Prospects on nucleon tomography

\[ \Delta \sigma \ [\text{pb GeV}^{-4}] \]

\[ \langle x_B \rangle = 0.5 \]
\[ \langle Q^2 \rangle = 6.3 \text{ GeV}^2 \]
\[ \langle -t \rangle = 0.735 \text{ GeV}^2 \]

INPC | Hervé MOUTARDE

Jul. 30, 2019
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?

Mass?
Spin?
Charge?

...
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?

Mass?
Spin?
Charge?
...

What are the relevant effective degrees of freedom and effective interaction at large distance?
Can one hear the shape of a proton? 
Experimental access to geometrical information.

Nucleon Tomography

Principle

Analogy
Experimental access

Phenomenology
Physical content
DVCS data
Neural network fits

Framework
Design
Releases

Conclusion

Can one hear the shape of a drum?
Kac, Am. Math. Mon. 74, 1 (1966)

In quantitative terms

\[
\Delta u + u = 0 \\
\partial u = 0
\]

H. Moutarde
INPC 2019
Can one hear the shape of a proton?
Experimental access to geometrical information.

"Can one hear the shape of a drum?"

Kac, Am. Math. Mon. 74, 1 (1966)
Can one hear the shape of a proton?
Experimental access to geometrical information.

"Can one hear the shape of a drum?"

Kac, Am. Math. Mon. 74, 1 (1966)
Can one hear the shape of a proton?
Experimental access to geometrical information.

"Can one hear the shape of a drum?"

Kac, Am. Math. Mon. 74, 1 (1966)

In quantitative terms

- Dirichlet problem for the Laplacian:

\[ \Delta u + \lambda u = 0 \quad \text{and} \quad u|_{\partial \Omega} = 0 \]
Can one hear the shape of a proton?
Harmonics and patterns.
Can one hear the shape of a proton? Harmonics and patterns.

What about the proton?

- "Hit" the proton, e.g. with a virtual photon:
- "Listen" to the distribution of produced particles:
- "Measure" harmonics:
Can one hear the shape of a proton?
Harmonics and patterns.

What about the proton?

- "Hit" the proton, e.g. with a virtual photon: hard
- "Listen" to the distribution of produced particles: exclusive
- "Measure" harmonics: amplitudes (Compton form factors)
Exclusive processes of current interest. Factorization, universality and event distributions.

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DVCS

$e^-$ $\gamma^*$ $Q^2$ $\gamma$ factorization $x + \xi$ $x - \xi$ $p$ $p$ $t$
Exclusive processes of current interest. Factorization, universality and event distributions.

- DVCS
  - Perturbative
  - Nonperturbative
  - Factorization

- DVMP
  - Perturbative
  - Nonperturbative
  - Factorization
Exclusive processes of current interest. Factorization, universality and event distributions.
Exclusive processes of current interest. Factorization, universality and event distributions.

- **Nucleon Tomography**
  - Principle
  - Analogy
  - Experimental access

- **Phenomenology**
  - Physical content
  - DVCS data
  - Neural network fits

- **Framework**
  - Design
  - Releases

- **Conclusion**

---

**DVCS**

- Perturbative
- Nonperturbative

**DVMP**

- Perturbative
- Nonperturbative

**TCS**

- Perturbative
- Nonperturbative
Exclusive processes of current interest.
Factorization, universality and event distributions.

Nucleon Tomography

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DVCS
\[ e^- \xrightarrow{\gamma^*} Q^2 \xrightarrow{\gamma} \]

DVMP
\[ e^- \xrightarrow{\gamma^*} Q^2 \xrightarrow{\pi, \rho, \ldots} \]

TCS
\[ e^+ \xrightarrow{\gamma} \gamma^* \xrightarrow{Q^2} e^- \]

H. Moutarde | INPC 2019 | 5 / 22
Anatomy of hadrons.
Generalized Parton Distributions (GPDs) and 3D structure.

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

### Deeply Virtual Compton Scattering (DVCS)

![Diagram of DVCS process]

**DVCS**

$e^-$

$\gamma^*$, $Q^2$

$x + \xi$

$x - \xi$

$p$

$p$

$\gamma$

factorization $\mu_F$

$R_{\perp}$

Transverse center of momentum $R_{\perp}$

$R_{\perp} = \sum_i x_i r_{\perp i}$
Anatomy of hadrons.
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**Deeply Virtual Compton Scattering (DVCS)**

\[
\text{DVCS} \quad e^- \quad e^- \\
\gamma^*, \quad Q^2 \\
\Rightarrow \quad x + \xi \\
\Rightarrow \quad x - \xi \\
\Rightarrow \quad t \\
\gamma \quad \text{factorization } \mu_F \\
\Rightarrow \quad R_\perp \Rightarrow \quad \sum_i x_i r_{\perp i} \\
\Rightarrow \quad \text{Impact parameter } b_\perp
\]
Anatomy of hadrons.
Generalized Parton Distributions (GPDs) and 3D structure.

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

Deeply Virtual Compton Scattering (DVCS)

\[
\begin{align*}
\text{DVCS} & : e^- + p \rightarrow e^- + \gamma + p \\
\gamma^* & : Q^2 \\
\text{factorization} & : \mu_F \\
\textbf{x} & + \xi \\
\textbf{x} & - \xi \\
p & \rightarrow \text{t} \\
\end{align*}
\]

Transverse center of momentum \( R_\perp \)
\[
R_\perp = \sum_i x_i r_{\perp i}
\]

Impact parameter \( b_\perp \)

Longitudinal momentum \( xP^+ \)
Anatomy of hadrons.
Generalized Parton Distributions (GPDs) and 3D structure.

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

### Deeply Virtual Compton Scattering (DVCS)

\[
\begin{align*}
\text{Transverse center of momentum } R_\perp &= \sum_i x_i r_{\perp i} \\
\text{Impact parameter } b_\perp &\\
\text{Longitudinal momentum } xP^+ &\quad -1 < x < +1 \\
\text{for leading and sub-leading twists.}
\end{align*}
\]

- 24 GPDs \( F^i(x, \xi, t, \mu_F) \) for each parton type \( i = g, u, d, \ldots \)
Bjorken regime: large $Q^2$ and fixed $xB \approx 2\xi/(1 + \xi)$

- Partonic interpretation relies on factorization theorems.
- All-order proofs for DVCS, TCS and some DVMP.
- GPDs depend on a (arbitrary) factorization scale $\mu_F$.
- **Consistency** requires the study of different channels.

- GPDs enter DVCS through **Compton Form Factors** :

$$\mathcal{F}(\xi, t, Q^2) = \int_{-1}^{1} dx \ C\left(x, \xi, \alpha_s(\mu_F), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

for a given GPD $F$.

- CFF $\mathcal{F}$ is a complex function.
Phenomenology
Anatomy of hadrons.  
3D hadron imaging.

- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

$$
\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2} \left[ H(x, 0, b_\perp^2) + \frac{b_\perp^j \epsilon_j S^i}{M} \frac{\partial E}{\partial b_\perp^2}(x, 0, b_\perp^2) \right. \\
\left. + \lambda \lambda_N \tilde{H}(x, 0, b_\perp^2) \right]
$$

- **Notations**: quark helicity $\lambda$, nucleon longitudinal polarization $\lambda_N$ and nucleon transverse spin $S_\perp$.


**Can we obtain this picture from exclusive measurements?**

**Probabilistic interpretation** of Fourier transform of $GPD(x, \xi = 0, t)$ in **transverse plane**.

$$\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2} \left[ H(x, 0, b_\perp^2) + \frac{b_\perp^j \epsilon_{ji} S^i_\perp}{M} \frac{\partial E}{\partial b_\perp^2}(x, 0, b_\perp^2) \right] + \lambda \lambda_N \tilde{H}(x, 0, b_\perp^2)$$

**Notations**: quark helicity $\lambda$, nucleon longitudinal polarization $\lambda_N$ and nucleon transverse spin $S_\perp$.


---

**Not quite, but close!**

Anatomy of hadrons.
Spin and energy-momentum structure.

- Energy momentum tensor between nucleon states:

\[
\left\langle N, P + \frac{\Delta}{2} \left| T_{\mu\nu} \right| N, P - \frac{\Delta}{2} \right\rangle = \bar{u} \left( P + \frac{\Delta}{2} \right) \left[ A(t) \gamma^{(\mu} P_{\nu)} \right.
\]

\[
+ B(t) P^{(\mu} i_{\sigma^\nu)} \frac{\Delta \lambda}{2M} + \frac{C(t)}{M} (\Delta_{\mu} \Delta_{\nu} - \Delta^2 \eta_{\mu\nu}) \left] u \left( P - \frac{\Delta}{2} \right) \right.
\]

with \( t = \Delta^2 \).

- Key observation: link between GPDs and gravitational form factors

\[
\int dx x H^q(x, \xi, t) = A^q(t) + 4\xi^2 C^q(t)
\]

\[
\int dx x E^q(x, \xi, t) = B^q(t) - 4\xi^2 C^q(t)
\]

See C. Lorcé’s talk today!
Need for global fits of world data.
Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities

Thomas Jefferson National Laboratory

DESY

CERN
Need for global fits of world data. Different facilities will probe different kinematic domains.
Need for global fits of world data.
Different facilities will probe different kinematic domains.

Valence quarks

Experimental data collected at 3 facilities

Thomas Jefferson National Laboratory

DESY
CERN

Sea quarks

Valence quarks

Different facilities will probe different kinematic domains.

Need for global fits of world data.
Need for global fits of world data. Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities, soon 4: EIC!

NSAC, Long Range Plan 2015: "We recommend [...] EIC as the highest priority for new facility construction"
Existing and future DVCS measurements. The field is changing with new data of unprecedented accuracy.

CLAS: preliminary results with 2% of approved beam time


Christiaens, APS DNP’18

See the talks by J. Roche, M. Defurne, G. Christiaens, S. Niccolai, P. Chatagnon and S. Scopetta on Thursday!
### Neural network global fit of CFFs.
All existing sets except $d^4 \sigma_{UU}^-$ from Hall A (2015-17).

<table>
<thead>
<tr>
<th>No.</th>
<th>Collab.</th>
<th>Year</th>
<th>Ref.</th>
<th>Observable</th>
<th>Kinematic dependence</th>
<th>No. of points used / all</th>
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<td>$x_{Bj}$</td>
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<td>$x_{Bj}$</td>
<td>18 / 24</td>
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<td>37</td>
<td>$A_C^{U}$</td>
<td>$i = 1$</td>
<td>12 / 12</td>
</tr>
</tbody>
</table>

**SUM:** 2624 / 3996

A selection of results.
2600+ measurements of 30 observables published during 2001-17.

CLAS

Hall A

HERMES

COMPASS

Nucleon Tomography

Principle
Analogy
Experimental access

Phenomenology
Physical content
DVCS data
Neural network fits

Framework
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Releases

Conclusion

A selection of results.
2600+ measurements of 30 observables published during 2001-17.

Compton form factor \( \text{Im}\mathcal{H}(\xi, t = -0.3 \text{ GeV}^2, Q^2 = 2. \text{ GeV}^2) \)

A selection of results.
2600+ measurements of 30 observables published during 2001-17.

Subtraction constant (related to pressure distribution)

The PARTONS framework

PARtmonic
Tomography
Of
Nucleon
Software
Computing chain design.
Differential studies: physical models and numerical methods.

- **Principle**
  - Analog
  - Experimental access

- **Phenomenology**
  - Physical content
  - DVCS data
  - Neural network fits

- **Framework**
  - Design
  - Releases

- **Conclusion**

---

**Nucleon Tomography**

- **Full processes**
  - Experimental data and phenomenology
- **Small distance**
  - Computation of amplitudes
- **Large distance**
  - First principles and fundamental parameters

---

**PARtonic Tomography Of Nucleon Software**

- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.
A computing framework for physics.
Done: tests, benchmarking, documentation, tutorials.

- **Nucleon Tomography**
  - Principle
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    - Experimental access
  - Phenomenology
    - Physical content
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    - Neural network fits
  - Framework
    - Design
    - Releases
    - Conclusion

- **3 stages:**
  1. Design.
  2. Integration and validation.

- 1 new physical development = 1 new module.

- **Aggregate knowledge and know-how:**
  - Models.
  - Measurements.
  - Numerical techniques.
  - Validation.

- What can be automated will be automated.

- Flexible software architecture.

Open source release.
Publicly available on CEA GitLab server.

Nucleon Tomography

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PARTONS
PARtonic Tomography Of Nucleon Software

Main Page

What is PARTONS?

PARTONS is a C++ software framework dedicated to the phenomenology of Generalized Parton Distributions (GPDs). GPDs provide a comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. In particular, GPDs provide a description of the nucleon as an extended object, referred to as 3-dimensional nucleon tomography, and give an access to the orbital angular momentum of quarks.

PARTONS provides a necessary bridge between models of GPDs and experimental data measured in various exclusive channels, like Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP). The experimental programme devoted to study GPDs has been carried out by several experiments, like HERMES at DESY (closed), COMPASS at CERN, Hall-A and CLAS at JLab. GPD subject will be also a key component of the physics case for the expected Electron Ion Collider (EIC).

PARTONS is useful to theorists to develop new models, phenomenologists to interpret existing measurements and to experimentalists to design new experiments.

Get PARTONS

Open source release. 
Publicly available on CEA GitLab server.

Nucleon Tomography

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Publicly available on CEA GitLab server.

PARTONS
PARtonic Tomography Of Nucleon Software

Contact
Main contact: partons@cea.fr.

Technical support
Problems with installation and usage: partons@cea.fr.

Newsletter
Sign up to the newsletter to be informed on the new releases by sending an email to sympa@saxifrage.saclay.cea.fr with this subject (no additional text needed): SUBSCRIBE partons-users.
To unsubscribe, use UNSUBSCRIBE instead in the subject.

Development team
The list of development team members can be found at our GitLab page.
If you want to join the development team of PARTONS, contact Hervé Moutarde.

Within the next four years.
Virtual Access Infrastructure 3DPartons in STRONG-2020.

Nucleon Tomography

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A workpackage of the EU-funded STRONG-2020 program

- Mutualize developments for GPD and TMD frameworks.
- Address the question of event generation.
- Open-source release and maintenance of computing codes related to 3D hadron structure.
Conclusion
Conclusion and prospects.
Putting all the pieces together.

- We now have tools to **systematically relate** models to experimental data in multi-channel analysis.
- We now have an **operating engine** for global CFF fits.
- We revisit the **mechanical properties** of hadrons to assess how much we can learn from GPD extractions.
- We can now build generic GPD models satisfying *a priori all theoretical constraints*.

New studies become possible!

- Global GPD fits.
- Energy-momentum structure of hadrons.
- Quantitative impact of nonperturbative QCD ingredients on 3D hadron structure studies.
- GPD and TMD studies in a common framework.
- ... And probably much more!