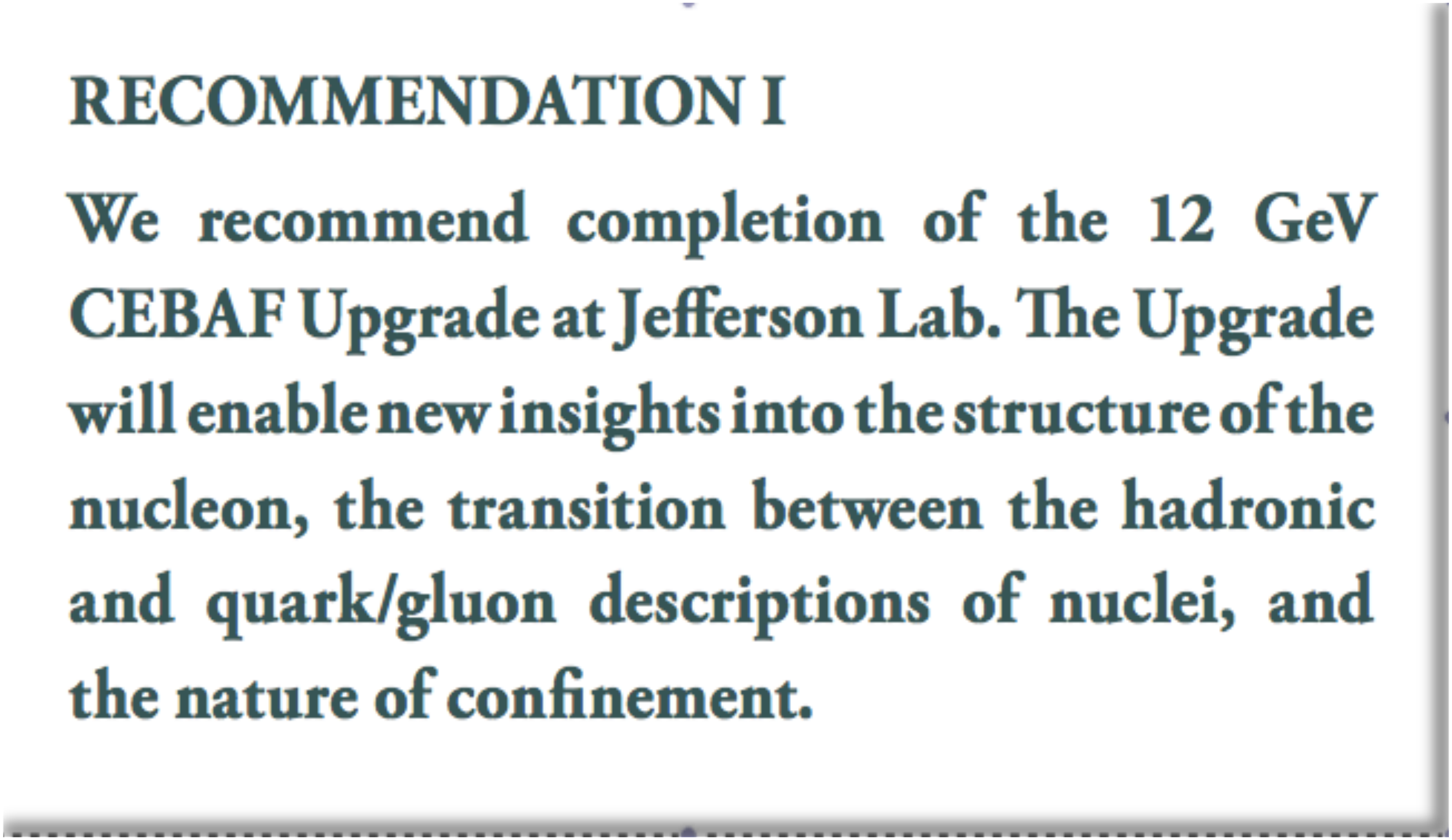
RHIC and LHC Overview: Where are we? Where are we going?

QCD Town Meeting
September 12th, 2014

W.A. Zajc
Columbia University

2007 Long Range Plan Recommendations


RECOMMENDATION I

We recommend completion of the 12 GeV CEBAF Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.

Ongoing

2007 Long Range Plan Recommendations

RECOMMENDATION II

We recommend construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.

Ongoing

2007 Long Range Plan Recommendations

RECOMMENDATION III

We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.

A complicated story…

2007 Long Range Plan Recommendations

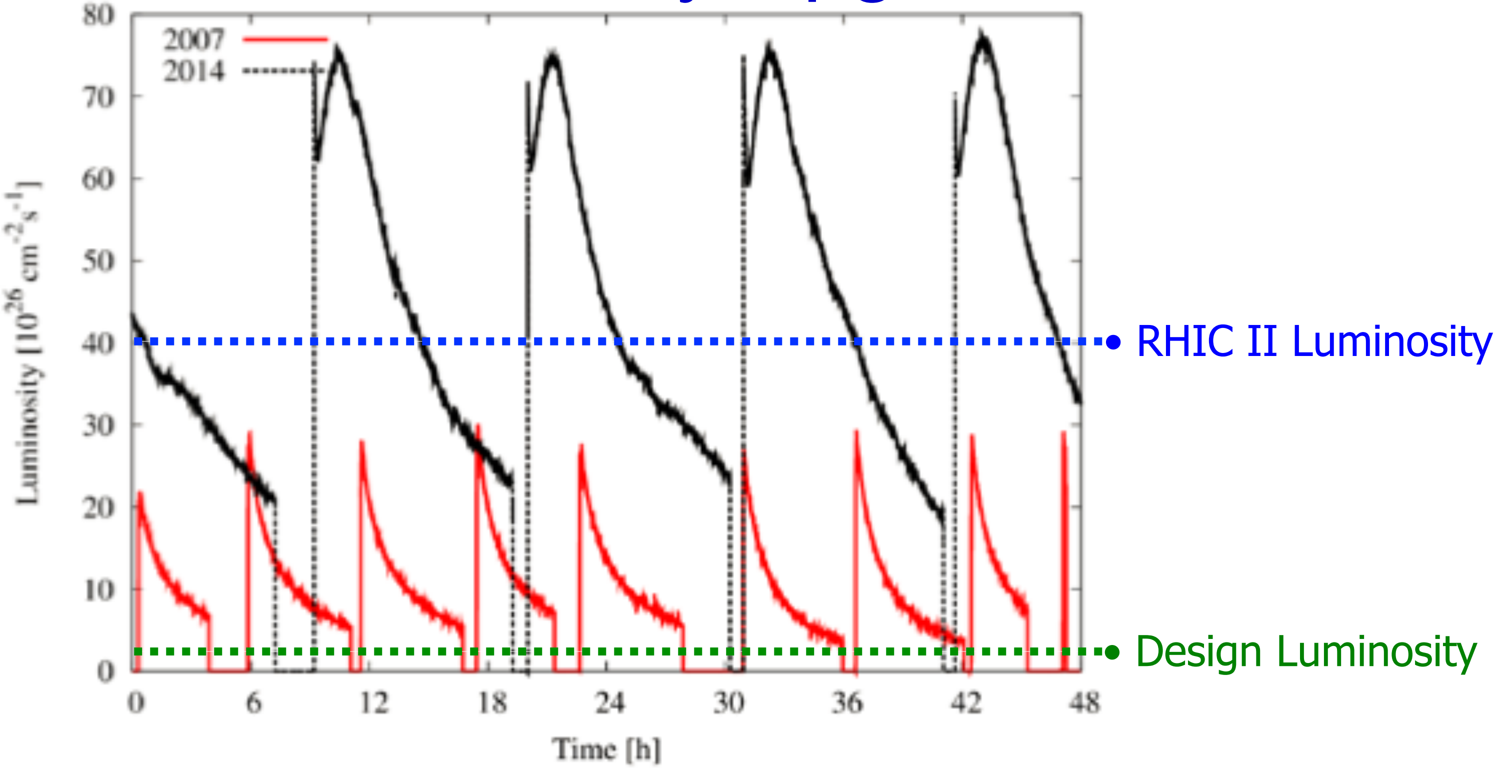
RECOMMENDATION IV

The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

DONE!

To Be Completely Clear :

- RHIC II Luminosity Upgrade *DONE!*



- "determine the properties of the matter" *Underway*
- Most importantly: *DONE! ≠ Finished!*

Where Are We?

Opened New Energy and Intensity Frontiers

RHIC → RHIC II

- First collisions 2000
- p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, U+U
- $\sqrt{s_{NN}}$ ~ 7 – 200 GeV
- Polarized protons

LHC

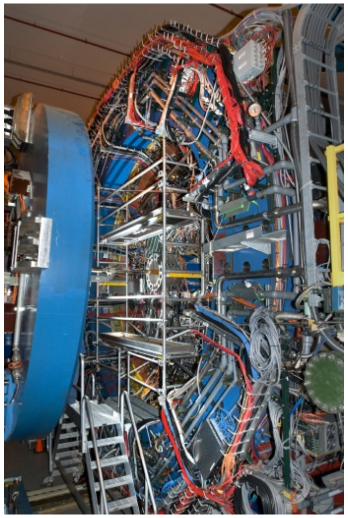
- First collisions 2010
- p+p, Pb+Pb, p+Pb
- $\sqrt{s_{NN}}$ =2.76 TeV
- (5.5 TeV in 2015-16)

Five Experiments

RHIC

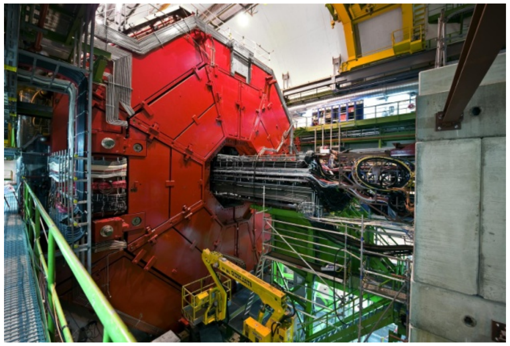
- PHENIX

- STAR

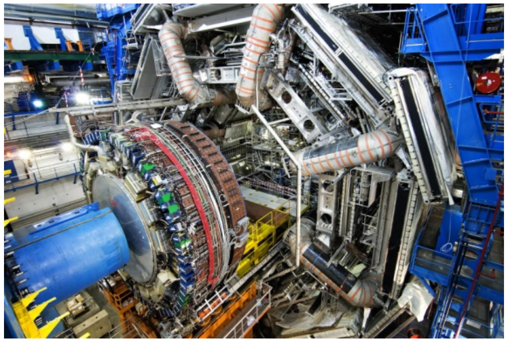


LHC

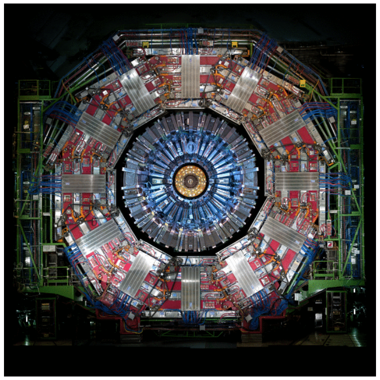
- ALICE



- ATLAS



- CMS

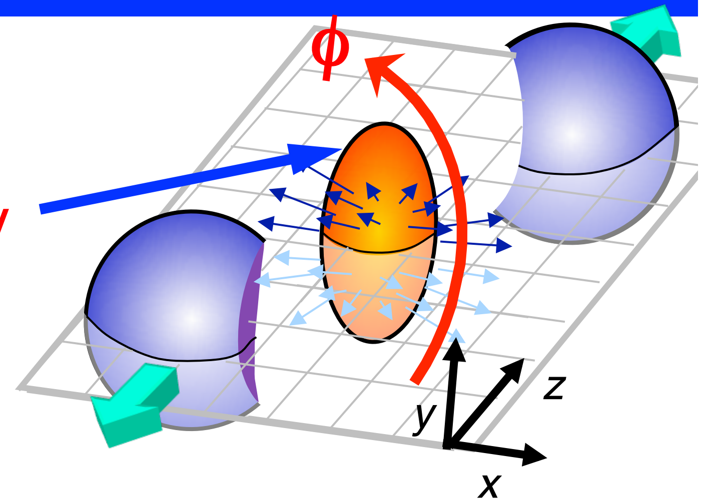


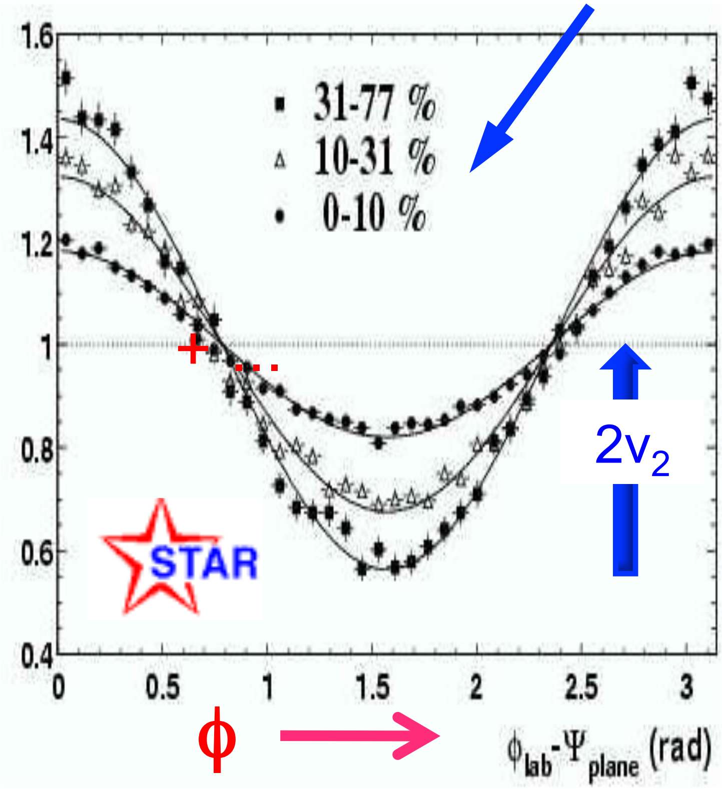
The First LHC Heavy Ion Discovery

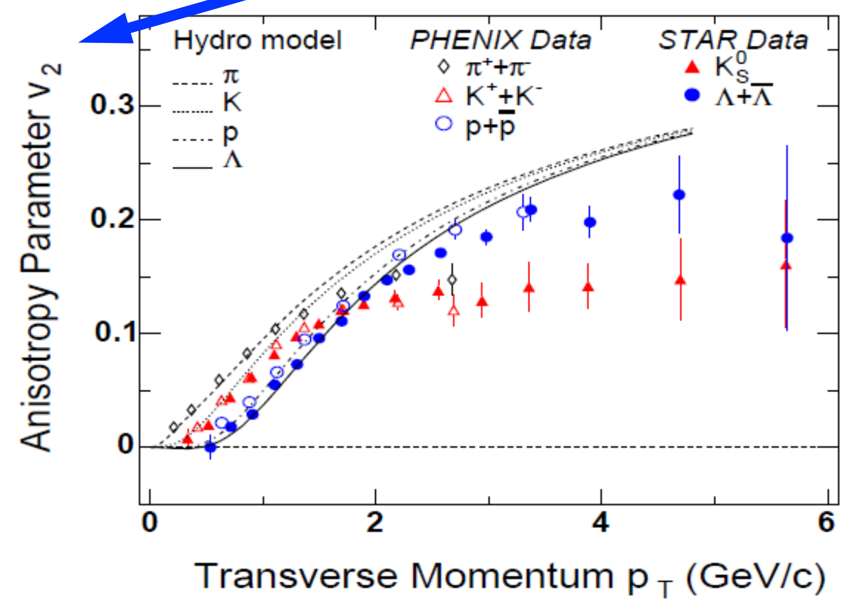
- The matter produced in LHC collisions exhibits the same qualitative features discovered at RHIC:
    - Strong hydrodynamic flow
    - Strong quenching of high momentum particles

An Aside on Nomenclature

- RHIC discovery
  - The initial state azimuthal asymmetry
  - produces a ***strong*** signal in the final state particle emission pattern $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi)$

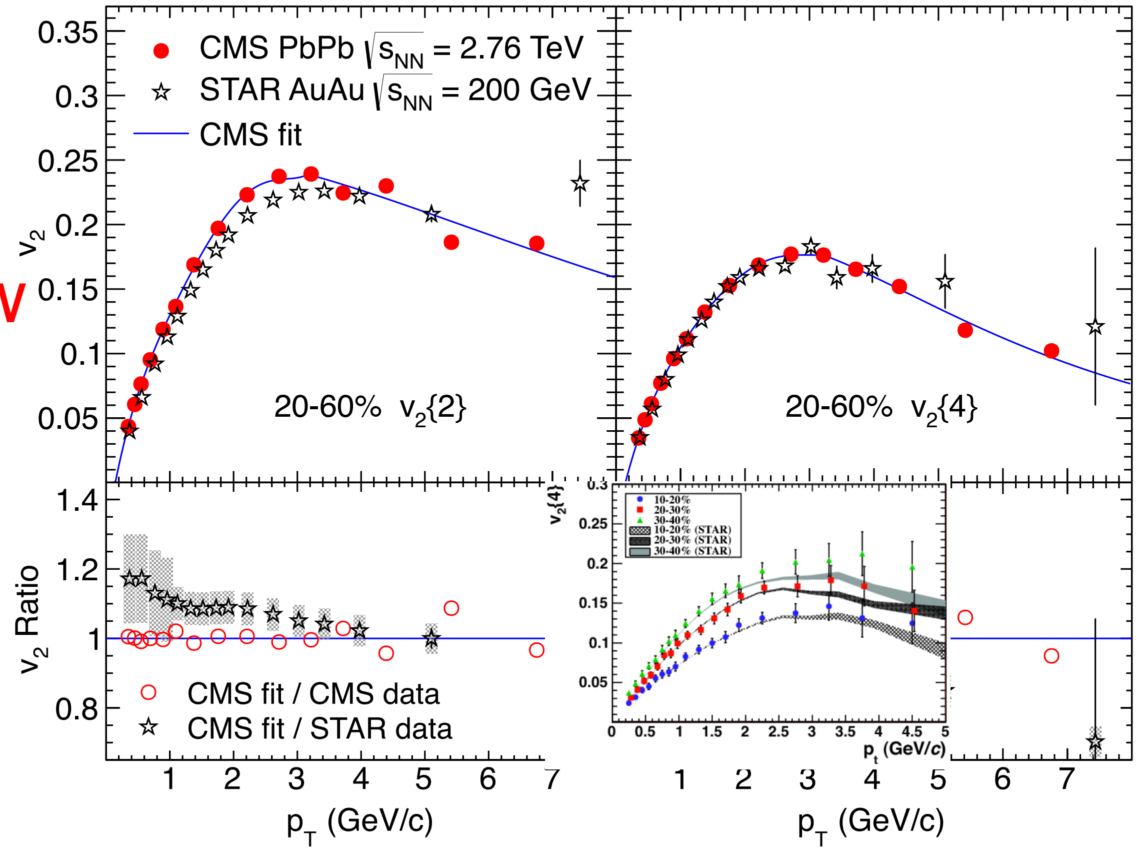






The First LHC Heavy Ion Discovery

- The matter produced in LHC collisions exhibits the same qualitative features discovered at RHIC:
  - Strong hydrodynamic flow
  - RHIC and LHC data well-described by relativistic viscous hydrodynamics



CMS, Phys. Rev. C87, 014902 (2013)

Theoretical Discovery 2003-4

- An ~~estimate~~ (bound?) on viscosity appeared from string theory's AdS/CFT correspondence:
  - *A Viscosity Bound Conjecture*,
    P. Kovtun, D.T. Son, A.O. Starinets,
    hep-th/0405231 (1300+ citations!)

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi} \sim 0.08\hbar$$

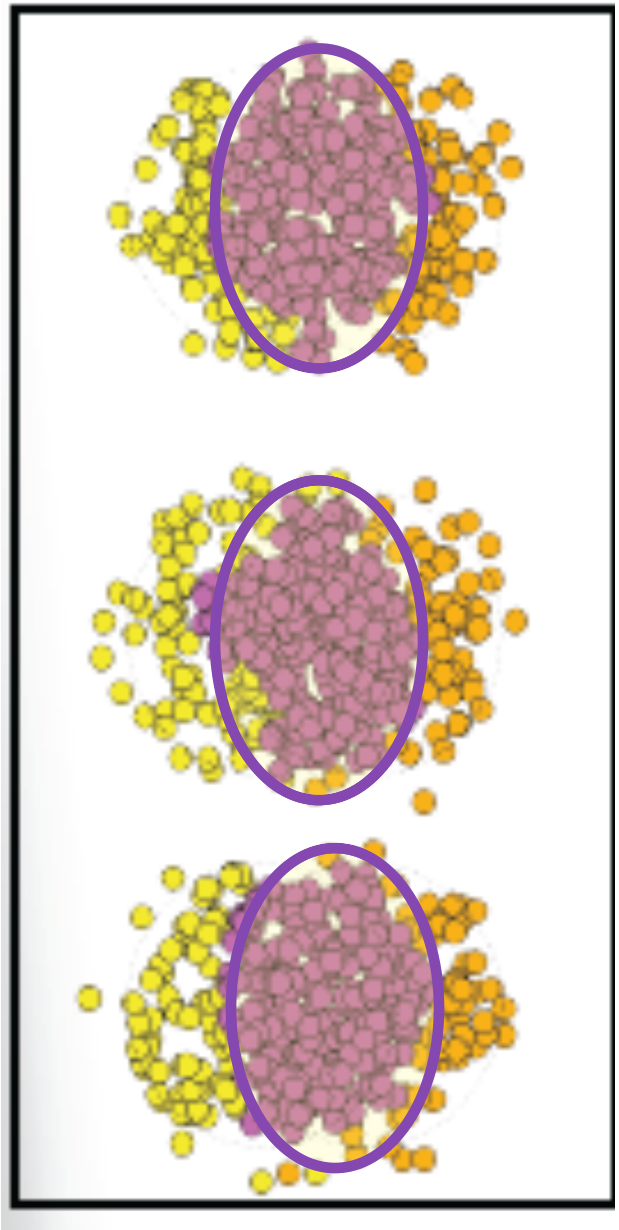
⟹ *Fundamental* measure of strong coupling

⟹ Cleanest result from gauge/gravity duality

⟹ A measure of "quantum liquidity"

2010: The Noise *Is* The Signal

- Importance of higher harmonics
- $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi) + \ldots$



B. Alver and G. Roland, Phys. Rev. C81, 054905 (2010)

2010: The Noise *Is* The Signal

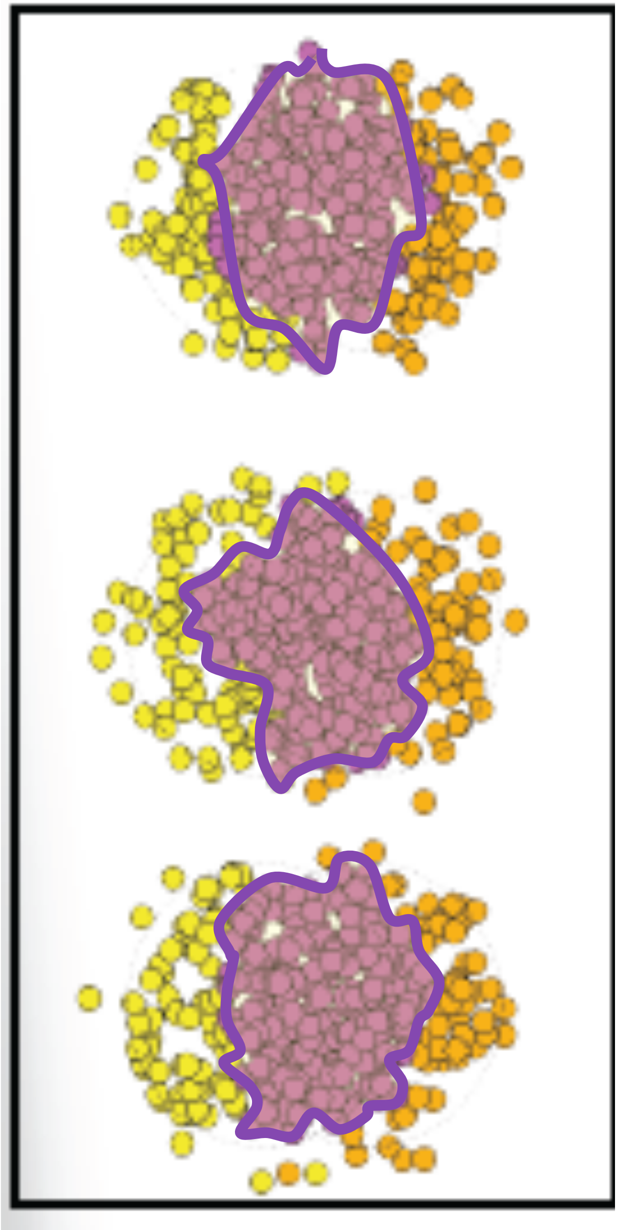
- Importance of higher harmonics

- $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$
  $+ 2\, v_3(p_T) \cos(3\phi)$
  $+ 2\, v_4(p_T) \cos(4\phi) + \ldots$

➢ Fluctuations critical for determining allowed range of η/s .

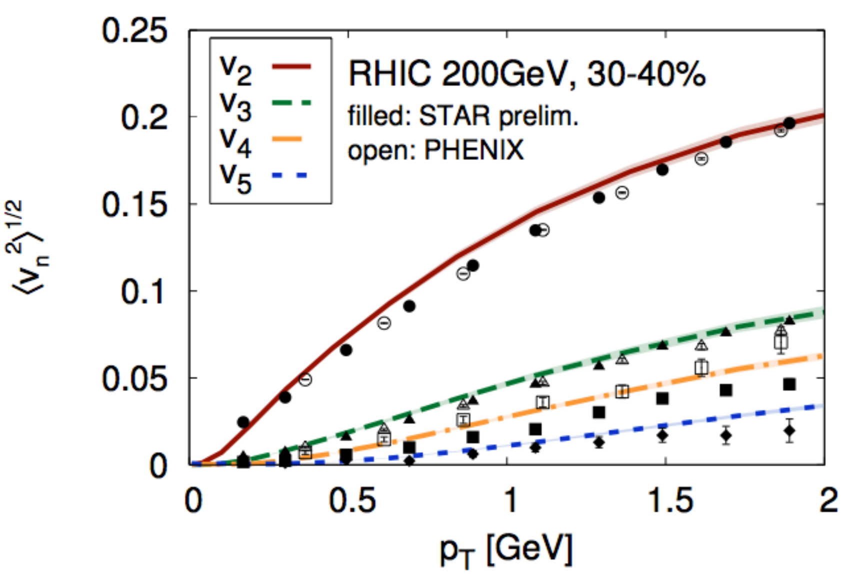
☛Persistence of "bumps"➔small η/s !

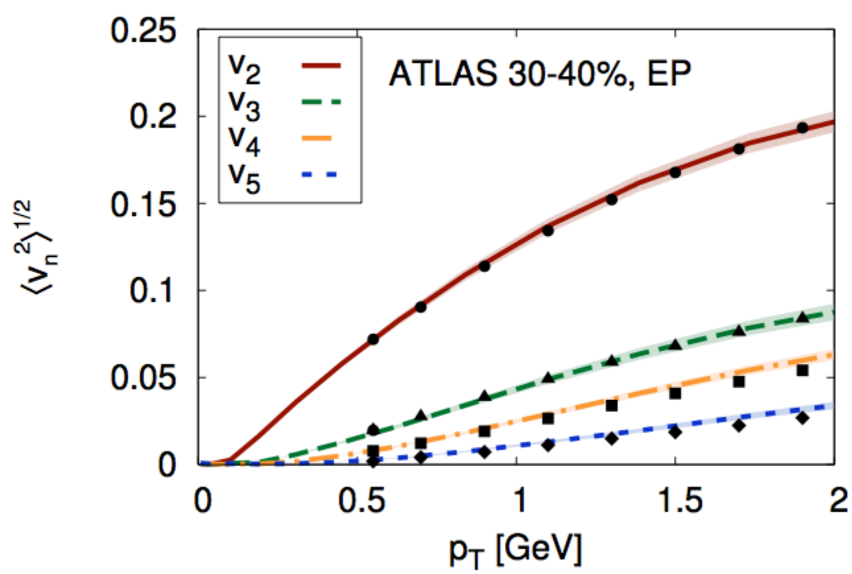
B. Alver and G. Roland, Phys. Rev. C81, 054905 (2010)



Higher Harmonics Used to Determine η/s

- *The fundamental matter formed at RHIC and the LHC is within a factor of 3 of KSS bound(!)*





$\eta/s \approx 0.12$ at $\sqrt{s} = 0.2$ TeV

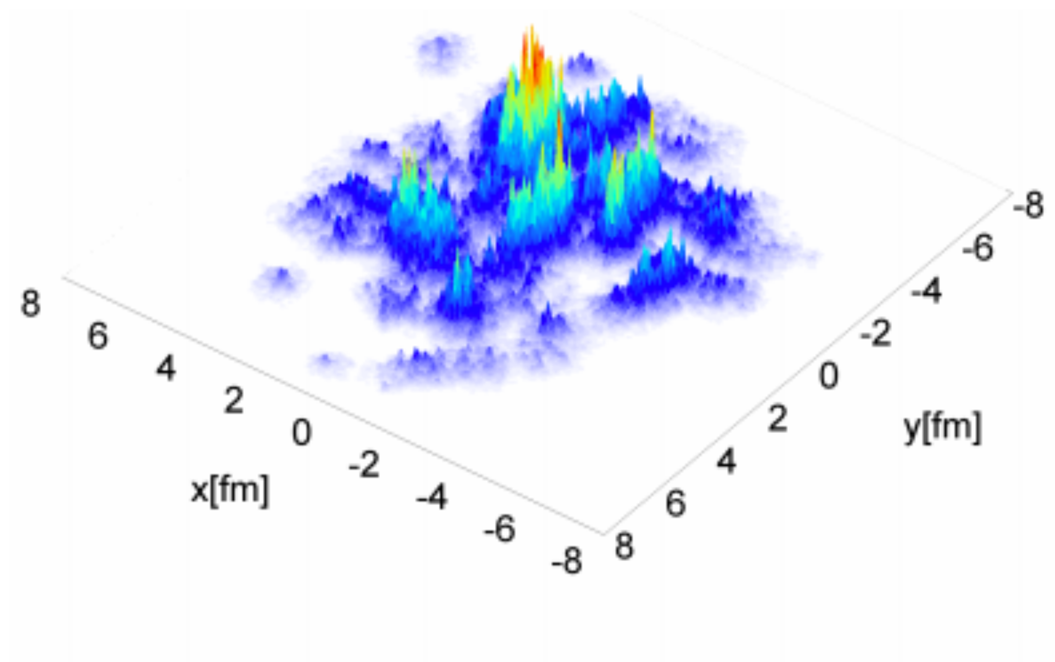
≈ 1.5 x KSS Bound

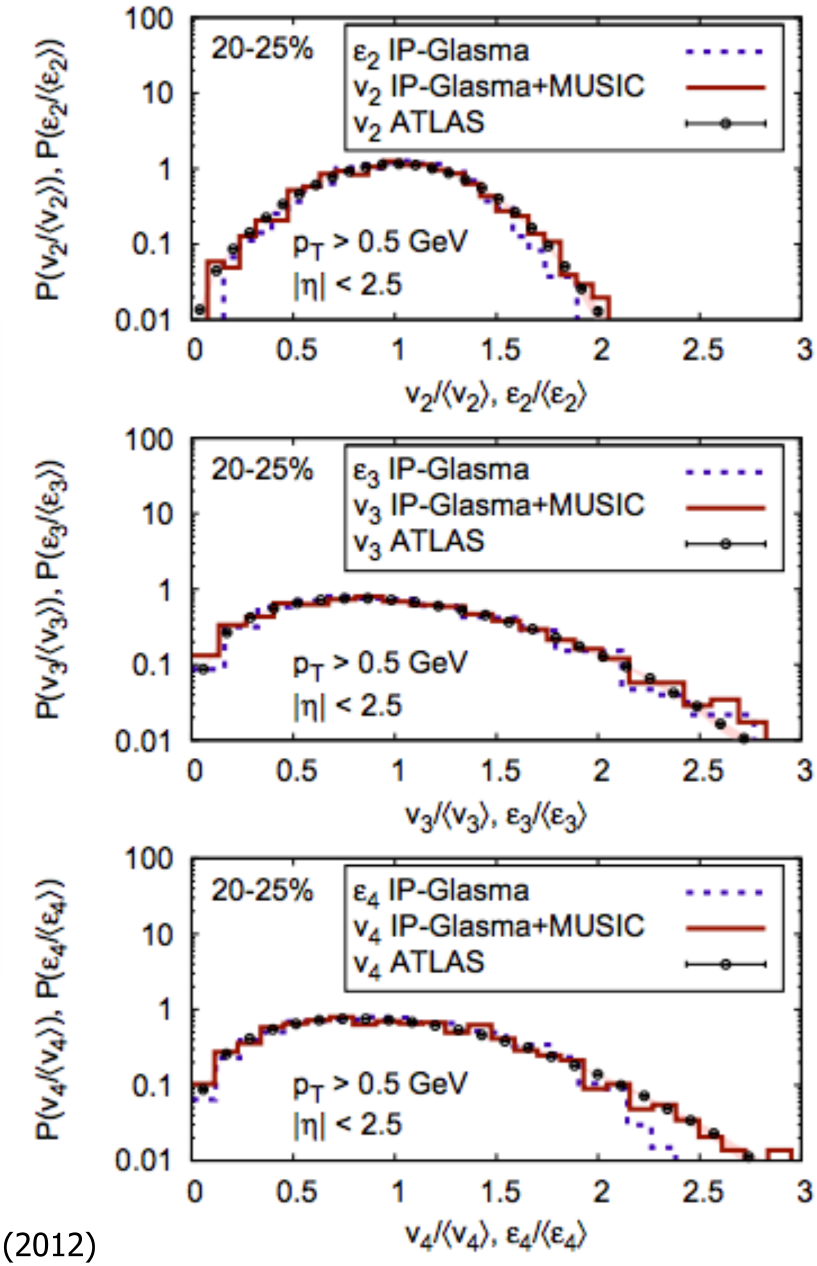
$\eta/s \approx 0.2$ at $\sqrt{s} = 2.76$ TeV

≈ 2.5 x KSS Bound

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)

Measuring and Predicting the Fluctuation *Spectrum*

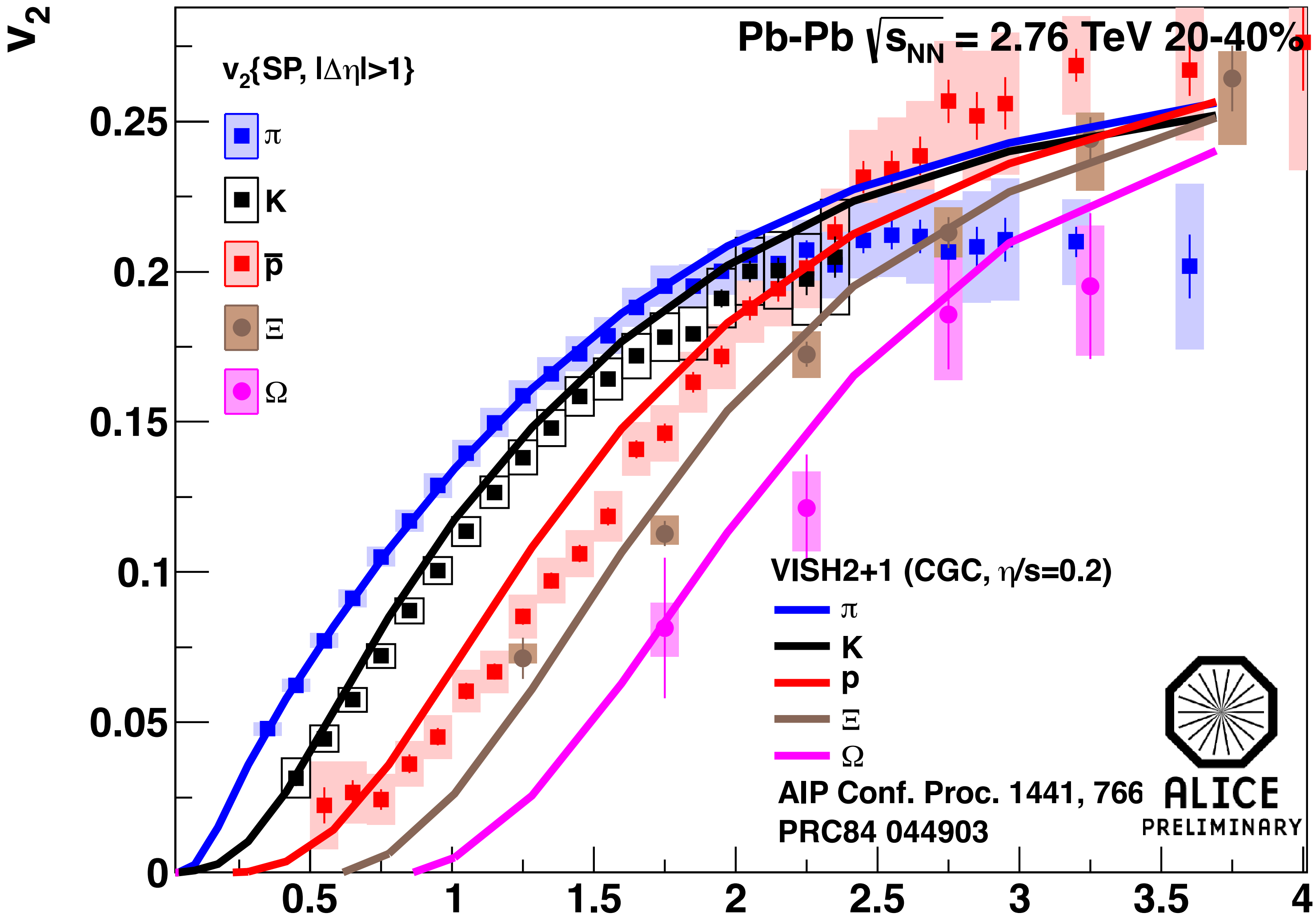




- C. Gale et al., Phys. Rev. Lett. 110, 012302 (2013)
- B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. Lett. 108, 252301 (2012)

Power of Hydrodynamics

"Fine structure" (mass ordering) in hydrodynamic response *predicted* for π, K, p, Ξ, Ω :



An Ahistorical Motivation

- *Small* value of η/s:

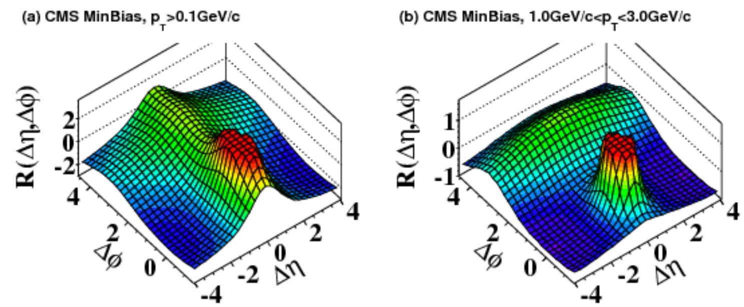
  $\Rightarrow$Persistence of v_n up to n ~ 4-5

  $\Rightarrow$Each 1/n-th *part* of the initial state flows

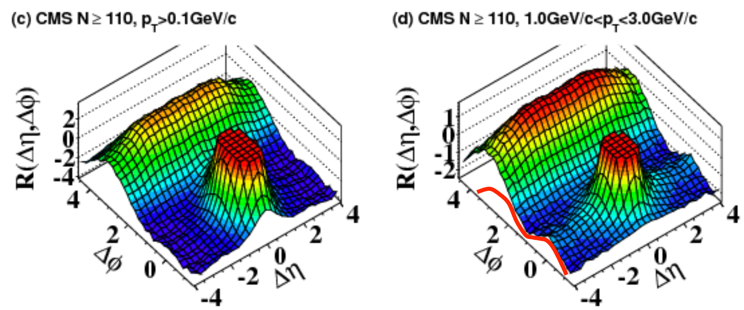
  $\Rightarrow$Test this by studying small systems

$\Rightarrow$ Ahistorical: in reality flow in small systems was discovered by experimentalists at the LHC

Discovery: Hydrodynamic Ubiquity



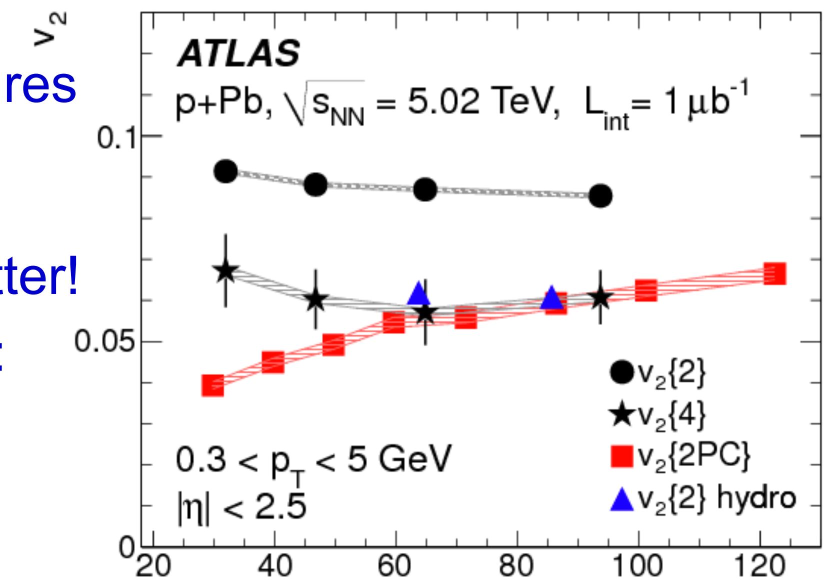
CMS, JHEP 1009, 091 (2010)



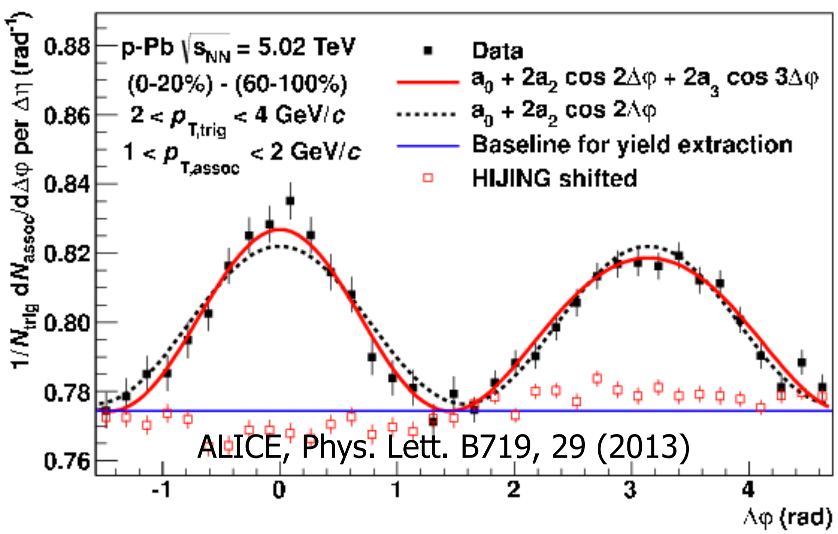
Flow signatures observed in smallest flecks of matter!

Collisions of:

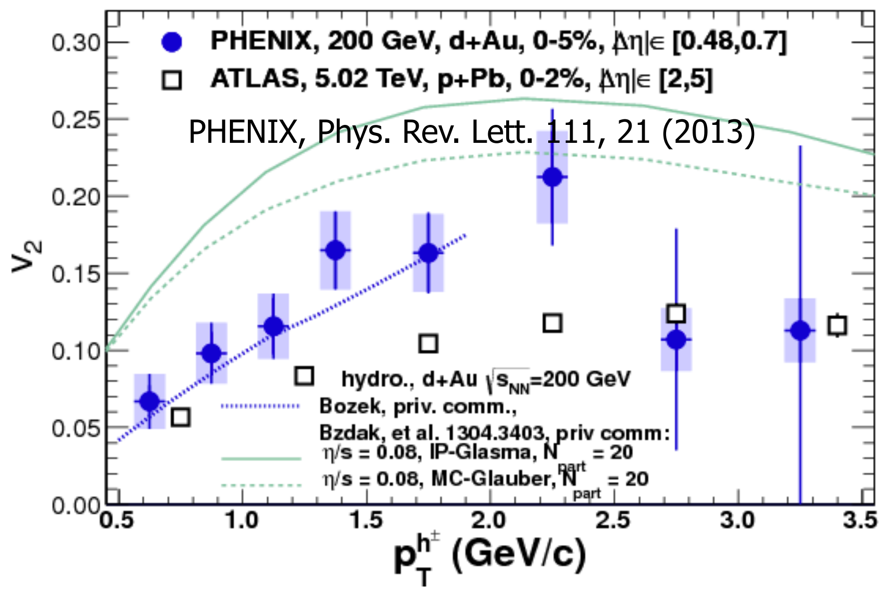
- p+p
- p+Pb,
- d+Au



ATLAS, Phys. Lett. B725, 60 (2013)



ALICE, Phys. Lett. B719, 29 (2013)



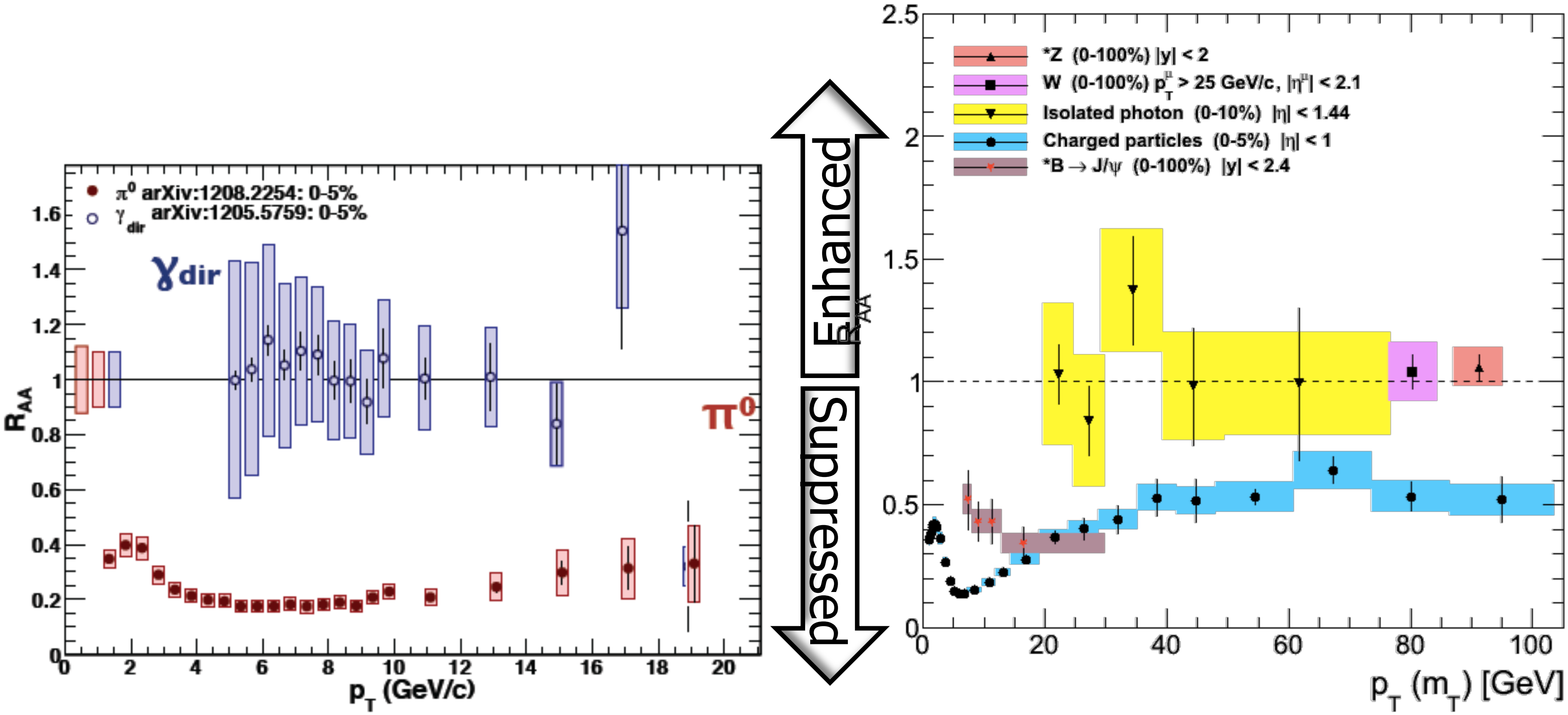
PHENIX, Phys. Rev. Lett. 111, 21 (2013)

The First LHC Heavy Ion Discovery

- The matter produced in LHC collisions exhibits the same qualitative features discovered at RHIC:
  - Strong hydrodynamic flow
  - Strong quenching of high momentum particles

More Nomenclature

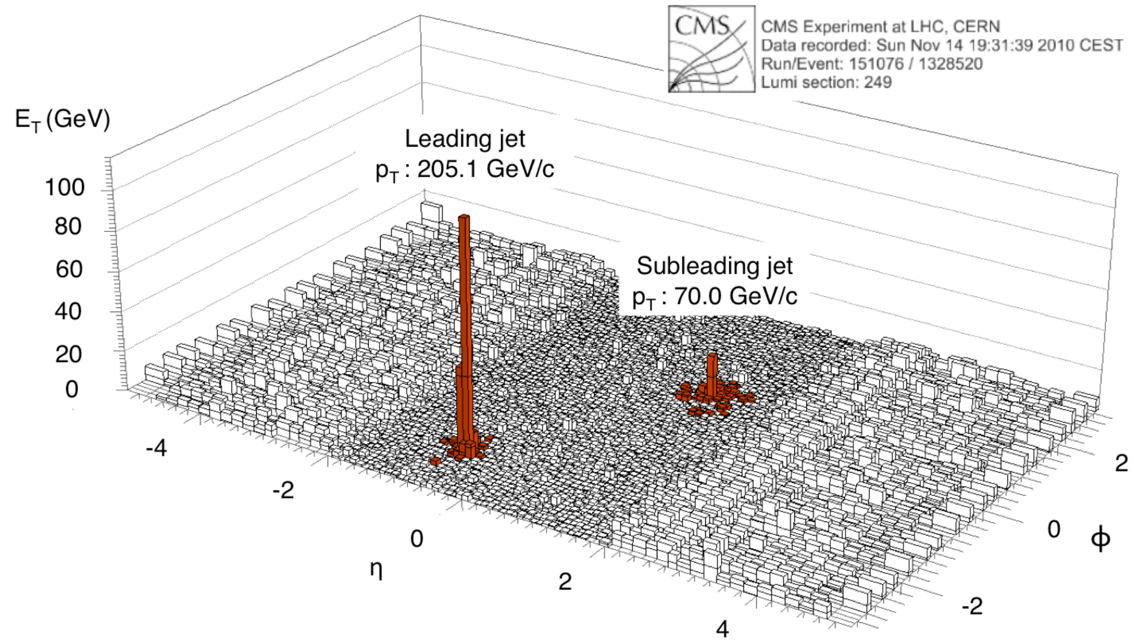
- 0-th order observable : for high pT diagnostics: $R_{AA}(p_T) \equiv \dfrac{\text{Measured Yield in } A+A}{\text{Expected Yield from Scaled } p+p}$

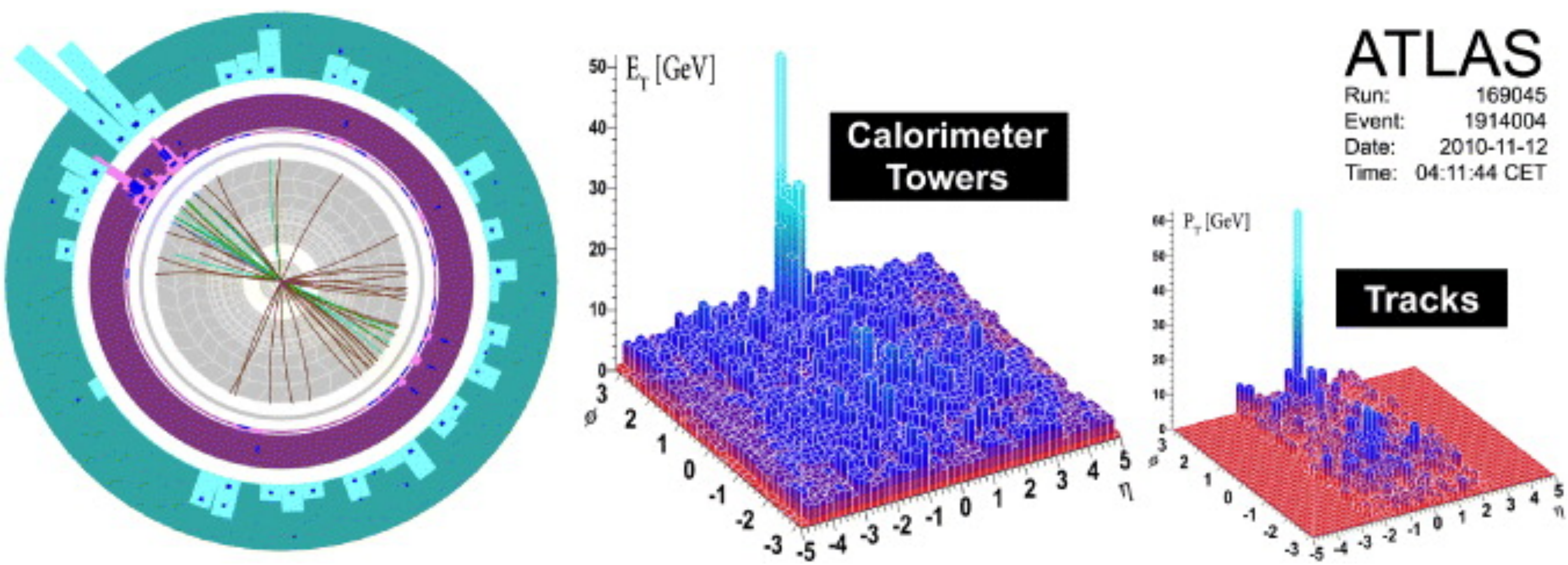


- 1^{st}, 2^{nd}, 3^{rd} order:
  - Differential studies versus: impact parameter, reaction plane, away-side partner; flavor tagging, tagged photons, complete jet reconstruction…

New Heavy Ion Physics at the LHC

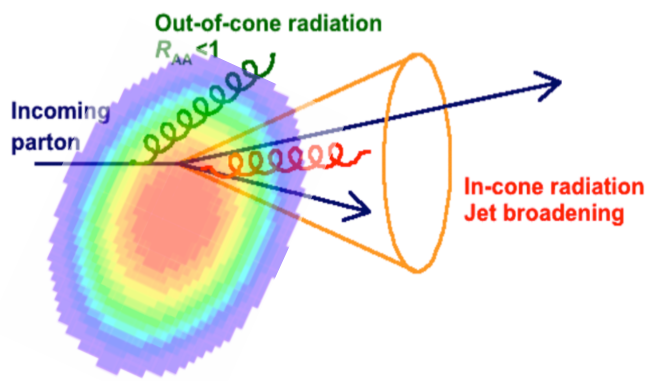
- Huge (and hugely visible) modifications to jets in Pb+Pb collisions





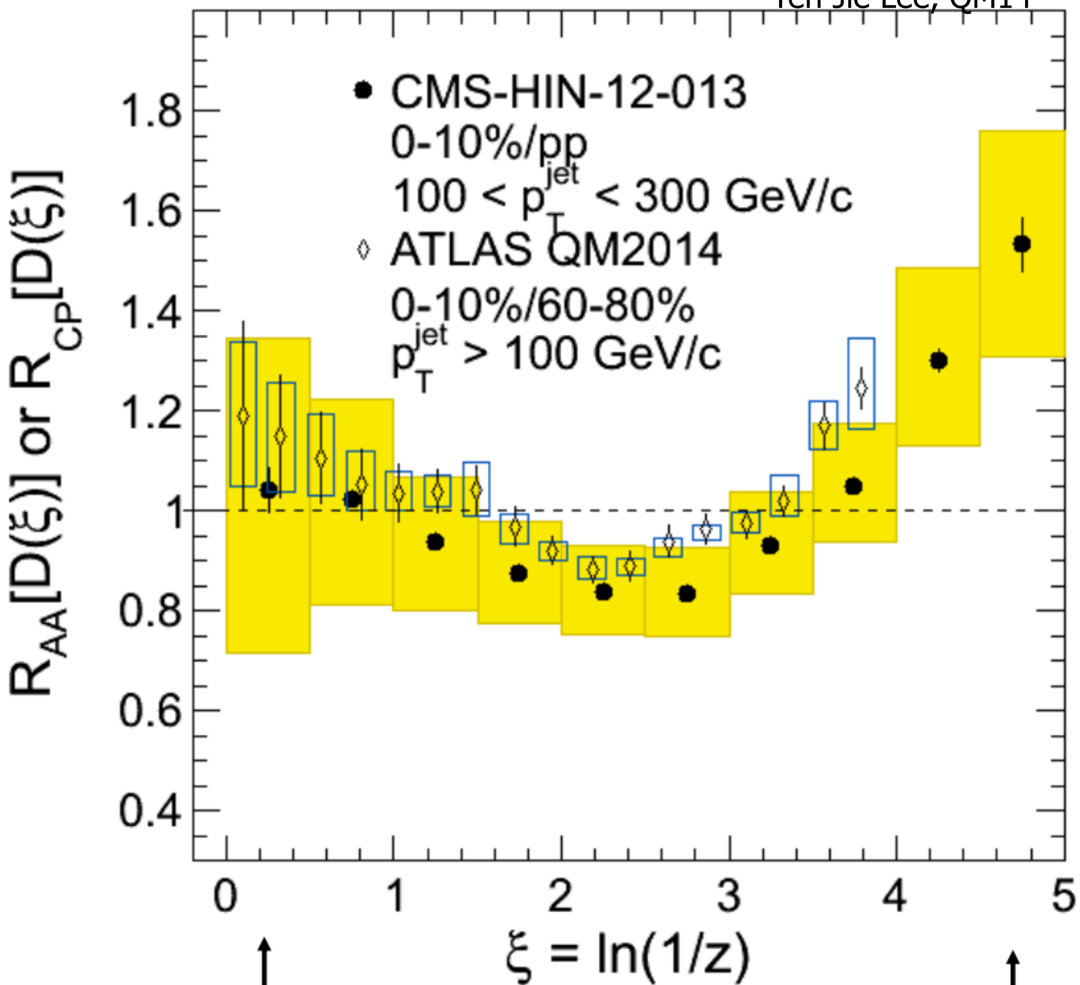
Modifications to Jet Fragmentation

- Extensive world data on fragmentation functions *D(z) in vacuo*
- Complete jet reconstruction in heavy ion collisions
  → *in medium D(z)*



☞ Compelling need for precision study versus
  - System size, √s, orientation, with photon-jet, b-tagging, …
  - To understand jet-medium coupling → ***degrees of freedom in the medium***

Yen-Jie Lee, QM14



High p_T particles

$$z \equiv \frac{p_{T,Track}}{p_{T,Jet}}$$

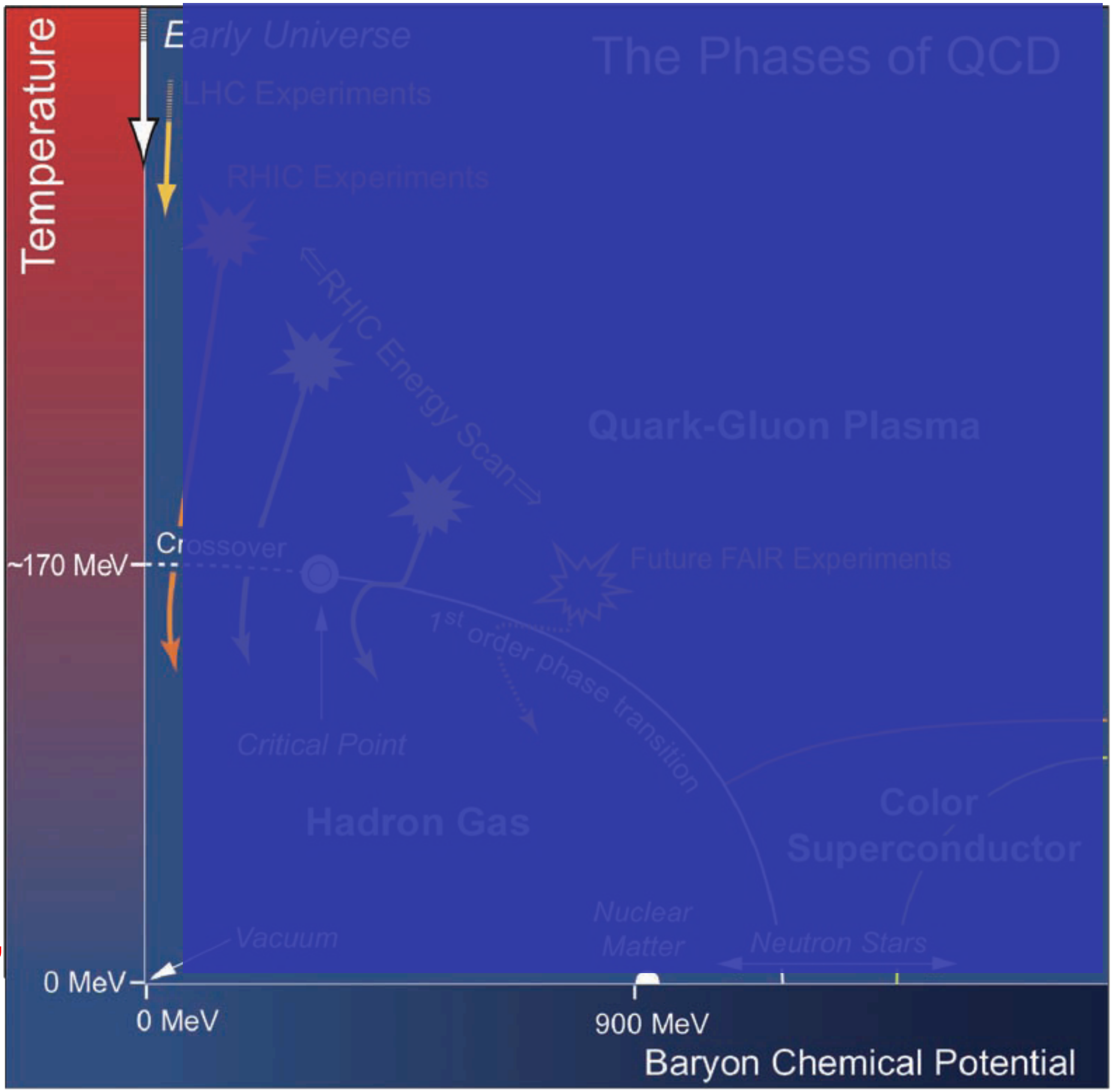
Low p_T particles

Surrounded By New Frontiers

- Heavy ion collisions at the LHC opened a fascinating new energy frontier in the field
  - Push towards temperatures and densities even closer to the early universe than 200 GeV RHIC collisions
  - (Even smaller values of μ_B/T)
- There is an equally compelling frontier at lower energies
  - Deliberately *increase* the value of μ_B/T
  - Search for a fundamental feature of thermal QCD: The critical end point and change to 1st order phase transition

√s Varies a True Control Parameter: μ_B

- Emphasis in first part of this talk:
  - "Recreating conditions in the early universe" with μ_b/T <<1
  - A *subset* of "exploring the QCD phase diagram"



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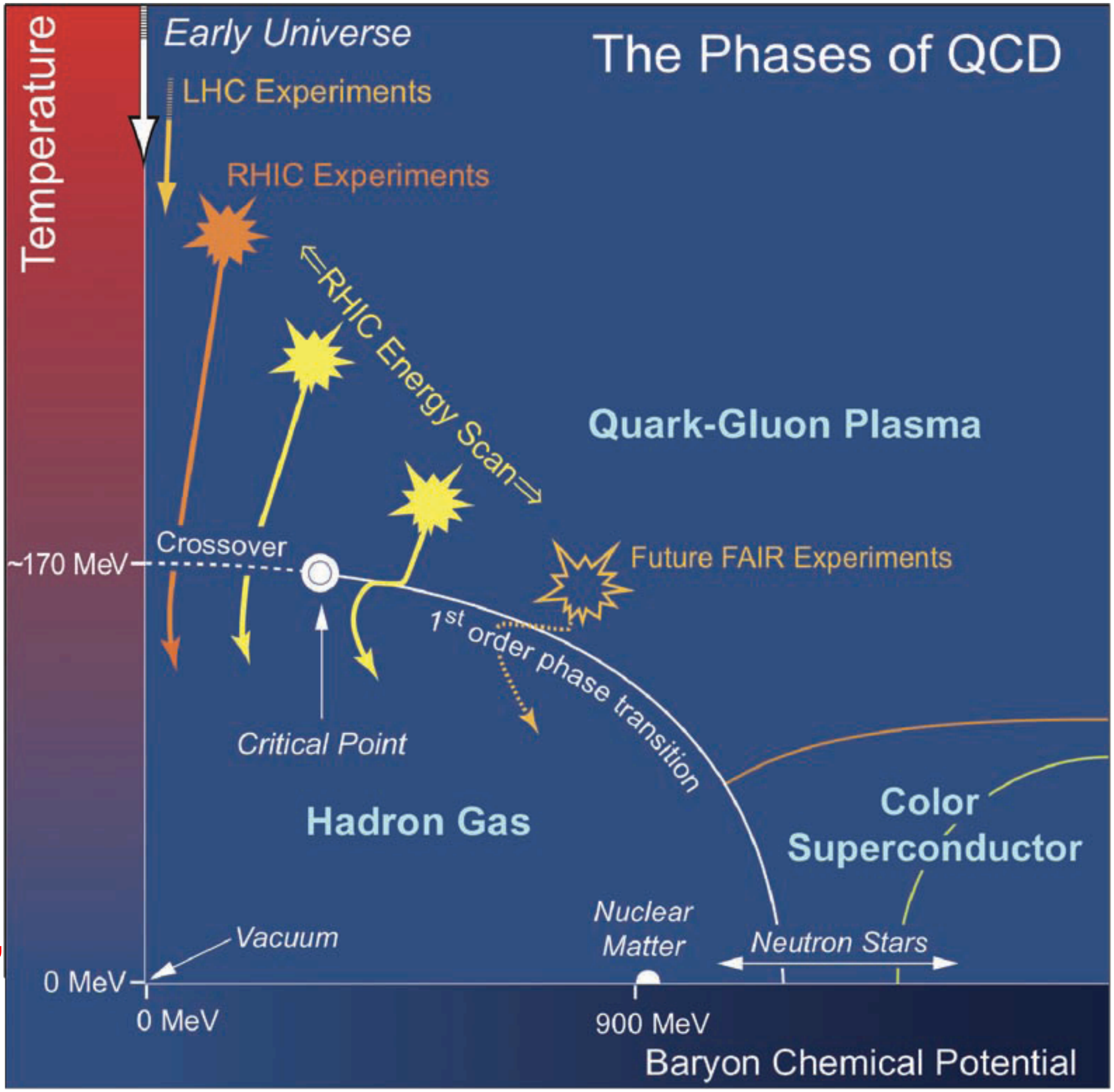
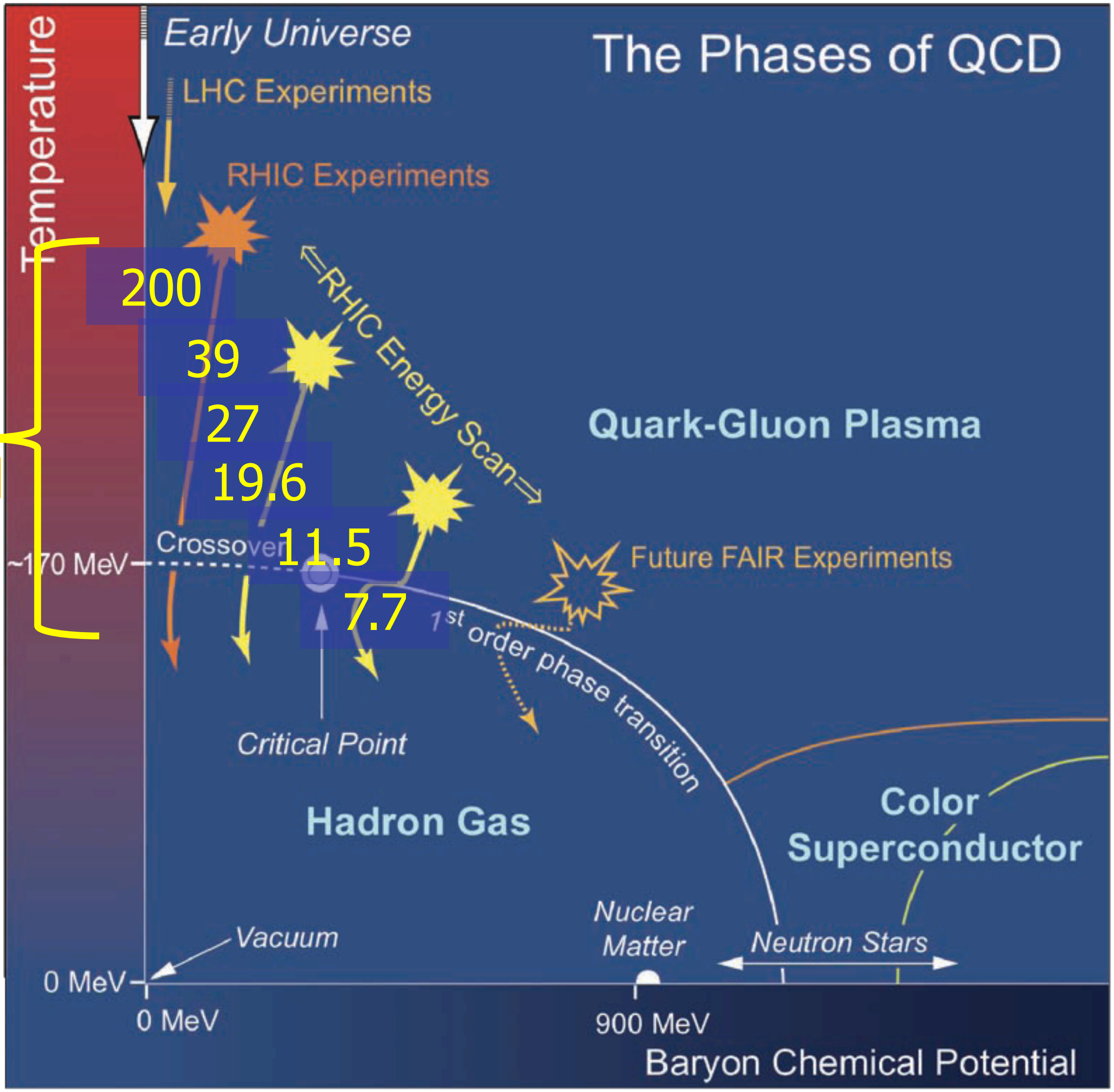


√s Varies a True Control Parameter: μ_B

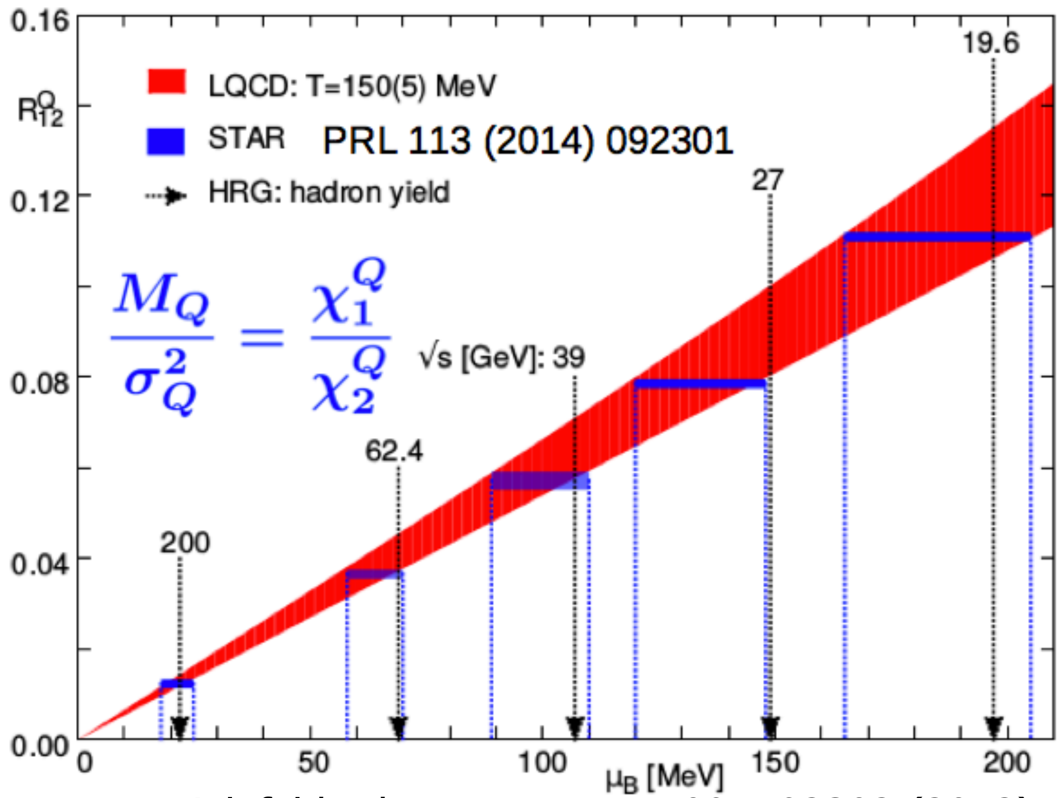
- Beam Energy Scan at RHIC
  - *Only at RHIC !*
    - **Note:** COLLIDER → complete control of systematics vs. √s
  - Range explored to date
    - **Note:** horizontal position accurate; vertical position schematic
  - "Exploring the QCD phase diagram" in search of the critical point



Our GPS on the Phase Diagram

Translate $\sqrt{s}$ to μ_B by:

- *Standard approach (to date):*
  - *Model observed particle abundances using known states and assuming thermal equilibrium to determine T, μ_B and μ_S.*
  - *Vertical black lines on plot*
- *21st century approach:*
  - *Use LQCD results compared to experimental observable (scaled charge fluctuations) to translate observable to μ_B.*
- *Impressive agreement*



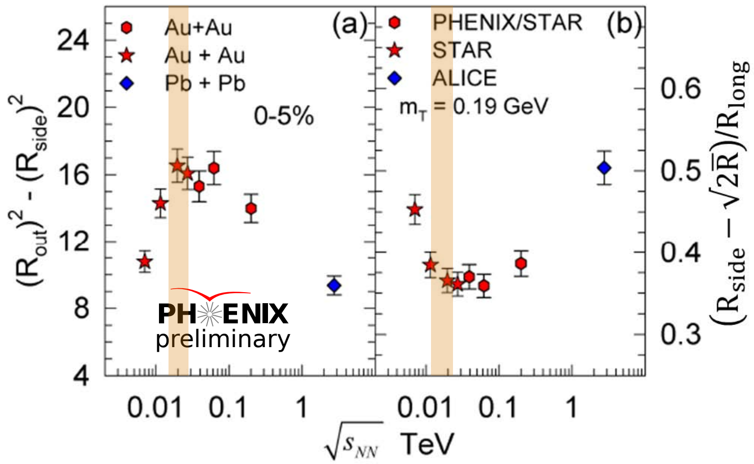
BNL-Bielefeld: Phys. Rev. Lett. 109, 192302 (2012)

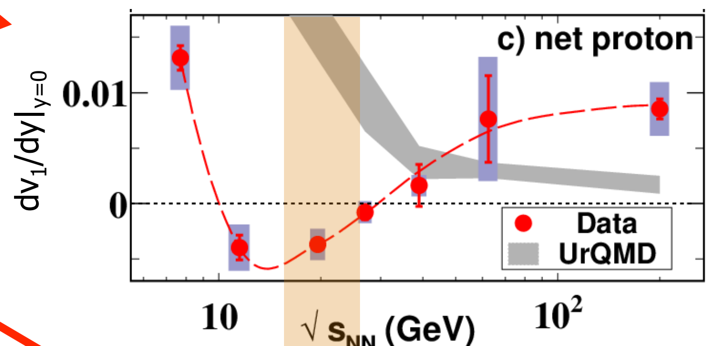
Results from Beam Energy Scan I

- Systematic study of various quantities as function of √s:
  - Source radii
  - Directed flow v_1
  - Scaled kurtosis (baryon fluctuations)
- Suggestive non-monotonic behavior at a ~common √s

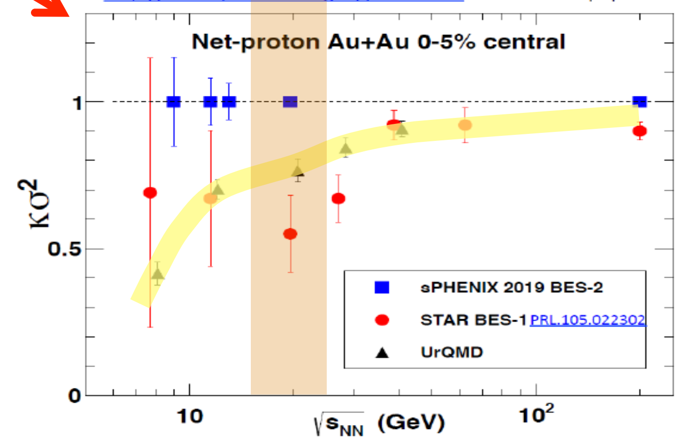
☞ *Compelling* need for RHIC Beam Energy Scan II

  - Greatly increase statistical precision
  - Additional √s points



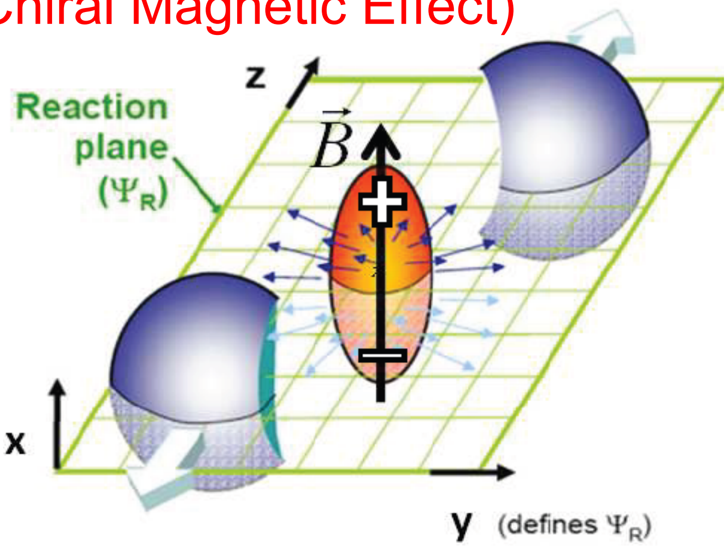


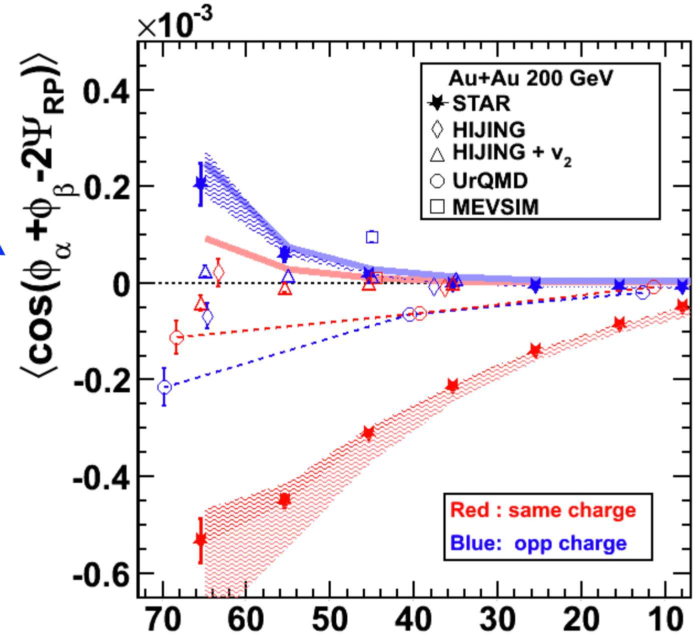
http://www.phenix.bnl.gov/plans.html - BES2 Whitepaper



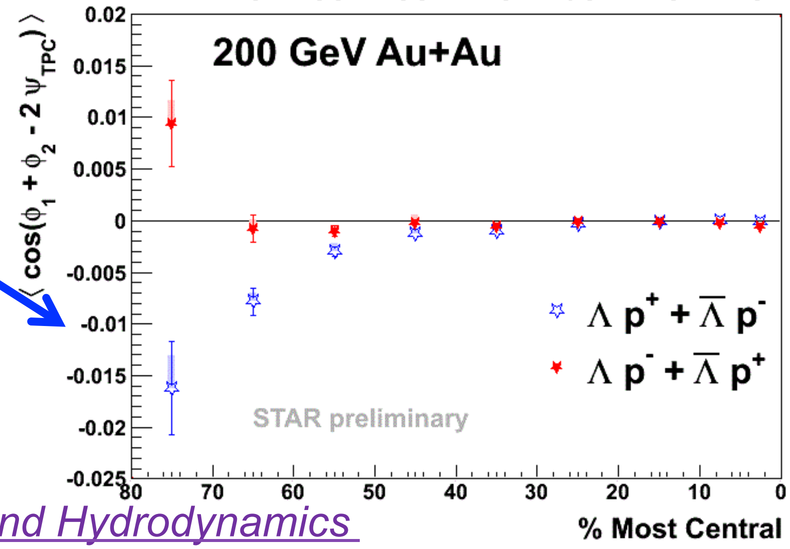
Search For QCD Anomalies

- Possible formation of parity-odd domains…
- Coupled with
  - Strong B-field → *Charge separation* (Chiral Magnetic Effect)





  - Fluid vorticity → *Baryon # separation* (Chiral Vortical Effect)



☞ *Direct contact with topologically non-trivial phases in condensed matter physics*

☞ Simons Center: Quantum Anomalies, Topology and Hydrodynamics

Summary: Where Are We?

- Since the last Long Range Plan, we have
  - Opened a new energy frontier – the LHC
  - Begun exploration of QCD phase diagram - RHIC
  - Developed sophisticated multi-scale models
  - Discovered hydrodynamic flow in small systems
  - Discovered the critical role of fluctuations
  - Extended connections to other fields
- Where are we?
  - We are in the midst of a paradigm shift in our quantitative understanding of thermal QCD

Where Are We Going?

Why "Done!" ≠ "Finished!"

- To date:

  Data from RHIC and LHC

  together with

  Mature and sophisticated theoretical modeling…

  Tell us what the QGP does.

- Yet we have only very limited insight into *How the QGP does it.*
  - Creates near-perfect fluidity
  - Approaches first order phase transition
  - Modifies jet fragmentation
  - Many other observed signals…

Key Science Drivers For The Next Decade

- How does the perfect liquid behavior emerge from the short-distance degrees of freedom?
- What conditions produce the most nearly perfect liquid behavior?
- Is there a critical end point and change to a 1^{st} order phase transition in the QCD phase diagram?
- Which mechanisms or conditions drive early thermalization in nuclear collisions?
- Can the effects of quantum anomalies be detected in the final state?

Wilczek, 2014

Quarks (and Glue) at the Frontiers of Knowledge

QCD has special features, that make its study especially attractive:

It is precisely defined

numerical ***realization***

It has enormous symmetry

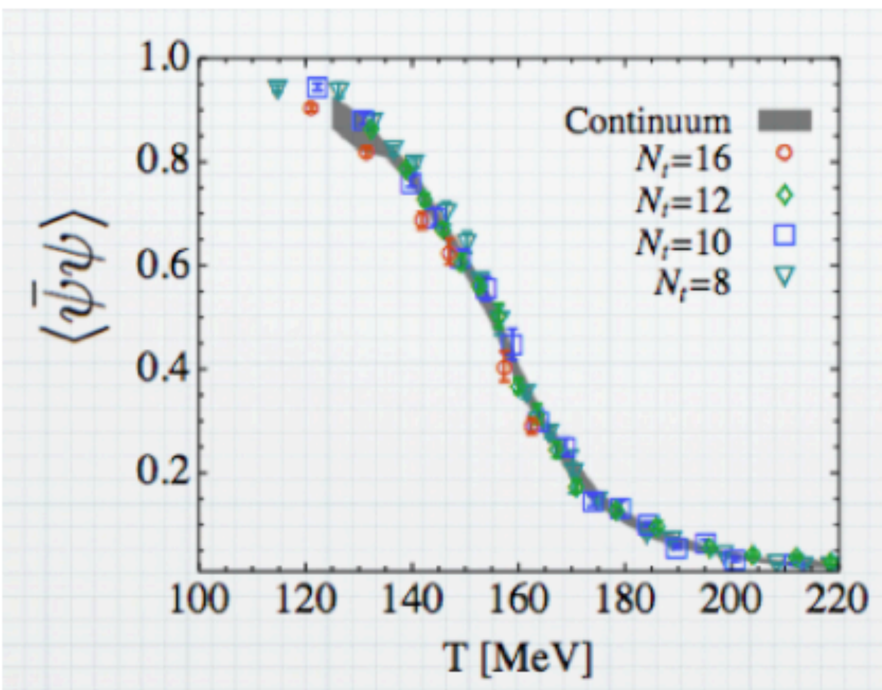
beauty, uniqueness

It *embodies* many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ...)

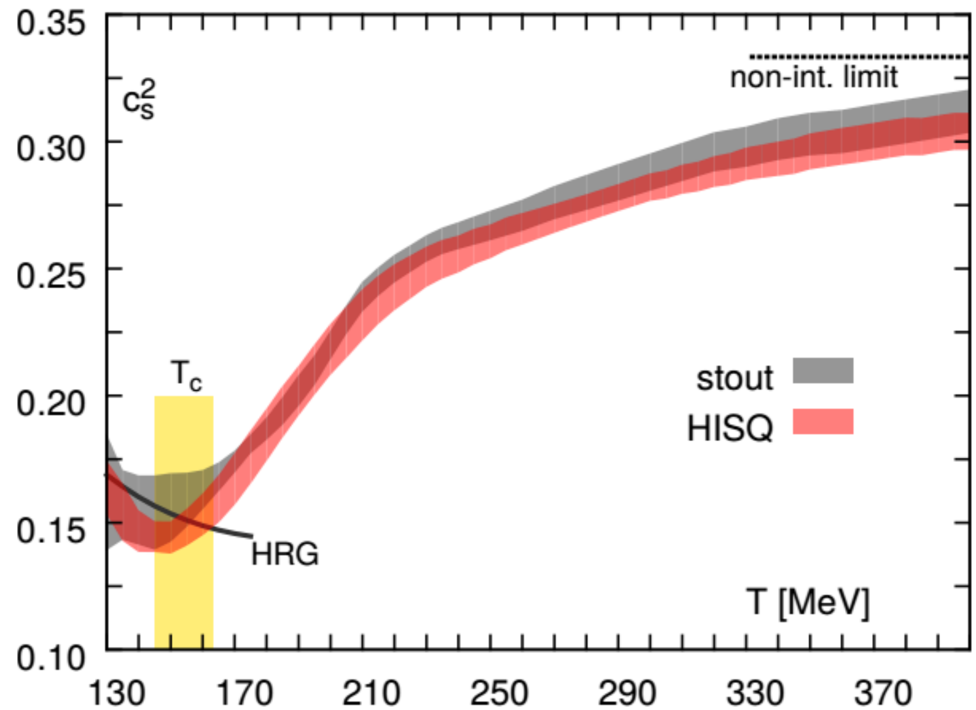
Latest Lattice Gauge Results

- Now a reliable guide (calculation) of many (static) medium properties:

Chiral symmetry restoration



Equation of State

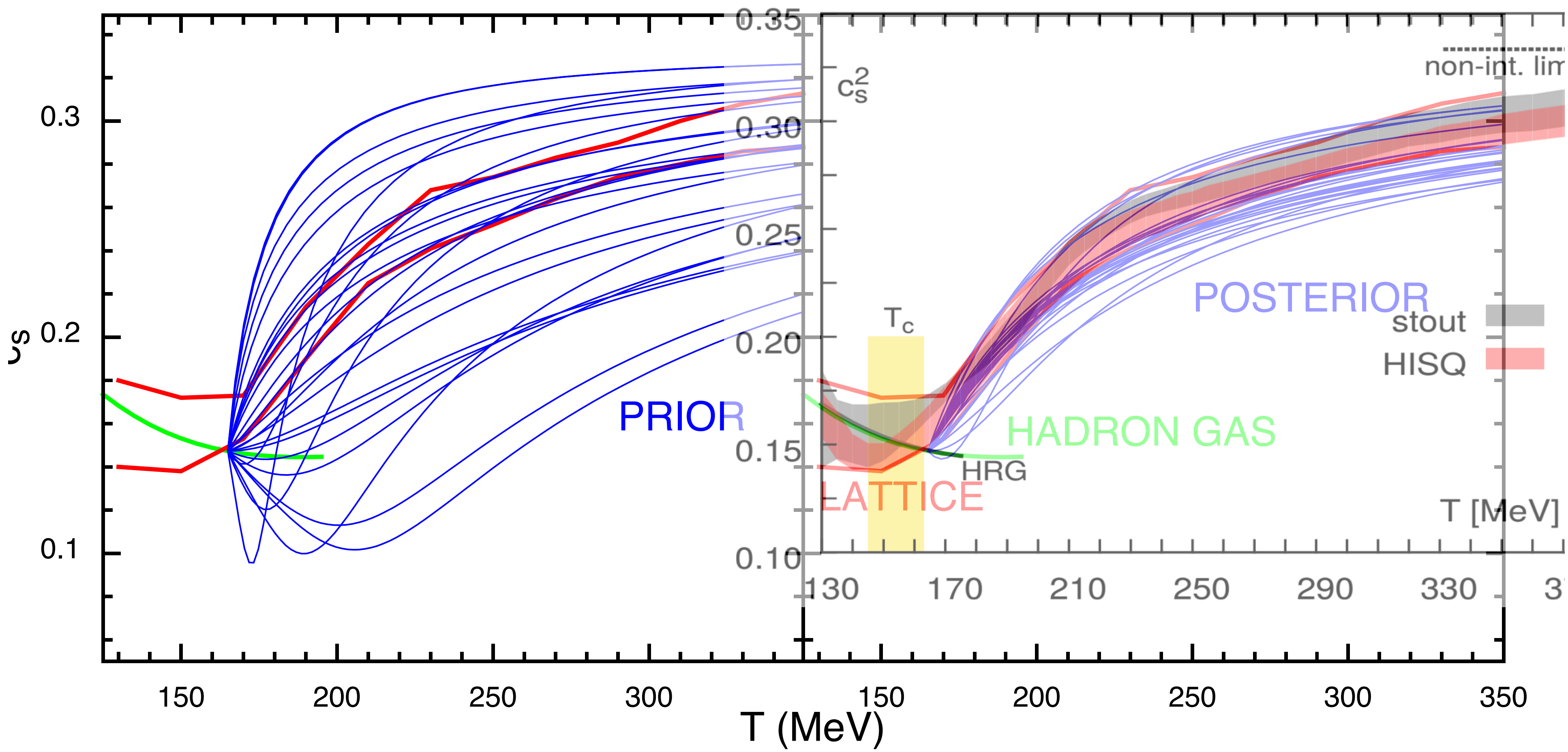


HotQCD, arXiv:1407.6387

Cross Fertilization (1)

- Model Emulations
  - Parameterize dependence of model outputs on input parameters via "Gaussian Process emulators".

    Determining Fundamental Properties of Matter Created in Ultrarelativistic Heavy-Ion Collisions, J. Novak et al., arXiv:1303:5769

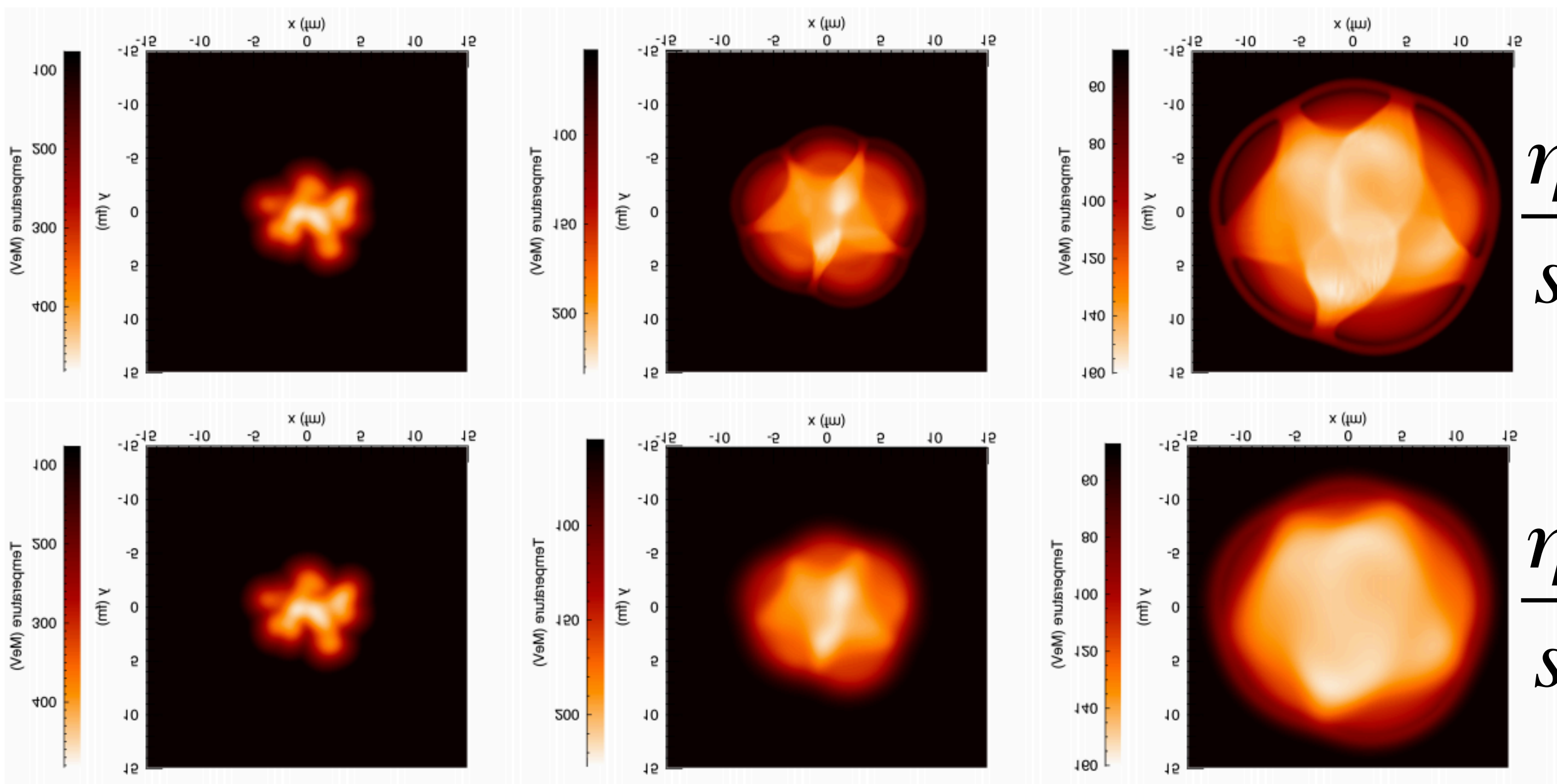


Cross Fertilization (2)

- ECHO-QGP: Based on existing astrophysics code ECHO:
  - Eulerian Conservative High Order scheme for relativistic magnetohydrodynamics in arbitrary GR background

Del Zanna et al. Astron.Astrophys., 473:11–30, 2007

Dell Zanna et al., Eur.Phys.J.,C73:2524, 2013

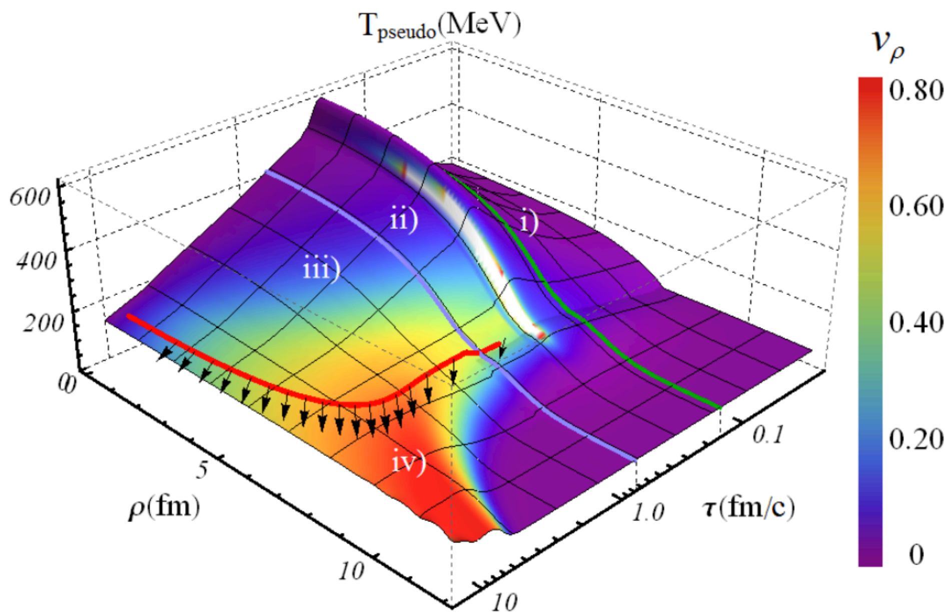


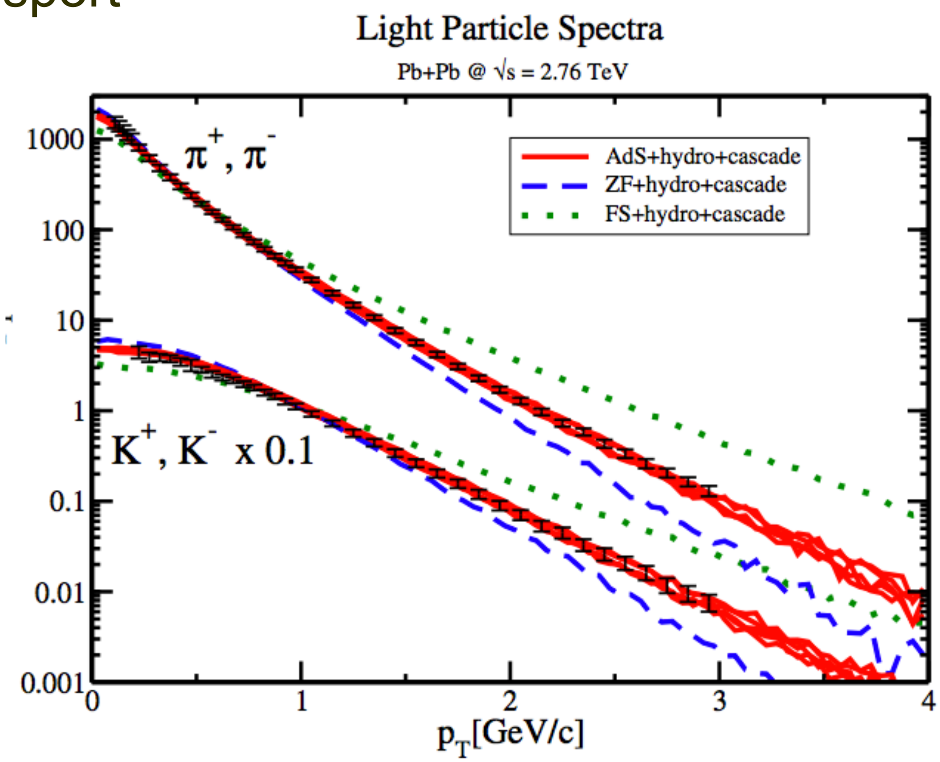
$$\frac{\eta}{s} = 0$$

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

Cross Fertilization (3)

- Numerical relativity
  - Hybrid model with
    - Pre-equilibrium: numerical relativity in Anti de Sitter space
    - Mid-stage: Viscous hydrodynamics
    - Final stage: Kinetic theory transport





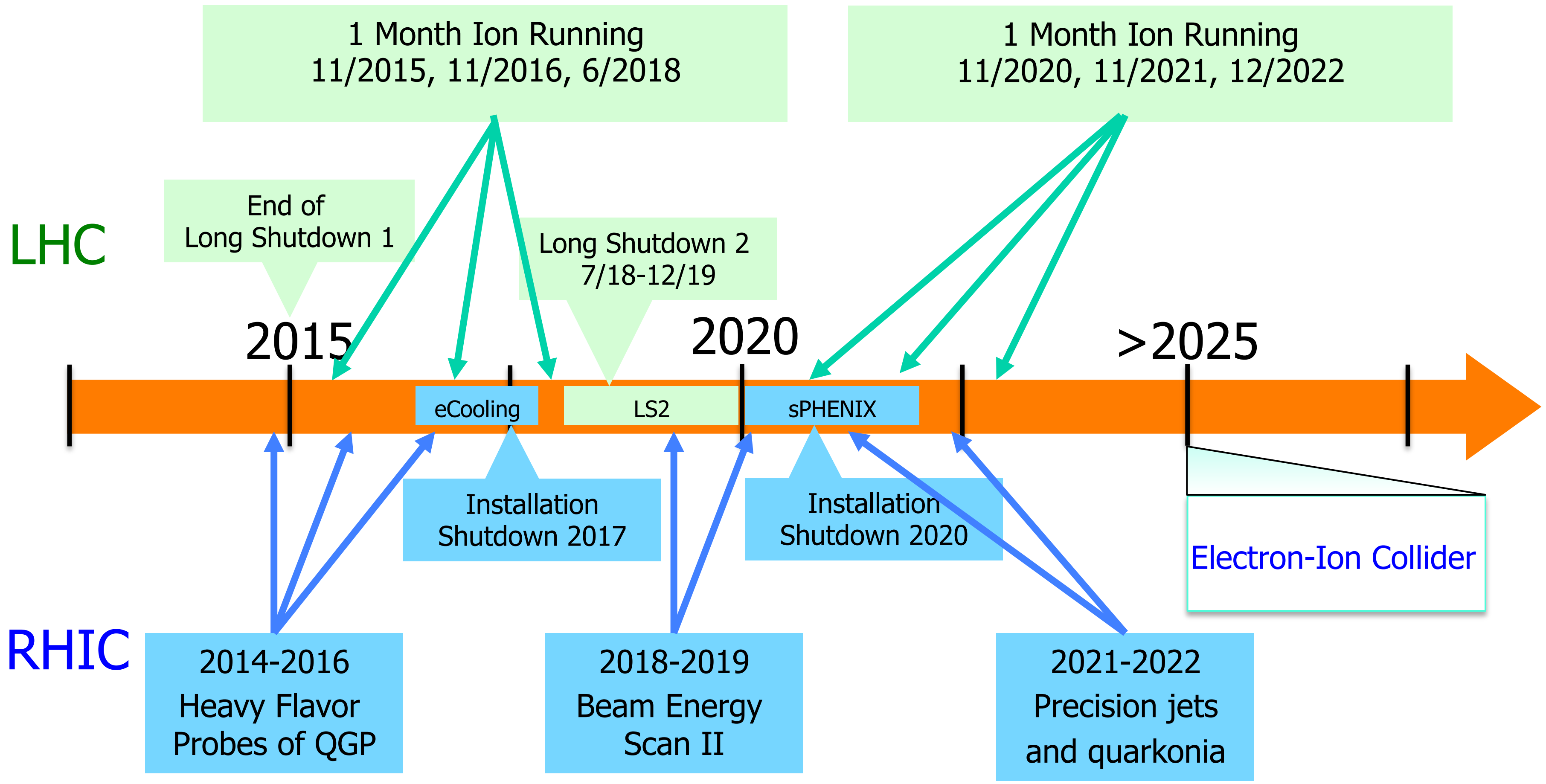
A fully dynamical simulation of central nuclear collisions, W. van der Schee, P. Romatschke and S. Pratt, arXiv:1307.2539

Wise Advice

- "QCD is an especially difficult theory in which to investigate this issue, and were it not for the data we would have no good intuition for the physics."

The Pomeron and Gauge/String Duality, R. Brower, J. Polchinski, M. Strassler and C.I. Tan, hep-th/0603115

RHIC / LHC Timeline

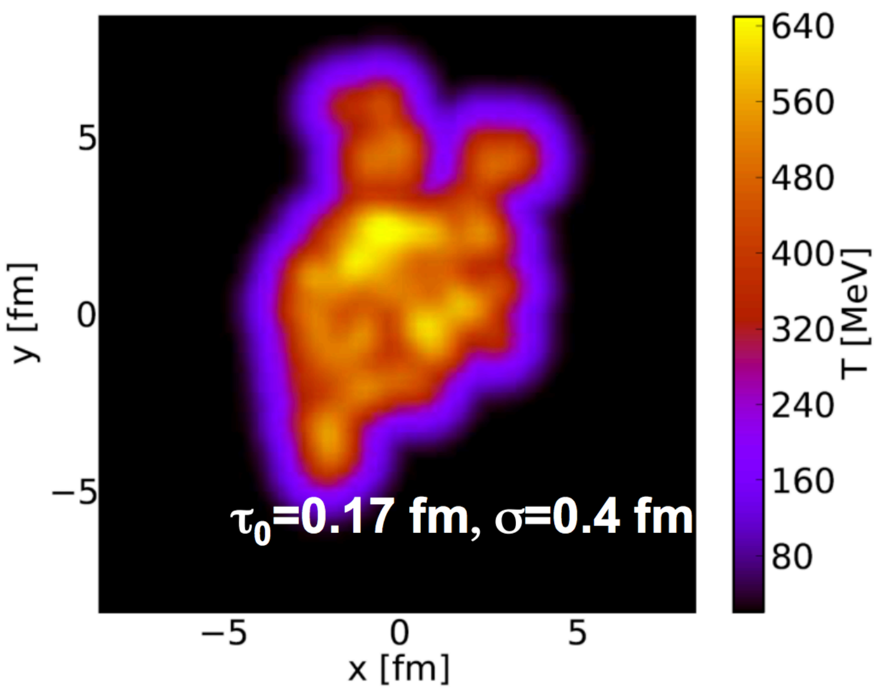


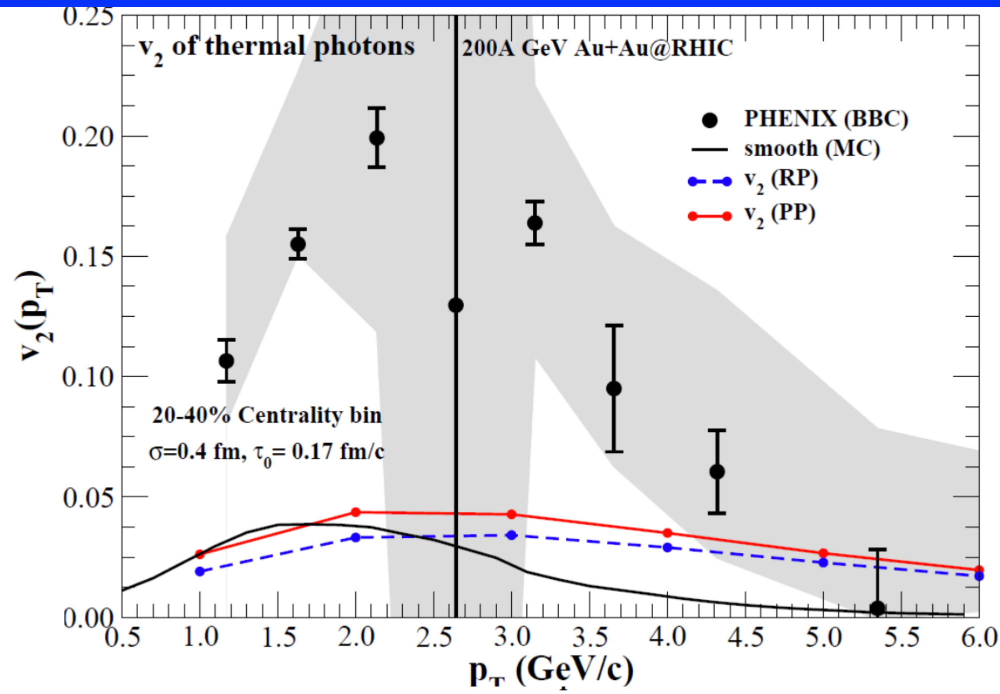
A (Deep) Puzzle to Solve: Photon Flow Signal

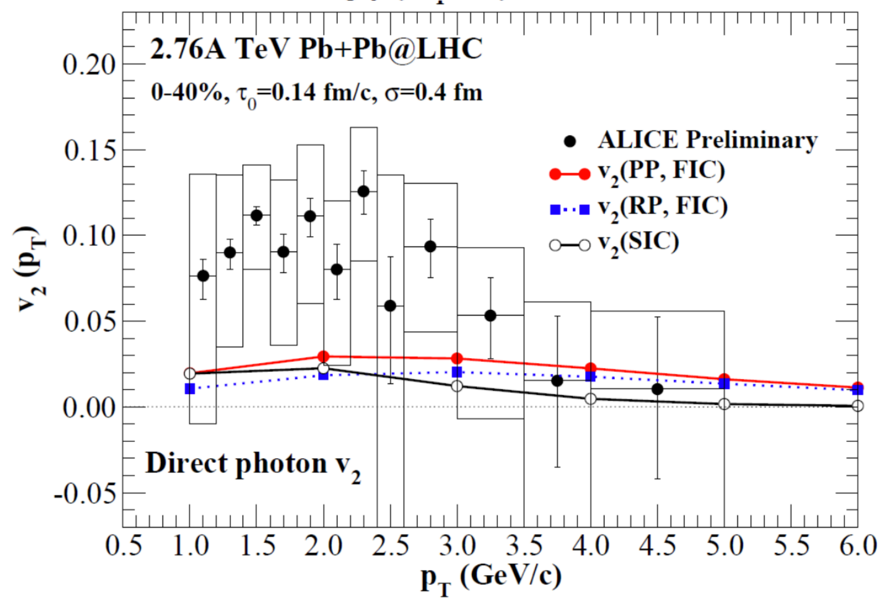
- Photons show no energy loss but have a strong flow signal

☞ Luminosity-hungry measurements are needed to resolve this challenge to our "standard model"

R. Chatterjee et al., Phys. Rev. C88, 034901 (2013)

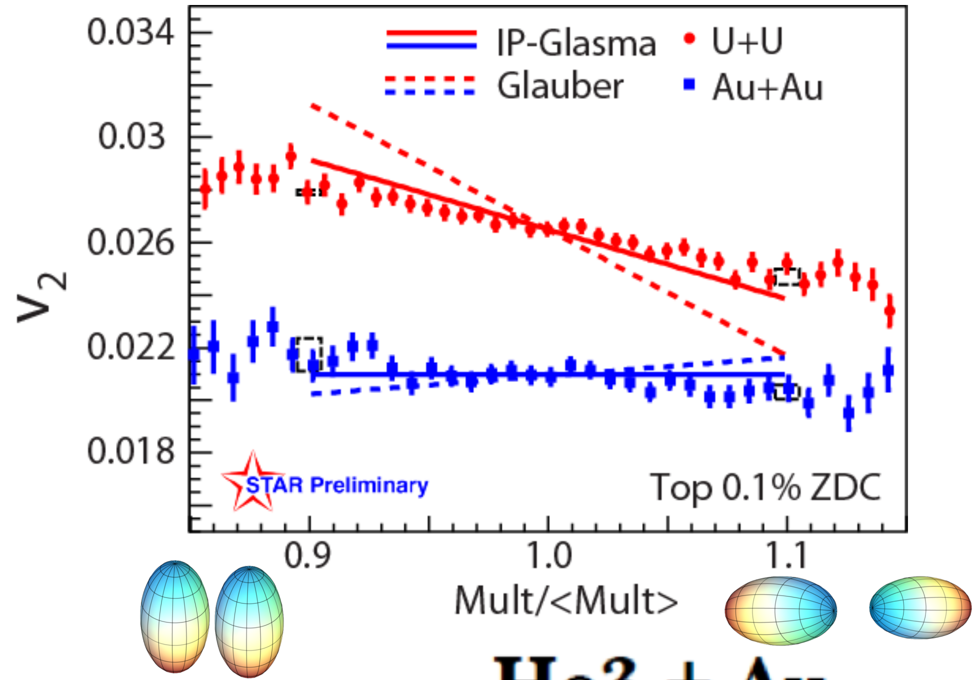




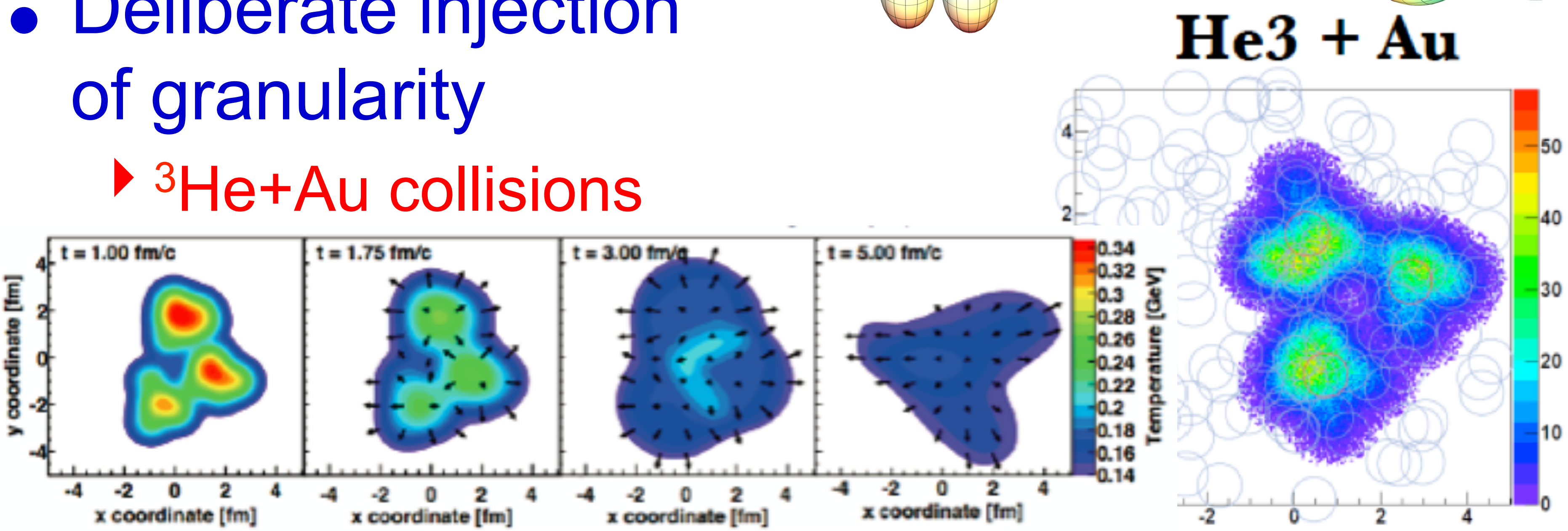


Tools and Techniques

- Deliberate distortion of initial state
  - U+U collisions

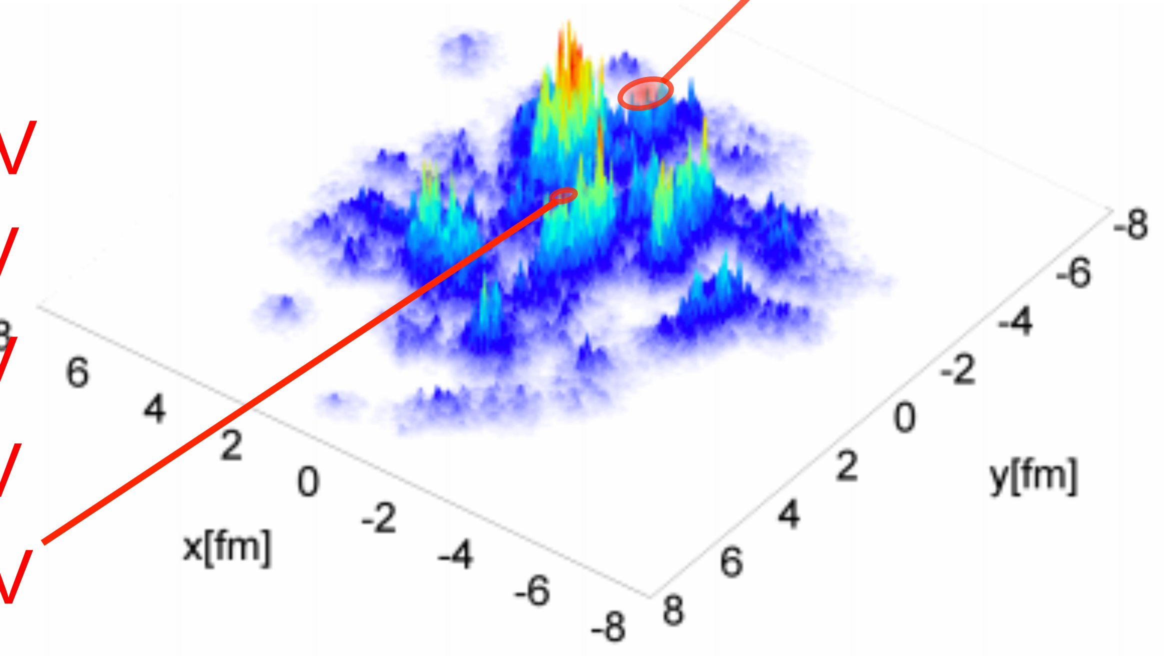


- Deliberate injection of granularity
  - ^{3}He+Au collisions



Plasma Diagnostics

- Needed: Tools to interrogate QGP at small distances
- Intrinsic scales of the QGP:
  - T ~ 200 MeV
  - gT ~ 500 MeV ~ gluon effective mass
- Hard processes provide a wide variety of perturbative scales:
  - M_c ~ 1.3 GeV
  - M_b ~ 4.2 GeV
  - M_W ~ 80 GeV
  - M_Z ~ 90 GeV
  - Q ~ 10-300 GeV



Completing RHIC's Mission

- Goal: to fully understand thermal QCD matter
- Organized as 3 campaigns:

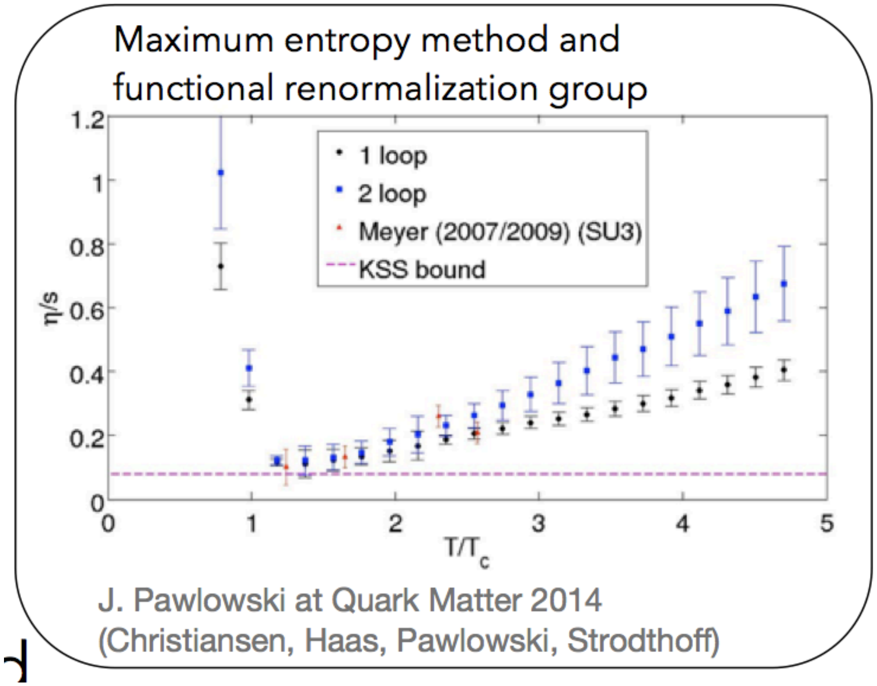
1. 2014-16: Heavy flavor probes of the QGP
    - 2017: Install low energy e-cooling
2. 2018-2019: Precision scan of QCD phase diagram
    - 2020: Install sPHENIX upgrade
3. 2021-2022: Precision measurements of jets and quarkonia

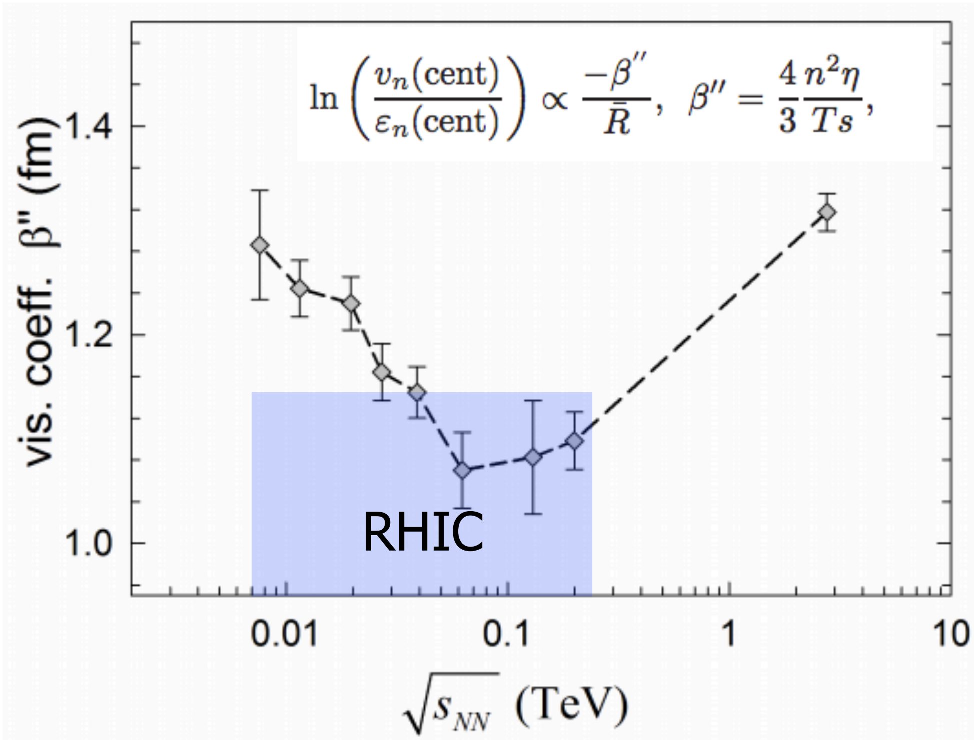
- In parallel with sustained theoretical studies, modeling and phenomenology

Where Is η/s Minimal ?

- What conditions produce the most nearly perfect liquid behavior?
  - We know (only) two points in √s :

$$\frac{\eta}{s}(0.2\ TeV) \sim 1.5 \times \frac{\hbar}{4\pi} \qquad \frac{\eta}{s}(2.76\ TeV) \sim 2.5 \times \frac{\hbar}{4\pi}$$

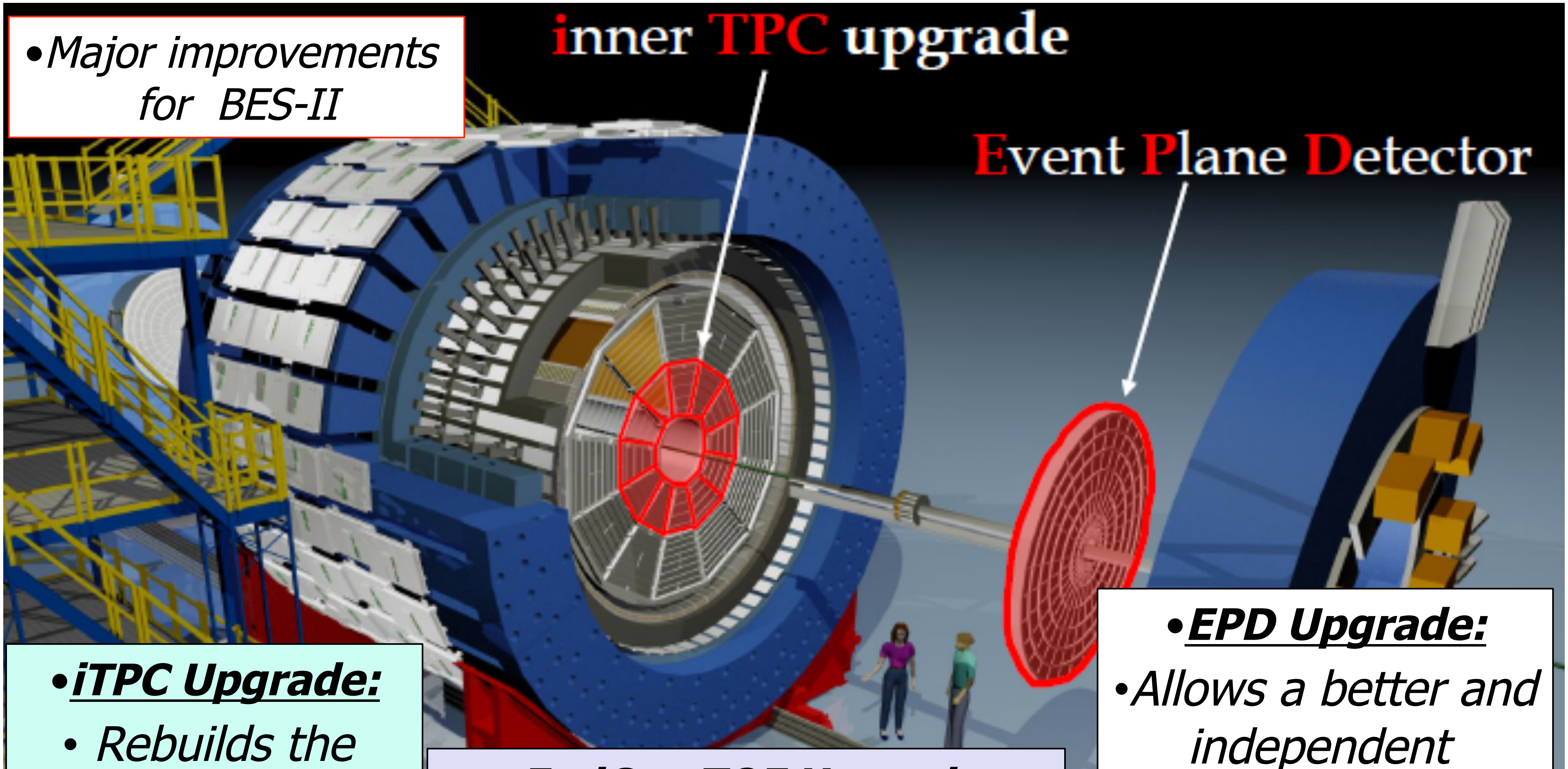




R. Lacey *et al.*, Phys. Rev. Lett. 112, 082302 (2014)

STAR Upgrades for Beam Energy Scan II

- *Major improvements for BES-II*



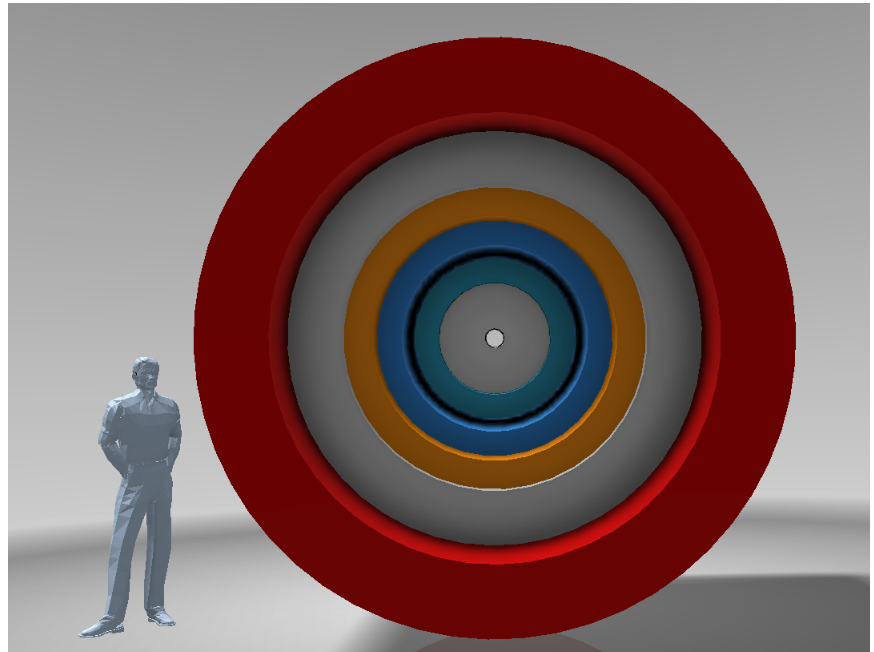
- ***iTPC Upgrade:***
  - *Rebuilds the inner sectors of the TPC*

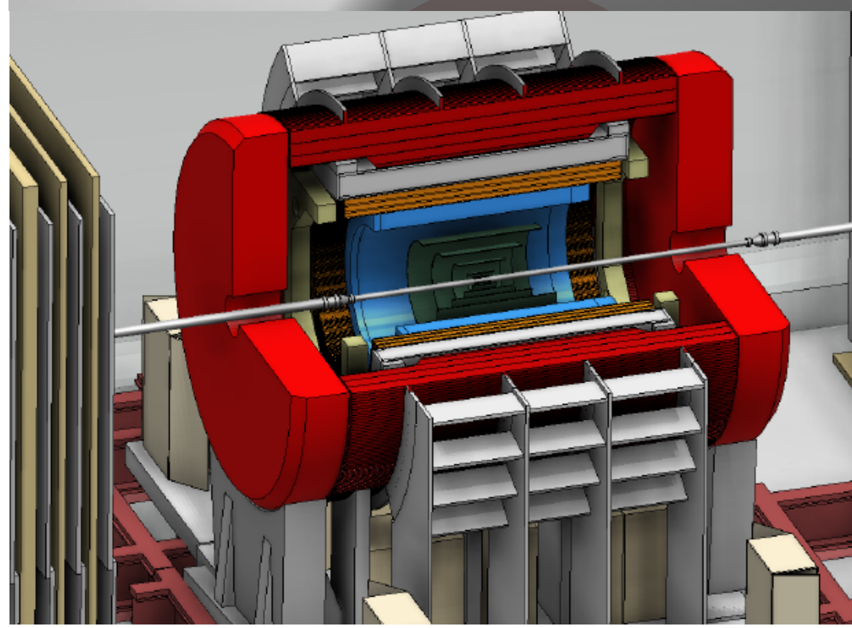
- ***EndCap TOF Upgrade:***
- *Rapidity coverage is critical for several proposed BES Phase II measurements*

- ***EPD Upgrade:***
- *Allows a better and independent reaction plane measurement critical to BES physics*

sPHENIX Upgrade

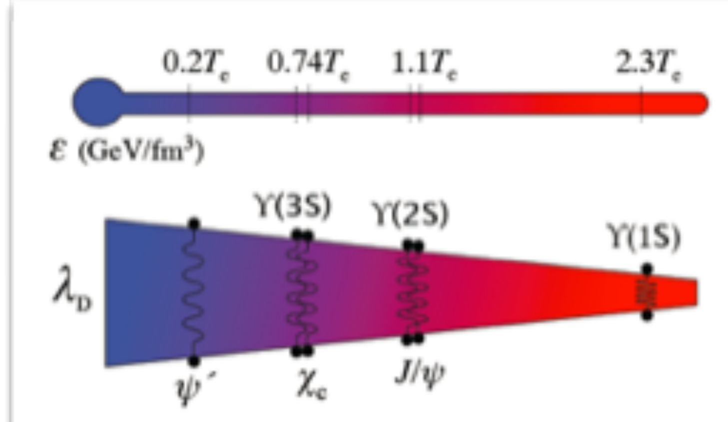
- Proposed sPHENIX:
  - EM+hadronic calorimetry over $|\eta| < 1.1$
  - Re-use existing BaBar 1.5T solenoid
  - Silicon tracking
  - DAQ rate ~ 10 kHz
- Will provide full suite of jet and quarkonia data
- Maximal overlap with LHC measurements





A Calibrated Length Scale in the Plasma

- Wide range of Bohr radii of quarkonium states:
  - Ψ' 0.88 fm → Υ(1s) 0.23 fm
- Should lead to sequential melting (from Debye screening)



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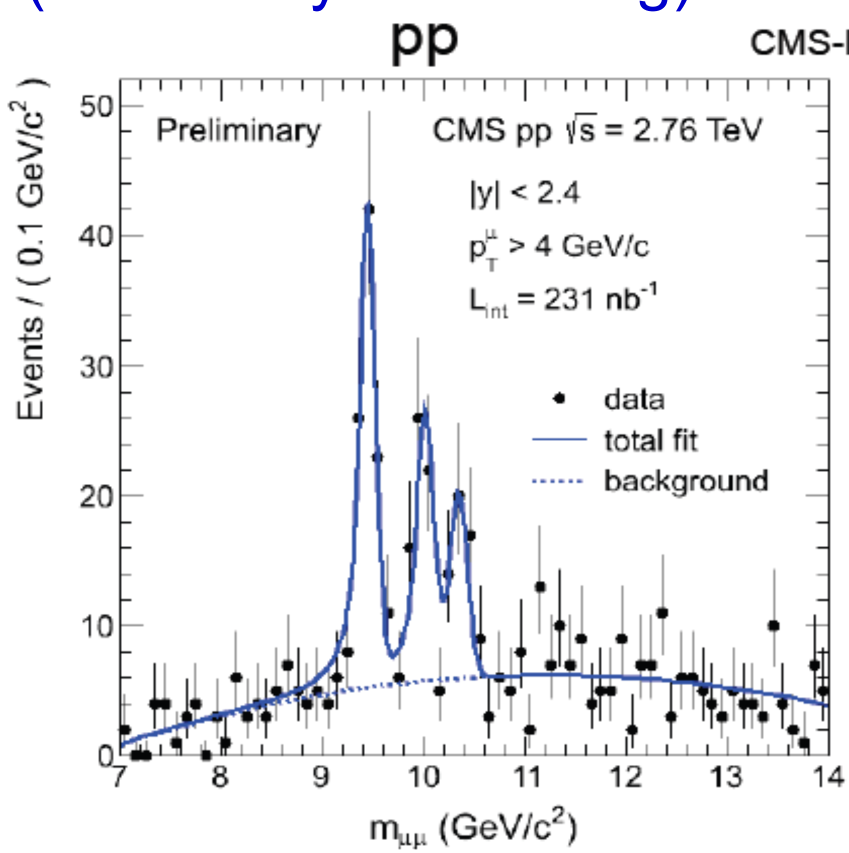

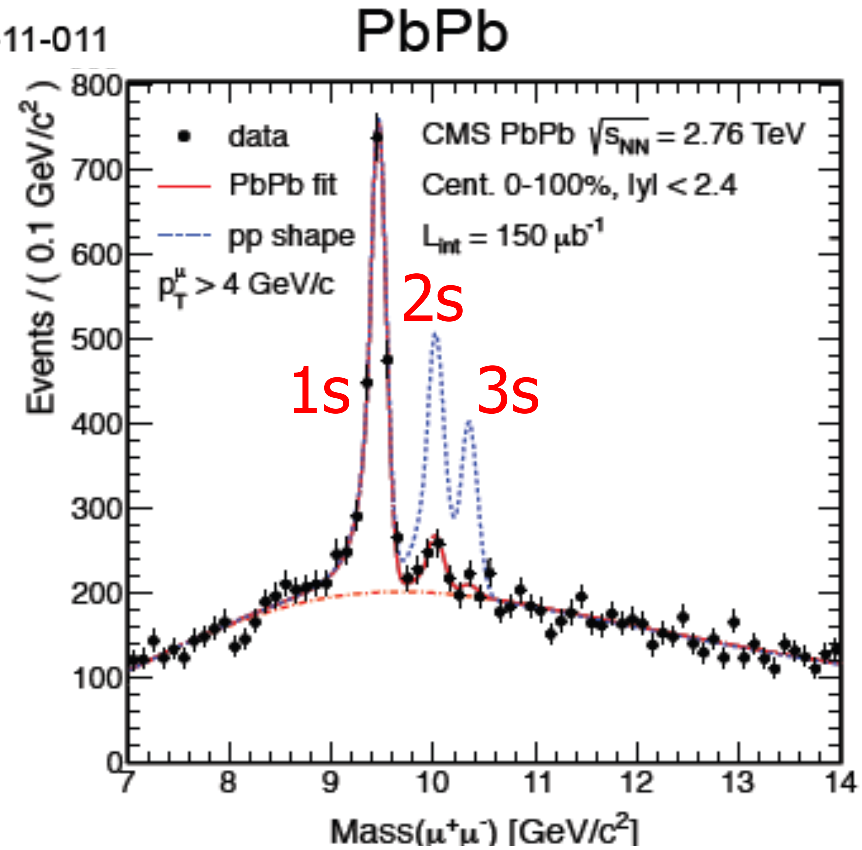

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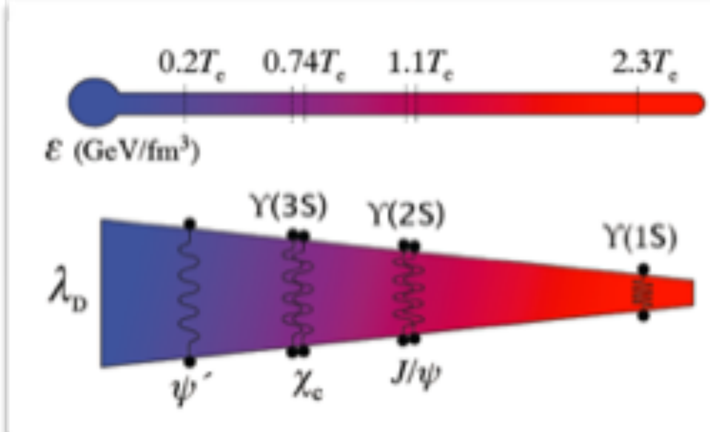

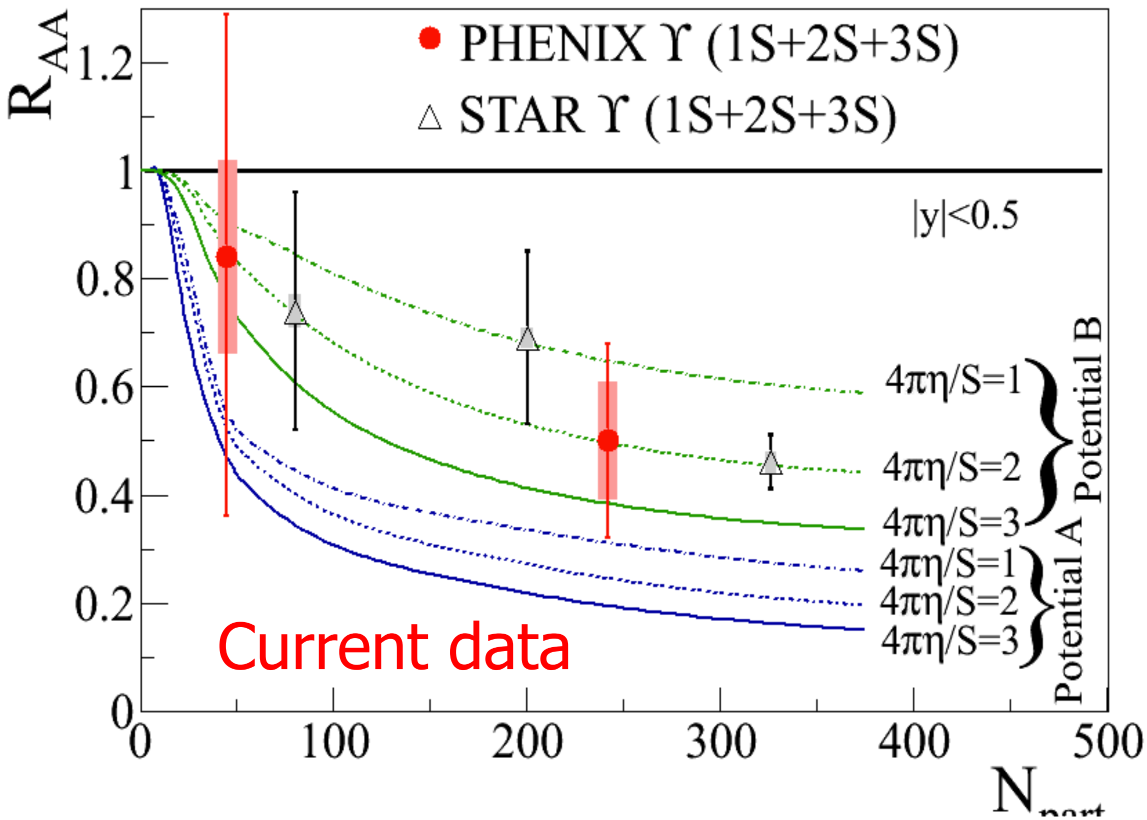

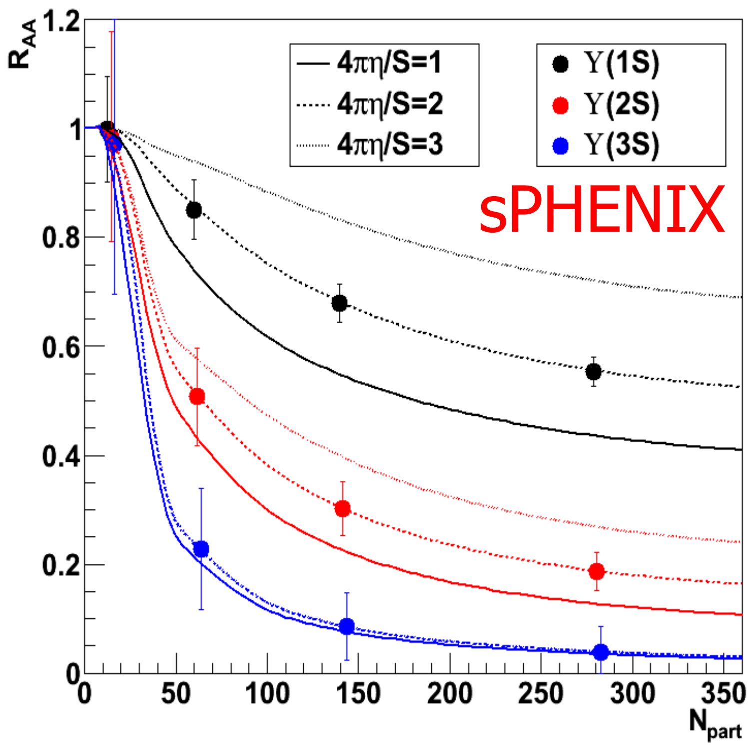

Wilczek, 2014

Quarks (and Glue) at the Frontiers of Knowledge

High Temperature

Why is the crossover so abrupt, and why does it happen at such low T?

Is there a usable "underlying" phase transition?

Why is the quark-gluon gas description, which is surely correct asymptotically, so poor at accessible T?

RHIC Beam Energy Scan

Precision jet and quarkonia data from RHIC & LHC

Wilczek, 2014

Quarks (and Glue) at the Frontiers of Knowledge

Is the intermediate state of real QCD continuously connected to the "ideal liquid" suggested by large N supersymmetric versions of QCD?

If so, can we draw out any reasonably precise, quantitative consequences?

From the suite of RHIC and LHC measurements
from strong to weak coupling,
in concert with continued theoretical effort.

Where Are We Going?

Forward in a rich science program designed to answer fundamental questions about the nature of thermal QCD matter.