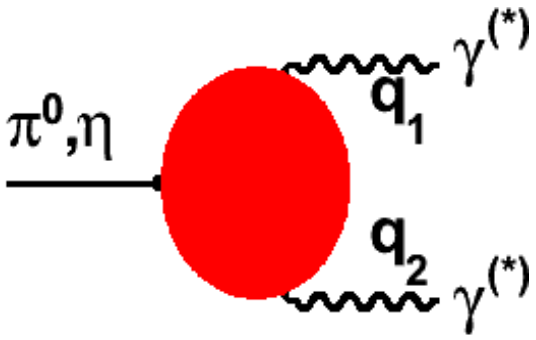
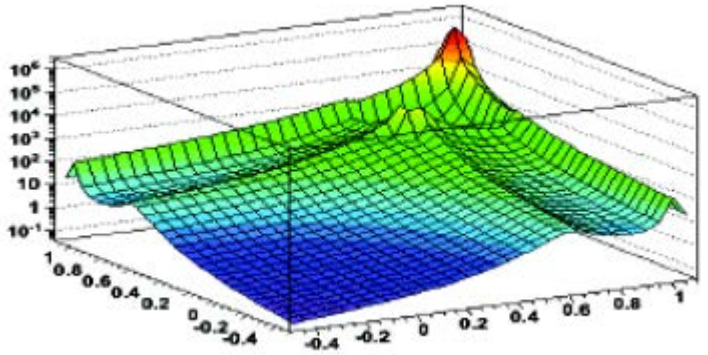
Transition form factors of light mesons





Andrzej Kupsc

Uppsala University

UPPSALA UNIVERSITET

JLab, April 17th, 2015

Outline

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

Transition Form Factors

- → relation anomalous magnetic moment of the muon
- Radiative decay width $\Gamma_{\gamma\gamma}$
- Dalitz Decays
- Dark photon searches
- Two photon production of pseudoscalar mesons
- Radiative decays $\eta, \eta' \rightarrow \pi^+\pi^-\gamma$ $\eta, \eta' \rightarrow \pi^0\gamma\gamma$
- Anomalous processes

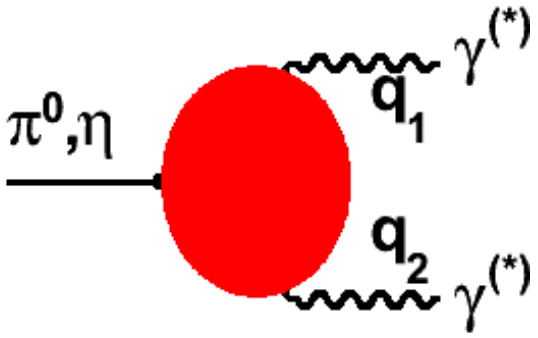
Meson Transition Form Factors (TFF)

Structure of light mesons

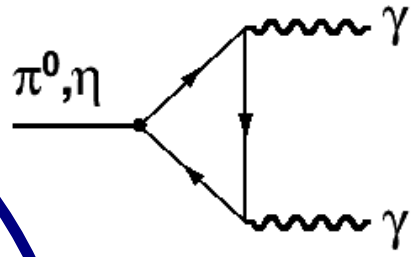
L/H energy QDC LAB

l^+l^- spectra in HIon

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



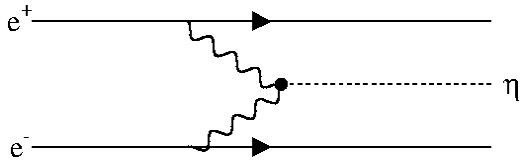
$F_P(q_1^2, q_2^2)$

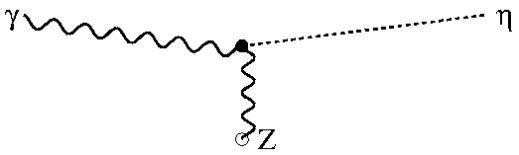


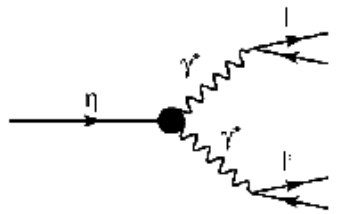
η: Γγγ

m_u/m_d

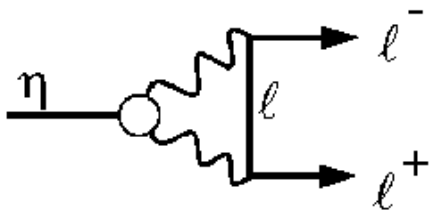
$F\pi^0$ $q^2 \to \infty$ puzzle

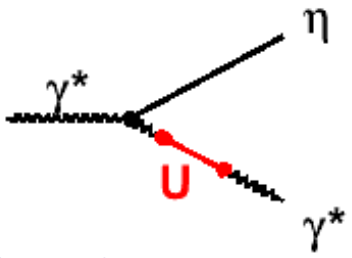




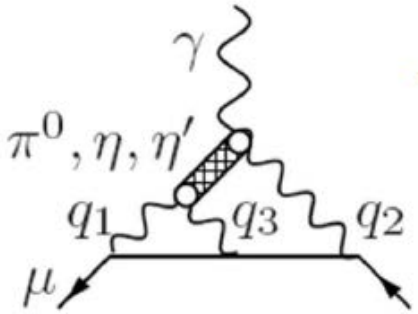


P → l+l-





Dark photon

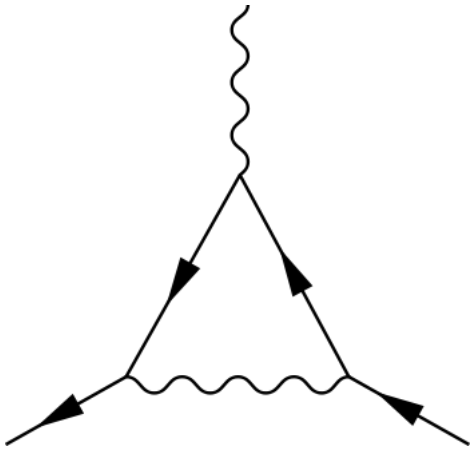


g-2 HLbL

Anomalous magnetic moment

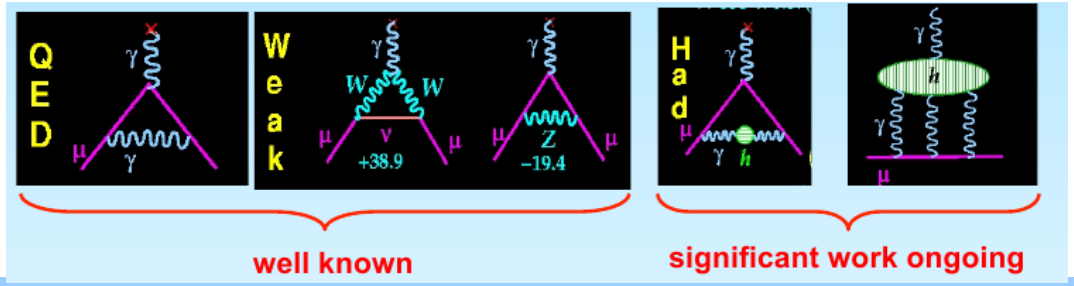
Anomalous magnetic moment of elementary fermion

$$a = \frac{g-2}{2}$$



$$a = \frac{\alpha}{2\pi} \approx 0.0011614$$

$$\alpha_\mu^{\rm SM} = \alpha_\mu^{\rm QED} + \alpha_\mu^{\rm EW} + \alpha_\mu^{\rm Hadron}.$$

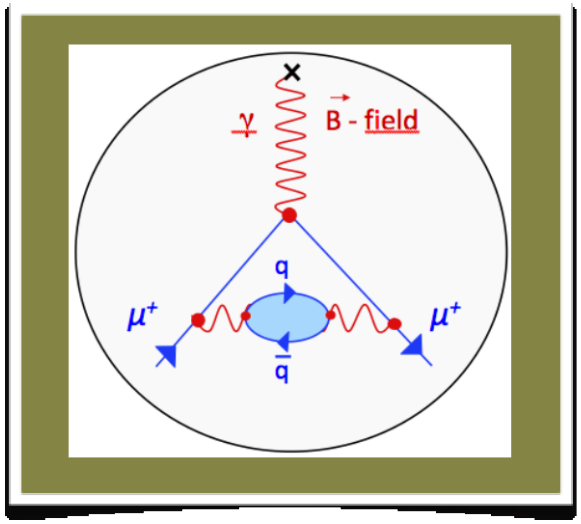


a_μ=(g-2)/2 muon

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

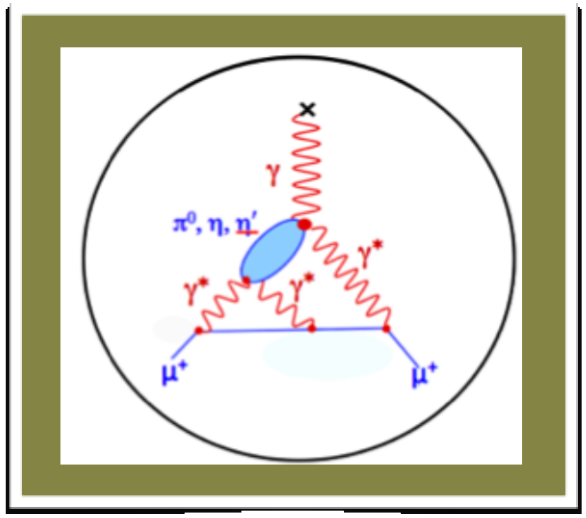
Hint of new physics or hadronic effect?

hadronic vacuum polarization (HVP)



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

hadronic light-by-light scattering (HLbL)

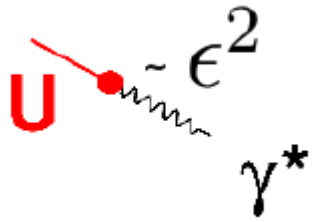


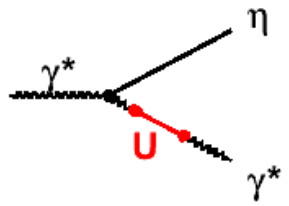
$$a_\mu^{HLbL} = (116 \pm 40) \cdot 10^{-11}$$

$$a_\mu^{E821} = (116\ 592\ 089 \pm 63) \cdot 10^{-11}$$

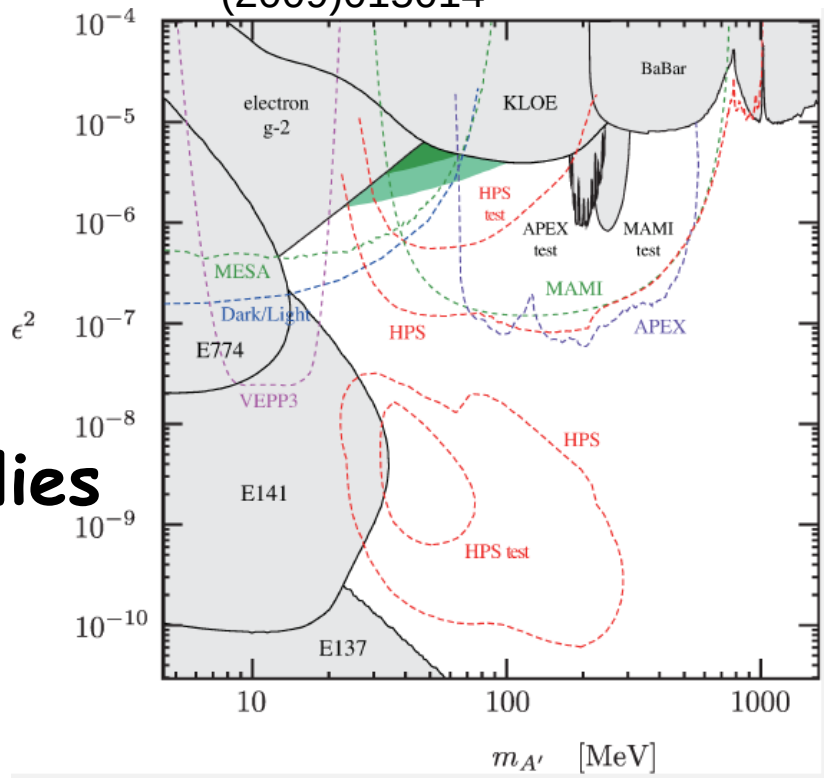
Dark matter photon

Hypothesis: Dark matter particles interact via a vector boson with mass 1 MeV – 1 GeV:
– can mix with photon (parameter ε)

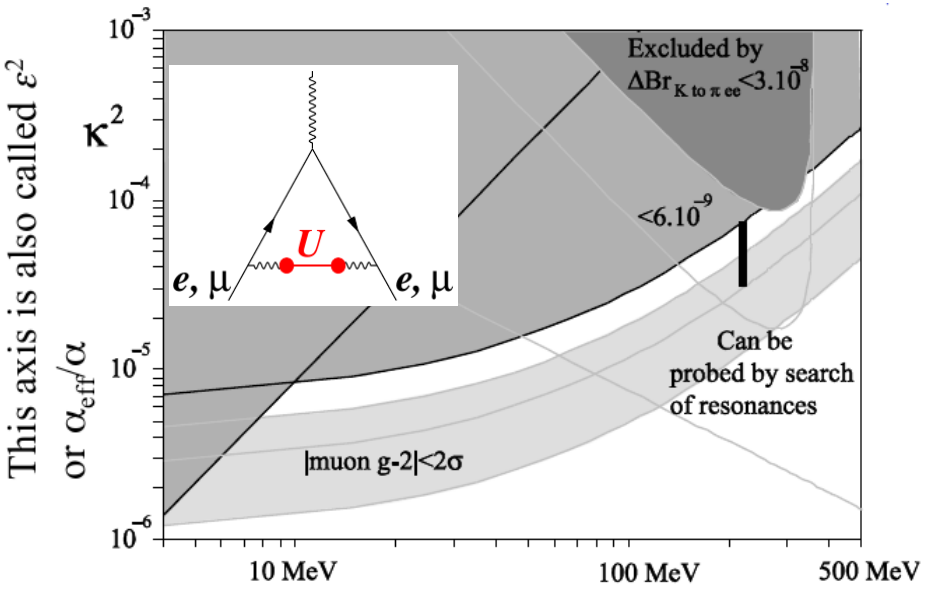




Arkani-Hamed PRD79 (2009)015014



It could explain astrophysics anomalies



World wide efforts:
dark/hidden photon, U boson, A'

fig PRD86 095029

New measurement

New FNAL exp.

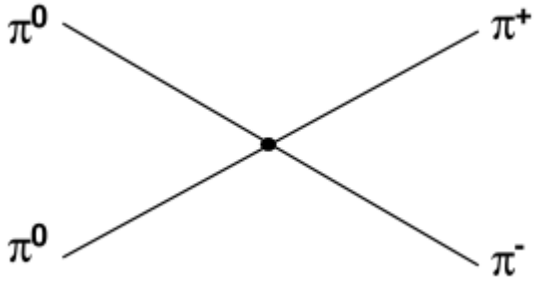
Goal reduce Δa_μ (10^{-11}):

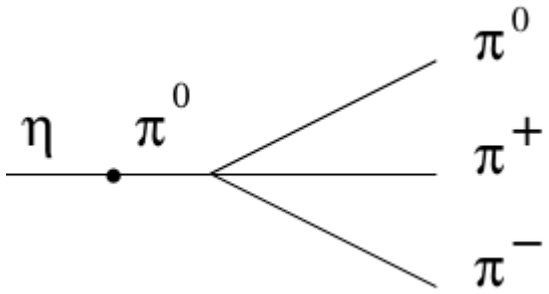
Experiment	63	→	16
HVP	42	→	11
HLbL	39/26	→	10

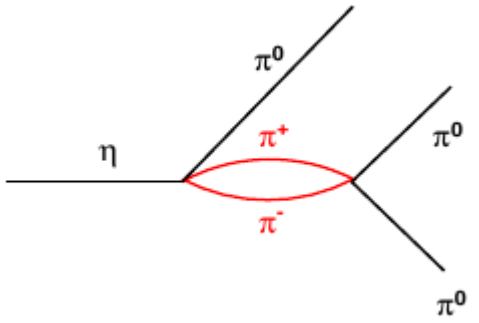
+JPARC

Low Energy meson QCD processes

Even # pseudoscalars PPPP



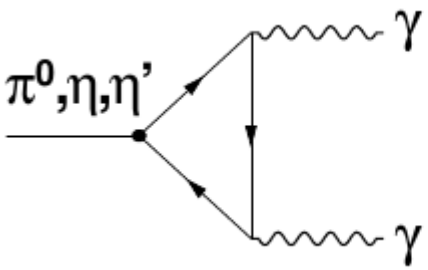


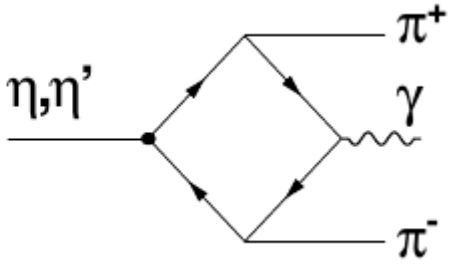


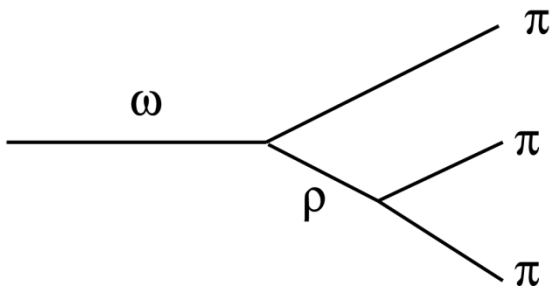
u-d quark masses

π-π,π-η scattering

Odd intrinsic parity: PVV/Pγγ, PPPV



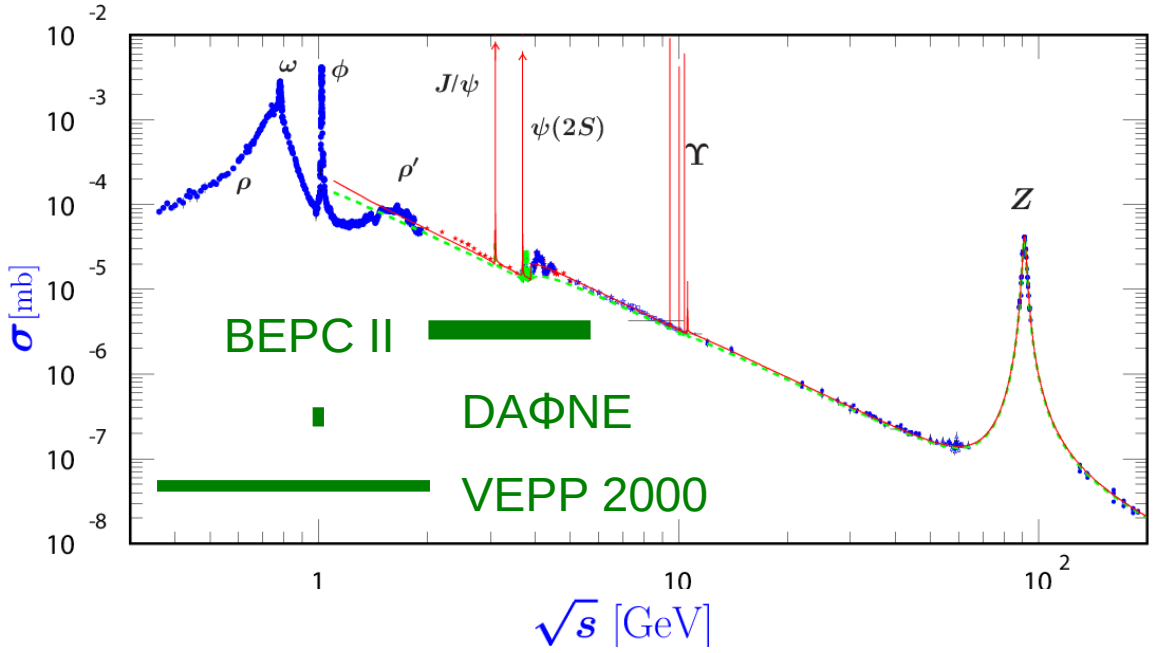




V → PV

Vector Meson Dominance

e+e- colliders



BEPCII L=6x10^{32} cm^{-2}s^{-1} at J/Ψ BESIII

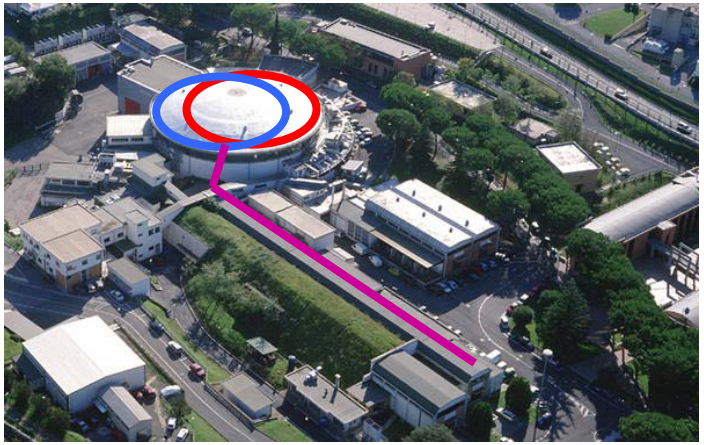
DAΦNE L= 10^{32} cm^{-2}s^{-1} at φ KLOE/KLOE-2

VEPP2000 L= 10^{32} cm^{-2}s^{-1} at 2GeV CMD-3,SND

DAΦNE luminosity upgrade

Frascati φ-factory

e^+e^- collider $\sqrt{s}$ = Mφ

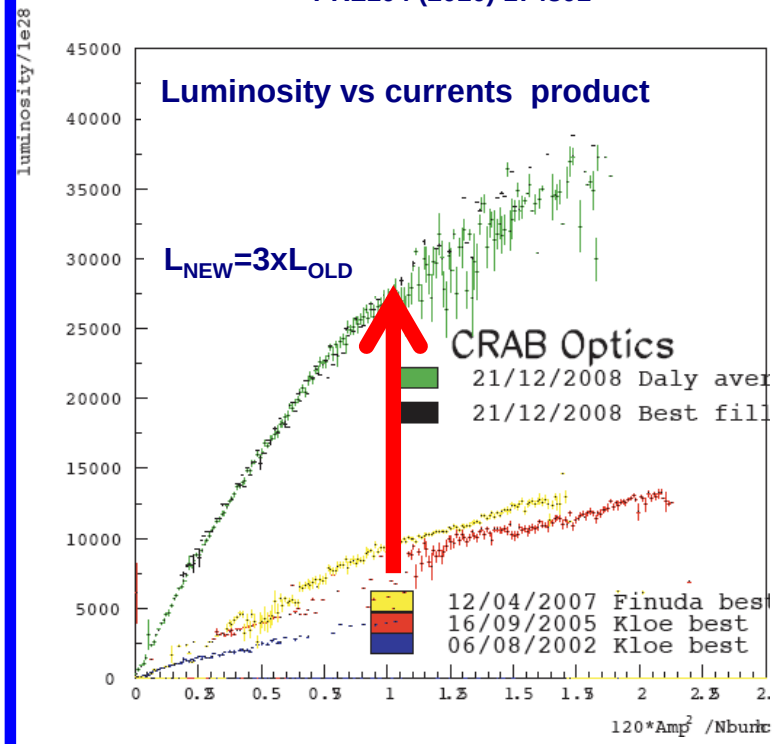


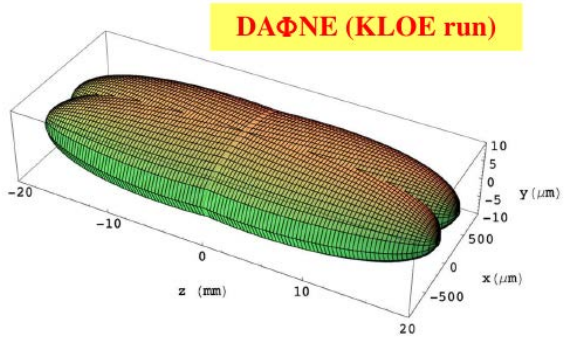
KLOE-2 IP collisions:
from 2010
Commissioning for KLOE-2

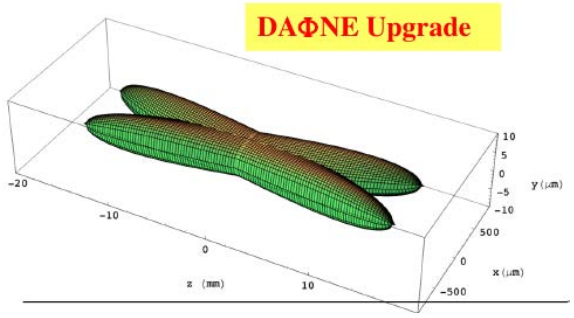
Status: $L = 1.5 \times 10^{32}\ cm^{-2}s^{-1}$ with 1.3 A + 700/800 mA, $7pb^{-1}$/day

Novel interaction scheme:
large angle beam crossing
+ crabbed waist sextupoles

PRL104 (2010) 174801





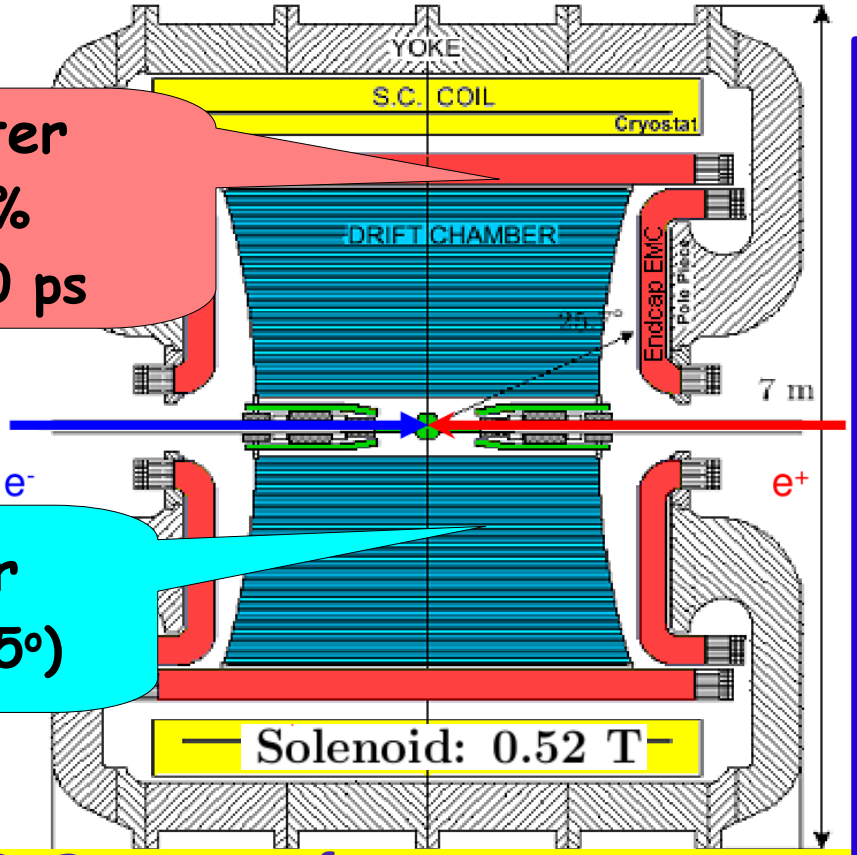


KLOE-2:
Extension of the KLOE physics program at upgraded DAΦNE

KLOE → KLOE-2

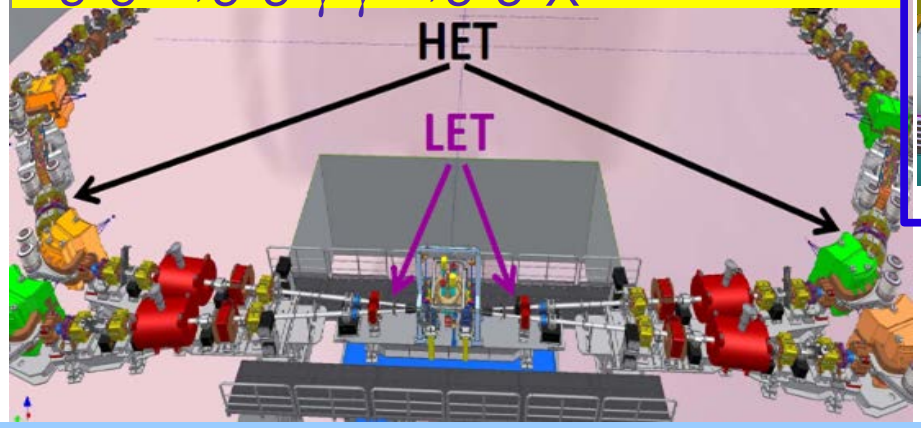
EM Calorimeter
$\delta E/E = 5.7/\sqrt{E}$ %
$\delta t = 57/\sqrt{E} \oplus 100$ ps

Drift Chamber
$\delta p_T \sim 0.4\%$ ($\theta < 45^\circ$)



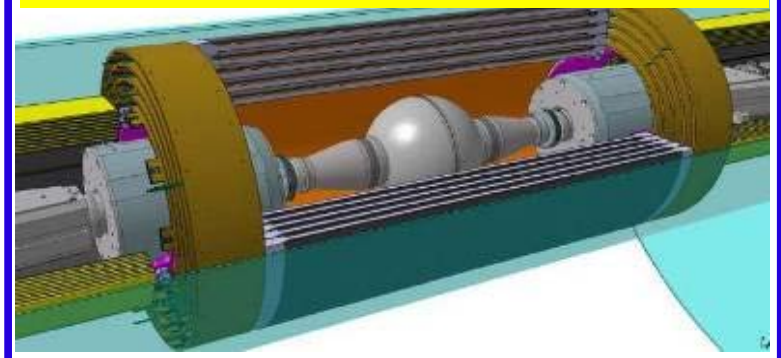
2+2 taggers for:

$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$

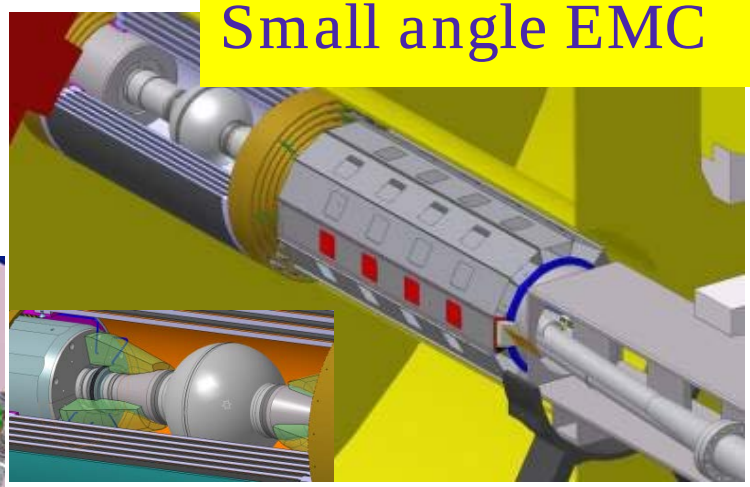


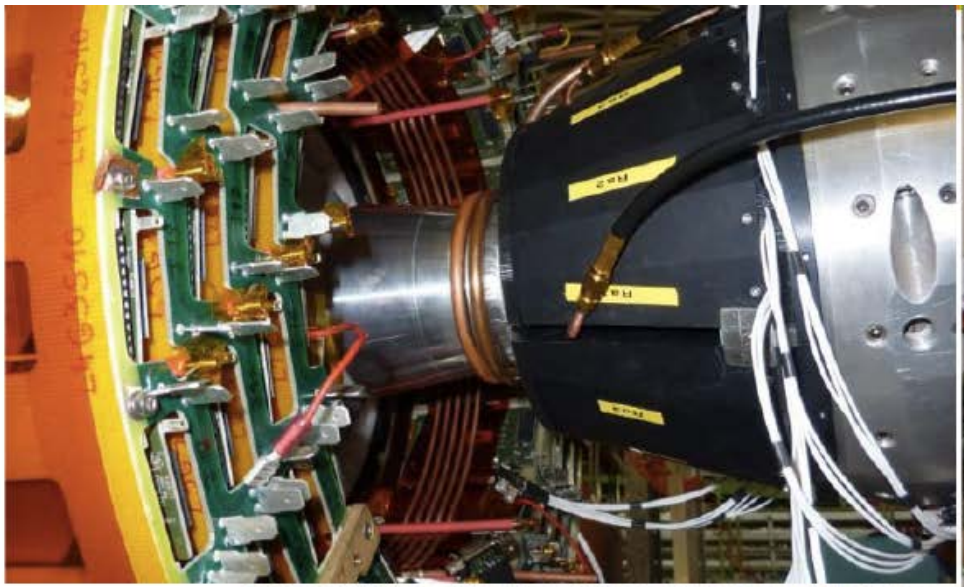
Upgrades

Inner Tracker: cyl. GEM



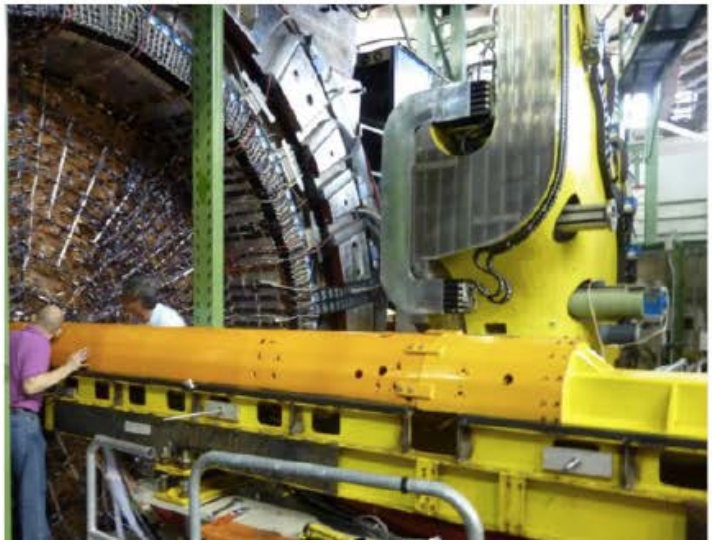
Small angle EMC





IT front-end and CCALT

IR insertion in DAFNE



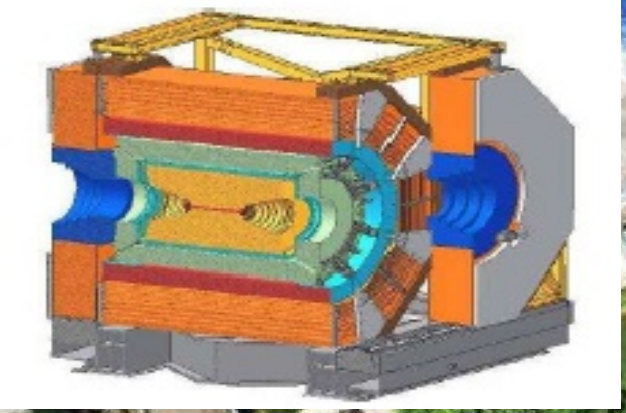
- Installation of the upgrades and the IR in DAFNE completed on July, 12th

BEPCII (Beijing)

Linac

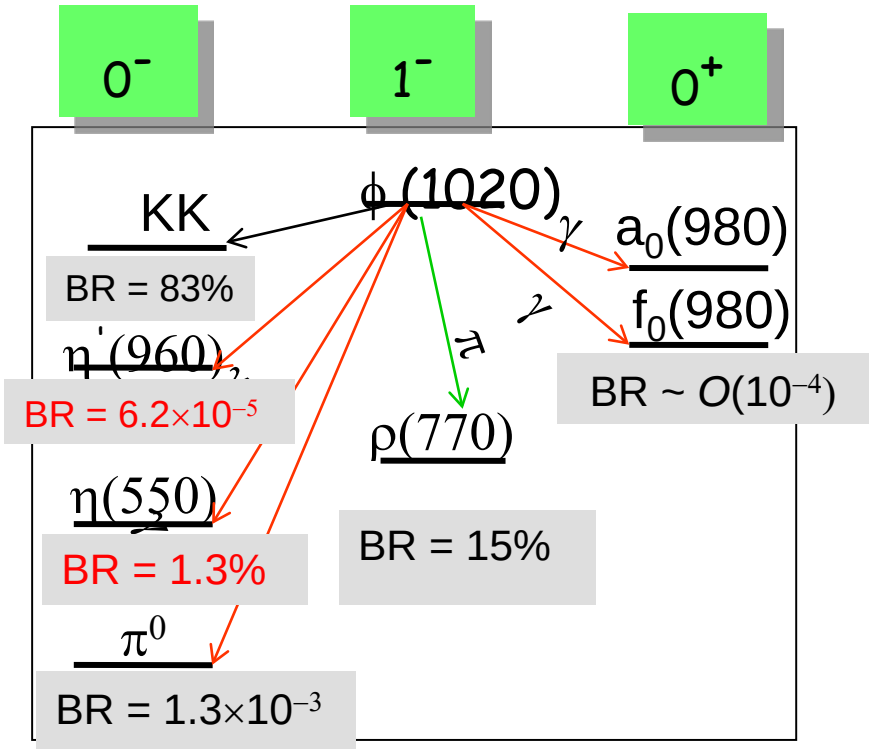
Storage ring

BESIII at BEPCII



τ –charm factory 2<√s<4.6 GeV:

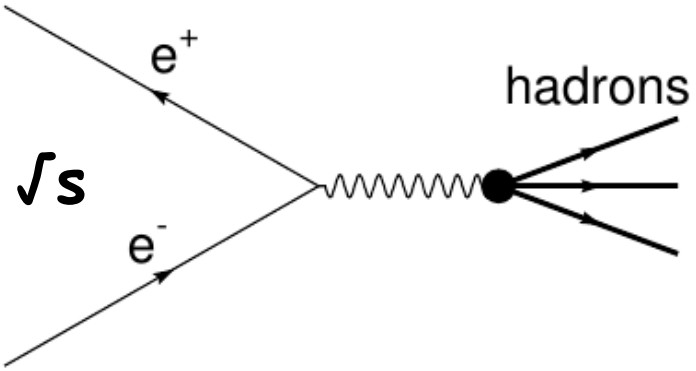
- Charmonium spectroscopy/decays
- Light hadron physics
- Charm physics
- τ physics
- R-scan



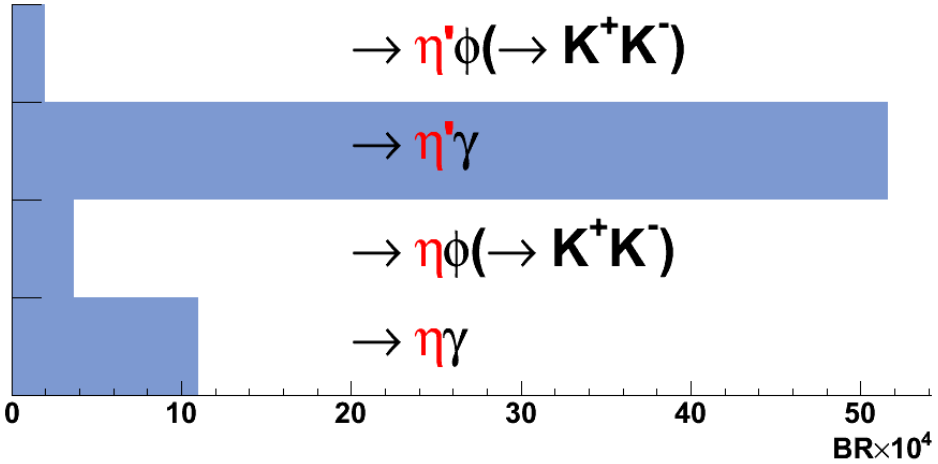
$\phi \rightarrow \eta^{(\prime)}\gamma$ (KLOE)

1×10^{10} ϕ events

KLOE 2001-2005 data/new data campaign started

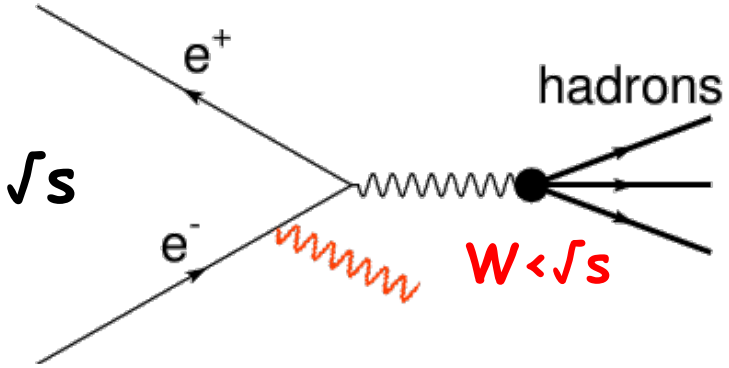


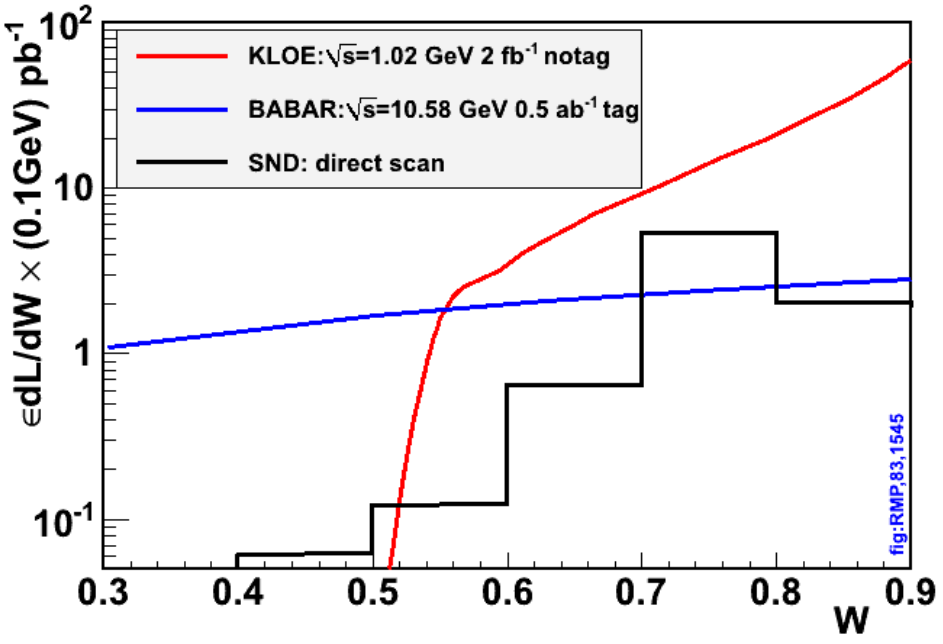
$J/\Psi \rightarrow \eta^{(\prime)}\gamma$ (BESIII)



1.3×10^{9} J/ψ events

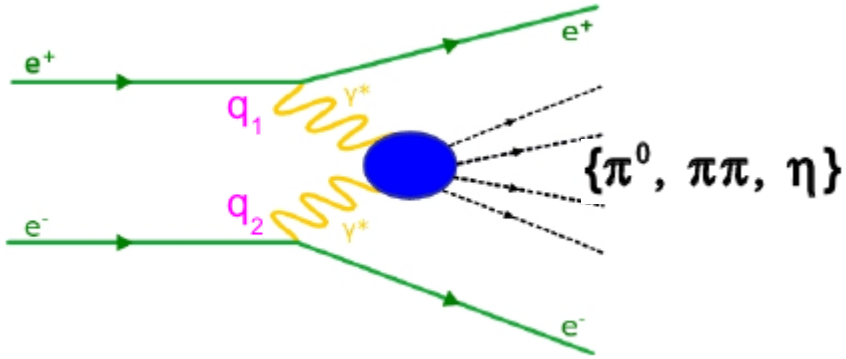
ISR | γγ

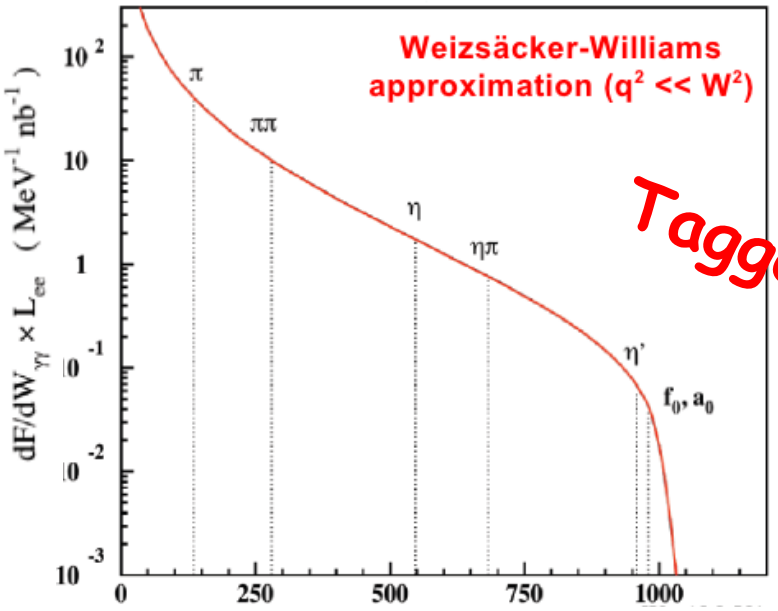




KLOE: Fv(W) in $e^+e^- \to \pi^+\pi^-(\gamma)$

Luminosity





Taggers

$$e^+ e^- \to e^+ e^- \gamma^* \gamma^* \to e^+ e^- X$$

to taggers (HET or LET)

in KLOE

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

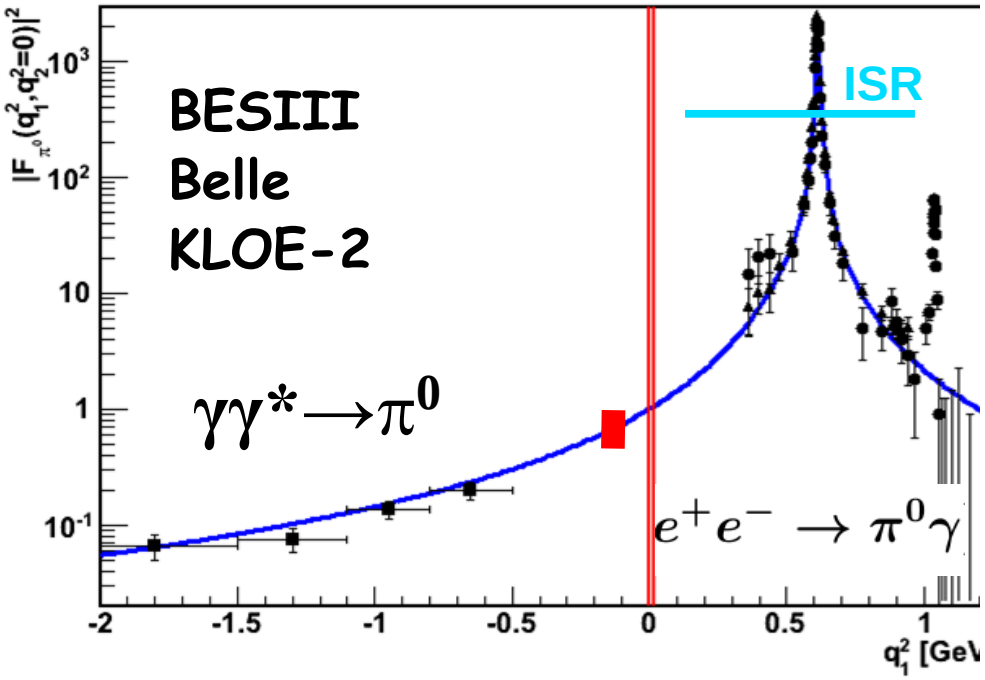
$\delta\Gamma(\eta \to \gamma\gamma)$ ~5%

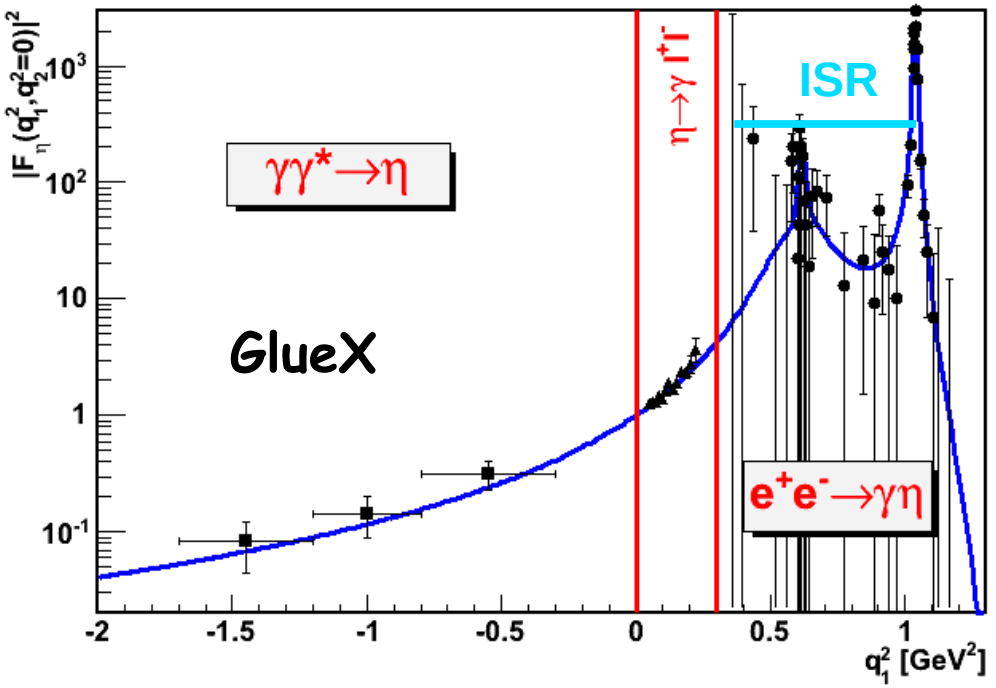
$\sigma(e^+e^- \to e^+e^-\eta, \sqrt{s}=1\text{GeV})$

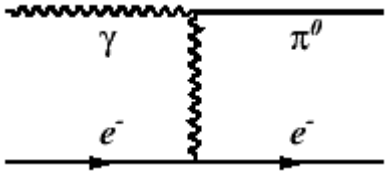
$\Gamma_{\gamma\gamma}=520\pm20_{stat}\pm13_{syst}$ eV

[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

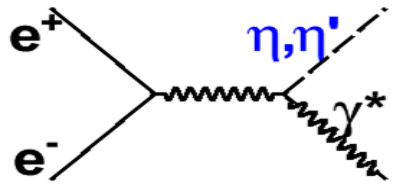
$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{s m_P}\right)^3$$

$P \to \gamma^*\gamma$

Dalitz decays:

KLOE, WASA,CBall,BESIII

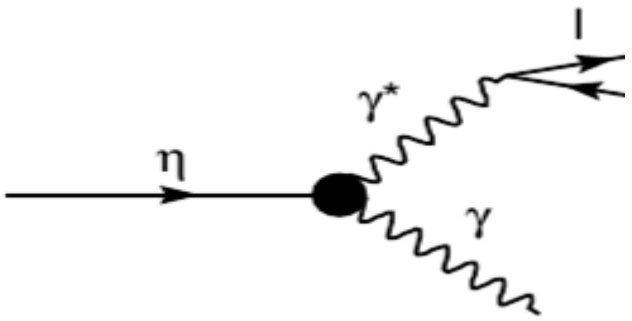
CLAS,NA48

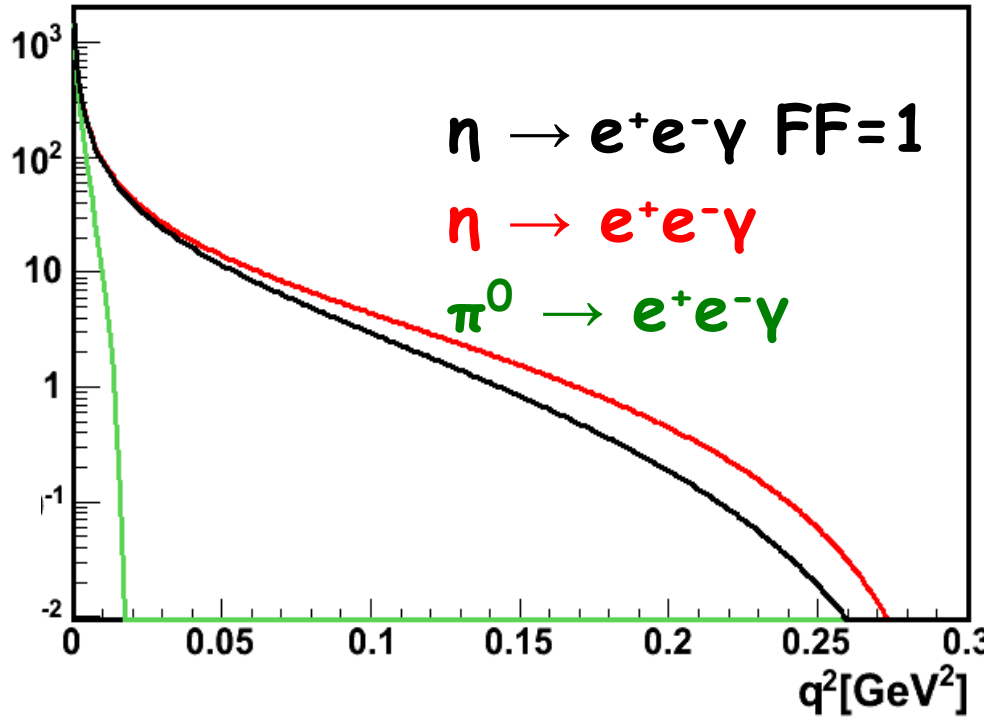


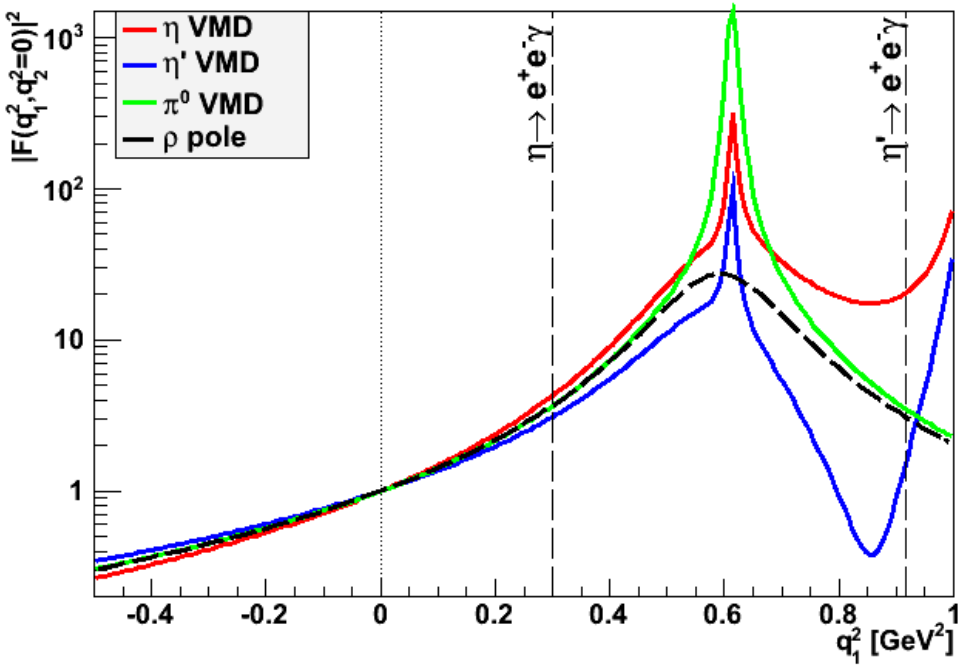
Data:CELLO,NA60,CB-MAMI,CMD-2,SND

Dalitz decays

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

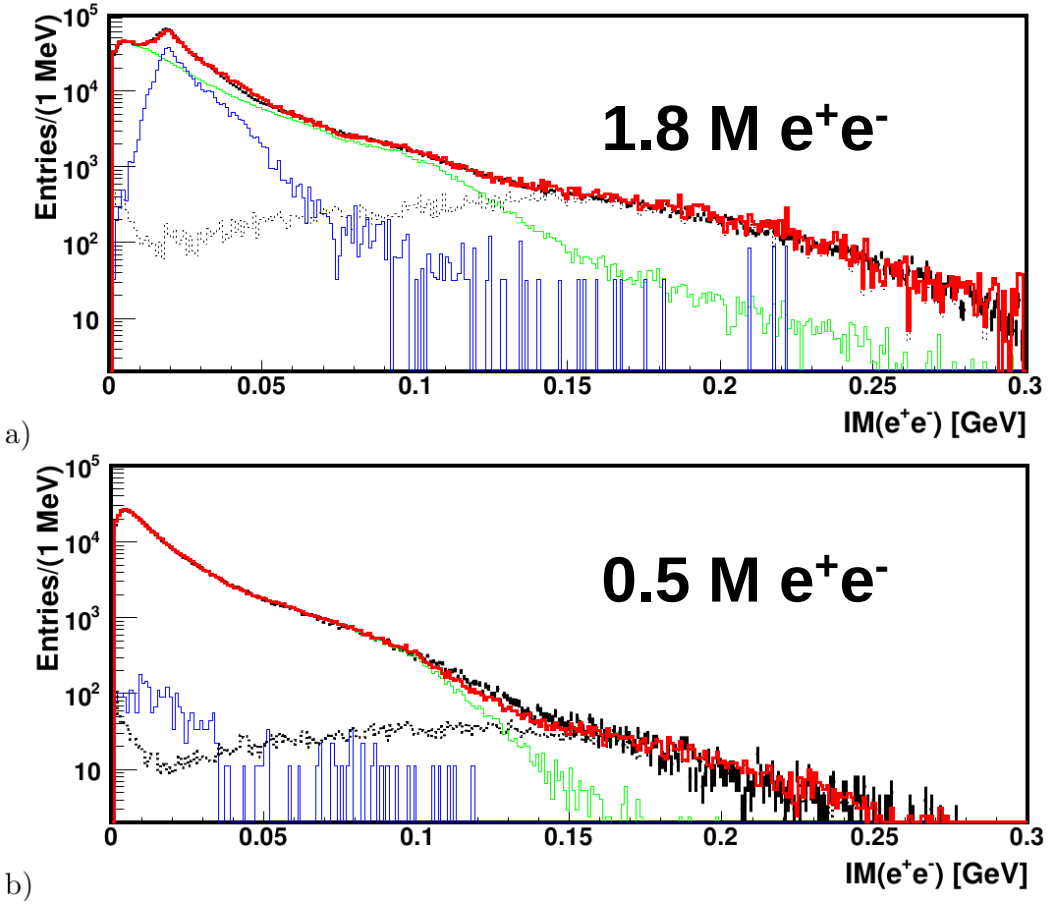


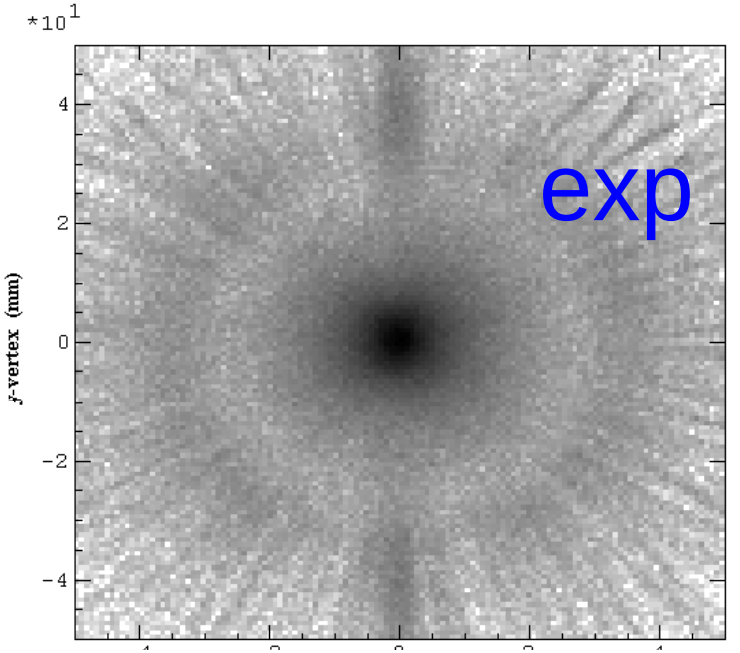


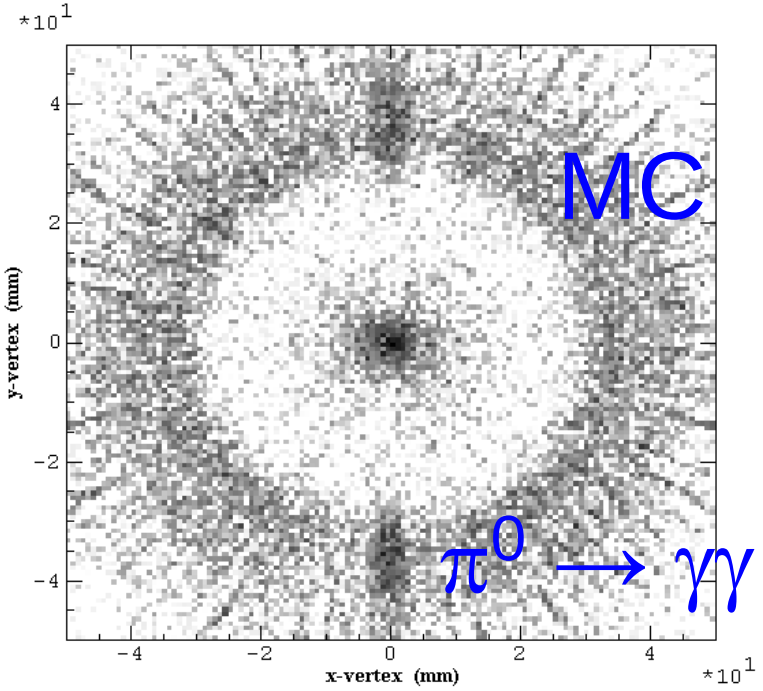


UPPSALA UNIVERSITET

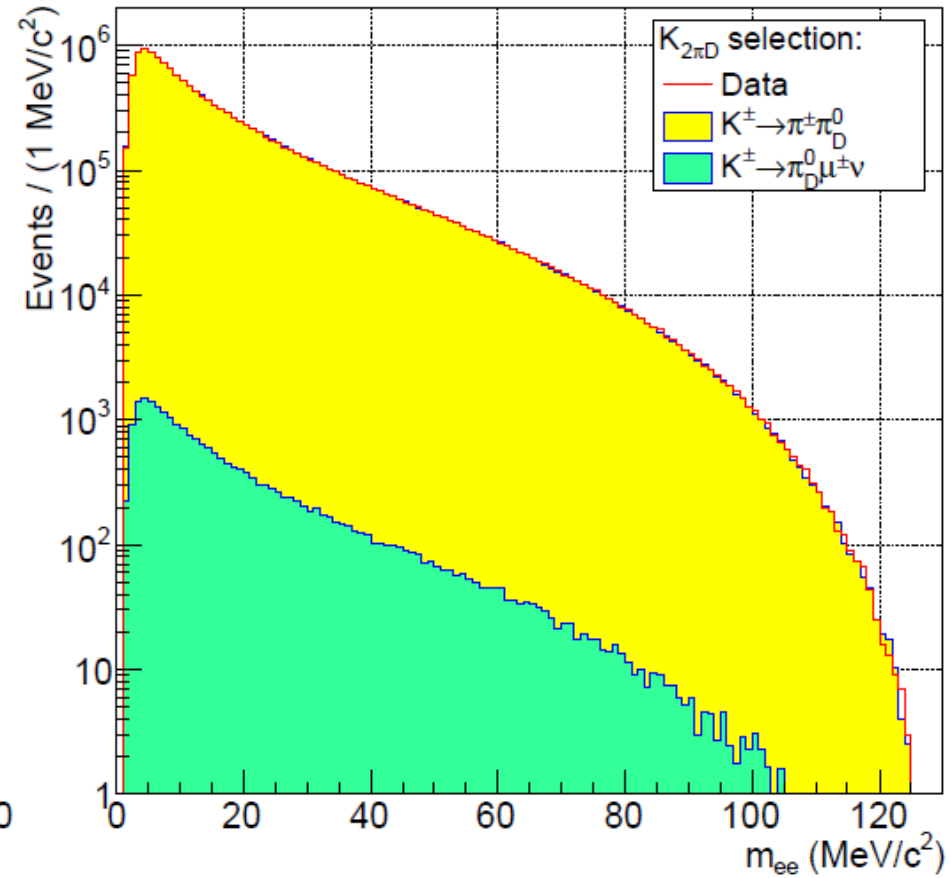
Data analysis: $\pi^0 \rightarrow \gamma e^+e^-$

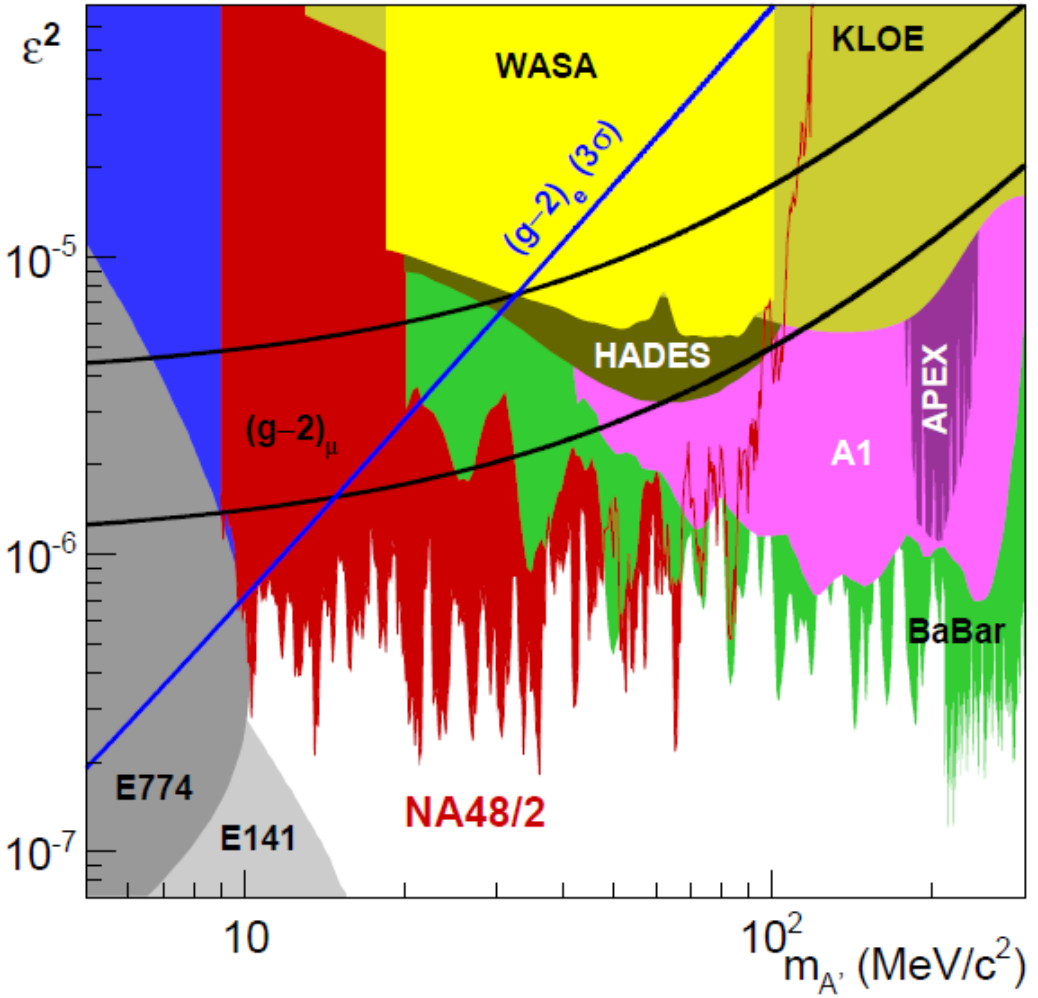






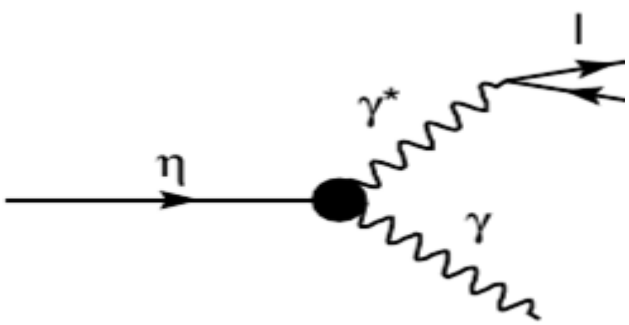
NA48/2 $\pi^0 \rightarrow e^+e^-\gamma$

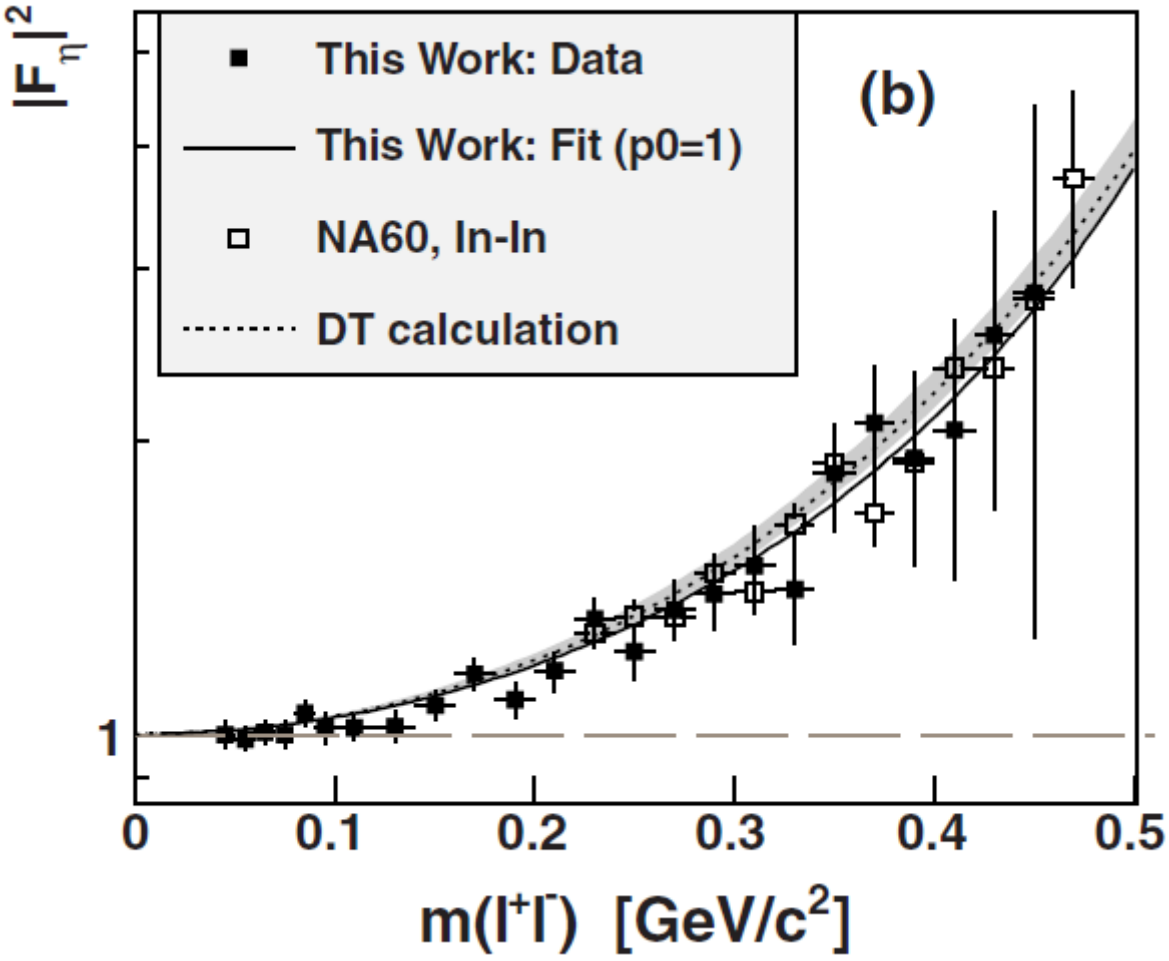




NA48/2: arXiv:1504.00607

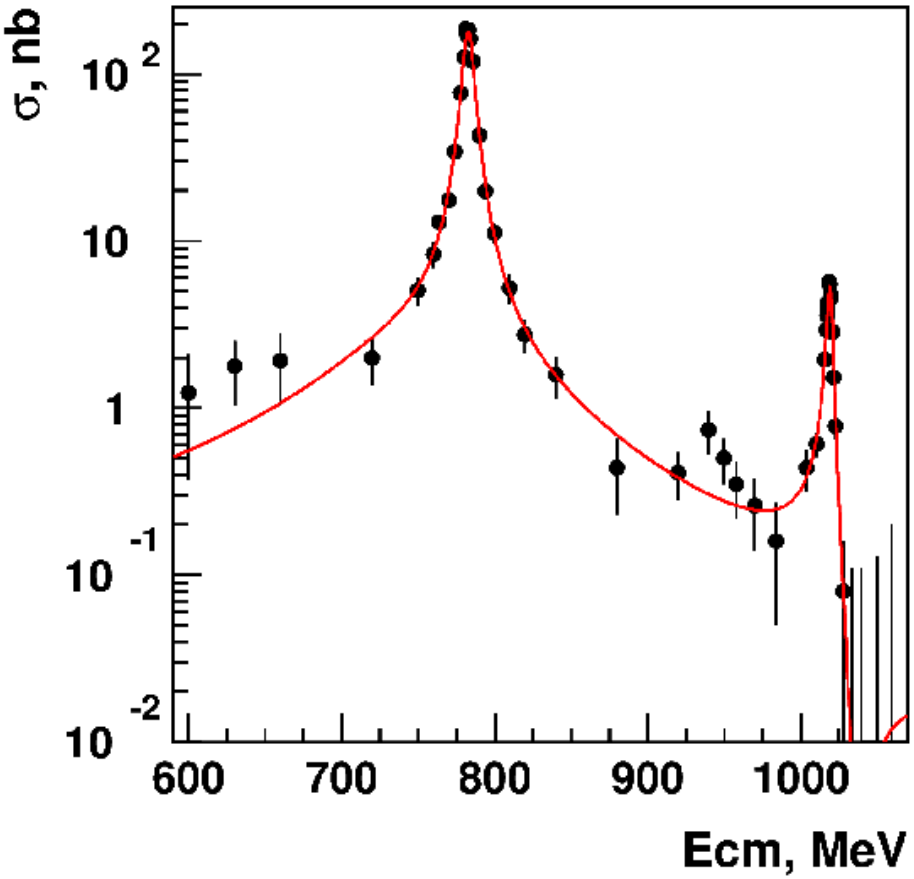
$\eta \to e^+e^-\gamma$

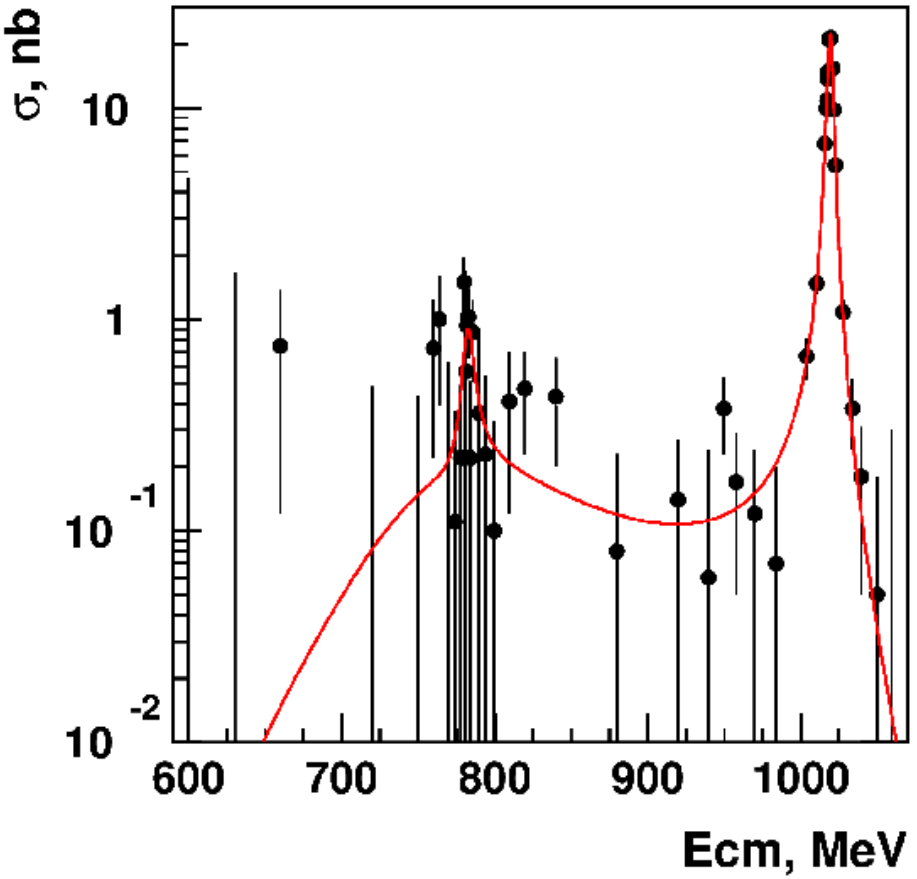


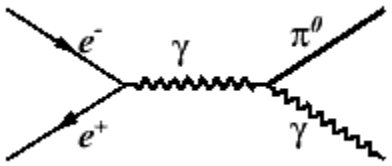


CB/TAPS: PRC89, 044608 (2014)

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



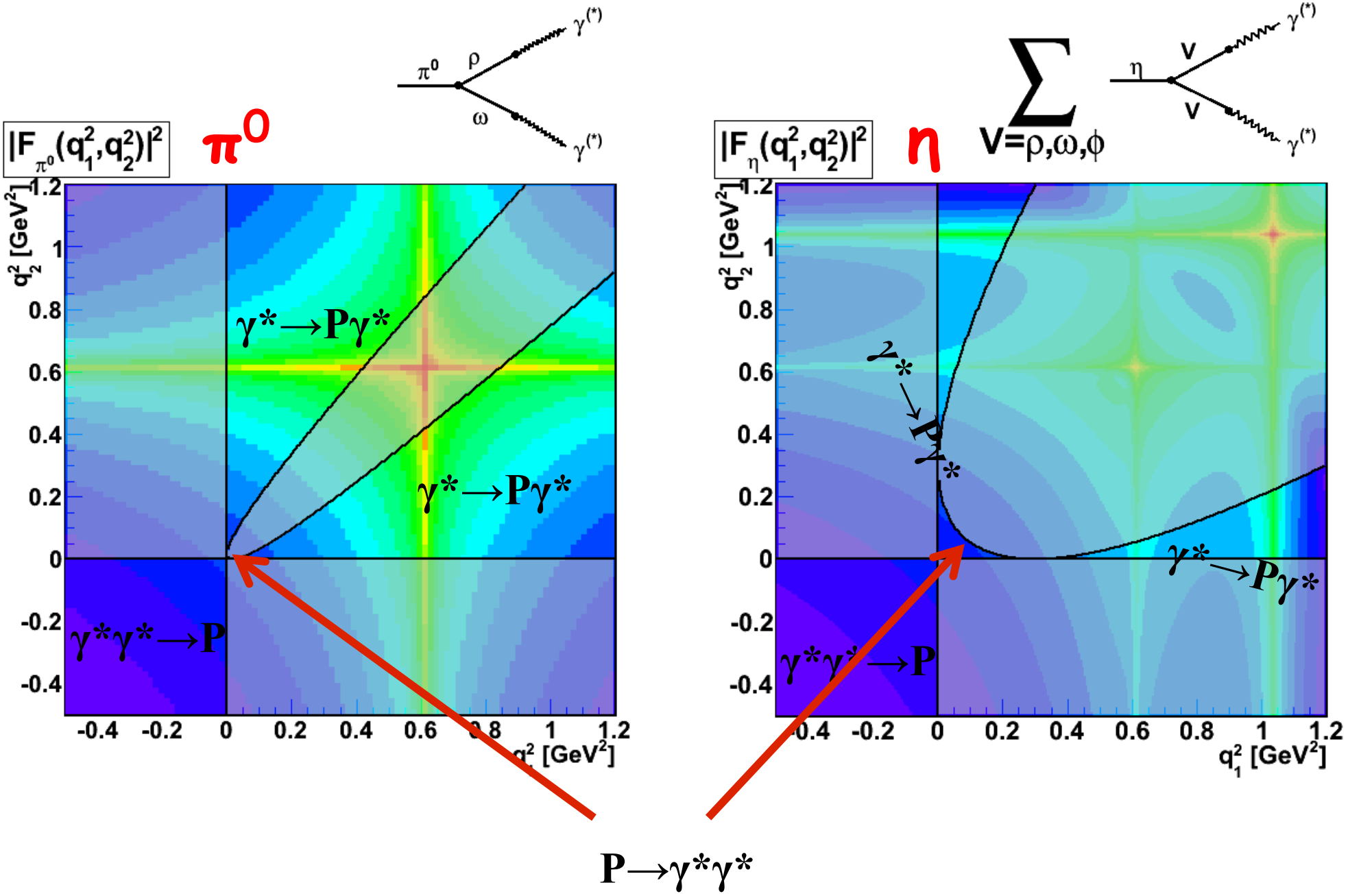




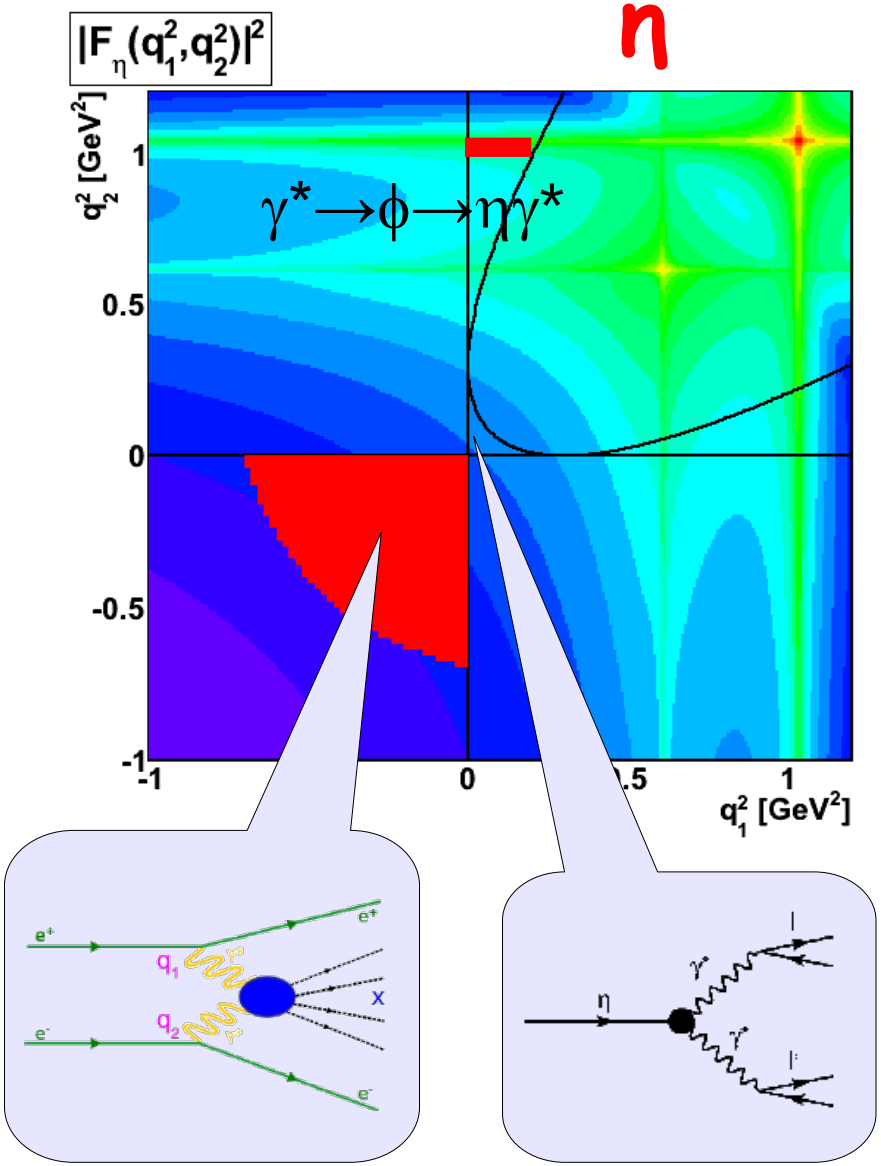
$$\sigma(e^+e^- \to P\gamma) = \frac{8}{3}\pi\alpha\,\Gamma_{\gamma\gamma}|F_P(s,0)|^2\left(\frac{s-m_P^2}{sm_P}\right)^3$$

Data: CMD-2,SND

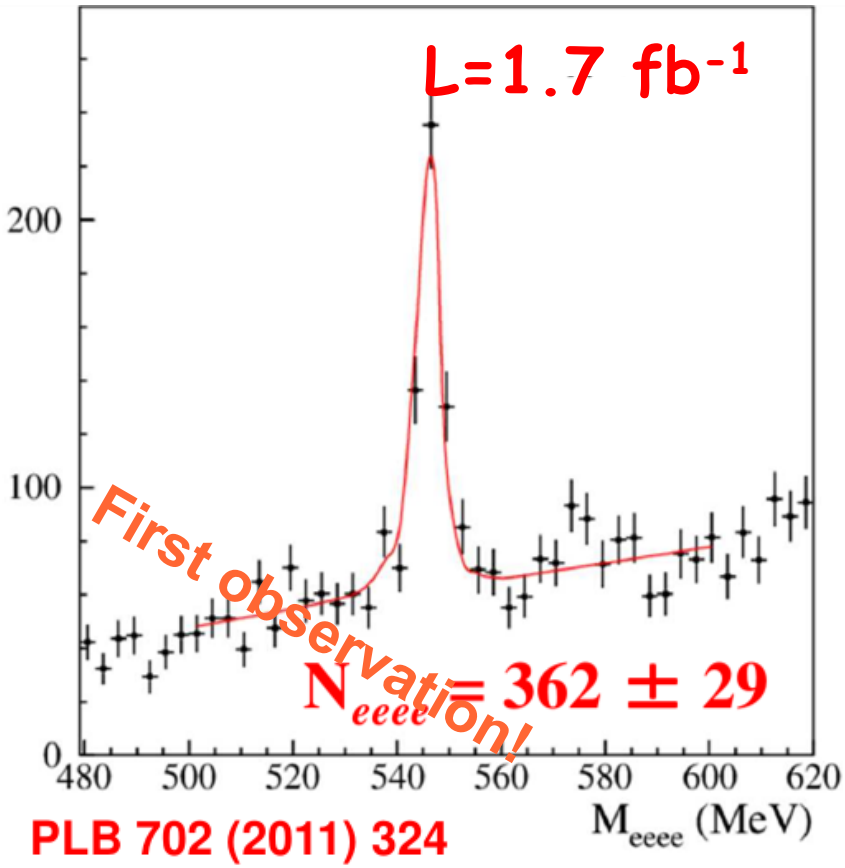
TFF kinematic regions: π^0, η



Double off shell TFF at KLOE



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



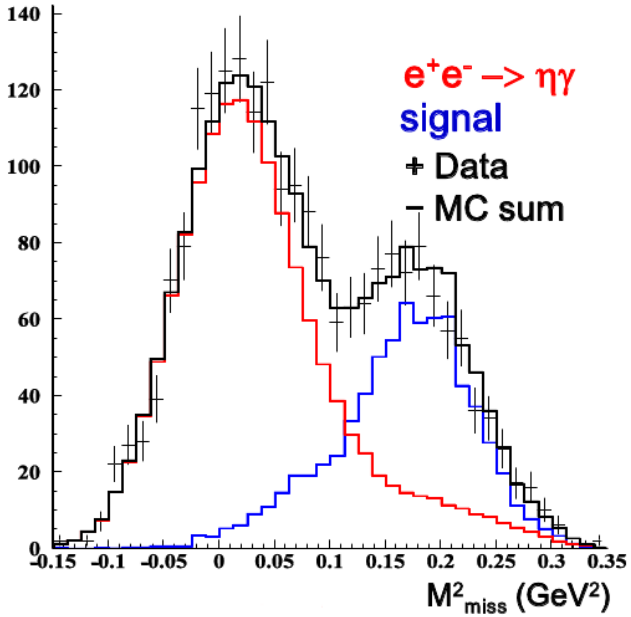
PLB 702 (2011) 324

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

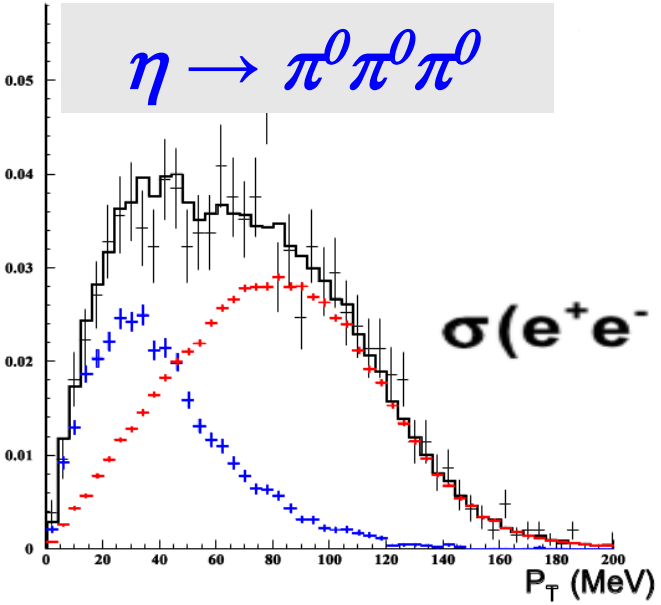
TFF=1 => BR=2.5×10^{-5}

TFF≠1 ΔBR ~ 5%

η meson radiative decay width



$\eta \to \pi^0\pi^0\pi^0$



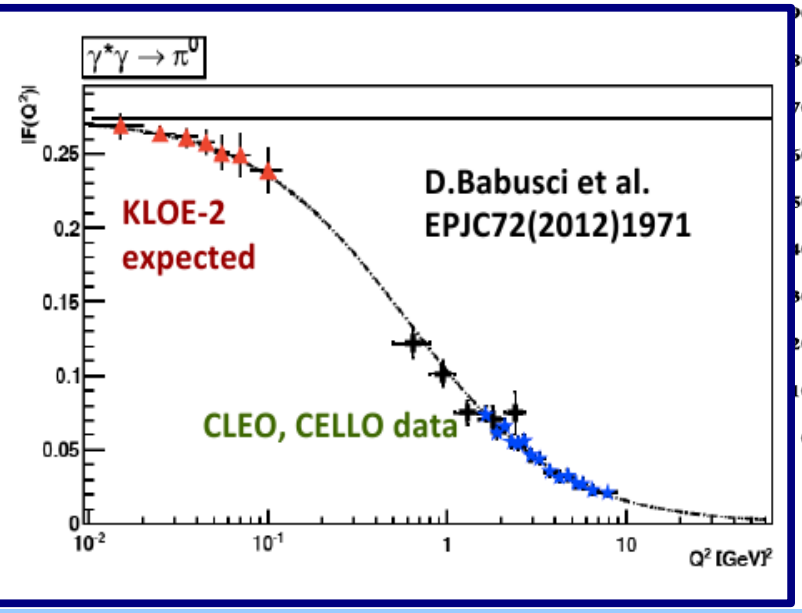
L=240 pb^{-1}

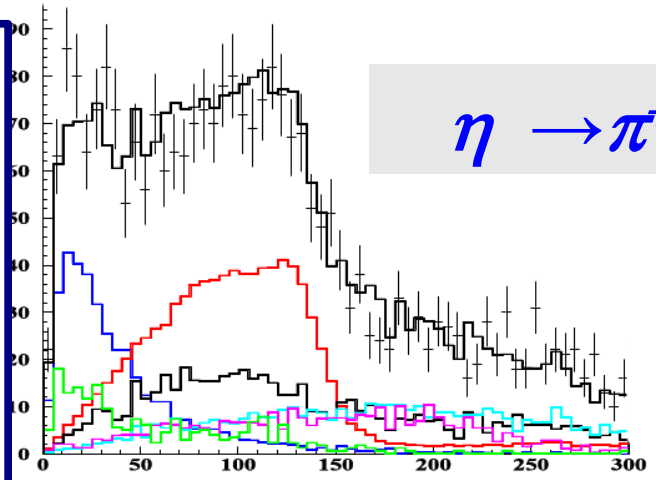
$\sigma(e^+e^- \to e^+e^-\eta,\ \sqrt{s}=1\text{GeV})$

Insensitive to TFF

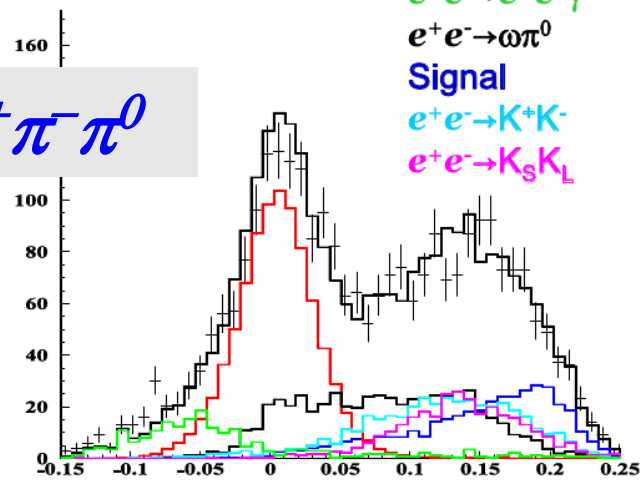
Γγγ=520±20±13 eV

32.0±1.5 ±0.9 pb



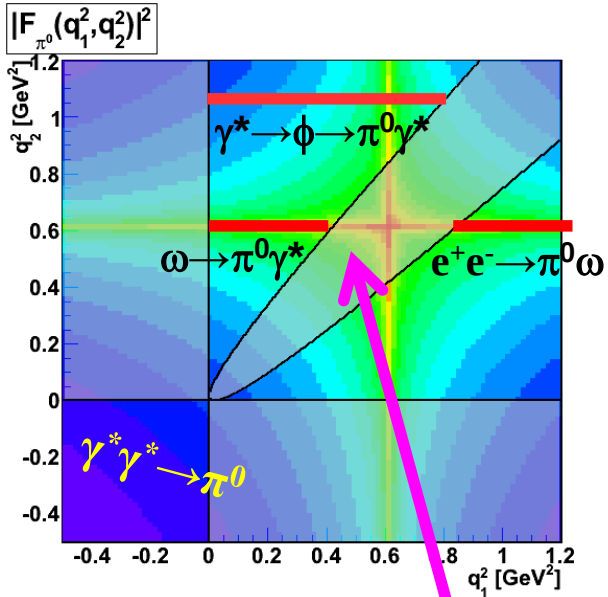


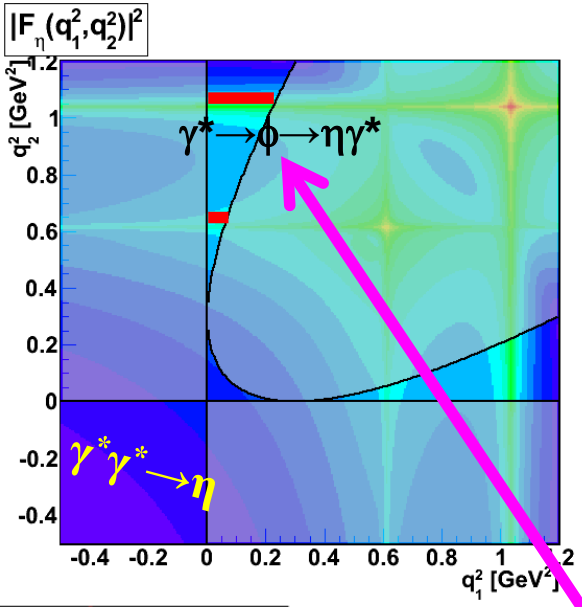
$\eta \to \pi^+\pi^-\pi^0$

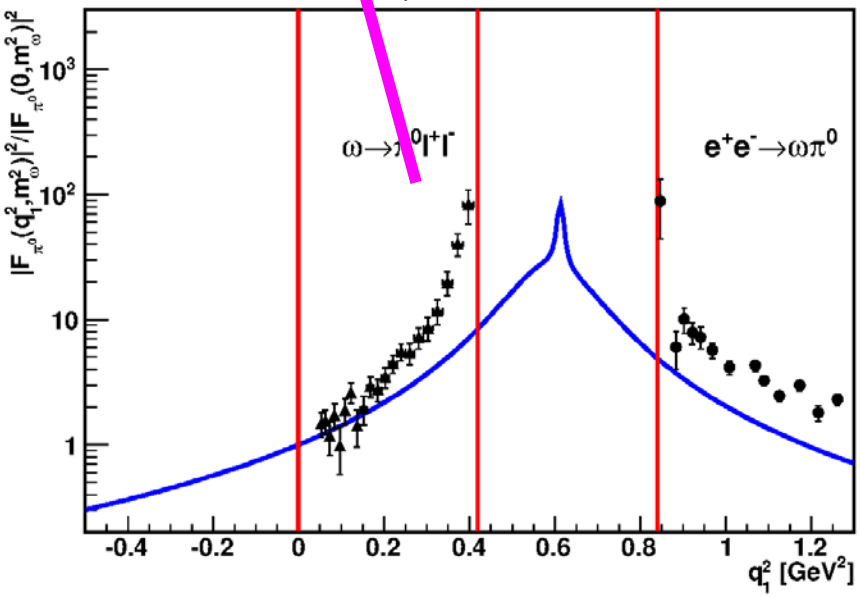


34.5±2.5 ±1.0 pb

V → Pγ* and e+e- → PV processes





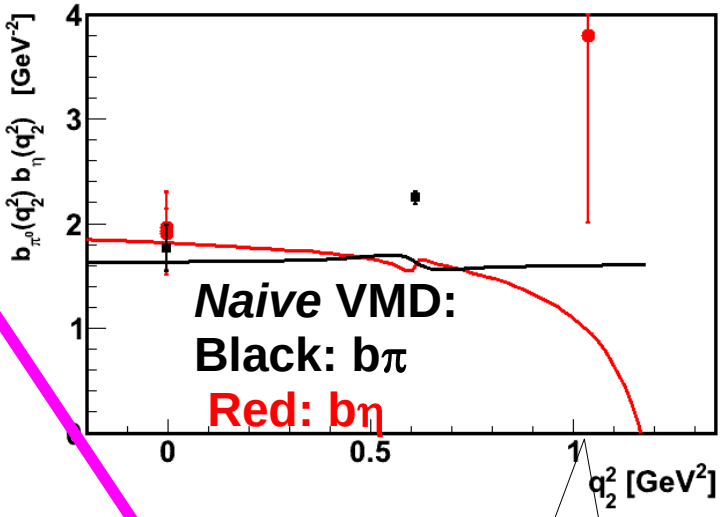


TH: Bonn, GSI, Uppsala, Kharkiv, JLab

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

slopes bπ, bη

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



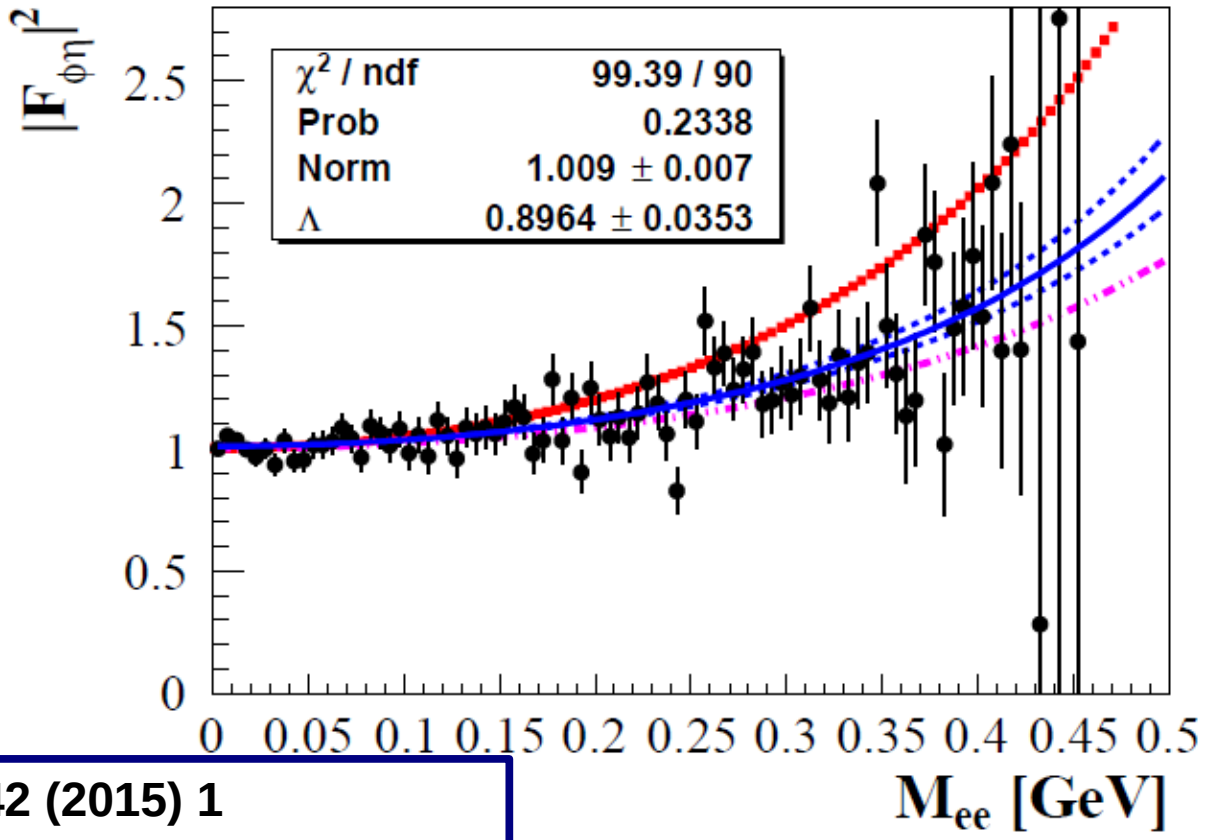
bη(m^2_ϕ)

KLOE results

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

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

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



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

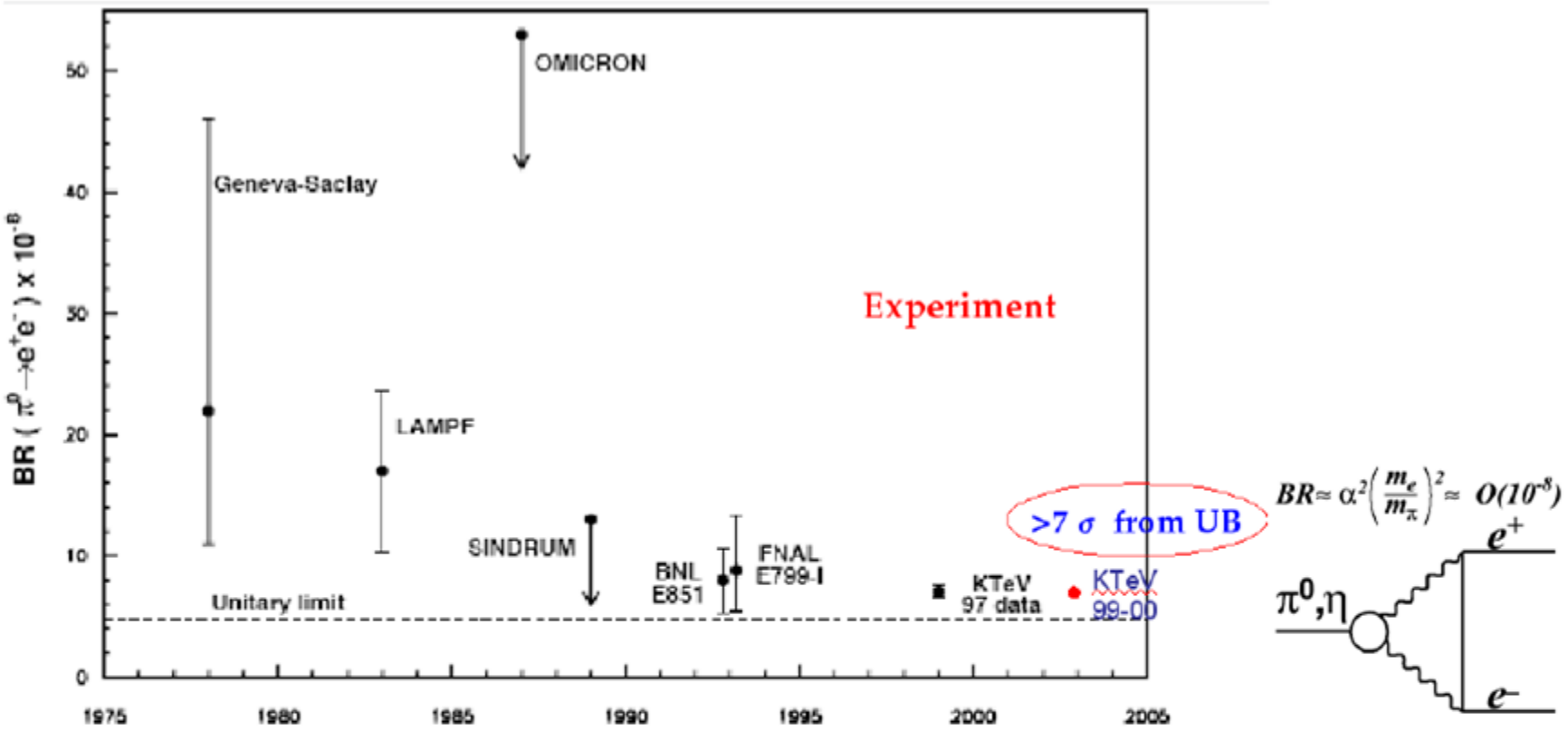
KLOE 2015

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

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

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

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



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

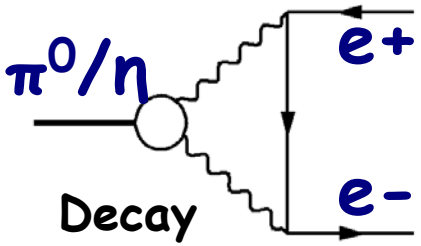
$$BR(\pi^0 \to e^+e^-) = (6.44 \pm 0.25_{stat} \pm 0.22_{syst}) \times 10^{-8}$$

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

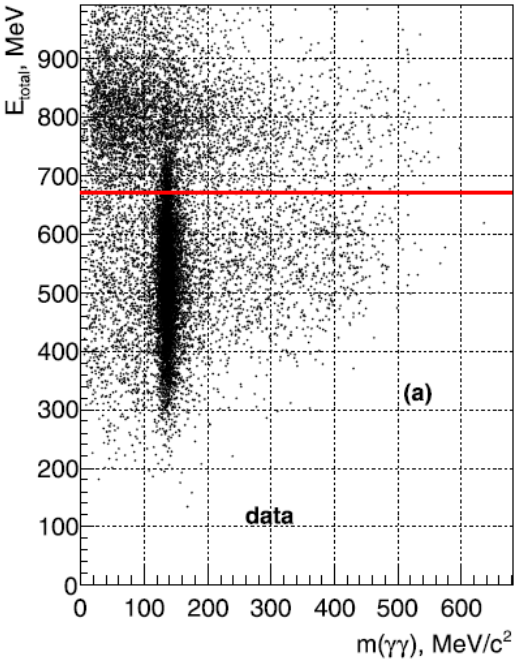
PRD75:012004(07)

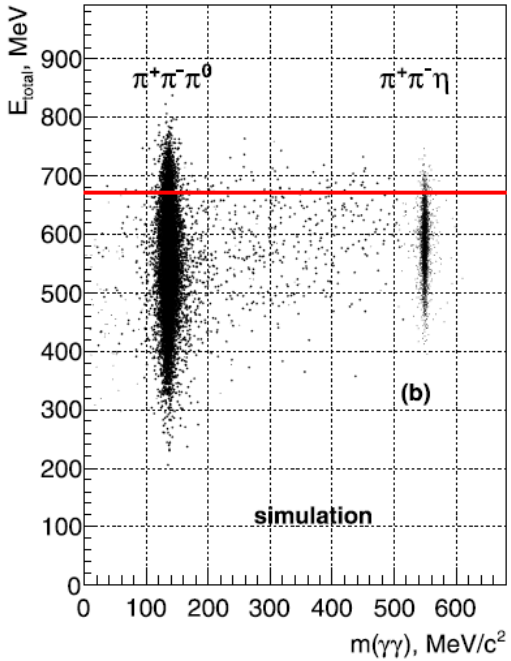
P → e+e-

$$\mathcal{B}_{\eta' \to e^+e^-} < 1.2 \times 10^{-8}$$



HADES
WASA
Cball,NA60

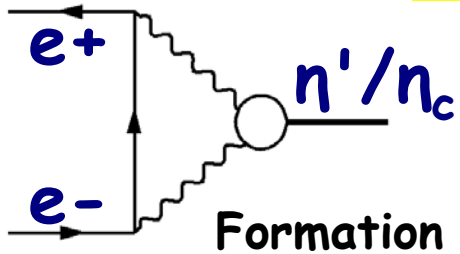




	UB	SM	EXP
$\mathcal{B}(\pi^0 \to e^+e^-) \times 10^8$	≥ 4.69	6.23 ± 0.12	7.49 ± 0.38 KTeV2007
$\mathcal{B}(\eta \to e^+e^-) \times 10^9$	≥ 1.78	5.2 ± 0.3	$\leq 5.6 \cdot 10^3$ HADES2012
$\mathcal{B}(\eta' \to e^+e^-) \times 10^{10}$	≥ 0.36	1.9 ± 0.3	$\leq 2.1 \cdot 10^3$ ND1988
$\mathcal{B}(\eta_c \to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

3σ diff

Dorokhov,PLB667,145



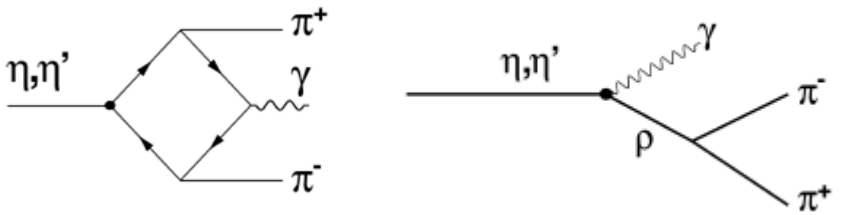
ND L=0.5pb^{-1}

B<1.2·10^{-7}

VEPP2000
BESIII

CMD3 PLB740, 273 (2015)

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

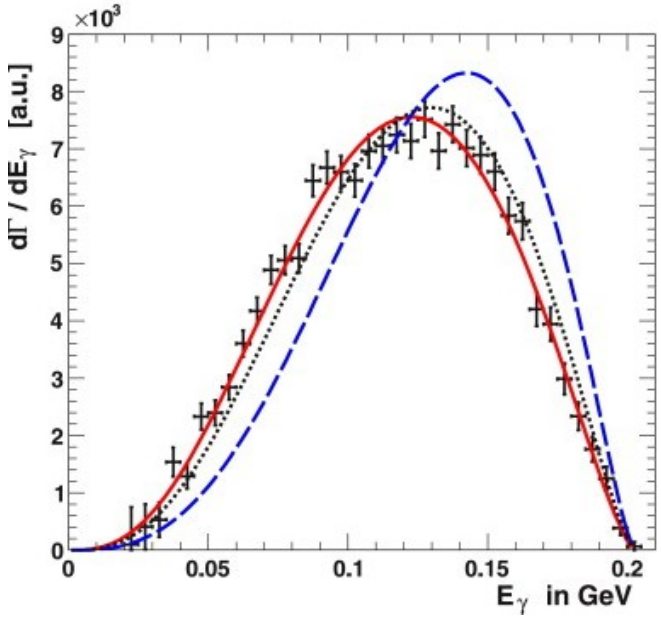


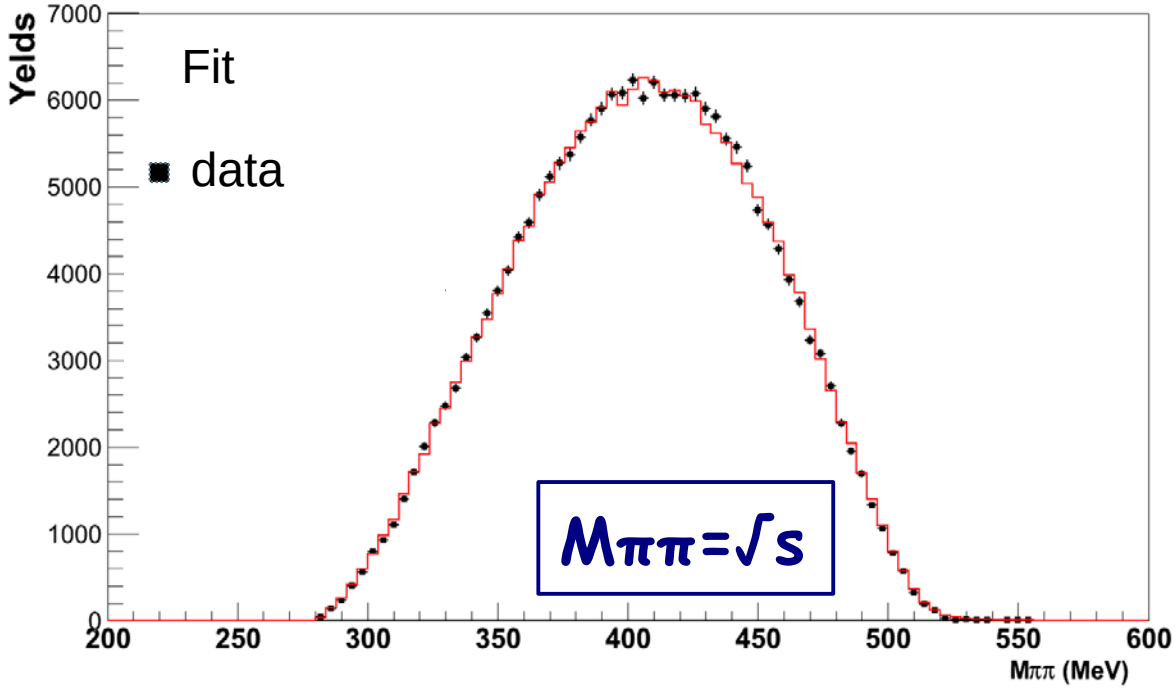
$$\frac{d\Gamma_{\eta(\eta')}}{ds_{\pi\pi}} \propto \left| C + \frac{1}{s_{\pi\pi} - m_\rho^2 - i m_\rho \Gamma_\rho} \right|^2$$

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

PLB707 (2012) 184

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





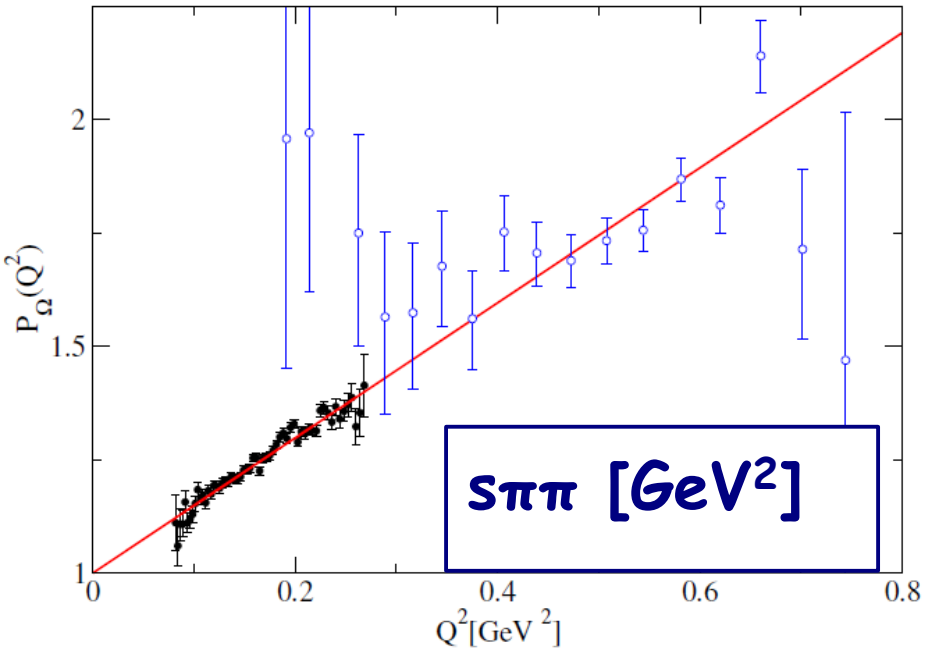
$\alpha = 1.89 \pm 0.25_{stat} \pm 0.59_{syst}$ GeV^{-2}

[WASA PLB707 (2012) 243]

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

[KLOE PLB718 (2013) 910]

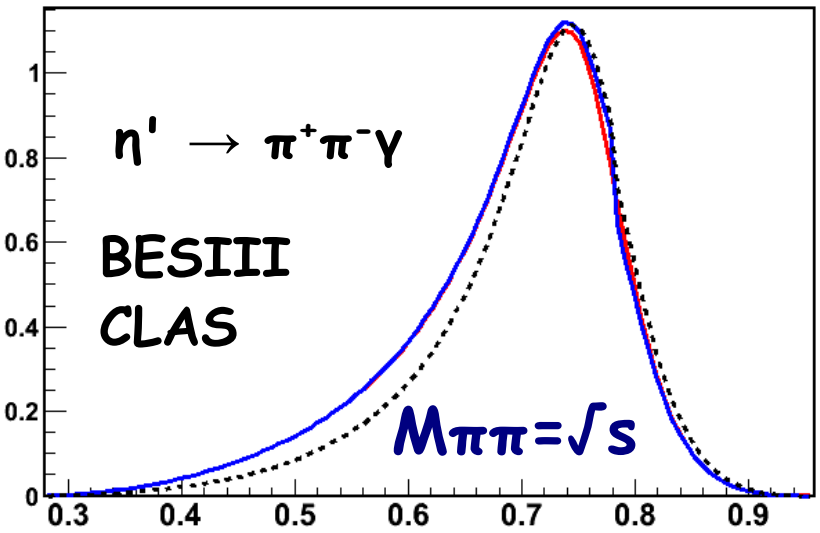
From $\eta \to \pi^+\pi^-\gamma$ to $\eta \to e^+e^-\gamma$

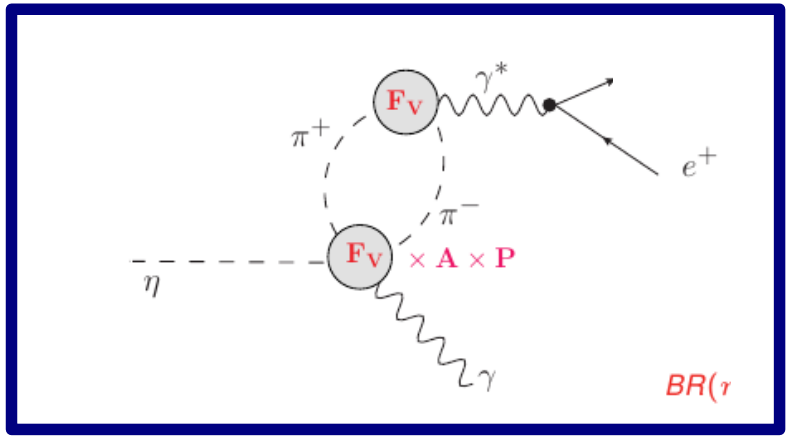


$$P(s_{\pi\pi}) = A_0(1 + \alpha s_{\pi\pi})$$

→ α reaction specific

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



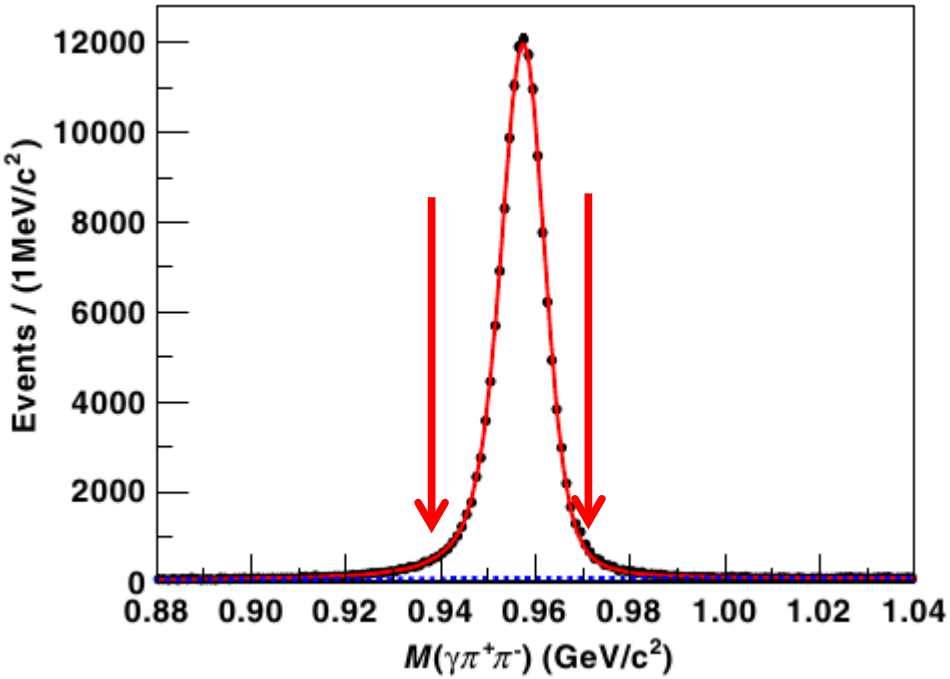


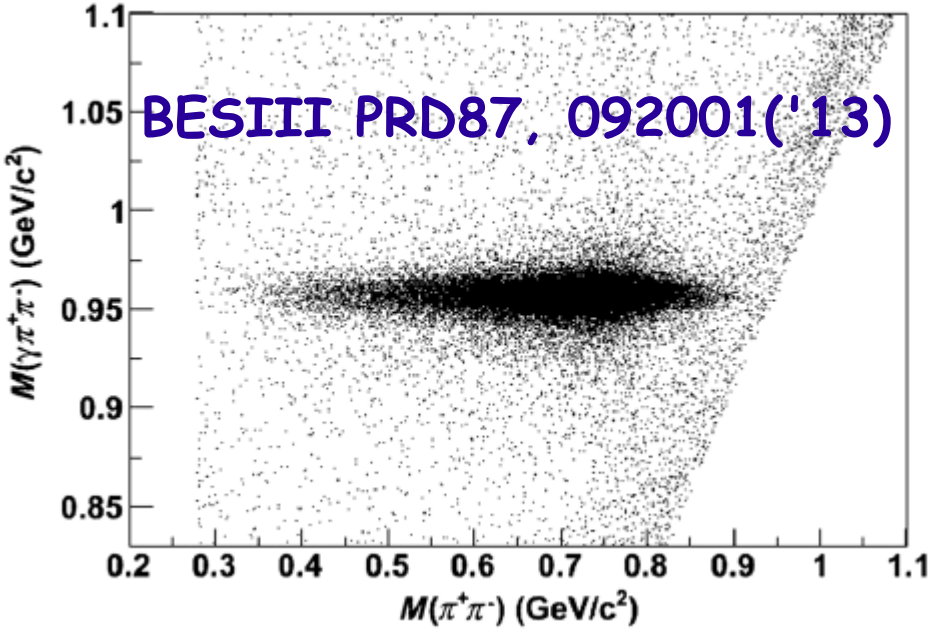
KLOE: A+α => $b_\eta(0) = 2.05^{+0.22}_{-0.10}$ GeV^{-2}

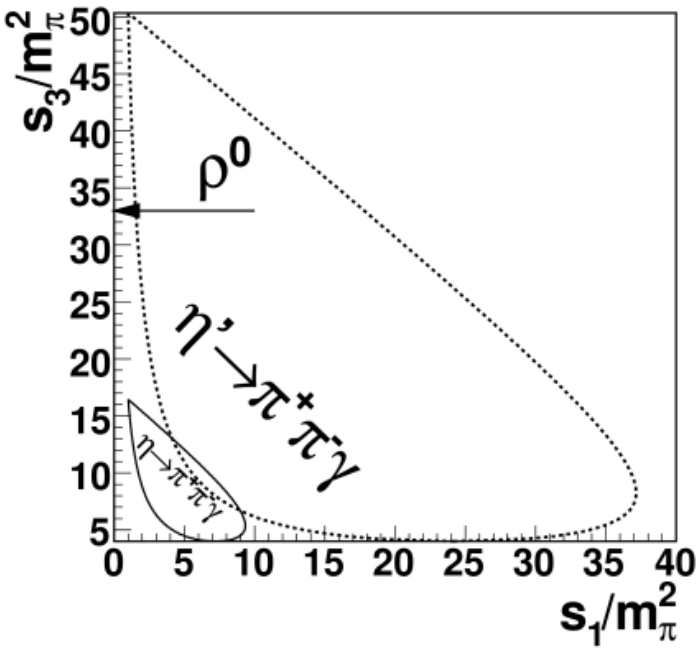
EPJC73(13)2668

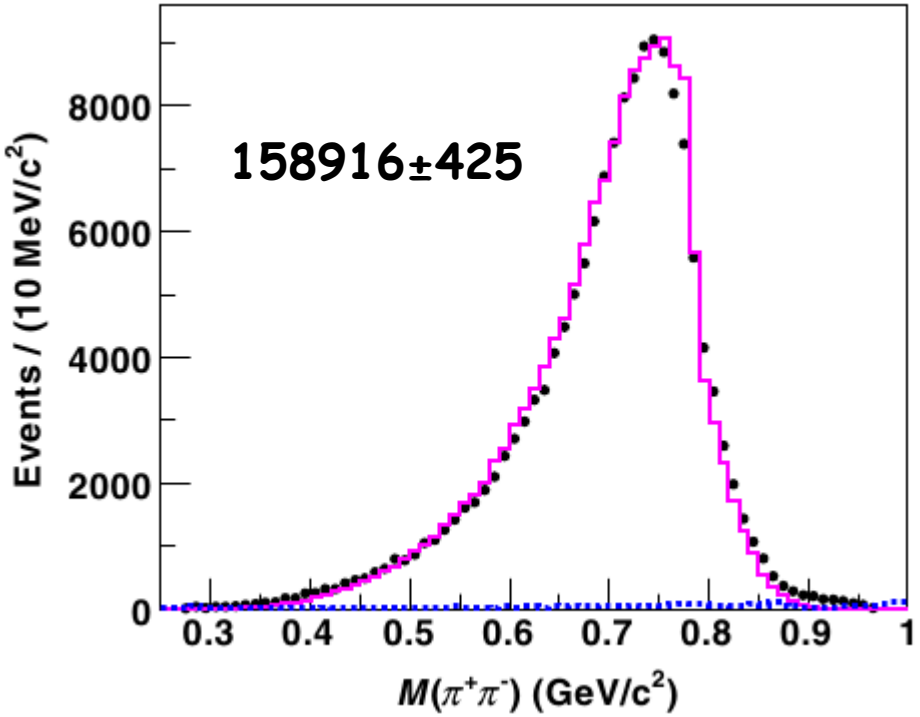
DATA: C Barrel PLB 402,195 ('97); KLOE PL B718, 910 ('13)

BESIII data sample on $\eta' \to \pi^+\pi^-\gamma$



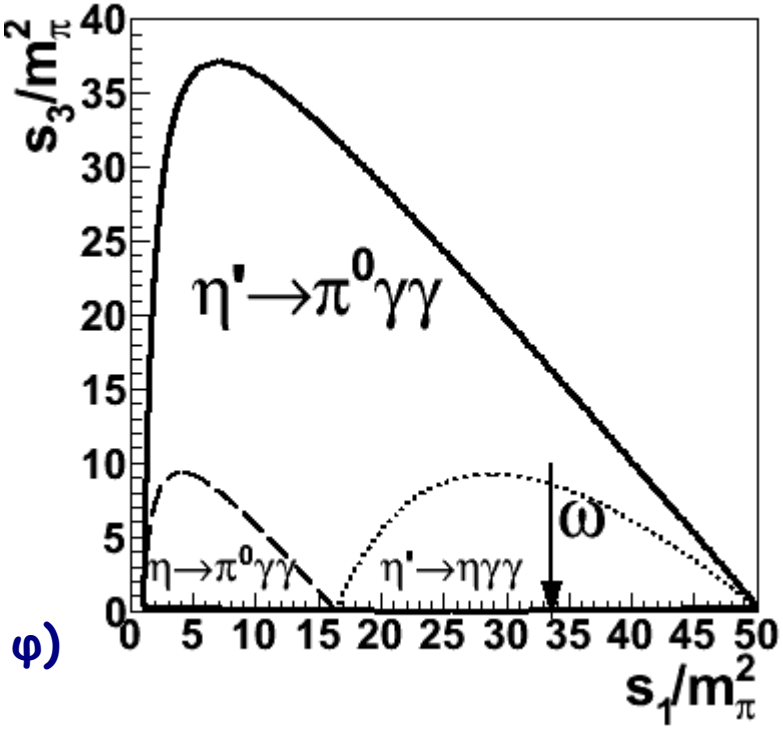




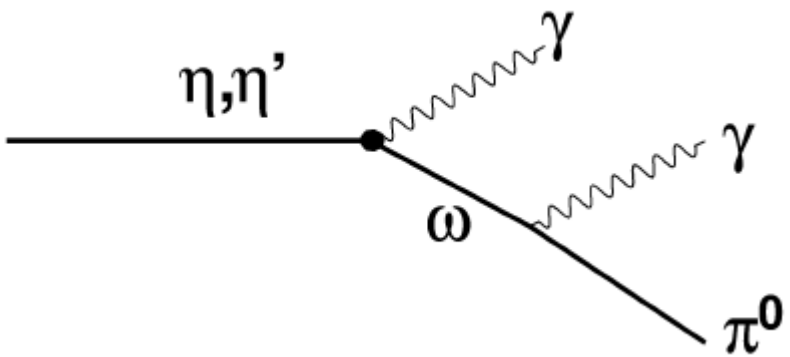


$\eta/\eta' \to \pi^0\gamma\gamma$

BRx10^4	VMD	Exp	
$\eta \to \pi^0\gamma\gamma$	2.1	2.7 ± 0.5	PDG
$\eta' \to \omega[\pi^0\gamma]\gamma$	52		
$\eta' \to \pi^0\gamma\gamma$	3	<8 (90% CL)	GAMS(87)
$\eta' \to \eta\gamma\gamma$	2.5	—	



$\eta' \to \pi^0\gamma\gamma$ 80% ω 4.6% ρ (+15% $\rho\omega$ interf? and φ)
Escribano (arXiv:1207.5400)



Dominant VMD contribution

Summary and outlook

- Neutral meson structure

- Relation to muon (g-2) HLbL

  → Dark photon searches ($\eta/\eta' \rightarrow \pi^0\gamma\gamma$)

- Tests of SM in π^0, η, η' decays
- KLOE,MAMI,WASA,HADES,JLAB,BESIII ($10^{10}\pi^0$, $10^9\eta$, $10^7\eta'$, $10^{10}\varphi$)