

# Meson Transition form factors of hadronic processes

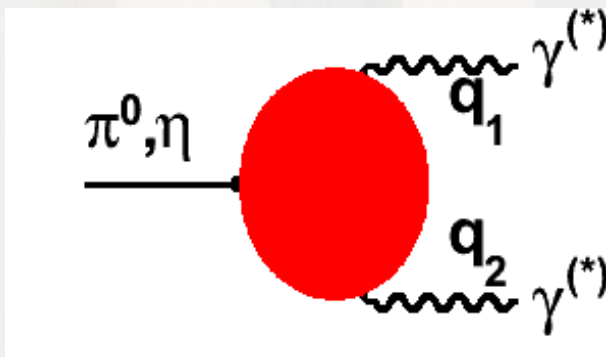
TFF  $\eta, \eta'$ :  $\eta, \eta' \rightarrow \pi^+ \pi^- \gamma$

TFF  $\pi^0$ :  $\omega, \varphi \rightarrow \pi^+ \pi^- \pi^0$

$F_V e^+ e^- \rightarrow \pi^+ \pi^-$

$e^+ e^- \rightarrow \eta \gamma, \eta \pi^+ \pi^-$

$e^+ e^- \rightarrow \pi \gamma, \pi^+ \pi^- \pi^0, \omega \pi^0$



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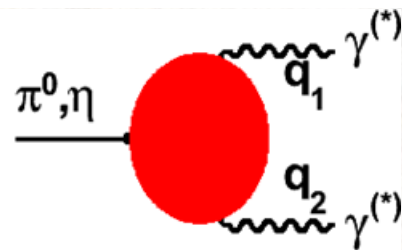
# $\pi^0, \eta, (\eta')$ Transition Form Factors (TFF)

Low energy QCD

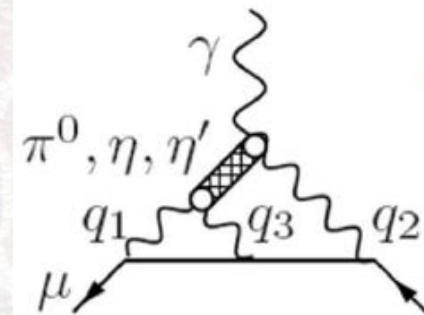
$I^+I^-$  spectra for HI

dark photon (U boson)

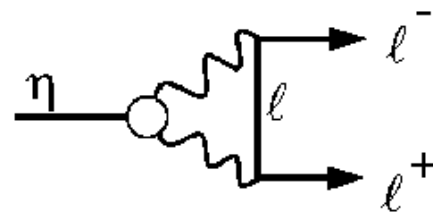
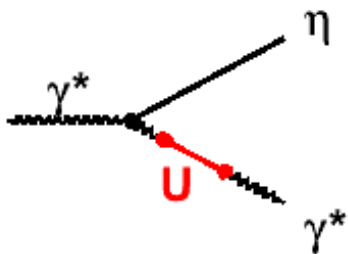
$$\Gamma(P \rightarrow \gamma\gamma)$$



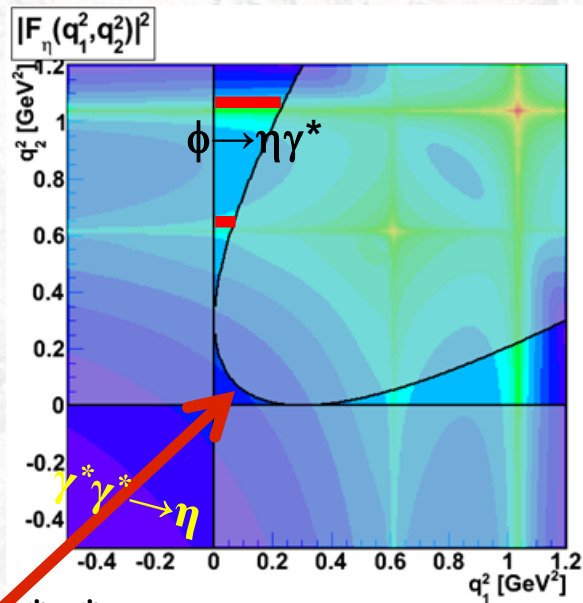
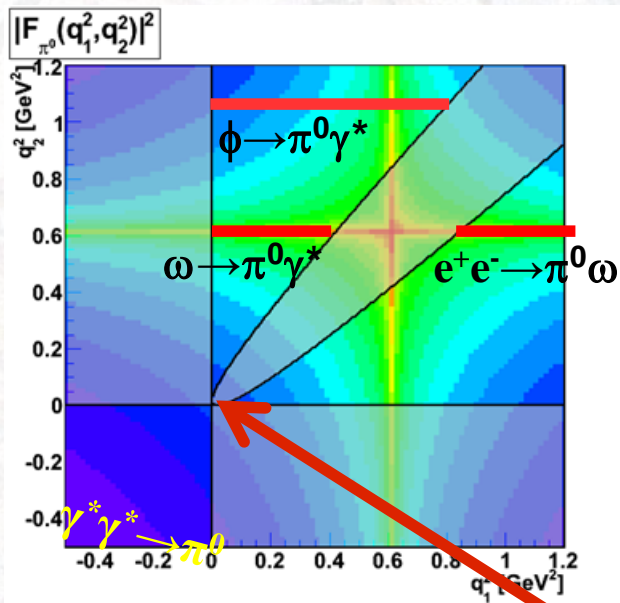
$$F_P(q_1^2, q_2^2)$$



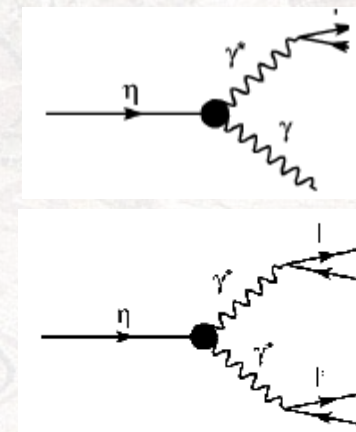
HLbL for  $\alpha\mu$



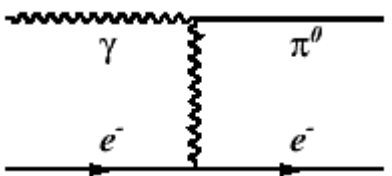
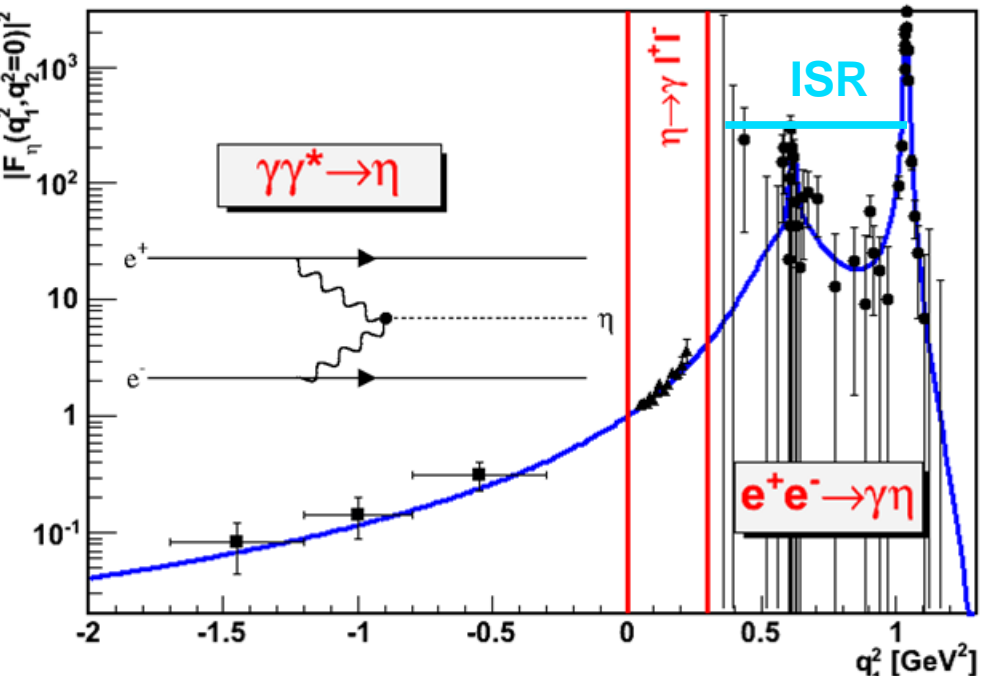
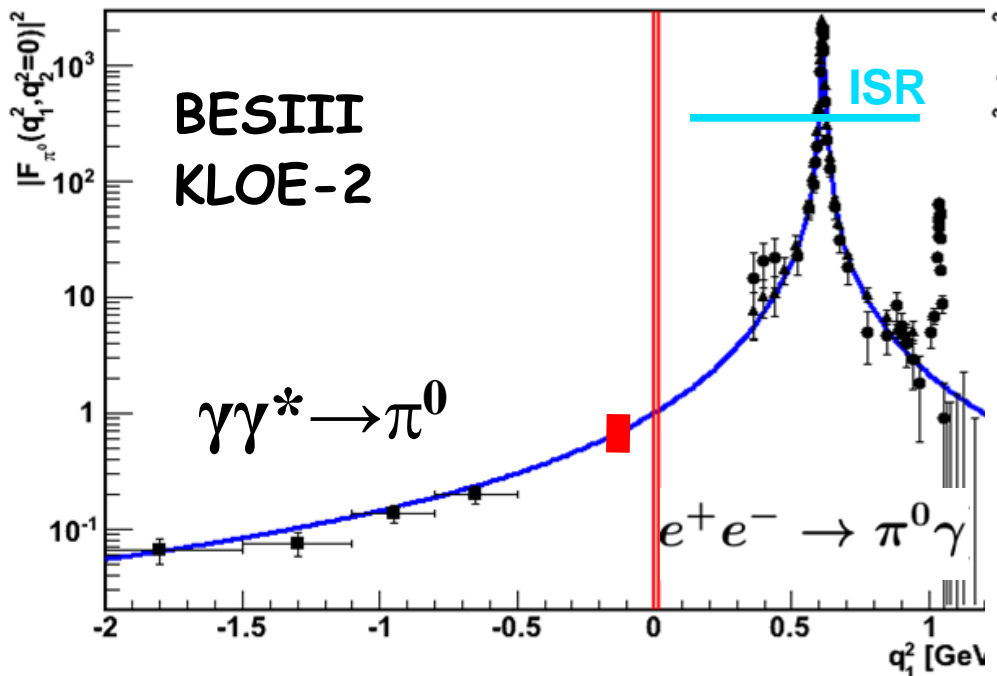
Access to  $q^2 < 0$



$$P \rightarrow \gamma^* \gamma^*$$



# $\eta, \pi^0$ single off shell TFF

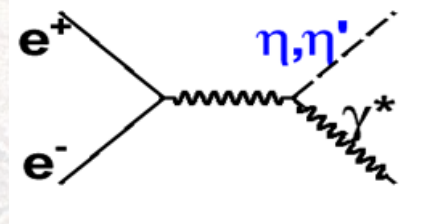


$\gamma^* \rightarrow P\gamma$   
VEPP 2000 0.3-2GeV  
KLOE-2 ISR, BESIII

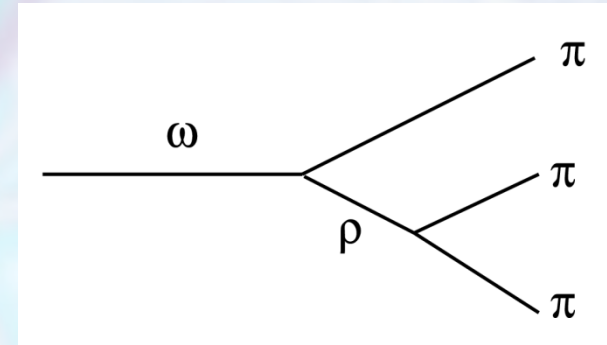
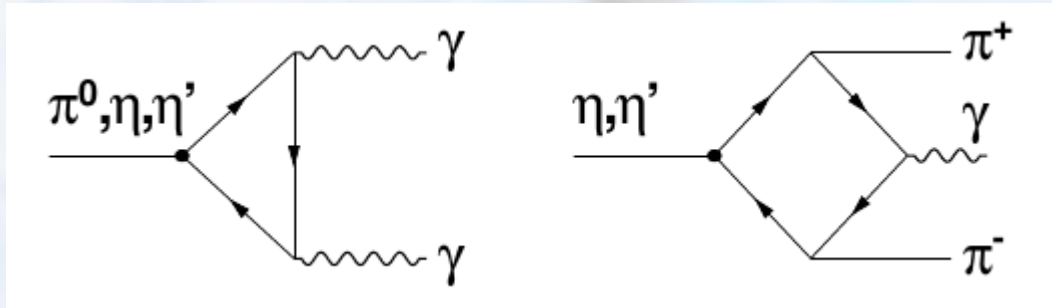
$$\frac{d\sigma}{dt}(e^- \gamma \rightarrow e^- P) = \frac{16 \pi \alpha}{3 s m_P^3} \Gamma_{\gamma\gamma} |F_P(t, 0)|^2 \frac{s - m_P^2 + t}{t}$$

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

$P \rightarrow \gamma^* \gamma$   
Dalitz decays:  
KLOE, WASA, CBall, BESIII  
CLAS, NA48

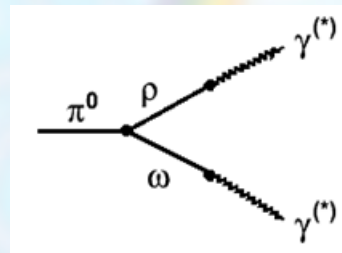


# Odd intrinsic parity (anomalous): $PVV/P\gamma\gamma$ , $PPP$



$V \rightarrow PV$

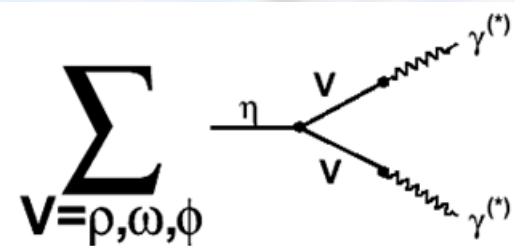
Vector Meson Dominance

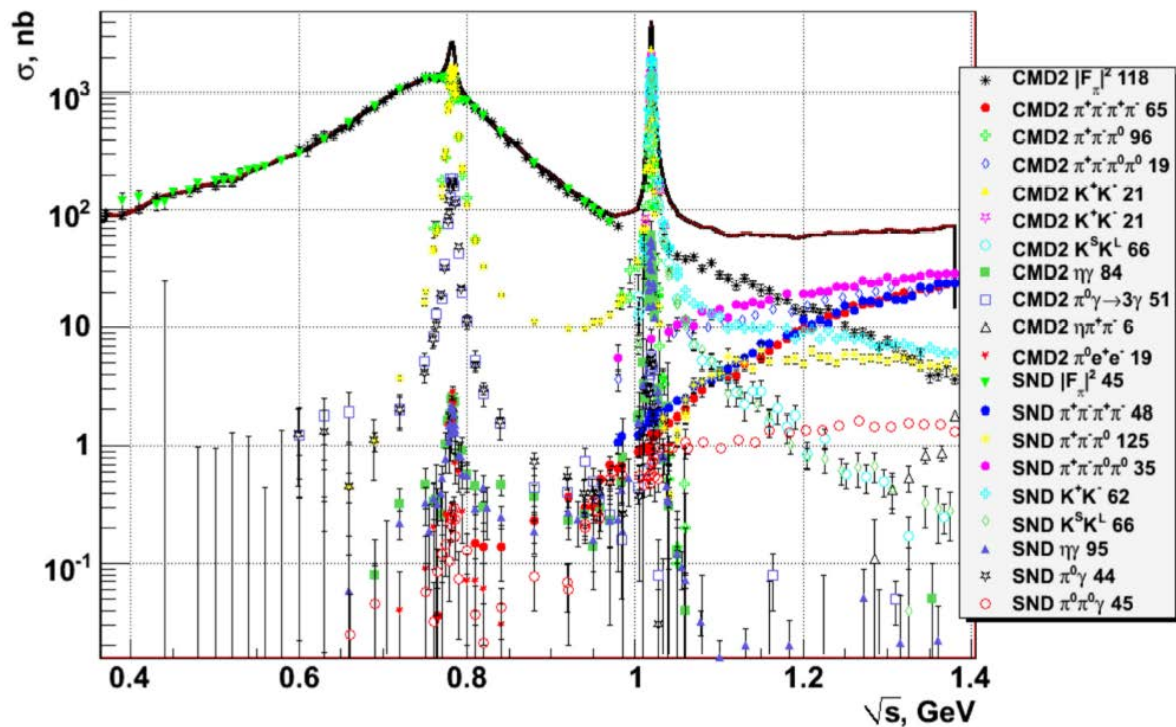


$\eta \rightarrow e^+e^-\gamma$  from

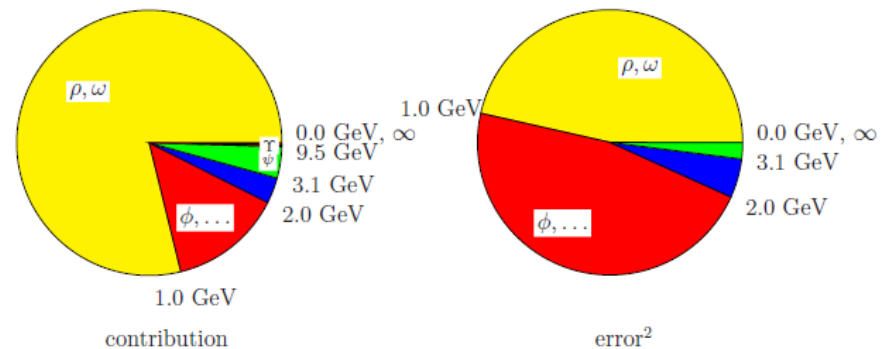
$\eta \rightarrow \pi^+\pi^-\gamma$

TFF

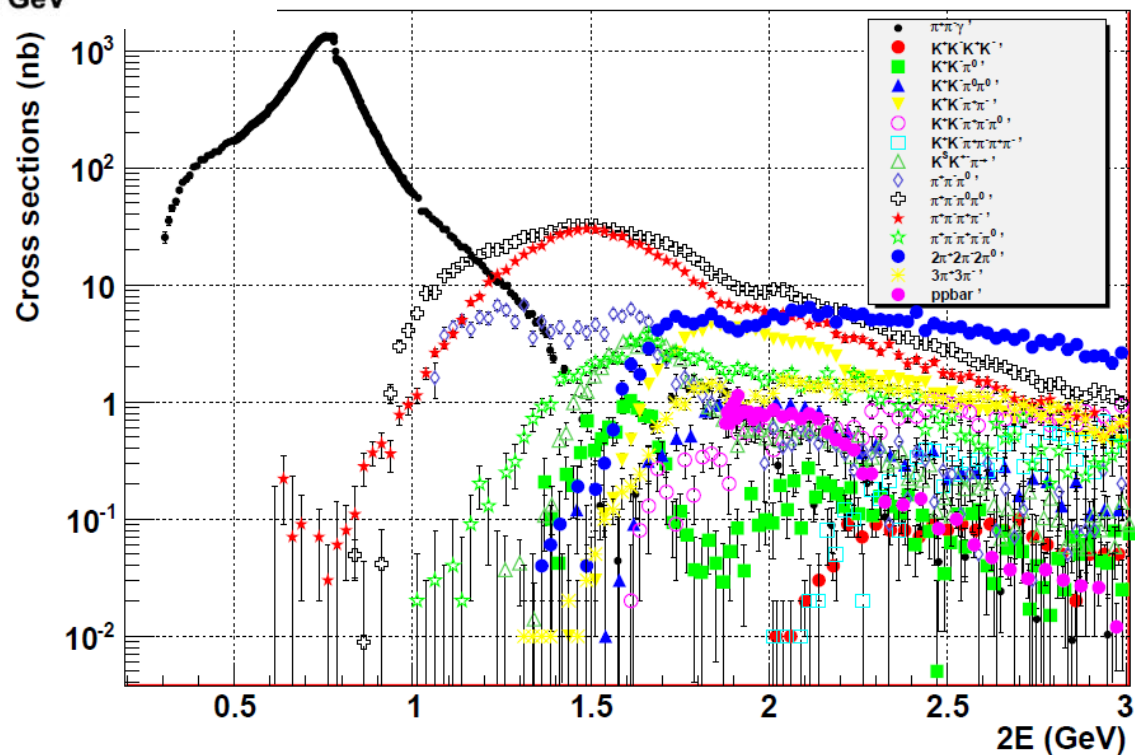




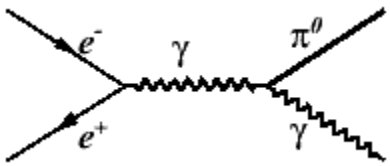
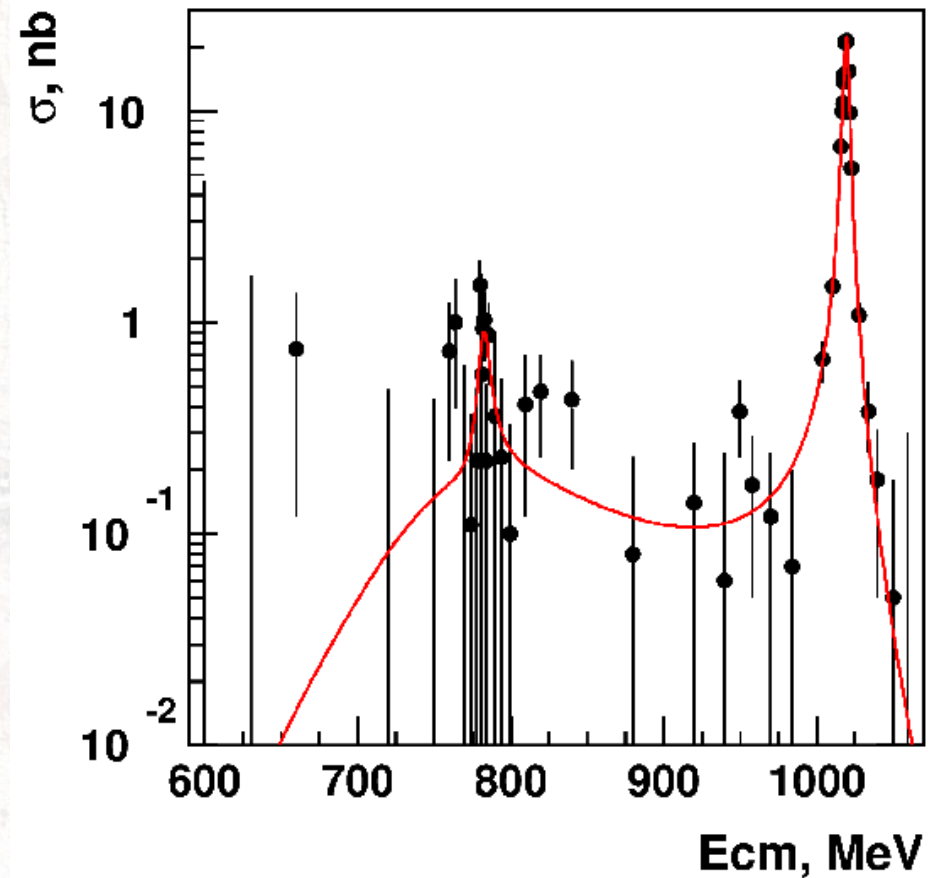
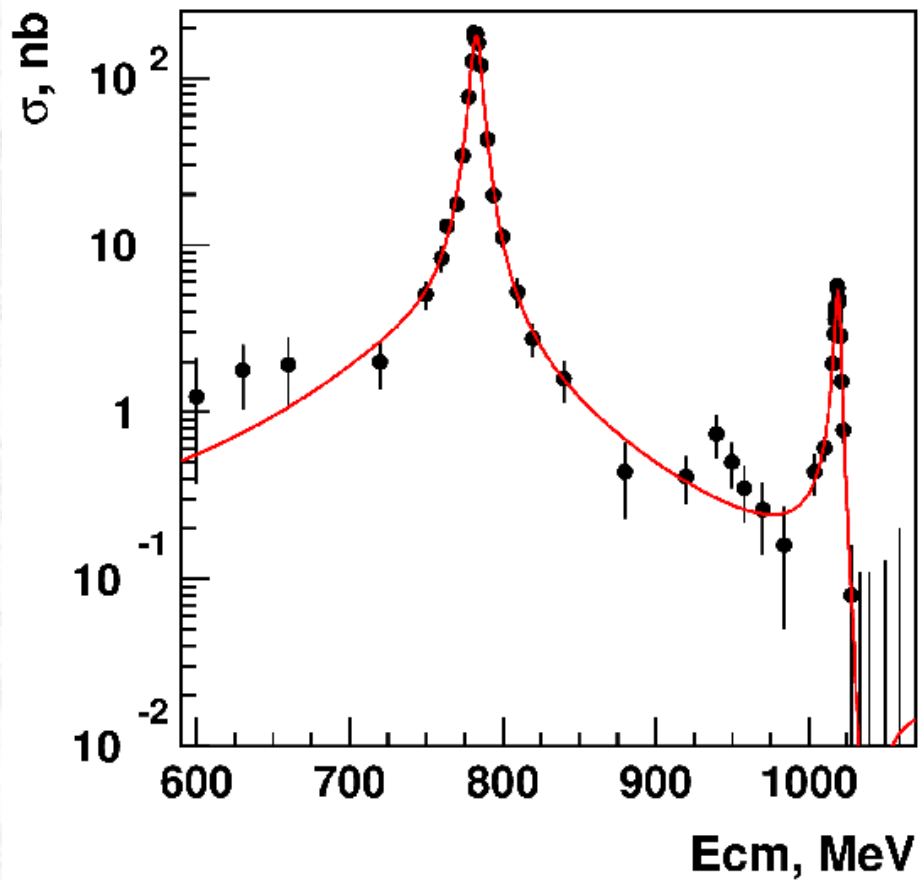
CMD-2, SND (scan at  $\sqrt{s} < 1.4$  GeV)  
 KLOE (ISR at  $\sqrt{s} < 1.0$  GeV)  
 S.Eidelman, F.Jegerlehner



Channel	HLMNT 11
$\eta\pi^+\pi^-$	$0.88 \pm 0.10$
$K^+K^-$	$22.09 \pm 0.46$
$K_S^0 K_L^0$	$13.32 \pm 0.16$
$\omega\pi^0$	$0.76 \pm 0.03$
$\pi^+\pi^-$	$505.65 \pm 3.09$
$2\pi^+2\pi^-$	$13.50 \pm 0.44$
$3\pi^+3\pi^-$	$0.11 \pm 0.01$
$\pi^+\pi^-\pi^0$	$47.38 \pm 0.99$
$\pi^+\pi^-2\pi^0$	$18.62 \pm 1.15$
$\pi^0\gamma$	$4.54 \pm 0.14$

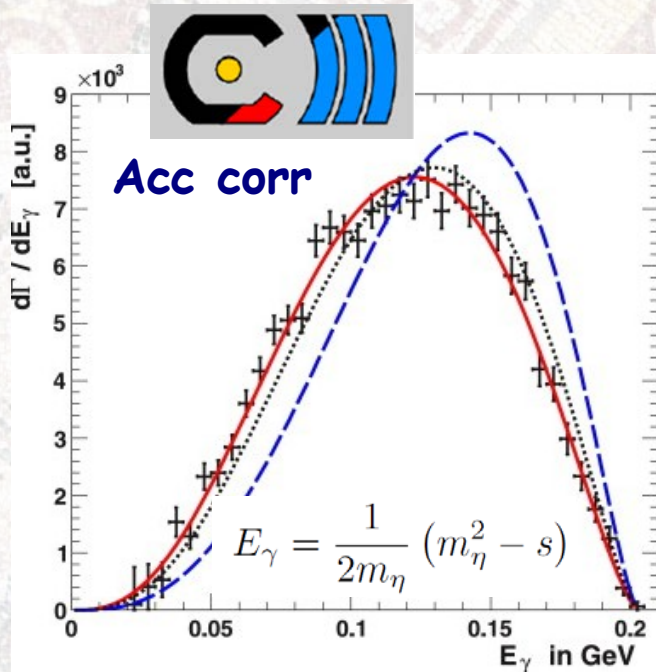


# $\sigma(e^+e^- \rightarrow \pi^0\gamma, \eta\gamma)$

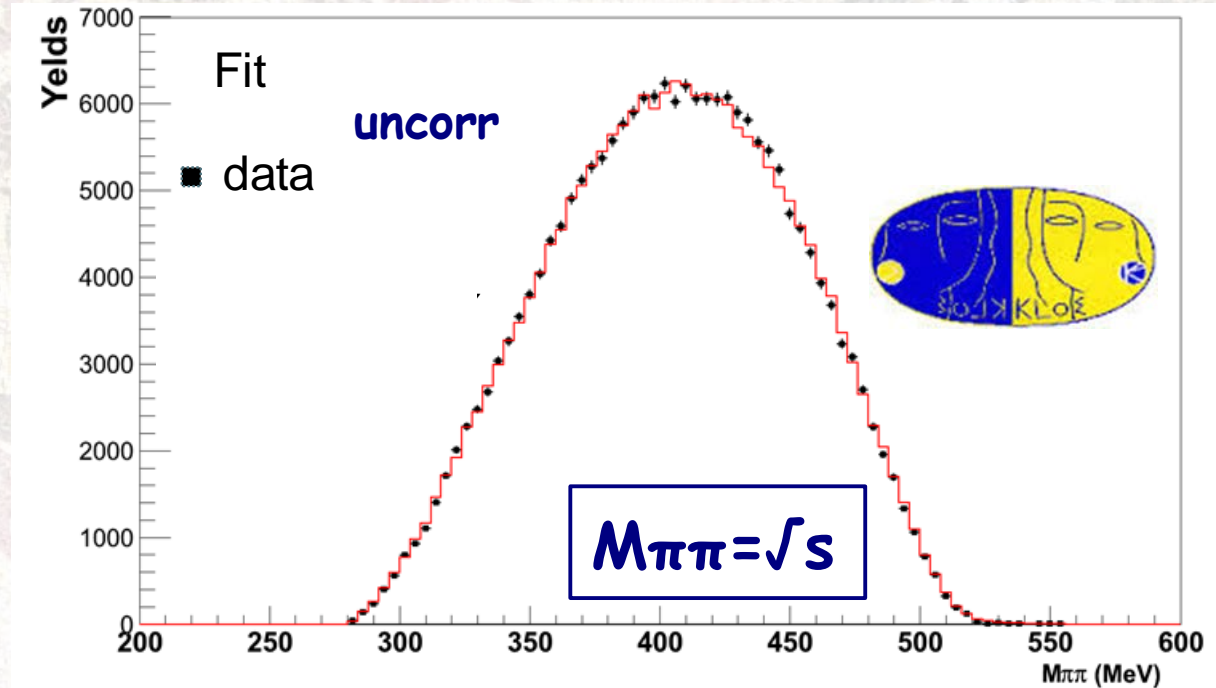


$$\sigma(e^+e^- \rightarrow P\gamma) = \frac{8}{3}\pi\alpha \mathbf{\Gamma}_{\gamma\gamma} |F_P(s, 0)|^2 \left( \frac{s - m_P^2}{sm_P} \right)^3$$

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



WASA PLB707 (2012) 243



KLOE PLB718 (2013) 910

## Model independent parametrization:

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

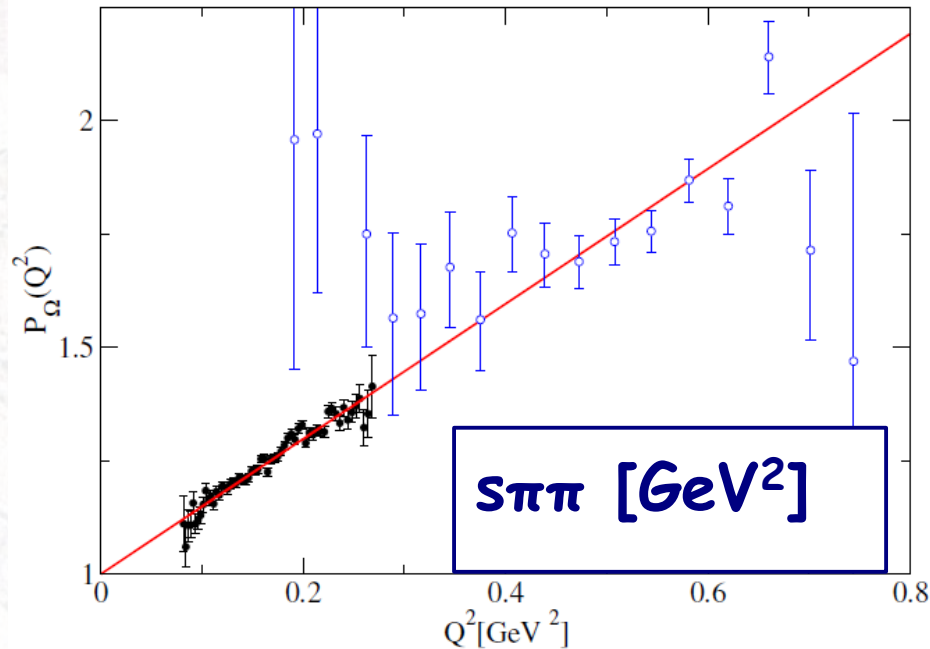
PLB707 (2012) 184

$$e^+e^- \rightarrow \pi^+\pi^-$$

$$\alpha = 1.89 \pm 0.25_{\text{stat}} \pm 0.59_{\text{syst}} \text{ GeV}^{-2}$$

$$\alpha = 1.31 \pm 0.08_{\text{stat}} \pm 0.40_{\text{syst}} \text{ GeV}^{-2}$$

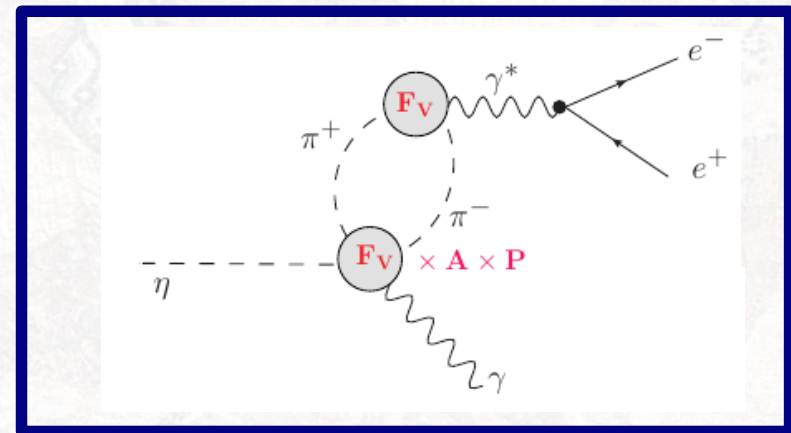
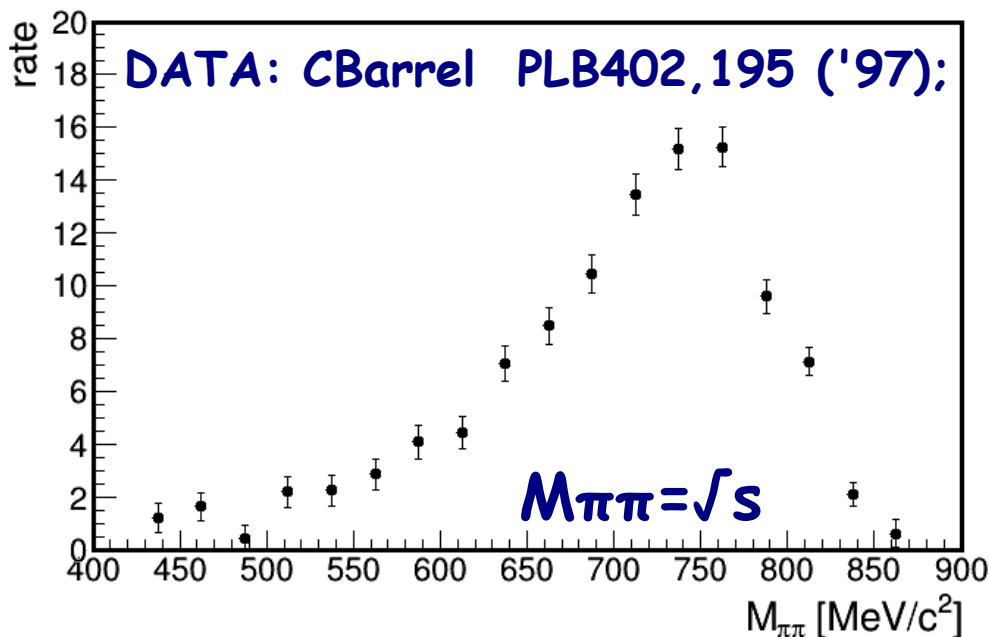
# From $\eta, \eta' \rightarrow \pi^+ \pi^- \gamma$ to $\eta, \eta' \rightarrow e^+ e^- \gamma$



$$P(s_{\pi\pi}) = A_0(1 + \alpha s_{\pi\pi})$$

→  $\alpha$  reaction specific

→  $\alpha[\eta] = \alpha[\eta']$  understood  
1-loop ChPT + large  $N_c$



$$A + \alpha \Rightarrow b_\eta(0) = 2.05^{+0.22}_{-0.10} \text{ GeV}^{-2}$$

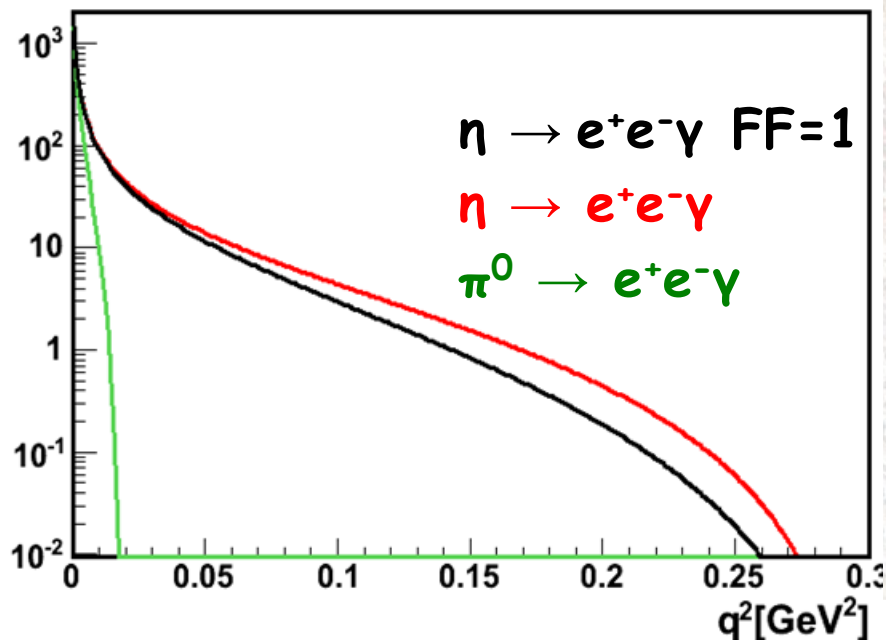
EPJC73(13)2668

DATA: C Barrel PLB 402,195 ('97); KLOE PLB718, 910 ('13)



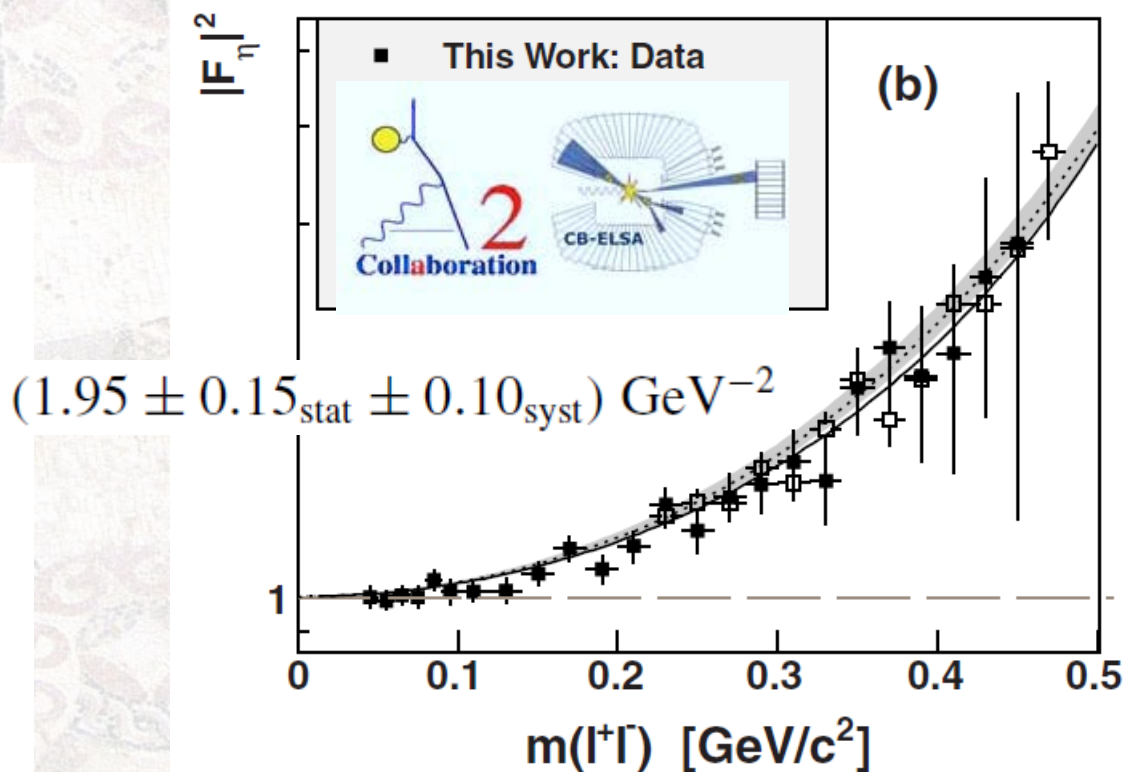
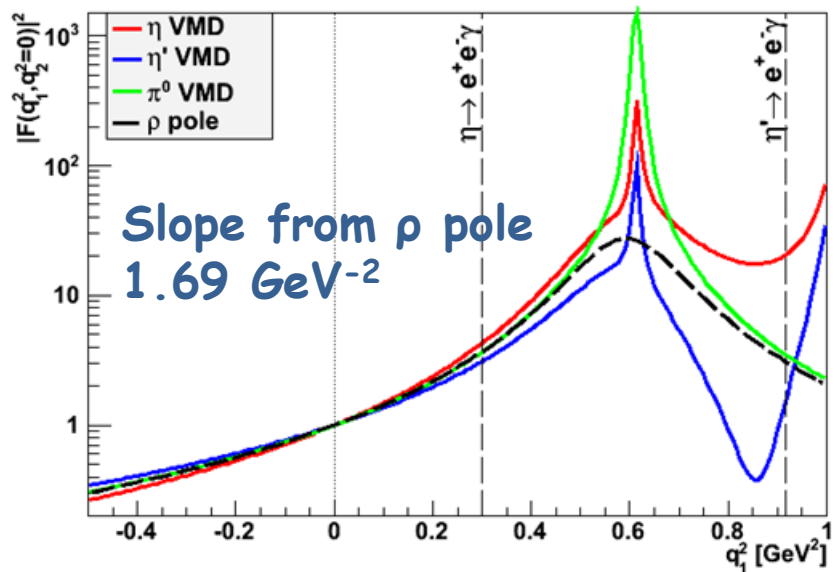
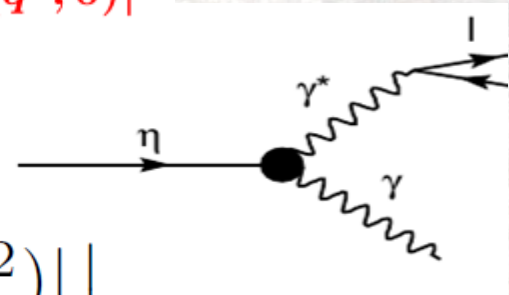
# Single Dalitz decays

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



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

CB/TAPS: PRC89, 044608 (2014)



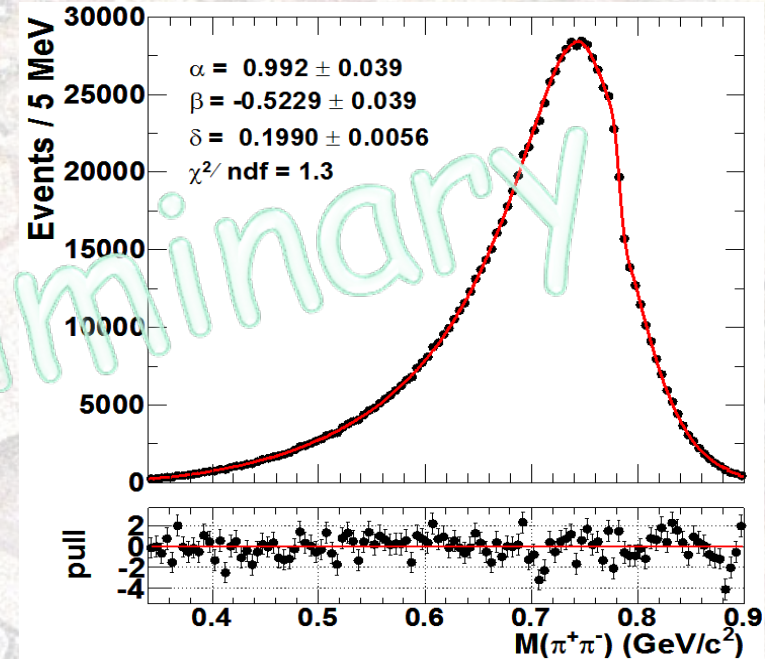
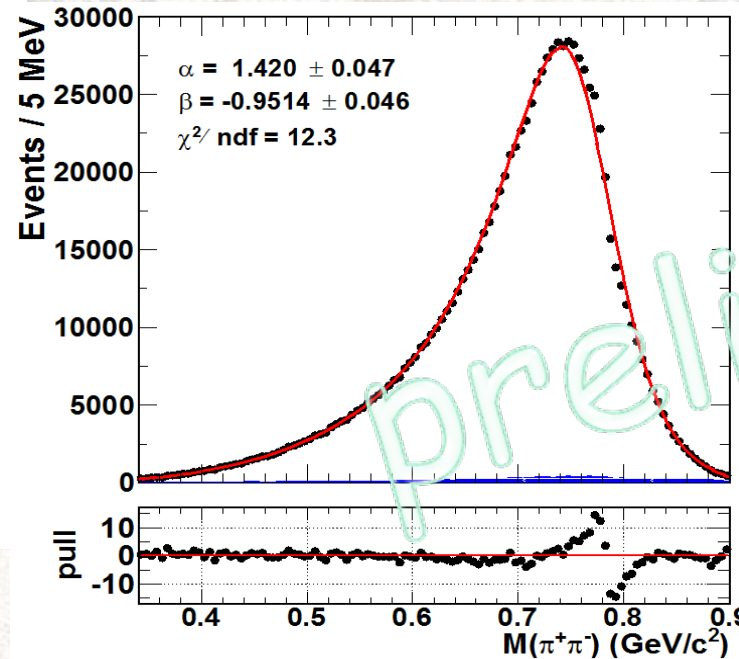
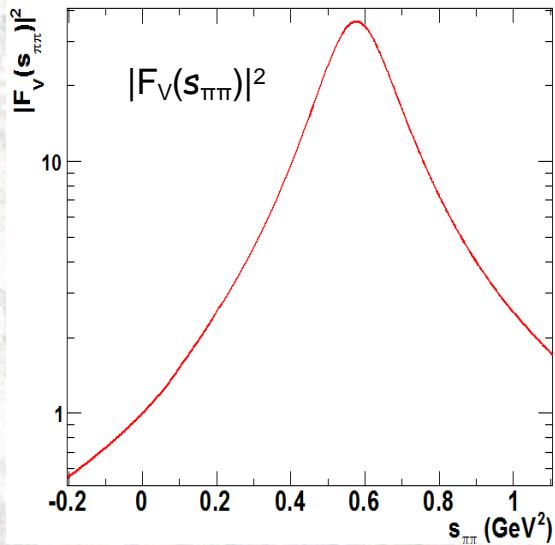
# Model-independent fit



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

$$P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \beta s_{\pi\pi}^2$$

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



$1.9 \times 10^6 \eta \rightarrow \pi^+\pi^-\gamma$

Crystal Barrel:  $\alpha = (1.80 \pm 0.49 \pm 0.04)\text{GeV}^{-2}$

$\beta = (0.04 \pm 0.36 \pm 0.03)\text{GeV}^{-4}$

GAMS-2000:  $\alpha = (2.7 \pm 1.0)\text{GeV}^{-2}$

$\omega$  contribution is necessary

Linear polynomial is insufficient...

$$\omega \rightarrow \pi^+ \pi^- \pi^0$$

$$F(Z, \Phi) = \mathcal{P} \cdot \left\{ 1 + 2\alpha Z + 2\beta Z^{3/2} \sin 3\Phi + 2\gamma Z^2 + \mathcal{O}(Z^{5/2}) \right\}$$

### Spin and Parity of the $\omega$ Meson\*

M. L. STEVENSON, L. W. ALVAREZ, B. C. MAGLIĆ, AND A. H. ROSENFELD  
Lawrence Radiation Laboratory, University of California, Berkeley, California

PR,125 (1962)687

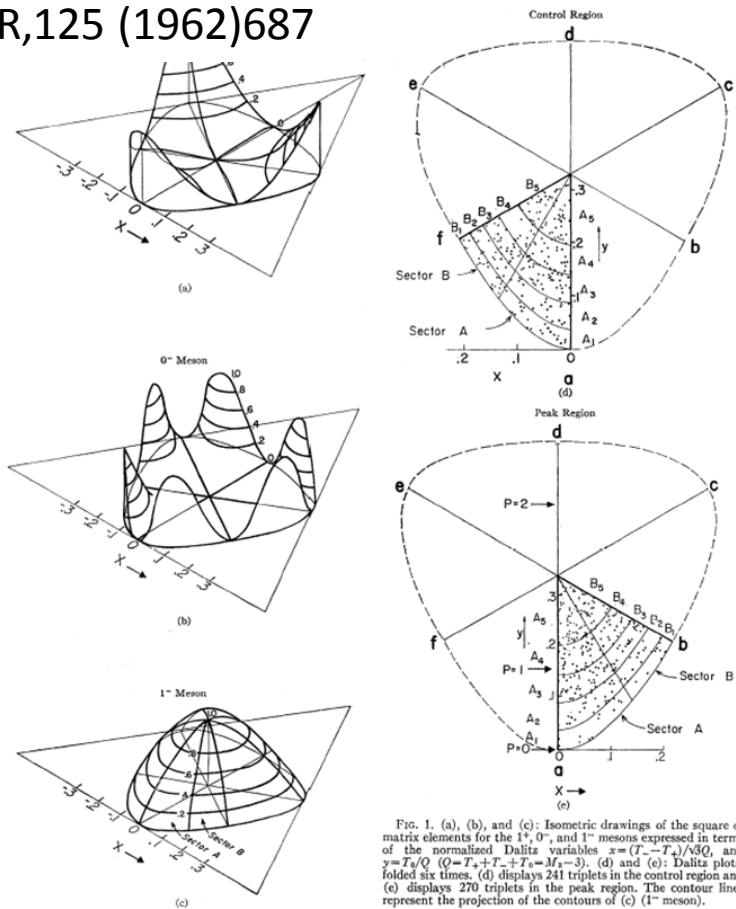
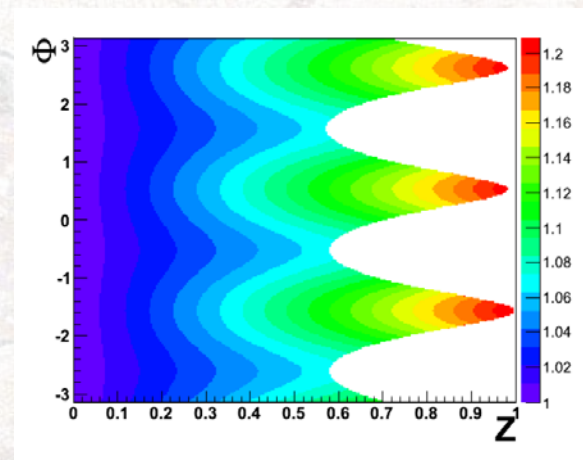
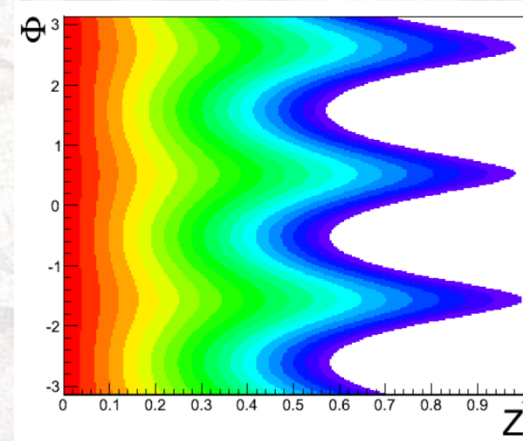


FIG. 1. (a), (b), and (c): Isometric drawings of the square of matrix elements for the  $1^+$ ,  $0^-$ , and  $1^-$  mesons expressed in terms of the normalized Dalitz variables  $x = (T_+ - T_-)/\sqrt{3}Q$ , and  $y = T_3/Q$  ( $Q = T_+ + T_- + T_3 = M_\pi - 3$ ). (d) and (e): Dalitz plots, folded six times. (d) displays 241 triplets in the control region and (e) displays 270 triplets in the peak region. The contour lines represent the projection of the contours of (c) ( $1^-$  meson).

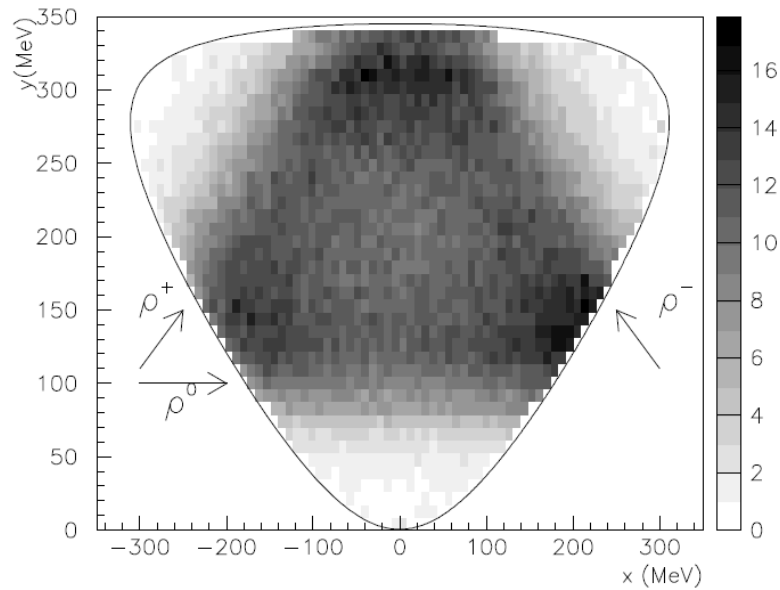


Soon new data: WASA-at-COSY, CLAS, BESIII

WASA: Lena Heijkenkjöld, Siddesh Sawant PhD

$$\psi \rightarrow \pi^+ \pi^- \pi^0$$

$$D(x, y) \propto |\vec{p}_+^* \times \vec{p}_-^*|^2 |A_{\rho\pi} + A_{\text{dir}} + A_{\omega\pi}|^2$$



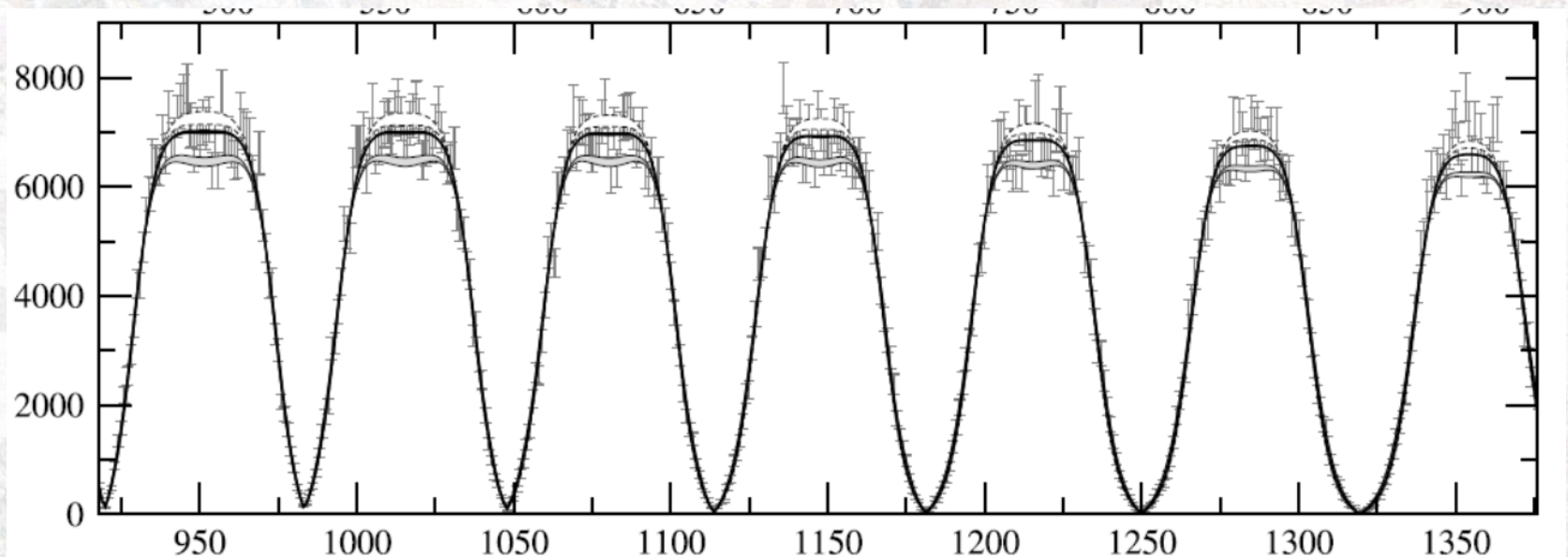
**Dispersive analysis:**

**Niecknig, Kubis, Schneider EPJC (2012) 72:2014**

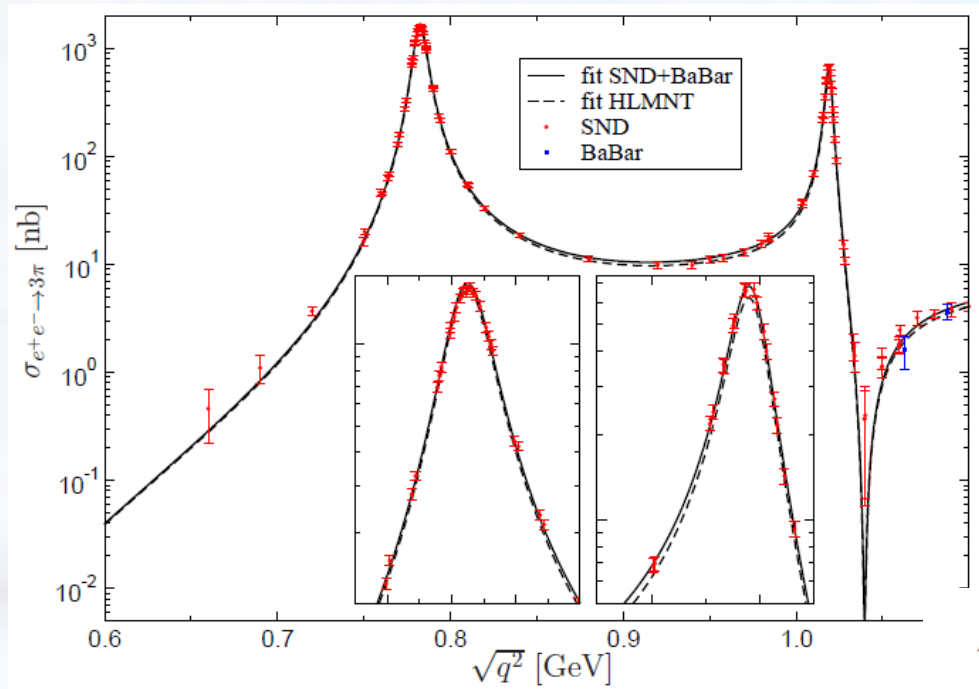
**JPAC PRD, 91, 094029 (arXiv:1409.7708)**

**KLOE, PLB 561 (2003) 55 ca  $2 \times 10^6$  events  $16 \text{ pb}^{-1}$**

**CMD2  $8 \times 10^4$  PLB 642 (2006) 203**

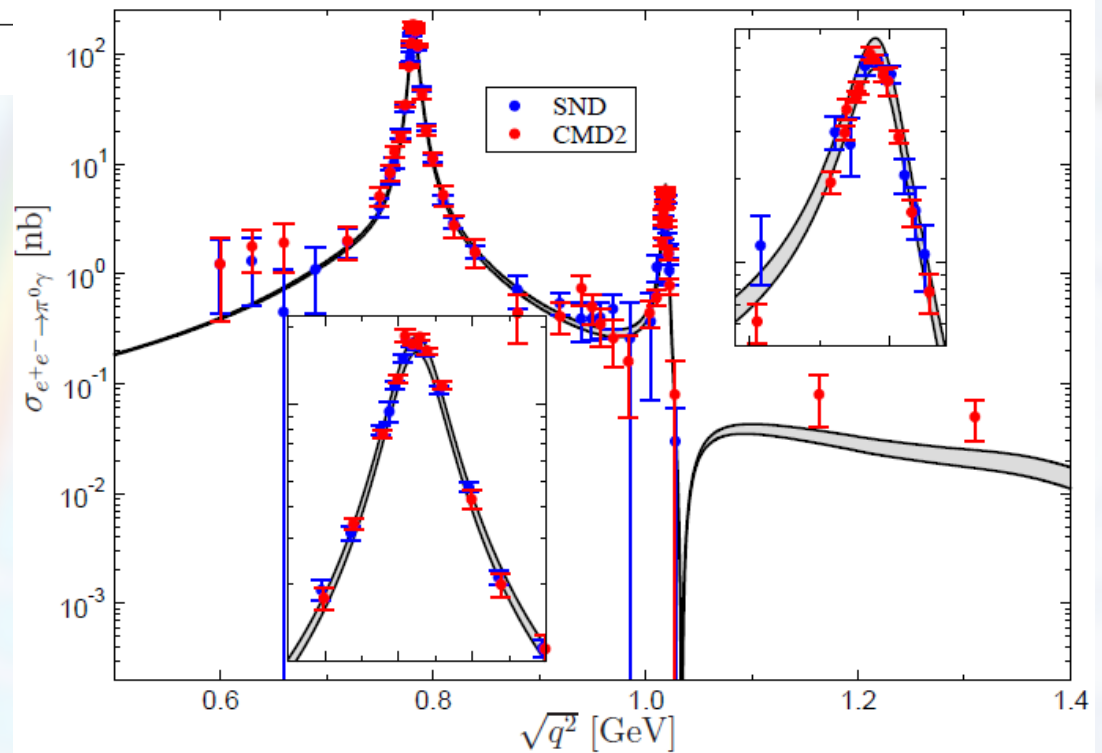


# From $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ to $\pi^0$ TFF



$\pi\pi$  phase shifts +  $e^+e^- \rightarrow 3\pi$  data

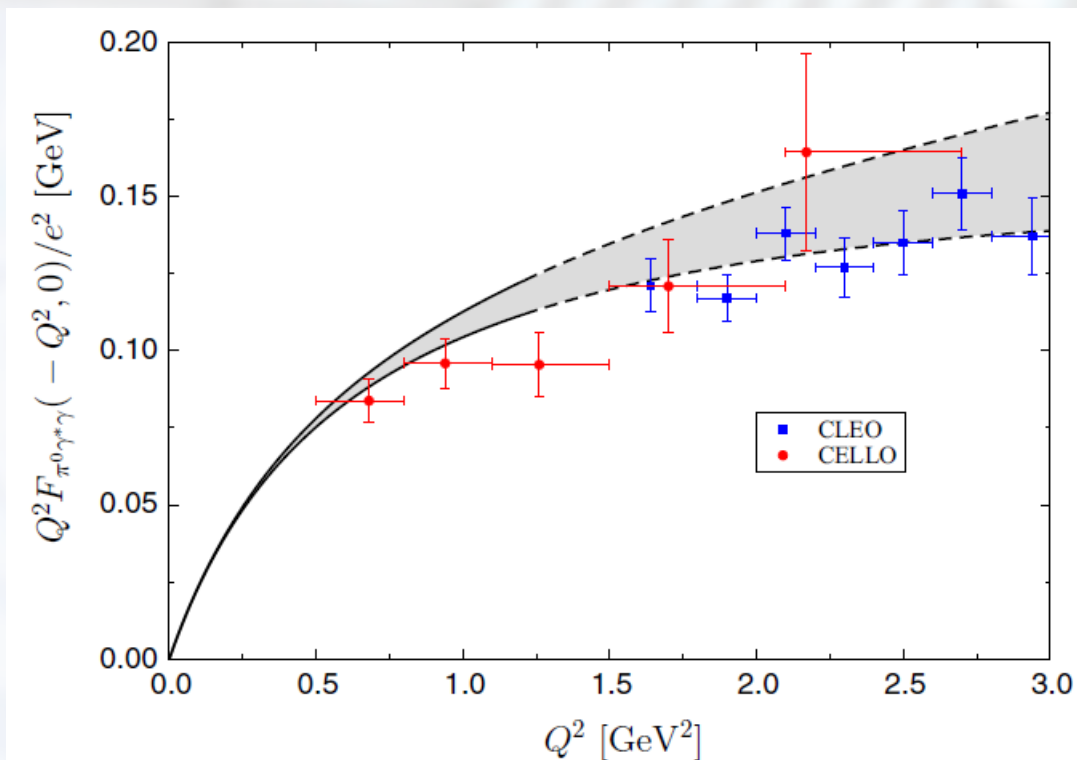
$e^+e^- \rightarrow \gamma\pi^0$



M. Hoferichter, B. Kubis, S. Leupold,  
F. Niecknig and  
S. P. Schneider  
Eur.Phys.J. C74 (2014) 3180

# From $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ to $\pi^0$ TFF

	SND+BaBar	HLMNT
Fit below 1.1 GeV	30.4 ... 31.2	30.1 ... 30.9
$\Lambda_{\pi^0} = 1.1$ GeV	0.989 ... 1.021	0.976 ... 1.008
Fit below 1.8 GeV	30.6 ... 31.4	30.4 ... 31.2
$\Lambda_{\pi^0} = 1.1$ GeV	0.992 ... 1.026	0.985 ... 1.019
Fit below 1.8 GeV	30.4 ... 31.2	30.3 ... 31.1
$\Lambda_{\pi^0} = 1.4$ GeV	0.959 ... 0.987	0.962 ... 0.990
Fit below 1.8 GeV	30.3 ... 31.1	30.2 ... 31.0
$\Lambda_{\pi^0} = 1.8$ GeV	0.944 ... 0.966	0.947 ... 0.970



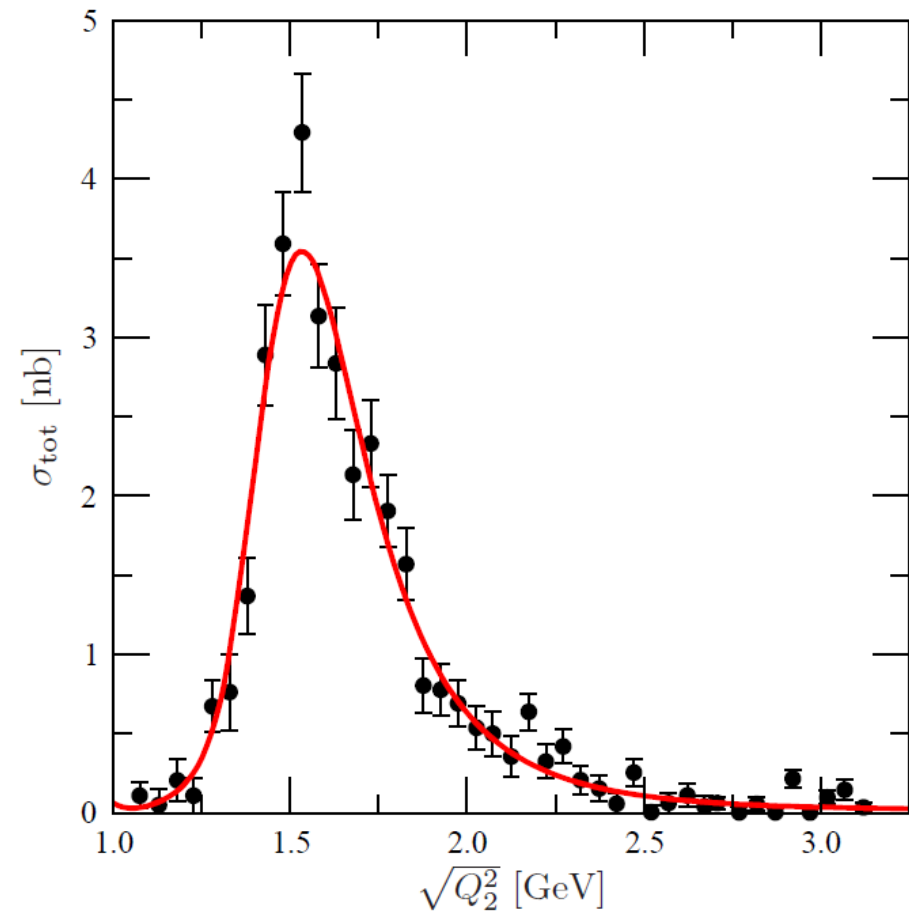
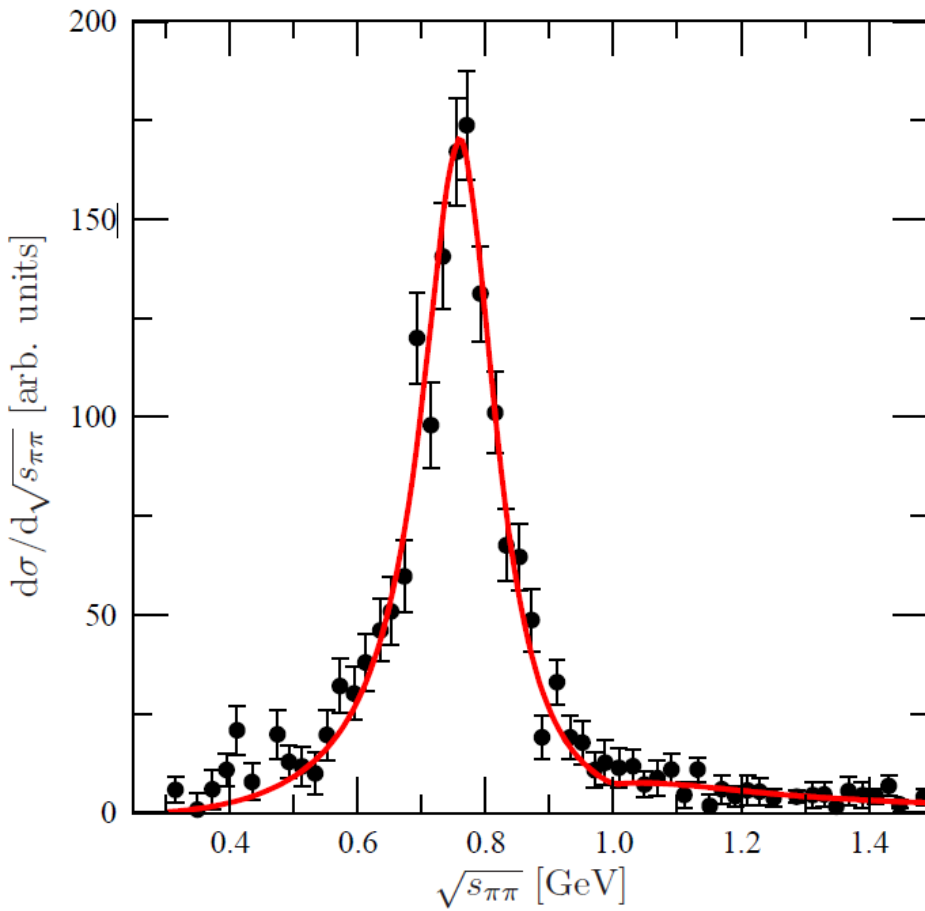
$$a_\pi = (30.7 \pm 0.6) \times 10^{-3}$$

$$b_\pi = (1.10 \pm 0.02) \times 10^{-3}$$

$$\text{EXP: } a_\pi = (32 \pm 4) \times 10^{-3}$$

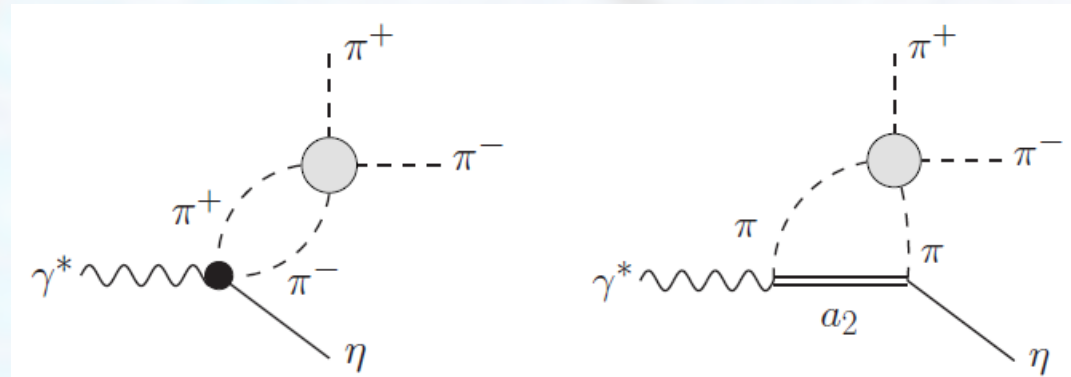
$\pi\pi$  phase shifts +  $e^+e^- \rightarrow 3\pi$  data  
 Eur.Phys.J. C74 (2014) 3180

# From $e^+e^- \rightarrow \pi^+\pi^-\eta$ to $\eta$ TFF

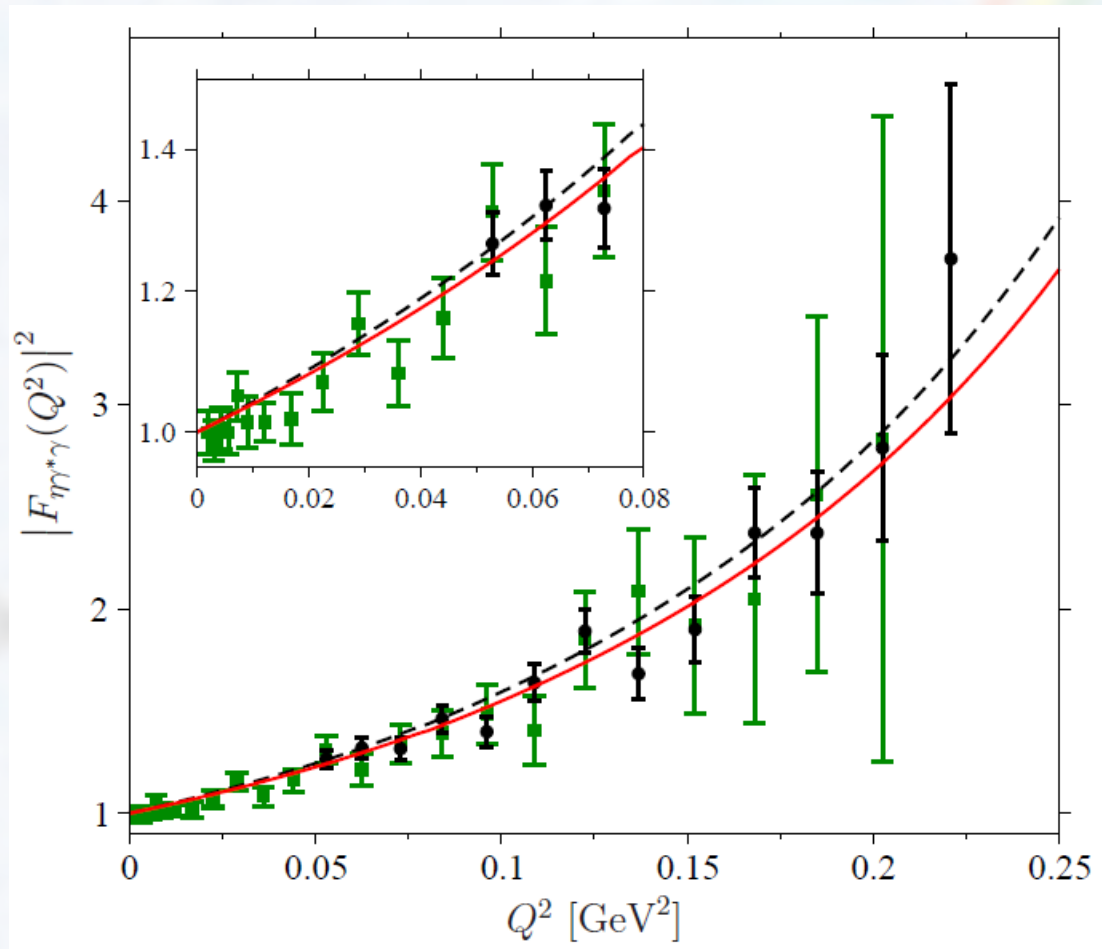


C.W.Xiao, T.Dato, C.Hanhart,  
B.Kubis, U.-G.Meißner, A. Wirzba

arXiv:1509.02194

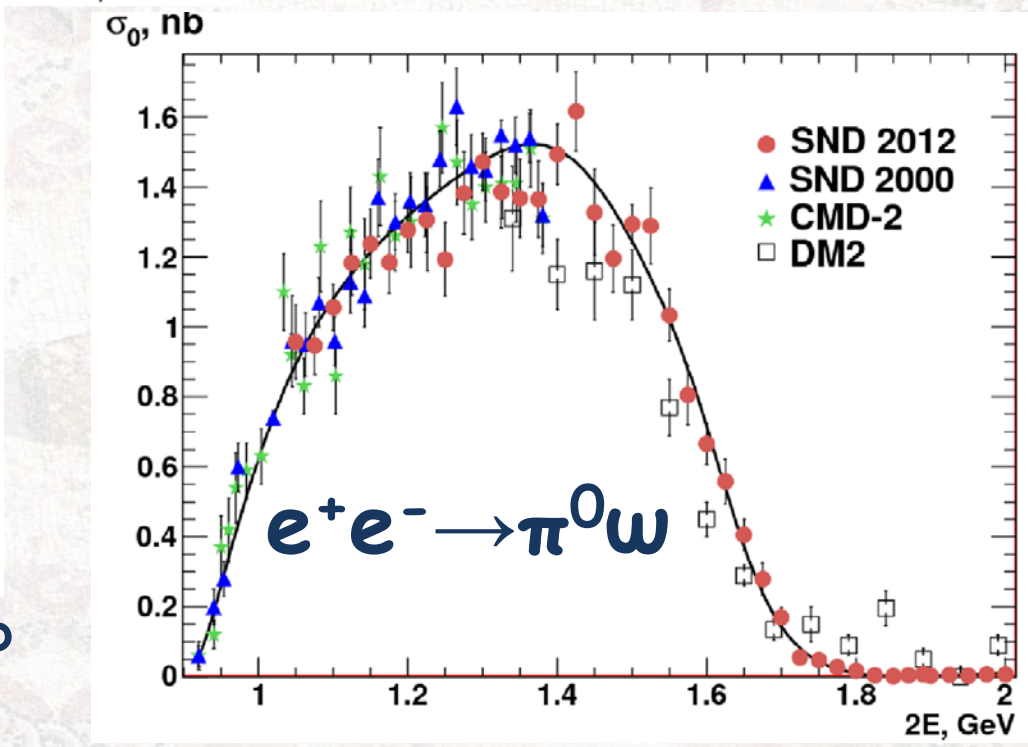
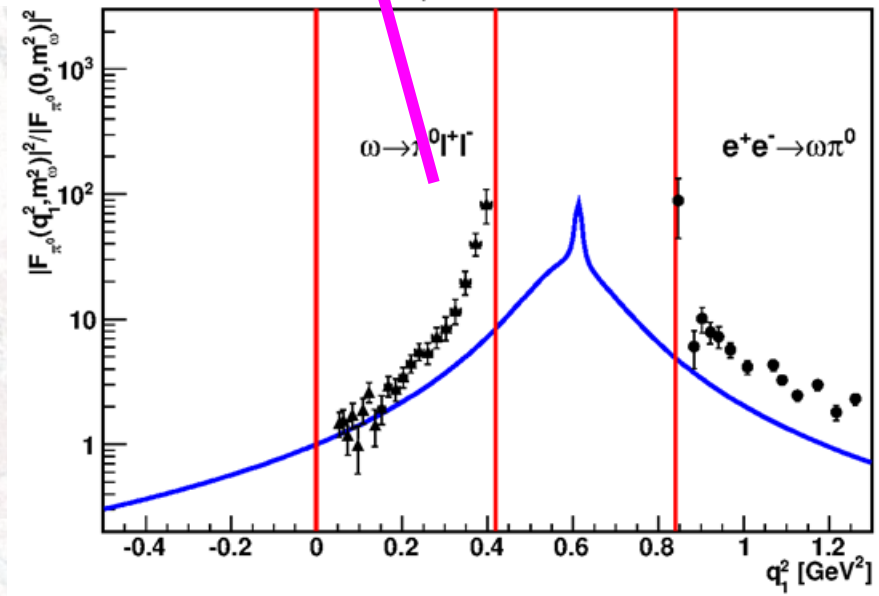
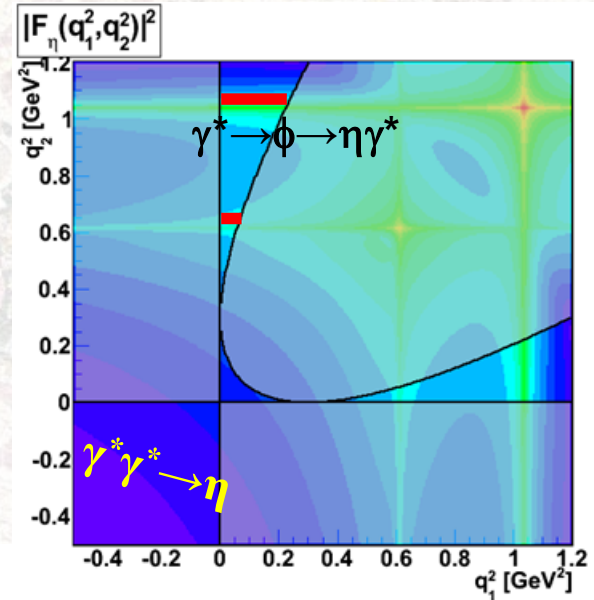
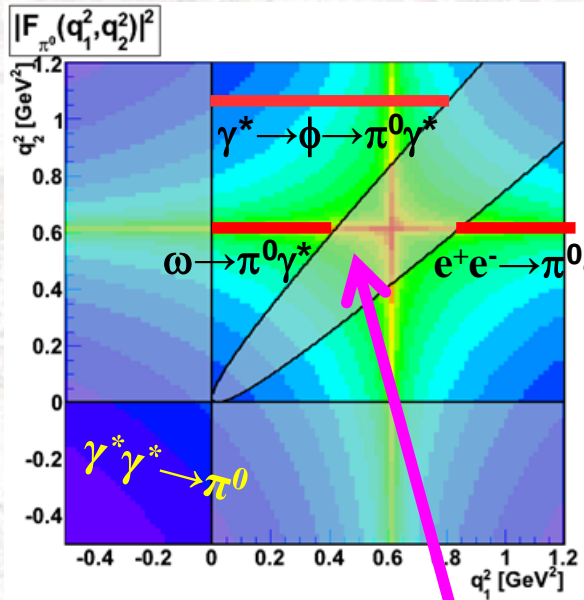


# From $e^+e^- \rightarrow \pi^+\pi^-\eta$ to $\eta$ TFF





# $V \rightarrow P\gamma^*$ and $e^+e^- \rightarrow PV$ processes



TH: Bonn, GSI, Uppsala, Kharkiv, JLab  
 Relation to  $\omega/\phi \rightarrow \pi^+\pi^-\pi^0$

# Summary and outlook

- Meson TFF from dispersion relations
- Relation to muon  $(g-2)$  HLbL
- Relation to HVP:  $e^+e^- \rightarrow$  hadrons  
data needed (not only cross sections)  
understand exp and theory errors:  
collaboration
- NuPECC, KLOE-2 WS 26-28/10, HPrecision, ...

$$\eta \rightarrow \pi^+ \pi^- \pi^0$$

