Exploring the Quantum Universe

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Why science?

“That’s where the money is”
“Willie Sutton’s reasoning for robbing banks”

Similarly

We do these things because

“----------------------------------”
The state of the universe

Universe: everything that exists!
Universe = invisible forms of (matter/energy) + visible matter/energy

governed by the same physical laws and constants throughout most of its extent and history

- Very nearly flat
- 13.7 billion years ago (Big Bang)
- Isotropic
The “visible” universe

Visible universe: ~ 150 billion galaxies
The Milky Way galaxy

~ 13.2 billion years old
Composed of 100,000 million Stars…
Visible universe contains ~ $10^{23}$ stars…
The solar system

The Sun: ~ 4.57 billion years old, 99.86% of the total mass of the solar system

The Earth: ~ 4.54 billion years old, life appeared on its surface ~ 1 billion years ago
The Atom

Basic unit of matter
Consist of a dense central nucleus surrounded by a cloud of negatively charged electrons

\[ M_{\text{proton}} \sim 1840 \, m_{\text{electron}} \]
The Quarks

Strong force: \(~98\%\) of the visible mass of the universe

Child-like question: What is the mass? Primary concept!
The origin of the mass? Dynamics origin for the (most) of the mass
The Standard Model

It works from the Plank length to the edge of the universe

60 ORDERS OF MAGNITUDE
Questions?

The most important product of knowledge is ignorance

Why all three forces due to local symmetries?

Why is $\alpha = 1/137.0369999708$..what it is?

Why are three families of quarks and leptons

Why is $M_{\text{top}}/M_{\text{up}} \sim 100,000$

Why is space 3 dimension?

Why the forces look so different?
The vacuum?

Symmetry breaking (Higgs mechanism) $\rightarrow$ Mass
Symmetry breaking $\rightarrow$ Possibility of new symmetries
AntiScreening (Asymptotic freedom) $\rightarrow$ Quark confinement & unification

The classical vacuum is empty
The quantum vacuum is full of fluctuating fields
The search for unification

String theory
Supersymmetry
Rotations in Superspace

In supersymmetric theories for every particle there exists a super-partner

Quark    Electron    Photon
Squark    Selectron   Photino

Supersymmetry helps unify the forces
Supersymmetry helps explain the mass hierarchy

Why is $M_{w}/M_{\text{Plank}} \sim 10^{-16}$?

Supersymmetry predicts a candidate for dark matter

IF MSUSY $\sim$ 1 TeV -> DM $\sim$ 90%
Quantum Gravity

The most glaring limitation of QFT is its inability to incorporate gravity— the dynamics of space-time. Since the quantum fluctuations of space-time seem uncontrollable at the Plank scale---space-time foam

We must go beyond Einstein’s theory!

STRING THEORY

GRAVITY APPEARS AUTOMATICALLY
The LHC machine

p-p collisions at $\sqrt{s} = 14$ TeV, $\mathcal{L}=10^{34}$ cm$^{-2}$s$^{-1}$, 8 mo/yr
Pb-Pb collisions at $\sqrt{s} = 5.5$ TeV, $\mathcal{L}=10^{27}$ cm$^{-2}$s$^{-1}$, 1 mo/yr
The LHC experiments (major)
Physics at RHIC
New physics at RHIC

- The partonic degrees of freedom are largely “frozen” in nuclear physics, just as the nucleonic ones are frozen in atomic physics.

Nuclear density
\[ \rho_0 \sim 0.15 \text{nucleons/fm}^3 \]

Specific volume \( v \sim 6 \text{fm}^3 \)

Typical hadronic volume
\[ \sim 1-3 \text{ fm}^3 \]

The average inter-nucleon distance in the nucleus \( \sim 1.8 \text{fm} \)

Is there new physics above \( \sim 3\rho_0 \)?
Physics opportunities at RHIC

Study the formation and character of QGP

The little Big Bang
Symmetries and (lack of symmetries), Matter and antimatter, etc…

Spin Physics

Proton’s spin crisis
The RHIC machine

Crossing rate ~ 10 MHz
The current experiments

As in typical high energy physics experiments, detectors design is driven by the delivered luminosity and DAQ.

Spectra

Correlations
The STAR detector

In full
At mid and forward η
At low and high p_T
Considerable capabilities for particle identifications
Reasonable efficiency for particle reconstructions

Correlation machine:
- In full Φ
- At mid and forward η
- At low and high p_T

STAR probes 0.001 < x < 0.2 in PDF at √s = 200 GeV

η coverage of STAR detectors

East

West
The perfect liquid
Particle productions - high pt

Produced from jet fragmentation of partons scattered with large $Q^2$
Rates: framework of pQCD in terms of the asymptotically free pointlike parton

Hard Scattering in vacuum-QCD

- p+p or peripheral Au+Au

Hard Scattering in QCD medium

- Central Au+Au

- Medium $D(z)$

Hadronization in/out medium? Formation time?

Hadronic absorption?

Gluon radiation and/or Elastic scattering?

- DIS off nuclei and Drell-Yan process on nuclear target: nPDF is universal and factorization holds up to NLO.

- What about the FFs (Fragment distributions in jet energy)? in NN collisions and in AA collisions?
Spectra, correlation in rapidity and azimuth.

- AA collision is not simple incoherent superposition of neither NA nor NN collisions
- Hadron suppression and di-jet results at mid rapidity manifest the final state effect

Surface-bias

$4 < p_{T, \text{trig}} < 6 \text{ GeV/C}$

Hard scattering

assoc $p_T > 2 \text{ GeV/C}$
More correlations and forward rapidity

Consistent with saturation at low $x$

Hard scattering $8 < p_T^{\text{trig}} < 15 \text{ GeV/C}$

$\checkmark$ non interacting jets
<table>
<thead>
<tr>
<th>Questions</th>
<th>Mid</th>
<th>Forward</th>
<th>Measurements</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is AA collision an incoherent superposition of NN/NA collisions?</td>
<td>No</td>
<td>?</td>
<td>Spectra and two/multi particle correlations in $\eta$ and $\Phi$ and correlations w.r.t reaction plane</td>
<td>Final state effect, surface bias emission?, inconsistency with $v_2$? non-interacting jets?, ridge?</td>
</tr>
<tr>
<td>Does NA collisions resemble NN collisions?</td>
<td>Yes except for Cronin effect</td>
<td>No</td>
<td>Spectra and two particle correlations in $\eta$ and $\Phi$</td>
<td>Onset of saturation at forward rapidity</td>
</tr>
<tr>
<td>What is the role of the precursor state, the proposed CGC, if it exists?</td>
<td>?</td>
<td>Onset of saturation</td>
<td>Spectra and two particle correlations in $\Phi$</td>
<td>Onset of saturation at forward rapidity, CGC?</td>
</tr>
</tbody>
</table>
Spectra and correlations

- Unexpected level of suppression for NPE
- Pre-hadronic collectivity
- Neither unique hadronic nor partonic hierarchy over the entire $p_T$ range, only quark number order at intermediate $p_T$
Phenomenological studies of jet energy loss

- Assumes that factorization holds and extract medium parameters.
  - LPM-effect based approaches: BDMPS & AMY
  - Opacity expansion: GLV & ASW
  - Medium enhanced higher twist effects
  - Medium modified MLLA

Relative phase:

\[ \tau_{\text{form}} \ll \lambda \]
\[ \frac{dE_{\text{rad}}}{dz} \propto C_R \alpha_s E \langle q_{\perp}^2 \rangle \]

\[ \tau_{\text{form}} \gg \lambda \]
\[ \frac{dE_{\text{rad}}}{dz} \propto C_R \alpha_s \ln(E) \langle q_{\perp}^2 \rangle \]

Static Medium \[ \frac{dE_{\text{rad}}}{dz} \propto \alpha L^2 \]
Dynamic Medium \[ \frac{dE_{\text{rad}}}{dz} \propto \alpha L \]

Scattering power of the medium \[ \hat{q} \equiv \rho \sigma \langle q_{\perp}^2 \rangle = \mu^2 / \lambda \]

\[ 1 / \mu \ll \lambda \]
Independent successive scattering centers

The parton propagation is “time-ordered” and time-oredered perturbation theory is the natural framework to calculate the radiation amplitude.

Different models successfully describe the data with very different medium parameters (\[ \hat{q} \sim 3-19 \text{ GeV}^2/\text{fm} \]).

Extracted parameters indicate a medium formation with much higher energy density than that of CNM.
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<th>Questions</th>
<th>Exp</th>
<th>Theory</th>
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<td>Hadron suppression: Hadron absorption and/or partonic energy loss?</td>
<td>?</td>
<td>Partonic energy loss for light quark</td>
<td>Spectra and correlations w.r.t reaction plane for many identified hadrons with different quarks contents</td>
<td>Th: suppression is too large to be described by hadronic absorption for light quarks. Exp: Neither hadronic nor partonic hierarchy, scaling with quark number at intermediate ( p_T )</td>
</tr>
<tr>
<td>What is the mechanism of energy loss (radiative/elastic)?</td>
<td>?</td>
<td>?</td>
<td>Spectra, two particle correlations in ( \Phi ), and correlation w.r.t reaction plane for heavy quarks</td>
<td>Exp: Unexpected level of suppression for non-photonic electrons.</td>
</tr>
<tr>
<td>What is the functional form of energy loss (( E,L,C_R,f ))?</td>
<td>?</td>
<td>( E, \ln(E), \sqrt{E}, L^2,L,C_R,f )</td>
<td>Spectra and two particle correlations in ( \Phi ) for direct photon spectra and jet-hadron correlation in ( \Phi ).</td>
<td>Exp: No strong dependence on ( E, L, C_R,f ) is observed</td>
</tr>
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Conclusions

Single hadron and di-jet analysis in NN, NA, and AA establish the final state effect in AA at mid $\eta$ and the onset of saturation at forward $\eta$.

A particular focus was to discuss to what extent the high-$p_T$ particles produced (RHIC) can be taken as evidence for the RHIC paradigm of jet quenching "Parton traverses QDC medium (partonic matter) and loses energy".

Measurements themselves do not establish unequivocal evidence for partonic energy loss in partonic matter; however, Theory - experiment comparison seems to favor the partonic energy loss (light quarks) over the hadronic absorptions in partonic and/or hadronic matter.

The basic question

Whether AA creates a medium long-lived and extend over sizable volume and reached the thermodynamics limit to have particular thermodynamic and transport properties?!

is awaiting future measurements of more evident results and demanding theoretical progress.
Physics at EIC
The role of gluons that bind us all
Scaling violation

Gluons dominate low-x wave function

\[ xG \times \frac{1}{20} \]

\[ xS \times \frac{1}{20} \]
The Issue With Our Current Understanding

Established Model:

Linear DGLAP evolution scheme
- Weird behavior of $xG$ and $F_L$ from HERA at small $x$ and $Q^2$
  - Could signal saturation, higher twist effects, need for more/better data?
- Unexpectedly large diffractive cross-section

more severe:

Linear Evolution has a built in high energy “catastrophe”
- $xG$ rapid rise for decreasing $x$ and violation of (Froissart) unitary bound
- $\Rightarrow$ must saturate
  - What’s the underlying dynamics?

$\Rightarrow$ Need new approach
The gluon density $x^*G(x,Q^2)$ grows rapidly as collision energy increases.

Classical dynamics applies when the action is large: $(\hbar \to 0)$

$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2 \hbar} \int d^4x \tr G^{\mu\nu}(x)G_{\mu\nu}(x) \gg 1$$

=> Need weak coupling and strong fields

Enhancement of $Q_s$ with $A$ ⇒ non-linear QCD regime reached at significantly lower energy in $A$ than in proton

Color Glass Condensate “saturation”

High gluon density
Strong classical fields
Connection to RHIC & LHC Physics

Matter at RHIC:
- thermalizes fast \( t_0 \sim 0.6 \text{ fm/c} \)
- We don’t know why and how?
- Initial conditions? \( \Rightarrow G(x, Q^2) \)

Role of saturation?
- RHIC \( \rightarrow \) forward region
- LHC \( \rightarrow \) midrapidity
  - bulk (low-\( p_T \) matter) & semi-hard jets

Jet Quenching:
- Need Reference: E-loss in cold matter
- No HERMES data for
  - charm energy loss
  - in LHC energy range

EIC provides new essential input:
  - Precise handle on \( x, Q^2 \)
Electron Ion Collider Concepts

- **eRHIC (BNL):** Add Energy Recovery Linac to RHIC
  \[ E_e = 10 \ (20) \text{ GeV} \]
  \[ E_A = 100 \text{ GeV (up to U)} \]
  \[ \sqrt{s_{eN}} = 63 \ (90) \text{ GeV} \]
  \[ L_{eAu} \text{ (peak)/n} \sim 2.9 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \]

- **ELIC (JLAB):** Add hadron beam facility to existing electron facility CEBAF
  \[ E_e = 9 \text{ GeV} \]
  \[ E_A = 90 \text{ GeV (up to Au)} \]
  \[ \sqrt{s_{eN}} = 57 \text{ GeV} \]
  \[ L_{eAu} \text{ (peak)/n} \sim 1.6 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \]

Both allow for polarized e+p collisions!
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