GPDs in heavy mesons production and Compton scattering

Jakub Wagner

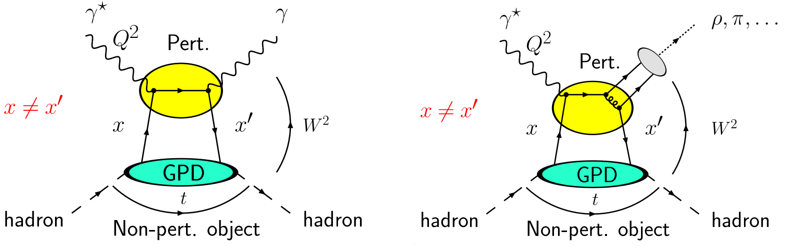
Theoretical Physics Department
National Center for Nuclear Research
Warsaw, Poland

POETIC6, Palaiseau

timelike-DVCS: B.Pire, L.Szymanowski, H.Moutarde, F.Sabatié

J/Ψ photoproduction: D.Ivanov, L.Szymanowski

Processes



- Universality of GPDs,
- Meson production - additional difficulties,

So, in addition to spacelike DVCS ...

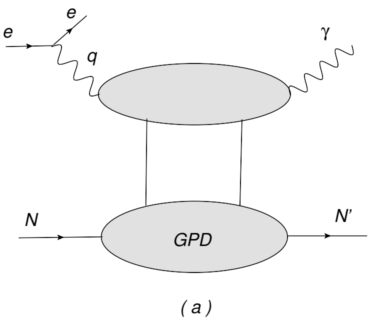


Figure : Deeply Virtual Compton Scattering (DVCS) : $lN \to l'N'\gamma$

we can also study timelike DVCS (TCS)

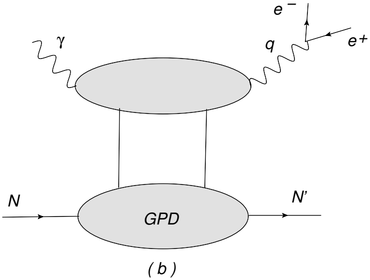


Figure : Timelike Compton Scattering (TCS): $\gamma N \to l^+ l^- N'$

Why TCS:

- universality of the GPDs,
- another source for GPDs (special sensitivity on real part of GPD H),
- spacelike-timelike crossing,
- more in M.Boer talk on Friday morning.

General Compton Scattering:

$$\gamma^*(q_{in})N(p) \to \gamma^*(q_{out})N'(p')$$

variables, describing the processes of interest in this generalized Bjorken limit, are the scaling variable ξ and skewness $\eta > 0$:

$$\xi = -\frac{q_{out}^2 + q_{in}^2}{q_{out}^2 - q_{in}^2}\eta\,, \quad \eta = \frac{q_{out}^2 - q_{in}^2}{(p+p')\cdot(q_{in}+q_{out})}\,.$$

- DDVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 > 0\,, \quad \eta \neq \xi$
- DVCS: $q_{in}^2 < 0\,, \quad q_{out}^2 = 0\,, \quad \eta = \xi > 0$
- TCS: $q_{in}^2 = 0\,, \quad q_{out}^2 > 0\,, \quad \eta = -\xi > 0$

Coefficient functions and Compton Form Factors

CFFs are the GPD dependent quantities which enter the amplitudes. They are defined through relations:

$$\mathcal{A}^{\mu\nu}(\xi,\eta,t) = -e^2 \frac{1}{(P+P')^+}\,\bar{u}(P')\left[g_T^{\mu\nu}\left(\mathcal{H}(\xi,\eta,t)\,\gamma^+ + \mathcal{E}(\xi,\eta,t)\,\frac{i\sigma^{+\rho}\Delta_\rho}{2M}\right)\right.$$
$$\left. + i\epsilon_T^{\mu\nu}\left(\widetilde{\mathcal{H}}(\xi,\eta,t)\,\gamma^+\gamma_5 + \widetilde{\mathcal{E}}(\xi,\eta,t)\,\frac{\Delta^+\gamma_5}{2M}\right)\right] u(P)\,,$$

,where:

$$\mathcal{H}(\xi,\eta,t) = +\int_{-1}^{1} dx \left(\sum_q T^q(x,\xi,\eta)H^q(x,\eta,t) + T^g(x,\xi,\eta)H^g(x,\eta,t)\right)$$
$$\widetilde{\mathcal{H}}(\xi,\eta,t) = -\int_{-1}^{1} dx \left(\sum_q \widetilde{T}^q(x,\xi,\eta)\widetilde{H}^q(x,\eta,t) + \widetilde{T}^g(x,\xi,\eta)\widetilde{H}^g(x,\eta,t)\right).$$

LO

- DVCS vs TCS

$$
\begin{aligned}
{}^{DVCS}T^q &= -e_q^2 \tfrac{1}{x+\eta-i\varepsilon} - (x \to -x) = & ({}^{TCS}T^q)^* \\
{}^{DVCS}\tilde{T}^q &= -e_q^2 \tfrac{1}{x+\eta-i\varepsilon} + (x \to -x) = & -({}^{TCS}\tilde{T}^q)^*
\end{aligned}
$$

$$
{}^{DVCS}Re(\mathcal{H}) \sim P\int \frac{1}{x \pm \eta} H^q(x,\eta,t)\,, \quad {}^{DVCS}Im(\mathcal{H}) \sim i\pi H^q(\pm\eta,\eta,t)
$$

- DDVCS

$$
{}^{DDVCS}T^q = -e_q^2 \frac{1}{x+\xi-i\varepsilon} - (x \to -x)
$$

$$
{}^{DDVCS}Re(\mathcal{H}) \sim P\int \frac{1}{x \pm \xi} H^q(x,\eta,t)\,, \quad {}^{DVCS}Im(\mathcal{H}) \sim i\pi H^q(\pm\xi,\eta,t)
$$

But this is only true at LO. At NLO all GPDs hidden in the convolutions.

Coefficient functions

Renormalized coefficient functions for DVCS are given by

$$
\begin{aligned}
T^q(x) &= \left[C_0^q(x) + C_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^q(x)\right] - (x \to -x)\,,\\
T^g(x) &= \left[C_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot C_{coll}^g(x)\right] + (x \to -x)\,,\\
\widetilde{T}^q(x) &= \left[\widetilde{C}_0^q(x) + \widetilde{C}_1^q(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot \widetilde{C}_{coll}^q(x)\right] + (x \to -x)\,,\\
\widetilde{T}^g(x) &= \left[\widetilde{C}_1^g(x) + \ln\left(\frac{Q^2}{\mu_F^2}\right) \cdot \widetilde{C}_{coll}^g(x)\right] - (x \to -x)\,.
\end{aligned}
$$

The results for DVCS and TCS cases are simply related:

$$
{}^{TCS}T(x,\eta) = \pm\left({}^{DVCS}T(x,\xi=\eta) + i\pi \cdot C_{coll}(x,\xi=\eta)\right)^*\,,
$$

D.Mueller, B.Pire, L.Szymanowski, J.Wagner, Phys.Rev.D86, 2012.

where $+$ $(-)$ sign corresponds to vector (axial) case.

Compton Form Factors - DVCS - $Re(\mathcal{H})$

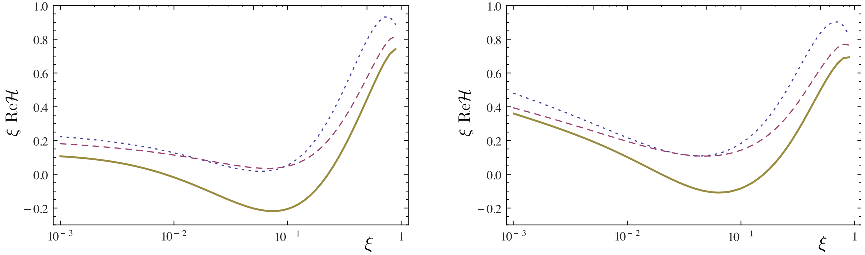


Figure : The real part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

Compton Form Factors - DVCS - $Im(\mathcal{H})$

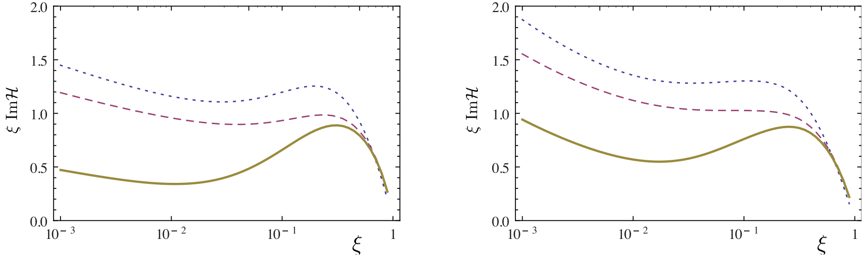


Figure : The imaginary part of the *spacelike* Compton Form Factor $\mathcal{H}(\xi)$ multiplied by ξ, as a function of ξ in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4\,\mathrm{GeV}^2$ and $t = -0.1\,\mathrm{GeV}^2$, at the Born order (dotted line), including the NLO quark corrections (dashed line) and including both quark and gluon NLO corrections (solid line).

Compton Form Factors - TCS - $Re(\mathcal{H})$

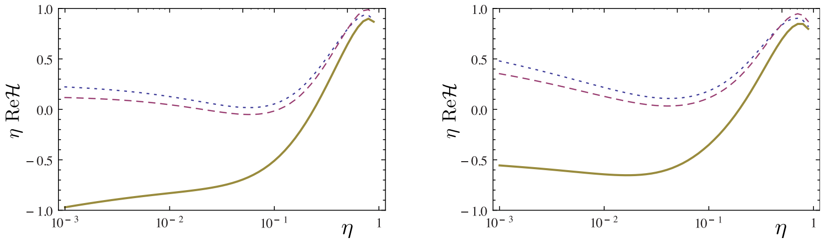


Figure : The real part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

Compton Form Factors - TCS - $Im(\mathcal{H})$

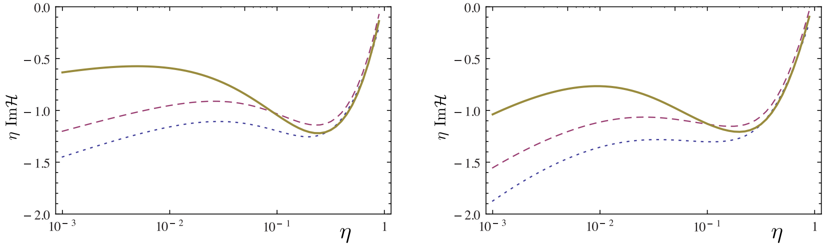


Figure : The imaginary part of the *timelike* Compton Form Factor $\mathcal{H}$ multiplied by η, as a function of η in the double distribution model based on Kroll-Goloskokov (upper left) and MSTW08 (upper right) parametrizations, for $\mu_F^2 = Q^2 = 4$ GeV^2 and $t = -0.1$ GeV^2. Below the ratios of the NLO correction to LO result of the corresponding models.

Few words about factorization scale

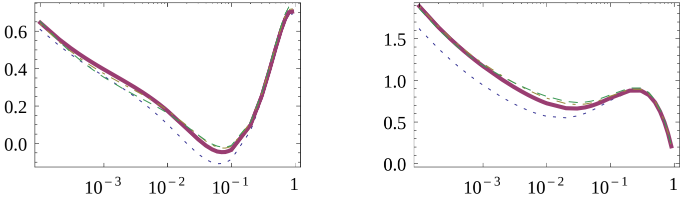


Figure : Full NLO result. Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$, $Q^2 = 4gev^2$, $\mu_F^2 = Q^2, Q^2/2, Q^2/3$

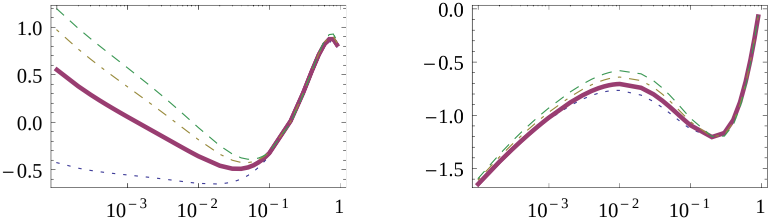
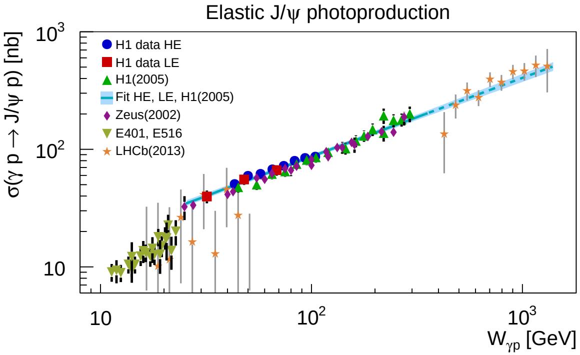


Figure : Full NLO result. Left column - $\xi \cdot Re(\mathcal{H}(\xi))$, right column - $\xi \cdot Im(\mathcal{H}(\xi))$

Heavy Vector Mesons Photoproduction

We have good data! See H1 2013 paper:



Heavy Vector Mesons Photoproduction

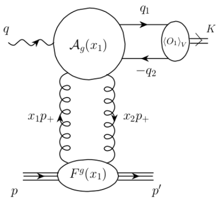


Figure 1: Kinematics of heavy vector meson photoproduction.

$$\mathcal{M} \sim \left(\frac{\langle O_1 \rangle_V}{m^3} \right)^{1/2} \int_{-1}^{1} dx \left[T_g(x,\xi)\, F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right] ,$$

$$F^{q,S}(x,\xi,t) = \sum_{q=u,d,s} F^q(x,\xi,t) \, .$$

$F^{g(q)}(x,\xi,t;\mu_F^2)$ – the gluon (quark) GPDs, m is a pole mass of heavy quark,
$\xi = M^2/(2W^2 - M^2)$ is the skewedness paramerer.
NRQCD – all information about the quarkonium structure is encoded in the NRQCD matrix element $\langle O_1 \rangle_V$ which enters the leptonic decay rate

$$\Gamma[V \to l^+ l^-] = \frac{2 e_q^2 \pi \alpha^2}{3} \frac{\langle O_1 \rangle_V}{m^2} \left(1 - \frac{8\alpha_S}{3\pi} \right)^2 .$$

Hard scattering kernels:

$$T_g(x,\xi) = \frac{\xi}{(x-\xi+i\varepsilon)(x+\xi-i\varepsilon)} \mathcal{A}_g\left(\frac{x-\xi+i\varepsilon}{2\xi}\right),$$
$$T_q(x,\xi) = \mathcal{A}_q\left(\frac{x-\xi+i\varepsilon}{2\xi}\right).$$

- LO

$$\mathcal{A}_g^{(0)}(y) = \alpha_S \quad \mathcal{A}_q^{(0)}(y) = 0\,.$$

- NLO

D. Yu. Ivanov , A. Schafer , L. Szymanowski and G. Krasnikov - **Eur.Phys.J. C34 (2004) 297-316**

$$T_q(x,\xi) = \frac{\alpha_S^2(\mu_R) C_F}{2\pi} f_q\left(\frac{x-\xi+i\varepsilon}{2\xi}\right),$$

$$\begin{aligned} f_q(y) = {}& \ln\left(\frac{4m^2}{\mu_F^2}\right)(1+2y)\left(\frac{\ln(-y)}{1+y} - \frac{\ln(1+y)}{y}\right) - \pi^2\frac{13(1+2y)}{48y(1+y)} + \frac{2\ln 2}{1+2y} \\ & + \frac{\ln(-y)+\ln(1+y)}{1+2y} + (1+2y)\left(\frac{\ln^2(-y)}{1+y} - \frac{\ln^2(1+y)}{y}\right) \\ & + \frac{3-4y+16y(1+y)}{4y(1+y)} Li_2(1+2y) - \frac{7+4y+16y(1+y)}{4y(1+y)} Li_2(-1-2y) \end{aligned}$$

Photoproduction amplitude and cross section - LO

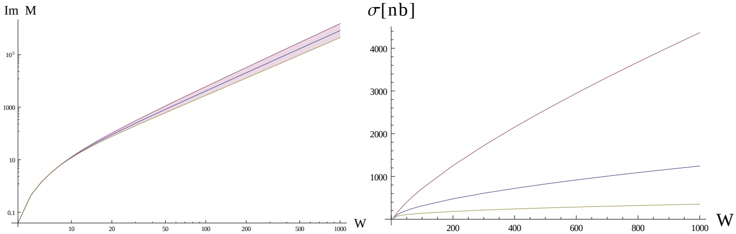


Figure : (left) Imaginary part of the amplitude $\mathcal{M}$ and (right) photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.

Photoproduction cross section - LO and NLO

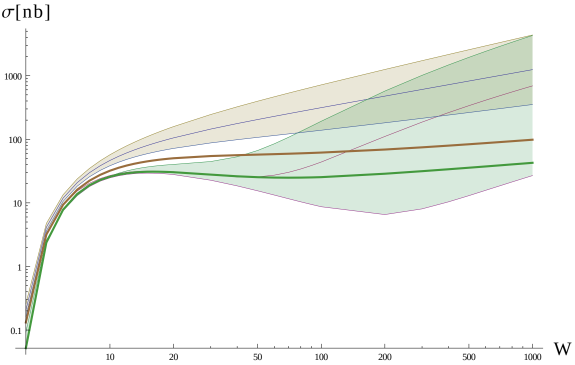
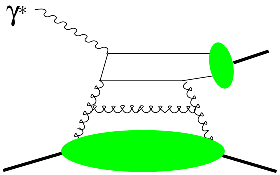


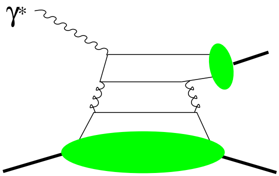
Figure : Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

- Jones & Martin & Ryskin & Teubner, arXiv:1507.06942. Choice of the factorization scale.
- Why NLO corrections are large at small x_B?
  large contribution comes from

$$ImA^g \sim H^g(\xi,\xi) + \frac{3\alpha_s}{\pi}\left[\log\frac{M_V^2}{\mu_F^2} - \log 4\right]\int_\xi^1 \frac{dx}{x} H^g(x,\xi)$$

$H^g(x,\xi) \sim xg(x) \sim const$, therefore $\int dx/x H^g(x,\xi) \sim \log(1/\xi) H^g(\xi,\xi)$





At higher orders powers of energy log are generated

$$\mathcal{I}m A^g \sim H^g(\xi,\xi) + \int_{\xi}^{1} \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1} \frac{x}{\xi}$$

$C_n(L)$ - polynomials of $L = \log \frac{Q^2}{\mu_F^2}$, maximum power is L^n

- for DIS a technique suggested by Catani, Ciafaloni and Hautmann; [Catani, Hautmann '94]
- One can calculate $C_n(L)$ in $D = 4 + 2\epsilon$ dimensions.
- Consistently with collinear factorization, in terms of corrections to coeff. functions and anomalous dimensions, in $\overline{MS}$ scheme
- The method used in DIS can be generalized to exclusive, nonforward processes.

Coeff. functions at small x / their Mellin moments at $N \to 0$

$$L = \log\left(\frac{Q^2}{\mu_F^2}\right) \quad , \quad x = \frac{\bar{\alpha}_s}{N}$$

Result for $J/\Psi, \Upsilon$

$$1 + x(L - \log 4) + \frac{x^2}{6}\left(\pi^2 + 3\log^2 4 + 3L(L - \log 16)\right) + \cdots + \mathcal{O}(x^{10})$$

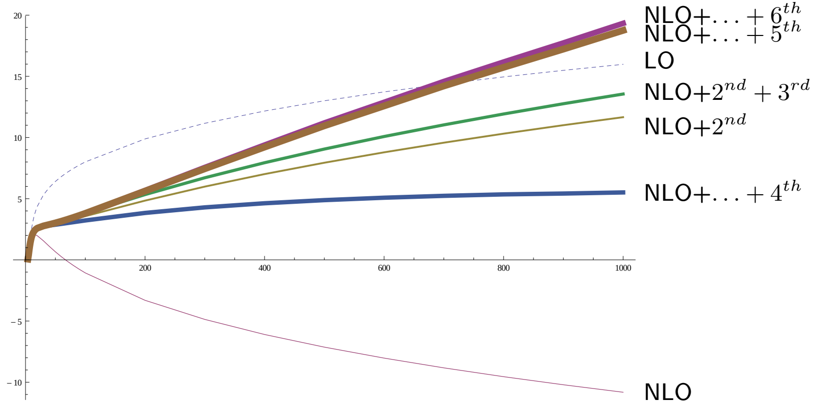
F_L – [Catani, Hautmann '94]

$\mu_F^2 = Q^2$

F_L: $\quad 1 - \frac{1}{3}\, x + 2.13\, x^2 + 2.27\, x^3 + 0.434\, x^4 + \ldots$

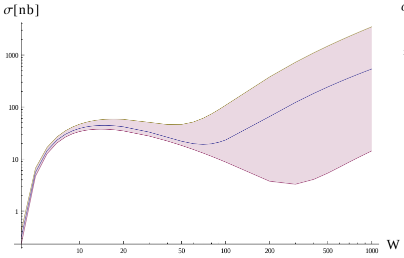
$J/\Psi, \Upsilon$: $\quad 1 - 1.39\, x + 2.61\, x^2 + 0.481\, x^3 - 4.96\, x^4 + \ldots$

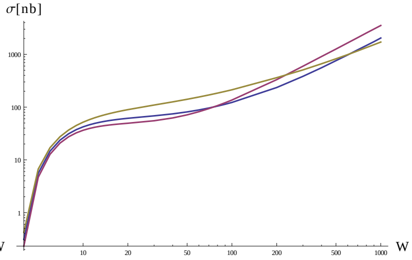
Resummed amplitude for J/ψ



Imaginary part of the amplitude for photoproduction of heavy mesons as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2$

Resummed cross section for J/ψ





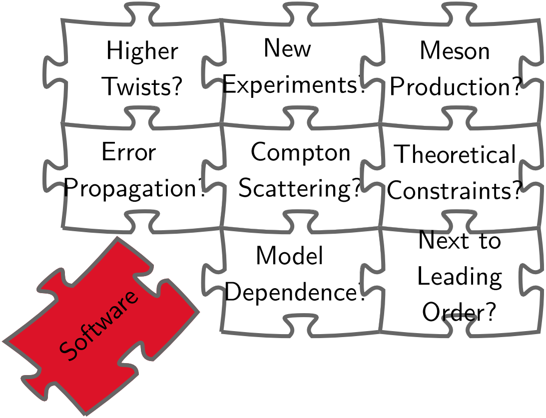
NLO Resumed

Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$

Summary

- GDPs enter factorization theorems for hard exclusive reactions in a similar manner as PDFs enter factorization theorem for DIS
- DVCS is a golden channel, a lot of new DVCS experiments planned - JLAB 12, COMPASS, EIC(?)
- GPDs in other exclusve processes - TCS, DVMP, photoproduction of heavy mesons...
- TCS already measured at JLAB 6 GeV, but much richer and more interesting kinematical region available after upgrade to 12 GeV
- Ultraperipheral collisions at hadron colliders opens a new way to measure GPDs,
- NLO corrections are very important: large for TCS; dramatic for VM photoproduction.
- High energy resummation needed for VM photoproduction (in progress).

PARTONS Project

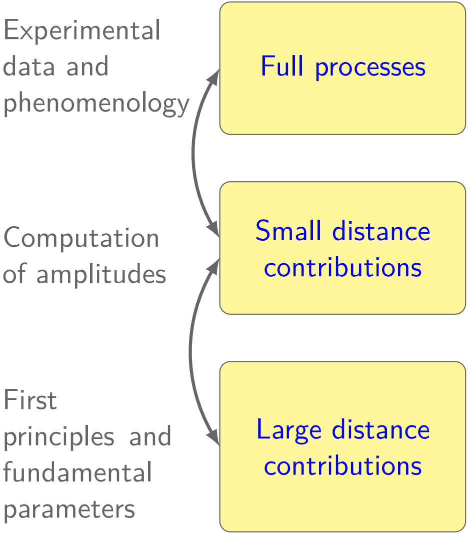


PARTONS Project

PARTONS

PARtonic
Tomography
Of
Nucleon
Software

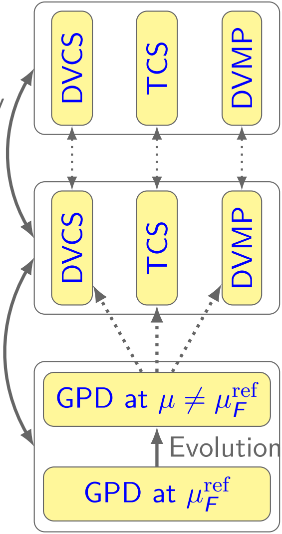
Experimental data and phenomenology	Full processes
Computation of amplitudes	Small distance contributions
First principles and fundamental parameters	Large distance contributions


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

Experimental data and phenomenology

Computation of amplitudes

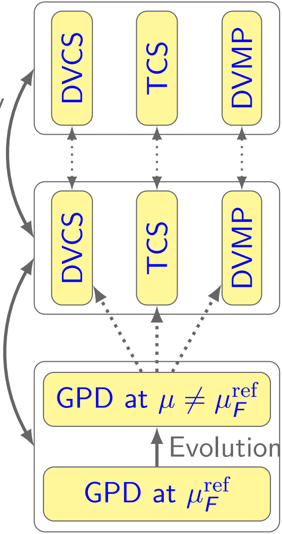
First principles and fundamental parameters



Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

Computing chain design.

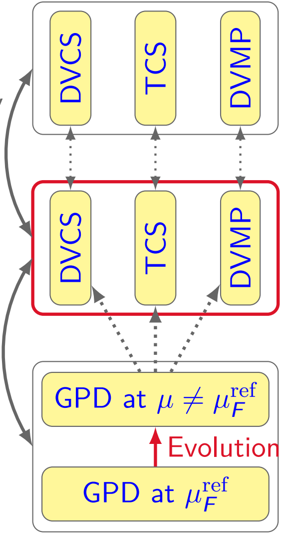
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

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

Computing chain design.

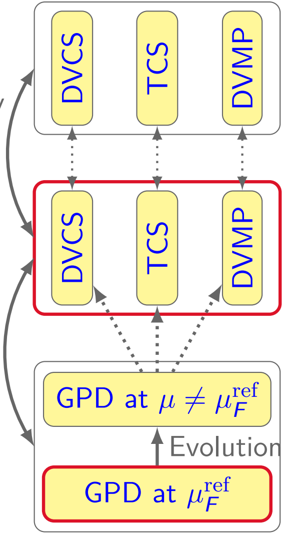
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

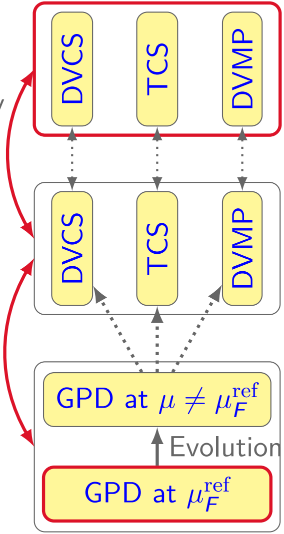
- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

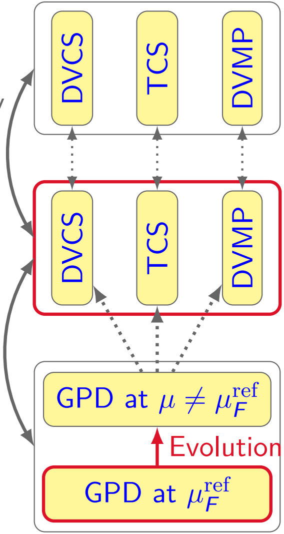
- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

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

Computing chain design.

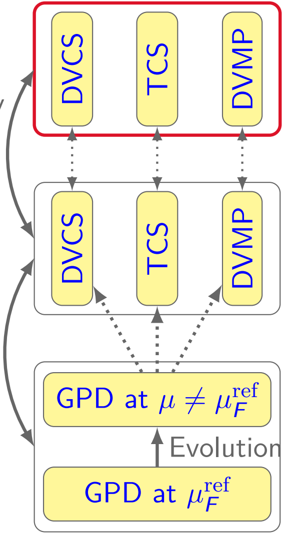
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters



- Many observables.
- Kinematic reach.

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

Status.

Currently: integration, tests, validation.

- 3 stages:
  1. Design.
  2. Integration and validation.
  3. Production.
- Flexible software architecture.
- 1 new physical development = 1 new module.
- What *can* be automated *will be* automated.
- Get ready for 12 GeV!

gpdEvolutionExample()

```
// Load QCD evolution module
EvolQCDModule* pEvolQCDModule = pModuleObjectFactory->
getEvolQCDModule( VinnikovEvolQCDModel::moduleID ) ;

// Configure QCD evolution module
pEvolQCDModule->setQcdOrderType( QCDOrderType::LO ) ;

// Load GPD module
GPDModule* pGK11Module =
pModuleObjectFactory->getGPDModule( GK11Model::moduleID ) ;

// Create kinematic configuration ( x, xi, t, MuF, MuR )
GPDKinematic gpdKinematic( 0.25, 0.29, -0.28, 1.82, 1.82 ) ;

// Compute GPD and store results
GPDOutputData results = pGPDService->
computeGPDModelWithEvolution( gpdKinematic, pGK11Module,
pEvolQCDModule, GPDComputeType::H ) ;

// Print results
std::cout << results.toString() << std::endl ;
```

GPD computing made simple.

Each line of code corresponds to a physical hypothesis.

gpdEvolutionExample()

```
// Load QCD evolution module
EvolQCDModule* pEvolQCDModule = pModul
getEvolQCDModule( VinnikovEvolQCDModel::n

// Configure QCD evolution module
pEvolQCDModule->setQcdOrderType( QCDO

// Load GPD module
GPDModule* pGK11Module =
pModuleObjectFactory->getGPDModule( GK1

// Create kinematic configuration ( x, xi , t, M
GPDKinematic gpdKinematic( 0.25, 0.29, -0.2

// Compute GPD and store results
GPDOutputData results = pGPDService->
computeGPDModelWithEvolution( gpdKinemat
pEvolQCDModule, GPDComputeType::H ) ;

// Print  results
std::cout << results.toString() << std::endl ;
```

Preliminary

Hu = 1.5435
Hu(-) = 2.04736
Hu(+) = 1.03964

Hd = 0.524068
Hd(-) = 1.00457
Hd(+) = 0.0435651

Hs = -0.539675
Hs(-) = 0
Hs(+) = -1.07935

Hg = -0.3086

Members and areas of expertise.

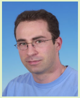
Collaborations at the national and international levels.

Development team


B. Berthou

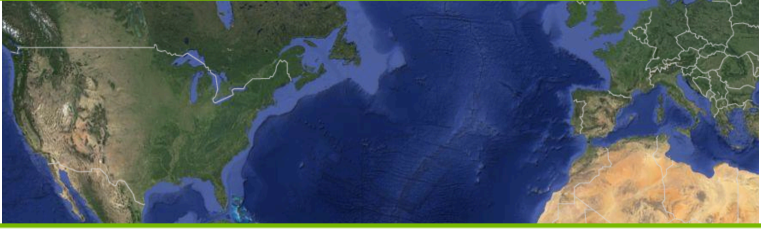

C. Mezrag


H. Moutarde


F. Sabatié


J. Wagner


P. Sznajder



IPN and LPT (Orsay), Irfu (Saclay) and CPhT (Polytechnique)

Experimental data analysis	Perturbative QCD
World data fits	GPD modeling