Quarks and Gluons in $p\bar{p}$ Annihilations

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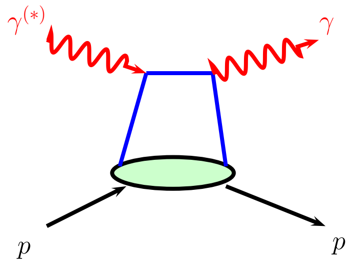
Outline:

- **Factorization schemes**
- **Handbag factorization in the time-like region**
- $B\bar{B}$ **distribution amplitudes**
- **Results for** $\gamma\gamma \leftrightarrow B\bar{B}$
- **The crossed process - wide-angle Compton scattering**
- $p\bar{p} \to \gamma M$
- **Gluons in exclusive charmonium decays**
- **Short and long range dynamics**
- **P-wave decays and the color-octet mechanism**
- **Summary**

Handbag factorization in excl. reactions

wide angles: large $s, -t, -u$ deeply virtual: large Q^2

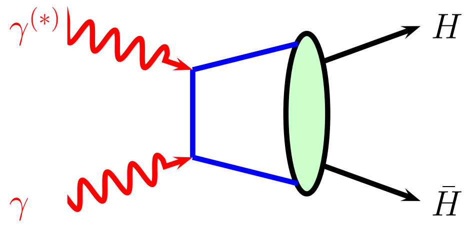
only one active parton (others are spectators, collinear fact.)



GPD

$\gamma^{(*)}p \to \gamma p$

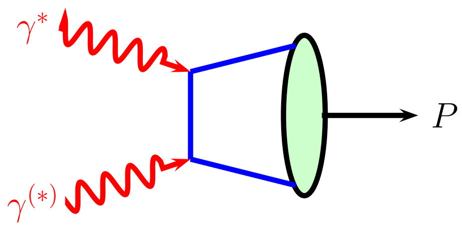
$\gamma^{(*)}p \to Mp$



TDA

$\gamma^{(*)}\gamma \to p\bar{p}, \pi\pi, \ldots$

$p\bar{p} \to \gamma^{(*)}\gamma, \gamma\pi, \ldots$

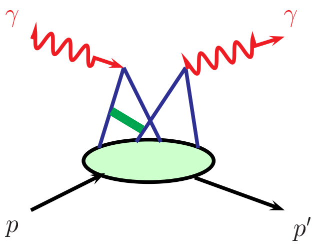


meson DA

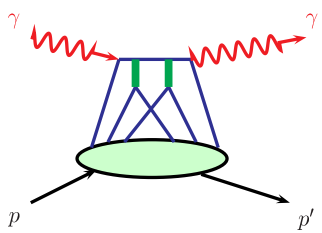
$\gamma\pi(\eta, \eta')$ transition FF

other topologies - expected to be suppressed

two active partons



three active partons



(hard gluons required)

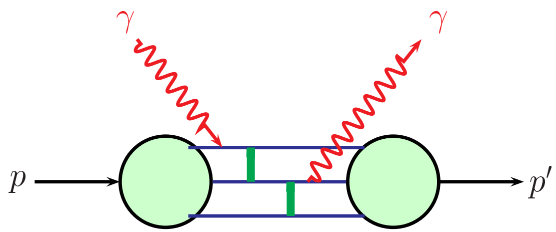
$\Longrightarrow$

valence

quark appr.

ERBL factorization

wide angles: large $s, -t, -u$ all valence quarks participate in hard process



GPD blob decays into two DAs

asymptotically dominant

handbag formally a power correction

e.g. proton: AS: $\Phi \propto x_1 x_2 x_3$ $\langle x_i \rangle = 1/3$

end-point dominated (CZ) $\langle x_i \rangle \simeq 0.1$

AS forms: results strongly suppressed by several orders of magnitude

CZ forms: $\simeq 10^{-1}$; e.g. Compton, $p\bar{p} \leftrightarrow \gamma\gamma$) (for pions closer to experiment)

Difficulty: gluon virtualities $\propto x_i y_j t$ tiny! use of pert. theory inconsistent

(limit $x_i y_j t \to 0$ handbag)

onset of ERBL region probably above $-t(-u) > 100\,\mathrm{GeV}^2$

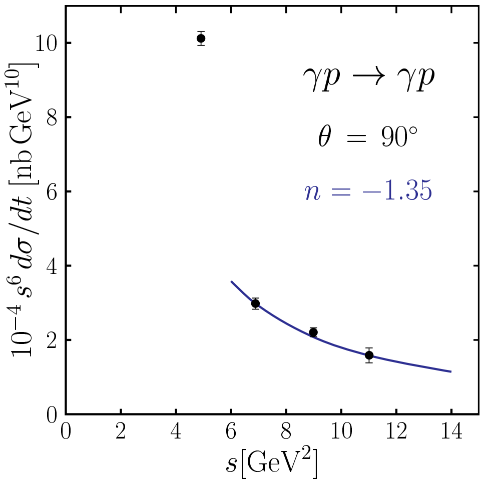
Modified pert. approach (Sterman et al)

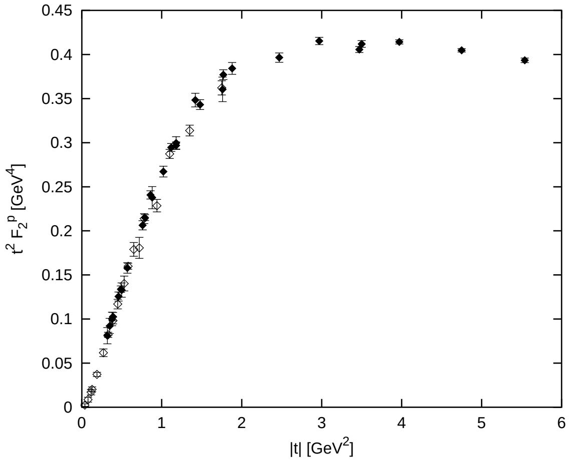
keep $k_\perp$ of quarks, accompanied by gluon radiation (Sudakov)

$\Rightarrow \propto x_i y_j t - k_\perp^2$ soft regions suppressed but results are small

Dimensional counting

Matveev et al; Brodsky-Farrar $\mathcal{O} \propto \frac{\Psi_1(0)\cdots\Psi_m(0)}{Q^{n(m)}}$ (+pert.logs) for $Q^2 \to \infty$





$d\sigma/dt(\gamma p \to \gamma p, \theta fixed) \sim s^{-(7\cdots 8)}$ $\quad s^{-6}$

$F_2^p(t) \sim t^{-2}$ $\quad t^{-3}$

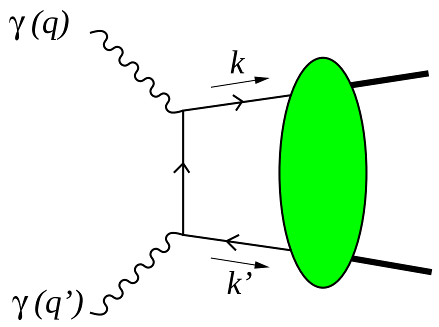
$\sigma(\gamma\gamma \to p\bar{p}) \sim s^{-7.2}$ $\quad s^{-5}$

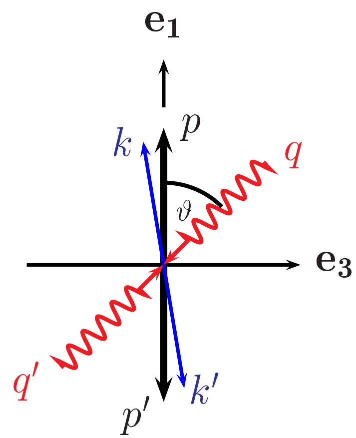
$\sigma(\gamma\gamma \to \pi^+\pi^-) \sim s^{-3.68}$ $\quad s^{-3}$

$\sigma(\gamma\gamma \to K^+K^-) \sim s^{-3.58}$ $\quad s^{-3}$

$d\sigma/dt(p\bar{p} \to p\bar{p}, \theta fixed) \sim ??$ $\quad s^{-10}$

$\gamma\gamma \Leftrightarrow p\bar{p}$





$s, -t, -u \gg \Lambda^2$ symmetrical frame: $p^+ = p'^+$ $\zeta = \frac{p^+}{(p+p')^+} = 1/2$

assumption: parton virtualities are small and $k^2_{\perp i}/x_i < \Lambda^2$

consequences: $2z - 1, \sin\phi \sim \Lambda^2/s$ $(z = k^+/(p^+ + p'^+))$

$\phi \simeq 0$: $k \simeq p$ - quark carries almost full proton momentum

$\phi \simeq \pi$: $k' \simeq p$ - antiquark carries almost full proton momentum (disfavored)

Taylor expansion around $z = 1/2$ and $\phi = 0$ leads to

facorization into hard $\gamma\gamma \leftrightarrow q\bar{q}$ annihilation

and a soft $q\bar{q} \leftrightarrow p\bar{p}$ transitions

$$\frac{d\sigma}{dt}(\gamma\gamma \leftrightarrow p\,\overline{p}\,) = \frac{4\pi\alpha^2_{\rm elm}}{s^2\sin^2\theta}\left\{\left|R^p_A(s) - R^p_P(s)\right|^2 + \cos^2\theta\left|R^p_V(s)\right|^2 + \frac{s}{4m^2}\left|R^p_P(s)\right|^2\right\}$$

can be generalized to $B\overline{B}$

Diehl-K-Vogt, hep-ph/0206288

$B\bar{B}$ distribution amplitudes

$$P^+ \int \frac{dx^-}{2\pi}\, e^{P^+(2z-1)x^-/2}\, \langle B(p)\bar{B}(p')|\bar{q}(\frac{\bar{x}}{2})\gamma^+ q(-\frac{\bar{x}}{2})|0\rangle$$
$$= \Phi_V^q(x,\zeta,s)\bar{u}(p)\gamma^+ v(p') + \Phi_S^q(x,\zeta,s)\frac{P^+}{2m}\bar{u}(p)v(p')$$

and two more TDAs for $\gamma^+\gamma_5$

sum rules

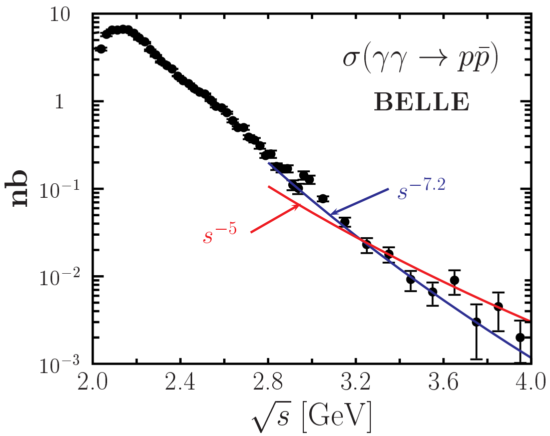
$$F_i^q = \int_0^1 dz \Phi_i^q(z,\zeta,s) \qquad i = V, A, P \qquad (2\zeta - 1)F_S^q = \int_0^1 dz \Phi_S^q(z,\zeta,s)$$

Form factors

$$G_M^p(s) = \sum_q e_q F_V^q(s) \qquad F_2^p(s) = \sum_q e_q F_S^q(s)$$

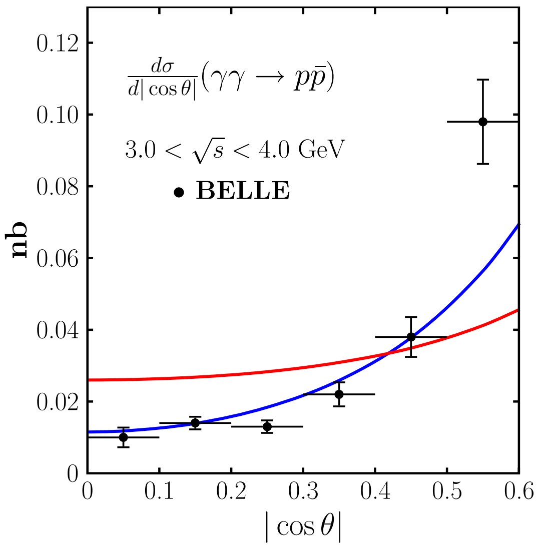
$$R_i^p(s) = \sum e_q^2 F_i^q(s) \qquad \mathrm{i = V, A, P}$$

$\gamma\gamma \to p\overline{p}$



$$s^2 R^p_{\text{eff}} = 2.9\text{GeV}^4 \left(\frac{s}{10.4}\right)^{-1.1}$$
$$s^2 R^p_V = 8.2\text{GeV}^4 \left(\frac{s}{10.4}\right)^{-1.1}$$
$$s^2 |G^p_M| \simeq 3\text{GeV}^4$$

$$R^p_{\text{eff}} = \sqrt{|R^p_A + R^p_P|^2 + \frac{s}{4m^2}|R^p_P|^2}$$



for point-like fermions:

$|R^p_V| = |R^p_A| \qquad R^p_P = 0:$

$\frac{d\sigma}{dt} \propto \frac{1+\cos^2(\theta)}{\sin^2(\theta)}$ (red)

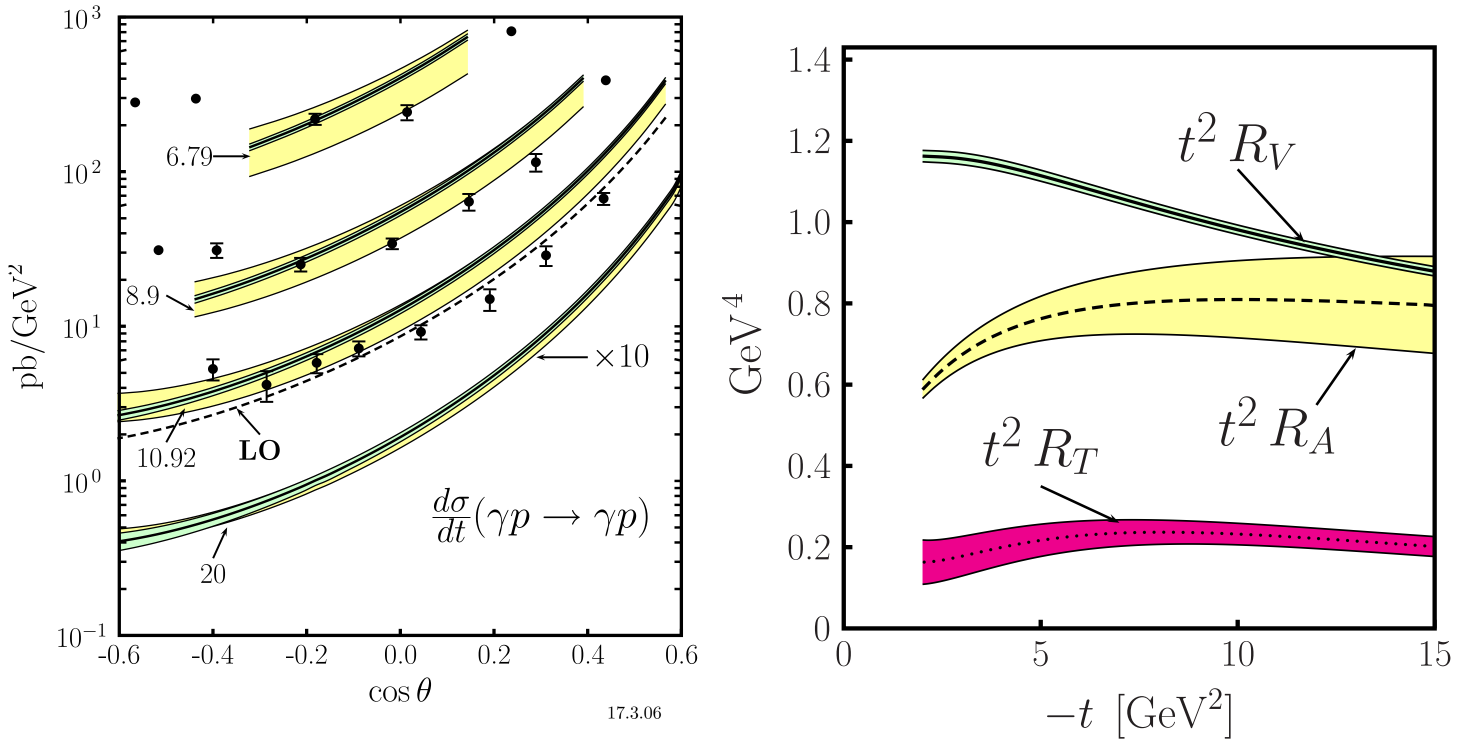
Diehl-K-Vogt, hep-ph/0206288

K-Schäfer, hep-ph/0505258

shopping list for $p\bar{p} \to \gamma\gamma$

- measure cross section at high energies
- extract form factors R_V^p, $R_{\rm eff}^p$
- factorization - form factors independent of t?
- helicity correlation of proton and antiproton allows to determine R_A^p and R_P^p separately
- together with form factors $G_M^{p(n)}$ and $F_2^{p(n)}$ one may attempt an analysis of the $p\bar{p}$ DAs

The Compton cross section



$$\frac{d\sigma}{dt} = \frac{d\hat{\sigma}}{dt}\Big\{\frac{1}{2}\,\frac{(s-u)^2}{s^2+u^2}\,\big[R_V^2(t) + \frac{-t}{4m^2}\,R_T^2(t)\big] + \frac{1}{2}\,\frac{(s+u)^2}{s^2+u^2}\,R_A^2(t)\Big\} + \mathcal{O}(\alpha_s)$$

$\frac{d\hat{\sigma}}{dt}(s,t)$ Klein-Nishina cross section data: JLab E99-114

Compton form factors known from analysis of nucleon FFs

$s \leftrightarrow t$ crossing

Diehl et al, hep-ph/0408173

Time-like reactions

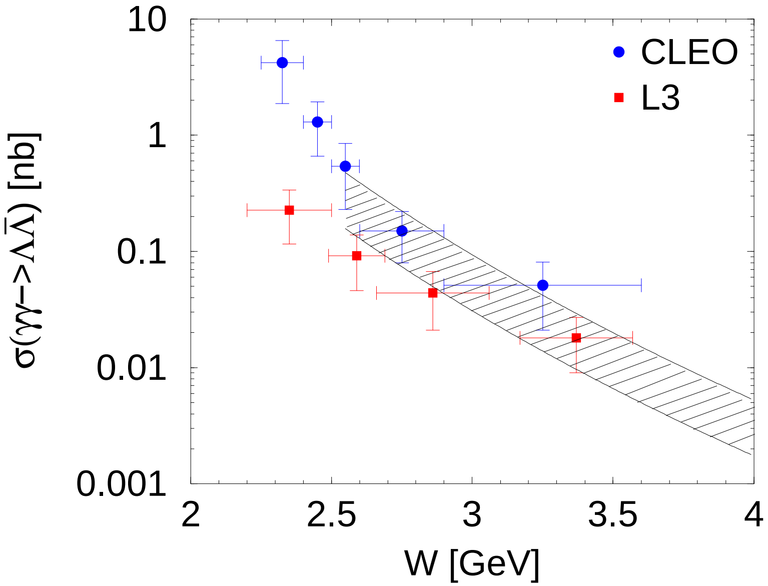
$\gamma\gamma \to p\bar{p}$ BELLE, CLEO, LEP

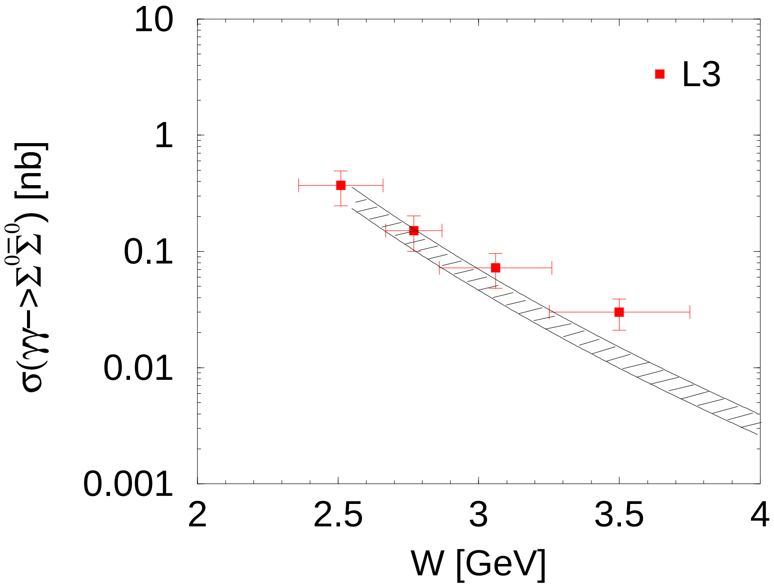
$\to \Lambda\overline{\Lambda},\ \Sigma\overline{\Sigma},\ \pi^+\pi^-,\ K^+K^-,\ K_S\bar{K}_S$

$p\bar{p} \to \gamma\gamma$ FERMILAB

$\to \gamma\pi^0$

$\gamma\gamma \to \Lambda\overline{\Lambda}\,, \Sigma^0\overline{\Sigma}^0$



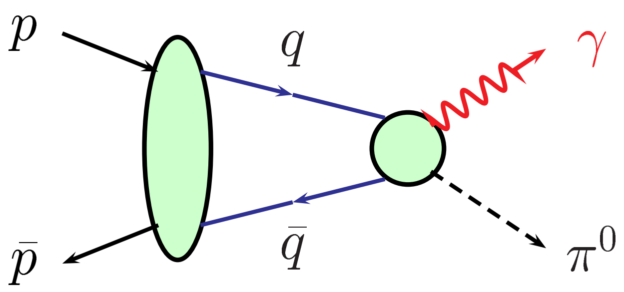


flavor symmetry and valence quark dominance $R_d^p(s) = \rho R_u^p(s)$
($\rho = 1/2$ from simple quark counting)

$W = \sqrt{s}$ cross section integrated over $|\cos\theta| < 0.6$
bands obtained with $\rho = 0.25 - 0.6$

Diehl, K., Vogt, hep-ph/0206288

$p\bar{p} \longrightarrow \gamma\pi^0$



subprocess: $q\bar{q}$ helicity flip only

$H_{+0,+-} = \sqrt{\frac{s}{2}}u\big[C_2 - C_3\big]$

$H_{+0,-+} = -\sqrt{\frac{s}{2}}t\big[C_2 + C_3\big]$

$R_i^{\pi^0} \simeq R_i^{\gamma}$ (universality of TDAs)

CGLN inv. fcts: $C_{2(3)}(t,u) = +(-)\,C_{2(3)}(u,t)$

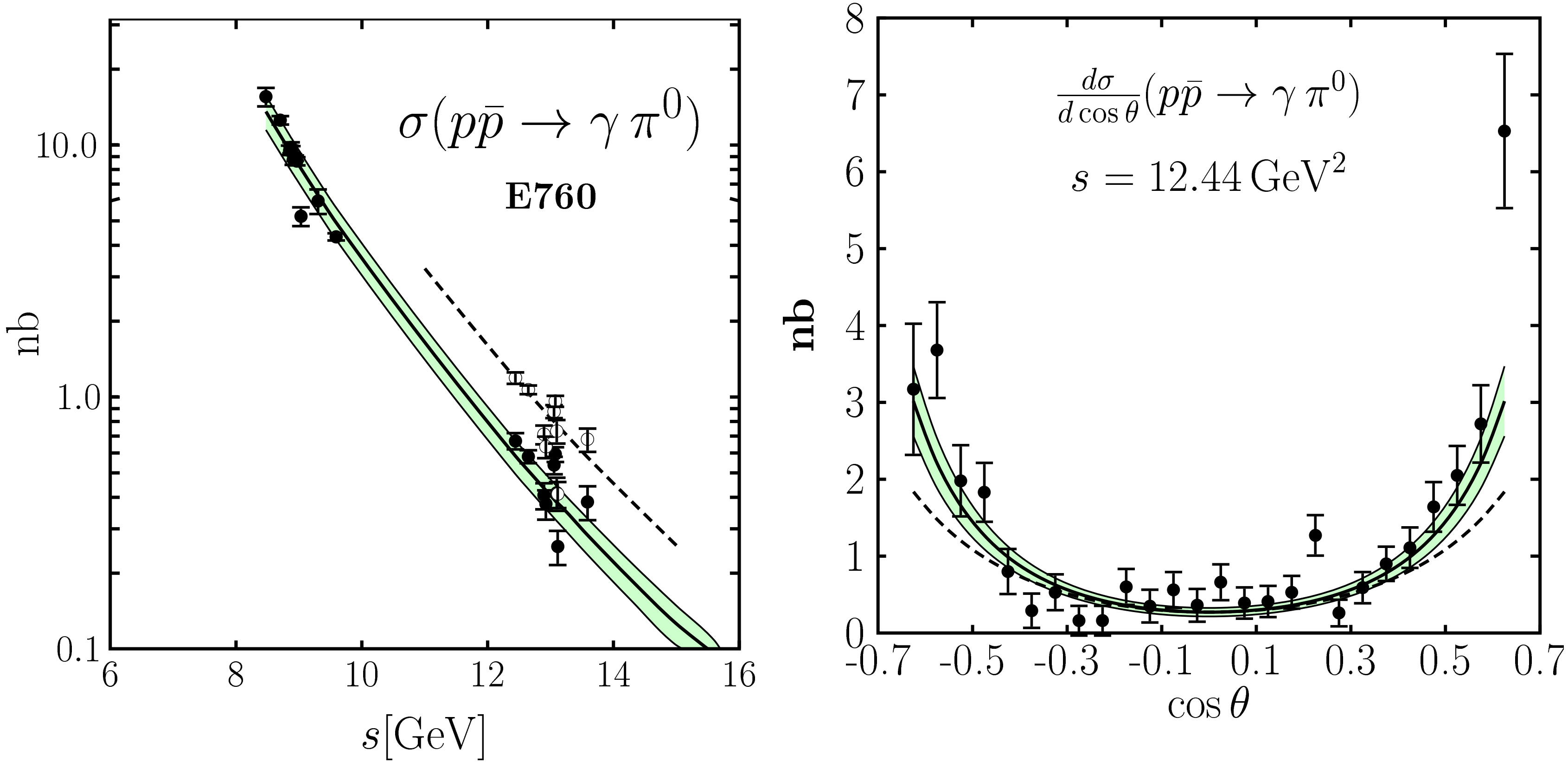
ansatz: $C_3 = 0 \quad C_2 = \frac{a}{tu}$ handbag singularities

$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha_{\rm elm}}{4s^6}\frac{|a|^2}{\sin^4\theta}\,\Big[|s^2R_{\rm eff}^{\pi^0}|^2 + \cos^2\theta\,|s^2R_V^{\pi^0}|^2\Big]$$

one-gluon exchange: same structure but a too small

power corrections? Belitsky: resummation of an infinite number of fermionic loops inserted in gluon propagator

large enhancement factor



data: FNAL E760

dashed lines: $|\cos\theta| \leq 0.6$ (l) $\propto \sin^{-2}\theta$ (r)

solid lines: $|\cos\theta| \leq 0.5$ (l) $\propto \sin^{-4}\theta$ (r)

K-Schäfer, hep-ph/0505258

PANDA: higher energies?

improved accuracy?

$C_2 \ll C_3 : \frac{d\sigma}{d\cos\theta}(90^\circ) = 0$

Extension to other photon-meson channels

$p\bar{p} \to \gamma\eta, \gamma\eta', \gamma V_L$ straightforward

role of two-gluon Fock component of η' may be explored
if it plays a minor role:

$$\frac{d\sigma(p\bar{p} \to \gamma\eta)}{d\sigma(p\bar{p} \to \gamma\eta')} = \cot(\phi)$$

γV_T channel more complicated (new type of TDA)

Gluons in excl. charmonium decays

- dominant mechanism: $c\bar{c} \to ng^* \to m(q\bar{q})$ Duncan-Mueller, BL, CZ
  n minimal number of gluons allowed by color conservation and charge conjugation: J/Ψ: $n=3$; η_c, χ_{cJ}: $n=2$
  factorization in formal limit $m_c \to \infty$

- $c\bar{c}$ annihilate at distances $\lesssim 1/m_c$ typical gluon virtuality $1-2\,\mathrm{GeV}^2$
  pQCD may be applicable

- dominance of $c\bar{c}$ annihilation reflected in narrow width of charmonium decays into light hadrons (appr. - decay into 3 real gluons)

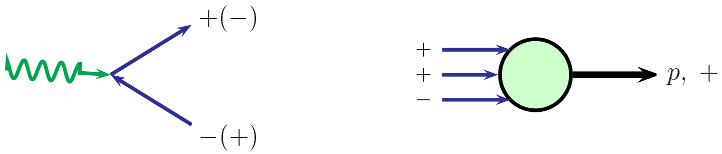
$$\Gamma(J/\Psi \to \mathrm{l.h.}) = \frac{10}{81}\,\frac{\pi^2-9}{\pi e_c^2}\,\frac{\alpha_s^3}{\alpha_{\mathrm{em}}^2}\Gamma(J/\Psi \to e^+e^-) = 205\mathrm{KeV}\,\left(\frac{\alpha_s}{0.3}\right)^3$$

exp: $\simeq 70\,\mathrm{KeV}$ (order of magnitude estimate)

- since $c\bar{c}$ annihilations are required a handbag not possible:
  l.t. contribution + higher twist + higher Fock state + power corrections

leading-twist versus higher-twist mechanism

no systematic discussion of charmonium decays - only a few remarks to highlight various issues



• leading-twist formation of l. h.: time-like g^* (γ^*) create light $q\bar{q}$ pairs with opposite helicities (vector nature of QCD (QED)) $\Longrightarrow \lambda_q + \lambda_{\bar{q}} = 0$
collinear partons form light hadrons
and transfer their helicities to the hadrons $\Longrightarrow \sum \lambda_{\rm had} = 0$
violation of hadronic helicity conservation signals presence of higher-twist and/or power corrections as well as orbital angular momentum

• Such processes have been observed exp. (often with sizeable br. ratios)
occur for P, V channels if $(-)^{J_c} P_c \neq (-)^{J_1+J_2} P_1 P_2$
for $J/\psi(\Psi') \to PV$: $M \propto \varepsilon(p_1, p_2, \epsilon_V, \epsilon_c)$ ($\epsilon(\lambda = 0) = ap_1 + bp_2$ Vs are transv. polarized)
$\eta_c, \chi_{c0} \to B\bar{B}$ angular mom. and parity conservation require $|\sum \lambda_{\rm had}| = 1$

- G parity and/or isospin violating decays

either QED or QCD $\propto m_u - m_d$ (probably small)

for C-even charmonia (e.g. $\eta_c, \chi_{c1} \to \rho\pi, \rho\eta$) not observed

probably mediated by $c\bar{c} \to 2\gamma^* \to h_1 h_2 \quad \mathcal{O}(\alpha_{\rm em}^4)$

many such decays observed for J/ψ (e.g. $\to \pi^+\pi^-$ (G parity), $\omega\pi^0$ (isospin))
typically suppressed by $10^{-2} - 10^{-1}$ as compared to allowed decays

electromag. decay $c\bar{c} \to \gamma^* \to h_1 h_2$

for strange mesons similar suppression by virtue of U-spin invariance

	PP	PV	VV
η_c	$-$	$(\surd)$	ϵ
J/ψ	$(\surd)$	ϵ	$(\surd)$
h_c	$-$	$\surd$	ϵ
χ_{c0}	$\surd$	$-$	$\surd$
χ_{c1}	$-$	$(\surd)$	ϵ
χ_{c2}	$\surd$	(ϵ)	$\surd$

$-$: forbidden by angular momentum and parity conservation

ϵ: forbidden to leading-twist accuracy (viol. of helicity s.r.)

$\surd$: allowed to leading-twist accuracy

$(\ )$: either G-parity or isospin invariance violated for non-strange mesons

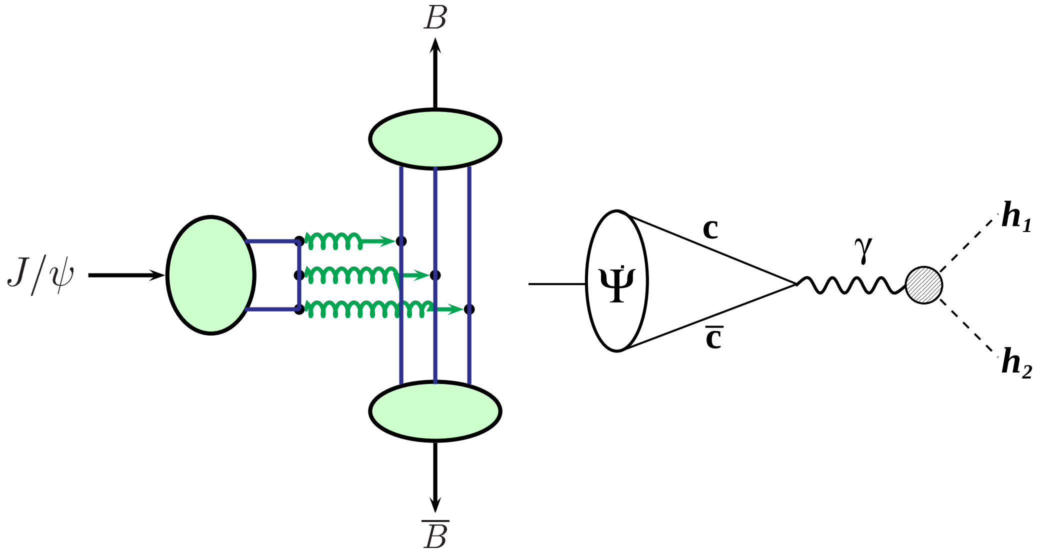
short-range versus long-range decay mechanisms

suppose

a decay mechanism

dominates that

- respects QCD factorization
- $c\bar{c}$ pair annihilates by a short distance mechanism (photons and/or gluons)



probes charmonium wave function at origin (decay constant)

$$\kappa_{12} = \frac{\mathcal{B}(\psi' \to h_1 h_2)}{\mathcal{B}(J/\Psi \to h_1 h_2)} \frac{\mathcal{B}(J/\Psi \to e^+e^-)}{\mathcal{B}(\Psi' \to e^+e^-)} \rho_{\text{p.s.corr}} \simeq 1$$

14% rule

channel	$10^4\mathcal{B}(J/\psi)$	$10^4\mathcal{B}(\Psi')$	κ
$p\overline{p}$	21.4 ± 1.0	2.73 ± 0.40	0.93 ± 0.15
$\Sigma^0\overline{\Sigma}^0$	12.7 ± 1.7	0.94 ± 0.48	0.49 ± 0.26
$\Lambda\overline{\Lambda}$	13.5 ± 1.4	2.11 ± 0.35	1.11 ± 0.24
$\Xi^-\overline{\Xi}^+$	9.0 ± 2.0	0.83 ± 0.30	0.54 ± 0.35
$\varrho\pi$	127 ± 9	< 0.83 (< 0.28*)	< 0.054 (< 0.018)
$\omega\pi^0$	4.2 ± 0.6	0.38 ± 0.20*	0.7 ± 0.4
$\varrho\eta$	1.93 ± 0.23		
$\omega\eta$	15.8 ± 1.6	< 0.33*	< 0.17
$\phi\eta$	6.5 ± 0.7		
$\varrho\eta'(958)$	1.05 ± 0.18		
$\omega\eta'(958)$	1.67 ± 0.25		
$\phi\eta'(958)$	3.3 ± 0.4		
$K^*(892)^\mp K^\pm$	50 ± 4	< 0.54(< 0.30*)	< 0.089 (< 0.049)
$\bar{K}^*(892)^0 K^0$+c.c.	42 ± 4	0.81 ± 0.29*	0.15 ± 0.05
$\pi^+\pi^-$	1.47 ± 0.23	0.8 ± 0.5	4.3 ± 2.7
K^+K^-	2.37 ± 0.31	1.0 ± 0.7	3.2 ± 2.3
$K_S^0K_L^0$	1.46 ± 0.26	0.52 ± 0.07*	2.7 ± 0.6
$\pi^\pm b_1(1235)^\mp$	30 ± 5	3.2 ± 0.8	0.79 ± 0.24
$K^\pm K_1(1270)^\mp$	< 30	10.0 ± 2.8	> 1.7
$\omega f_2(1270)$	43 ± 6	2.1 ± 0.6*	0.34 ± 0.11
$\varrho a_2(1320)$	109 ± 22	2.6 ± 0.9*	0.17 ± 0.07
$\phi f_2'(1525)$	12.3 ± 2.1	0.44 ± 0.16*	0.22 ± 0.09

data from PDF (* BES)

lowest Fock state versus higher Fock state decay mechanism

lowest Fock state usually dominates

higher Fock state contributions suppressed by inverse powers of hard scale

consider decays of P-wave charmonia χ_{cJ}:

dimensional counting $\Psi_P(0) = 0 \Rightarrow \partial\Psi_P/\partial r(0)$

$$\Gamma \propto \partial\Psi_P/\partial r(0)\Psi_1(0)\Psi_2(0)m_c^{-n}$$

derivative of two-particle wf has same dimension as three-particle wf

valence Fock state $c\bar{c}_1 \; (^3P_J)$ color singlet

$c\bar{c}g$ Fock state $c\bar{c}_8 g \; (^3S_1)$ color octet

both contribute to same order in $1/m_c$

$$M(\chi_{cJ} \to h_1 h_2) \; = \; a_1\alpha_s^2 + a_8\alpha_s^{5/2}$$

($\alpha_s \simeq 0.3 - 0.4 : \sqrt{\alpha_s}$ no real suppression)

cannot be ignored, consequences not fully explored, lack of accurate data

Bolz-K-Schuler, hep-ph9704378

Summary

- There are many applications of the handbag approach to space- and time-like wide-angle exclusive processes; seems to work reasonably well for momentum transfers of the order of 10 GeV^2
- predictions for WACS - soft form factors known from recent GPD analysis
- rich phenomenology of time-like processes
  $\gamma\gamma \to B\overline{B}, M\overline{M}$, $p\bar{p} \to \gamma\gamma, \gamma M$
- FAIR: handbag approach can be probed over a larger range of energy and perhaps with higher precicion
  polarization of p and $\bar{p}$ is helpful
- Exclusive charmonium decays - interesting interplay of perturbative and non-perturbative QCD
  systematic investigation of exclusive charmonium decays still lacking

$\gamma\gamma \to M\overline{M}$

$$\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-) = \frac{8\pi\alpha_{\rm elm}^2}{s^2 \sin^4\theta} |R_{2\pi}(s)|^2$$

$$R_{2\pi}^q = \frac{1}{2}\int_0^1 dz(2z-1)\Phi_{2\pi}^q(z,1/2,s); \quad R_{2\pi} = \sum_q e_q^2\, R_{2\pi}^q; \quad F_\pi^q = \int_0^1 dz \Phi_{2\pi}^q$$

$q\overline{q}$ intermediate state: isospin 0,1 only

For pions isospin 1 excluded $\Rightarrow$

$$\frac{d\sigma}{dt}(\gamma\gamma \to \pi^0\pi^0) = \frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)$$

robust prediction, differs drastically from ERBL result, not yet measured

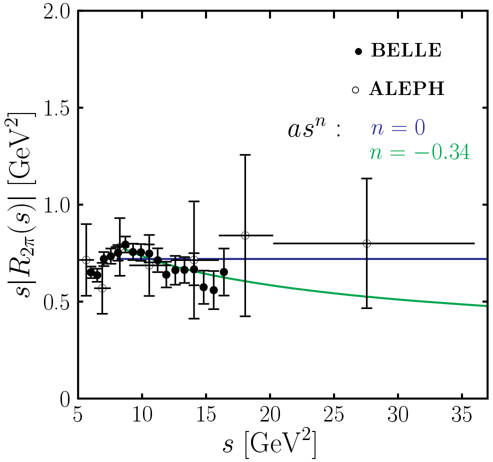
should also hold for the $\rho\rho$ channel; measureable at BELLE?

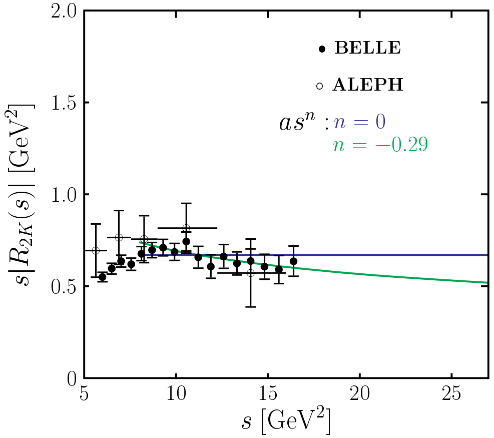
In flavor symmetry limit:

$$\frac{d\sigma}{dt}(\gamma\gamma \to K_S\overline{K}_S) = \frac{2}{25}\frac{d\sigma}{dt}(\gamma\gamma \to K^+K^-)$$

Diehl-K-Vogt, hep-ph/0112274

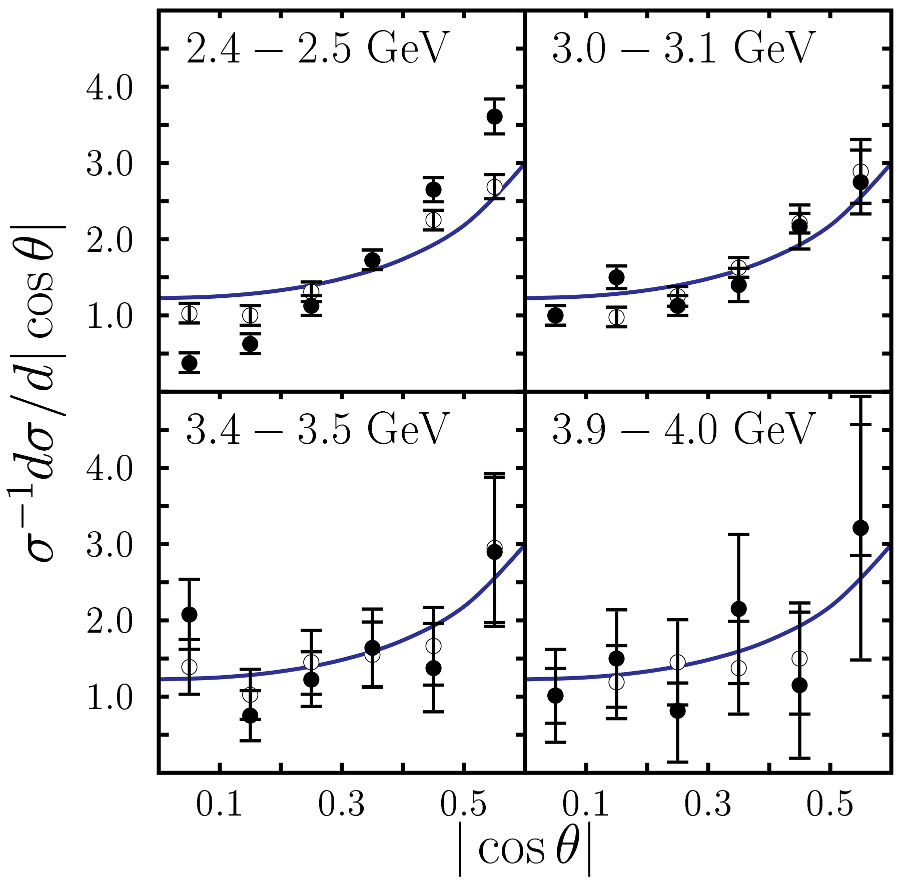
$\gamma\gamma \to MM$





BELLE

$\gamma\gamma \to \pi^+\pi^-(\bullet), K^+K^-(\circ)$



$s|F_\pi| = 0.93 \pm 0.12 \text{GeV}^2$

$\propto \sin^4\theta$

photoproduction of mesons

$s \leftrightarrow t$ crossing

$\overline{C}_2 = \frac{a}{su}\,, \qquad \overline{C}_3 = 0\,,$

in fair agreement with old Cornell data on $d\sigma/dt$
New data from Jlab?

$A_{LL}^{\pi^0} \simeq A_{LL}^{\text{Compton}}$

$$\frac{d\sigma(\gamma n \to \pi^- p)}{d\sigma(\gamma p \to \pi^+ n)} \simeq \left[\frac{e_d u + e_u s}{e_u u + e_d s}\right]^2$$

dominance of $\overline{C}_3$ fails badly