BNL Nuclear Theory Group

Raju Venugopalan

RHIC S&T review, September 16-18, 2019

BNL NTG: A flagship of DOE Nuclear Theory

- **Excellence** in scientific research aimed towards accomplishing goals set by BNL and DOE Office of Science
- **Support and guidance** for experimental programs at RHIC & elsewhere
- **Training** a new generation of nuclear theorists
- Chart the course **for future directions** in Nuclear Physics

Nuclear Theory Group Staff

Long term Scientific Staff:

I Y. Hatta

II. D. Kharzeev (joint with SBU)

III. Y. Mehtar-Tani

IV. S. Mukherjee

V. P. Petreczky

VI. R. Pisarski

VII. B. Schenke

VIII. R. Venugopalan (Group Leader)

Group Administrator:

D. Davis

Note: F. Karsch retired from BNL in April 2019

Post-doctoral Fellows:

I. R. Boussarie (LDRD)

II. N. Karthik (BEST)

III. R. Larsen

IV. A. Rajan (LDRD)

V. A. Soto-Ontoso (LDRD)

VI. P. Steinbrecher (SciDac)

VII. A. Tarasov (TMD, departs 10/19)

VIII. S. Valgushev (LDRD)

IX. Y. Zhao (TMD, started 09/19)

Students:

I. K. Roy (CFNS, SBU)

II. F. Salazar-Wong (NTG, SBU)

III. C. Schugert (SBU)

Visiting Post-doctoral Fellows:

I. I. Kolbe (LDRD, 8/19-12/18)

II. N. Mueller (DFG, Germany)

III. F. Renecke (DFG, Germany)

Scientific Productivity and Recognition: 2018-

Scientific Productivity:

- From January 2018- August 2019, 132 publications (73 refereed + 59 conference) approximately 7 per month. These include 17 letter publications
- 165 plenary and invited talks, colloquia and seminars by group members

Awards and Honors:

- Alba Soto-Ontoso: Outstanding Doctoral Thesis Award, Frankfurt U.
- Heikki Mantysaari: Mikael Bjoernberg Prize, Finland
- Yuji Hirono, Junior Group Leader, APCTP, South Korea
- Chun Shen: Joint RIKEN/BEST Faculty Fellow at Wayne State Univ.
- Swagato Mukherjee: co-PI INCITE Computing Award
- Bjoern Schenke: Adjunct Prof., Stony Brook U
- Dima Kharzeev: Distinguished Prof., Stony Brook U
- Raju Venugopalan: 2018 BNL S&T Award; Distinguished Asian American Award, Suffolk County, NY

Nuclear Theory Activities @ BNL

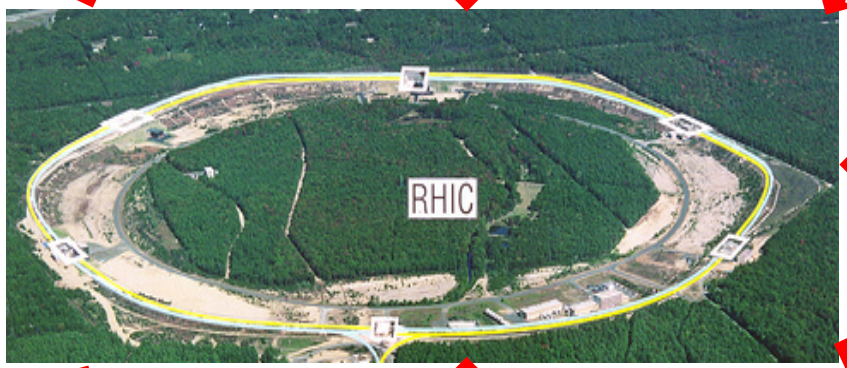
- *Focus on 2 of the 5 Research Areas identified in 2015 NSAC LRP Document:*
  - Area 1 – QCD and the structure of hadrons and nuclei
  - Area 2 – QCD and the phases of strongly interacting matter
- *Support the RHIC physics program – polarized proton and heavy ion collisions*

Initial conditions: QCD at small x,
Hatta, Kharzeev, Mehtar-Tani,
Schenke, Venugopalan

Pre-equlibrium dynamics:
long-range rapidity correlations,
local strong parity violation, …
Hatta, Kharzeev, Schenke,
Mehtar-Tani, Venugopalan

Properties of sQGP:
Transport coefficients,
viscous hydro, …
Hatta, Kharzeev, Mukherjee,
Petreczky, Pisarski,
Schenke, Venugopalan

EIC



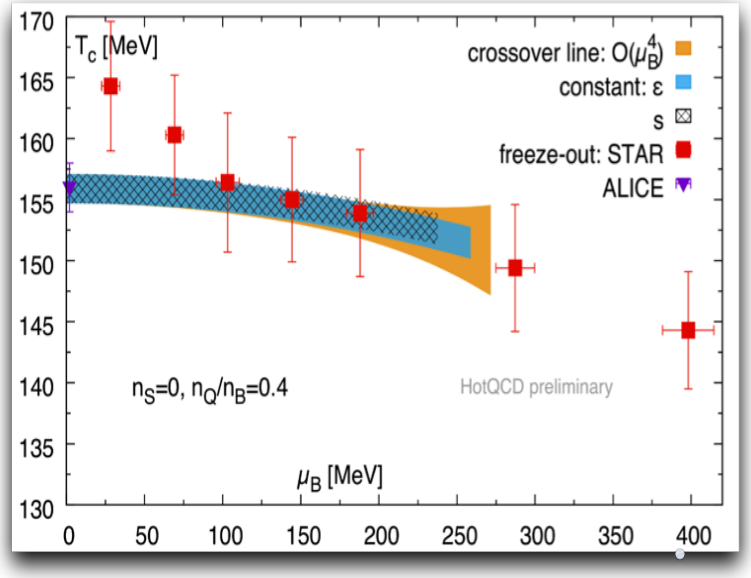
QCD phase diagram and
critical point, RHIC BES, …
Kharzeev,Mukherjee,
Petreczky, Pisarski, Schenke,
Venugopalan

QCD and hadron structure:
factorization – probes,
spin physics, 3D structure, …
Hatta, Kharzeev, Mukherjee,
Petreczky, Venugopalan

Hard probes of QGP:
jets, heavy quarks, di-leptons, …
Hatta, Kharzeev, Mehtar-Tani
Petreczky, Schenke, Venugopalan,

Quarkonium:
Production – pp, pA, AA,
heavy quark transport, …
Hatta, Kharzeev, Mehtar-Tani,
Petreczky, Schenke, Venugopalan

Selected research highlights: lattice QCD



$T_c(\mu_B = 0) = 156.5 \pm 1.5\ MeV$

Chiral crossover temp. for $\mu_B \leq 300\ MeV$

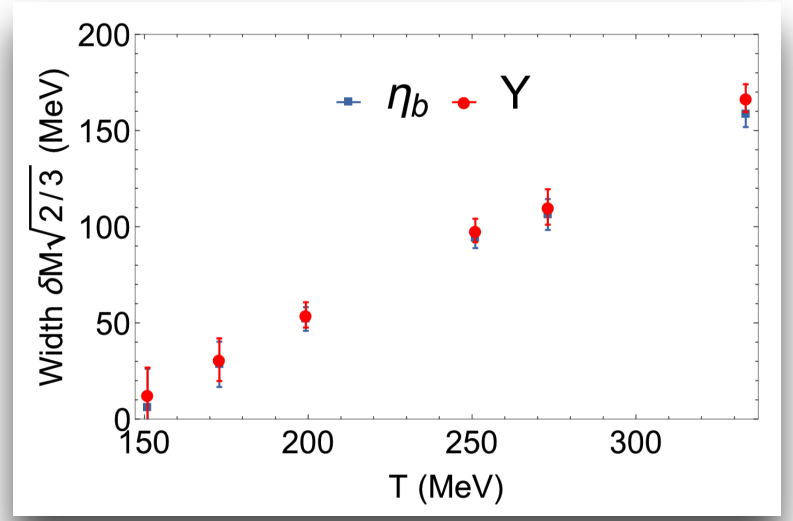
-improved lattice constraints on QCD critical point

HotQCD: Phys. Lett. B795, 15-21 (2019)

Determination of chiral critical temperature for massless u and d quarks and physical strange quark

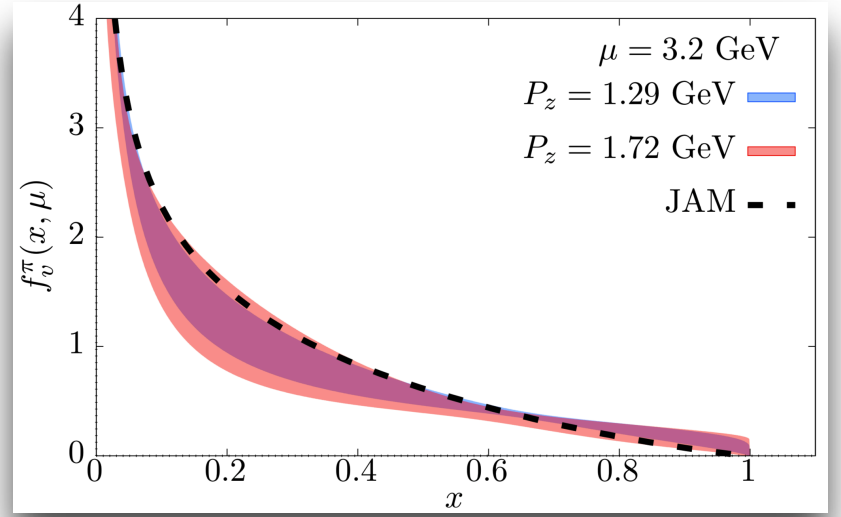
$T_c(m_{u,d}=0, \mu_B = 0) = 132$ +3-6 MeV

HotQCD: Phys. Rev. Lett.123, 062002 (2019)



Thermal broadening of bottomonia

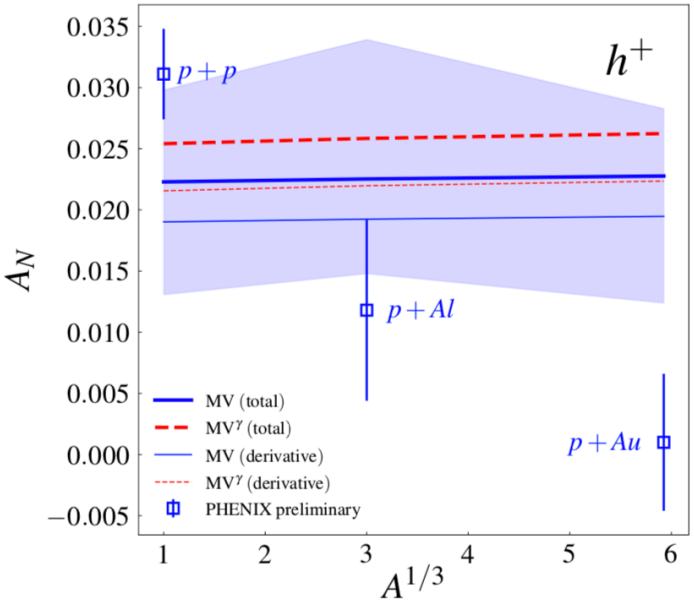
Larsen *et.al.*: arXiv:1908.08437



Parton distribution function of pion

BNL-SBU: Phys. Rev. D100, 034516 (2019)

Selected research highlights: spin, small x, jets



Computation of single spin asymmetries: $p^\uparrow p \rightarrow \pi^0 X$

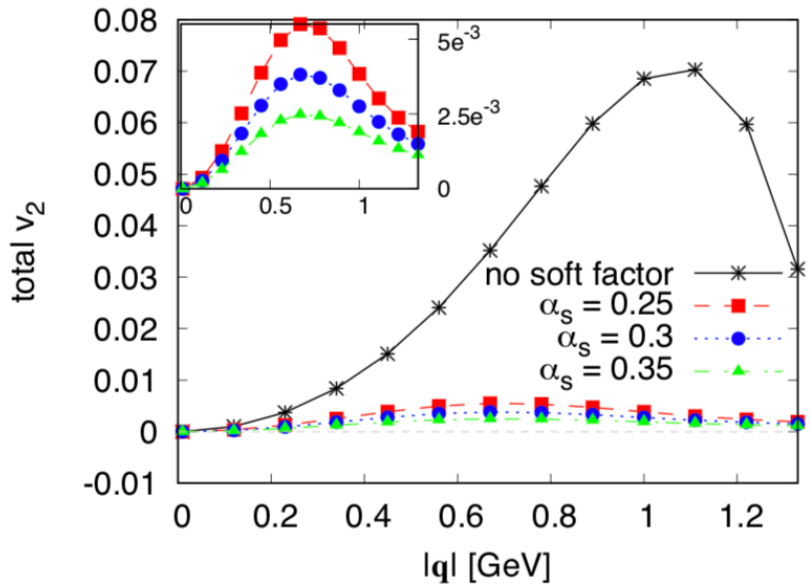
Benic, Hatta: PRD99 (2019) 094012

Evolution of proton spin at small x in pQCD:

$$\Delta G \approx \frac{1}{x^{1.01}}\,;\; L_g(x) \approx -2\,\Delta G(x)\,;\; L_q \approx -2\,\Delta\Sigma$$

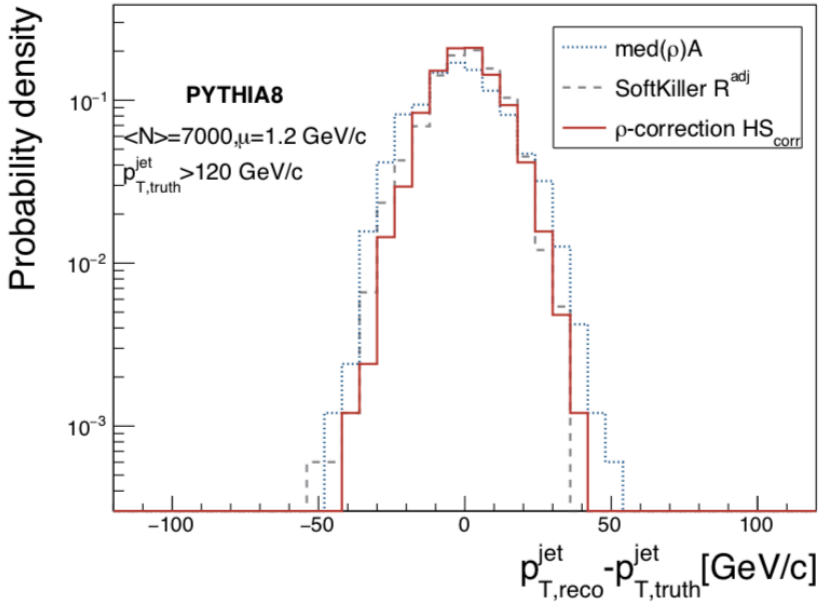
Boussarie,Hatta,Yuan, PLB797 (2019) 134817

Extensive work on orbital motion by Hatta et al.



v_2 at EIC in diffractive dijets ?

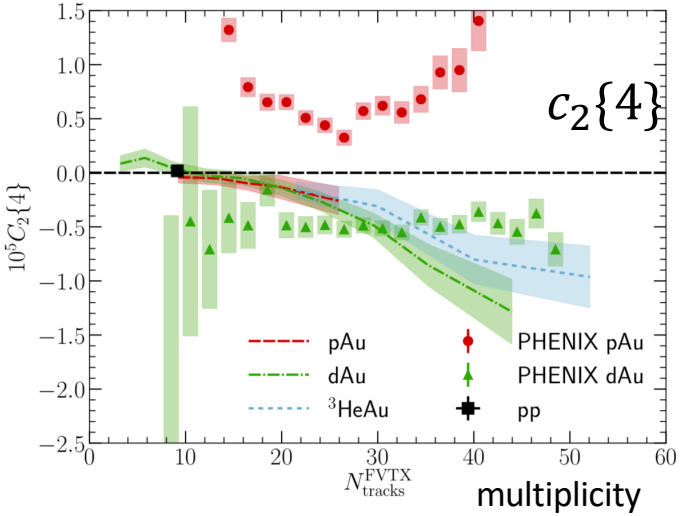
Hatta,Mueller,Ueda,Yuan, arXiv:1907.09491



Background estimator for jet studies in A+A

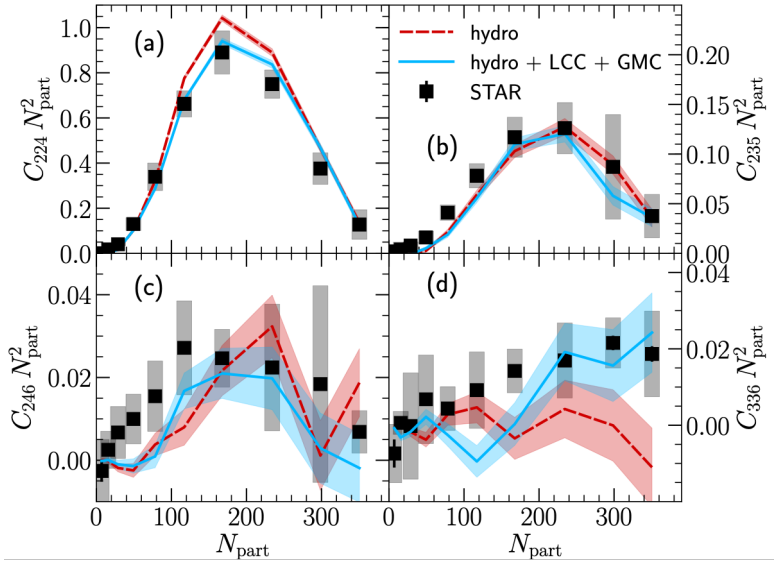
Mehtar-Tani,Soto-Ontoso,Verweij, arXiv:1904.12815

Selected research highlights: hydro simulations



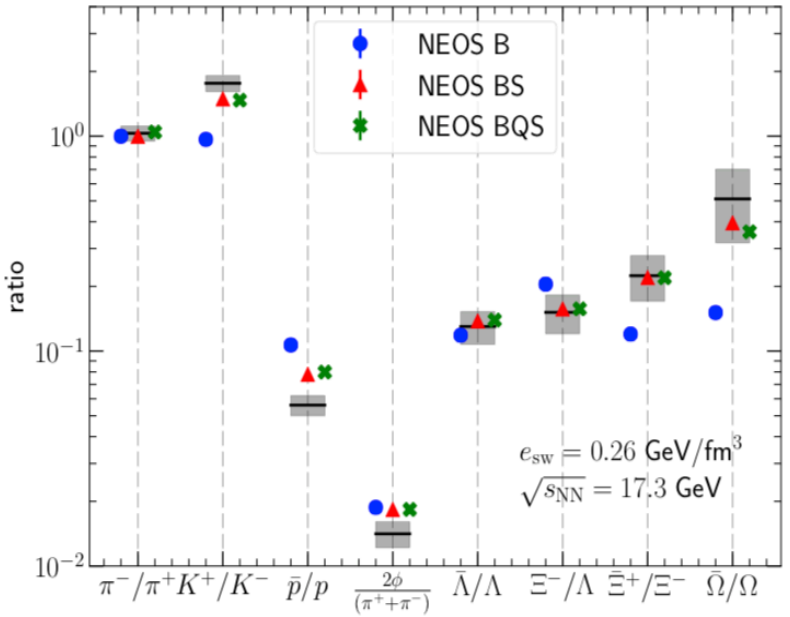
Small systems: first calculation of $c_2\{4\}$ for pp, pAu, dAu, ^{3}HeAu

Effect of initial state momentum anisotropy on observables Schenke, Shen, Tribedy, arXiv:1908.06212



Multi-particle correlations: charge inclusive and charge dependent 3 &4- particle correlations

For CME search Schenke, Shen, Tribedy, PRC99 (2019) 044908



Beam Energy Scan hydro simulations with EOS at finite densities (q, b, s); initial state with fluctuating baryon densities; Net-baryon diffusion

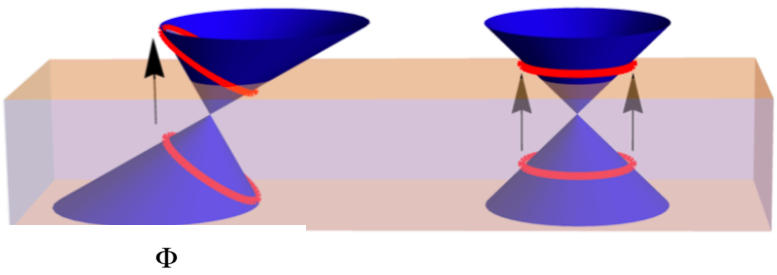
G.S. Denicol, C. Gale, Jeon, A. Monnai, B. Schenke, C. Shen, Phys.Rev. C98 (2018) 034916

C. Shen, B. Schenke, Phys.Rev. C97 (2018) 024907

A. Monnai, B. Schenke, C. Shen, Phys.Rev. C100 (2019) 024907

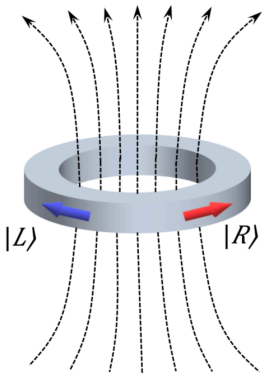
Selected research highlights: interdisciplinary effort

Helical Magnetic Effect in asymmetric Weyl semi-metals



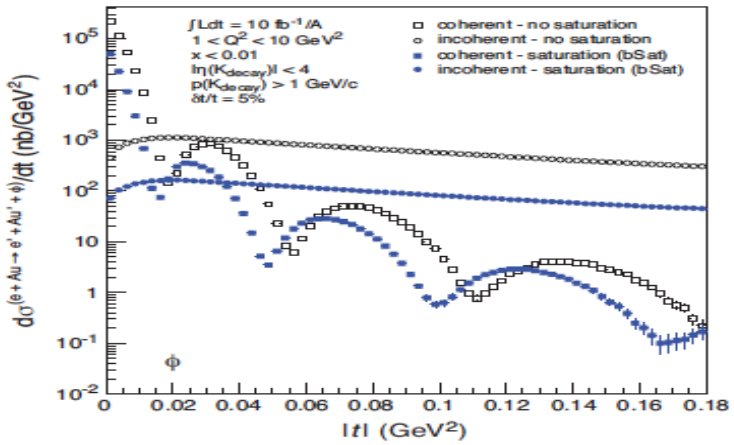
Kharzeev,Kikuchi, Meyer, Tanizaki PRB98 (2018) 014305

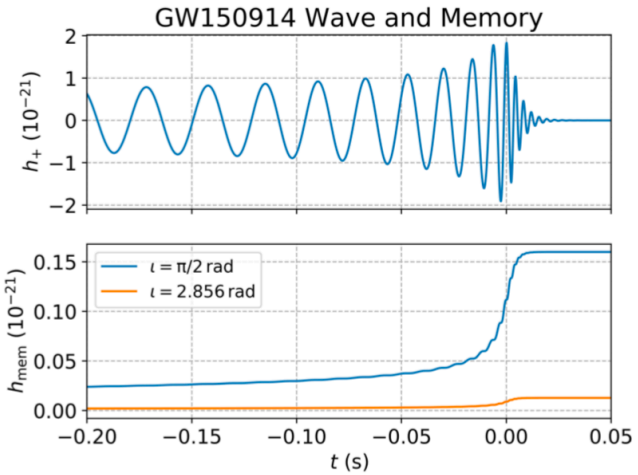
Huge increase in photo-response to Tera Hz frequency light – possible application to development of photo-sensors



Using the Chiral Magnetic Effect (first discussed in context of HI collisions) in Weyl/Dirac semi-metals to construct a quantum computer Kharzeev, Li, arXiv: 1903.07133

Color memory in diffractive DIS





Striking correspondence of gravitational memory (measurable by eLISA) and color memory (measurable at EIC)

Ball,Pate,Raclariu, Strominger,Venugopalan, Annals Phys. 407 (2019) 15

BNL NTG: synergistic activities

Active participation in DOE Topical collaborations:

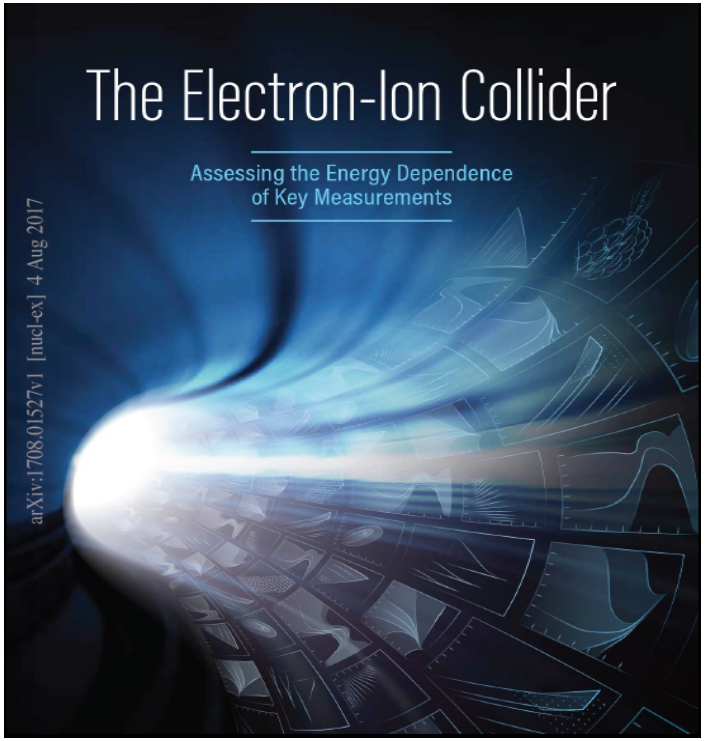
BEST collaboration: Mukherjee is PI, Kharzeev, Schenke, Venugopalan are co-PI's; Karthik supported by BEST. Group members contribute to lattice studies, hydro simulations, CME signals and novel ideas in the critical point search

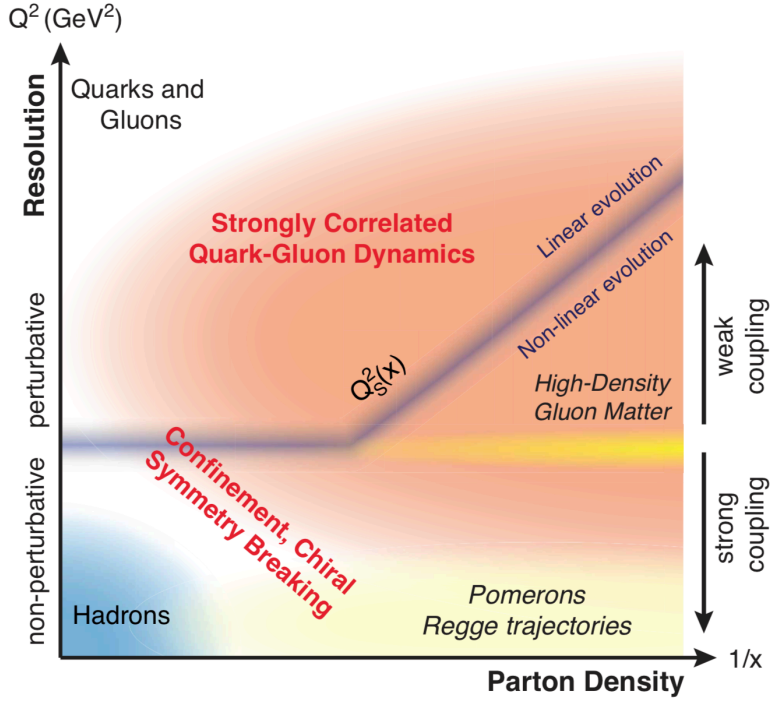
TMD collaboration: Venugopalan is co-PI, Tarasov and Zhao are supported by TMD. Several group members are actively involved in TMD activities, including contributions to the TMD handbook being prepared by the collaboration

Other key scientific synergies:

- **Schenke and Mehtar-Tani contribute to activities of the JETSCAPE collaboration Mukherjee is co-PI of the SciDac-4 collaboration, interacting closely with USQCD**
- **NTG and the RIKEN-BNL Research Center (RBRC): Group members have administrative roles, mentor and collaborate with RBRC Faculty and post-doctoral Fellows, and help organize meetings and NT/RBRC joint seminars**
- **Strong collaboration with BNL HET (Lattice and Quantum Information Science), SBU NT (Heavy-Ions, EIC) and YITP (jet physics,spin); *mentorship of SBU students***

BNL NTG and EIC





BNL Report on EIC Science: Reports on Progress in Physics (2019)
Contributions from Mantysaari, Schenke and Venugopalan (co-Editor)

Strong synergy between NTG EIC activities and BNL EIC Taskforce as well as new BNL/SBU Center for Frontiers in Nuclear Science (CFNS)

NTG and CFNS EIC activities

Abhay Deshpande is Director of CFNS (see dedicated talk on CFNS)
Kharzeev and Venugopalan serve on the CFNS Steering Committee.

- ✓ **Joint Bi-monthly seminars alternating at BNL and SBU**
- ✓ **Large number of topical workshops: 14 organized/planned in 2018-19**
- ✓ **First annual CFNS EIC summer school in August 2019**
- ✓ **BNL theory post-docs and students hired on EIC related LDRDs on Jets/Spin/Saturation closely integrated with BNL EIC Taskforce and SBU counterparts working on similar topics under aegis of CFNS**
- ✓ **Active visitor program. ~200 CFNS visitors at BNL/SBU thus far**

NT LDRD Awards

I. *Interplay of the many-body dynamics of parton spin with gluon saturation at the EIC* (PI: Venugopalan; co-PI's: Yoshitaka Hatta, Abhay Deshpande, Yuri Kovchegov(OSU), Ernst Sichtermann (LBNL), Andrey Tarasov (BNL))

II. *Jets at the EIC* (PI: Venugopalan; co-PI's: Megan Connors (GSU/RBRC) Abhay Deshpande, Yacine Mehtar-Tani (BNL), George Sterman (SBU), Thomas Ullrich (BNL))

III. *Studying confinement and nuclear structure through correlations and quantum entanglement at an EIC (*PI: Thomas Ullrich (BNL); co-PI's: Abhay Deshpande, Dima Kharzeev (BNL/SBU), Raju Venugopalan (BNL))

IV. *Finding a Lifshitz Point with the Beam Energy Scan II* (PI: R. Pisarski; co-PI, A. Tsvelik)

NTG Initiative: QIS for Nuclear Physics

Compelling questions in extreme QCD that could benefit from Quantum computation:

- ***QCD phase diagram – location of critical point***
- ***Early time preequilibrium dynamics of the QGP***
- ***Real time correlations in DIS and HI collisions***
- ***Entanglement in multiparticle production at RHIC/EIC***

1) D. E. Kharzeev and E. M. Levin, "*Deep inelastic scattering as a probe of entanglement*," Phys. Rev. D 95, 114008 (2017)

2)O. K. Baker and D. E. Kharzeev, "*Thermal radiation and entanglement in proton-proton collisions at the LHC*" Phys. Rev. D98, 054007 (2018)

3) J. Berges, S. Floerchinger, R. Venugopalan, "*Dynamics of entanglement in expanding quantum fields*", JHEP 1804 (2018) 145

4) J. Berges, S. Floerchinger, R. Venugopalan "*Thermal excitation spectrum from entanglement in an expanding quantum string*", Phys.Lett. B778 (2018) 442-446

5) R. Pisarski and V. Skokov, "*Chiral matrix model of the semi-QGP in QCD*", PRD94 (2016) 034015

6)K. Tu,D. Kharzeev, T. Ullrich, *EPR paradox and quantum entanglement at sub-nucleon scale,* arXIv:1904.11974

7) N. Mueller, A. Tarasov, R. Venugopalan, *DIS structure functions on a hybrid quantum computer,* arXiv:1908.07051

Close collaboration with Computational Sciences Initiative and Photon Sciences

Summary and Outlook

- **The BNL NT Group is a vibrant, diverse and active group that has seen a significant change in profile since 2016. Our goal is to further diversify the scientific staff in the group in the decade ahead**

- **NT Group successfully addressed recommendations of the 2016 Review of National Lab Theory Groups**

- **Group is taking a lead in RHIC BES physics, has taken new initiatives in sPHENIX physics and is playing a strong leadership role towards EIC.**

- **Group has new initiatives in lattice gauge theory and in quantum information science**

- **Funding scenario is challenging in achieving all these objectives. We rely on continued and hopefully enhanced funding necessary to maintain our scientific excellence and flagship role in high energy nuclear physics**

Backup slides

Key Synergistic Activities

Hatta: RBRC Deputy Theory Group Head

D. Kharzeev: Program committee, DNP; Editor Int. J. Mod. Phys. E;
RBRC Theory Group Head, CFNS Steering Committee;co-PI, BEST

Mehtar-Tani: JETSCAPE collaboration External Member

S. Mukherjee: Executive Committee of USQCD;
Lead PI of the BEST collaboration, co-PI SciDac-4

P. Petreczky: Co-Chair APS DComp Program Committee,
Topical Convener quarkonium working group

R. Pisarski: Associate Editor of Phys. Rev. D

B. Schenke RHIC/AGS Users Executive Committee; Convener, BEST
Collaboration Working Group, Associate Member, JETSCAPE
External Member, ISOQUANT

R. Venugopalan: DNP Executive Committee (2016-18); co-Chair, CFNS Steering Committee;
Editor, Annals of Physics; Chair-line APS GHP (2014-17);
National Advisory Committee INT Seattle (2015-17);
EMMI (GSI) Advisory Committee (2016-18), co-PI: BEST, TMD, ISOQUANT

Group members serve on numerous International Advisory Committees of major international conferences, meetings, panels & workshops, and lecture at many international summer/winter schools