Form factor in VPγ^* transitions and study of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot at KLOE

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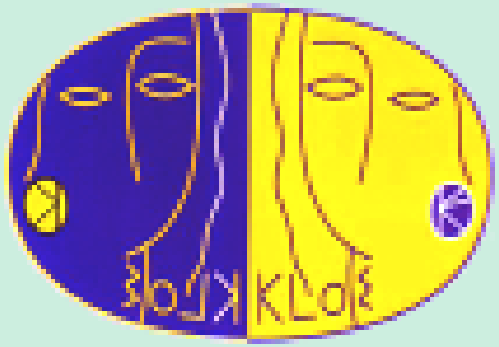
on behalf of the KLOE-2 Collaboration

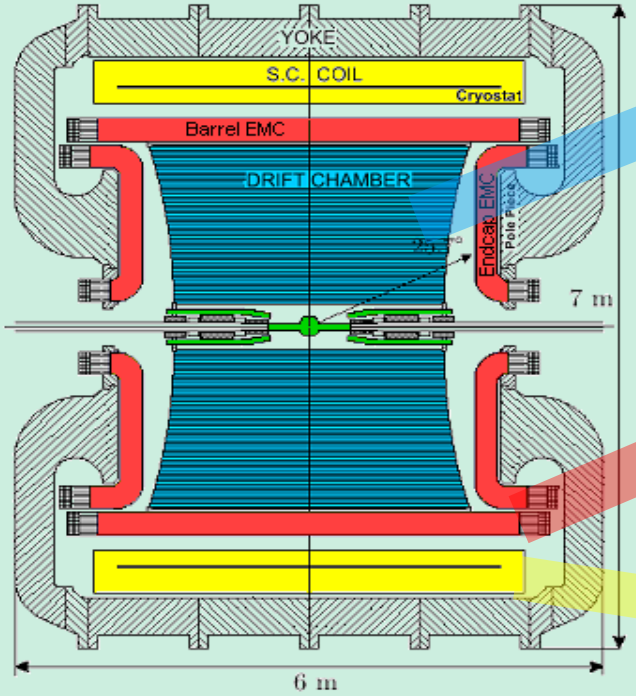


8th International Workshop on Chiral Dynamics
Pisa, 29 June – 3 July 2015

Outline

- The KLOE detector
- Results on hadron physics with KLOE data:
  - Dynamics of the $\eta \to \pi^+\pi^-\pi^0$ decay
  - Transition form factor for $\phi \to \eta e^+e^-$ / $\phi \to \pi^0 e^+e^-$
- Status of KLOE-2
- Perspectives on $\gamma\gamma$ physics @ KLOE-2
- Conclusions

The KLOE experiment



Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ ($\theta > 45^\circ$)**
- **$\sigma_{xy} \approx 150$ μm ; $\sigma_z \approx 2$ mm**

Electromagnetic calorimeter

- lead/scintillating fibers
- 98% solid angle coverage
- **$\sigma_E / E = 5.7\% / \sqrt{(E(GeV))}$**
- **$\sigma_t = 57$ ps $/ \sqrt{(E(GeV))} \oplus 100$ ps**
- **PID capabilities**

Magnetic field: 0.52 T

- The KLOE experiment at the DAΦNE ϕ-factory took data in 2001-2006
- 2.5 fb^{-1} integrated @ 1.02 GeV, 250 pb^{-1} @ 1 GeV
- Excellent quality data set for precision measurements on:
  - ✓ Kaon physics
  - ✓ Light meson spectroscopy
  - ✓ Hadron production in $\gamma\gamma$ collisions
  - ✓ Search for dark force mediator
  - ✓ $\pi^+\pi^-$contribution to $(g-2)_\mu$

ϕ decay	Events/fb^{-1}
K^+K^-	1.5×10^9
K_LK_S	1.0×10^9
η	5×10^7
η'	2×10^5

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

Isospin violating decay, sensitive to light quark mass difference.

From ChPT: Leutwyler,Mod.Ph.Lett.A28(2013)1360014

$$\Gamma = \left(\frac{Q_D}{Q}\right)^4 \overline{\Gamma} \quad \text{with} \quad Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

$Q_D = 24.2$

$\overline{\Gamma}$: decay width evaluated in the Dashen limit

A very accurate determination of Q can be obtained:

1. **Measure Γ** 2. **Test $\eta \to \pi\pi\pi$ dynamics** 3. **Calculate $\overline{\Gamma}$**

Largest statistics measurement: KLOE08 (450 pb^{-1}, 1.34×10^6 events)

Dalitz plot density parametrized as polynomial expansion around X=Y=0:

$$|A(X,Y)^2| \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 \ldots$$

$$X = \frac{\sqrt{3}}{Q}(T_{\pi+} - T_{\pi-}), \qquad Y = \frac{3T_{\pi^0}}{Q} - 1$$

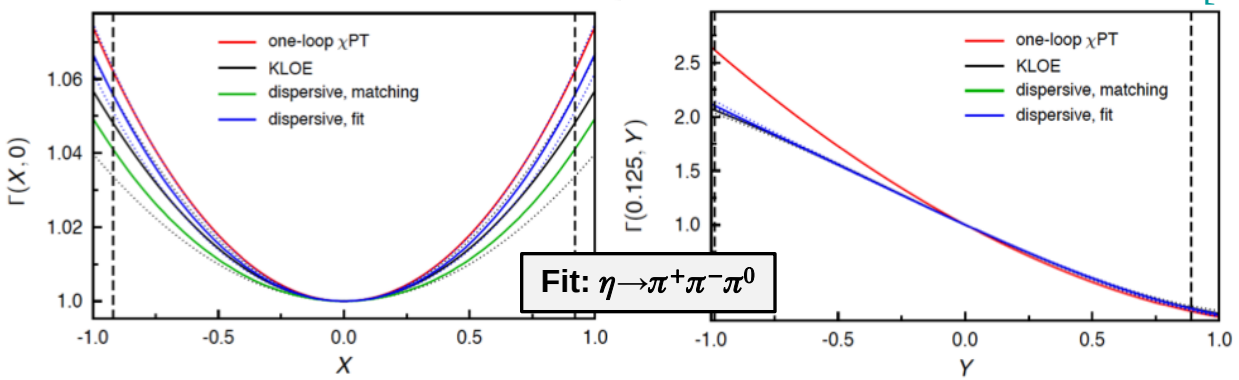
a	$-1.090 \pm 0.005\ ^{+0.008}_{-0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006\ ^{+0.007}_{-0.016}$
e	$-0.006 \pm 0.007\ ^{+0.005}_{-0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
$P(\chi^2)$	73%

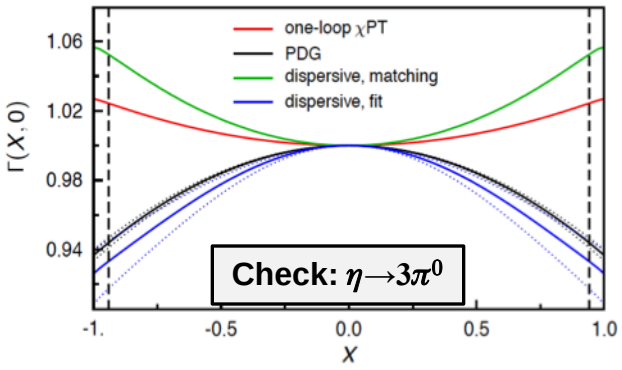
JHEP05 (2008) 006

Q mass ratio constraints from KLOE data

Dispersive analyses of $\eta \to 3\pi$ based on fits to KLOE measurement:

[Colangelo et al. PoS(EPS-HEP2011) 304]





$$Q = 21.3 \pm 0.6$$

using $\hat{m}$ and m_S from lattice QCD:

$$m_u = (2.02 \pm 0.14) MeV$$
$$m_d = (4.91 \pm 0.11) MeV$$

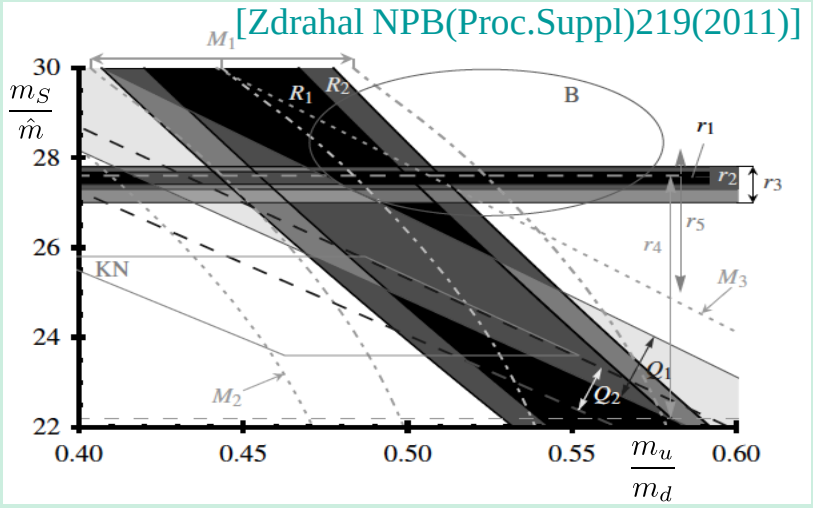
$$R = \frac{m_S - \hat{m}}{m_d - m_u} = 37.7 \pm 3.3$$

[Kampf et al., PRD84(2011)114015]

using $\hat{m}$ and m_S from lattice QCD:

$$m_u = (2.23 \pm 0.14) MeV$$
$$m_d = (4.63 \pm 0.14) MeV$$

[Zdrahal NPB(Proc.Suppl)219(2011)]



$\eta \to \pi^+\pi^-\pi^0$ with new KLOE data set

New analysis on KLOE data:

- Larger and independent data set (1.7 fb^{-1}, ~ 4 times KLOE08)
- New analysis scheme
- Improved MC simulation

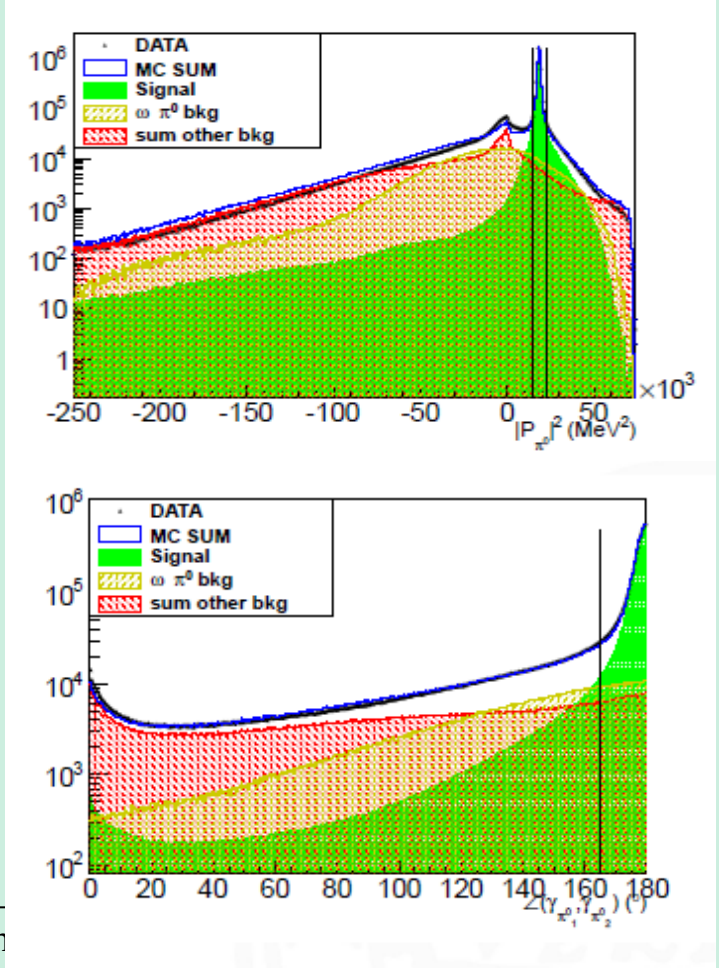
> Reduce systematics

$$e^+e^- \to \phi \to \eta\gamma_\phi \to \pi^+\pi^-\gamma\gamma\gamma_\phi$$

- Most energetic photon assigned to γ_ϕ
- Primary photon energy from 2-body kinematics
- Decay kinematics to assign photons from π^0
- Cuts on:

  MM($\phi - \gamma_{rad} - \pi^+ - \pi^-$) – m($\pi^0$)| < 15 MeV

  $\gamma\gamma$ opening angle in the π^0 rest frame > 165°



- **Background scaling factors from fit**
- **Signal efficiency 37.6%**
- **Residual background contamination 0.96%**

$\eta \to \pi^+\pi^-\pi^0$ with new KLOE data set

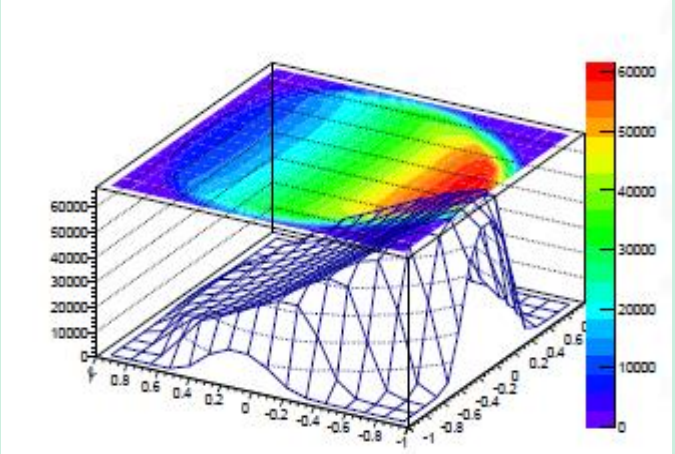
Fit to the data-bckg distribution with:

$$N_{th} = \int N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3)\, dP(X,Y)$$

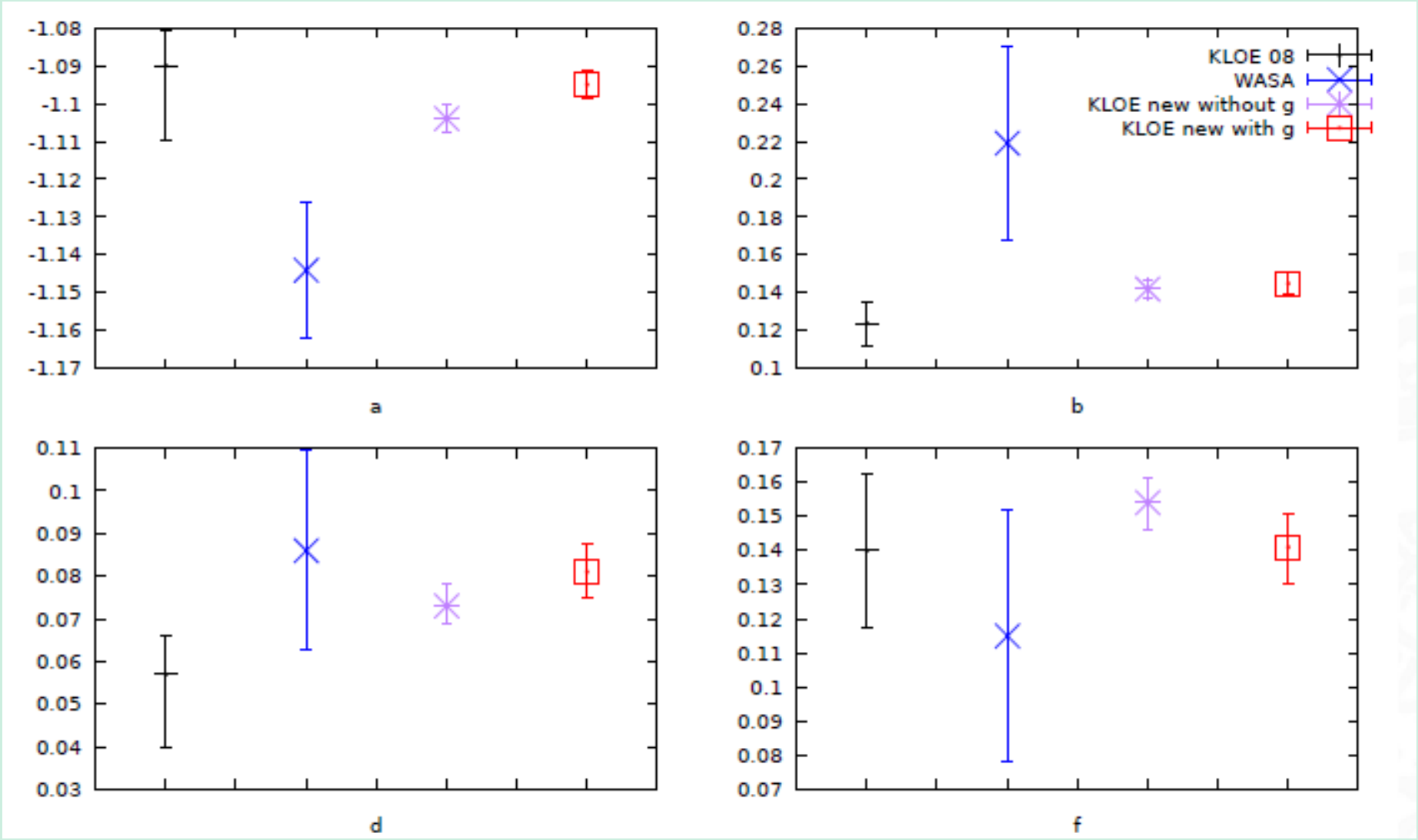
folded with smearing matrix and analysis efficiency. Bin size ~$3 \times \sigma_{X,Y} \sim 0.06, 0.1$

	$-a$	b	d	f	$-g$	$Prob(\chi^2)$
KLOE08	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)	—	
This work	$1.104(3)(2)$	$0.142(3)(^{+5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$	—	0.24
This work	$1.095(3)(^{+3}_{-2})$	0.145(3)(5)	$0.081(3)(^{+6}_{-5})$	$0.141(7)(^{+7}_{-8})$	$-0.044(9)(^{+12}_{-13})$	0.56

- In agreement with previous KLOE result
- *g* parameter different from 0 at 3 σ level
- *c*, *e*, *h*, *l* consistent with 0 (C-invariance condition) when used as free fit parameters



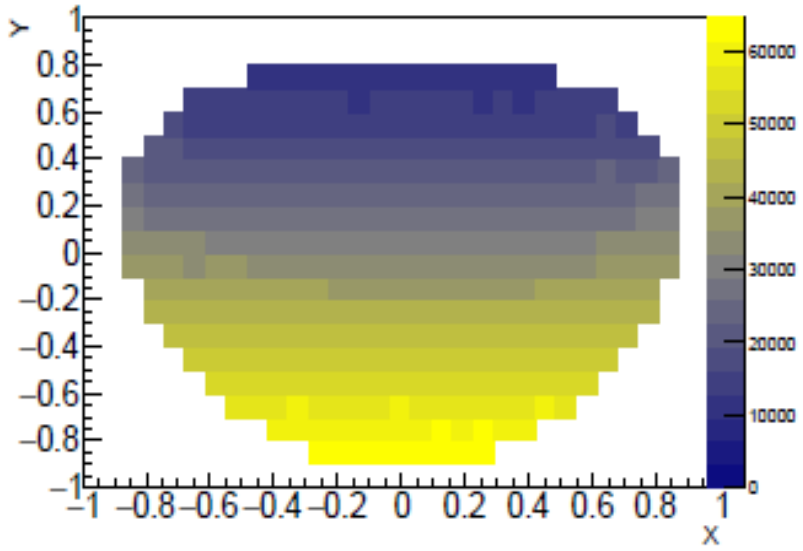
$\eta \to \pi^+\pi^-\pi^0$: comparison of latest exp. results



$\eta \to \pi^+\pi^-\pi^0$: acceptance corrected data

Smearing matrix close to diagonal

Acceptance corrected data to directly fit theory



Full smearing matrix

$$a = -1.095(3)(^{+3}_{-2})$$
$$b = 0.145(3)(5)$$
$$d = 0.081(3)(^{+6}_{-5})$$
$$f = 0.141(7)(^{+7}_{-8})$$
$$g = -0.044(9)(^{+12}_{-13})$$

Acc corrected data

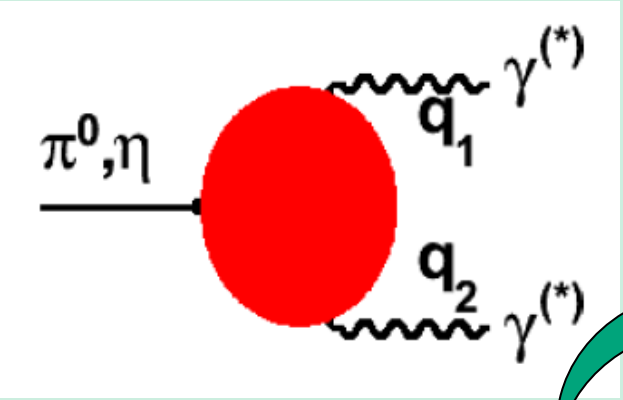
$$a = -1.092(3)$$
$$b = 0.145(3)$$
$$d = 0.081(3)$$
$$f = 0.137(6)$$
$$g = -0.044(8)$$

$$a = -1.104(3)(2)$$
$$b = 0.142(3)(^{+5}_{-4})$$
$$d = 0.073(3)(^{+4}_{-3})$$
$$f = 0.154(6)(^{+4}_{-5})$$

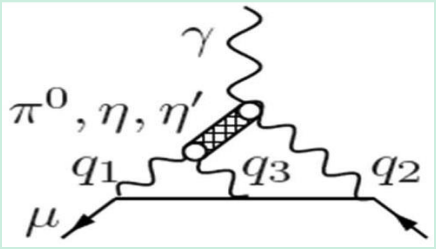
$$a = -1.101(3)$$
$$b = 0.142(3)$$
$$d = 0.072(3)$$
$$f = 0.150(6)$$

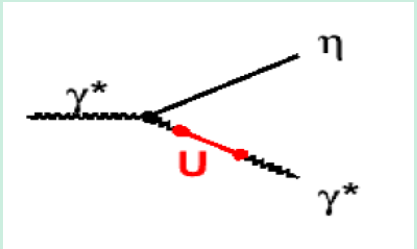
Results in agreement within 1 σ_{fit}

Meson transition form factor



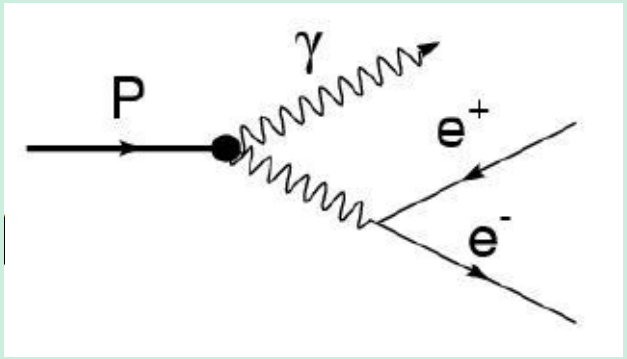
- Low energy QCD
  - Enters in th. description of QCD processes
  - Evolution with Q^2 predicted by pQCD: models can be tested using data on Q^2 dependence
- Light-by-light contribution to a_μ
- Search for light dark force mediator



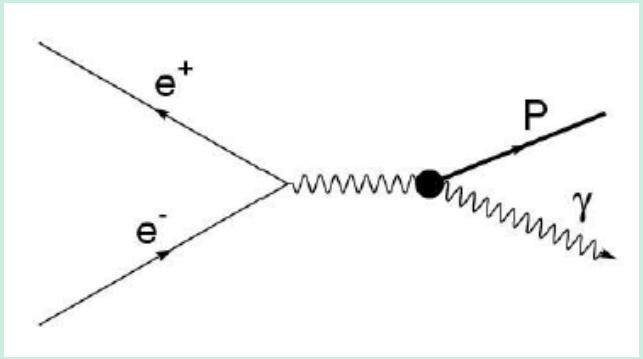


Experimentally:

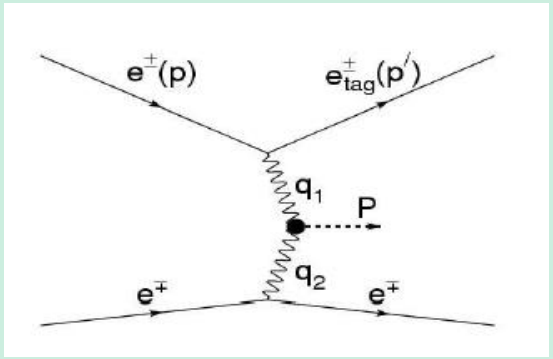
Dalitz decays



Annihilation processes



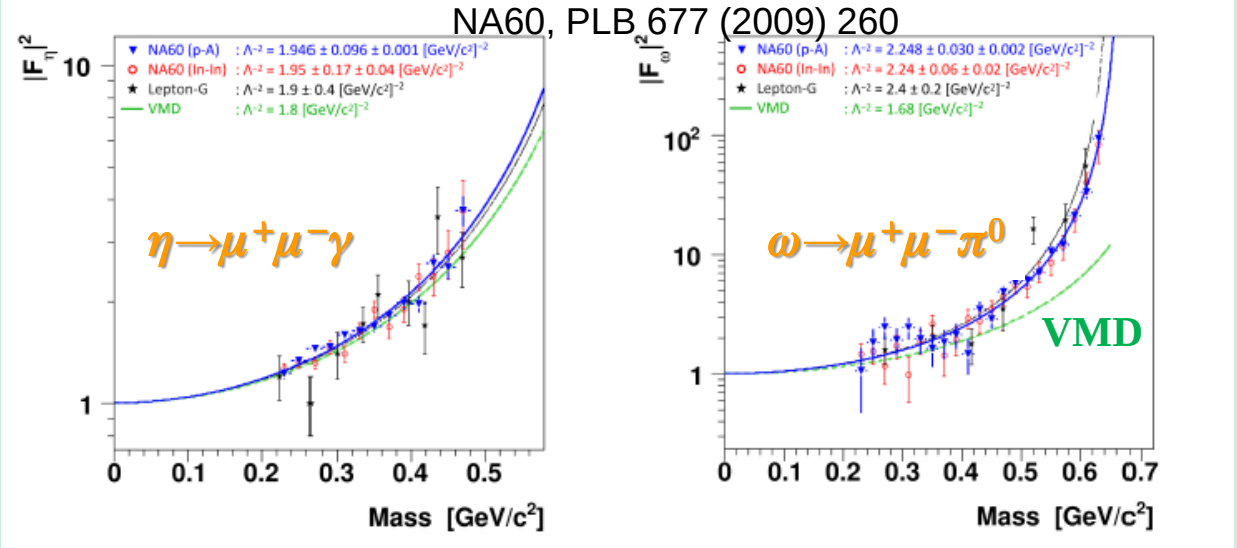
Two photon production



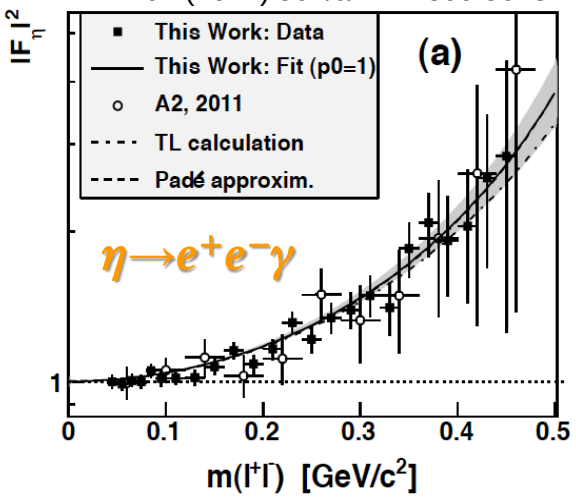
TFF from Dalitz decays

Naive VMD approach well describes $\eta \to \gamma \ell^+ \ell^-$, but fails for $\omega \to \pi^0 \ell^+ \ell^-$

NA60, PLB 677 (2009) 260



A2: PLB 701 (2011) 562/arXiv:1309.5648



Theory:

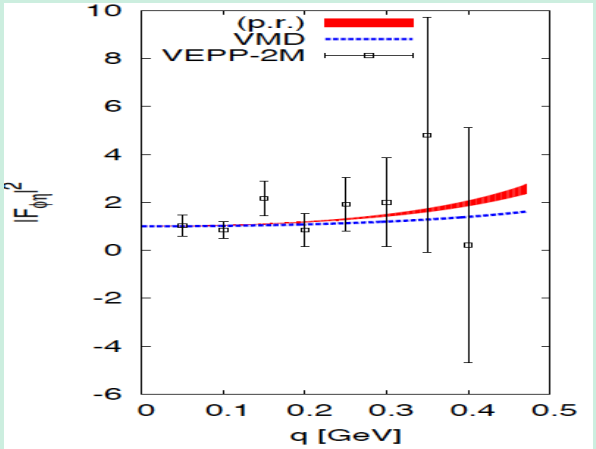
- Terschlusen and Leupold, Phys. Lett. B 691 191 (2009)
- Ivashyn, Prob. Atom. Sci. Tech. 2012N1 179 (2012)
- Schneider Kubis Nieking, Phys. Rev. D86 054013 (2012)

Experimental needs: 1. New measurement of $\omega \to \pi^0 \ell^+ \ell^-$ TFF
2. Study of other V→Pγ^* transitions

The only existing measurement is from $\phi \to \eta e^+ e^-$ (213 events):

$$b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} = (3.8 \pm 1.8)\ \mathrm{GeV}^{-2}$$

[SND, PLB 504 (2001) 275]



VMD: $(q^2 = M^2_{\ell^+\ell^-})$ $F(q^2) = \dfrac{1}{1 - q^2/\Lambda^2}$ $b_{\phi\eta} \sim M_\phi^{-2} \sim 1\ \mathrm{GeV}^{-2}$

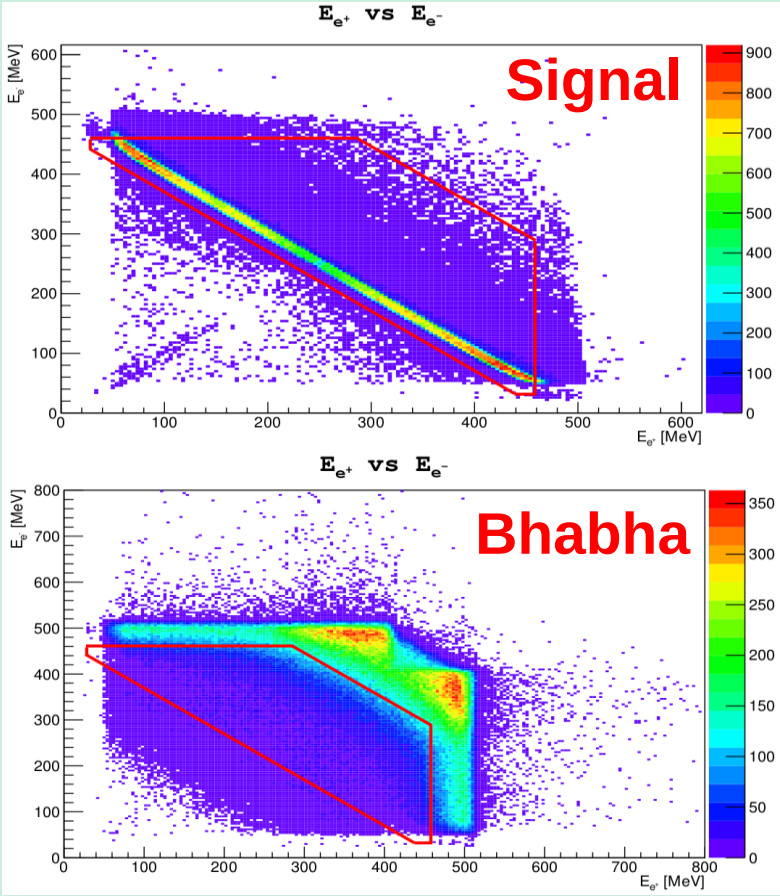
$\phi \to \pi^0 e^+ e^-$: selection cuts

- No data available for $F_{\phi\pi}(q^2)$
- 30-40% error on BR

- SND: $(1.01 \pm 0.40) \times 10^{-5}$ [JETP 75 (2002) 449]
- CMD-2: $(1.22 \pm 0.40) \times 10^{-5}$ [PLB 503 (2001) 237]

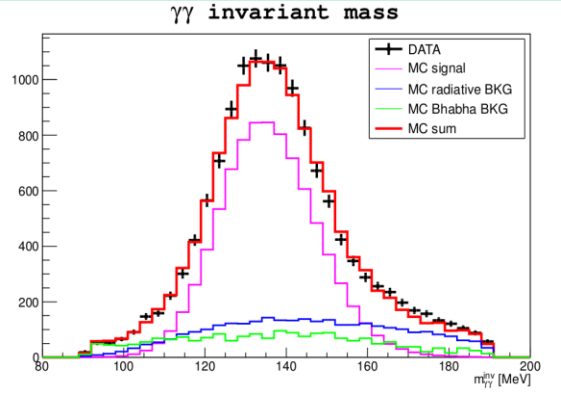
- Background from radiative Bhabha scattering events and $V \to P\gamma$: several orders of magnitude larger

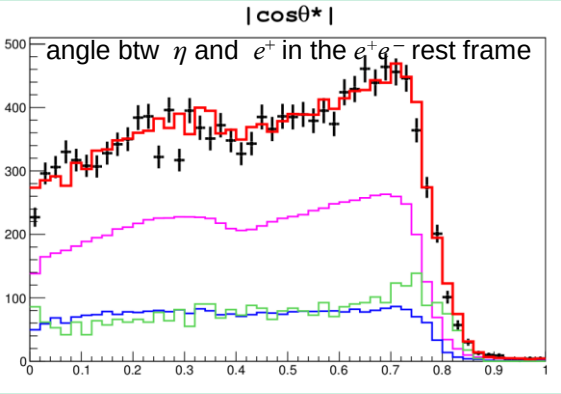
- Selection cuts:
  - $E_e < 460$ MeV
  - $470 < E_{e+} + E_{e-} < 750$ MeV
  - $300 < E_{\gamma 1} + E_{\gamma 2} < 670$ MeV
  - $\theta_{open}(ee) < 145^o$, $27^o < \theta_{open}(\gamma\gamma) < 57^o$
  - $90 < M_{2\gamma} < 190$ MeV
  - $80 < M_{miss}(ee) < 180$ MeV
  - Cut to reject γ conversions

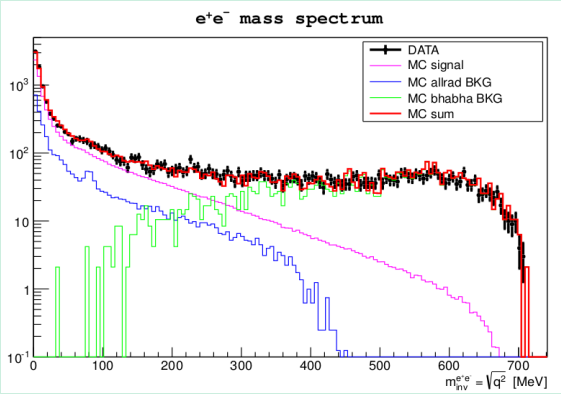


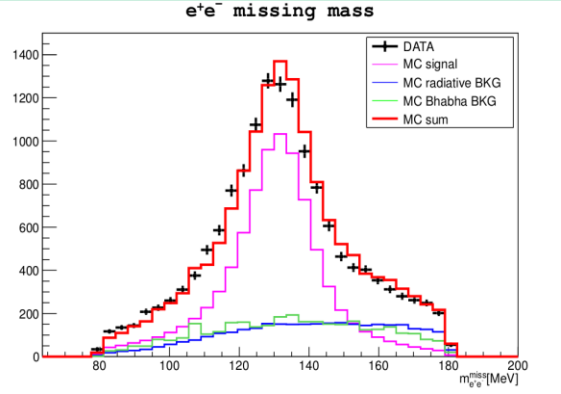
$\phi \to \pi^0 e^+ e^-$: data-MC comparison

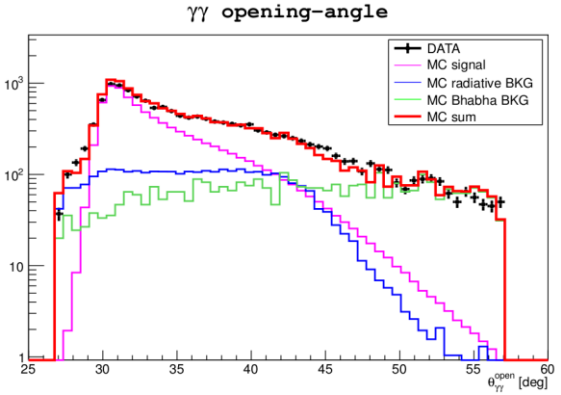
- L_{int} = 1.7 fb^{-1}
- 8777 signal events
- Global efficiency from 15% at low M_{ee} to 2% at 0.6 GeV

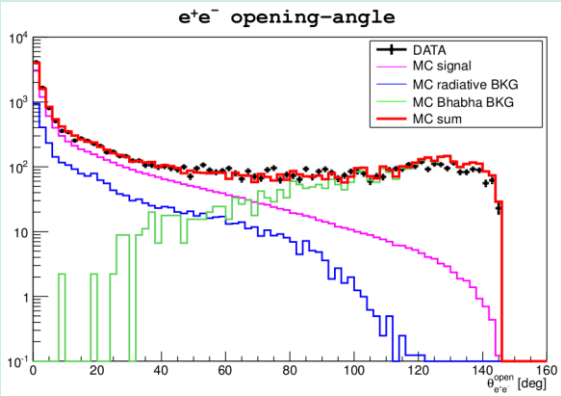








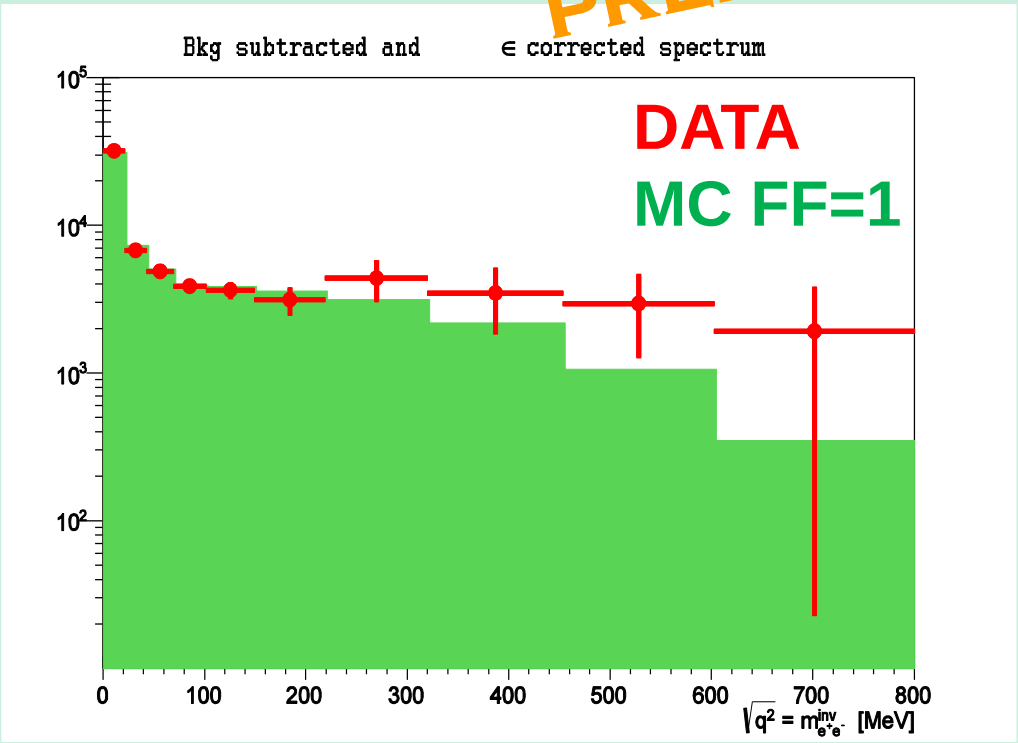


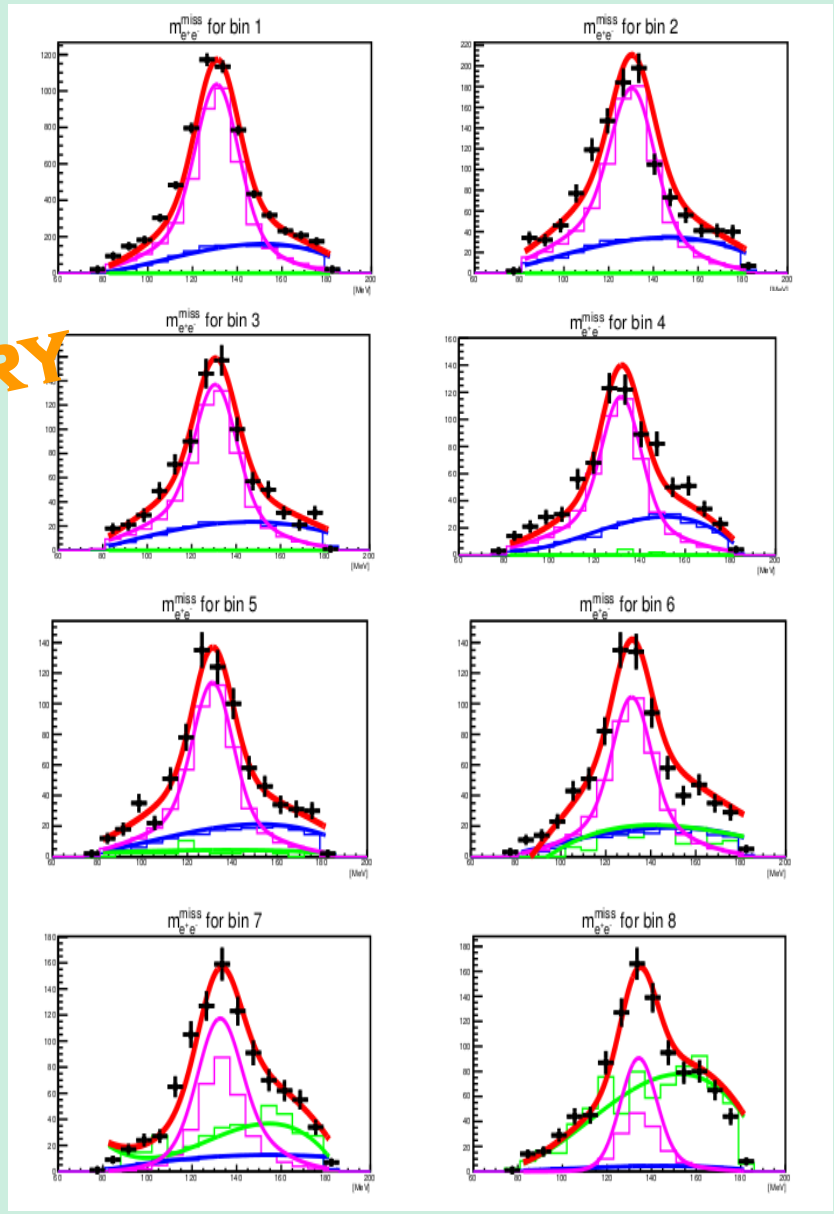


$\phi \to \pi^0 e^+ e^-$: transition form factor

- Bckg subtraction still in progress, evaluated for each M_{ee} value with a fit to the e^+e^- missing mass
- Fit systematics currently limited by Bhabha MC statistics

PRELIMINARY



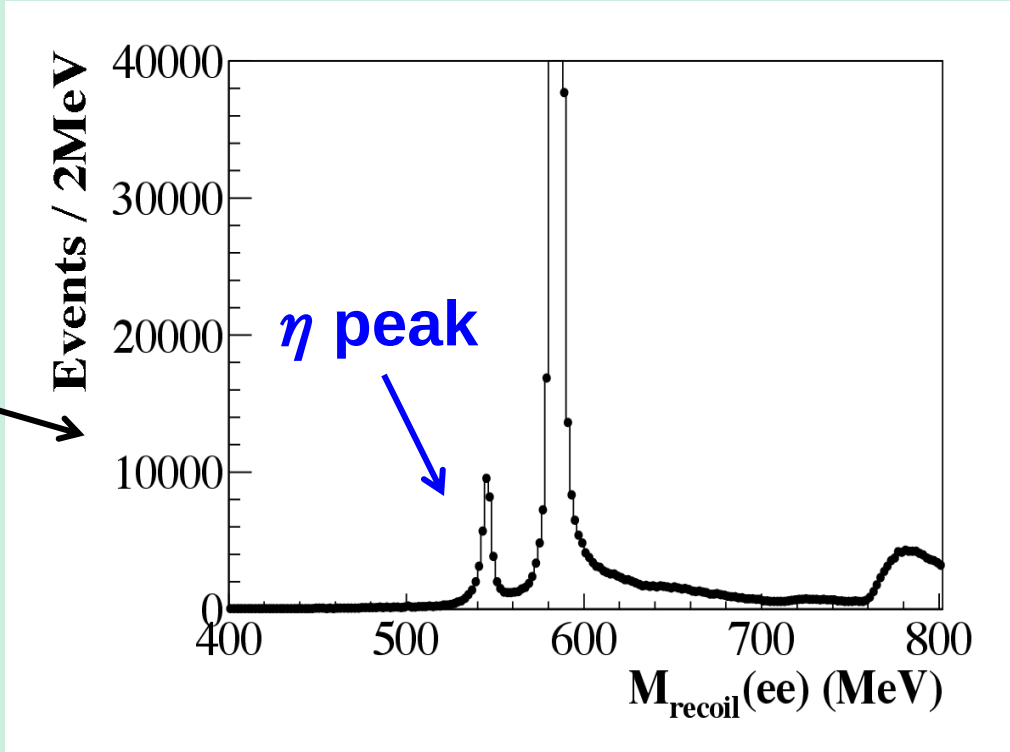


$\phi \to \eta e^+ e^-, \eta \to \pi^0\pi^0\pi^0$: analysis scheme

Analysis performed using L_{int} = 1.7 fb^{-1}

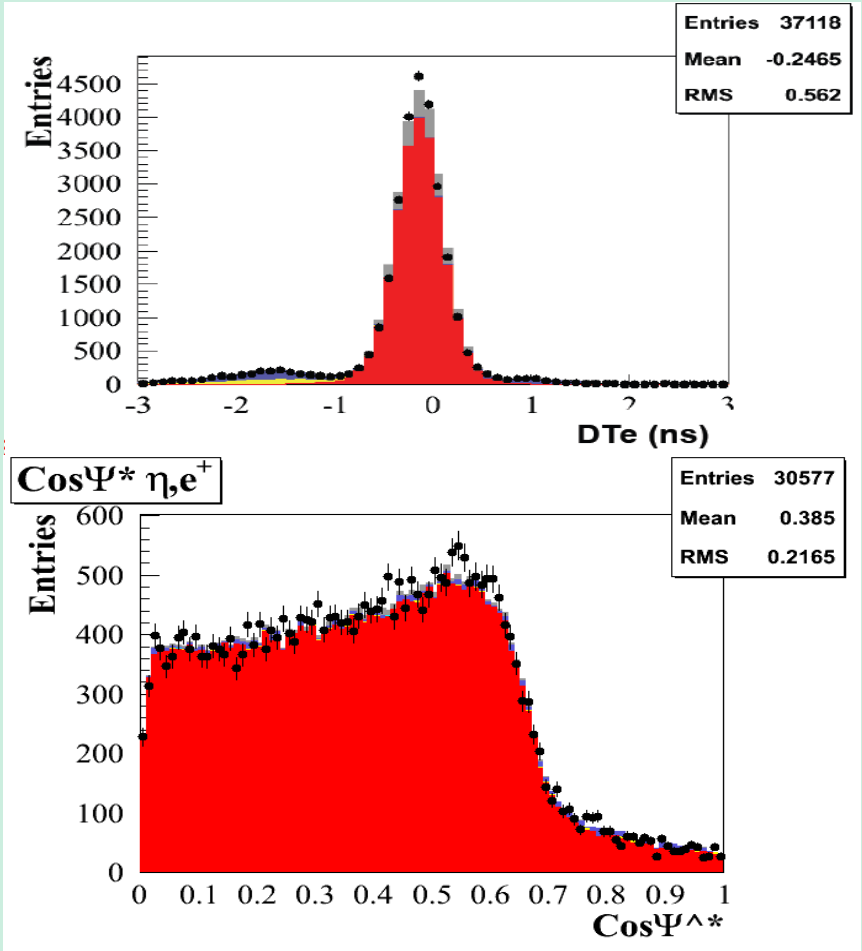
Selection:

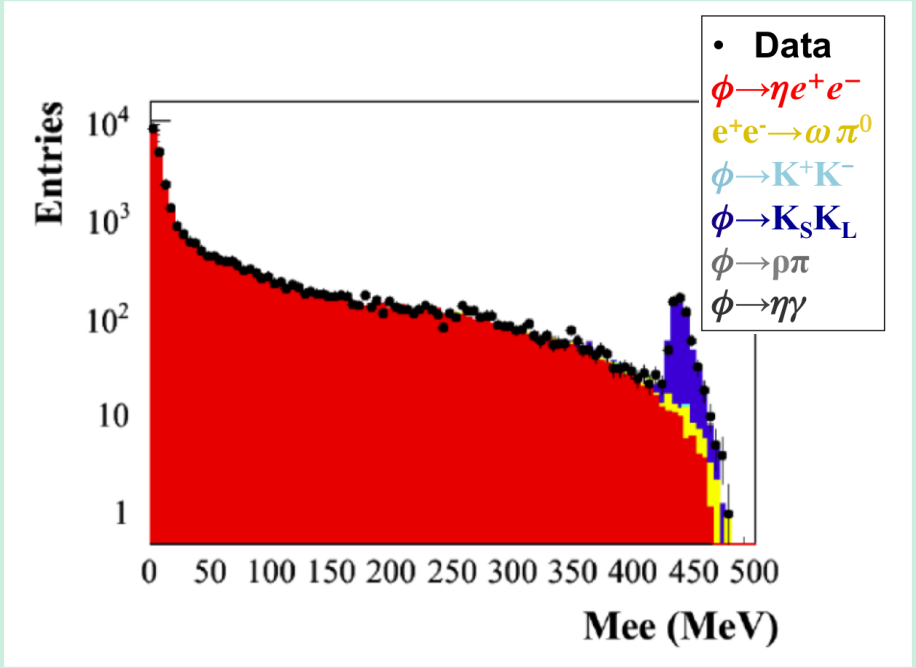
- 2 tracks in a cylinder around IP + 6 photon candidates
- $400 < M_{6\gamma} < 700$ MeV
- $536.5 < M_{recoil}(ee) < 554.5$ MeV
- Photon conversion cut
- ToF cuts to reject pions



After all analysis cuts: ~15% global efficiency
~ 30000 signal events
small background contribution (<3%)

$\phi \to \eta e^+ e^-$, $\eta \to \pi^0\pi^0\pi^0$: BR evaluation





Ψ*: angle between the η and the e^+ in the e^+e^- rest frame

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$$BR(\phi \to \eta e^+ e^-) = (1.075 \pm 0.007 \pm 0.038) \times 10^{-4}$$

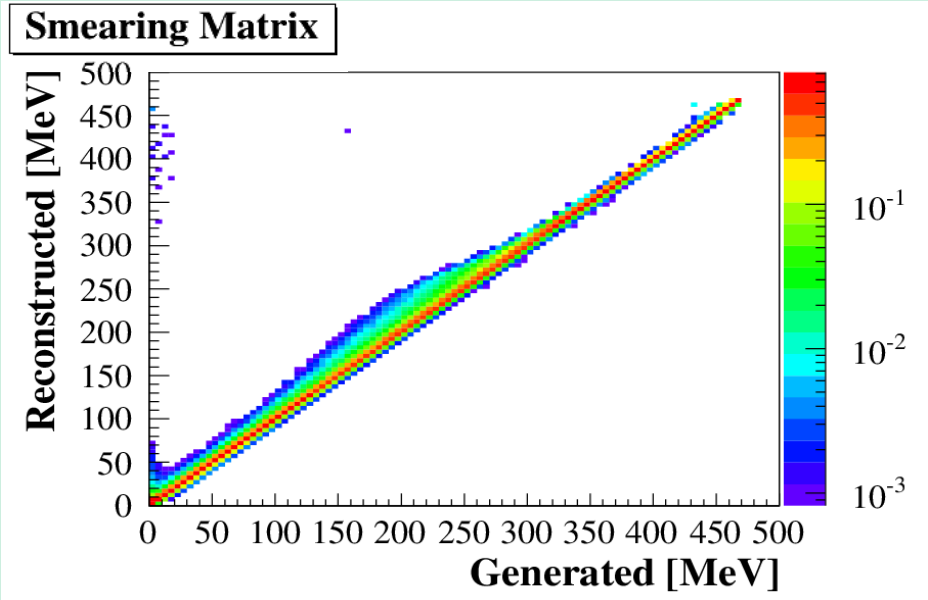
- VMD: 1.1
- SND: $(1.19 \pm 0.31) \times 10^{-4}$ [PLB 504 (2001) 275]
- CMD-2: $(1.14 \pm 0.16) \times 10^{-4}$ [PLB 501 (2001) 191]

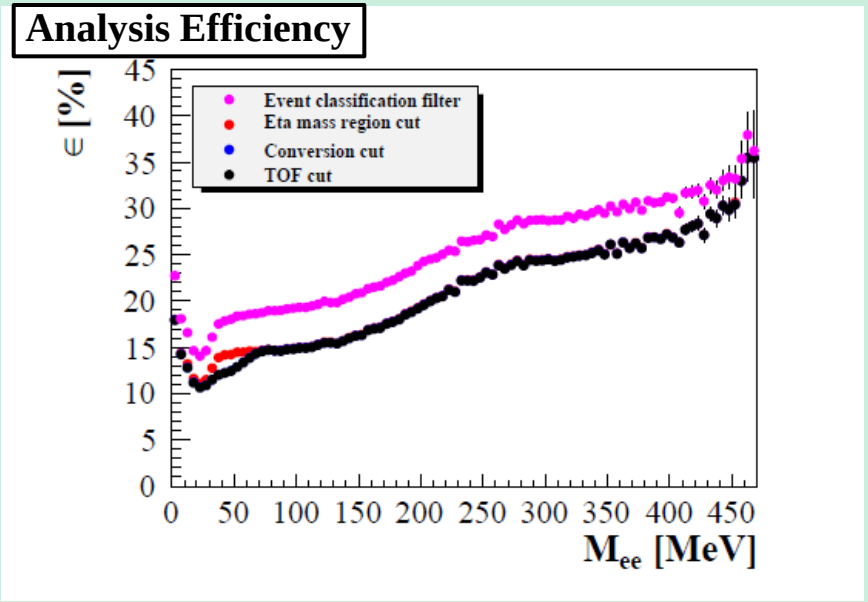
$\phi \to \eta e^+ e^-$: fit to the di-lepton inv. mass

Fit to M_{ee} distribution with decay parametrization from PR128 (1985) 301, to extract transition form factor

$$\frac{d}{dq^2}\frac{\Gamma(\phi \to \eta e^+ e^-)}{\Gamma(\phi \to \eta\gamma)} = \frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2 q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

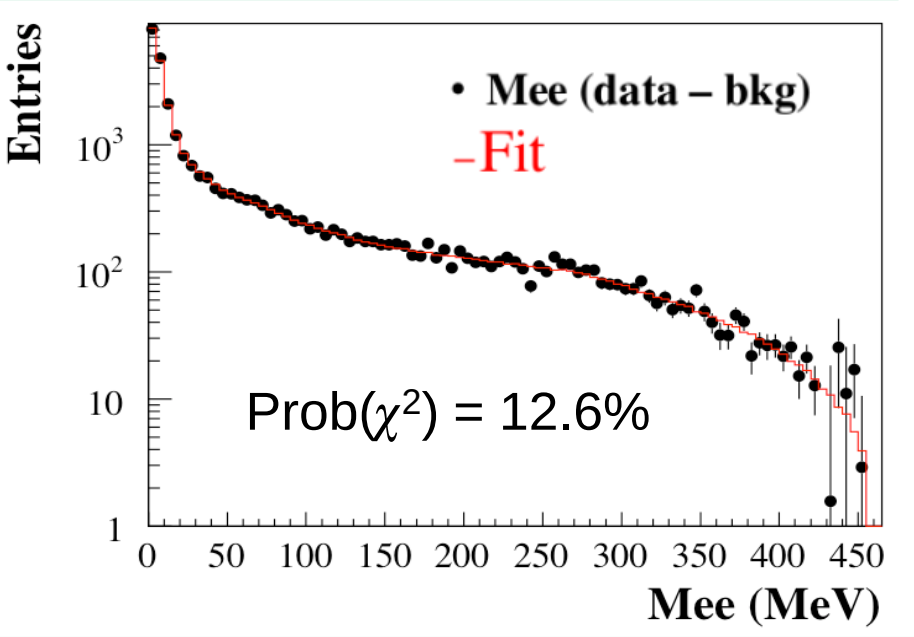
Smearing matrix, bin-by-bin analysis efficiency properly taken into account



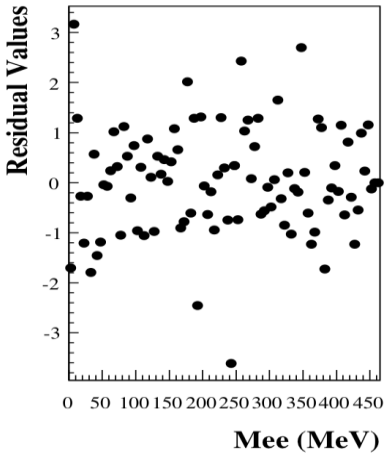


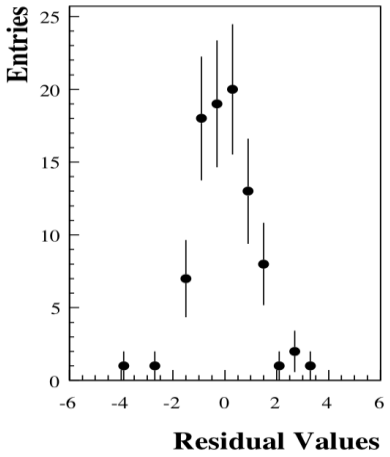
Photons from FSR included in the event generator

$\phi \to \eta e^+ e^-$: transition form factor



Fit residuals





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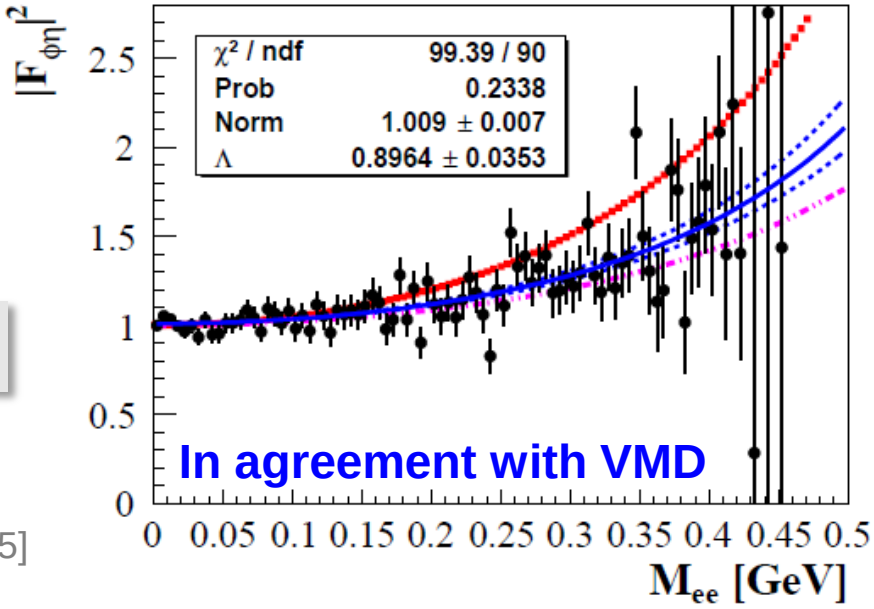


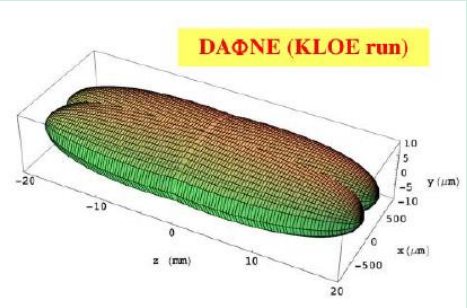
$b_{\phi\eta} = (1.17 \pm 0.10\ ^{+0.07}_{-0.11})\ \text{GeV}^{-2}$

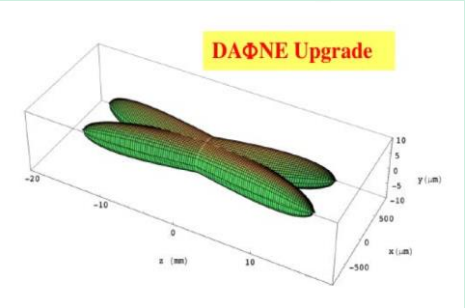
- VMD: ~ 1.0 GeV^{-2}
- SND: (3.8 ± 1.8) GeV^{-2} [PLB 504 (2001) 275]

Status of KLOE-2 run

DAΦNE: new interaction scheme

- Large angle beam crossing
- Crabbed waist sextupoles





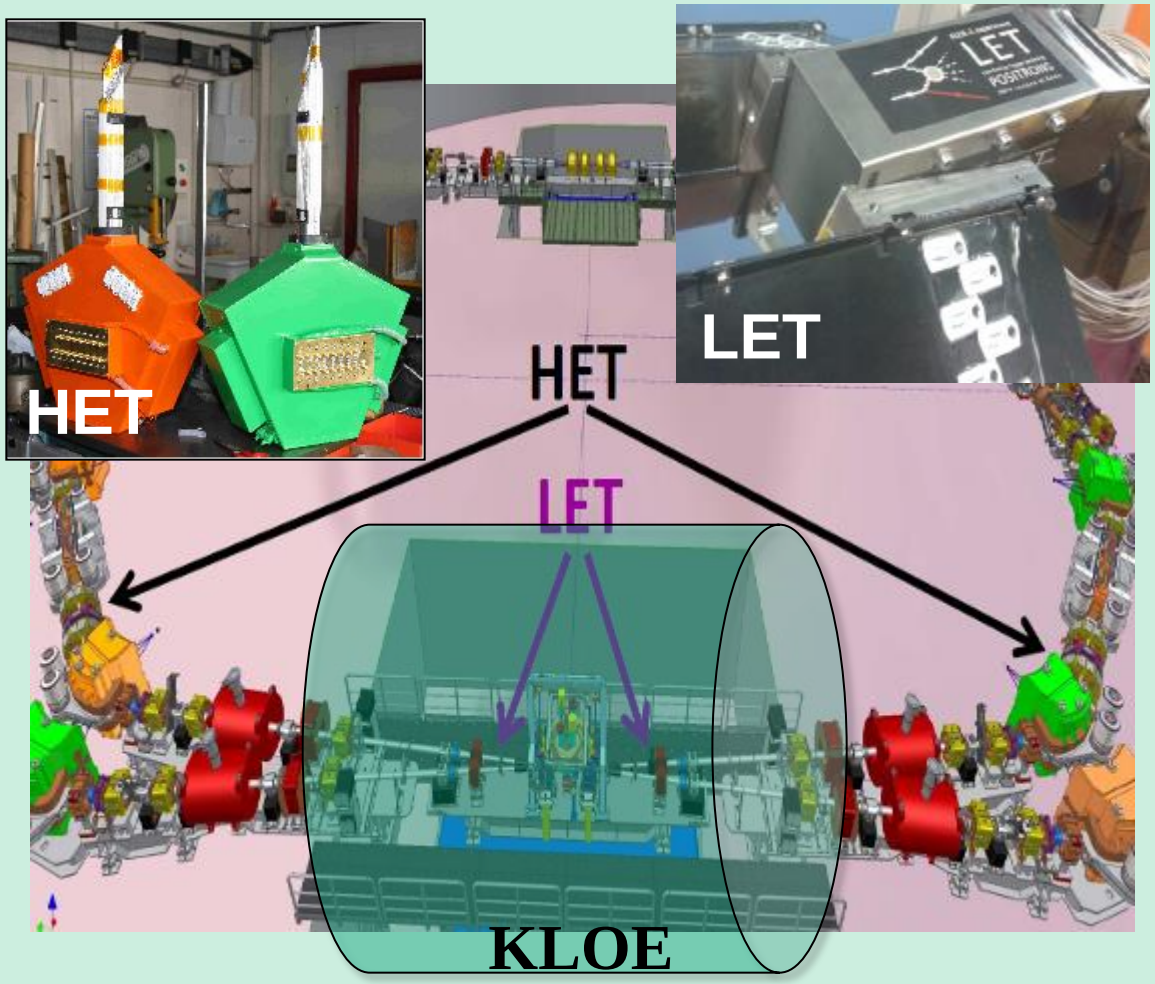
KLOE-2:

- Detector upgrade
- Extension of the KLOE physics program [Eur. Phys. J. C 68 (2010), 619]
- Expected ≥ 5 fb^{-1} in three years running

- **KLOE-2 run since November 2014 for machine/detector commissioning**
- **Milestone: 1 fb^{-1} by the end of June → DELIVERED!**
- **DAΦNE performance: $L_{peak} = 2 \times 10^{32}$ cm^{-2}s^{-1}, $L_{int} = 12$ pb^{-1}/day**
- **KLOE-2 detectors operational**
- **Background levels much higher then in the past + random beam losses**

The KLOE-2 upgrade: $\gamma\gamma$ taggers

2+2 $\gamma\gamma$ taggers installed and ready for the KLOE-2 run
Measurement of lepton momenta in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$



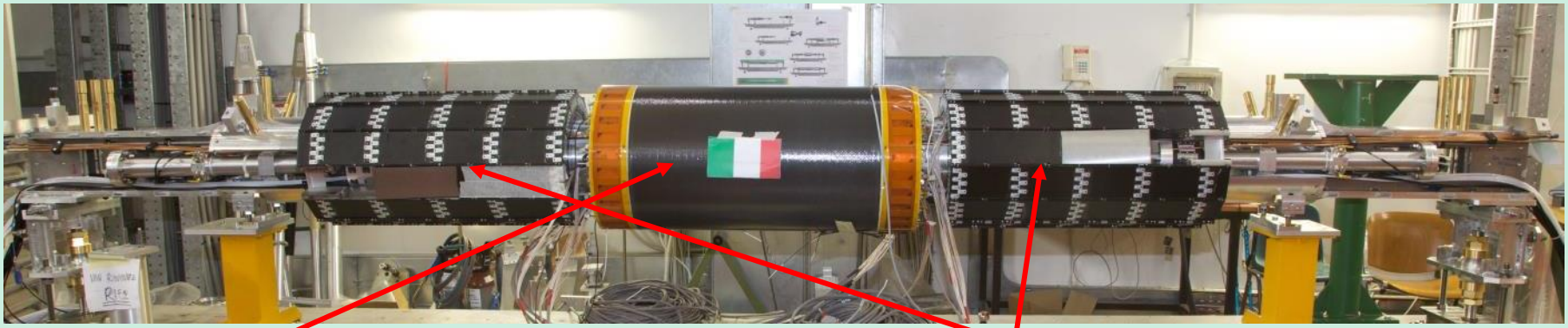
LET : E=160–230 MeV

- Inside KLOE detector
- LYSO+SiPM
- σ_E<10% for E>150 MeV

HET : E > 400 MeV

- 11 m from IP
- Scintillator hodoscopes
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps

The KLOE-2 upgrade: IR region



INNER TRACKER

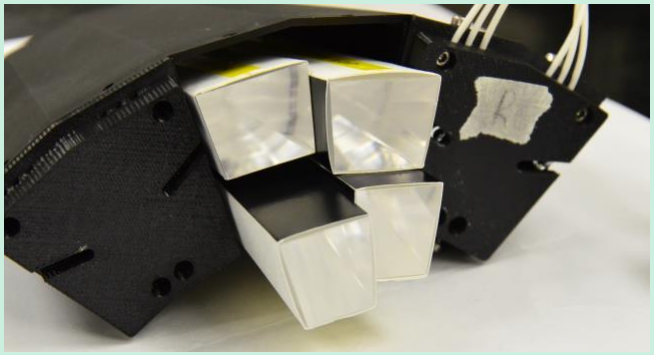
- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

QCALT

- W + scintillator tiles + WLS/SiPM
- QUADS coverage for K_L decays

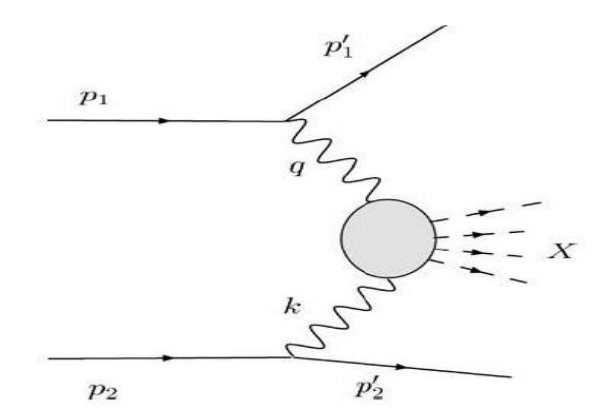
CCALT

- LYSO + SiPM
- Increase acceptance for γ's from IP ($21^o \rightarrow 10^o$)



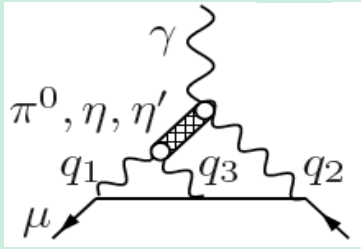
Installation completed. Commissioning in progress with DAΦNE beams

TFF from $\gamma\gamma$ interactions



$$\sigma_{\gamma\gamma\to R}(q_1,q_2) \propto \Gamma_{R\to\gamma\gamma}\frac{8\pi^2}{M_R}\delta((q_1+q_2)^2-M_R^2)\left|F(q_1^2,q_2^2)\right|^2$$

- Transition form factors crucial for hadronic light-by-light contributions to g-2
- $\Gamma_{\gamma\gamma}$ should be known precisely



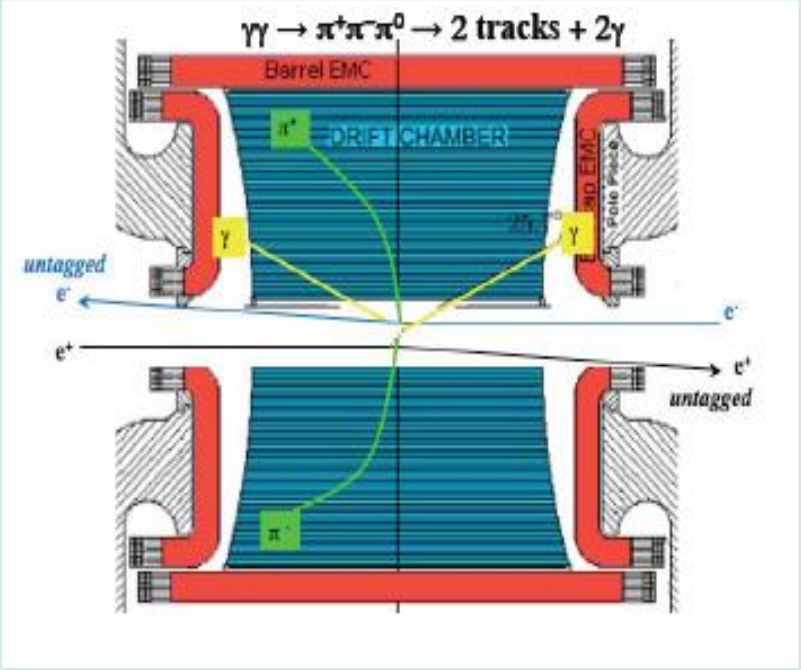
$\gamma\gamma$ physics @ KLOE/KLOE-2:

KLOE: no $e^{\pm}$ tagging

⇒ $\sqrt{s}$ = 1 GeV

KLOE-2: tagger to reduce background from ϕ and to close kinematics

⇒ $\sqrt{s} = M_\phi$



$\Gamma(\eta\to\gamma\gamma)$ @ KLOE

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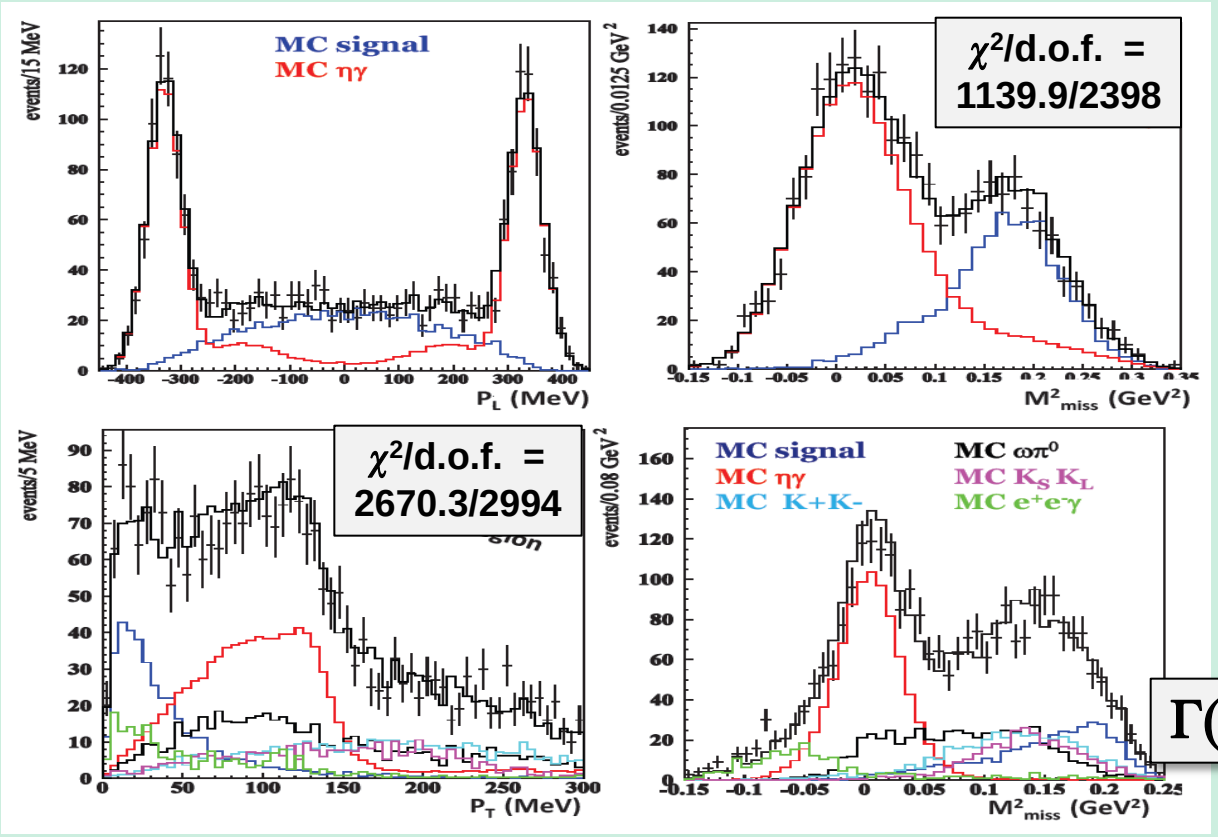
- From $\gamma\gamma\to\eta$ events. No $e^{\pm}$ tagging
- Data sample: **240 pb^{-1} @ $\sqrt{s}$ = 1 GeV** (reduced background from ϕ)
- Selected channels: $\eta\to\pi^+\pi^-\pi^0/\pi^0\pi^0\pi^0$
- Main background: $\phi\to\eta\gamma$ with undetected recoil photon
- 2D fit to $M_{miss}^2 - p_{L/T}$ plane with signal and background MC shapes



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

- ✓ $e^+e^-\to\phi\to\eta\gamma$ contribution free

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

- ✓ $e^+e^-\to\phi\to\eta\gamma$ constrained
- ✓ Background weights checked in control regions

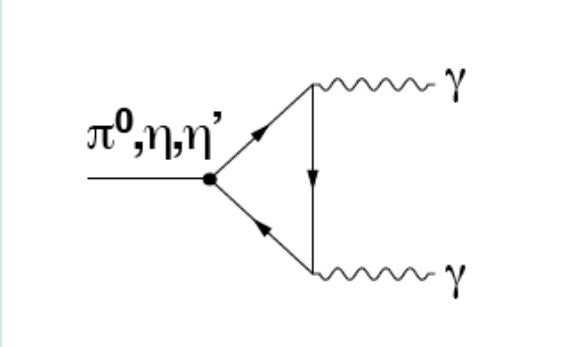
$$\Gamma(\eta\to\gamma\gamma)=(520\pm20\pm13)\ \text{eV}$$

most precise measurement to date

Perspectives for $\gamma\gamma \to \pi^0$ @ KLOE-2

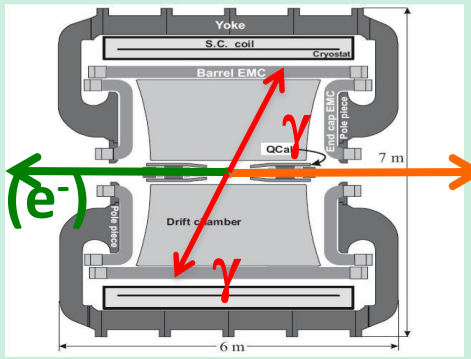
EPJC (2012) 72:1927

$\Gamma(\pi^0 \to \gamma\gamma)$ width



$\Gamma(\pi^0 \to \gamma\gamma)$: best measurement from Primakoff-process, PrimEX @ Jlab, at 2.8%: PRL 106(2011)162303

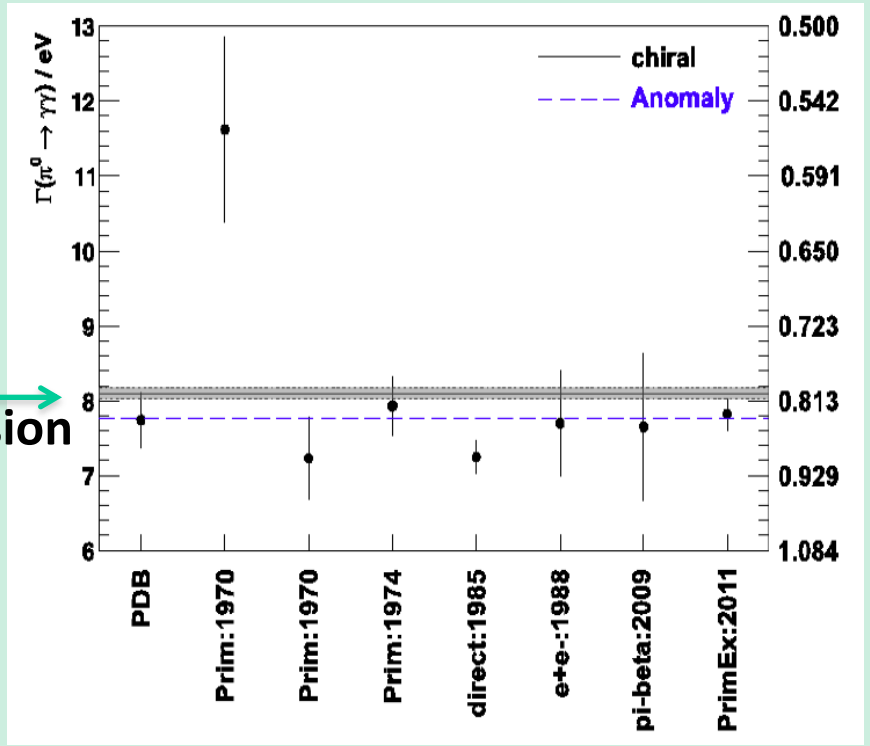
$\Gamma(\pi^0 \to \gamma\gamma)$ at 1% feasible at KLOE-2 with 5-6 fb^{-1}
The coincidences between KLOE central detector and HET taggers SELECT a very clean sample of ~ 1900 events per fb^{-1}
(σ_{eff} = 3.4 pb)
The radiative Bhabha-scattering events fully cut out by KLOE-HET coincidence



HET (e^-)

HET (e^+)

Theory and KLOE-2 precision



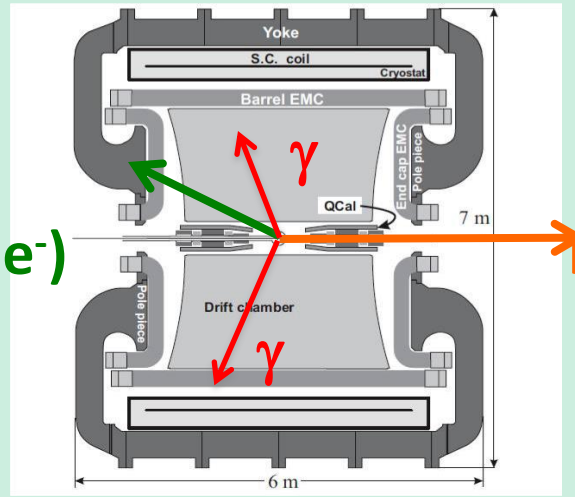
Perspectives for $\gamma\gamma \to \pi^0$ @ KLOE-2

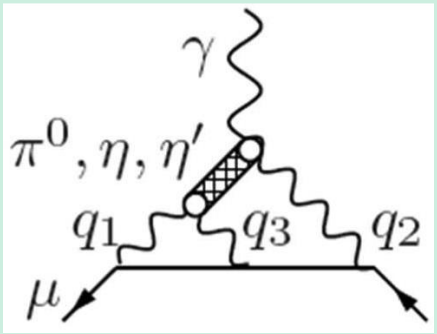
EPJC (2012) 72:1927

$\pi^0 \to \gamma\gamma^*$ transition form factor in the space-like region at low Q^2

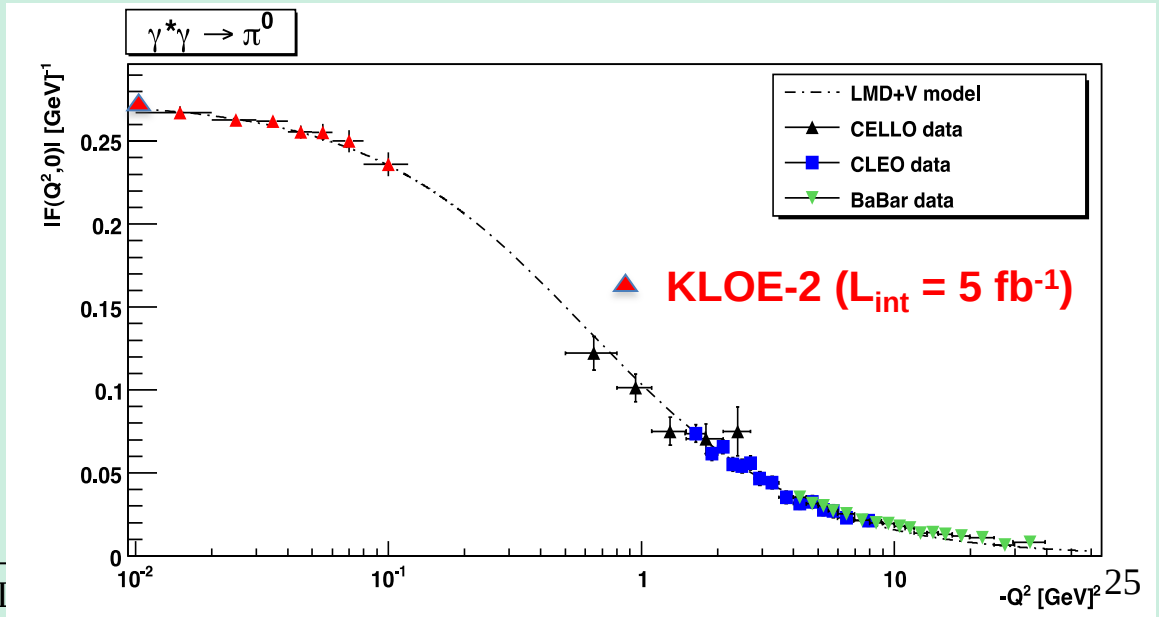
$F_{\pi^0 \gamma\gamma^*}$ at 5-6% feasible at KLOE-2 with 5 fb^{-1}

The coincidences between KLOE central detector and one of the HET stations are used





Light-by-light term to muon anomaly : both measurements, width and $F_{\pi^0 \gamma\gamma^*}$ contribute to a factor of ~2 reduction in the theoretical error, dominated by pseudoscalar (π^0) contribution



Conclusion

- Large data sample of light mesons available at KLOE provides important results on decay dynamics and transition form factor, together with limits on new physics, giving the most precise measurements for:
  - $\eta \to \pi^+\pi^-\pi^0$
  - TFF in $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$

- KLOE-2 run in progress
  - Rich physics program [Eur. Phys. J. C 68 (2010), 619]
  - We will continue high precision investigation of light meson properties
  - Ideal tool for π^0/η TFF @ $|q^2|<1$ GeV^2