PARTONS view on Transverse Polarized Target TCS

C. Mezrag

INFN Roma 1

On behalf of the PARTONS team

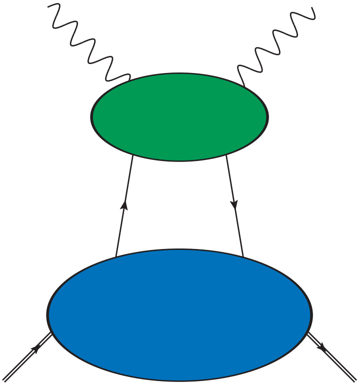
PARTONS

- PARtonic Tomography Of Nucleon Software: a software dedicated to the study of GPDs and exclusive processes.
  B. Berthou *et al.*, *PARTONS: a computing platform for the phenomenology of Generalized Parton Distributions*

  arXiv:1512.06174
- Such a study requires a flexible software architecture.
- Maximal automation to focus on physics.
- The V1 code is ready and working. All features have been tested and implemented.
- We obtained the final cybersecurity authorisation for the PARTONS website:

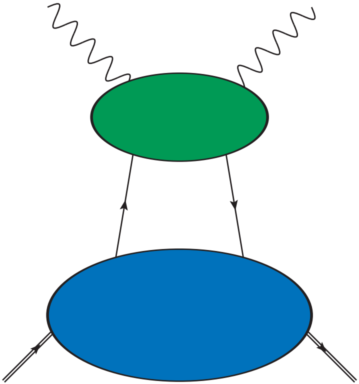
  http://partons.cea.fr

  The code and virtual machine will be released there as soon as we will have finished the companion paper.



- Hard Part: Short distance interactions computed through perturbation theory.
- Soft Part: Long distance interactions encoded in GPDs; realm of non-perturbative QCD.

TCS at Leading Twist



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Deep Exclusive Processes are understood thanks to a combination of both perturbative and non perturbative QCD.

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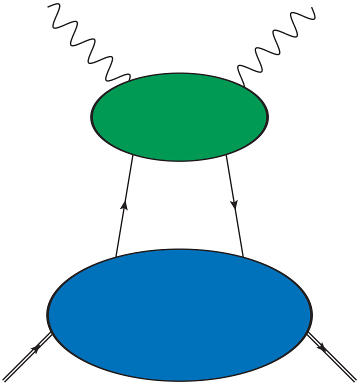

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Deep Exclusive Processes are understood thanks to a combination of both perturbative and non perturbative QCD.

This entanglement requires a flexible software to perform extensive studies

Long Range Correlations: GPDs domain

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$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,z=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}\gamma^+u + E^q(x,\xi,t)\bar{u}\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u\right].$$

$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\gamma_5\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,z=0}$$
$$= \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}\gamma^+\gamma_5 u + \tilde{E}^q(x,\xi,t)\bar{u}\frac{\gamma_5\Delta^+}{2M}u\right].$$

D. Müller *et al.*, Fortsch. Phy. 42 101 (1994)
X. Ji, Phys. Rev. Lett. **78**, 610 (1997)
A. Radyushkin, Phys. Lett. **B380**, 417 (1996)

4 GPDs without helicity transfer + 4 helicity flip GPDs

Long Range Correlations: GPDs domain

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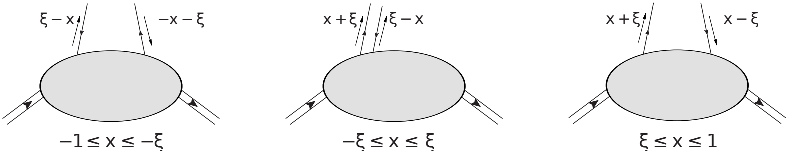

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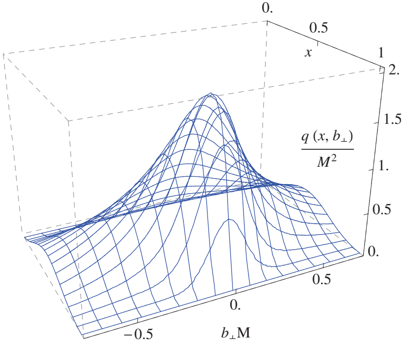
M. Burkardt, Phys. Rev. **D62**, 071503 (2000)



Pion GPD in Impact parameter space from:
CM *et al.*, Phys. Lett. **B741**, 190-196 (2015)

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  - can split in terms of quark flavour and gluon contributions,
  - can be related to the 2+1D parton number density when $\xi \to 0$.
  - are univeral, *i.e.* are related to the Compton Form Factors (CFFs) of various exclusive processes through convolutions:

$$\mathcal{H}(\xi, t) = \int \mathrm{d}x \; C(x, \xi, t) H(x, \xi, t)$$

- Polynomiality Property:

$$\int_{-1}^{1} \mathrm{d}x \; x^m H^q(x,\xi,t) = \sum_{j=0}^{\left[\frac{m}{2}\right]} \xi^{2j} C_{2j}^q(t) + mod(m,2)\xi^{m+1} C_{m+1}^q(t)$$

Lorentz Covariance

GPDs: What we know from the theory side

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

$$\left| H^q(x,\xi,t) - \frac{\xi^2}{1-\xi^2} E^q(x,\xi,t) \right| \leq \sqrt{\frac{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)}{1-\xi^2}}$$

A. Radysuhkin, Phys. Rev. **D59**, 014030 (1999)
B. Pire *et al.*, Eur. Phys. J. **C8**, 103 (1999)
M. Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)
P.V. Pobilitsa, Phys. Rev. **D65**, 114015 (2002)

Positivity of Hilbert space norm

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

$$x \in [-1; 1]$$

M. Diehl and T. Gousset, Phys. Lett. **B428**, 359 (1998)

Relativistic quantum mechanics

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- Soft pion theorem (pion GPDs only)

  M.V. Polyakov, Nucl. Phys. **B555**, 231 (1999)
  CM *et al.*, Phys. Lett. **B741**, 190 (2015)

  Dynamical Chiral Symmetry Breaking

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  Dynamical Chiral Symmetry Breaking

How can we implement all these constraints?

- There is still no GPDs models relying only on first principles,
- This may change with our recent work on the Radon Transform,

  N. Chouika *et al.* EPJC 77 906 and arXiv:1711.11548

- Still several "phenomenological" approaches have been developed

Phenomenological approaches of GPDs

- Double Distribution models:
  I.V. Musatov and A.V. Radysuhkin, Phys. Rev. **D61**, 074029 (2000)
  M. Guidal *et al.*, Phys. Rev. **D72**, 054013 (2005)
  S.V. Goloskokov and P. Kroll, Eur. Phys. J. **C42**, 281 (2005)
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- Mellin-Barnes approach and Dual models are in fact equivalent
  D. Müller *et al.*, JHEP **1503**, 52 (2014)

What is inside PARTONS?

- Four phenomenological models have been implemented:
  - updated version of the Goloskokov-Kroll model (Eur. Phys. J. **C42**, 281 (2005))
  - the Mezrag-Moutarde-Sabatié model (Phys. Rev. **D88**, 014001 (2013))
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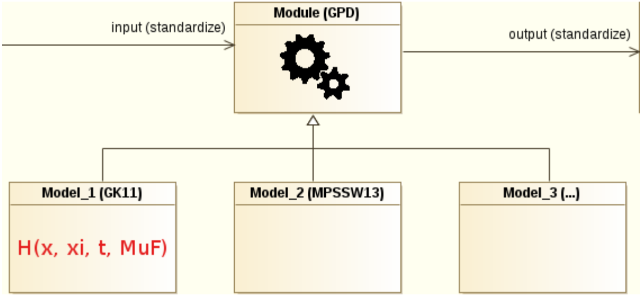
- Make as easy as possible for users to add their own favourite model through the modular architecture



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- Designed to be able to deal with forthcoming models based on Light-Front Wave Functions.

CM *et al.*, Phys. Lett. **B741**, 190-196 (2015)
CM *et al.*, Few Body Sys. 57 (2016) 729-772
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- Inbuilt evolution kernel is fully automatised, even for non-inbuilt models.

Evolution

- The evolution is performed using the so-called Vinnikov code (A. Vinnikov hep-ph/0604248) translated in C++.
- The code solves the evolution equations behaving like:

$$\frac{\partial H}{\partial \ln \mu_F^2}(x,\xi,t,\mu) = \int \mathrm{d}y V(x,y,\xi) H(y,\xi,t,\mu_F^2)$$

  using the Runge-Kutta of order 4 technique.
- Evolution can be done this way for any model, including those you may want to add.
- The number of flavour is fixed to 3, this will be improved in future releases.

Short range interaction

Short range interaction

- Compton Form Factors (CFF):

$$\mathcal{H}(\xi, t) = \int \mathrm{d}x \; C(x, \xi, t) H(x, \xi, t)$$

$$\begin{cases} \Re\mathcal{H}(\xi, t) = \int \mathrm{d}x \, C_R(x, \xi, t) H(x, \xi, t) \\ \Im\mathcal{H}(\xi, t) = \int \mathrm{d}x \, C_I(x, \xi, t) H(x, \xi, t) \end{cases}$$

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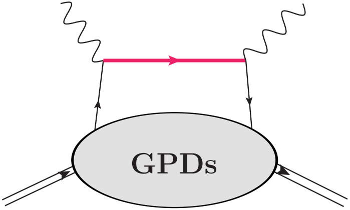
- At LO only quarks contribute to the hard kernel (TCS):
  The imaginary part of the CFF is proportional to the GPD at $x = \xi$.



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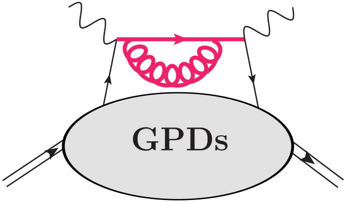
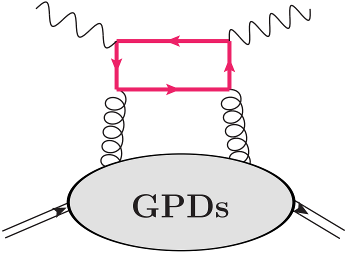
- At LO only quarks contribute to the hard kernel (TCS): The imaginary part of the CFF is proportional to the GPD at $x = \xi$.
- At NLO, both quarks and gluons contribute.





Observables (DVCS)

Experiment	Observable	Normalized CFF dependence
HERMES	$A_{\mathrm{C}}^{\cos 0\phi}$	$\mathrm{Re}\mathcal{H} + 0.06\mathrm{Re}\mathcal{E} + 0.24\mathrm{Re}\widetilde{\mathcal{H}}$
	$A_{\mathrm{C}}^{\cos \phi}$	$\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\mathcal{E} + 0.15\mathrm{Re}\widetilde{\mathcal{H}}$
	$A_{\mathrm{LU,I}}^{\sin \phi}$	$\mathrm{Im}\mathcal{H} + 0.05\mathrm{Im}\mathcal{E} + 0.12\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{+,\sin \phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.10\mathrm{Im}\mathcal{H} + 0.01\mathrm{Im}\mathcal{E}$
	$A_{\mathrm{UL}}^{+,\sin 2\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} - 0.97\mathrm{Im}\mathcal{H} + 0.49\mathrm{Im}\mathcal{E} - 0.03\mathrm{Im}\widetilde{\mathcal{E}}$
	$A_{\mathrm{LL}}^{+,\cos 0\phi}$	$1 + 0.05\mathrm{Re}\widetilde{\mathcal{H}} + 0.01\mathrm{Re}\mathcal{H}$
	$A_{\mathrm{LL}}^{+,\cos \phi}$	$1 + 0.79\mathrm{Re}\widetilde{\mathcal{H}} + 0.11\mathrm{Im}\mathcal{H}$
	$A_{\mathrm{UT,DVCS}}^{\sin(\phi-\phi_S)}$	$\mathrm{Im}\mathcal{H}\mathrm{Re}\mathcal{E} - \mathrm{Im}\mathcal{E}\mathrm{Re}\mathcal{H}$
	$A_{\mathrm{UT,I}}^{\sin(\phi-\phi_S)\cos\phi}$	$\mathrm{Im}\mathcal{H} - 0.56\mathrm{Im}\mathcal{E} - 0.12\mathrm{Im}\widetilde{\mathcal{H}}$

Tables from P. Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

Observables (DVCS)

Experiment	Observable	Normalized CFF dependence
CLAS	$A_{\mathrm{LU}}^{-,\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.06\mathrm{Im}\mathcal{E} + 0.21\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{-,\sin\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.12\mathrm{Im}\mathcal{H} + 0.04\mathrm{Im}\mathcal{E}$
	$A_{\mathrm{UL}}^{-,\sin 2\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} - 0.79\mathrm{Im}\mathcal{H} + 0.30\mathrm{Im}\mathcal{E} - 0.05\mathrm{Im}\widetilde{\mathcal{E}}$
HALL A	$\Delta\sigma^{\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.07\mathrm{Im}\mathcal{E} + 0.47\mathrm{Im}\widetilde{\mathcal{H}}$
	$\sigma^{\cos 0\phi}$	$1 + 0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos\phi}$	$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

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Observables (DVCS)

Experiment	Observable	Normalized CFF dependence
HERA	σ_{DVCS}	$\mathcal{H}\mathcal{H}^* + 0.09\mathcal{E}\mathcal{E}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*$

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- Forthcoming experiments:
  - DVCS, DVMP and TCS at JLab 12
  - On going DVCS program at COMPASS
  - Exclusive processes at EIC for gluon tomography

Why PARTONS?

- From GPDs to observables
  - Flexibility in the choice of models
  - Flexibility in the scale of GPDs (evolution)
  - Computation of CFFs
  - Flexibility in the choice of pertubative approximation (α_s)
  - Flexibility in changing twist approximations ($1/Q$)
  - Computations of a given set of observables

PARTONS contains the tools to compare your GPD model to available data

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- From observables to GPDs:
  - Flexibility in the choice of observables
  - Extraction of CFFs
  - Flexibility in changing twist approximations ($1/Q$)
  - Extraction of GPDs at a given scale (evolution)
  - Flexibility in the choice of pertubative approximation (α_s)

PARTONS allows you to extract GPDs from your favourite data set.

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

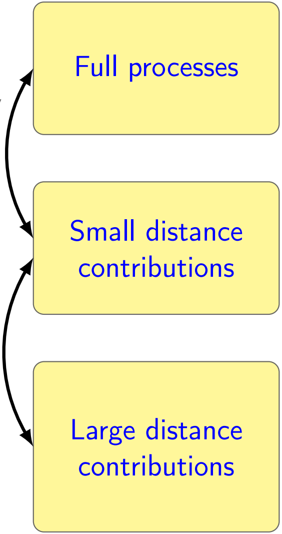
Computing chain design.

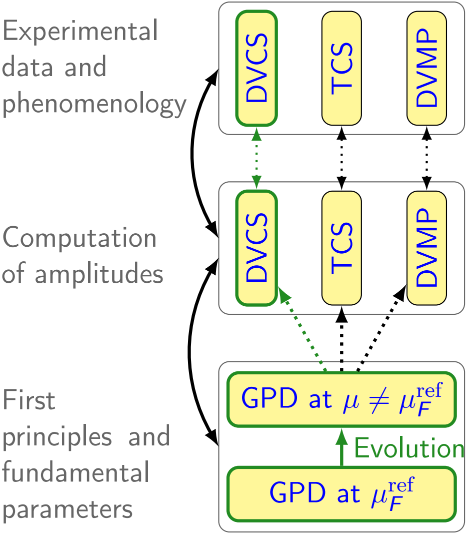
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

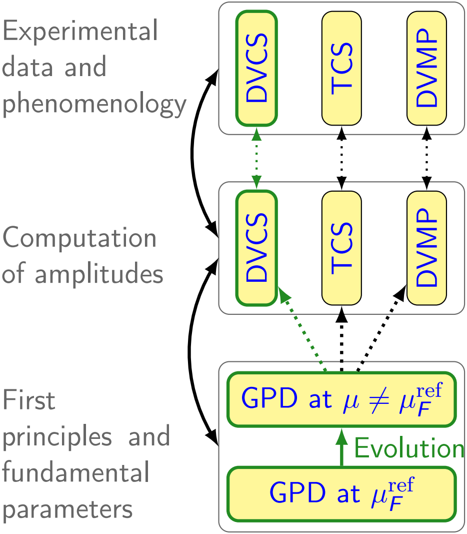
Computation of amplitudes

First principles and fundamental parameters





- DVCS chain is done and working
- Including LO evolution and NLO CFF



- DVCS chain is done and working
- Including LO evolution and NLO CFF

- TCS code exists at NLO but needs to be implemented in PARTONS
- DVMP requires more work due to meson PDAs

Recipes on xml

```xml
<!-- Indicate service and its methods to be used and indicate if the result should be stored in the database -->
<task service="ObservableService" method="computeObservable" storeInDB="0">

   <!-- Define DVCS observable kinematics -->
   <kinematics type="ObservableKinematic">
      <param name="xB" value="0.2" />
      <param name="t" value="-0.1" />
      <param name="Q2" value="2." />
      <param name="E" value="6." />
   </kinematics>

   <!-- Define physics assumptions -->
   <computation_configuration>

      <!-- Select DVCS observable -->
      <module type="Observable" name="DVCSAllMinus">

         <!-- Select DVCS process model -->
         <module type="ProcessModule" name="DVCSProcessGV08">

            <!-- Select scales module -->
            <!-- (it is used to evaluate factorization and renormalization scales out of kinematics) -->
            <module type="ScalesModule" name="ScalesQ2Multiplier">

               <!-- Configure this module -->
               <param name="lambda" value="1." />
            </module>

            <!-- Select xi-converter module -->
            <!-- (it is used to evaluate GPD variable xi out of kinematics) -->
            <module type="XiConverterModule" name="XiConverterXBToXi">
            </module>

            <!-- Select DVCS CFF model -->
            <module type="ConvolCoeffFunctionModule" name="DVCSCFFStandard">

               <!-- Indicate pQCD order of calculation -->
               <param name="qcd_order_type" value="NLO" />

               <!-- Select GPD model -->
               <module type="GPDModule" name="GPDMMS13">
               </module>

            </module>

         </module>

      </module>

   </computation_configuration>
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    <param name="t" value="-0.1" />
    <param name="Q2" value="2." />
    <param name="E" value="6." />
</kinematics>
```

Recipes on xml

```
<!-- Define physics assumptions -->
<computation_configuration>

   <!-- Select DVCS observable -->
   <module type="Observable" name="DVCSAllMinus">

      <!-- Select DVCS process model -->
      <module type="ProcessModule" name="DVCSProcessGV08">

         <!-- Select scales module -->
         <!-- (it is used to evaluate factorization and renormalization scales out of kinematics) -->
         <module type="ScalesModule" name="ScalesQ2Multiplier">

            <!-- Configure this module -->
            <param name="lambda" value="1." />
         </module>

         <!-- Select xi-converter module -->
         <!-- (it is used to evaluate GPD variable xi out of kinematics) -->
         <module type="XiConverterModule" name="XiConverterXBToXi">
         </module>

         <!-- Select DVCS CFF model -->
         <module type="ConvolCoeffFunctionModule" name="DVCSCFFStandard">

            <!-- Indicate pQCD order of calculation -->
            <param name="qcd_order_type" value="NLO" />

            <!-- Select GPD model -->
            <module type="GPDModule" name="GPDMMS13">
            </module>

         </module>

      </module>

   </module>
```

Provided Examples

- At GPD level:
  - How to get a given set of GPD at one defined $(x, \xi, t, \mu_R, \mu_F)$ kinematics
  - How to get a list of results from a file containing multiple kinematics.
  - How to plot the results stored in the database.
  - How to use evolution equations
  - How to change integration routines
- at CFF level:
  - How to get a set of CFF at one defined (x_B, t, Q^2) kinematics
  - How to get multiple results from multiple kinematic stored in a given file.
  - How to plot the results from the database.
  - How to change integration routines
- at Observable level:
  - Same thing than CFF with additionnal angular dependence.

C++ Users

```cpp
void computeSingleKinematicsForGPD() {

    // Retrieve GPD service
    PARTONS::GPDService* pGPDService =
            PARTONS::Partons::getInstance()->getServiceObjectRegistry()->getGPDService();

    // Create GPD module with the BaseModuleFactory
    PARTONS::GPDModule* pGPDModel =
            PARTONS::Partons::getInstance()->getModuleObjectFactory()->newGPDModule(
                    PARTONS::GPDMMS13::classId);

    // Create a GPDKinematic(x, xi, t, MuF, MuR) to compute
    PARTONS::GPDKinematic gpdKinematic(0.1, 0.2, -0.1, 2., 2.);

    // Run computation
    PARTONS::GPDResult gpdResult = pGPDService->computeGPDModel(gpdKinematic,
            pGPDModel);

    // Print results
    PARTONS::Partons::getInstance()->getLoggerManager()->info("main", __func__,
            gpdResult.toString());

    // Remove pointer reference ; Module pointers are managed by PARTONS.
    PARTONS::Partons::getInstance()->getModuleObjectFactory()->updateModulePointerReference(
            pGPDModel, 0);
    pGPDModel = 0;
}
```

PARTONS

PARtonic Tomography Of Nucleon Software

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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 carrying 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. A detailed description of the project can be found here.

Table of Contents

Get PARTONS

Here you can learn how to get your own version of PARTONS. We offer two ways.

You can use our provided virtual machine with an out-of-the-box PARTONS runtime and development environment. This is the easiest way to start your experience with PARTONS.

Using PARTONS with our provided Virtual Machine

You can also build PARTONS by your own on either GNU/Linux or Mac OS X. This is useful if you want to have PARTONS on your computer without using the virtualization technology or if you want to use PARTONS on computing farms.

Using PARTONS on GNU/Linux

Using PARTONS on Mac OS X

Configure PARTONS

If you are using **our virtual machine**, you will find all configuration files set up and ready to be used. However, if you want to tune the configuration or if you have installed PARTONS by your own, this tutorial will be helpful for

http://partons.cea.fr

Website

PARTONS

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Class List

Here are the classes, structs, unions and interfaces with brief descriptions:

[detail level 1 2]

▼ N PARTONS	
C ActiveFlavorsThresholds	Interval of factorization scale with fixed number of flavors
C ActiveFlavorsThresholdsModule	Abstract class for modules defining number of quark flavors intervals
C ActiveFlavorsThresholdsQuarkMasses	Number of active quark flavors intervals corresponding to quark masses
C AutomationService	Automation service is designed to dynamically run complex tasks (by calling service object methods) or to create some complex C++ objects, all described by an XML file
C BaseObject	**BaseObject** is the "zeroth-level-object" of the architecture
C BaseObjectData	Container to store data to be used by base objects
C BaseObjectFactory	Provides a clone (returned as a **BaseObject** pointer) of an object identified by its class name and previously stored in the **BaseObjectRegistry**
C BaseObjectRegistry	The Registry is the analog of a phonebook, which lists all available objects (modules or services most of the time) identified by a unique integer identifier or by a unique string (class name) for translation
C BaseType	
C BCSimplifiedVertex	Simplified Ball-Chiu Vertex
C BCVertex	Ball-Chiu Vertex
C CCFModuleNullPointerException	Exception to indicate missing CFF module
C CompareUtils	Set of utility tools to perform comparisons
C ComparisonData	Comparison report for single data point
C ComparisonMode	Definition of comparison modes
C ComparisonReport	Comparison report
C ComparisonService	
C Computation	Class to store computation information
C ComputationDao	**Computation** information Data Access Object (DAO)
C ComputationDaoService	**Computation** information Data Access Object (DAO) service
C ConvolCoeffFunctionKinematicDao	Compton form factor (CFF) kinematics Data Access Object (DAO)
C ConvolCoeffFunctionKinematicDaoService	Compton form factor (CFF) kinematics Data Access Object (DAO) service
C ConvolCoeffFunctionModule	Abstract class that provides a skeleton to implement a Convolution of Coefficient Function module

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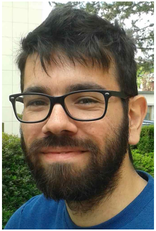

L. Colaneri
IPNO

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- **I am afraid to be lost in the code, where can I find help?**
  - We plan to release also various examples to help new users.
  - A documentation is also available online.
- **What if I find a bug?**
  - We try to make the software as reliable as possible. But if you still find a bug please contact us.
  - We will face the good side of Murphy's law: users will find a way to use PARTONS developers will not have thought about.

- The complete DVCS chain will be released
- Leading twist approximation in the BMJ and GV formalisms.
- NLO correction of the hard kernel, including heavy quark masses corrections
- LO GPD evolution equations from Vinnikov code
- 4 different phenomenological models based on Double Distributions.

Perspectives on PARTONS

- TCS channel
  - The code exists at NLO but needs to be implemented in C++.

Future experiments on Transversaly Polarised Target TCS is a great motivation for us to push our development of the TCS branch in PARTONS.

- For DVCS channel:
  - BMP finite t corrections
- DVMP channel
  - Add a Meson Distribution Amplitude Machinery
  - Implementations of higher-twists, in particular in the case of the pion.
- "Recent channels": double photon production, meson-photon production...

Summary and Conclusion

- Deep studies of GPDs require a flexible and reliable software.
- PARTONS is an answer to this need:
  - Flexibility through modular architecture
  - Reliability ensured by systematic non-regression tests.
  - Performance is also one of our main targets.
- Try to make it as user friendly as possible.
- We do our best to release it as soon as possible.

Thank you for your attention