Exclusive heavy vector meson production in UPCs: hopes and troubles

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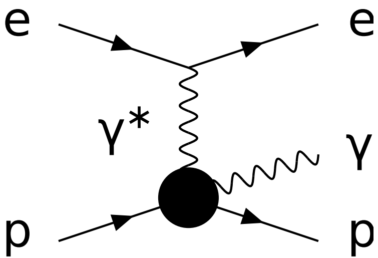
From initial gluons . . . , Universite Paris-Saclay, 24-25 October 2022

DVCS

The simplest and best known process is Deeply Virtual Compton Scattering:
$e\,p \to e\,p\,\gamma$



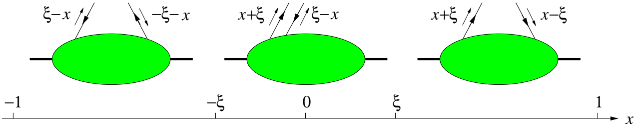
Factorization into **GPDs** and perturbative coefficient function - on the level of **amplitude**.

DIS :	$\sigma =$ **PDF** $\otimes$ **partonic cross section**
DVCS :	$\mathcal{M} =$ **GPD** $\otimes$ **partonic amplitude**

GPD definition.

$$
\begin{aligned}
F^q &= \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-}\, \langle p'|\, \bar{q}(-\frac{1}{2}z)\,\gamma^+ q(\frac{1}{2}z)\,|p\rangle\Big|_{z^+=0,\,\mathbf{z}=0} \\
&= \frac{1}{2P^+}\left[H^q(x,\xi,t)\,\bar{u}(p')\gamma^+u(p) + E^q(x,\xi,t)\,\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right], \\
F^g &= \frac{1}{P^+}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-}\, \langle p'|\, G^{+\mu}(-\frac{1}{2}z)\, G_\mu{}^+(\frac{1}{2}z)\;|p\rangle\Big|_{z^+=0,\,\mathbf{z}=0} \\
&= \frac{1}{2P^+}\left[H^g(x,\xi,t)\,\bar{u}(p')\gamma^+u(p) + E^g(x,\xi,t)\,\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right],
\end{aligned}
$$

- interpretation, ERBL, DGLAP



- Factorization scale dependance,
- Three variables x, ξ, t .

GPD - properties,

- Forward limit:

$$
\begin{aligned}
H^q(x,0,0) &= q(x)\,, \quad \text{for} \quad x>0\,,\\
H^q(x,0,0) &= -\bar{q}(x)\,, \quad \text{for} \quad x<0\,,\\
H^g(x,0,0) &= xg(x)\,,
\end{aligned}
$$

similarly for polarized disributions and PDFs.

- Reduction to form factors:

$$
\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t), \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t),
$$

where the Dirac and Pauli form factors

$$
\langle p'|\,\bar{q}(0)\gamma^\mu q(0)\,|p\rangle = \bar{u}(p')\left[F_1^q(t)\,\gamma^\mu + F_2^q(t)\,\frac{i\sigma^{\mu\alpha}\Delta_\alpha}{2m}\right]u(p),
$$

- positivity, polynomiality

Energy momentum tensor and D-term

- Ji sum rule:

$$\lim_{t\to 0}\int_{-1}^{1} dx\; x\,[H_f(x,\xi,t)+E_f(x,\xi,t)] = 2J_f$$

  where J_f is fraction of the proton spin carried by quark f (including spin and orbital angular momentum).

- Gravitational Form Factors:

$$\langle p',s'|\hat{T}^a_{\mu\nu}(x)|p,s\rangle = \bar{u}'\Big[A^a(t)\,\frac{P_\mu P_\nu}{m} + J^a(t)\,\frac{i\,P_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{2m} + \mathbf{D^a(t)}\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\,\bar{c}^a(t)g_{\mu\nu}\Big]u\;e^{i(p'-p)x}.$$

- Form Factor $\mathbf{D(t)}$ connected to pressure
- fixed-t dispersion relation for DVCS

$$Re\mathcal{H}(\xi,t) = \mathbf{\Delta(t)} + \mathrm{P.V.}\int_0^1 \frac{1}{\pi} Im\mathcal{H}(x,t)\left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x}\right)\mathrm{d}x\,.$$

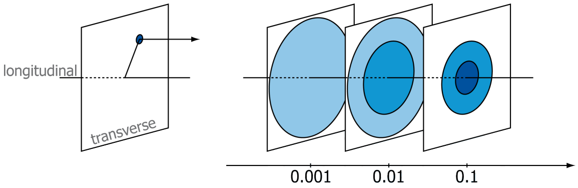
  with some approximations: $\mathbf{\Delta(t)} \sim \sum_q \mathbf{D^q(t)} + \ldots$ First attempts made (Burkert et al, Nature 557 (2018)), but difficult to perform in a model independent way.

Impact parameter representation

At $\xi = 0 \quad \Rightarrow \quad -t = \Delta_\perp^2$:

$$H(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H(x, 0, -\mathbf{\Delta}_\perp)$$

can be interpreted as probability of finding a parton with longitudinal momentum fraction x at a given $\mathbf{b}_\perp$.



DVCS data

Table 3: DVCS data used in this analysis.

No.	Collab.	Year	Ref.	Observable		Kinematic dependence	No. of points used / all
1	HERMES	2001	13	A_{LU}^{+}		ϕ	10 / 10
2		2006	119	$A_{C}^{\cos i\phi}$	$i=1$	t	4 / 4
3		2008	120	$A_{C}^{\cos i\phi}$	$i=0,1$	$x_{\rm Bj}$	18 / 24
				$A_{UT,\rm DVCS}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0$		
				$A_{UT,\rm I}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0,1$		
				$A_{UT,\rm I}^{\cos(\phi-\phi_S)\sin i\phi}$	$i=1$		
4		2009	121	$A_{LU,\rm I}^{\sin i\phi}$	$i=1,2$	$x_{\rm Bj}$	35 / 42
				$A_{LU,\rm DVCS}^{\sin i\phi}$	$i=1$		
				$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
5		2010	122	$A_{UL}^{+,\sin i\phi}$	$i=1,2,3$	$x_{\rm Bj}$	18 / 24
				$A_{LL}^{+,\cos i\phi}$	$i=0,1,2$		
6		2011	123	$A_{LT,\rm DVCS}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1$	$x_{\rm Bj}$	24 / 32
				$A_{LT,\rm DVCS}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1$		
				$A_{LT,\rm I}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1,2$		
				$A_{LT,\rm I}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1,2$		
7		2012	124	$A_{LU,\rm I}^{\sin i\phi}$	$i=1,2$	$x_{\rm Bj}$	35 / 42
				$A_{LU,\rm DVCS}^{\sin i\phi}$	$i=1$		
				$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
8	CLAS	2001	14	$A_{LU}^{-,\sin i\phi}$	$i=1,2$	—	0 / 2
9		2006	125	$A_{UL}^{-,\sin i\phi}$	$i=1,2$	—	2 / 2
10		2008	126	A_{LU}^{-}		ϕ	283 / 737
11		2009	127	A_{LU}^{-}		ϕ	22 / 33
12		2015	128	A_{LU}^{-}, A_{UL}^{-}, A_{LL}^{-}		ϕ	311 / 497
13		2015	129	$d^4\sigma_{UU}^{-}$		ϕ	1333 / 1933
14	Hall A	2015	117	$\Delta d^4\sigma_{LU}^{-}$		ϕ	228 / 228
15		2017	118	$\Delta d^4\sigma_{LU}^{-}$		ϕ	276 / 358
16	COMPASS	2018	56	b		—	1 / 1
						SUM:	2600 / 3970

DVCS data

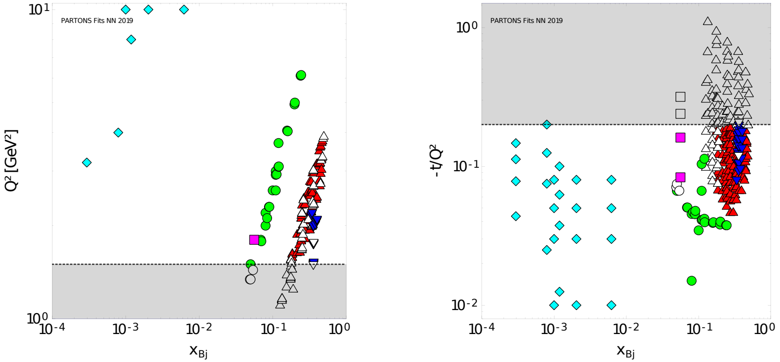


Figure: Coverage of the (x_{Bj}, Q^2) (left) and $(x_{\mathrm{Bj}}, -t/Q^2)$ (right) phase-spaces by the experimental data used in DVCS CFFs fit. The data come from the Hall A (▼, ▽), CLAS (▲, △), HERMES (●, ○), COMPASS (■, □) and HERA H1 and ZEUS (♦, ◊) experiments. The gray bands (open markers) indicate phase-space areas (experimental points) being excluded from this analysis due to the cuts.

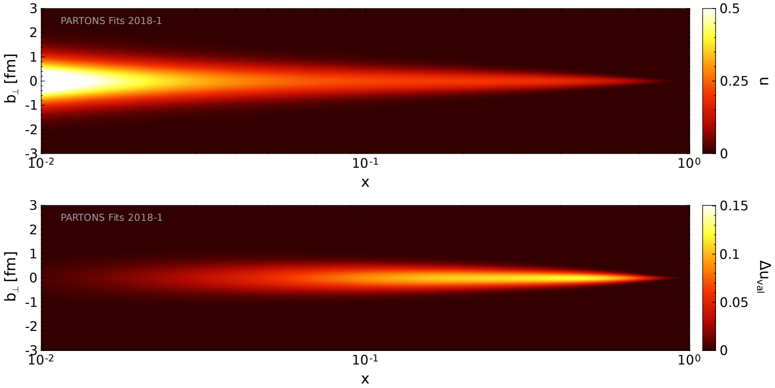


Figure: Position of up quarks in an unpolarized proton (upper plot) and longitudinal polarization of those quarks in a longitudinally polarized proton (lower plot) as a function of the longitudinal momentum fraction x. For the lower plot only the valence contribution is shown.

results for CFFs

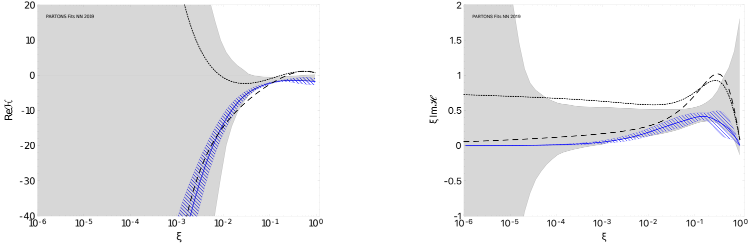


Figure: Real (left) and imaginary (right) parts of the CFF $\mathcal{H}$ as a function of ξ for $t = -0.3\ \mathrm{GeV}^2$ and $Q^2 = 2\ \mathrm{GeV}^2$. The blue solid line surrounded by the blue hatched band denotes the result of our previous analysis.

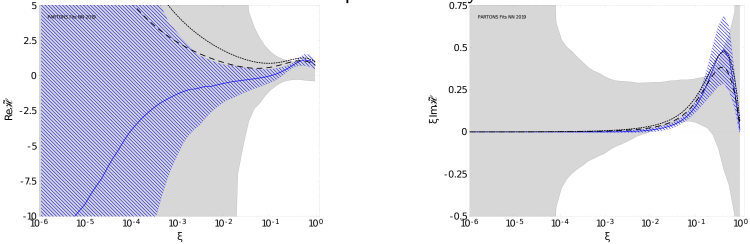
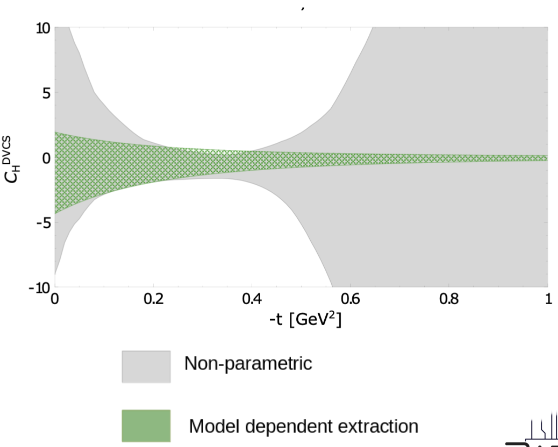


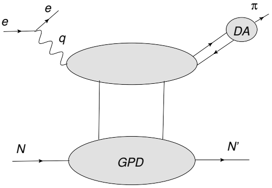
Figure: Real (left) and imaginary (right) parts of the CFF $\widetilde{\mathcal{H}}$ as a function of ξ for $t = -0.3\ \mathrm{GeV}^2$ and $Q^2 = 2\ \mathrm{GeV}^2$.

Subtraction Constant

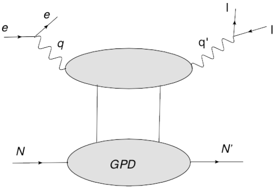


Other channels - what else is needed

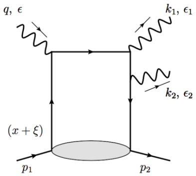
- flavour separation:
  - DVCS on neutron
  - Deeply Virtual Meson Production (also with CC)
- $x = \xi$ line, deconvolution problem:
  - Double Deeply Virtual Compton Scattering (DDVCS) - Solid, HL-CLAS, EIC, JLAB20+
  - Hard photo- and electroproduction of a diphoton with a large invariant mass
- Universality checks, sensitivity to NLO effects:
  - **Timelike Compton Scattering (TCS)**
- Sensivity to gluons:
  - **Photoproduction of heavy mesons**



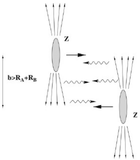
(c)



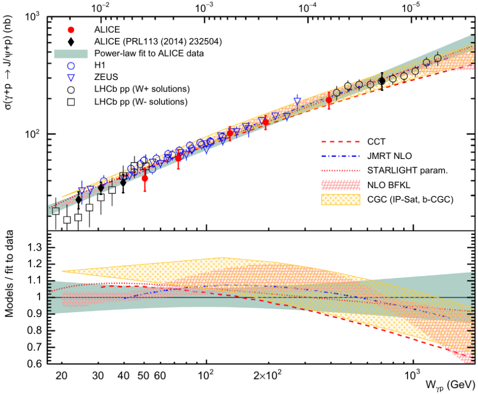
(c)



Photoproduction proceses in Ultraperipheral Collisions:

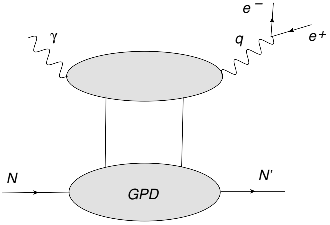


$$\sigma^{AB} = \int dk_A \frac{dn^A}{dk_A} \sigma^{\gamma B}(W_A(k_A)) + \int dk_B \frac{dn^B}{dk_B} \sigma^{\gamma A}(W_B(k_B))$$



TCS - same final state as J/ψ

Berger, Diehl, Pire, 2002



(b)

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

First measurement: P. Chatagnon et al. (CLAS), PRL 127, 262501 (2021)

PHYSICAL REVIEW LETTERS **127,** 262501 (2021)

First Measurement of Timelike Compton Scattering

P. Chatagnon,[20,*] S. Niccolai,[20] S. Stepanyan,[36] M. J. Amaryan,[29] G. Angelini,[12] W. R. Armstrong,[1] H. Atac,[35] C. Ayerbe Gayoso,[44,†] N. A. Baltzell,[36] L. Barion,[13] M. Bashkanov,[42] M. Battaglieri,[36,15] I. Bedlinskiy,[25] F. Benmokhtar,[7] A. Bianconi,[39,19] L. Biondo,[15,18,40] A. S. Biselli,[8] M. Bondi,[15] F. Bossù,[3] S. Boiarinov,[36] W. J. Briscoe,[12] W. K. Brooks,[37,36]

Gluon GPDs in the UPC production of heavy mesons

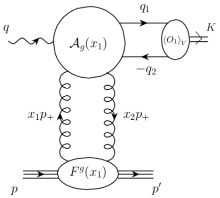


Figure 1: Kinematics of heavy vector meson photoproduction.

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

The amplitude $\mathcal{M}$ is given by factorization formula:

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

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

where m is a pole mass of heavy quark, $\langle O_1\rangle_V$ is given by NRQCD through leptonic meson decay rate.

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

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

- Single Transverse Spin Asymmetry:

$$\mathcal{A}_{\mathcal{N}}^{\gamma} \sim \mathrm{Im}\,(\mathcal{H}^g \mathcal{E}^{g\star})$$

sensitive to poorly known GPD E^g, important for the spin rule.

Single Transverse Spin Asymmetry

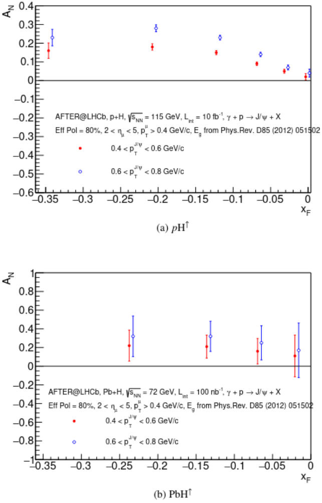
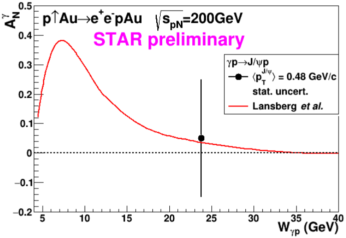
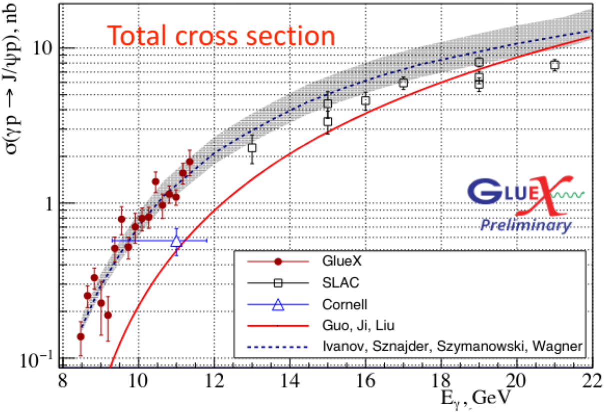


Figure 7: STSAs in the exclusive J/ψ photo-production in UPCs with a proton beam (a) and a lead beam (b) on an transversely polarised hydrogen target.



Low energy



Total cross section
$\sigma(\gamma p \to J/\psi p)$, nb
10
1
10^{-1}
8
10
12
14
16
18
20
22
E_γ, GeV
GlueX
Preliminary
GlueX
SLAC
Cornell
Guo, Ji, Liu
Ivanov, Sznajder, Szymanowski, Wagner

Troubles

- Odderon (in p-p)
- Factorization scale dependence

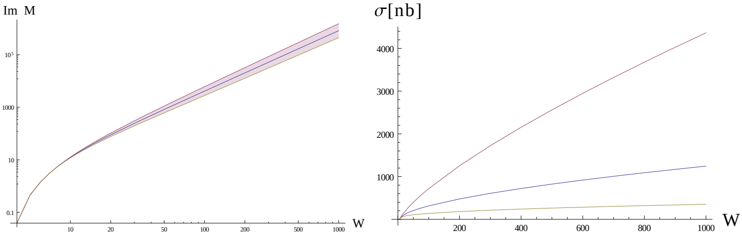


Figure: (left) Imaginary part of the amplitude $\mathcal{M}$ and (right) photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$.

Photoproduction amplitude and cross section - LO and NLO.

NLO/LO for large W:

$$\sim \frac{\alpha_S(\mu_R)N_c}{\pi}\ln\left(\frac{1}{\xi}\right)\ln\left(\frac{\frac{1}{4}M_V^2}{\mu_F^2}\right)$$

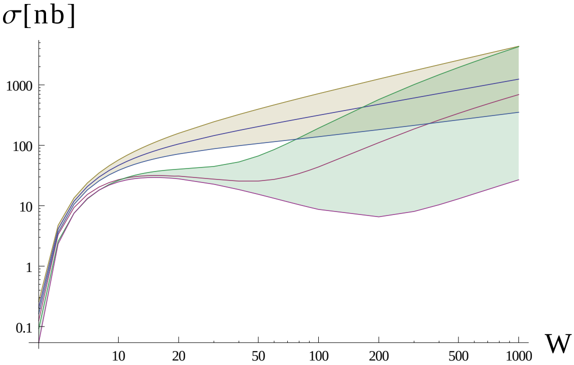


Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO

Scale fixing

Flett, Jones, Martin, Ryskin, Teubner, PRD106 (2022)

- Scale fixed to $\mu_F = \mu_R = 1/2 M_V$
- Reduction (for small x) of GPD to PDF and skewing correction

FLETT, JONES, MARTIN, RYSKIN, and TEUBNER PHYS. REV. D **106,** 074021 (2022)

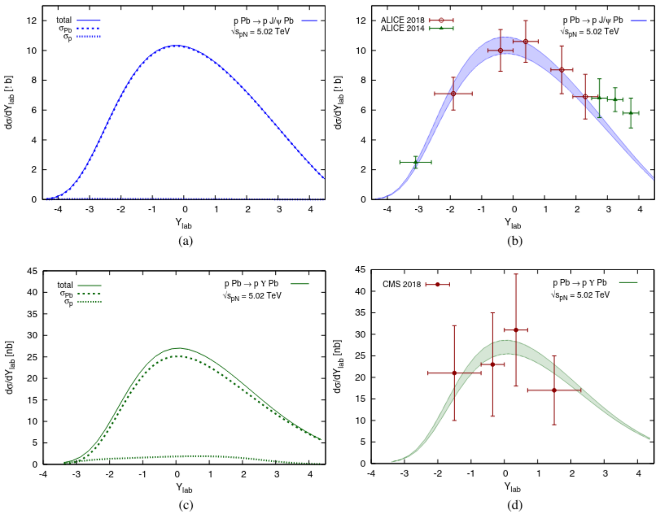


FIG. 6. Theoretical predictions for coherent exclusive J/ψ and Υ photoproduction rapidity differential cross sections in p-Pb

Resummation

D.Yu. Ivanov, Blois 2007 Conference arXiv:0712.3193

At higher orders powers of energy log are generated

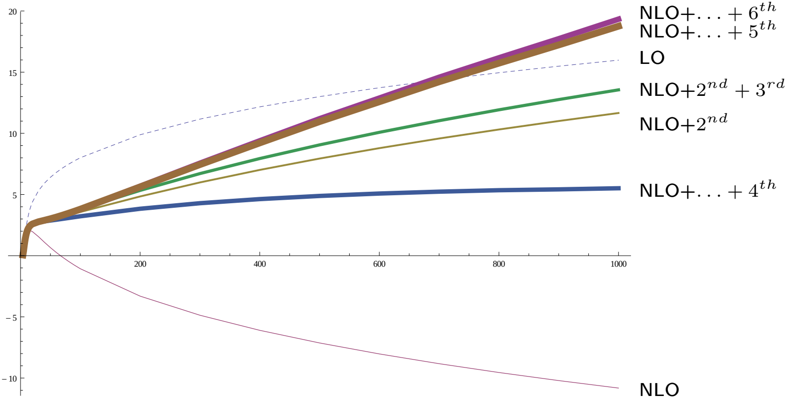
$$\mathcal{I}m A^g \sim H^g(\xi,\xi) + \int_\xi^1 \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1} \frac{x}{\xi}$$

$C_n(L)$ - 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.

Resummed amplitude for J/ψ

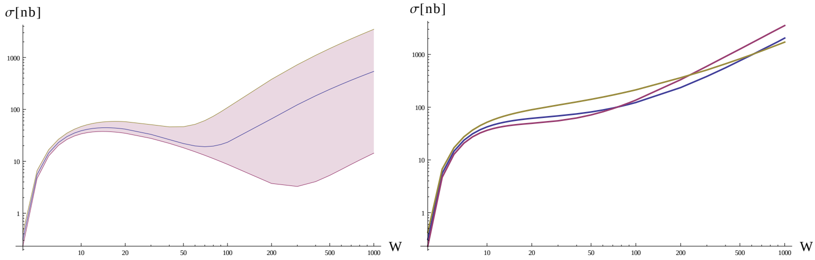
Ivanov, Pire, Szymanowski, Wagner, EPJ Web Conf. 112 (2016) 01020, arXiv:1601.07338



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

Ivanov, Pire, Szymanowski, Wagner, EPJ Web Conf. 112 (2016) 01020, arXiv:1601.07338



NLO

Resumed

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

Remarks: only forward evolution, $\mu_R = Q$.

Summary

- GPDs enable 3 dimensional "tomography" of hadrons, spin decomposition etc.
- Heavy meson production sensitive to gluon GPDs
- Measured in UPC at LHC and RHIC
- J/ψ photoproduction amplitude unstable wrt higher order corrections
  - factorization scale choice ?
  - resummation ?
  - situation better for Υ (smaller α_S, larger ξ)
- The same final state in Timelike Compton Scattering.