Diffraction and semi-exclusive physics at AFTER

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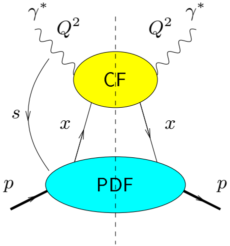
Extensions from DIS

- DIS: inclusive process $\longrightarrow$ forward amplitude ($t = 0$) *(optical theorem)*

  (DIS: Deep Inelastic Scattering)

  ex: $e^{\pm}p \rightarrow e^{\pm}X$ at HERA

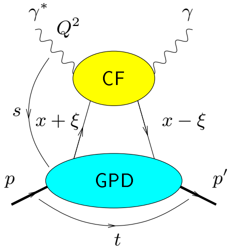


Structure Function

= Coefficient Function (hard) $\otimes$ Parton Distribution Function (soft)

- DVCS: exclusive process $\longrightarrow$ non forward amplitude ($-t \ll s = W^2$)

  (DVCS: Deep Vitual Compton Scattering)



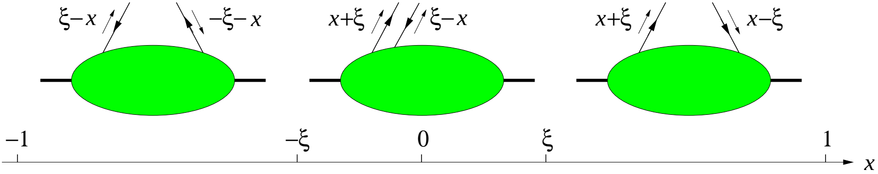
Amplitude

= Coefficient Function (hard) $\otimes$ Generalized Parton Distribution (soft)

Müller et al. '91 - '94; Radyushkin '96; Ji '97

Twist 2 GPDs

Physical interpretation for GPDs



Emission and reabsoption of an antiquark
∼ PDFs for antiquarks
DGLAP-II region

Emission of a quark and emission of an antiquark
∼ meson exchange
ERBL region

Emission and reabsoption of a quark
∼ PDFs for quarks
DGLAP-I region

Twist 2 GPDs

Classification of twist 2 GPDs

- For quarks, one should distinguish the exchanges
  - without helicity flip (chiral-even Γ' matrices): 4 chiral-even GPDs:
    $H^q \xrightarrow{\xi=0,t=0}$ PDF q, E^q, $\tilde{H}^q \xrightarrow{\xi=0,t=0}$ polarized PDFs Δq, $\tilde{E}^q$

$$F^q = \frac{1}{2}\int \frac{dz^+}{2\pi}\, e^{ixP^-z^+} \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, \gamma^- q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z^-=0,\, z_\perp=0}$$

$$= \frac{1}{2P^-}\left[H^q(x,\xi,t)\, \bar{u}(p')\gamma^- u(p) + E^q(x,\xi,t)\, \bar{u}(p')\frac{i\,\sigma^{-\alpha}\Delta_\alpha}{2m} u(p)\right],$$

$$\tilde{F}^q = \frac{1}{2}\int \frac{dz^+}{2\pi}\, e^{ixP^-z^+} \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, \gamma^-\gamma_5\, q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z^-=0,\, z_\perp=0}$$

$$= \frac{1}{2P^-}\left[\tilde{H}^q(x,\xi,t)\, \bar{u}(p')\gamma^-\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\, \bar{u}(p')\frac{\gamma_5\,\Delta^-}{2m} u(p)\right].$$

  - with helicity flip (chiral-odd Γ' mat.): 4 chiral-odd GPDs:
    $H_T^q \xrightarrow{\xi=0,t=0}$ quark transversity PDFs $\Delta_T q$, E_T^q, $\tilde{H}_T^q$, $\tilde{E}_T^q$

$$\frac{1}{2}\int \frac{dz^+}{2\pi}\, e^{ixP^-z^+} \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, i\,\sigma^{-i}\, q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z^-=0,\, z_\perp=0}$$

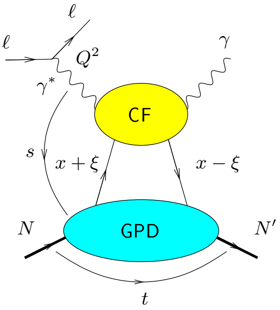
$$= \frac{1}{2P^-}\bar{u}(p')\left[H_T^q\, i\sigma^{-i} + \tilde{H}_T^q\,\frac{P^-\Delta^i - \Delta^- P^i}{m^2} + E_T^q\,\frac{\gamma^-\Delta^i - \Delta^-\gamma^i}{2m} + \tilde{E}_T^q\,\frac{\gamma^- P^i - P^-\gamma^i}{m}\right]$$

Twist 2 GPDs

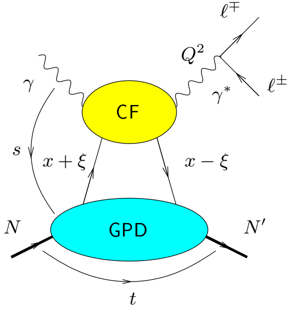
Classification of twist 2 GPDs

- analogously, for gluons:
  - 4 gluonic GPDs without helicity flip:
    $H^g \xrightarrow{\xi=0, t=0}$ PDF $x\, g$
    E^g
    $\tilde{H}^g \xrightarrow{\xi=0, t=0}$ polarized PDF $x\, \Delta g$
    $\tilde{E}^g$
  - 4 gluonic GPDs with helicity flip:
    H_T^g
    E_T^g
    $\tilde{H}_T^g$
    $\tilde{E}_T^g$
    (no forward limit reducing to gluons PDFs here: a change of 2 units of helicity cannot be compensated by a spin 1/2 target)

DVCS and TCS



Deeply Virtual Compton Scattering
$lN \to l'N'\gamma$

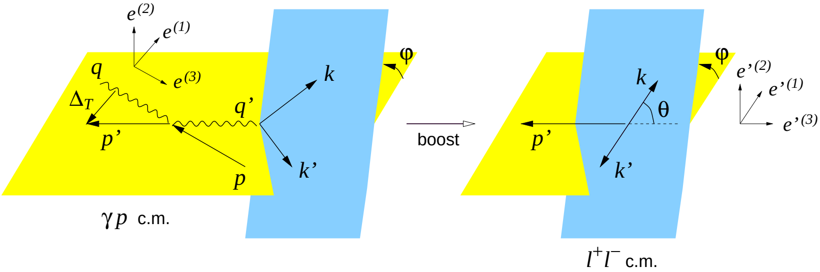


Timelike Compton Scattering
$\gamma N \to l^+l^-N'$

- TCS versus DVCS:
  - universality of the GPDs
  - another source for GPDs (special sensitivity on real part)
  - spacelike-timelike crossing and understanding the structure of the NLO corrections
- Where to measure TCS? In Ultra Peripheral Collisions AFTER is good place, since:
  - a very large cms energy is not necessary
  - a high luminosity is needed
  - it would be complementary to JLab and COMPASS programs

Coordinates for TCS

Kinematical variables and coordinate axes



Berger, Diehl, Pire, 2002

The Bethe-Heitler contribution

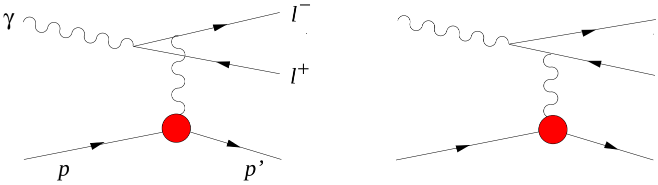
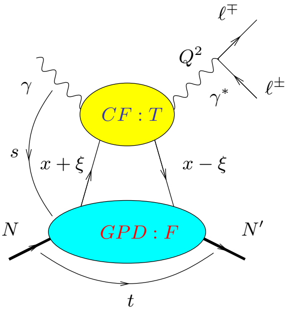


Figure: The Feynman diagrams for the Bethe-Heitler amplitude.

$$\frac{d\sigma_{BH}}{dQ'^2 dt\, d\cos\theta} \approx 2\alpha^3 \frac{1}{-t\, Q'^4} \frac{1+\cos^2\theta}{1-\cos^2\theta} \left(F_1(t)^2 - \frac{t}{4M_p^2} F_2(t)^2 \right),$$

For small θ BH contribution becomes very large

The Compton contribution



Amplitude

$$\mathcal{A}^{\mu\nu} = g_T^{\mu\nu}\,\mathcal{F}(\xi,t)$$

given in terms of Compton Form Factors:

$$\mathcal{F}(\xi,t) \quad = \quad \int_{-1}^{1} dx\, T(x,\xi,Q')\, F(x,\xi,t)$$

Interference

Interference part of the cross-section

- Consider $\gamma p \to \ell^+ \ell^- \, p$ with unpolarized protons and photons
- At leading order

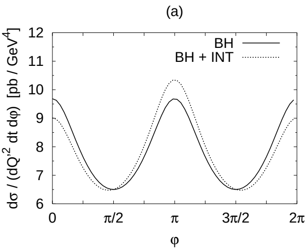
$$\frac{d\sigma_{INT}}{dQ'^2 \, dt \, d\cos\theta \, d\varphi} \sim \cos\varphi \; \mathrm{Re}\, \mathcal{H}(\xi, t)$$

  - linear in GPD's
  - odd under exchange of the ℓ^+ and ℓ^- momenta $(\varphi \leftrightarrow \pi + \varphi)$

$\Rightarrow$ angular dist. of $\ell^+\ell^-$ pair = good tool to study the interference term

Berger, Diehl, Pire, 2002

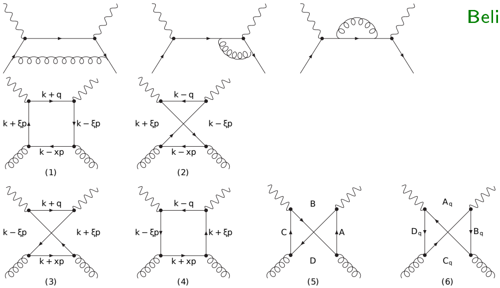
- B-H dominant for small energies



- B-H is negligible at HERA energies

TCS at NLO

One loop contributions



Belitsky, Mueller, Niedermeier, Schafer, Phys.Lett.B474, 2000

Pire, Szymanowski, Wagner Phys.Rev.D83, 2011

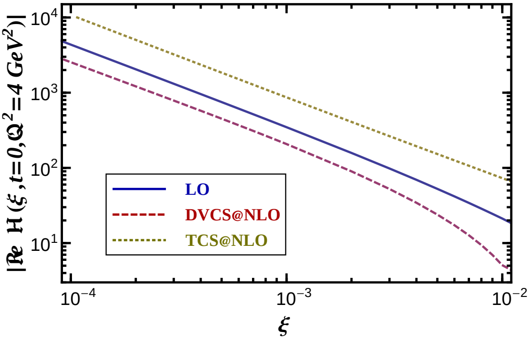
$$\mathcal{A}^{\mu\nu} = g_T^{\mu\nu} \int_{-1}^{1} dx \left[\sum_q^{n_F} T^q(x)\, F^q(x) + T^g(x)\, F^g(x) \right]$$

Renormalized coefficient functions given by:

$$T^q = C_0^q + C_1^q + C_{coll}^q \ln\left(\frac{Q^2}{\mu_F^2}\right)$$

$$T^g = C_1^g + C_{coll}^g \ln\left(\frac{Q^2}{\mu_F^2}\right)$$

TCS Compton Form Factors at NLO



The real part of CFF $\mathcal{H}$ vs. ξ with $\mu^2 = Q^2 = 4\ \mathrm{GeV}^2$ and $t = 0$

- solid: LO
- DVCS NLO: dashed
- TCS NLO: its (negative) value is shown as dotted curve

Resummation for Coefficient functions

Soft-collinear singularity of the coefficient function

- The Coefficient functions are singular in the limit $x \to \pm\xi$

$$T^q = C_0^q + C_1^q + C_{coll}^q \ln\left(\frac{|Q^2|}{\mu_F^2}\right)$$

with the LO and NLO quark coefficient functions:

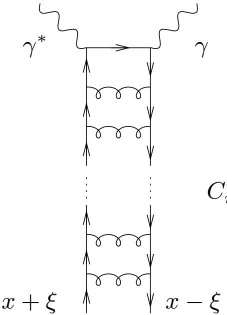
$$\begin{aligned} C_0^q &= e_q^2 \left(\frac{1}{x-\xi+i\varepsilon} + \frac{1}{x+\xi-i\varepsilon}\right) \\ C_1^q &= \frac{e_q^2\,\alpha_S\,C_F}{4\pi}\left\{\frac{1}{x-\xi+i\varepsilon}\left[\ln^2\left(1-\frac{x}{\xi}-i\varepsilon\right)+\ldots\right]\right. \\ &\left.+\frac{1}{x+\xi-i\varepsilon}\left[\ln^2\left(1+\frac{x}{\xi}-i\varepsilon\right)+\ldots\right]\right\}, \end{aligned}$$

- The singularity is typical of a soft-collinear singularities (cf. Sudakov form factors)

Resummation for Coefficient functions

Soft-collinear resummation effects for the coefficient function

- The resummation easier when using the axial gauge $p_1 \cdot A = 0$ $(p_\gamma \equiv p_1)$
- The dominant diagram are ladder-like



resommed formula (for DVCS), for $x \to \xi$:

$$C^q_{res}(x,\xi) \approx A \frac{e^{\sqrt{K C_F \alpha_s \, log^2(x-\xi)}} + e^{-\sqrt{K C_F \alpha_s \, log^2(x-\xi)}}}{x - \xi + i\epsilon}$$

T. Altinoluk, B. Pire, L. Szymanowski, S. Wallon, in preparation

- Moment space (Gegenbauer polynomials) ??
  unknown analog of the N-Mellin space for $x_{Bj} \to 1$ in DIS

Spin transversity in the nucleon

What is transversity?

- Tranverse spin content of the proton:

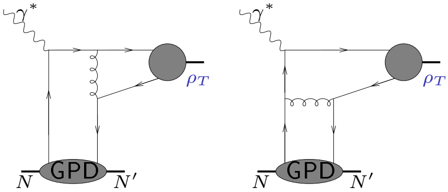
$$\begin{array}{ccc} |\uparrow\rangle_{(x)} & \sim & |\rightarrow\rangle + |\leftarrow\rangle \\ |\downarrow\rangle_{(x)} & \sim & |\rightarrow\rangle - |\leftarrow\rangle \\ \text{spin along } x & & \text{helicity state} \end{array}$$

- An observable sensitive to helicity spin flip gives thus access to the transversity $\Delta_T q(x)$, which is very badly known (first data have recently been obtained by COMPASS)
- The transversity GPDs are completely unknown
- Chirality: $q_\pm(z) \equiv \frac{1}{2}(1 \pm \gamma^5)q(z)$ with $q(z) = q_+(z) + q_-(z)$
  Chiral-even: chirality conserving
  $\bar{q}_\pm(z)\gamma^\mu q_\pm(-z)$ and $\bar{q}_\pm(z)\gamma^\mu\gamma^5 q_\pm(-z)$
  Chiral-odd: chirality reversing
  $\bar{q}_\pm(z) \cdot 1 \cdot q_\mp(-z)$, $\bar{q}_\pm(z) \cdot \gamma^5 \cdot q_\mp(-z)$ and $\bar{q}_\pm(z)[\gamma^\mu, \gamma^\nu]q_\mp(-z)$
- For a massless (anti)particle, chirality = (-)helicity
- Transversity is thus a chiral-odd quantity
- QCD and QED are chiral even $\Rightarrow \mathcal{A} \sim$ (Ch.-odd)$_1 \otimes$ (Ch.-odd)$_2$

Accessing transversity in the nucleon

How to get access to transversity?

- The dominant DA for ρ_T is of twist 2 and chiral-odd ($[\gamma^\mu, \gamma^\nu]$ coupling)
- Unfortunately $\gamma^* N^\uparrow \to \rho_T N' = 0$
  - this is true at any order in perturbation theory (i.e. corrections as powers of α_s), since this would require a transfer of 2 units of helicity from the proton: impossible! Collins, Diehl '00
  - diagrammatic argument at Born order:



vanishes: $\gamma^\alpha[\gamma^\mu, \gamma^\nu]\gamma_\alpha = 0$

Diehl, Gousset, Pire '99

Accessing transversity in the nucleon

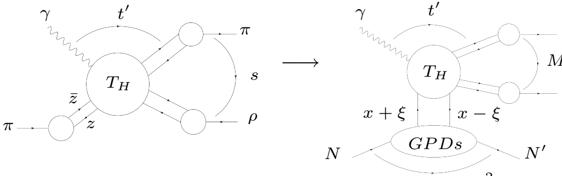
Can one circumvent this vanishing?

- This vanishing is true only a twist 2
- At twist 3 this process does not vanish
- However processes involving twist 3 DAs may face problems with factorization (end-point singularities: see later)
- The problem of classification of twist 3 chiral-odd GPDs is still open: Pire, Szymanowski, S.W. in progress, in the spirit of our Light-Cone Collinear Factorization framework recently developped (Anikin, Ivanov, Pire, Szymanowski, S. W.)

Accessing transversity in the nucleon

$\gamma N \to \pi^+ \rho_T^0 N'$ gives access to transversity

- Factorization à la Brodsky Lepage of $\gamma + \pi \to \pi + \rho$ at large s and fixed angle (i.e. fixed ratio $t'/s, u'/s$)
  $\Longrightarrow$ factorization of the amplitude for $\gamma + N \to \pi + \rho + N'$ at large $M^2_{\pi\rho}$

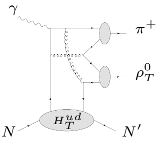


π^+ chiral-even twist 2 DA

ρ_T^0 chiral-odd twist 2 DA

$t \ll M^2_{\pi\rho}$ chiral-odd twist 2 GPD

- a typical non-vanishing diagram:



M. El Beiyad, P. Pire, M. Segond, L. Szymanowski, S.W Phys.Lett.B688:154-167,2010

see also, at large s, with $\mathbb{P}$omeron exchange:

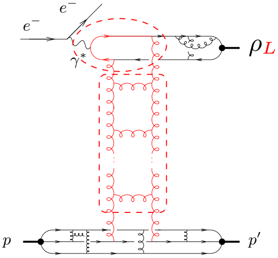
R. Ivanov, B. Pire, L. Symanowski, O. Teryaev '02

R. Enberg, B. Pire, L. Symanowski '06

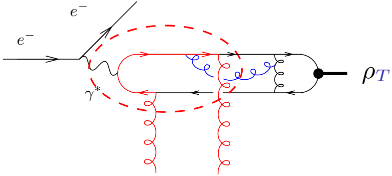
- These processes with 3 body final state can give access to all GPDs: $M^2_{\pi\rho}$ plays the role of the γ^* virtuality of usual DVCS (here in the time-like domain) JLab, COMPASS

Exclusive vector meson production at HERA

Diffractive exclusive process $e^- p \to e^- \, p \, \rho_{L,T}$



new



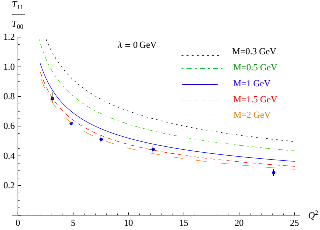
first description combining beyond leading twist

- collinear factorisation
- k_T −factorisation

I. V. Anikin, D .Yu. Ivanov, B. Pire, L. Szymanowski, S.W.

Phys.Lett.B682 (2010) 413-418
Nucl.Phys.B828 (2010) 1-68

HERA, LHeC project



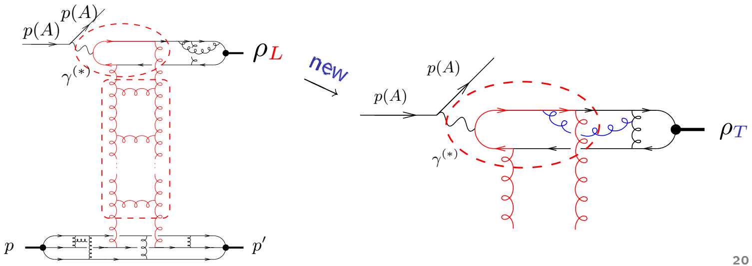
HERA (H1) data

I. V. Anikin, A. Besse, D .Yu. Ivanov, B. Pire, L. Szymanowski, S.W.
Phys.Rev. D84 (2011) 054004

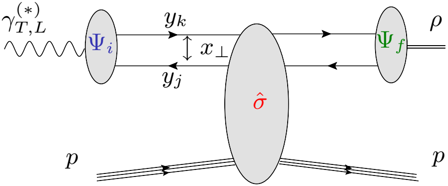
Exclusive vector meson production in UPC at LHC

Diffractive exclusive process $p(A)\,p \to p(A)\,p\,\rho_{L,T}$

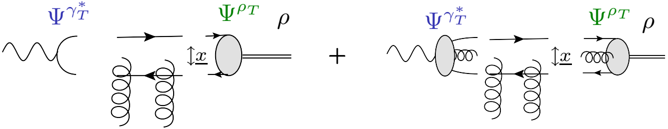
- For large impact parameter, γ exchange from $p(A)$ dominates the pure strong-interaction processes: Ultra-Peripheral Collisions
  - Coulomb pole for UPC $1/p_T^2$ *versus* $\exp(-B\,p_T^2)$ for strong interaction events
  - in heavy ion mode, detection of neutrons produced by the giant dipole resonance as a signal of UPC
  - γ, i.e. $\gamma^*(Q^2)$ with $Q^2 \simeq 0$ strongly dominates the Weizsäcker-Williams spectrum
  - Hard scale $= -t$
- Can one tag the outgoing p or A in order to get access to $\gamma^*(Q^2)$ with $Q^2 \gg \Lambda^2_{QCD}$ at LHC?



Dipole representation and saturation effects



- Initial Ψ_i and final Ψ_f states wave functions of projectiles
- Universal scattering amplitude $\hat{\sigma} \equiv \hat{\sigma}_{\text{dipole-target}}$ Golec-Biernat Wusthoff
  - color transparency for small $x_\perp$: $\hat{\sigma}_{\text{dipole-target}} \sim x_\perp^2$
  - saturation for large $x_\perp \sim 1/Q_{\text{sat}}$: $T < 1$
- The dipole representation is consistent with the twist 2 Collinear approximation
- New: still consistent with collinear factorization at higher twist order:



twist 2 + kinematical twist 3 genuine twist 3

A. Besse, L. Szymanowski, S. W., arXiv:1204.2281 [hep-ph]

γ case for large $|t|$? Phenomenology?

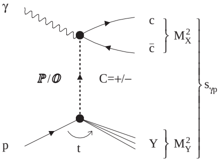
Finding the hard Odderon

- colorless gluonic exchange
  - $C = +1$: $\mathbb{P}$omeron, in pQCD described by BFKL equation
  - $C = -1$: $\mathbb{O}$dderon, in pQCD described by BJKP equation
- best but still weak evidence for $\mathbb{O}$: pp and $p\bar{p}$ data at ISR
- no evidence for perturbative $\mathbb{O}$

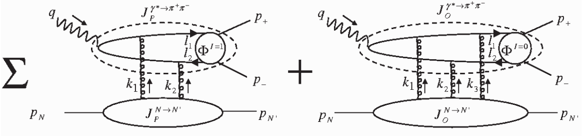
Finding the hard Odderon

$\mathbb{O}$ exchange much weaker than $\mathbb{P}$ $\Rightarrow$ two strategies in QCD

- consider processes, where $\mathbb{P}$ vanishes due to C-parity conservation:
  exclusive $\eta, \eta_c, f_2, a_2, ...$ in ep; $\gamma\gamma \to \eta_c\eta_c \sim |\mathcal{M}_{\mathbb{O}}|^2$
  exclusive $J/\Psi, \Upsilon$ in pp ($\mathbb{P}\mathbb{O}$ fusion, not $\mathbb{P}\mathbb{P}$))
- consider observables sensitive to the interference between $\mathbb{P}$ and $\mathbb{O}$
  (open charm in ep; $\pi^+\pi^-$ in ep)$\sim \mathrm{Re}\,\mathcal{M}_{\mathbb{P}}\mathcal{M}_{\mathbb{O}}^*$ $\Rightarrow$ observable linear in $\mathcal{M}_{\mathbb{O}}$



Brodsky, Rathsman, Merino 1999



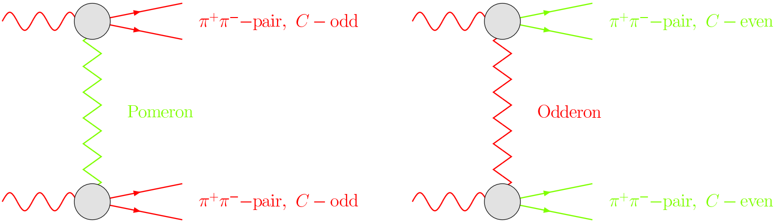
Ivanov, Nikolaev, Ginzburg 2001 in photo-production

Hägler, Pire, Szymanowski, Teryaev 2002 in electro-production

Finding the hard Odderon

$\mathbb{P} - \mathbb{O}$ interference in double UPC

$\mathbb{P} - \mathbb{O}$ interference in $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$



Hard scale $= t$

B. Pire, F. Schwennsen, L. Szymanowski, S. W.
Phys.Rev.D78:094009 (2008)

pb at LHC: pile-up!

Conclusion

Many exclusive studies could be performed using AFTER

- prospects depends on the detection facilities
- the main interest is the high luminosity, which is a prerequisite for rare processes
- TCS in UPC is very promising
- other processes could be measured with dedicated detectors