Recent developments in exclusive nucleon science at EIC

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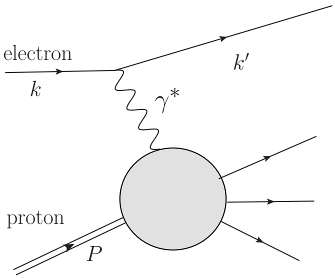
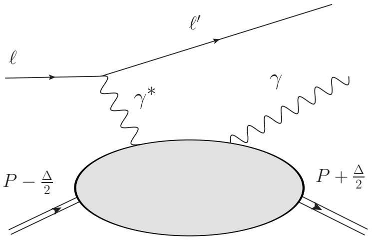
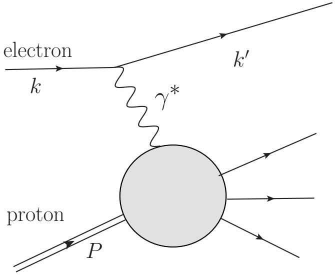
Why deep exclusive processes ?

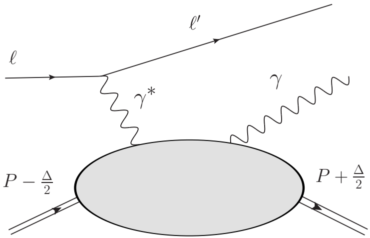




- Deep exclusive processes are generally more difficult to measure than inclusive ones

Why deep exclusive processes ?





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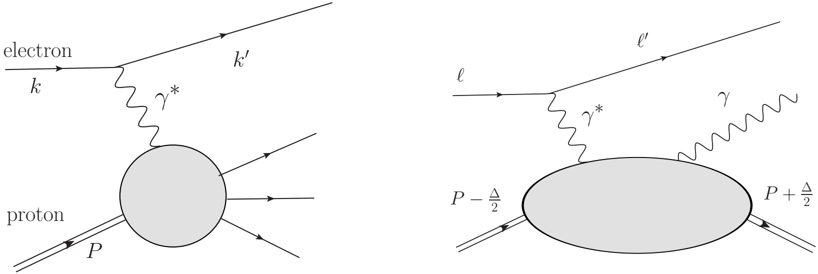
- Reason : we require *not* to break the proton $\rightarrow$ small cross sections

Why deep exclusive processes ?



- Deep exclusive processes are generally more difficult to measure than inclusive ones
- Reason : we require *not* to break the proton $\rightarrow$ small cross sections

A curse and a blessing

Not breaking the proton allows one to study the distribution of quarks and gluons in coordinate space

Nucleon tomography through Generalized Partons Distributions (GPDs)

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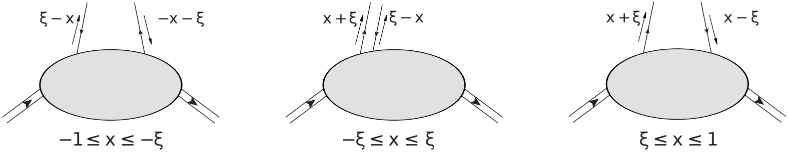
  - "hadron-parton" amplitudes which depend on three variables (x, ξ, t) and a scale μ,



  - ⋆ x: average momentum fraction carried by the active parton
  - ⋆ ξ: skewness parameter $\xi \simeq \frac{x_B}{2-x_B}$
  - ⋆ t: the Mandelstam variable

Generalized Parton Distributions

- Generalized Parton Distributions (GPDs):
  - "hadron-parton" amplitudes which depend on three variables (x, ξ, t) and a scale μ,
  - are defined in terms of a non-local matrix element,

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

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

D. Müller *et al.*, Fortsch. Phy. 42 101 (1994)
X. Ji, Phys. Rev. Lett. **78**, 610 (1997)
A. Radyushkin, Phys. Lett. **B380**, 417 (1996)

4 GPDs without helicity transfer + 4 helicity flip GPDs

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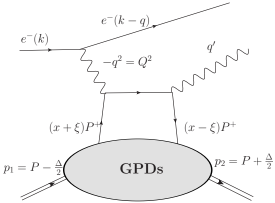
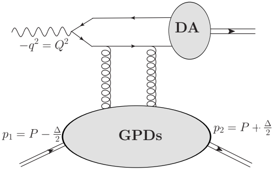
  - are related to PDF in the forward limit $H(x, \xi = 0, t = 0; \mu) = q(x; \mu)$
  - are universal, *i.e.* are related to the Compton Form Factors (CFFs) of various exclusive processes through convolutions

$$\mathcal{H}(\xi, t) = \int \mathrm{d}x \; C(x, \xi) H(x, \xi, t)$$





- Polynomiality Property:

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

X. Ji, J.Phys.G 24 (1998) 1181-1205
A. Radyushkin, Phys.Lett.B 449 (1999) 81-88

Special case :

$$\int_{-1}^{1} \mathrm{d}x\ H^q(x,\xi,t;\mu) = F_1(t)$$

Lorentz Covariance

Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

$$\left| H^q(x,\xi,t) - \frac{\xi^2}{1-\xi^2} E^q(x,\xi,t) \right| \leq \sqrt{\frac{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)}{1-\xi^2}}$$

A. Radysuhkin, Phys. Rev. **D59**, 014030 (1999)
B. Pire *et al.*, Eur. Phys. J. **C8**, 103 (1999)
M. Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)
P.V. Pobilitsa, Phys. Rev. **D65**, 114015 (2002)

Positivity of Hilbert space norm

Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

$$x \in [-1;1]$$

M. Diehl and T. Gousset, Phys. Lett. **B428**, 359 (1998)

Relativistic quantum mechanics

Properties

- Polynomiality Property:

  Lorentz Covariance

- Positivity property:

  Positivity of Hilbert space norm

- Support property:

  Relativistic quantum mechanics

- Scale evolution property
  $\rightarrow$ generalization of DGLAP and ERBL evolution equations

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

  Renormalization

Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

Relativistic quantum mechanics

- Scale evolution property

Renormalization

Problem

- There is no model (until now) fulfilling *a priori* all these constraints.
- Lattice QCD computations remain very challenging.

- In the limit $\xi \to 0$, one recovers a density interpretation:
  - 1D in momentum space (x)
  - 2D in coordinate space $\vec{b}_\perp$ (related to t)

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

Interpretation of GPDs I

2+1D structure of the nucleon

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- Possibility to extract density from experimental data

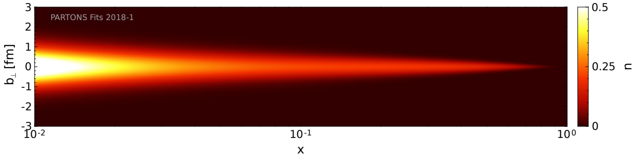

figure from H. Moutarde *et al.*, EPJC 78 (2018) 890

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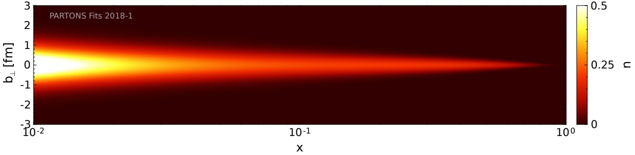

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- Correlation between x and $b_\perp$ $\to$ going beyond PDF and FF.

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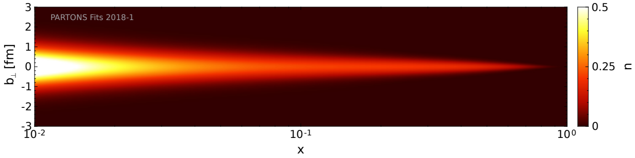

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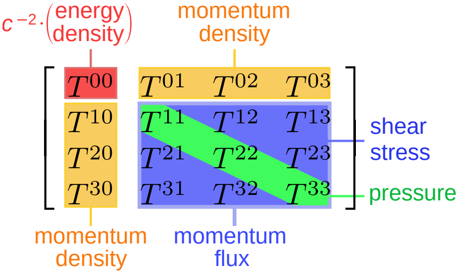
- Correlation between x and $b_\perp \to$ going beyond PDF and FF.
- Caveat: no experimental data at $\xi = 0$
  $\to$ extrapolations (and thus model-dependence) are necessary

Interpretation of GPDs II

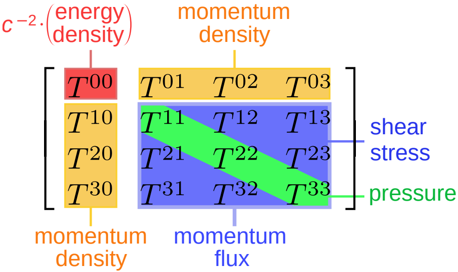
Connection to the Energy-Momentum Tensor



How energy, momentum, pressure are shared between quarks and gluons

Caveat: renormalization scheme and scale dependence

C. Lorcé *et al.*, PLB 776 (2018) 38-47,
M. Polyakov and P. Schweitzer, IJMPA 33 (2018) 26, 1830025
C. Lorcé *et al.*, Eur.Phys.J.C 79 (2019) 1, 89



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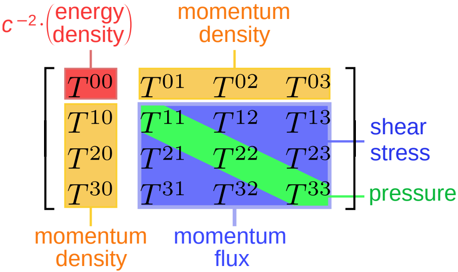
$$\langle p', s' | T^{\mu\nu}_{q,g} | p, s \rangle = \bar{u} \Bigg[P^{\{\mu}\gamma^{\nu\}} A_{q,g}(t;\mu) + \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{M} C_{q,g}(t;\mu) + M g^{\mu\nu} \bar{C}_{q,g}(t;\mu) + \frac{P^{\{\mu} i\sigma^{\nu\}\Delta}}{2M} B_{q,g}(t;\mu) + \frac{P^{[\mu} i\sigma^{\nu]\Delta}}{2M} D_{q,g}(t;\mu) \Bigg] u$$



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$$\int_{-1}^{1} \mathrm{d}x\, x\, H_q(x,\xi,t;\mu) = A_q(t;\mu) + (2\xi)^2 C_q(t;\mu)$$

$$\int_{-1}^{1} \mathrm{d}x\, x\, E_q(x,\xi,t;\mu) = B_q(t;\mu) - (2\xi)^2 C_q(t;\mu)$$

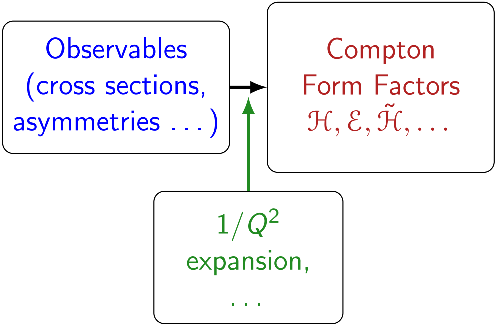
- Ji sum rule
- Fluid mechanics analogy

X. Ji, PRL 78, 610-613 (1997)
M.V. Polyakov PLB 555, 57-62 (2003)

Experimental connection to GPDs

Observables
(cross sections,
asymmetries . . .)

Experimental connection to GPDs



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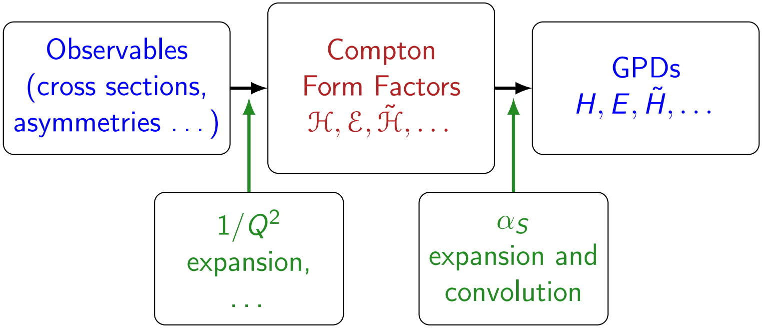

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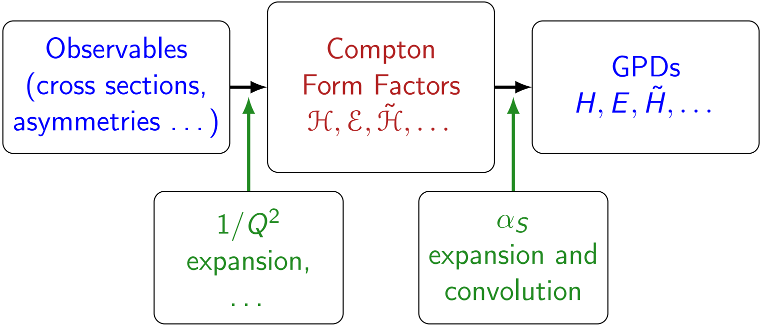
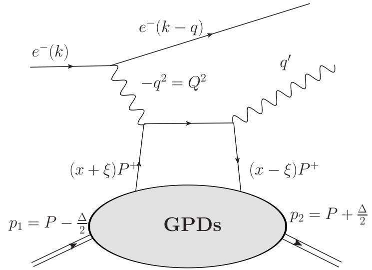
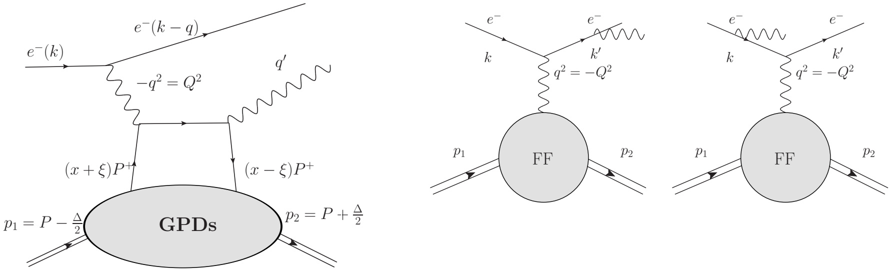


- CFFs play today a central role in our understanding of GPDs
- Extraction generally focused on CFFs



- Best studied experimental process connected to GPDs
  $\rightarrow$ Data taken at Hermes, Compass, JLab 6, JLab 12



- Best studied experimental process connected to GPDs
  → Data taken at Hermes, Compass, JLab 6, JLab 12
- Interferes with the Bethe-Heitler (BH) process
  - Blessing: Interference term boosted w.r.t. pure DVCS one
  - Curse: access to the angular modulation of the pure DVCS part difficult

M. Defurne *et al.*, Nature Commun. 8 (2017) 1, 1408

QCD corrections to DVCS

- At LO, the DVCS coefficient function is a QED one

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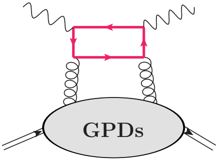
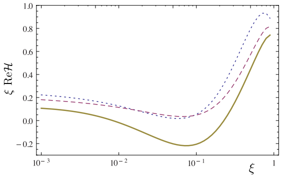
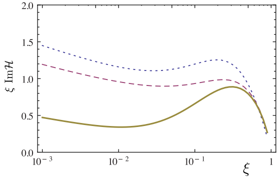
- At NLO, gluon GPDs play a significant role in DVCS







H. Moutarde *et al.*, PRD 87 (2013) 5, 054029

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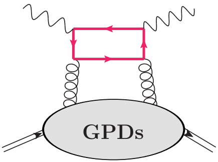

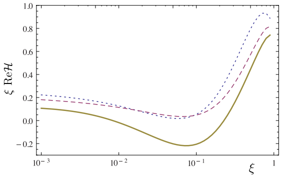

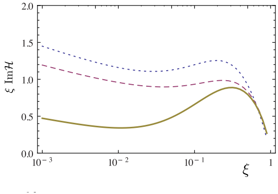

H. Moutarde *et al.*, PRD 87 (2013) 5, 054029

- Recent N2LO studies, impact needs to be assessed

V. Braun *et al.*, JHEP 09 (2020) 117

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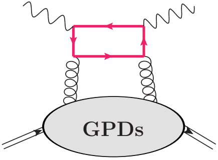

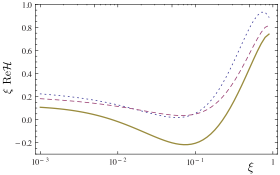

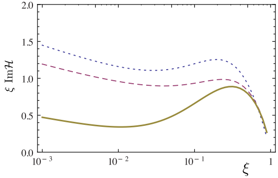

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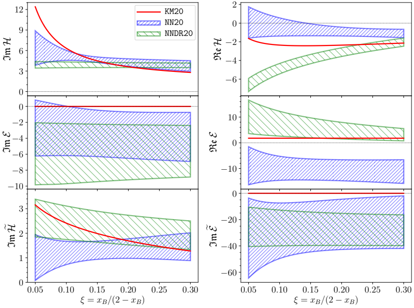
V. Braun *et al.*, JHEP 09 (2020) 117

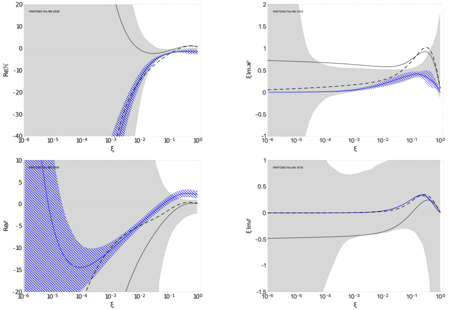
- Evolution equations: needs for open evolution codes

A. Vinnikov, hep-ph/0604248

Recent CFF extractions



M. Cuìc *et al.*, PRL 125, (2020), 232005



H. Moutarde *et al.*, EPJC 79, (2019), 614

- Recent effort on bias reduction in CFF extraction (ANN)

  additional ongoing studies, J. Grigsby *et al.*, arXiv:2012.04801

- Studies of ANN architecture to fulfil GPDs properties (dispersion relation,polynomiality,. . .)
- Recent efforts on propagation of uncertainties (allowing impact studies for EIC and EICC)

Dispersion relation and the D-term

- At all order in α_S, dispersion relations relate the real and imaginary parts of the CFF.

I. Anikin and O. Teryaev, PRD 76 056007
M. Diehl and D. Ivanov, EPJC 52 (2007) 919-932

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- For instance at LO:

$$Re(\mathcal{H}(\xi,t)) = \frac{1}{\pi}\int_{-1}^{1}\mathrm{d}x\ Im(\mathcal{H}(x,t))\left[\frac{1}{\xi-x}-\frac{1}{\xi+x}\right] + \underbrace{2\int_{-1}^{1}\mathrm{d}\alpha\frac{D(\alpha,t)}{1-\alpha}}_{\text{Independent of }\xi}$$

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- $D(\alpha, t)$ is related to the EMT (pressure and shear forces)

M.V. Polyakov PLB 555, 57-62 (2003)

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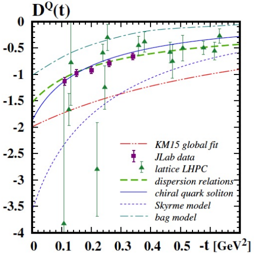


figure from M. Polyakov and P Schweitzer, IJMPA 33 (2018) 26, 1830025
data from Burkert *et al.*, Nature 557 (2018)

- First attempt from JLab 6 *GeV* data
  Warning: Systematic uncertainties are not reported on figure

Burkert *et al.*, Nature 557 (2018) 7705, 396-399

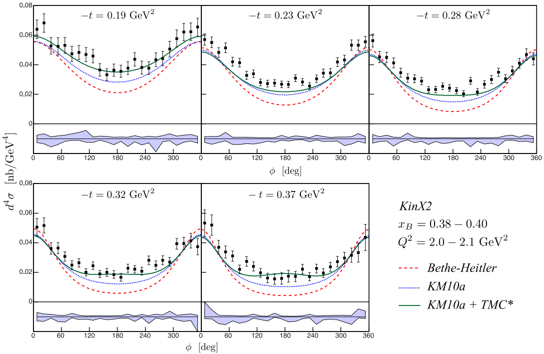
- Tensions with other studies

K. Kumericki, Nature 570 (2019) 7759, E1-E2
H. Moutarde *et al.*, Eur.Phys.J.C 79 (2019) 7, 614

- Model dependence, scheme/scale dependence

Kinematical corrections in t/Q^2 and M^2/Q^2

V. Braun *et al.*, PRL 109 (2012), 242001



M. Defurne *et al.* PRC 92 (2015) 55202

- Sizeable even for $t/Q^2 \sim 0.1$
- Not currently included in global fits.

DVCS on Nuclei

- DVCS off the deuteron

F. Cano *et al.*, EPJA 19 (2004) 423
M. Benali *et al.*, Nature Phys. 16 (2020) 2, 191-198

  - Incoherent scattering : DVCS off the quasi-free neutron
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    M. Cuic *et al.*, PRL 125 (2020) 23, 232005

  - Coherent scattering : probing partons inside a deuteron
    $\rightarrow$ Spin 1 target: richer spin structure $\rightarrow$ more GPDs
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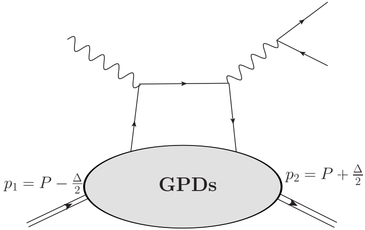
- DVCS off He^4

M. Hattawy *et al.*, PRL 119 (2017) 20, 202004

  - Coherent scattering on a scalar target
    $\rightarrow$ Less spin structure $\rightarrow$ less GPDs
  - Incoherent scattering: information on the structure of a bound nucleon

S. Fucini *et al.*,arXiv:2008.11437

Timelike Compton Scattering



- Amplitude related to the DVCS one ($Q^2 \to -Q^2, \ldots$)
  $\to$ theoretical development for DVCS can be extended to TCS
  E. Berger *et al.*, EPJC 23 (2002) 675
- Excellent test of GPD universality

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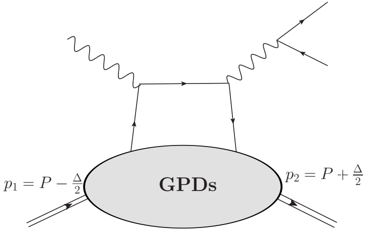

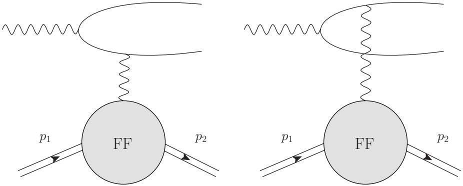

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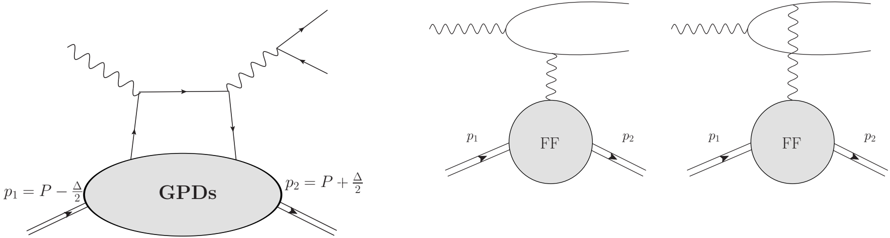

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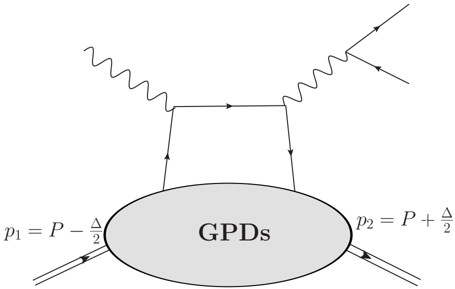
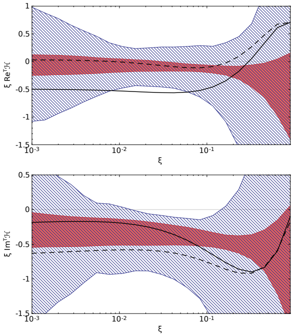
- Same type of final states as exclusive quarkonium production



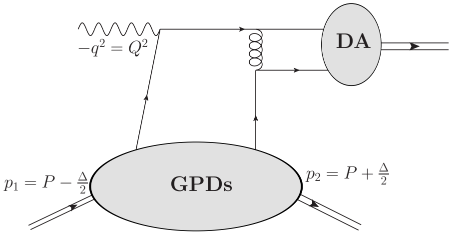


O. Grocholski *et al.*, EPJC 80, (2020) 61

- DVCS Data-driven prediction for TCS at LO and NLO
- First experimental measurement at JLab through forward-backward asymmetry (interference term)

P. Chatagnon *et al.*, in preparation

Deep Virtual Meson Production



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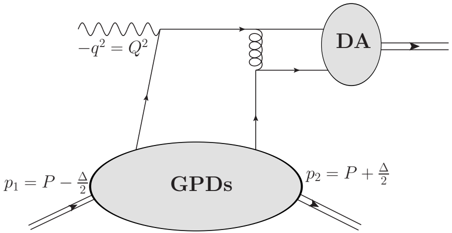

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  - Help flavour separation
  - Leading-order access to gluon GPDs

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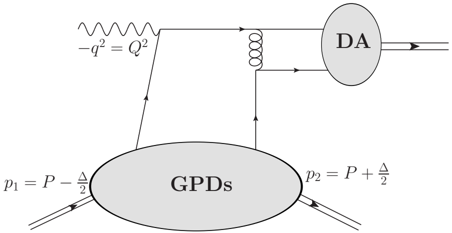

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  - Help flavour separation
  - Leading-order access to gluon GPDs
- Factorisation proven $\neq$ factorisation visible at achievable Q^2
  - Leading-twist dominance at a given Q^2 is process-dependent $\rightarrow$ for DVMP it can change between mesons.
  - At JLab kinematics, higher-twist contributions are very strong $\rightarrow$ hide factorisation of σ_L

Status of DVMP

- π^0 electroproduction
  - $\sigma_T > \sigma_L$ at JLab 6 and likely at JLab 12 kinematics $(Q^2 = 8.3 GeV^2)$

    M. Dlamini *et al.*, arXiv:2011.11125
  - No extraction of σ_L at JLab 12 yet
  - Model-dependent treatment of σ_T using higher-twist contributions

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    see *e.g.* L. Favart, EPJA 52 (2016) 6, 158
  - $\sigma_T \neq 0$ though $\rho_{0;T}$ production vanishes at leading twist
    $\rightarrow$ No LT access to chiral-odd GPDs.

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  - Sizeable higher-twist effects need to be understood

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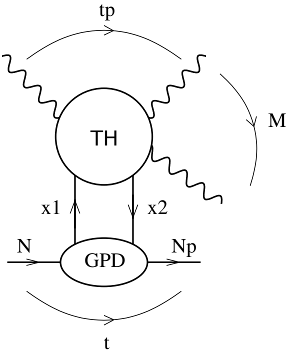
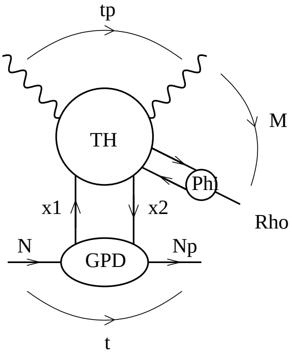
DVMP is as interesting as challenging
Higher Q^2 data would be more than welcome

New channels: Multiparticle production



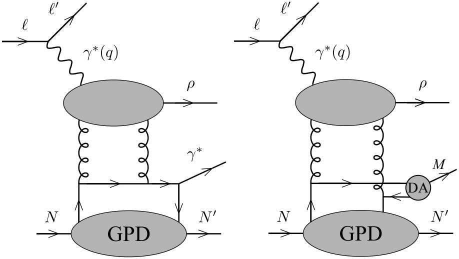
A. Pedrak *et al.*, PRD 96 (2017) 7, 074008



R. Boussarie *et al.*, JHEP 02 (2017) 054

- New combination of CFFs → welcome in global fits.
- LT access to chiral-odd GPDs in the (γ, ρ) case.
- Electroproduction done for $\gamma\gamma$.
- Additional particle in the final state → more luminosity

New Channels: Diffractive Events



D. Ivanov *et al.* PLB 550 (2002) 65
B. Pire *et al.*, PRD 101 (2020) 7, 074005
W. Cosyn *et al.*, PRD 102 (2020) 5, 054003

- Rapidity gap between the ρ and the (γ^*, N) or (M, N) system
- Only sensitive to the $-\xi < x < \xi$ region of the GPDs
- No gluon GPDs (discrete symmetries)
- On-going evaluations of observables at the EIC kinematics

PARTONS and Gepard

PARTONS

partons.cea.fr

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

Gepard

calculon.phy.hr/gpd/server/index.html

K. Kumericki, EPJ Web Conf. 112 (2016) 01012

- Similarities : NLO computations, BM formalism, ANN, ...
- Differences : models, evolution, dissemination, ...

Physics impact

These integrated softwares are the mandatory path toward reliable multichannel analyses.

GPDs addendum

- Phenomenological parametrisations (KM, GK, VGG, MSW, ...)
- Extension of the relation between CFF and observables

B. Kriesten *et al.* PRD 101 (2020) 054021

- New modelling efforts

N. Chouika *et al.*, EPJC 77, (2017) 906
S. Rodini, B. Pasquini *et al.*, in preparation

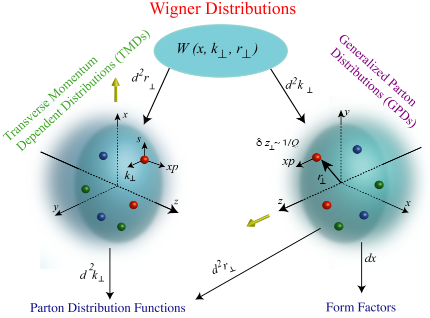
- Forthcoming Lattice and Continuum QCD computations

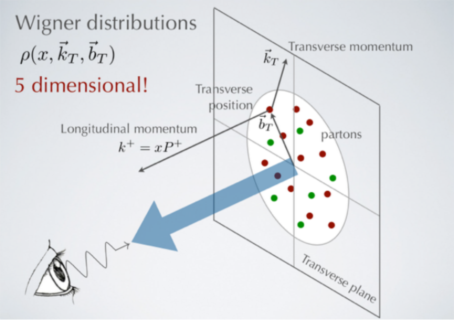
see e.g. M. Constantinou *et al.*, arXiv:2006.08636
Jin-Lin Zhang *et al.*, arXiv:2009.11384
A. Freese *et al.*, Phys.Rev.C 101 (2020) 3, 035203

- Exclusive charmonium production
- Transition GPDs
- ...

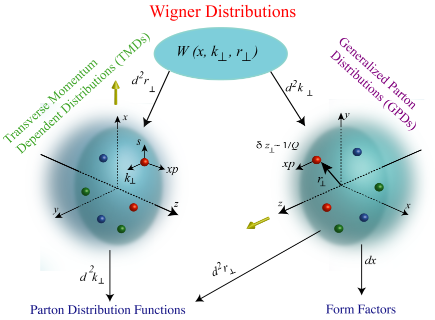
A glimpse at the nucleon 5D structure?

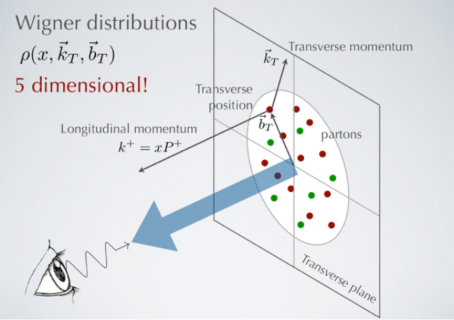
Wigner Distributions





Wigner Distributions

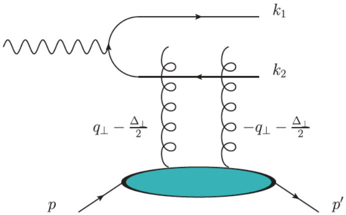




- Not probability density
- Encode more information than TMDs and GPDs (correlations between $b_\perp$ and $k_\perp$)
  $\rightarrow$ important for Orbital Angular Momentum

X. Ji, PRL 91(2003)-62001
C. Lorcé and B. Pasquini, PRD84(2011)014015
C. Lorcé *et al.*, PRD85 (2012) 114006
Hatta, PLB708 (2012) 186

Observables for GTMDs



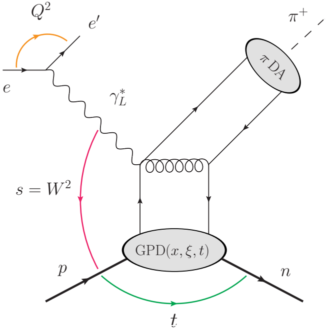
- $\Delta_\perp \sim -(k_{\perp,1} + k_{\perp,2})$
- $k_\perp \sim P_\perp = -\frac{k_{\perp,1} - k_{\perp,2}}{2}$
- $|P_\perp| >> |k_{\perp,1} + k_{\perp,2}|$

Hatta, Xiao, Huan, PRL 116, 2016, 202301

- **Not** standard exclusive process
- Reconstruction of full dijet kinematics and measure the azimuthal modulations in the angle between $P_\perp$ and $\Delta_\perp$
- At small x: sensitivity to gluon GTMDs
- With proton polarization one may access $F^g_{1,4}$

New perspective on hadron structure through backward exclusive processes

Forward vs. Backward kinematics in Bjorken limit



figures from K. Park *et al.*, PLB 780 (2018) 340-345

- $|t|$ small $\rightarrow$ pion produced in the forward direction w.r.t to the photon ($\gamma^* p$ center of mass frame)

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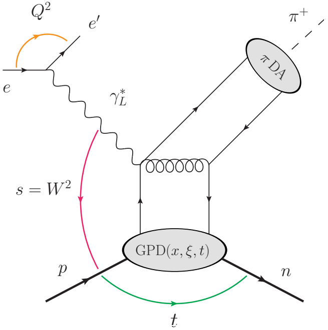

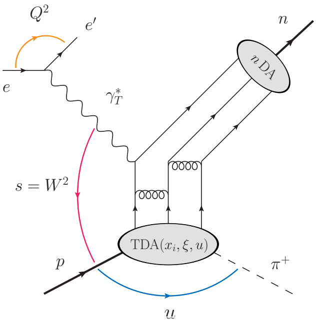

figures from K. Park *et al.*, PLB 780 (2018) 340-345

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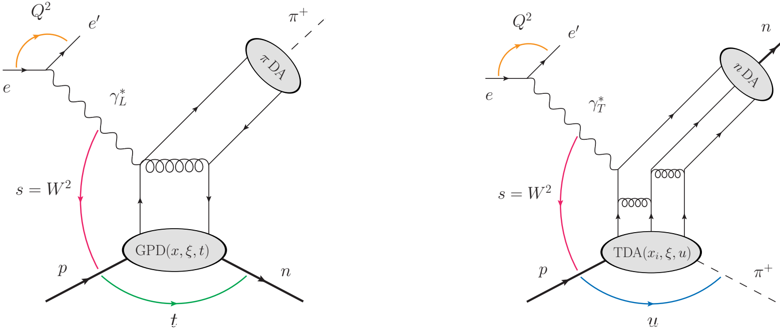
Forward vs. Backward kinematics in Bjorken limit



figures from K. Park *et al.*, PLB 780 (2018) 340-345

- $|t|$ small $\rightarrow$ pion produced in the forward direction w.r.t to the photon ($\gamma^* p$ center of mass frame)
- $|u|$ small $\rightarrow$ pion produced in the backward direction
- New type of physics: explore meson content of the proton with TDA

L. Frankfurt *et al.*, PRD 60 (1999) 014010
B. Pire and L. Szymanowski, PRD 71, 111501 (2005)

Transition Distribution Amplitudes

- They depend on five variables $(x_1, x_2, \xi, u; \mu)$

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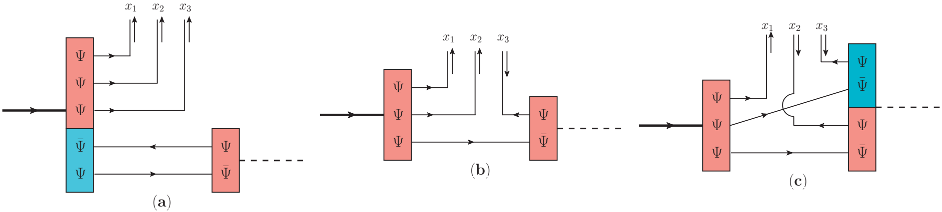
- They present interesting interpretations in terms of lightfront wave functions



J.-P. Lansberg *et al.*, PRD 85 (2012) 054021

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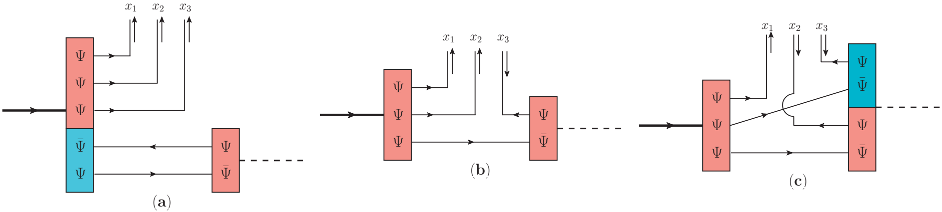

J.-P. Lansberg *et al.*, PRD 85 (2012) 054021

- They obey polynomiality property in ξ and support properties
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B. Pire *et al.*, PRD 82 (2010) 094030

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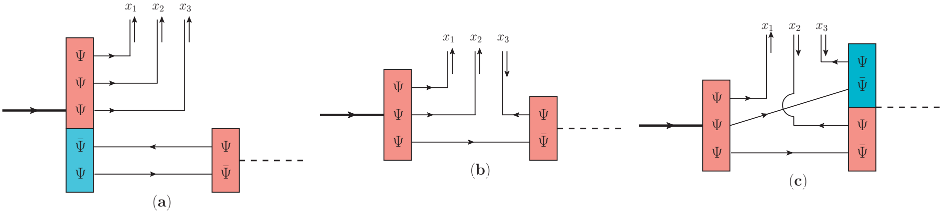

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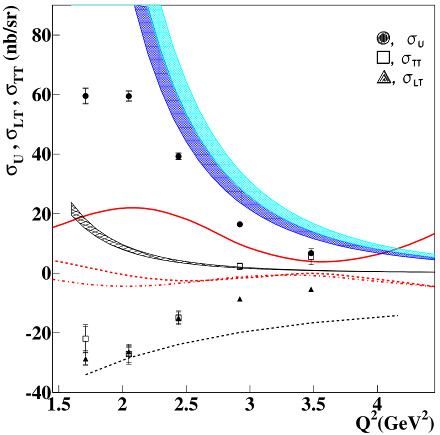
B. Pire *et al.*, PRD 82 (2010) 094030

- In the limit $\xi \rightarrow 1$ they yield the nucleon distribution amplitude (soft pion theorem)

B. Pire *et al.*, PRD84, 074014

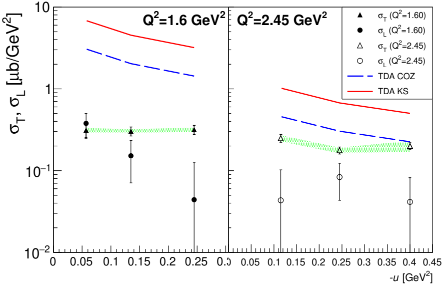
Experimental hint of TDA



K. Park *et al.*, PLB 780 (2018) 340-345

- nucleon to pion TDA
- $\sigma_T \gg \sigma_L$
  - Complete rosenbluth separation not possible here
  - Hint: σ_{TT} and σ_{LT} sizeable
- Dependence in $\sigma_T \sim \frac{1}{Q^8}$
  - Strong dependence in Q^2
  - More data necessary

Experimental hint of TDA



W.B. Li *et al.*,PRL 123 (2019) 18, 182501

- nucleon to ω TDA
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  - For $Q^2 = 2.45 GeV^2$, σ_T dominates
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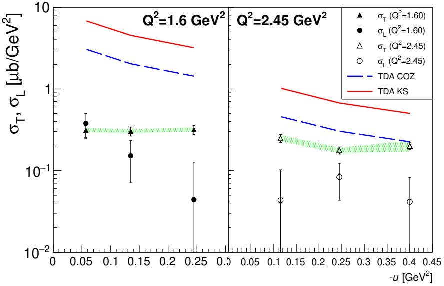

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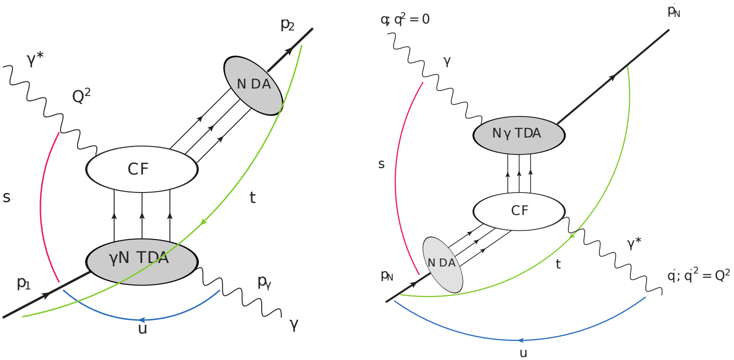
More data required to validate the TDA framework

Nucleon to γ TDA



Backward Compton Scattering

Spacelike and timelike backward (large $|t|$, small $|u|$) Compton scattering possible
$\rightarrow$ New kind of information on the nucleon brightness!

Conclusion

Summary

- Deep exclusive processes are challenging to measure...
- .. but worth the effort !
- Many theory progresses, but not all are taken advantage of yet
- Until now, the lack of data has been a limiting factor

Perspectives

- Future high-luminosity facilities will improve our knowledge of exclusive processes
- Higher Q^2 measurements are strongly desirable
- There is interesting physics in higher-twist correlation functions

Thank you for your attention