Summary and Conclusions of EIC Yellow Report on Complementarity

RHIC/AGS Users Meeting

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Background

- Funding considerations aside, colliders usually have (at least) two detectors

- Much of the work done for Yellow Report focused on a ‘reference detector’

- Second detector more of a blank page → opportunity to refine and enhance EIC physics program by thinking in terms of complementarity from the outset.

- Yellow Report Complementarity group charged with collecting arguments why two detectors will enhance scientific output
This talk is already (ancient) history

- Considerations shown here all pre-date ongoing EIC collaboration formation / detector proposals exercise.

- No statements on relative merits are intended.

[see session on Wednesday]
First Detector

Well developed reference concept for first detector and interaction region

- Based on 1.5 - 3T solenoid
- Technologies to be decided

[See Tanja Horn’s talk]
What do we want from ‘Complementary’
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1) **Cross-checking important results** (obvious!)

- Many examples of wrong turns in history of nuclear and particle physics.

- Independent cross checks (detector, community, analysis tools) are essential for timely verifications and corrections
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- Independent cross checks (detector, community, analysis tools) are essential for timely verifications and corrections.

e.g.: Pentaquarks in 2004 ($K_sp$ & $D^*p$ at HERA)
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1) **Cross-checking important results** (obvious!)

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e.g: Pentaquarks in 2004 ($K_S p \& D^* p$ at HERA)
What do we want from ‘Complementary’

2) Cross calibration

- Combining data gave well beyond the $\sqrt{2}$ statistical improvement …
- Different dominating H1, ZEUS systematics…
- Effectively use H1 electrons with ZEUS hadrons
… not all optimal solutions have to be in one detector…
What do we want from ‘Complementary’

3) **Technology Redundancy** … applying different detector technologies and philosophies to similar physics aims
- mitigates technology risk v unforeseen backgrounds
- differently optimises precision and systematics
3) **Technology Redundancy**

... applying different detector technologies and philosophies to similar physics aims
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- differently optimises precision and systematics

4) **Different primary physics focuses ...**

... EIC has unusually broad physics programme
(from exclusive single particle production to high multiplicity eA or γA with complex nuclear fragmentation)
→ Impossible to optimise for the full programme in a single detector.
Complementarity Working Group Activities

1) Discussed detailed aims and needs with Physics Working Group conveners
   “Have you identified key physics aims that conflict with the current baseline / schematic detector and IR design?”

2) Discussed with Detector Working Group conveners
   “Assuming we have two detectors, how you could build in complementarity within the overall constraints imposed by the accelerator and associated considerations?”

   [Many subsidiary questions and iterations]

   ... no compelling argument for a second detector with specialised / limited physics focus.

   → Working assumption → two complementary GPDs
General Requirements for any EIC GPD:

1) Boundary Conditions from Machine

- Second detector design must be compatible with machine / IR design at IP8
- Solenoid aligned with electron beam (to limit synchrotron load)
- Main detector coverage limited to $|\eta| \leq 4$ by crossing angle / synchrotron
- Main detector length limited to $\pm 4.5\text{m}$ by first focusing quadrupole (lumi)
- Fwd / Bwd detector angular range limited to $\sim 1.5^\circ$ by synchrotron
- Longitudinal space for Fwd / Bwd detectors limited to $\pm 35\text{m}$ (crab cavities)
General Requirements for any EIC GPD  

2) Physics Considerations  

- Able to perform well over entire EIC $\sqrt{s}$ and luminosity range  

- Efficient scattered electron ID down to low energies ($10^{-4}$ e/$\pi$ separation)  

- ECAL resolution (for scattered electron) pivotal ($\sim 2%/\sqrt{E}$)  

- Tracking momentum resolution better than 2%, whilst keeping material budget low ($<\sim 5% X_0$). Vertex resolution ($\sim 20 \mu$m for all three coordinates)  

- PID separating $\pi$, K, p (nominally $3\sigma$ $\pi/K$ separation) up to high $p_T \sim 50$GeV  

- HCAL matching tracking and ECAL acceptance ($\sim 50%/\sqrt{E}$).  

- Large forward acceptance / precise measurement of protons, neutrons; also nuclear fragment, photon tagging. Backward e, $\gamma$ coverage for lumi and low $Q^2$  

- Precision luminosity and polarimetry measurements  

- Control of systematics matching statistical precision (redundancy!)
**Complementarity from Solenoid Field Choice**

- **High field → high $p_T$ precision:** Many good physics aims associated with scattered electron, heavy flavours, precision spectroscopy …

- **Low field → low $p_T$ acceptance:** eg 1.5T field - acceptance to $p_T \sim 150$ MeV

- **SIDIS spectra dominated by low $p_T$ ($< 1$ GeV).**
  - TMDs, Fragmentation Fns, Samples for spectroscopy (HF etc)
Field Choice also coupled with PID Acceptance

- Suppose silicon / microvertex detector has $r_{min} \sim 3\text{cm}$ and innermost particle ID-capable detector has $r_{min} \sim 1\text{m}$ ...

... $p_T$ acceptance cut-offs significantly higher for PID than for basic track reconstruction ...

<table>
<thead>
<tr>
<th>lowest $p_T$ with PID @1m</th>
<th>0.5 Tesla</th>
<th>1 Tesla</th>
<th>3 Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>no PID</td>
<td>25 MeV</td>
<td>50 MeV</td>
<td>100 MeV</td>
</tr>
</tbody>
</table>

- Solenoid bore radius, length, space for cryostat also have strong influence on detector design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>New Magnet</th>
<th>BABAR/sPHENIX Magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Central Field (T)</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>Coil length (mm)</td>
<td>3600</td>
<td>3512</td>
</tr>
<tr>
<td>Warm bore diameter (m)</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Uniformity in tracking region (z = 0, r &lt; 80 cm) (%)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Conductor</td>
<td>NbTi in Cu Matrix</td>
<td>Al stabilized NbTi</td>
</tr>
<tr>
<td>Operating Temperature (K)</td>
<td>4.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

(CORE compact 2.5T baseline)

(ATHENA) (ECCE)
Complementarity through Technology Choices

<table>
<thead>
<tr>
<th>system</th>
<th>system components</th>
<th>reference detectors</th>
<th>detectors, alternative options considered by the community</th>
</tr>
</thead>
<tbody>
<tr>
<td>tracking</td>
<td>vertex</td>
<td>MAPS, 20 um pitch</td>
<td>MAPS, 10 um pitch</td>
</tr>
<tr>
<td></td>
<td>barrel</td>
<td>TPC</td>
<td>TPC¹</td>
</tr>
<tr>
<td></td>
<td>forward &amp; backward</td>
<td>MAPS, 20 um pitch &amp; sTGGe</td>
<td>MAPS, 20 um pitch</td>
</tr>
<tr>
<td></td>
<td>very far-forward</td>
<td>MAPS, 20 um pitch &amp; AC-LGAD⁴</td>
<td>TimePix (very far-backward)</td>
</tr>
<tr>
<td></td>
<td>&amp; far-backward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECal</td>
<td>barrel</td>
<td>W powder/ScFi or Pb/Sc Shashlyk</td>
<td>SciGlass</td>
</tr>
<tr>
<td></td>
<td>forward</td>
<td>W powder/ScFi</td>
<td>SciGlass</td>
</tr>
<tr>
<td></td>
<td>backward, inner</td>
<td>PbWO₄</td>
<td>SciGlass</td>
</tr>
<tr>
<td></td>
<td>backward, outer</td>
<td>SciGlass</td>
<td>PbWO₄</td>
</tr>
<tr>
<td></td>
<td>very far-forward</td>
<td>Si/W</td>
<td>W powder/ScFi or W/Sc Shashlyk</td>
</tr>
<tr>
<td>h-PID</td>
<td>barrel</td>
<td>High performance DIRC &amp; dE/dx (TPC)</td>
<td>reuse of BABAR DIRC bars</td>
</tr>
<tr>
<td></td>
<td>forward, high p</td>
<td>double radiator RICH (fluorocarbon gas, aerogel)</td>
<td>fine resolution TOF</td>
</tr>
<tr>
<td></td>
<td>forward, medium p</td>
<td></td>
<td>fluorocarbon gaseous RICH</td>
</tr>
<tr>
<td></td>
<td>forward, low p</td>
<td>TOF</td>
<td>high pressure Ar RICH</td>
</tr>
<tr>
<td></td>
<td>backward</td>
<td>modular RICH (aerogel)</td>
<td>proximity focusing aerogel</td>
</tr>
<tr>
<td>e/h separation at low p</td>
<td>barrel</td>
<td>hpDIRC &amp; dE/dx (TPC)</td>
<td>very fine resolution TOF</td>
</tr>
<tr>
<td></td>
<td>forward</td>
<td>TOF &amp; aerogel</td>
<td>adding TRD</td>
</tr>
<tr>
<td></td>
<td>backward</td>
<td>modular RICH</td>
<td>Hadron Blind Detector</td>
</tr>
<tr>
<td>HCal</td>
<td>barrel</td>
<td>Fe/Sc</td>
<td>RPC/DHCAL</td>
</tr>
<tr>
<td></td>
<td>forward</td>
<td>Fe/Sc</td>
<td>Pb/Sc</td>
</tr>
<tr>
<td></td>
<td>backward</td>
<td>Fe/Sc</td>
<td>RPC/DHCAL</td>
</tr>
<tr>
<td></td>
<td>very far-forward</td>
<td>quartz fibers/ scintillators</td>
<td>Pb/Sc</td>
</tr>
</tbody>
</table>

Multiple proposals / alternatives in YR for each subdetector ...

→ Different space requirements
  e.g. trade-offs between tracking and dedicated PID
→ Different material budgets / systematics
→ Some combine multiple functions
  eg e-h separation + tracking with TRDs
  eg PID (from ToF) + tracking with AC-LGADs
→ Different risks / technology-readiness

... Making different choices in IR1 and IR2 detectors provides natural technology redundancy, plus ‘independent’ cross checking and cross-calibration
Example Complementarity through Detector Technology Choices: Tracking Region

<table>
<thead>
<tr>
<th>Function</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>All Silicon</td>
<td></td>
<td>Silicon + TPC</td>
<td></td>
</tr>
<tr>
<td>(includes 5 cm support)</td>
<td>50 cm</td>
<td>60 cm</td>
<td>85 cm</td>
<td></td>
</tr>
<tr>
<td>Hadron PID</td>
<td>RICH</td>
<td>50 cm</td>
<td>DIRC</td>
<td>10 cm</td>
</tr>
<tr>
<td>EM Calorimetry</td>
<td>30 cm</td>
<td>50 cm</td>
<td>High-Resolution to achieve P &lt; 2 GeV</td>
<td>50 cm</td>
</tr>
<tr>
<td>PID &amp; EMCal Support Structure</td>
<td>10 cm</td>
<td>15 cm</td>
<td>10 cm</td>
<td>15 cm</td>
</tr>
<tr>
<td>Total</td>
<td>140 cm</td>
<td>175 cm</td>
<td>155 cm</td>
<td>160 cm</td>
</tr>
</tbody>
</table>

- Si + gas version provides PID from dE/dx & keeps low material budget

- All Si version slightly improves momentum, vertex performance and is more compact (e.g. allowing high $p_T$ PID beyond tracker or reducing magnet bore)

... Here (and in many other places), detailed multi-detector simulation tools are needed to optimise combinations
Complementarity by Mitigating Acceptance Gaps

- All detectors have gaps and cracks
  ... e.g. place gap in scattered electron acceptance between main detector and dipole/tagger in different places?

- Similar arguments apply to directional peaks in dead material
Complementarity Between Interaction Points

EIC science needs point to (staged) programme with multiple CMS energies

... Could there be two IRs operating simultaneously, but optimised to different $\sqrt{s}$?

→ Subtly different overall physics goals at different $\sqrt{s}$

→ For a given process, complementary of kinematic regions matching central acceptance at different $\sqrt{s}$

IR6, IR8 Crossing angles can also be different

→ Larger crossing angle reduces parasitic interactions

→ Incorporation of secondary focus to improve acceptance.

→ Influences detector design, in particular beamline instrumentation

... significant progress since completion of Yellow Report ...
Concept for Increased Luminosity at Lower $\sqrt{s}$

- **High Energy Optimization of IR**
  - **Doublet focusing**
  - **Low Energy Optimization of IR**

- **Schematics of concept**
  - Change polarity of quads DDF to FDF
    - Needs to be done only on the rear side (incoming hadron beam) hadron quads
    - Change polarity of quads at low $E_{CM}$

- **Diagram**
  - Hadron beam
  - Forward and Rear sections
  - Q1APR, Q1BPR, Q2PR, Q2PF, Q1BPF, Q1APF

Concept for Increased Luminosity at Lower $\sqrt{s}$

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![Diagram showing schematics of concept and Luminosity vs Center of Mass Energy graph.](image)
Concept for Increased Luminosity at Lower $\sqrt{s}$

- Can be done at IP6 or IP8
- Some cost in terms of low $p_T$ acceptance for far-forward particles
# Summary of Recent Complementary IR Design

<table>
<thead>
<tr>
<th>Geometry:</th>
<th>1st IR (IP-6)</th>
<th>2nd IR (IP-8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ring inside to outside</td>
<td>ring outside to inside</td>
</tr>
<tr>
<td></td>
<td>tunnel and assembly hall are larger</td>
<td>tunnel and assembly hall are smaller</td>
</tr>
<tr>
<td>Tunnel: $\varnothing$ 7m +/- 140m</td>
<td>25 mrad</td>
<td>35 mrad</td>
</tr>
<tr>
<td></td>
<td>different blind spots</td>
<td>secondary focus</td>
</tr>
<tr>
<td></td>
<td>different forward detectors and acceptances</td>
<td></td>
</tr>
<tr>
<td></td>
<td>different acceptance of central detector</td>
<td></td>
</tr>
<tr>
<td></td>
<td>more luminosity at lower $E_{CM}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>optimize Doublet focusing FDD vs. FDF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\rightarrow$ impact of far forward $p_T$ acceptance</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Luminosity:</th>
<th>1.5 Tesla or 3 Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment:</td>
<td>different subdetector technologies</td>
</tr>
</tbody>
</table>
- Essential to robustness of science programme to have two detectors

- Yellow report exercise recommended two GPDs with complementarity in details such as solenoid field, technology choices.

- Novel IR design optimised to reduced $\sqrt{s}$ emerged as key consideration

- For cross-checks and cross-calibration, IR2 time-line should not be (very) different from IR1

- Further progress will ultimately require detailed simulations

- Things are moving fast!
  - Some of complementarity discussion already superseded by collaboration formation discussions