What can we learn about quarks, gluons and proton’s internal structure from supercomputer simulations?

Krzysztof Cichy
Adam Mickiewicz University, Poznań, Poland

The speaker is supported by the National Science Center of Poland SONATA BIS grant No 2016/22/E/ST2/00013 (2017-2022).
Outline of the talk

1. Standard Model and QCD
2. Lattice QCD
3. Structure of the proton
4. Summary and prospects

Some papers with results presented here:


Quantum Chromodynamics (QCD)

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Non-perturbative methods needed ⇒ **Lattice QCD**.
We introduce a 4D hypercubic lattice:

- quark fields on lattice sites,
- gluon fields on lattice links.
Lattice formulation

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• Remove the regulator:
  ★ continuum limit $a \to 0$,
  ★ infinite volume limit $L \to \infty$. 
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  - typical lattice size: \( 48 \times 48 \times 48 \times 96, 64 \times 64 \times 64 \times 128 \),
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  This gives integral dimension of order $10^8$–$10^9$.
- Hence, huge computational resources needed!
- QCD was one of the first branches of science that “asked” for such computational resources and thus inspired the development of supercomputers.
Simulating QCD on the lattice

- Many machines dedicated to Lattice QCD were constructed:
  - 1985 – GF11, 11 GFlops
  - 1995-2005 – APE100, APEmille, 100 GFlops – 15 TFlops
  - 1998-2005 – QCDSP, QCDOC, 1 TFlops – 10 TFlops
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Overall, a lattice QCD collaboration (20-50 people) needs annually order $O(1)$ Pflop-years ($O(200)$ million CPU-hours).
Supercomputers in Poland

PROMETHEUS (AGH Kraków)
2.4 PFlops, 53568 cores
279 TB RAM, TOP500 #131

TRYTON (CI TASK Gdańsk)
1.4 PFlops, 38568 cores
180 TB RAM, TOP500 #421

EAGLE (PCSS Poznań)
1.4 PFlops, 32984 cores
121 TB RAM, TOP500 #415

OKEANOS (ICM Warszawa)
1.1 PFlops, 26016 cores
139 TB RAM, TOP500 #480
Some machines used by our collaboration (Extended Twisted Mass Collaboration)

- **Piz Daint (Cray)** – CSCS, Switzerland (25.3 PFlops)
- **Stampede 2 (Dell)** – UT Austin, USA (18 PFlops)
- **Titan (Cray)** – Oak Ridge National Laboratory, USA (17.6 PFlops)
- **JUQUEEN (IBM)** – Forschungszentrum Jülich, Germany (5.9 PFlops)
- **SuperMUC (IBM)** – Garching, Germany (3 PFlops)
- **Prometheus (HP)** – AGH Kraków, Poland (2.4 PFlops)
- **JURECA (T-Platforms)** – Forschungszentrum Jülich, Germany (2.2 PFlops)
- **Fermi (IBM)** – CINECA, Italy (2.1 PFlops)
- **Eagle (Huawei)** – PCSS Poznań, Poland (1.4 PFlops)
- **Okeanos (Cray)** – ICM Warszawa, Poland (1.1 PFlops)
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Some collaborations in LQCD:

- Alpha, BMW, CLS, CP-PACS, ETMC, HALQCD, hotQCD, JLQCD, LHC, LSD, Mainz, MILC, NME, NPLQCD, QCDSF, PNDME, RBC, RQCD, SWME, tmFT, TWQCD, UKQCD, USQCD, WHOT-QCD

in total $\approx 500 - 600$ physicists
Length scales and the interior of proton

- Atom: ~10^{-9} cm
- Nucleus: ~10^{-12} cm
- Proton (neutron): ~10^{-13} cm
- Electron: <10^{-16} cm
- Quark: <10^{-16} cm
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Krzysztof Cichy
Proton structure

Source: Ignazio Scimemi, review talk on EIC physics, Cracow 2018
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Proton is a very complicated system...
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Different aspects:
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Quantifying proton structure

Outline of the talk
The Standard Model
QCD
Lattice formulation
QCD simulations
Proton structure
PDFs
Quasi-PDFs
Proton spin
Summary

Interactions of constituents of the colliding protons, the so-called partons (quarks, gluons)

Source: LHC, CERN
Different functions characterizing the behavior of partons:

- **parton distributions functions (PDFs)** – probability that a parton carries fraction \( x \) of hadron’s longitudinal momentum,
Quantifying proton structure

Different functions characterizing the behavior of partons:

- **parton distributions functions (PDFs)** – probability that a parton carries fraction $x$ of hadron’s longitudinal momentum,
- **generalized parton distributions (GPDs)** – probe the three-dimensional structure,
- **transverse momentum dependent parton distribution functions (TMDs)** – complement the 3D picture.

Source: LHC, CERN
Parton distribution functions (PDFs)

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\[
\sigma_{AB} = \sum_{a,b=q,g} \sigma_{ab} \otimes f_{a|A}(x_1, Q^2) \otimes f_{b|B}(x_2, Q^2)
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MSTW 2008 NLO PDFs (68% C.L.)


\(x\) – probability of finding parton with a given fraction of proton’s momentum
PDFs on the lattice

- PDFs have non-perturbative nature ⇒ LATTICE?
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• But: PDFs given in terms of non-local light-cone correlators – intrinsically Minkowskian – problem for the lattice!
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\[ \bar{q}(x, \mu^2, P_3) = \int \frac{dz}{4\pi} e^{ixP_3z} \langle N|\bar{\psi}(z)\Gamma A(z, 0)\psi(0)|N \rangle. \]

- *Match* quasi-PDFs to physical PDFs: Large Momentum Effective Theory (LaMET)

\[ q(x, \mu) = \int_{-\infty}^{\infty} \frac{d\xi}{|\xi|} C\left(\xi, \frac{\mu}{xP_3}\right) \tilde{q}\left(\frac{x}{\xi}, \mu, P_3\right). \]
Nucleon momentum $\frac{10\pi}{48}$, $Q^2 = 4$ GeV$^2$

Unpolarized PDF

Quasi-PDFs

Nucleon momentum \( \frac{10\pi}{48} \), \( Q^2 = 4 \text{ GeV}^2 \)

Unpolarized PDF

Polarized PDF

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Unpolarized PDF

$u - d$

Polarized PDF

$\Delta u - \Delta d$

Matched PDF + TMCs

Nucleon momentum $\frac{10\pi}{48}$, $Q^2 = 4 \text{ GeV}^2$

Unpolarized PDF

Polarized PDF

Review Article

A Guide to Light-Cone PDFs from Lattice QCD: An Overview of Approaches, Techniques, and Results

Krzysztof Cichy$^1$ and Martha Constantinou$^2$

$^1$Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland
$^2$Department of Physics, Temple University, Philadelphia, PA 19122 - 1801, USA


Special issue Transverse Momentum Dependent Observables from Low to High Energy: Factorization, Evolution, and Global Analyses,

- discusses in detail quasi-distributions:
  - nucleon: non-singlet quark qPDFs, qGPDs, qTMDs, singlet qPDFs, gluon qPDFs; pion: qPDFs, qDAs
- reviews also other approaches:
  - hadronic tensor, auxiliary scalar quark, auxiliary heavy quark, auxiliary light quark, pseudo-distributions, “OPE without OPE”, lattice cross sections
• **Proton spin puzzle.** EMC experiment at CERN (1988): only 4-24% of proton spin carried by the 3 valence quarks!
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C. Alexandrou, M. Constantinou et al. (ETMC), Phys. Rev. Lett. 119 (2017) 142002
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<th>$S$</th>
<th>$L$</th>
<th>$J = S + L$</th>
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<tr>
<td>$u$</td>
<td>0.42(1)</td>
<td>-0.11(4)</td>
<td>0.31(4)</td>
</tr>
<tr>
<td>$d$</td>
<td>-0.19(1)</td>
<td>0.25(4)</td>
<td>0.05(4)</td>
</tr>
<tr>
<td>$s$</td>
<td>-0.02(1)</td>
<td>0.07(2)</td>
<td>0.05(2)</td>
</tr>
<tr>
<td>$g$</td>
<td>0.13(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quarks</td>
<td>0.20(2)</td>
<td>0.21(8)</td>
<td>0.41(8)</td>
</tr>
<tr>
<td>total</td>
<td>0.54(8)</td>
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C.Alexandrou, M.Constantinou et al. (ETMC), Phys.Rev.Lett. 119 (2017) 142002
Proton spin

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C. Alexandrou, M. Constantinou et al. (ETMC), Phys.Rev.Lett. 119 (2017) 142002

SPIN DECOMPOSITION

\[ J_N \]

\( u \) shaded: valence quark contributions
\( d \) solid: sea quark and gluon contributions
\( s \) shaded: valence quark contributions
\( u+d+s \) solid: sea quark and gluon contributions
\( g \) shaded: valence quark contributions
\( \text{Total} \) solid: sea quark and gluon contributions

MOMENTUM DECOMPOSITION

\[ \langle x \rangle \]

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Krzysztof Cichy

Zjazd Fizyków Polskich 2019 – Kraków – 21 / 22
• QCD is a very complex theory, possessing perturbative and non-perturbative features.
Summary and prospects

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- The latter can only be studied *ab initio* using Lattice QCD.
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• But: this requires lots of computing resources!
• One of the crucial areas studied with LQCD: hadron structure.
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• One of the crucial areas studied with LQCD: hadron structure.
• Lattice approach allows one to calculate proton properties from first principles, with fully controlled systematics.
QCD is a very complex theory, possessing perturbative and non-perturbative features. The latter can only be studied \textit{ab initio} using Lattice QCD. But: this requires lots of computing resources! One of the crucial areas studied with LQCD: hadron structure. Lattice approach allows one to calculate proton properties from first principles, with fully controlled systematics. Still a lot to do to claim full understanding of the proton!
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One of the crucial areas studied with LQCD: hadron structure.

Lattice approach allows one to calculate proton properties from first principles, with fully controlled systematics.

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Recent insights into the proton spin and 1D structure.
Summary and prospects

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- But: this requires lots of computing resources!
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- Lattice approach allows one to calculate proton properties from first principles, with fully controlled systematics.
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- Current directions: systematics of the above, proton mass, 3D structure.
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Thank you for your attention!