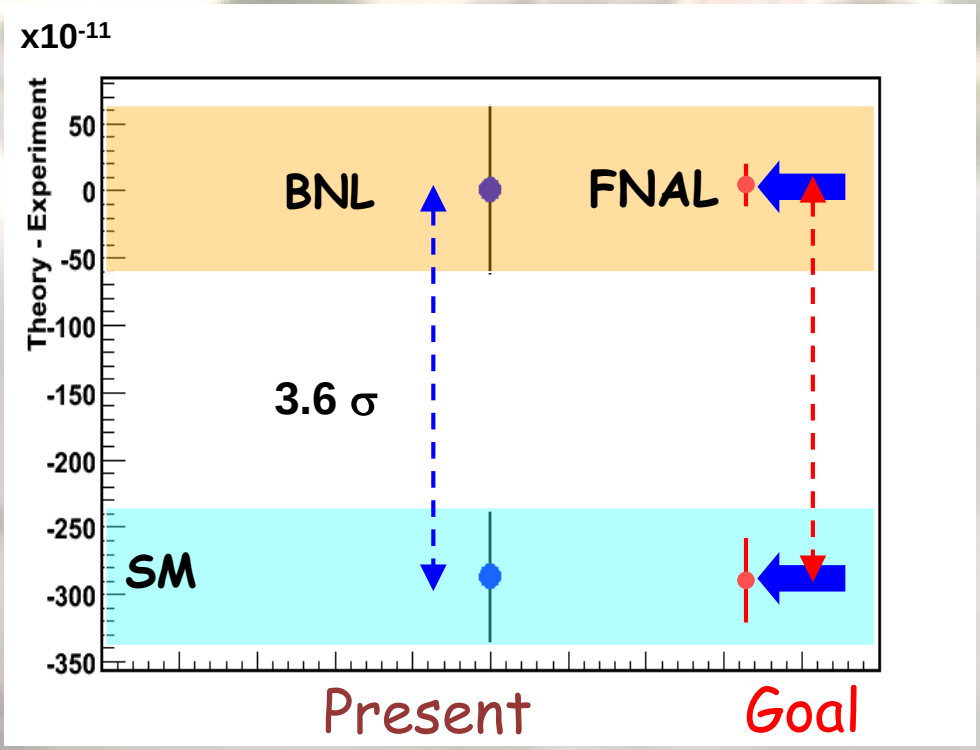
Experimental input and cross checks for HLbL contribution to muon g-2

A.Kupsc Uppsala U.



D.Hertzog, arXiv:1512.00928

FCCP2019, Anacapri, 2019-08-29

Hadronic contribution

$$a_\mu^{BNL} = (116\ 592\ 091 \pm 63) \cdot 10^{-11}$$

$$a_\mu^{exp} - a_\mu^{SM} = (249 \pm 87) \cdot 10^{-11} \quad (3\sigma)$$

hadronic vacuum polarization (HVP)

hadronic light-by-light scattering (HLbL)

$$a_\mu^{HVP} = (6\ 923 \pm 42) \cdot 10^{-11}$$

$$a_\mu^{HLbL} = (116 \pm 40) \cdot 10^{-11}$$

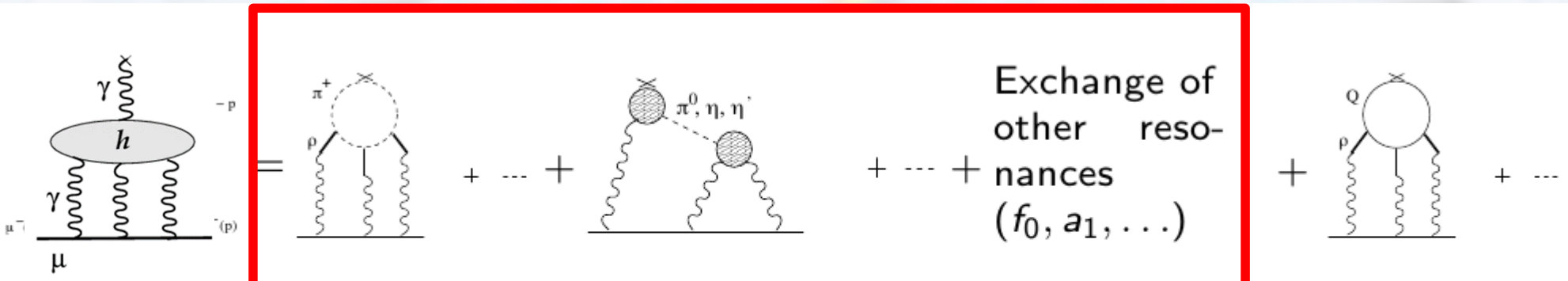
$a_\mu^{exp} - a_\mu^{SM}$: 4% HVP

215% HLbL
(1% of leptonic LbL)

Hadronic Light by Light

"must be calculated using **hadronic models** that correctly reproduce properties of QCD"

$$a_\mu^{\mathrm{HLbL}} = 10.5(2.6) \times 10^{-10}$$

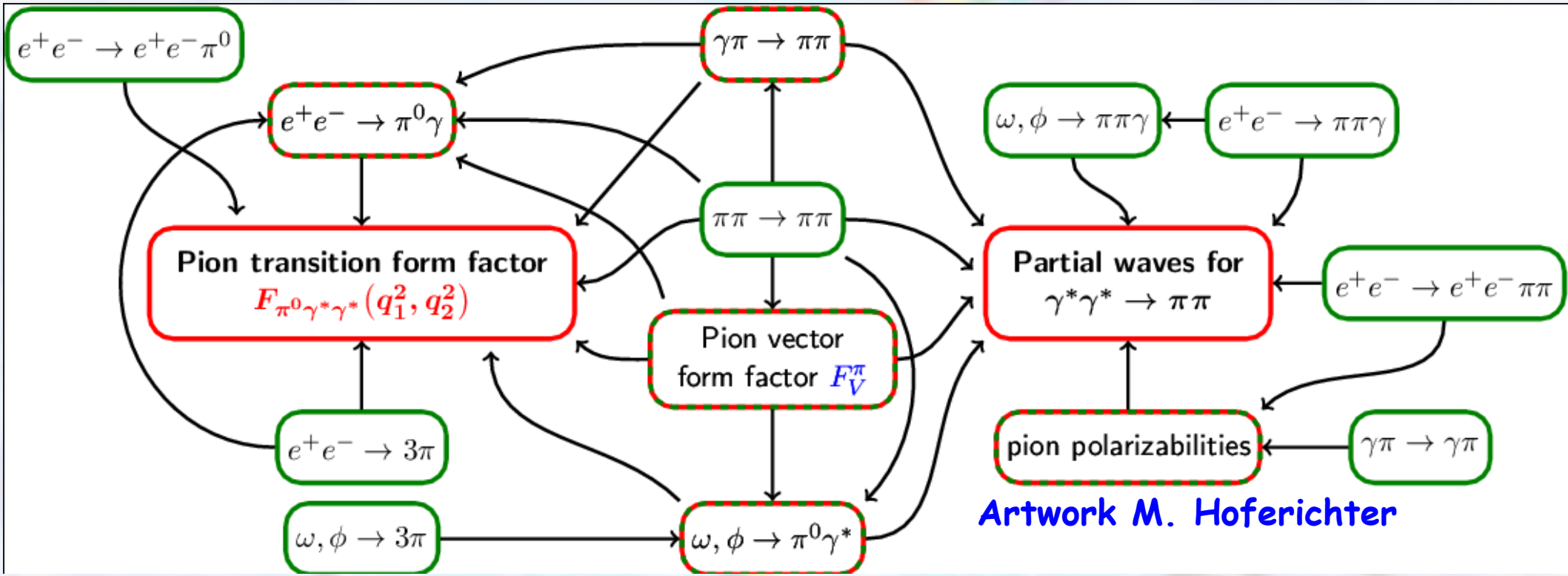


PdRV	$(-1.9 \pm 1.9) \cdot 10^{-10}$	$(11.4 \pm 1.3) \cdot 10^{-10}$	$(0.8 \pm 1.1) \cdot 10^{-10}$	$0.23 \cdot 10^{-10}$

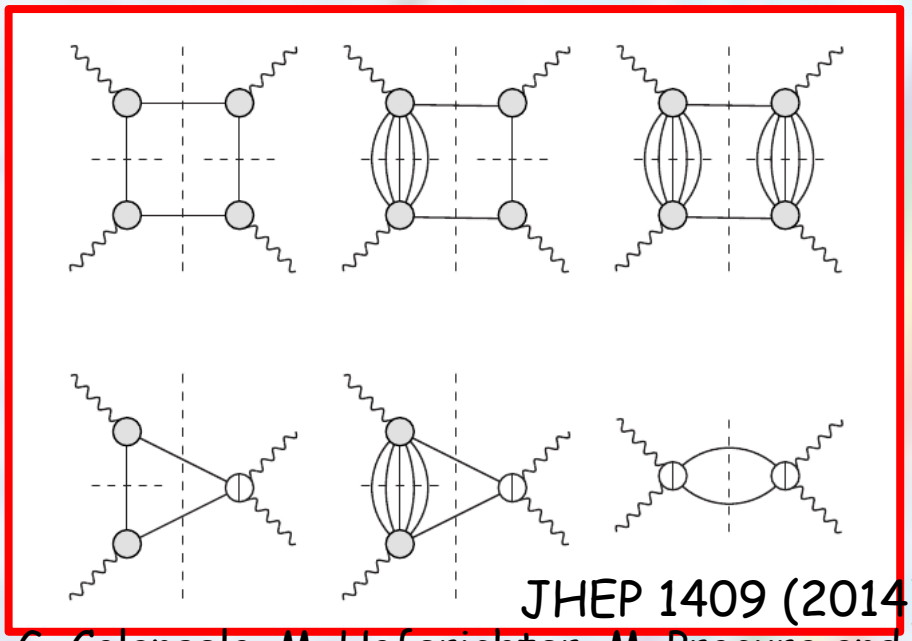
E. de Rafael, "Hadronic contributions to the muon g-2 and low-energy QCD," Phys. Lett. **B322** (1994) 239-246. [hep-ph/9311316].

Slide: J. Bijnens, A.Nyffeler

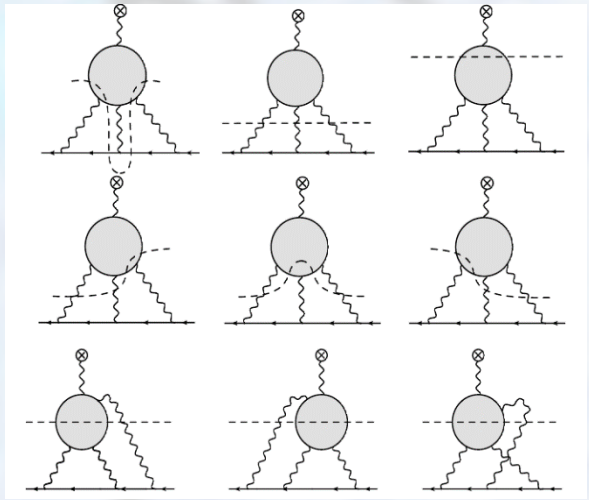
Data driven dispersive HLbL



Artwork M. Hoferichter



JHEP 1409 (2014) 091
G. Colangelo, M. Hoferichter, M. Procura and P. Stoffer



PRD90 (2014)113012
M. Vanderhaeghen,V. Pauk

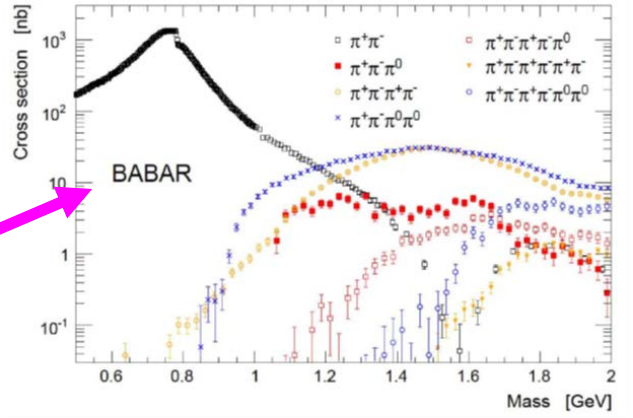
Data for dispersive HLbL

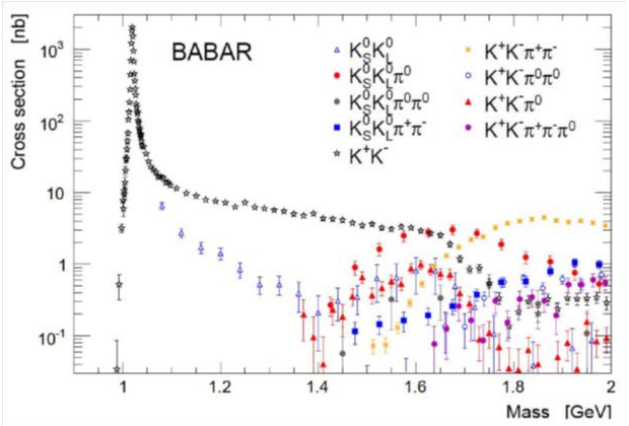
F_{π^0}

$F_\eta, F_{\eta'}$

F_V

F_K

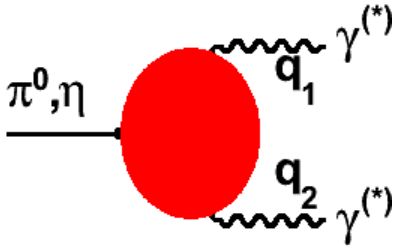




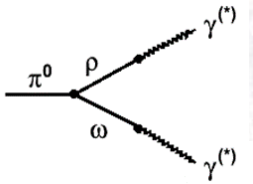
ππ, πK, ηπ, KK phase shifts

π^0,η,η' Transition Form Factors (TFF)

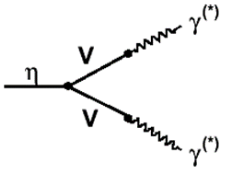
$$\Gamma(P \to \gamma\gamma)$$

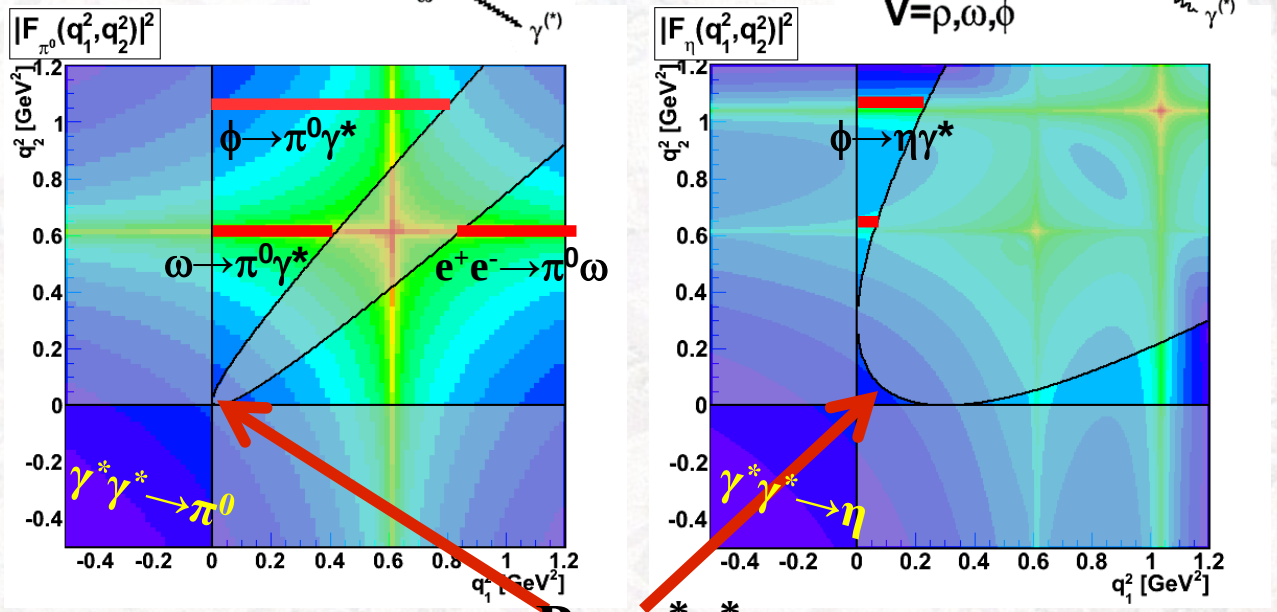


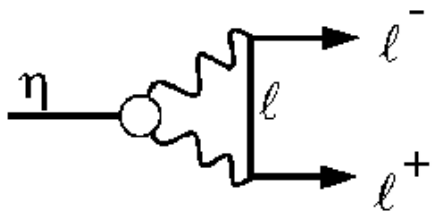
$$F_P(q_1^2, q_2^2)$$



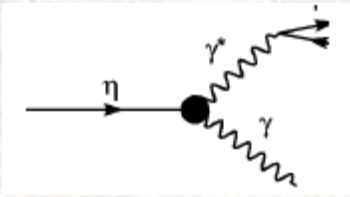
$$\sum_{V=\rho,\omega,\phi}$$

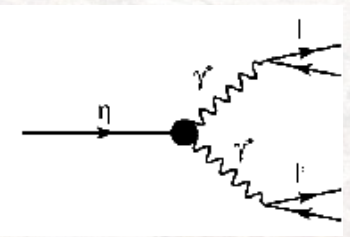






Access to $q^2<0$





Radiative widths of η, π^0

η: 5×10^{-19} s; Γ=1.3 keV $\eta \to \gamma\gamma$

π^0: 8×10^{-17} s; $c\tau$=25 nm $\pi^0 \to \gamma\gamma$

Two exp. techniques:

$\gamma Z \to \eta, \pi^0$ Primakoff

PrimEx PRL 106,162303(2011)

PrimEx-II:

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.80eV ± 0.7% stat. ± 1.5% syst.

e^+e^-: $\gamma\gamma \to \pi^0$

KLOE-2 Taggers

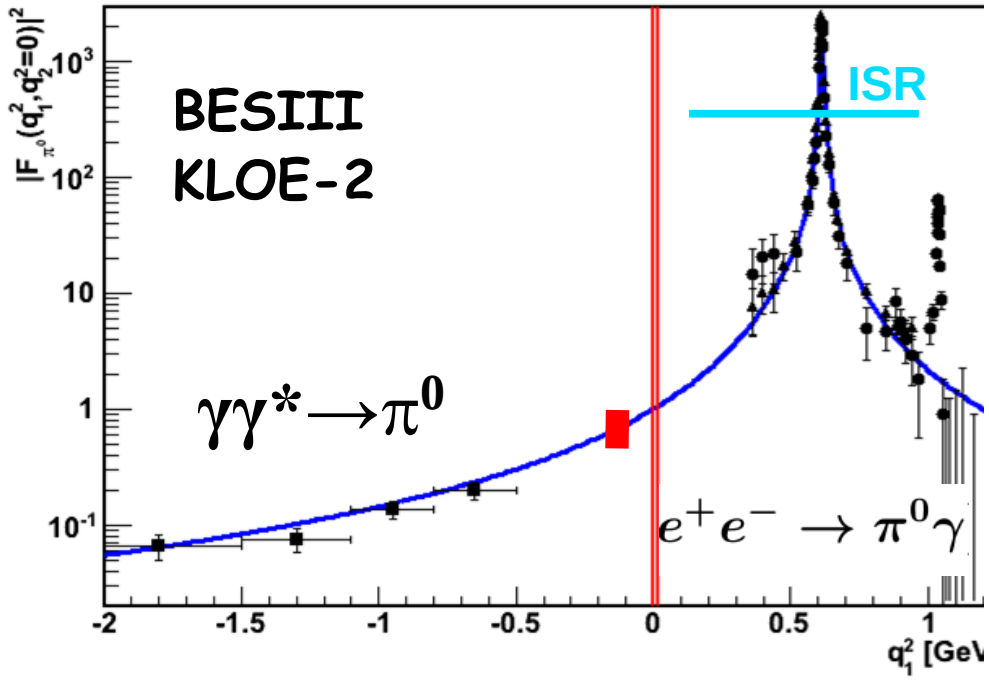
$5fb^{-1}$ => $\delta\Gamma(\pi^0\to\gamma\gamma)$

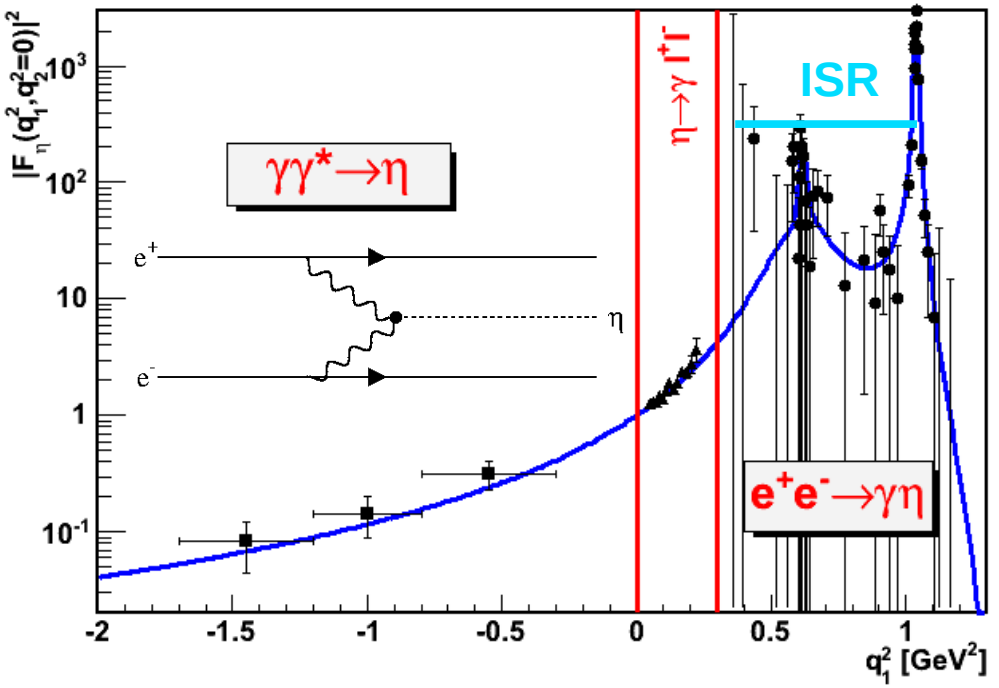
Details: [EPJC 72, 1917 (2012)]

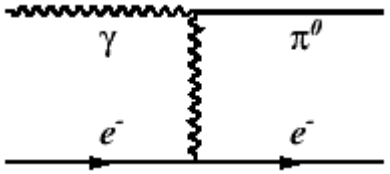
$\delta\Gamma(\eta\to\gamma\gamma)$ ~3.5%

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
0.515 ± 0.018	**OUR FIT**				
0.516 ± 0.018	**OUR AVERAGE**				
0.520 ±0.020 ±0.013		BABUSCI	2013A	KLOE	$e^+ e^- \to e^+e^-\eta$
0.51 ±0.12 ±0.05	36	BARU	1990	MD1	$e^+ e^- \to e^+e^-\eta$
0.490 ±0.010 ±0.048	2287	ROE	1990	ASP	$e^+ e^- \to e^+e^-\eta$
0.514 ±0.017 ±0.035	1295	WILLIAMS	1988	CBAL	$e^+ e^- \to e^+e^-\eta$
0.53 ±0.04 ±0.04		BARTEL	1985E	JADE	$e^+ e^- \to e^+e^-\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.476 ±0.062	[1]	RODRIGUES	2008	CNTR	Reanalysis
0.64 ±0.14 ±0.13		AIHARA	1986	TPC	$e^+ e^- \to e^+e^-\eta$
0.56 ±0.16	56	WEINSTEIN	1983	CBAL	$e^+ e^- \to e^+e^-\eta$
0.324 ±0.046		BROWMAN	1974B	CNTR	Primakoff effect
1.00 ±0.22	[2]	BEMPORAD	1967	CNTR	Primakoff effect

η,π^0 single off shell TFF







$\gamma^* \to P\gamma$

VEPP 2000 0.3-2GeV

KLOE-2 ISR, BESIII

$$\frac{d\sigma}{dt}(e^-\gamma \to e^- P) = \frac{16}{3}\frac{\pi\alpha}{s m_P^3}\,\Gamma_{\gamma\gamma}|F_P(t,0)|^2\,\frac{s-m_P^2+t}{t}$$

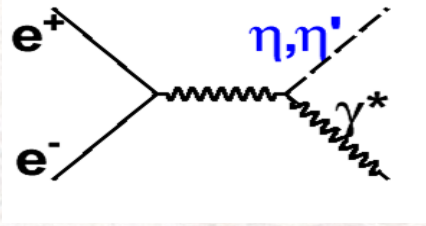
$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{s m_P}\right)^3$$

$P \to \gamma^*\gamma$

Dalitz decays:

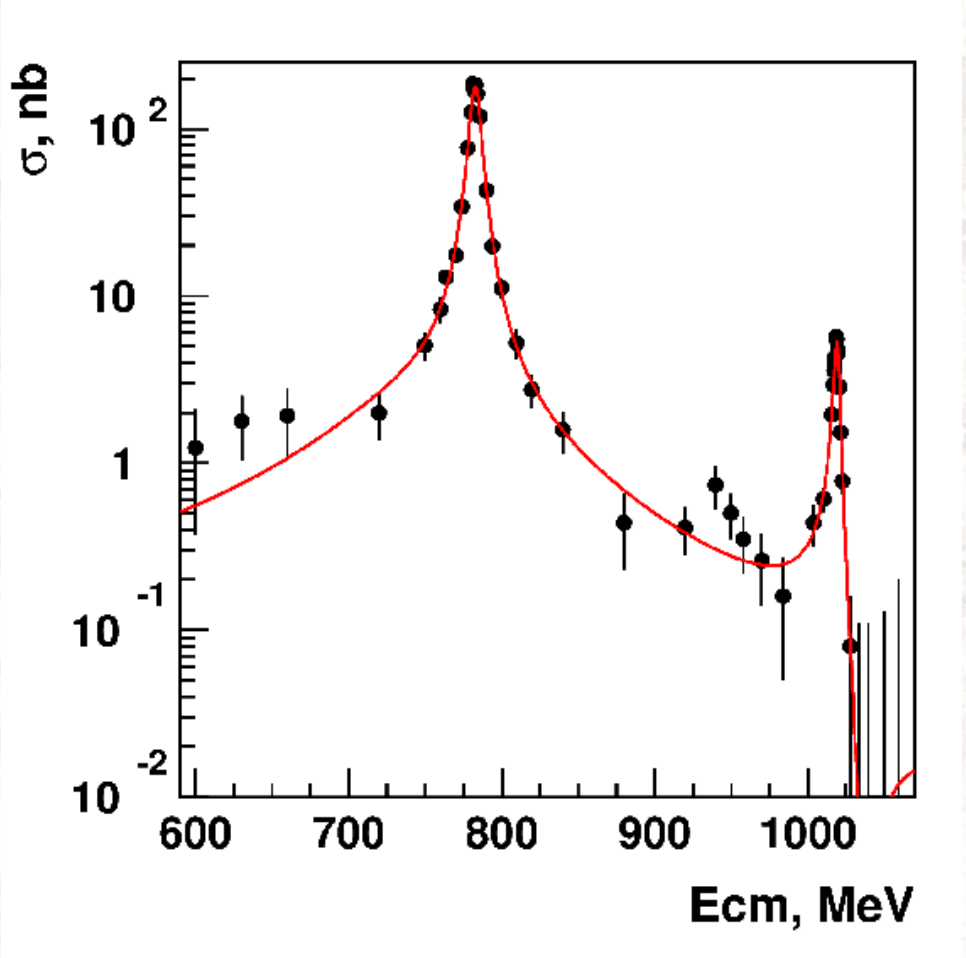
KLOE, WASA,CBall,BESIII

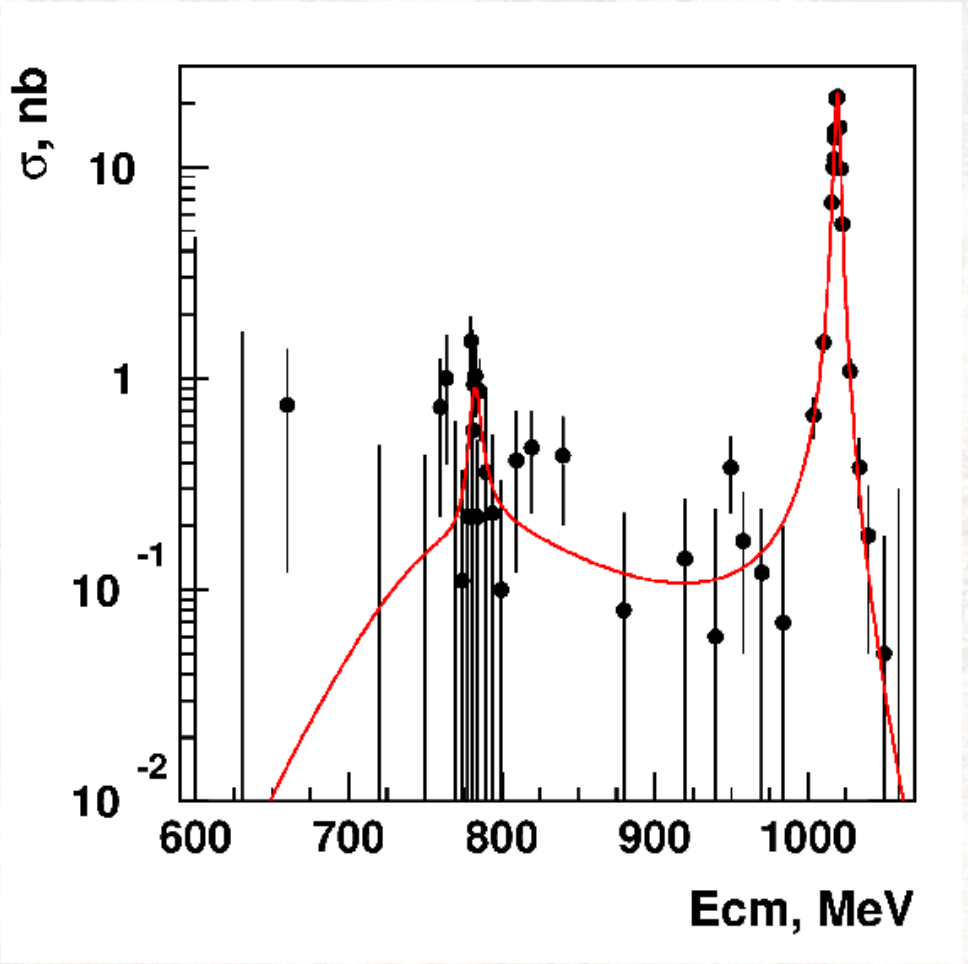
CLAS,NA48

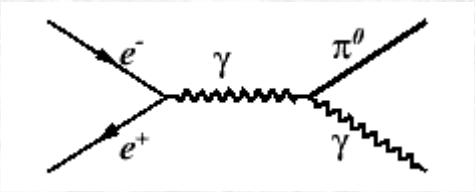


Data:CELLO,NA60,CB-MAMI,CMD-2,SND

$\sigma(e^+e^- \to \pi^0\gamma, \eta\gamma)$



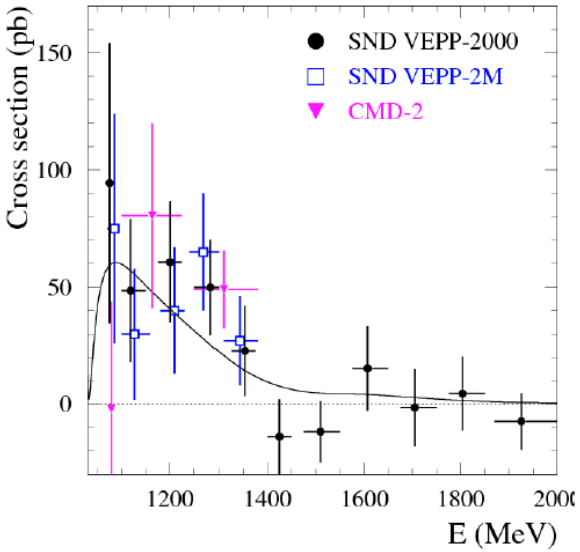




$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

Data: CMD-2,SND

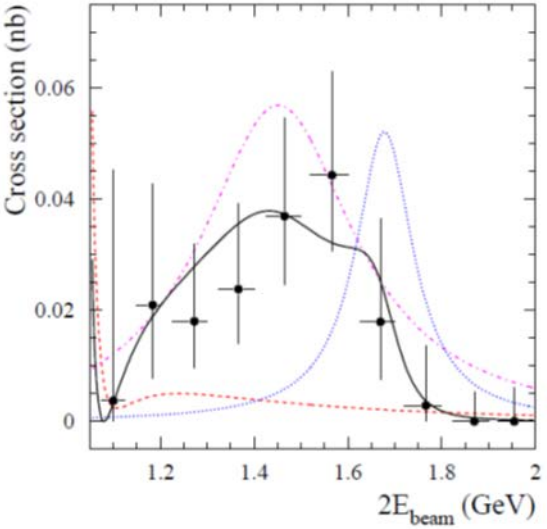
$e^+e^- \to \pi^0\gamma$ at SND



The first search above 1.4 GeV, preliminary

No signal above the background

$e^+e^- \to \eta\gamma$ at SND



The first measurement above 1.4 GeV, Phys. Rev. D90 (2014) 032002

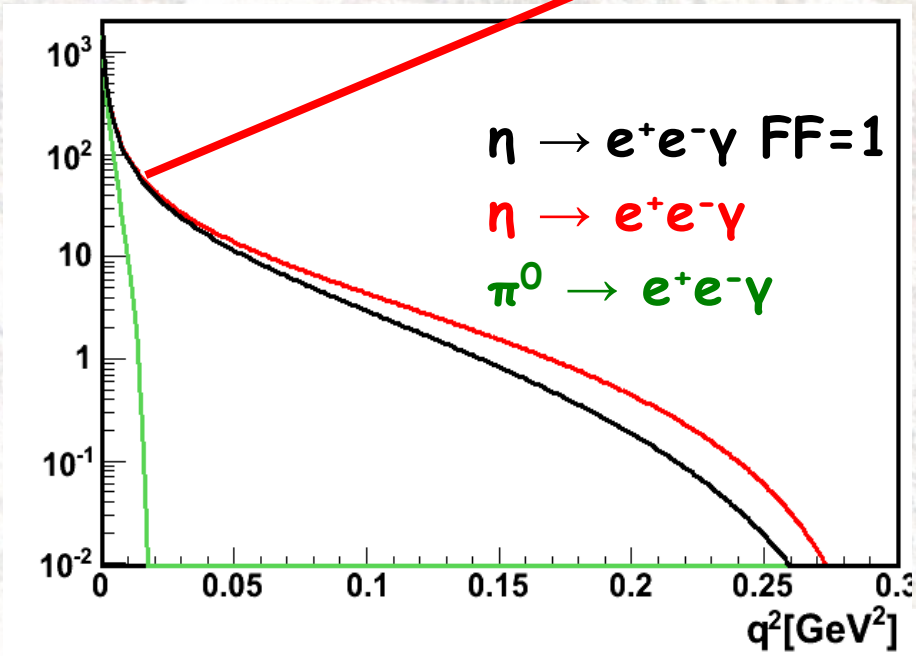
Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

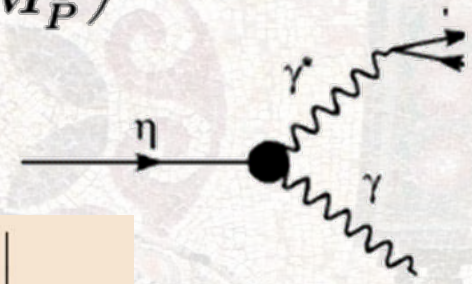
Data: CMD-2,SND

Dalitz decays

Single Dalitz decays

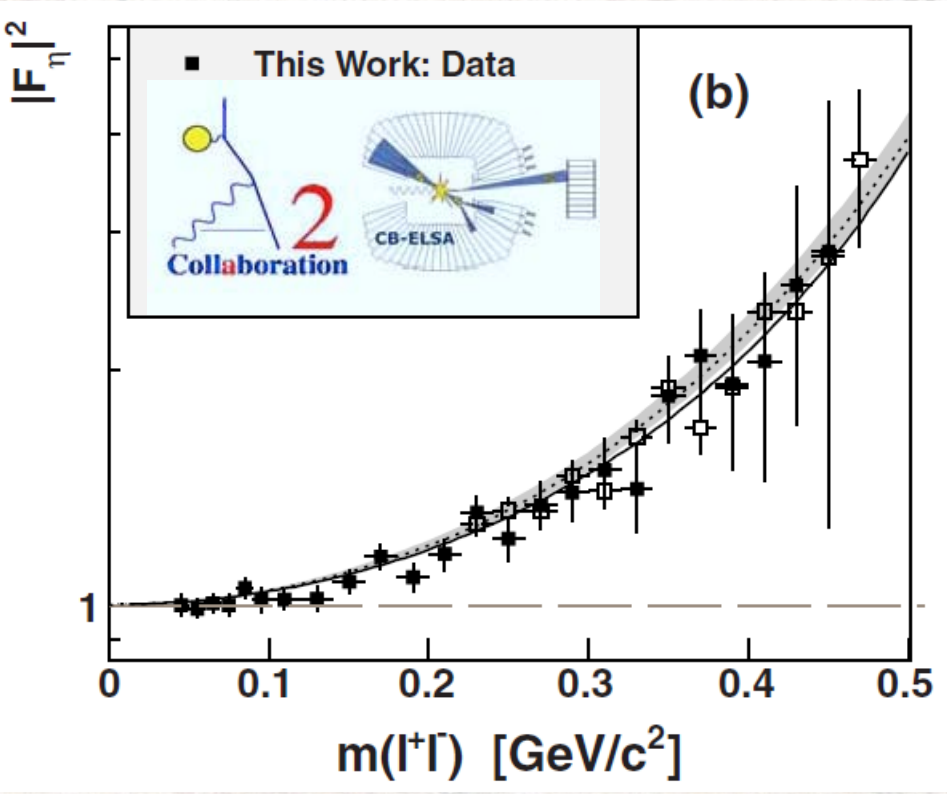
$$\frac{d\Gamma(P \to \ell^+\ell^-\gamma)}{dq^2\Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_\ell^2}{q^2}}\left(1+\frac{2m_\ell^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$

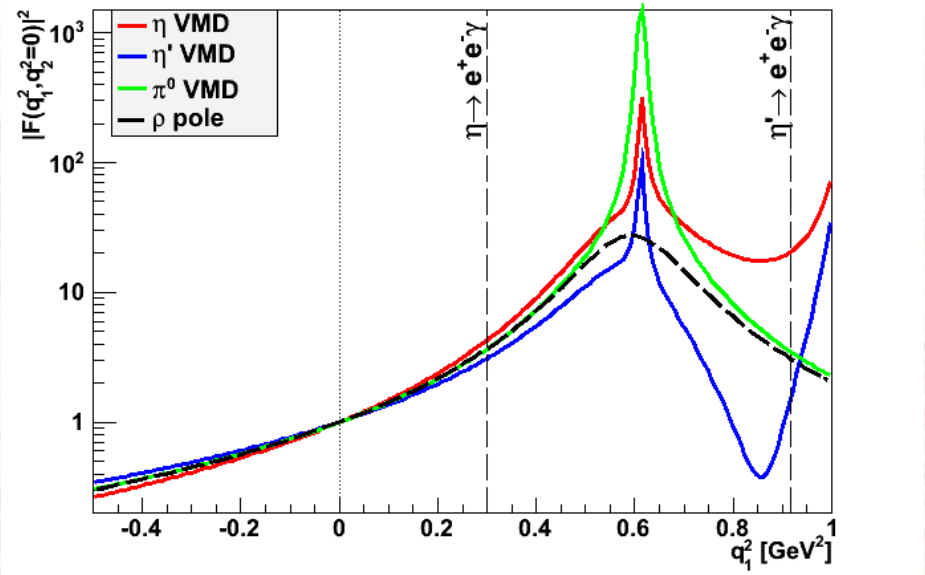




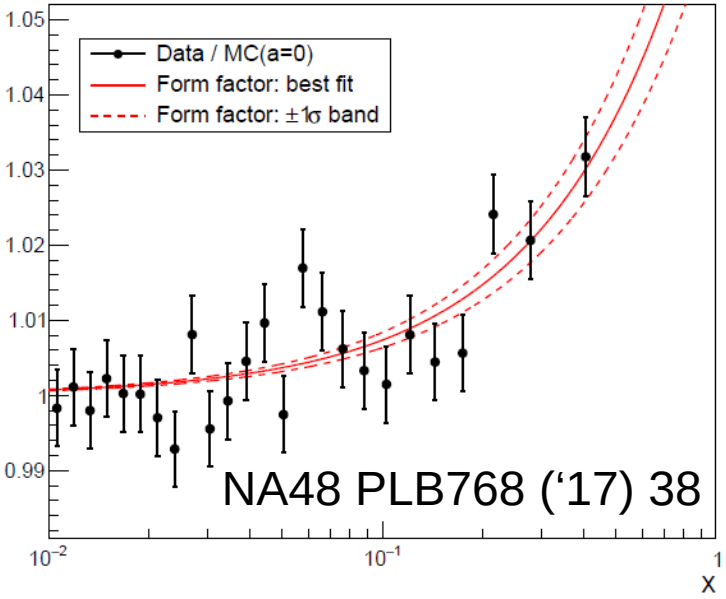
$$b_P = \left.\frac{d\ln|F_P(q^2)|}{dq^2}\right|_{q^2=0}$$

CB/TAPS: PRC89, 044608 (2014)





$\pi^0 \to e^+e^-\gamma$



$a_\pi=(3.68\pm0.57)\times10^{-2}$

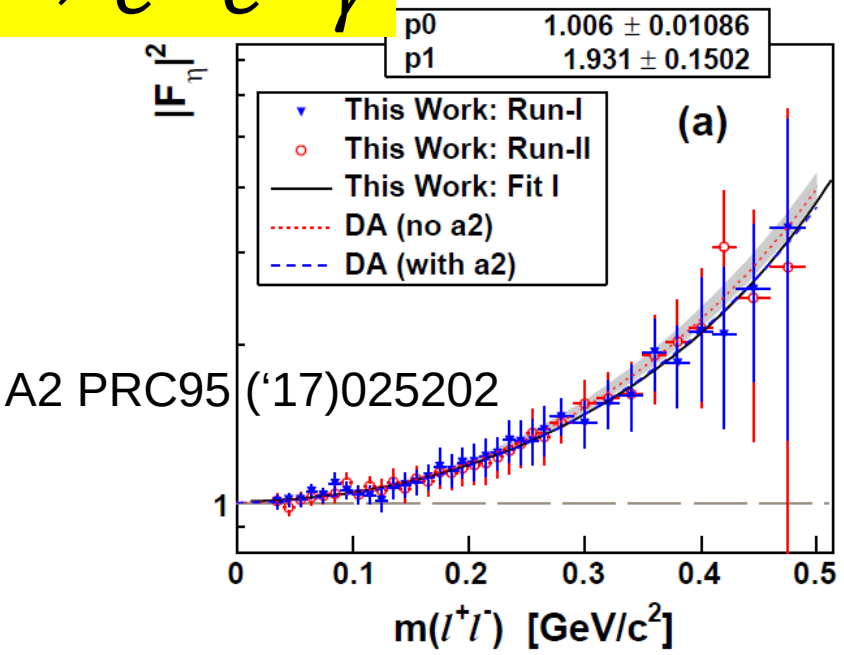
$a_\pi=(3.0 \pm 1.0)\times10^{-2}$ A2 PRC

PDG_{AVG} $a_\pi=(3.35 \pm 0.31)\times10^{-2}$

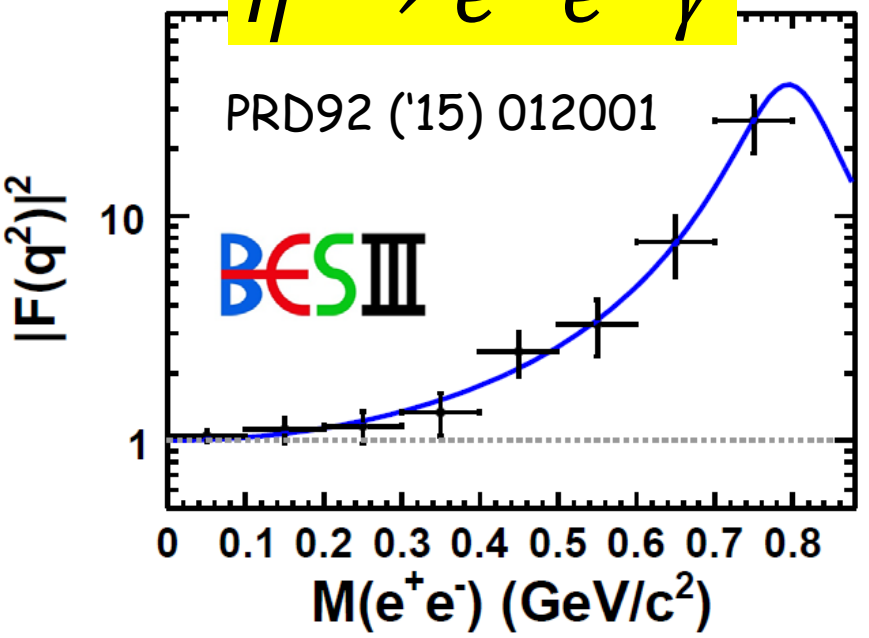
DR: $a_\pi=(3.15 \pm 0.09)\times10^{-2}$ arXiv:1808.04823

$$F_{\pi^0\gamma}(m_{ee}) = 1 + a_\pi \frac{m_{ee}^2}{m_{\pi^0}^2}$$

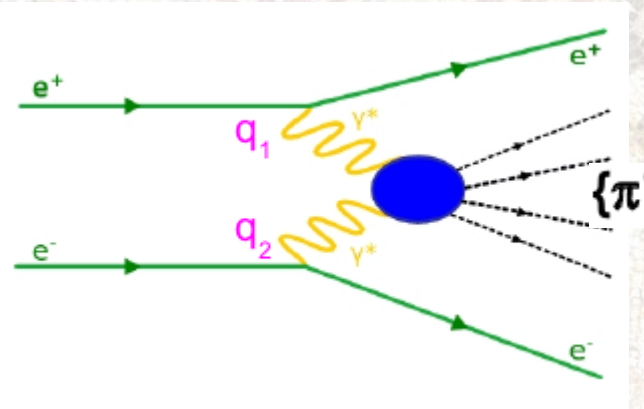
$\eta \to e^+e^-\gamma$



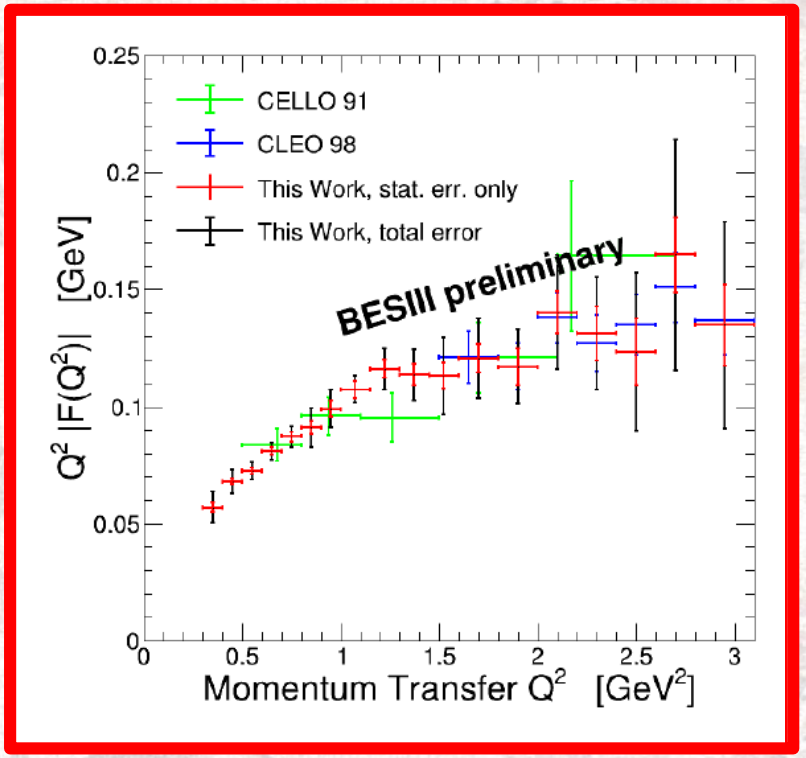
$\eta' \to e^+e^-\gamma$

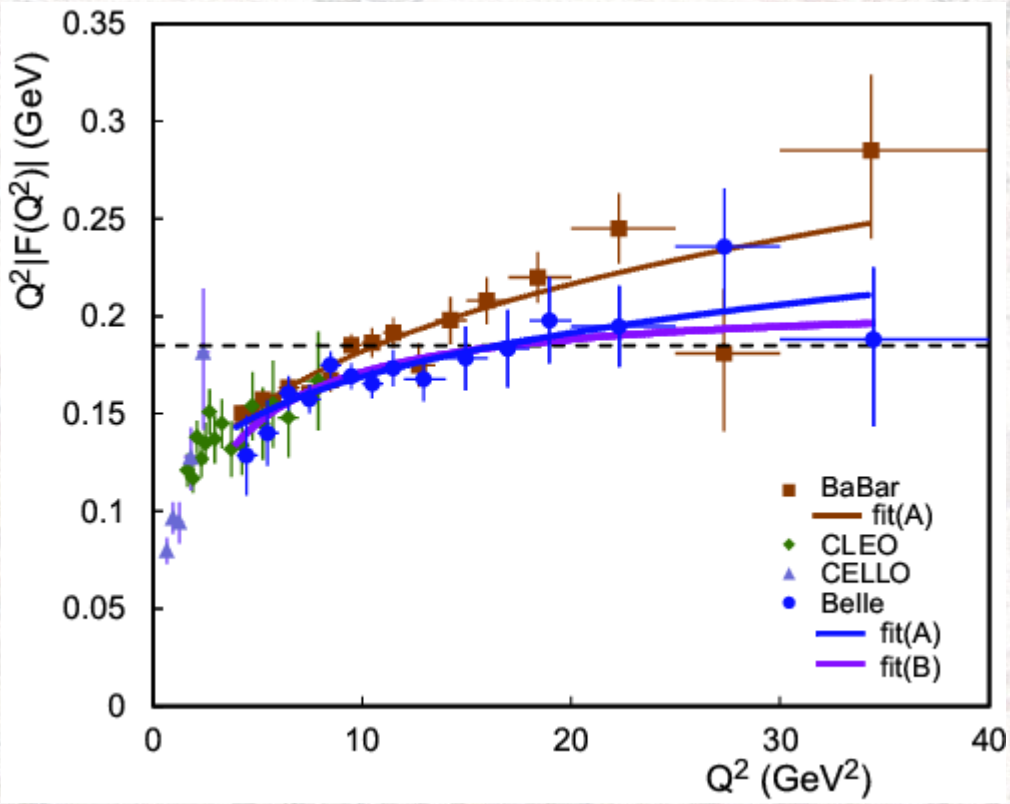


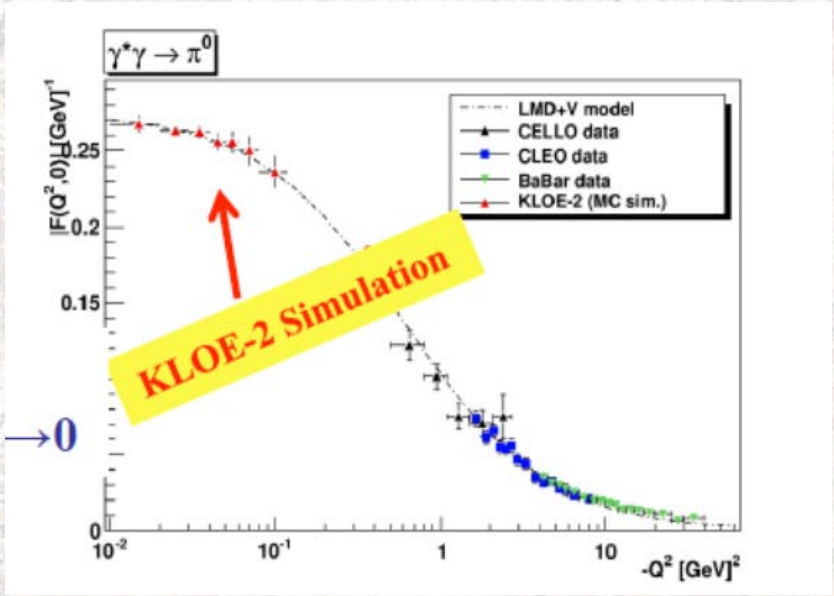
$\gamma\gamma^* \rightarrow \pi^0$



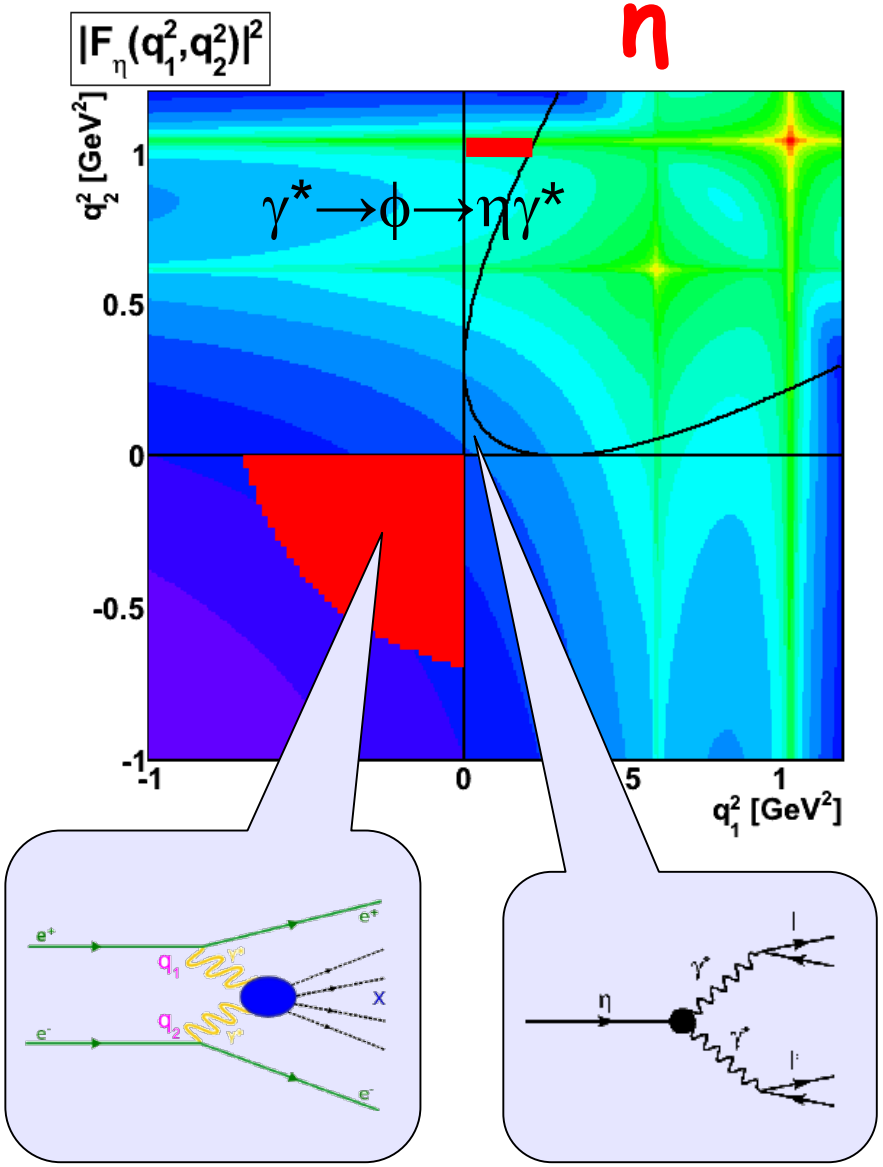
$\{\pi^0, \pi\pi, \eta\}$



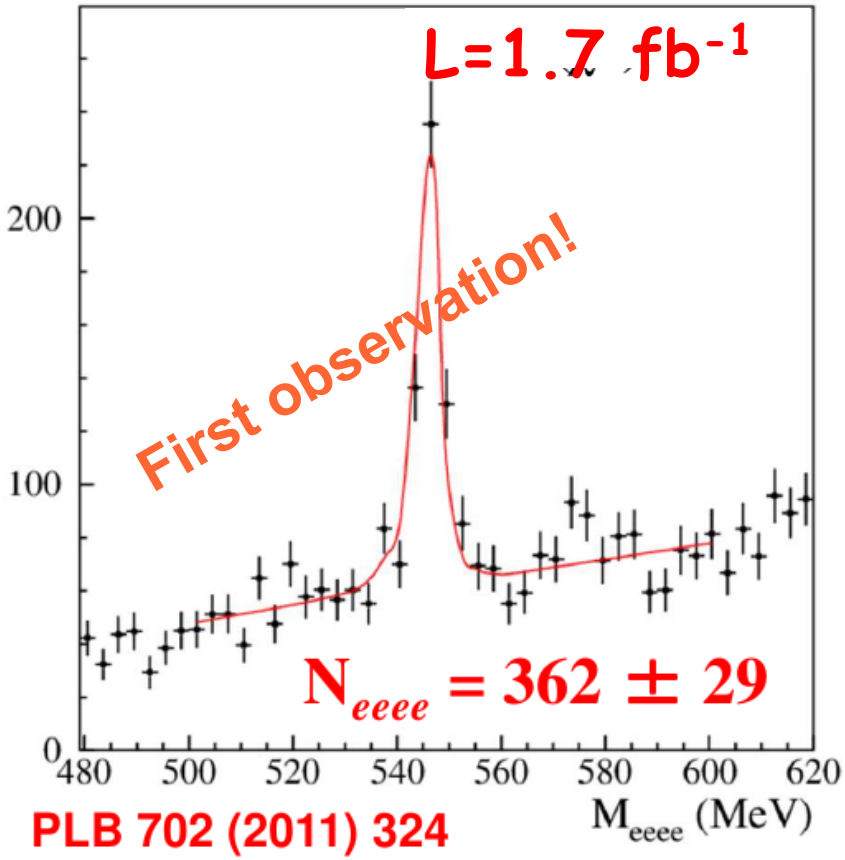




Double off shell TFF



$\eta \to e^+e^-e^+e^-$



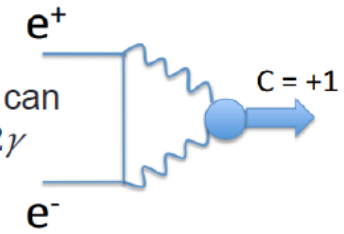
PLB 702 (2011) 324

BR($\eta \to e^+e^-e^+e^-(\gamma)$)= (2.4 ± 0.2$_{stat}$ ± 0.1$_{syst}$) × 10^{-5}

⇨BESIII

Search for e+e- → η'(958)

Phys.Lett. B740 (2015) 273-277



C-even resonances can be produced via 2γ

Theory: assuming real γ
$B(\eta' \to e^+ e^-) = 3.7 \cdot 10^{-11}$

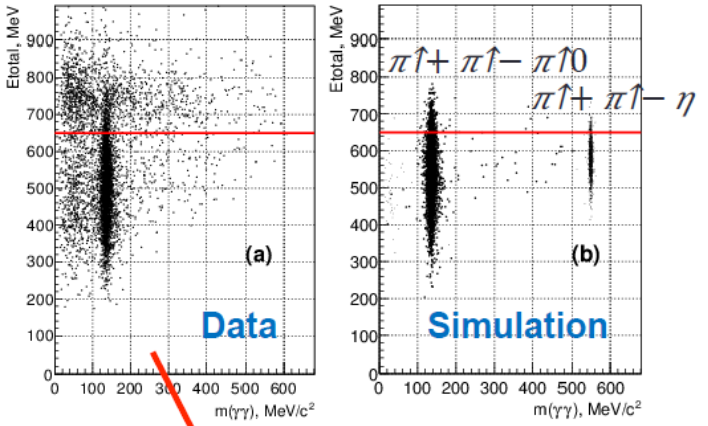
γ virtuality and transition form factor can enhance it

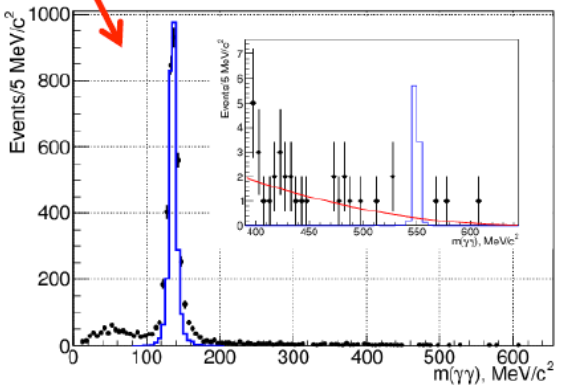
New limit:

$B(\eta' \to e^+e^-) < 5.6 \times 10^{-9}$ (90%CL) - SND+CMD-3

Dedicated data taking at $\sqrt{s} = M_\eta$

Continuous beam energy monitoring is crucial

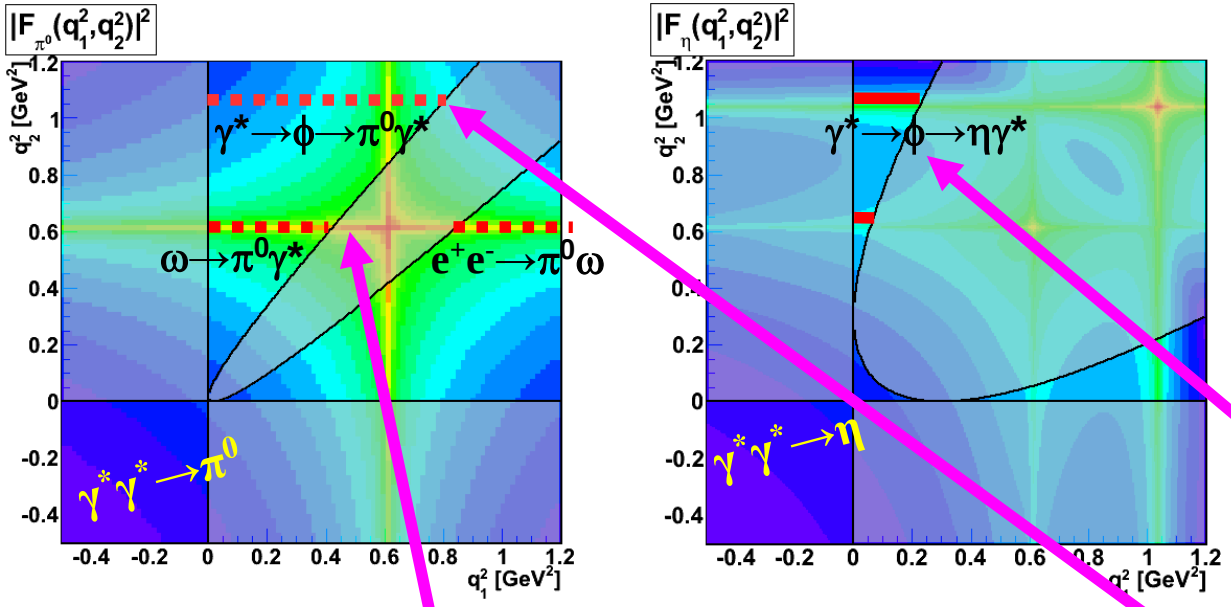


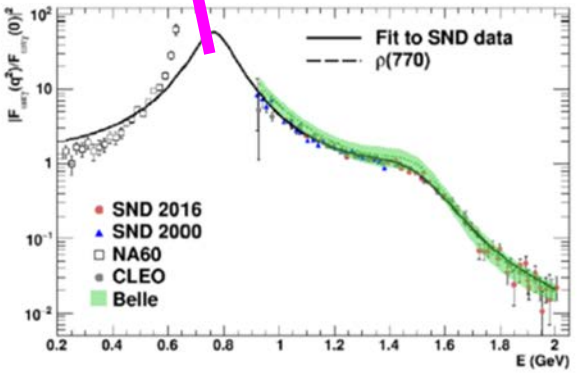


SND+CMD-3

Slide: E.Solodov CMD-2,SND

V → Pγ* and e+e- → PV processes





In addition to SND and NA60, other data on $\mathcal{F}(\gamma\omega\pi)$ exist:
CLEO ($\tau^- \to \omega\pi^-\nu_\tau$), K.W. Edwards et al., Phys. Rev. D61 (2000) 072003
Belle ($\bar{B}^0 \to D^{*+}\omega\pi^-$), D. Matvienko et al., Phys. Rev. 92 (2015) 012013
NA60 studied inclusively $\omega \to \pi^0\mu^+\mu^-$

KLOE

result $b\eta(m^2_\phi)$
$\phi\to\eta\gamma^*$ BR 10^{-4}

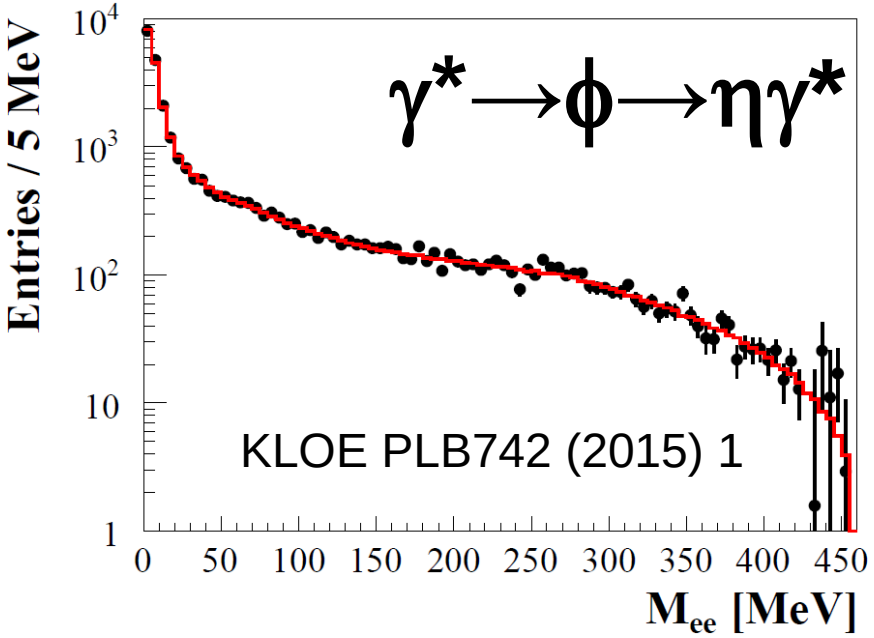
Phys.Lett. B742 (2015) 1-6

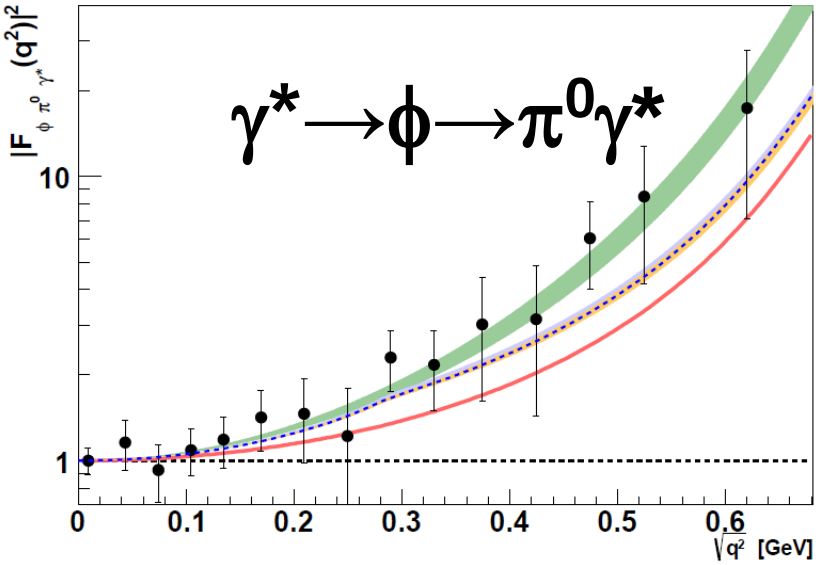
$b_{\varphi\eta} = (1.17 \pm 0.10^{+0.07}_{-0.11})\text{GeV}^{-2}$

$b\pi^0(m^2_\phi)$ $\phi\to\pi^0\gamma^*$ BR 10^{-5}

Phys.Lett. B757 (2016) 362-367

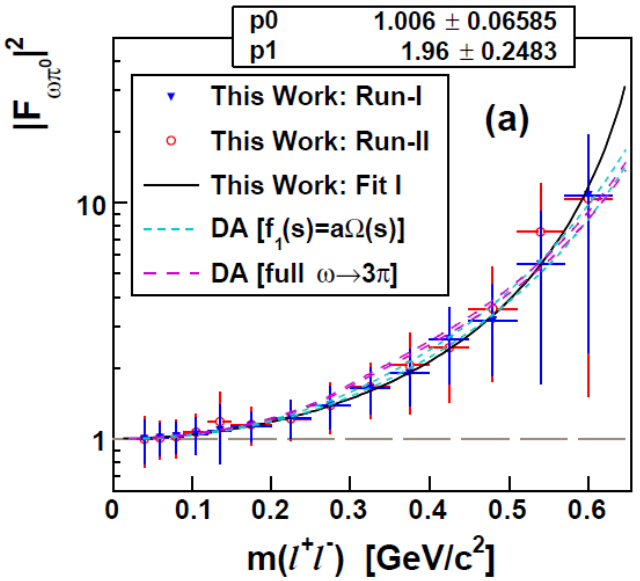
$b\varphi\pi 0 = (2.02\pm0.11)\ \text{GeV}^{-2}$





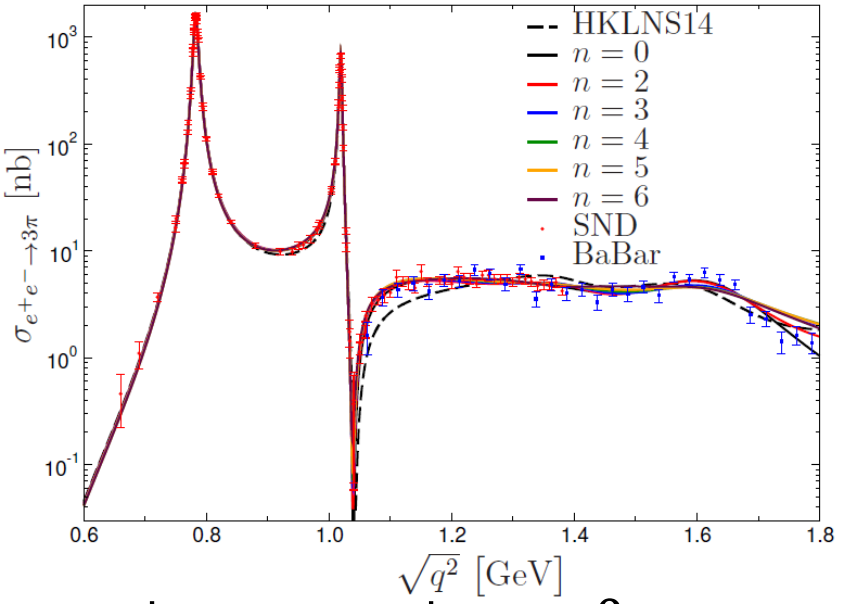
KLOE PLB757 (2016) 362

γ*→ π⁰ω

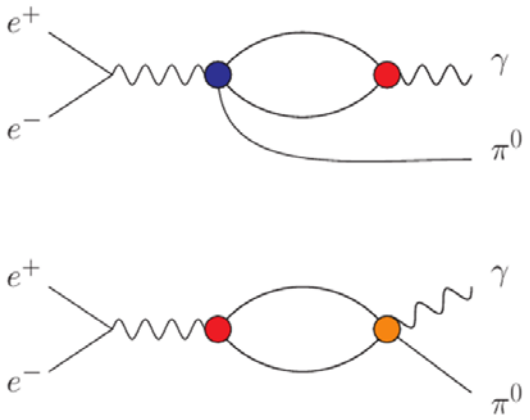


A2 Phys.Rev. C95 (2017) 025202

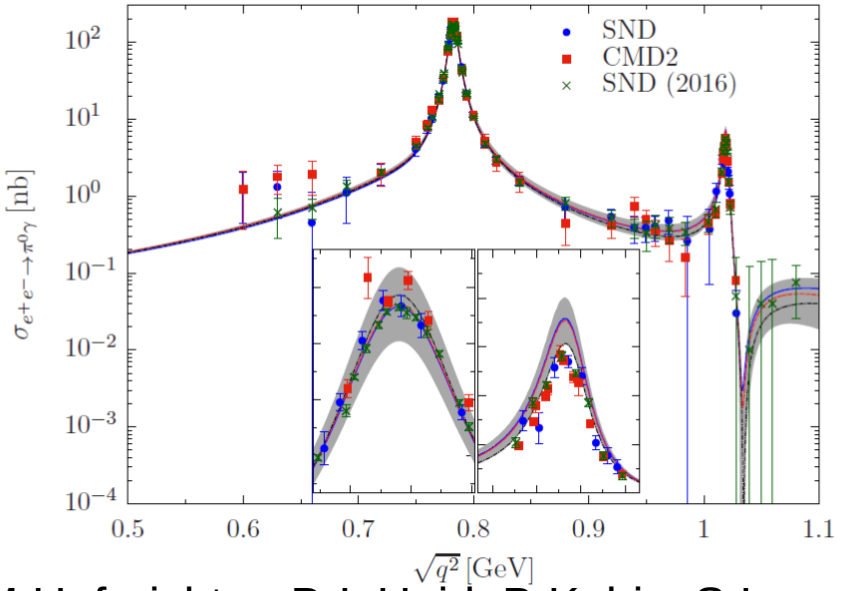
DP: e+e- → π+π-π⁰ to π⁰ TFF

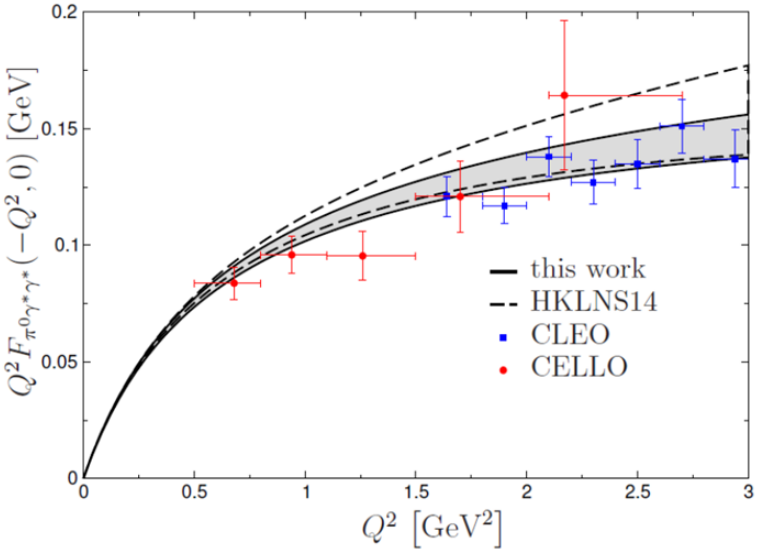


$e^+e^- \to \pi^+\pi^-\pi^0$



ππ phase shifts + e+e- → 3 π data
Eur.Phys.J. C74 (2014) 3180

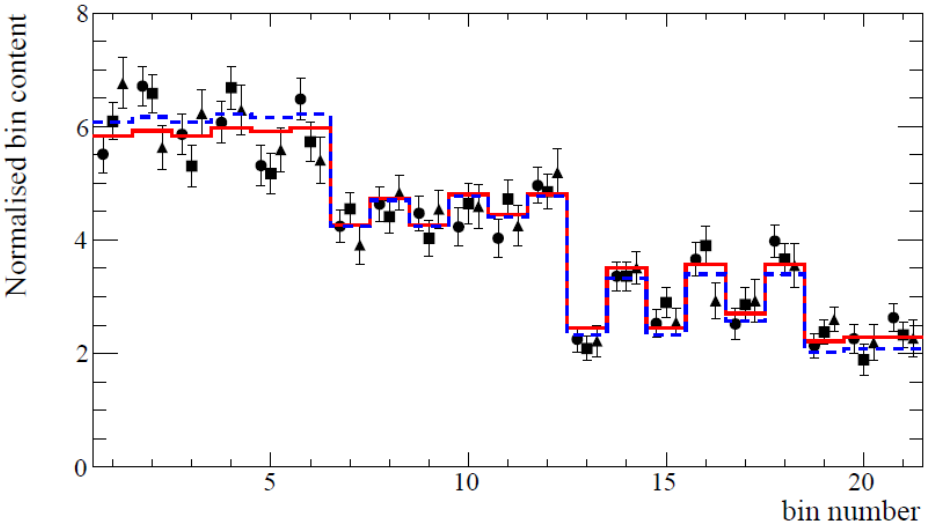




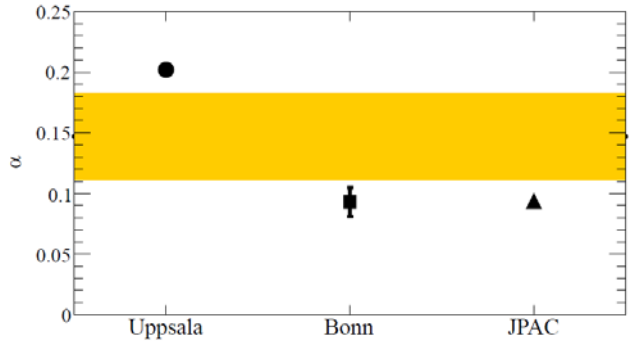
M Hoferichter, B-L Hoid, B Kubis, S Leupold, S P. Schneider

arXiv:1808.04823

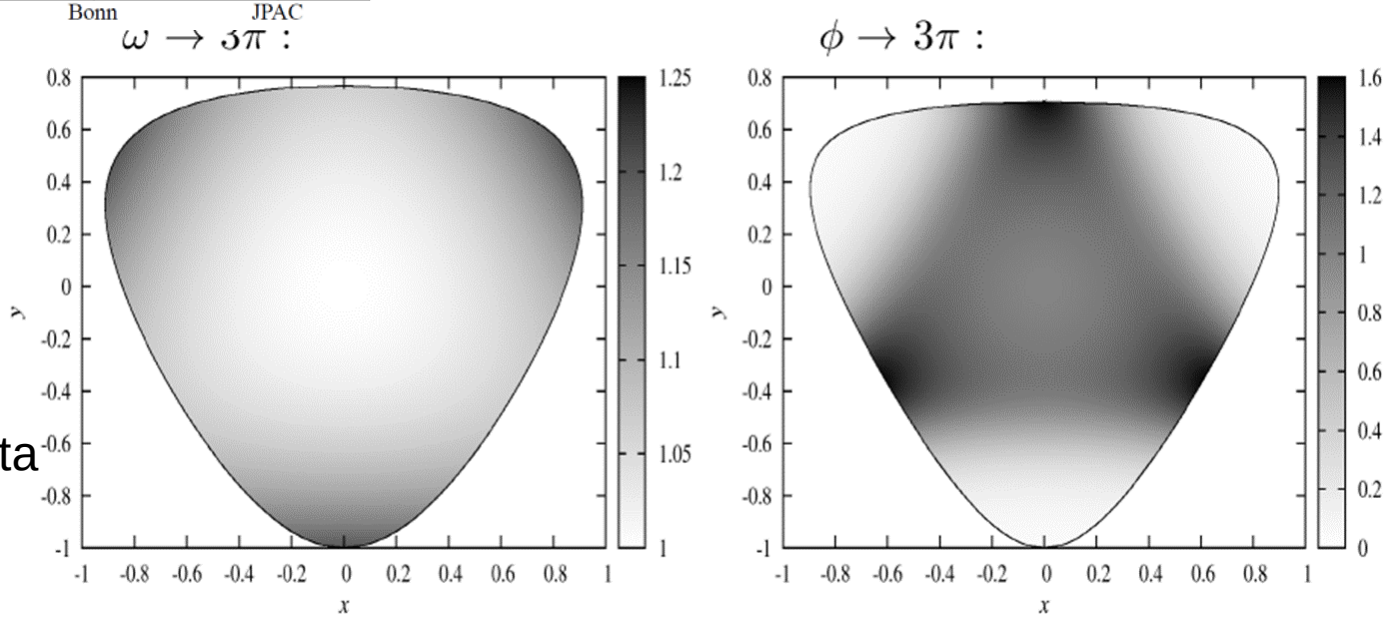
$$\omega/\phi \to \pi^+\pi^-\pi^0$$



WASA PLB770 (2017) 418



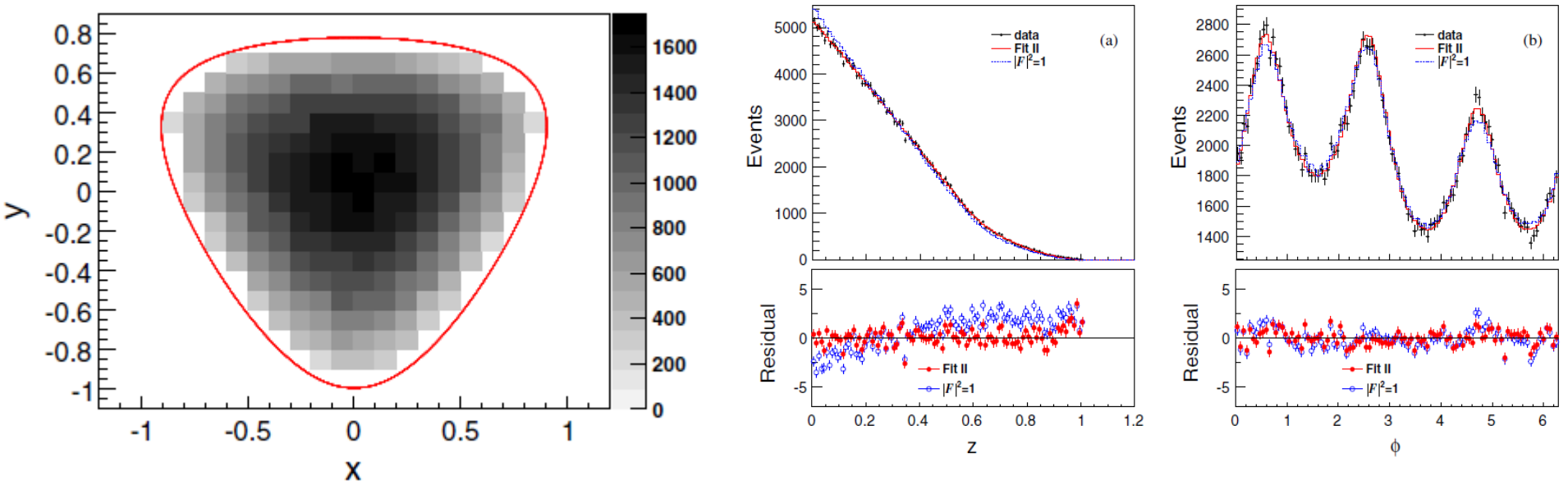
BESIII



for ϕ precise data from CMD2 and KLOE

Eur.Phys.J. C72 (2012) 2014

Slide: Bastian Kubis



BESIII: PRD98, 112007(2018)

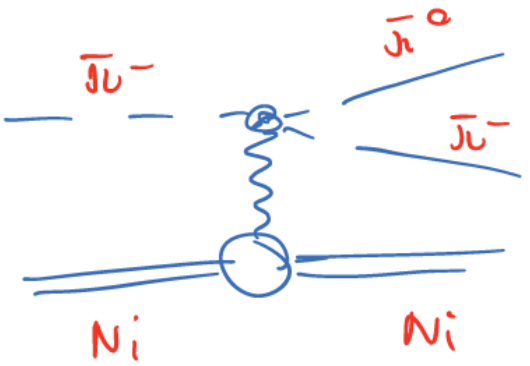
TABLE III. Predictions and fit results for the $\mathcal{F}$ parametrizations. The predictions are from Danilkin *et al.* [4], Niecknig *et al.* [5], and Terschlüsen *et al.* [19]. Theoretical predictions without incorporating crossed-channel effects are indicated by w/o and those with crossed-channel effects by w.

		Theoretical predictions					Experiment
		Ref. [4]		Ref. [5]			
	Para. $\times 10^3$	w/o	w	w/o	w	Ref. [19]	BESIII
Fit I	α	136	94	(137,148)	(84,96)	202	$132.1 \pm 6.7 \pm 4.6$
Fit II	α	125	84	(125,135)	(74,84)	190	$120.2 \pm 7.1 \pm 3.8$
	β	30	28	(29,33)	(24,28)	54	$29.5 \pm 8.0 \pm 5.3$

Goal of COMPASS experiment

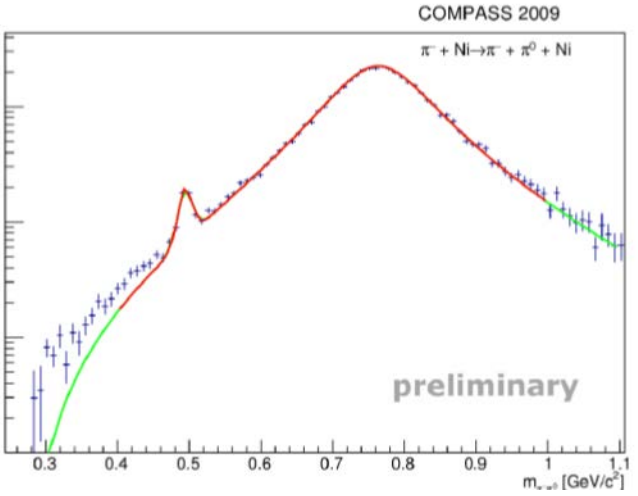
- Test ChPT predictions for pion-photon reactions $\pi^-\gamma \to X^-$ with various final states X^-

$$\pi^- + \gamma^{(*)} \to \begin{cases} \pi^- + \gamma & \text{Compton reaction, pion polarisabilities} \\ \pi^- + \pi^0 & \text{single-pion production, chiral anomaly} \\ \pi^- + \pi^0 + \pi^0 & \text{double-pion prod., chiral tree \& loop} \\ \dots \end{cases}$$

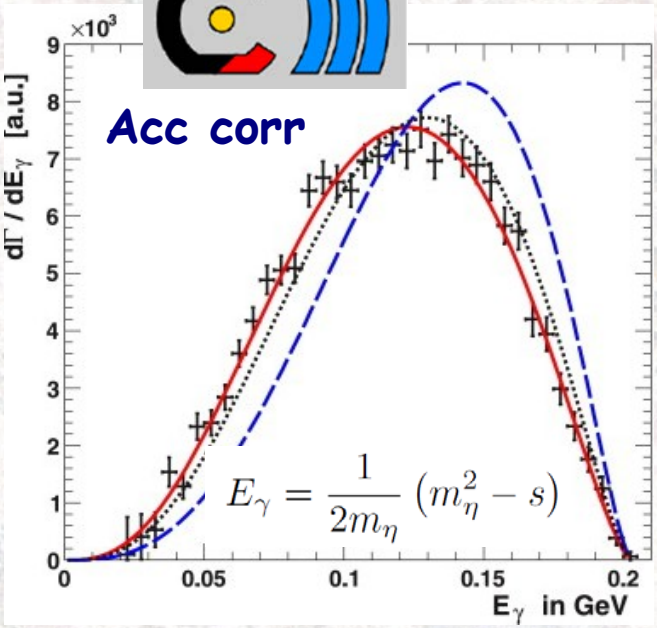


COMPASS has acquired large Primakoff data set

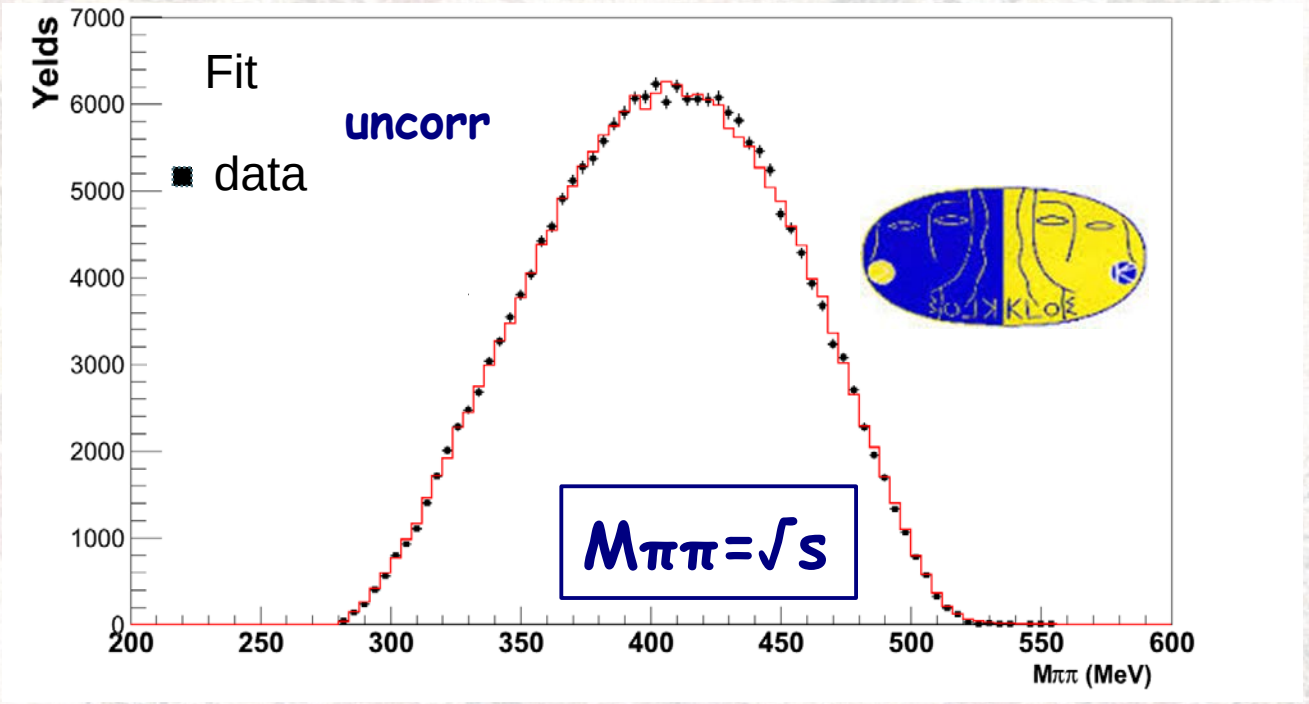
- Measurements from channel $\pi^- + \gamma^{(*)} \to \pi^-\pi^0$:
  - Chiral anomaly $\gamma \to 3\pi$
  - Radiative width of light-quark isovector mesons $(\rho(770)^- \to \pi^-\gamma)$
- Data from run 2009 give consistent picture:
  - Fit in good agreement with data
  - Normalizing to radiative width of $\rho(770)$ yields value for $F_{3\pi}$ in agreement with theoretical result
- 4x larger data set to come from 2012 data
- Possibility to extend analysis to measure radiative couplings of excited ρ states



TFF from radiative processes (ex $\eta \to \pi^+\pi^-\gamma$)



WASA PLB707 (2012) 243



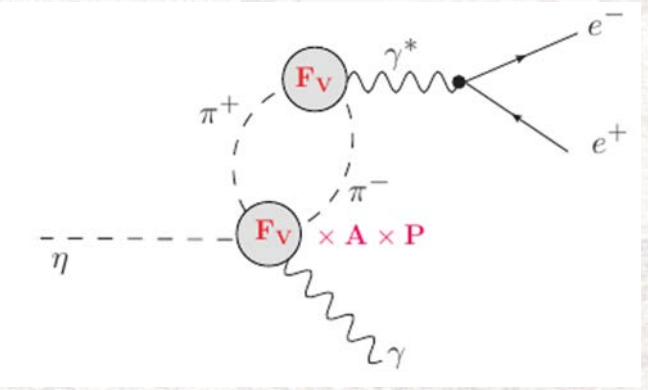
KLOE PLB718 (2013) 910

Model independent parametrization:

$$\frac{d\Gamma}{ds} = |A(1 + \alpha s + ...)F_V(s)|^2 K_P(s)$$

PLB707 (2012) 184

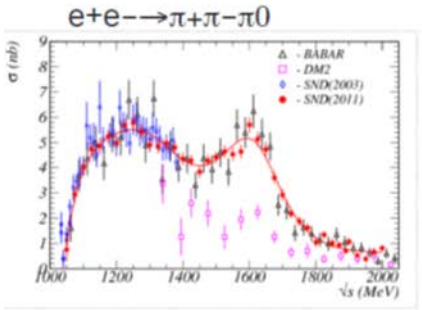
$e^+e^- \to \pi^+\pi^-$



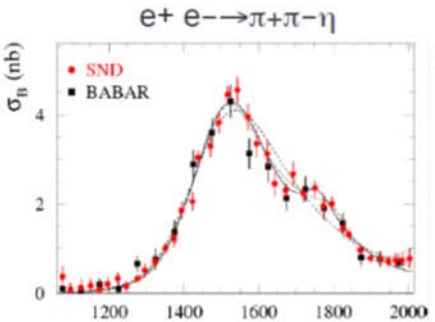
$a=1.89\pm0.25_{stat}\pm0.59_{syst}$ GeV^{-2}

$a=1.31\pm0.08_{stat}\pm0.40_{syst}$ GeV^{-2}

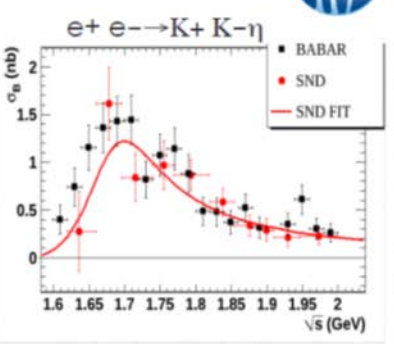
Some SND results overview



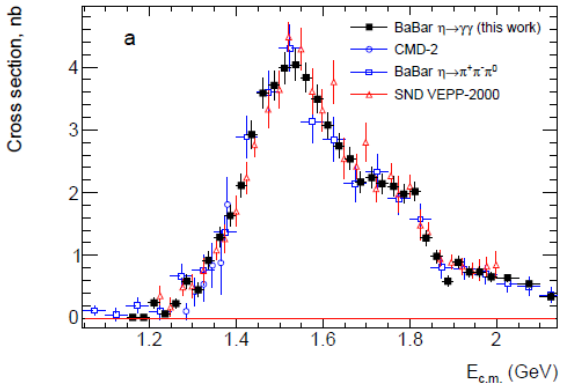
J.Exp.Theor.Phys. 121 (2015) 1.

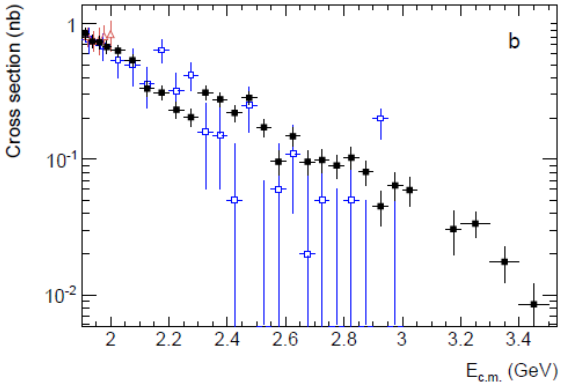


Phys. Rev. D 91, 052013 (2015)



$e^+e^- \to \eta\pi^+\pi^-$ at BaBar





More precise result ⇒ first observation of the $\rho(1700)$ in $\eta\pi^+\pi^-$

J.P. Lees et al., Phys. Rev. D97 (2018) 052007

DP Similar strategy for η as for π^0

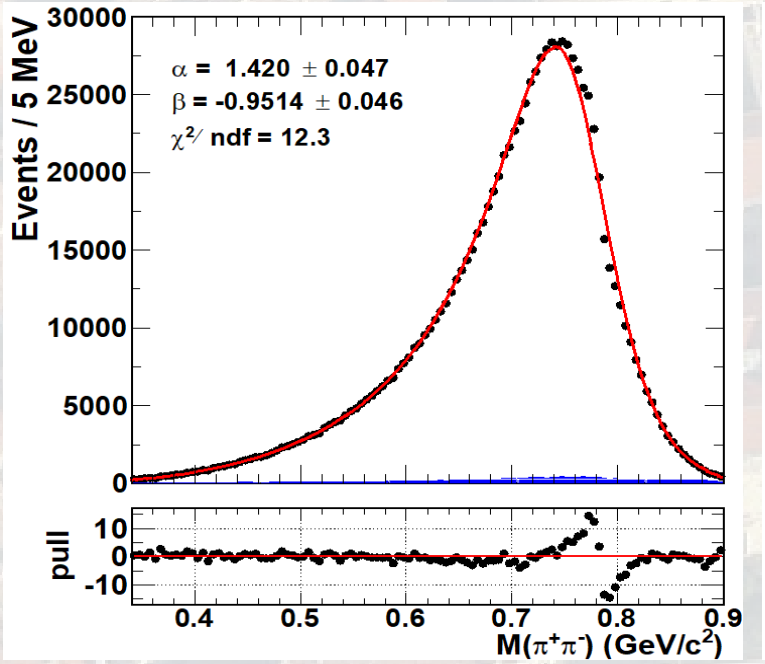
From e+e- → π+π-η to η TFF

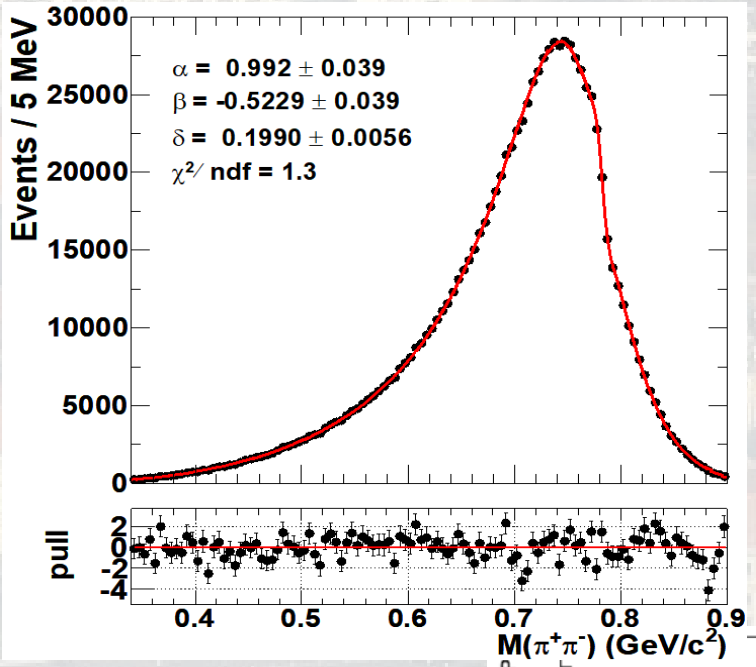
arXiv:1509.02194

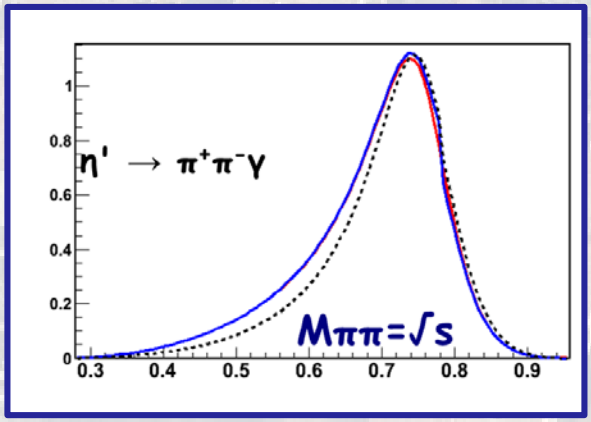
Analysis based on 0.9 x 10^6 η' → π+π-γ

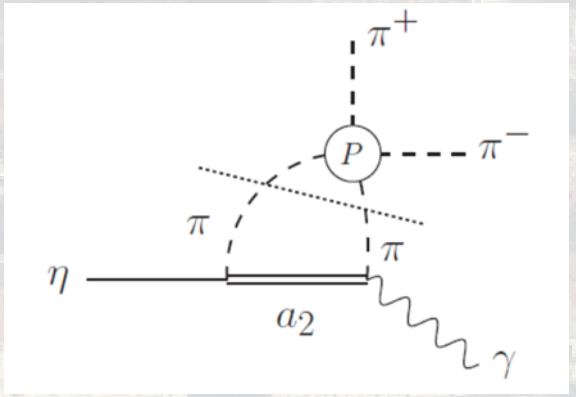
$$\frac{d\Gamma}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2 \Gamma_0(s_{\pi\pi})$$

$P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \beta s^2_{\pi\pi}$ $\quad$ $P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \beta s^2_{\pi\pi} + \delta BW_\omega$





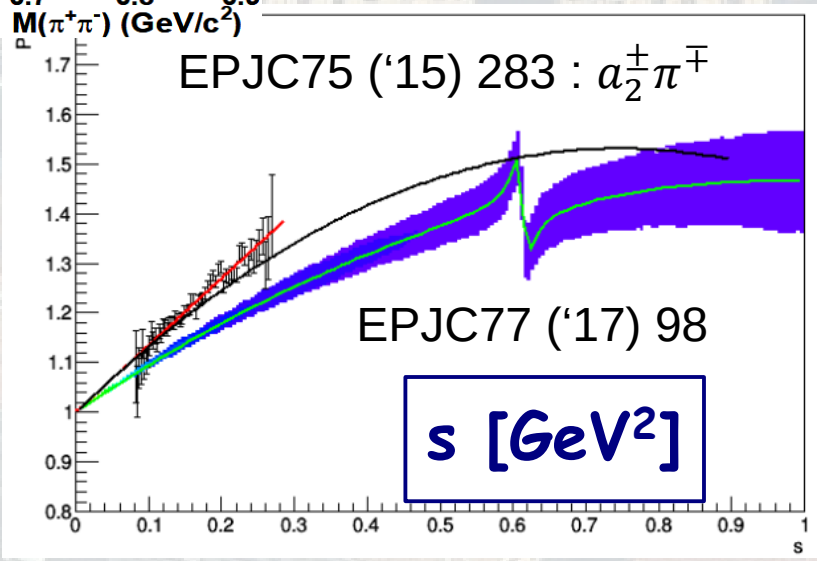




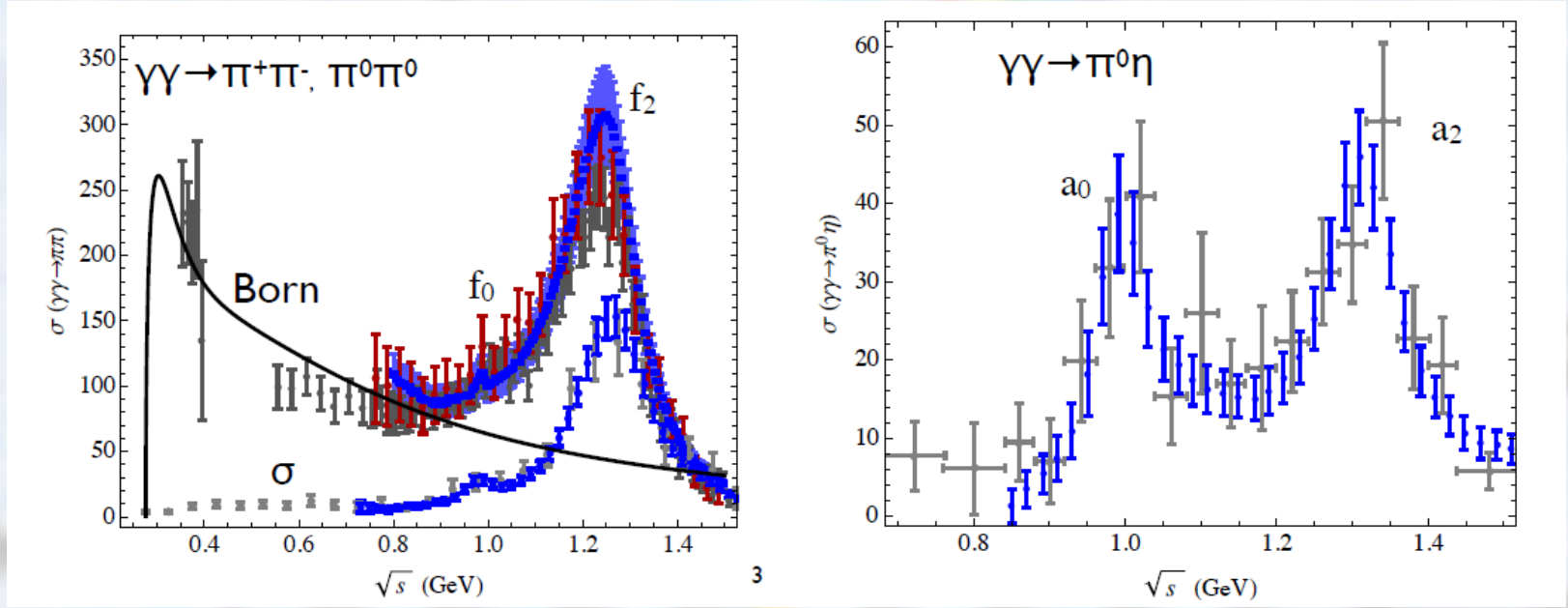
ω contribution necessary

Linear polynomial is insufficient...

Phys.Rev.Lett. 120 (2018) 242003

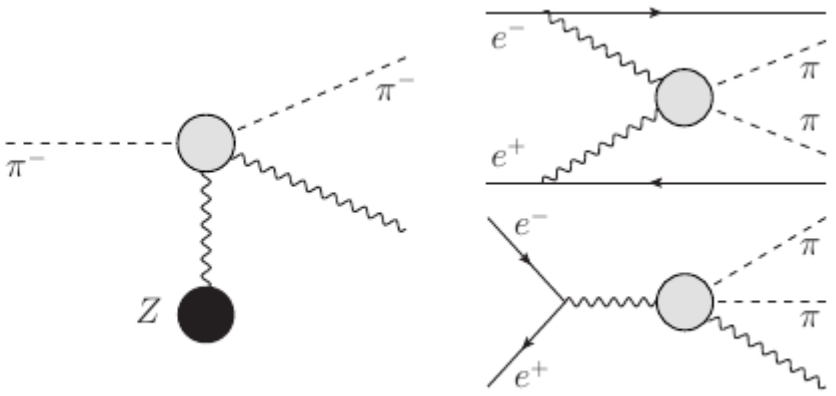


$\gamma^{(*)}\,\gamma^{(*)} \to \pi\pi;\ \eta\pi;\ KK$



γγ→ππ, KK, ηη, πη (Belle: 07,08, 09,10, ..)
γγ*→ππ, πη (BESIII in progress)

- Low energy: pion polar., ChPT
- Primakoff: $\gamma\pi \to \gamma\pi$ at COMPASS, JLAB
- Scattering: $e^+e^- \to e^+e^-\pi\pi$, $e^+e^- \to \pi\pi\gamma$
- Decays: $\omega, \phi \to \pi\pi\gamma$



Slide: G. Colangelo, I.Danilkin

Data driven DR HLbL determination:

Transition Form Factors of π^0, η, η'

- Direct measurements
- Input and checks for DR approach to TFF

Pion and Kaon Form Factors…

Two photon production of PS pairs

HLbL error: - input experiments
- high energy behavior

=> error budget