From T_c to Q_s: Quarks and Gluons at High Temperature and High Density

3rd International Symposium
Quest for the Origin of Particles and the Universe
KMI, Nagoya, Japan

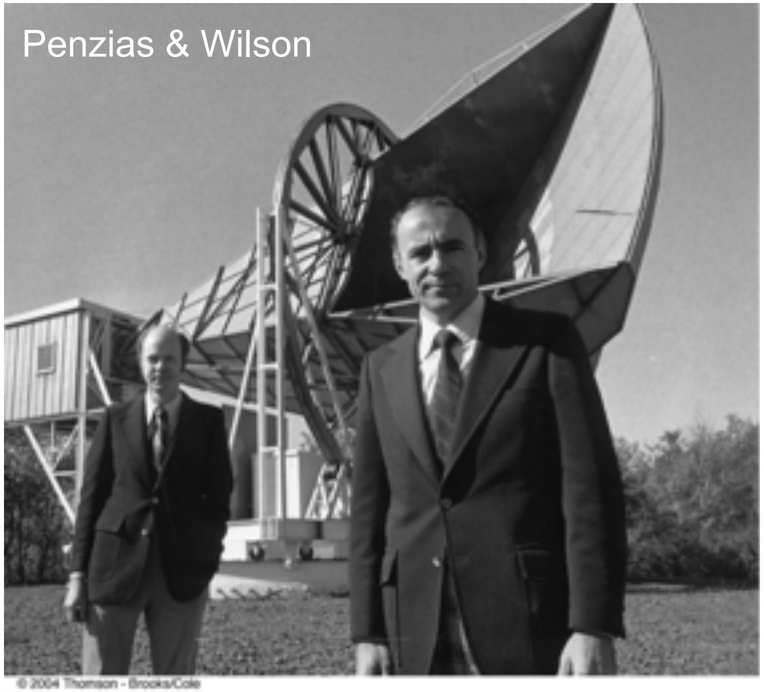
Berndt Mueller

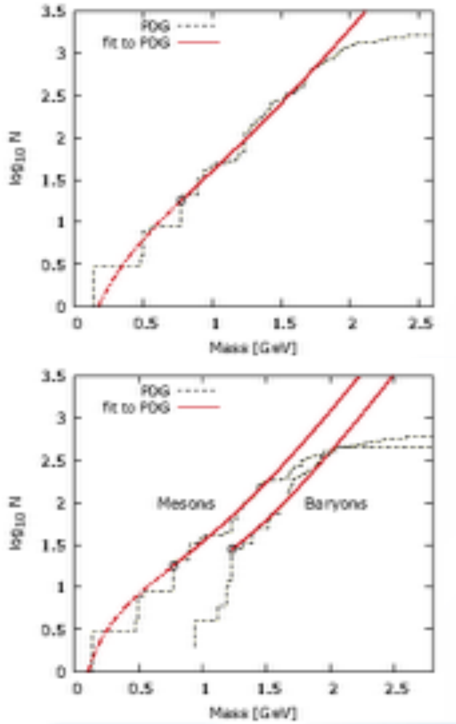
January 5-7, 2017

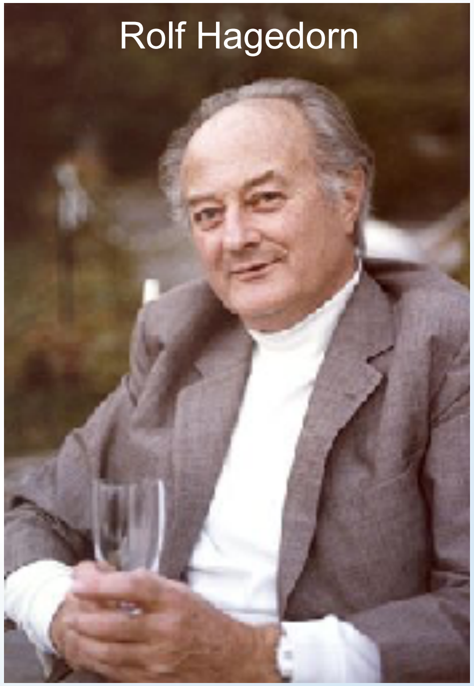
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
Office of Science
U.S. DEPARTMENT OF ENERGY

1965

A year of momentous discoveries







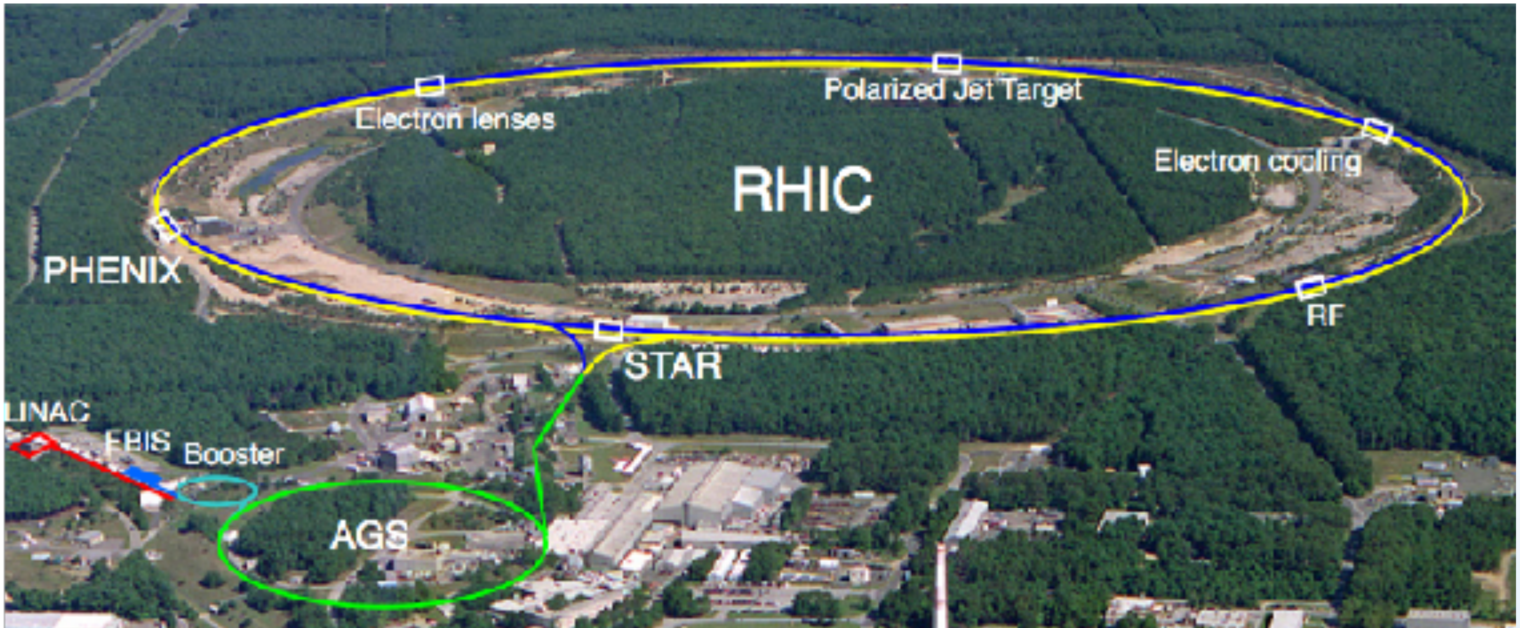
Cosmic microwave background

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 lattice.
- The experiments at RHIC showed (and the LHC confirmed) that matter above $T_c \approx 155$ MeV is composed of unconfined quarks and gluons and flows like an almost inviscid liquid with η/s near the quantum limit $(4\pi)^{-1}$.

RHIC: Champion of versatility



LHC: Champion of energy

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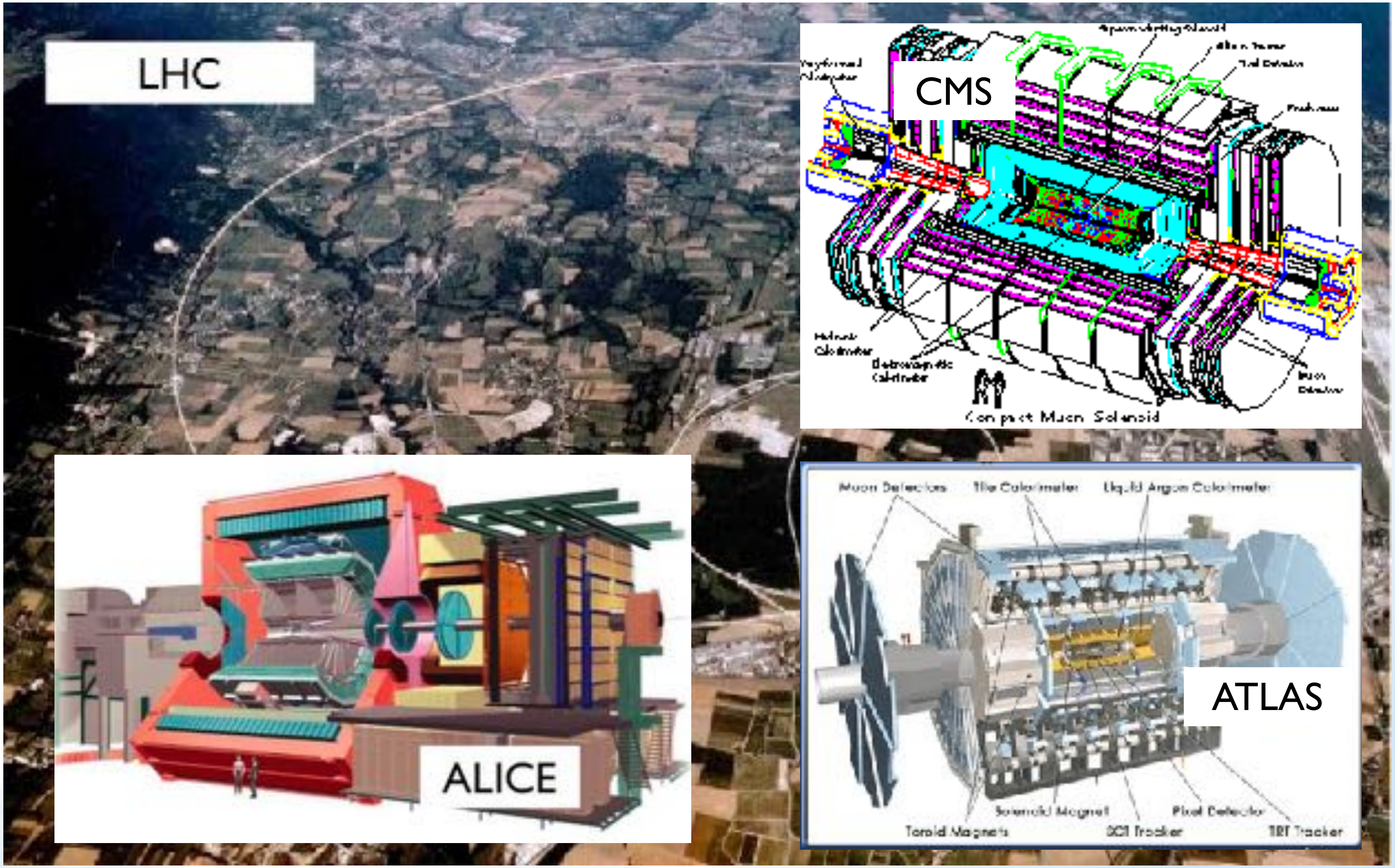


Exploring the Phases of Nuclear Matter

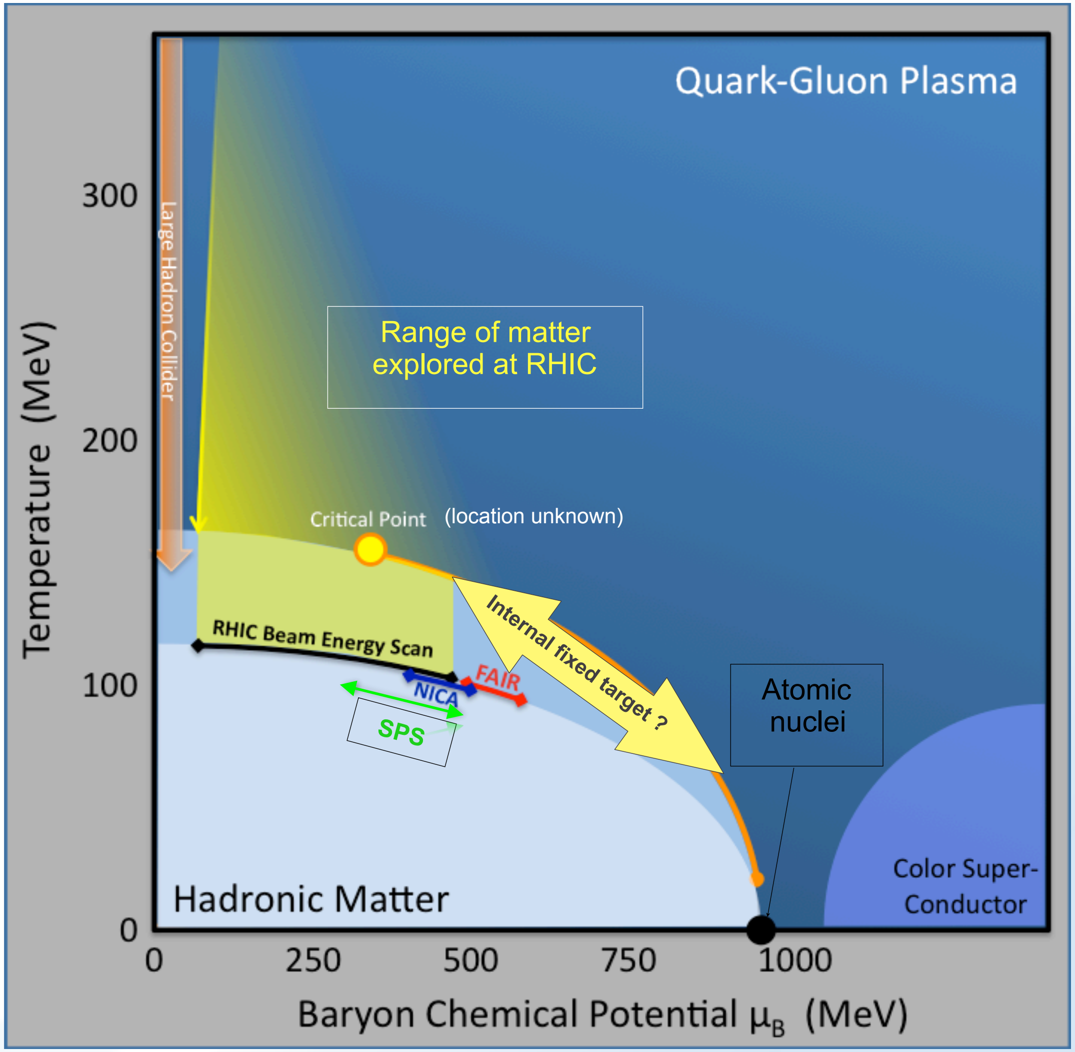
RHIC is ideally suited to explore the Quark-Gluon Plasma and map the QCD matter phase diagram.

RHIC has defined a multi-year program to execute its scientific mission. We just completed Year 3.

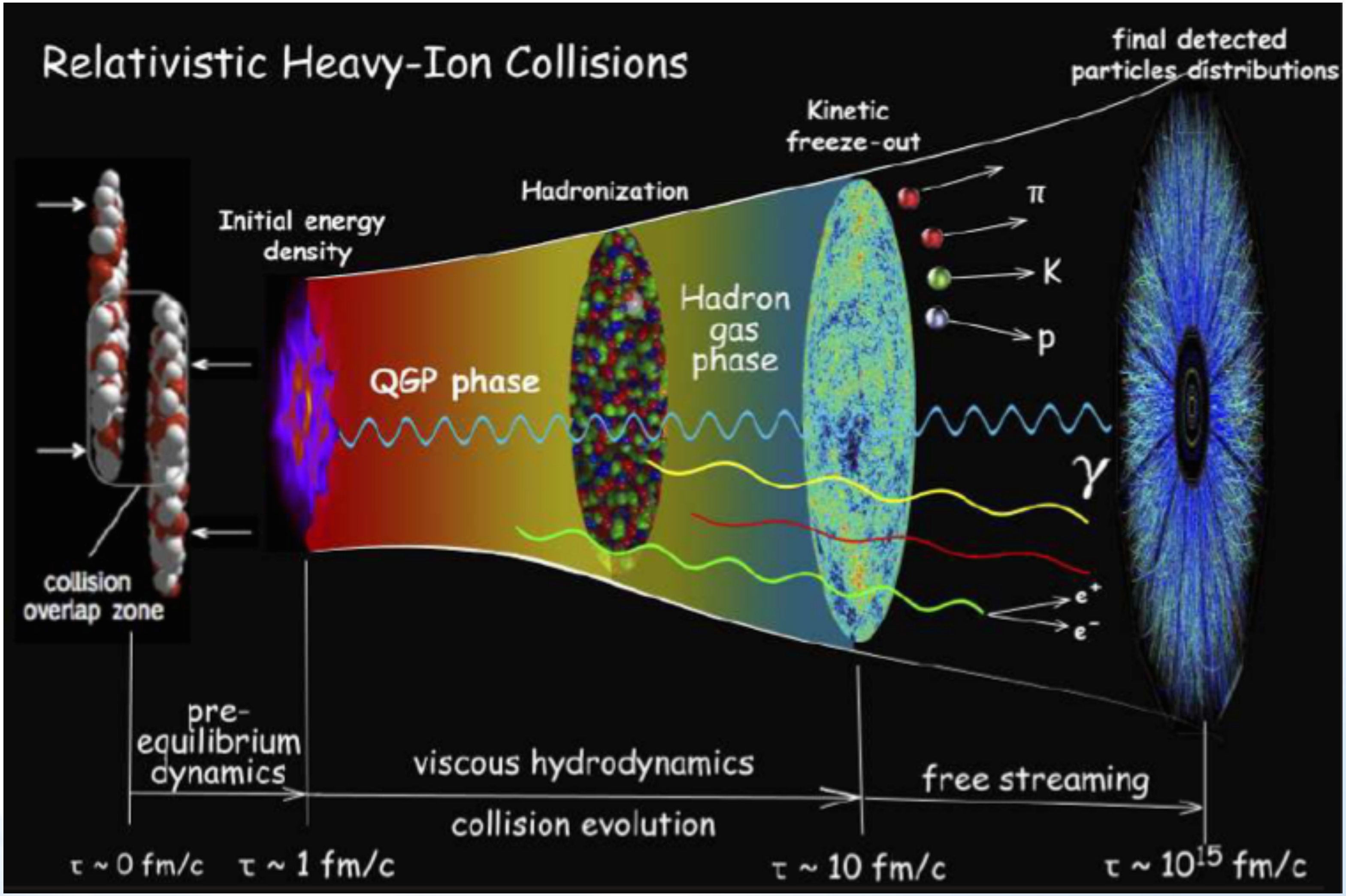
Major components of this program are:

- *Search for a possible critical point in the QCD phase diagram*
- *Find unambiguous evidence for the restoration of chiral symmetry*
- *Discover novel phenomena caused by topological QGP excitations*
- *Unravel the mechanism behind the near "perfect" fluidity of the QGP discovered at RHIC*

In addition, RHIC is the first and only polarized proton collider in the world. It is uniquely positioned to elucidate the dynamics of spin in QCD. RHIC has already discovered that gluons make up part of the spin of the proton.



Standard model of the "Little Bang"



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

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

Shear viscosity: anisotropic collective flow

Very Hard for LQCD

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

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

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

Momentum/energy diffusion:
parton energy loss, jet fragmentation

Hard for LQCD

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

QGP Radiance: Lepton pairs, photons

Easy for LQCD

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

Color screening: Quarkonium states

Scientific Methodology

- Cosmology:
  - One universe, but many causally disconnected domains (after inflation)
  - Precision measurements + concordance model simulations
  - Global fits to multiple observables
- Relativistic heavy ion collisions:
  - Many independent events with the same global constraints
  - Precision measurements + concordance model simulations
  - Global fits to multiple observables (just beginning now)
  - Example: E-by-E fluctuations of locally conserved quantitities (*Q, B*)

Expt.: mean: M_Q
variance: σ_Q^2
skewness: S_Q
kurtosis: κ_Q

$$\sqrt{s} \Leftrightarrow (T, \mu_B)$$

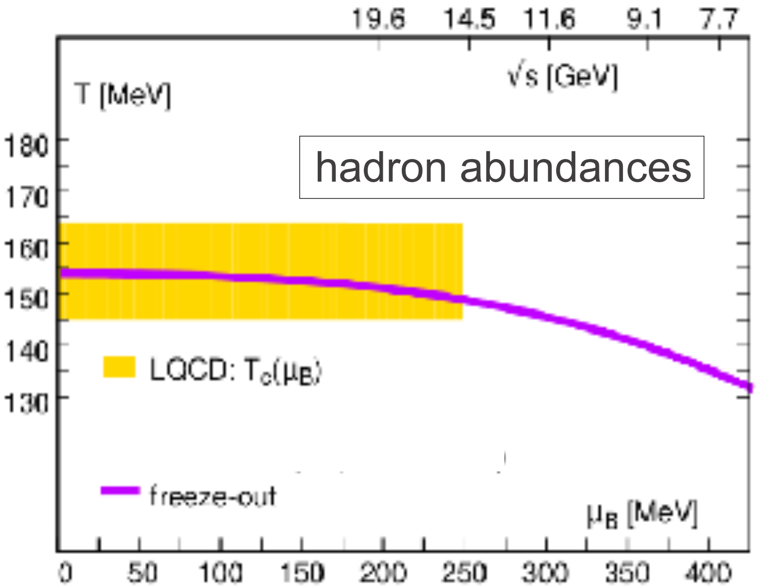
Lattice gauge theory:

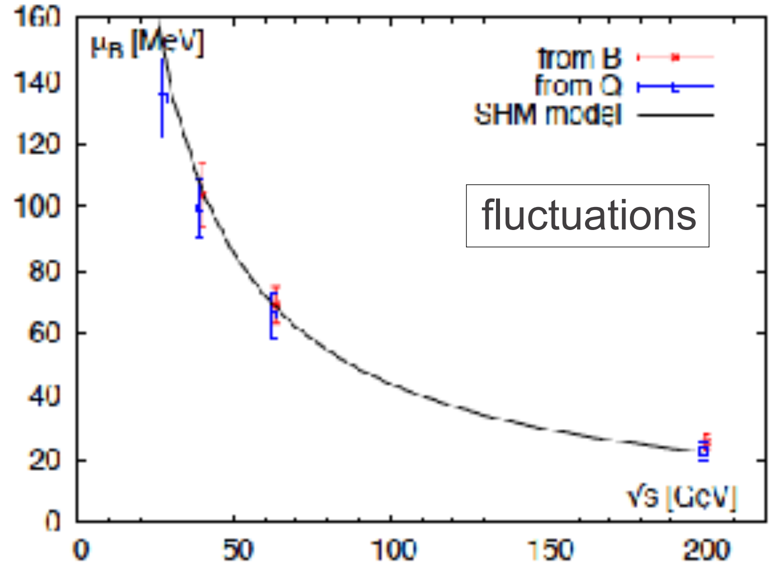
$$\chi_n^X(T,\mu_X) = \frac{\partial^n \left(p(T,\mu_X)/T^4\right)}{\partial(\mu_X/T)^n}$$

Ratios are independent of the (unknown) freeze-out volume

Chemical freeze-out

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

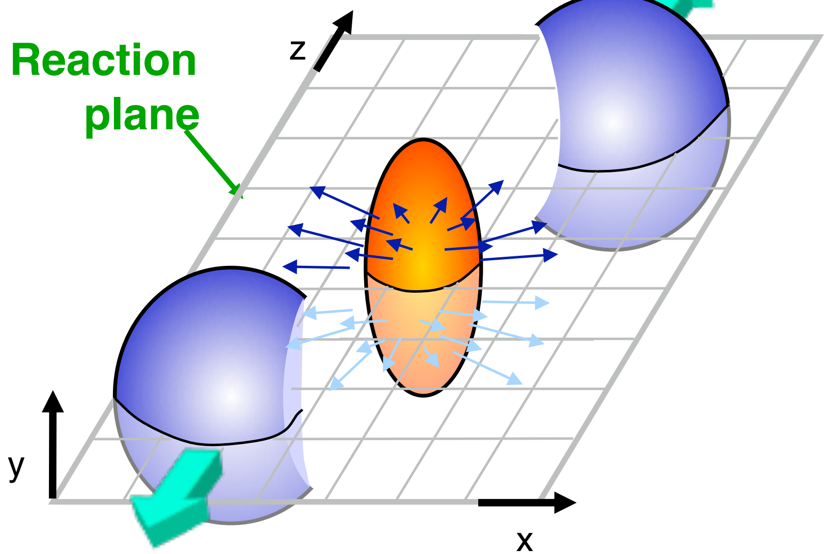


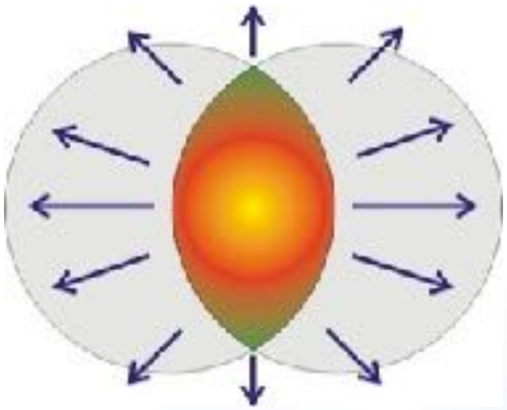


Consistency of freeze-out parameters from mean hadron abundances and from fluctuations (*Q*, *B*) opens the door to search for a critical point in the QCD phase diagram by looking for enhanced critical fluctuations as function of beam energy.

Anisotropic flow

Nuclei collide rarely head-on, but mostly with an offset:





Only matter in the overlap area gets compressed and heated

Event-by-event fluctuations of the density introduce all Fourier components

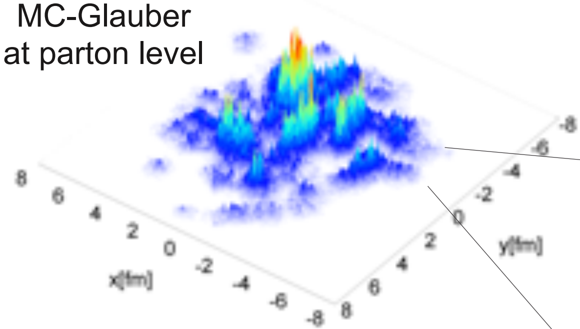
$$2\pi \frac{dN}{d\phi} = N_0 \left(1 + 2\sum_n \mathrm{v}_n(p_T,\eta)\cos n\big(\phi - \psi_n(p_T,\eta)\big) \right)$$

anisotropic flow coefficients

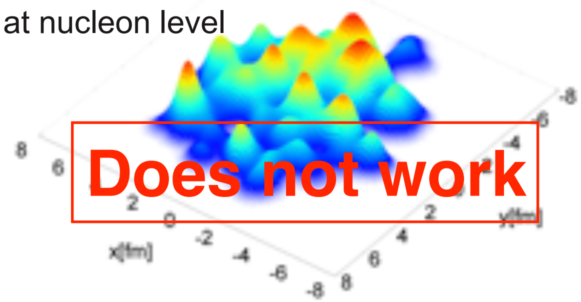
event plane angle

Flow analysis today

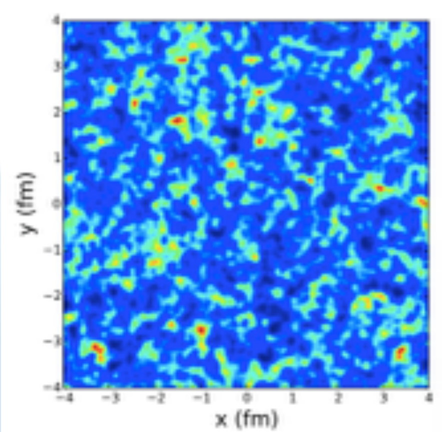
MC-Glauber
at parton level



MC-Glauber
at nucleon level

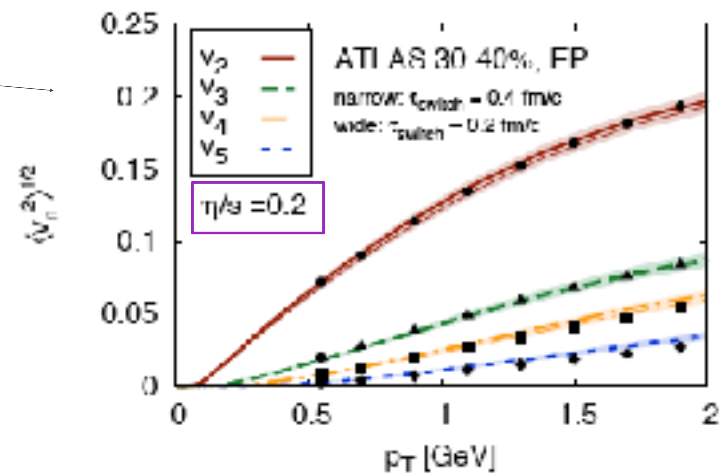


Does not work

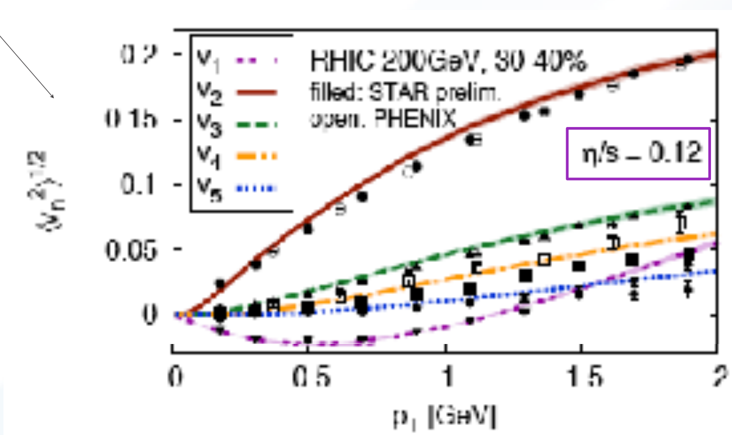


Gaussian gluons energy density fluctuations:
BM & A. Schäfer, PRD 85 (2012) 114030
Moreland, Qiu & Heinz, NPA 904-5 (2013) 815c

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



LHC



RHIC

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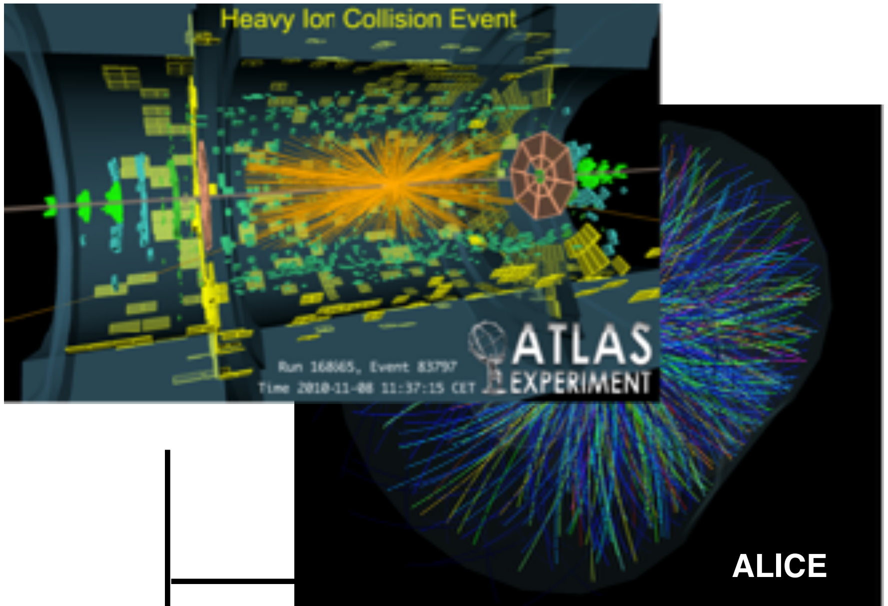
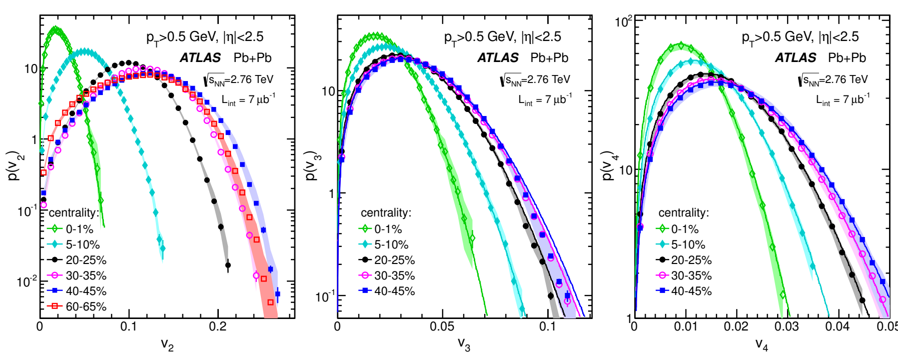
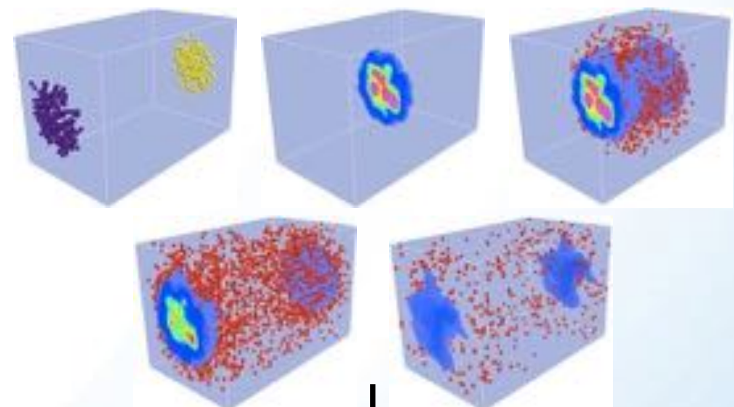
Model-data comparison today

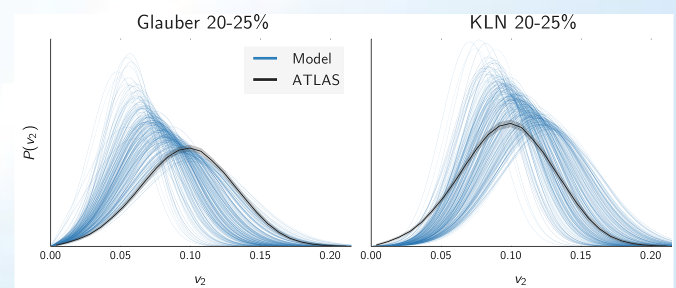
Data:





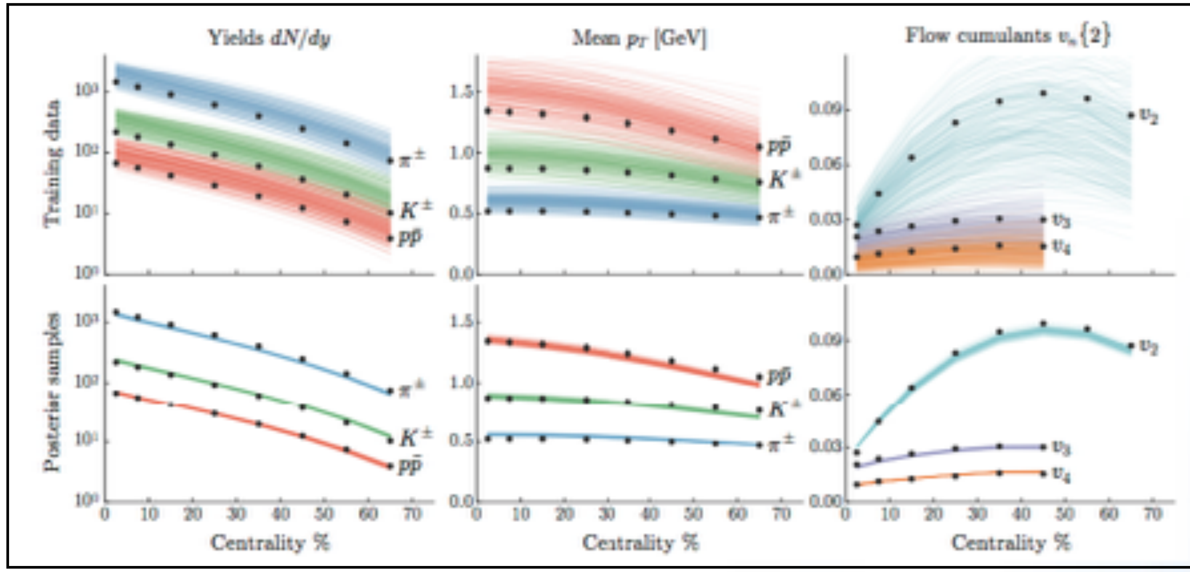
Model:
initial conditions, τ_0, η/s, ζ/s, ….

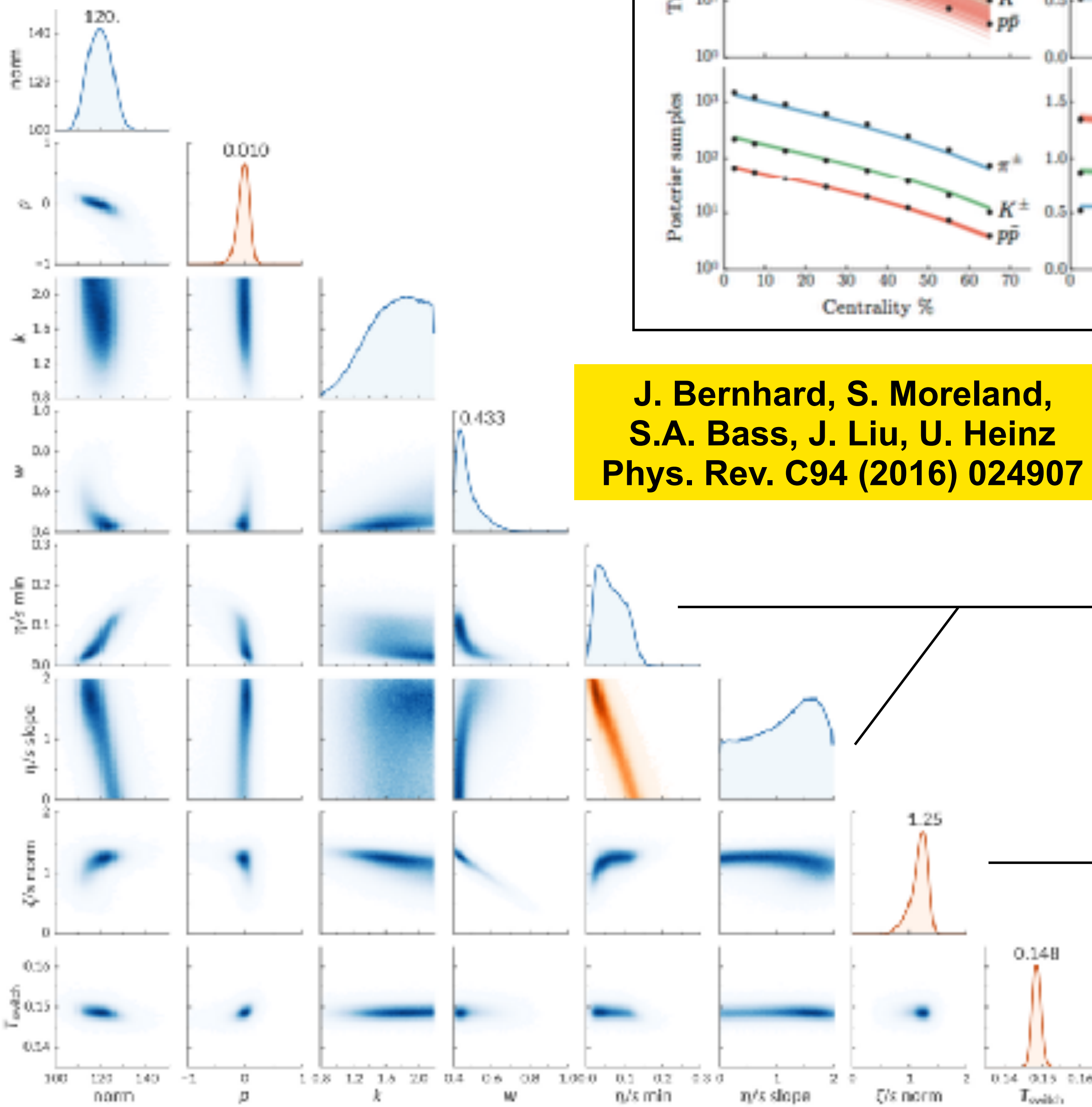




extracted QGP properties: η/s, …

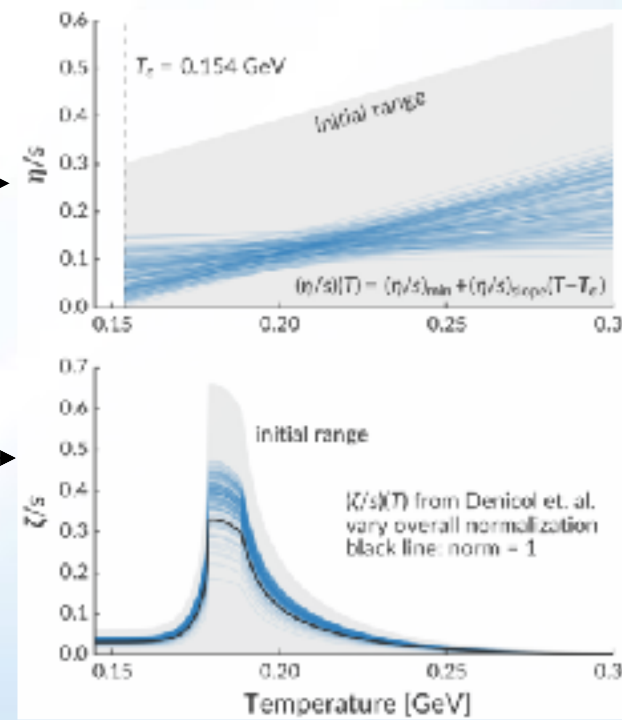
Calibrated posterior distributions:



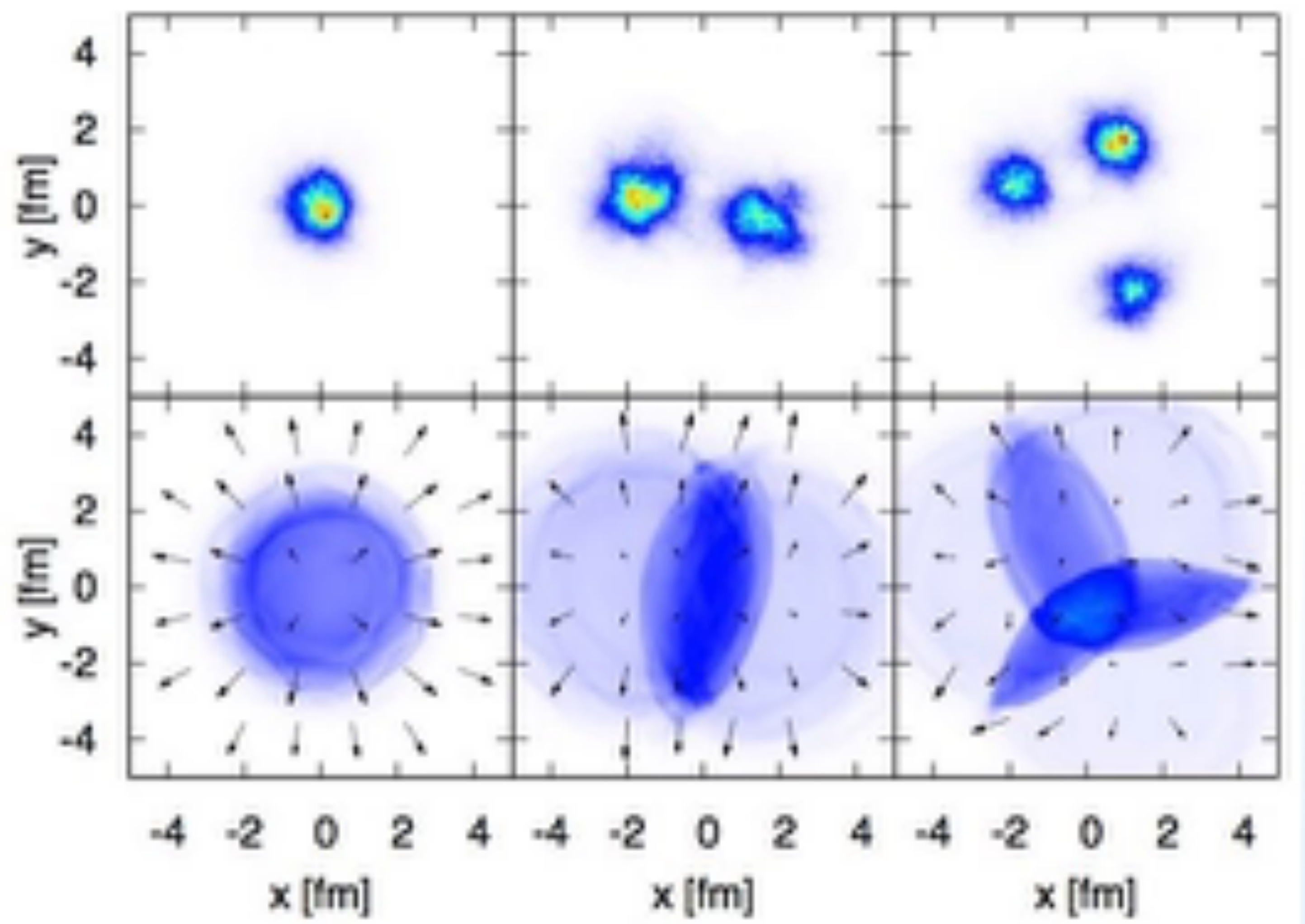


J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz Phys. Rev. C94 (2016) 024907

Temperature-dependent viscosities from the calibrated posterior:



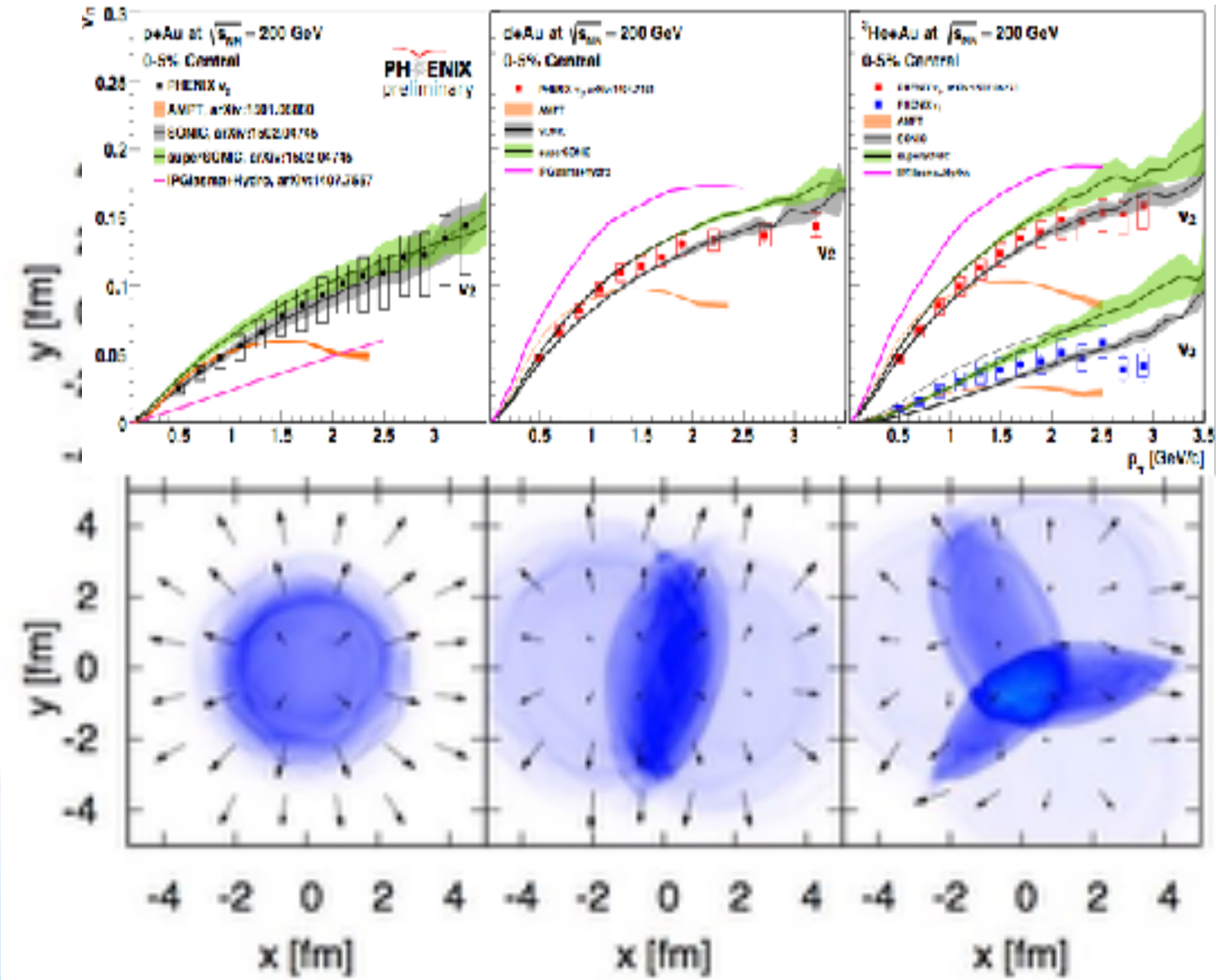
Tiny drops of QGP?



Initial state

Final state

Tiny drops of QGP?

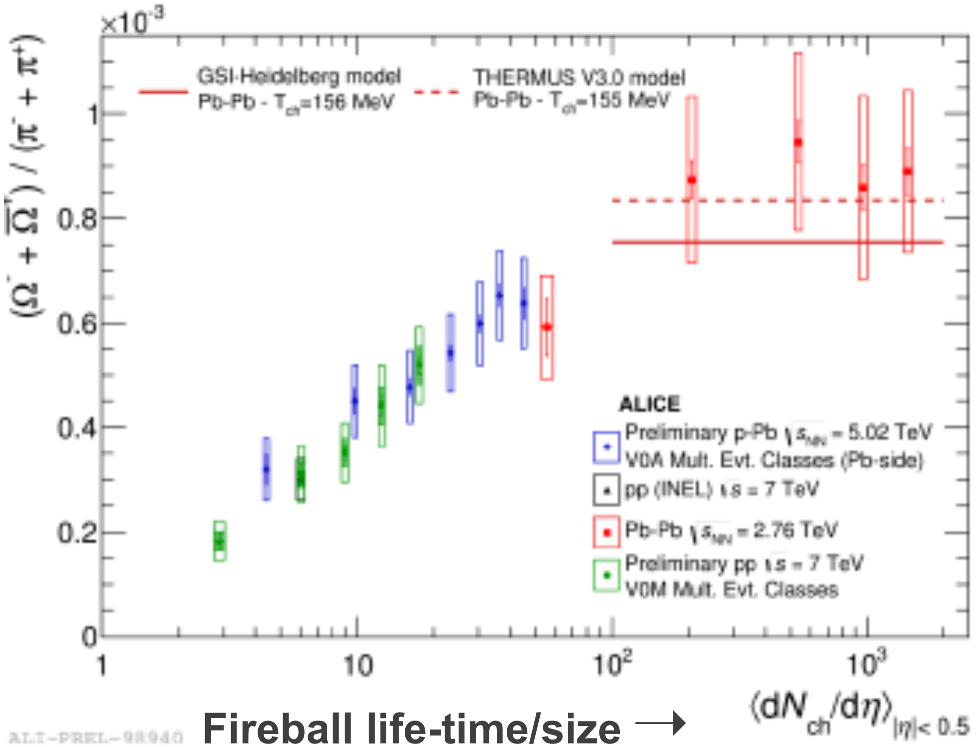


Data-Theory comparison confirms hydrodynamic collective flow

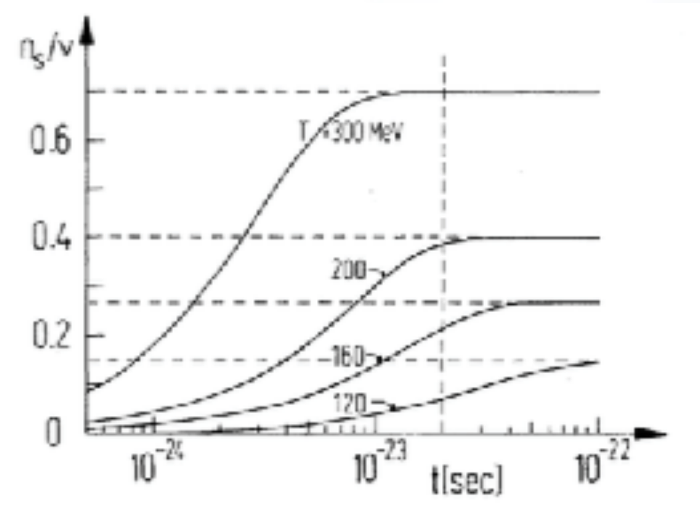
Final state

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.

Future Science 2017-20s

Highlights of RHIC runs 2017-23

- *Run 2017:*
  - High luminosity $\sqrt{s}$ = 510 GeV transverse polarized p+p run (400 pb^{-1})
  - Study scale evolution of the Sivers effect in W-boson production; possibly confirm sign change of the Sivers effect relative to DIS
- *Run 2018:*
  - Isobar system (^{96}Ru - ^{96}Zr) comparison run (1.2B events each)
  - Test of signatures of Chiral Magnetic Effect
- *Runs 2019-20:*
  - Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.8, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity
  - Search for signs of critical phenomena in event-by-event fluctuations
- *Runs 2022-23+:*
  - Full energy ($\sqrt{s_{NN}}$ = 200 GeV) Au+Au, p+p, p+Au, etc.
  - Precision measurements of fully resolved jets and Upsilon states using the new sPHENIX detector

Transverse polarized p+p collisions

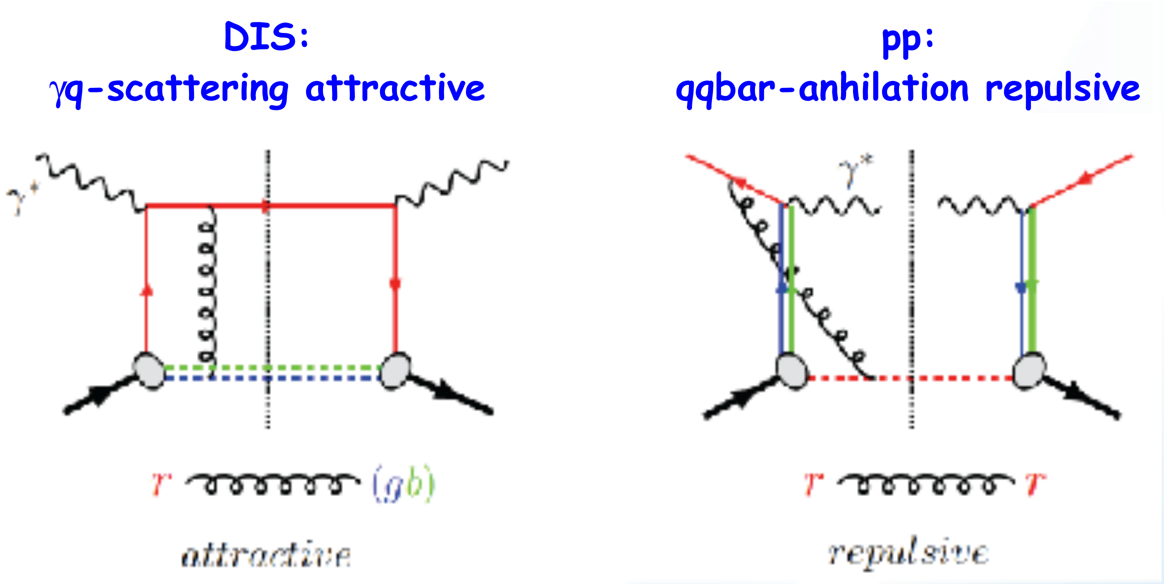
Access the dynamic structure of protons:

→ Test and confirm QCD structure of color spin interactions

→ Non-universality of transverse momentum dependent functions

→ $\text{Sivers}_{DIS} = - \text{Sivers}_{pp}$

→ Observable: A_N for Drell-Yan and $W^{+/-}$ production



→ Test scale evolution of transverse momentum dependent functions

→ Observable: compare magnitude of A_N for Drell-Yan and $W^{+/-}$

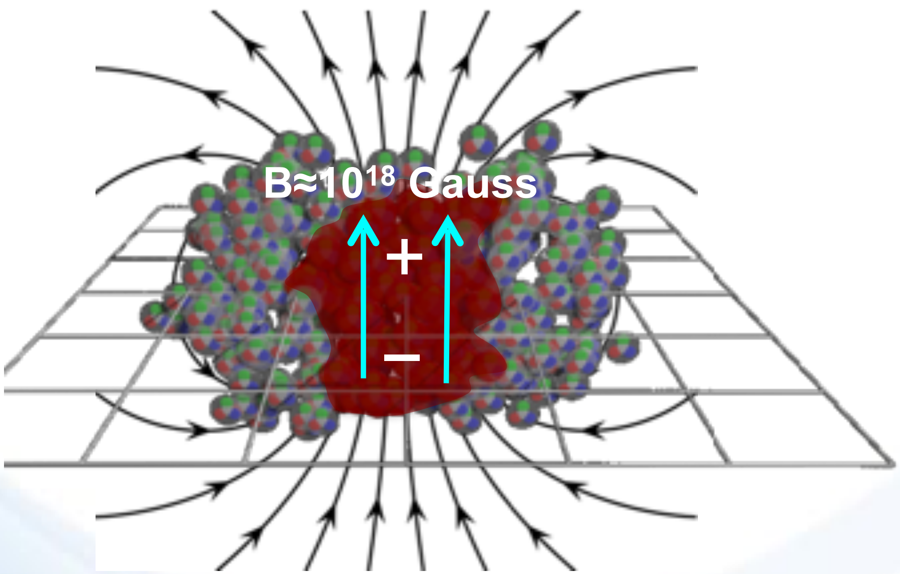
Scale: DY: $Q^2 \sim 16\ \text{GeV}^2$ $W^{+/-}$: $Q^2 \sim 6400\ \text{GeV}^2$

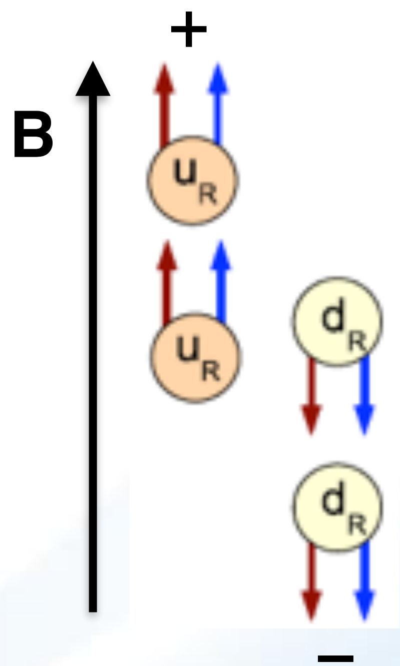
Probing Chiral Symmetry with Quantum Currents

The chiral anomaly of QCD creates fluctuating differences in the number of left and right handed quarks, characterized by a chiral chemical potential μ_5.

In a chirally symmetric QGP, this imbalance generates an electric current along the magnetic field (chiral magnetic effect).

electric charge separation





μ5 > 0

Spin

Momentum

$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5\,\vec{B}$$

$$\left\langle \mu_5^2 \right\rangle \neq 0$$

$$\left\langle JJ \right\rangle \neq 0$$

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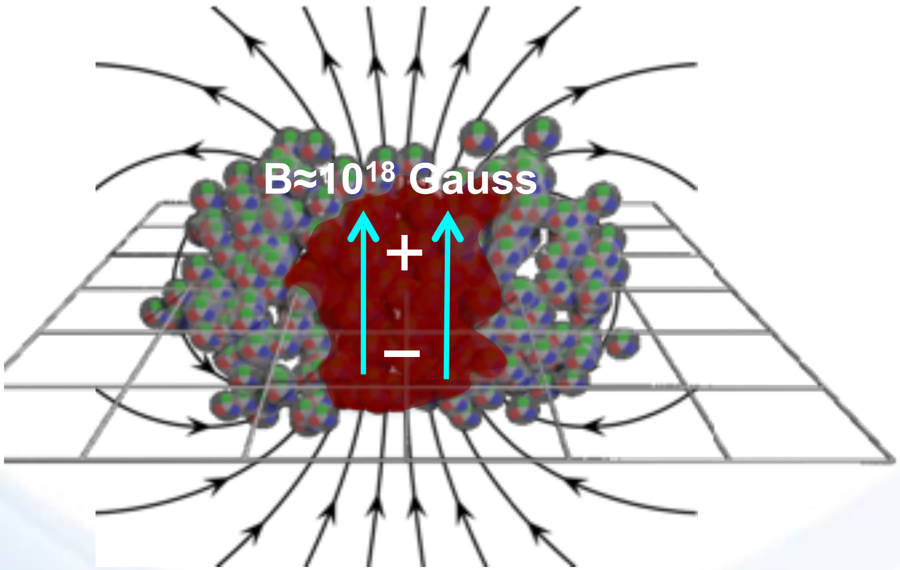
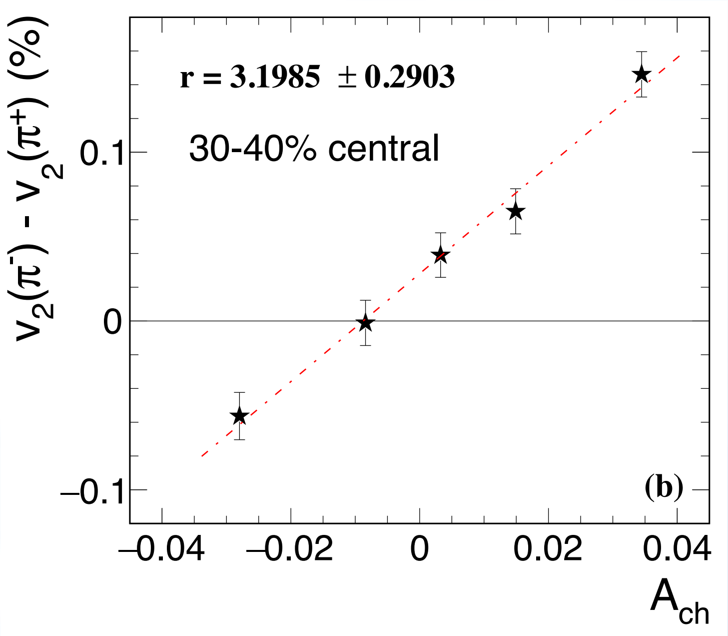
electric charge separation



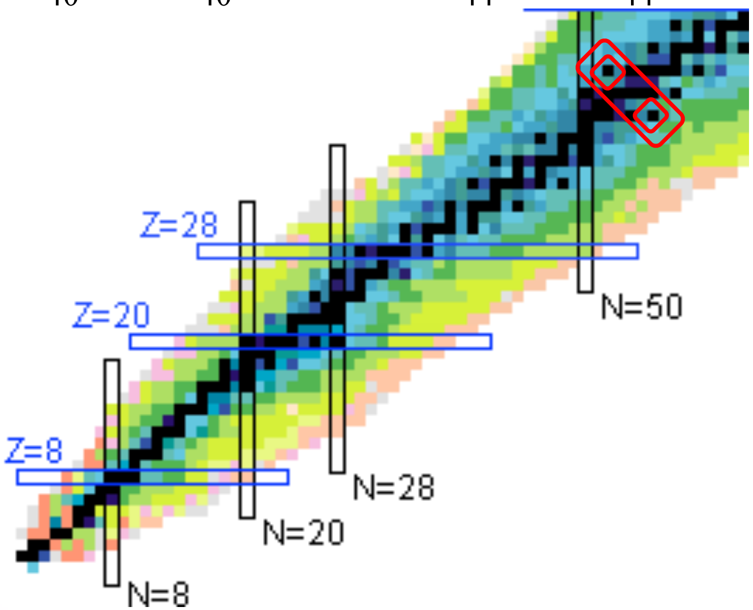
Charge asymmetry of elliptic flow as function of total charge asymmetry



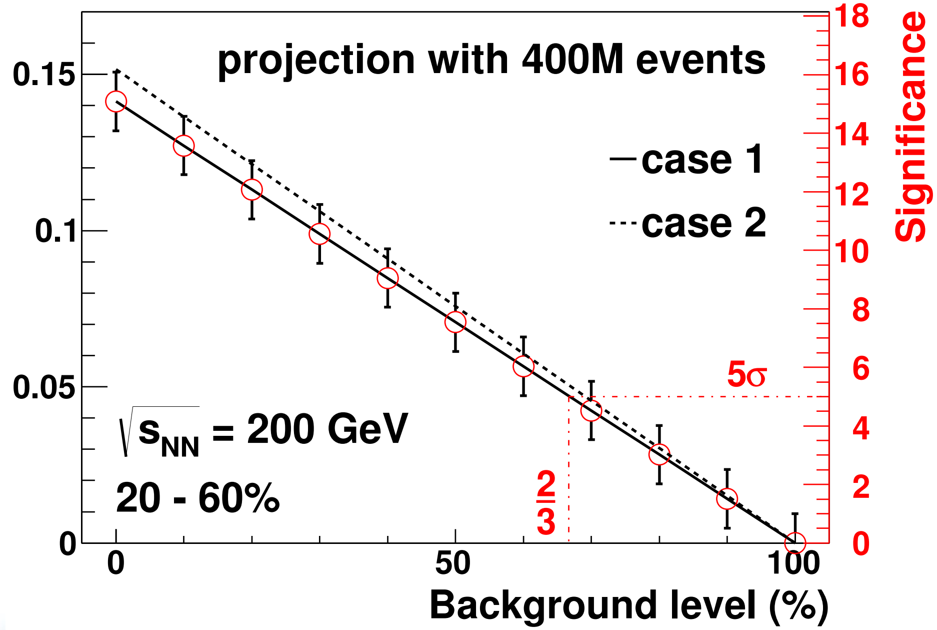
Probing Chiral Symmetry (Run-18)

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. $^{96}_{44}Ru + ^{96}_{44}Ru$



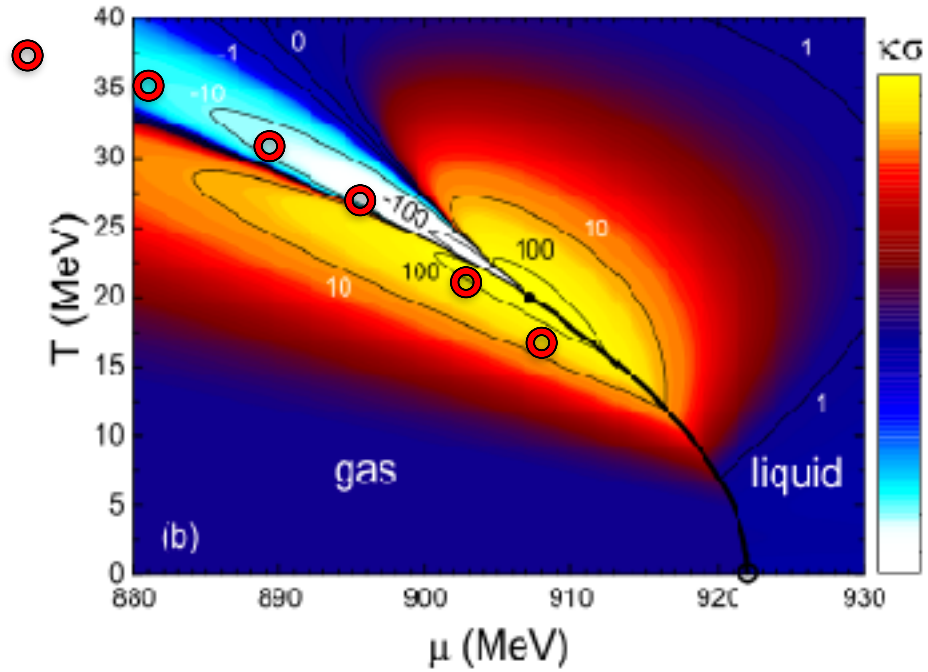
Relative difference in charge separation effects (Ru vs Zr)

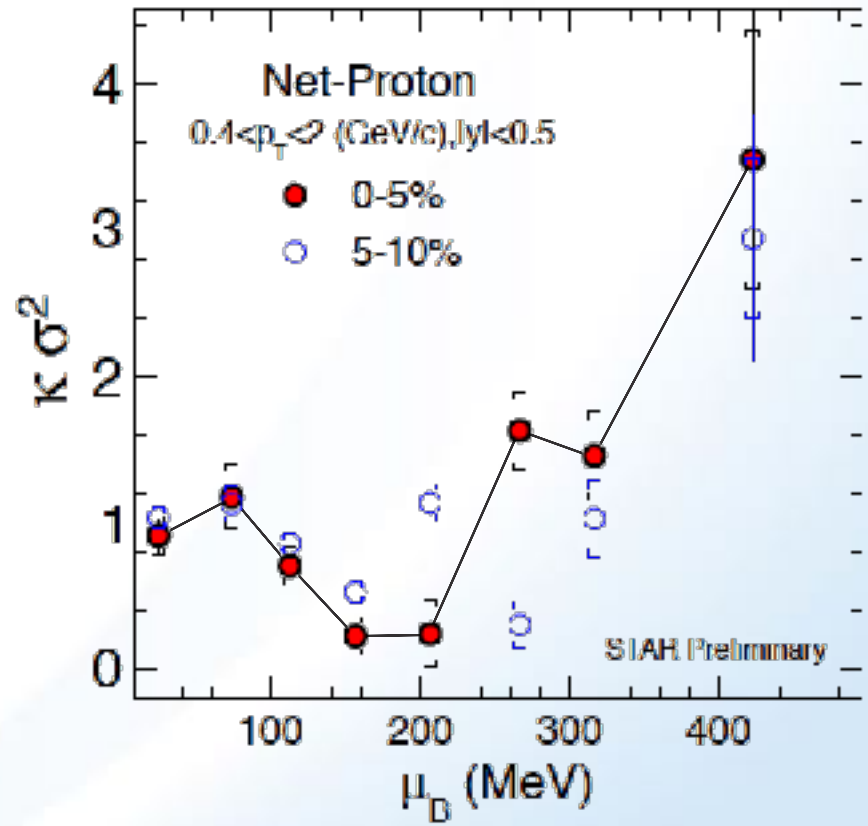


Isobar collisions will tell us what fraction of the charge separation is due to CME to within +/- 6% of the observed signal, allowing for a 5σ measurement if CME is 1/3 of the observed effect.

Critical behavior?

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

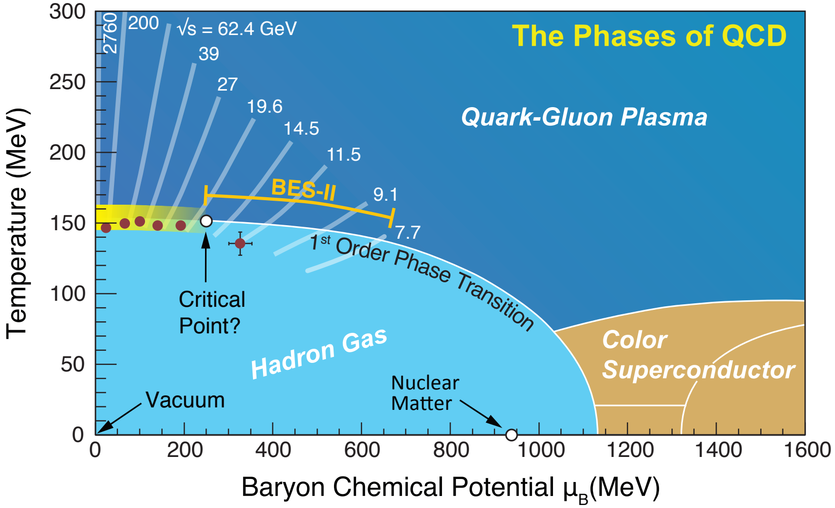


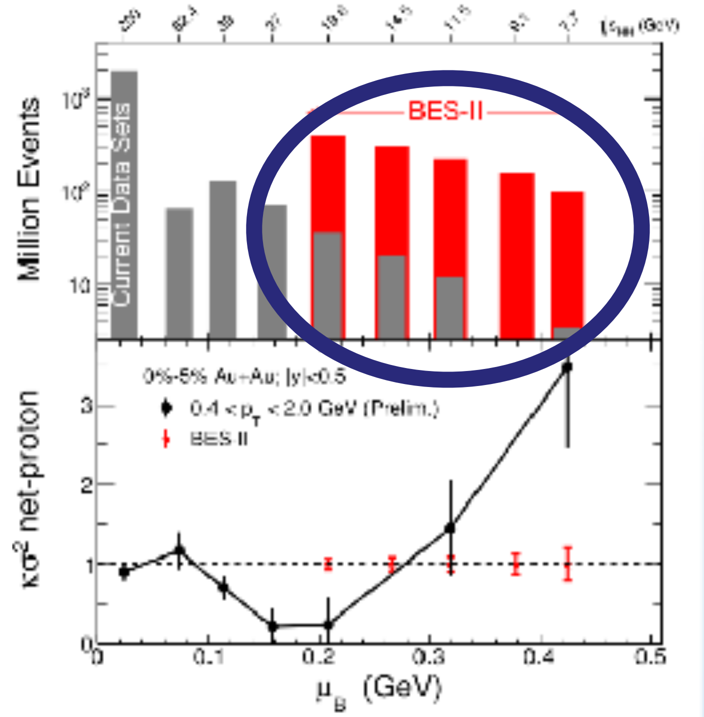


Higher moments like kurtosis*variance $\kappa\sigma^2$ change sign near the critical point

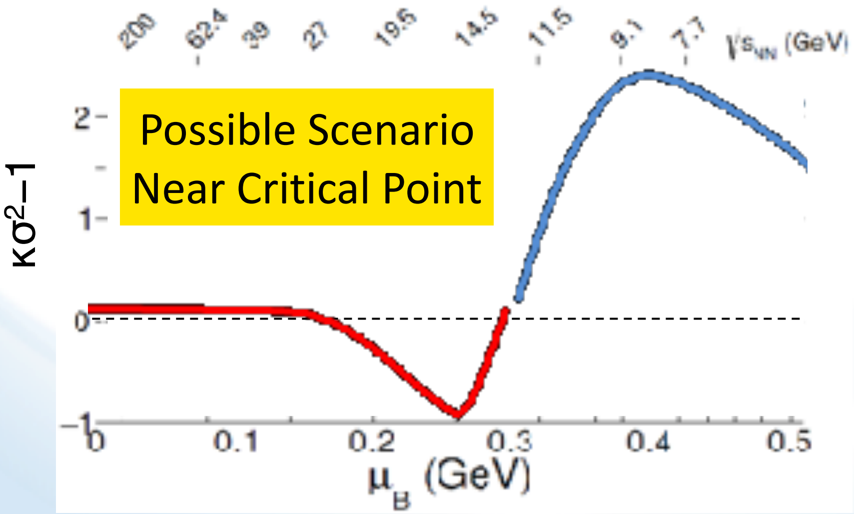
Non-monotonic trend observed in BES-I with limited statistical precision!

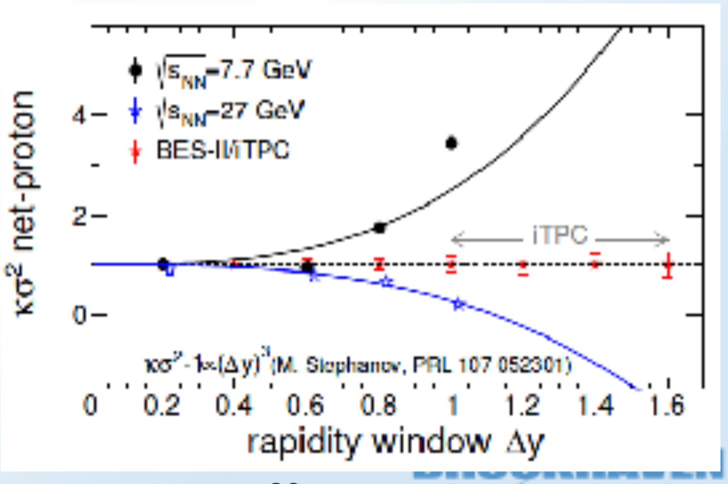
Beam Energy Scan II



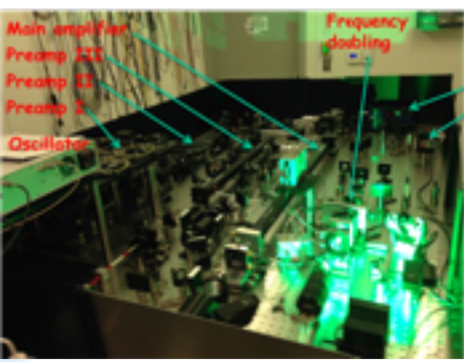


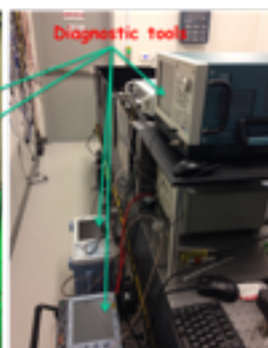
Model independent structure of net baryon number kurtosis

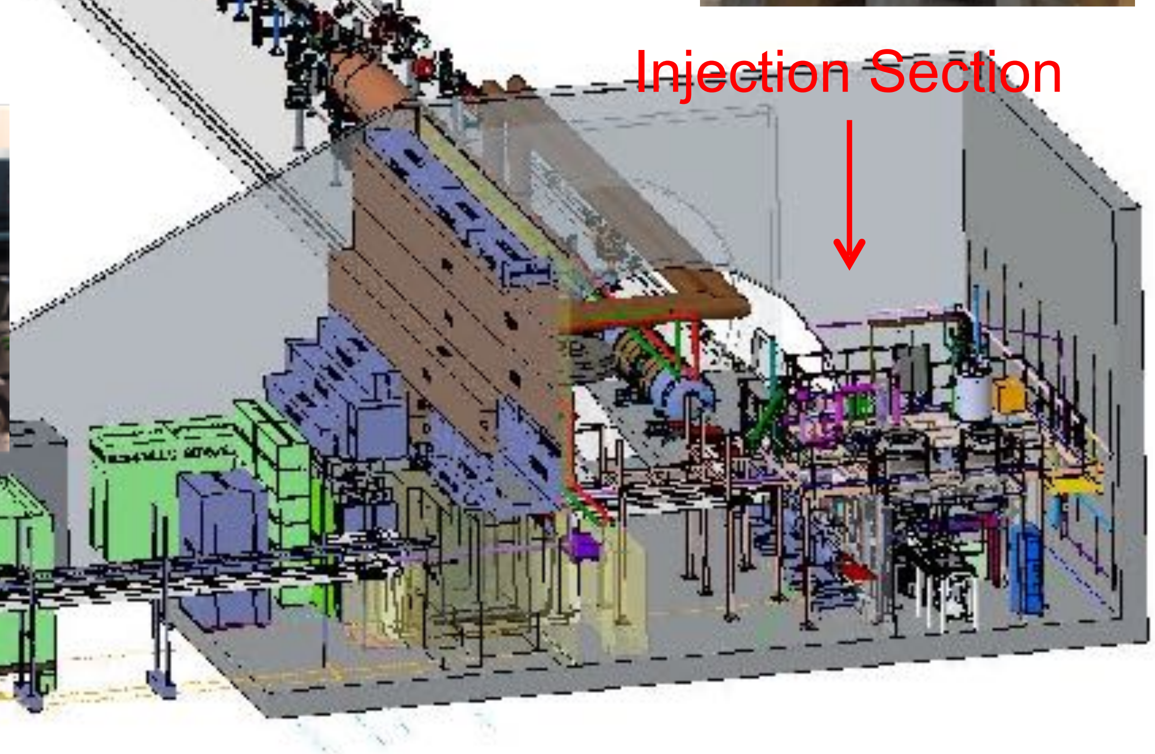




LEReC Layout

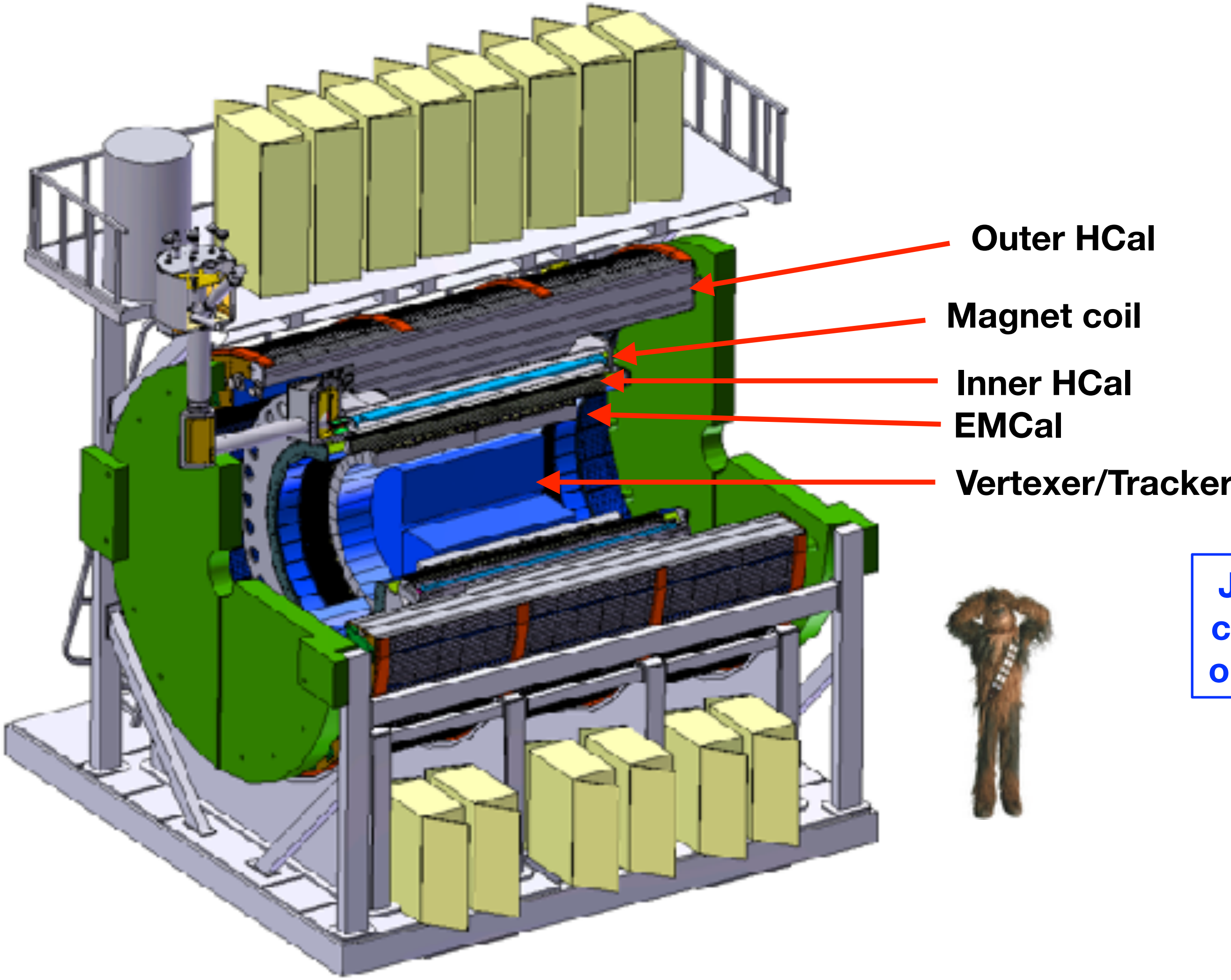






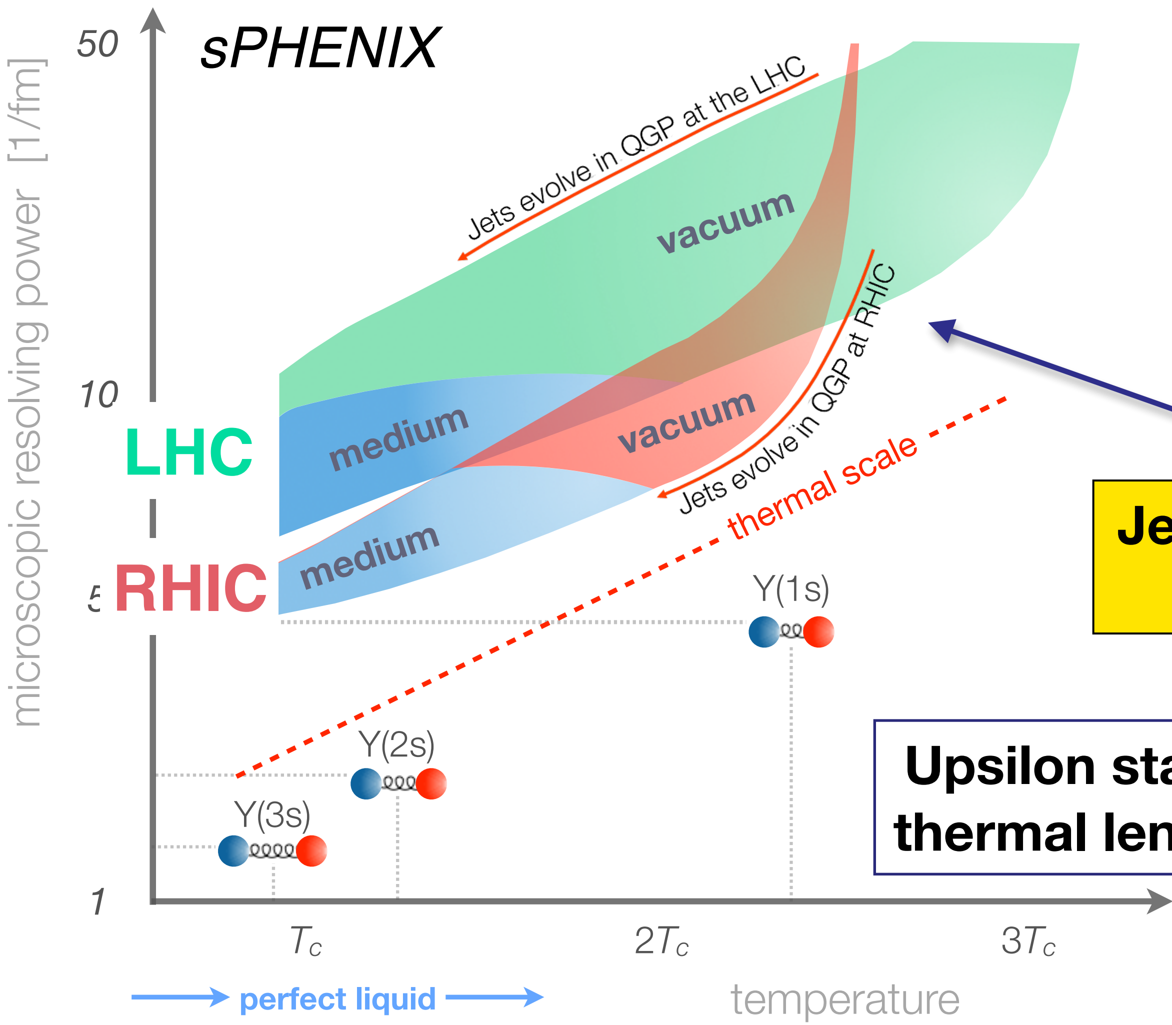
sPHENIX

High-rate capable, large acceptance detector built around the former BaBar 1.5T solenoid, with full EM and hadronic calorimetry and precision tracking and vertexing,



Japan (RIKEN) contributes the outer Si tracker

Probing scales in the medium



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

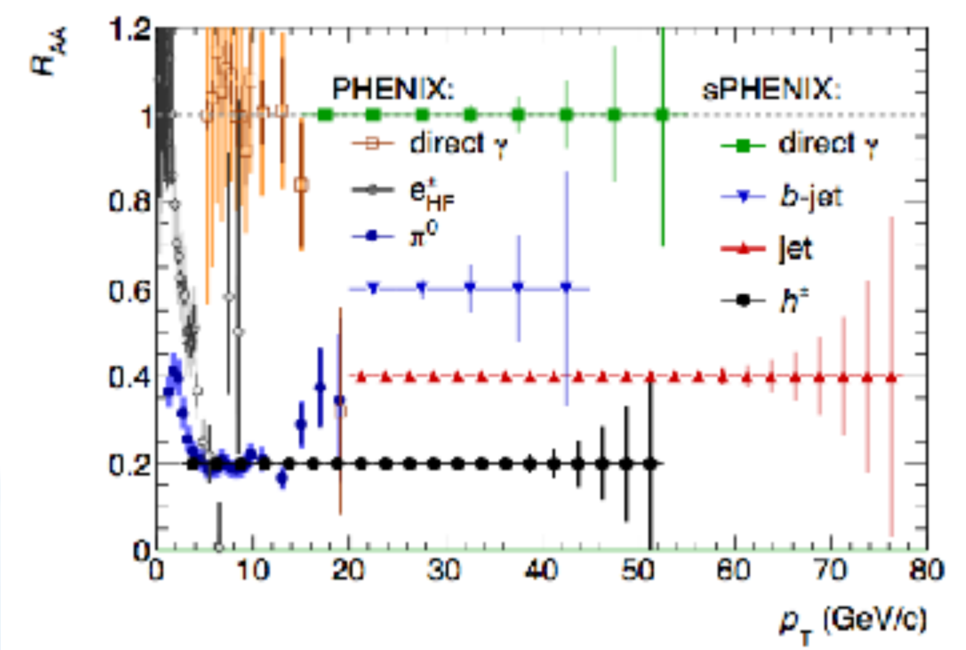
Jets probe sub-thermal length scales

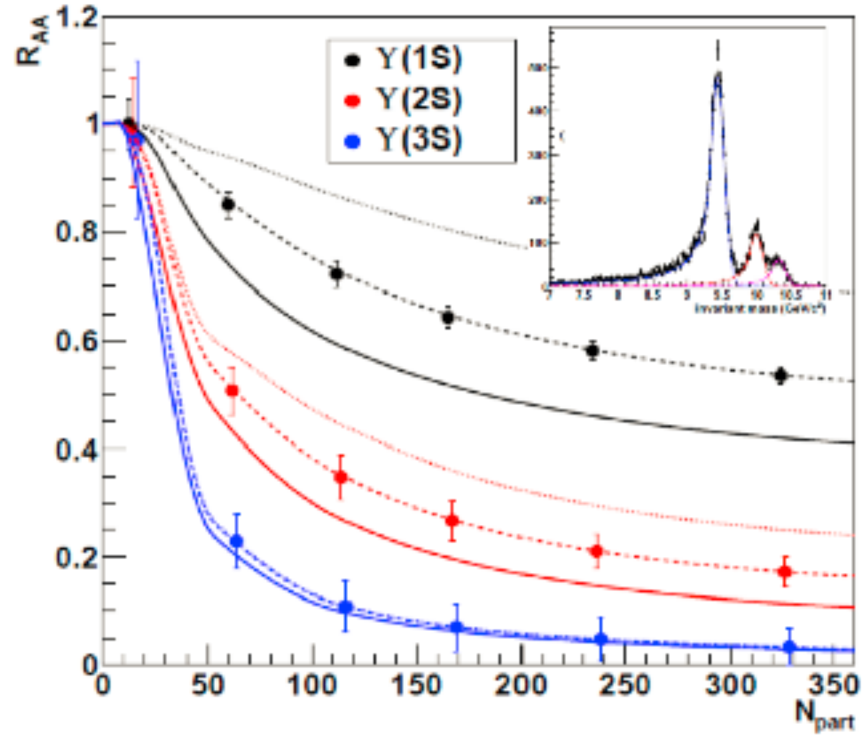
Upsilon states probe thermal length scales

Jets & Upsilon states

sPHENIX capabilities

Complete calorimetric jet spectroscopy



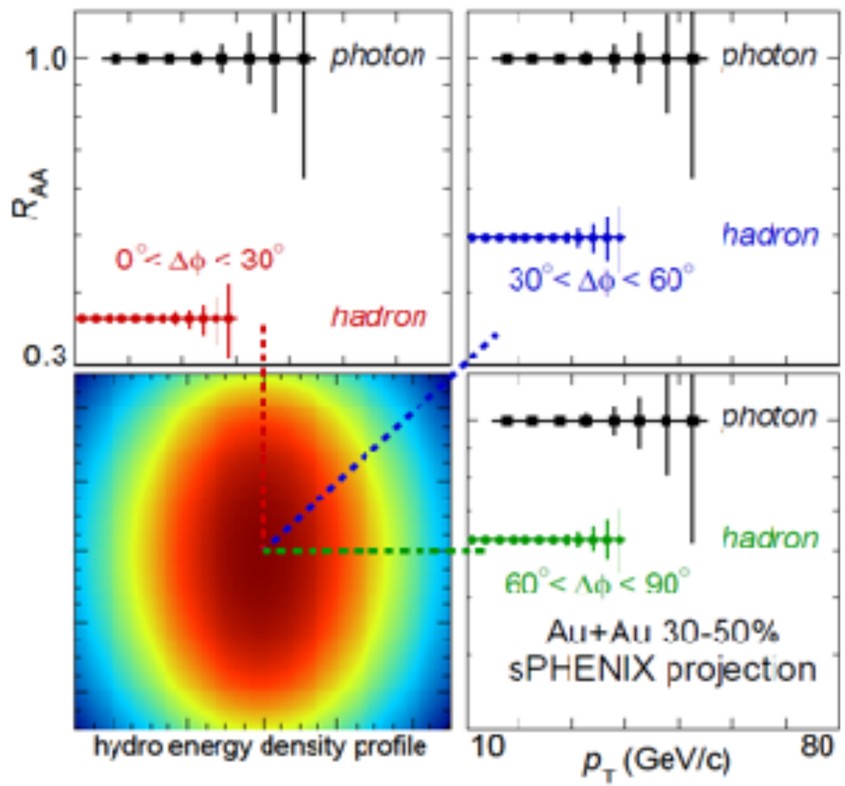


Completely resolved Upsilon spectroscopy

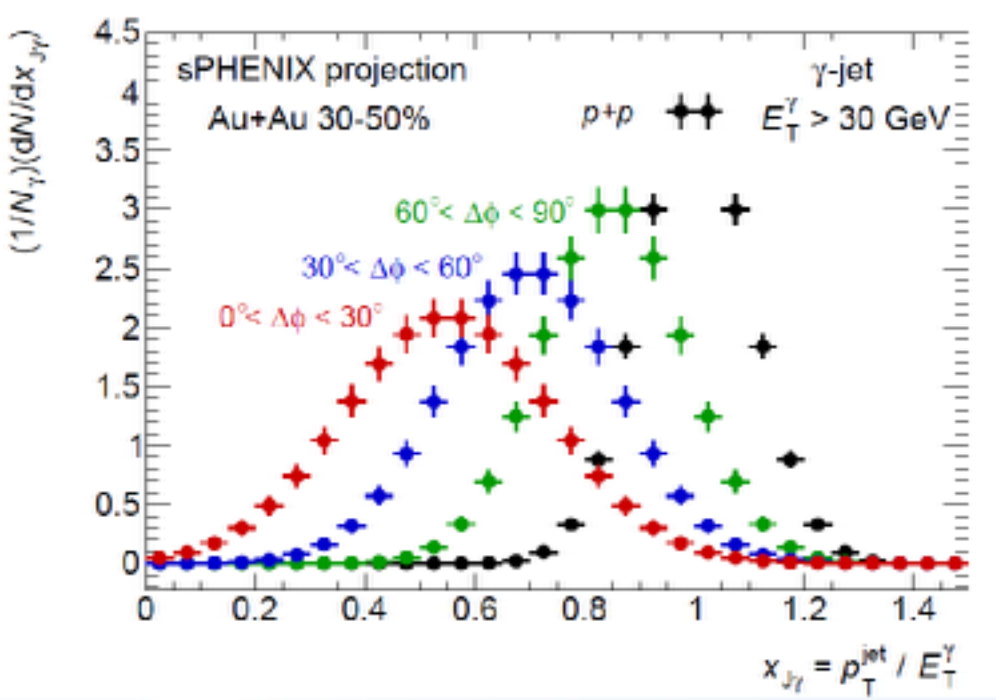
Rate enabled measurements

Example: Length dependent jet quenching

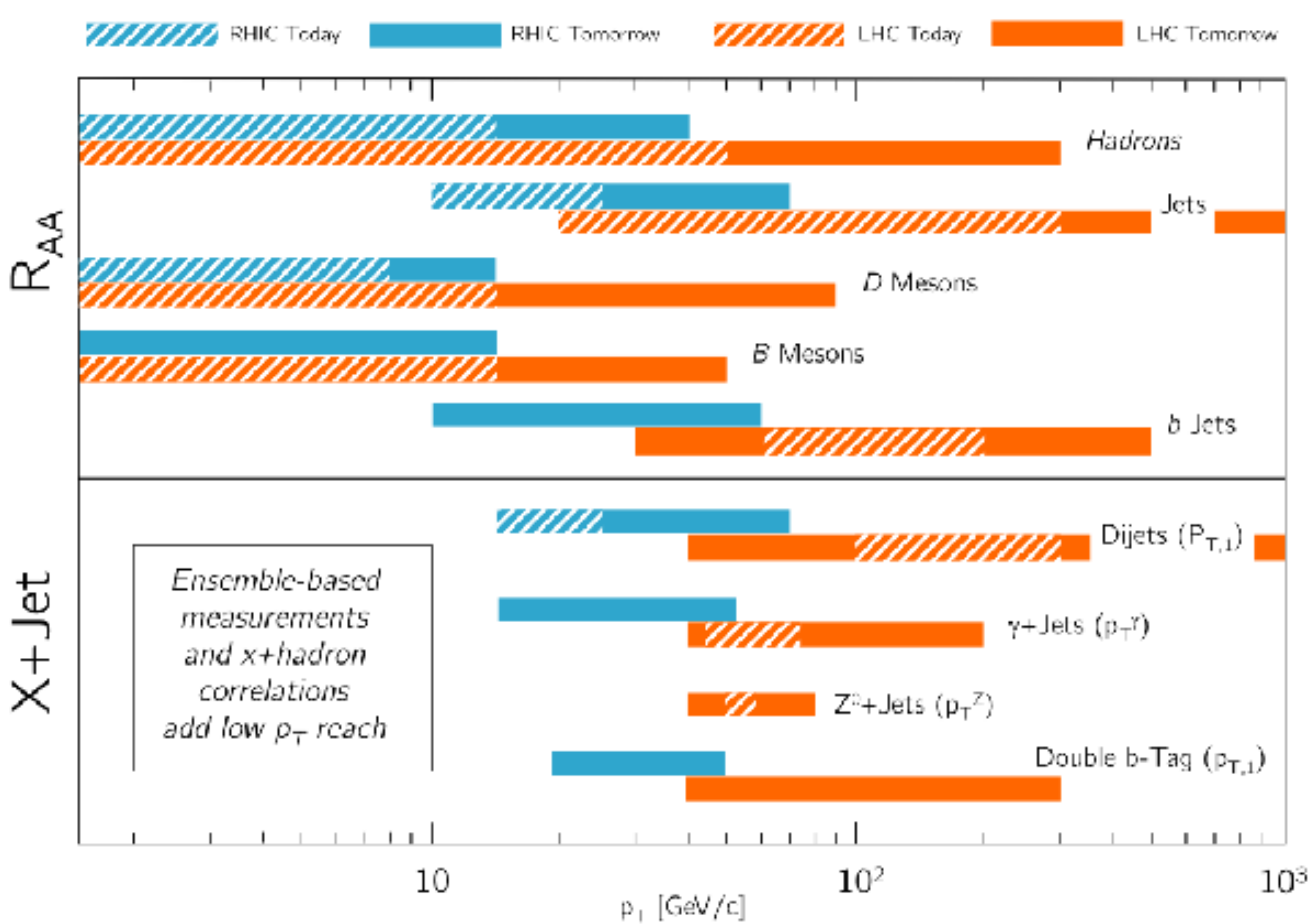
Length dependent suppression R_{AA}



Length dependent energy loss in photon tagged jet events



RHIC & LHC complementarity



BROOKHAVEN NATIONAL LABORATORY

Beyond RHIC

2015 NSAC Long Rang Plan

RECOMMENDATION III

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

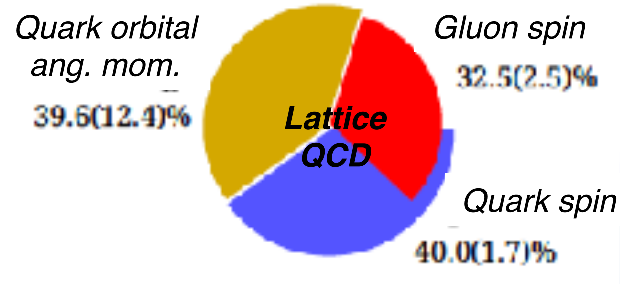
The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

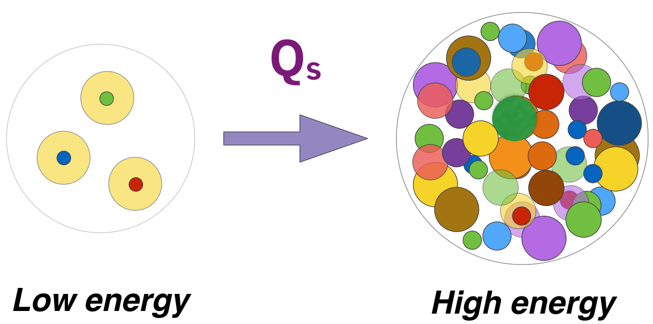
Big Questions

Proton spin:

Quark spin contributes only ~30% to the proton's spin
How do quark and gluon dynamics generate
the remainder of the proton's spin?

The EIC will definitively resolve this question.





Gluon saturation:

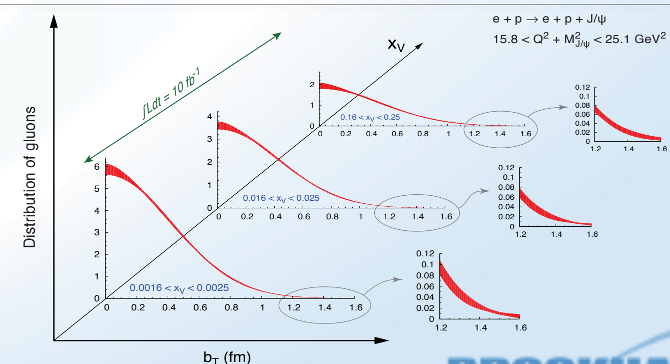
Gluons proliferate at high energy (small Bjorken-x)
How does the gluon density saturate to avoid violation
of fundamental principles like unitarity?

The EIC will explore this question using heavy nuclei.

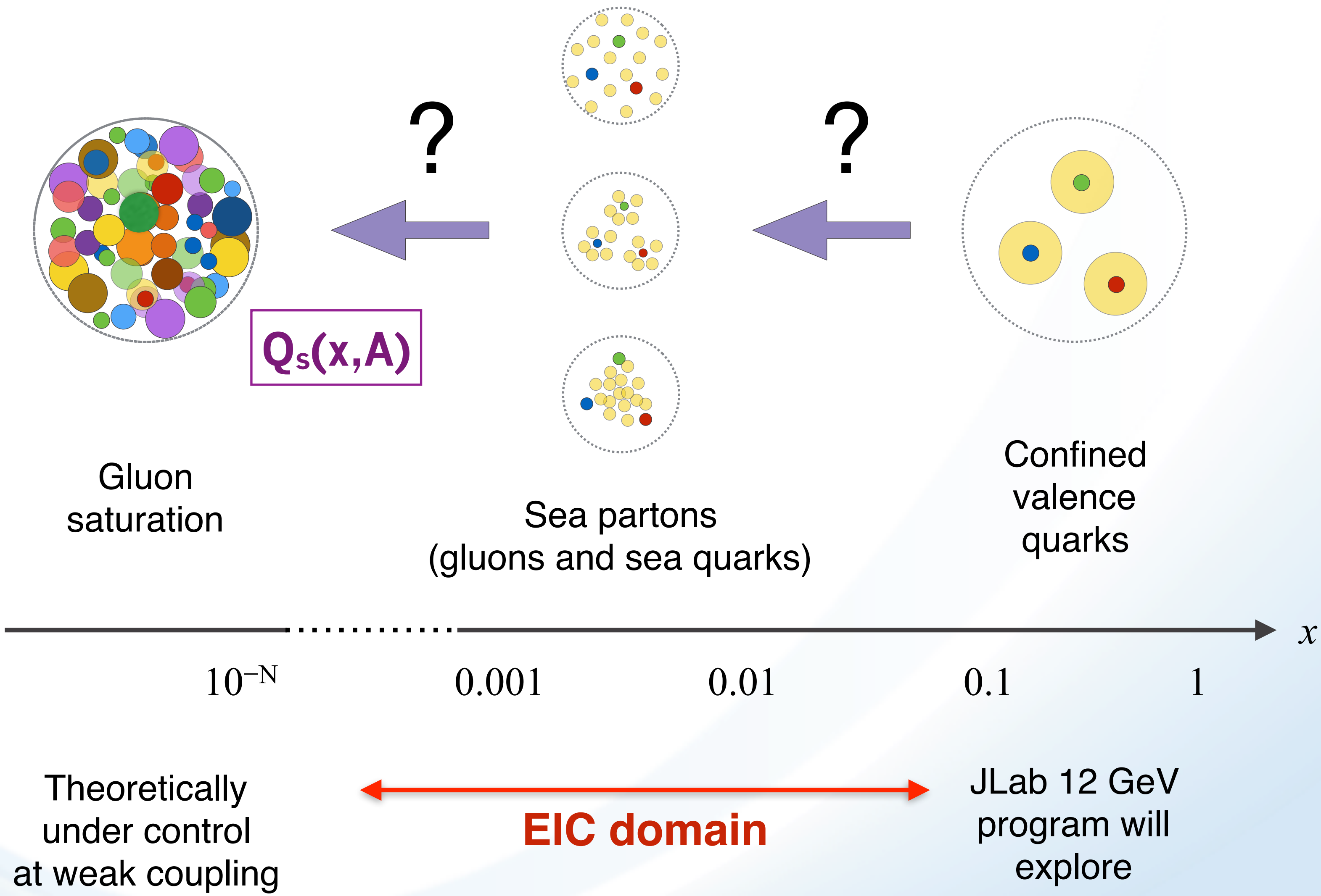
Proton transverse structure:

We know the 1-D (longitudinal) structure of a
moving proton very well
What does the proton look like in 3 dimensions?

The EIC will definitively answer this question.

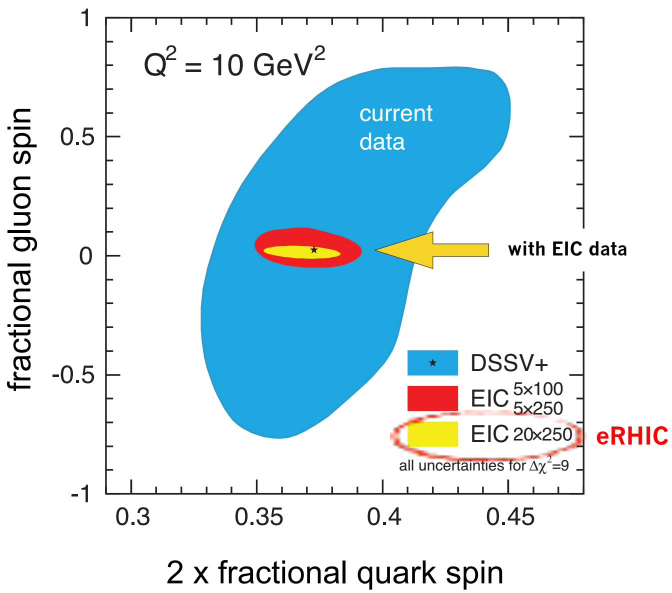


Partons at Q^2 ~ few GeV^2

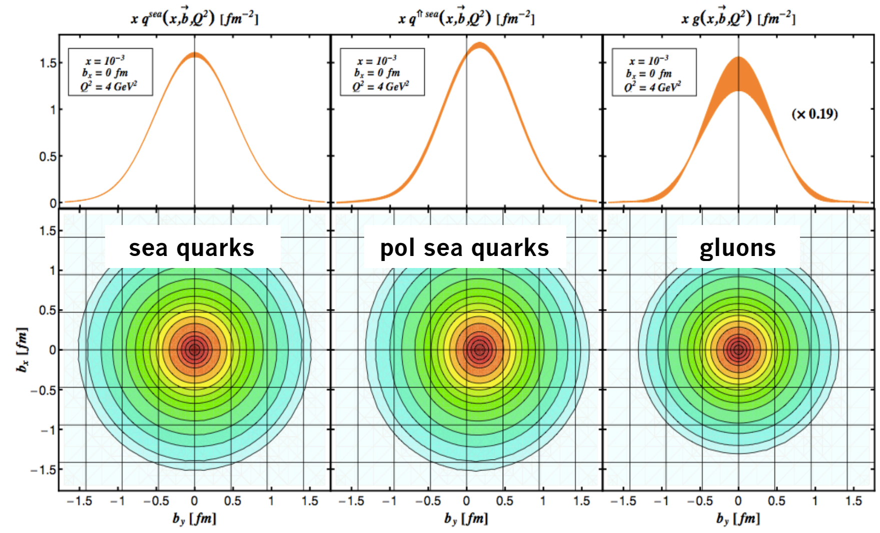


Key physics areas

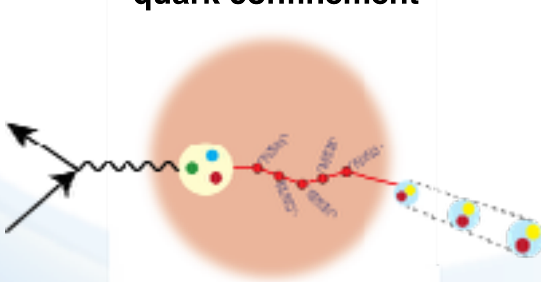
Proton spin decomposition

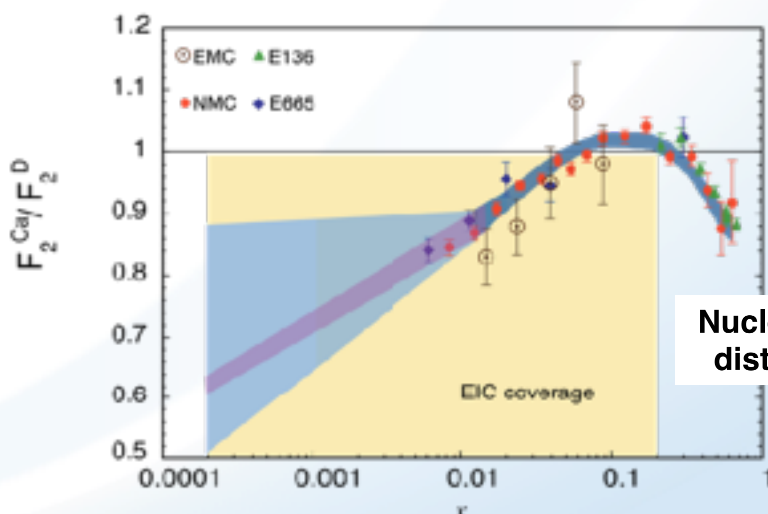


Imaging using GPDs and TMDs



Nuclei as a probes of quark confinement



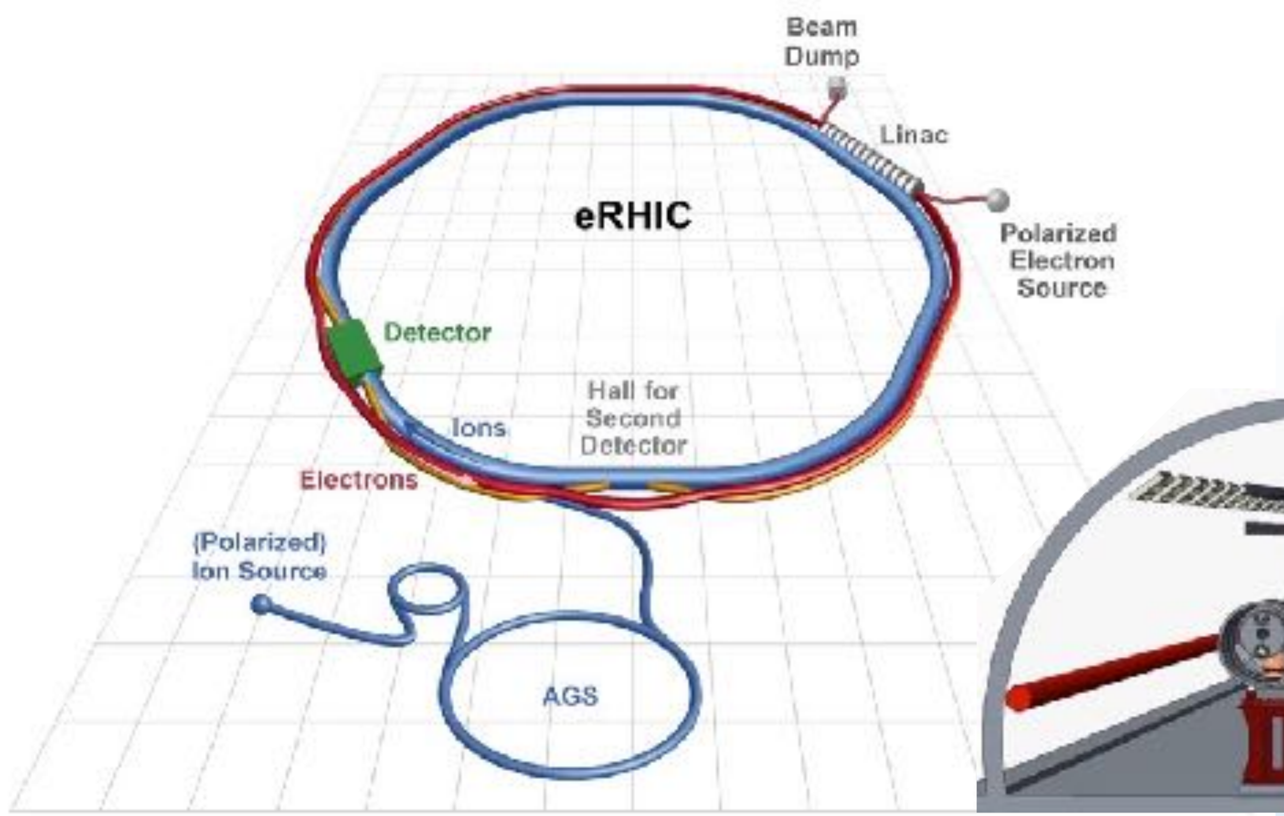


Nuclear parton distributions

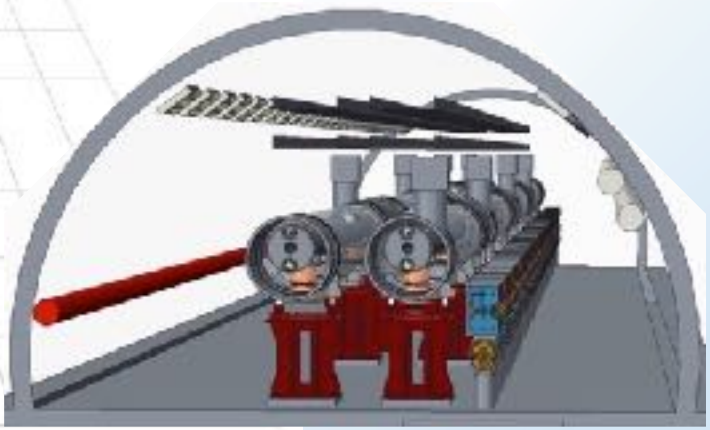
BNL EIC Design: eRHIC

eRHIC ERL + FFAG ring design @ 10^{33}–10^{34}/cm^{2}s

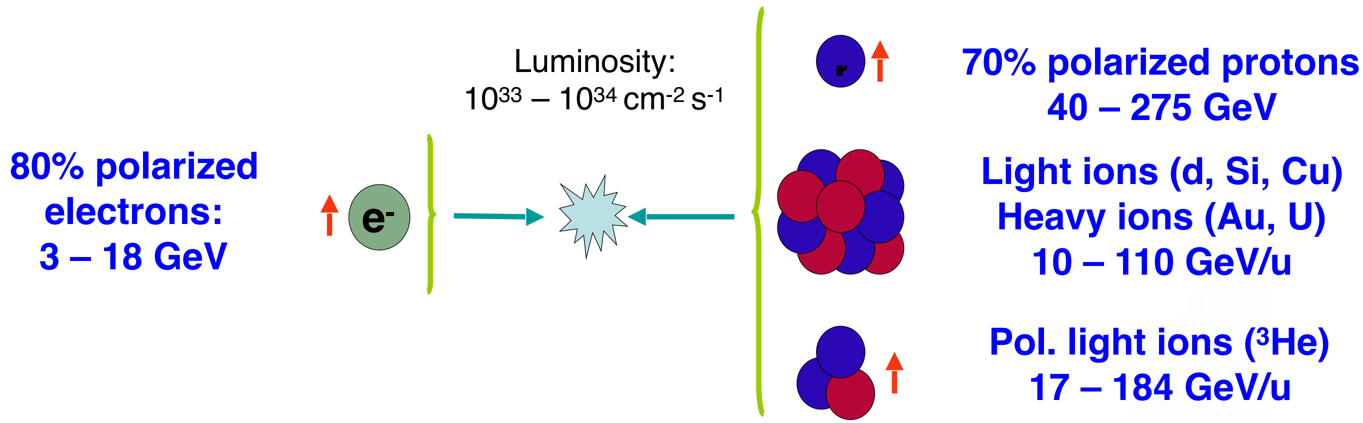
~20 GeV e$^-$ + 255 GeV p or 100 GeV/u Au.



Day-1 Detector



Primary eRHIC Design Goals



Maximum Peak Luminosity	$\geq 10^{34}$ cm^{-2}s^{-1}
Accepted Luminosity for Initial Operation	10^{33} cm^{-2}s^{-1}
Center of Mass Energies (ep)	20 GeV - 140 GeV
Proton Polarization	70%
Electron Polarization	80%
Detector forward acceptance:	
p_T acceptance	200 MeV/c – 1.3 GeV/c
forward neutron acceptance	4 mrad
Minimized construction and operational cost of the accelerator	

Summary

- **RHIC is planning a unique forefront science program with continued discovery potential as laid out in NSAC LRP:**
  - **Quantify the transport properties of the QGP *near* T_c using heavy quarks as probes**
  - **Measure gluon and sea quark contributions to proton spin and explore transverse momentum-spin dynamics of QCD**
  - **High statistics map of the QCD phase diagram, including search for a possible critical point**
  - **Probe internal structure of the *most liquid* QGP using fully reconstructed jets and resolved Upsilon states as probes**
- **Important machine and detector upgrades underway for BES II (LEReC, iTPC, EPD)**
- **Major detector upgrade underway (sPHENIX)**
- **Transition from RHIC to eRHIC in mid-2020s**