Exclusive processes in the PARTONS computational framework

VÍCTOR MARTÍNEZ-FERNÁNDEZ

POSTDOC AT IRFU/CEA (PARIS-SACLAY, FRANCE) AND CFNS (NY, USA)

Outline

- Introduction to GPDs.
- `PARTONS` software and `EpIC` MC generator.
- Predictions for DDVCS with `PARTONS` and `EpIC`.
- Take aways.

GPDs

Generalized Parton Distributions

GPD

Generalized Parton Distribution ≈ "3D version of a PDF (Parton Distribution Function)." With x the average fraction of the hadron's longitudinal momentum carried by a quark:

$$H_f(x,\xi,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{p}^+z^-} \langle p'|\bar{\mathfrak{q}}_f(-z/2)\gamma^+\mathcal{W}[-z/2,z/2]\mathfrak{q}_f(z/2)|p\rangle\Big|_{z_\perp=z^+=0}$$

$$t = \Delta^2 = (p'-p)^2\,, \quad \xi = -\frac{\Delta n}{2\bar{p}n}\,, \quad \bar{p} = \frac{p+p'}{2}$$

Importance

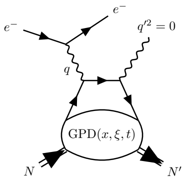
- Connected to **QCD energy-momentum tensor**. GPDs are a way to study "mechanical" properties and to address the hadron's spin puzzle (*X. Ji's sum rule**).
- **Tomography:**$ distribution of quarks in terms of the longitudinal momentum and in the transverse plane.

$$f(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{4\pi^2}\, e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H_f(x,0,t=-\vec{\Delta}_\perp^2)$$

*PRD 55 (1997) 7114-7125; $Burkardt, Int. J. Mod. Phys. A 21 (2006) 926-929.

Accessing GPDs: DVCS

- In the 1990s, Müller et al.,[†] Ji[*] and Radyushkin[#] introduced GPDs and deeply virtual Compton scattering (DVCS):



- At LO ($O(\alpha_s^0)$) and LT ($\Lambda/Q^2 \to 0$, $\Lambda \in \{|t|, M^2\}$):

$$\mathcal{H}_{\mathrm{DVCS}}(\xi,t) = -\mathrm{PV}\left(\int_{-1}^{1} dx\, \frac{1}{x-\xi} H^{(+)}(x,\xi,t)\right) + \int_{-1}^{1} dx\;\, i\pi\delta(x-\xi) H^{(+)}(x,\xi,t)\,,$$

$$H^{(+)}(x,\xi,t) = H(x,\xi,t) - H(-x,\xi,t)\,.$$

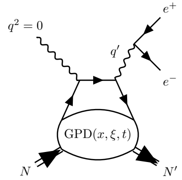
- $\xi = \frac{-n\Delta}{2\bar{p}n}\,, \quad \bar{p} = \frac{p+p'}{2}\,, \quad \Delta = p' - p\,, \quad t = \Delta^2\,.$

[†] Fortsch. Phys. 42 (1994) 101-141. [*] PRD 55 (1997) 7114-7125. [#] PLB 449 (1999) 81-88.

Higher-twist corrections to DVCS off proton: Braun et al., PRD 111 (2025) 7, 076011... and earlier works.

Other processes

- Timelike Compton scattering (TCS)

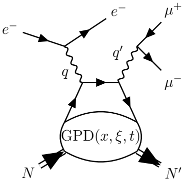


Like DVCS but $\xi \to -\xi$.

LT: Berger, Diehl and Pire, EPJC 23, 675–689 (2002).

Higher twists: VMF, Pire, Sznajder & Wagner, PRD 111 (2025) 7, 074034.

- **Double** deeply virtual Compton scattering (**D**DVCS)



LT: Belitsky & Müller, PRL 90, 022001 and PRD 68, 116005 (2003); Guidal & Vanderhaeghen, PRL 90, 012001 (2003); Deja, VMF, Pire, Sznajder & Wagner, PRD 107, 094035 (2023); Alvarado, Hoballah & Voutier, PRC 111 (2025) 6, 065205.

Higher twists: VMF, Pire, Sznajder & Wagner, PRD 111 (2025) 7, 074034.

$$\mathrm{Im}\,(\mathcal{H}_{\mathrm{DDVCS}}(\rho, \xi, t)) \propto H^{(+)}(\rho, \xi, t)\,, \qquad \rho \overset{\mathrm{LT}}{=} \xi \frac{Q^2 - Q'^2}{Q^2 + Q'^2}$$

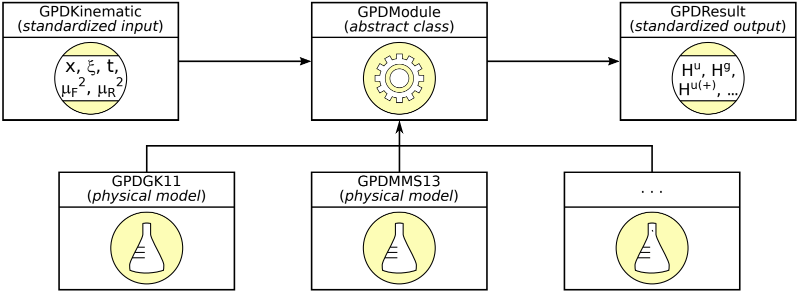
PARTONS and EpIC

PARtonic Tomography Of Nucleon Software

Berthou et al., EPJC 78, 478 (2018).

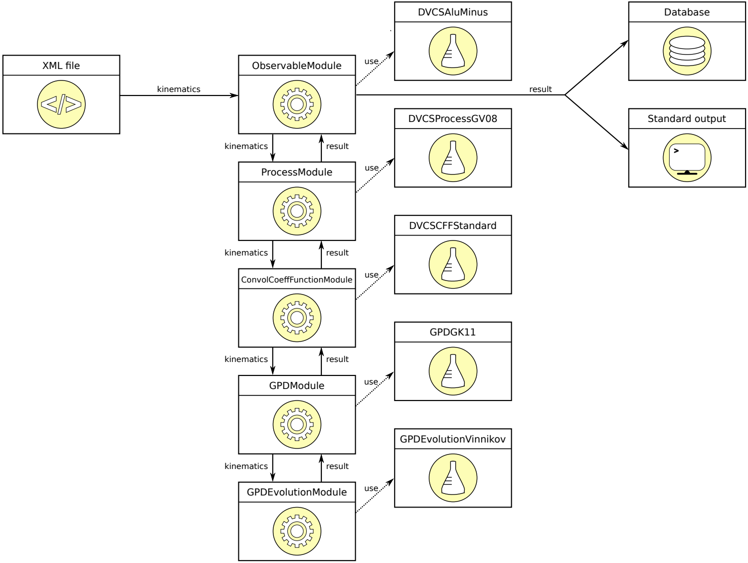
- C++ open-source platform: `https://partons.cea.fr/`
- Common framework enabling systematic comparisons.
- Updates should not endanger previously existing code → **modularity.**
- **All than can be automated has been, is and will be automated.**
- XML scenarios for automated running: **no need to know C++.**
- Virtual machine → run PARTONS independently of user's OS.
- **v4 version is now available.**

Modularity



From Berthou et al., EPJC 78, 478 (2018).

Automation



From Berthou et al., EPJC 78, 478 (2018).

Progress in PARTONS: v1 to v4

v4 is the latest released version of PARTONS.

v1 (2018)	v4 (2025)
DVCS (NLO + LT)	DVCS, TCS & GAM2 (NLO + LT). DVMP* & DDVCS (LO + LT)
Vinnikov GPD evolution	Vinnikov & APFEL++ GPD evolution

GAM2 (no BH): $\gamma + N \to \gamma + \gamma + N'$

In PARTONS you can find:

- GPD models: GK, VGG, MMS, Vinnikov.
- Running of α_s to 4 loops.
- Observables: cross-sections and its moments, asymmetries.
- Integration with LHAPDF (modern PDF sets) & APFEL++ (evolution).

* Production of pseudo-scalar mesons only.

EpIC MC event generator

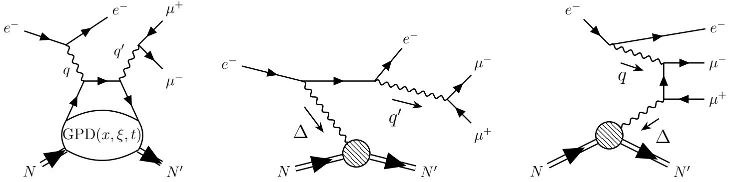
Aschenauer et al.,
EPJC 82 (2022) 9, 819.

- Multi-channel Monte Carlo event generator: `https://github.com/pawelsznajder/epic`
- Based on the PARTONS framework.
- Includes radiative corrections.
- DVCS, TCS, DDVCS, DVMP (only π^0).
- Modular architecture.

PARTONS and EpIC for DDVCS

Reminder: Double DVCS

- **Goal:** phenomenology for JLab12, JLab20+ and EIC.
- **What is DDVCS?** Subprocess in the electroproduction of a lepton pair:



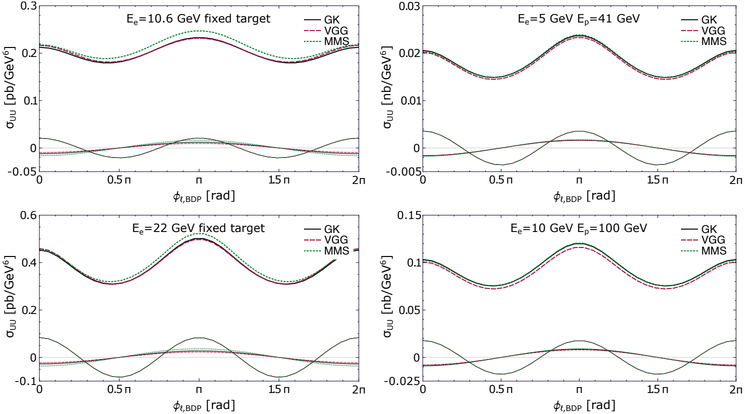
From left to right: DDVCS, BH1, BH2. Complementary crossed-diagrams are not shown

What follows is at LO+LT accuracy.

1st ever calculation of kinematic higher twists for DDVCS and TCS: VMF, Pire, Sznajder & Wagner, PRD 111 (2025) 7, 074034.

Check-out tomorrow's talks on DDVCS by Vutier, Paremuzyan & Biswas.

Deja, VMF, Pire, Sznajder & Wagner, PRD 107 (2023) 9, 094035.

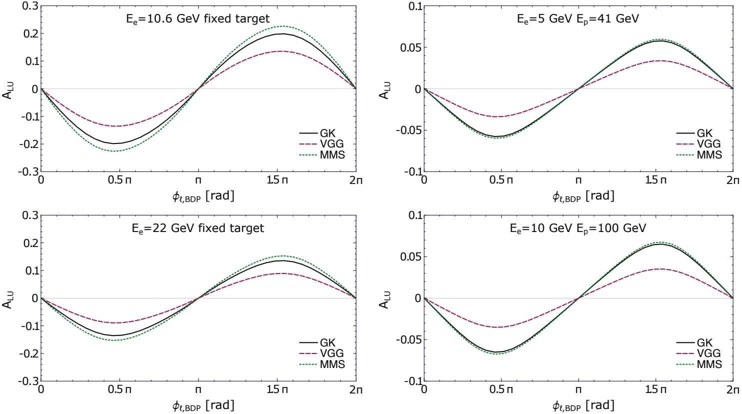


JLab12, JLab20+ EIC 5x41, EIC 10x100

Experiment	Beam energies [GeV]	y	$\|t\|$ [GeV^2]	Q^2 [GeV^2]	Q'^2 [GeV^2]
JLab12	$E_e = 10.6,\ E_p = M$	0.5	0.2	0.6	2.5
JLab20+	$E_e = 22,\ E_p = M$	0.3	0.2	0.6	2.5
EIC	$E_e = 5,\ E_p = 41$	0.15	0.1	0.6	2.5
EIC	$E_e = 10,\ E_p = 100$	0.15	0.1	0.6	2.5

Observables: beam-spin asymmetry

Deja, VMF, Pire, Sznajder & Wagner, PRD 107 (2023) 9, 094035.



JLab12, JLab20+: **15-20%** EIC 5x41, EIC 10x100: **3-7%**

Experiment	Beam energies [GeV]	y	$\lvert t\rvert$ [GeV^2]	Q^2 [GeV^2]	Q'^2 [GeV^2]
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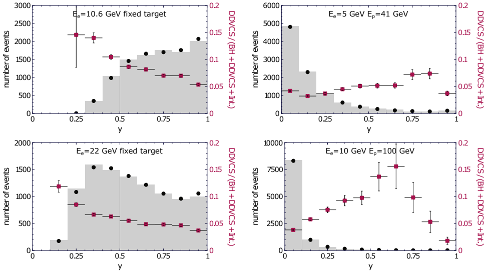
Monte Carlo study: distribution in y

Deja, VMF, Pire, Sznajder & Wagner, PRD 107 (2023) 9, 094035.



JLab12, JLab20+ EIC 5x41, EIC 10x100

- EpIC MC
- ● integrated cross-section
- pure DDVCS fraction

Kinematic cuts:
$Q^2 \in (0.15, 5)$ GeV^2
$Q'^2 \in (2.25, 9)$ GeV^2
JLab: $-t \in (0.1, 0.8)$ GeV^2
EIC: $-t \in (0.01, 1)$ GeV^2
$\phi, \phi_\ell \in (0.1, 2\pi - 0.1)$ rad
$\theta_\ell \in (\pi/4, 3\pi/4)$ rad
JLab: $y \in (0.1, 1)$
EIC: $y \in (0.05, 1)$

10000 events/distribution. Neither acceptance nor detectors response are taken into account in this study. For that, cf. Alvarado, Hoballah & Voutier, PRC 111 (2025) 6, 065205.

Experiment	Beam energies [GeV]	Range of $\|t\|$ [GeV^2]	$\sigma\|_{0<y<1}$ [pb]	$\mathcal{L}^{10k}\|_{0<y<1}$ [fb^{-1}]	$y_{\min}$	$\sigma\|_{y_{\min}<y<1}/\sigma\|_{0<y<1}$
JLab12	$E_e = 10.6,\ E_p = M$	$(0.1, 0.8)$	0.14	70	0.1	1
JLab20+	$E_e = 22,\ E_p = M$	$(0.1, 0.8)$	0.46	22	0.1	1
EIC	$E_e = 5,\ E_p = 41$	$(0.05, 1)$	3.9	2.6	0.05	0.73
EIC	$E_e = 10,\ E_p = 100$	$(0.05, 1)$	4.7	2.1	0.05	0.32

Take aways

- **30** years of exclusive physics **in one** tool: `PARTONS` **!!**
- Working in tandem with `EpIC` for simulations.
- Modularity $\rightarrow$ updating without endangering already existing and well-tested code.
- `PARTONS` includes:
  1. Many GPD models and processes.
  2. Evolution of GPDs in x-space and through conformal expansion.
  3. Running of α_s.
  4. Automation via XML so **you do NOT need to know C++.**
- **Future prospects:** already computed kin. twist corrections for different processes to be implemented soon in `PARTONS`.

Thank you!

Complementary slides

QCD energy-momentum tensor (EMT), $\Theta^{\mu\nu}$

$\Theta^{\mu\nu}$ parameterization $\rightarrow$ gravitational form factors (GFFs):

$$\langle p', s' | \Theta_a^{\mu\nu}(0) | p, s \rangle \overset{spin-1/2}{=}$$

$$= \bar{u}(p', s') \left\{ \frac{\bar{p}^\mu \bar{p}^\nu}{M} A_a(t) + \frac{\Delta^\mu \Delta^\nu - \eta^{\mu\nu} \Delta^2}{M} C_a(t) + M \eta^{\mu\nu} \bar{C}_a(t) \right.$$

$$\left. + \frac{\bar{p}^{\{\mu} i\sigma^{\nu\}\rho} \Delta_\rho}{4M} [A_a(t) + B_a(t)] + \frac{\bar{p}^{[\mu} i\sigma^{\nu]\rho} \Delta_\rho}{4M} D_a(t) \right\} u(p, s) \, .$$

$a =$ quarks and gluons.

GPDs and GFFs:

$$\int dx \, x^{1-\mathscr{P}_{f,g}} \begin{Bmatrix} H_{f,g}(x, \xi, t) \\ E_{f,g}(x, \xi, t) \end{Bmatrix} = \begin{Bmatrix} A_{f,g}(t) + 4\xi^2 C_{f,g}(t) \\ B_{f,g}(t) - 4\xi^2 C_{f,g}(t) \end{Bmatrix} ,$$

$$J_{f,g} = \frac{A_{f,g}(0) + B_{f,g}(0)}{2} = \frac{1}{2} \int dx \; x^{1-\mathscr{P}_{f,g}} \left[H_{f,g}(x, \xi, 0) + E_{f,g}(x, \xi, 0) \right] ,$$

and other relations.

$\mathscr{P}_{f,g} = 0$ for quarks with flavor f; and 1 for gluons g.

Observables: cross-section & cosine moments

- For unpolarized beam and target:

$$\sigma_{UU}(\phi_{\ell,\mathrm{BDP}}) = \int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} d\theta_{\ell,\mathrm{BDP}} \ \sin\theta_{\ell,\mathrm{BDP}}$$

$$\times\left(\frac{d^7\sigma^{\rightarrow}}{dx_B dQ^2 dQ'^2 d|t| d\phi d\Omega_{\ell,\mathrm{BDP}}} + \frac{d^7\sigma^{\leftarrow}}{dx_B dQ^2 dQ'^2 d|t| d\phi d\Omega_{\ell,\mathrm{BDP}}}\right)$$

- Cosine components:

$$\sigma_{UU}^{\cos\left(n\phi_{\ell,\mathrm{BDP}}\right)}(\phi_{\ell,\mathrm{BDP}}) = M_{UU}^{\cos\left(n\phi_{\ell,\mathrm{BDP}}\right)} \cos\left(n\phi_{\ell,\mathrm{BDP}}\right)$$

- Cosine moments:

$$M_{UU}^{\cos\left(n\phi_{\ell,\mathrm{BDP}}\right)} = \frac{1}{N}\int_0^{2\pi} d\phi_{\ell,\mathrm{BDP}} \cos\left(n\phi_{\ell,\mathrm{BDP}}\right)\sigma_{UU}(\phi_{\ell,\mathrm{BDP}})$$

$N = 2\pi$ for $n = 0$, $N = \pi$ for $n > 0$.

Observables: beam-spin asymmetry

- Single beam-spin asymmetry for longitudinally polarized electrons:

$$A_{LU}(\phi_{\ell,\mathrm{BDP}}) = \frac{\Delta\sigma_{LU}(\phi_{\ell,\mathrm{BDP}})}{\sigma_{UU}(\phi_{\ell,\mathrm{BDP}})}$$

$$\Delta\sigma_{LU}(\phi_{\ell,\mathrm{BDP}}) = \int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} d\theta_{\ell,\mathrm{BDP}} \;\sin\theta_{\ell,\mathrm{BDP}}$$

$$\times \left(\frac{d^7\sigma^{\rightarrow}}{dx_B dQ^2 dQ'^2 d|t| d\phi d\Omega_{\ell,\mathrm{BDP}}} - \frac{d^7\sigma^{\leftarrow}}{dx_B dQ^2 dQ'^2 d|t| d\phi d\Omega_{\ell,\mathrm{BDP}}} \right)$$

- We consider $Q'^2 > Q^2$: timelike-dominated DDVCS.

- Avoid resonances: $Q'^2 \in (2.25, 9)$ GeV^2.