# Some news on GPDs and TDAs

# from diverse reactions at JLab and EIC (+UPC)

**in electroproduction and in (real or quasi-real )photoproduction.**

**Work** *still in progress* **with W. Cosyn, K Semenov-Tian-Shansky, L Szymanowski, J. Wagner**

*B. Pire, CPHT, CNRS, Ecole polytechnique, Palaiseau*

# Understanding the proton structure through GPDs

**25 years of successful theoretical physics progresses → early scaling for DVCS**

**First (positive) attempts to extract GPDs from DVCS (JLab program)**

**and TCS :**

Timelike Compton scattering: exclusive photoproduction of lepton pairs

E.R. Berger, M. Diehl & B. Pire

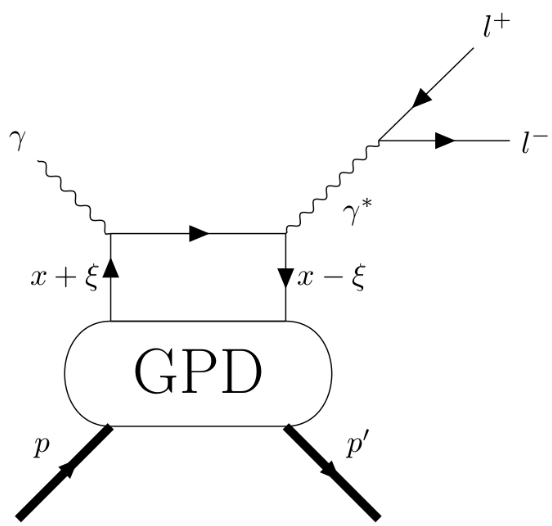
*The European Physical Journal C - Particles and Fields* **23**, 675–689 (2002)

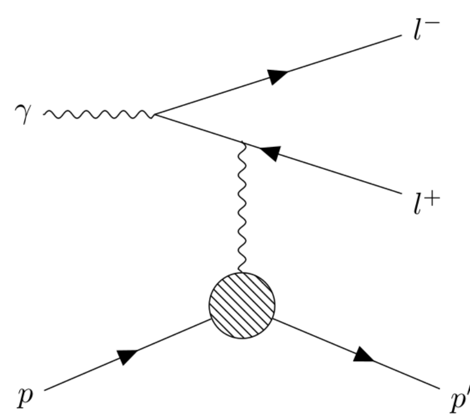
**First-time observation of Timelike Compton Scattering**

Pierre Chatagnon* and Silvia Niccolai
*IJCLab*

Stepan Stepanyan
*Jlab*

(CLAS Collaboration)
(Dated: June 8, 2021)



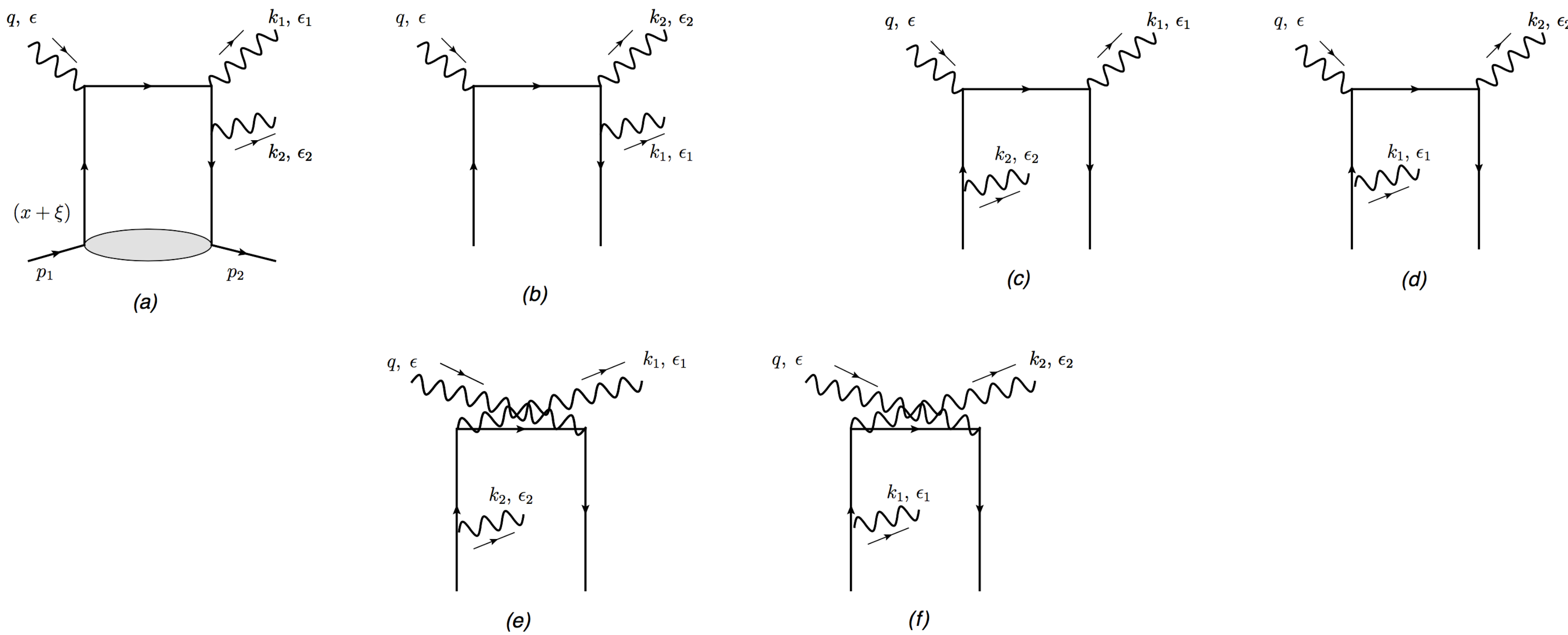



# diphoton photo-production (or electroproduction)

**QED process at Born level, as DVCS and TCS !**

**diphoton invariant mass $M_{\gamma\gamma}$ is the large scale**

**simplest $2 \rightarrow 3$ process**




**Only the charge-odd quark GPDs contribute, contrarily to DVCS or TCS**

# diphoton photo-production at LO

$$\begin{aligned}
\mathscr{H}^q(\xi) &= \int_{-1}^{1} dx C F_q^V(x,\xi) H^q(x,\xi) = (-e_q^3)\left[A^V \mathscr{H}^q_{A^V}(\xi) + B^V \mathscr{H}^q_{B^V}(\xi) + C^V \mathscr{H}^q_{C^V}(\xi)\right] \\
&= (-e_q^3)(\alpha_1 A^V + \alpha_2 B^V)\frac{i\pi}{\xi s^2 \alpha_1 \alpha_2}\left(H^q(\xi,\xi) + H^q(-\xi,\xi)\right), \\
\tilde{\mathscr{H}}^q(\xi) &= \int_{-1}^{1} dx C F_q^A(x,\xi) \tilde{H}^q(x,\xi) = (-e_q^3)\left[A^A \tilde{\mathscr{H}}^q_{A^A}(\xi) + B^A \tilde{\mathscr{H}}^q_{B^A}(\xi)\right] \\
&= (-e_q^3)(\alpha_1 A^A + \alpha_2 B^A)\frac{-i\pi}{\xi s^2 \alpha_1 \alpha_2}\left(\tilde{H}^q(\xi,\xi) - \tilde{H}^q(-\xi,\xi)\right),
\end{aligned}$$

**The hard amplitude is purely imaginary and proportional to $\delta(x \pm \xi)$**

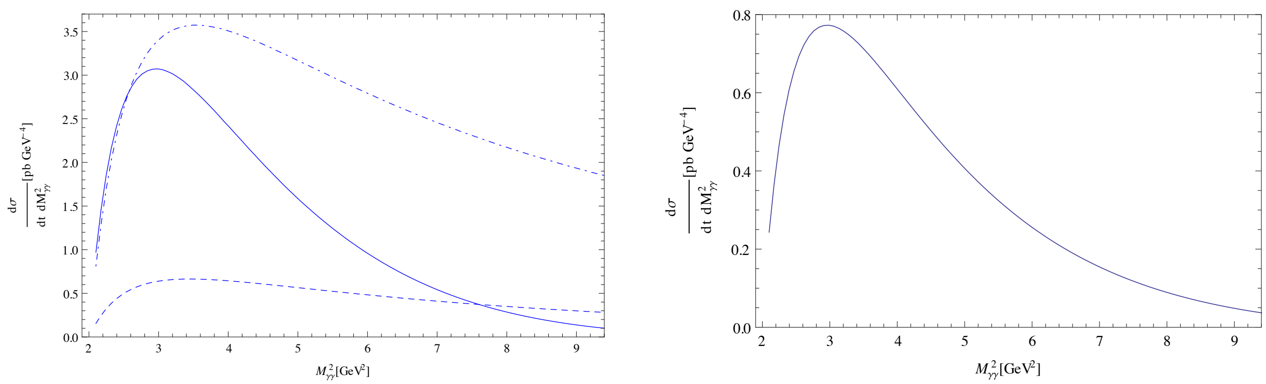
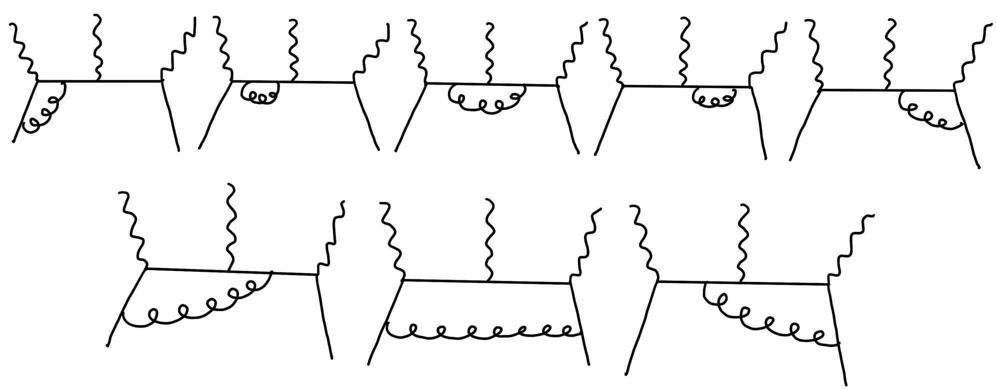



**Figure 2:** The $M^2_{\gamma\gamma}$ dependence of the unpolarized differential cross section $\frac{d\sigma}{dM^2_{\gamma\gamma}dt}$ on a proton(left panel) and on a neutron(right panel) at $t = t_{min}$ and $S_{\gamma N} = 20$ GeV$^2$ (full curves), $S_{\gamma N} = 100$ GeV$^2$ (dashed curve) and $S_{\gamma N} = 10^6$ GeV$^2$ (dash-dotted curve, multiplied by $10^5$).

**The cross-section is large enough for JLab**

## diphoton photo-production at NLO

**Calculate $O(\alpha_s)$ corrections : the first step of a factorization proof.**



**48 (=8 x 6 $\gamma$ permutations) diagrams**

**(Oskar Grocholski MSc thesis)**

# Technicalities

$$\mathcal{A} = \sum_q \int_{-1}^{1} dx\, \mathrm{GPD}^q(x)\mathcal{T}^q(x), \qquad \mathcal{T}^q(x) = \mathcal{C}_0^q + \frac{\alpha_S}{2\pi}\left(\frac{M_{\gamma\gamma}^2 e^{\gamma}}{4\pi\mu_R^2}\right)^{-\varepsilon/2}\left(\frac{2}{\varepsilon}\mathcal{C}_{coll.}^q + \mathcal{C}_1^q\right).$$

$$\mathcal{C}_0^q(x) = i \times \mathrm{C} \times \mathrm{Im}\left(\frac{1}{(x+\xi-i0^+)(x-\xi+i0^+)}\right).$$

$$\mathcal{C}_{coll.}^q = iC_F \times \mathrm{C} \times \mathrm{Im}\left[\frac{3}{(x-\xi+i0^+)(x+\xi-i0^+)} + \right.$$
$$\left. + \frac{1}{\xi}\frac{\log\left(\frac{x-\xi+i0^+}{-2\xi}\right)}{x-\xi+i0^+} - \frac{1}{\xi}\frac{\log\left(\frac{x+\xi-i0^+}{2\xi}\right)}{x+\xi-i0^+}\right].$$

**QCD evolution means :**

$$\mathrm{GPD}^q(x) = \mathrm{GPD}_R^q(x;\mu_F) + \frac{\alpha_S}{2\pi}\left(-\frac{2}{\varepsilon} + \ln\frac{\mu_F^2 e^{\gamma}}{4\pi\mu_R^2}\right)\int dx'\, K^{qq}(x,x')\mathrm{GPD}_R^q(x';\mu_F)\ ,$$

**and you can verify that :**

$$\mathcal{C}_{coll.}^q(x) = \int_{-1}^{1} dy\, K^{qq}(y,x)\mathcal{C}_0^q(y).$$

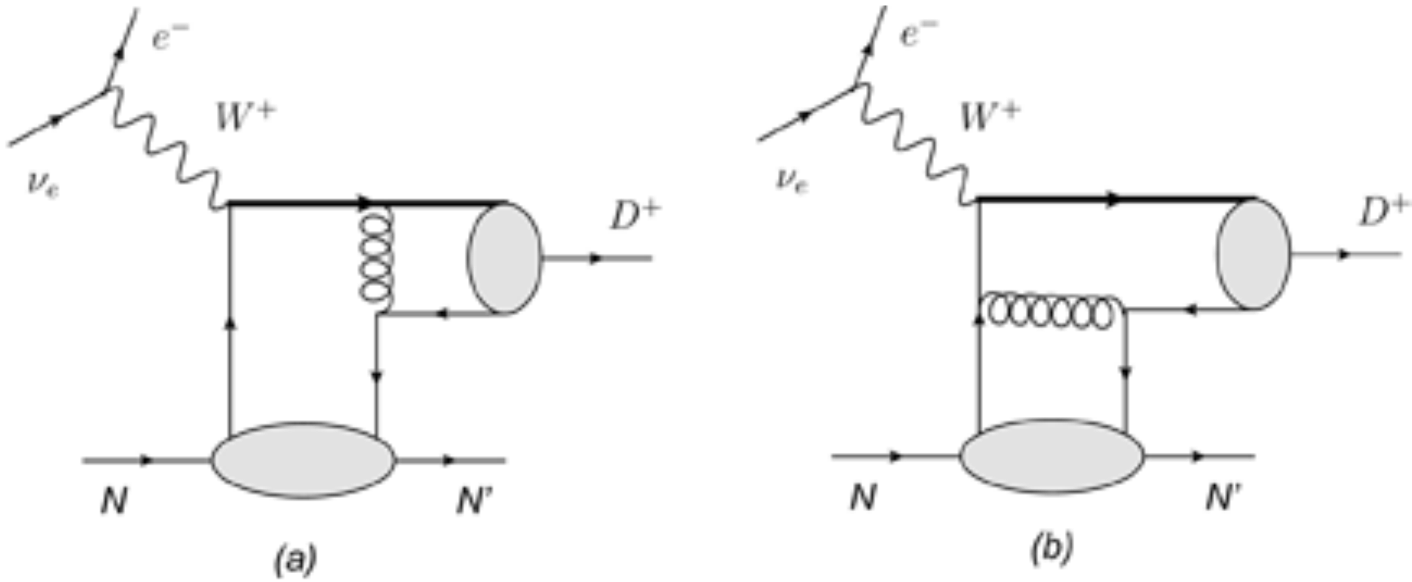
**Factorization is proven at NLO (first time for such a $2 \to 3$ process)**

$$\mathcal{A} = \sum_q \int_{-1}^{1} dx \mathrm{GPD}_R^q(x;\mu_F)\left(\mathcal{C}_0^q(x) + \frac{\alpha_S}{2\pi}\left[\mathcal{C}_1^q(x) + \ln\left(\frac{\mu_F^2}{M_{\gamma\gamma}^2}\right)\mathcal{C}_{coll.}^q(x)\right]\right)$$

**Phenomenolgy still to be performed !**

# heavy meson neutrino-production

**Difficulty with chiral-odd sector : proposal to use heavy quark property of helicity changing propagation (2015-2017)**

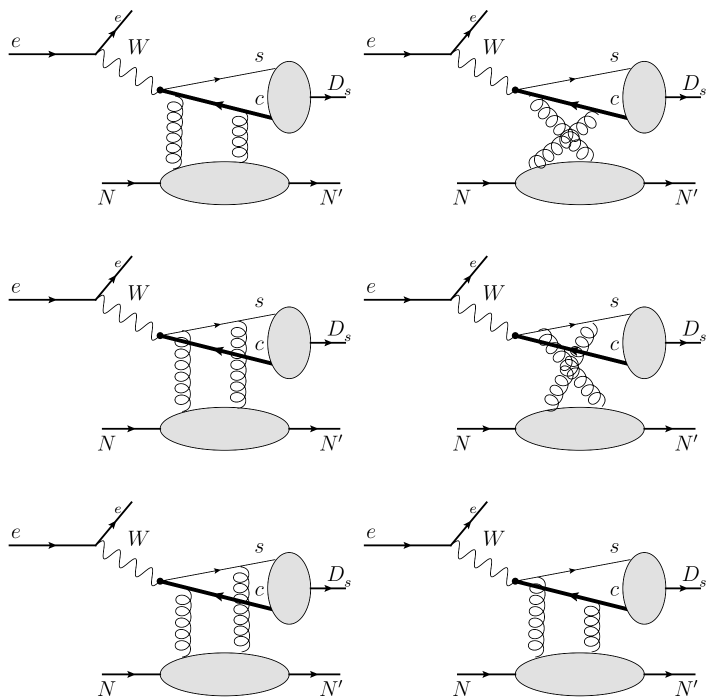



Graphes de Feynman pour la neutrino-production d'un méson D ; la ligne épaisse désigne le quark charme, la ligne en forme de ressort désigne un gluon.

BP et al, Phys Rev Lett. 115, PRD 95 ; PRD 96

**but experimentalists with neutrino beams do not care about GPDs !**

# Exclusive electroweak heavy meson production at EIC




The thick line represents the heavy quark.

mplitude proportional to CKM matrix element, so production of $D_s$ $(1968)$ or $D_s^*$ $(2112)$ charmed and strange meson dominates.

# Exclusive electroweak heavy meson production at EIC

**The hard amplitude is very different from the DVCS/TCS case** $\frac{1}{x+\xi-i\epsilon} \pm \frac{1}{x-\xi+i\epsilon}$

The symmetric and antisymmetric hard amplitudes read:

$$\mathcal{M}^S = \left\{ \frac{Tr_a^S}{D_1 D_2} + \frac{Tr_b^S}{D_3 D_4} + \frac{Tr_c^S}{D_4 D_5} \right\} + \{ x \to \quad x \} \,,$$
$$\mathcal{M}^A = \left\{ \frac{Tr_a^A}{D_1 D_2} + \frac{Tr_b^A}{D_3 D_4} + \frac{Tr_c^A}{D_4 D_5} \right\} \quad \{ x \to \quad x \} \,,$$

and the denominators read (with $\quad = \frac{2\xi M^2}{M^2+Q^2}$, $\beta = \frac{2\xi(\bar{z}^2 M^2 \quad m_c^2)}{\bar{z}(M^2+Q^2)}$ ):

$$D_1 = z[\quad \bar{z} M_D^2 \quad Q^2 + i\varepsilon] \,,$$
$$D_2 = z \frac{Q^2+M_D^2}{2\xi} (x \quad \xi + \quad z + i\epsilon) \,,$$
$$D_3 = \quad \bar{z}(Q^2+M_D^2) + \bar{z}^2 M_D^2 \quad m_c^2 + i\epsilon \,,$$
$$D_4 = \bar{z} \frac{Q^2+M_D^2}{2\xi} (x \quad \xi + \beta + i\epsilon) \,,$$
$$D_5 = z \frac{Q^2+M_D^2}{2\xi} ( \quad x \quad \xi + \quad z + i\epsilon) \,.$$

# Exclusive electroweak heavy meson production at EIC

## small but measurable at EIC !

### (not at JLab)

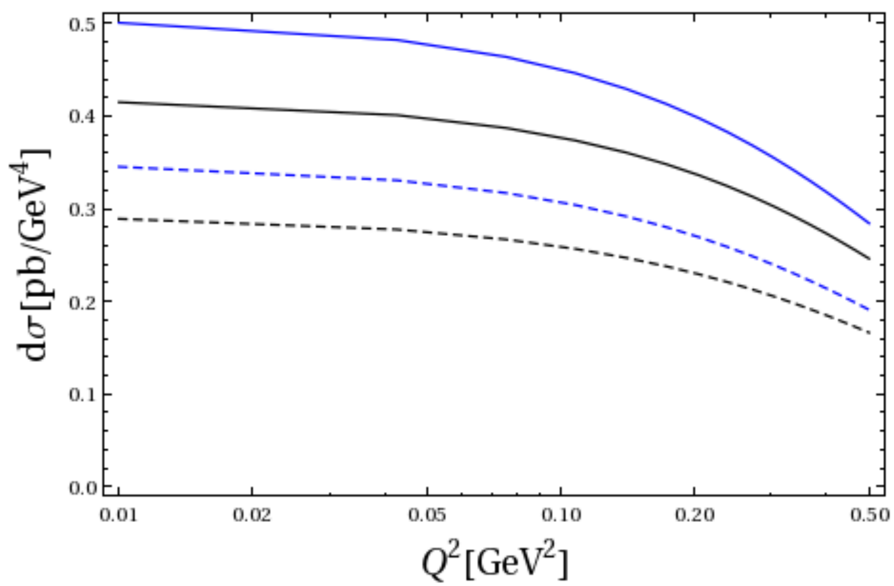
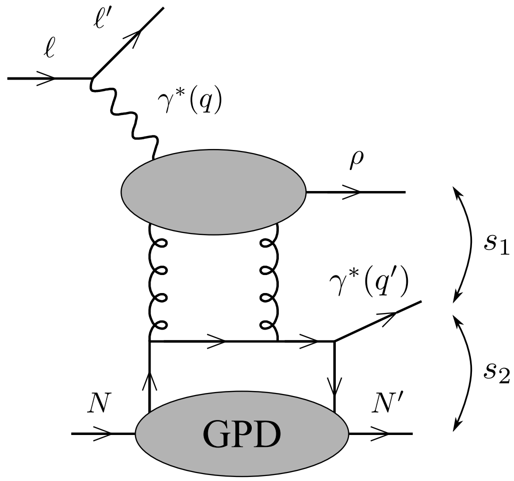
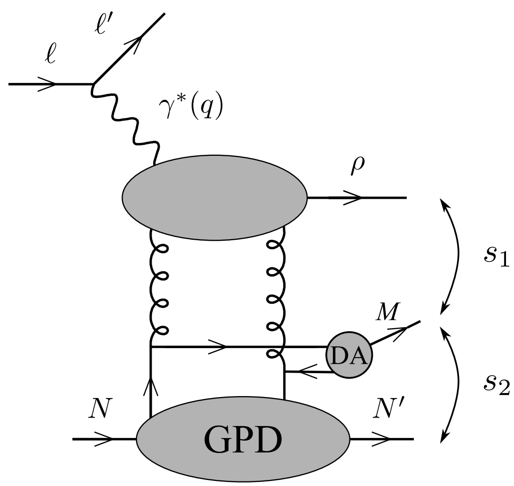



Figure: The $Q^2$ dependence of the cross section $\frac{d\sigma(e\quad N\to\nu N D_s\ )}{dy\, dQ^2\, dt}$ (in pb GeV $^{\ 4}$) for $_T = 0$ and $s = 20000$ GeV$^2$ and $y = 10\ ^{\ 4}$ with GK (blue lines), and simple (black lines) GPD models, and with D  s from [Kurimoto et al, PRD 65] (solid lines) and [Serna et al, EPJC  0] (dashed lines).

# Diffractive exclusive reactions: 2 case studies




- diffractive vector meson + dilepton pair (top) or 2nd meson (bottom)
- Large rapidity gap between diffractive $\rho$ and other hadrons: $s_1 \ggg s_2 \ggg \Lambda^2_{\rm QCD}$
- Hard scales $Q^2$, $Q'^2$ (top); $(q - p_\rho)^2$ (bottom) ensure small-sized dipole + GPD vertex

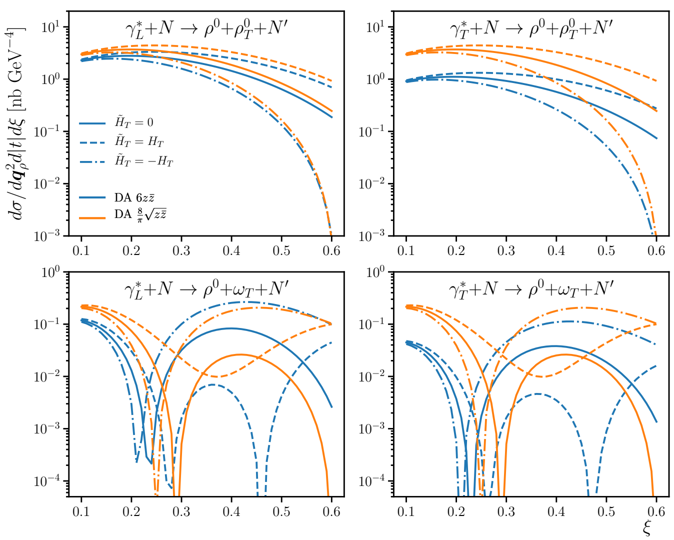
- No gluon GPD contribution (C-even)
- (virtual)photoproduction cross section **independent** of $s$
- Probes ERBL region of the GPDs
- In two meson case: probe transversity with polarized $M_T$

$\gamma^*_{L/T} + N \to \rho^0_L + (\rho^0_T/\omega_T) + N'$

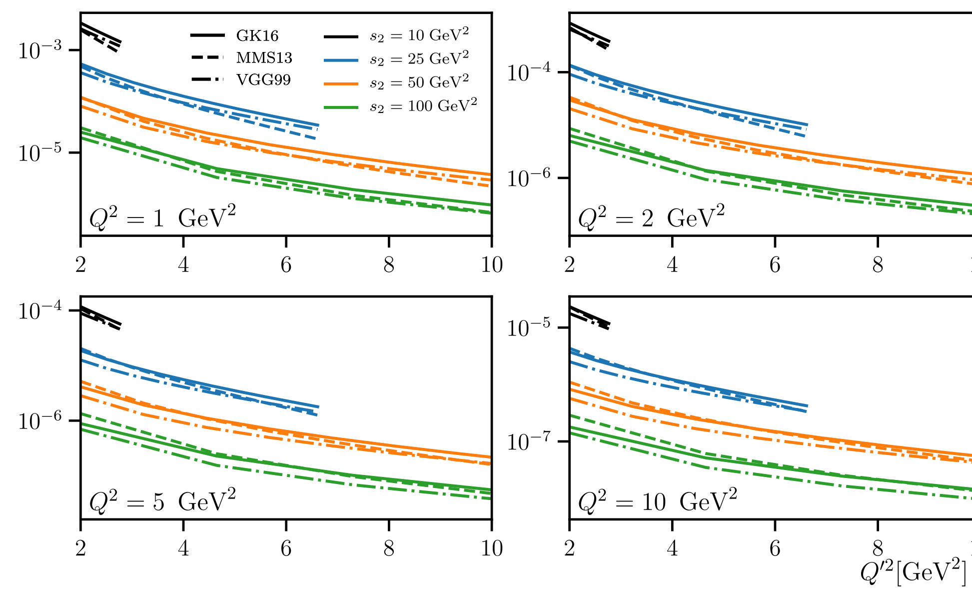
$\rho$ + dilepton pair production: $t_N = -0.1$ GeV$^2$, $t_\rho = t_\rho^{\min}$

**nanobarn/GeV$^4$**

**picobarn/GeV$^8$**




$[Q^2 = 1\text{GeV}^2,\ t_\rho = -2\text{GeV}^2,\ t_N = t_N^{\min}]$

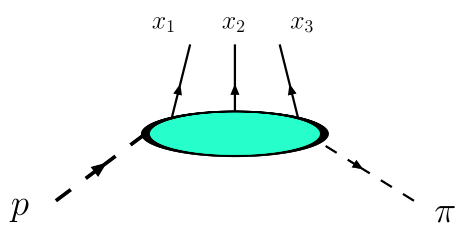


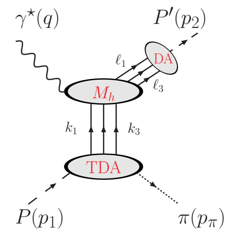

**promising**

**undetectable !**

**WE WILL TRY OTHER CHANNELS**

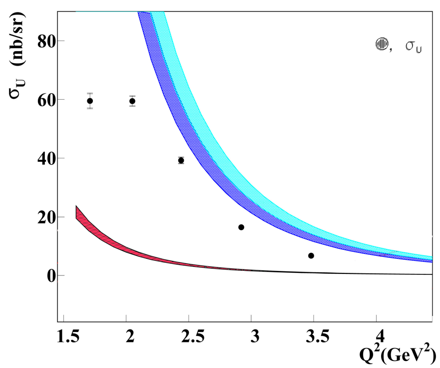
# Backward meson electroproduction : from GPDs to TDAs

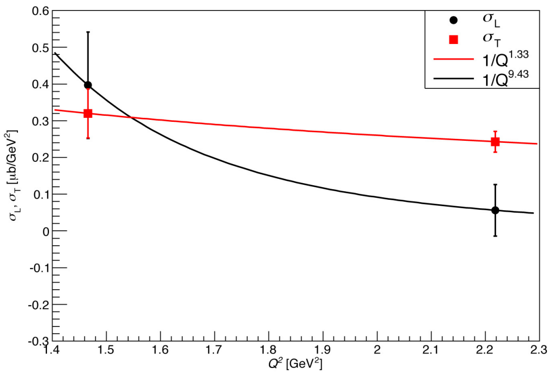



Theory developments from 2005 BP and L.Sz., PL B622 $\to$ 2021 BP et al, submitted to Physics Reports

First experimental signals at JLab 2018 Park et al., PL B877 and 2019 Li et al., Phys.Rev.Lett. 123




Right order of magnitude

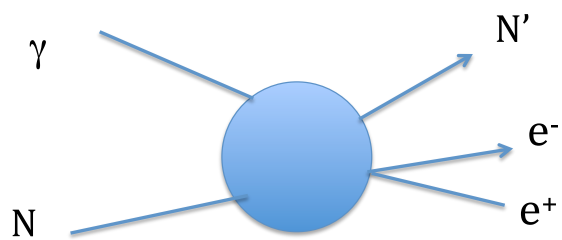
Dominance of $\sigma_T$ for large $Q^2$

# Backward timelike Compton Scattering

$$\gamma\ N \to N'\gamma^*(Q'^2) \to N'\ (e^+e^-)$$

**or**

**When and where does the proton emit a photon ?**




**Real or quasi-real photoproduction.**

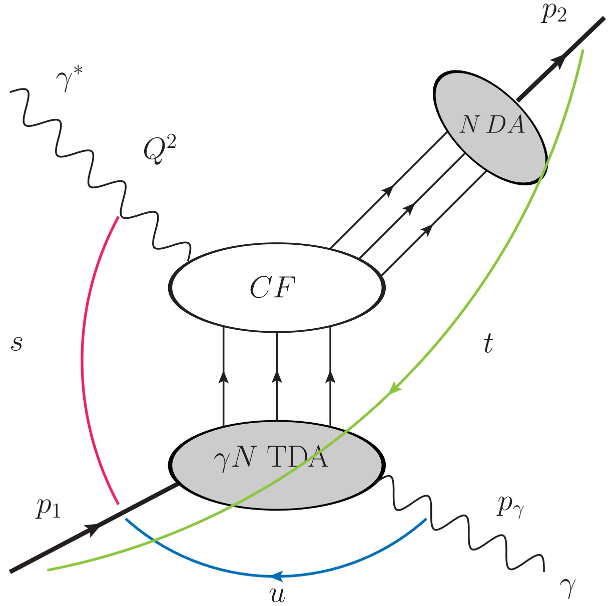
**JLab, EIC or Ultraperipheral collisions in proton/nucleus collisions**

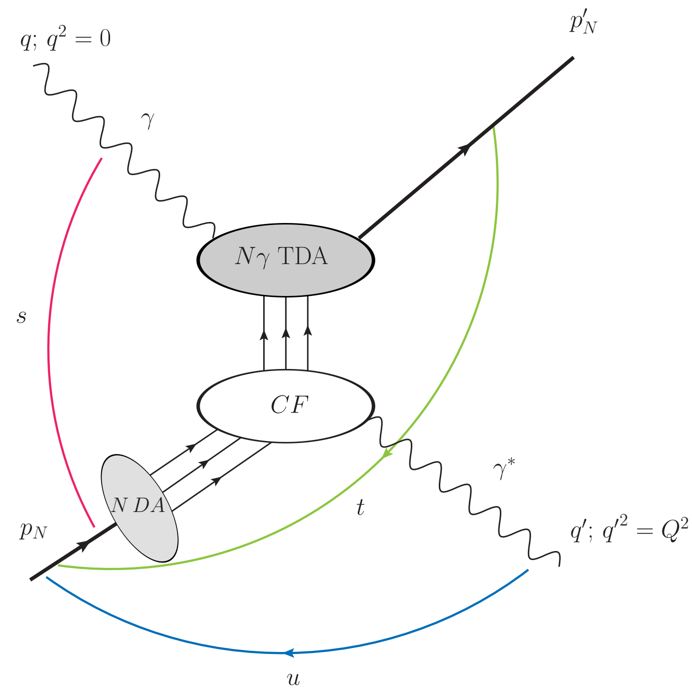
**From nucleon to meson TDAs $\rightarrow$ Nucleon to photon TDAs**

**Work still** *in progress*

# Backward timelike Compton Scattering

**Backward photon electroproduction $\leftrightarrow$ Backward lepton pair photoproduction**




**Small $-u$ i.e. Large $-t$**

**i.e. backward kinematics (in $\gamma N$ CMS)**

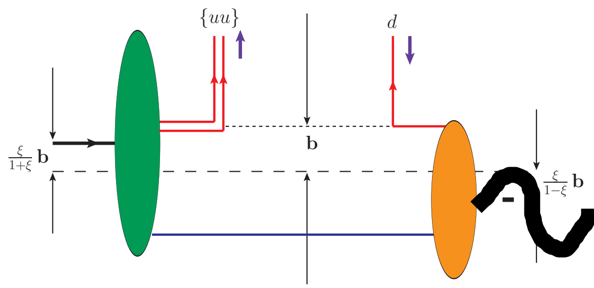
**and**

**large $Q^2$ to access quark and gluon level**

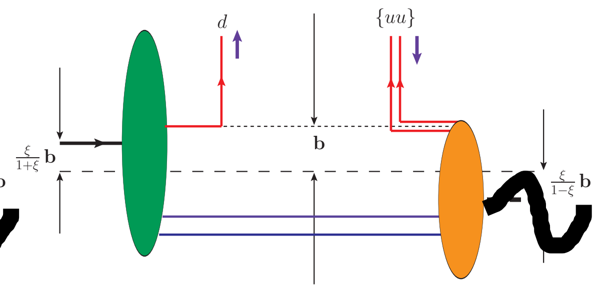
**large $s$ to avoid resonance effects.**

# Impact picture Nucleon to photon TDAs

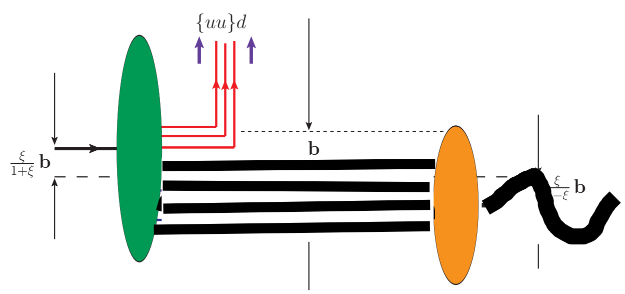
## Fourier transform to impact parameter : $\Delta_T \to b_T$




DGLAP I : $x_3 = w_3 - \xi \leq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$



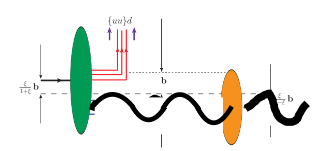

DGLAP II : $x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \leq 0;$




ERBL : $x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$

**Where in the transverse plane does the nucleon emit a photon ?**

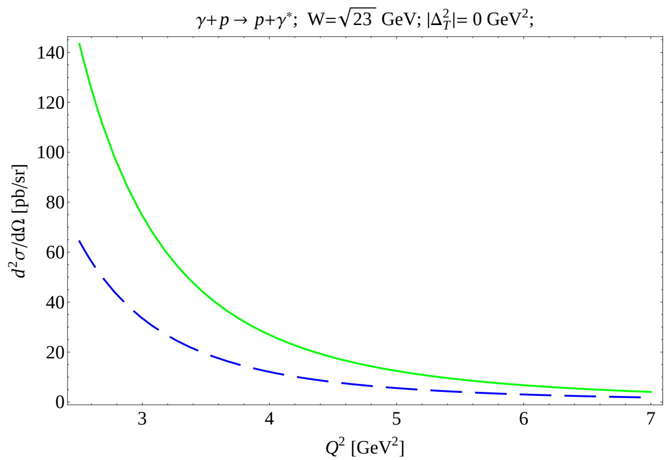
**ERBL region : Do we see the inner light within the Nucleon ?**

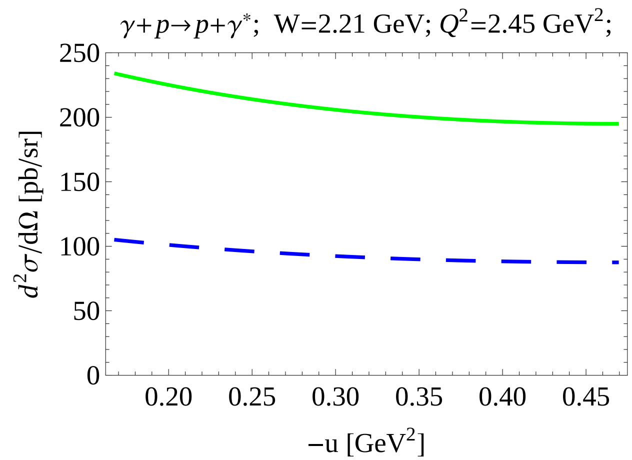


ERBL : $x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$

# Phenomenology

Order of magnitude estimate : multiply $\rho$ electroproduction predictions by $\frac{e^2}{f_\rho^2} \approx \frac{\alpha_{em}}{2.6}$




deduced from $N \to \rho$ TDA model PRD 91 based on COZ and KS nucleon DA models.

To get $\frac{d\sigma^{\gamma N \to e^+ e^- N'}}{d\Omega dQ'^2 dcos\theta}$ multiply by $\frac{2\alpha_{em}(1+cos^2\theta)}{\pi Q'^2}$

- Bethe-Heitler contribution is negligible (to be precisely checked)
- need to detect lepton pair with small momentum but large invariant mass :

each lepton should be easily detectable

- data probably already exist at JLab !

They need to be analyzed !

# Conclusions

GPD and TDA phenomenology just becoming exploitable !

Need more than DVCS to perform nucleon tomography.

Thank you for your attention !

Post scriptum : Color transparency workshop 2 weeks ago

Why not explore nuclear transparency of backward meson electroproduction

to settle the question whether a small proton is produced in a hard reaction