Discussing the light-meson DAs

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Outline

Exclusive processes: pQCD leading-twist prediction

$$\mathcal{M}(Q^2) = \mathcal{M}^{(0)}(Q^2) + \frac{\alpha_s(\mu_R^2)}{4\pi}\mathcal{M}^{(1)}(Q^2) + \frac{\alpha_s^2(\mu_R^2)}{(4\pi)^2}\mathcal{M}^{(2)}(Q^2, \mu_R^2) + \cdots$$

$Q^2 \ldots$ characteristic large scale of the process

$\mu_R^2 \ldots$ renormalization scale

- higher-order corrections ($\mathcal{M}^{(2)}(Q^2, \mu_R^2), \ldots$) are important: stabilizing effect reducing the dependence of the predictions on the scales and schemes
- only a handful of exclusive processes analyzed to NLO

Factorization

$$\mathcal{M}(Q^2) = T_H(x_1, \cdots; \cdots; Q^2, \mu_{F1}^2, \cdots) \otimes \prod_i \Phi_i(x_i; \cdots; \mu_{Fi}^2)$$

x_i... momentum fraction, $\mu_{F(i)}^2$... factorization scale(s)

eg.

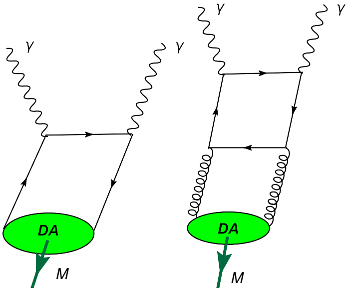
$$T_H(x; Q^2, \mu_F^2) = T_H^{(0)}(x, Q^2) + \frac{\alpha_s(\mu_R^2)}{4\pi} T_H^{(1)}(x, Q^2, \mu_F^2) + \frac{\alpha_s^2(\mu_R^2)}{(4\pi)^2} T_H^{(2)}(x, Q^2, \mu_R^2, \mu_F^2) + \cdots$$

$$\Phi(x; \mu_F^2, \mu_0^2) = \Phi^{(0)}(x, \mu_F^2, \mu_0^2) + \frac{\alpha_s(\mu_F^2)}{4\pi} \Phi^{(1)}(x, \mu_F^2, \mu_0^2) + \frac{\alpha_s^2(\mu_F^2)}{(4\pi)^2} \Phi^{(2)}(x, \mu_F^2, \mu_0^2) + \cdots$$

Elementary hard-scattering amplitudes to NLO

Meson transition form factors

$$\gamma^*\gamma^{(*)} \to (q\bar{q}),\ \gamma^*\gamma^{(*)} \to (gg)$$



NLO: [...]

β_0 proportional NNLO: [Melić, Nižić, P-K '02]

NNLO from conf. sym: [Melić, Müller, P-K '02]

Elementary hard-scattering amplitudes to NLO

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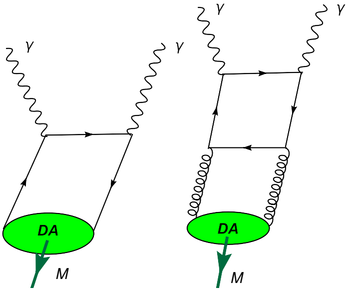


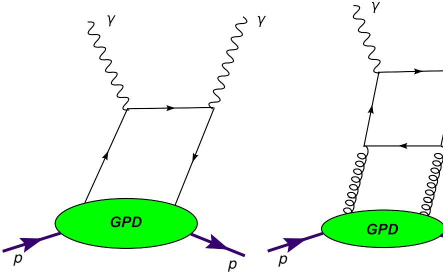
NLO: [...]

β_0 proportional NNLO: [Melić, Nižić, P-K '02]

NNLO from conf. sym: [Melić, Müller, P-K '02]

(D)DVCS

$$\gamma^* q \to \gamma^{(*)} q,\ \gamma^* g \to \gamma^{(*)} g$$



NLO: [Ji, Belitsky et al, Mankiewicz et al, '97]

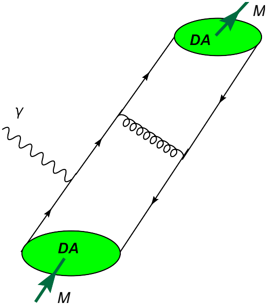
β_0 proportional NNLO: [Belitsky, Schäfer '98]

NNLO from conf. sym: [Müller '05, Kumerički et al. '07]

Elementary hard-scattering amplitudes to NLO

Meson em form factor

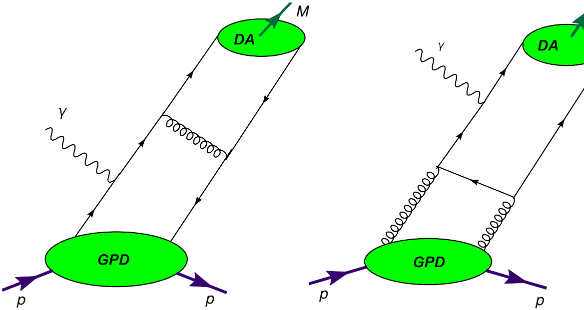
$$\gamma^*(q\bar{q}) \to (q\bar{q})$$



NLO: [...]

DVMP

$$\gamma^* q \to (q\bar{q})q,\ \gamma^* g \to (q\bar{q})g$$



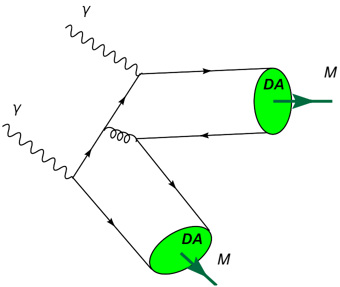
NLO: [Belitsky and Müller '01, Ivanov et al '04,]

[Duplančić, Müller, KPK '17]

Elementary hard-scattering amplitudes to NLO

Meson pair production

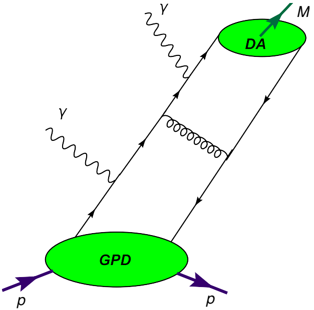
$$\gamma^*\gamma \to (q\bar{q})(q\bar{q})$$



NLO: [Nižić '87, Duplačić, Nižić '06]

Photon-meson production

$$\gamma^* q \to \gamma q(q\bar{q})$$

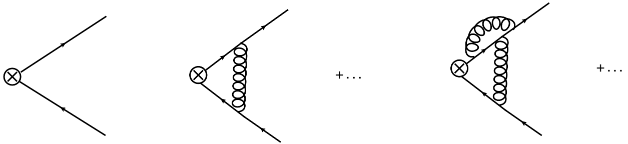


LO V mesons: [Boussarie, Pire, Szymanowsky, Wallon '16]

LO PS mesons: [Duplančić, P-K, Pire, Szymanowski, Wallon '18]

NLO: *work in progress*

DAs



(LO) (NLO, 1–loop) (NNLO, 2–loop)

LO evolution <=> Phi^(0), V1   NLO evolution <=> Phi^(1), V_2

$$V = \frac{\alpha_s(\mu_F^2)}{4\pi} V_1 + \frac{\alpha_s^2(\mu_F^2)}{(4\pi)^2} V_2 + \cdots$$

$$\mu_F^2 \frac{\partial}{\partial \mu_F^2} \Phi = V \otimes \Phi \Leftrightarrow \text{resummation of } \left(\alpha_s \ln(\mu_F^2/\mu_0^2)\right)^n$$

NLO evolution : [Müller '94]

3-loop kernels: [Braun, Manashov, Moch, Strohmaier '17]

DAs

$$\phi_P(x,\mu_F^2) = 6x\,(1-x)\left[1+\sum_{n=2,4,\ldots} a_{Pn}(\mu_F^2)\,C_n^{3/2}(2x-1)\right]$$

$\int_0^1 dx \phi_P(x,\mu_F^2) = 1$

$$a_{Pn}(\mu_F^2) = a_{Pn}^{LO}(\mu_F^2) + \frac{\alpha_S(\mu_F^2)}{4\pi} a_{Pn}^{NLO}(\mu_F^2)$$

$$a_{Pn}^{LO}(\mu_F^2) = \left(\frac{\alpha_S(\mu_0^2)}{\alpha_S(\mu_F^2)}\right)^{\gamma_n/\beta_0} a_{Pn}^{LO}(\mu_0^2) \qquad (\leq a_{Pn}^{LO}(\mu_0^2))$$

$$a_{Pn}^{NLO}(\mu_F^2) = f(\mu_F^2, \mu_0^2, a_{Pk}(\mu_0^2)) \qquad (k \leq n)$$

Pion transition form factor

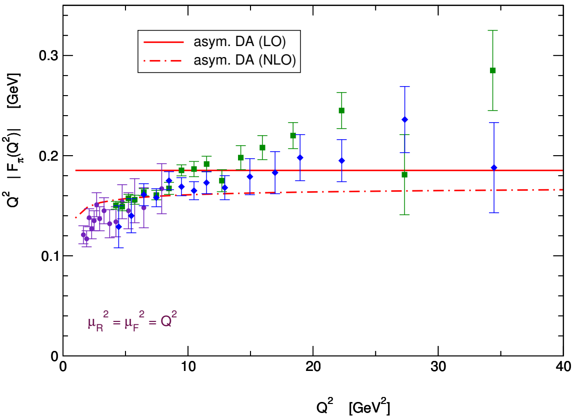
$$F_{\pi\gamma}(Q^2) = F^{(0)}_{\pi\gamma}(Q^2) + \frac{\alpha_S(\mu_R^2)}{4\pi} F^{(1)}_{\pi\gamma}(Q^2) + \cdots$$

$\mu_R^2 = \mu_R^2(Q^2) \ldots$ renormalization scale

$$\begin{aligned} F_{\pi\gamma}(Q^2) \quad = \quad & \frac{6 f_\pi C_\pi}{Q^2} \Big\{ 1 + a_2(\mu_F^2) + a_4(\mu_F^2) + \cdots \\ & + \frac{\alpha_s}{\pi} \Bigg[-1.667 + \left(0.403 - 1.389 \ln\left(\frac{Q^2}{\mu_F^2}\right)\right) a_2(\mu_F^2) \\ & \qquad + \left(2.482 - 2.022 \ln\left(\frac{Q^2}{\mu_F^2}\right)\right) a_4(\mu_F^2) + \cdots \Bigg] \\ & + \mathcal{O}(\alpha_s^2) \Big\} \end{aligned}$$

DA: experimental situation for pion tff

CLEO '97, BABAR '09, BELLE '12

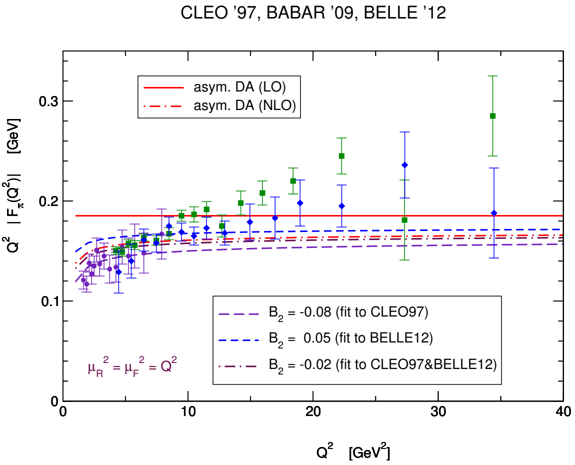


CLEO '97 (purple)

BABAR '09 (green)

BELLE '12 (blue)

DA: example fits



CLEO '97 (purple)

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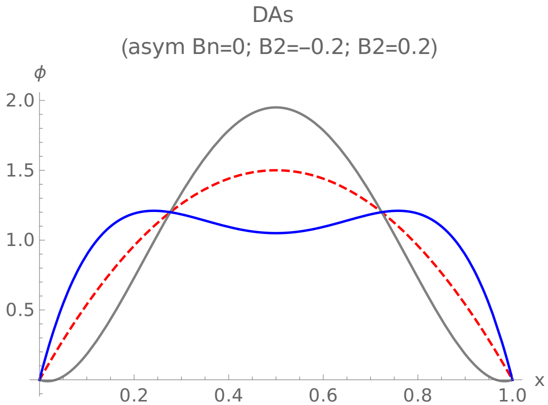
DAs



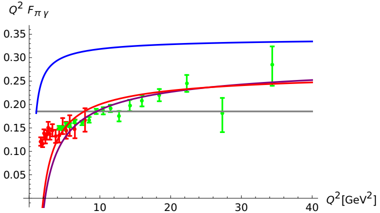
$B_i = 0$ (asym.) ... red

$B_2(1\text{GeV}^2) = -0.2$ ... gray

$B_2(1\text{GeV}^2) = 0.2$ ... blue

What about BaBar '09 data?

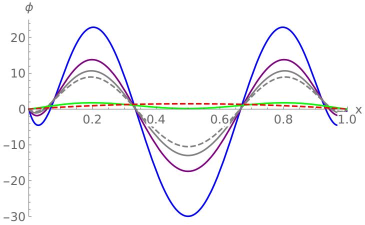
Toy example:



$$B_2(1\text{GeV}^2) = 6.2$$
$$B_4(1\text{GeV}^2) = -6.22$$

LO (blue)

NLO (red, purple)



$\phi(1\text{GeV}^2)\ldots$ blue

$\phi(10\text{GeV}^2)\ldots$ purple

$\phi(100\text{GeV}^2)\ldots$ grey

$\phi(1000\text{GeV}^2)\ldots$ dashed grey

$\phi(Q^2 \to \infty) = \phi_{\text{asy}}\ldots$ dashed red

On literature...

Impact of tff results on literature:

- Round 1: a number of papers trying to accommodate BABAR '09 results, eg. flat DA [Radyuskin '09, Polyakov '09] . . .

- Round 2: no definitive proof (neither from experimental nor theoretical side) but BELLE '12 results favoured in the literature

On fits...

How much can the fits tell us?

$$Q^2 F_{\pi\gamma}(Q^2) = 6 f_\pi C_\pi \left[1 + \sum_{n=2}^{\infty}{}' a_n(Q^2) + \frac{\alpha_S(Q^2)}{\pi} \left(-1.667 + \sum_{n=2}^{\infty}{}' \, T_n^{NLO} \, a_n(Q^2) \right) \right]$$

On fits...

How much can the fits tell us?

$$\stackrel{t=\alpha_S(Q^2)}{=} 6 f_\pi C_\pi \left[1 + {\sum_{n=2}^{\infty}}' a_n(\mu_0^2) \left(\frac{t}{t_0}\right)^{-\gamma_n/\beta_0} + \frac{t}{\pi}\left(-1.667 + {\sum_{n=2}^{\infty}}' T_n^{NLO}\, a_n(\mu_0^2) \left(\frac{t}{t_0}\right)^{-\gamma_n/\beta_0} \right) \right]$$

- fractional polynomial in $t = \alpha_S(Q^2)$ variable
- $0.4 > t > 0.2(0.26)$ for $2 < Q^2 < 34(8)$GeV^2

$\Rightarrow$ large correlations for a_ns

$\Downarrow$

- one (effective) coefficient (a_2) to be determined

On fits...

How much can the fits tell us?

We can rewrite the tff contribution in terms of a linear fit:

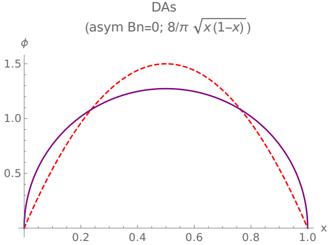
$$F(X(t)) = a_2 + a_4\, X(t)$$

data range $(0.9 < X(t) < 1.2)$ is narrow and away from the ordinate

$\Rightarrow$ strong correlation between a_2 and a_4

Beyond the truncation of the Gegenbauer series

- from AdS/QCD [Brodsky, Teramond '08]:



$B_i = 0$ (asym.) ... red

$\phi_\pi = \frac{8}{\pi}\sqrt{x(1-x)}$ ... purple

- parameterizing the deviation from conformal expansion [Ball, Talbot '05]

- summing the series...

Inspiration by DVCS calculation (conformal moment series representation)

- factorization formula in momentum fraction space (x-space):

$$F_{M\gamma}(Q^2;\mu_R^2) = \int \mathrm{d}x \;\; T_H(x,Q^2,\mu_R^2,\mu_F^2)\; \Phi(x,\mu_F^2)$$

- ...in terms of conformal moments (n-space)

(analogous to Mellin moments in DIS: $x^n \to C_n^{3/2}(x), C_n^{5/2}(x)$):

$$= \sum_{n=0}^{\infty} T_n(Q^2,\mu_R^2,\mu_F^2)\; a_n(\mu_F^2)$$

$$T_n(Q^2,\mu_R^2,\mu_F^2)) = \int_0^1 x(1-x) C_n^{3/2}(2x-1)\; T_H(x,Q^2,\mu_R^2,\mu_F^2)$$

- series summed using Mellin-Barnes integral over complex n:

$$= \frac{1}{2i}\int_{c-i\infty}^{c+i\infty} dn\left[i+\tan\left(\frac{\pi n}{2}\right)\right] T_n(Q^2,\mu_R^2,\mu_F^2)\; a_n(\mu_F^2)$$

$\Rightarrow$ complete summation (inclusion of NLO evolution easier...) but modeling of meson DA coefficients $a_n(\mu_F^2)$ needed

η, η' transition form factors

Novel features:

1. flavour-mixing (singlet-octet mixing)

2. $|gg\rangle$ states contribute

   $\Rightarrow$ mixing of $q\bar{q}_1$ and gg DAs under evolution

$$(\Phi_{M1} \equiv \Phi_{Mq}) \quad (\Phi_{Mg})$$

$$\downarrow$$

$$\mu_F^2 \frac{\partial}{\partial \mu_F^2} \begin{pmatrix} \Phi_{Mq} \\ \Phi_{Mg} \end{pmatrix} = \begin{pmatrix} V_{qq} & V_{qg} \\ V_{gq} & V_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Phi_{Mq} \\ \Phi_{Mg} \end{pmatrix}$$

1. flavour-mixing [review Feldman '00]

$$\downarrow$$

simplest possibility: to take particle dependence and the flavour-mixing to be solely embedded in the decay constants f_M^i

- $\boxed{\Phi_{Mi} = f_M^i \, \phi_i}$ $i \in \{1, 8\}$
- the decay constants parametrized as

$$f_\eta^8 = f_8 \cos\theta_8 \qquad f_\eta^1 = -f_1 \sin\theta_1$$

$$f_{\eta'}^8 = f_8 \sin\theta_8 \qquad f_{\eta'}^1 = f_1 \cos\theta_1$$

[Leutwyler '98, Felmann, Kroll, Stech, '98,'99]

$$F_{P\gamma}(Q^2) = \frac{6 f_P^1 C_1}{Q^2} \Big\{ 1 + a_2^1(\mu_F^2) + a_4^1(\mu_F^2) + \cdots$$

$$+ \frac{\alpha_s}{\pi} \Big[-1.667 + \left(0.403 - 1.389 \ln\left(\frac{Q^2}{\mu_F^2}\right)\right) a_2^1(\mu_F^2)$$

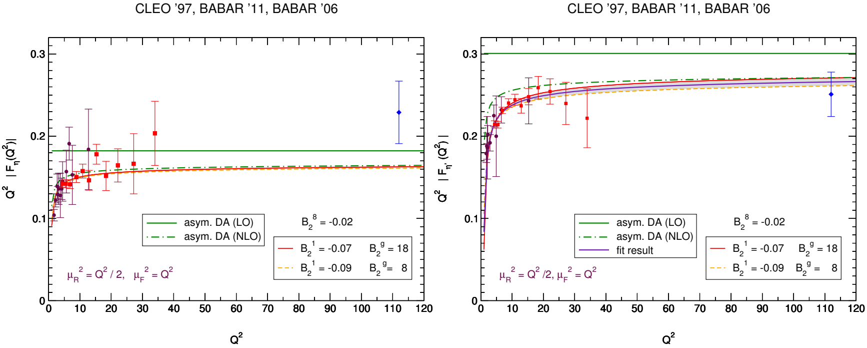
$$+ \left(2.482 - 2.022 \ln\left(\frac{Q^2}{\mu_F^2}\right)\right) a_4^1(\mu_F^2) + \cdots \Big]$$

$$+ \frac{\alpha_s}{\pi} \Big[\left(-1.801 + 0.463 \ln\left(\frac{Q^2}{\mu_F^2}\right)\right) a_2^g(\mu_F^2)$$

$$+ \left(-2.510 + 0.519 \ln\left(\frac{Q^2}{\mu_F^2}\right)\right) a_4^g(\mu_F^2) + \cdots \Big]$$

$$+ \mathcal{O}(\alpha_s^2) \Big\}$$

Experimental situation and fits for η and η' tff



CLEO '97 (purple), BABAR '11 (red),

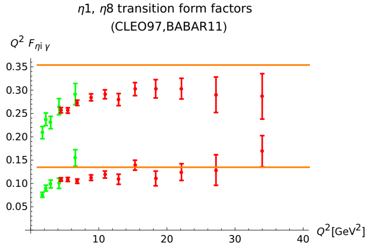
BABAR '06 (blue) . . . timelike! (not used in fits)

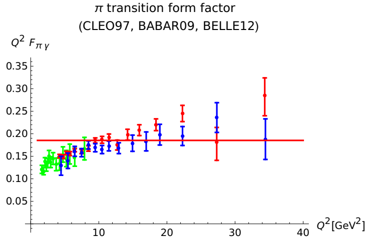
best fit:

$$a_2^8 = -0.05 \pm 0.02 \quad a_2^1 = -0.12 \pm 0.01 \quad a_2^g = 0.63 \pm 0.17$$

[Kroll, KPK '13]

Flavour singlet and flavour nonsinglet analysis

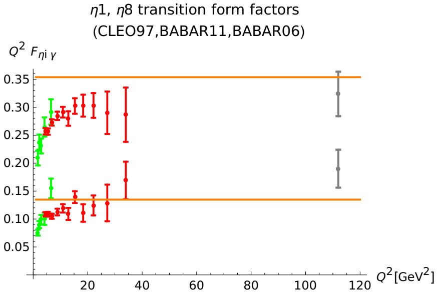




CLEO ’97 (green)

BABAR ’09,
BABAR ’11 (red)

BELLE ’12 (blue)



CLEO '97 (green)

BABAR '11 (red)

BELLE '06 (gray)

. . . timelike!

On fits...

How much can the fits tell us?

- We can rewrite the flavour-octet contribution in terms of a linear fit:

$$F_8(X_8(t)) = a_2^8 + a_4^8 \; X_8(t)$$

data range $0.9 < X_8(t) < 1.2$ is narrow and away from the ordinate
$\Rightarrow$ strong correlation between a_2^8 and a_4^8,
only effective a_2^8 to be determined

- We can rewrite the flavour-singlet contribution in terms of a linear fit:

$$F_1(X_1(t)) = a_2^1 + a_2^g \; X_1(t)$$

data range $-0.0029 < X_1(t) < 0.032$ (for $2 < Q^2 < 34\text{Gev}^2$) is near the ordinate $\Rightarrow$ moderate correlation between a_2^1 and a_2^g,
both a_2^1 and a_2^g to be determined

Scalar transition form factor

- BELLE 2015 data on the scalar $f_0(980)$ (and tensor $f_2(1270)$) meson transition form factor
- [Kroll '16]: $f_0(980)$ mainly $s\bar{s}$ state considered in modified approach with quark transverse moment effects included
- we discuss here standard hard-scattering approach with gluons included (NLO taken from DVCS)

- PSEUDOSCALAR CASE

$$\phi_{Pq}(x,\mu_F^2) = 6x(1-x)\left[1+\sum_{n=2,4,\dots} a^{q}_{Pn}(\mu_F^2)\, C_n^{3/2}(2x-1)\right]$$

$$\phi_{Pg}(x,\mu_F^2) = 30\,x^2(1-x)^2 \sum_{n=2,4,\dots} a^{g}_{Pn}(\mu_F^2)\, C_{n-1}^{5/2}(2x-1)$$

$$\int_0^1 dx\phi_{Pq}(x,\mu_F^2) = 1,\ \gamma_0^q = 0 \Rightarrow a^{q}_{P0} = \text{cte} \to 1$$

- SCALAR CASE

$$\phi_{Sq}(x,\mu_F^2) = 6x(1-x)\left[a^{q}_{S1}(\mu_F^2) C_1^{3/2}(\dots) + \sum_{n=3,5,\dots} a^{q}_{Sn}(\mu_F^2)\, C_n^{3/2}(\dots)\right]$$

$$\phi_{Pg}(x,\mu_F^2) = 30\,x^2(1-x)^2\left[a^{g}_{S1}(\mu_F^2) + \sum_{n=3,5,\dots} a^{g}_{Sn}(\mu_F^2)\, C_n^{3/2}(\dots)\right]$$

$$\int_0^1 dx\phi_{Pg}(x,\mu_F^2) = a^{g}_{S1}(\mu_F^2),\ \gamma_1^+ = 0 \Rightarrow a^{+}_{S1} = \text{cte}$$

$$a^{q}_{Mn}(\mu_F^2) = a^{+}_{Mn}(\mu_F^2) + \rho_n^-\ a^{-}_{Mn}(\mu_F^2)$$

$$a^{g}_{Mn}(\mu_F^2) = \rho_n^+\ a^{+}_{Mn}(\mu_F^2) + a^{-}_{Mn}(\mu_F^2)$$

$$a^{\pm}_{Mn}(\mu_F^2) = \left(\frac{\alpha_S(\mu_0^2)}{\alpha_S(\mu_F^2)}\right)^{\frac{\gamma_n^\pm}{\beta_0}} a^{\pm}_{Mn}$$

- SCALAR CASE

$$\phi_{Sq}(x,\mu_F^2) = 6x(1-x)\left[a^q_{S1}(\mu_F^2)C_1^{3/2}(\ldots) + \sum_{n=3,5,\ldots} a^q_{Sn}(\mu_F^2)\,C_n^{3/2}(\ldots)\right]$$

$$\phi_{Pg}(x,\mu_F^2) = 30\,x^2(1-x)^2\left[a^g_{S1}(\mu_F^2) + \sum_{n=3,5,\ldots} a^g_{Sn}(\mu_F^2)\,C_n^{3/2}(\ldots)\right]$$

$$\int_0^1 dx\phi_{Pg}(x,\mu_F^2) = a^g_{S1}(\mu_F^2),\ \gamma_1^+ = 0 \Rightarrow a^+_{S1} = \text{cte}$$

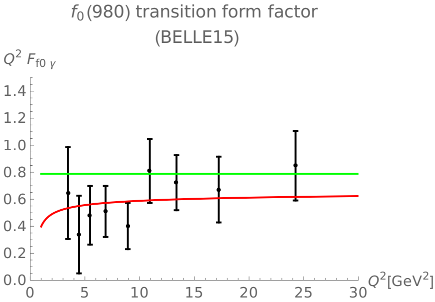
$$a^q_{Mn}(\mu_F^2) = a^+_{Mn}(\mu_F^2) + \rho_n^-\ a^-_{Mn}(\mu_F^2)$$
$$a^g_{Mn}(\mu_F^2) = \rho_n^+\ a^+_{Mn}(\mu_F^2) + a^-_{Mn}(\mu_F^2)$$

$$a^\pm_{Mn}(\mu_F^2) = \left(\frac{\alpha_S(\mu_0^2)}{\alpha_S(\mu_F^2)}\right)^{\frac{\gamma_n^\pm}{\beta_0}} a^\pm_{Mn}$$

choice:

$$\begin{array}{lll} a^+_{S1} = 1/\rho_1^+ = 5/6 & & a^q_{S1}(\mu_F^2) = 1/\rho_1^+ \\ & \Rightarrow & \\ a^-_{S1} = 0 & & a^g_{S1}(\mu_F^2) = 1 \end{array}$$

$f_0(980)$ transition form factor (experiment and fits)



BELLE '15 (black)

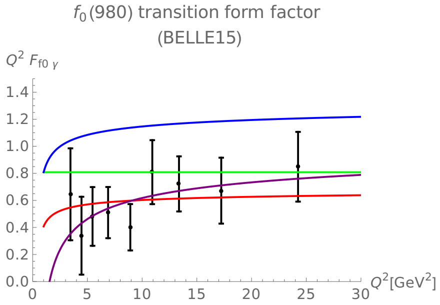
LO (green)

NLO (red)

$f_1 = 0.41 \pm 0.05$ GeV

$a_q(\mu^2) = 5/6,\ a_g(\mu^2) = 1$

$f_0(980)$ transition form factor (experiment and fits)



BELLE '15 (black)

LO (green)

NLO (red)

$f_1 = 0.41 \pm 0.05$ GeV

$a_q(\mu^2) = 5/6$, $a_g(\mu^2) = 1$

LO (blue)

NLO (purple)

$f_1 = 0.42 \pm 0.05$ GeV

$a_q(\mu_0^2) = 5/6$

$a_g(1\text{GeV}^2) = 2.82 \pm 1.66$

$\gamma^*\gamma^* \to \eta'$

BaBar 2018 $\Rightarrow$ [Ji, Vladimirov '19; Kroll, P-K '19, ...]

$\gamma^*(q_1)\gamma^*(q_2) \to M$:

$$Q_1^2 = -q_1^2 \qquad Q_2^2 = -q_2^2$$

$$\bar{Q}^2 = \frac{Q_1^2 + Q_2^2}{2} \qquad \omega = \frac{Q_1^2 - Q_2^2}{Q_1^2 + Q_2^2} \;\; (0 \leq \omega \leq 1)$$

expansion in ω:

$$F_{M\gamma*}(\bar{Q}^2, \omega) \sim \sum_m \omega^m \sum_{l \leq m} a_{Ml} T_l$$

[Diehl, Kroll, Vogt '01; Melić, Müller, P-K '02] ($M = \pi$), [Kroll, P-K '19] ($M = (\eta,)\eta'$)

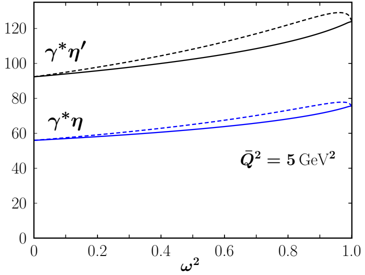
$$F^1_{P\gamma*}(\bar{Q}^2,\omega)$$
$$= \frac{4f^1_P\,C_1}{2\bar{Q}^2}\Bigg\{\left(1-\frac{\alpha_s}{\pi}\right)$$
$$+\omega^2\Big[0.2+0.343\ a^1_2$$
$$+\frac{\alpha_s}{\pi}\left(-0.333+0143\ a^1_2-0.397\ a^g_2\right)\Big]$$
$$+\omega^4\Big[0.086+0.229\ a^1_2+0.104\ a^1_4$$
$$+\frac{\alpha_s}{\pi}\big(-0.187+0.183\ a^1_2-0.326\ a^g_2$$
$$+0.201\ a^1_4-0.166\ a^g_4\big)\Big]+\mathcal{O}(\omega^6)\Bigg\}_{(\mu^2_F=2\bar{Q})}$$

- for $\omega=0$ no dependence on a_i
- for $\omega<1$ offers insight in the leading Gegenbauer coefficients

[Kroll, P-K '19]:

$\bar{Q}^2[GeV^2]$	ω	$\bar{Q}^2 F^{\text{exp}}_{\eta'\gamma^*}[MeV]$	$\bar{Q}^2 F_{\eta'\gamma^*}[MeV]$	$\bar{Q}^2 F_{\eta\gamma^*}[MeV]$
6.48	0.000	92.8 ± 13.8	92.7 ± 3.9	56.2 ± 3.3
16.85	0.000	90.1 ± 37.3	93.8 ± 3.9	56.8 ± 3.3
9.55	0.553	78.7 ± 13.5	98.7 ± 4.1	59.9 ± 3.5
26.53	0.436	161.0 ± 44.2	97.7 ± 4.1	59.2 ± 3.5
45.63	0.000	397.4 ± 400.9	94.6 ± 4.0	57.4 ± 3.4

$\bar{Q}^2 F_{\eta' \gamma^*}$, $\bar{Q}^2 F_{\eta \gamma^*}$ [Kroll, P-K '19]:



solid line

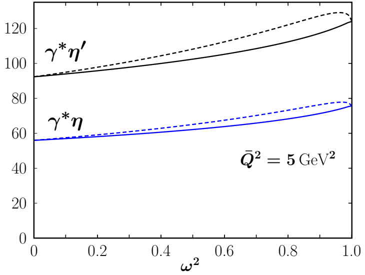
$a_2^8 = -0.05,\, a_2^1 = -0.12,\, a_2^g = 0.63$

[Kroll, P-K '13]

dashed line

$a_2^8 = a_2^1 = 0.25,\, a_2^g = 0.63$
$a_4^8 = -0.31,\, a_4^1 = -0.38$

$\bar{Q}^2 F_{\eta'\gamma^*}$, $\bar{Q}^2 F_{\eta\gamma^*}$ [Kroll, P-K '19]:



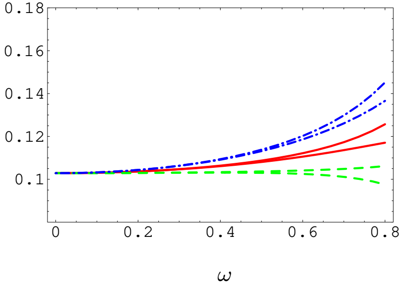
solid line

$a_2^8 = -0.05, a_2^1 = -0.12, a_2^g = 0.63$
[Kroll, P-K '13]

dashed line

$a_2^8 = a_2^1 = 0.25, a_2^g = 0.63$
$a_4^8 = -0.31, a_4^1 = -0.38$

$\bar{Q}^2 F_{\pi\gamma^*}$ [Melić, Müller, P-K '02]:



$a_2 \in \{0, -0.5, 0.5\}$ (red, green, blue)
$a_4 \in \{-0.25, 0.25\}$ (lower, upper)

Conclusions, questions, outlook...

- light-meson DAs were discussed in light of the pQCD twist-2 analysis of several photon-light-meson transition form factors
- Gegenbauer expansion limitations outlined
- many fits inconclusive and cannot be improved significantly but could be tested on other processes (pion em form factor)
- $\gamma^*\gamma^* \to M$ process and expansion in ω offer new cleaner insight in a_is
- calculational restrictions on ϕs and a_is?
  (evolution easier, summation possible ...?)
  restrictions on a_is from other sources?
  restrictions and possibilities from experiment?
  (BELLE II data ?) ...