From Jefferson Lab to the LHC:
The quest to understand the building blocks of the universe

Nobuo Sato
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Colloquium at ODU, Mar 2 2017
What is the universe made of?

- Democritus held that everything is composed of “atoms” (460 BC)
What is the universe made of?

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- Today we know that
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Fructose
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Fructose

Carbon
What is the universe made of?

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- Also we know that

And we have a model for their interactions
\[-\frac{1}{2} \partial_\nu g^\mu_\nu \partial_\nu g^\alpha_\mu - gs f^{abc} \partial_\mu g^b_\nu g^c_\mu g^\alpha_\nu + \frac{1}{4} g^2 f^{abc} f^{ade} g^b_\mu g^c_\mu g^d_\nu g^e_\nu + \frac{1}{2} i g^2 \left( \bar{q}_n q^\mu q^\alpha g^\mu_\nu + \bar{c}^\alpha \partial^2 G^\alpha + gs f^{abc} \partial_\mu \bar{c}^\alpha G^b g^c_\mu \right) - \partial_\nu W^\mu_+ \partial_\nu W^- - M^2 W^\mu_+ W^- \frac{1}{\partial_\nu Z^0_\mu \partial_\nu Z^0_\nu} - \frac{1}{2} \partial_\mu Z^0_\mu \partial_\nu Z^0_\nu - \frac{1}{2} \partial_\mu A_\nu \partial_\nu A_\mu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_H^2 H^2 \]
\[-\partial_\mu \phi^+ \partial_\mu \phi^+ - M^2 \phi^+ \phi^+ - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2} m_H^2 \left( \frac{2 M^2}{g^2} + \frac{2 M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-) \right) \frac{2 M^4}{g^2} \alpha_h - ig_{cw} [\partial_\nu Z^0_\mu (W^\mu_+ W^-_\nu - W^\mu_\nu W^-_\nu - W^\nu_+ W^-_\mu + Z^0_\nu (\partial_\nu W^\mu_+ - W^-_\mu \partial_\nu W^\mu_+ + Z^0_\mu (\partial_\nu W^\mu_- - W^-_\mu \partial_\nu W^\mu_-]]
\[-ig_{sw} [\partial_\nu A_\mu (W^\mu_+ W^-_\nu - W^\mu_\nu W^-_\nu - W^\mu_- W^\mu_\nu - W^\mu_+ W^-_\mu + W^\mu_- W^\mu_\nu)] - \frac{1}{2} g^2 Z^0_\mu Z^0_\nu Z^0_\mu Z^0_\nu + g_2^2 (Z^0_\mu Z^0_\nu Z^0_\mu Z^0_\nu) - g_{sw}^2 (A_\mu W^\mu_+ A_\nu W^\nu_+ - A_\mu A_\nu W^\mu_+ W^\nu_+) + g_{sw}^2 (A_\mu Z^0_\mu W^\mu_+ W^\nu_+ - W^\mu_+ W^\nu_+ - 2 A_\mu Z^0_\mu W^\mu_+ W^\nu_+)
\[-g_0 [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4 (\phi^+)^2 \phi^0 + 4 H^2 \phi^+ \phi^- + 2 (\phi^+)^2 H^2] - g MW^\mu_+ W^-_\mu H
\[-\frac{1}{2} \frac{g^2 Z^0_\mu Z^0_\nu Z^0_\mu H - \frac{1}{2} ig [W^\mu_+ (\phi^0 \partial_\mu \phi^- - \phi^+ \partial_\mu \phi^0)] - \frac{1}{2} g [W^\mu_+ (H \phi^+ \phi^- - \phi^- \partial_\mu H - W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H) - \frac{1}{2} \frac{g^2 s w^2}{c_w} Z^0_\mu \phi^0 (\phi^+ \phi^- - \phi^- \partial_\mu \phi^0) - \frac{1}{4} \frac{g^2 s w^2}{c_w} Z^0_\mu [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \frac{1}{4} \frac{g^2 s w^2}{c_w} Z^0_\mu [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \frac{1}{4} g^2 s w^2 Z^0_\mu \phi^0 (\phi^+ \phi^- + W^\mu_+ W^-_\mu)
\[-\frac{1}{2} \frac{g^2 s w^2}{c_w} Z^0_\mu H (W^\mu_+ \phi^- - W^-_\mu \phi^+)] + \frac{1}{2} g^2 s w A_\mu \phi^0 W^\mu_+ \phi^+ + \frac{1}{2} g^2 s w A_\mu H (W^\mu_+ \phi^- - W^-_\mu \phi^+) + g^2 s w (2 c_w - 1) Z^0_\mu A_\mu \phi^+ \phi^-
\[-g^2 s w A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_\mu e^\lambda) e^\lambda - \bar{e}^\lambda \gamma \partial \nu \lambda - \bar{u}^\lambda (\gamma \partial + m_\mu u^\lambda) u^\lambda - \bar{d}^\lambda (\gamma \partial + m_\mu d^\lambda) d^\lambda + ig_{sw} A_\mu [- (\bar{e}^\lambda \gamma \mu e^\lambda) + \bar{u}^\lambda (\gamma \mu u^\lambda) - \frac{1}{3} (\bar{d}^\lambda \gamma \mu d^\lambda)]
\[+ \frac{1}{2} i g_{sw}^2 Z^0_\mu [(\bar{e}^\lambda \gamma \mu (1 + \gamma^\mu) e^\lambda) + (\bar{e}^\lambda \gamma \mu (4 s_w - 1 - \gamma^5) e^\lambda)] + (\bar{u}^\lambda \gamma ^\mu (\frac{4}{3} s_w - 1 - \gamma^5) u^\lambda) + (\bar{d}^\lambda \gamma ^\mu (1 - \frac{8}{3} s_w - 5 d^\lambda)]
\[+ \frac{1}{2} i g_{sw}^2 W^\mu_+ [(\bar{e}^\lambda \gamma \mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda \gamma ^\mu (1 + \gamma^5) u^\lambda) + (\bar{d}^\lambda \gamma ^\mu (1 + \gamma^5) u^\lambda)]
\[+ \frac{1}{2} i g_{sw}^2 M \left[ - \phi^+ (\bar{v}^\lambda (1 - \gamma^\mu) + \phi^- (\bar{v}^\lambda (1 - \gamma^\mu)) \right] - \frac{g m^\lambda_\mu}{2 M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma \mu e^\lambda)] + \frac{ig}{2 M \nu^2} \phi^+ [- m_\mu (\bar{u}^\lambda C_\lambda \gamma (1 - \gamma^5) u^\lambda) + m_\mu (\bar{u}^\lambda C_\lambda \gamma (1 - \gamma^5) d^\lambda)]
\[+ \frac{ig}{2 M \nu^2} \phi^+ [m_\mu (\bar{d}^\lambda C_\lambda \gamma (1 + \gamma^5) u^\lambda) - m_\mu (\bar{d}^\lambda C_\lambda \gamma (1 - \gamma^5) u^\lambda)] - \frac{g m^\lambda_\mu}{2 M} [H (\bar{u}^\lambda u^\lambda) - \frac{g m^\lambda_\mu}{2 M} [H (\bar{d}^\lambda d^\lambda) + \frac{g m^\lambda_\mu}{2 M} \phi^0 (\bar{u}^\lambda \gamma ^\mu u^\lambda) + \frac{ig}{2 M \nu^2} \phi^0 (\bar{d}^\lambda \gamma ^5 d^\lambda)]]
\[+ \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} (\partial^2 - \frac{M^2}{c_w^2}) Y + ig_{cw} W^\mu_+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0)
\[+ ig_{sw} W^\mu_+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + ig_{cw} W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^-) + ig_{sw} W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^-) + ig_{cw} Z^0_\mu (\partial_\mu \bar{X}^+ X^0 - \partial_\mu \bar{X}^- X^-)
\[+ ig_{sw} A_\mu (\partial_\mu \bar{X}^+ + \partial_\mu \bar{X}^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{2} \bar{X}^0 X^0 H] + \frac{1}{2} \frac{c_w}{2} [1 + \frac{2 s_w}{c_w} i g M [\bar{X}^0 X^0 \phi^+ - \bar{X}^- X^- \phi^-] + \frac{1}{2} \frac{c_w}{2} ig M [\bar{X}^+ X^+ \phi^+ - \bar{X}^- X^- \phi^-]]
Theory of strong interactions
Key questions

- How do the quarks and gluons carry the spin of protons?
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- What is the detailed partonic structure of the nucleons?
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- What is the detailed partonic structure of the nucleons?
- How does confinement work?

To answer these questions we need to look inside the hadrons
How to zoom in

Chloroplast Cells

$10^{-6} \text{m}$

Microscope
How to zoom in

Chloroplast Cells

Fructose

$10^{-6}$m

$10^{-9}$m

Microscope

Mass Spectrometer
How to zoom in

Chloroplast Cells

Fructose

Hadron

$10^{-6}_m$

$10^{-9}_m$

$10^{-15}_m$

Microscope

Mass Spectrometer

Particle accelerators
An example of a scattering experiment
Deep inelastic scattering (DIS) at HERA

1992-2007

DESY UND HERA
ep-Collider im Herzen von Hamburg

Umfang 6.3 km
$E_e = 27.5$ GeV
$E_p = 920$ GeV
A DIS event: $e^+P \rightarrow e^+X$

ATTENTION: this is just a single event!

\[ Q^2 = 25030 \text{ GeV}^2, \ y = 0.56, \ M = 211 \text{ GeV} \]
A DIS event: $e^+ P \rightarrow \nu + X$

ATTENTION: this is just a single event!

Hadrons $X$

$e^+$

$P$

$\nu$

$X$
Gauge bosons ($\gamma, Z, W^\pm$) as probes

\[ Q^2 = 25030 \text{GeV}^2 \]

\[ Q^2 = 20000 \text{GeV}^2 \]

- \[ Q^2 \equiv -q^2 \]
- Bosons propagation length $\sim 1/Q$
- Proton radius $\sim 0.84$ fm
- $1 \text{ GeV}^{-1} \sim 0.2$ fm $= 0.2 \times 10^{-15}$ m
- Interaction range $\ll 10^{-15}$ m
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- Interaction range \(\ll 10^{-15}\) m
How small is $1 \text{ fm} = 10^{-15} \text{ m}$?

$L_{\text{int}} \sim 10^{-15} \text{ m}$

$L_{\text{det}} \sim 10 \text{ m}$
How small is $1 \text{ fm} = 10^{-15} \text{ m}$?

$L_{\text{int}} \sim 10^{-15} \text{ m}$

$L_{\text{det}} \sim 10 \text{ m}$

$L_{\text{Earth}} \sim 10^7 \text{ m}$

$L_X \sim 10^{25} \text{ m}$

- $L_X = (L_{\text{det}}/L_{\text{int}})L_{\text{Earth}} \sim 10^9 \text{ ly}$
- Diameter of Milky Way $\sim 10^5 \text{ ly}$
- Distance to Andromeda $\sim 10^6 \text{ ly}$
- High energy experiments allows one to resolve the inner structure of protons from far away detectors
How do we describe the data?
Events and cross sections

\[ \frac{dN}{d\Omega} = \mathcal{L} \frac{d\sigma}{d\Omega} \]

- Number of events
- Integrated Luminosity
- Differential cross section
- Phase space volume
Events and cross sections

\[
\frac{dN}{d\Omega} = L \frac{d\sigma}{d\Omega}
\]

Number of events

Integrated Luminosity

Differential cross section

Phase space volume

i.e. \( d\Omega = d\phi d\eta \)
Events and cross sections

\[ \frac{dN}{d\Omega} = L \frac{d\sigma}{d\Omega} \]

- Number of events
- Integrated Luminosity
- Differential cross section
- Phase space volume

\[ d\Omega = d\phi d\eta \]

Calculable using QCD
Events and cross sections

\[ \frac{dN}{d\Omega} = \int \frac{d\sigma}{d\Omega} \, d\Omega \]

Number of events

Integrated Luminosity

Differential cross section

Phase space volume

i.e. \( d\Omega = d\phi d\eta \)

The events can be separated into subprocesses

\[ \frac{dN}{d\Omega} = \frac{dN(e^+ P \rightarrow e^+ X)}{d\Omega} + \frac{dN(e^+ P \rightarrow \nu X)}{d\Omega} + \ldots \]

\[ \frac{d\sigma}{d\Omega} = \frac{d\sigma(e^+ P \rightarrow e^+ X)}{d\Omega} + \frac{d\sigma(e^+ P \rightarrow \nu X)}{d\Omega} + \ldots \]

Calculable using QCD
Theoretical cross sections

\[ d\sigma = \frac{1}{\text{flux}} |\Psi|^2 d\Omega \]
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Theoretical cross sections

$$d\sigma = \frac{1}{\text{flux}} |\Psi|^2 d\Omega$$

- The upper part of the diagram can be calculated using QED
- The lower part is more complicated → Factorization
Factorization in inclusive DIS

The lower blob represents a collection of Feynman diagrams

It is possible to identify the most relevant contributions to the blob classifying them into different regions (Libby-Sterman). Using kinematic approximations one can disentangle the various regions assuming $Q^2 = -q^2$ is large.
The lower blob represents a collection of Feynman diagrams.

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Schematically

$$d\sigma \sim |H|^2 \int dk^- dk_\perp L(xP^+, k^-, k_\perp) \int dl^+ U(l^+) d\Omega$$

- **Hard**
- **Parton densities**
- **Jet function**
Additional information about the lower blob can be accessed by measuring hadrons in the final state (i.e., flavor separation, intrinsic transverse momentum)
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The upper blob along with tagged hadrons characterizes formation of hadrons from partons.
Factorization in SIDIS

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Additional information about the lower blob can be accessed by measuring hadrons in the final state (i.e., flavor separation, intrinsic transverse momentum). The upper blob along with tagged hadrons characterizes the formation of hadrons from partons. Factorization of these regions assumes large $Q^2 = -q^2$.

Schematically:

$$d\sigma \sim |H|^2 \int dk^- dk^\perp L(xP^+, k^-, k^\perp) \int dk_h^+ dk_h^\perp U(k_h^+, zP_h^-, k_h^\perp) d\Omega$$

- **Hard**:
  - $L(xP^+, k^-, k^\perp)$
- **Parton densities**:
  - $U(k_h^+, zP_h^-, k_h^\perp)$
- **Fragmentation function**:
  - $d\sigma$
Extensions to hadron-hadron collisions
Extend the formalism to hadron-hadron collisions
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Extend the formalism to hadron-hadron collisions

\[ d\sigma \sim |H|^2 \int dk^- dk_\perp L(x_a P_A^+, k^-, k_\perp) \int dl^- dl_\perp U(x_b P_B^+, l^-, l_\perp) \, d\Omega \]

Schematically
Example: The LHC and the Higgs
Example: The LHC and the Higgs
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Example: The LHC and the Higgs

\[ g \rightarrow h \rightarrow Z \rightarrow \mu \rightarrow \mu \rightarrow e^+ \rightarrow e^- \rightarrow g \]
The LHC and the Higgs $P, P \rightarrow h \rightarrow ZZ \rightarrow \nu \bar{\nu}, e^+e^-$
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The parton densities and nucleon structure

- Factorization allows us to characterize nucleon structure

\[ f(x) = \int dk^- dk^\perp L(xP^+, k^-, k^\perp) \]

\( f(x) \): Probability of finding a quark/gluon with momentum fraction \( x = k^+/P \)
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\[ f(x) : \text{Probability of finding a quark/gluon with momentum fraction } x = k^+/P \]
**PDFs and LHC**

**H → ZZ**

*Systematics*

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<td>VBF tagging efficiency (experimental)</td>
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The parton densities and nucleon structure

- Helicity distributions

\[ f(x) = f^\uparrow(x) + f^\downarrow(x) \]

\[ \Delta f(x) = f^\uparrow(x) - f^\downarrow(x) \]
The parton densities and nucleon structure

- Helicity distributions

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- Spin of the proton

\[ \frac{1}{2} = \int_0^1 dx \left( \frac{1}{2} \Delta \Sigma(x) + \Delta g(x) \right) + \mathcal{L} \]
The parton densities and nucleon structure

- Helicity distributions
  \[ f(x) = f^{\uparrow}(x) + f^{\downarrow}(x) \]
  \[ \Delta f(x) = f^{\uparrow}(x) - f^{\downarrow}(x) \]

- Spin of the proton
  \[
  \frac{1}{2} = \int_0^1 dx \left( \frac{1}{2} \Delta \Sigma(x) + \Delta g(x) \right) + \mathcal{L}
  \]

- From existing analysis
  - \( \Delta \Sigma^{(1)} = 0.28 \pm 0.04 \)
  - \( \Delta g^{(1)} = 1 \pm 15 \)
Fragmentation functions

- Factorization allows us to characterize nucleon structure

\[ D(z) = \int dk_h^+ dk_{h}^\perp U(k_h^+, zk_h^-, k_{h}^\perp) \]

\( D(z) \): Probability of finding a hadron from quark with momentum fraction \( z = P_h^- / k^- \)
\[ \pi \text{ analysis} \quad (\chi^2 / N_{\text{npts}} = 1.31) \]

- \( z_{\text{cut}} > 0.1 \) for low energies
- \( z_{\text{cut}} > 0.05 \) for high energies
- We use BaBar prompt data set
- Belle data set needs 10\% normalization
- Good agreement at low--\( z \) for inclusive data sets
- Data inconsistencies at large--\( z \) for \( Q^2 = \frac{M^2}{z} \)
$K$ analysis \hspace{1cm} ($\chi^2/N_{\text{npts}} = 1.01$)

- $z_{\text{cut}} > 0.2$ for low energies to avoid hadron mass corrections
- $z_{\text{cut}} > 0.05$ for high energies
- Smaller $\chi^2$ that $\pi$ due to larger errors
- Consistent shapes across all $z$
- Inconsistencies mostly due to normalizations
The collinear master plan

- Extract reliable collinear polarized and unpolarized parton distribution functions (PDFs) and fragmentation functions (FFs)

- Improvements in fitting methodology: Iterative Monte Carlo

- Reliable description of $q_T$ integrated SIDIS data.
PDF/HT

DIS \( (q + \bar{q}) \)

DY \( (q, \bar{q}) \)

JETS \( (g) \)

W_{ASY} \( (u, d) \)

pp \( \rightarrow \gamma X \) \( (g) \)

ΔPDF/HT

ΔDIS \( (q + \bar{q}) \)

ΔSIDIS \( (q, \bar{q}) \)

ΔJETS \( (g) \)

W_{ASY} \( (u, d) \)

ΔW_{ASY} \( (u, d) \)

\( \bar{p}p \rightarrow \pi X \)

FF

D_{q}^{\pi,K}

SIA \( (q + \bar{q}) \)

SIDIS \( (q, \bar{q}) \)

pp \( \rightarrow \pi X \)
Milestones

- Global analysis of all inclusive polarized DIS data

  Iterative Monte Carlo analysis of spin-dependent parton distributions

  Nobuo Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, and A. Accardi

  (Jefferson Lab Angular Momentum Collaboration)
Milestones

- Global analysis of all inclusive polarized DIS data
  
  **Iterative Monte Carlo analysis of spin-dependent parton distributions**
  
  Nobuo Sato,¹ W. Melnitchouk,¹ S. E. Kuhn,² J. J. Ethier,³ and A. Accardi⁴,†
  
  (Jefferson Lab Angular Momentum Collaboration)

- Global analysis of all SIA data
  
  **First Monte Carlo analysis of fragmentation functions from single-inclusive $e^+e^-$ annihilation**
  
  Nobuo Sato,¹ J. J. Ethier,² W. Melnitchouk,¹ M. Hirai,³ S. Kumano,⁴,⁵ and A. Accardi¹,⁶
  
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- Invited talk in FCCee workshop

  **Parton Radiation and Fragmentation from LHC to FCC-ee**


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  S. Jadach (IFJ-PAN Krakow), T. Kaufmann (U. Tübingen), S. Kluth (T.U. München),
Summary and outlook

- Factorization is a powerful framework to study nucleon structure.
Summary and outlook

- Factorization is a powerful framework to study nucleon structure.
- It allows to separate short distance scales from the long distance scales so that nonperturbative scales can be studied.

- Reliable extractions of nucleon structures depend on how good is the factorization framework and the fitting methodology.
- Parton distributions are universal and they play an important role for LHC physics.
- JLab 12 has just started and the new theoretical and analysis innovations will allow the nucleon's quark structure to be revealed in unprecedented detail.
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