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

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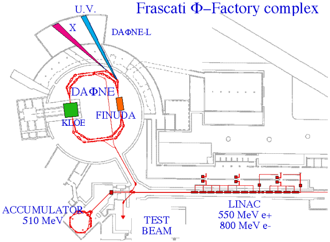
PANIC 2014

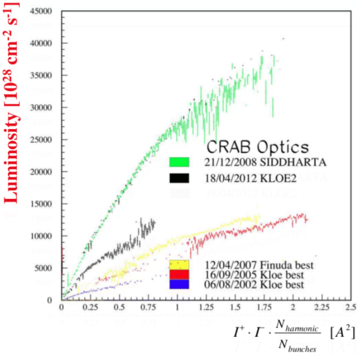
DAϕNE ϕ factory



- e^+e^- collider at $\sqrt{s} = M_\phi$
- 2 interaction regions
- separate e^+e^- rings
- 105+105 bunches
- 2.7 ns bunch spacing
- $I^{+/-}_{peak} \sim 2.4/1.5$ A
- $\theta_{cross} = 2 \cdot 12.5$ mrad

Best performances (1999-2007)

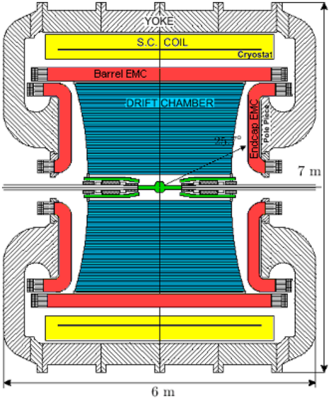
- $L_{peak} = 1.4 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int L\,dt = 8.5 \mathrm{pb}^{-1}/\mathrm{day}$



2008, new interaction scheme

$L_{new} \sim 3 \cdot L_{old}$

KLOE Experiment



KLOE: DC and EMC in ~ 0.52T
Drift Chamber (4 m diameter, 3.75m long)

- Gas Mixture 90% He +10% C_4H_{10}
- $\sigma_{xy} = 150\ \mu$m; $\sigma_z = 2$ mm
- $\frac{\delta p_t}{p_t} < 0.4\%\ (\theta > 45^\circ)$

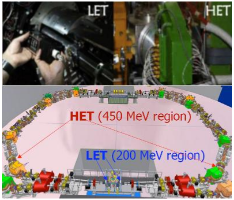
Electromagnetic Calorimeter

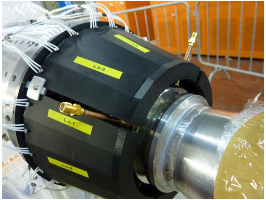
- lead/scintillating fibers
- 98% solid angle coverage
- $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(\mathrm{GeV})}}$
- $\sigma_t = \frac{57\ \mathrm{ps}}{\sqrt{E(\mathrm{GeV})}} \oplus 100$ ps
- PID capabilities

KLOE data taking ended 2006

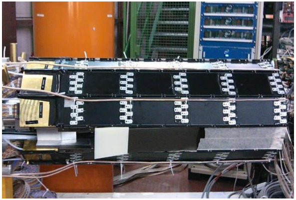
- 2.5 fb^{-1} at $\sqrt{s} = \mathrm{M}_\phi$
- ~ 10 pb^{-1} at $1010, 1018, 1023, 1030$ MeV
- 250 pb^{-1} at 1000 MeV

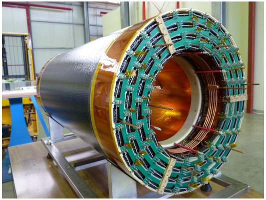
KLOE-2 Upgrade





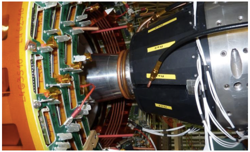
- High energy tagger, Low energy tagger (tag e^+e^- for $\gamma\gamma$ physics)
- 2 new calorimeters (for low angle γs & γs from K_L decays)
- Inner tracker (cylindrical GEM, for better vertex reconstruction and larger low p_t track accepatance)

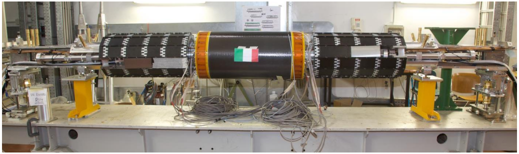


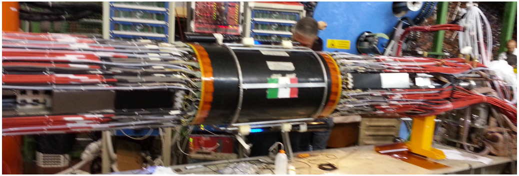


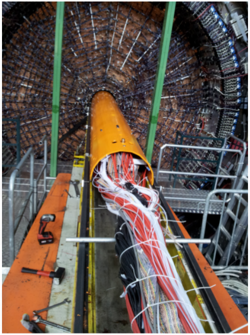
KLOE-2 Upgrade

- New detectors installed
- Comissioning of detector and accelerator in progress
- KLOE-2 goal: collect 5 fb^{-1} in next 2-3 years



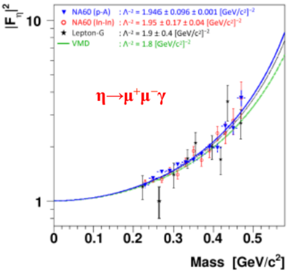


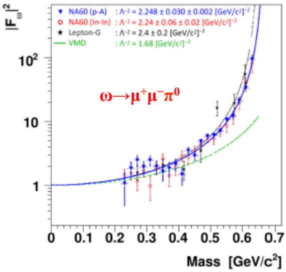




Transition form factor

Vector→Pseudoscalar $\gamma*$ and Pseudoscalar →Vector $\gamma*$ not fully described by VMD:
Works for $\eta \to l^+ l^- \gamma$ but not for $\omega \to l^+ l^- \pi^0$





Data

NA60 [In-In] [Phys. Lett. B 677 260-266 (2009)]

NA60 [p-A] [Nucl. Phys. A 855 189-196 (2011)]

Lepton-G [Phys. Lett. B 102 296-298 (1981)]

New theoretical models

- Terschlusen and Leupold [Phys. Lett. B 691 191 (2009)]
- Ivashyn S. [Prob. Atom. Sci. Tech. 2012N1 179 (2012)]
- Schneider, Kubis, Nieking [Phys. Rev. D 86 054013 (2012)]

Experimental results

Existing results on TFF and BR of $\phi \to \eta e^+e^-$ and $\phi \to \pi^0 e^+e^-$ have large errors

- Branching ratio

decay	SND	CMD-2	PDG avg.
$BR(\phi \to \eta e^+e^-)\ \times 10^4$	$(1.19 \pm 0.19 \pm 0.07)$	$(1.14 \pm 0.10 \pm 0.06)$	(1.15 ± 0.10)
$BR(\phi \to \pi^0 e^+e^-)\ \times 10^5$	$(1.01 \pm 0.28 \pm 0.29)$	$(1.22 \pm 0.34 \pm 0.21)$	(1.12 ± 0.28)

J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012)

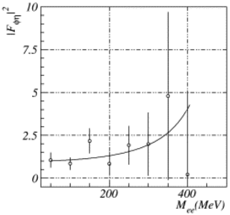
- Form factor

$F(q^2) = \frac{1}{1-q^2/\Lambda^2}$ with $q^2 = M^2_{l^+l^-}$

slope parameter $b = \frac{dF(q^2)}{dq^2}\big|_{q^2=0} = \Lambda^{-2}$

$\phi \to \eta e^+e^-$: $\Lambda^{-2} = (3.8 \pm 1.8)\ \mathrm{GeV}^{-2}$ SND at VEPP-2M
VMD: $\Lambda^{-2} \approx M_\phi^{-2} \approx 1\ \mathrm{GeV}^{-2}$

$\phi \to \pi^0 e^+e^-$: No data availbale on FF slope
VMD: $\Lambda^{-2} \approx 1.6\ \mathrm{GeV}^{-2}$

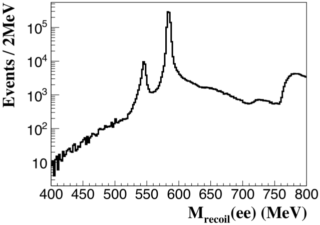


SND @ VEPP-2M [Phys.Lett. B 504 275-281 (2001)]

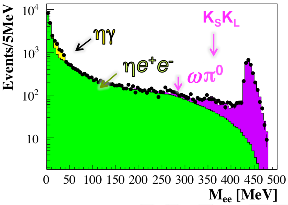
$\phi \to \eta e^+e^-$ with $\eta \to 3\pi^0$

Selection:

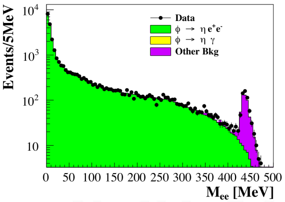
- 2 tracks
- 6 photons
- $400 < M_{6\gamma} < 700$ MeV
- $536.5 < M_{eerecoil} < 554.5$ MeV
- Conversion on beam pipe and drift chamber cut
- TOF cut



After $M_{eerecoil}$ cut



After all cuts



$\mathcal{L} \sim 1.7$ fb^{-1}, small residual background ($< 3\%$, from $\phi \to \eta\gamma$ and $\phi \to K_SK_L$)

After background subtraction: 29625 ± 178 events

Branching ratio $\phi \to \eta e^+ e^-$

With $\eta \to 3\pi^0$

$$BR(\phi \to \eta e^+ e^-) = \frac{\sum_i N_i/\epsilon_i}{\sigma_\phi \cdot \mathcal{L} \cdot BR(\eta \to 3\pi^0)}$$

i bin in Mee

Systematic effects

Cut	BR variation
$M_{eerecoil}$ $+1\sigma$	-0.1%
-1σ	$+0.6\%$
TOF $+1\sigma$	$+0.01\%$
-1σ	-0.1%
Conv. (small box)	-0.1%
(large box)	$+0.1\%$
Efficiencies	-0.1%
	-0.2%
	$+0.6\%$

	VMD (theory)[1]	SND (exp.)[2]	CMD-2 (exp)[3]	Our Analysis (Norm) (Stat) (Syst)
BR(10^{-4})	1.1	$1.19 \pm 0.19 \pm 0.07$	$1.14 \pm 0.10 \pm 0.06$	$1.075 \pm 0.038 \pm 0.007^{+0.006}_{-0.002}$

[1]Phys.Rev.C 61, 035206 (2000), [2]Phys.Lett.B 504, 275 (2001), [3]Phys.Lett.B 501, 191 (2001)

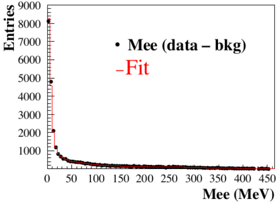
TFF $\phi \to \eta e^+ e^-$

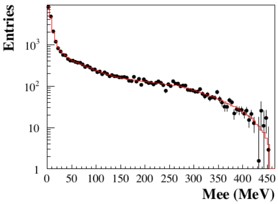
With $\eta \to 3\pi^0$

Fit data to Landsberg decay parametrization [1]

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

with $F(q^2) = \frac{1}{1-q^2/\Lambda^2}$





Cut	$b_{\phi\eta}$ variation
$M_{eerecoil}$ $+1\sigma$	$+3.3\%$
-1σ	-4.6%
TOF $+1\sigma$	-2.5%
-1σ	$+1.5\%$
Conv. (small box)	-5.9%
(large box)	$+1.7\%$
Fit range	$\pm 4.4\%$
	-9.0%
	$+6.0\%$

	VMD(theory)	SND(exp.)	Our Analysis
$b_{\phi\eta}$	1.0	3.8 ± 1.8	$1.17 \pm 0.10(stat)^{+0.07}_{-0.11}(sys)$

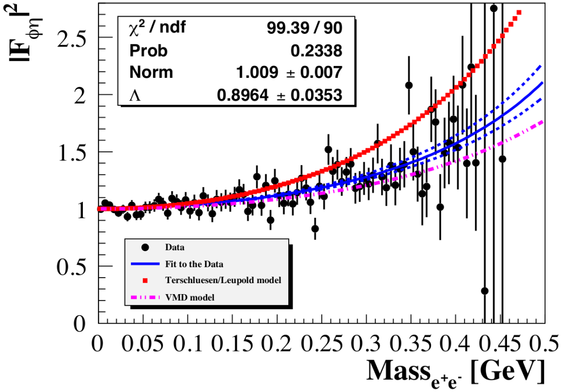
[1] Landsberg, L.G., Phys. Rep. 128 (1985) 301

TFF $\phi \to \eta e^+ e^-$ as function of Mee

With $\eta \to 3\pi^0$

Extracted by dividing bin by bin data Mee distribution by the reconstructed MC Mee distribution with $F_{\phi\eta} = 1$

MC sample normalized to first data bin



$b_{\phi\eta} =$
$(1.25 \pm 0.10)\ \mathrm{GeV}^{-2}$

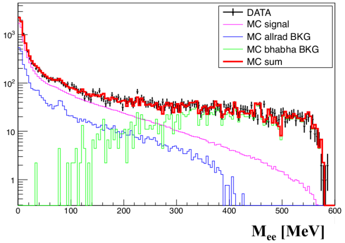
$\phi \to \pi^0 e^+ e^-$

$\mathrm{BR}(\phi \to \pi^0 e^+ e^-) = (1.12 \pm 0.28) \cdot 10^{-5}$ 25% uncertainty!
(SND: 52 events, CMD-2 46 events)

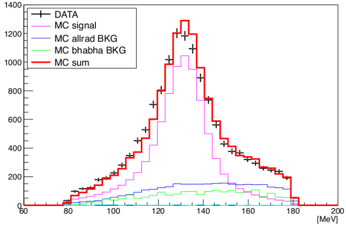
Analyzing sample from 1.7 fb^{-1}

- 2 tracks + 2 photons
- selection cuts
- main backgrounds
  - double radiative Bhabha scattering ($e^+e^- \to e^+e^-\gamma\gamma$)
  - $\phi \to \pi^0\gamma$ with photon conversion

e+e- mass spectrum



e-e+ missing mass



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

At the end of analysis 14680 events

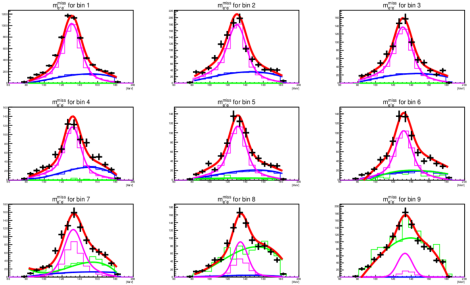
- $\sim 22\%$ $e^+e^- \to e^+e^-\gamma\gamma$
- $\sim 20\%$ $\phi \to \pi^0\gamma$ +conversion

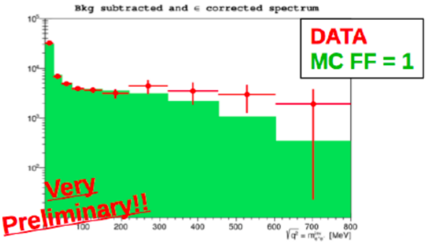
For each bin in Mee

- fit $M_{eerecoil}$
- subtract background result from the fit

Finalizing background subtraction

Results on TFF and BR soon!



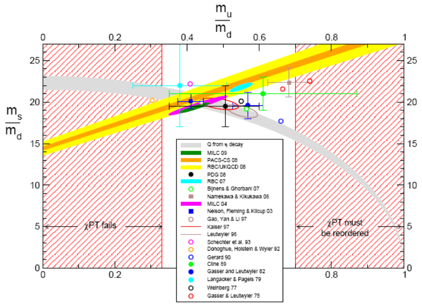


$\eta \to \pi^+\pi^-\pi^0$ motivation

$\eta \to \pi^+\pi^-\pi^0$ isospin breaking decay

$\Gamma(\eta \to \pi^+\pi^-\pi^0) \propto Q^{-4}$

$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\qquad \hat{m} = \frac{1}{2}(m_d + m_u)$



Determining Q constrains the quark mass ratios [1]

χPT:

- $\Gamma_{LO} \sim 70$eV
- $\Gamma_{NLO} = 160 \pm 50$eV
- $\Gamma_{exp} = 295 \pm 16$eV

$\rightarrow$ final state interactions important

$\rightarrow$ dynamics of decay important

$\rightarrow$ measure Dalitz plot

- Dispersion relations can be applied to improve theoretical results

[1] Leutwyler, PoS CD09 (2009)

$\eta \to \pi^+\pi^-\pi^0$ Dalitz plot in KLOE

In KLOE $\phi \to \eta\gamma$ ($E_\gamma = 363$ MeV)

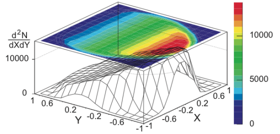
- Previous KLOE analysis (2001-2002 data) [1]
  - 450 $\text{pb}^{-1} \Rightarrow 1.34 \cdot 10^6$ events
  - Event classification efficiency biggest contribution to systematic errors
- New analysis (2004-2005 data)
  - 1.6 $\text{fb}^{-1} \Rightarrow 4.48 \cdot 10^6$ events
  - independent data sample
  - different analysis scheme
  - reduced systematics expected (better MC, better way of determining event classification efficiency)

In η-rest frame

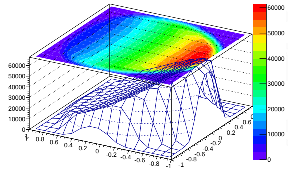
$$X = \sqrt{3}\frac{T_+ - T_-}{Q_\eta}$$

$$Y = \frac{3T_0}{Q_\eta} - 1$$

$$(Q_\eta = T_+ + T_- + T_0)$$



data



[1] JHEP 0805 (2008) 006

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

Fit the data to

- $N_{theory} = \int |A(X,Y)|^2 dPh(X,Y)$
- $|A(X,Y)|^2 \simeq N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y)$
- previous analysis: by average value in bin
- new analysis: using Monte Carlo integration

$c, e = 0$ (C-invariance), we find c and e consistent with 0

Experiment	-a	b	d	f
Gormley[1]	1.17(2)	0.21(3)	0.06(4)	-
Layter[2]	1.080(14)	0.03(3)	0.05(3)	-
CBarrel[3]	1.22(7)	0.22(11)	0.06(fixed)	-
KLOE[4]	$1.090(5)(^{+19}_{-8})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
WASA[5]	1.144(18)	0.219(19)(37)	0.086(18)(18)	0.115(37)
KLOE (13)	1.104(3)	0.144(3)	0.073(3)	0.155(6)

KLOE(13) PRELIMINARY, only statistical errors

[1] M. Gormley *et al.* Phys. Rev. D2, 501 (1970)
[2] J. Layter *et al.* Phys. Rev. D7, 2565 (1973)
[3] Crystal Barrel Collaboration Phys. Lett. B417, 197 (1998)
[4] The KLOE collaboration JHEP, Vol 5, page 006 (2008)
[5] WASA-at-COSY collaboration, arXiv:1406.2505 (2014)

Conclusions and Outlook

Conclusions

- KLOE high statistics data sample still producing results in light hadronic physics
  - $\phi \to \eta e^+ e^-$ TFF and BR measured with $\eta \to 3\pi^0$
  - in agreement with VMD expectations
  - preparing paper

Outlook

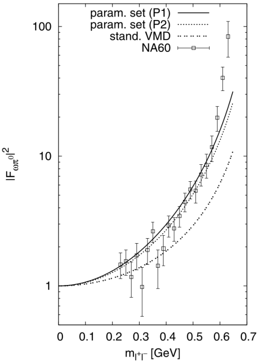
- Some analysis still to be finalized
  - $\phi \to \pi^0 e^+ e^-$ TFF and BR, finalizing background subtraction
  - $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot, investigating systematic effects
- New interaction region installed, comissioning ongoing
- KLOE-2 run coming up, goal to collect 5 fb^{-1} in next 2-3 years (physics program at EPJC68 619 (2010))

Spares

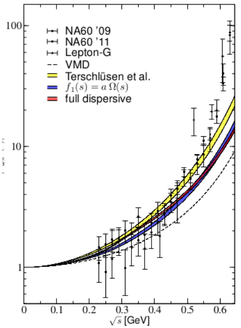
TFF theoretical calculations

$$|F_{\omega\pi^0\gamma^*}|^2$$

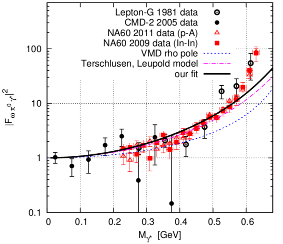
Phys. Lett. B 691 191 (2009)



Phys. Rev. D **86** (2012) 05401



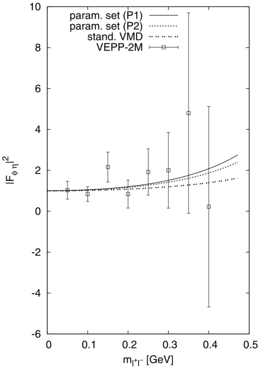
Prob. Atom. Sci. Tech. 2012N1 179 (2012)



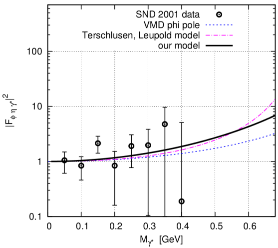
TFF theoretical calculations

$|F_{\phi\eta\gamma^*}|^2$ $|F_{\phi\pi^0\gamma^*}|^2$

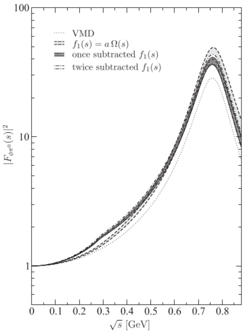
Phys. Lett. B 691 191 (2009)



Prob. Atom. Sci. Tech. 2012N1 179 (2012)



PHYSICAL REVIEW D **86**, 054013 (2012)

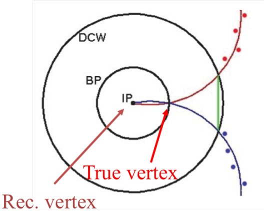


TFF $\phi \to \eta e^+ e^-$

Background rejection

Photon conversion

Photon from interaction region converts in the beam pipe or drift chamber wall (mainly $\phi \to \eta\gamma$)



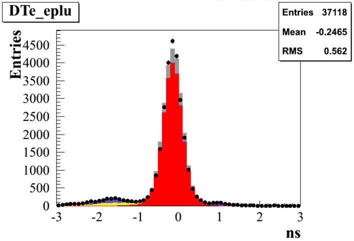
At surface

- e^+e^- invariant mass
- distance between e^+e^-

Time of flight

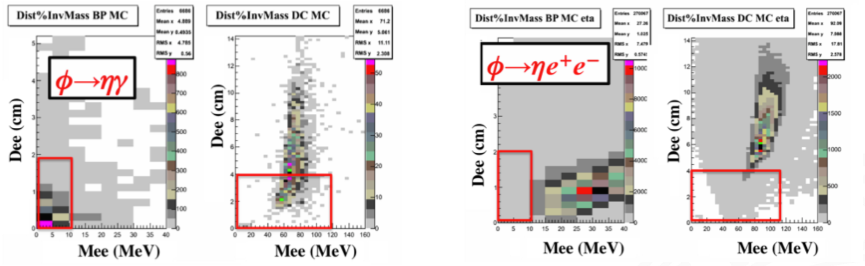
Background with $\pi^+\pi^-$ in final state (mainly from $\phi \to K_S K_L$ and $e^+e^- \to \omega\pi^0$)

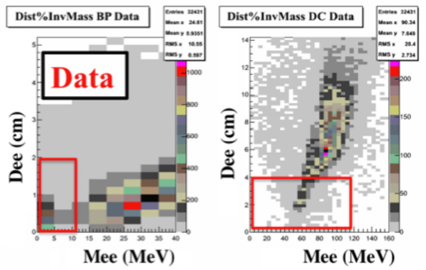
DTe= $T_{track} - T_{cluster}$ in electron hypothesis



-0.9 ns $<$ DTe $<$ 0.62 ns

Background rejection - conversion



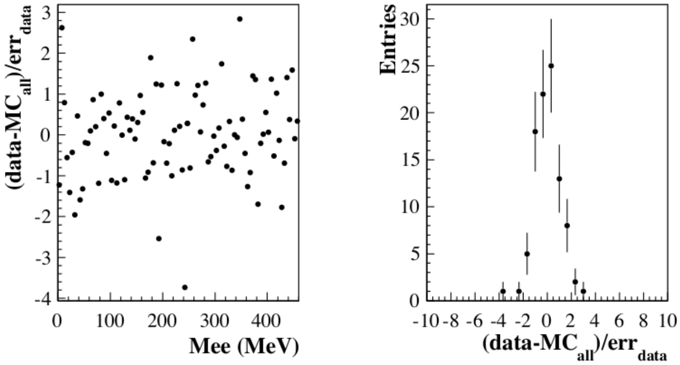


Cuts

- BP $Mee < 10$ MeV and $D < 2$ cm
- DC $Mee < 120$ MeV and $D < 4$ cm

Events inside the red boxes rejected

Data/MC comparison at the end of analysis
Mee “residuals”



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

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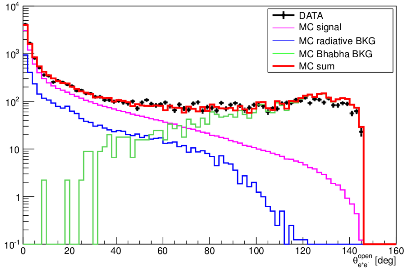
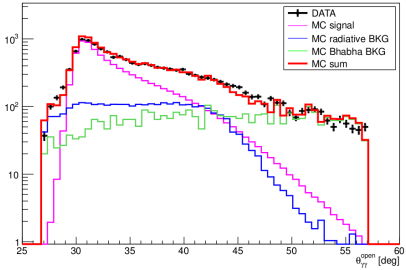
$30 < E_{e+,e-} < 460$ MeV $470 < E_{e+} + E_{e-} < 750$ MeV $E_{\gamma1,\gamma2} > 70$ MeV $300 < E_{\gamma1} + E_{\gamma2} < 670$ MeV	$35° < \theta_i < 135°$ $\theta_{(e-,e+)} < 145°$ $27° < \theta_{(\gamma1,\gamma2)} < 57°$	$d_{traks} > 2$ cm $m_{e+e-} > 10$ MeV $d_{traks} > 3$ cm $m_{e+e-} > 80$ MeV	$90 < m_{\gamma\gamma\text{-inv}} < 190$ MeV $90 < m_{ee\text{-miss}} < 190$ MeV $m_\phi - 30 < m_{\gamma\gamma e+e-} < m_\phi + 30$ MeV
Energy cuts	**Angular cuts**	**Conversion cuts**	**Invariants cuts**

e^+e^- opening-angle



$\gamma\gamma$ opening-angle



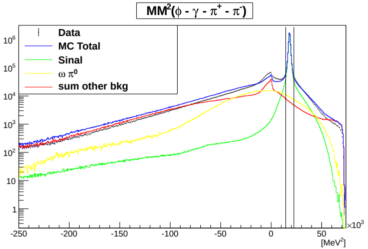
$\eta \to \pi^+\pi^-\pi^0$

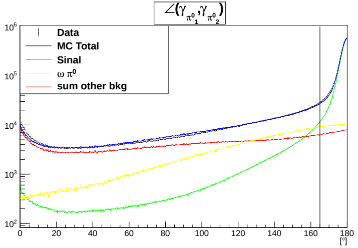
Data-MC comparison

After event reconstruction and cuts for backround suppression:

- Signal efficiency $\epsilon_{sig} = 37.6\%$
- Background contamination 0.96%

Fit of Monte Carlo to data to get scaling factors for background





Dalitz plot variables - resolution

Evaluated with Monte Carlo:

Look at $X_{rec} - X_{gen}$ and $Y_{rec} - Y_{gen}$, fit with 2 gaussians.

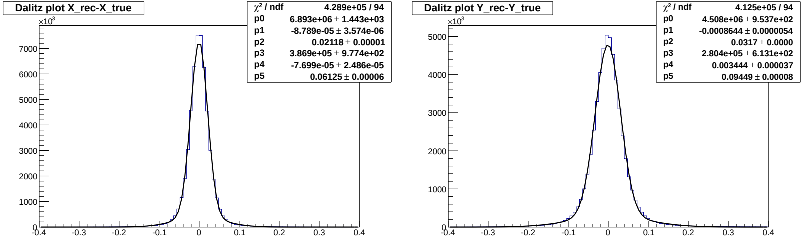


Figure: MonteCarlo distribution for resolution of X and Y.

Taking the width of the "core" gaussian as an estimate of the resolution:

$$\delta X = 0.021 \qquad \delta Y = 0.032$$

Dalitz plots made with 16 bins, $\Delta X = 0.125 \quad \Delta Y = 0.125$

Data-fit comparison

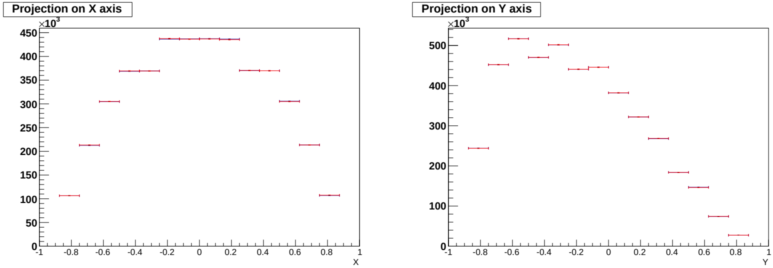


Figure: Projection on X and Y variables, data and smeared fitted function