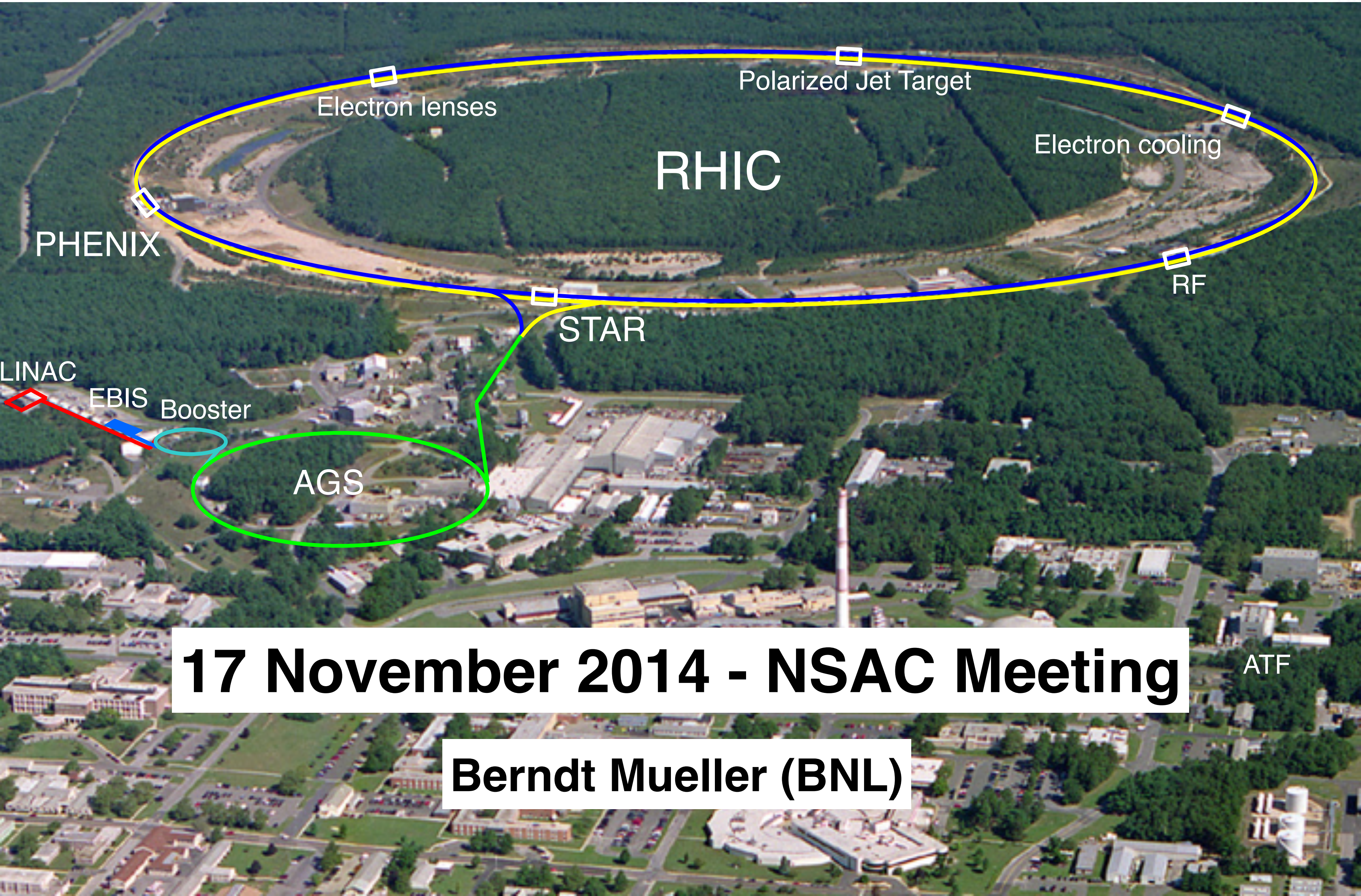
Completing the RHIC Science Mission



17 November 2014 - NSAC Meeting

Berndt Mueller (BNL)

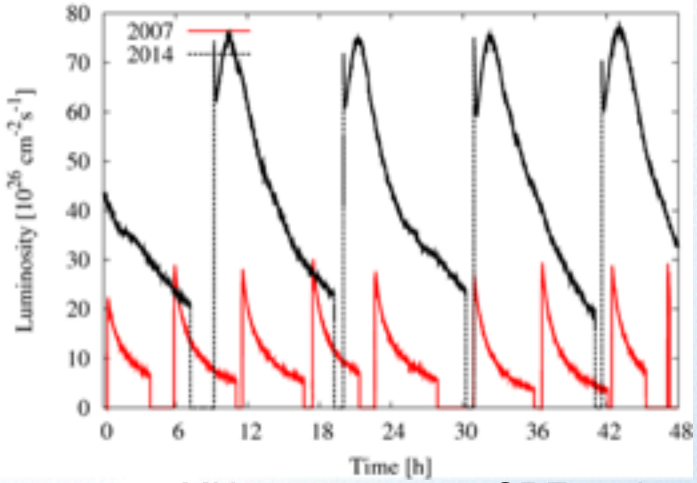
The Facility

RHIC – the First Heavy Ion Collider

- After continuous improvements and upgrades RHIC reached 25x design luminosity, exceeding "RHIC II" goal
- Unparalleled flexibility of operation:
  - Wide energy range ($\sqrt{s_{NN}}$ = 7 – 200 GeV)
  - Capability of colliding different species with detector in center-of-mass frame
  - 6 modes (Au+Au, d+Au, Cu+Cu, Cu+Au, U+U, ^{3}He+Au) and 15 energies to date
- Ongoing upgrades:
  - 56 MHz SRF cavity to compress vertex and increase usable luminosity (commissioned)
  - Low Energy RHIC electron Cooling: 3 – 10x Au-Au luminosity for $\sqrt{s_{NN}}$ < 20 GeV

BNL Electron Beam Ion Source

Au-Au luminosity with 3-D cooling



56 MHz quarter wave SRF cavity

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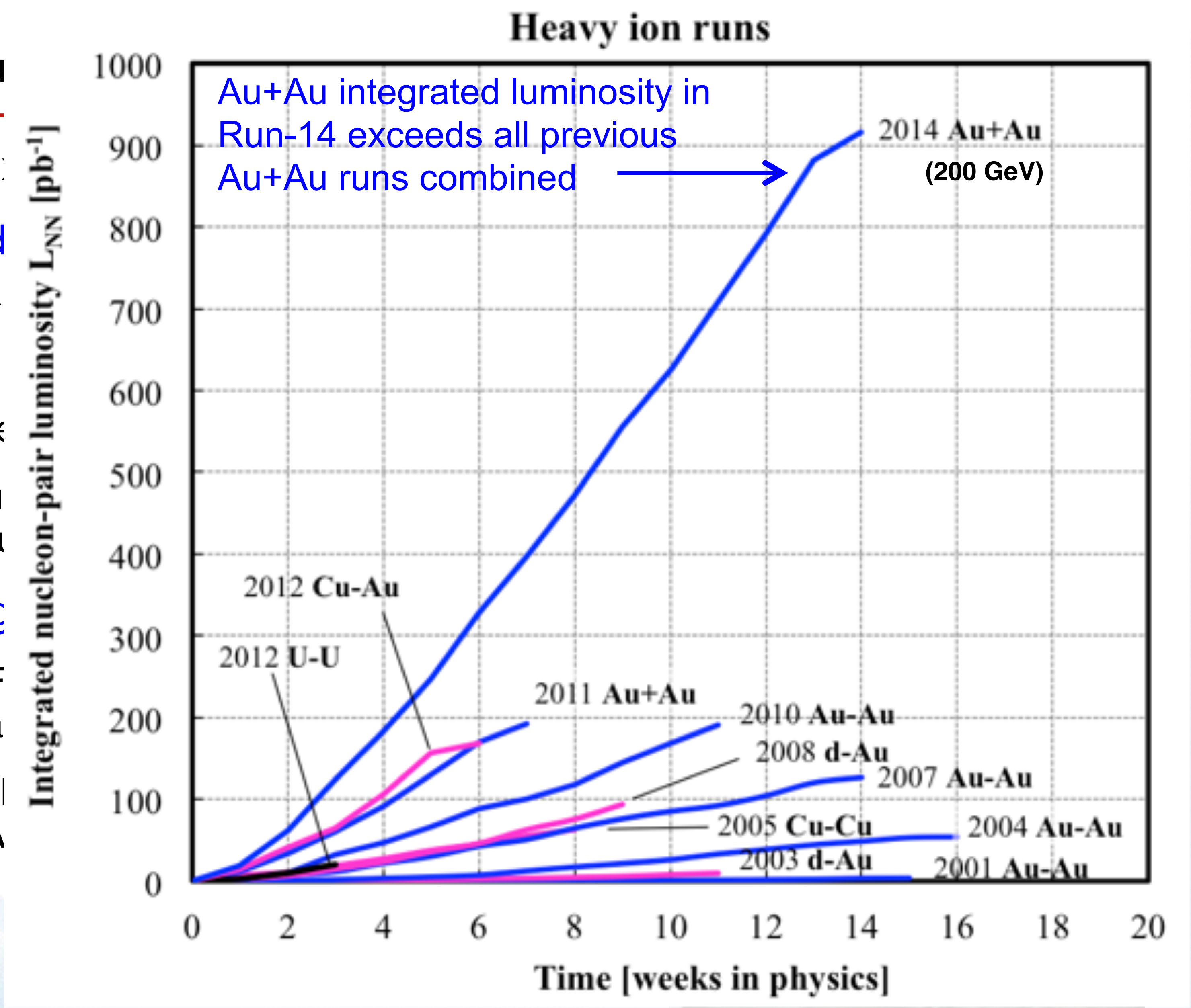


RHIC explores the Phases of Nuclear Matter

LHC: High energy collider at CERN with 13.8 - 27.5 times higher beam energy: Pb+Pb, p+Pb, p+p collisions only.

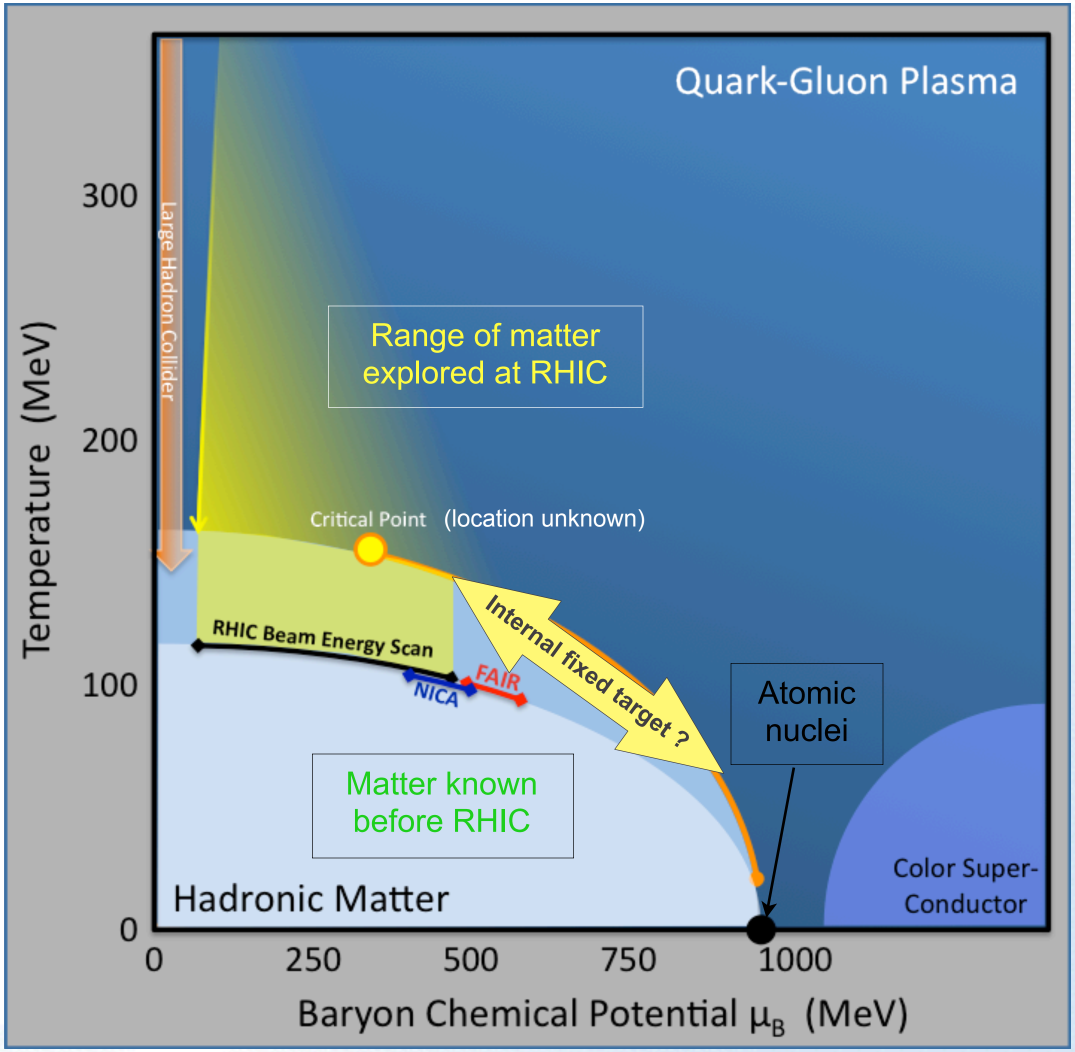
FAIR & NICA: Planned European facilities at lower energies.

RHIC: Spans largest swath of the phase diagram in the preferred collider mode.

Message

RHIC is perfectly suited to explore the phases of nuclear matter and the perfectly liquid quark-gluon plasma.

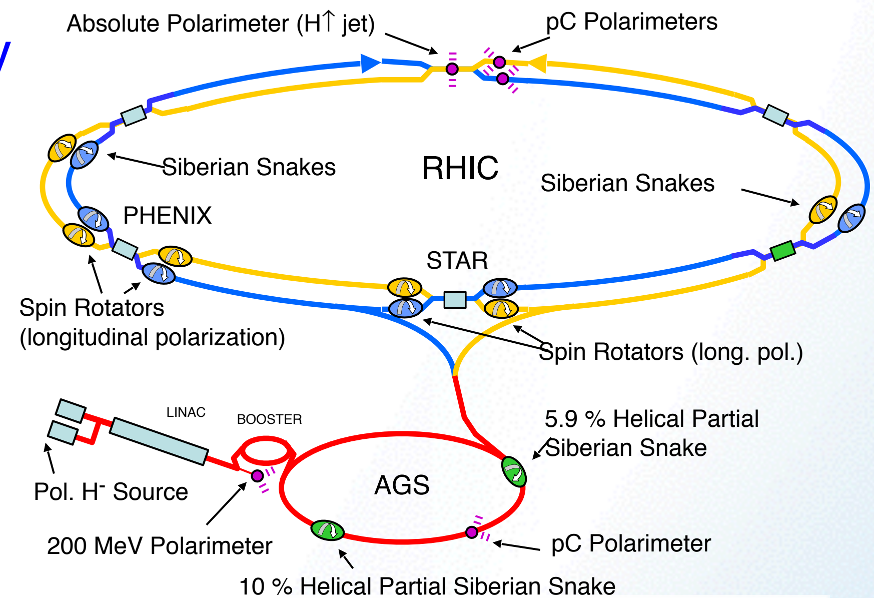
If RHIC did not exist, someone would have to build it (...but no one could afford it - a >$2B value!)



BROOKHAVEN NATIONAL LABORATORY

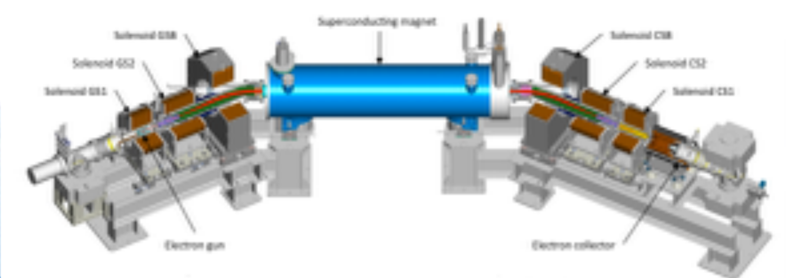
RHIC – the First Polarized Proton Collider

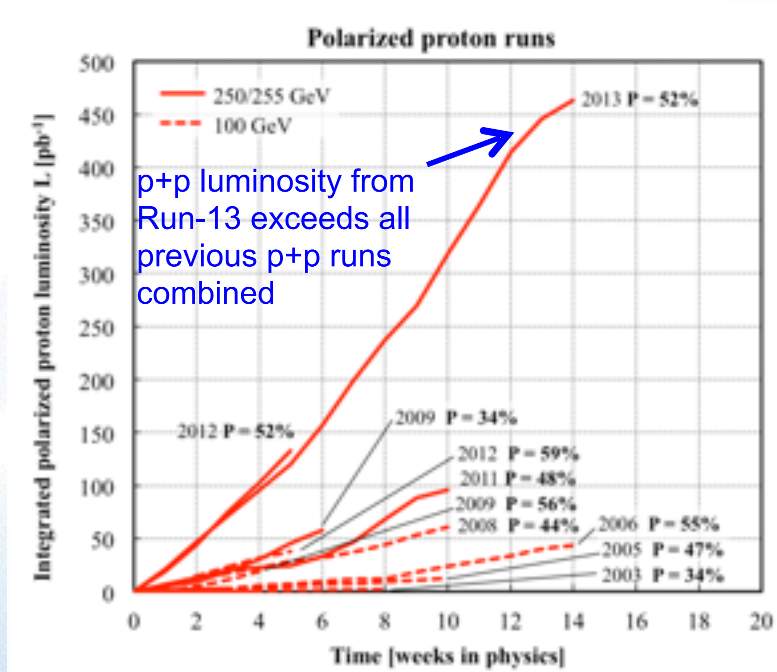
- Successful development of all necessary tools to accelerate polarized protons in the injector and in RHIC (polar. source, [partial] Siberian snakes, polarimeters)



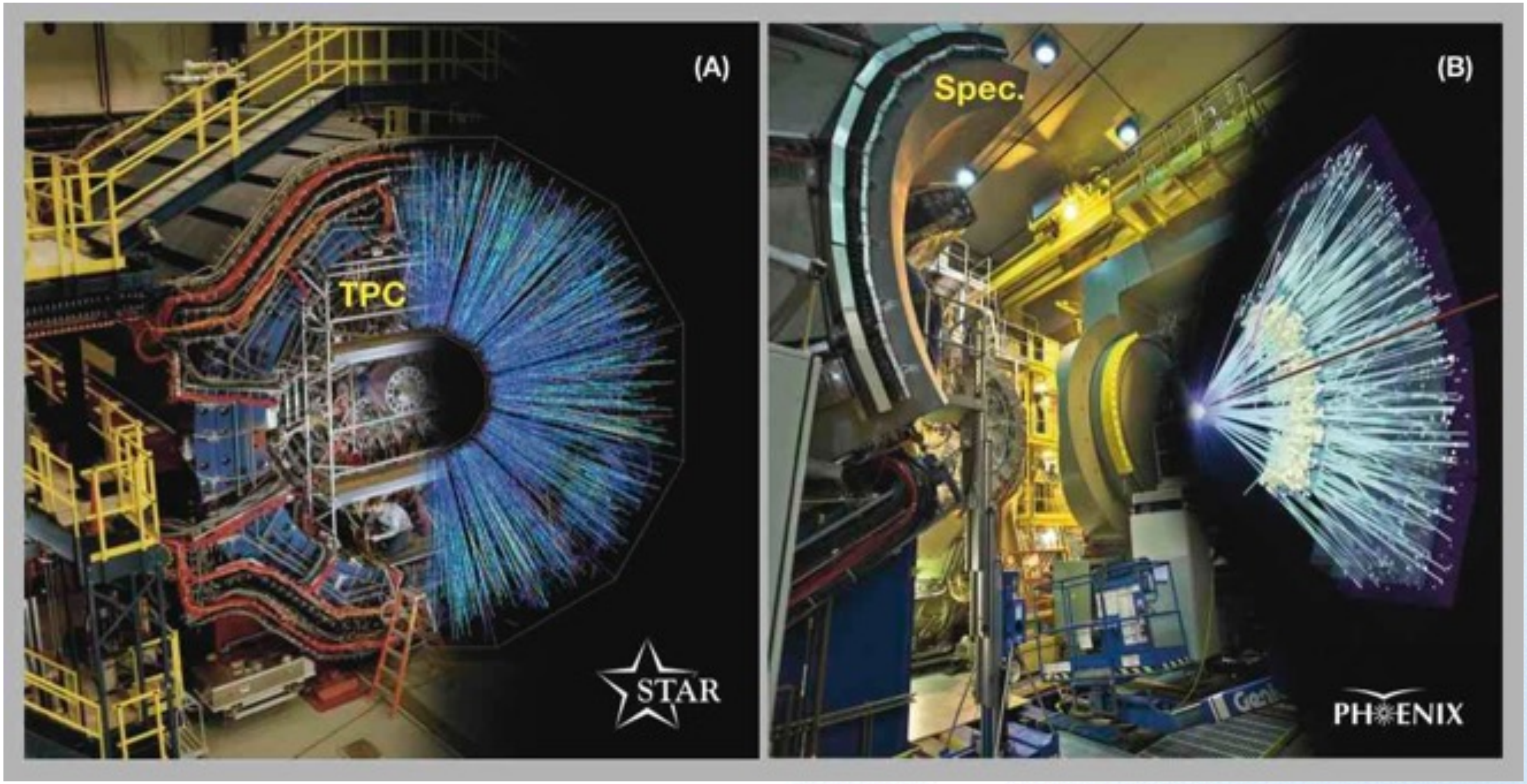
- Polarized proton collisions in RHIC:
  - $\sqrt{s}$=200 GeV: P~59%, L_{peak}~0.5×10^{32} $cm^{-2}s^{-1}$
  - $\sqrt{s}$=510 GeV: P~52%, L_{peak}~2.5×10^{32} $cm^{-2}s^{-1}$

- Ongoing upgrade: Luminosity increase with electron lenses to compensate for beam-beam interactions (commissioned)





RHIC Detectors



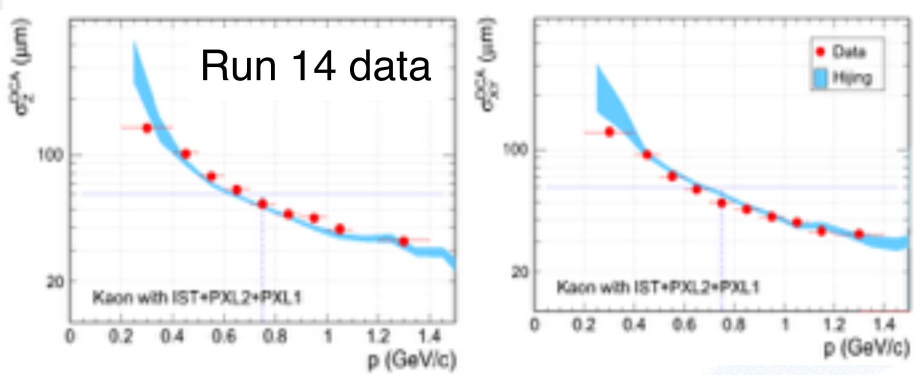
~580 collaborators from 13 countries

~550 collaborators from 15 countries

Recent RHIC Detector Upgrades

Fully reconstruct open charm/beauty hadrons with displaced vertex

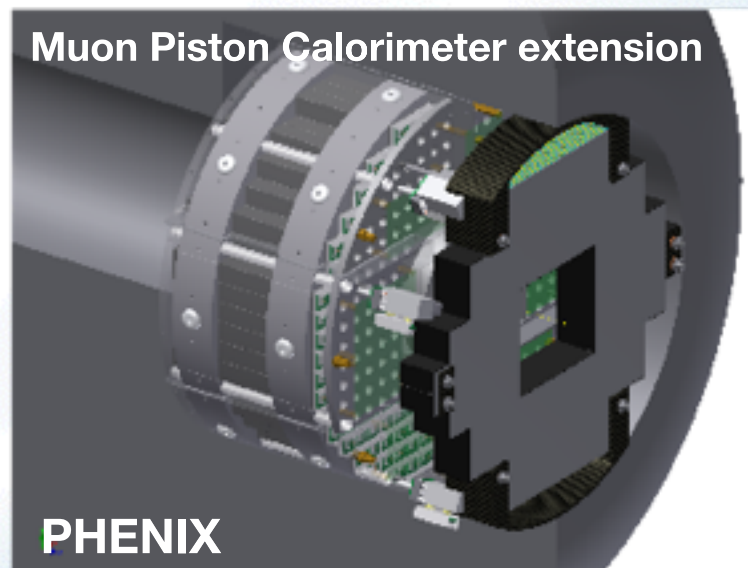
Completed on schedule and below cost



Distance of Closest Approach to Vertex

Enhances triggering capabilities for heavy quarkonia

Enables forward γ detection in Run15



The Science

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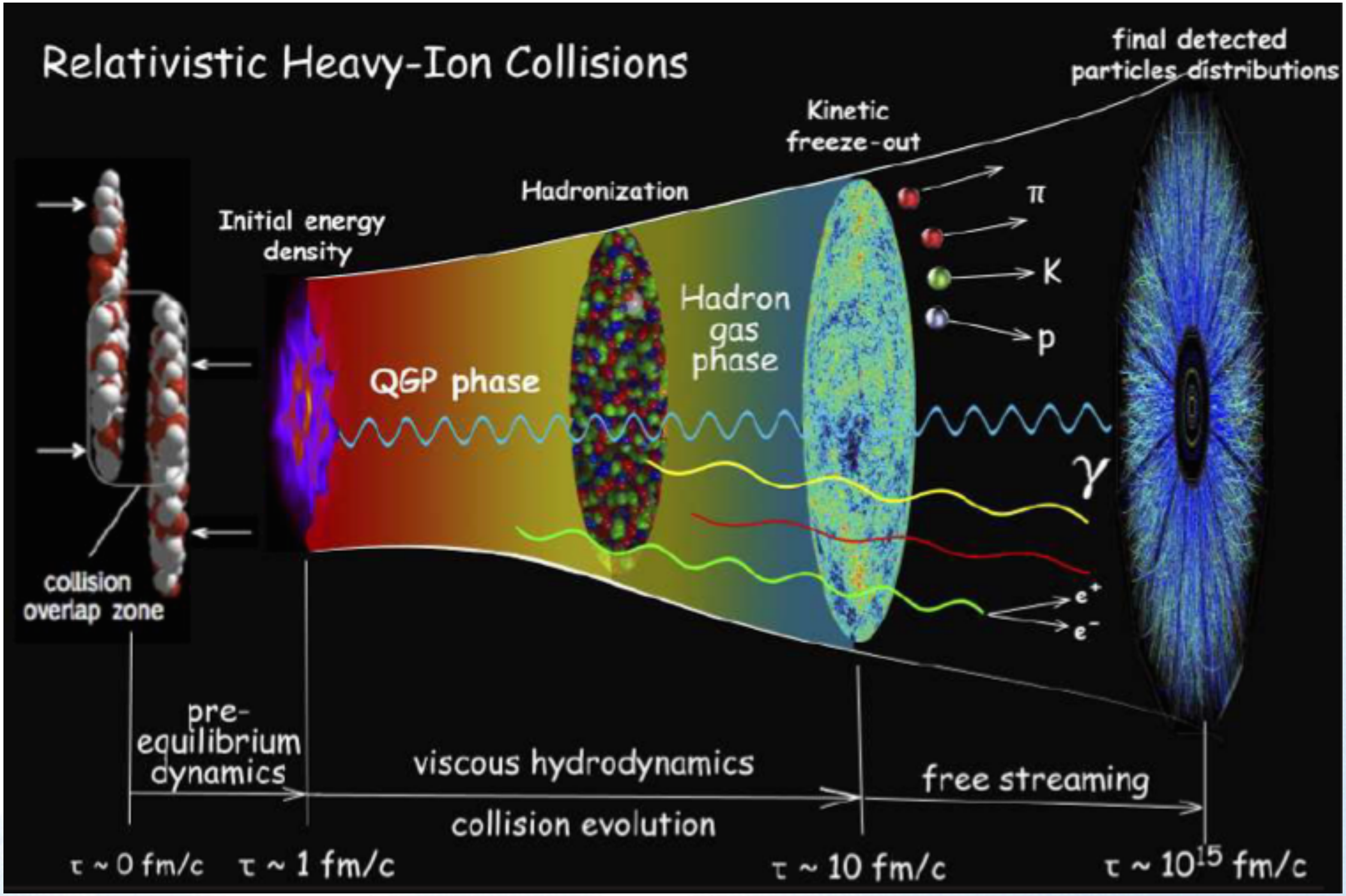
- **Gluon spin** contributes a sizable fraction to the **proton spin**.

Standard model of the "Little Bang"



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- Can we find evidence for chiral symmetry restoration?

Hot QCD matter properties

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Shear viscosity: **Momentum transport**

Very Hard for LQCD

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0) \rangle$$

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Momentum/energy diffusion: **Gluon structure of the QGP**

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QGP Radiance: **Quark currents in the QGP**

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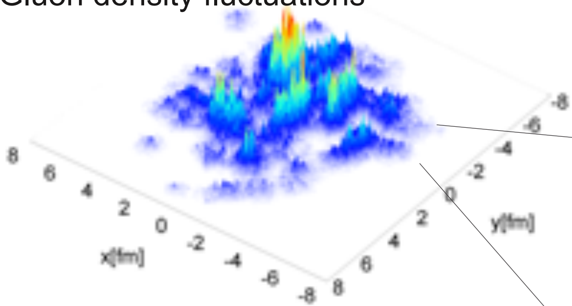
$$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln \left\langle U^\dagger E^a(x) U E^a(0) \right\rangle$$

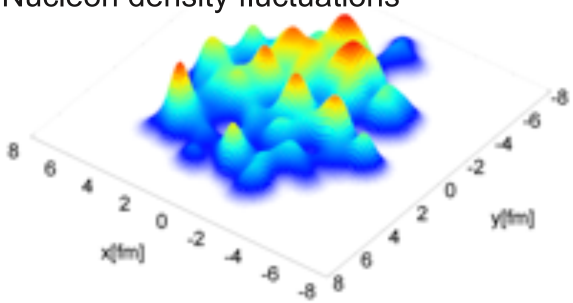
Screening mass: **Color screening**

Beyond discovery: η/s

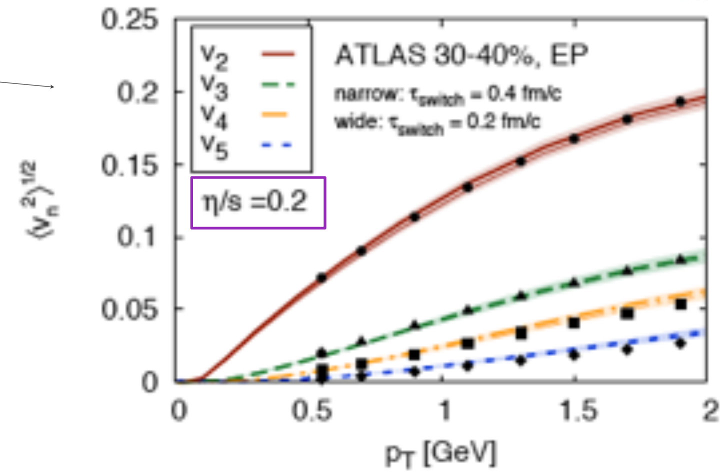
Gluon density fluctuations



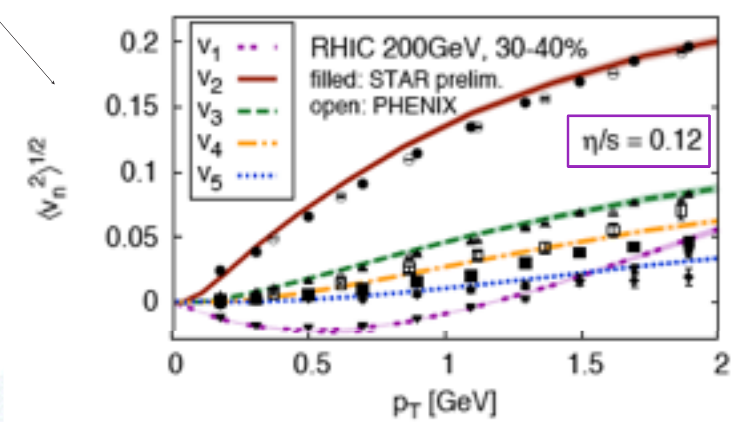
Nucleon density fluctuations



Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330



LHC

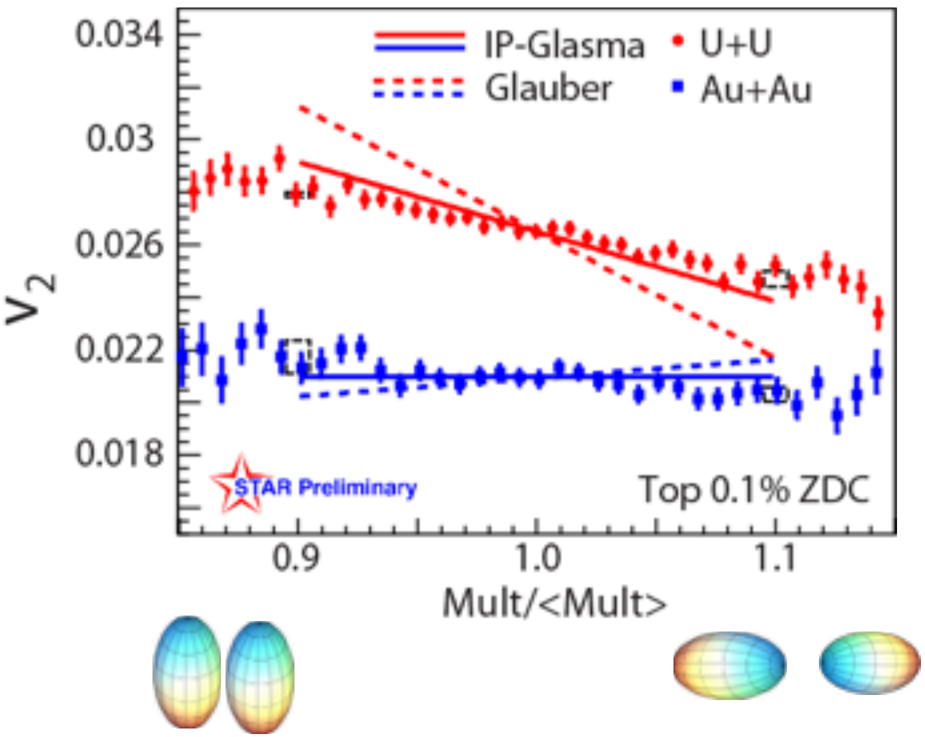


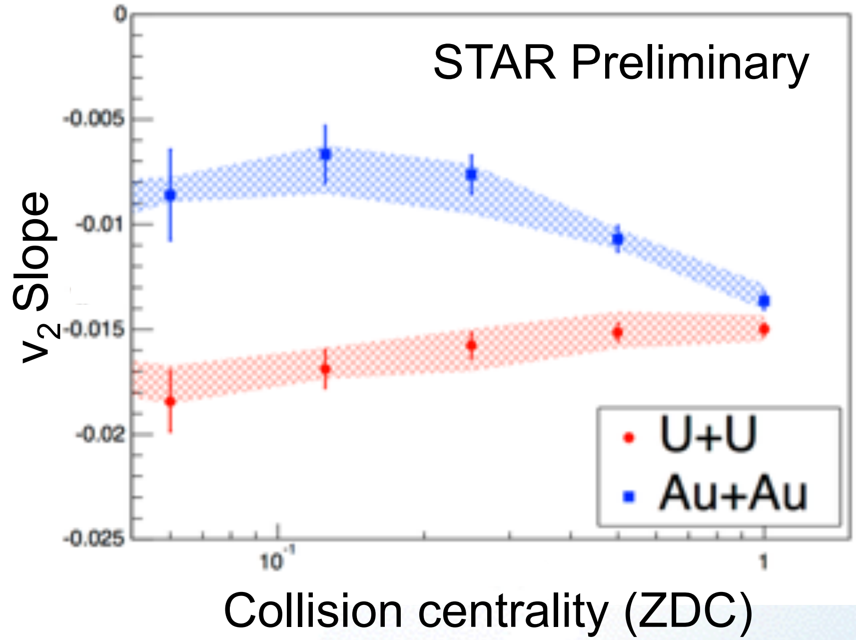
RHIC

η/s determination from data depends on assumption of the the scale of graininess of the density of the colliding nuclei.

Is it the nucleon size (~1 fm) or the gluon saturation scale ($Q_s \sim$ 0.1 fm)? Or some other scale?

Shape Matters: U+U Collisions



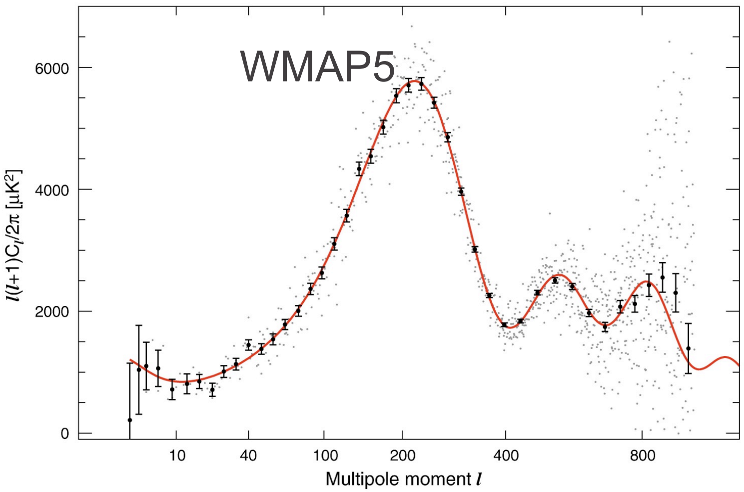


- U+U collisions use geometry to “engineer” 20% increase in energy density in very central collisions by selecting **tip-tip orientation** enhanced samples
- IP-Glasma model, assuming saturated gluon densities in the colliding nuclei, is consistent with the observation

Bjoern Schenke, et al. arXiv:1403.2232 *Maciej Rybczyński, et. al. PRC87,044908(13)*

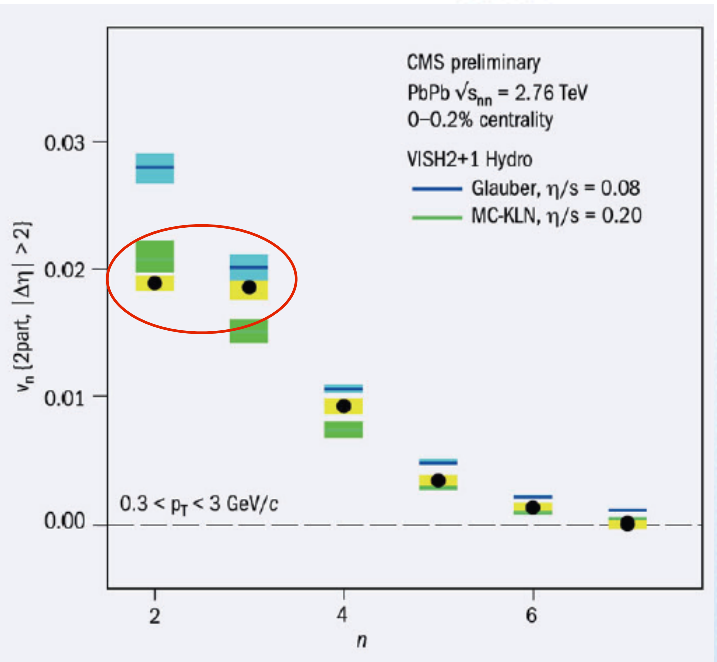
Fluctuation spectrum

Can the power spectrum of v_n be used to determine scale of parton density fluctuations in colliding nuclei as function of x ?



The RHIC/LHC advantage:
There are many knobs to turn, not just a single universe to observe.

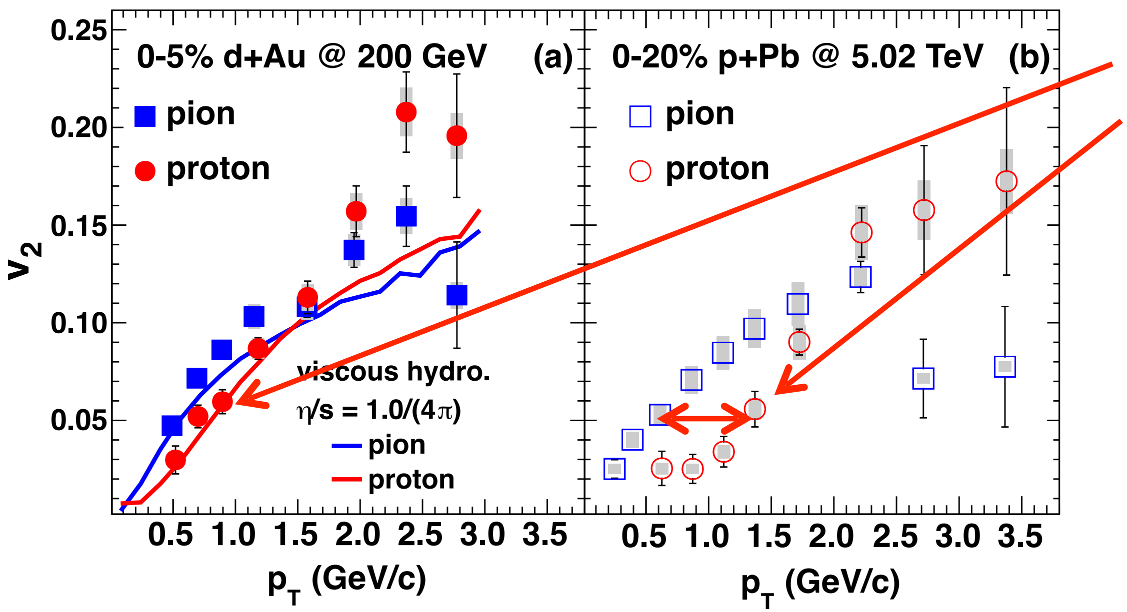
Power spectrum in ultracentral Pb+Pb collisions
Data: CMS. Theory: U. Heinz, arXiv:1304.3634



Data (v_3/v_2) indicate more fluctuations relative to global geometric effects than predicted by nucleon-scale granularity of initial state.

How small can a QGP droplet be?

PHENIX arXiv:1404.7461 **ALICE** Phys. Lett. B726, 164 (2013)



Mass ordering of $v_2(p_T)$ for identified charged particles is observed in both d+Au and p+Pb – consistent with hydrodynamic flow

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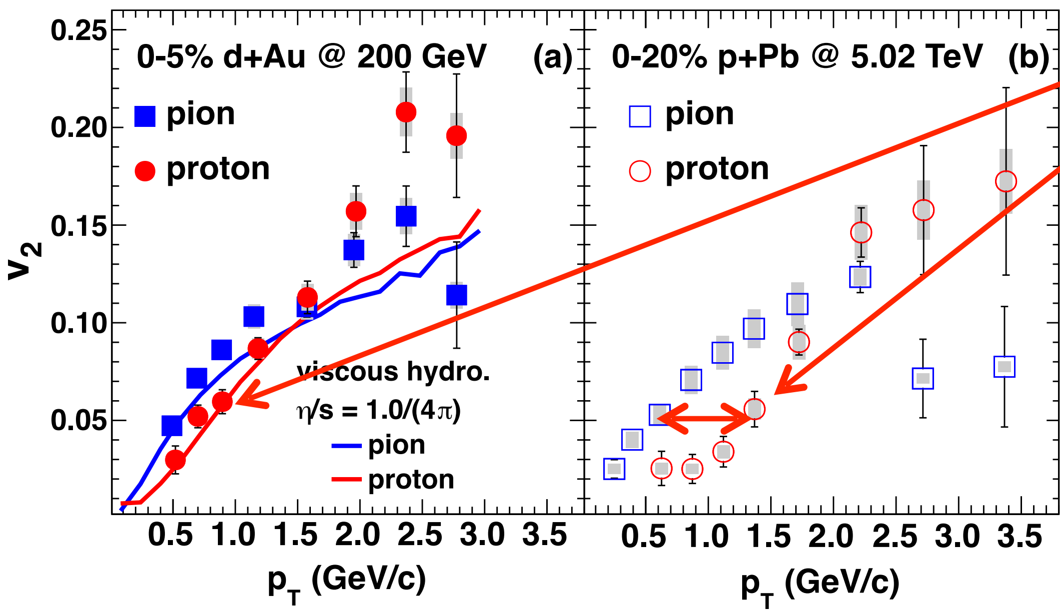

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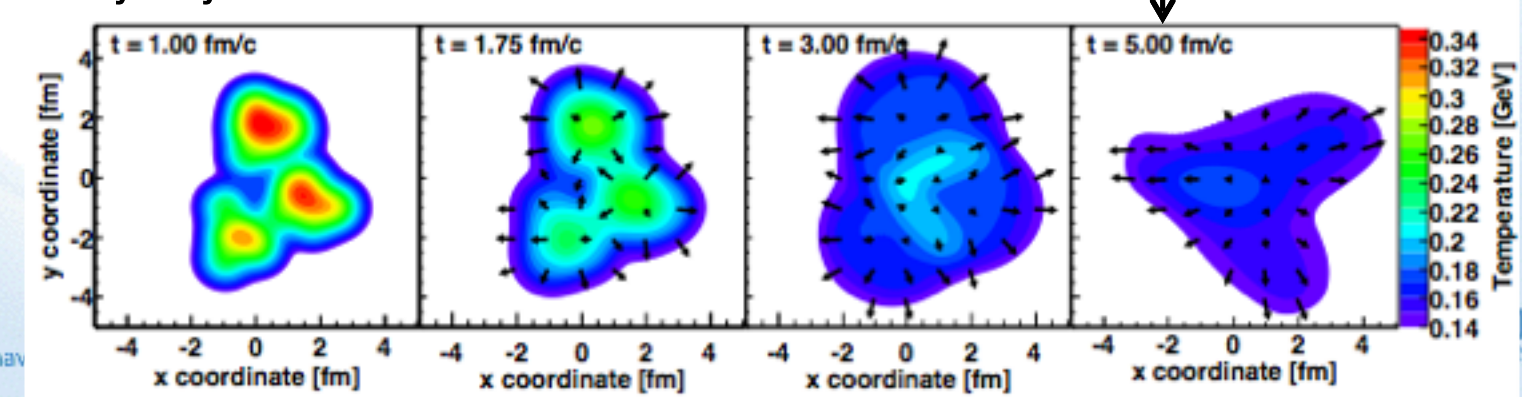
Very successful 3-week run resulted in 2.2 **billion** recorded (PHENIX) minimum bias ^{3}He+Au collisions – plus a sample using a new centrality trigger – in 2014.

Powerful additional handle on connection of coordinate space ε_3 to momentum space v_3. Analysis under way

^{3}He+Au hydrodynamic simulation



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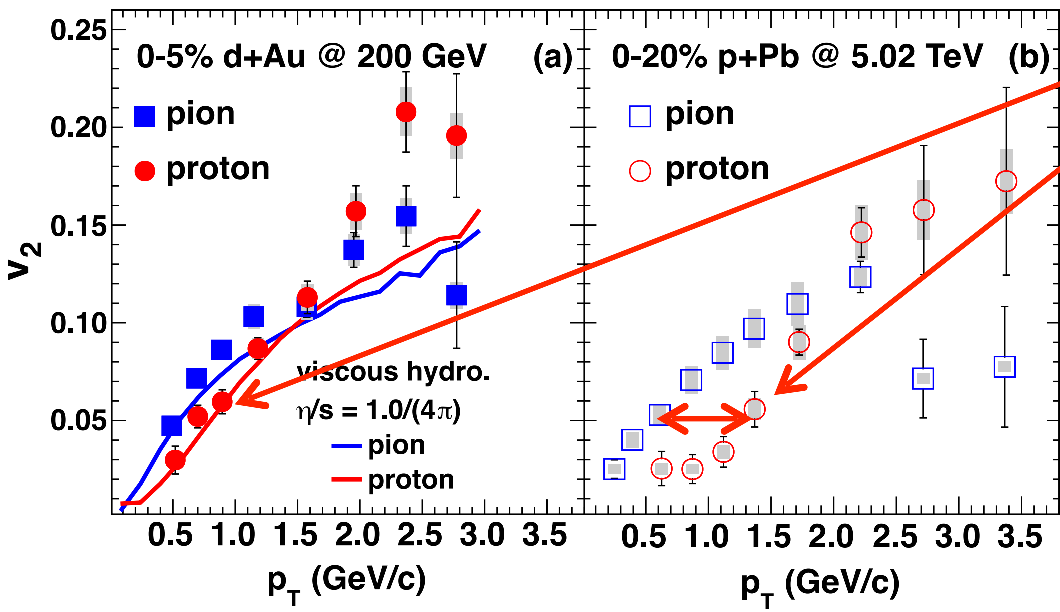

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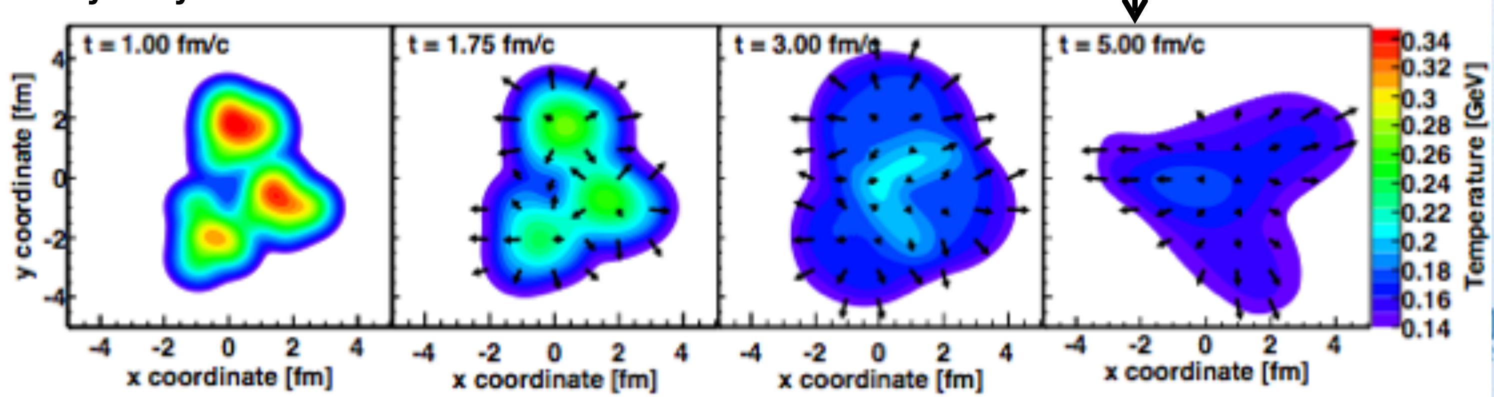
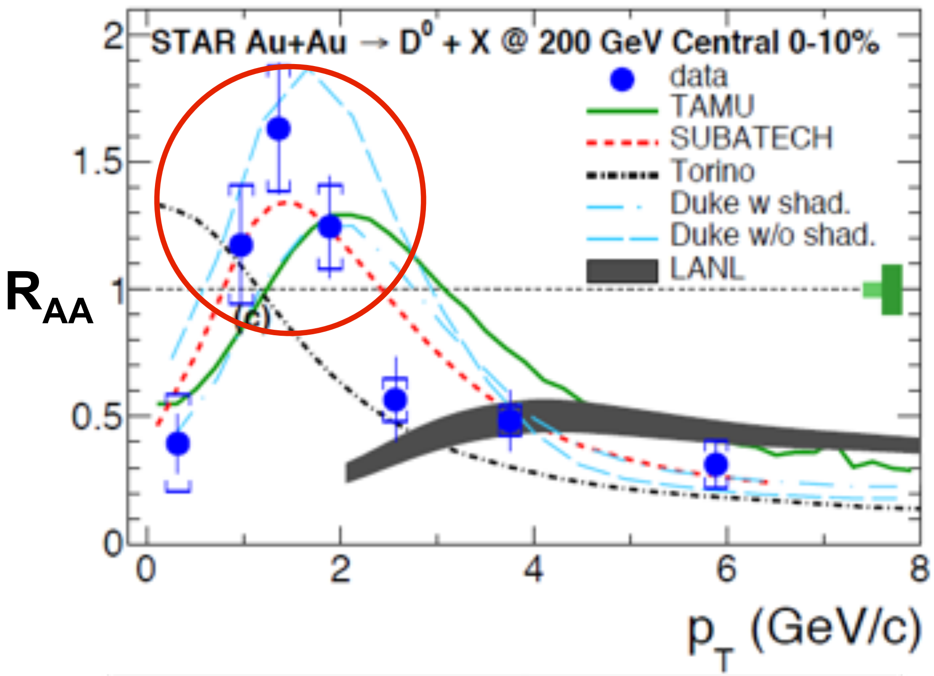
How short is the mean free path?

^{3}He+Au hydrodynamic simulation



Charm quark flow: $D_{c,b}$

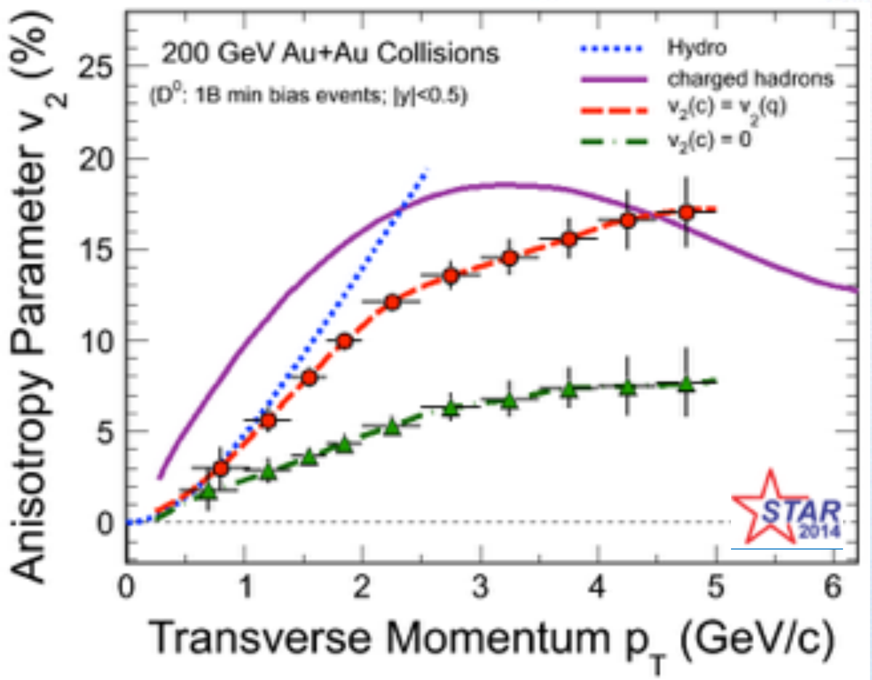
STAR: PRL 113, 142301



First measurement of reconstructed charmed hadron radial flow at RHIC:

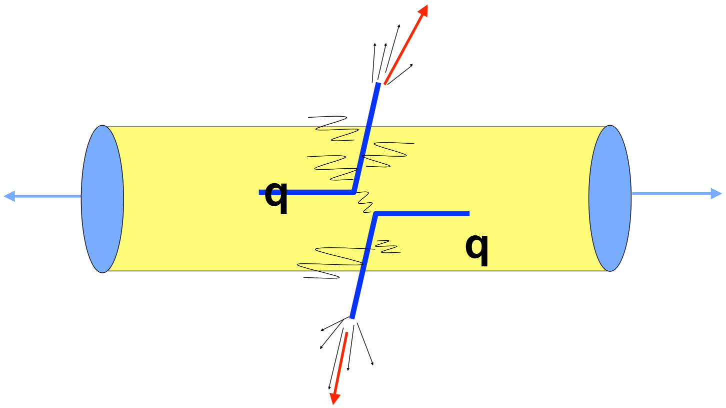
R_{AA} > 1 in low p_T region

HFT Projection for Au+Au **runs 14+16**



Quantify charm quark flow and recombination with high-statistics datasets
Probe *c,b* quark diffusion

Beyond discovery: q^

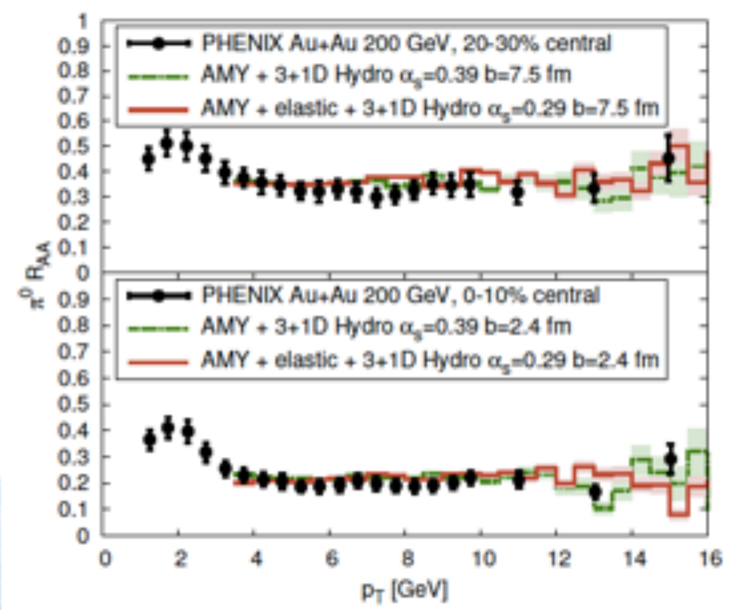


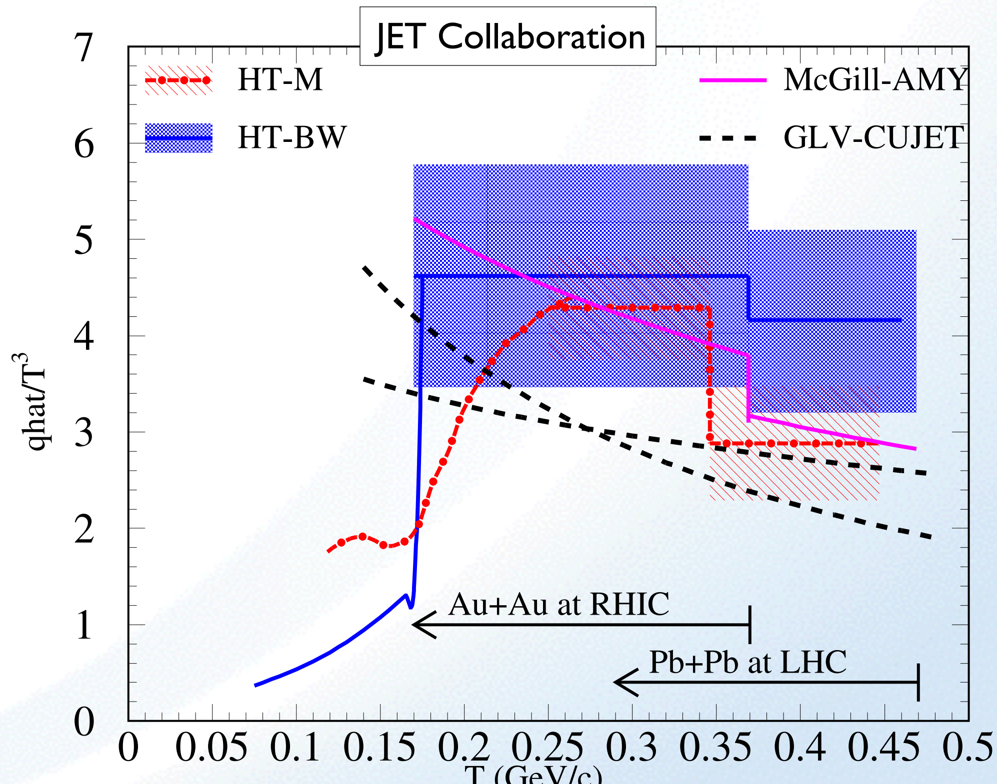
$$\frac{dE}{dx} = -C_2 \alpha_s \hat{q} L$$

Radiative

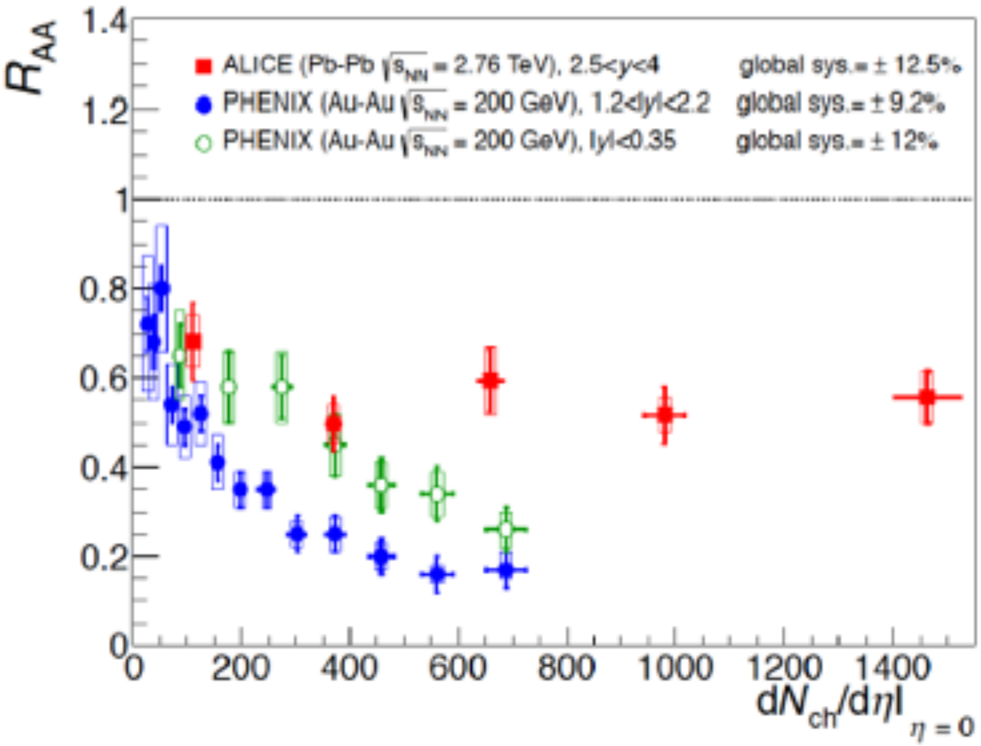
$$\frac{dE}{dx} = -C_2 \hat{e}$$

Collisional

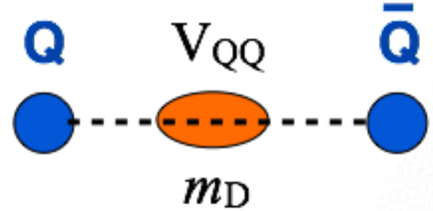




Quarkonium melting: m_D

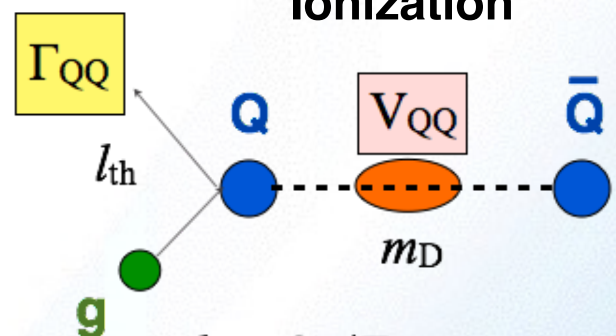


Color screening



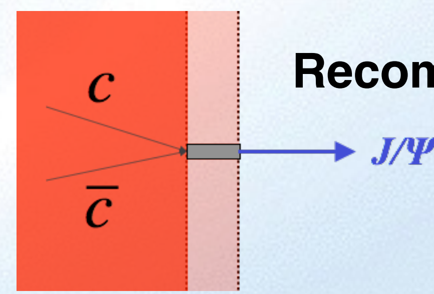
$m_D \sim gT$

Ionization



$l_{th} \sim 2\pi/T, \quad m_D \sim gT$

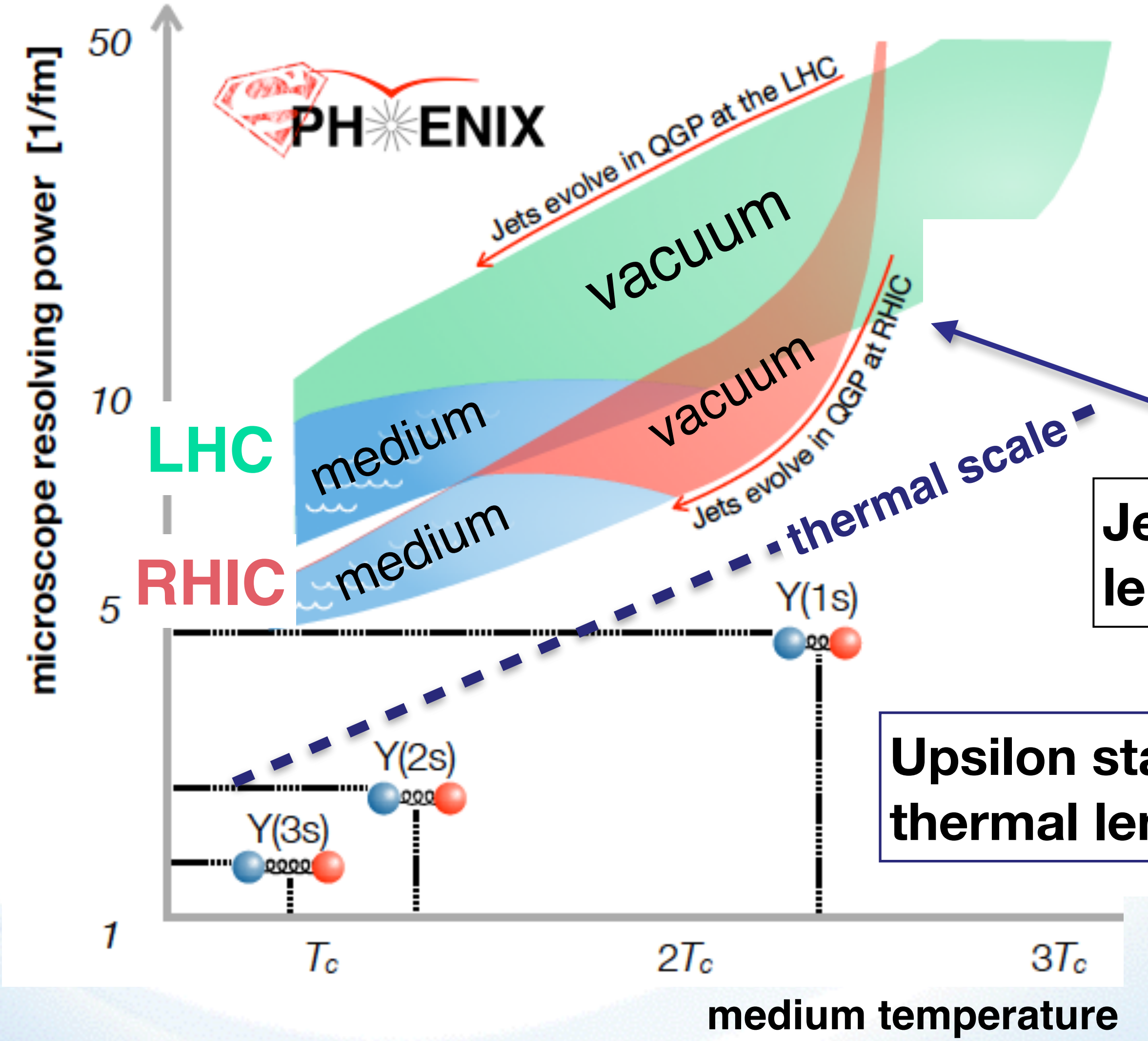
Stronger J/ψ suppression at RHIC than LHC: c-cbar recombination explains the data.



Recombination

Resolved measurement of Upsilon states required at RHIC (recomb. negligible)

Probing scales of QGP structure

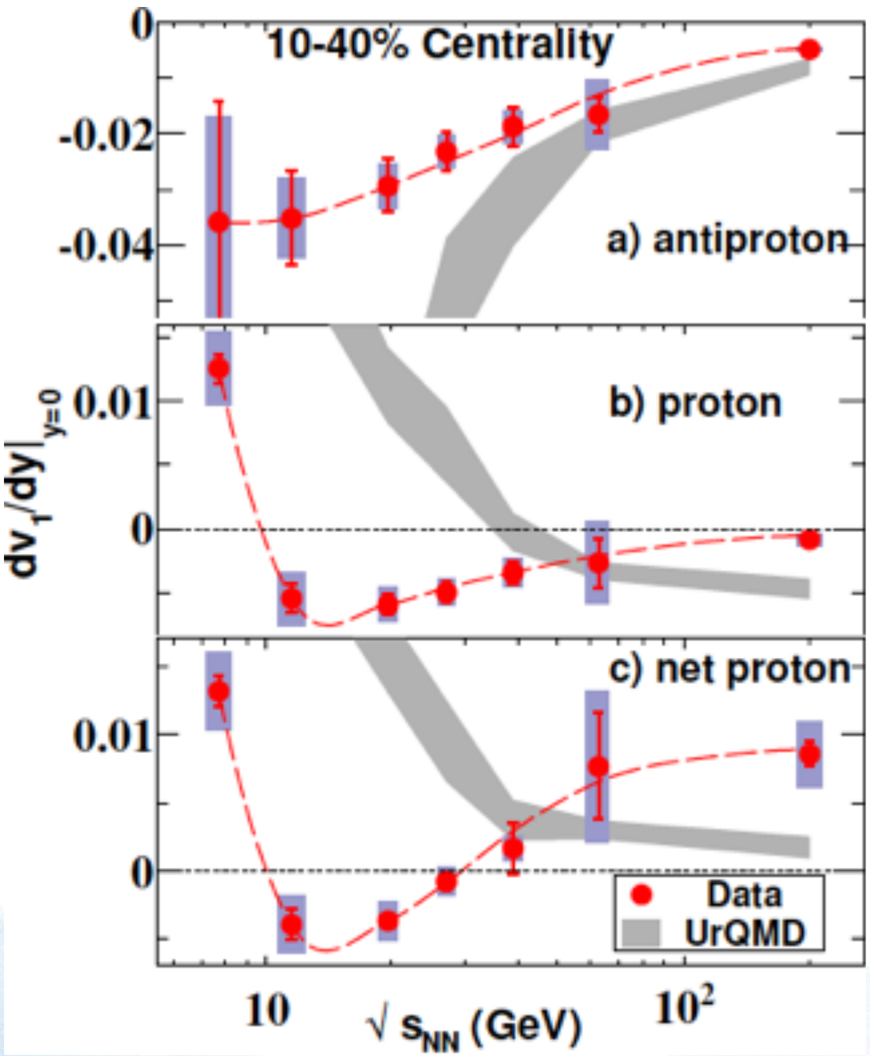


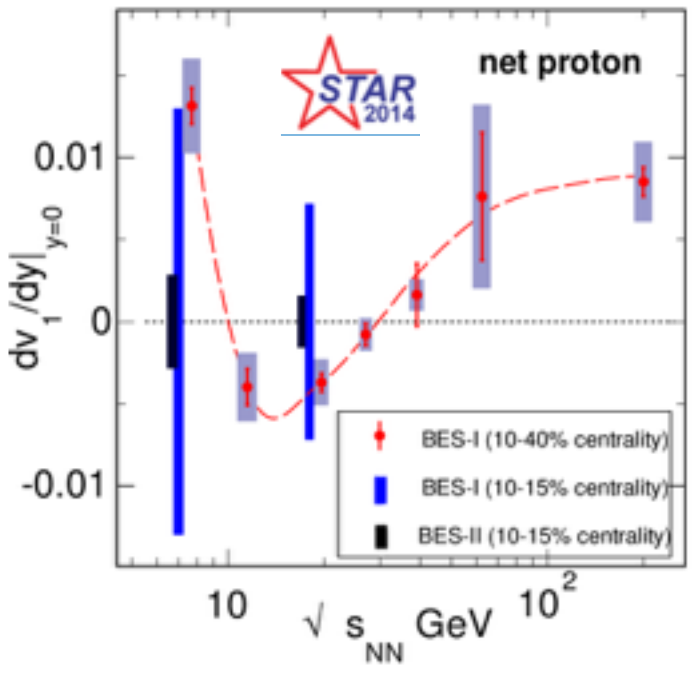
How does the perfect fluidity of the QGP emerge from the asymptotically free theory of QCD?

Jets probe sub-thermal length scales

Upsilon states probe thermal length scales

Equation of State: v_1

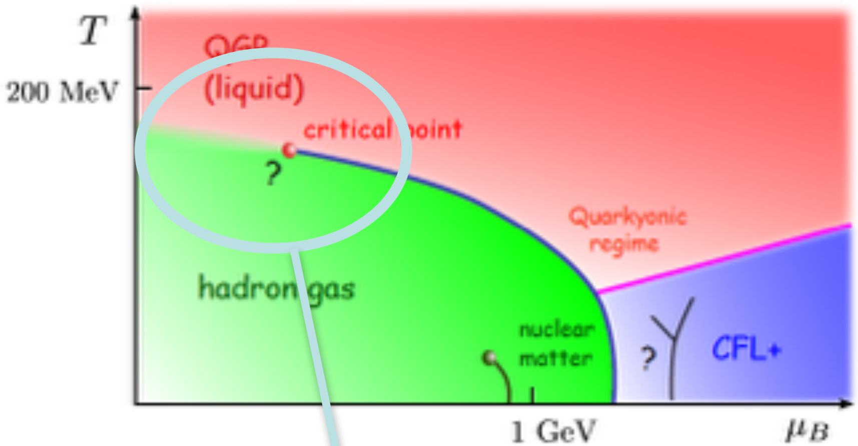


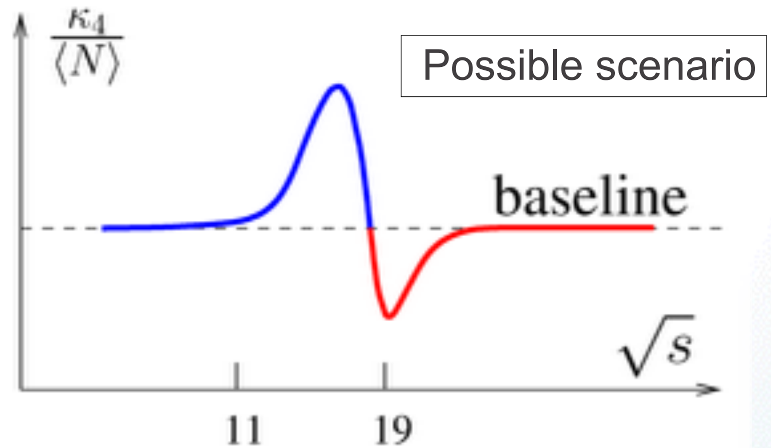


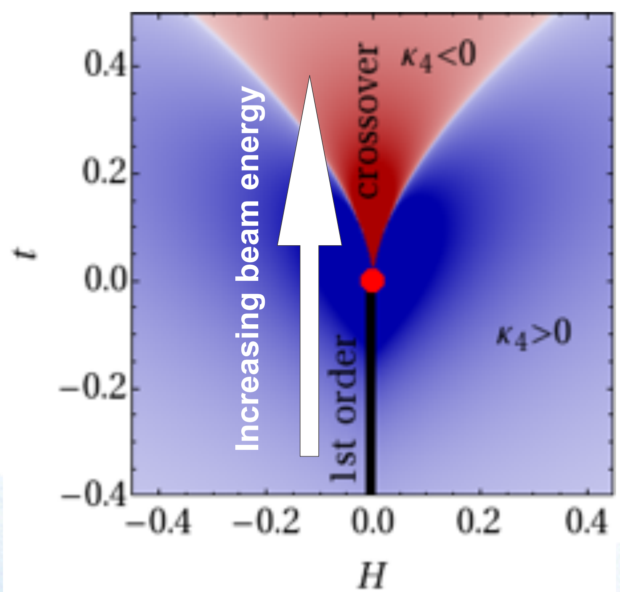
- Minimum in v_1 is consequence of the softening of the equation of state in the transition region of the phase diagram.
- Precision measurement requires BES-II data allowing dv_1/dy to be measured with tightly specified centrality.

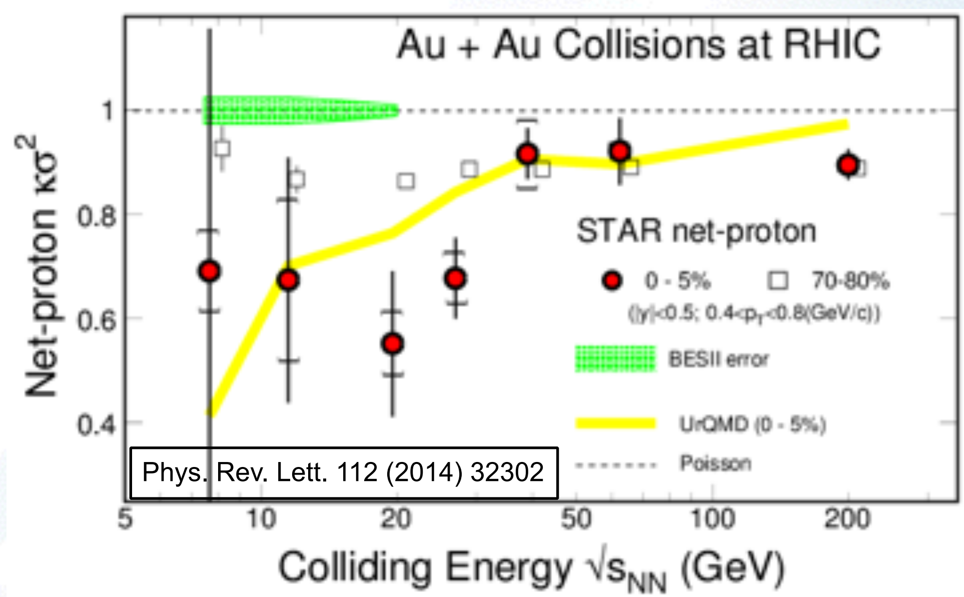
Phys. Rev. Lett, 112 (2014) 162301

Quest for critical fluctuations







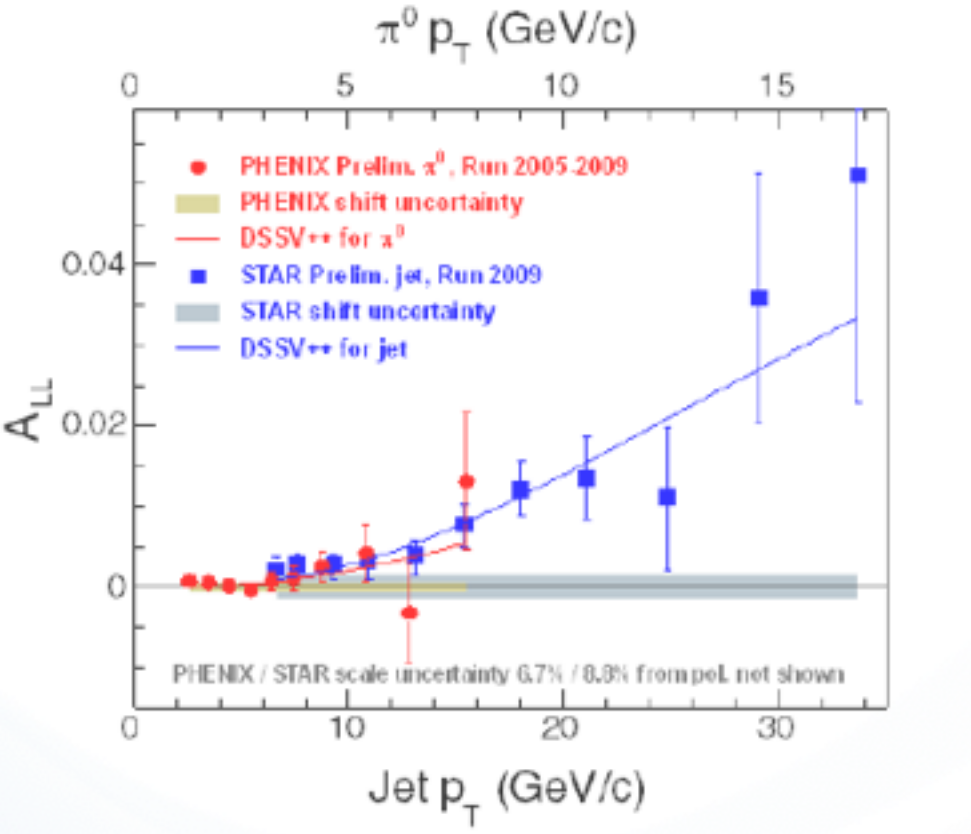


Sign change of net baryon **kurtosis κ_4**

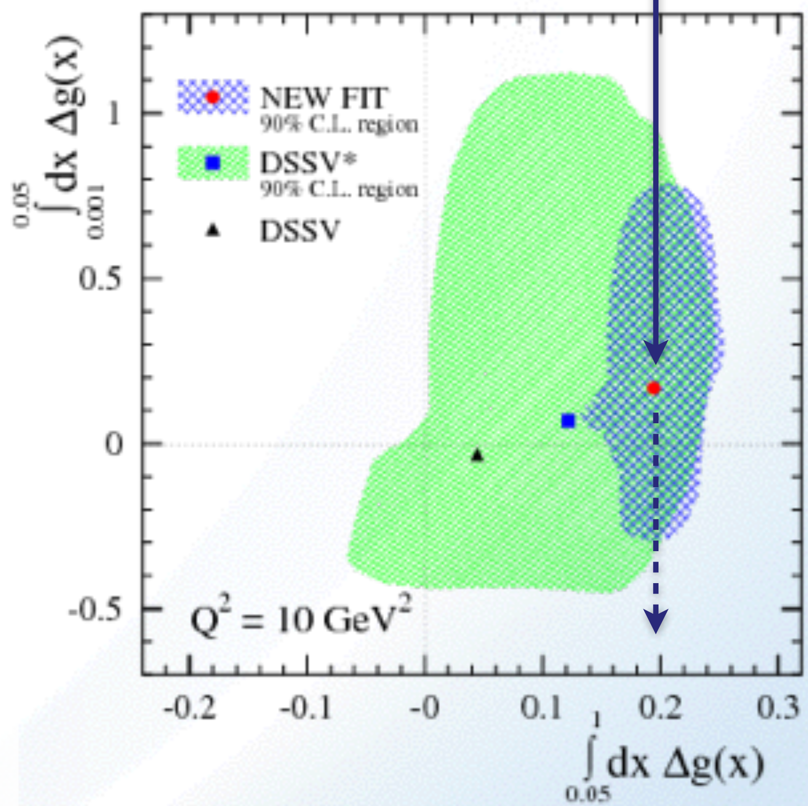
Δg from π^0 and jets

W. Vogelsang et al., PRL 113 (2014) 012001

E.R. Nocera et al., Nucl. Phys. B887 (2014) 276

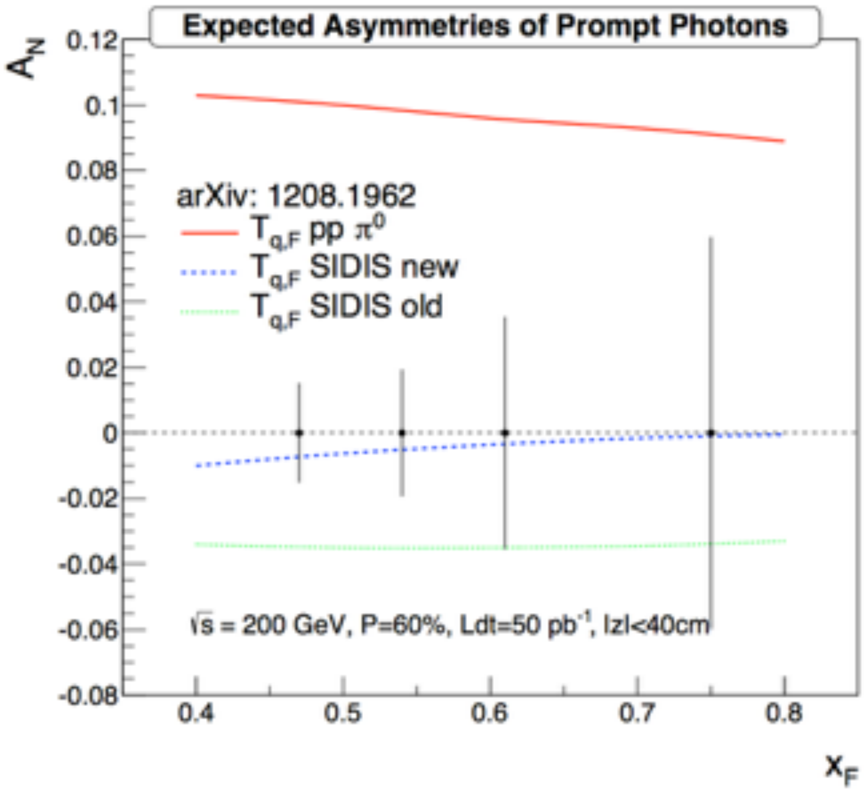


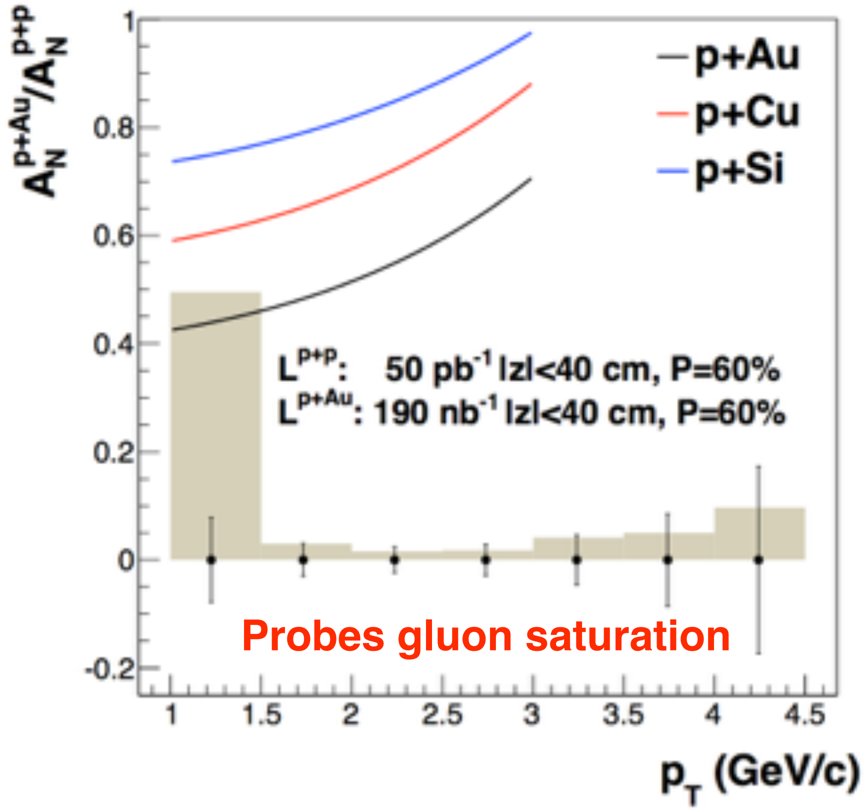
New QCD global fits result in first clear observation of a large gluon contribution to the proton spin in a definite x-range (0.05 < x < 1).



Large further improvements expected from Run 13 / 15 data

Transverse spin physics





New insight in A_N: forward photon and diffractive capabilities

Initial exploration of polarized p+A.

The Strategy

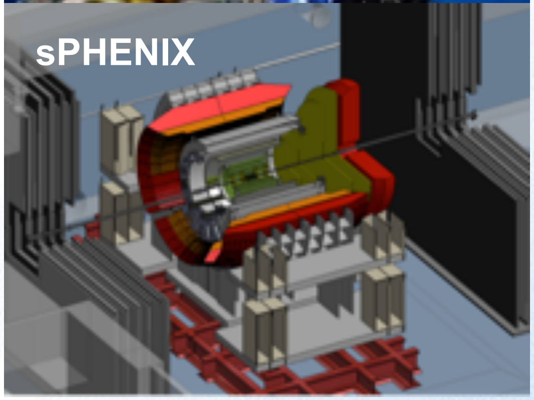
Completing the RHIC science mission

Status: RHIC-II configuration is complete

- Vertex detectors in STAR (HFT) and PHENIX
- Luminosity reaches 25x design luminosity

Plan: Complete the RHIC mission in 3 campaigns:

- **2014–16: Heavy flavor probes of the QGP using the micro-vertex detectors Transverse spin physics**
- 2017: Install low energy e-cooling
- **2018/19: High precision scan of the QCD phase diagram & search for critical point**
- 2020: Install sPHENIX upgrade
- **2021/22: Precision measurements of jet quenching and quarkonium suppression**
- 2023-25: Transition to eRHIC



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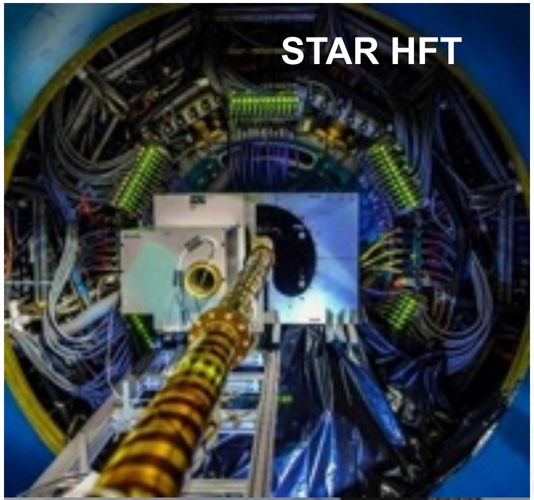
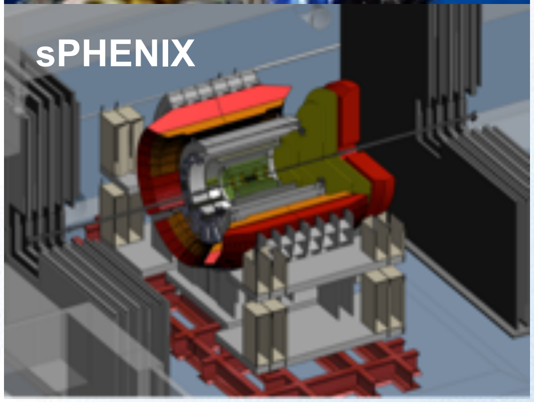
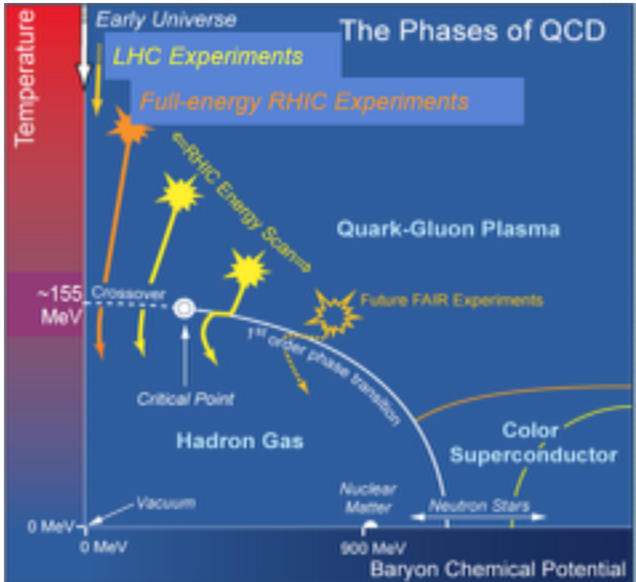




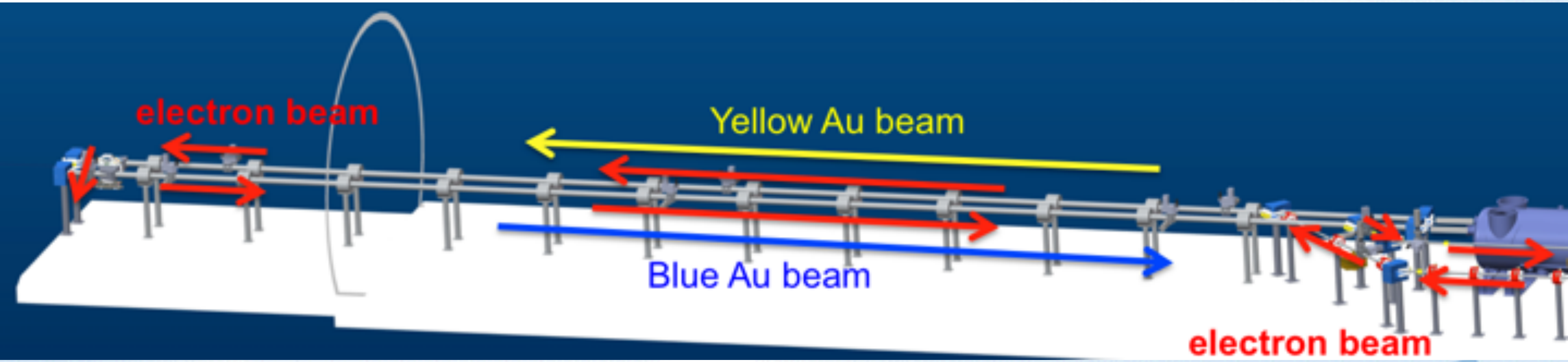
RHIC remains a unique discovery facility

Low Energy e-Cooling for Au+Au

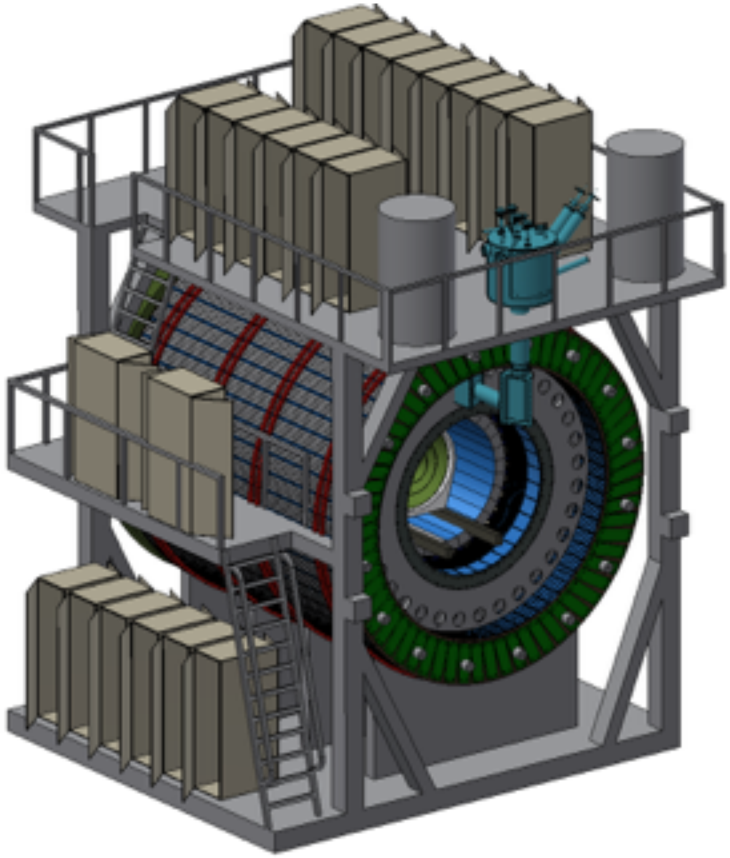
- Cooling of low energy heavy ion beams (3.8–10 GeV/n) with bunched electron beam increases luminosity by up factor 10
- Enables a QCD critical point search with second, high luminosity Beam Energy Scan
- Use Cornell-built DC gun and existing SRF cavity for cost effective implementation
- Start commissioning in 2018



Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

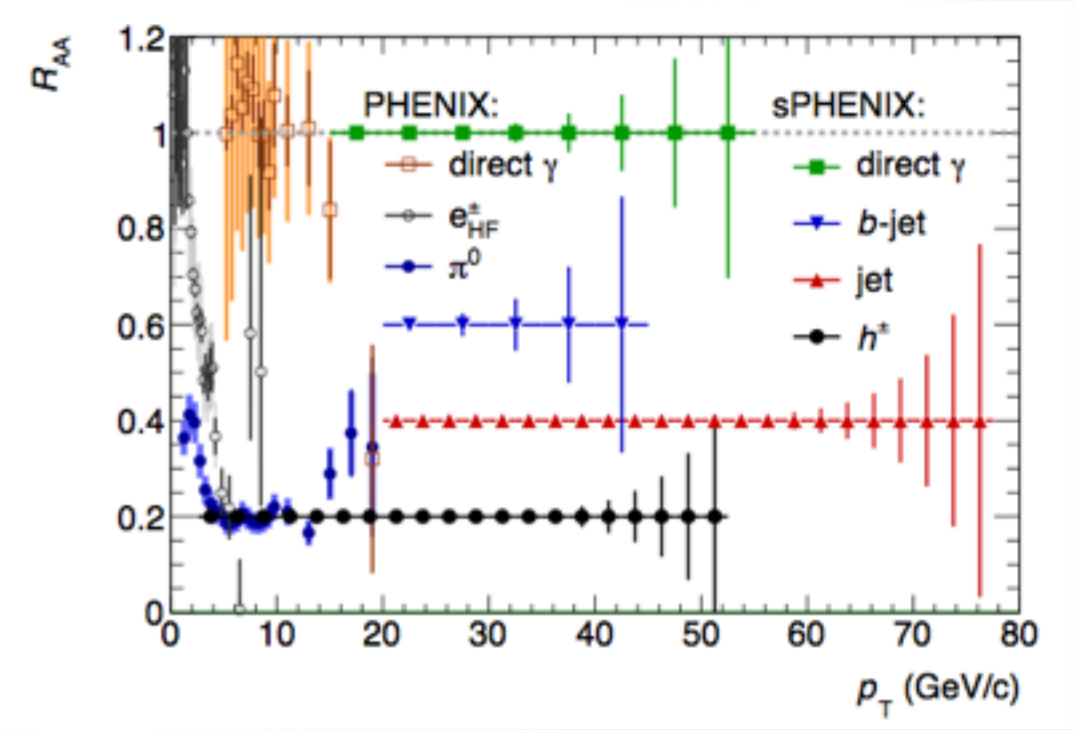


sPHENIX upgrade



Built around the BaBar solenoid – now being shipped to BNL

An (almost) complete makeover of the PHENIX detector to make precision measurements of hard probes of the QGP at strongest coupling (near T_c) and with the largest resolution range



What RHIC will deliver

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- **Campaign 1:**
  - QCD equation of state at $\mu_B \approx 0$
  - Precision measurement of $\eta/s(T \approx T_c)$
  - Measurement of heavy quark diffusion constant $D_{c/b}$
  - Determination of the scale of nuclear granularity
  - Origin of single spin asymmetries
  - Δg, flavor dependence of spin in the quark sea

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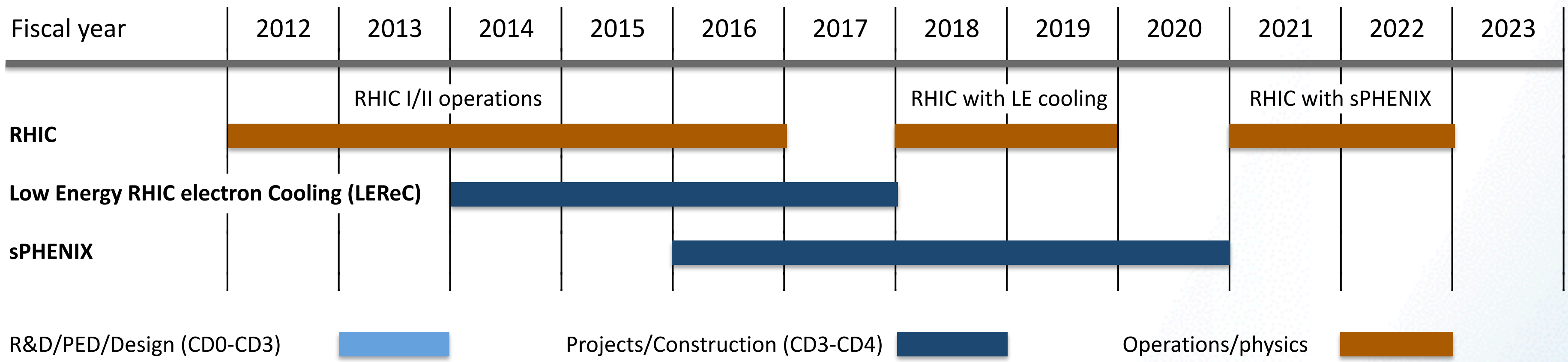
- **Campaign 3:**
  - Precision measurement of $\hat{q}(T \approx T_c)$ and $\hat{e}(T \approx T_c)$
  - Scale dependence of QGP structure
  - *Many insights we can't even imagine yet !*

Our Plan for RHIC Operations



- Continue RHIC II operation through FY16
- Installation of Low Energy RHIC electron Cooling during FY17
- Run the second Beam Energy Scan (BES II) in FY18 and FY19
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- Run RHIC with STAR and sPHENIX in FY21 and FY22

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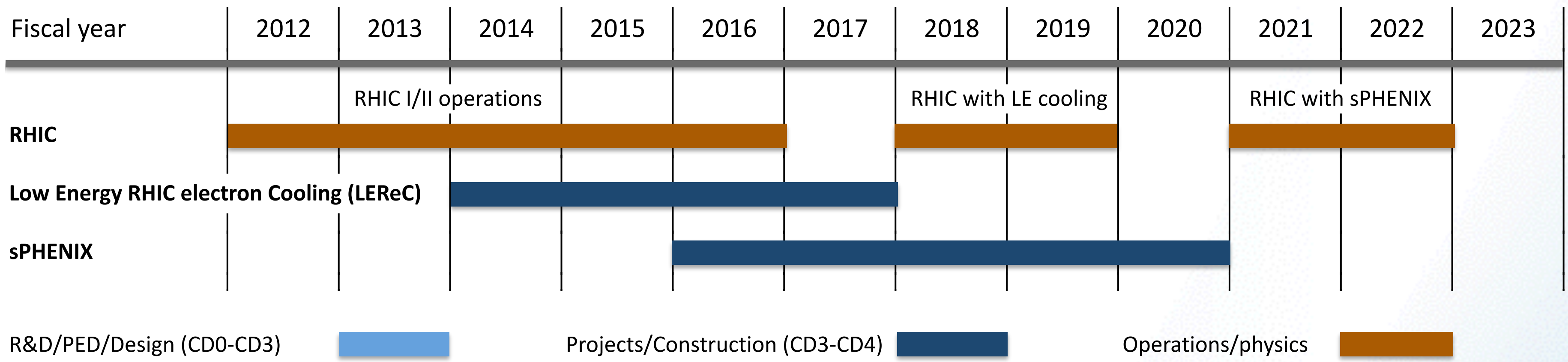

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- **Plan can be executed within constant level of effort budget scenario**
- **Tremendous scientific payoff with continued discovery potential**

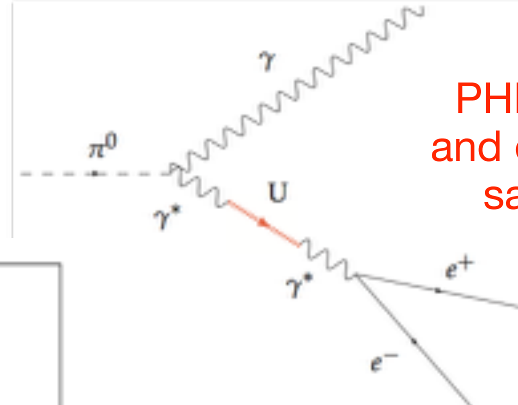
Thank You !

Backup slides

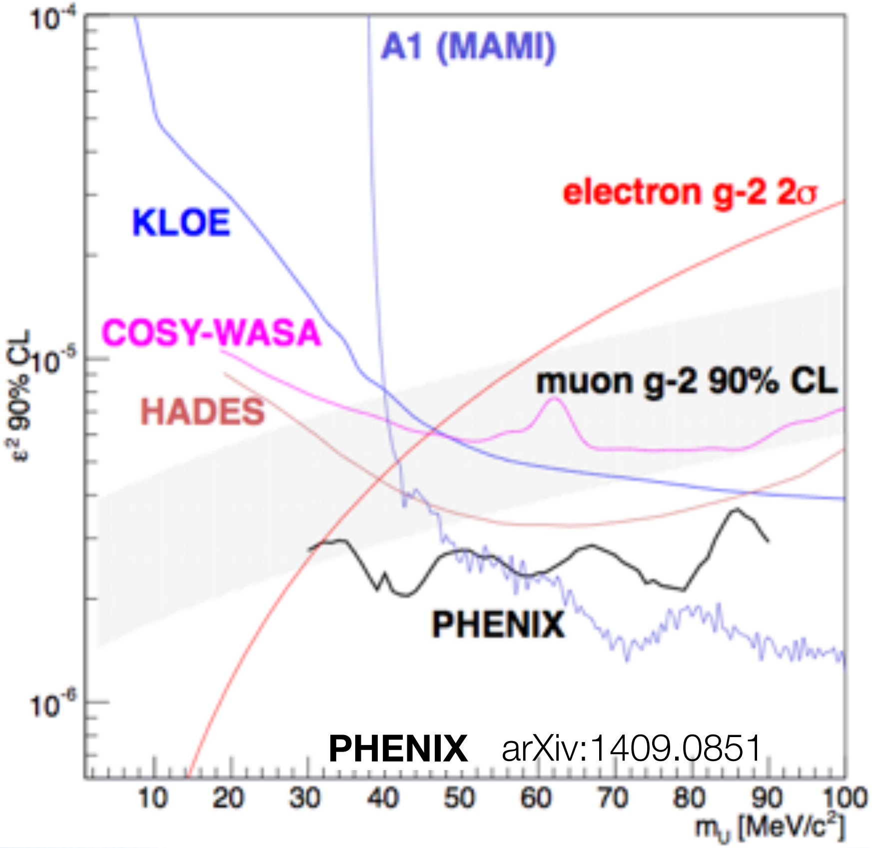
Proposed run schedule for RHIC

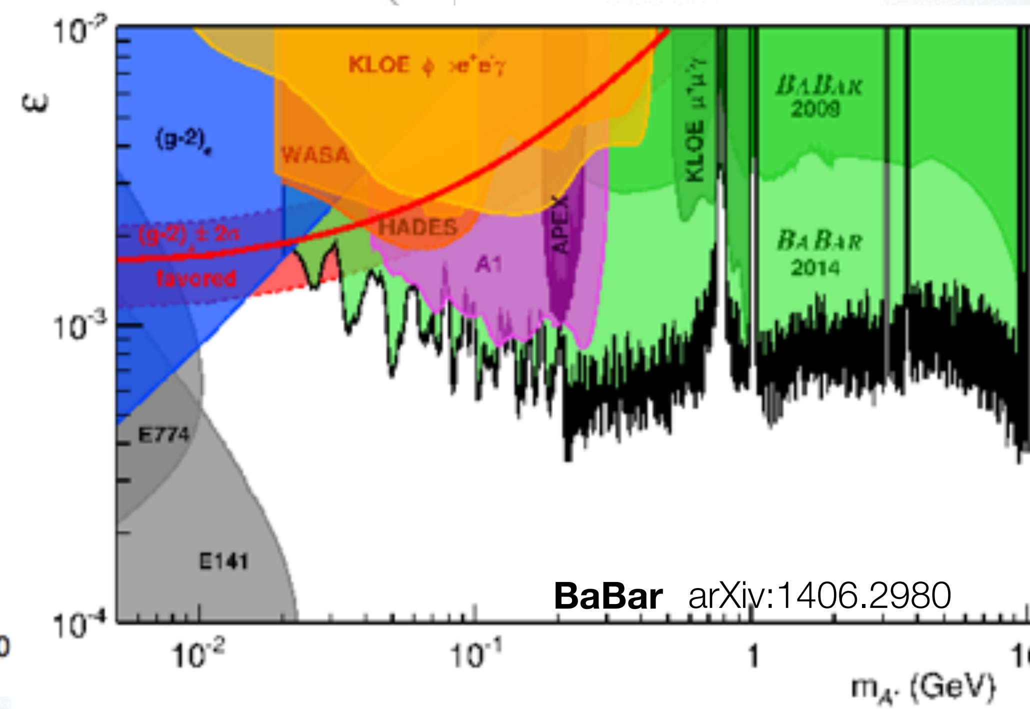
Years	Beam Species and	Science Goals	New Systems
2014	15 GeV Au+Au 200 GeV Au+Au ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	Pol. p+p at 200 GeV p+Au, p+Si at 200 GeV High statistics Au+Au Pol. p+p at 510 GeV or Au+Au at 62 GeV	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	200 GeV Au+Au with upgraded detectors Pol. p+p, p+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

Dark photons?



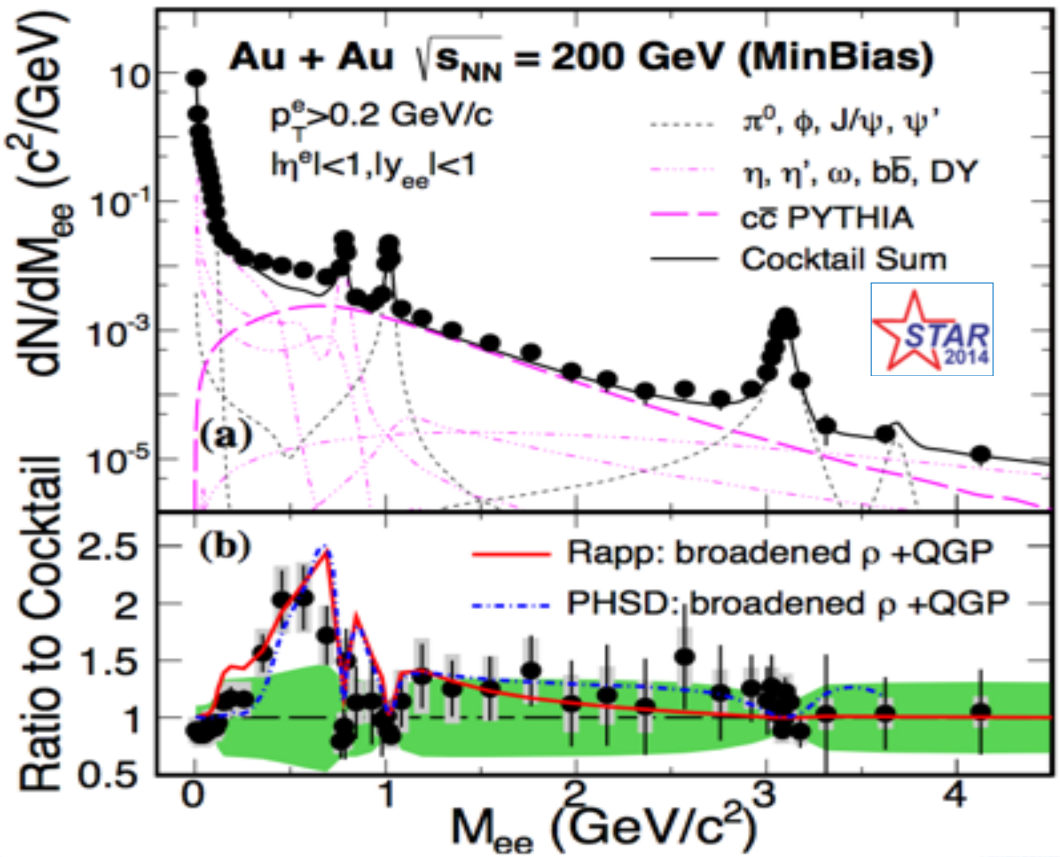
PHENIX: excellent electron ID and e^+e^- mass resolution – huge sample of π^0 Dalitz decays





Recent combined limits – WASA, HADES, A1, BaBar, PHENIX, NA62 – rule out essentially all parameter space for the minimal version of a dark photon explaining the $(g-2)_\mu$ anomaly

Dileptons: Chiral symmetry restoration



LMR

$\rho \rightarrow e^+e^-$

IMR

$q\,\bar{q} \rightarrow l^+l^-$

J/Ψ, DY, ϒ(1,2,3)

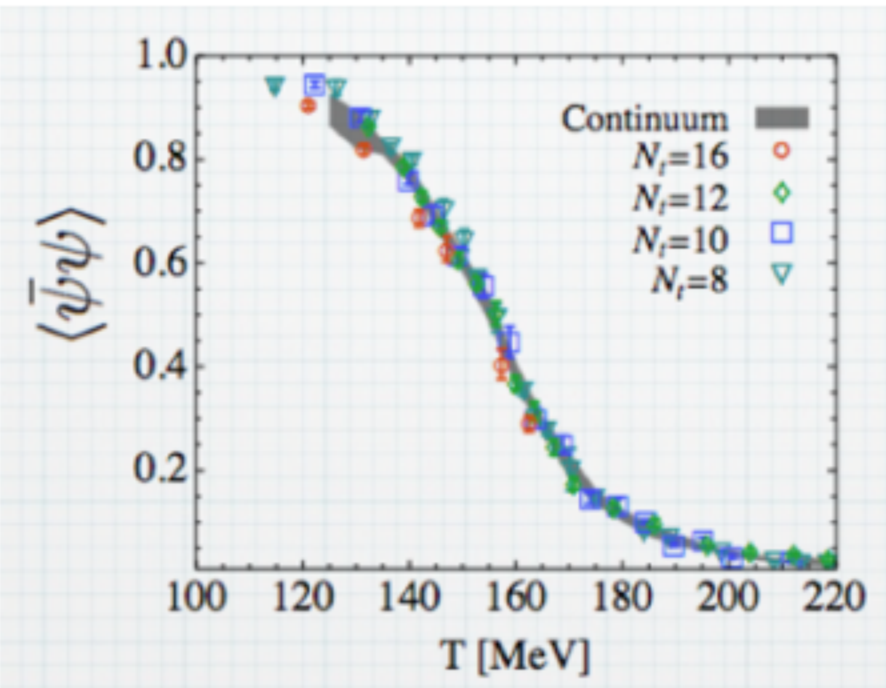
Phys. Rev. Lett, 113 (2014) 022301

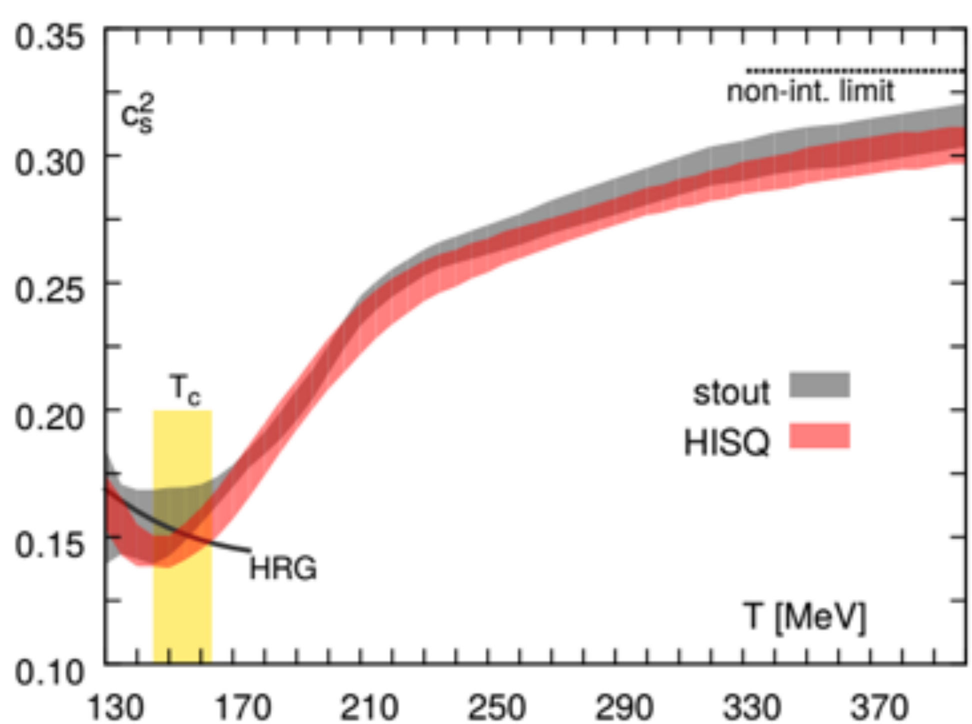
- Observed excess at low mass consistent with broadening ρ
- Observing chiral symmetry restoration from dileptons: hadronic structure (vector meson peaks) dissolves into continuous thermal distribution
- Need to subtract dominant charm contributions to isolate thermal QGP radiation
- Will be measured as function of beam energy

Latest Lattice Gauge Results

Now a reliable guide for many (static) medium properties:

Chiral symmetry breaking | **Equation of state**

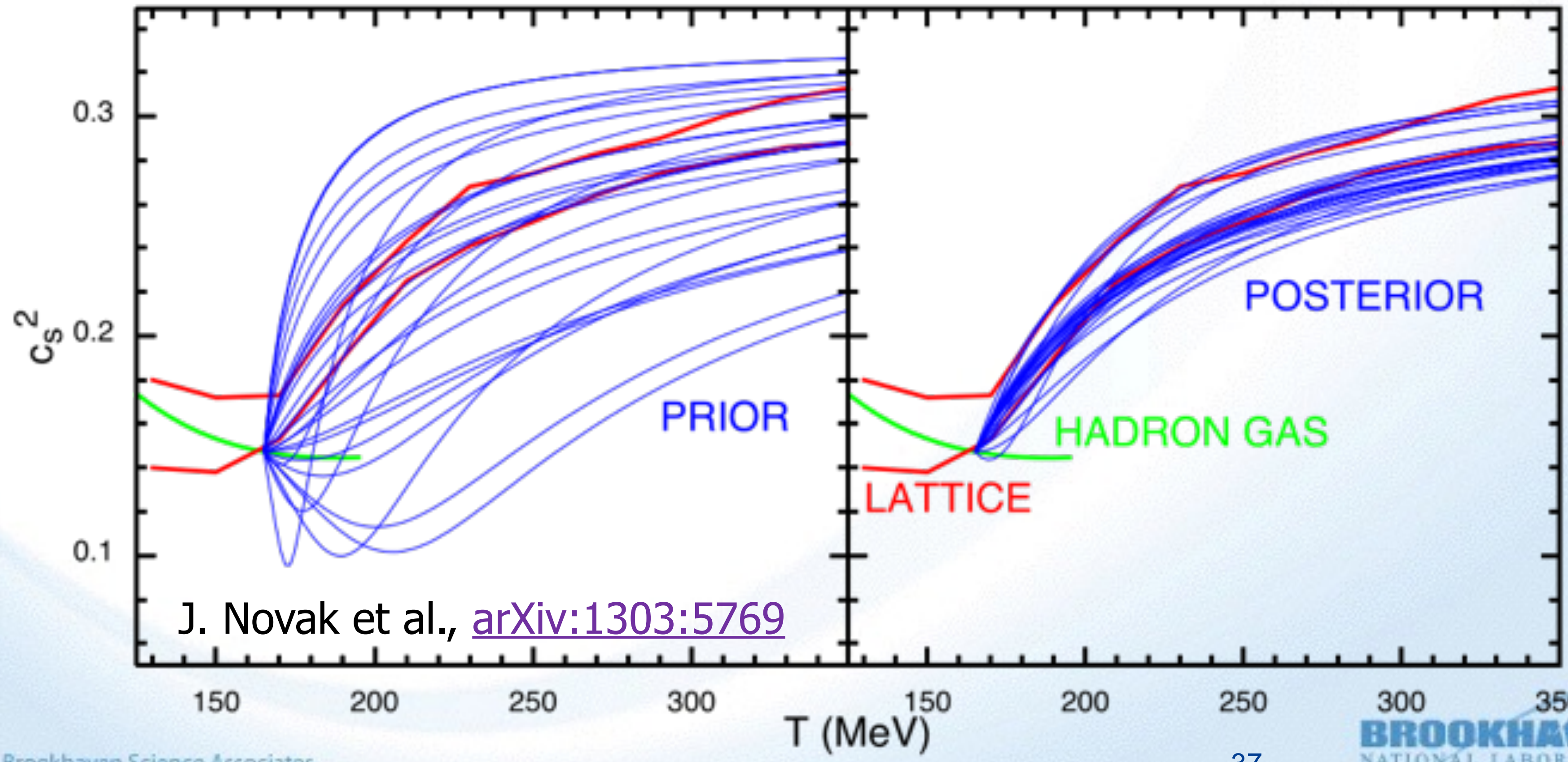




HotQCD, arXiv:1407.6387

From Data to Insight: QCD EoS

- **Unbiased model - data comparison enabled by state-of-the-art model parametrization via Gaussian emulators**
  - Equation of state determination from comparison of hydrodynamic calculations and RHIC data.



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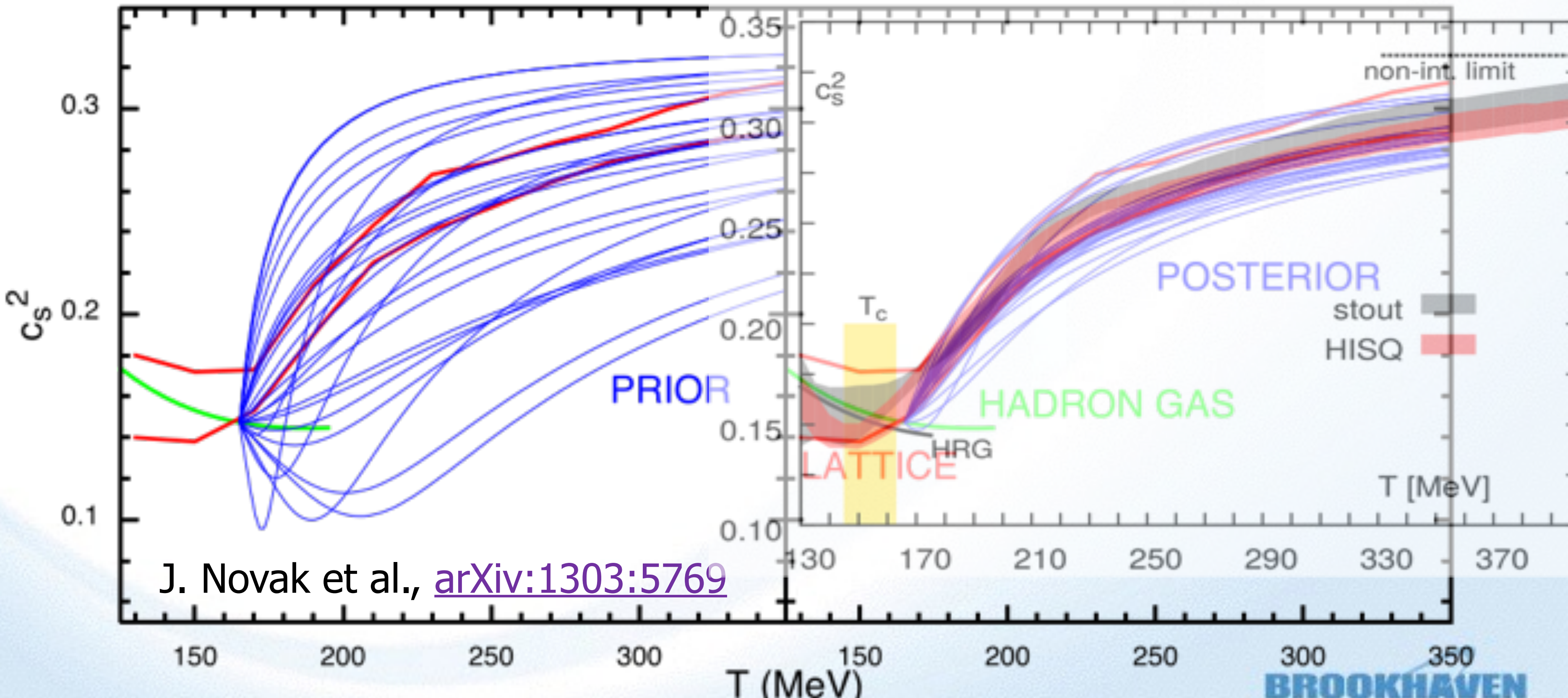

J. Novak et al., arXiv:1303:5769