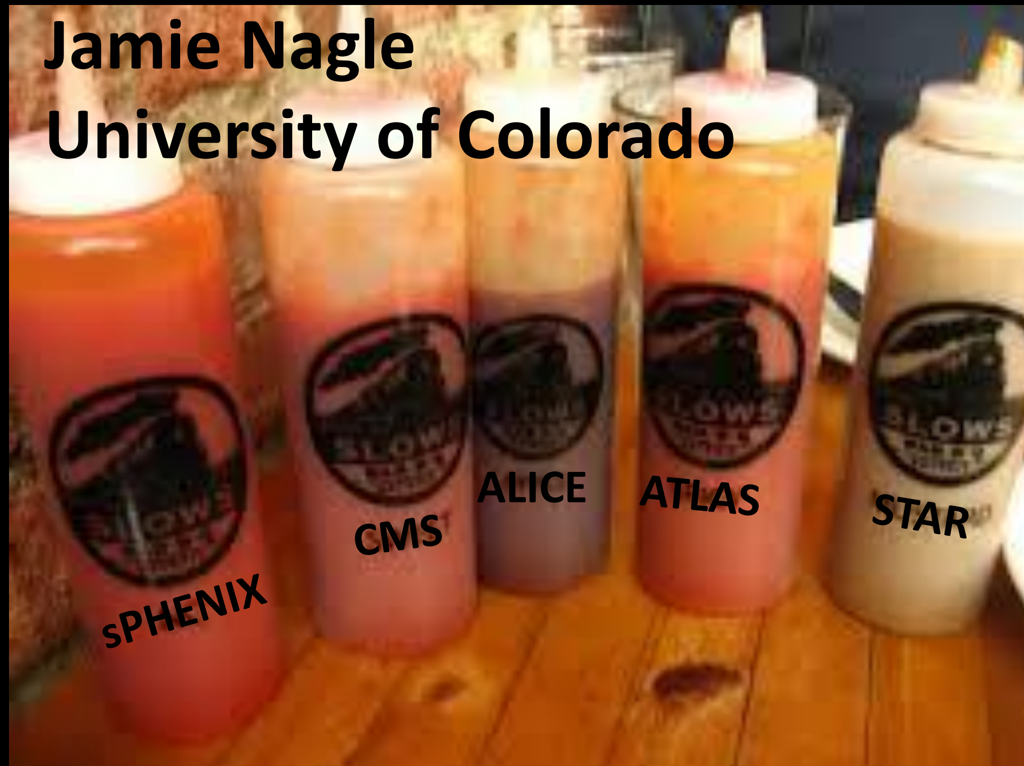
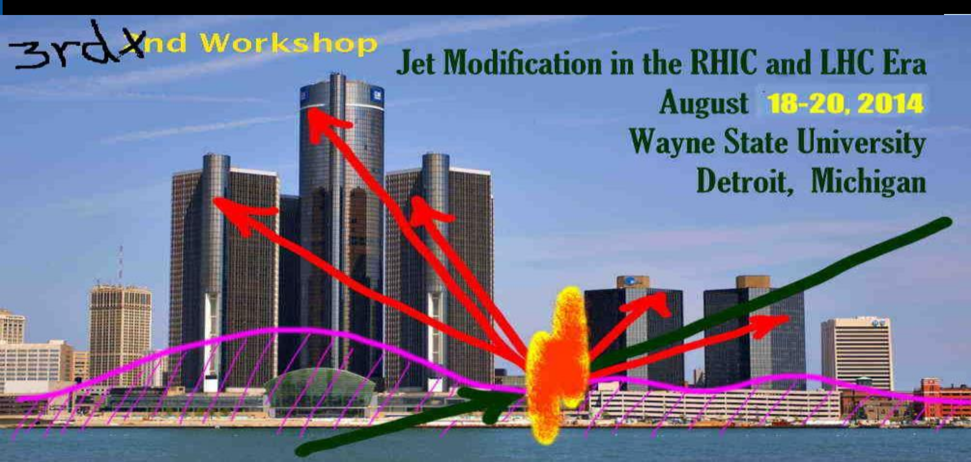
Answering the How and Why of the QGP

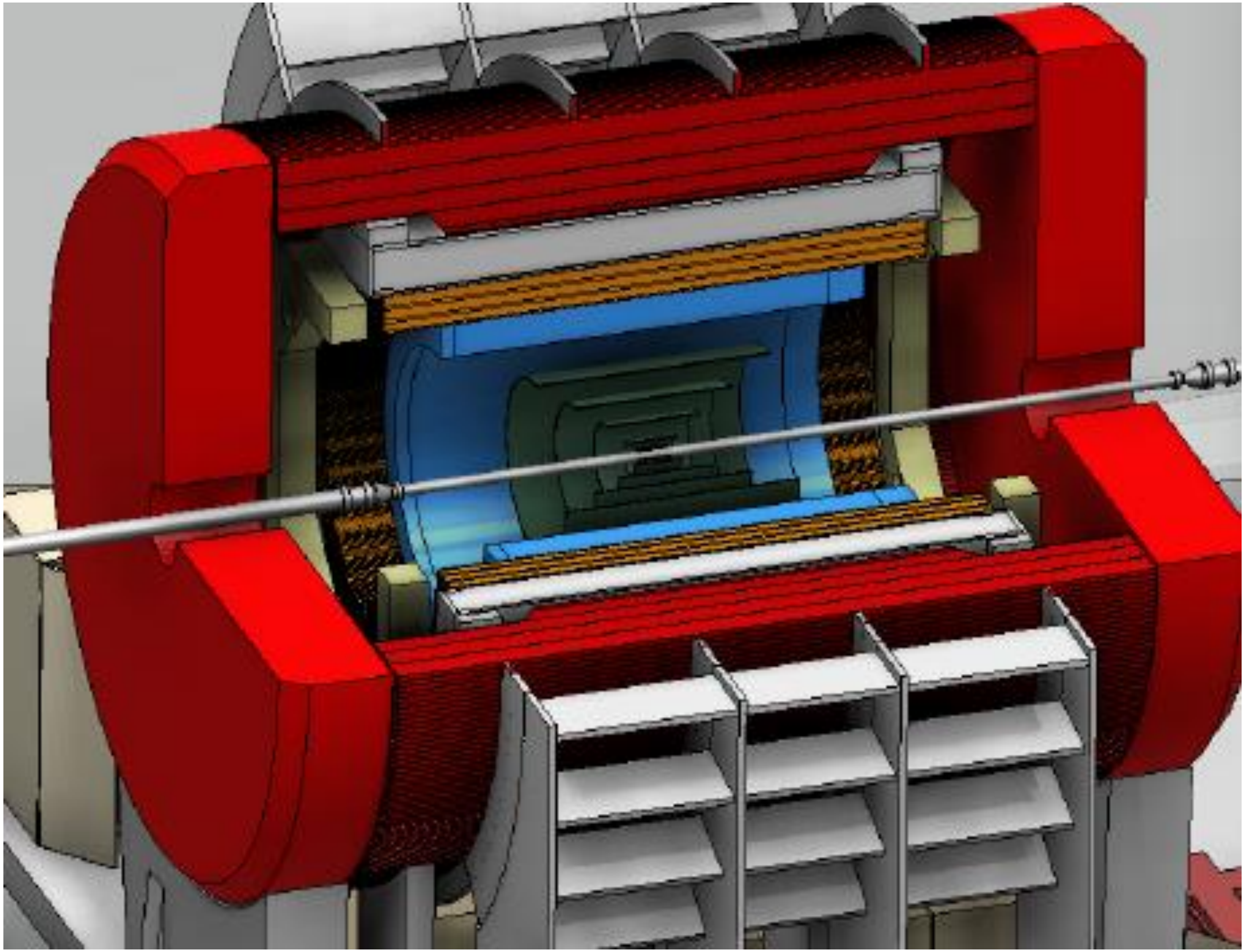
Probing the BBQ Across Taste Scales



Probing the QGP Across Length Scales



SPHENIX



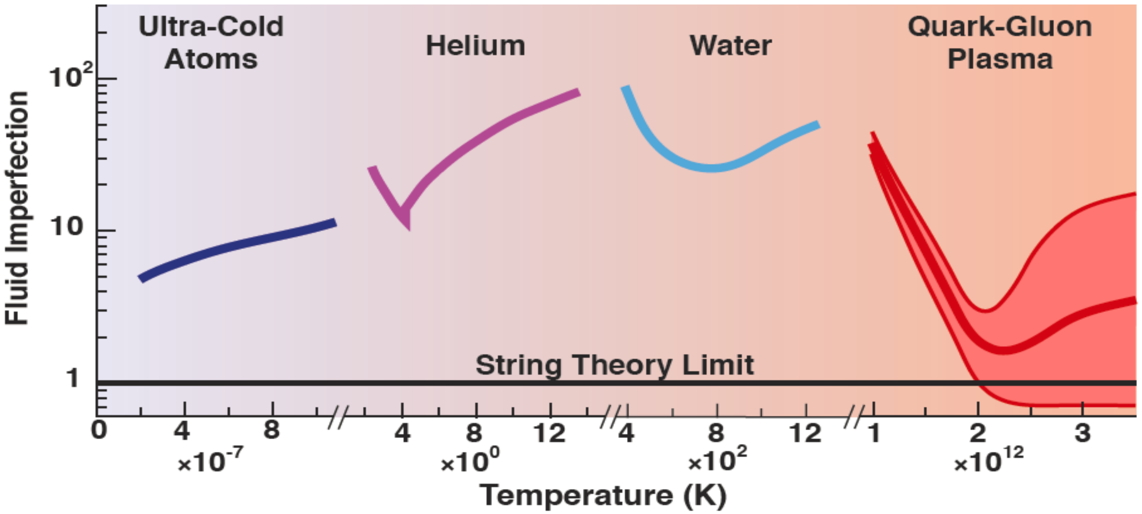
Fundamental Physics Goals

Mission Need

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

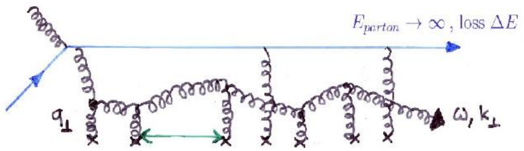


Pinning down the fluid imperfection (η/s) tells us the nature of the QGP, while leaving open the "how" and "why" questions

Probing the QGP across Length Scales

To address these questions, need to probe the QGP at different length scales and particularly in the region of strongest coupling (RHIC)

Hard Scattered Partons Traversing the QGP
(Jets, Dijets, γ-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 (Υ(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

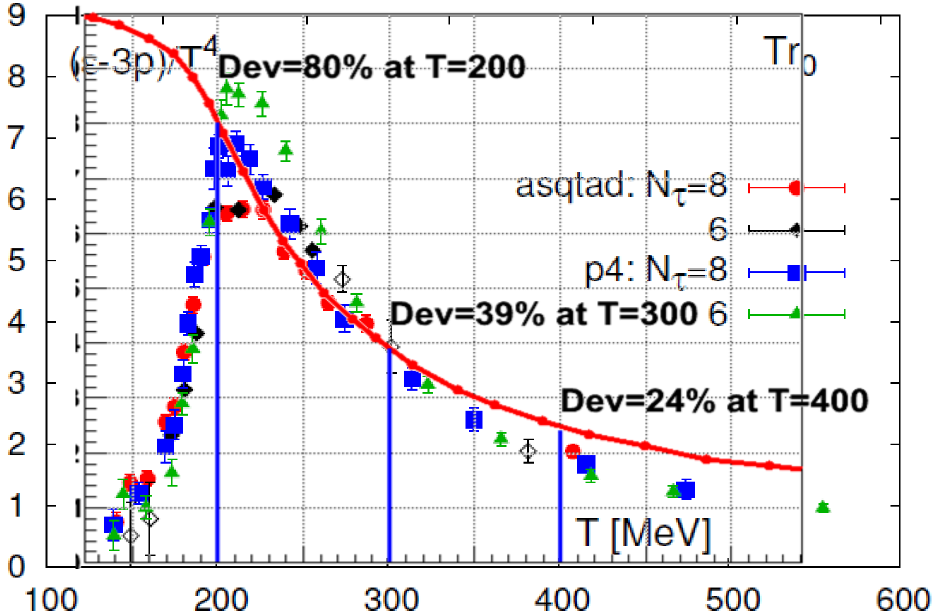
Jet observables at RHIC enabled by the sPHENIX upgrade are critical to providing this explanation by probing the QGP near 1-2 T_c and over a broad ranges of scales

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)

Getting at the Fundamental Science

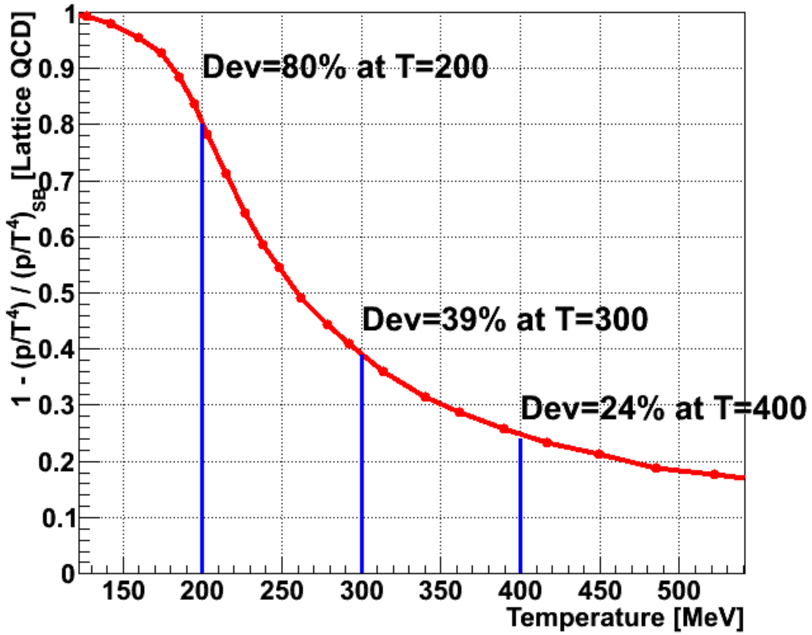
Strongest QGP Coupling Near 1-2 T_c?

Lattice Trace Anomaly



P/T⁴ deviation from Free Gas

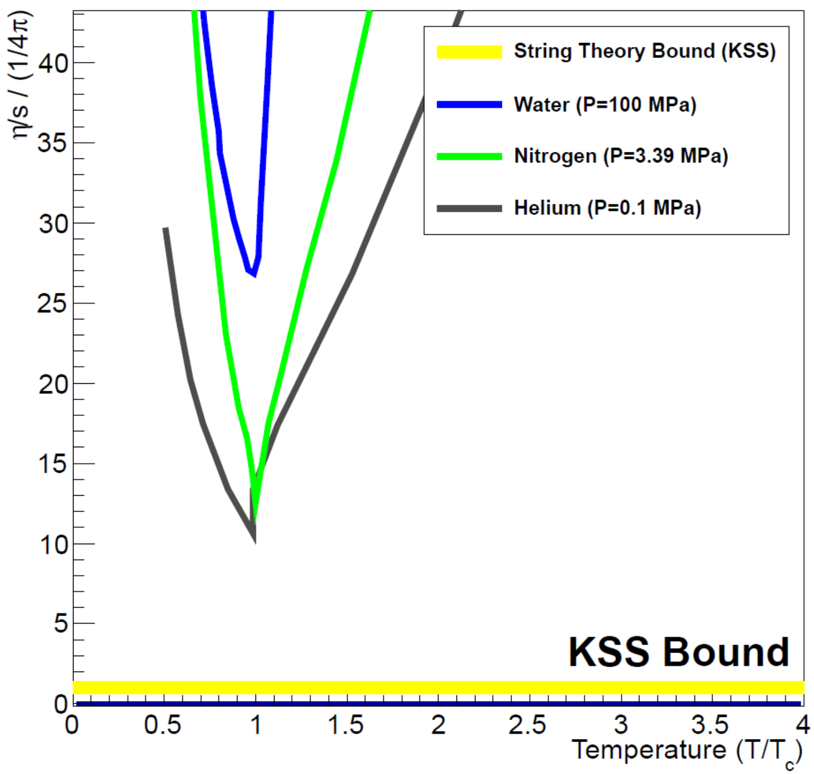
Data from Phys. Rev. D80, 014504 (2009)

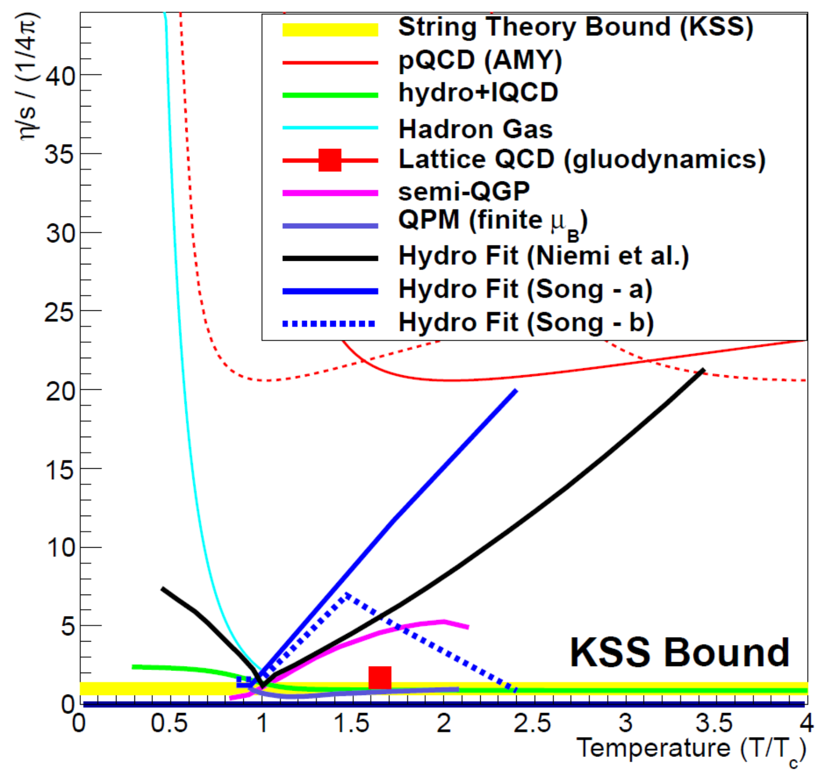


RHIC and LHC give a key lever arm in Temperature.

If the QGP properties are not different, <u>why not</u>?

Perfect Fluidity

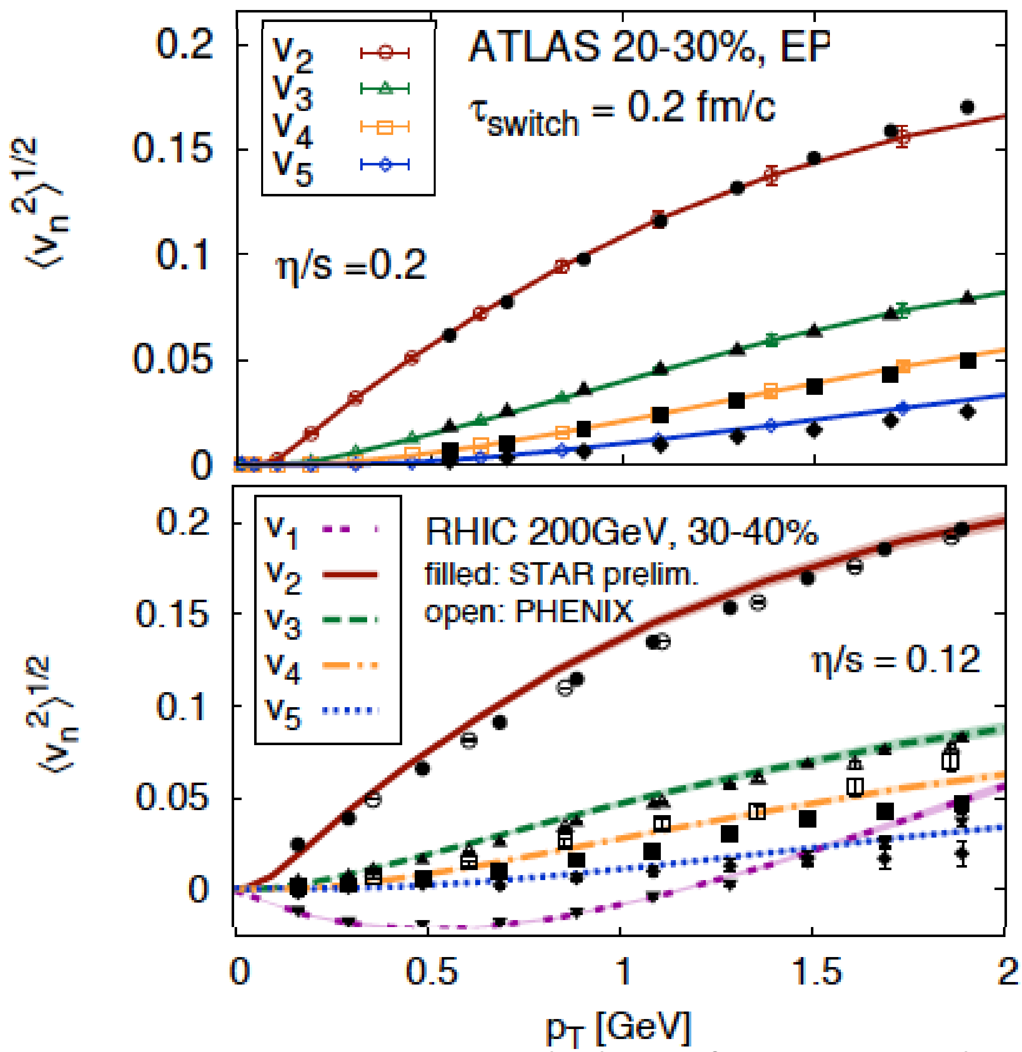




Many systems have minimum shear viscosity to entropy density near phase transformation

Theory for Quark-Gluon Plasma is not yet well constrained on this question

Indications of Stronger Coupling at RHIC



Calculation from Bjoern Schenke

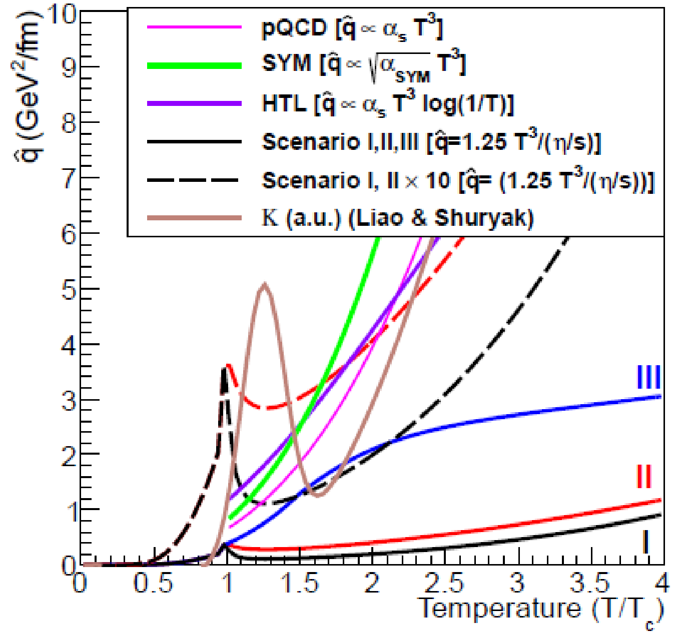
There are indications that the QGP is most strongly coupled as created at RHIC

What are the underlying changes in QGP properties near the transition?

Super-Strong Coupling near T_c?

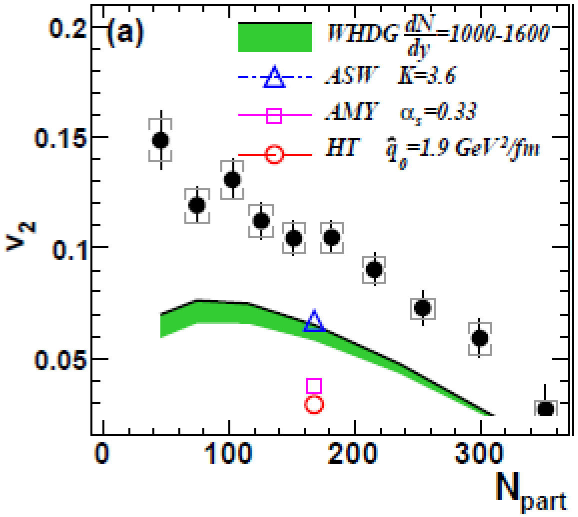
"Jet Quenching is a few times <u>stronger</u> near T_c relative to the QGP at $T > T_c$."

Liao and Shuryak, PRL (2009)



"The surprisingly transparent sQGP at the LHC [compared to RHIC]"

Horowitz and Gyulassy, NPA (2011)



"Large v_2 is striking in that it exceeds expectations of pQCD models even at 10 GeV/c."

PHENIX, PRL (2010)

NTC = Near Tc Enhancement

Thorsten Renk:

http://arxiv.org/pdf/1402.5798.pdf

"Comparing weak coupling scenarios with data, NTC is favored. An answer to this question will require a systematic picture across several different high p_T observables."

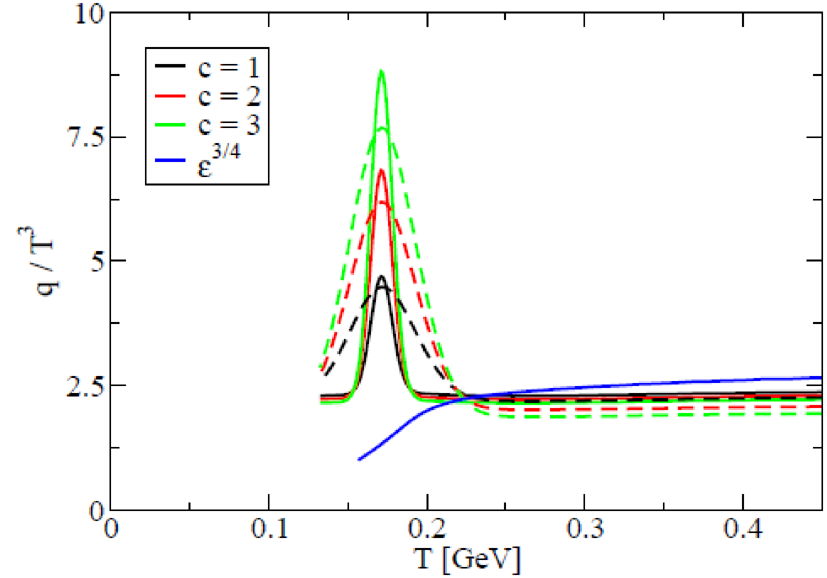


FIG. 1: Temperature dependence of the scaled transport coefficient $\hat{q}/T^3$ for various near T_C enhancement scenarios (see text) as deterimed by fits to R_{AA} in 2.76 ATeV 0-10% central Pb-Pb collisions at $P_T = 10$ GeV. Shown are $\sigma = 10$ MeV (solid) and $\sigma = 30$ MeV (dashed).

Theorists need to work on acronyms.

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**)

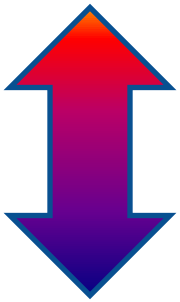
Can we observe the strongest coupling near T_c definitively

How do the parton shower and medium evolve together?

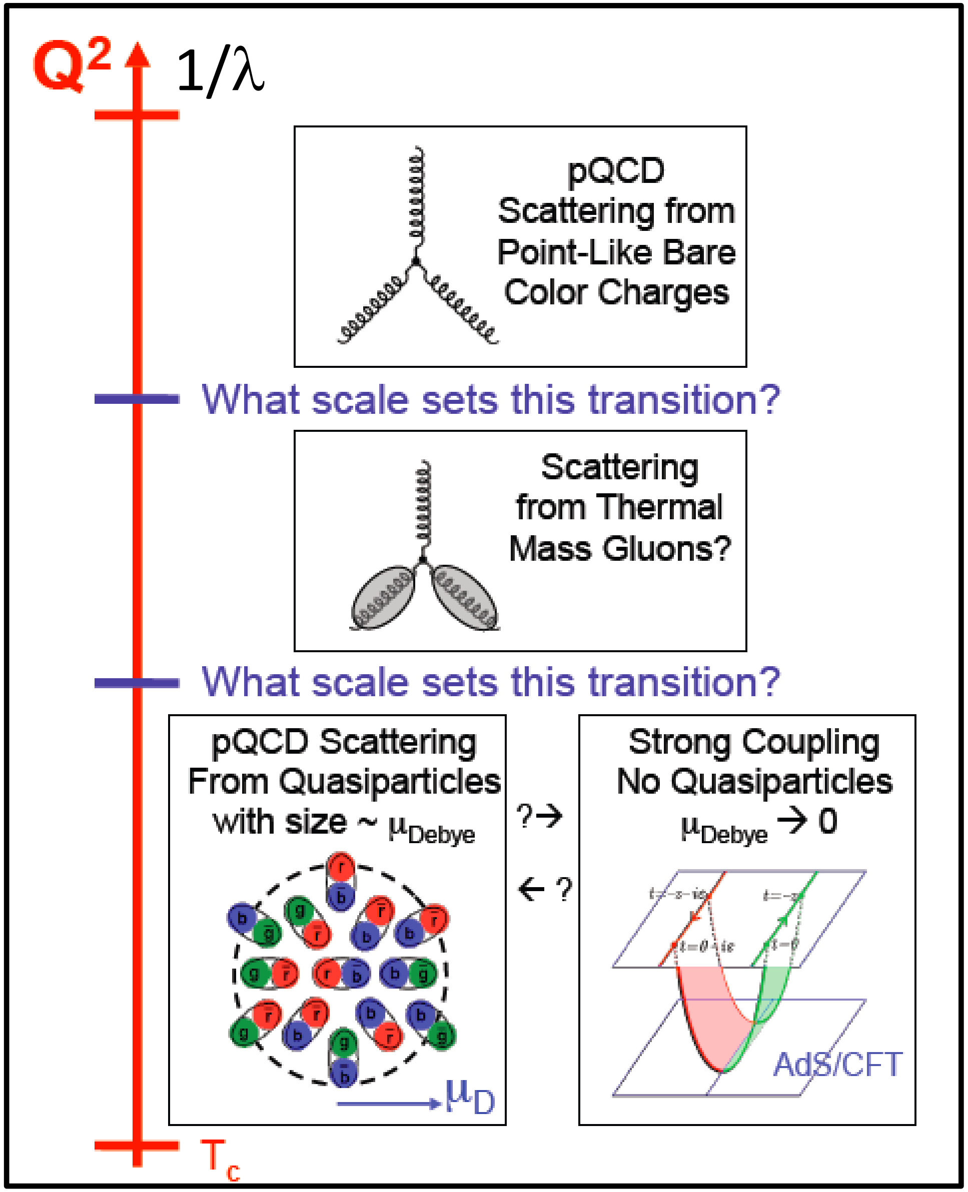
What are the inner workings? (quasiparticles, fields, modes)

At what length scale is the medium probed?

Do the highest energy jets at LHC see point-like color charges?



Do the lowest energy jets at RHIC scatter from coherent fields or only excite sound waves?



W. Horowitz

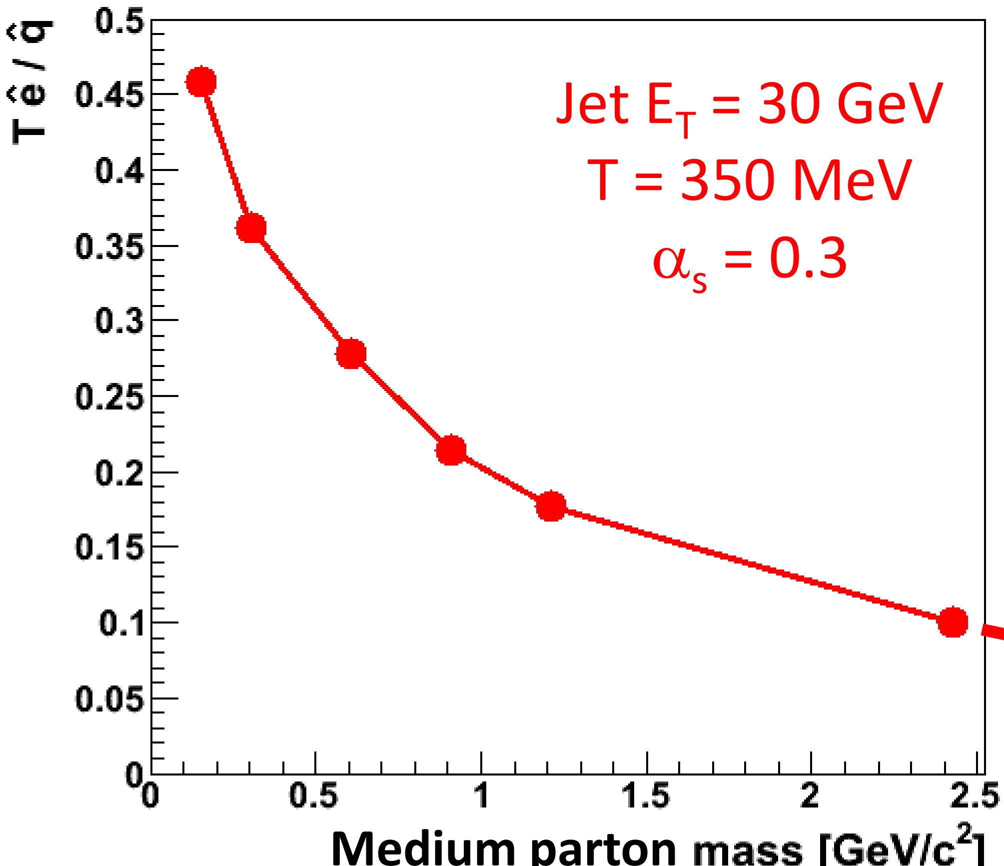
QGP Constituent Mass Dependence

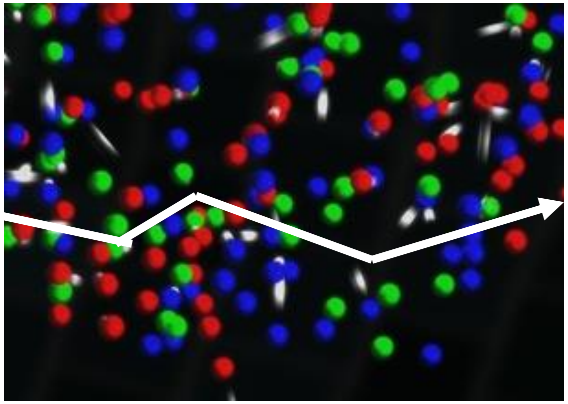
C. E. Coleman-Smith* and B. Müller
Department of Physics, Duke University, Durham, NC 27708-0305

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

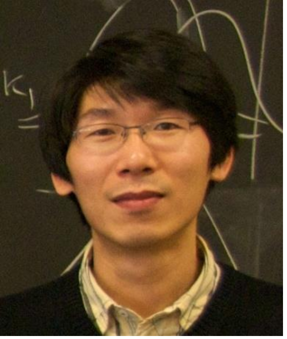
qhat → scattering of leading parton → radiation e-loss

ehat → energy transferred to the QGP medium



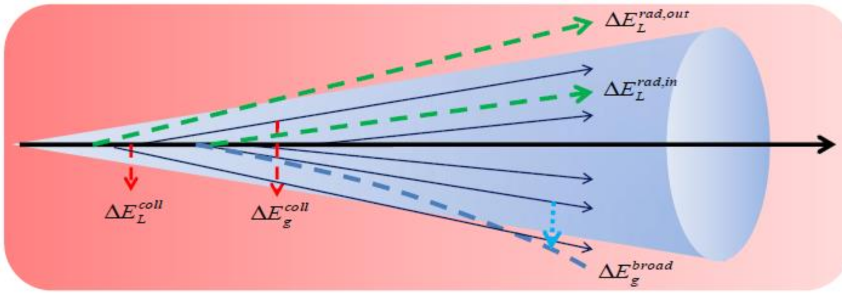


Limit of infinitely massive scattering centers yields all radiative e-loss.

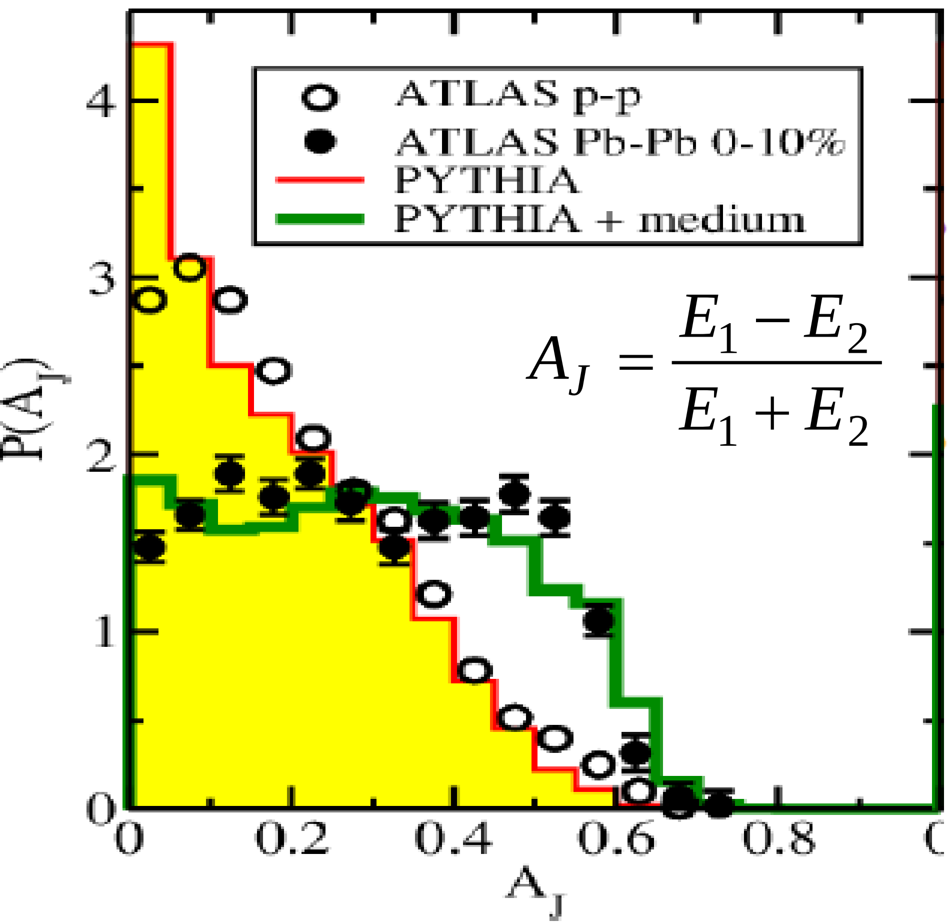


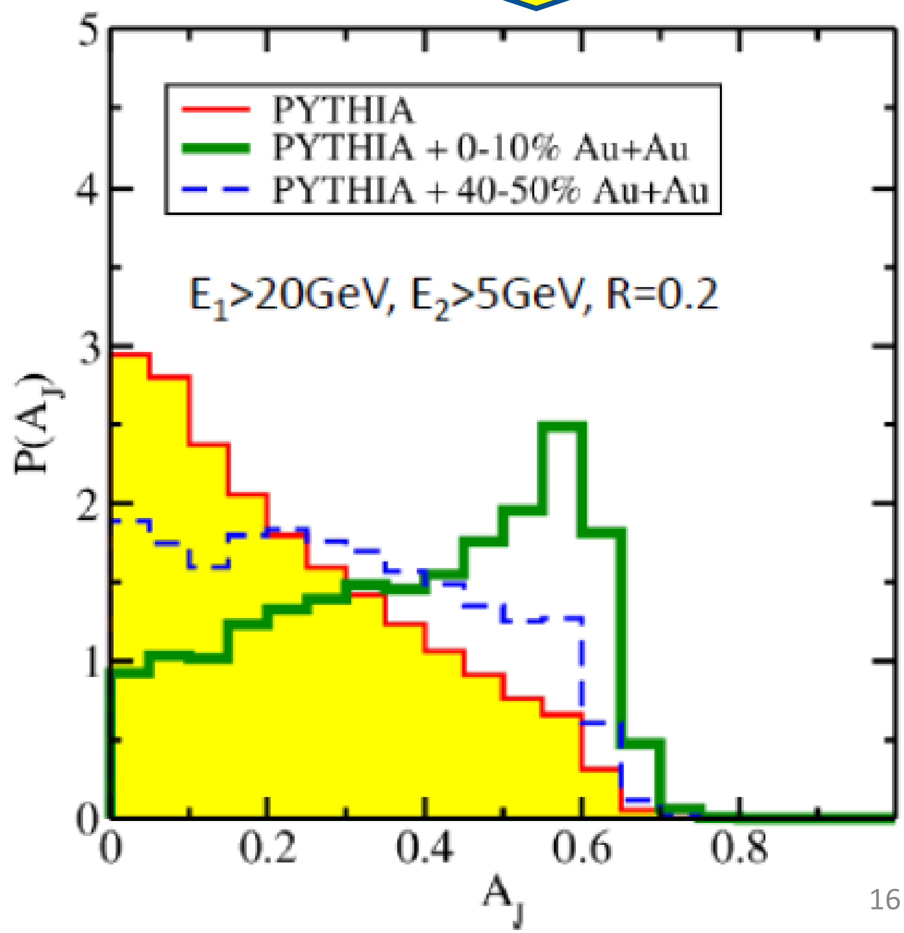
PRL 2011

Guangyou Qin, Berndt Muller

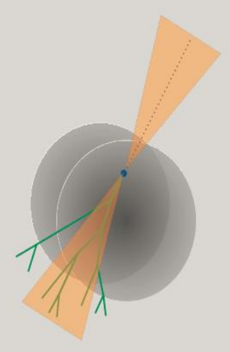


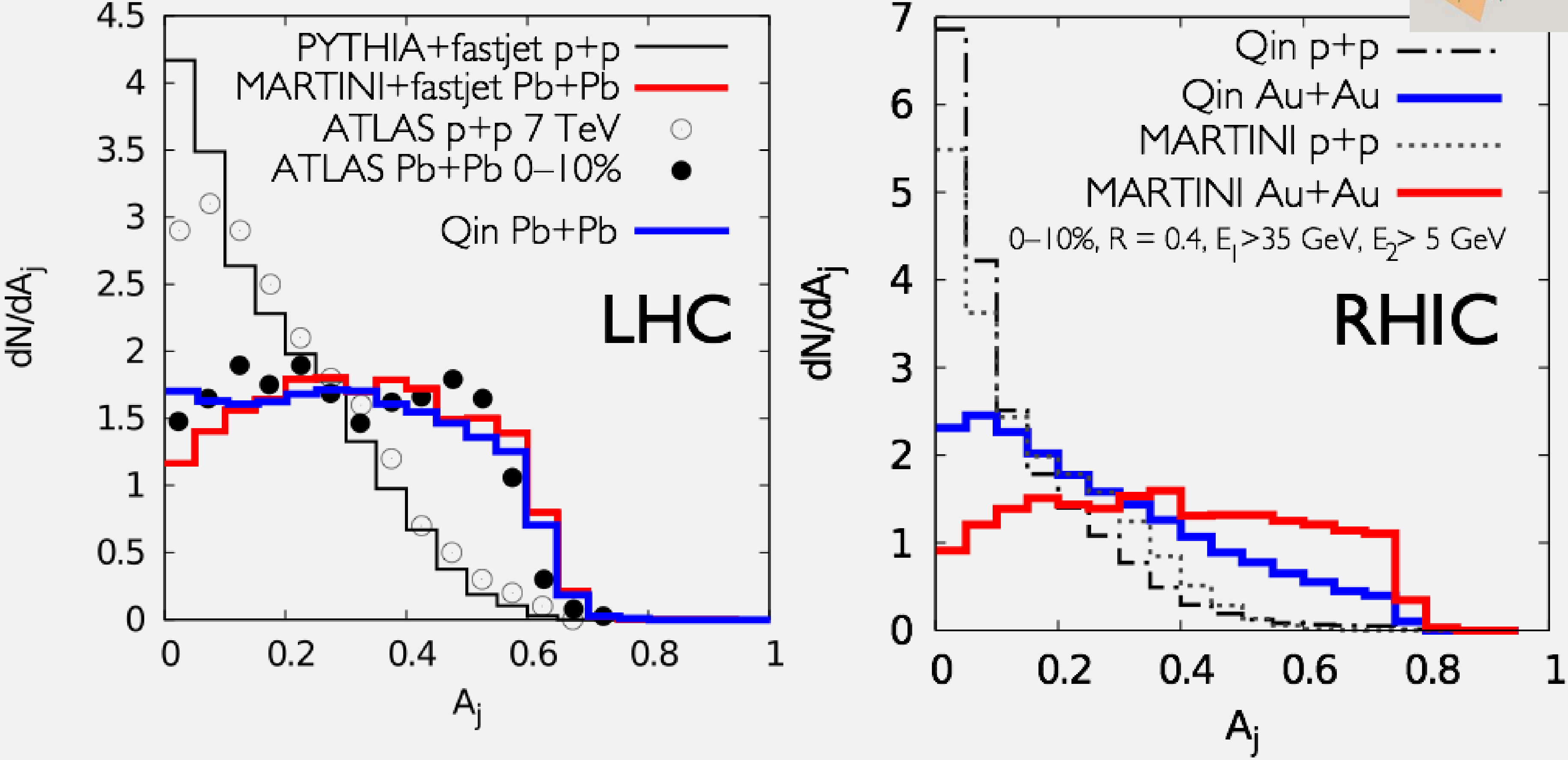
Larger modification at RHIC, more of parton shower equilibrated into medium.





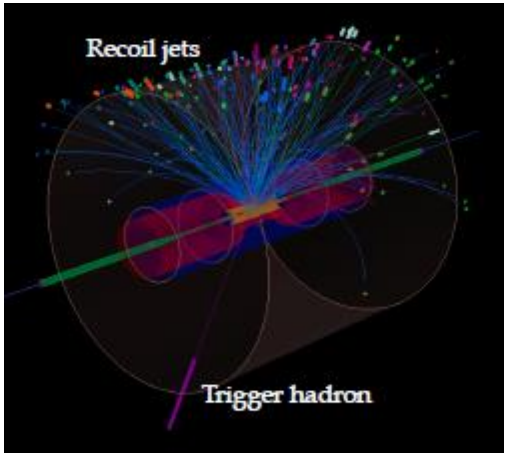
RHIC Jet Discriminating Power





$$A_J = \frac{E_1 - E_2}{E_1 + E_2}$$

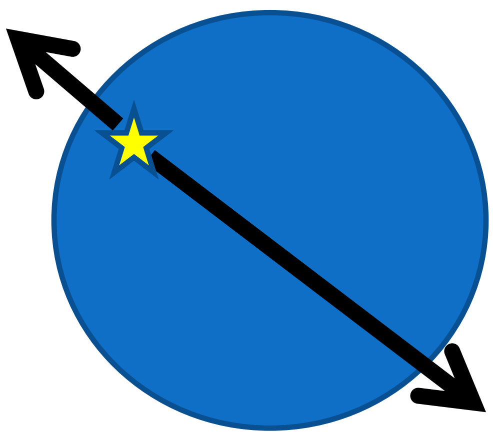
STAR Jet Program



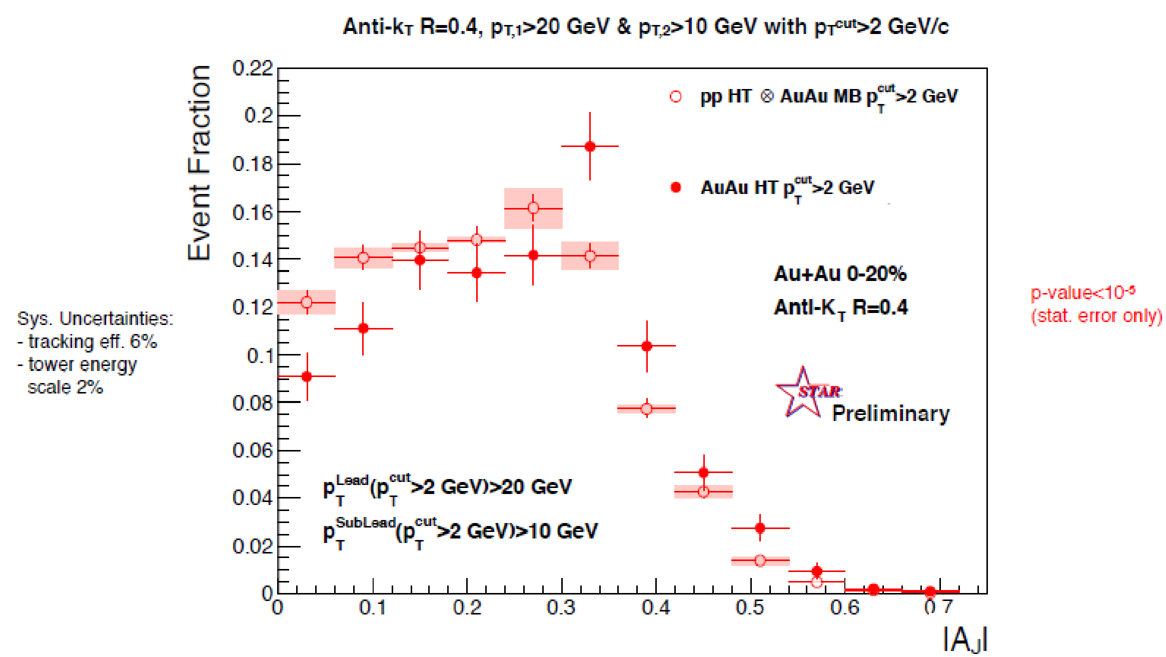
Very good jet capabilities
Large acceptance, tracking + EMCal

Exciting recent results from QM2014
Trigger on jet > 20 GeV requiring online trigger of > 5.4 GeV in one EMCal tower and all p_T > 2 GeV

Expect Surface Bias on Trigger
And Long Path on Opposite Side



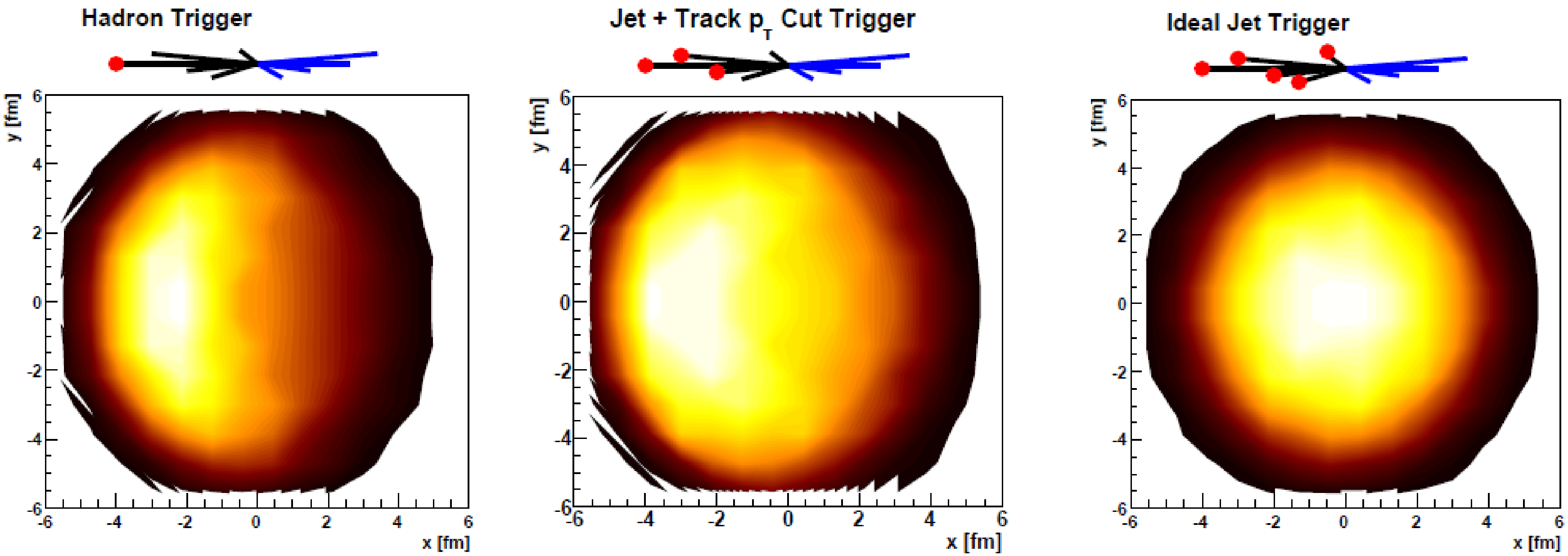
However, only modest suppression of balanced jets



Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

Bias Engineering or 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.

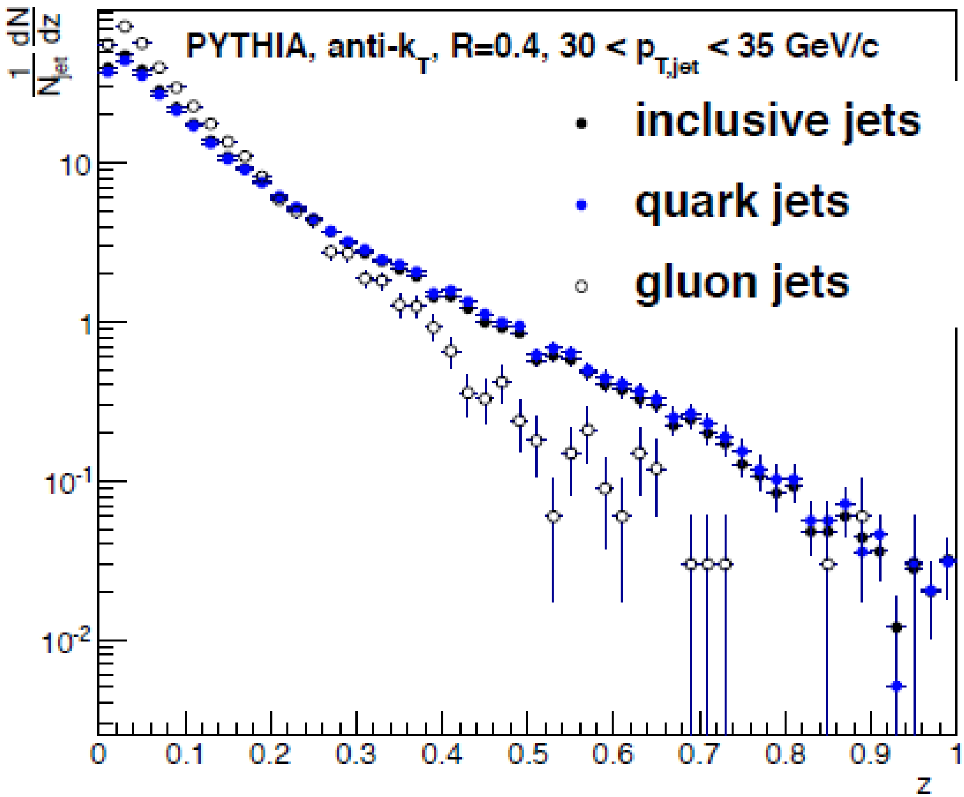


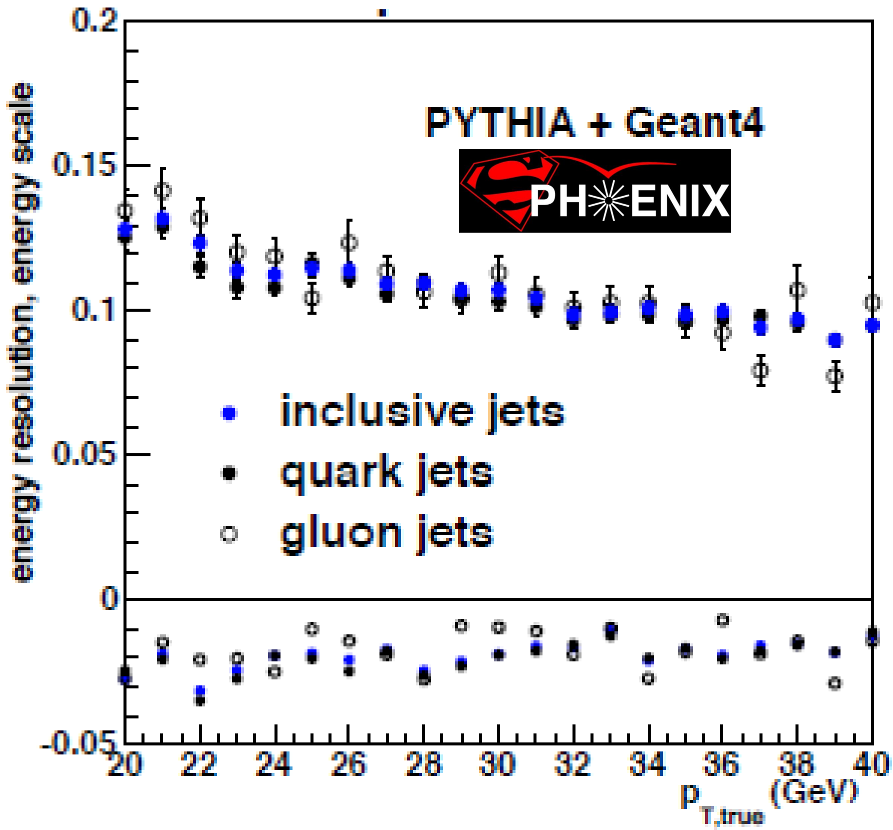
sPHENIX can measure these jets with no minimum p_T selection and no online trigger bias. Thus, one can explore the full range of engineered geometries.   High statistics and full jet energy range enabled. Systematic measurements enabled “tomography”

Recently it was proposed that medium response can only be seen when energy loss near surface (so not damped out by medium)

Calorimeter Measure Unbiased on FF

Quark and Gluons have very different fragmentation functions





sPHENIX calorimetric measurement gives the same energy scale and resolution.
Critical for extracting longitudinal redistribution of energy.

Theory Tools

A host of Monte Carlo parton shower codes are now available to fully interpret the combined set of sPHENIX, RHIC and LHC jet observables.

The close collaboration between experimentalists and theorists is necessary to incorporate the full suite of observables and test the basic physics and then constrain the detail parameters.

Continued RHIC and LHC data up through sPHENIX program fuels this collaboration.

YaJEM (now publicly available)

JEWEL (now publicly available)

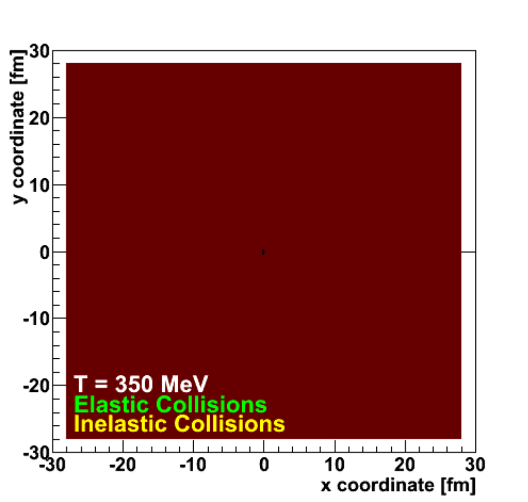
MARTINI

CUJET

MATTER

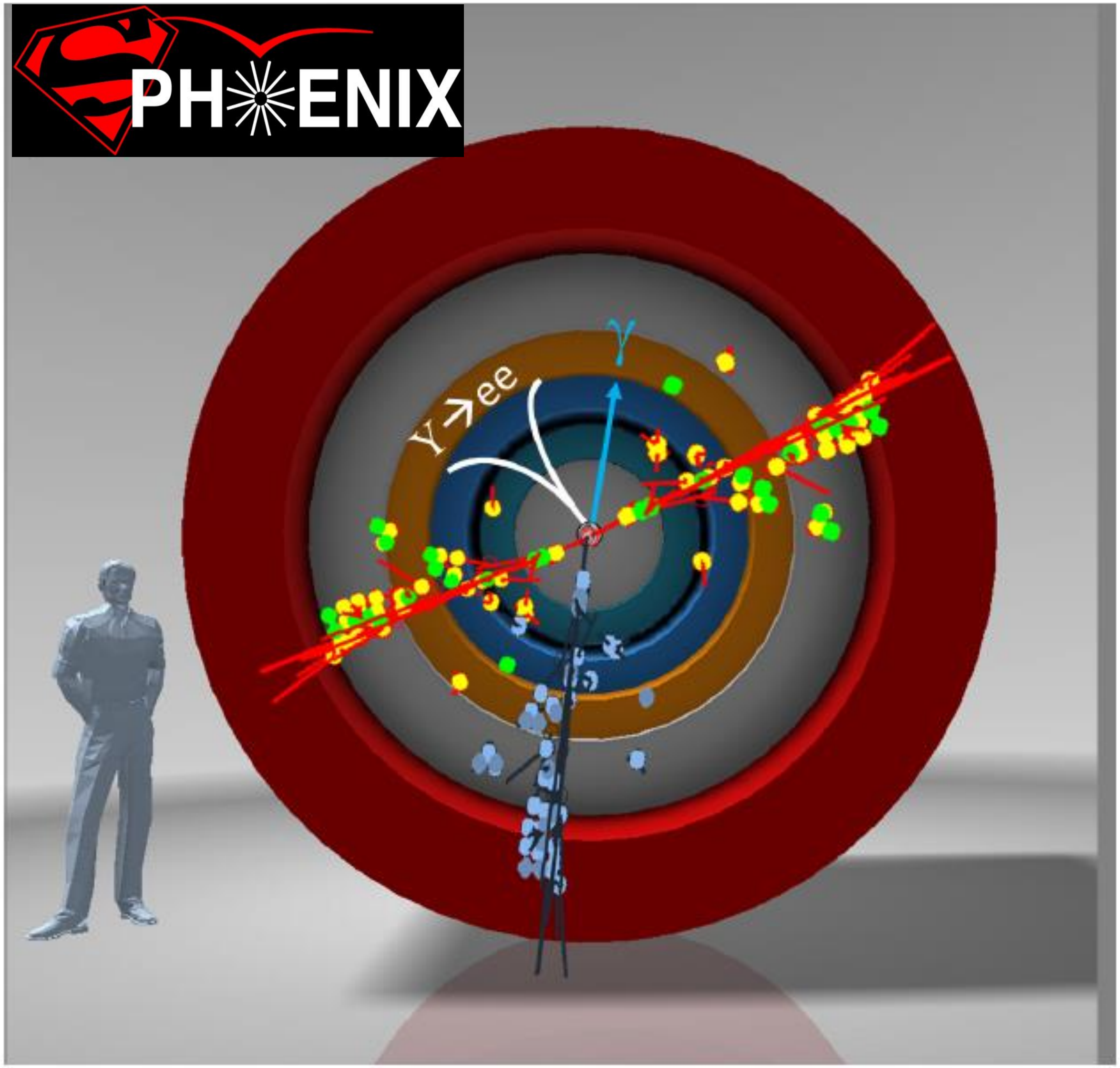
Q-PYTHIA

VNI



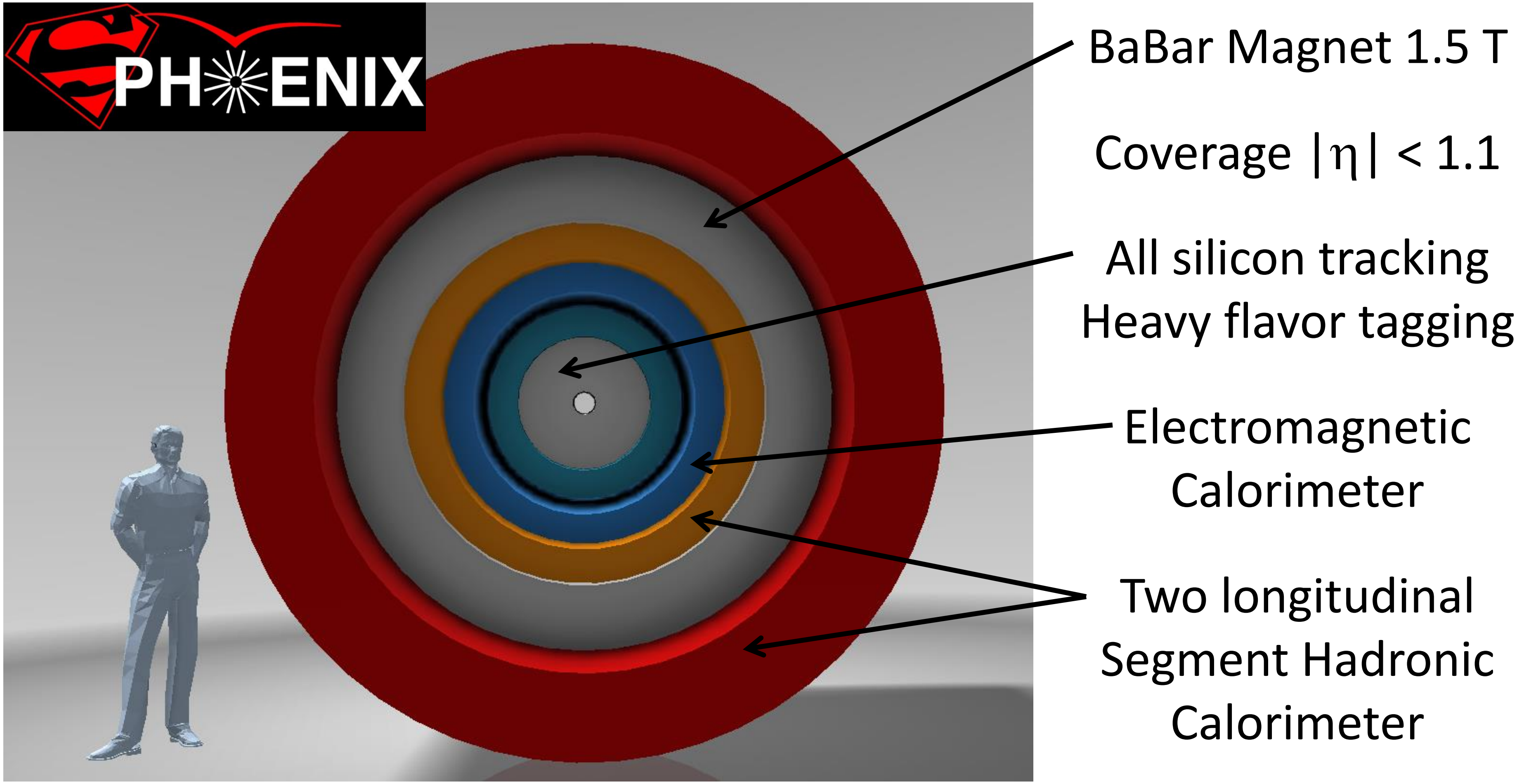
sPHENIX Physics Delivery

Physics → sPHENIX → Knowledge



How does sPHENIX enable access to this physics?

sPHENIX in a Nutshell



Common Silicon Photomultiplier readout for Calorimeters
Full clock speed digitizers, digital information for triggering
High data acquisition rate capability ~ 10 kHz

sPHENIX Run Plan

Two years of physics running 2021 and 2022 with 30-cryo week runs

20 weeks Au+Au @ 200 GeV
10+ weeks p+p @ 200 GeV [comparable baseline statistics]
10+ weeks p+Au @ 200 GeV [comparable baseline/new physics stats]

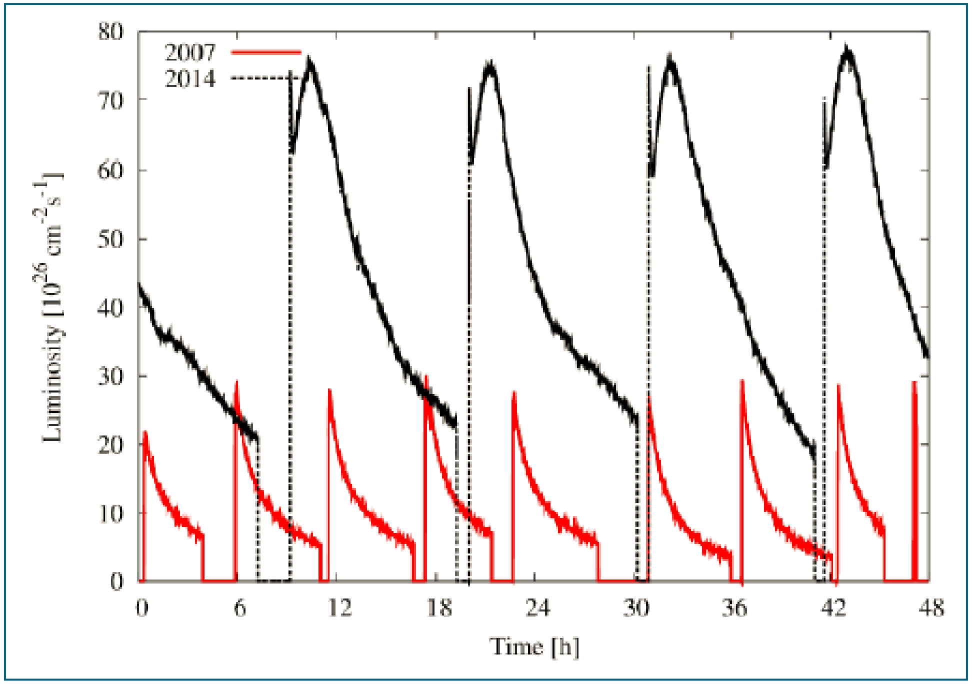
sPHENIX maintains very high PHENIX DAQ rate
sPHENIX maintains fast detector capability – no pile up problems

If we just record Au+Au minimum bias events (no trigger bias), in 20 weeks with current RHIC performance and PHENIX livetime, we record **50 billion events within |z| < 10 cm** [optimal for silicon tracking]

Note this is not sampled, but recorded. Full range of differential measurements and centralities with no trigger biases.

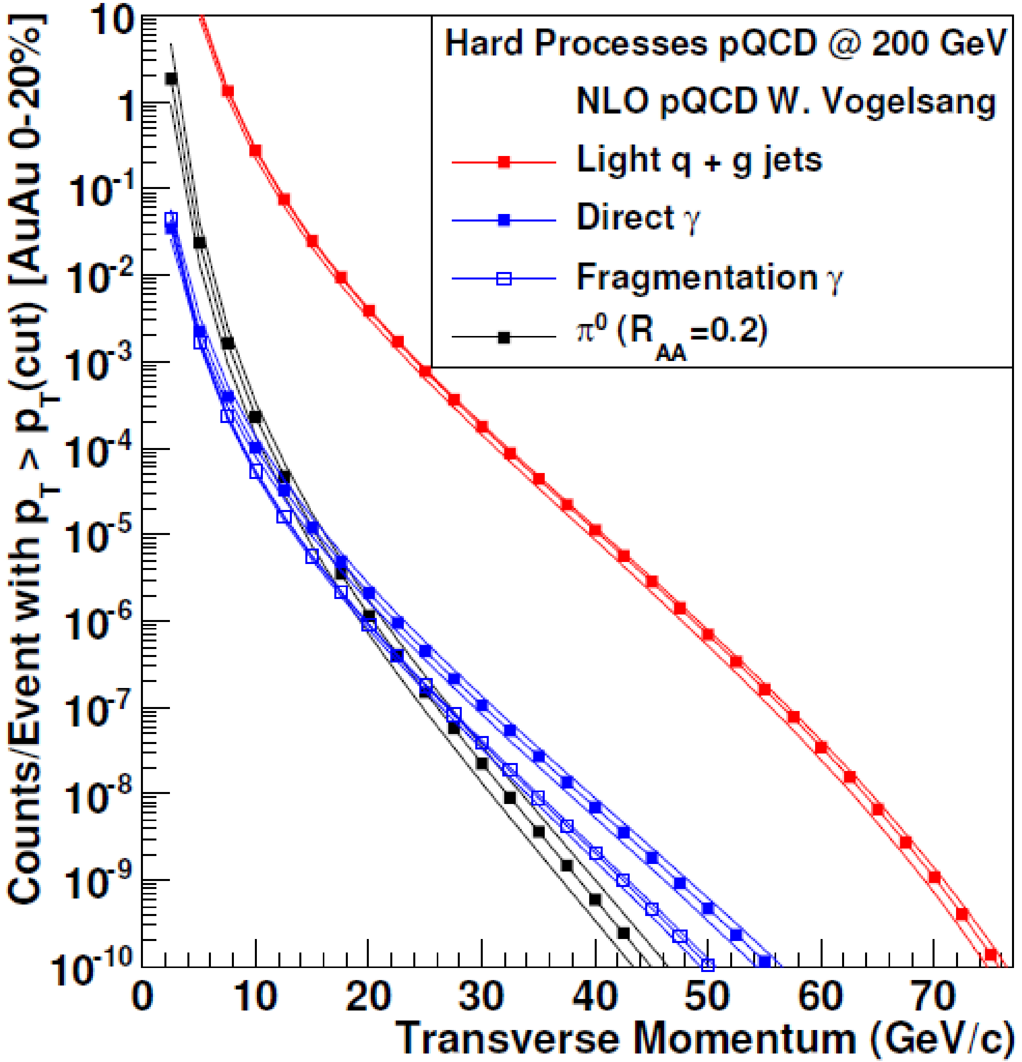
Fantastic C-AD Performance

Run-14 Au+Au @ 200 GeV has been so successful that with minimal trigger requirements, for high energy jets and photons [with acceptance over the whole z-vertex range] we could sample almost **<u>200 billion in 20 weeks</u>**. This assumes no performance improvements from C-AD!



<u>Level-1 triggering</u>: EmCal and HCal electronics digitize at full clock speed. Thus, fully digital triggering is a feature with entire calorimeter information brought into one electronics module (i.e. very flexible for jet patch triggering, pairs, etc.) .
Also, crucial for p+p and p+Au with minimal bias on jet fragmentation functions, quark versus gluon jets, single high p_T hadrons, etc.

sPHENIX Rates: Jets, Dijets, γ-Jet



Recording 50 billion Au+Au events in one year

10^7 jets > 20 GeV
10^6 jets > 30 GeV
80% are dijet events

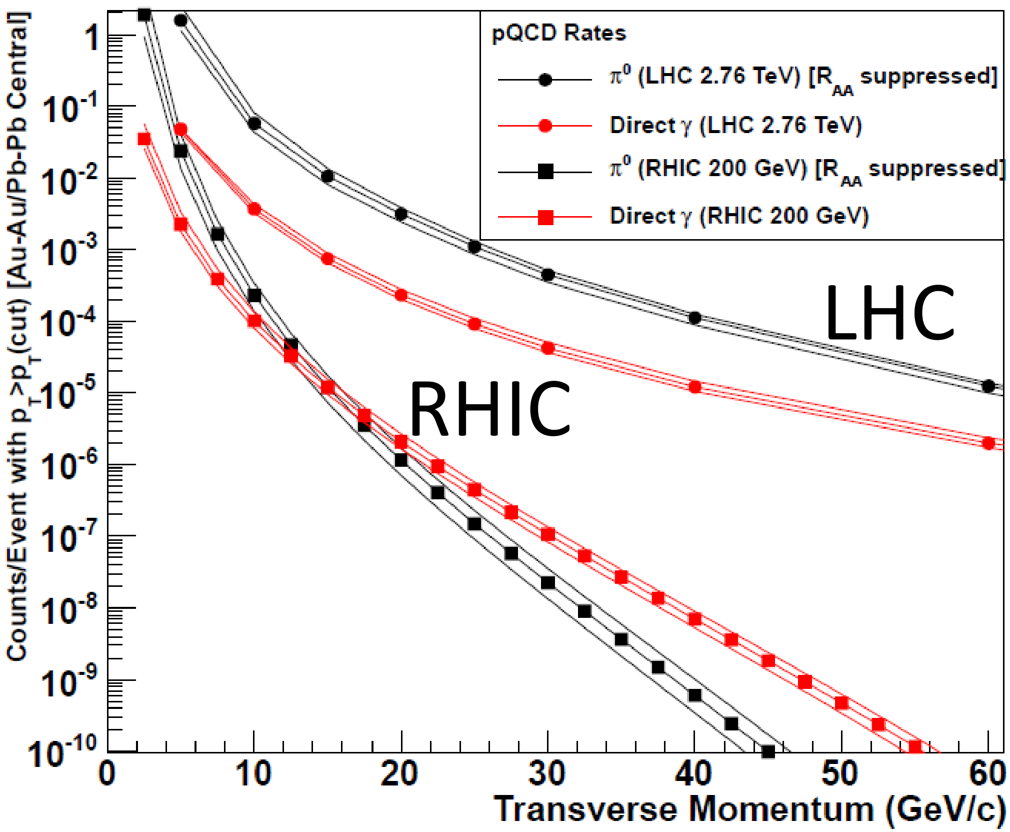
10^4 direct γ > 20 GeV

p+p
p(d)+A
Differential measures

With C-AD delivered results now, of order 200 billion sampled

Direct Photon-Jet/h

sPHENIX has excellent direct photon capabilities



In Au+Au central collisions for $p_T > 20$ GeV, direct photons dominate S/B > 3

Simple isolation cuts with full calorimetry give additional handle and enable p+p and p+A comparison measurements

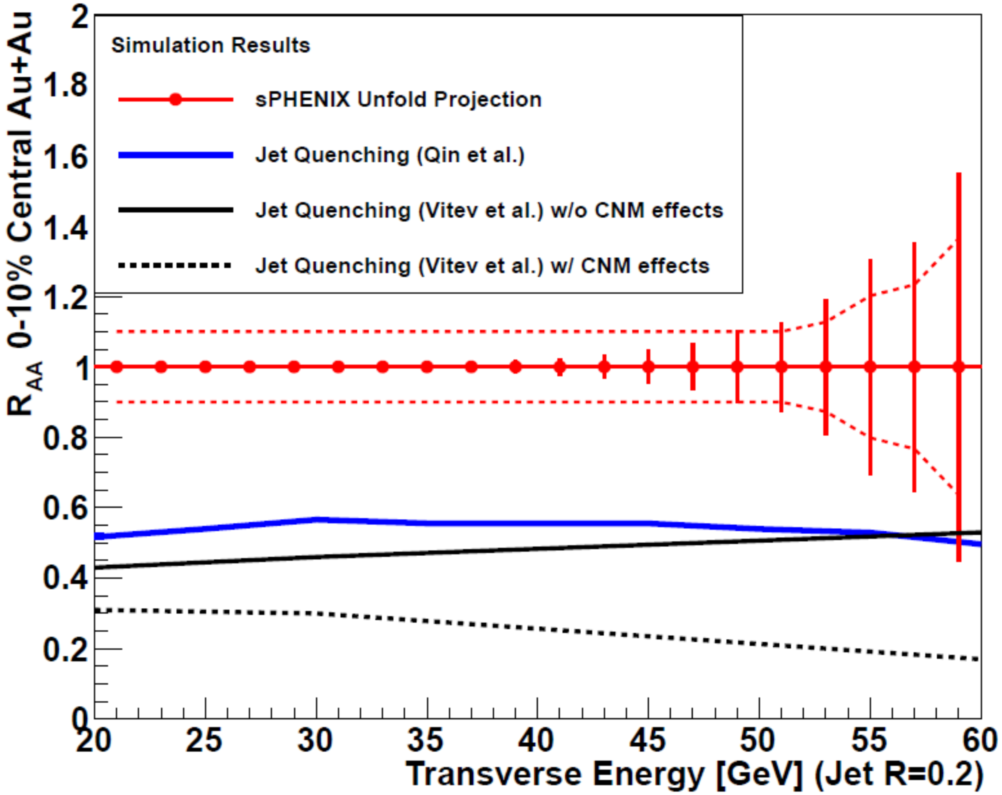
Inclusive Jet Spectra

Example ROOUNFOLD Iterative Bayes

Method shows very good result.

Full GEANT-4 simulation with FastJet Reconstruction gives good resolution.

50 billion MB events



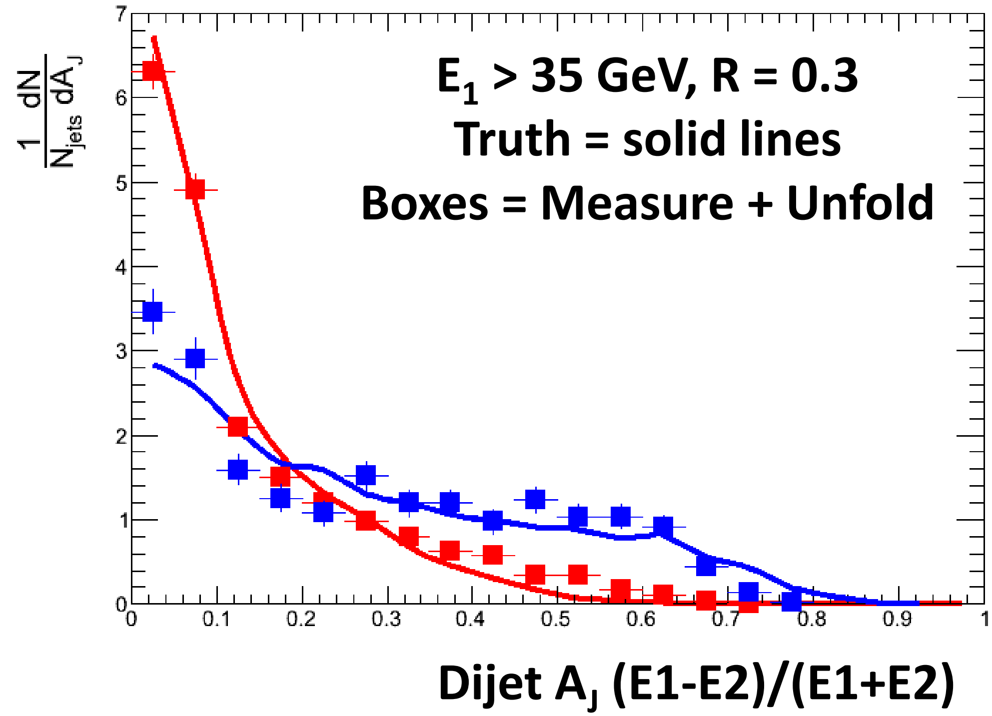
Jet R_{AA} measurable with high stats

Dijet Asymmetries

- **PYTHIA (vacuum case)**
- **PYQUEN (quenched case)**

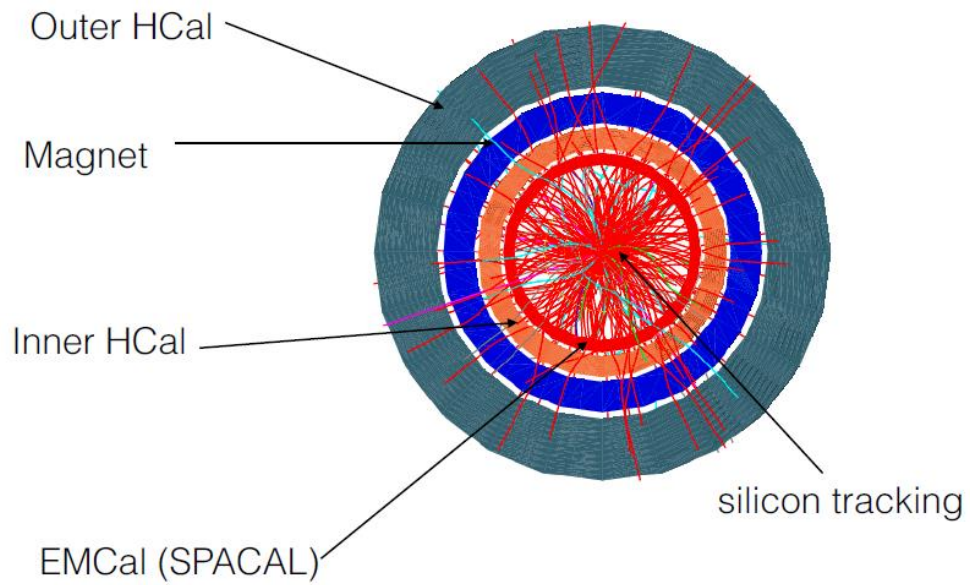
Full jets + HIJING background + detector resolution + FastJet + underlying event subtraction

Very easily discriminated (large effect)

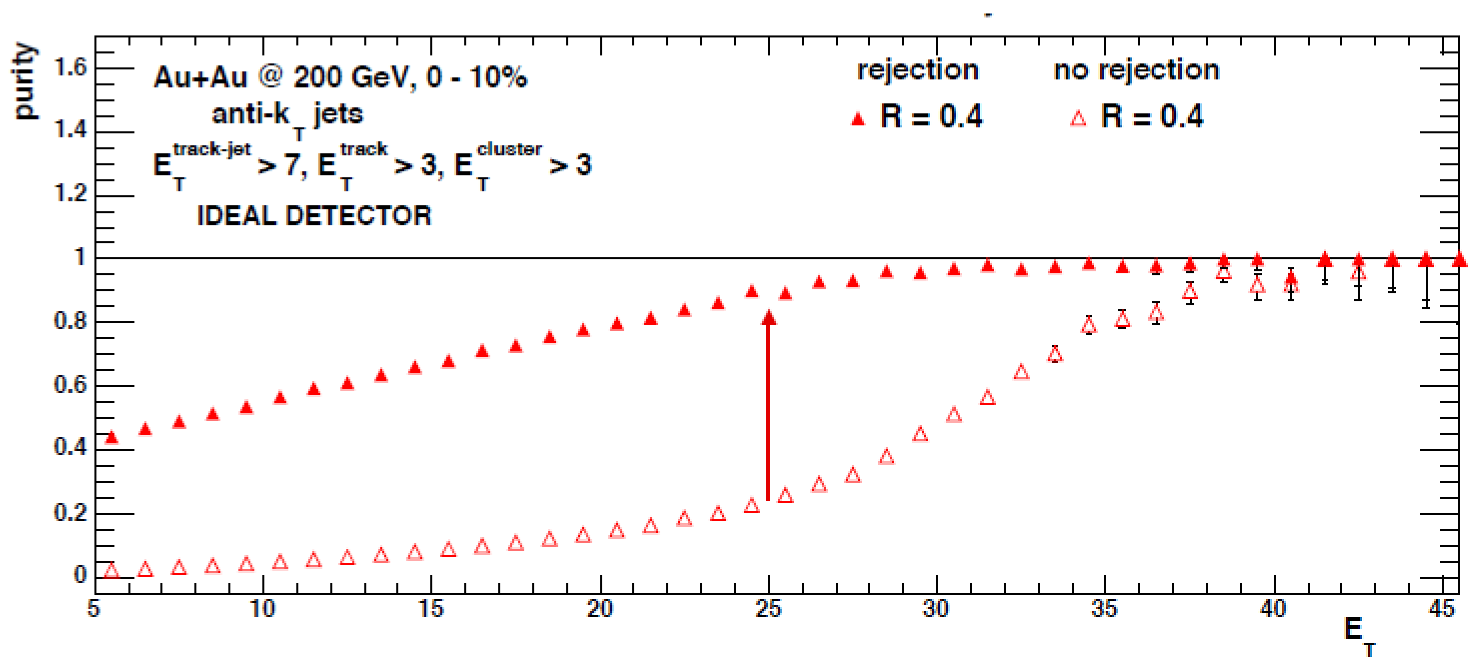


Using core calorimeter energy cuts and also hybrid tracking methods one can also reproduce the STAR biased dijet result, again scanning the range of surface bias engineering

Tracking & Jets (like a mini-CMS)

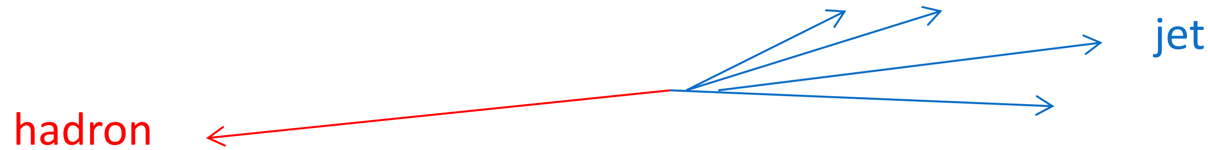


One can use pure calorimetric jets, hybrid track jets, combinations in between



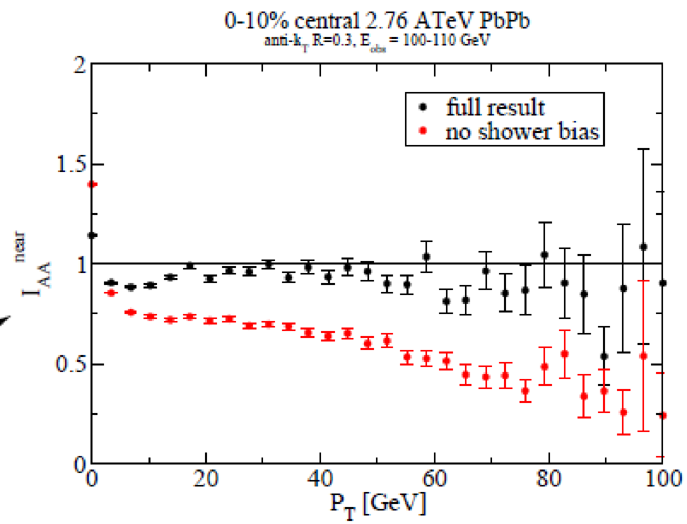
Additional Studies in Progress

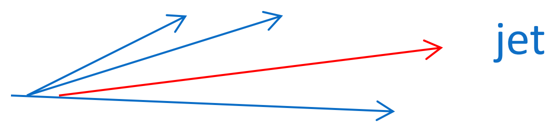
Example – hadron triggered jet ←→ jet triggered hadrons



Exploring maximum jet R value with good purity in central and mid-central Au+Au
Can also measure FF of opposing jet
Bias to longer path length, much higher statistics to compare with γ-jet/h
sPHENIX very high rates, trigger on hadrons in HCal in p+p and p+A

Example – jets > 30 GeV with associated hadron pT > 10 GeV





Exploring maximum jet R value with good purity in central and mid-central Au+Au
One can measure the relative change in FF for z > 0.3
Is energy really lost outside the cone or lost within the cone (to the UE)

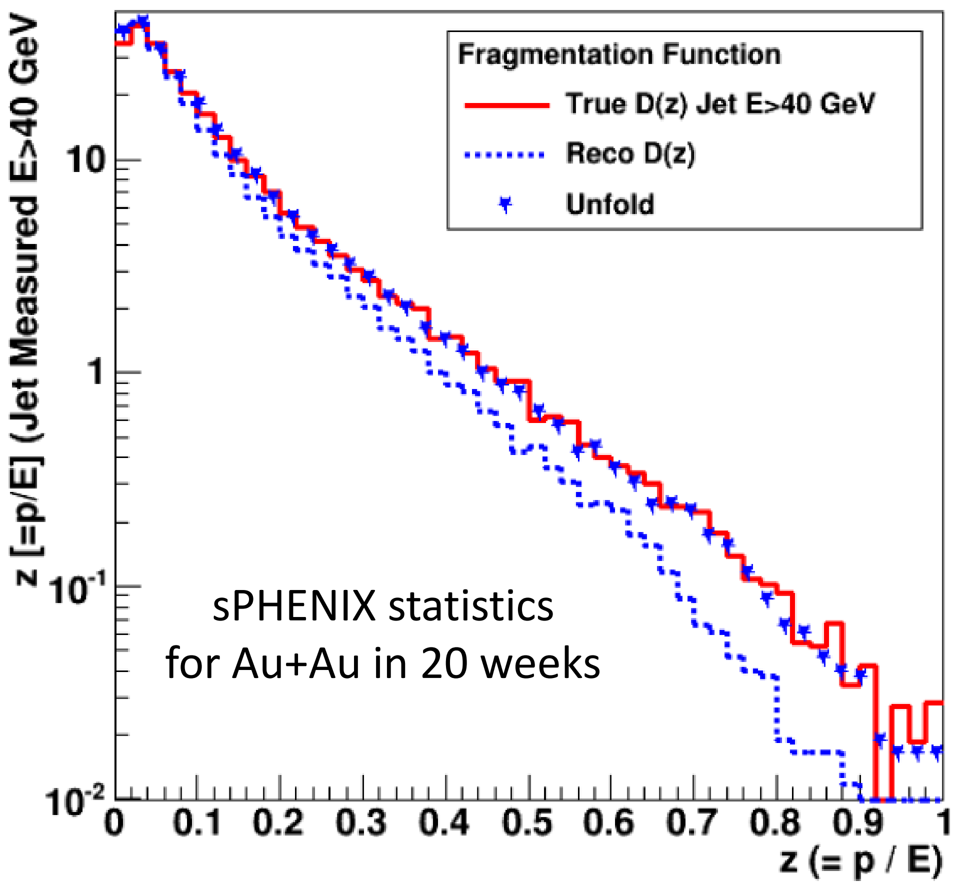
Fragmentation Functions

sPHENIX combination of excellent tracking and calorimetric jet reconstruction enable FF measurements

Very beneficial that numerator (charge track) and denominator (jet energy) are measured separately. Dramatically reduces high-z backgrounds

Again, key measurement across all Au+Au centralities and with different jet definitions

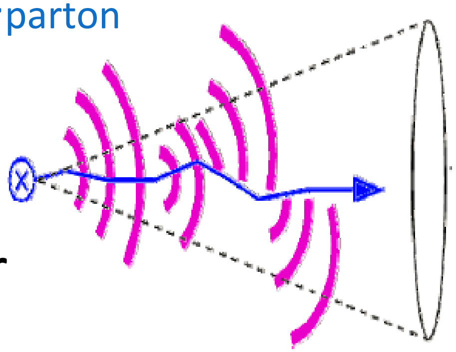
Key to compare with γ-h

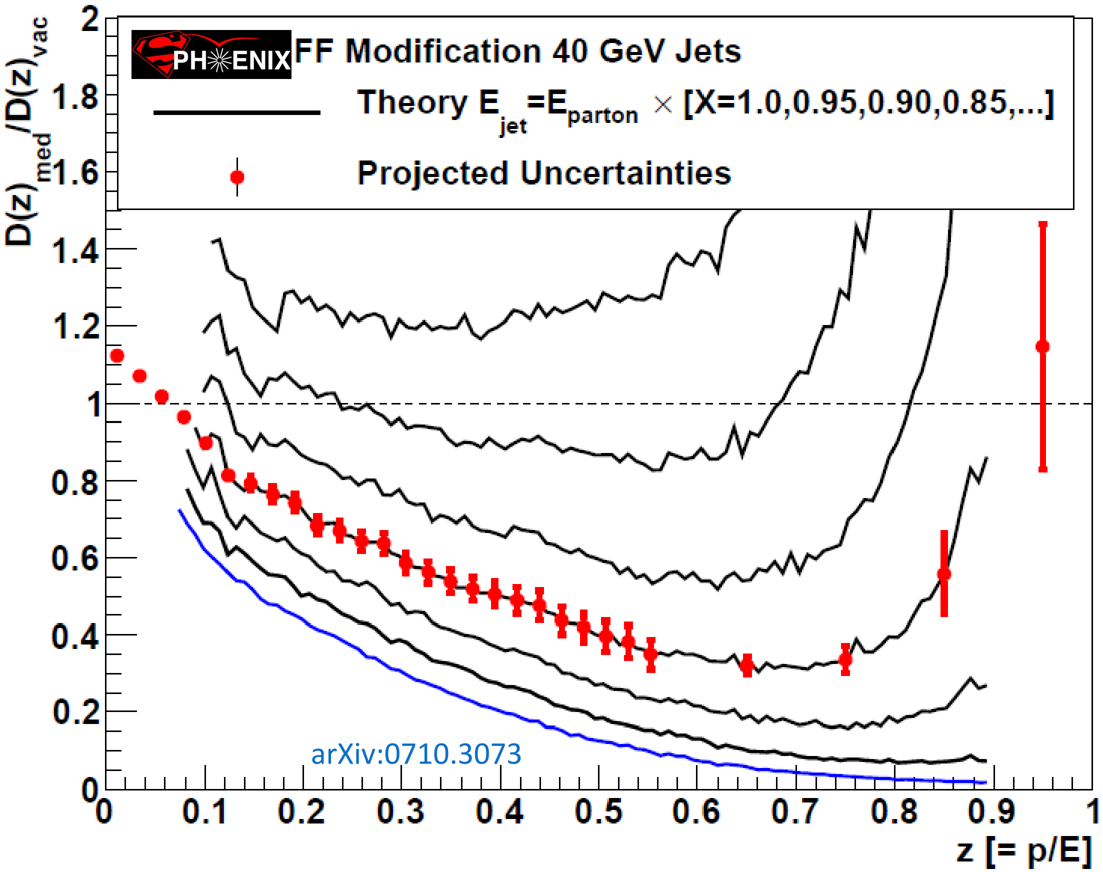


Unique Measurement Example

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

JEWEL Monte Carlo Investigation

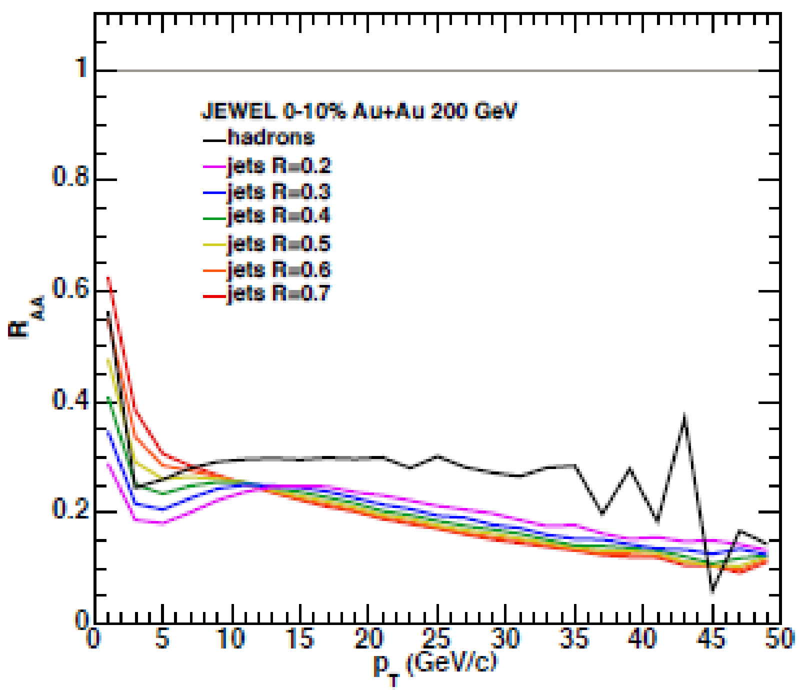
Goal: JEWEL → HEPMC output → GEANT-4 sPHENIX

Work by **Mike McCumber (LANL)** and Kurt Hill (Colorado)

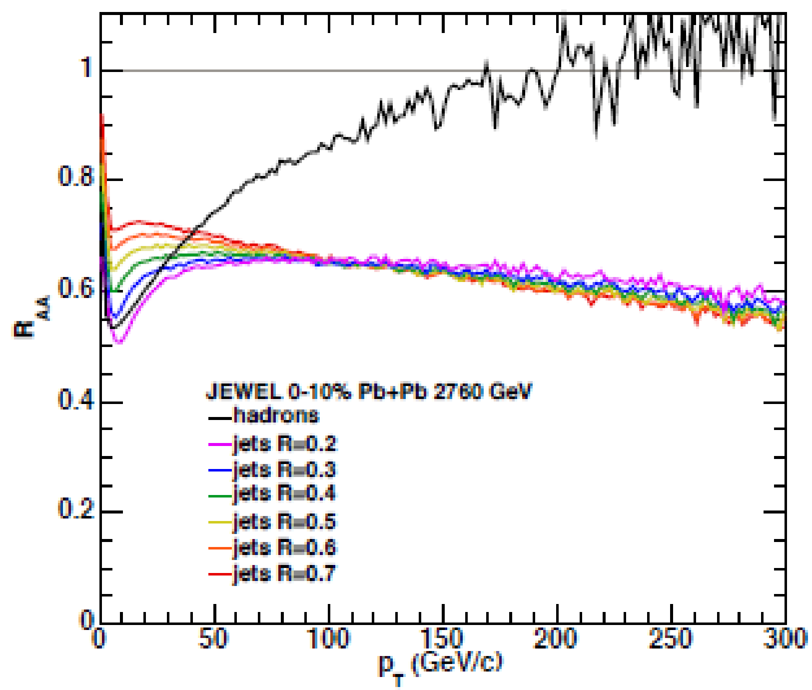
Thanks to help from Korinna Zapp and Urs Wiedemann

Works in Progress (needs further checks)

RHIC



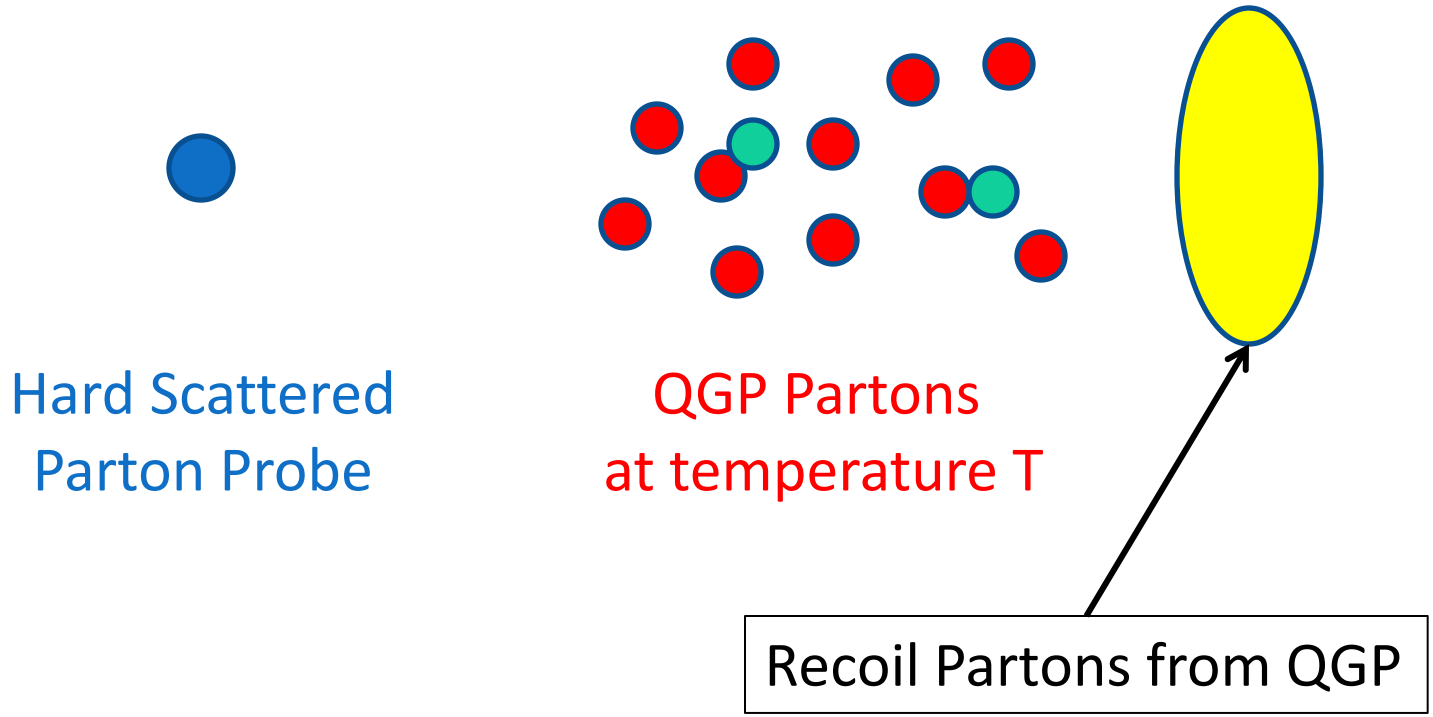
LHC



Qualitative match to RHIC hadron R_{AA}, LHC hadron R_{AA}, single R=0.2-0.4 jet R_{AA}

What is the Medium Made of?

Cartoon of QGP medium (free gas of partons in JEWEL)



JEWEL has two options:

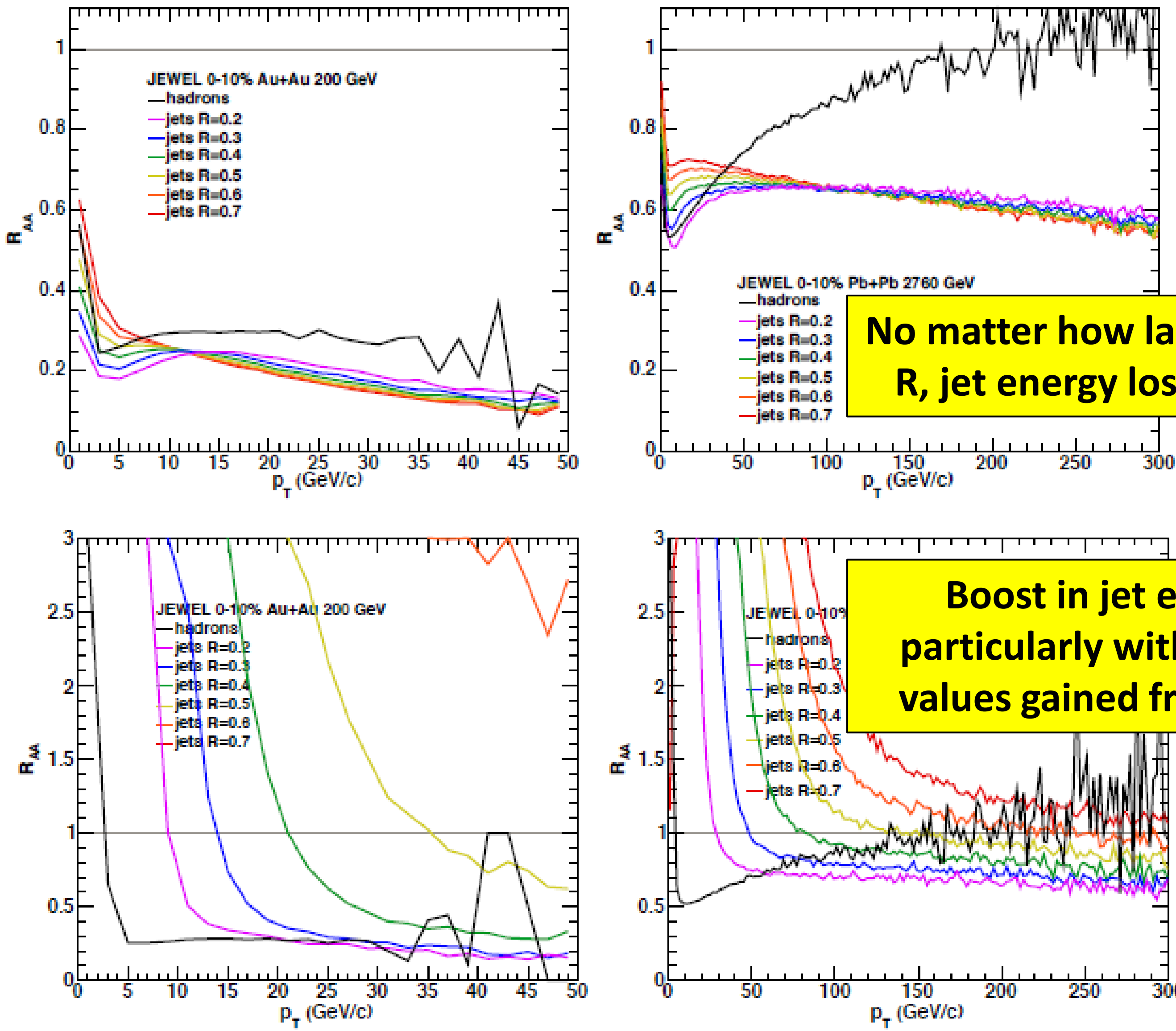
1) write out recoil parton
   (energy not conserved, extra extracted from QGP)
2) do not write them out
   (energy not conserved, lost into QGP)

Recoils Important – Lesson on Medium?

RHIC | LHC

No recoil

Recoil



No matter how large the jet R, jet energy lost to QGP

Boost in jet energy particularly with large R values gained from QGP

No one key Observable, Instead a Data Army

Bulk QGP Constraints (η/s example)

Very close coordinated effort by experimentalists and theorists
spectra, v_2 → v_n, HBT → HBT versus Ψ_n, direct photons → photon v_n
Over-constraining the theory →

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.

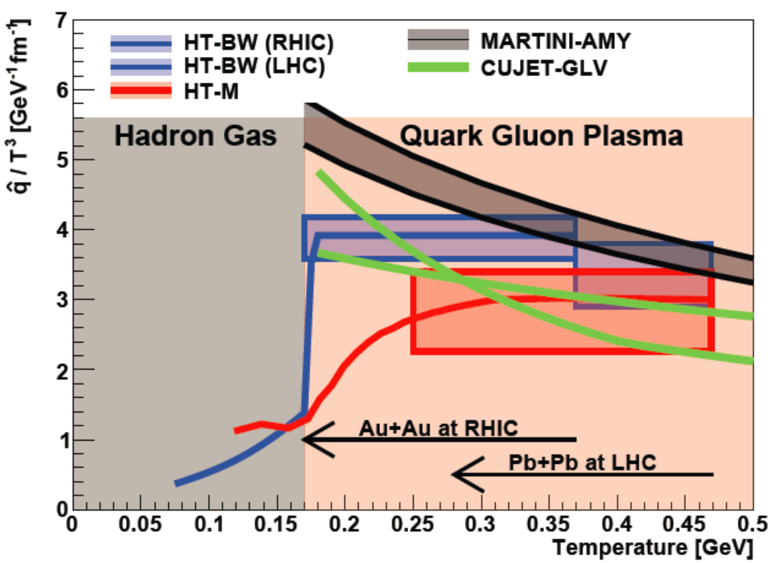
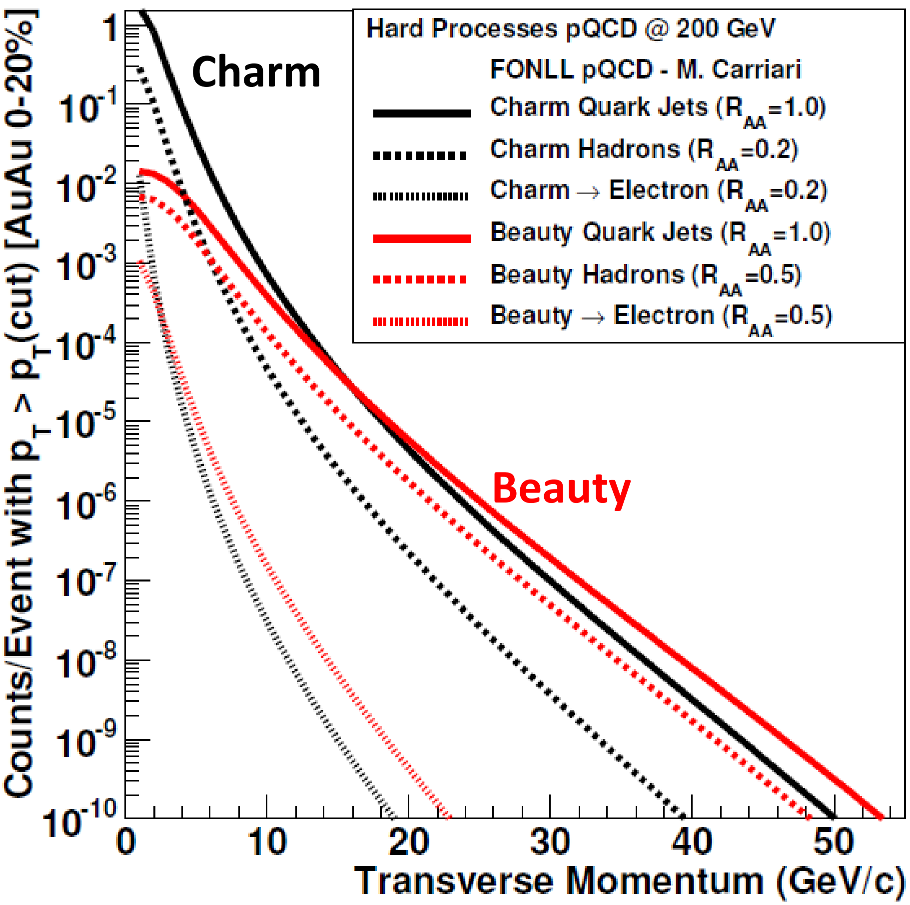


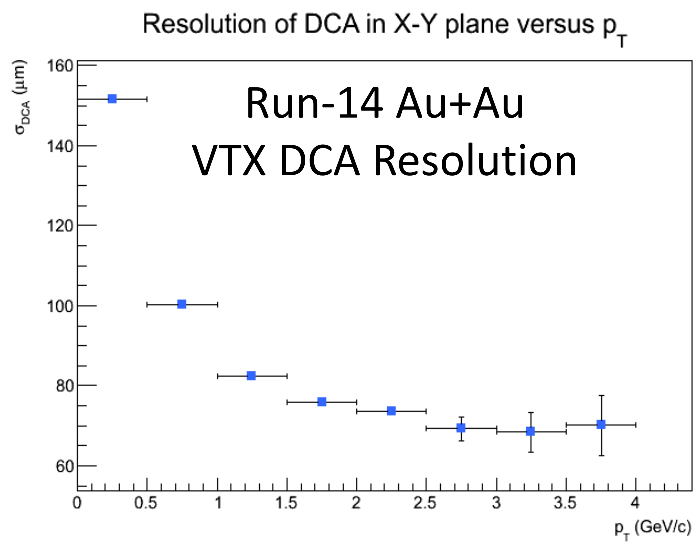
Figure 1.12: Calculations from four jet quenching frameworks constrained by RHIC and LHC R_{AA} data with results for $\hat{q}/T^3$ as a function of temperature. Details of the calculation are given in Ref. [1].

Beauty Tagged Jets



Beauty tagged jets with sPHENIX

Substantial rate and tagged with large displaced vertex using inner silicon detector



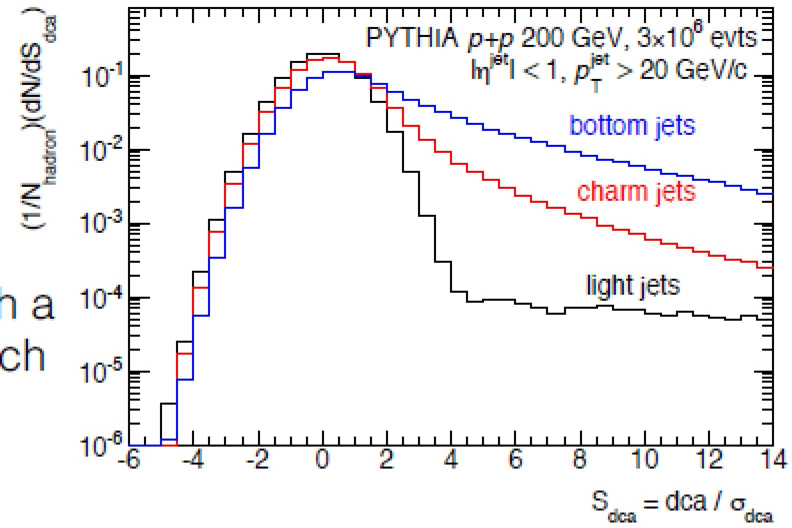
Key tests of mass dependence of radiative energy loss

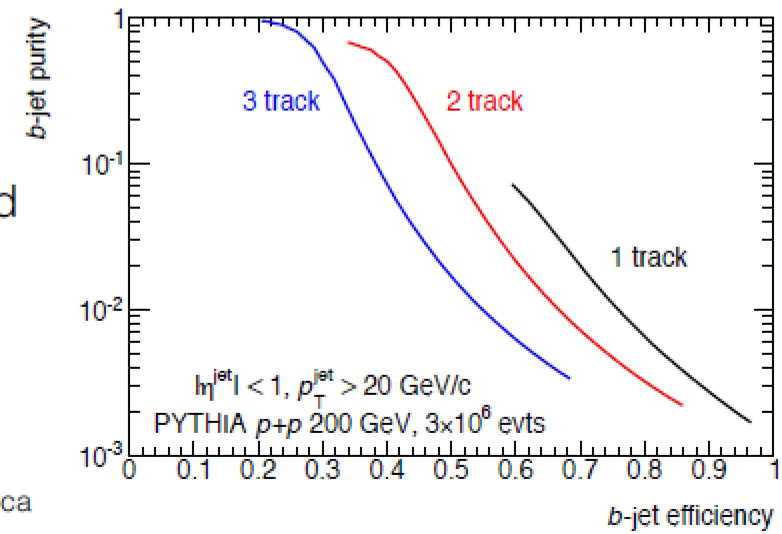
Again, crucial to have overlapping energy ranges with RHIC and LHC

sPHENIX b-jet Tagging

b-jet tagging with the VTX

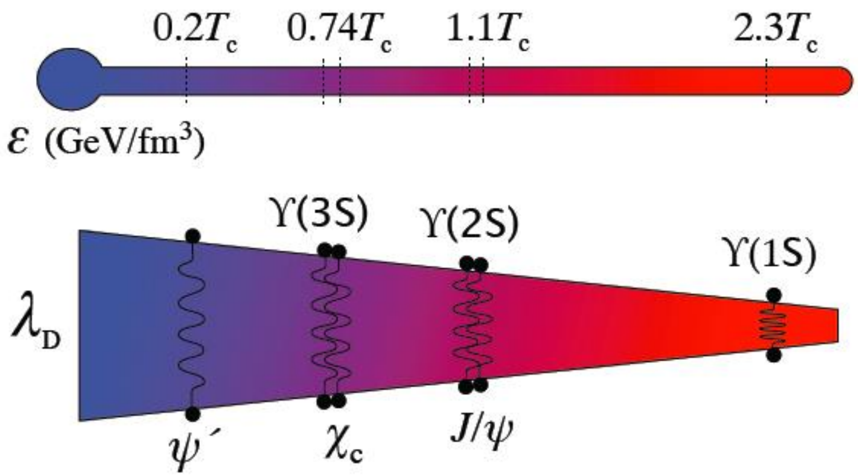
- sPHENIX has explored *b*-jet tagging through requiring tracks in the jet with a large 2-D distance of closest approach (d.c.a) to the primary vertex
  - exploits the long flight time of B hadrons
- Truth-level study with parameterized d.c.a. resolution, σ_{dca} = 70 μm
  - Top: d.c.a. significance of charged particles, with K_L^0 and Λ^0 decays removed
  - Bottom: *b*-jet efficiency vs. *b*-jet purity for cuts requiring 1, 2, 3 or more tracks with some minimum S_{dca}



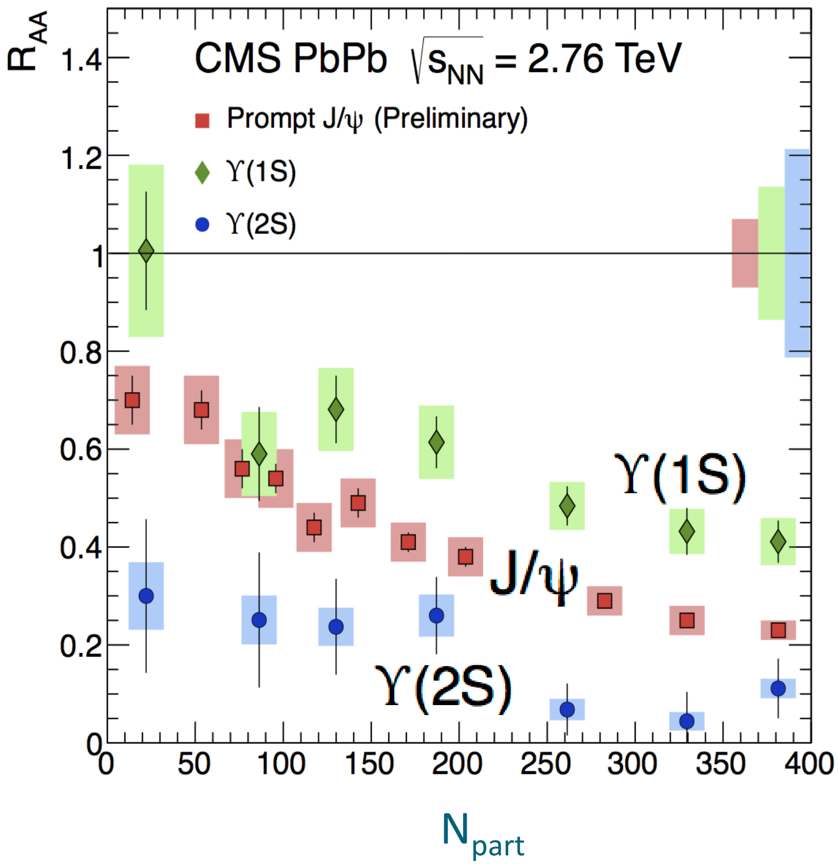


Slide from Dennis Perepelitsa

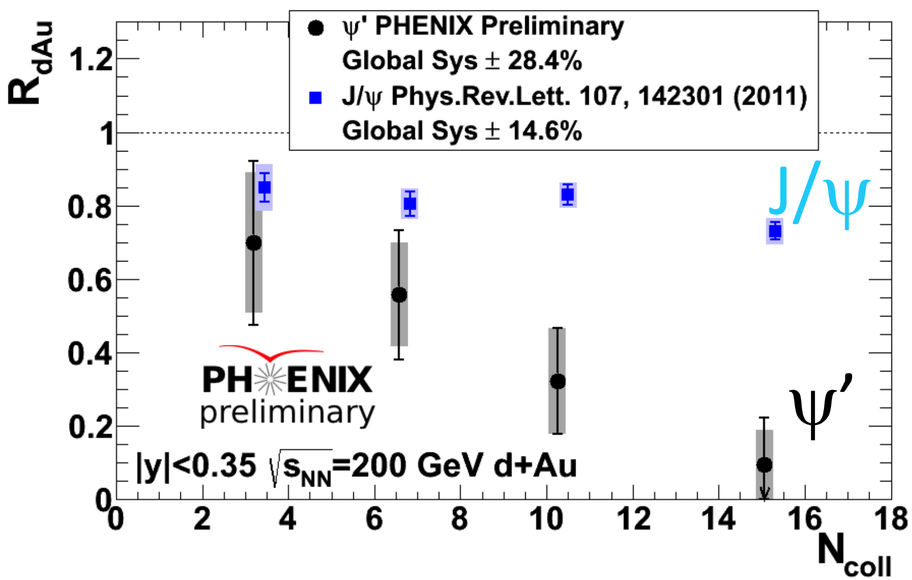
Length Scale QQbar Probes



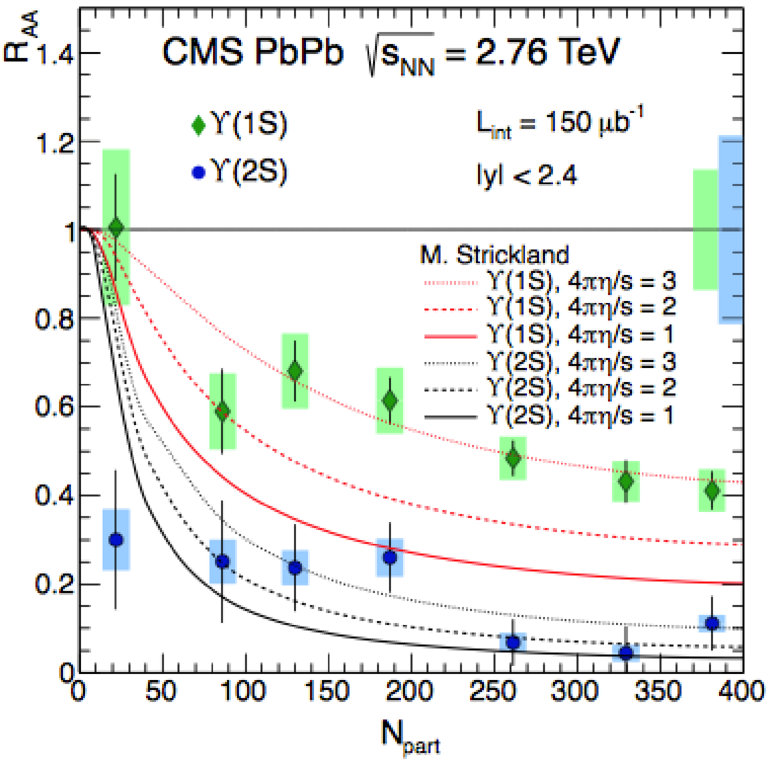
PHENIX, STAR, and CMS data consistent with *melting* of Υ(2s,3s)

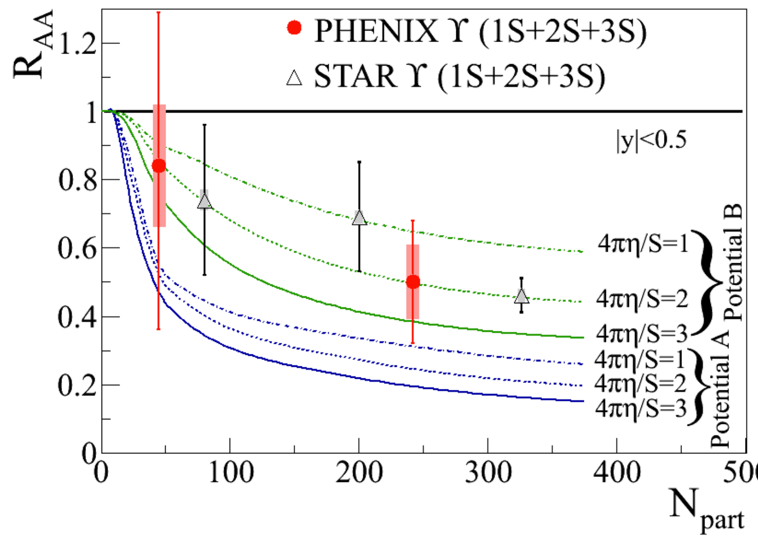


Controls: PHENIX d+Au

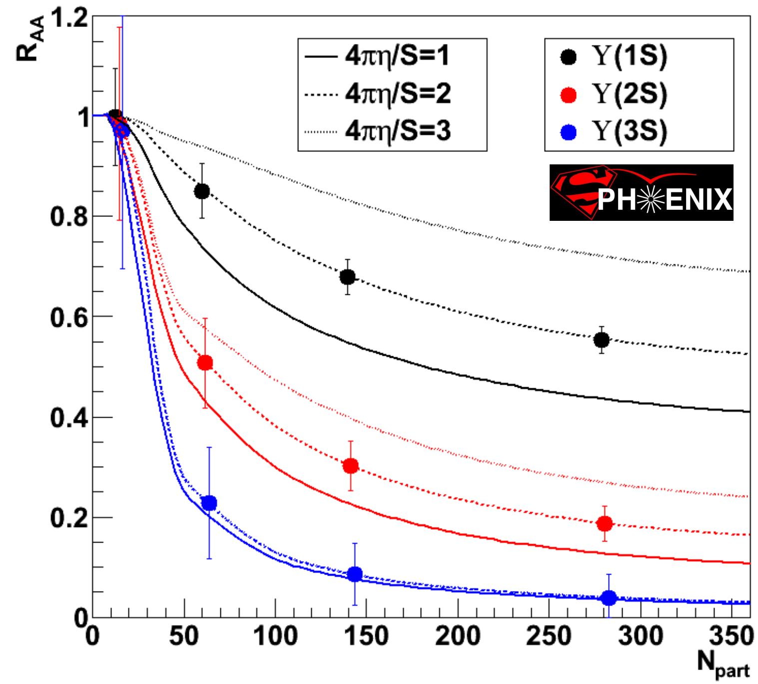


World Upsilon Look Forward





Current RHIC & LHC Picture



Picture in 2023

- CMS with reduced uncertainties
- sPHENIX with unique combination of lever arm and precision
- Constraining key QGP properties

Optimizing the Tracking

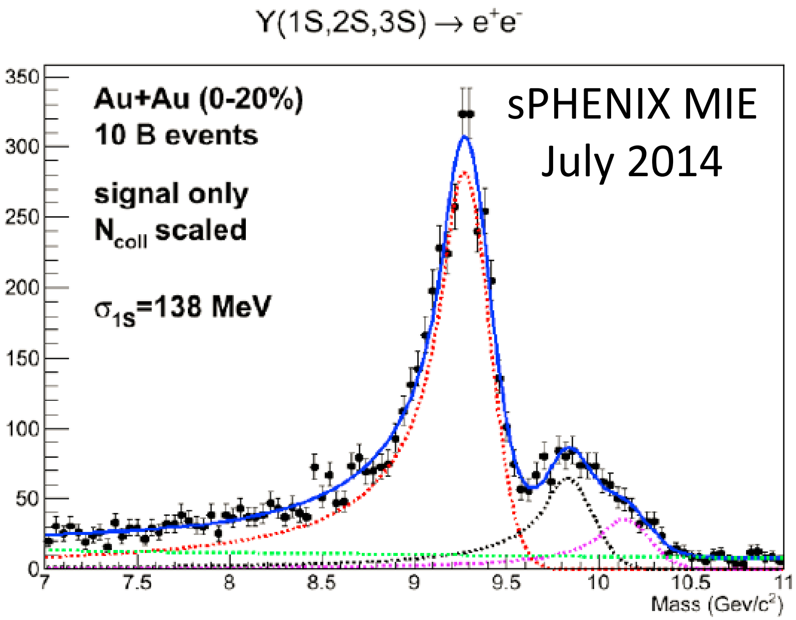
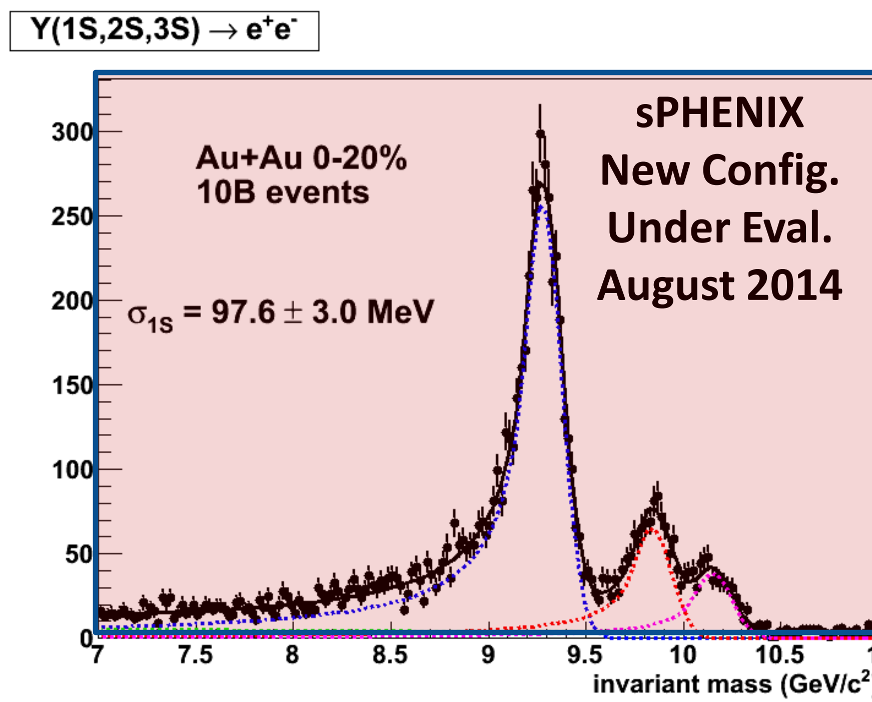


Figure of mass resolution and expected counts (without backgrounds) from sPHENIX Proposal

Received suggestion to further optimize tracking and see performance/cost tradeoff

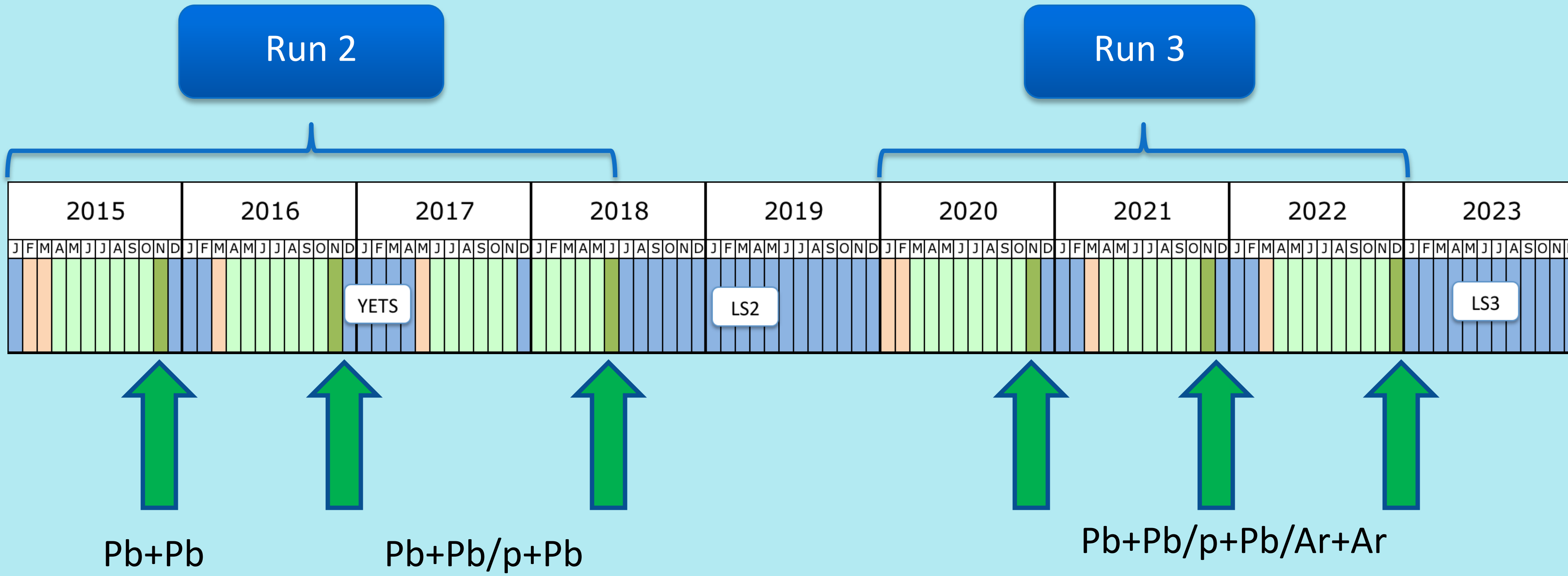
This is a work in progress for a particular modified configuration (still under evaluation for all performance metrics) that shows promising resolution results. This just shows the resolution and statistics as our first step in evaluating this configuration.

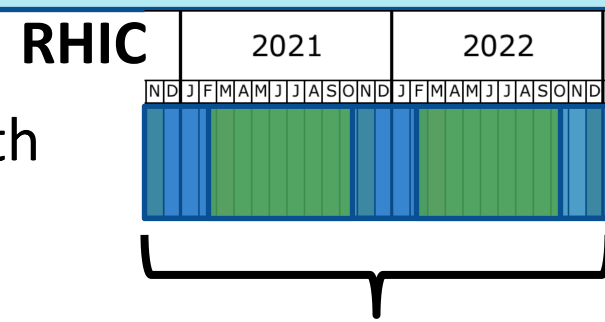


Brookhaven Lab Proposed 10 Year Plan

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2014	15 GeV Au+Au 200 GeV Au+Au	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p+p at 200 GeV p+Au, d+Au, ^{3}He+Au at 200 GeV High statistics Au+Au	Extract $\eta/s(T)$ + constrain initial quantum fluctuations More heavy flavor studies Sphaleron tests Transverse spin physics	PHENIX MPC-EX 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 Partial commissioning of sPHENIX (in 2019)
2020	No Run		Complete sPHENIX installation STAR forward upgrades
2021-22	Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia	sPHENIX
2023-24	No Runs		Transition to eRHIC

LHC Physics in the Next Ten Years





sPHENIX measurements well timed with LHC Run-3 measurements

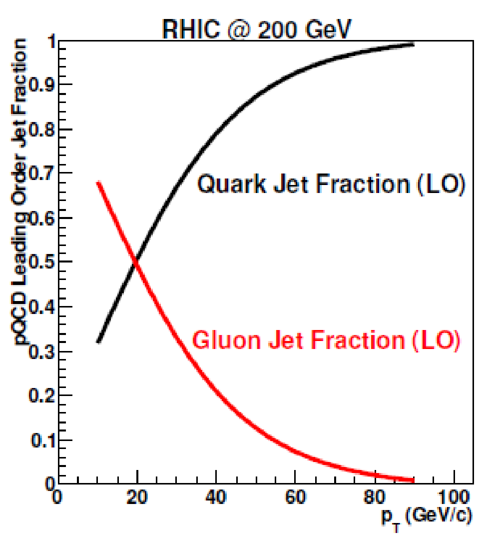
Very good for enabling theory focus on simultaneous understanding

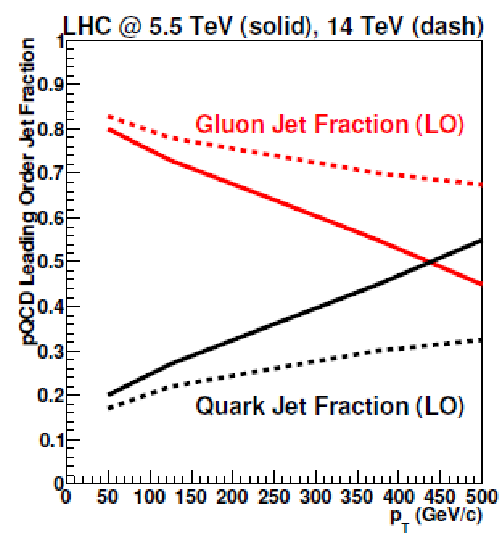
RHIC and LHC Together

It is fundamental to making major (paradigm changing) advances in the field to probe the QGP (through different temperature evolutions) at a range of length scales.

That program requires sPHENIX for precision overlapping and unique measurements from both RHIC and LHC

Kinematic differences also play a major role with sPHENIX changing the data landscape and constraining the underlying physics and QGP properties

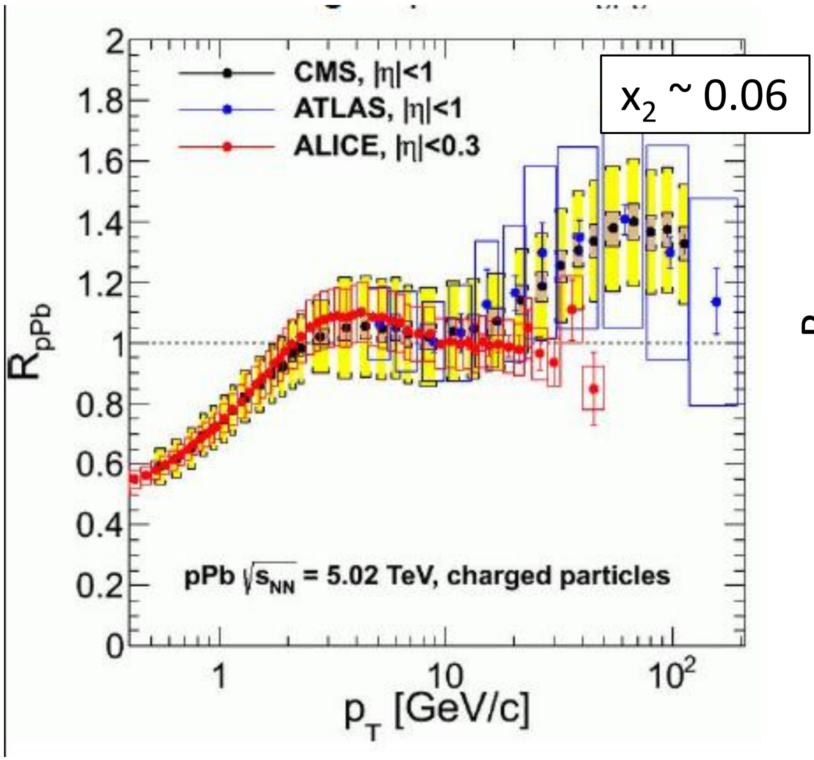


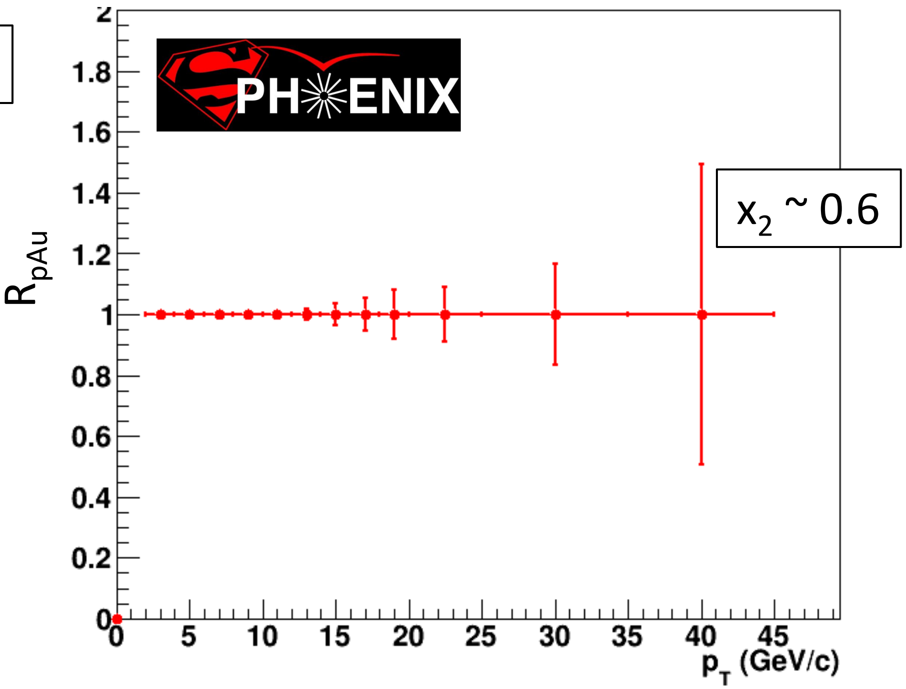


Proton+Nucleus Surprises

sPHENIX provides discriminating power on p+A physics explanations

Enabled by p+p/p+A Hcal triggering (as done in CMS for example)

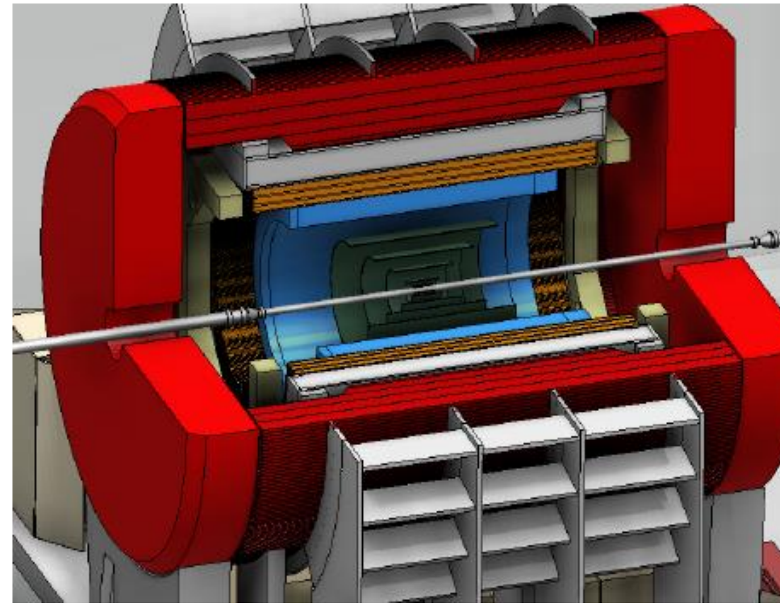




sPHENIX covers up to very high Bjorken x_2.

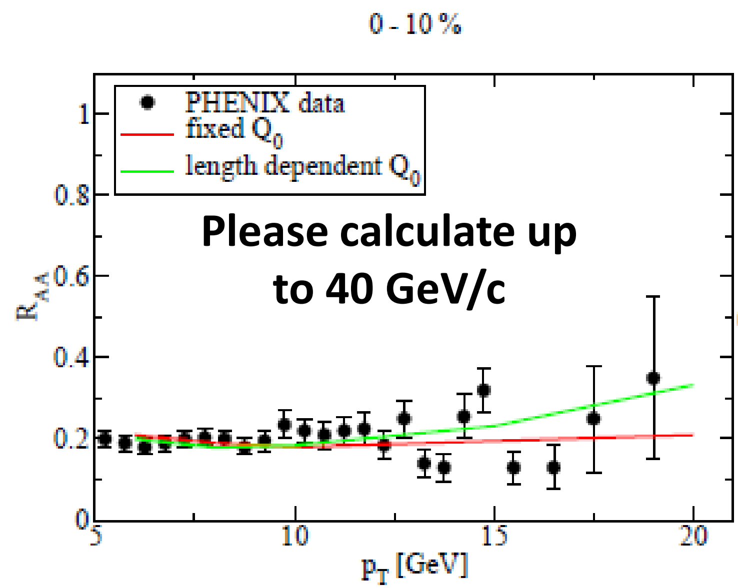
More than 2 Years of Running?

Strengthening the program
- better tracking (Upsilon, b-tag)
- additional forward calorimeter coverage (instrument end return)



Extending the program
- Lower Energy Running (39, 62 GeV)

Energy	Hadron p_T	Jet p_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)

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

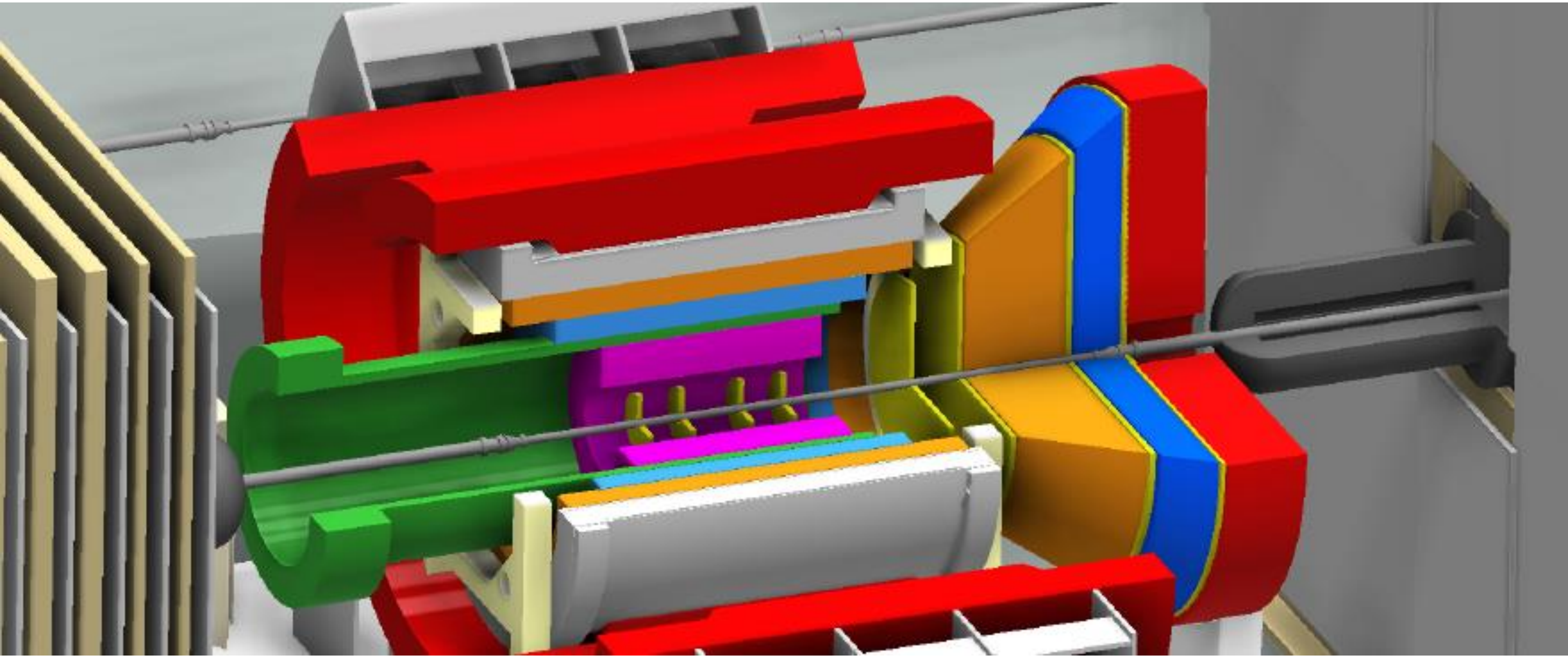

sPHENIX
CMS
ALICE
ATLAS
STAR


STOP!
YOU CAN'T DO THIS! — IT'S IMPOSSIBLE!
THANKS FOR LETTING ME KNOW!


SLOWS

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

EIC Concept Review (January 10, 2014)

Reviewers: Sam Aronson (BNL); Krishna Kumar (UMass-Amherst); Jianwei Qiu (BNL); Veljko Radeka (BNL); Paul E. Reimer (ANL); Jim Thomas (LBNL); Glenn Young (JLab)

"The review team was unanimous in its praise for the LOI.

It was clear (and encouraging) to the review team that key elements of the LOI were prepared and presented by some of the more junior members of the collaboration. The review team found merit in the path chosen by the PHENIX Collaboration in responding to the Laboratory's plans for evolving the facility from RHIC to eRHIC.

This approach allows for a cost-effective way of providing the capability to address the physics agenda of eRHIC from Day-1 of eRHIC operation.

We thought it well demonstrated that [this EIC detector] would be a good day-one detector capable of addressing almost all of the physics that can be covered by eRHIC. It also appears to be a solid foundation for future upgrades so that it can explore the full physics potentials available as eRHIC itself evolves."