Ultra-relativistic Heavy ion collisionz

The future is bright

Heinz-Fest
CERN

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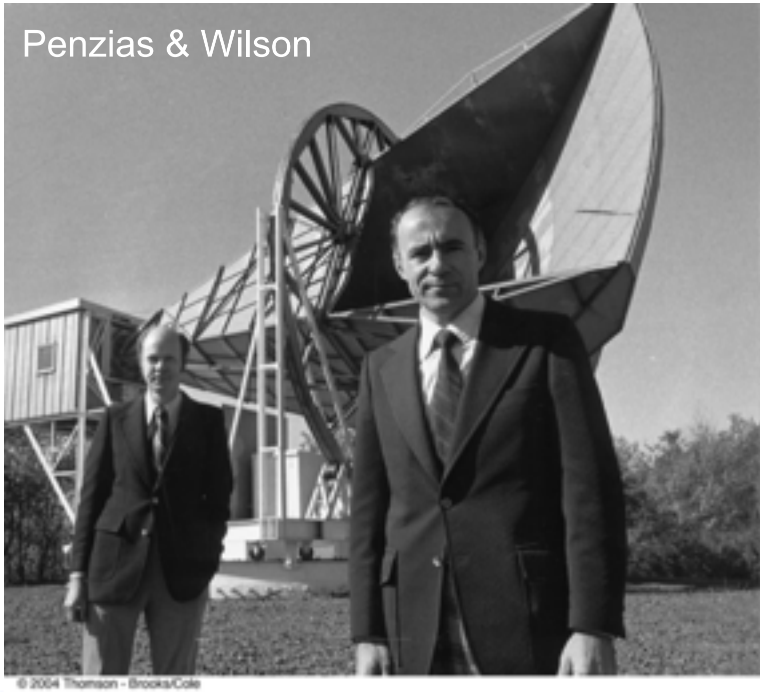
BROOKHAVEN NATIONAL LABORATORY

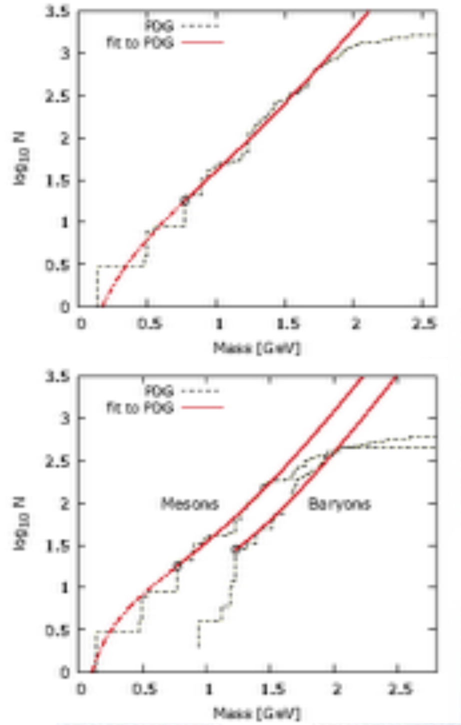
a passion for discovery

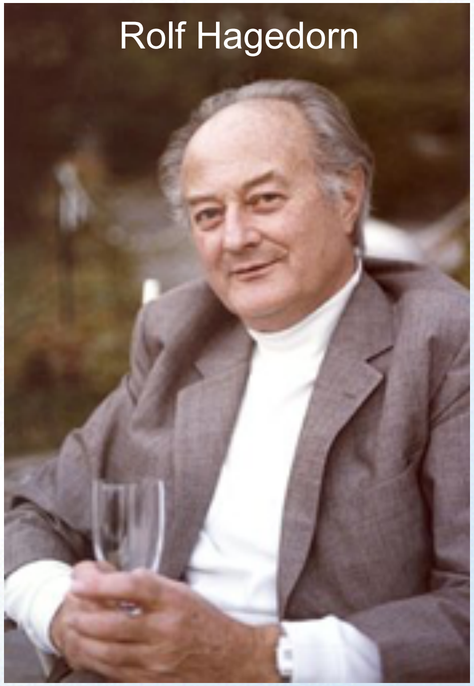
Office of Science
U.S. DEPARTMENT OF ENERGY

50 years ago

Momentous discoveries







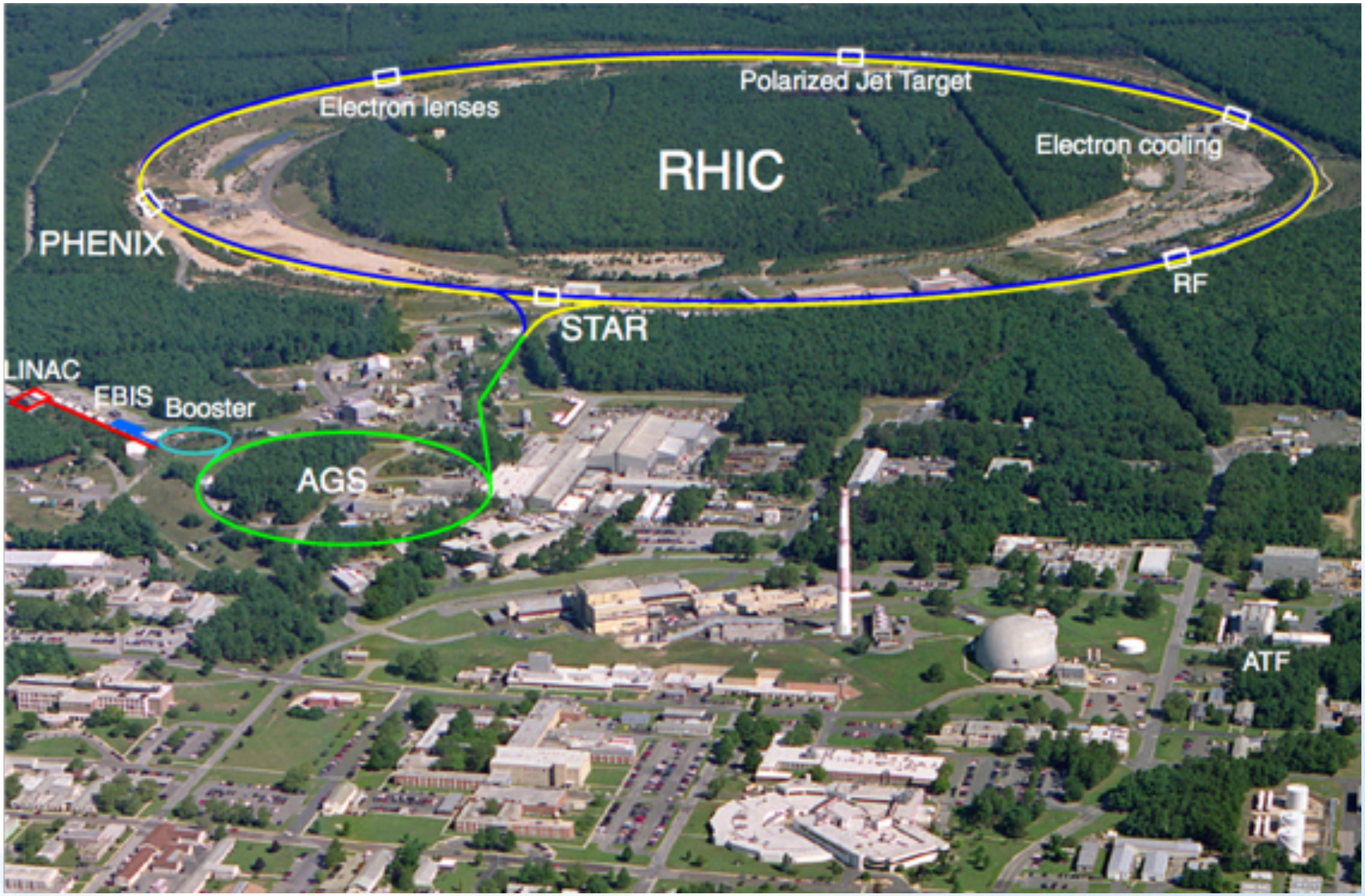
Cosmic microwave background

Exponential mass spectrum

What is the hottest matter?

- The CMB discovery raised the question: What kind of matter filled the universe at its hot beginning?
- Hagedorn's exponential mass spectrum hypothesis implied that matter, in the form of a dense gas of hadron resonances, cannot exceed $T_H \approx 180$ MeV.
- In the early 1970s scientists realized that temperatures in this range can be reached in collisions of heavy nuclei.
- First experiments at LBNL (Bevalac) confirmed this concept in the years 1975−1980.
- The insight that all hadrons are composed of quarks and gluons suggested that T_H may not be the highest possible temperature, but that matter would dissolve into a novel type of plasma containing quarks and gluons (ca. 1978).
- This led to experiments at AGS, SPS, RHIC and LHC and motivated theorists to calculate properties of quarks and gluons at high temperature on the

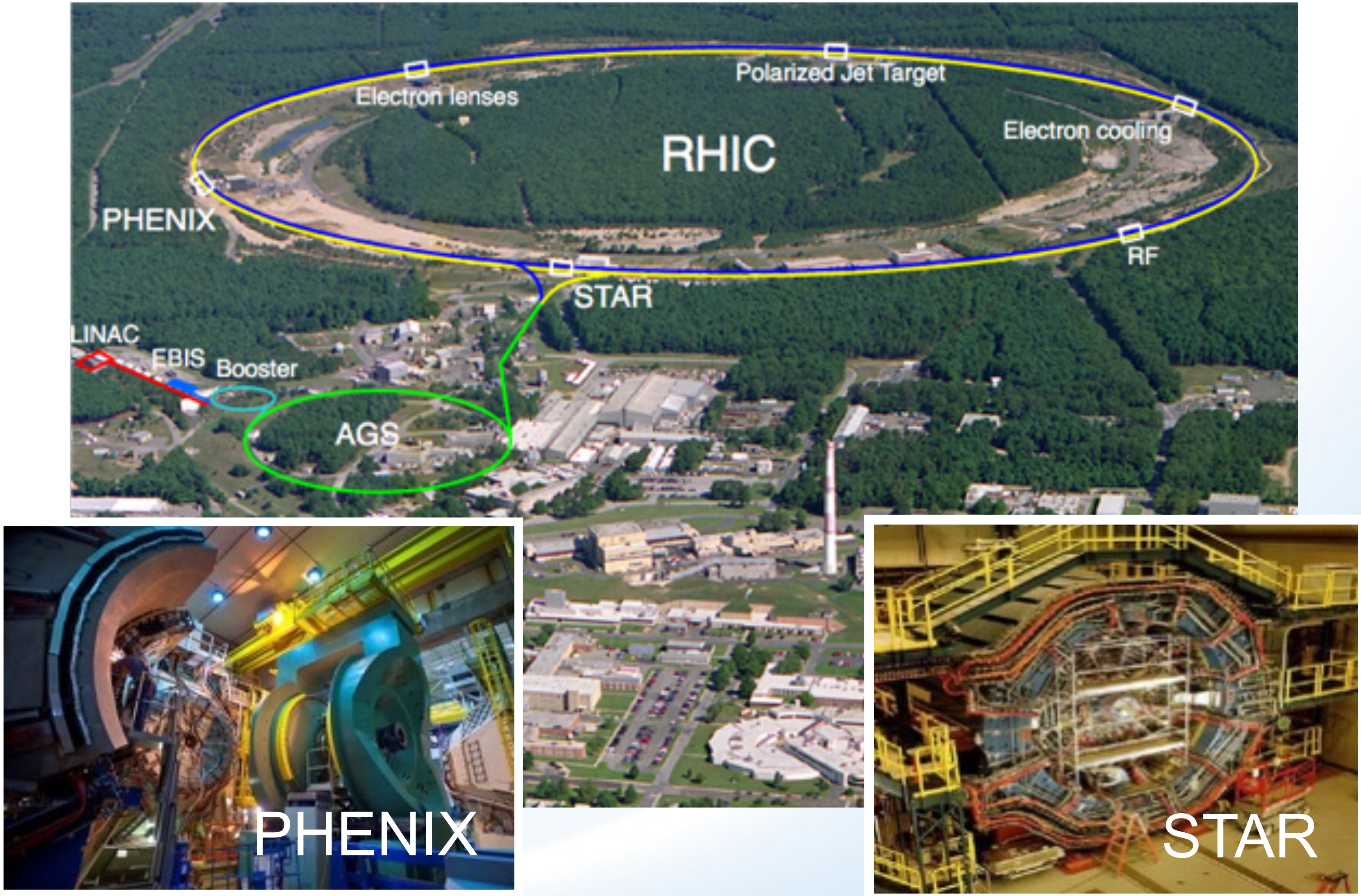
RHIC: Champion of versatility



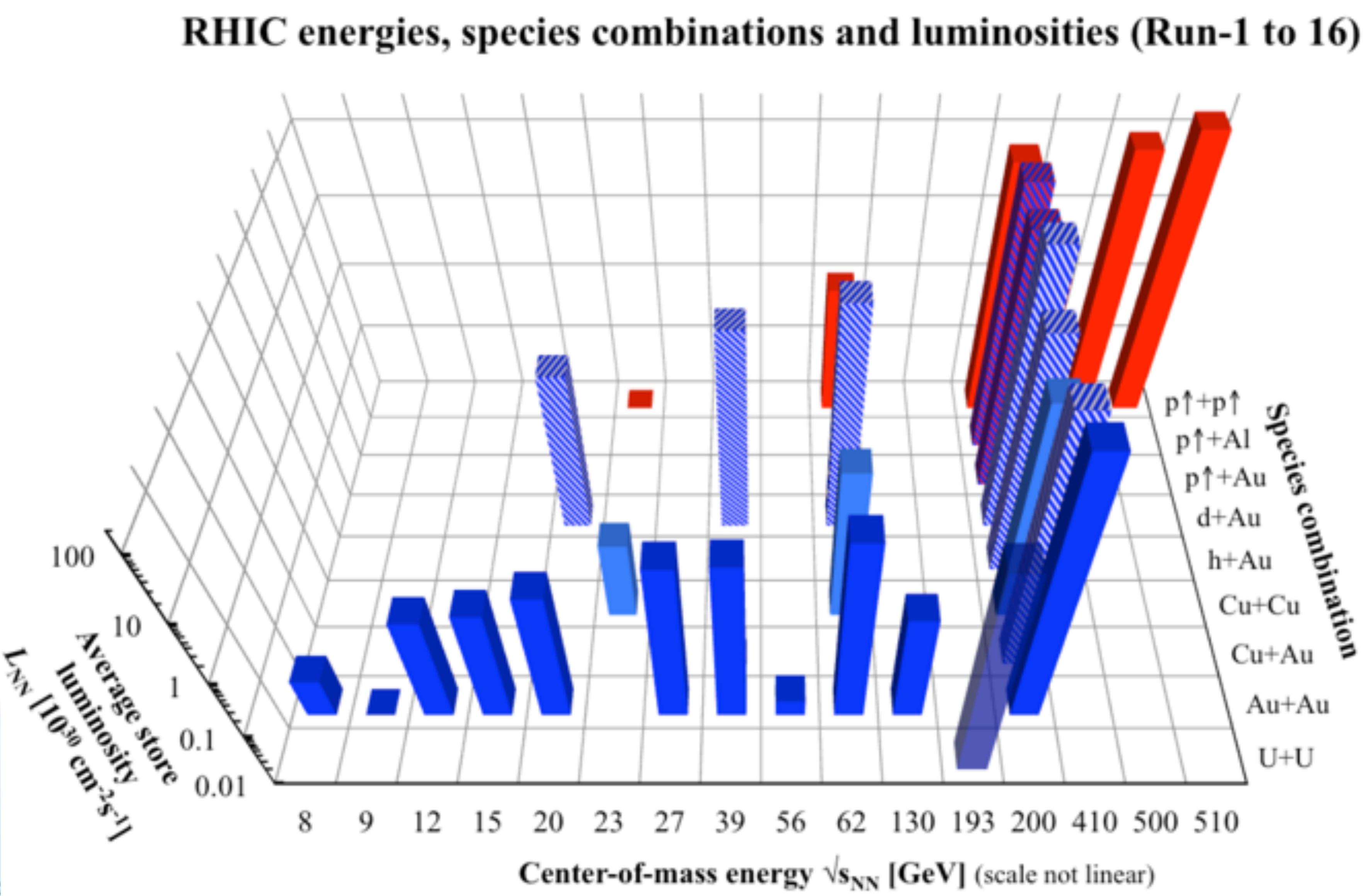
PHENIX

STAR

RHIC: Champion of versatility

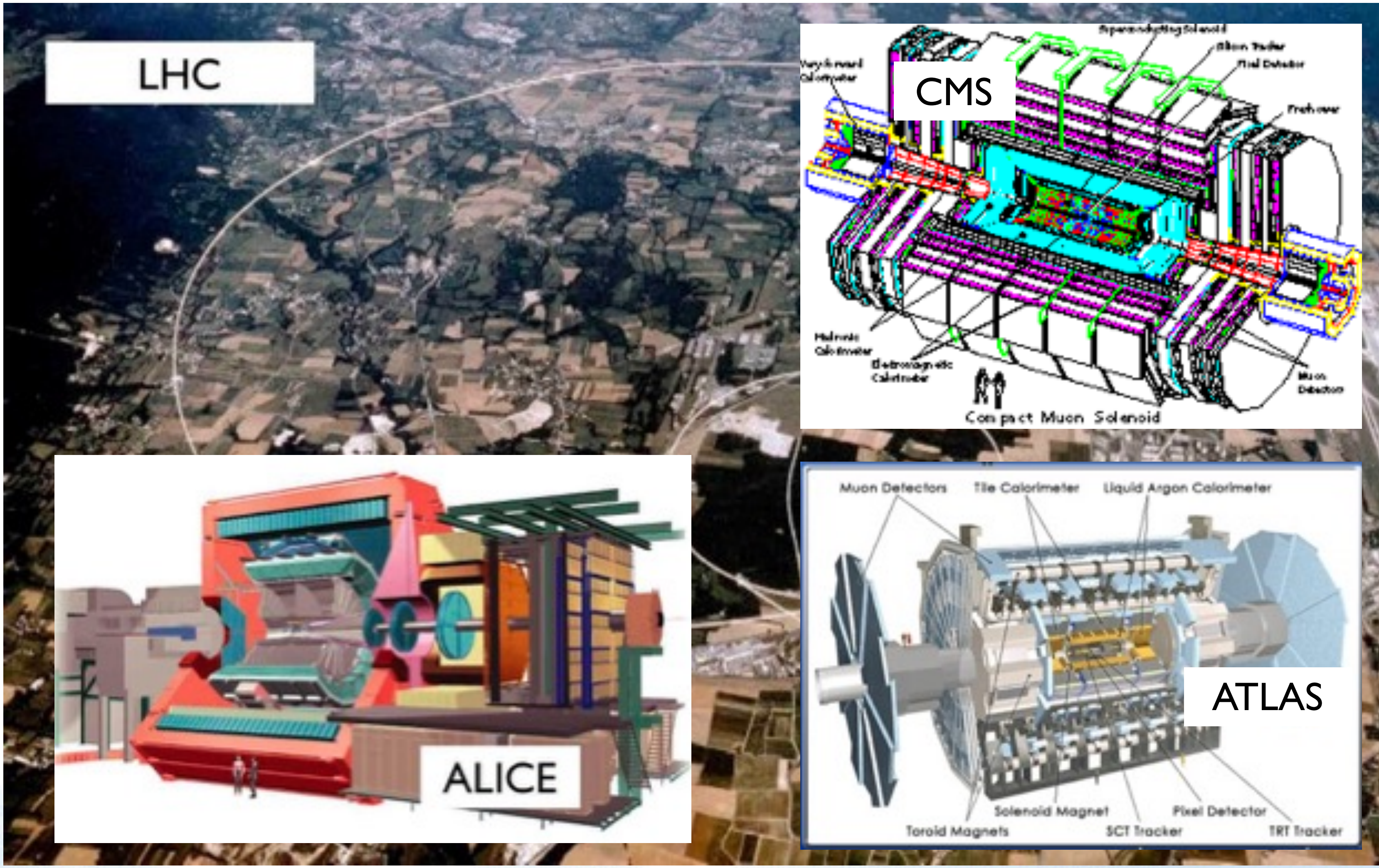


You want it - you can have it!



LHC: Champion of energy

LHC: Champion of energy



Ulrich Heinz: Setting the pace

Comprehensive models

PHYSICAL REVIEW C VOLUME 48, NUMBER 5 NOVEMBER 1993

Thermal phenomenology of hadrons from 200A GeV S+S collisions

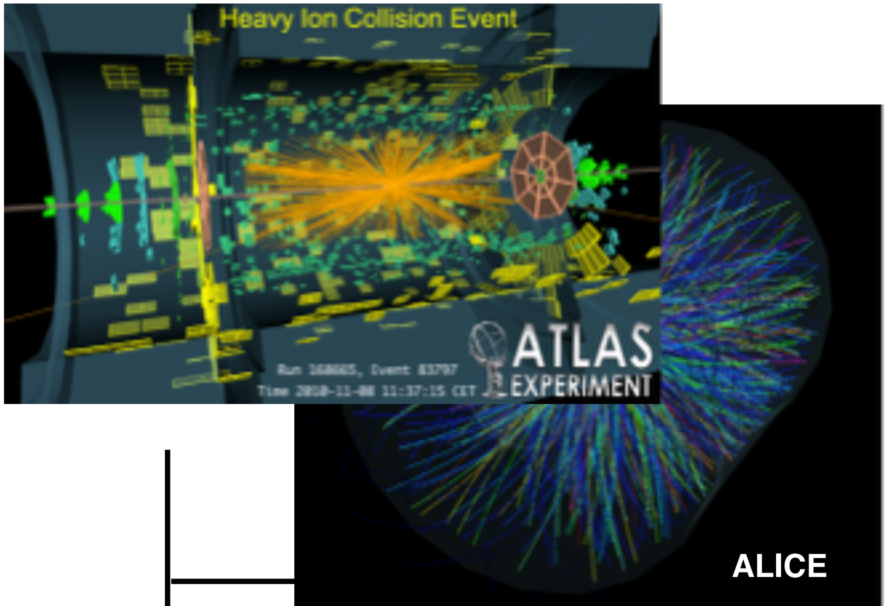
Ekkard Schnedermann,[1,2] Josef Sollfrank,[1] and Ulrich Heinz[1]
[1]*Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*
[2]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973*
(Received 14 July 1993)

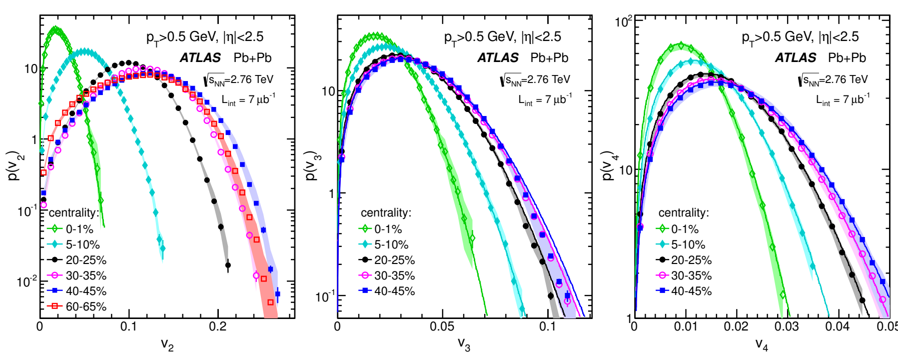
We develop a complete and consistent description for the hadron spectra from heavy ion collisions in terms of a few collective variables, in particular temperature, longitudinal, and transverse flow. To achieve a meaningful comparison with presently available data, we also include the resonance decays into our picture. To disentangle the influences of transverse flow and resonance decays in the m_T spectra, we analyze in detail the shape of the m_T spectra.

694 citations on inSPIRE-HEP

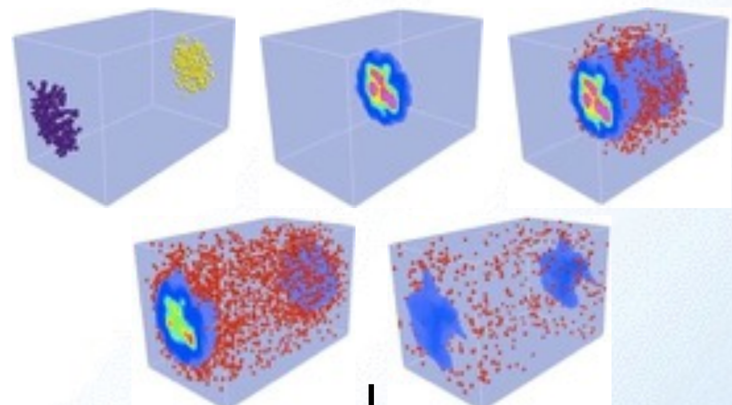
Model-data comparison today

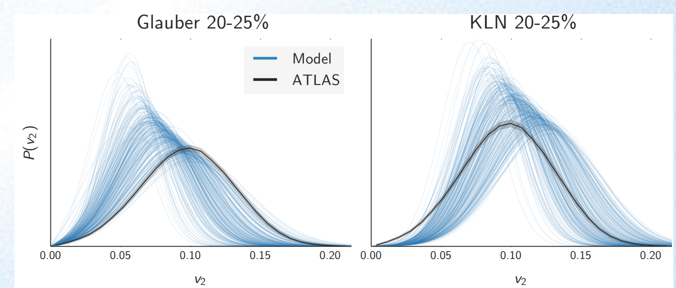
Data:





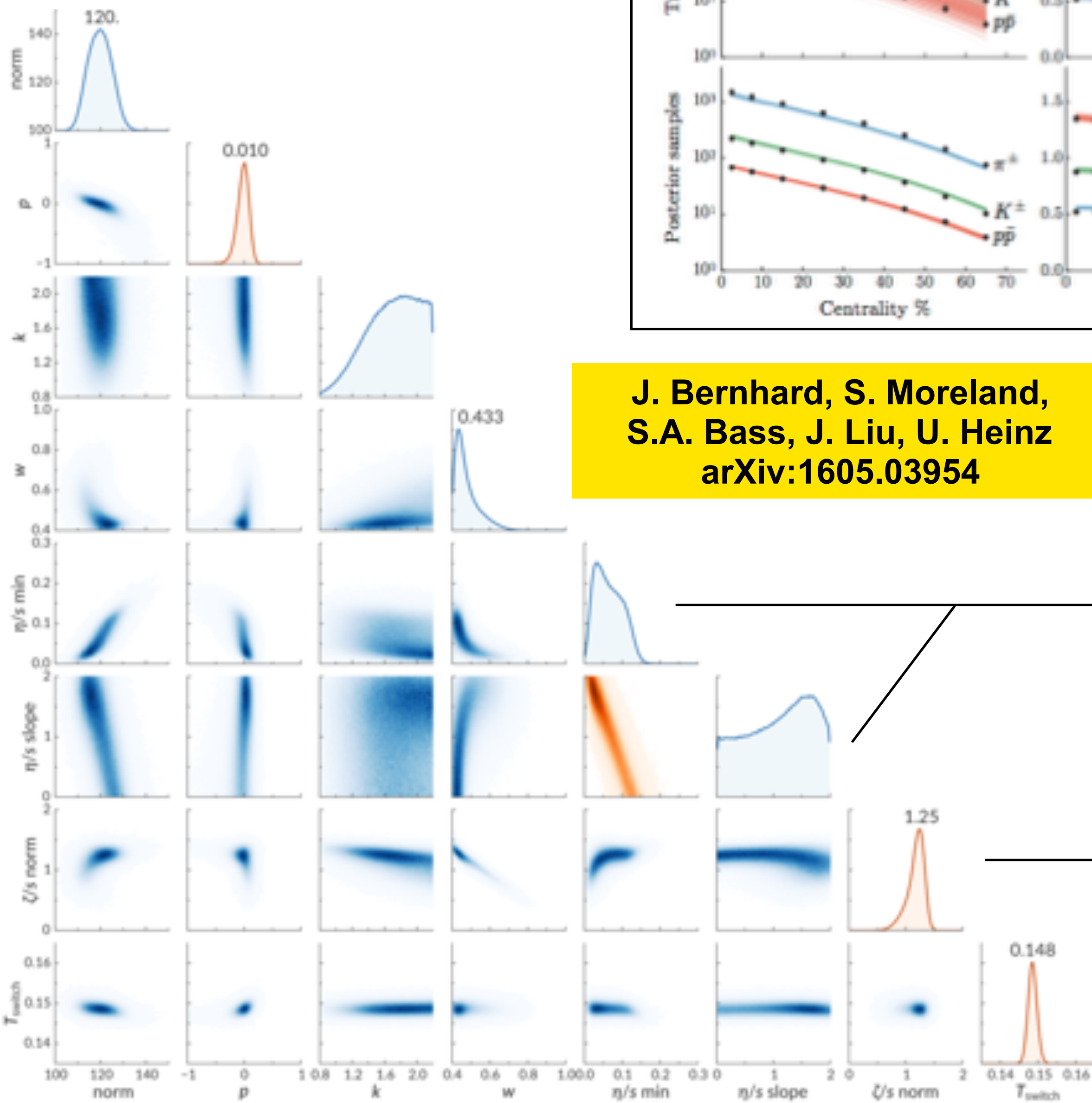
Model:
initial conditions, τ_0, η/s, ζ/s, ….

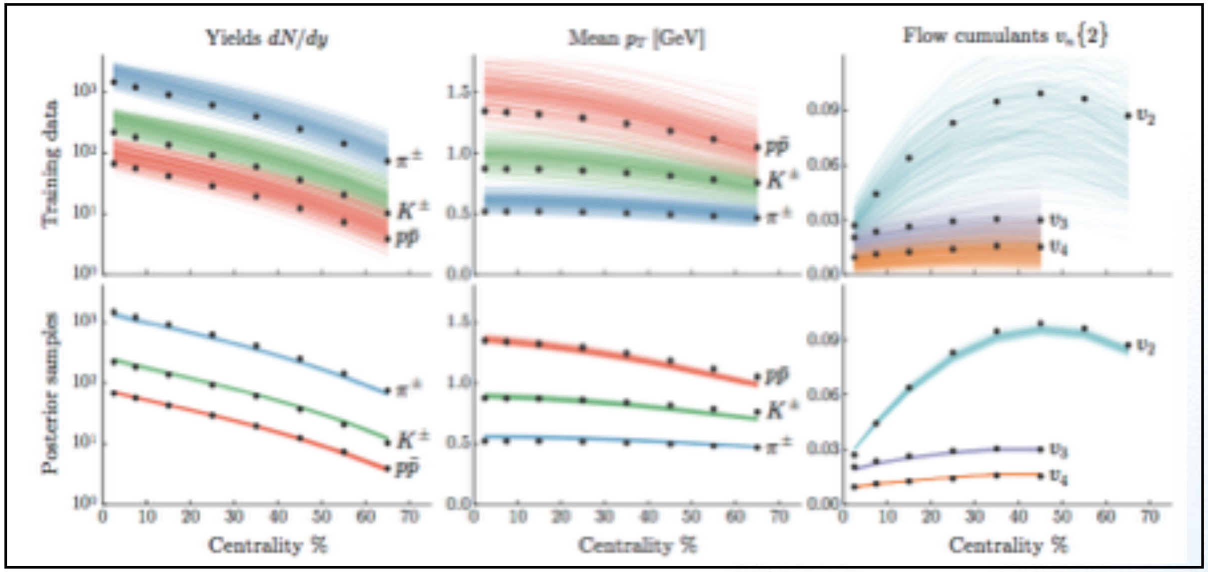




extracted QGP properties: η/s, …

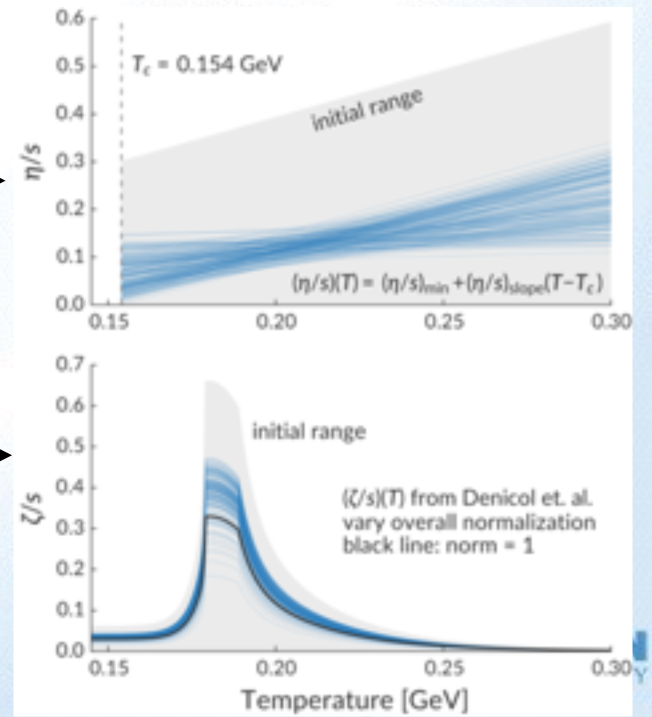
Calibrated posterior distributions:





J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz arXiv:1605.03954

Temperature-dependent viscosities from the calibrated posterior:



ELSEVIER

Physics Letters B

Volume 503, Issues 1–2, 22 March 2001, Pages 58–64

Open Access

Radial and elliptic flow at RHIC: further predictions

P. Huovinen[a], P.F. Kolb[b, c], U. Heinz[b], P.V. Ruuskanen[d], S.A. Voloshin[e]

Show more

doi:10.1016/S0370-2693(01)00219-2

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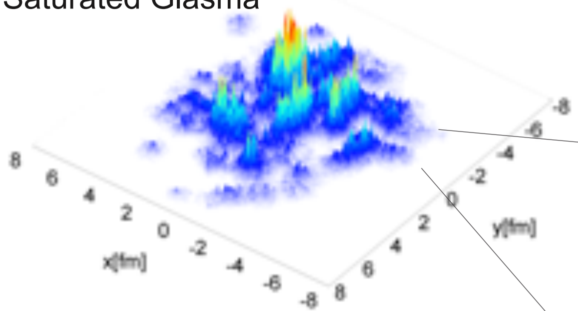
Abstract

Using a hydrodynamic model, we predict the transverse momentum dependence of the spectra and the elliptic flow for different hadrons in Au+Au collisions at $\sqrt{s} = 130A$ GeV. The dependence of the differential and p_t-integrated elliptic flow on the hadron mass, equation of state and freeze-out temperature is studied both numerically and analytically.

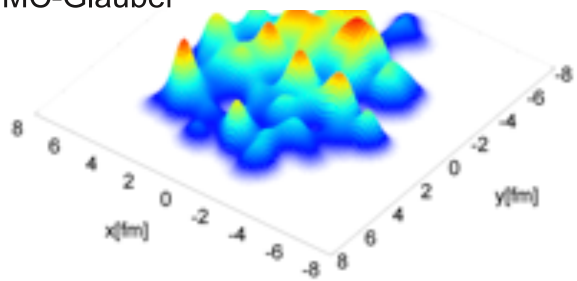
752 citations on inSPIRE-HEP

Flow analysis today

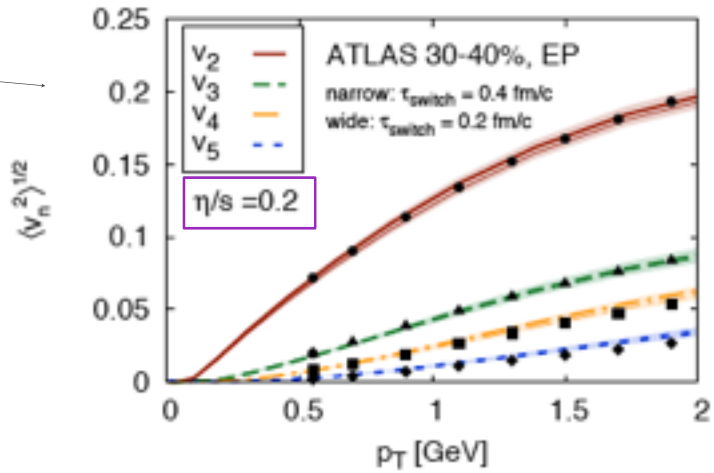
Saturated Glasma



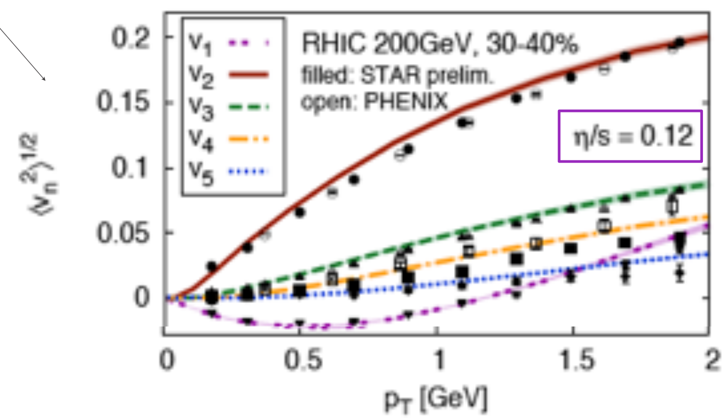
MC-Glauber



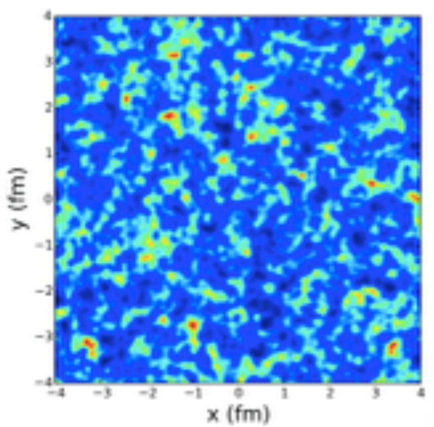
Gale, Jeon, Schenke, Tribedy, Venugopalan, arXiv:1209.6330



LHC



RHIC



Gaussian gluons energy density fluctuations:
BM & A. Schäfer, PRD 85 (2012) 114030
Moreland, Qiu & Heinz, NPA 904-5 (2013) 815c

ELSEVIER

Nuclear Physics A702 (2002) 269c–280c

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

Early thermalization at RHIC*

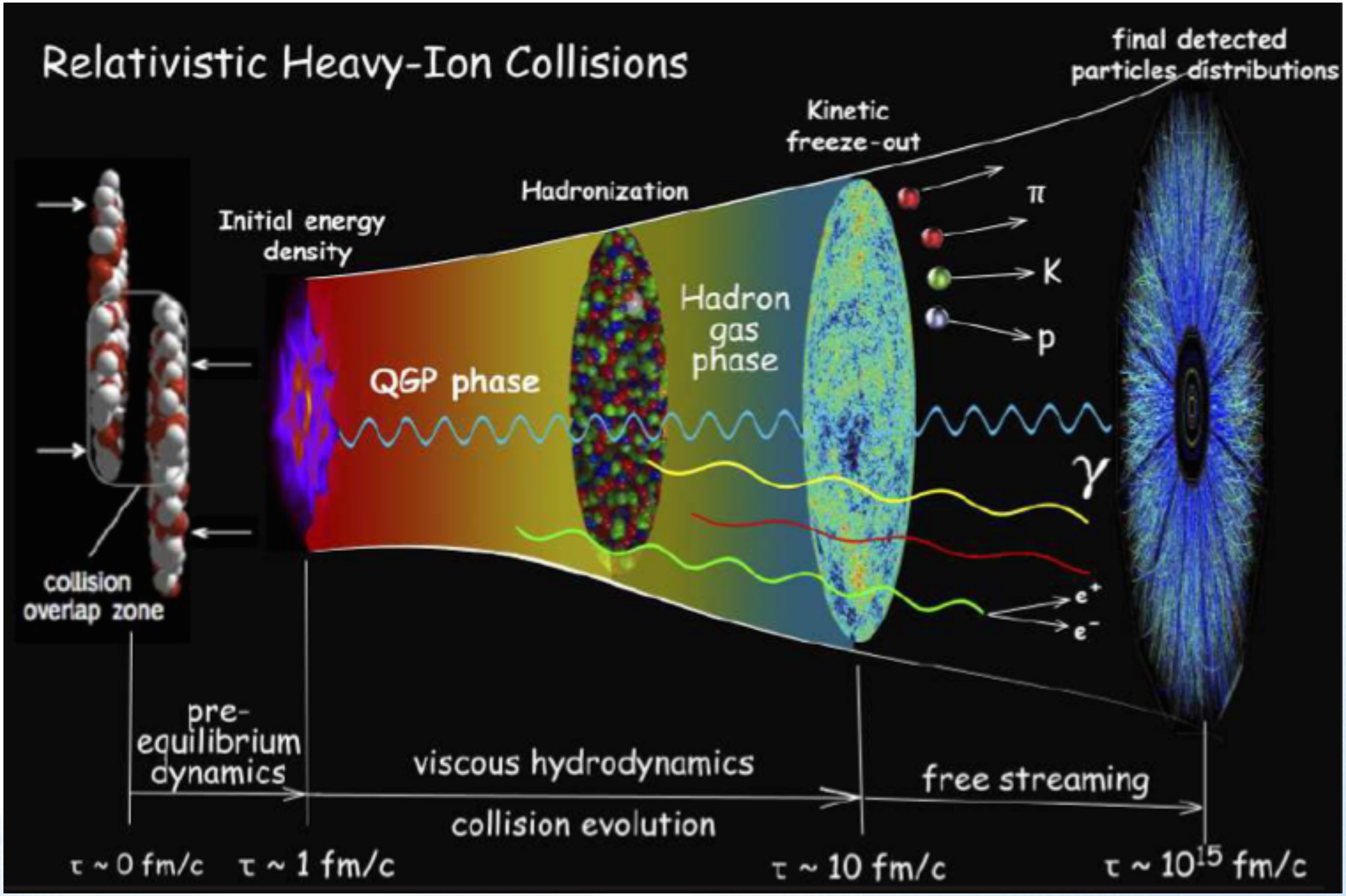
Ulrich Heinz† and Peter Kolb

Department of Physics, The Ohio State University, Columbus, OH 43210, USA

It is shown that recent RHIC data on hadron spectra and elliptic flow can be excellently reproduced within a hydrodynamic description of the collision dynamics, and that this provides strong evidence for rapid thermalization while the system is still in the quark-gluon plasma phase. But even though the hydrodynamic approach provides an impressive description of the single-particle momentum distributions, it fails to describe the two-particle momentum correlation (HBT) data for central Au+Au collisions at RHIC. We suggest that this is not likely to be repaired by further improvements in our understanding of the early collision stages, but probably requires a better modelling of the freeze-out process. We close with a prediction of the phases of the azimuthal oscillations of the HBT radii in noncentral collisions at RHIC.

272 citations on inSPIRE-HEP

Standard model of the "Little Bang"



VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

Fluctuation Probes of Quark Deconfinement

Masayuki Asakawa,[1] Ulrich Heinz,[2] and Berndt Müller[3]
[1]*Department of Physic, Nagoya University, Nagoya 464-8602, Japan*
[2]*Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*
[3]*Department of Physic, Duke University, Durham, North Carolina 27708-0305*
(Received 17 March 2000)

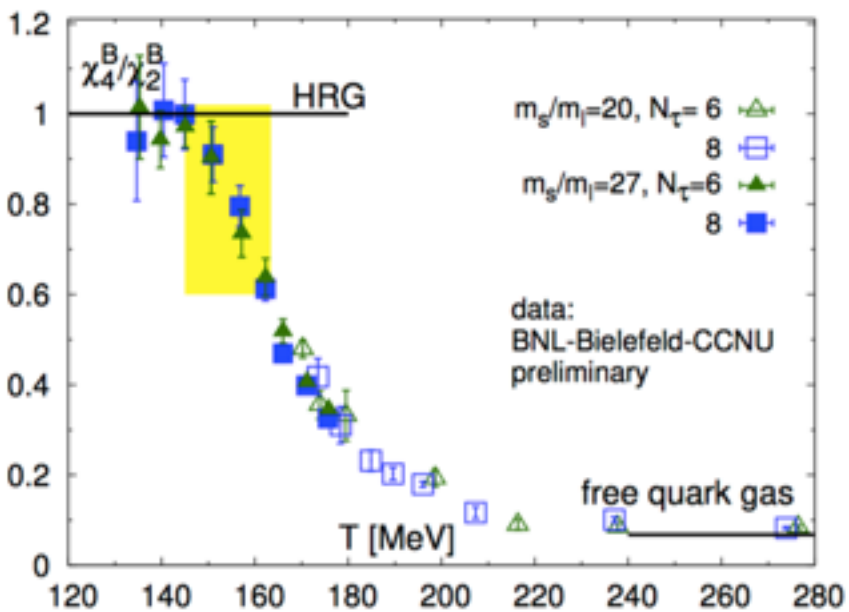
The size of the average fluctuations of net baryon number and electric charge in a finite volume of hadronic matter differs widely between the confined and deconfined phases. These differences may be exploited as indicators of the formation of a quark-gluon plasma in relativistic heavy-ion collisions, because fluctuations created in the initial state survive until freeze-out due to the rapid expansion of the hot fireball.

345 citations on inSPIRE-HEP

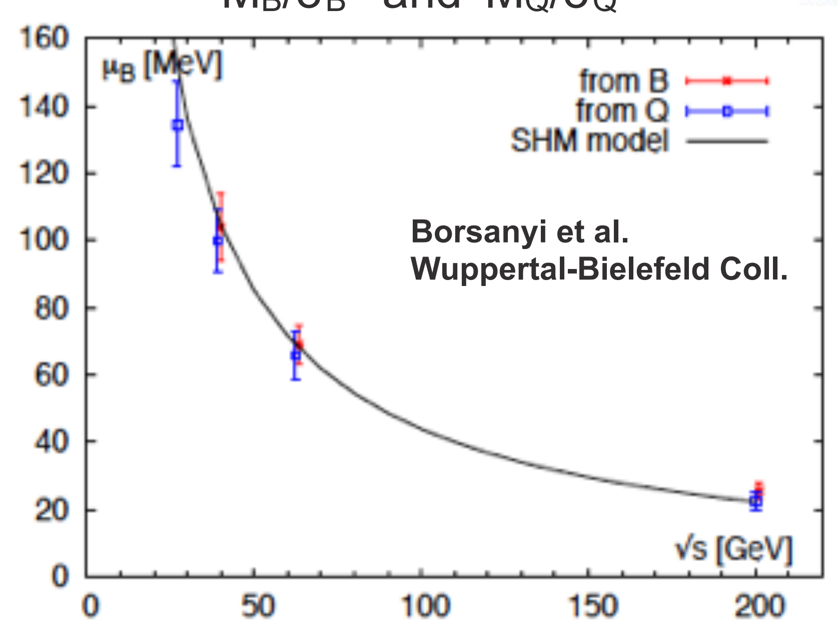
Chemical freeze-out today

… from fluctuations of conserved quantum numbers (*Q*, *B*):

Quark deconfinement from LGT

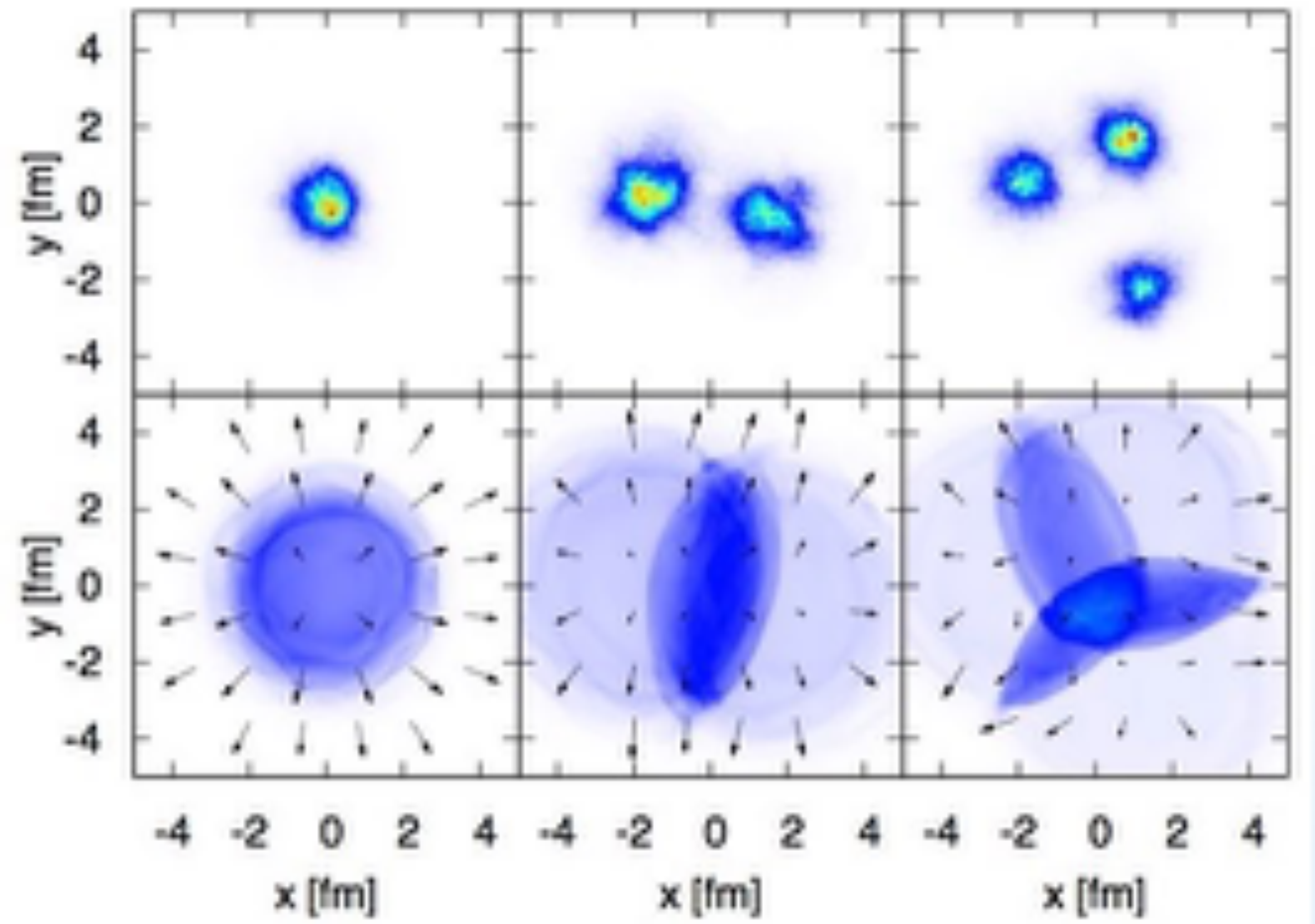


M_B/σ_B^2 and M_Q/σ_Q^2



Comparison of lattice results with the STAR data for the μ_B and Q fluctuation ratios in the temperature range 140−150 MeV permits to read off μ_B. Both methods are consistent with each other.

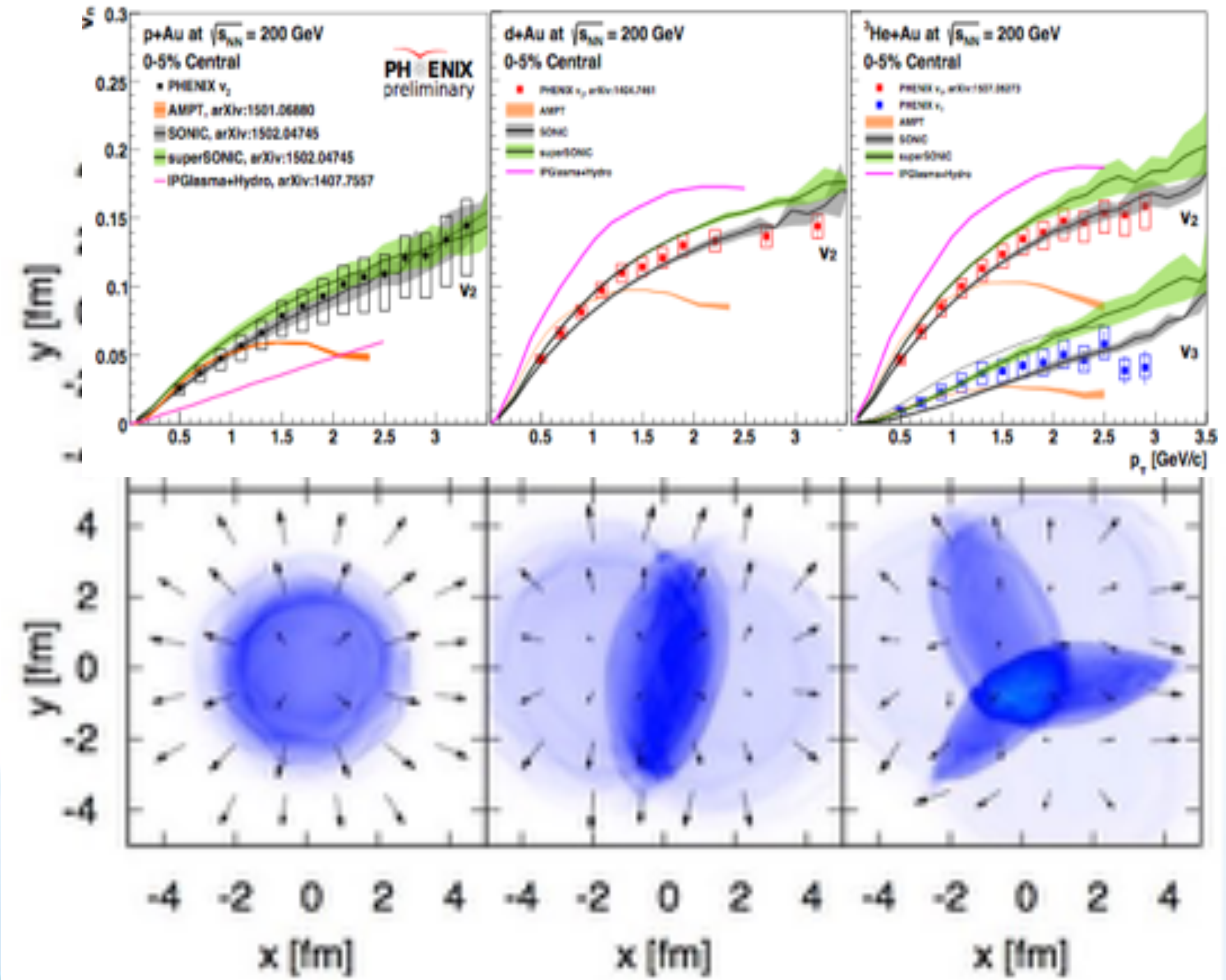
Tiny drops of QGP?



Initial state

Final state

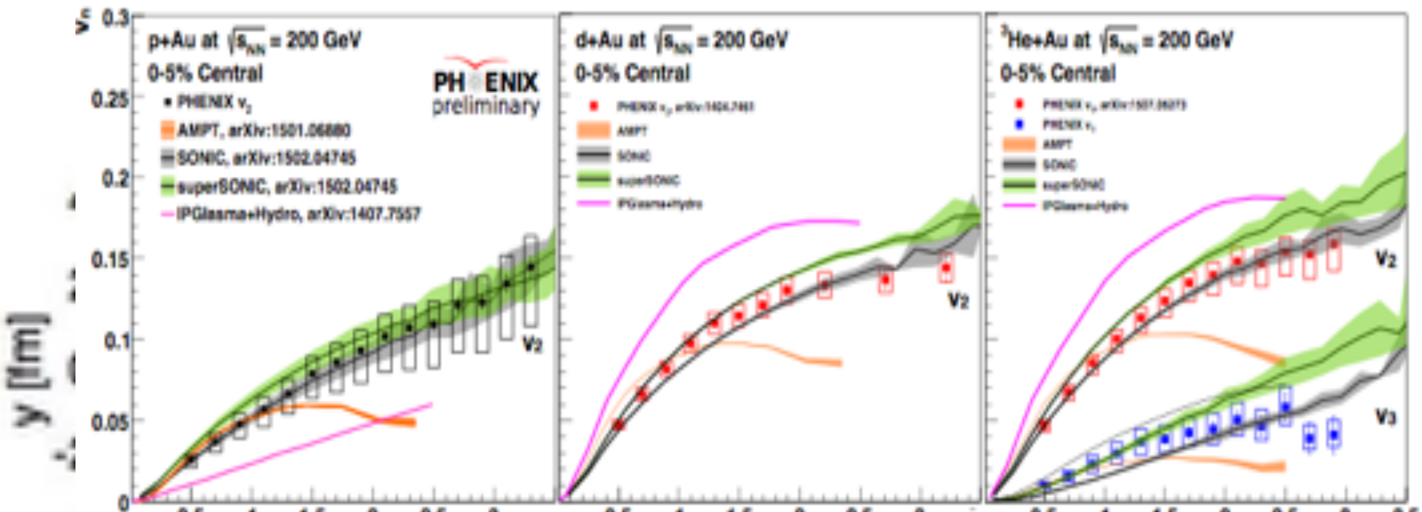
Tiny drops of QGP?



Data-Theory comparison confirms hydrodynamic collective flow

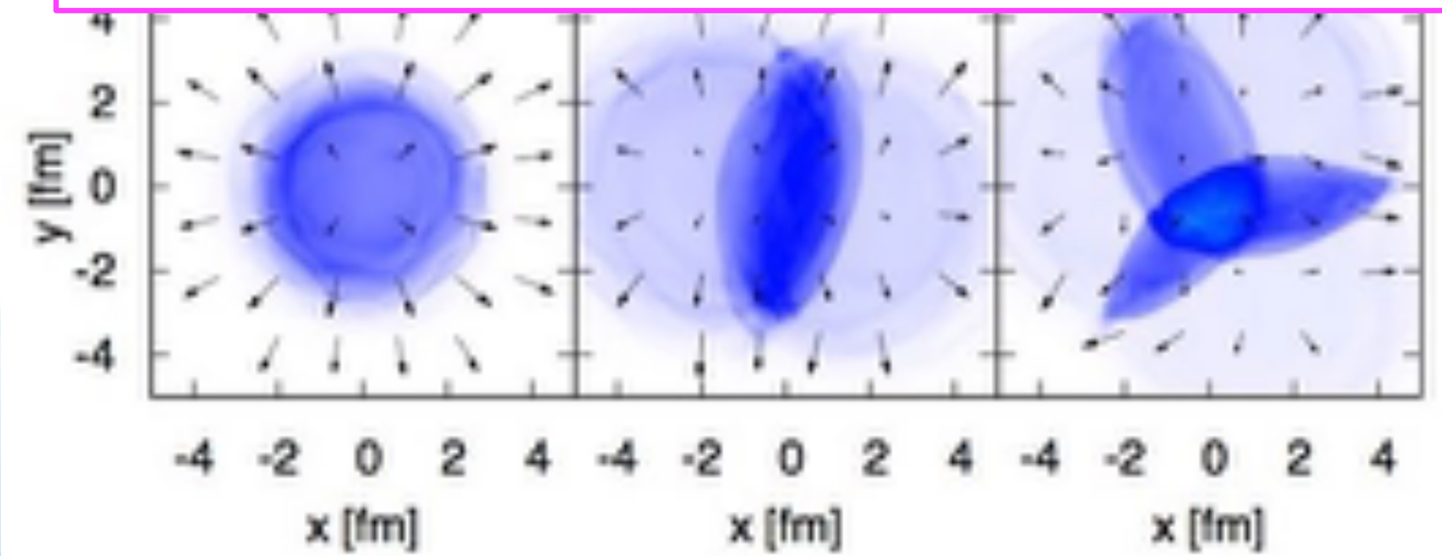
Final state

Tiny drops of QGP?



Data-Theory comparison confirms hydrodynamic collective flow

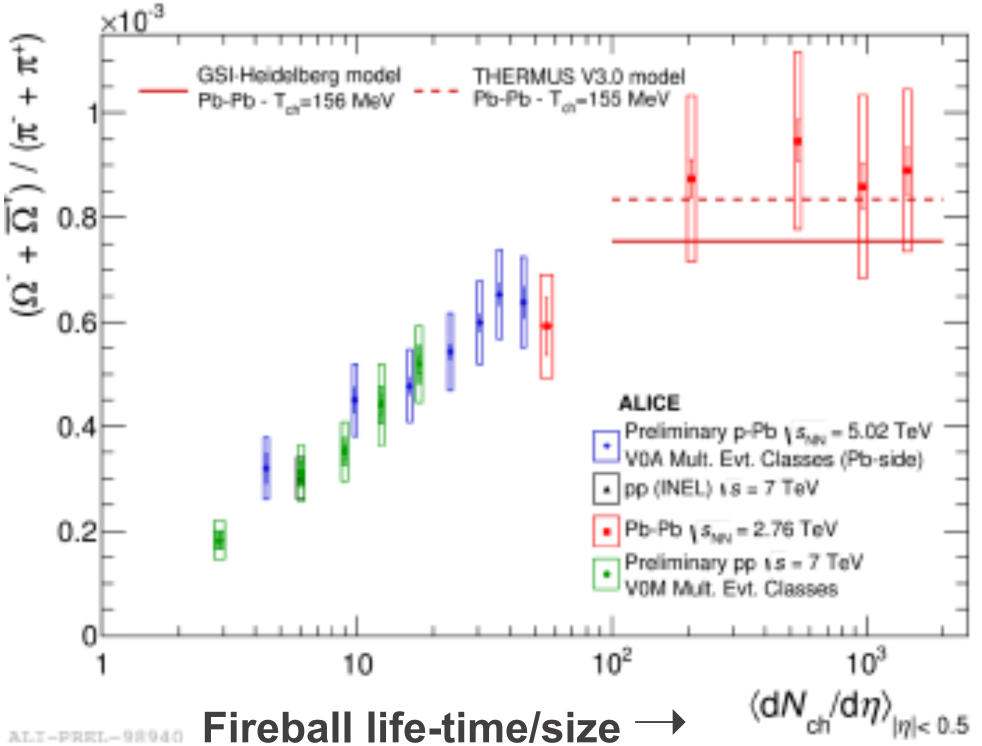
An opportunity for heavy ion theory being tackled now



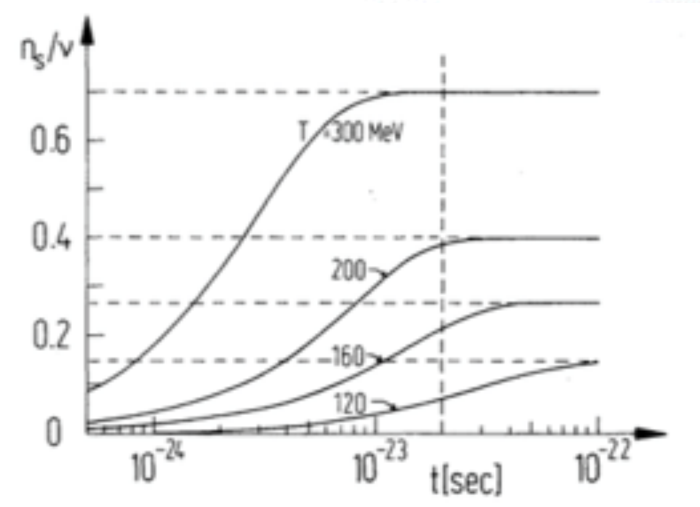
Final state

s-enhancement probes τ_{QGP}

Strangeness enhancement grows with fireball life-time / size and saturates at grand canonical equilibrium in Pb+Pb collisions



Fireball life-time/size →



J. Rafelski & BM,
PRL 48 (1982)1066

The LHC data, soon to be complemented by RHIC data from p+Au, will permit a systematic study of quark chemistry equilibration as function of the life-time and size of the QGP fireball.

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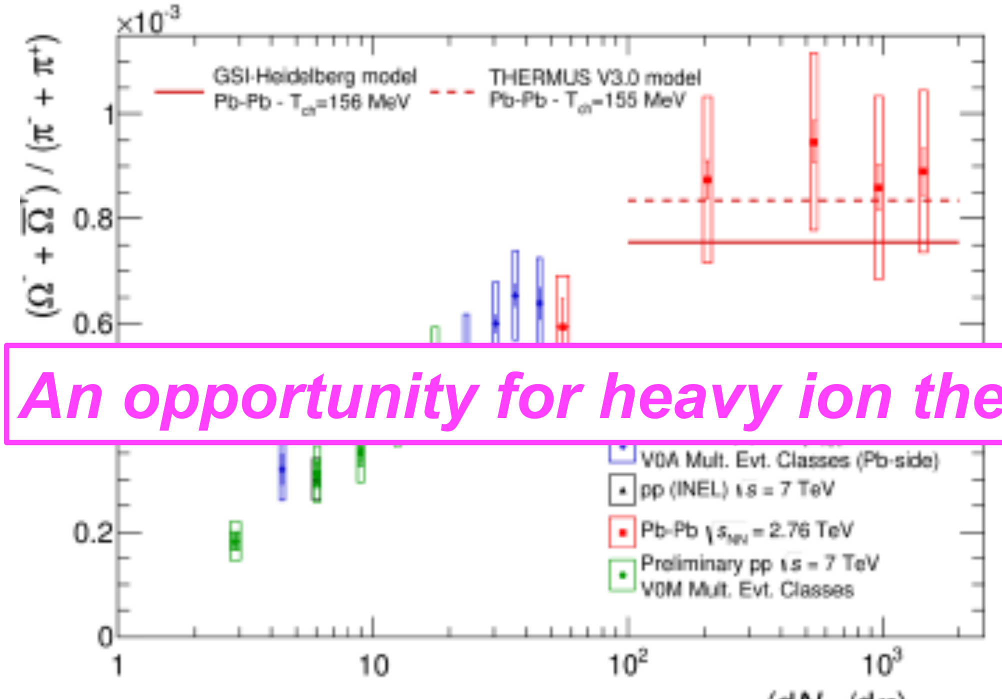
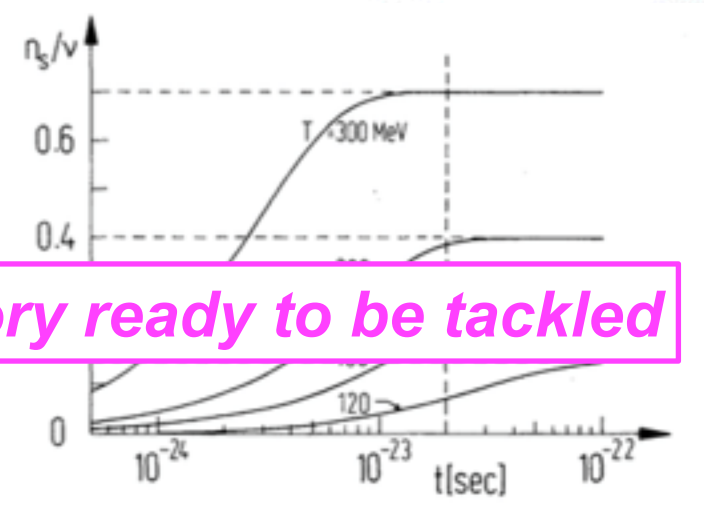


Fireball life-time/size →

An opportunity for heavy ion theory ready to be tackled



J. Rafelski & BM, PRL 48 (1982)1066

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Hot QCD matter properties & probes

Which **properties of hot QCD matter** can we hope to determine and how ?

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$$T_{\mu\nu} \Leftrightarrow \varepsilon, p, s$$

Equation of state: spectra, coll. flow, fluctuations

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$$\eta = \frac{1}{T}\int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$$

Shear viscosity: anisotropic collective flow

Very Hard for LQCD

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

$$\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0) \right\rangle$$

$$\kappa = \frac{4\pi \alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \right\rangle$$

Momentum/energy diffusion: parton energy loss, jet fragmentation

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Momentum/energy diffusion:
parton energy loss, jet fragmentation

Hard for LQCD

$$\Pi^{\mu\nu}_{\text{em}}(k) = \int d^4x\, e^{ikx} \left\langle j^\mu(x) j^\nu(0) \right\rangle$$

QGP Radiance: Lepton pairs, photons

Hot QCD matter properties & probes

Which **properties of hot QCD matter** can we hope to determine and how ?

Easy for LQCD	$T_{\mu\nu} \Leftrightarrow \varepsilon, p, s$	**Equation of state**: spectra, coll. flow, fluctuations
	$\eta = \frac{1}{T}\int d^4x \langle T_{xy}(x) T_{xy}(0)\rangle$	**Shear viscosity**: anisotropic collective flow
Very Hard for LQCD	$\hat{q} = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0)\rangle$ $\hat{e} = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \langle i U^\dagger \partial^- A^{a+}(y^-) U A^{a+}(0)\rangle$ $\kappa = \frac{4\pi\alpha_s}{3N_c}\int d\tau \langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b\rangle$	**Momentum/energy diffusion**: parton energy loss, jet fragmentation
Hard for LQCD	$\Pi_{\rm em}^{\mu\nu}(k) = \int d^4x\, e^{ikx}\langle j^\mu(x) j^\nu(0)\rangle$	**QGP Radiance**: Lepton pairs, photons
Easy for LQCD	$m_D = -\lim_{\lvert x\rvert\to\infty}\frac{1}{\lvert x\rvert}\ln\langle U^\dagger E^a(x) U E^a(0)\rangle$	**Color screening**: Quarkonium states

Hot QCD matter properties & probes

Which **properties of hot QCD matter** can we hope to determine and how ?

The ultimate challenge for heavy ion theory

Difficulty	Quantity	Property: probes
Easy for LQCD	$T_{\mu\nu} \Leftrightarrow \varepsilon, p, s$	**Equation of state**: spectra, coll. flow, fluctuations
	$\eta = \frac{1}{T}\int d^4x \langle T_{xy}(x) T_{xy}(0) \rangle$	**Shear viscosity**: an[illegible]ctive flow
Very Hard for LQCD	$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle U^\dagger F^{a+i}(y^-) U F^{a+} \ldots$ [illegible] $\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N^2 \ldots}$ [illegible] $\ldots) U A^{a+}(0) \rangle$ [illegible] $\ldots N_c} \int d\tau \langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b \rangle$	**Momentum/energy diffusion**: parton energy loss, jet fragmentation
Hard for LQCD	$\Pi^{\mu\nu}_{\rm em}(k) = \int d^4x\, e^{ikx} \langle j^\mu(x) j^\nu(0) \rangle$	**QGP Radiance**: Lepton pairs, photons
Easy for LQCD	$m_D = -\lim_{\lvert x \rvert \to \infty} \frac{1}{\lvert x \rvert} \ln \langle U^\dagger E^a(x) U E^a(0) \rangle$	**Color screening**: Quarkonium states

RHIC:
Looking Ahead

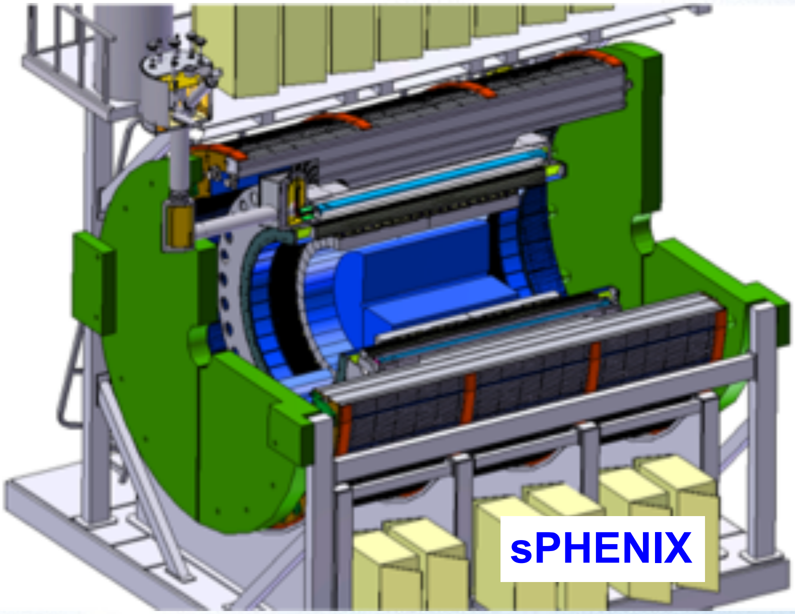
Continuing the RHIC scientific mission

Status: RHIC-II configuration is operational

- **RHIC reached 44 times design luminosity**

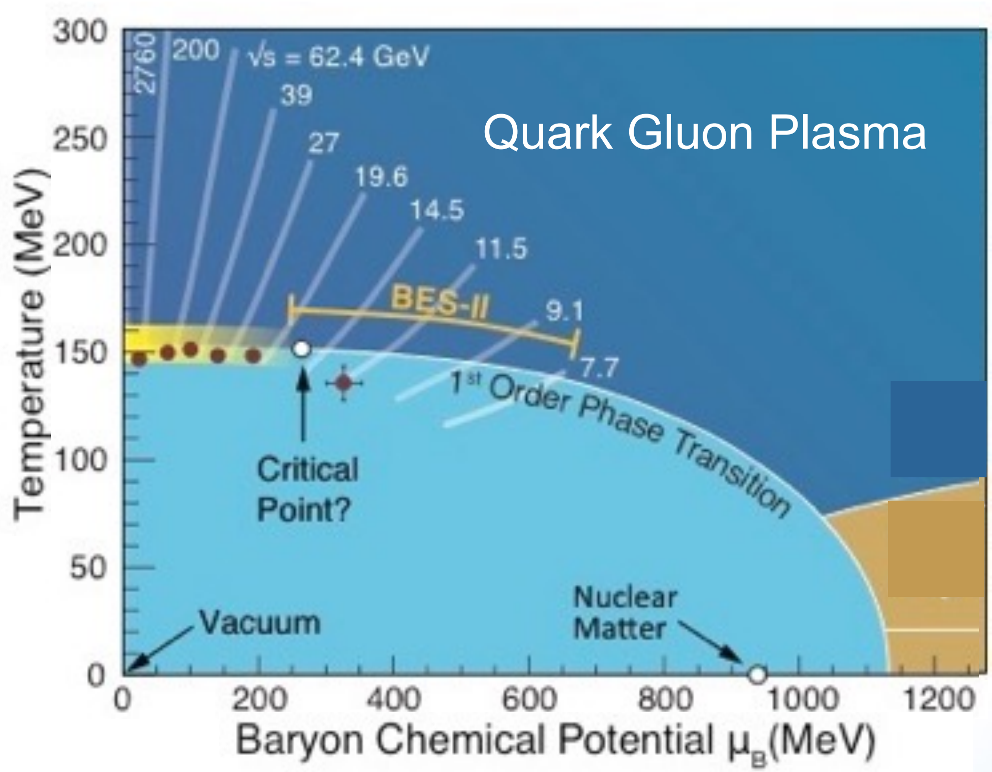
Plan:

- **2014−16: Heavy flavor program (complete)**
- **2017: Transverse spin physics in QCD**
- **2018: Isobar system test of chiral symmetry**
- ***2018: Low energy e-cooling & iTPC upgrade***
- **2019−20: High precision scan of the QCD phase diagram & search for critical point**
- ***2021: Install sPHENIX***
- **2022−??: Probe structure of perfect liquid QGP with precision measurements of jet quenching and other hard QCD probes**



RHIC remains a unique discovery facility

Studying the Phases of QCD with RHIC



Breaking of chiral symmetry in QCD generates most of the visible mass of the universe. Is chiral symmetry restored in these collisions?

At low density, the phase transition between QGP and hadrons is smooth. Is there a 1st order transition and a critical point at higher density?

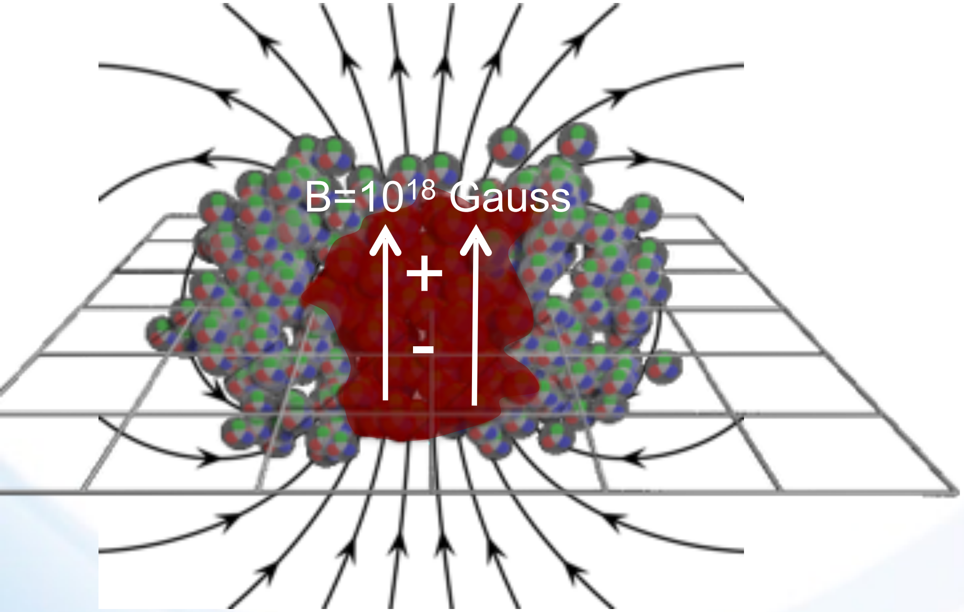
Probing Chiral Symmetry with Quantum Currents

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

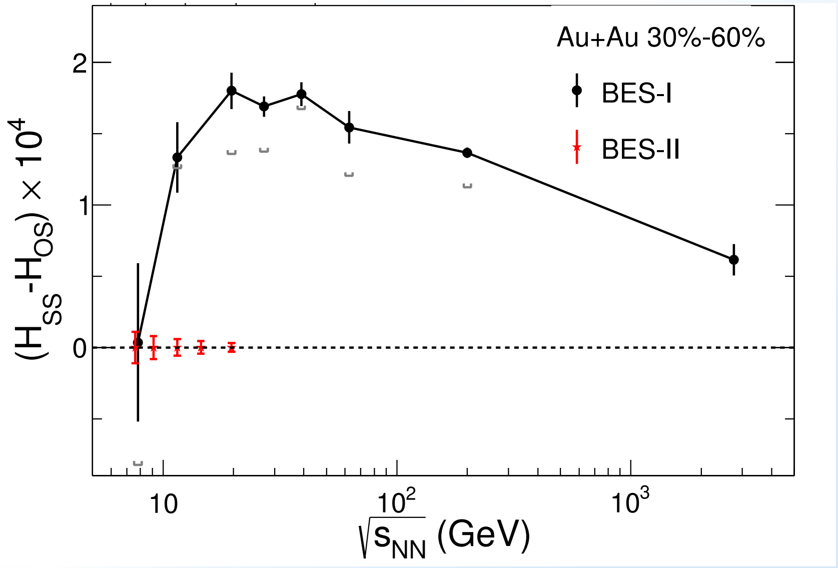
A similar mechanism in the electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

In a chirally symmetric QGP, this imbalance can create charge separation along the magnetic field (chiral magnetic effect – just discovered in CM at BNL)

charge separation



observed at all but the lowest energy

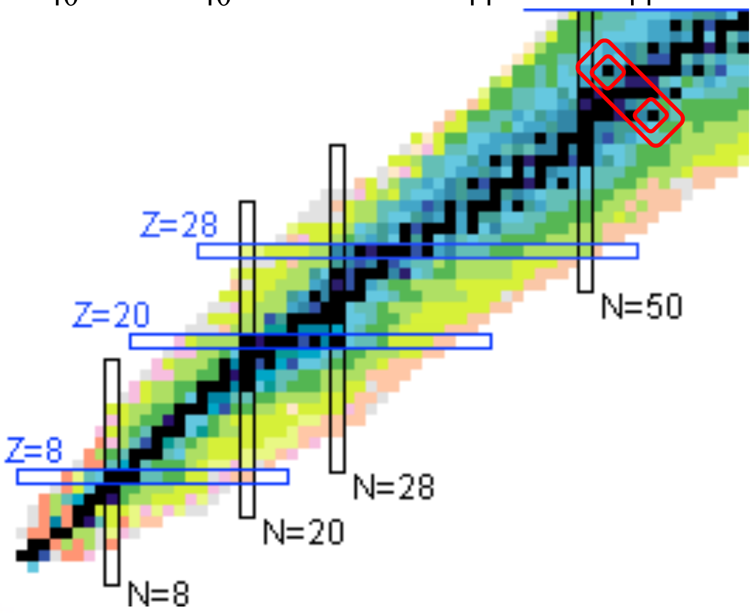


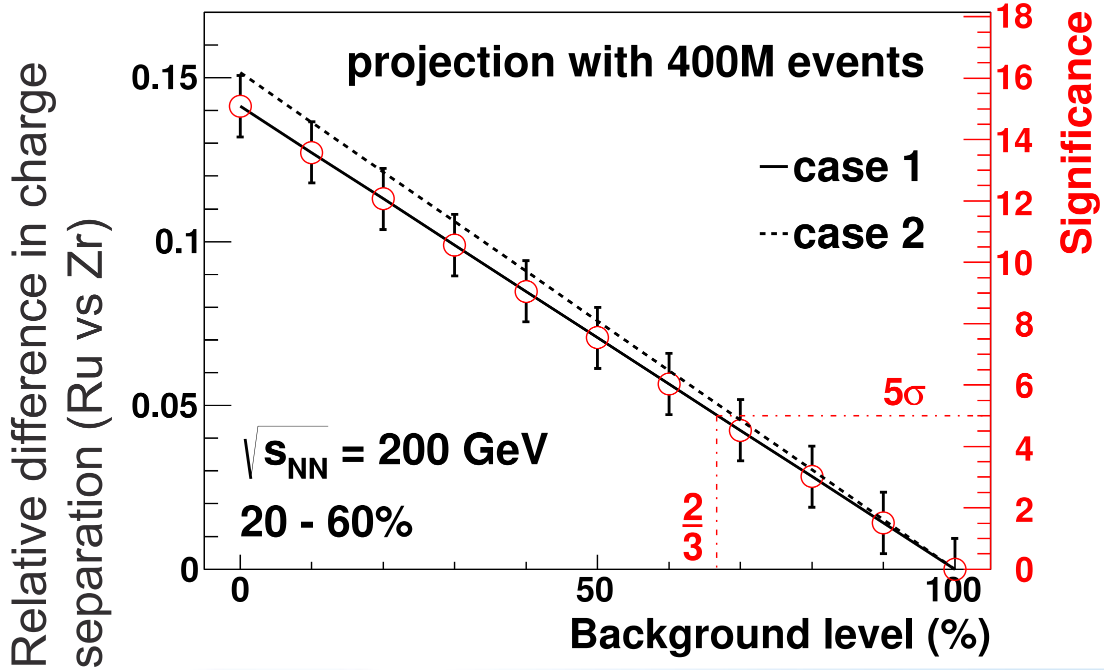
But models with magnetic field-independent flow backgrounds can also be tuned to reproduce the observed charge separation.

Probing Chiral Symmetry (Run-18)

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation

$^{96}_{40}Zr + ^{96}_{40}Zr$ vs. $^{96}_{44}Ru + ^{96}_{44}Ru$

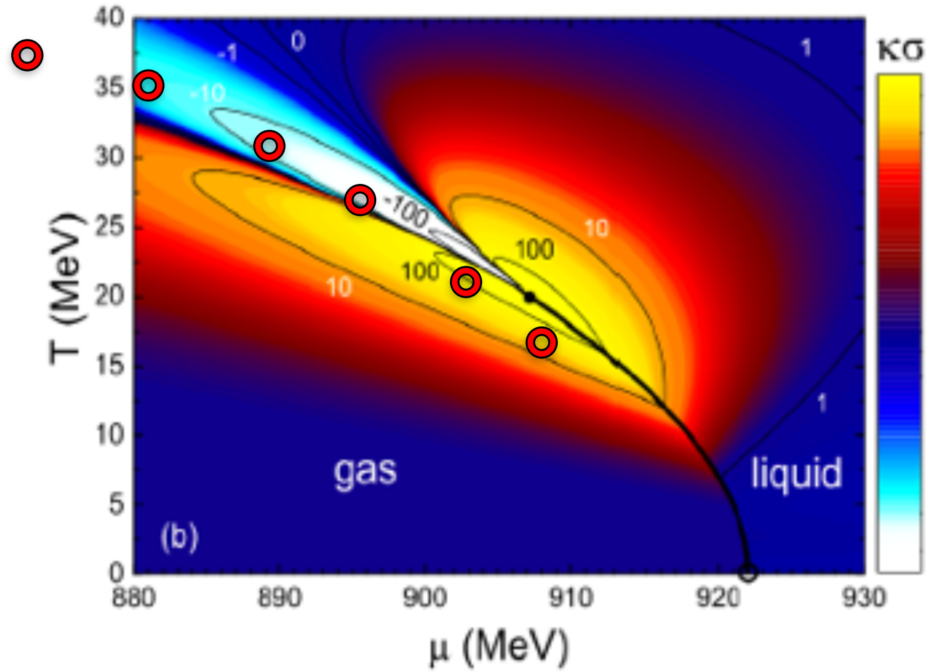


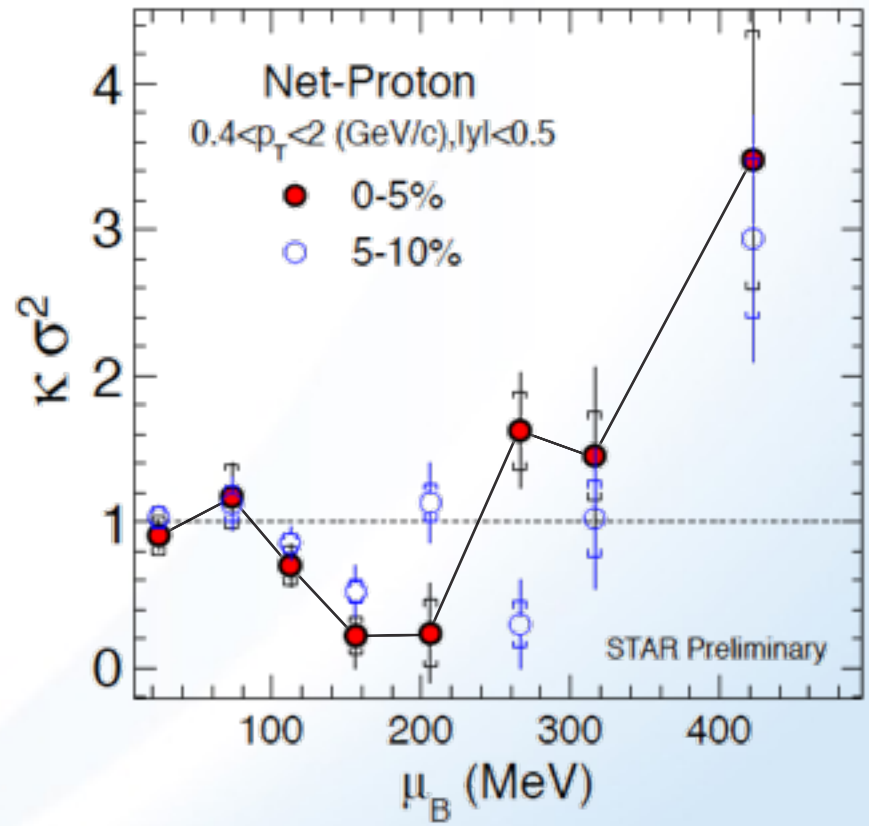


Isobar collisions will tell us what fraction of the charge separation is due to CME to within +/- 6% of the observed signal

Critical behavior?

The moments of the distributions of conserved charges are related to susceptibilities and are sensitive to critical fluctuations





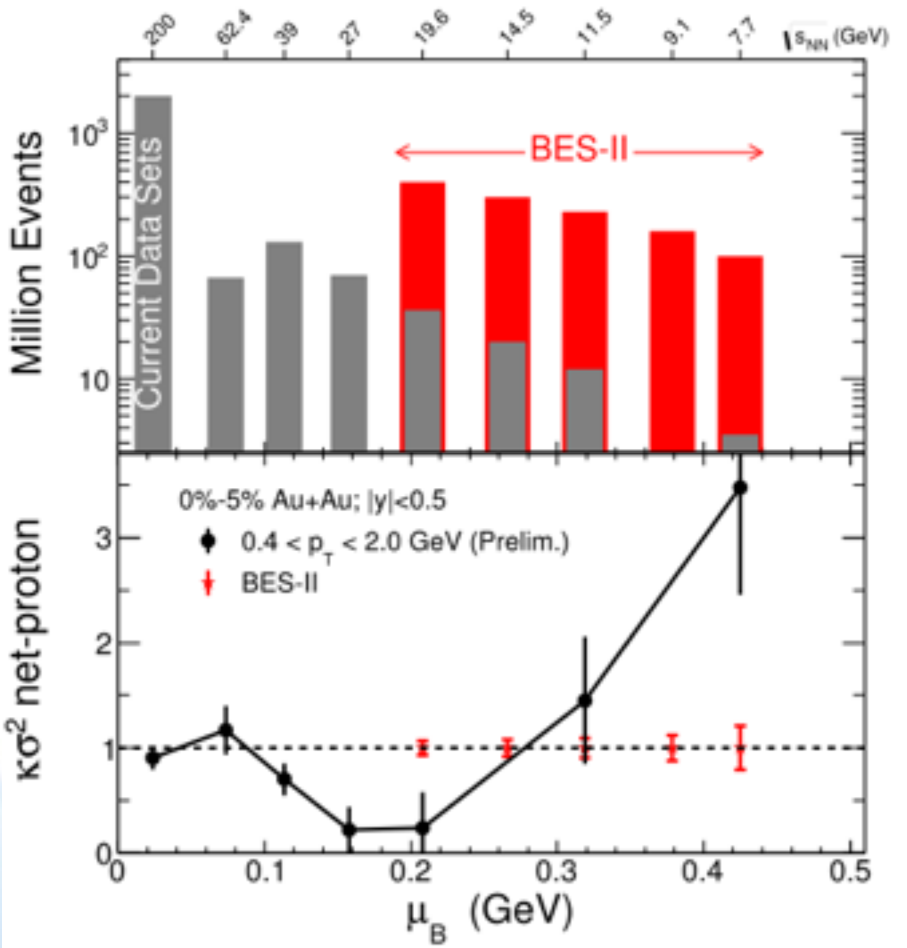
Higher moments like kurtosis*variance $\kappa\sigma^2$ change sign near the critical point

Non-monotonic trend observed in BES-I with limited statistical precision!

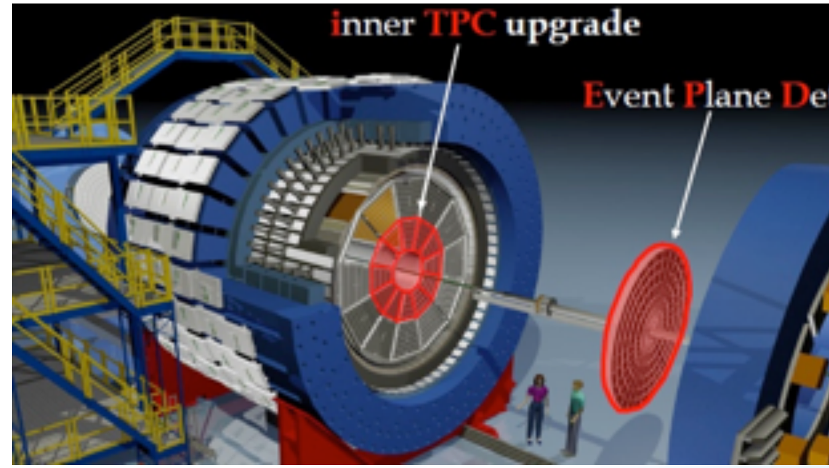
Mapping the QCD phase diagram in BES-II

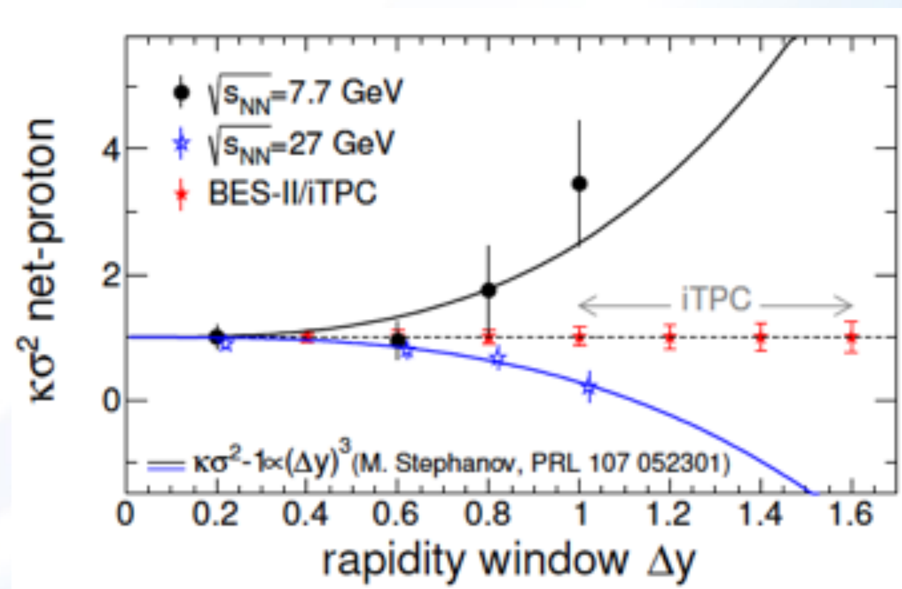
Higher statistics

Low energy RHIC electron cooling upgrade



Larger acceptance





The overarching scientific question:

How do asymptotically free quarks and gluons
create the near-perfect liquidity of the QGP?

or

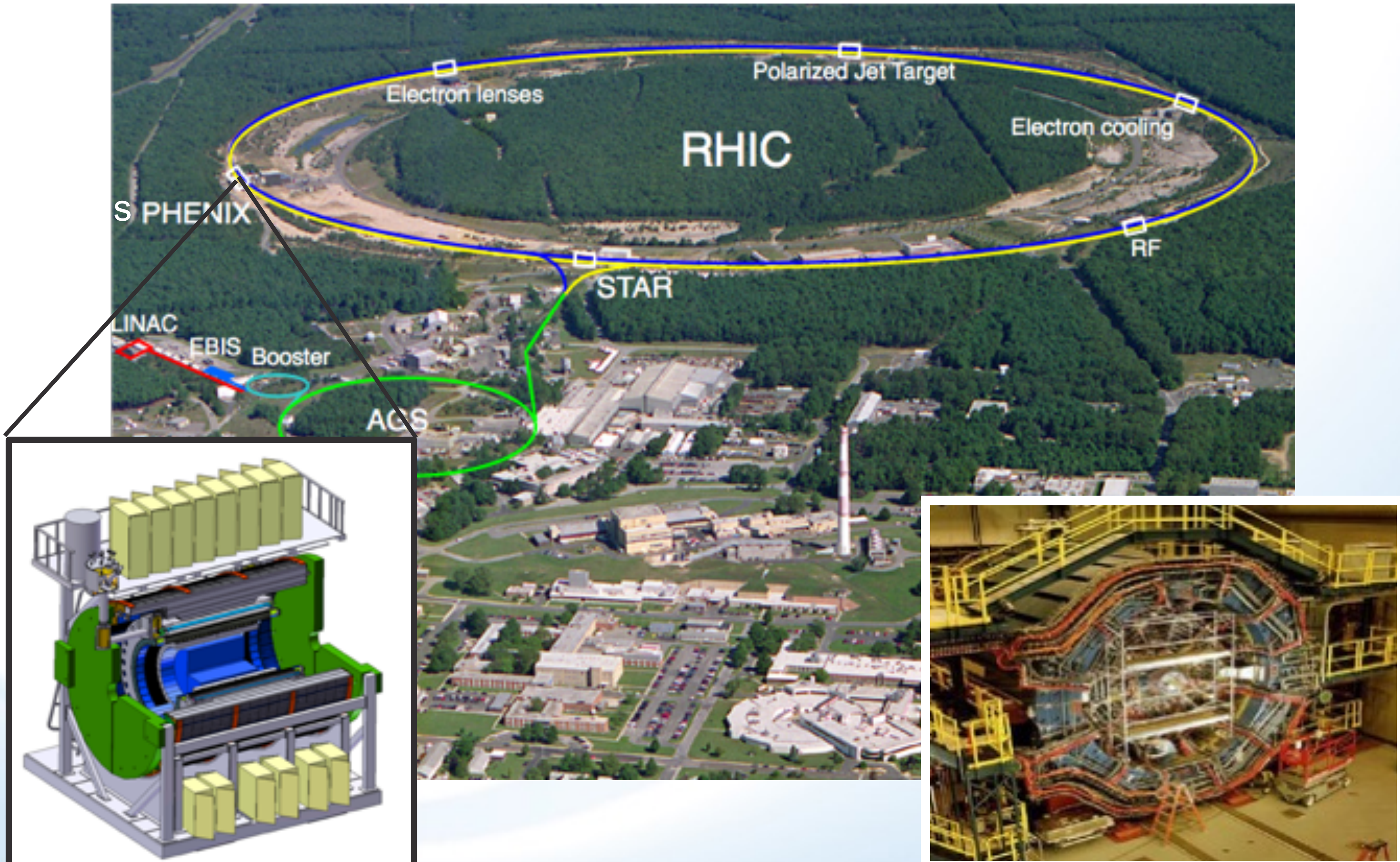
What degrees of freedom
not manifest in the QCD Lagrangian
produce the near-perfect liquidity of the QGP?

The (experimental) answer:

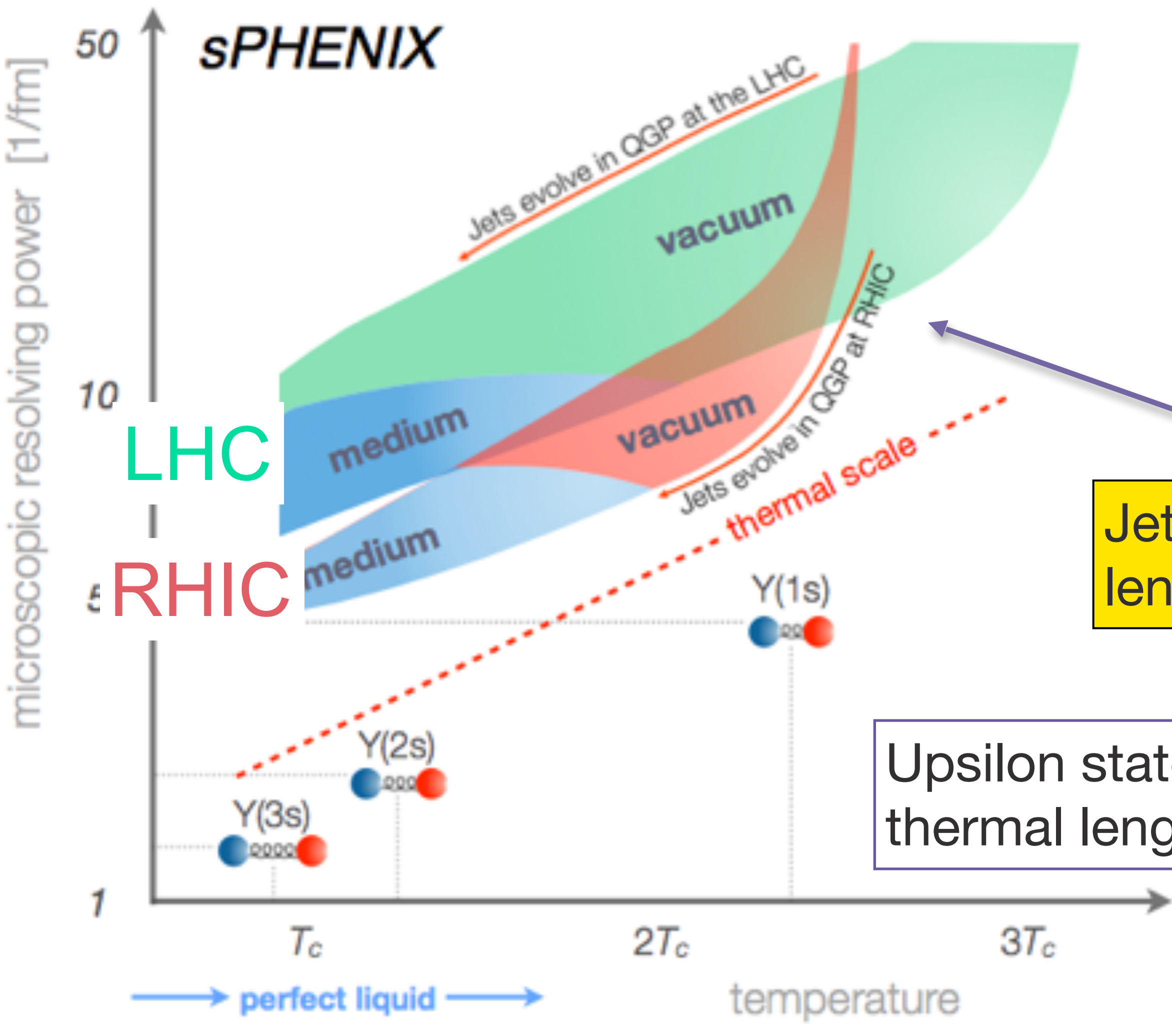
Deploy probes with a resolution that reaches well
below the thermal ~ 1 fm scale of the bulk:

Jets & b-quark (Upsilon) states

The RHIC Facility in 2022



Probing scales in the medium

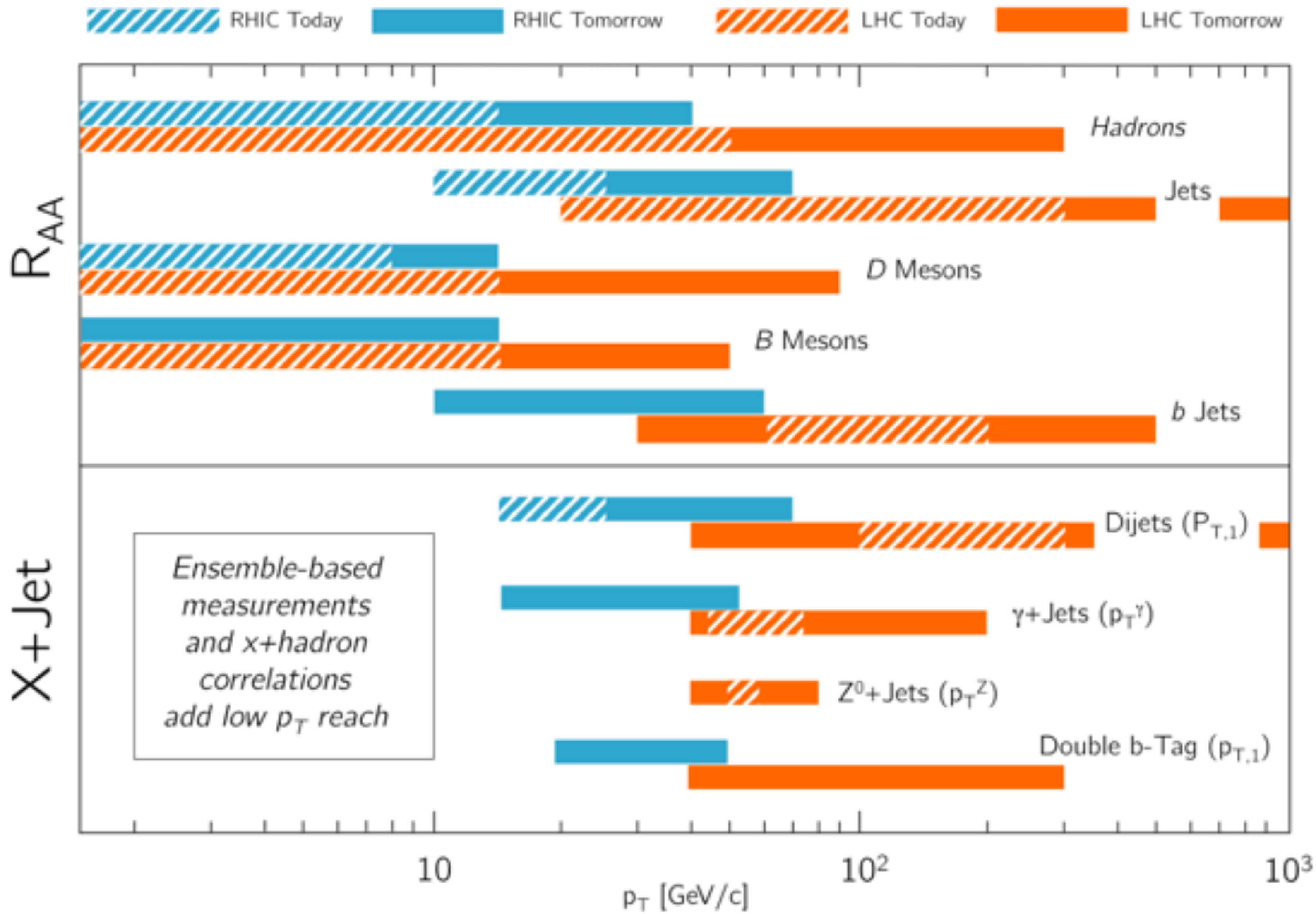


How does the perfect fluidity of the QGP emerge from the asymptotically free theory of QCD?

Jets probe sub-thermal length scales

Upsilon states probe thermal length scales

RHIC & LHC complementarity



The Future of Ultrarelativistic Heavy-ion Collisionz is Bright !