Electroproduction of hybrid 1-+ mesons

Samuel Wallon

Laboratoire de Physique Théorique
Orsay

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in collaboration with
I. V. Anikin (JINR, Dubna), B. Pire (CPhT-X, Palaiseau) O. V. Teryaev (JINR, Dubna) and L. Szymanowski (SINS, Varsaw)

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Outline

Exotic hybrid mesons
Spectroscopy

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:

$$\begin{array}{llll} S=0\,, & L=J, & J=0,\,1,\,2,\ldots: & J^{PC}=0^{-+},\,1^{+-},\,2^{-+},\,3^{+-},\,\ldots \\ S=1\,, & L=0\,, & J=1\,: & J^{PC}=1^{--} \quad \rho-\text{meson} \\ & L=1\,, & J=0,\,1,\,2\,: & J^{PC}=0^{++},\,1^{++},\,2^{++} \\ & L=2\,, & J=1,\,2,\,3\,: & J^{PC}=1^{--},\,2^{--},\,3^{--} \\ \ldots & & & \end{array}$$

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

Exotic hybrid mesons

Experimental status

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 $\pm$ 20 MeV $\quad \Gamma = 180 \pm 30$ MeV
  - E852 '97 (BNL): $\pi^- \, p \to \eta \, \pi^- \, p$
    M=1370 $\pm$ 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 $\pm$ 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 $\pm$ 20 MeV $\quad \Gamma = 310 \pm 50$ MeV
    and M=1360 $\pm$ 25 MeV $\quad \Gamma = 220 \pm 90$ MeV

Exotic hybrid mesons

Experimental status

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 $b_1(1235)\pi^-$)

Exotic hybrid mesons
Motivation for hard production

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: $q\bar{q}g \Rightarrow$ higher Fock-state component $\Rightarrow$ twist-3 $\Rightarrow$ hard electroproduction suppressed as $1/Q$
- This is not true!! Electroproduction of hybrid is similar to electroproduction of usual $\rho-$meson: it is twist 2

A short journey in collinear factorization
Extensions from DIS

A short journey in collinear factorization

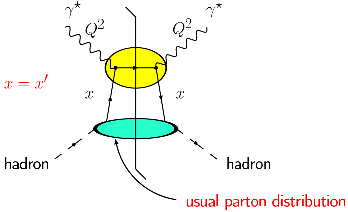
- DIS: inclusive process $\longrightarrow$ forward amplitude ($t = 0$)

  (DIS: Deep Inelastic Scattering)

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

  Structure Function

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

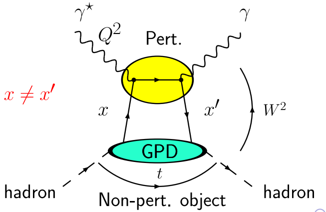


- DVCS: exclusive process $\longrightarrow$ non forward amplitude ($-t \ll s = W^2$)

  (DVCS: Deep Vitual Compton Scattering)

  Amplitude

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



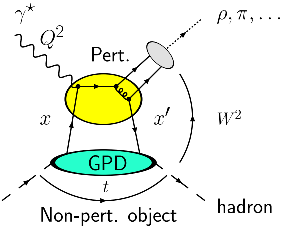
A short journey in collinear factorization
Extensions from DIS

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

Amplitude

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

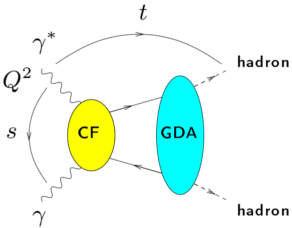
$x \neq x'$



- Crossed process: $s \ll -t$

Amplitude

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



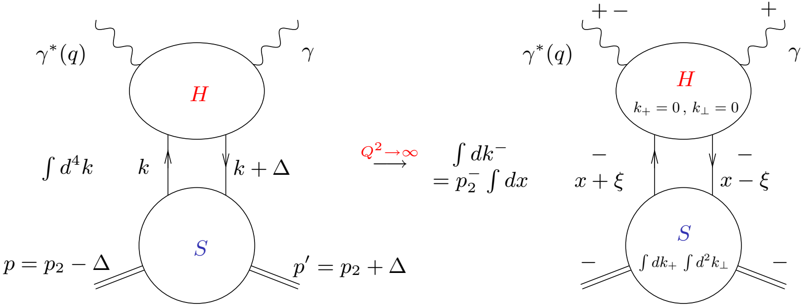
Diehl, Gousset, Pire, Teryaev '98

$\rho-$electroproduction
DVCS and GPD

Two steps for factorization

- momentum factorization: use Sudakov decomposition

$$\underset{}{k} = \underset{+}{\alpha\, p_1} + \underset{-}{\beta\, p_2} + \underset{\perp}{k_\perp} \quad (p_1^2 = p_2^2 = 0,\ 2p_1 \cdot p_2 = s)$$



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

- supplement with Fierz identity in spinor + color space

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

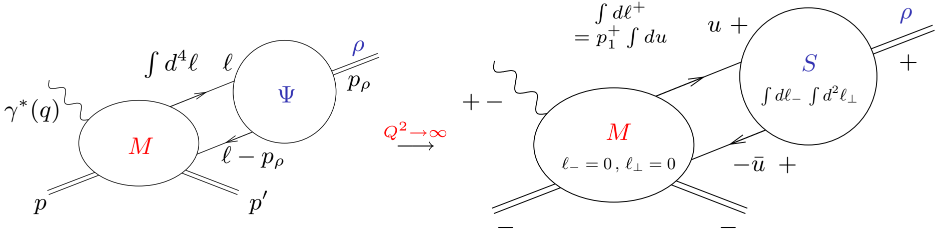
Müller et al. '91 - '94; Radyushkin '96; Ji '97

$\rho-$electroproduction

$\rho-$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



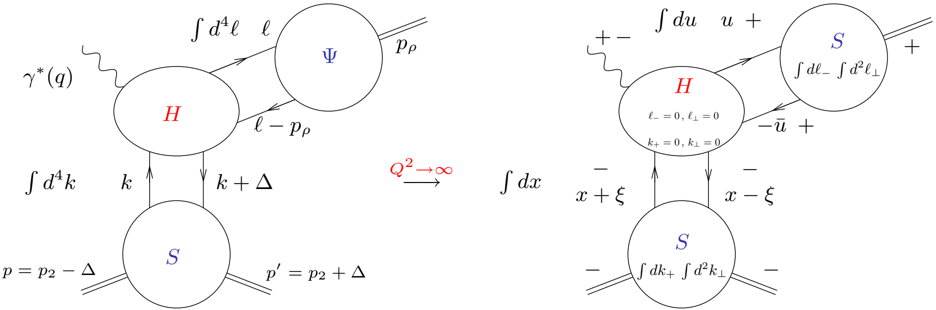
$$\int d^4\ell\; M(q,\,\ell,\,\ell - p_\rho)\Psi(\ell,\,\ell - p_\rho) \;= \int d\ell^+\, M(q,\,\ell^+,\,\ell^+ - p_\rho^+)\;\int d\ell^- \int^{|k_\perp^2| < \mu_F^2} d^2\ell_\perp\,\Psi(\ell,\,\ell - p_\rho)$$

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)

$\rho-$electroproduction

$\rho-$meson production: factorization with a GPD and a DA



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

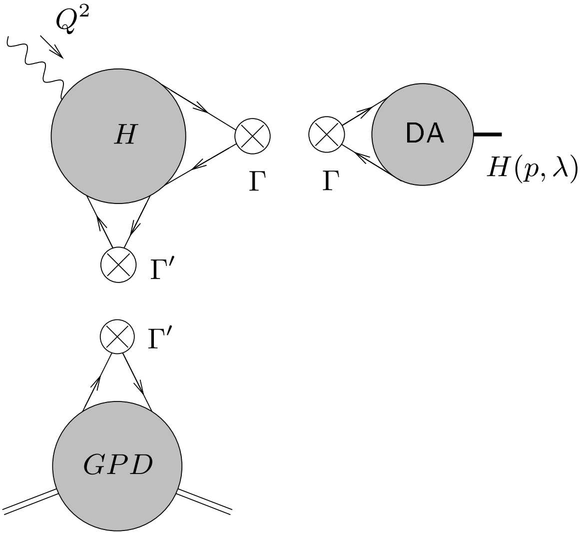
$$= \int dk^- d\ell^+ \int dk^+ \int^{|k_\perp^2| < \mu_{F_2}^2} d^2k_\perp\, S(k,\, k+\Delta)\, H(q;\, k^-,\, k^- + \Delta^-;\ell^+,\, \ell^+ - p_\rho^+) \int d\ell^- \int^{|\ell_\perp^2| < \mu_{F_1}^2} d^2\ell_\perp\, \Psi(\ell,\, \ell - p_\rho)$$

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

Collins, Frankfurt, Strikman '97; Radyushkin '97

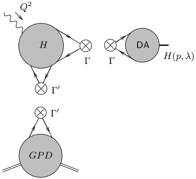
Factorization for hybrid meson electroproduction

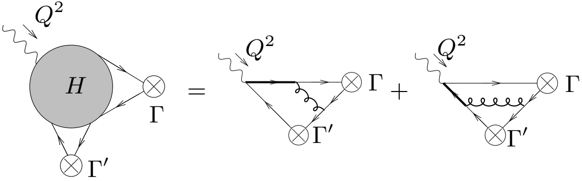
Factorization framework



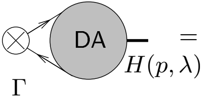
Factorization for hybrid meson electroproduction

The building blocks

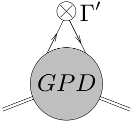




hand-bag diagrams



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



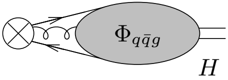
$= \langle N(p')|\mathcal{O}'(\Psi,\ \bar{\Psi}\ A)|N(p)\rangle$ matrix element of a non-local light-cone operator

Hybrid Distribution Amplitude

Hybrid DA from non-local twist 2 operator

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 explicitely 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 with respect to usual ρ-production (which is twist 2)
- But one of the main progress is the understanding of hard exclusive processes in terms of non-local light-cone operators, like 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 which thus hides gluonic degrees of freedom: the needed gluon is there, at twist 2. This does not requires to introduce explicitely A!

Hybrid Distribution Amplitude
Hybrid DA from non-local twist 2 operator

Distribution amplitude and quantum numbers: C-parity

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

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

- Inserting $\mathcal{C}$-parity operator gives antisymmetric DA for H^0

$$\phi_L^H(y) = -\phi_L^H(1-y) \quad \text{while the usual } \rho \text{ DA is symmetric}$$

- Expansion in terms of local operators

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

D_μ = usual covariant derivative and $\overset{\leftrightarrow}{D}_\mu = \frac{1}{2}(\vec{D}_\mu - \overset{\leftarrow}{D}_\mu)$.

- Special case $n = 0$:

$$\langle H(p,0)\ |\psi(0)\gamma_\mu\psi(0)|\ 0\rangle = i f_H M_H e_\mu^{(0)}\int_0^1 dy\,\phi_L^H(y) = 0$$

$$C = (+) \qquad C = (-)$$

no surprise: we expect here the $C = (-)$ $\rho-$meson

Hybrid Distribution Amplitude

Hybrid DA from non-local twist 2 operator

Distribution amplitude and quantum numbers: C-parity and P-parity

- the hybrid selects the odd-terms

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

- Special case $n=1$:

$$\mathcal{R}_{\mu\nu} = \mathsf{S}_{(\mu\nu)}\bar{\psi}(0)\gamma_\mu \overleftrightarrow{D}_\nu \psi(0),$$

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

- Relation with hybrid DA:

$$\langle H(p,\lambda)|\mathcal{R}_{\mu\nu}|0\rangle = \frac{1}{2} f_H\, M_H\, \mathsf{S}_{(\mu\nu)}\, e_\mu^{(\lambda)}\, p_\nu \int_0^1 dy(1-2y)\phi^H(y), \qquad (1)$$

- C-parity: $C(R_{\mu\nu}) = +$
- P-parity: $P(R_{k0}) = -$ ($\leftarrow$ after going to rest-frame: $p_i = 0$ and $e_0 = 0$)

Hybrid Distribution Amplitude

Normalization

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

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

Hybrid electroproduction

H versus ρ

Amplitude for H versus ρ electroproduction

- At leading twist 2:
$$\mathcal{A}(\gamma_L^* \, p \to H_L^0 \, p) = \int_0^1 dz \int_{-1}^1 dx \, \Phi_H(z, \mu_F^2, \mu_R^2) \, H(x, z, Q^2, \mu_F^2, \mu_R^2) \, F(x, \mu_F^2, \mu_R^2)$$
μ_F^2 = factorization scale; μ_R^2 = renormalization scale; we take $\mu_F = \mu_R$.
- $C-$parity:

$$\begin{bmatrix} C_H = (+) \text{ odd DA labeled } M^- \\ C_\rho = (-) \text{ even DA labeled } M^+ \end{bmatrix} \times (C_\gamma = (-)) = \begin{bmatrix} C_{q-\bar{q}} = (-) \text{ even GPD under } x \leftrightarrow -x \\ C_{q+\bar{q}} = (+) \text{ odd GPD under } x \leftrightarrow -x \end{bmatrix}$$

$$\mathcal{A}_{\gamma_L^* p \to M_L^{(\pm)0} p} = \frac{e\pi\alpha_s f_H \, C_F}{\sqrt{2} \, N_c \, Q} \left[e_u \mathcal{H}_{uu}^{\pm} - e_d \mathcal{H}_{dd}^{\pm} \right] \mathcal{V}^{(M,\pm)},$$

$$\mathcal{H}_{ff}^{\pm} = \frac{1}{P^-} \int_{-1}^{1} dx \left[\bar{u}(p_2)\gamma^- u(p_1) H_{ff}(x,\xi) + \bar{u}(p_2) \frac{i\sigma_{-\alpha}\Delta^\alpha}{2M} u(p_1) E_{ff}(x,\xi) \right] \left[\frac{1}{x+\xi-i\epsilon} \pm \frac{1}{x-\xi+i\epsilon} \right]$$

$$\mathcal{V}^{(M,\pm)} = \int_0^1 dy \, \phi^M(y) \left[\frac{1}{y} \pm \frac{1}{1-y} \right].$$

- No end-point singularity $\frac{1}{y}$ since $\phi^H(y)$ vanishes for $y \to 0, 1$

Hybrid electroproduction
H versus ρ

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.* $x \in [0,1]$

    $\Rightarrow ImA_H$ and ImA_ρ are equal up to the factor $\mathcal{V}^M$
  - Neglect the effect of $Re\mathcal{A}$

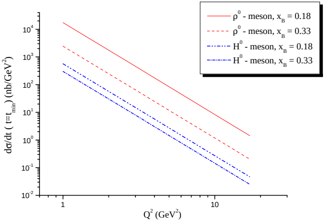
$$\frac{d\sigma^H(Q^2, x_B, t)}{d\sigma^\rho(Q^2, x_B, t)} \approx \left(\frac{5 f_H}{3 f_\rho} \right)^2 \approx 0.15$$

Hybrid electroproduction
H versus ρ

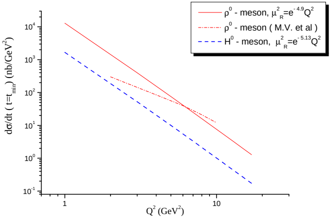
Counting rates for H versus ρ electroproduction: more precise study

- use standard description of GPDs based on Double Distributions
- $\mu_R^2 = Q^2$ versus BLM scale from NLO (at the level of cross-section)

$\xi = 0.2$	$\mu_R^2 = e^{-4.9}Q^2$	ρ	$\xi = 0.1$	$\mu_R^2 = e^{-4.68}Q^2$	ρ
(or $x_B \approx 0.33$)	$\mu_R^2 = e^{-5.13}Q^2$	H	(or $x_B \approx 0.18$)	$\mu_R^2 = e^{-5.0}Q^2$	H



$\mu_R^2 = \mu_F^2 = Q^2$



$\mu_R^2 = \mu_F^2 = \mu_{BLM}^2 \quad x_B \approx 0.33$

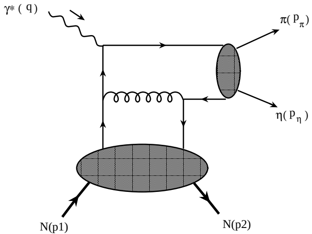
Ratio $d\sigma^H/d\sigma^\rho$: rather scale-fixing independent

x_B	0.33				0.18			
Q^2 (GeV^2)	3.0	7.0	11.0	17.0	3.0	7.0	11.0	17.0
$\mu_R^2 = Q^2$	0.123	0.123	0.123	0.123	0.0325	0.0326	0.0326	0.0326
$\mu_R^2 = \mu_{BLM}^2$	0.131	0.133	0.133	0.134	0.0356	0.0362	0.0365	0.0367

Hybrid in electroproduction of $\pi\eta$ pair

Hard hybrid production study through its decay mode

- We consider here for illustration the $\pi_1(1400)$
- Dominant decay mode: $\pi\eta$
- $\pi\eta$ can be $J^{PC} = 0^{++}\ (f_0, a_0),\ 1^{-+}(\pi_1),\ 2^{++}\ (a_2)$ for $L = 0,\ 1,\ 2$
- Mass region around 1400 MeV dominated by the strong $a_2(1329)(2^{++})$ resonance
  $\Rightarrow$ look for interference of the amplitudes for H and a_2 production
  $\Rightarrow$ identify the hybrid production events if there is no recoil detector
- This study can be performed in the hard factorization framework:
  Distribution Amplitude ϕ^H $\longrightarrow$ Generalized Distribution Amplitude $\phi^{\pi\eta}$

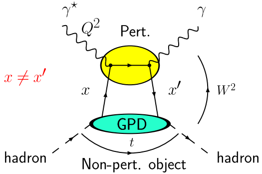


Hybrid in electroproduction of $\pi\eta$ pair

$\pi^0\eta$ GDA

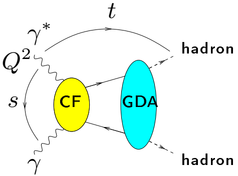
GDA

- GDA is obtained from GPD by $s \leftrightarrow t$ crossing



GPD : $s \gg -t$ limit, with $Q^2 \gg \Lambda^2_{QCD}$

$\rightarrow$ GDA : $-t \gg s$ limit, with $Q^2 \gg \Lambda^2_{QCD}$



- kinematics: (x, ξ) (GPD) $\longrightarrow$ (y, ζ) (GDA)

$$y = \frac{\text{long. momentum of the quark}}{\text{total outgoing hadronic momentum}} \qquad \zeta = \frac{p_+}{p_+ + p'_+} = \frac{\text{long. momentum of one of the hadron}}{\text{total outgoing hadronic momentum}}$$

- For $\pi^0\eta$: $\langle \pi^0(p_\pi)\eta(p_\eta)|\bar{\psi}_{f_2}(-z/2)\gamma^\mu[-z/2;z/2]\tau^3_{f_2 f_1}\psi_{f_1}(-z)|0\rangle$

$$= p^\mu_{\pi\eta}\int_0^1 dy e^{i(\bar{y}-y)p_{\pi\eta}\cdot z/2}\Phi^{(\pi\eta)}(y,\zeta,m^2_{\pi\eta}) + \dots$$ (only twist 2 part displayed here)

Hybrid in electroproduction of $\pi\eta$ pair

$\pi^0\eta$ GDA and polar angle distribution

From GDA to polar angle distribution

- Two particles of equal mass: $\zeta \longrightarrow$ two different particles $\tilde{\zeta}$:

$$\tilde{\zeta} = \frac{p_\pi^+}{(p_\pi + p_\eta)^+} - \frac{m_\pi^2 - m_\eta^2}{2m_{\pi\eta}^2}\,, \qquad 1 - \tilde{\zeta} = \frac{p_\eta^+}{(p_\pi + p_\eta)^+} + \frac{m_\pi^2 - m_\eta^2}{2m_{\pi\eta}^2}$$

- Relation with the polar angle of the π meson in the $\pi\eta$ c.m.s:

$$2\tilde{\zeta} - 1 = \beta\,\cos\theta_{cm}\,, \qquad \beta = \frac{2|\mathbf{p_{cms}}|}{m_{\pi\eta}}$$

- Expansion of the $C = (+)$ GDA (now with $\zeta \longrightarrow \tilde{\zeta}$):

$$\Phi^{q(+)}(y, \tilde{\zeta}, ; \mu^2) = 10z(1-z) \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sum_{\substack{l=0 \\ \text{even}}}^{n+1} B_{nl}^q(m_{\pi\eta}, \mu^2)\, C_n^{3/2}(2y-1)\, P_l(2\tilde{\zeta}-1)$$

  - $l < n+1$ from polynomiality (relation of y-moments with matrix elements of local operators, constrainted by Lorentz invariance)
  - as for DA, Legendre polynomials $C_n^{3/2}$ appear due to conformal invariance: basis for QCD evolution with respect to the scale μ^2, like x^n for PDFs

Hybrid in electroproduction of $\pi\eta$ pair

$\pi^0\eta$ GDA and polar angle distribution

From GDA to polar angle distribution: model

- We consider the asymptotical limit $\mu^2 \to \infty$:

$$\Phi^{(\pi\eta),\,a}(y,\tilde{\zeta},m^2_{\pi\eta}) = 10y(1-y)C_1^{(3/2)}(2y-1)\sum_{l=0}^{2} B_{1l}(m^2_{\pi\eta})P_l(\cos\theta)$$

Keeping only $L=1$ (π_1) and $L=2$ (a_2) terms:

$$\Phi^{(\pi\eta)}(y,\zeta,m^2_{\pi\eta}) = 30y(1-y)(2y-1)\Big[B_{11}(m^2_{\pi\eta})P_1(\cos\theta)+B_{12}(m^2_{\pi\eta})P_2(\cos\theta)\Big]$$

- $B_{11}(m^2_{\pi\eta})$ and $B_{12}(m^2_{\pi\eta})$ are related to corresponding Breit-Wigner amplitudes for $m^2_{\pi\eta} \approx M^2_{a_2},\, M^2_H$:

$$B_{11}(m^2_{\pi\eta})\Big|_{m^2_{\pi\eta}\approx M^2_H} = \frac{5}{3}\,\frac{g_{H\pi\eta}f_H M_H\beta}{M^2_H - m^2_{\pi\eta} - i\Gamma_H M_H}$$

and

$$B_{12}(m^2_{\pi\eta})\Big|_{m^2_{\pi\eta}\approx M^2_{a_2}} = \frac{10}{9}\,\frac{i g_{a_2\pi\eta}f_{a_2}M^2_{a_2}\beta^2}{M^2_{a_2} - m^2_{\pi\eta} - i\Gamma_{a_2}M_{a_2}}.$$

Hybrid in electroproduction of $\pi\eta$ pair

$\pi^0\eta$ cross-section

Differential cross-section for $\pi^0\eta$ electroproduction

- Amplitude of $\pi^0\eta$ electroproduction
(for $e(k_1) + N(p_1) \to e(k_2) + \pi^0(p_\pi) + \eta(p_\eta) + N(p_2)$):

$$|T^{\pi^0\eta}|^2 = \frac{4e^2(1-y_l)}{Q^2 y_l^2} |\mathcal{A}^{\pi^0\eta}_{(q)}|^2 .$$

with (for $\gamma^*(q) + N(p_1) \to \pi^0(p_\pi) + \eta(p_\eta) + N(p_2)$):

$$\mathcal{A}^{\pi^0\eta}_{(q)} = \frac{e\pi\alpha_s C_F}{N_c\, Q}\left[e_u\mathcal{H}_{uu} - e_d\mathcal{H}_{dd}\right]$$

$$\times\left[B_{11}(m^2_{\pi\eta})P_1(\cos\theta_{cm}) + B_{12}(m^2_{\pi\eta})P_2(\cos\theta_{cm})\right]$$

twist 2 scaling like for the usual $\rho \to \pi^+\pi^-$ channel

- Differential cross-section for
$e(k_1) + N(p_1) \to e(k_2) + \pi^0(p_\pi) + \eta(p_\eta) + N(p_2)$:

$$\frac{d\sigma^{\pi^0\eta}}{dQ^2\, dy_l\, d\hat{t}\, dm_{\pi\eta}\, d(\cos\theta_{cm})} = \frac{1}{4(4\pi)^5}\,\frac{m_{\pi\eta}\beta}{y_l\lambda^2(\hat{s},-Q^2,m_N^2)}\,|T^{\pi^0\eta}|^2$$

$\hat{t} = (p_2 - p_1)^2$, $y_l = \frac{p_1\cdot q}{p_1\cdot k_1}$

Hybrid in electroproduction of $\pi\eta$ pair

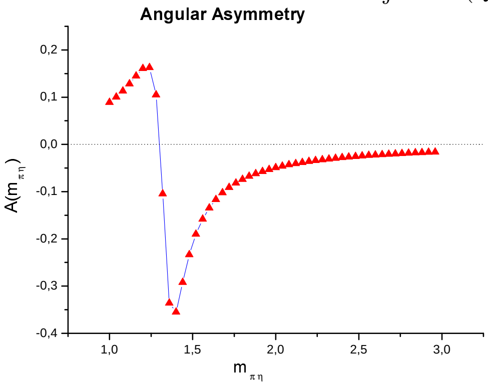
Angular asymmetry

Angular asymmetry to unravel the hybrid meson

- π_1 has rather small amplitude with respect to the a_2 background
- Asymmetry sensitive to their interference:

$$A(Q^2, y_l, \hat{t}, m_{\pi\eta}) = \frac{\int \cos\theta_{cm}\, d\sigma^{\pi^0\eta}(Q^2, y_l, \hat{t}, m_{\pi\eta}, \cos\theta_{cm})}{\int d\sigma^{\pi^0\eta}(Q^2, y_l, \hat{t}, m_{\pi\eta}, \cos\theta_{cm})}$$

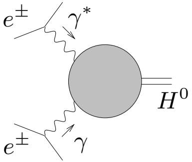
$$= \frac{\frac{8}{15}\mathcal{R}e\left[B_{11}(m^2_{\pi\eta})B_{12}{}^*(m^2_{\pi\eta})\right]}{\frac{2}{3}\left|B_{11}(m^2_{\pi\eta})\right|^2 + \frac{2}{5}\left|B_{12}(m^2_{\pi\eta})\right|^2}$$



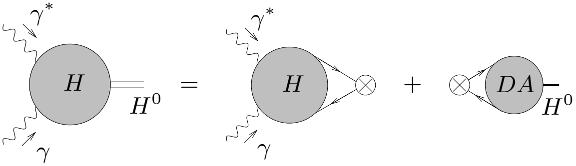
Hybrid meson production in $\gamma^*\gamma$
Factorized picture

Hybrid meson production in e^+e^- colliders

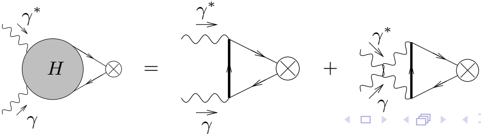
- Hybrid can be copiously produced in $\gamma^*\gamma$, i.e. at e^+e^- colliders with one tagged out-going electron



- This can be described in a hard factorization framework:



with



Hybrid meson production in $\gamma^*\gamma$

Cross-section

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 asymptotic DAs:

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

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

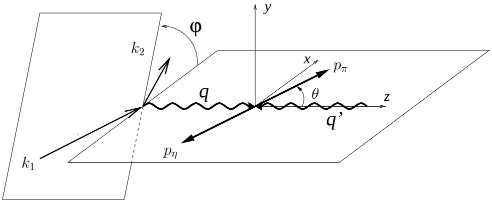
$$\frac{d\sigma^H}{d\sigma^{\eta}} \approx 46\%$$

Hybrid meson production in $\gamma^*\gamma$

$\pi\eta$ channel

Cross-section for $\gamma^*\gamma \to \pi\eta$ and angular distribution

- An estimation of the cross-section can be done using a model for the $\pi\eta$ GDA
- It requires to model the background, and results are rather model dependent for $\sigma^{\pi\eta}$
- A detailled study of the (φ, θ) angular distribution of the $\pi\eta$ final state could give a direct access to the strength of the twist 3 amplitude



Hybrid meson production in $\gamma^*\gamma$

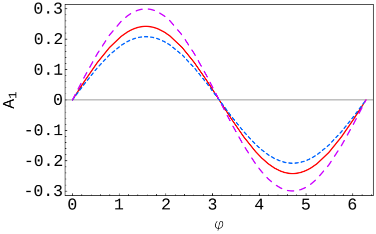
$\pi\eta$ channel

SSA for $\gamma^*\gamma \to \pi\eta$ with polarized lepton

- Scattering of a longitudinally polarized lepton on an unpolarized photon: direct access to the interference of twist 2 with twist 3 amplitudes through the Single Spin Asymmetry

$$\mathcal{A}_1(s_{e\gamma}, Q^2, W^2; \varphi) = \frac{\int d\cos\theta_{cm}(d\sigma^{(\rightarrow)} - d\sigma^{(\leftarrow)})}{\int d\cos\theta_{cm}(d\sigma^{(\rightarrow)} + d\sigma^{(\leftarrow)})}$$

- Results for a background phase $\alpha = 0$ and various choices of background amplitudes: sizable asymmetry



$W = 1.4\,\text{GeV}$, $Q^2 = 5.0\,\text{GeV}^2$, $s_{e\gamma} = 10\,\text{GeV}^2$, $\alpha = 0$. The solid line corresponds to $K = 0.8$, the short-dashed line to $K = 1.0$, the long-dashed line to $K = 0.5$

Conclusion

- Hybrid mesons H are a key stone for our understanding of QCD
- There are now strong candidates for $J^{PC} = 1^{-+}$
- As a first step, one should determine their mass, width and quantum numbers, as well as their decay modes
- A second step should be to determine their partonic content
- These questions can be adressed in hard processes
- $\Rightarrow$ Access to their light-cone wave function (Distribution Amplitudes)
- Hard hybrid production is governed by twist 2 operators
- The non-perturbative coupling f_H can be evaluated from QCD sum-rules
- The rates for electroproduction (or muoproduction!) are very sizable:

$$\frac{d\sigma^H(Q^2, x_B, t)}{d\sigma^\rho(Q^2, x_B, t)} \approx \left(\frac{5 f_H}{3 f_\rho}\right)^2 \approx 15\% \quad \rightarrow \text{JLab, COMPASS}$$

- The DA can be replaced by the GDA of the decay modes
- $\Rightarrow$ Framework for angular asymmetry with the dominant background (e.g. $\pi_1(1400)(1^{-+}) + a_2(1329)(2^{++})$ interference within the $C = (+)$ $\pi\eta$ GDA)
- $\gamma^*\gamma \rightarrow H^0$ at e^+e^- colliders is also very promising

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

- H subleading twist content accessible using SSA with polarized lepton