Hard exclusive processes

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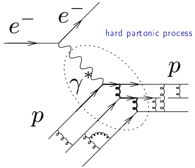
Exclusive processes are challenging

Can one extract information on hadrons using hard exclusive processes?

- The aim is to reduce the process to interactions involving a small number of *partons* (quarks, gluons), despite confinement
- This is possible if the considered process is driven by short distance phenomena ($d \ll 1\,\text{fm}$)
  $\Longrightarrow \alpha_s \ll 1$: Perturbative methods
- One should hit strongly enough a hadron
  Example: electromagnetic probe and form factor



τ electromagnetic interaction $\sim \tau$ parton life time after interaction
$\ll \tau$ caracteristic time of strong interaction

To get such situations in exclusive reactions is very challenging:
the cross section are very small

Counting rules

The partonic point of view... and its limitations

- Counting rules:

$$F_n(q^2) \simeq \frac{C}{(Q^2)^{n-1}} \qquad n = \text{number of minimal constituents: } \begin{cases} \text{meson: } n = 2 \\ \text{baryon: } n = 3 \end{cases}$$

Brodsky, Farrar '73

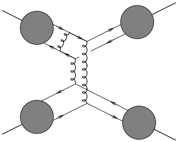
- Large angle (i.e. $s \sim t \sim u$ large) elastic processes $h_a\, h_b \to h_a\, h_b$

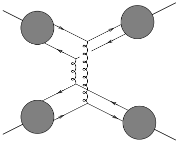
e.g. : $\pi\pi \to \pi\pi$ or $p\,p \to p\,p$

$$\frac{d\sigma}{dt} \sim \left(\frac{\alpha_S(p_\perp^2)}{s}\right)^{n-2} \quad n = \#\text{ of external fermionic lines } (n = 8 \text{ for } \pi\pi \to \pi\pi)$$

Brodsky, Lepage '81

Other contributions might be significant, even at large angle: e.g. $\pi\pi \to \pi\pi$





Brodsky Lepage mecanism: $\dfrac{d\sigma_{BL}}{dt} \sim \left(\dfrac{1}{s}\right)^6$

Lanshoff '74 mecanism: $\dfrac{d\sigma_L}{dt} \sim \left(\dfrac{1}{s}\right)^5$

absent with at least one $\gamma^{(*)}$ (point-like coupling)

From inclusive to exclusive processes

Experimental effort

- Inclusive processes are not $1/Q$ suppressed (e.g. DIS)
- Going from inclusive to exclusive processes is difficult
- High luminosity accelerators and high-performance detection facilities

HERA (H1, ZEUS), HERMES, JLab@6 GeV (Hall A, CLAS), BaBar, Belle, BEPC-II (BES-III)

future: LHC, COMPASS-II, JLab@12 GeV, Super-B, LHeC, EIC, ILC

- What to do, and where?
  - Proton form factor: JLab@6 GeV future: PANDA (timelike proton form factor through $p\bar{p} \to e^+e^-$)
  - e^+e^- in $\gamma^*\gamma$ single-tagged channel: Transition form factor $\gamma^*\gamma \to \pi$, exotic hybrid meson production BaBar, Belle, BES,...
  - Deep Virtual Compton Scattering (GPD)
    HERA (H1, ZEUS), HERMES, JLab@6 GeV
    future: JLab@12GeV, COMPASS-II, EIC
  - Non exotic and exotic hybrid meson electroproduction (GPD and DA), etc...
    NMC (CERN), E665 (Fermilab), HERA (H1, ZEUS), COMPASS, HERMES, CLAS (JLab)
  - TDA (PANDA at GSI)
  - TMDs (BaBar, Belle, COMPASS, ...)
  - Diffractive processes, including ultraperipheral collisions
    LHC (with or without fixed targets), ILC

From inclusive to exclusive processes

Theoretical efforts

Very important theoretical developments during the last decade

- Key words:

  DAs, GPDs, GDAs, TDAs ... TMDs
- Fundamental tools:
  - At medium energies (for a particle physicist!):

    JLab, HERMES, COMPASS, BaBar, Belle, PANDA, Super-B, EIC

    collinear factorization
  - At asymptotical energies:

    HERA, Tevatron, LHC, LHeC, ILC (EIC and COMPASS at the boundary)

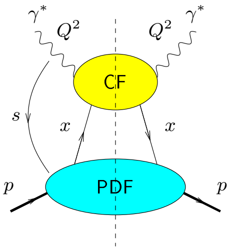
    k_T-factorization

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

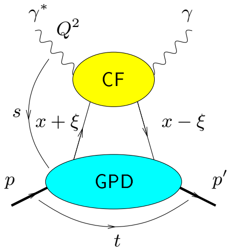


Structure Function

= 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)

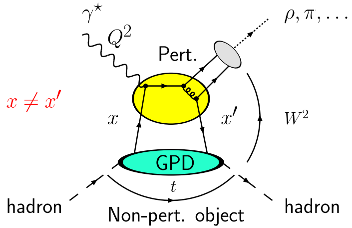
Müller et al. '91 - '94; Radyushkin '96; Ji '97

Extensions from DVCS

- Meson production: γ replaced by $\rho,\ \pi, \cdots$

Amplitude

= GPD (soft) $\otimes$ CF (hard) $\otimes$ Distribution Amplitude (soft)

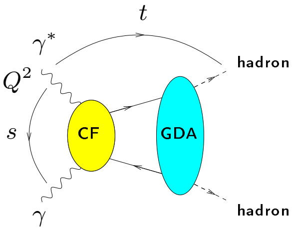


Collins, Frankfurt, Strikman '97; Radyushkin '97

- Crossed process: $s \ll -t$

Amplitude

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



Diehl, Gousset, Pire, Teryaev '98

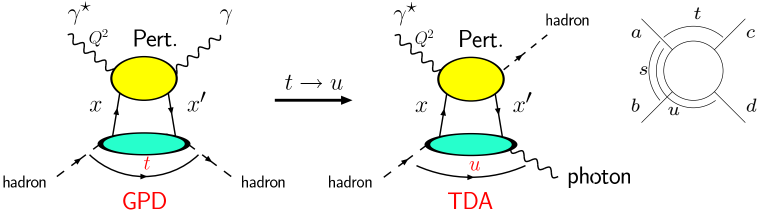
Extensions from DVCS

- Starting from usual DVCS, one allows: initial hadron $\neq$ final hadron (in the same octuplet): transition GPDs

Even less diagonal:

baryonic number $_{\text{(initial state)}}$ $\neq$ baryonic number $_{\text{(final state)}}$ $\rightarrow$ TDA

Example:



Pire, Szymanowski '05

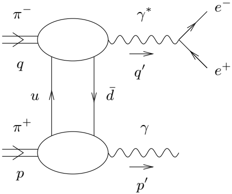
which can be further extended by replacing the outoing γ by any hadronic state

Amplitude	=	Transition Distribution Amplitude (soft)	$\otimes$	CF (hard)	$\otimes$	DA (soft)

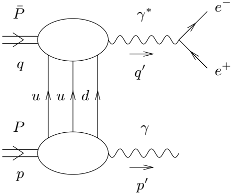
Lansberg, Pire, Szymanowski '06

Extensions from DVCS

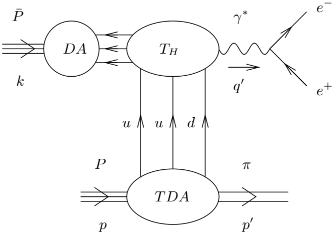
TDA at PANDA



TDA $\pi \to \gamma$



TDA $p \to \gamma$ at PANDA (forward scattering of $\bar{p}$ on a p probe)

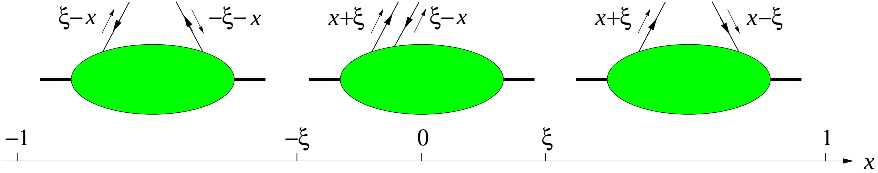


TDA $p \to \pi$ at PANDA (forward scattering of $\bar{p}$ on a p probe)

Spectral model for the $p \to \pi$ TDA: Pire, Semenov, Szymanowski '10

Twist 2 GPDs

Physical interpretation for GPDs



Emission and reabsoption of an antiquark $\sim$ PDFs for antiquarks DGLAP-II region	Emission of a quark and emission of an antiquark $\sim$ meson exchange ERBL region	Emission and reabsoption of a quark $\sim$ 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)

Spin transversity in the nucleon

What is transversity?

- Tranverse spin content of the proton:

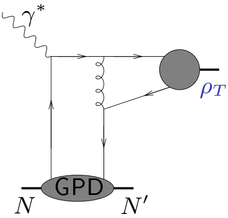
$$
\begin{array}{ccc}
|\uparrow\rangle_{(x)} & \sim & |\rightarrow\rangle + |\leftarrow\rangle \\
|\downarrow\rangle_{(x)} & \sim & |\rightarrow\rangle - |\leftarrow\rangle \\
\text{spin along } x & & \text{helicity state}
\end{array}
$$

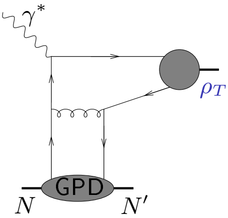
- An observable sensitive to helicity spin flip gives thus access to the transversity $\Delta_T q(x)$, which is very badly known (first data have recently been obtained by COMPASS)
- The transversity GPDs are completely unknown
- Chirality: $q_\pm(z) \equiv \frac{1}{2}(1 \pm \gamma^5) q(z)$ with $q(z) = q_+(z) + q_-(z)$
  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 $\Rightarrow \mathcal{A} \sim (\text{Ch.-odd})_1 \otimes (\text{Ch.-odd})_2$

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

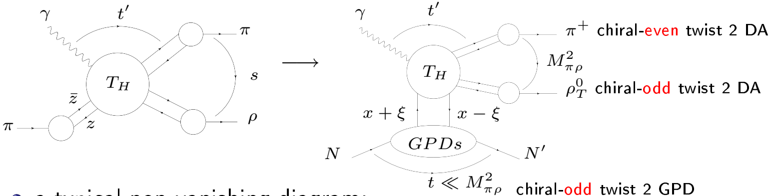
Can one circumvent this vanishing?

- 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 framework recently developped:
  Light-Cone Collinear Factorization
  Anikin, Ivanov, Pire, Szymanowski, S. W.
  Phys. Lett. B682:413-418, 2010; Nucl.Phys. B 828:1-68, 2010

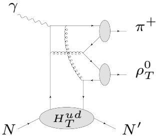
Accessing transversity in the nucleon

$\gamma N \to \pi^+ \rho^0_T N'$ 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 $M^2_{\pi\rho}$



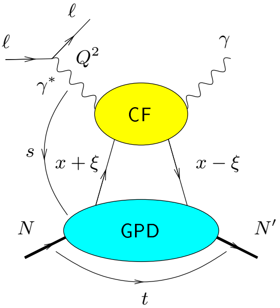
- a typical non-vanishing diagram:



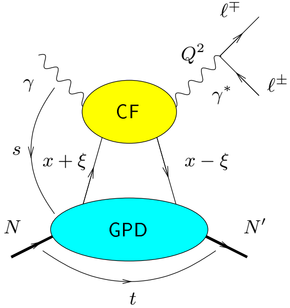
M. El Beiyad, P. Pire, M. Segond, L. Szymanowski, S.W
Phys.Lett.B688:154-167,2010
see also, at large s, with $\mathbb{P}$omeron exchange:
R. Ivanov, B. Pire, L. Symanowski, O. Teryaev '02
R. Enberg, B. Pire, L. Symanowski '06

- 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

DVCS and TCS



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

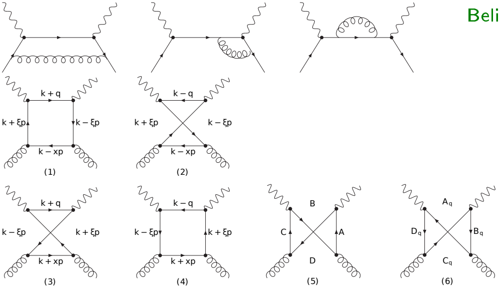


Timelike Compton Scattering
$\gamma N \to l^+l^-N'$

- 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
  LHC, JLab, COMPASS, AFTER

DVCS and TCS at NLO

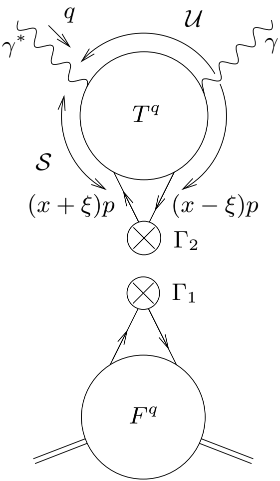
One loop contributions



Belitsky, Mueller, Niedermeier, Schafer,
Phys.Lett.B474, 2000
Pire, Szymanowski, Wagner
Phys.Rev.D83, 2011

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

Resummations effects are expected



- The renormalized quark coefficient functions T^q is

$$T^q = C_0^q + C_1^q + C_{coll}^q \log\frac{|Q^2|}{\mu_F^2}$$

$$C_0^q = e_q^2\left(\frac{1}{x-\xi+i\varepsilon} - (x\to -x)\right)$$

$$C_1^q = \frac{e_q^2\alpha_S C_F}{4\pi(x-\xi+i\varepsilon)}\left[\log^2\left(\frac{\xi-x}{2\xi}-i\varepsilon\right)+\ldots\right] - (x\to -x)$$

- Usual collinear approach: single-scale analysis w.r.t. Q^2
- Consider the invariants $\mathcal{S}$ and $\mathcal{U}$:

$$\mathcal{S} = \frac{x-\xi}{2\xi}Q^2 \quad \ll \quad Q^2 \quad \text{when } x\to\xi$$

$$\mathcal{U} = -\frac{x+\xi}{2\xi}Q^2 \quad \ll \quad Q^2 \quad \text{when } x\to -\xi$$

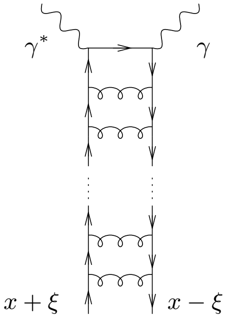
$\Rightarrow$ two scales problem; threshold singularities to be resummed

analogous to the $\log(x-x_{Bj})$ resummation for DIS coefficient functions

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



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

$$(T^q)^{\rm res} = \left(\frac{e_q^2}{x-\xi+i\epsilon} \left\{ \cosh\left[D \log\left(\frac{\xi - x}{2\xi} - i\epsilon \right) \right] - \frac{D^2}{2} \left[9 + 3 \frac{\xi - x}{x+\xi} \log\left(\frac{\xi - x}{2\xi} - i\epsilon \right) \right] \right\} + C_{coll}^q \log \frac{Q^2}{\mu_F^2} \right) - (x \to -x) \quad \text{with} \quad D = \sqrt{\frac{\alpha_s C_F}{2\pi}}$$

T. Altinoluk, B. Pire, L. Szymanowski, S. W.
to appear in JHEP [arXiv:1207.4609]; [arXiv:1206.3115]

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

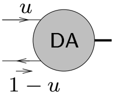
$\rho-$electroproduction: Selection rules and factorization status

- chirality = helicity for a particule, chirality = $\ominus$helicity for an antiparticule
- for massless quarks: QED and QCD vertices = chiral even (no chirality flip during the interaction)
  $\Rightarrow$ the total helicity of a $q\bar{q}$ produced by a γ^* should be 0
  $\Rightarrow$ helicity of the γ^* $= L_z^{q\bar{q}}$ (z projection of the $q\bar{q}$ angular momentum)
- in the pure collinear limit (i.e. twist 2), $L_z^{q\bar{q}}$=0 $\Rightarrow$ γ_L^*
- at $t = 0$, no source of orbital momentum from the proton coupling $\Rightarrow$ helicity of the meson = helicity of the photon
- in the collinear factorization approach, $t \neq 0$ change nothing from the hard side $\Rightarrow$ the above selection rule remains true
- thus: 2 transitions possible ($s-$channel helicity conservation (SCHC)):
  - $\gamma_L^* \to \rho_L$ transition: QCD factorization holds at t=2 at any order in perturbation (i.e. LL, NLL, etc...)

    Collins, Frankfurt, Strikman '97 Radyushkin '97
  - $\gamma_T^* \to \rho_T$ transition: QCD factorization has problems at t=3

    Mankiewicz-Piller '00

    $\int_0^1 \frac{du}{u}$ or $\int_0^1 \frac{du}{1-u}$ diverge (end-point singularity)



$\rho-$electroproduction: Selection rules and factorization status

Improved collinear approximation: a solution?

- keep a transverse $\ell_\perp$ dependency in the q, $\bar{q}$ momenta, used to regulate end-point singularities
- soft and collinear gluon exchange between the valence quark are responsible for large double-logarithmic effects which are conjectured to exponentiate
- this is made easier when using the impact parameter space $b_\perp$ conjugated to $\ell_\perp$ $\Rightarrow$ Sudakov factor

$$\exp[-S(u, b, Q)]$$

- S diverges when $b_\perp \sim O(1/\Lambda_{QCD})$ (large transverse separation, i.e. small transverse momenta) or $u \sim O(\Lambda_{QCD}/Q)$ Botts, Sterman '89
$\Rightarrow$ regularization of end-point singularities for $\pi \to \pi\gamma^*$ and $\gamma\gamma^*\pi^0$ form factors, based on the factorization approach Li, Sterman '92
- it has been proposed to combine this perturbative resummation tail effect with an ad-hoc non-perturbative gaussian ansatz for the DAs

$$\exp[-a^2 \, |k_\perp^2|/(u\bar{u})]$$

which gives back the usual asymptotic DA $6u\bar{u}$ when integrating over $k_\perp$
$\Rightarrow$ practical tools for meson electroproduction phenomenology
Goloskokov, Kroll '05

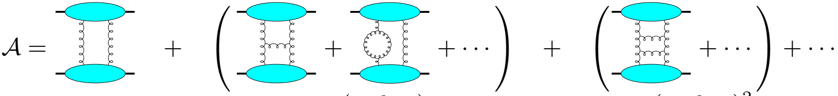
Theoretical motivations

A particular regime for QCD:
The perturbative Regge limit $s \to \infty$

Consider the diffusion of two hadrons h_1 and h_2:

- $\sqrt{s}\,(= E_1 + E_2$ in the center-of-mass system$)$ $\gg$ other scales (masses, transfered momenta, ...) eg $x_B \to 0$ in DIS
- other scales comparable (virtualities, etc...) $\gg \Lambda_{QCD}$

regime $\alpha_s \ln s \sim 1 \implies$ dominant sub-series:



$\sim s$ $\qquad \sim s\,(\alpha_s \ln s)$ $\qquad \sim s\,(\alpha_s \ln s)^2$

$$\implies \sigma_{tot}^{h_1\, h_2 \to tout} = \frac{1}{s} Im\, \mathcal{A} \sim s^{\alpha_{\mathbb{P}}(0)-1}$$

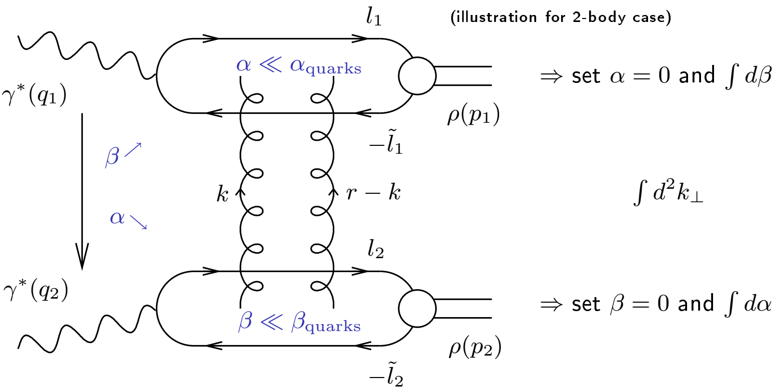
with $\alpha_{\mathbb{P}}(0) - 1 = C\,\alpha_s$ $(C > 0)$ hard Pomeron (Balitsky, Fadin, Kuraev, Lipatov '75)

- This result violates QCD S matrix unitarity
  $(S\,S^\dagger = S^\dagger\,S = 1$ i.e. $\sum Prob. = 1)$
- Until when this result could be applicable, and how to improve it?
- How to test this dynamics experimentally, in particular based on exclusive processes?

k_T factorization

$\gamma^* \gamma^* \to \rho \rho$ as an example

- Use Sudakov decomposition $k = \alpha\, p_1 + \beta\, p_2 + k_\perp$ $(p_1^2 = p_2^2 = 0,\ 2p_1 \cdot p_2 = s)$
- write $d^4k = \frac{s}{2}\, d\alpha\, d\beta\, d^2k_\perp$
- $t-$channel gluons with non-sense polarizations $(\epsilon_{NS}^{up} = \frac{2}{s}\, p_2,\ \epsilon_{NS}^{down} = \frac{2}{s}\, p_1)$ dominate at large s

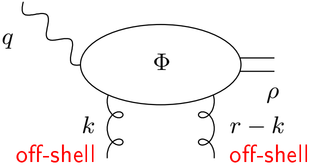


k_T factorization

Impact representation for exclusive processes $\underline{k}$ = Eucl. $\leftrightarrow k_\perp$ = Mink.

$$\mathcal{M} = is \int \frac{d^2\,\underline{k}}{(2\pi)^2 \underline{k}^2\,(\underline{r}-\underline{k})^2} \Phi^{\gamma^*(q_1)\to\rho(p_1^\rho)}(\underline{k},\underline{r}-\underline{k})\;\Phi^{\gamma^*(q_2)\to\rho(p_2^\rho)}(-\underline{k},-\underline{r}+\underline{k})$$

$\Phi^{\gamma^*(q_1)\to\rho(p_1^\rho)}$: $\gamma^*_{L,T}(q) g(k_1) \to \rho_{L,T}\, g(k_2)$ impact factor



Meson production at HERA

Diffractive meson production at HERA

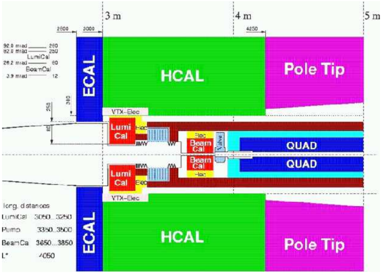
HERA (DESY, Hambourg): first and single $e^{\pm}p$ collider (1992-2007)

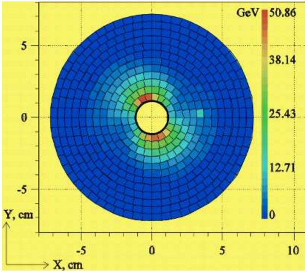
- The "easy" case (from factorization point of view): J/Ψ production ($u \sim 1/2$: non-relativistic limit for bound state) combined with k_T-factorisation
  Ryskin '93; Frankfurt, Koepf, Strikman '98; Ivanov, Kirschner, Schäfer, Szymanowski '00; Motyka, Enberg, Poludniowski '02
- Exclusive vector meson photoproduction at large t (= hard scale):
  $\gamma(q) + P \to \rho_{L,T}(p_1) + P$
  based on k_T-factorization:
  Forshaw, Ryskin '95; Bartels, Forshaw, Lotter, Wüsthoff '96; Forshaw, Motyka, Enberg, Poludniowski '03
    - H1, ZEUS data seems to favor BFKL
    - but end-point singularities for ρ_T are regularized with a quark mass: $m = m_\rho/2$
    - the spin density matrix is badly described
- Exclusive electroproduction of vector meson
  $\gamma^*_{L,T}(q) + P \to \rho_{L,T}(p_1) + P$ Goloskokov, Kroll '05
  based on improved collinear factorization for the coupling with the meson DA and collinear factorization for GPD coupling

Phenomenological applications: exclusive test of $\mathbb{P}$omeron

An example of realistic exclusive test of $\mathbb{P}$omeron: $\gamma^{(*)}\gamma^{(*)} \to \rho\,\rho$
as a subprocess of $e^-\,e^+ \to e^-\,e^+\,\rho_L^0\,\rho_L^0$

- ILC should provide $\begin{cases} \text{very large } \sqrt{s} \; (= 500 \text{ GeV}) \\ \text{very large luminosity } (\simeq 125 \text{ fb}^{-1}/\text{year}) \end{cases}$
- detectors are planned to cover the very forward region, close from the beampipe (directions of out-going e^+ and e^- at large s)



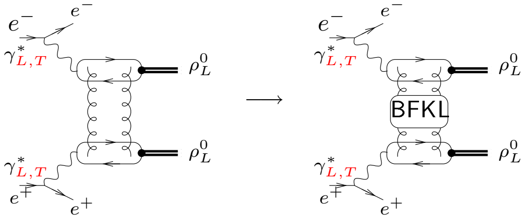


good efficiency of tagging for outgoing $e^\pm$ for $E_e > 100$ GeV and $\theta > 4$ mrad (illustration for LDC concept)

- could be equivalently done at LHC based on the AFP project

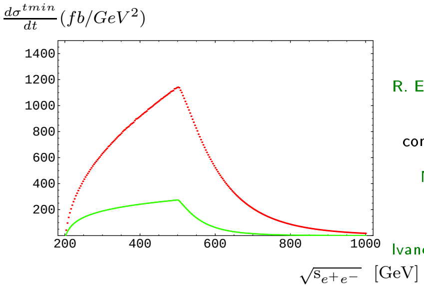
Phenomenological applications: exclusive test of $\mathbb{P}$omeron

QCD effects in the Regge limit on $\gamma^{(*)}\gamma^{(*)} \to \rho\,\rho$



$\simeq 4.10^3$ events/year

$\simeq 2.10^4$ events/year



proof of feasibility:
B. Pire, L. Szymanowski and S. W.
Eur.Phys.J.C44 (2005) 545

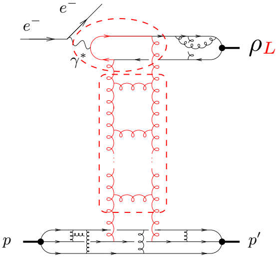
proof of visible BFKL enhancement:
R. Enberg, B. Pire, L. Szymanowski and S. W.
Eur.Phys.J.C45 (2006) 759

comprensive study of γ^* polarization effects
and event rates:
M. Segond, L. Szymanowski and S. W.
Eur. Phys. J. C **52** (2007) 93

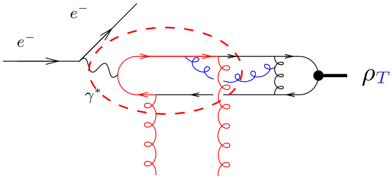
NLO BFKL study:
Ivanov, Papa '06 '07; Caporale, Papa, Vera '08

Exclusive vector meson production at HERA

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



new →



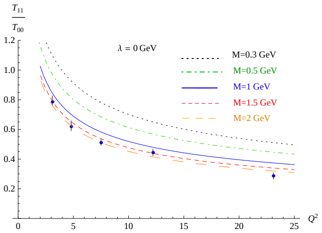
first description combining beyond leading twist

- 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

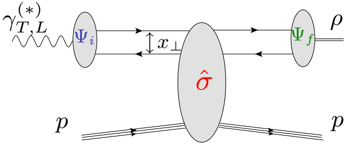
HERA, LHeC, AFP@LHC



HERA (H1) data

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

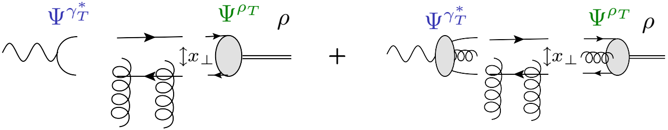
Dipole representation and saturation effects



Nikolaev, Zakharov '91

- 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 $x_\perp \sim 1/Q_{\text{sat}}$: $T < 1$
- Data for ρ prod. calls for models encoding saturation

  Munier, Stasto, Mueller '04; Kowalski, Motyka, Watt '06
- The dipole repr. is consistent with the twist 2 collinear factorization
- 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], to appear in NPB

Phenomenology: A. Besse, L. Szymanowski, S. W. in preparation

γ case for large $|t|$? b-dependence?

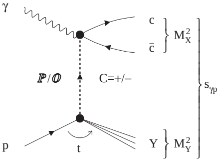
Finding the hard Odderon

- 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 $\mathbb{O}$

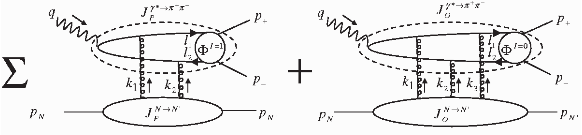
Finding the hard Odderon

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

- consider processes, where $\mathbb{P}$ vanishes due to C-parity conservation:
  exclusive $\eta, \eta_c, f_2, a_2, \ldots$ in ep; $\gamma\gamma \to \eta_c\eta_c \sim |\mathcal{M}_{\mathbb{O}}|^2$ Braunewell, Ewerz '04
  exclusive $J/\Psi, \Upsilon$ in pp ($\mathbb{P}\mathbb{O}$ fusion, not $\mathbb{P}\mathbb{P}$)) Bzdak, Motyka, Szymanowski, Cudell '07
- 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 '99

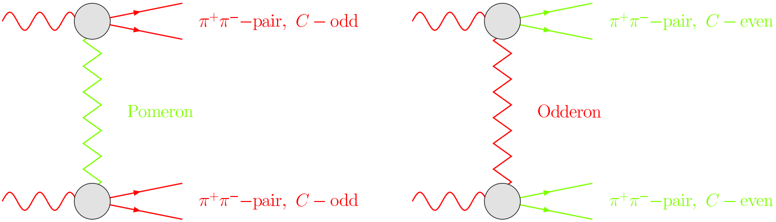


Ivanov, Nikolaev, Ginzburg '01 in photo-production
Hägler, Pire, Szymanowski, Teryaev '02 in electro-production

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

- Since a decade, there have been much progress in the understanding of hard exclusive processes
  - at medium energies, there is now a conceptual framework starting from first principle, allowing to describe a huge number of processes
  - at high energy, the impact representation is a powerful tool for describing exclusive processes in diffractive experiments; they are and will be essential for studying QCD in the hard Regge limit ($\mathbb{P}$omeron, $\mathbb{O}$dderon, saturation...)
- till, some problems remain:
  - proofs of factorization have been obtained only for very few processes (ex.: $\gamma^* p \to \gamma p$, $\gamma_L^* p \to \rho_L p$)
  - for some other processes factorization is highly plausible, but not fully demonstrated at any order (ex.: processes involving GDAs and TDAs)
  - some processes explicitly show sign of breaking of factorization (ex.: $\gamma_T^* p \to \rho_T p$ which has end-point singularities at Leading Order)
  - models and results from the lattice for the non-perturbative correlators entering GPDs, DAs, GDAs, TDAs are needed, even at a qualitative level!
  - the effect of QCD evolution, the NLO corrections with potential resummation effects, choice of renormalization/factorization scale, power corrections will be very relevant to interpret and describe the forecoming data
- Links between theoretical and experimental communities are very fruitful

  HERA, HERMES, Tevatron, LHC, JLab, COMPASS, BaBar, BELLE, Super-B, EIC, LHeC, ILC

  This is very hot and pleasant domain. Everybody is welcome!