIC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DETAILS

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Committee on U.S.-Based Electron-Ion Collider Science Assessment; Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

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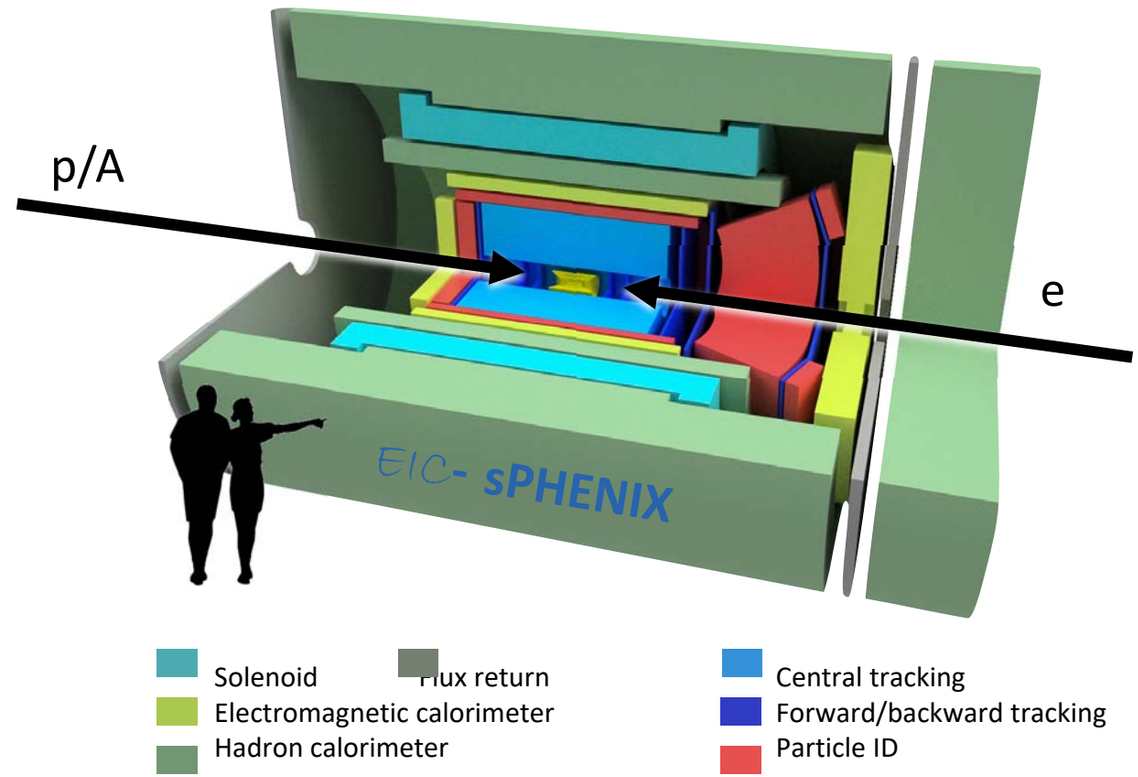
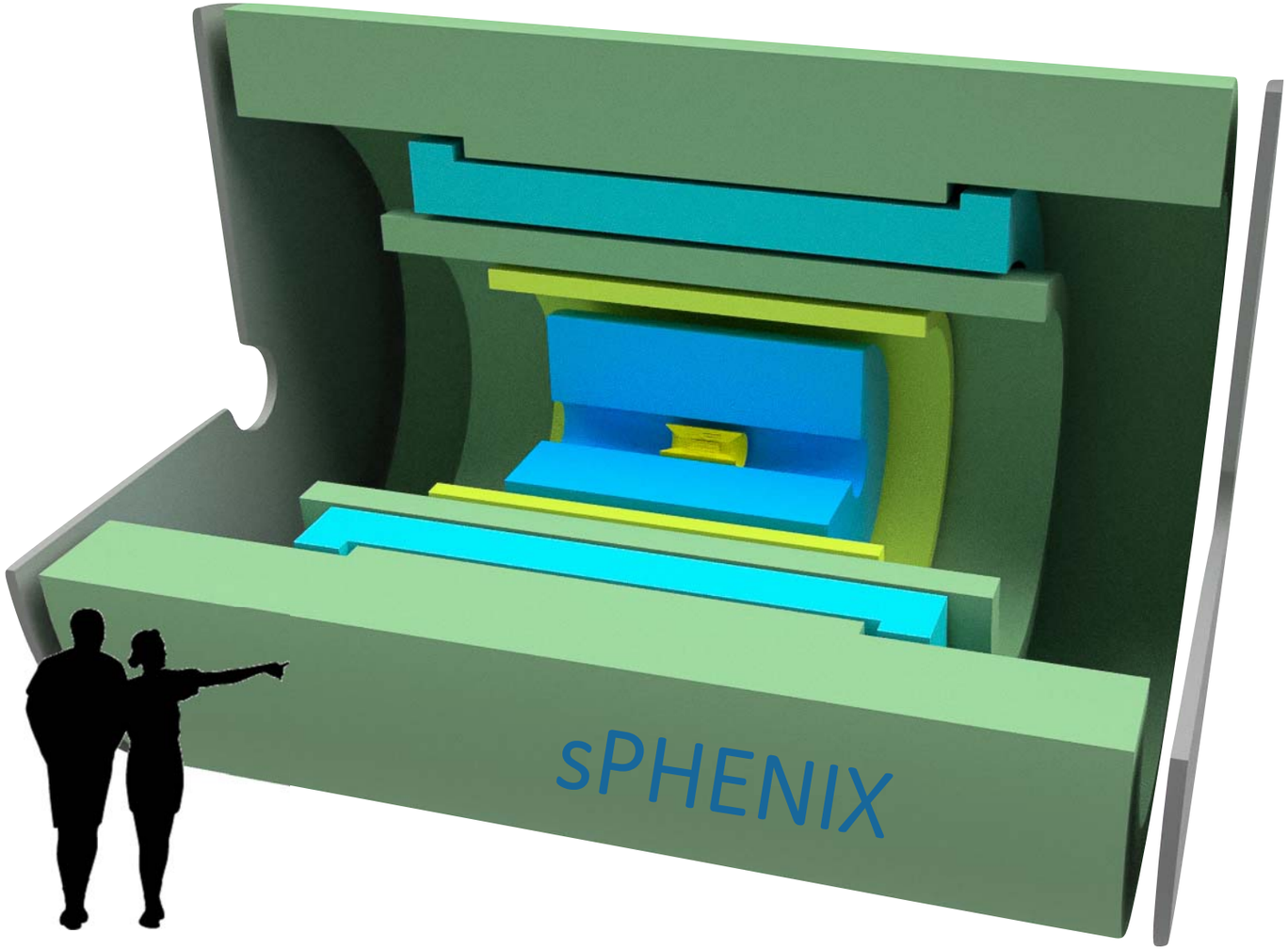
Timely: US National Academies of Science recommend construction of EIC

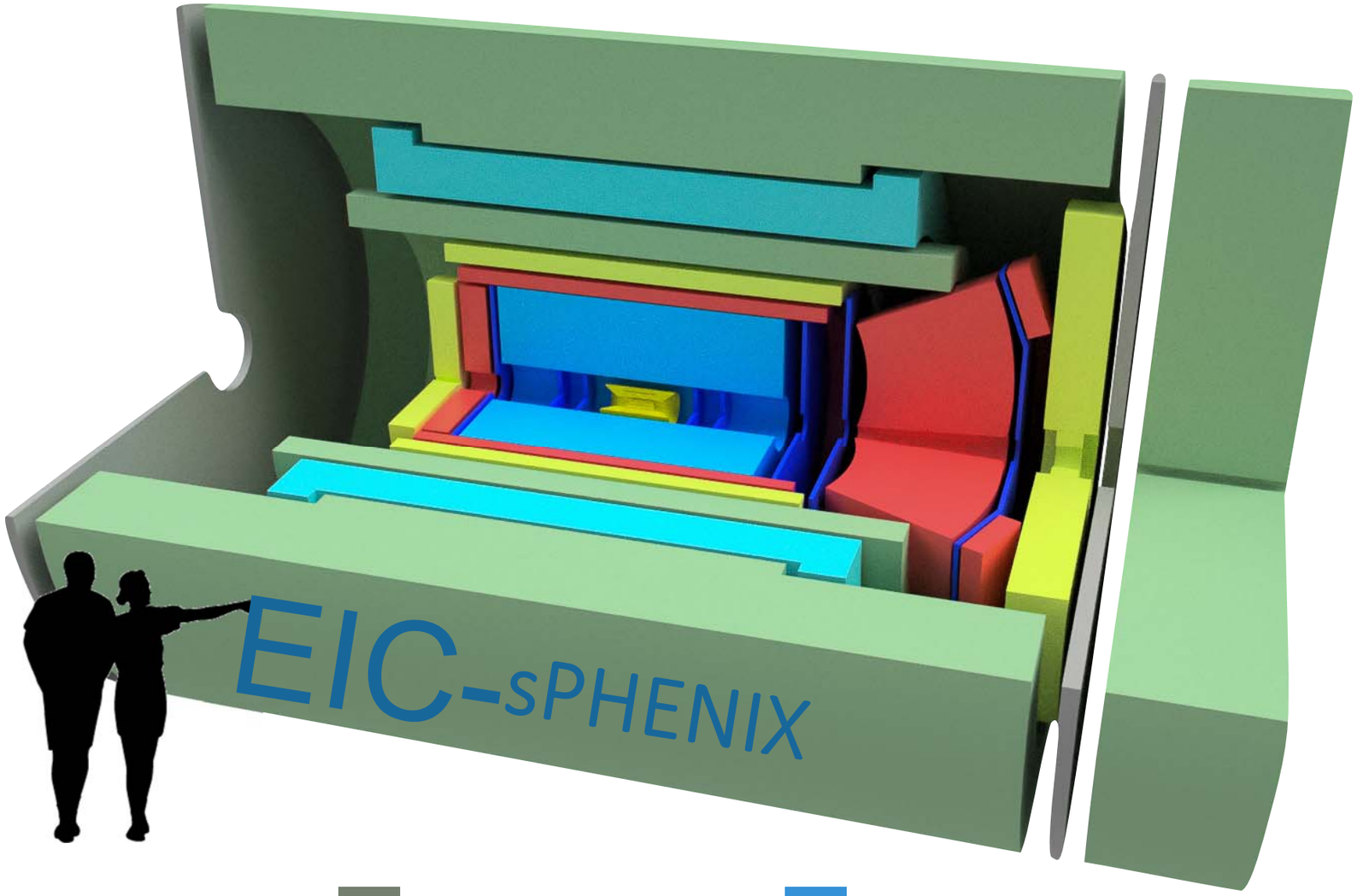
Study group (incl. non-sPHENIX members) working on EIC detector design based on sPHENIX



Deliver Design Update by October '18

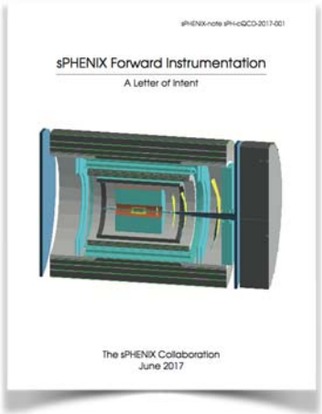


Solenoid
Flux return
Central tracking
Electromagnetic calorimeter
Hadron calorimeter



Solenoid
Flux return
Central tracking
Electromagnetic calorimeter
Forward tracking
Hadron calorimeter
Particle ID

Strong interest in Cold QCD with sPHENIX

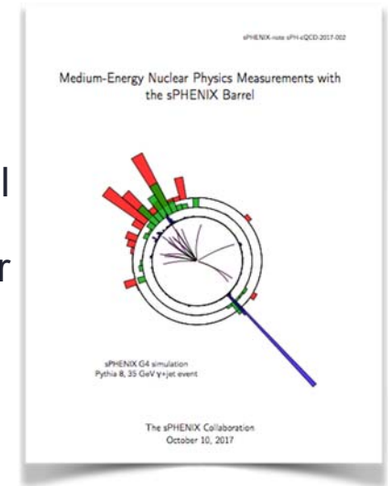


June ’17: Modest forward upgrade, following invitation by ALD to STAR and sPHENIX.

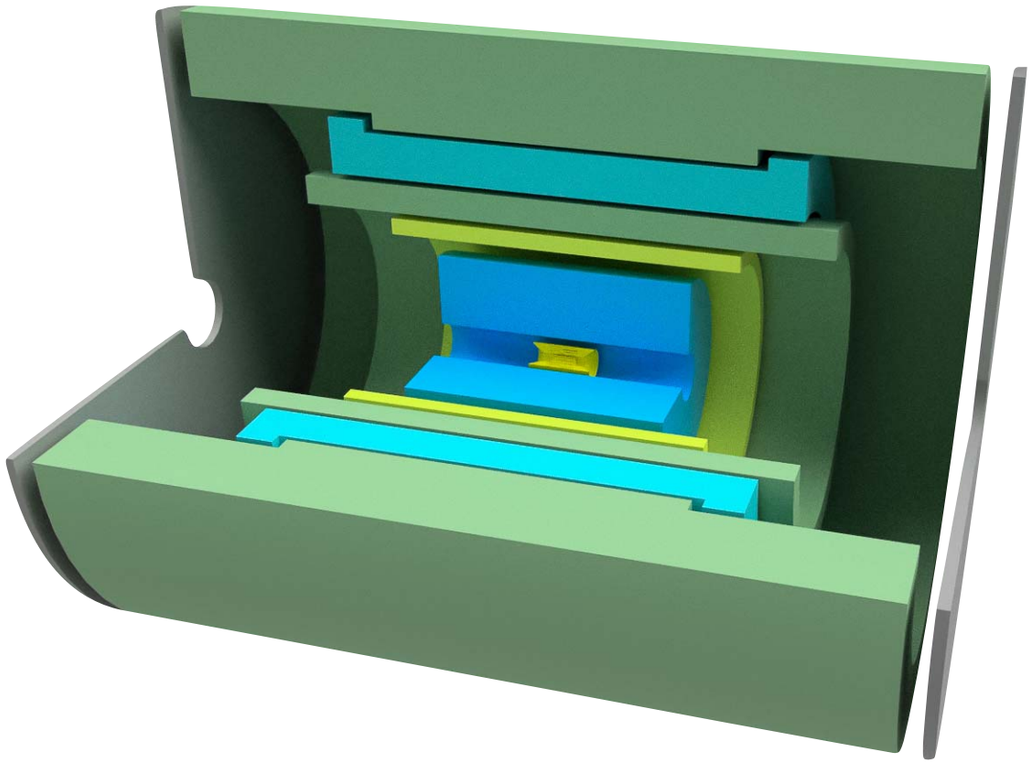
Exciting p+p and p+A program, but also strengthening of core sPHENIX program through high-rate, high resolution, large acceptance calorimetry and tracking

Oct ’17: Medium-energy physics with sPHENIX Barrel

Demonstrates wide range of physics opportunities with MIE detector

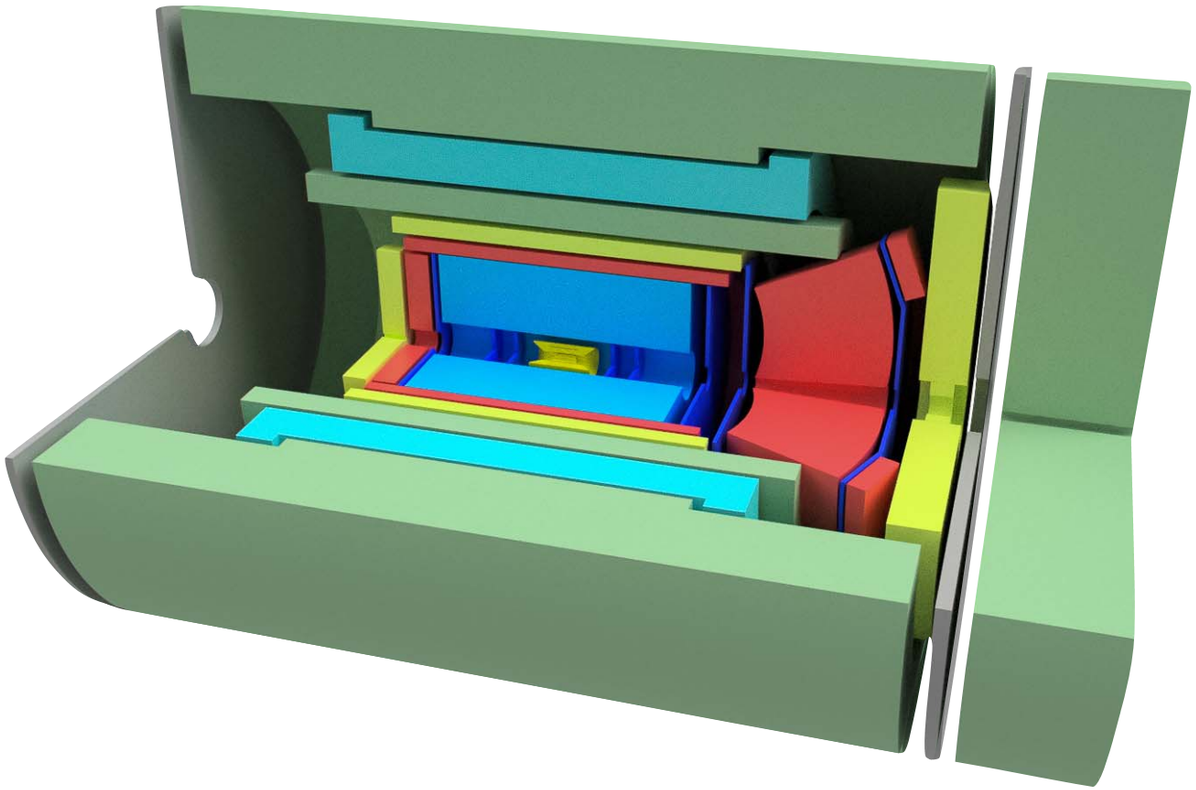


Forward sPHENIX



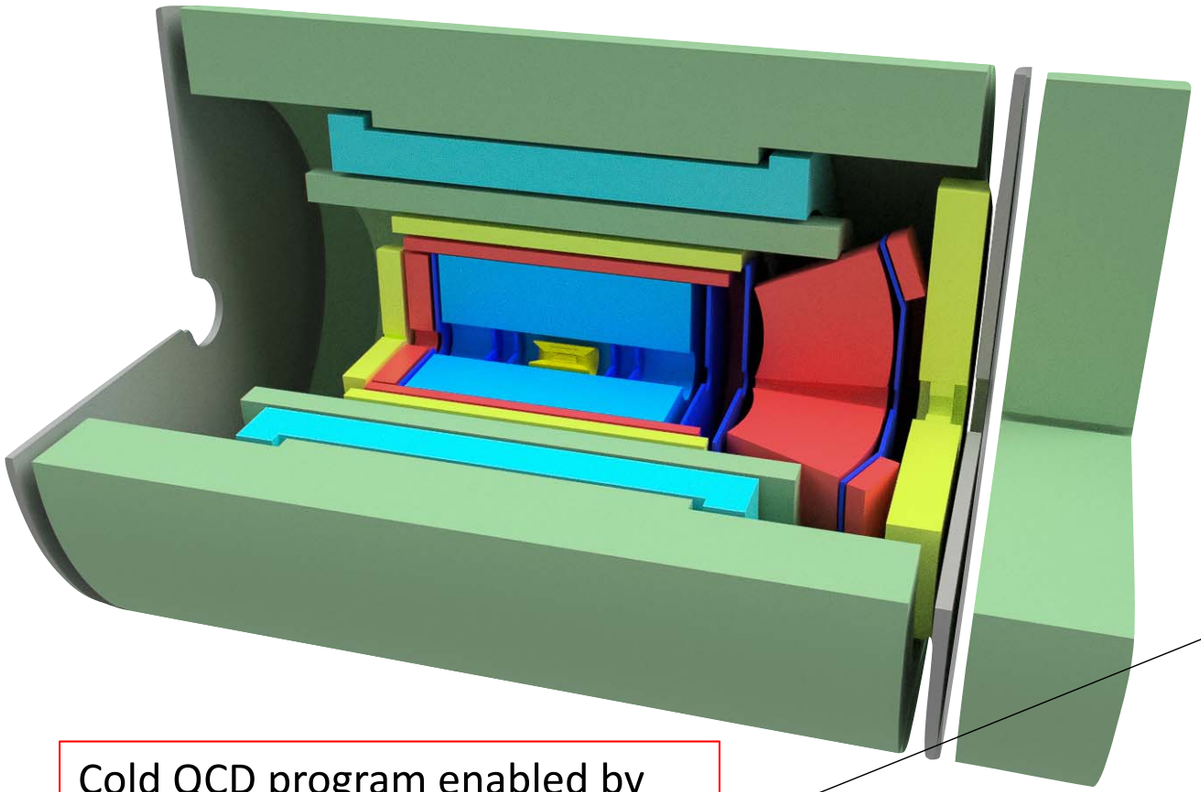
- sPHENIX
  - HCal/Flux return
  - Solenoid
  - Central EMCal
  - Silicon strip tracking
  - TPC
  - MAPS

Forward sPHENIX



- EIC-sPHENIX detector
  - HCal/Flux return
  - Solenoid
  - Extended Central EMCal
  - Central hadron PID
  - TPC
  - MAPS
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

Forward sPHENIX



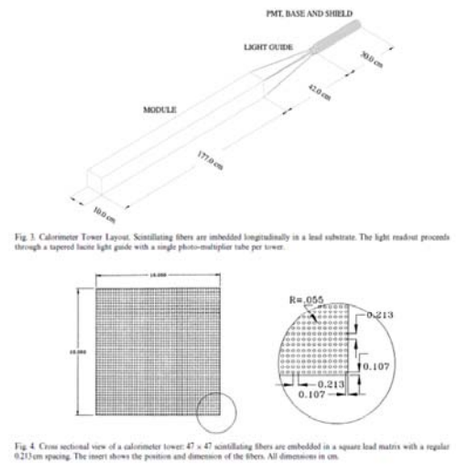
- EIC-sPHENIX detector
  - HCal/Flux return
  - Solenoid
  - Extended Central EMCal
  - Central hadron PID
  - TPC
  - MAPS
  - Forward and backward tracking
  - Forward and backward hadron PID
  - Backward crystal EMCal
  - Forward EMCal
  - Forward HCal

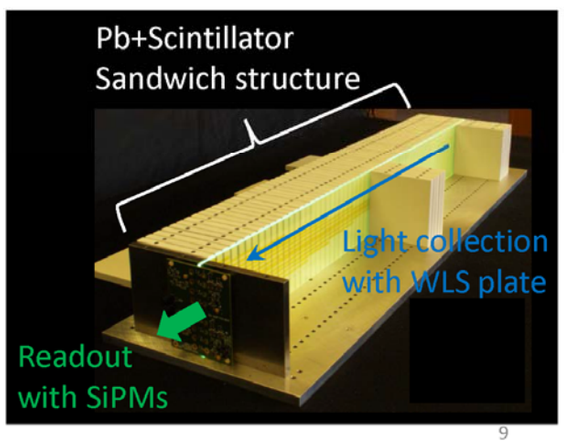
Cold QCD program enabled by early realization of some EIC-sPHENIX detector components!

Forward sPHENIX Technologies

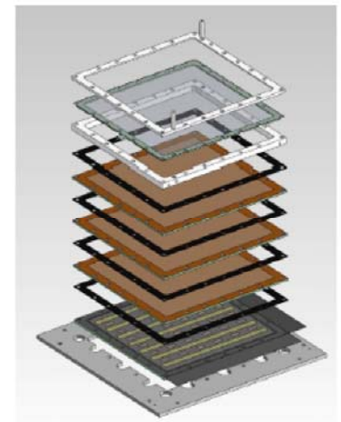
Forward HCal

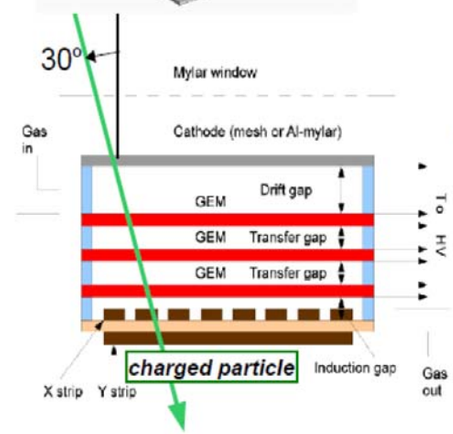
- Technology choices
  - UCLA HCal for STAR FCS (O. Tsai)
  - E864 SPACAL (J. Lajoie)
  - …
- UCLA Hadron calorimeter for STAR FCS
  - 10cm x 10cm x 81cm tower
  - 4 interaction length
  - 64 layers of 10mm Pb (or Fe) absorber + 2.5mm scintillator
  - WLS plate for light collection
  - SiPM for readout





9

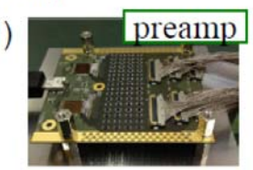




5

GEM Tracker

- 100x100, 200x200, and 300x300 mm^2
- $Ar+CO_2$ (70:30), Gain: 1~4 x 10^4
- 2D strip readout PCB
- Readout electronics:
  - preamp using APV25 chip
  - FEM: SRS (by RD51)



- position resolution
  - 100um for angled track(up to 30°) in the bending plane (x-direction), and 300um for the vertical (y) direction
  - confirmed for all three sizes by beam tests

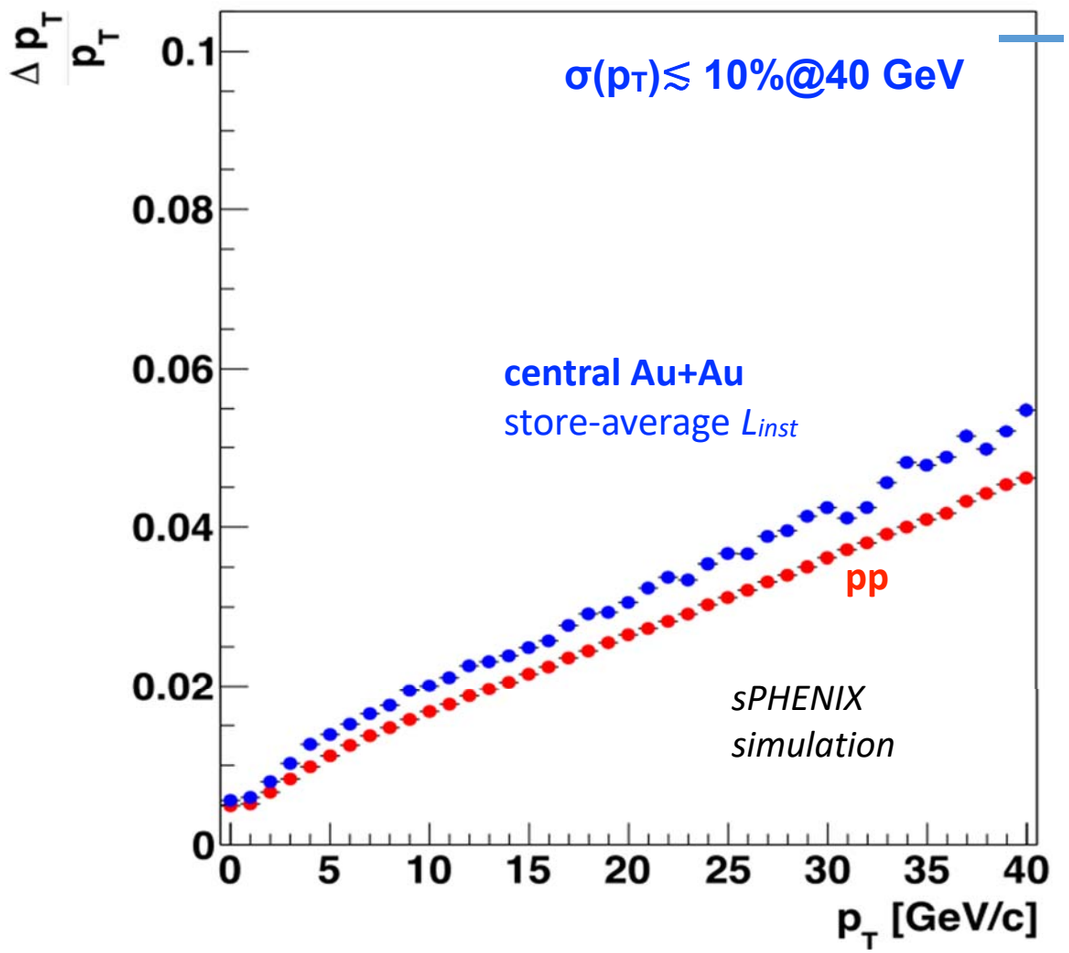
Outlook

- sPHENIX will probe microscopic structure of strongly coupled QGP
- New state of the art detector at RHIC, complementing capabilities at the LHC:
    - Jet suppression and substructure
    - Upsilon spectroscopy
    - Open heavy flavor over full kinematic range
- International collaboration, growing to include EIC and forward interests
- Work on sPHENIX is in full swing!
- Exciting physics program at RHIC in 2020's, and possibly beyond at EIC

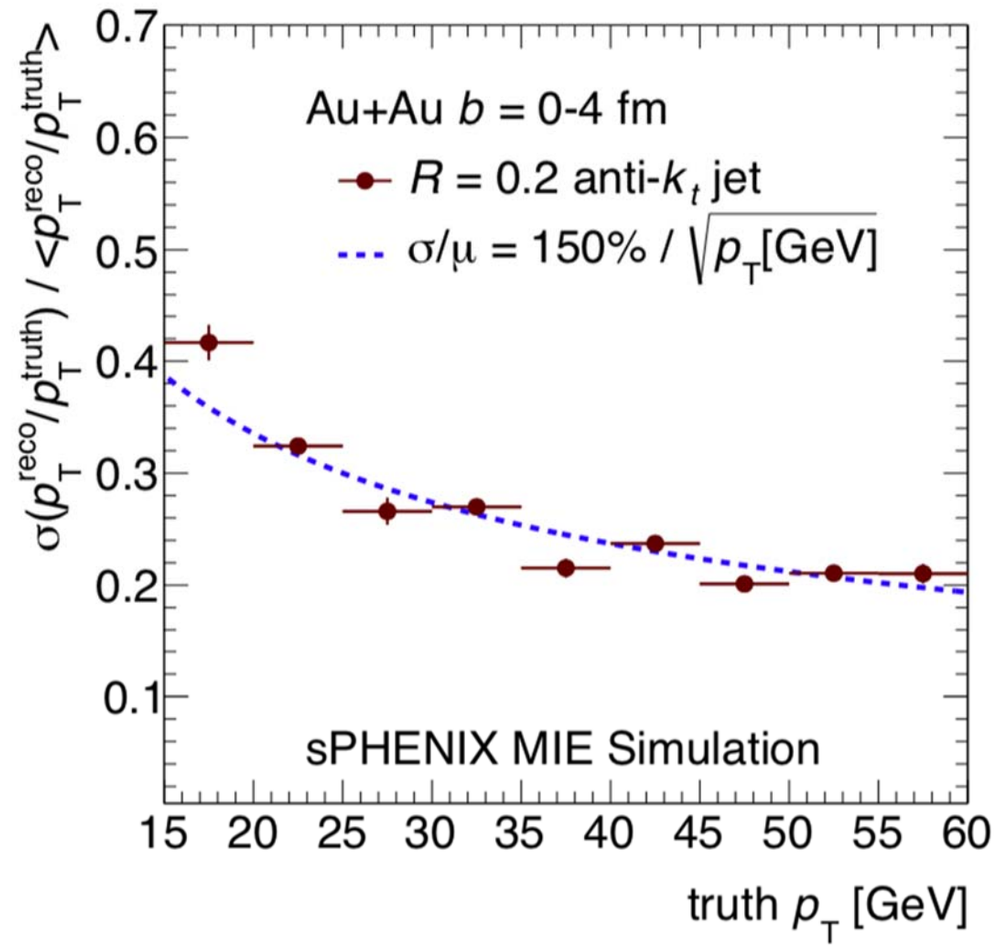
BACKUP

Performance Simulation: Track and Jet resolution

Track p_T resolution (central Au+Au)



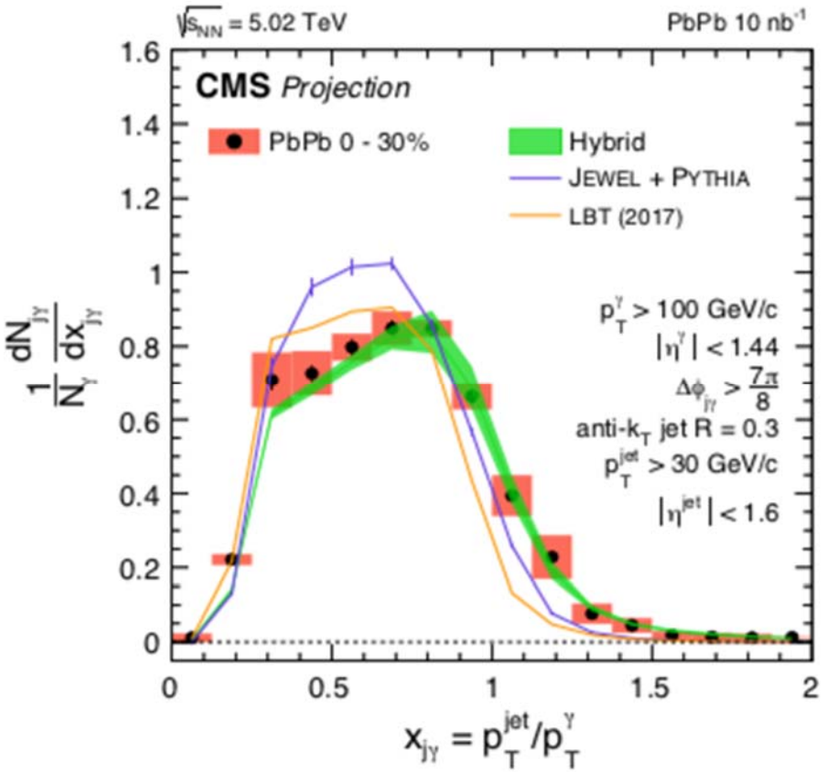
Single jet resolution (central Au+Au)



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

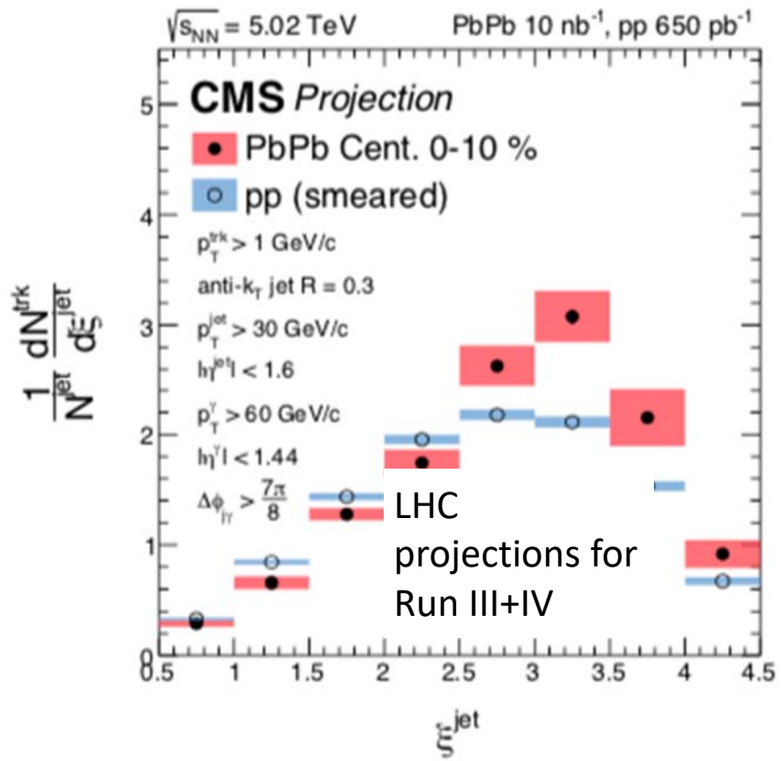
Jets in sPHENIX vs. LHC

γ+Jet momentum balance



Direct measure of parton energy loss in QGP

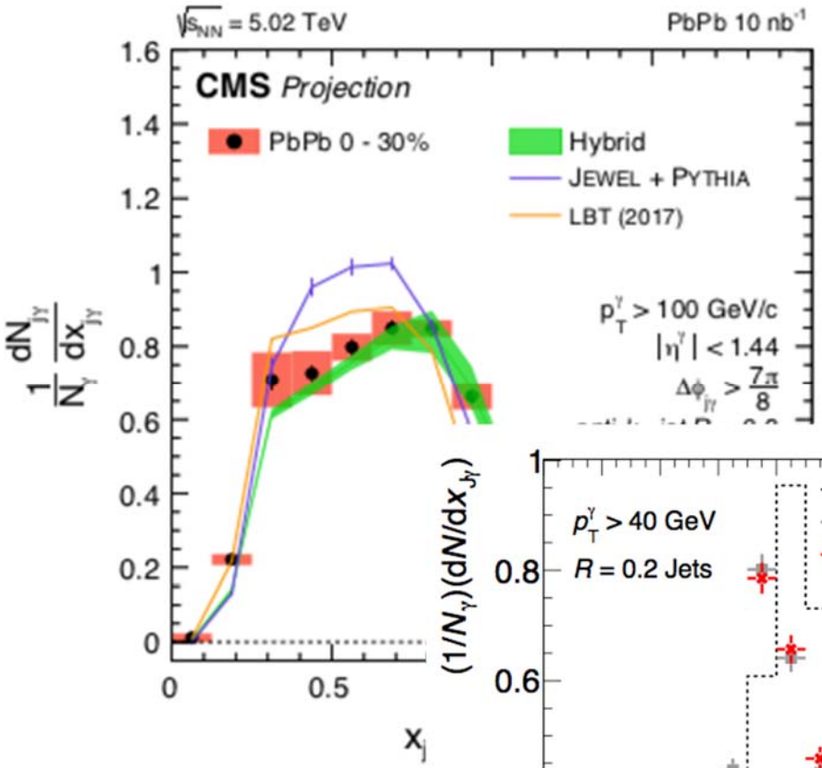
γ+Jet fragmentation function



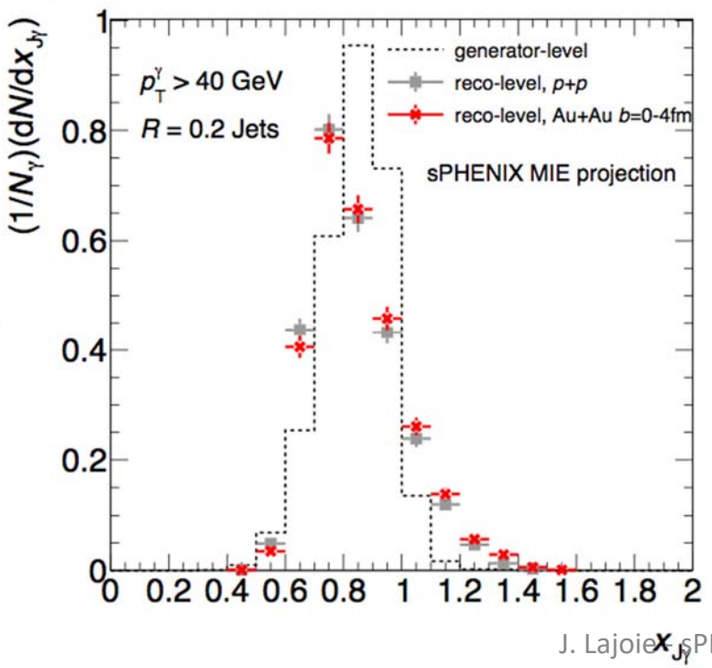
Modification of parton shower in QGP

Jets in sPHENIX vs. LHC

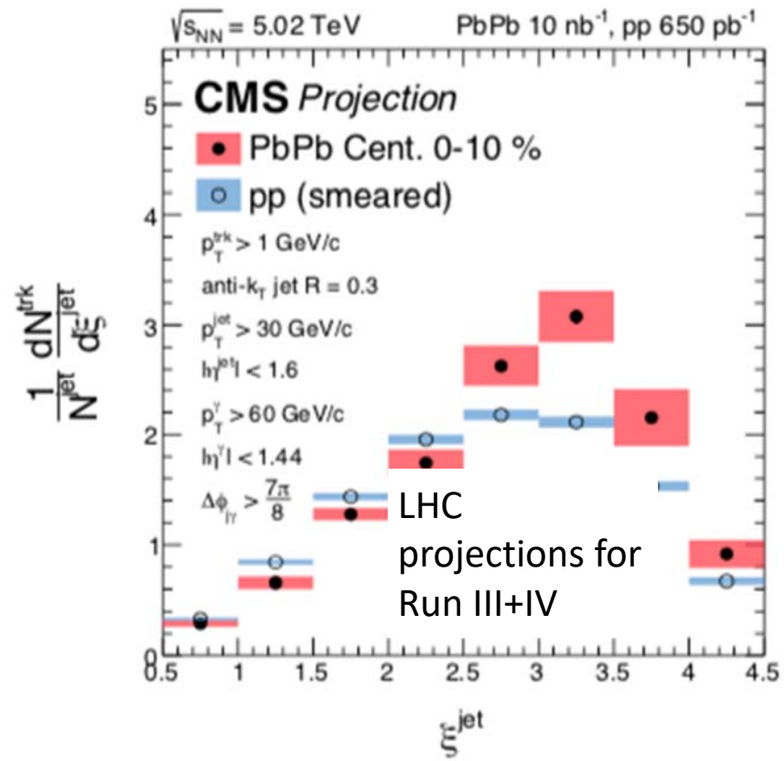
γ+Jet momentum balance



Direct measure of parton energy loss in QGP



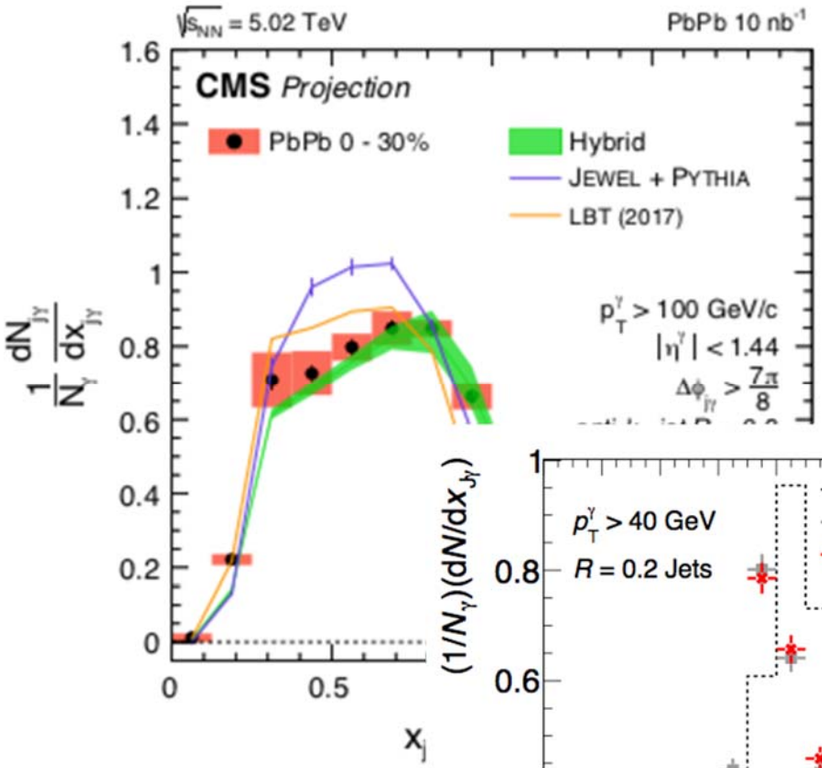
γ+Jet fragmentation function



Modification of parton shower in QGP

Jets in sPHENIX vs. LHC

γ+Jet momentum balance



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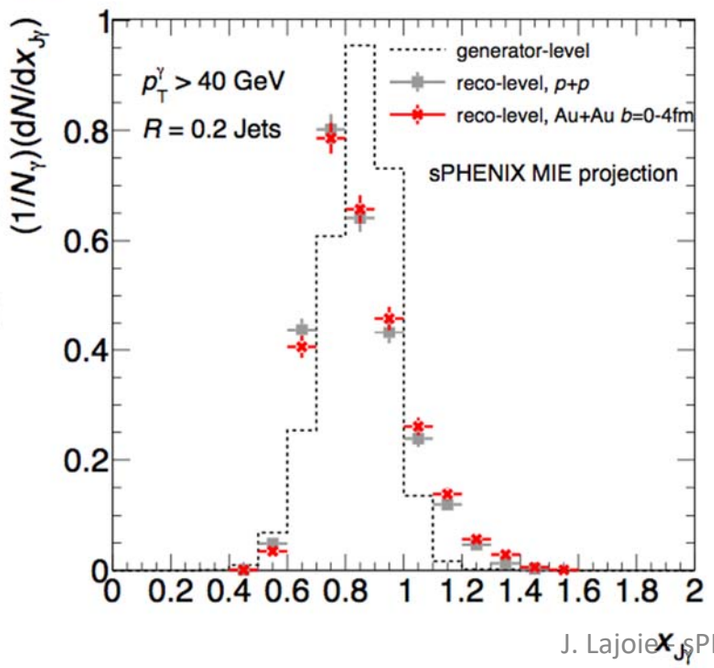
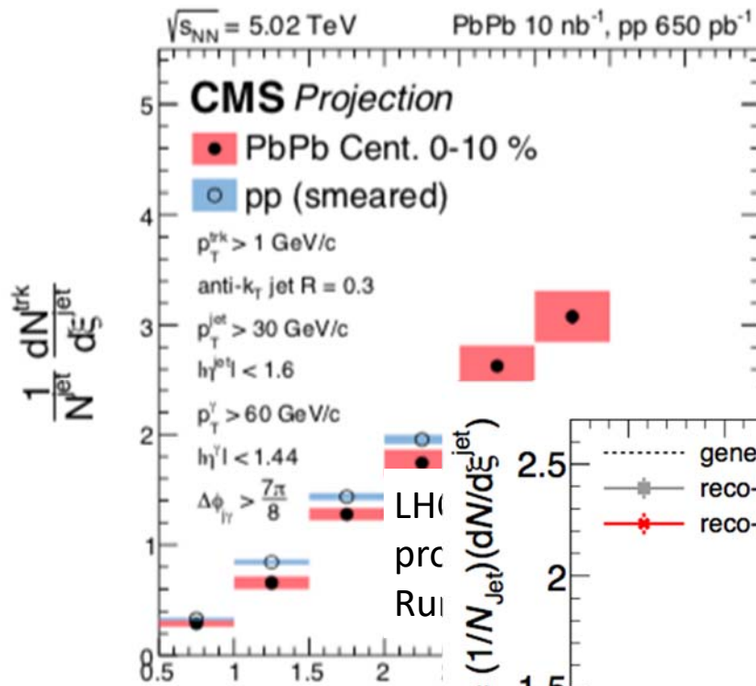
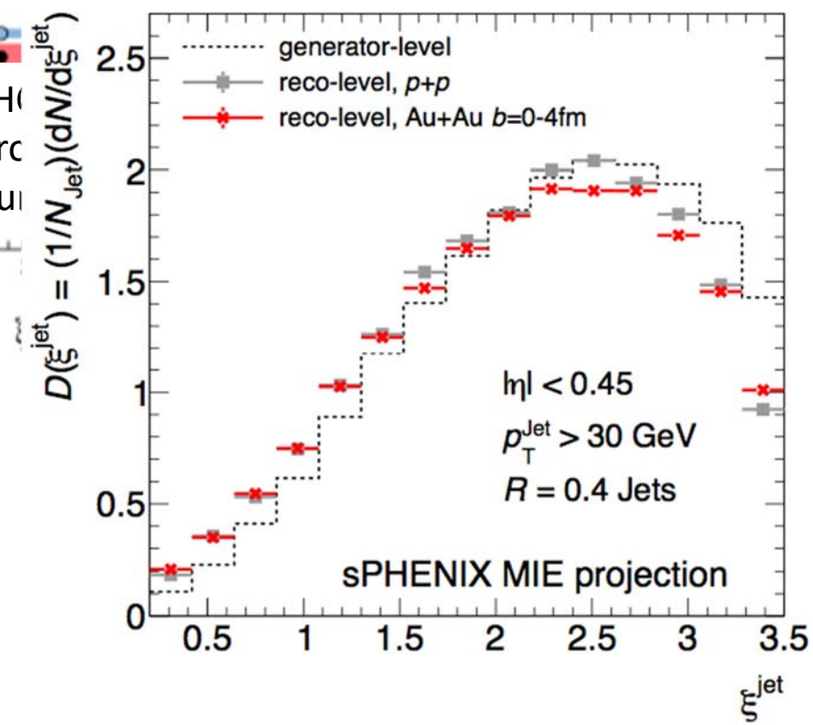


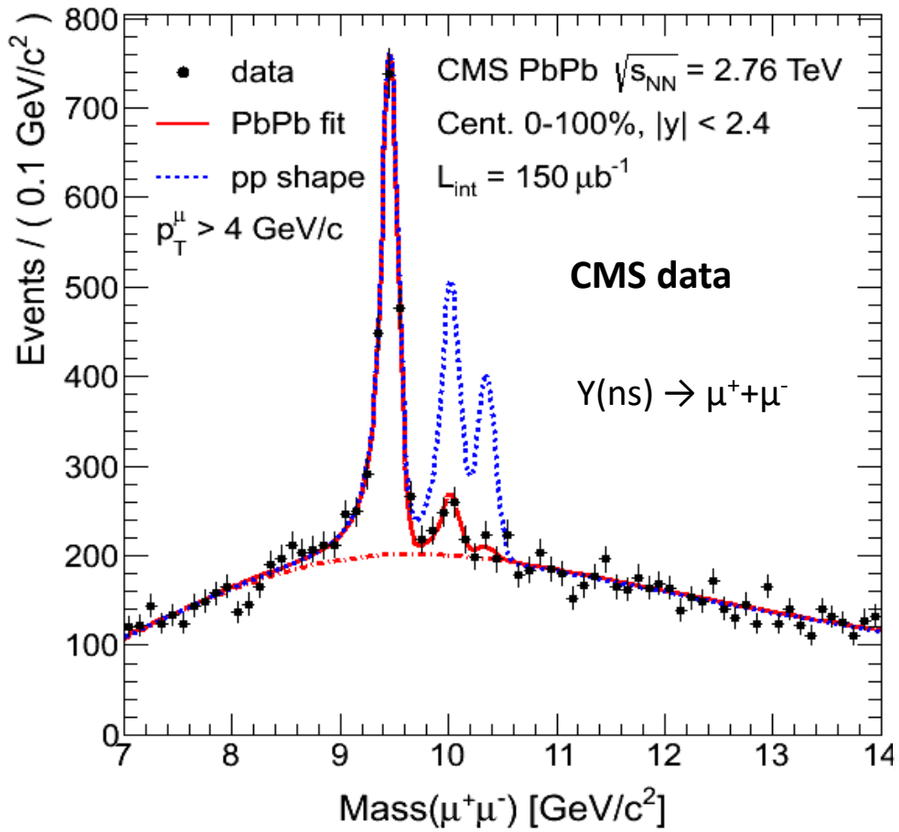
γ+Jet fragmentation function

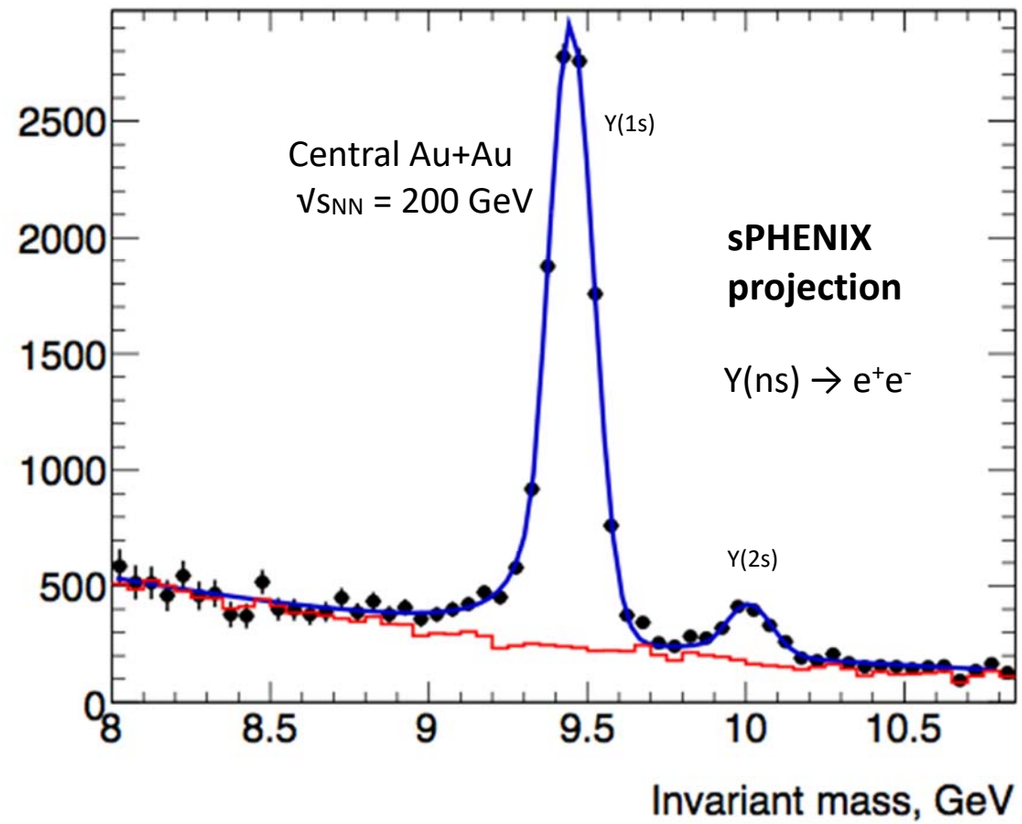


Modification of parton shower in QGP



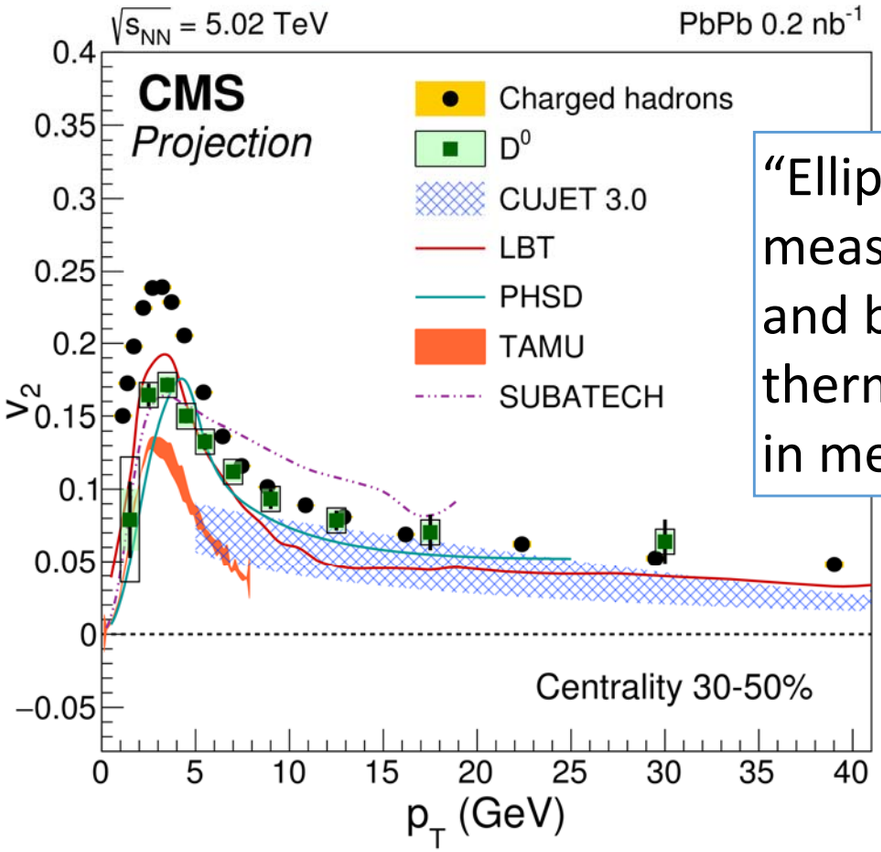
Upsilons at sPHENIX vs. LHC



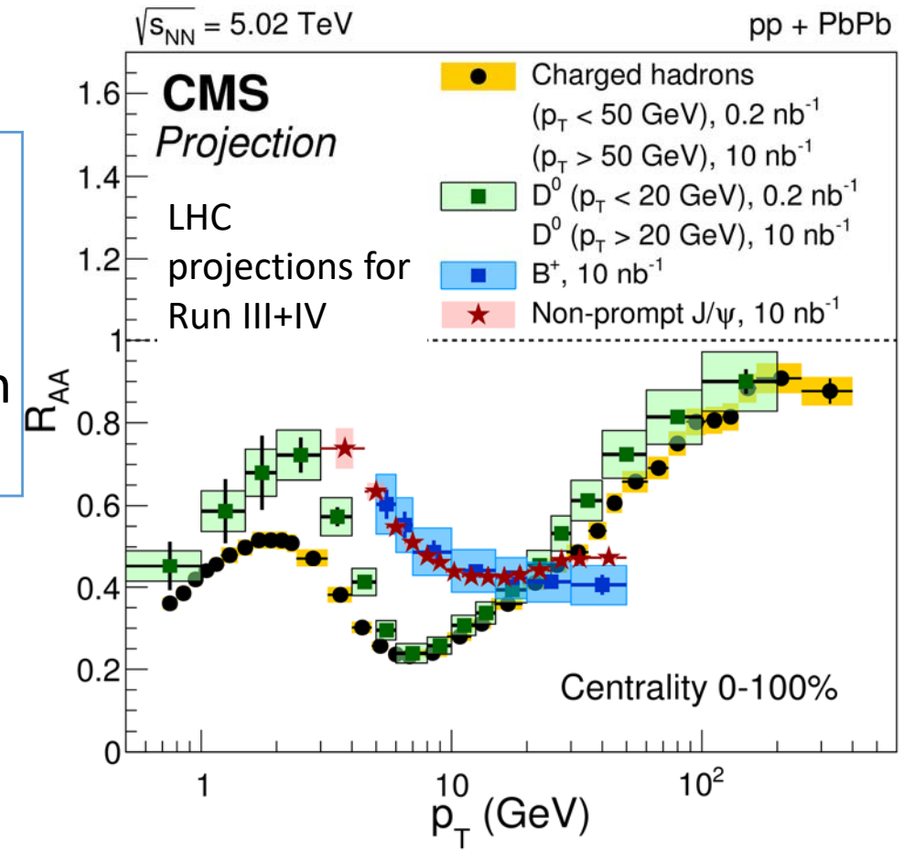


Sequential suppression of Υ(nS) states reveals QGP Debye screening length
As at LHC, Υ(3s) will be challenging to see in Au+Au at RHIC

Heavy flavor at sPHENIX vs. LHC

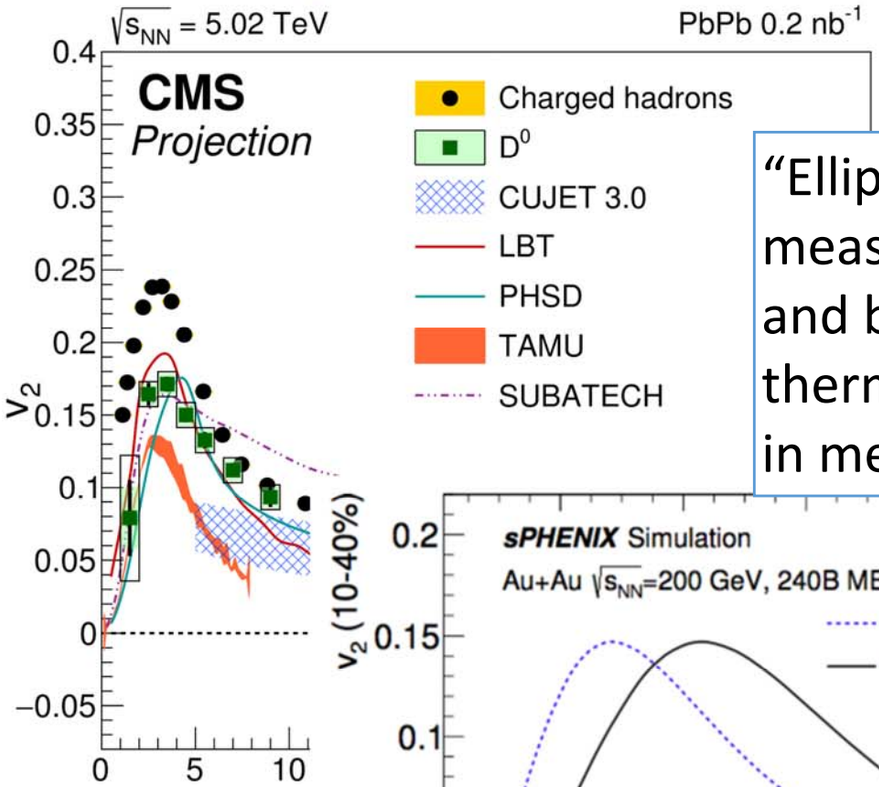


"Elliptic flow" measures c and b quark thermalization in medium



Open heavy flavor suppression probes flavor dependence of energy loss

Heavy flavor at sPHENIX vs. LHC



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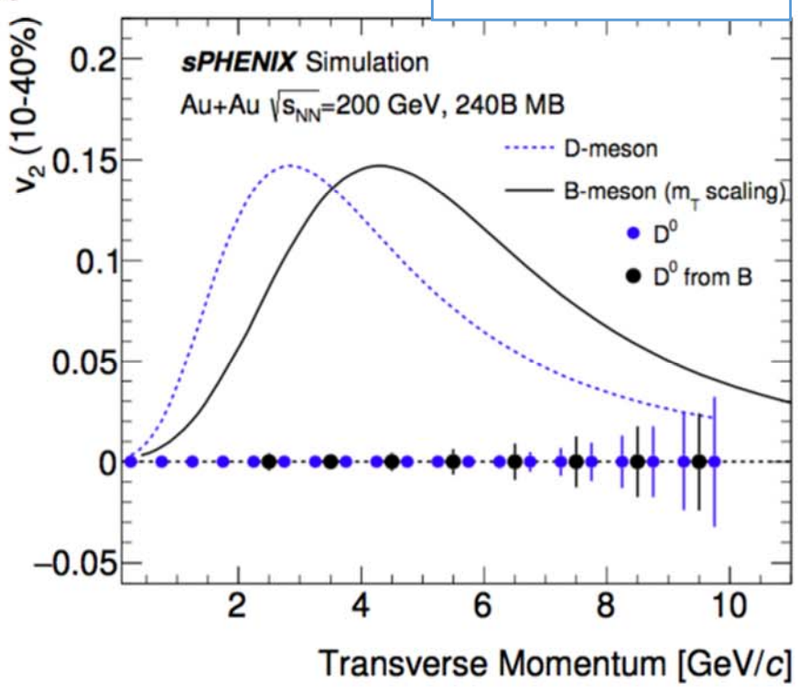
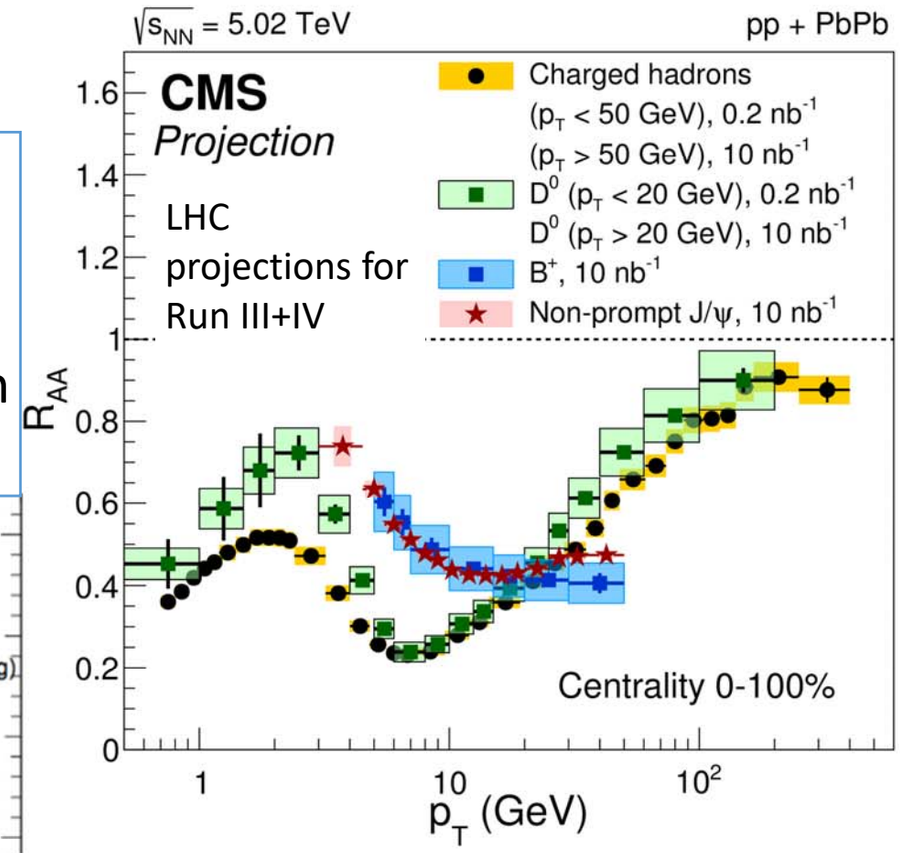
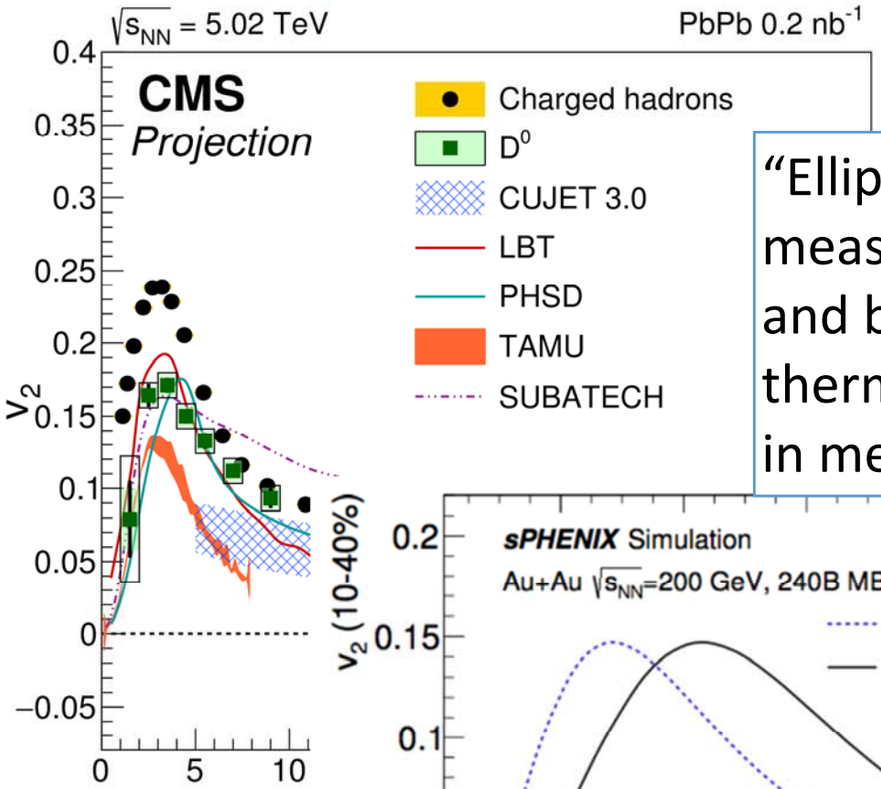


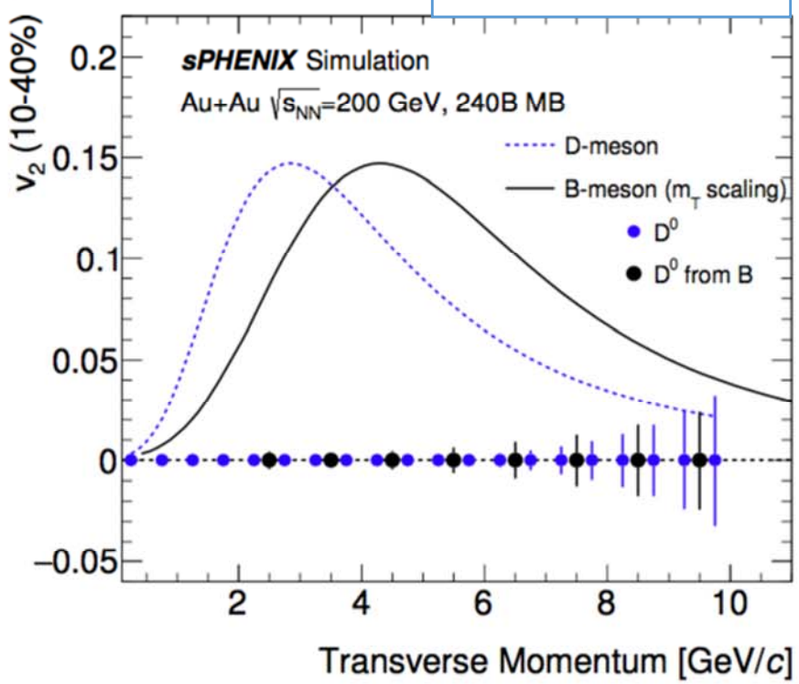


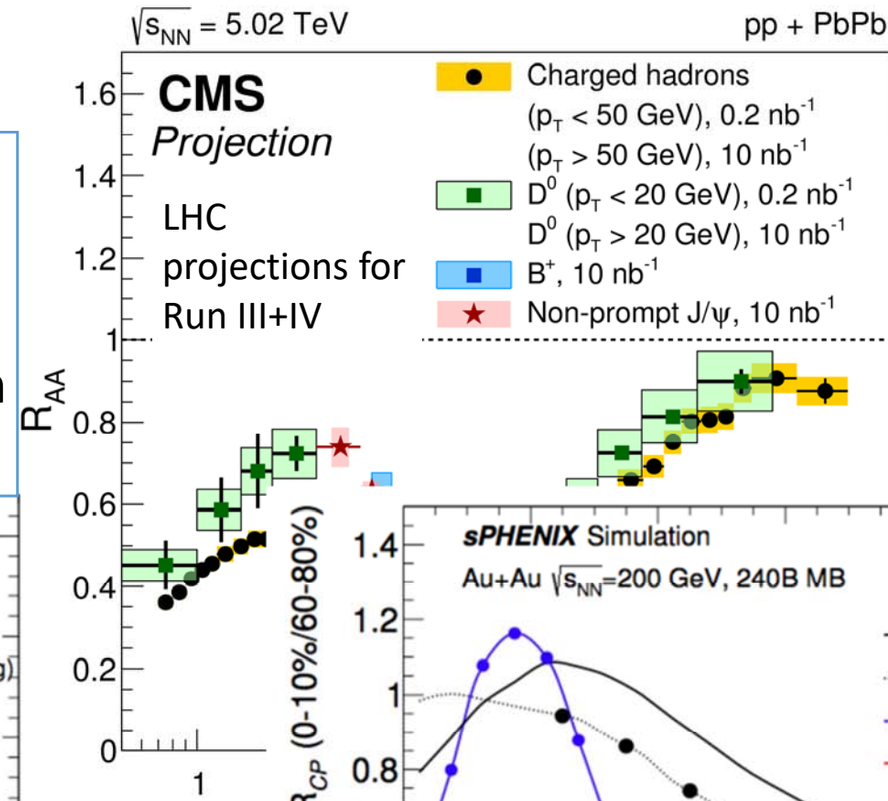
Open heavy flavor suppression probes flavor dependence of energy loss

Heavy flavor at sPHENIX vs. LHC

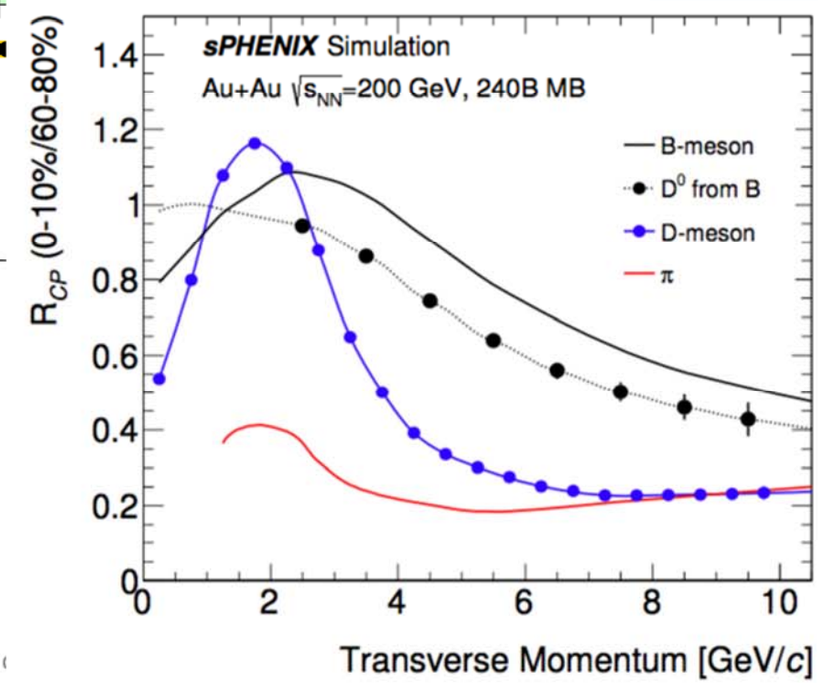


"Elliptic flow" measures c and b quark thermalization in medium

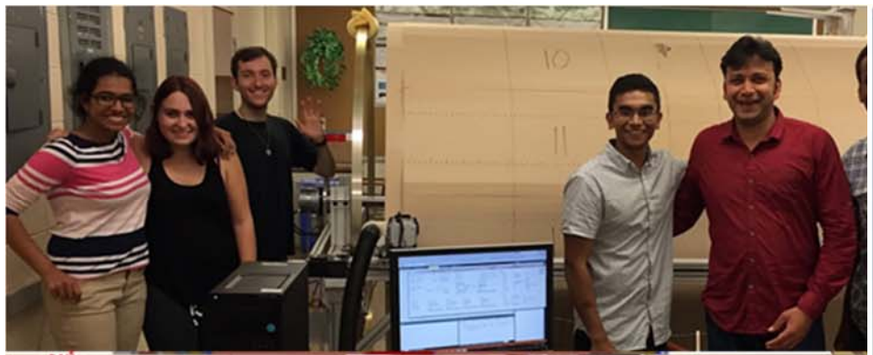


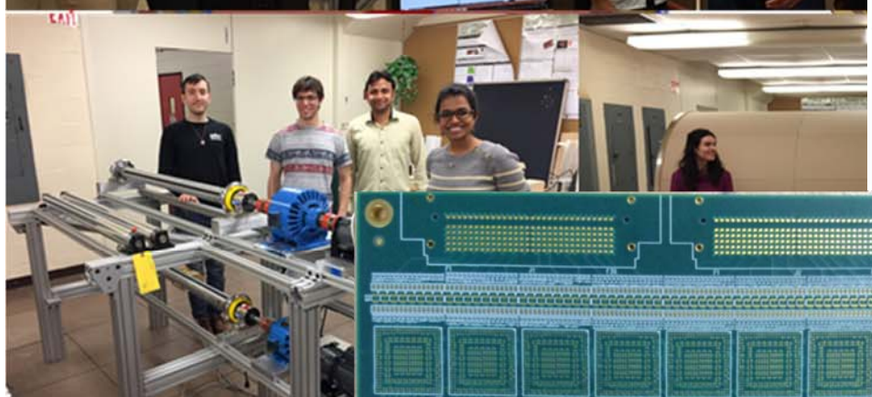


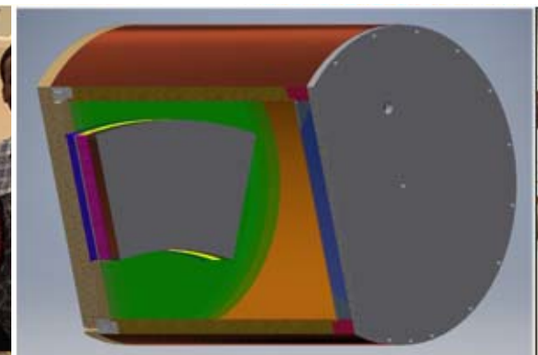
Open heavy flavor suppression probes flavor dependence of energy loss

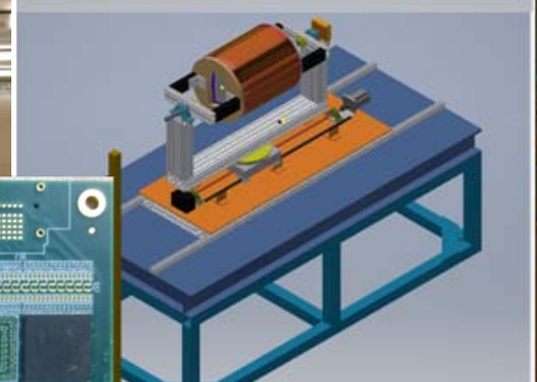


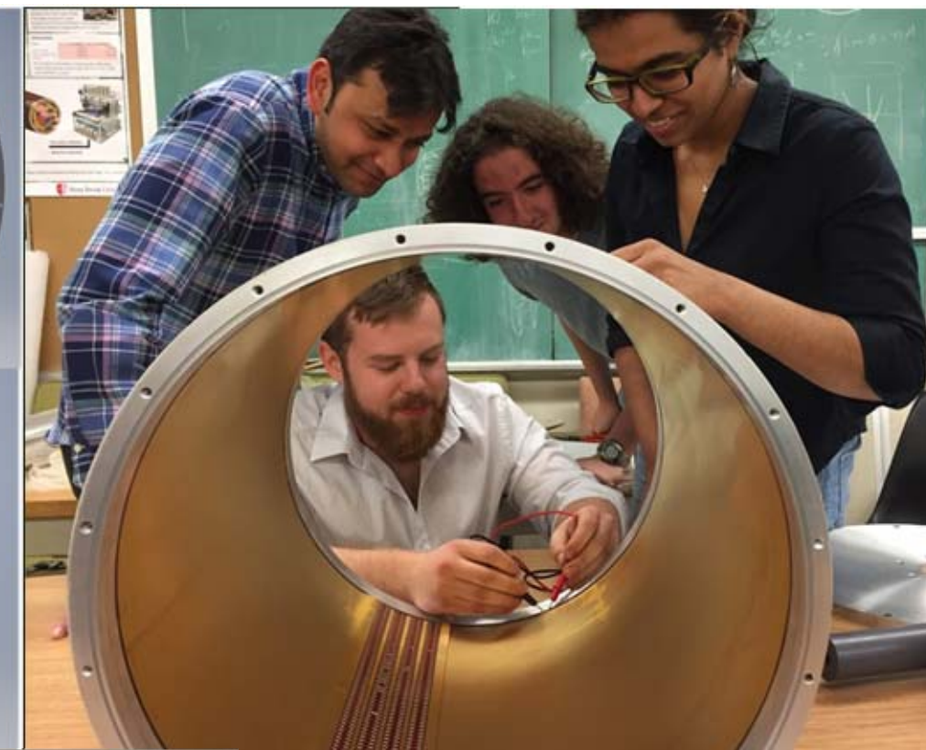
TPC Status & Highlights

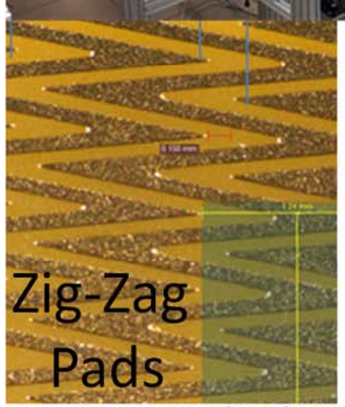








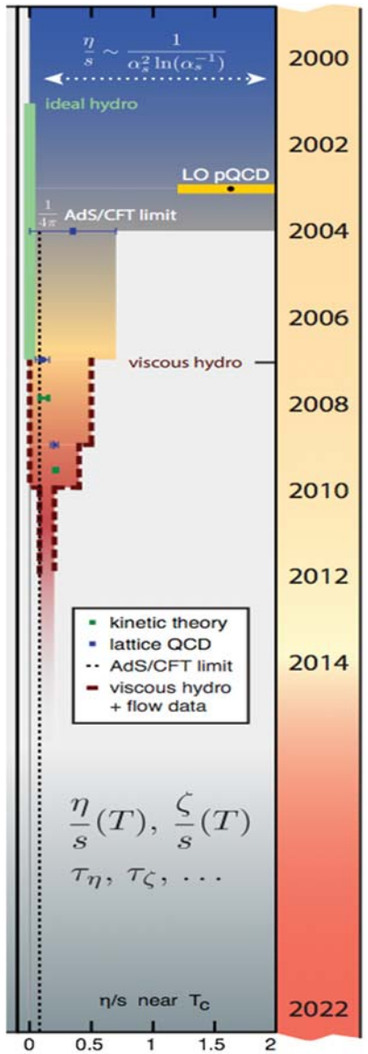


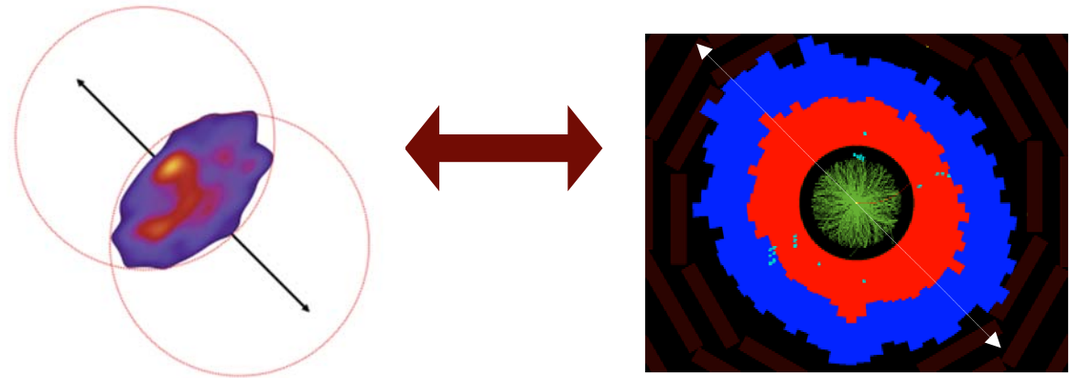


RHIC Comp Facility

Field Cage	1
Modules	72+spare
FEE	624+spare
DAM	24+spare
EDBC	24+spare

Strongly-Coupled Quark-Gluon Plasma





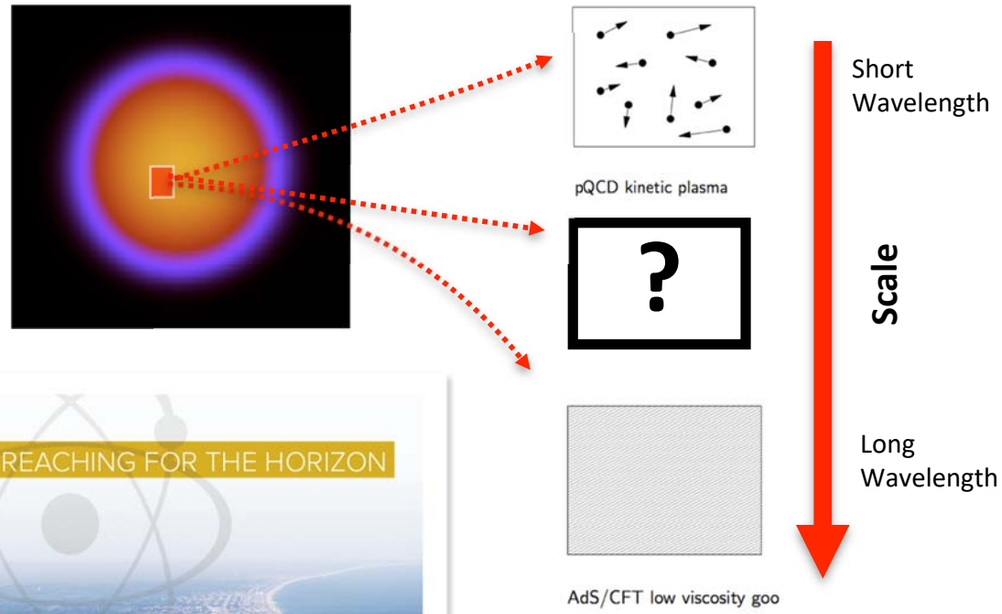
Established **viscous hydrodynamics** as effective theory of long-wavelength dynamics of QGP

Direct connection of final state correlations to structure and fine-structure of initial state

Extracted QGP properties quantitatively, most prominently **transport coefficient η/s ~ 1/(4π): *most perfect liquid***

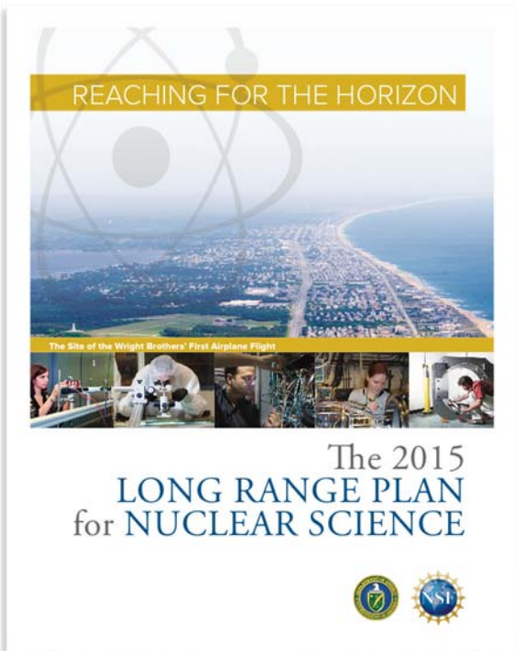
Connections to strong coupled matter in many fields of physics (string theory to cold atoms)

sPHENIX Science Mission



How does QGP work?

What is its microscopic structure?



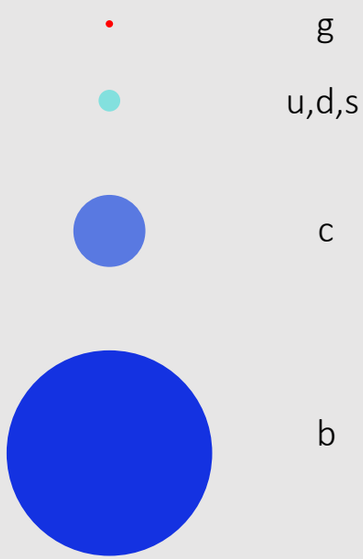
Section 2.2, page 22

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.

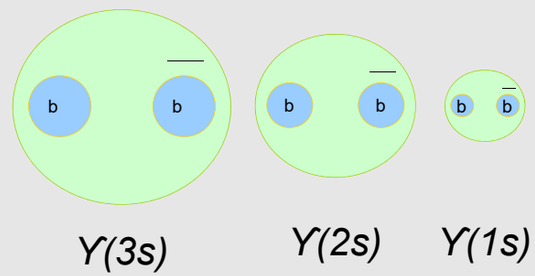
NP LRP: “Probe the inner workings of QGP”

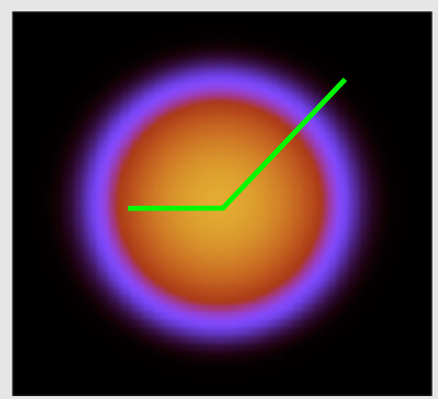
Three key approaches to study QGP structure at multiple scales:

Parton energy loss
vary mass/momentum of probe

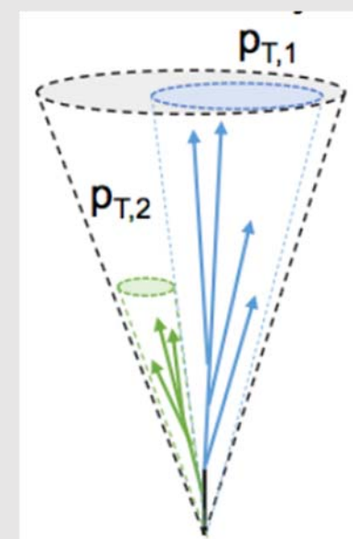


Quarkonium spectroscopy
vary size of probe



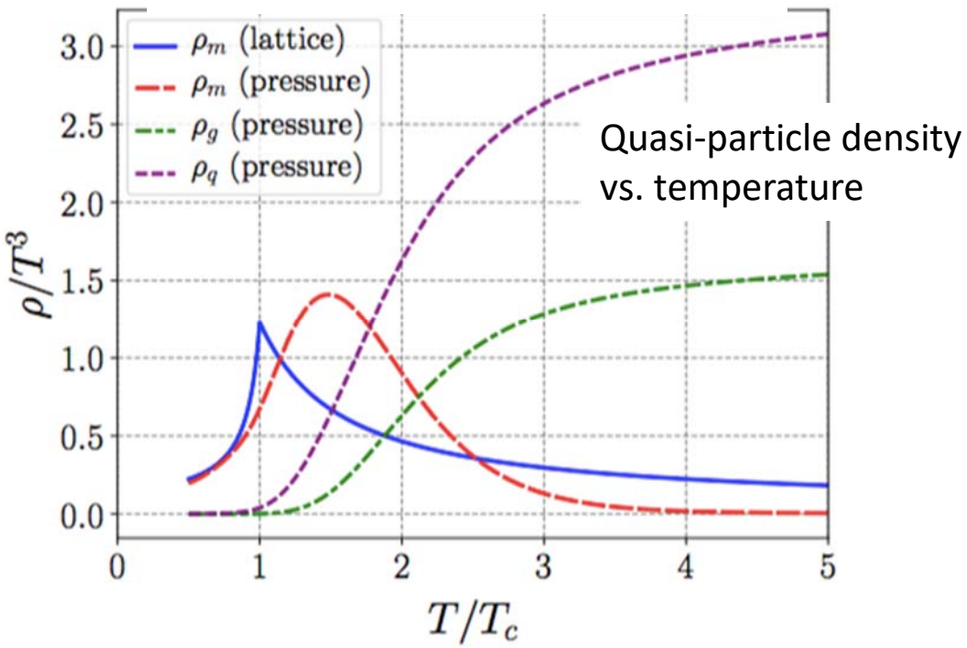


Jet structure
vary momentum/angular scale of probe

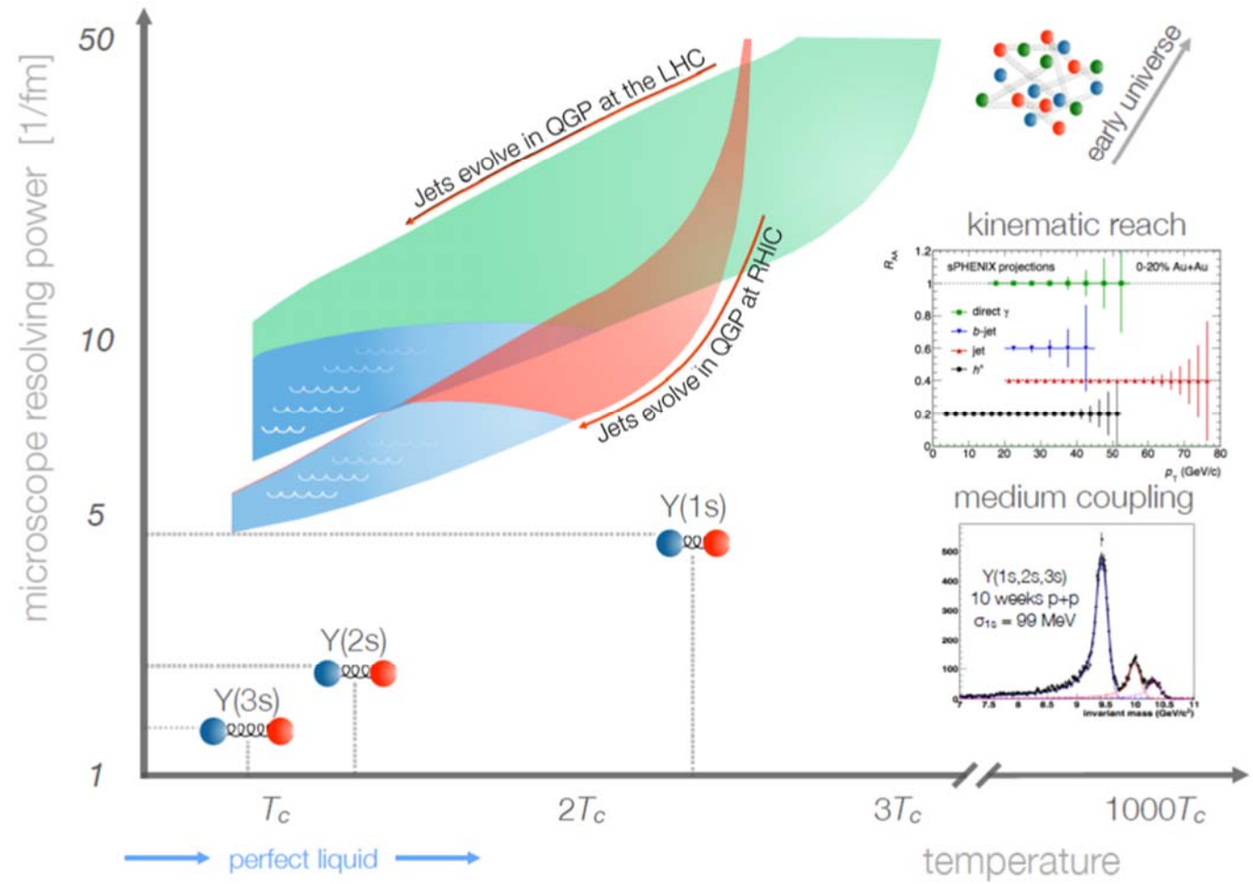


Complementarity: Why RHIC *and* LHC?

A. Ramamurti, E. Shuryak,arXiv:1708.04254



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



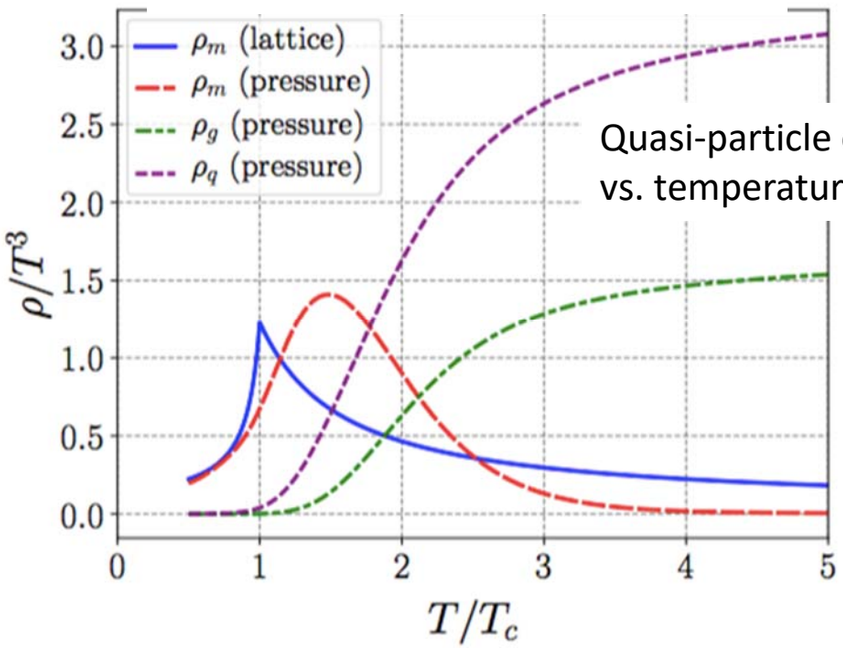
Structure of QGP expected to depend on T

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

RHIC QGP spends more time near T_c

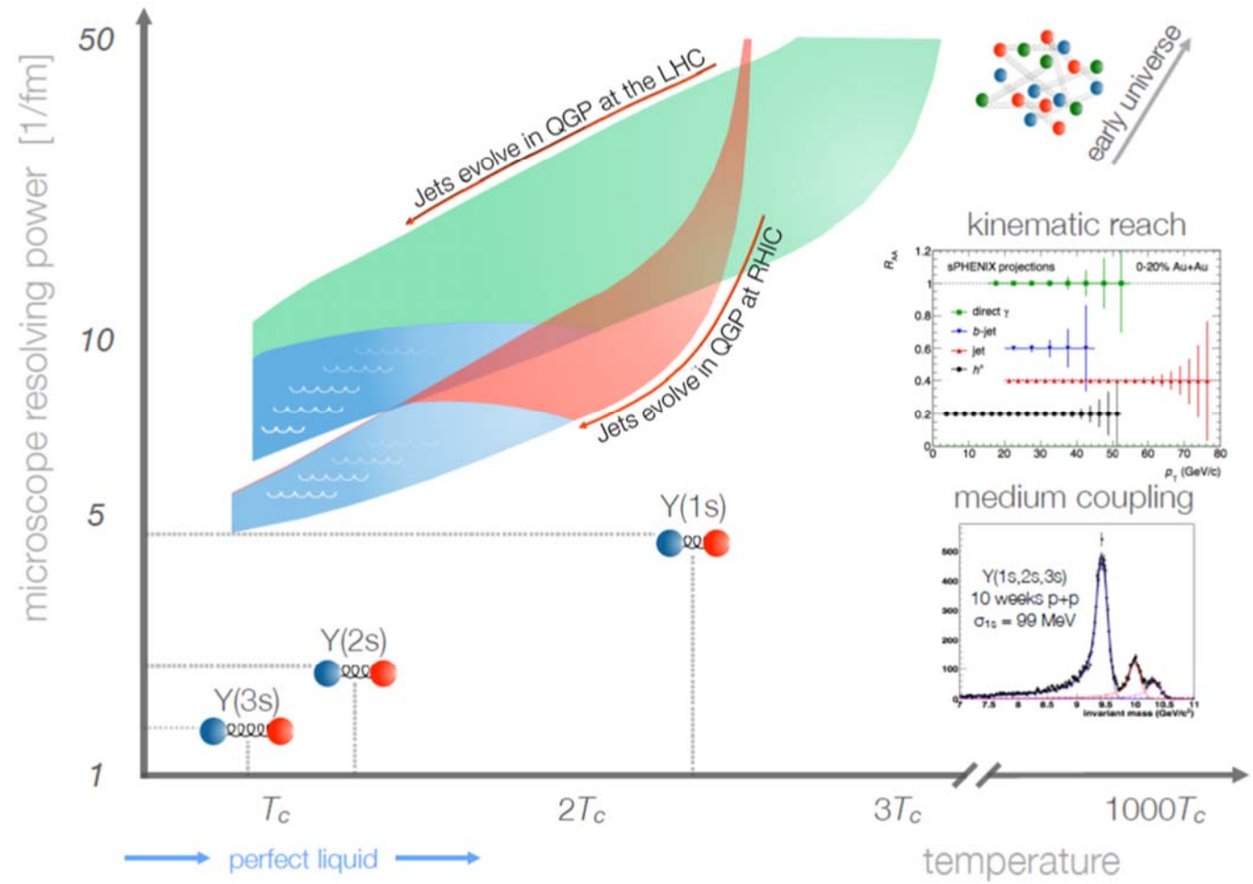
Complementarity: Why RHIC *and* LHC?

A. Ramamurti, E. Shuryak,arXiv:1708.04254



Quasi-particle density vs. temperature

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



Structure of QGP expected to depend on T

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

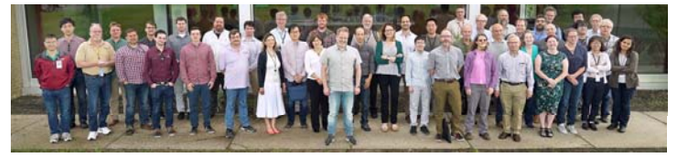
RHIC QGP spends more time near T_c

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

sPHENIX collaboration: 70+ institutions

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

Growth of collaboration since CD-0

2016

Berkeley UNIVERSITY OF CALIFORNIA

TEMPLE UNIVERSITY

BERKELEY LAB Lawrence Berkeley National Laboratory

2017

PURDUE UNIVERSITY

cea

CENTRAL CHINA NORMAL UNIVERSITY

2018

University of Science and Technology of China 1958

FUDAN UNIVERSITY 1905

TSINGHUA UNIVERSITY 1911

SUN YAT-SEN UNIVERSITY

IMP

SINAP

北京大学 PEKING UNIVERSITY

IAE

Broad expertise in relevant physics, silicon, TPCs, calorimetry

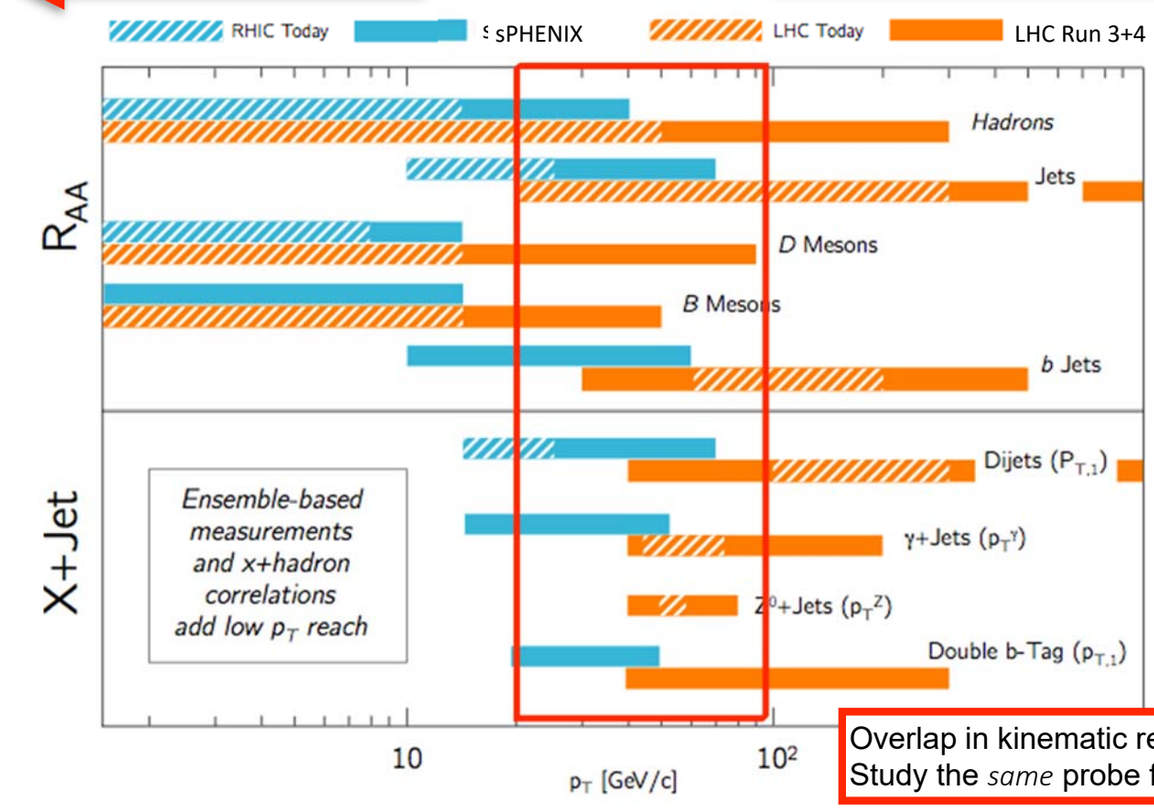
Complementarity of RHIC and LHC

Low p_T @RHIC:
Extend kinematic reach vs LHC
Lower background fluctuations

High p_T @LHC:
Extend kinematic reach vs RHIC
Add new probes

Single Hadrons and Jets

Jet+jet and photon+jet correlations



Overlap in kinematic reach:
Study the *same* probe for *different* QGP evolution

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}

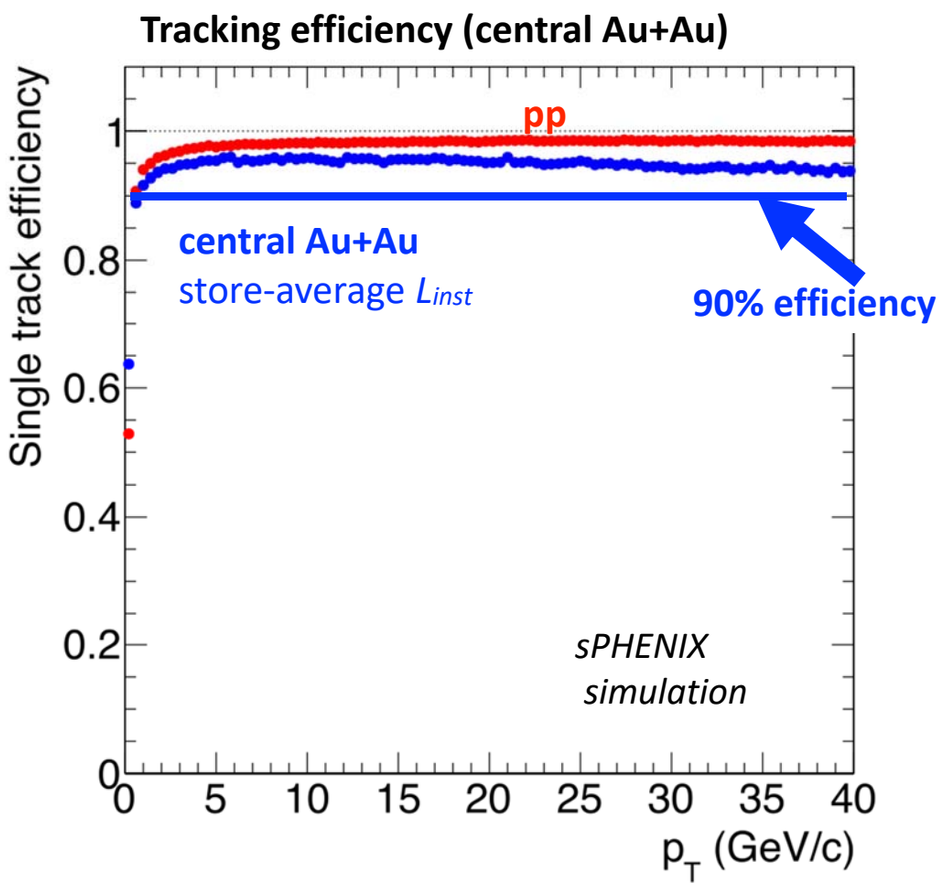
- Consistent with DOE CD-0 “mission need” document
- Incorporates BNL C-AD guidance on luminosity evolution
- Incorporates commissioning time in first year

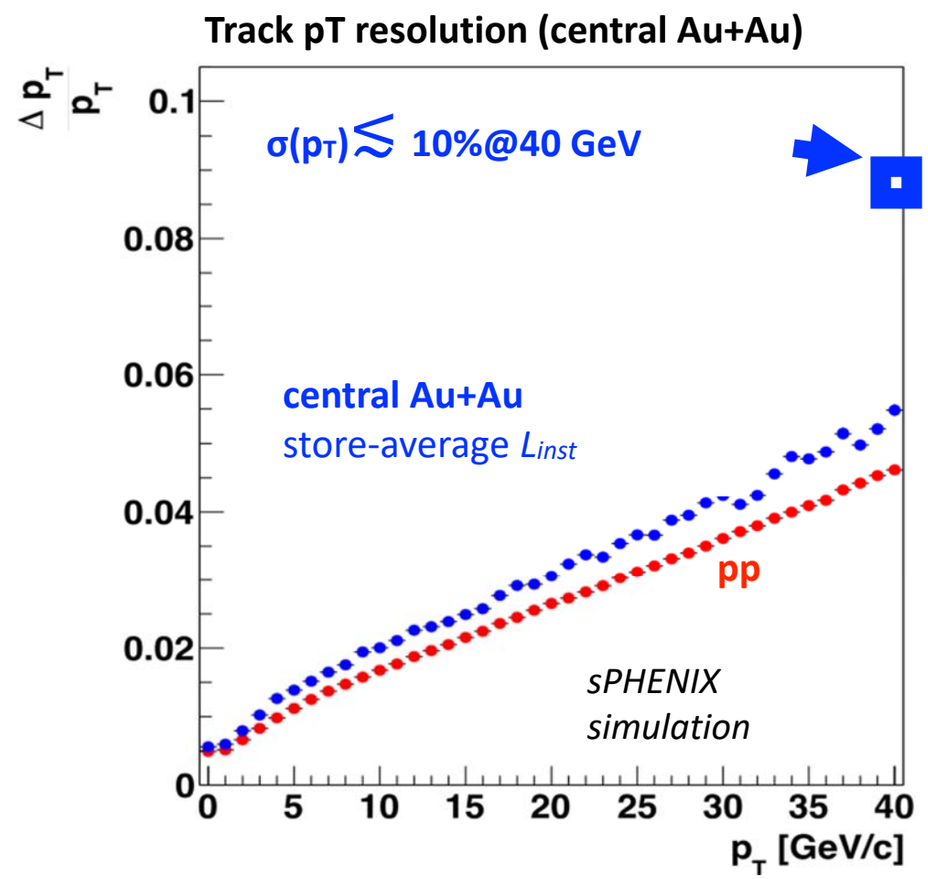
Minimum bias Au+Au at 15 kHz for |z| < 10 cm:

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.

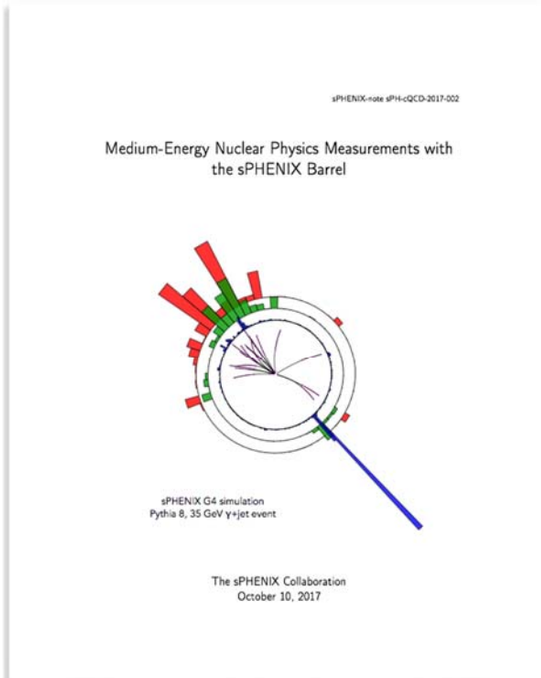
Tracking efficiency and resolution





Cold QCD with sPHENIX barrel

Charge from ALD, delivered 10/2017

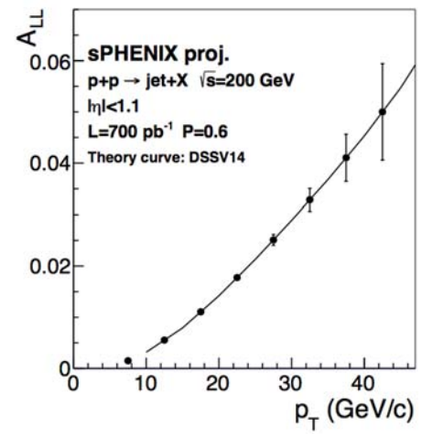

sPHENIX-note sPH-cQCD-2017-002

Medium-Energy Nuclear Physics Measurements with the sPHENIX Barrel

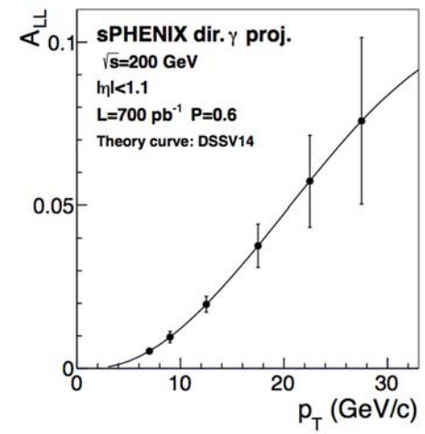
sPHENIX G4 simulation
Pythia 8, 35 GeV γ+jet event

The sPHENIX Collaboration
October 10, 2017

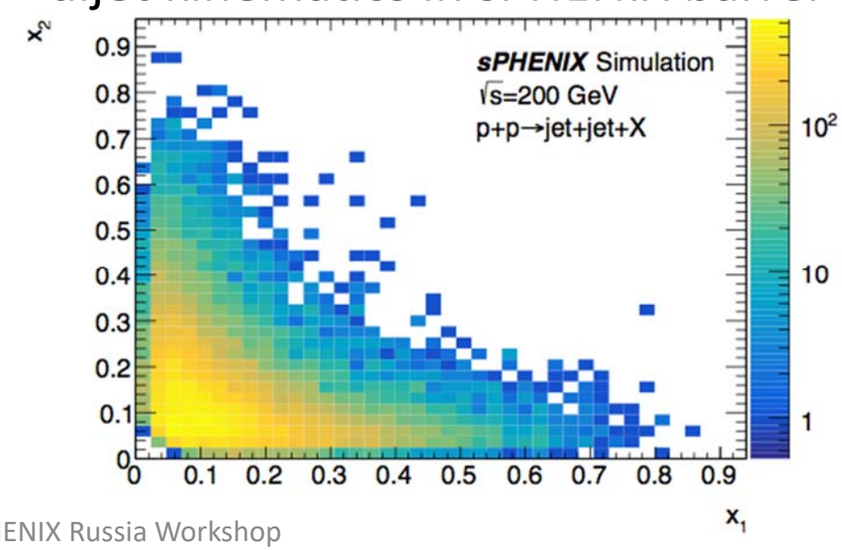
jet A_{LL}



direct γ A_{LL}



dijet kinematics in sPHENIX barrel

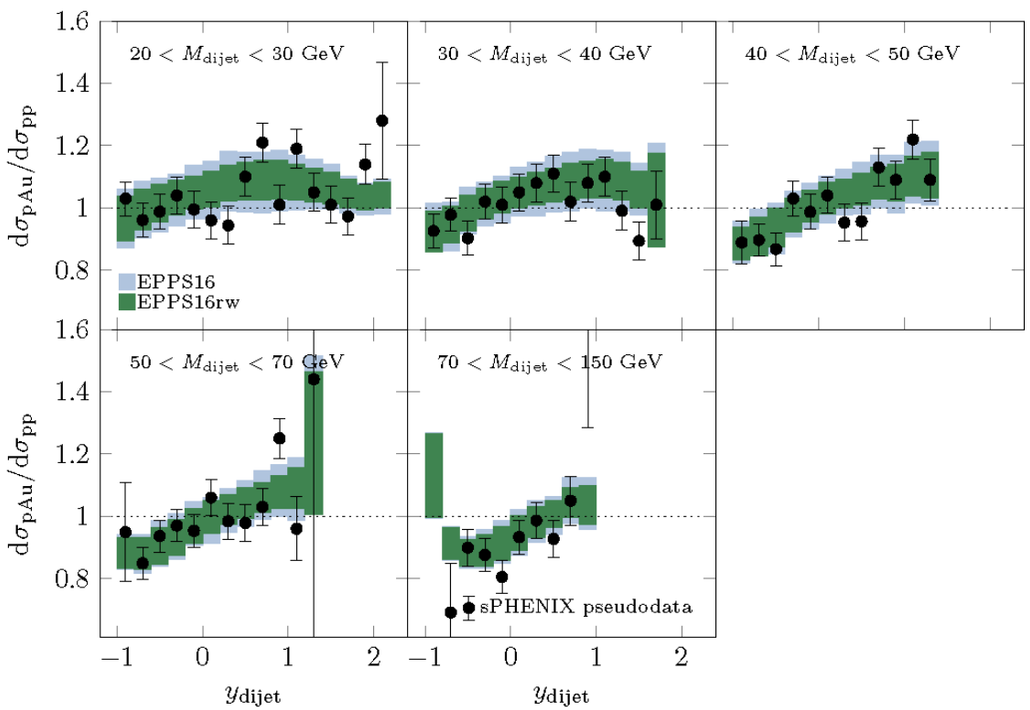


Projected capabilities for observables in longitudinally, transversely polarized collisions, nPDFs

Nuclear PDF's

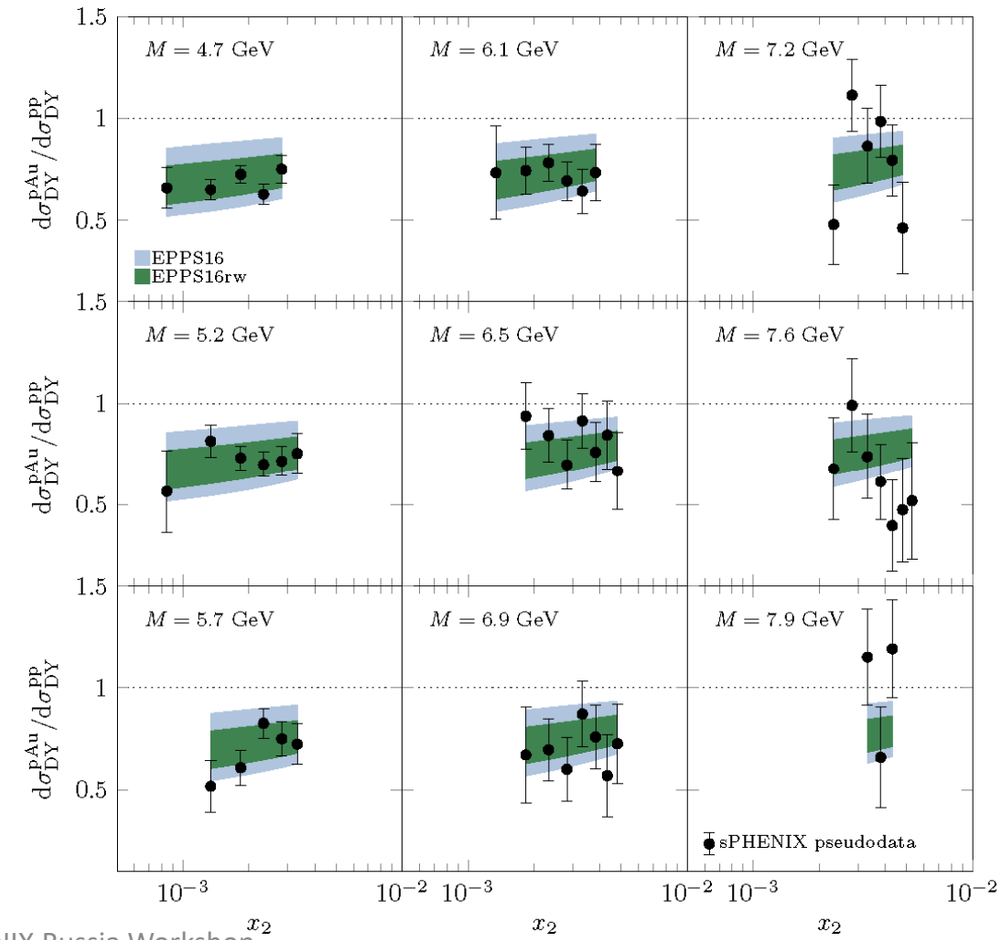
Can we use multiple datasets (with similar systematics) to overcome the normalization limitation?

Central (|η|<1) + Forward dijets (1.6<η<3.6)
(used primarily to fix normalization)



EPPS16 reweighting by H. Paukunen and P. Paakkinen

Forward DY (after normalization fixed)



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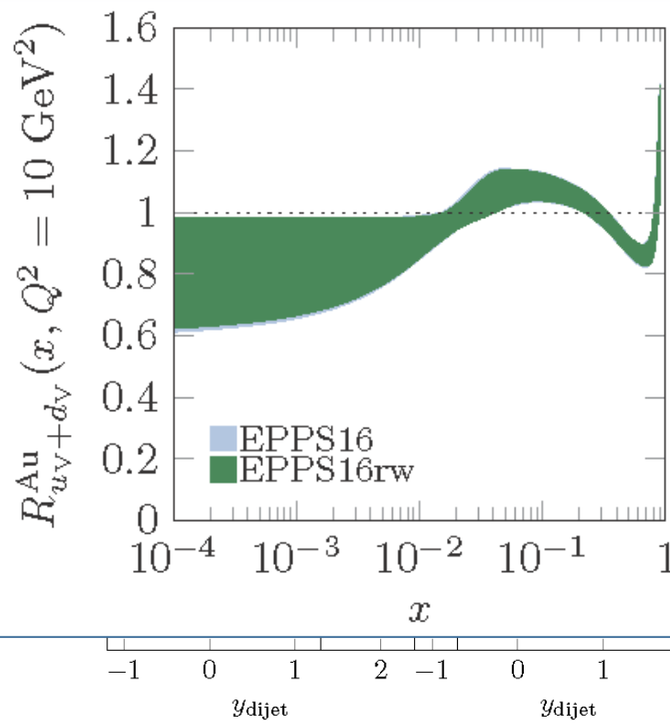
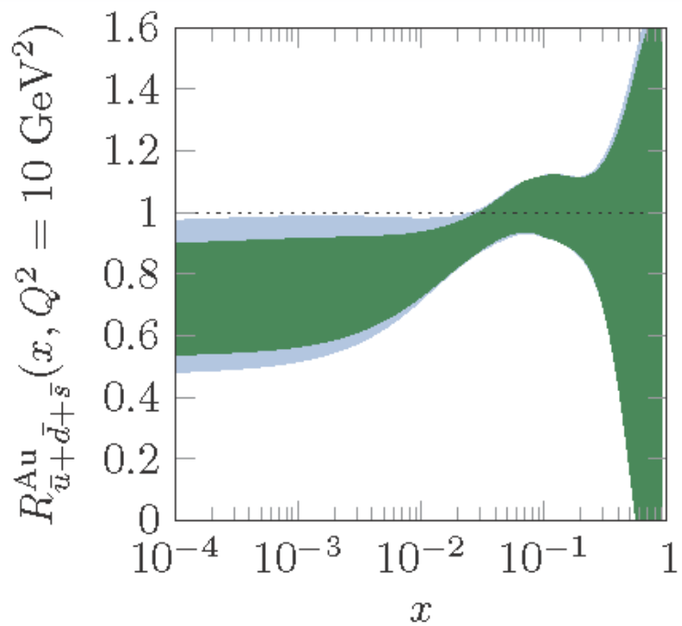
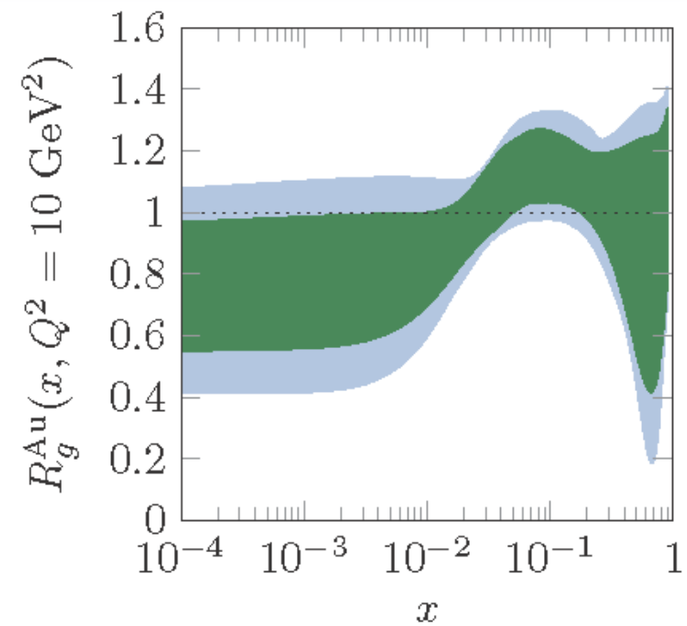
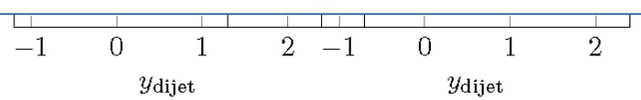
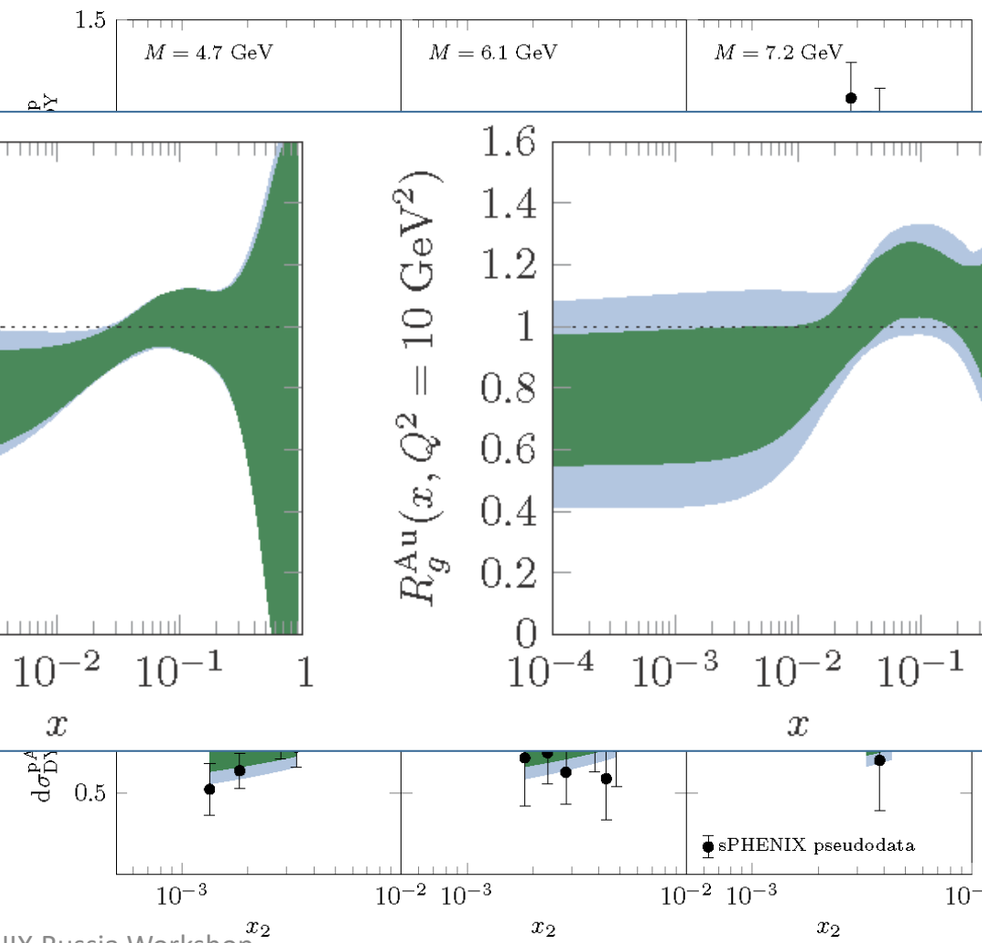






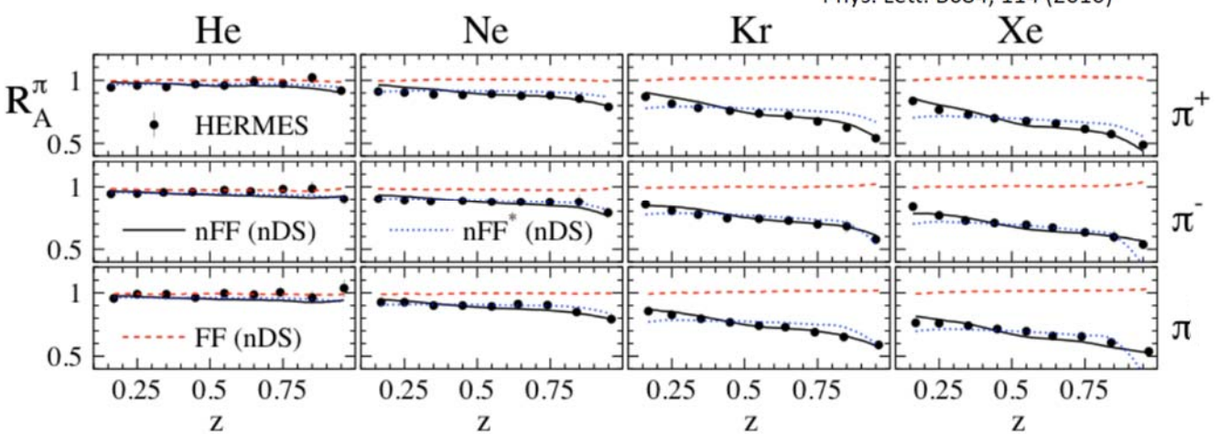




EPPS16 reweighting by H. Paukunen and P. Paakkinen

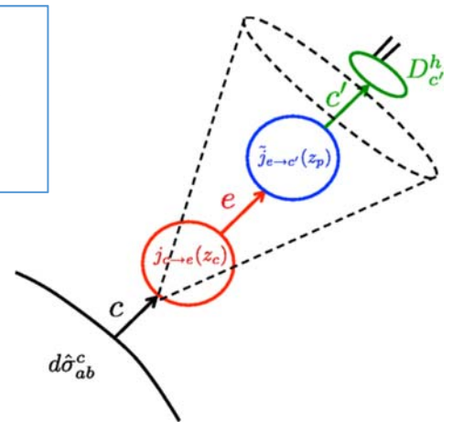
Fragmentation in a Nuclear Environment

Phys. Lett. B577, 37 (2003)
Phys. Lett. B684, 114 (2010)

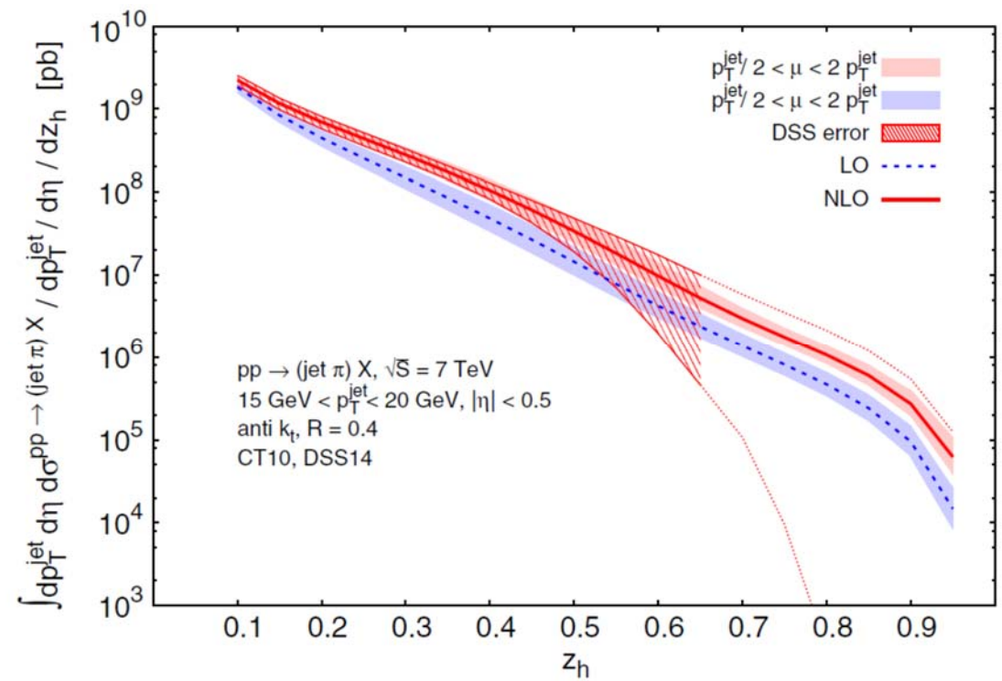


Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect!

Access fragmentation functions (FF) through p+p(A) -> (jet *h*) X



Kaufmann, Mukherjee and VogelsangPhys.Rev.D 92 5, 054015



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Phys. Lett. B577, 37 (2003)
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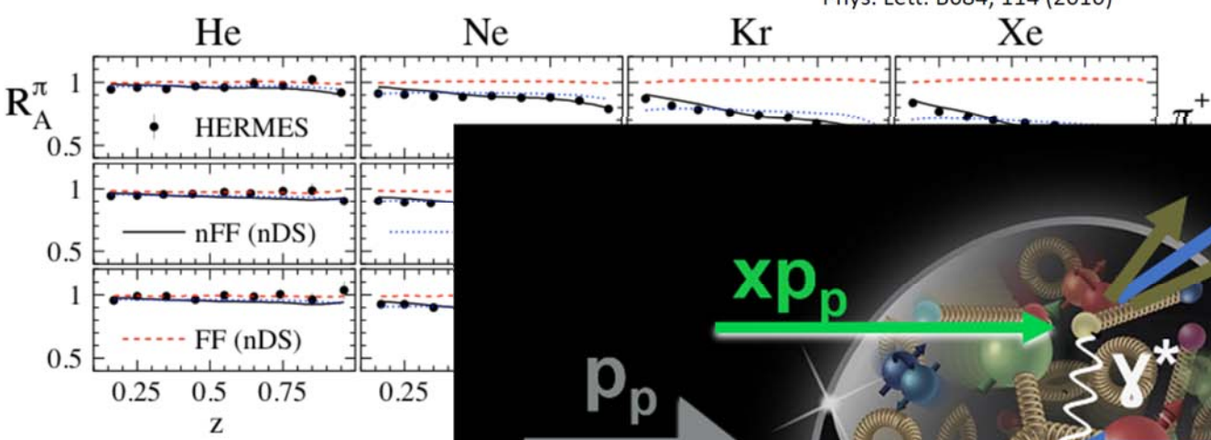

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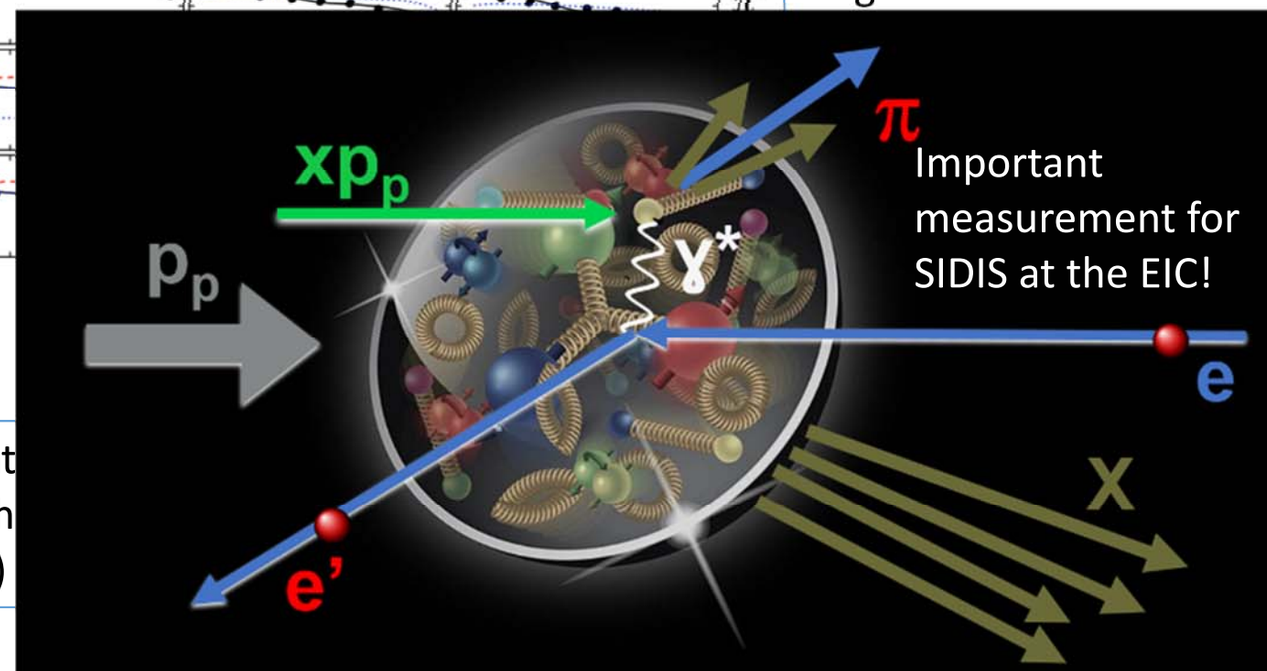
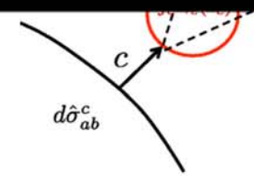
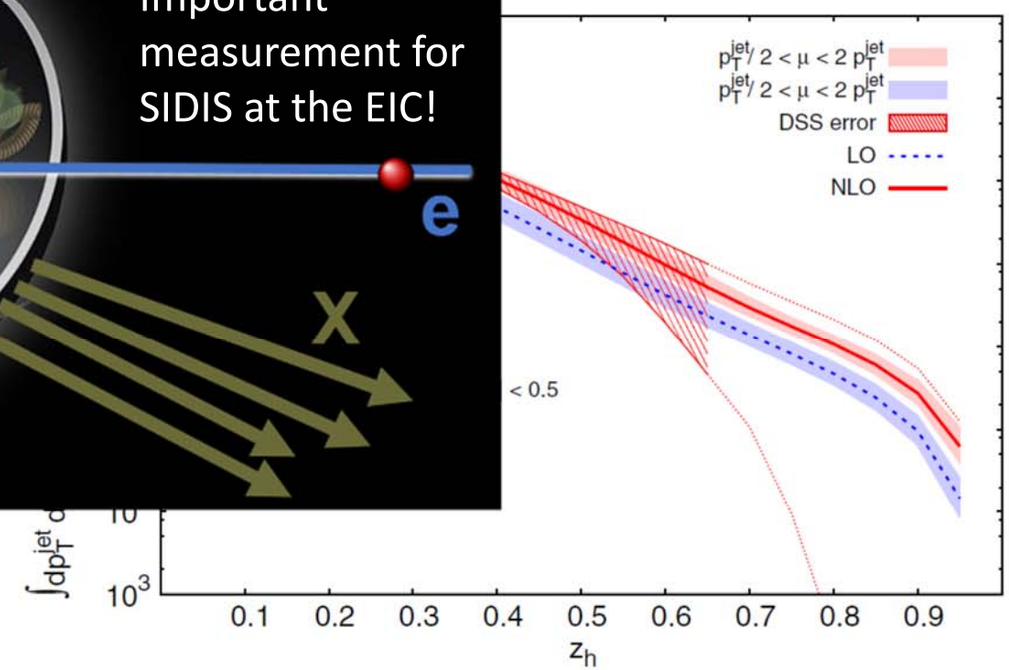


Important measurement for SIDIS at the EIC!

Access fragment
functions (FF) th
p+p(A) -> (jet *h*)

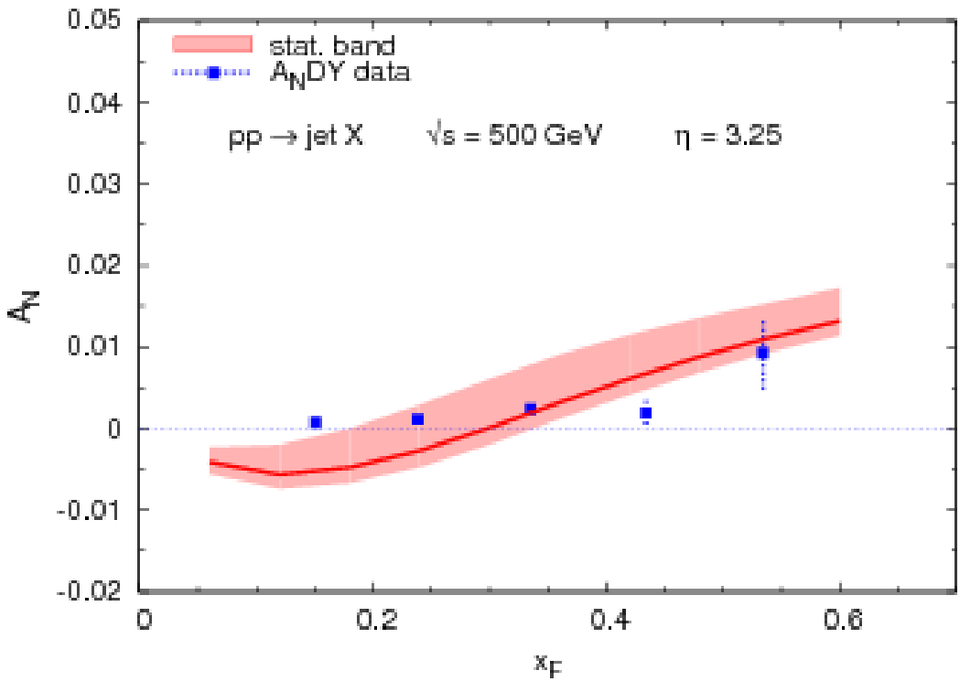


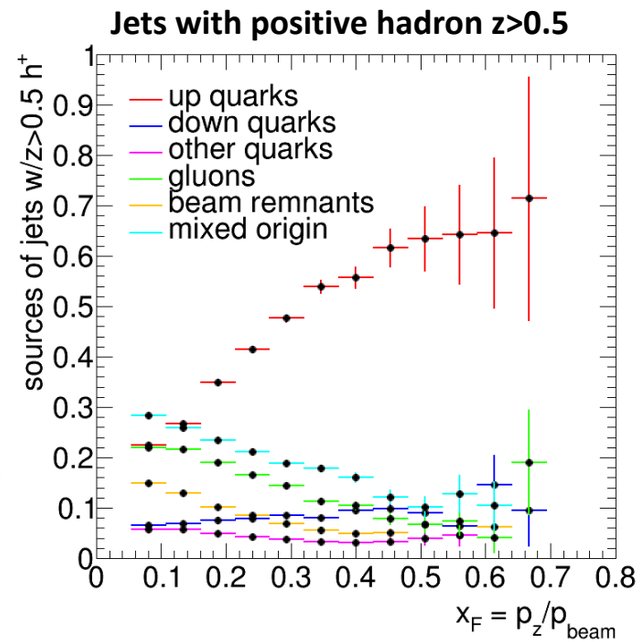
VogelsangPhys.Rev.D 92 5, 054015

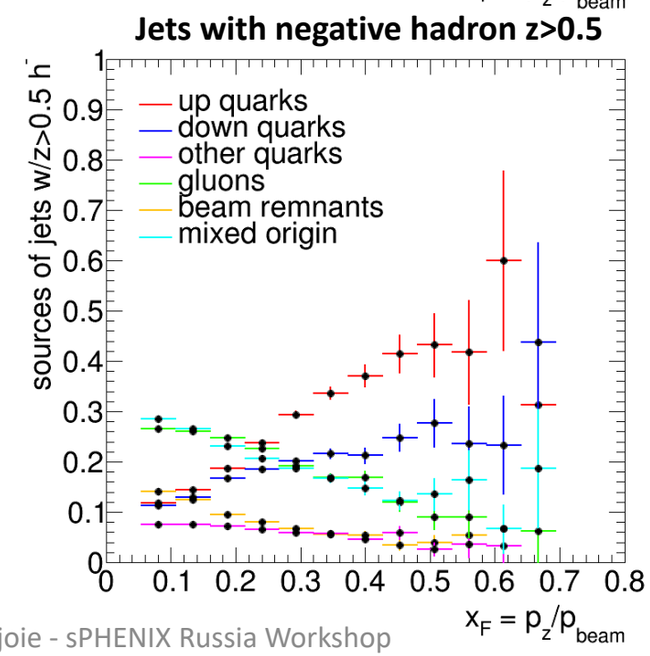


An Unresolved Mystery…

AnDY: Phys. Lett. B750 (2015) 660



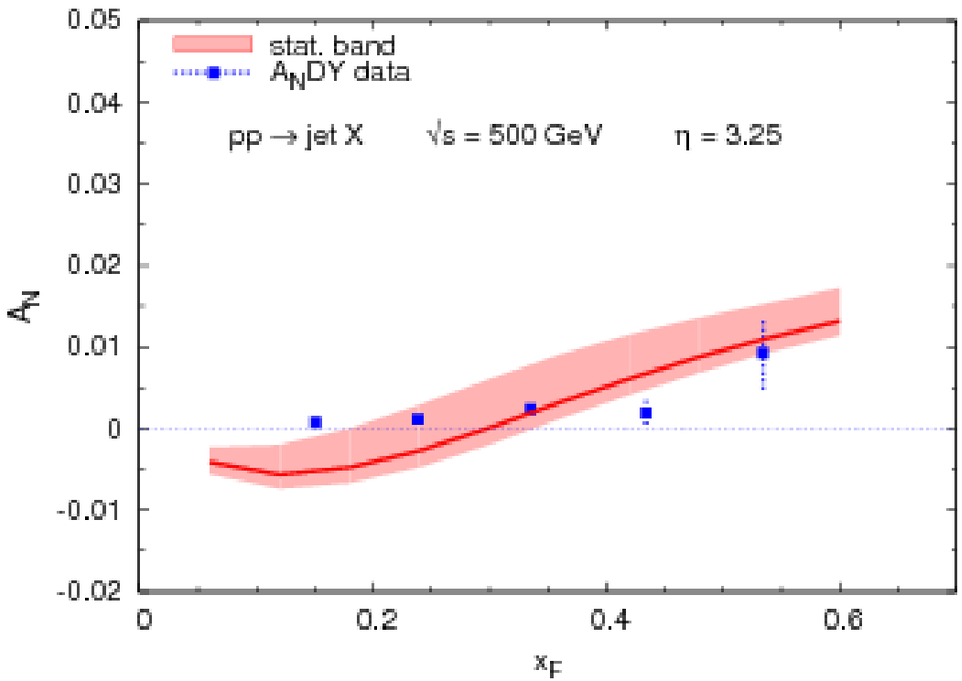


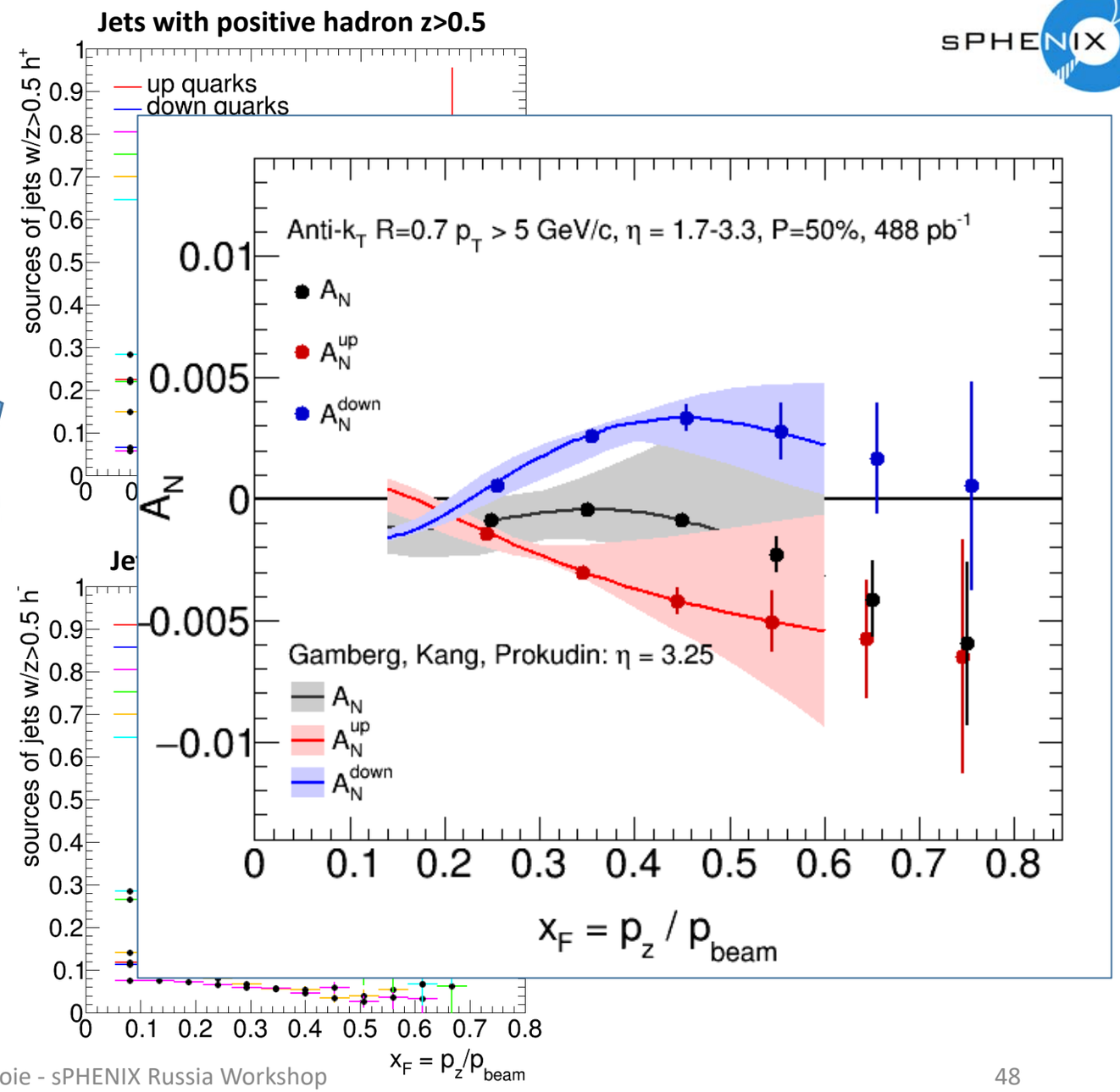


A cut on the charge of the leading hadron changes the composition of the jet sample (Pythia simulation).

An Unresolved Mystery…

AnDY: Phys. Lett. B750 (2015) 660

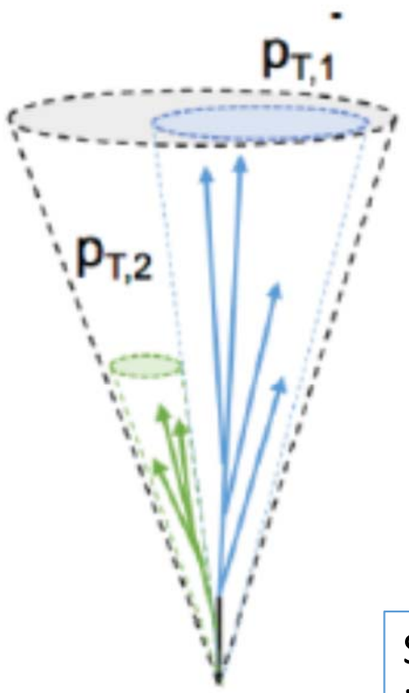




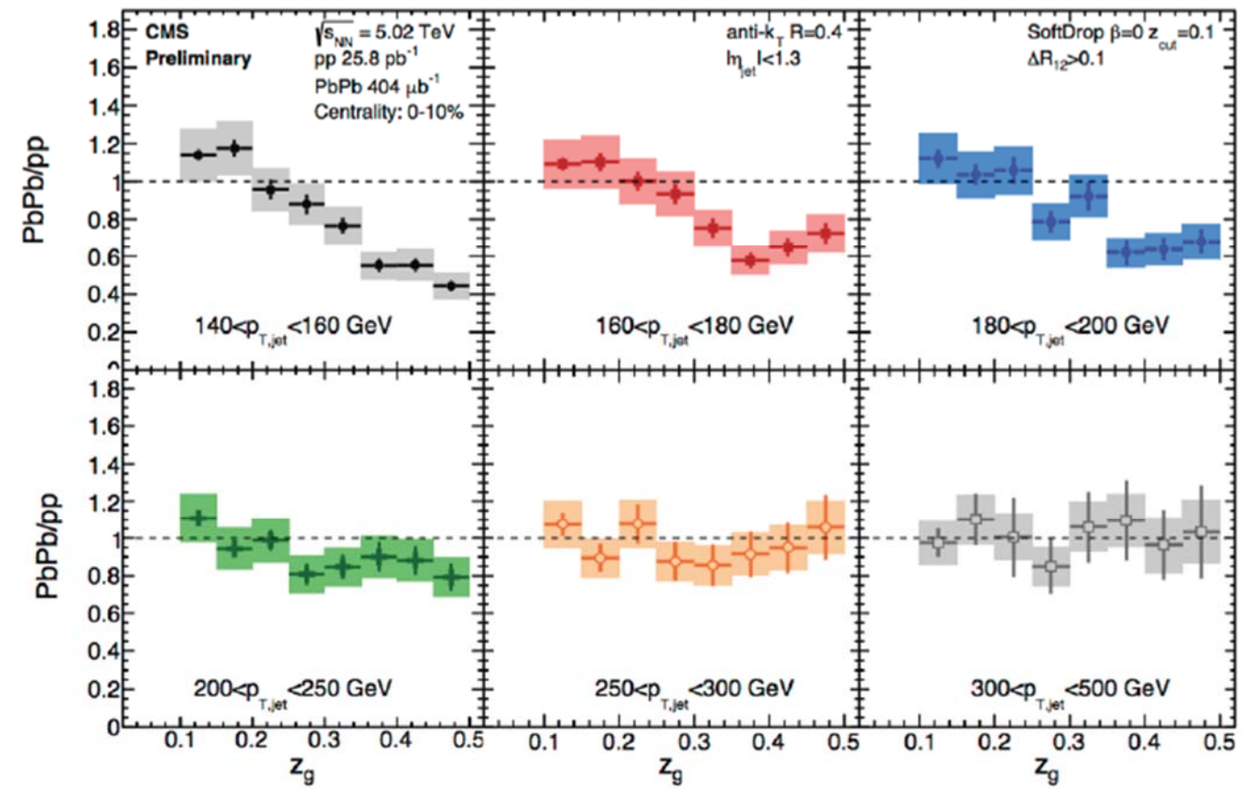
A cut on the charge of the leading hadron changes the composition of the jet sample (Pythia simulation).

Jet Substructure

CMS PAS HIN-16-006



$$z_g = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$



Soft-drop grooming combined with a Cambridge-Aachen type decomposition of a jet found with an anti-k_T algorithm – provides detailed information about the first parton splitting!

An excellent way to study cold QCD effects in fragmentation <u>in detail</u>!