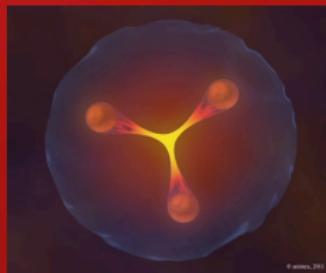


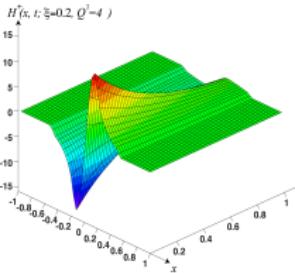
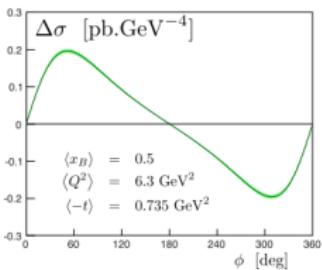
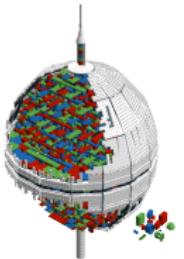
DE LA RECHERCHE À L'INDUSTRIE



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Generalized parton distributions from experiments



Science Opportunities with EIC | Hervé MOUTARDE

Jul. 19, 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

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PARIS-SACLAY

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EIC event generator

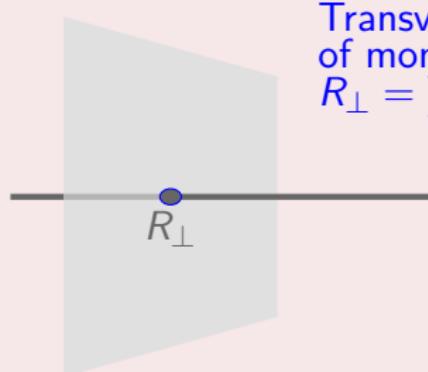
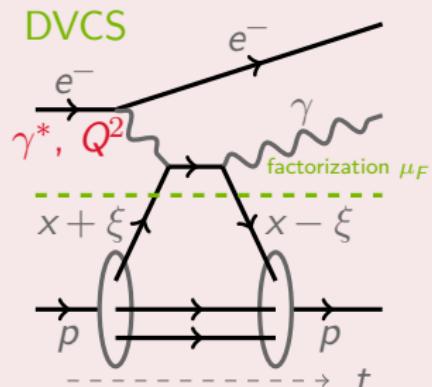
GPD evolution

Conclusion

Abbreviations

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

Deeply Virtual Compton Scattering (DVCS)



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

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Deconvolution problem

DVCS off the pion

Ecosystem

Design

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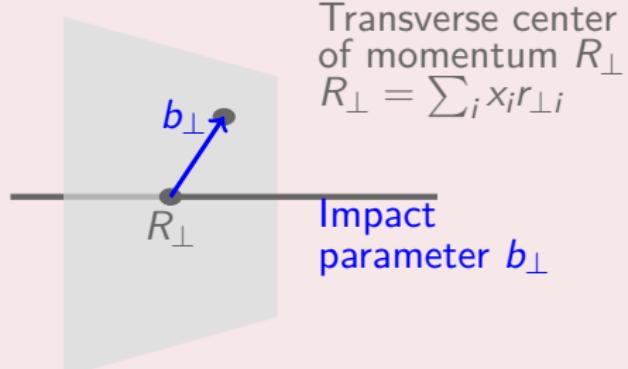
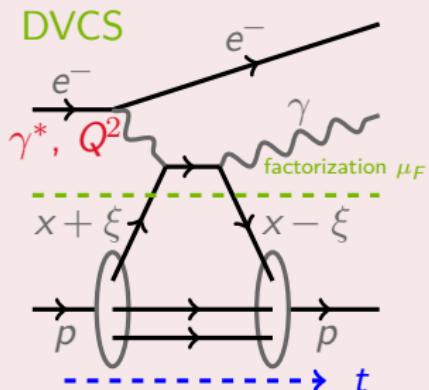
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Deeply Virtual Compton Scattering (DVCS)



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EIC event generator

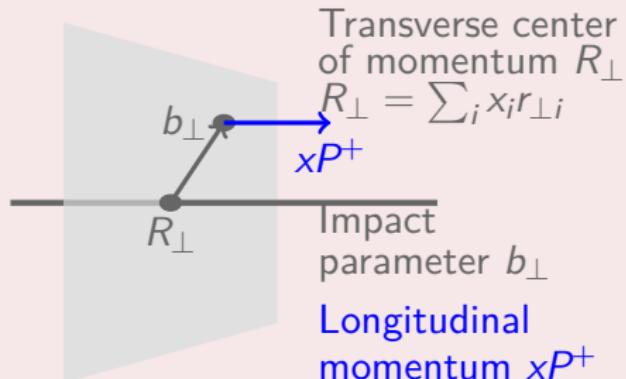
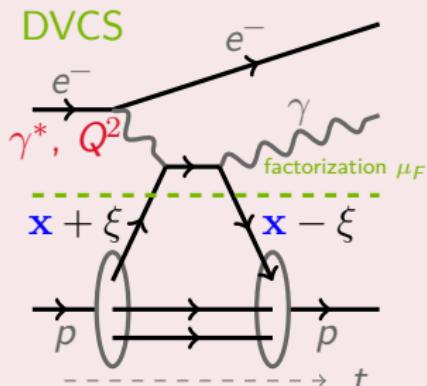
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Deeply Virtual Compton Scattering (DVCS)



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

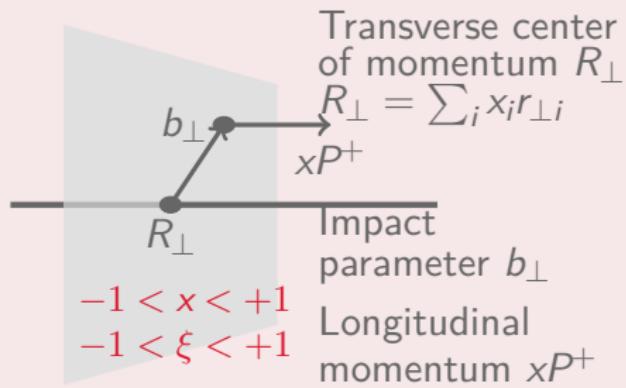
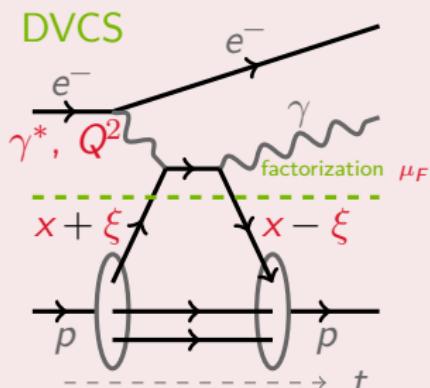
GPD evolution

Conclusion

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- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

Deeply Virtual Compton Scattering (DVCS)



- **24 GPDs** $F^i(x, \xi, t, \mu_F)$ for each parton type $i = g, u, d, \dots$ for leading and sub-leading twists.

Fits to deeply virtual Compton scattering

GPDs from experiments

Physical content

DVCS fits

Experimental access

- Fit status

- Neural network fits

Complementary analysis

- Impact study: TCS

- Impact study:
positrons

- Internal pressure

- Deconvolution
problem

- DVCS off the pion

Ecosystem

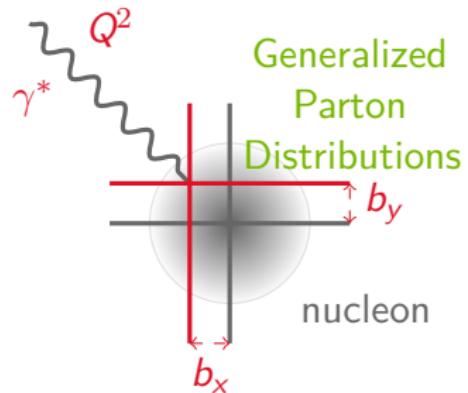
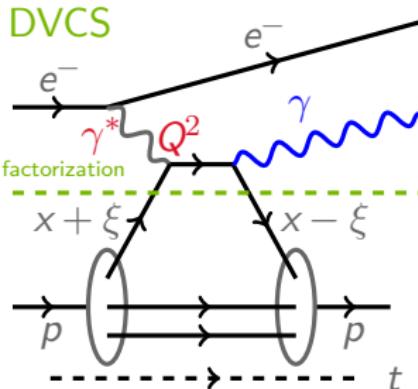
- Design

- EIC event
generator

- GPD evolution

Conclusion

Abbreviations



Exclusive processes of current interest.

Factorization and universality.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

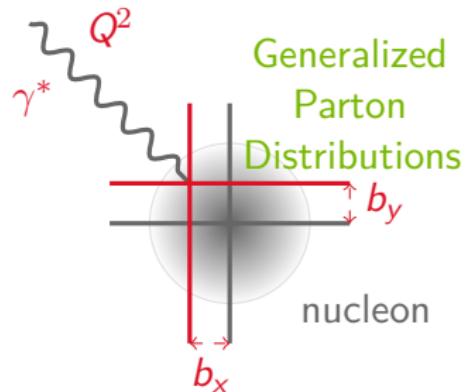
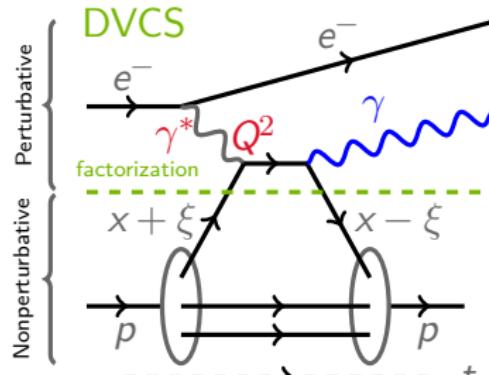
Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations



Exclusive processes of current interest.

Factorization and universality.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

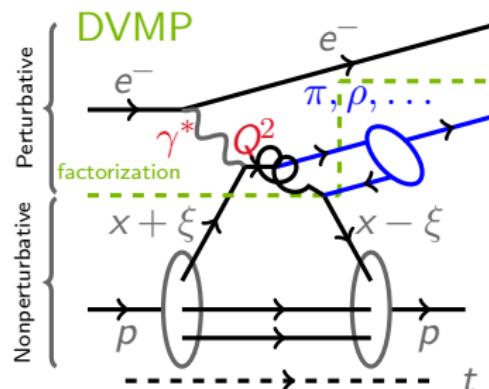
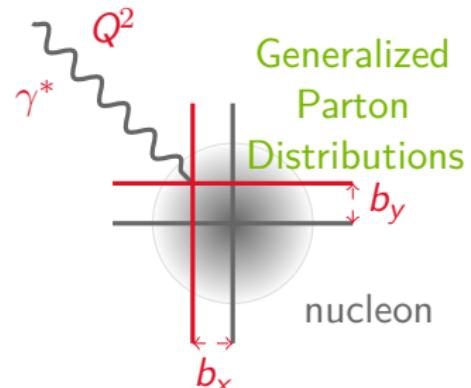
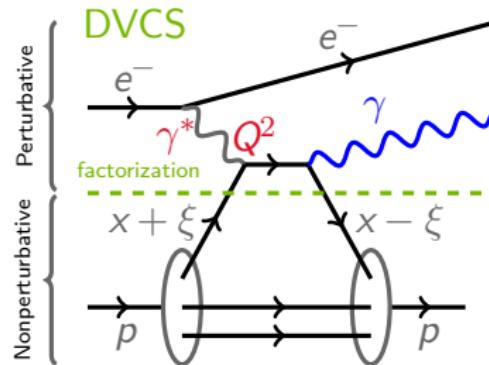
Design

EIC event generator

GPD evolution

Conclusion

Abbreviations



Exclusive processes of current interest.

Factorization and universality.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

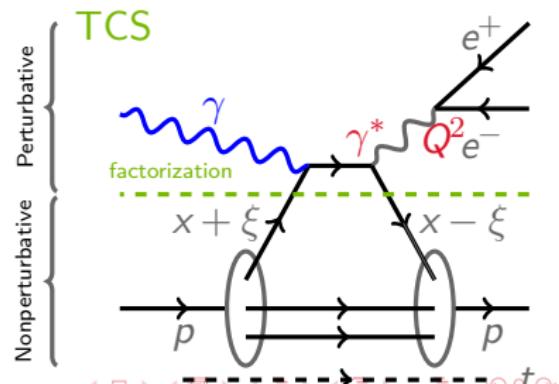
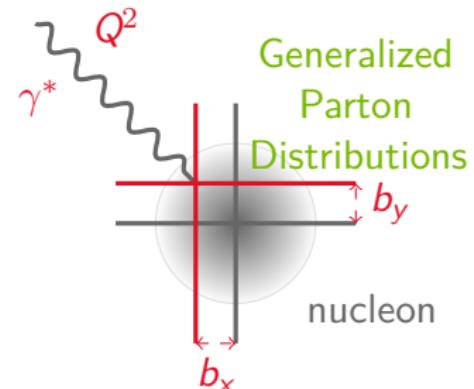
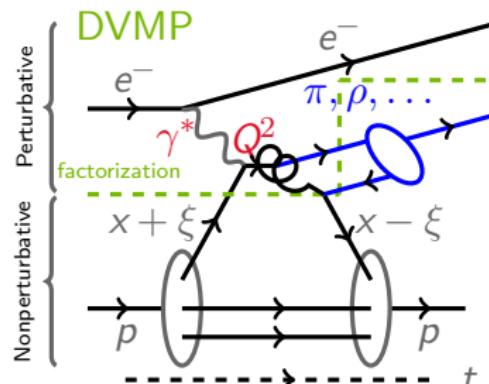
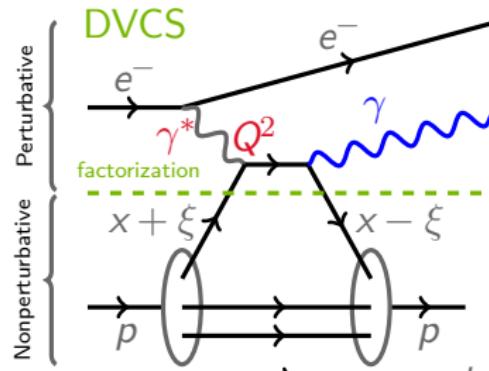
Design

EplC event generator

GPD evolution

Conclusion

Abbreviations



Exclusive processes of current interest.

Factorization and universality.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

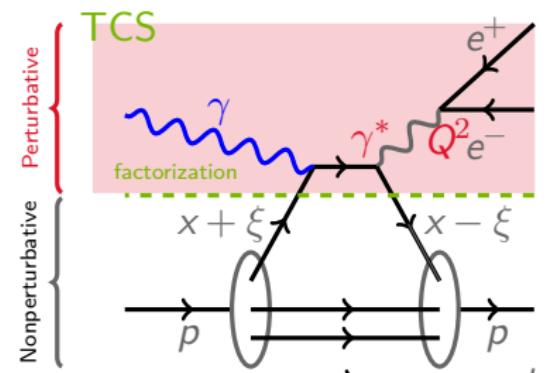
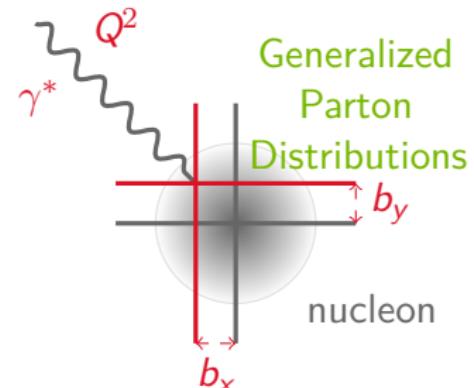
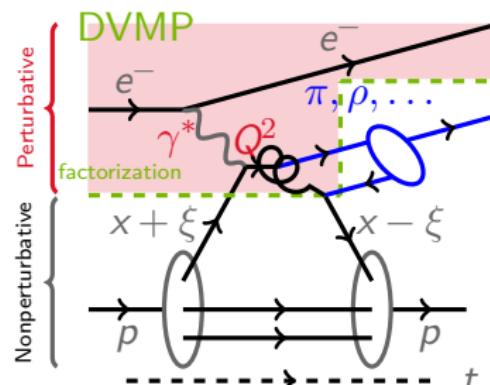
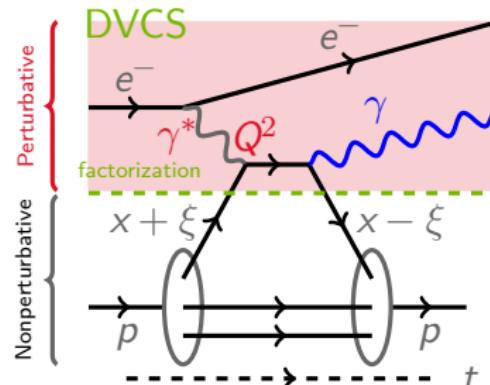
Design

EplC event generator

GPD evolution

Conclusion

Abbreviations



Exclusive processes of current interest.

Factorization and universality.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

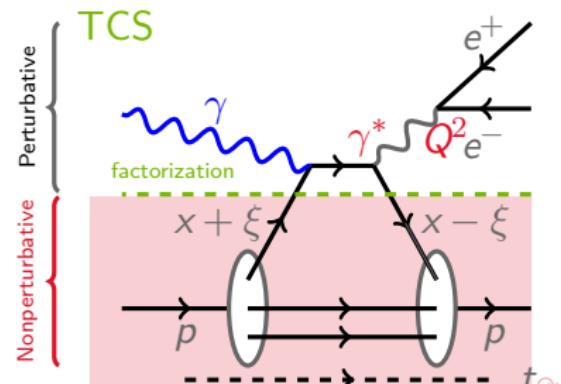
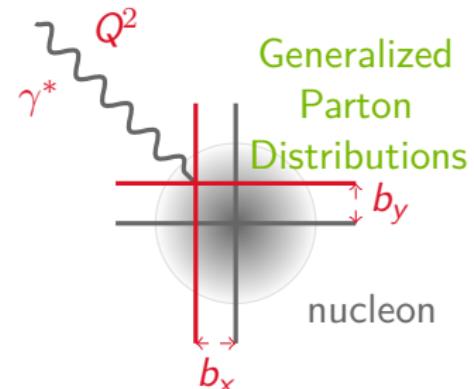
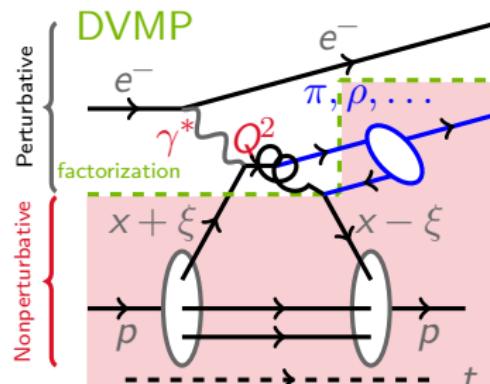
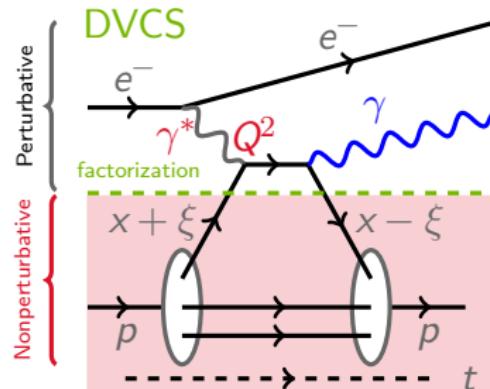
Design

EplC event generator

GPD evolution

Conclusion

Abbreviations



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EplC event generator

GPD evolution

Conclusion

Abbreviations

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**.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

- Reduction to PDFs or elastic form factors.
- Implement *a priori* **positivity** and **polynomiality**. Still uncommon in many models or parameterizations used for phenomenology.
- **General solution** starting from overlap of (potentially effective) light front wave functions.
- Use of **evolution equations** to implement further constraints on the GPD functional form.
- Work **beyond leading-order** and depart from the parton model...
- Systematic impact study or use of **kinematic corrections** still missing.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

- GPD fits **only in the small x_B region** with a **flexible parameterization** (kinematic simplifications).
- Global fits of CFFs in the sea, valence and glue regions.
- Some GPD models with non-flexible parameterizations adjusted to experimental DVCS or DVMP data.
 [Kumerički et al. \(2016\)](#)

Almost all existing DVCS data sets.

2600+ measurements of 30 observables published during 2001-17.

GPDs from experiments

No.	Collab.	Year	Ref.	Observable	Kinematic dependence	No. of points used / all
1	HERMES	2001	[40]	A_{LU}^+	ϕ	10 / 10
2		2006	[41]	$A_C^{\cos i\phi}$	$i = 1$	4 / 4
3		2008	[42]	$A_C^{\cos i\phi}$	$i = 0, 1$	x_{Bj}
				$A_{UT,DVCS}^{\sin(\phi-\phi_S) \cos i\phi}$	$i = 0$	
				$A_{UT,I}^{\sin(\phi-\phi_S) \cos i\phi}$	$i = 0, 1$	
				$A_{UT,I}^{\cos(\phi-\phi_S) \sin i\phi}$	$i = 1$	
4		2009	[43]	$A_{LU,I}^{\sin i\phi}$	$i = 1, 2$	x_{Bj}
				$A_{LU,DVCS}^{\sin i\phi}$	$i = 1$	
				$A_C^{\cos i\phi}$	$i = 0, 1, 2, 3$	
5		2010	[44]	$A_{UL}^{+, \sin i\phi}$	$i = 1, 2, 3$	x_{Bj}
				$A_{UL}^{+, \cos i\phi}$	$i = 0, 1, 2$	
6		2011	[45]	$A_{LT,DVCS}^{\cos(\phi-\phi_S) \cos i\phi}$	$i = 0, 1$	x_{Bj}
				$A_{LT,DVCS}^{\sin(\phi-\phi_S) \sin i\phi}$	$i = 1$	
				$A_{LT,I}^{\cos(\phi-\phi_S) \cos i\phi}$	$i = 0, 1, 2$	
				$A_{LT,I}^{\sin(\phi-\phi_S) \sin i\phi}$	$i = 1, 2$	
7		2012	[46]	$A_{LU,I}^{\sin i\phi}$	$i = 1, 2$	x_{Bj}
				$A_{LU,DVCS}^{\sin i\phi}$	$i = 1$	
				$A_C^{\cos i\phi}$	$i = 0, 1, 2, 3$	
8	CLAS	2001	[47]	$A_{LU}^{\sin i\phi}$	$i = 1, 2$	—
9		2006	[48]	$A_{UL}^{-, \sin i\phi}$	$i = 1, 2$	—
10		2008	[49]	A_{LU}^-	ϕ	283 / 737
11		2009	[50]	A_{LU}^-	ϕ	22 / 33
12		2015	[51]	$A_{LU}^-, A_{UL}^-, A_{LL}^-$	ϕ	311 / 497
13		2015	[52]	$d^4\sigma_{UU}^-$	ϕ	1333 / 1933
14	Hall A	2015	[34]	$\Delta d^4\sigma_{LU}^-$	ϕ	228 / 228
15		2017	[35]	$\Delta d^4\sigma_{LU}^-$	ϕ	276 / 358
16	COMPASS	2018	[36]	$d^3\sigma_{U^-U}^-$	t	2 / 4
17	ZEUS	2009	[37]	$d^3\sigma_{U^-U}^+$	t	4 / 4
18	H1	2005	[38]	$d^3\sigma_{U^-U}^0$	t	7 / 8
19		2009	[39]	$d^3\sigma_{UU}^\pm$	t	12 / 12

Conclusion

SUM: 2624 / 3996

Abbreviations

Moutarde et al. (2019)

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

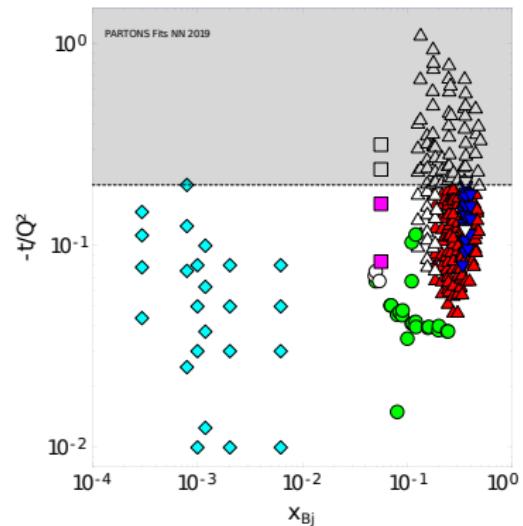
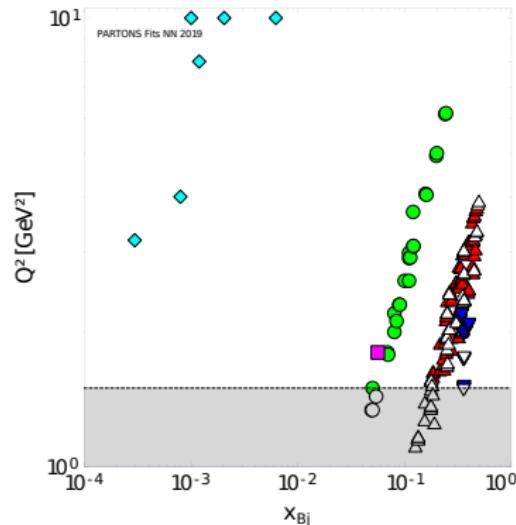
Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution
problem

DVCS off the pion



▼ Hall A
▲ CLAS

● HERMES
◆ H1 and ZEUS

■ COMPASS

Moutarde *et al.* (2019)

Ecosystem

Design

EplC event
generator

GPD evolution

Conclusion

Abbreviations

Modeling of \mathcal{H} , $\tilde{\mathcal{H}}$, \mathcal{E} and $\tilde{\mathcal{E}}$. Independent descriptions of real and imaginary parts.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

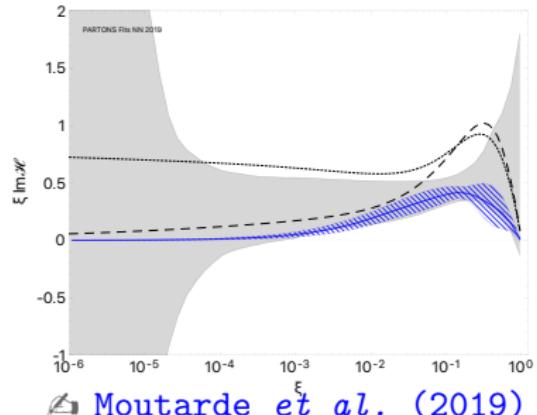
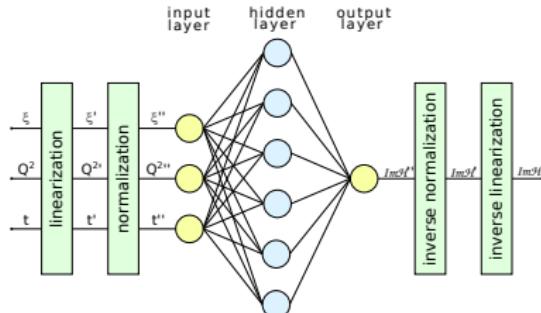
EpiC event generator

GPD evolution

Conclusion

Abbreviations

- Real and imaginary parts of CFFs parameterized by **neural networks**.
- Propagation of uncertainties through **replica method** and evaluation of 68 % **confidence levels**.



Complementary analysis

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EplC event generator

GPD evolution

Conclusion

Abbreviations

- Relation between **spacelike** (DVCS) and **timelike** (TCS) CFFs worked out at NLO:

$$T_{\mathcal{H}} \stackrel{\text{LO}}{=} s_{\mathcal{H}^*},$$

$$T_{\mathcal{H}} \stackrel{\text{NLO}}{=} s_{\mathcal{H}^*} - i\pi Q^2 \frac{\partial}{\partial Q^2} s_{\mathcal{H}^*},$$

with Q the virtuality of the incoming or outgoing photon.

 Müller et al. (2012)

- Using a **global CFF fit** to DVCS measurements, the **first multi-channel data-driven** analysis of exclusive processes beyond LO becomes possible.
- Allow detailed studies of **sensitivity to higher-order contributions**.
- Towards **multi-channel fits** to exclusive processes!

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

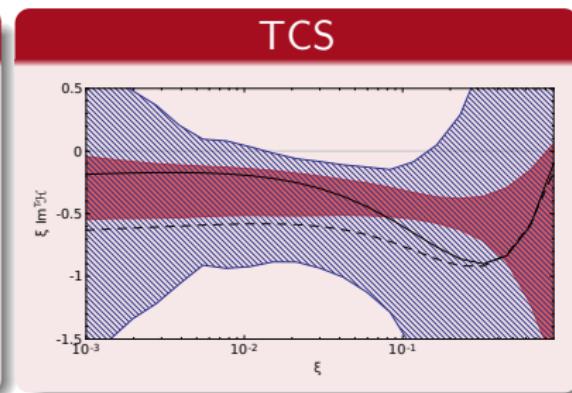
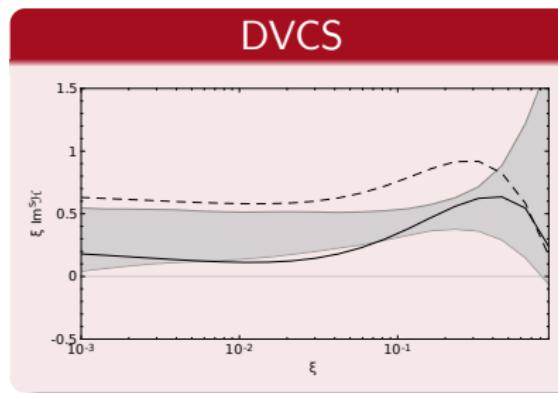
EIC event generator

GPD evolution

Conclusion

Abbreviations

- Spacelike and timelike CFFs depending on ξ at common kinematics: $Q^2 = 2 \text{ GeV}^2$ and $t = -0.3 \text{ GeV}^2$.
- ξ range from EIC to Jefferson Lab kinematics.
- Comparison with phenomenological model at LO (dashed) and NLO (solid).
- Large uncertainty reflecting our **limited knowledge** of DVCS CFFs, especially of their Q^2 dependence.



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

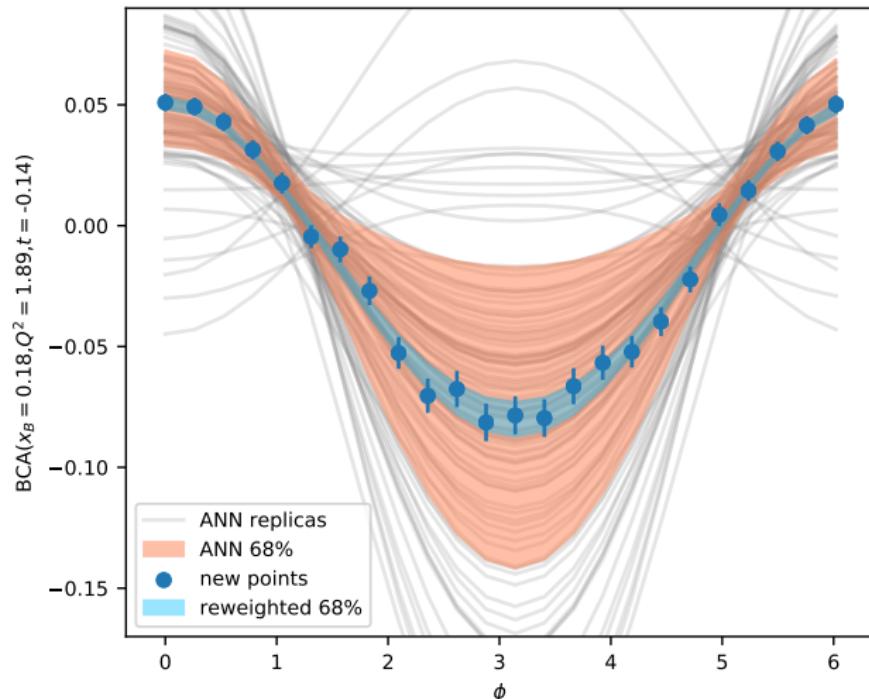
Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

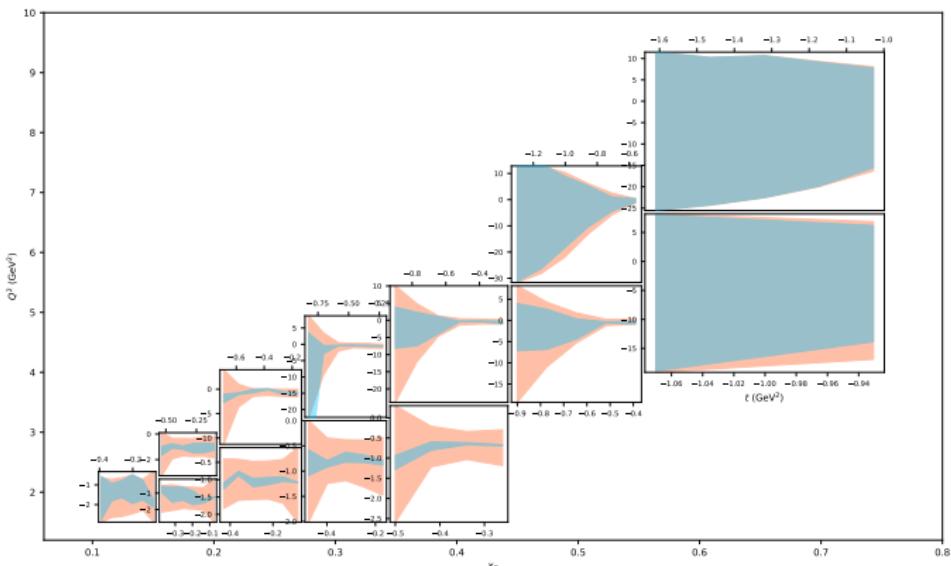
Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations



 Dutrieux et al. (2021)

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

■ Matrix element in the Breit frame ($a = q, g$):

$$\left\langle \frac{\Delta}{2} |T_a^{\mu\nu}(0)| - \frac{\Delta}{2} \right\rangle = M \left\{ \eta^{\mu 0} \eta^{\nu 0} \left[A_a(t) + \frac{t}{4M^2} B_a(t) \right] + \eta^{\mu\nu} \left[\bar{C}_a(t) - \frac{t}{M^2} C_a(t) \right] + \frac{\Delta^\mu \Delta^\nu}{M^2} C_a(t) \right\}$$

■ Anisotropic fluid in relativistic hydrodynamics:

$$\Theta^{\mu\nu}(\vec{r}) = [\varepsilon(r) + p_t(r)] u^\mu u^\nu - p_t(r) \eta^{\mu\nu} + [p_r(r) - p_t(r)] \chi^\mu \chi^\nu$$

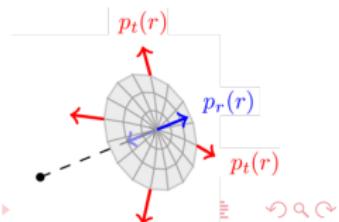
where u^μ and $\chi^\mu = x^\mu/r$.

■ Define isotropic pressure and pressure anisotropy:

$$p(r) = \frac{p_r(r) + 2p_t(r)}{3}$$

$$s(r) = p_r(r) - p_t(r)$$

 Lorcé et al. (2019)



GPDs from experiments

Physical content

$$\frac{\varepsilon_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ A_a(t) + \bar{C}_a(t) + \frac{t}{4M^2} [B_a(t) - 4C_a(t)] \right\}$$

DVCS fits

Experimental access
Fit status
Neural network fits

$$\frac{p_{r,a}(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) - \frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d}{dt} \left(t^{3/2} C_a(t) \right) \right\}$$

Complementary analysis

Impact study: TCS
Impact study: positrons

$$\frac{p_{t,a}(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) + \frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d}{dt} \left[t \frac{d}{dt} \left(t^{3/2} C_a(t) \right) \right] \right\}$$

Internal pressure

Deconvolution problem
DVCS off the pion

$$\frac{p_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) + \frac{2}{3} \frac{t}{M^2} C_a(t) \right\}$$

Ecosystem

Design
EIC event generator
GPD evolution

$$\frac{s_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d^2}{dt^2} \left(t^{5/2} C_a(t) \right) \right\}$$

Conclusion

Abbreviations

Lorcé et al. (2019)

GPDs from experiments

Physical content

$$\frac{\varepsilon_a(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ A_a(t) + \bar{C}_a(t) + \frac{t}{4M^2} [B_a(t) - 4C_a(t)] \right\}$$

DVCS fits

Experimental access
Fit status
Neural network fits

$$\frac{p_{r,a}(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) - \frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d}{dt} \left(t^{3/2} C_a(t) \right) \right\}$$

Complementary analysis

Impact study: TCS
Impact study:
positrons

$$\frac{p_{t,a}(r)}{M} = \int \frac{d^3\vec{\Delta}}{(2\pi)^3} e^{-i\vec{\Delta} \cdot \vec{r}} \left\{ -\bar{C}_a(t) + \frac{4}{r^2} \frac{t^{-1/2}}{M^2} \frac{d}{dt} \left[t \frac{d}{dt} \left(t^{3/2} C_a(t) \right) \right] \right\}$$

Internal pressure

Deconvolution problem
DVCS off the pion

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Ecosystem

Design
EplC event generator
GPD evolution

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Conclusion

Abbreviations

Lorcé et al. (2019)

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

■ Link between GPDs and gravitational form factors

$$\int dx x \mathbf{H}^q(x, \xi, t) = \mathbf{A}^q(t) + 4\xi^2 \mathbf{C}^q(t)$$

$$\int dx x \mathbf{E}^q(x, \xi, t) = \mathbf{B}^q(t) - 4\xi^2 \mathbf{C}^q(t)$$

↳ Ji (1997)

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

1 Expand D-term on Gegenbauer polynomials

$$D_{\text{term}}^q(z, t, \mu_F^2) = (1 - z^2) \sum_{\text{odd } n} d_n^q(t, \mu_F^2) C_n^{3/2}(z)$$

2 Write dispersion relation for CFF

$$\mathcal{C}_H(t, Q^2) = \text{Re}\mathcal{H}(\xi) - \frac{1}{\pi} \int_0^1 d\xi' \text{Im}\mathcal{H}(\xi) \left(\frac{1}{\xi - \xi'} - \frac{1}{\xi + \xi'} \right)$$

3 Compute subtraction constant at LO

$$\mathcal{C}_H(t, Q^2) = 4 \sum_q e_q^2 \sum_{\text{odd } n} d_n^q(t, \mu_F^2 \equiv Q^2)$$

4 Retrieve gravitational form factor

$$d_1^q(t, \mu_F^2) = 5 C_q(t, \mu_F^2)$$

GPDs from experiments

Physical
content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

**Impact study:
positrons**

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

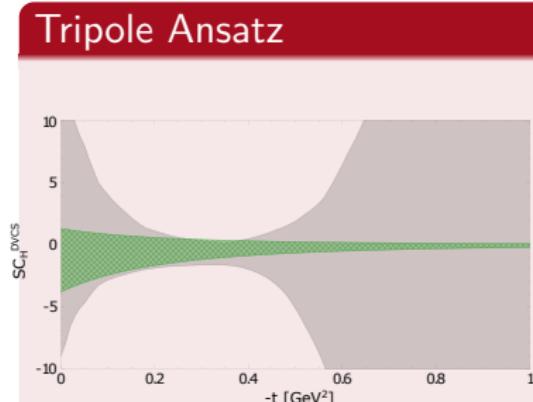
EpiC event generator

CBD evolution

Conclusion

Abbreviations

- 1 Subtraction constant assumed equal to d_1 .
 - 2 Equal values for light quark contributions d_1^{uds} .
 - 3 Radiative generation of gluon d_1^g and charm d_1^c contributions.
 - 4 Tripole Ansatz for the t -dependence of d_1 .



Parameter	Value
$d_1^{uds}(\mu_F^2)$	-0.45 ± 0.92
$d_1^c(\mu_F^2)$	-0.0020 ± 0.0041
$d_1^g(\mu_F^2)$	-0.6 ± 1.3

Dutrieux et al. (2021)

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

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d_1 from DVCS data



Parameter	Value
$d_1^{uds}(\mu_F^2)$	-0.45 ± 0.92
$d_1^c(\mu_F^2)$	-0.0020 ± 0.0041
$d_1^g(\mu_F^2)$	-0.6 ± 1.3

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GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

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Summary of existing determinations

No.	Marker in Fig. 3	$\sum_q d_1^q(\mu_F^2)$	μ_F^2 in GeV^2	# of flavours	Type	Ref.
1	○	$-2.30 \pm 0.16 \pm 0.37$	2.0	3	from experimental data	[13]
2	□	0.88 ± 1.69	2.2	2	from experimental data	[14]
3	◊	-1.59 -1.92	4 4	2 2	t -channel saturated model t -channel saturated model	[55] [55]
4	△	-4	0.36	3	χ QSM	[30]
5	▽	-2.35	0.36	2	χ QSM	[10]
6	▣	-4.48	0.36	2	Skyrme model	[56]
7	田	-2.02	2	3	LFWF model	[57]
8	⊗	-4.85	0.36	2	χ QSM	[58]
9	⊕	-1.34 ± 0.31 -2.11 ± 0.27	4 4	2 2	lattice QCD ($\overline{\text{MS}}$) lattice QCD ($\overline{\text{MS}}$)	[59] [59]

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations

- Assume CFF \mathcal{H} is perfectly known. Solve inverse problem?

$$\mathcal{H}^q(\xi, Q^2) = \int_{-1}^1 \frac{dx}{\xi} T^q \left(\frac{x}{\xi}, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2) \right) H^q(x, \xi, \mu^2)$$

- Question raised about 20 years ago and has remained essentially open. Evolution proposed as a crucial element.
 - ↳ Freund (2000)
- There exist **non-zero GPDs with vanishing forward limit** and **vanishing CFF up to order α_s^2** .
- The DVCS deconvolution problem is **ill-posed**. ↳ Bertone et al. (2021)
- **Same conclusion holds** for several other hard exclusive processes.
- **Define and implement** further criterions in fitting strategies to select one solution among infinitely many.

From CFFs to GPDs.

Shadow GPDs have null LO and NLO CFF.

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

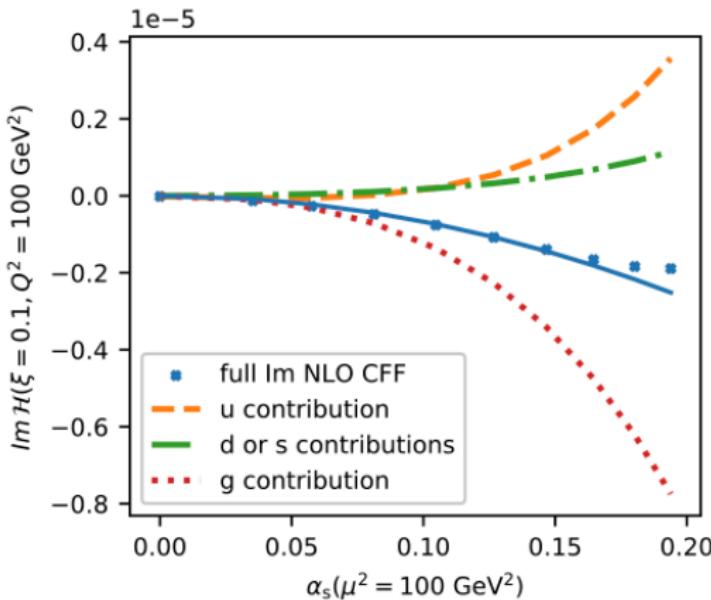
EIC event generator

GPD evolution

Conclusion

Abbreviations

- Start with shadow GPD for flavor u at 1 GeV^2 .
- Generate d , s and g while evolving up to 100 GeV^2 .
- Compute resulting CFF.



GPDs from experiments

Physical content

DVCS fits

Experimental access
Fit status
Neural network fits

Complementary analysis

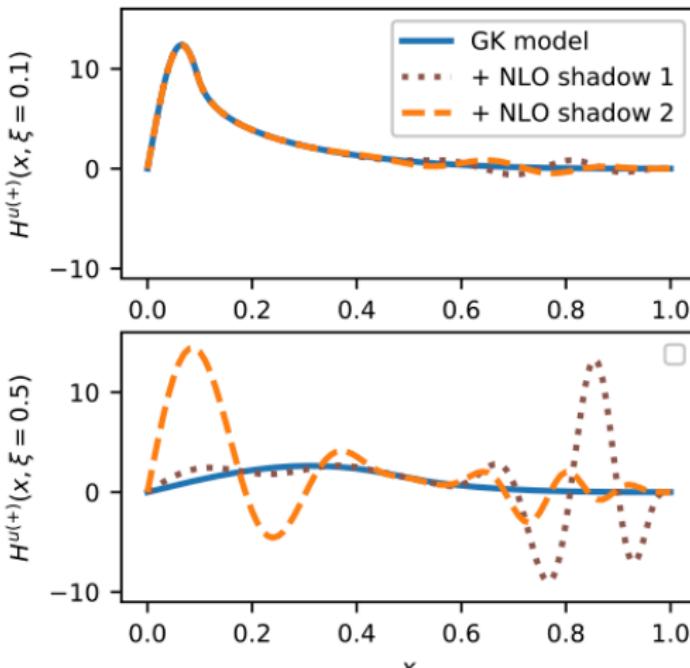
Impact study: TCS
Impact study: positrons
Internal pressure
Deconvolution problem
DVCS off the pion

Ecosystem

Design
EpiC event generator
GPD evolution

Conclusion

Abbreviations



Bertone et al. (2021)

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

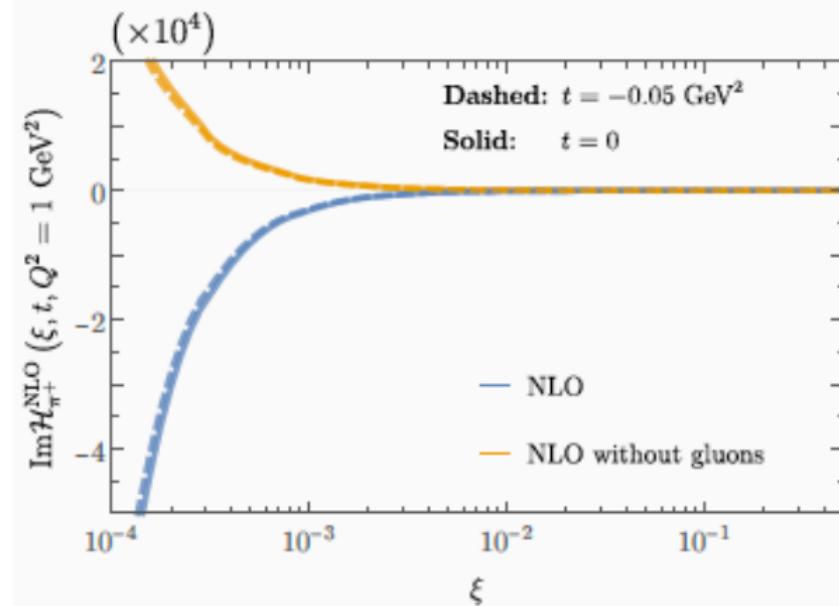
Design

EpiC event generator

GPD evolution

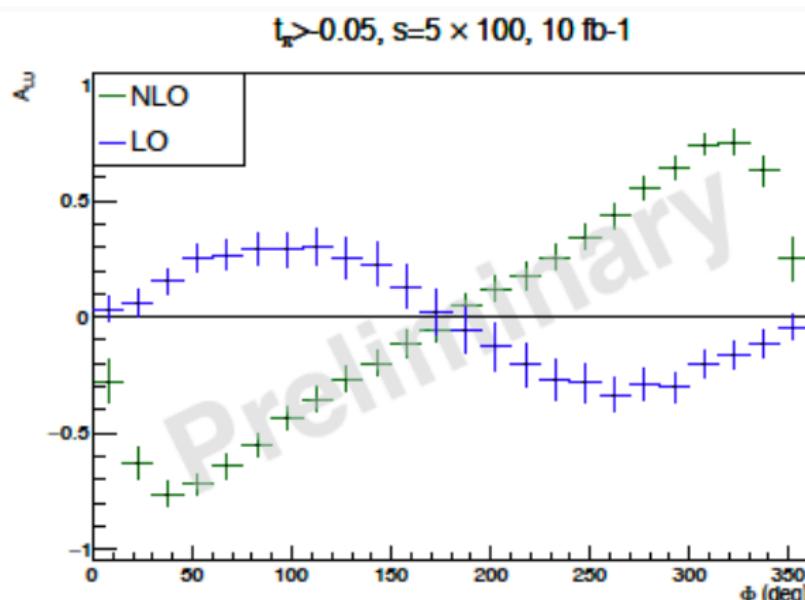
Conclusion

Abbreviations



Morgado et al., in progress

GPDs from experiments



Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EplC event generator

GPD evolution

Conclusion

Abbreviations

Morgado et al., in progress

The PARTONS ecosystem



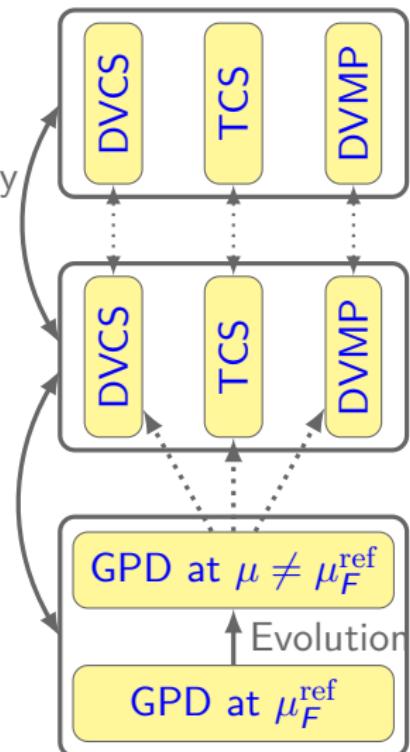
PARtonic
Tomography
Of
Nucleon
Software

Computing chain design.

Differential studies: physical models and numerical methods.

- GPDs from experiments
- Physical content
- DVCS fits
 - Experimental access
 - Fit status
 - Neural network fits
- Complementary analysis
 - Impact study: TCS
 - Impact study: positrons
 - Internal pressure
 - Deconvolution problem
 - DVCS off the pion
- Ecosystem
- Design
 - Epic event generator
 - GPD evolution
- Conclusion
- Abbreviations

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



PARtonic
Tomography
Of
Nucleon
Software



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

GPDs from experiments

EpiC – DVCS

Longitudinally polarized target, $E_e = 10 \text{ GeV}$, $E_p = 1 \text{ GeV}$

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution
problem

DVCS off the pion

Ecosystem

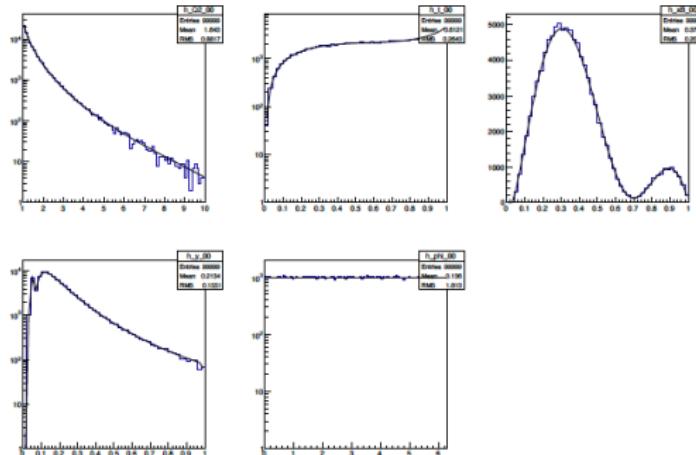
Design

EpiC event generator

GPD evolution

Conclusion

Abbreviations



GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EpiC event generator

GPD evolution

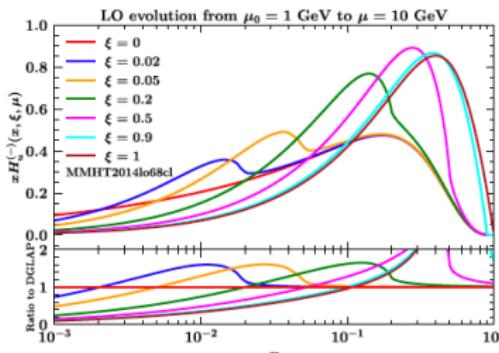
Conclusion

Abbreviations

Forward limit and DGLAP equations



- When $\kappa \rightarrow 0$, one recovers the forward DGLAP equations
 - Only the $\Theta(1-y)\mathcal{P}_1^{-(0)}(y; \kappa)$ term contributes to the evolution
 - No spurious singularity as $x < y < 1 < 1/\kappa$



- no ξ dependence in input
- Excellent agreement with native Apfel++ DGLAP evolution (red curve)
- Strong ξ dependence generated
- Continuity guaranteed at $x = \xi$ (cusp ?)

First validations

$x = \xi$ continuity, DGLAP limit and spurious divergences handling

Cédric Mezrag (Irfu-DPhN)

Apfel ++

May 31st, 2021

11 / 18

Bertone *et al.*, in progress

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study:
positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

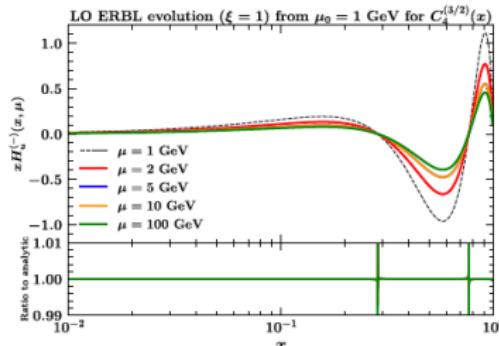
EpiC event generator

GPD evolution

ERBL Limit and Gegenbauer polynomials



- When $\kappa \rightarrow 1/x$ (i.e. $\xi \rightarrow 1$) one recovers the ERBL kernel
 - Eigen basis known $\rightarrow 3/2$ -Gegenbauer Polynomials
 - Direct (albeit restricted to $\xi = 1$) comparison between x-space and conformal space evolution



- $H(x, 1) \propto (1 - x^2) C_4^{(3/2)}(x)$
- $\frac{H(x, 1, \mu)}{H(x, 1, \mu_0)} = \left(\frac{\alpha_S(\mu)}{\alpha_S(\mu_0)} \right)^{\gamma_A/\beta_0}$
- Ratio is independent of x
- Excellent agreement between Apfel++ and conformal evolution in the ERBL limit

Additional validations

conformal evolution when $\xi \rightarrow 1$ guaranteeing the ERBL limit

Cédric Mezrag (Irfu-DPhN)

Apfel ++

May 31st, 2021

12 / 18

Bertone *et al.*, in progress

Conclusion

Conclusion and prospects.

New studies made possible with the development of new tools!

GPDs from experiments

Physical content

DVCS fits

Experimental access

Fit status

Neural network fits

Complementary analysis

Impact study: TCS

Impact study: positrons

Internal pressure

Deconvolution problem

DVCS off the pion

Ecosystem

Design

EIC event generator

GPD evolution

Conclusion

Abbreviations

- Engine for global CFF fits and impact studies.
- Tools to systematically relate models to experimental data in multi-channel analysis.
- Development of an ecosystem of computing codes for hadron structure: evolution, PDFs, GPDs, TMDs, etc.
- Design of future experiments and pioneering studies of new channels, e.g. DVCS off the pion at EIC.
- Concept of internal pressure well-defined and suitable for phenomenological analysis.
- The GPD deconvolution problem is ill-posed. Need for multi-channel analysis beyond LO and large Q^2 lever arm as provided by collider experiments.
- Benefiting from new inputs or constraints from nonperturbative QCD is highly desirable.

Abbreviations

Abbreviations used in this presentation.

GPDs from experiments	ANN	artificial neural network
	APFEL	a PDF evolution library
Physical content	CFF	Compton form factor
	DGLAP	Dokshitzer-Gribov-Lipatov-Altarelli-Parisi
DVCS fits	DVCS	deeply virtual Compton scattering
Experimental access	DVMP	deeply virtual meson production
Fit status	EIC	electron-ion collider
Neural network fits	ERBL	Efremov-Radyushkin-Brodsky-Lepage
Complementary analysis	GK	Goloskokov-Kroll
Impact study: TCS	GPD	generalized parton distribution
Impact study: positrons	LO	leading order
Internal pressure	NLO	next-to-leading order
Deconvolution problem	PDF	parton distribution function
DVCS off the pion	TCS	timelike Compton scattering
Ecosystem	TMD	transverse momentum dependent PDF
Design	VGG	Vanderhaeghen-Guichon-Guidal
EpiC event generator		
GPD evolution		
Conclusion		
Abbreviations		

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