SuperB: an ideal place for uncovering hadronic structure in $\gamma^* \gamma^{(*)}$ exclusive reactions

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in collaboration with
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Introduction: Exclusive processes at medium/high energy QCD
Motivation

Since a decade, there have been many developments in studies of hard exclusive processes.

- form factors $\longrightarrow$ Distribution Amplitudes
- DVCS$\longrightarrow$ Generalized Parton Distributions,
- $\cdots$

These tests are possible in fixed target experiments

- $e^{\pm}p$: HERA (HERMES), JLab, ...

as well as in colliders, mainly for fixed s

- $e^{\pm}p$ colliders: HERA (H1,ZEUS)
- $e^{+}e^{-}$ colliders: LEP, Belle, BaBar, BEPC

At the same time, the interest for phenomenological tests of hard Pomeron and related resummed approaches has become pretty wide:

- inclusive tests (total cross-section) and semi-inclusive tests (diffraction, forward jets, ...)
- exclusive tests (meson production, ...)

These tests concern all type of collider experiments:

- $e^{\pm}p$: (HERA: H1, ZEUS)
- $p\bar{p}$ (TEVATRON: CDF, D0)
- $e^{+}e^{-}$ colliders (LEP, ILC)

We will focus on a specific exclusive process:

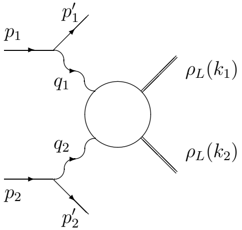
$$\boxed{\gamma^* \gamma^* \longrightarrow \rho_L^0 \rho_L^0} \qquad \text{with both } \gamma^* \text{ hard}$$

It is a beautiful theoretical laboratory for investigating different dynamics (collinear, multiregge) and factorization properties of high energy QCD:

- at low energy (fixed s) it provides an (almost) full perturbative laboratory for extended GPDs: GDA and TDA
- at high energy (asymptotic s) it provides an (almost) full perturbative laboratory for BFKL and related resummed effects, at amplitude level.

The corresponding experimental process is

$$e^+ e^- \longrightarrow e^+ e^- \rho_L^0 \rho_L^0$$



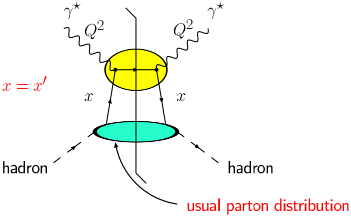
with double tagged outoing leptons.

GPD and GDA for $\gamma^*\gamma^* \to \rho_L^0 \rho_L^0$: collinear factorization

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

Structure Function

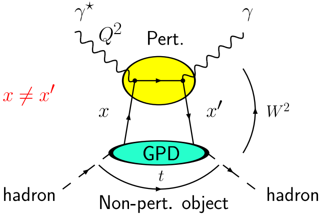
= Coefficient Function (hard) $\otimes$ Parton Distribution Funct (soft)



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

Amplitude

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

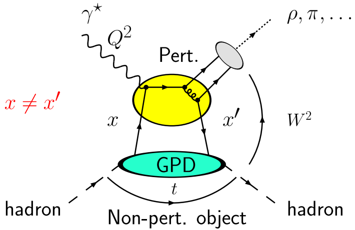


Extensions:

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

Amplitude

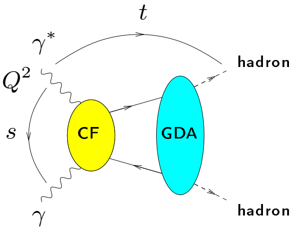
= GPD (soft) $\otimes$ CF (hard) $\otimes$ Distribution Amplitude (soft)



- Crossed process: $s \ll -t$

Amplitude

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

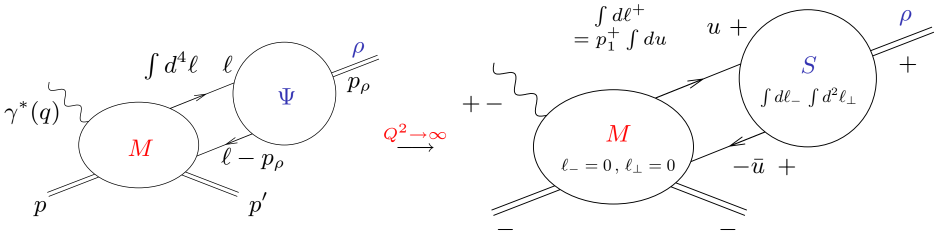


What is $\rho-$meson in QCD ?

Chernyak, Zhitnitsky '77; Brodsky, Lepage '79; Efremov, Radyushkin '80; ...

Example: the electroproduction of ρ_L-meson

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 $\Phi(u,\mu_F^2)$

What is $\rho-$meson in QCD ?

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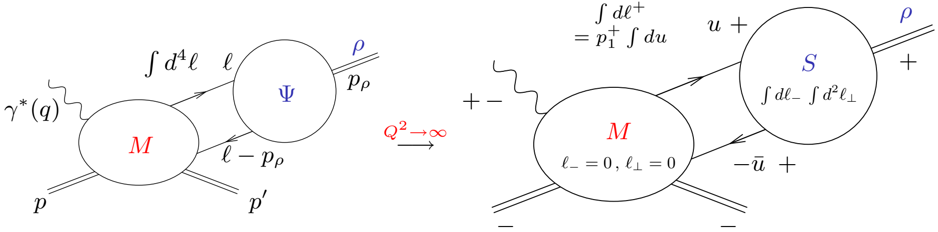


$$\int d^4\ell\ M(q,\,\ell,\,\ell-p_\rho)\Psi(\ell,\,\ell-p_\rho) = \int d\ell^+\ M(q,\,\ell^+,\,\ell^+-p_\rho^+)\ \int d\ell^-\int^{|k_\perp^2|<\mu_F^2} d^2\ell_\perp\ \Psi(\ell,\,\ell-p_\rho)$$

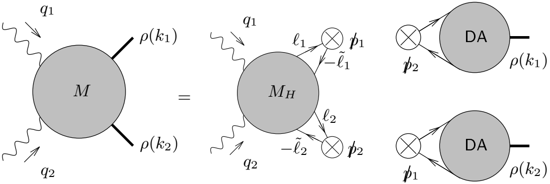
Hard part — DA $\Phi(u,\mu_F^2)$

$$\langle 0|\bar{q}(x)\,\gamma^\mu\ q(-x)|\rho_L(p)=\bar{q}q\rangle = f_\rho\ p^\mu \int_0^1 dz\, e^{i(2z-1)(px)}\phi(z)$$

with $\phi(z) = 6z(1-z)\left(1+\sum_{n=1}^{\infty} a_{2n}C_{2\,n}^{3/2}(2z-1)\right)$

Collinear factorization at $q\bar{q}\rho$ vertices

$Q^2_{1,2}$: hard scales $\Rightarrow$ collinear approximation at each $q\bar{q}\rho$ vertex



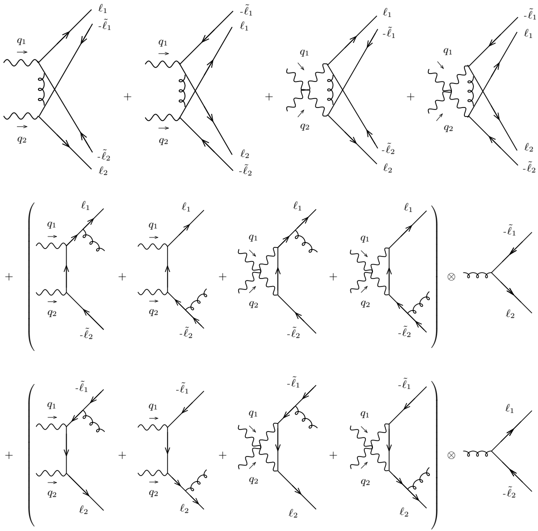
i.e. we neglect the transverse relative (anti-)quark momenta in the ρ mesons:

$$\ell_1 \sim z_1\, k_1 \qquad \ell_2 \sim z_2\, k_2$$
$$\tilde{\ell}_1 \sim \bar{z}_1\, k_1 \qquad \tilde{\ell}_2 \sim \bar{z}_2\, k_2$$

We limit ourselves to longitudinaly polarized mesons

Transversally polarized photons

One needs to compute 12 diagrams.



Transversally polarized photons

Results

$$T^{\alpha\,\beta} g_{T\,\alpha\,\beta} = -\frac{e^2(Q_u^2+Q_d^2)\,g^2\,C_F\,f_\rho^2}{4\,N_c\,s}\int\limits_0^1 dz_1\,dz_2\,\phi(z_1)\,\phi(z_2)$$

$$\times\left\{2\left(1-\frac{Q_2^2}{s}\right)\left(1-\frac{Q_1^2}{s}\right)\left[\frac{1}{(z_2+\bar z_2\frac{Q_1^2}{s})^2(z_1+\bar z_1\frac{Q_2^2}{s})^2}+\frac{1}{(\bar z_2+z_2\frac{Q_1^2}{s})^2(\bar z_1+z_1\frac{Q_2^2}{s})^2}\right]+\right.$$

$$\left.\left(\frac{1}{\bar z_2\,z_1}-\frac{1}{\bar z_1\,z_2}\right)\left[\frac{1}{1-\frac{Q_2^2}{s}}\left(\frac{1}{\bar z_2+z_2\frac{Q_1^2}{s}}-\frac{1}{z_2+\bar z_2\frac{Q_1^2}{s}}\right)-\frac{1}{1-\frac{Q_1^2}{s}}\left(\frac{1}{\bar z_1+z_1\frac{Q_2^2}{s}}-\frac{1}{z_1+\bar z_1\frac{Q_2^2}{s}}\right)\right]\right\}$$

Same remark:

Q_1^2 and Q_2^2 are non-zero and DA vanishes at $z_i=0$

$\Rightarrow$ no end-point singularity in the z_i integration

Interpretation in terms of QCD Factorization

GDA for transverse photon in the limit $\Lambda^2_{QCD} \ll W^2 \ll Max(Q_1^2, Q_2^2)$

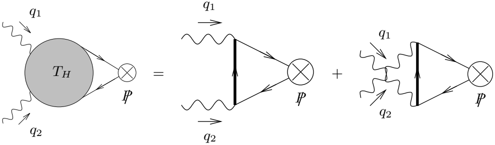
When W^2 is smaller then the highest photon virtuality the result obtained from direct calculation simplifies into

$$T^{\alpha\,\beta} g_{T\,\alpha\,\beta} \approx \frac{e^2(Q_u^2+Q_d^2)\,g^2\,C_F\,f_\rho^2}{4\,N_c\,W^2} \times \int_0^1 dz_1\,dz_2 \left(\frac{1}{\bar z_1 + z_1\frac{Q_2^2}{s}} - \frac{1}{z_1 + \bar z_1\frac{Q_2^2}{s}}\right)\left(\frac{1}{\bar z_2\,z_1} - \frac{1}{\bar z_1\,z_2}\right)\phi(z_1)\,\phi(z_2)$$

Interpretation in terms of QCD Factorization

GDA for transverse photon in the limit $\Lambda^2_{QCD} \ll W^2 \ll Max(Q_1^2, Q_2^2)$: PROOF

Hard Part computation at Born order



In the case of one flavored quark, it equals:

$$T_H(z) = -4\, e^2\, N_c\, Q_q^2 \left(\frac{1}{\bar{z} + z\, \frac{Q_2^2}{s}} - \frac{1}{z + \bar{z}\, \frac{Q_2^2}{s}} \right)$$

Interpretation in terms of QCD Factorization

GDA for transverse photon in the limit $\Lambda^2_{QCD} \ll W^2 \ll Max(Q_1^2, Q_2^2)$: PROOF

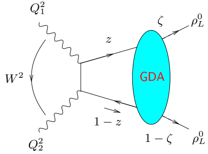
GDA computation

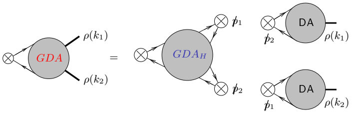
At leading twist, the GDA is calculated in the Born order of perturbation theory

$$\langle \rho_L^0(k_1)\, \rho_L^0(k_2) | \bar{q}(-\alpha\, n/2)\, \not{n}\, \exp\left[ig \int_{-\frac{\alpha}{2}}^{\frac{\alpha}{2}} dy\, n_\nu\, A^\nu(y) \right] q(\alpha\, n/2) | 0 \rangle$$

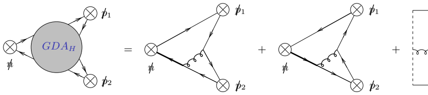
$$= \int_0^1 dz\, e^{-i(2z-1)\alpha(nP)/2}\, \Phi^{\rho_L^0 \rho_L^0}(z, \zeta, W^2)$$

$(P \sim p_1$ and $n \sim p_2$ for $Q_1 > Q_2)$





with



$$\Phi^{\rho_L \rho_L}(z, \zeta \approx 1, W^2) = -\frac{f_\rho^2\, g^2\, C_F}{2\, N_c\, W^2} \int_0^1 dz_2\, \phi(z)\, \phi(z_2) \left[\frac{1}{z \bar{z}_2} - \frac{1}{\bar{z} z_2} \right]$$

Interpretation in terms of QCD Factorization

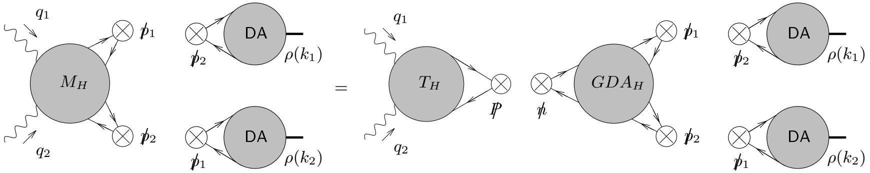
GDA for transverse photon in the limit $\Lambda^2_{QCD} \ll W^2 \ll Max(Q_1^2, Q_2^2)$

Thus the result obtained from direct calculation

$$T^{\alpha\,\beta} g_{T\,\alpha\,\beta} \approx \frac{e^2 (Q_u^2 + Q_d^2)\, g^2\, C_F\, f_\rho^2}{4\, N_c\, W^2}$$

$$\times \int_0^1 dz_1\, dz_2 \left(\frac{1}{\bar{z}_1 + z_1 \frac{Q_2^2}{s}} - \frac{1}{z_1 + \bar{z}_1 \frac{Q_2^2}{s}} \right) \left(\frac{1}{\bar{z}_2\, z_1} - \frac{1}{\bar{z}_1\, z_2} \right) \phi(z_1)\, \phi(z_2)$$

factorises as

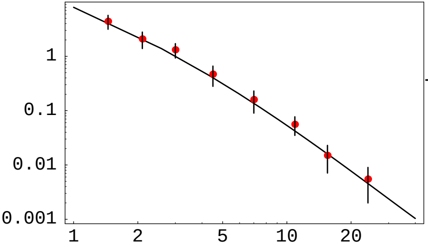


with calculable the hard T_H and the "soft" $\rho_L\ \rho_L$ GDA

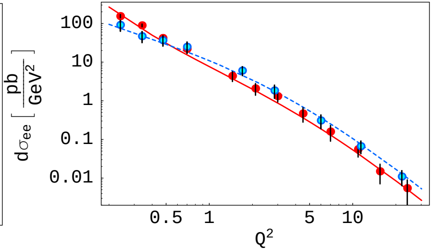
$\rho\ \rho$-GDA and L3 data

Anikin et al Phys. Rev. D 69 (2004) 014018

Check of the scaling in Q^2



$\rho^0\ \rho^0$



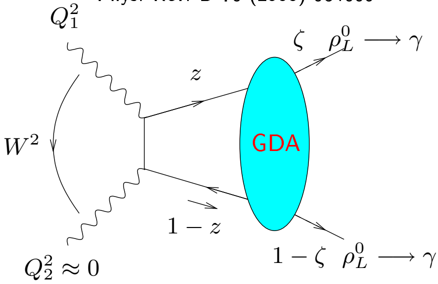
$\rho^0\ \rho^0$ (red) vs $\rho^+\ \rho^-$ (blue)

- early scaling
- higher twist component (isospin 2 contribution or $q\,\bar{q}\,q\,\bar{q}$)

Anomalous $\gamma\gamma$ GDA

QED calculations

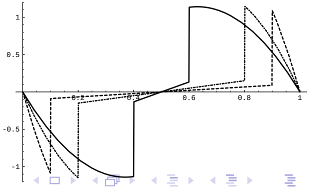
Phys. Rev. D 78 (2008) 034009



6 one-loop QED diagrams in LLA

$$\Phi_1^q(z,\zeta,0) = \frac{N_C\, e_q^2}{2\pi^2} \log\frac{Q^2}{m^2}\left[\frac{\bar{z}(2z-\zeta)}{\bar{\zeta}}\theta(z-\zeta) + \frac{\bar{z}(2z-\bar{\zeta})}{\zeta}\theta(z-\bar{\zeta})\right.$$

$$\left. + \frac{z(2z-1-\zeta)}{\zeta}\theta(\zeta-z) + \frac{z(2z-1-\bar{\zeta})}{\bar{\zeta}}\theta(\bar{\zeta}-z)\right]$$



unpolarized anomalous GDA

Realistic predictions for π π GDA

M. Diehl, T. Gousset, B. Pire Phys. Rev. D 62 073014

- predictions with experimental cuts of BABAR

	BABAR e^- tagged	BABAR e^+ tagged
α_{1L}^{min} [mrad]	300	684
$(\pi - \alpha_{1L}^{max})$ [mrad]	684	300
θ_L^{min} [mrad]	300	684
$(\pi - \theta_L^{max})$ [mrad]	684	300
σ [fb]	329	433
σ_G [fb]	6	12
σ_B [fb]	323	422
$S_{ee}(\mathrm{sgn}(\cos\varphi))$ [fb]	−31	48
$S_{ee}(\cos\varphi)$ [fb]	−24	38
$\sqrt{N}\,\delta(\mathrm{sgn}(\cos\varphi))$	10.5	8.9
$\sqrt{N}\,\delta(\cos\varphi)$	9.0	7.8

TABLE II. As Table I but with cuts imposed on the detection angles as specified, and in addition a minimum transverse momentum for the tagged lepton and for both pions of 100 MeV in the laboratory. E_1, E_2 and α_{2L}^{max} for each column are the same as in Table I.

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 $\Gamma = 180 \pm 30$ MeV
  - E852 '97 (BNL): $\pi^- \, p \to \eta \, \pi^- \, p$
    M=1370 $\pm$ 16 MeV $\Gamma = 385 \pm 40$ 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 $\Gamma = 287 \pm 25$ 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 $\Gamma = 310 \pm 50$ MeV
    and M=1360 $\pm$ 25 MeV $\Gamma = 220 \pm 90$ 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?

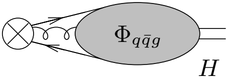
- hybrid mesons = $q\bar{q}g$ states T. Barnes '77; R. L. Jaffe, K. Johnson, and Z. Ryzak, G. S. Bali
- popular belief: $q\bar{q}g \Rightarrow$ higher Fock-state component $\Rightarrow$ twist-3 $\Rightarrow$ hard electroproduction suppressed as $1/Q$
- This is not true!! Electroproduction of hybrid is similar to electroproduction of usual $\rho-$meson: it is twist 2

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
- $1/Q^2$ suppression of H production with respect to ρ_L-production (TWIST 2)

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.)

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

- Inserting C-parity operator gives antisymmetric DA for H^0

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

- 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:

$$\langle H(p,\lambda)|\mathcal{R}_{\mu\nu}|0\rangle = \frac{1}{2} f_H M_H \ \mathsf{S}_{(\mu\nu)}\, e^{(\lambda)}_\mu p_\nu \int\limits_0^1 dy(1-2y)\phi^H(y),$$

- 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)
- Lattice does not yet give information
- 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

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 ReA

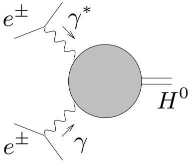
$$\frac{d\sigma^H(Q^2, x_B, t)}{d\sigma^\rho(Q^2, x_B, t)} \approx \left(\frac{5 f_H}{3 f_\rho}\right)^2 \approx 0.15$$

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

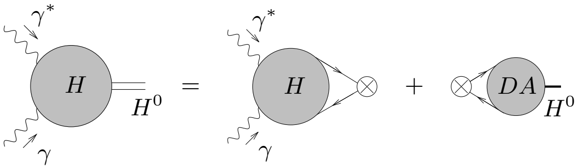
Factorized picture

Hybrid meson production in e^+e^- colliders

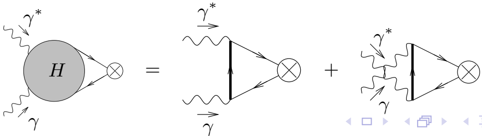
- Hybrid can be copiously produced in $\gamma^*\gamma$, i.e. at e^+e^- colliders with one tagged out-going electron



- 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:

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

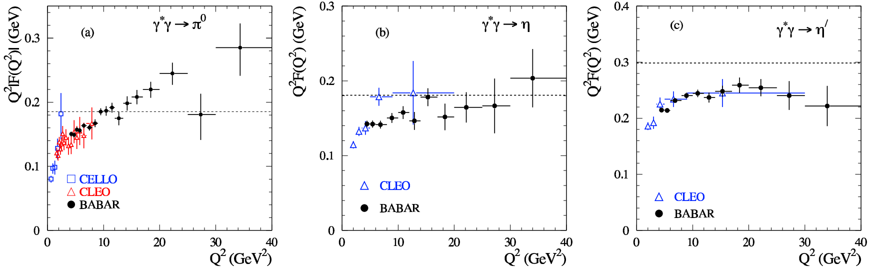
still larger than 20% at $Q^2\approx 1$ GeV^2 (including kinematical twist-3 effects à la Wandzura-Wilczek for the H^0 DA) and similarly

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

BABAR data

Experimental possibilities

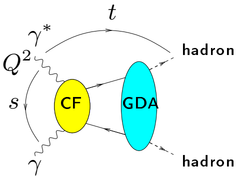
BABAR



Hybrid in electroproduction of $\pi\eta$ pair

$\pi^0\eta$ GDA

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



- GDA variables: (y, ζ)

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

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

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

Hybrid in electroproduction of $\pi\eta$ pair

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

Model of $\pi\eta$ GDA

- 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:

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

- $B_{11}(m^2_{\pi\eta})$ 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

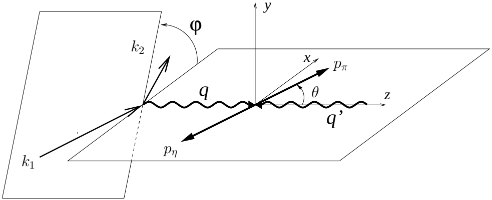
$$B_{12}(m^2_{\pi\eta})\Big|_{m^2_{\pi\eta}\approx M^2_{a_2}} = \frac{10}{9}\,\frac{ig_{a_2\pi\eta}f_{a_2}M^2_{a_2}\beta^2}{M^2_{a_2} - m^2_{\pi\eta} - i\Gamma_{a_2}M_{a_2}}.$$

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

$\pi\eta$ channel

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

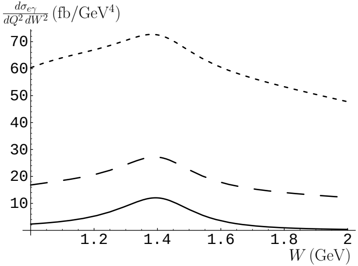
- An estimation of the cross-section can be done using a model for the $\pi\eta$ GDA
- It requires to model the background, and results are rather model dependent for $\sigma^{\pi\eta}$
- A detailled study of the (φ, θ) angular distribution of the $\pi\eta$ final state could give a direct access to the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



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

$\pi\eta$ channel

Predictions for differential cross section



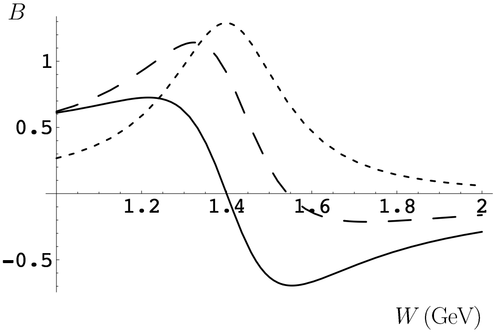
The differential cross section for $\pi\eta$ pair production as a function of W for $Q = 3$GeV, $y = 0.3$, for different background magnitudes: K=0 (solid), 0.5 (dashed), 1 (dotted)

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

$\pi\eta$ channel

Angular distribution of $\pi\eta$ pair

$$W(\theta,\phi) = \left(\frac{d\sigma(Q^2,W^2)}{dQ^2 dW^2}\right)^{-1} \frac{d\sigma_{e\gamma\to e\,\pi\eta}}{dQ^2\,dW^2\,d\cos\theta\,d\varphi} = \frac{1}{4\pi}[A + B\cos\theta + C\cos^2\theta + D\sin 2\theta\cos\phi + E\sin\theta\cos\phi]$$



gure 7: The B component of the angular distribution function as a function of the $\pi\eta$ mass W for $Q = 3\,\text{GeV}$, $y = 0.3$
nd $K = 1$, for different background phases $\alpha = 0$ (solid curve), $\pi/4$ (dashed curve) and $\pi/2$ (dotted curve).

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

Conclusion

There is a lot of exciting physics in studies of

exclusive processes in $\gamma^{(*)}\,\gamma^{(*)}$ scattering in which

SuperB can play VERY IMPORTANT role !

Refs.:

Phys.Lett.B556 (2003)129, Phys.Rev.D70 (2004) 011501, Phys.Rev.D71 (2005) 034021, Eur.Phys.J.C42 (2005) 163, Eur.Phys.J.C47 (2006) 71.