Generalised Parton Distributions and the PARTONS project

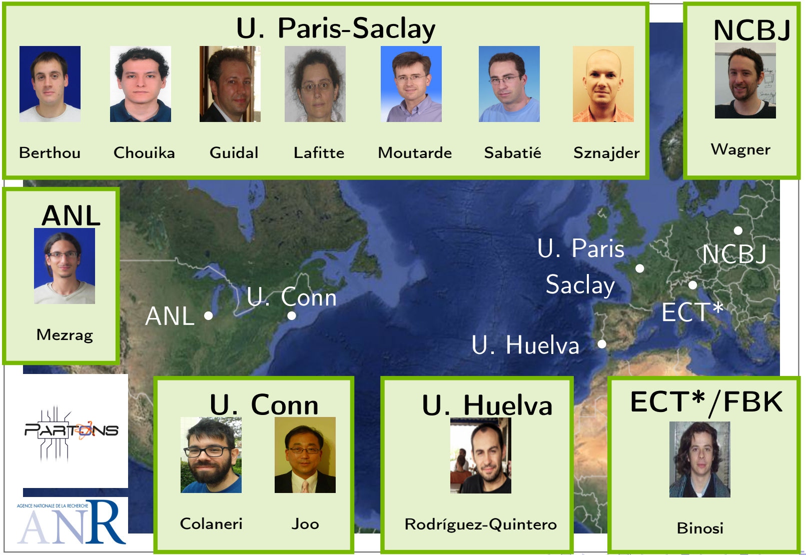
C. Mezrag

Argonne National Laboratory

On behalf of the PARTONS team

1 multidisciplinary team over 5 countries

Theorists, experimentalists, 1 mathematician + 1 software engineer

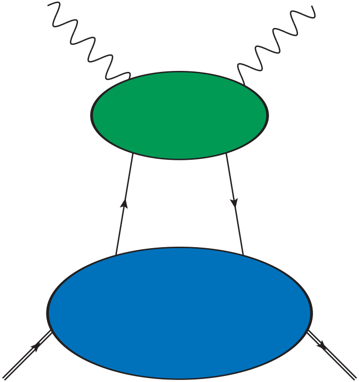


PARTONS

- 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*

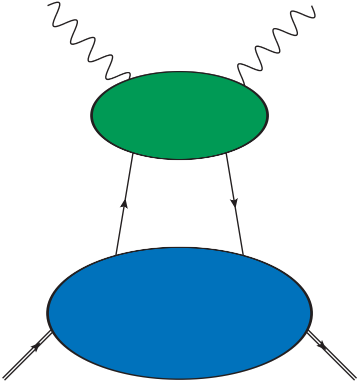
  arXiv:1512.06174

- Such study requires a flexible software architecture.
- 1 new physical development = 1 new module.
- What *can* be automated *will be* automated.
- *Aggregate* **knowledge** and **know-how**:
  - Models
  - Measurements
  - Numerical techniques
  - Validation



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

DVCS 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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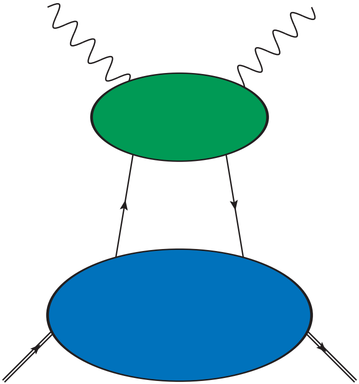

- Hard Part: Short distance interactions computed through perturbation theory.
- Soft Part: Long distance interactions encoded in GPDs; realm of non-perturbative QCD.

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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- Generalised Parton Distributions (GPDs):

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- Generalised Parton Distributions (GPDs):
  - are defined according to a non-local matrix element,

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

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

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

- Generalised Parton Distributions (GPDs):
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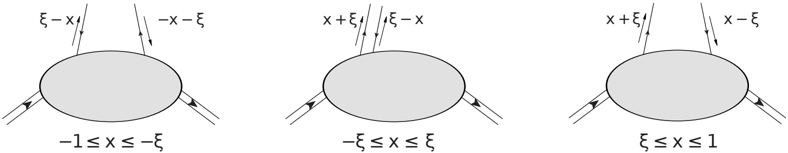
  - depend on three variables (x, ξ, t),



Long Range Correlations: GPDs domain

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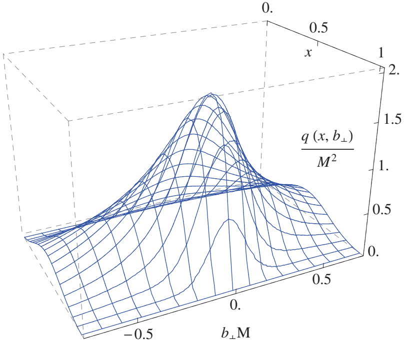
M. Burkardt, Phys. Rev. **D62**, 071503 (2000)



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

Long Range Correlations: GPDs domain

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  - depend on three variables (x, ξ, t),
  - 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:

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

Lorentz Covariance

- 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

GPDs: What we know from the theory side

- 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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- Positivity property:

  Positivity of Hilbert space norm

- Support property:

  Relativistic quantum mechanics

- Soft pion theorem (pion GPDs only)

  Dynamical Chiral Symmetry Breaking

How can we implement all these constraints?

- There is still no GPDs models relying only on first principles
- 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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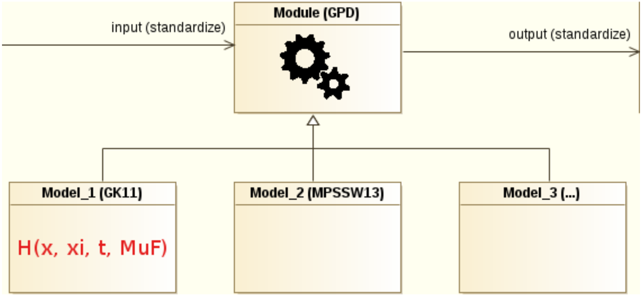
- Make as easy as possible for users to add their own favourite model through the modular architecture



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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.

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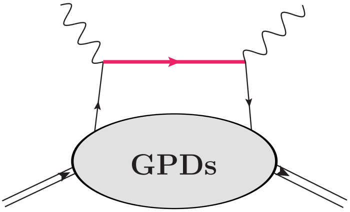
- At LO only quarks contribute to the hard kernel (DVCS): The imaginary part of the CFF is proportional to the GPD at $x = \xi$.



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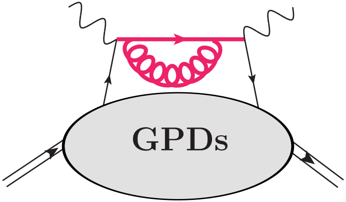
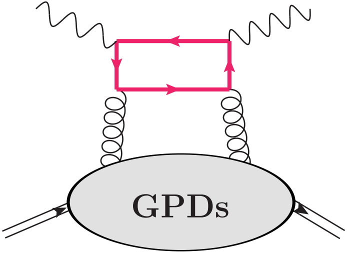
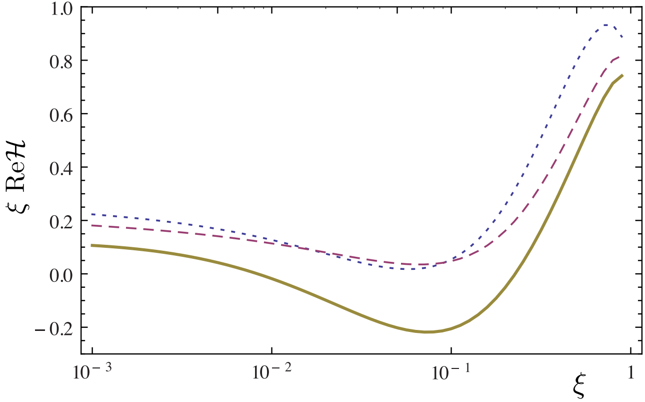
- At LO only quarks contribute to the hard kernel (DVCS): The imaginary part of the CFF is proportional to the GPD at $x = \xi$.
- At NLO, both quarks and gluons contributes.





Effects of NLO correction on CFF

An example on the Goloskokov-Kroll model:



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

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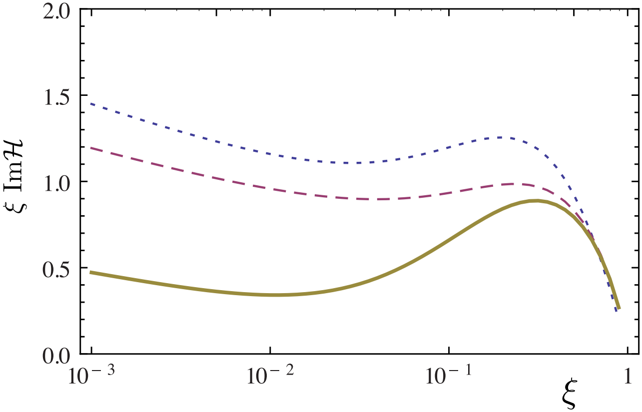

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Effects of Heavy quarks at NLO

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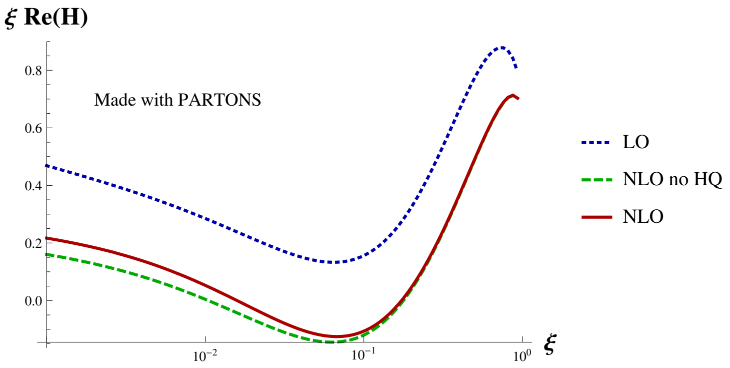

Plots from the PARTONS Collaboration

HQ Kernel from J. Noritzsch, Phys. Rev. **D69**, 094016 (2004)

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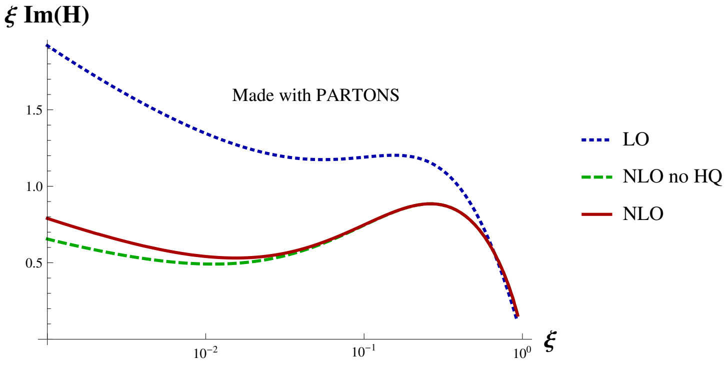

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Observables

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)

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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	$\Delta\sigma^{\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.07\mathrm{Im}\mathcal{E} + 0.47\mathrm{Im}\widetilde{\mathcal{H}}$
	$\sigma^{\cos 0\phi}$	$1 + 0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos\phi}$	$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

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

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

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

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HERA	$\sigma_{\rm DVCS}$	$\mathcal{H}\mathcal{H}^* + 0.09\mathcal{E}\mathcal{E}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*$

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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

GPD Study

- From GPDs to observables
  - Flexibility in the choice of models,
  - 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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PARTONS contains the tools to compare your GPD model to available data

- From observables to GPDs:
  - Flexibility in the choice of observables,
  - Extraction of CFFs,
  - Flexibility in changing twist approximations ($1/Q$),
  - Extraction of GPDs from CFFs,
  - Flexibility in the choice of pertubative approximation (α_s)

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

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

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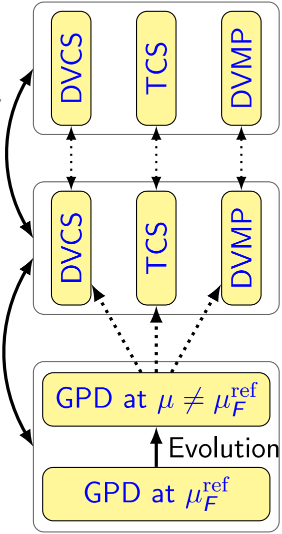

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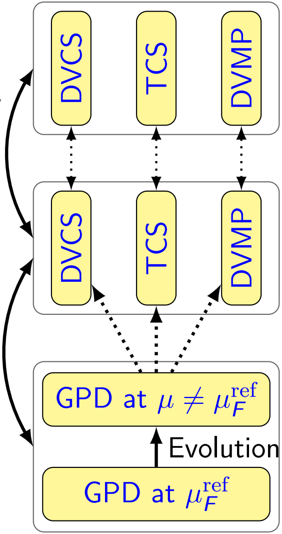

- Many observables.
- Kinematic reach.

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Need for modularity

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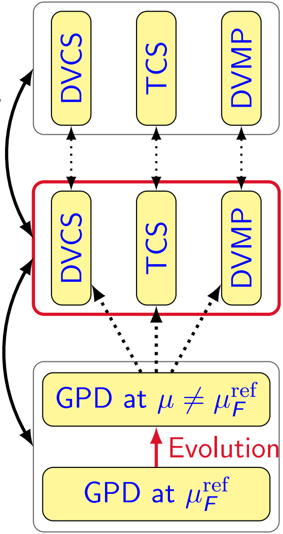
First principles and fundamental parameters



- Many observables.
- Kinematic reach.

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

Computing chain design.

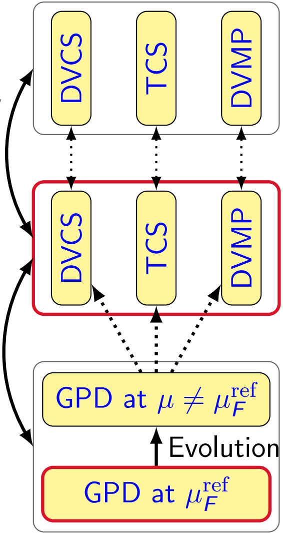
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



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- Accuracy and speed.

Computing chain design.

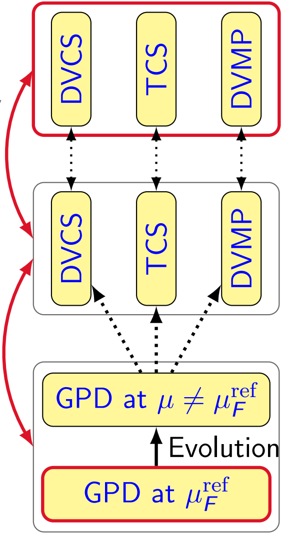
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



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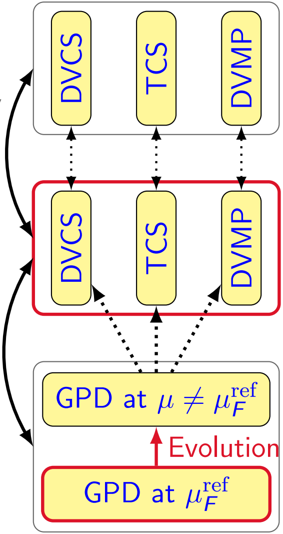

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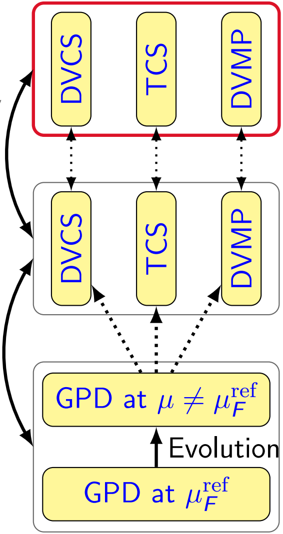

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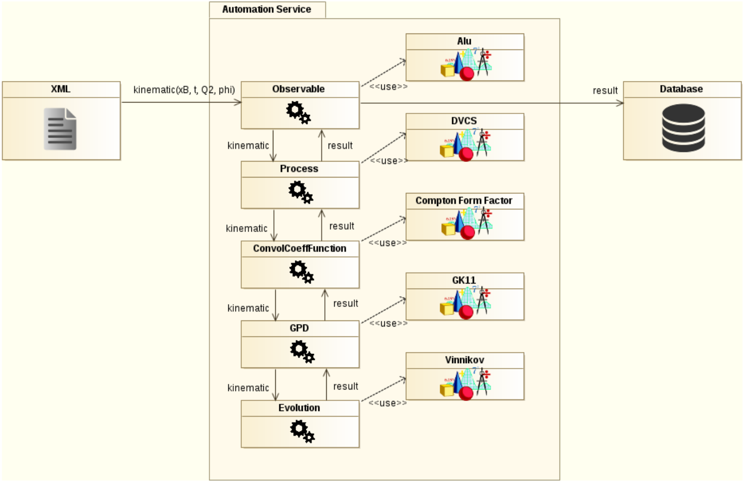
Parse XML file, compute and store result in database.



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Towards the first beta release

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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 will be also available online.

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 expect a release this year but have no precise schedule yet.

Thank you for your attention