Highlights from BNL and RHIC 2015

For previous years with more details see:

2009: IJMPA 26 (2011)5299 1406.0830

2011-2013: IJMPA 29 (2014)1430017 1406.1100

2014: arXiv1504.02771

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA

International School of Subnuclear Physics,
“The Future of our Physics Including New Frontiers”
53rd Course-Erice, Sicily, Italy June 24- July 3, 2015

Erice 2015

M. J. Tannenbaum
The Relativistic Heavy Ion Collider (RHIC) at BNL is 1 of the 2 remaining colliders—it is visible from space. BNL also has many other facilities.
BNL M&O contract awarded to BSA again

By Peter Genzer | January 20, 2015

Department of Energy, Brookhaven Science Associates Sign New Brookhaven Lab Management Contract

On Dec. 18, 2014, representatives from the U.S. Department of Energy (DOE), Brookhaven Science Associates (BSA), and New York State held a ceremonial signing of a new five-year, $3.25 billion contract for BSA to manage and operate Brookhaven National Laboratory for the DOE.

Established as a partnership between Stony Brook University and Battelle, BSA has managed Brookhaven Lab since 1998. The new contract begins on Jan. 5, 2015, and has a base term of five years, with up to 15 additional years that can be earned through award-term incentives.
National Synchrotron Light Source II Achieves 'First Light'
The National Synchrotron Light Source II detects its first photons, beginning a new phase of the facility's operations. Scientific experiments at NSLS-II are expected to begin before the end of the year.

October 23, 2014

A crowd gathered on the experimental floor of the National Synchrotron Light Source II to witness "first light," when the x-ray beam entered a beamline for the first time at the facility.

UPTON, NY — The brightest synchrotron light source in the world has delivered its first x-ray beams. The National Synchrotron Light Source II (NSLS-II) at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory achieved "first light" on October 23, 2014, when operators opened the shutter to begin commissioning the first experimental station (called a beamline), allowing powerful x-rays to travel to a phosphor detector and capture the facility's first photons. While considerable work remains to realize the full potential of the new facility, first light counts as an important step on the road to facility commissioning.

Energy Secretary Moniz Dedicates the World's Brightest Synchrotron Light Source
NSLS-II at Brookhaven National Lab will accelerate unprecedented advances in energy, environmental science, and medicine

February 6, 2015

UPTON, NY – U.S. Department of Energy (DOE) Secretary Ernest Moniz today dedicated the world's most advanced light source, the National Synchrotron Light Source II (NSLS-II) at Brookhaven National Laboratory (BNL). The NSLS-II is a $912-million DOE Office of Science User Facility that produces extremely bright beams of x-ray, ultraviolet, and infrared light used to examine a wide range of materials, including superconductors and catalysts, geological samples, and biological proteins to accelerate advances in energy, environmental science, and medicine.

NSLS-II will enable a future generation of scientists to continue building on the 32-year legacy of research at Brookhaven's first light source, NSLS, which directly resulted in two Nobel Prizes and contributed to a third. With $150 million in funding through the American Recovery and Reinvestment Act of 2009, NSLS-II has come online on time and under budget to usher in the next chapter of light source capability. The planning, design,
RHIC – the First Heavy Ion Collider

After continuous improvements and upgrades RHIC reached 25x design luminosity, exceeding “RHIC II” goal, 3 years early & at 1/7 of estimated cost

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
- 8 modes (Au+Au, d+Au, Cu+Cu, Cu+Au, U+U, $^3$He+Au, p+Au, p+Al) 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
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: $P\sim 59\%$, $L_{\text{peak}} \sim 0.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- $\sqrt{s}=510$ GeV: $P\sim 52\%$, $L_{\text{peak}} \sim 2.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$

Luminosity increase with electron lenses
Compensate for beam-beam interactions
Successful operation in Run 15
... and even better

2.5 times increase in peak luminosity enabled by:
- Polarized H- source upgrade
- Incremental AGS improvements
- Electron lenses
# C-A Operations-FY15

**as run, planned**

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<th>Program Element</th>
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<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tr>
<td>RHIC STAR &amp; PHENIX</td>
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<td>27</td>
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<tr>
<td>RHIC Research with $\sqrt{s} = 200$ GeV $pp$</td>
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<td>10.9 weeks</td>
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<td>5 wks</td>
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<td>RHIC Research with $\sqrt{s} = 200$ GeV/n $pAu$</td>
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<tr>
<td>RHIC Research with $\sqrt{s} = 200$ GeV/n $pAl$</td>
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</tbody>
</table>

**PHENIX Integr. Sampled Lumi vs Day**

- **Wide vertex**: 322.19 nb\(^{-1}\)
- **30 cm vertex**: 164.50 nb\(^{-1}\)
- **10 cm vertex**: 64.12 nb\(^{-1}\)

**MPC-EX Integr. Sampled Lumi vs Day**

- **40 cm vertex**: 197.67 nb\(^{-1}\)
Approx 500 tracks result from a Au+Au ion collision

p+p at $v_s=510$ GeV max
Au+Au at $v_s=200$ GeV max
Started at Year 2000
collided various beams
pp, dAu, CuCu, CuAu
AuAu, UU, $\text{He}^3$Au, pAu,pAl
Mike, is there a ‘real collider detector’ at RHIC?” ---J. Steinberger about PHENIX

PHENIX is a special purpose detector designed and built to measure rare processes involving leptons and photons at the highest luminosities.

- possibility of zero magnetic field on axis
- minimum of material in aperture 0.4% $X_0$
- EMCAL RICH $e^\pm$ i.d. and lvl-1 trigger
  - $\gamma \pi^0$ separation up to $p_T \sim 25$ GeV/c
  - EMCAL and precision TOF for $h^\pm$ pid
  - Main Central detector $|\eta|<0.35$
  - Muon arms $1.1<|\eta|<2.3$
  - BBC, MPC $3.1<|\eta|<3.9$

Comparison to scale with a wedge of CMS
PHENIX FVTX and VTX in place-displaced $e^{\text{HF}}$, $\mu^{\text{HF}}$
STAR Detector System

EEMC  Magnet  MTD  BEMC  TPC  TOF  BBC

HFT

Erice 2015  M. J. Tannenbaum  13
RHIC: Recent Detector Upgrades

- Fully reconstruct open charm/beauty hadrons with displaced vertex
- Muon Telescope Detector (STAR)
- Muon Piston Calorimeter extension
  - Enhances triggering capabilities for heavy quarkonia

Completed on schedule and below cost

- STAR Preliminary
  - Au+Au \(|\sqrt{s_{NN}}| = 200 \text{ GeV}
  - RHIC Run 2014

- PHENIX
  - Critical for transverse spin physics Run15
The MPC-EX Detector

A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

- $\pi^0$ rejection (direct photons)
- $\pi^0$ reconstruction out to >80GeV
- Charged track identification

3.1<\eta<3.8
MPC Damage-Yellow Abort Kicker Prefires

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<thead>
<tr>
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<th>19050</th>
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<td>May 11</td>
<td>May 28</td>
<td>June 1</td>
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<tr>
<td>Damaged South</td>
<td>We got lucky</td>
<td>The end of the</td>
<td></td>
</tr>
<tr>
<td>Impacted North</td>
<td>No add’t’l damage</td>
<td>MPC in Run 15</td>
<td></td>
</tr>
</tbody>
</table>

Energy Per Crystal, SMPC Trigger 0

Energy Per Crystal, NMPC Trigger 0

South

North

Erice 2015

Matin L. Purschke
Giant Electromagnet Arrives at Brookhaven Lab to Map Melted Matter

A 20-ton superconducting magnet traveled from California’s SLAC Lab to New York’s Brookhaven Lab as part of a proposed upgrade to the Relativistic Heavy Ion Collider’s PHENIX detector.

The massive, just-delivered magnet leaves the truck inside Brookhaven’s Superconducting Magnet Division.

Why did the 40,000-pound superconducting magnet cross the country? The full answer to this twist on the old joke is complicated, but here’s the short version: to unlock the secrets...
SC-Magnet From SLAC to BNL
Former BaBar Solenoid on the AGS Floor

Erice 2015
SC-Magnet Warm Acceptance Test

- SC-Magnet Acceptance Test Complete in 912. All is OK
- Tests Performed by Mike Aneralla and SMD crew with C-AD help
  - Hypot test
  - Impulse tests
  - He Leak check
  - Inductance measurement
SC-Magnet Warm Acceptance Test

- 13 page traveler

**SC-Magnet Warm Acceptance Test**

**Superconducting Magnet Division**

**sPhenix Solenoid Inspection & Acceptance**

**MDC No. sPhenix-010 Rev: A**

**Page 2 of 10**

**Rev: Date:** 04/03/2015

**Author:** M. Anerella

**Approved:** 04/06/2015

---

**OP** | Description | Name/Last # | Date | DR
---|---|---|---|---
50 | Technicians performing Pressure Testing shall be instructed in the procedures prescribed by the SMBM Subject Area by the Copignot Engineer or Technical Supervisor:  
- Compressed Gas Cylinders and Related Systems  
- Pressure Safety  
- Cryogenics Safety  

All relief devices and gauges used for pressure tests shall meet the requirements of the SMBM Subarea. Examine all pressure test equipment before pressure is applied to ensure it is tightly connected.  
Suitable precautions shall be taken during pressure testing to eliminate hazards to personnel in the proximity of the test in the event of a rupture. The area shall be roped off.

---

53 | All work performed herein shall be done in a manner compliant with the document "Work Plan for sPhenix Magnet". All work which has not been categorized as "worker planned work" shall require an approved work permit.

---

110 | Inspect, tag, and inventory all voltage tap, strain gauge and other instrumentation wires. Record lead ID's on Table 2.

---

120 | Remove and inspect heat shield shipping restraints. There are 3 restraints at each end of the magnet. Photograph and record damage, if any, on a discrepancy report.

Tag and store the shipping restraints for future use.

---

130 | Perform visual inspection of the magnet. Photograph and record damage, if any, on a discrepancy report.

---

140 | Set power supply to 26 VDC maximum and apply 1 amp to coil. Measure and record voltage drops and record in Table 1.

---

**OP** | Description | Name/Last # | Date | DR
---|---|---|---|---
150 | Measure overall resistance, coil inductance and quality factor. Perform tests at three frequencies, 20Hz, 60Hz, and 1kHz. Record data below:

- **Temp:** 22°C

- R: 2.536Ω, 2.536Ω, 2.536Ω

- L: 1432H, 1432H, 8133H

- Q: 1.7, 1.7, 1.7, 1.7

- DC Inductance: 2.5H

---

160 | Prepare coil for hypot & impulse testing:

1. Verify (3) blank-off flanges at LE & (3) blank-off flanges at NLE are installed.

2. Locate magnet lead feedthrough assembly along with O-rings to the glinned dessicating single magnet lead to feedthrough.

3. Dress all other leads and tags instrumentation into the chamber in preparation for bolting of the feedthrough.

4. Bolt the feedthrough in place.

5. Install lead box covers.

6. Connect mechanical vacuum pump to the feedthrough.

7. Start pump. Continue pumping down until an absolute pressure of <50 millitorr is reached in the vacuum space.
Looking Forward: Advanced Instrumentation to Help Complete the Mission

A rendering of the proposed upgrade showing the inner silicon tracker (VTX), the solenoid, and the calorimeters. The solenoid has a diameter of 1.4 m.
Following up on the afternoon discussion, which concluded that we should move expeditiously to form a new detector collaboration to take advantage of the physics opportunities offered by a large acceptance detector for jets and heavy quarkonia built around the BaBar magnet, we are inviting all interested scientists and institutions who are considering joining this effort to declare their interest in joining this new collaboration. We request that they do so by sending an electronic message to Peter Yamin yamin@bnl.gov including their name, institution, and email address no later than July 16, 2015. If there is more than one interested scientist at the same institution, we ask them to identify the person who will serve on the provisional Institutional Board (IB) for the new detector collaboration.
Billion-dollar particle collider gets thumbs up

Proposed US electron–ion smasher wins endorsement from influential nuclear-science panel.

Edwin Cartlidge

19 May 2015

The machine should also solve a puzzle about the proton that has baffled physicists for nearly 30 years. The proton has a quantum-mechanical property called spin, but, strangely, the spins of its three constituent quarks add up to only about one-third of its own spin. The EIC would determine what makes up the difference: options include the spin of the proton’s gluons, the angular momentum of its quarks or of the gluons from their orbital motion, or a mixture of all three.

Robert McKeown, deputy director for science at the Jefferson lab, thinks that limited funds might delay the start up of the EIC until at least 2030. And Michael Lubell, director of public affairs at the American Physical Society, questions whether it is feasible for the EIC to be built by the United States alone. He notes that the $1.5-billion Long-Baseline Neutrino Experiment became an international project after a slimmed-down $600-million version failed to pass scientific muster. “It is hard to see how to do this unless you get international buy-in,” he says.
Proton Spin Structure

Manohar-Jaffe sum rule:

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \Delta L_q + \Delta L_g \]

Know very little

\[ \Delta \Sigma = \Delta u + \Delta d + \Delta \bar{u} + \Delta \bar{d} + \ldots \]

Poorly constrained

\[ \sim 0.33 \] (small)

Poorly constrained

Xiaorong Wang, RHIC/AGS AUM 2015
NATURE didn’t know about the latest RHIC results

Elke Aschenauer says a factor of 2 reduced uncertainty at $x=10^{-3}$

First time a significant non-zero $\Delta g(x)$

$\int dx \Delta g \sim 0.2^{+0.06}_{-0.07} @ 10 \text{ GeV}^2$

$\int dx \Delta g \sim 0.36 @ 10 \text{ GeV}^2$

Erice 2015
Overall Review Committee Summary

• The accelerator total project cost was presented to be $755.9M in FY15$ including 31% contingency.

• eRHIC incorporates certain technical advances which are beyond the state of the art; the 31% contingency is, in the opinion of the subcommittee insufficient.

• MEIC is based on largely conventional technology with fewer technical risks; the proposed 35% contingency is marginally sufficient.

• An EIC could be built for about $1.5B in FY15$.
  • This is equal to the MEIC TPC and $0.5B higher than the eRHIC TPC to account for the higher technical risk.
4.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \text{ for } \sqrt{s} = 126 \text{ GeV} \text{ (15.9 GeV e^{+} on 250 GeV p^{+})}
<table>
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<th>Time</th>
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<tr>
<td>15:00</td>
<td>Welcome, Herwig SCHOPPER, Main Auditorium, CERN</td>
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<tr>
<td>15:30</td>
<td>Accelerator Design, Oliver BRUNING, Main Auditorium, CERN</td>
</tr>
<tr>
<td>16:00</td>
<td>Concept of a High Intensity Energy Recovery Linac Facility, Erk JENSEN</td>
</tr>
</tbody>
</table>
The Perfect Liquid 10th Anniversary Celebration and 2015 RHIC & AGS Annual Users' Meeting

By Justin Frantz

Please join us for the 2015 Relativistic Heavy Ion Collider (RHIC) & Alternating Gradient Synchrotron (AGS) Users' Meeting, June 9-12 at Brookhaven Lab. This year's theme is "The Perfect Liquid at RHIC: 10 Years of Discovery" and we will celebrate the 10th anniversary of the 2005 announcement that marked the discovery of the "Perfect Liquid," also known as the strongly-coupled Quark-Gluon-Plasma (QGP).

The Perfect Liquid is made by smashing together nuclei at ultra-relativistic energies. As a kind of QGP, it is composed of quarks and gluons that...
The QGP was discovered at RHIC, announced on April 19, 2005 as ‘the perfect fluid’ (10th anniversary celebrated this year), published NPA750,757(2005)1-171,1-283 with properties quite different from the ‘new state of matter claimed’ by the CERN fixed target heavy ion program on February 10, 2000 (“unpublished”)
How to find the **Quark Gluon Plasma** (QGP) in A+A collisions c.1990:--a medium of quarks and gluons deconfined from their original nucleons covering a volume that is many units of the confinement length scale (~1fm) in which the q and g with their color charge fully exposed freely traverse the medium composed of a large density of similarly exposed color charges.
The gold-plated signature for the QGP J/ψ Suppression-1986

- In 1986, T. Matsui & H. Satz PL B178, 416 (1987) said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the cc-bar couldn’t bind. QGP thermometer

Jet Quenching: Parton energy loss by coherent LPM radiative energy loss in the QGP-1997

- In 1997, Baier, Dokshitzer, Mueller Peigne, Schiff also Zakharov, see ARNPS 50, 37 (2000), said that the energy loss from coherent LPM radiation for hard-scattered partons exiting the QGP would “result in an attenuation of the jet energy and a broadening of the jets”

The energy loss, $-\frac{dE}{dx}$, of an outgoing parton per unit length (x) of a medium with total length L, due to coherent gluon bremsstrahlung is proportional to the $q^2$ and takes the form:

$$\frac{-dE}{dx} \approx \alpha_s \left\langle q^2(L) \right\rangle = \alpha_s \mu^2 L / \lambda_{mfp} \equiv \alpha_s \hat{q} L$$

where $\mu$, is the mean momentum transfer per collision (~the Debye screening mass). Thus, the total energy loss in the medium goes like $L^2$. 

J/ψ PHENIX design goal 1990-1991
Y sPHENIX design goal 2015

Erice 2015
PHENIX M. J. Tannenbaum 34
QGP Discoveries at RHIC

- Suppression of high $p_T$ hadrons from hard-scattering of initial state partons; also modification of the away-side jet
- Elliptic Flow at the Hydrodynamic limit as a near ideal fluid with shear viscosity/entropy density at or near the quantum lower bound $\eta/s\approx 1/(4\pi)$
- Elliptic flow of particles proportional to the number of the valence (constituent) quark count.
- Charged particle multiplicity proportional to the number of constituent quark participants
- Higher order flow moments proportional to density fluctuations of the initial colliding nuclei
- Suppression and flow of heavy quarks roughly the same as that of light quarks; QCD hard direct photons not suppressed, don’t flow.
- Production and flow of thermal soft photons.
Constituent quarks are Gell-Mann’s quarks from Phys. Lett. 8 (1964)214, proton=uud [Zweig’s Aces]. These are relevant for static properties and soft physics, low $Q^2<2 \text{ GeV}^2$; resolution $>0.14 \text{ fm}$.

For hard-scattering, $p_T>2 \text{ GeV/c}$, $Q^2=2p_T^2>8 \text{ GeV}^2$, the partons (~massless current quarks, gluons and sea quarks) become visible.

Resolution $\sim 0.5 \text{ fm}$
Resolution $\sim 0.1 \text{ fm}$
Resolution $<0.07 \text{ fm}$
Some special Issues for A+A collisions

Schematic of collision in N-N c.m. system of two Lorentz contracted nuclei with radius $R$ and impact parameter $b$. The curve with ordinate $d\sigma/dn_{ch}$ represents the relative probability of charged particle multiplicity $n_{ch}$ which is proportional to the number of participating nucleons $N_{part}$. The degree of overlap of the two nuclei is called the centrality. More central means smaller $b$. 
Collision Centrality defined by the number of participating nucleons $N_{\text{part}}$ can be measured from spectators in Zero Degree Calorimeter for fixed target but not at a collider.

- Number of Spectators (i.e. non-participants) $N_s$ can be measured directly in Zero Degree Calorimeters in fixed target experiments.
- Enables unambiguous measurement of (projectile) participants $= A_p - N_s$
- For symmetric A+A collision $N_{\text{part}} = 2 \times N_{\text{projpart}}$
- At a collider can not measure the spectators which may be free neutrons, protons or clusters. If $Z/A$ of cluster is same as the beam, it stays in the beam; but the neutrons can be detected at zero degrees. The distribution of Energy in Beam Beam Counters can be measured and the centrality defined by upper percentile of the distributions, but $N_{\text{part}}$ is model dependent and may have biases.
Au+Au Multiplicity--\(dN_{ch}/d\eta/(0.5N_{qp})\) vs Constituent Quark Participants (\(N_{qp}\))

\[N_{qp} = \text{Quark participant scaling works well } \sqrt{s_{NN}} = 62-200 \text{ GeV}\]

\[WNM = \text{Participant nucleon scaling works well } \sqrt{s_{NN}} \leq 27 \text{ GeV}\]

Charged Multiplicity is proportional to the Number of Constituent Quark Participants at RHIC & LHC \(\sqrt{s_{NN}}\)

---

Erice 2015
Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions

- spatial anisotropy $\Rightarrow$ momentum anisotropy

$\phi = \text{atan} \frac{p_y}{p_x}$

Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane

$v_2$ is the 2nd harmonic Fourier coefficient

\[
\frac{E d^3 N}{d p^3} = \frac{d^3 N}{p_T dp_T dy d\phi} = \frac{d^3 N}{2\pi p_T dp_T dy} \left[ 1 + 2v_1 \cos(\phi - \Phi_R) + 2v_2 \cos 2(\phi - \Phi_R) + \cdots \right]
\]

\[
v_1 = \langle \cos \phi \rangle \quad v_2 = \langle \cos 2\phi \rangle
\]

Directed flow

zero at midrapidity

Elliptical flow dominant

at midrapidity
Elliptic Flow $v_2$ in AuAu Central 200 GeV
Universal in constituent quark Kinetic Energy

• large $v_2$ for high and low $p_T$, plateaus for $p_T>2$ GeV/c for mesons, scales in KE/constituent quark
• $\phi$-meson (not shown) follows same scaling: further implies flow is partonic not hadronic
• KE scaling suggests Hydrodynamic origin.
• $v_2$ for $p_T>1$ GeV/c suggests low viscosity, D.Teaney, PRC 68 (2003) 034913, ``the perfect fluid’’ ??
• Quantum Viscosity Bound from string theory reinforces this idea, Kotvun, Son, Starinets, PRL 94 (2005) 111601
Latest big discovery, \(\pi\) and \(p\) flow in dAu

\[ v_2 \sim <\cos2\Phi> \] asymmetry around reaction plane due to ellipsoidal shape is a collective effect. In hydrodynamics, for a given expansion velocity \(\beta\), protons have larger \(p_T = \gamma\beta m\) than \(\pi\) as clearly shown by the d+Au data, as in Au+Au

\[ v_2(p_T) \] seems larger at in d+Au at RHIC. We measured He\(^3\)+Au in 2014 to see if \(v_3\) appears due to 3 nucleons
How small can a QGP droplet be?

Very successful 3-week run resulted in 2.2 billion recorded minimum bias $^3$He+Au collisions (PHENIX)

Strong $v_3/v_2$ in $^3$He+Au! p+Au run just completed will be the crucial test
Jet quenching: a parton-medium Effect

Toward quantitative measurement of basic medium properties: $q$-hat

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

Radiative

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

Collisional

Partons lose energy going through the medium so that there are fewer partons or jet fragments at a given $p_T$. The ratio of measured AA to scaled pp cross section for no effect is:

$$R_{AA}(p_T) = \frac{d^2N_{AA}^\pi / dp_T dy N_{AA}^{inel}}{\langle T_{AA} \rangle d^2\sigma_{pp}^\pi / dp_T dy}$$

JET Collaboration


$$\frac{\hat{q}}{T^3} = \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC} \end{cases}$$

QGP @ RHIC is more strongly coupled than QGP@ LHC.

QGP @ RHIC is more strongly coupled than QGP@ LHC.
RHI physics is based on Precision Msmts + QCD

- This one figure encodes rigorous control of systematics

PRL94 (2005) 232301

PRL101 (2008) 232301

- in four different measurements over many orders of magnitude

Direct photons unaffected by QGP medium in Au+Au → \( \pi^0 \) suppression is medium effect

QM2006-Direct $e^\pm$ in Au+Au indicate a theoretical crisis

- heavy quarks suppressed the same as light quarks, and they flow, but less.
- This disfavors the hypothesis of energy loss by gluon bremsstrahlung in medium but brings string theorists into the game, see references in PRL 98 (2007) 172301.

**p-p beautiful agreement of $e^\pm$ with $c\ b$ production PHENIX PRL97(2006)252002**

**Au+Au PHENIX PRL 98 (2007)172301**
Jet Quenching vanishes for $\sqrt{s_{NN}} \leq 30$ GeV

Non identified charged particles central/peripheral
Low $p_T$ photons in AuAu: thermal, flow

AuAu direct $\gamma$ spectra vs centrality compared to scaled pp spectrum. Note exponential distribution of $\gamma$ in AuAu which is lacking in pp.

- $\nu_2 \rightarrow 0$ where qcd hard direct-$\gamma$ dominate no effect of the medium.
- $\nu_2$ large ($\sim 15\%$) at $p_T < 3$ GeV thermal region--- $\gamma$'s from the medium.
## The Future: RHIC run Schedule 2014--≥2023

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<th>Science Goals</th>
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<td>Au+Au at 15 GeV</td>
<td>Heavy flavor flow, energy loss, thermalization, etc.</td>
<td>Electron lenses 56 MHz SRF</td>
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<td>Au+Au at 200 GeV</td>
<td></td>
<td>STAR HFT STAR MTD</td>
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<td></td>
<td>$^3\text{He} + \text{Au}$ at 200 GeV</td>
<td>Quarkonium studies</td>
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<td>QCD critical point search</td>
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<tr>
<td>2015-16</td>
<td>p↑+p↑ at 200 GeV</td>
<td>Extract $\eta/s(T)$ + constrain initial quantum fluctuations</td>
<td>PHENIX MPC-EX</td>
</tr>
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<td></td>
<td>p↑+Au, p↑+Al at 200 GeV</td>
<td>Complete heavy flavor studies</td>
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<td>High statistics Au+Au</td>
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<td>Au+Au at 62 GeV ?</td>
<td>Parton saturation tests</td>
<td>Coherent e-cooling test</td>
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<tr>
<td>2017</td>
<td>p↑+p↑ at 510 GeV</td>
<td>Transverse spin physics</td>
<td>Low energy e-cooling install.</td>
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<tr>
<td></td>
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<td>Sign change in Sivers function</td>
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<tr>
<td>2018</td>
<td>No Run</td>
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<tr>
<td>2019-20</td>
<td>Au+Au at 5-20 GeV (BES-2)</td>
<td>Search for QCD critical point and onset of deconfinement</td>
<td>Low energy e-cooling</td>
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<tr>
<td>2021-22</td>
<td>Au+Au at 200 GeV</td>
<td>Jet, di-jet, $\gamma$-jet probes of parton transport and energy loss mechanism</td>
<td>sPHENIX</td>
</tr>
<tr>
<td></td>
<td>p↑+p↑, p↑+Au at 200 GeV</td>
<td>Color screening for different quarkonia</td>
<td>Forward upgrades ?</td>
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<td></td>
<td>Forward spin &amp; initial state physics</td>
<td></td>
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<tr>
<td>≥ 2023</td>
<td>No Runs</td>
<td></td>
<td>Transition to eRHIC</td>
</tr>
</tbody>
</table>

Erice 2015
Key questions to be answered by RHIC before completion of its “mission” from the RHI community white paper

- a beam-energy scan program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out the transition region from hadronic to deconfined matter.

- the quantitative determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependence of the shear-viscosity to entropy-density ratio $\eta/s$ (including an assessment of whether the conjectured lower bound has been reached to within a precision of 10%), and that of the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.

- a jet physics program to study the nature of parton energy loss and the quasi-particle nature of the QGP.

- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium, as well as quarkonia measurements that will provide standard candles for the temperatures obtained in the early stages of a heavy-ion reaction.

- a systematic forward physics program to study the nature of gluon saturation at low $x$.

This last bullet leads naturally to the physics program of an Electron Ion collider
If the “medium is the message”, then what exactly is the medium?

- The QCD Plasma is strongly coupled, but at what scales?
- Does it contain quasiparticles or does the strong coupling completely wipe out long-lived collective excitations?
- What impact does the coupling have on color screening? Is there a characteristic screening length? If so, what is it?
- What is the mechanism for parton QGP interactions and how does the QGP respond to energy deposited in it?
- At what scale do discrete scattering centers “dissolve” into a collectively acting, continuous, flowing medium?

Point-like scattering centers: $1/q^4$ tail

Quasi-continuous medium: Gaussian
BEAM Energy Scan
Search for Critical Endpoint
Helped by Lattice QCD
Proposed Phase diagrams Nuclear matter
Hot off the presses-LBL Press release June 24, 2011
Lattice and Experiment Compared-a first?

When Matter Melts

By comparing theory with data from STAR, Berkeley Lab scientists and their colleagues map phase changes in the quark-gluon plasma

June 23, 2011

Theory:Lattice shows huge deviation of $T^2 \chi^{(4)}/\chi^{(2)}$ from 1 near 20 GeV, suggesting critical fluctuations. Expt $\kappa \sigma^2$: maybe but with big errors.

I had to do lots of work to address this issue in my second in 2011 lecture to understand if this physics by press-release (not published in PRL) made sense.
Hot off the presses-LBL Press release June 24, 2011
Higher Moments of Net-Proton Distributions

- 1\textsuperscript{st} moment: mean = \( \mu = \langle x \rangle \)
- 2\textsuperscript{nd} cumulant: variance \( \kappa_2 = \sigma^2 = \langle (x-\mu)^2 \rangle \)
- 3\textsuperscript{rd} cumulant: \( \kappa_3 = \mu_3 = \langle (x-\mu)^3 \rangle \)
- 3\textsuperscript{rd} standardized cumulant: skewness = \( S = \kappa_3 / \kappa_2^{3/2} = \langle (x-\mu)^3 \rangle / \sigma^3 \)
- 4\textsuperscript{th} cumulant: \( \kappa_4 = \langle (x-\mu)^4 \rangle - 3\kappa_2^2 \)
- 4\textsuperscript{th} standardized cumulant: kurtosis = \( \kappa = \kappa_4 / \kappa_2^2 = \langle (x-\mu)^4 \rangle / \sigma^4 \) - 3
- Calculate moments from the event-by-event net proton distribution.
  ✓ Have similar plots for net-charge and net-kaon distributions.

MJT-If you know the distribution, you know all the moments, but statistical mechanics and Lattice QCD use Taylor expansions, hence moments/cumulants
Statistical Mechanics uses derivatives of the free energy to find susceptibilities

- Theoretical analyses tend to be made in terms of a Taylor expansion of the free energy \( F = -T \ln Z \) around the critical temperature \( T_c \) where \( Z \) is the partition function or sum over states, \( Z \approx \exp \left[-\left(E - \sum_i \mu_i Q_i\right)/kT\right] \) and \( \mu_i \) chemical potentials associated with conserved charges \( Q_i \).

- The terms of the Taylor expansion are called susceptibilities or \( \chi^{(m)} \) which are proportional to the correlation length, e.g. \( \chi^{(3)} \sim \xi^6 \), \( \chi^{(4)} \sim \xi^8 \).

- The connection of this method to mathematical statistics is that the Cumulant generating function is also a Taylor expansion of the \( \ln \) of an exponential, so \( \chi^{(m)} \) predicts measured Cumulants \( \kappa_m \):

\[
g_x(t) = \ln \langle e^{tx} \rangle = \sum_{n=1}^{\infty} \kappa_n \frac{t^n}{n!} \quad \kappa_m = \left. \frac{d^m g_x(t)}{dt^m} \right|_{t=0}
\]
Taylor expansion of the pressure

\[
\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V, T, \mu_B, \mu_S, \mu_Q) \\
= \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS} \left( \frac{\mu_B}{T} \right)^i \left( \frac{\mu_Q}{T} \right)^j \left( \frac{\mu_S}{T} \right)^k
\]

generalized susceptibilities: 

\[
\chi_{ijk}^{BQS} = \left. \frac{\partial^{i+j+k} p/T^4}{\partial \hat{\mu}_B^i \partial \hat{\mu}_Q^j \partial \hat{\mu}_S^k} \right|_{\mu=0}
\]

conserved charge fluctuations: 

\[
\chi_n^X(T, \mu_B, \ldots) = \frac{\partial^n P/T^4}{\partial (\mu_X/T)^n}
\]

\[
\frac{M_X}{\sigma_X^2} = \frac{\chi_1^X(T, \mu)}{\chi_2^X(T, \mu)} \quad , \quad S_X \sigma_X = \frac{\chi_3^X(T, \mu)}{\chi_2^X(T, \mu)} \quad , \quad \kappa_X \sigma_X^2 = \frac{\chi_4^X(T, \mu)}{\chi_2^X(T, \mu)}
\]
Moments and Distributions

• The moments of a distribution $P(x)$ are defined as

$$\mu'_k \equiv \langle x^k \rangle \equiv \int_{-\infty}^{\infty} x^k P(x) dx \rightarrow \sum_{i=1}^{n} x_i^k P(x_i)$$

where $\mu'_1 \equiv \mu = \langle x \rangle$ and $\sigma^2 = \mu_2 \equiv \langle (x - \mu)^2 \rangle$ is the variance.

• Cumulants are moments with all combinations of lower order moments subtracted.

• Combinations of moments and cumulants which are sensitive to fluctuations (thus correlations) will be used. For instance, the second “normalized binomial cumulant” $A. H. Mueller PRD 4,151 (1971)$

$$K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu}$$

vanishes for a Poisson distribution (no correlations).

• Most people use the normalized variance $\frac{\sigma^2}{\mu}$ which is 1 for a Poisson. It has its purpose, but not what everybody thinks.
Binomial Distribution

- A **Binomial** distribution is the result of repeated independent trials, each with the same two possible outcomes: success, with probability $p$, and failure, with probability $q=1-p$. The probability for $m$ successes on $n$ trials ($m,n \geq 0$) is:

$$P(m|n) = \frac{n!}{m!(n-m)!} p^m (1-p)^{n-m}$$

- The moments are:

$$\mu = \langle m \rangle = np \quad \sigma_m^2 = np(1-p)$$

$$K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = -\frac{1}{n} \quad \frac{\sigma^2}{\mu} = 1 - p \leq 1$$

- Example: distributing a total number of particles $n$ onto a limited acceptance. Note that if $p \to 0$ with $\mu=np=\text{constant}$ we get a
A **Poisson** distribution is the limit of the Binomial Distribution for a large number of independent trials, $n$, with small probability of success $p$ such that the expectation value of the number of successes $\mu = \langle m \rangle = np$ remains constant, i.e. the probability of $m$ counts when you expect $\mu$.

$$P(m|_\mu = \frac{\mu^m e^{-\mu}}{m!}$$

- Moments: $\langle m \rangle = \mu$, $\sigma^2_m = \mu$

- Example: The Poisson Distribution is intimately linked to the exponential law of Radioactive Decay of Nuclei, the time distribution of nuclear disintegration counts, giving rise to the common usage of the term “statistical fluctuations” to describe the Poisson statistics of such counts. The only assumptions are that the decay probability/time of a nucleus is constant, is the same for all nuclei and is independent of the decay of other nuclei.
Negative Binomial Distribution NBD

• For statisticians, the **Negative Binomial Distribution** represents the first departure from statistical independence of rare events, i.e. the presence of correlations. There is a second parameter $1/k$, which represents the correlation: NBD $\rightarrow$ Poisson as $k \rightarrow \infty$, $1/k \rightarrow 0$

$$P(m|\mu) = \frac{(m + k - 1)!}{m!(k - 1)!} \frac{(\frac{\mu}{k})^m}{(1 + \frac{\mu}{k})^{m+k}}$$

**Moments:** $\langle m \rangle = \mu$

\[
K_2 = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = \frac{1}{k} \\
\frac{\sigma^2}{\mu} = 1 + \frac{\mu}{k}
\]

• The $n$-th convolution of NBD is an NBD with $k \rightarrow nk$, $\mu \rightarrow n\mu$ such that $\mu/k$ remains constant. Hence constant $\sigma^2/\mu$ vs $N_{part}$ means multiplicity added by each participant is independent.

• Example: Multiplicity Distributions in p+p and A+A are NBD. There are both long-range and short-range correlations in rapidity.
K₂ in Binomial, Poisson and NBD

Binomial

\[ K₂ = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = -\frac{1}{n} \]

Poisson, no correlation

\[ K₂ = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = 0 \]

NBD correlation = 1/k

\[ K₂ = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu} = \frac{1}{k} \]

Becomes Poisson if \( k \to \infty, 1/k \to 0 \)

- Example: Multiplicity Distributions in p+p and A+A are NBD. There are both long-range and short-range correlations in rapidity.
From one of Jeff Mitchell’s talks 2001: “Multiplicity Fluctuations”

PHENIXAuAu Multiplicity $N_{ch}$ PRC 78, (2008) 044902

Early work: BNL-61074 Divonne 1994
http://www.osti.gov/scitech/servlets/purl/10108142

It’s not a Gaussian... it’s a Gamma distribution!

Also: It’s not Poisson, it’s negative binomial

Erice 2015
If you measure the distribution, then you know all the cumulants

<table>
<thead>
<tr>
<th>Cumulant</th>
<th>Poisson</th>
<th>Binomial</th>
<th>Negative Binomial</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_1 = \mu$</td>
<td>$\mu$</td>
<td>$np$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>$\kappa_2 = \mu_2 = \sigma^2$</td>
<td>$\mu$</td>
<td>$\mu(1 - p)$</td>
<td>$\mu(1 + \mu/k)$</td>
</tr>
<tr>
<td>$\kappa_3 = \mu_3$</td>
<td>$\mu$</td>
<td>$\sigma^2(1 - 2p)$</td>
<td>$\sigma^2(1 + 2\mu/k)$</td>
</tr>
<tr>
<td>$\kappa_4 = \mu_4 - 3\kappa_2^2$</td>
<td>$\mu$</td>
<td>$\sigma^2(1 - 6p + 6p^2)$</td>
<td>$\sigma^2(1 + 6\mu/k + 6\mu^2/k^2)$</td>
</tr>
</tbody>
</table>

$S \equiv \kappa_3/\sigma^3$ $1/\sqrt{\mu}$ $(1 - 2p)/\sigma$ $(1 + 2\mu/k)/\sigma$

$\kappa \equiv \kappa_4/\kappa_2^2$ $1/\mu$ $(1 - 6p + 6p^2)/\sigma^2$ $(1 + 6\mu/k + 6\mu^2/k^2)/\sigma^2$

$S\sigma = \kappa_3/\kappa_2$ $1$ $(1 - 2p)$ $(1 + 2\mu/k)$

$\kappa\sigma^2 = \kappa_4/\kappa_2$ $1$ $(1 - 6p + 6p^2)$ $(1 + 6\mu/k + 6\mu^2/k^2)$

Thanks to Gary Westfall of STAR in a paper presented at Erice-International School of Nuclear Physics 2012, I found out that the cumulants of the difference of samples from two such distributions $P(n-m)$ where $P^+(n)$ and $P^-(m)$ are both Poisson, Binomial or NBD with Cumulants $\kappa_j^+$ and $\kappa_j^-$ respectively is the same as if they were statistically independent, so long as they are not 100% correlated. I call this the NBD Cumulant Theorem.

$$K_j = K_j^+ + (-1)^j K_j^-$$
So $\sigma$ clearly favors NBD, not Poisson (!). No non-monotonic behavior in $\sigma$ or $\kappa\sigma^2$ but $\kappa\sigma^2 = -1.5$ at $\sqrt{s_{NN}} = 20$ can’t be ruled out.

$\kappa\sigma^2 = -1.5$ at $\sqrt{s_{NN}} = 20$ can be ruled out. $\kappa\sigma^2$ changes for $\sqrt{s_{NN}} \leq 30$ GeV but antiprotons become negligible $\leq 0.02$ p.
Au+Au Collisions
Net-proton
0.4<p_t<2 (GeV/c), |y|<0.5

- 0-5%
- 5-10%
- 30-40%
- 70-80%

Colliding Energy $\sqrt{s_{NN}}$ (GeV)

X. Luo, arXiv:1503.02558

How can adding tracks >0.8 GeV/c make such changes in $\kappa \sigma^2$ but not in $S\sigma$

Show me the distributions!
NEW! PHENIX net-charge fluctuations

\[ \Delta N_{ch} = N^+ - N^- \] distribution in \(|\eta|<0.35, \delta\phi=\pi, 0.3<p_T<2.0 \text{ GeV/c}\]
Not corrected for detection efficiency \(\varepsilon \approx 0.70\) in acceptance

PHENIX  arXiv:1506.07834
To compare with Lattice QCD theory, ratios of cumulants are used so that the dependence on volume $V$ cancels.
The centrality dependence is minimal for all ratios while the $\sqrt{s_{NN}}$ dependence is weak for $\kappa_4 / \kappa_2$ and $\kappa_3 / \kappa_1$, very strong for $\mu / \sigma^2$ and strong for $S_0 \sigma$.
Note that the `data' calculations from the $\Delta N_{ch} = N^+ - N^-$ distributions agree with the NBD fits to the $N^+$ and $N^-$ distribution and the NBD Cumulant Theorem.
The $N^+$, $N^-$ (and $N^+ + N^-$) distributions are NBD

**PHENIX:** centrality 0-5%
$\sqrt{s_{NN}} = 7.7$ GeV

**hproxNPos3_0**
- Entries: 52796
- Mean: 6.421
- RMS: 2.737
- $\chi^2 / \text{ndf}$: 22.73 / 19
- $k$: 44.95 ± 7.30
- $\mu$: 6.326 ± 0.054
- const: 1.016 ± 0.029

**hproxNNeg3_0**
- Entries: 52796
- Mean: 3.77
- RMS: 2.037
- $\chi^2 / \text{ndf}$: 5.288 / 14
- $k$: 38.26 ± 5.66
- $\mu$: 3.753 ± 0.023
- const: 1.003 ± 0.015

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M. J. Tannenbaum 71
The key difference of the PHENIX and STAR results is that the error on all corrected cumulant ratios is 20-30% for PHENIX while for STAR the error on e.g. $S_0$ is ~50%, on $\kappa \sigma^2$ is >100% but <1% for $\sigma^2/\mu$!!! (which turns out to be important)
BNL Lattice QCD group predictions for cumulant ratios $R_{31}$ and $R_{12}$ vs $T_f$ and $\mu_B$ at freezeout (when QGP hadronizes).

Pos(CPOD2014)005.
PRL 109 (2012) 192302
STAR measurement of $R_{31} = \kappa_3 / \kappa_1$ has such a huge error that the central value could go anywhere in the dashed region, while $R_{12}$ has such a small error that it is constrained to the region of the horizontal line by the assumption $140 < T_f < 150 \text{MeV}$.

PHENIX measurement with comparable errors on $R_{31}$ and $R_{12}$ enables both $T_f$ and $\mu_B$ to be determined from the Lattice QCD calculations:

Pos(CPOD2014)005

PRL 113 (2014) 052301
STAR’s opinion of PHASE diagram 2014

\[
\frac{\bar{p}}{p} = \frac{e^{-(E+\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-(2\mu_B)/T}
\]

\[\frac{\bar{p}}{p} \approx 0.02\]

\[T=160 \text{ MeV} \quad \mu_B=300 \text{ MeV} \quad \sqrt{s_{NN}} \approx 27 \text{ GeV}\]

Actually this plot has wrong \(\mu_B\) scale

\[\sqrt{s_{NN}} = 27 \text{ GeV}\]

\[\bar{p} / p \]

\[T=160 \text{ MeV} \quad \mu_B = 300 \text{ MeV} \quad \sqrt{s_{NN}} \approx 27 \text{ GeV}\]

\[\frac{\bar{p}}{p} \approx 0.02\]

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\[T=160 \text{ MeV} \quad \mu_B = 300 \text{ MeV} \quad \sqrt{s_{NN}} \approx 27 \text{ GeV}\]

\[\frac{\bar{p}}{p} \approx 0.02\]
Experimental result on net-charge cumulants + Lattice QCD calculation gives both freezeout $T_f +$ Baryon Chemical Potential $\mu_B$ without particle identification!! I think this is a first and it also agrees with the best accepted calculations from baryon/anti-baryon ratios, PRC73(2006)034905
Why are STAR errors on R31 so large?

It must be that statistical errors and efficiency corrections are a BIG issue in these measurements even though the correction is simply Binomial; and analytical for NBD N⁺ and N⁻ distributions (k unchanged, \( \mu_t = \mu/p \) where p is the efficiency). So use the NBD “integer value Levy process” cumulant theorem:

Tarnowsky, Westfall PLB 724 (2013) 51
http://www.economics.ox.ac.uk/materials/papers/4382/paper490.pdf

\[
\kappa_j = \kappa_j^+ + (-1)^j \kappa_j^-
\]
From PHENIX net-charge fluctuations

\[ \Delta N_{ch} = N^+ - N^- \text{ distribution in } |\eta|<0.35, \delta \phi=\pi, 0.3<p_T<2.0 \text{ GeV/c} \]
Not corrected for detection efficiency \( \varepsilon \approx 0.70 \) in acceptance

The raw moments of the uncorrected distributions can be easily calculated

\[ \mu'_k \equiv \langle x^k \rangle \equiv \sum_{i}^{n} x_i^k E(x_i) / \sum_{i}^{n} E(x_i) \]
\[ \mu'_1 \equiv \mu = \langle x \rangle \text{ and } x_i \text{ is a bin in the } \Delta N_{ch} \text{ plot with } E(x_i) \text{ events.} \]
Statistical errors--the complications begin

\[ \mu'_k \equiv \langle x^k \rangle \equiv \frac{\sum_{i=1}^{n} x_i^k E(x_i)}{\sum_{i=1}^{n} E(x_i)} \]

The statistical errors for every \( \mu'_k \) can be calculated from the statistical errors of each data point \( E(x_i) \pm \sigma_{E(x_i)} \). Even though the \( \sigma_{E(x_i)} \) on each point are independent, the errors on each \( \mu'_k \) are not independent because the same \( \sigma_{E(x_i)} \) appears in all the moments.

Next one computes the cumulants \( \kappa_i \) from the raw (aka) non-central moments:

\[ \mu = \kappa_1 = \mu'_1 \]
\[ \sigma^2 = \mu_2 = \kappa_2 = \mu'_2 - \mu'_1^2 \]
\[ \mu_3 = \kappa_3 = \mu'_3 - 3\mu'_2\mu'_1 + 2\mu'_1^3 \]
\[ \mu_4 - 3\mu_2^2 = \kappa_4 = \mu'_4 - 4\mu'_3\mu'_1 - 3\mu'_2^2 + 12\mu'_2\mu'_1^2 - 6\mu'_1^4 \]
A certain random fraction of the tracks that fall on the acceptance are not detected because of inefficiency---a clearly random, thus binomial effect. This is further complicated if the $N^+$ and $N^-$ measurements have different efficiencies.
Efficiency corrected cumulants in terms of corrected double Factorial moments

\[ \kappa_1 = \langle N_+ \rangle - \langle N_- \rangle = \frac{\langle n_+ \rangle}{\epsilon_+} - \frac{\langle n_- \rangle}{\epsilon_-}, \]

\[ \kappa_2 = N - \kappa_1^2 + F_{02} - 2F_{11} + F_{20}, \]

\[ \kappa_3 = \kappa_1 + 2 \kappa_1^3 - F_{03} - 3F_{02} + 3F_{12} + 3F_{20} - 3F_{21} + F_{30} - 3\kappa_1(N + F_{02} - 2F_{11} + F_{20}), \]

\[ \kappa_4 = N - 6\kappa_1^4 + F_{04} + 6F_{03} + 7F_{02} - 2F_{11} - 6F_{12} - 4F_{13} + 7F_{20} - 6F_{21} + 6F_{22} + 6F_{30} - 4F_{31} + F_{40} + 12\kappa_1^2(N + F_{02} - 2F_{11} + F_{20}) - 3(N + F_{02} - 2F_{11} + F_{20})^2 - 4\kappa_1(\kappa_1 - F_{03} - 3F_{02} + 3F_{12} + 3F_{20} - 3F_{21} + F_{30}) \]

Here you can see the nice subtraction of the lower order moments; but new quantities, double Factorial Moments are introduced and very difficult to compute \( P(13^+, 11^-) =? \) so you need to know both \( N_+ \) and \( N_- \) distributions and their correlations. The \( F_{ik} \) can be calculated from the data by making a 3d Lego plot with base axes \( N_+ \) and \( N_- \) and height \( P(N_+, N_-) \) which costs statistical error but other methods \"Bootstrap\" are used.
If you measure the distribution, then you know all the corrected cumulants

Use the NBD Cumulant Theorem allowing ε=p to be different for N⁺ and N⁻

\[ K_j = K_j^+ + (-1)^j K_j^- \]
The error on $\mu_t <<$ than the error on $\mu_t/k$ so is neglected. The errors are highly correlated for the sums of powers of $\mu_t/k$ in both the numerator and denominator. These correlations are handled by varying the $(\mu_t/k)^+$ and $(\mu_t/k)^-$ by $\pm 1\sigma$ independently and adding the variations in quadrature.
Short range multiplicity correlations do not vanish in A+A collisions!

- Short range multiplicity correlations in p-p collisions come largely from hadron decays such as $\rho \rightarrow \pi \pi$, $\Lambda \rightarrow \pi^{-} p$, etc., with correlation length $\xi \sim 1$ unit of rapidity.

- In A+A collisions the chance of getting two particles from the same $\rho$ meson is reduced by $\sim 1/N_{\text{part}}$ so that the only remaining correlations are Bose-Einstein Correlations---when two identical Bosons, e.g. $\pi^{+} \pi^{+}$, occupy nearly the same coordinates in phase space so that constructive interference occurs due to the symmetry of the wave function from Bose statistics---a quantum mechanical effect, which remains at the same strength in A+A collisions: the amplitudes from the two different points add giving a large effect also called Hanbury-Brown Twiss (HBT).

The normalized two-particle short range rapidity correlation $R_2(y_1,y_2)$ is defined as

$$R_2(y_1,y_2) \equiv \frac{C_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} = \frac{\rho_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1 = R(0,0) e^{-\frac{|y_1-y_2|}{\xi}},$$  

where $\rho_1(y)$ and $\rho_2(y_1,y_2)$ are the inclusive densities for a single particle (at rapidity $y$) or 2 particles (at rapidities $y_1$ and $y_2$), $C_2(y_1,y_2) = \rho_2(y_1,y_2) - \rho_1(y_1)\rho_1(y_2)$ is the Mueller correlation function for 2 particles (which is zero for the case of no correlation), and $\xi$ is the two-particle short-range rapidity correlation length[3] for an exponential parameterization.

$$K_2(\delta \eta) = 2R(0,0)(\frac{\delta \eta}{\xi} - 1 + e^{-\delta \eta/\xi})$$

for NBD: $k(\delta \eta) = 1/K_2(\delta \eta)$

The rapidity correlation length $\xi = 0.2$ for Si+Au E802, PRC56(1977) 1544 is from HBT.

**if $\delta \eta \ll \xi$, $k \rightarrow 1/R(0,0)$=constant**  **if $\delta \eta \gg \xi$, $k/\delta \eta \approx k/\mu \rightarrow$constant**

For HBT analyses of two particles with $p_1$ and $p_2$, $C_{HBT}^{2}(q) = R_2(p_1 - p_2) + 1$ and the random (un-correlated) distribution is taken from particles with $p_1$ and $p_2$ on different events. The HBT correlation function is taken as a Gaussian not an exponential as in (8) and is written:

$$C_{HBT}^{2} = 1 + \lambda \exp \left( - \left( R_{side}^2 q_{side}^2 + R_{out}^2 q_{out}^2 + R_{long}^2 q_{long}^2 \right) \right)$$
- 3D Gaussian fits
- Bertsch-Pratt coord.
- LCMS ($p_{1z}+p_{2z}=0$)
- Coulomb Corrected

\[ C_2^\text{HBT}(q) \]

\[ \frac{R_{\text{long}}}{R_{\text{out}}} \text{ increases smoothly with } \sqrt{s_{NN}} \]

\[ R_{\text{side}} R_{\text{out}} \sim \text{constant at RHIC, increase at LHC} \]
Emission duration and expansion/lifetime

\[ (R_{\text{out}})^2 - (R_{\text{side}})^2 \] measures emission duration

\[ R_{\text{side}} / R_{\text{long}} \] indicates expansion/lifetime

\[ 10 \leq \sqrt{s_{NN}} \leq 62 \text{ GeV} \] is the ‘sweet spot’ for something
Roy Lacey claims critical point

\[ \sqrt{s_{NN}}(V) = \sqrt{s_{NN}(\infty)} - k \times \tilde{R}^{(1/\nu)} \left( R_{\text{out}}^2 - R_{\text{side}}^2 \right)_{\text{max}} \propto \tilde{R}^{\gamma/\nu} \]

A finite-size scaling (FSS) analysis of these data suggests a second order phase transition with the estimates \( T^{\text{cep}} \approx 165 \text{ MeV} \) and \( \mu_B^{\text{cep}} \approx 95 \text{ MeV} \) for the location of the critical end point. The critical exponents \( (\nu \approx 0.66 \text{ and } \gamma \approx 1.2) \) extracted via the same FSS analysis place this CEP in the 3D Ising model universality class. \( \sqrt{s_{NN}(\infty)} \approx 47.5 \text{ GeV} \) critical end point???
Scientists See Ripples of a Particle-Separating Wave In Primordial Plasma

Key sign of quark-gluon plasma (QGP) and evidence for a long-debated quantum phenomenon

How does one prove what it is?

\[ A_{ch} = \frac{(N_+ - N_-)}{(N_+ + N_-)} \]
Chiral Magnetic Wave

Peak magnetic field $\sim 10^{15}$ Tesla!
(Kharzeev et al. NPA 803 (2008) 227)

$$j_A = \frac{N_c e}{2\pi^2 \mu_v B}$$

$$j_v = \frac{N_c e}{2\pi^2 \mu_A B}$$

CSE + CME $\rightarrow$ Chiral Magnetic Wave:
- collective excitation
- signature of chiral symmetry restoration
Polarized Proton Physics at RHIC-started at BNL Snowmass82---approved 1995

Operation of RHIC with two beams of highly polarized protons (70%, either longitudinal or transverse) at high luminosity $\mathcal{L} = 2 \cdot 10^{32}$ cm$^{-2}$ sec$^{-1}$ for two months/year will allow high statistics studies of polarization phenomena in the perturbative region of hard scattering where both QCD and ElectroWeak theory make detailed predictions for polarization effects.

- **Spin Structure Functions** which require measurements in hadron collisions to complement DIS electron measurements:
  
  - $G(x)$ and $\Delta G(x)$ by inclusive $\gamma$ and $\gamma+$Jet measurements.
  - $\Delta \bar{q}$ from Drell-Yan, $\Delta \bar{u}$ from $W^-$, $\Delta \bar{d}$ from $W^+$.

1997: To exploit spin physics and lattice gauge theory, RIKEN (Japan) provided one muon arm in PHENIX and money to support the snakes and spin rotators in RHIC. Also: the RIKEN BNL Research Center (RBRC) was established at BNL with T.D. Lee as founding Director.
Use Parity Violation of W: coupled to flavor
Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics

\[
A_L = \frac{1}{P_1} \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}
\]

\[
A_{L}^{W^+} \approx \frac{-\Delta u(x_1) \bar{d}(x_2)(1 - \cos \theta)^2 + \Delta \bar{d}(x_1) u(x_2)(1 + \cos \theta)^2}{u(x_1) \bar{d}(x_2)(1 - \cos \theta)^2 + \bar{d}(x_1) u(x_2)(1 + \cos \theta)^2}
\]

\[
A_{L}^{W^-} \approx \frac{-\Delta d(x_1) \bar{u}(x_2)(1 + \cos \theta)^2 + \Delta \bar{u}(x_1) d(x_2)(1 - \cos \theta)^2}{d(x_1) \bar{u}(x_2)(1 + \cos \theta)^2 + \bar{u}(x_1) d(x_2)(1 - \cos \theta)^2}
\]

\[
\langle x_1 \rangle \gg \langle x_2 \rangle : A_{L}^{W^-} \approx \frac{\Delta d}{d}
\]

\[
\langle x_1 \rangle \ll \langle x_2 \rangle : A_{L}^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}
\]

\[
\langle x_1 \rangle \gg \langle x_2 \rangle : A_{L}^{W^+} \approx -\frac{\Delta u}{u}
\]

\[
\langle x_1 \rangle \ll \langle x_2 \rangle : A_{L}^{W^+} \approx \frac{\Delta \bar{d}}{\bar{d}}
\]
Results Expected with 800 pb\(^{-1}\) at 500 GeV c.1995

We thought we could calculate LO \(x_1\) and \(x_2\) for \(p+p \rightarrow X + q\bar{q} \rightarrow W^\pm \rightarrow \mu^\pm + \nu\). Works well for \(\mu\) \(p_T\) but more complicated than we thought-kinematic ambiguity.

mid rapidity \(W \rightarrow e + \nu\)

forward rapidity \(W \rightarrow \mu + \nu\) \(1.1 < |y| < 2.3\)
PHENIX prelim $W^\pm \rightarrow e^\pm + \nu$  2013 run

Signal region: $30 < p_T < 50$ GeV
Background region: $10 < p_T < 20$ GeV

Background estimation using two independent methods:
- Gaussian Processes for Regression (GPR)
- Modified power law $f(p_T) = \frac{1}{p_T[0]+[1]+\log(p_T)}$

$W^+$ signal $\sim 95\%$
$W^-$ signal $\sim 81\%$

Erice 2015

M. J. Tannenbaum  94
**PHENIX** $W^\pm \rightarrow e^\pm + \nu$  

$
\begin{align*}
\frac{dN}{dp_T^e} &= 10^2 \\
\frac{dN}{dp_T^\mu} &= 10
\end{align*}$

(a) Data  
- Jacobian peak with GPR fit  
- Background

(b) Uncertainty in background  
- $W$/$Z \rightarrow e^+$  
- $Z \rightarrow e^+e^-$

---

PHENIX Run 2011 (500 GeV)  
PHENIX Run 2012 (510 GeV) $|h_{\perp}|<0.35$

PHENIX Run 2013 p+p 510 GeV $|h_{\perp}|<0.35$

- $p_T > 30$ GeV/c  
- (3.5% polarization scale uncertainties not shown)

CHE NLO calculations  
- DSSV 14  
- NNPDFpol1.1

---

Erice 2015
Neither PHENIX nor STAR quotes

\[ \frac{\Delta \bar{u}}{u}(x), \frac{\Delta \bar{d}}{d}(x) \]
Proton Spin Structure -- "Spin Puzzle"

- Manohar-Jaffe sum rule:
  \[
  \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \Delta L_q + \Delta L_g
  \]

- PHENIX Spin Program
  - Longitudinal spin program
    - Gluon polarization distribution
      \[
      \Delta G = \int_0^1 dx \cdot \Delta g(x)
      \]
    - Anti-quark sea polarization
      \[
      A_L(u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu) \\
      A_L(\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu})
      \]
  - Transverse spin program
    - sensitivity to \(<Lz> + transversity\)
End
Status of $R_{AA}$ in AuAu at $\sqrt{s_{NN}}=200$ GeV 2013

Notable are that ALL particles are suppressed for $p_T>2$ GeV/c (except for direct-$\gamma$), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)
Recent PHENIX Transverse Spin Runs

<table>
<thead>
<tr>
<th>Year</th>
<th>√s [GeV]</th>
<th>Recorded L</th>
<th>Pol [%]</th>
<th>FOM (P^2L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 (Run 15)</td>
<td>200</td>
<td>110 pb⁻¹</td>
<td>57</td>
<td>35 pb⁻¹</td>
</tr>
<tr>
<td>2012 (Run 12)</td>
<td>200</td>
<td>9.2 pb⁻¹</td>
<td>59</td>
<td>3.3 pb⁻¹</td>
</tr>
<tr>
<td>2008 (Run 8)</td>
<td>200</td>
<td>5.2 pb⁻¹</td>
<td>45</td>
<td>1.1 pb⁻¹</td>
</tr>
</tbody>
</table>
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

NB: P-even quantity (strength of P-odd fluctuations)
BES results shows charge separation starts to diminish at lower energies.


How does one prove what it is?
U.S.-CERN Agreement Paves Way for New Era of Scientific Discovery

Department of Energy and National Science Foundation sign agreement for U.S. participation in particle physics research.

May 7, 2015

WASHINGTON – A new agreement between the United States and the European Organization for Nuclear Research (CERN) signed today will pave the way for renewed collaboration in particle physics, promising to yield new insights into fundamental particles and the nature of matter and our universe.

The agreement, signed in a White House ceremony by the U.S. Department of Energy, U.S. National Science Foundation and CERN—the renowned European organization based in Geneva, Switzerland—will enable continued scientific discoveries in particle physics and advanced computing.

U.S. Energy Secretary Honors Brookhaven Lab Team for Building Large Hadron Collider Magnets

May 11, 2015

UPTON, NY — Following the much-anticipated recent restart of the Large Hadron Collider (LHC) at CERN, the European Organization for Nuclear Research, a 17-member team primarily based at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory was recognized with one of DOE's most prestigious awards for successfully completing two superconducting magnets for the 17-mile-circumference collider.
Results from 2011

Lattice shows huge deviation of $T^2 \chi^{(4)}/\chi^{(2)}$ from 1 near 20 GeV, suggesting critical fluctuations. Expt $\kappa \sigma^2$ suggests not; but with big errors. Need more data. Above plot is different from PRL105

Is JPG38 plot Evidence for phase transition from resonance gas to QGP at $T_c=175$ MeV ?????????!!
Bayes Rule and Conditional Probability

Bayes rule is one of the most powerful yet seemingly simple rules in probability. Let $A$ and $B$ be two possible outcomes with probabilities $P(A)$ and $P(B)$. Bayes Rule defines the conditional probabilities, where $P(A \text{ and } B)$ is the probability for both outcomes to occur:

$$P(A \text{ and } B) = P(A) \times P(B) |_A = P(B) \times P(A) |_B$$

The apriori or prior probabilities $P(A)$ and $P(B)$ are very different from the conditional probabilities $P(A) |_B$, the conditional probability of $A$ given that $B$ has occurred, and $P(B) |_A$, the conditional probability of $B$ given that $A$ has occurred. However the conditional probabilities are simply related to each other:

$$P(A) |_B = \frac{P(A) \times P(B) |_A}{P(B)} = P(B) |_A \times \frac{P(A)}{P(B)}$$

An interesting example of the application of Bayes rule is given in my book.

Also don’t forget that if $A$ and $B$ are statistically independent, then

$$P(A) |_B = P(A)$$

$$P(B) |_A = P(B)$$

so that

$$P(A \text{ and } B) = P(A) \times P(B)$$