## Hot and Cold QCD Matter



## Hot QCD Matter



## RHIC: A Flexible Machine



To do condensed matter at the femto-scale,
need to tune matter properties over a wide range

## The Most Vortical Fluid

Nature 548, 62-64 (03 August 2017)



STAR: Lambda spin is polarized with respect to reaction plane Apparently strongest at lowest energies
Consistent with vorticity $(9 \pm 1) \times 10^{21} \mathrm{~s}^{-1}$, far greater than previously observed in any system
Potential: measurement of late-time magnetic field

## Everything Flows: Heavy Quarks




Technology: High precision low-mass Monolithic Active Pixels
>10-year development: First use in a collider experiment
Next generation currently being built, at larger scale, for ALICE ITS Charm ( $m=\sim 5-10$ * T ) flows just as strongly as lighter quarks

## Everything Flows: Small Systems



Signatures of Collective Flow in smallest systems from the highest LHC to the lowest RHIC energies

$d+A u$


$$
2008
$$



## QGP Signatures even in Proton+Proton

ALICE: Nature Physics 13, 535-539 (2017)


Strangeness enhancement (or absence of suppression):

- Long-standing signature of QGP formation
- Observed in high multiplicity p+p collisions at the LHC
- Smoothly interpolates to $\mathrm{Pb}+\mathrm{Pb}$ and matches in magnitude

Simplest explanation: QGP created
Couples with other observations, such as flow signatures in high multiplicity p+p

## Observing Topological Chawisel/ransitions

## To observe in the lab

- add massless fermions



## The Chiral Magnetic Effect

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.
a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe
spin alignment in B-field: opposite direction for opposite charges
handedness: momentum and spin, aligned or anti-aligned
E

negative goes up positive goes down
chirality left
right


positive goes up negative goes down


An excess of right or left handed quarks should lead to a current flow along, the magnetic field

## Resolving the Question Definitively with Isobars

Measurements consistent with CME, but potential backgrounds Resolve question by changing magnetic field, with all else constant


CME Task Force: V. Skokov, P. Sorensen, V. Koch, S. Schlichting, J. Thomas, S. Voloshin, G. Wang, H.-U. Yee, arXiv:1608.00982 Isobar collisions in 2018 can tell us what percent of the charge separation is due to CME to within $+/-6 \%$ of the current signal

## Hints of Critical Behavior

Expected behavior near critical point


Near critical point, correlation length diverges (opalescence)
Correlations: enhancement of non-Gaussian moments in net-proton distribution
Tantalizing hint, but not enough precision
Machine and detector upgrades: Beam Energy Scan - II Lower energies (reversion to zero):

Covered both worldwide and by fixed target in STAR

## Enabling Technology for BES-II




Enhanced detector coverage
63.9 m to IP2

Beam cooling for increased luminosity


## Jet Probes of QCD Structure

Parton virtuality evolves quickly and is sensitive to the medium at the scale it probes




## Enabling Technology for Jet Probes: sPHENIX

SC BaBar Solenoid 1.5 T

Coverage $|\eta| \leq 1.1$

High Precision Tracking

Projective Electromagnetic
Calorimeter

Hadronic Calorimeter


Capable of sampling 0.6 trillion Au+Au interactions in one year optimizing the use of RHIC ( $\sim 50 \times$ design) luminosity

## Future RHIC Runs and Upgrades

| 2018 |  | Isobar run: definitive test of Chiral Phenomena |
| :---: | :---: | :---: |
| $\begin{gathered} 2019- \\ 2020 \end{gathered}$ |  | Beam Energy Scan <br> Phase 2: definitive search for critical point |
| $\begin{aligned} & 2022- \\ & 2023+ \end{aligned}$ |  | sPHENIX for definitive use of jets to probe QGP substructure |

Upgrades to Machine and Detectors to greatly increase capabilities Well matched to world program:

Crucial to change matter conditions over widest possible range

## Cold QCD Matter

## Jlab 12 GeV



## 12 GeV Scientific Capabilities



Hall D - exploring origin of confinement by studying exotic mesons


Hall B - understanding nucleon structure via generalized parton distributions and transverse momentum distributions

Hall C - precision determination of valence quark properties in nucleons and nuclei


Hall A - short range correlations, form factors, hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

## $1^{\text {st }}$ Results from JLAB 12 GeV



The new GlueX results (PRC 95 (2017) 042201) show:

- The reaction mechanism for neutral pions is dominated by pure vector coupling.
- The first data for beam asymmetry for $\eta$ production $>3 \mathrm{GeV}$.
- The GlueX experiment in Hall D can produce timely results.

Nex: $\gamma \mathrm{p} \rightarrow \mathrm{pJ} / \Psi$

- J/ $\Psi$ photoproduction at threshold
- Gives insight on J/ $\Psi$
- Can also point to
production mechanism (2-gluon vs 3-gluon) nature of charmed LHCb pentaquark


The overall normalization of the GlueX data will shift the black points up or down, but the size of the errors is preserved on the log scale.

## EMC Effect in very light nuclei


$d R / d x=$ slope of line fit to $A / D$ ratio over region

$$
x_{B}=0.3 \text { to } 0.7
$$

Nuclear density extracted from ab initio GFMC calculation - scaled by (A-1)/A to remove contribution to density from "struck" nucleon

## Partonic Dynamics and N-N Correlations

EMC effect: quark momentum in nucleus is altered

N-N Correlations: pairing due to tensor force and strong repulsive core


12 GeV science quest:

- isospin dependence: ${ }^{3} \mathrm{H},{ }^{3} \mathrm{He},{ }^{6,7} \mathrm{Li},{ }^{9} \mathrm{Be}$,

$$
{ }^{10,11} \mathrm{~B},{ }^{40,48} \mathrm{Ca}
$$

- spin dependence
- "tagged" deep-inelastic scattering off ${ }^{2} \mathrm{H}$ with both slow and fast protons




## 2+1 dimensional Imaging of Quarks \& Gluons

Momentum space

(Spin-dependent) 2+1D transverse

(Spin-dependent) 2+1D spatial images from exclusive scattering


Recent theoretical work indicates direct access to Gluon Wigner function through diffractive di-jets in UPC (arXiv:1706.01765)

Dunlop Hot and Cold QCD

## Tomography in the Valence Region: ${ }^{4} \mathrm{He}$



## Beyond Longitudinal: RHIC Spin



Phys. Rev. Lett. 116 (2016) 132301


From QCD color factors, unique prediction:
Sign change from DIS to $p+p$ of a specific TMD: Sivers
"Universality" test vs. future Electron-Ion Collider program 2017 Run (just completed) will test this prediction with precision
+Evolution scheme via comparison to Drell-Yan

## FUTURE: ELECTRON-ION COLLIDER



## QCD Landscape Explored by EIC

Weak QCD at high resolution $\left(Q^{2}\right)$ —uncorrelated quarks and gluons are well-described


## Summary



## Backup

## Proton Momenta in the Nucleus



Projected measurements @ 12 GeV of ${ }^{2} \mathrm{H}(\mathrm{e}, \mathrm{e}$ 'p) cross section mapping high proton momenta induced by short-range repulsive NN core

${ }^{48} \mathrm{Ca} \rightarrow{ }^{40} \mathrm{Ca}$ (adding 8 neutron to a f $7 / 2$ subshell ) $40 \%$ more neutrons

Map ratio of ${ }^{48} \mathrm{Ca}(\mathrm{e}, \mathrm{e}$ 'p) and ${ }^{40} \mathrm{Ca}(\mathrm{e}, \mathrm{e}$ 'p) cross sections at high proton momenta


Lonardoni, et al., arXiv. 1705.04337 [nucl-theory] 2017

## Uniqueness of EIC among all DIS Facilities



