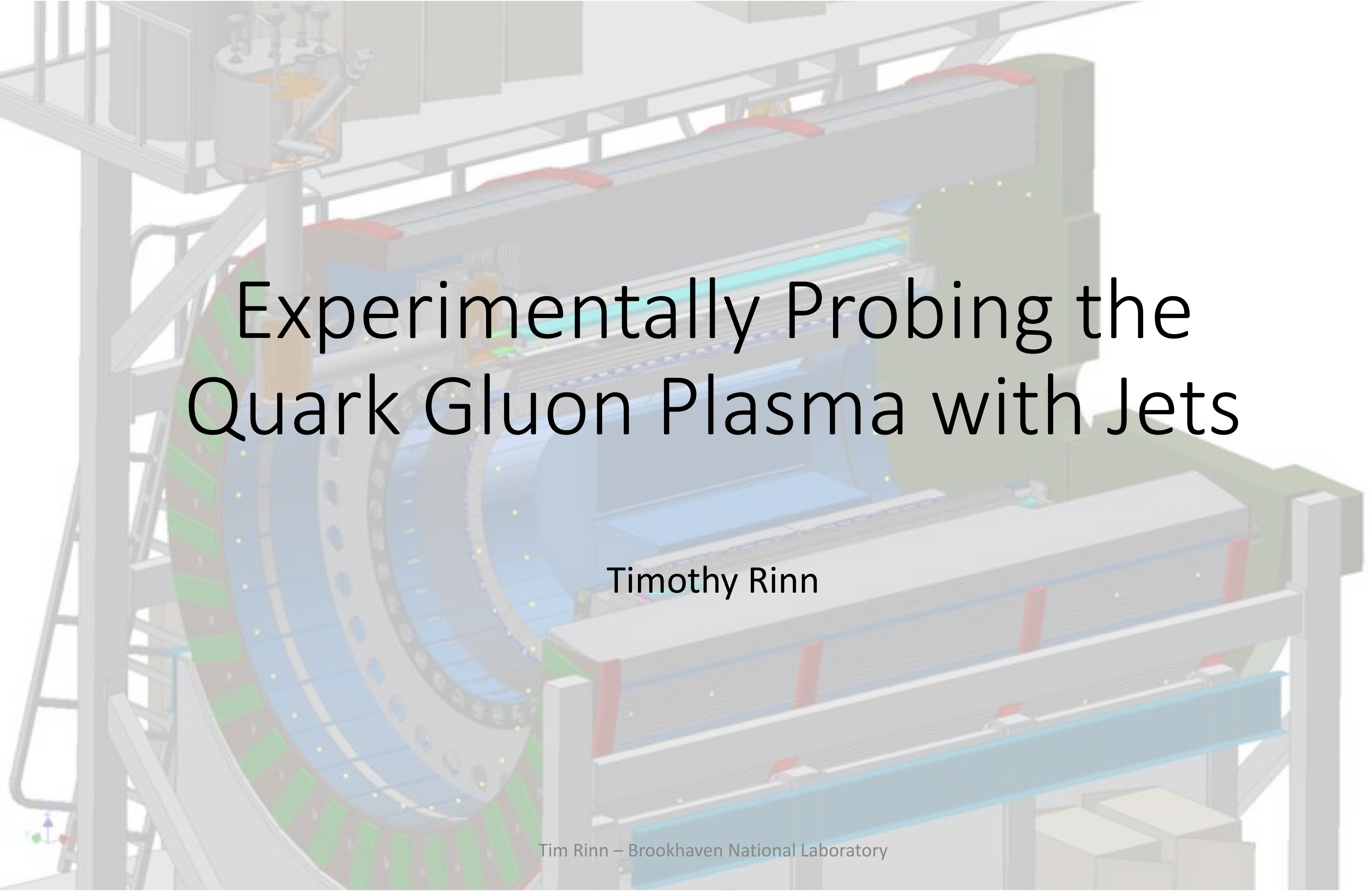
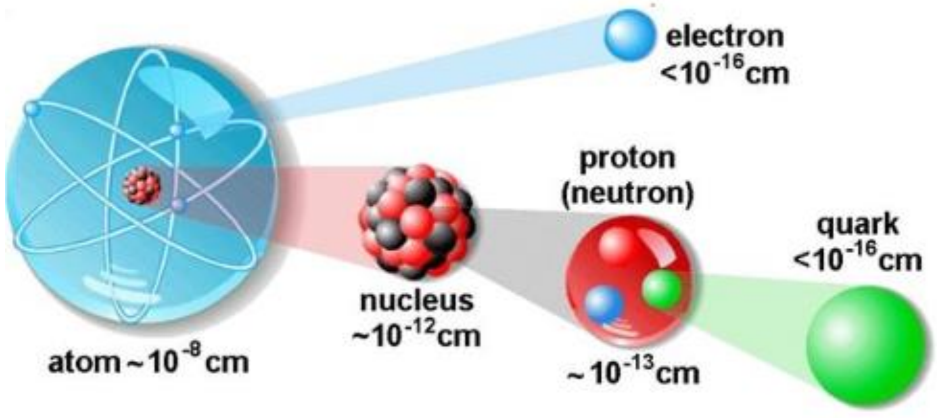
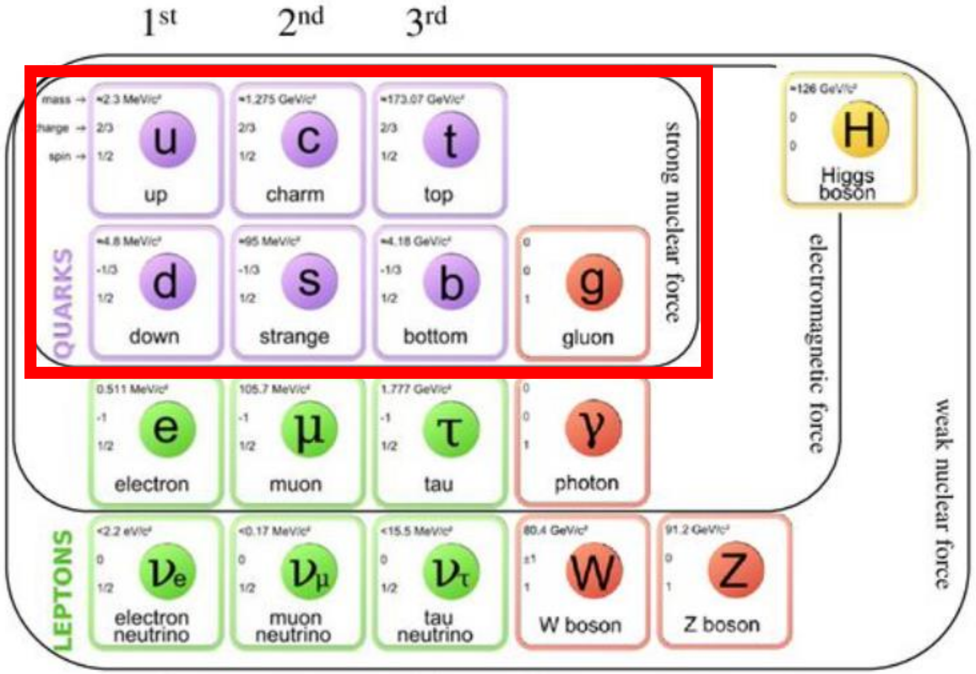


Experimentally Probing the Quark Gluon Plasma with Jets

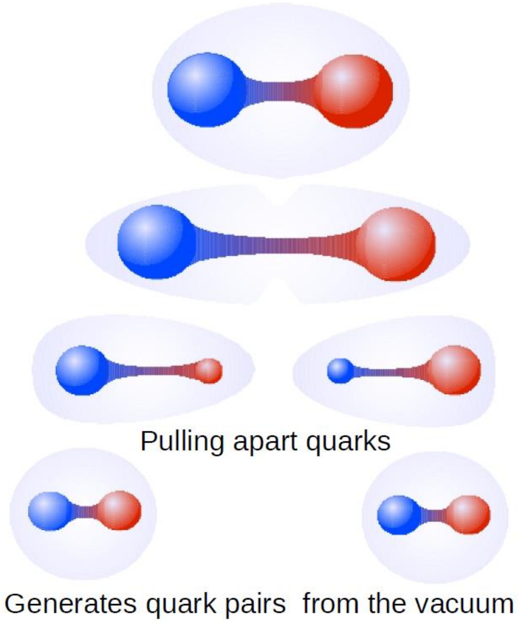
Timothy Rinn

Constituents of Matter





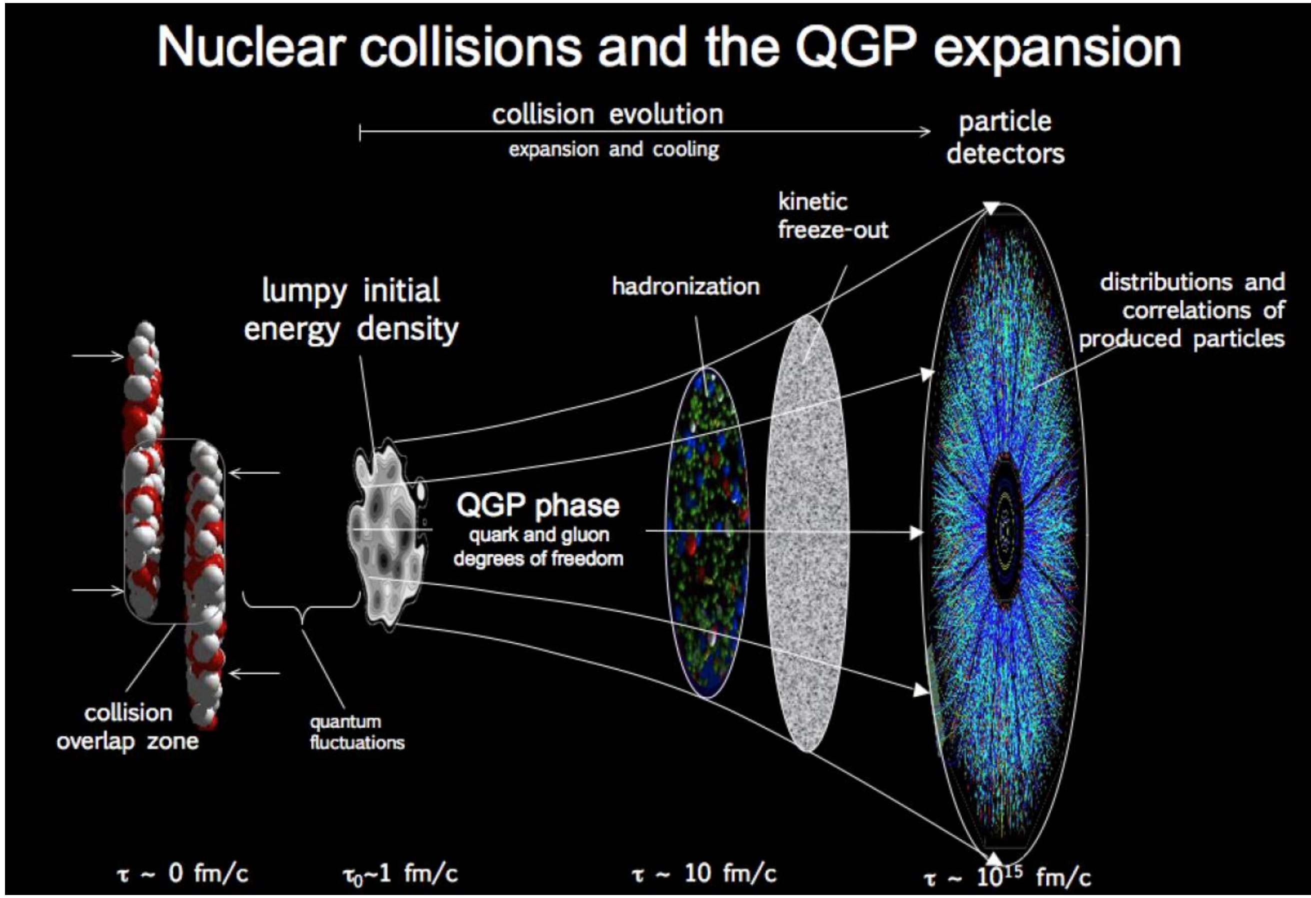
Confinement- quarks stick together

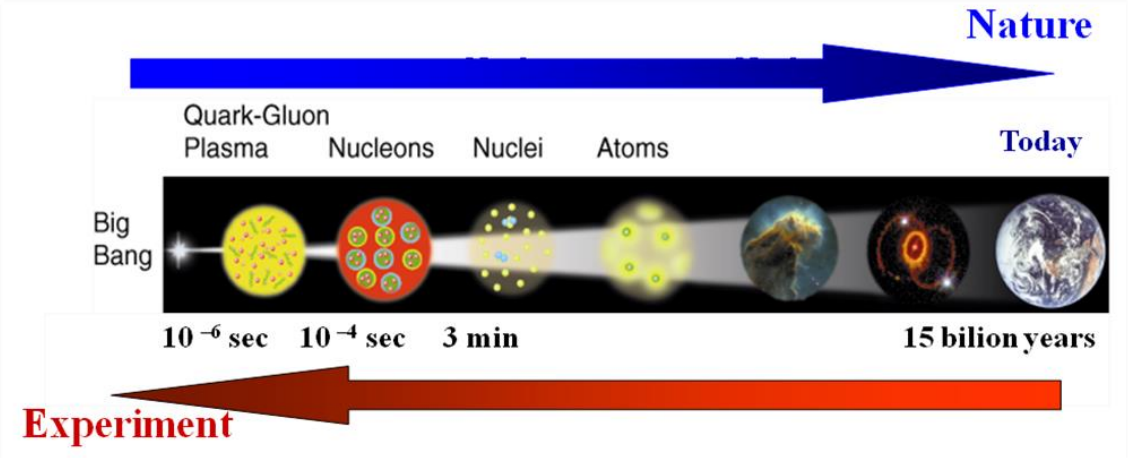


Understanding the properties of the strong force is one of the principal goals of experimental nuclear physics

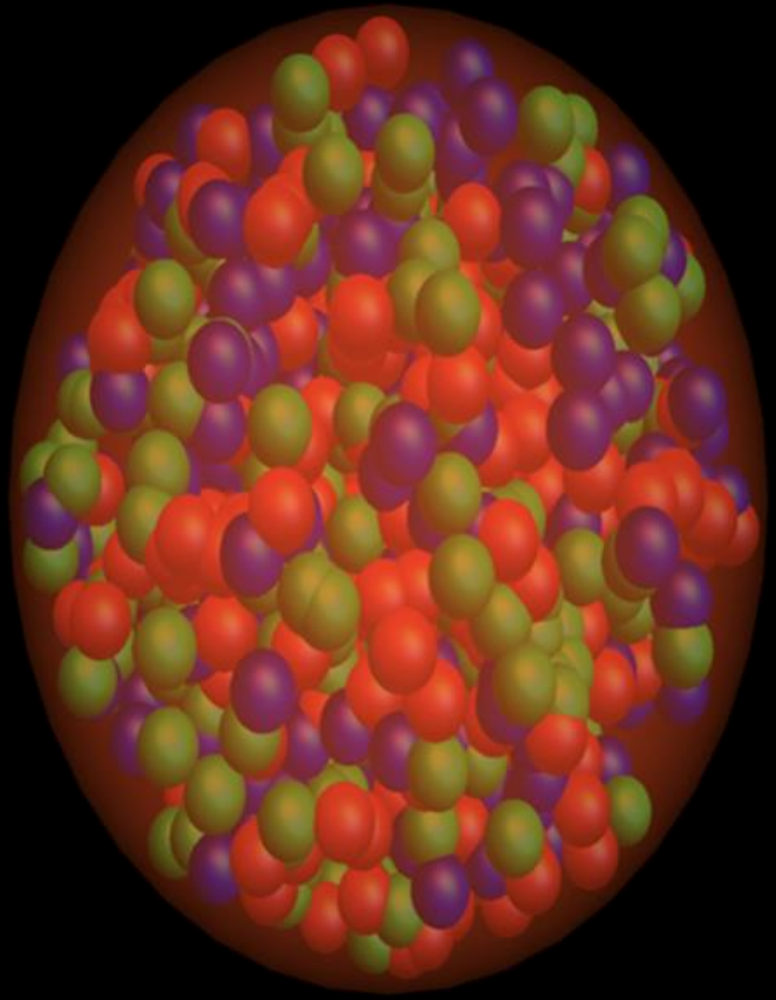
Heavy Ion Collisions

Ultra relativistic Heavy ion collisions enables the creation of a high temperature high density medium in which to study the strong force





The Quark Gluon Plasma (QGP)



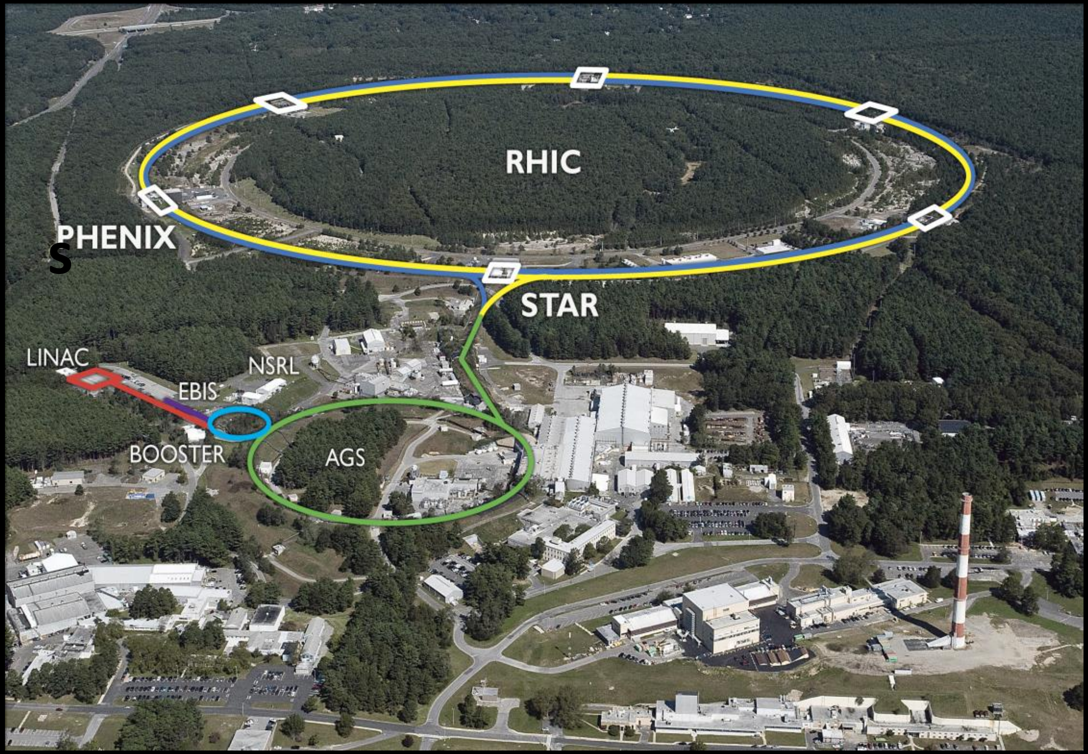
QGP is a phase of matter quarks and gluons form a nearly perfect liquid

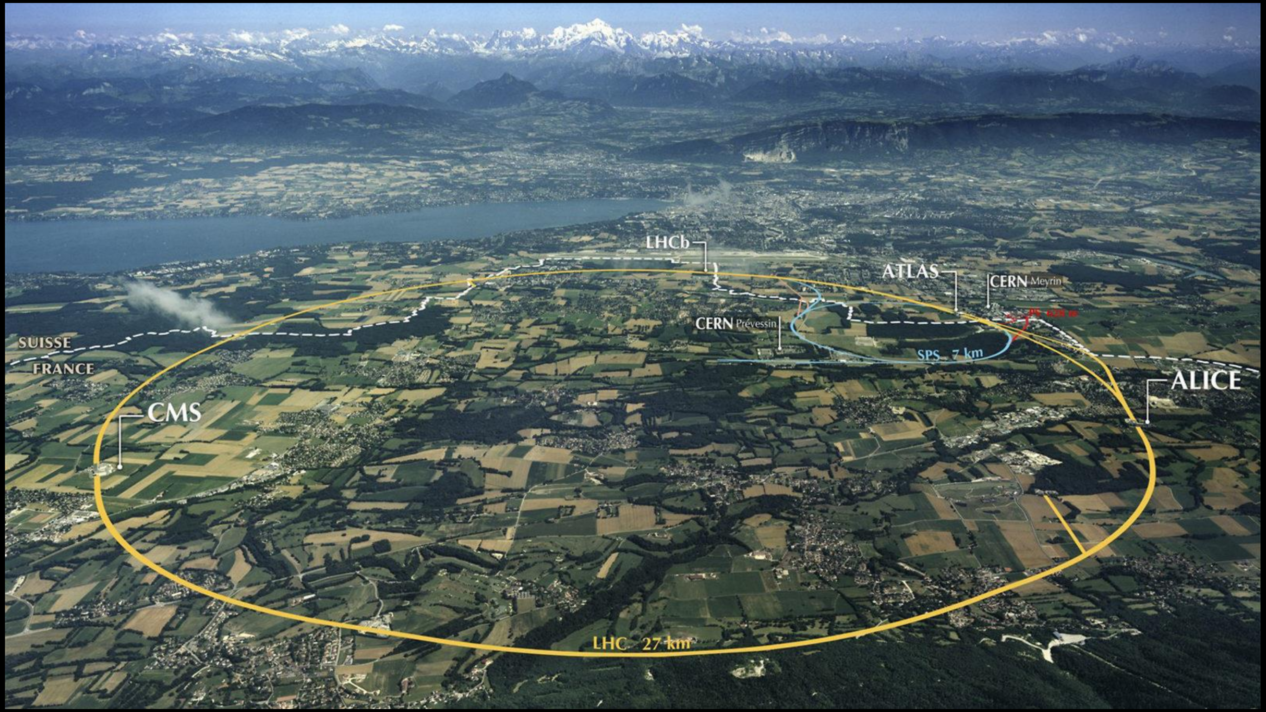
Quarks and gluons are no longer bound together by confinement

Enables studying the properties of the strong force previously hidden behind confinement

How we produce heavy ion collisions

- Two collider facilities!
  - Relativistic Heavy Ion Collider on Long Island New York
  - The Large Hadron Collider at CERN in Switzerland/France





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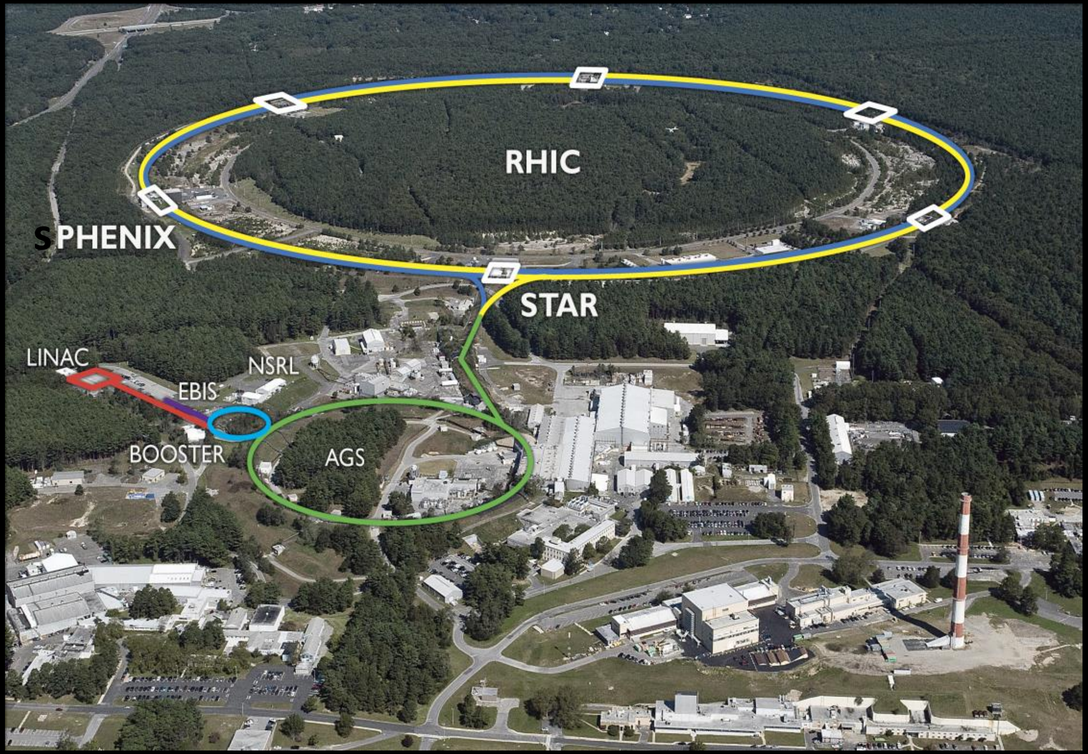


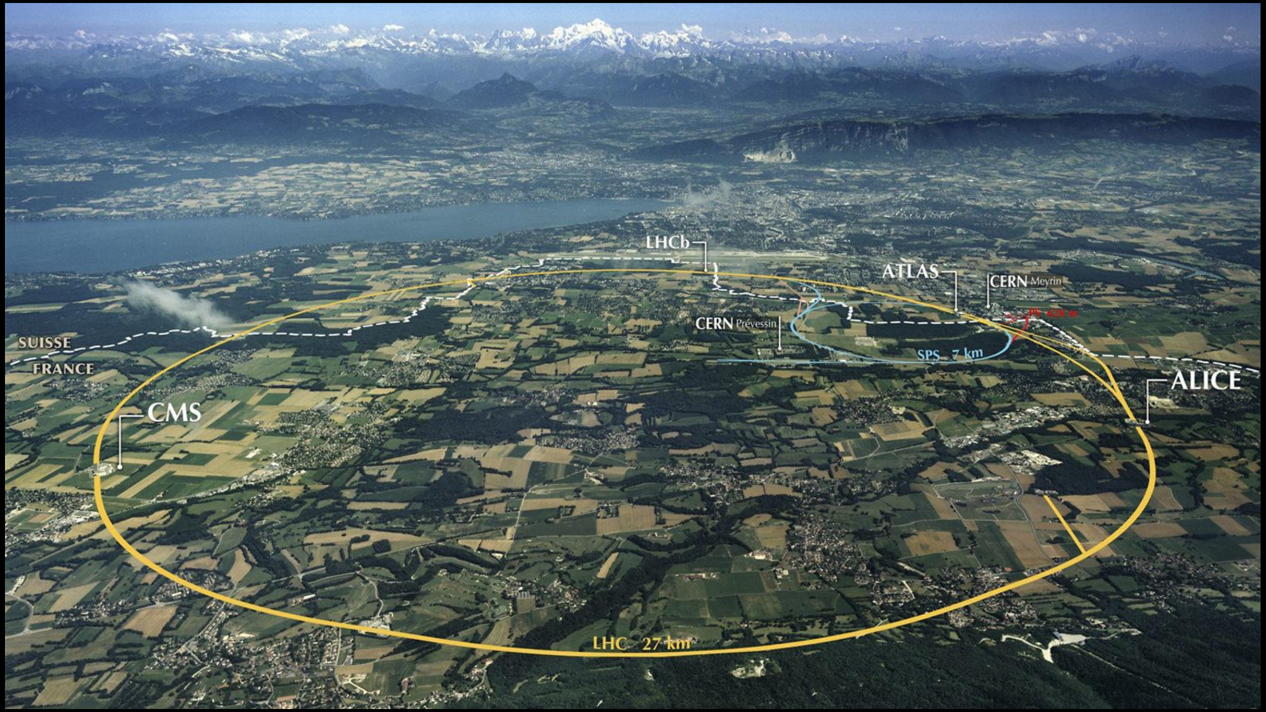
- ➢ Specifically designed for the study of heavy ion collisions
- ➢ Versatile Colliding facility!
  - ➢ Collides a vast range of nuclei:
    - Au+Au, Cu+Cu, d+Au, U+U, p+Au, He^3+Au
  - ➢ Capable of producing transversely polarized proton beams
- ➢ Tunable "low" collision energy of ≤200 GeV
  - ➢ Produces a Quark Gluon Plasma (QGP) with T ~ 220 MeV (1-2 Trillion ℃)

https://arxiv.org/pdf/1308.2440.pdf

How we produce heavy ion collisions

- Two collider facilities!
  - Relativistic heavy Ion Collider on Long Island New York
  - The Large Hadron Collider at CERN in Switzerland/France

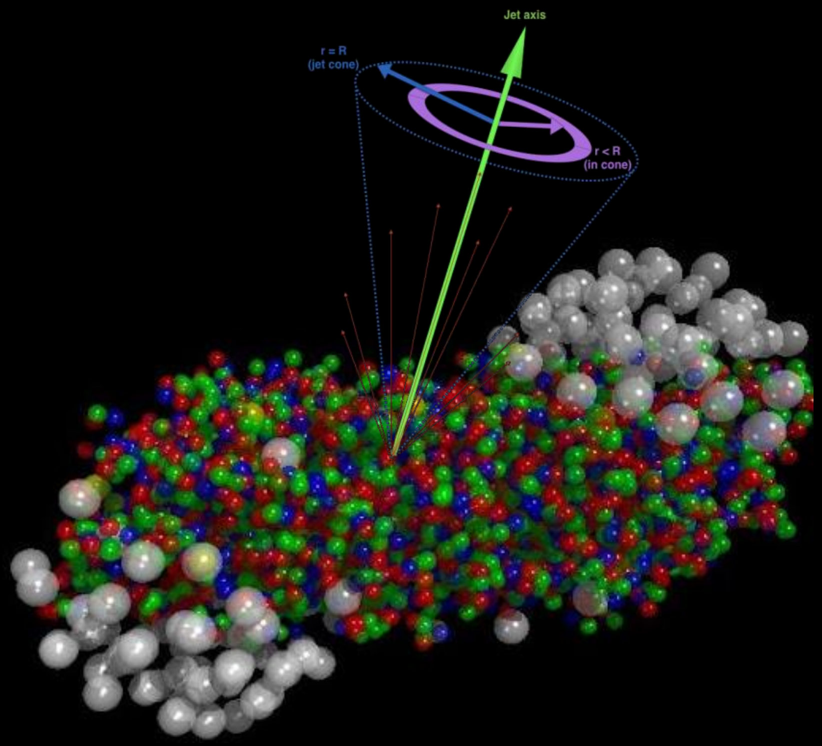
- ➢ Joint facility for high energy particle and heavy ion physics
  - ➢ Share running time between Particle and Nuclear physics efforts
- ➢ High luminosity collider facility
  - ➢ ~ 30 kHz event rate in Pb+Pb
    - ➢ Run3 will enable 50 kHz running
- ➢ High collision energy of 5.02 TeV
  - ➢ Produces a QGP with T ~ 300 MeV



https://arxiv.org/pdf/1308.2440.pdf

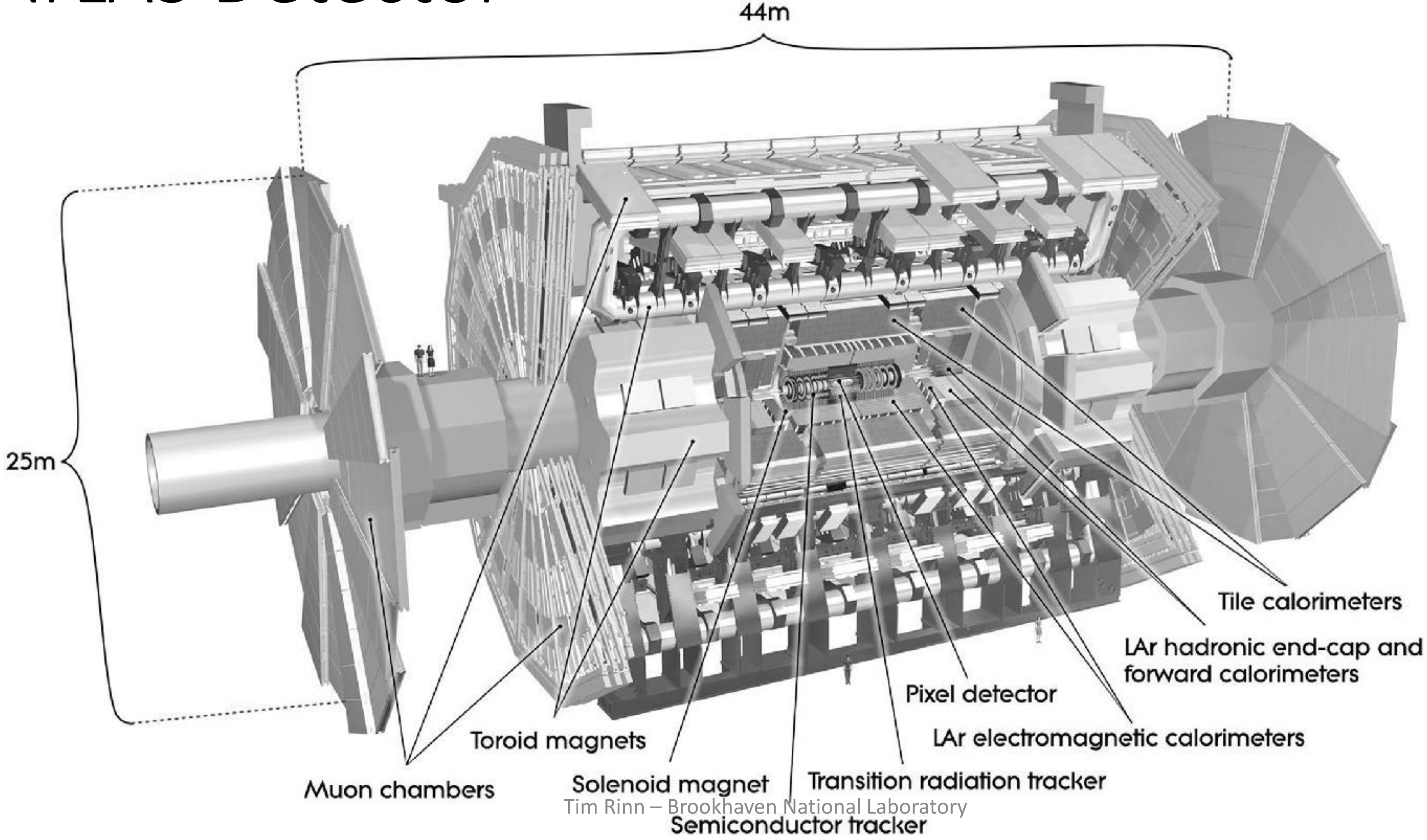
Probing the properties of the QGP

- In order to understand the properties of interactions within the QGP we want to probe it at short length scales
  - Requires high momentum probes such as jets of high p_T particles
- By studying heavy flavor quarks (bottom and charm) we are also able to probe the mass dependence of interactions



Located at the LHC

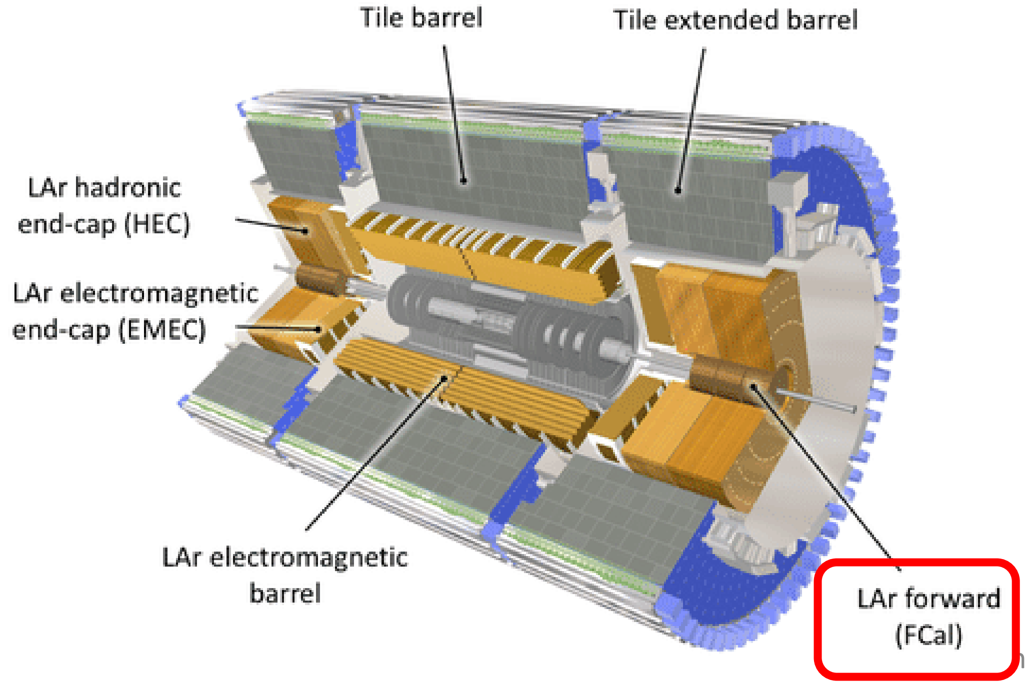
ATLAS Detector

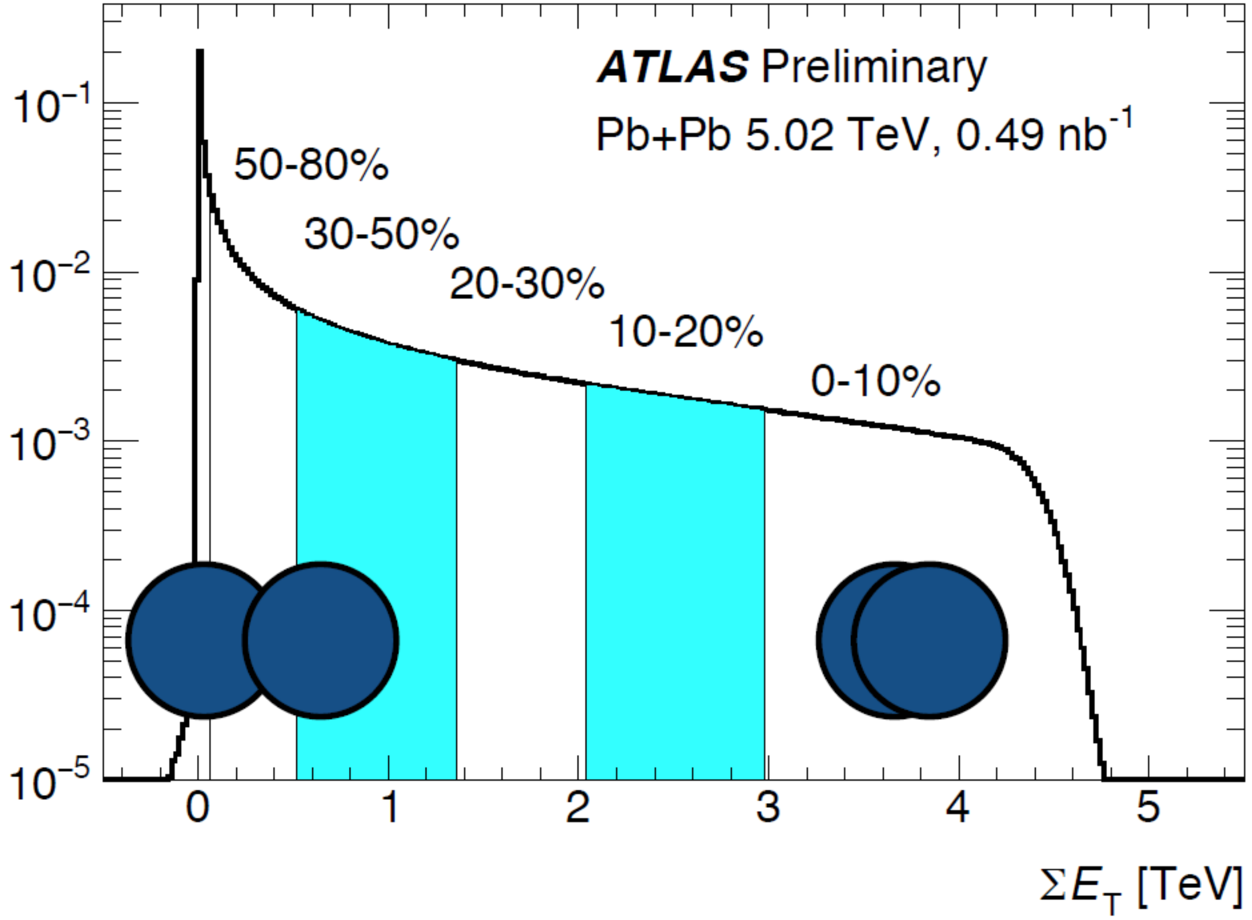


Event Classification in ATLAS

Events are classified the ΣE_T in the forward calorimeters

- Correlated with the impact parameter



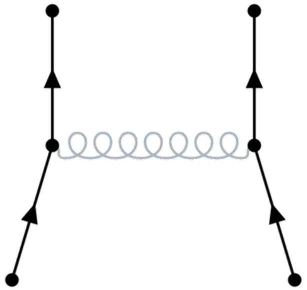


$E_T \equiv E * \sin(\theta)$

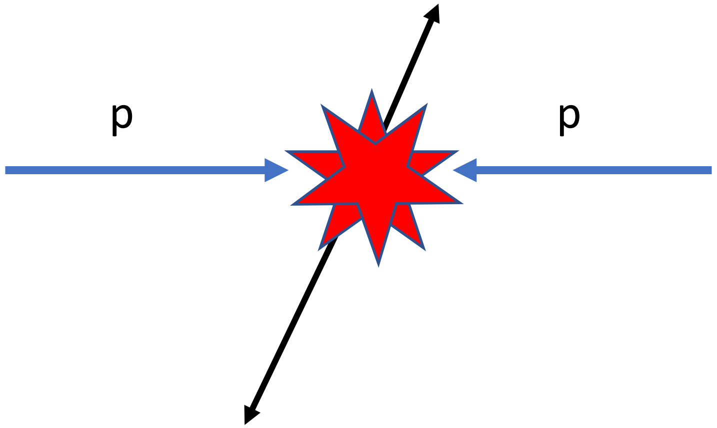
QCD Jets

Produced in large momentum transfer QCD interactions:

- Such as:
  q + q -> q + q



- Calculable using perturbative techniques



QCD Jets

Produced in large momentum transfer QCD interactions:

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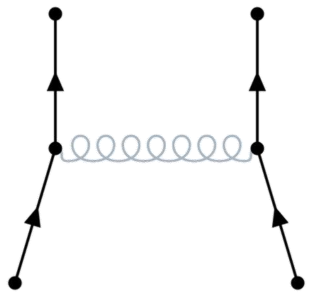
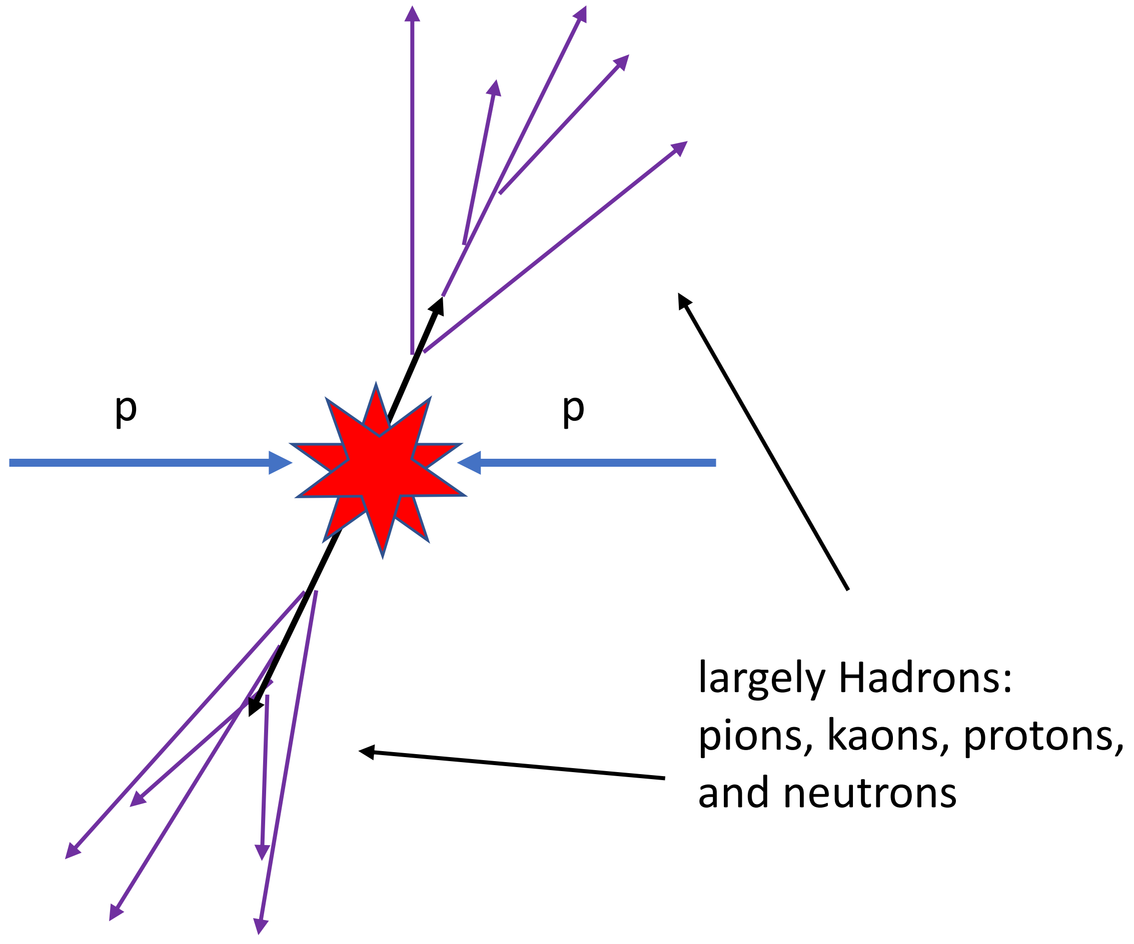


- ➢ Calculable using perturbative techniques

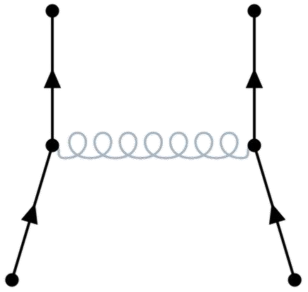
➢ Initial produced quarks/gluons evolve into a particle shower through fragmentation and hadronization



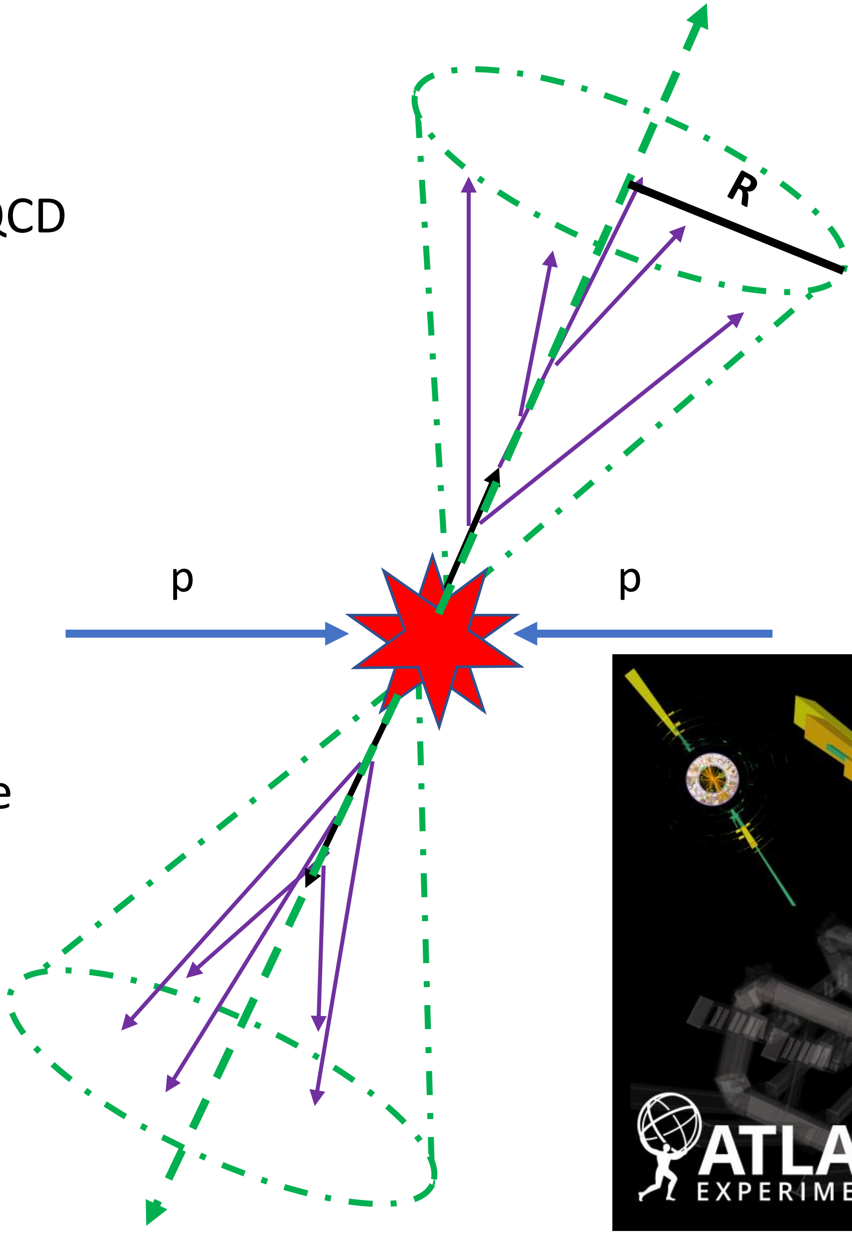
QCD Jets

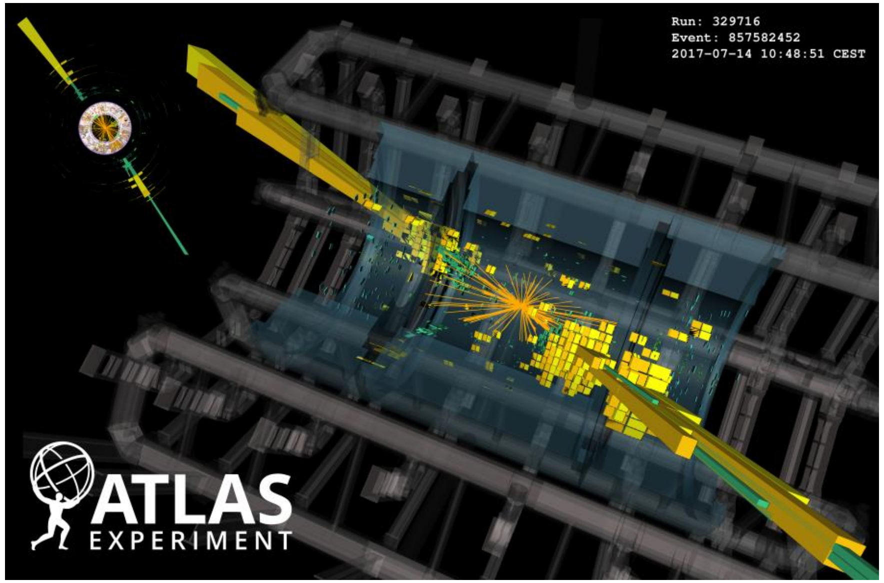
Produced in large momentum transfer QCD interactions:

- Such as:
  q + q -> q + q



- Calculable using perturbative techniques





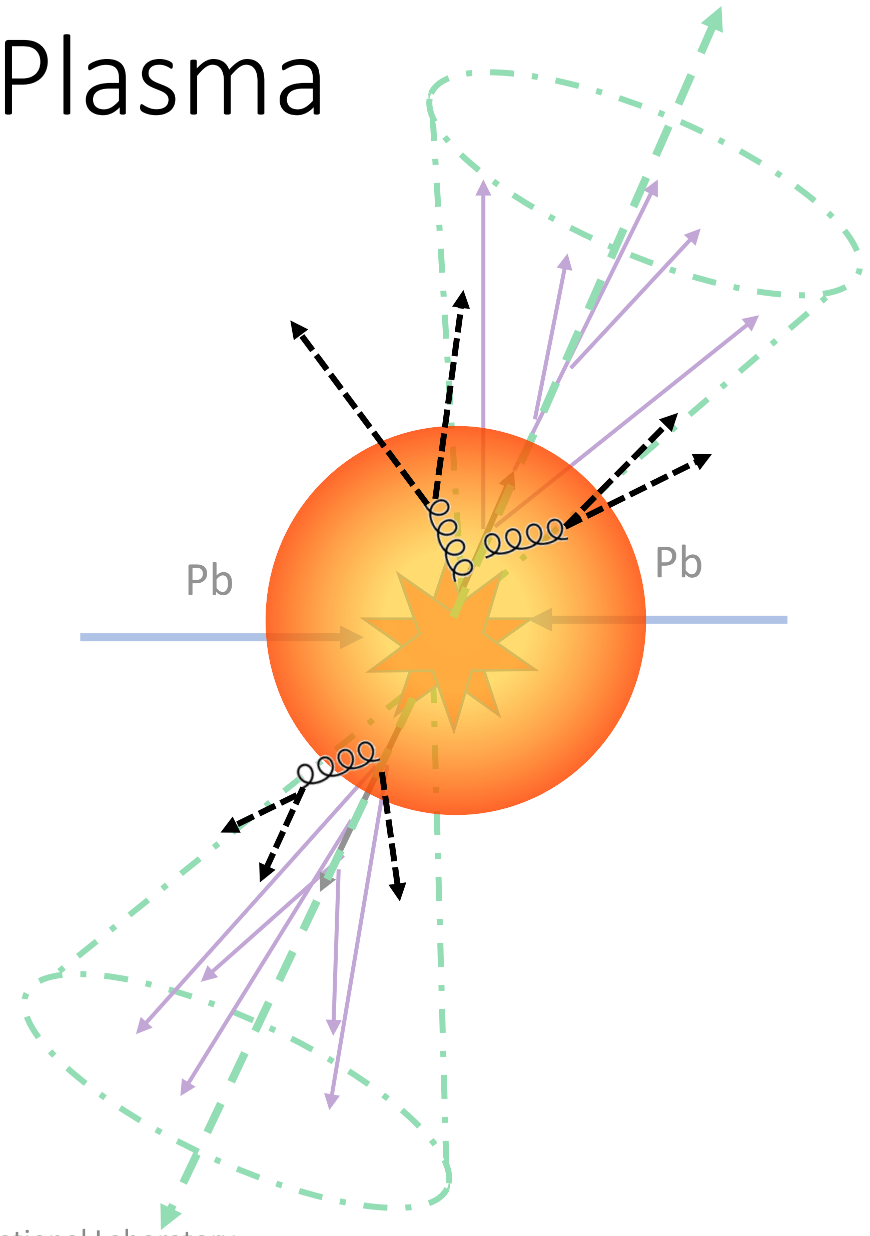
- Initial produced quarks/gluons evolve into a particle shower through fragmentation and hadronization

- Final state particles identified as jets using “jet finding algorithms”

Jets in the Quark Gluon Plasma

Jet constituents are modified as they traverse the nuclear medium

- Multiple scatterings with quarks and gluons
- Experience medium induced gluon radiation
- Pressure gradients from the initial geometry through the evolving medium

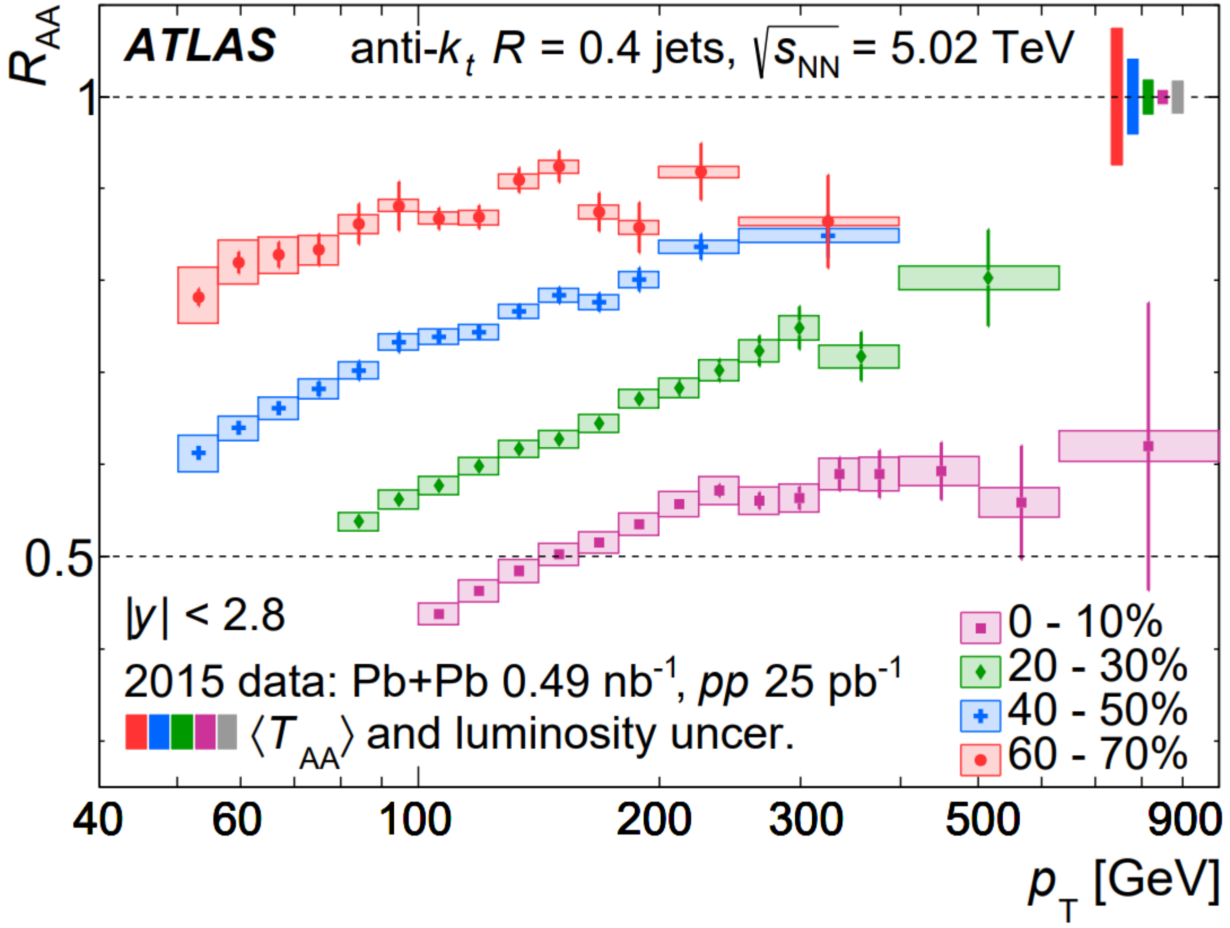


$$R_{AA} \equiv \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$$\langle T_{AA} \rangle \equiv \langle N_{coll} \rangle / \sigma^{pp}$$

Nuclear modification of Jets

Jets in central Pb+Pb collisions observe significant energy loss



How do the jets lose energy?

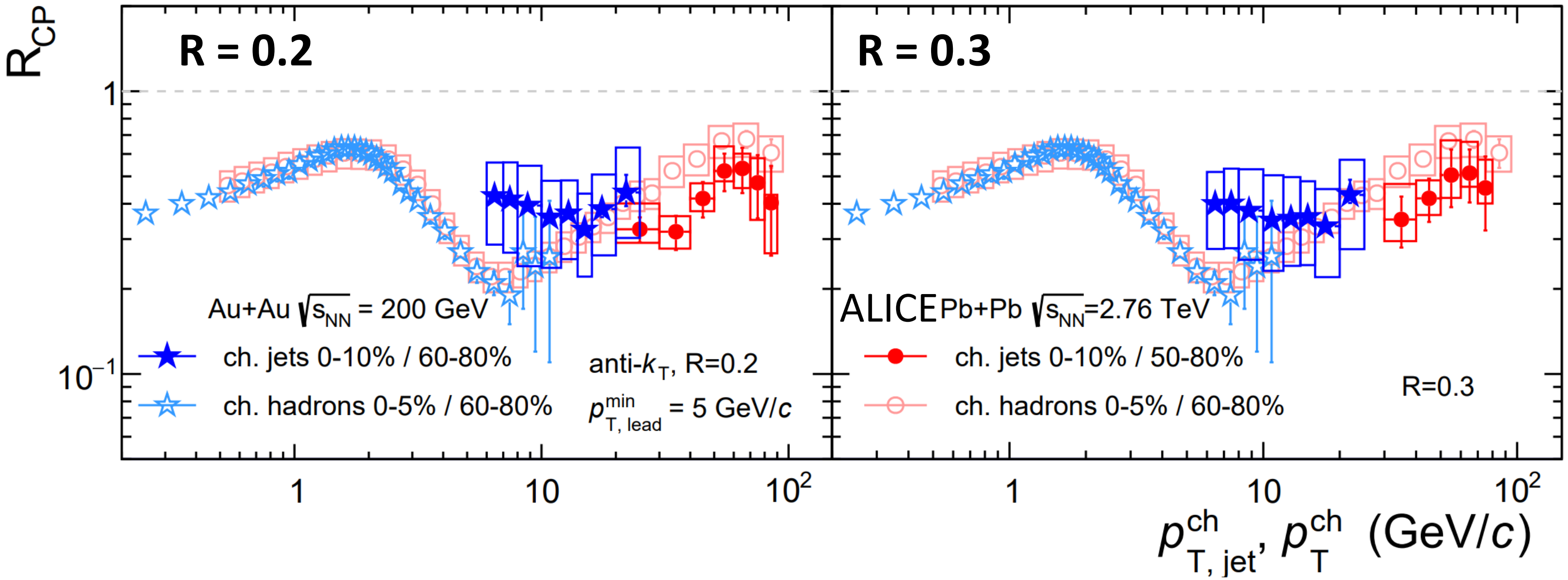
- **Does it depend on the path length?**
- **Where in the jet is the energy lost?**

Where does the energy go?

Phys.Letters.B.2018.10.076

Nuclear Modification of Jets in Au+Au at RHIC:

https://arxiv.org/pdf/2006.00582.pdf

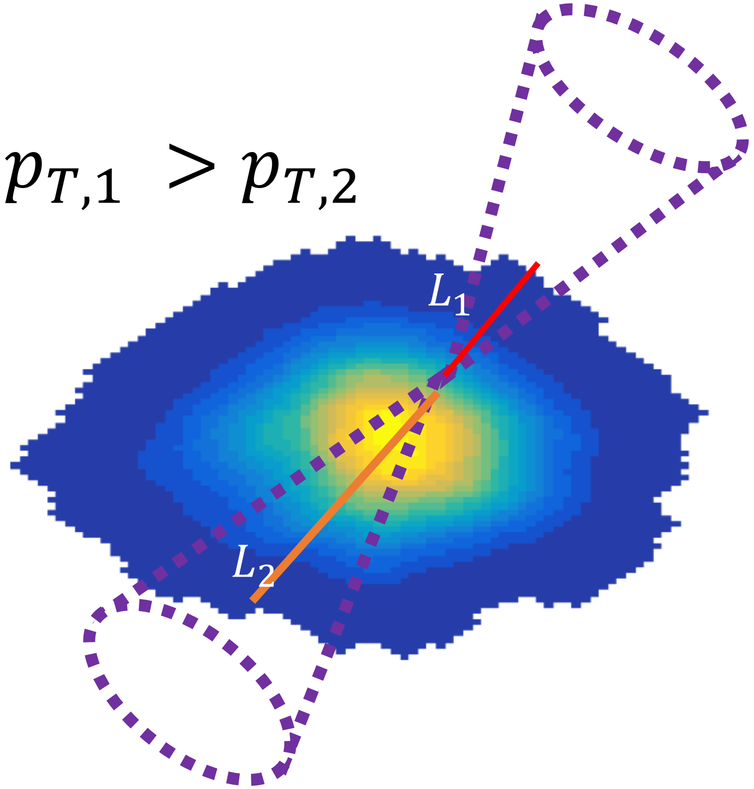


- Similar level of jet and charged hadron suppression observed at RHIC and LHC energies
  - Different underlying spectral shapes at 200 GeV versus 2.76 TeV

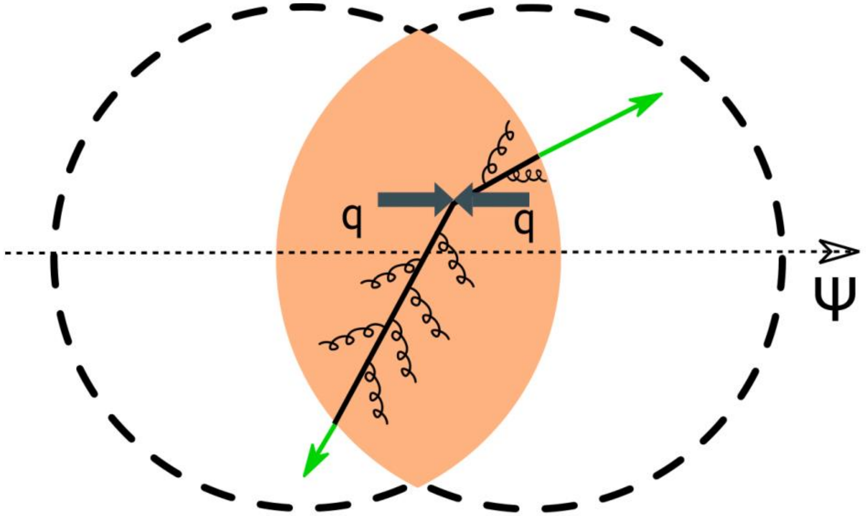
- No clear evidence for jet size or p_T dependence to the R_{CP} observed by STAR

Probing Jet Energy Loss

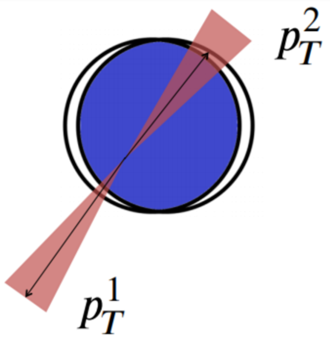
$L_2 > L_1 \Rightarrow p_{T,1} > p_{T,2}$



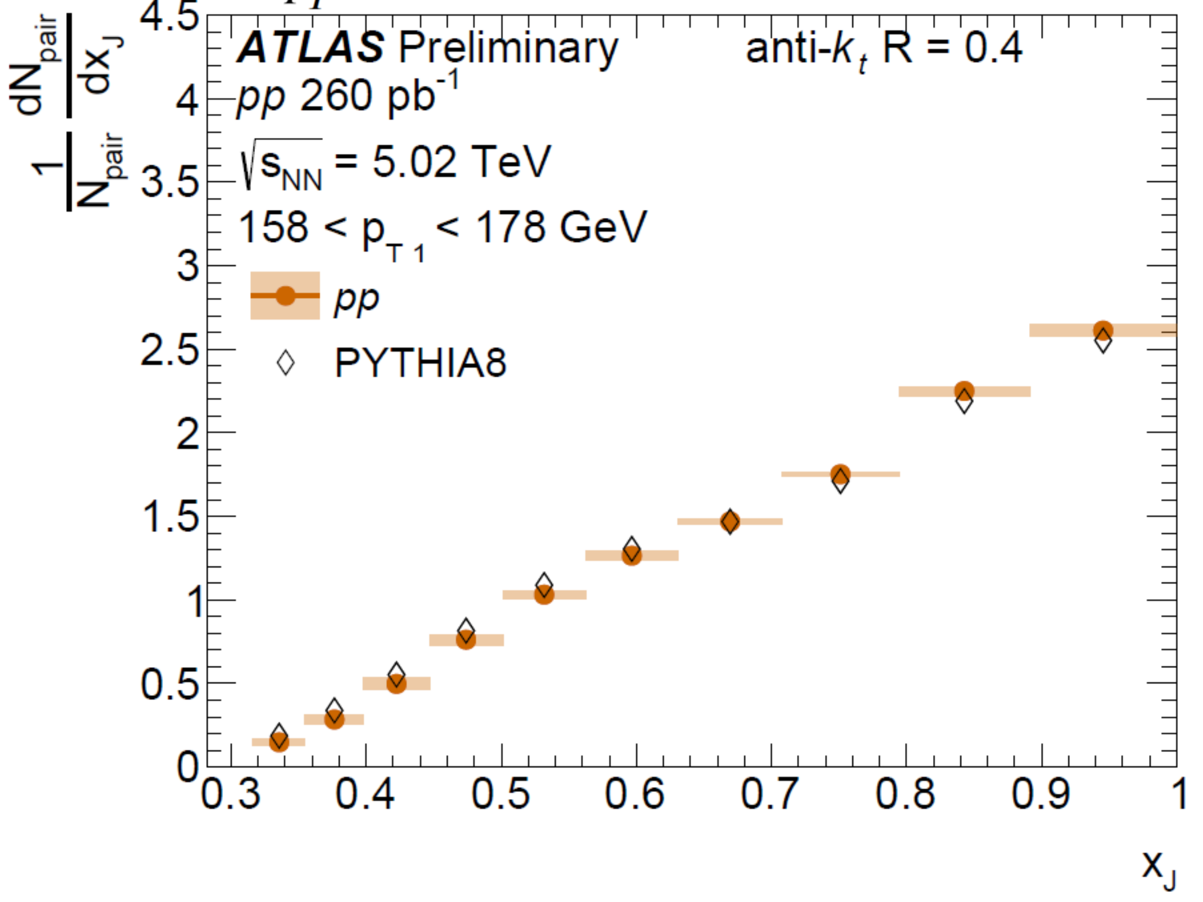
- Dijet Momentum Balance ($x_J = p_{T,2}/p_{T,1}$)
  - ➢Sensitive to path length dependent energy loss and fluctuations
- Jet v_2
  - ➢Path length dependent energy loss can cause enhanced jet yield in-plane vs. out-of-plane: positive v_2



DiJet Momentum Balance



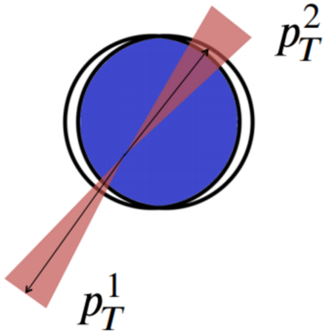
$x_J = p_{T,2}/p_{T,1}$



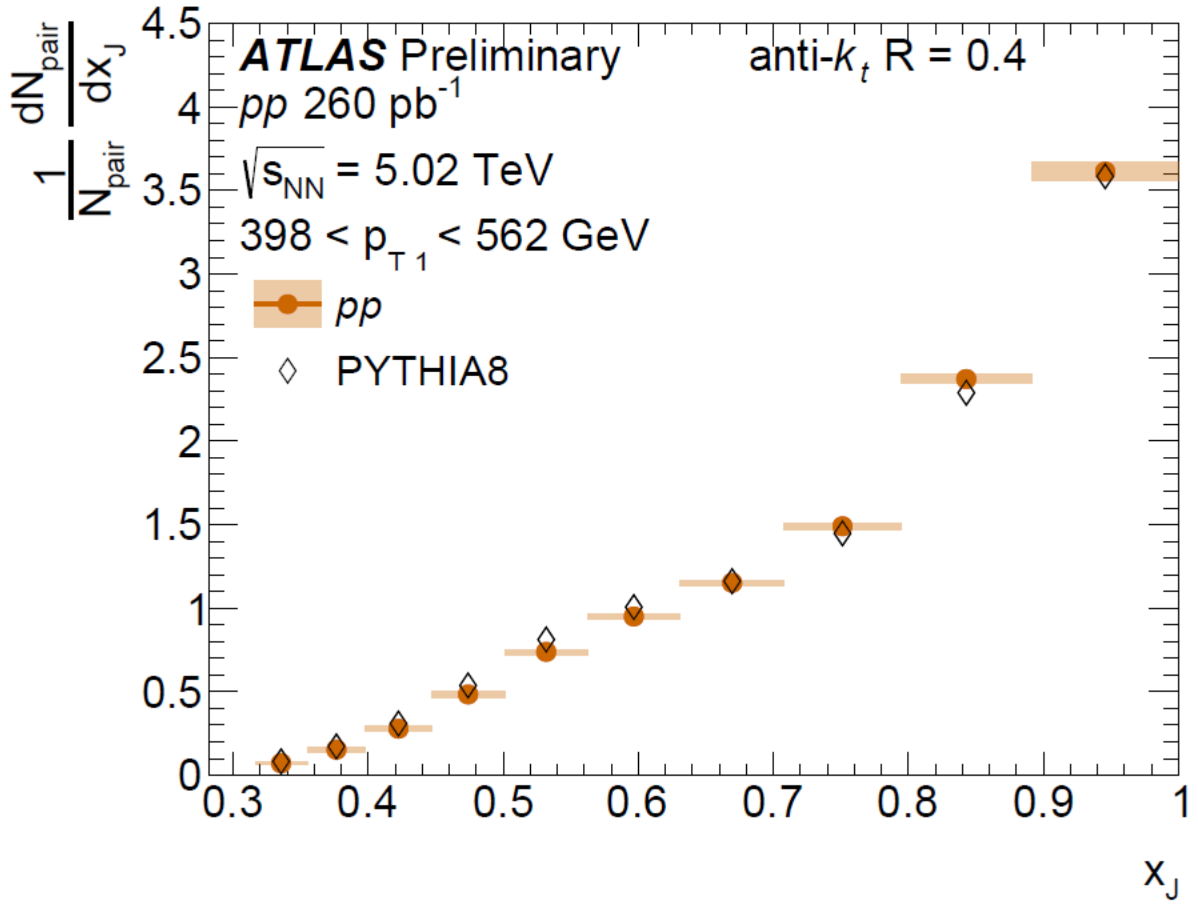
In *pp* collisions where no QGP is formed dijets favor symmetric momentum

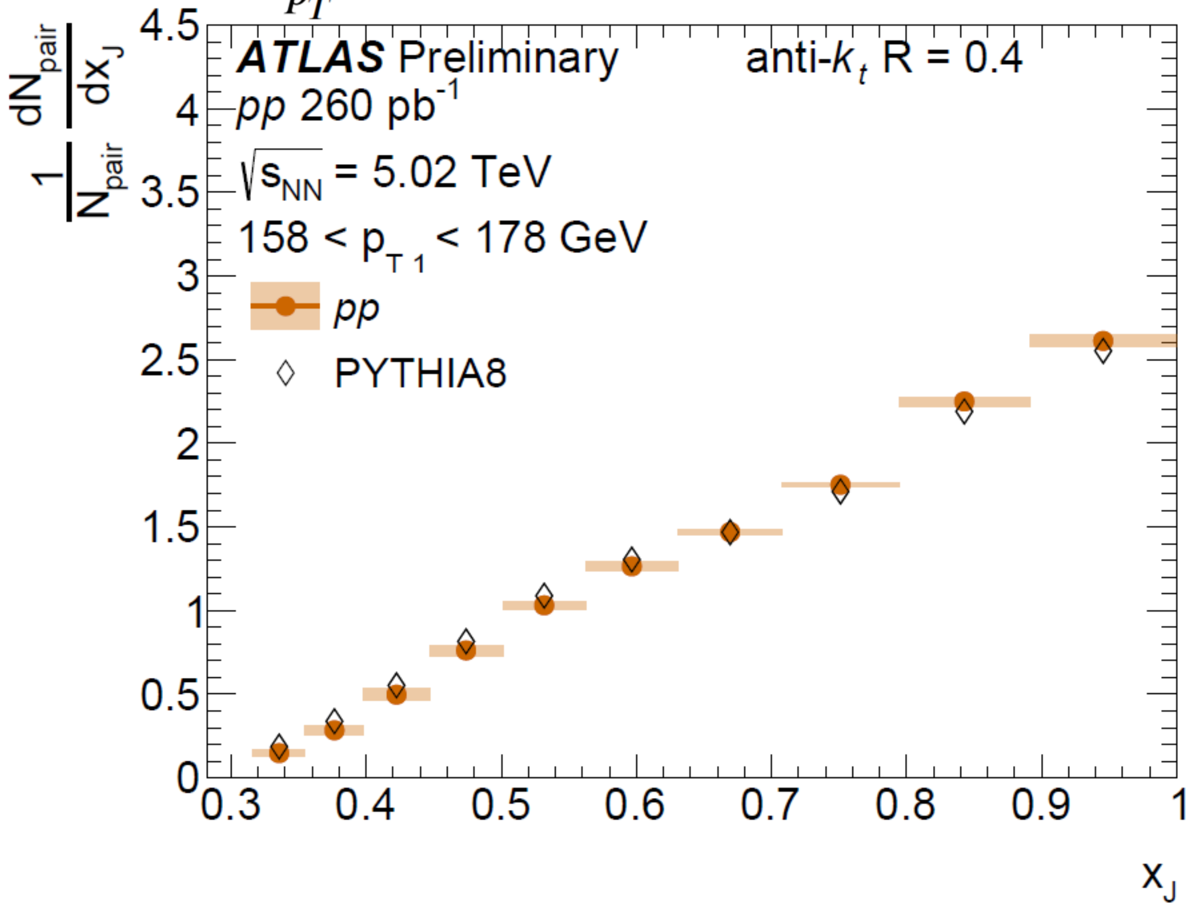
https://cds.cern.ch/record/2720247

DiJet Momentum Balance



$x_J = p_{T,2}/p_{T,1}$



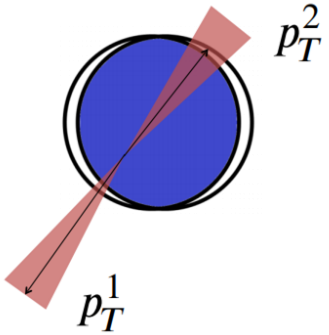


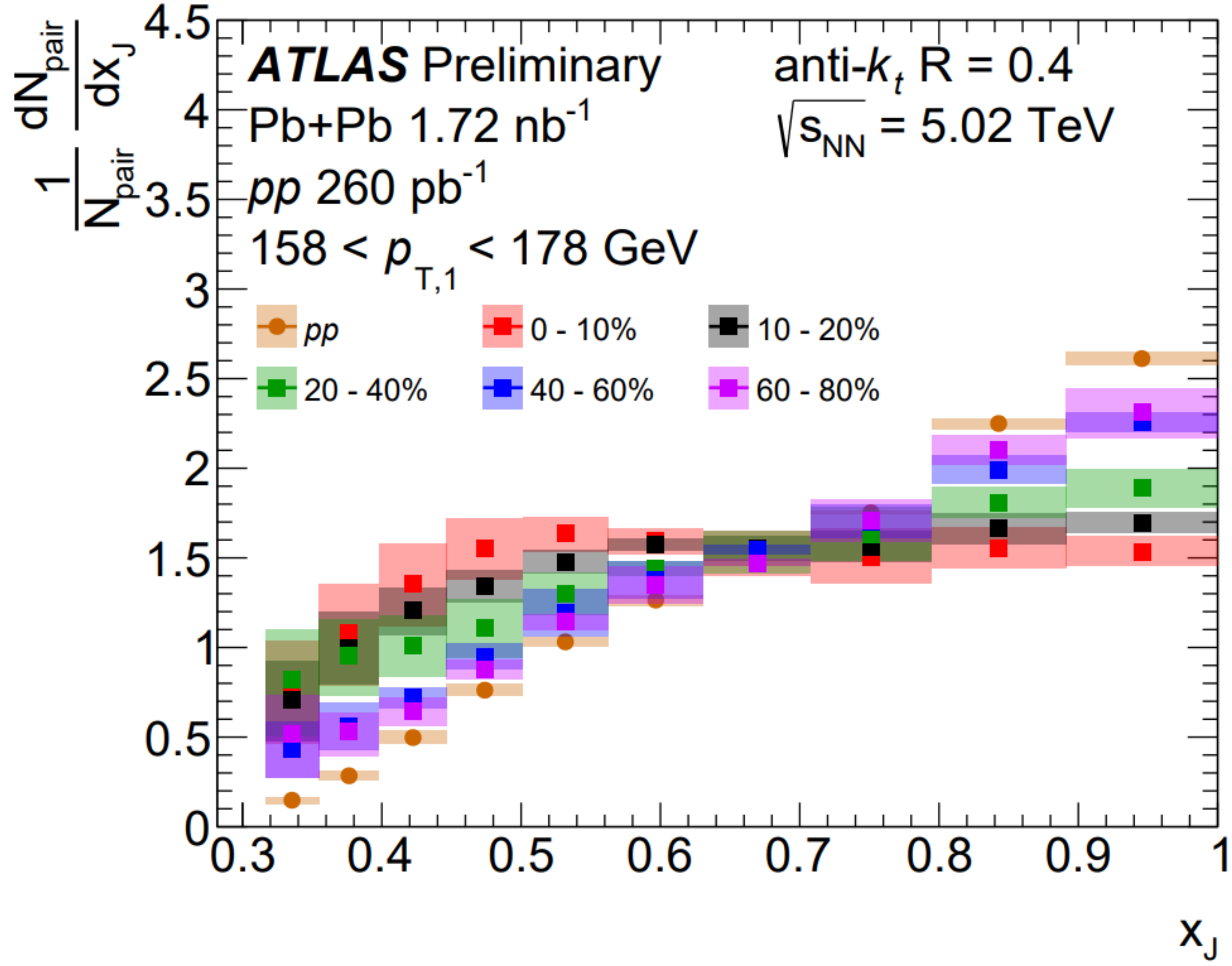
As we increase the p_T of the jets they become more collimated and dijets become more symmetric

DiJet Momentum Balance

- ➢Observe significant suppression of symmetric dijets Pb+Pb collisions

- ➢Clear reduction in modification between central collisions and peripheral Pb+Pb



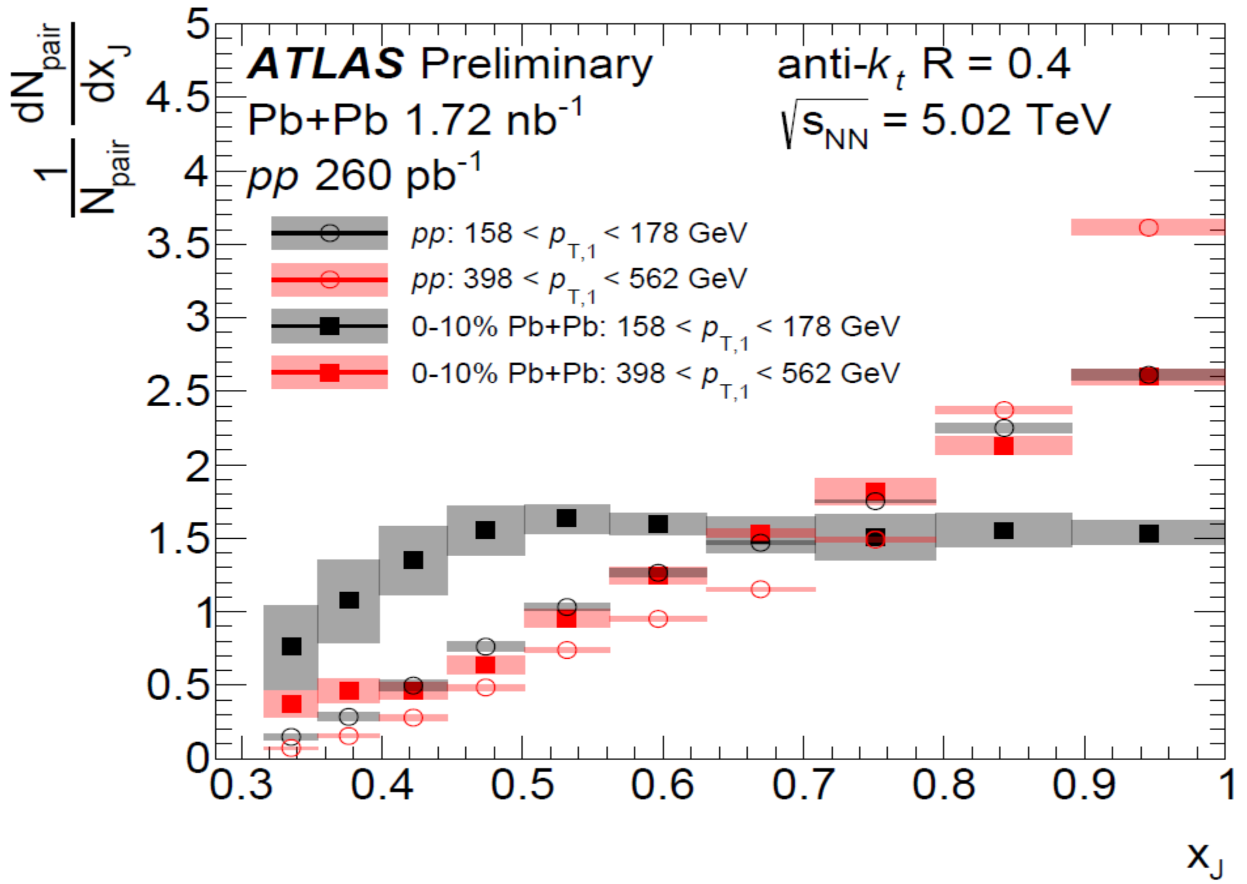


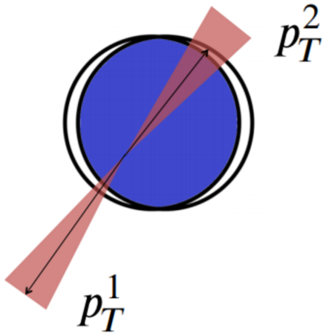
https://cds.cern.ch/record/2720247

DiJet Momentum Balance

Observe significant suppression of symmetric dijets in Central Pb+Pb across jet p_T

- subleading jet having loses more energy than the leading jet potentially due to traversing a larger distance in the medium

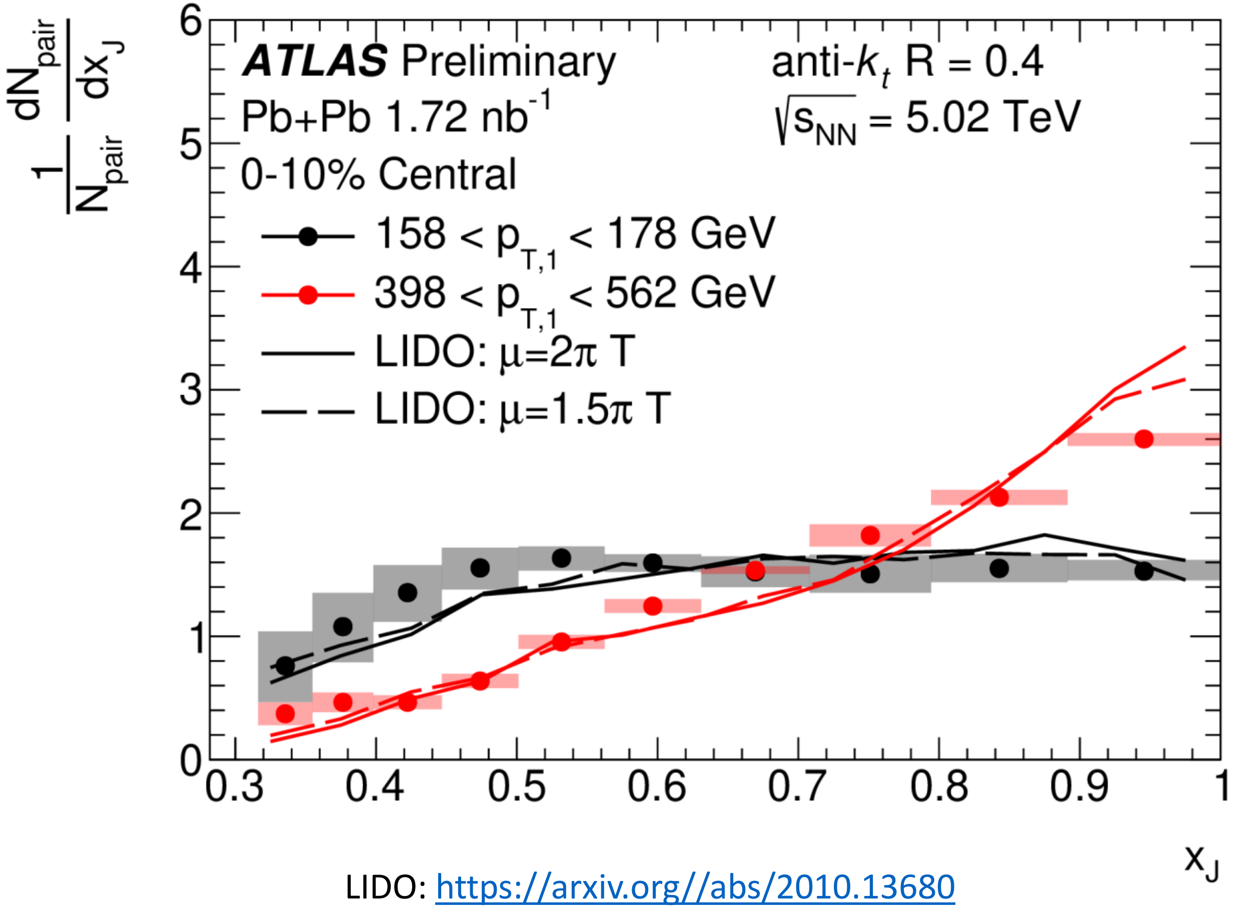




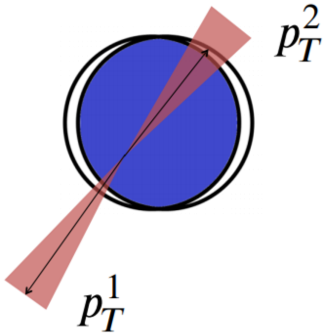
DiJet Momentum Balance

Predictions made from the LIDO group agree well with the measured x_J distributions:

- LIDO is a global data calibrated partonic transport model



LIDO: https://arxiv.org//abs/2010.13680



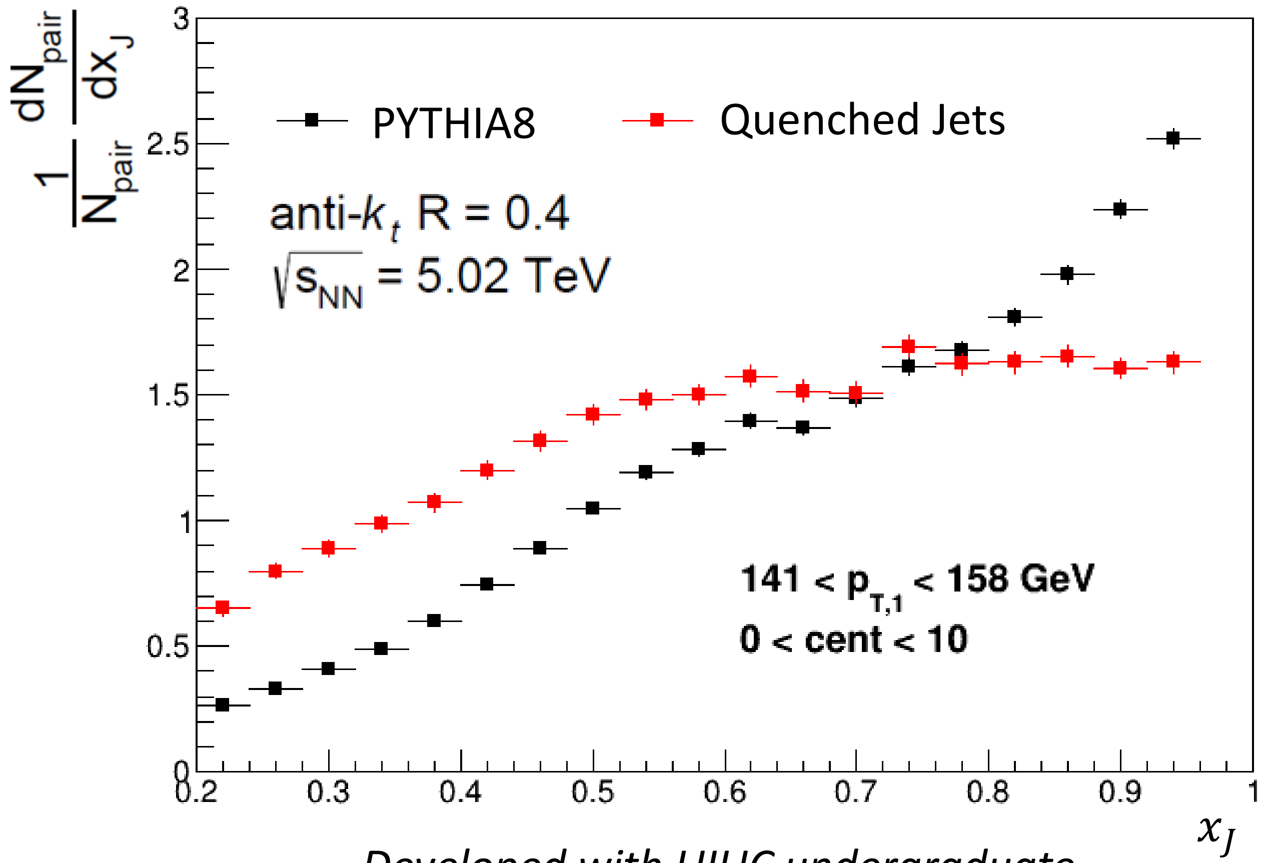
Contributions to the DiJet momentum Balance

Nicholas Nusgart

With an undergraduate student we developed a phenomenological model of path length dependent energy loss

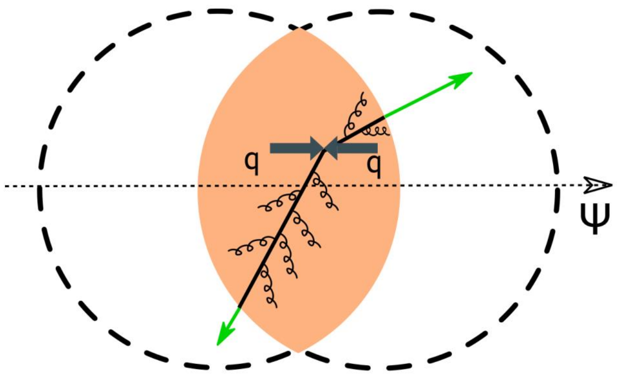
- $\Delta p_T \propto \alpha p_T^{\beta} \ell^2$
- Momentum loss tuned with the jet R_{AA}
- Medium modeled using Glauber simulations

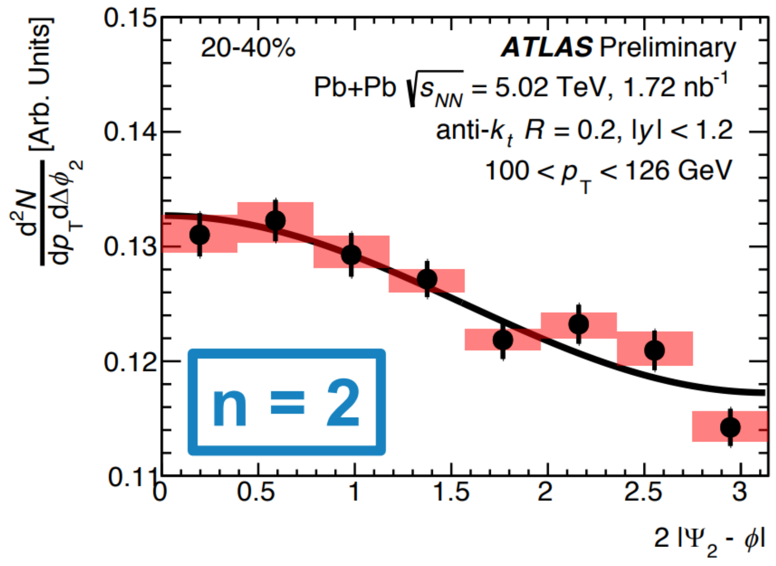
Highlights that the dijet momentum balance is particularly sensitive to path length dependent energy loss

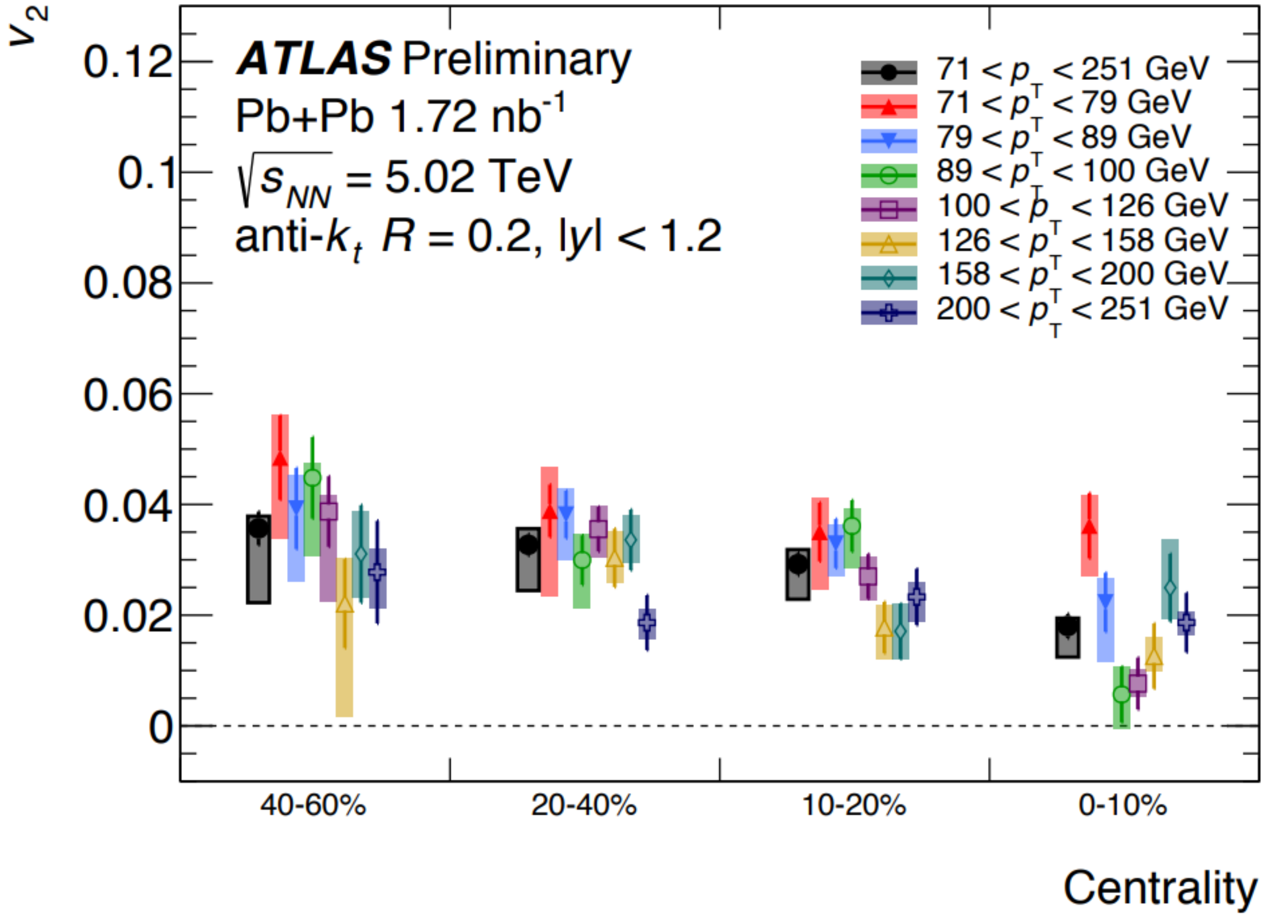


Developed with UIUC undergraduate student Nicholas Nusgart

Jet v_2







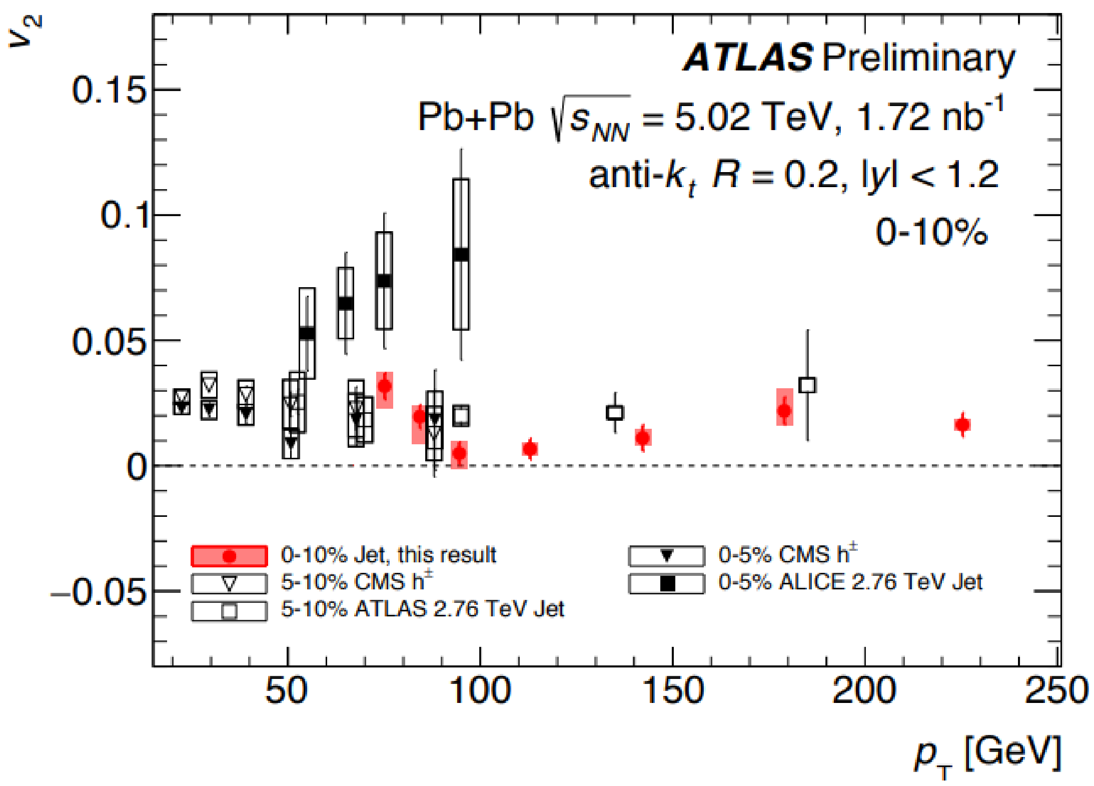
ATLAS observes for $R = 0.2$ Jets a significant 1-4% jet v_2 on inclusive jet p_T

- ➢ v_2 is enhanced in more elliptical initial states (mid central, peripheral)

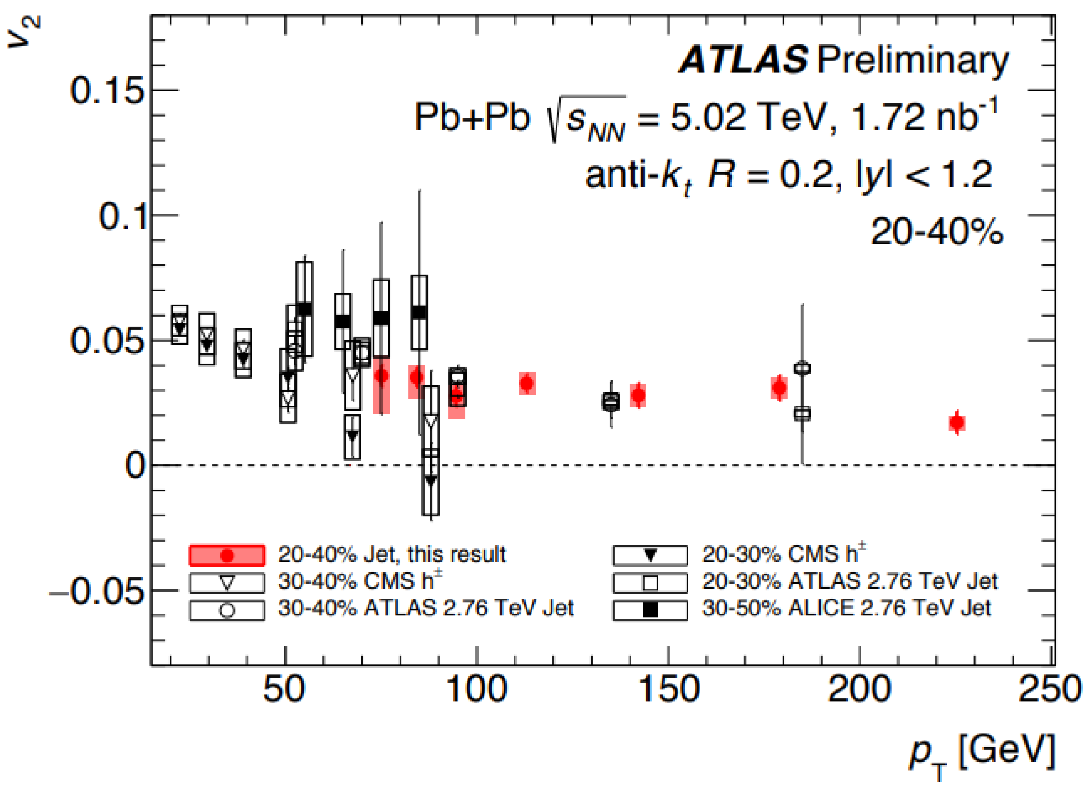
ATLAS-CONF-2020-019
CMS charged particle: arXiv:1702.00630
ATLAS 2.76 TeV: arXiv:1306.6469
ALICE 2.76 TeV: arXiv:1509.07334

Jet v_2

0-10%



20-40%

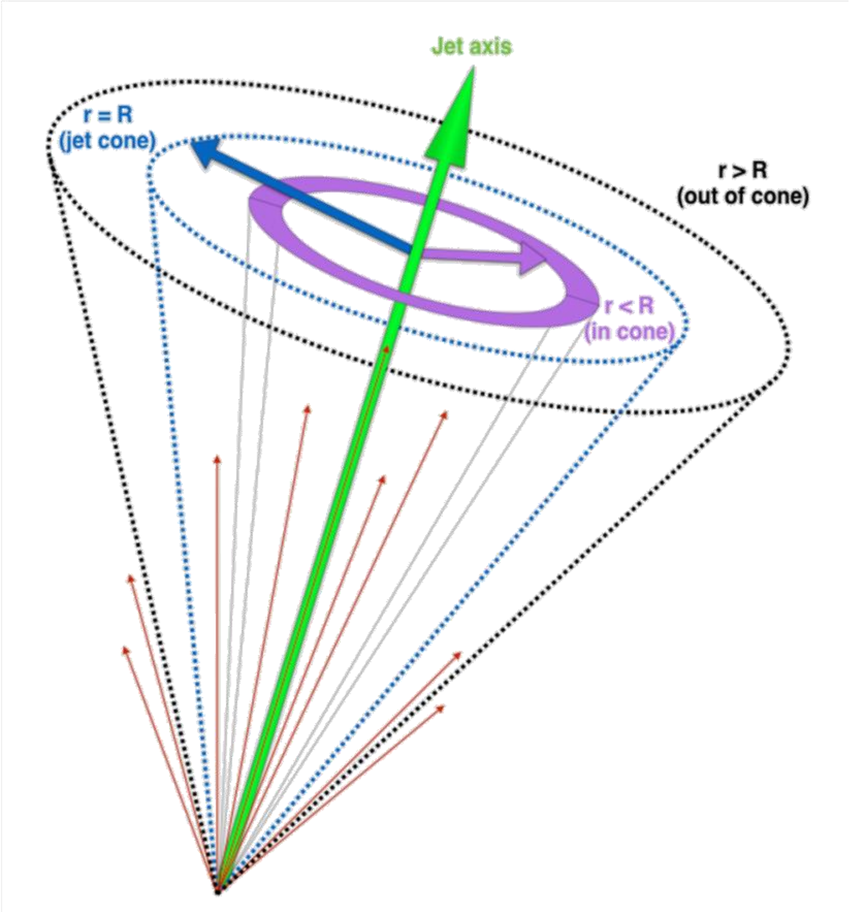


- Significant increase in precision compared to global data!

Jet Fragmentation

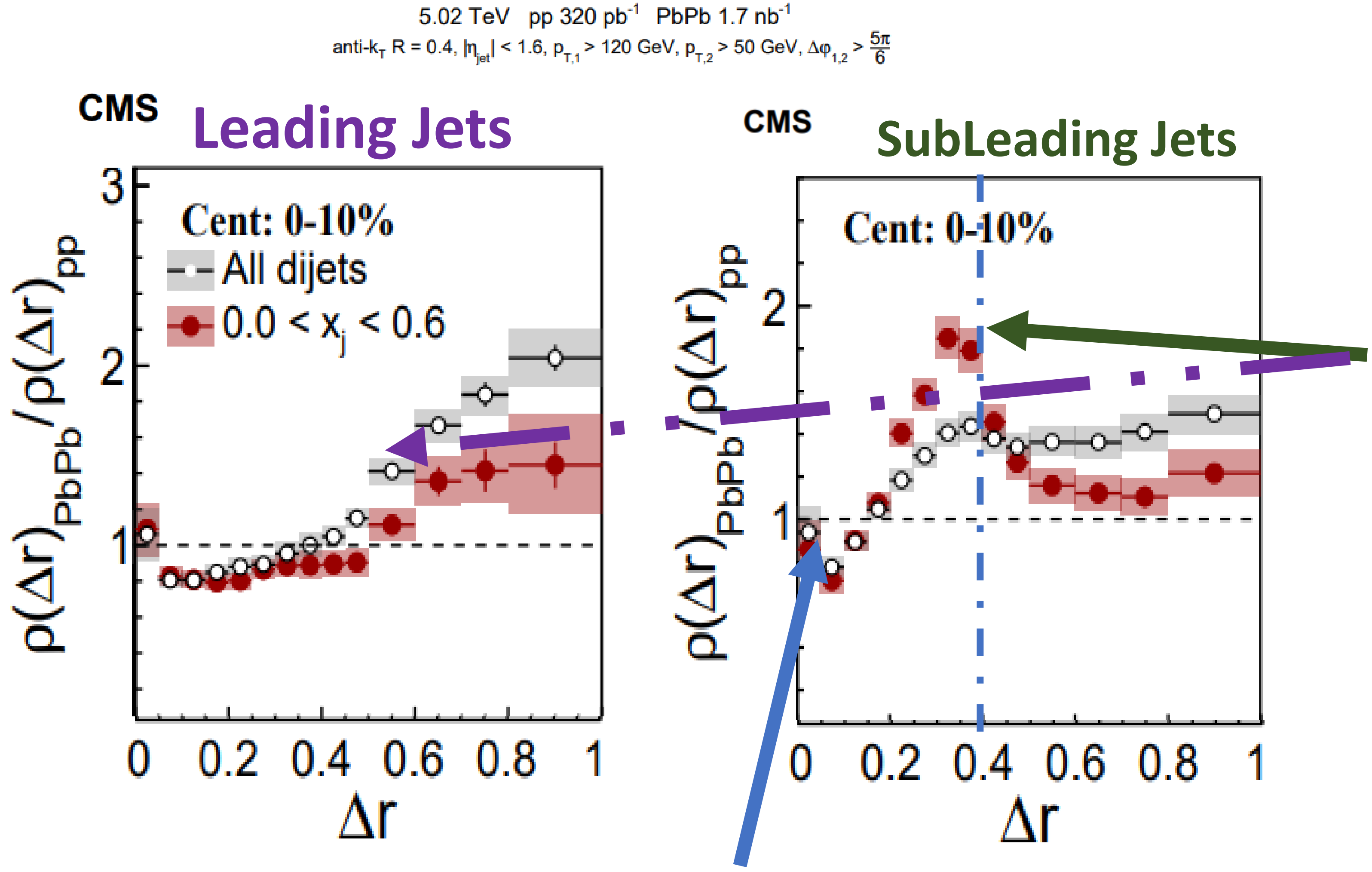
Where does this lost energy go?

- ➢Look for energy around the jet
- ➢How does the energy make up of the jet change through the QGP
  - ➢Do we observe a loss of high energy particles?
  - ➢Where in the jet do we see the energy loss?



arXiv:2101.04720

ρ is proportional to track momentum density in a radius window



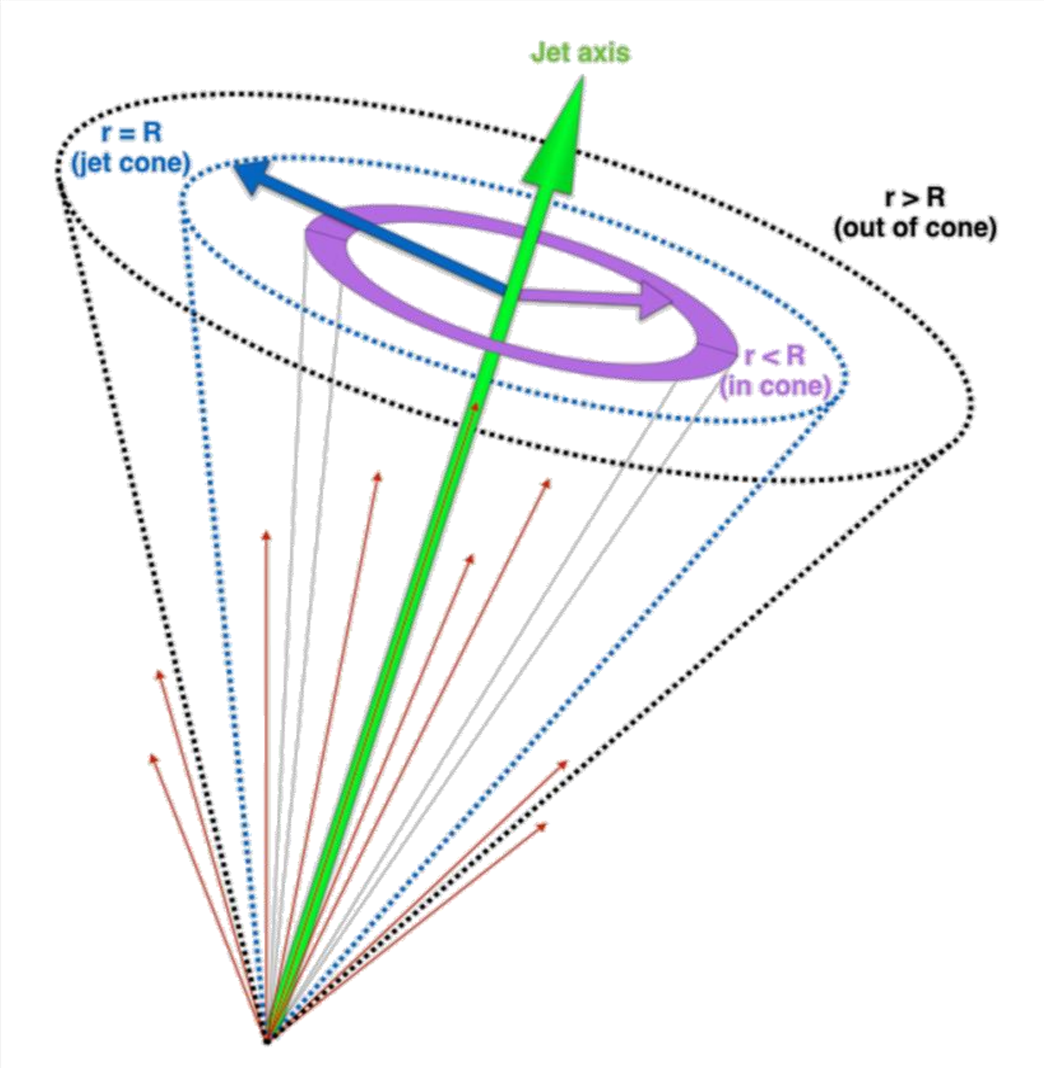
Clear enhancement of momentum caried near the edges of the **subleading jet** compared to the **leading jet**

Clear depletion of momentum near the core of the jet for the **subleading jet**

Quenched jets observe significant broadening

Where next?

- How does jet quenching depend on the size of the jet
  - Do broader jets lose more energy?
- Do jets from heavy flavor quarks experience different energy loss
  - Radiative energy loss is expected to be mass dependent
- How does jet energy loss depend on system size
- How does the medium interactions depend on temperature
  - Need a state of the art jet detector at RHIC to provide "low" temperature QGP medium

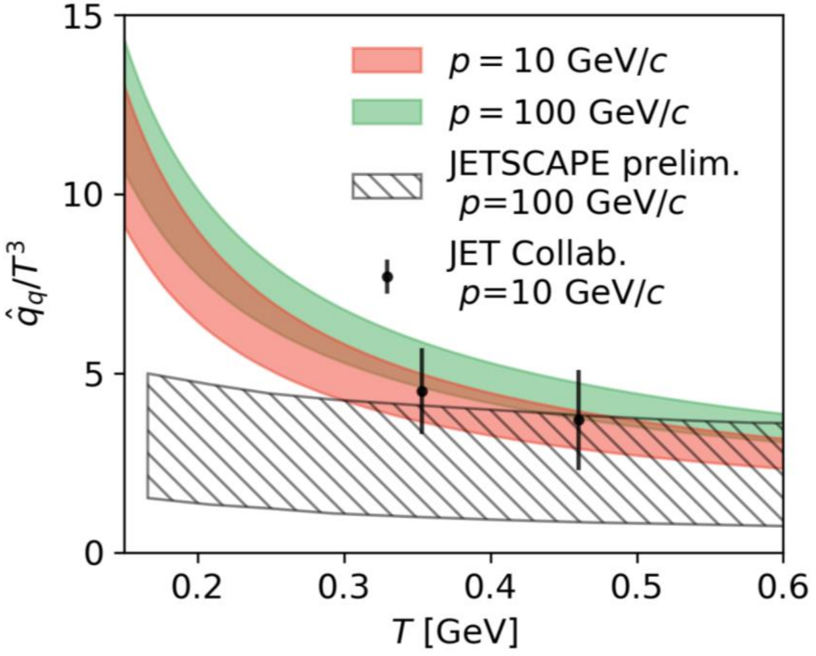


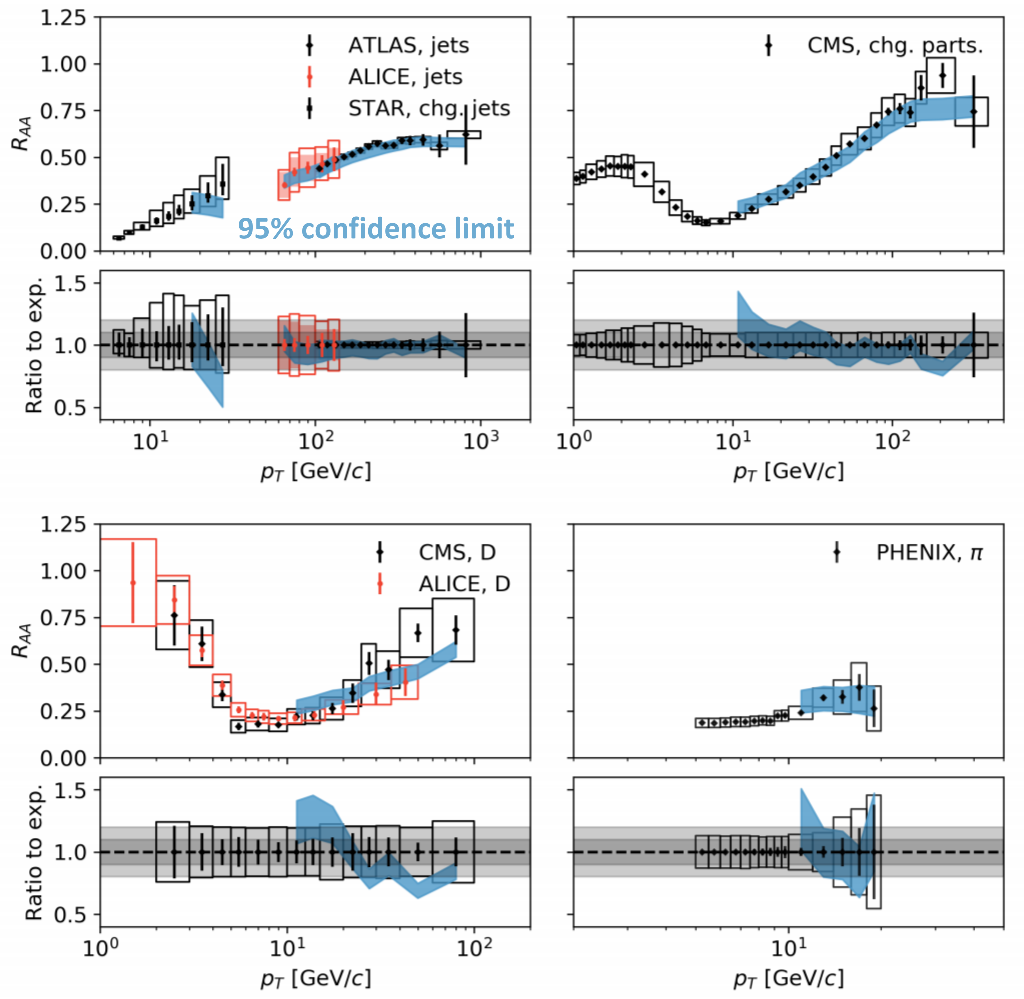
Global Bayesian Analyses

https://arxiv.org/pdf/2010.13680.pdf

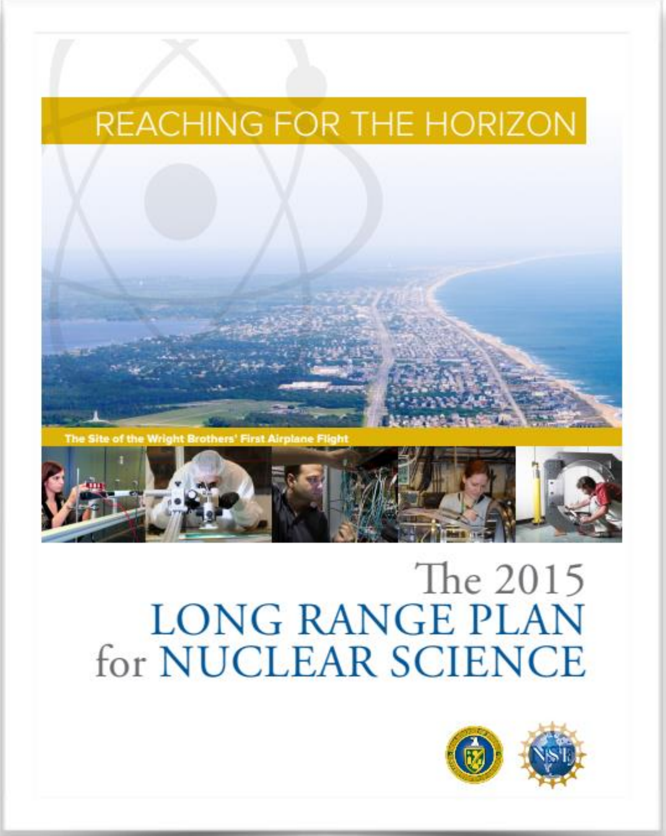
Theory collaborations use R_{AA} measurements from both RHIC and LHC experiments in Bayesian analyses to extract insight on the QGP properties

- Recent publications by Weiyao Ke and Xin-Nian Wang, as well as the JETSCAPE collaboration highlight extractions of jet transport coefficient $\hat{q}$





sPHENIX: state-of-the-art Jet Detector at RHIC



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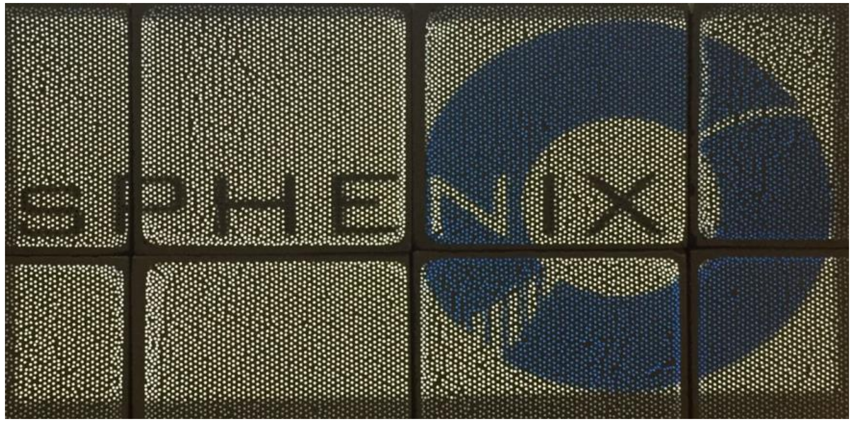
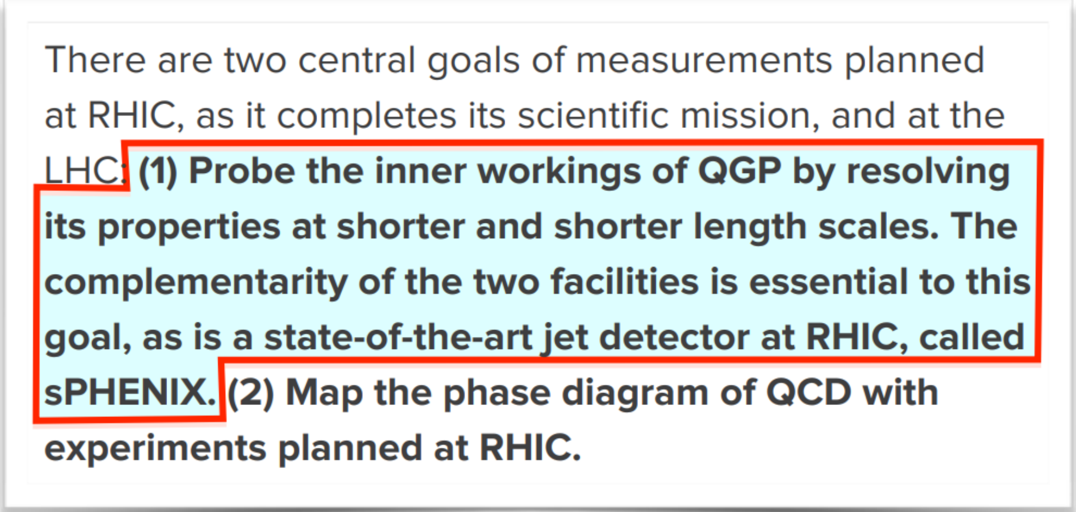
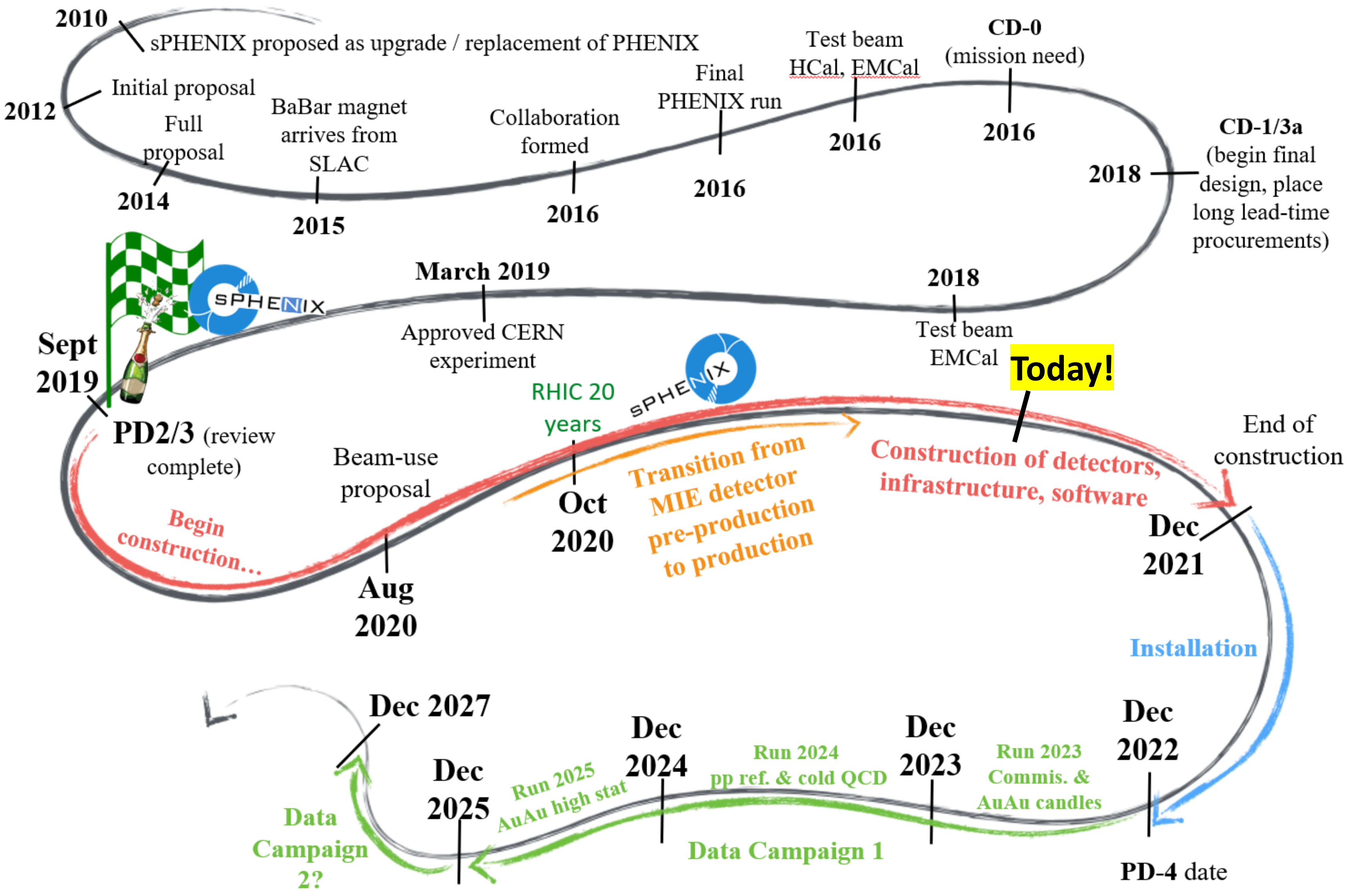
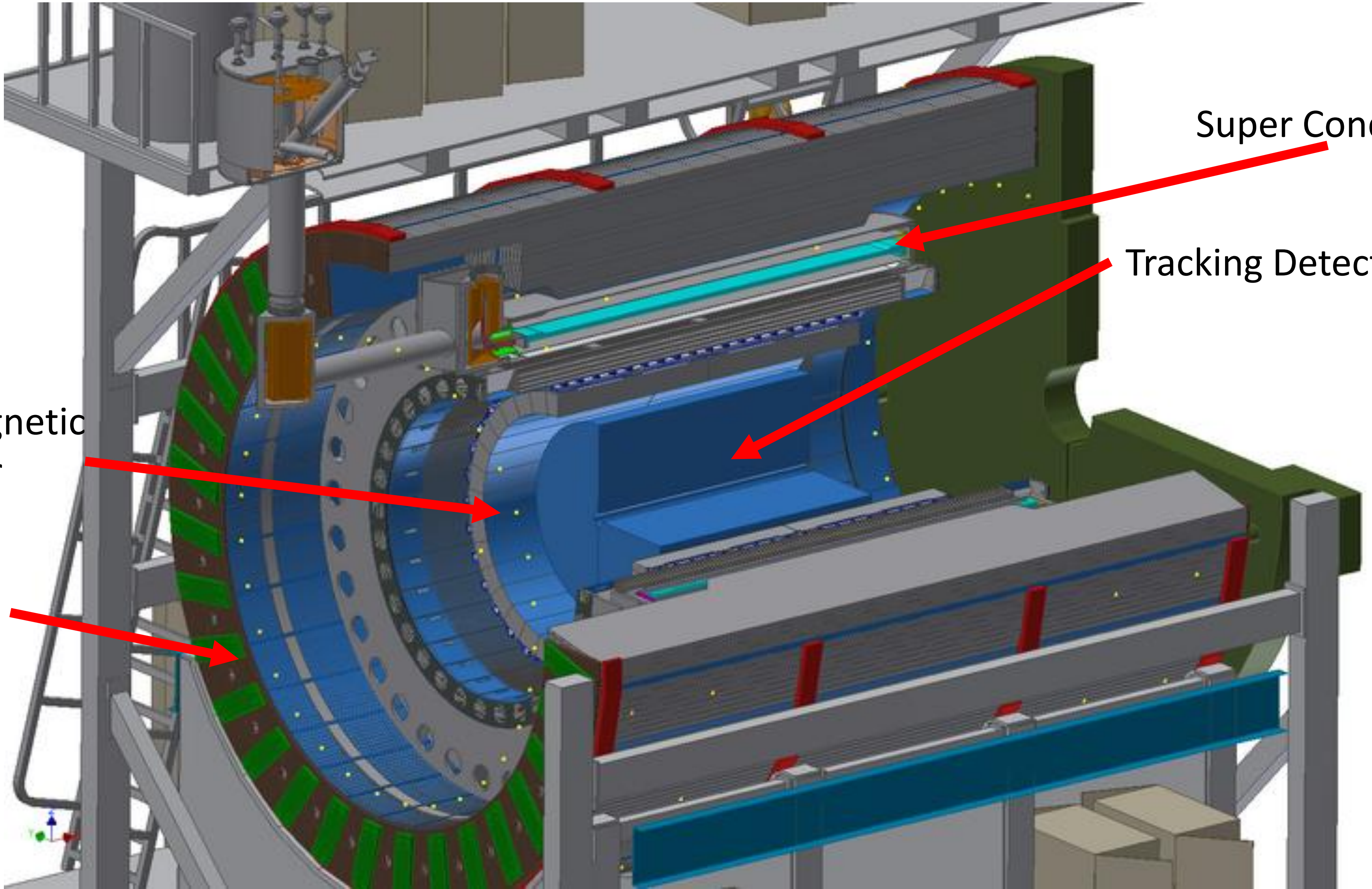



There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art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

sPHENIX: A Timeline



The sPHENIX Detector



Super Conducting Magnet

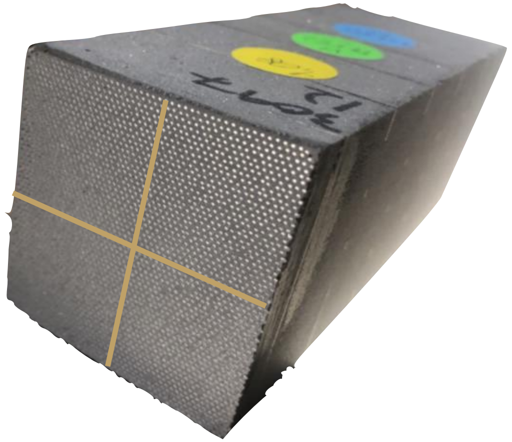
Tracking Detectors:

Electro magnetic Calorimeter

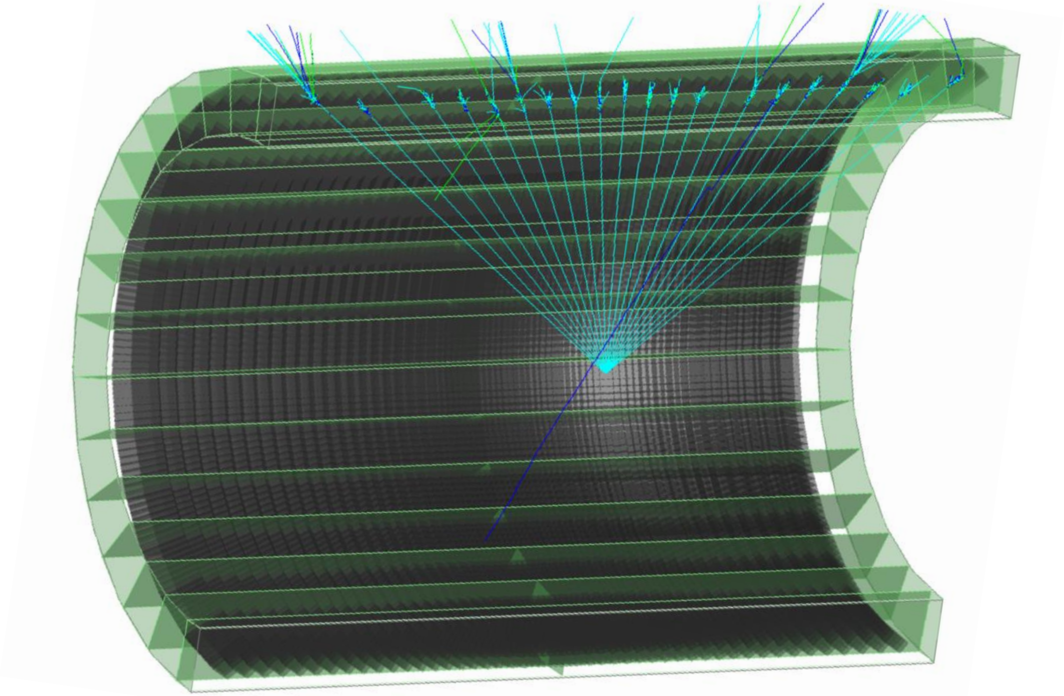
Hadron Calorimeter

Large acceptance calorimeter system ideal for jet measurements

Electromagnetic calorimeter

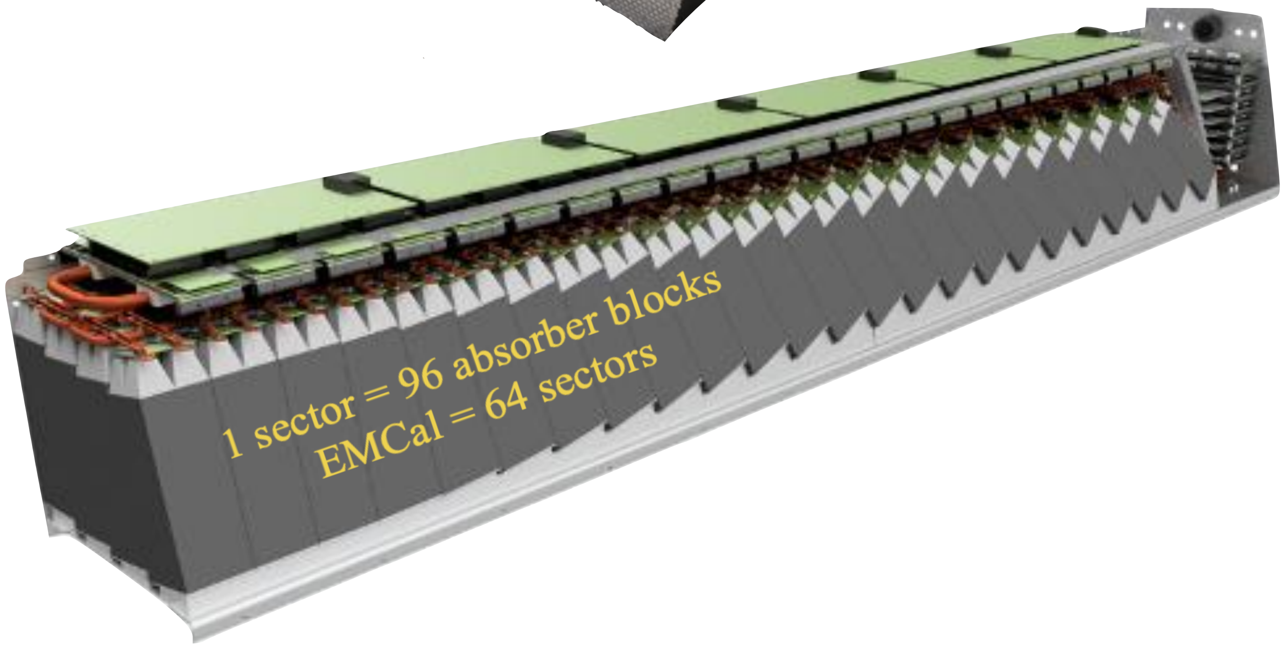


- Projective in both η and ϕ
  - All fibers point to collision vertex



$|\eta| < 1.1$

24,576 towers

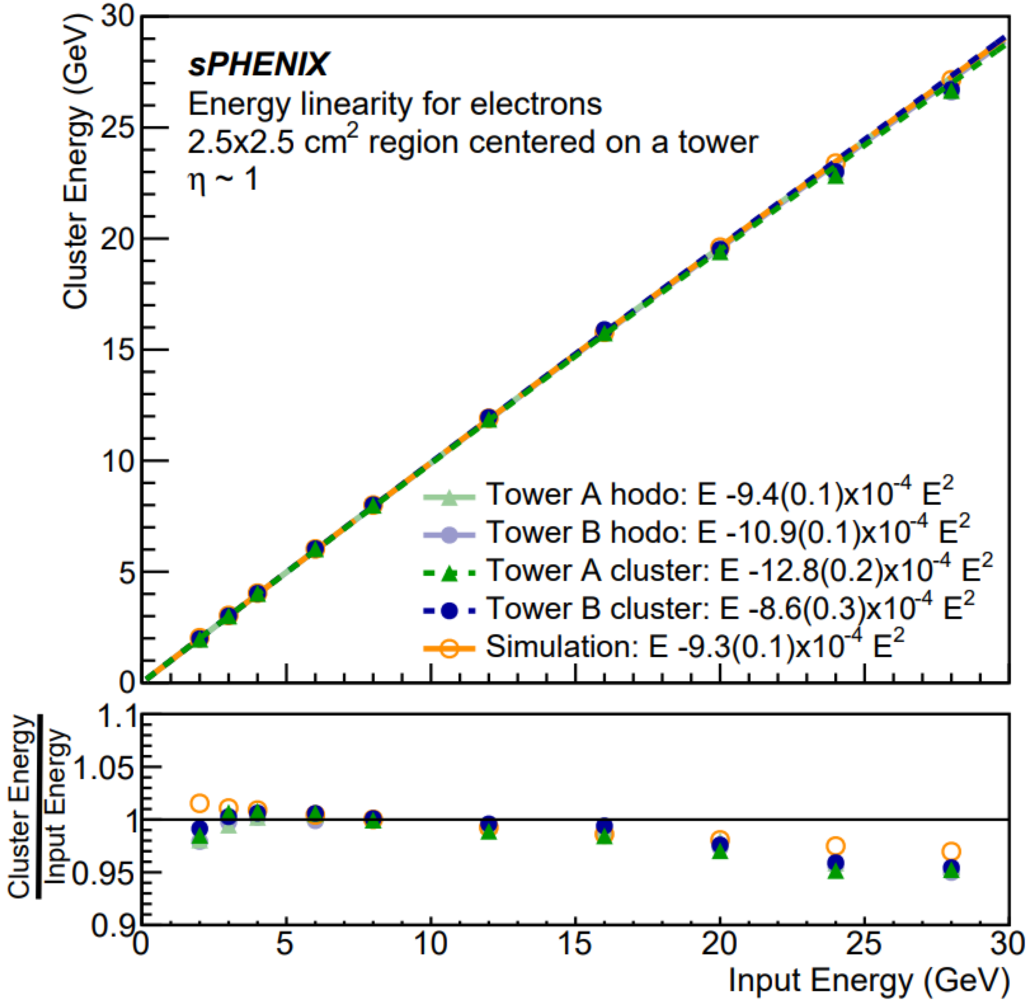


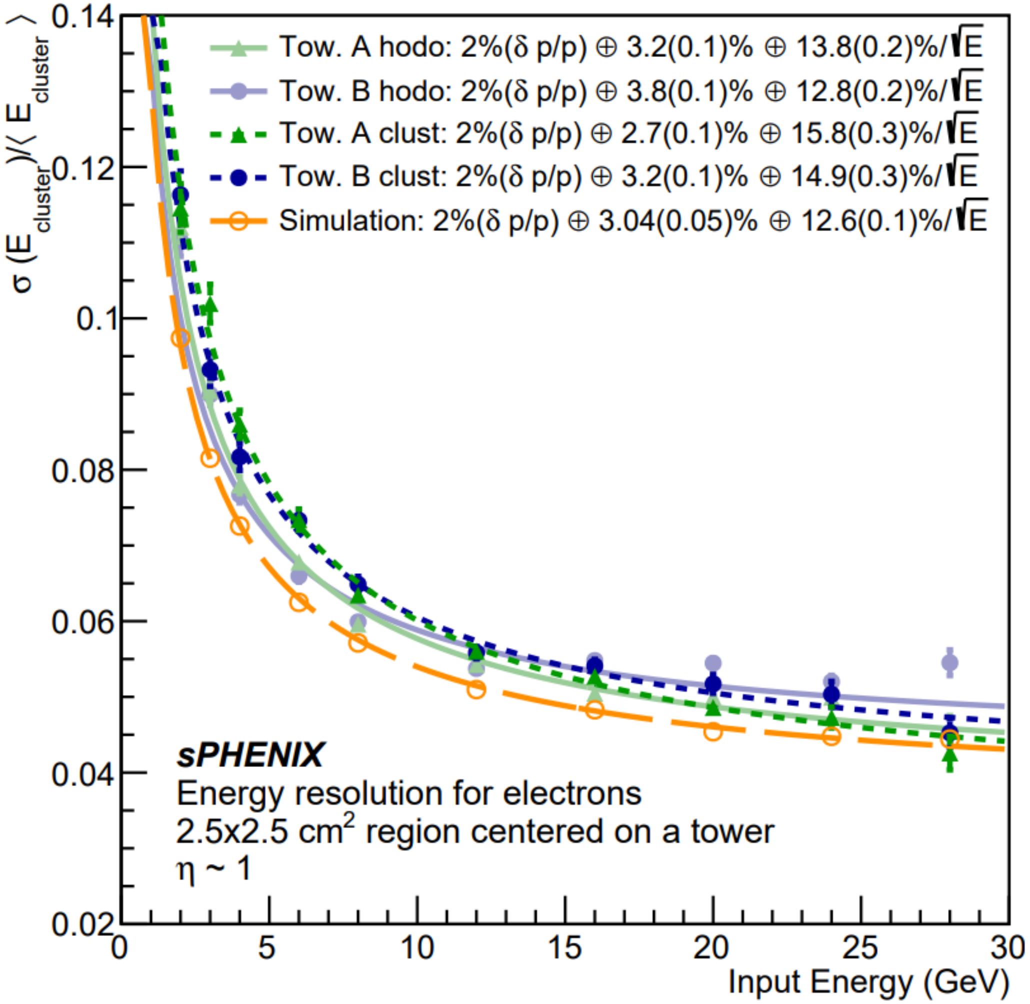
- Tungsten Powder and Scintillating Fiber matrix
- Enables compact design through compact showers
  - $R_m \approx 2.3$ cm
  - Module ~20 radiation lengths ~14 cm

IEEETNS.2020.3034643

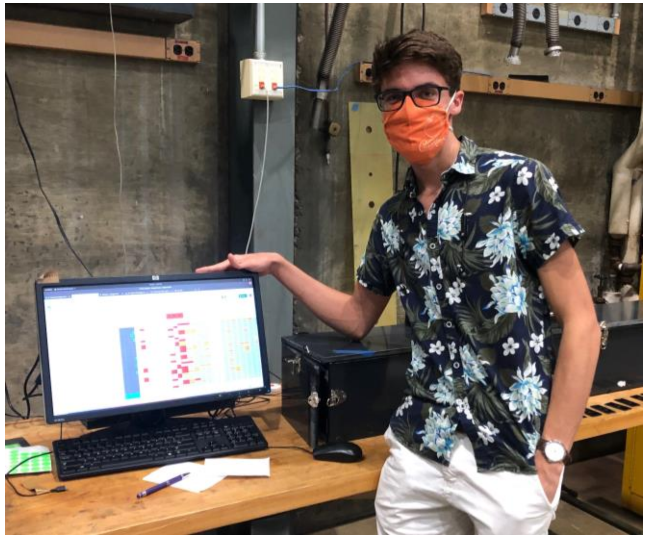
Test Beam Results:

High resolution calorimeter with strong energy linearity!





sPHENIX Calorimeter team at UIUC



Mason Housenga

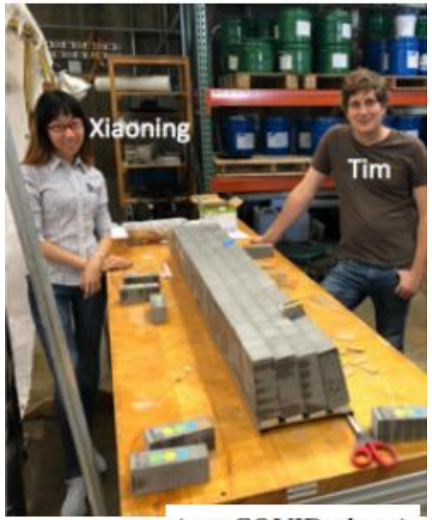
Erin Cook

Saad Altaf

Currently:
22 Undergraduate students
2 Graduate students

Mina Mazeikis

Adin Hrnjic (GS)



(pre-COVID photo)

Xiaoning Wang (GS)

Adam Wehe

sPHENIX run plan

An extensive three-year sPHENIX run is currently planned

- Variety of collision systems!

Additional running is proposed incase the EIC experiences delays

Anticipated run plan from beam use proposal

Year	Species	Energy	Physics Running Weeks	Sampled Luminosity $\|z\| < 10$ cm
2022		Installation and commissioning		
2023	Au+Au	200 GeV	13	$6.9\ nb^{-1}$
2024	p+p	200 GeV	16	$62\ pb^{-1}$
2024	p+Au	200 GeV	5	$0.11\ pb^{-1}$
2025	Au+Au	200 GeV	24.5	$25\ nb^{-1}$

Proposed expanded run plan

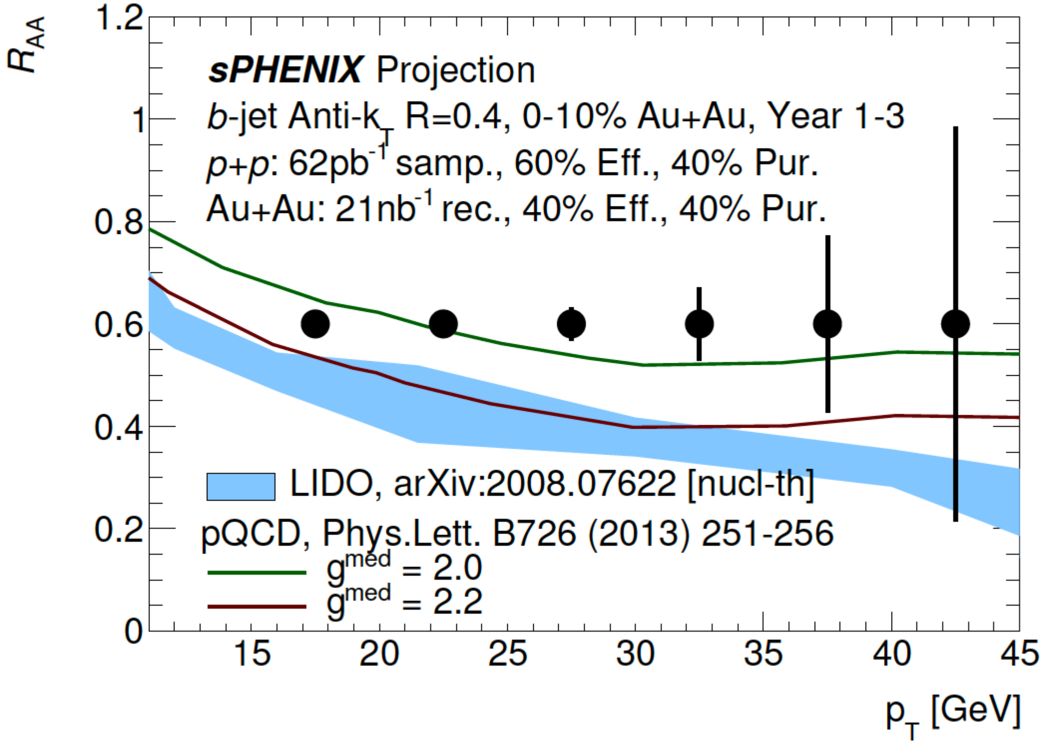
Year	Species	Energy	Physics Running Weeks	Sampled Luminosity $\|z\| < 10$ cm
2026	p+p	200 GeV	15.5	$80\ pb^{-1}$
2026	O+O	200 GeV	13	$37\ nb^{-1}$
2026	Ar+Ar	200 GeV	16	$12\ nb^{-1}$
2027	Au+Au	200 GeV	24.5	$30\ nb^{-1}$

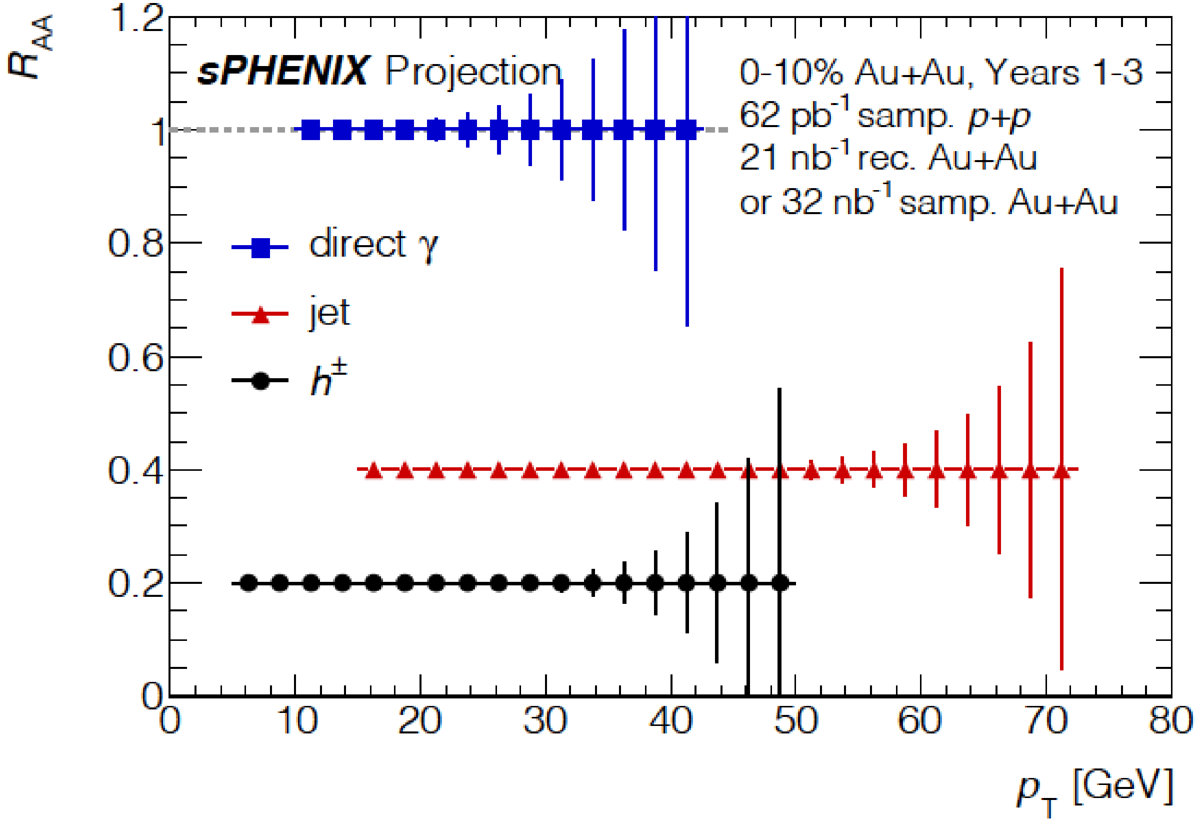
sPHENIX Beam Use Proposal

sPHENIX Projections: Jets

High-statistics data will enable multi-dimensional studies of jets and heavy flavor jets

- ➢Tons of jets!

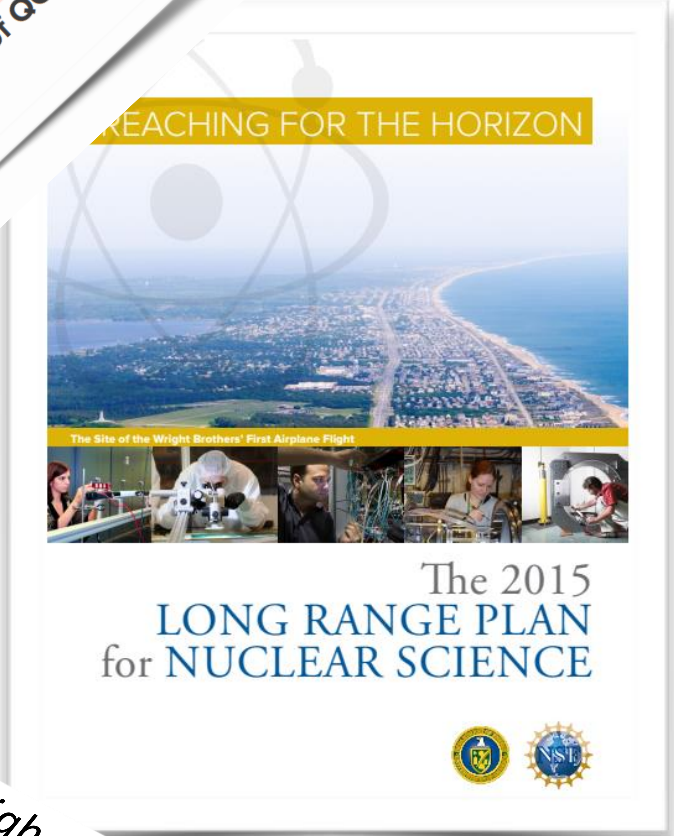




Summary

- ➢Heavy ion physics provides key insights to the properties of the quark gluon plasma
- ➢Jet measurements from both RHIC and the LHC
- ➢Precise jet measurements from sPHENIX will provide critical information on jet quenching at RHIC energies!
  - ➢Enhanced constraint for theoretical models

There are two central goals of measurements planne 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 plann at RHIC.



"We recommend a high-energy high-luminosity polarized **EIC as the highest priority for new facility** following the completion of FRIB"

Backups

Direct Photons, hadrons, and Jets:

https://arxiv.org/pdf/2102.11337.pdf

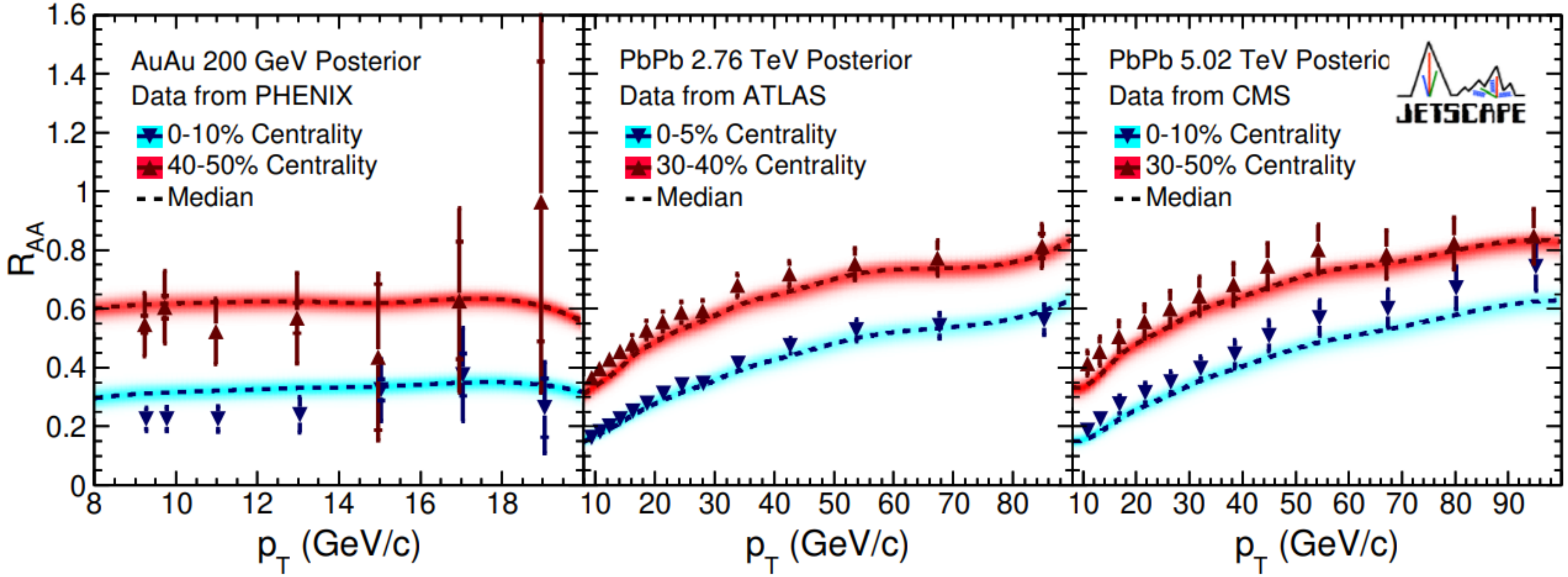


FIG. 7. (Color online) Posterior predictive distributions of inclusive hadron R_{AA} using LBT compared to the same data as Fig. 6.

- Bayesian analysis of world charged hadron R_{AA} data to extract the jet transport coefficient, $\hat{q}$, using the JETSCAPE framework

Direct Photons, hadrons, and Jets:

https://arxiv.org/pdf/2102.11337.pdf

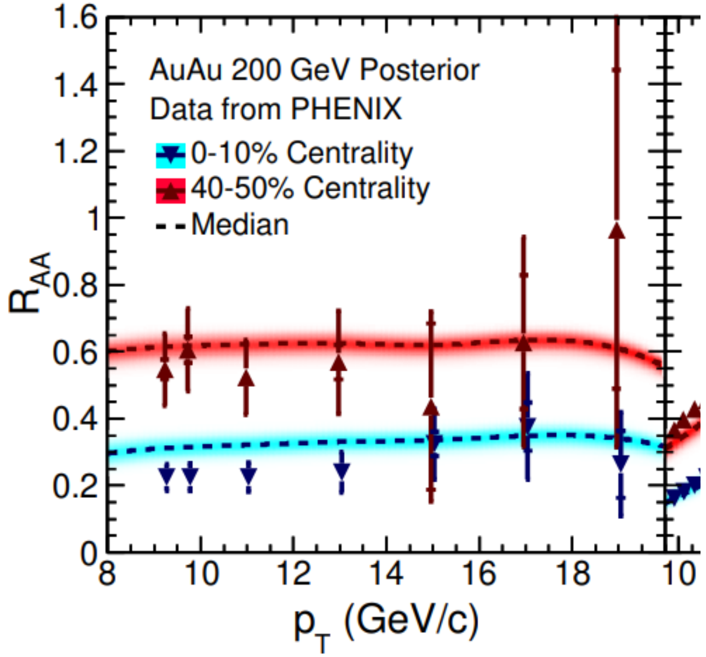
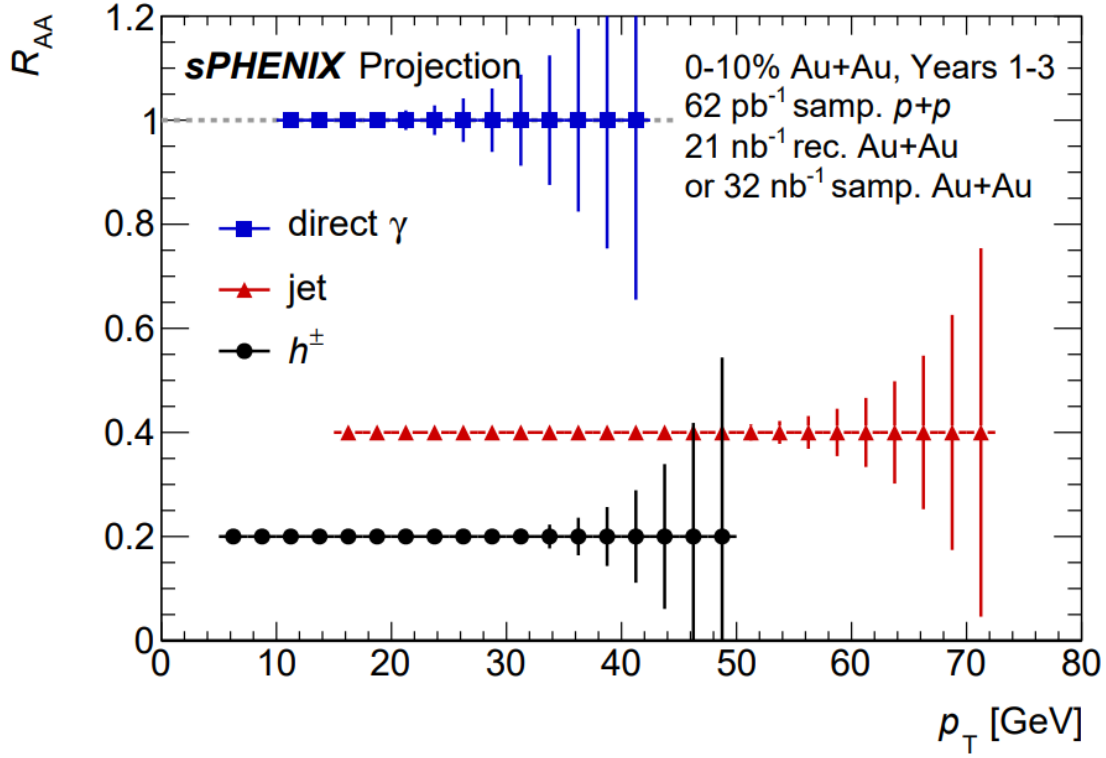


FIG. 7. (Color online) Posterior predictive distri
Fig. 6.

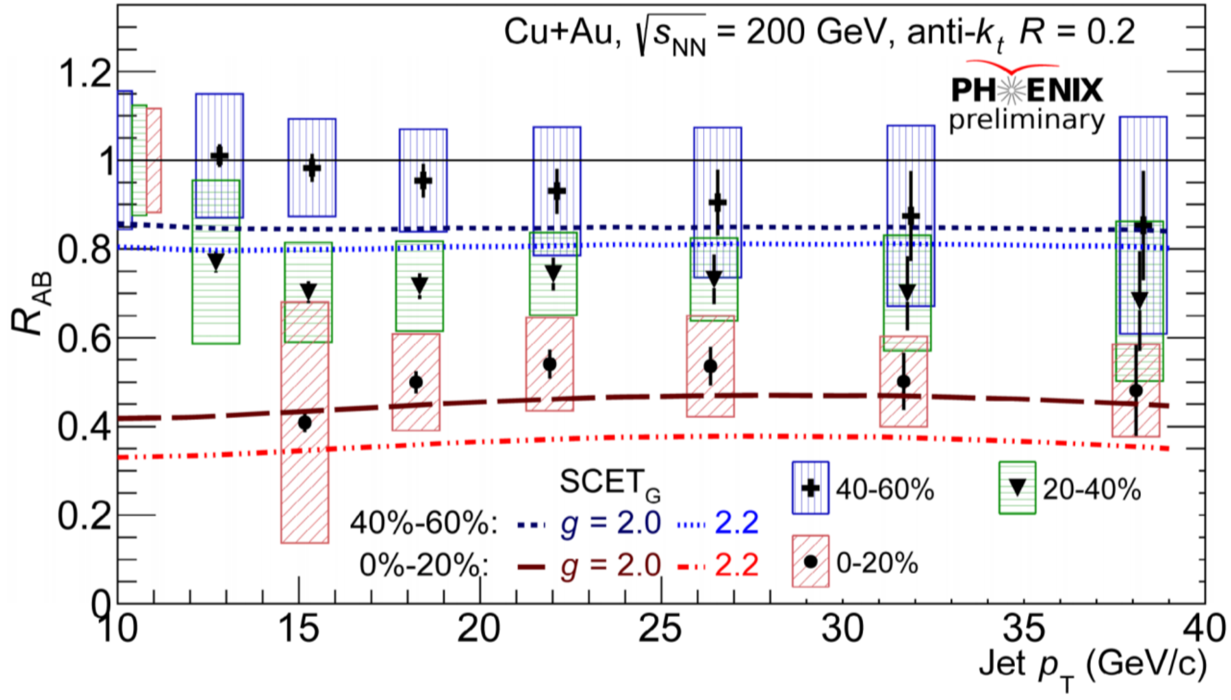


ıa as

- ➢ Bayesian analysis of world charged hadron R_{AA} data to extract the jet transport coefficient, $\hat{q}$, using the JETSCAPE framework
- ➢ Enhanced charged R_{AA} precision and reach compared to PHENIX will provide constraint to theoretical models at RHIC energies

Nuclear Modification of Jets in Cu+Au

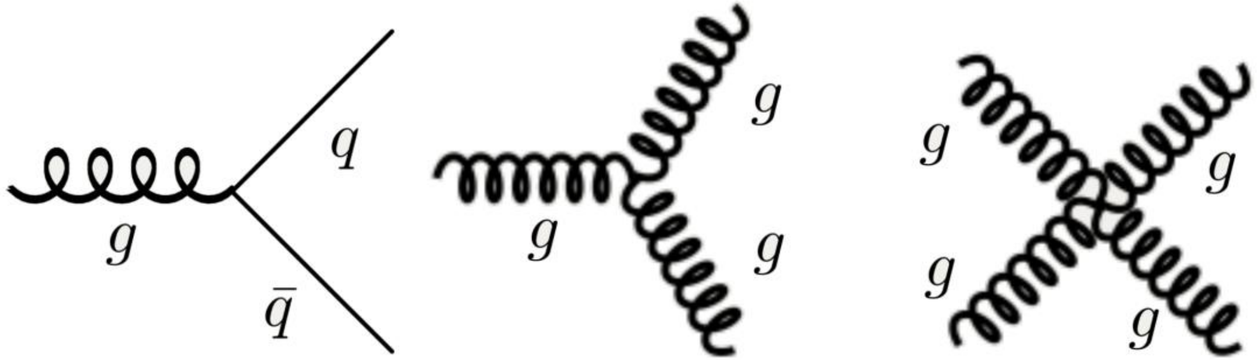
- Clear centrality dependence to modification
- No significant p_T dependence observed
- Similar suppression as seen in 0-20% Cu+Au events as observed in Au+Au (R_{CP}) and Pb+Pb (R_{AA}) collisions



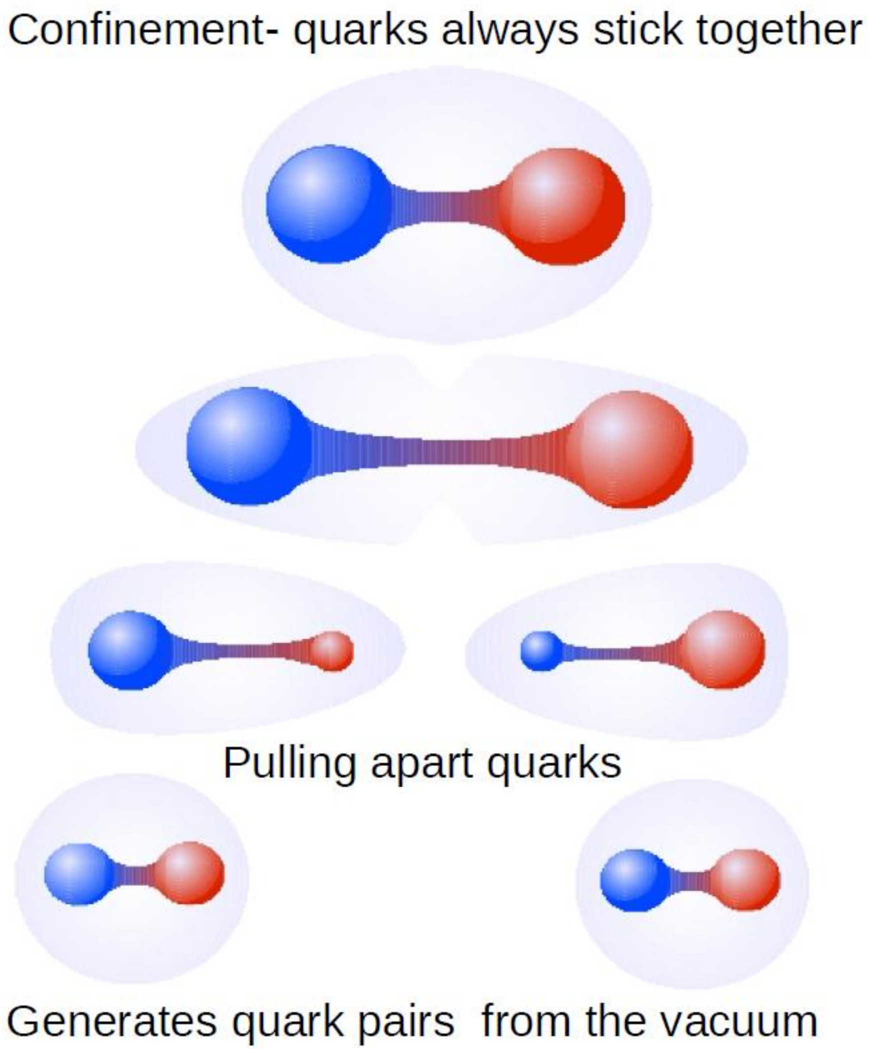
Quantum Chromodynamics

Quantum Chromo Dynamics (QCD) describes interactions between quarks and gluons

Contains 3 principal interactions based upon *color charge*



Understanding the properties of the strong force is one of the principle goals of experimental nuclear physics



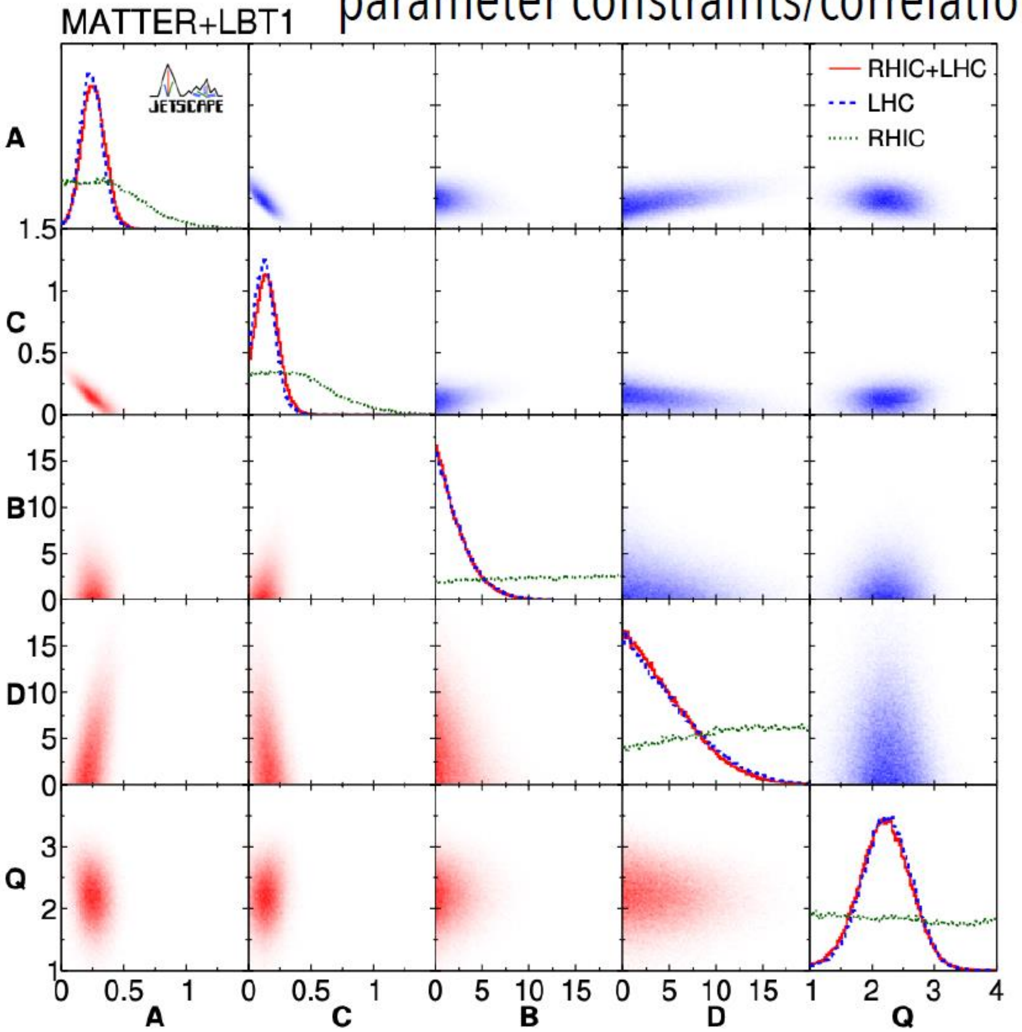
Global Bayesian Analysis: JetScape

$$\frac{\hat{q}\,(E,T)\,|_{A,B,C,D}}{T^3} = 42C_R\frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2\left\{\frac{A\left[\ln\left(\frac{E}{\Lambda}\right)-\ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2}+\frac{C\left[\ln\left(\frac{E}{T}\right)-\ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}\right\}$$

Constraint in the JETScape Bayesian analysis comes primarily from LHC data

Future data from sPHENIX with increased kinematic reach and precision will be able to help constrain the temperature dependence to $\hat{q}$

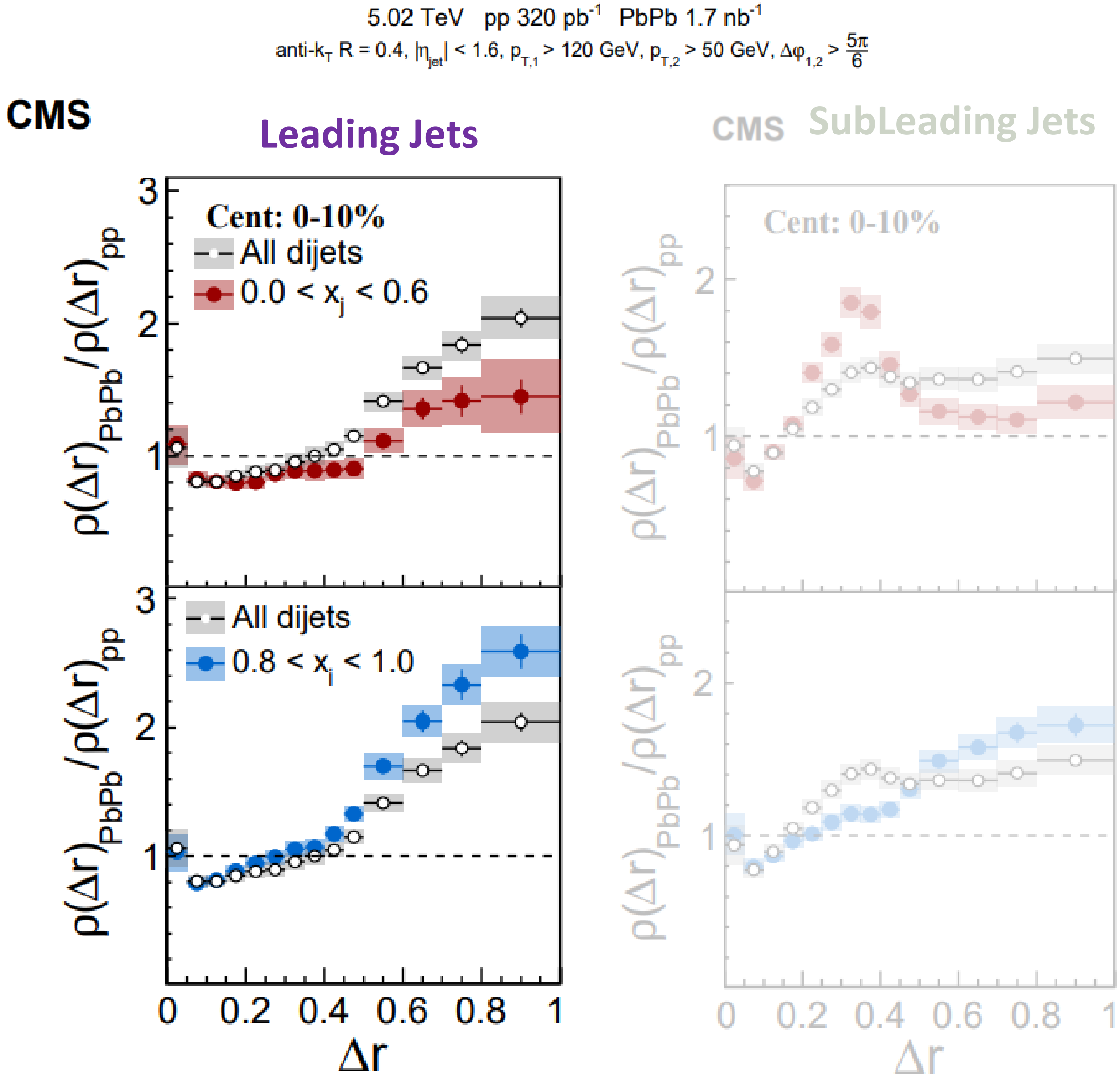
parameter constraints/correlations



arXiv:2101.04720

Leading Dijet Fragmentation

ρ is proportional to track momentum density in a radius window



No significant modification from **inclusive** dijets to the jet shape of the **leading jet** for highly **asymmetric** dijets

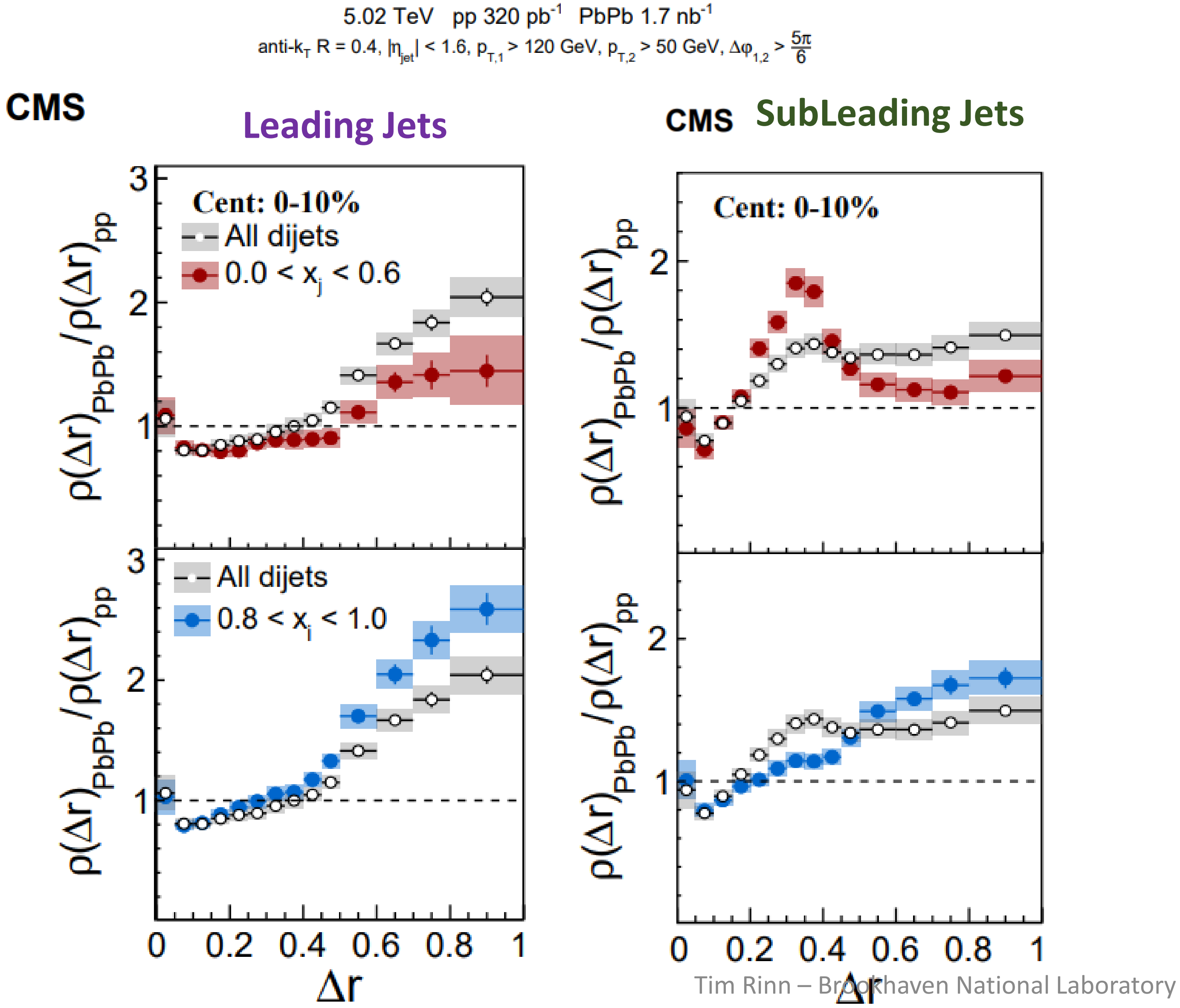
$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\Sigma_{\text{tracks}\in(\Delta r_a,\Delta r_b)}\, p_T^{ch},$$

$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{\text{jets}}\Sigma_{\text{tracks}\in\Delta r<1}\, p_T^{ch}}.$$

arXiv:2101.04720

ρ is proportional to track momentum density in a radius window

Leading Dijet Fragmentation

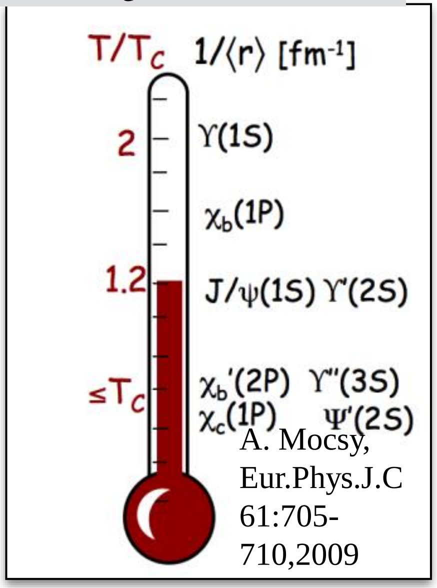


No significant modification from **inclusive** dijets to the jet shape of the **leading jet** for highly **asymmetric** dijets

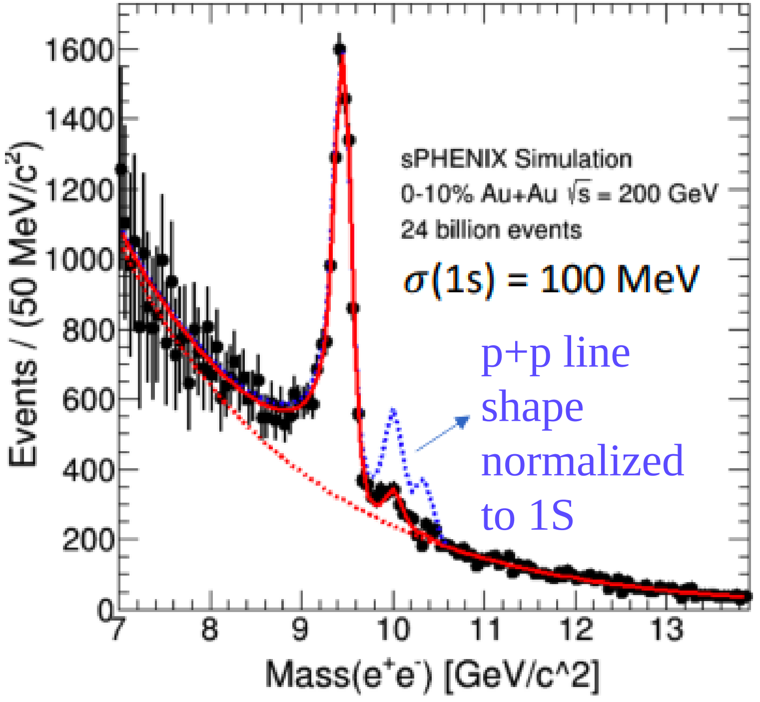
The **subleading** jet for $x_J < 0.6$ observes significant enhancement of fragment momentum between $0.2 < \Delta R < 0.4$

For **symmetric jets** similar modification is seen for the leading and **subleading** jet

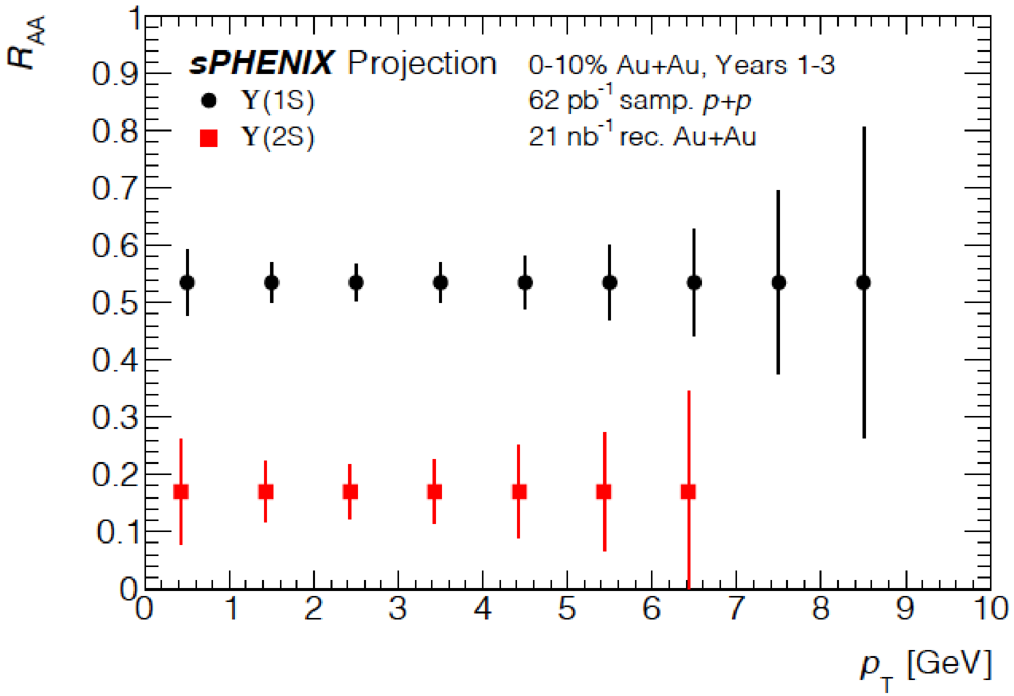
Upsilon Spectroscopy



A. Mocsy, Eur.Phys.J.C 61:705-710,2009



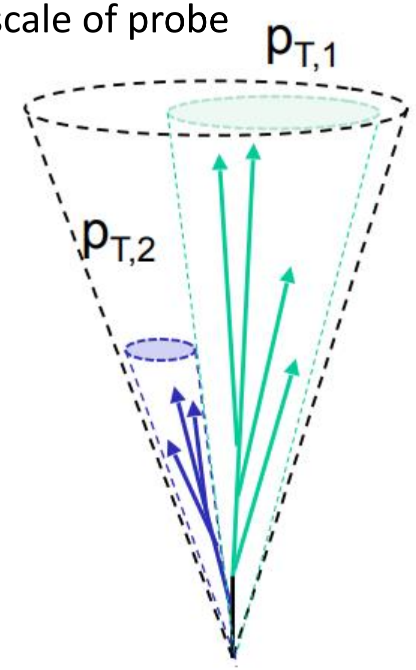
Enables precision measurements of ϒ(1S) and ϒ(2S)



sPHENIX Core Physics Program

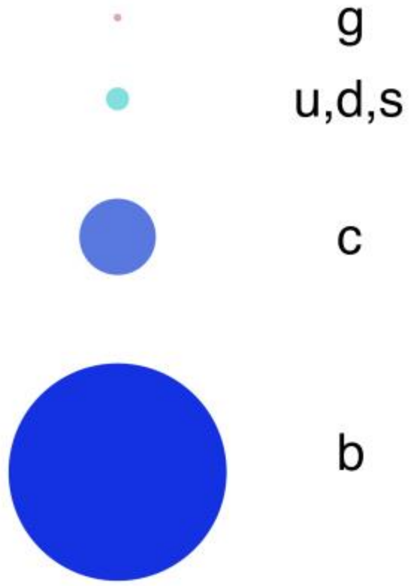
Jet cor. & substructure

Vary momentum/angular scale of probe



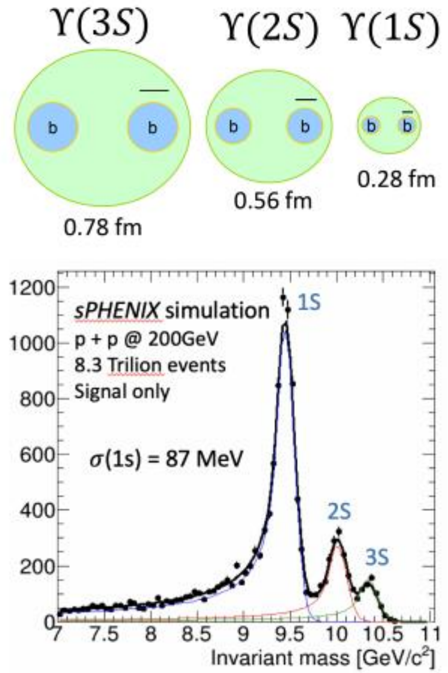
Open heavy flavors

Vary mass/momentum of probe



Upsilon spectroscopy

Vary size of the probe



Yuanjing Ji qm-2019

Resources needed for block construction:

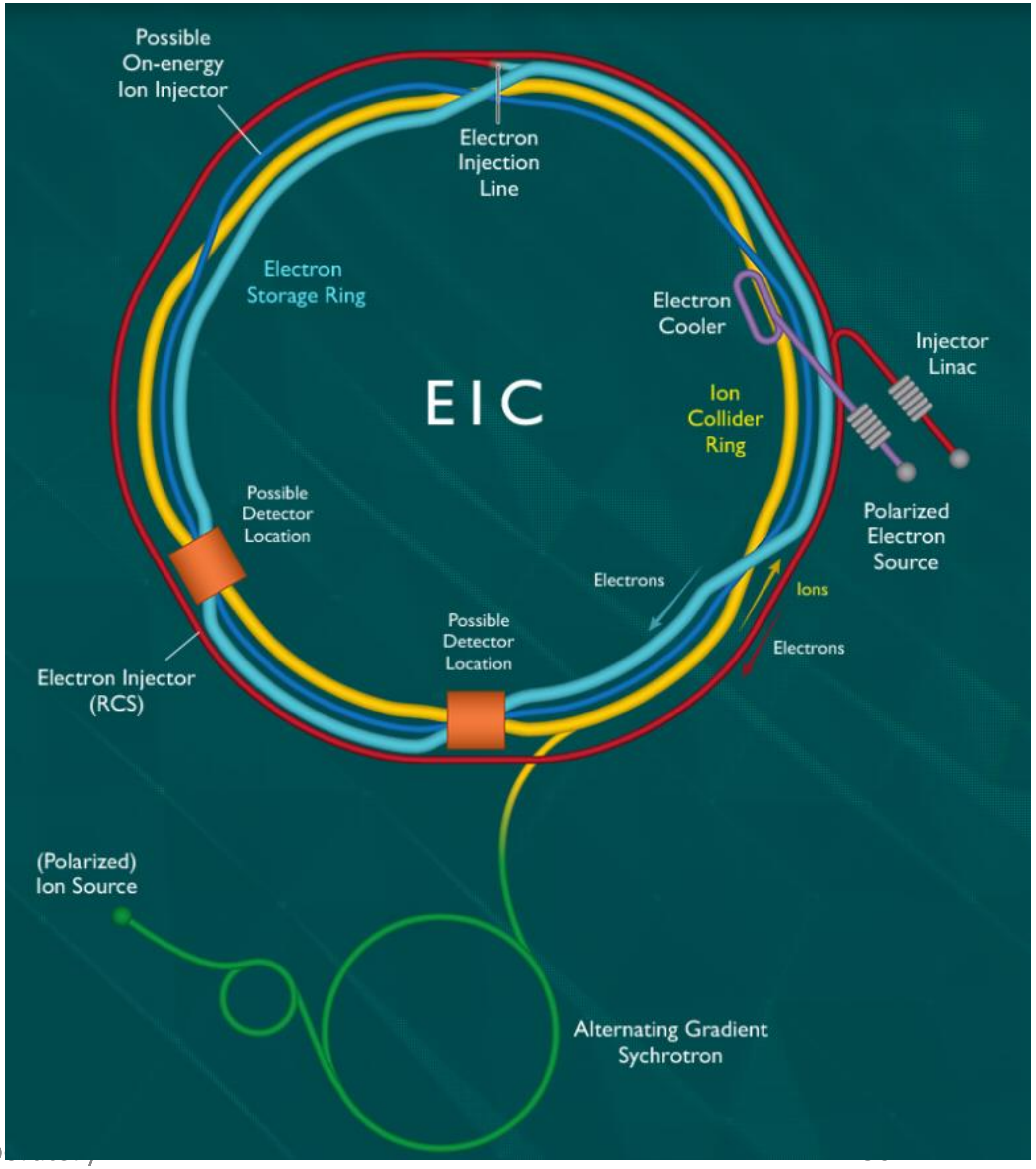
Block Construction Cost: $844 per block + $250 at BNL

• 2600 km of Scintillating Fibers	**$406 per block**
• 665 kg of epoxy	**$19 per block**
• 123 Gallons of Ethanol	**insignificant**
• 88 Square meters of Brass screens	**$36 per block**
• 20 metric tons of Tungsten Powder	**$232 per block**
• Hundreds of Cans of Flex Seal	**~$2 per block**

Labor: $122 per block

The Electron Ion Collider

- Under development high energy electron Ion collider to be located at Brookhaven National Laboratory
  - Utilizes the powerful RHIC accelerator to produce beams of heavy ions and polarized protons
- Expected first beams in 2030!
  - Less than 10 years away
- 2015 Long Range plan for Nuclear Physics: *"We recommend a high-energy high-luminosity polarized* **EIC as the highest priority for new facility** *following the completion of FRIB"*



Key physics questions for the EIC:

Far from an inclusive list!

- What is the mass dependence to the hadronization process?
  - Why do we see light and heavy mesons losing similar amounts of energy in Pb+Pb collisions at the LHC?
- What is the path length dependence to interactions with cold nuclear matter?
  - Versatile collider facility can scan effective path length through varying the target ion
- How do the nucleonic properties such as mass and spin emerge from partons and their interactions
  - ~2 orders of magnitude of improvement in x and Q^2 compared to previous experiments

The ECCE Consortium

- The ECCE consortium looks to build off of the sPHENIX detector to be a day one EIC experiment
  - Natural evolution from sPHENIX to the EIC
  - 47 member institutions
- Expression of Interest submitted in response to the 2020 EIC-EIO call from BNL and Jlab
- Formal proposal is being drafted and will be submitted by years end

Expression of Interest (EOI) for the EIC Collider Detector ("ECCE") Consortium

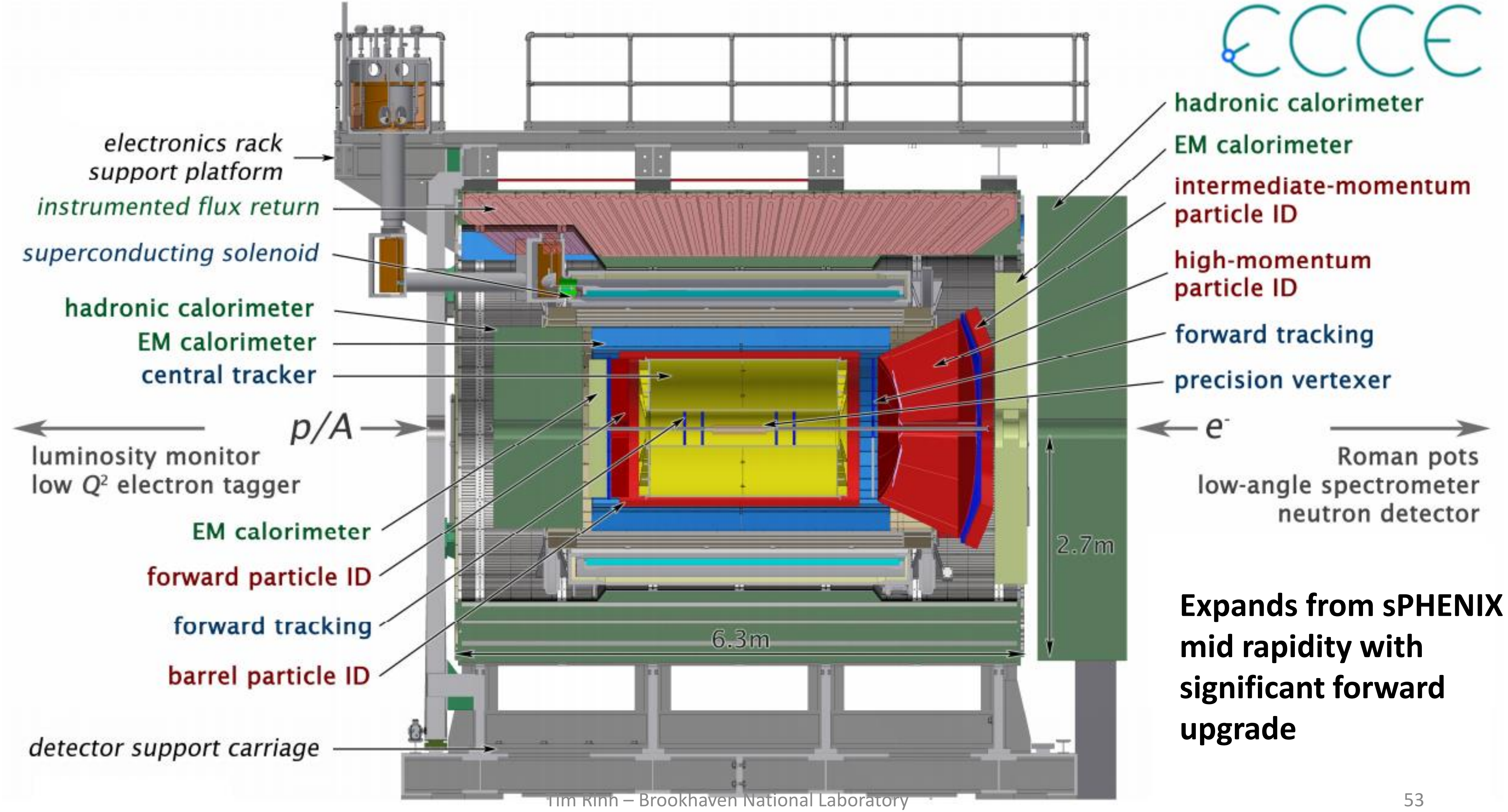
Contact persons for this submission:
Or Hen (hen@mit.edu)
Tanja Horn (hornt@cua.edu)
John Lajoie (lajoie@iastate.edu)

Institutions collectively involved in this submission of interest:
AANL/Armenia, Academia Sinica/Taiwan, BGU/Israel, BNL, CU Boulder, CUA, Charles U./Prague, Columbia, FIU, GWU, GSU, IJCLab-Orsay/France, ISU, JLab, Kentucky, LANL, LLNL, Lehigh, MIT, National Cheng Kung University/Taiwan, National Central University/Taiwan, National Taiwan University/Taiwan, National Tsing Hua University/Taiwan, ODU, Ohio University, ORNL, Rice, Rutgers, SBU, TAU/Israel, UConn, UIUC, UNH, UVA, Vanderbilt, Wayne State, and WI/Israel.

Items of interest for potential equipment cooperation:
The EIC enables an exciting research program which will advance our understanding of the structure of hadronic matter. A state-of-the-art collider detector for the EIC, which is needed to realize its physics program, will be extremely complex. It will require extensive infrastructure, and will need to be integrated into the operation of the accelerator to a very high degree. The technically driven reference schedule for the EIC project is aggressive and presents a significant challenge for an EIC detector to be designed, built, commissioned, and ready to start delivering science when the machine begins to deliver collisions. The substantial resources needed to construct a state-of-the-art detector for the EIC present an additional challenge. Time-tested strategies for addressing such challenges include the reuse of existing infrastructure where suitable and leveraging the hard-won expertise gained through previous successful projects.

The EIC Collider dEtector (ECCE) consortium comprises 36 institutions assembled around the idea of building on the foundation of existing infrastructure available at RHIC IP8 and experimental equipment available there and elsewhere at JLab and RHIC. The consortium includes institutions with wide-ranging world-class detector expertise, strong familiarity with the EIC-suitable characteristics of IP8, and an understanding of the approach to DOE project management. Appropriate use of existing infrastructure will help mitigate several technical and schedule risks of an EIC detector project. The technical expertise in the consortium can build on and extend upon the base provided by existing equipment to provide a complete detector with capabilities mandated by the EIC science requirements as defined by the recent EIC Yellow-Report community effort. The substantial project management experience of the involved institutions provides credible "out of the box" know-how for realizing such a sophisticated detector.

ECCE Detector



Expands from sPHENIX mid rapidity with significant forward upgrade

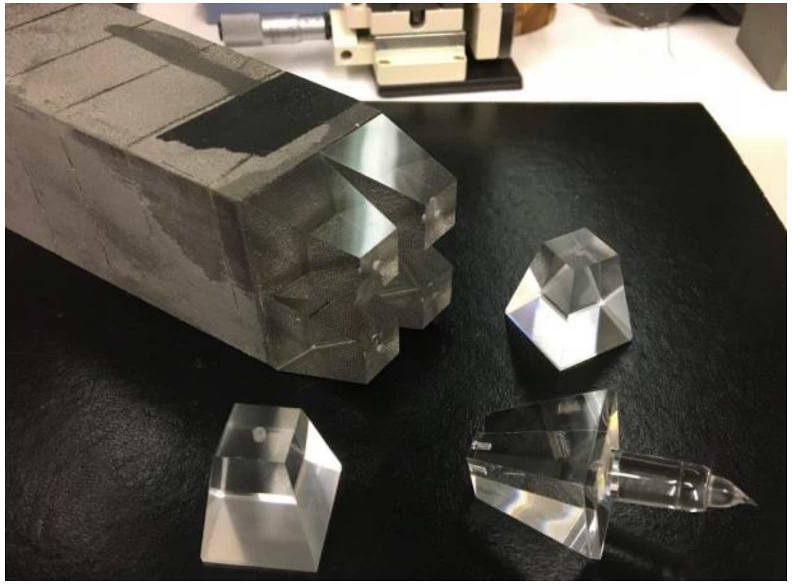
EIC detector construction

- Opportunity to pursue DOE/NSF funding to develop and produce the forward calorimeter systems
  - Build off experience constructing the sPHENIX calorimeter
  - Collaboration with other universities such as Iowa State University, University of Illinois, and Georgia State University

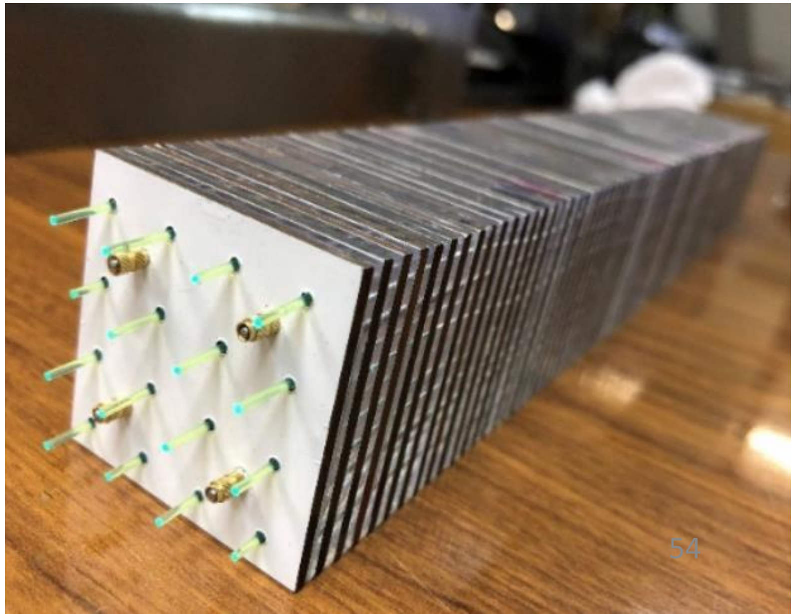
- Significant opportunities for early involvement
  - Establish as system experts in time for day one physics
  - Great opportunity for students to have hands on experience in detector construction

- Several design ideas already being explored!

Tungsten powder scintillating fiber



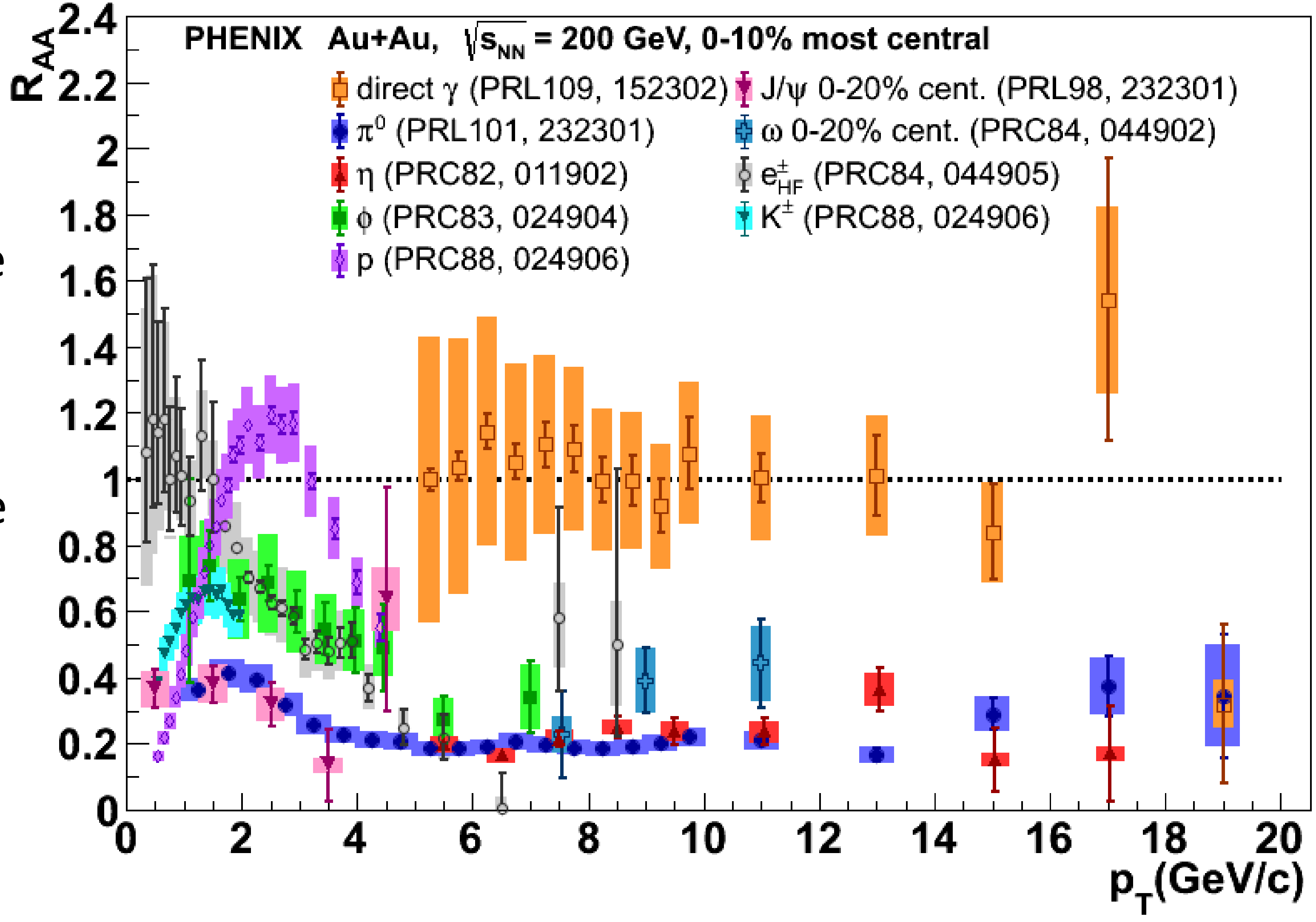
Tungsten/scintillating tile calorimeter



Key Evidence for QGP as strongly interacting medium

Energy Loss of color charged probes

- Quarks and gluons lose energy as they propagate through the plasma
- Direct photons (γ) do not interact strongly and therefore and experience no energy loss

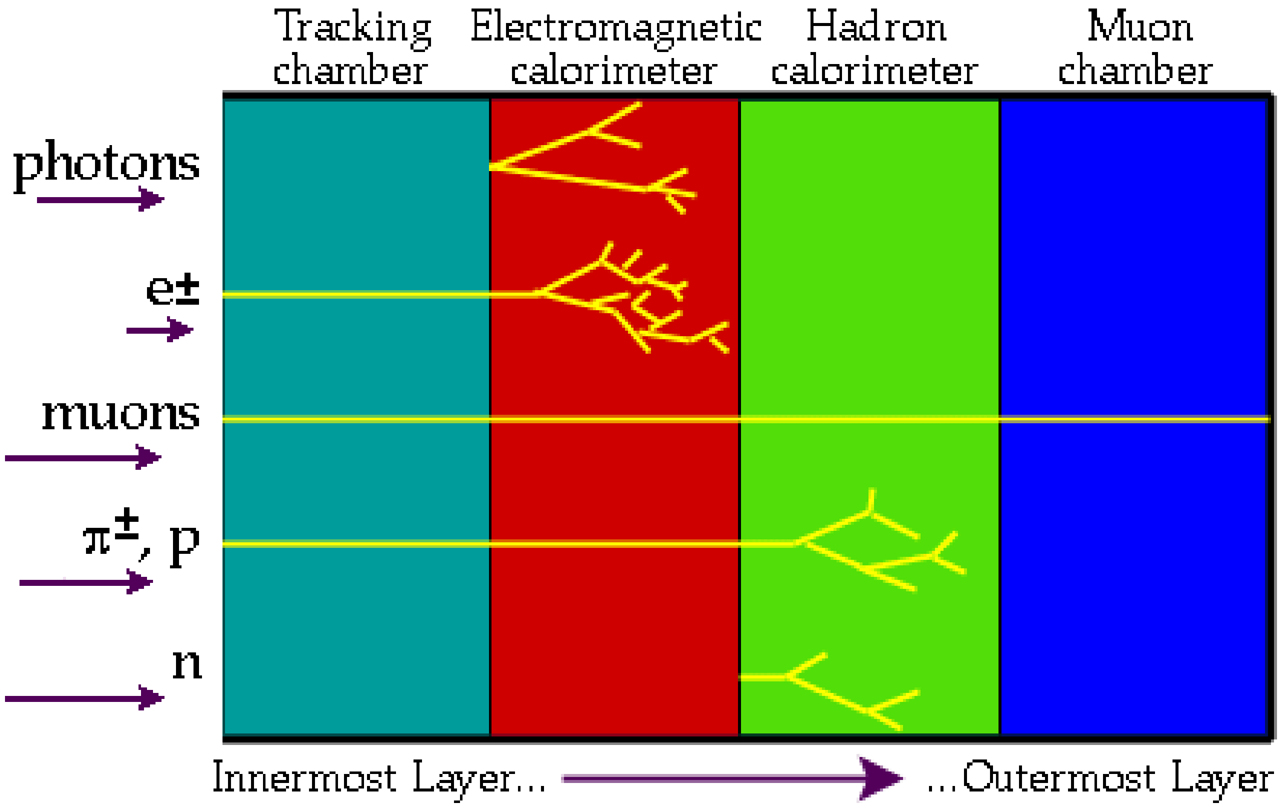


$$R_{AA} \equiv \frac{1}{\langle \mathrm{T_{AA}} \rangle} \frac{\mathrm{dN_{AA}}/\mathrm{dp_T}}{\mathrm{d}\sigma_{pp}/dp_T}$$

$$\langle T_{AA} \rangle \equiv \langle N_{coll} \rangle / \sigma^{pp}$$

Measuring various types of particles

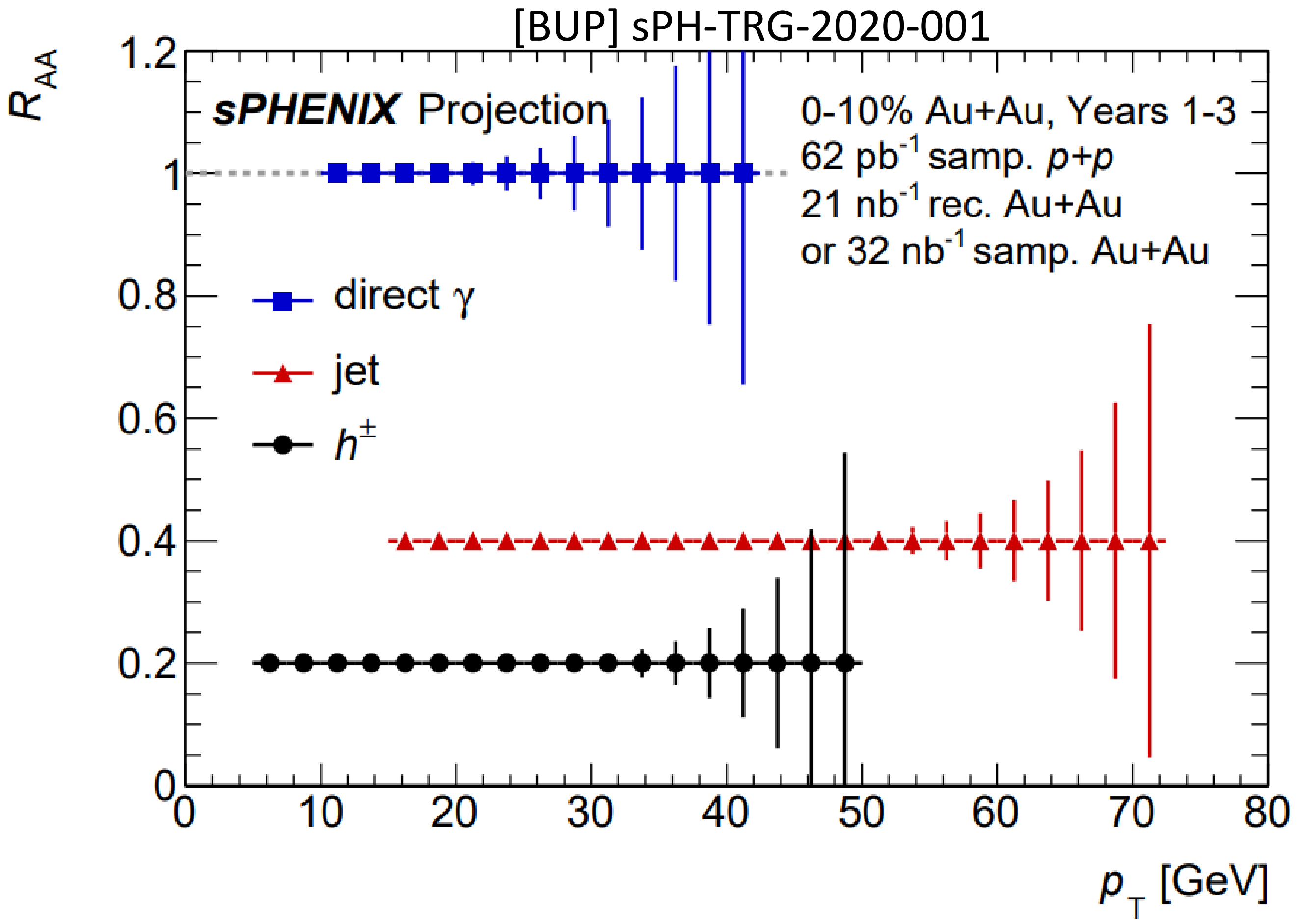
Typical detectors have up to 4 main classes of detector systems



$$R_{AA} \equiv \frac{1}{N_{Coll}} \frac{\frac{d^2 N_{AA}}{dy dp_T}}{\frac{d^2 N}{dy dp_T}}$$

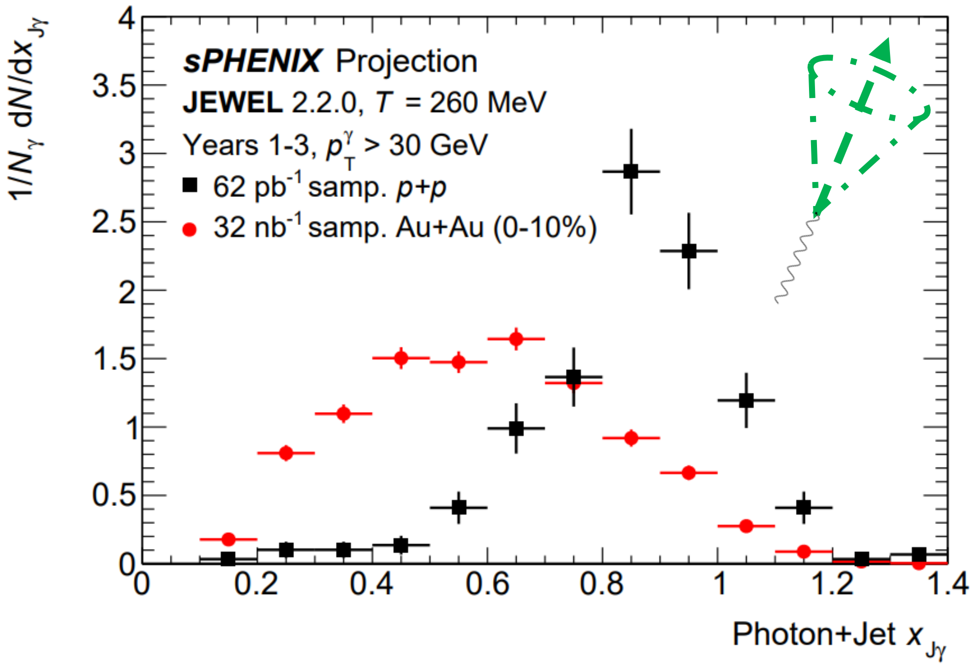
Direct Photons, hadrons, and Jets:

Signal	Au+Au 0–10% Counts	$p+p$ Counts
Jets $p_T > 20$ GeV	22 000 000	11 000 000
Jets $p_T > 40$ GeV	65 000	31 000
Direct Photons $p_T > 20$ GeV	47 000	5 800
Direct Photons $p_T > 30$ GeV	2 400	290
Charged Hadrons $p_T > 25$ GeV	4 300	4 100

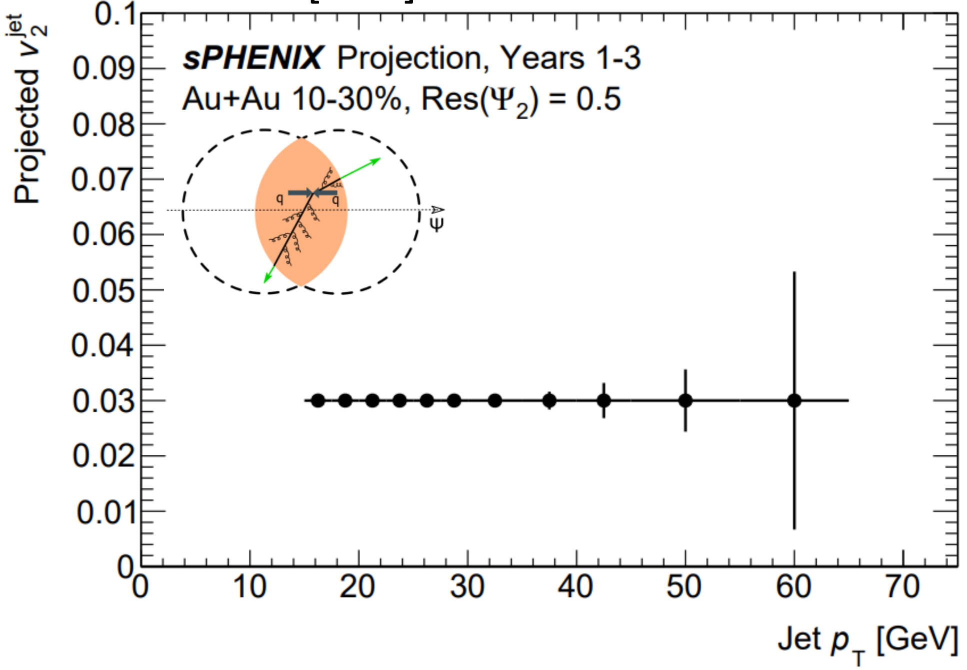


Large statistic data samples will enable multi dimensional jet studies with new high p_T reach!

Jet Correlations:



[BUP] sPH-TRG-2020-001



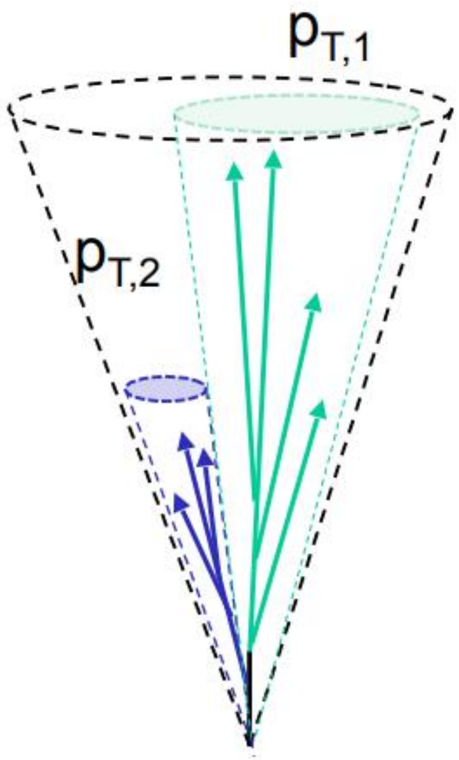
Large statistical sample enables high precision measurement of photon-jet balance

Ability to study event plane dependence to jet quenching

- Enable simultaneous comparison of models across LHC and RHIC energies

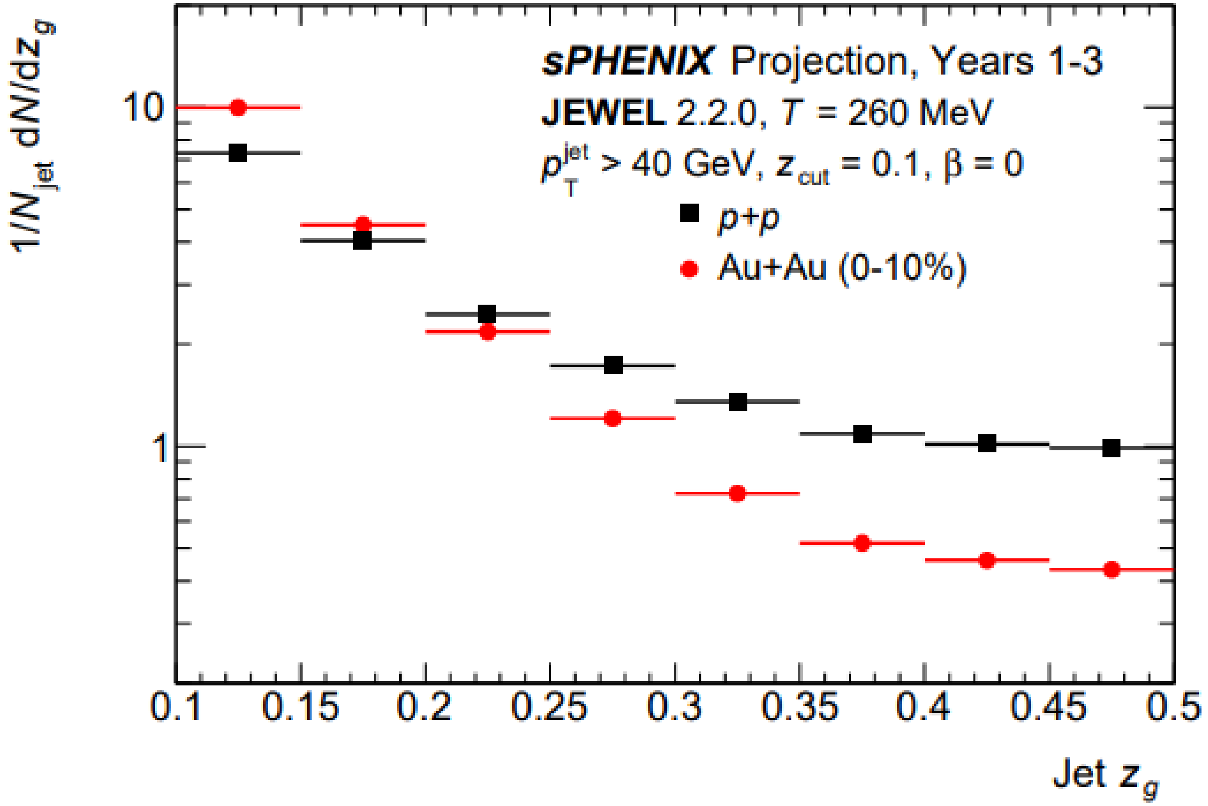
Jet Sub-structure:

sPHENIX fine segmentation in the calorimeter and tracking resolution will enable studies of jet sub-structure



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

Jet Sub-structure:
Splitting function

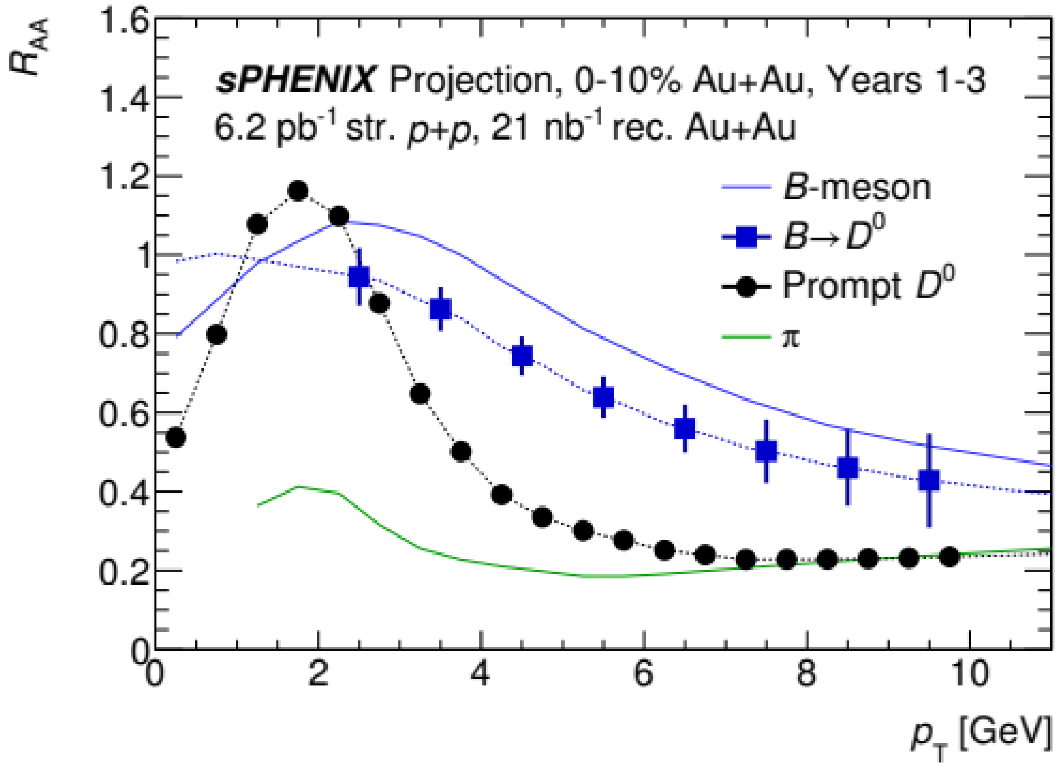


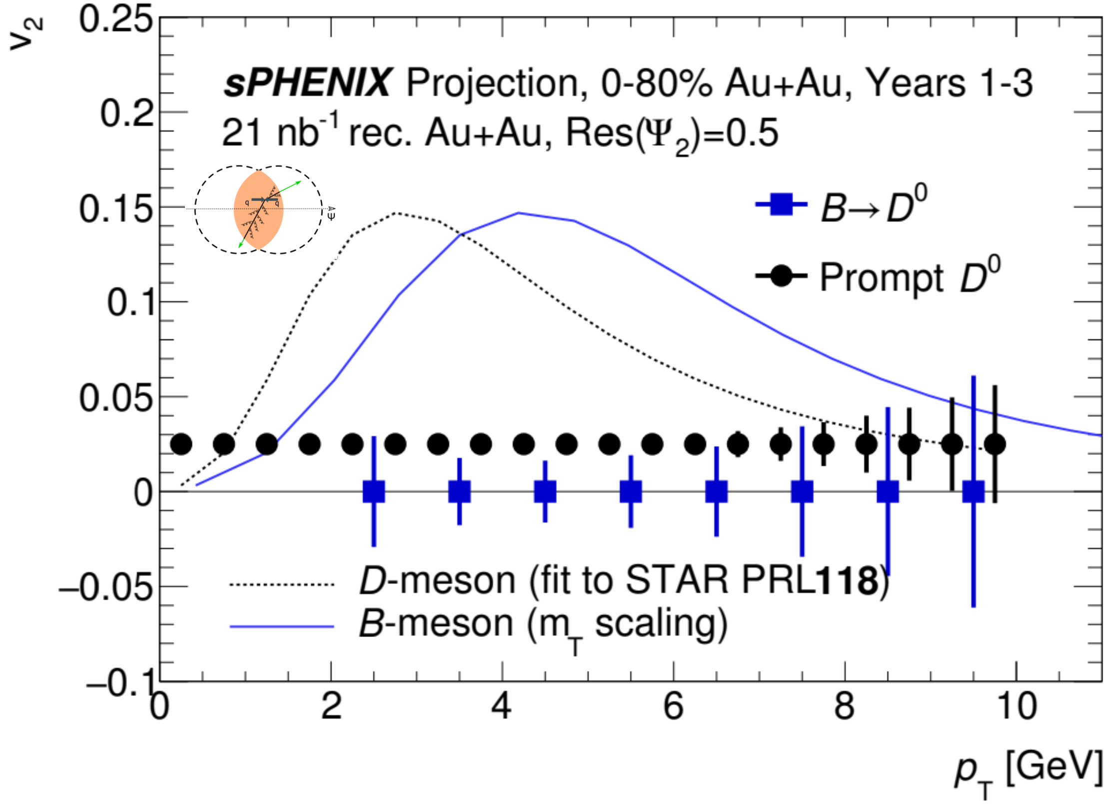
[BUP] sPH-TRG-2020-001

Open Heavy Flavor:

Precision tracking and vertexting will enable extensive heavy flavor measurements in sPHENIX

[BUP] sPH-TRG-2020-001

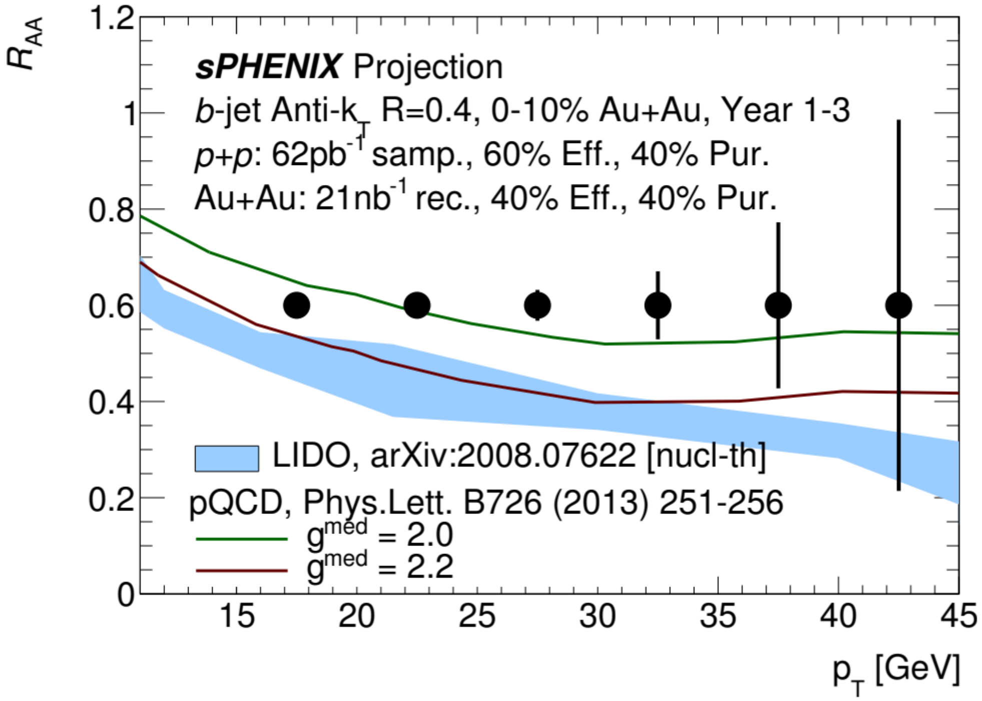


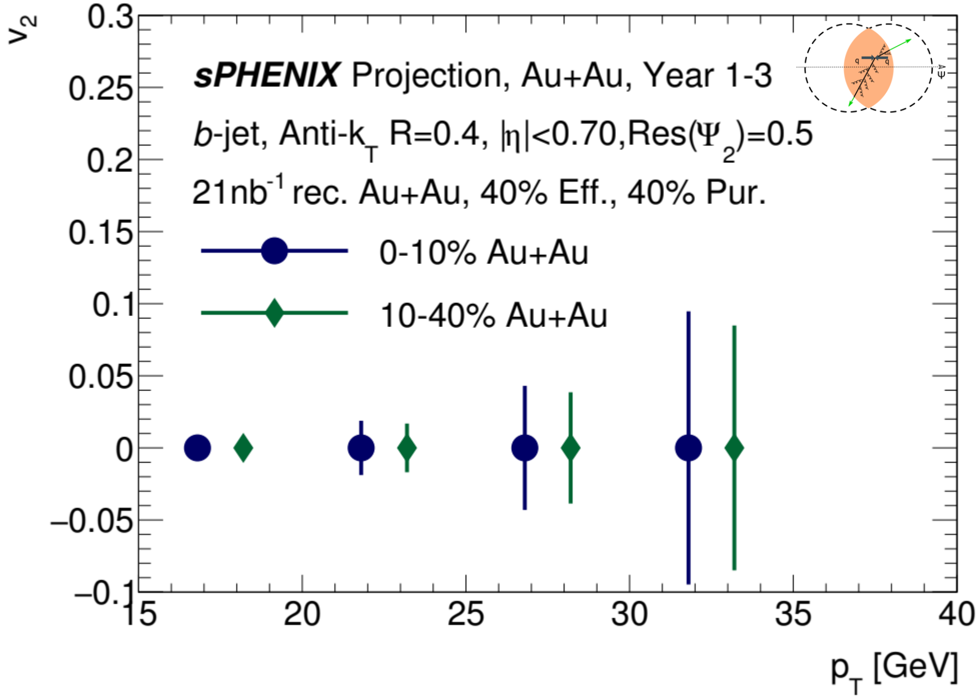


Heavy flavor quarks enables a powerful range with which to study the mass dependence to interactions within the QGP

Heavy Flavor Jets:

[BUP] sPH-TRG-2020-001

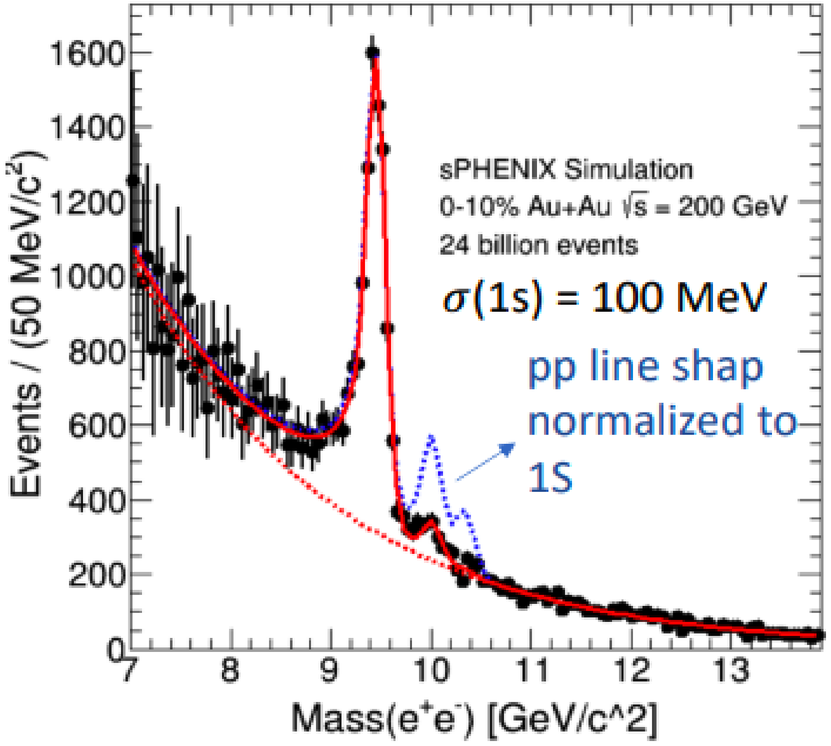


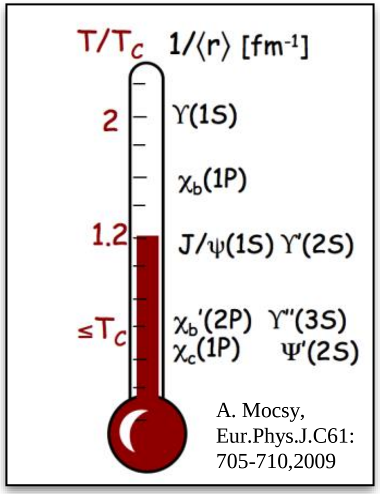


MVTX will enable heavy flavor jet tagging!

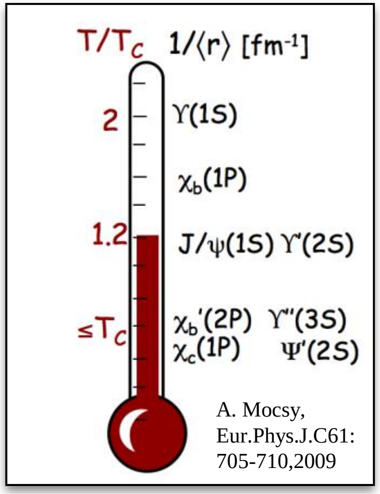
- ➢ Enables study at of heavy flavor at high p_T where the mass difference between heavy and light quarks is less significant

Upsilon Spectroscopy:



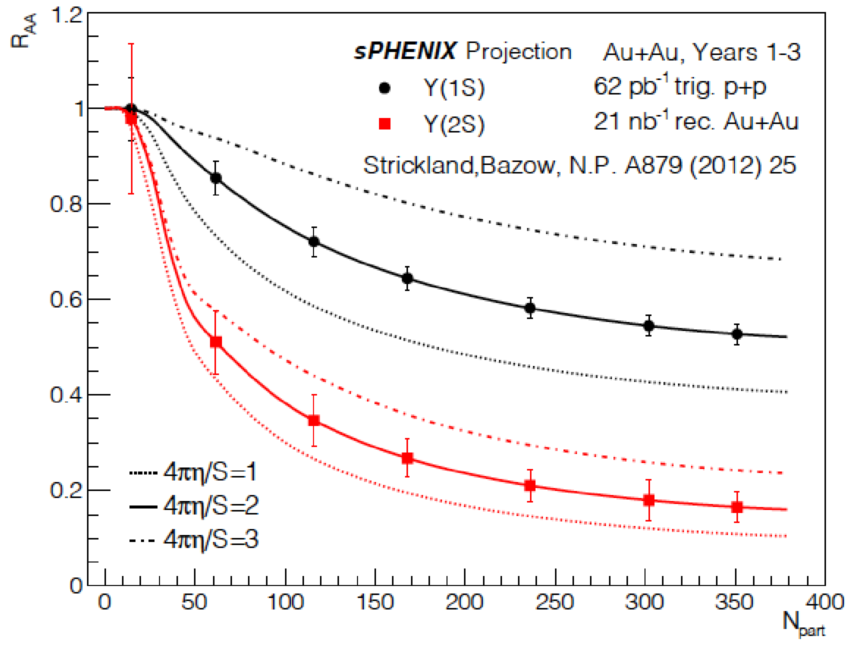


- The high-temperature medium induces melting of Upsilon states
  - Higher-mass states melt more readily at a fixed medium temperature
- Precise mass resolution of sPHENIX tracking will enable separation of ϒ states in both Au+Au and *pp*:
  - First for RHIC

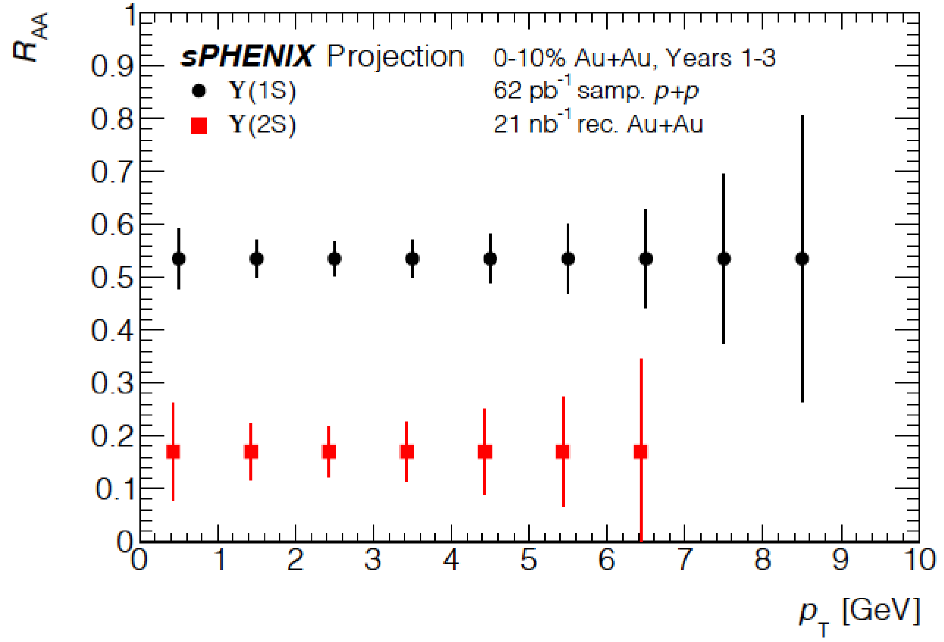


Upsilon Spectroscopy:

R_{AA} number of participant dependence



p_T dependence of ϒ modification



- sPHENIX will enable precise modification factor measurements of ϒ suppression across centrality and ϒ p_T for 1S and 2S states

sPHENIX Detector:

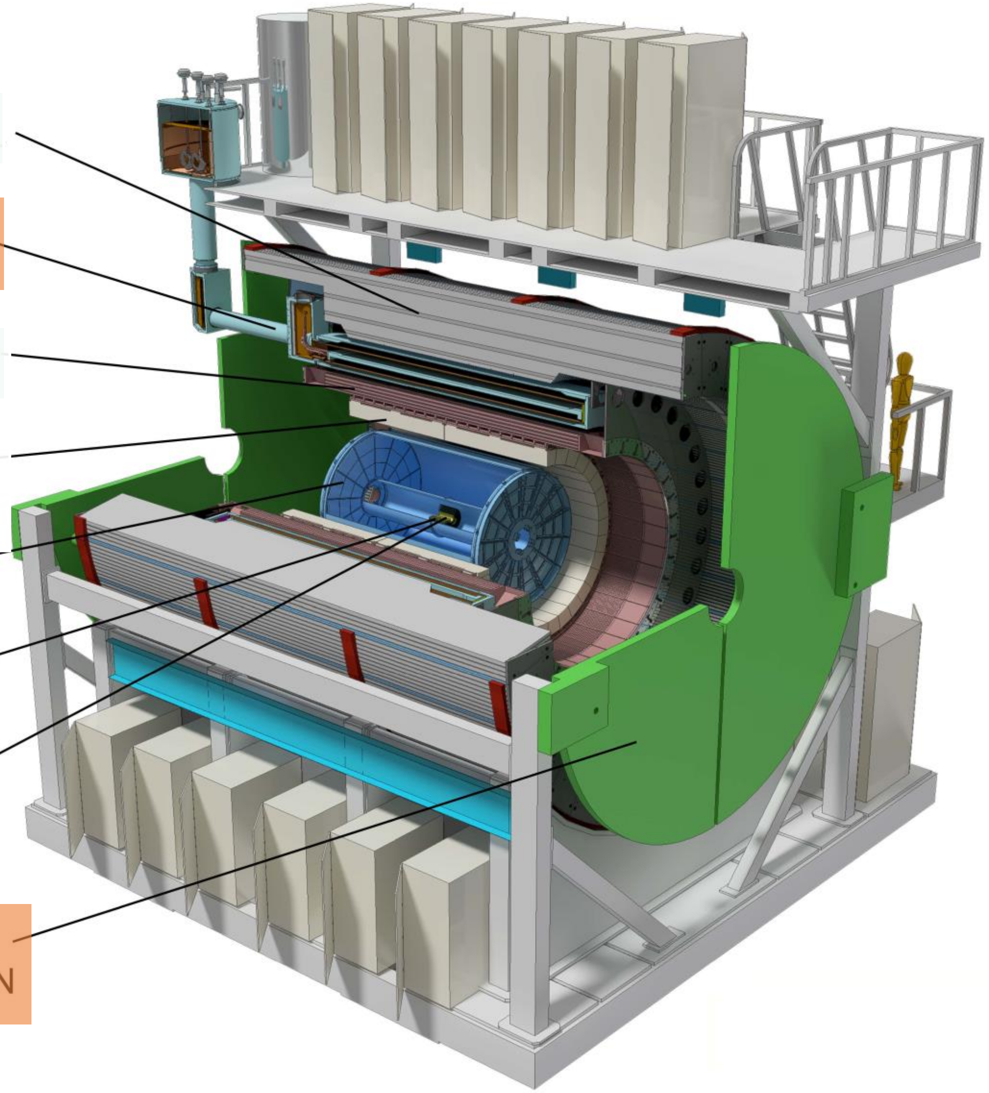
Tracking system:
MAPS-based Vertex Tracker (MVTX)
Intermediate Silicon Tracker (INTT)
Time Projection Chamber (TPC)

Superconducting Magnet (1.4 T solenoid)

Calorimetry:
Electromagnetic Calorimeter (EMCal)
inner Hadronic Calorimeter
outer Hadronic Calorimeter

High Rate DAQ and trigger system:

15 kHz Trigger, >10 GB/s DAQ



sPHENIX Tracking:

MAPS-based Vertex Tracker (MVTX)

- 3 layers of Monolithic Active Pixel Sensors (ALICE)
- Short integration time (few μs)
- Great spatial resolution < 6 [μm]
- Ultra-thin ~0.3%X_0

precise vertexing

Intermediate Silicon Tracker (INTT)

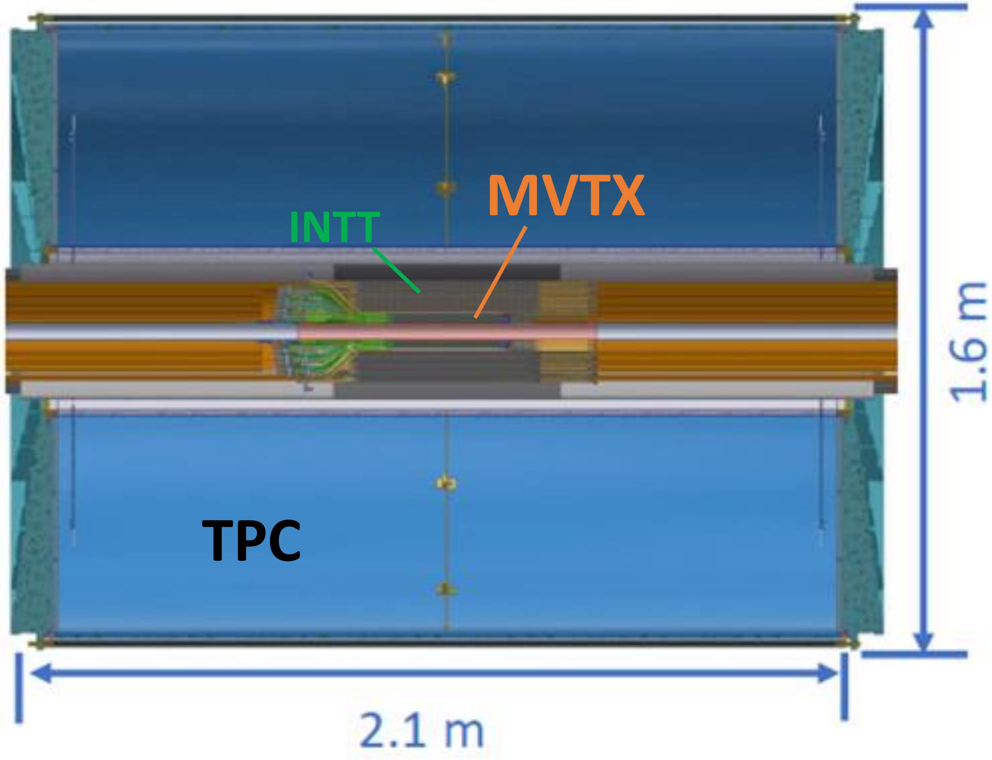
- 2 layers of strip silicon sensors

pattern recognition & timing

Time Projection Chamber (TPC)

- Compact: 20 < r [cm] < 78
- Spatial resolution < 200 μm
- Charge collection via GEMs

momentum measurement



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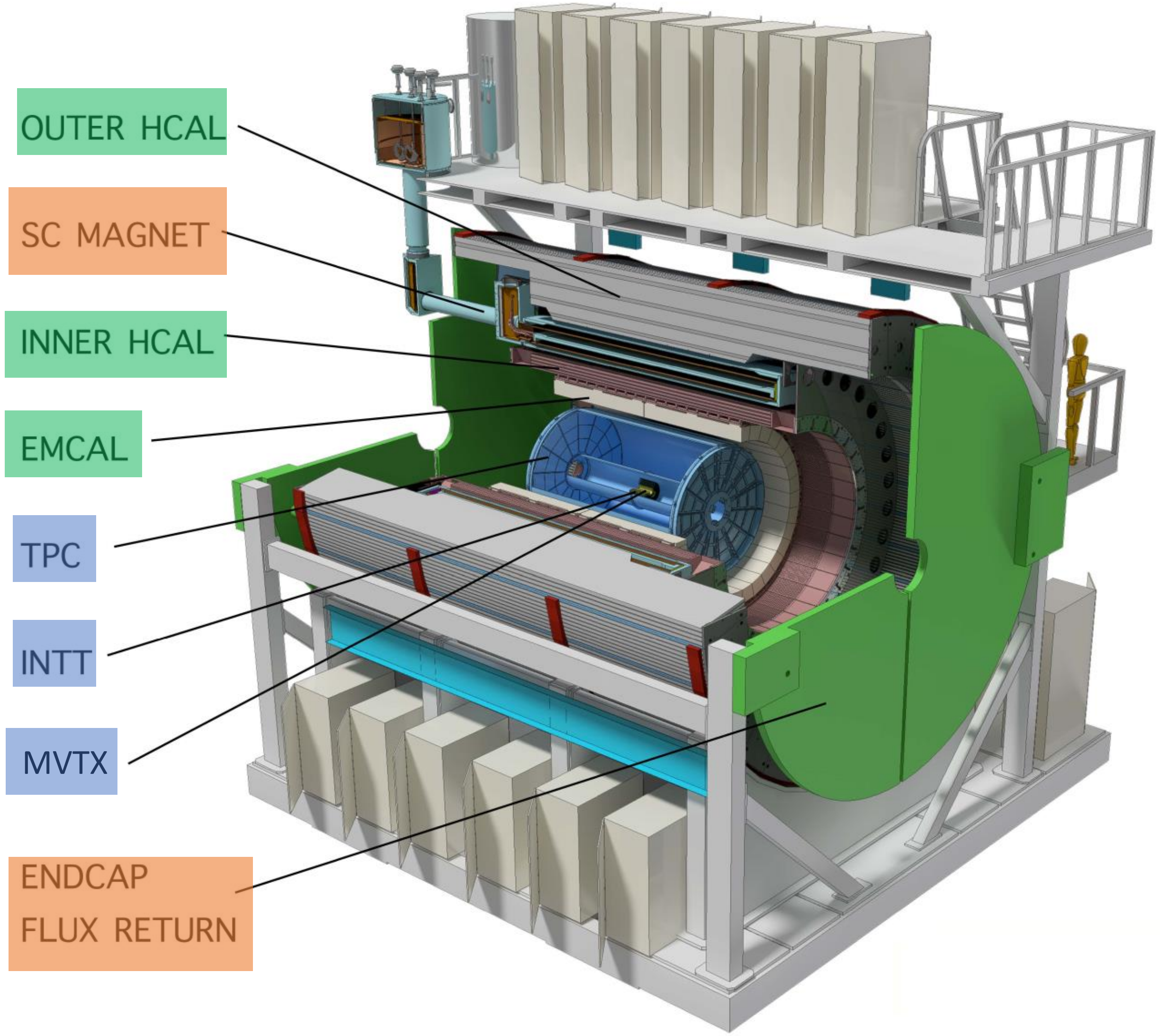


sPHENIX Calorimetry:

Full Electromagnetic and Hadronic calorimeter system!

- Large Acceptance: $|1.1| < \eta$ and full 2π azimuthal coverage
- SiPM used for light collection/readout

outer Hadronic Calorimeter (Outer HCal)

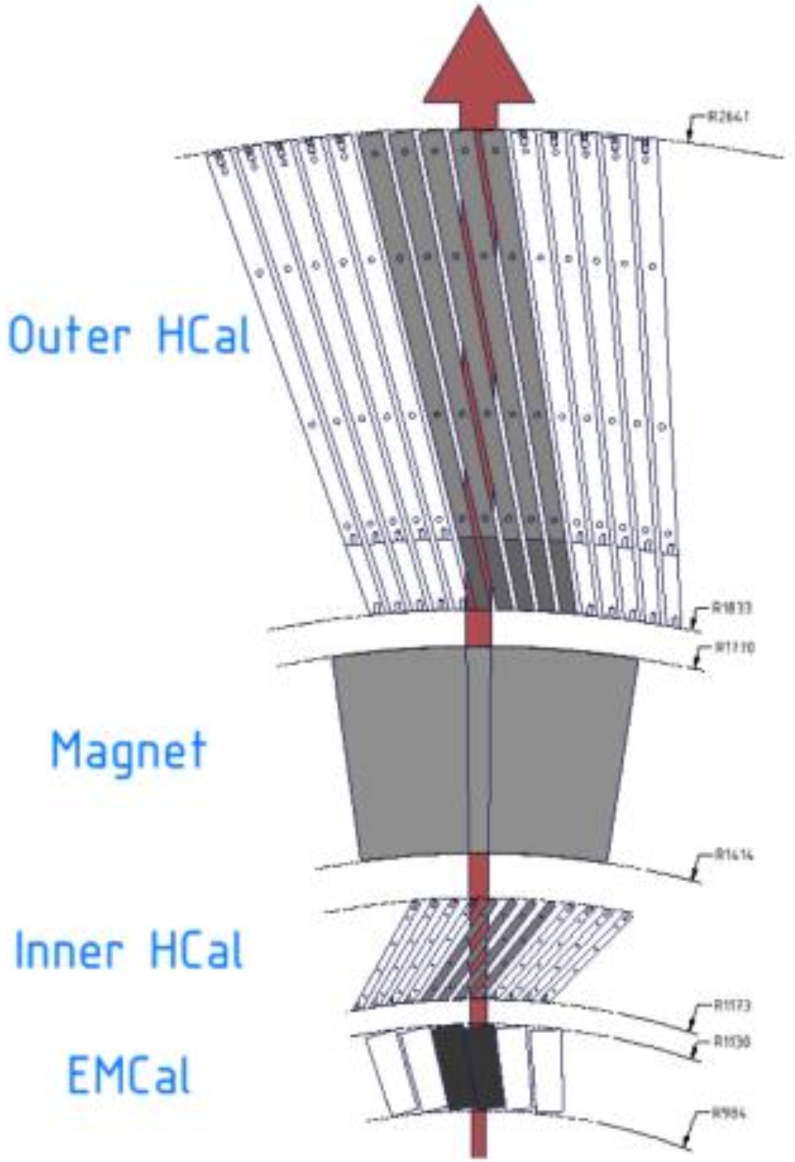
- Steel absorber plates and scintillating tiles with embedded WLS fibers
- $\Delta\eta \times \Delta\phi \approx 0.1 \text{ x } 0.1$

inner Hadronic Calorimeter (iHCal)

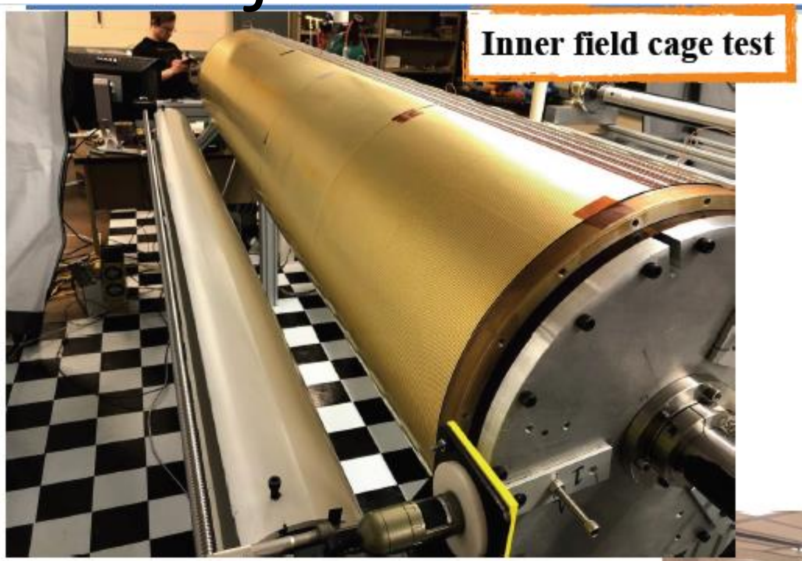
- Aluminum absorber plates and scintillating tiles with embedded WLS fibers

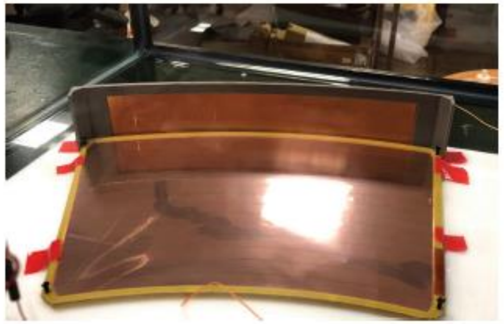
Electromagnetic Calorimeter (EMCal)

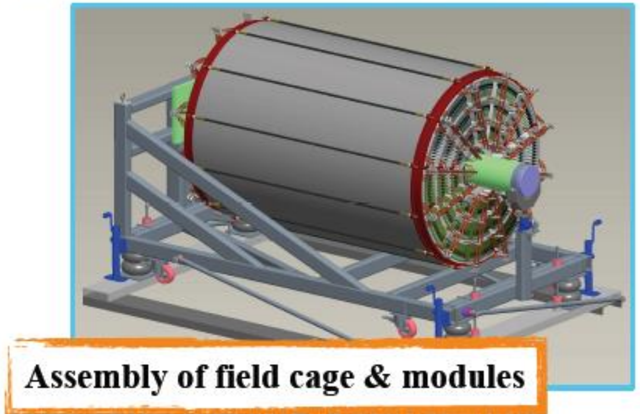
- Tungsten powder with embedded scintillating fiber matrix
- $\Delta\eta \times \Delta\phi \approx 0.025 \text{ x } 0.025$
- Compact design with large radiation length of material: $\sim$14cm $\approx 20X_0$



Time Projection Chamber Construction

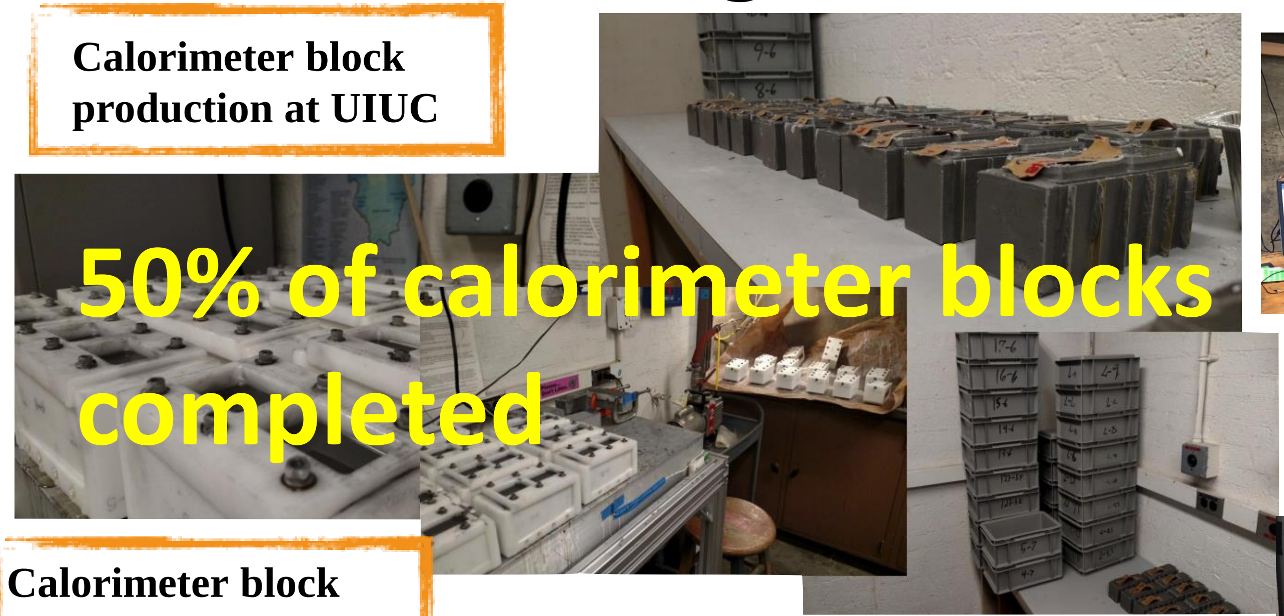




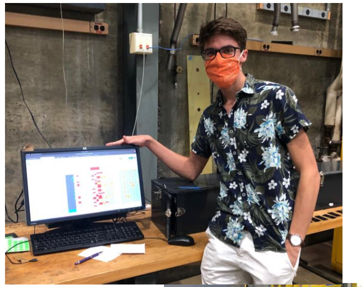


Electro-Magnetic Calorimeter Construction

Calorimeter block production at UIUC



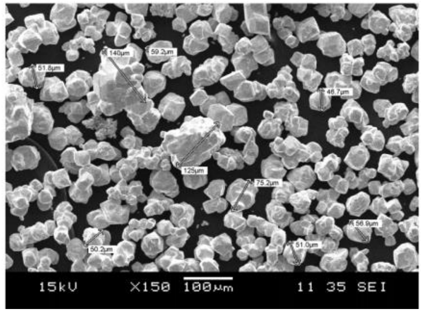
50% of calorimeter blocks completed



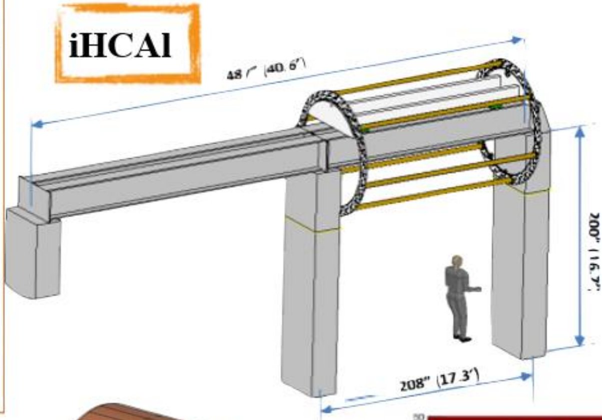
Sector Assembly and testing at BNL

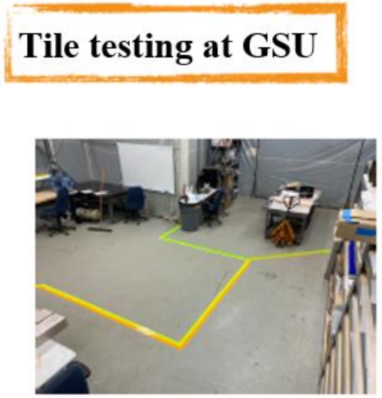
Calorimeter block production at Fudan

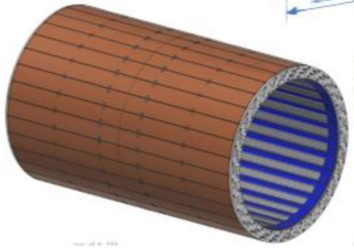
SEM - HC Starck

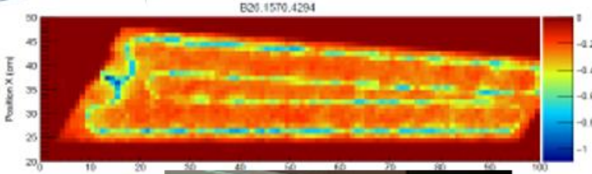


Hadronic Calorimeter Construction



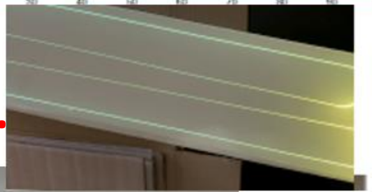






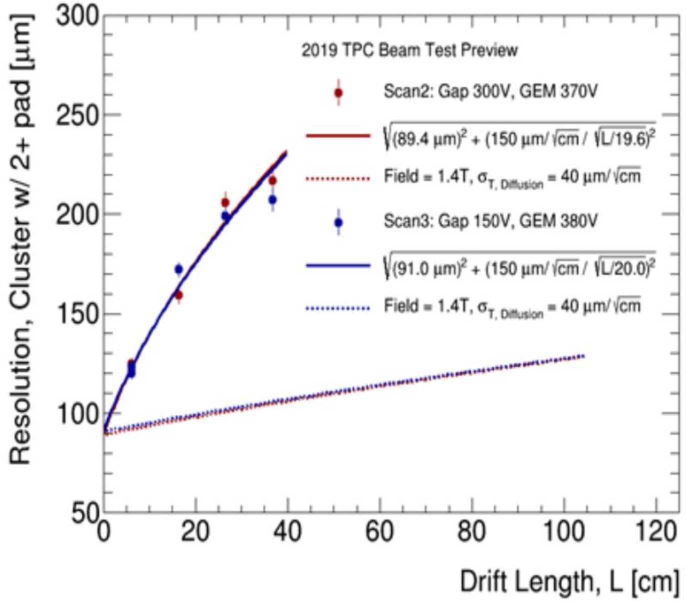
Sector 22_1 being put in storage

The OHCAL Sectors are complete.

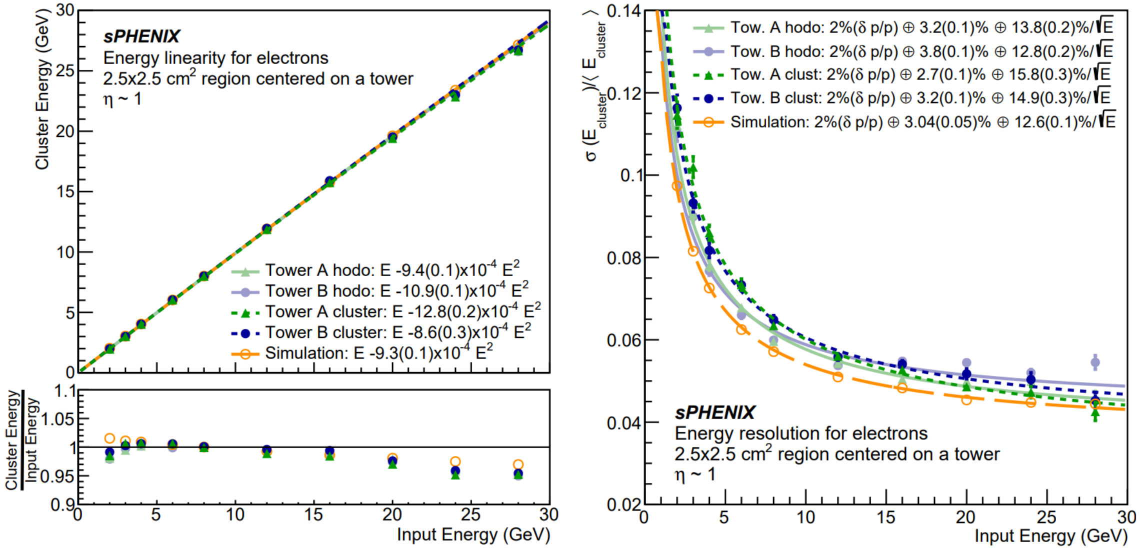


Test Beams at FNAL:

Time Projection Chamber:



Electro Magnetic Calorimeter



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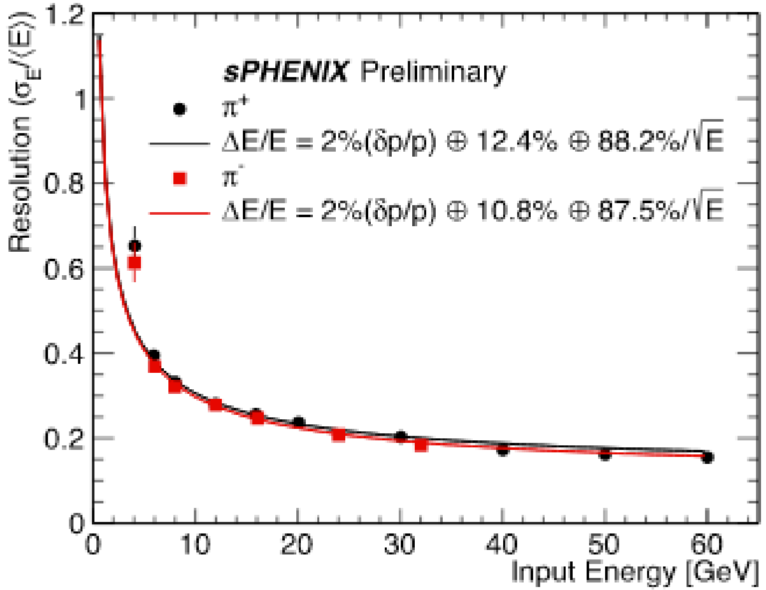
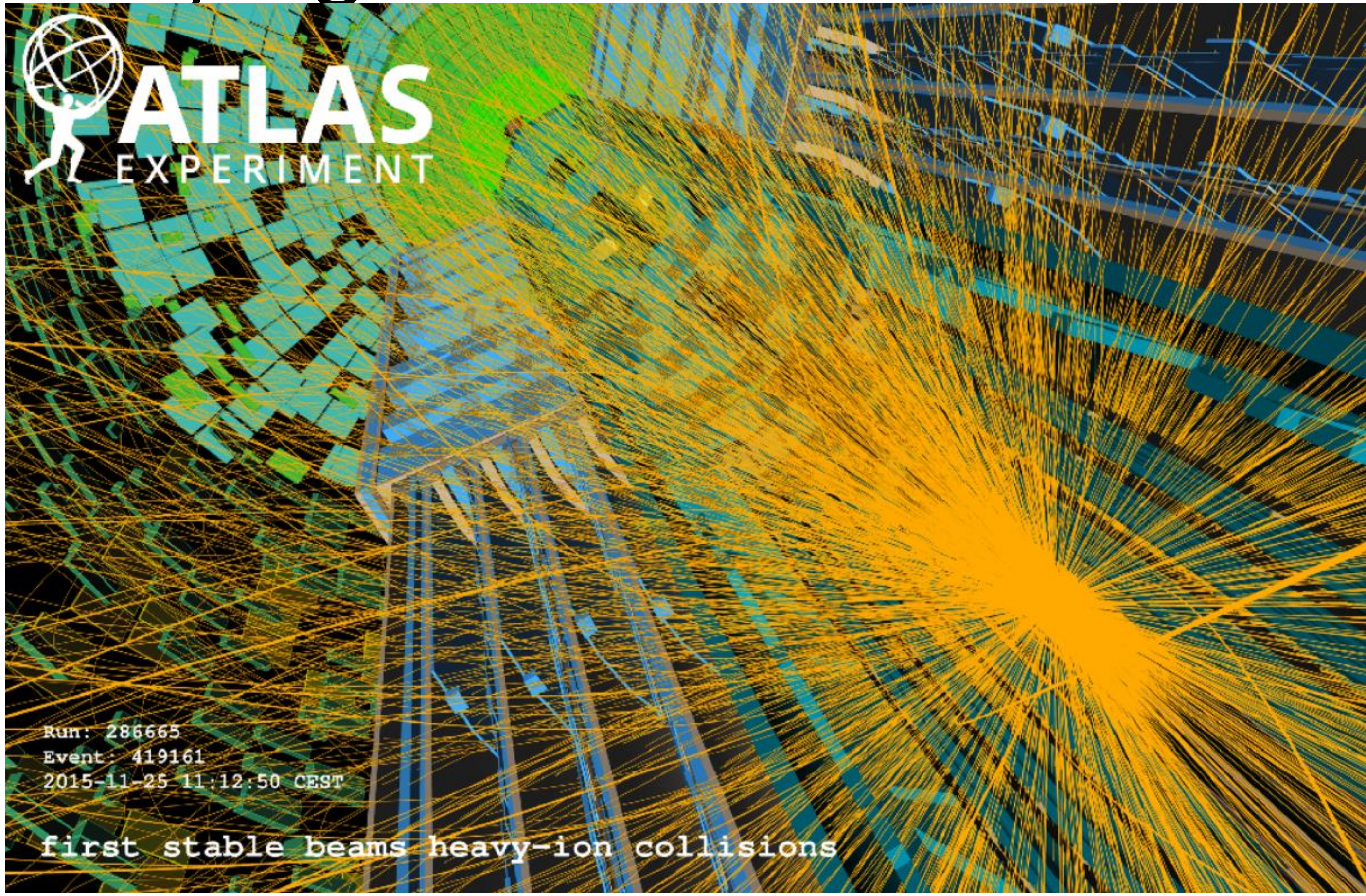
Hadronic Calorimeter



Some challenges of studying the QGP

- Lifetime of the QGP ~ 10 fm/c
    - Too short to use external probes
- Large number of particles produced in heavy ion collisions
    - Significant backgrounds to account for

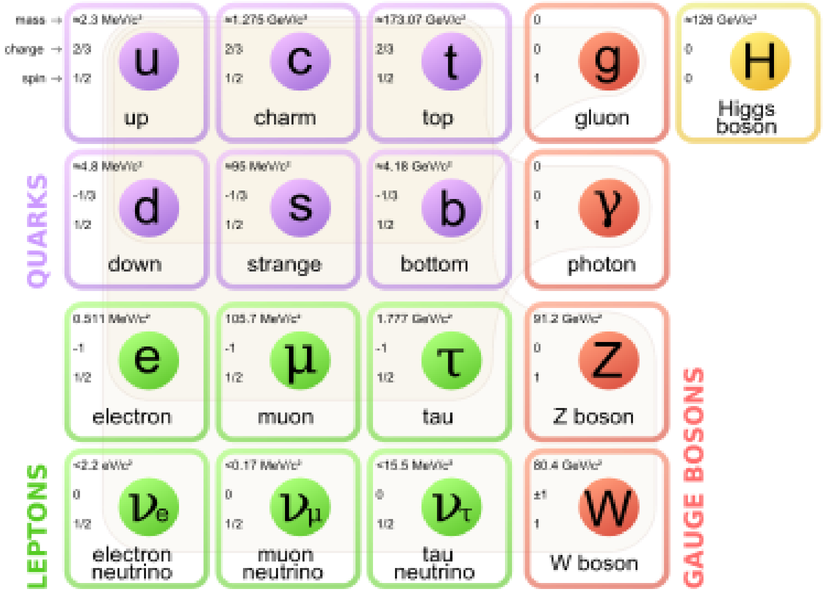


$\sim 10^4$ particles created in most central collisions

The Standard Model

In the standard model, matter is typically made up of quarks and leptons (such as electrons):

- For example a Proton is made up of two up and one down quark.



There are 6 flavors of quarks: Up, Down, Charm, Strange, Top, Bottom

There are 6 types leptons: Electron, Muon, Tau and their corresponding neutrinos.

These subatomic particles interact with one another through 3 different types of forces.

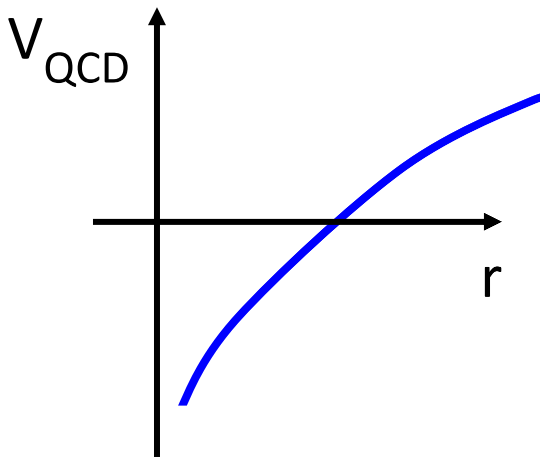
- **Strong force:** Described by Quantum Chromodynamics (QCD), and uses gluon as the force carrier.
- **Electromagnetic force:** Described by Quantum Electrodynamics (QED), and uses Photons as the force carrier.
- **Weak force:** Described by the Electro-Weak theory, Uses W and Z bosons as the force carriers.

Quantum Chromodynamics

Goal of experimental Nuclear physics is to understand properties of the Strong force

Quarks interact with one another based on *color charge* using gluons as the force carrier.

The potential from the strong force scales linearly with distance, which results in an affect called "confinement".

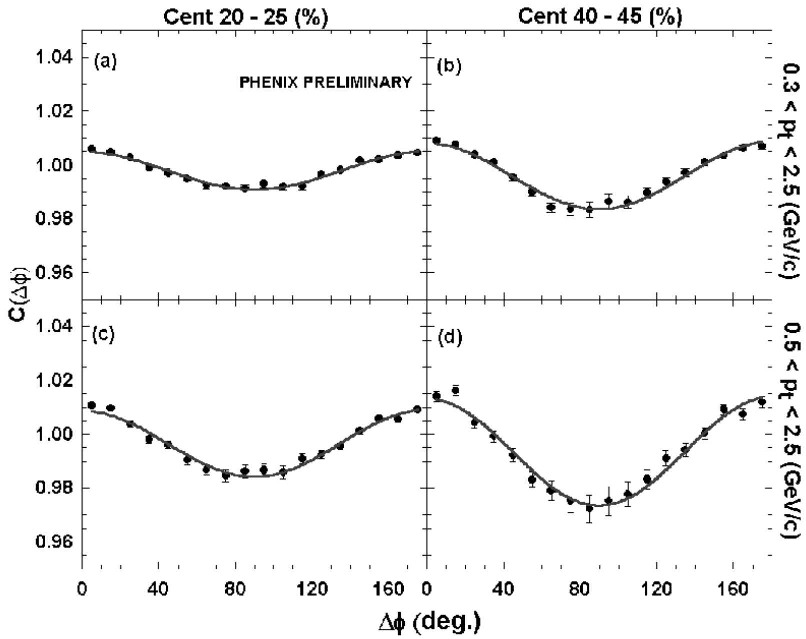


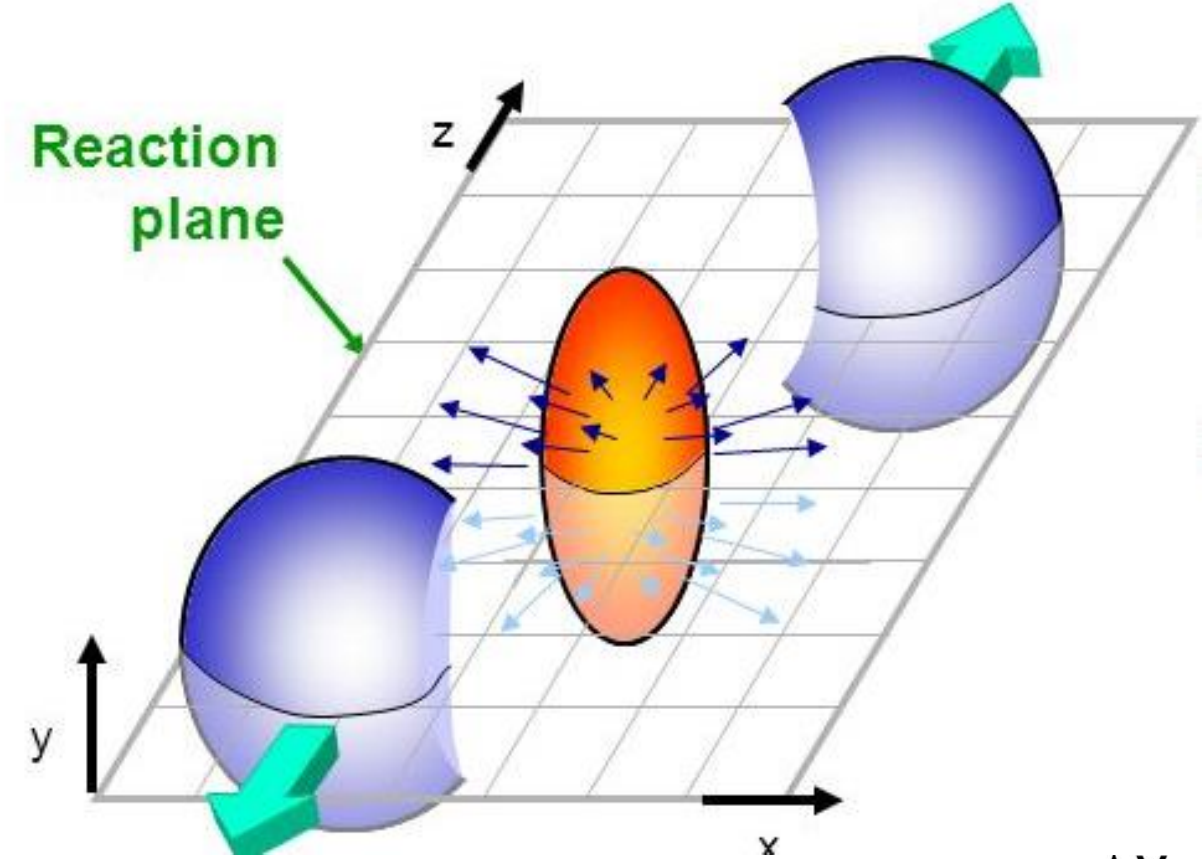
Due to confinement it is impossible to study isolated quarks, so instead they must be studied as part of a system

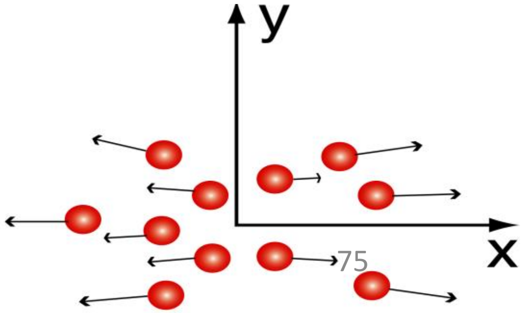
$$V_s(r) = -\frac{\alpha_s}{r} + kr$$

Key Evidence for QGP as nearly perfect fluid

- Flow
  - Pressure gradients in the medium cause angular dependence to particle production







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Heavy Flavor mass puzzle

Dead cone effect expected to reduce radiative energy loss for heavier mass quarks

Prompt D^0 similarly suppressed to light hadrons

Evidence of mass hierarchy to energy loss observed between B and D hadrons below 20 GeV