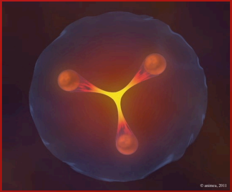
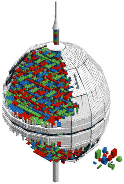
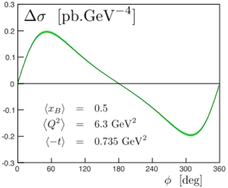
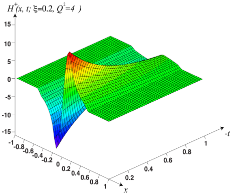
DE LA RECHERCHE À L'INDUSTRIE

Methods for Multidimensional Proton Imaging









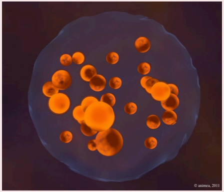
CLAS Coll. Meeting 2015 | Hervé MOUTARDE

Oct. 21st, 2015

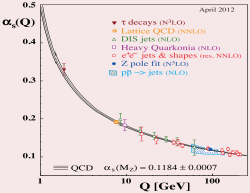
Motivation.

Study nucleon structure to shed new light on nonperturbative QCD.

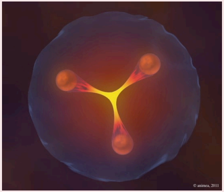
Perturbative QCD



Asymptotic freedom



Nonperturbative QCD

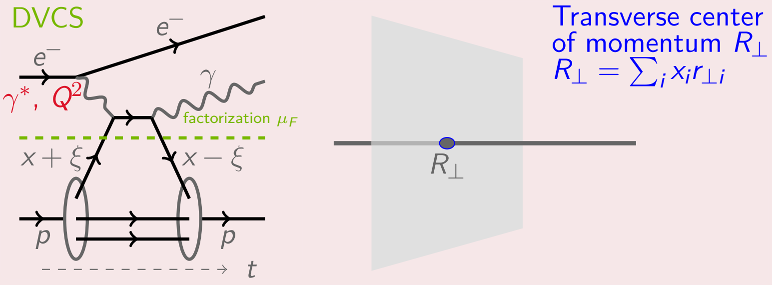


Perturbative AND nonperturbative QCD at work

- Define **universal** objects describing 3D nucleon structure: **Generalized Parton Distributions** (GPD).
- Relate GPDs to measurements using **factorization**: **Virtual Compton Scattering** (DVCS, TCS), **Deeply Virtual Meson production** (DVMP).
- Get **experimental knowledge** of nucleon structure.

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

Deeply Virtual Compton Scattering (DVCS)



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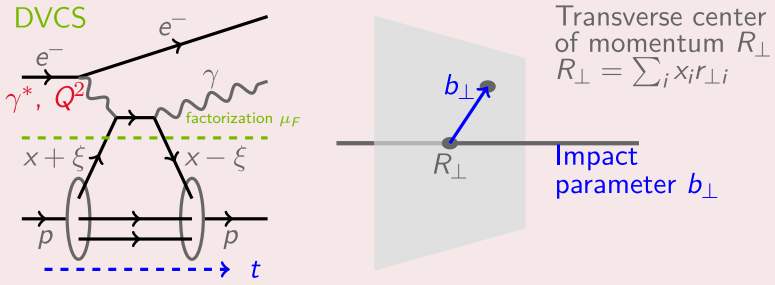

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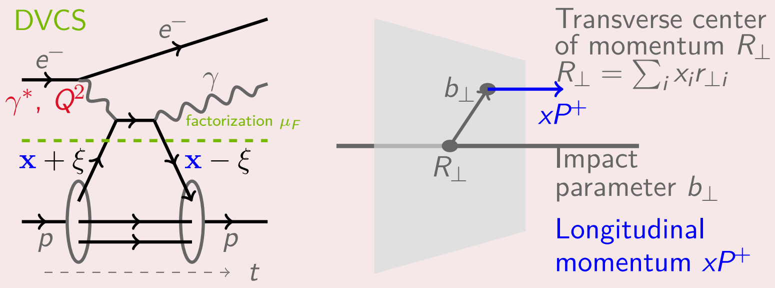
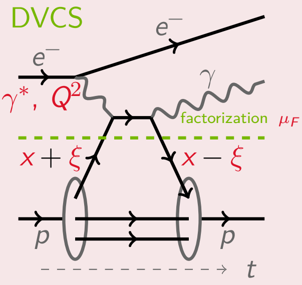


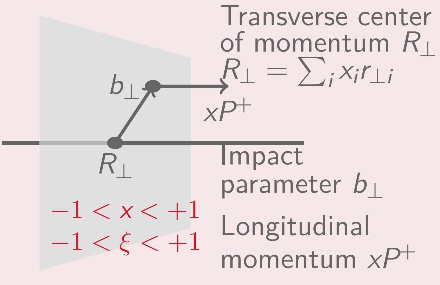
Anatomy of the nucleon.

GPDs, 3D nucleon imaging, and beyond.

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

Deeply Virtual Compton Scattering (DVCS)

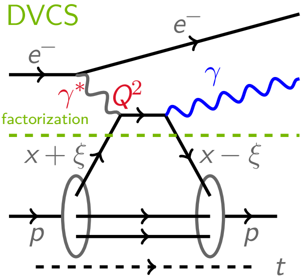


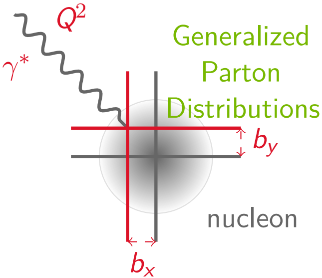


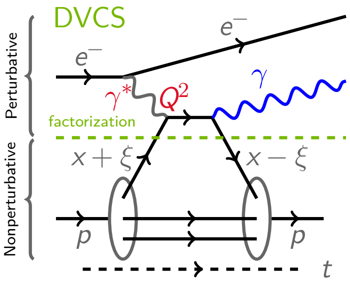
- **24 GPDs** $F^i(x, \xi, t, \mu_F)$ for each parton type $i = g, u, d, \ldots$ for leading and sub-leading twist.

1. Measuring GPDs to image the nucleon.
2. Designing the tools.
3. Aggregating knowledge and know-how in the PARTONS software platform.

Towards 3D Imaging


DVCS
e^-
e^-
γ^*
Q^2
γ
factorization
$x+\xi$
$x-\xi$
p
p
t


Q^2
γ^*
Generalized
Parton
Distributions
b_y
nucleon
b_x


DVCS
Perturbative
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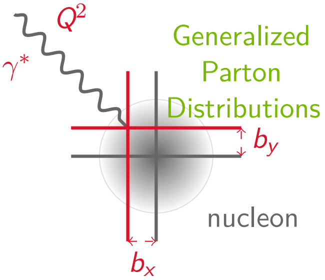
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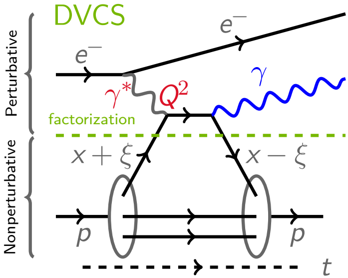
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e^-
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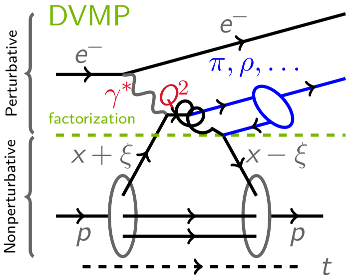
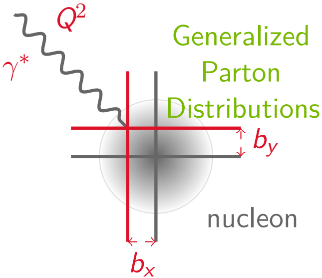
p
t


DVMP
Perturbative
Nonperturbative
e^-
e^-
$\pi, \rho, \ldots$
γ^*
Q^2
factorization
$x+\xi$
$x-\xi$
p
p
t


Q^2
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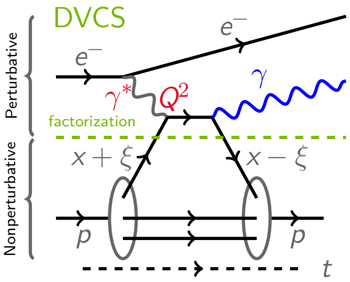
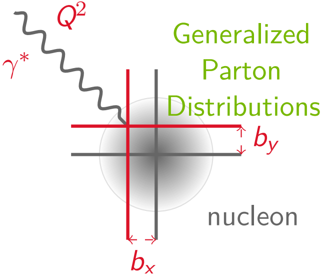
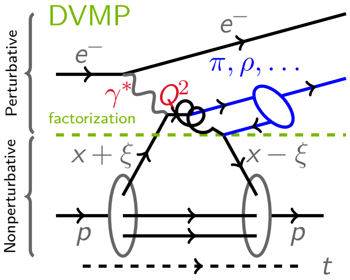
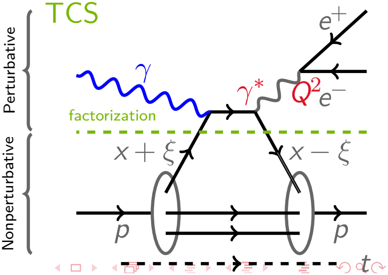
Exclusive processes of current interest.

Factorization and universality.









Exclusive processes of current interest.

Factorization and universality.

Methods for 3D Imaging

Introduction

Towards 3D Imaging

Experimental access

Kinematic reach of DVCS

From observables to 3D images

Case studies

Data selection

Subdominant contributions

Model dependence

Challenges

PARTONS Project

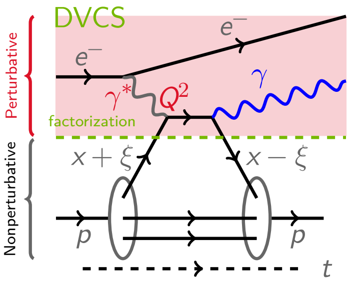
Computing chain

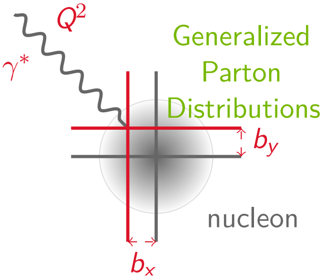
Examples

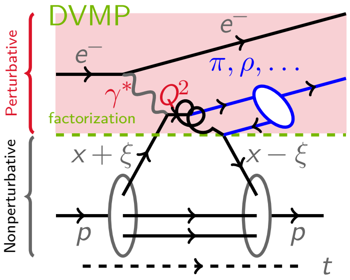
Architecture

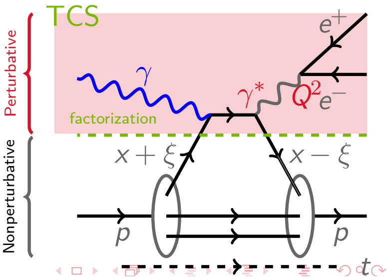
Team

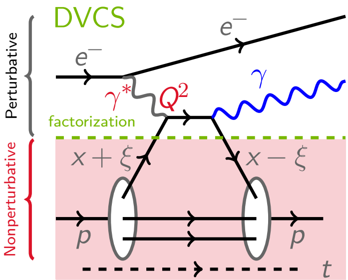
Conclusions











DVCS
Perturbative
Nonperturbative
e^-
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factorization
$x+\xi$
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p
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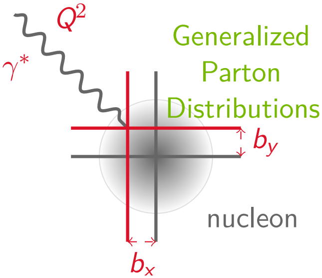
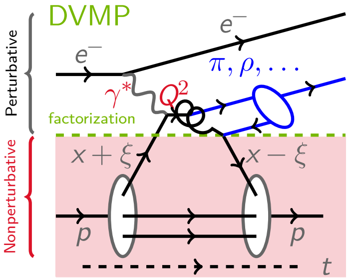


Q^2
γ^*
Generalized Parton Distributions
b_y
nucleon
b_x



DVMP
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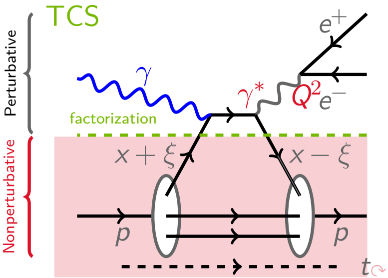
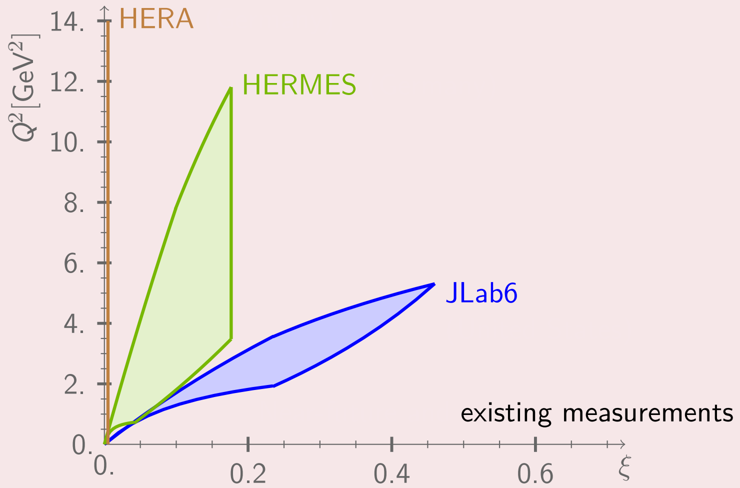


TCS
Perturbative
Nonperturbative
e^+
γ
γ^*
Q^2
e^-
factorization
$x+\xi$
$x-\xi$
p
p
t

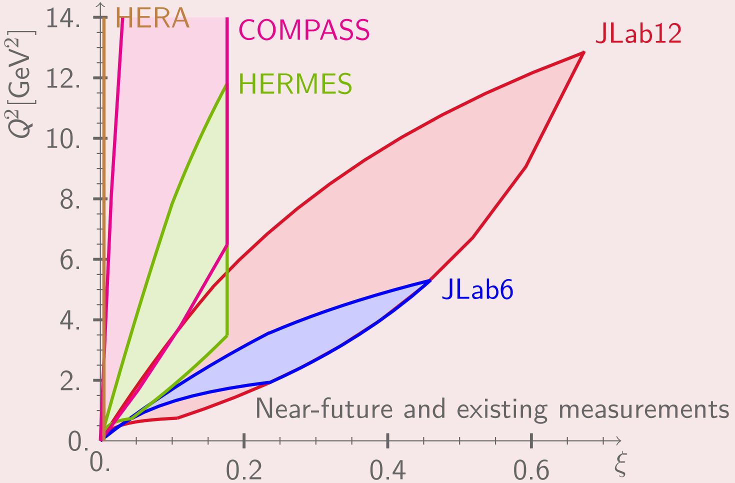
Kinematic reach of existing or near-future DVCS measurements



Need for global fits of world data.

Different facilities will probe different kinematic domains.

Kinematic reach of existing or near-future DVCS measurements



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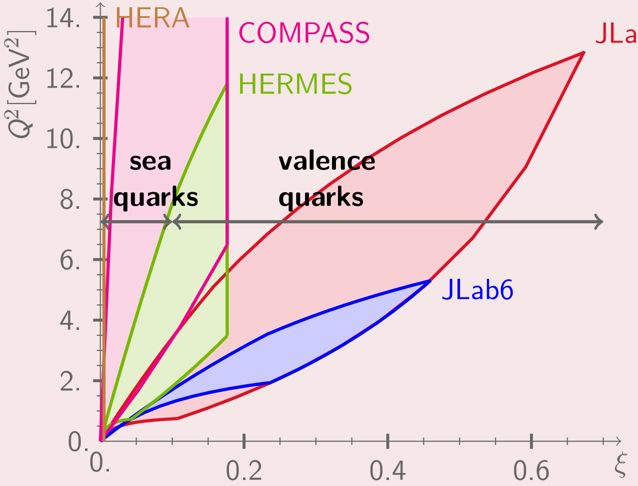

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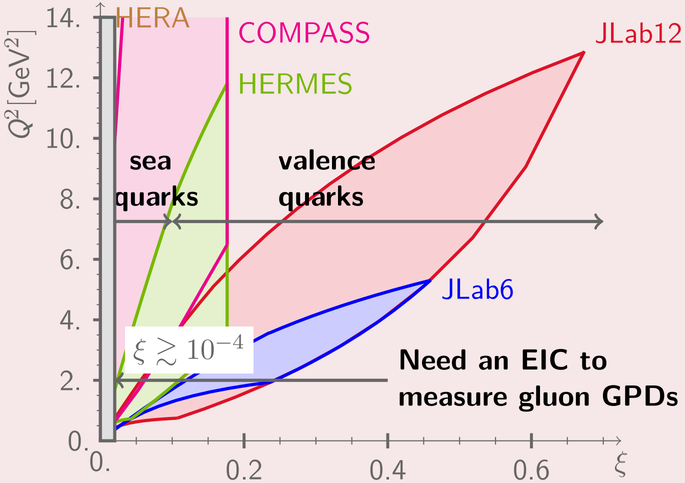
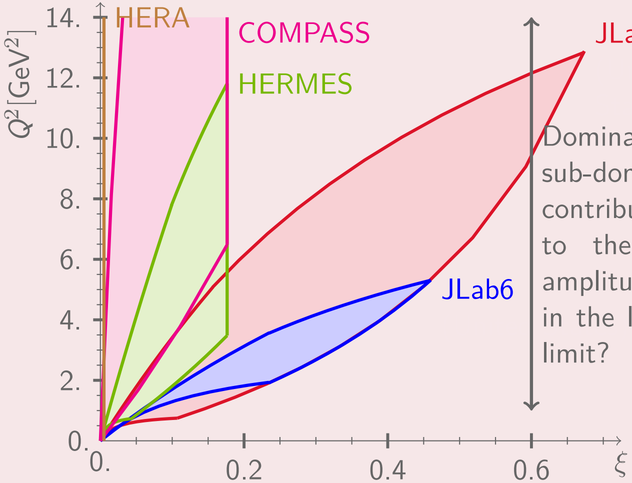


Need an EIC to measure gluon GPDs

Need for global fits of world data.

Different facilities will probe different kinematic domains.

Kinematic reach of existing or near-future DVCS measurements



Dominant and sub-dominant contributions to the DVCS amplitude in the large Q^2 limit?

1. **Extract** $H(x, \xi, t, \mu_F^{\mathrm{ref}})$ from experimental data.
2. **Extrapolate** to vanishing skewness $H(x, 0, t, \mu_F^{\mathrm{ref}})$.
3. **Compute** 2D Fourier transform in transverse plane:

$$H(x, b_\perp) = \int_0^{+\infty} \frac{\mathrm{d}\Delta_\perp}{2\pi} \Delta_\perp J_0(b_\perp \Delta_\perp) H(x, 0, -\Delta_\perp^2)$$

4. **Propagate** uncertainties.

Case studies

Case studies

Lessons from past

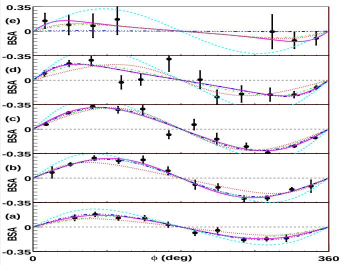
"An expert is a man who has made all the mistakes which can be made in a very narrow field."

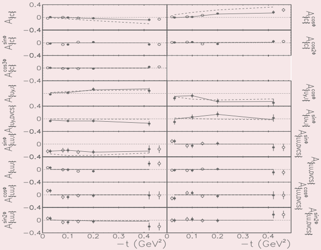
N. Bohr

Handling multi-data sets.

What is the impact of one particular set of data?

Fits to CLAS and HERMES data



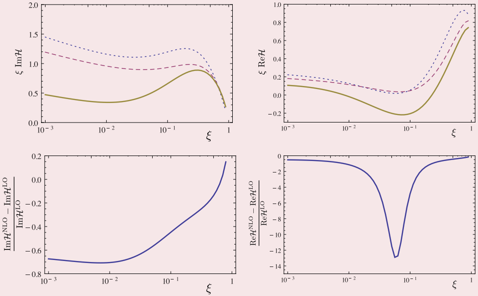


Moutarde, Phys. Rev. **D79**, 094021 (2009)

Guidal and Moutarde, Eur. Phys. J. **A42**, 71 (2009)

- Two separate studies. Large code rewriting to mix both.
- Kinematic cuts not easy.
- Treat all observables **generically**, including **multi-channel** analysis.

$\mathcal{H}$ at LO and NLO ($t = -0.1$ GeV^2, $Q^2 = \mu_F^2 = 4.$ GeV^2)



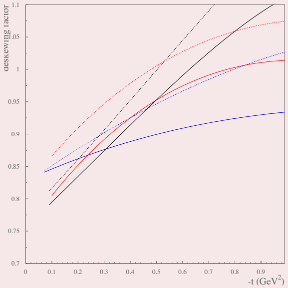
Moutarde *et al.*, Phys. Rev. **D87**, 054029 (2013)

- **Systematic** tests of perturbative QCD assumptions.
- **Wide kinematic range** (from JLab to EIC).
- **Accuracy** set by JLab 12 GeV expected statistical accuracy.
- **Modularity** for integration methods (time vs accuracy).

Estimating parameterization uncertainties.

What is the model dependence of the theoretical prediction?

Model-estimates of $H(\xi, 0, t)/H(\xi, \xi, t)$



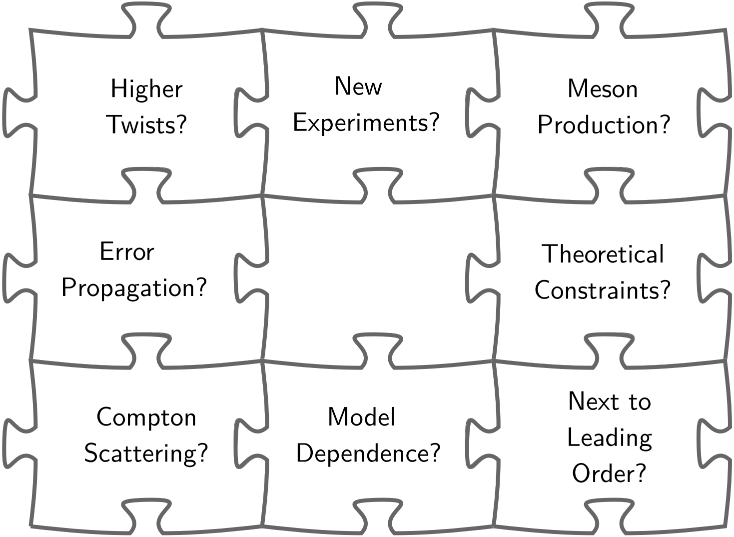
- VGG
- dual Model
- GK
- Solid: $\xi \simeq 0.05$
- Dashed: $\xi \simeq 0.14$

Guidal *et al.*, Rept. Prog. Phys. **76**, 066202 (2013)

- **Systematic** computations with different GPD models.
- **Modularity** for GPD models. **Easy** integration.
- **No parameterization** relying on first principles only.
- **Relevant** for experiment design.

Software for the phenomenology of GPDs.

Different questions to be answered with the same tools.



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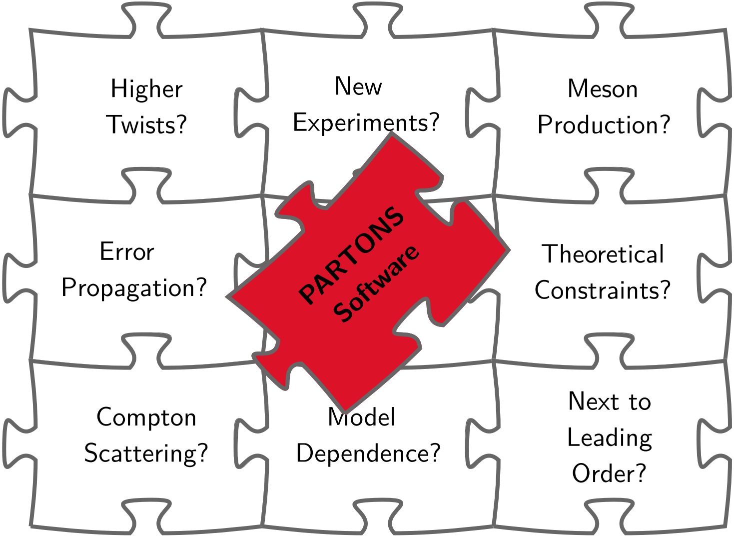


PARTONS Project

PARtonic
Tomography
Of
Nucleon
Software

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

Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology → **Full processes**

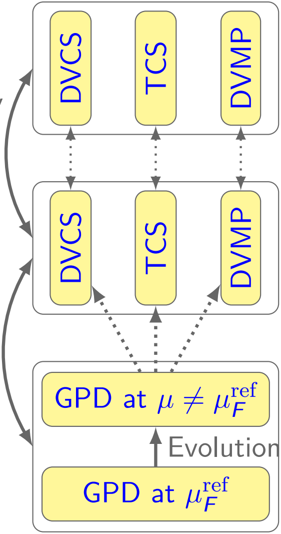
Computation of amplitudes → **Small distance contributions**

First principles and fundamental parameters → **Large distance contributions**

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



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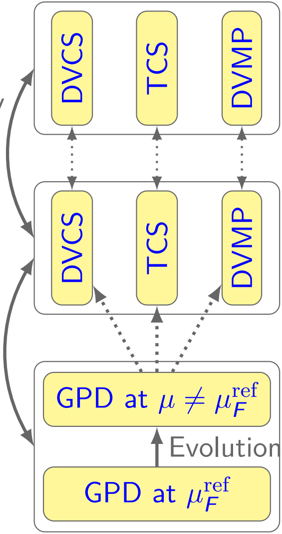
Computation of amplitudes

First principles and fundamental parameters



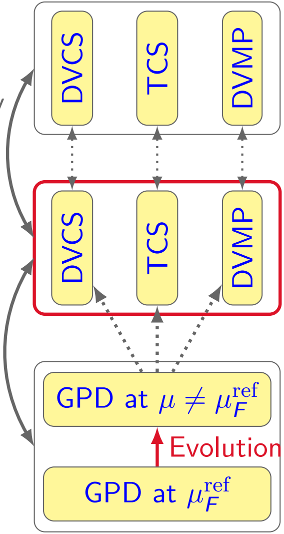
- Many observables.
- Kinematic reach.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

Computing chain design.

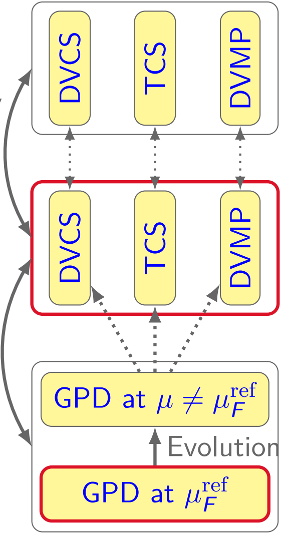
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



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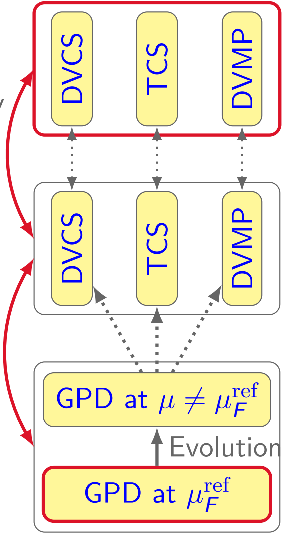

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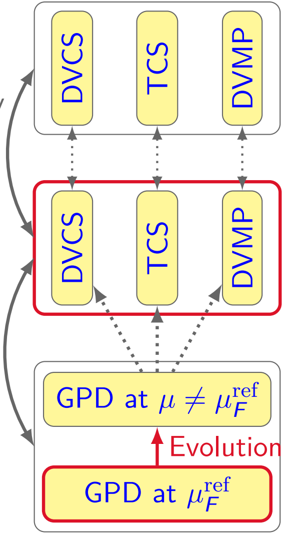

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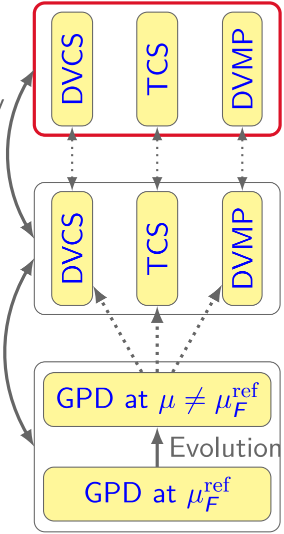


- Many observables.
- Kinematic reach.

- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

Status.

Currently: integration, tests, validation.

- 3 stages:
  1. Design.
  2. Integration and validation.
  3. Production.
- Flexible software architecture.

  B. Berthou *et al.*, *PARTONS: a computing platform for the phenomenology of Generalized Parton Distributions*
- 1 new physical development = 1 new module.
- *Aggregate* knowledge and know-how. *Do not* reinvent the wheel!
- What *can* be automated *will be* automated.
- Get ready for 12 GeV!

gpdExample()

```
// Lots of includes
#include <src/Partons.h>
...

// Retrieve GPD service
GPDService* pGPDService = ServiceObjectRegistry::getGPDService();
// Load GPD module with the BaseModuleFactory
GPDModule* pGK11Model = ModuleObjectFactory::newGPDModule(
GK11Model::classId);
// Create a GPDKinematic(x, xi, t, MuF, MuR)
GPDKinematic gpdKinematic(0.1, xBToXi(0.001), -0.3, 8., 8.);
// Compute data and store results
GPDResult gpdResult = pGPDService->
computeGPDModelRestrictedByGPDType(gpdKinematic, pGK11Model,
GPDType::ALL);
// Print results
std :: cout << gpdResult.toString() << std::endl;

delete pGK11Model;
pGK11Model = 0;
```

GPD computing automated.

Each line of code corresponds to a physical hypothesis.

computeOneGPD.xml

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<scenario id="01" date="" description="Example␣:␣computation␣of␣one␣GPD␣model␣(GK11)␣without␣evolution">
    <!-- Select type of computation -->
    <task service="GPDService" method="computeGPDModel" >
        <!-- Specify kinematics -->
        <GPDKinematic>
            <param name="x" value="0.1" />
            <param name="xi" value="1.00050025" />
            <param name="t" value="-0.3" />
            <param name="MuF2" value="8" />
            <param name="MuR2" value="8" />
        </GPDKinematic>
        <!-- Choose GPD model and set parameters -->
        <GPDModule>
            <param name="id" value="GK11Model" />
        </GPDModule>
    </task>
</scenario>
```

GPD computing automated.

Each line of code corresponds to a physical hypothesis.

computeOneGPD

```
<?xml version="1.0" encoding="UTF-8" stand
<scenario id="01" date="" description="Exam                    D
␣model␣(GK11)␣without␣evolution">
    <!-- Select type of computation -->
    <task service="GPDService" method=
        <!-- Specify kinematics -->
        <GPDKinematic>
            <param name="x" valu
            <param name="xi" va
            <param name="t" valu
            <param name="MuF2"
            <param name="MuR2"
        </GPDKinematic>
        <!-- Choose GPD model and
        <GPDModule>
            <param name="id" va
        </GPDModule>
    </task>
</scenario>
```

$$H^u = 0.822557$$
$$H^{u(+)} = 0.165636$$
$$H^{u(-)} = 1.47948$$

$$H^d = 0.421431$$
$$H^{d(+)} = 0.0805182$$
$$H^{d(-)} = 0.762344$$

$$H^s = 0.00883408$$
$$H^{s(+)} = 0.0176682$$
$$H^{s(-)} = 0$$

$$H^g = 0.385611$$

and E, $\tilde{H}$, $\tilde{E}$, ...

CFF computing automated.

Each line of code corresponds to a physical hypothesis.

computeOneCFF.xml

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<scenario id="03" date="" description="Example␣:␣computation␣of␣one␣convol␣coeff␣function␣model␣(DVCSCFF)␣with␣GPD␣model␣(GK11)">
        <task service="DVCSConvolCoeffFunctionService" method="computeWithGPDModel">
                <DVCSConvolCoeffFunctionKinematic>
                        <param name="xi" value="0.5" />
                        <param name="t" value="-0.1346" />
                        <param name="Q2" value="1.5557" />
                        <param name="MuF2" value="4" />
                        <param name="MuR2" value="4" />
                </DVCSConvolCoeffFunctionKinematic>
                <GPDModule>
                        <param name="id" value="GK11Model" />
                </GPDModule>
                <DVCSConvolCoeffFunctionModule>
                        <param name="id" value="DVCSCFFModel" />
                        <param name="qcd_order_type" value="LO" />
                </DVCSConvolCoeffFunctionModule>
        </task>
</scenario>
```

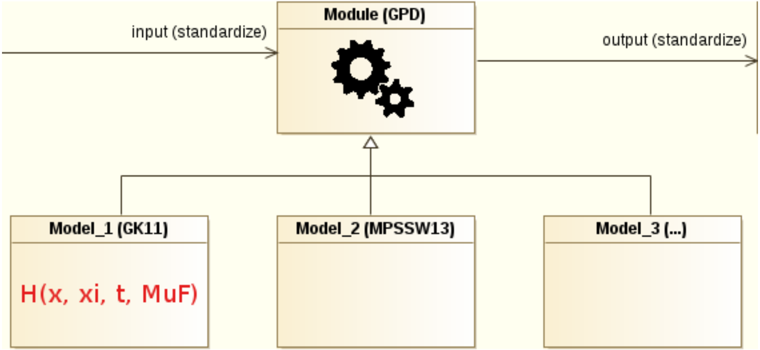
CFF computing automated.

Each line of code corresponds to a physical hypothesis.

computeOneCFF.xml

```
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<scenario id="03" date="" description="Example␣:␣computation␣of␣one␣convol␣coeff␣function␣model␣(DVCSCFF)␣with␣GPD␣model␣(GK11)">
        <task service="DVCSConvolCoeffFunctionService" method="computeWithGPDModel">
                <DVCSConvolCoeffFunctionKinematic>
                        <param name="xi" value="0.5" />
                        <param name="t" value="-0.1346" />
                        <param name="Q2" value="1.5557" />
                        <param name="MuF2" value="4" />
                        <param name="MuR2" value="4" />
                </DVCSConvolCoeffFunctionKinematic>
                <GPDModule>
                        <param name="id" value="GK11Model" />
                </GPDModule
                <DVCSConvolC
                        <para                                        >
                        <para                                        />
                </DVCSConvol
        </task>
</scenario>
```

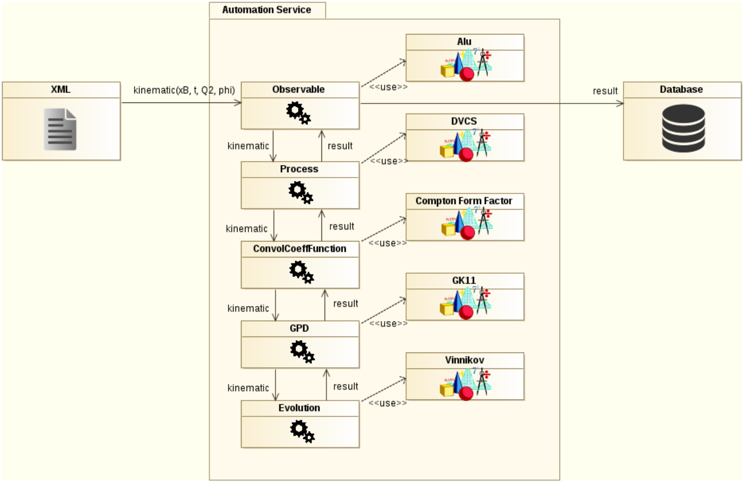
$$\mathcal{H} = 1.47722 + 1.76698\ i$$
$$\mathcal{E} = 0.12279 + 0.512312\ i$$
$$\widetilde{\mathcal{H}} = 1.54911 + 0.953728\ i$$
$$\widetilde{\mathcal{E}} = 18.8776 + 3.75275\ i$$



- Steps of logic sequence in parent class.
- Model description and related mathematical methods in daughter class.

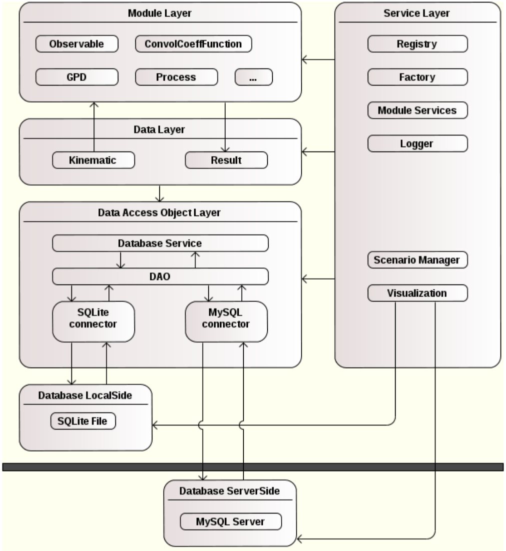
Modularity and automation.

Parse XML file, compute and store result in database.



Modularity and layer structure.

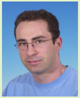
Modifying one layer does not affect the other layers.

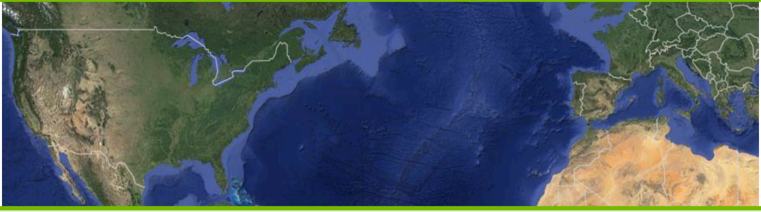


Members and areas of expertise.

Collaborations at the national and international levels.

Development team

						
B. Berthou	N. Chouika	C. Mezrag	H. Moutarde	F. Sabatié	P. Sznajder	J. Wagner
(Irfu)	(Irfu)	(ANL)	(Irfu)	(Irfu)	(NCBJ)	(NCBJ)



IPN and LPT (Orsay), Irfu (Saclay) and CPhT (Polytechnique)

Experimental data analysis — Perturbative QCD

World data fits — GPD modeling

Conclusions

Conclusions.
Versatile tools for hadron structure studies.

- PARTONS software Platform for GPD phenomenology near completion for DVCS channel.
- Designed to simplify:
  - Integration of new modules.
  - Systematic differential studies.
- Aim: up-to-date and validated GPD tools for:
  - Tests of pQCD assumptions.
  - Tests of model dependence.
  - Predictions of observables.
  - Experiment design.
  - Fits.
  - 3D nucleon imaging.
- Fitting test in 2016.

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Irfu
SPhN