The sPHENIX Detector:
The Future of Heavy-Ion Collisions at RHIC, and a Foundation for an EIC Detector

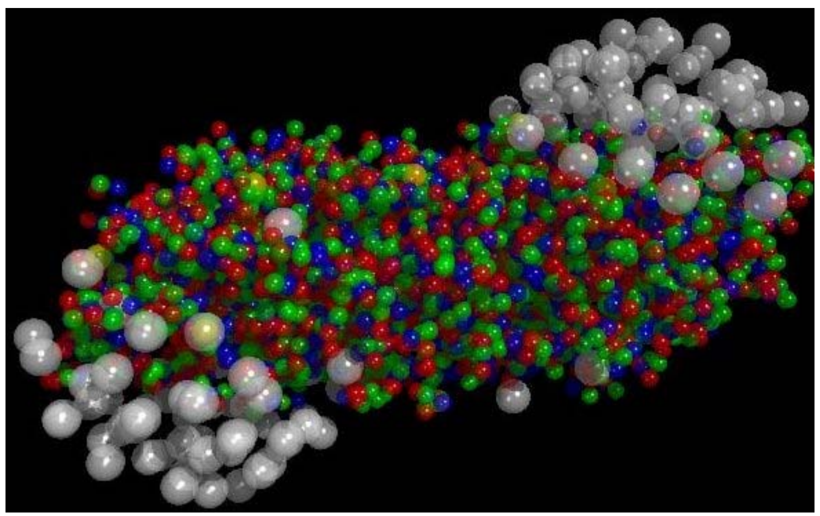
John Lajoie

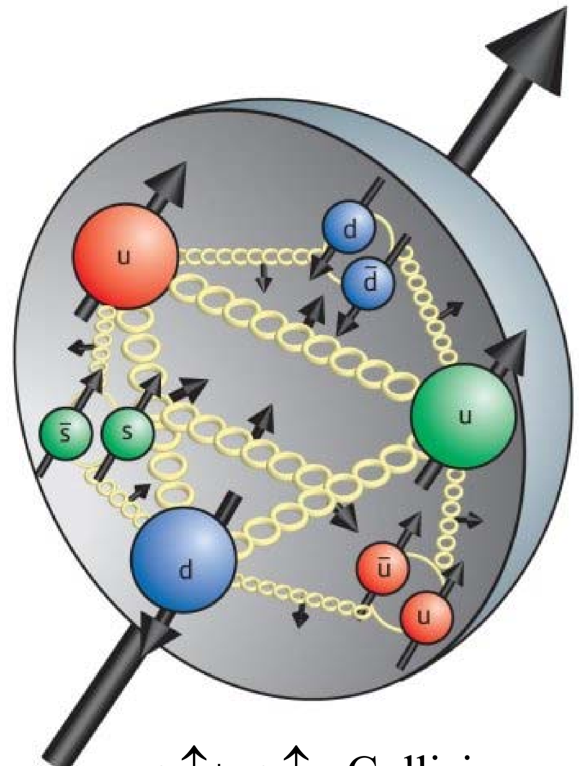
Iowa State University

sPHENIX

The Big Picture at RHIC (and the EIC…)

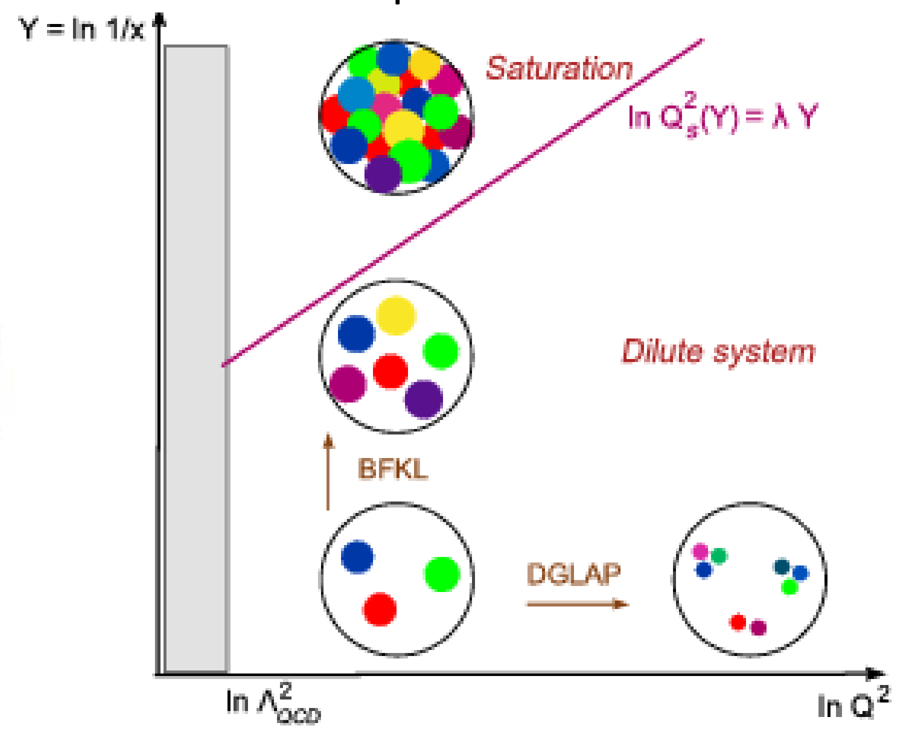
A+A Collisions





$p\uparrow + p\uparrow$ Collisions

p+A Collisions

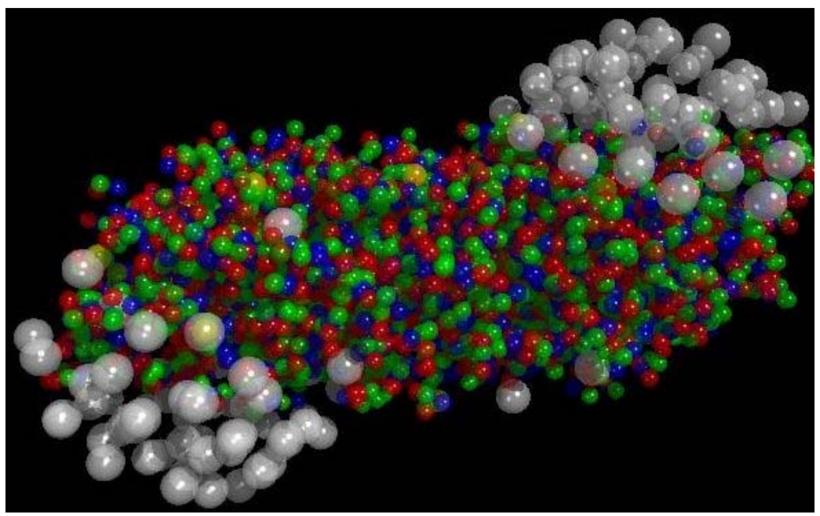


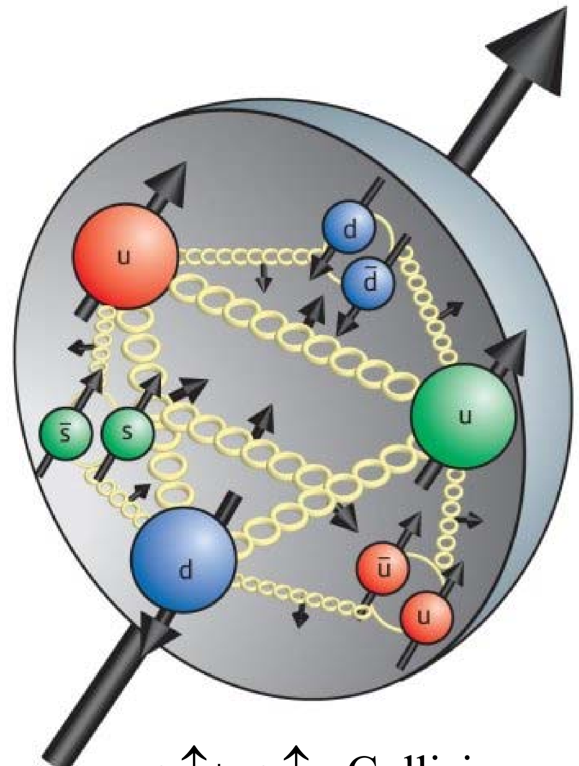
sPHENIX

The Big Picture at RHIC (and the EIC…)

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

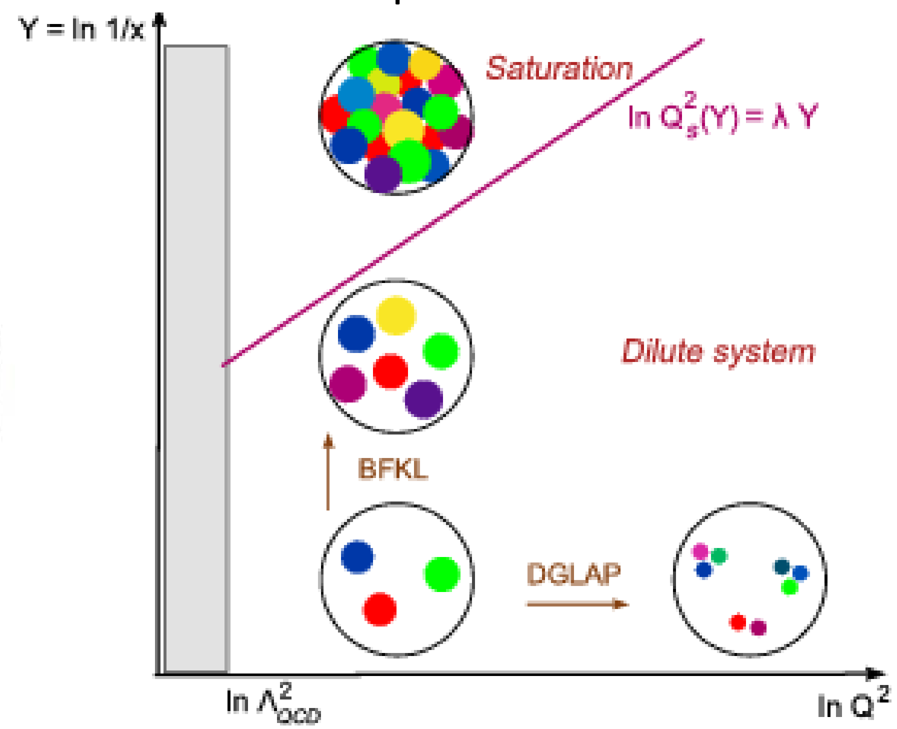
A+A Collisions



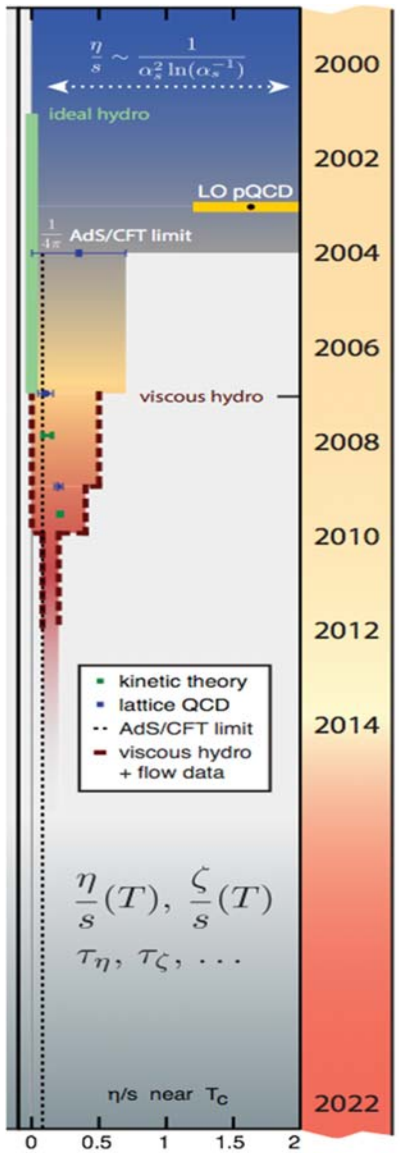


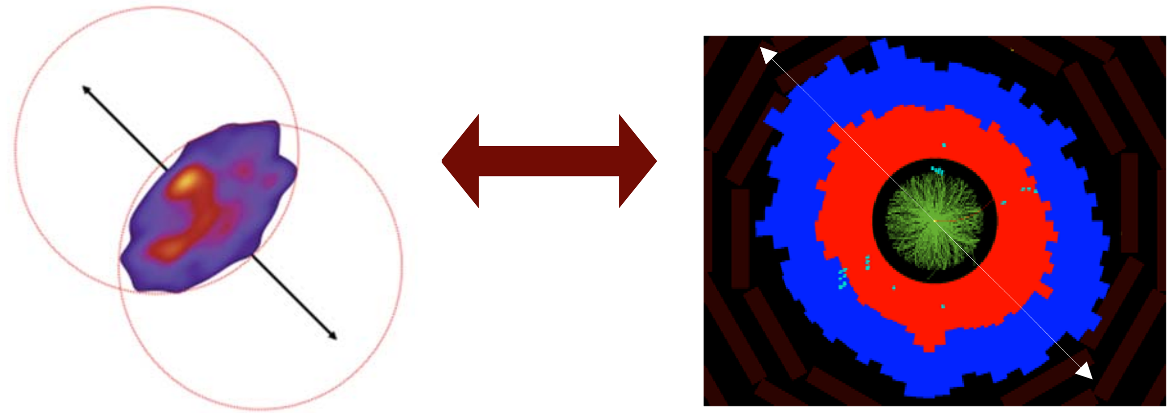
$p\uparrow + p\uparrow$ Collisions

p+A Collisions



Strongly-Coupled Quark-Gluon Plasma





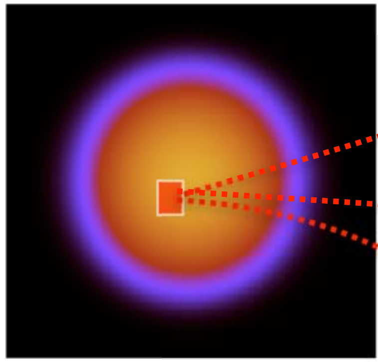
Established **viscous hydrodynamics** as effective theory of long-wavelength dynamics of QGP

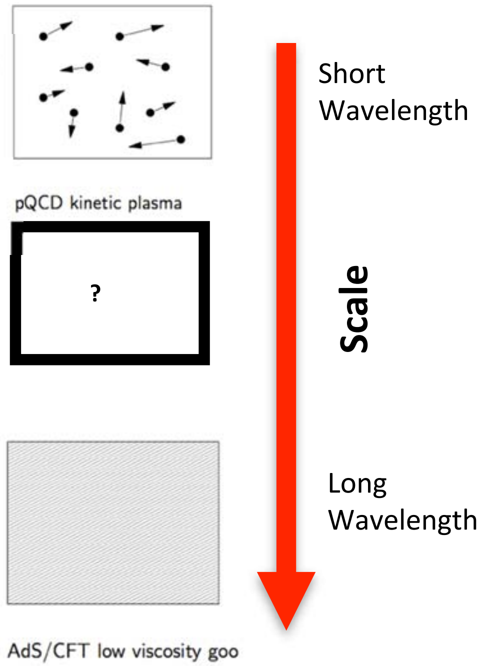
Direct connection of final state correlations to structure and fine-structure of initial state

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)

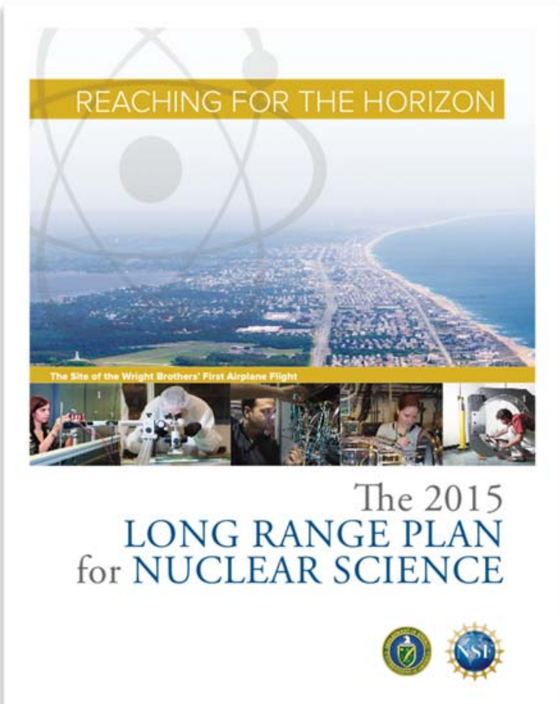
sPHENIX Science Mission





How does QGP work?

What is its microscopic structure?



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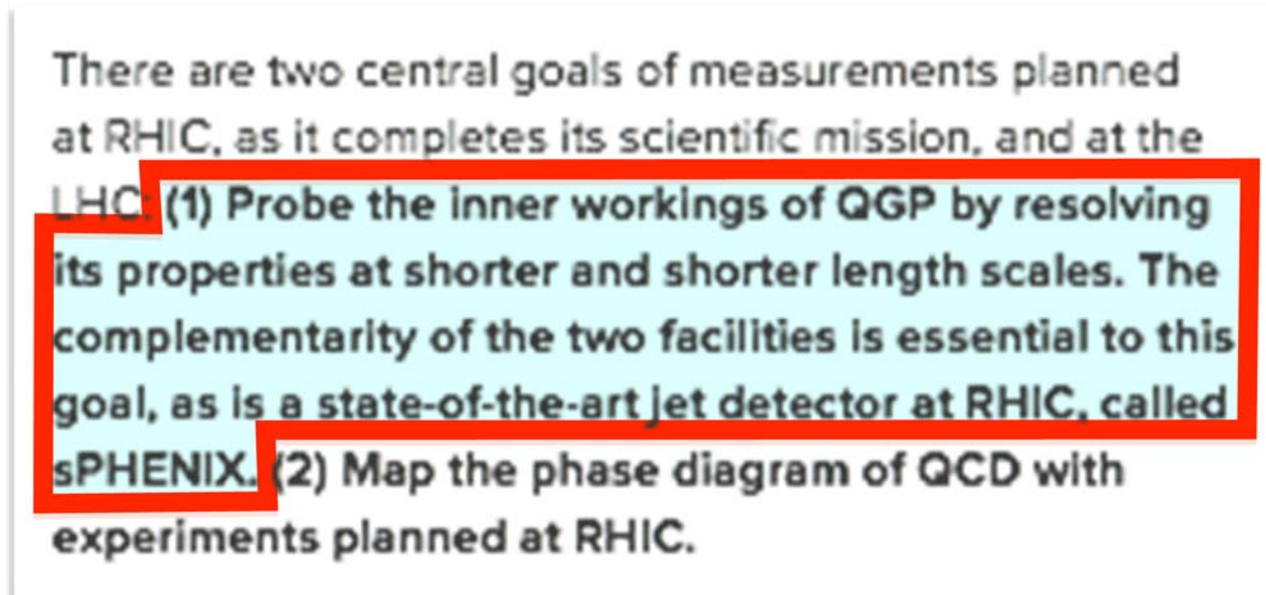
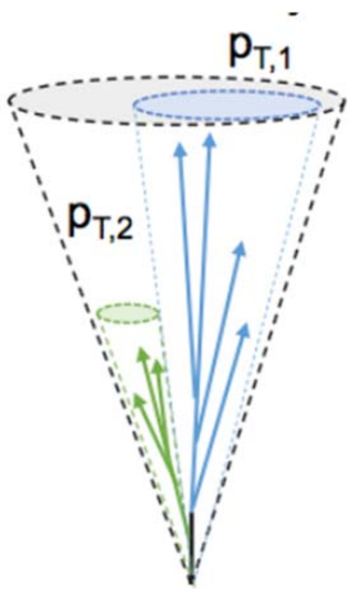


There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art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

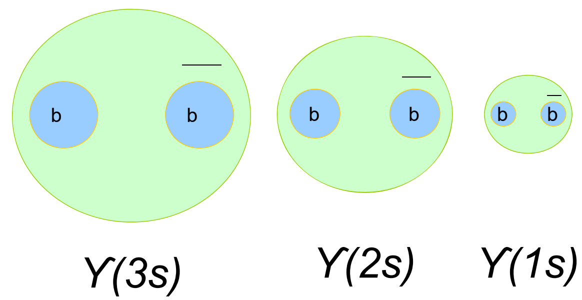
NP LRP: “Probe the inner workings of QGP”

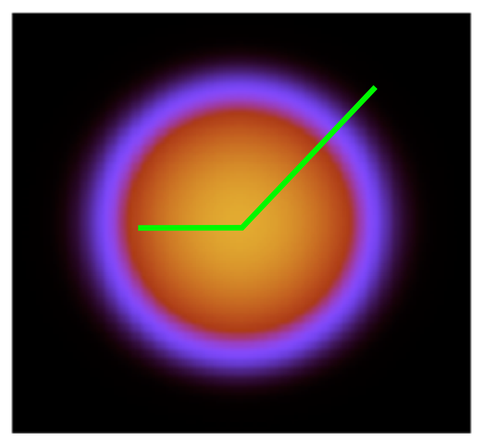
Three key approaches to study QGP structure at multiple scales:

Jet structure
vary momentum/angular scale of probe

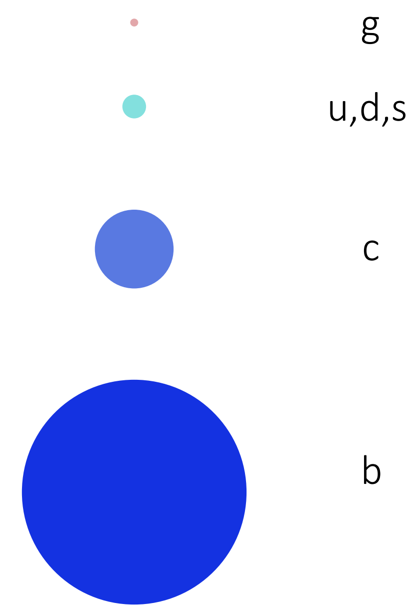


Quarkonium spectroscopy
vary size of probe



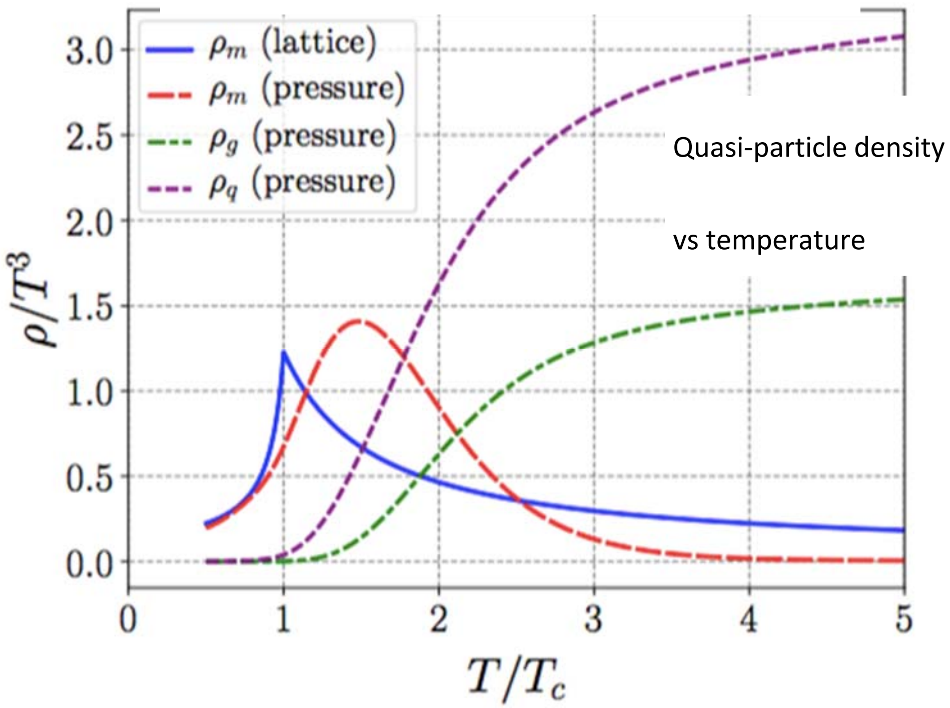


Parton energy loss
vary mass/momentum of probe

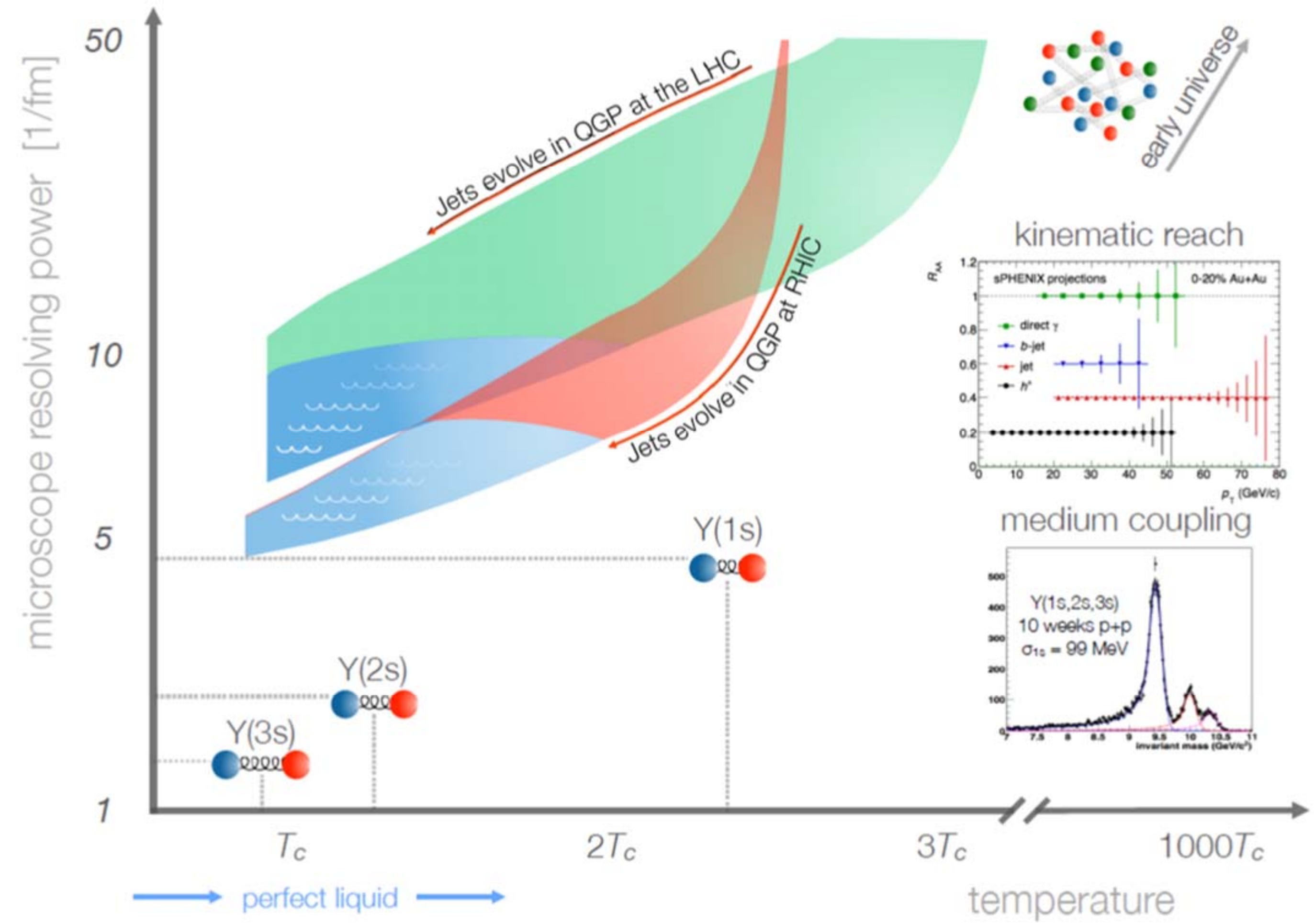


Complementarity: Why RHIC *and* LHC?

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?

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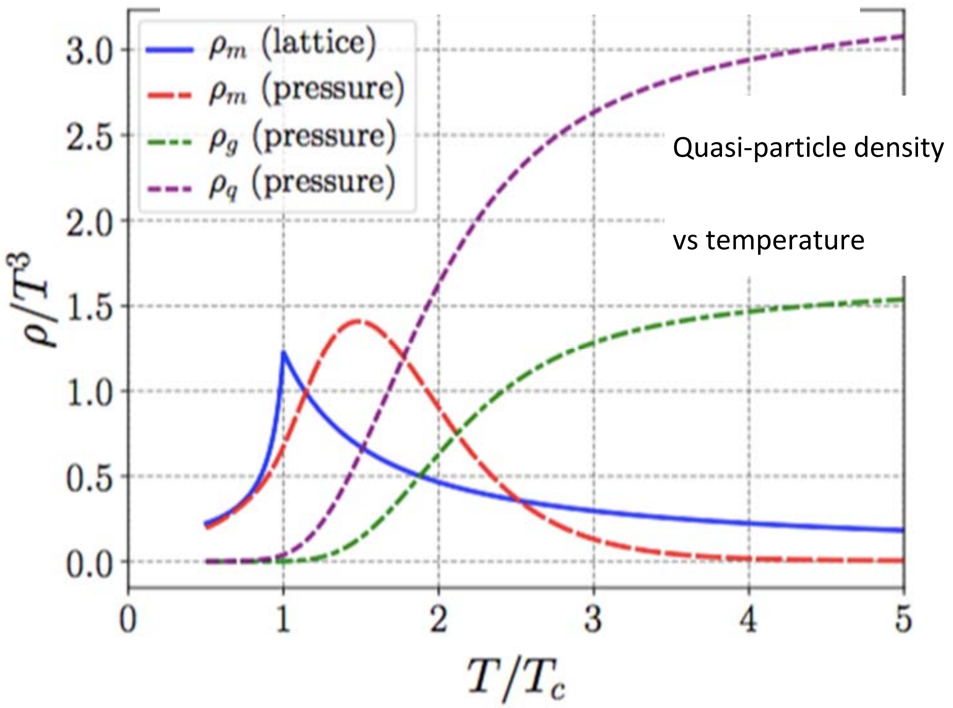
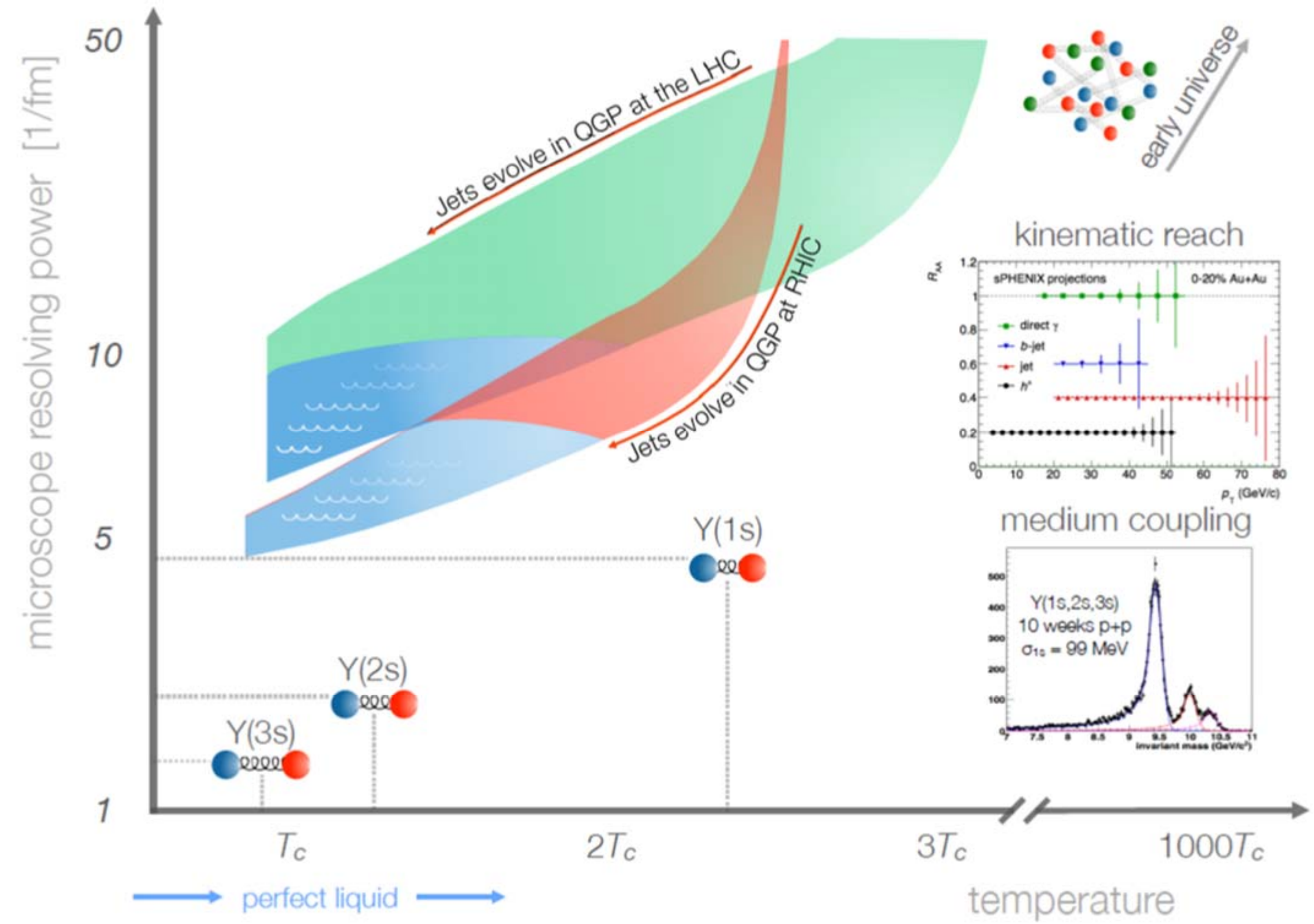




Structure of QGP expected to depend on T

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

RHIC QGP spends more time near T_c

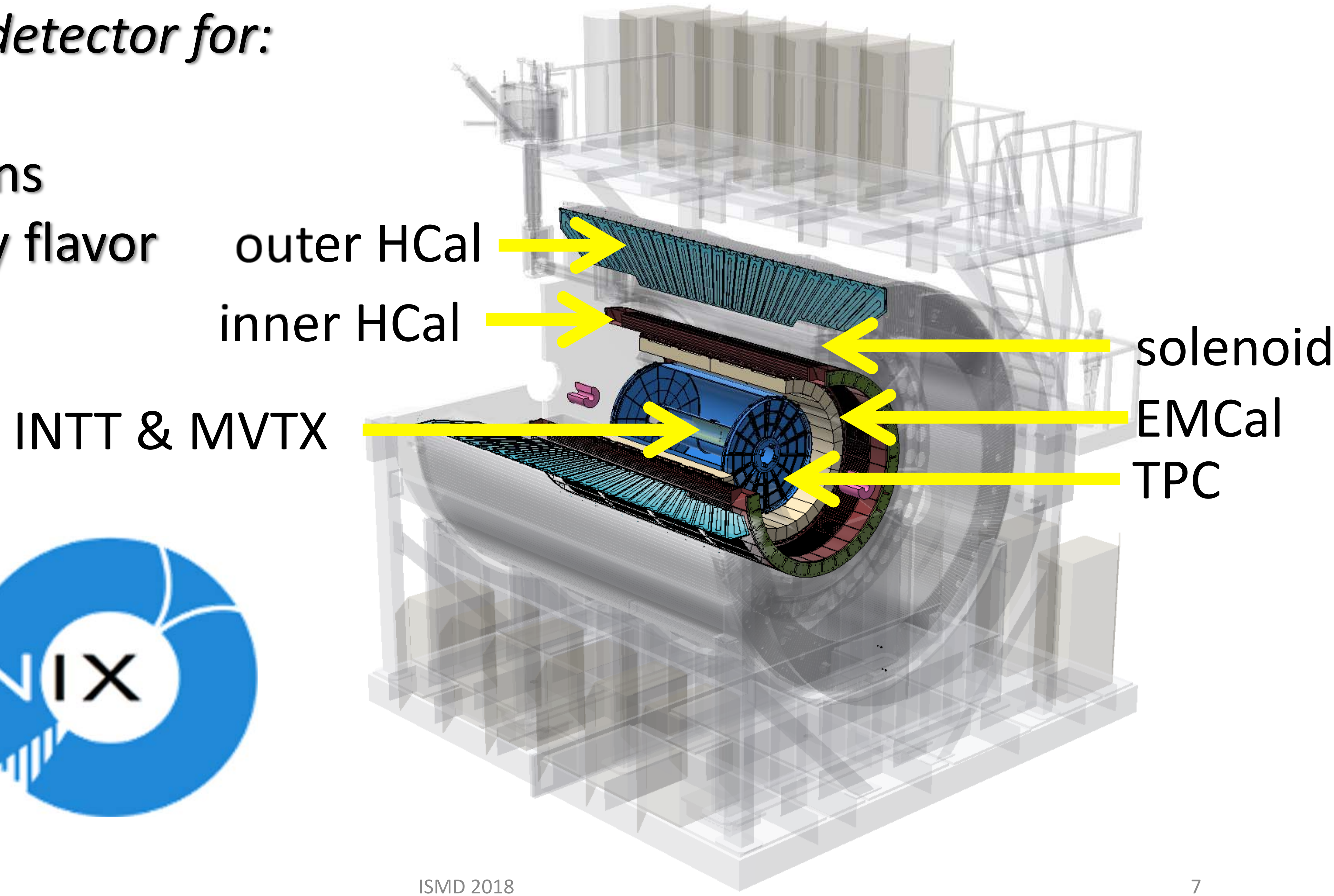
➥ Use **combined RHIC and LHC data** to extract T dependence

State of the art detector for:

Jets

Upsilons

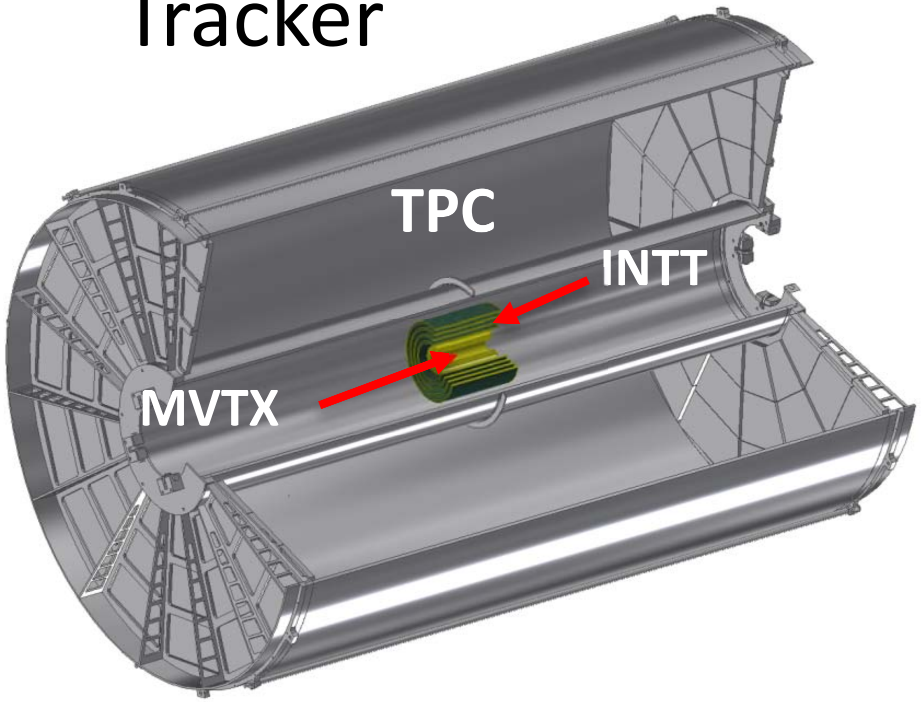
Open heavy flavor



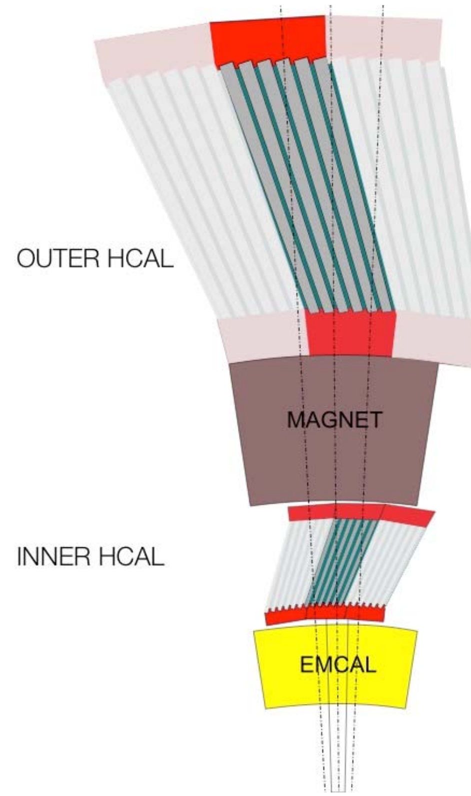
sPHENIX

SPHENIX Subdetectors

Tracker



Calorimeter stack

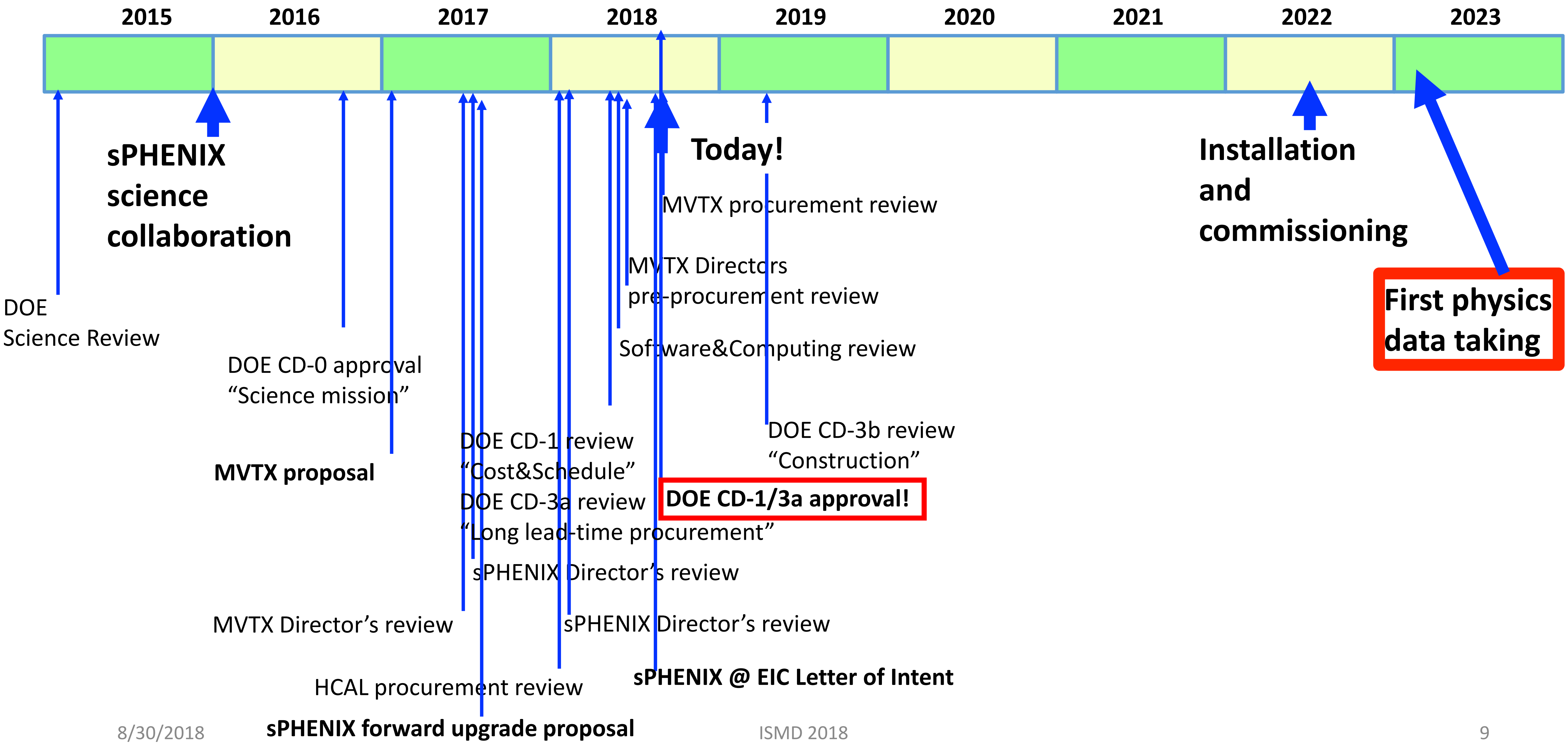


Continuous readout TPC
Si strip intermediate tracker
3-layer MAPS-based μ vertex

Tungsten/SciFi EMCal
Steel/plastic scintillator HCAL
SiPM readout

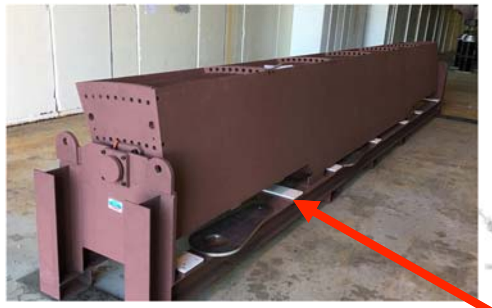
15kHz readout in Au+Au to match expected collision rate in |z| < 10cm

Realizing sPHENIX

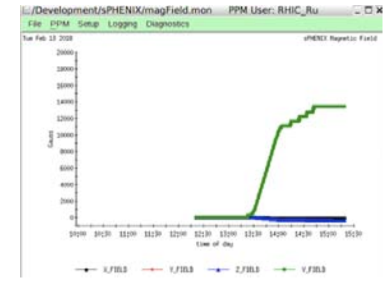


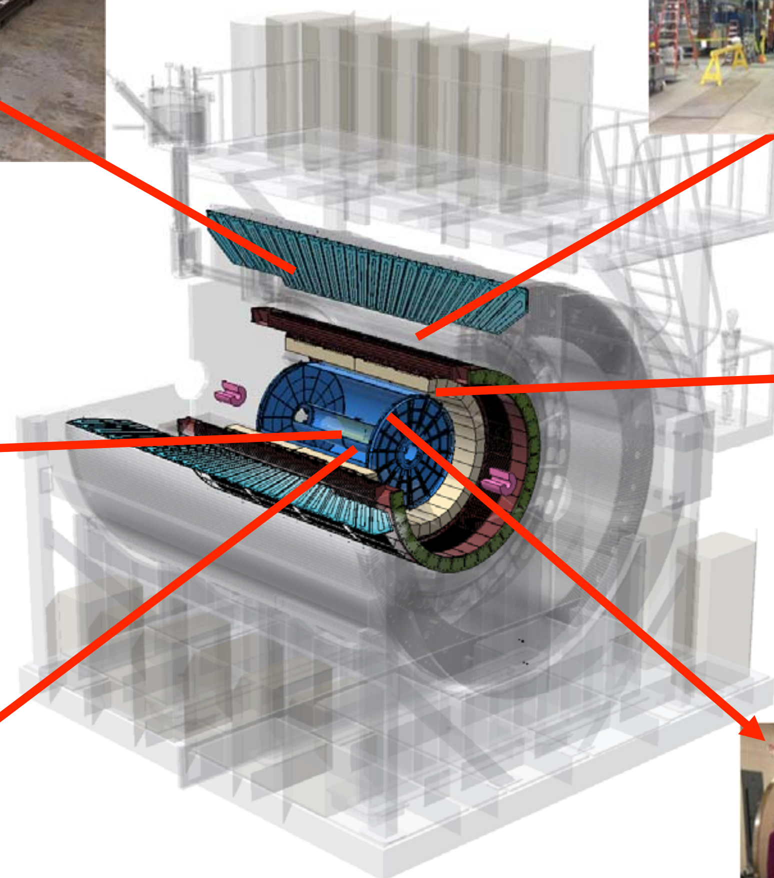
Realizing sPHENIX

Flux return/**oHCAL** absorber
Production sectors will start arriving September '18

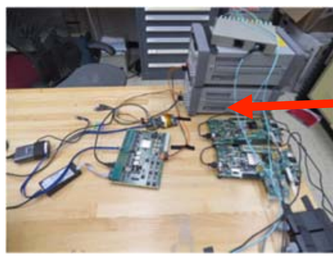


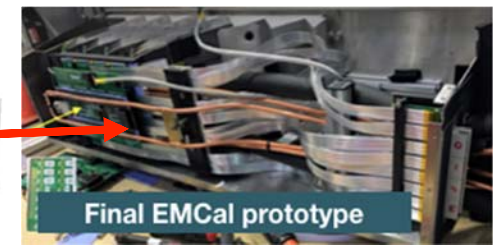
Full field **magnet** test at 1.4T at BNL on 2/13/2018



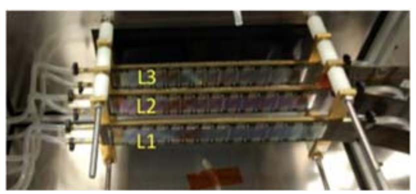


MVTX full chain test and beam test in Spring 2018
Expecting stave procurement in late 2018

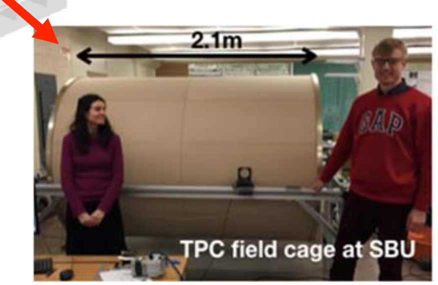




EMCAL materials purchase underway; "Sector 0" production starting 2018



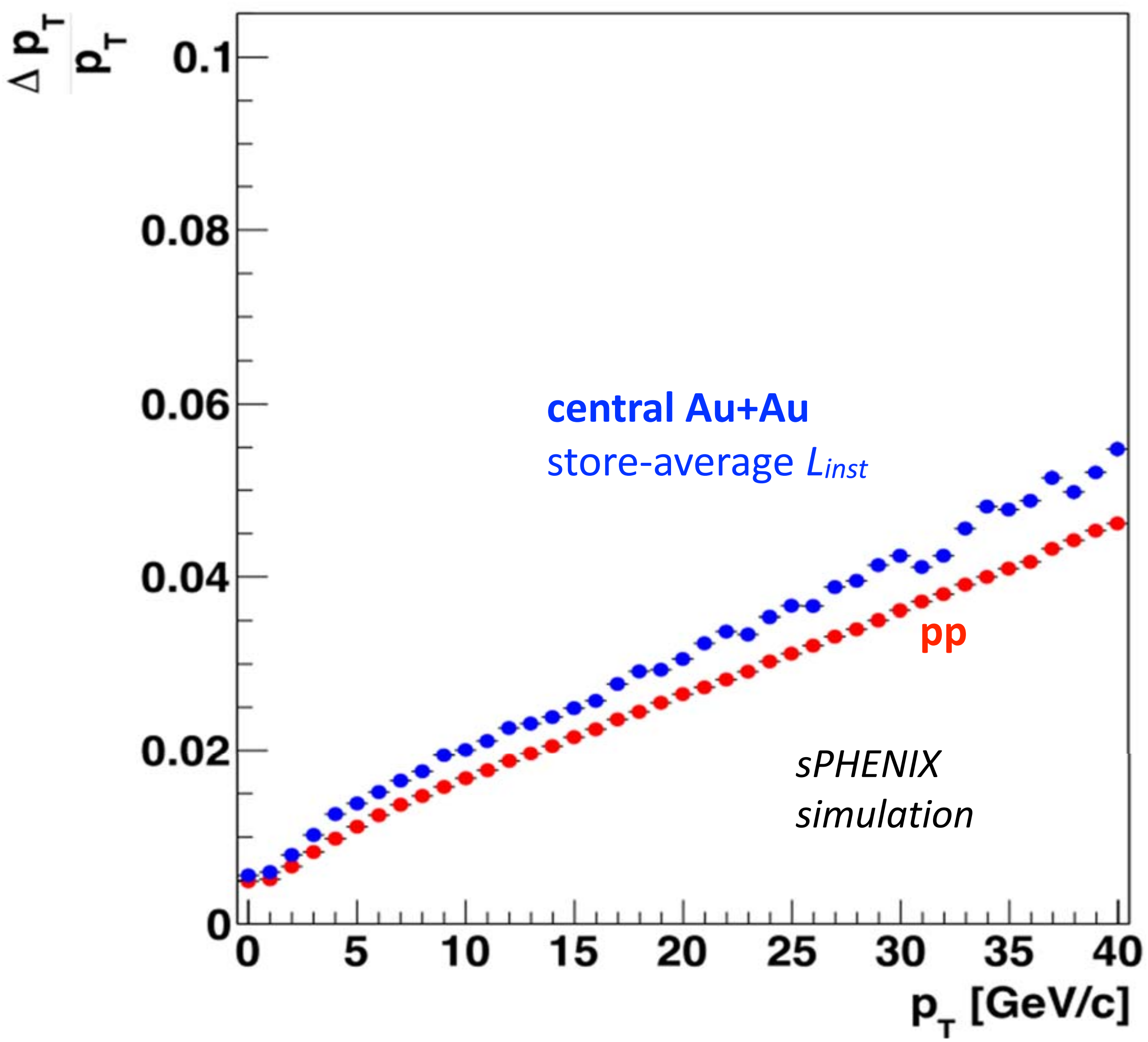
INTT telescope beam test in Spring 2018
Detector will be delivered by Riken



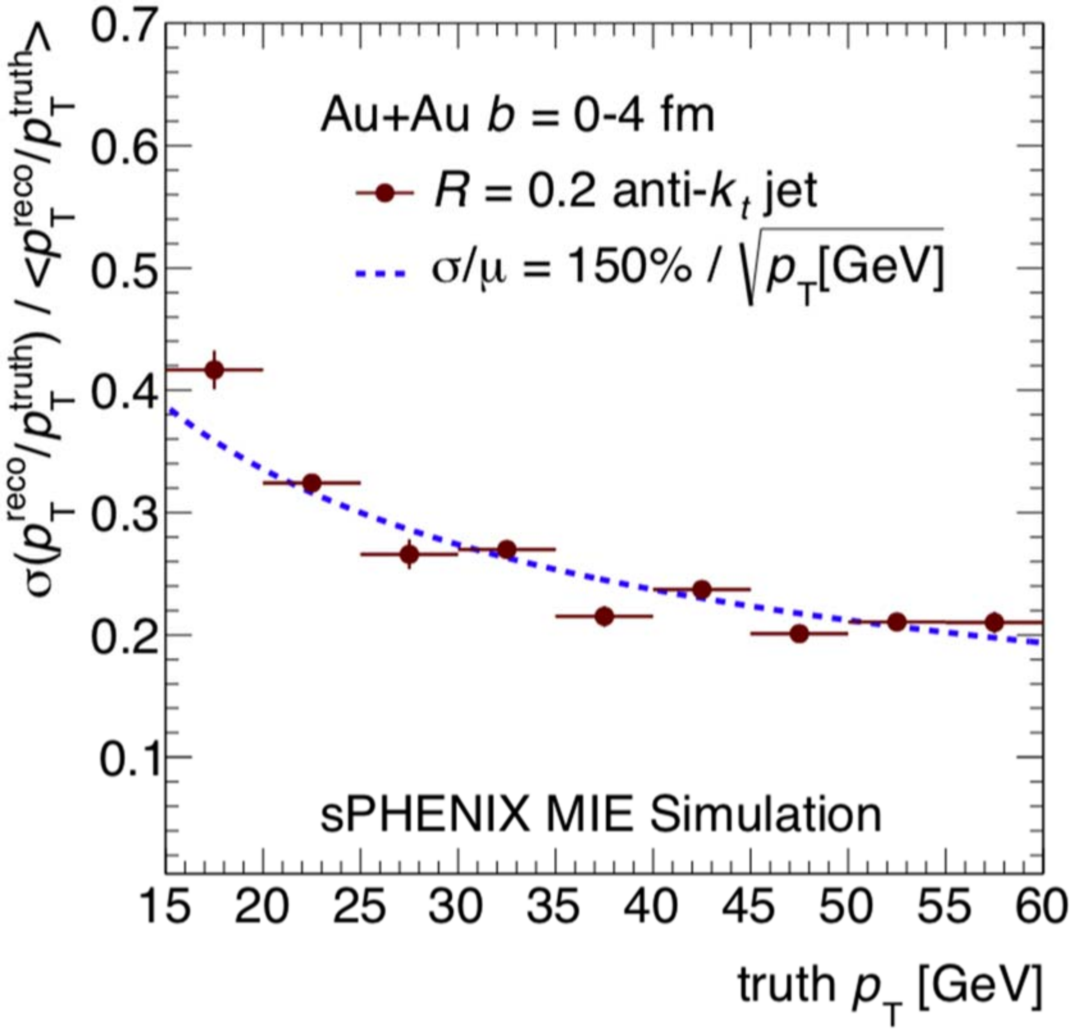
Beam test of **TPC** prototype in June 2018
Ready for producing of full-size field cage "prototype"

Performance simulation: Track and Jet resolution

Track pT resolution (central Au+Au)



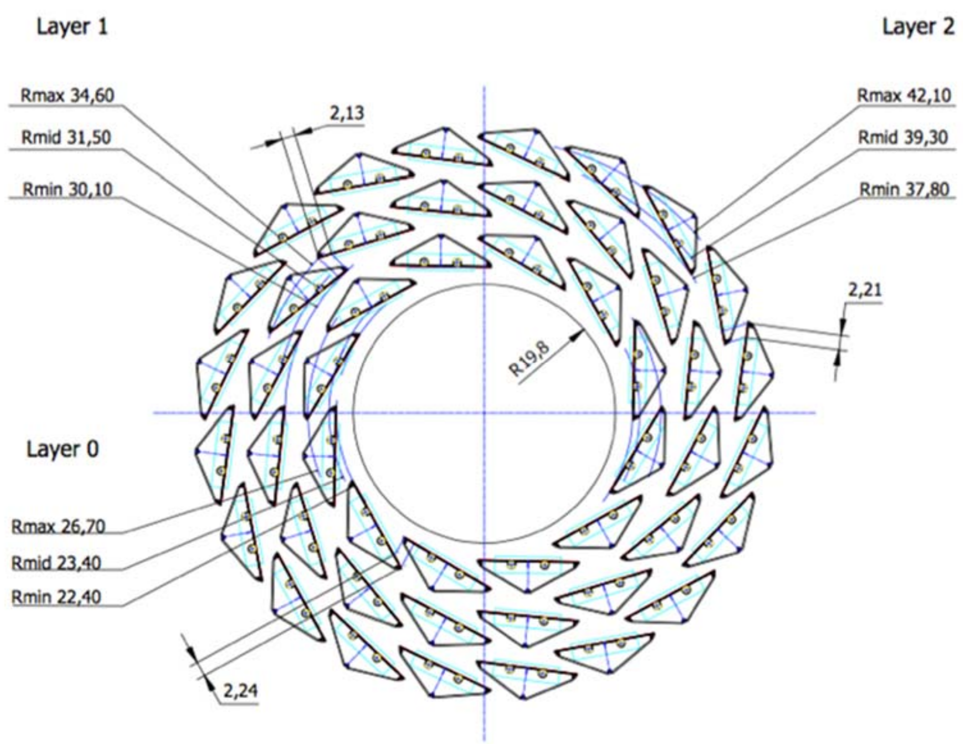
Single jet resolution (central Au+Au)



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

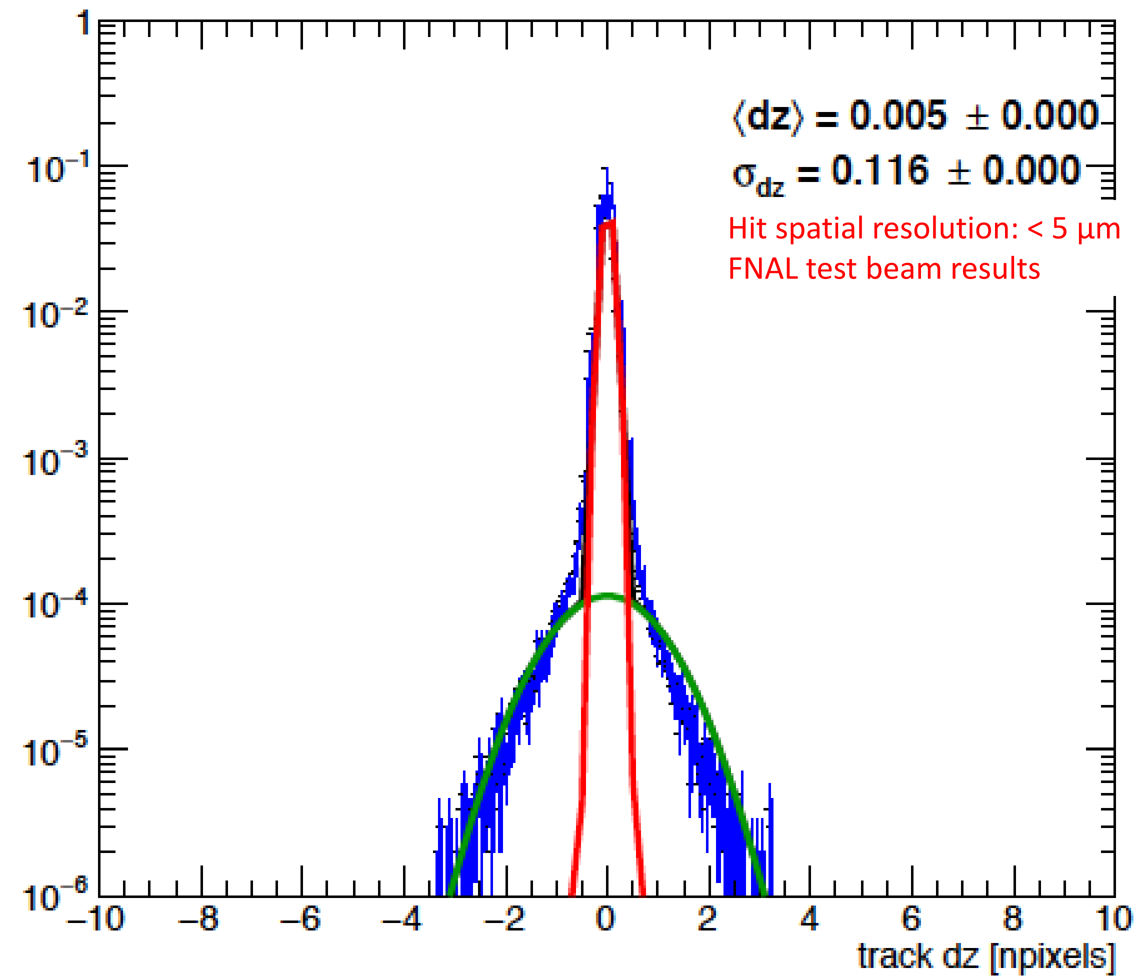
MVTX enables world-class HF science program

Stave layout beam view

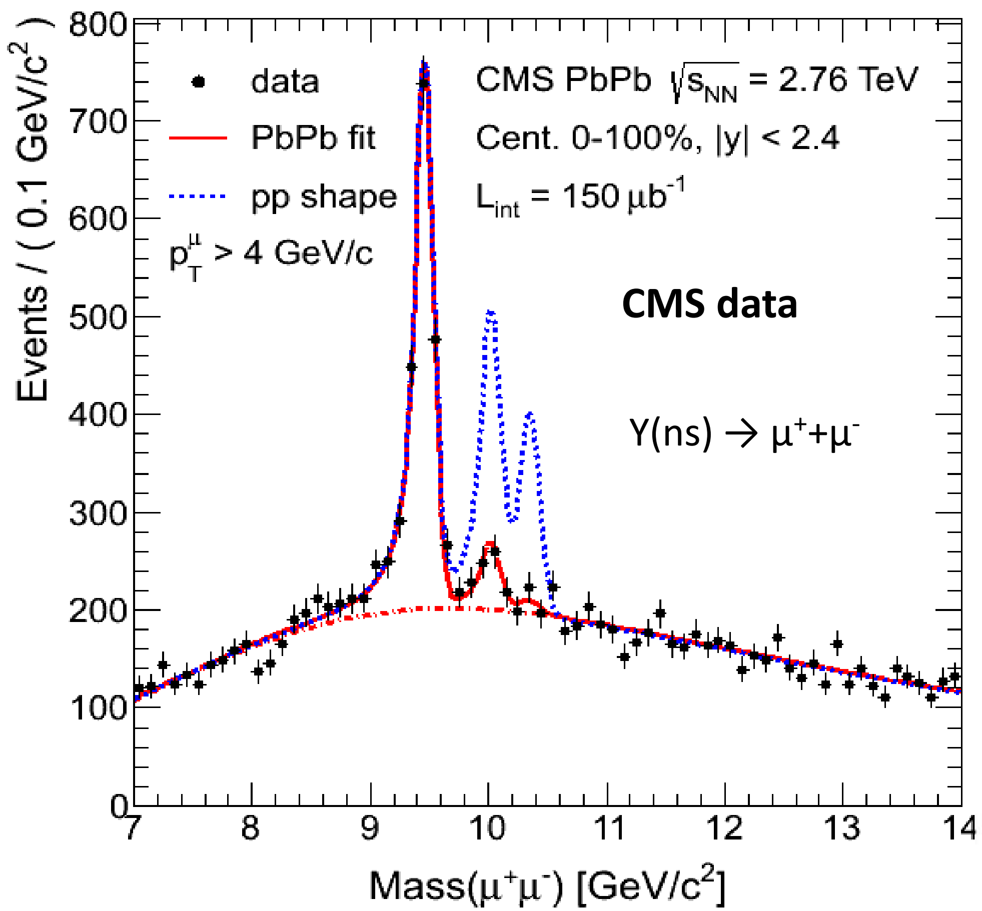


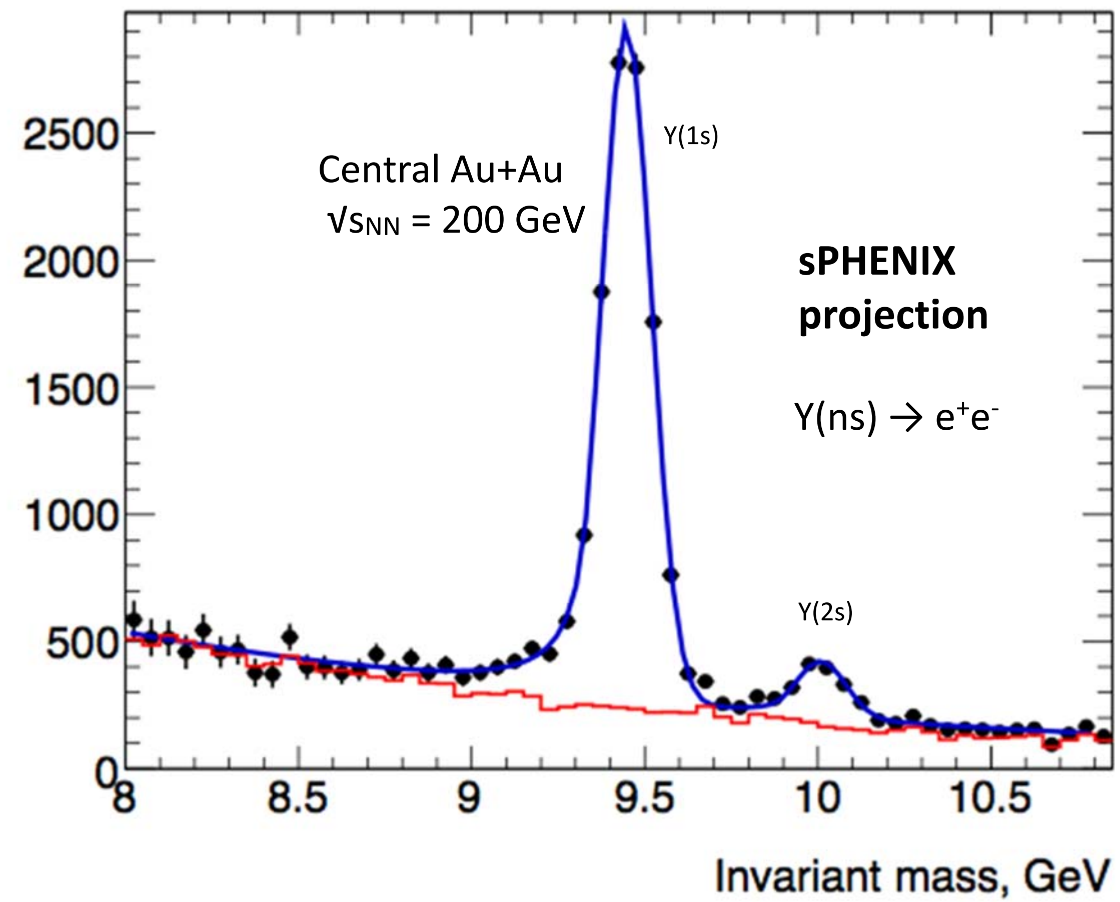
MVTX based on copy of ALICE staves with support structure modified for sPHENIX

MVTX spatial resolution



Upsilons at sPHENIX vs. LHC



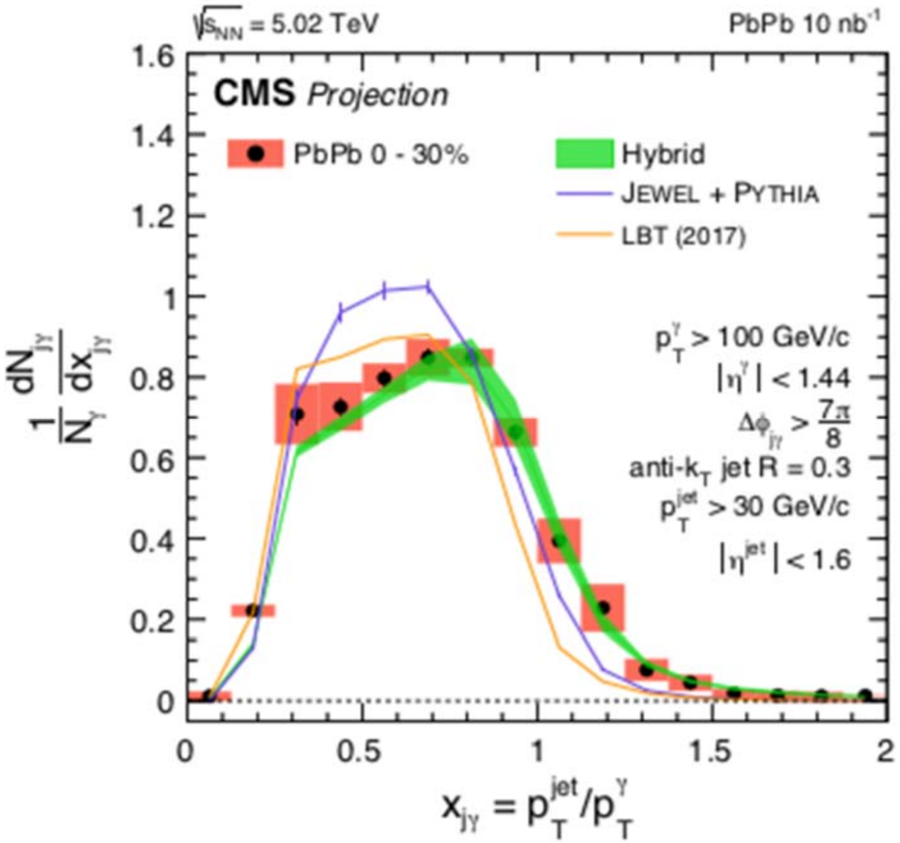


Sequential suppression of Y(nS) states reveals QGP Debye screening length

As at LHC, Y(3s) will be challenging to see in Au+Au at RHIC

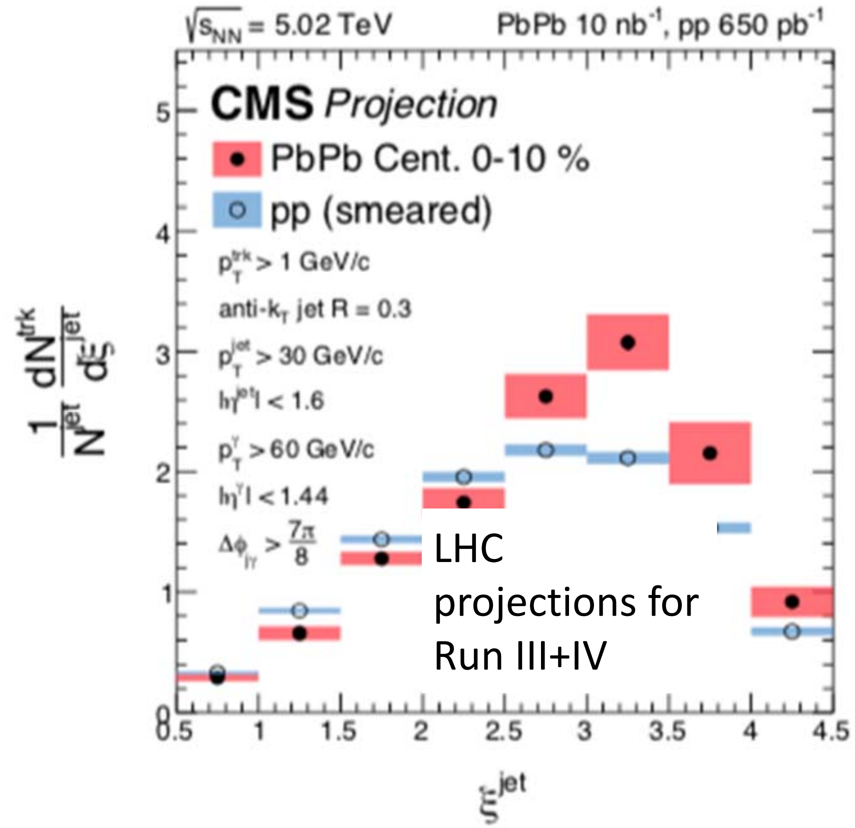
Jets in sPHENIX vs. LHC

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

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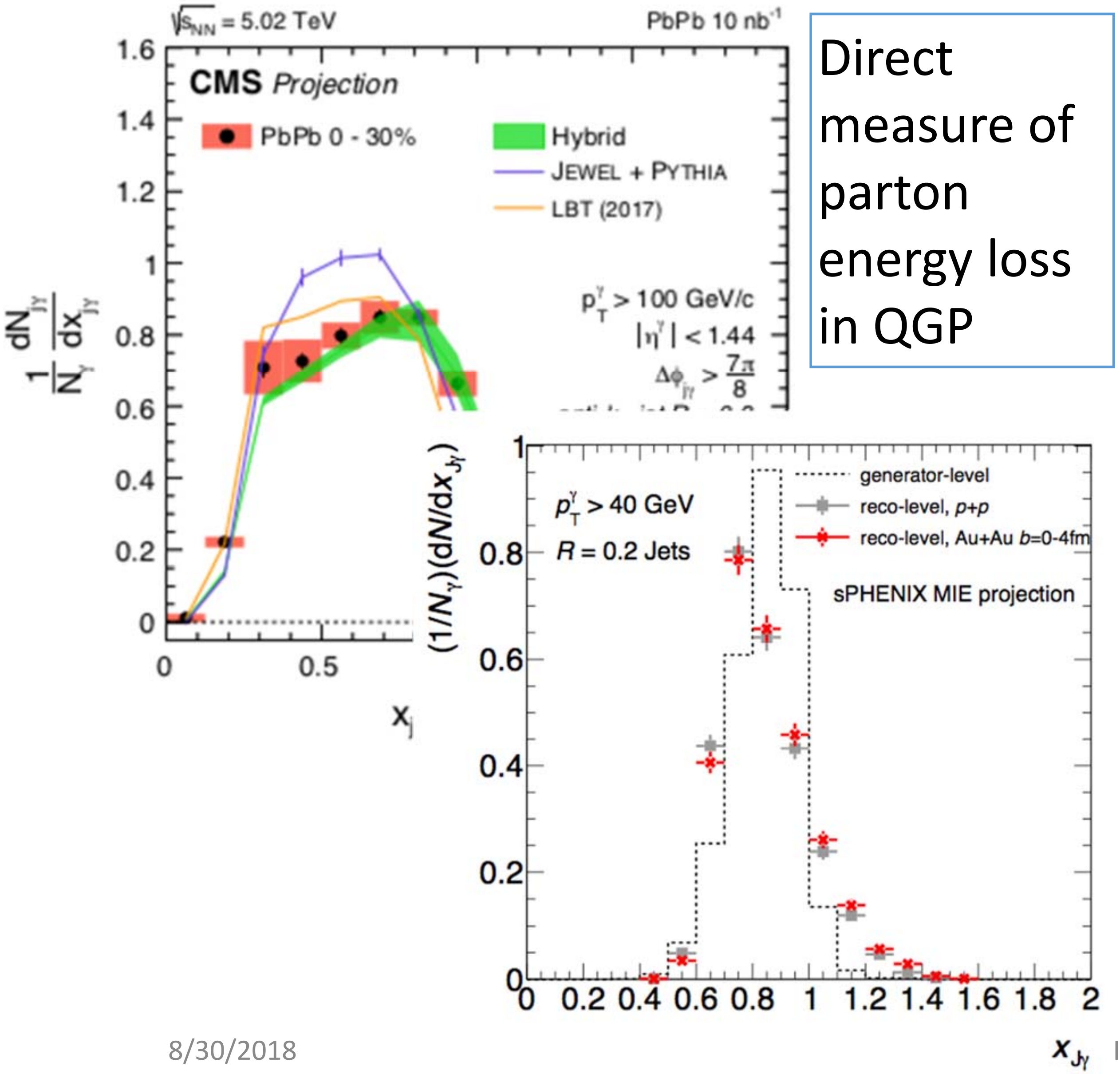

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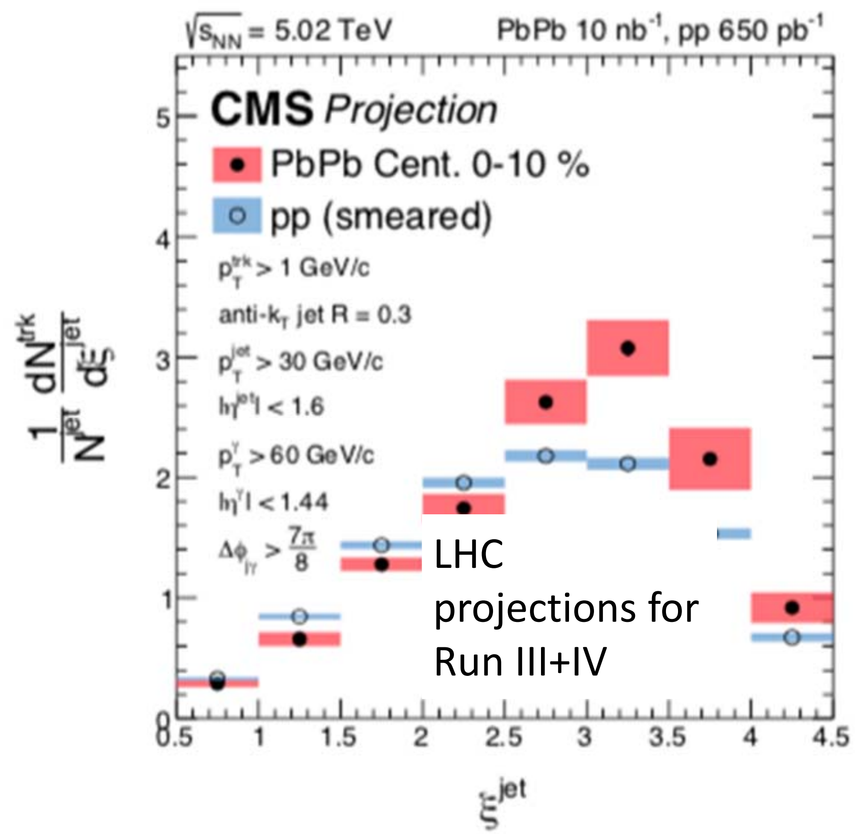

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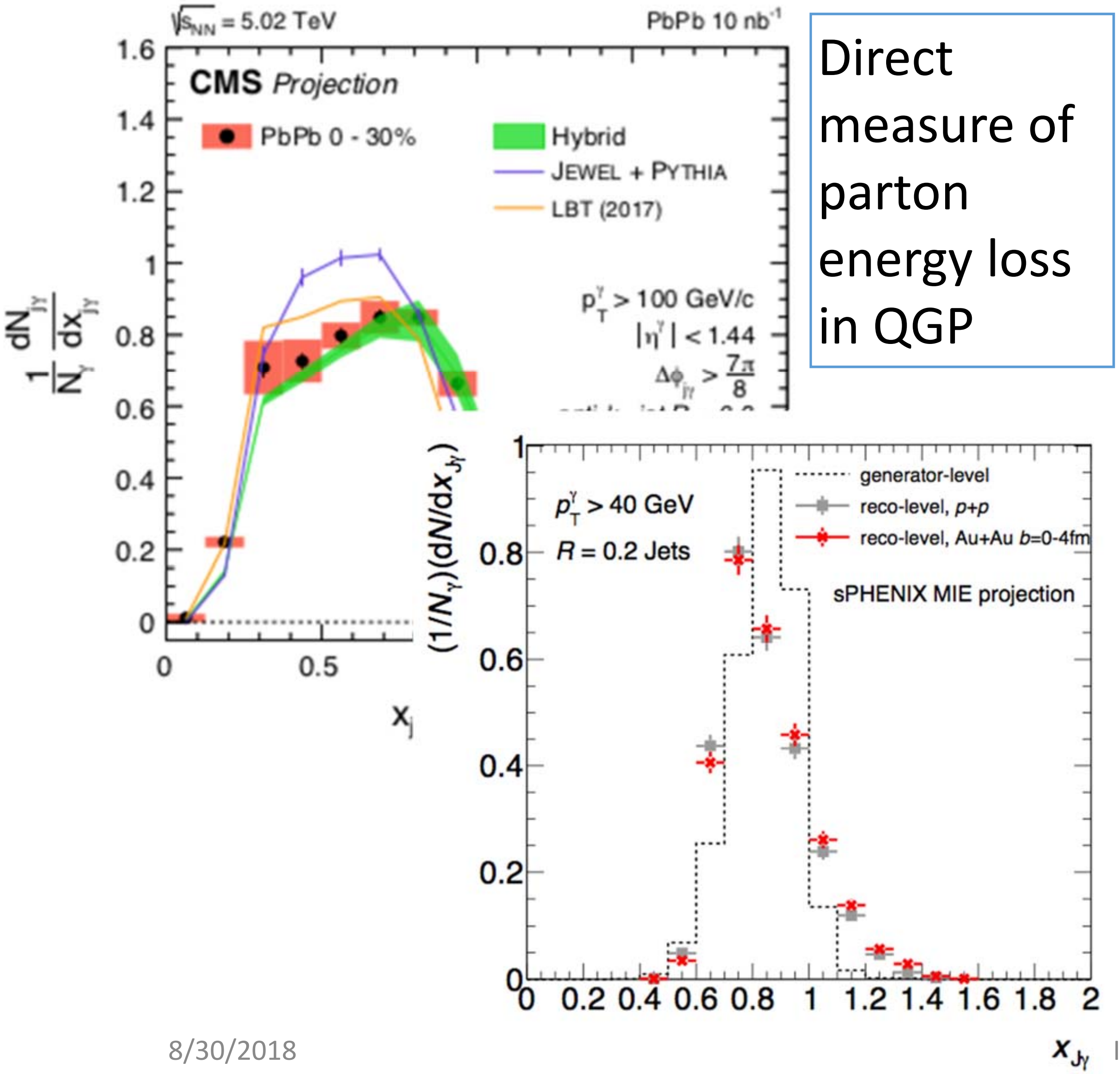

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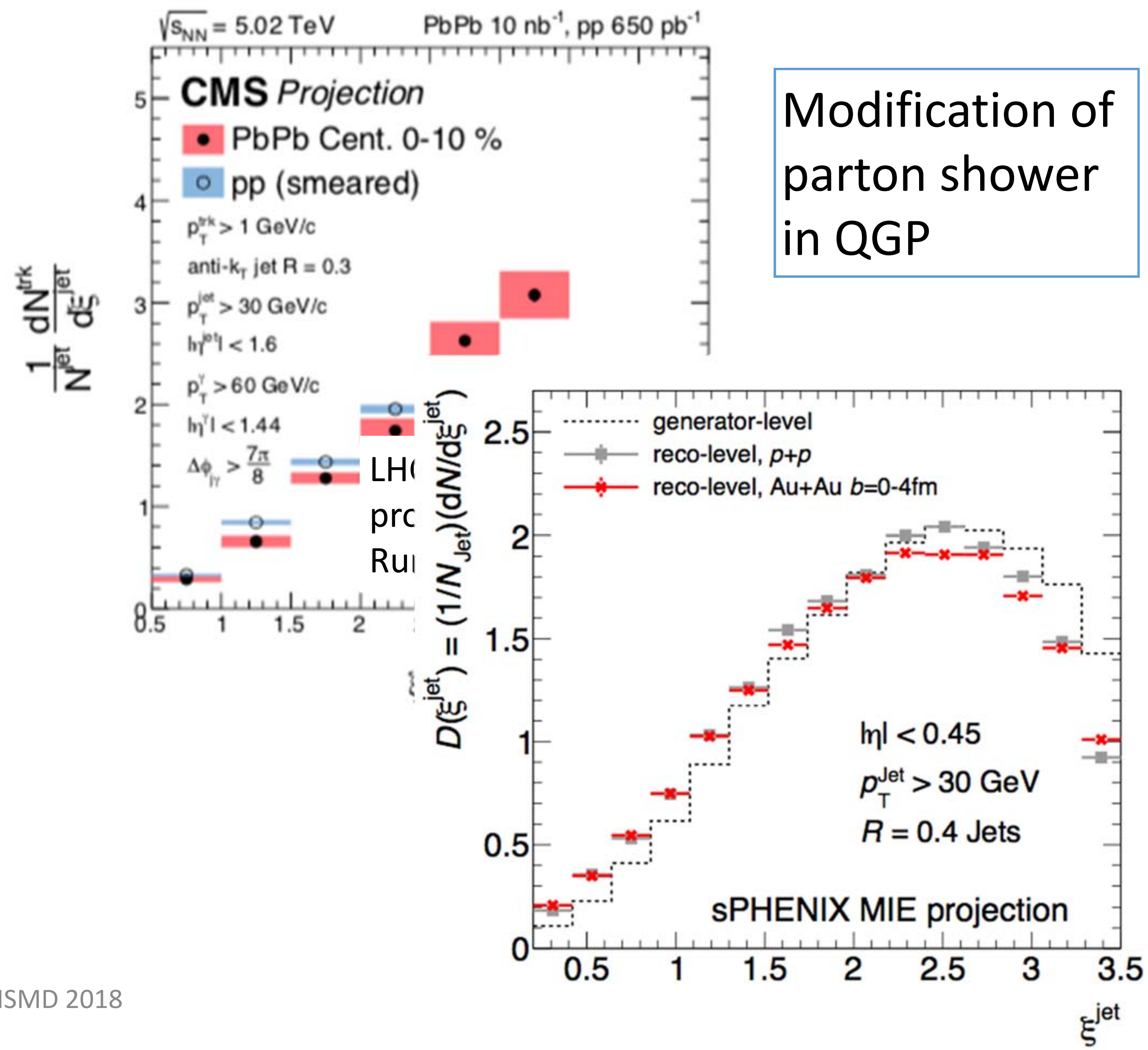
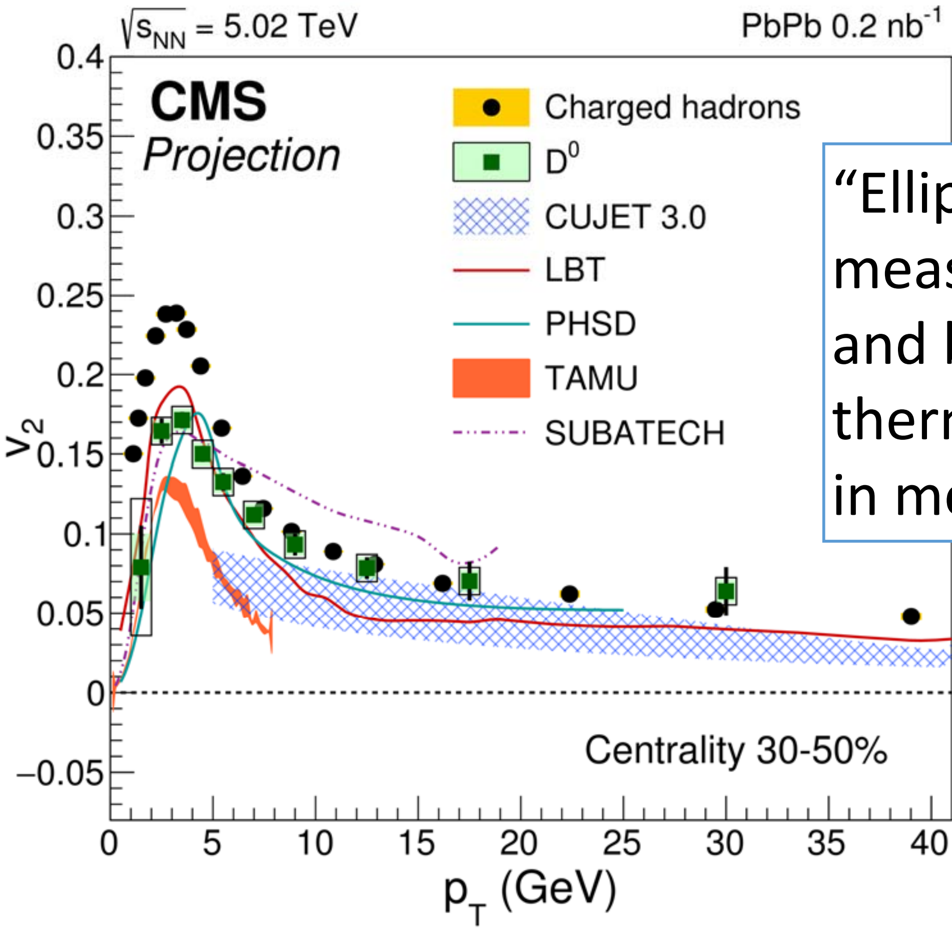
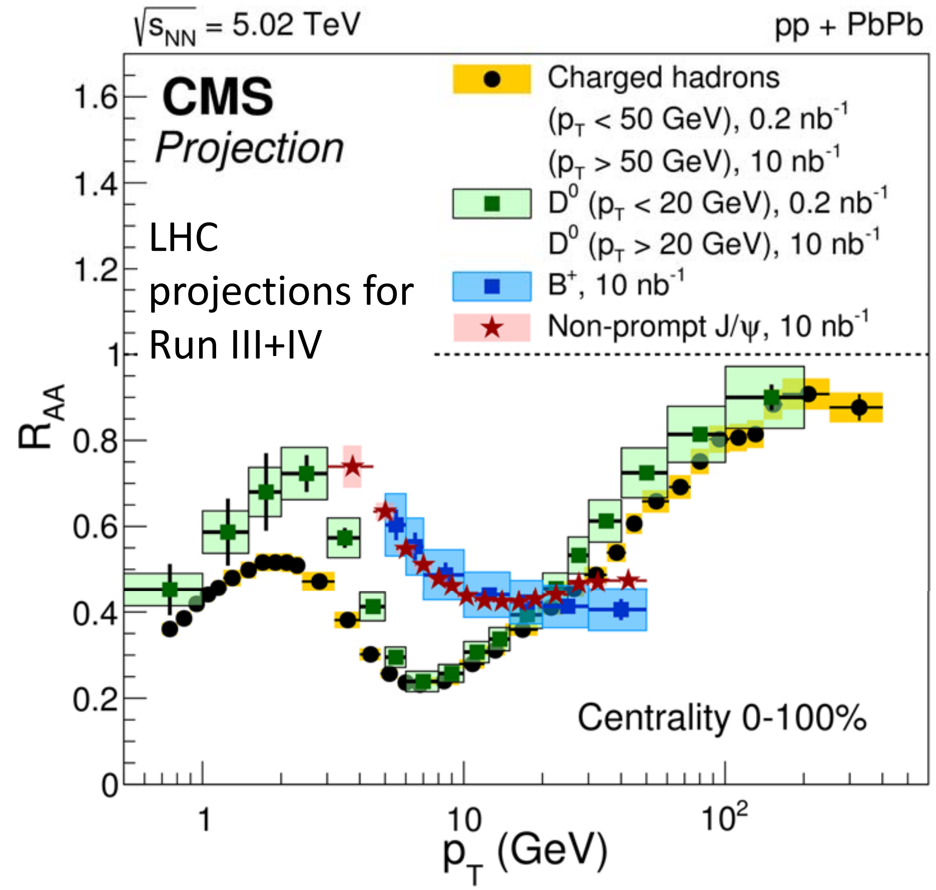


Modification of parton shower in QGP

Heavy flavor at sPHENIX vs. LHC

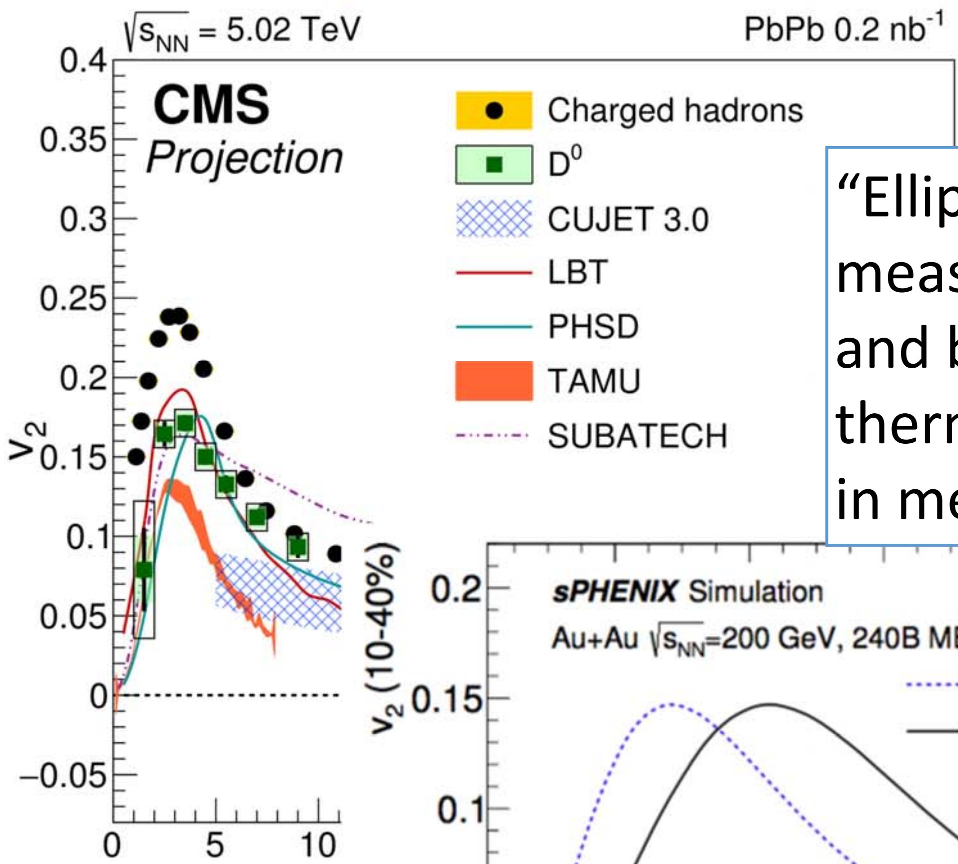


"Elliptic flow" measures c and b quark thermalization in medium



Open heavy flavor suppression probes flavor dependence of energy loss

Heavy flavor at sPHENIX vs. LHC



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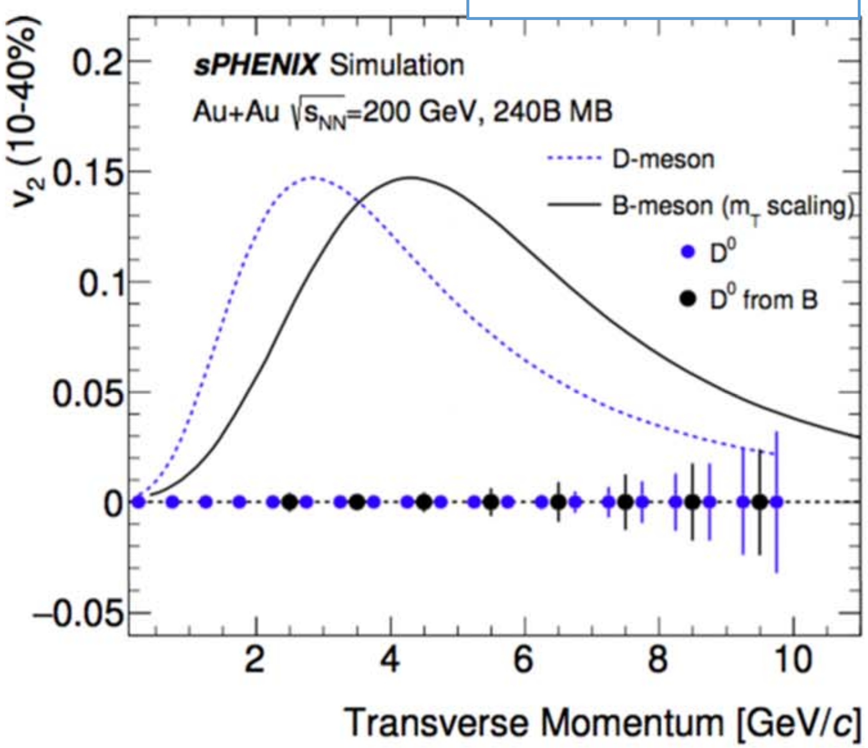

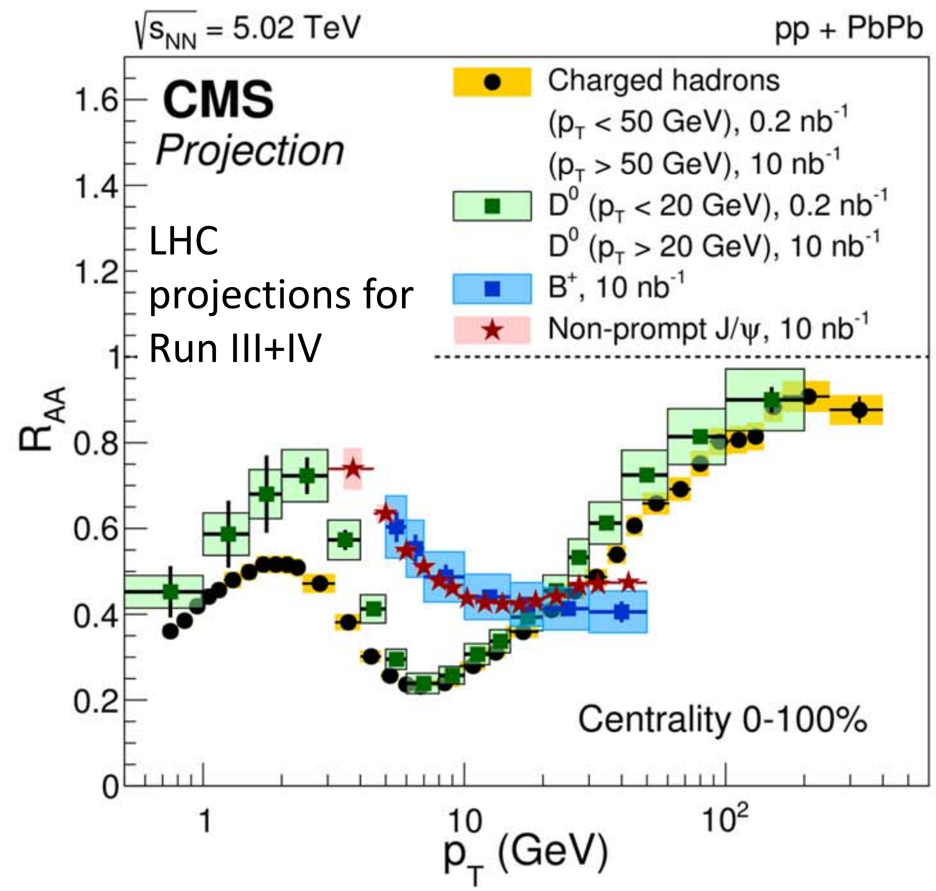

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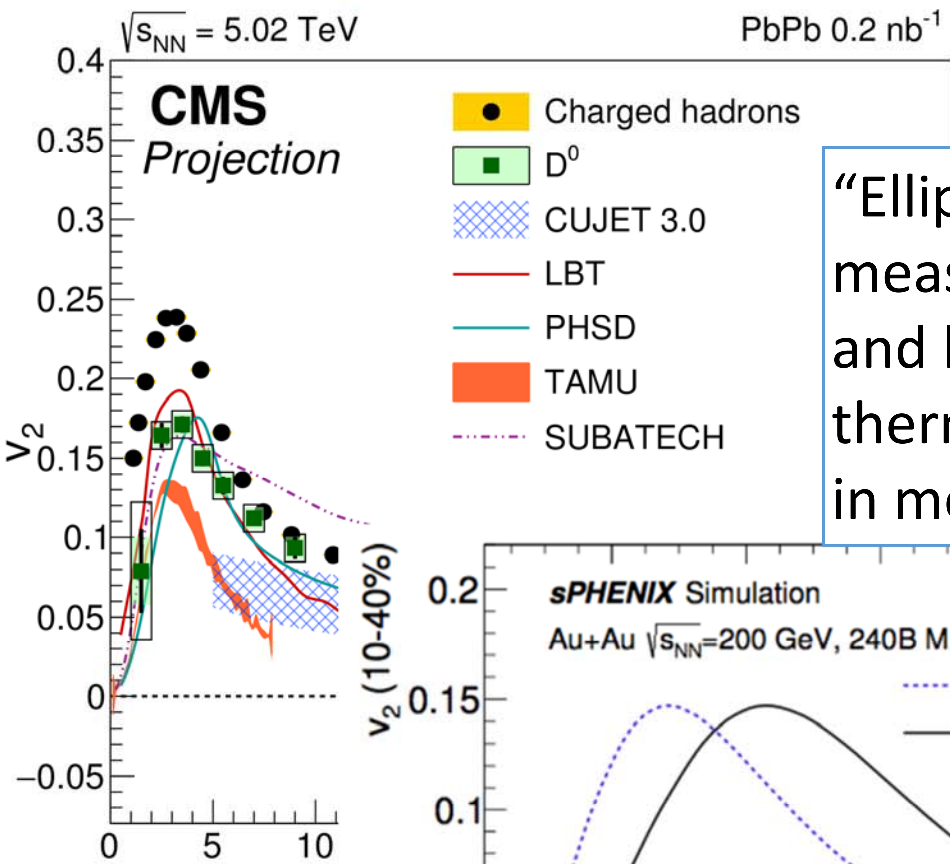
Heavy flavor at sPHENIX vs. LHC



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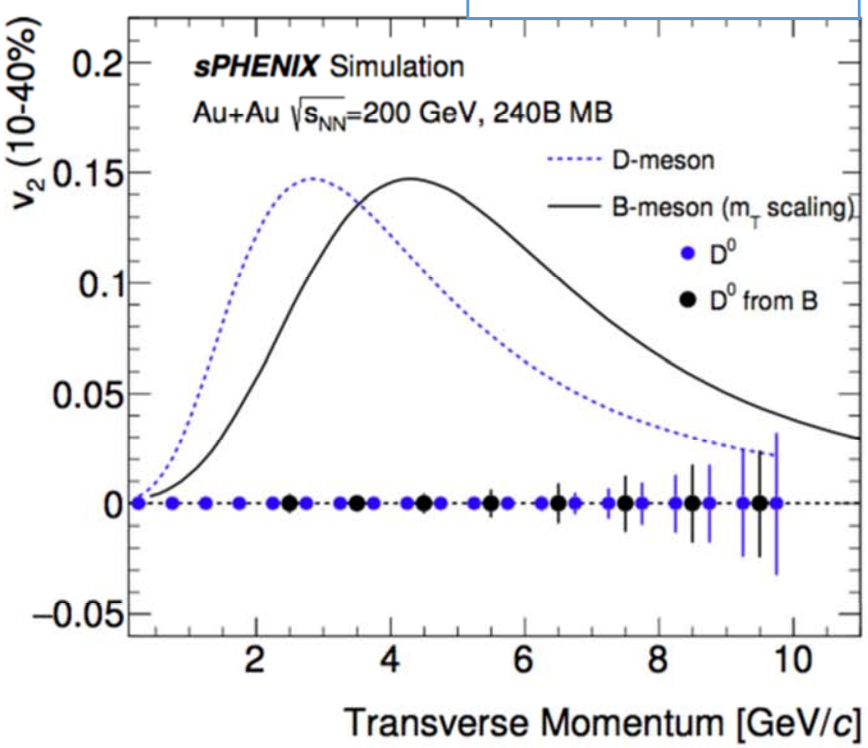
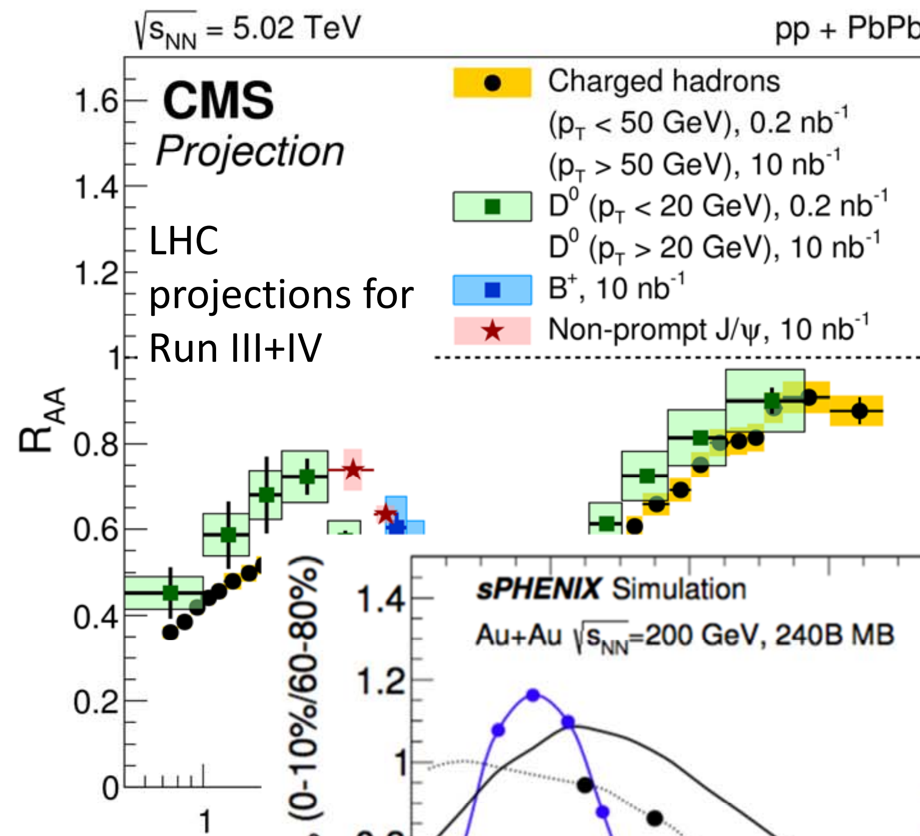
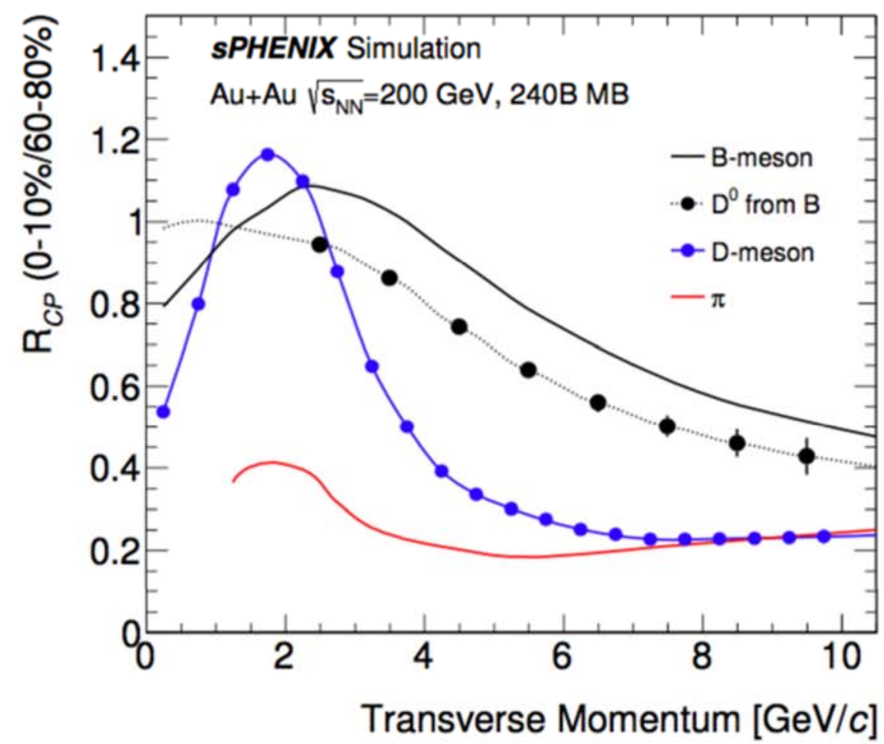
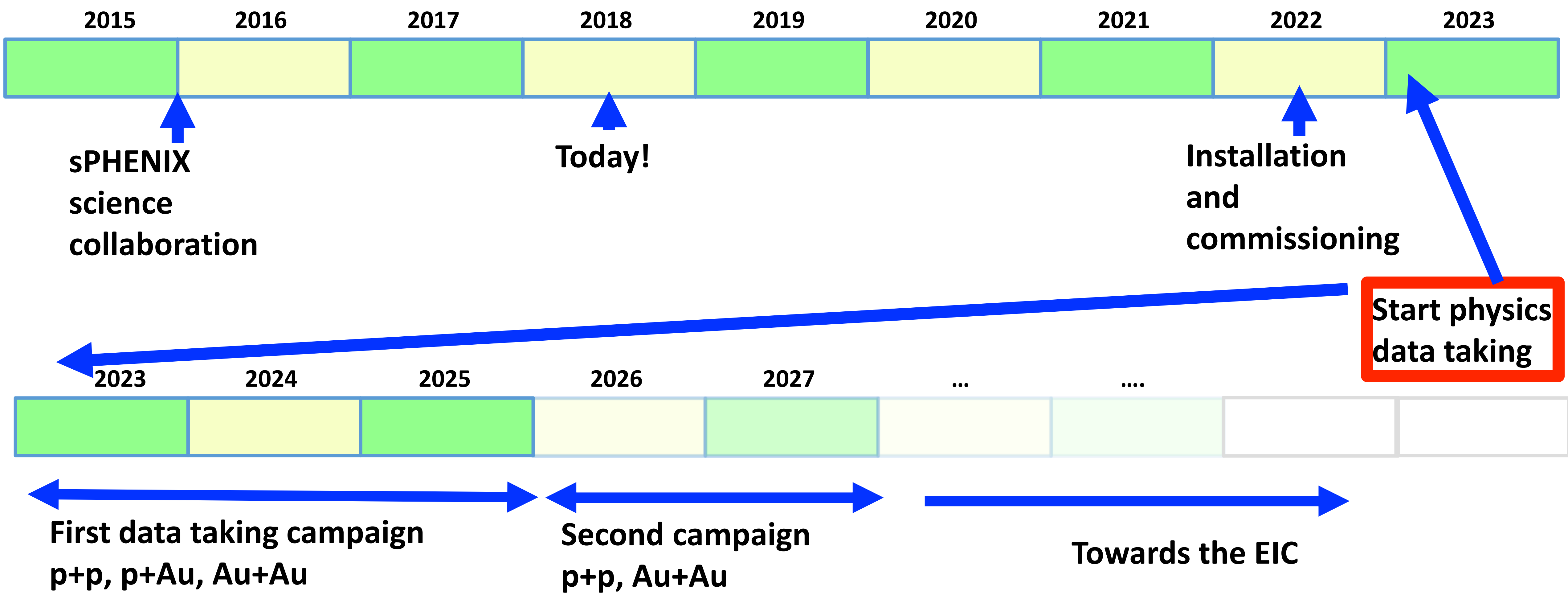




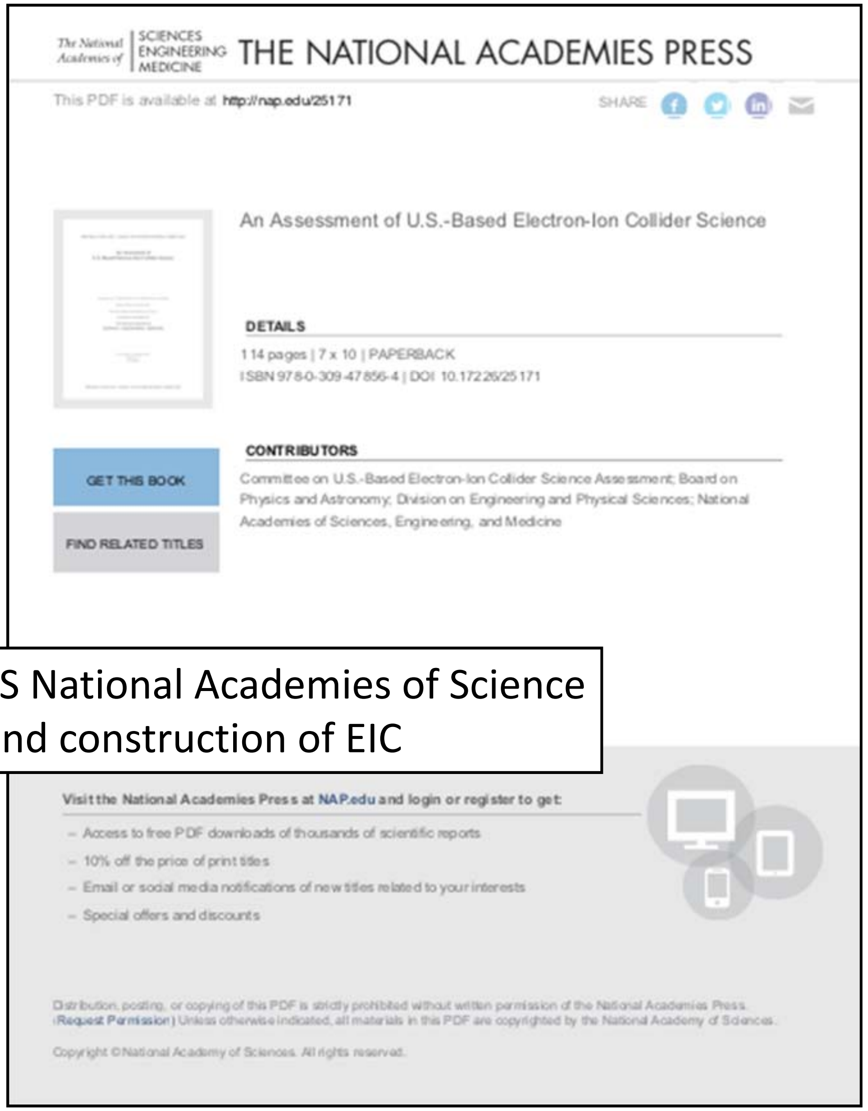
Open heavy flavor suppression probes flavor dependence of energy loss



Realizing and running sPHENIX



sPHENIX @ EIC



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An Assessment of U.S.-Based Electron-Ion Collider Science

DETAILS

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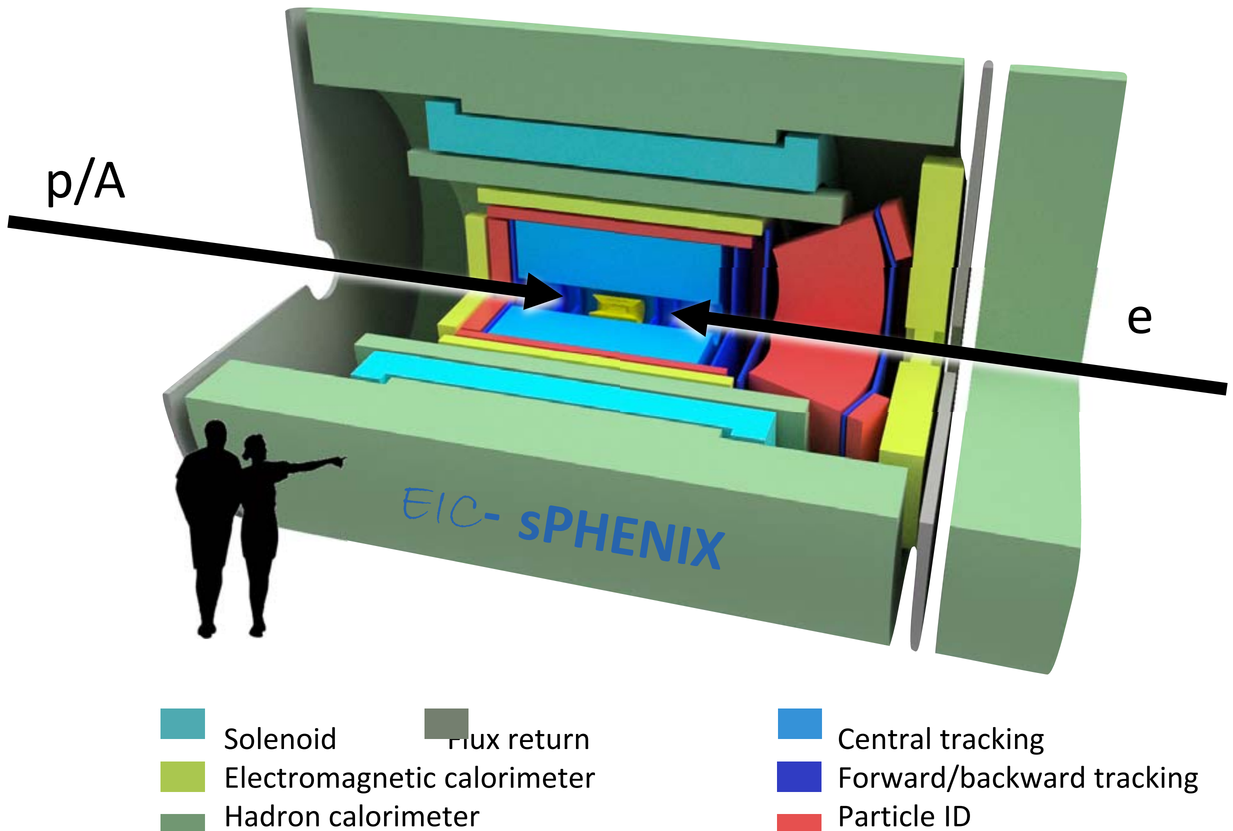
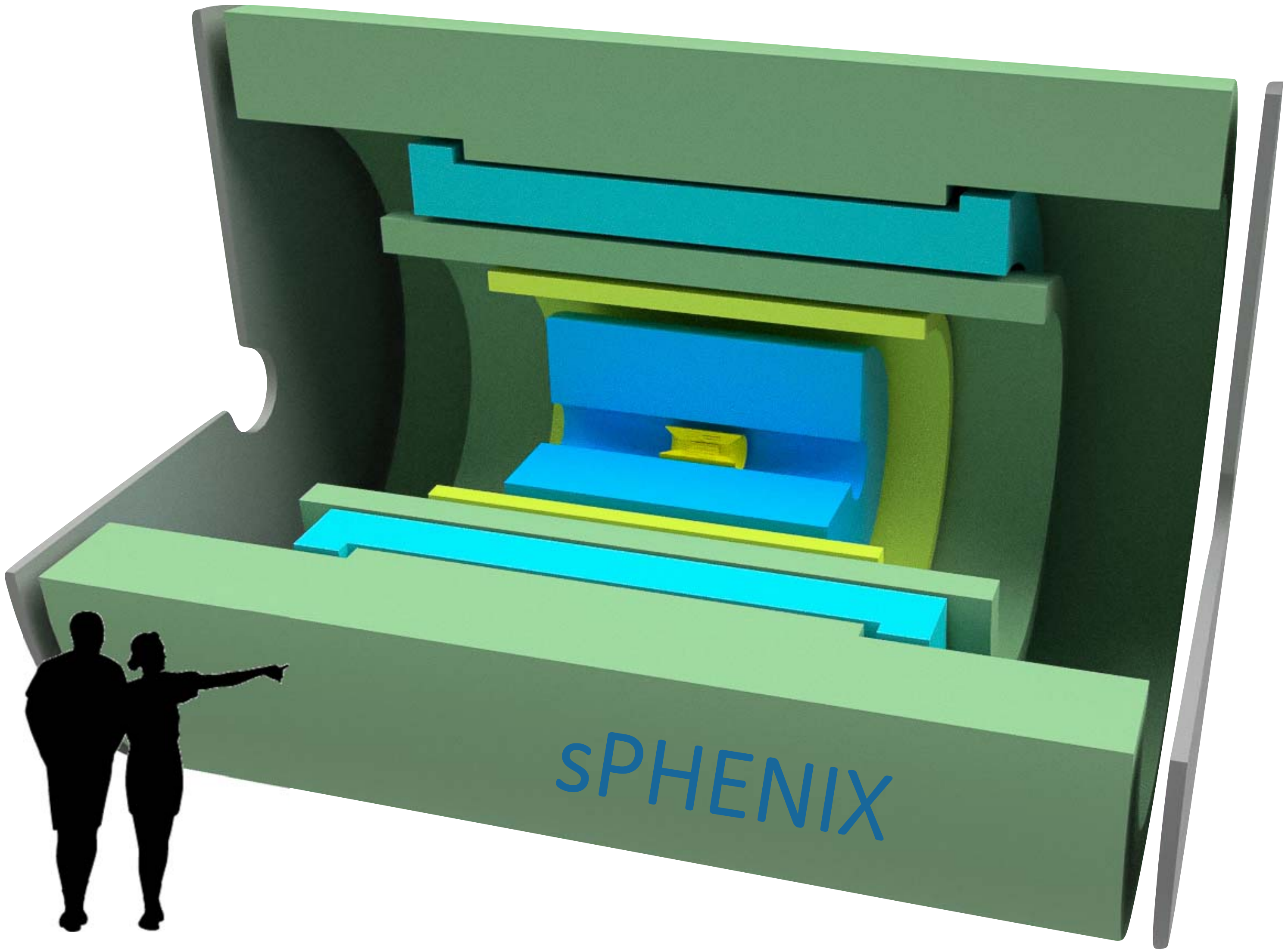
Timely: US National Academies of Science recommend construction of EIC

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



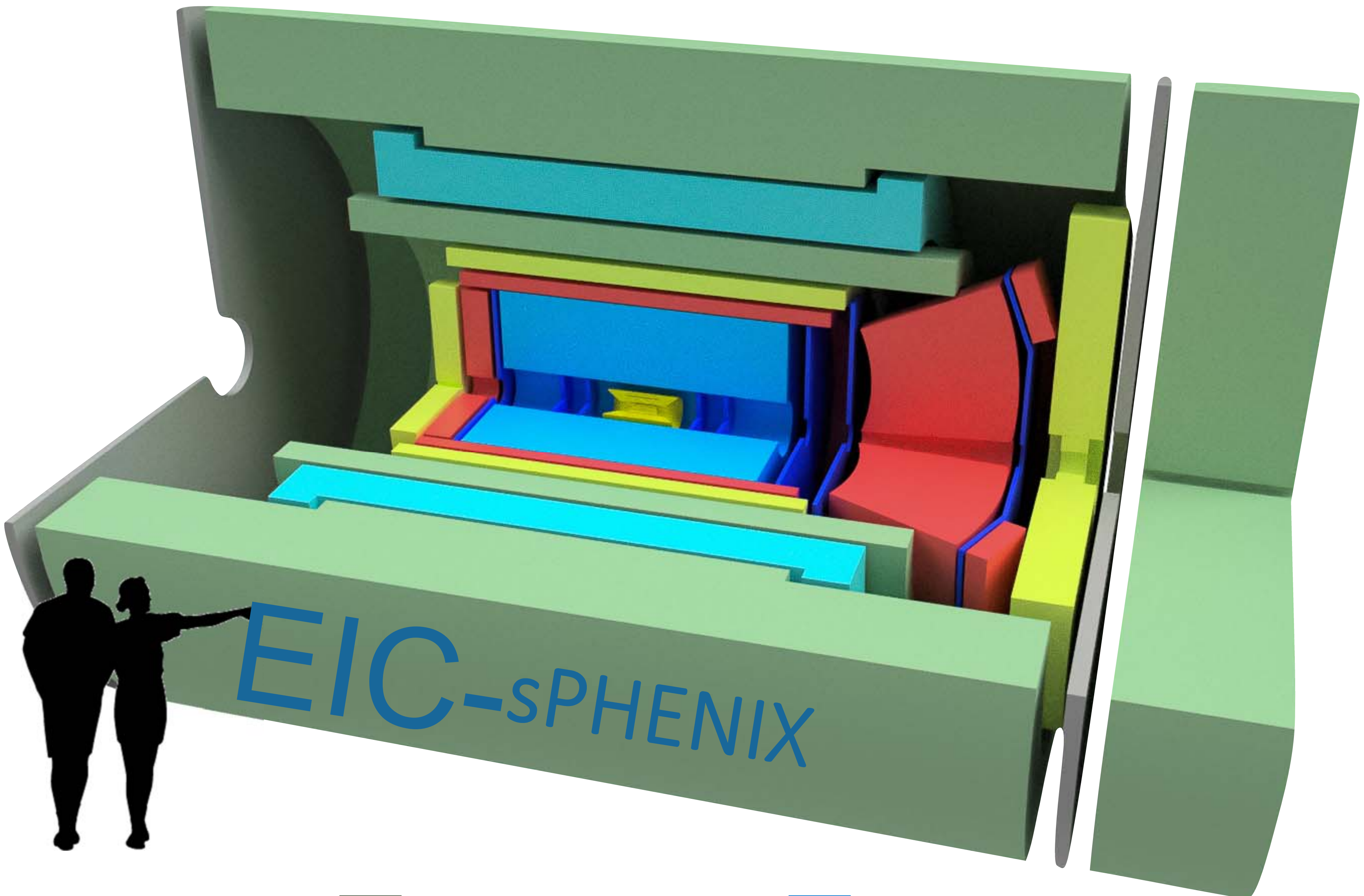
Deliver LOI by end of September '18



Solenoid Flux return Central tracking

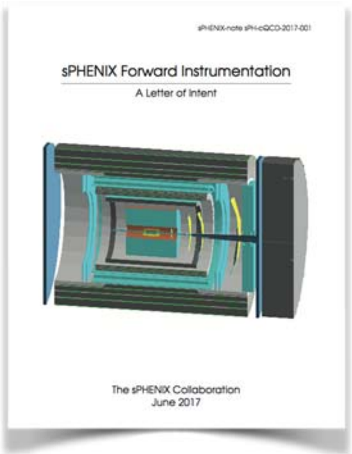
Electromagnetic calorimeter

Hadron calorimeter



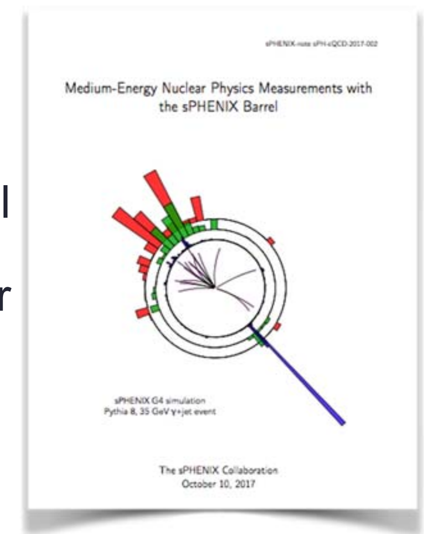
Solenoid
Flux return
Central tracking
Electromagnetic calorimeter
Forward tracking
Hadron calorimeter
Particle ID

Strong interest in Cold QCD with sPHENIX



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

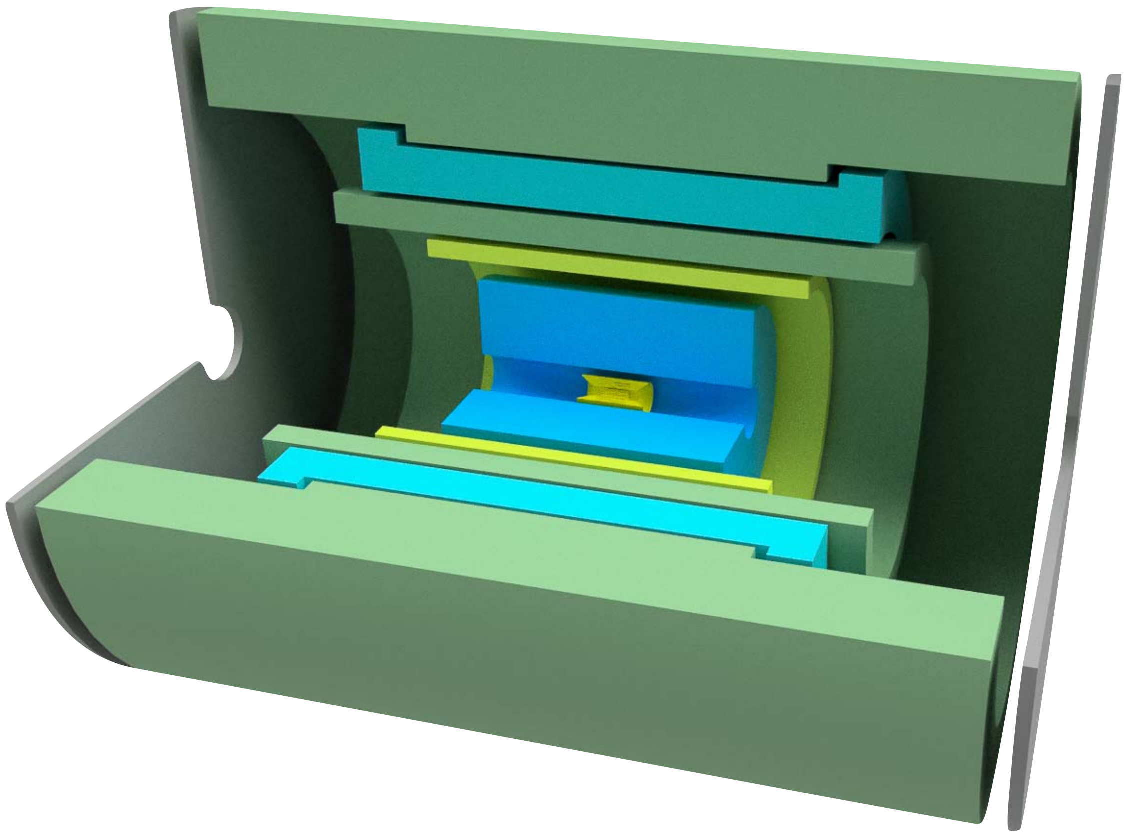
Exciting p+p and p+A program, but also strengthening of core sPHENIX program through high-rate, high resolution, large acceptance calorimetry and tracking



Oct ’17: Medium-energy physics with sPHENIX Barrel

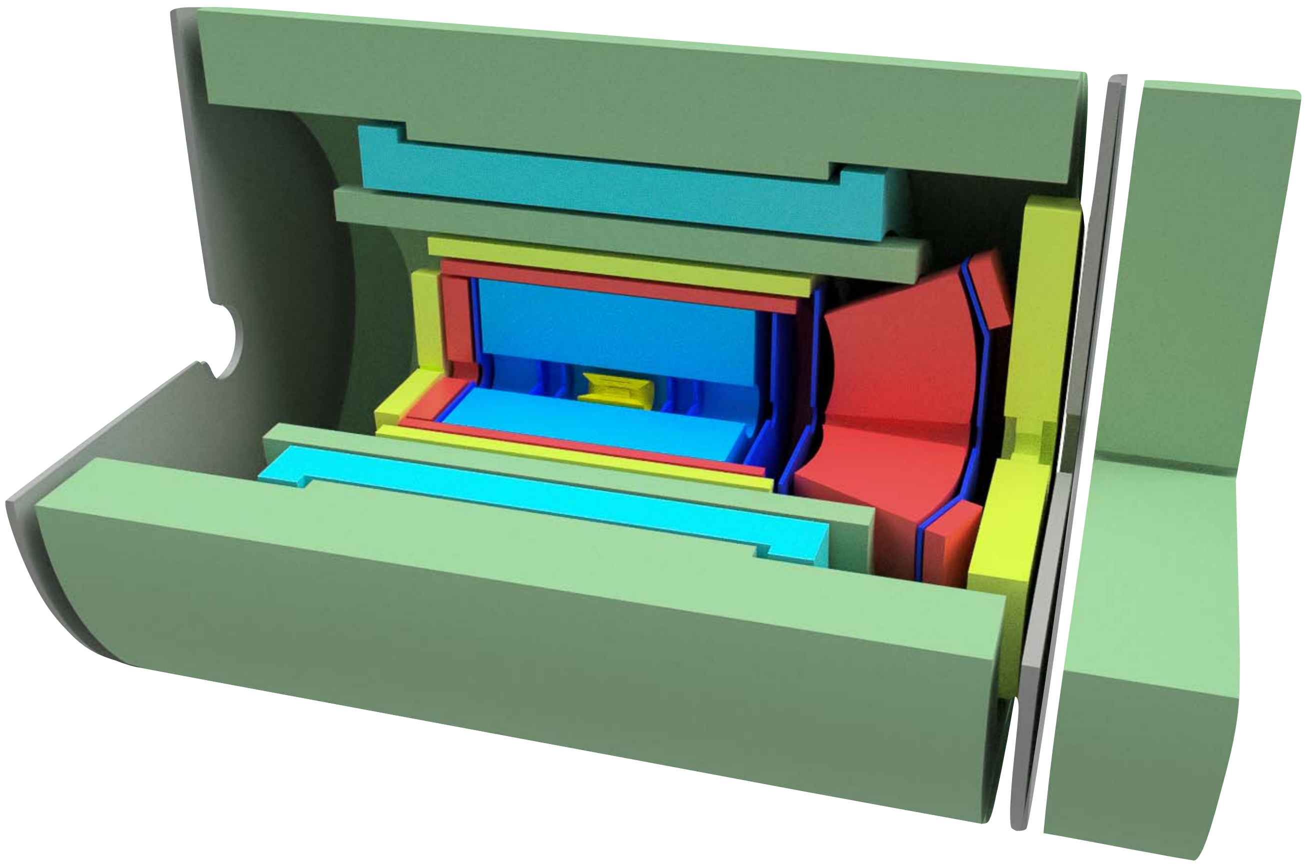
Demonstrates wide range of physics opportunities with MIE detector

Forward sPHENIX



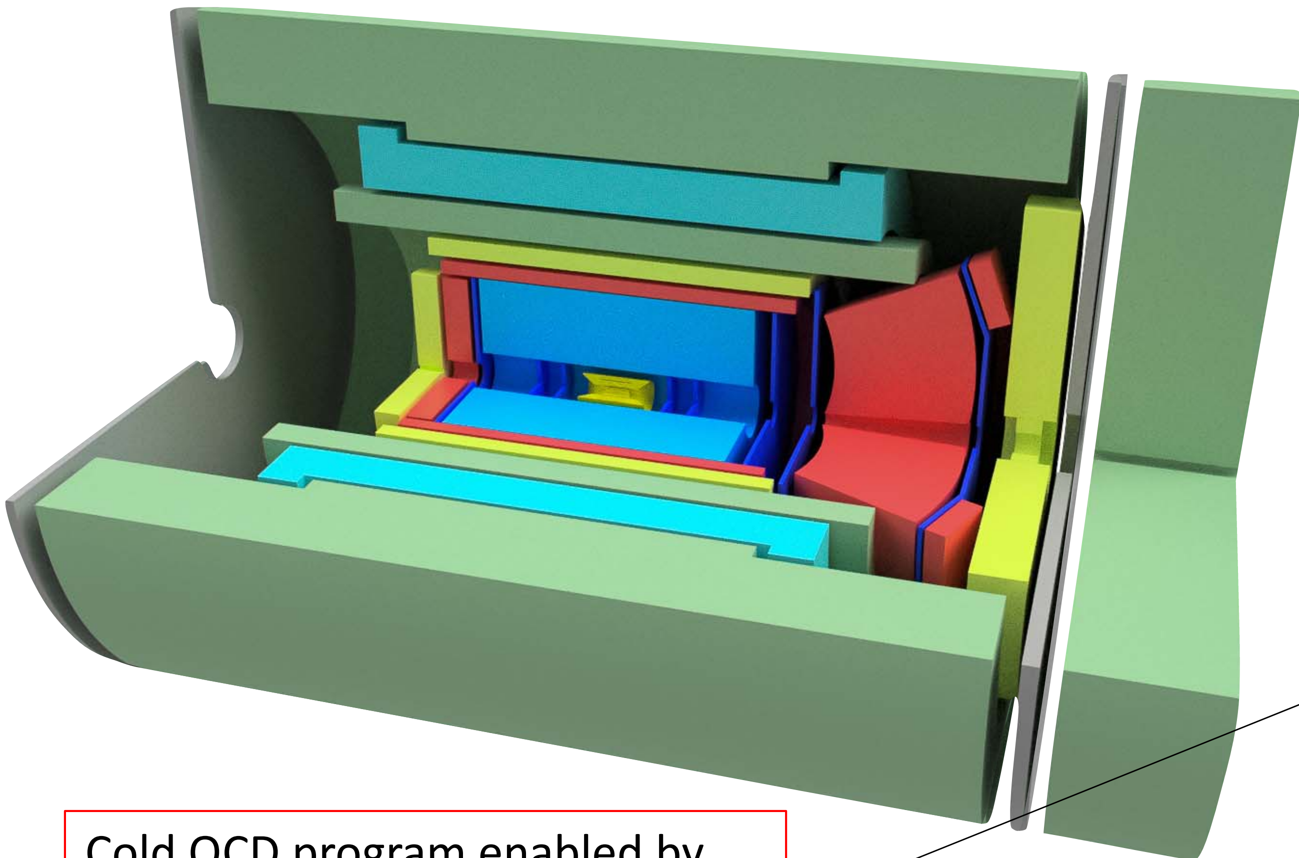
- sPHENIX
  - HCal/Flux return
  - Solenoid
  - Central EMCal
  - Silicon strip tracking
  - TPC
  - MAPS

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



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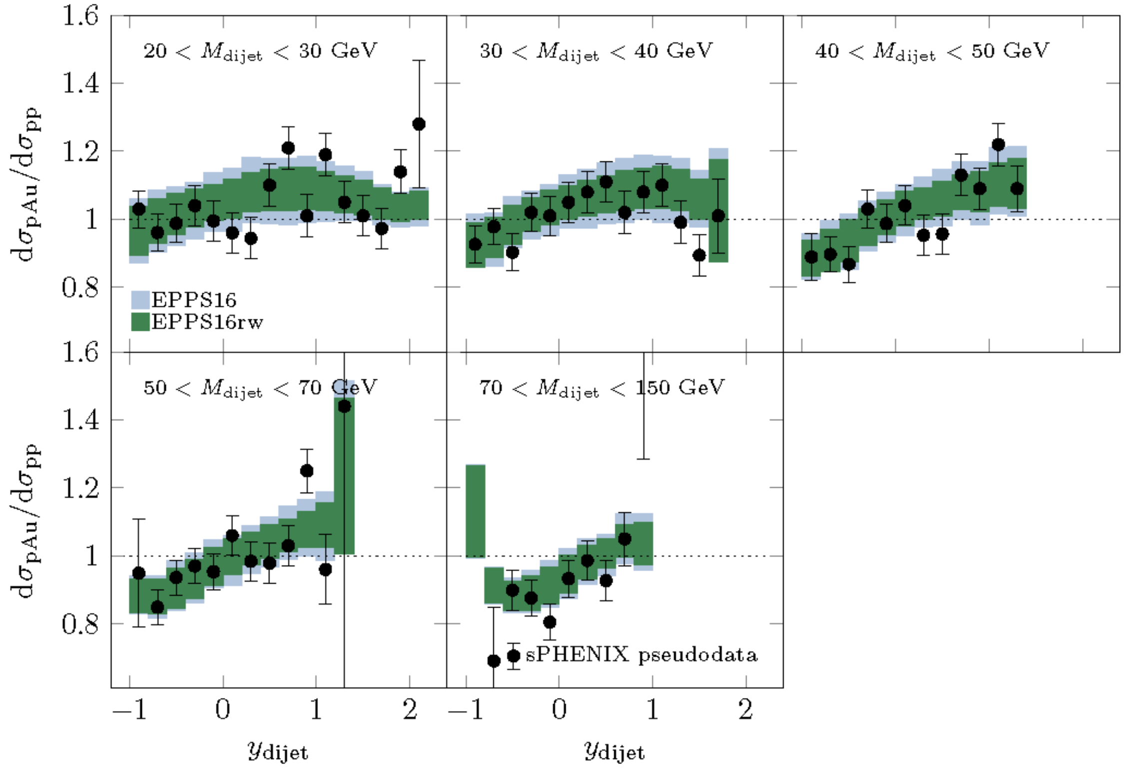
Cold QCD program enabled by early realization of some EIC-sPHENIX detector components!

Multiple Datasets…

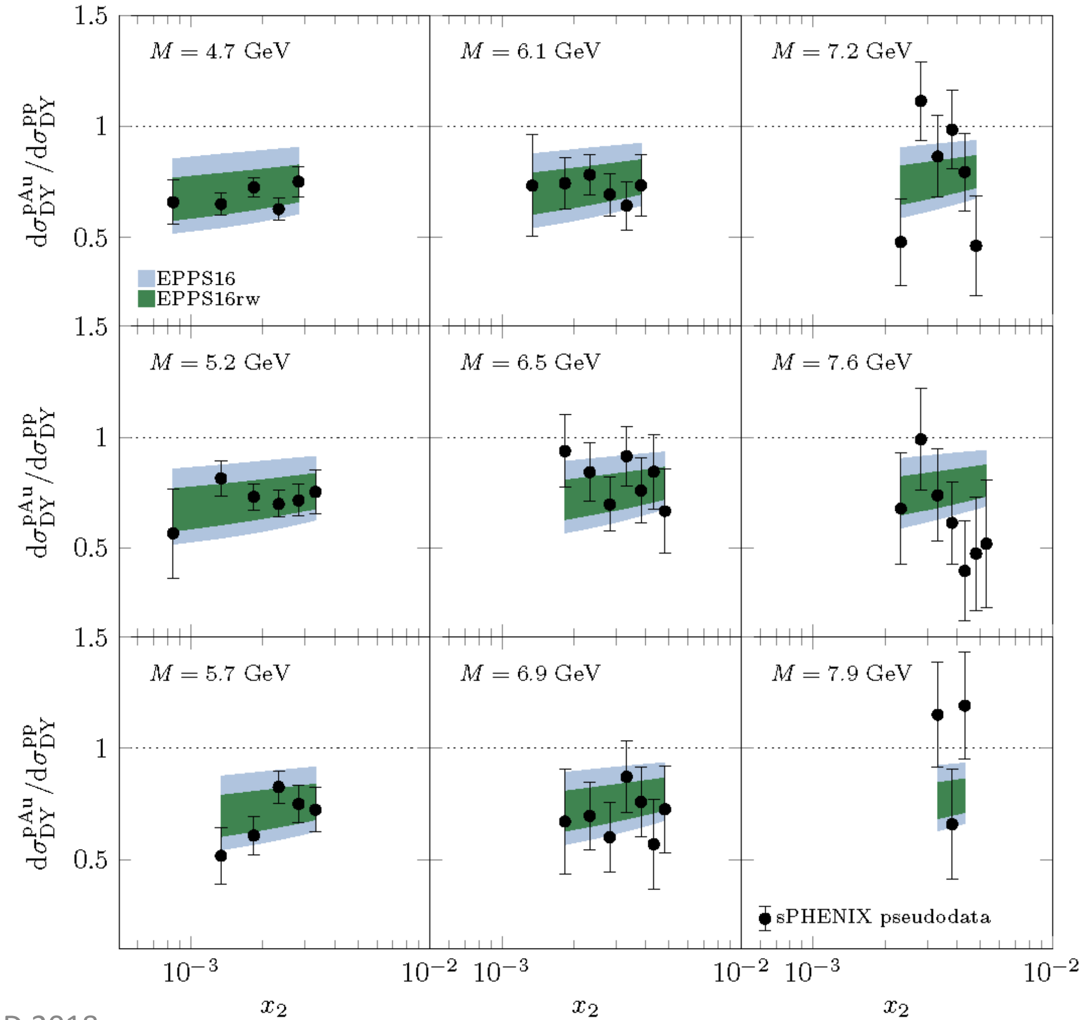
Can we use multiple datasets (with similar systematics) to overcome the normalization limitation?

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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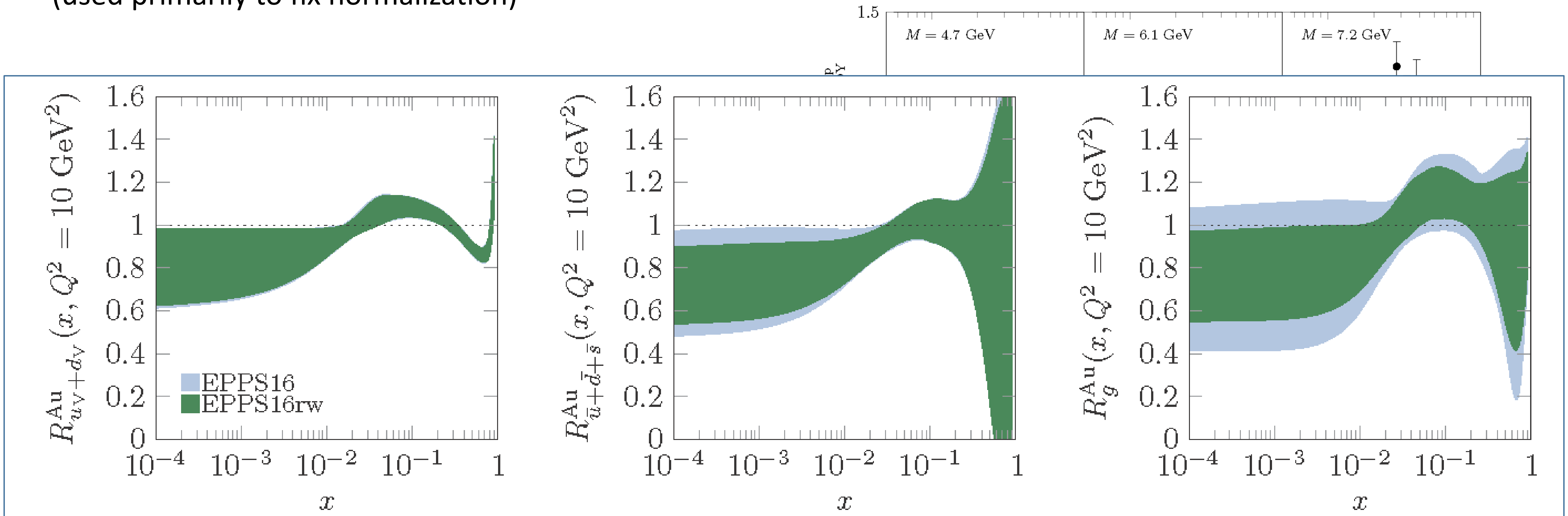
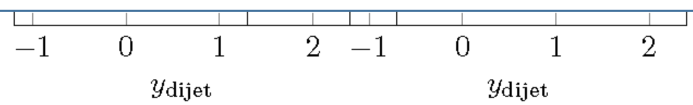




EPPS16 reweighting by H. Paukunen and P. Paakkinen

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

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

BACKUP

Growth of collaboration since CD-0

2016

2017

2018

Broad expertise in relevant physics, silicon, TPCs, calorimetry

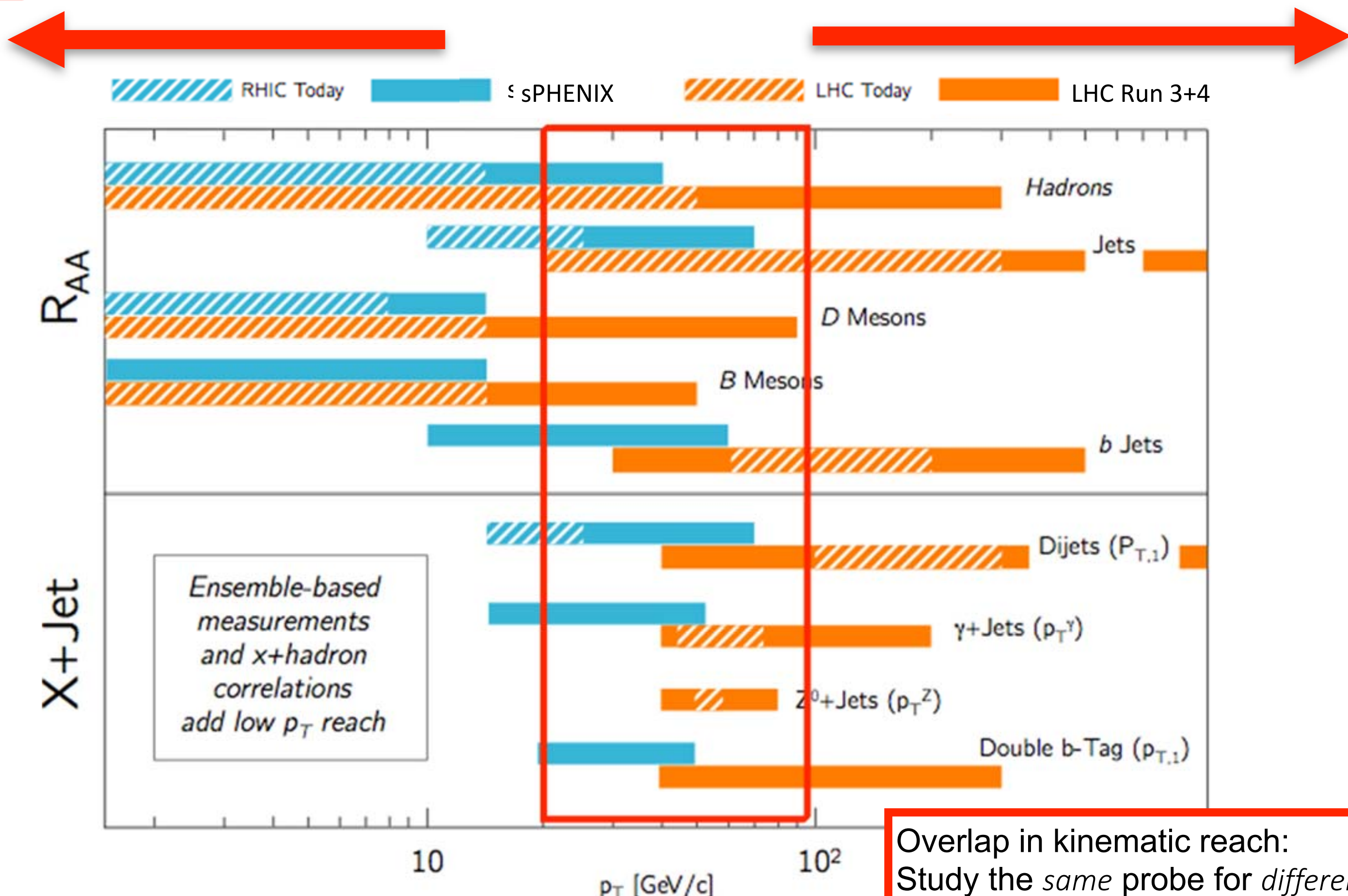
Complementarity of RHIC and LHC

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

A Comprehensive nPDF Program…

- Existing RHIC data will provide some info to the nPDF global fits…
- Real progress will require comprehensive set of measurements made with the same detector, in the same run, with the same MB trigger conditions…
  - Of course, two detectors doing complementary things would allow for a suite of systematic crosschecks

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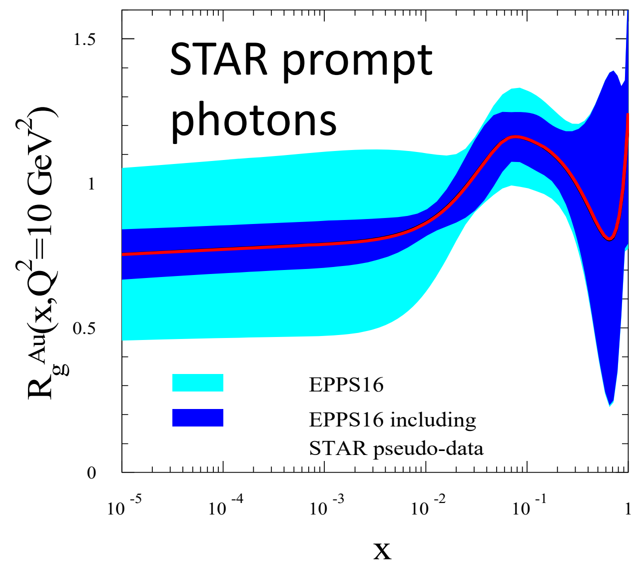

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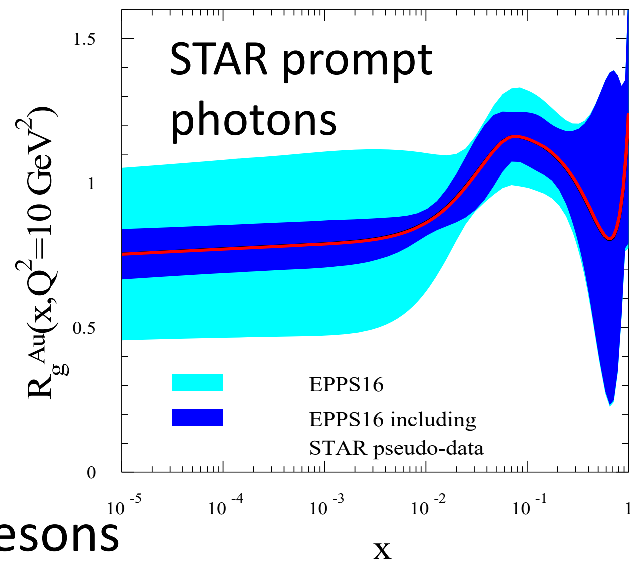

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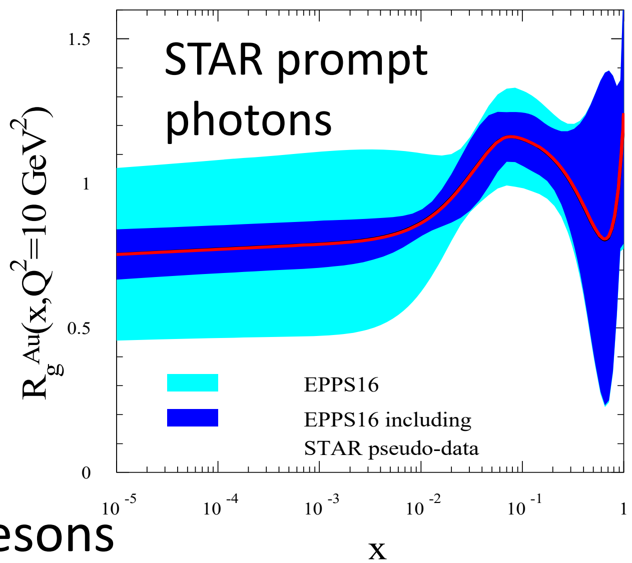
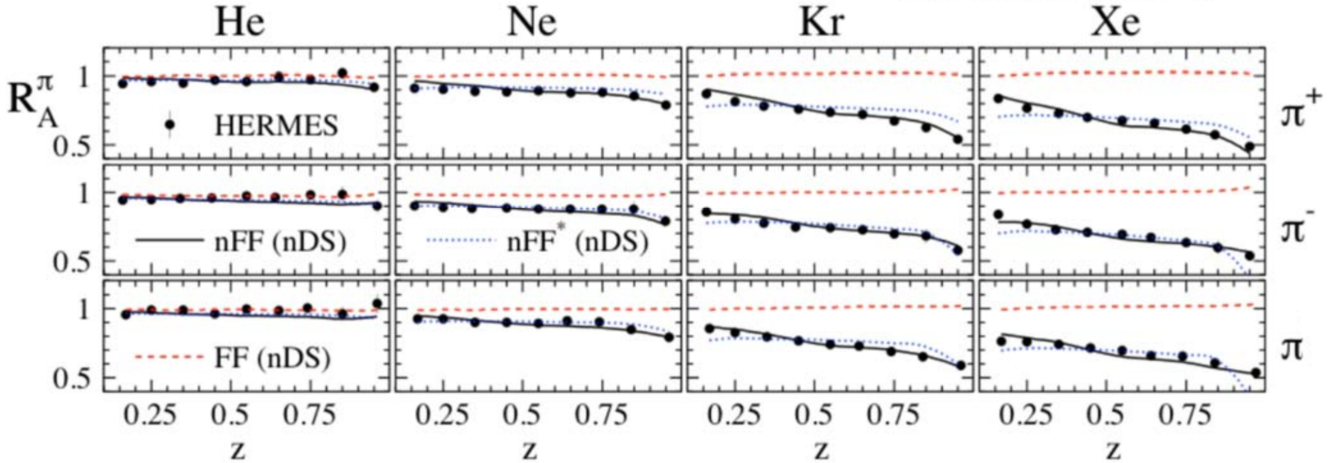
A comprehensive p+A program at RHIC, with already planned running time, could make significant progress in improving our understanding of nPDF's!



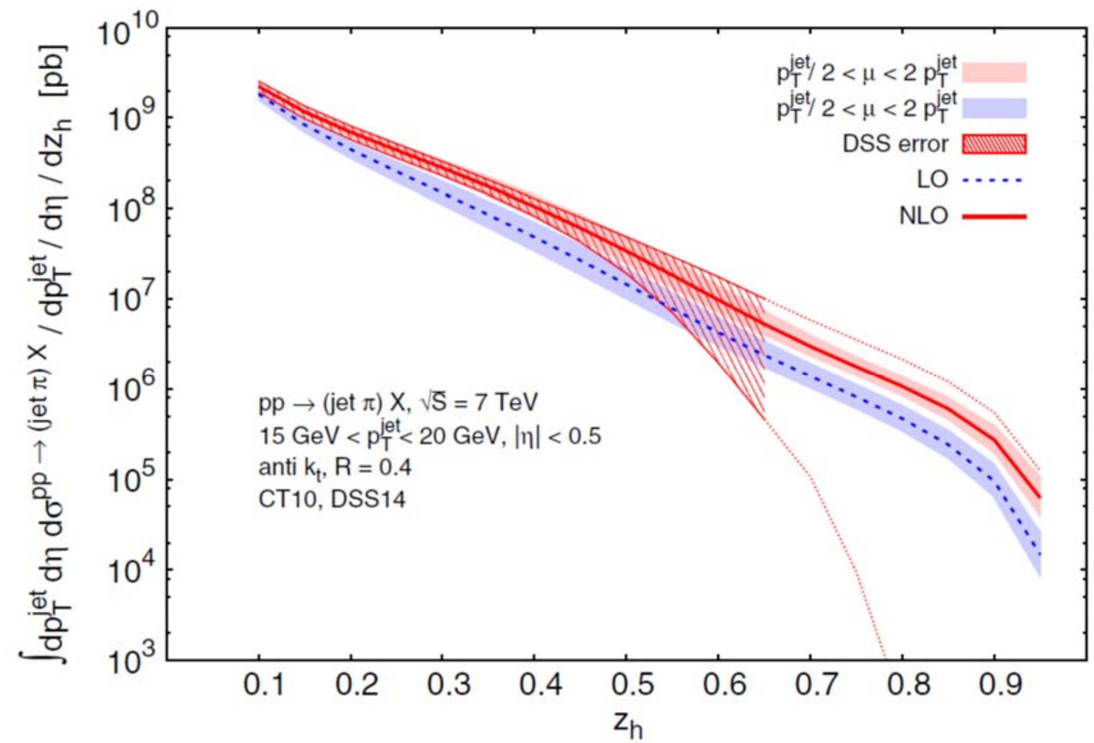
Fragmentation in a Nuclear Environment

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

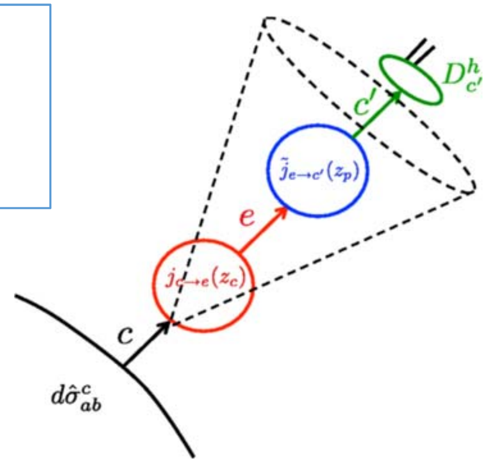


Hadron production in e+A suppressed compared to e+p – must be a fragmentation effect!

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



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



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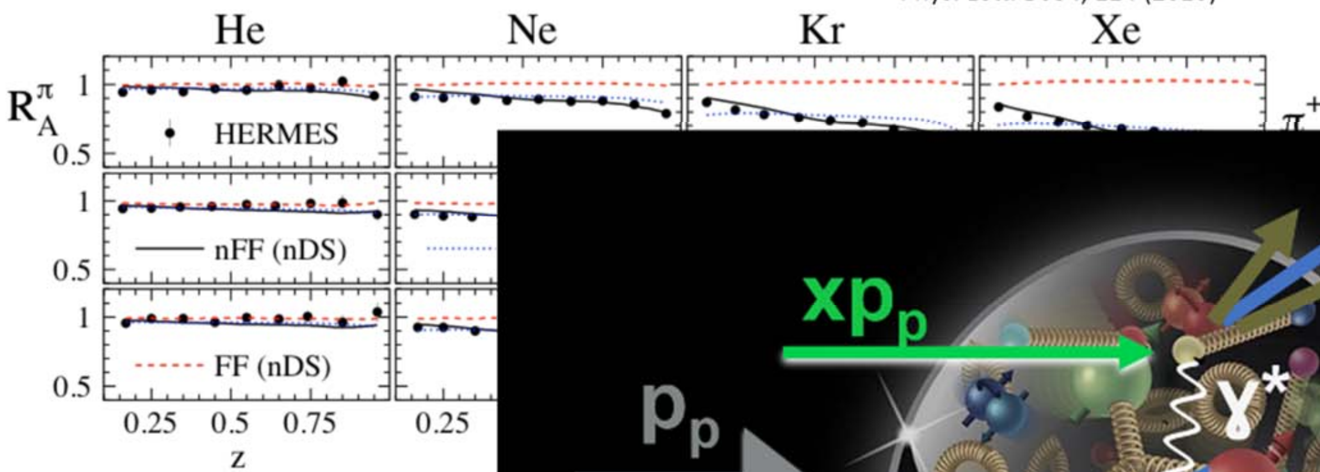

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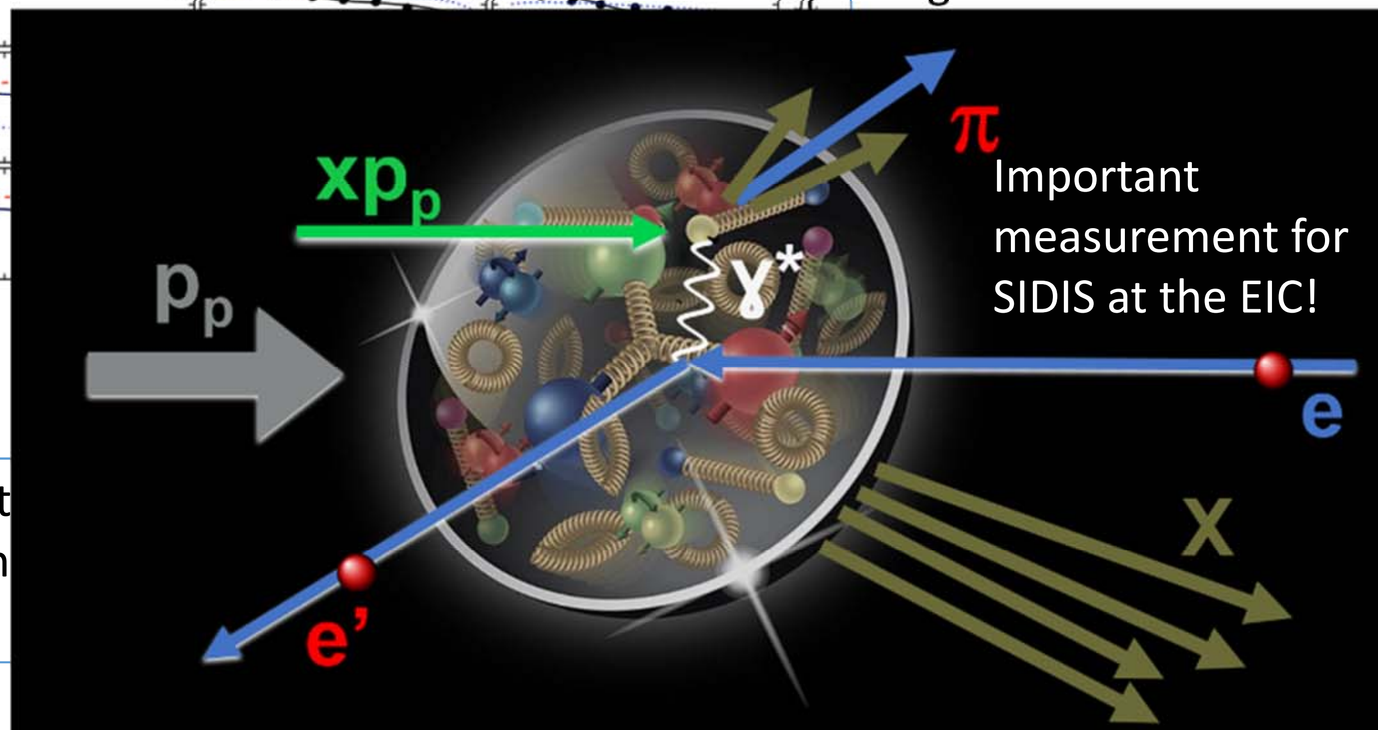
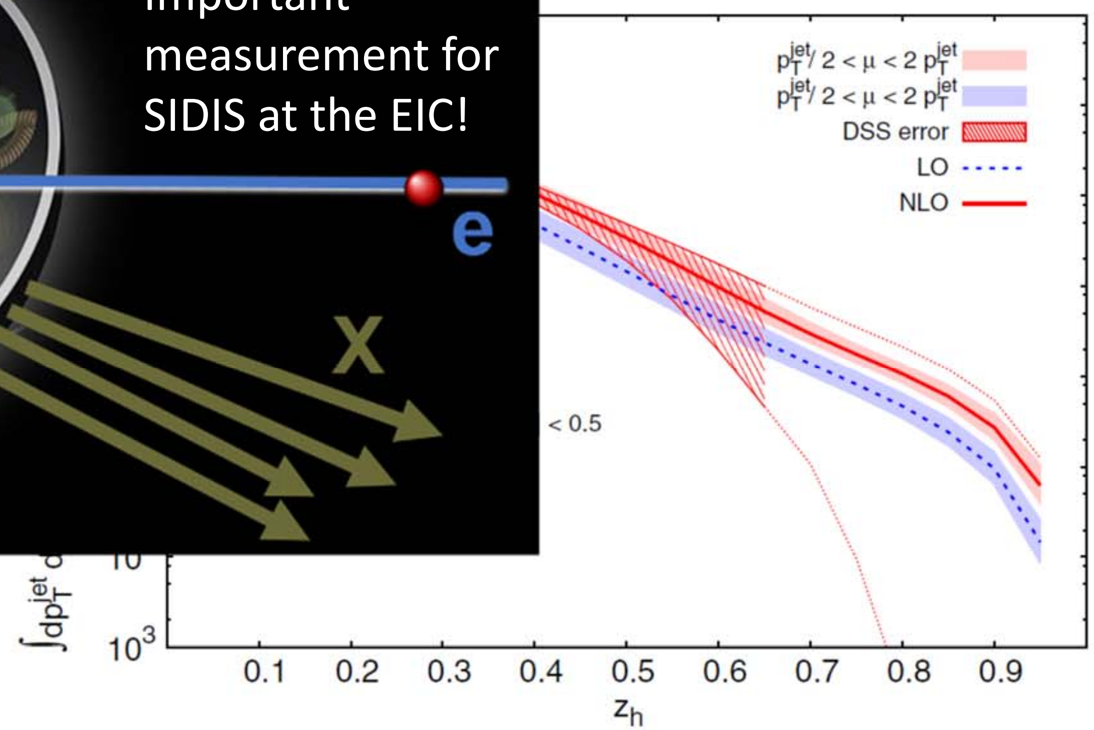


VogelsangPhys.Rev.D 92 5, 054015



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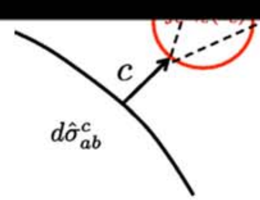


Multi-year run plan for sPHENIX

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}

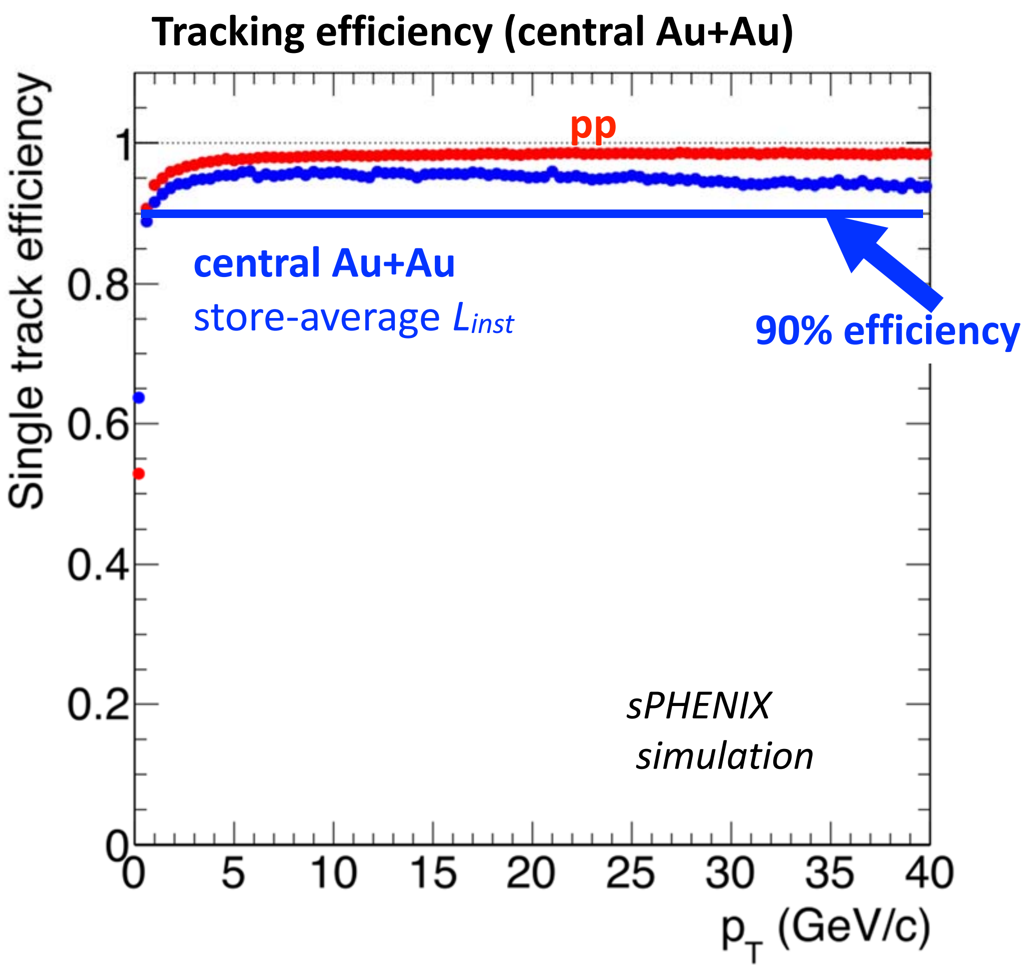
- Consistent with DOE CD-0 “mission need” document
- Incorporates BNL C-AD guidance on luminosity evolution
- Incorporates commissioning time in first year

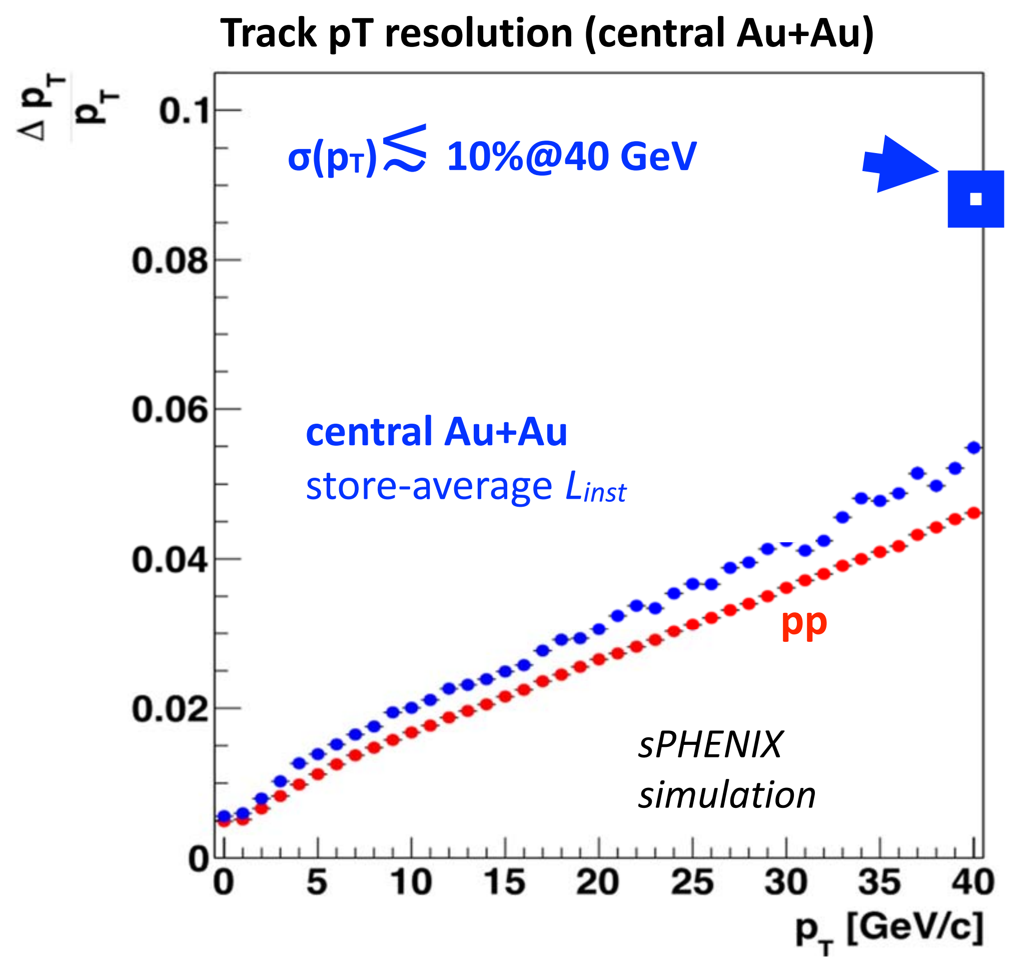
Minimum bias Au+Au at 15 kHz for $|z| < 10$ cm:

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

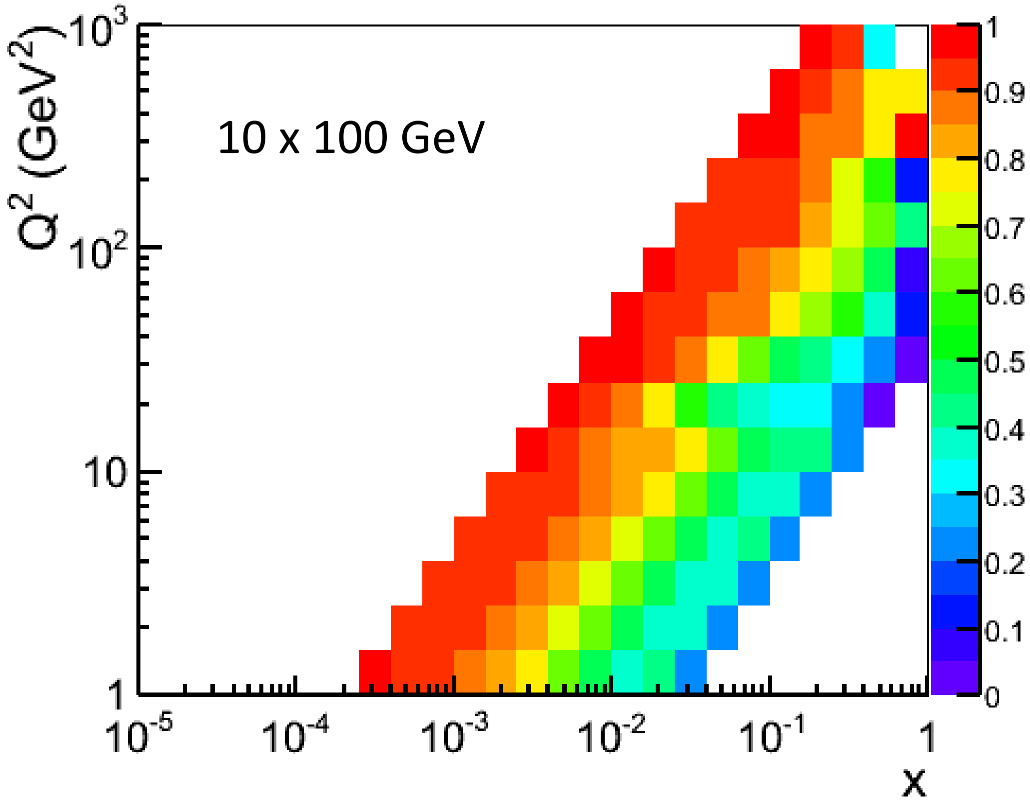
For topics with Level-1 selective trigger (e.g. high p_T photons), one can sample within $|z| < 10$ cm a total of 550 billion events.

Tracking efficiency and resolution





Inclusive DIS: x, Q2 resolution based on scattered electron detection sufficient for EIC science program

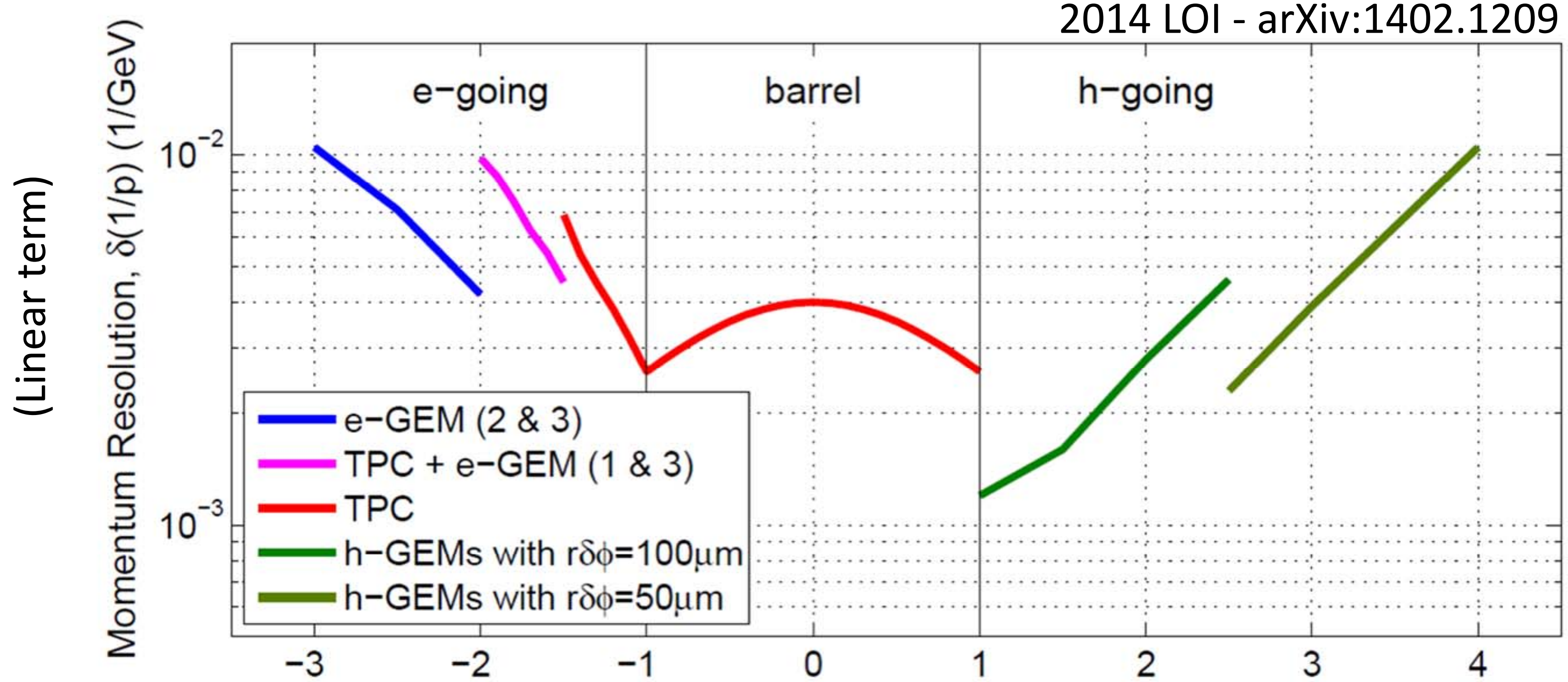


Precise recovery of event kinematics from smearing effects possible using unfolding.

Fraction of events reconstructed in correct x, Q^2 bin

Continuous tracking from -4 < η < 4

2014 LOI - arXiv:1402.1209



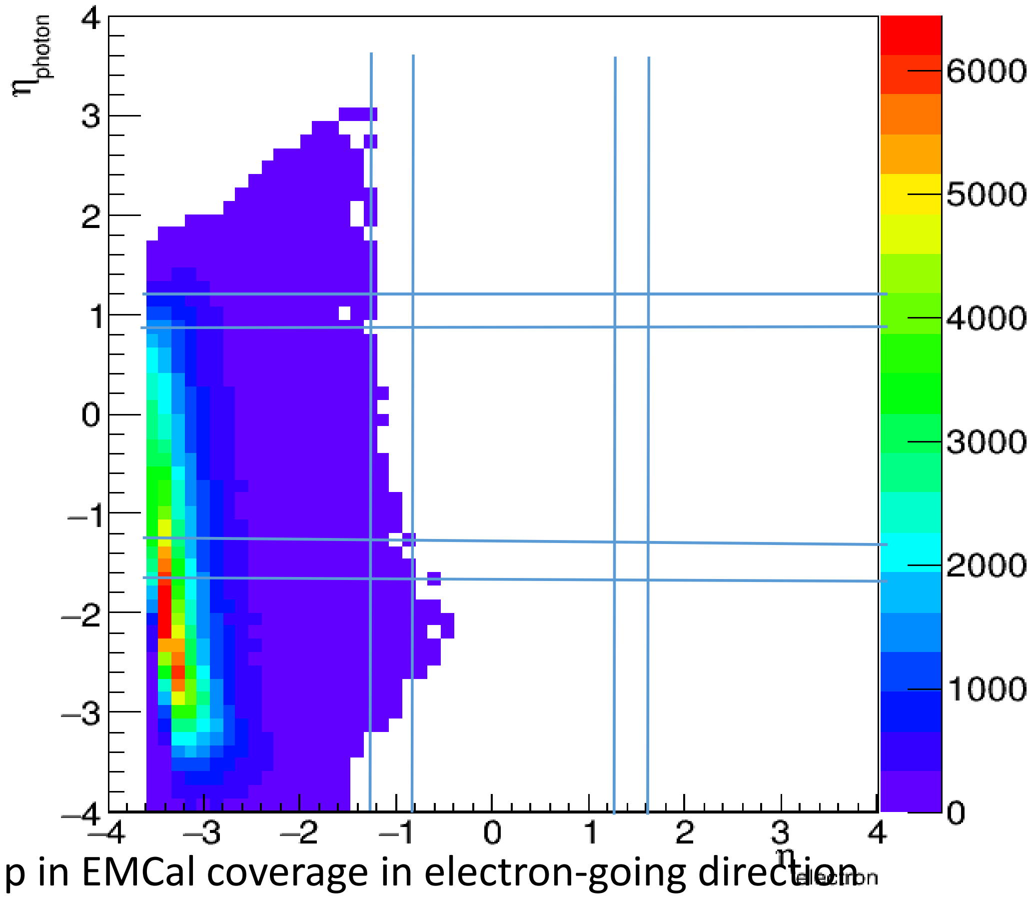
Since 2014 LOI:

- Full GEANT4 simulations now
  - Forward/backward pattern recognition from truth hits, then Kalman filter for fitting
- Extended backward tracking to η = -4

- Improved TPC resolution based on sPHENIX design
- MVTX added
- 5 forward GEM stations now rather than 3

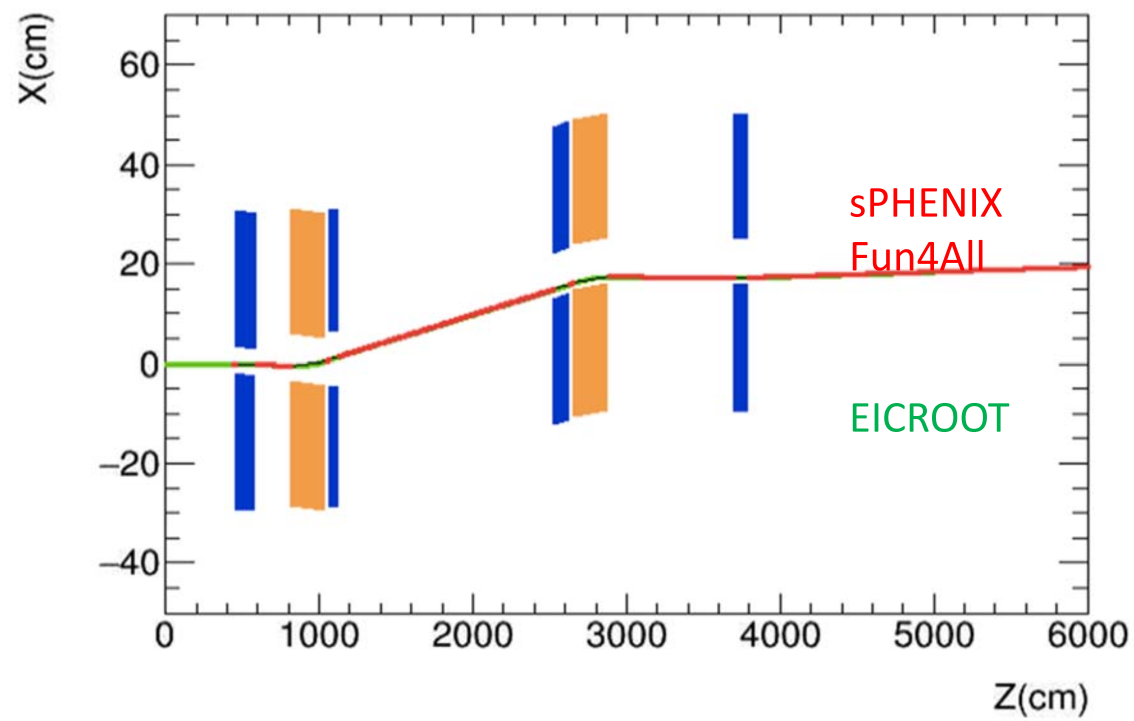
Calorimeter coverage to η= -4 captures all DVCS photons

18 x 275 GeV $1 < Q^2 < 100$ GeV^2



Gap in EMCal coverage in electron-going direction would impact photon detection in particular

- less for higher energy electron beam



Detection of scattered (intact) proton

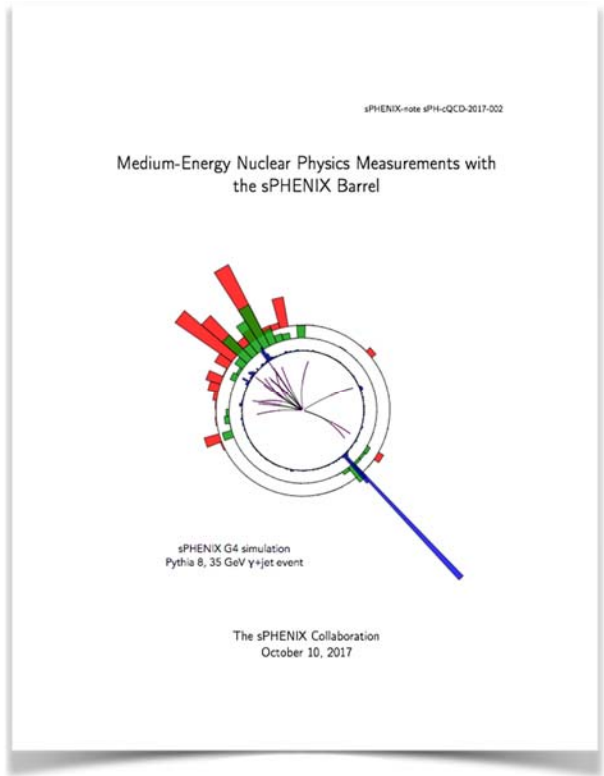
- Beam line dipoles and quadrupoles included in GEANT

Calorimeter coverage $-4 < \eta < 4$

$-4 < \eta < -1.55$	$PbWO_4$	2 cm x 2 cm	$\frac{2.5\%}{\sqrt{E}} \oplus 1\%$
$-1.55 < \eta < 1.24$	W-SciFi	0.025 x 0.025	$\frac{16\%}{\sqrt{E}} \oplus 5\%$
$1.24 < \eta < 3.3$	PbScint	5.5 cm x 5.5 cm	$\frac{8\%}{\sqrt{E}} \oplus 2\%$
$3.3 < \eta < 4$	$PbWO_4$	2.2 cm x 2.2 cm	$\frac{12\%}{\sqrt{E}}$
$-1.1 < \eta < 1.1$	Fe Scint + Steel Scint	0.1 x 0.1	$\frac{81\%}{\sqrt{E}} \oplus 12\%$
$-1.24 < \eta < 5$	Fe Scint	10 cm x 10 cm	$\frac{70\%}{\sqrt{E}}$

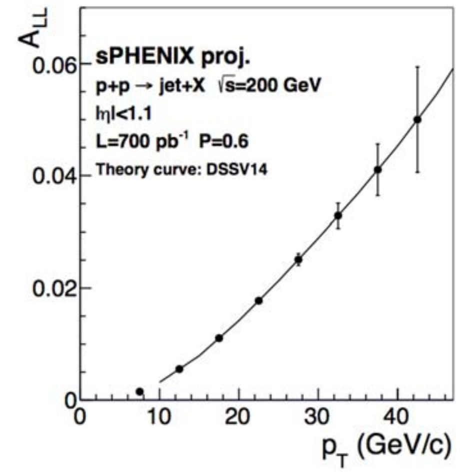
Cold QCD with sPHENIX barrel

Charge from ALD, delivered 10/2017

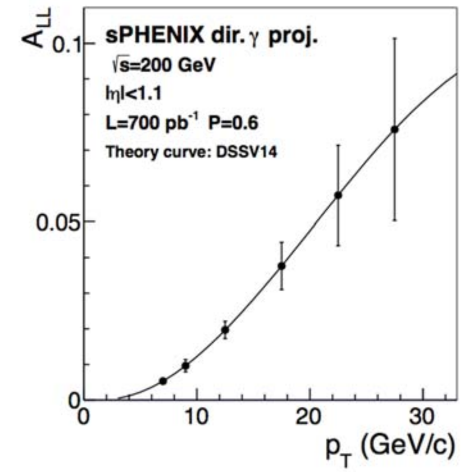


Projected capabilities for observables in longitudinally, transversely polarized collisions, nPDFs

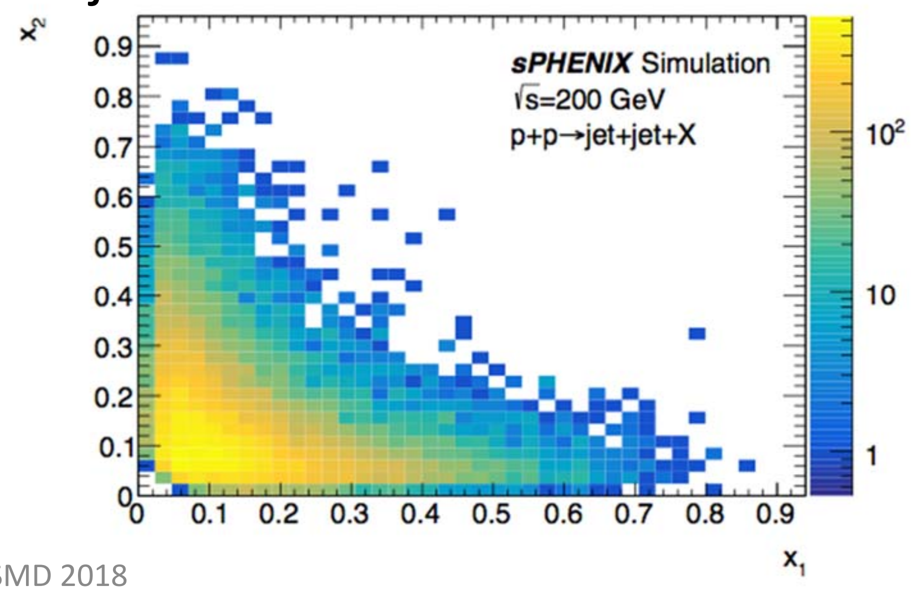
jet A_{LL}



direct γ A_{LL}

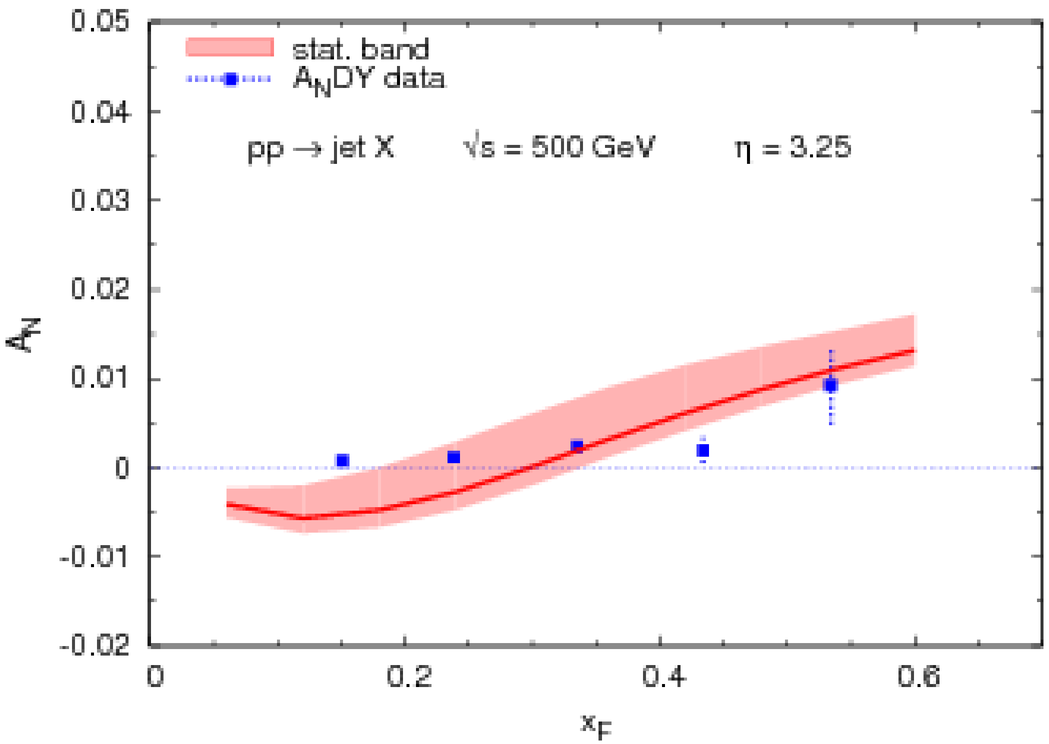


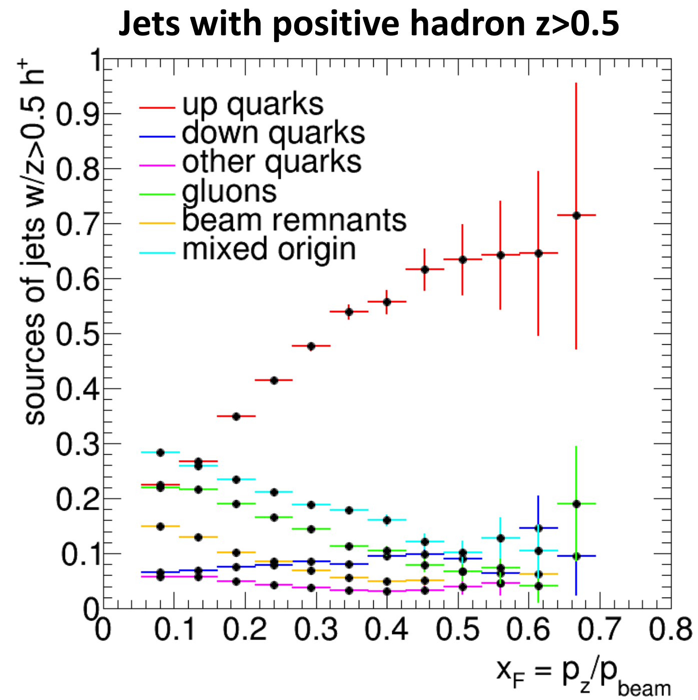
dijet kinematics in sPHENIX barrel

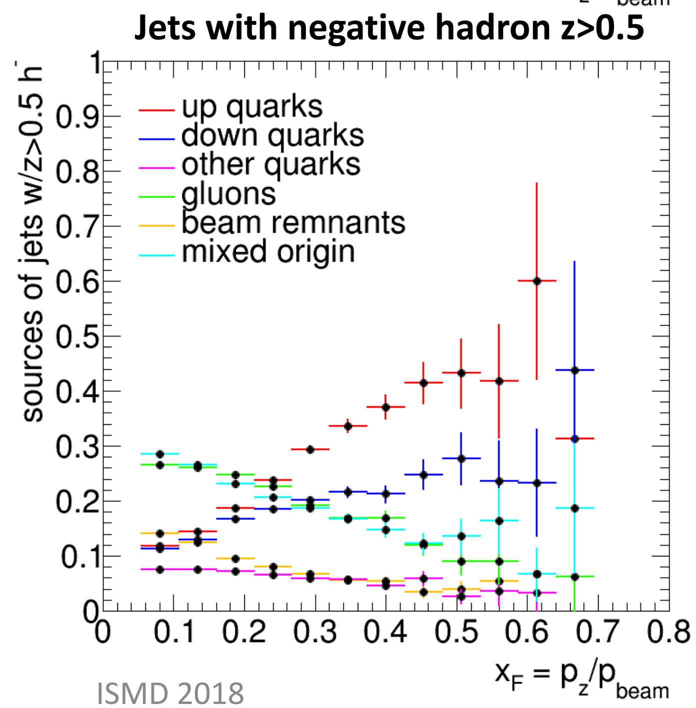


An Unresolved Mystery…

AnDY: Phys. Lett. B750 (2015) 660







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

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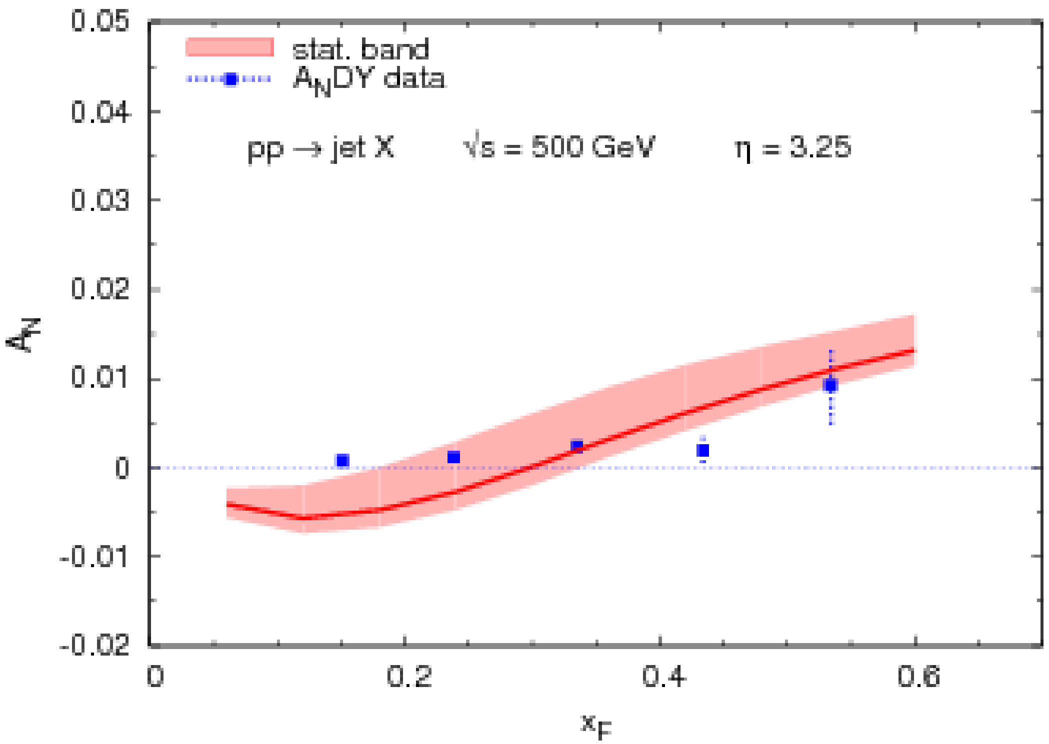

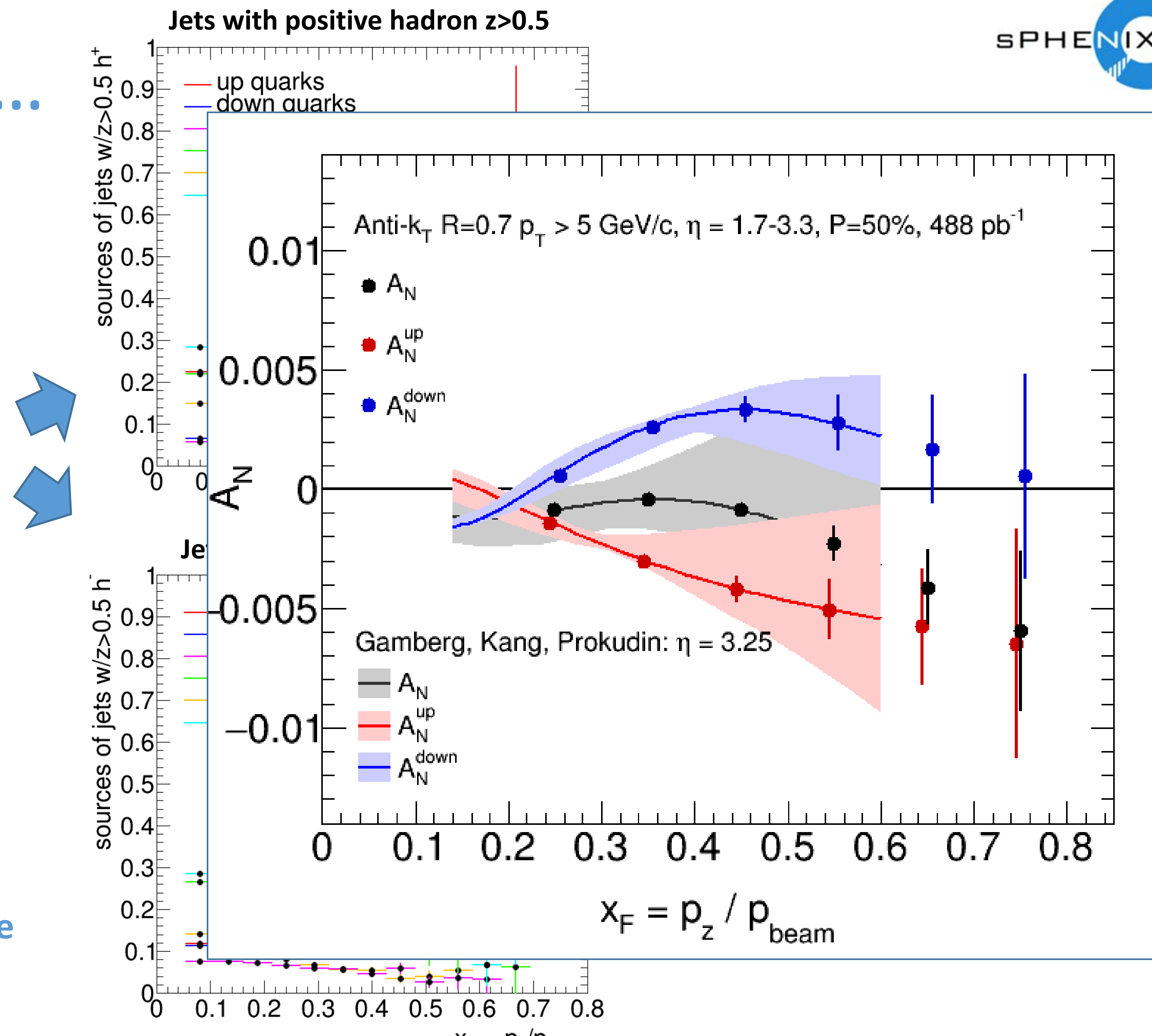

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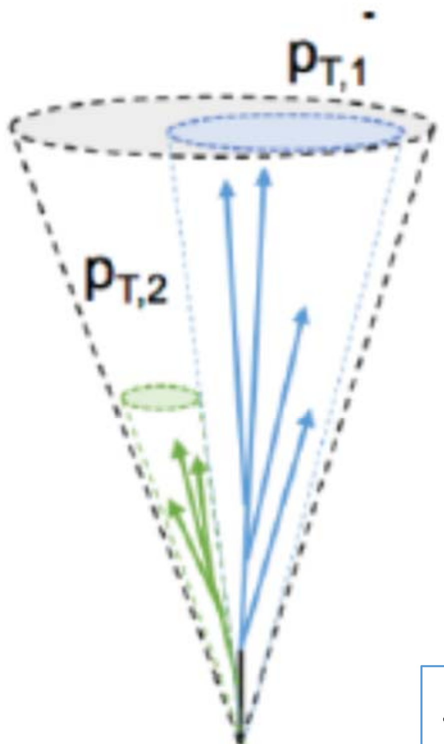
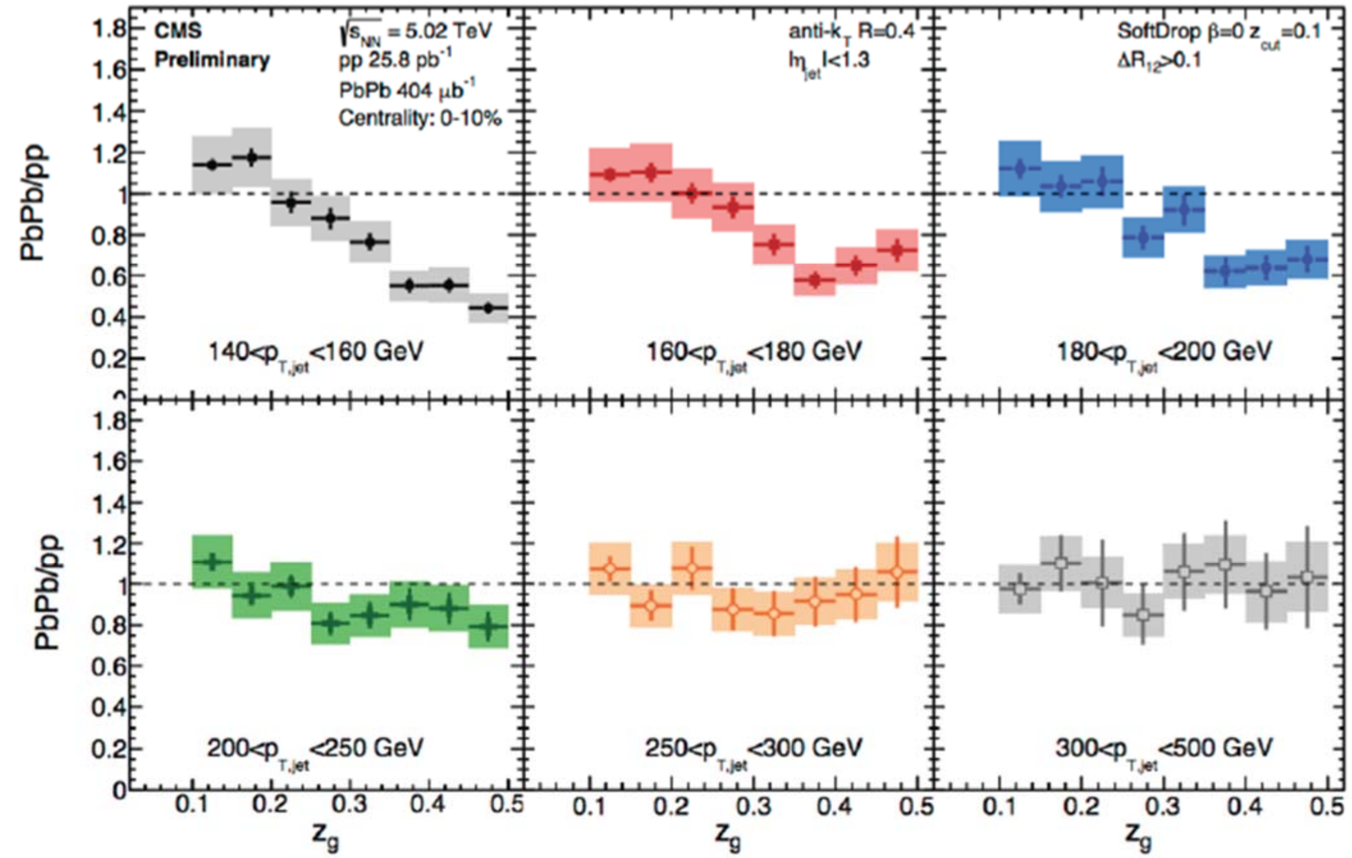
Jet Substructure

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>!