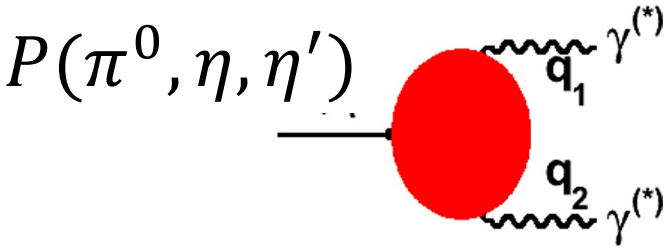
UPPSALA UNIVERSITET

Transition form factors

Andrzej Kupsc

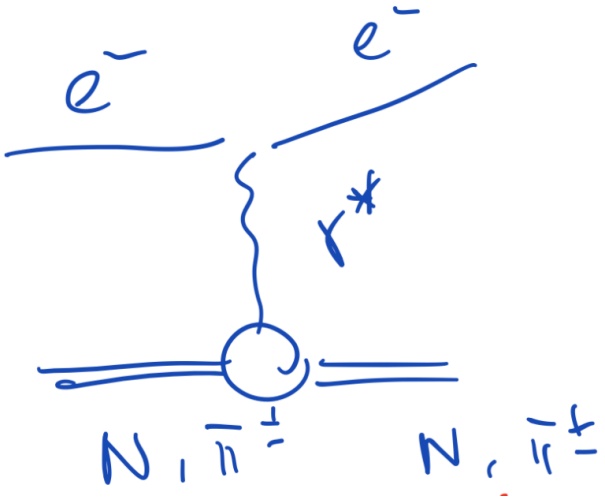
Electromagnetic TFF $\gamma^* M_1 M_2$

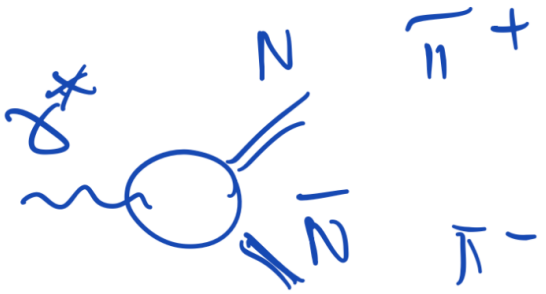


NCBJ ŚWIERK

Electromagnetic Form factors (FFs)

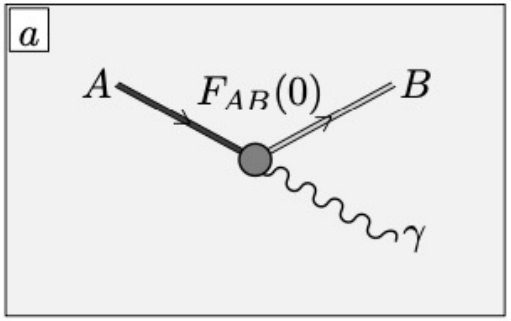
Elastic FFs



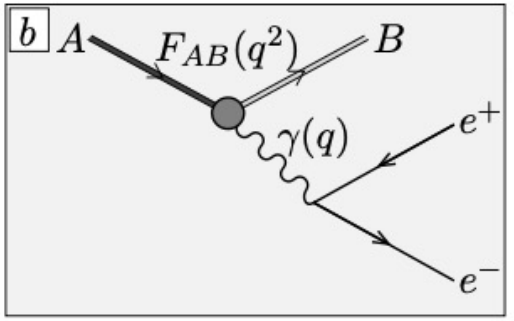


Transition FFs…

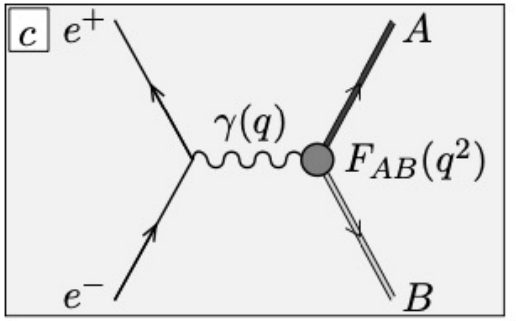
Transition form factors (TFFs)



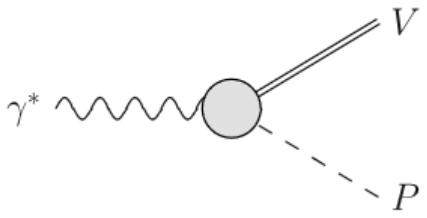
$q^2 = 0$

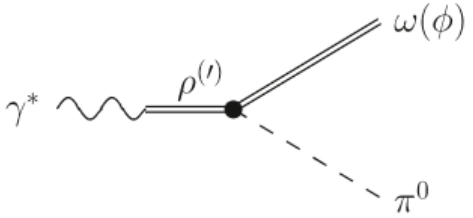


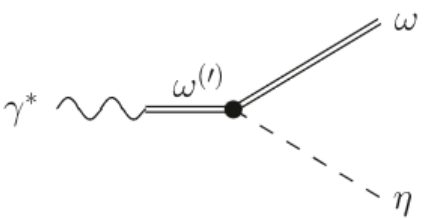
$(2m_e)^2 < q^2 < (M_A - M_B)^2$

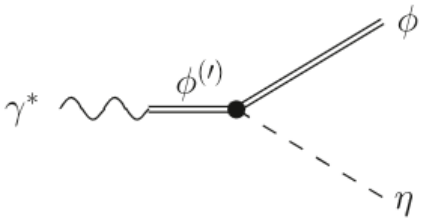


$q^2 > (M_A + M_B)^2$







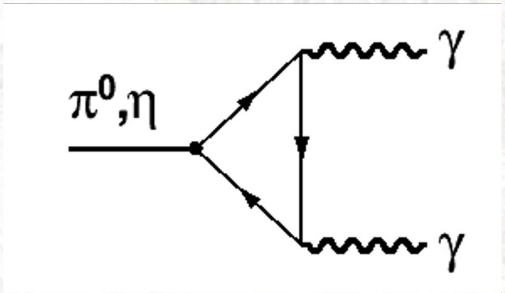


$$\Gamma(V \to P\gamma) = \frac{\alpha}{3} E_\gamma^3 |F_{VP}(0)|^2 , \qquad \Gamma(P \to V\gamma) = \alpha E_\gamma^3 |F_{VP}(0)|^2 ,$$

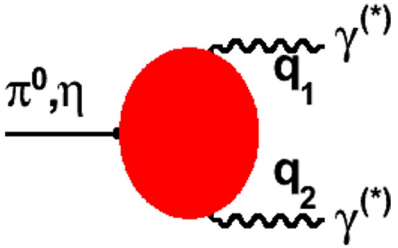
$$\sigma(e^+e^- \to VP) = \frac{4\pi\alpha^2}{3s^{3/2}} |F_{VP}(s)|^2 P_f(s)$$

Landsberg Phys. Rep., 128 (1985) 301
Pacetti Eur.Phys.J.A 38 (2008) 331
Fang, Kubis,AK Prog.Part.Nucl.Phys. 120 (2021) 103884

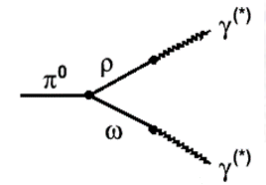
π^0,η,η' Transition Form Factors



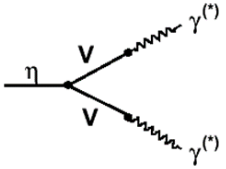
$$\Gamma(P \to \gamma\gamma)$$

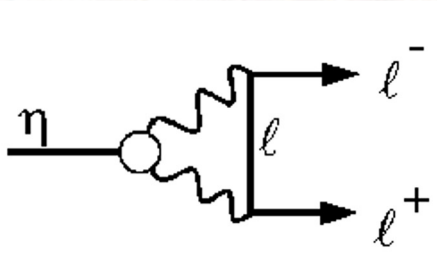


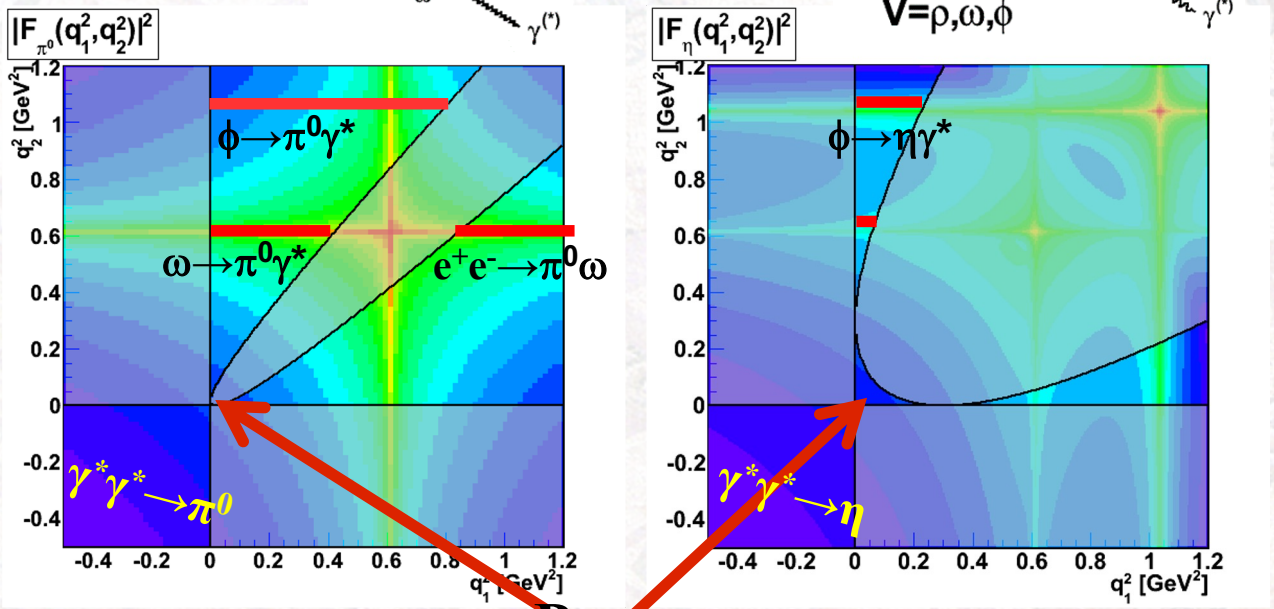
$$F_P(q_1^2, q_2^2)$$

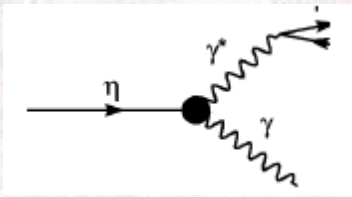


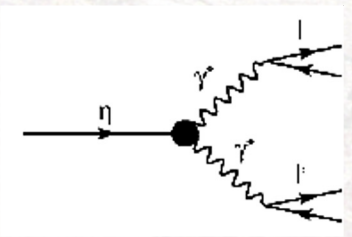
$$\sum_{V=\rho,\omega,\phi}$$











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

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

KLOE-2 Taggers

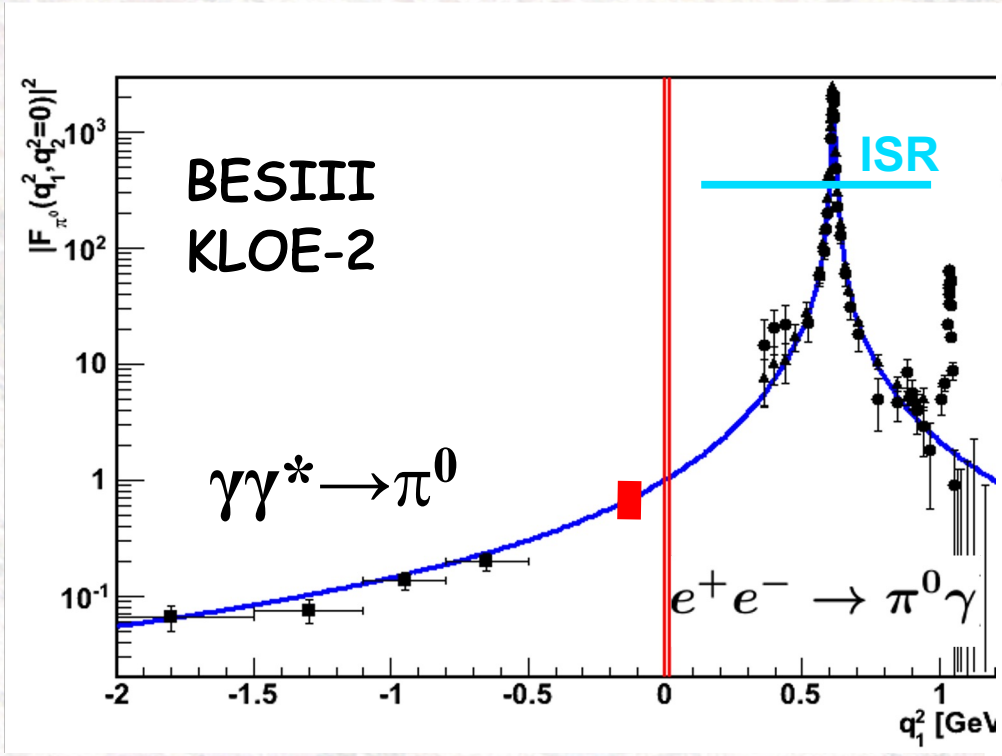
PrimEx(II) PRL 106,162303(2011),
Science 368,506 (2020)

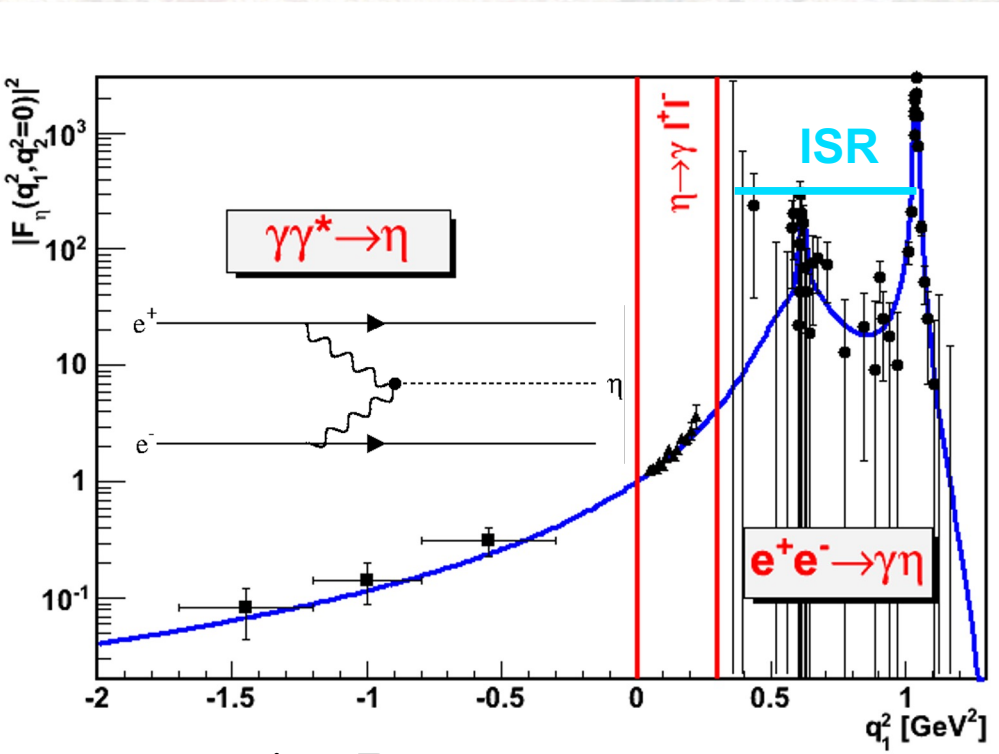
$\Gamma(\pi^0\to\gamma\gamma)$ = 7.802eV ± 0.052 stat. ± 0.105 syst.

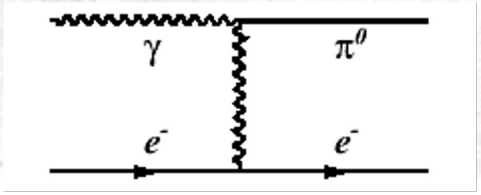
$$\Gamma(\pi^0 \to \gamma\gamma) = 7.11 \pm 0.44_{\rm stat} \pm 0.21_{\rm syst}\ {\rm eV}$$
$$\Gamma(\eta \to \gamma\gamma) = 338 \pm 94_{\rm stat} \pm 35_{\rm syst}\ {\rm eV}$$
$$\Gamma(\eta' \to \gamma\gamma) = 3.4 \pm 1.0_{\rm stat} \pm 0.4_{\rm syst}\ {\rm keV}\,.$$

→LQCD: 2305.04570

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

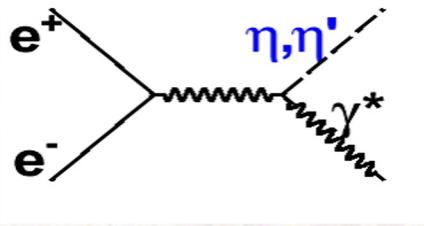
$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{s m_P}\right)^3$$

$P \to \gamma^*\gamma$

Dalitz decays:

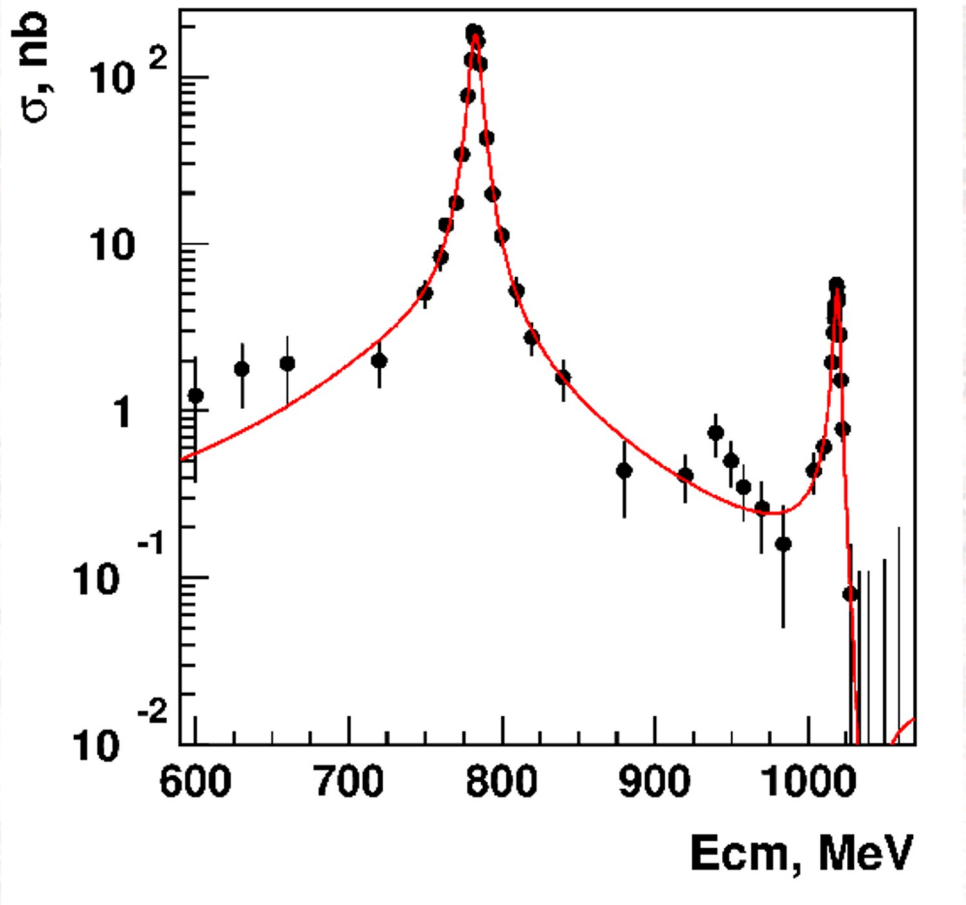
KLOE, WASA,CBall,BESIII

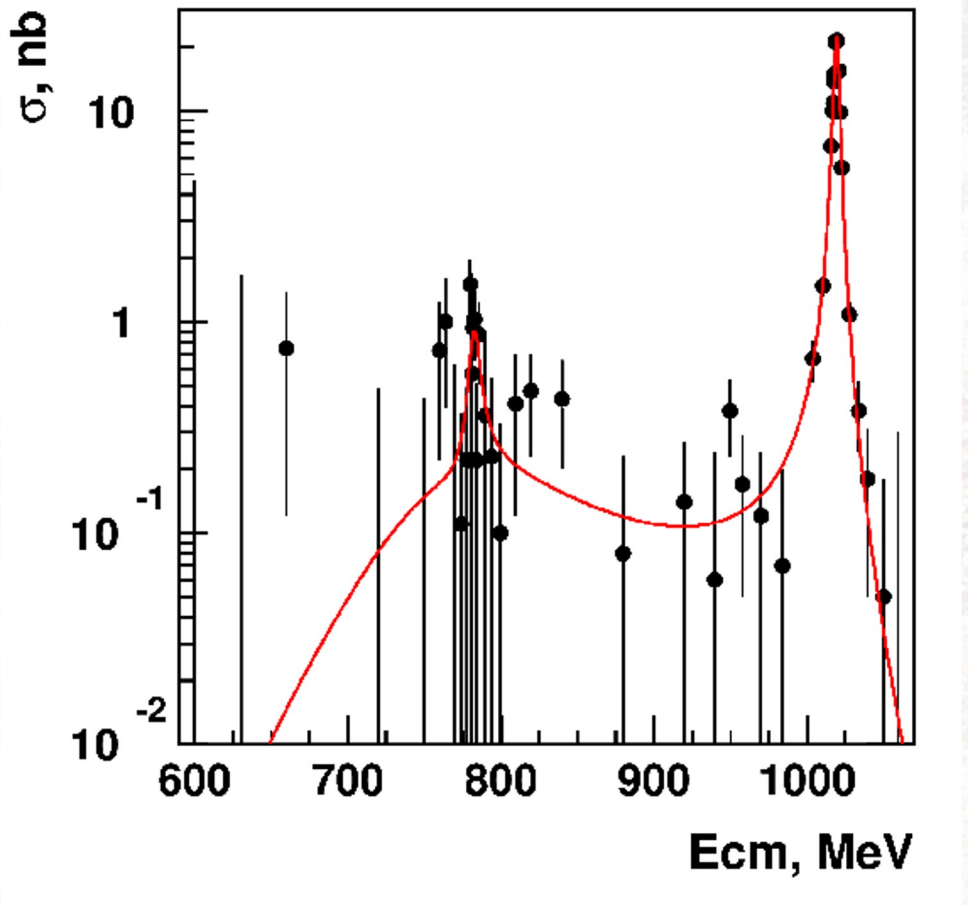
CLAS,NA48

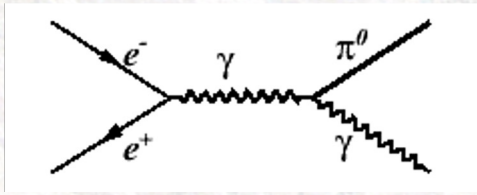


Data:CELLO,NA60,CB-MAMI,CMD-2,SND

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



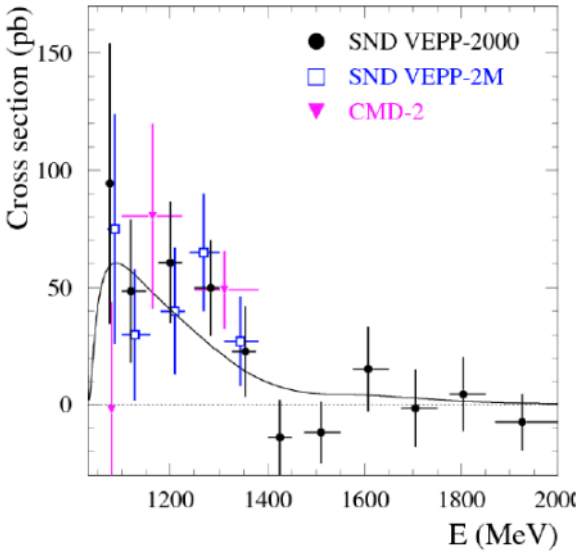




$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

Data: CMD-2,SND

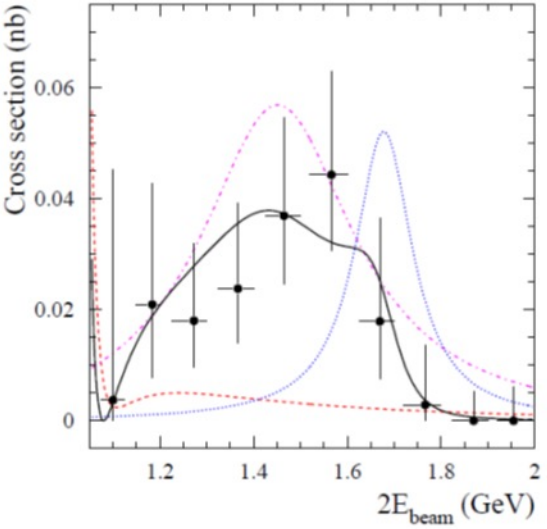
$e^+e^- \to \pi^0\gamma$ at SND



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

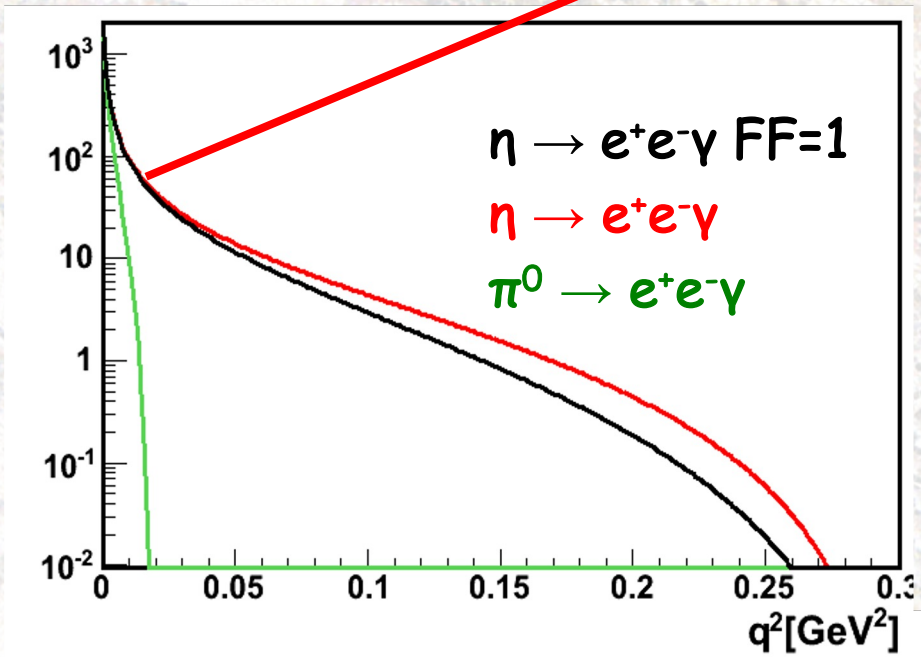
Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

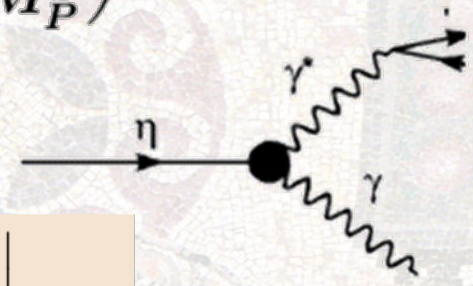
Slide from Simon Eidelman

Dalitz decays

Single Dalitz decays

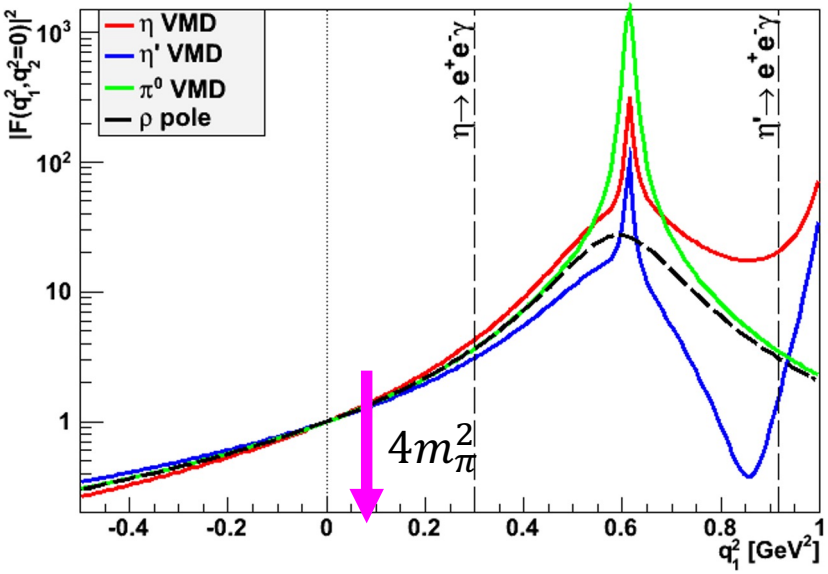
$$\frac{d\Gamma(P \to \ell^+\ell^-\gamma)}{dq^2\Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_\ell^2}{q^2}}\left(1+\frac{2m_\ell^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$

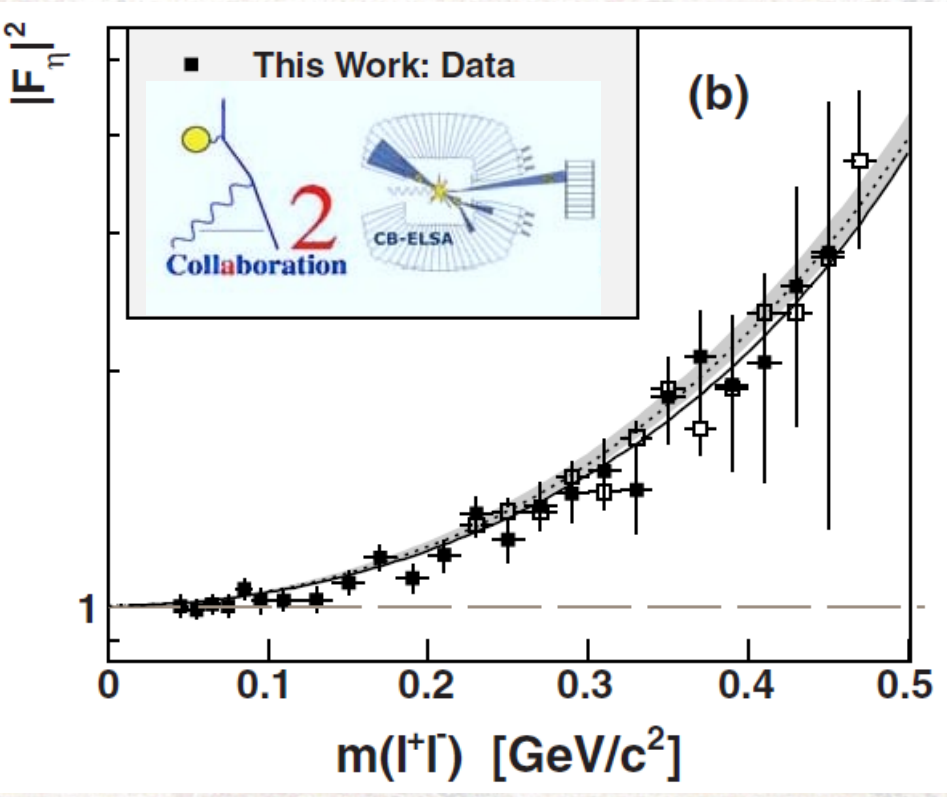




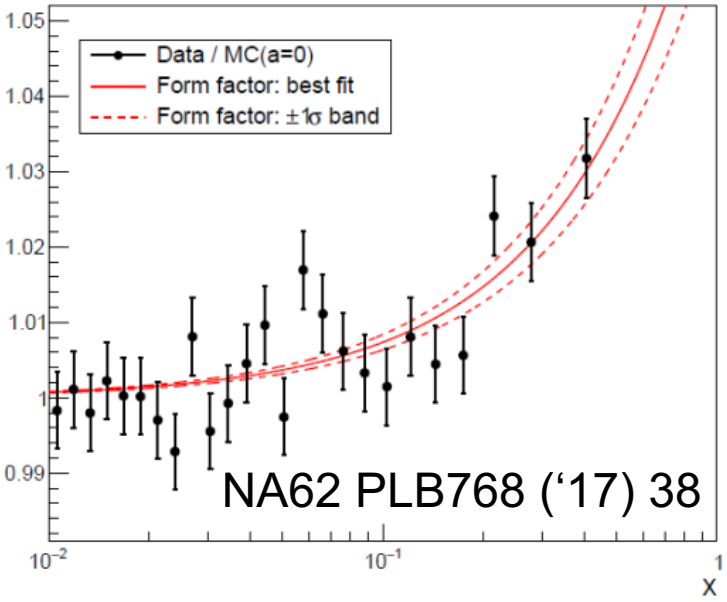
$$b_P = \left.\frac{d\ln|F_P(q^2)|}{dq^2}\right|_{q^2=0}$$

CB/TAPS: PRC89, 044608 (2014)





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



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

A2 PRC 95 ('17) 025202

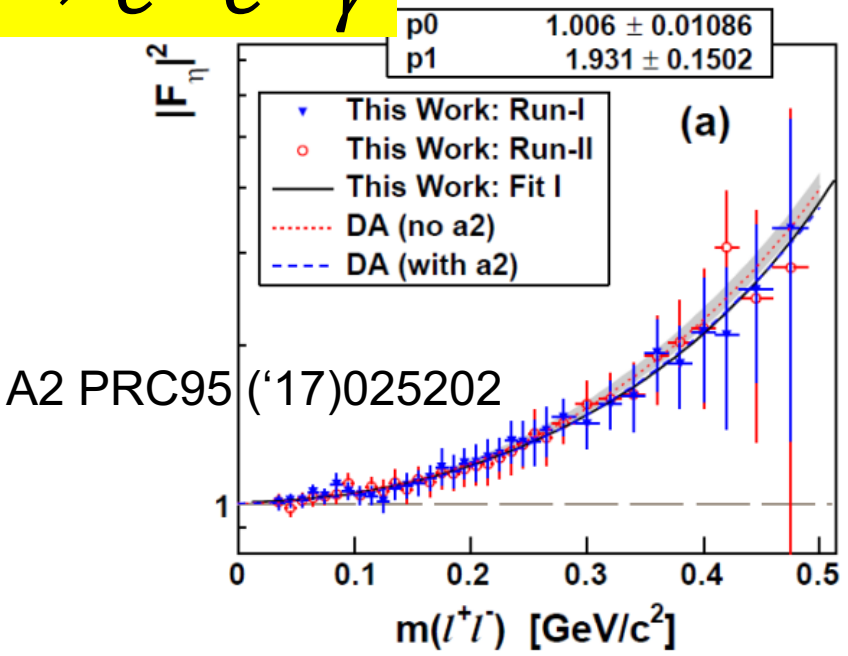
$a_\pi=(3.0 \pm 1.0)\times10^{-2}$

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

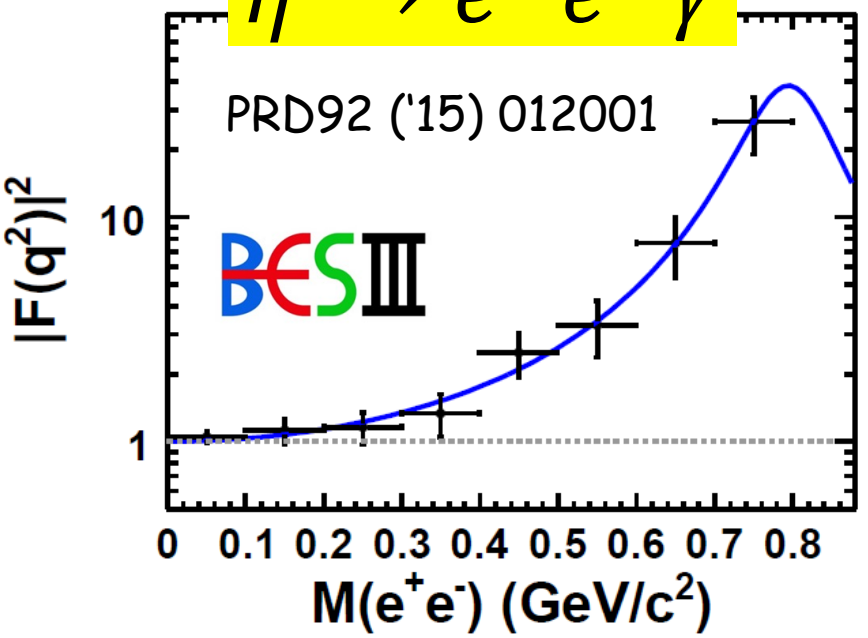
DR: $a_\pi=(3.15 \pm 0.09)\times10^{-2}$ *JHEP* 10 (2018) 141

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

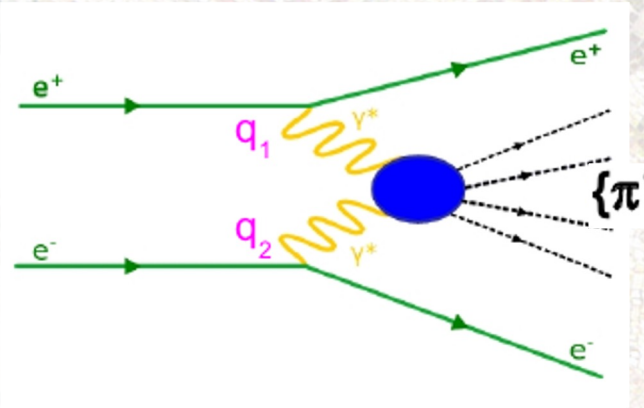
$\eta \to e^+e^-\gamma$



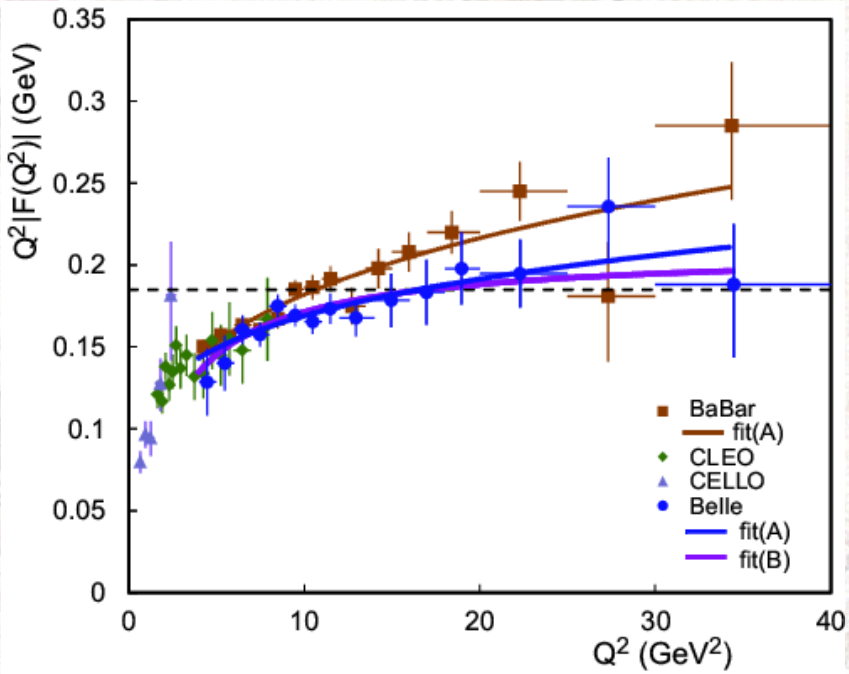
$\eta' \to e^+e^-\gamma$



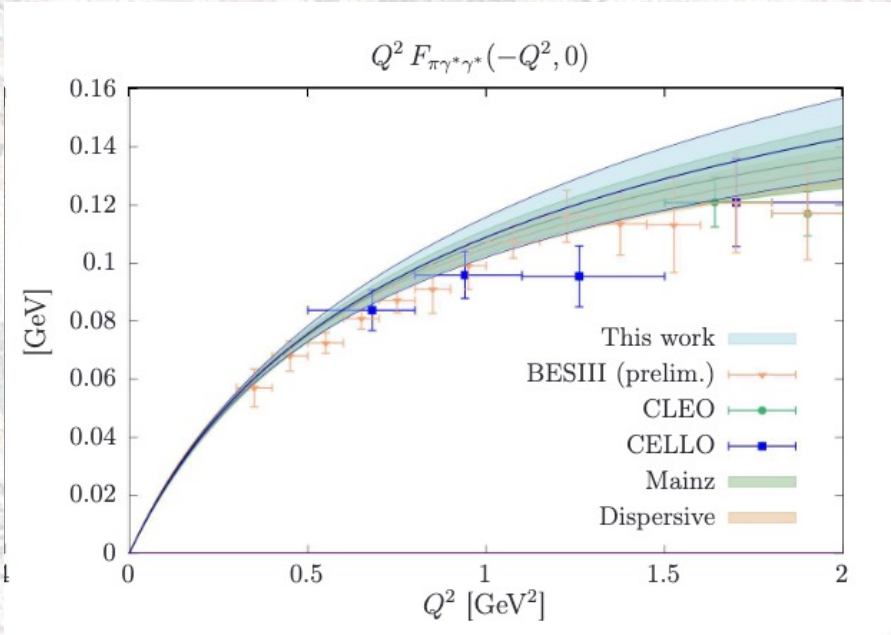
$\gamma\gamma^* \to \pi^0$



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

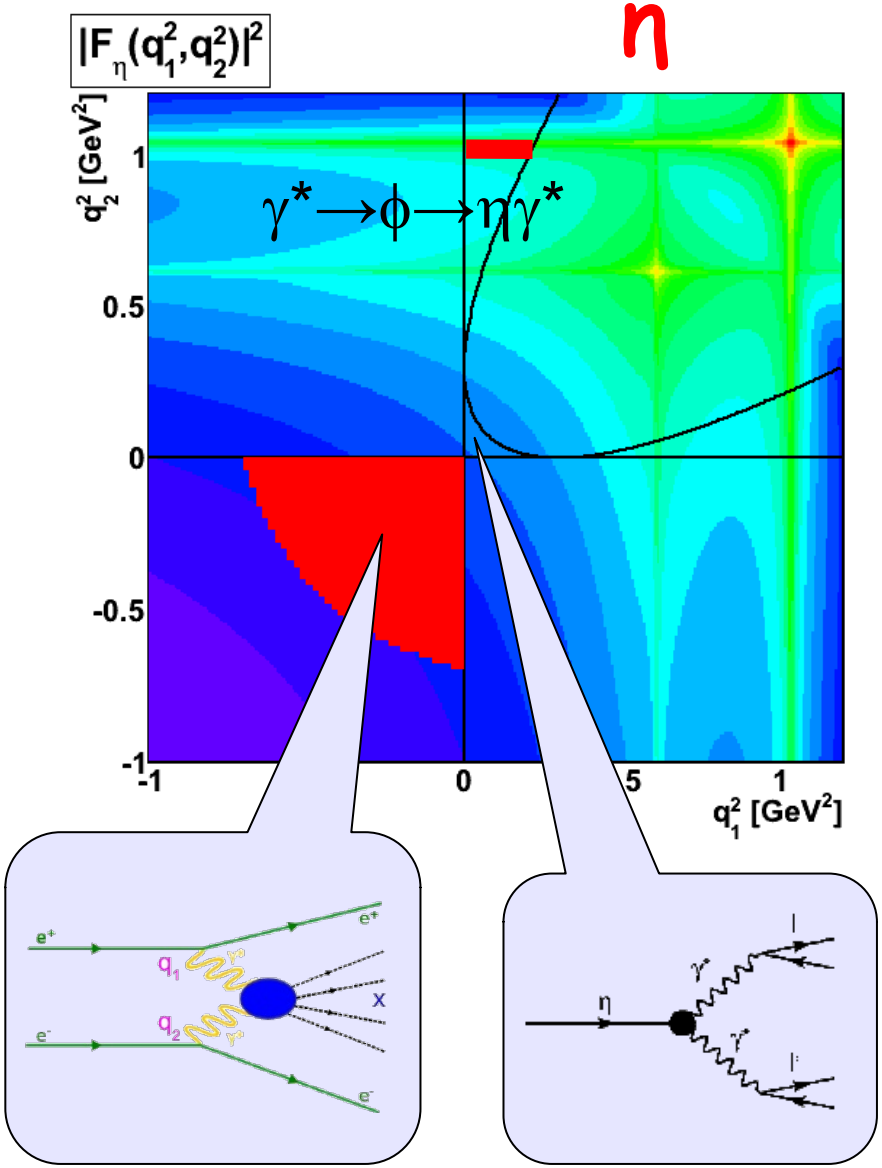


→ Antoine LQCD talk

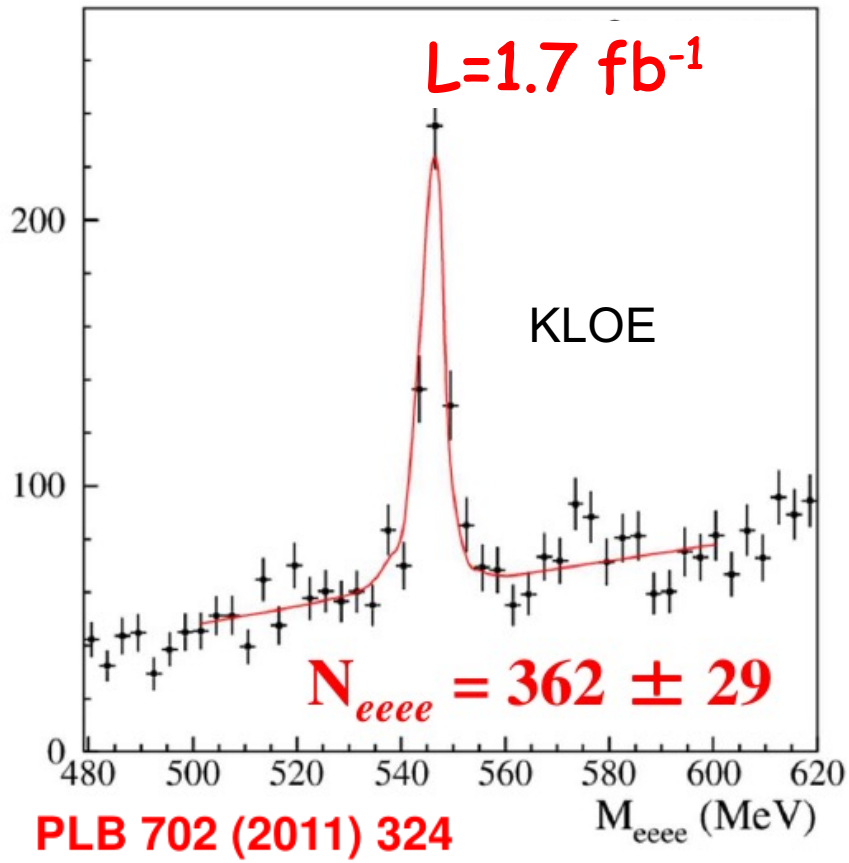


Lattice calculation of the π0, η and η′ transition form factors 2305.04570

Double off shell TFF



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



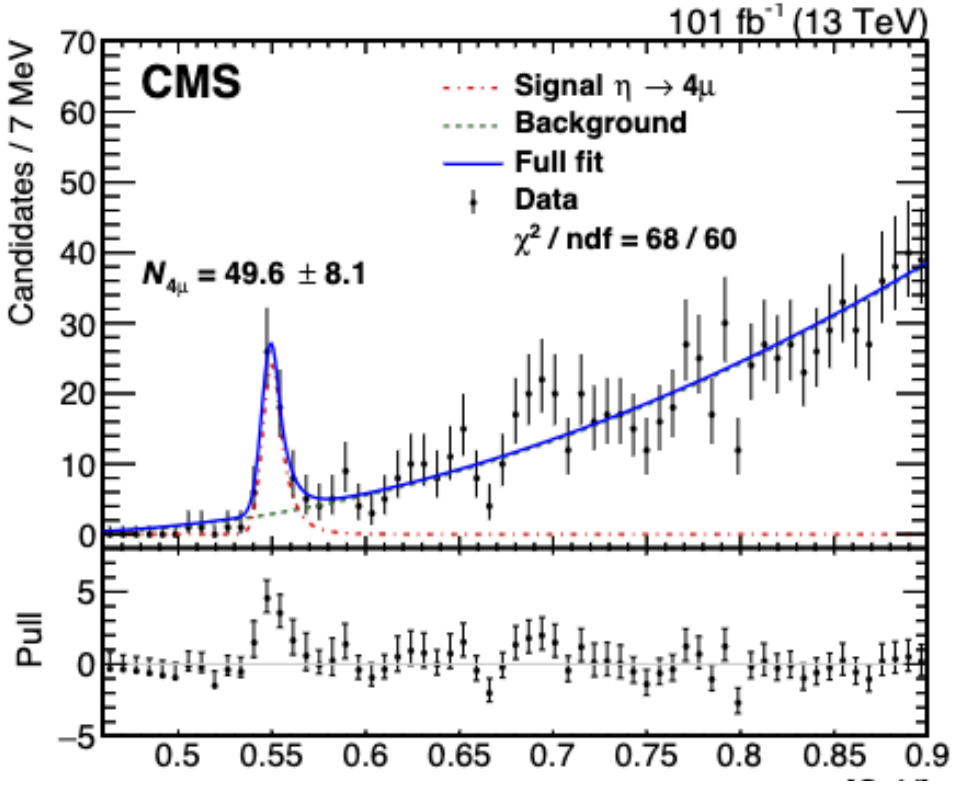
$BR(\eta\to e^+e^-e^+e^-(\gamma))= (2.4 \pm 0.2_{stat} \pm 0.1_{syst}) \times 10^{-5}$

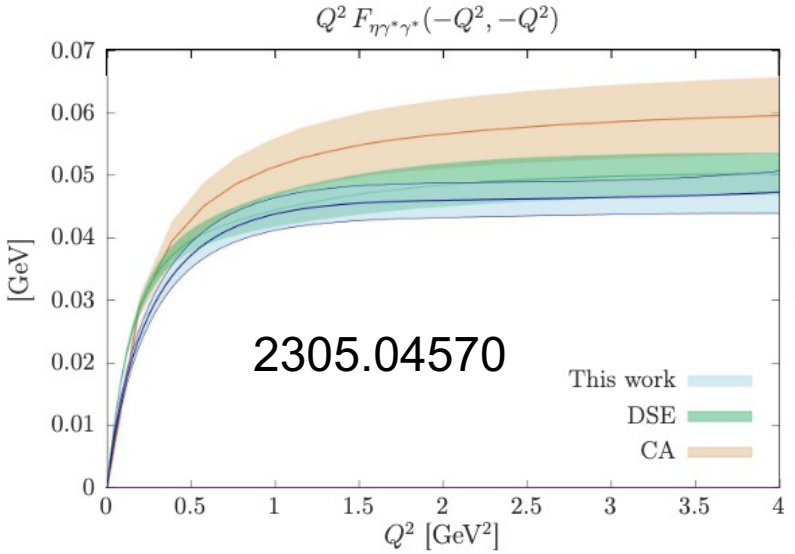
Shuangshi BESIII talk

BESIII, PRD 105 (2022) 112010

$$\mathcal{B}(\eta' \to e^+e^-e^+e^-) = (4.5 \pm 1.0(\text{stat.}) \pm 0.5(\text{sys.})) \times 10^{-6}$$

$\eta \to \mu^+\mu^-\mu^+\mu^-$





$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.86 \pm 0.14\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-3}$$

CMS arXiv:2305.04904

$\Gamma(\eta \to \mu^+\mu^-\mu^+\mu^-)/\Gamma_{\gamma\gamma}(10^{-9})$	FF=1 6.511	mVMD 9.7(1)
$\Gamma(\eta \to \mu^+\mu^-)/\Gamma_{\gamma\gamma}(10^{-6})$	mVMD 13(1)	Exp. 15(2)

T.Petri arxiv:1010.2378

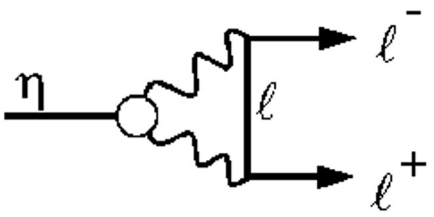
$e^+e^- \to \eta, \eta', f_1 \ldots (C-\text{even})$

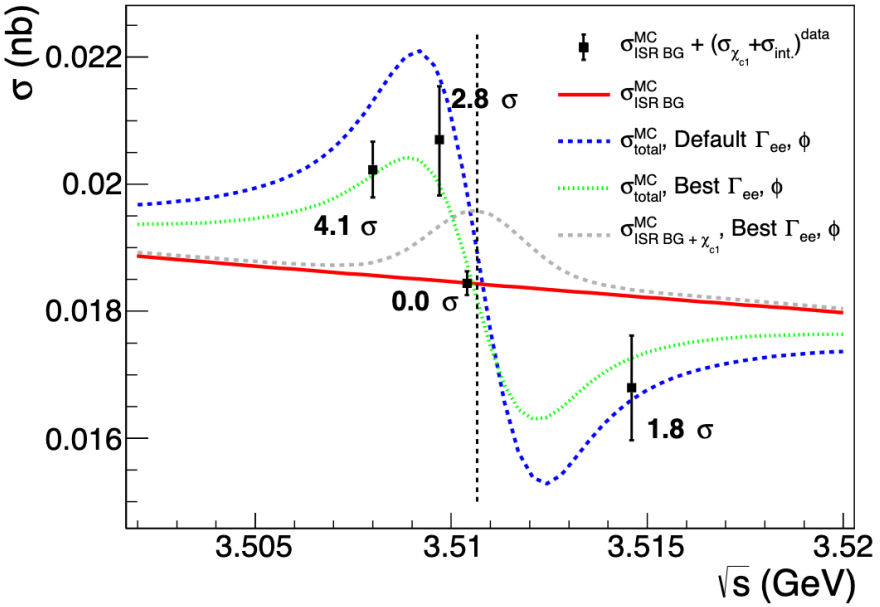
CMD-3 Phys.Lett.B 740 (2015) 273
SND, Phys.Rev.D 91 (2015) 092010

$B(\eta' \to e^+e^-) < 5.6\times10^{-9}$ 90% CL

SND Phys.Rev.D 98 (2018) 5, 052007

$B(\eta \to e^+e^-) < 7.7\times10^{-7}$ 90% CL

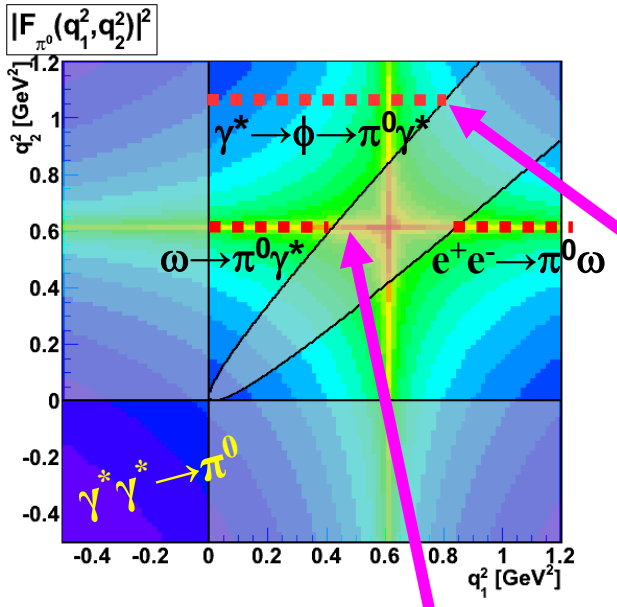


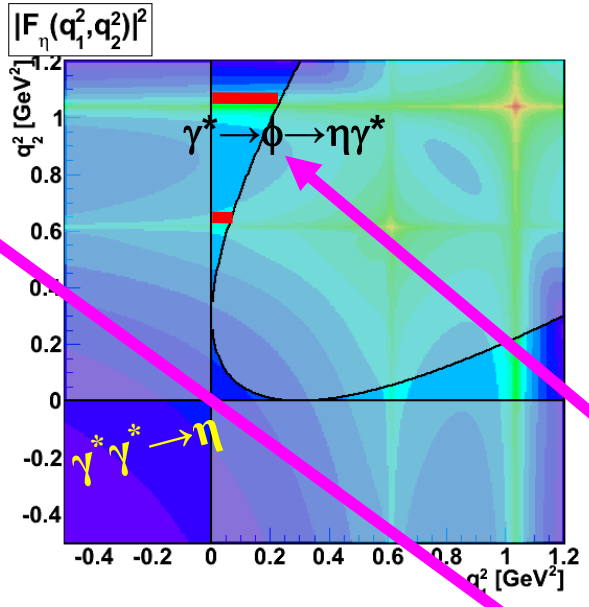


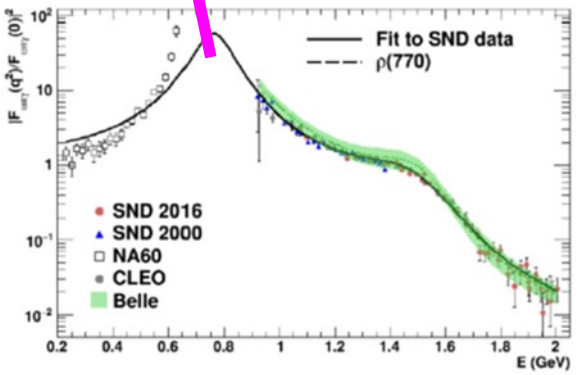
BESIII Phys.Rev.Lett. 129 (2022) 12

Interference $e^+e^- \to J/\psi\,\gamma \to \gamma\mu^+\mu^-$ *and* $e^+e^- \to \chi_{c1}$

$V \to P\gamma^*$ and $e^+e^- \to PV$ 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

$$F_{\omega\pi}(s) = \frac{g_{\rho\omega\pi}}{g_\rho}\left(\mathrm{BW}_\rho^{GS}(s) + c_1\mathrm{BW}_{\rho'}(s) + c_2\mathrm{BW}_{\rho''}(s) + \cdots\right)$$

from Simon Eidelman

KLOE

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

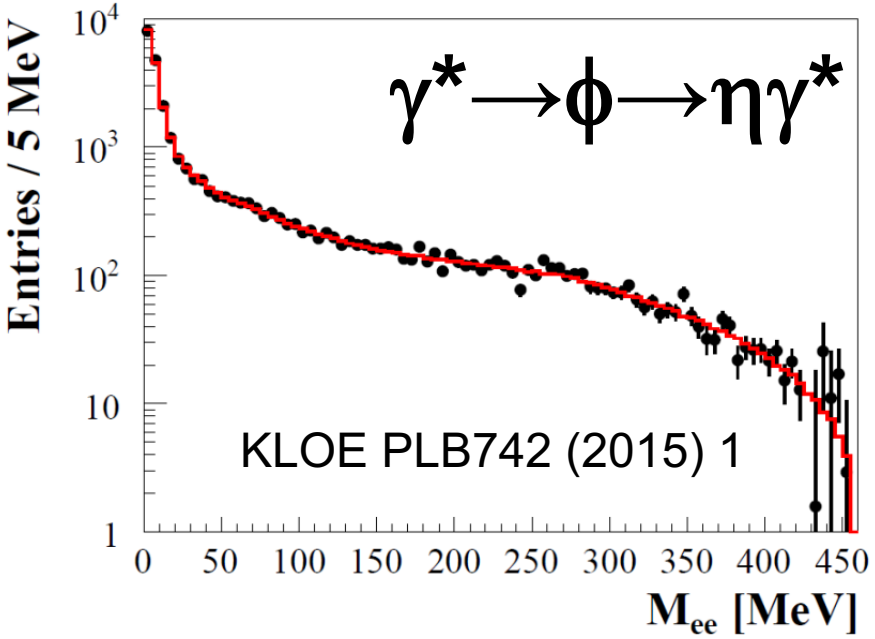
Phys.Lett. B742 (2015) 1-6

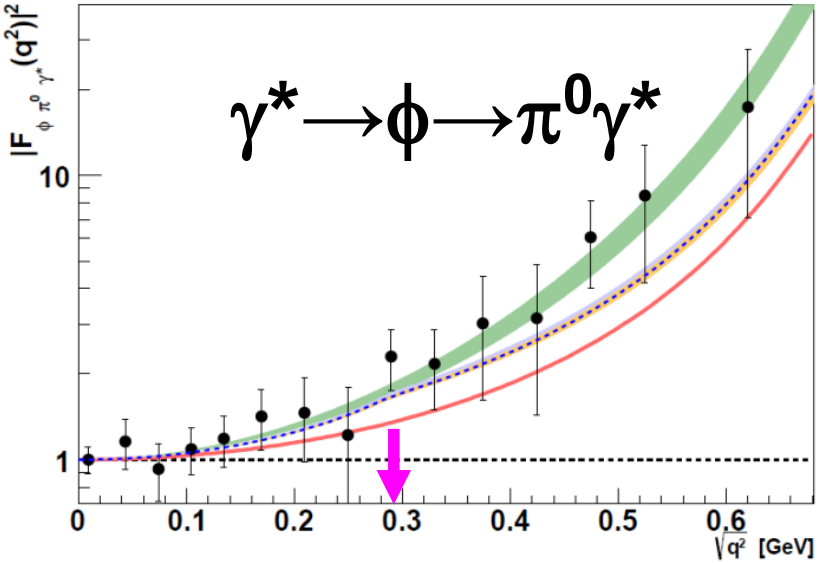
$b_{\varphi\eta} = (1.17 \pm 0.10^{+0.07}_{-0.11})\,\mathrm{GeV}^{-2}$

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

Phys.Lett. B757 (2016) 362-367

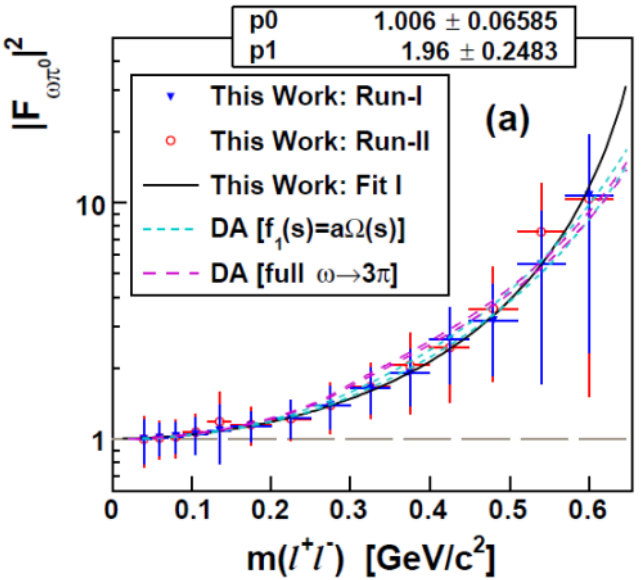
$b\varphi\pi^0 = (2.02\pm0.11)\ \mathrm{GeV}^{-2}$





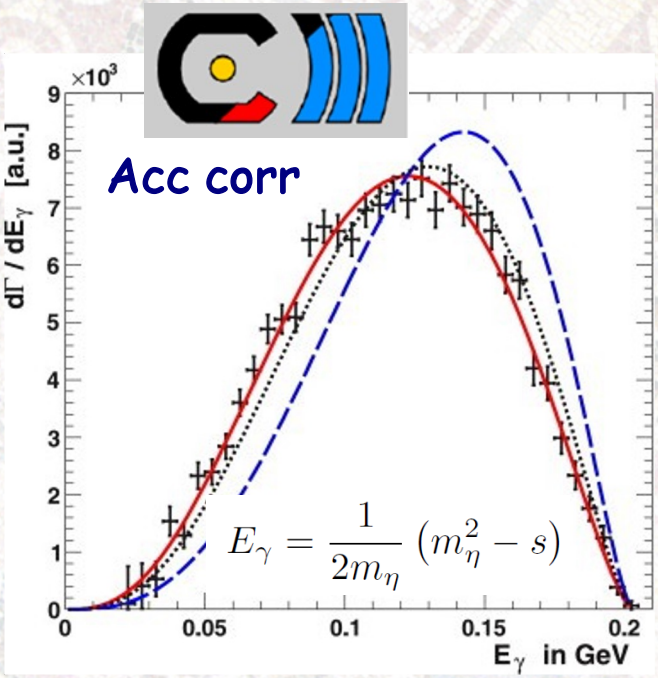
KLOE PLB757 (2016) 362

γ*→ π⁰ω

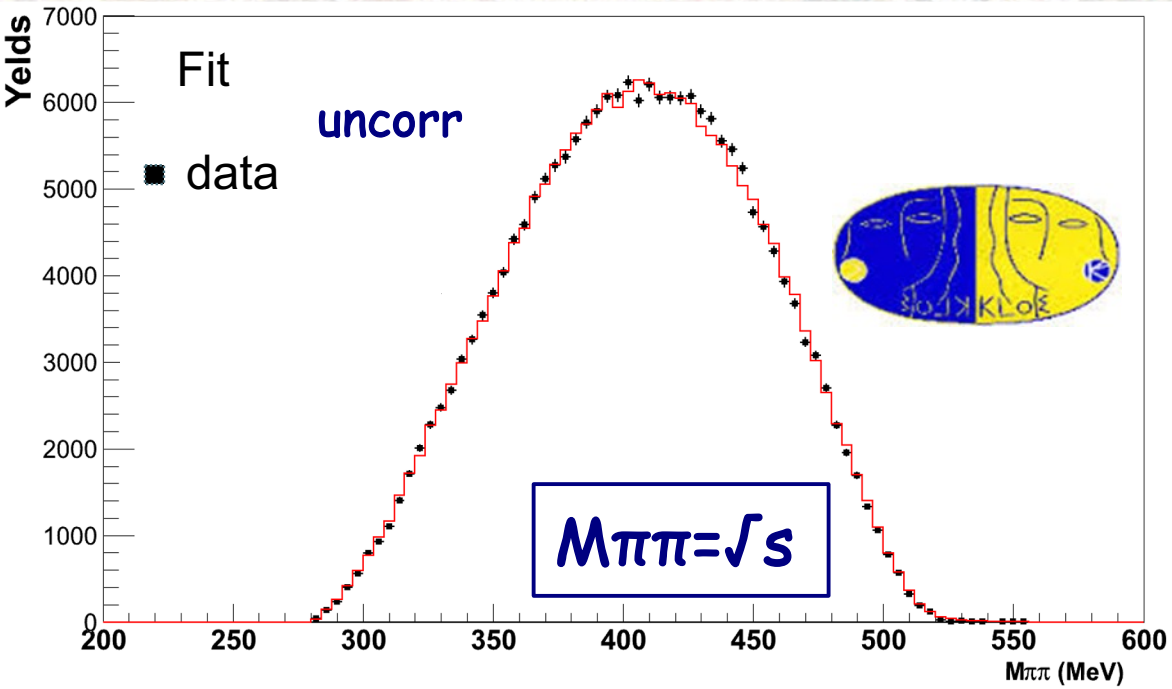


A2 Phys.Rev. C95 (2017) 025202

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



WASA PLB707 (2012) 243



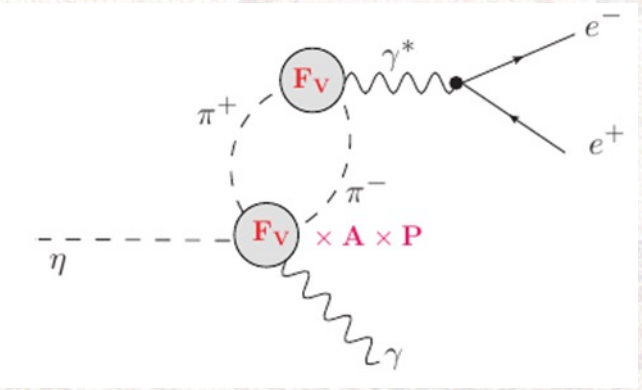
KLOE PLB718 (2013) 910

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}

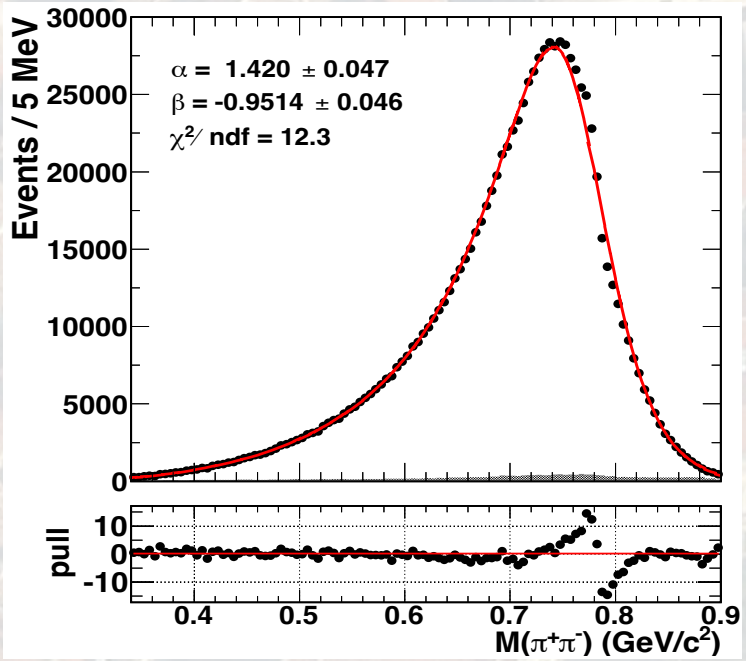
$a=1.31\pm0.08_{stat}\pm0.40_{syst}$ GeV^{-2}

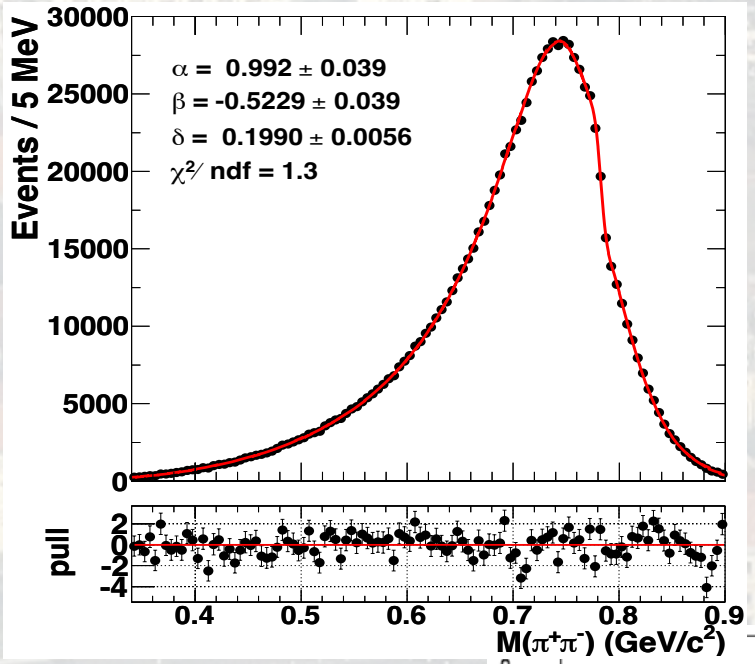
Analysis based on 0.9 x 10^6 $\eta' \to \pi^+\pi^-\gamma$

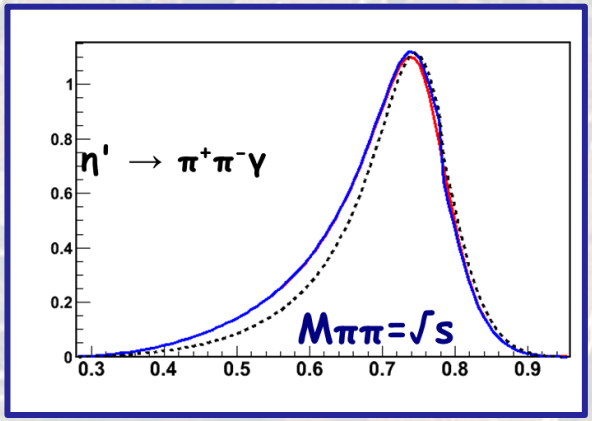
$$\frac{d\Gamma}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2 \Gamma_0(s_{\pi\pi})$$

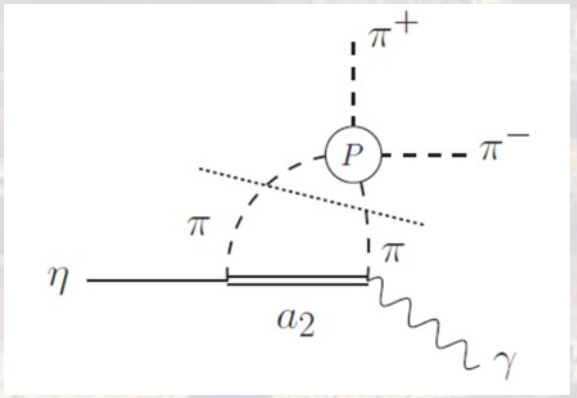
$P(s_{\pi\pi}) = 1 + \alpha\, s_{\pi\pi} + \beta\, s^2_{\pi\pi}$

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





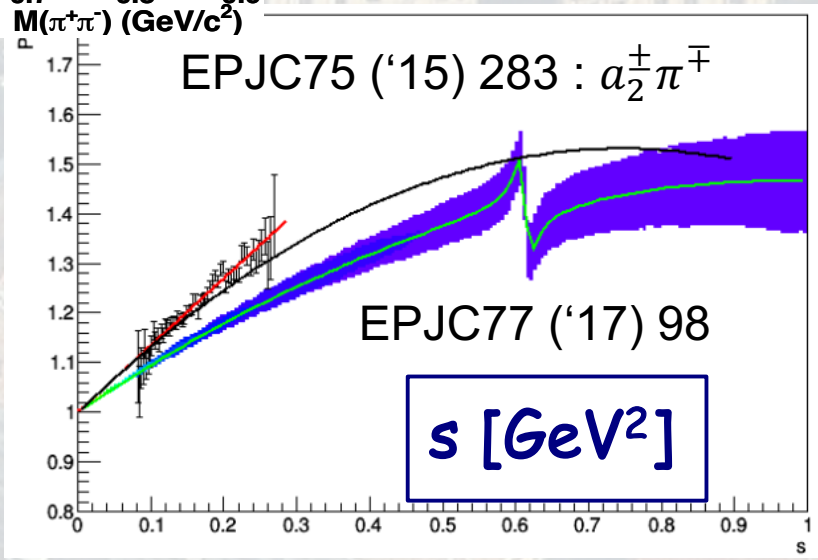




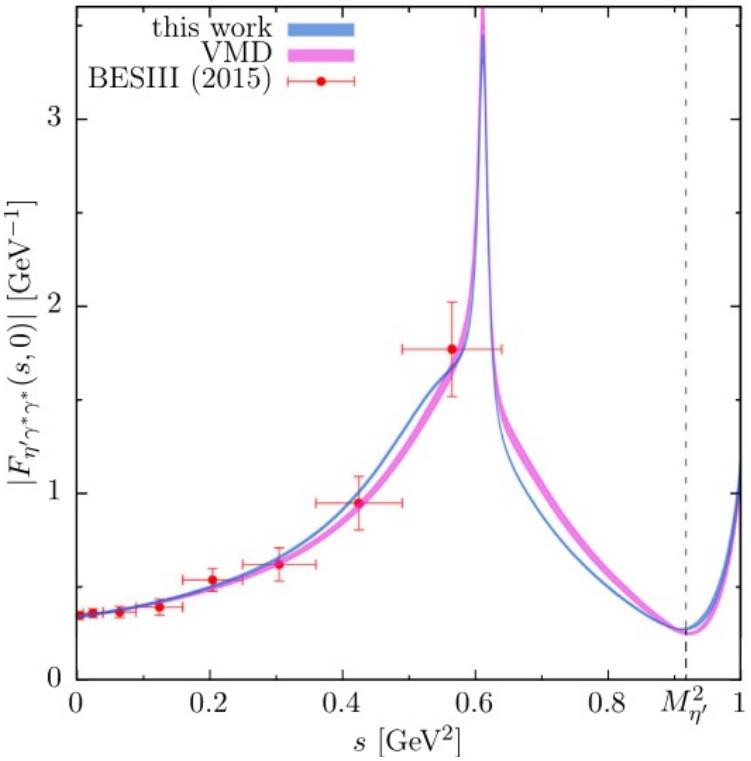
ω contribution necessary

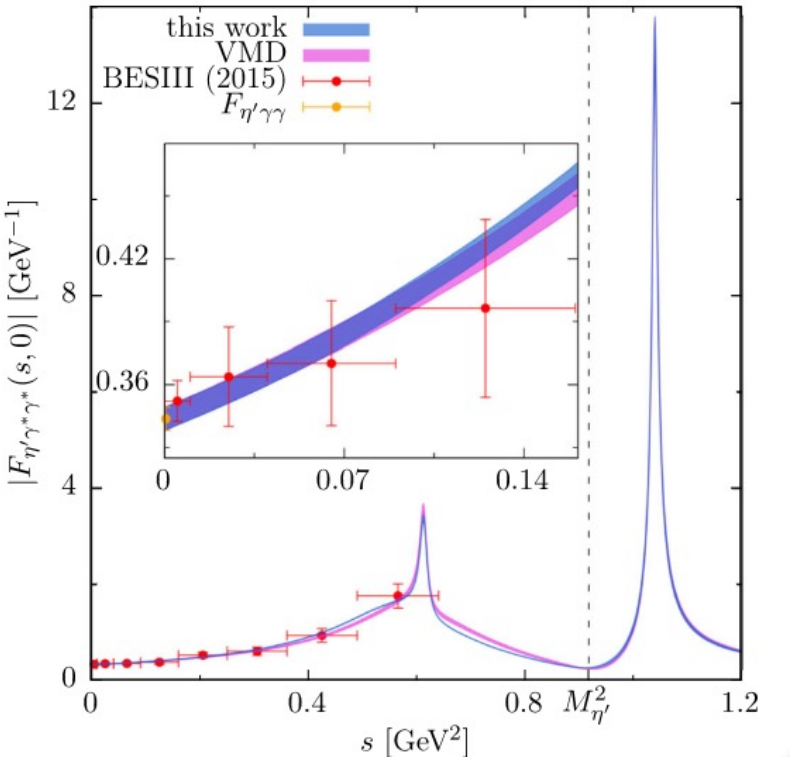
Linear polynomial is insufficient...

Phys.Rev.Lett. 120 (2018) 242003



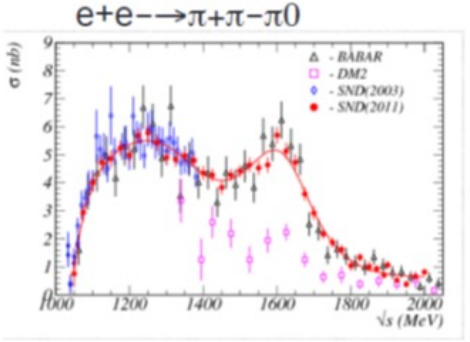
$\eta' \to e^+e^-\gamma$



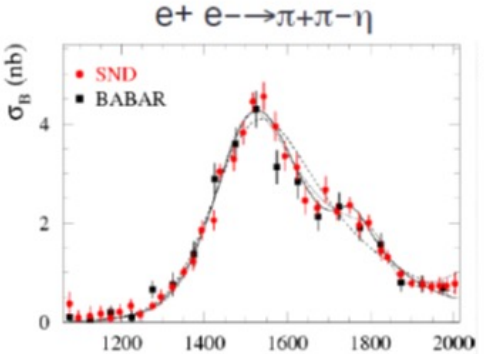


→Simon talk Eur. Phys. J. C (2022) 82:434

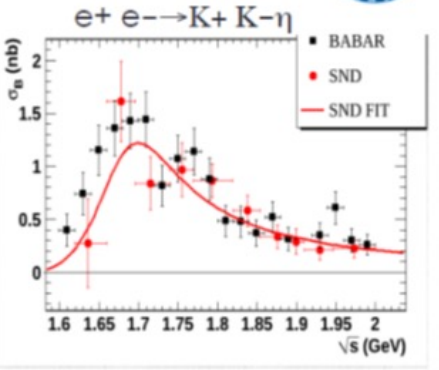
Some SND results overview



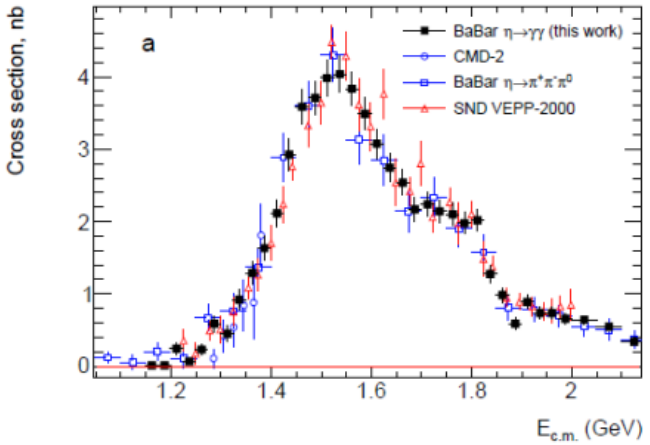
J.Exp.Theor.Phys. 121 (2015) 1.

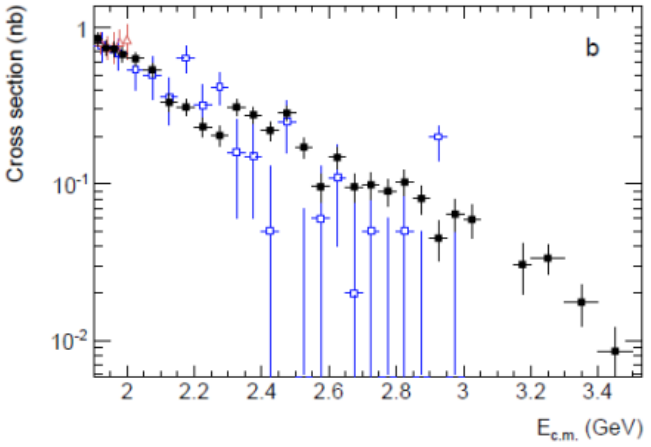


Phys. Rev. D 91, 052013 (2015)



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



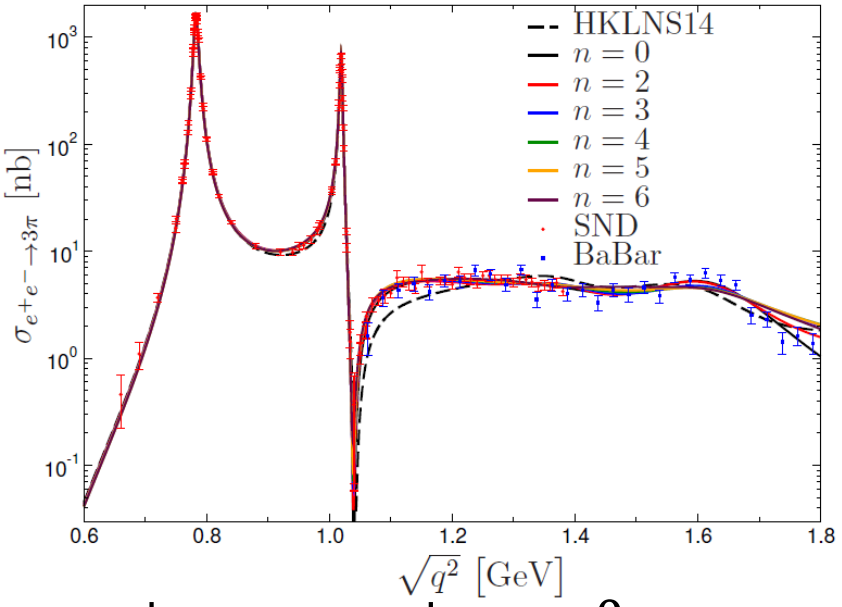


More precise result ⇒ first observation of the $\rho(1700)$ in $\eta\pi^+\pi^-$

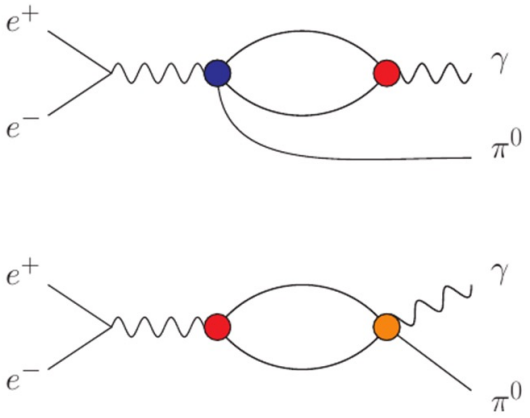
J.P. Lees et al., Phys. Rev. D97 (2018) 052007

Slide from Simon Eidelman

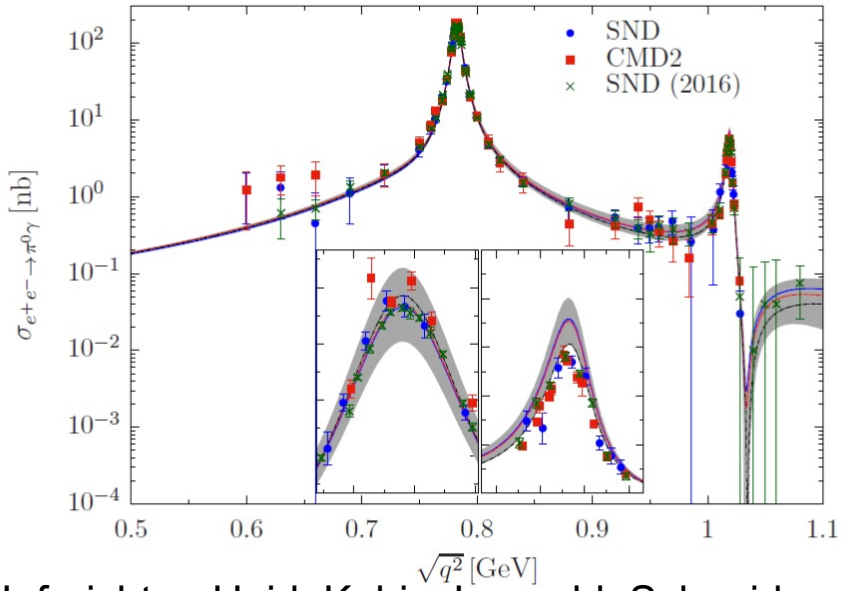
DR for π^0 TFF



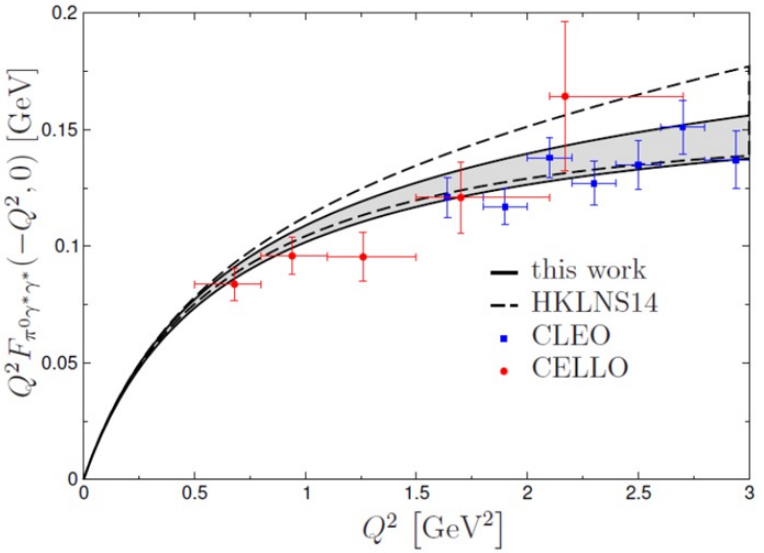
$e^+e^- \to \pi^+\pi^-\pi^0$



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



Hoferichter, Hoid, Kubis, Leupold, Schneider
JHEP 10 (2018) 141



Electromagnetic TFF

Dispersive/ChPT calculations:

Exp input: $\Gamma(P \to \gamma\gamma)$, hadronic and single ratiative processes

Exp double (virtual)radiative processes less precise
and exp is mainly used for crosscheck

except (maybe) CMS with $> 10^{11}$ η

Lattice: Precision results

Relation to weak TFF…