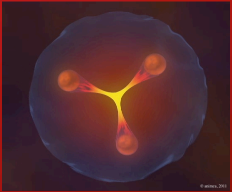
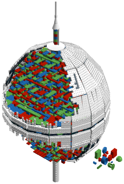
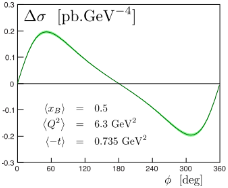
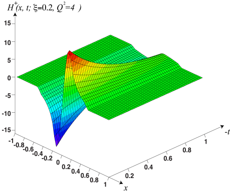
DE LA RECHERCHE À L'INDUSTRIE

The PARTONS framework









Nucleon and resonance structure | Hervé MOUTARDE

May 31st, 2017

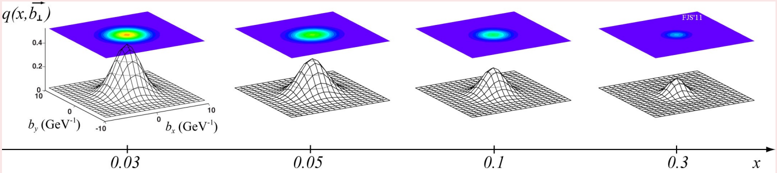
www.cea.fr

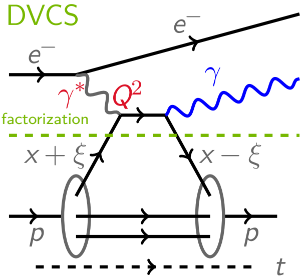
Motivations.

3D imaging of nucleon's partonic content but also...

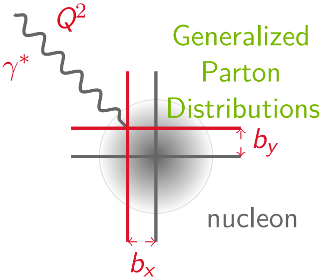
- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in the nucleon.
- Insights on:
  - **Spin** structure,
  - **Energy-momentum** structure.
- **Probabilistic interpretation** of Fourier transform of $\mathrm{GPD}(x, \xi = 0, t)$ in **transverse plane**.

Transverse plane density (Goloskokov and Kroll model)

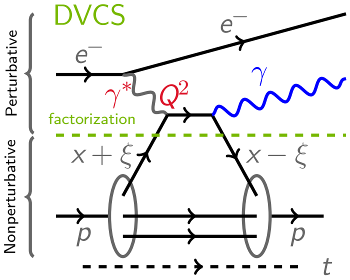




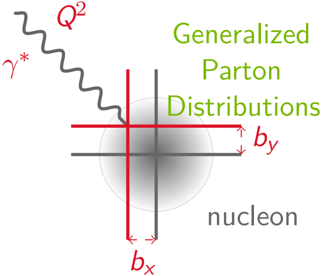
DVCS
e−
e−
γ*
Q2
γ
factorization
x + ξ
x − ξ
p
p
t



Q2
γ*
Generalized
Parton
Distributions
by
nucleon
bx



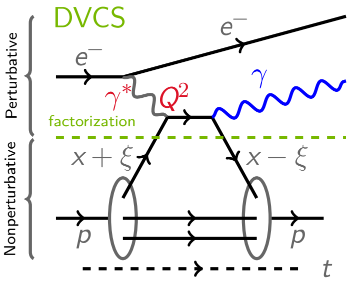
DVCS
Perturbative
Nonperturbative
e^-
e^-
γ^*
Q^2
γ
factorization
$x+\xi$
$x-\xi$
p
p
t

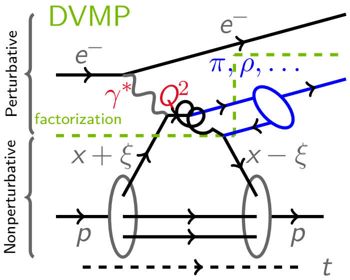


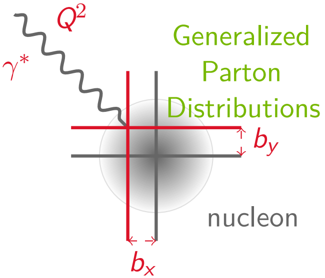
Q^2
γ^*
Generalized
Parton
Distributions
b_y
nucleon
b_x

Exclusive processes of current interest (1/2).

Factorization and universality.

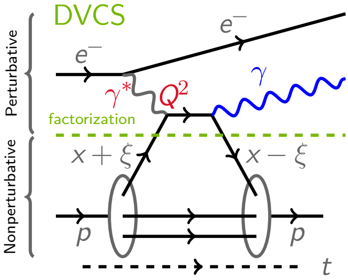


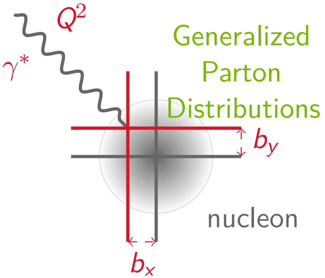


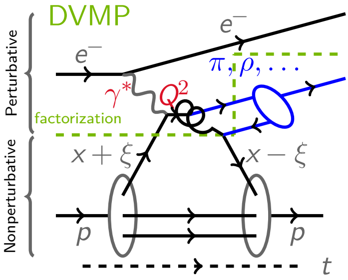


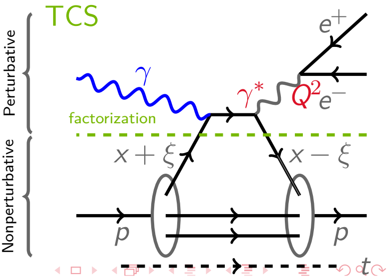
Exclusive processes of current interest (1/2).

Factorization and universality.



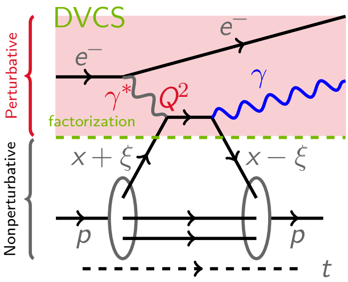


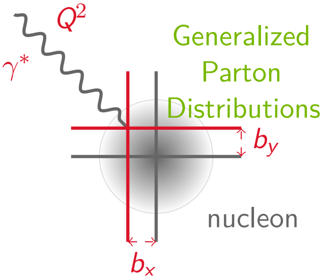


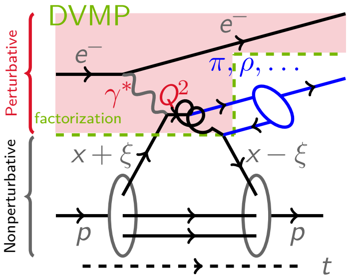


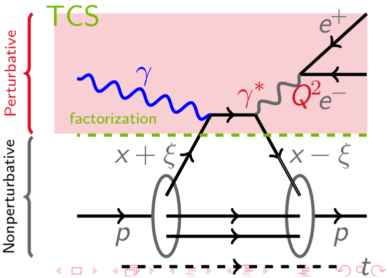
Exclusive processes of current interest (1/2).

Factorization and universality.



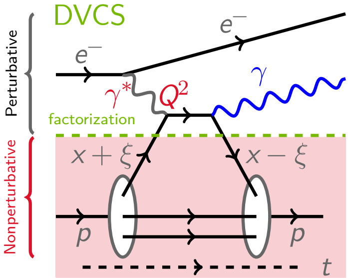


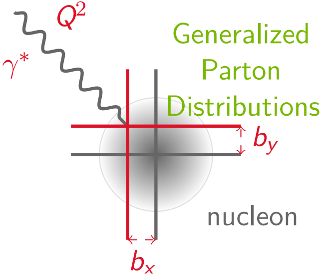


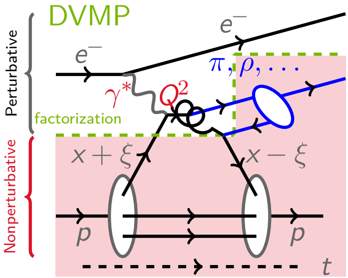


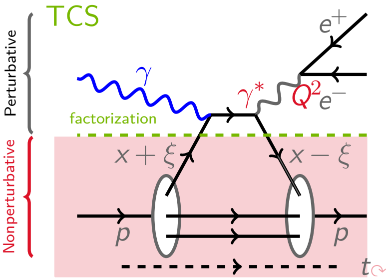
Exclusive processes of current interest (1/2).

Factorization and universality.









Exclusive processes of present interest (2/2).

Factorization and universality.

Bjorken regime : large Q^2 and fixed $xB \simeq 2\xi/(1+\xi)$

- Partonic interpretation relies on **factorization theorems**.
- All-order proofs for DVCS, TCS and some DVMP.
- GPDs depend on a (arbitrary) factorization scale μ_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**.

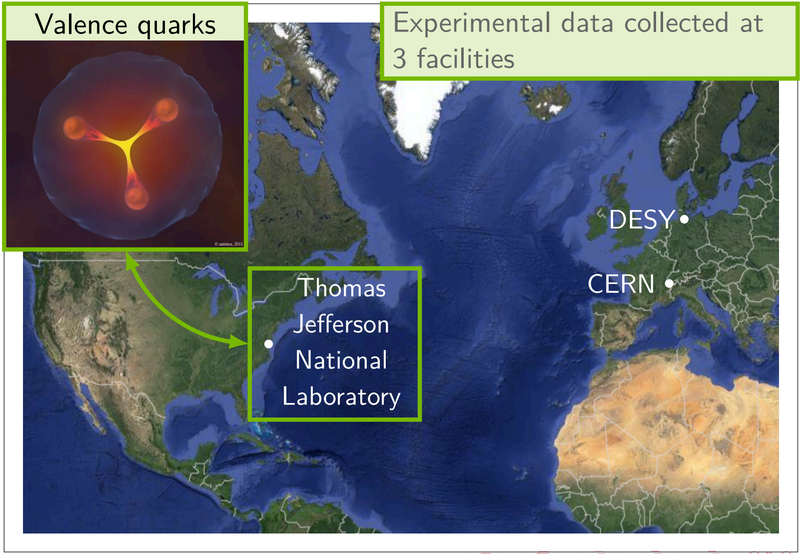
Need for global fits of world data.

Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities

Need for global fits of world data.

Different facilities will probe different kinematic domains.



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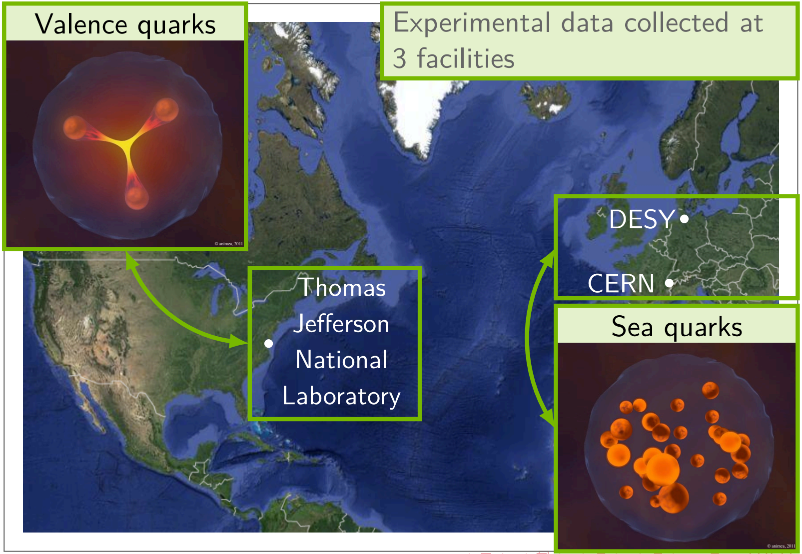

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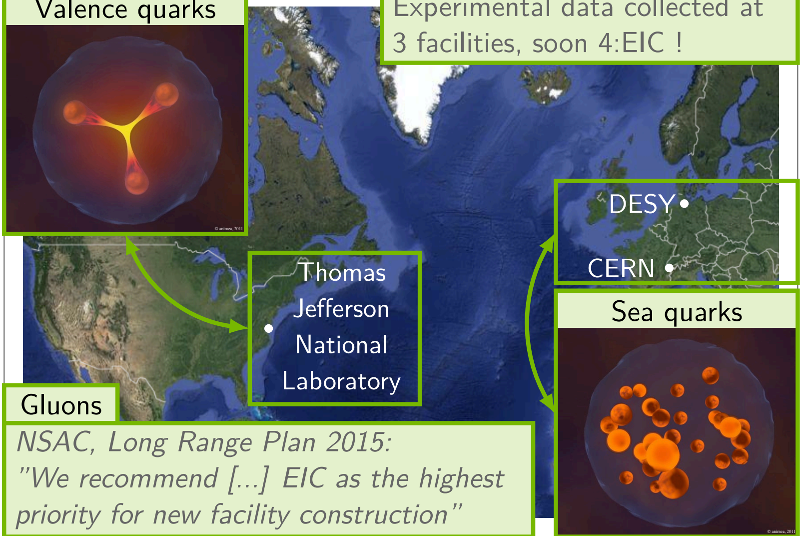


Experimental data collected at 3 facilities, soon 4:EIC !

Valence quarks

Sea quarks

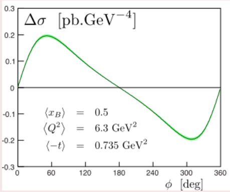
Gluons

NSAC, Long Range Plan 2015:
"We recommend [...] EIC as the highest priority for new facility construction"

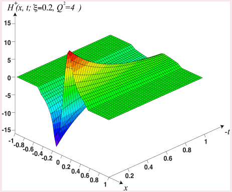
Imaging the nucleon. How?

Extracting GPDs is not enough...Need to extrapolate!

1. Experimental data fits



2. GPD extraction



3. Nucleon imaging

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

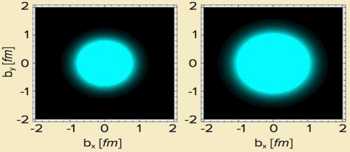
Reaching for the Horizon

The 2015 Long Range Plan for Nuclear Science

Sidebar 2.2: The First 3D Pictures of the Nucleon

A computed tomography (CT) scan can help physicians pinpoint minute cancer tumors, diagnose tiny broken bones, and spot the early signs of osteoporosis. Now physicists are using the principles behind the procedure to peer at the inner workings of the proton. This breakthrough is made possible by a relatively new concept in nuclear physics called generalized parton distributions.

An intense beam of high-energy electrons can be used



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. **Extrapolate** $H(x, 0, t, \mu_F^{\mathrm{ref}})$ up to infinite t and down to vanishing t.
4. **Compute** 2D Fourier transform in transverse plane:

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

5. **Propagate** uncertainties.
6. **Control** extrapolations with an accuracy matching that of experimental data with **sound** GPD models.

1. The PARTONS framework.
2. Features and performances.
3. Releases.

The PARTONS framework

PARtonic
Tomography
Of
Nucleon
Software

Computing chain design.

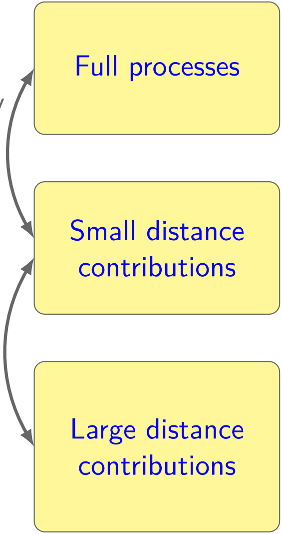
Differential studies: physical models and numerical methods.

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



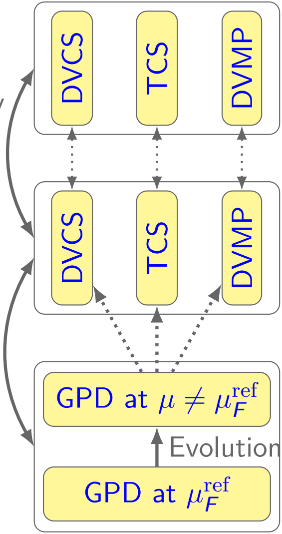
Computing chain design.

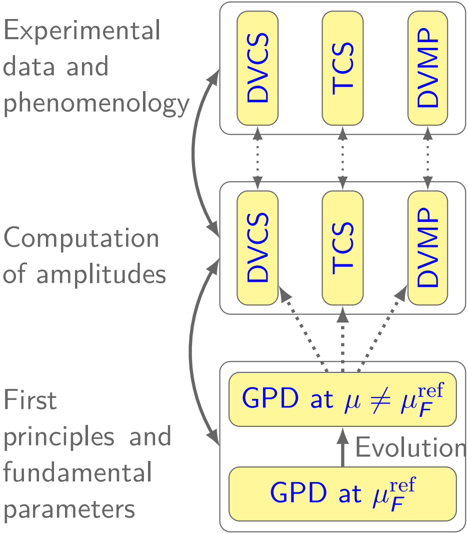
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters





- Many observables.
- Kinematic reach.

Computing chain design.

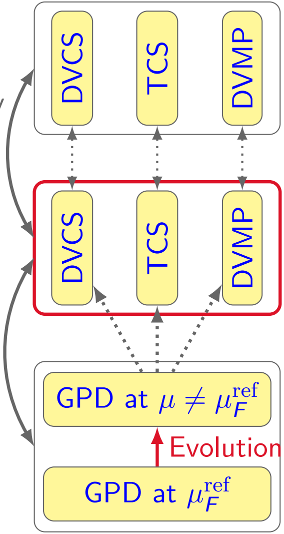
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

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

Computing chain design.

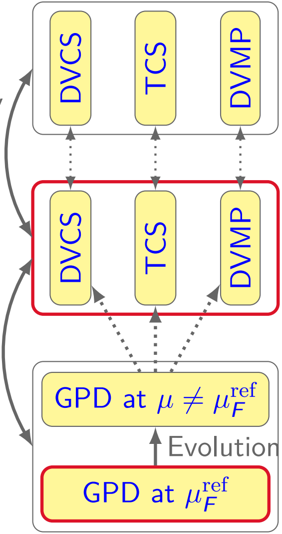
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



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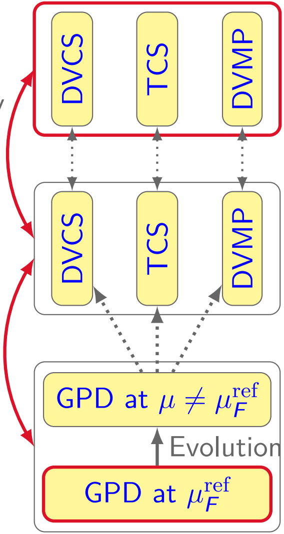

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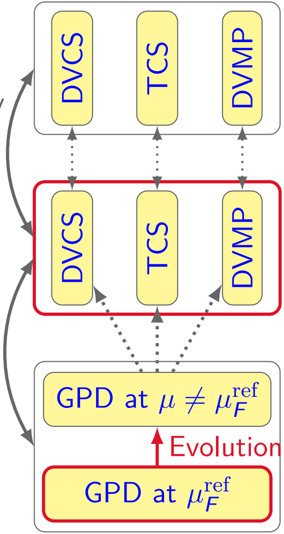

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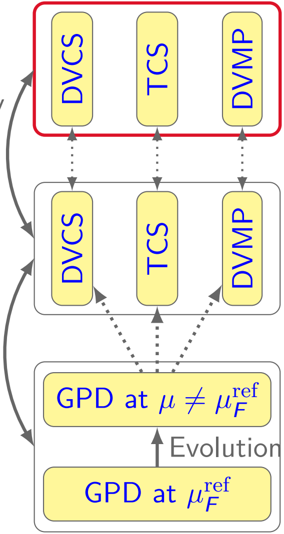

- Many observables.
- Kinematic reach.

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Towards the first release.

Currently: tests, benchmarking, documentation, tutorials.

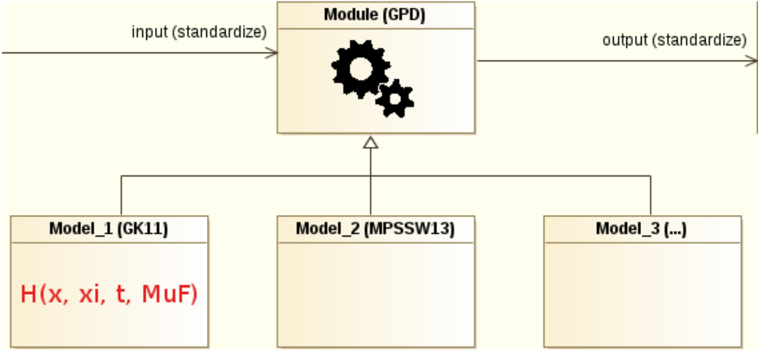
- 3 stages:
  1. Design.
  2. Integration and validation.
  3. Benchmarking and production.
- Flexible software architecture.

  B. Berthou *et al.*, *PARTONS: a computing platform for the phenomenology of Generalized Parton Distributions*

  arXiv:1512.06174, *to appear in Eur. Phys. J. C.*
- 1 new physical development = 1 new module.
- *Aggregate* **knowledge** and **know-how**:
  - Models
  - Measurements
  - Numerical techniques
  - Validation
- What *can* be automated *will be* automated.

Modularity.

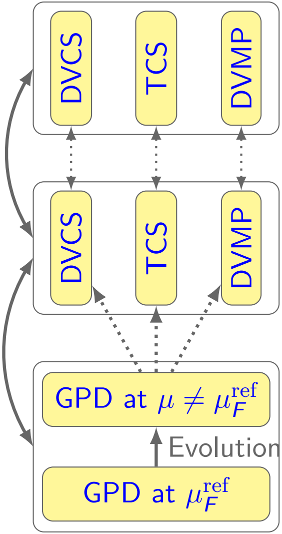
Inheritance, standardized inputs and outputs.



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

Flexibility.

Example: implementation of new coefficient functions.



- A DVCS coefficient function module generically outputs a complex number when provided $(\xi, t, Q^2, \mu_F^2, \mu_R^2)$.

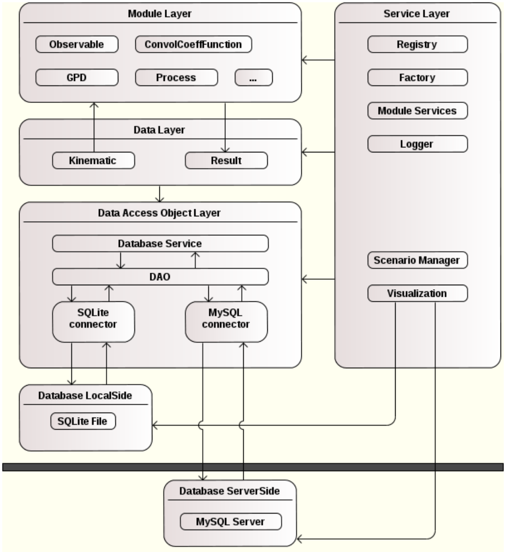
ConvolCoeffFunctionModule.h

```
virtual std::complex<double> compute(
double xi, double t, double Q2, double MuF2,
 double MuR2, GPDType::Type gpdType) =
0;
```

- This module can be anything:
  - Constant CFFs for local fits.
  - CFFs for massless quarks.
  - CFFs for heavy quarks.
  - CFFs with TMC.
  - ...

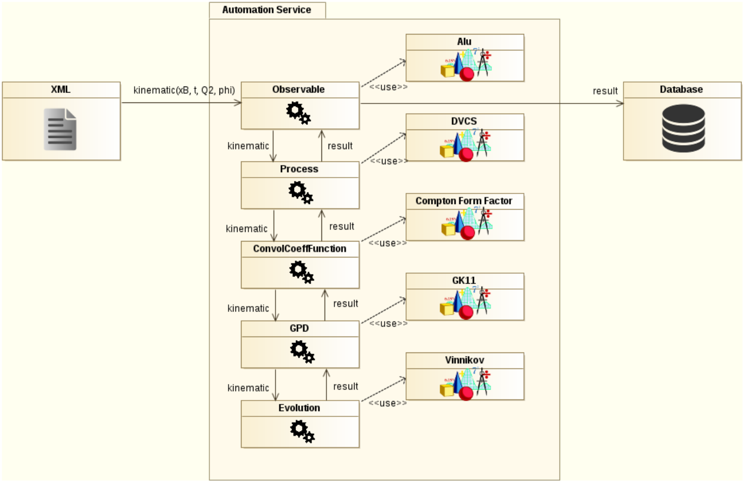
Modularity and layer structure.

Modifying one layer does not affect the other layers.

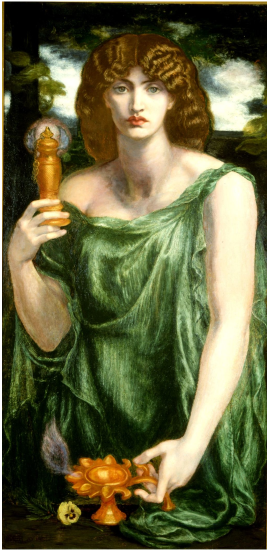


Modularity and automation.

Parse XML file, compute and store result in database.



- Keep track of validated results.
- Systematic nonregression tests.
- Help preparing new releases.
- Store experimental data.
- Store grids of new models.
- Post processing?
- Time consuming fits?



Handling experimental data.
Using the power of SQL for data selections (1/2).

- **All fixed-target DVCS data collected at Jefferson Lab** are stored in the database used for fits.
- No data about TCS or DVMP so far.
- Including **all existing DVCS data sets** in a database is **a matter of hours**.
- Data selection from SQL requests for fits.

insert_CLAS_asymmetries.sql

```sql
-- Kinematics --
INSERT INTO observable_kinematic (bin_id, xB, t, Q2, E, phi) VALUES(0, 0.19400, -0.11000, 1.68000, 5.93200, 25.00000);
SET @last_observable_kinematic_id = LAST_INSERT_ID();
-- Value and uncertainties --
INSERT INTO observable_result (observable_name, observable_value, stat_error_lb, stat_error_ub, syst_error_lb, syst_error_ub, total_error, observable_kinematic_id) VALUES('Alu', 0.37000, 0.23000, 0.23000, 0.01000, 0.01000, 0.00000, @last_observable_kinematic_id);
```

Handling experimental data.

Using the power of SQL for data selections (2/2).

- The database can be used for fits too!
- In fact, observable layer has been **designed for fits**: all observables correspond to the **same kind of object** from a software point of view.

fit_scenario.xml

```
...
<!-- 3th step : write your custom SQL query to select your observables -->
<task service="FitsService" method="selectObservables">
    <kinematics type="ObservableResult">
        <param name="SQLQuery" value="SELECT␣*␣FROM␣
observable_result␣obsr,␣observable_kinematic␣obsk␣WHERE␣(obsr.
observable_result_id␣BETWEEN␣4965␣AND␣5420)␣AND␣-obsk.t/obsk.Q2␣<␣
0.2␣AND␣obsk.Q2␣>␣1.5;" />
    </kinematics>
</task>
...
```

gpdExample()

```
// Lots of includes
#include <src/Partons.h>
...
// Retrieve GPD service
GPDService* pGPDService = Partons::getInstance()->getServiceObjectRegistry
()->getGPDService();
// Load GPD module with the BaseModuleFactory
GPDModule* pGK11Model = Partons::getInstance()->getModuleObjectFactory
()->newGPDModule(GK11Model::classId);
// Create a GPDKinematic(x, xi, t, MuF, MuR) to compute
GPDKinematic gpdKinematic(0.1, 0.00050025, -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 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 kinematic -->
        <kinematics type="GPDKinematic">
            <param name="x" value="0.1" />
            <param name="xi" value="0.00050025" />
            <param name="t" value="-0.3" />
            <param name="MuF2" value="8" />
            <param name="MuR2" value="8" />
        </kinematics>
    <!-- Select GPD model and set parameters -->
    <computation_configuration>
            <module type="GPDModule">
                <param name="className" value="GK11Model" />
            </module>
    </computation_configuration>
</task>
</scenario>
```

computeOneGPD.xml

```xml
<?xml version="1.0" encoding="UTF-8" stand
<scenario id="01" date="" description="Examp
␣model␣(GK11)␣without␣evolution">
    <!-- Select type of computation -->
    <task service="GPDService" method="com
        <!-- Specify kinematic -->
        <kinematics type="GPDKinematic">
            <param name="x" value="0.1" />
            <param name="xi" value="0.000
            <param name="t" value="-0.3" /
            <param name="MuF2" value="8" /
            <param name="MuR2" value="8" /
        </kinematics>
    <!-- Select GPD model and set parameter
    <computation_configuration>
            <module type="GPDModule">
                <param name="className" va
            </module>
    </computation_configuration>
</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, $\tilde{H}$, $\tilde{E}$, ...

Observable computing automated.

Each line of code corresponds to a physical hypothesis.

computeManyKinematicsOneModel.xml

```
<scenario date="2016-10-18" description="Use␣kinematics␣list">
    <task service="ObservableService" method="
computeManyKinematicOneModel" storeInDB="1">
        <kinematics type="ObservableKinematic">
            <param name="file" value="observable_kinematics.dat" />
        </kinematics>
        <computation_configuration>
            <module type="Observable">
                <param name="className" value="Alu" />
            </module>
            <module type="DVCSModule">
                <param name="className" value="BMJ2012Model" />
                <param name="beam_energy" value="1066" />
            </module>
            <module type="DVCSConvolCoeffFunctionModule">
                <param name="className" value="DVCSCFFModel" />
                <param name="qcd_order_type" value="LO" />
            </module>
            <module type="GPDModule">
                <param name="className" value="GK11Model" />
            </module>
        </computation_configuration>
```

Features and performances

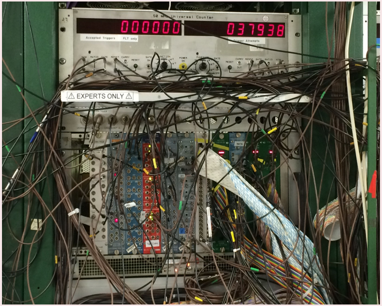
Systematic studies made easy.

A faster and safer way to GPD phenomenology.

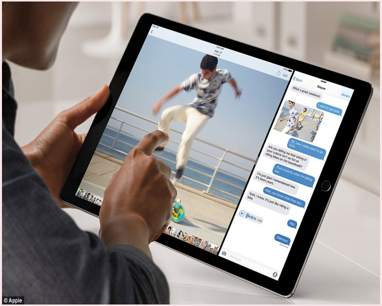
Automation allows...:

- to run **numerous computations** with various physical assumptions,
- to run **nonregression** tests.
- to perform **fits** with various models.
- physicists to **focus on physics**!

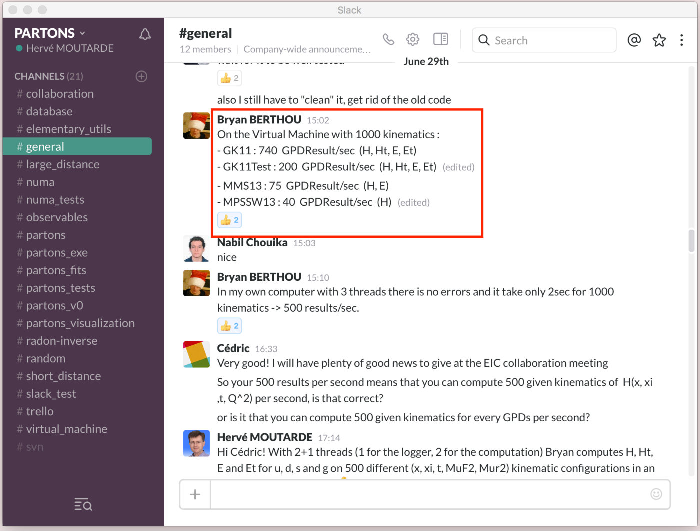
Without PARTONS



With PARTONS



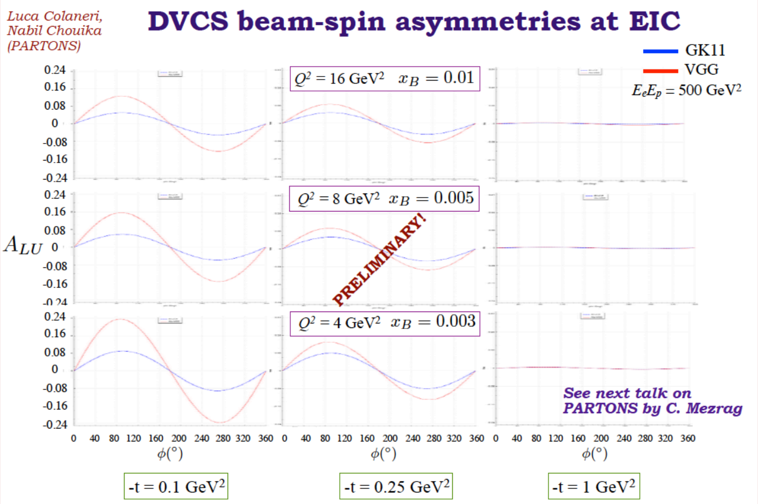
GPD computations with or without threads



Systematic studies made fast (1/2).

What can be done from scratch in about 1 hour.

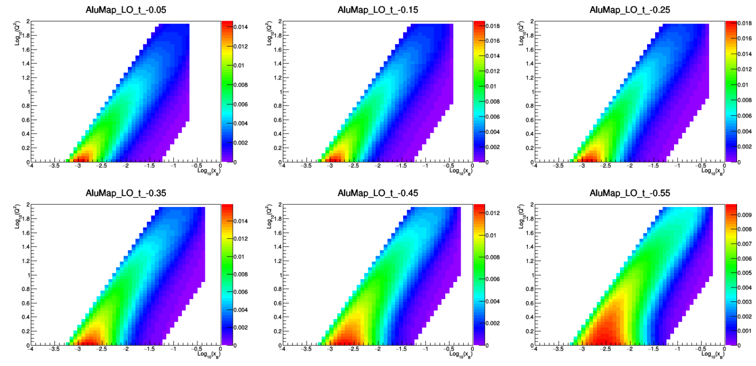
From D. Sokhan's talk, EIC User Group Meeting, ANL, 2016



Systematic studies made fast (2/2).

EIC observables computed with different pQCD assumptions.

(Preliminary) $A_{\mathrm{LU}}(90°)$ at LO with Goloskokov-Kroll model

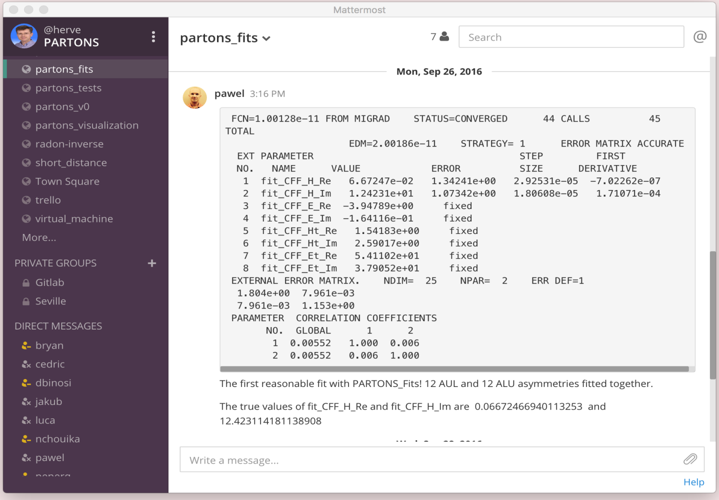


Colaneri *et al.*, *Work in progress*

GPD or CFF fits (1/4).

Local fit of CFFs.

First local fit of pseudo DVCS data, Sep. 26^{th}, 2016



Parametric global fit of JLab DVCS data, Apr. 5th, 2017

RESULTS

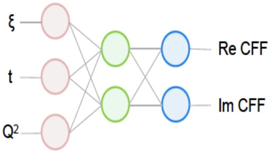
- Kinematic cuts — $Q^2 > 1.5$ GeV^2 (*where we can rely on LO approximation*)
  $-t / Q^2 < 0.25$ (*where we can rely on GPD factorization*)
- χ^2 / ndf — 3272.6 / (3433 - 7) ≈ 0.96
- Free parameters — a_{Hsea}, $a_{\tilde{H}val}$, $a_{\tilde{H}sea}$, C_{sub}, a_{sub}, N_E, $N_{\tilde{E}}$
- χ^2 / ndf per data set

[1] Phys. Rev. C 92, 055202 (2015)
[2] Phys. Rev. Lett. 115, 212003 (2015)
[3] Phys. Rev. D 91, 052014 (2015)

Experiment	Reference	Observables	N points all	N points selected	chi2	chi2 / ndf
Hall A	[1] KINX2	σUU	120	120	135.0	1.19
Hall A	[1] KINX2	ΔσLU	120	120	98.9	0.88
Hall A	[1] KINX3	σUU	108	108	274.8	2.72
Hall A	[1] KINX3	ΔσLU	108	108	107.3	1.06
CLAS	[2]	σUU	1933	1333	1089.2	0.82
CLAS	[2]	ΔσLU	1933	1333	1171.9	0.88
CLAS	[3]	AUL, ALU, ALL	498	305	338.1	1.13

Neural network global fit of CLAS asymmetries, May 31^{st}, 2017

NEURAL NETWORK



- Our very first attempt to use NN technique → proof of feasibility
- Genetic algorithm (GA) to learn NN
- NN and GA libraries by PARTONS group

- Very simple design of NN
- CLAS asymmetry data only
- χ^2 / ndf = 273.9 / (305 - 68) ≈ 1.16

Paweł Sznajder | Nucleon and Resonance Structure Workshop 2017 | 23

GPD or CFF fits (4/4).

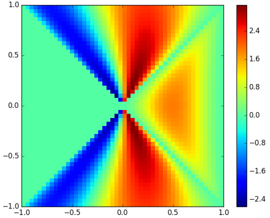
From local to global fits in 8 months!

- PARTONS architecture allows focusing on **parameterization** and **fitting engine**.
- The **same machinery** is used for local **and** global fits.
- **Fast** and **constant** progress since the first fits.

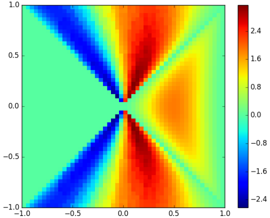
See Pawel Sznajder's talk today!

Covariant and positive GPD models.

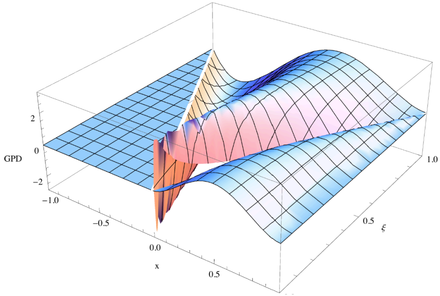
First systematic procedure to build models satisfying all constraints.



Analytic result



Numerical result



Algebraic Dyson Schwinger LFWF

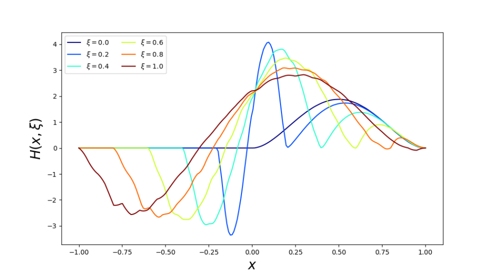
Chouika et al.

Work in progress

Covariant and positive GPD models.

First systematic procedure to build models satisfying all constraints.

(Preliminary) AdS/QCD LFWF



Chouika *et al.*, *Work in progress*

See José Rodríguez-Quintero's talk today!

- Numerics under control for **smooth** LFWFs.
- Situation with **Regge behavior** currently studied.
- Towards **consistent modeling and fit** of GPDs and TMDs? Wigner functions?

Releases

First release content.

DVCS channel only.

GPD modules

- GK
- VGG
- Vinnikov (evolution)
- MPSSW13 (NLO study)
- MMS13 (DD study)

DVCS modules

- VGG
- BMJ

CFF modules

- LO
- NLO
- NLO Noritzsch

Evolution modules

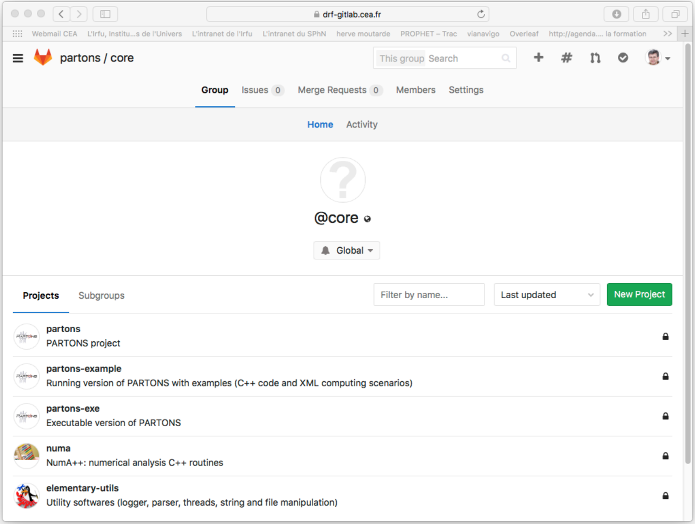
- Vinnikov (LO)

α_s modules

- 4-loop perturbation
- constant value

Open-source release.

Soon publicly available on CEA GitLab server.



Future releases.

A lot remains to be integrated...Contributors welcome!

PARTONS

Channel modules

- DVMP
- TCS
- ???

Other modules

- Mellin moments (EM tensor, lattice QCD)
- ???

Hadron structure modules

- DAs
- DDs
- Form factors
- PDFs
- LFWFs
- ???

Nonperturbative QCD modules

- Gap equation solver
- ???

- Still **room for improvement** in first version but framework should become available to a wide community of users.
- User feedback much welcome! However the PARTONS team **will not provide support** for major modifications like *e.g.* translation into Java.
- It took years to design, write and validate PARTONS in C++. Time to **produce physics** with it; starting another software project would be **much premature**.
- PARTONS team will take responsibility only for **main branch**.
- Please make any new module **available to the whole community** through the main PARTONS branch.

Conclusion

Conclusions and prospects.
Towards a unifying framework for GPD studies.

- **A lot has been achieved in the last few years!**
- Initiated as an experimentalist companion, grown as a **multidisciplinary project** attracting theorists to the field.
- **Challenging constraints** expected from Jefferson Lab, COMPASS and EIC.
- Development of the PARTONS framework for **phenomenology** and **theory** purposes.
- **Fitting engine** ready for global and local fits. **Original global CFF fits** recently achieved, meeting initial aim!
- Forthcoming **open-source release** of PARTONS.

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