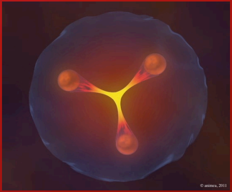
DE LA RECHERCHE À L'INDUSTRIE



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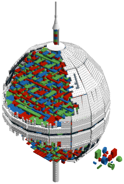
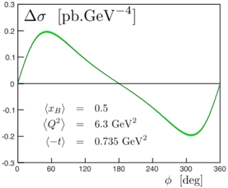
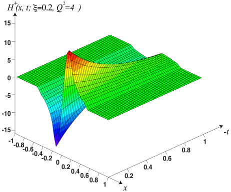
Tools for 3D hadron structure with a high luminosity EIC







HL-EIC | Hervé MOUTARDE

universite PARIS-SACLAY

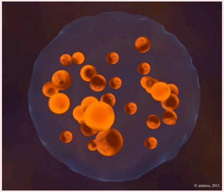
Jun. 22, 2022

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

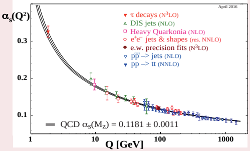
Perturbative and nonperturbative QCD.

Study hadron structure to shed new light on nonperturbative QCD.

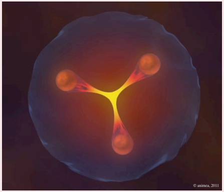
Perturbative QCD



Asymptotic freedom



Nonperturbative QCD



Interface between perturbative and nonperturbative regimes

- Define **universal** objects describing 3D hadron 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 hadron structure.

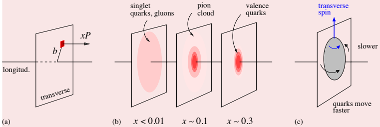
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

$$\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2}\left[H(x, 0, b_\perp^2) + \frac{b_\perp^j \epsilon_{ji} S_\perp^i}{M} \frac{\partial E}{\partial b_\perp^2}(x, 0, b_\perp^2) + \lambda \lambda_N \tilde{H}(x, 0, b_\perp^2)\right]$$

- Notations : quark helicity λ, nucleon longitudinal polarization λ_N and nucleon transverse spin $S_\perp$.

✍ Burkardt (2000)

Can we obtain this picture from exclusive measurements?



✍ Weiss (2009)

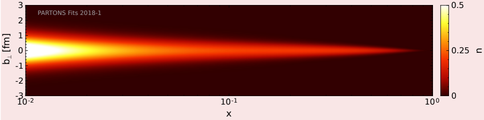
- **Probabilistic interpretation** of Fourier transform of GPD$(x, \xi = 0, t)$ in **transverse plane**.

$$\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2}\Big[H(x, 0, b_\perp^2) + \frac{b_\perp^j \epsilon_{ji} S_\perp^i}{M} \frac{\partial E}{\partial b_\perp^2}(x, 0, b_\perp^2) + \lambda\lambda_N \tilde{H}(x, 0, b_\perp^2)\Big]$$

- Notations : quark helicity λ, nucleon longitudinal polarization λ_N and nucleon transverse spin $S_\perp$.

✍ Burkardt (2000)

Nucleon tomography in the quark sector



✍ Moutarde *et al.* (2018)

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

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

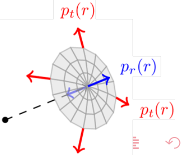
- Anisotropic fluid in **relativistic hydrodynamics**:

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

where u^μ and $\chi^\mu = x^\mu / r$.

- Define **isotropic pressure** and **pressure anisotropy**:

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



✍ Lorcé et al. (2019)

- Write dictionary between quantum and fluid pictures:

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

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

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

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

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

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✍ Lorcé *et al.* (2019)

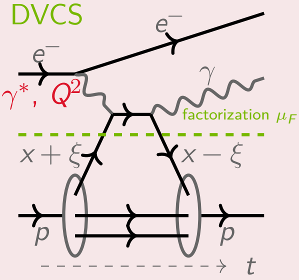
Link between GPDs and GFFs

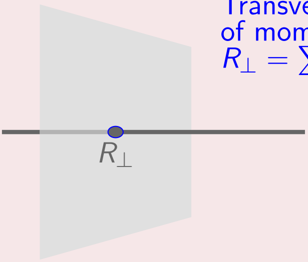
$$\int \mathrm{d}x\, x H^q(x, \xi, t) = A^q(t) + 4\xi^2 C^q(t)$$

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

✍ Ji (1997), ✍ Goeke (2001)

Deeply Virtual Compton Scattering (DVCS)





Transverse center of momentum $R_\perp$
$R_\perp = \sum_i x_i r_{\perp i}$

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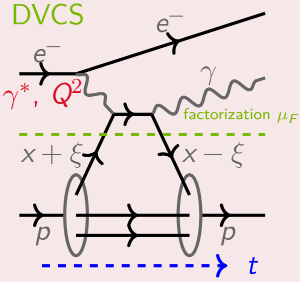
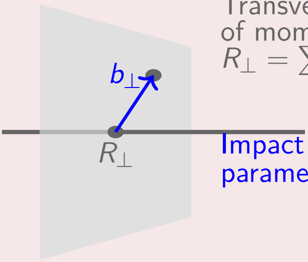




Transverse center of momentum $R_\perp$
$R_\perp = \sum_i x_i r_{\perp i}$

Impact parameter $b_\perp$

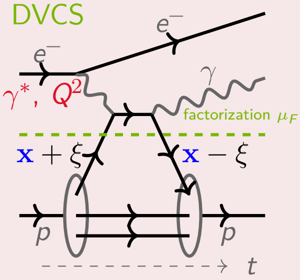
Link between GPDs and GFFs

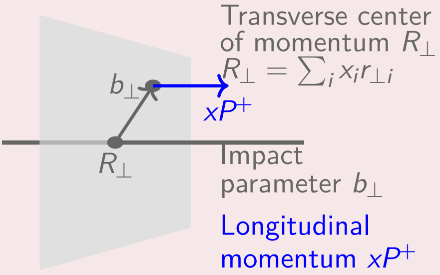
$$\int \mathrm{d}x\, x H^q(x, \xi, t) = A^q(t) + 4\xi^2 C^q(t)$$

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

✍ Ji (1997), ✍ Goeke (2001)

Deeply Virtual Compton Scattering (DVCS)





Connection to experimental data.

Gravitational form factors from generalized parton distributions.

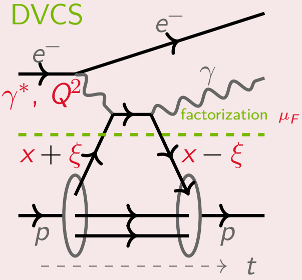
Link between GPDs and GFFs

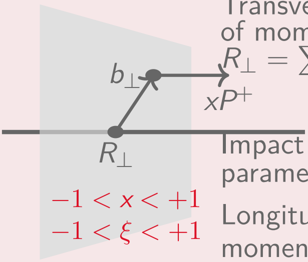
$$\int \mathrm{d}x\, x H^q(x, \xi, t) = A^q(t) + 4\xi^2 C^q(t)$$

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

✍ Ji (1997), ✍ Goeke (2001)

Deeply Virtual Compton Scattering (DVCS)





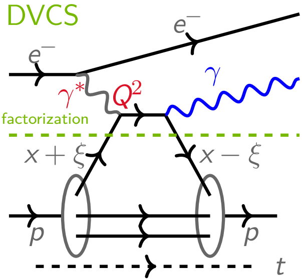
Transverse center of momentum $R_\perp$
$R_\perp = \sum_i x_i r_{\perp i}$

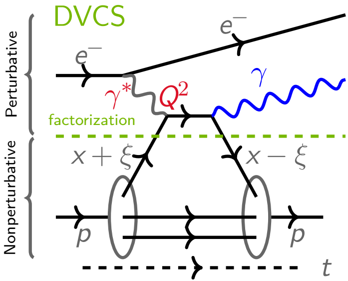
Impact parameter $b_\perp$

Longitudinal momentum xP^+

Exclusive processes of current interest.

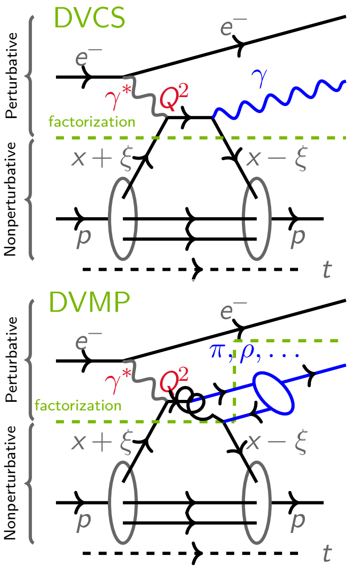
Factorization, universality and need for high luminosity.

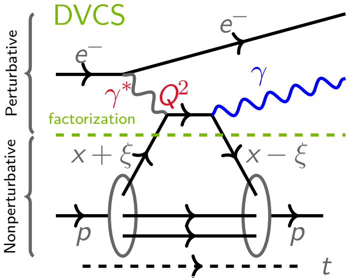



DVCS
Perturbative
Nonperturbative
e^-
e^-
γ^*
Q^2
γ
factorization
$x+\xi$
$x-\xi$
p
p
t

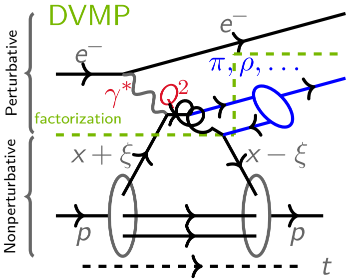
Exclusive processes of current interest.

Factorization, universality and need for high luminosity.

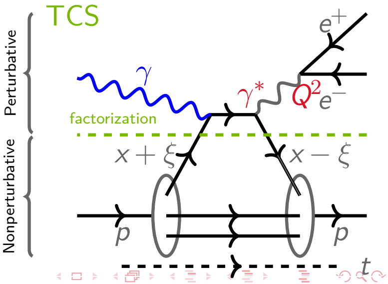




DVCS
Perturbative
Nonperturbative
e^-
e^-
γ^*
Q^2
γ
factorization
$x+\xi$
$x-\xi$
p
p
t



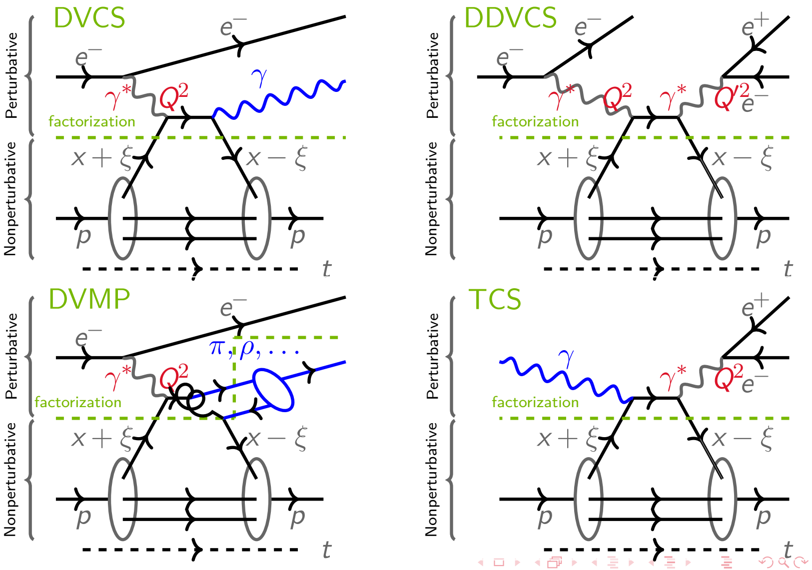
DVMP
Perturbative
Nonperturbative
e^-
e^-
γ^*
Q^2
$\pi, \rho, \ldots$
factorization
$x+\xi$
$x-\xi$
p
p
t



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

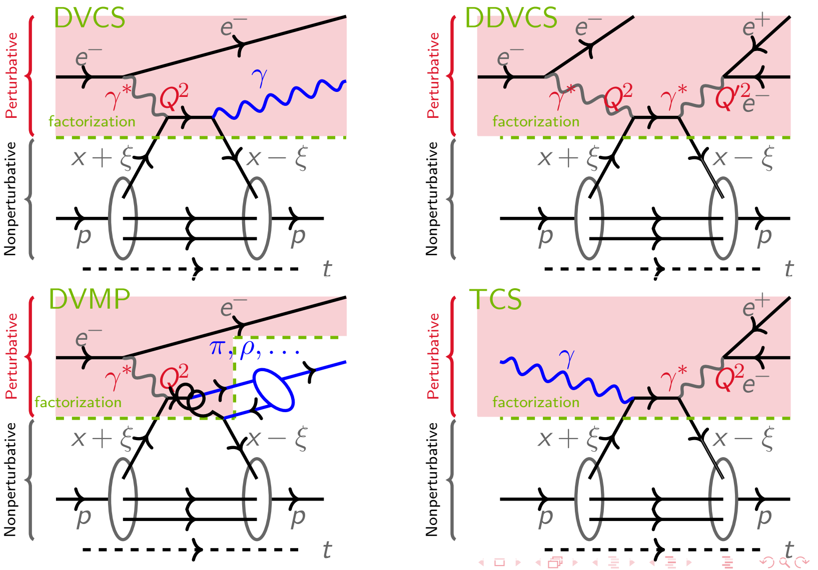
Exclusive processes of current interest.

Factorization, universality and need for high luminosity.



Exclusive processes of current interest.

Factorization, universality and need for high luminosity.



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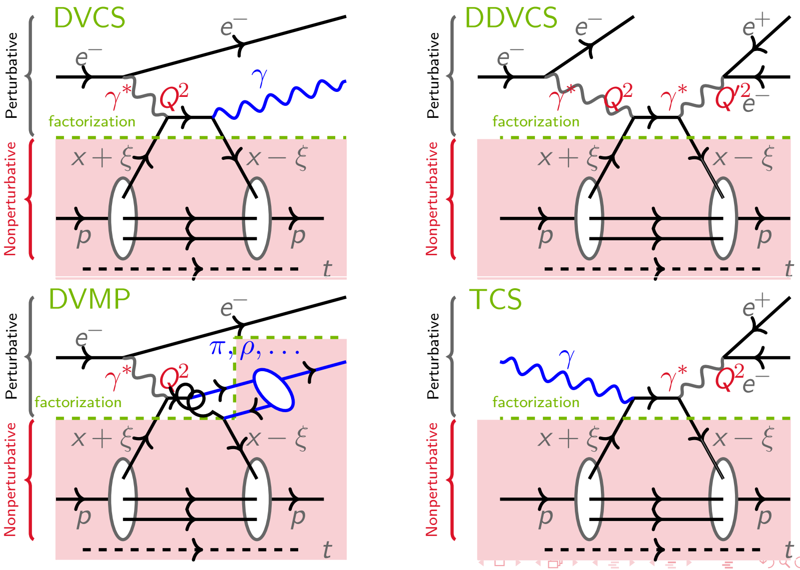
Factorization, universality and need for high luminosity.



Bjorken regime : large Q^2 and fixed $xB \simeq 2\xi/(1+\xi)$

- Partonic interpretation relies on **factorization theorems**.
- All-order proofs for DVCS.
- GPDs depend on a (arbitrary) factorization scale μ_F.
- **Consistency** requires the study of **different channels**.

- GPDs enter DVCS through **Compton Form Factors** :

$$\mathcal{F}(\xi, t, Q^2) = \int_{-1}^{1} dx\, T\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

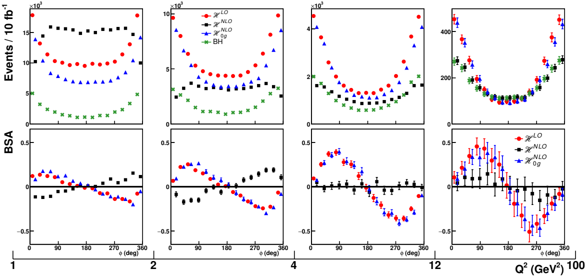
for a given GPD F.

- CFF $\mathcal{F}$ is a **complex function**.

An aside on pion GPDs.

DVCS off a pion target through the meson cloud of the proton.

- Unique role of the pion as a **bound state** and a **Goldstone boson** for chiral symmetry.
- GPD Framework not restricted to nucleon: can we access the 3D structure of the pion?
- DVCS beam spin asymmetries seem **measurable at EIC**!
- **May need more precise data** for actual GPD fits by comparison with phenomenology of DVCS off the proton.



✍ Morgado-Chávez *et al.* (2022)

Phenomenology

Almost all existing DVCS data sets.

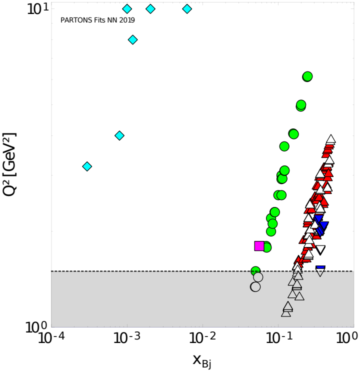
2600+ measurements of 30 observables published during 2001-17.

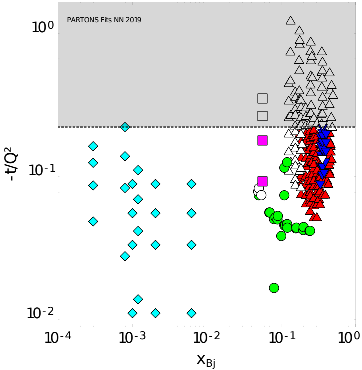
No.	Collab.	Year	Ref.	Observable		Kinematic dependence	No. of points used / all
1	HERMES	2001	[40]	A_{LU}^{+}		ϕ	10 / 10
2		2006	[41]	$A_{C}^{\cos i\phi}$	$i=1$	t	4 / 4
3		2008	[42]	$A_{C}^{\cos i\phi}$	$i=0,1$	x_{Bj}	18 / 24
				$A_{UT,\mathrm{DVCS}}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0$		
				$A_{UT,\mathrm{I}}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0,1$		
				$A_{UT,\mathrm{I}}^{\cos(\phi-\phi_S)\sin i\phi}$	$i=1$		
4		2009	[43]	$A_{LU,\mathrm{I}}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
				$A_{LU,\mathrm{DVCS}}^{\sin i\phi}$	$i=1$		
				$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
5		2010	[44]	$A_{UL}^{+,\sin i\phi}$	$i=1,2,3$	x_{Bj}	18 / 24
				$A_{LL}^{+,\cos i\phi}$	$i=0,1,2$		
6		2011	[45]	$A_{LT,\mathrm{DVCS}}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1$	x_{Bj}	24 / 32
				$A_{LT,\mathrm{DVCS}}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1$		
				$A_{LT,\mathrm{I}}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1,2$		
				$A_{LT,\mathrm{I}}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1,2$		
7		2012	[46]	$A_{LU,\mathrm{I}}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
				$A_{LU,\mathrm{DVCS}}^{\sin i\phi}$	$i=1$		
				$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
8	CLAS	2001	[47]	$A_{LU}^{-,\sin i\phi}$	$i=1,2$	—	0 / 2
9		2006	[48]	$A_{UL}^{-,\sin i\phi}$	$i=1,2$	—	2 / 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]	$d^3\sigma_{UU}^{\pm}$		t	2 / 4
17	ZEUS	2009	[37]	$d^3\sigma_{UU}^{+}$		t	4 / 4
18	H1	2005	[38]	$d^3\sigma_{UU}^{+}$		t	7 / 8
19		2009	[39]	$d^3\sigma_{UU}^{\pm}$		t	12 / 12
						SUM:	2624 / 3996

✍ Moutarde *et al.* (2019)

Almost all existing DVCS data sets.

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





▼ Hall A ● HERMES ■ COMPASS
▲ CLAS ◆ H1 and ZEUS

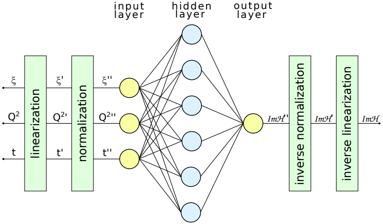
✍ Moutarde *et al.* (2019)

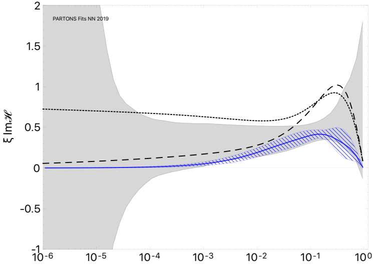
Need many more precise data at small x_B, large Q^2 and also as close as possible to the valence region.

Modeling of $\mathcal{H}$, $\widetilde{\mathcal{H}}$, $\mathcal{E}$ and $\widetilde{\mathcal{E}}$.

Independent descriptions of real and imaginary parts.

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





Moutarde *et al.* (2019)

1. Expand D-term on Gegenbauer polynomials

$$D^q_{\mathrm{term}}(z, t, \mu_F^2) = (1 - z^2) \sum_{\text{odd } n} d^q_n(t, \mu_F^2)\, C_n^{3/2}(z)$$

2. Write dispersion relation for CFF (true at all pQCD orders)

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

3. Compute subtraction constant

$$\mathcal{C}_H^{q,g}(t, Q^2) = \frac{2}{\pi} \int_1^{+\infty} \mathrm{d}\omega \, \mathrm{Im}\, T^{q,g}(\omega) \int_{-1}^1 \mathrm{d}z \, \frac{D^{q,g}(z)}{\omega - z}$$

✍ Diehl & Ivanov (2007)

4. Retrieve GFF

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

1 Expand D-term on Gegenbauer polynomials

$$D^q_{\mathrm{term}}(z, t, \mu_F^2) = (1 - z^2) \sum_{\text{odd } n} d^q_n(t, \mu_F^2)\, C_n^{3/2}(z)$$

2 Write dispersion relation for CFF (true at all pQCD orders)

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

3 Compute subtraction constant at LO

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

✍ Diehl & Ivanov (2007)

4 Retrieve GFF

$$d^q_1(t, \mu_F^2) = 5\, C_q(t, \mu_F^2)$$

Experimental data

GFF C
Internal pressure

Extracting chain.

Implementing this first-principle connection.

Experimental data

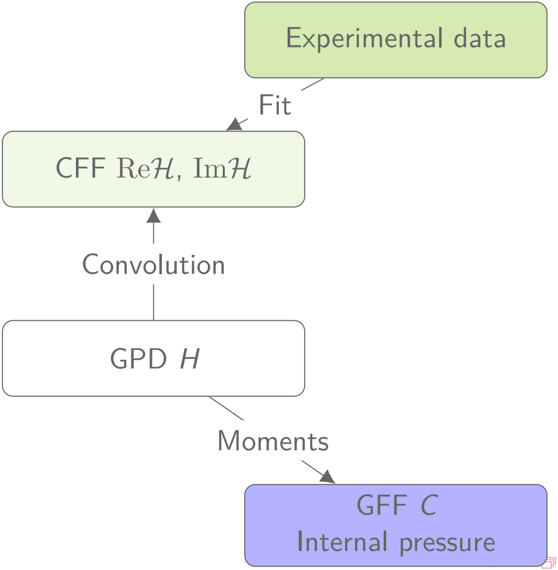
GPD H

Moments

GFF C
Internal pressure

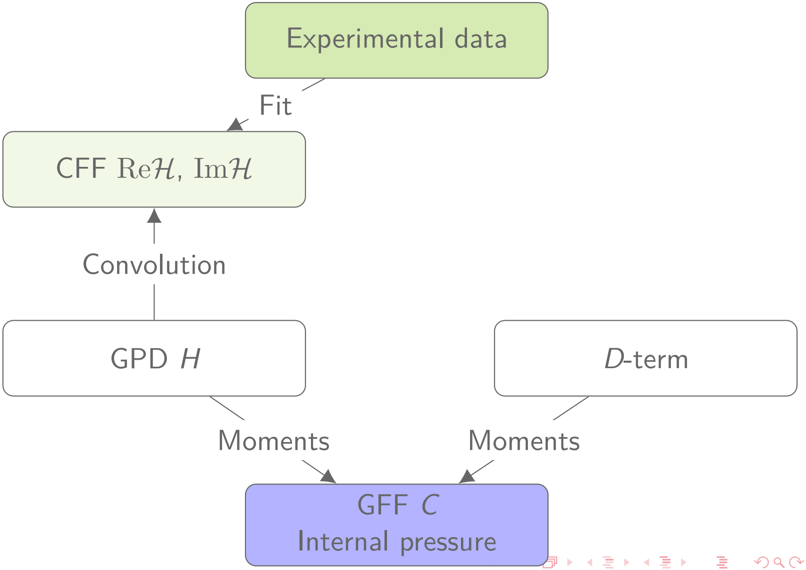
Extracting chain.

Implementing this first-principle connection.



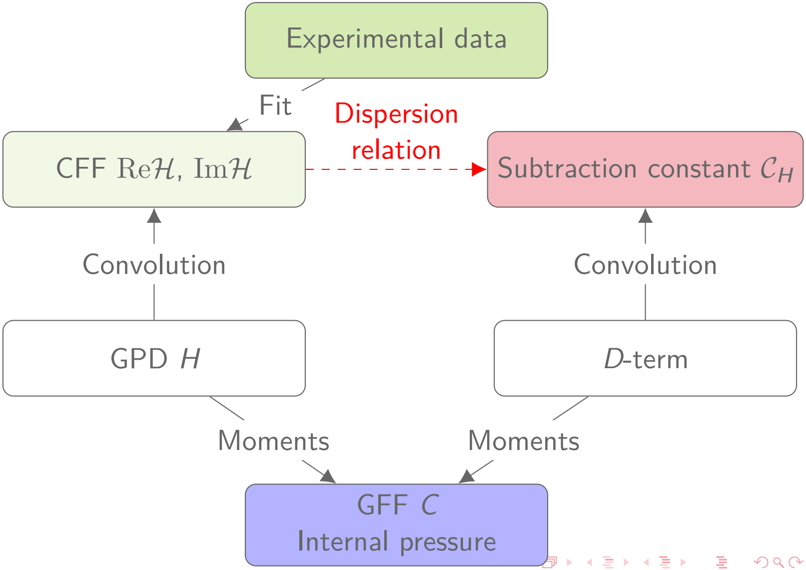
Extracting chain.

Implementing this first-principle connection.



Extracting chain.

Implementing this first-principle connection.



Extracting chain.

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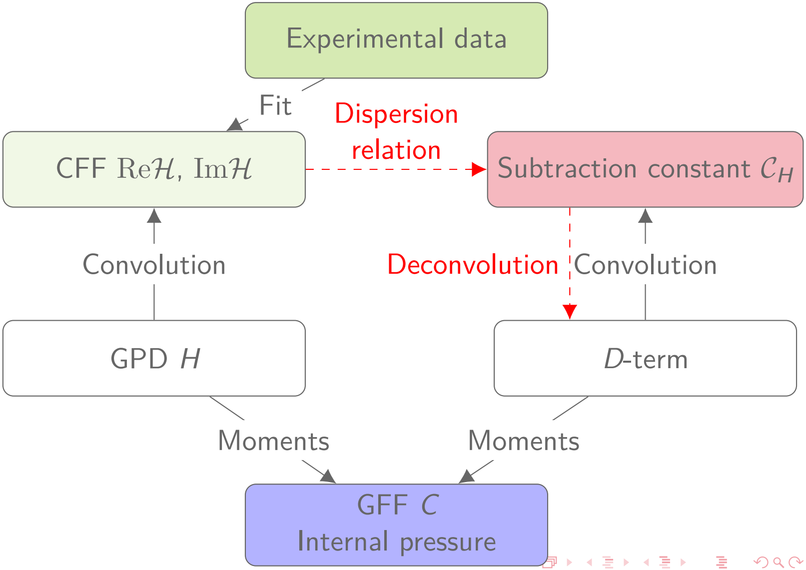
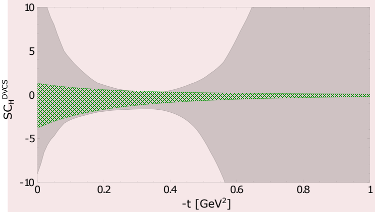


Pressure forces from DVCS measurements.

Working assumptions.

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.

Tripole Ansatz



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)

1. Subtraction constant assumed equal to d_1.
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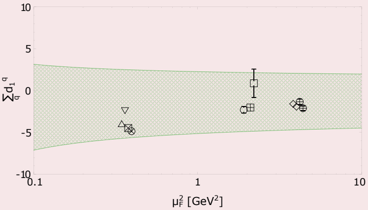
d_1 from DVCS data



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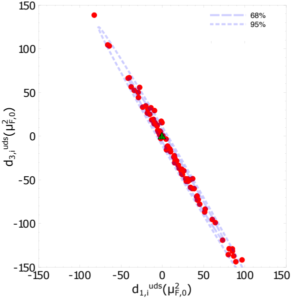
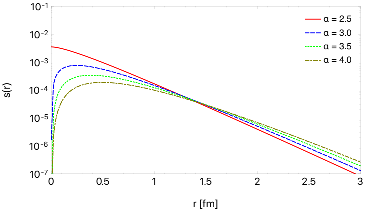
Summary of existing determinations

No.	Marker in Fig. 3	$\sum_q d_1^q(\mu_F^2)$	μ_F^2 in GeV²	# 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	4	2	t-channel saturated model	[55]
		-1.92	4	2	t-channel saturated model	[55]
4	△	-4	0.36	3	χQSM	[30]
5	▽	-2.35	0.36	2	χQSM	[10]
6	⊠	-4.48	0.36	2	Skyrme model	[56]
7	⊞	-2.02	2	3	LFWF model	[57]
8	⊗	-4.85	0.36	2	χQSM	[58]
9	⊕	-1.34 ± 0.31	4	2	lattice QCD ($\overline{\mathrm{MS}}$)	[59]
		-2.11 ± 0.27	4	2	lattice QCD ($\overline{\mathrm{MS}}$)	[59]

✍ Dutrieux *et al.* (2021)

- **No justification to truncate the subtraction constant expansion to its first term** and assume that it is the d_1 coefficient related to the energy-momentum tensor.
- Shape of pressure profile is **fixed** by multipole Ansatz. Actual value is **extremely sensitive** to its parameters.





✍ Dutrieux *et al.* (2021)

- Leading contributions of d_1 and d_3, higher order terms neglected.

Pressure forces from DVCS measurements.

Relaxing some modelling assumptions.

- Leading contributions of d_1 and d_3, higher order terms neglected.
- 3 active quark flavors (uds), and radiative generation of c contribution.

Pressure forces from DVCS measurements.

Relaxing some modelling assumptions.

- Leading contributions of d_1 and d_3, higher order terms neglected.
- 3 active quark flavors (uds), and radiative generation of c contribution.
- 4 parameters

$$d_1^{uds}(\mu_0) \qquad d_3^{uds}(\mu_0) \qquad d_1^{g}(\mu_0) \qquad d_3^{g}(\mu_0)$$

Investigate 3 fitting scenarios

4 parameters

$$d_1^{uds}(0.1\mathrm{GeV}^2)$$
$$d_1^{g}(0.1\mathrm{GeV}^2)$$
$$d_3^{uds}(0.1\mathrm{GeV}^2)$$
$$d_3^{g}(0.1\mathrm{GeV}^2)$$

Investigate 3 fitting scenarios

4 parameters

$d_1^{uds}(0.1\mathrm{GeV}^2)$

$d_1^{g}(0.1\mathrm{GeV}^2)$

$d_3^{uds}(0.1\mathrm{GeV}^2)$

$d_3^{g}(0.1\mathrm{GeV}^2)$

Free

Fixed

1. Nominal fit:
   - 1 free parameter for light quarks.
   - Gluon and charm radiatively generated.

	LO	NLO
$d_1^{uds}(0.1\mathrm{GeV}^2)$	-0.7 ± 1.7	-0.8 ± 2.0
$d_1^{uds}(2\mathrm{GeV})$	-0.5 ± 1.2	-0.5 ± 1.4
$d_1^{g}(2\mathrm{GeV})$	-0.6 ± 1.6	-0.7 ± 1.9
$d_1^{c}(2\mathrm{GeV})$	-0.002 ± 0.0005	-0.002 ± 0.006

Investigate 3 fitting scenarios

4 parameters

$d_1^{uds}(0.1\mathrm{GeV}^2)$

$d_1^{g}(0.1\mathrm{GeV}^2)$

$d_3^{uds}(0.1\mathrm{GeV}^2)$

$d_3^{g}(0.1\mathrm{GeV}^2)$

Free

Fixed

2. Alternative fit:
   - 2 free parameters: light quarks and gluons.
   - Charm radiatively generated.

	LO	NLO
$d_1^{uds}(0.1\mathrm{GeV}^2)$	-6.2 ± 14	-0.4 ± 2.3
$d_1^{g}(0.1\mathrm{GeV}^2)$	68 ± 152	6.3 ± 22
$d_1^{uds}(2\mathrm{GeV})$	-0.7 ± 1.2	0.4 ± 2.8
$d_1^{g}(2\mathrm{GeV})$	51 ± 111	5.3 ± 19
$d_1^{c}(2\mathrm{GeV})$	0.2 ± 0.4	0.02 ± 0.06

Pressure forces from DVCS measurements.

From leading order to next-to-leading order.

Investigate 3 fitting scenarios

4 parameters

$d_1^{uds}(0.1\mathrm{GeV}^2)$

$d_1^{g}(0.1\mathrm{GeV}^2)$

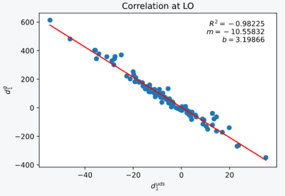
$d_3^{uds}(0.1\mathrm{GeV}^2)$

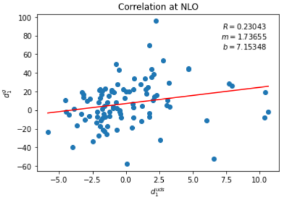
$d_3^{g}(0.1\mathrm{GeV}^2)$

Free

Fixed

2. Alternative fit:
   - 2 free parameters: light quarks and gluons.
   - Charm radiatively generated.





Decorrelation of d_1^g and d_1^{uds} at NLO.

Investigate 3 fitting scenarios

3. Alternative fit:
   - 2 free parameters: d_1 and d_3 for light quarks.
   - Gluon and charm radiatively generated.

4 parameters

$d_1^{uds}(0.1\mathrm{GeV}^2)$

$d_1^{g}(0.1\mathrm{GeV}^2)$

$d_3^{uds}(0.1\mathrm{GeV}^2)$

$d_3^{g}(0.1\mathrm{GeV}^2)$

Free

Fixed

	LO	NLO
$d_1^{uds}(0.1\mathrm{GeV}^2)$	16 ± 37	15 ± 34
$d_3^{uds}(0.1\mathrm{GeV}^2)$	-26 ± 59	-18 ± 39
$d_1^{uds}(2\mathrm{GeV})$	11 ± 25	11 ± 23
$d_1^{g}(2\mathrm{GeV})$	15 ± 34	15 ± 32
$d_1^{c}(2\mathrm{GeV})$	-0.05 ± 0.1	-0.05 ± 0.1
$d_3^{uds}(2\mathrm{GeV})$	-11 ± 26	-7.7 ± 17
$d_3^{g}(2\mathrm{GeV})$	-1.8 ± 3.9	-1.2 ± 2.6
$d_3^{c}(2\mathrm{GeV})$	-0.04 ± 0.01	-0.003 ± 0.007

Investigate 3 fitting scenarios

4 parameters

$d_1^{uds}(0.1\mathrm{GeV}^2)$

$d_1^{g}(0.1\mathrm{GeV}^2)$

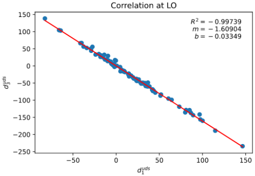
$d_3^{uds}(0.1\mathrm{GeV}^2)$

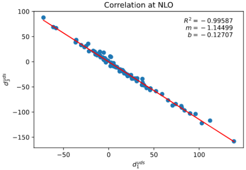
$d_3^{g}(0.1\mathrm{GeV}^2)$

Free

Fixed

3. Alternative fit:
   - 2 free parameters: d_1 and d_3 for light quarks.
   - Gluon and charm radiatively generated.





Strong correlation of d_1^{uds} and d_3^{uds} both at LO and NLO.

From CFFs to GPDs.

Can we actually recover a GPD from the knowledge of a CFF?!

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

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

- 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. **Key role** of DDVCS: direct access to GPDs.
- **Large** Q^2 **lever arm** and **highly precise data** are much needed: unique feature of EIC.

The PARTONS ecosystem

PARtonic
Tomography
Of
Nucleon
Software

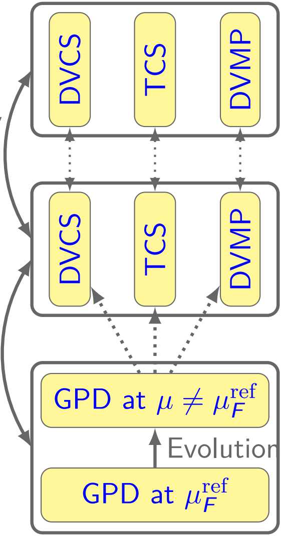
Computing chain design.

EIC perspective considered at the time of design.

Full processes
Experimental data and phenomenology

Small distance
Computation of amplitudes

Large distance
First principles and fundamental parameters



PARTONS

PARtonic **T**omography **O**f **N**ucleon **S**oftware

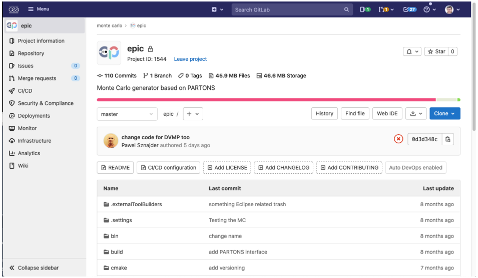
- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

Berthou *et al.* (2015)

Generic exclusive event generators EpIC.

Modular structure compatible with the architecture of PARTONS.

- Includes treatment of radiative corrections.
- Can be extended to simulate other exclusive processes.
- **Already used** in the EIC community and run at BNL.
- **Publicly released** simultaneously with PARTONSv3.



✍ Aschenauer *et al.* (2022)

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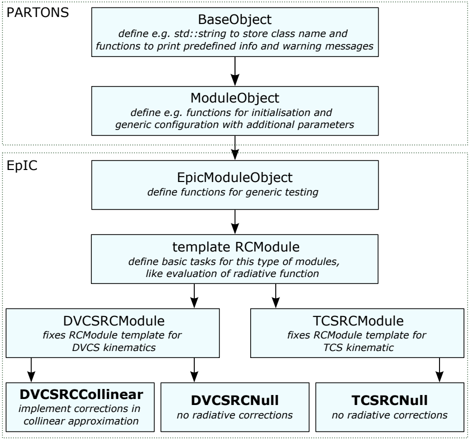


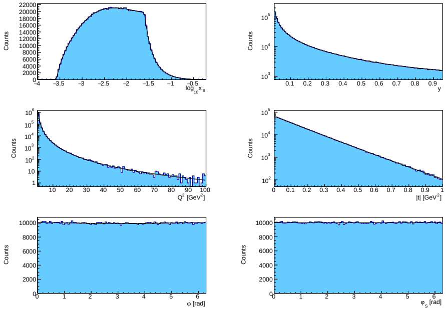
✍ Aschenauer *et al.* (2022)

Generic exclusive event generators EpIC.

Modular structure compatible with the architecture of PARTONS.

Tools for precision 3D hadron structure

- Includes treatment of radiative corrections.
- Can be extended to simulate other exclusive processes.
- **Already used** in the EIC community and run at BNL.
- **Publicly released** simultaneously with PARTONSv3.

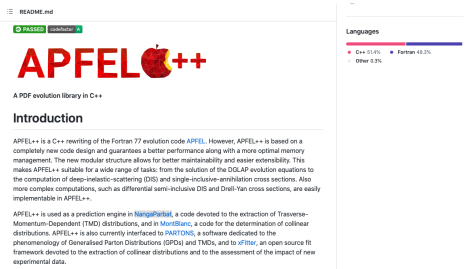


Aschenauer *et al.* (2022)

GPD evolution with APFEL++.

Connecting different computing codes for hadron structure.

- Evolution code for PDFs, GPDs and TMDs.
- APFEL++ numerically solves evolution equations in x-space.
- Fully modular.
- Heavy quark threshold crossing.



README.md

PASSED codefactor A

APFEL++

A PDF evolution library in C++

Introduction

APFEL++ is a C++ rewriting of the Fortran 77 evolution code APFEL. However, APFEL++ is based on a completely new code design and guarantees a better performance along with a more optimal memory management. The new modular structure allows for better maintainability and easier extensibility. This makes APFEL++ suitable for a wide range of tasks: from the solution of the DGLAP evolution equations to the computation of deep-inelastic-scattering (DIS) and single-inclusive-annihilation cross sections. Also more complex computations, such as differential semi-inclusive DIS and Drell-Yan cross sections, are easily implementable in APFEL++.

APFEL++ is used as a prediction engine in NangaParbat, a code devoted to the extraction of Trasverse-Momentum-Dependent (TMD) distributions, and in MontBlanc, a code for the determination of collinear distributions. APFEL++ is also currently interfaced to PARTONS, a software dedicated to the phenomenology of Generalised Parton Distributions (GPDs) and TMDs, and to xFitter, an open source fit framework devoted to the extraction of collinear distributions and to the assessment of the impact of new experimental data.

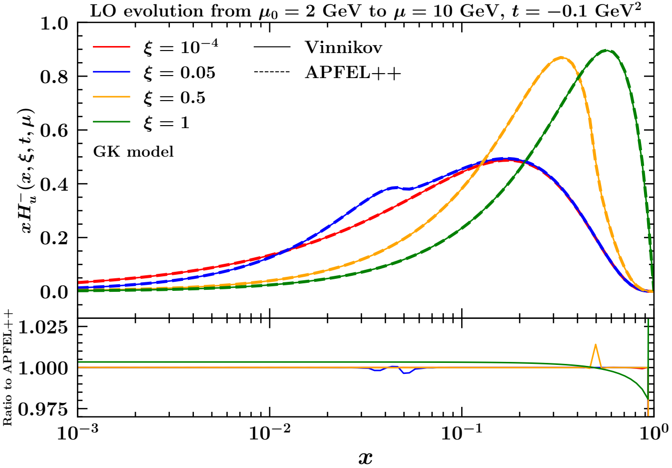
Languages

C++ 51.4% Fortran 48.3% Other 0.3%

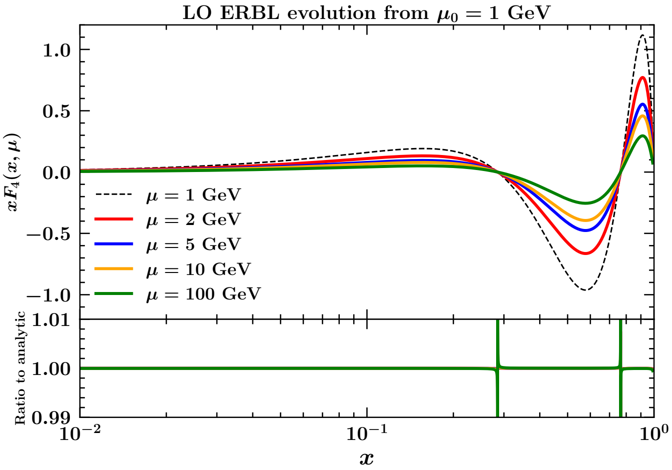
✍ Bertone *et al.* (2022)

GPD evolution with APFEL++.

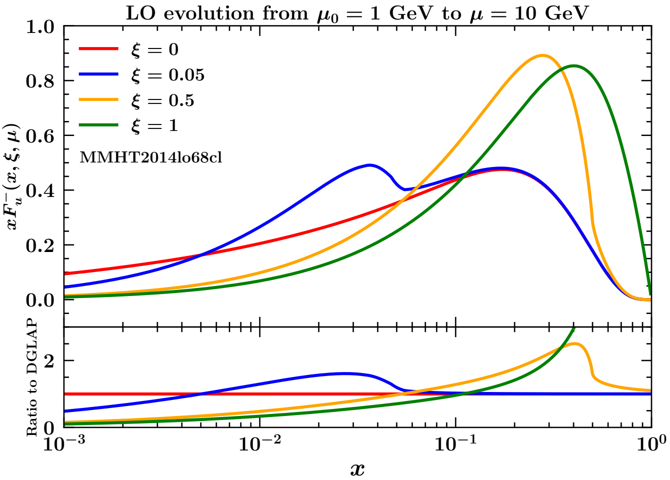
Connecting different computing codes for hadron structure.



Bertone *et al.* (2022)



Bertone *et al.* (2022)



✍ Bertone *et al.* (2022)

Conclusion

Conclusion and prospects.

The quest towards 3D proton structure.

- Strong **first-principle connection** between concepts and experimental data.
- Need for **multi-channel** analysis of **precise data** with a Q^2 **lever arm** on a **wide kinematic coverage**.
- EIC much needed for these studies.
- Several studies presumably require a **high luminosity**:
  - 3D structure of the pion.
  - Extraction of pressure forces from DVCS measurements.
  - Deconvolution of GPDs from CFFs.
- Development of a **open source software ecosystem** around `PARTONS` for GPD phenomenology, in particular:
  - Generic event generator for impact studies and design of new experiments: `EpIC`.
  - Accurate and efficient solver for evolution equations to exploit the EIC kinematic reach: `APFEL++`.

Abbreviations

Abbreviations used in this presentation.

ANN	artificial neural network
CFF	Compton form factor
DDVCS	double deeply virtual Compton scattering
DGLAP	Dokshitzer-Gribov-Lipatov-Altarelli-Parisi
DVCS	deeply virtual Compton scattering
DVMP	deeply virtual meson production
EIC	electron-ion collider
EFF	elastic form factor
ERBL	Efremov-Radyushkin-Brodsky-Lepage
GFF	gravitational form factor
GPD	generalized parton distribution
LO	leading order
NLO	next-to-leading order
PDF	parton distribution function
TCS	timelike Compton scattering

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DRF
Irfu
DPhN