Prepare (e)STAR as an EIC detector

Zhangbu Xu (BNL)

- Introduction (eSTAR)
  - Physics Cases
    - STAR (status) → eSTAR
- R&D Projects
  - FCS/BSO/iTPC/TRD
  - On-going simulations
- Summary
RHIC: eight key unanswered questions

1: Properties of the sQGP
2: Mechanism of energy loss: weak or strong coupling?
3: Is there a critical point, and if so, where?
4: Novel symmetry properties
5: Exotic particles

Partonic structure

6: Spin structure of the nucleon
7: How to go beyond leading twist and collinear factorization?
8: What are the properties of cold nuclear matter?
A Long Term (Evolving) Strategic View for RHIC

Luminosity upgrade:
Further luminosity upgrades (pp, low-E)

Staged approach to eRHIC LHC HI starts
RHIC-II science by-bypassing RHIC-II project
Opportunity for upgrade* or 1st EIC stage (eRHIC-I)

EIC = Electron-Ion Collider;
eRHIC = BNL realization by adding e beam to RHIC

* New PHENIX and STAR Decadal Plans provide options for this period.
Dedicated storage ring for novel charged-particle EDM measurements another option.

S. Vigdor
## Golden Probes in eA

<table>
<thead>
<tr>
<th>Physics</th>
<th>Measurements</th>
<th>requirements</th>
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<tr>
<td>Structure functions of heavy nuclei (F2,FL)</td>
<td>Scattered electron ((Q^2,x))</td>
<td>Precise electron p and PID</td>
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<tr>
<td>Semi-inclusive final-state correlation</td>
<td>Scattered electron ((Q^2,x)) and hadrons</td>
<td>Electron ID and hadron spectra</td>
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<tr>
<td>Exclusive Vector Meson</td>
<td>J/ψ and other vector meson</td>
<td>Electron/muon ID and full coverage detector</td>
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<tr>
<td>Cold Nuclear Energy Loss</td>
<td>Jets and leading hadrons</td>
<td>Electron and Hadron PID</td>
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<tr>
<td>Heavy-Flavor Energy Loss</td>
<td>Charm PID</td>
<td>Secondly vertex detector</td>
</tr>
<tr>
<td>Exotics</td>
<td>Heavy-flavor hypernuclei</td>
<td>Forward Secondly vertex detector</td>
</tr>
</tbody>
</table>
Imaging nuclei

Figure 3.20: $d\sigma/dt$ distributions for exclusive $J/\psi$ (left) and $\phi$ (right) production in coherent and incoherent events in diffractive $eAu$ collisions. Predictions from saturation and non-saturation models are shown.

Colored dipole directly images gluon distribution
Proof of Principle of exclusive Diffractive in Au+Au
Proven STAR Capabilities

(a) p+p

(b) Au+Au 10-40%

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \pi^+ \times 100 \]
\[ \pi^- \times 100 \]
\[ K^0 \times 235 \]
\[ K^- \times 182 \]
\[ \rho \times 62 \]
\[ \omega \times 101 \]
\[ \eta \times 454 \]
\[ \phi \times 349 \]
\[ J/\psi \times 29601 \]

TBW fit

Data/Cocktail

\[ p+p \rightarrow p+p \text{ at } \sqrt{s} = 200 \text{ GeV} \]

\[ A_N \text{ vs } -t \]
## Deliverables with polarized e+p collider

<table>
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<tr>
<th>Science Deliverable</th>
<th>Basic Measurement</th>
<th>Uniqueness Feasibility Relevance</th>
<th>M. Stratmann: eRHIC workshop Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin structure at small ( x ) contribution of ( \Delta g, \Delta \Sigma ) to spin sum rule</td>
<td>Inclusive DIS</td>
<td></td>
<td>Minimal large ( x,Q^2 ) coverage about 10 fb(^{-1} )</td>
</tr>
<tr>
<td>Full flavor separation in large ( x,Q^2 ) range strangeness, ( s(x) = \bar{s}(x) ) polarized sea</td>
<td>Semi-inclusive DIS</td>
<td></td>
<td>Very similar to DIS excellent particle ID improved FFs (Belle, LHC, ...)</td>
</tr>
<tr>
<td>Spatial structure down to small ( x ) through TMDs and GPDs</td>
<td>SIDIS azim. asym. &amp; exclusive processes</td>
<td></td>
<td>( p_T^{H} ) binning, ( t ) resolution, exclusivity, Roman pots, large ( (x,Q^2) ) range</td>
</tr>
</tbody>
</table>
Cross Sections in pp compared to pQCD

Inclusive Jet Cross Section
pp @ 200 GeV
Cone Radius = 0.7
-0.8 < η < 0.8

\[ \int L dt = 5.39 \text{ pb}^{-1} \]

NLO pQCD calc.
KKP FF
Kretzer FF

p+p → π⁰+X \quad \sqrt{s}=200 \text{ GeV}

π⁰ mesons
- 3.7 < η < 4.15
- 3.4 < η < 4.0
- 3.05 < η < 3.45

E dσ/df (µb GeV/³)

PRL 108 (2012)

Theory: FEWZ and MSTW08 NLO PDFs

RHIC: the only polarized proton collider!

\[ \sqrt{s} = 200 \text{ GeV} \quad \vec{p} + \vec{p} \rightarrow \text{jet} + X \quad |\eta| < 1 \]

\[ \triangle \frac{\bar{u}}{u} \quad \triangle \frac{\bar{d}}{d} \]

\[ A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

\[ \Delta \bar{u} \]

\[ \Delta d \]

\[ \text{Syst. uncertainty due to background, w/o pol. norm. uncertainty of 9.2%} \]

\[ \pi^- \quad \pi^+ \]

\[ 2006 \text{ STAR Preliminary} \]
Current STAR Experiment
STAR Concept

- Large Coverage
- Low Material
- Electron and hadron ID with gas detector and TOF, EMC
- Extend this concept to hadron direction
  - GEM tracker (VFGT)
  - Hadron PID?
  - Forward Calorimetry
- Extend this concept to electron direction
  - Reinstrument inner TPC
  - TRD+TOF
DIS – eSTAR Kinematics

a) Scattered Electron Angle  5+100 GeV

b) Scattered Electron Energy  5+100 GeV

- STAR TPC+BEMC+TOF
- Resolution!

x = E_e/E_p

- Upgrade
- PID
- Jets

c) Struck Quark Angle  5+100 GeV

d) Struck Quark Energy  5+100 GeV

- Bjorken-x
**STAR forward instrumentation upgrade**

- Forward instrumentation optimized for \( p+A \) and *transverse spin* physics
  - Charged-particle tracking
  - \( e/h \) and \( \gamma/n^0 \) discrimination
  - Baryon/meson separation

**eSTAR specific upgrades:**
- EToF: \( e, \pi, K \) identification,
- ETRD: electron ID and hadron tracking
- BSO: 5 GeV, 10 GeV, ... electron beams
- Re-instrument HFT

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**Forward Calorimeter System (FCS)**

- FHC (E864)
- Pb-Sc HCal
- W-Powder EMCal
- RICH/Threshold
- Baryon/meson separation

- \( \sim 6 \) GEM disks
- Tracking: \( 2.5 < \eta < 4 \)

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**STAR Science for the Decade – QM2011 – Carl Gagliardi**
Occupancy and pile-up ii)

**QED $\alpha=1/137$ and low multiplicity $\rightarrow$ an order of magnitude lower pile-up than RHIC**

<table>
<thead>
<tr>
<th>Beam species</th>
<th>Sqrt(s)</th>
<th>Peak Luminosity (cm$^{-2}$s$^{-1}$)</th>
<th>Cross section (cm$^2$)</th>
<th>Nch/d$\eta$</th>
<th>Track density (dNch/d$\eta$ MHz)</th>
<th>Hit density impact hit finding</th>
<th>Space charge impact tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+p</td>
<td>5x250</td>
<td>$10^{34}$</td>
<td>$10^{-28}$</td>
<td>0.7</td>
<td>0.7</td>
<td>Minor</td>
<td>Corrected to good precision</td>
</tr>
<tr>
<td>Au+Au</td>
<td>100x100</td>
<td>$5x10^{27}$</td>
<td>$7x10^{-24}$</td>
<td>161</td>
<td>6</td>
<td>Minor</td>
<td>Corrected to good precision</td>
</tr>
<tr>
<td>p+p</td>
<td>100x100</td>
<td>$5x10^{31}$</td>
<td>$3x10^{-26}$</td>
<td>2</td>
<td>3</td>
<td>Minor</td>
<td>Corrected to good precision</td>
</tr>
<tr>
<td>p+p</td>
<td>250x250</td>
<td>$1.5x10^{32}$</td>
<td>$4x10^{-26}$</td>
<td>3</td>
<td>18</td>
<td>Significant for inner</td>
<td>Corrected to acceptable</td>
</tr>
</tbody>
</table>
Spaghetti Tungsten powder with fibers

Approved EIC R&D project from May 2011, UCLA, TAMU, PSU

T1018
Jan. 30, 2012

Very successful Run

Got “proof-of-principle”

L. Dunkelberger, H.Z. Huang, G. Igo, K. Landry, Y. Pan, S. Trentalange, O. Tsai, W. Xu, Q. Zhang (UCLA)
C. Gagliardi (Texas A&M)
C. Dilks, S. Heppelman (Penn State)
## Crystal Calorimeter (BSO)

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Density (g cm(^{-3}))</th>
<th>Rad. length (mm)</th>
<th>Decay time (ns)</th>
<th>Peak emission (nm)</th>
<th>Relative light output</th>
<th>Price ($/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSO</td>
<td>6.80</td>
<td>11.5</td>
<td>~ 100</td>
<td>480</td>
<td>0.04</td>
<td>13-18</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>11.2</td>
<td>~ 300</td>
<td>480</td>
<td>0.10 – 0.21</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>PWO</td>
<td>8.28</td>
<td>8.9</td>
<td>~ 10-30</td>
<td>410 - 450</td>
<td>0.003</td>
<td>10-13</td>
</tr>
</tbody>
</table>

- **Very Forward Electron Detection** (\(\eta<2.5\))
- BSO is produced by replacing Ge in BGO with Si, the material cost for BSO reduced by x3-4.
- Collaborators: USTC, SINAP, THU
- Vendor: Shanghai SICCAS High Technology Corporation
- R&D proposal partially funded by BNL/DOE

![Energy Resolution Graph](image)
First Stage eRHIC electron/hadron PID

Electron coverage: 1>eta>-2.5
PID e/h: 1000
Low material: photon conversion

INT report (arXiv:1108.1713) Fig.7.18.
Midrapidity electron PID (TOF)

Figure 3.5: Electron efficiency vs. hadron contamination fraction by varying the $dE/dx$ cut to selection electrons for 4 $p_T$ bins.
Midrapidity electron PID (EMC)

Figure 3.5: Electron efficiency vs. hadron contamination fraction by varying the $dE/dx$ cut to selection electrons for 4 $p_T$ bins.
Current Inner Sector Limitations

- Staggered readout
  - Only 13 maximum possible points
    - Issues in Tracking: recognition and resolution
  - Only reads ~20% of possible gas path length
    - Inner sectors essentially not used in dE/dx
- Essentially limits TPC effective acceptance to $|\eta| < 1$

Inner TPC Upgrade

New GEANT Geometry

- Outer Pads: 6.2 mm x 19.5 mm
  - Total of 3,940 Pads
  - 6.7 x 20mm Centers

- Inner Pads: 2.85 mm x 11.5 mm
  - Total of 1,750 Pads

\[
\begin{align*}
\eta &= \pm 1 \\
\eta &= \pm 1.2 \\
\eta &= \pm 2
\end{align*}
\]
Sector Replacement is possible but not Trivial

Physics and Instrumentation R&D

- Optimize number of rows to match available funds & Eng. factors
- Optimize pad size for greatest physics return
- Join existing R&D efforts for PASA and Altro chips

Technical Challenges (R&D by another name)

- Pad plane design – traces & connector technology, alignment
- Winding large wire planes ... an art rather than a science
- Factory – assembly line, QA and efficiency
TRD+TOF at Endcap (-2<\eta<-1)

- Inner tracking
- TPC (endcap region): TRD + TOF/Absorber sandwich
  - Within <70cm space inside endcap
  - TOF as start-time for BTOF and MTD
    - TOF + dE/dx for electron ID
    - TOF for hadron PID
  - Extend track pathlength with precise points
  - High-precision dE/dx (Xe+CO2) TRD

Ming Shao (USTC)
R&D on GEM based TRD

dE/dx with Xe+CO₂
position resolution
TRD gain

Collaboration: VECC/India, USTC/China, BNL, Yale et al.
Proposal funded by EIC R&D committee

1. Ionization chamber: 6mm
2. Energy Resolution: 16% for $^{55}\text{Fe}$
   @ Gain = 3700 Ar/iC$_4$H$_{10}$(97/3%)
3. Spatial resolution: 0.25mm

Test performed at Yale
Simulation Geometry
A Pythia Simulation Event

Only TPC and ETTIE are shown
Acceptance and Resolution (first simulation)

Haven't optimized vertex finder (some events without vertex constraint)
Physics Simulations in Progress

5x250 ep collisions:

1. $g_1$ vs $(x,Q^2)$, generator PEPSI
2. Semi-inclusive with PID: $\Delta G$ vs $(x, Q^2)$

**eA (electron+Pb):**

1. $F_2, F_L$ 5x50, 5x75, 5x100 (DJANGO)
2. $d\phi$ of di-hadron for given $(x,Q^2)$ relative to virtual photon direction (as $z$): PYTHIA
3. Semi-inclusive $R(eA/ep) (\nu, Q^2, z, p_t)$ PID (PYTHIA6.x)
4. $J/\Psi$ exclusive (SARTRE)

For event generators, see EIC-TF webpage: https://wiki.bnl.gov/eic/index.php/Simulations#Event_Generators
Plans

- Continue to sharpen the physics cases
- Possible R&D projects:
  1. Tracking and PID (hadron side)
  2. Calorimetry (hadron side)
  3. Tracking+eID (electron side)
  4. End-Cap TOF (electron side)
  5. Very forward electron ID
  6. Roman Pots (not really R&D, but necessary)
- Simulation of feasibilities
- Update Decadal Plan
- Discuss with CAD and EIC TF on IR design and detector R&D
Summary

- eSTAR a possible option for first-stage EIC detector
- Near-term upgrades for RHIC have optimized for eSTAR option as well
- R&D projects and EIC simulation in progress
- STAR Collaboration is committed to the eSTAR path
- Inputs/helps from groups (theorists and experimental colleagues)
Semi-inclusive final state correlation

Dominguez, Xiao, Yuan (2010)

Systematic depletion of away-side peak seen with increasing nuclear size/energy

No pedestal effect here!
dE/dx and TR signals for electron and hadron discrimination

High-position tracklet for hadron momentum reconstruction