Transition Form Factors of Pseudoscalars

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Outline

1. TFF in decays and low energy e^+e^-
2. TFF from Belle and BaBar
3. Conclusions

Transition Form Factors - I (General)

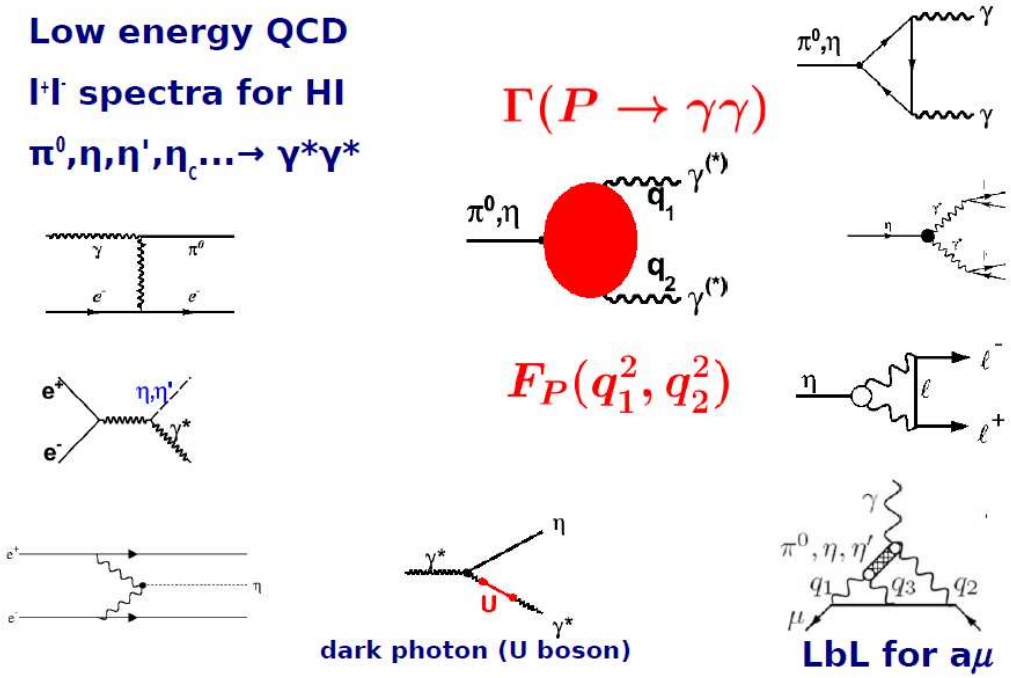
Low energy QCD

l^+l^- spectra for HI

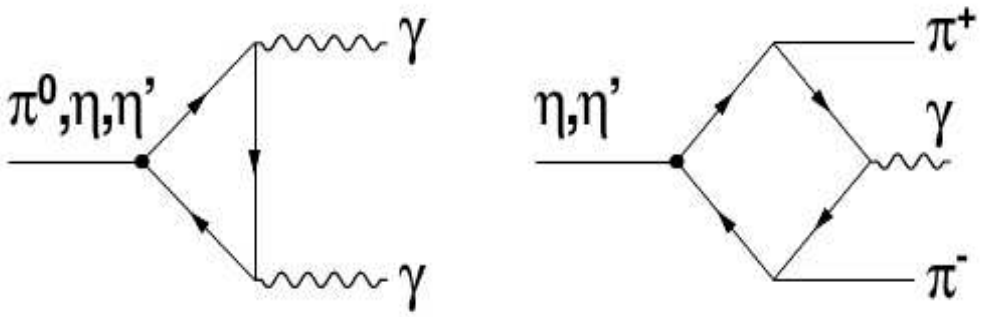
$\pi^0,\eta,\eta',\eta_c \ldots \to \gamma^*\gamma^*$

$\Gamma(P \to \gamma\gamma)$

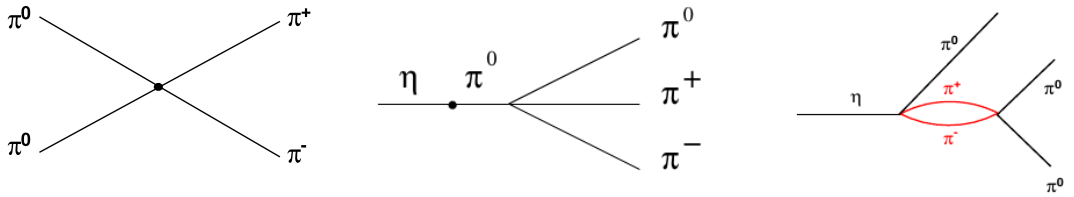
$F_P(q_1^2, q_2^2)$



Transition Form Factors - II (General)



Transition Form Factors - III (General)



Transition Form Factors - Relevant Processes and Experiments – I

1. $P = \pi^0,\ \eta,\ \eta'$
   - $P \to \gamma\gamma,\ \gamma e^+e^-,\ e^+e^-e^+e^-,\ e^+e^-$
   - $e^+e^- \to P\gamma,\ Pe^+e^-$
   - $\gamma e^- \to Pe^-$
   - $\gamma\gamma^* \to P$
2. $P = \pi^0,\ \eta,\ \eta', V = \rho,\ \omega,\ \phi$
   - $e^+e^- \to P\gamma,\ Pe^+e^-$
   - $e^+e^- \to VP$
   - $\eta^{'} \to \pi^+\pi^-\gamma$

All of them probe $\mathcal{F}(q_1^2, q_2^2)$ in different q_i^2 regions

Transition Form Factors - Relevant Processes and Experiments – II

There are also experiments at JLAB; old data from BaBar, Belle;
new data to come from CMD-3, SND, KLOE, BES3 and BelleII at SuperKEKB

- CMD-3 and SND have been running at the VEPP-2000 e^+e^- collider in Novosibirsk since 2010, $2m_\pi < \sqrt{s} < 2$ GeV, $L = 10^{32}$ cm^{-2}s^{-1}, contributing to measurements of R, p/n form factors and TFF
- BelleII at the SuperKEKB B factory at KEK should start data taking in 2016 with $9 < \sqrt{s} < 11$ GeV, $L = 8 \cdot 10^{35}$ cm^{-2}s^{-1},
  via ISR contributing to R, p/n FF and TFF in a broad energy range

$P \to l^+l^-$

In the unitarity limit (both photons are real):

$$\mathcal{B}_{P\to l^+l^-} = \mathcal{B}_{P\to\gamma\gamma}\frac{\alpha^2}{2\beta}(\frac{m_e}{m_P})^2[ln(\frac{1+\beta}{1-\beta})]^2,$$

where $\beta = \sqrt{1-4(\frac{m_e}{m_P})^2}$.
This lower bound can be significantly enhanced
by photon virtuality and the transition form factor.
Decays to an electron pair are strongly suppressed with respect
to those to a muon pair because of helicity suppression:

$$\mathcal{B}_{P\to e^+e^-}/\mathcal{B}_{P\to\mu^+\mu^-} \propto m_e^2\Phi_{e^+e^-}/m_\mu^2\Phi_{\mu^+\mu^-} = 2.3\cdot 10^{-5}\Phi_{e^+e^-}/\Phi_{\mu^+\mu^-},$$

where$\Phi_{l^+l^-}$ is the phase space for l^+l^-.

Status of $P \to l^+l^-$ Studies

Decay mode	$\mathcal{B}_{\rm exp}$	Events	Group	$\mathcal{B}_{\rm unit.bound}$
$\pi^0 \to e^+e^-$	$(6.46 \pm 0.33) \cdot 10^{-8}$	794	KTEV, 2008	$4.8 \cdot 10^{-8}$
$\eta \to e^+e^-$	$< 2.3 \cdot 10^{-6}$	–	HADES, 2012	$1.8 \cdot 10^{-9}$
$\eta \to \mu^+\mu^-$	$(5.7 \pm 0.9) \cdot 10^{-6}$	114	SATURNEII, 1994	$4.3 \cdot 10^{-6}$
$\eta' \to e^+e^-$	$< 5.6 \cdot 10^{-9}$	–	CMD-3/SND, 2015	$3.75 \cdot 10^{-11}$
$K_L^0 \to e^+e^-$	$(9^{+6}_{-4}) \cdot 10^{-12}$	4	B871, 1998	$3.0 \cdot 10^{-12}$
$K_L^0 \to \mu^+\mu^-$	$(6.84 \pm 0.11) \cdot 10^{-9}$	6210	B871, 2000	$6.8 \cdot 10^{-9}$

Search for $e^+e^- \to \eta'(958)$ at VEPP-2000

- CMD-3 used 2.69 pb^{-1} at $\sqrt{s} \sim m_{\eta'}$ to look for
  $e^+e^- \to \eta'(958),\ \eta' \to \eta\pi^+\pi^-,\ \eta \to 2\gamma,$
  $\Gamma(\eta' \to e^+e^-) < 0.0024$ eV at 90%CL, Phys. Lett. B740 (2015) 273
- SND used 2.9 pb^{-1} to look for $e^+e^- \to \eta'(958)$:
  $\eta' \to \eta\pi^+\pi^-,\ \eta \to 2\gamma,\ 3\pi^0,$
  $\eta' \to \eta\pi^0\pi^0,\ \eta \to 2\gamma,\ 3\pi^0,\ \pi^+\pi^-\pi^0,$
  $\Gamma(\eta' \to e^+e^-) < 0.0020$ eV at 90%CL, Phys. Rev.D91 (2015) 092010
- SND combines their data with CMD-3:
  $\Gamma(\eta' \to e^+e^-) < 0.0011$ eV at 90%CL,
  $\mathcal{B}(\eta' \to e^+e^-) < 5.6 \cdot 10^{-9}$ at 90%CL
- The unitarity limit $\mathcal{B}(\eta' \to e^+e^-) > 3.75 \cdot 10^{-11}$

Search for $e^+e^- \to \eta$ at VEPP-2000

- SND used 110 nb^{-1} for a feasibility study of $e^+e^- \to \eta,\ \eta \to 3\pi^0$, $\eta \to 2\gamma,\ \pi^+\pi^-\pi^0$ dominated by QED background, $\mathcal{B}(\eta \to e^+e^-) < 3 \cdot 10^{-6}$ at 90%CL
- The best limit is by HADES in Phys. Lett. B731 (2014) 265, $\mathcal{B}(\eta \to e^+e^-) < 2.3 \cdot 10^{-6}$ at 90%CL
- The HADES limit can be improved after a 2-week run at VEPP-2000, see M.N. Achasov et al., JETP Lett. 102 (2015) 266
- The unitarity limit is $\mathcal{B}(\eta \to e^+e^-) > 1.8 \cdot 10^{-9}$

Study of $P \to l^+l^-\gamma$

Decay mode	$\mathcal{B}$	Events	Group	Process
$\pi^0 \to e^+e^-\gamma$	$(1.174 \pm 0.035) \cdot 10^{-2}$	12k	ALEPH	$e^+e^- \to Z$, 2008
$\eta \to e^+e^-\gamma$	$(6.9 \pm 0.4) \cdot 10^{-3}$	1345	Cr.Ball	$\gamma p \to p\eta$, 2011
$\eta \to \mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \cdot 10^{-4}$	600	SERP	$\pi^- p \to \eta n$, 1980
$\eta' \to e^+e^-\gamma$	$(4.69 \pm 0.31) \cdot 10^{-4}$	864	BES3	$e^+e^- \to J/\psi \to \eta'\gamma$, 2015
$\eta' \to \mu^+\mu^-\gamma$	$(1.08 \pm 0.27) \cdot 10^{-4}$	33	SERP	33 $\pi^- p \to \eta' n$, 1980

Study of $P \to l^+l^-l'^+l'^-$

Decay mode	$\mathcal{B}$	Events	Group	Process
$\pi^0 \to e^+e^-e^+e^-$	$(3.38 \pm 0.16) \cdot 10^{-5}$	30.5k	KTEV	$K_L^0 \to \pi^0\pi^0\pi^0$, 2008
$\eta \to e^+e^-e^+e^-$	$(2.4 \pm 0.2) \cdot 10^{-5}$	362	KLOE	$e^+e^- \to \phi \to \eta\gamma$, 2011
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \cdot 10^{-4}$	90%CL	WASA	$pd \to \eta\ ^3$He, 2008
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \cdot 10^{-4}$	90%CL	WASA	$pd \to \eta\ ^3$He, 2008
$\eta \to e^+e^-\pi^+\pi^-$	$(2.68 \pm 0.12) \cdot 10^{-4}$	1555	KLOE	$e^+e^- \to \phi \to \eta\gamma$, 2009
$\eta \to \mu^+\mu^-\pi^+\pi^-$	$< 3.6 \cdot 10^{-4}$	90%CL	WASA	$pd \to \eta\ ^3$He, 2008
$\eta' \to e^+e^-\pi^+\pi^-$	$(2.11 \pm 0.18) \cdot 10^{-3}$	429	BES3	$e^+e^- \to J/\psi \to \eta'\gamma$, 2013
$\eta' \to \mu^+\mu^-\pi^+\pi^-$	$< 0.29 \cdot 10^{-4}$	90%CL	BES3	$e^+e^- \to J/\psi \to \eta'\gamma$, 2013

Study of $P \to V\gamma$ and $P \to Vl^+l^-$

Decay mode	$\mathcal{B}$	Events	Group	Process
$\eta \to \pi^+\pi^-\gamma$	$(4.22 \pm 0.08) \cdot 10^{-2}$	200k	KLOE	$e^+e^- \to \phi \to \eta\gamma$, 2013
$\eta' \to \pi^+\pi^-\gamma$	$(29.2 \pm 0.5) \cdot 10^{-2}$	200	CLEO	$e^+e^- \to J/\psi \to \eta'\gamma$, 2009
$\eta' \to \omega\gamma$	$(2.55 \pm 0.16) \cdot 10^{-2}$	33.2k	BES3	$e^+e^- \to J/\psi \to \eta'\gamma$, 2015
$\eta' \to \omega e^+e^-$	$(1.97 \pm 0.38) \cdot 10^{-4}$	66	BES3	$e^+e^- \to J/\psi \to \eta'\gamma$, 2015

Study of $V \to P\gamma$

Decay mode	$\mathcal{B}$	Events	Group	Process
$\rho \to \pi^0\gamma$	$(6.0 \pm 0.8) \cdot 10^{-4}$	130k	SND	$e^+e^- \to \pi^0\gamma$, 2016
$\rho \to \eta\gamma$	$(3.00 \pm 0.20) \cdot 10^{-4}$	33k	SND	$e^+e^- \to \eta\gamma$, 2007
$\omega \to \pi^0\gamma$	$(8.28 \pm 0.28) \cdot 10^{-2}$	130k	SND	$e^+e^- \to \pi^0\gamma$, 2016
$\omega \to \eta\gamma$	$(4.6 \pm 0.4) \cdot 10^{-4}$	33k	SND	$e^+e^- \to \eta\gamma$, 2007
$\phi \to \pi^0\gamma$	$(1.27 \pm 0.06) \cdot 10^{-3}$	130k	SND	$e^+e^- \to \pi^0\gamma$, 2016
$\phi \to \eta\gamma$	$(1.309 \pm 0.024) \cdot 10^{-2}$	33k	SND	$e^+e^- \to \eta\gamma$, 2007
$\phi \to \eta'\gamma$	$(6.25 \pm 0.21) \cdot 10^{-5}$	3.4k	KLOE	$e^+e^- \to \eta'\gamma$, 2007

$\mathcal{B}(\pi^0\gamma)$ will change after taking into account
the new analysis of the full old SND dataset just published in
M.N. Achasov et al., Phys. Rev. D 93, 092001 (2016)

Study of $V \to Pl^+l^-$

Decay mode	$\mathcal{B}$	Events	Group	Process
$\rho \to \pi^0 e^+ e^-$	$< 1.2 \cdot 10^{-5}$	90%CL	SND	$e^+e^- \to \pi^0 e^+ e^-$, 2008
$\rho \to \eta e^+ e^-$	$< 0.7 \cdot 10^{-5}$	90%CL	CMD-2	$e^+e^- \to \eta e^+ e^-$, 2005
$\omega \to \pi^0 e^+ e^-$	$(7.7 \pm 0.6) \cdot 10^{-4}$	232	CMD-2	$e^+e^- \to \pi^0 e^+ e^-$, 2005
$\omega \to \eta e^+ e^-$	$< 0.7 \cdot 10^{-5}$	90%CL	CMD-2	$e^+e^- \to \eta e^+ e^-$, 2005
$\phi \to \eta e^+ e^-$	$(1.075 \pm 0.039) \cdot 10^4$	31k	KLOE	$e^+e^- \to \eta e^+ e^-$, 2015

Future Possibilities – I

- ϕ meson decays at KLOE-2,
  ω mesons are more readily produced at COSY, JLAB etc.
- J/ψ and $\psi(2S)$ meson decays at BES-III,
  but $\psi(2S)$ are not promising
- π^0 mesons from $K^\pm \to \pi^\pm\pi^0$ decays, NA48/2 collected $2 \cdot 10^{11}$ $K^\pm$ decays
  corresponding to 10^{10} completely reconstructed π^0's,
  NA62 will have 50 times more, but downscaled (E. Goudzovski),
  a few thousands expected (KTEV ~ 800 from $K_L^0 \to 3\pi^0$ decays)
- Promising numbers of π^0, η, η' can come from
  hadronic collisions (Crystal Ball at MAMI, Crystal Barrel at ELSA,
  GLUEX and CLAS at JLAB)

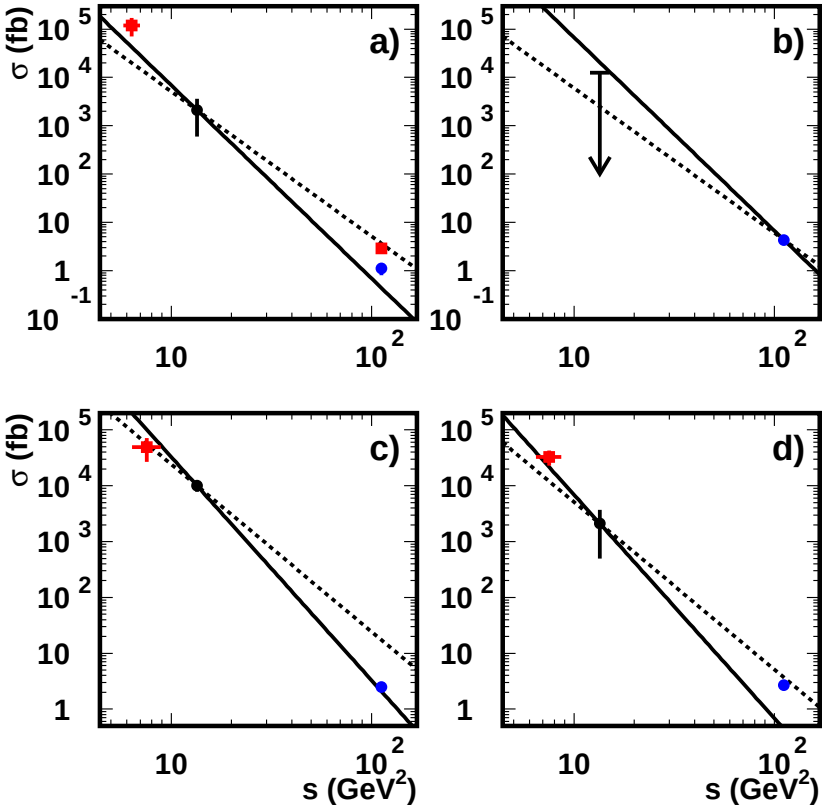
Future Possibilities – II

Decay	ϕ	J/ψ	$\psi(2S)$
$\pi^0\gamma$	$1.3 \cdot 10^{-3}$ (10^7)	$3.5 \cdot 10^{-5}$ $(3.5 \cdot 10^5)$	$1.6 \cdot 10^{-6}$
$\eta\gamma$	$1.3 \cdot 10^{-2}$ (10^8)	$1.1 \cdot 10^{-3}$ (10^7)	$1.4 \cdot 10^{-6}$
$\eta'\gamma$	$6.2 \cdot 10^{-5}$ $(6 \cdot 10^5)$	$5.2 \cdot 10^{-3}(5 \cdot 10^7)$	$1.2 \cdot 10^{-4}$

It is clear that $\psi(2S)$ mesons can't compete with the J/ψ

The numbers in () correspond to the numbers of PS mesons produced in radiative decays. We assume 10^{10} of both ϕ and J/ψ available (about 5 fb^{-1} at KLOE-2 and $\times 7$ at BESIII)

$\gamma^* \to VP$ – I



(a) $\phi\eta$, (b) $\phi\eta'$, (c) $\rho\eta$, (d) $\rho\eta'$

Solid – $1/s^4$, dashed – $1/s^3$

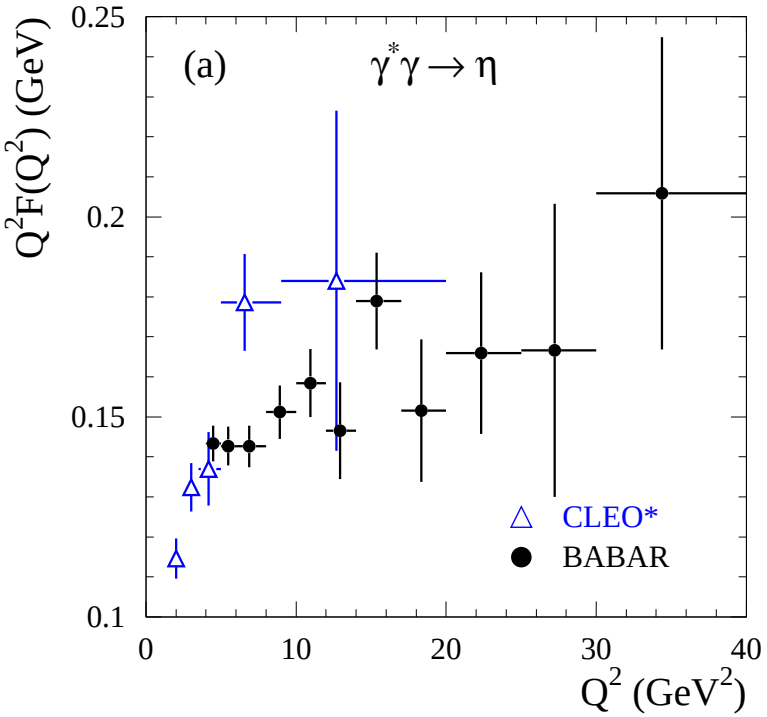
$\gamma^* \to VP$ – II

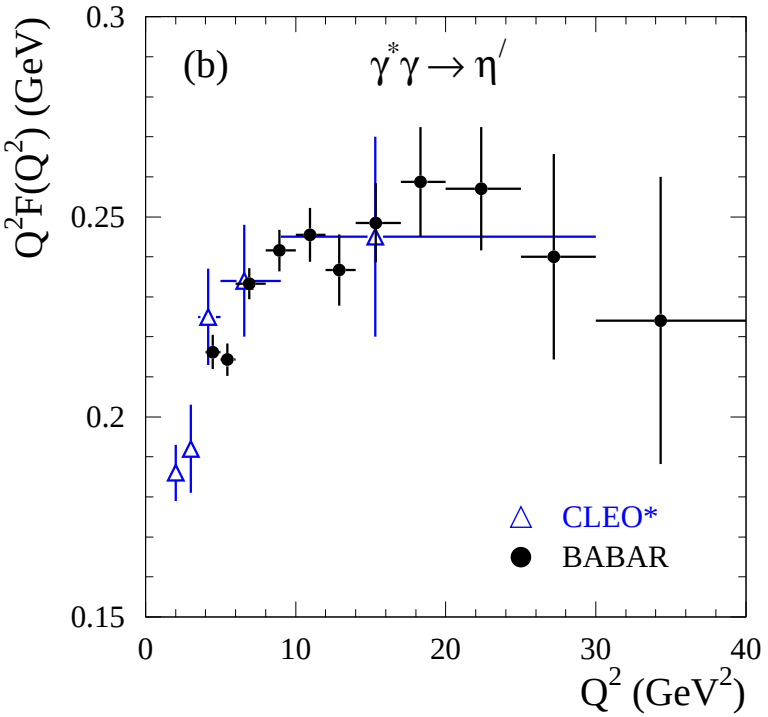
Cross sections of $e^+e^- \to VP$ in fb

Mode	Belle [3]	[4]	[5]	BaBar [2]
$\phi\eta$	$1.4 \pm 0.4 \pm 0.1$	3.3-4.3	2.4-3.4	$2.9 \pm 0.5 \pm 0.1$
$\phi\eta'$	$5.3 \pm 1.1 \pm 0.4$	4.4-5.8	3.5-5.0	–
$\phi\eta$	$3.1 \pm 0.5 \pm 0.1$	2.4-3.1	2.4-3.5	–
$\phi\eta'$	$3.3 \pm 0.6 \pm 0.2$	1.5-2.1	1.6-2.3	–

G.S. Adams et al. (CLEO)	Phys. Rev. D 73, 012002 (2006)	[1]
B. Aubert et al. (BaBar)	Phys. Rev. D 74, 111103 (2006)	[2]
K. Belous et al. (Belle)	Phys. Lett. B 681, 400 (2009)	[3]
C.D.Lu et al. (Light cone)	Phys. Rev. D 75, 094020 (2007)	[4]
V.V. Braguta et al. (Light cone)	Phys. Rev. D 78, 074032 (2008)	[5]

Transition Form Factors - I (η, η')



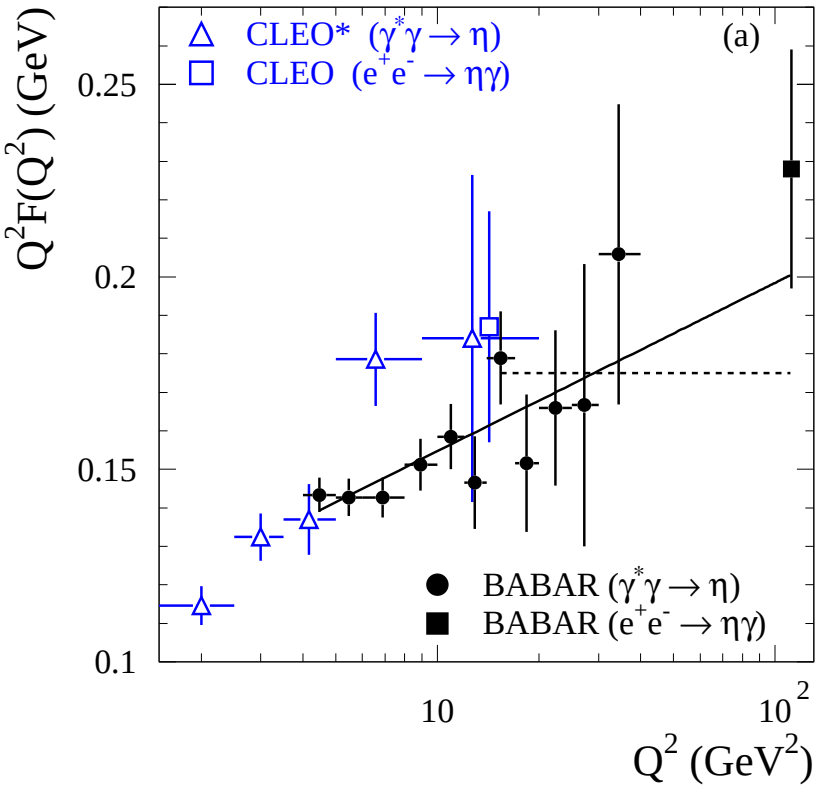


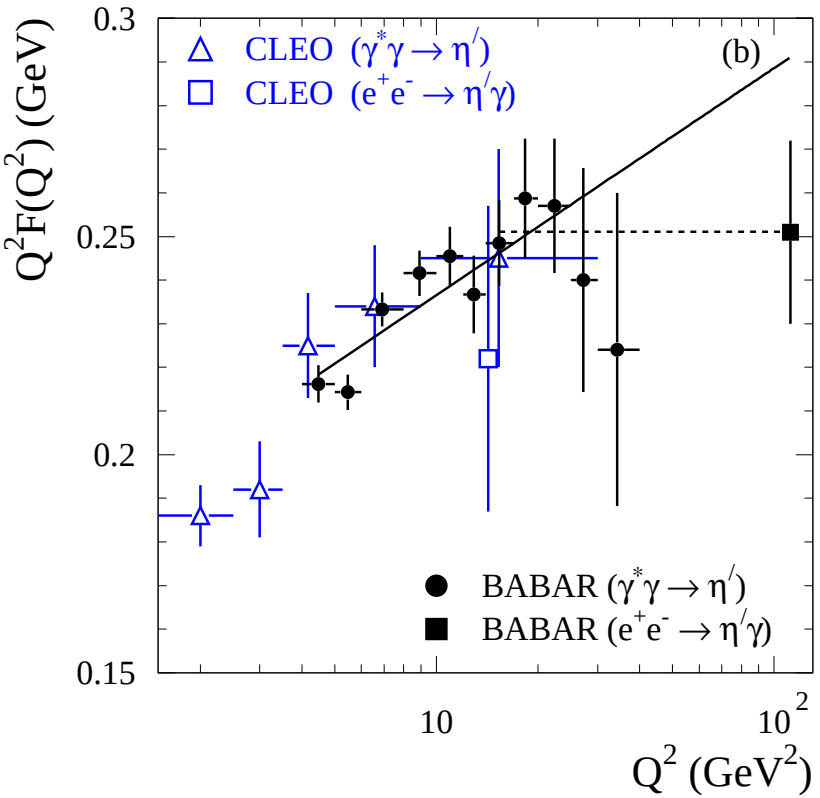
Single-tag measurements probe $\gamma\gamma^*$

P. del Amo Sanchez et al. (BaBar), Phys. Rev. D 84, 052011 (2011)

J. Gronberg et al. (CLEO), Phys. Rev. D 57, 33 (1998)

Transition Form Factors - II (η, η')

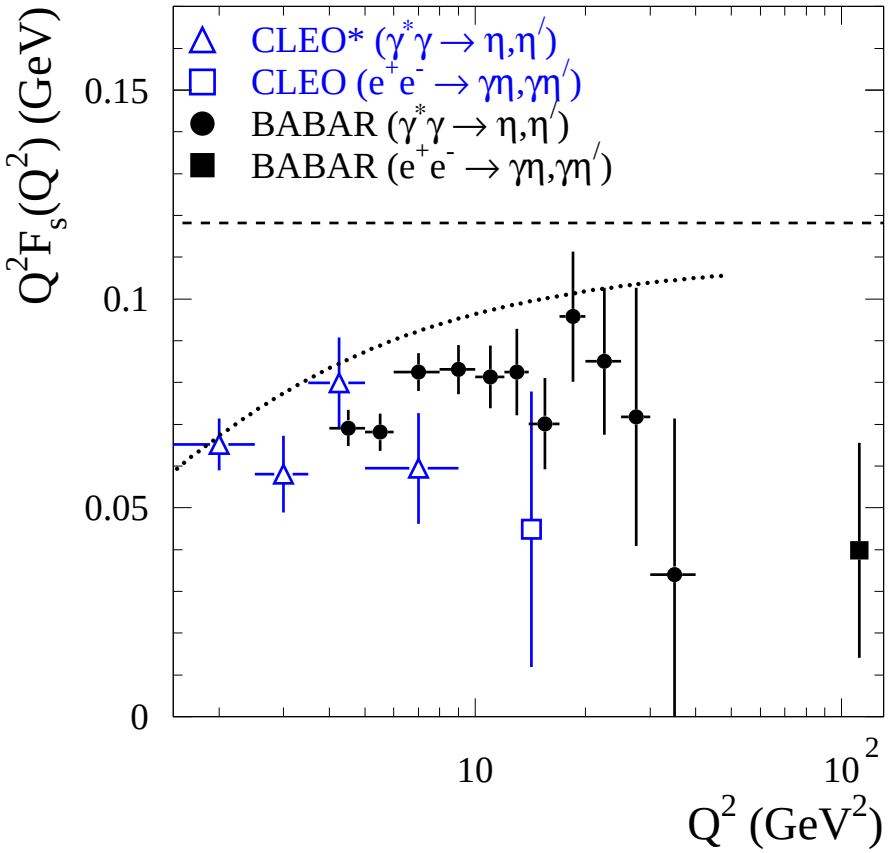




B. Aubert et al. (BaBar), Phys. Rev. D 74, 012002 (2006)

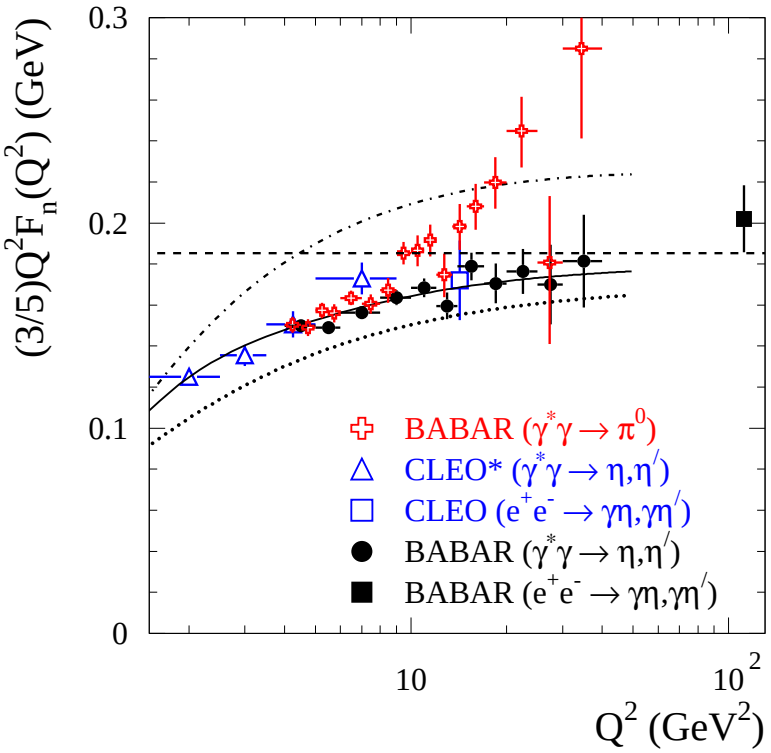
T.K. Pedlar et al. (CLEO), Phys. Rev. D 79, 111101 (2009)

Transition Form Factors - III (η, η')



The s part of the meson distribution amplitude

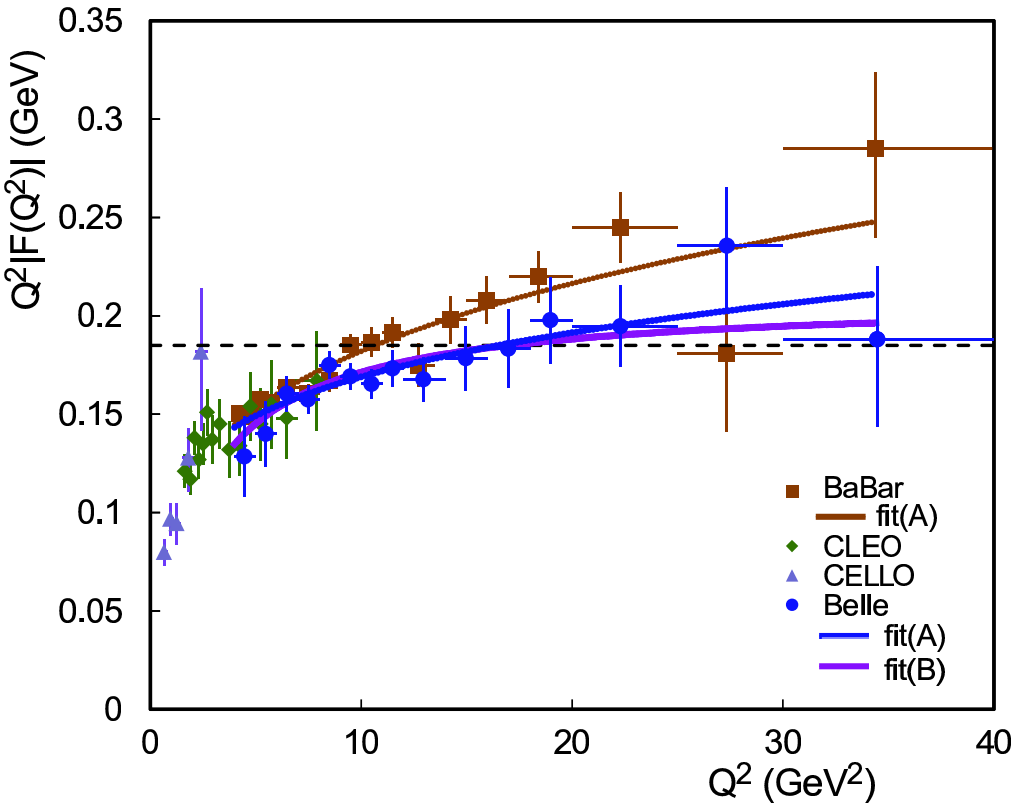
Transition Form Factors - IV (η, η' and π^0)



The u, d part of the meson distribution amplitude

B. Aubert et al. (BaBar), Phys. Rev. D 80, 052002 (2009)

Transition Form Factors - V (π^0)



Belle data do not confirm fast rise observed at BaBar

S. Uehara et al., Phys. Rev. D 86 (2012) 092007

Conclusions

- In P decay sector: good progress with η' from BES3,
  much more work needed for π^0 and η,
  branching fractions measured, but not yet slopes of TFF
- In V decay sector: good progress with ϕ from KLOE,
  expect serious progress at ρ/ω from VEPP-2000
- Low energy $\gamma\gamma$ physics at KLOE
- Studies of transition form factors, potentially interesting for hLbL,
  are also going on at MAMI, JLAB, Julich, ...