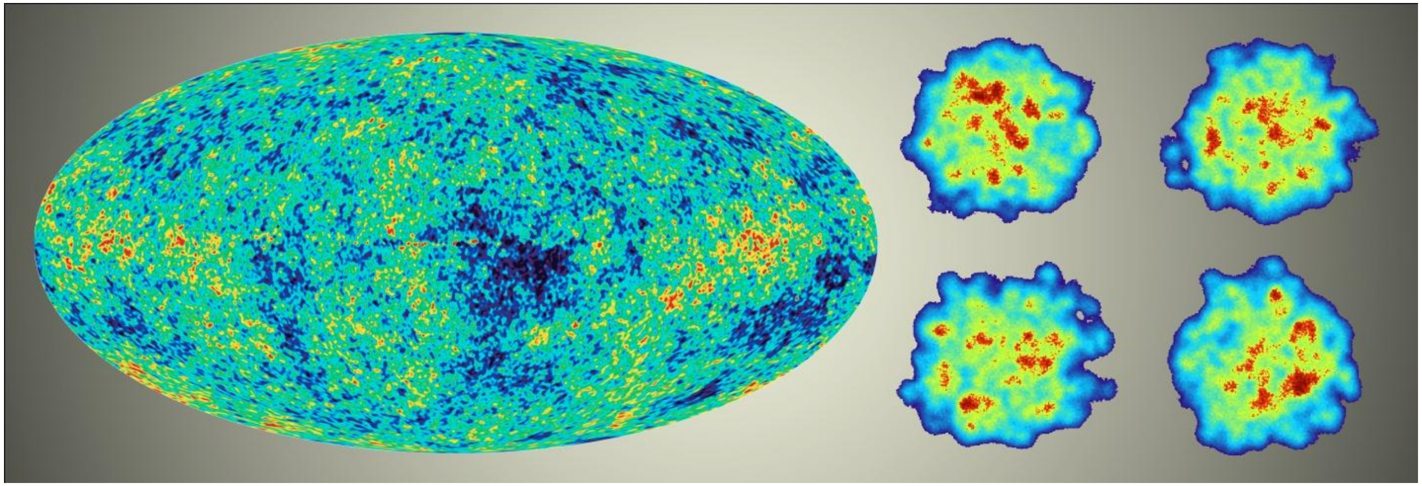
# What jets studies at RHIC can tell us about QGP properties

**Jamie Nagle**
**University of Colorado**

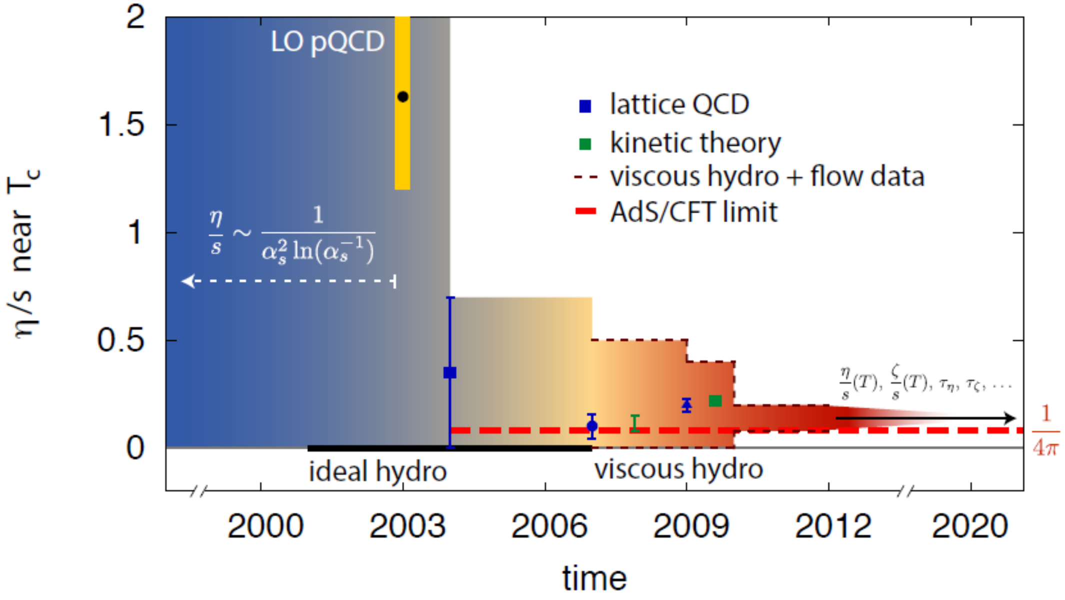

Fat Jacks in Philly

APS Division of Nuclear Physics: 2014 Long-range plan
Joint Town Meetings on QCD
Temple University
September 13-15, 2014

# Great Accomplishments in the Field



“Little Bang” Standard Model of Quark-Gluon Plasma



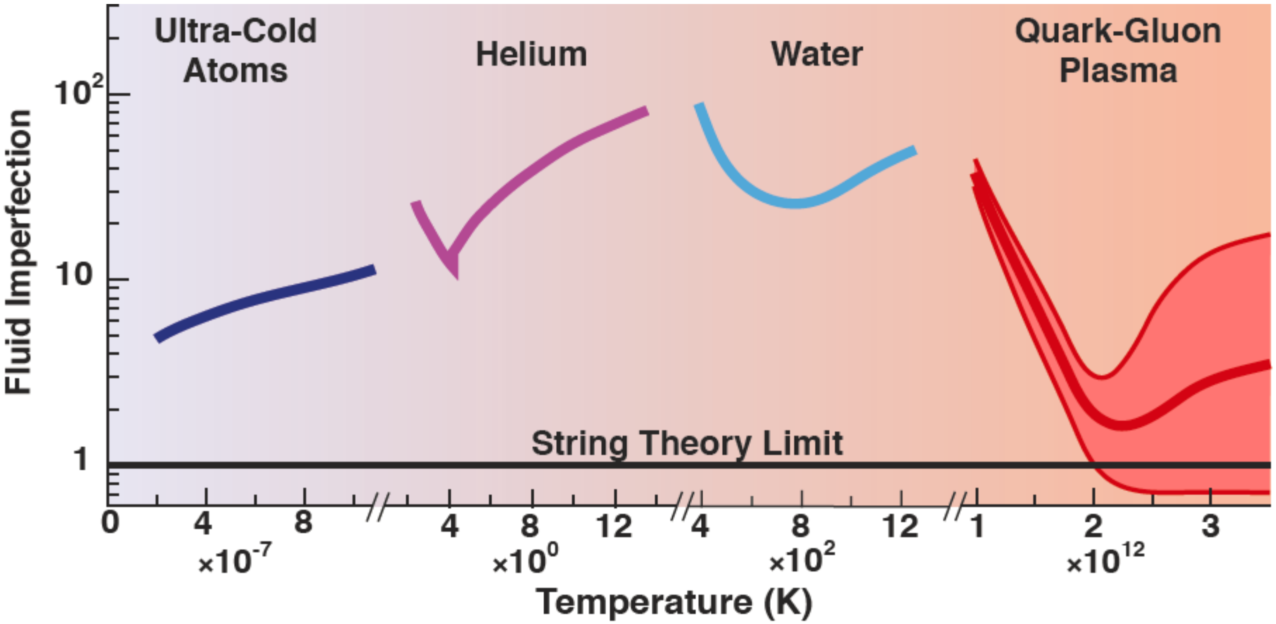
SM allows us to ask a new class of questions

Note the critical role of theory and modeling, and theory-experiment collaboration

# Emergent Phenomena

Connection from the QCD Lagrangian to phenomena of confinement and asymptotic freedom was fundamental

Connection from QCD to the emergent phenomena of near perfect fluidity of the Quark-Gluon Plasma near the phase transformation is just as fundamental

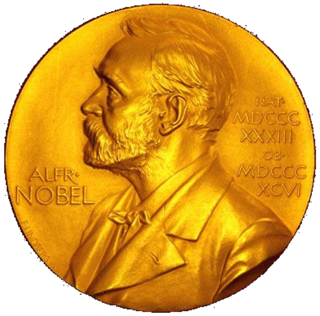


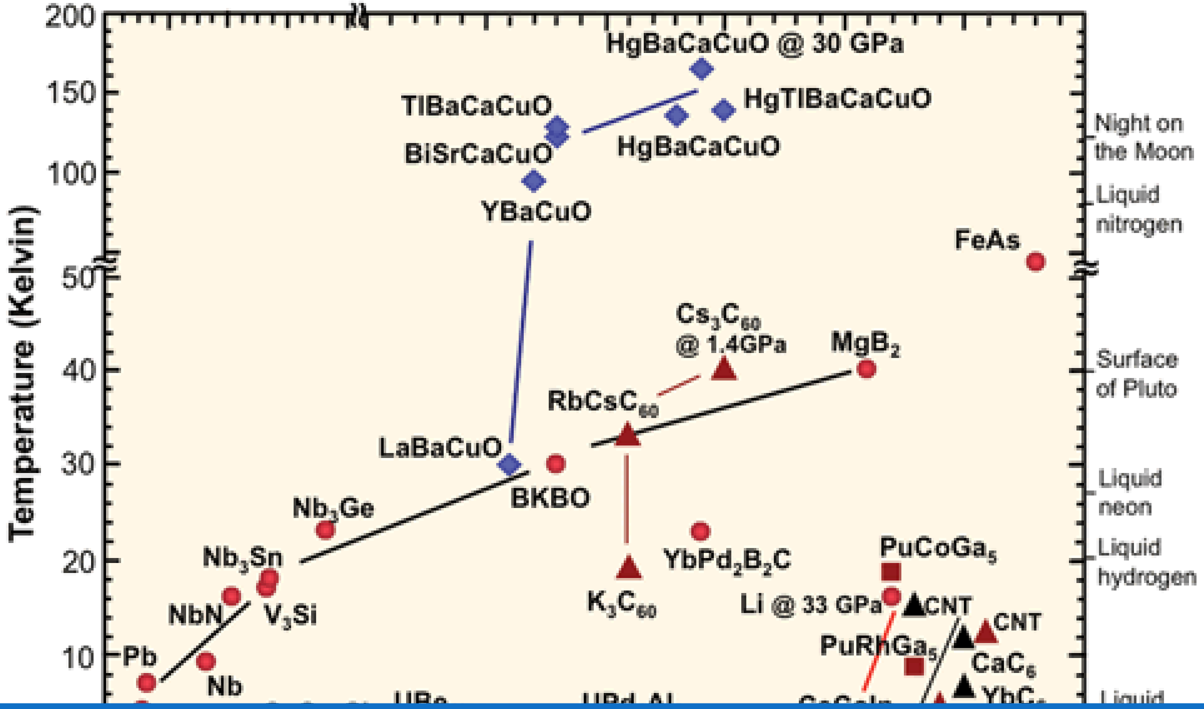
Pinning down the $\eta/s$ tells us the nature of the QGP, while leaving open the "**how**" and "**why**" questions

# How and Why Questions

High Temperature superconductivity

Nobel prize for discovery…





and another Nobel prize awaiting the answer to the “how” and “why” questions

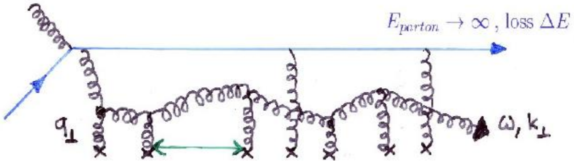
> “One shouldn’t work on semiconductors, that is a filthy mess; who knows whether any semiconductors exist.”
> Wolfgang Pauli [1931]
>
> Perhaps like thinking on heavy ion collisions before perfect fluid discovery…

# Probing the QGP across Length Scales

**Hard Scattered Partons Traversing the QGP**

(Jets, Dijets, $\gamma$-Jet, Fragmentation, Medium Response)

Length scale set by initial energy, coherent energy lost
20-50 GeV (0.01-0.004 fm), 1-5 GeV (0.2-0.05 fm)



**Beauty Quarkonia**

Length scale set by size of state ($\Upsilon$(1s,2s,3s) ~ 0.28, 0.56, 0.78 fm)

Krishna refers to this as
microscopy of the QGP

Critical to push jets to lower energy,
looking for hard radiation to understand
what it's being scattered from?

# RHIC Probing Region of Strongest Coupling

The textbook (or Wiki entry) on the Quark-Gluon Plasma will be incomplete without

*a fundamental explanation for how the perfect fluid emerges at strong coupling near $T_c$*
*from an asymptotically free theory of quarks and gluons*

Jet observables at RHIC enabled by the sPHENIX upgrade are critical to providing this explanation by probing the QGP near 1-2 $T_c$ and over a broad ranges of scales

Measurements of jets only at the LHC will leave these questions with an incomplete answer
(particularly right where the coupling <u>may</u> be strongest)

# Critical Knobs to Turn

Temperature dependence of the QGP by **beam energy** variation

Time dependence of the QGP by virtuality variation (**hard process $Q^2$**)

Length scale within the QGP by interaction hardness (**interaction $Q^2$**)

Can we observe the strongest coupling near $T_c$ definitively

How do the parton shower and medium evolve together?

What are the inner workings? (quasiparticles, fields, modes)

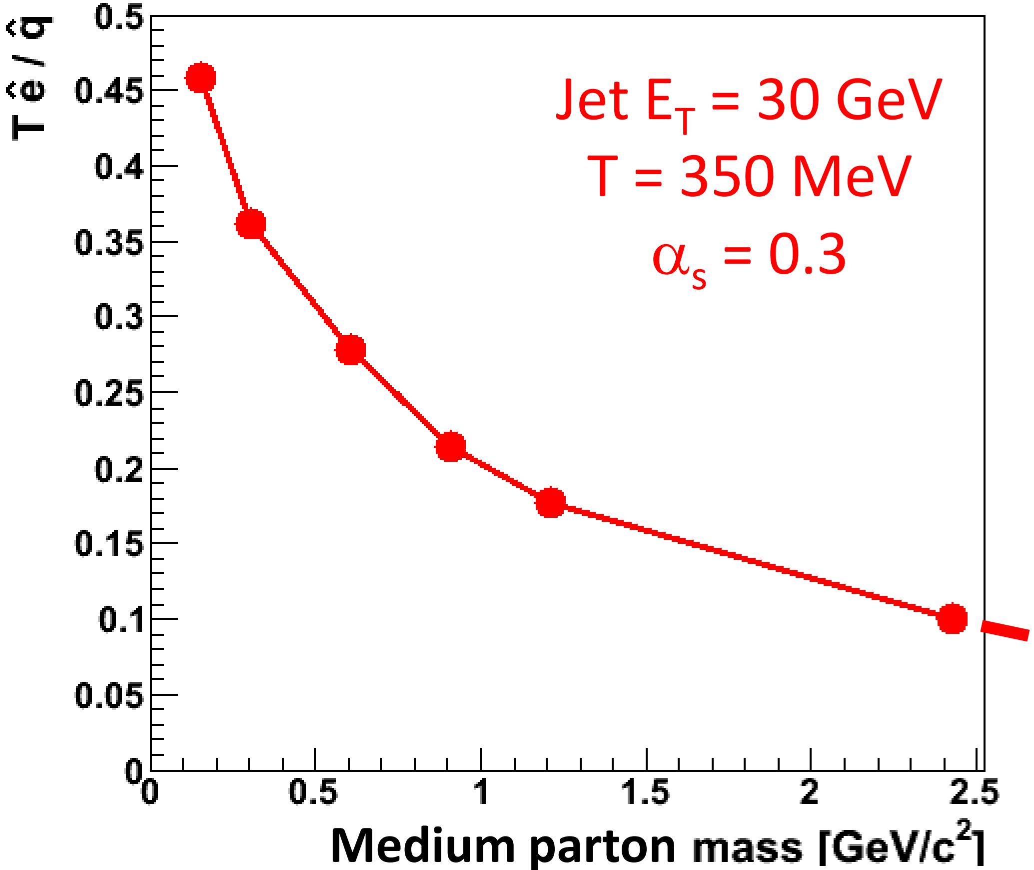
# QGP Constituent Mass Dependence

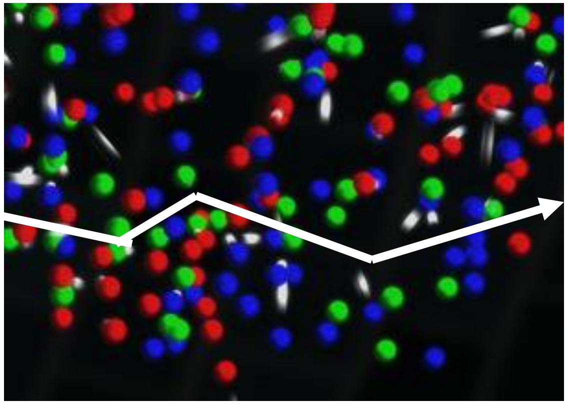
C. E. Coleman-Smith* and B. Müller
*Department of Physics, Duke University, Durham, NC 27708-0305*

http://arxiv.org/abs/arXiv:1209.3328

qhat → scattering of leading parton → radiation e-loss

ehat → energy transferred to the QGP medium





Limit of infinitely massive scattering centers yields all radiative e-loss.

# No one key Observable, Instead a Data Army

## Bulk QGP Constraints ($\eta/s$ example)

Very close coordinated effort by experimentalists and theorists
spectra, $v_2 \rightarrow v_n$, HBT $\rightarrow$ HBT versus $\Psi_n$, direct photons $\rightarrow$ photon $v_n$
Over-constraining the theory $\rightarrow$

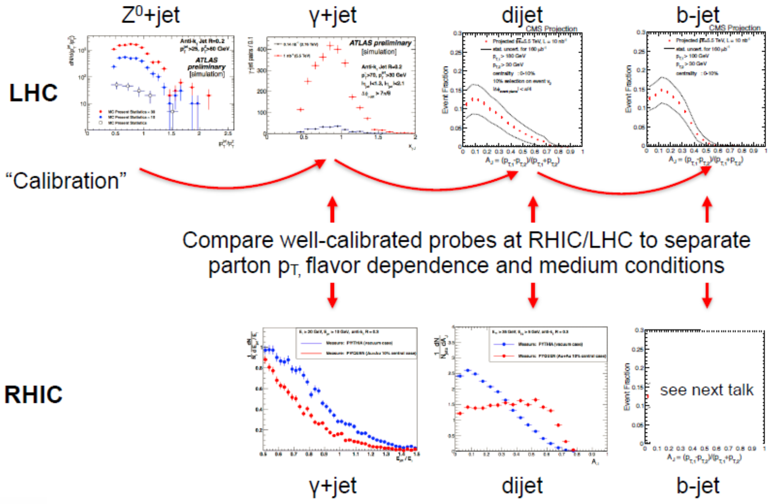
Current "Standard Little Bang" Model
Path to precision QGP bulk properties

## Jet Probe Physics

Not one key observable alone.

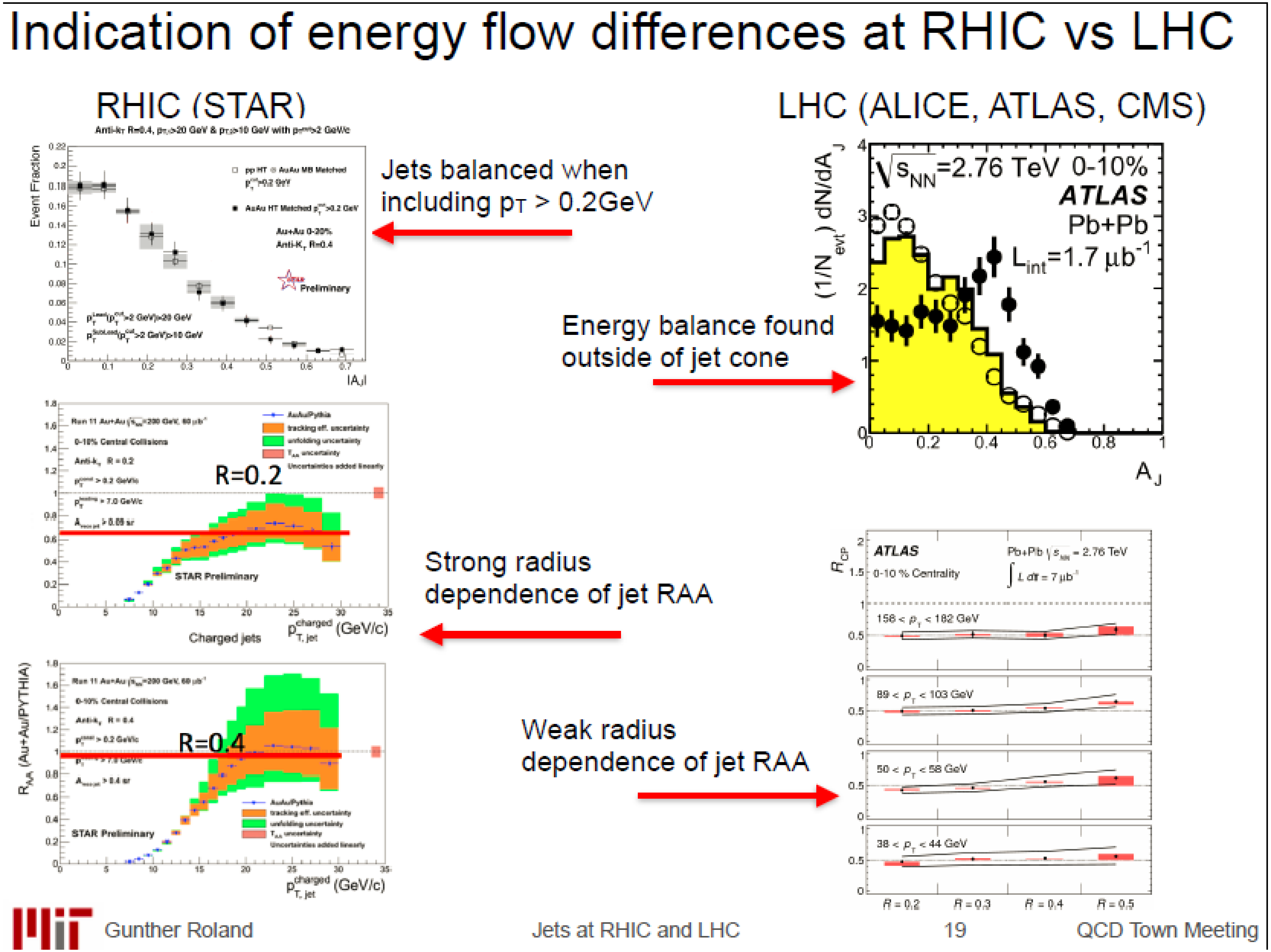
It is the army of observables in concert with theory that has the physics pay-off.

Nicely shown in Gunther's talk



Compare well-calibrated probes at RHIC/LHC to separate parton $p_T$, flavor dependence and medium conditions

# RHIC and LHC Jet Observables



## Indication of energy flow differences at RHIC vs LHC

RHIC (STAR)

LHC (ALICE, ATLAS, CMS)

Jets balanced when including $p_T > 0.2$GeV

Energy balance found outside of jet cone

Strong radius dependence of jet RAA

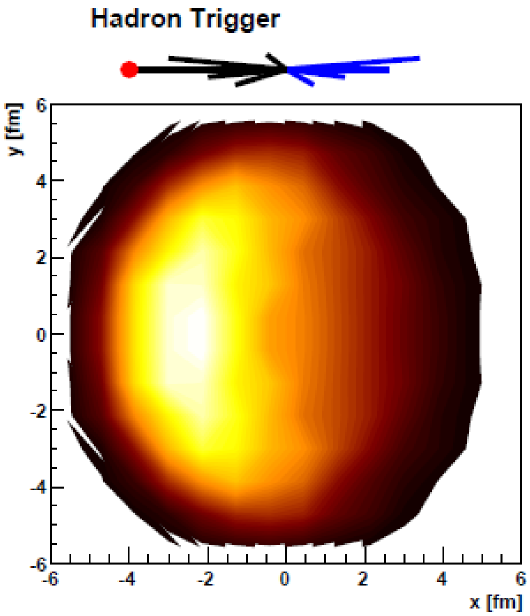
Weak radius dependence of jet RAA

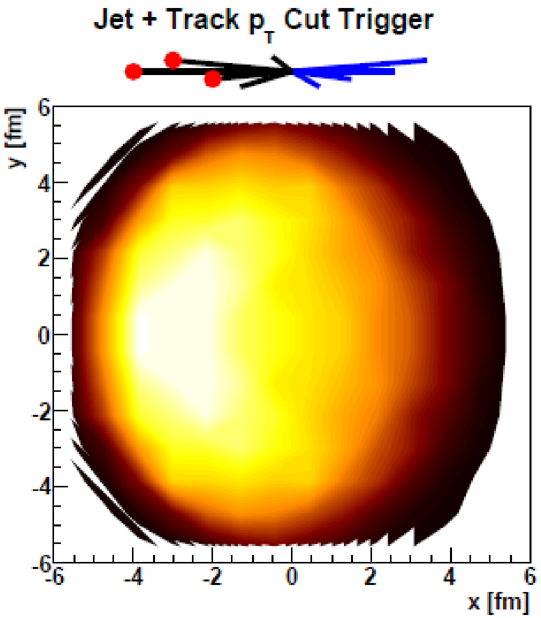
Gunther Roland Jets at RHIC and LHC 19 QCD Town Meeting

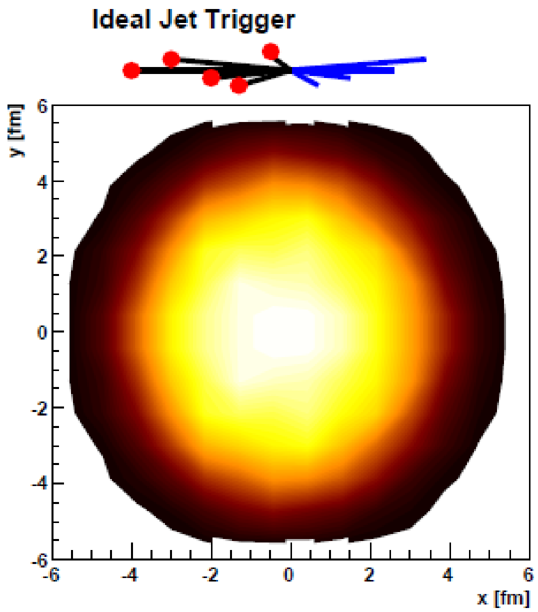
# Jet Geometry Engineering

Thorsten Renk has explored the ability to engineer
the surface and energy loss bias to gain more information.

Works particularly well at RHIC due to steeply falling jet spectrum.


Hadron Trigger

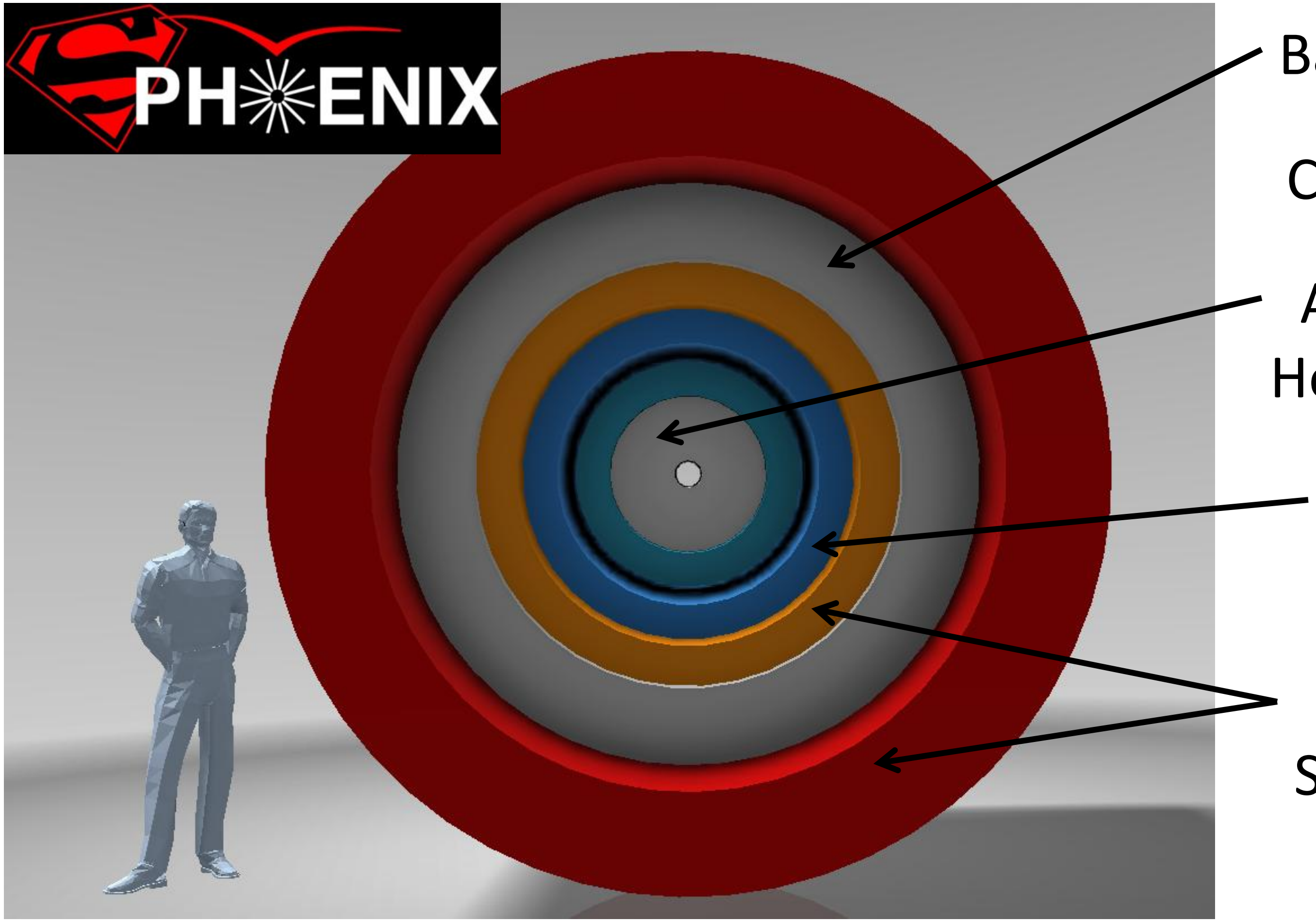

Jet + Track $p_T$ Cut Trigger


Ideal Jet Trigger

Key to measure jets with no minimum $p_T$ selection and no trigger bias.
Thus, one can explore the full range of engineered geometries.

Systematic measurements enabled "tomography"

# sPHENIX in a Nutshell



BaBar Magnet 1.5 T

Coverage |η| < 1.1

All silicon tracking
Heavy flavor tagging

Electromagnetic
Calorimeter

Two longitudinal
Segment Hadronic
Calorimeter

Common Silicon Photomultiplier readout for Calorimeters
Full clock speed digitizers, digital information for triggering
High data acquisition rate capability ~ 15 kHz

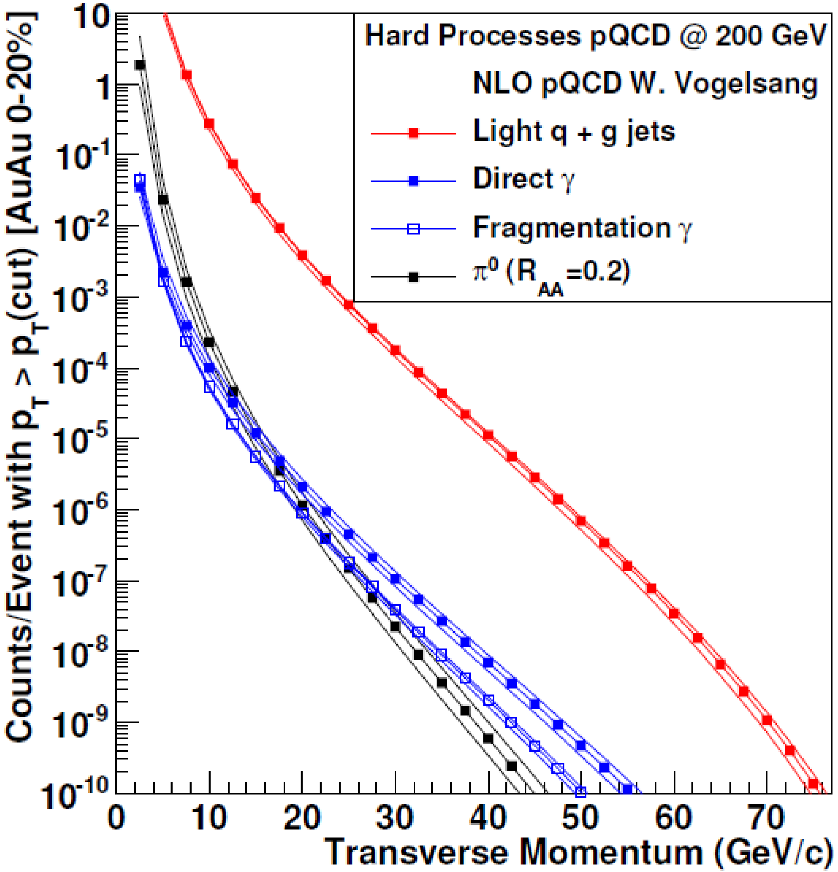
# RHIC II Luminosities → Opening New Doors

RHIC II + sPHENIX can record
**50 billion events**
within |z|<10cm in 20-weeks

Run-14 performance so successful, same delivery would allow sampling of **200 billion** events for jets and direct photons

New C-AD projection will allow Au+Au sampling of <u>0.5 **trillion** events</u>

Critical similar statistics in p+p and p+A



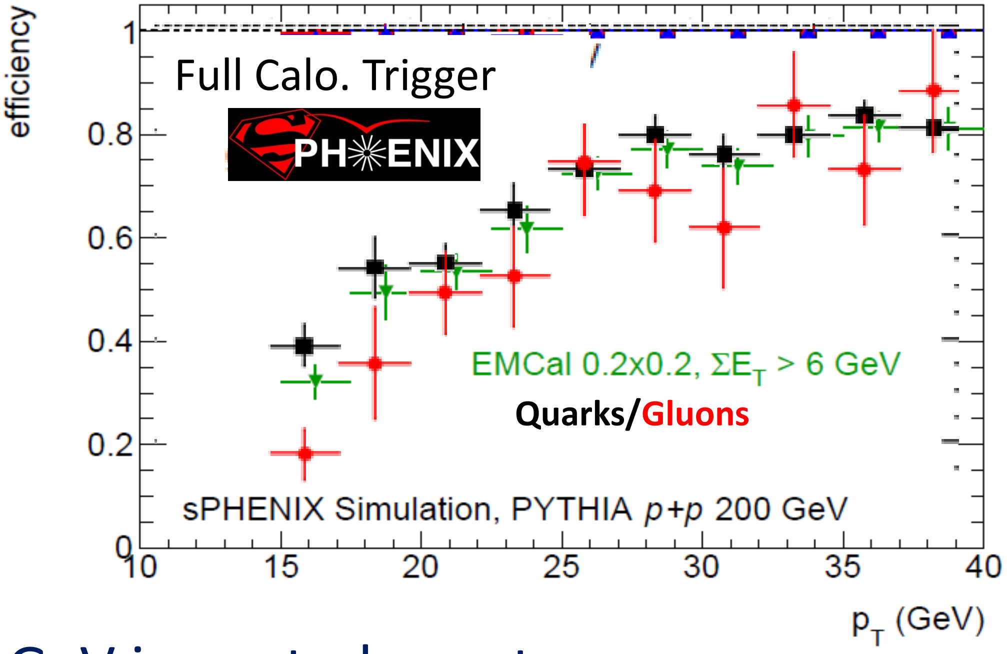
$10^7$ jets > 20 GeV recorded
$10^4$ photons > 20 GeV recorded

e.g. $10^5$ photons > 20 GeV sampled from ½ trillion evts (S/B > 3)

# Jets Near Term and Long Term

LHC Run-3 provides great jet statistics for fully differential measurements (e.g. jets > 120 GeV)

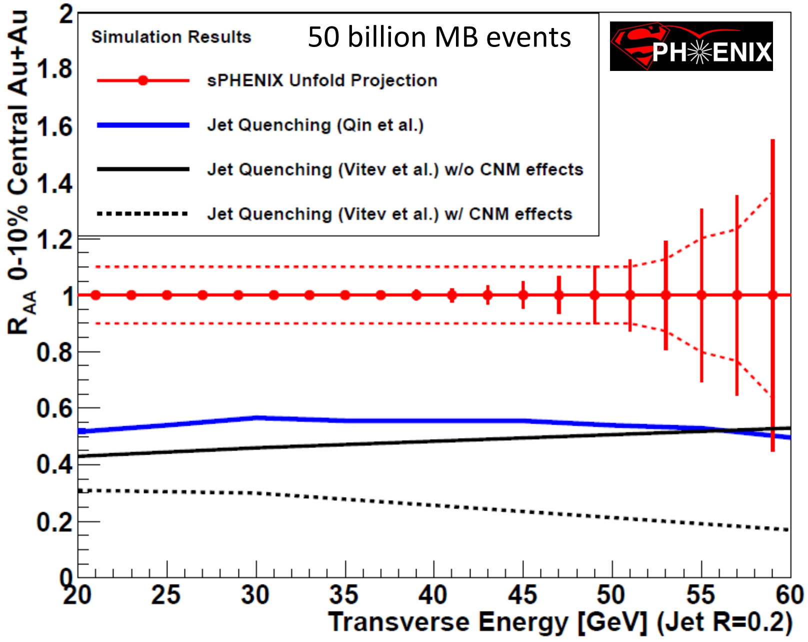
Similarly great jet statistics at RHIC for jets > 20 GeV!
Benefits of strong sPHENIX and STAR programs (different jet approaches with overlap too)

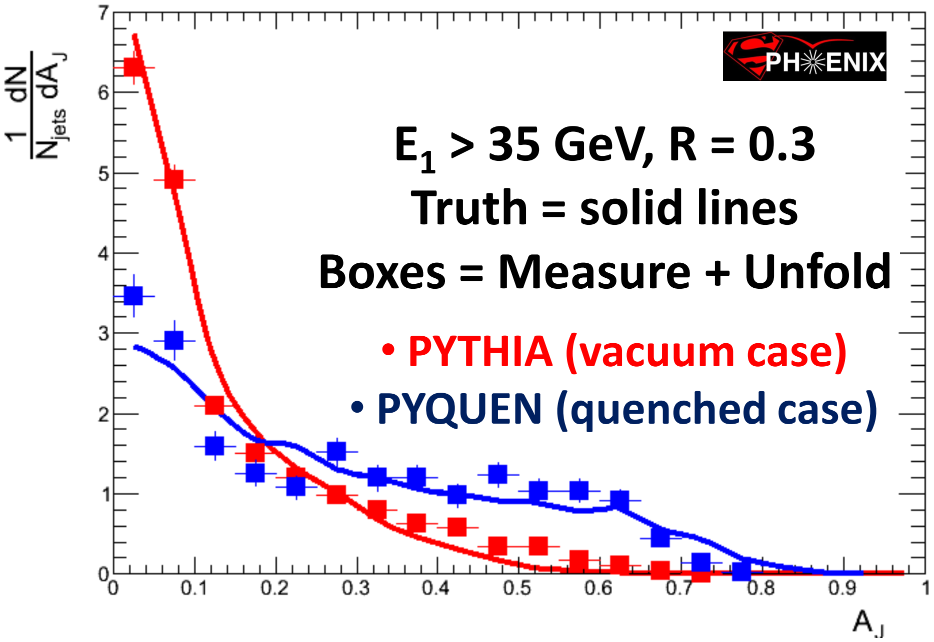


Run-14 + 16:
STAR mb ~ 400 jets > 50 GeV
EMCal triggered ~ 8,000 jets

Run-2020's
STAR min. bias ~ 1,200 jets > 50 GeV in central events
sPHENIX min. bias ~ 9,000 jets > 50 GeV in central events
sPHENIX full calorimeter Trigger ~ 50,000 jets > 50 GeV in central events

# Jet Observables





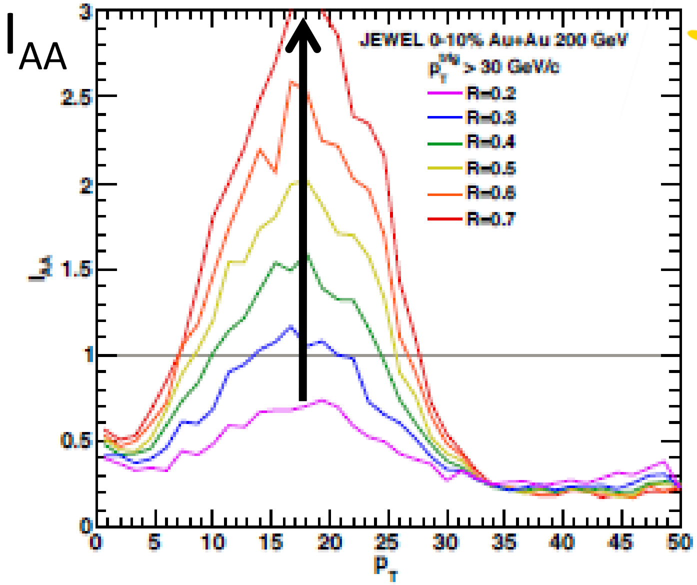
Full suite of jet observables. With and without tracking information.

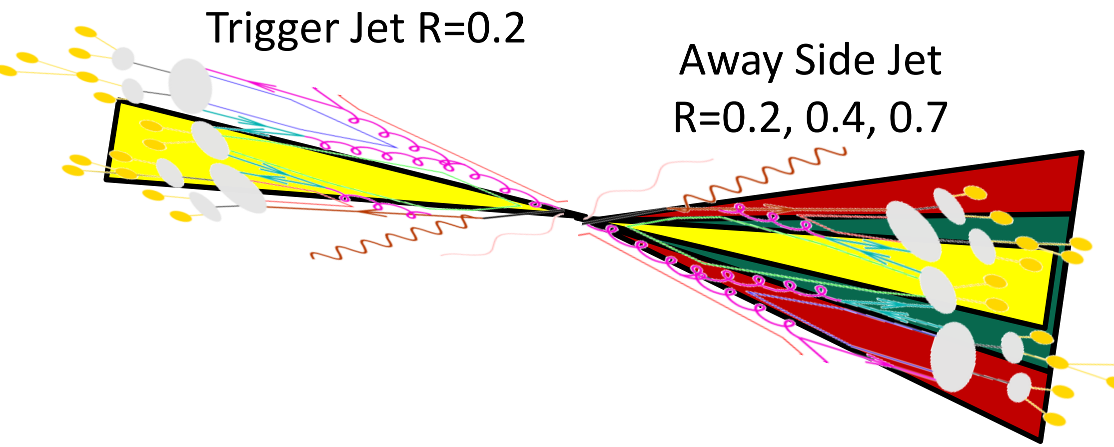
- Single hadrons (up to 40 GeV/c)
- Di-hadrons
- Hadron-jet
- Jet-hadron
- Jet (narrow) – jet (wide)

- Photon – hadron
- Photon – jet
- Very differential
- All centralities and geometries
- Same energy p+p, p+A

# Jet Observables

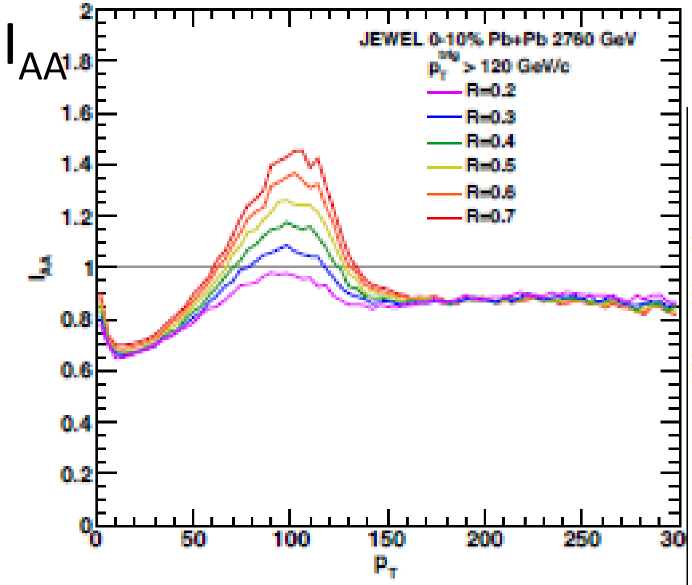
**RHIC**



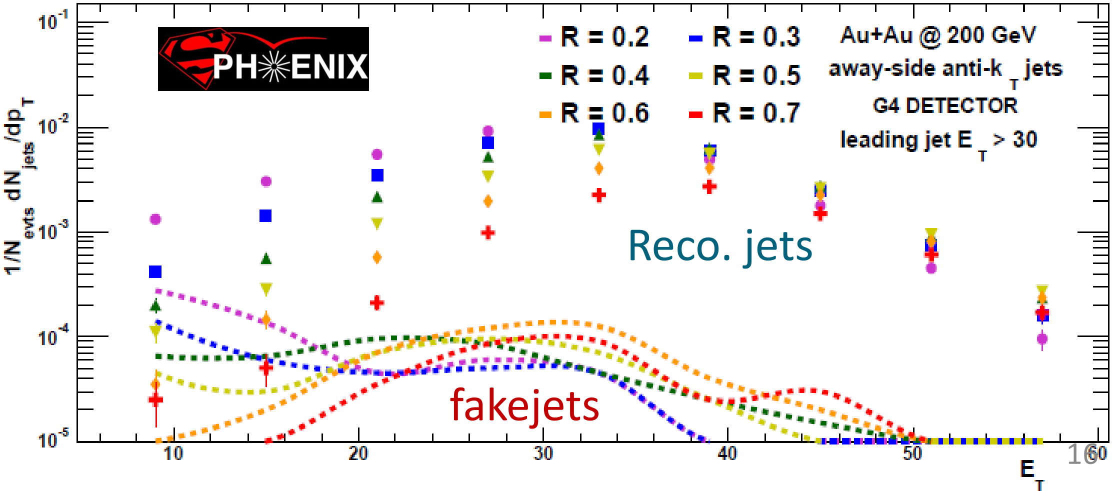


Look for jet energy shifted to larger radius or underneath and equilibrated. **JEWEL predicts huge effect at RHIC.**

**LHC**



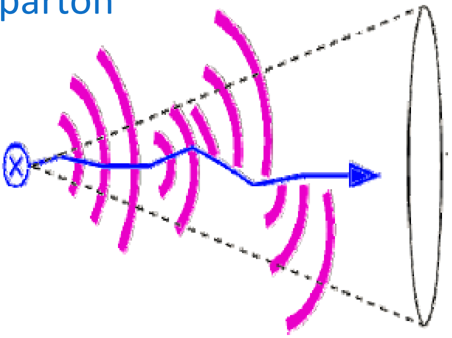
Good purity even for large R jets!

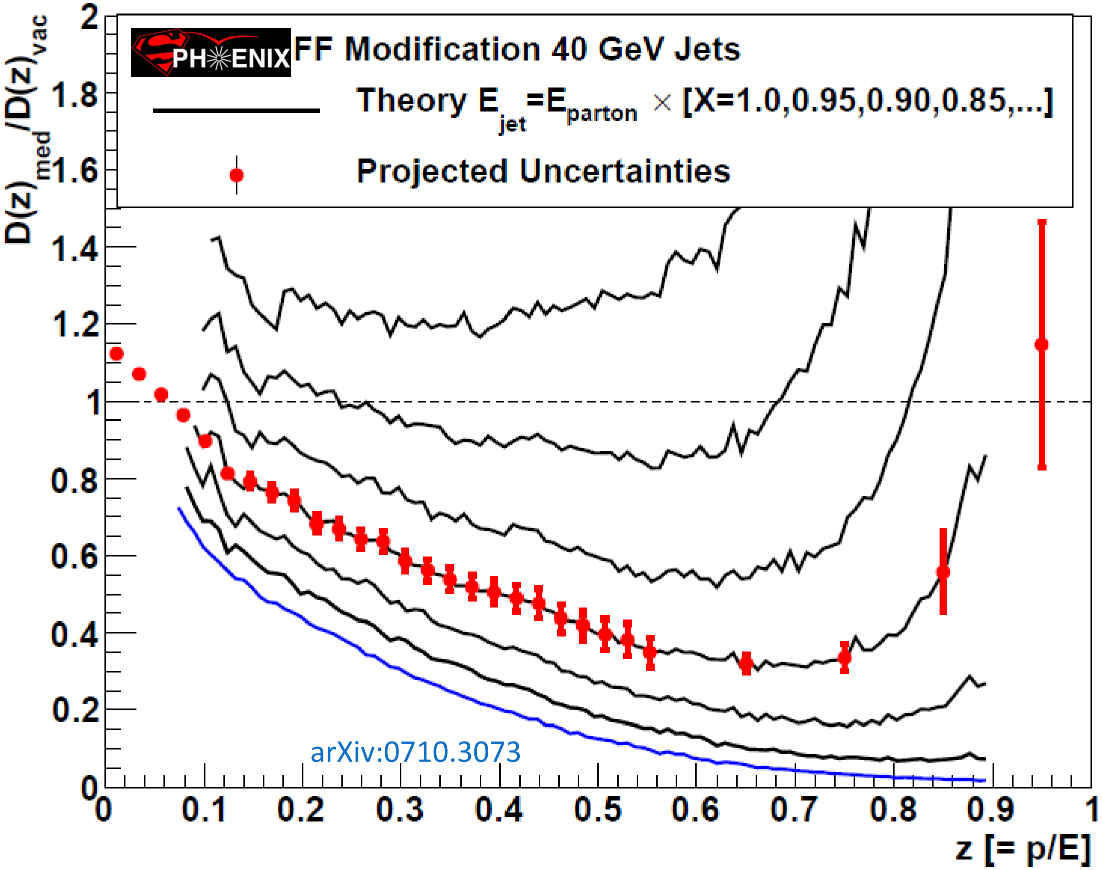


# Unique Measurements

Predictions that Fragmentation Function $D(z) = p / E_{parton}$ will have dramatic high-z suppression

If $E_{jet} < E_{parton}$ in A+A due to out of cone radiation or medium excitation or … then shifting z denominator



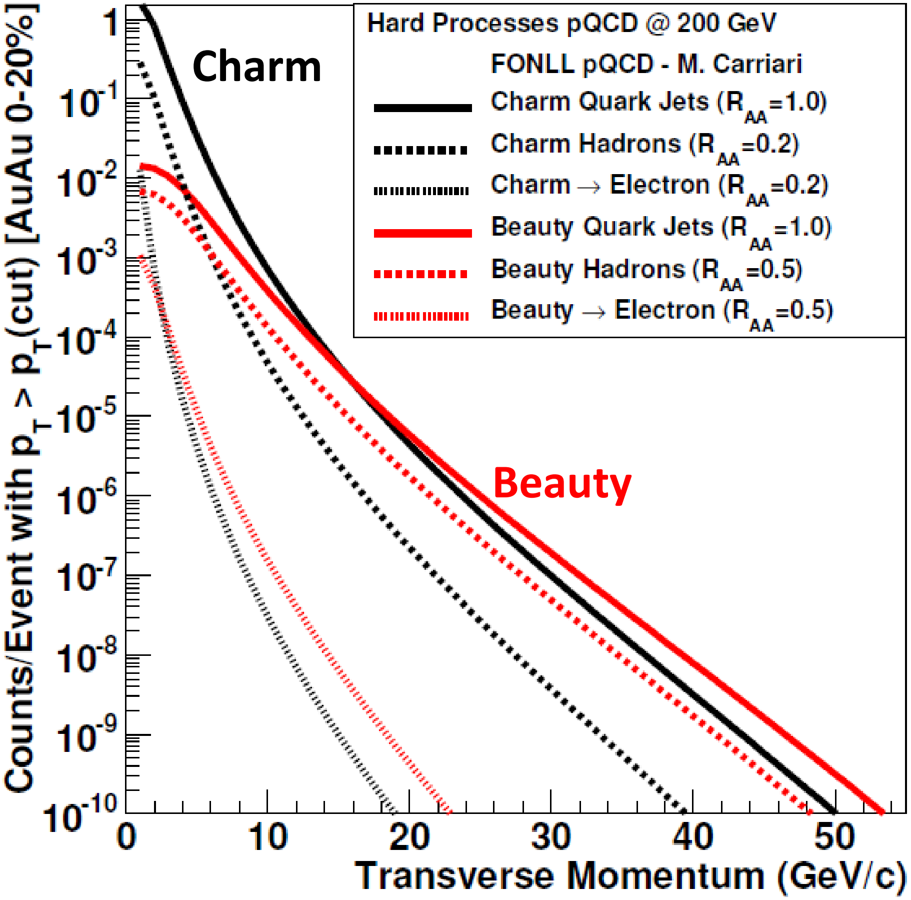


sPHENIX enables precision measurement

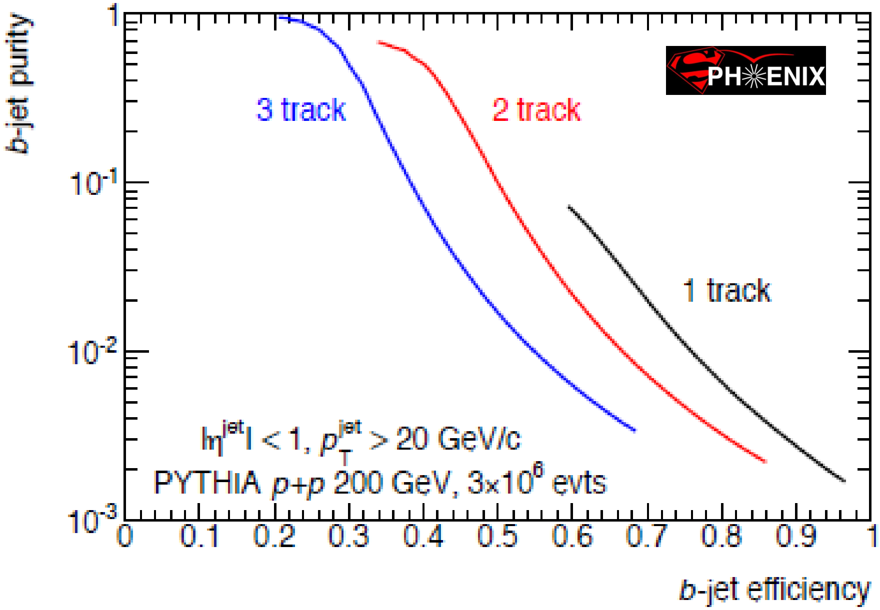
Cannot be done otherwise at RHIC

Coupled with precision measure at LHC across different jet energies and different QGP couplings
→Definitive Answers

# Beauty Tagged Jets at RHIC and LHC



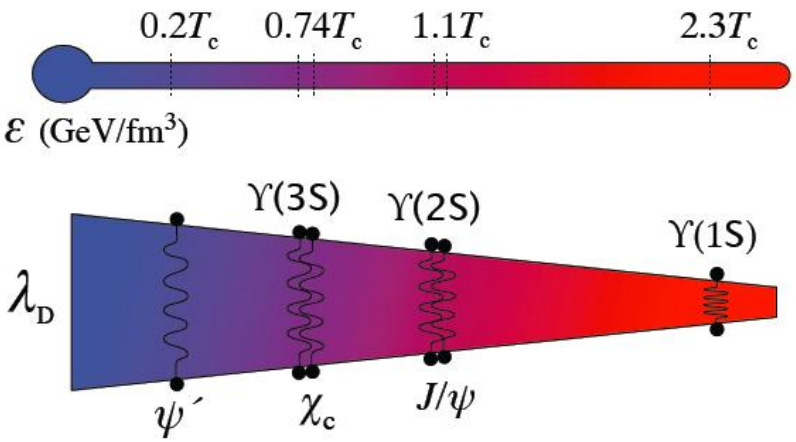
Variety of proven techniques: soft lepton tagging, track counting, secondary vertex reconstruction

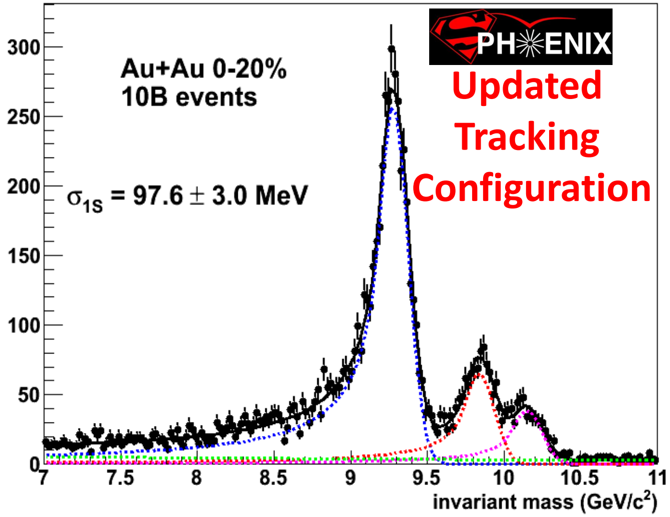


Key tests of mass dependence of radiative energy loss

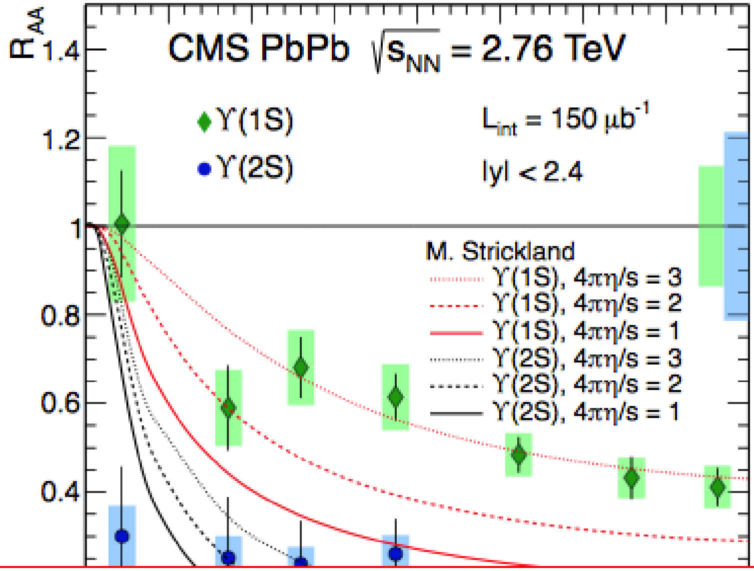
Again, crucial to have overlapping energy ranges with RHIC and LHC

# Another Key Length Scale Probe

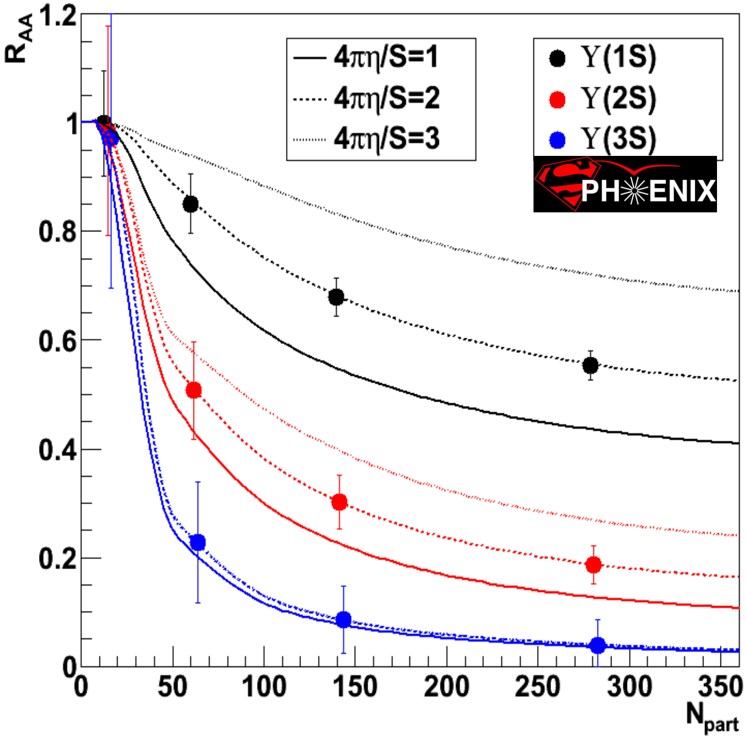




**Updated Tracking Configuration**



Expect x10 reduction in statistical uncertainties with LHC Run-3



# Brookhaven Lab Proposed 10 Year Plan

| Years | Beam Species and Energies | Science Goals | New Systems Commissioned |
|---|---|---|---|
| 2014 | 15 GeV Au+Au<br>200 GeV Au+Au | Heavy flavor flow, energy loss, thermalization, etc.<br>Quarkonium studies<br>QCD critical point search | Electron lenses<br>56 MHz SRF<br>STAR HFT<br>STAR MTD |
| 2015-16 | p+p at 200 GeV<br>p+Au, d+Au, $^3$He+Au at 200 GeV<br>High statistics Au+Au | Extract η/s(T) + constrain initial quantum fluctuations<br>More heavy flavor studies<br>Sphaleron tests<br>Transverse spin physics | PHENIX MPC-EX<br>Coherent e-cooling test |
| 2017 | No Run | | Low energy e-cooling upgrade |
| 2018-19 | 5-20 GeV Au+Au (BES-2) | Search for QCD critical point and onset of deconfinement | STAR ITPC upgrade<br>Partial commissioning of sPHENIX (in 2019) |
| 2020 | No Run | | Complete sPHENIX installation<br>STAR forward upgrades |
| 2021-22 | | Jet, di-jet, γ-jet probes of parton ransport and energy loss mechanism<br>Color screening for different quarkonia | sPHENIX |
| 2023-24 | No Runs | | Transition to eRHIC |

Excellent timing with Run-3 at LHC

# Not Leaving Key Physics on the Floor

**Only two years of sPHENIX running?**

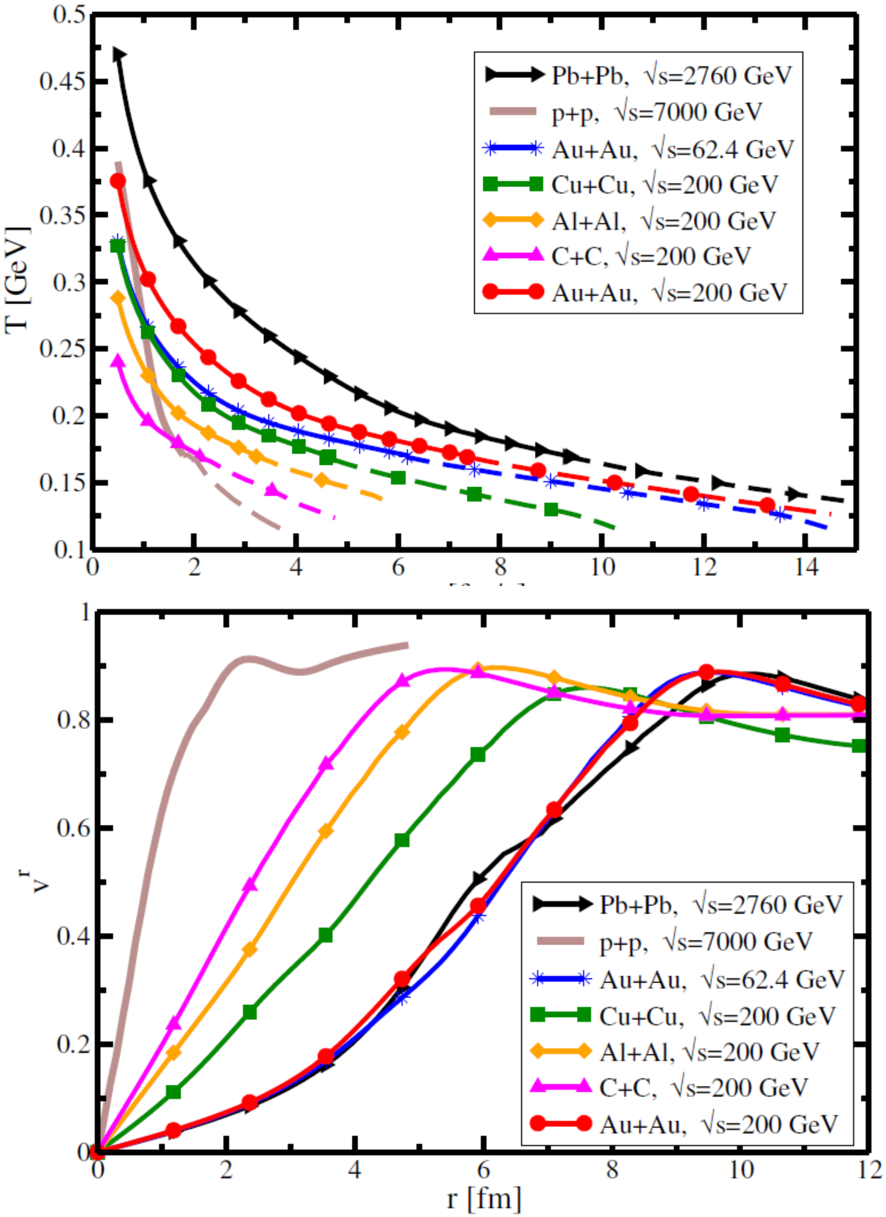
**Extending the program**

- Lower Energy Running (39, 62 GeV)

| Energy | Hadron $p_T$ | Jet $E_T$ |
|---|---|---|
| 200 | 40 GeV/c | 70 GeV |
| 100 | 23 GeV/c | 35 GeV |
| 62.4 | 18 GeV/c | |
| 39 | 12 GeV/c | |

-Lighter Ion Running (C+C, Al+Al)

- Strengthened p+A program



arXiv:1409.0040

# World Context Summary

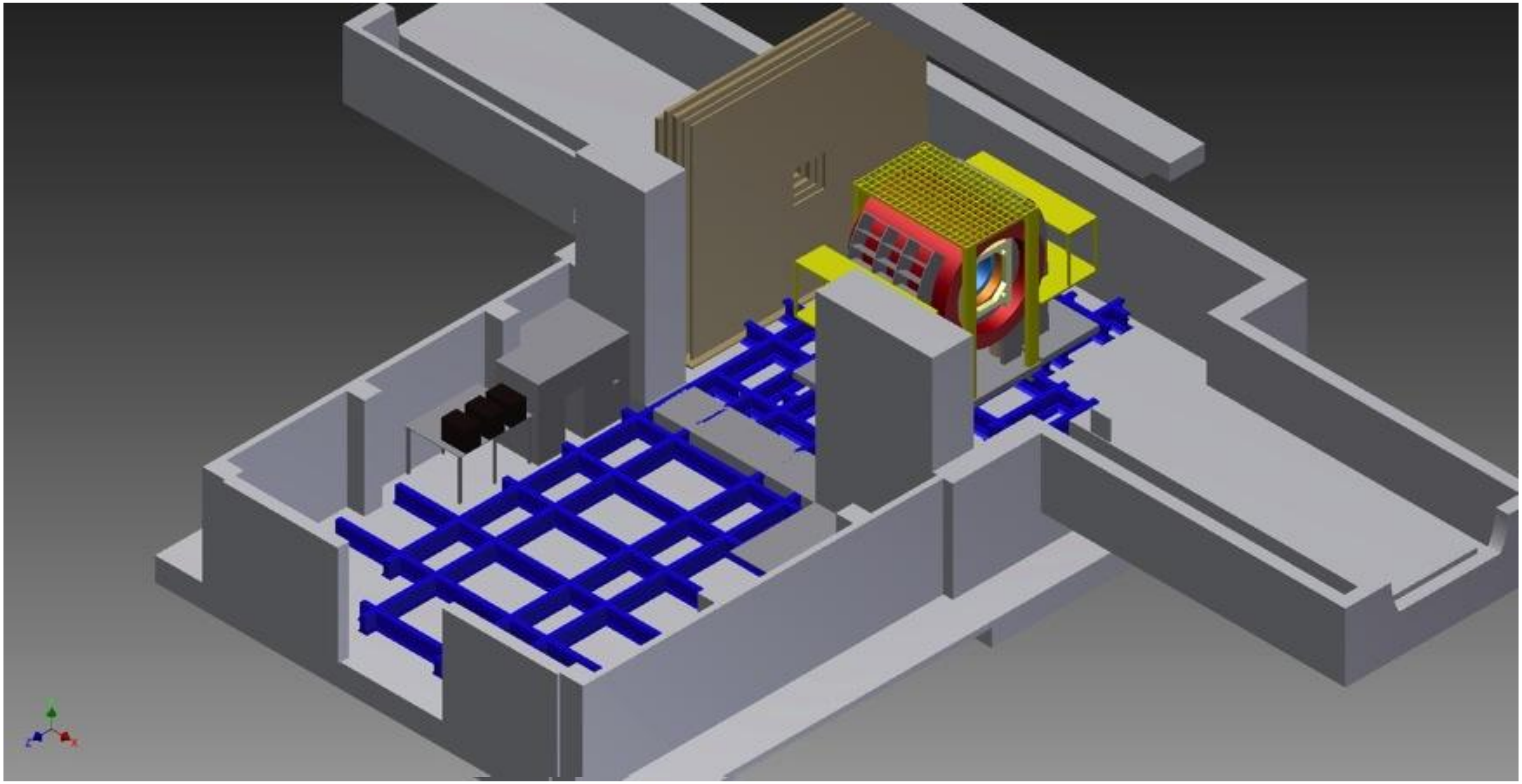
The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities

sPHENIX is crucial to the advancement of our knowledge of the QGP in key areas

sPHENIX will provide key measurements that will add uniquely to our picture of strongly interacting matter

‘How’ and ‘why’ questions on the QGP will be left with incomplete answers without sPHENIX
in conjunction with STAR at RHIC
and ALICE, ATLAS, CMS at LHC

# sPHENIX to Reality

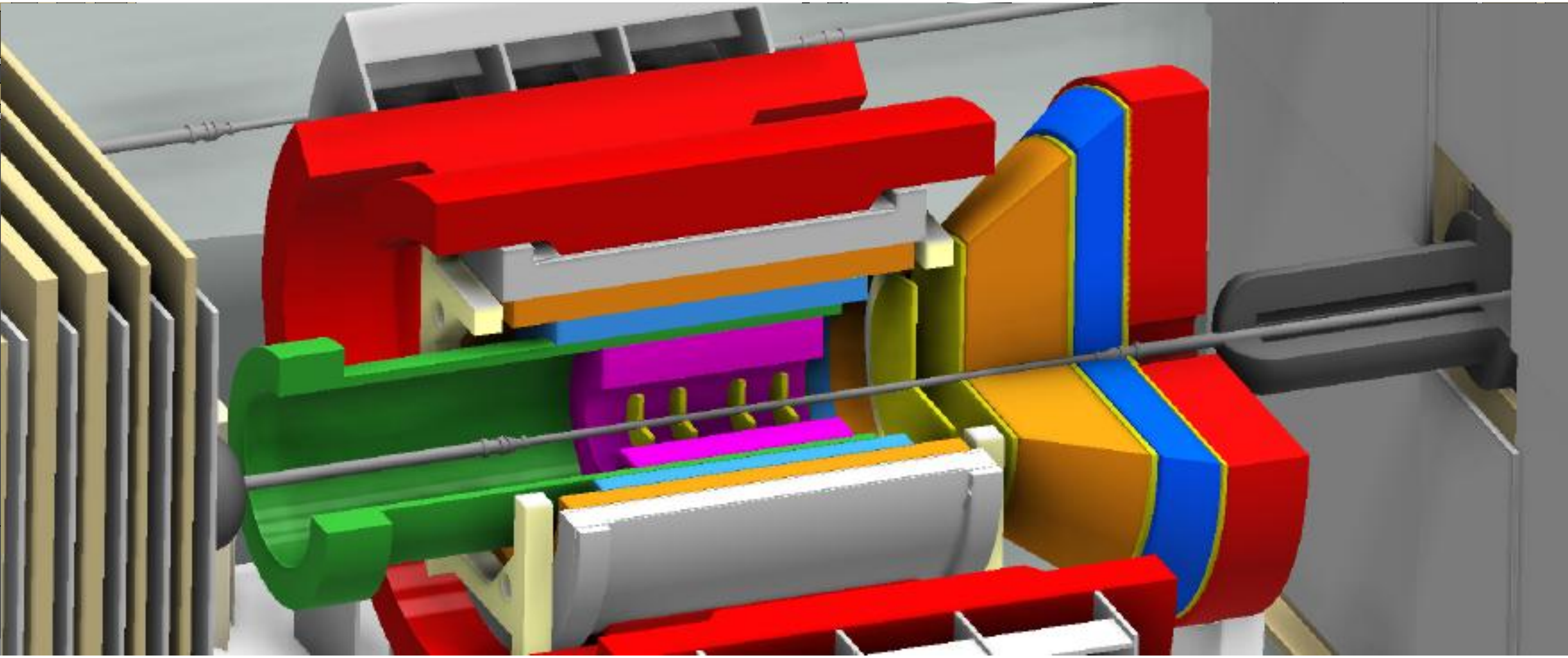


Now witness the firepower of this fully operational sPHENIX

# EXTRAS

# Electron Ion Collider (EIC) Detector Concept

Built around the BaBar Magnet and sPHENIX Calorimetry



- BaBar magnet has extra coil density near the ends – with proper flux return shaping, provides good analyzing power at very forward angles
- sPHENIX EMCal meets EIC detector specifications

http://arxiv.org/abs/arXiv:1402.1209