The Electron-Ion Collider

A new facility enables “tomography” of nucleons and nuclei

Acknowledgement: Some of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …
The Electron-Ion Collider
A machine that will unlock the secrets of the strongest force in Nature

What we learn from EIC will open a new frontier in physics and power the technologies of tomorrow.
Frontiers of QCD and Strong Interaction

- Understanding where did we come from?
  
  QCD at high temperature, high densities, phase transition, ...
  
  Facilities – Relativistic heavy ion collisions: SPS, RHIC, the LHC, ...

- Understanding the visible world at 3ºK – what are we made of?

  How did hadrons are emerged from quarks and gluons?
  
  What is the internal structure of hadrons?
  
  How does the glue bind us all?

  Facilities – CEBAF, EIC, ...

  Nuclear Femtography:
  Search for answers to these questions at a Fermi scale!
Outline of my talk

- From atomic structure to hadron structure:
  - From nano-science to femto-science – a quantum jump!
  - Nano: electromagnetism, quantum physics, ...
  - Femto: quantum fluctuation, asymptotic freedom, confinement, ...

- Great intellectual challenges for Nuclear Femtography
  - Probing quarks and gluons & exploring their interactions without being able to “see” them – color confinement!

- What is an Electron-Ion Collider (EIC)?
  - JLab12 – a prerequisite of EIC
  - US EIC – two options of realization

- What an EIC can do and why other machine cannot do?
  - Major Nuclear Science issues to be studied at an EIC
  - EIC is an international effort

- Summary and outlook
Atomic structure

- Structure – “a still picture”
  - Crystal Structure:
    - NaCl, B1 type structure
    - FeS2, C2, pyrite type structure
  - Nano-material:
    - Fullerene, C60

Motion of nuclei is much slower than the speed of light!

- Atomic structure: dating back to Rutherford’s experiment:
  - Experiment: \( \alpha + Au \rightarrow \alpha + X \)
  - Theory: Quantum orbitals

Discovery: ✿ Tiny nucleus – less than 1 trillionth in volume of an atom
✿ Quantum probability – the Quantum World!

Infinite opportunities to create & improve … !
A modern “Rutherford” experiment (about 50 years ago):

Nucleon: The building unit of all atomic nuclei

\[ e + p \rightarrow e + X \]

Discovery:

- Partons/Quarks – moving relativistically
- Quantum fluctuation – parton number is not fixed!

NO “still picture” for hadron’s partonic structure!

For the atomic world:

Birth of Quantum Chromodynamics (QCD) – gluons & color force!
Unprecedented intellectual challenge!

- The challenge:
  - How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, ..., if we cannot see quarks and gluons?
  - Gluons are bark, but, carry color!

- NO separation between color charges! Color is fully entangled!

- The “helper” – QCD Asymptotic Freedom:
  - Interaction strength: Nobel Prize, 2004
  \[ \alpha_s(\mu_2) = \frac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi} \alpha_s(\mu_1) \ln \left( \frac{\mu_2^2}{\mu_1^2} \right)} \equiv \frac{4\pi}{-\beta_1 \ln \left( \frac{\mu_2^2}{\Lambda_{QCD}^2} \right)} \]

Controllable perturbative QCD calculations at HIGH ENERGY!
Unprecedented intellectual challenge!

The challenge:

✧ How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, ..., if we cannot see quarks and gluons?

✧ Gluons are bark, but, carry color!

NO separation between color charges! Color is fully entangled!

The need – “hard/controllable” probe to “see” quarks and gluons:

\[ B^+ (u\bar{b}) \]

Brown-Muck

\[ \text{Boost} = \text{time dilation} \]

\[ k = x P \]

Hard probe \((t \sim 1/Q << fm)\) ➔ Probability to “catch” the parton!

Feynman:

or “catch” the quantum fluctuation

At \(t \sim 1/Q << fm\), the probe is only sensitive to the momentum fraction of the probed quark (or gluon) \(xP \sim Q\) and the probability \(f(x)\)
The challenge:

- How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, ..., if we cannot see quarks and gluons?

- Gluons are bark, but, carry color!

NO separation between color charges! Color is fully entangled!

The need – quantify the hadron’s partonic structure:

\[ \sigma_{\text{DIS}}(x, Q^2) = \left| \right|^2 \approx \left| \right|^2 \]

\[ e^- + p \rightarrow e^- + X \]

NO “still picture” for hadron structure!
Unprecedented success of QCD and SM!

SM: Electroweak processes + QCD perturbation theory works!
From nano-science to femto-science

- The idea:
  - Color Confinement
  - Asymptotic freedom

- QCD landscape of nucleons and nuclei:
  - Nano-science (1-100 nm)
  - Femto-science (0.1-10 fm)

- Quantum Probability:
  \[ \langle P, S | O(\psi, A^\mu, ...) | P, S \rangle \]
  \[ f_{q/p}(x, k_T; \mu^2) \]
  \[ H_{q/p}(x, \xi, t; \mu) \]

- QCD at the Fermi Scale: Femto-science (0.1-10 fm)
  - The most interesting, rich, and complex regime of the theory!
  - All emergent phenomena depend on the scale at which we probe them!

Need new facility capable of exploring this!
Why do we need a lepton-hadron facility?

- Hadrons are produced from the energy in e+e- collisions:
  - No hadron to start with
  - Emergence of hadrons

- Hadrons are produced in hadron-hadron collisions:
  - Partonic structure
  - Emergence of hadrons
  - Heavy ion target or beam(s)

- Hadrons are produced in lepton-hadron collisions:
  - Colliding hadron can be broken or stay intact!
  - Imaging partonic structure
  - Emergence of hadrons
  - Heavy ion target or beam

One facility covers all!
Lepton-hadron facility in the US now:

12 GeV CEBAF Upgrade Project was just complete, on-time and on-budget!

- Search for exotic hadrons, …
- Explore for 3D hadron structure, …
- Search for dark matter, photon, …
- Advance accelerator technology, …
- …

Highest luminosity ever achieved by a lepton-hadron facility
$10^{38}$ (cm$^{-2}$ s$^{-1}$)
A long journey, a joint effort of the full community:

… answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics.”

... three profound questions:
How does the mass of the nucleon arise?
How does the spin of the nucleon arise?
What are the emergent properties of dense systems of gluons?

On January 9, 2020:

The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider

A new era to explore the emergent phenomena of QCD!
The winning design - BNL:

- **Center of Mass Energies:**
  
  \[ 20 \text{ GeV} - 141 \text{ GeV} \]

- **Required Luminosity:**
  
  \[ 10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

- **Hadron Beam Polarization:**
  
  80%

- **Electron Beam Polarization:**
  
  80%

- **Ion Species Range:**
  
  *p to Uranium*

- **Number of interaction regions:**
  
  up to two
U.S. - based Electron-Ion Collider

The winning design - BNL:

July, 2021:
The U.S. DOE granted Critical Decision 1 (CD-1) for the EIC – start of project execution phase
The Electron-Ion Collider (EIC) – the Future!

- **A sharpest “CT”** – “imagine” quark/gluon structure without breaking the hadron
  - “cat-scan” the nucleon and nuclei with a better than 1/10 fm resolution
  - “see” proton “radius” of quark/gluon density comparing with the radius of EM charge density

  To discover color confining radius, hints on confining mechanism!

- **A giant “Microscope”** – “see” quarks and gluons by breaking the hadron

  To discover/study color entanglement of the non-linear dynamics of the glue!
US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - HERA discovered: 15% of e-p events is diffractive – Proton not broken!
  - US-EIC: 100-1000 times luminosity – Critical for 3D tomography!

- **Quantum interference & entanglement:**
  - US-EIC: Highly polarized beams – Origin of hadron property: Spin, … Direct access to chromo-quantum interference!

- **Nonlinear quantum dynamics:**
  - US-EIC: Light-to-heavy nuclear beams – Origin of nuclear force, … Catch the transition from chromo-quantum fluctuation to chromo-condensate of gluons, …
    - Emergence of hadrons (femtometer size detector!), – “a new controllable knob” – Atomic weight of nuclei
Why existing facilities, even with upgrades, cannot do the same?

- Emergence of hadrons
- Hadron properties: mass, spin, …
- Hadron’s 3D partonic structure: confined motion, spatial distribution, color correlation, fluctuation, saturation, …
- Quantum correlation between hadron properties and parton dynamics, …

…

Due to the time, only a few examples to be presented in this talk!
Emergence of Hadrons from quarks & gluons

- Femtometer sized detector:

  \[ \nu = \frac{Q^2}{2mx} \]

  Control of \( \nu \) and medium length!

- Mass dependence of hadronization

- Heavy quark energy loss:

Need the collider energy of EIC and its control on parton kinematics
How does the mass of the nucleon arise?

- **Nucleon Mass** – dominates the Mass of visible world!

  Nucleon – a relativistic bound state of quarks and gluons
  Mass is the **Energy** of the nucleon when it is at the **Rest**!
  Mass = Rest Mass of quarks and gluons + Their Energy

- **Higgs mechanism** is NOT enough – **mass without mass**!

  *Higgs mechanism is far from enough!!!*

- **Consistency check:**

  **Bag model:**
  - **Kinetic energy** of three quarks: $K_q \sim 3/R$
  - **Bag energy** (bag constant $B$): $T_b = \frac{4}{3} \pi R^3 B$
  - **Minimize** $K + T$:

    $$M_p \sim \frac{4}{R} \sim \frac{4}{0.84\text{fm}} \sim 938 \text{ MeV}$$

  ![Bag model diagram](image-url)
Who ordered the hadron mass scale?

- Hadron mass from lattice QCD calculation:

QCD is the right theory!
How to quantify and verify this, theoretically and experimentally?
### The Proton Mass: Decomposition

- **Role of quarks and gluons?**
  - Trace of the QCD energy-momentum tensor:
    \[
    T^\alpha = \frac{\beta(g)}{2g} F^\mu\nu,\alpha F^\alpha_{\mu\nu} + \sum_{q=u,d,s} m_q (1 + \gamma_m) \bar{\psi}_q \psi_q \quad \Rightarrow \quad M_p^2 \propto \langle P | T^\alpha | P \rangle
    \]
    - QCD trace anomaly
    - Chiral symmetry breaking

- **Hadron mass:** *Gluon quantum effect + Chiral symmetry breaking!*

- **Decomposition or sum rules – could be frame dependent!**
  - Relativistic motion
  - $\chi$ Symmetry Breaking
  - Quantum fluctuation
  - Trace Anomaly

  **Sum Rule is useful iff ALL individual terms can be measured independently!**

- **Critical measurement:**
  - Probing Trace anomaly:
    - Probe parton’s energy distribution inside the proton?
Three-pronged approach to explore the origin of hadron mass

- Lattice QCD
- Mass decomposition – roles of the constituents
- Model calculation – approximated analytical approach

INT workshop (INT-20-77W):
Origin of the Visible Universe: Unraveling the Proton Mass
June 13-17, 2022,
I. Cloet, Z.-E. Meziani, B. Pasquini

14-16 January 2021, Argonne National Lab
How does the spin of the nucleon arise?

- **Nucleon Spin** – without it, our visible world would not be the same!
  
  Spin is the **Angular Momentum** of the nucleon when it is at the Rest!
  
  Spin = Spin of quarks and gluons + Orbital Angular Momentum
  
  Helicity = Helicity of quarks and gluons + Their transverse motion

- **An incomplete story:**

  Proton Spin

  \[
  \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g)
  \]

  - **Quark helicity**
    Best known

  \[
  \frac{1}{2} \int dx \left( \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right)
  \sim 30\%
  \]

  - **Gluon helicity**
    Start to know

  \[
  \Delta G = \int dx \Delta g(x)
  \sim 40\% \text{(with RHIC data)}
  \]

  - **Net effect of partons’ transverse motion?**

  Orbital Angular Momentum of quarks and gluons
  Little known
The Proton Spin: from JLab12 to EIC

- **The power & precision of EIC:**

- **What an EIC could help:**

![Diagram showing polarized DIS at EIC](image-url)
The Proton Spin: from JLab12 to EIC

- Complementary between JLab12 and EIC – White Paper:

- What the EIC could do/help – EIC Yellow Report:

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Room for orbital momentum
Hadron’s 3D partonic structure

- Single scale hard probe is too “localized”:
  - It pins down the particle nature of quarks and gluons
  - But, not very sensitive to the detailed structure of hadron ~ fm
  - Transverse confined motion: \( k_T \sim 1/\text{fm} \ll Q \)
  - Transverse spatial position: \( b_T \sim \text{fm} \gg 1/Q \)

- Cross sections with two-momentum scales observed:
  \[
  Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\text{QCD}}
  \]
  - Hard scale: \( Q_1 \) To localize the probe particle nature of quarks/gluons
  - “Soft” scale: \( Q_2 \) could be more sensitive to the hadron structure ~ 1/fm

Hit the hadron “very hard” without breaking it, clean information on the structure!
Hadron’s 3D partonic structure

- **Two-scale observables are natural in lepton-hadron scattering**
  - A controlled “probe” – virtual photon
  - Can either break or not break the hadron
    \[ Q^2 = -q^2 \]

- **Inclusive events:** \( e+p/A \rightarrow e'+X \) (Single scale \( Q \gg \Lambda_{QCD} \))
  - Detect only the scattered lepton in the detector
    (Modern Rutherford experiment!)

- **Semi-Inclusive events:** \( e+p/A \rightarrow e'+h(p,K,p,\text{jet})+X \) \( Q \gg P_{hT} \)
  - Detect the scattered lepton along with identified hadrons/jets
    (Initial hadron is broken – confined motion! – cleaner than h-h collisions)

- **Exclusive events:** \( e+p/A \rightarrow e'+p'/A'+ h(p,K,p,\text{jet}) \) \( Q \gg \sqrt{-t} \)
  - Detect every things including scattered proton/nucleus (hadron is NOT broken – tomography! – almost impossible for h-h collisions)
Theory is solid – A unified description

- Wigner distributions in 5D (or GTMDs):

\[
\int d^2b_T \quad \text{Momentum Space} \quad \int d^2k_T \quad \text{Coordinate Space}
\]

\[
\text{TMDs} \quad \text{GPDs}
\]

\[
f(x,k_T) \quad \text{Confined motion} \quad f(x,b_T) \quad \text{Spatial distribution}
\]

- TMDs & SIDIS as an example:

- **Low** \( P_{hT} \ (P_{hT} \ll Q) \) – TMD factorization:

\[
\sigma_{\text{SIDIS}}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q) \otimes \Phi_f(x, k_{\perp}) \otimes D_{f \rightarrow h}(z, p_{\perp}) \otimes S(k_{s\perp}) + O\left[\frac{P_{h\perp}}{Q}\right]
\]

- **High** \( P_{hT} \ (P_{hT} \sim Q) \) – Collinear factorization:

\[
\sigma_{\text{SIDIS}}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f \rightarrow h} + O\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)
\]

- **\( P_{hT} \) Integrated - Collinear factorization**:

\[
\sigma_{\text{SIDIS}}(Q, x_B, z_h) = \hat{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f \rightarrow h} + O\left(\frac{1}{Q}\right)
\]

- **Very high** \( P_{hT} \gg Q \) – Collinear factorization:

\[
\sigma_{\text{SIDIS}}(Q, P_{h\perp}, x_B, z_h) = \sum_{abc} \hat{H}_{ab \rightarrow c} \otimes \phi_{\gamma \rightarrow a} \otimes \phi_b \otimes D_{c \rightarrow h} + O\left(\frac{1}{Q}, \frac{Q}{P_{h\perp}}\right)
\]
Explore the Flavor-Spin-Motion Correlation

- **Quark TMDs with polarization:**

<table>
<thead>
<tr>
<th>Nuclear Polarization</th>
<th>Quark Polarization</th>
<th>Longitudinally Polarized (L)</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1(x, k_T^2)$</td>
<td>$h_{1L}^T(x, k_T^2)$</td>
<td>Boer-Mulders</td>
</tr>
<tr>
<td>L</td>
<td>$g_1(x, k_T^2)$</td>
<td>$h_{1T}^L(x, k_T^2)$</td>
<td>Long-Transversity</td>
</tr>
<tr>
<td>T</td>
<td>$f_1^T(x, k_T^2)$</td>
<td>$g_{1T}(x, k_T^2)$</td>
<td>Trans-Helicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$h_1^T(x, k_T^2)$</td>
<td>Pretzelosity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$h_{1T}^T(x, k_T^2)$</td>
<td></td>
</tr>
</tbody>
</table>

- **Semi-Inclusive DIS (SIDIS):**

\[
e(l) + N(P, \uparrow) \rightarrow e(l') + h(P_h) + X
\]

In photon-hadron frame:

- **Collins Asymmetry**
  \[ A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^T \]
- **Sivers Asymmetry**
  \[ A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^T \otimes D_1 \]
- **Pretzelosity Asymmetry**
  \[ A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T} \otimes H_1^T \]

Angular modulation provides the best way to separate TMDs
Explore the Flavor-Spin-Motion Correlation

- **Intrinsic & confined parton motion:**
  - Fundamental information sensitive to how partons are bound together
  - Responsible for dynamical contribution to emergent hadron properties, such as spin, mass, ..

- **Quantum correlation between hadron spin and parton motion:**
  - Sivers effect – Sivers function
  - Hadron spin influences parton’s transverse motion

- **Quantum correlation between parton’s spin and its hadronization:**
  - Collins effect – Collins function
  - Parton’s transverse polarization influences its hadronization

Fig. 2.7 NAS Report
How to explore hadron’s spatial tomography?

- How Color Charge is distributed inside a nucleon (clue for color confinement?)

  Elastic electric form factor → Charge distributions

  ![Graph showing charge distributions for protons and neutrons.]

- But, there is NO elastic “color” form factor!

  Generalized form factor for quarks and gluons

  Generalized PDFs (GPDs) – without breaking the proton

  \[ f_{q/h}(x, \xi, t) \]

  skewness \[ \xi = \frac{(P - P')^+}{(P + P')^+} \]

- Two-scale observables for extracting GPDs:

  DVCS: \( Q^2 >> |t| \)
  DVMP
  DVHQ

  \[ Q^2 \equiv -q^2 \]
  \[ t = (p - p')^2 \]
  \[ Q^2 \gg |t| \]
Gluon GPD: Spatial imaging of gluon density

- "Seeing" the glue at EIC:

  - $J/\psi, \Phi, \ldots$
  - $d\sigma/dQ^2d\xi dt$
  - $t$-dep

- How fast does glue density fall?

- How far does glue density spread?

- Proton radius of gluons ($x$)!

- Proton radius

- Factorization $Q^2 \gg |t|

- GPDs: $f_i/h(x, \xi, t; \mu)$

- F.T. $t_T$ to $b_T$

- at $\xi \propto (p - p')^+ \rightarrow 0$
Gluon GPD: Spatial imaging of gluon density

“Seeing” the glue at EIC:

$J/\psi, \Phi, \ldots$

Factorization

$$Q^2 \gg |t|$$

GPDs:

$$f_i/n(x, \xi, t; \mu)$$

F.T. $t_T$ to $b_T$

at $\xi \propto (p - p')^+ \to 0$

Proton radii of quark and gluon spatial distribution, $r_q(x) \& r_g(x)$

Should $r_q(x) > r_g(x)$, or vice versa?

Could $r_g(x)$ saturates as $x \to 0$?

How do they compare with the “known” proton radius (EM charge)? … …

How fast does glue density fall?

How far does glue density spread?

Proton radius of gluons ($x$)!
Emergent properties of dense systems of gluons?

- Understanding the Glue that binds us all:
  - Gluons are weird particles!
    - Massless, yet, responsible for a lot of visible mass
    - Carry color charge, unlike photon, responsible for color confinement but, also for asymptotic freedom, as well as the abundance of glue!

Without gluons, there would be
NO nucleons, NO atomic nuclei...
NO visible world!

- What are the emergent properties of dense systems of gluons?
- What does a nucleus look like if we only see quarks and gluons?
- What is the coherent length of color force? ...
Emergent properties of dense systems of gluons?

- Run away gluon density at small-\(x\)?
  
  No! QCD dynamics does not allow:

  What are the emergent properties of dense systems of gluons, when the occupation number is \(\sim O(1)\)?

- Color entanglement enhanced at small-\(x\):

  
  - Color entangled or correlated between two active partons

  \[
  \sigma_{\text{DIS tot}} \sim \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O} \left( \frac{Q_s^2}{Q^2} \right) + \mathcal{O} \left( \frac{Q_s^4}{Q^4} \right) + \ldots
  \]

- Saturation:

  Counting single parton is meaningless if every term is equally important!

  Color Glass Condensate (CGC) (An EFT of QCD)

  The phenomenon is a part of QCD, where to find it?
- **EMC discovery:**
  
  Nuclear landscape
  ≠ Superposition of nucleon landscape

- **Simple, but fundamental, questions:**
  
  ✴ What does a nucleus look like *if we only see quarks and gluons*?

  ✴ Does the color of nucleon “A” know the color of nucleon “B”?

  *IF YES,* Nucleus could act like a bigger proton at small-x, and could reaching the saturation much sooner!

  *IF NOT,* Observed nuclear effect in cross-section is a coherent collision effect

  *EIC can tell!*
A simple experiment to address a “simple” question:
Will the EMC suppression/shadowing continue to fall as x decreases?

Color localized
Inside nucleons

Nucleus as a bigger proton

Color leaks outside nucleons
Proton radius of soft gluon is larger!

EIC can tell!
US EIC – An International Effort

- EIC Users Group – EICUG.ORG:
  >1100 collaborators, 30 countries,
  205 institutions ... (since 2016 & growing)
  (no students included yet!)

Map of institutions’ locations
QCD has been very successful in describing the short-distance dynamics owing to its “Asymptotic Freedom”, a defining property of QCD.

QCD’s another defining property, “Confinement”, makes the QCD and its emergent phenomena extremely rich, opening up a new femto-science.

EIC is a ultimate QCD machine and a facility, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue.

US-EIC is sitting at a sweet spot for rich QCD dynamics, capable of taking us to the next frontier of Nuclear Science!

Thanks!

To understand the hadrons, spectroscopy and structure, in the most fundamental way!

The total project cost is expected to range from $1.7-2.8 billion.
Quantum Chromo-dynamics (QCD)

= A quantum field theory of quarks and gluons =

- **Fields:**
  - **Quark fields:** spin-\(\frac{1}{2}\) Dirac fermion (like electron)
    - Color triplet: \(i = 1, 2, 3 = N_c\)
    - Flavor: \(f = u, d, s, c, b, t\)
  - **Gluon fields:** spin-1 vector field (like photon)
    - Color octet: \(a = 1, 2, ..., 8 = N_c^2 - 1\)

- **QCD Lagrangian density:**
  \[
  \mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[ (i \partial_\mu \delta_{ij} - g A_{\mu,a}(t_a)_{ij}) \gamma^\mu - m_f \delta_{ij} \right] \psi_j^f \\
  - \frac{1}{4} \left[ \partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - g C_{abc} A_{\mu,b} A_{\nu,c} \right]^2 \\
  + \text{gauge fixing + ghost terms}
  \]

- **QED – force to hold atoms together:**
  \[
  \mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}_i^f \left[ (i \partial_\mu - e A_\mu) \gamma^\mu - m_f \right] \psi_j^f - \frac{1}{4} \left[ \partial_\mu A_\nu - \partial_\nu A_\mu \right]^2
  \]

QCD is much richer in dynamics than QED

Gluons interact with themselves, NO quarks and gluons “seen” in isolation!
Unprecedented success of QCD and SM!

Data sets for Global Fits:

<table>
<thead>
<tr>
<th>Process</th>
<th>Subprocess</th>
<th>Partons</th>
<th>x range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ p, n \rightarrow e^+ X$</td>
<td>$\gamma^* g \rightarrow g$</td>
<td>$q, q, g$</td>
<td>$x \gtrsim 0.01$</td>
</tr>
<tr>
<td>$e^+ n / p \rightarrow e^+ X$</td>
<td>$\gamma^* d / u \rightarrow d / u$</td>
<td>$d / u$</td>
<td>$x \gtrsim 0.01$</td>
</tr>
<tr>
<td>$pp \rightarrow \mu^+ \mu^- + X$</td>
<td>$u d, d d \rightarrow \gamma^*$</td>
<td>$q$</td>
<td>$0.015 \lesssim x \lesssim 0.35$</td>
</tr>
<tr>
<td>$pn / pp \rightarrow \mu^+ \mu^- + X$</td>
<td>$(u d)/(u u) \rightarrow \gamma^*$</td>
<td>$d / u$</td>
<td>$0.015 \lesssim x \lesssim 0.35$</td>
</tr>
<tr>
<td>$\nu N \rightarrow \mu^+ (\mu^-) + X$</td>
<td>$W^- q \rightarrow q'$</td>
<td>$q, q$</td>
<td>$0.01 \lesssim x \lesssim 0.5$</td>
</tr>
<tr>
<td>$\nu N \rightarrow \mu^+ \mu^- + X$</td>
<td>$W^- s \rightarrow c$</td>
<td>$s$</td>
<td>$0.01 \lesssim x \lesssim 0.2$</td>
</tr>
<tr>
<td>$\nu N \rightarrow \mu^+ \mu^- + X$</td>
<td>$W^- s \rightarrow c$</td>
<td>$s$</td>
<td>$0.01 \lesssim x \lesssim 0.2$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow e^+ + X$</td>
<td>$\gamma^* g \rightarrow g$</td>
<td>$g, q, q$</td>
<td>$0.0001 \lesssim x \lesssim 0.1$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \nu + X$</td>
<td>$W^+ [d, s] \rightarrow [u, c]$</td>
<td>$d, s$</td>
<td>$x \gtrsim 0.01$</td>
</tr>
<tr>
<td>Collider DIS</td>
<td>$e^+ e^- \rightarrow e^+ e^- + X$</td>
<td>$\gamma^* c \rightarrow c, \gamma^* g \rightarrow c c$</td>
<td>$c, g$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow b b + X$</td>
<td>$\gamma^* b \rightarrow b, \gamma^* g \rightarrow b b$</td>
<td>$b, g$</td>
<td>$10^{-4} \lesssim x \lesssim 0.01$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \nu \nu + X$</td>
<td>$\gamma^* g \rightarrow q q$</td>
<td>$g$</td>
<td>$0.01 \lesssim x \lesssim 0.1$</td>
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</tbody>
</table>

Collider DIS

<table>
<thead>
<tr>
<th>Process</th>
<th>Subprocess</th>
<th>Partons</th>
<th>x range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \mu^+ \mu^- + X$</td>
<td>$g g, q g, q q \rightarrow 2 j$</td>
<td>$g, q$</td>
<td>$0.01 \lesssim x \lesssim 0.5$</td>
</tr>
<tr>
<td>$pp \rightarrow (W^z \rightarrow \mu^+ \nu^-) + X$</td>
<td>$u d \rightarrow W^+, u d \rightarrow W^-$</td>
<td>$u, d, u, d, g$</td>
<td>$x \gtrsim 0.05$</td>
</tr>
<tr>
<td>$pp \rightarrow (Z \rightarrow \mu^+ \mu^-) + X$</td>
<td>$u u, d d \rightarrow Z$</td>
<td>$u, d$</td>
<td>$x \gtrsim 0.05$</td>
</tr>
<tr>
<td>$pp \rightarrow \mu^+ \mu^- + X$</td>
<td>$q q \rightarrow \mu^+ \mu^-$</td>
<td>$q$</td>
<td>$x \gtrsim 0.1$</td>
</tr>
</tbody>
</table>

Tevatron

<table>
<thead>
<tr>
<th>Process</th>
<th>Subprocess</th>
<th>Partons</th>
<th>x range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \mu^+ \mu^- + X$</td>
<td>$g g, q g, q q \rightarrow 2 j$</td>
<td>$g, q$</td>
<td>$0.001 \lesssim x \lesssim 0.5$</td>
</tr>
<tr>
<td>$pp \rightarrow (W^z \rightarrow \mu^+ \nu^-) + X$</td>
<td>$u d \rightarrow W^+, u d \rightarrow W^-$</td>
<td>$u, d, u, d, g$</td>
<td>$x \gtrsim 10^{-3}$</td>
</tr>
<tr>
<td>$pp \rightarrow (Z \rightarrow \mu^+ \mu^-) + X$</td>
<td>$q q \rightarrow Z$</td>
<td>$q, q, g$</td>
<td>$x \gtrsim 10^{-3}$</td>
</tr>
<tr>
<td>$pp \rightarrow (\gamma^* \rightarrow \gamma^*) + X$</td>
<td>$q q \rightarrow \gamma^*$</td>
<td>$g, q$</td>
<td>$x \gtrsim 0.01$</td>
</tr>
<tr>
<td>$pp \rightarrow (\gamma^* \rightarrow \gamma^*) + X, Low mass$</td>
<td>$q q \rightarrow \gamma^*$</td>
<td>$g, q$</td>
<td>$x \gtrsim 10^{-4}$</td>
</tr>
<tr>
<td>$pp \rightarrow (\gamma^* \rightarrow \gamma^*) + X, High mass$</td>
<td>$q q \rightarrow \gamma^*$</td>
<td>$q$</td>
<td>$x \gtrsim 0.1$</td>
</tr>
<tr>
<td>$pp \rightarrow W^+ c, W^- c$</td>
<td>$s g \rightarrow W^+ c, s g \rightarrow W^- c$</td>
<td>$s, g$</td>
<td>$x \sim 0.01$</td>
</tr>
<tr>
<td>$pp \rightarrow \bar{\nu} + X$</td>
<td>$g g \rightarrow \bar{\nu}$</td>
<td>$g$</td>
<td>$x \gtrsim 0.01$</td>
</tr>
<tr>
<td>$pp \rightarrow D, B + X$</td>
<td>$g g \rightarrow c c, b b$</td>
<td>$b$</td>
<td>$x \gtrsim 10^{-6}, 10^{-5}$</td>
</tr>
<tr>
<td>$pp \rightarrow J/\psi, Y + pp$</td>
<td>$\gamma^* (g g) \rightarrow c c, bb$</td>
<td>$g$</td>
<td>$x \gtrsim 10^{-6}, 10^{-5}$</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma + X$</td>
<td>$g q(q) \rightarrow \gamma q(q)$</td>
<td>$g$</td>
<td>$x \gtrsim 0.005$</td>
</tr>
</tbody>
</table>

LHC

Kinematic Coverage:

Fit Quality:

$\chi^2 / \text{dof} \sim 1 \Rightarrow \text{Non-trivial check of QCD}$

<table>
<thead>
<tr>
<th>All data sets</th>
<th>LO</th>
<th>NLO</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>3706 / 2763</td>
<td>3267 / 2996</td>
<td>2717 / 2663</td>
<td></td>
</tr>
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</table>
Running of weak interaction – high luminosity:

- Fills in the region that has never been measured
- Have a real impact on testing the running of weak interaction