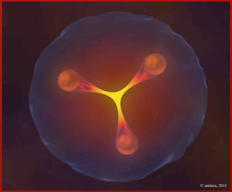
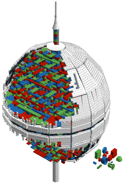
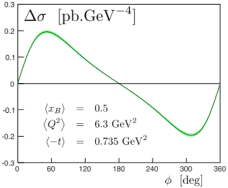
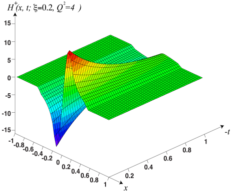
DE LA RECHERCHE À L'INDUSTRIE

PARTONS: A versatile framework for the phenomenology of GPDs









3D Nucleon Tomography Workshop 2017 | Hervé MOUTARDE

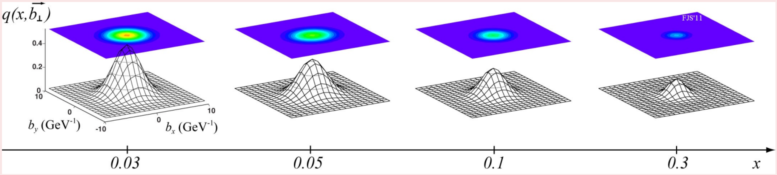
Mar. 16$^{\text{th}}$, 2017

Motivation.

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 GPD$(x, \xi = 0, t)$ in **transverse plane**.

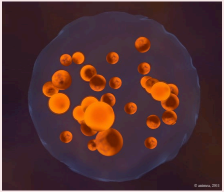
Transverse plane density (Goloskokov and Kroll model)



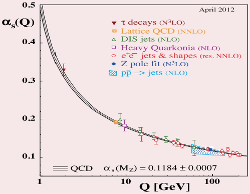
Motivation.

Study nucleon structure to shed new light on nonperturbative QCD.

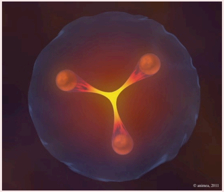
Perturbative QCD



Asymptotic freedom



Nonperturbative QCD

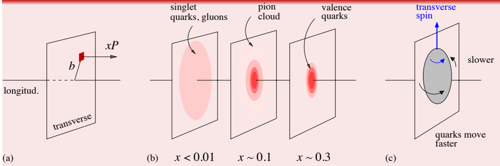


Perturbative AND nonperturbative QCD at work

- 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.

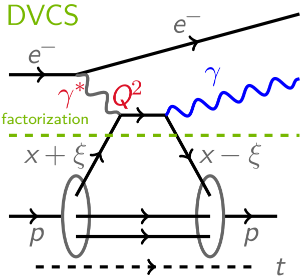
1. **The problem of 3D imaging:**
   What do we want?
2. **Phenomenology, GPD models, experimental images:**
   What can we actually do?
3. **Computing framework:**
   What can we expect from the near future?

Can we obtain this picture from exclusive measurements?

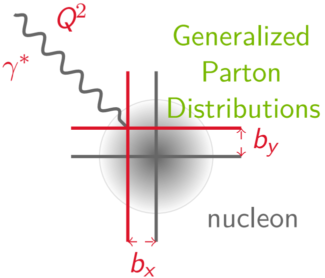


Weiss, AIP Conf. Proc. **1149**, 150 (2009)

Principles of nucleon 3D imaging



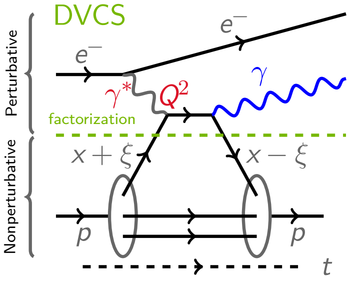
DVCS
e^-
e^-
γ^*
Q^2
γ
factorization
$x+\xi$
$x-\xi$
p
p
t

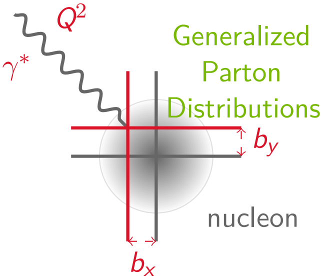


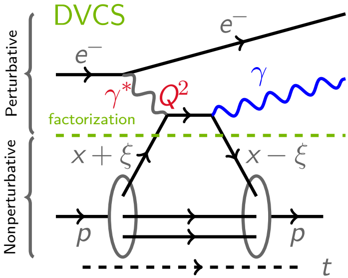
Q^2
γ^*
Generalized Parton Distributions
b_y
nucleon
b_x

Exclusive processes of current interest (1/2).

Factorization and universality.






DVCS
Perturbative
Nonperturbative
e^-
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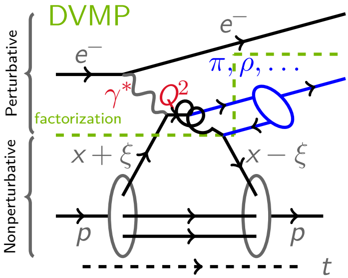
p
p
t


DVMP
Perturbative
Nonperturbative
e^-
e^-
γ^*
Q^2
$\pi, \rho, \ldots$
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p
p
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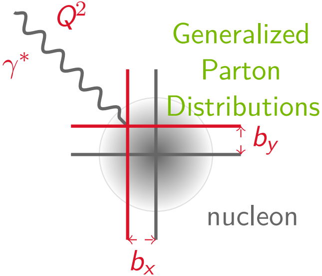
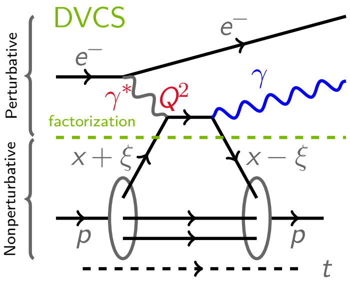

Q^2
γ^*
Generalized
Parton
Distributions
b_y
nucleon
b_x



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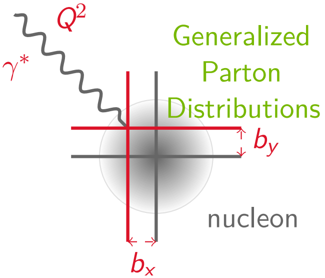
p
p
t



Q^2
γ^*
Generalized
Parton
Distributions
b_y
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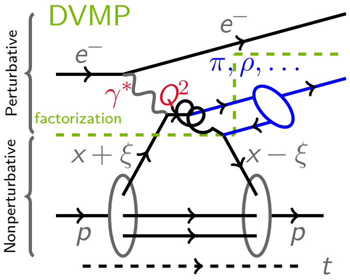
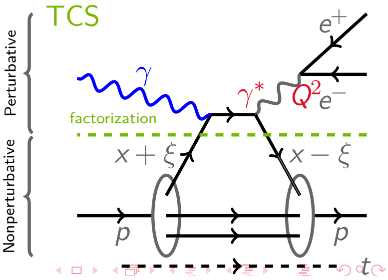
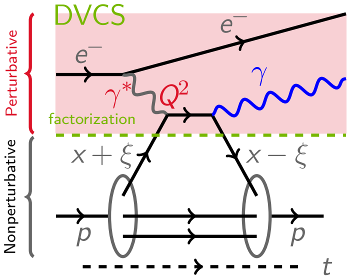


DVMP
Perturbative
Nonperturbative
e^-
e^-
$\pi, \rho, \ldots$
γ^*
Q^2
factorization
$x+\xi$
$x-\xi$
p
p
t



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


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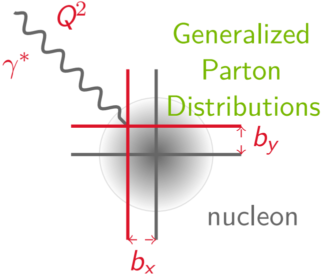
p
t


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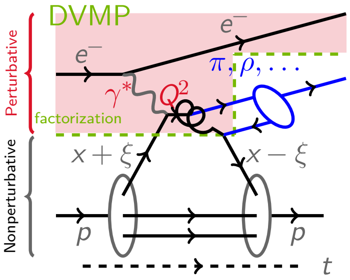
DVMP
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factorization
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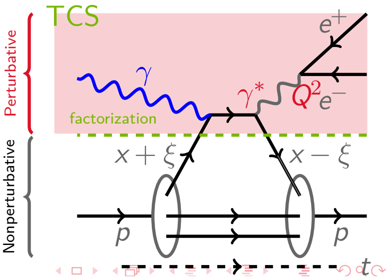
TCS
Perturbative
Nonperturbative
e^+
γ
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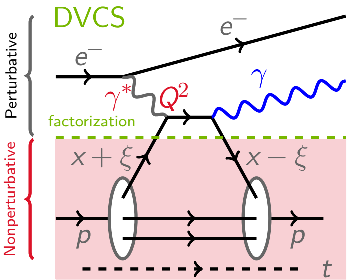
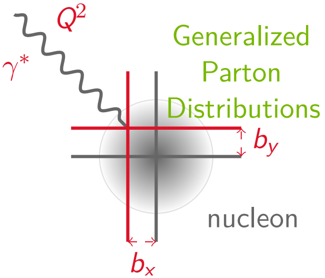
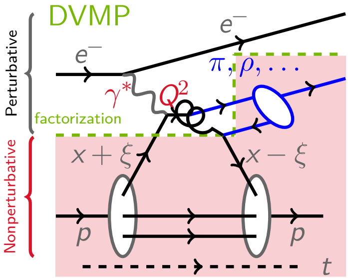
Q^2
e^-
factorization
$x+\xi$
$x-\xi$
p
p
t

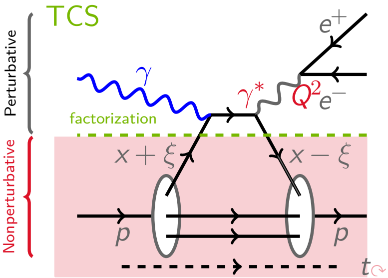
Exclusive processes of current interest (1/2).

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.

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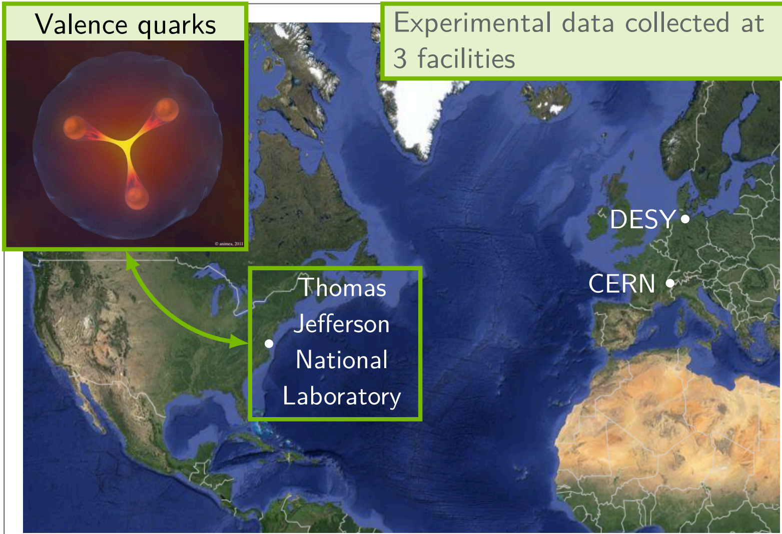
Experimental data collected at 3 facilities



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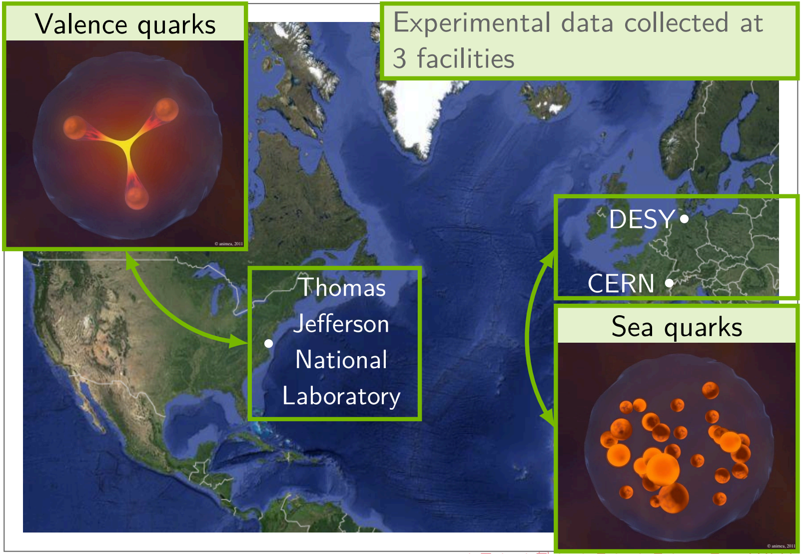
Different facilities will probe different kinematic domains.



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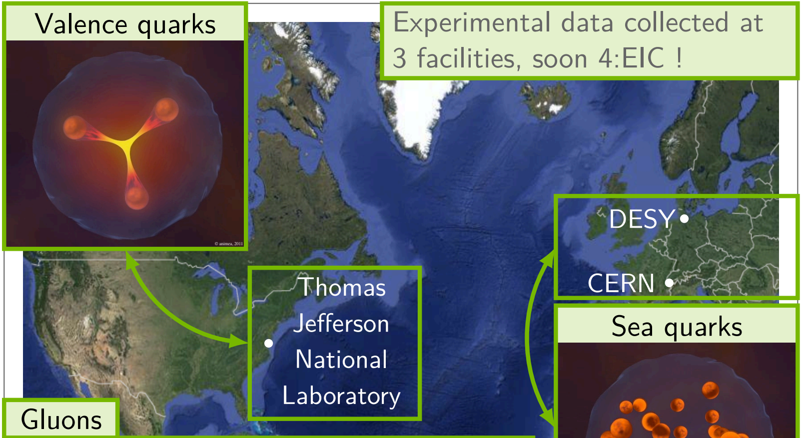
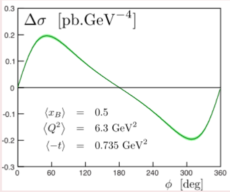


NSAC, Long Range Plan 2015:
"We recommend [...] EIC as the highest priority for new facility construction"

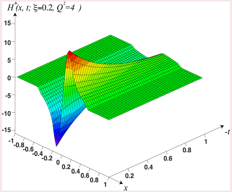
Imaging the nucleon. How?

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

1. Experimental data fits

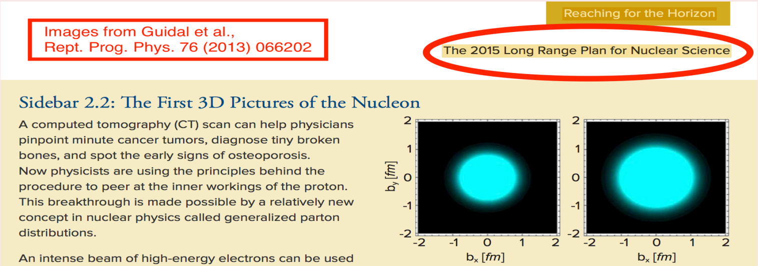


2. GPD extraction



3. Nucleon imaging

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



Imaging the nucleon. How?

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

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.
4. **Compute** 2D Fourier transform in transverse plane:

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

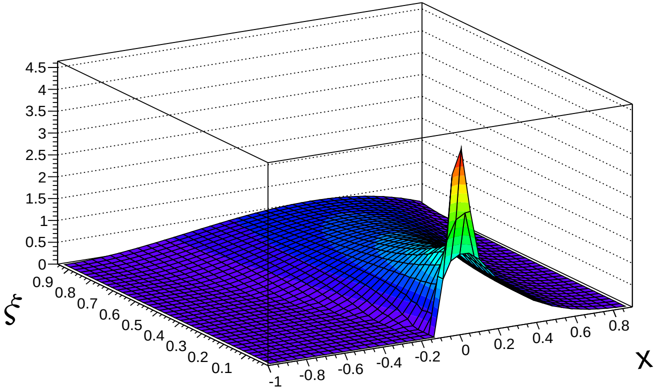
5. **Propagate** uncertainties.
6. **Control** extrapolations with an accuracy matching that of experimental data with **sound** GPD models.

Practice of nucleon 3D imaging

From principles to actual data.

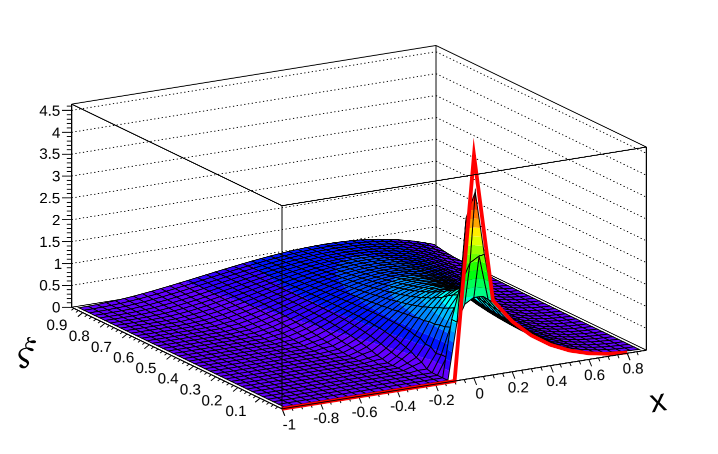
Direct experimental access to a restricted kinematic domain.

GPD H at $t = -0.23$ GeV^2 and $Q^2 = 2.3$ GeV^2.



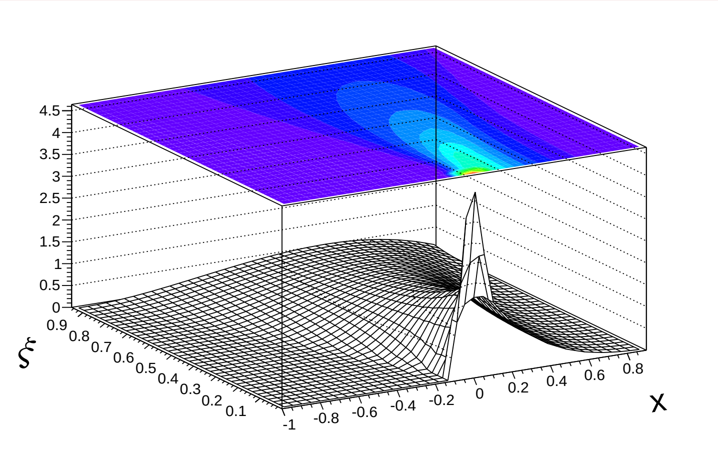
GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

Need to know $H(x, \xi = 0, t)$ to do transverse plane imaging.



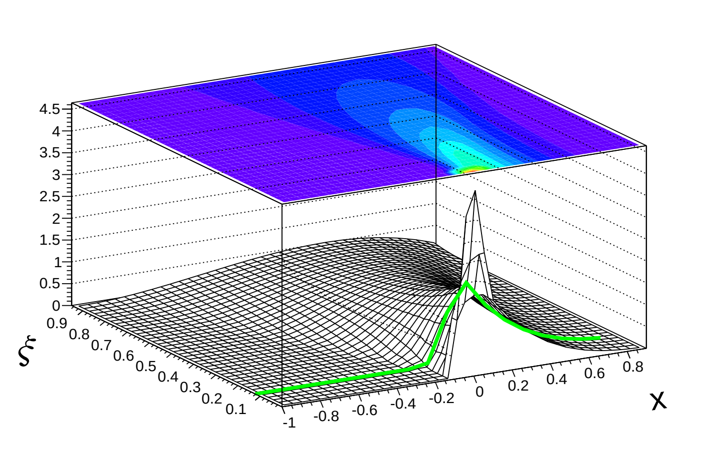
GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

What is the physical region?



GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

ξ_{min} from finite beam energy.

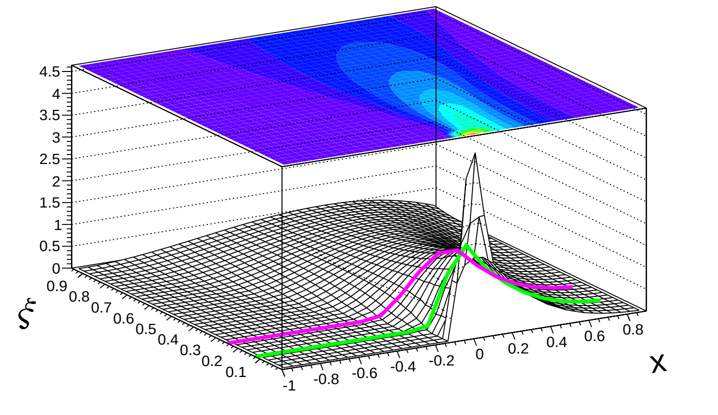


GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

From principles to actual data.

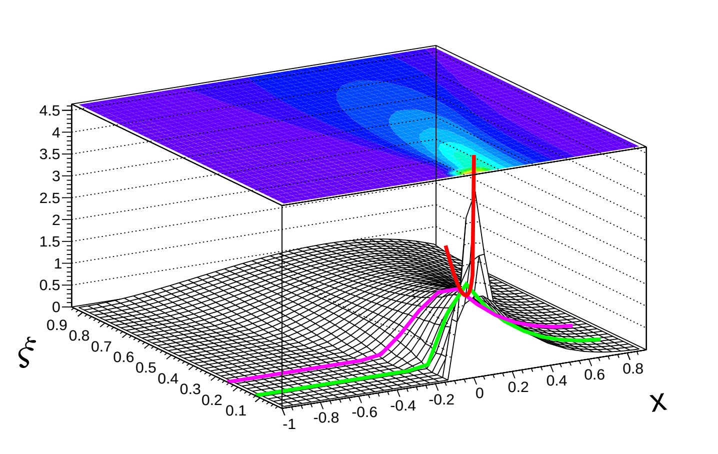
Direct experimental access to a restricted kinematic domain.

$\xi_{\max}$ from kinematic constraint on 4-momentum transfer.



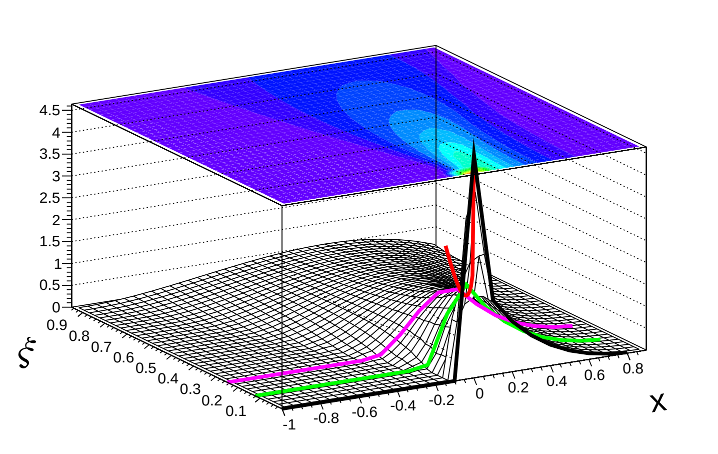
GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

The cross-over line $x = \xi$.



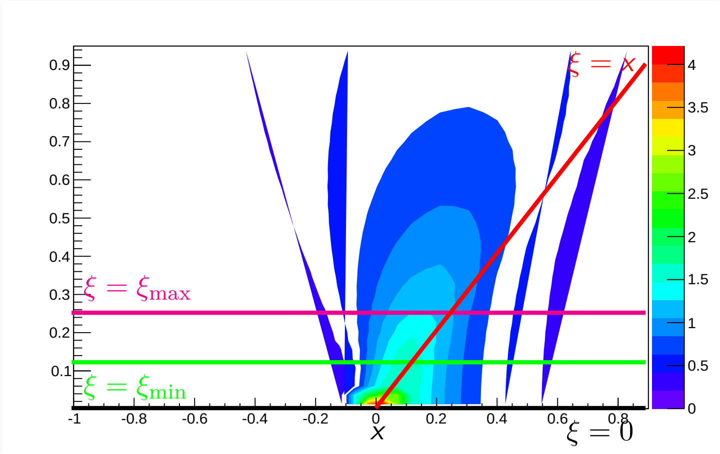
GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

The black curve is what is needed for transverse plane imaging!



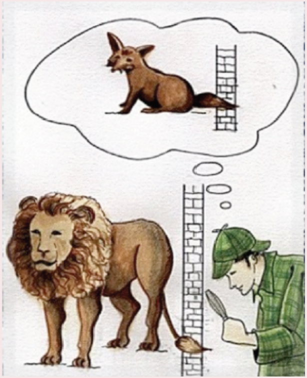
GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

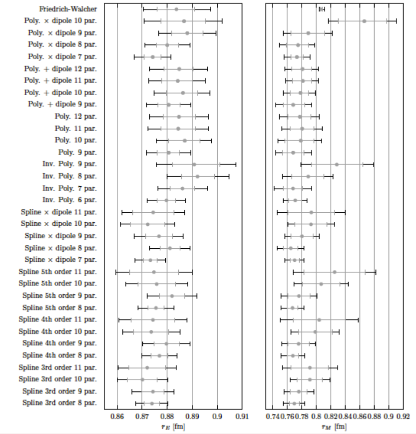
Density plot of H at $t = -0.23$ GeV^2 and $Q^2 = 2.3$ GeV^2



GPD model: see Kroll *et al.*, Eur. Phys. J. **C73**, 2278 (2013)

Extrapolations...





Bernauer *et al.*(A1 Coll.), Phys. Rev. **C90**, 015206 (2014)

A simplification brought by GPDs?!

We don't need to know the GPD everywhere to image the proton!

General idea

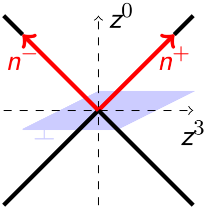
- Assume $H(x, \xi, t)$ is known for all x and $\xi \in [\xi_{\mathrm{min}}, \xi_{\mathrm{max}}]$.
- Then all Mellin moments are known for $\xi \in [\xi_{\mathrm{min}}, \xi_{\mathrm{max}}]$.
- Mellin moments are **polynomials** in ξ and in particular can be evaluated at $\xi = 0$.
- The knowledge of the Mellin moments at $\xi = 0$ **uniquely determines** the transverse plane density $H(x, 0, b_\perp)$.
- *Caveat*: **ill-posed problem** in the sense of Hadamard.

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

$$H^q_\pi(x, \xi, t) \quad = \quad \frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}\left(-\frac{z}{2}\right) \gamma^+ q\left(\frac{z}{2}\right) \middle| \pi, P - \frac{\Delta}{2} \right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)
Ji, Phys. Rev. Lett. **78**, 610 (1997)
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF **forward limit**

$$H^q(x, 0, 0) = q(x)$$

Spin-0 Generalized Parton Distribution.

Definition and simple properties.

$$H^q_\pi(x,\xi,t) \;=\; \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \left\langle \pi, P+\frac{\Delta}{2} \middle| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right) \middle| \pi, P-\frac{\Delta}{2} \right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

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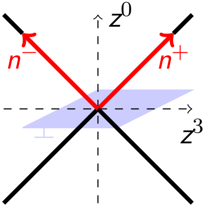

References

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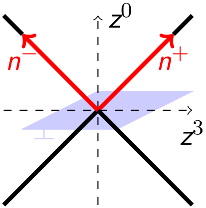
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF **forward limit**
- Form factor **sum rule**

$$\int_{-1}^{+1} dx\, H^q(x,\xi,t) = F_1^q(t)$$

$$H^q_\pi(x, \xi, t) = \frac{1}{2} \int \frac{\mathrm{d}z^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P + \frac{\Delta}{2} \middle| \bar{q}\left(-\frac{z}{2}\right) \gamma^+ q\left(\frac{z}{2}\right) \middle| \pi, P - \frac{\Delta}{2} \right\rangle_{\substack{z^+=0 \\ z_\perp=0}}$$

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



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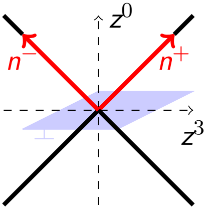
Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF **forward limit**
- Form factor **sum rule**
- H^q is an **even function** of ξ from time-reversal invariance.

$$H^q_\pi(x, \xi, t) = \frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P+\frac{\Delta}{2} \middle| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right) \middle| \pi, P-\frac{\Delta}{2} \right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

with $t = \Delta^2$ and $\xi = -\Delta^+/(2P^+)$.



References

Müller *et al.*, Fortschr. Phys. **42**, 101 (1994)

Ji, Phys. Rev. Lett. **78**, 610 (1997)

Radyushkin, Phys. Lett. **B380**, 417 (1996)

- PDF **forward limit**
- Form factor **sum rule**
- H^q is an **even function** of ξ from time-reversal invariance.
- H^q is **real** from hermiticity and time-reversal invariance.

Polynomiality.

Mixed constraint from Lorentz invariance and discrete symmetries.

- Express Mellin moments of GPDs as **matrix elements**:

$$\int_{-1}^{+1} \mathrm{d}x\, x^m H^q(x, \xi, t) = \frac{1}{2(P^+)^{m+1}} \left\langle P + \frac{\Delta}{2} \middle| \bar{q}(0)\gamma^+(i\overleftrightarrow{D}^+)^m q(0) \middle| P - \frac{\Delta}{2} \right\rangle$$

- Identify the **Lorentz structure** of the matrix element:

linear combination of $(P^+)^{m+1-k}(\Delta^+)^k$ for $0 \leq k \leq m+1$

- Remember definition of **skewness** $\Delta^+ = -2\xi P^+$.
- Select **even powers** to implement time reversal.
- Obtain **polynomiality condition**:

$$\int_{-1}^{1} \mathrm{d}x\, x^m H^q(x, \xi, t) = \sum_{\substack{i=0 \\ \text{even}}}^{m} (2\xi)^i C^q_{mi}(t) + (2\xi)^{m+1} C^q_{mm+1}(t) \,.$$

- Choose $F^q(\beta, \alpha) = 3\beta\theta(\beta)$ ad $G^q(\beta, \alpha) = 3\alpha\theta(\beta)$:

$$H^q(x, \xi) = 3x \int_\Omega \mathrm{d}\beta \mathrm{d}\alpha \, \delta(x - \beta - \alpha\xi)$$

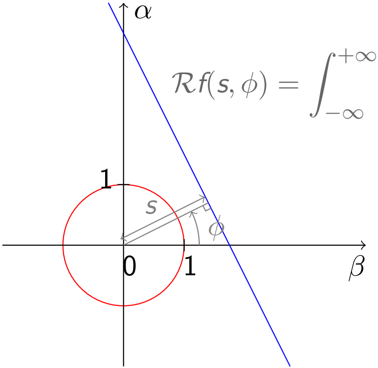
- Simple analytic expressions for the GPD:

$$\begin{aligned} H(x, \xi) &= \frac{6x(1-x)}{1-\xi^2} \text{ if } 0 < |\xi| < x < 1, \\ H(x, \xi) &= \frac{3x(x+|\xi|)}{|\xi|(1+|\xi|)} \text{ if } -|\xi| < x < |\xi| < 1. \end{aligned}$$

- Compute first Mellin moments.

n	$\int_{-\xi}^{+\xi} \mathrm{d}x\, x^n H(x,\xi)$	$\int_{+\xi}^{+1} \mathrm{d}x\, x^n H(x,\xi)$	$\int_{-\xi}^{+1} \mathrm{d}x\, x^n H(x,\xi)$
0	$\frac{1+\xi-2\xi^2}{1+\xi}$	$\frac{2\xi^2}{1+\xi}$	1
1	$\frac{1+\xi+\xi^2-3\xi^3}{2(1+\xi)}$	$\frac{2\xi^3}{1+\xi}$	$\frac{1+\xi^2}{2}$
2	$\frac{3(1-\xi)(1+2\xi+3\xi^2+4\xi^3)}{10(1+\xi)}$	$\frac{6\xi^4}{5(1+\xi)}$	$\frac{3(1+\xi^2)}{10}$
3	$\frac{1+\xi+\xi^2+\xi^3+\xi^4-5\xi^5}{5(1+\xi)}$	$\frac{6\xi^5}{5(1+\xi)}$	$\frac{1+\xi^2+\xi^4}{5}$
4	$\frac{1+\xi+\xi^2+\xi^3+\xi^4+\xi^5-6\xi^6}{7(1+\xi)}$	$\frac{6\xi^6}{7(1+\xi)}$	$\frac{1+\xi^2+\xi^4}{7}$

- Expressions get more complicated as n increases... But they always yield polynomials!



For $s > 0$ and $\phi \in [0, 2\pi]$:

$$\mathcal{R}f(s,\phi) = \int_{-\infty}^{+\infty} \mathrm{d}\beta \mathrm{d}\alpha \, f(\beta,\alpha)\delta(s - \beta\cos\phi - \alpha\sin\phi)$$

and:

$$\mathcal{R}f(-s,\phi) = \mathcal{R}f(s,\phi \pm \pi)$$

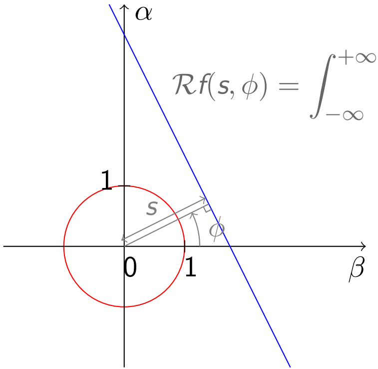
Relation to GPDs:

$$x = \frac{s}{\cos\phi} \text{ and } \xi = \tan\phi$$

Relation between GPD and DD in Belistky *et al.* gauge

$$\frac{\sqrt{1+\xi^2}}{x} H(x,\xi) = \mathcal{R}f_{\mathrm{BMKS}}(s,\phi) \; ,$$

The Radon transform.
Definition and properties.



For $s > 0$ and $\phi \in [0, 2\pi]$:

$$\mathcal{R}f(s,\phi) = \int_{-\infty}^{+\infty} \mathrm{d}\beta \mathrm{d}\alpha \, f(\beta,\alpha)\delta(s - \beta\cos\phi - \alpha\sin\phi)$$

and:

$$\mathcal{R}f(-s,\phi) = \mathcal{R}f(s,\phi \pm \pi)$$

Relation to GPDs:

$$x = \frac{s}{\cos\phi} \text{ and } \xi = \tan\phi$$

Relation between GPD and DD in Pobylitsa gauge

$$\frac{\sqrt{1+\xi^2}}{1-x} H(x,\xi) = \mathcal{R}f_{\mathrm{P}}(s,\phi) \, ,$$

The range of the Radon transform.

The polynomiality property a.k.a. the Ludwig-Helgason condition.

- The Mellin moments of a Radon transform are **homogeneous polynomials** in $\omega = (\sin\phi, \cos\phi)$.
- The converse is also true:

Theorem (Hertle, 1983)

Let $g(s,\omega)$ an even compactly-supported distribution. Then g is itself the Radon transform of a compactly-supported distribution if and only if the ***Ludwig-Helgason consistency condition*** *hold:*

(i) *g is C^∞ in ω,*

(ii) *$\int \mathrm{d}s\, s^m g(s,\omega)$ is a homogeneous polynomial of degree m for all integer $m \geq 0$.*

- Double Distributions and the Radon transform are the **natural solution** of the polynomiality condition.

Support theorem.

We don't need to know the GPD everywhere to image the proton!

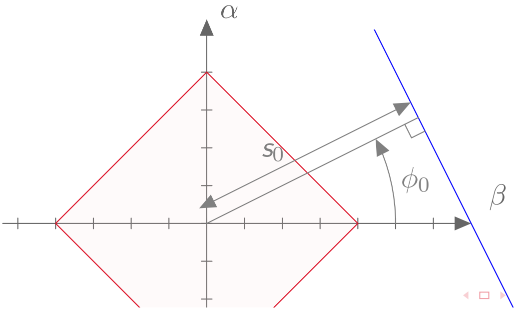
Theorem

Let f be a compactly-supported summable function defined on $\mathbb{R}^2$ and $\mathcal{R}f$ its Radon transform.

Let $(s_0, \omega_0) \in \mathbb{R} \times S^1$ and U_0 an open neighborhood of ω_0 s.t.:

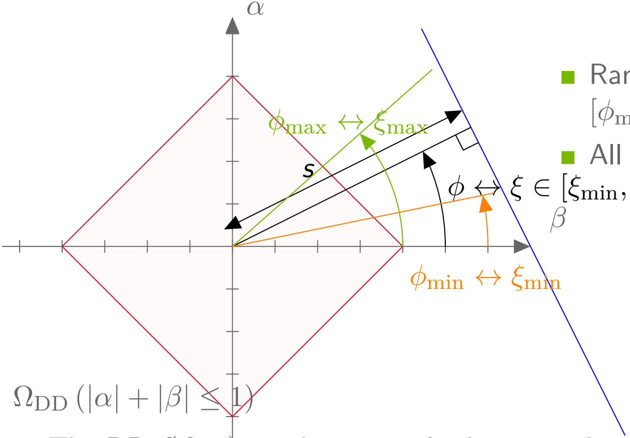
$$\text{for all } s > s_0 \text{ and } \omega \in U_0 \quad \mathcal{R}f(s, \omega) = 0 \, .$$

Then $f(\aleph) = 0$ on the half-plane $\langle \aleph | \omega_0 \rangle > s_0$ of $\mathbb{R}^2$.



- $\omega_0 = (\cos \phi_0, \sin \phi_0)$.
- $\aleph = (\beta, \alpha)$.

- Assume deconvolution of CFF achieved.
- Data: $H(x, \xi)$ for all $x \in [-1, +1]$ and $\xi \in [\xi_{\min}, \xi_{\max}]$.



- Range $\phi \in [\phi_{\min}, \phi_{\max}]$.
- All values of s.

- The DD $f(\beta, \alpha)$ can be **uniquely** determined.
- $H(x, \xi = 0)$ **uniquely** constrained by **Lorentz covariance**!

- Decompose an hadronic state $|H; P, \lambda\rangle$ in a Fock basis:

$$|H; P, \lambda\rangle = \sum_{N,\beta} \int [\mathrm{d}x\mathrm{d}\mathbf{k}_\perp]_N \psi_N^{(\beta,\lambda)}(x_1, \mathbf{k}_{\perp 1}, \ldots, x_N, \mathbf{k}_{\perp N}) \, |\beta, k_1, \ldots, k_N\rangle$$

- Derive an expression for the pion GPD in the DGLAP region $\xi \leq x \leq 1$:

$$H^q(x, \xi, t) \propto \sum_{\beta,j} \int [\mathrm{d}\bar{x}\mathrm{d}\bar{\mathbf{k}}_\perp]_N \delta_{j,q} \delta(x - \bar{x}_j) \left(\psi_N^{(\beta,\lambda)}\right)^* (\hat{x}', \hat{\mathbf{k}}'_\perp) \psi_N^{(\beta,\lambda)}(\tilde{x}, \tilde{\mathbf{k}}_\perp)$$

with $\tilde{x}, \tilde{\mathbf{k}}_\perp$ (resp. $\hat{x}', \hat{\mathbf{k}}'_\perp$) generically denoting incoming (resp. outgoing) parton kinematics.

Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)

- Similar expression in the ERBL region $-\xi \leq x \leq \xi$, but with overlap of N- and $(N+2)$-body LFWFs.

- Physical picture.
- Positivity relations are fulfilled **by construction**.
- Implementation of **symmetries of** N**-body problems**.

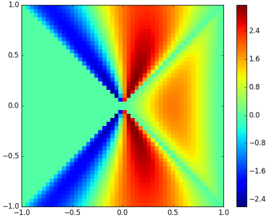
What is not obvious anymore

What is *not* obvious to see from the wave function representation is however the **continuity of GPDs at** $x = \pm\xi$ and the **polynomiality** condition. In these cases both the DGLAP and the ERBL regions must cooperate to lead to the required properties, and this implies **nontrivial relations between the wave functions** for the different Fock states relevant in the two regions. An *ad hoc* Ansatz for the wave functions would **almost certainly lead** to GPDs that **violate the above requirements**.

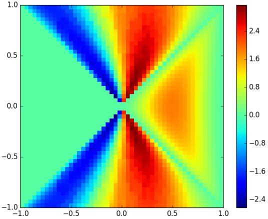
Diehl, Phys. Rept. **388**, 41 (2003)

Covariant and positive GPD models.

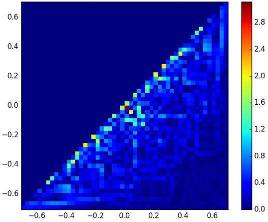
First systematic procedure to build models satisfying all constraints.



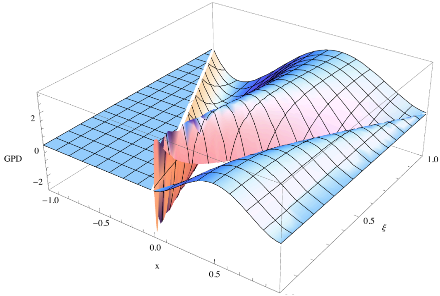
Analytic result



Numerical result



Difference



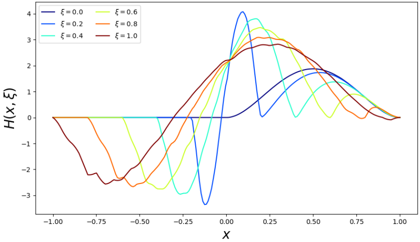
Algebraic Dyson Schwinger LFWF

Chouika

Work in progress

Covariant and positive GPD models.

First systematic procedure to build models satisfying all constraints.



Gaussian LFWF

Chouika
Work in progress

- Numerics under control for **smooth** LFWFs.
- Still need to investigate situation with Regge behavior.
- Towards **common modeling** of GPDs and TMDs?

Building the tools for high precision: the PARTONS project

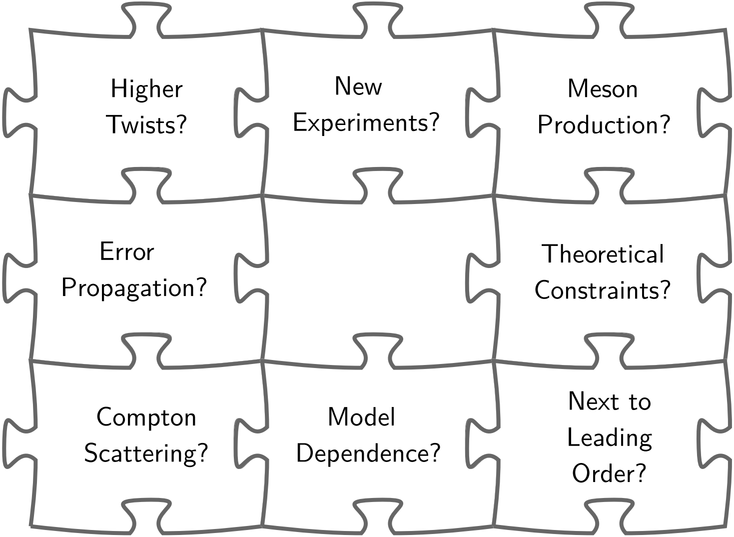
PARtonic
Tomography
Of
Nucleon
Software

- Evaluation of the impact of **higher order** effects.
- Evaluation of the impact of **target mass and finite-t** corrections.
- Evaluation of the contribution of **higher twist** GPDs.
- DVMP: sensitivity to **DA models**.
- Extrapolations with **GPD models**.

Software for the phenomenology of GPDs.

Different questions to be answered with the same tools.

PARTONS Framework



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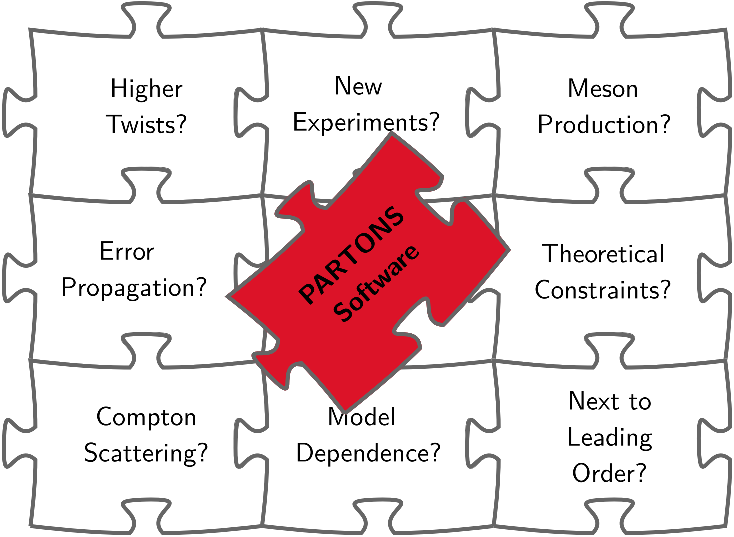
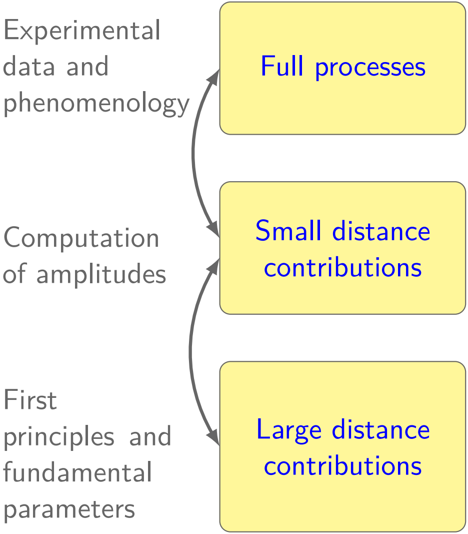


Experimental data and phenomenology	Full processes
Computation of amplitudes	Small distance contributions
First principles and fundamental parameters	Large distance contributions

Computing chain design.

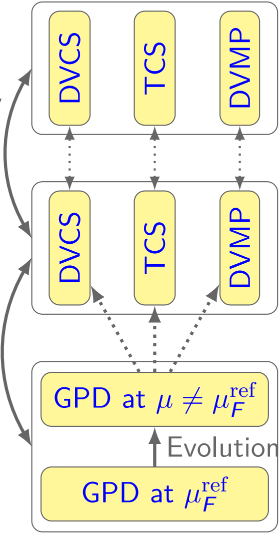
Differential studies: physical models and numerical methods.



Experimental data and phenomenology

Computation of amplitudes

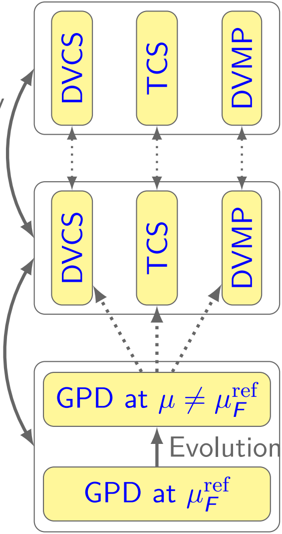
First principles and fundamental parameters



Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



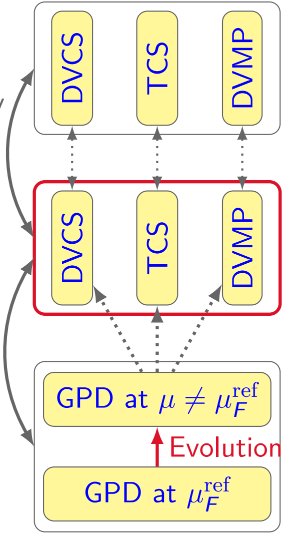
- Many observables.
- Kinematic reach.

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.

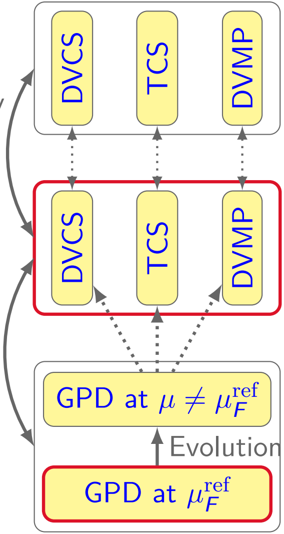
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



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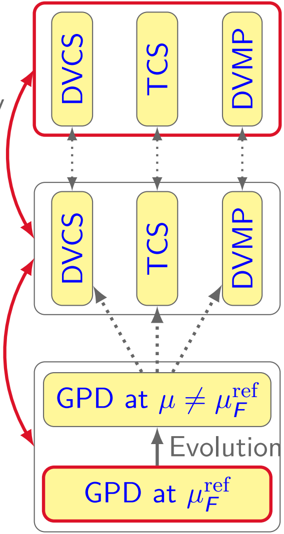
Computation of amplitudes

First principles and fundamental parameters



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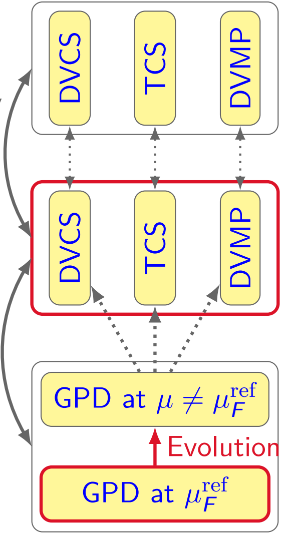
First principles and fundamental parameters



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Computing chain design.

Differential studies: physical models and numerical methods.

Experimental data and phenomenology

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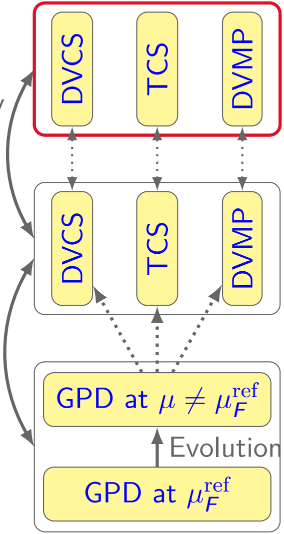
Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

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

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.

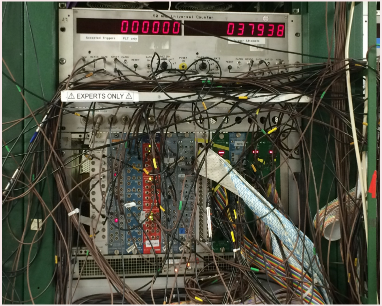
Systematic studies made easy.

A faster and safer way to GPD phenomenology.

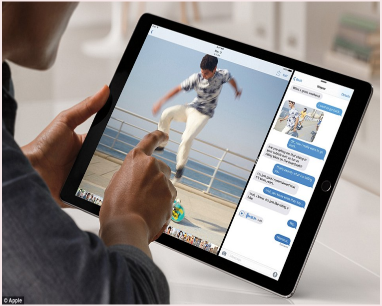
Automation allows...:

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

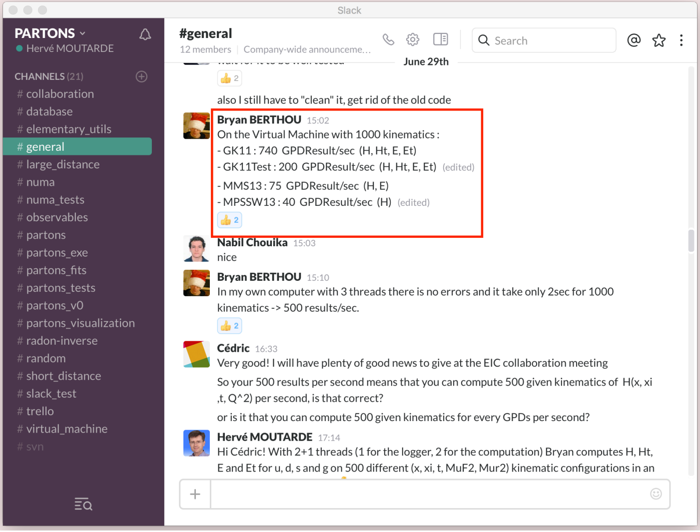
Without PARTONS



With PARTONS



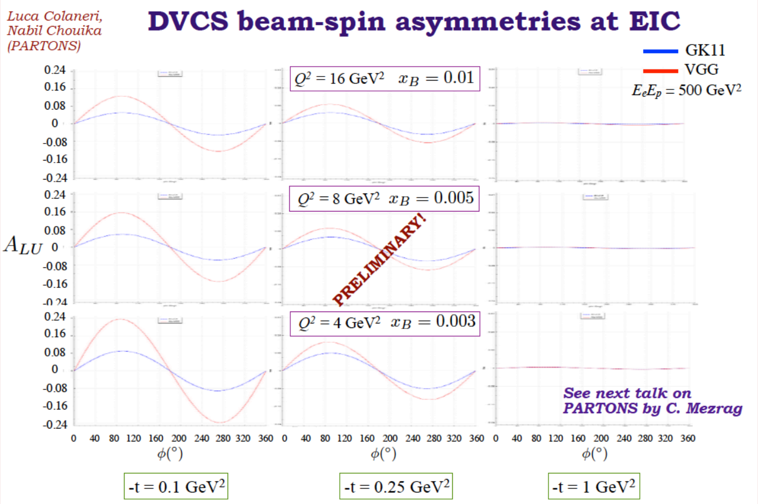
GPD computations with or without threads



Systematic studies made fast (1/2).

What can be done from scratch in about 1 hour.

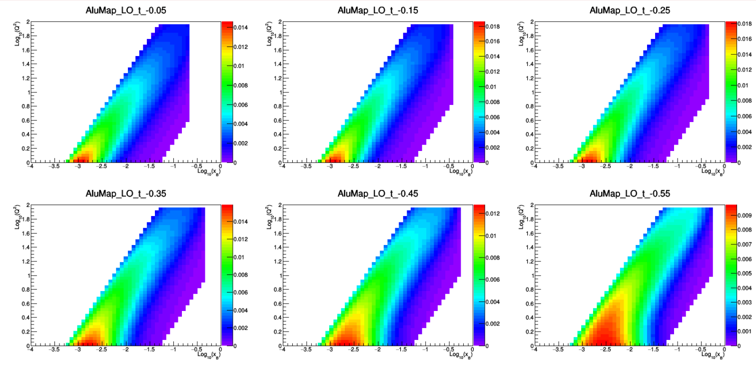
From D. Sokhan's talk, EIC User Group Meeting, ANL, 2016



Systematic studies made fast (2/2).

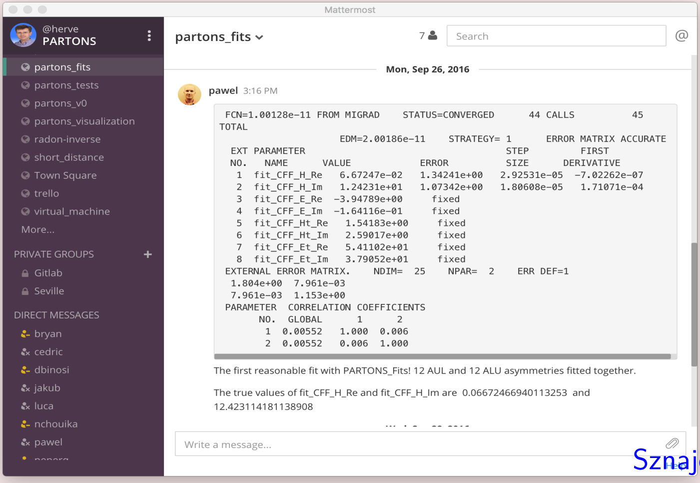
EIC observables computed with different pQCD assumptions.

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



Colaneri, *Work in progress*

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



Sznajder

Work in progress

(Preliminary) On-going global fit of Jefferson Lab DVCS data

- Kinematic cuts: $Q^2 > 1.5$ GeV^2 *where we can relay on LO approximation*
  $-t/Q^2 < 0.2$ *where we can relay on GPD factorization*
- $\chi 2$ / nPoints: 3317.1 / 3433 ≈ 0.97
- $\chi 2$ / nPoints per data set:

Experiment	Reference	Observables	N points all	N points selected	chi2	chi2/nPoints
Hall A	[1] KINX2	σUU	120	120	103.2	0.86
Hall A	[1] KINX2	ΔσLU	120	120	98.8	0.82
Hall A	[1] KINX3	σUU	108	108	223.1	2.07
Hall A	[1] KINX3	ΔσLU	108	108	107.3	0.99
CLAS	[2]	σUU	1933	1333	1215.2	0.91
CLAS	[2]	ΔσLU	1933	1333	1171.4	0.88
CLAS	[3]	AUL, ALU, ALL	498	305	341.9	1.12

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

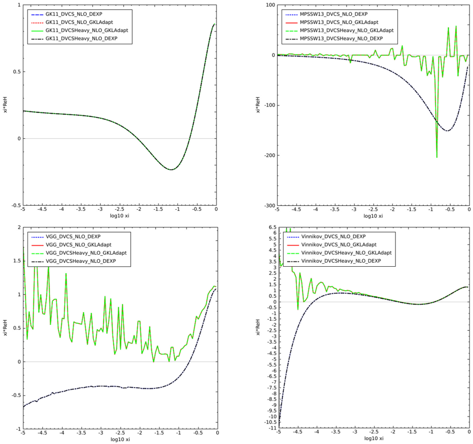
- Fixed and fitted parameters:

GPD	Parameter	Value	Error	
H	Cu val	1.21	fixed	skewness function
H	Cu sea	1.27	fixed	
H	Cd val	1.20	fixed	
H	Cd sea	1.27	fixed	
Htilde	Cu val	1.07	fixed	
Htilde	Cu sea	1.06	fixed	
Htilde	Cd val	1.11	fixed	
Htilde	Cd sea	1.07	fixed	
H	a val	0.74	fixed	Regge-like slopes
H	a sea	53.4	69.8	
Htilde	a val	2.88	0.35	
Htilde	a sea	0.41	0.66	
H	C sub	-1.38	0.15	subtraction constant
H	a sub	0.21	0.34	
E	N	-7.38	0.44	CFF E and $\tilde{E}$
Etilde	N	-0.54	0.05	

Sznajder

Work in progress

Coefficient functions, from EIC to Jefferson Lab kinematics



- Previous tests of integration routines.
- Preparation of **nonregression tools**.
- **Flexibility** at work: **physical** models and **numerical** techniques.
- $\simeq 2 \times 10^4$ GPD computed in $\lesssim 1'$.

GPD computing made simple.

Each line of code corresponds to a physical hypothesis.

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
<?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>
```

GPD computing automated.

Each line of code corresponds to a physical hypothesis.

computeOneGPD.xml

```
<?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="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, $\tilde{H}$, $\tilde{E}$, ...

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="ConvolCoeffFunctionService" method="computeWithGPDModel"
        <kinematics type="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" />
        </kinematics>
        <computation_configuration>
            <module type="GPDModule">
            <param name="className" value="GK11Model" />
        </module>
        <module type="DVCSConvolCoeffFunctionModule">
            <param name="className" value="DVCSCFFModel" />
            <param name="qcd_order_type" value="LO" />
        </module>
        </computation_configuration>
    </task>
```

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="ConvolCoeffFunctionService" method="computeWithGPDModel"
        <kinematics type="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" />
        </kinematics>
        <computation_configuration>
            <module type="GPDModule">
            <param name="className" value="GK11Model" />
        </module>
        <module type="DVCSCo
            <param name="cl
            <param name="q
        </module>
        </computation_configu
    </task>
```

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

Observable computing automated.

Each line of code corresponds to a physical hypothesis.

CEA - Saclay

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>
```

Observable plotting automated.

Plot production is automated too!

QueryDatabaseObservablePlotFile.xml

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<scenario date="2016-10-18" description="...">
    <!-- Generate plot file from database for GK model-->
    <task service="ObservableService" method="generatePlotFile">
        <task_param type="output">
            <param name="filePath" value="observable_GK11_plot.csv" />
        </task_param>
        <!-- Variables of 2d plot -->
        <task_param type="select">
            <param name="xPlot" value="phi" />
            <param name="yPlot" value="observable_value" />
        </task_param>
        <!-- Select results in database -->
        <task_param type="where">
            <param name="xB" value="0.1763" />
            <param name="t" value="-0.1346" />
            <param name="Q2" value="1.3651" />
            <param name="computation_id" value="2" />
        </task_param>
    </task>
</scenario>
```

Observable plotting automated.

Plot production is automated too!

QueryDatabaseObservablePlotFile.xml

```
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<scenario date="2016-10-18" description="...">
    <!-- Generate plot file from database for GK model-->
    <task service="ObservableService" method="generatePlotFile">
        <task_param type="output">
            <param name="filePath" value="observable_GK11_plot.csv" /
>
        </task_param>
        <!-- Variables of 2d plot -->
        <task_param ty
            <param nar
            <param nar
        </task_param>
        <!-- Select re
        <task_param ty
            <param nar
            <param nar
            <param nar
            <param nar
        </task_param>
    </task>
</scenario>
```

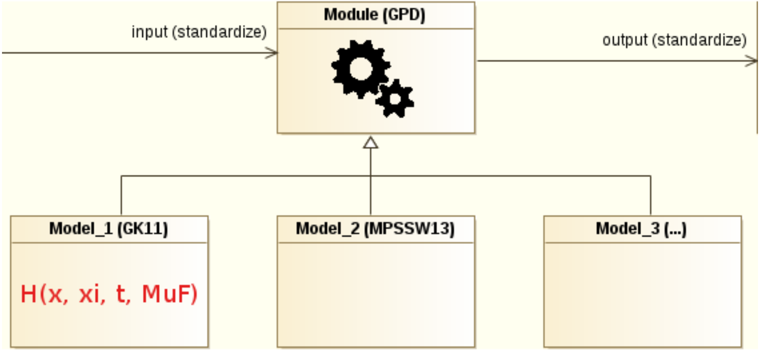
ϕ [deg]	A_{LU}
0.	0.
10.	0.024736075012605108
20.	0.048810639423911277
30.	0.071572336121144678
...	...
350.	-0.024736075012605111
360.	-9.0547874403168658e-17

Fit parameterization.

Save time for physics analysis!

FitScenario.xml

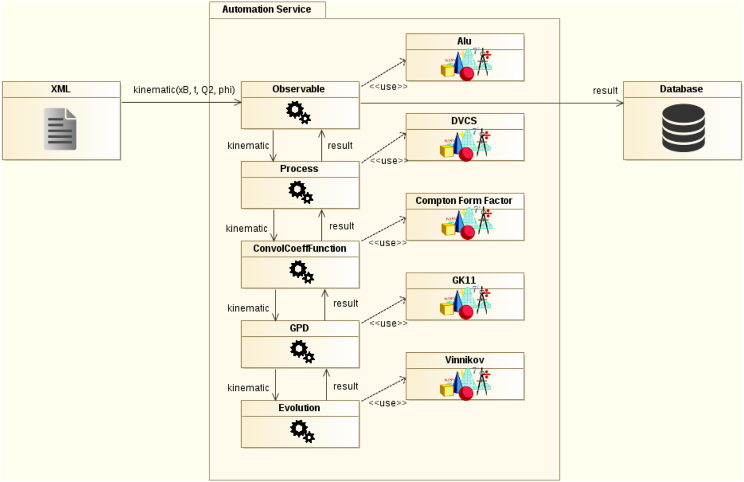
```
...
<!-- 2nd step : kinematic cuts -->
<task service="FitsService" method="defineKinematicCuts">
    <kinematics type="kinematicCuts">
        <param name="list" value="-t/Q2␣lt␣0.2;␣Q2␣gt␣1.5" />
    </kinematics>
</task>
...
<!-- 5th step : Fitting Ansatz -->
<task service="FitsService" method="configureFitsModule">
    <computation_configuration>
        <module type="FitsModelModule" name="Partons0117FitsModel">
        </module>
    </computation_configuration>
</task>
<!-- 6th step : Minimizer  -->
<task service="FitsService" method="configureMinimizerModule">
    <computation_configuration>
        <module type="MinimizerModule" name="ROOTMinimizer">
        <param name="root_minimizer_package_name" value="Minuit" />
        </module>
    </computation_configuration>
```



- 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.



Conclusion

- **Challenging constraints** expected from Jefferson Lab in valence region and later from EIC in gluon sector.
- **Good theoretical control** on the path between GPD models and experimental data.
- Success of physics program requires new GPD models with **proper implementations of symmetries**.
- Development of the PARTONS framework for **phenomenology** and **theory** purposes.
- **Fitting engine** ready for local fits. Global fits *in progress*.
- **First release** of PARTONS... *as soon as possible!*

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