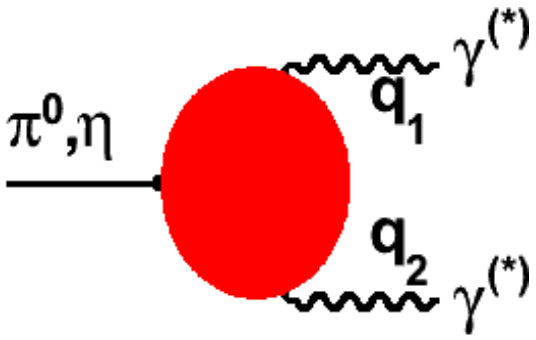
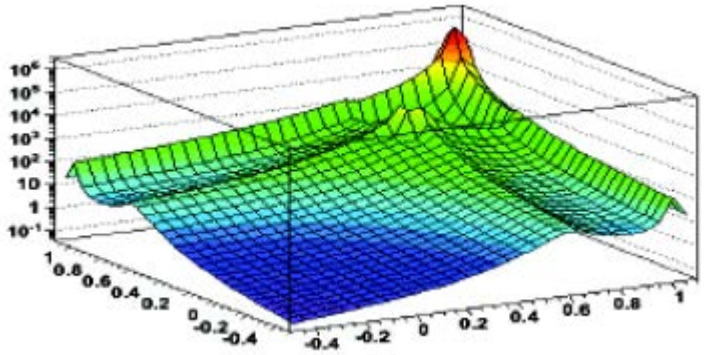
Transition form factors of light mesons





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FCCP2015, Anacapri, September 11th, 2015

Outline

- $\pi^0, \eta, \eta', \omega, \varphi$ meson factories/data samples (pN, γp, e^+e^-)

Transition Form Factors /Anomalous processes

- $\gamma^*\gamma \rightarrow \eta, \pi^0$ ($\Gamma\gamma\gamma$)
- $\eta, \pi^0 \rightarrow e^+e^-\gamma$
- $e^+e^- \rightarrow \eta\gamma$
- $\eta \rightarrow e^+e^-e^+e^-$
- $\phi \rightarrow \eta/\pi^0 e^+e^-$ (TFF)
- $P \rightarrow e^+e^-$
- $\eta, \eta' \rightarrow \pi^+\pi^-\gamma$, $e^+e^- \rightarrow \eta\pi\pi$, $\pi\pi\pi$
- Belle $\gamma^*\gamma \rightarrow \pi^0\pi^0$ arXiv:1508.06757

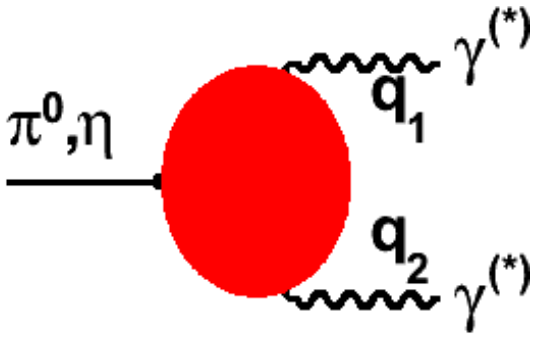
Meson Transition Form Factors (TFF)

Structure of light mesons

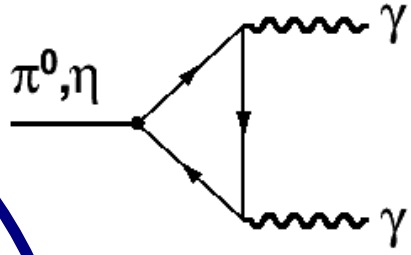
L/H energy QDC LAB

l^+l^- spectra in HIon

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



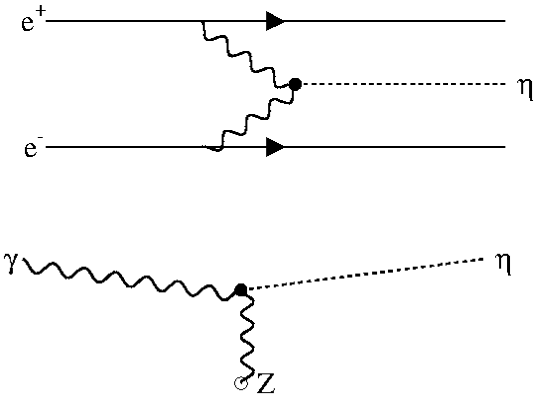
$$F_P(q_1^2, q_2^2)$$

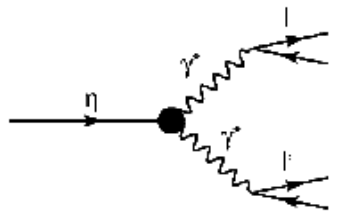


η: Γγγ

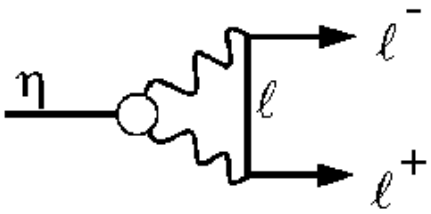
m_u/m_d

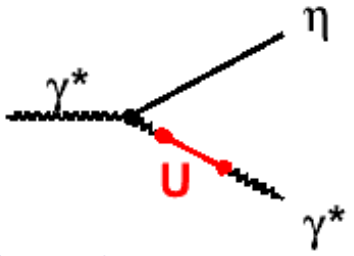
$F\pi^0$ $q^2 \to \infty$ puzzle



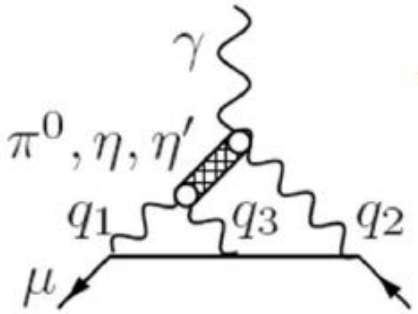


P → l+l-





Dark photon



g-2 HLbL

Radiative widths of η, π^0

η, π^0 : narrow and short lived

=> $\Gamma_{tot}=\Gamma_{\gamma\gamma}/BR_{\gamma\gamma}$

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

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

Two exp. techniques:

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

$\delta\Gamma(\pi^0 \to \gamma\gamma)$ ~2.8%

PrimEx PRL 106,162303(2011)

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

KLOE-2 Taggers

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

Details: [EPJC 72, 1917 (2012)]

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT
0.510 ± 0.026	OUR FIT				
0.510 ± 0.026	OUR AVERAGE				
0.51 ± 0.12 ± 0.05	36	BARU	90	MD1	$e^+e^- \to e^+e^-\eta$
0.490 ± 0.010 ± 0.048	2287	ROE	90	ASP	$e^+e^- \to e^+e^-\eta$
0.514 ± 0.017 ± 0.035	1295	WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-\eta$
0.53 ± 0.04 ± 0.04		BARTEL	85E	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	08	CNTR	Reanalysis
0.64 ± 0.14 ± 0.13		AIHARA	86	TPC	$e^+e^- \to e^+e^-\eta$
0.56 ± 0.16	56	WEINSTEIN	83	CBAL	$e^+e^- \to e^+e^-\eta$
0.324 ± 0.046		BROWMAN	74B	CNTR	Primakoff effect
1.00 ± 0.22	[2]	BEMPORAD	67	CNTR	Primakoff effect

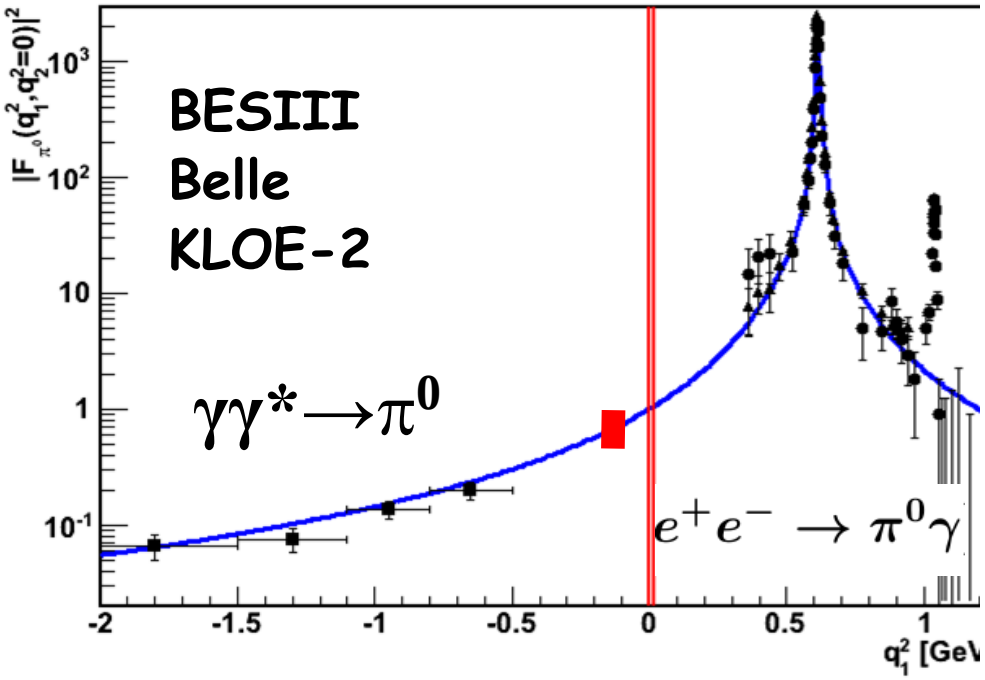
$\delta\Gamma(\eta \to \gamma\gamma)$ ~5%

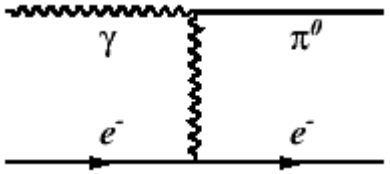
$\sigma(e^+e^- \to e^+e^-\eta, \sqrt{s}=1\text{GeV})$

$\Gamma_{\gamma\gamma}=520\pm20_{stat}\pm13_{syst}$ eV

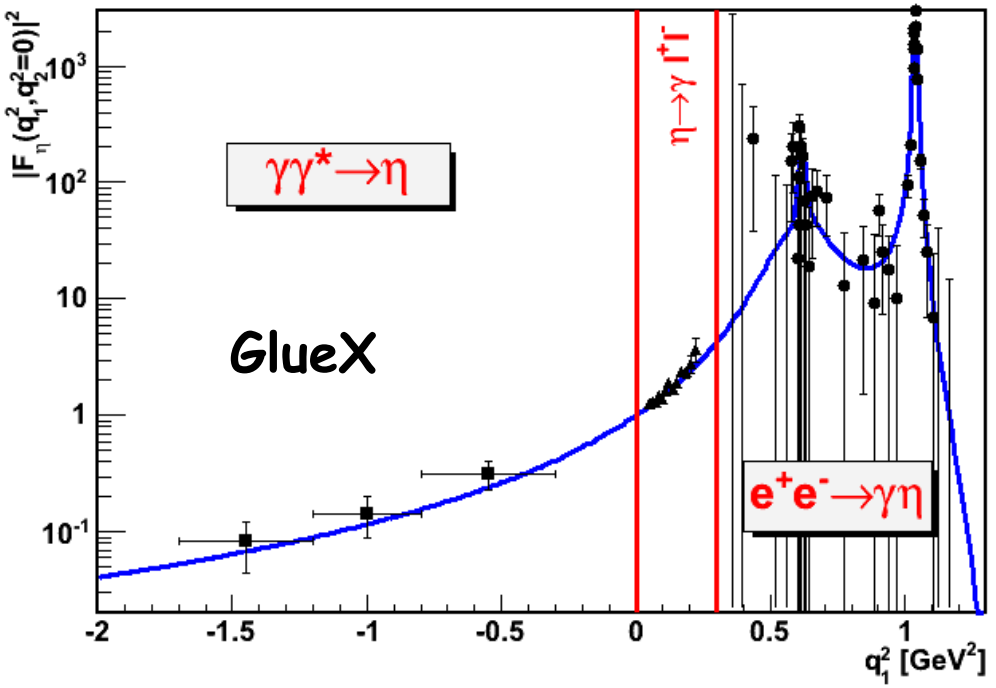
[KLOE JHEP1301 (2013) 119]

η,π^0 single off shell TFF





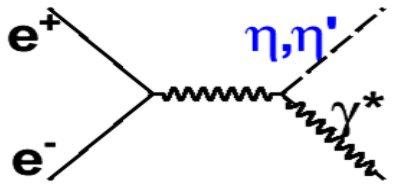
$$\frac{d\sigma}{dt}(e^-\gamma \to e^- P) = \frac{16}{3}\frac{\pi\alpha}{s m_P^3}\,\Gamma_{\gamma\gamma}|F_P(t,0)|^2\,\frac{s-m_P^2+t}{t}$$



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

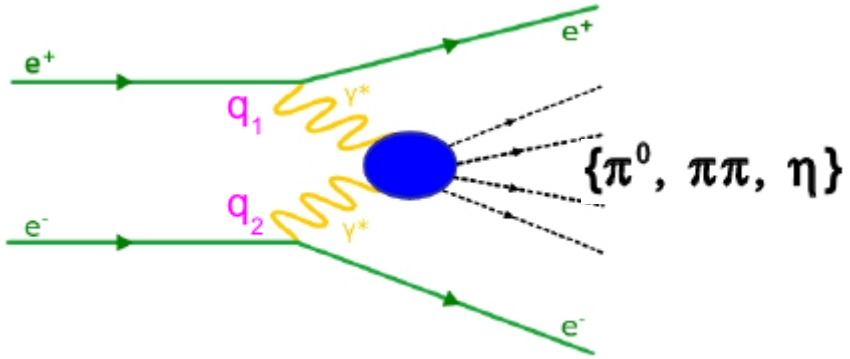
$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{s m_P}\right)^3$$

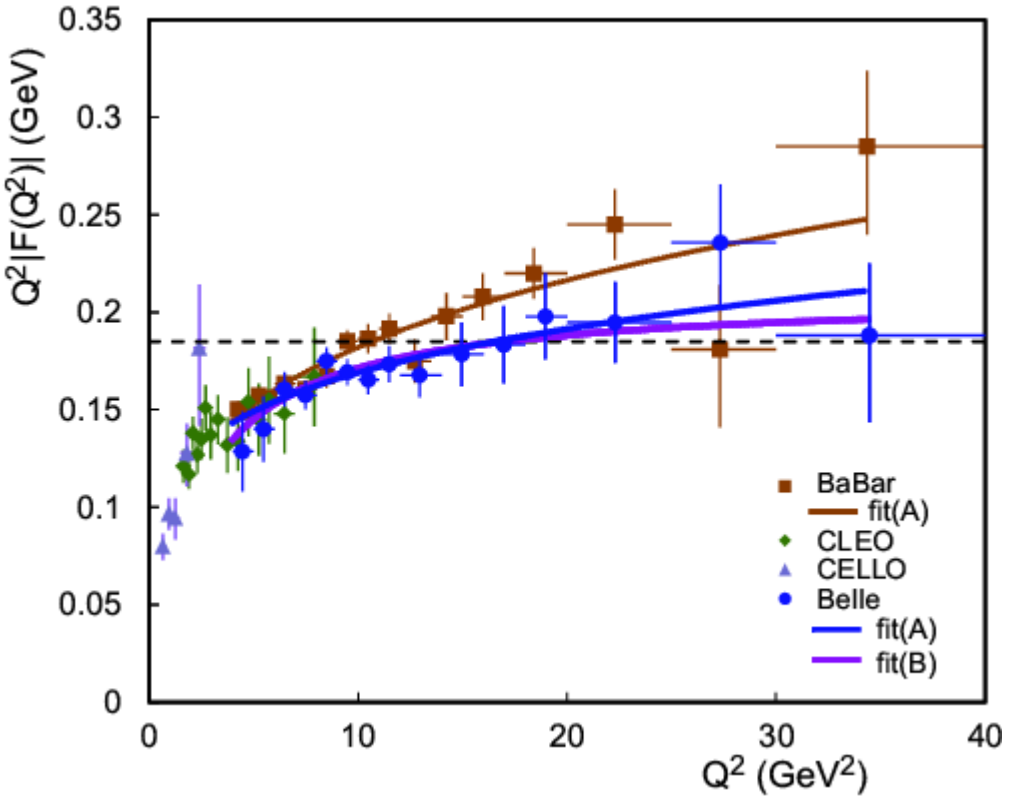
$P \to \gamma^*\gamma$
Dalitz decays:
KLOE, WASA,CBall,BESIII
CLAS,NA48

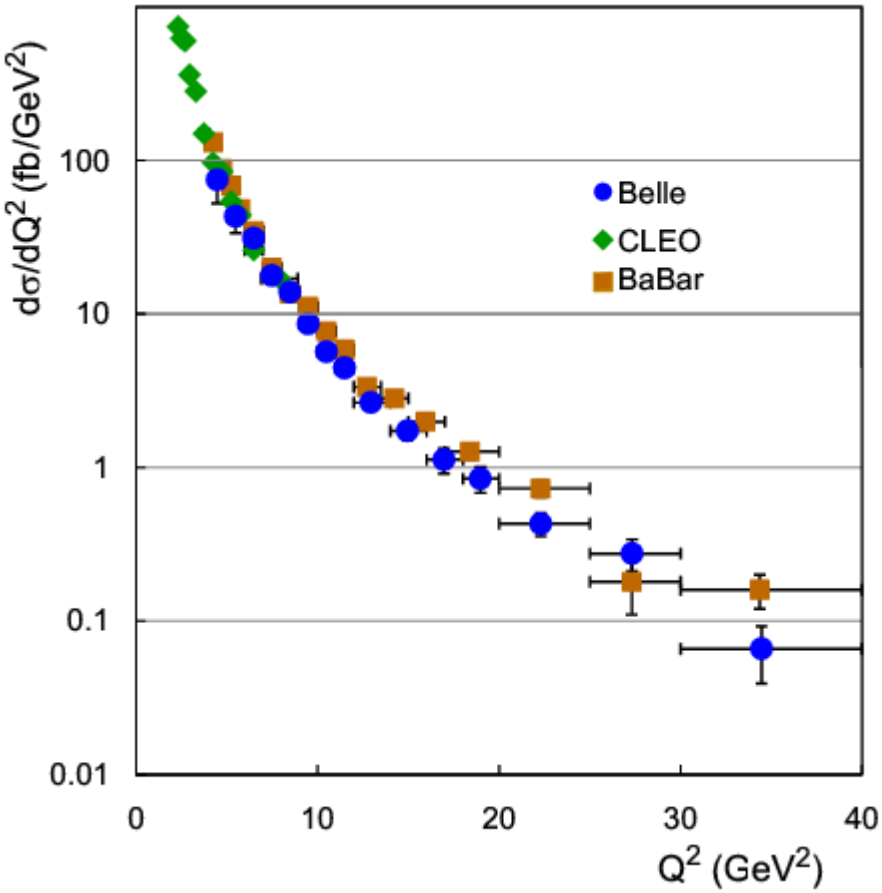


Data:CELLO,NA60,CB-MAMI,CMD-2,SND

$\gamma\gamma^* \to \pi^0$

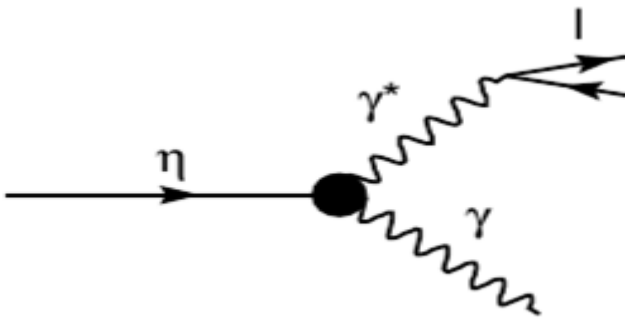


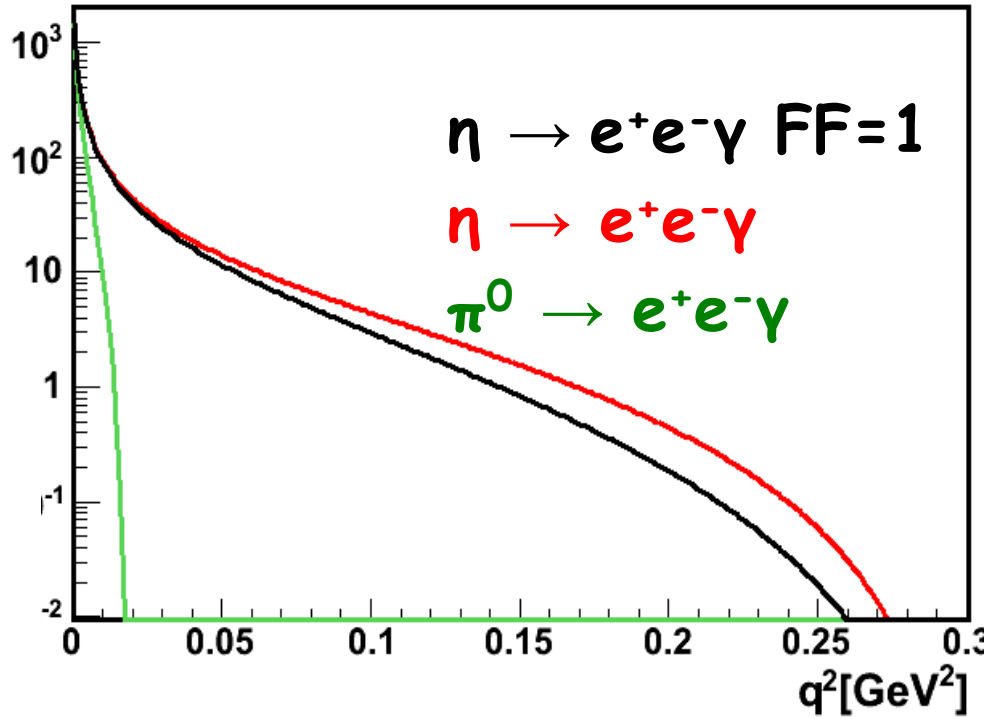


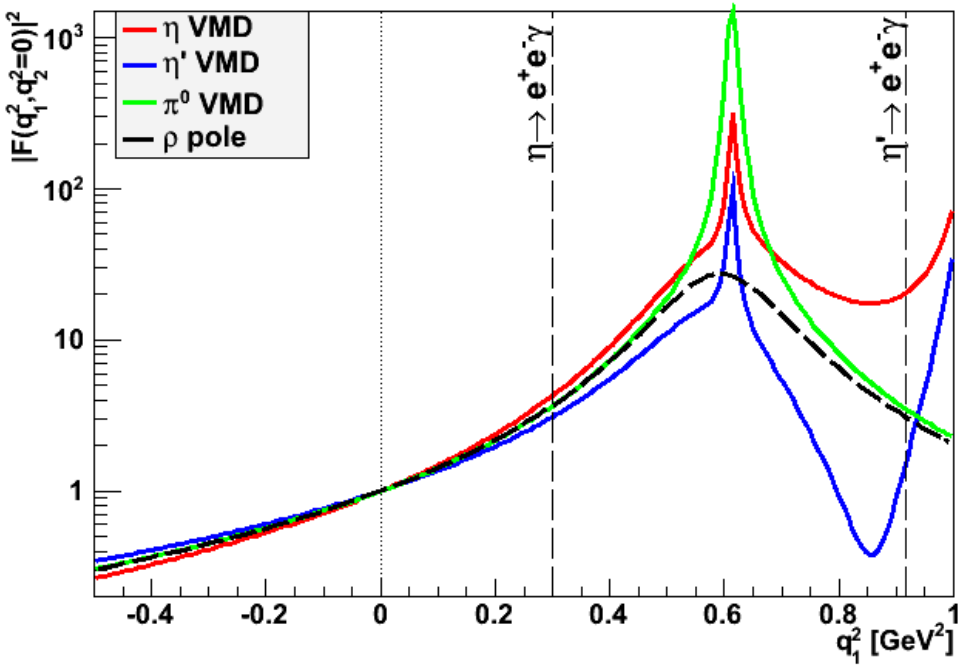


Dalitz decays

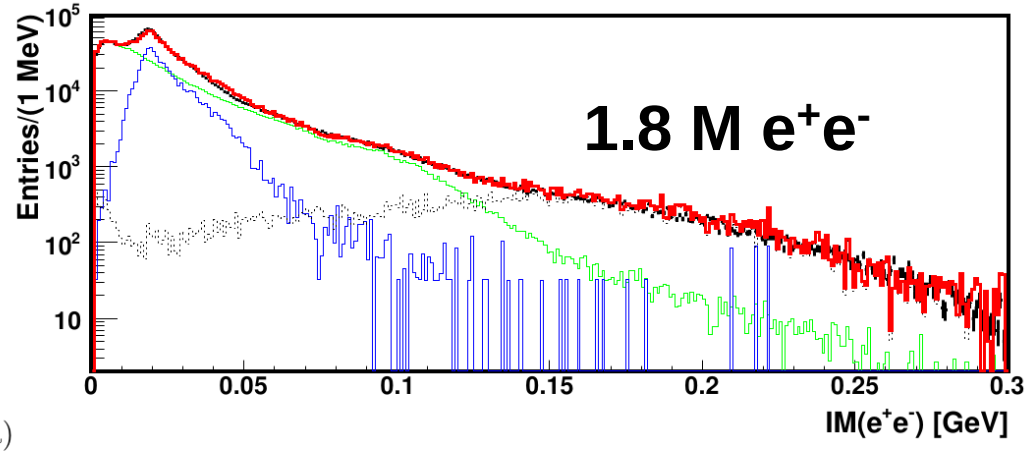
$$\frac{d\Gamma(P \to \ell^+\ell^-\gamma)}{dq^2\Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_\ell^2}{q^2}}\left(1+\frac{2m_\ell^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$



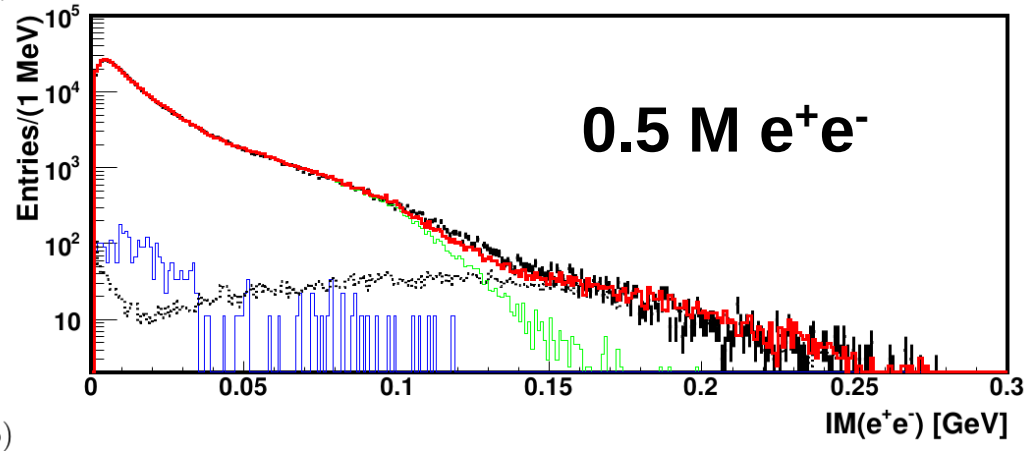




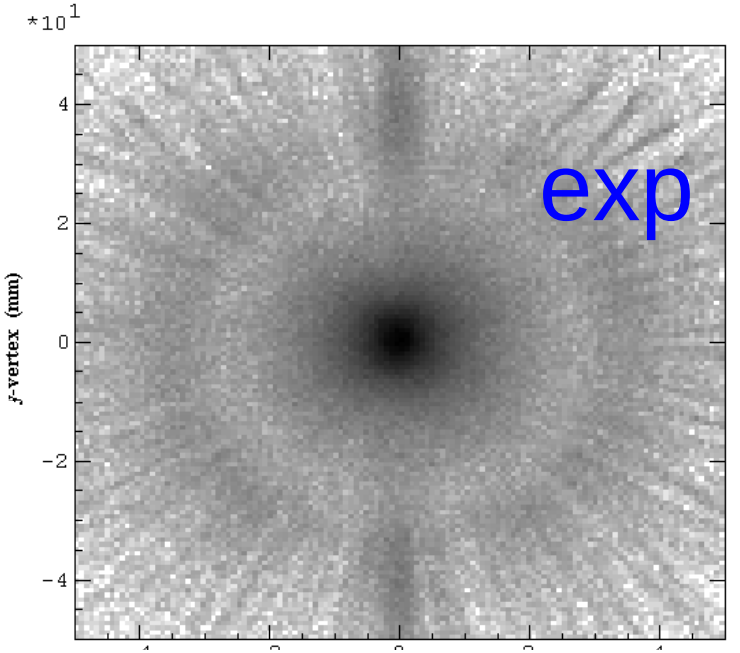
Data analysis: $\pi^0 \rightarrow \gamma e^+e^-$

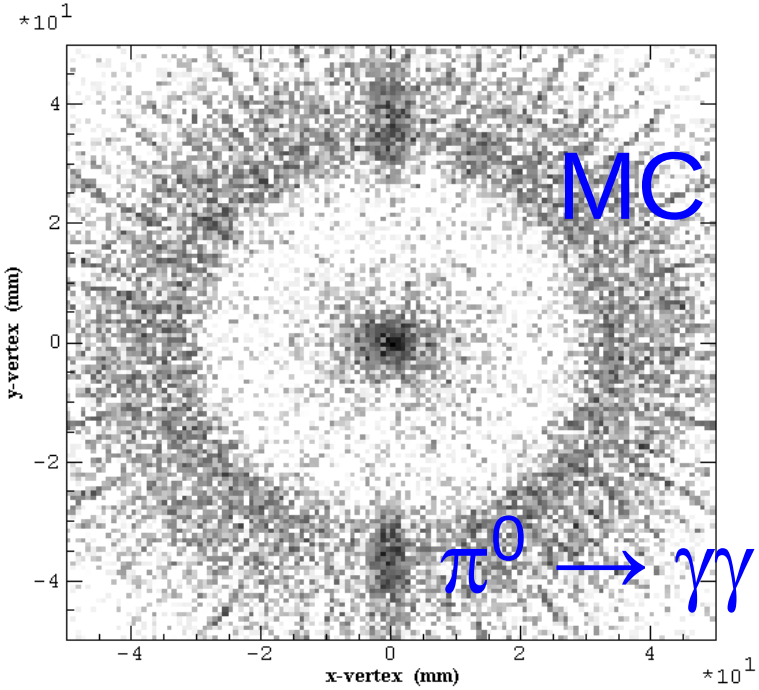


a)

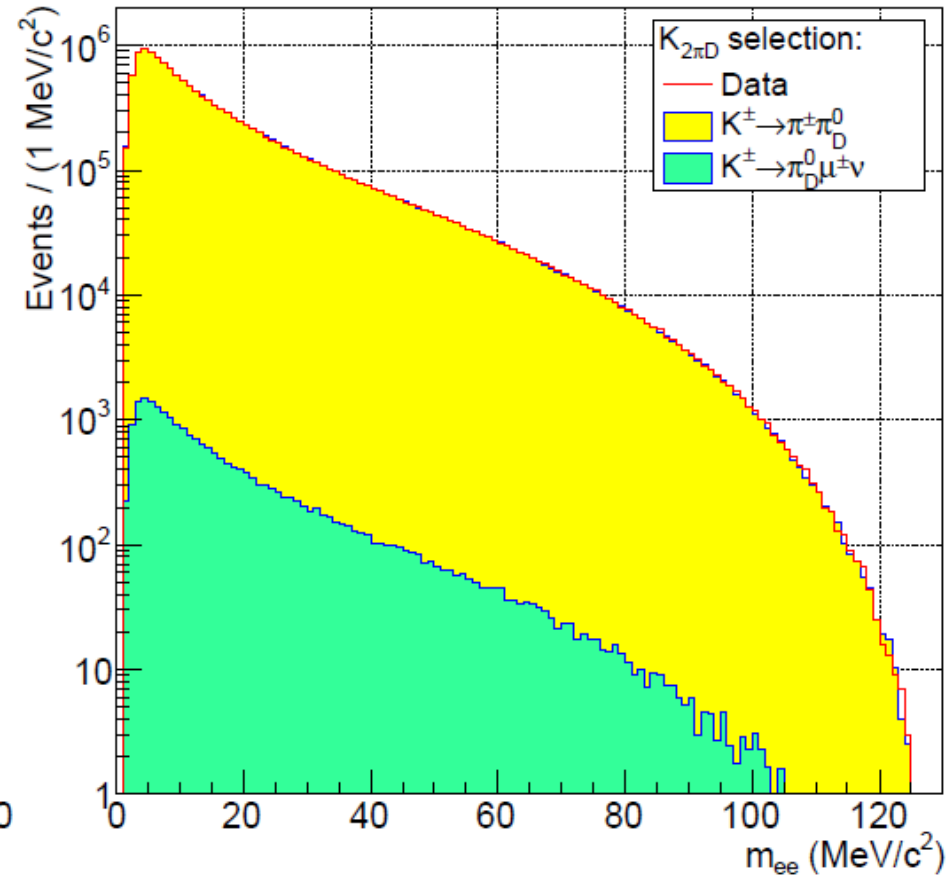


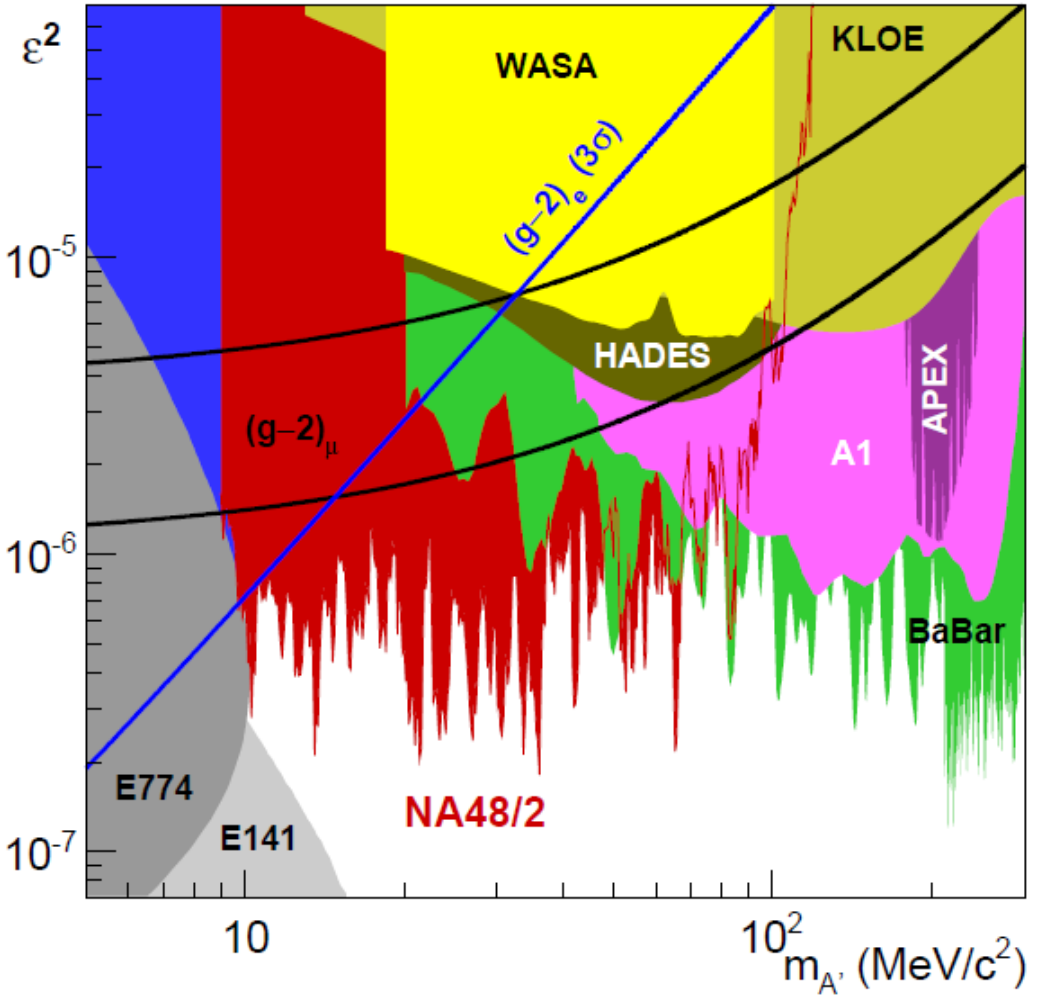
b)





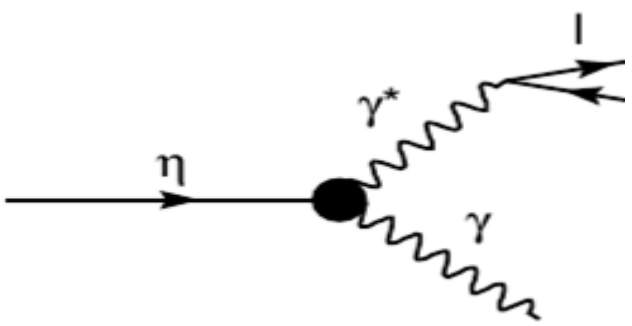
NA48/2 $\pi^0 \rightarrow e^+e^-\gamma$

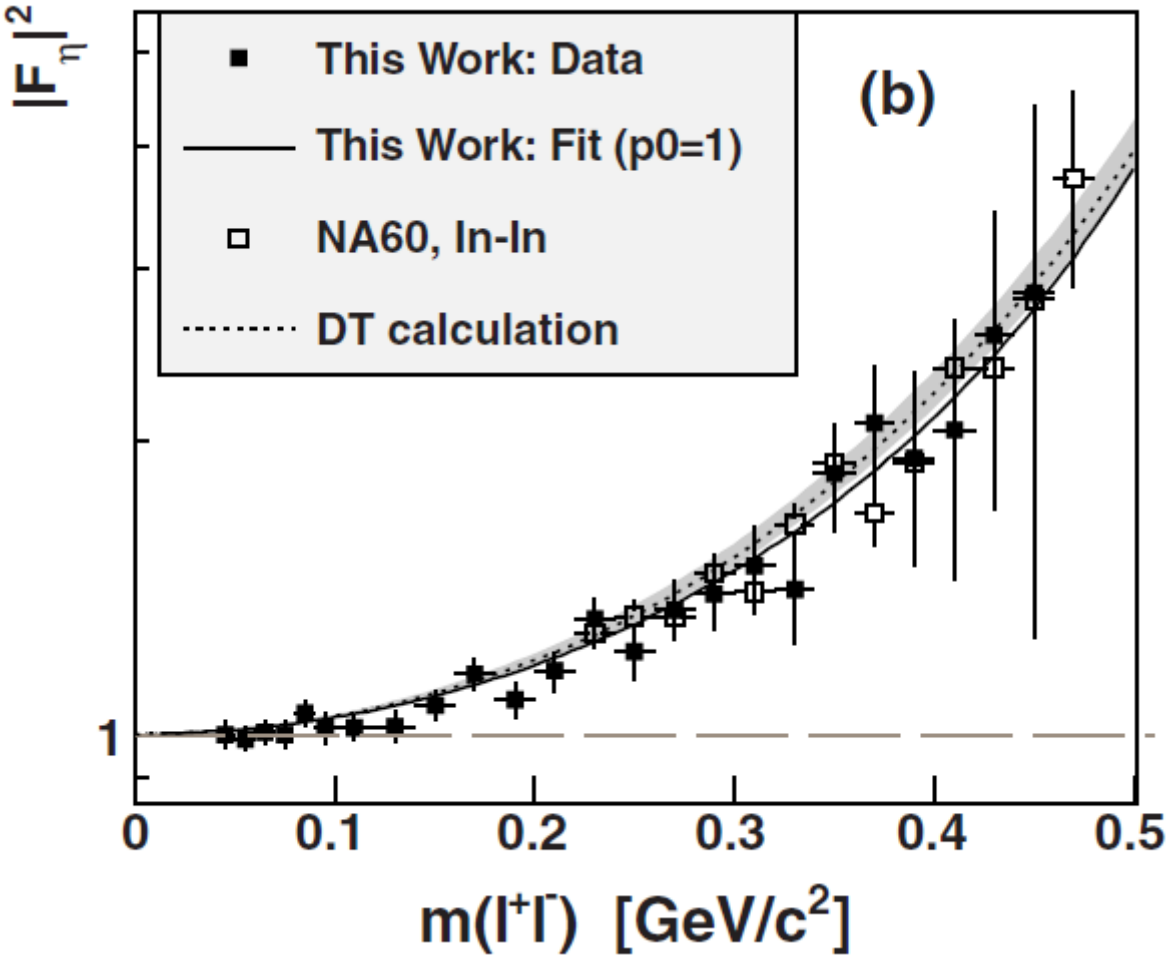




NA48/2: arXiv:1504.00607

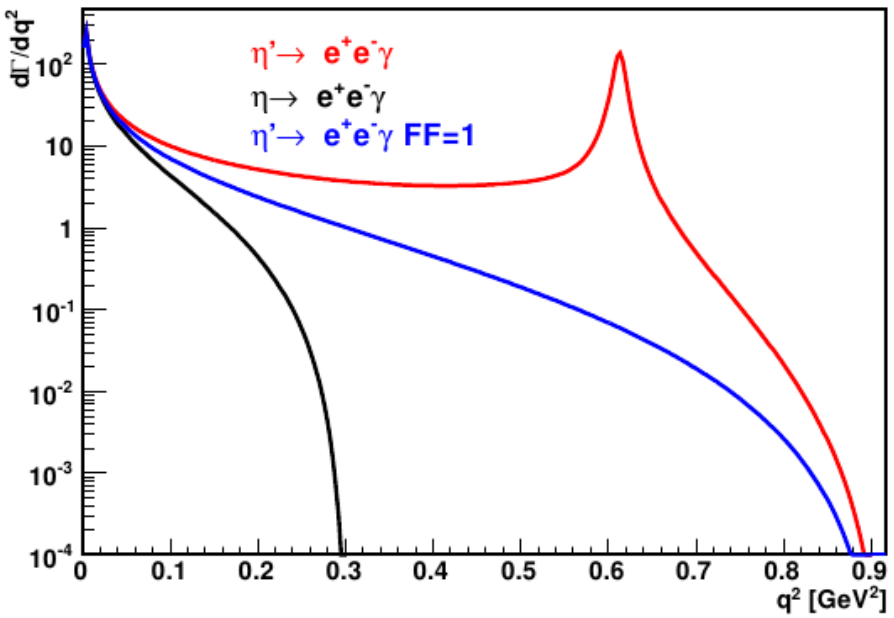
$\eta \to e^+e^-\gamma$

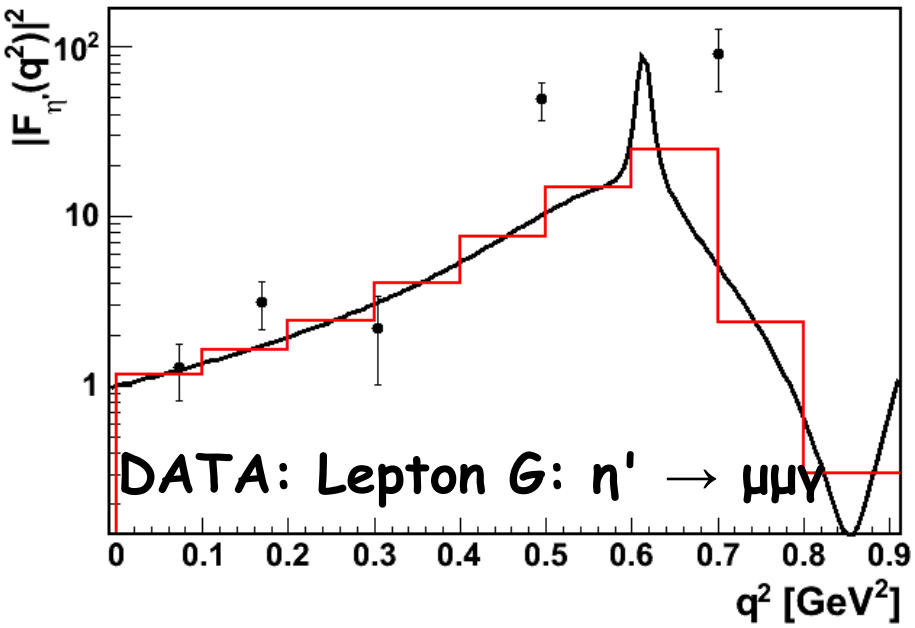


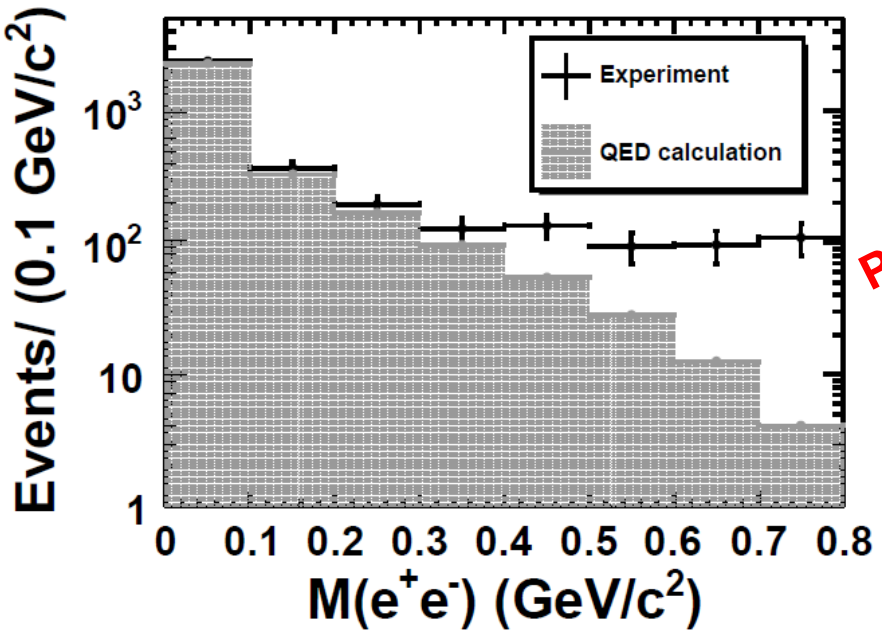


CB/TAPS: PRC89, 044608 (2014)

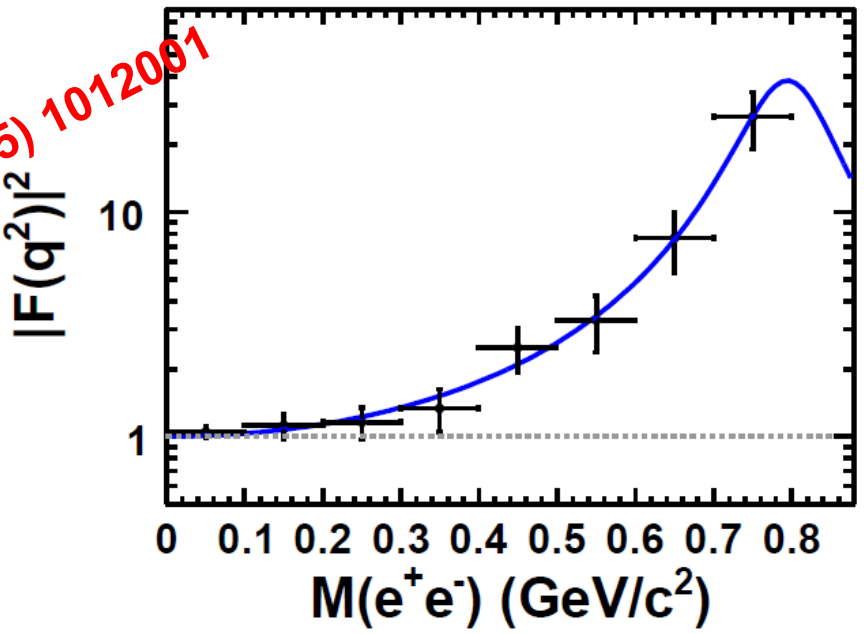
BESIII: Observation of η'→γe+e-



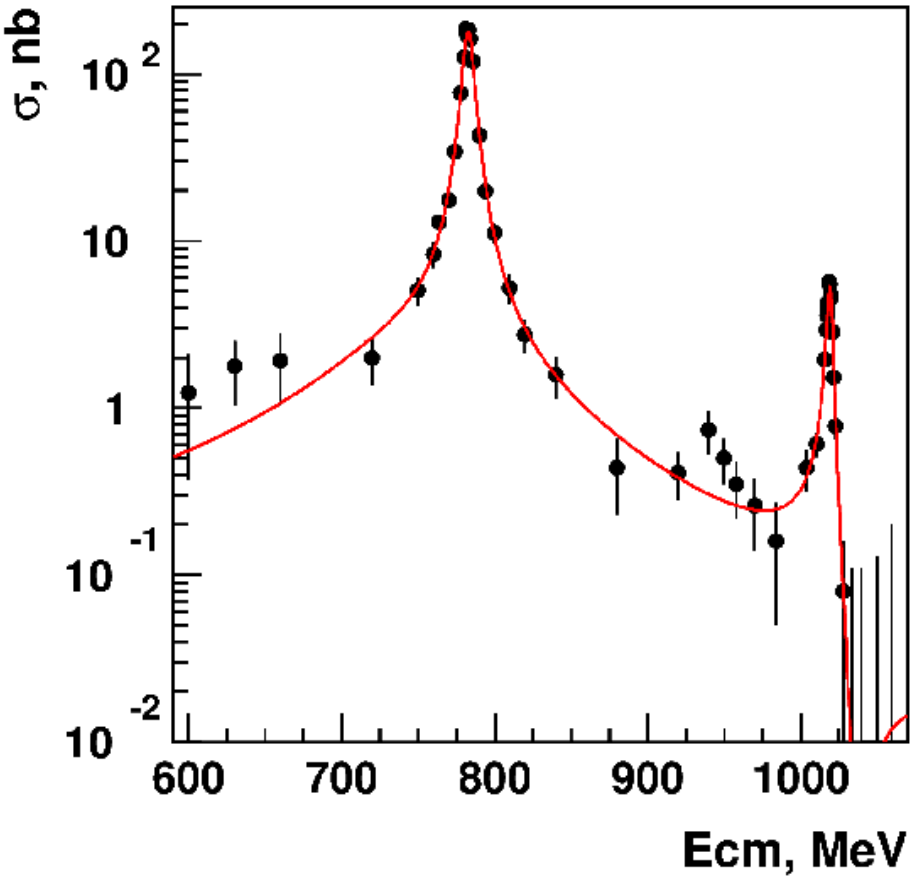


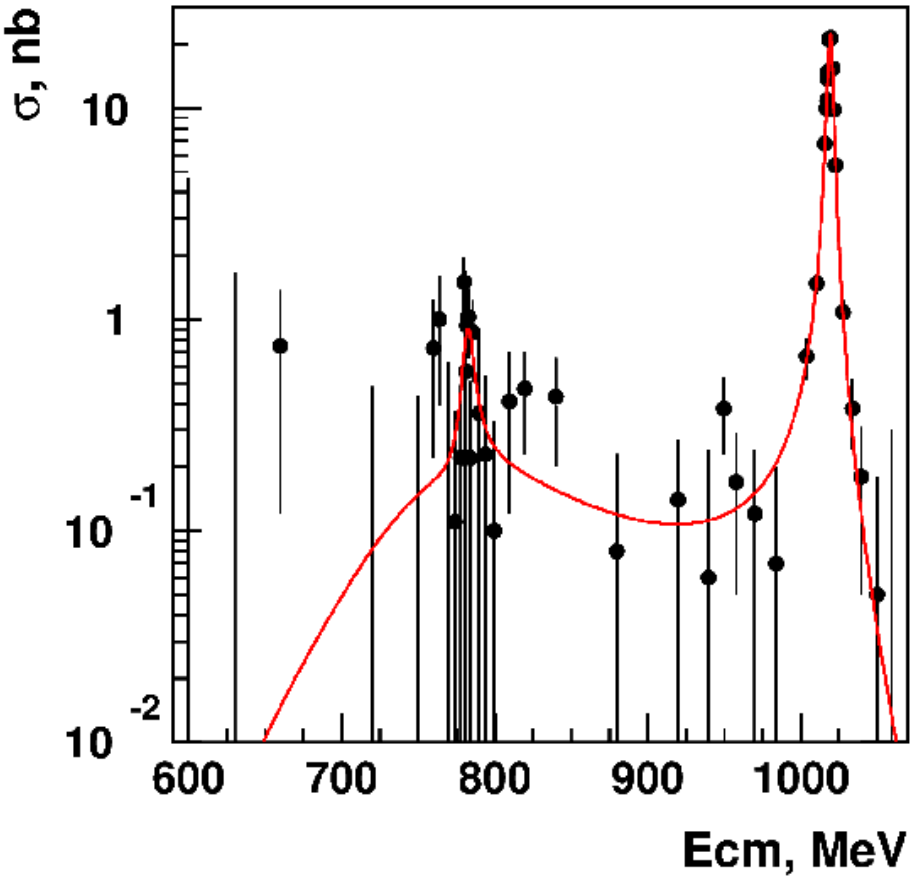


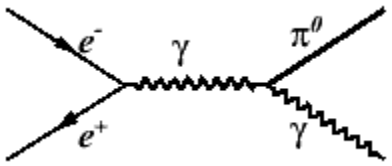
PRD92 (2015) 1012001



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

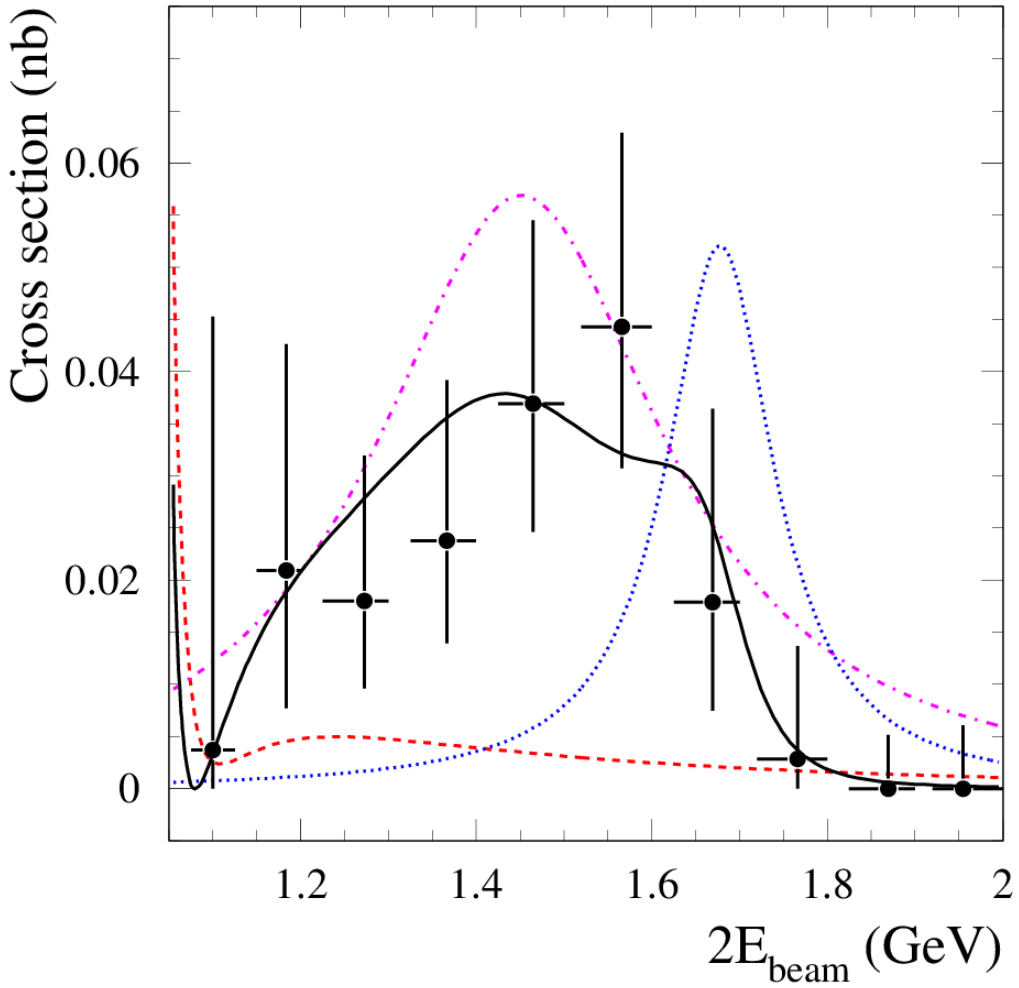






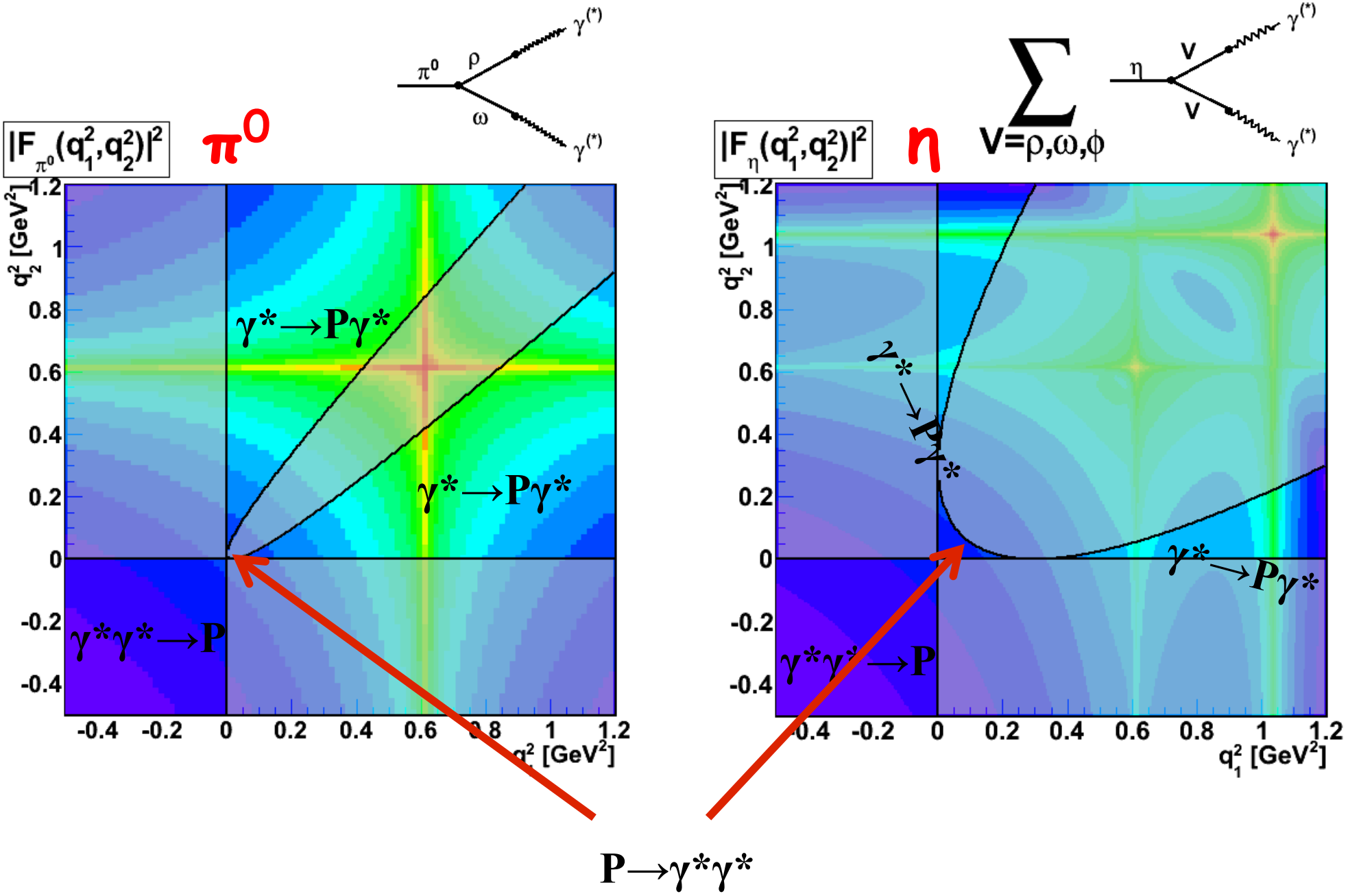
$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

Data: CMD-2,SND

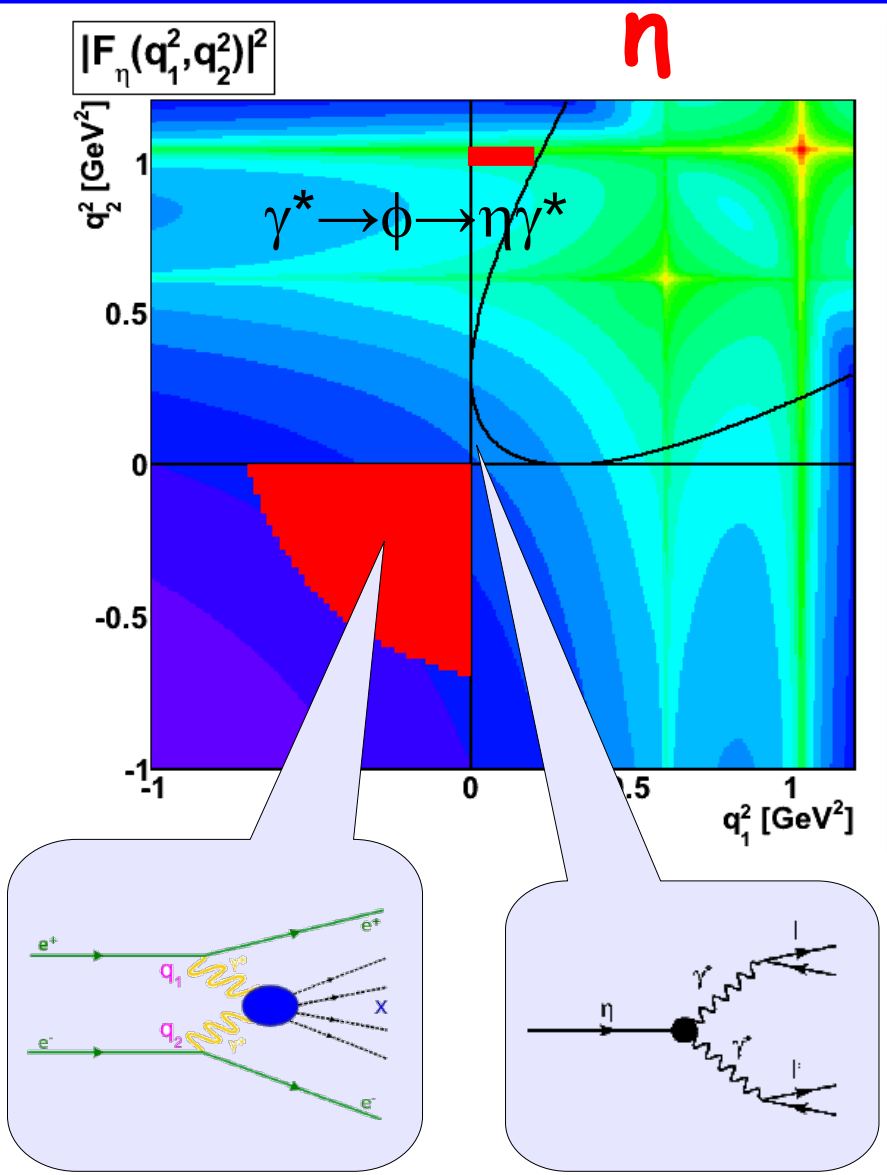


e+e- → ηγ SND PRD 90 (2014) 032002

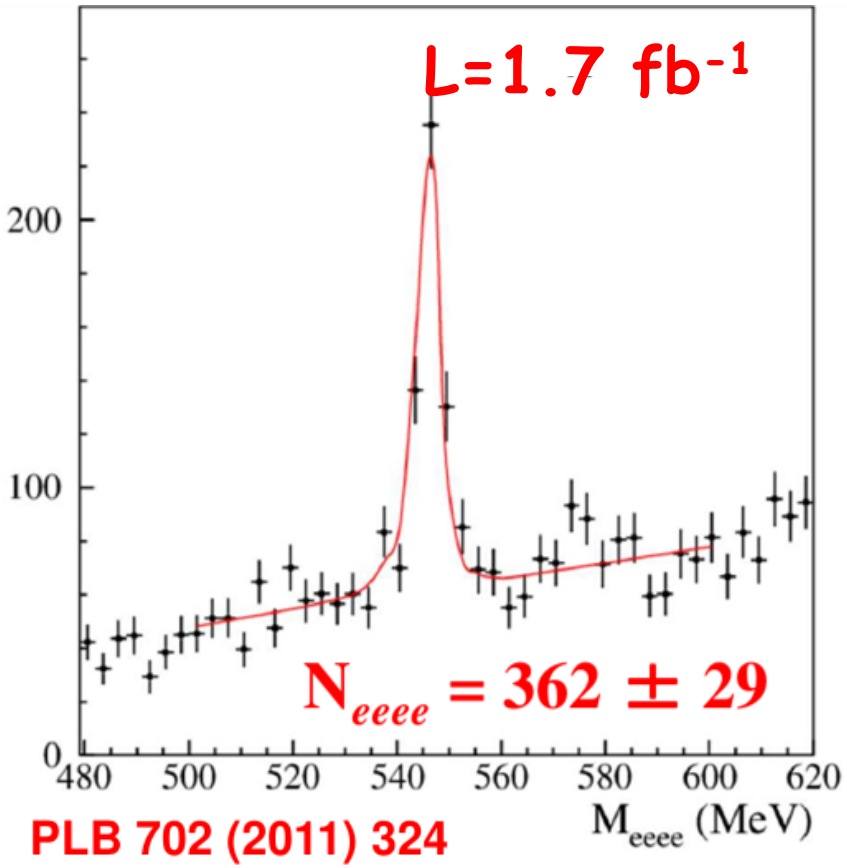
TFF kinematic regions: π^0, η



Double off shell TFF at KLOE



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



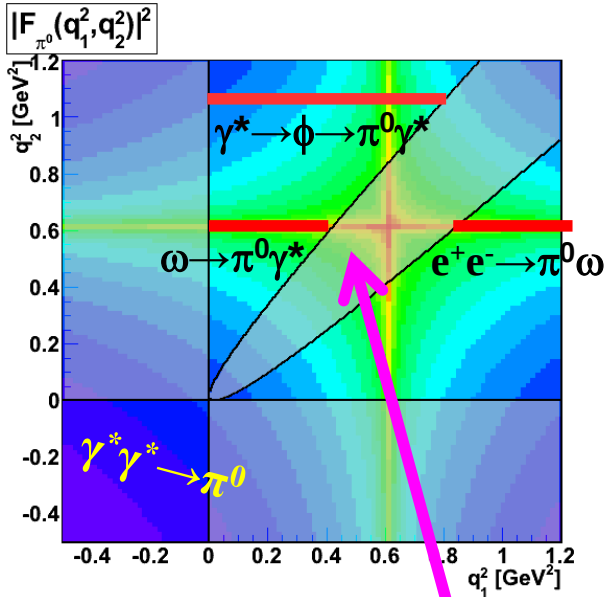
PLB 702 (2011) 324

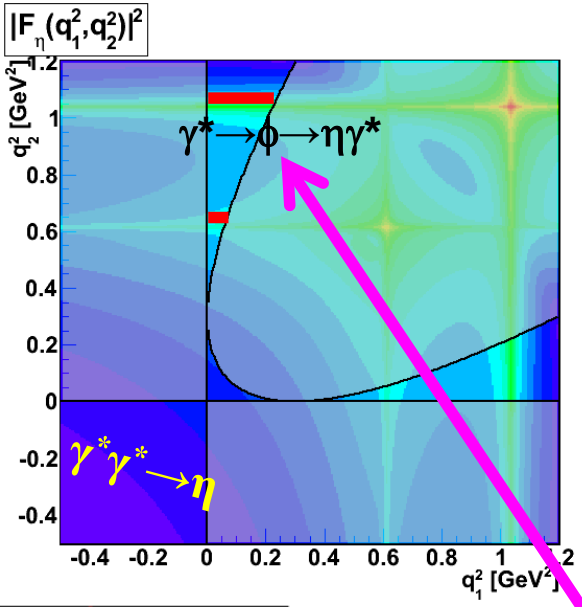
$BR(\eta \to e^+e^-e^+e^-(\gamma)) = (\ 2.4 \pm 0.2_{stat} \pm 0.1_{syst}\ ) \times 10^{-5}$

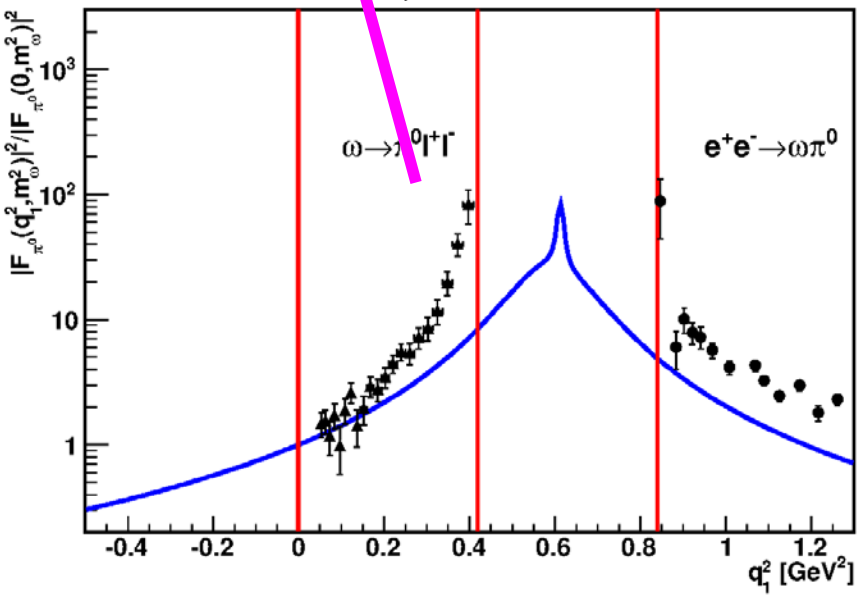
TFF=1 => BR=2.5×10^{-5}

TFF≠1 ΔBR ~ 5%

V → Pγ* and e+e- → PV processes





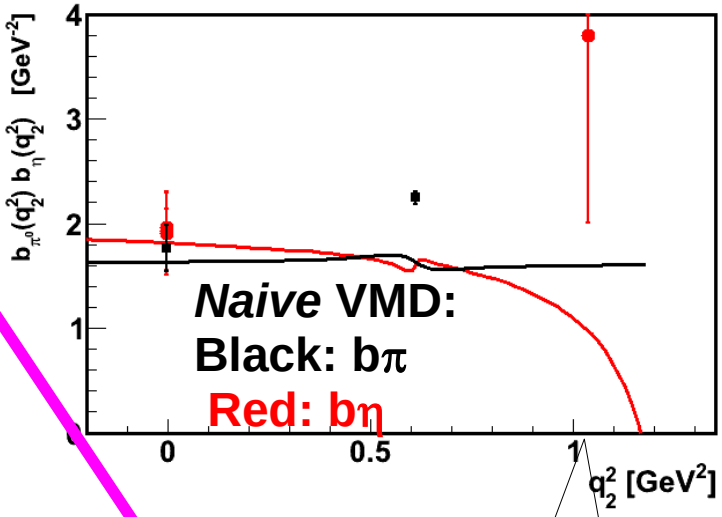


TH: Bonn, GSI, Uppsala, Kharkiv, JLab

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

slopes bπ, bη

$$b_P(q_2^2) = \left.\frac{\partial \ln |F(q_1^2, q_2^2)|}{\partial q_1^2}\right|_{q_1^2=0}$$



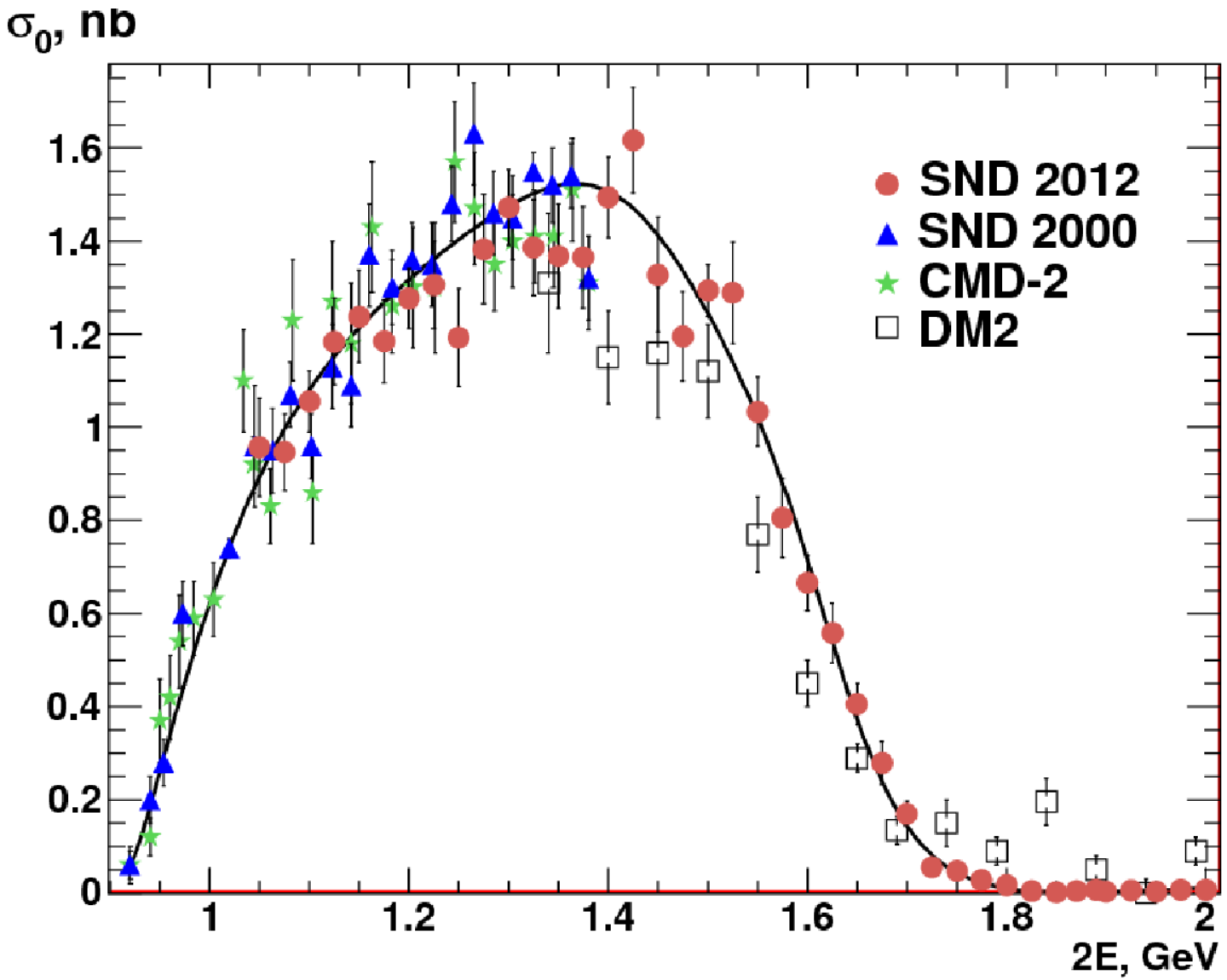
$b\eta(m^2_\phi)$

KLOE results

$\phi\to\eta\gamma^*$ BR 10^{-4}

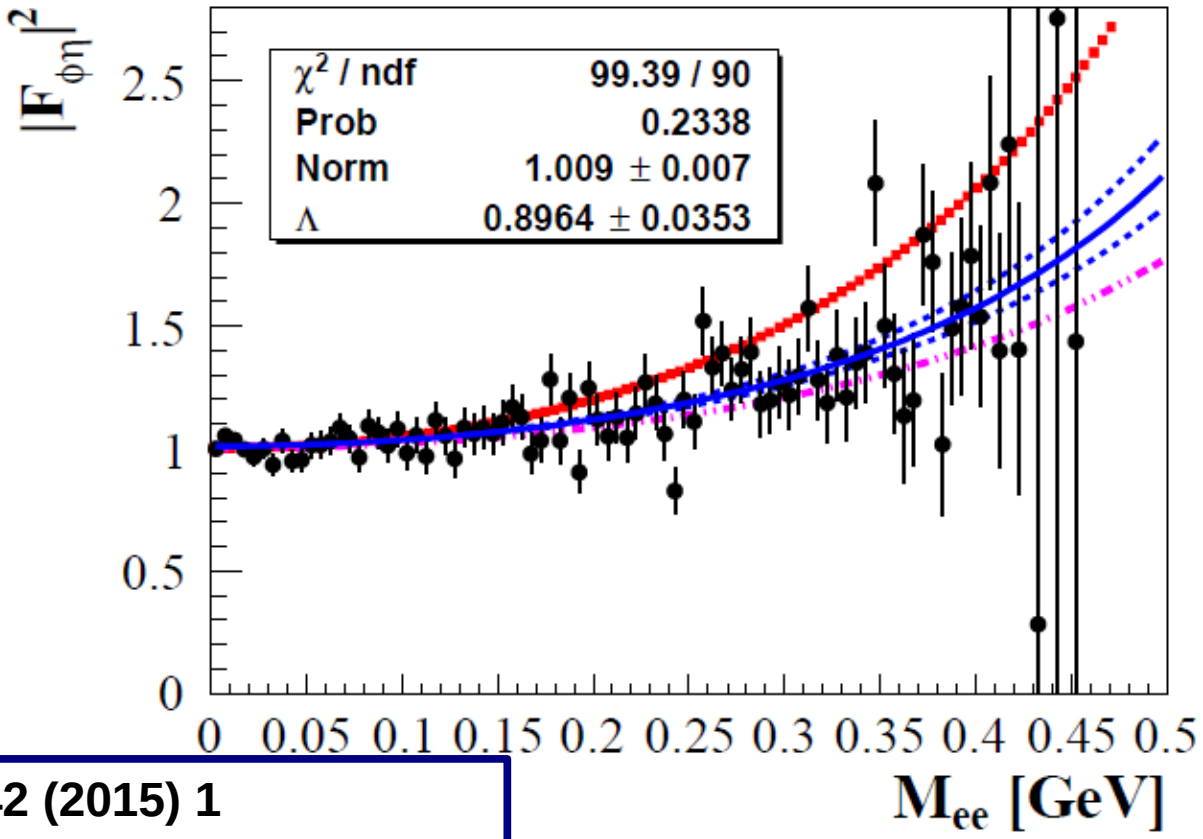
$b\pi^0(m^2_\phi)$ $\phi\to\pi^0\gamma^*$ BR 10^{-5}

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



SND PRD 88 (2013) 054013

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



Form factor/BR: **Phys.Lett. B742 (2015) 1**

	SND/CMD-2 (2001)
$b_{\phi\eta}$ [GeV $^{-2}$]	3.8 ± 1.8/ --
BR (x10^4)	1.19 ± 0.31 / 1.14 ± 0.16

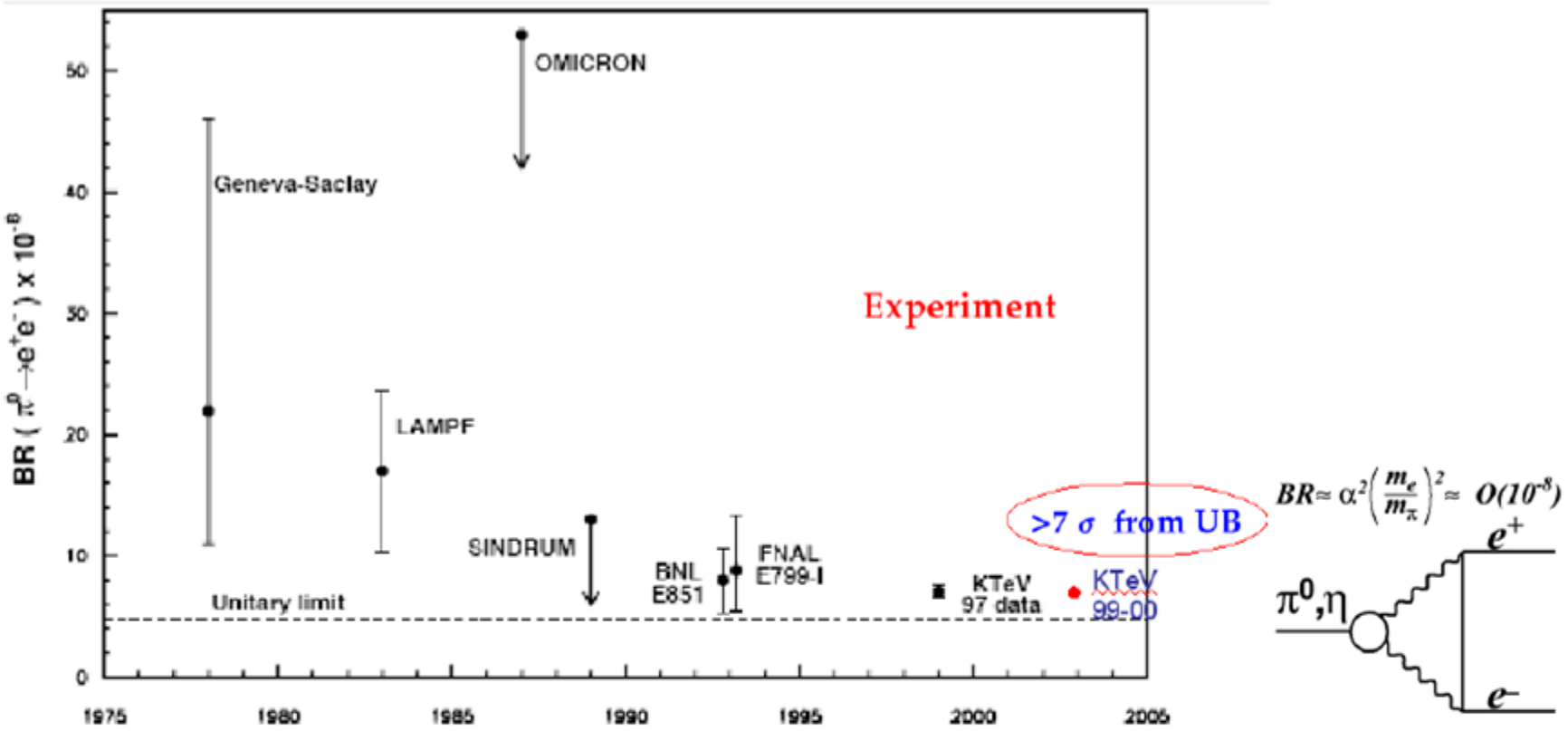
KLOE 2015

$$1.17 \pm 0.10^{+0.07}_{-0.11}$$

$$(1.075 \pm 0.007 \pm 0.038$$

$$F_\eta(q^2, m_\phi^2) \propto \frac{1}{1 - b_\eta(m_\phi^2)q^2}$$

History of $\pi^0 \to e^+e^-$ measurements



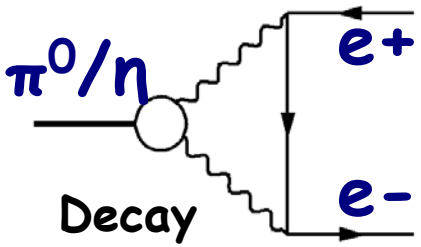
- Unitary bound (model independent) $BR \geq 4.75 \cdot 10^{-8}$
- Experiment: KTeV (794 events from $K_L \to 3\pi^0$):

$$BR(\pi^0 \to e^+e^-) = (6.44 \pm 0.25_{stat} \pm 0.22_{syst}) \times 10^{-8}$$

$$BR_{\text{no-rad}}(\pi^0 \to e^+e^-) = (7.48 \pm 0.29_{stat} \pm 0.25_{syst}) \times 10^{-8}$$

PRD75:012004(07)

$P \to e^+e^-$



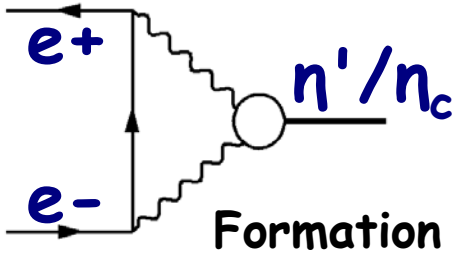
Decay

HADES
WASA
Cball,NA60

	UB	SM	EXP
$\mathcal{B}(\pi^0 \to e^+e^-) \times 10^8$	≥ 4.69	6.23 ± 0.12	7.49 ± 0.38 KTeV2007
$\mathcal{B}(\eta \to e^+e^-) \times 10^9$	≥ 1.78	5.2 ± 0.3	$\leq 5.6 \cdot 10^3$ HADES2012
$\mathcal{B}(\eta' \to e^+e^-) \times 10^{10}$	≥ 0.36	1.9 ± 0.3	$\leq 2.1 \cdot 10^3$ ND1988
$\mathcal{B}(\eta_c \to e^+e^-) \times 10^{14}$	≥ 4.2		

3σ diff

Dorokhov,PLB667,145



Formation

ND L=0.5pb^{-1}

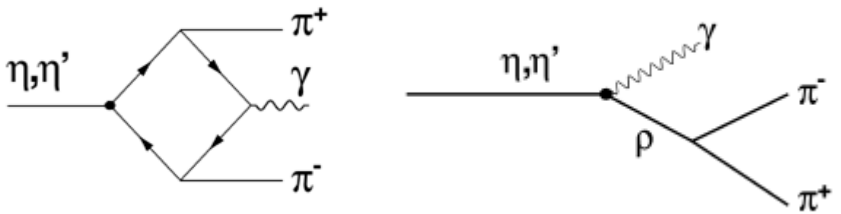
B<1.2 · 10^{-7}

VEPP2000
BESIII

$\mathcal{B}_{\eta' \to e^+e^-}$

CMD3 PLB740, 273 (2015)
SND PRD91 092010 (2015)
2.9 pb^{-1}/exp
Combined B< 5.6· 10^{-9} 90% CL

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

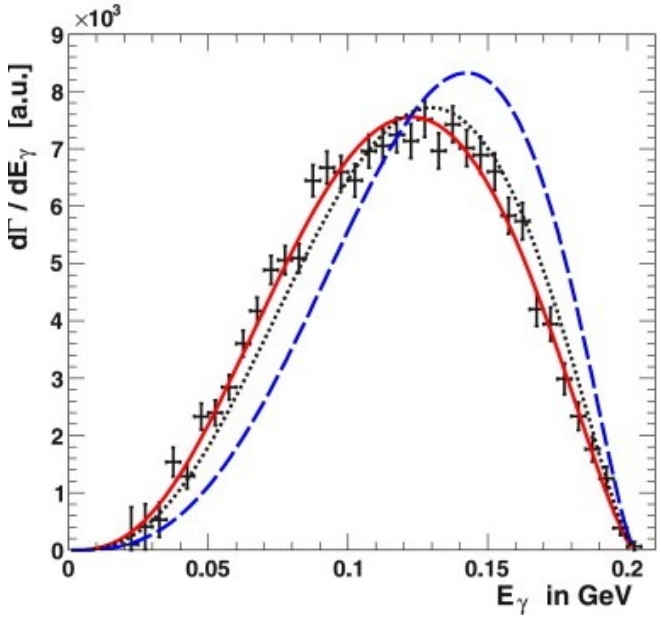


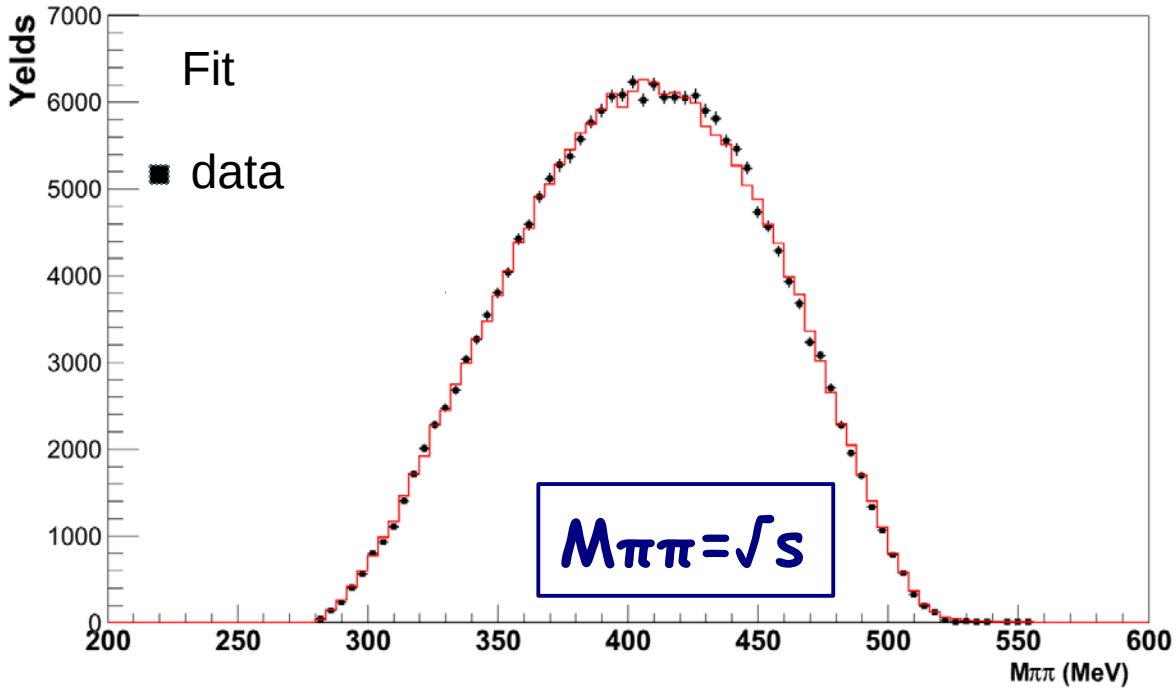
$$\frac{d\Gamma_{\eta(\eta')}}{ds_{\pi\pi}} \propto \left| C + \frac{1}{s_{\pi\pi} - m_\rho^2 - i m_\rho \Gamma_\rho} \right|^2$$

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

PLB707 (2012) 184

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





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

[WASA PLB707 (2012) 243]

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

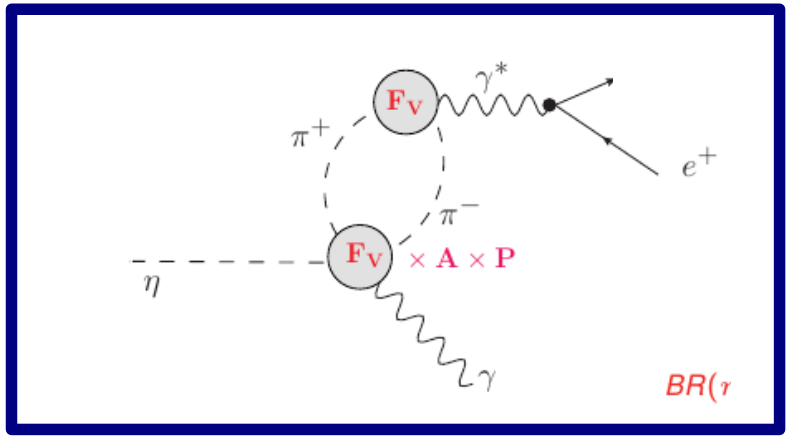
[KLOE PLB718 (2013) 910]

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

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

$\to$ α reaction specific

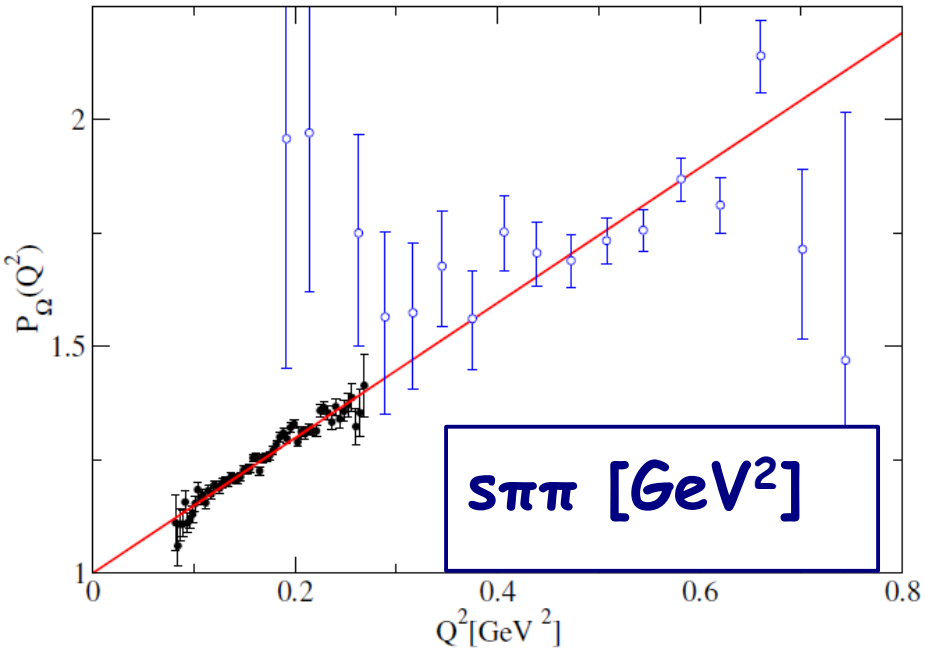
$\to$ $\alpha[\eta] = \alpha[\eta']$ understood
1-loop ChPT + large N_c



KLOE: $A+\alpha$ => $b_\eta = 2.05^{+0.22}_{-0.10}$ GeV^{-2}

EPJC73(13)2668

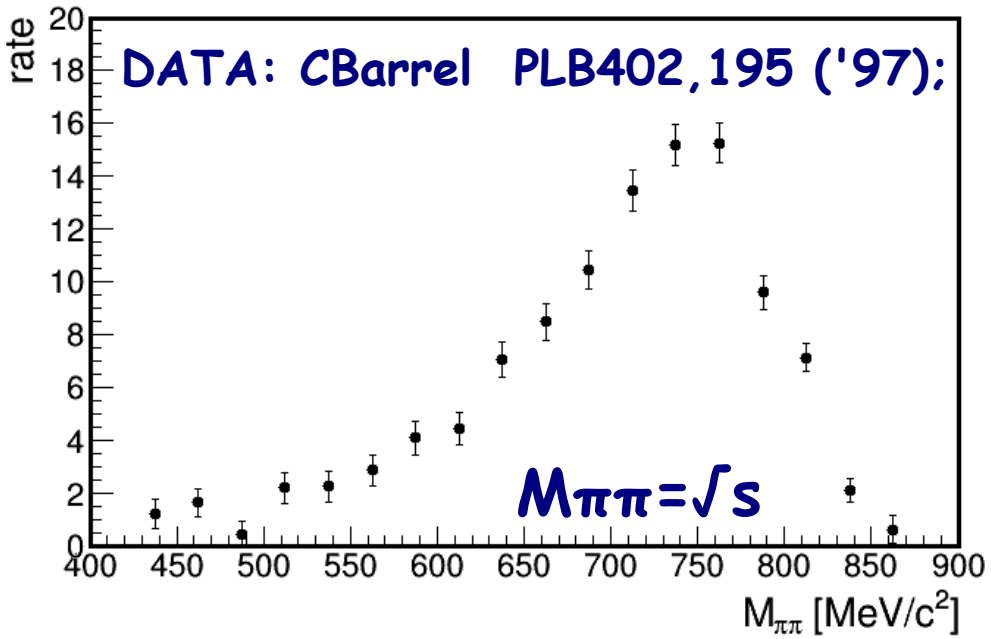
$\eta' \to \pi^+\pi^-\gamma$

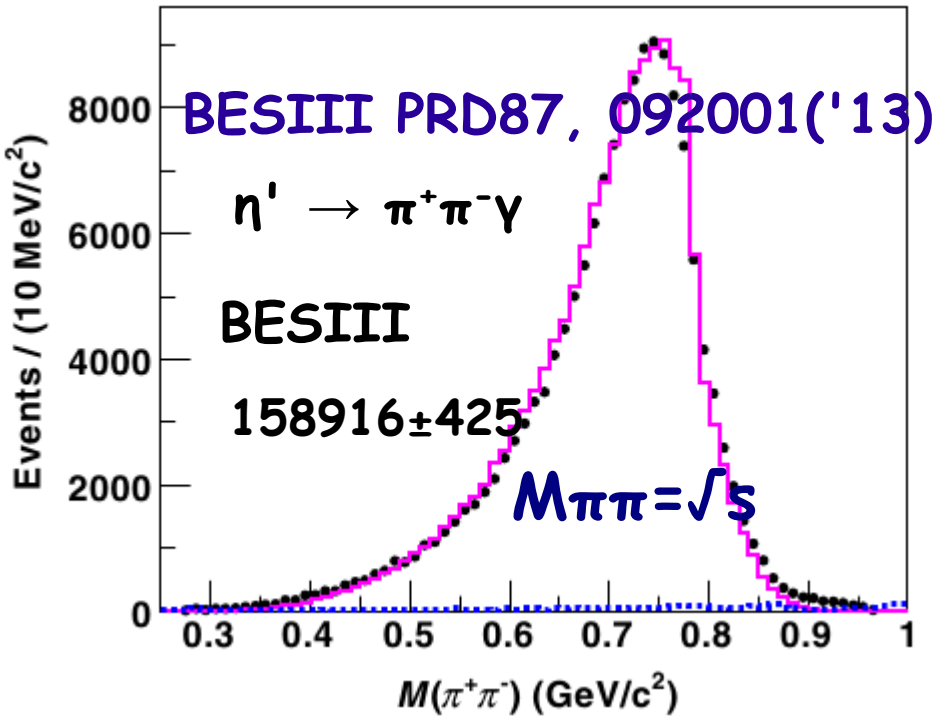


$$P(s_{\pi\pi}) = A_0(1 + \alpha s_{\pi\pi})$$

→ α reaction specific

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





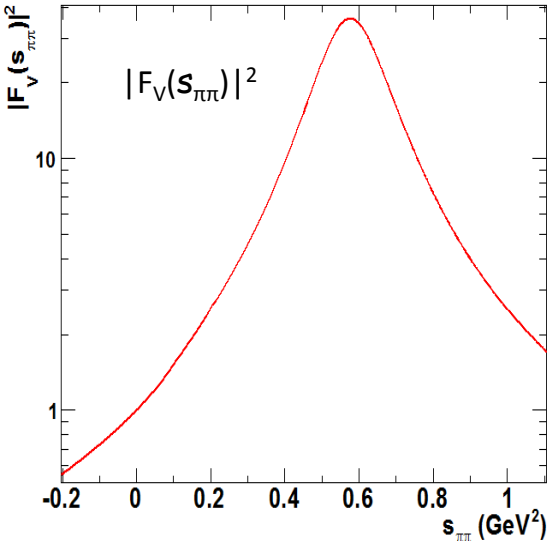
KLOE PL B718, 910 ('13)

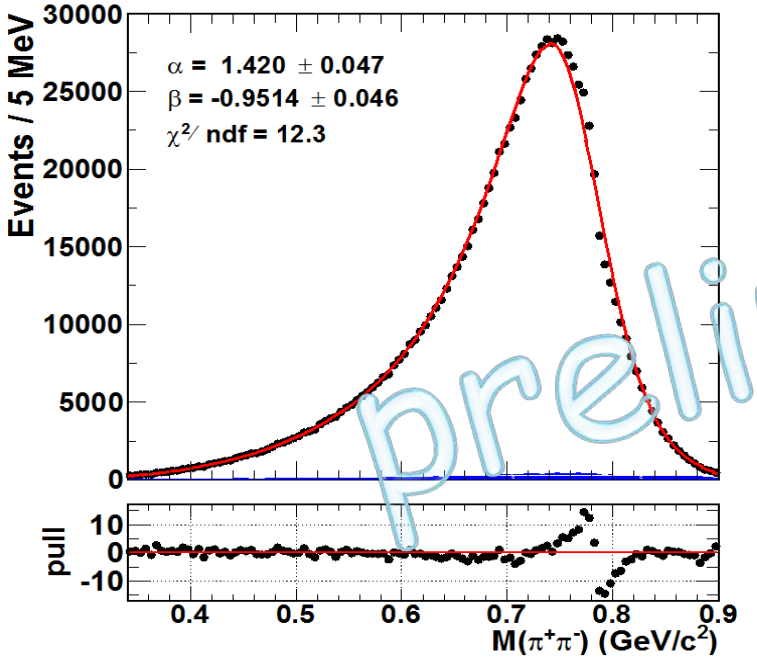
BESIII: Model-independent fit

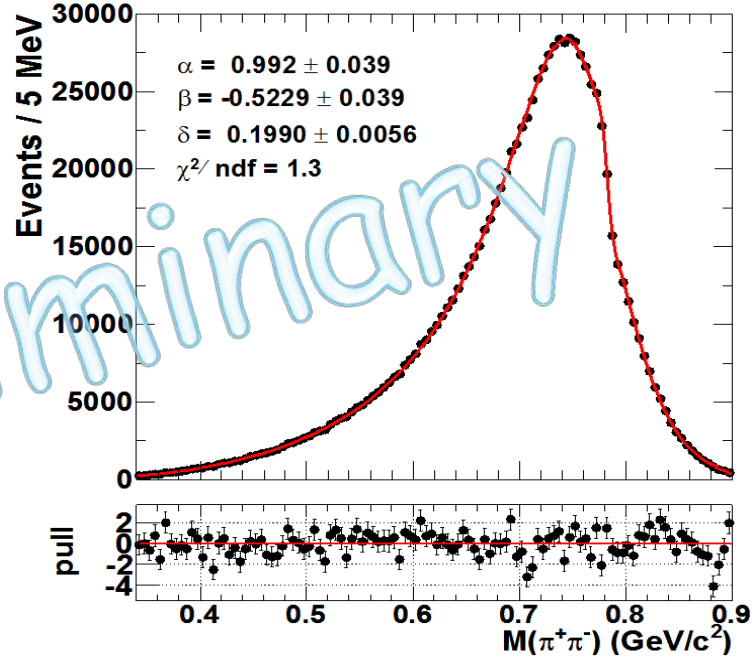
$$\frac{d\Gamma}{ds_{\pi\pi}} = \left|AP(s_{\pi\pi})F_V(s_{\pi\pi})\right|^2 \Gamma_0(s_{\pi\pi})$$

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

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







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

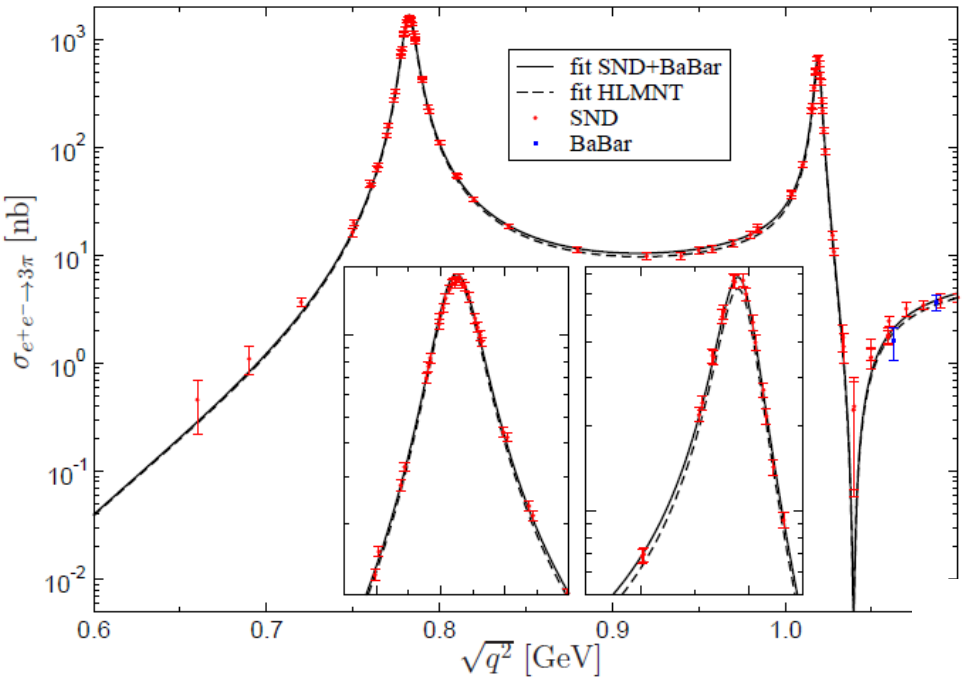
Crystal Barrel: $\alpha = (1.80 \pm 0.49 \pm 0.04)\text{GeV}^{-2}$
$\beta = (0.04 \pm 0.36 \pm 0.03)\text{GeV}^{-4}$

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

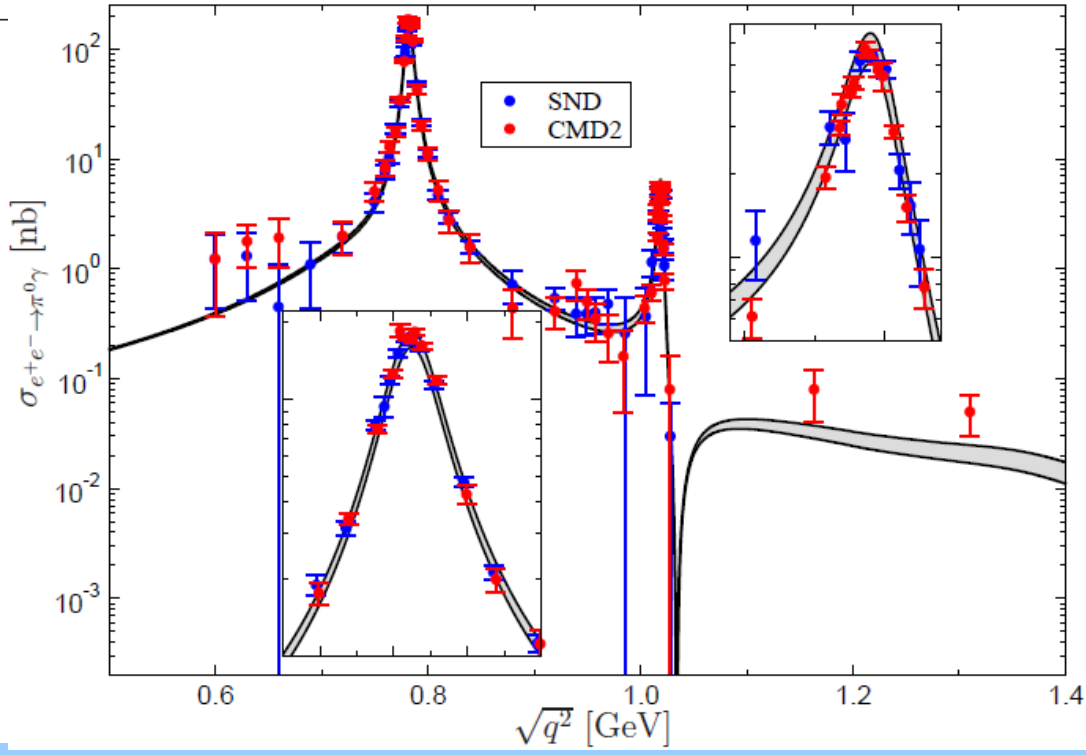
ω contribution is necessary

Linear polynomial is insufficient…

From e+e- → π+π-π⁰ to π⁰ TFF



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



Similar strategy for η
From e+e- → π+π-η to η TFF

arXiv:1509.02194

Summary and outlook

- TFF Neutral meson structure
- Relation to muon (g-2) HLbL
- Relation to HVP: e+e- → hadrons
- Dark photon searches
- P → e+e-
- Tests of SM in π^0, η, η' decays
- Data samples:

KLOE,MAMI,NA62,WASA,HADES,JLAB,

BESIII… ($10^{10}\pi^0$, $10^9\eta$, $10^7\eta'$, $10^{10}\varphi$)