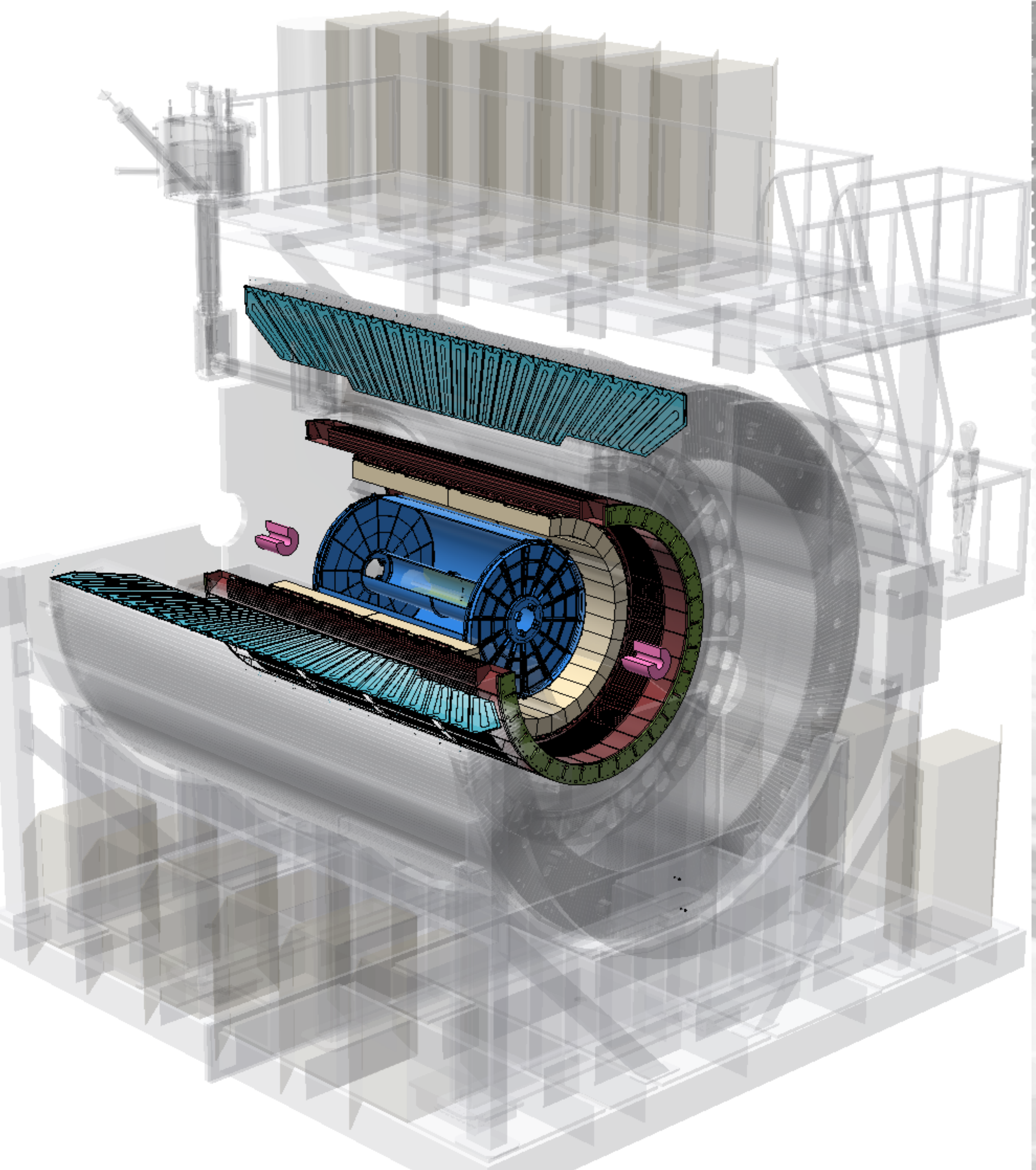
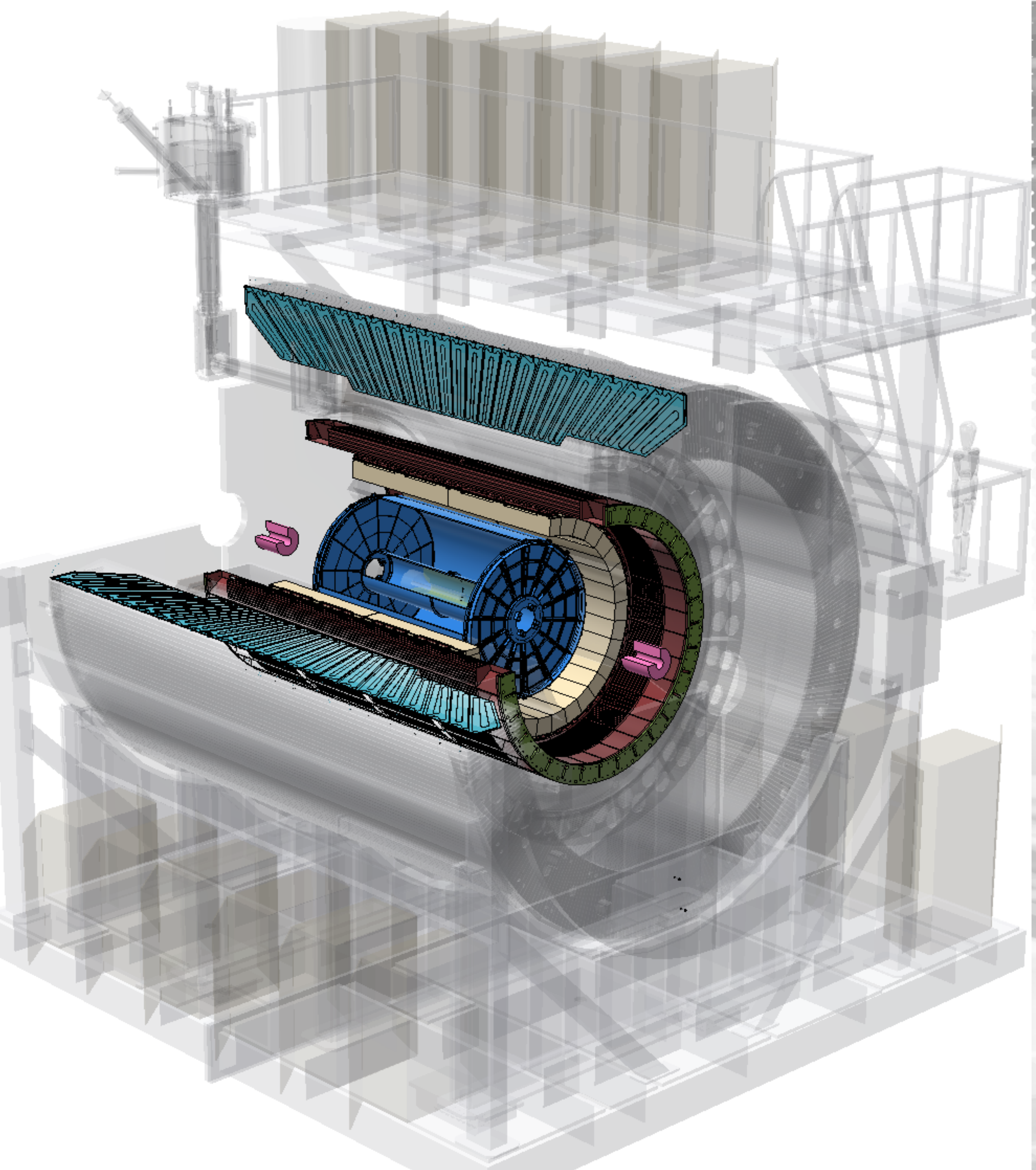


sPHENIX Physics Program

Dave Morrison (BNL)
Gunther Roland (MIT)
for the collaboration

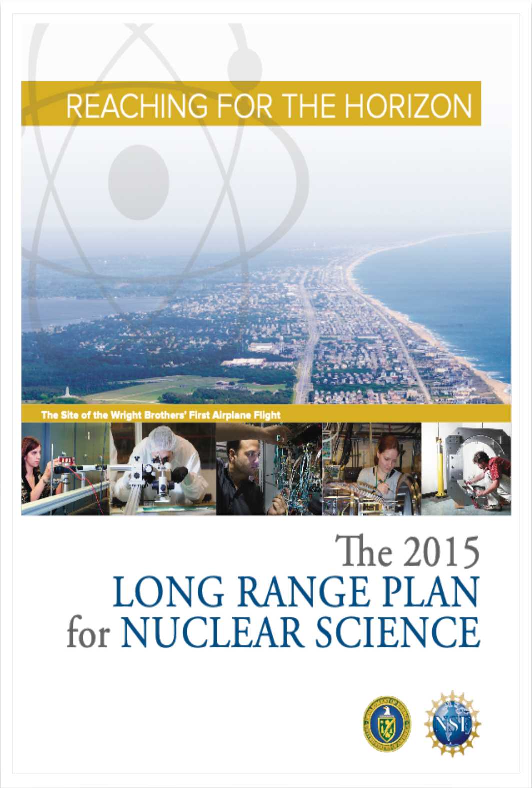


Points of Discussion for the FY 2019 S&T Review of RHIC

- The quality, productivity, and significance of the laboratory's scientific and technical accomplishments and the merit, feasibility and impact of its future planned physics program;
  - Plans for utilization of existing data sets and completing analysis of existing RHIC data
  - Plans for analyzing large volume sets of future sPHENIX data within envelop of existing computing resources.
  - Only an overview presentation on theory is needed, including articulation of accomplishments in last year, and update on LQCD efforts @ BNL.
- The effectiveness and appropriateness of facility operations and the planning for future facility upgrades in support of the research program;
  - Overview of instrumentation efforts, including MVTX, plans for calorimeter restoration for sPHENIX, sPHENIX schedule, and small CE efforts.
  - Status of LEReC performance
  - Description of main activities of Collider-Accelerator Department (C-AD), including plans and approach to possible pursuit of CeC.
- The effectiveness of management in strategic planning, developing appropriate core competencies, implementing a prioritized and optimized program, and promoting and implementing a diverse, inclusive, and safe work environment;
- The leadership, creativity, and productivity of the facility's scientific and technical staff in carrying out the above activities; and
- The quality and appropriateness of the laboratory's interactions with, and nurturing of, its scientific community.
  - Describe the interface and synergies with the Center for Frontiers for Nuclear Science at Stonybrook
  - Description of how community resources leverage the RHIC program

sPHENIX science mission

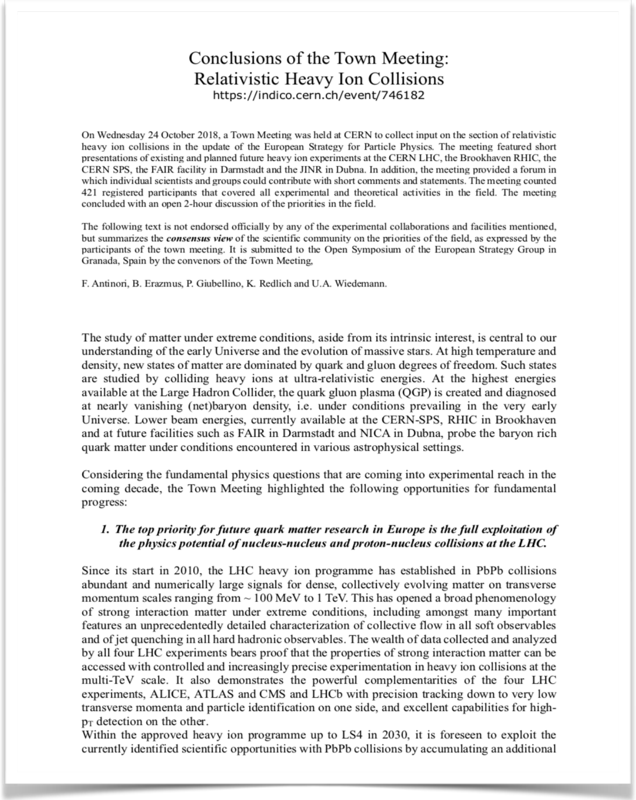
2015 US NP LRP



“Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of [RHIC and the LHC] is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.”

Reaffirmed in ECFA heavy-ion (WG5) discussion

WG5 for 2019 ECFA process



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.***

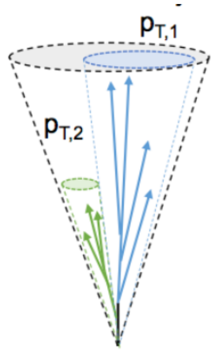
Since its start in 2010, the LHC heavy ion programme has established in PbPb collisions abundant and numerically large signals for dense, collectively evolving matter on transverse momentum scales ranging from ~ 100 MeV to 1 TeV. This has opened a broad phenomenology of strong interaction matter under 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

“The Town Meeting observes that the recently approved sPHENIX proposal targets these opportunities by bringing greatly extended capabilities to RHIC …”

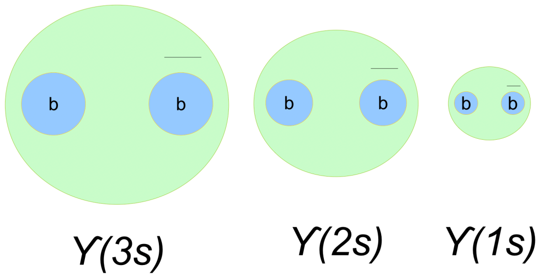
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

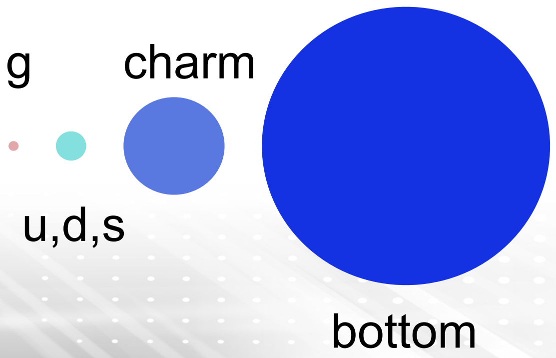
Hard Probes: sPHENIX/LHC complementarity



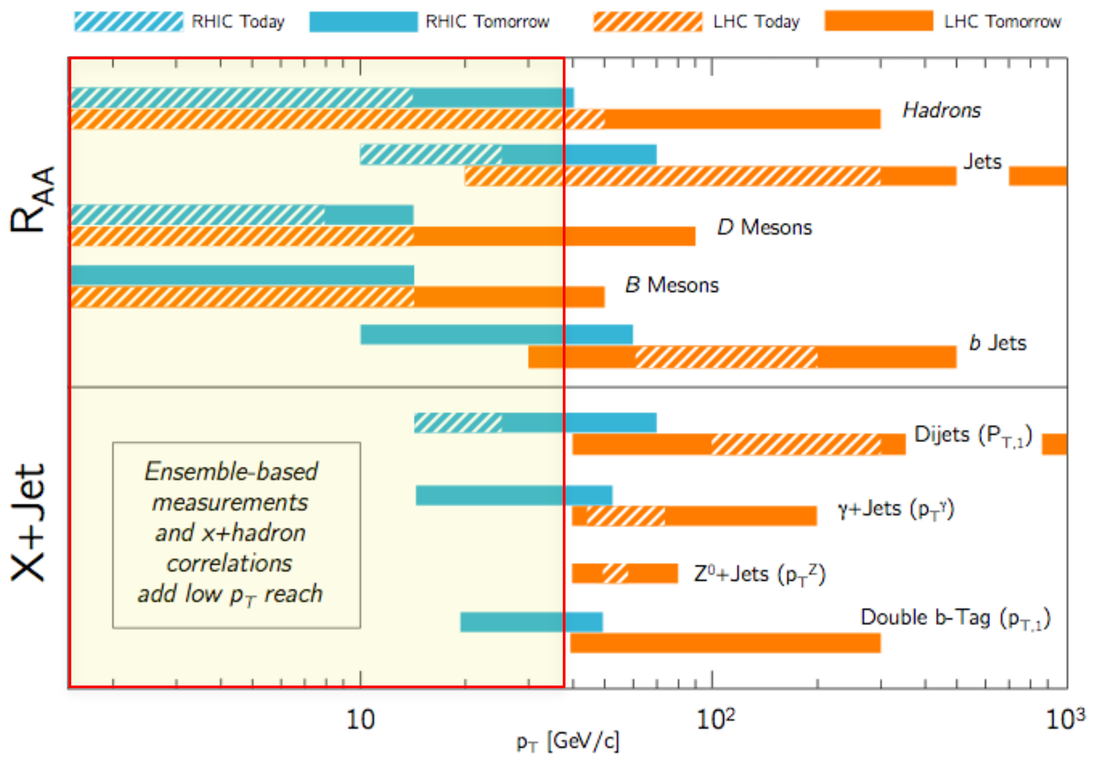
Jet structure
vary momentum/
angular scale of probe



Quarkonium spectroscopy
vary size of probe

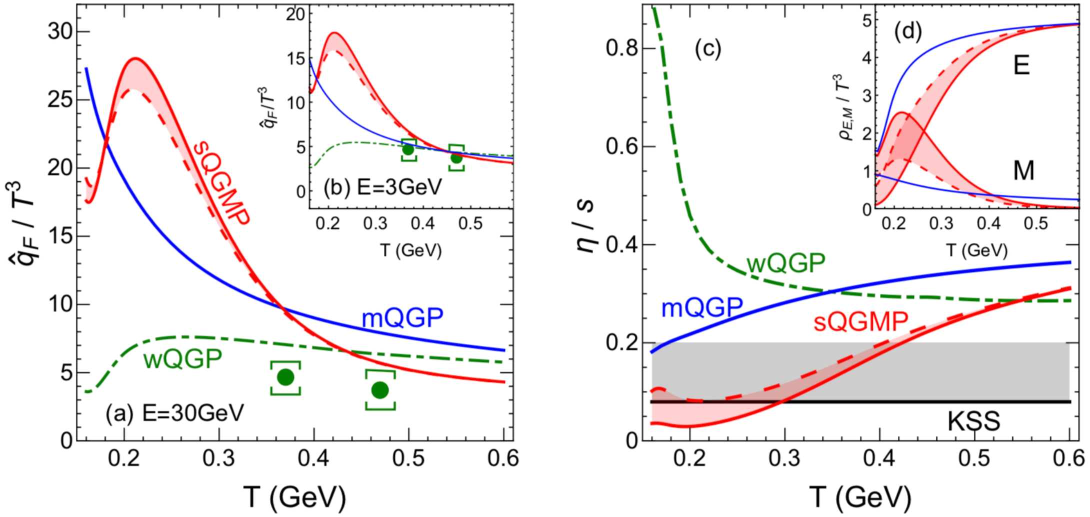


Parton energy loss
vary mass/momentum of probe

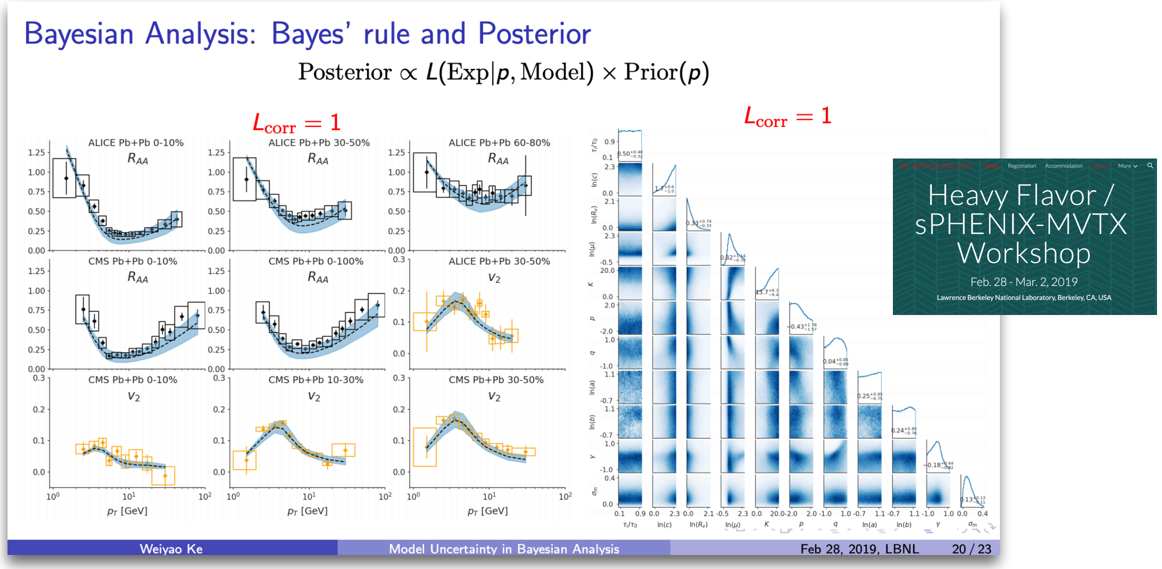


Engagement with theory community

Description of how community resources leverage the RHIC program



T-dependence of QGP structure, as reflected e.g. in transport coefficients has been sPHENIX focus since beginning



Bayesian inference key approach for both HF and jet sector (started in soft sector)

Data from two energy regimes, RHIC & LHC, essential to constrain T dependence

Many points of contact between sPHENIX and theory/LHC communities (e.g., LBNL HF workshop, work with Duke group, JETSCAPE collaboration).

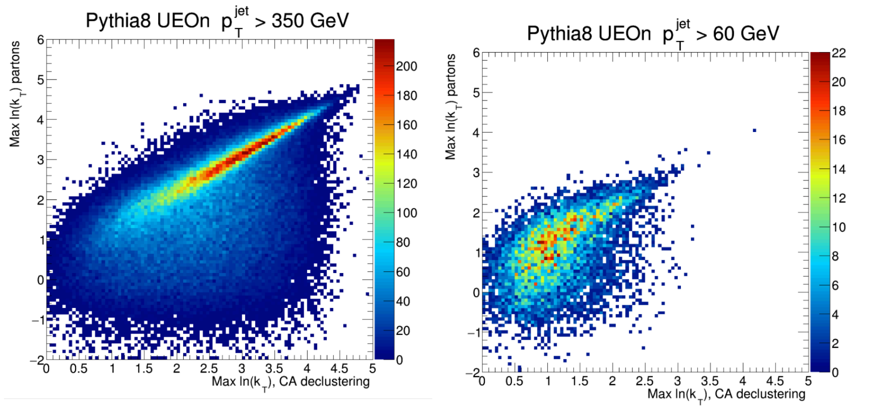
Engagement with theory community

sPHENIX

Description of how community resources leverage the RHIC program

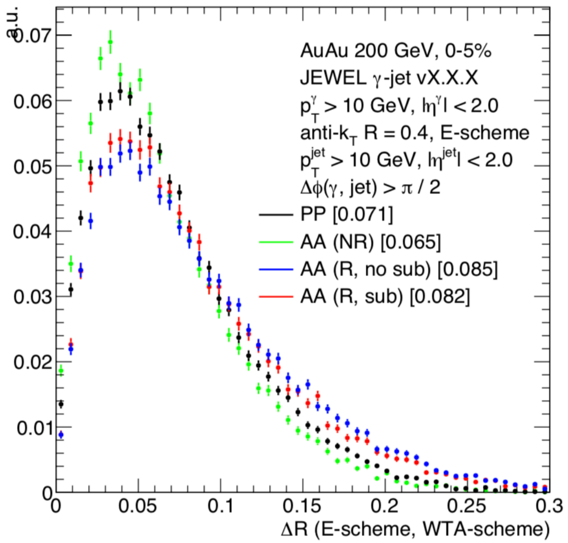
350GeV jets   60GeV jets

Parton shower



Hadron level C-A declustering

Q: To which extent is parton level structure of jet evolution accessible in final state?



Increasing interest and significant progress regarding jet substructure modifications, e.g., JetTools workshops at CERN, Bergen, EMMI RRTF in Aug ’19

Decorrelation of jet axes in QGP for low p_T jets

Distinct strengths and drawbacks in different energy regimes

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

LHC & sPHENIX: Jet substructure

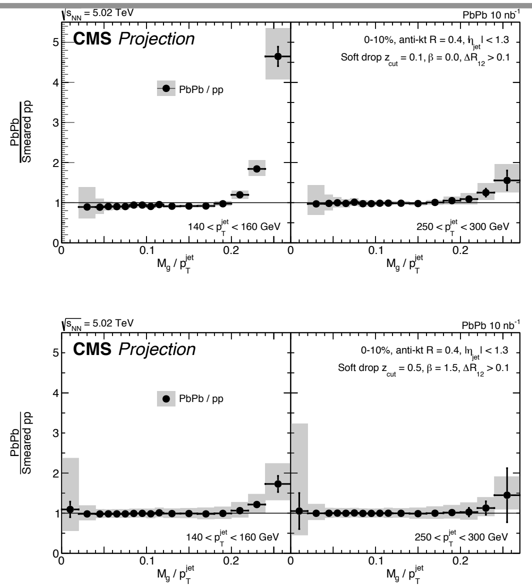
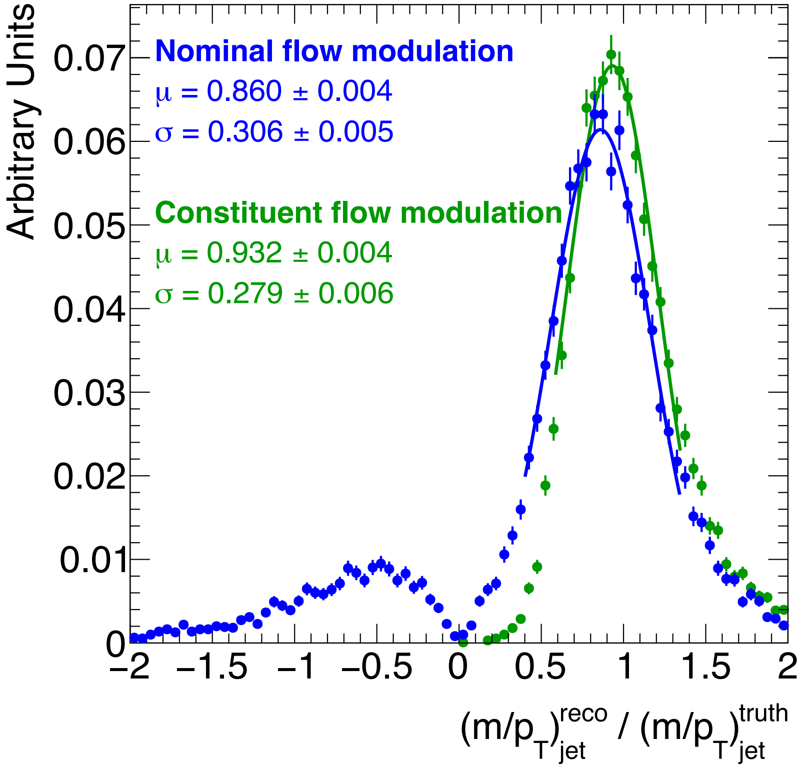


Fig. 37: Jet mass distribution with grooming setting $(z_{cut}, \beta) = (0.1, 0.0)$ (Upper panels) and $(z_{cut}, \beta) = (0.5, 1.5)$ (Lower panels). [8]

CERN Yellow Report projections for Runs 3, 4

cf. Berta, Spousta, Miller, Leitner, JHEP 1406 (2014) 092



Jet substructure measurements (e.g. jet mass) focus of current and Run 3,4 LHC measurements

State-of-the-art constituent background subtraction implemented in sPHENIX

Enables wide range of jet substructure studies

sPHENIX & LHC: photon-jet balance

CERN Yellow Report projections for Runs 3, 4

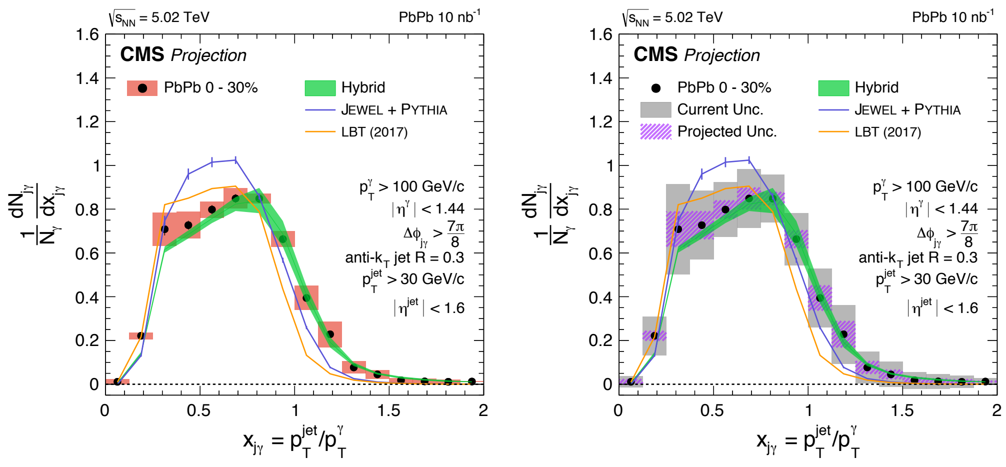
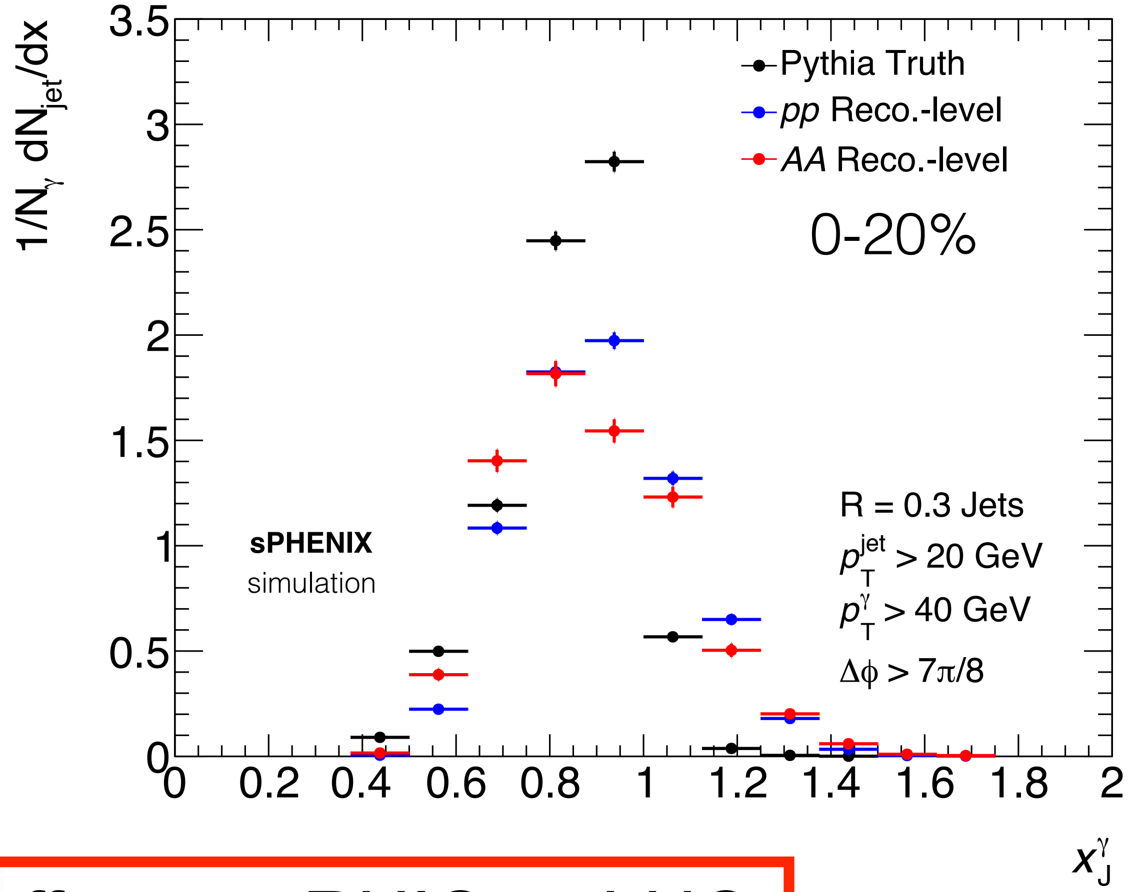


Fig. 29: (Left Panel) Photon-jet momentum balance $x_{j\gamma}$ distribution for isolated-photon+jets of $p_\gamma >$ 100 GeV/c and $|\eta_\gamma| < 1.44$, $p_{\rm jet} > 30$ GeV/c and $|\eta_{\rm jet}| < 1.6$ in the HL-LHC data (Right Panel). Comparison between the current performance with 0.4 nb^{-1} of Pb–Pb data collected in 2015 and with HL-LHC data [8].

Photon-tagged jets in sPHENIX

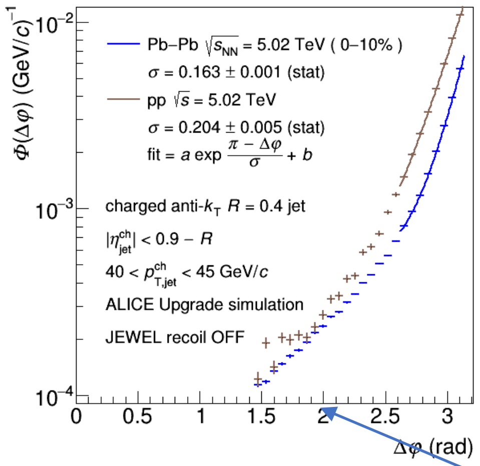


Direct comparison of QGP effects at RHIC vs LHC for "same" hard scattering process

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

sPHENIX vs LHC: ISR/FSR

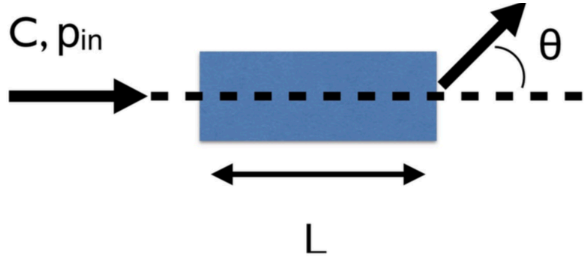


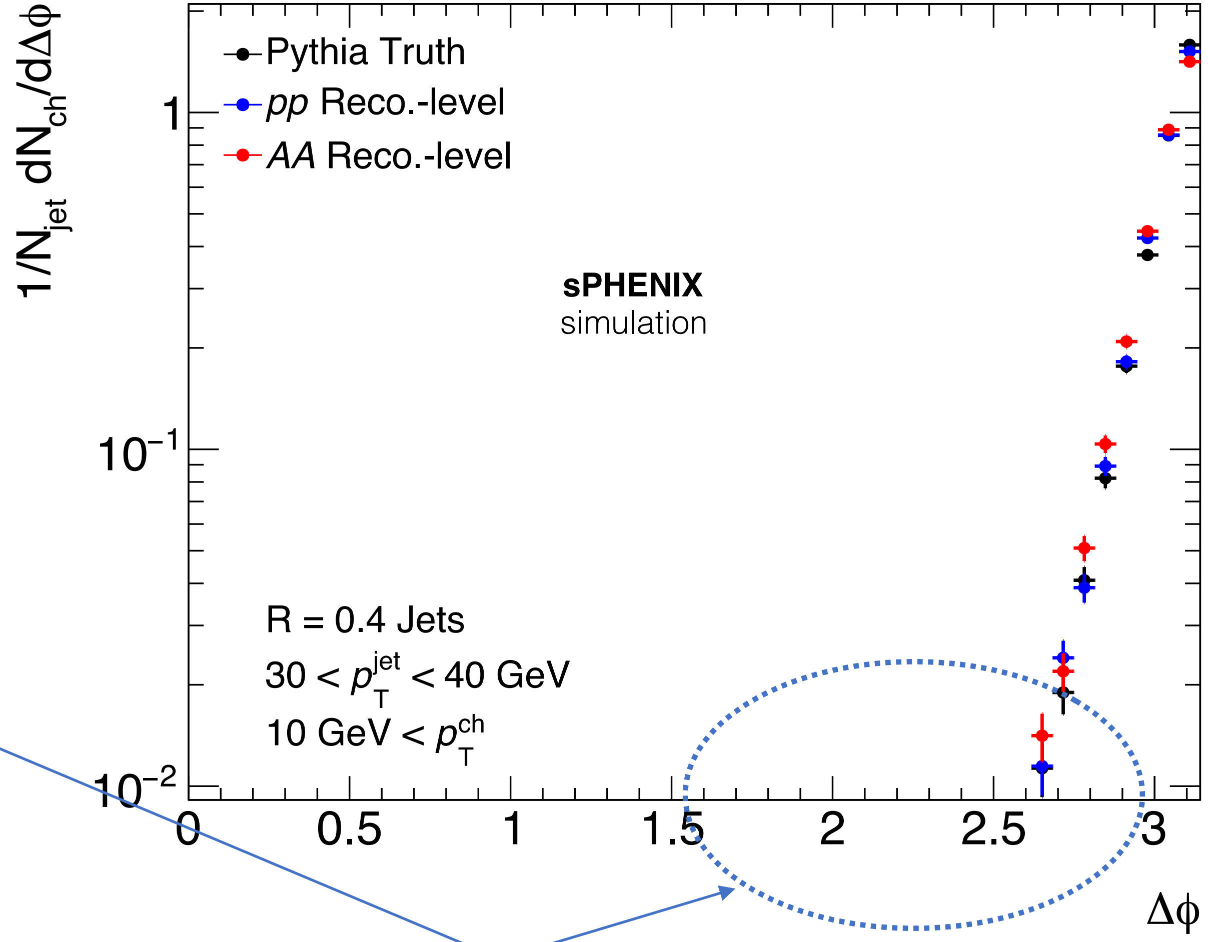
CERN Yellow Report projections for Runs 3, 4

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]

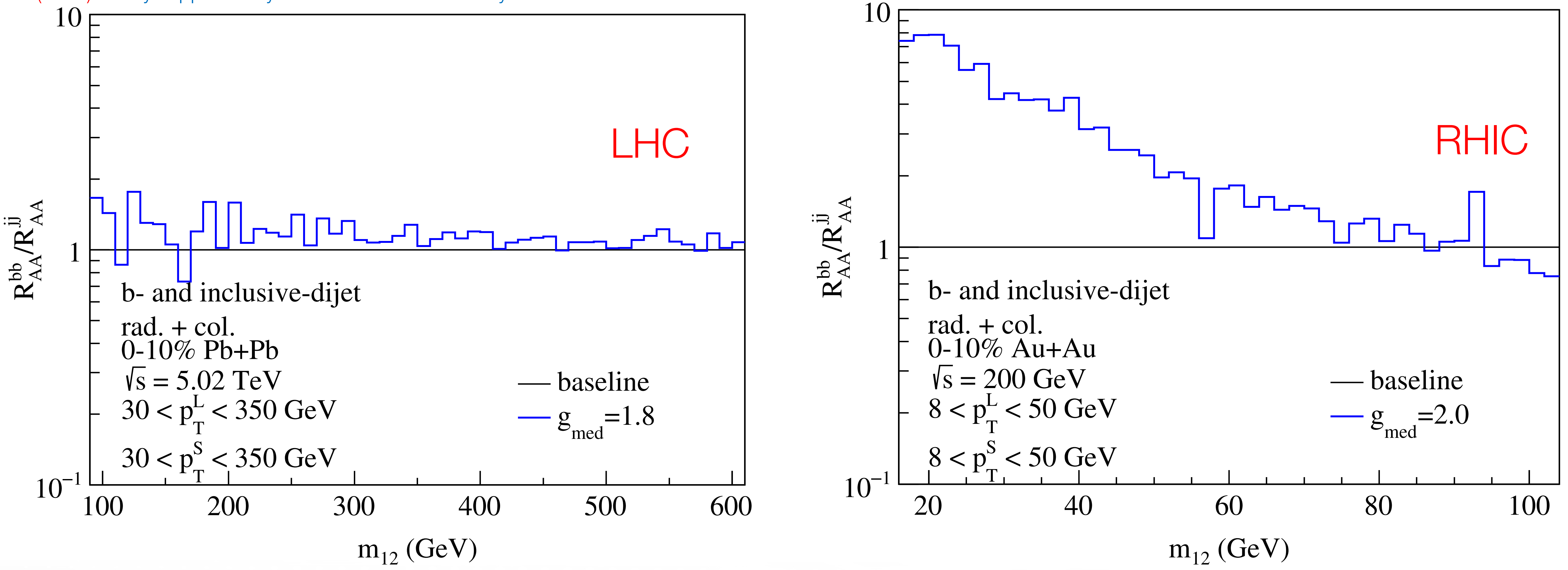




At comparable jet energies, much smaller contribution from ISR/FSR at RHIC, as well as smaller smearing from UE fluctuations

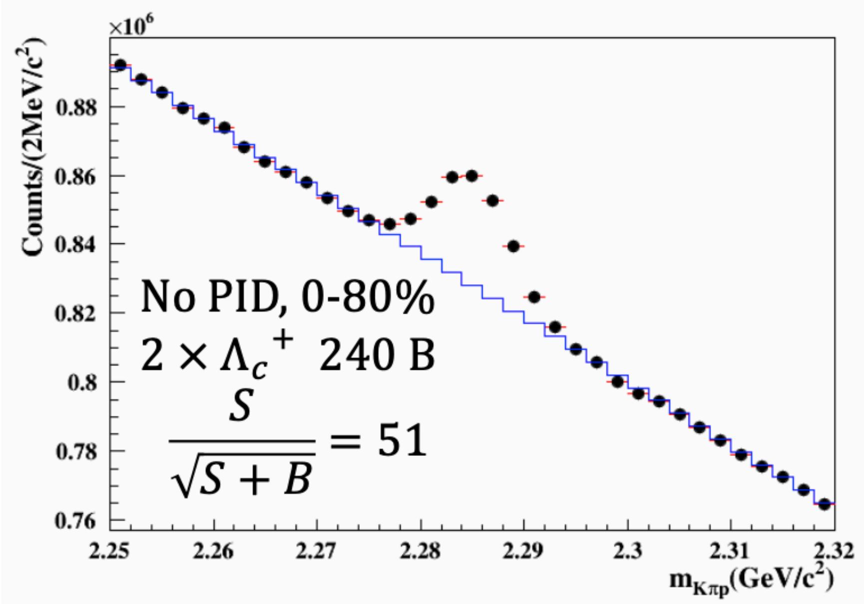
sPHENIX vs LHC: Medium coupling

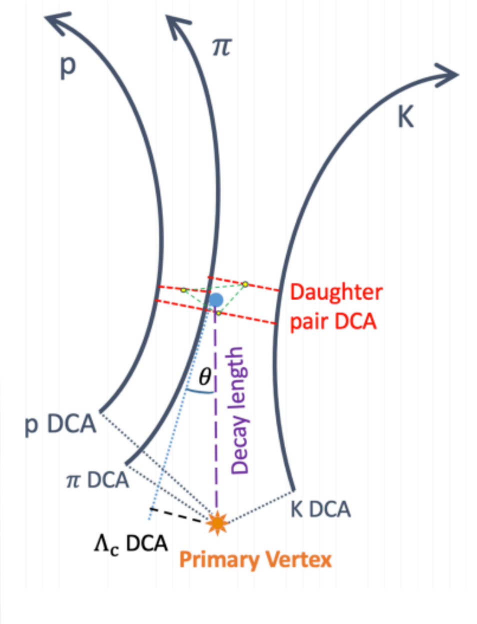
Z-B Kang, J Reiten, I Vitev, B Yoon, "Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions", Phys. Rev. D99 034006 (2019) Partly supported by LANL LDRD motivated by and connected to sPHENIX



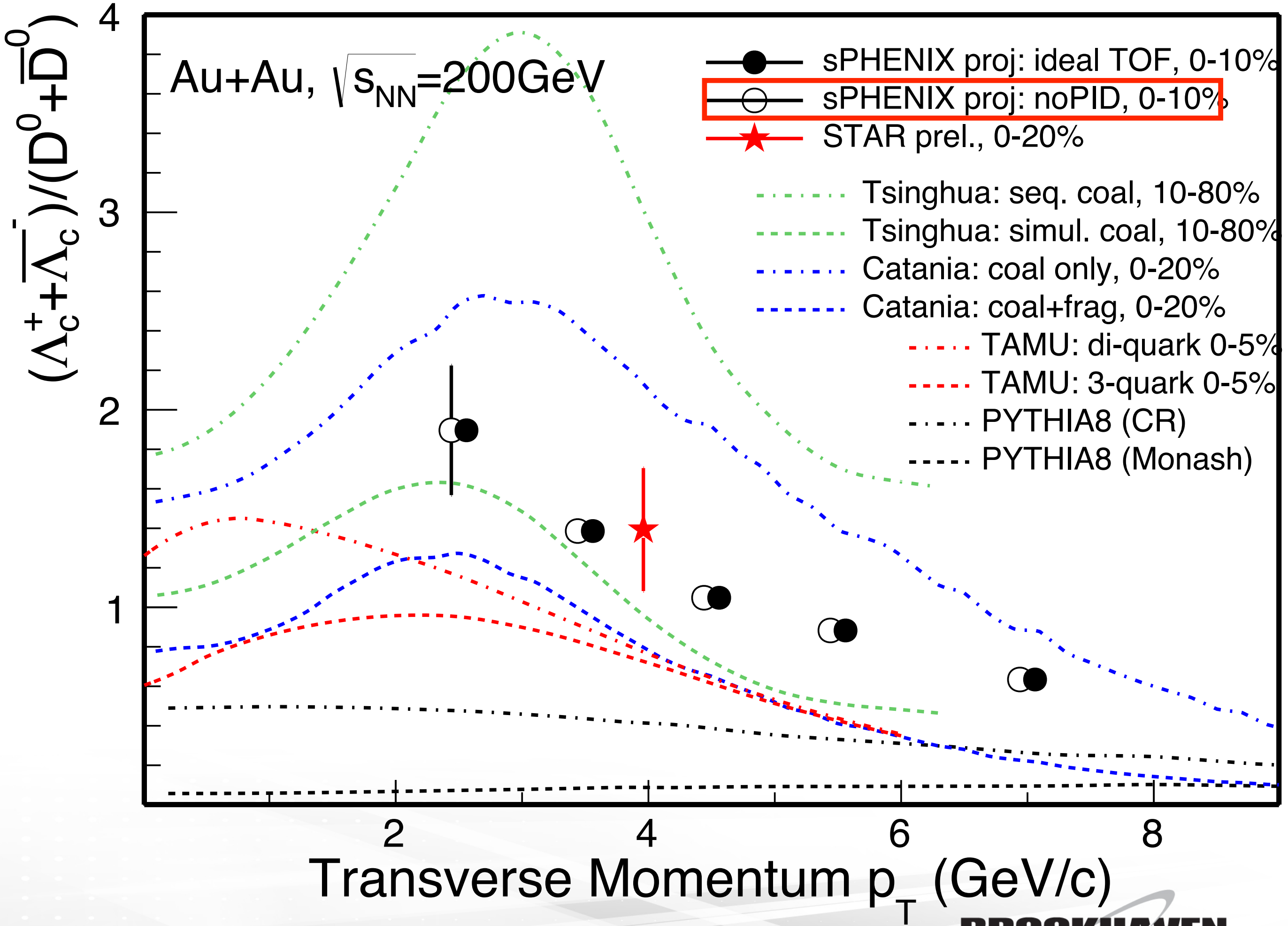
New class of observables enabled at RHIC by b-tagging capability in sPHENIX

Improving the state-of-the-art: Λ_c - Hadronization





complex decay topologies enable high S/B in baseline sPHENIX



Collaboration update

- Steady growth after CD-0
  - 18 new institutions (77 total)
- CERN recognized experiment (April '19)
- Established task forces to address critical challenges
  - 1) Tracker optimization, 2) Computing plan, 3) Detector calibration
- Steady evolution of collaboration organization

2016	2017	2018	2019
Berkeley (University of California)	Purdue University	University of Science and Technology of China	UNC Greensboro
Temple University	cea	Fudan University	U. Sao Paulo
Berkeley Lab (Lawrence Berkeley National Laboratory)	Central China Normal University	Tsinghua University	NCU, Taiwan
		Sun Yat-sen University	Sejong University
		IMP	Florida AMU
		SINAP	
		北京大学 Peking University	

List of Recognized Experiments

CERN

RE status at CERN

Ref.	Experiment	since	until
RE 33	LIGO	2016	31-MAR-2022
RE 34	JUNO	2017	31-MAR-2020
RE 35	SNO+	2017	31-MAR-2020
RE 36	Mu3e	2018	31-MAR-2021
RE 37	DarkSide 20k	2018	31-MAR-2021
RE 38	DAMIC-M	2019	31-MAR-2022
RE 39	sPHENIX	2019	31-MAR-2022

Description of how community resources leverage the RHIC program

sPHENIX Organization

sPHENIX

Collaboration

Institutional Board
Institution representatives

Executive Council
Project and collaboration representatives

Diversity Office
V. Greene

Speaker's Bureau
M. Rosati

established in 2019

re-elected in Jan '19

sPHENIX Collaboration Co-Spokespersons
D. Morrison
G. Roland

Topical Groups

Jet structure
D. Perepelitsa, R. Reed

Y spectroscopy
T. Frawley, M. Rosati

Heavy flavor
J. Huang, X. Dong

Cold QCD
C. Aidala, A. Bazilevsky

Project

DOE- Office of Nuclear Physics
T. Hallman
Associate Director of the Office of Science for Nuclear Physics
J. Gillo
Director Facilities and Project Management Division
J. Hawkins
Federal Program Manager

DOE –Brookhaven Site Office
R. Gordon
Site Manager

BNL Director's Office
D. Gibbs
Laboratory Director

BNL Nuclear and Particle Physics Directorate
B. Mueller
Associate Lab Director
Maria Chamizo Llatas
Co-Director Office Project Planning and Oversight

Project Management Group

BNL Physics Dept
H. Ma
J. Dunlop

BNL Collider Accelerator Dept
T. Roser

sPHENIX Project Office

E. O'Brien	Project Director
G. Young	Project Manager
J. Haggerty	Project Scientist
J. Mills	Project Engineer
C. Lavelle	Resource Coordinator
R. Feder	Chief Mechanical Engineer
I Sourikova	Project Controls Manager

Project Support Office

L. Stiegler	ES&H
C. Gortakowski	QA
E. Desmond	Software support

Project Office of System Integration
M. Chiu Chief System/Integration Scientist

Project Management Office
WBS 1.1
I. Sourikova
E. Menter

sPHENIX Control Account/Level-2 Managers

T. Hemmick	WBS 1.2 Time Projection Chamber
C. Woody	WBS 1.3 Electromagnetic Calorimeter
J. Lajoie	WBS 1.4 Hadronic Calorimeter
E. Mannel	WBS 1.5 Calorimeter Electronics
M. Purschke	WBS 1.6 DAQ/Trigger
M. Chiu	WBS 1.7 Minimum Bias Detector

Multi-year run plan for sPHENIX

sPHENIX schedule,

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

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}

- Main Au+Au running mode: 15kHz min bias for $|z_{vtx}| < 10$cm
- Year-1 (commissioning) + Year-2,3 (high statistics production): **145 billion** Au+Au collisions
  - cf. more than 20x STAR 2016 data set of 6.5 billion events (PAC 2017 presentation)

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}

- Collaboration sees strong science case for additional running
- Improve uncertainties and respond to discoveries in first years

Ongoing discussions with C-AD to optimize RHIC running for sPHENIX

Plans for analyzing large volume sets of future sPHENIX data within envelop of existing computing resources.

sPHENIX software and computing status

sPHENIX

Plans for analyzing large volume sets of future sPHENIX data within envelop of existing computing resources.

- Software and computing is key focus of collaboration effort
- Subject of two S&C reviews at BNL w/ experts from RHIC, LHC, RACF
  - May 2018, September 2019
- 2018 review generated a number of recommendations
- 2019: All recommendations either addressed or part of ongoing effort

sPHENIX software and computing status

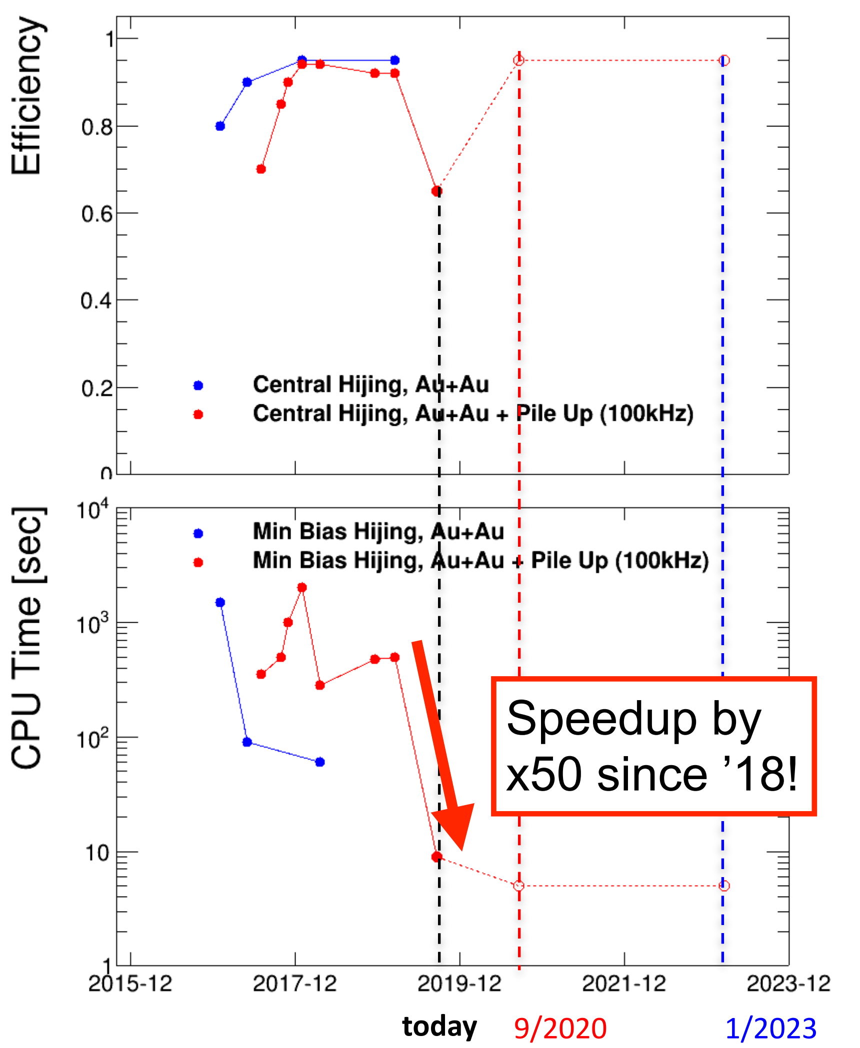
Plans for analyzing large volume sets of future sPHENIX data within envelop of existing computing resources.

- Software and computing is key focus of collaboration effort
- Subject of two S&C reviews at BNL w/ experts from RHIC, LHC, RACF
  - May 2018, September 2019
- 2018 review generated a number of recommendations
- 2019: A ... g effort

Thank you for a well prepared Review!

The panel thanks sPHENIX project for excellent presentations, documentation and for being responsive to our requests for information. The committee was pleased to see much progress and follow-ups from the past review recommendations and an incredible amount of work being done to design and commission sPHENIX Software & Computing.

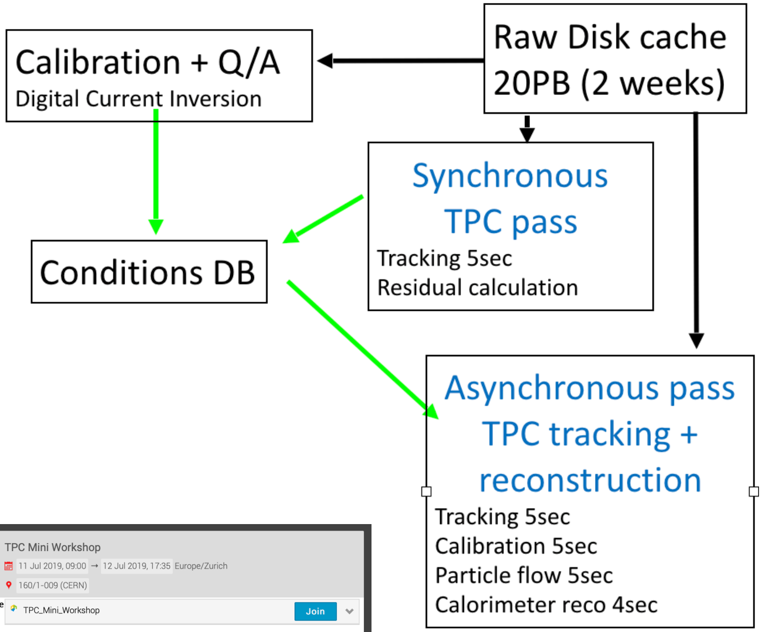
S&C focus: TPC reconstruction



Plans for analyzing large volume sets of future sPHENIX data within envelop of existing computing resources.

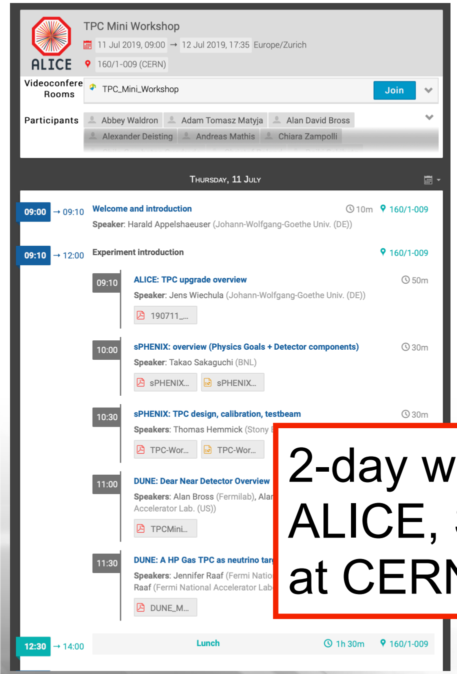
- TPC reconstruction main resource driver
  - In 2018, set goal of 5s/event (vs 500s/event reality in 2018)
- Recent Algorithmic improvements provided **speedup by x50**: currently 10s/event
- Goal: 5s/event and 90% efficiency by 9/2020
  - estimate of 3-4s/event based on studies of ATLAS/ALICE code
- ➔Computing plan calls for 190k CPU cores

S&C focus: TPC calibration



Plans for analyzing large volume sets of future sPHENIX data within envelop of existing computing resources.

- TPC distortion calibration key element of reconstruction software workforce needs
- Close coordination with ALICE effort/technology
  - Urgent ramp-up of expert workforce
- As presented at 2019 S&C review: timely opportunity for key contribution by BNL *Nuclear and Particle Physics Software* group



2-day workshop with ALICE, STAR, DUNE at CERN in July ‘19

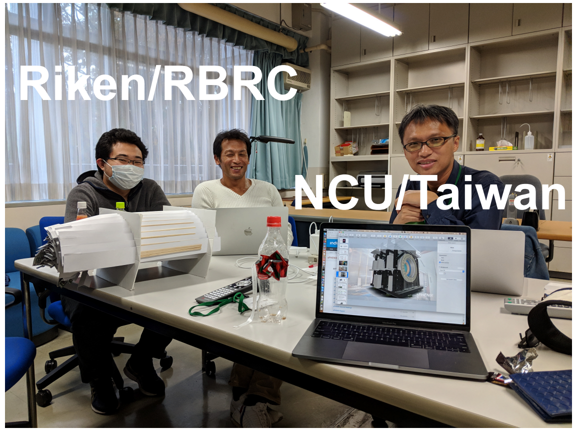
Based on ALICE experience, TPC calibration will use ≈10% of sPHENIX CPU resources

Description of how community resources leverage the RHIC program

BROOKHAVEN NATIONAL LABORATORY

Engagement with non-US institutions

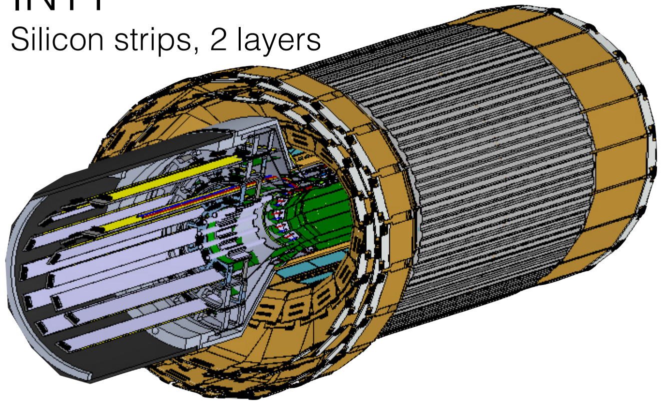
Description of how community resources leverage the RHIC program

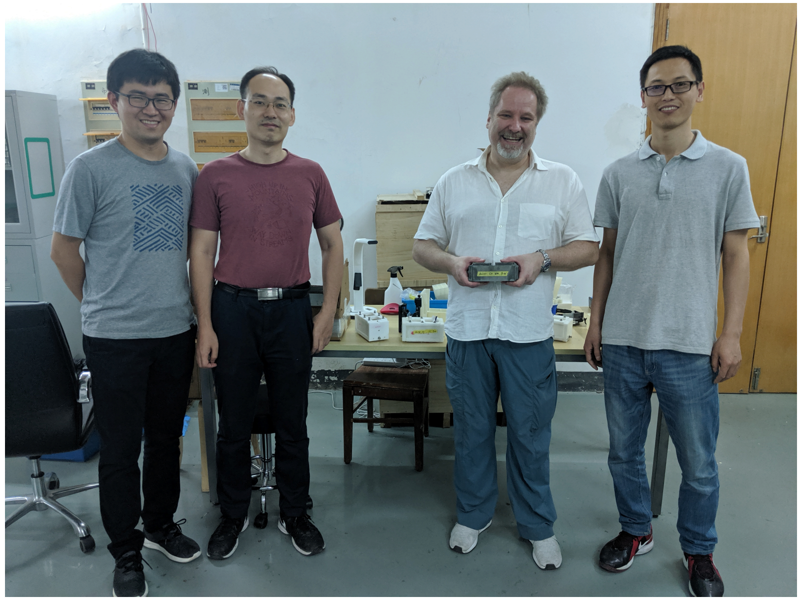


INTT contributed by Riken
assembly/testing at NCU/Taiwan

INTT
Silicon strips, 2 layers

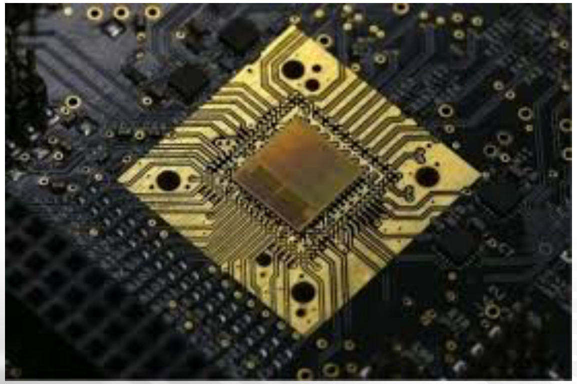
MVTX





EMCal prototype block
production at Fudan University

Block production to extend
EMCAL acceptance to $|\eta| < 1.1$
by Chinese consortium

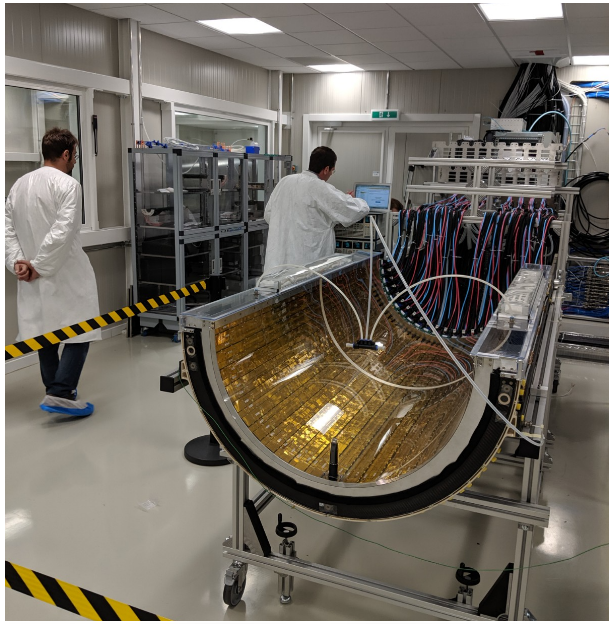


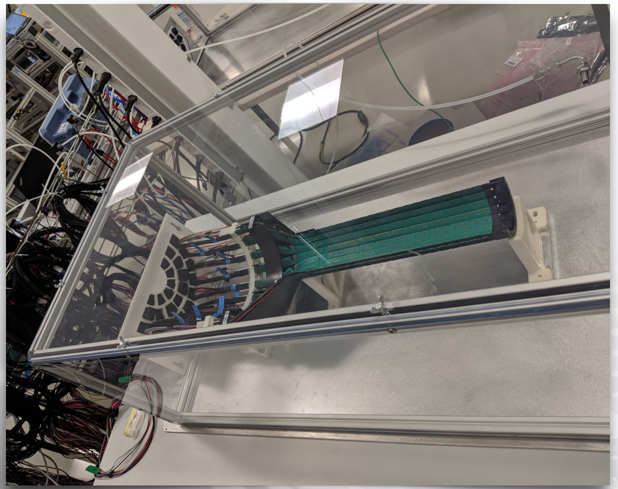
Sampa TPC FE chip
sPHENIX specific v5
U. Sao Paulo

U.S. DEPARTMENT OF ENERGY

Overview of instrumentation efforts, including MVTX, plans for calorimeter restoration for sPHENIX, sPHENIX schedule, and small CE efforts.

Engagement with ALICE: MVTX





- Largely common design of MVTX and ALICE ITS IB
- sPHENIX collaborators (LANL, MIT) embedded in ITS effort
  - major responsibility, e.g., for ITS slow control, online monitoring software; role in ITS commissioning
- Gain expertise for sPHENIX MVTX; opportunity for US ALICE groups to contribute to sPHENIX
- Regular contact at CERN and in sPHENIX workfests

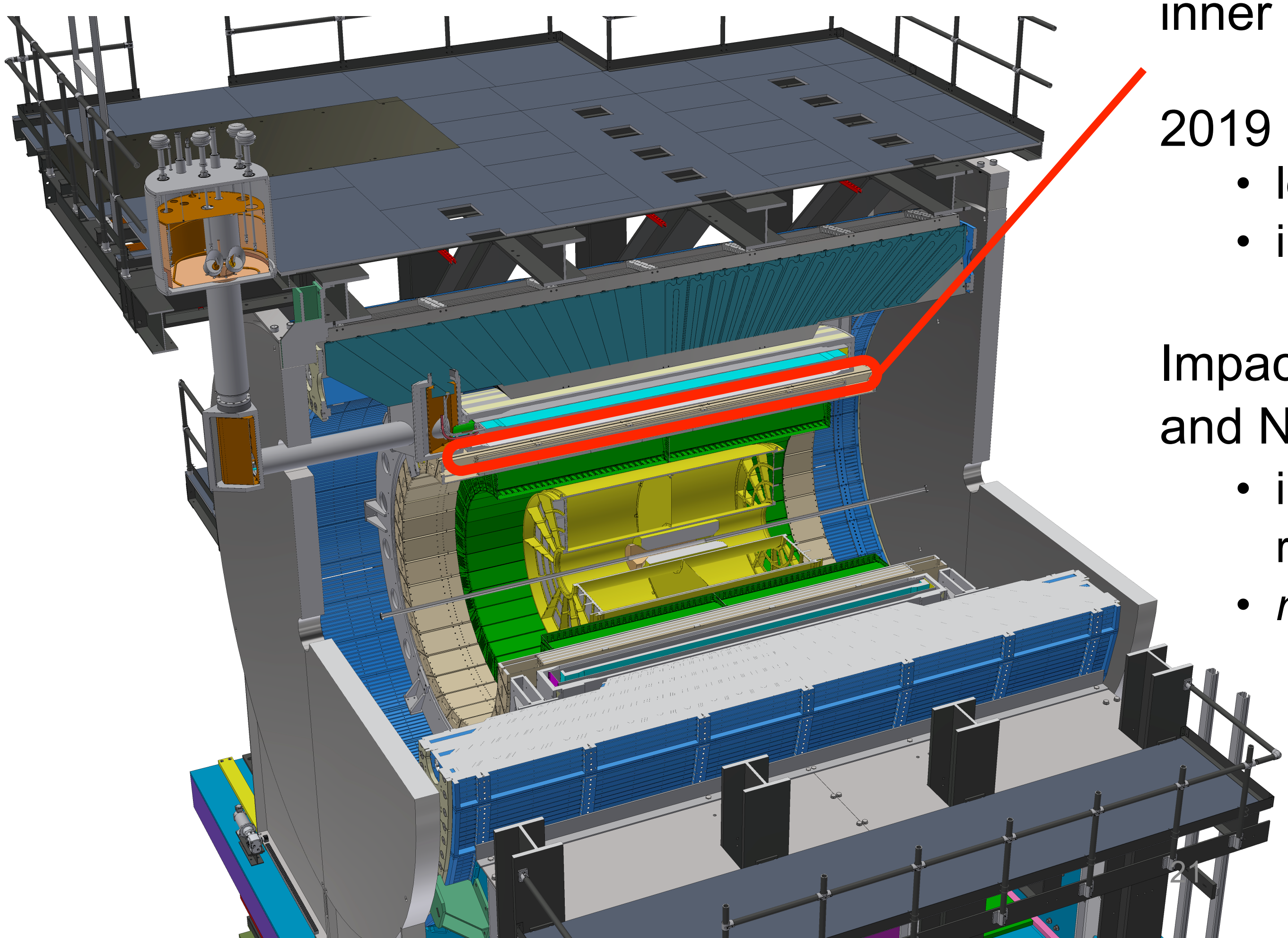
Description of how community resources leverage the RHIC program

BROOKHAVEN NATIONAL LABORATORY

Challenge: Calorimeter restoration - iHCAL

Description of how community resources leverage the RHIC program

Overview of instrumentation efforts, including MVTX, plans for calorimeter restoration for sPHENIX, sPHENIX schedule, and small CE efforts.



Collaboration continues to explore paths to restore inner HCAL instrumentation

2019 NSF MRI proposal (<$1M) was not funded

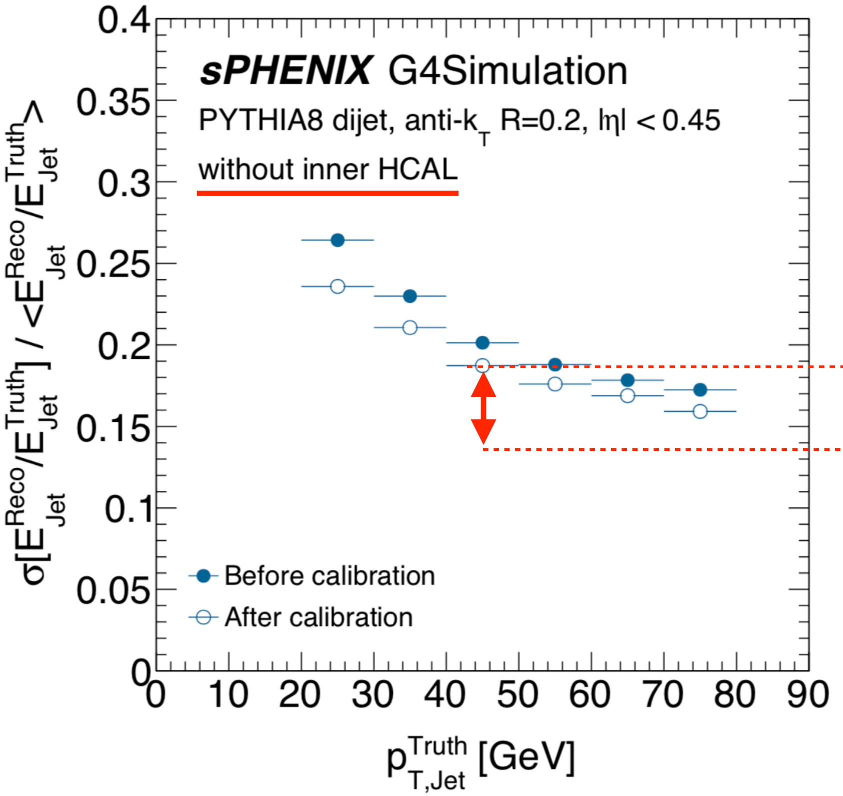
- led by Megan Connors and Sevil Salur
- involvement of undergrads (Augustana, UNC)

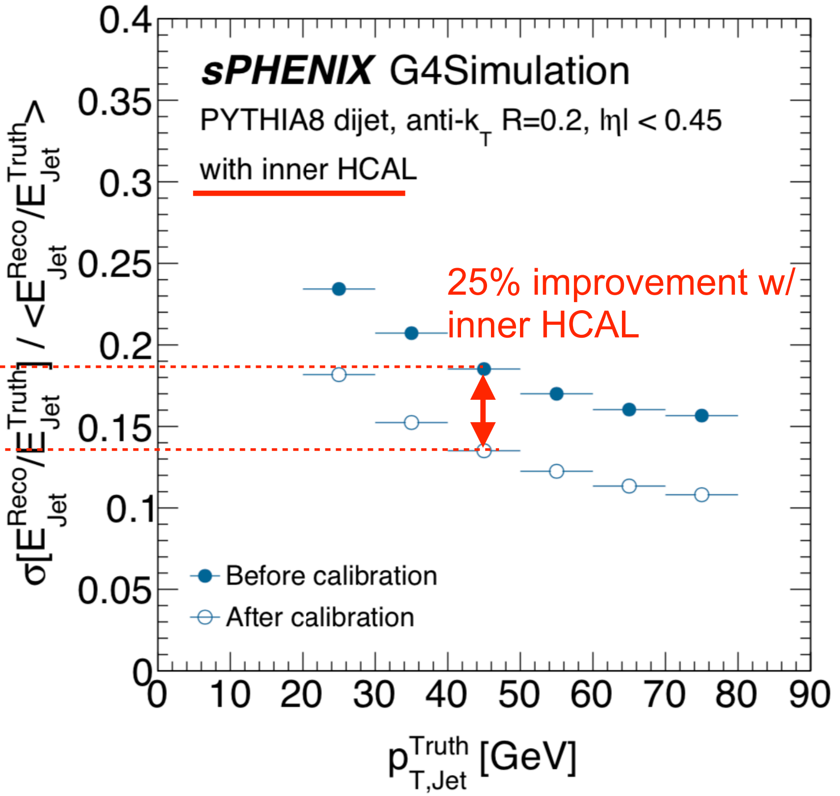
Impact on jet program documented in notes to ALD and NSF proposal

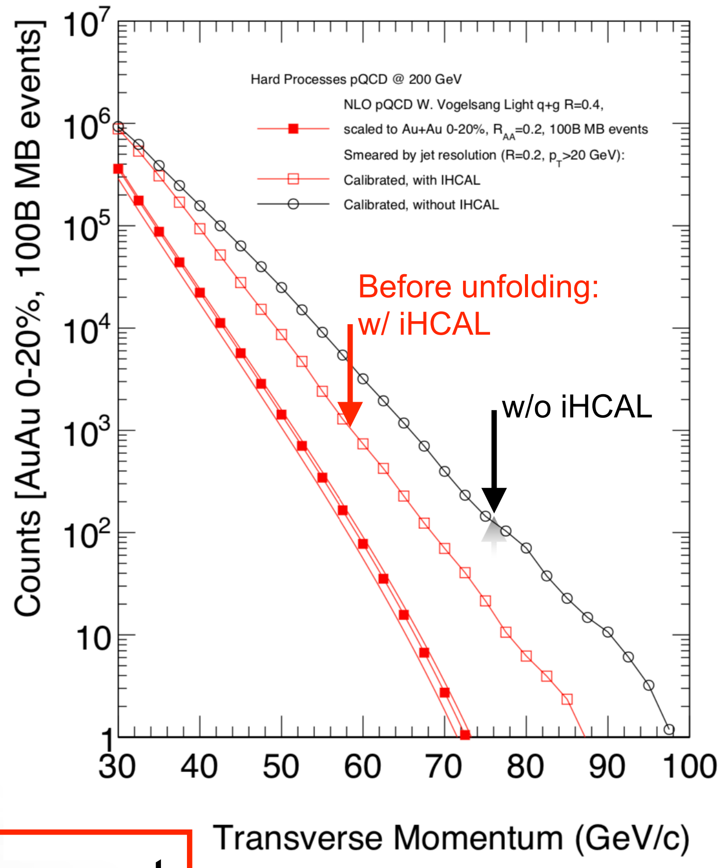
- iHCAL provides significant improvement of jet resolution
- *note:* UPPs do not assume iHCAL instrumentation

Challenge: Calorimeter restoration - iHCAL

Overview of instrumentation efforts, including MVTX, plans for calorimeter restoration for sPHENIX, sPHENIX schedule, and small CE efforts.

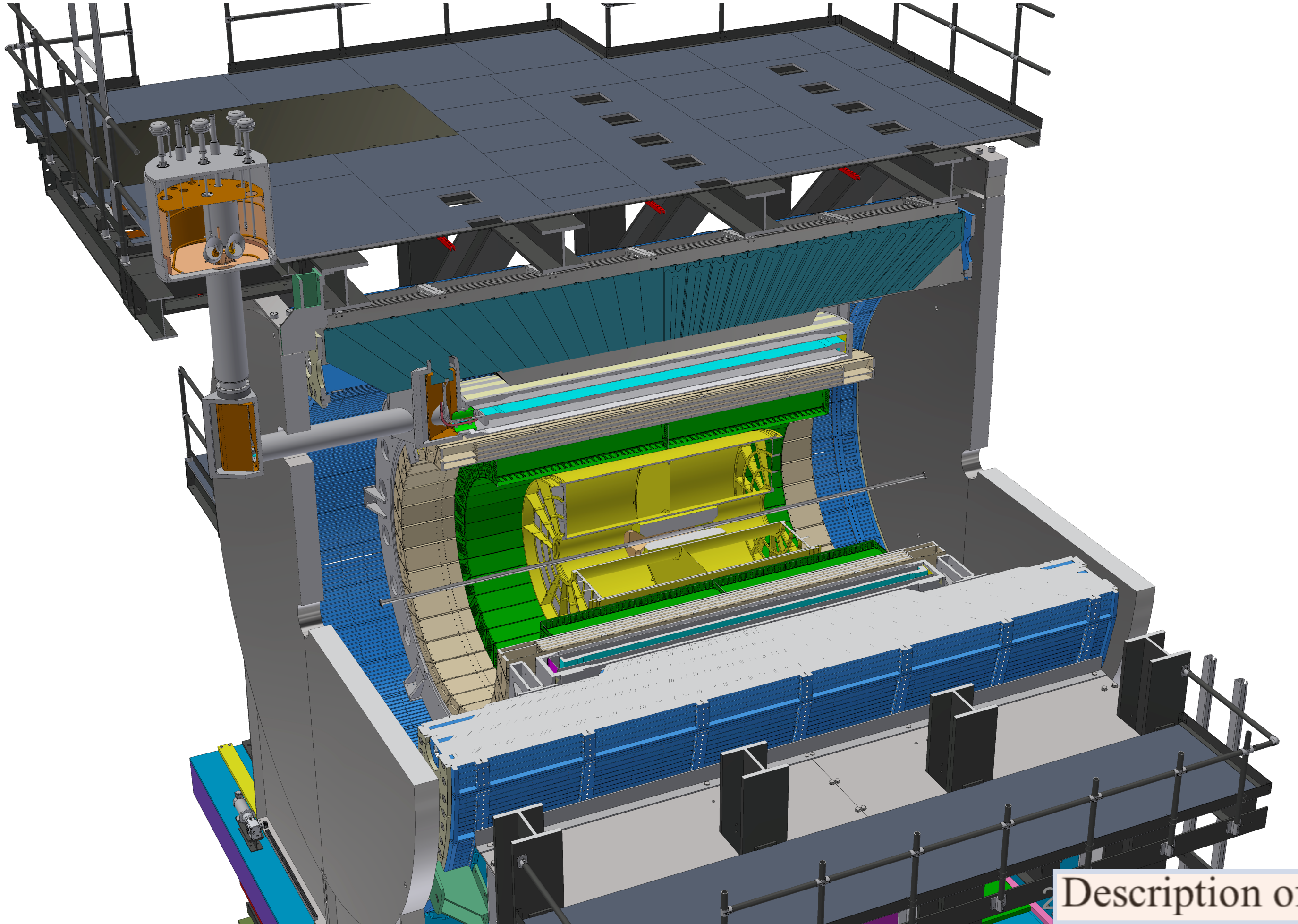






iHCAL improves sampling of calo-shower development
Significantly improved jet resolution

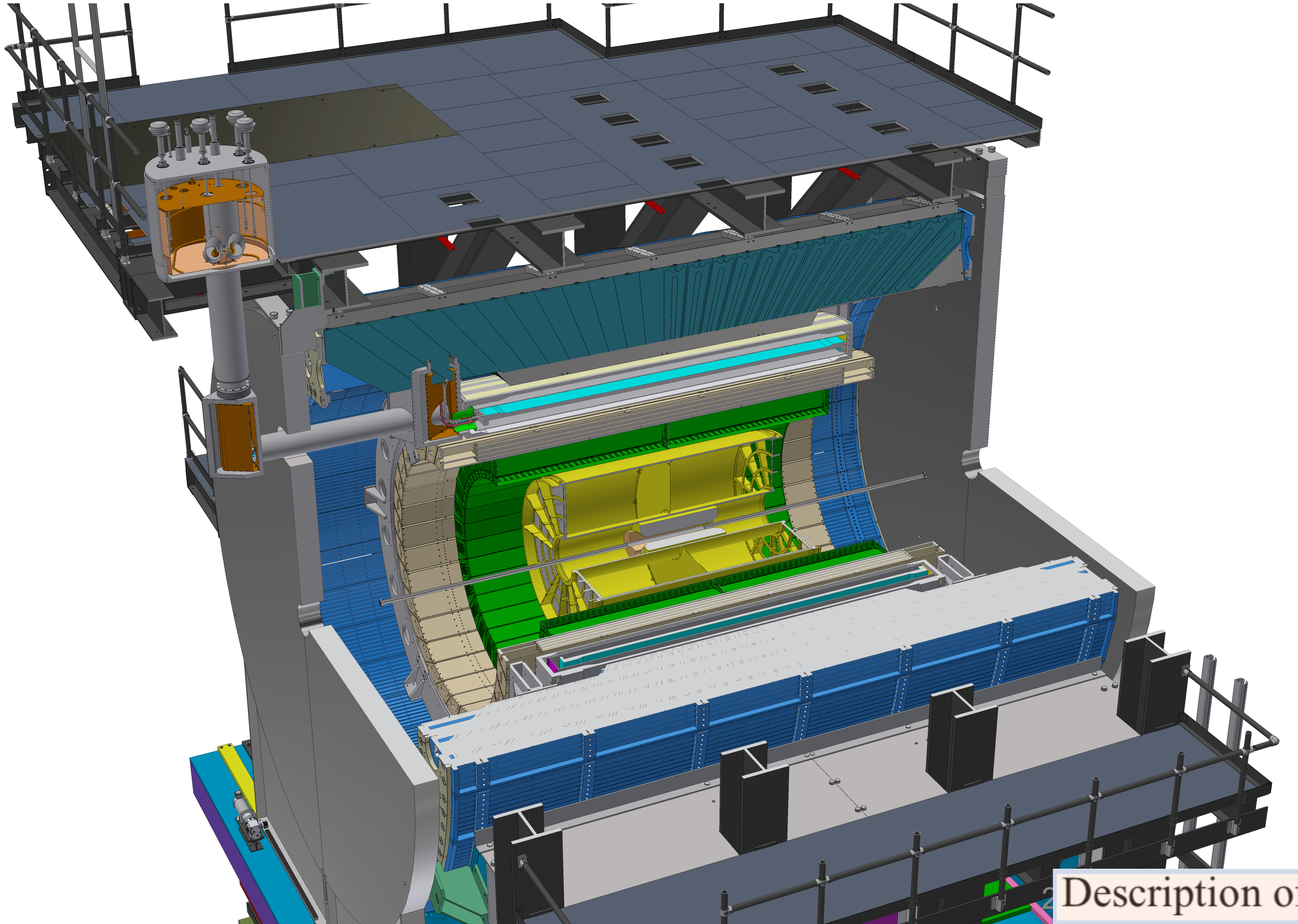
Strong connections to cold QCD and EIC community



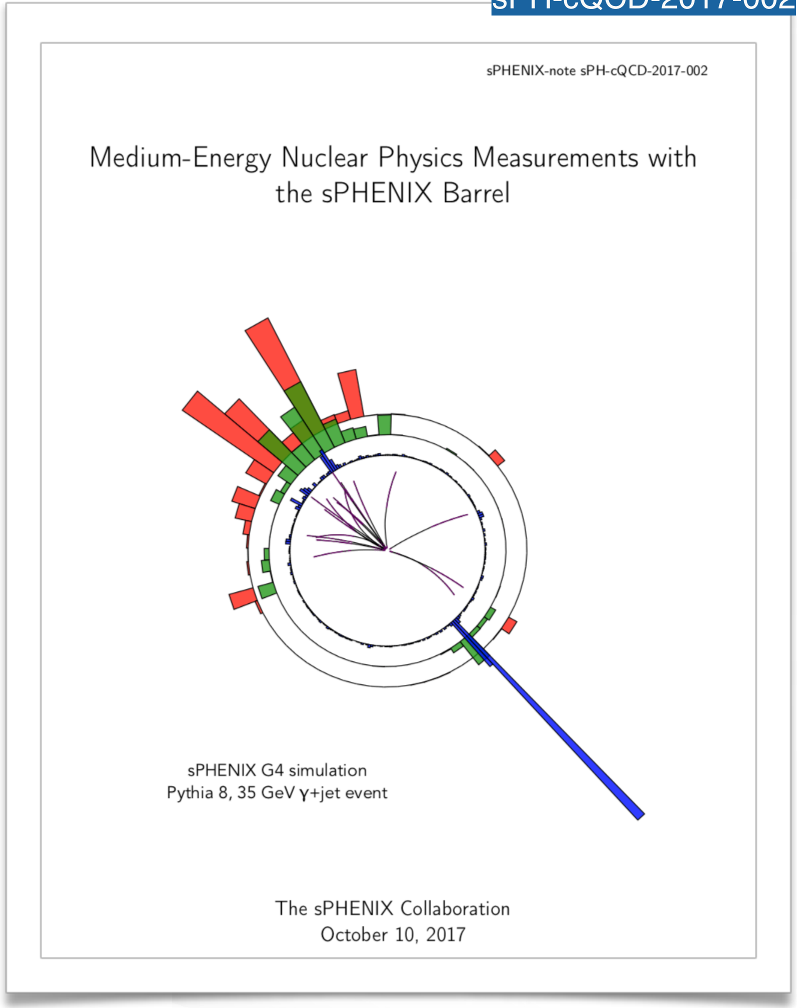
Description of how community resources leverage the RHIC program

2017: Cold QCD opportunities with sPHENIX barrel

sPHENIX



sPH-cQCD-2017-002



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

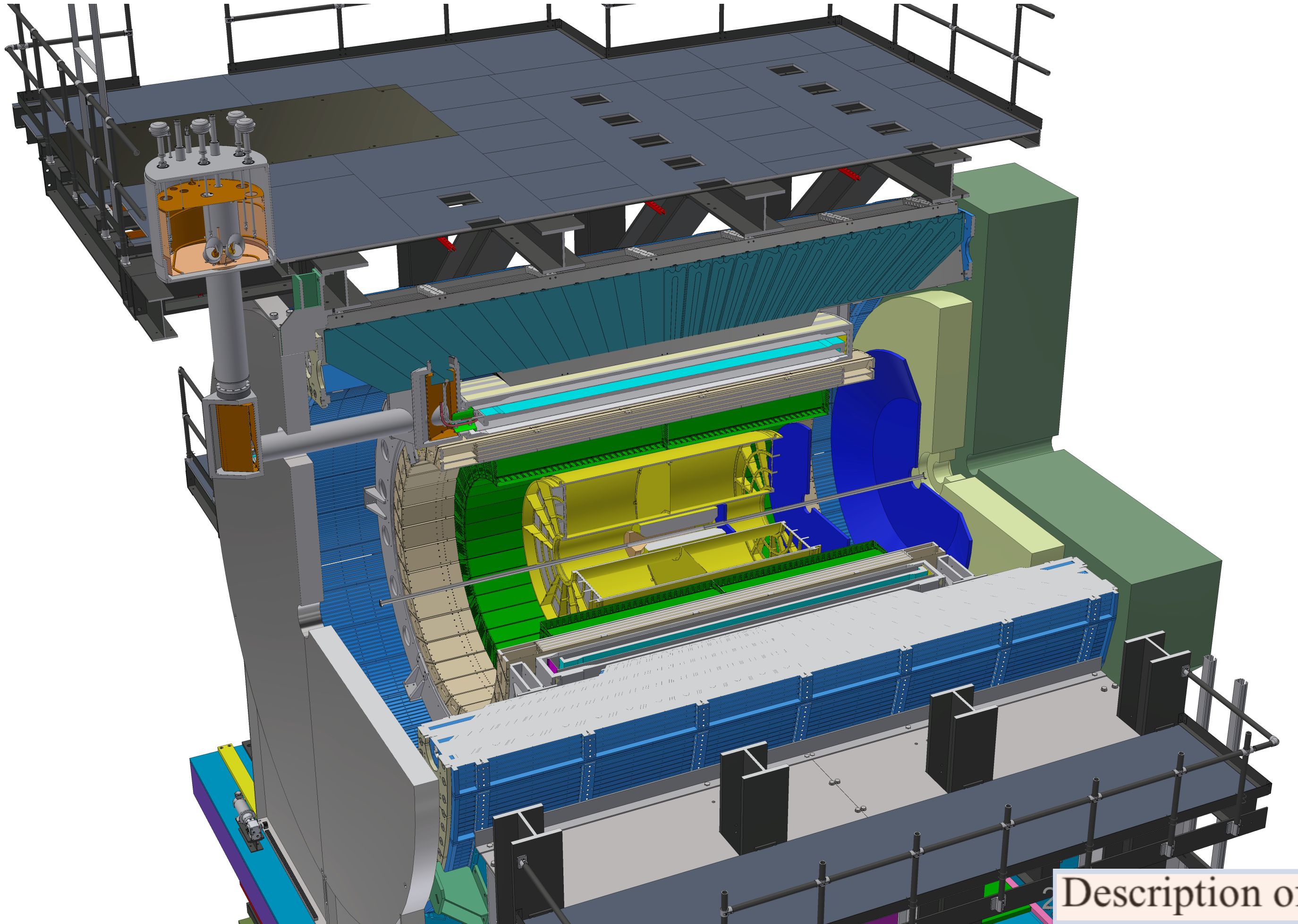
BROOKHAVEN NATIONAL LABORATORY

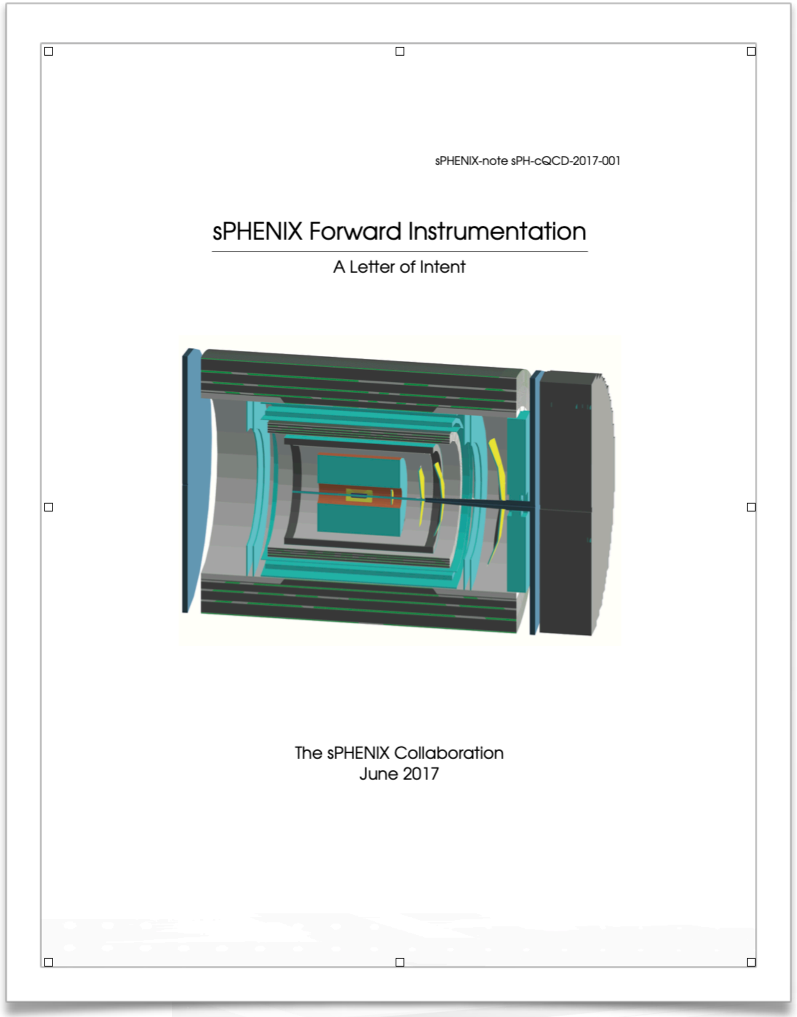
Description of how community resources leverage the RHIC program

2017: Cold QCD opportunities with sPHENIX modest forward upgrade

sPHENIX

sPH-cQCD-2017-001




sPHENIX-note sPH-cQCD-2017-001

sPHENIX Forward Instrumentation

A Letter of Intent

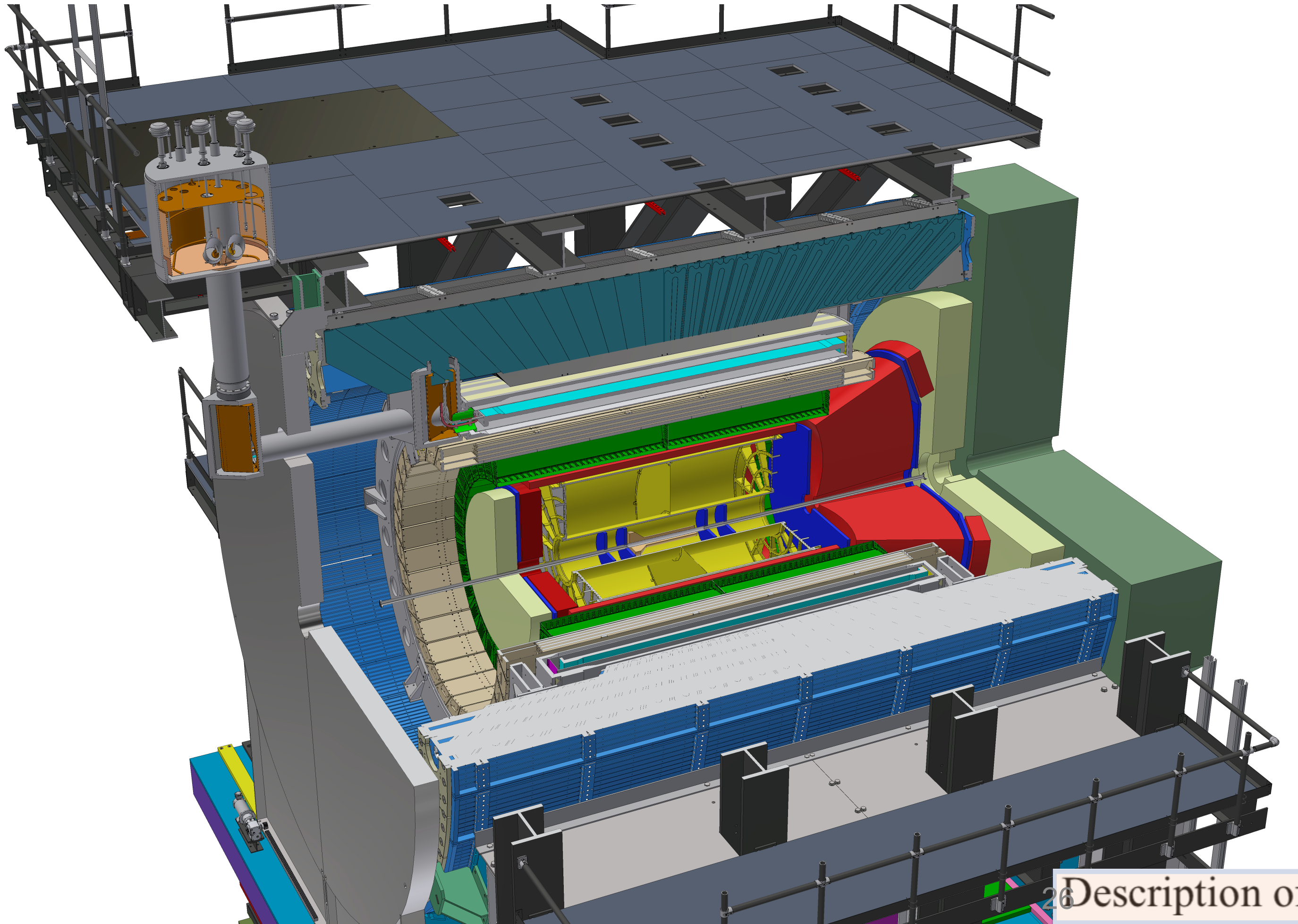
The sPHENIX Collaboration
June 2017

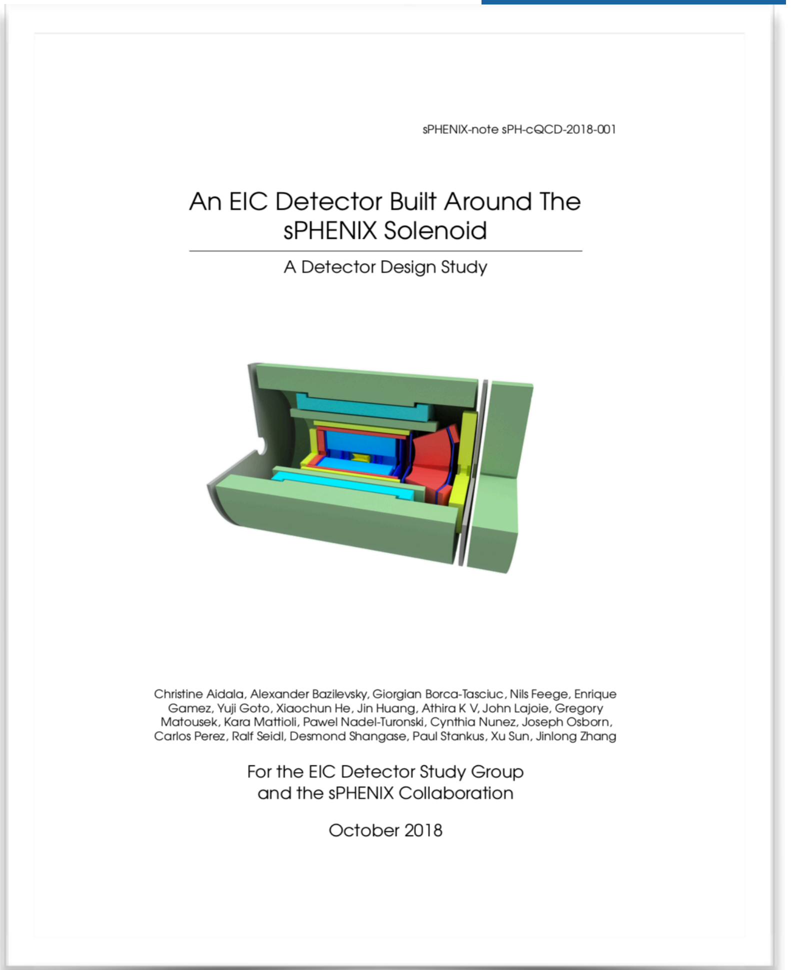
BROOKHAVEN
NATIONAL LABORATORY

Description of how community resources leverage the RHIC program

2018: Case study for EIC detector built around sPHENIX solenoid

sPH-cQCD-2018-001




sPHENIX-note sPH-cQCD-2018-001

An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study

Christine Aidala, Alexander Bazilevsky, Giorgian Borca-Tasciuc, Nils Feege, Enrique Gamez, Yuji Goto, Xiaochun He, Jin Huang, Athira K V, John Lajoie, Gregory Matousek, Kara Mattioli, Pawel Nadel-Turonski, Cynthia Nunez, Joseph Osborn, Carlos Perez, Ralf Seidl, Desmond Shangase, Paul Stankus, Xu Sun, Jinlong Zhang

For the EIC Detector Study Group and the sPHENIX Collaboration

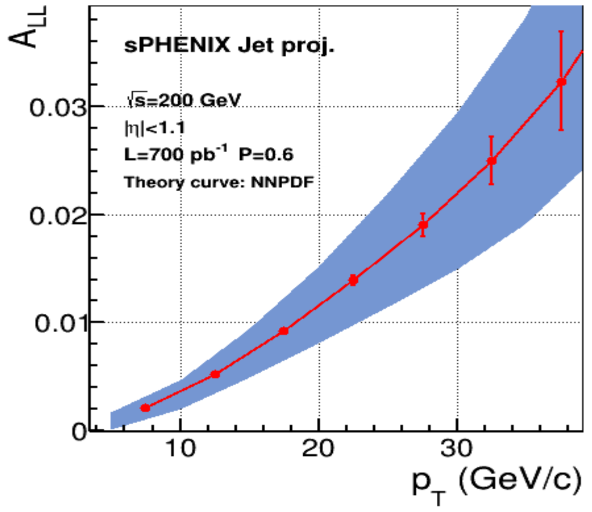
October 2018

BROOKHAVEN NATIONAL LABORATORY

Description of how community resources leverage the RHIC program

Cold QCD Highlights

sPHENIX barrel



High precision ΔG measurements

Will crucially improve ΔG constraint at x>0.05

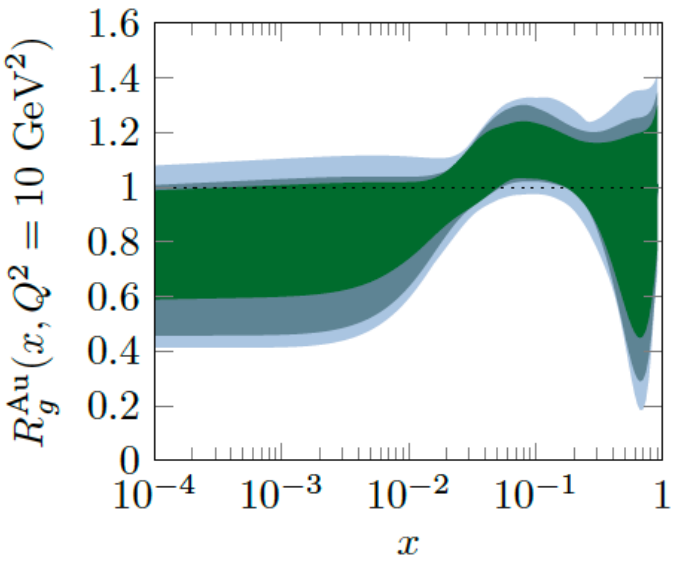
Multiple channels with different theory/ exp. uncertainites

- **γ**, *h*, *jet*, *di-jet*
- Crucial syst. cross check

Complementary to EIC

- Crucial universality test in the overlapping x-range

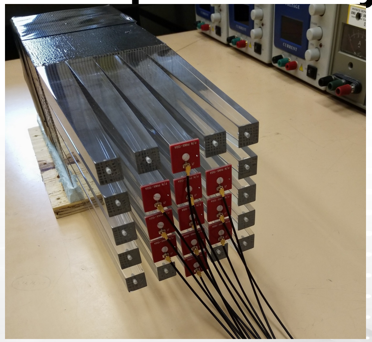
sPHENIX forward upgrade



Robust nPDF measurements

DY, **γ**, di-jet

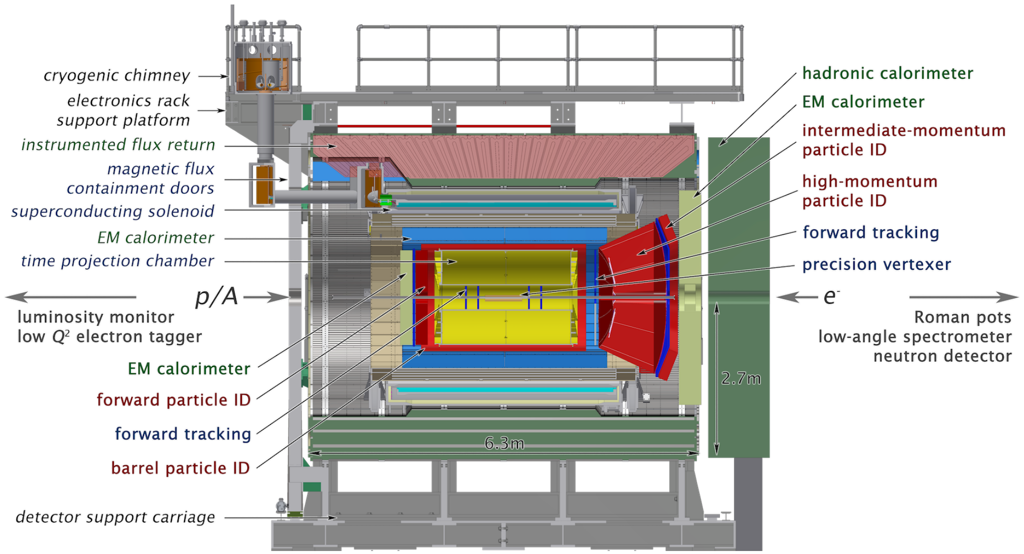
Complementary to EIC



R&D ongoing
Japanese groups
+ Iowa State, UCLA

Repurposed E864 modules

EIC-sPHENIX



Design study for general purpose EIC detector

- sPHENIX augmented with barrel PID, and forward/backward tracking, calorimetry and PID
- Full GEANT4 simulation

Important input to thinking about EIC day-1 detector

Summary

- Continued growth of collaboration since last S&T review
- Strong connections with non-US institutions, theory and EIC community
  - Experimental contributions/connections and science case
- Progress on software & computing challenges
  - Opportunity for NPPS to provide expert workforce
- Inner HCAL restoration challenge continues
- Ready to enter construction phase in 2019 for start of physics in 2023!

Backup

A corpus of one, many to come

Citesummary excluding self-citations or RPP citations

Generated on 2019-06-10

1 papers found, 1 of them citeable (published or arXiv)

Citation summary results	Citeable papers	Citeable papers excluding self cites
Total number of papers analyzed:	1	1
Total number of citations:	9	6
Average citations per paper:	9.0	6.0
Breakdown of papers by citations:		
Renowned papers (500+)	0	0
Famous papers (250-499)	0	0
Very well-known papers (100-249)	0	0
Well-known papers (50-99)	0	0
Known papers (10-49)	0	0
Less known papers (1-9)	1	1
Unknown papers (0)	0	0
h_{HEP} index [?]	1	1

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 65, NO. 12, DECEMBER 2018 2901

Design and Beam Test Results for the sPHENIX Electromagnetic and Hadronic Calorimeter Prototypes

C. A. Aidala, V. Bailey, S. Beckman, R. Belmont, C. Biggs, J. Blackburn, S. Boose, M. Chiu, M. Connors, E. Desmond, A. Franz, J. S. Haggerty, X. He, M. M. Higdon, J. Huang, K. Kauder, E. Kistenev, J. LaBounty, J. G. Lajoie, M. Lenz, W. Lenz, S. Li, V. R. Loggins, E. J. Mannel, T. Majoros, M. P. McCumber, J. L. Nagle, M. Phipps, C. Pinkenburg, S. Polizzo, C. Pontieri, M. L. Purschke, J. Putschke, M. Sarsour, T. Rinn, R. Ruggiero, A. Sen, A. M. Sickles, M. J. Skoby, J. Smiga, P. Sobel, P. W. Stankus, S. Stoll, A. Sukhanov, E. Thorsland, F. Toldo, R. S. Towell, B. Ujvari, S. Vazquez-Carson, and C. L. Woody

***Abstract*—The super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) at the Relativistic Heavy Ion Collider will perform high-precision measurements of jets and heavy flavor observables for a wide selection of nuclear collision systems, elucidating the microscopic nature of strongly interacting matter ranging from nucleons to the strongly coupled quark–gluon plasma. A prototype of the sPHENIX calorimeter system was tested at the Fermilab Test Beam Facility as experiment T-1044 in the spring of 2016. The electromagnetic calorimeter (EMCal) prototype is composed of scintillating fibers embedded in a mixture of tungsten powder and epoxy. The hadronic calorimeter (HCal) prototype is composed of tilted steel plates alternating with the plastic scintillator. Results of the test beam reveal the energy resolution for electrons in the EMCal is $2.8\% \oplus 15.5\%/\sqrt{E}$ and the energy resolution for hadrons in the combined EMCal plus HCal system is $13.5\% \oplus 64.9\%/\sqrt{E}$. These results demonstrate that the performance of the proposed calorimeter system satisfies the sPHENIX specifications.**

***Index Terms*—Calorimeters, electromagnetic calorimetry, hadronic calorimetry, performance evaluation, prototypes, Relativistic Heavy Ion Collider (RHIC), silicon photomultiplier (SiPM), simulation, "Spaghetti" Calorimeter (SPACAL), super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX).**

Manuscript received June 28, 2018; revised August 23, 2018; accepted September 7, 2018. Date of publication November 1, 2018; date of current version December 14, 2018. This work was supported in part by the Office of Nuclear Physics in the Office of Science of the Department of Energy and in part by the National Science Foundation.

C. A. Aidala and M. J. Skoby are with the Department of Physics, University of Michigan, Ann Arbor, MI 48109-1040 USA.

V. Bailey, J. Blackburn, M. M. Higdon, S. Li, V. R. Loggins, M. Phipps, A. M. Sickles, P. Sobel, and E. Thorsland are with the Department of Physics, University of Illinois at Urbana–Champaign, Urbana, IL 61801-3003 USA.

S. Beckman, R. Belmont, J. L. Nagle, and S. Vazquez-Carson are with the Department of Physics, University of Colorado Boulder, Boulder, CO 80309-0390 USA.

C. Biggs, S. Boose, M. Chiu, E. Desmond, A. Franz, J. S. Haggerty, J. Huang, E. Kistenev, J. LaBounty, M. Lenz, W. Lenz, E. J. Mannel, C. Pinkenburg, S. Polizzo, C. Pontieri, M. L. Purschke, R. Ruggiero, S. Stoll, A. Sukhanov, F. Toldo, and C. L. Woody are with the Brookhaven National Laboratory, Upton, NY 11973-5000 USA (e-mail: jhuang@bnl.gov).

M. Connors is with the Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30302-5060 USA, and also with the RIKEN BNL Research Center, Upton, NY 11973-5000 USA.

X. He and M. Sarsour are with the Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30302-5060 USA.

K. Kauder is with the Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201-3718 USA, and also with the Brookhaven National Laboratory, Upton, NY 11973-5000 USA.

J. G. Lajoie, T. Rinn, and A. Sen are with the Department of Physics and Astronomy, Iowa State University, Ames, IA 50011-3160 USA.

T. Majoros and B. Ujvari are with the Institute of Physics, University of Debrecen, H-4032 Debrecen, Hungary.

M. P. McCumber is with the Los Alamos National Laboratory, Los Alamos, NM 87545-0001 USA.

J. Putschke is with the Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201-3718 USA.

J. Smiga is with the Department of Physics, University of Maryland, College Park, MD 20742-4111 USA.

P. W. Stankus is with the Oak Ridge National Laboratory, Oak Ridge, TN 37830-8050 USA.

R. S. Towell is with the Department of Engineering and Physics, Abilene Christian University, Abilene, TX 79699-9000 USA.

Digital Object Identifier 10.1109/TNS.2018.2879047

I. Introduction

THE super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) is a planned experiment [1] at the Relativistic Heavy Ion Collider (RHIC). RHIC is a highly versatile machine that collides a diverse array of nuclear beams from protons to heavy ions and supports a very broad physics program for the study of both hot and cold quantum chromodynamics matter. sPHENIX is specifically designed for the measurements of jets, quarkonia, and other rare processes originating from hard scatterings to study the microscopic nature of strongly interacting matter ranging from nucleons [2] to the strongly coupled quark–gluon plasma (QGP) created in collisions of gold ions at $\sqrt{s_{NN}} =$ 200 GeV [3]–[6]. sPHENIX is equipped with a tracking system and a three-segment calorimeter system, both of which have a full 2π acceptance in azimuth and a pseudorapidity coverage of $|\eta| < 1.1$. sPHENIX has acquired the former BaBar magnet, which has an inner radius of 1.4 m and an outer radius of 1.75 m [7]. The sPHENIX calorimeter system includes an electromagnetic calorimeter (EMCal) and an inner hadronic calorimeter (HCal), which sit inside the solenoid, and an outer HCal located outside of the magnet. The EMCal will be used for identifying photons, electrons, and positrons. Photons can be used to tag the energy of opposing jets traversing the QGP, while electrons and positrons will

First peer-reviewed sPHENIX paper

Comparison of projected FF uncertainties

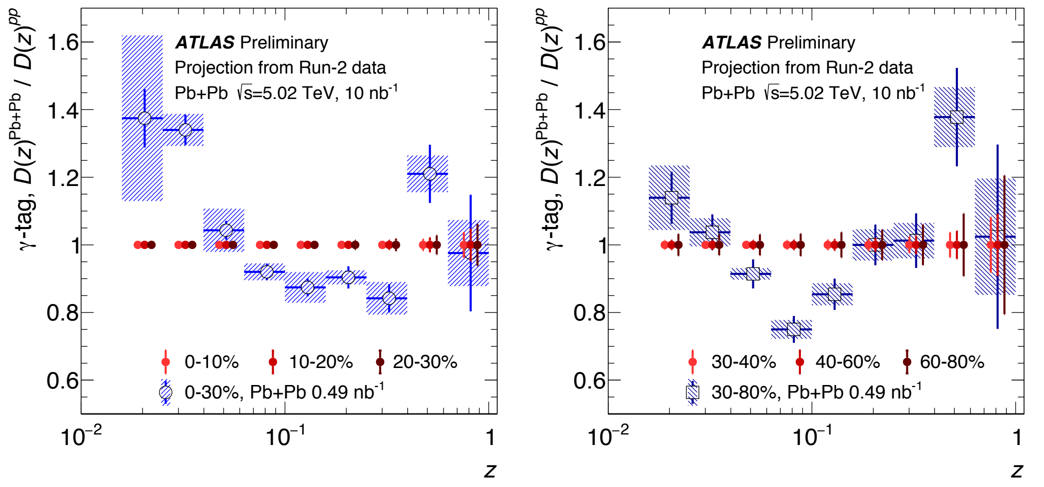


Fig. 35: Projection of the statistical precision that can be reached for the ratio of jet fragmentation functions in Pb–Pb and pp collisions, $R_{D(z)}$, of jets recoiling from a photon. The left panel shows the projection for the most central collisions while the right panel for the more peripheral events [5].

CERN Yellow Report projections for Runs 3, 4

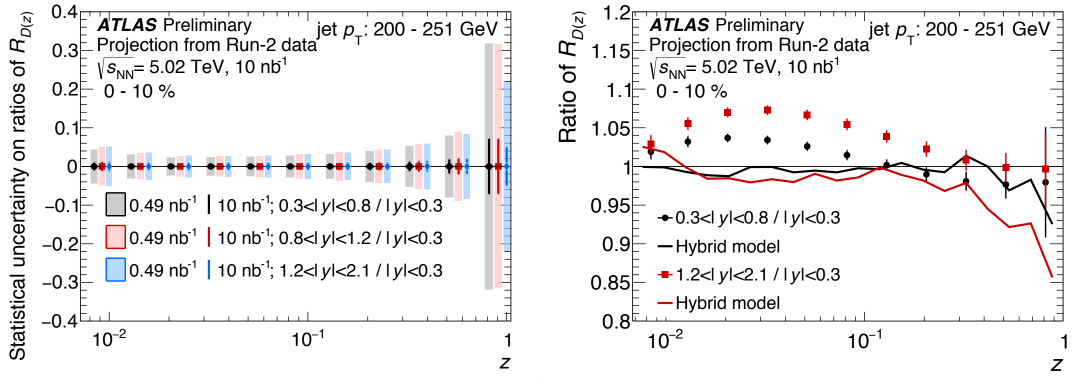
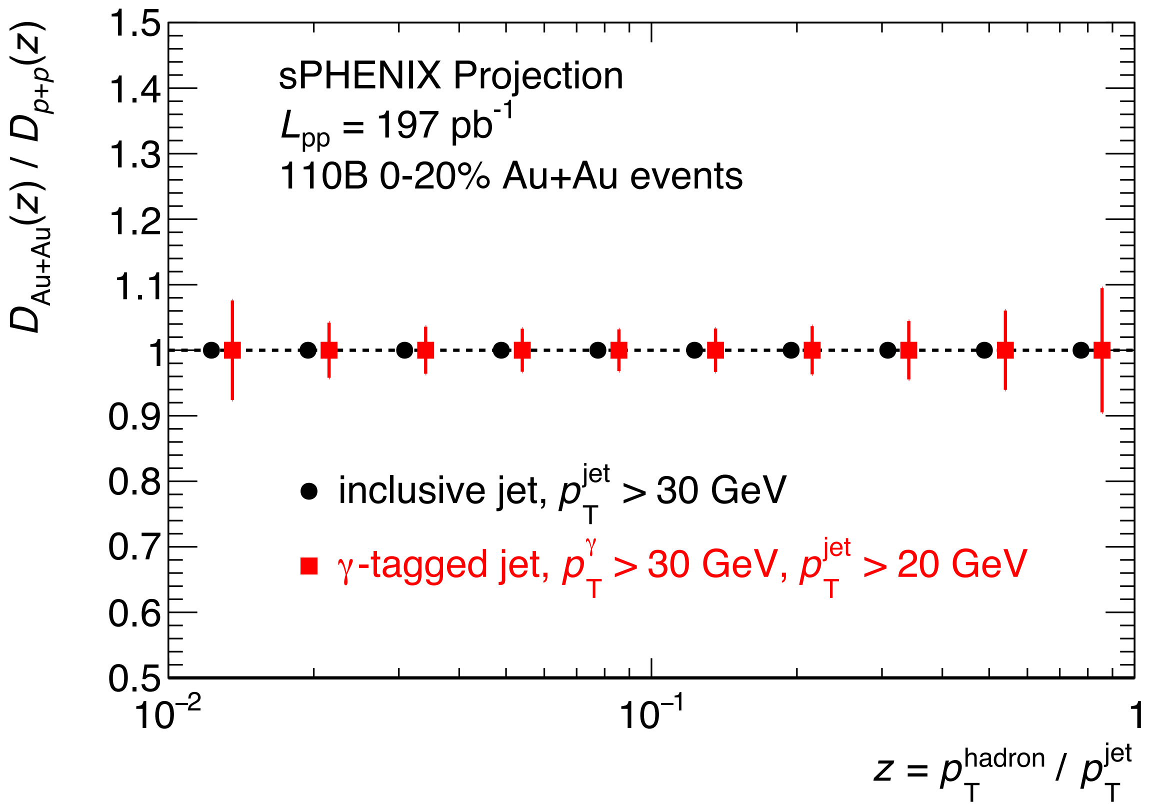


Fig. 33: Projection of the precision that can be reached for the modification of jet fragmentation function, $R_{D(z)}$, measured in jet p_{T} interval $200 - 251$ GeV/c. In the left panel the statistical uncertainty on the measurement with the shaded boxes corresponding to 0.49 nb^{-1} while the vertical bars are for 10 nb^{-1}. The right panel shows a comparison of $R_{D(z)}$ with a theory model (see text for more details) [5].



- different min. hadron & jet p_{T} at LHC (>1 GeV, ~100's of GeV) vs. RHIC (>0.4 GeV, ~30-40 GeV), but coincidentally similar low-z reach
- matched x-axis range & binning, jet

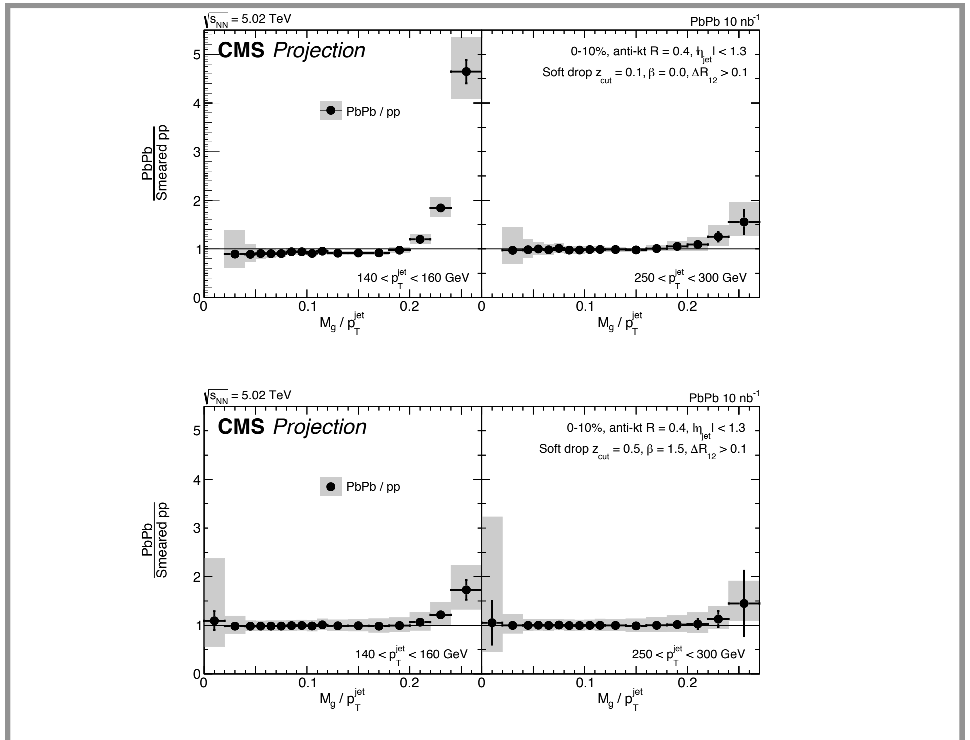
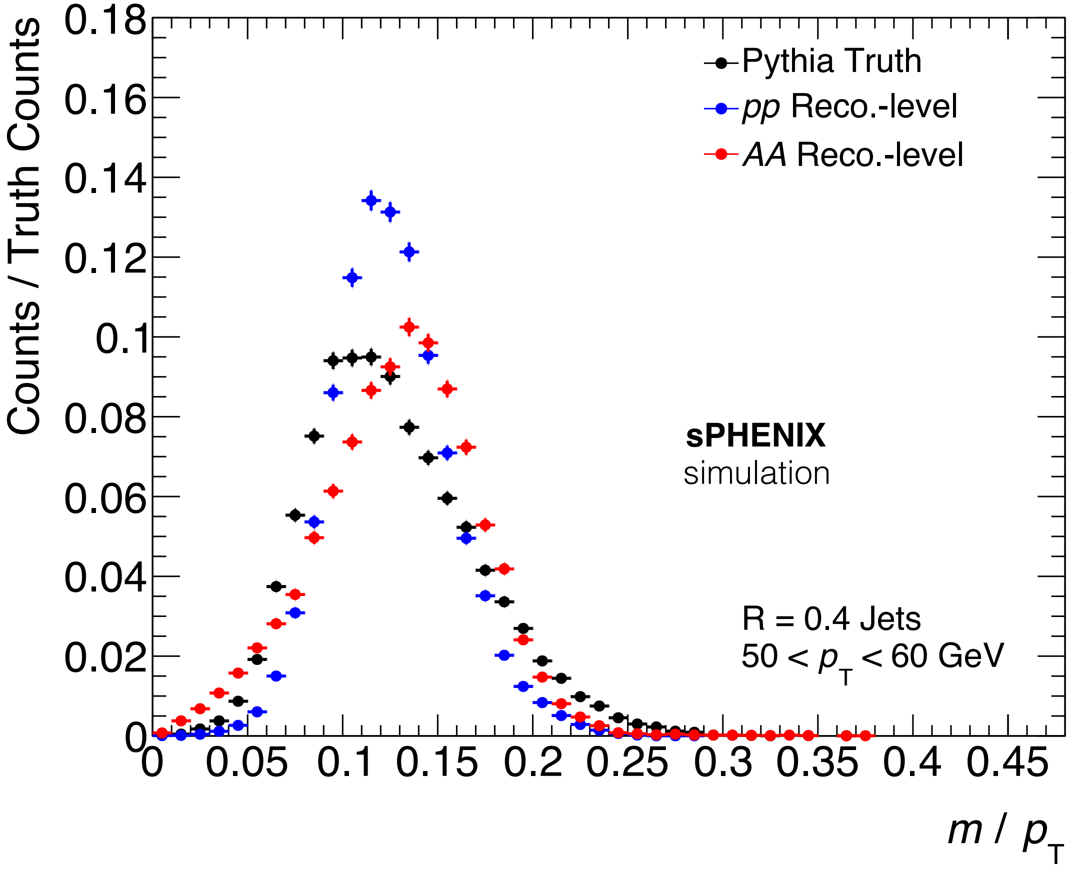


Fig. 37: Jet mass distribution with grooming setting $(z_{cut}, \beta) = (0.1, 0.0)$ (Upper panels) and $(z_{cut}, \beta) = (0.5, 1.5)$ (Lower panels). [8]

CERN Yellow Report projections for Runs 3, 4



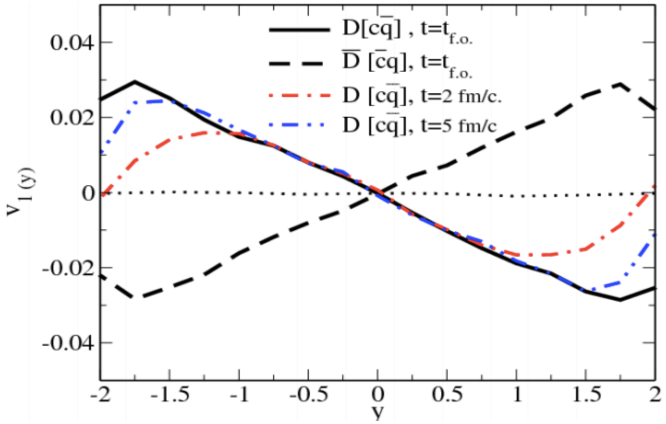
CMS groomed mass / p_T (left) — c.f. sPHENIX version w/ <u>ungroomed</u> mass (right)

➡ new observable enabled by constituent mass subtraction

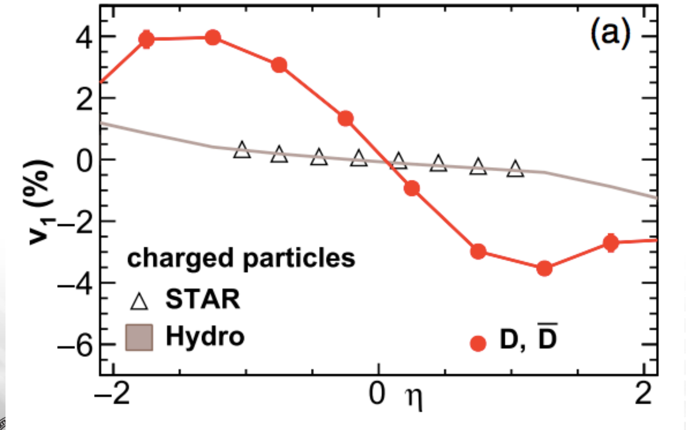
➡ general conclusion: can pick kinematic regions where UE effects are small

D^0 v_1 - Direct Access to Initial B Field

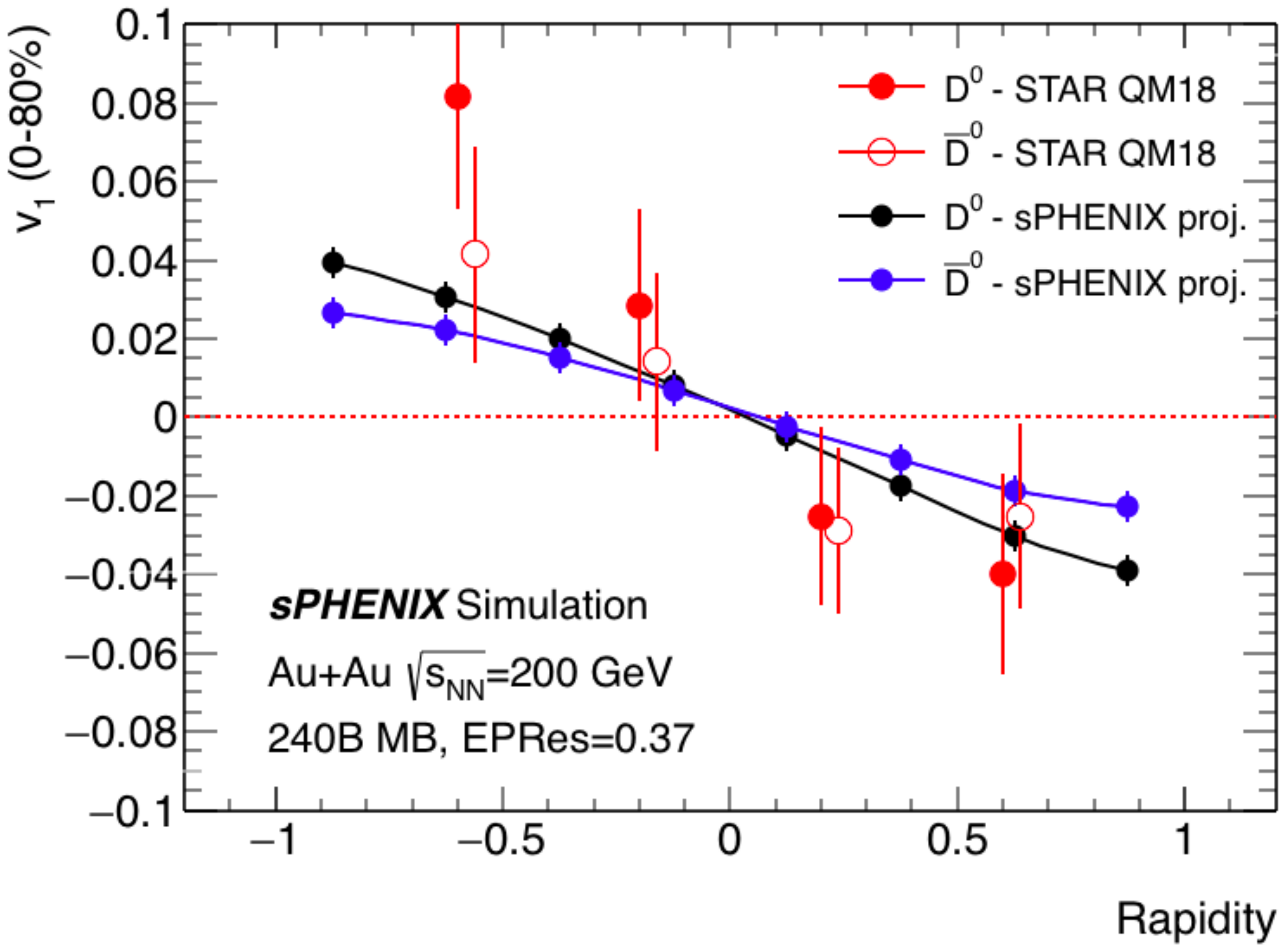
init. B -> v1(D) = -v1(Dbar)



tilt QGP -> v1(D) = v1(Dbar) >> v1(h)

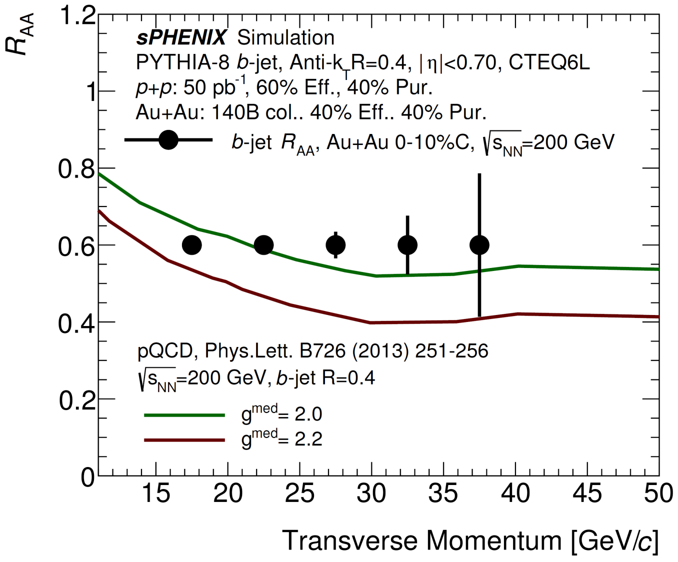


Need: Good ZDC-SMD detector to improve 1st EP resolution

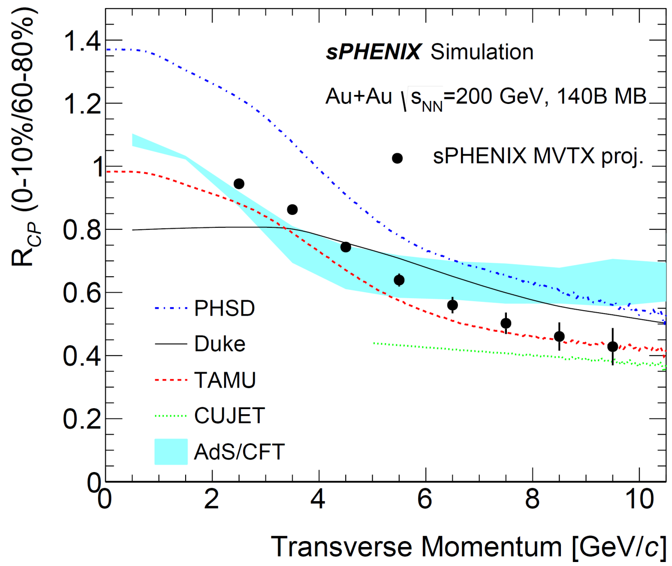


Open HF observables – b-tagged jets, B mes

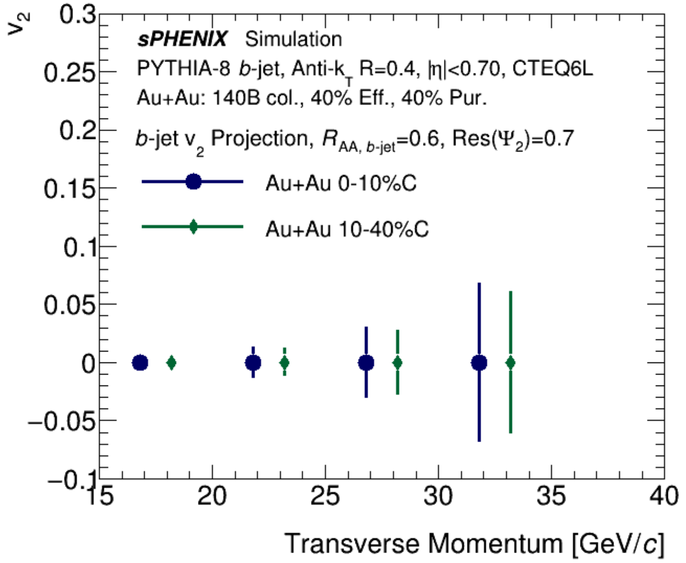
b-tagged jet R_{AA}



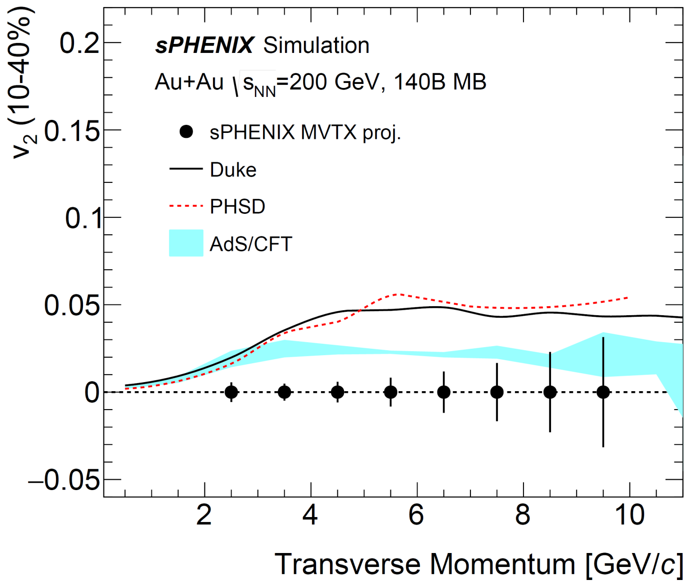
B-meson R_{CP}



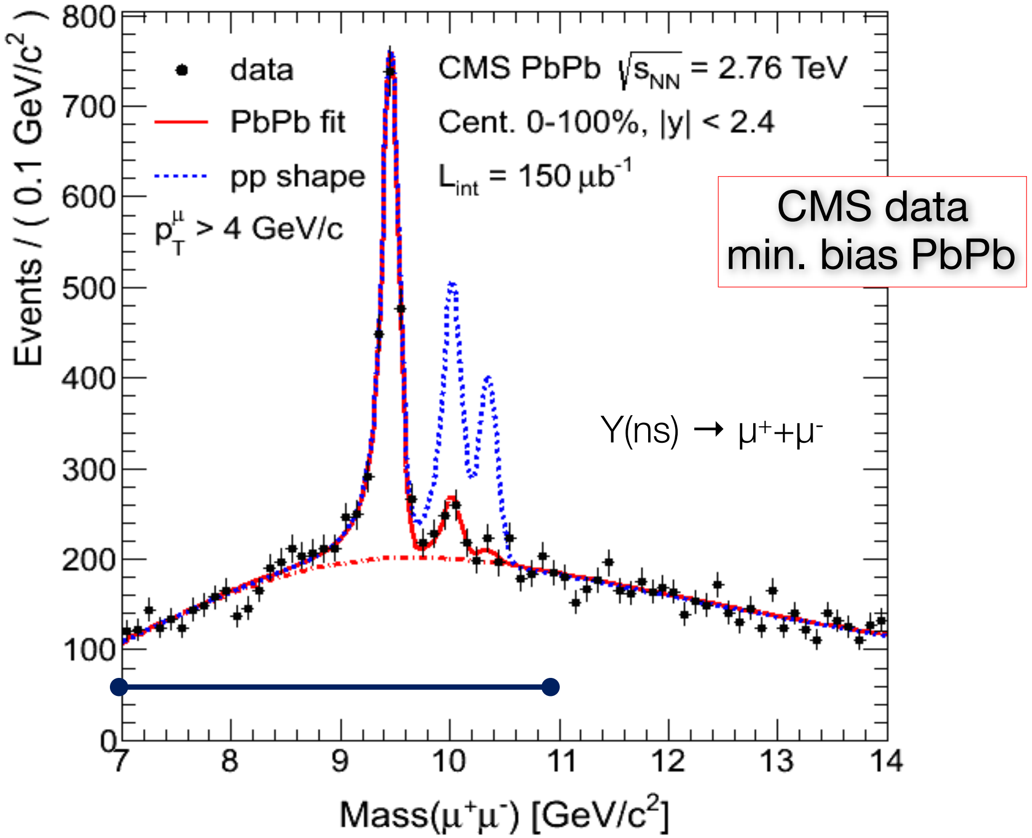
b-tagged jet v_2

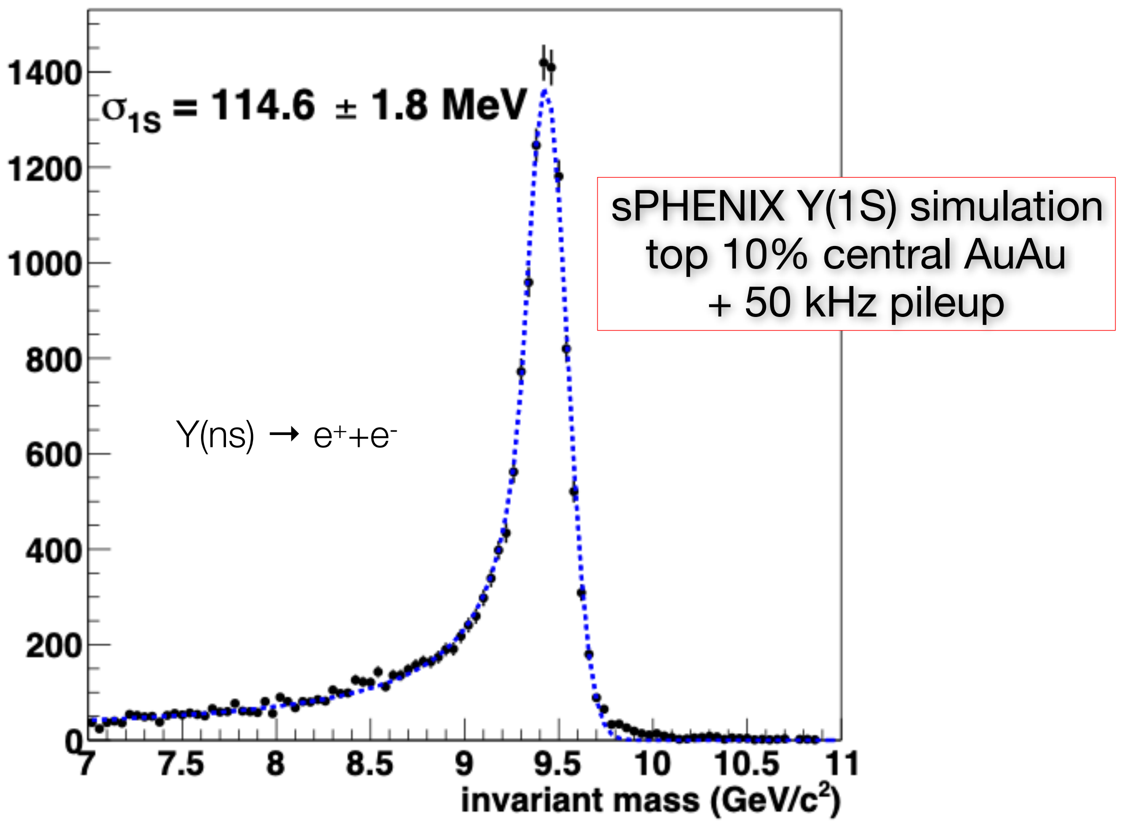


B-meson v_2



Upsilons at sPHENIX and LHC





Differential suppression of Υ(nS), temperature dependence of QGP Debye screening length

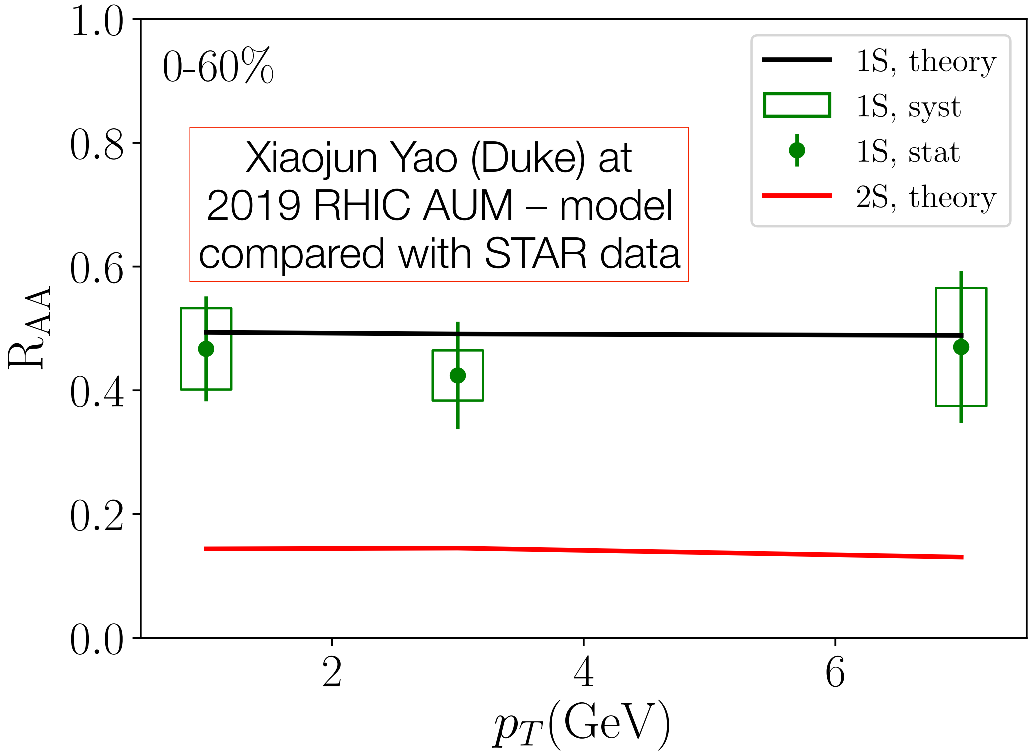
Υ(1S) width key f.o.m. in work of Inner Detector Optimization Task Force – deciding INTT configuration (pattern recognition vs. radiative tails and conversions)

Quarkonium in the medium – recent work

sPHENIX

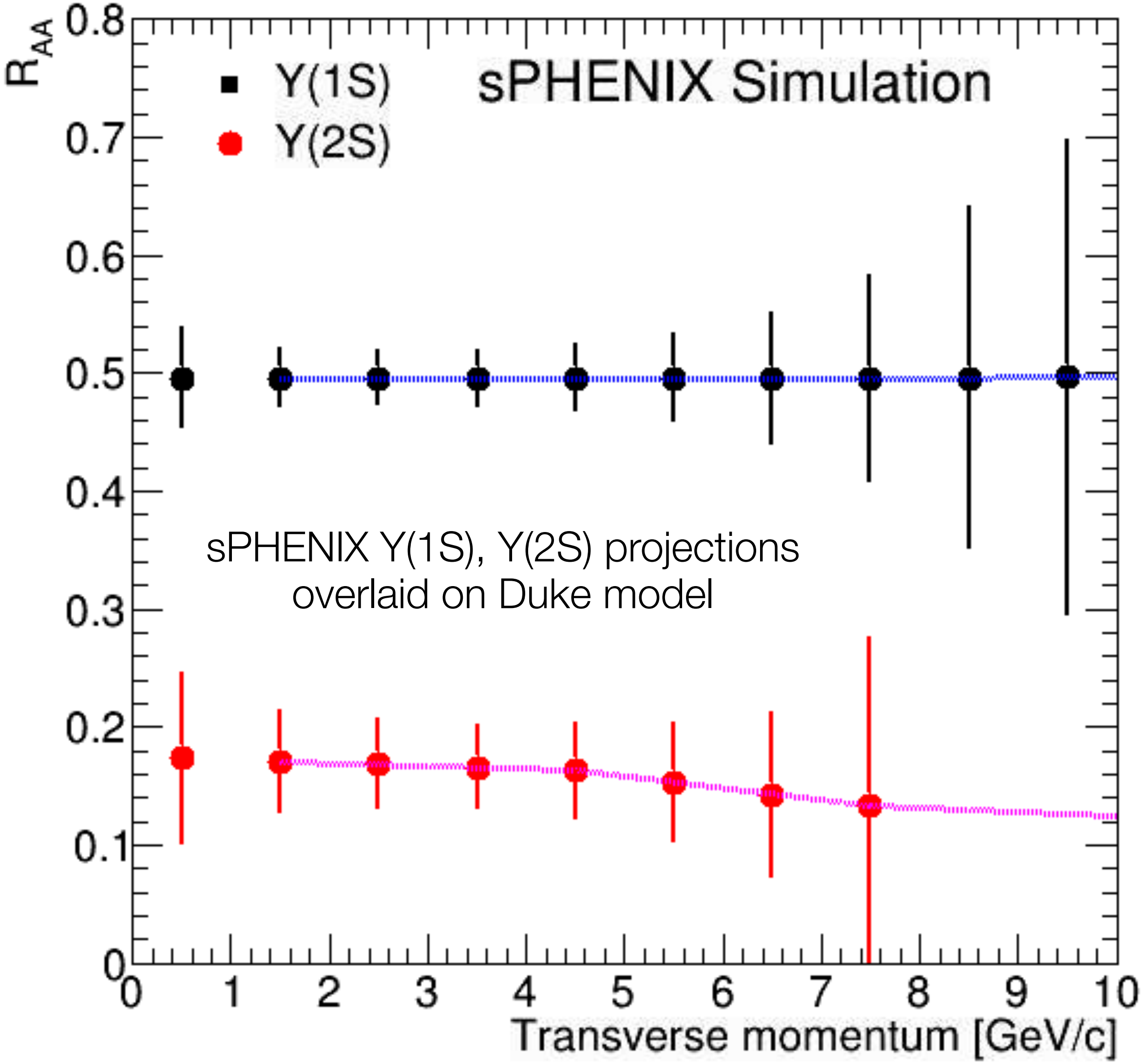
Detailed balance affected by dissociation, strong energy loss of bare HQ, recombination

See X. Yao, B. Mueller, arXiv:1811.09644



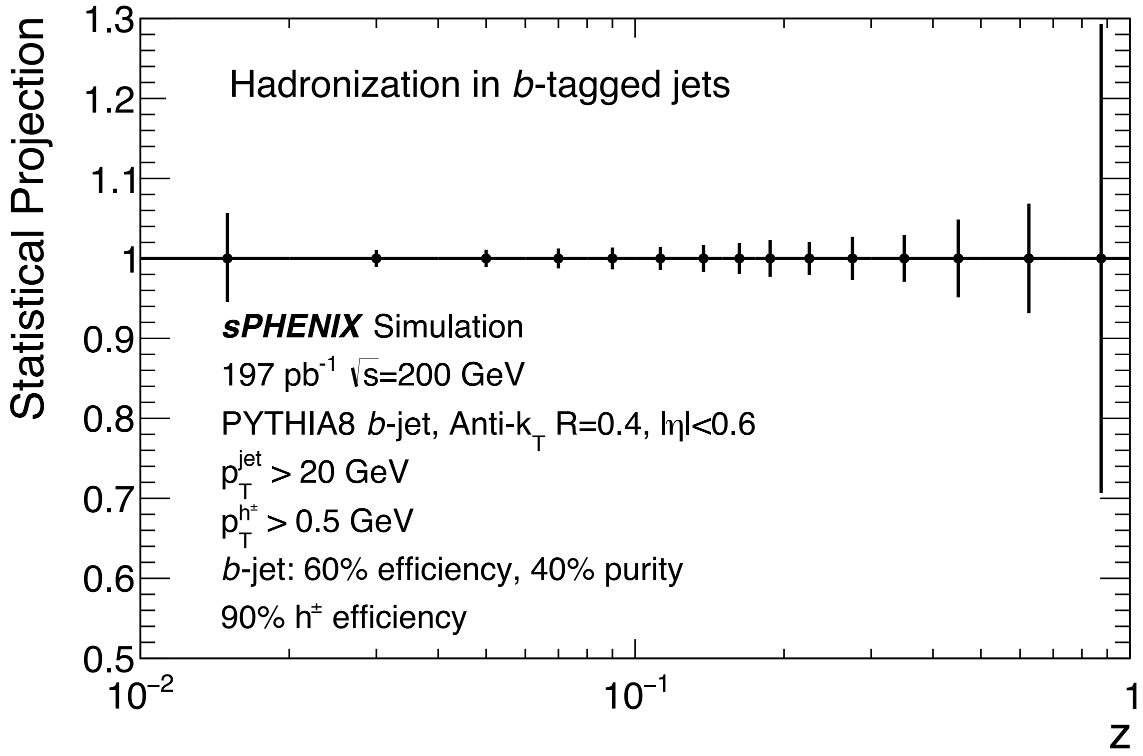
Xiaojun Yao (Duke) at 2019 RHIC AUM – model compared with STAR data

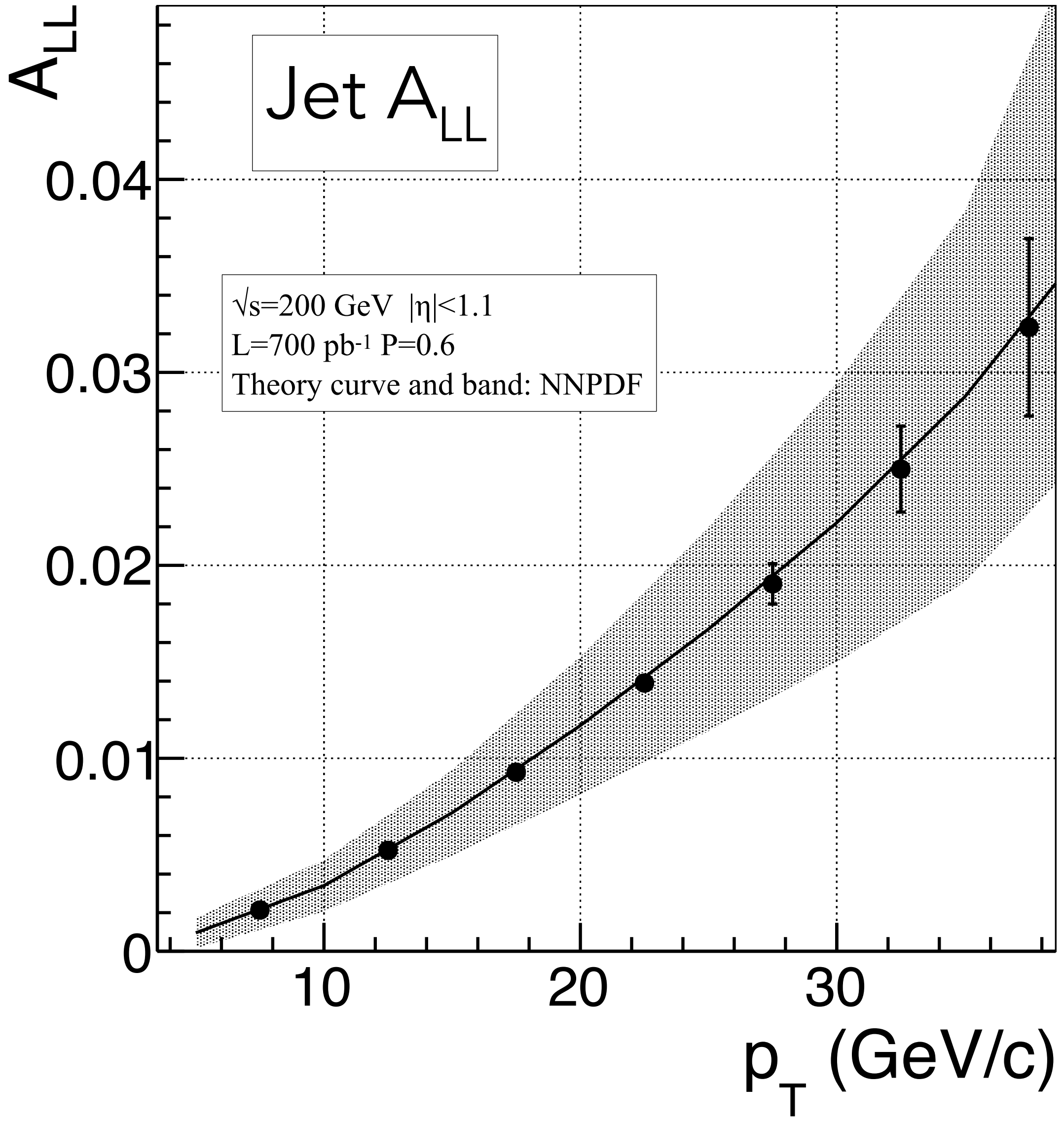
Following discussions with sPHENIX collaborators X.Yao generated projections in sPHENIX acceptance



sPHENIX Υ(1S), Υ(2S) projections overlaid on Duke model

Central Barrel Opportunities

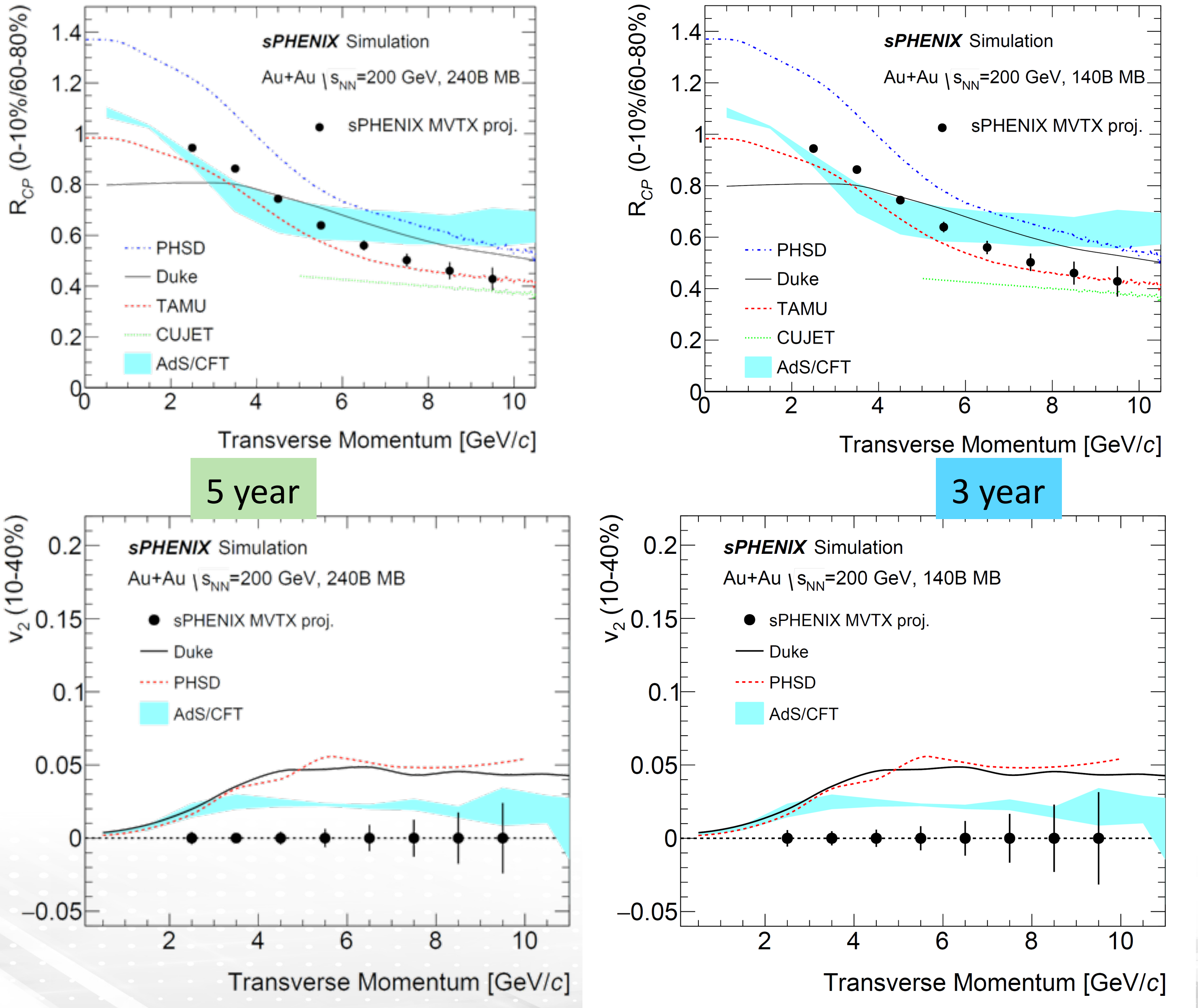




- Builds on October 2017 study of ME physics with sPHENIX barrel ( )
- Spin structure, parton dynamics, hadronization, (n)PDFs, quarkonia…
- Utilize jet, heavy flavor, and direct photon strengths of sPHENIX barrel

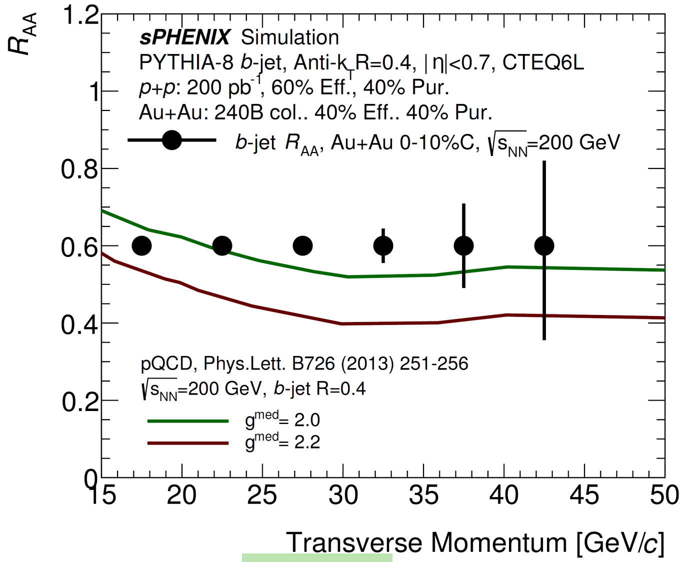
U.S. DEPARTMENT OF ENERGY

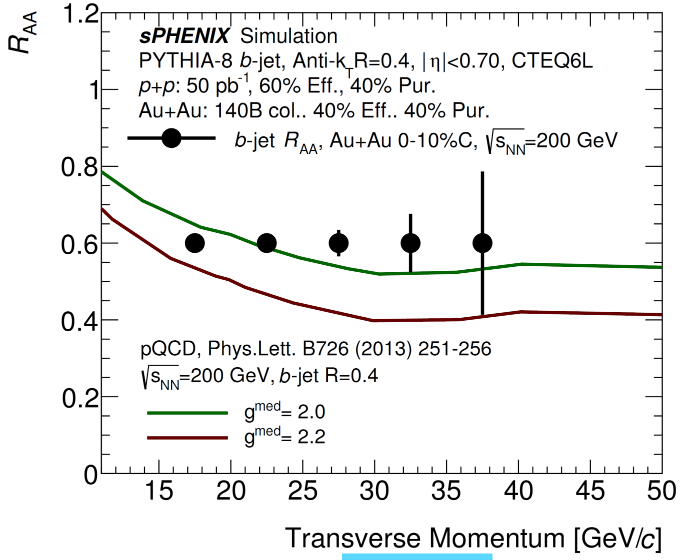
5-yr vs. 3-yr



sPHENIX Simulation
Au+Au √sNN=200 GeV, 240B MB
sPHENIX MVTX proj.
PHSD
Duke
TAMU
CUJET
AdS/CFT
RCP (0-10%/60-80%)
Transverse Momentum [GeV/c]
sPHENIX Simulation
Au+Au √sNN=200 GeV, 140B MB
sPHENIX MVTX proj.
PHSD
Duke
TAMU
CUJET
AdS/CFT
RCP (0-10%/60-80%)
Transverse Momentum [GeV/c]
5 year
3 year
sPHENIX Simulation
Au+Au √sNN=200 GeV, 240B MB
sPHENIX MVTX proj.
Duke
PHSD
AdS/CFT
v2 (10-40%)
Transverse Momentum [GeV/c]
sPHENIX Simulation
Au+Au √sNN=200 GeV, 140B MB
sPHENIX MVTX proj.
Duke
PHSD
AdS/CFT
v2 (10-40%)
Transverse Momentum [GeV/c]

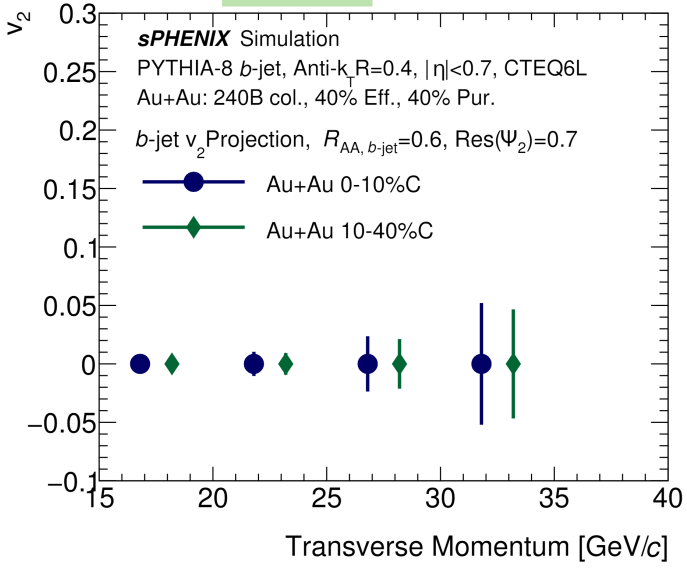
5-yr vs. 3-yr

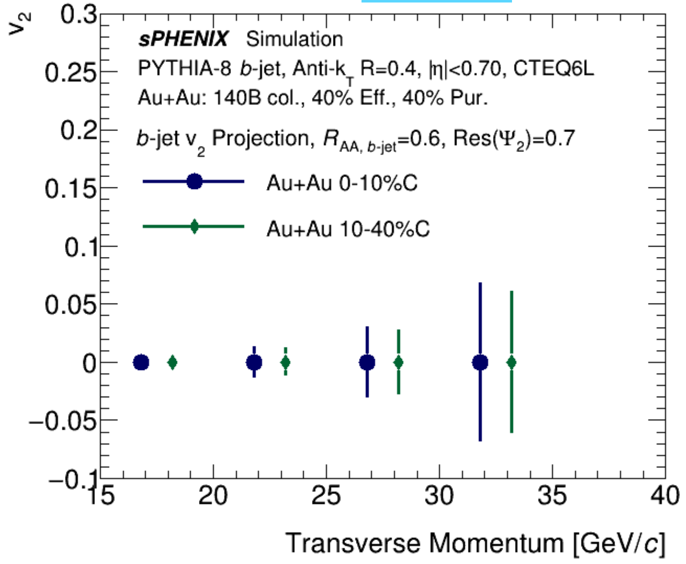




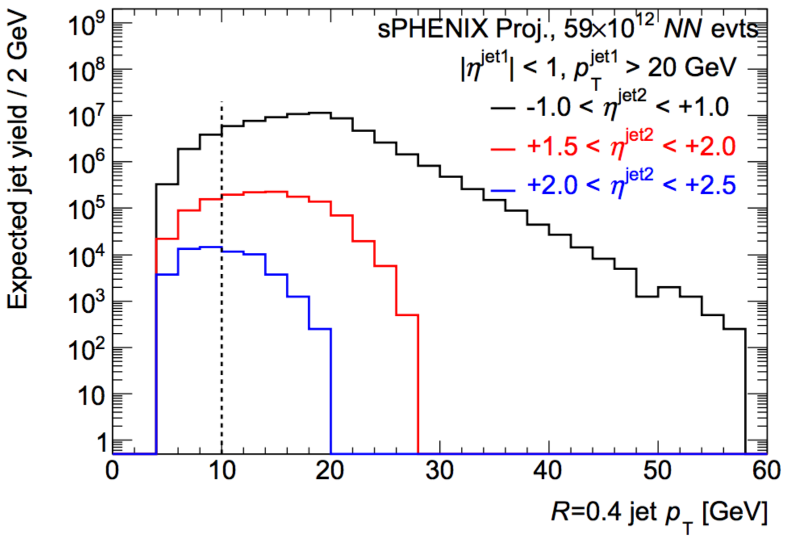
5 year

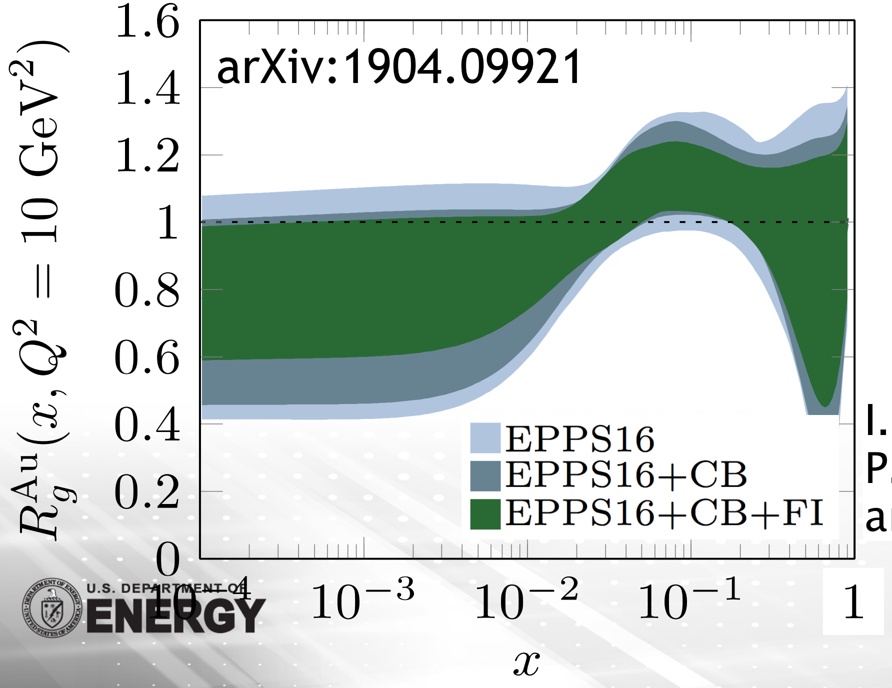
3 year





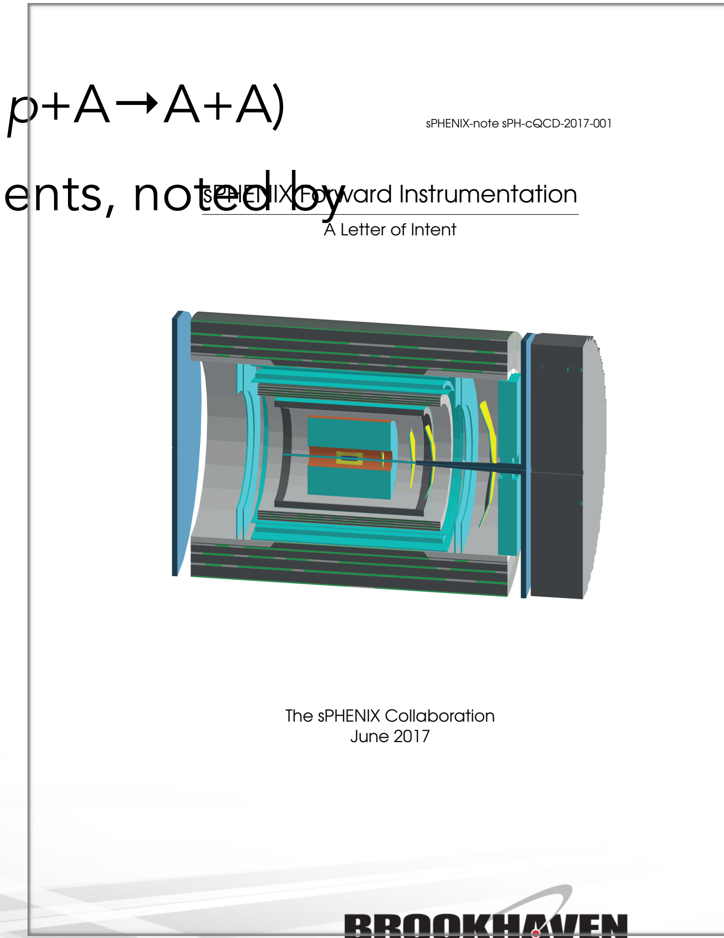
Forward Arm Physics





- Builds on June 2017 study of forward instrumentation ( )
  - Forward calorimetry expands sPHENIX QGP jet tomography program
  - Long range correlations (p+p→p+A→A+A)
  - Enables robust nPDF measurements, noted by broader nHEP community
  - Forward spin phenomena
  - Direct photons
  - Forward quarkonia

I. Helenius, J. Lajoie, J. Osborn, P. Paakkinen, H. Paukkunen arXiv:1904.09921


sPHENIX-note sPH-cQCD-2017-001

sPHENIX Forward Instrumentation

A Letter of Intent

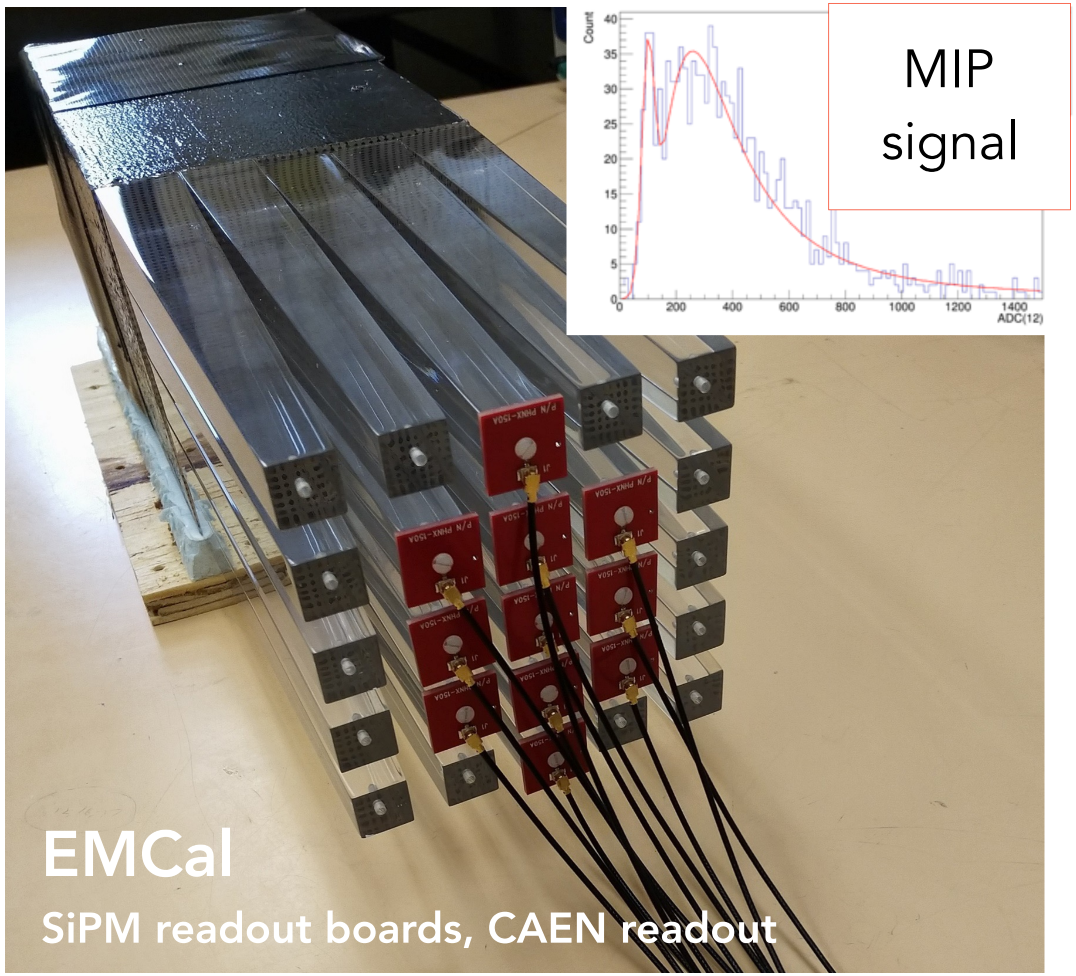
The sPHENIX Collaboration
June 2017

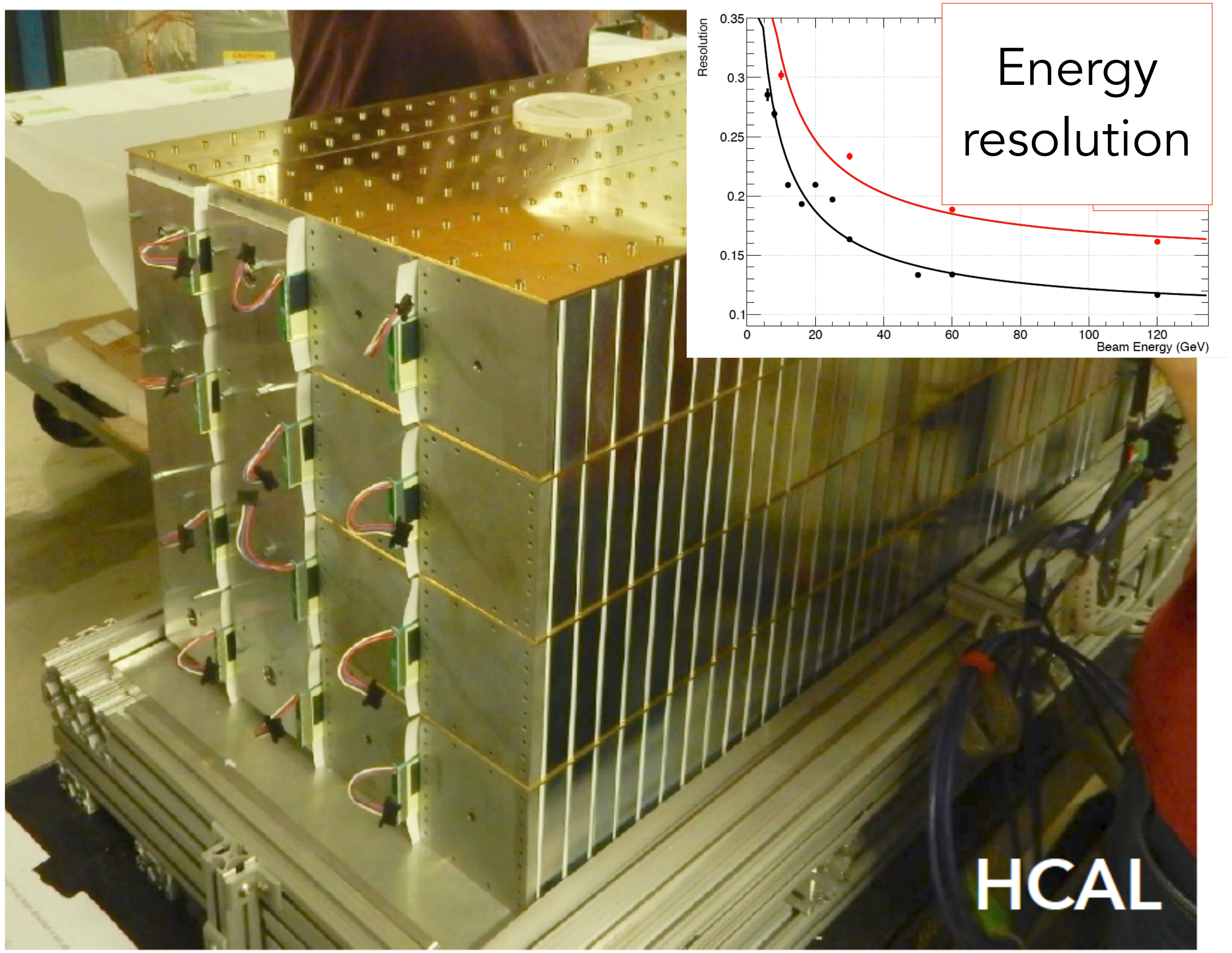
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Potential of forward upgrades

sPHENIX





Cut E864 module for use as a high granularity EMCal: cosmic tests ongoing at Iowa State University

Hadronic calorimeter: test beam recently finished by RIKEN in collaboration with STAR/UCLA

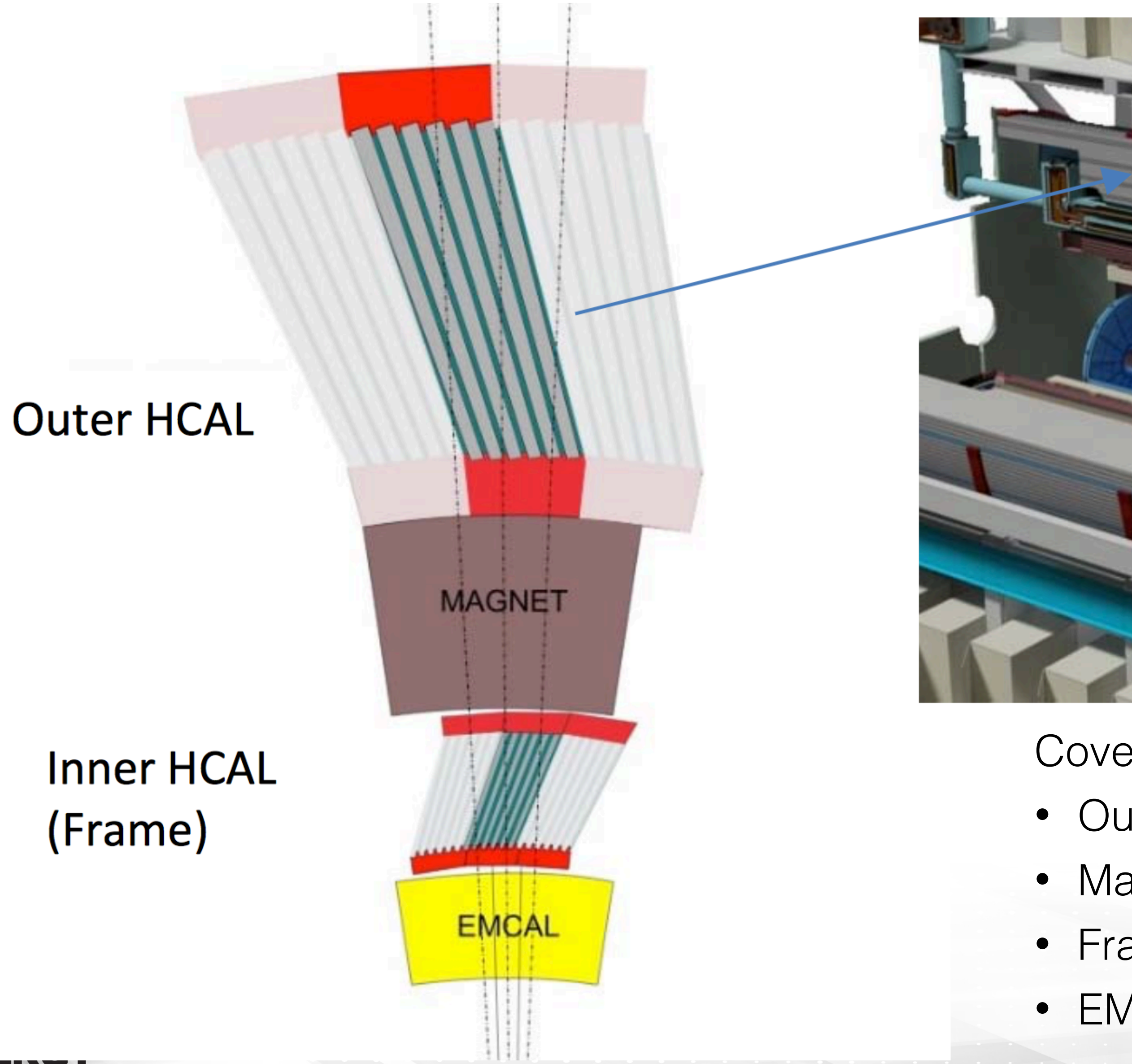
U.S. DEPARTMENT OF ENERGY

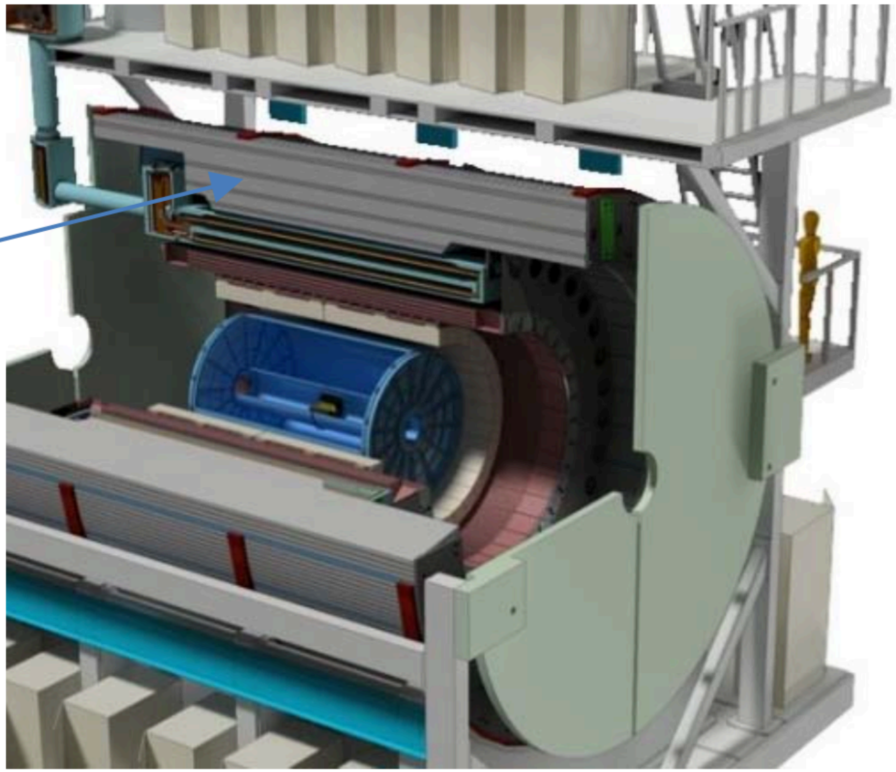
BROOKHAVEN NATIONAL LABORATORY

UPPs

Physics Goal	Analysis Requirement	Ultimate Performance Parameter
Maximize statistics for rare probes	Accept/sample full delivered luminosity	**Data taking rate of 15kHz for Au+Au**
Precision Upsilon spectroscopy	Resolve Υ(1s), Υ(2s), (Υ3s) states	**Υ(1s) mass resolution ≤ 125MeV in central Au+Au**
High jet efficiency and resolution	Full hadron and EM calorimetry Jet resolution dominated by irreducible background fluctuations	**$\sigma/\mu \leq 150\%/\sqrt{p_{Tjet}}$ in central Au+Au for R=0.2 jets**
Full characterization of jet final state	High efficiency tracking for $0.2 < p_T < 40$GeV	**Tracking efficiency ≥ 90% in central Au+Au** **Momentum resolution ≤ 10% for p_T = 40 GeV**
Control over initial parton p_T	Photon tagging with energy resolution dominated by irreducible higher order processes	**Single photon resolution ≤ 8% for p_T = 15 GeV in central Au+Au**

Calorimeter stack

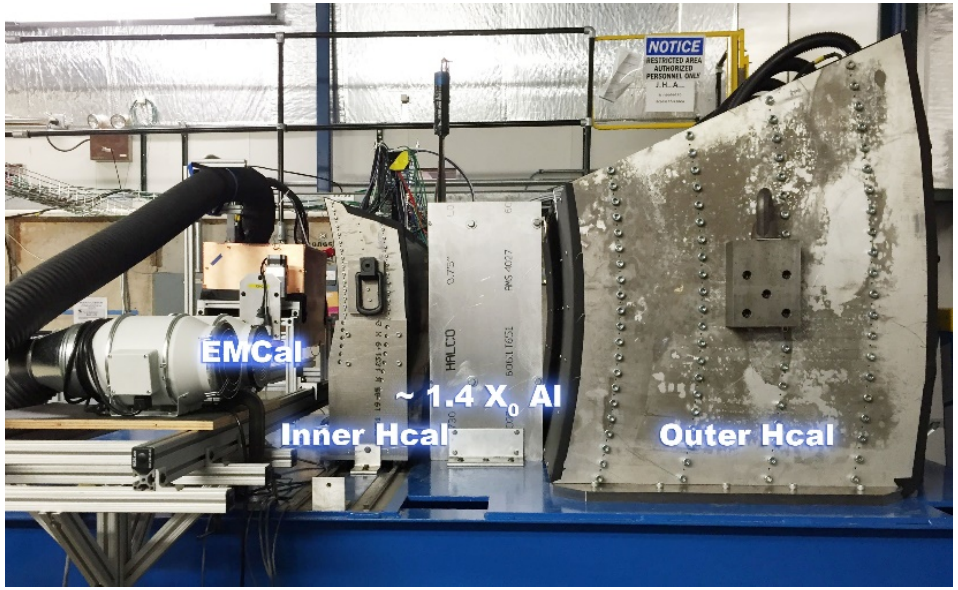


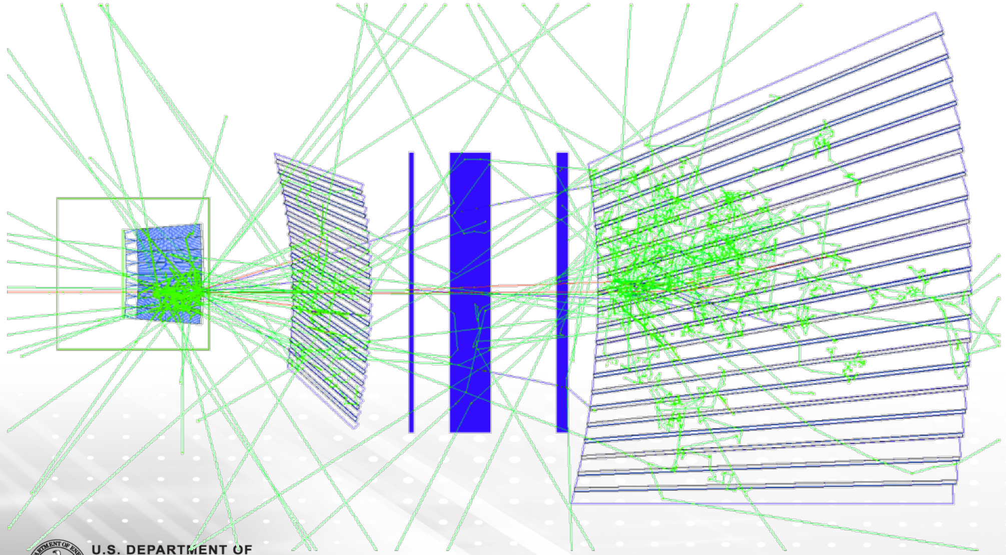


Covering $-1.1<\eta<1.1$:

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

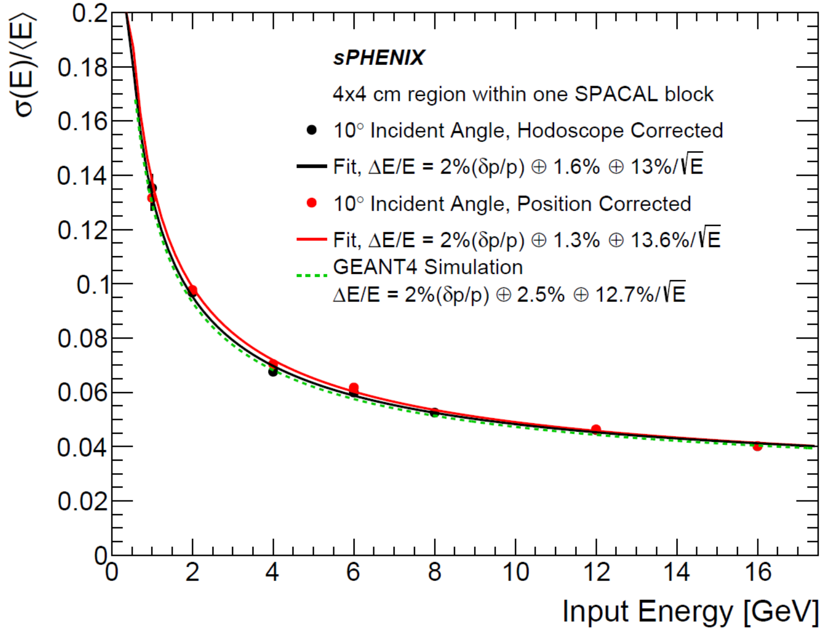
Calorimeter beam test





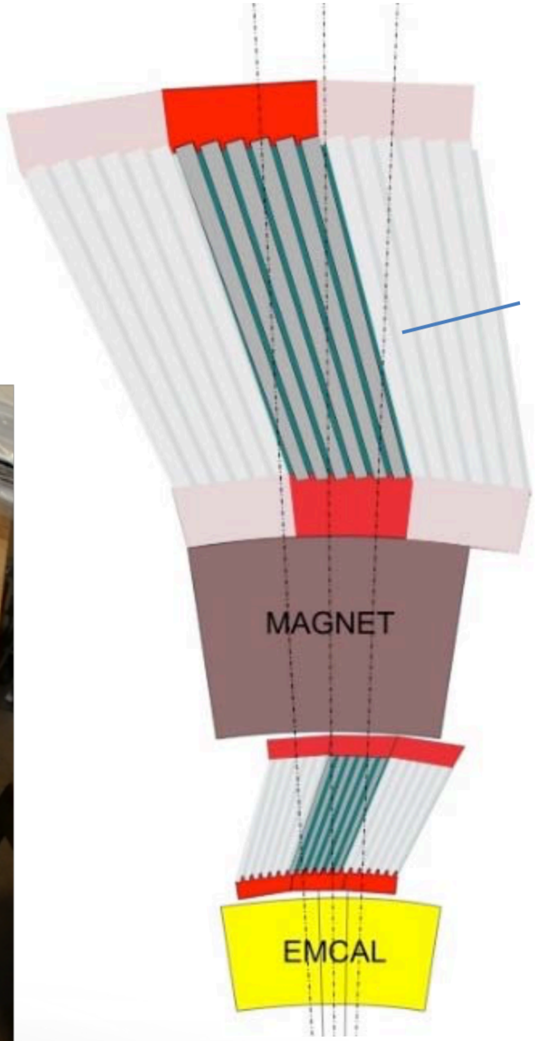
- EMCAL (sim and test) for photons $\Delta E_T/E_T < 8\%$ at 15 GeV pT
- HCAL (sim) for jets $\Delta E_T/E_T < 150\%/\sqrt{E_T}$
- In all configurations, meets sPHENIX spec

Calorimeter energy resolution



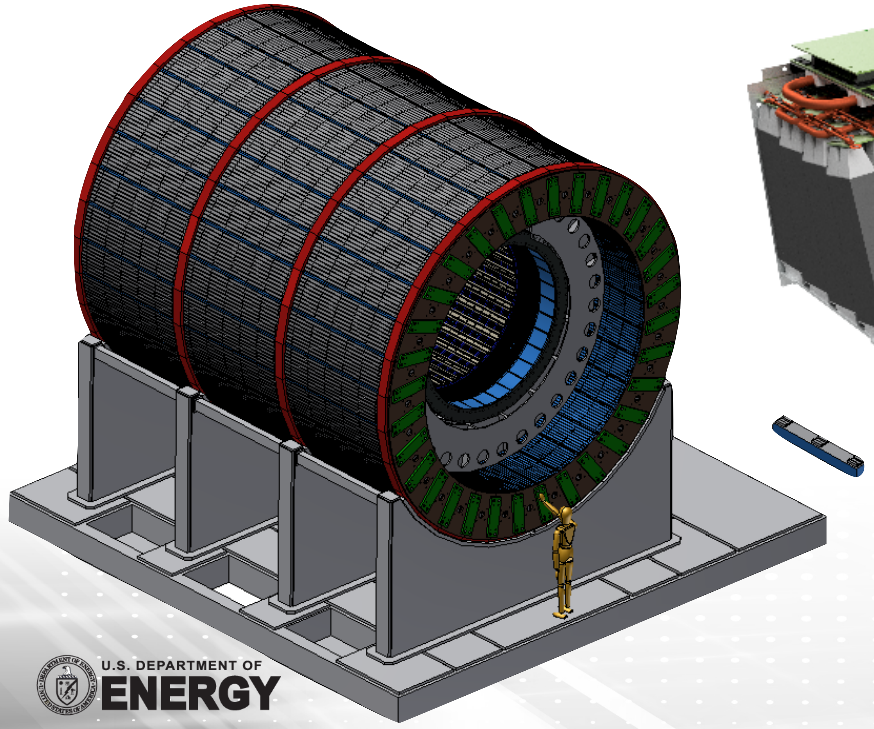
HCAL

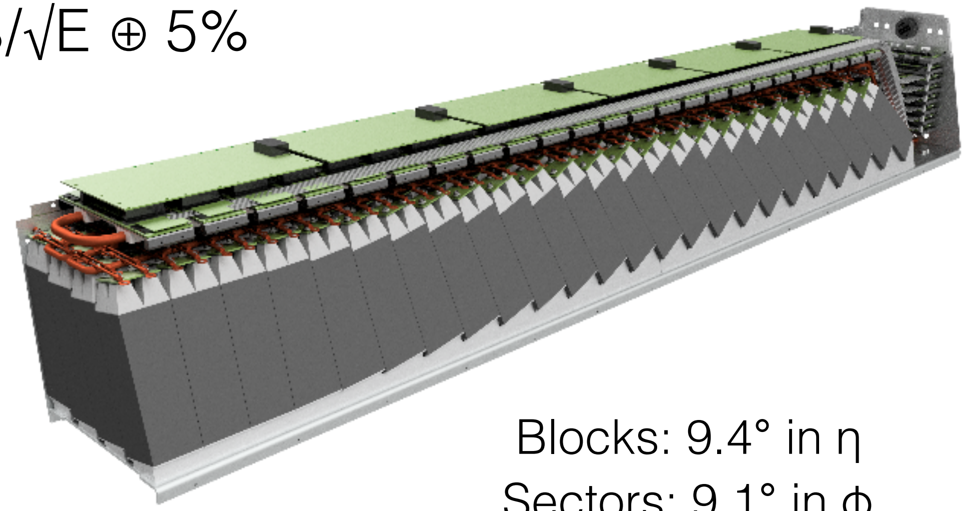
- Provides energy resolution for hadrons and jets
- Scintillating tiles interleaved in steel magnetic flux return
- Analog SiPM signals from 5 tiles combined into one tower
- 48 towers ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$) per sector
- 32 azimuthal sectors 6.3m x 0.7m, 13.5 tons each

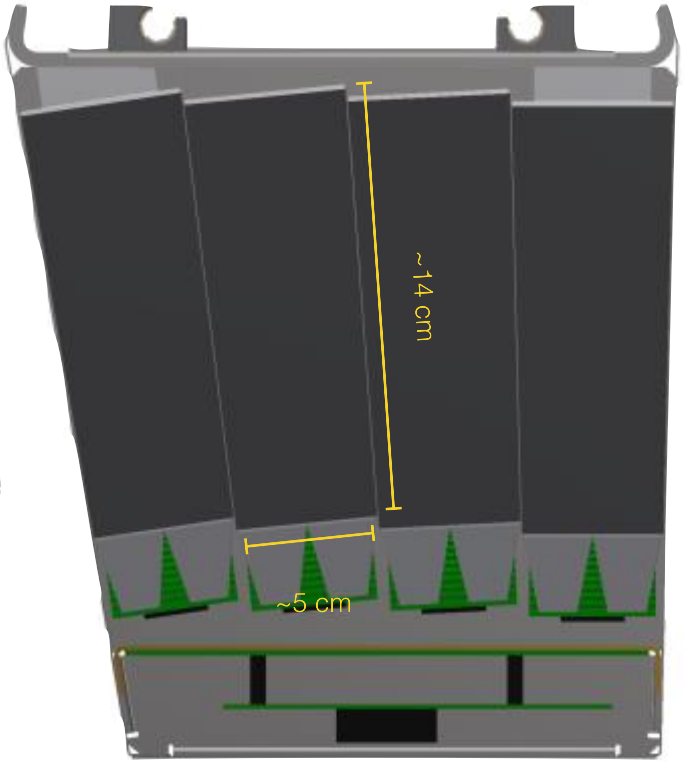


EMCAL

- Provides energy resolution for EM particles and jets
- W/SciFi SPACAL design for compactness
- Segmentation: $\Delta\eta \times \Delta\phi \approx 0.025 \times 0.025$
- Channels: 96 x 256 = 24576 2-D projective towers
- Energy resolution: $< 16\%/\sqrt{E} \oplus 5\%$

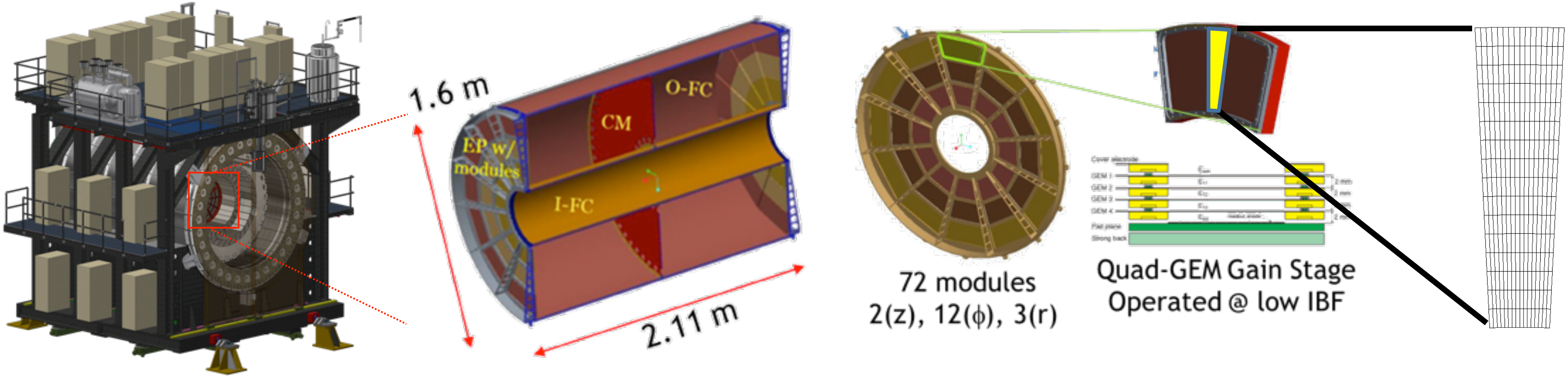






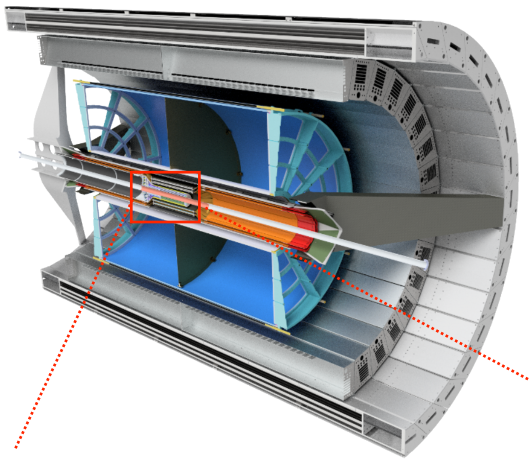
Blocks: 9.4° in η
Sectors: 9.1° in ϕ

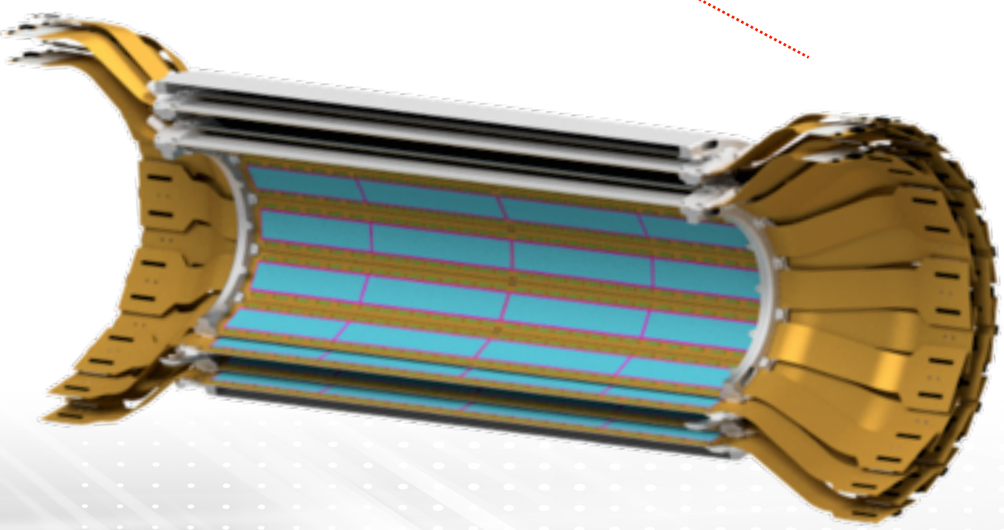
TPC

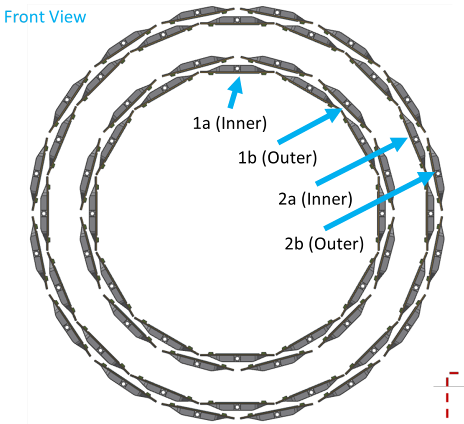


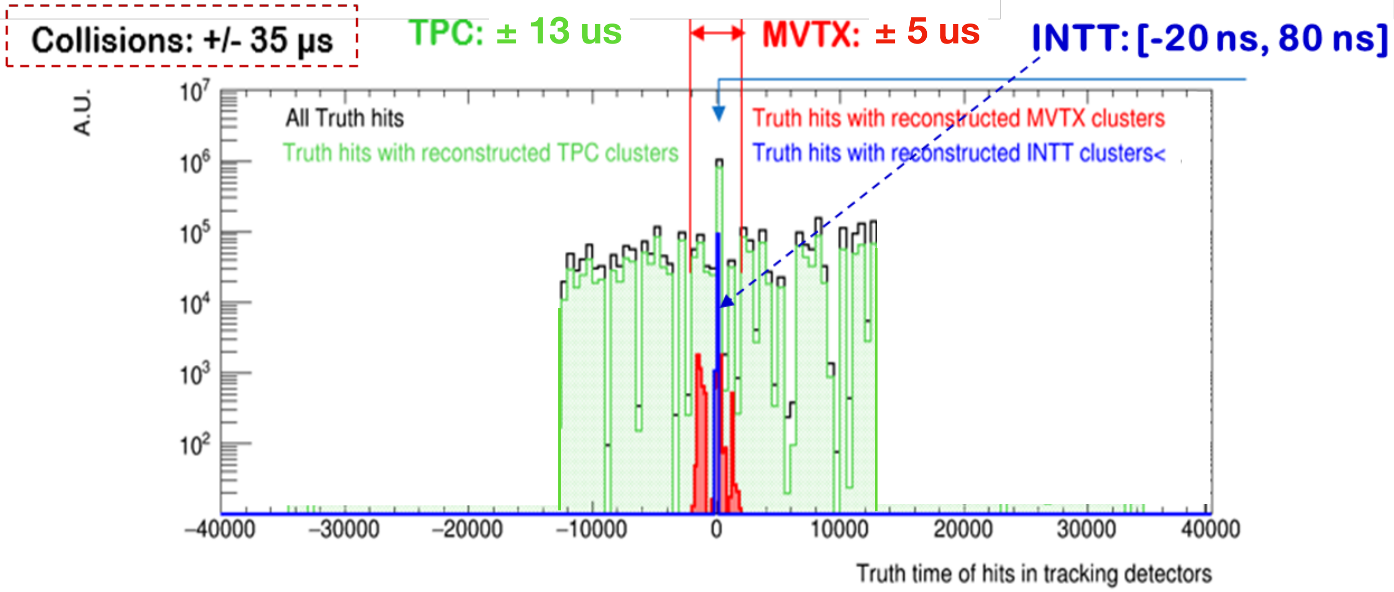
- Provides momentum reconstruction
- Operates in continuous readout mode
- Gas-Electron Multiplier (GEM) avalanche for low Ion Back Flow (IBF)
- FEE, Data Aggregation from ALICE and ATLAS

INTT



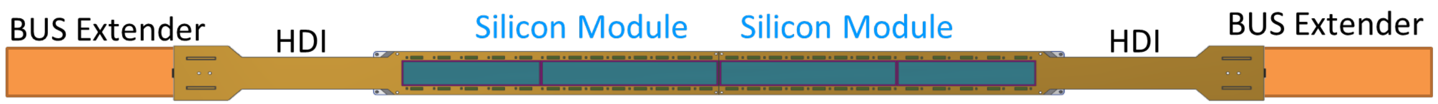


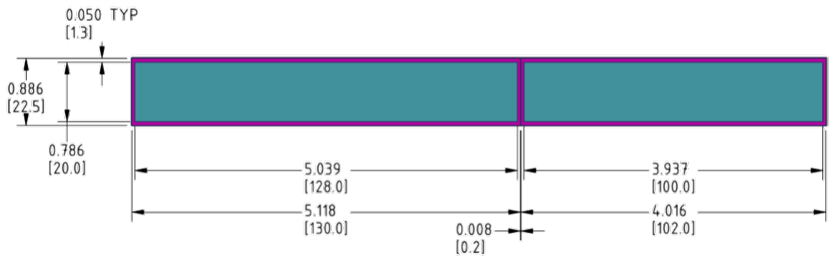

Front View
1a (Inner)
1b (Outer)
2a (Inner)
2b (Outer)

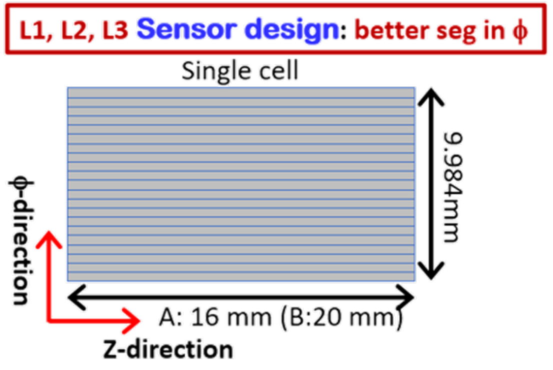

Collisions: +/- 35 μs
TPC: ± 13 us
MVTX: ± 5 us
INTT: [-20 ns, 80 ns]
A.U.
All Truth hits
Truth hits with reconstructed TPC clusters
Truth hits with reconstructed MVTX clusters
Truth hits with reconstructed INTT clusters<
−40000
−30000
−20000
−10000
0
10000
20000
30000
40000
Truth time of hits in tracking detectors

INTT

- Sensors from HPK
  - **78 μ pitch**
  - **single-sided**
  - **AC coupled**
  - **320 μ thick**
- Two sizes of sensors
  - **128x20 mm**
  - **100x20 mm**
- FPHX ASIC (developed for PHENIX)
  - **128 channels**
  - **3 bit ADC**
  - **64 mW/chip**
  - **200 MHz data port**
- Near detector Readout Cards (ROC's) from PHENIX FVTX
- Data acquisition by FVTX FEM + DCM II/JSEB II
  - **Alternative under consideration**



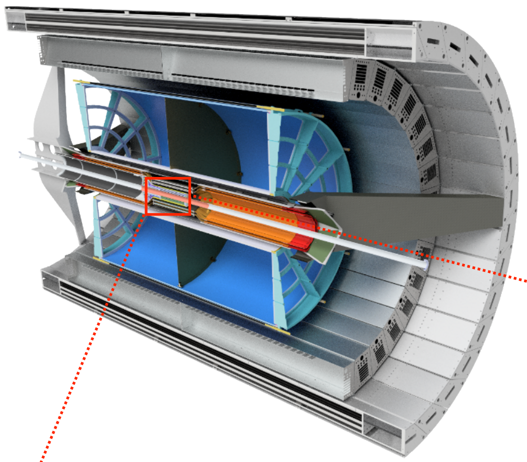


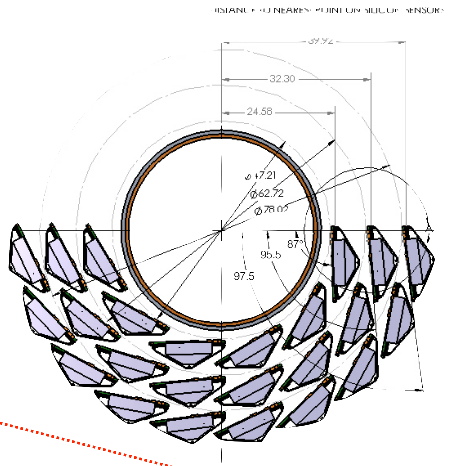


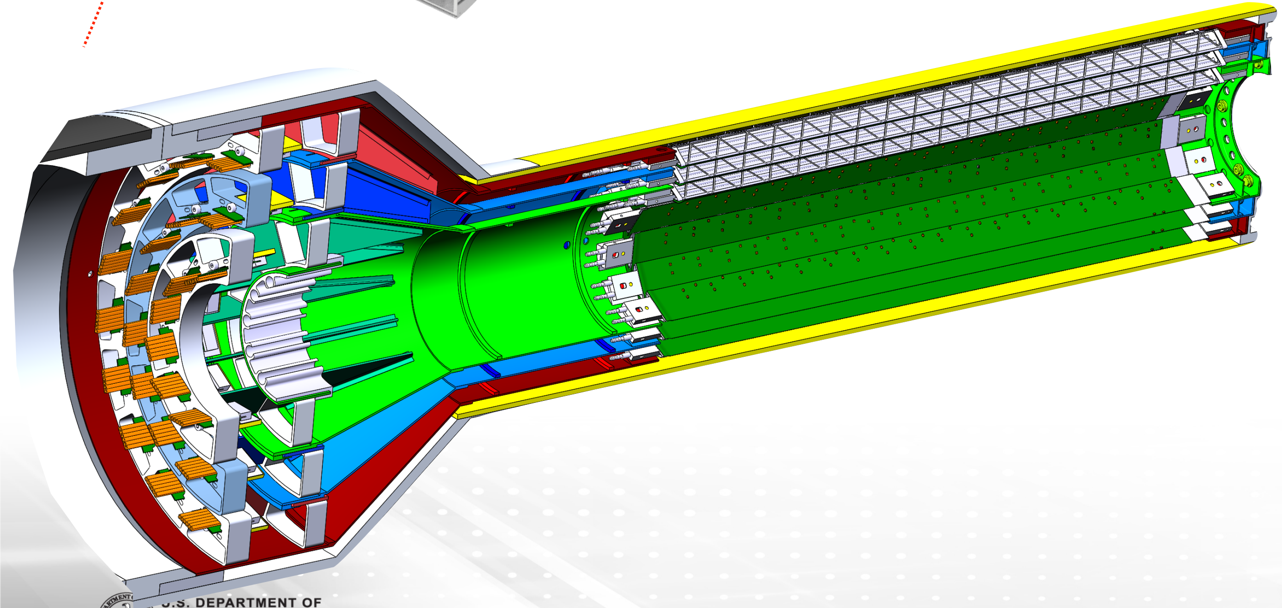
Type A: Single sensor = 8 x 2 cells
Type B: Single sensor = 5 x 2 cells

Thickness: 320 um
Pitch: 9.984 mm/128 = 78 um
Φ-length (single sensor) = 22.5 mm
F-length (active area) = 20.0 mm
Z-length type-A (single sensor) = 130.0 mm
Z-length type-A (active area) = 128.0 mm
Z-length type-B (single sensor) = 102.0 mm
Z-length type-B (active area) = 100.0 mm

MVTX

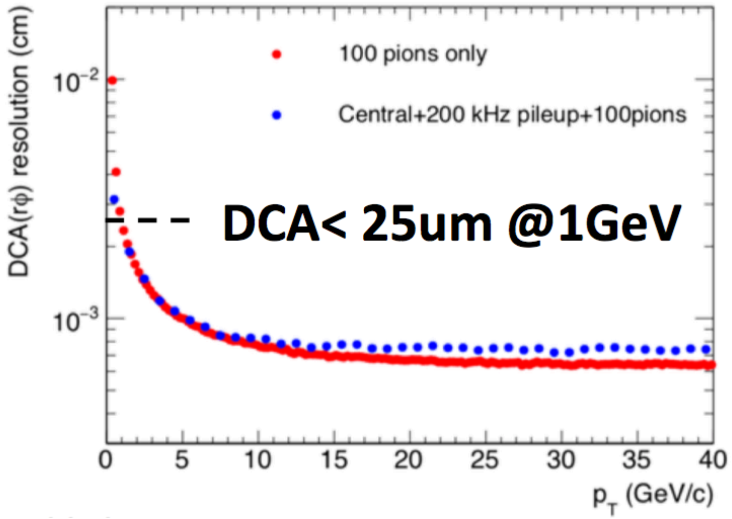






- Provides spatial resolution for displaced vertices
- 3 layers of hermetic Monolithic Active Pixel sensors
- ALICE ITS design modified to fit sPHENIX envelope

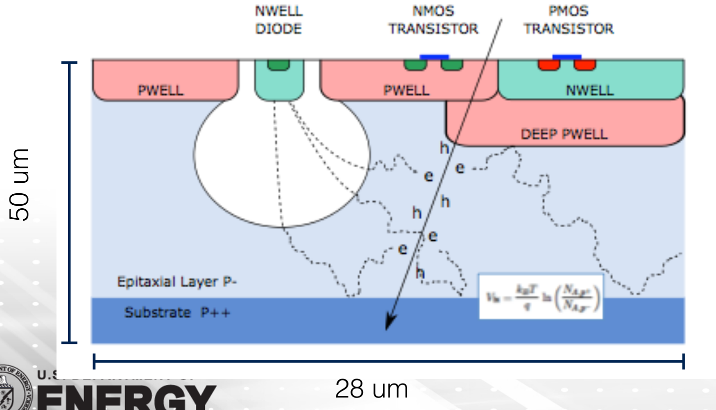
Displaced Vertex Resolution

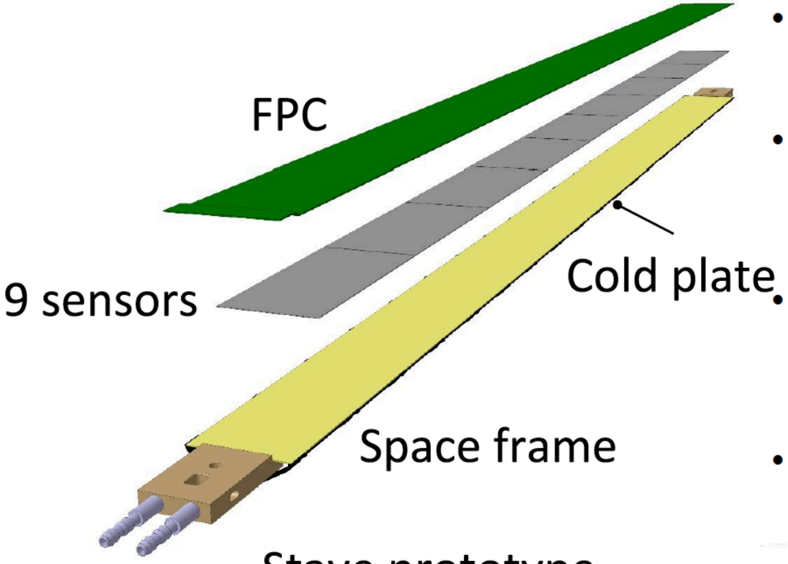


MVTX

ALICE Pixel Detector

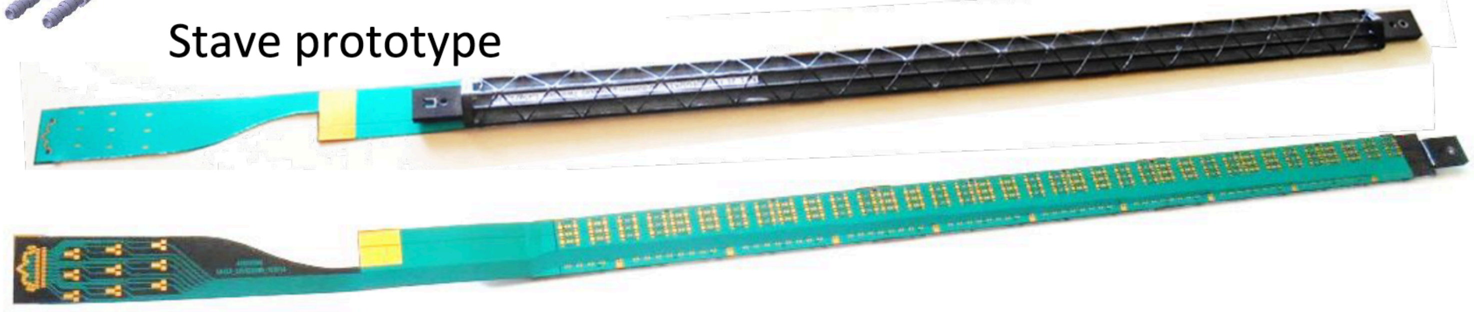
- Very fine pitch (27μm x 29μm), for superb spatial resolution
- High efficiency (>99%) and low noise (<10^{-6}), for excellent tracking
- Time resolution, as low as ~5 μs, for less pileup
- Ultra-thin/low mass, 50μm (~0.3% X_0), for less multiple scattering
- 0.5M channels with on-pixel digitization, for zero-suppression and fast readout
- Low power dissipation, 40mW/cm^2, for minimal service materials



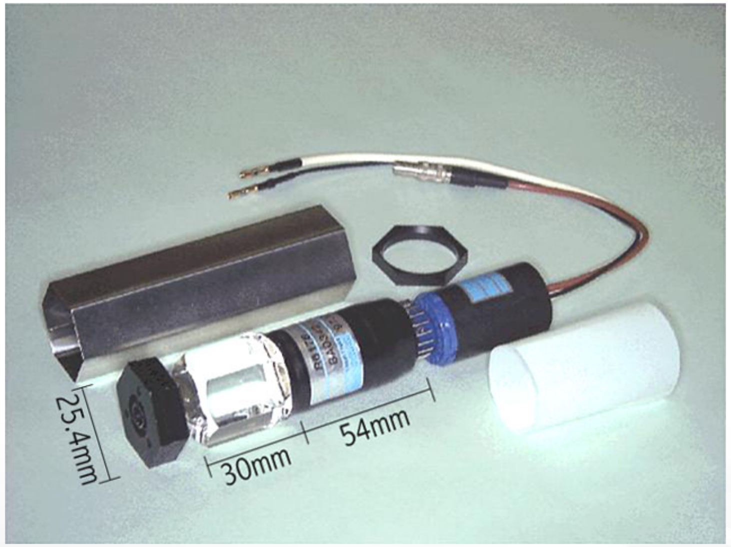


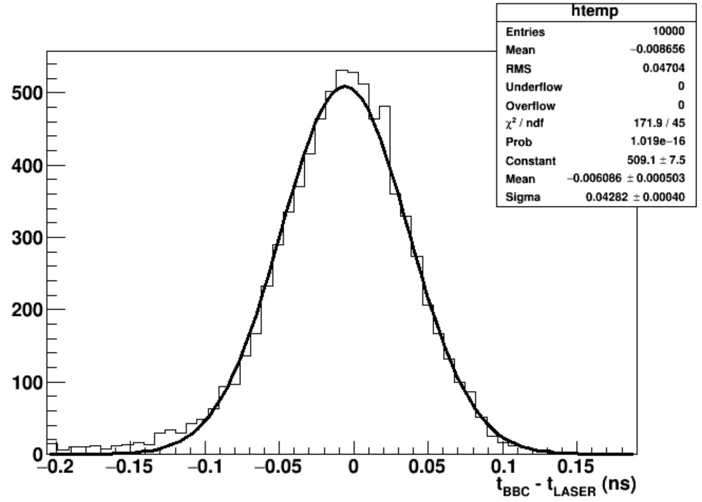
- **Staves:** detector modules consisting of a Hybrid Integrated Circuit (HIC) mounted on carbon fiber mechanical support structure
- **HIC:** a row of 9 ALPIDE sensors wire-bonded to a Flexible Printed Circuit (FPC). Area covered by the chips: 15x271.2 mm^2, including a gap of 150 μm between adjacent chips.
- **Mechanical support:** single light structure composed of a Space Frame, providing the required stiffness, and a Cold Plate, high-thermal conductivity carbon fiber sheet with embedded polyamide cooling pipes.
- **Heat Dissipation** – The ALPIDE sensors dissipate only 40 mW/cm^2.

Stave prototype



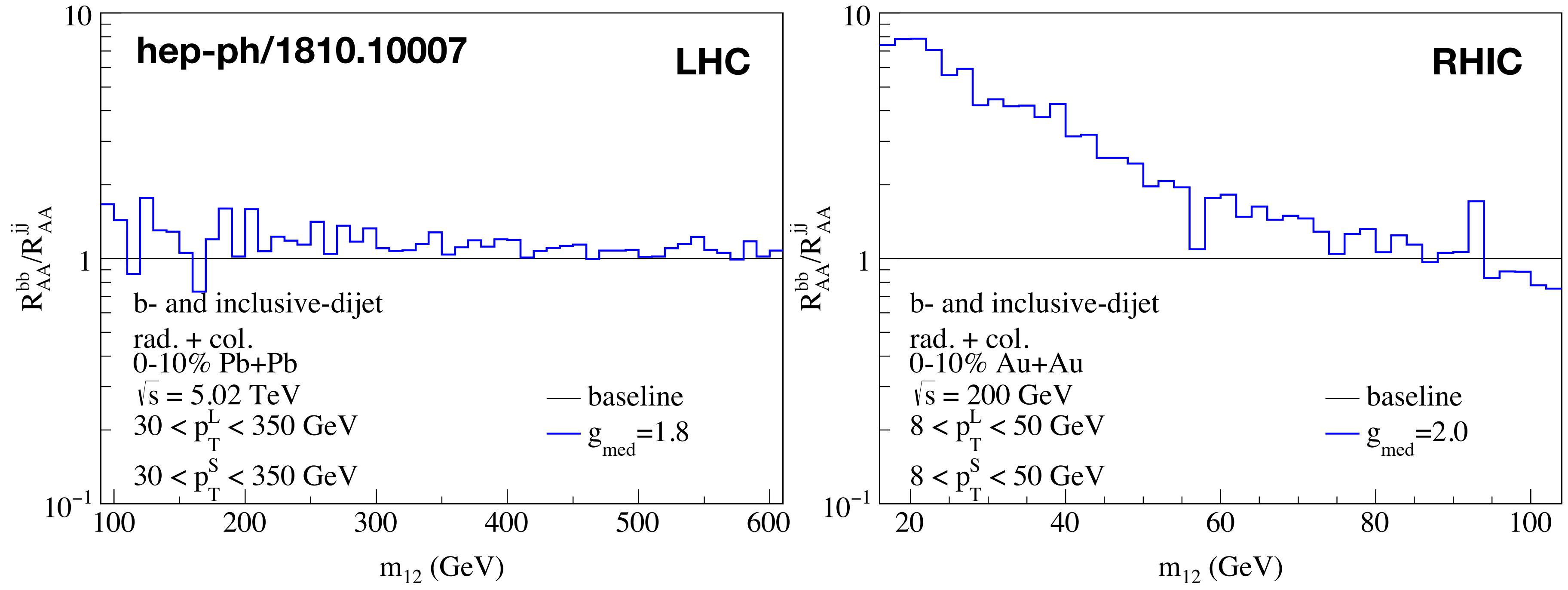
MBD





U.S. DEPARTMENT OF ENERGY

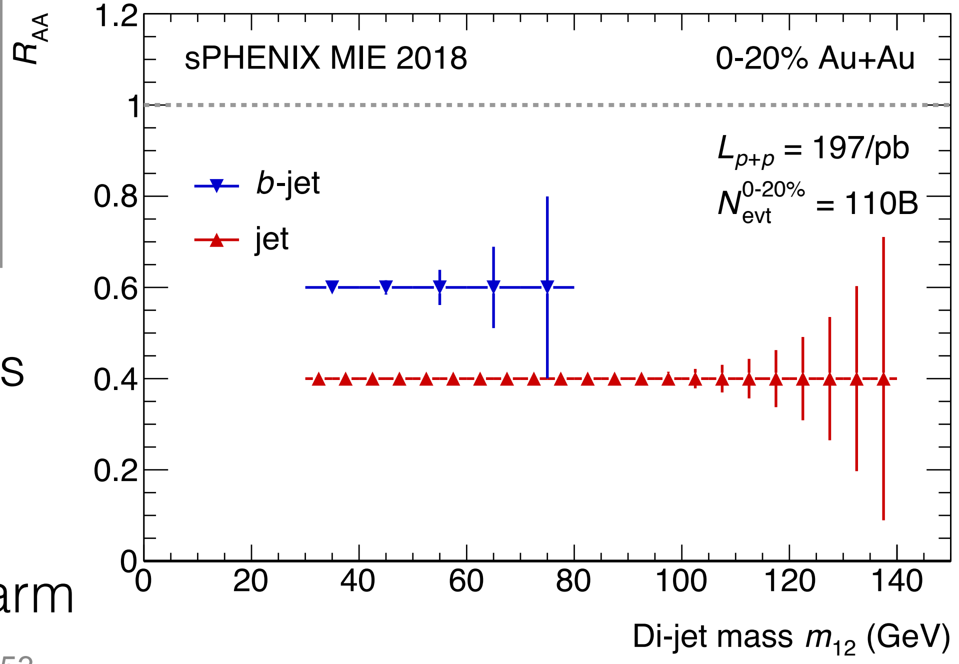
BROOKHAVEN NATIONAL LABORATORY



Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions

Zhong-Bo Kang,[1,2,3,*] Jared Reiten,[1,2,†] Ivan Vitev,[3,‡] and Boram Yoon[3,§]
[1] *Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[2] *Mani L. Bhaumik Institute for Theoretical Physics, University of California, Los Angeles, California 90095, USA*
[3] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
(Dated: February 22, 2019)

- In theory community, many examples of phenomena/observables more visible at RHIC:
  - ➡ sPHENIX provides crucial level arm

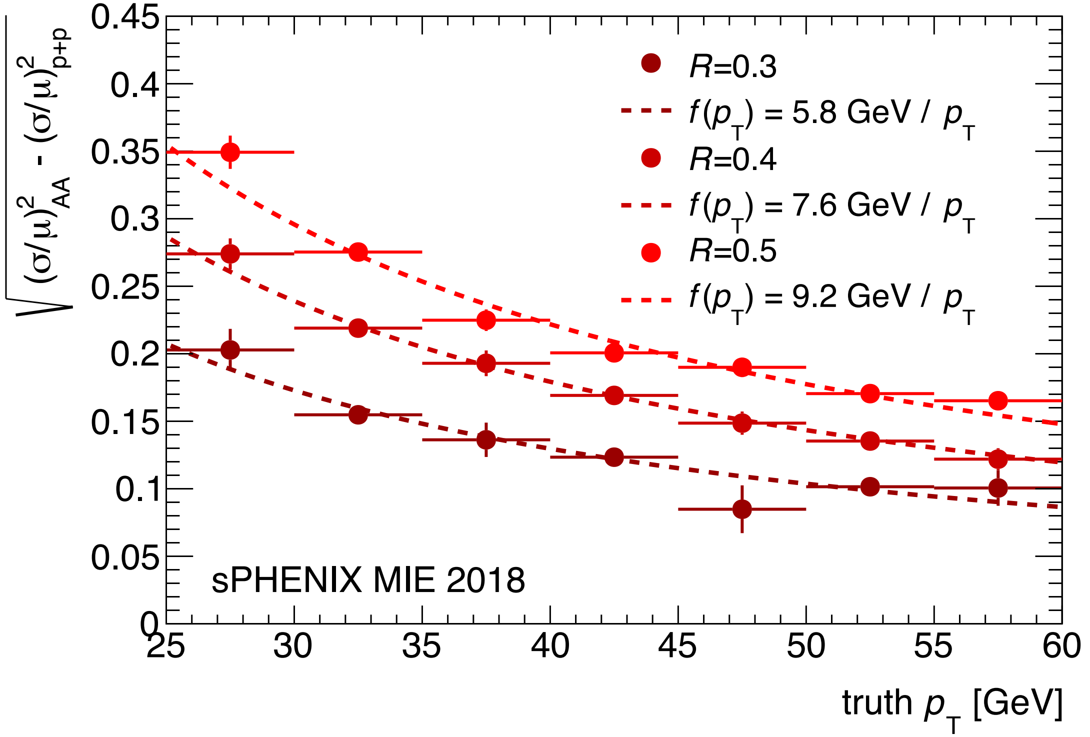


Jet performance

Deconvolution of UE term in Au+Au response

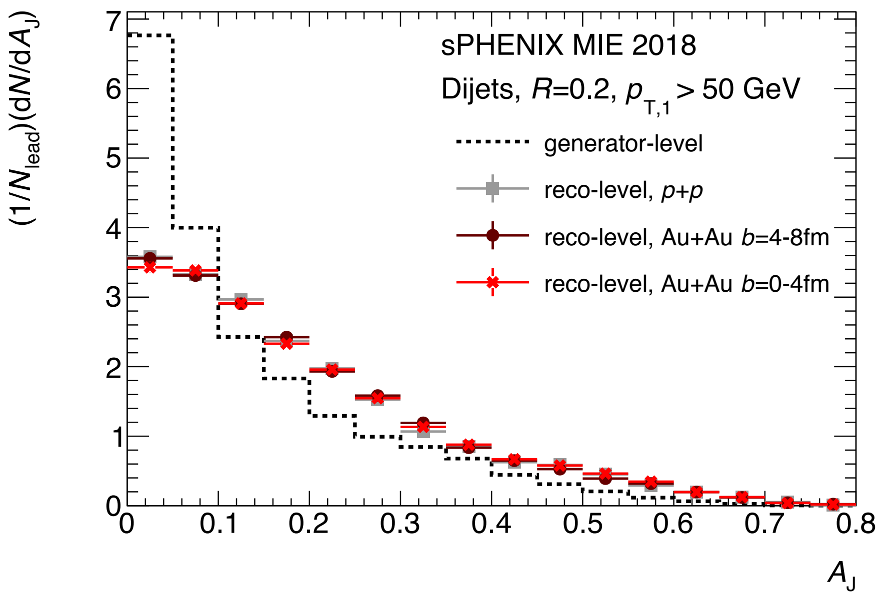
$$\frac{\sigma_{p_T}}{p_T} = \frac{n}{p_T} \oplus \frac{s}{\sqrt{p_T}} \oplus c$$

Noise | Stochastic | Constant

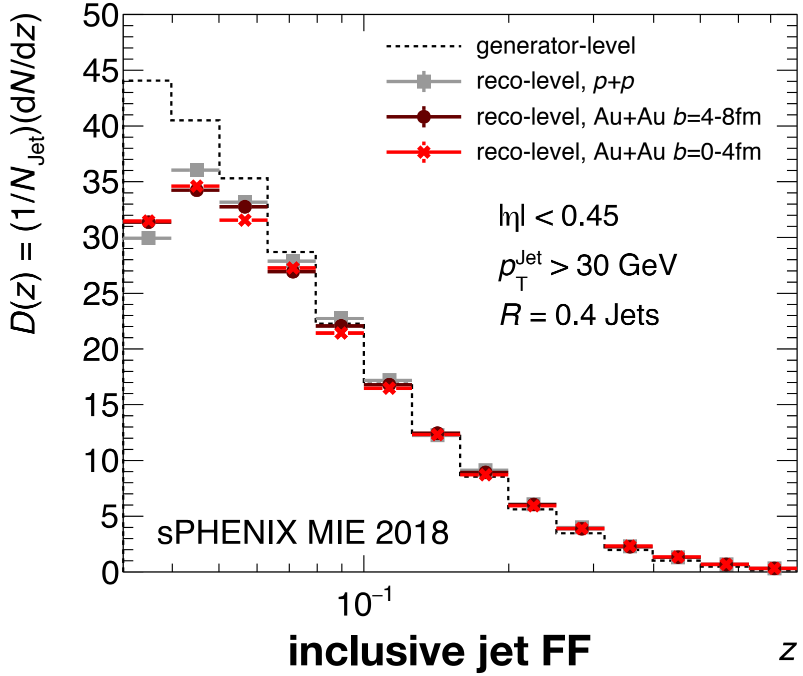


- One advantage of purely calorimetric measurement: reconstruction proceeds identically in *pp* and Au+Au
  - ➡ can understand Au+Au response as *pp* response ⊗ UE
  - ➡ identical, i.e. sensitivity of response to fragmentation, in both systems

Jet performance summary



di-jet p_T balance

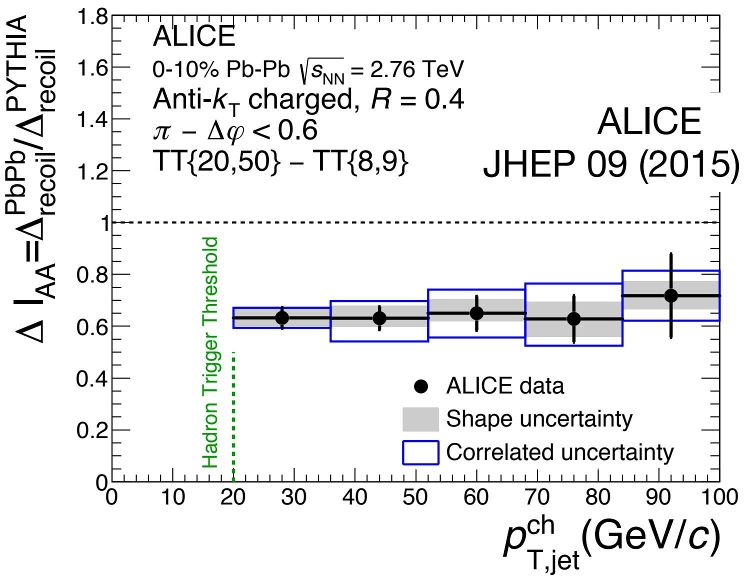


inclusive jet FF

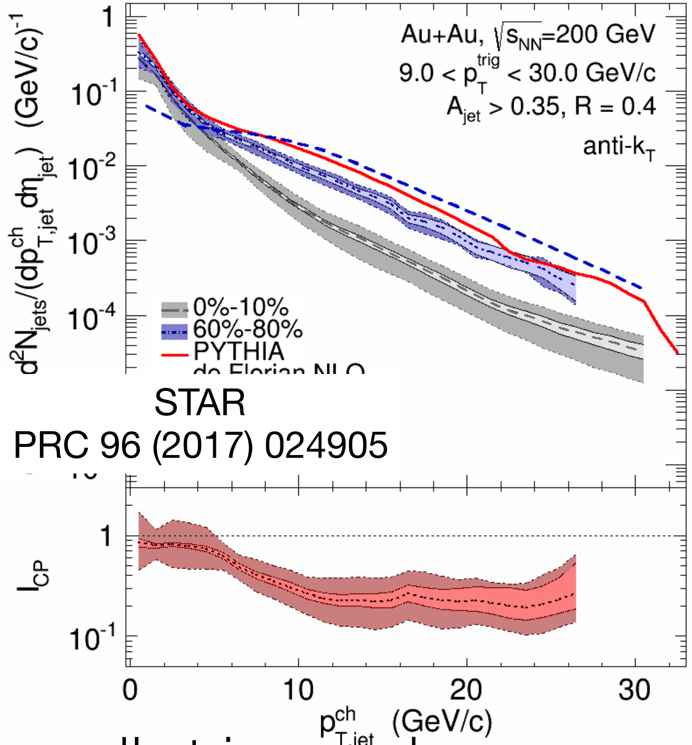
Good news: kinematic regions where $p+p$ ~ Au+Au

➡ but want to make measurements in difficult regions too (detector corrections via unfolding, etc.…)

Semi-inclusive jet measurements



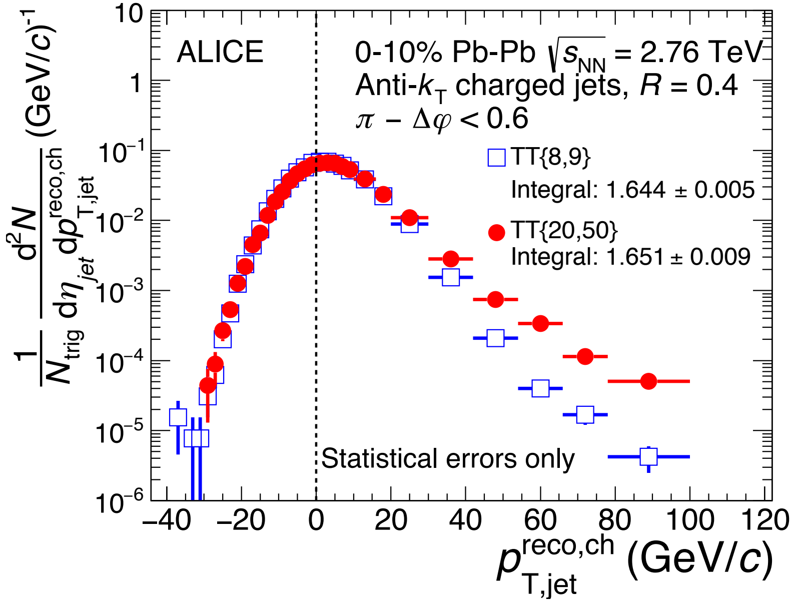
ALICE
JHEP 09 (2015) 170

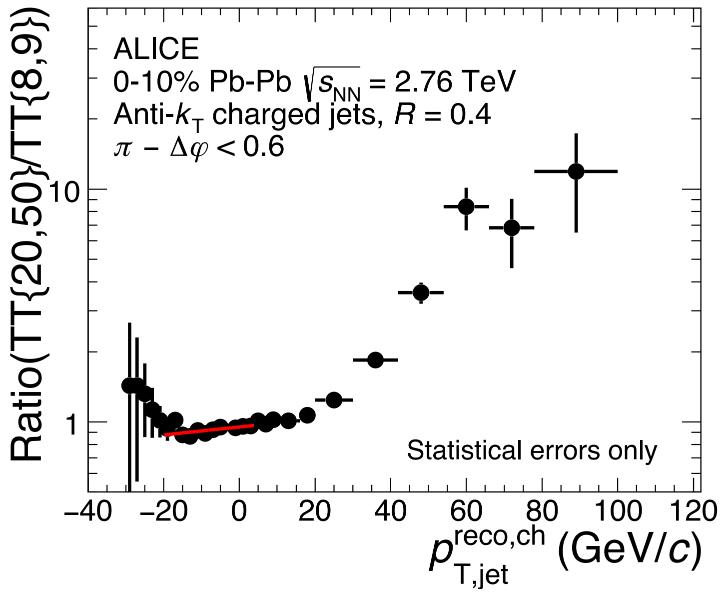


STAR
PRC 96 (2017) 024905

- ➡ different philosophy: write out all jets in an event (usually triggered, i.e. *h*+jet), including obvious UE-fluctuated-dominated “jets”
  - ➡ extract hard-scattering component via statistical subtraction
- ➡ benefit: push to much significantly lower p_T without fake jet rejection

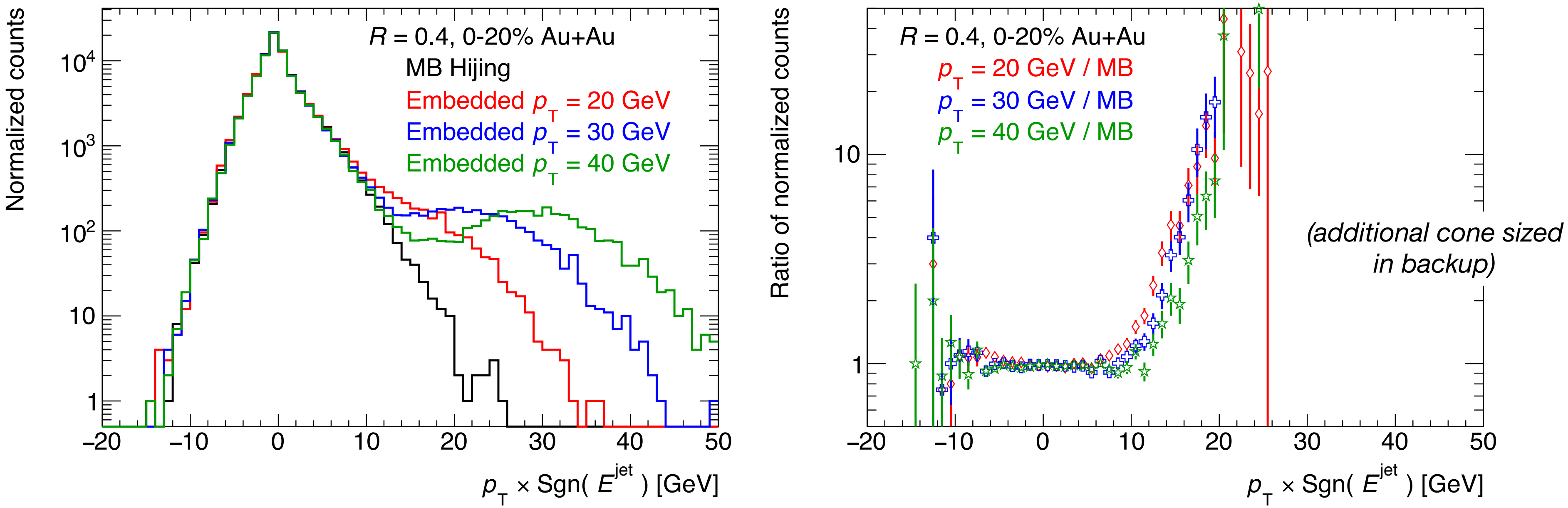
Hadron-triggered recoil jets





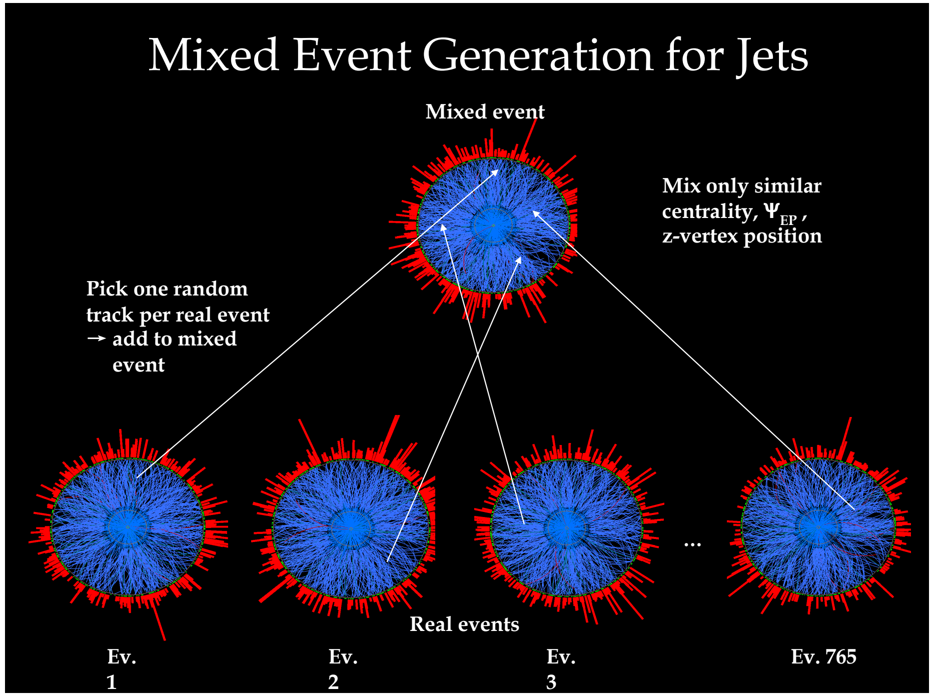
- ➡ In ALICE: use **hadron trigger** to select jet-enhanced sample on the away side
  - ➡ report all charged-jets, including those at negative jet p_T (possible from scalar equation $p_T^{jet} = p_T^{raw} - \rho_{UE} A_{jet}$)
  - ➡ combinatoric jet sample comes **lower-p_T hadron trigger**
- ➡ *Right*: significant S > B in the region p_T > 20 GeV

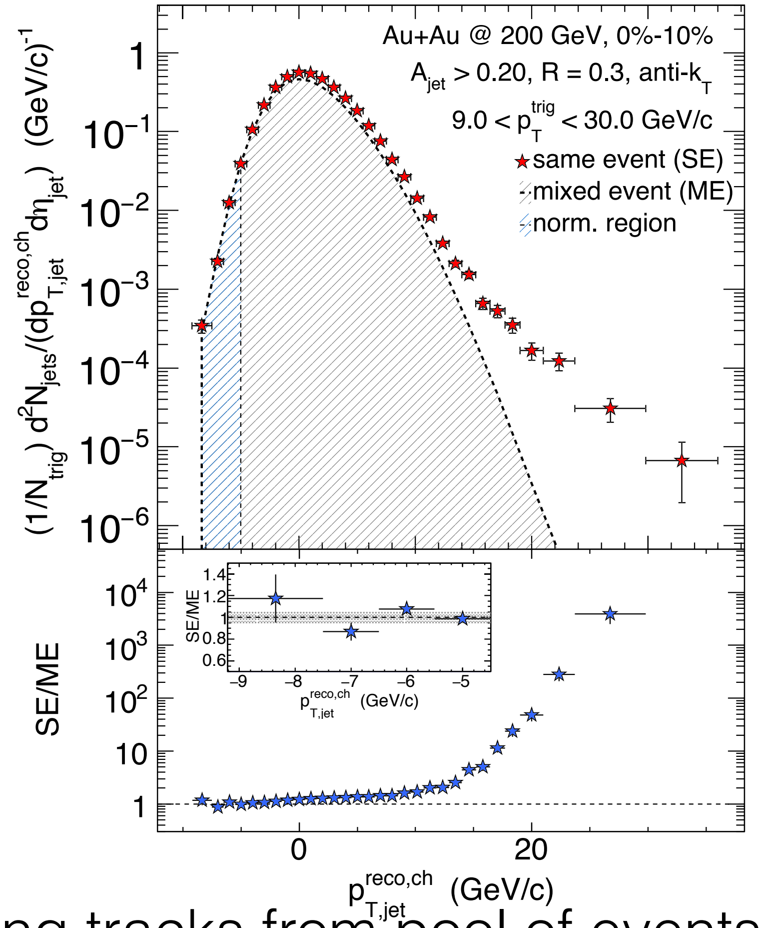
Hadron-triggered recoil jets



- Mock up hadron trigger with our Pythia dijet embedded samples
- Note: in our reco, full jet four-vector gets updated for subtracted UE
  - ➡ *p* for negative-*E* jets points opposite to "geometric" direction, represent these a a signed quantity via $p_T \times$ sgn(E_{jet})
- *Right*: jet-triggered / MB ratio is flat in UE-dominated region
  - ➡ then clear S > B starting past some minimum p_T

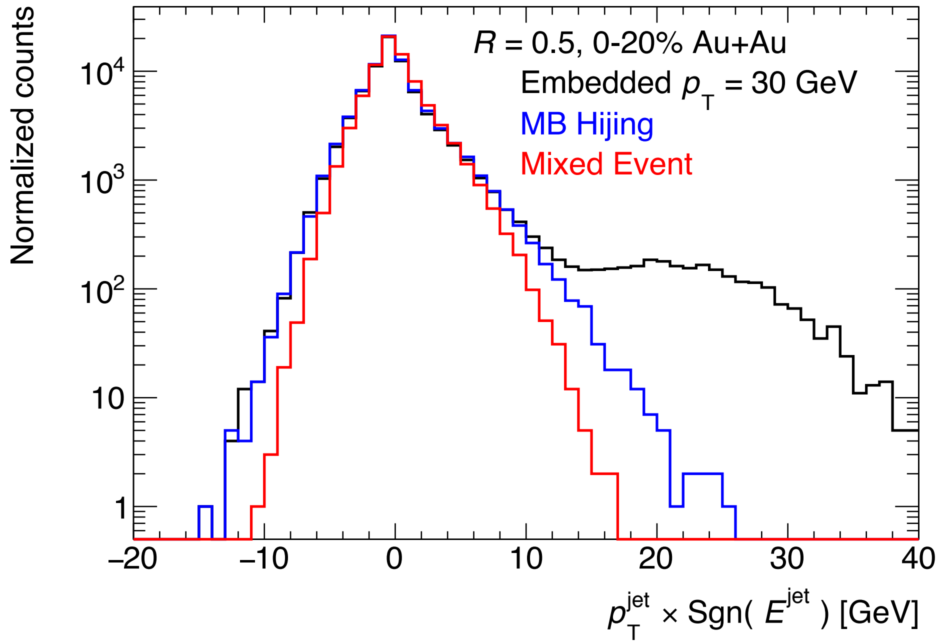
Mixed event construction





- STAR: construct a synthetic “mixed” event, using tracks from pool of events with matched multiplicity, Ψ_2, z_{vtx}
  - ➡ replaces need for lower-trigger-threshold reference distribution
- In sPHENIX, conceptually different calorimetric jet reconstruction
  - ➡ we are “mixing" square-sized regions of overlapping showers, not distinct particles

Mixed event construction

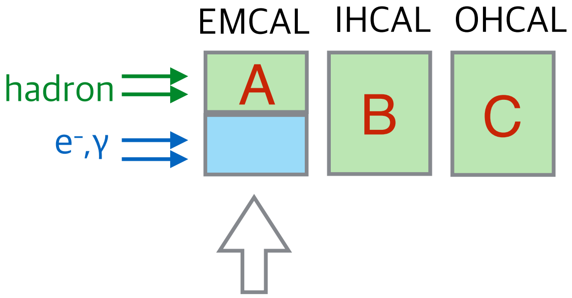


- Take each of the 1536 subtracted 0.1x0.1 CEMC+I+OHCal tower triplets from 1536 distinct events
  - ➡ loose but imperfect matching of b, Ψ_2 (limited stats. of Hijing HITS)
  - ➡ run jet reconstruction on mixed event
- **Mixed event** distribution undershoots UE-jet width in **MB** or **jet-embed**
  - ➡ some aspect of intra-event correlations not being properly captured
  - ➡ may require more detailed technical development to work

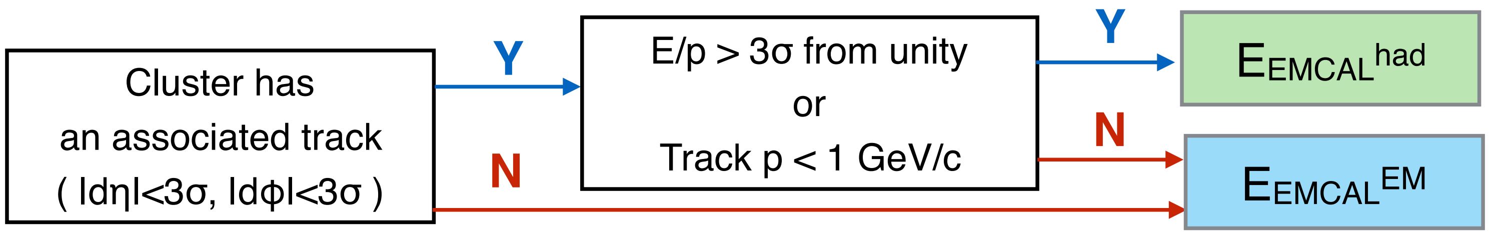
Jet energy calibration

[Songkyo Lee]

$$E^{RECO} = D \cdot (E_{EMCAL}^{EM} + A \cdot E_{EMCAL}^{had} + B \cdot E_{IHCAL} + C \cdot E_{OHCAL})$$



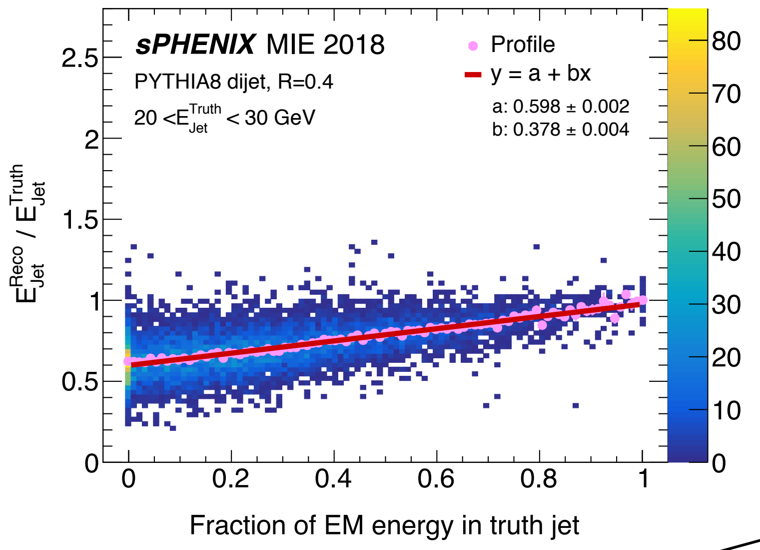
- Flow chart for EMCAL cluster selection

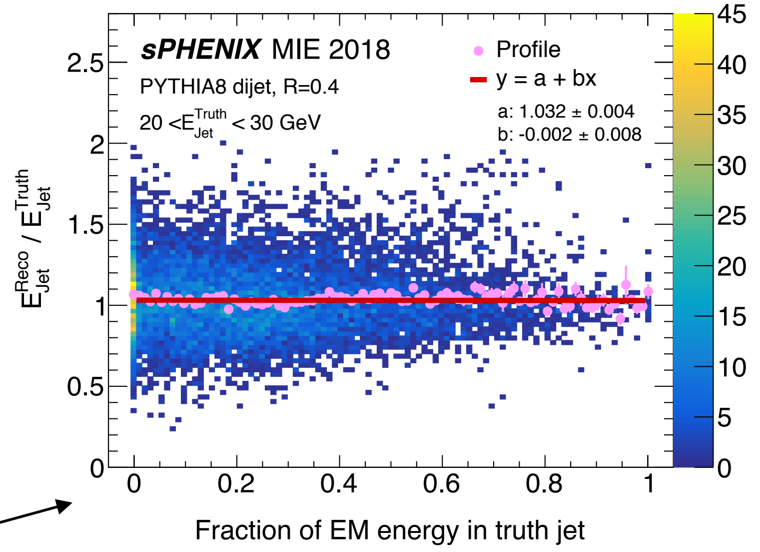


slide from Songkyo

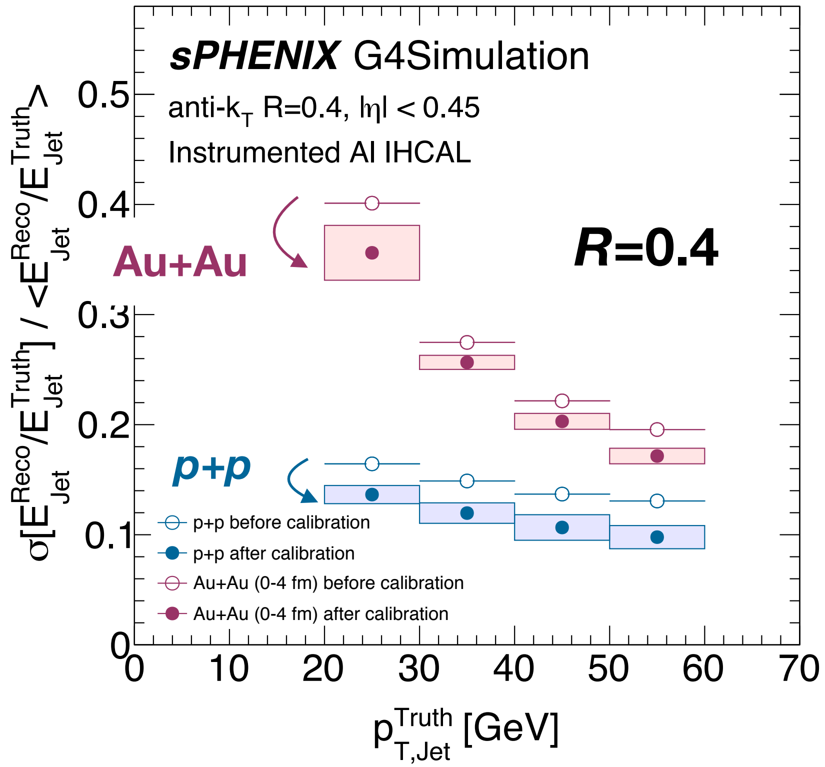
Exploring calibration schemes based on multiplicative scale factors for each calorimeter layer

- separation of EMCal energy into e/γ (no track or E/p ~ 1 track) and hadronic (track with $E^{EM}/p < 1$)
- discussion of *in situ* validation with γ+jet events in *p*+*p*

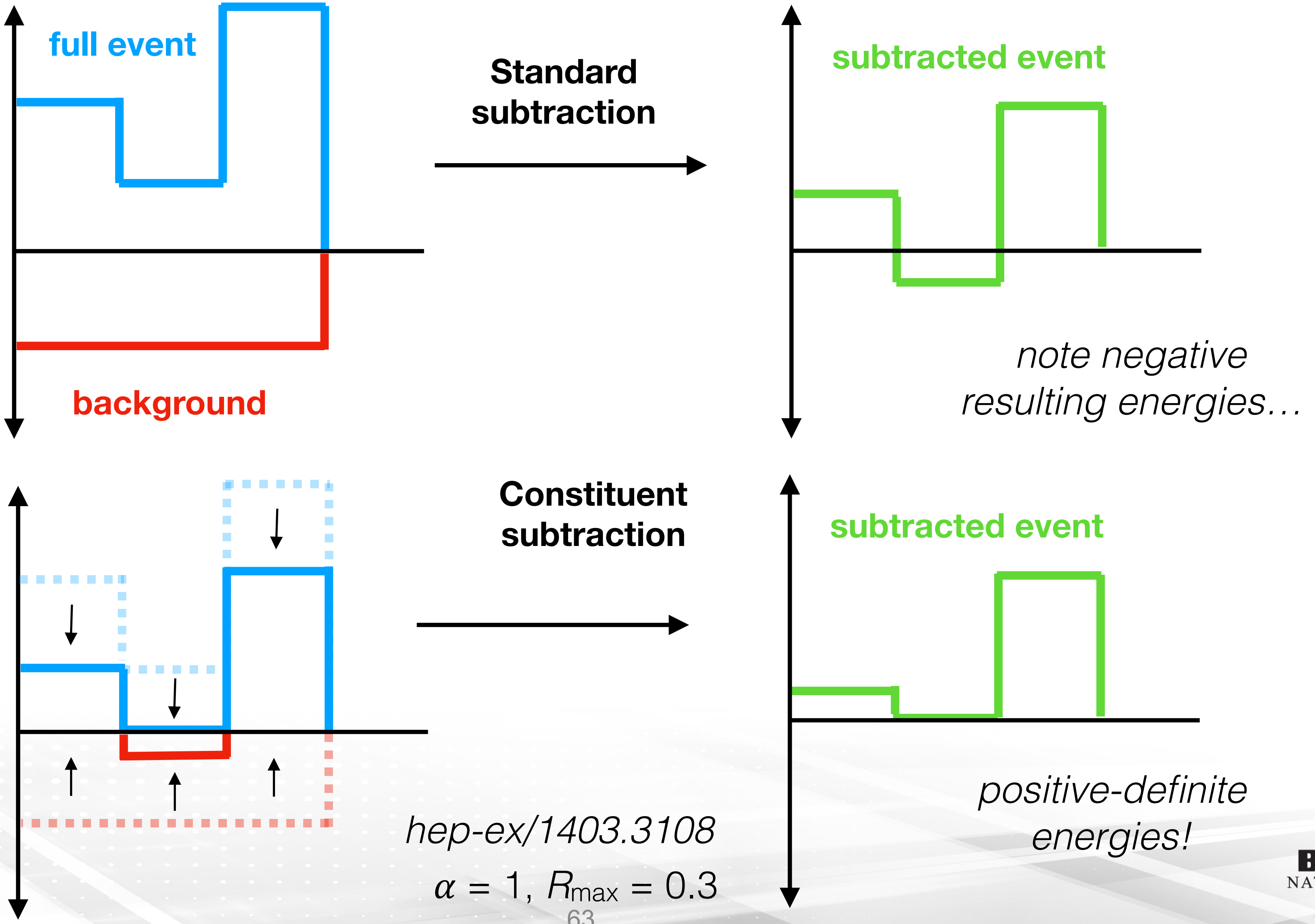




Response nearly independent of truth-EM fraction (i.e. fragmentation) in p+p

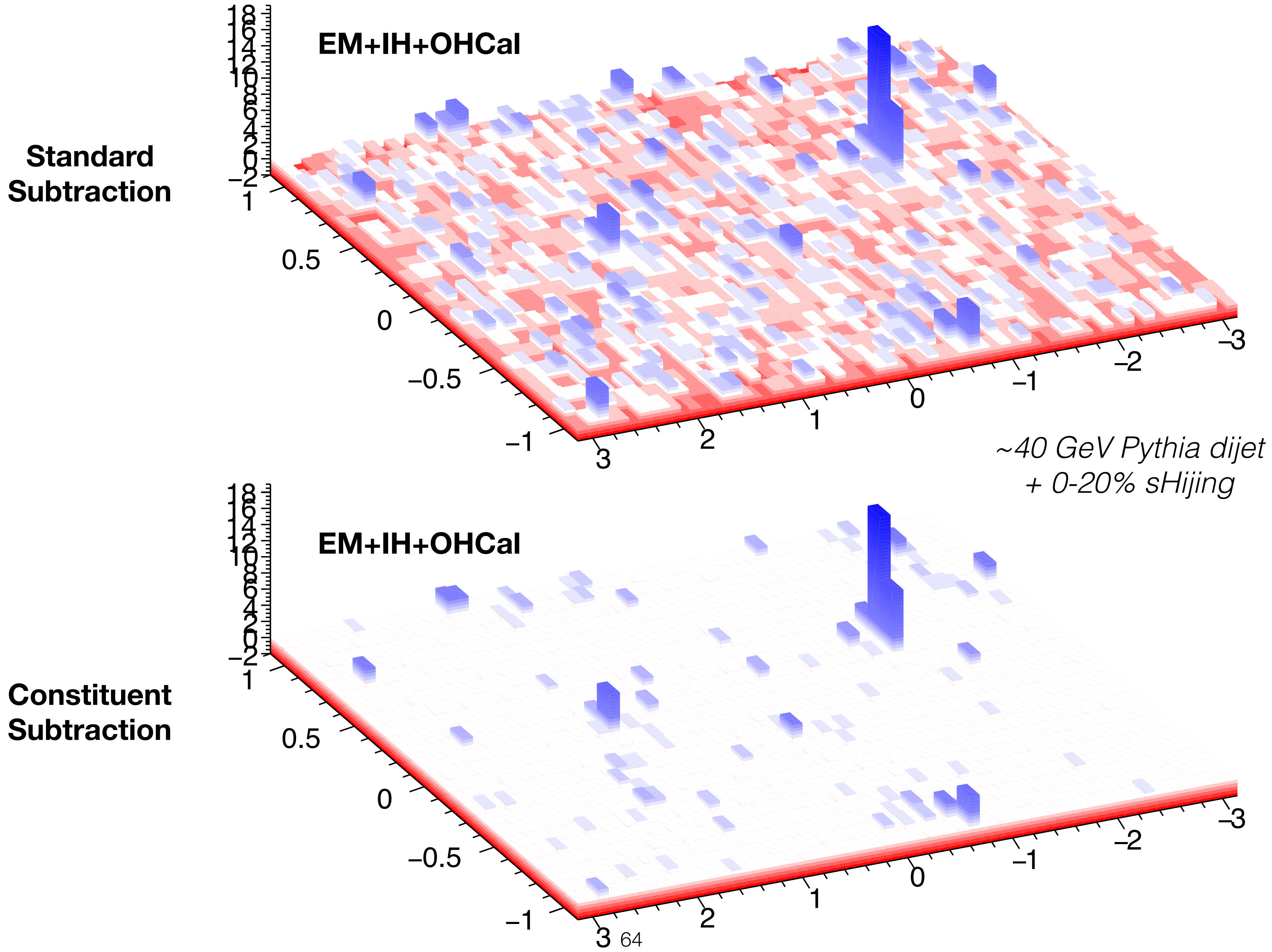


Our UE determination and subtraction “factorize”: *Constituent subtraction* in sPHENIX



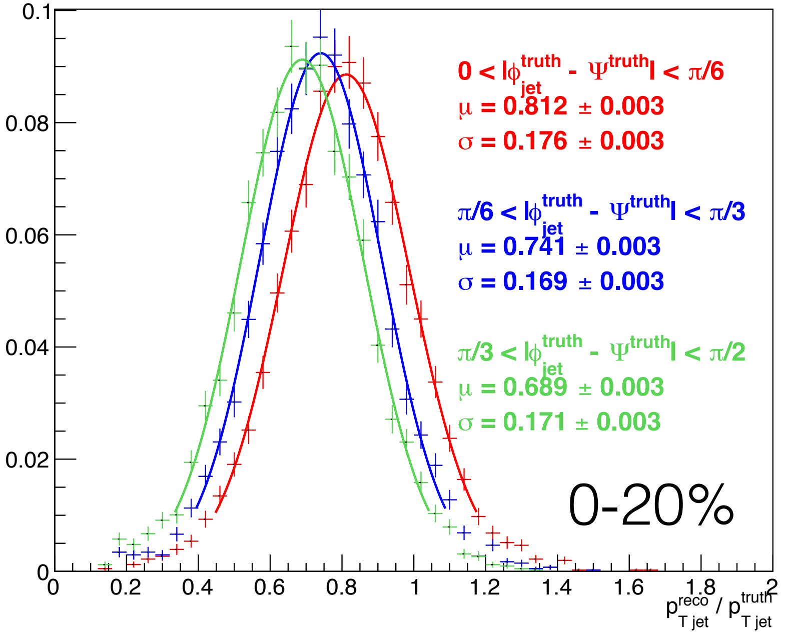
hep-ex/1403.3108

$\alpha = 1$, $R_{max} = 0.3$

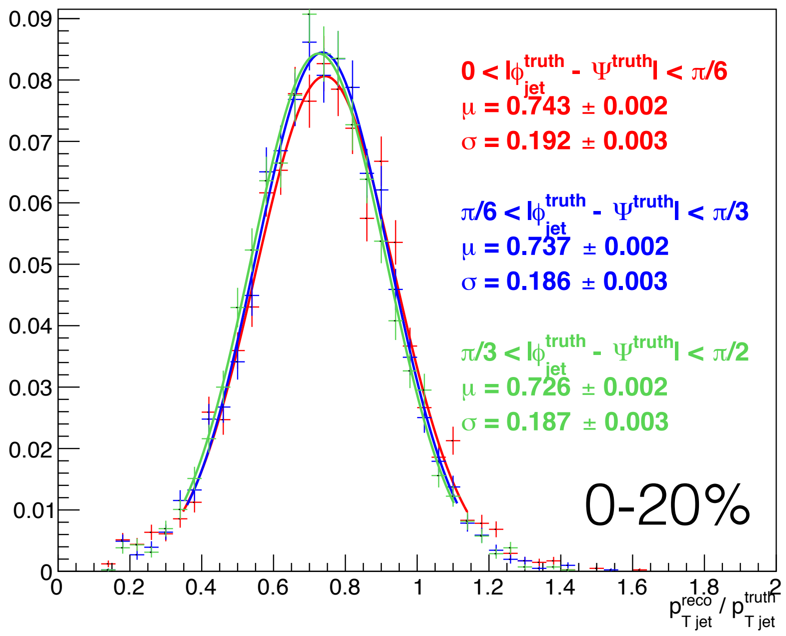

Standard
Subtraction
EM+IH+OHCal
~40 GeV Pythia dijet
+ 0-20% sHijing
Constituent
Subtraction
EM+IH+OHCal

ϕ-dependent jet performance

HI jet reco w/o flow determination…

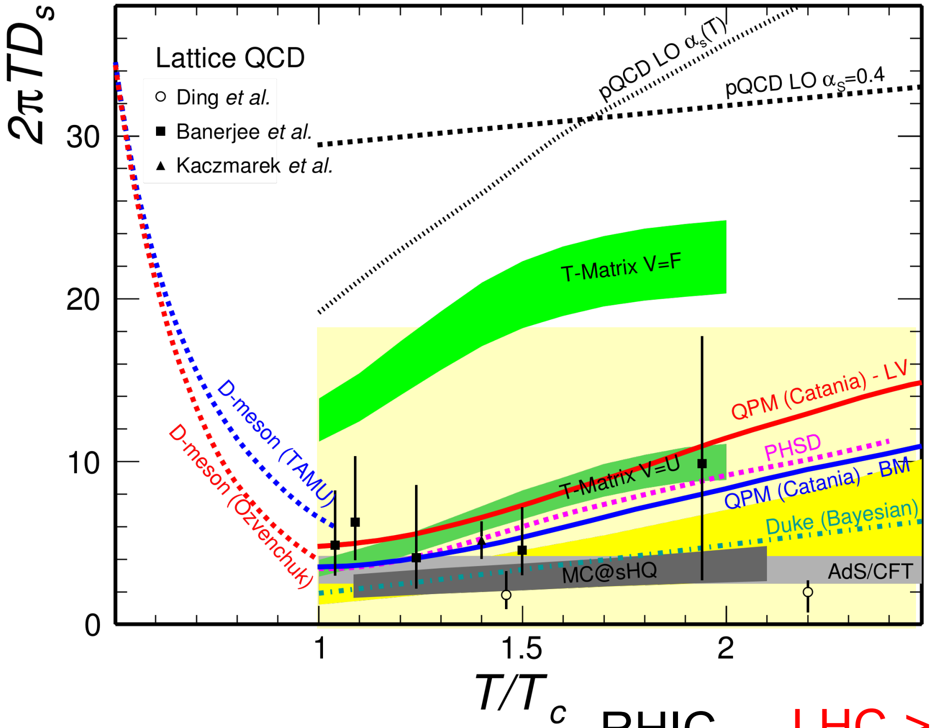


HI jet reco **WITH** flow determination



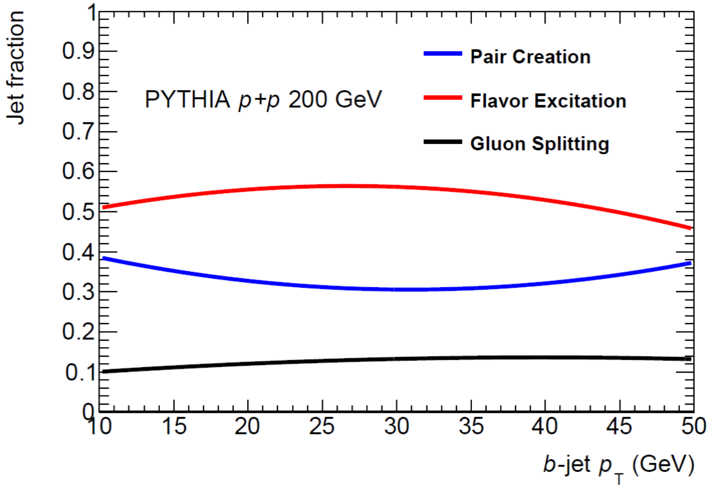
- Jet response vs. ($\phi^{jet,truth}$ - Ψ_2^{truth}): **in-plane**, **mid-plane**, **out-of-plane**
  - ➡ *left*: ~15% *E*-scale difference b/w in- vs. out-of-plane(!!)
  - ➡ *right*: including flow modulation reduces this to ~2%
    - ➡ enables reaction plane dependent jet measurements
    - ➡ control of flow likely sets the ultimate limit on low-p_T / large-*R* reach…

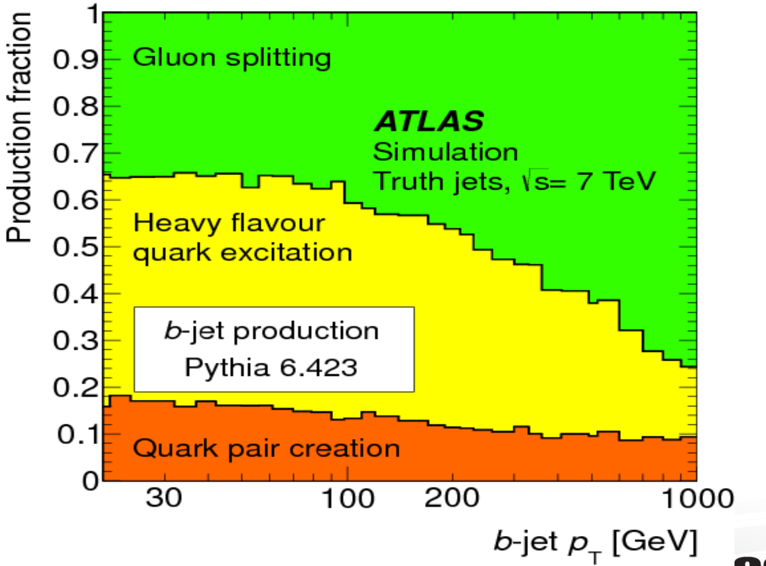
RHIC vs. LHC



RHIC LHC->

A. Adare et al., 1501.06197





Complementarity: RHIC vs. LHC
- Sensitive to different temperature regions

Uniqueness at RHIC (vs. LHC)
- Gluon splitting contribution is much less (~10%)