From HERA to the Future of DIS
OUTLINE

• Introduction

• Structure and Interaction
  – A history of investigation of structure of matter
  – QCD and collinear factorization: investigation of interaction rather than structure
  – Return of structure as transverse quantities.
  – DIS as a eq collider

• Proposed DIS colliders
  – Capabilities
  – Timelines
  – Status

• Summary
Introduction

- Deep Inelastic Scattering appears to cover many different arenas
  - Parton distributions, pQCD, resummations
  - Low-x and saturation
  - Heavy Flavors
  - Spin physics, transverse quantities, TMDs, GPDs
  - EW, BSM searches, Higgs physics

- Two approaches to thinking about nature
  - Structure: what are things made of?
  - Interactions: fundamental forces
  - Obviously you need both, but emphasis has gone back and forth in DIS.
    - Some parting of the strands have occurred.
    - Some strands are coming back together.

- Discuss history and future in this light. (DIS Colliders)
Rutherford Scattering: Discovering the nucleus

\[ \sigma(\theta) = \frac{Z^2 Z'^2 e^4}{16E^2 \sin^4 \frac{1}{2} \theta} \]

Discovery of atomic nucleus

→ N. Bohr Old Quantum theory...
SLAC-MIT Experiment: Discovering the quark (50 years!)

HERA to the future of DIS
Investigating structure of matter

Trying to understand characteristics of matter in terms of their constituents

Democritus

Dalton

Thomson

Rutherford

Taylor, Kendall, Freidman

Chadwick
Understanding atomic structure of matter (together with EM) leads to new sciences and much of modern technology.

Condensed matter, molecular biology.. are emergent phenomena.
(i.e. new degrees of freedom arises from fundamental ones)
Beginnings of Nuclear Structure Theory (after neutron discovery)

- How do the properties of the nuclei emerge from the protons and neutrons that make them up?
- Liquid Drop model (Weizsacker 1935)
- Nuclear Shell model (Wigner, Mayer, Jensen 1949)

Highly successful description of nuclei

FRIB
Trying to make sense of hadrons and their structure

Quark model, too, arises out of desire to explain the characteristics of hadrons.

Eight-fold way $\rightarrow$ quark model

CERN conference 1962
Scaling and Collinear factorization

Results from SLAC-MIT experiment

Parton Model

Leads to QCD improved parton model and Parton Distribution Functions.

Co-linear factorization meant the we determined parton distribution in terms of Bjorken-x (and $Q^2$).

DGLAP equations showed us how to handle evolution
QCD→Asymptotic Freedom → partons = quarks and gluons → collinear factorization → DGLAP evolution → PDFs

In the end Infrared Slavery meant that we had enormous difficulty in the hadronic region eventually leading to:

Somewhere here NP and HEP points of view begins to diverge..

Also implies quark-gluon plasma
Parton Densities: Energy Frontier needs parton luminosities

HL-LHC gluino production

LHeC projection: arXiv: 1211.5102

LHeC projection
Investigating pQCD (NLO and NNLO) to the future of DIS

Now proton could be decomposed into their constituent quarks and gluons.

We could investigate, e.g. effect of using higher order terms in the analysis of the data.
Investigating pQCD (Heavy Quark production)

Investigating pQCD, example: Heavy Quarks and jets
Looking at compatibility/complementarity using different probes

Tension between scaling violation and HQ production in DIS

Using HQ and jets to constrain strong coupling
Investigating pQCD (low-x resummation)

x-Fitter developers EPJC 78 (2018) 8, 621

Is the low-x HERA data telling us something about $1/x$ terms? If so what are the implications?
Shadow of the protons.. Saturation? Diffraction

DIS diffraction discovered at HERA

Proton stays intact: this process carries information about the proton wave function.

What sets the saturation scale?
Quark/Gluon structure and Nucleon/Nuclear characteristics

EMC Experiment

Quark and gluon structure has something to do with nucleon spin and but what?
Parton Distribution Functions:
Longitudinal only—
No way to interpret nucleon partonic structure in rest frame

3D (Transverse) Structure
TMD’s, GPD’s—
Now we know what to measure to understand the 3D structure of nucleons

Transverse Momentum Dependent Distributions (TMD): $k_t$
Generalized Parton Distributions (GPD): $b_t$
From 1D structure to 3D structure → EIC

EIC Challenge

Can we relate this to what we understand from:

LQCD

also for nuclei...
The other extreme: LHeC as a Higgs Factory:

Max Klein

**Transformation of the LHC into a High Precision Higgs Facility**

- LHC
- LHeC
- ep+pp
- ep+pp, no thy unc

**Comparison of LHeC and CLIC Prospects**

LHeC: 60 GeV x 7 TeV. CLIC: 350 GeV [arXiv:1608.07538, “model dependent fit”, 0.5ab]
BSM, Precision EW

LHeC projection

**NC couplings**

![Diagram of NC couplings](image)

Britzger, MK, Spiessberger, Zhang – work still in progress

Dark Photon search with AWAKE fixed target

![Graph of Dark Photon search](image)
Approaching the hadron from the high energy limit

LHeC projections

Hadron-hadron scattering

What is the relation between rise of $F_2$ at low-$x$, saturation and the high energy limit of $\sigma_{\gamma p}$
Planned DIS Colliders around the world

<table>
<thead>
<tr>
<th>Facility</th>
<th>Years</th>
<th>$E_{cm}$ (GeV)</th>
<th>Luminosity ($10^{33} \text{ cm}^{-2} \text{s}^{-1}$)</th>
<th>Ions</th>
<th>Polarization</th>
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<tr>
<td>EIC in US</td>
<td>&gt; 2028</td>
<td>20 - 100 → 140</td>
<td>2 - 30</td>
<td>p → U</td>
<td>e, p, d, $^3\text{He}$, Li</td>
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<td>EIC in China</td>
<td>&gt; 2028</td>
<td>16 - 34</td>
<td>1 → 100</td>
<td>p → Pb</td>
<td>e, p, light nuclei</td>
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<td>LHeC (HE-LHeC)</td>
<td>&gt; 2030</td>
<td>200 - 1300 (1800)</td>
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<td>depends on LHC</td>
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<td>PEPIC</td>
<td>&gt; 2025</td>
<td>530 → 1400</td>
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<td>depends on LHC</td>
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<td>VLEeP</td>
<td>&gt; 2030</td>
<td>1000 - 9000</td>
<td>$10^{-5} - 10^{-4}$</td>
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<td>FCC-eh</td>
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<td>depends on FCC-hh</td>
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LHeC (also with HE-LHC) and FCCeh

Max Klein

- $U(ERL) = 1/n U(LHC)$: 60 GeV: 1/3
- BSM, top, Higgs, Low x all want maximum $E_e$
- Cost goes almost linearly down with $E_e$

For FCC can realise ep/A collisions
With IR at point L, not far from CERN
$U(ERL) = 1/11 U(FCC)$

60 GeV e-beam from ERL and 7 TeV proton beam (for LHeC)
Create multi-TeV electron beam using proton wakefield in plasma
EicC (China)

Follow on to High Intensity Heavy Ion Accelerator Facility (HIAF) under construction

From JP Chen, INT-18, 2018

EicC-I: 20GeV p + 3.5GeV e =16.7GeV
EicC-II: 60GeV p + 5GeV e =34.6GeV

Collider Ring (2 km):
Up: Polarized electron, 10 GeV
Down: Polarized proton, 60-100GeV

Electron injector:
SRF Linac-ring, 3.5-10GeV
Two realization concepts being developed

- Highly polarized (~70%) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 – ~100 GeV, upgradable to ~140 GeV
- High collision luminosity $\sim 10^{33-34}$ cm$^{-2}$s$^{-1}$
- Possibilities of having more than one interaction region
DIS Collider Plan Comparison (from EPPSU DIS document)

EicC-China
EIC-US
LHeC
FCC-eh

Luminosity (cm$^{-2}$s$^{-1}$)

10 GeV
100 GeV
1 TeV
10 TeV $\sqrt{s}$

CERN/HEP (e pol possible, ion depends on LHC/FCC)
NP (e, light ions polarized, heavy ions)
DIS Collider Earliest Possible Timelines (EPPSU DIS Document)

- HERA to the future of DIS
- RHIC/JLAB12
- EIC-US
- EicC-I-China
- LHeC
- VLEeP
- FCC-eh

LHC Long term

- LHC
- HL-LHC
- LS2
- LS3
- ATLAS - CMS upgrade phase 1
- ALICE - LHCb upgrade
- 14 TeV
- 5 to 7 x nominal luminosity
- 2020 - 2040

COMPASS2, SMOG2

LHC-Spin
10-page submissions to EPPSU (there are 160)

- DIS Collider submissions (ref #)
  - DIS document: EIC, LHeC, FCC-eh, VHEeP (103)
  - Electron-Ion colliders: LHeC (159), FCCeh (140), AWAKE (VHEeP, PEPIC) (58,35,50) US EIC (99,74)

- Related submissions (probably there are others)
  - QCD Theory 163
  - Heavy Ion Program: 110, 48, 37, 47
  - Hadron physics program: COMPASS 143, LHC Spin 111, Fixed Target program 67, [Nuclear Structure: Isolde 39]
  - Accelerator: PERLE 147
### EicC (China)

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#### HIαF

- R&D
- In operation

#### EicC-I

- R&D and construction
- In operation

\[ \sqrt{s} \sim 20 \text{GeV}, \sim 10^{33} / \text{sec cm}^2 \]

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From JP Chen, INT-18, 2018

Start of the next 5 year plan

HERA to the future of DIS
**National of Academy of Sciences : 2018 Assessment of US EIC**

In summary, the committee finds a *compelling scientific case for such a facility.*

**Volume 4, Page 272:**

“The Request for Construction and Major Items of Equipment (MIEs) includes:”

…

“Other Project Costs (OPC) funding to support high priority, critically needed accelerator R&D to retire high risk technical challenges for the proposed U.S.-based EIC. Subsequent to the FY 2018 National Academy of Science Report confirming the importance of a domestic EIC to sustain U.S. world leadership in nuclear science and accelerator R&D core competencies. **Critical Decision-0, Approve Mission Need, is planned for FY 2019.”**

**Approval needed in FY2019 to justify budget in FY2020**
Summary

• Discussed the history of DIS in terms of
  - Investigation of structure
  - Investigation of interactions
  - Where they intersect
• These ideas can be thought of as driving the various direction of DIS research
• And the current proposals for new facilities.
• The DIS collider proposals on the table are very much complementary in capability
  - The next step for the CERN based proposals is the EPPSU 2020 process.
  - For EicC it is the next 5 year plans beginning 2021
  - DOE in US plans to make the EIC a project in FY2019
Extra
HERA to the future of DIS
current data for Collins and Sivers asymmetry:

- COMPASS: $P_{nT} < 1.6$ GeV
- HERMES: $Q^2 \eta, K^*; P_{nT} < 1$ GeV
- JLab Hall-A: $\pi^+; P_{nT} < 0.45$ GeV
- JLab 12 (upcoming)
- RHIC 500 GeV: $1 < \eta < 1$ Collins
- RHIC 200 GeV: $1 < \eta < 1$ Collins
- RHIC 500 GeV: $1 < \eta < 4$ Collins
- STAR W bosons
- STAR-pp DY: $\sqrt{s} = 500$ GeV

$Q^2$ [GeV$^2$]

- Upgrade EIC: $\sqrt{s} = 140$ GeV, $\Delta y_{coll} = 0.95$
- EIC $\sqrt{s} = 100$ GeV, $\gamma = 0.95$
- EIC $\sqrt{s} = 20$ GeV, $\gamma = 0.05$