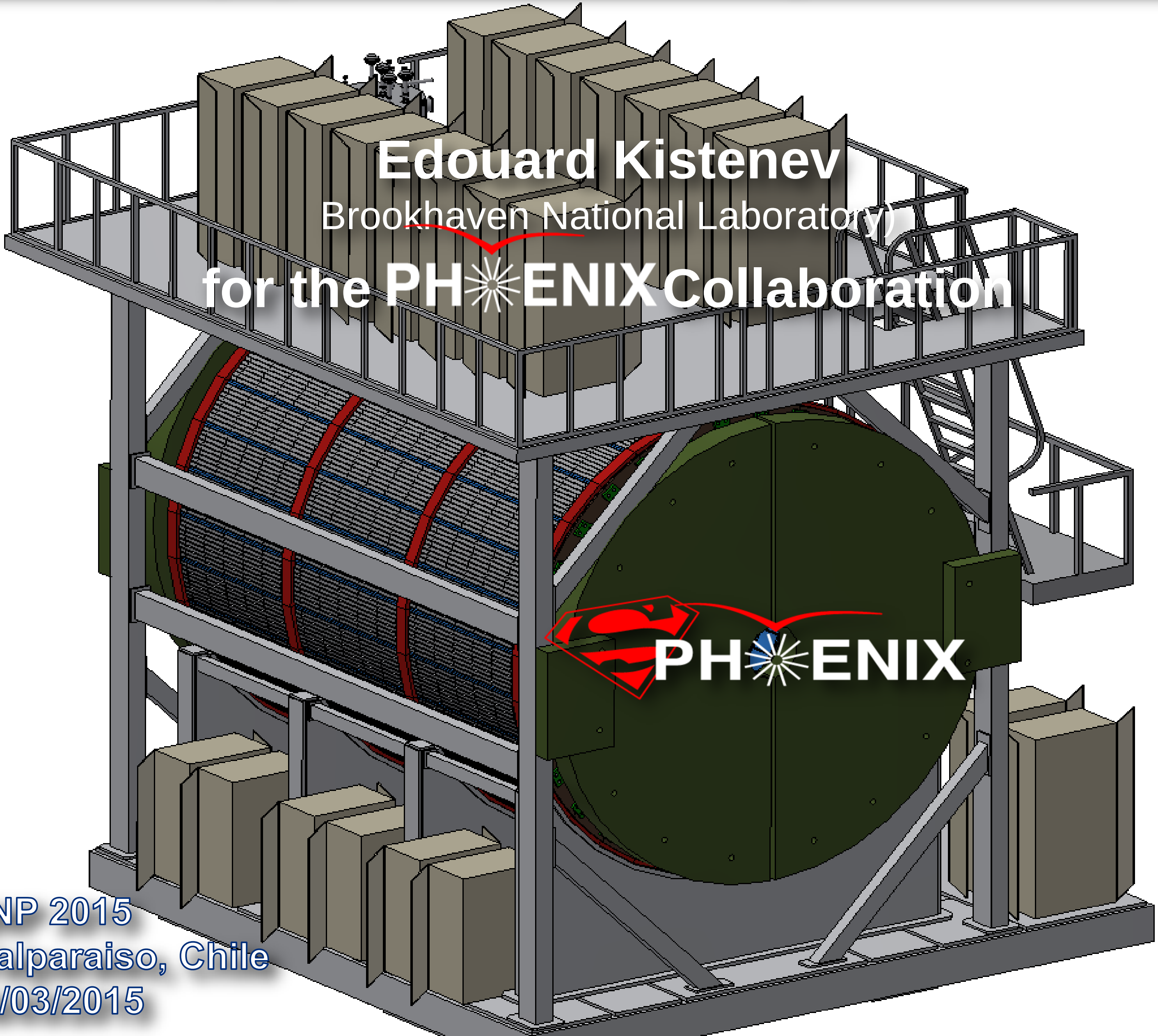
RHIC & (s)PHENIX Physics & Plans

Edouard Kistenev

Brookhaven National Laboratory)

for the PHENIX Collaboration



QNP 2015

UTFSM, Valparaiso, Chile

2-6/03/2015

RHIC & LHC - next generation

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 -> LHC II

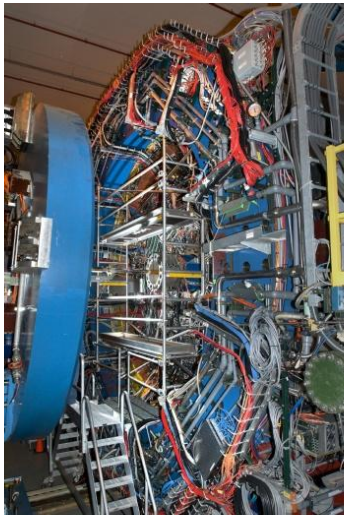
- First collisions 2010
- p+p, Pb+Pb, p+Pb
- $\sqrt{s_{NN}}$ =2.76 TeV
- (5.5 TeV in 2015-16)

RHIC+LHC Today: Five Experiments

RHIC

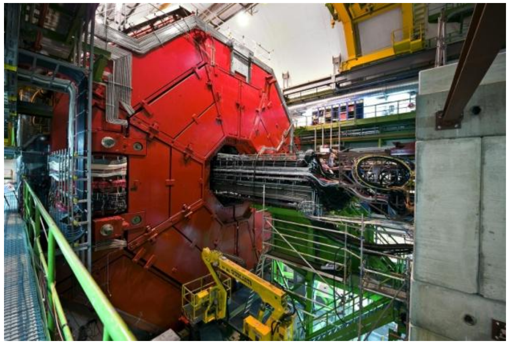
- PHENIX

- STAR

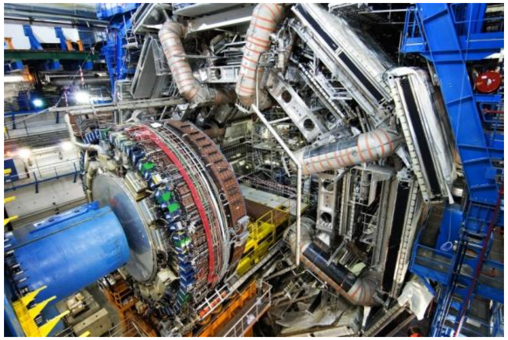


LHC

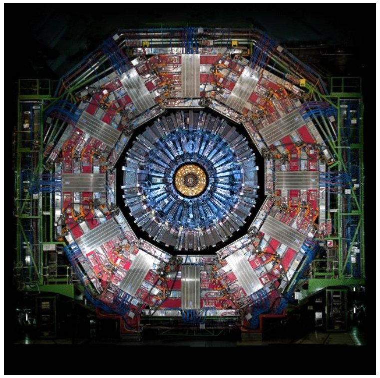
- ALICE



- ATLAS



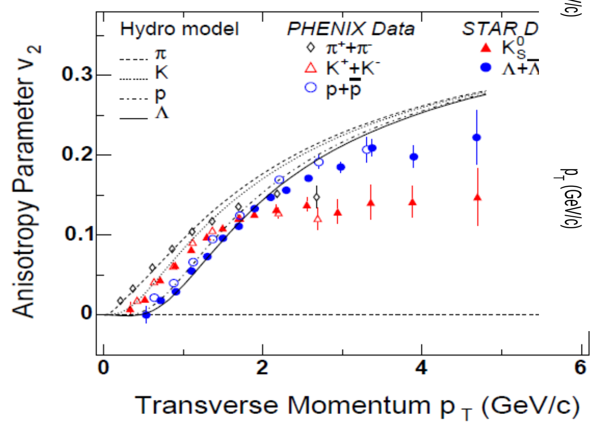
- CMS

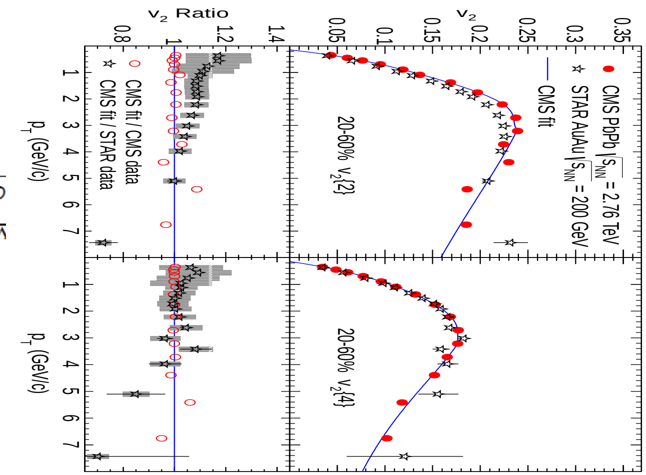


5 years of RHIC/LHC complementarity

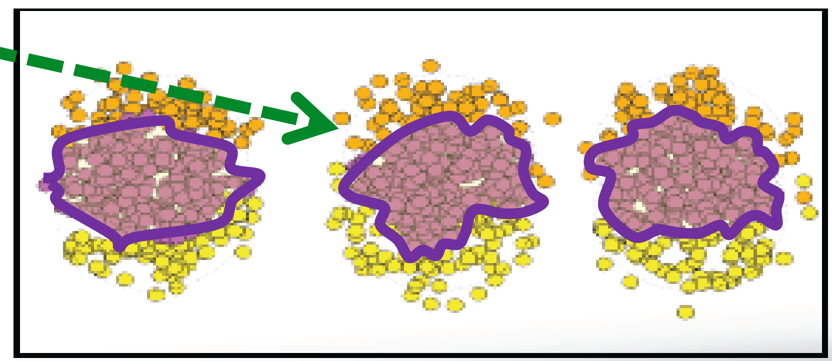
- **The matter produced in LHC collisions exhibits the same qualitative features discovered at RHIC:**

    - **Strong hydrodynamic flow**
    - **Strong fluctuations: high harmonics of flow**
    - **Strong quenching of high momentum particles**





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



See P.Sorensen talk

Theoretical Break-Through 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!)

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

Degree of imperfection

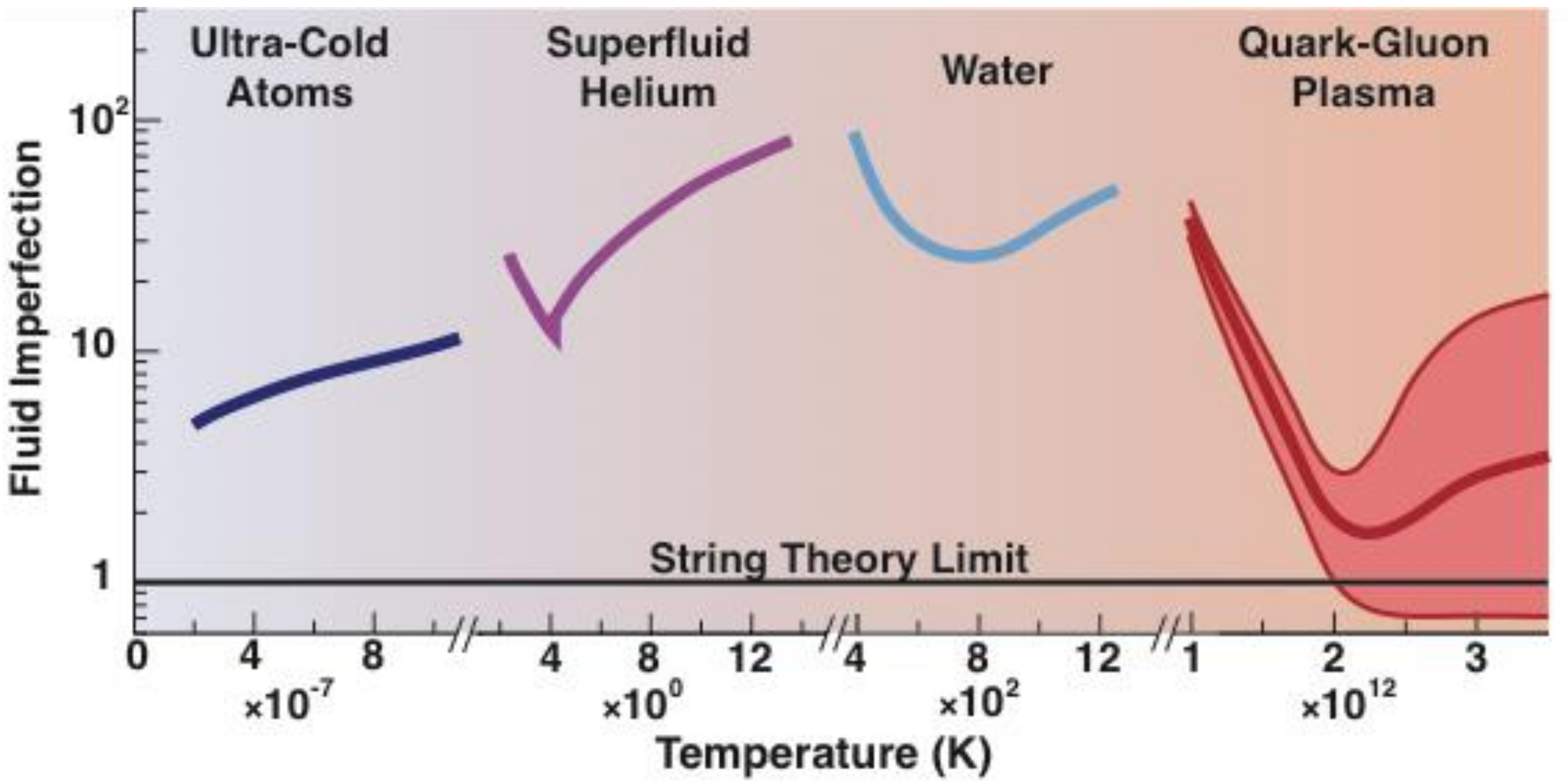
$\Rightarrow$ *Fundamental* measure of strong coupling

$\Rightarrow$ Cleanest result from gauge/gravity duality

$\Rightarrow$ **A measure of "quantum liquidity"**

Viscosity near Phase Transitions

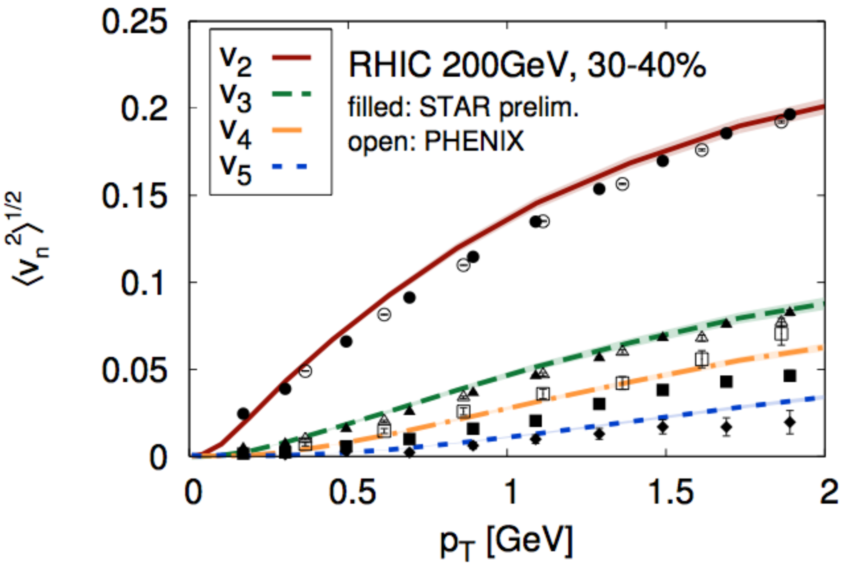
η/s

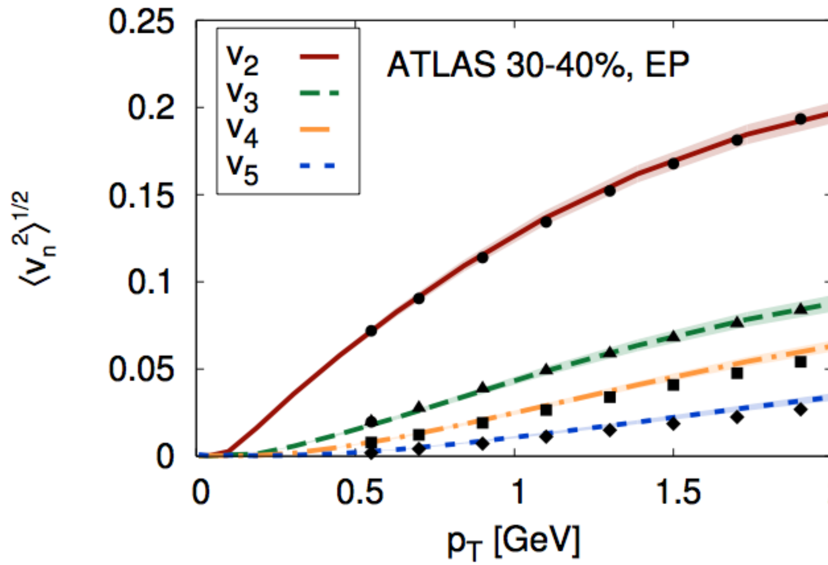


Many systems have minimum shear viscosity to entropy density near phase transformation

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

Difference in viscosity – next is the hard sector





$\eta/s \approx 0.12$ 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

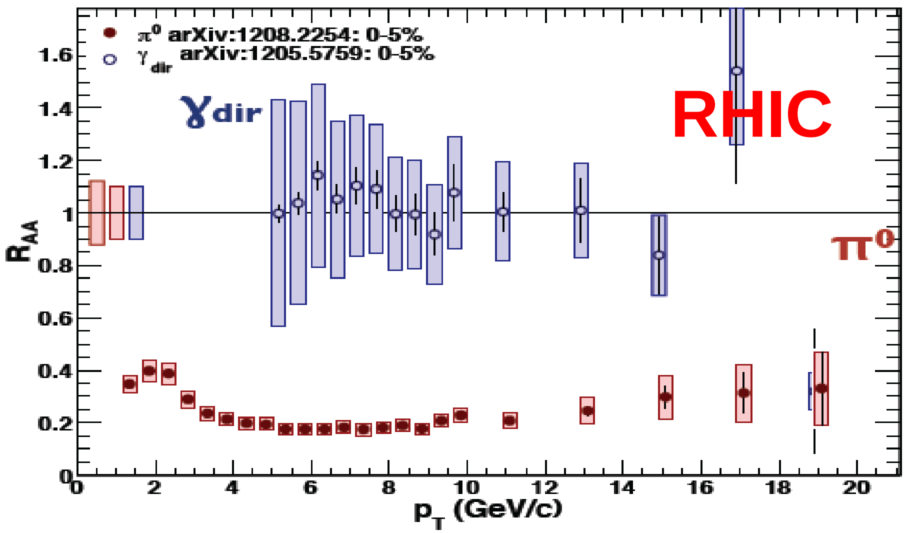
The *fundamental* matter formed at RHIC and the LHC is within a factor of 3 of KSS bound(!)

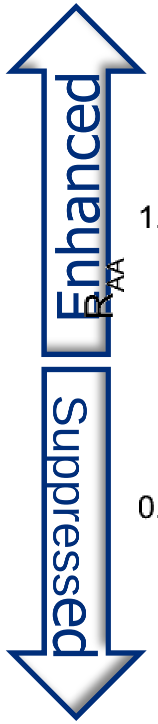
C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)

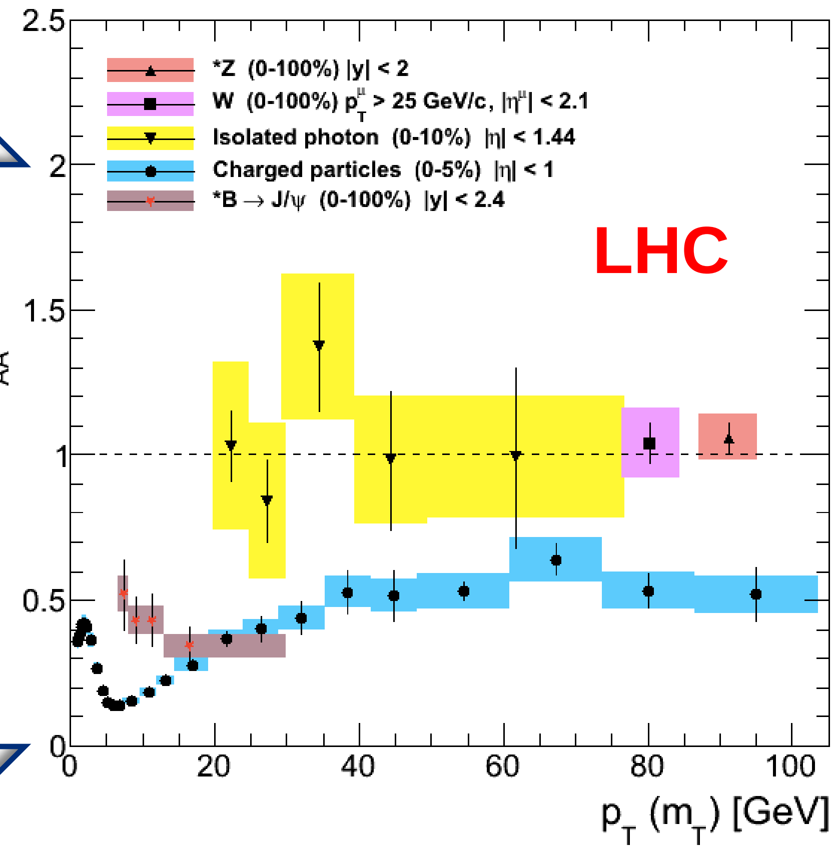
Hard Sector

- **0-th order observable for high pT diagnostics:**

$$R_{AA}(p_T) \equiv \frac{\text{Measured Yield in } A+A}{\text{Expected Yield from Scaled } p+p}$$







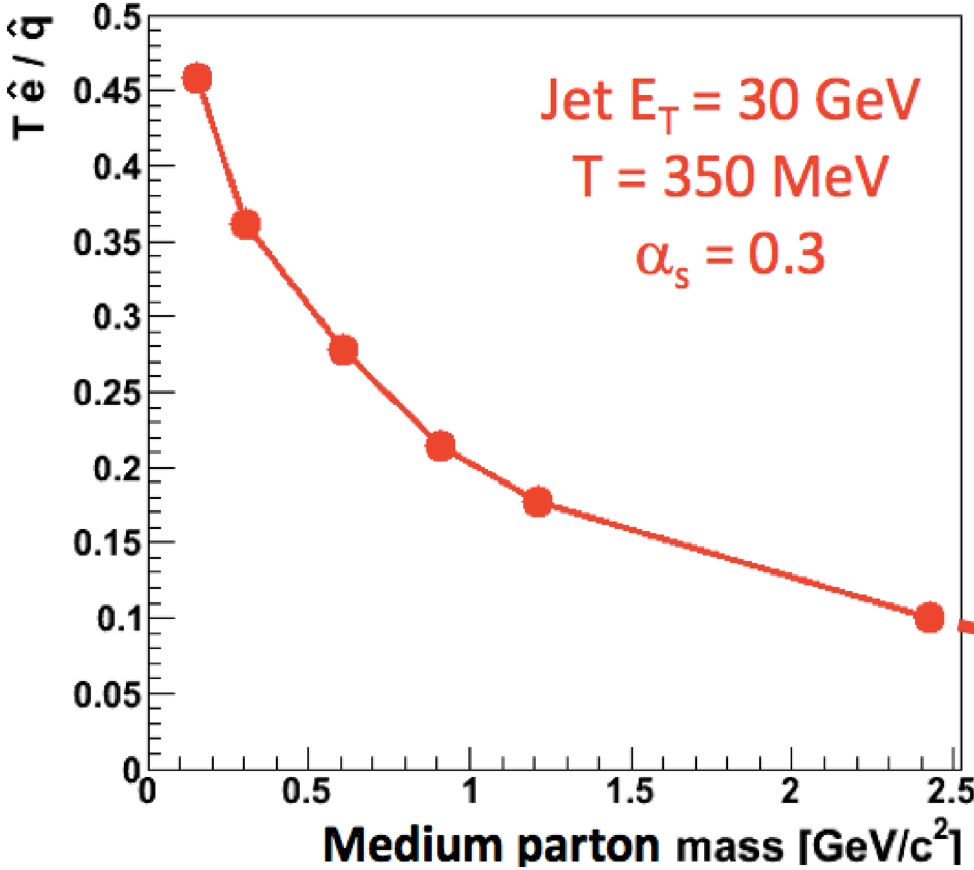
- Higher orders:
  - **Differential studies** versus: **impact parameter, reaction plane, away-side partner;**
  - **flavor tagging, tagged photons,** complete jet reconstruction…

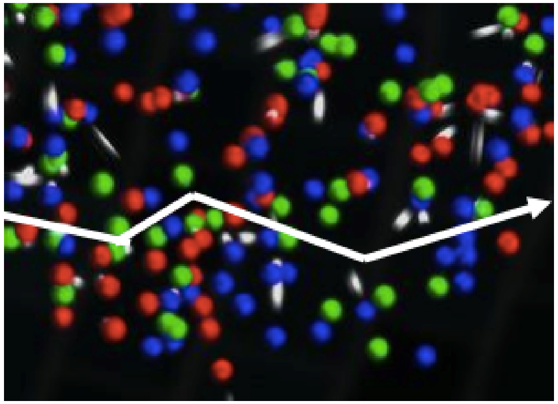
W.Zajc,

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.

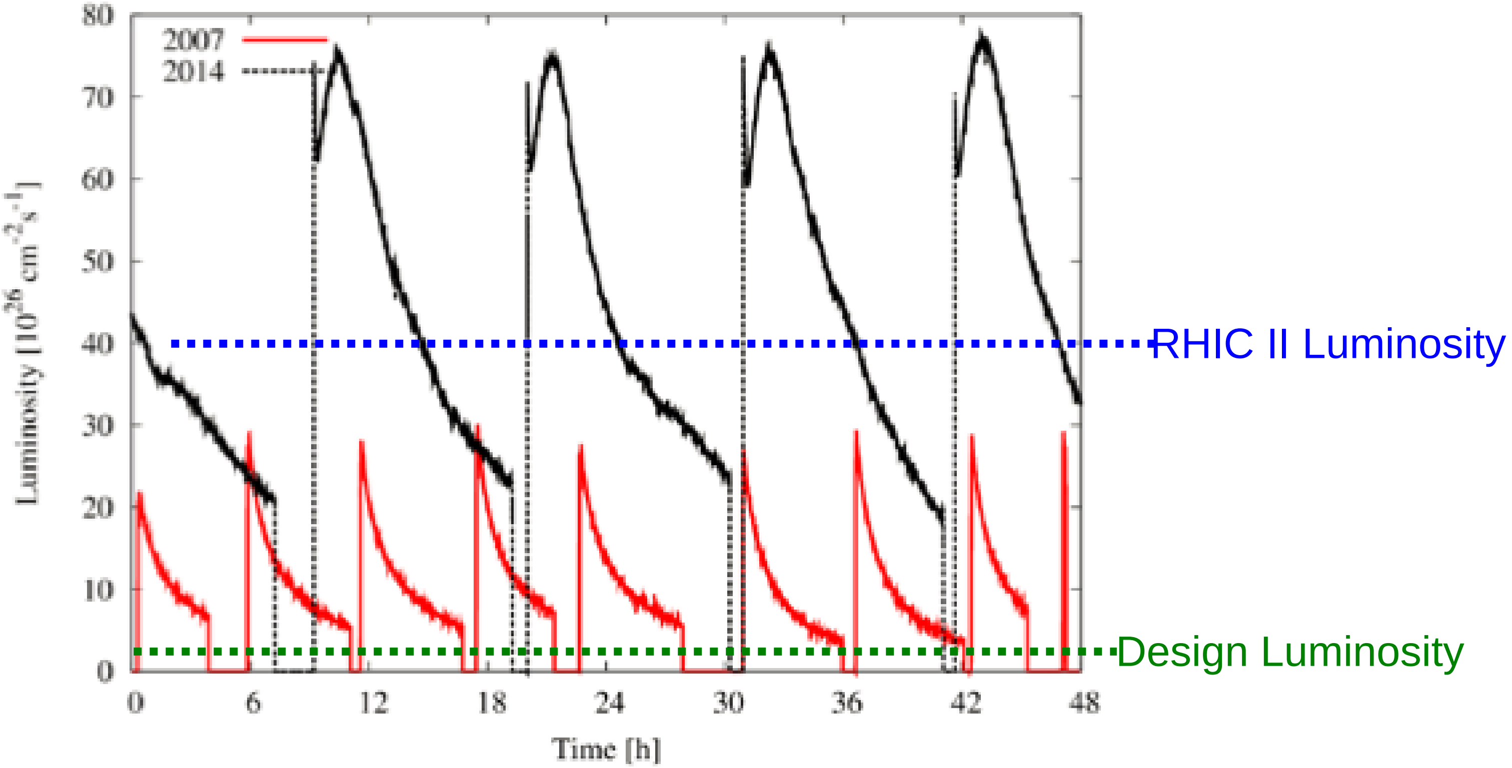
2007 Long Range Plan Recommendations

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.

By this time RHIC II Upgrade is DONE

DONE!



DONE! ≠ Finished!

Sharpening the program and upgrading tools

Where we are and Why "Done!" ≠ "Finished!"

- To date:

  Data from RHIC and LHC

  together with theoretical modeling…

  Tell us what the QGP does.

Discovered:
- ◆ hydrodynamic flow in small systems
- ◆ the critical role of fluctuations

- 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…

- ◆ Opened a new energy frontier – the LHC
- ◆ Begun exploration of QCD phase diagram - RHIC
- ◆ Developed sophisticated multi-scale models

√s Varies a True Control Parameter: μ_B

- Beam Energy Scan at RHIC
  - Only at RHIC !
    - ☞ **Note:** COLLIDER ...

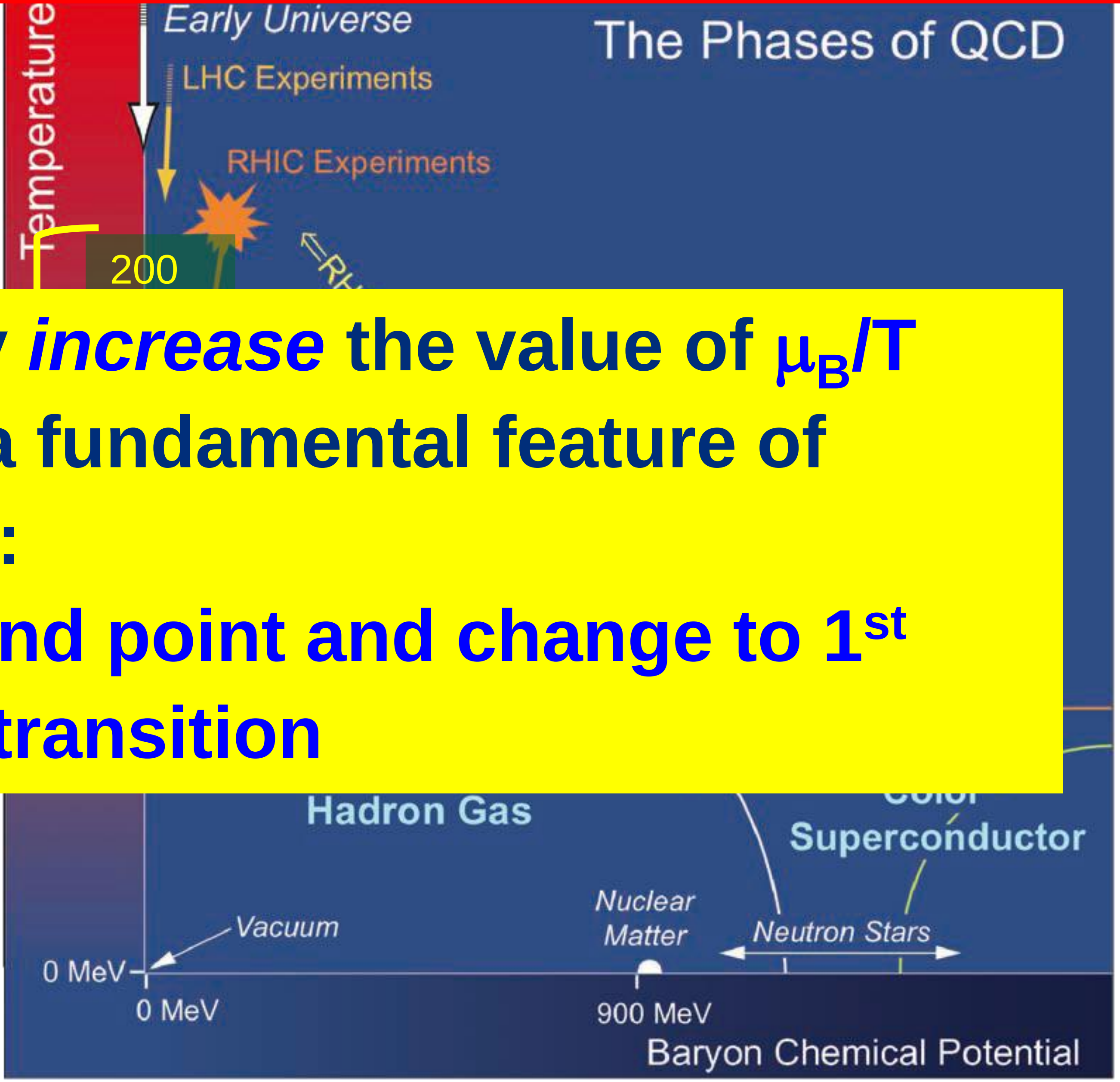
Deliberately *increase* the value of μ_B/T

Search for a fundamental feature of thermal QCD:

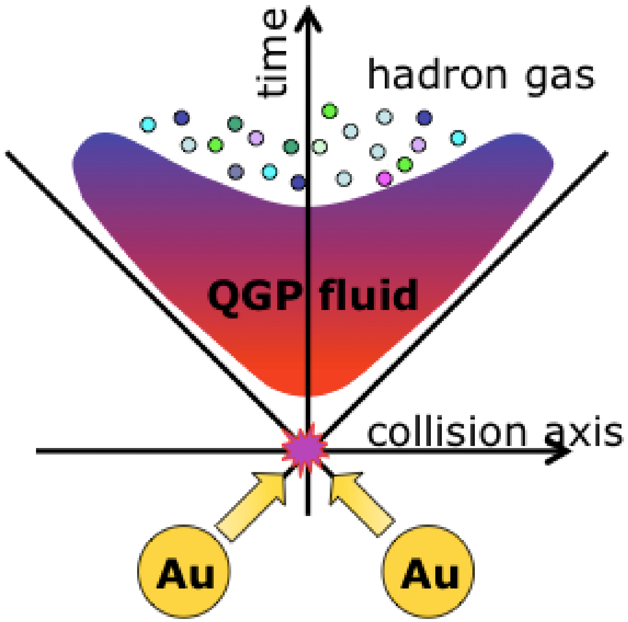
The critical end point and change to 1st order phase transition

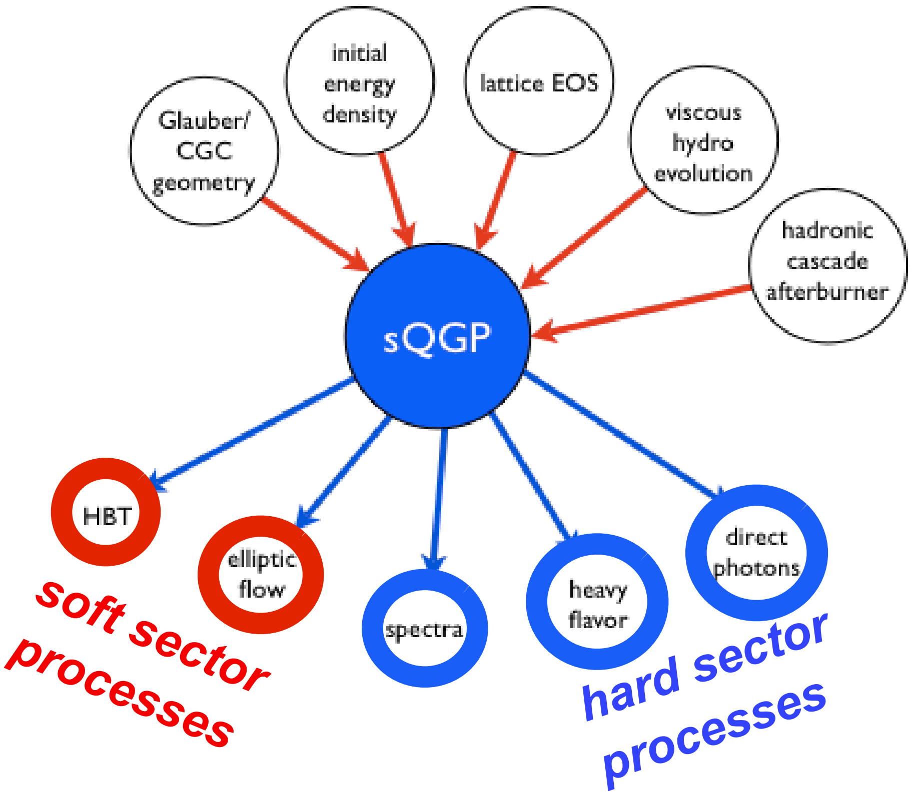
schematic

Exploring the QCD phase diagram"in search of the critical point



Strongly Coupled (s)QGP Paradigm





small-viscosity hydrodynamic evolution of QGP implies a strong-coupling and is at the heart of a "*standard model*" for heavy ion collisions

To become comprehensive this "standard model" needs examination from the hard sector:

parton energy loss and *quarkonia suppression*

Hard Sector – case for new experiment

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

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

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

(1) **Physics case** for a **jet detector at RHIC** (**sPHENIX**) and the key measurement observables

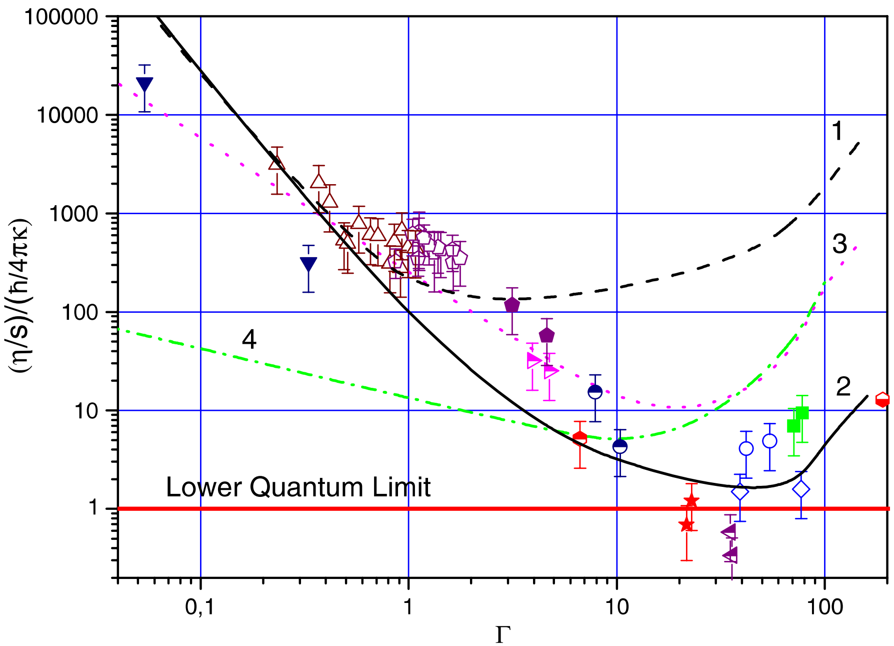
(2) What should be **detector configuration** to fit jet observables

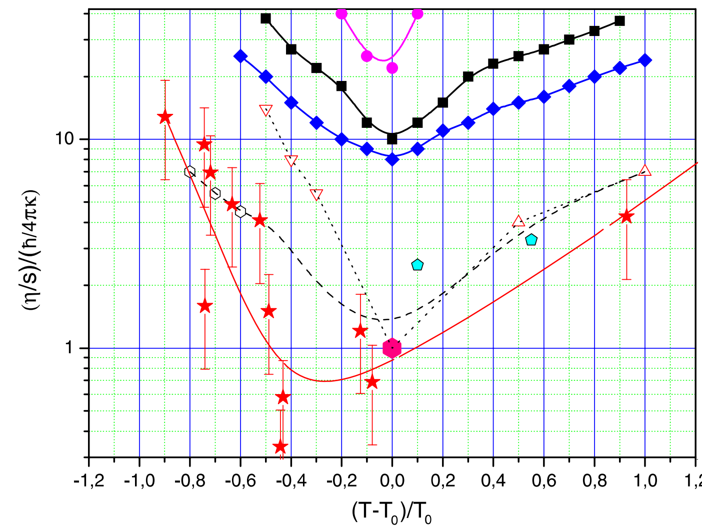
Can a detector be built on time to make these measurements?

Transition of the physical system to the perfect frictionless fluid with increasing the interparticle interaction

smaller viscosity ⇨ larger coupling ⇨ larger interaction with jets

V. E. Fortov[1] and V. B. Mintsev[2] PRL **111,** 125004 (2013) **Quantum Bound of the Shear Viscosity of a Strongly Coupled Plasma**





η/s vs coupling parameter.
1,2 – calculations for different screening mass, 3 – one component plasma.

Comparison between different fluids.. Data : filled circle-H2O, filled square-N2, filled rhombus-He, filled hexagon-relativistic heavy ion collider, open bottom faced triangle-meson gas, open top faced triangle- quark gluon plasma, open hexagon-intermediate-energy colli- sions; filled pentagon-quark gluon plasma; filled star-strongly coupled plasma, present work.

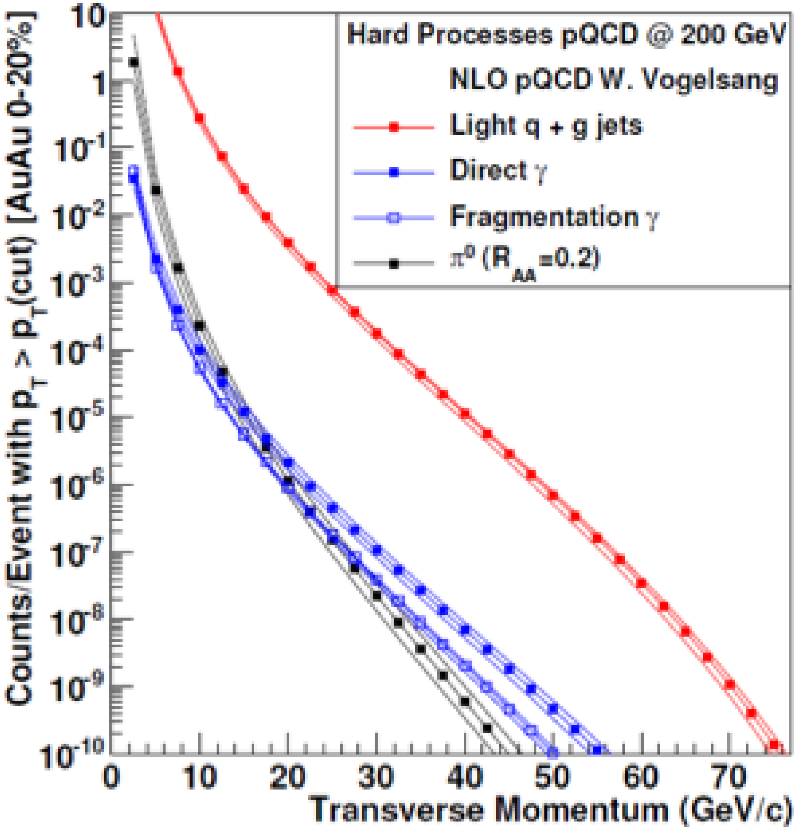
$$\Gamma = \frac{E_I}{E_K} = \frac{Z^2 e^2}{4\pi\varepsilon_0 d k_B T},$$

where E_i is the mean Coulomb interaction energy, $E_K = k_B T$ is the mean thermal energy, Z is the charge of plasma particles, $d^3 = (3/4\pi n)$ is the distance between the particles with the density n, and T is the plasma temperature.

$$\eta \approx k_\gamma \frac{1}{Z^3} \frac{\sqrt{m_e M}}{e^2} k T_i \sigma_{\mathrm{sp}},$$

where k ~ 0:69 at Z= 1 for the Boltzmann statistics and K ~ 0:4 for the Fermi-Dirac statistics.

Rates: jets, di-jets, γ-jets



Events: 50 billion collected, 200 billion sampled

$-1 < \eta < 1$	Au+Au (central 20%)	p+p	d+Au
>20GeV	10^7 jets 10^4 photons	10^6 jets 10^3 photons	10^7 jets 10^4 photons
>30GeV	10^6 jets 10^3 photons	10^5 jets 10^2 photons	10^6 jets 10^3 photons
>40GeV	10^5 jets	10^4 jets	10^5 jets
>50GeV	10^4 jets	10^3 jets	10^4 jets

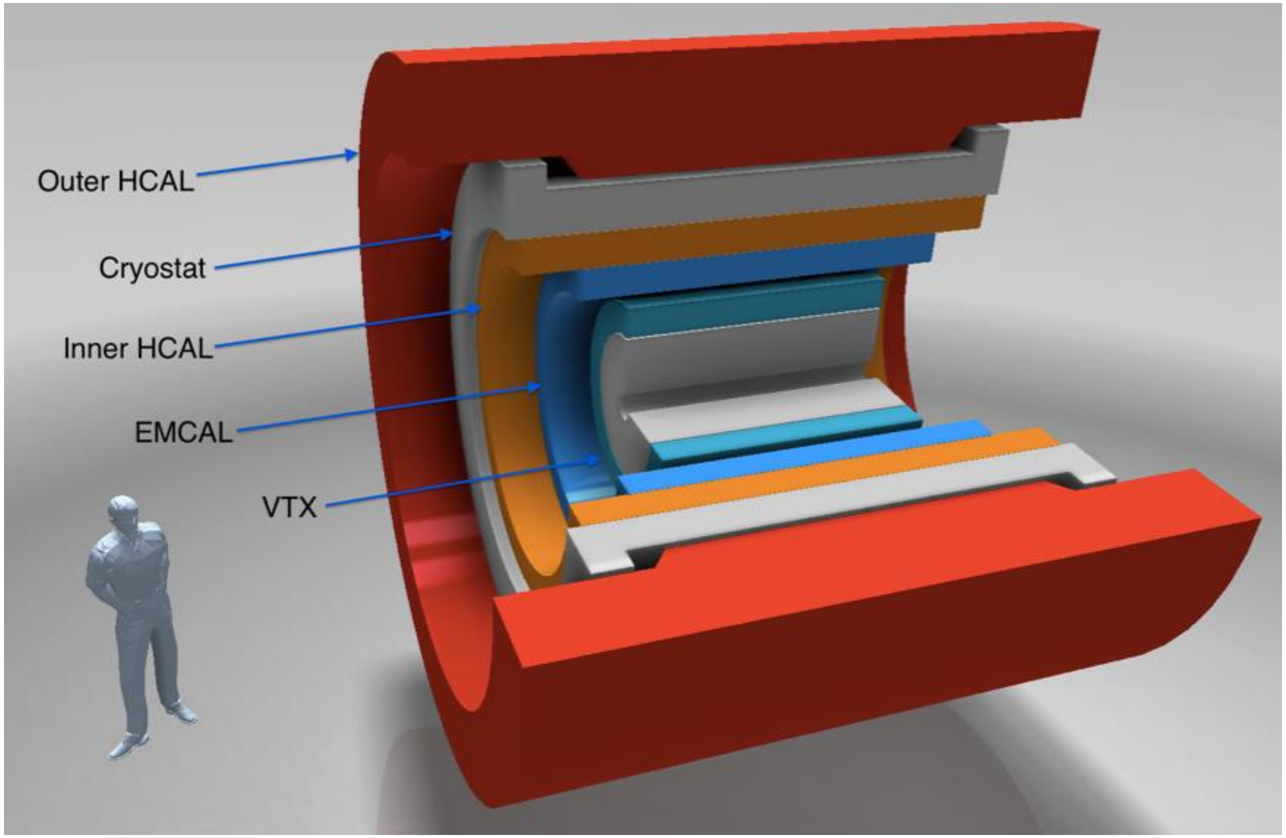
Rates based on full stochastic cooling, but no additional accelerator upgrades

Huge rates allow differential measurements with geometry (v_2, v_3, A+B, U+U, …) & precise control measurements (p(d)+Au & p+p).
~80% as dijets!

PHENIX - > sPHENIX to the challenge

- Single jets, direct photons: R_{AA}, v_N
- Intra-jet hadron correlations (longitudinal and radial modifications)
- Jet-jet, photon-jet correlation: I_{AA}, $\mathbf{A_J}$
- Jet-hadron correlations (global response)
- Heavy flavor jets
- Separated Upsilon States
- **Compatibility with future EIC detector**

sPHENIX detector



BaBar Magnet 1.5 T

Coverage $|\eta| < 1.1$

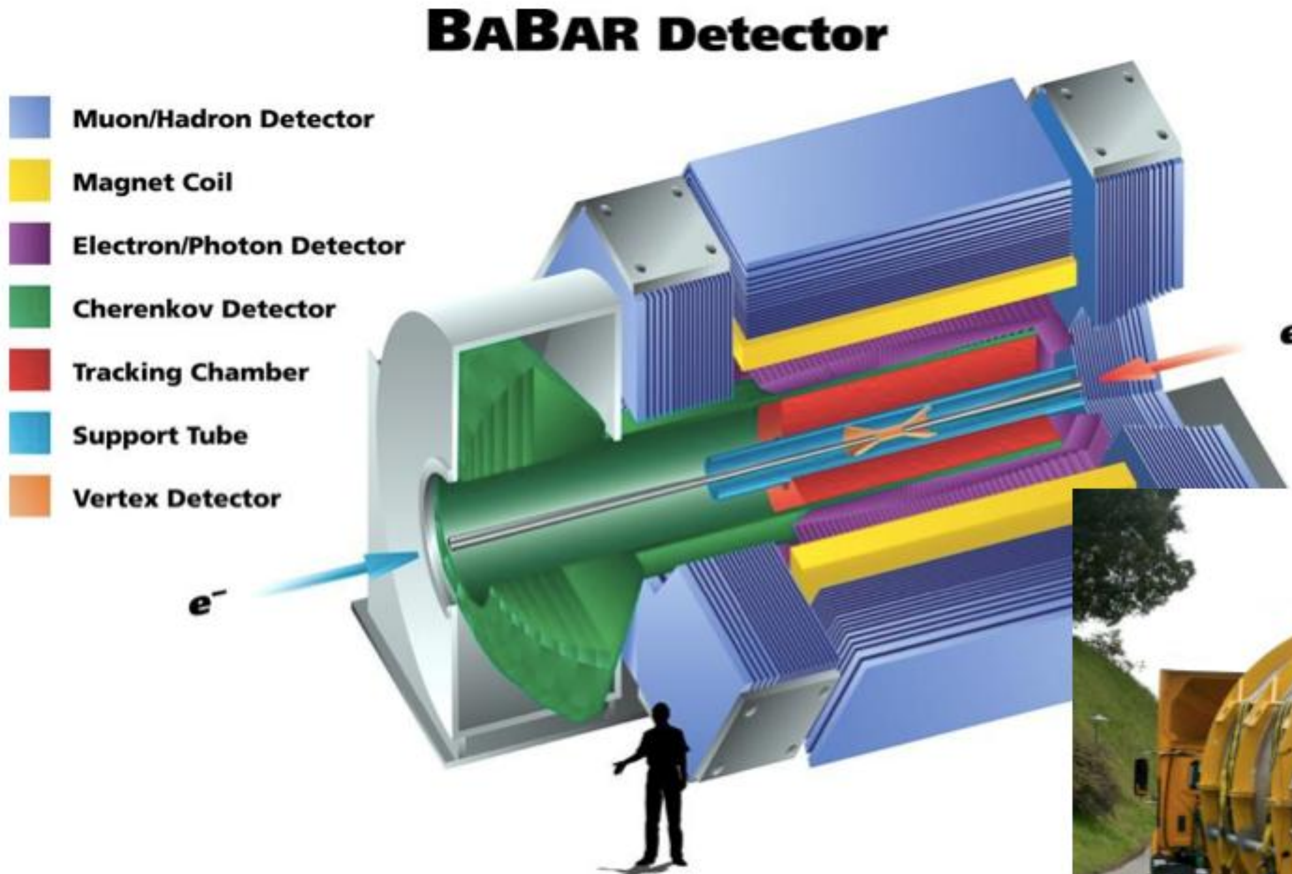
All silicon tracking
Heavy flavor tagging

SPACAL EmCal
12%/sqrt(E) resolution

Two longitudinal segments of HCal
5 interaction lengths

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

Acquisition of the BaBar Magnet



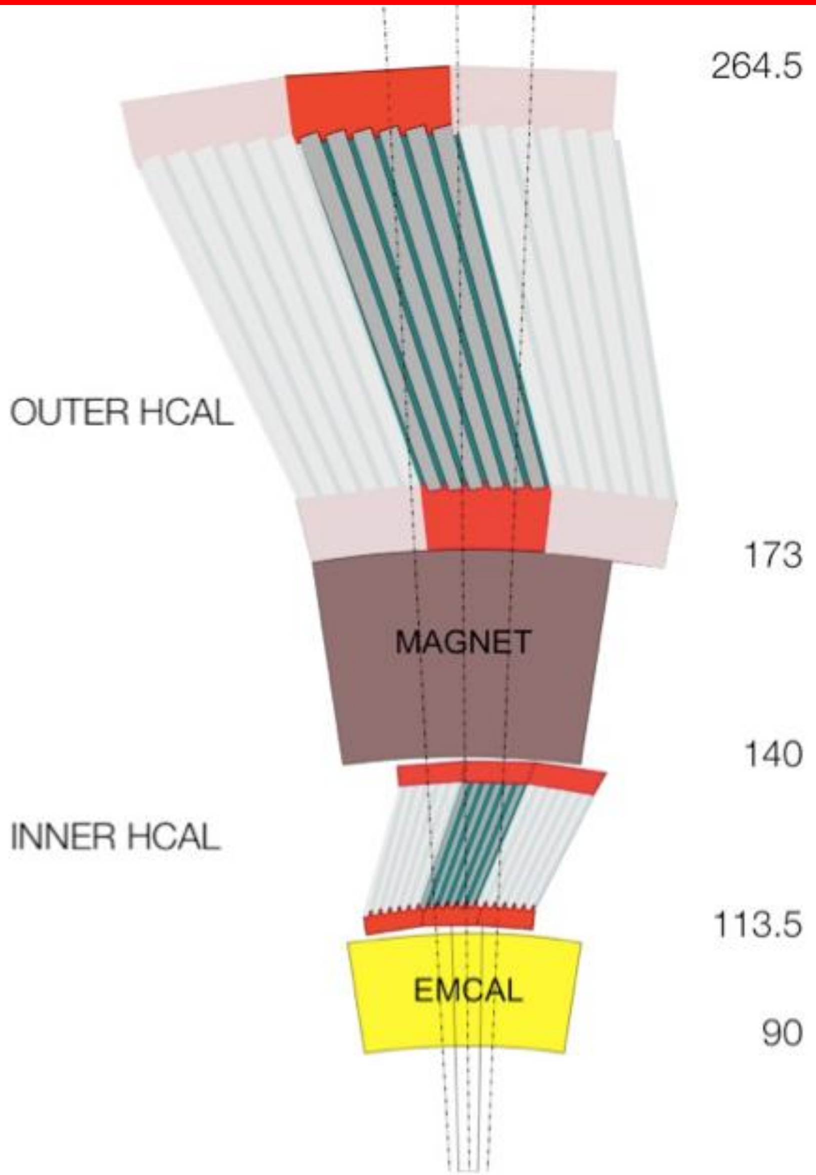
ITEM NO. (b)	DESCRIPTION (Include noun name, FSC Group and Class, Condition Code and if available, National Stock Number) (c)	UNIT (d)	QUANTITY (e)	ACQUISITION COST UNIT (f)	ACQUISITION COST TOTAL (g)
	Administrative Transfer				
1	BaBar Solenoid and Components Date of Mfr: 1996 (See attached list)	ea	1	12,000,000.00	$ 12,000,000.00
			Total Acquisition Cost		$ 12,000,000.00

sPHENIX Calorimeters

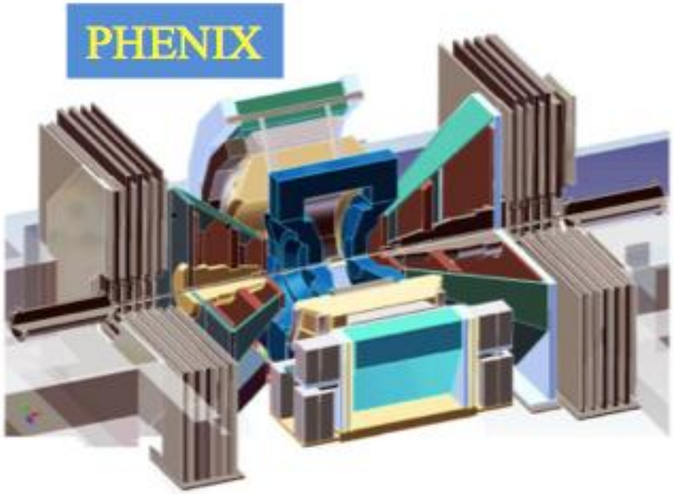
- EMCAL $\approx 18X_0 \approx 1\lambda_I$
- Inner HCAL $\approx 1\lambda_I$
- Magnet $\approx 1X_0$
- Outer HCAL $\approx 4\lambda_I$

HCal 5λ deep (plus EMCal 1λ deep) leads to few percent energy leakage for hadrons above 50 GeV; comparable to other contributions to energy resolution constant term.

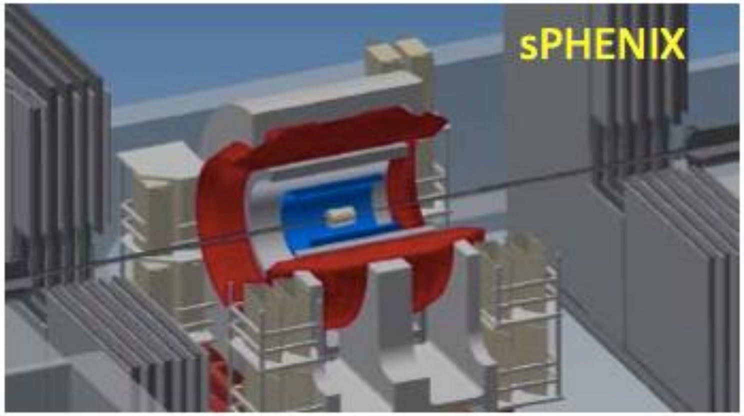
Key difference with calorimeters for much higher energy jets.



sPHENIX evolution



~2021-22



~2025

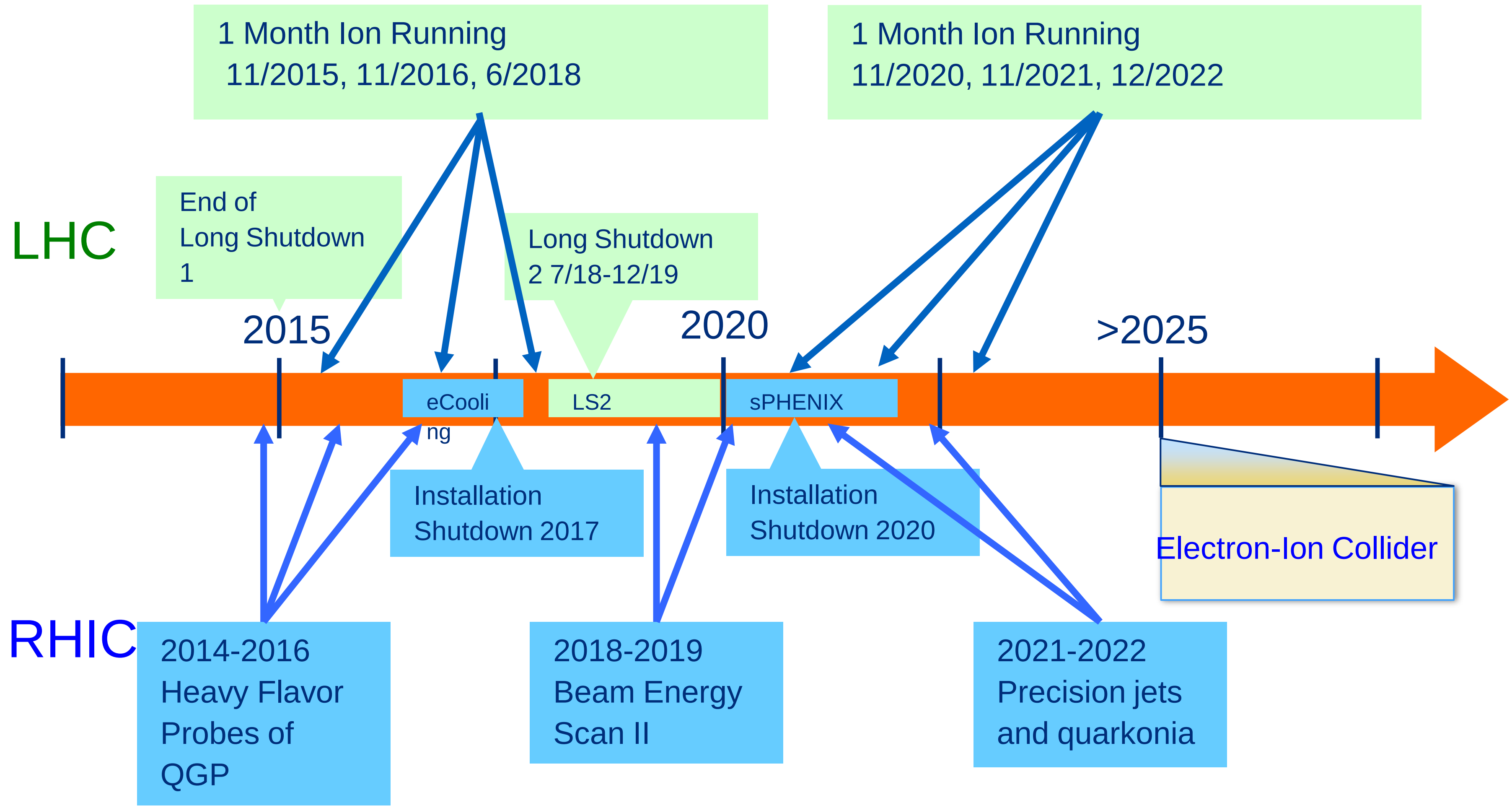
Evolve sPHENIX (pp and HI detector) to an EIC Detector (ep and eA detector):

- To utilize e and p (A) beams at eRHIC with *e*-energy up to 15 GeV and *p*(*A*)-energy up to 250 GeV (100 GeV/n)
- *e*, *p*, He^3 polarized
- Stage-1 luminosity ~10^{33} cm^{-2} s^{-1} (~$1fb^{-1}$ /month)

BNL 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

RHIC / LHC Timeline



Summary: 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**

Supported with sustained theoretical studies, modeling and phenomenology

B.Muller

The End