A short review of the theory of hard exclusive processes

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Meeting in honour of J. Cugnon and H.J. Pirner,
"30 years of strong interactions", April 7th 2011

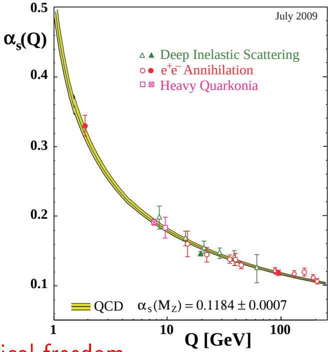
QCD

Quantum chromodynamics (QCD) is THE theory of strong interaction, one of the four elementary interactions of the universe

- it is a relativistic quantum field theory of Yang-Mills type (with an $SU(3)$ gauge group)
- the quarks and gluons elementary fields are confined in hadrons:
  - mesons $(\pi,\, \eta,\, f_0,\, \rho,\, \omega \cdots)$

    $$|q\bar{q}\rangle + |q\bar{q}g\rangle + |qq\bar{q}\bar{q}\rangle + \cdots$$
  - baryons $(p,\, n,\, N,\, \Delta \cdots)$

    $$|qqq\rangle + |qqqg\rangle + |qqqq\bar{q}\rangle + \cdots$$

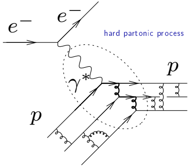


- in contrast with electrodynamics, strong interaction increases with distance, or equivalently decreases when energy increases: this phenomena is called asymptotical freedom

$$\text{coupling} \qquad \alpha_s(Q) \ll 1 \qquad \text{for} \qquad Q \gg \Lambda_{QCD} \simeq 200\ \text{MeV}$$

What to do with QCD?

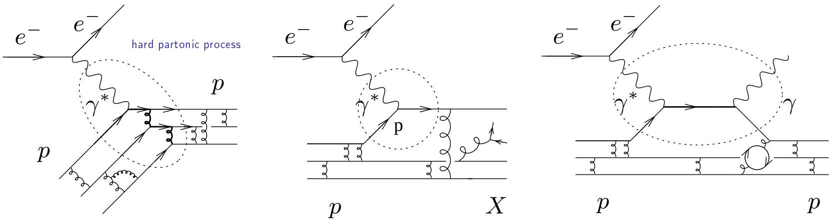
- How however describe and understand the internal structure of hadrons, starting from their elementary constituents?
- In the non-perturbative domain, the two available tools are:
  - Chiral perturbation theory: systematic expansion based on the fact that u and d quarks have a very small mass, the π mass being an expansion parameter outside the chiral limit
  - Discretization of QCD on a 4-d lattice: numerical simulations
- Can one extract information reducing 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 $(d \ll 1\,\mathrm{fm})$
    $\Longrightarrow \alpha_s \ll 1$: Perturbative methods
  - One should hit strongly enough a hadron
    Example: electromagnetic probe and form factor



$\tau_{\text{electromagnetic interaction}} \sim \tau_{\text{parton life time after interaction}}$
$\ll \tau_{\text{caracteristic time of strong interaction}}$

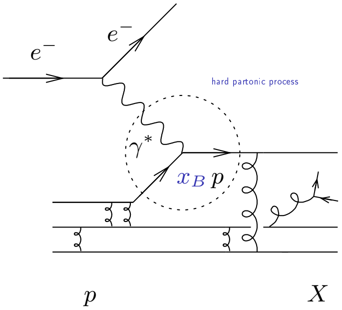
Hard processes in QCD

- This is justified if the process is governed by a hard scale:
  - virtuality of the electromagnetic probe
    in elastic scattering $e^\pm\, p \to e^\pm\, p$
    in Deep Inelastic Scattering (DIS) $e^\pm\, p \to e^\pm\, X$
    in Deep Virtual Compton Scattering (DVCS) $e^\pm\, p \to e^\pm\, p\,\gamma$
  - Total center of mass energy in $e^+e^- \to X$ annihilation
  - t-channel momentum exchange in meson photoproduction $\gamma\, p \to M\, p$
- A precise treatment relies on factorization theorems
- The scattering amplitude is described by the convolution of the partonic amplitude with the non-perturbative hadronic content



Accessing to the perturbative proton content

example: DIS



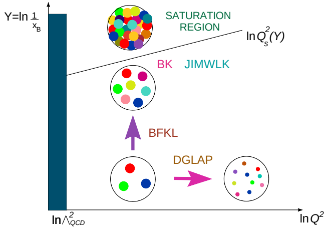
$$s_{\gamma^* p} = (q_\gamma^* + p_p)^2 = 4\, E^2_{\rm c.m.}$$

$$Q^2 \equiv -q^2_{\gamma^*} > 0$$

$$x_B = \frac{Q^2}{2\, p_p \cdot q_\gamma^*} \simeq \frac{Q^2}{s_{\gamma^* p}}$$

- x_B = proton momentum fraction carried by the scattered quark
- $1/Q$ = transverse resolution of the photonic probe $\ll 1/\Lambda_{QCD}$

The various regimes governing the perturbative content of the proton



- "usual" regime: x_B moderate ($x_B \gtrsim .01$):
  Evolution in Q governed by the QCD renormalization group
  (Dokshitser, Gribov, Lipatov, Altarelli, Parisi equation)

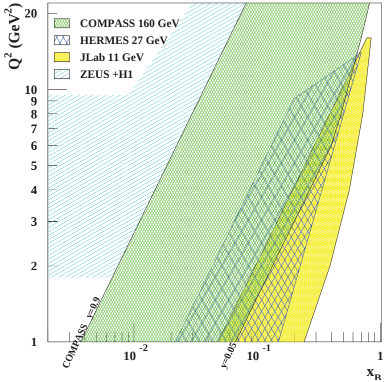
$$\underbrace{\sum_n (\alpha_s \ln Q^2)^n}_{\text{LLQ}} + \underbrace{\alpha_s \sum_n (\alpha_s \ln Q^2)^n}_{\text{NLLQ}} + \cdots$$

- perturbative Regge limit: $s_{\gamma^* p} \to \infty$ i.e. $x_B \sim Q^2/s_{\gamma^* p} \to 0$
  in the perturbative regime (hard scale Q^2)
  (Balitski Fadin Kuraev Lipatov equation)

Introduction

From inclusive to exclusive processes

An very important effort is being realized in order to get access to the hadron structure through exclusive processes



Kinematical accessible domain for hard exclusive processes

Experimental effort

Going from inclusive to exclusive processes is difficult: exclusive processes = rare!

- 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, 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, ...) (see talk of C. Lorcé)
  - Diffractive processes, including ultraperipheral collisions
    LHC (with or without fix target), ILC

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

    collinear factorization
  - At asymptotical energies:

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

    k_T-factorization

Introduction
Extensions from DIS

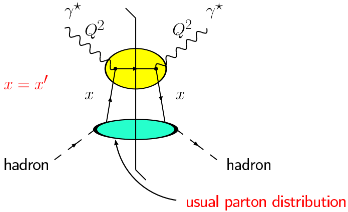
- DIS: inclusive process $\longrightarrow$ forward amplitude ($t = 0$) *(optical theorem)*

(DIS: Deep Inelastic Scattering)

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

Structure Function

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

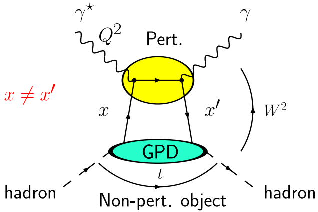


- DVCS: exclusive process $\longrightarrow$ non forward amplitude ($-t \ll s = W^2$)

(DVCS: Deep Vitual Compton Scattering)

Amplitude

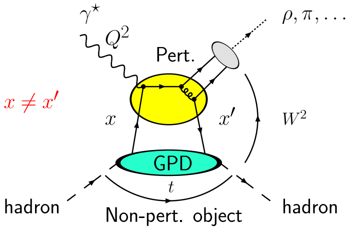
= Coefficient Function (hard) $\otimes$ Generalized Parton Distribution (soft)



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

Introduction
Extensions from GPD

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

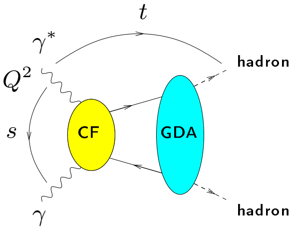


Amplitude

= 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

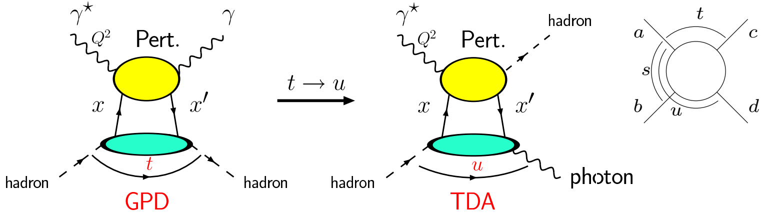
Introduction
Extensions from GPD

- 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

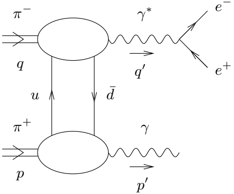
which can be further extended by replacing the outoing γ by any hadronic state

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

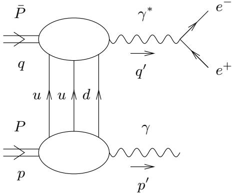
Lansberg, Pire, Szymanowski '06

Introduction
Extensions from GPD

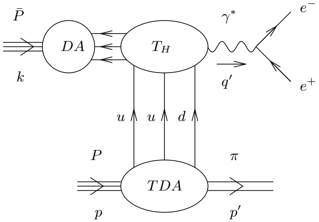
TDA at PANDA



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

Colinear factorization

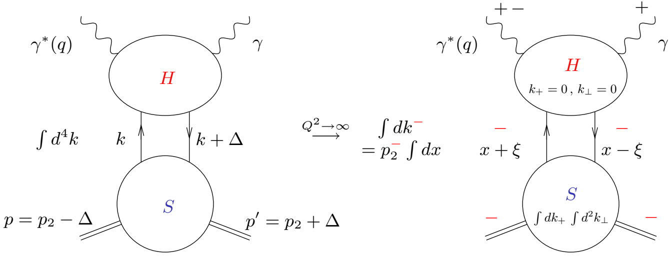
A bit more technical: DVCS and GPDs

Two steps for factorization

- momentum factorization: light-cone vector dominance for $Q^2 \to \infty$

$p_1,\, p_2$: the two light-cone directions $\begin{cases} p_1 = \frac{\sqrt{s}}{2}(1, 0_\perp, 1) \\ p_2 = \frac{\sqrt{s}}{2}(1, 0_\perp, -1) \end{cases}$ $(p_1^2 = p_2^2 = 0,\ 2\, p_1 \cdot p_2 = s \sim s_{\gamma^* p})$

Sudakov decomposition: $k \;=\; \underset{+}{\alpha\, p_1} \;+\; \underset{-}{\beta\, p_2} \;+\; \underset{\perp}{k_\perp}$



$$\int d^4k\; S(k,\, k+\Delta)\, H(q,\, k,\, k+\Delta) \;=\; \int dk^- \int dk^+ d^2k_\perp\; S(k,\, k+\Delta)\;\; H(q,\, k^-,\, k^- + \Delta^-)$$

- Quantum numbers factorization (Fierz identity: spinors + color)

$$\Rightarrow \qquad \mathcal{M} = \text{GPD} \otimes \text{Hard part}$$

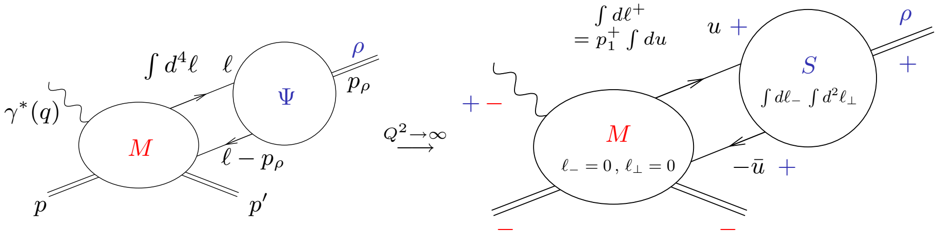
Müller et al. '91 - '94; Radyushkin '96; Ji '97

Collinear factorization

$\rho-$meson production: from the wave function to the DA

What is a $\rho-$meson in QCD?

It is described by its wave function Ψ which reduces in hard processes to its Distribution Amplitude



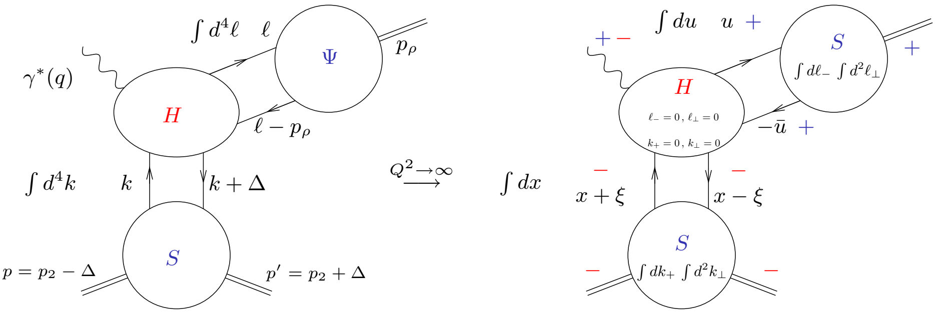
$$\int d^4\ell \; M(q,\,\ell,\,\ell-p_\rho)\Psi(\ell,\,\ell-p_\rho) \;= \int d\ell^+ \, M(q,\,\ell^+,\,\ell^+-p_\rho^+) \; \int d\ell^- \int^{|\ell_\perp^2|<\mu_F^2} d^2\ell_\perp \, \Psi(\ell,\,\ell-p_\rho)$$

Hard part — DA $\Phi(u,\mu_F^2)$

(see Chernyak, Zhitnitsky '77; Brodsky, Lepage '79; Efremov, Radyushkin '80; ... in the case of form-factors studies)

Collinear factorization

Meson electroproduction: factorization with a GPD and a DA



$\int d^4k\, d^4\ell$ $\quad S(k,\, k+\Delta)$ $\quad H(q,\, k,\, k+\Delta)$ $\quad \Psi(\ell,\, \ell - p_\rho)$

$$= \int dk^- d\ell^+ \int dk^+ \int^{|k_\perp^2| < \mu_{F_2}^2} d^2k_\perp\, S(k,\, k+\Delta)\, H(q;\, k^-,\, k^- + \Delta^-; \ell^+,\, \ell^+ - p_\rho^+) \int d\ell^- \int^{|\ell_\perp^2| < \mu_{F_1}^2} d^2\ell_\perp \Psi(\ell,\, \ell - p_\rho)$$

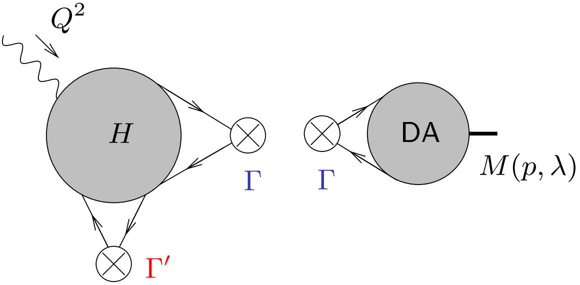
GPD $F(x,\, \xi, t, \mu_{F_2}^2)$ $\quad$ Hard part $T(x/\xi, u, \mu_{F_1}^2, \mu_{F_2}^2, \mu_R)$ $\quad$ DA $\Phi(u, \mu_{F_1}^2)$

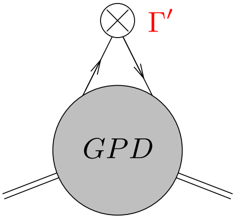
Collins, Frankfurt, Strikman '97; Radyushkin '97

Collinear factorization

Meson electroproduction: factorization with a GPD and a DA

The building blocks





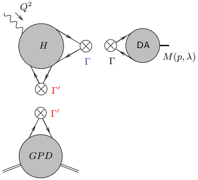
Γ, Γ' : Dirac matrices compatible with quantum numbers: C, P, T, chirality

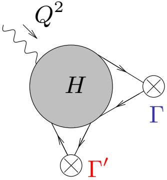
Similar structure for gluon exchange

Collinear factorization

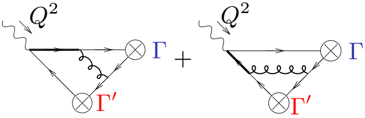
Meson electroproduction: factorization with a GPD and a DA

The building blocks

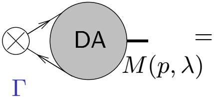




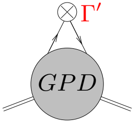
$=$



hand-bag diagrams



$=$ $\langle M(p,\lambda)|\mathcal{O}(\Psi,\,\bar{\Psi}\,A)|0\rangle$ matrix element of a non-local light-cone operator

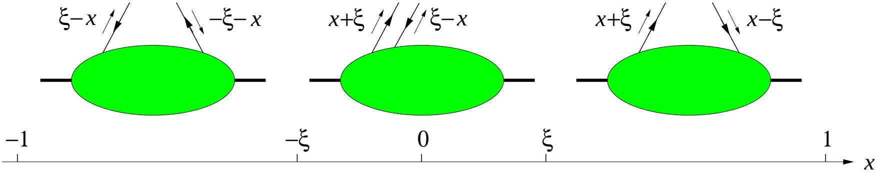


$=$ $\langle N(p')|\mathcal{O}'(\Psi,\,\bar{\Psi}\,A)|N(p)\rangle$ matrix element of a non-local light-cone operator

Collinear factorization

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

Collinear factorization
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, $\tilde{H}_T^q$, $\tilde{E}_T^q$

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

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

Collinear factorization
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)

A few applications
Electroproduction of an exotic hybrid meson

Quark model and meson spectroscopy

- spectroscopy: $\vec{J} = \vec{L} + \vec{S}$; neglecting any spin-orbital interaction
  $\Rightarrow S,\ L =$ additional quantum numbers to classify hadron states

$$\vec{J}^2 = J(J+1)\,, \quad \vec{S}^{\,2} = S(S+1)\,, \quad \vec{L}^{\,2} = L(L+1),$$

  with $J = |L-S|\,, \cdots, L+S$

- In the usual quark-model: meson $= q\bar{q}$ bound state with

$$C = (-)^{L+S} \quad \text{and} \quad P = (-)^{L+1}.$$

- Thus:

$$\begin{array}{llll}
S=0\,, & L=J, & J=0,\,1,\,2,\ldots: & J^{PC} = 0^{-+}(\pi,\eta),\ 1^{+-}(h_1,b_1),\ 2^{-+},\ 3^{+-},\ \ldots \\
S=1\,, & L=0\,, & J=1\ : & J^{PC} = 1^{--}(\rho,\omega,\phi) \\
 & L=1\,, & J=0,\,1,\,2\ : & J^{PC} = 0^{++}(f_0,a_0),\ 1^{++}(f_1,a_1),\ 2^{++}(f_2,a_2) \\
 & L=2\,, & J=1,\,2,\,3\ : & J^{PC} = 1^{--},\ 2^{--},\ 3^{--}
\end{array}$$

...

- $\Rightarrow$ the exotic mesons with $J^{PC} = 0^{--},\ 0^{+-},\ 1^{-+},\ \cdots$ are forbidden

A few applications

Electroproduction of an exotic hybrid meson

Experimental candidates for light hybrid mesons (1)

three candidates:

- $\pi_1(1400)$
  - GAMS '88 (SPS, CERN): in $\pi^- \, p \to \eta \, \pi^0 \, n$ (through $\eta \, \pi^0 \to 4\gamma$ mode)
    M= 1406 ± 20 MeV $\quad \Gamma = 180 \pm 30$ MeV
  - E852 '97 (BNL): $\pi^- \, p \to \eta \, \pi^- \, p$
    M=1370 ± 16 MeV $\quad \Gamma = 385 \pm 40$ MeV
  - VES '01 (Protvino) in $\pi^- \, Be \to \eta \, \pi^- \, Be$, $\pi^- \, Be \to \eta' \, \pi^- \, Be$,
    $\pi^- \, Be \to b_1 \, \pi^- \, Be$
    M = 1316 ± 12 MeV $\quad \Gamma = 287 \pm 25$ MeV
    but resonance hypothesis ambiguous
  - Crystal Barrel (LEAR, CERN) '98 '99 in $\bar{p} \, n \to \pi^- \, \pi^0 \, \eta$ and $\bar{p} \, p \to 2\pi^0 \, \eta$
    (through $\pi\eta$ resonance)
    M=1400 ± 20 MeV $\quad \Gamma = 310 \pm 50$ MeV
    and M=1360 ± 25 MeV $\quad \Gamma = 220 \pm 90$ MeV

A few applications

Electroproduction of an exotic hybrid meson

Experimental candidates for light hybrid mesons (2)

- $\pi_1(1600)$
  - E852 (BNL): in peripheral $\pi^- p \to \pi^+ \pi^- \pi^- p$ (through $\rho\pi^-$ mode) '98 '02,
    M = 1593 ± 8 MeV $\Gamma = 168 \pm 20$ MeV $\pi^- p \to \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$ (in $b_1(1235)\pi^- \to (\omega\pi^0)\pi^- \to (\pi^+\pi^-\pi^0)\pi^0\pi^-$ '05 and $f_1(1285)\pi^-$ '04 modes), in peripheral $\pi^- p$ through $\eta' \pi^-$ '01
    M = 1597 ± 10 MeV $\Gamma = 340 \pm 40$ MeV
    but E852 (BNL) '06: no exotic signal in $\pi^- p \to (3\pi)^- p$ for a larger sample of data!
  - VES '00 (Protvino): in peripheral $\pi^- p$ through $\eta' \pi^-$ '93, '00, $\rho(\pi^+\pi^-)\pi^-$ '00, $b_1(1235)\pi^- \to (\omega\pi^0)\pi^-$ '00
  - Crystal Barrel (LEAR, CERN) '03 $\bar{p}p \to b_1(1235)\pi\pi$
  - COMPASS '10 (SPS, CERN): diffractive dissociation of π^- on Pb target through Primakov effect $\pi^- \gamma \to \pi^- \pi^- \pi^+$ (through $\rho\pi^-$ mode)
    M = 1660 ± 10 MeV $\Gamma = 269 \pm 21$ MeV
- $\pi_1(2000)$: seen only at E852 (BNL) '04 '05 (through $f_1(1285)\pi^-$ and $b_1(1235)\pi^-$)

A few applications

Electroproduction of an exotic hybrid meson

What about hard processes?

- Is there a hope to see such states in hard processes, with high counting rates, and to exhibit their light-cone wave-function?
- hybrid mesons = $q\bar{q}g$ states T. Barnes '77; R. L. Jaffe, K. Johnson, and Z. Ryzak, G. S. Bali
- popular belief: $H = q\bar{q}g \Rightarrow$ higher Fock-state component $\Rightarrow$ twist-3 $\Rightarrow$ hard electroproduction of H versus ρ suppressed as $1/Q$
- This is not true!! Electroproduction of hybrid is similar to electroproduction of usual $\rho-$meson: it is twist 2 dominated

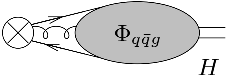
I. V. Anikin, B. Pire, O. V. Teryaev, L. Szymanowski, S.W.
Phys.Rev.D70 (2004) 011501
Phys.Rev.D71 (2005) 034021
Eur.Phys.J.C42 (2005) 163
Eur.Phys.J.C47 (2006) 71-79.

A few applications

Electroproduction of an exotic hybrid meson

Distribution amplitude of exotic hybrid mesons at twist 2

- One may think that to produce $|q\bar{q}g\rangle$, the fields Ψ, $\bar{\Psi}$, A should appear explicitly in the non-local operator $\mathcal{O}(\Psi,\, \bar{\Psi}\, A)$



- If one tries to produce $H = 1^{-+}$ from a local operator, the dominant operator should be $\bar{\Psi}\gamma^\mu G_{\mu\nu}\Psi$ of twist = dimension - spin = 5 - 1 = 4
- It means that there should be a $1/Q^2$ suppression in the production amplitude of H versus the usual ρ-production (which is twist 2 dominated)
- But collinear approach describes hard exclusive processes in terms of non-local light-cone operators, among which are the twist 2 operator

$$\bar{\psi}(-z/2)\gamma_\mu[-z/2; z/2]\psi(z/2)$$

where $[-z/2; z/2]$ is a Wilson line, necessary to fullfil gauge invariance (i.e. a "color tube" between q and $\bar{q}$) which thus hides gluonic degrees of freedom: the needed gluon is there, at twist 2. This does not requires to introduce explicitely A!

A few applications

Electroproduction of an exotic hybrid meson

Distribution amplitude and quantum numbers: C-parity

- Define the H DA as (for long. pol.)

$$\langle H(p,0)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle\Big|_{\substack{z^2=0\\ z+=0\\ z_\perp=0}} = i f_H M_H e_\mu^{(0)}\int_0^1 dy\, e^{i(\bar{y}-y)p\cdot z/2}\phi_L^H(y)$$

- Expansion in terms of local operators

$$\langle H(p,\lambda)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle = \sum_n \frac{1}{n!} z_{\mu_1}..z_{\mu_n}\langle H(p,\lambda)|\bar{\psi}(0)\gamma_\mu \overleftrightarrow{D}_{\mu_1}\,..\,\overleftrightarrow{D}_{\mu_n}\,\psi(0)|0\rangle,$$

- $C-$parity: $\begin{cases} H \text{ selects the odd-terms:} & C_H = (-) \\ \rho \text{ selects even-terms:} & C_\rho = (-) \end{cases}$

$$\langle H(p,\lambda)|\bar{\psi}(-z/2)\gamma_\mu[-z/2;z/2]\psi(z/2)|0\rangle = \sum_{n\ odd} \frac{1}{n!} z_{\mu_1}..z_{\mu_n}\langle H(p,\lambda)|\bar{\psi}(0)\gamma_\mu \overleftrightarrow{D}_{\mu_1}\,..\,\overleftrightarrow{D}_{\mu_n}\,\psi(0)|0\rangle$$

- Special case $n=1$: $\quad \mathcal{R}_{\mu\nu} = \mathsf{S}_{(\mu\nu)}\bar{\psi}(0)\gamma_\mu \overleftrightarrow{D}_\nu\,\psi(0)$

$\mathsf{S}_{(\mu\nu)}$ = symmetrization operator: $\mathsf{S}_{(\mu\nu)}T_{\mu\nu} = \frac{1}{2}(T_{\mu\nu}+T_{\nu\mu})$

A few applications

Electroproduction of an exotic hybrid meson

Non perturbative imput for the hybrid DA

- We need to fix f_H (the analogue of f_ρ)
- This is a non-perturbative imput
- Lattice does not yet give information
- The operator $\mathcal{R}_{\mu\nu}$ is related to quark energy-momentum tensor $\Theta_{\mu\nu}$:

$$\mathcal{R}_{\mu\nu} = -i\,\Theta_{\mu\nu}$$

- Rely on QCD sum rules: resonance for $M \approx 1.4$ GeV
  I. I. Balitsky, D. Diakonov, and A. V. Yung

$$f_H \approx 50\,\mathrm{MeV}$$

  $f_\rho = 216$ MeV

- Note: f_H evolves according to the γ_{QQ} anomalous dimension

$$f_H(Q^2) = f_H \left(\frac{\alpha_S(Q^2)}{\alpha_S(M_H^2)}\right)^{K_1} \qquad K_1 = \frac{2\,\gamma_{QQ}(1)}{\beta_0}\,,$$

A few applications

Electroproduction of an exotic hybrid meson

Counting rates for H versus ρ electroproduction: order of magnitude

- Ratio:

$$\frac{d\sigma^H(Q^2,x_B,t)}{d\sigma^\rho(Q^2,x_B,t)} = \left| \frac{f_H}{f_\rho} \frac{(e_u \mathcal{H}^-_{uu} - e_d \mathcal{H}^-_{dd})\, \mathcal{V}^{(H,-)}}{(e_u \mathcal{H}^+_{uu} - e_d \mathcal{H}^+_{dd})\, \mathcal{V}^{(\rho,+)}} \right|^2$$

- Rough estimate:
  - neglect $\bar{q}$ *i.e.* $x \in [0,1]$

    $\Rightarrow Im\mathcal{A}_H$ and $Im\mathcal{A}_\rho$ are equal up to the factor $\mathcal{V}^M$
  - Neglect the effect of $Re\mathcal{A}$

$$\frac{d\sigma^H(Q^2,x_B,t)}{d\sigma^\rho(Q^2,x_B,t)} \approx \left(\frac{5 f_H}{3 f_\rho}\right)^2 \approx 0.15$$

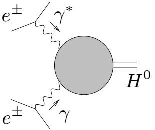
- More precise study based on *Double Distributions* to model GPDs + effects of varying μ_R: order of magnitude unchanged

- The range around 1400 MeV is dominated by the $a_2(1329)(2^{++})$ resonance
  - possible interference between H and a_2
  - identification through the $\pi\eta$ GDA, main decay mode for the $\pi_1(1400)$ candidate, through angular asymmetry in θ_π in the $\pi\eta$ cms

A few applications
Electroproduction of an exotic hybrid meson

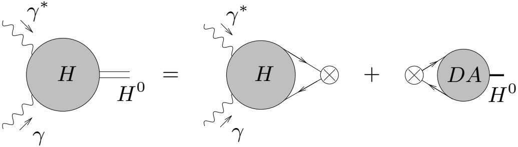
Hybrid meson production in e^+e^- colliders

- Hybrid can be copiously produced in $\gamma^*\gamma$, i.e. at e^+e^- colliders with one tagged out-going electron

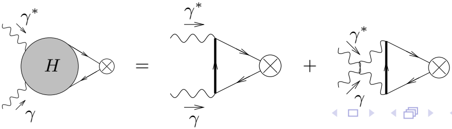


BaBar, Belle, Super-B

- This can be described in a hard factorization framework:



with



A few applications

Electroproduction of an exotic hybrid meson

Counting rates for H^0 versus π^0

- Factorization gives:

$$\mathcal{A}^{\gamma\gamma^* \to H^0}(\gamma\gamma^* \to H_L) = (\epsilon_\gamma \cdot \epsilon^*_\gamma) \frac{(e_u^2 - e_d^2) f_H}{2\sqrt{2}} \int_0^1 dz\, \Phi^H(z) \left(\frac{1}{\bar{z}} - \frac{1}{z} \right)$$

- Ratio H^0 versus π^0:

$$\frac{d\sigma^H}{d\sigma^{\pi^0}} = \left| \frac{f_H \int_0^1 dz\, \Phi^H(z) \left(\frac{1}{z} - \frac{1}{\bar{z}} \right)}{f_\pi \int_0^1 dz\, \Phi^\pi(z) \left(\frac{1}{z} + \frac{1}{\bar{z}} \right)} \right|^2$$

- This gives, with *asymptotical* DAs (i.e. limit $Q^2 \to \infty$):

$$\frac{d\sigma^H}{d\sigma^{\pi^0}} \approx 38\%$$

still larger than 20% at $Q^2 \approx 1$ GeV^2 (including kinematical twist-3 effects à la Wandzura-Wilczek for the H^0 DA) and similarly

$$\frac{d\sigma^H}{d\sigma^\eta} \approx 46\%$$

A few applications
Spin transversity in the nucleon

What is transversity?

- Tranverse spin content of the proton:

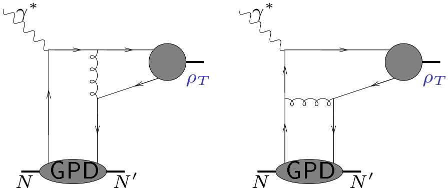
$$
\begin{array}{ccc}
|\uparrow\rangle_{(x)} & \sim & |\rightarrow\rangle + |\leftarrow\rangle \\
|\downarrow\rangle_{(x)} & \sim & |\rightarrow\rangle - |\leftarrow\rangle \\
\text{spin along } x & & \text{helicity state}
\end{array}
$$

- 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: $q_\pm(z) \equiv \frac{1}{2}(1 \pm \gamma^5) q(z)$ avec $q(z) = q_+(z) + q_-(z)$
  Chiral-even: chirality conserving
  $\bar{q}_\pm(z)\gamma^\mu q_\pm(-z)$ et $\bar{q}_\pm(z)\gamma^\mu\gamma^5 q_\pm(-z)$
  Chiral-odd: chirality reversing
  $\bar{q}_\pm(z)\cdot 1 \cdot q_\mp(-z)$, $\bar{q}_\pm(z)\cdot\gamma^5\cdot q_\mp(-z)$ et $\bar{q}_\pm(z)[\gamma^\mu,\gamma^\nu]q_\mp(-z)$
- For a massless (anti)particle, chirality = (-)helicity
- Transversity is thus a chiral-odd quantity
- QCD and QED are chiral even $\Rightarrow \mathcal{A} \sim (\text{Ch.-odd})_1 \otimes (\text{Ch.-even})_2$

A few applications
Spin 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

A few applications

Spin transversity in the nucleon

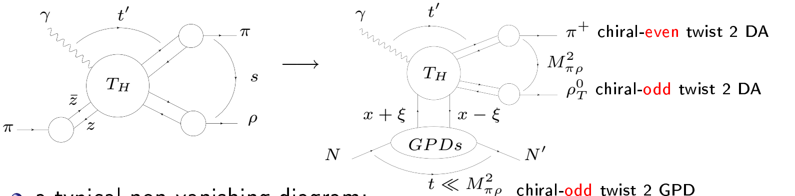
Can one circumvent this vanishing?

- 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.)

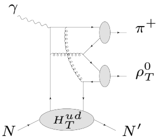
A few applications
Spin transversity in the nucleon

$\gamma N \to \pi^+ \rho^0_T N'$ 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

Problems

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

- chirality = helicity for a particule, chirality = -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)

Problems

$\rho-$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

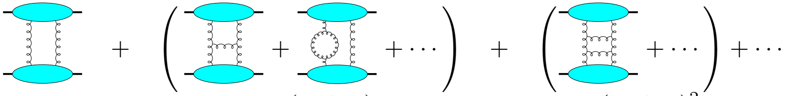
QCD at large s
Theoretical motivations

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:

$\mathcal{A} =$ 

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

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

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

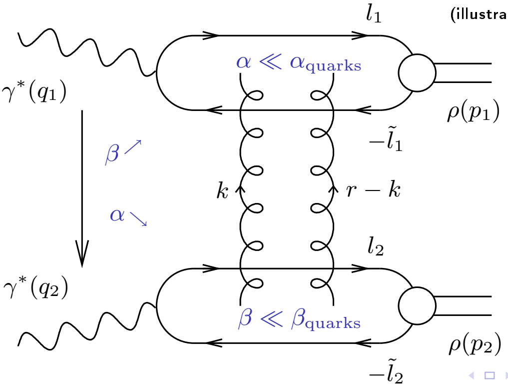
- This result violates QCD S matrix unitarity
  $(S\, S^\dagger = S^\dagger\, S = 1$ i.e. $\sum Prob. = 1)$
- Until when this result could be applicable, and how to improve it?
- How to test this dynamics experimentally, in particular based on exclusive processes?

QCD at large s
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

(illustration for 2-body case)



$\Rightarrow$ set $\alpha = 0$ and $\int d\beta$

$\int d^2k_\perp$

$\Rightarrow$ set $\beta = 0$ and $\int d\alpha$

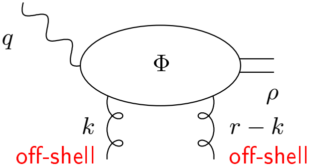
QCD at large s

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



Gauge invariance of QCD:

- probes are color neutral
  $\Rightarrow$ their impact factor should vanish s'annuller when $\underline{k} \to 0$ or $\underline{r}-\underline{k} \to 0$
- At twist-3 level (for the $\gamma^*_T \to \rho_T$ transition), gauge invariance is a non-trivial constraint when combining 2- *and* 3-body correlators

QCD at large s

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

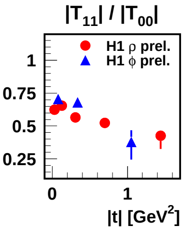
QCD at large s
Meson production at HERA

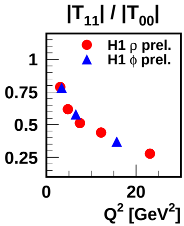
Polarization effects in $\gamma^* P \to \rho P$ at HERA

- Very precise experimental data on the spin density matrix (i.e. correlations between γ^* and ρ polarizations)
- for $t = t_{min}$ one can experimentally distinguish

$$\begin{cases} \gamma^*_L \to \rho_L : \text{dominates} & (\text{“twist 2”: amplitude } |\mathcal{A}| \sim \frac{1}{Q}) \\ \gamma^*_T \to \rho_T : \text{visible} & (\text{“twist 3”: amplitude } |\mathcal{A}| \sim \frac{1}{Q^2}) \end{cases}$$

- How to calculate the $\gamma^*_T \to \rho_T$ transition from first principles?





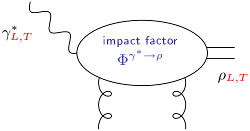
QCD at large s

Meson production at HERA

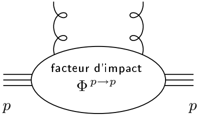
Exclusive vector meson production:

First consistent computation at twist 3 ever made

Impact factor computation $\Phi^{\gamma^* \to \rho}$ at twist 3:



- The obtained impact factor is gauge invariant
- No end-point singularities due to k_T in $t-$channel
- This remains true in the Wandzura-Wilczek approximation (i.e. 3-body correlators = 0, the twist 3 effects arising only from kinematical corrections and not from gluonic dynamical degrees of freedom)



I. V. Anikin, D. Y. Ivanov, B. Pire, L. Szymanowski and S. W. Phys. Lett. B 688:154-167, 2010 B; Nucl. Phys. B 828:1-68, 2010.

Very powerful method which can be applied for various exclusive processes governed by higher twist contributions (see later)

QCD at large s

Meson production at HERA

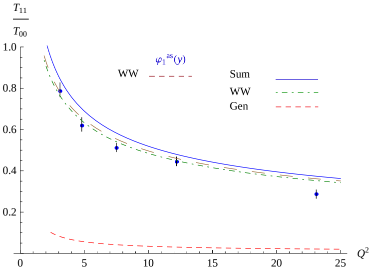
Exclusive vector meson production:
Comparaison of our model with H1 data

- Model for the proton impact factor:

$$\Phi_{N\to N}(\underline{k},\underline{\Delta};M^2) = A\,\delta_{ab}\left[\frac{1}{M^2+\left(\frac{\underline{\Delta}}{2}\right)^2} - \frac{1}{M^2+\left(\underline{k}-\frac{\underline{\Delta}}{2}\right)^2}\right].$$

$\Phi_{N\to N} \to 0$ if $\underline{k} \to 0$ or $\underline{\Delta} - \underline{k} \to 0$

- Very satisfying results: (note that the sign is also a prediction)



A. Besse, I. V. Anikin, D. Y. Ivanov, B. Pire, L. Szymanowski and S. W, to be submitted

The specific case of QCD at large s

Phenomenological applications: exclusive processes at Tevatron, RHIC, LHC, ILC

Exclusive $\gamma^{(*)}\gamma^{(*)}$ processes = gold place for testing QCD at large s

Proposals in order to test perturbative QCD in the large s limit (t-structure of the hard $\mathbb{P}$omeron, saturation, $\mathbb{O}$dderon...)

- $\gamma^{(*)}(q) + \gamma^{(*)}(q') \to J/\Psi\, J/\Psi$ Kwiecinski, Motyka '98
- $\gamma^*_{L,T}(q) + \gamma^*_{L,T}(q') \to \rho_L(p_1) + \rho_L(p_2)$ process in $e^+e^- \to e^+e^-\rho_L(p_1) + \rho_L(p_2)$ with double tagged lepton at ILC

  Pire, Szymanowski, S. W. '04; Pire, Szymanowski, Enberg, S. W. '06; Ivanov, Papa '06; Segond, Szymanowski, S. W. '07

  conclusion: feasible at ILC (high energy and high luminosity); BFKL NLL enhancement with respect to Born and DGLAP contributions
- What about the $\mathbb{O}$dderon? C-parity of $\mathbb{O}$dderon = -1
  consider $\gamma + \gamma \to \pi^+\pi^-\pi^+\pi^-$: $\pi^+\pi^-$ pair has no fixed C-parity
  $\Rightarrow$ Odderon and Pomeron can interfere
  $\Rightarrow$ Odderon appears linearly in the charge asymmetry
  Pire, Schwennsen, Szymanowski, S. W. '07
  = example of possibilities offered by ultraperipheral exclusive processes (p, $\bar{p}$ or A as effective sources of photon)
  but the distinction with pure QCD processes (with gluons intead of a photon) is tricky...

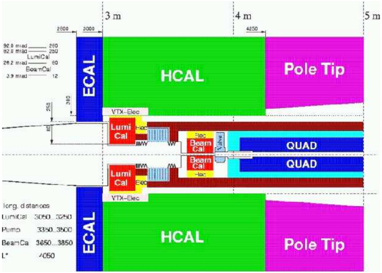
The specific case of QCD at large s

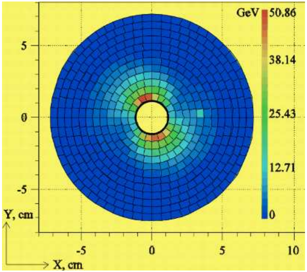
Phenomenological applications: exclusive test of $\mathbb{P}$omeron

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

It make sense to focus on tests of QCD in the perturbative Regge limit at future ILC for rare exclusive processes:

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



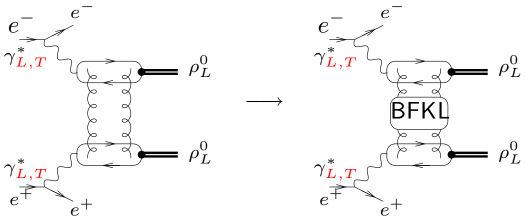


good efficiency of tagging for outgoing $e^\pm$ for $E_e > 100$ GeV and $\theta > 4$ mrad (illustration for LDC concept)

The specific case of QCD at large s

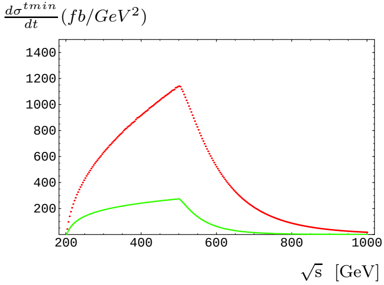
Phenomenological applications: exclusive test of $\mathbb{P}$omeron

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

Beyond leading twist

Light-Cone Collinear Factorization versus Covariant Colinear Factorization

- The Light-Cone Collinear Factorization, a new self-consistent method, while non-covariant, is very efficient for practical computations
  Anikin, Ivanov, Pire, Szymanowski, S.W. '09
  - inspired by the inclusive case
    Ellis, Furmanski, Petronzio '83; Efremov, Teryaev '84
  - axial gauge
  - parametrization of matrix element along a light-like prefered direction $z = \lambda\, n \ (n = 2\, p_2/s)$.
  - non-local correlators are defined along this prefered direction, with contributions arising from Taylor expansion up to needed term for a given twist order computation
  - their number is then reduced to a minimal set combining equations of motion and $n-$independency condition
- Another approach (Braun, Ball), fully covariant but much less convenient when practically computing coefficient functions, can equivalently be used
- We have established the dictionnary between these two approaches
- This as been explicitly checked for the $\gamma^*_T \to \rho_T$ impact factor at twist 3
  Anikin, Ivanov, Pire, Szymanowski, S.W. '09

Beyond leading twist
Light-Cone Collinear Factorization

Light-Cone Collinear Factorization

- Sudakov expansion in the basis $p \sim p_\rho,\, n$ ($p^2 = n^2 = 0$ and $p \cdot n = 1$)

$$l_\mu \;=\; u\, p_\mu \;+\; l^\perp_\mu \;+\; (l\cdot p)\, n_\mu, \qquad u = l \cdot n$$

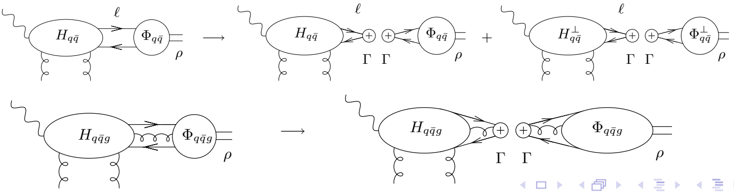
$$1 \qquad\qquad 1/Q \qquad\qquad 1/Q^2$$

- Taylor expansion of the hard part $H(\ell)$ along the collinear direction p:

$$H(\ell) = H(up) \;+\; \left.\frac{\partial H(\ell)}{\partial \ell_\alpha}\right|_{\ell=up} (\ell - u\,p)_\alpha + \dots \quad \text{avec} \quad (\ell - u\,p)_\alpha \approx \ell^\perp_\alpha$$

- $l^\perp_\alpha \xrightarrow{Fourier}$ derivative of the soft term: $\int d^4z\, e^{-i\ell\cdot z} \langle \rho(p)|\psi(0)\, i\, \overleftrightarrow{\partial_{\alpha\perp}}\, \bar\psi(z)|0\rangle$

- after Fierz, this gives



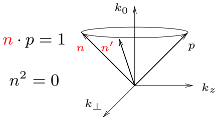
Beyond leading twist

Light-Cone Collinear Factorization

Minimal set of DAs

- Number of non-perturbative quantities Φ: a priori 7 at twist 3
- Non-perturbative correlators cannot be obtained perturbatively!
- One should reduce their number to a minimal set before any use of a model or any measure on the QCD lattice
- independence w.r.t the choice of the vector n defining
  - the light-cone direction z: $z = \lambda n$
  - the ρ_T polarization vector: $e_T \cdot n = 0$
  - the axial gauge: $n \cdot A = 0$

$$\mathcal{A} = H \otimes S \qquad \frac{d\mathcal{A}}{dn_\perp^\mu} = 0 \Rightarrow S \text{ are related}$$



- We have proven that 3 independent Distribution Amplitude are necessary:

$$\begin{cases} \text{Equations of motion} & \text{2 equations} \\ \text{Arbitrariness in the choice of } n & \text{2 equations} \end{cases}$$

$\phi_1(y) \quad \leftarrow$ 2-body twist 2 correlator
$B(y_1, y_2) \quad \leftarrow$ 3-body genuine twist 3 vector correlator
$D(y_1, y_2) \quad \leftarrow$ 3-body genuine twist 3 axial correlator

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 (see talk of L. Szymanowski), 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, ILC

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