Measurement of the transition form factor in $\Phi \rightarrow \eta e^+e^-$ and $\Phi \rightarrow \pi^0 e^+e^-$ decays at KLOE

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on behalf of the
KLOE-2 collaboration

Meson 2014

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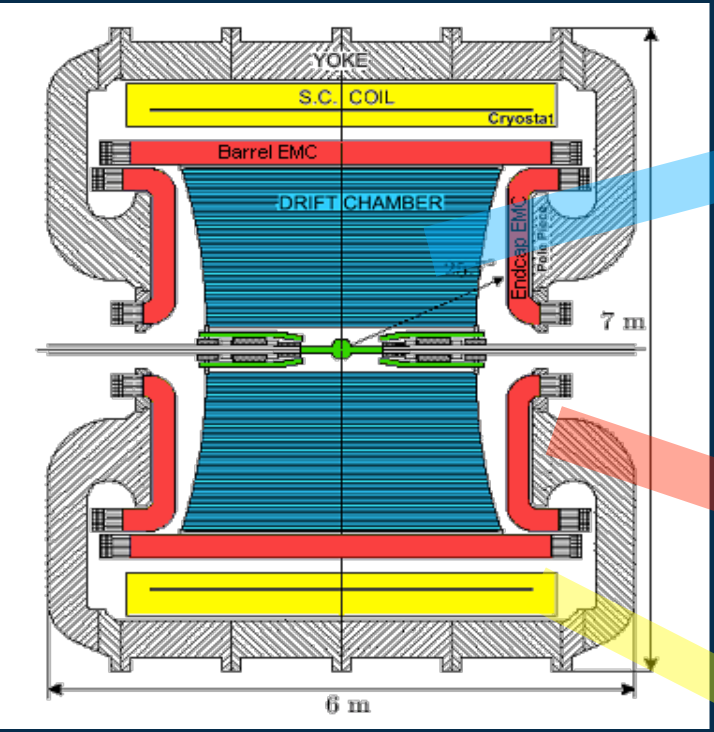
Krakow, Poland

The KLOE experiment

The KLOE experiment @ DAϕNE (the e^+e^- collider in Frascati) is mainly dedicated to the studies of the ϕ (1020 MeV) meson decays.



Drift chamber

- Gas mixture: 90% He + 10% C_4H_{10}
- $\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ 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

DAΦNE: e^+e^- collider @ $\sqrt{s} \sim 1020$ MeV ~ M_ϕ

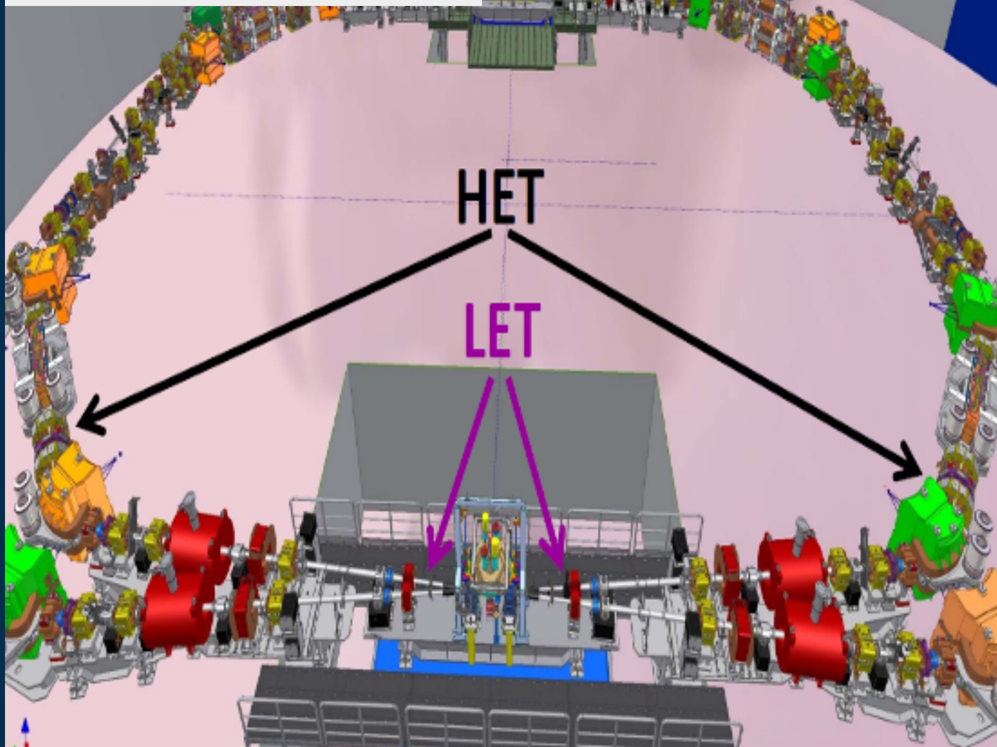
$\sigma_{peak} \sim 3.1$ mb

KLOE: 2.5 fb^{-1} @ $\sqrt{s} = M_\phi$ (~ 8×10^9 ϕ produced)

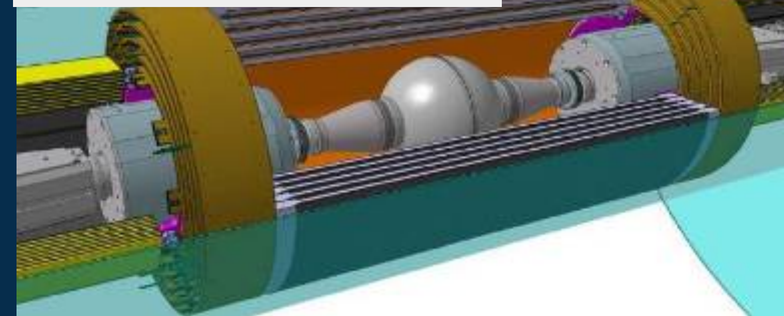
+ 250 pb^{-1} @ 1000 MeV (off-peak data)

From KLOE to KLOE-2

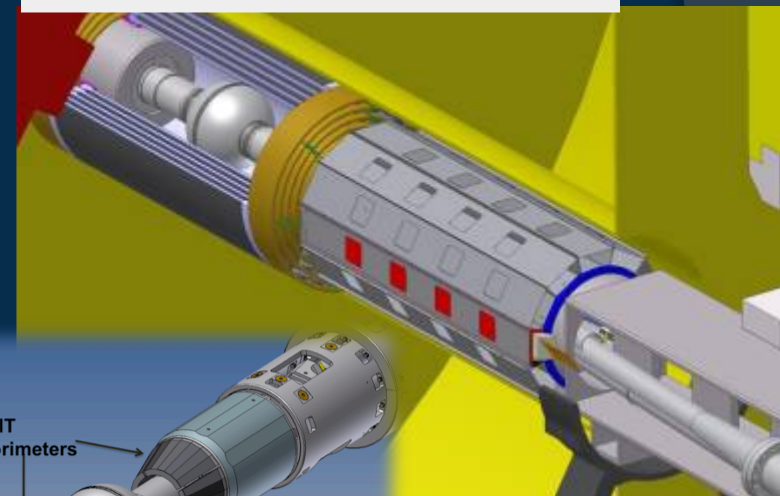
2+2 $\gamma\gamma$ taggers

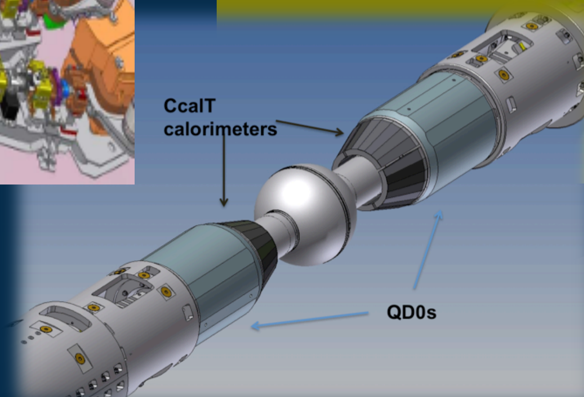


INNER TRACKER



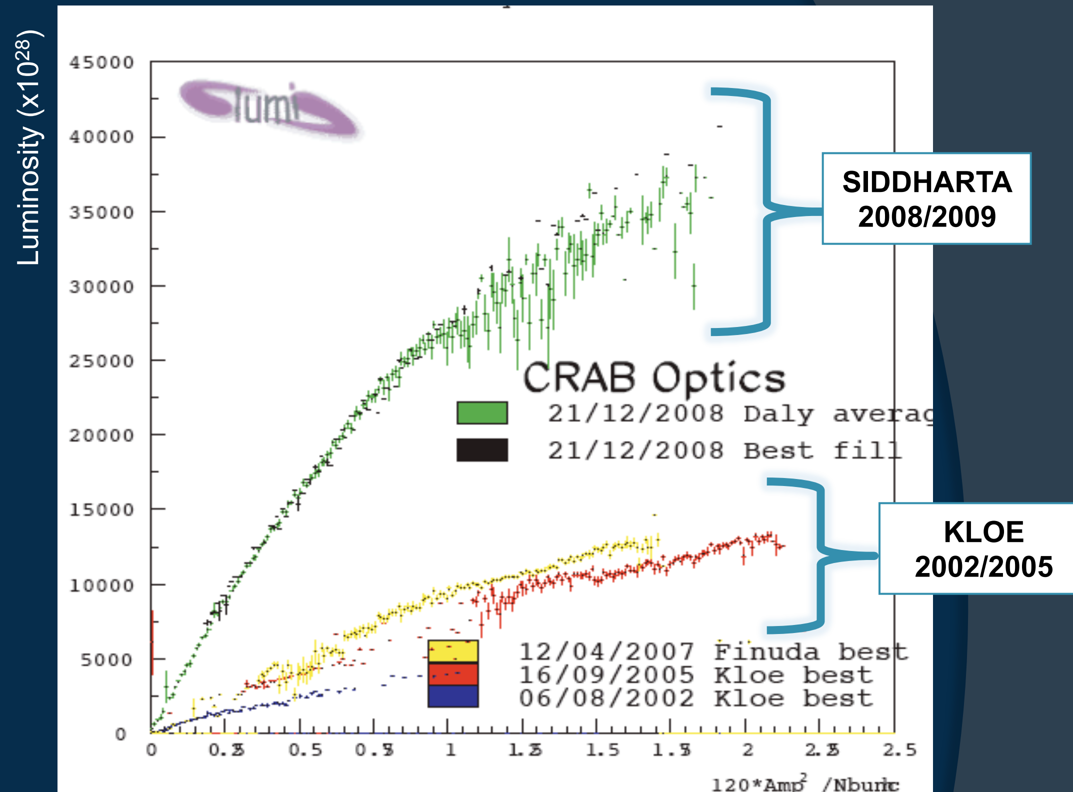
SMALL ANGLE EMCs





DAΦNE and KLOE-2

Since the beginning of 2008, DAΦNE has implemented a new interaction scheme. Results obtained during run of SIDDHARTA were very good: an increase of a peak luminosity per day by a factor of **~ 3** and of the integrated luminosity by **~ 2**.



- **Installation of the new DAΦNE IR + KLOE-2 upgrades completed in July 2013**
- **KLOE-2 goal: collect ~ 5 fb^{-1} in the next 2 -3 years**
  [Eur.Phys.J.C68(2010),619]

The data sample already collected at KLOE has been used to study the transition form factor and the BR for the following decays:

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

Physics motivation -1-

Test the modellings of the TFF: the naïve VMD approach is satisfactory in the description of $\eta \to \gamma\, \mu^+\mu^-$ but dramatically fails in $\omega \to \pi^0\, \mu^+\mu^-$

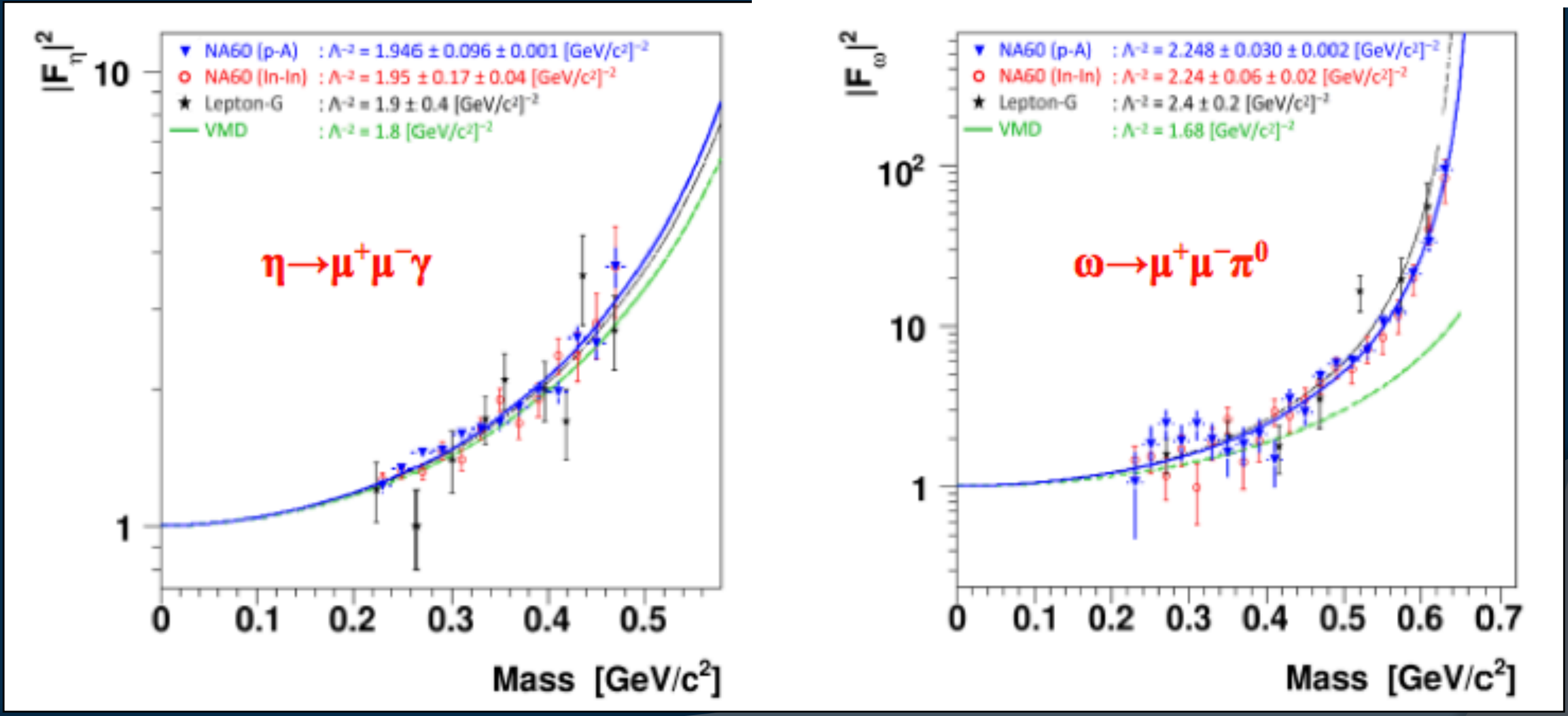
$$b = \Lambda^{-2} = \frac{dF(q^2)}{dq^2}\Big|_{q^2=0}$$

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)]

Theory

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



Physics motivation -2-

- The knowing of the value of the transition form factor fix also the upper limit for the U boson searches in $\phi \rightarrow \eta\ e^+e^-$ [Phys. Lett. B720 111-115 (2013)]

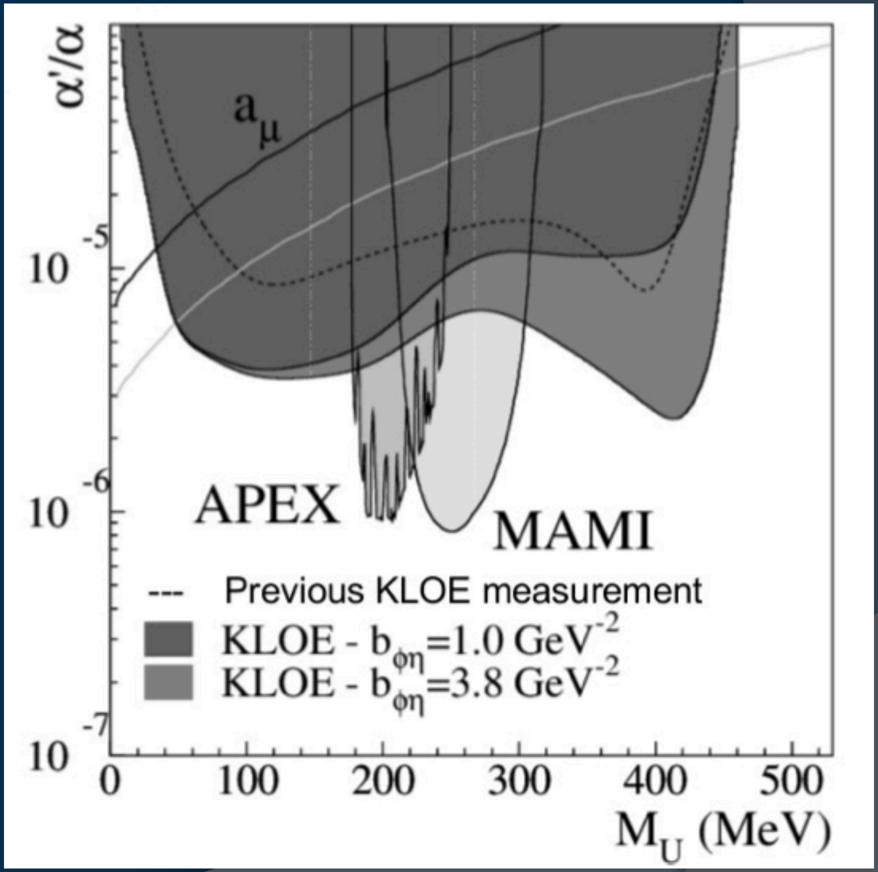
Associated decay of ϕ into a PS and a U suggested by M. Reece and L.T. Wang [JHEP 0907:051 (2009)]

$BR(X \rightarrow YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times BR(X \rightarrow Y\gamma)$

✔ **Upper limit for α'/α (90% C.L.)**

$\alpha'/\alpha < 1.7 \times 10^{-5}$ for $30 < M_U < 400$ MeV

($\alpha'/\alpha < 8.0 \times 10^{-6}$ for $50 < M_U < 210$ MeV)



Experimental Results

There are few results available for the transition form factor and the BR of the $\phi \rightarrow \eta e^+e^-$ and $\phi \rightarrow \pi^0 e^+e^-$ decays.

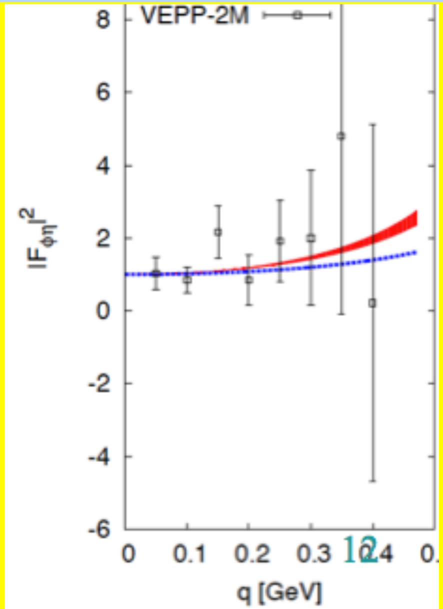
- $\phi \rightarrow \eta e^+e^-$: $\Lambda^{-2} = (3.8 \pm 1.8)$ GeV^{-2} (~ 50% error) SND @ VEPP-2M
  VMD $\Rightarrow$ $\Lambda^{-2} \approx M_\phi^{-2} \approx 1$ GeV^{-2}
- $\phi \rightarrow \pi^0 e^+e^-$: no data available on FF slope; VMD $\Rightarrow$ $\Lambda^{-2} \approx 1.6$ GeV^{-2}

BR decay	SND	CMD-2	PDG av.	Tot err.
$\phi \rightarrow \eta e^+e^-$ (10^{-4})	(1.19 ± 0.19 ± 0.07)	(1.14 ± 0.10 ± 0.06)	**(1.15 ± 0.10)**	~ 8.7 %
$\phi \rightarrow \pi^0 e^+e^-$ (10^{-5})	(1.01 ± 0.28 ± 0.29)	(1.22 ± 0.34 ± 0.21)	**(1.12 ± 0.28)**	~ 25 %

[J. Beringer et al. Phys. Rev. D 86 (2012)]

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

b_{exp} = (3.8 ± 1.8) GeV^{-2}
$b_{VMD} \approx$ 1.0 GeV^{-2}



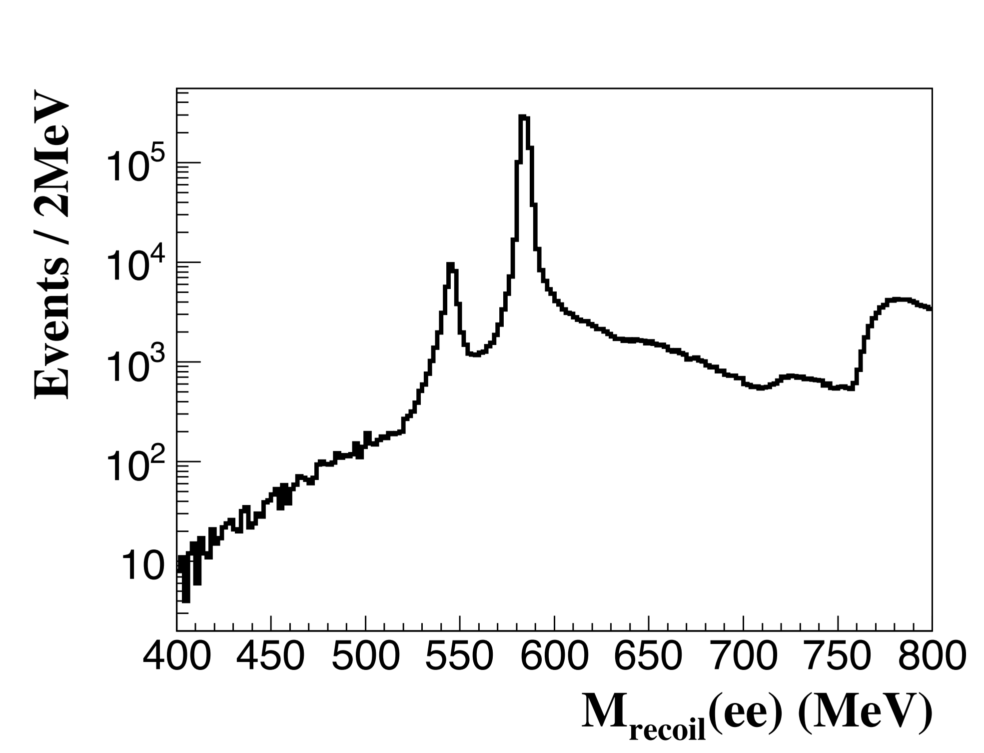
$\phi \to \eta e^+e^-$, $\eta \to 3\pi^0$ decay channel

We measured the transition form factor from the invariant mass of the e^+e^- pair:

Analysis performed using 1.7 fb^{-1}

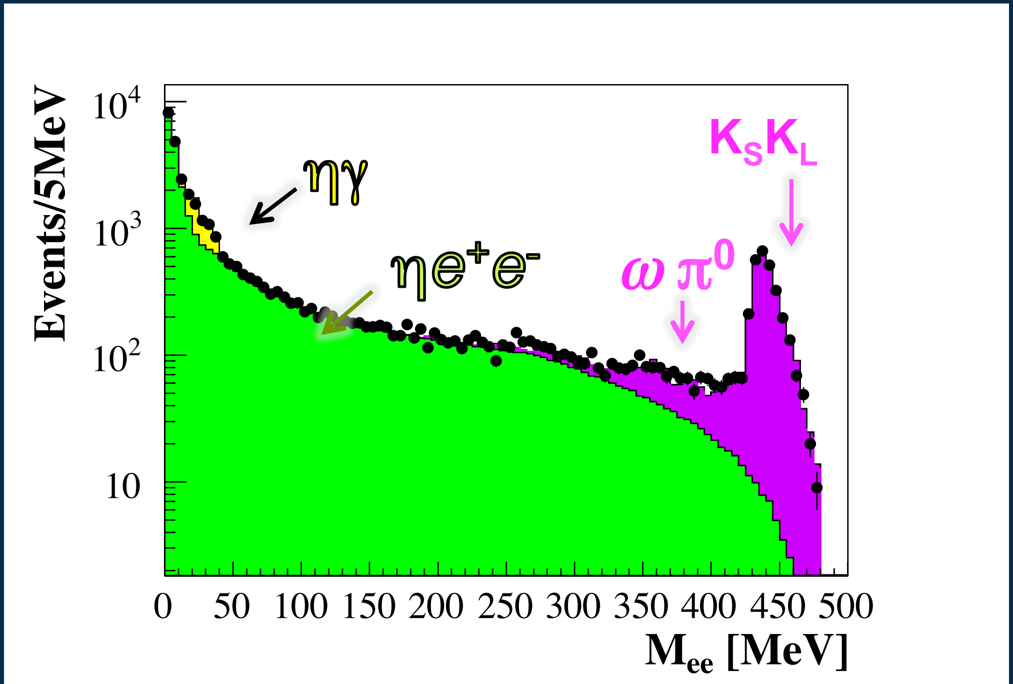
- 2 tracks (1 negative and 1 positive) in a cylinder around IP

- 6 prompt photons candidates, i.e. energy clusters with E > 7 MeV not associated to any track, in an angular acceptance $|\cos\theta\gamma| < 0.92$ and in the expected time window for a prompt photon ($|T_\gamma - R_\gamma/c| < MIN(3\sigma_T, 2\ ns)$)

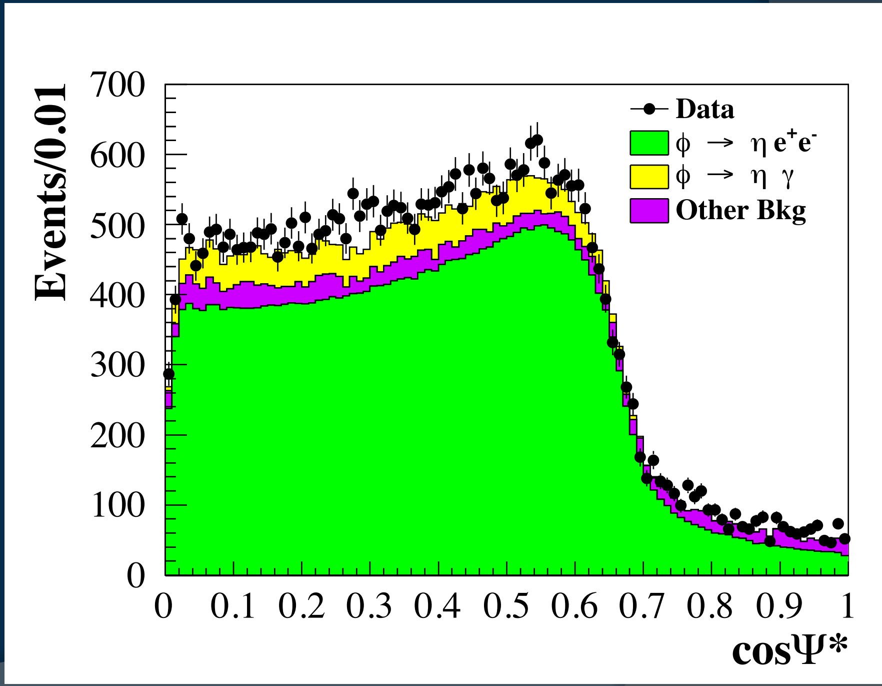


- **$400 < M_{6\gamma} < 700$ MeV**
- **536.5 < Mrecoil < 554.5**
- **Conversion on BP and DC cut**
- **TOF cut**

Data-MC comparison after pre-selection and cut on Mrecoil



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

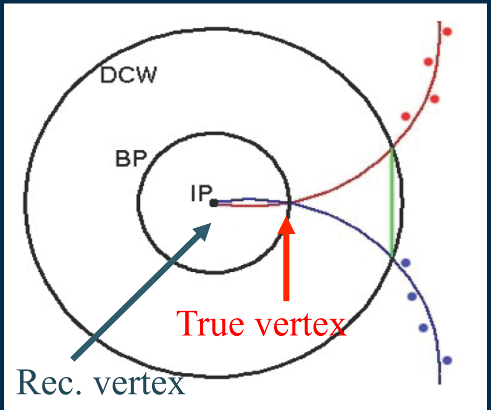


- **Background contamination ~ 20%**

Bkg Rejection

Photon conversions

Photons produced in the interaction region, can convert on the beam pipe (BP) or on the drift chamber walls (DCW), simulating an e^+e^- pair from the interaction point



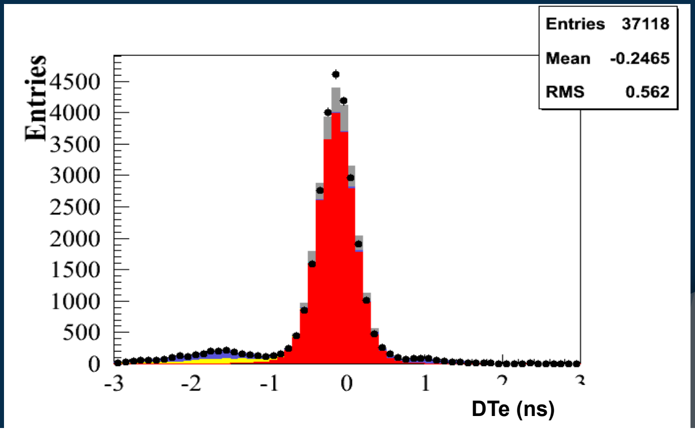
This residual background contamination, due mainly to $\Phi \rightarrow \eta\gamma$ events, is rejected by tracking back to BP/DCW surfaces the e^+ and e^- candidates and then reconstructing the electron-positron invariant mass Mee(BP/DCW) and the distance between the two particles, Dee(BP/DCW).

Both quantities are small if coming from photon conversion.

Time Of Flight

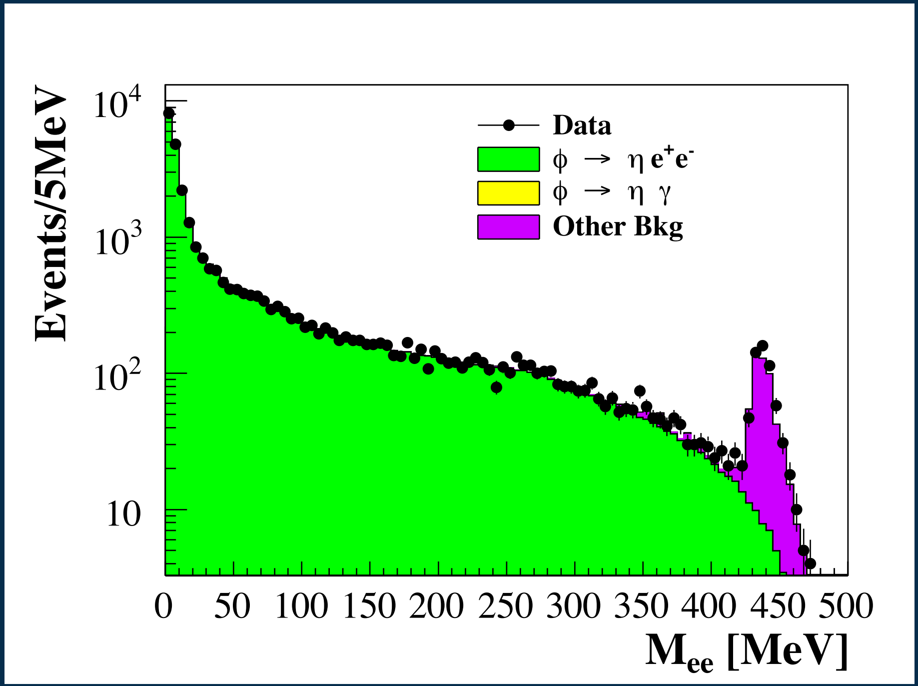
The residual background contamination, originated by $\Phi \rightarrow K_S K_L$ decays ($K_S \rightarrow \pi^+ \pi^-$ and $K_L \rightarrow 3\pi^0$) and $e^+e^- \rightarrow \omega\pi^0$ surviving the analysis cuts, has two charged pions in the final state and is suppressed using the Time of Flight of tracks to the calorimeter.

When an energy cluster is connected to a track, the arrival time to the calorimeter is evaluated using the calorimeter timing ($T_{cluster}$) and the particle trajectory ($T_{track} = L_{track}/\beta c$).

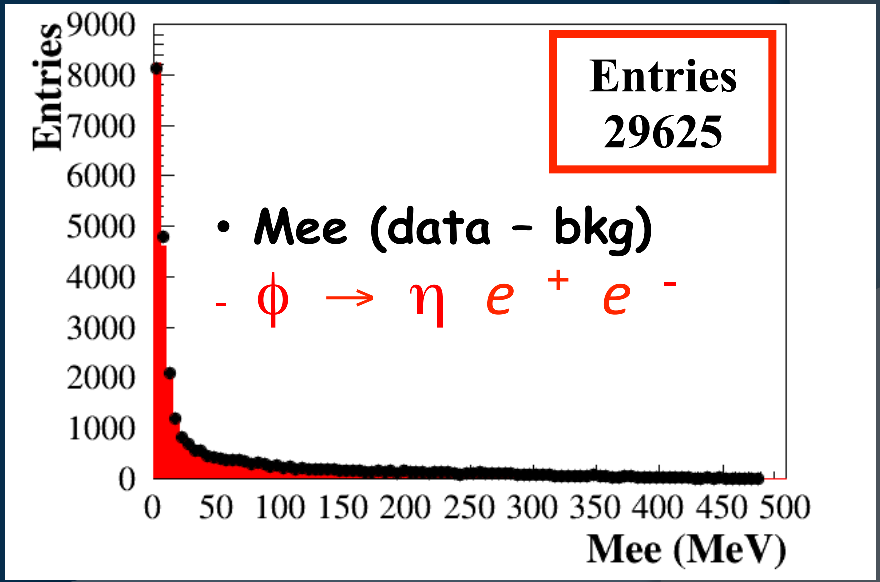


DTe: difference between the measured time and the expected one in the "electron" hypothesis

Data/MC comparison at the end of analysis



Data subtracted



- **Very small residual bkg contamination from $\phi \to \eta\gamma$ and $\phi \to K_S K_L$ events (<3%)**
- **~ 30000 $\phi \to \eta e^+e^-$ with $\eta \to 3\pi^0$**

Branching Ratio

We have measured the $\phi \to \eta e^+e^-$ Branching Ratio using the candidate events and efficiencies for each mass bin:

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

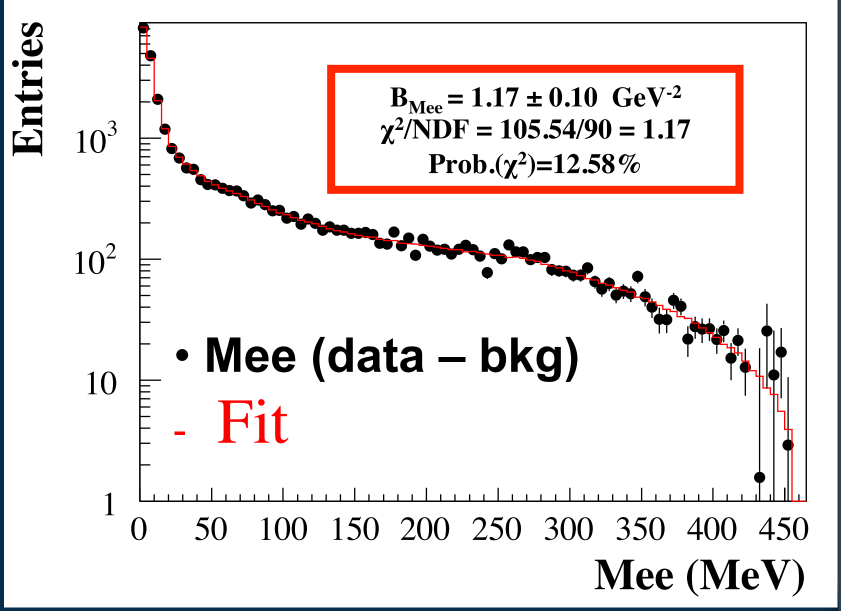
The systematics error has been evaluated moving by ±1σ Mrec and TOF cuts.
For the conversions, the cut is moved by ±20% on the BP/DC distance and invariant-mass variables respectively.

CUT	BR Variation
$M_{REC.} + 1\sigma$ -1σ	-0.1% +0.6%
$TOF + 1\sigma$ -1σ	+0.01% -0.1%
$Conv.(small\ box)$ $(large\ box)$	-0.1% +0.1%
$Efficiencies$	-0.1%
	-0.2% **0.6%**

	VMD (theory)	**SND (exp.)**	**CMD-2 (exp.)**	**Our Analysis** Norm. Stat. Sys.
BR(10^{-4})	1.1 Phys. Rev.459 C 61, 035206 (2000)	1.19±0.19±0.07 Phys. Lett. B 504, 275 (2001);	1.14±0.10±0.06 Phys. Lett. B 501, 191 (2001)	**1.075 ± 0.038 ± 0.007 + 0.006 - 0.002**

Fit result

The fit has been performed using the decay parametrization from L.G. Landsberg (Phys. Rep. 128 (1985) 301), folded with the analysis efficiency and smearing effects.



The systematic on fit has been evaluated moving the fit limits and considering the RMS of the deviations from the fit value

CUT	$b_{\phi\eta}$ Variation
$M_{REC.} + 1\sigma$	+3/3%
-1σ	-4.6%
$TOF + 1\sigma$	-2.5%
-1σ	1.5%
Conv.(small box)	-5.9%
(large box)	+1.7%
Fit	± 4.4%
	-9.0% **6.0%**

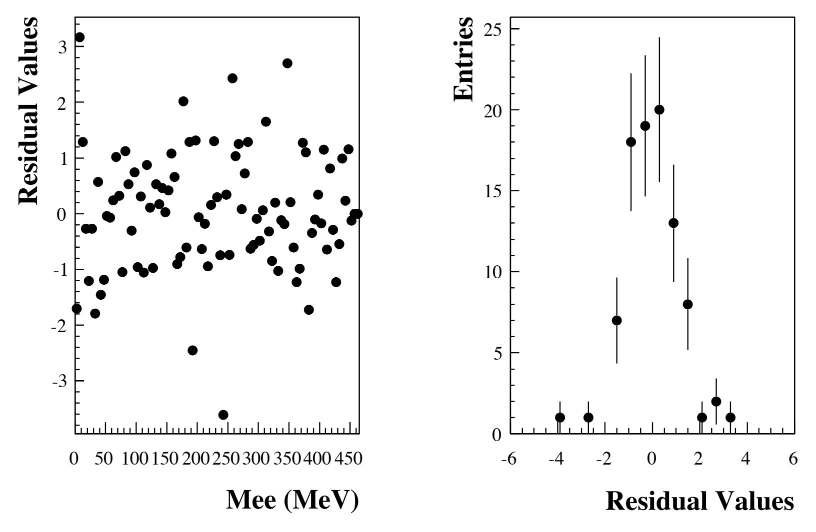
	VMD (theory)	SND (exp.)
$b_{\Phi\eta}$	1.0 Phys. Rev.459 C 61, 035206 (2000)	3.8±1.8 Phys. Lett. B 504, 275 (2001);

Our Analysis

Stat. Sys.

1.17 ± 0.10 + 0.07 - 0.11

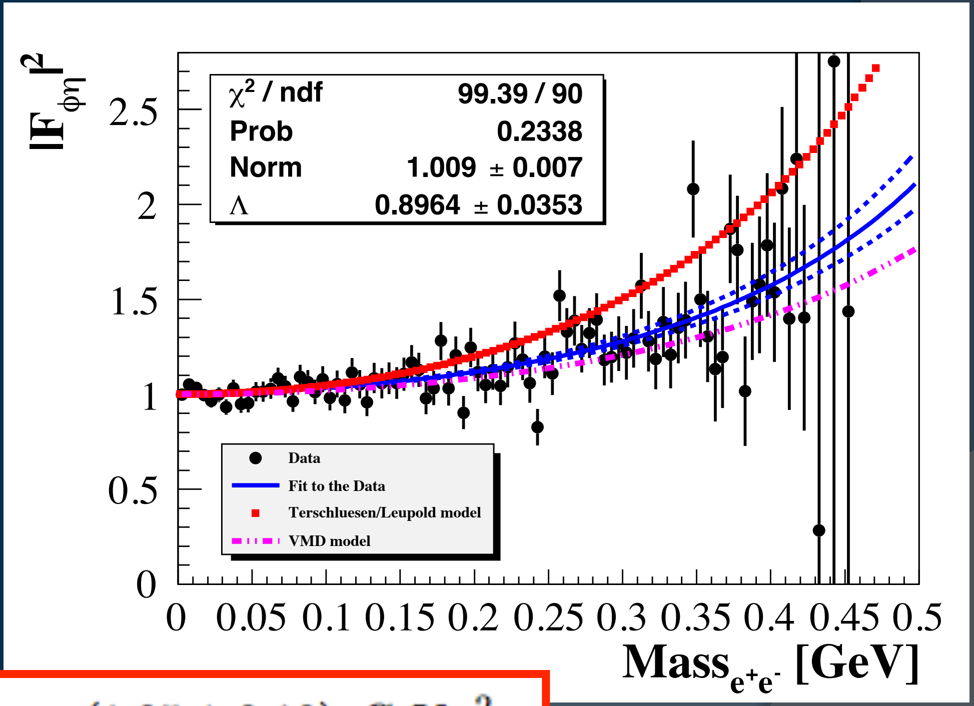
Fit Residuals



Form factor as a function of M_{ee}

The TFF as a function of the e^+e^- invariant mass has been extracted dividing bin by bin the M_{ee} data distribution and the reconstructed M_{ee} shape obtained for MC events, generated with $F_{\phi\eta} = 1$, after all analysis cut.

- We normalized the MC sample in order to reproduce the number of events in the first bin of the data distribution.



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

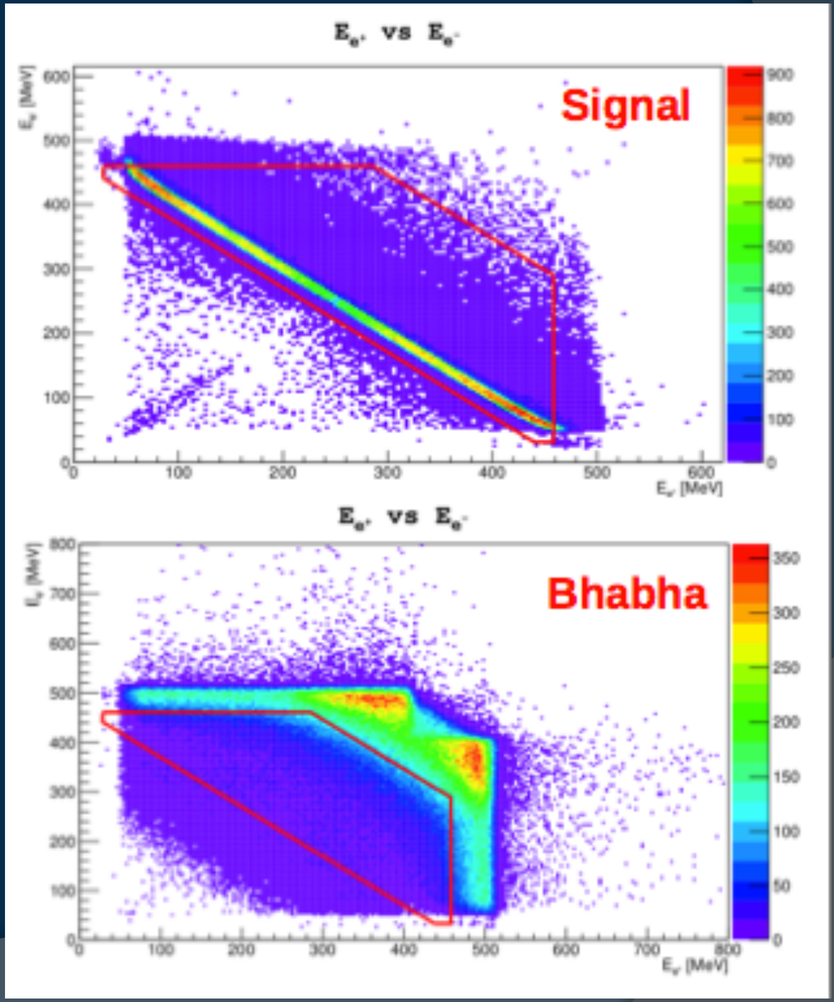
$\phi \rightarrow \pi^0 e^+ e^-$ decay channel

- BR($\phi \rightarrow \pi^0 e^+e^-$) = $(1.12\pm0.28)\times10^{-5}$ ⇒ **25% uncertainty**
  SND ⇒ 52 events; CMD-2 ⇒ 46 events
- TFF never measured before

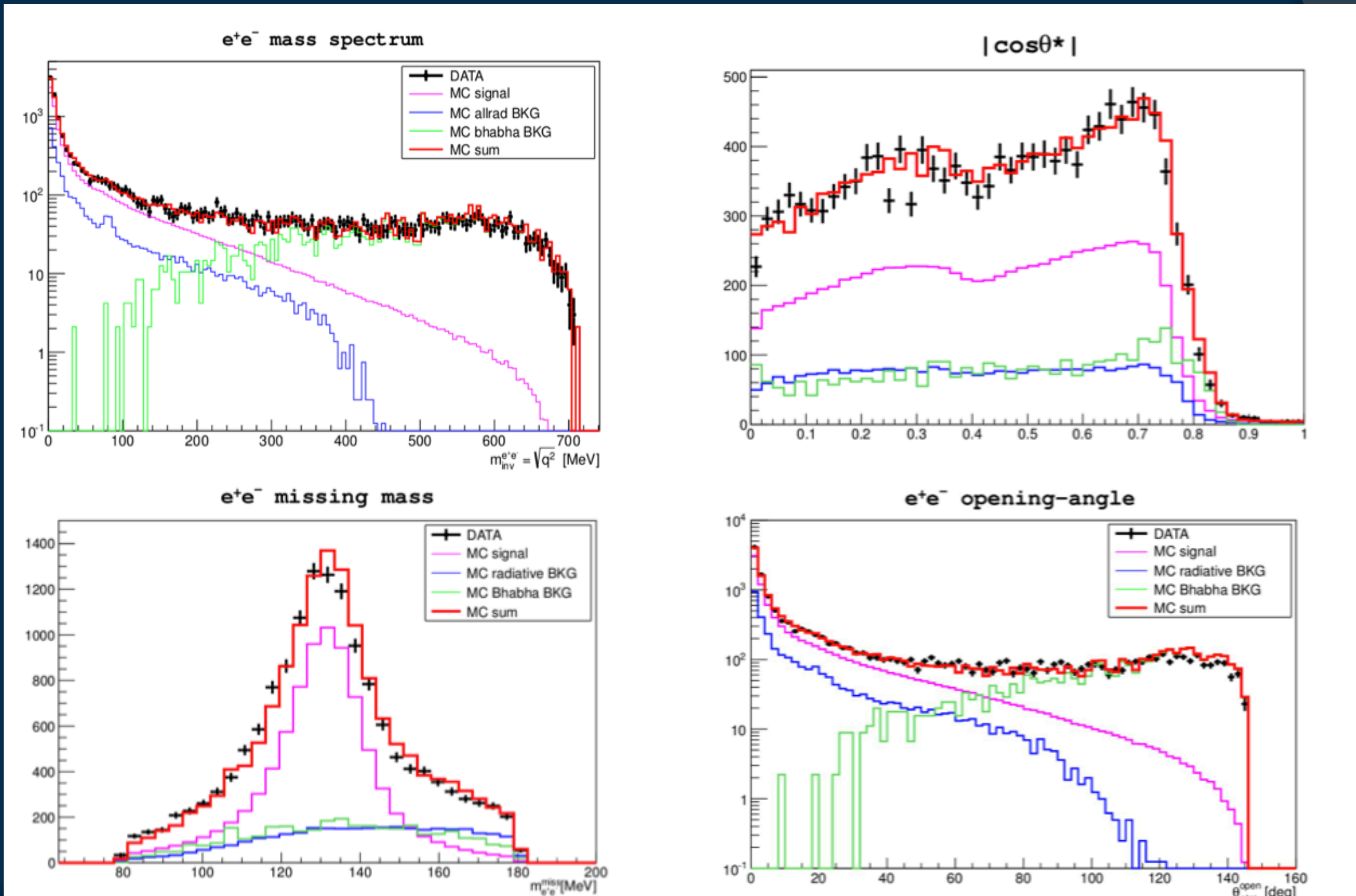
Analyzed sample: 1.7 fb^{-1}

- Events with 2 tracks + 2 prompt photons
- Background:

radiative Bhabha scattering $\phi \rightarrow \pi^0\gamma$ with photon conversion



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

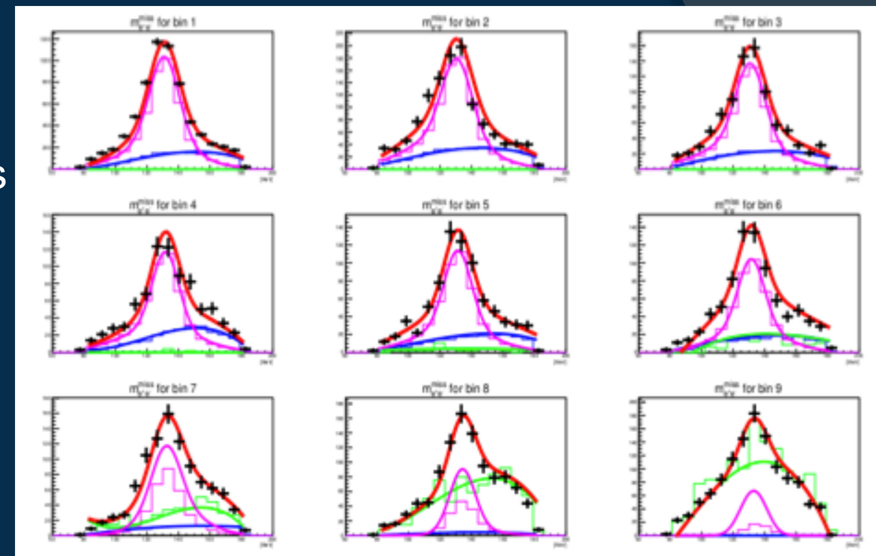


$\phi \to \pi^0 e^+ e^-$: preliminary VMD comparison

✓ At the end of the analysis path, there are 14680 events:

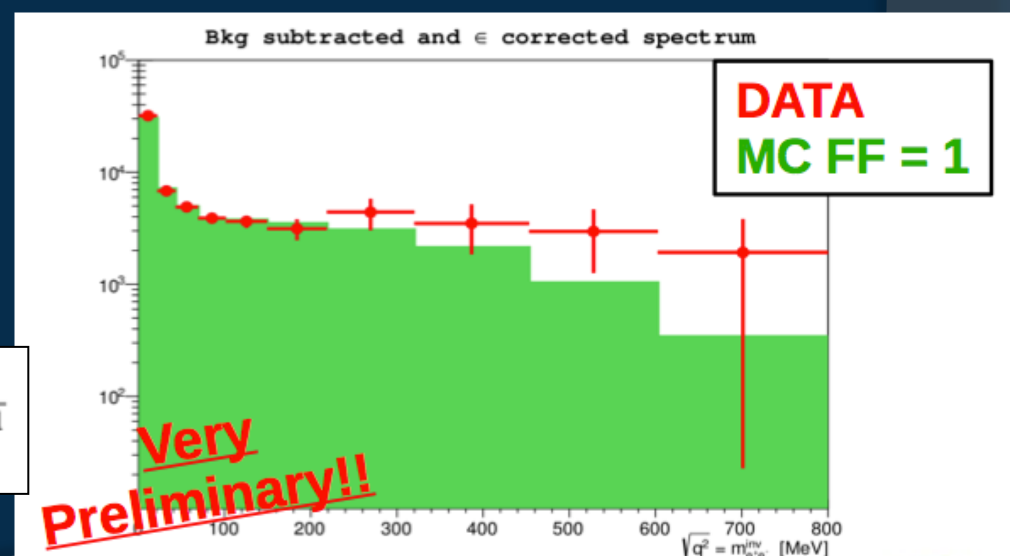
~20% of them are coming from radiative decays background and
~22% from Bhabha scattering events.

The background contribution is bin-by-bin removed by subtracting the fits to each single background component from data points.



✓ The bkg subtraction is in progress
→ fit systematics is due to the limited statistics of the Bhabha MC production

$$\langle |F(q^2)|^2 \rangle_i = \frac{1}{\mathcal{L}_{\rm int} \times \sigma_\phi \times BR(\phi \to \pi^0 e^+ e^-) \times BR(\pi^0 \to \gamma\gamma)} \frac{n_i}{\xi_i^{FF=1}}$$



Conclusions

❑ **We measured TFF and BR with the $\phi \to \eta e^+e^-$, with $\eta \to 3\pi^0$ decay channel:**

- $b_{\phi\eta} = (1.17 \pm 0.10 + 0.07 - 0.11)$ GeV^{-2}
- $BR = (1.075 \pm 0.038 \pm 0.007 + 0.006 - 0.002) \times 10^{-4}$

Both results are in agreement with VMD predictions within 1σ

✓ We are preparing the paper to submit to PLB.
We will list the form factor values as a function of the di-lepton invariant mass.

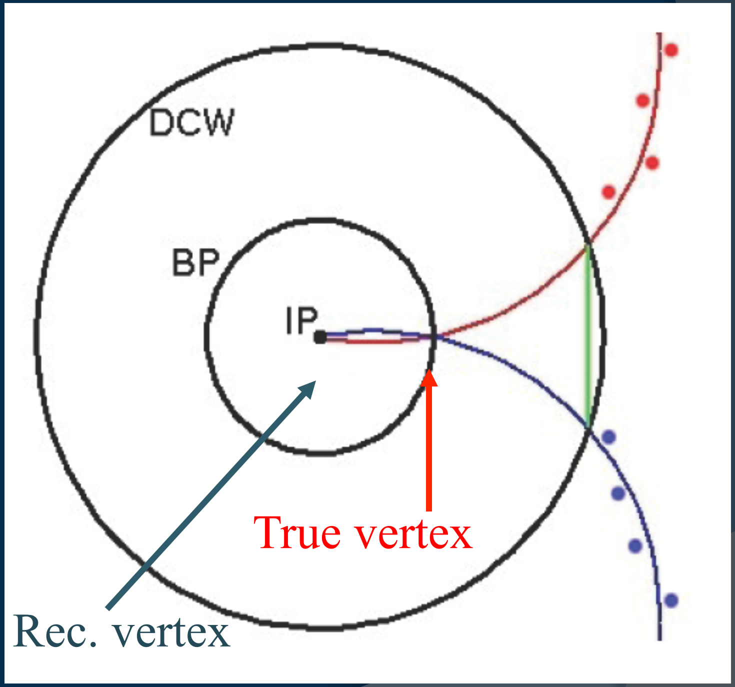
❑ **The analysis of the $\phi \to \pi^0 e^+e^-$ channel is almost finalized. BR and TFF will be soon provided.**

SPARES

Photon conversions

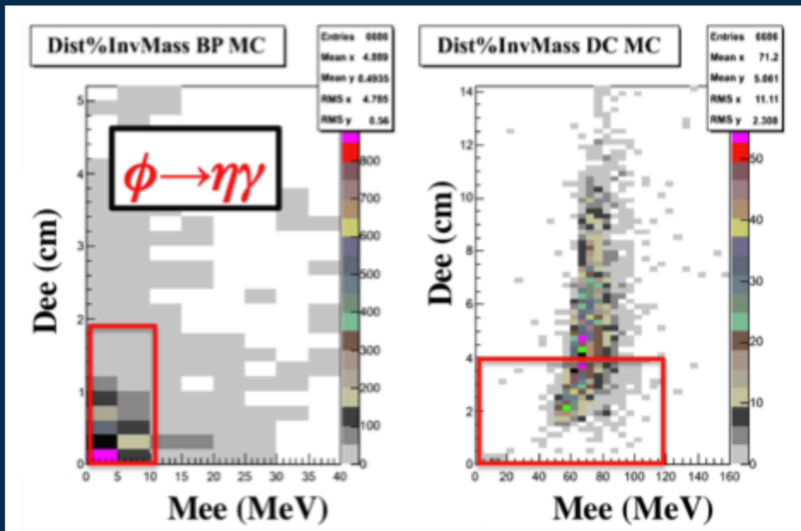
Photons produced near the interaction region, can convert on the beam pipe (BP) or on the drift chamber walls (DCW), simulating an e^+e^- pair from the interaction point

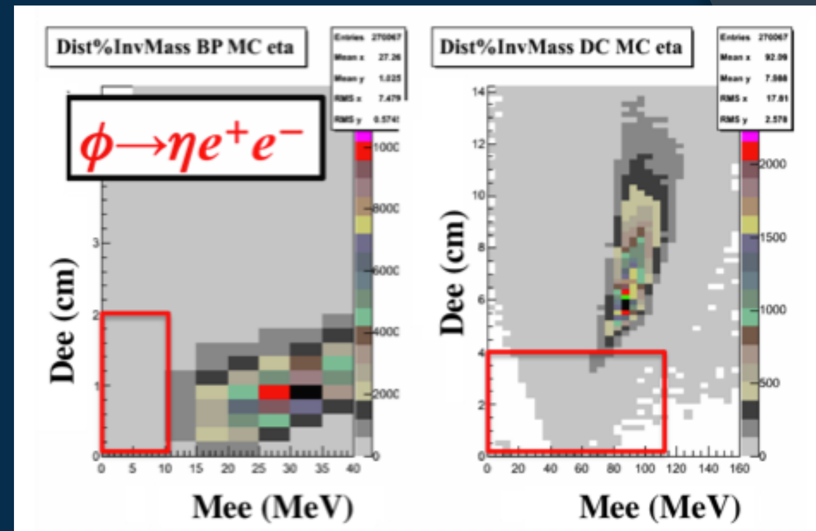
This residual background contamination, due mainly to $\Phi \rightarrow \eta\gamma$ events, is rejected by tracking back to BP/DCW surfaces the e^+ and e^- candidates and then reconstructing the electron-positron invariant mass Mee(BP/DCW) and the distance between the two particles, Dee(BP/DCW).



- **Both quantities are small if coming from photon conversion.**

Background rejection: photon conversions

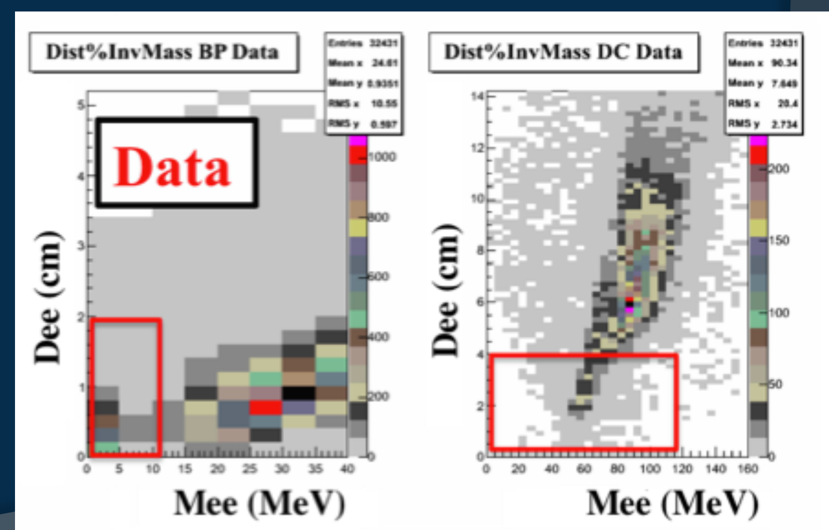




BP and DC cuts applied:

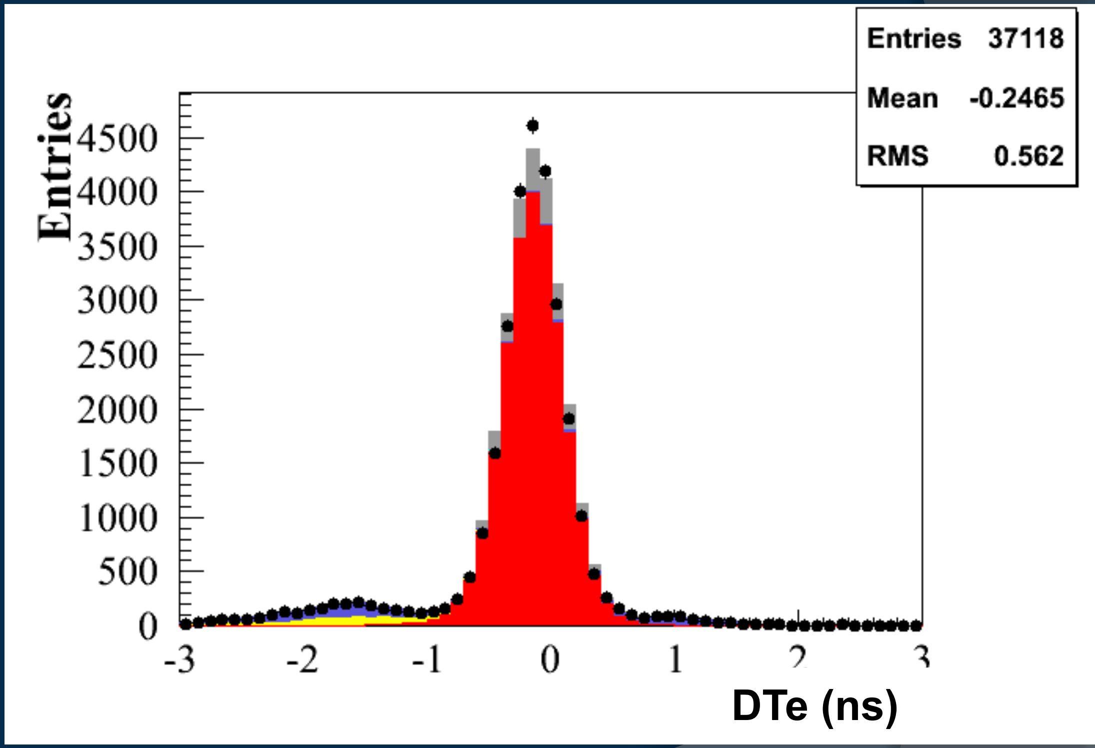
- ✓ Mee < 10 MeV && Dist < 2 cm on BP
- ✓ Mee < 120 MeV && Dist < 4 cm on DC

➢ **Events inside the red boxes are rejected**



Background rejection: Time Of Flight

The residual background contamination, originated by $\Phi \rightarrow K_S K_L$ decays ($K_S \rightarrow \pi^+ \pi^-$ and $K_L \rightarrow 3\pi^0$) and $\omega\pi^0$ surviving the analysis cuts, has two charged pions in the final state and is suppressed using the Time of Flight of tracks to the calorimeter.



- **When an energy cluster is connected to a track, the arrival time to the calorimeter is evaluated using the calorimeter timing ($T_{cluster}$) and the particle trajectory ($T_{track} = L_{track}/\beta c$).**

- **Dte: difference between the measured time and the expected one in the "electron" hypothesis**

TOF procedure:
Events with an e^+ OR e^- candidate inside a 3 σ's window on the DTe variables are **kept : DTe > -0.9 ns & DTe < 0.62 ns**

Branching Ratio – systematics

The systematics error has been evaluated moving by ±1σ Mrec and TOF cuts. For the conversion, the cut is moved by ±20% on the BP/DC distance and invariant mass variables respectively.

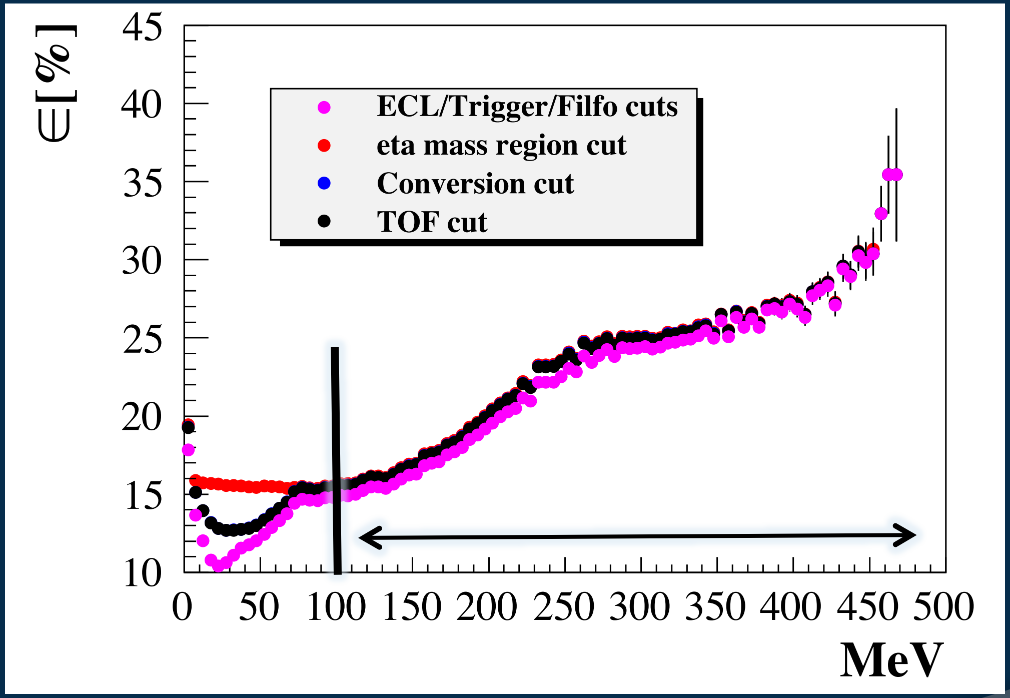
- The total systematic error is the sum in quadrature of all contributions

CUT	BR Variation
$M_{REC.} + 1\sigma$	-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%**

$$BR(\phi \to \eta e^+ e^-) = (1.075 \pm 0.007 \pm 0.038^{+0.006}_{-0.002}) \times 10^{-4}$$

Branching Ratio - systematics

The BR has been measured considering only Mee > 100 MeV. The BR variation is -0.1%. This value has been considered as systematics due to the shape of the efficiency.



Fit to M_{ee} shape

Decay parametrization from L.G. Landsberg, Phys. Rep. 128 (1985) 301:

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

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

We fit our data with the theoretical function folding with the:
- Analysis Efficiencies
- Smearing matrix

FF slope:

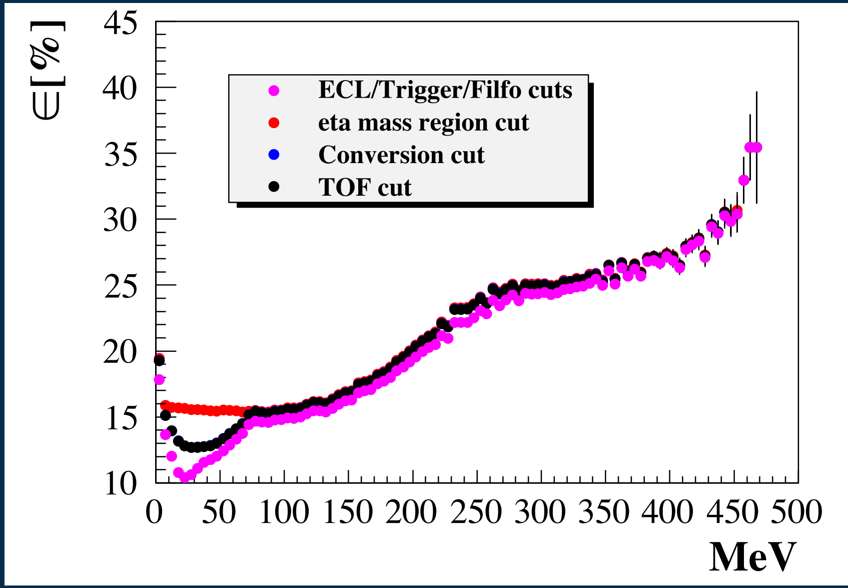
$$\begin{cases} b = dF/dq^2|_{q^2=0} \\ b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} \approx 1/m_\phi^2 \approx 1\ \text{GeV}^{-2} \end{cases}$$

VMD expected value

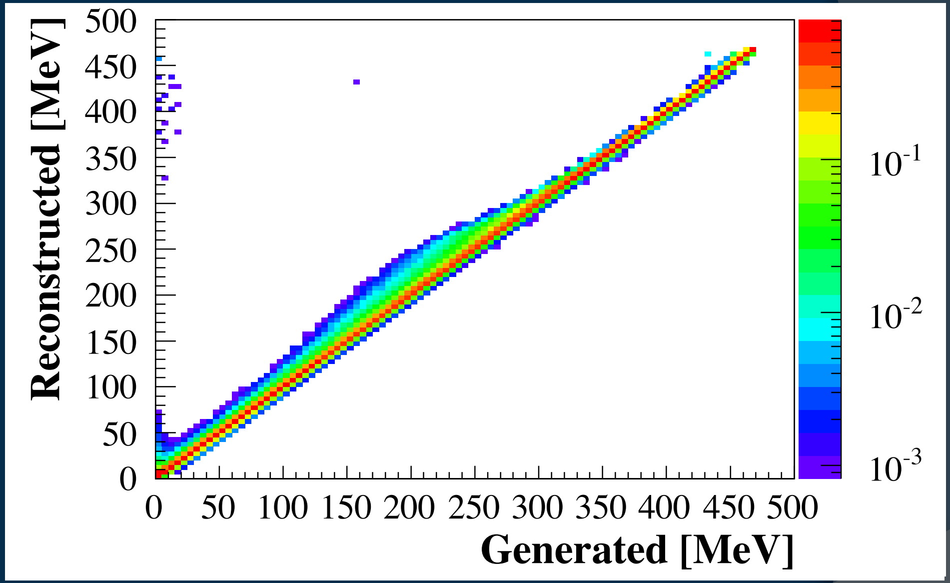
Fit on Mee shape

Reconstruction inputs used to perform the fit:

Analysis Efficiencies at different analysis steps



Smearing Matrix



Fit results

$B_{Mee} = 1.17 \pm 0.10\ \text{GeV}^{-2}$
$\chi^2/NDF = 105.54/90 = 1.17$
Prob.(χ^2)=12.58%

```
COVARIANCE MATRIX CALCULATED SUCCESSFULLY

 FCN=   105.5369     FROM MIGRAD    STATUS=CONVERGED    101 CALLS      103
TOTAL
              EDM=   .11E-06    STRATEGY= 1      ERROR MATRIX ACCURATE

  EXT PARAMETER                                  STEP        FIRST
  NO.   NAME        VALUE          ERROR         SIZE      DERIVATIVE
   1      P1         84070.         539.33         3.2254       -.75121E-06
   2      P2         925.73         39.365         .23612       -.30667E-05

 EXTERNAL ERROR MATRIX.    NDIM=  50     NPAR=  2     ERR DEF=  1.00
  .291E+06  .823E+04
  .823E+04  .155E+04

 PARAMETER  CORRELATION COEFFICIENTS
       NO.  GLOBAL     1     2
        1   .38772  1.000  .388
        2   .38772   .388 1.000
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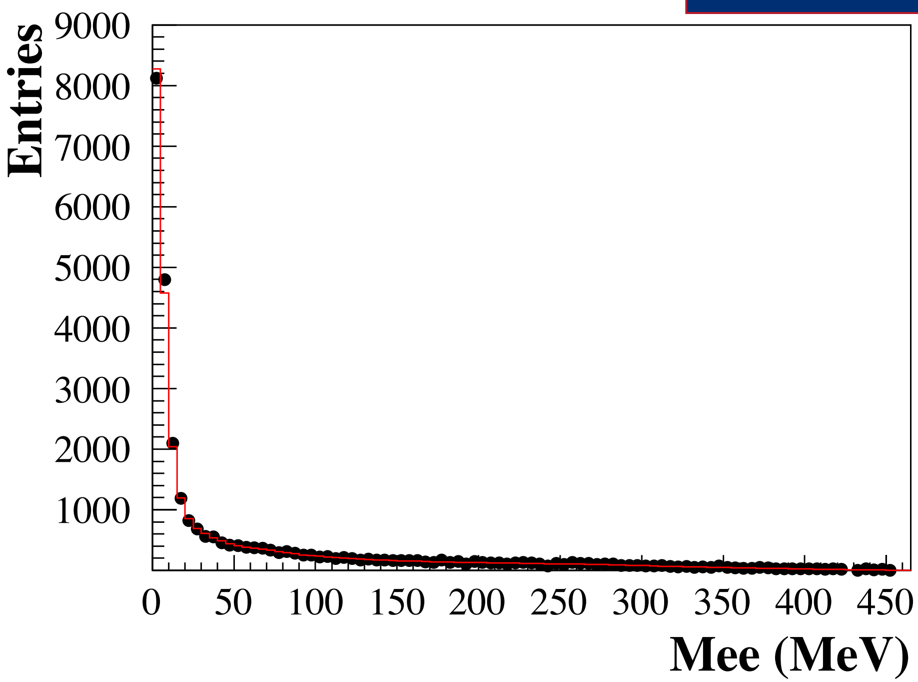
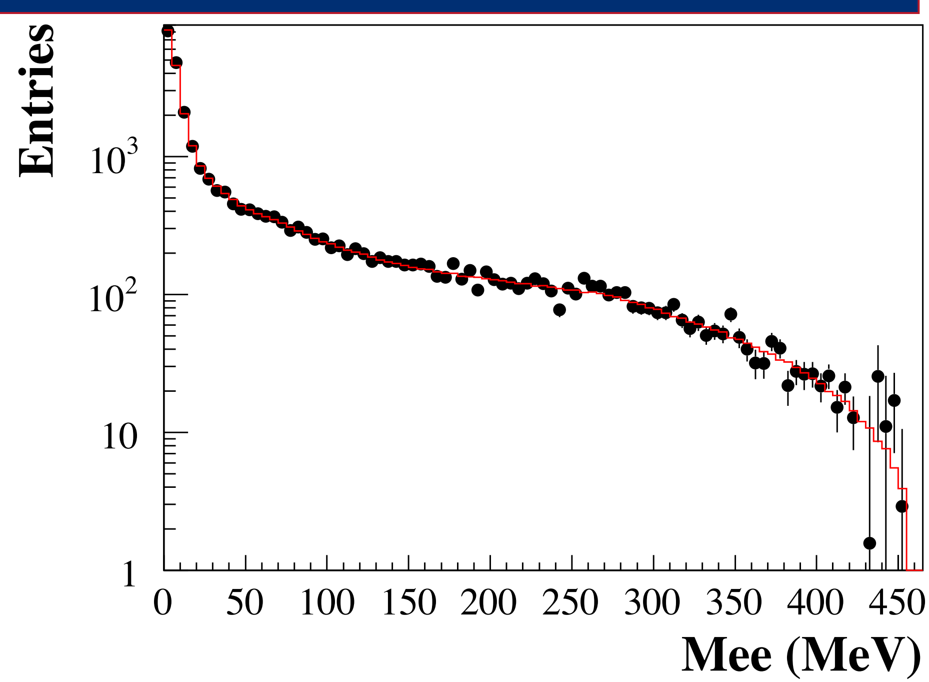
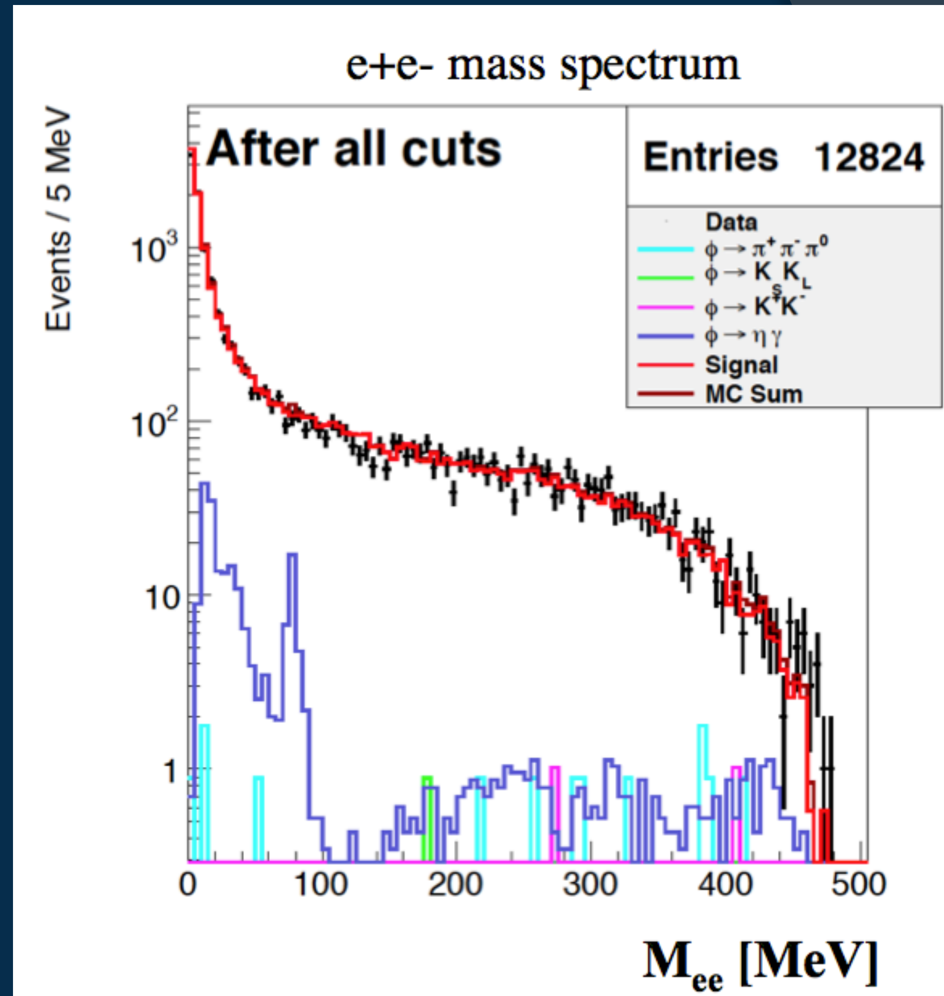




$\phi \to \eta e^+e^-$, $\eta \to \pi^+\pi^-\pi^0$ decay channel

- We are studing also the $\eta \to \pi^+\pi^-\pi^0$ decay channel on 1.5 fb^{-1}

- 4 tracks in a cylinder around IP + 2 photon candidates
- Best $\pi^+\pi^-\gamma\gamma$ match to the η mass using the pion hypothesis for tracks. Other two tracks assigned to e^+/e^-
- $495 < M_{\pi\pi\gamma\gamma} < 600$ MeV
  $70 < M_{\gamma\gamma} < 200$ MeV
  $535 < M_{recoil}(ee) < 560$ MeV
- Photon conversion + ToF cuts



At the end of analysis: ~13000 candidates

→ fit checks and systematics evaluation in progress

Fit result - systematics

The systematics error has been evaluated moving by ±1σ Mrec and TOF cuts respectively and then repeating the fit procedure .
For the conversion the cut is moved by ±20% on the BP/DC distance and invariant mass variables.

- The systematic on fit has been evaluated moving the fit limits and considering the RMS of the deviations from the fit value

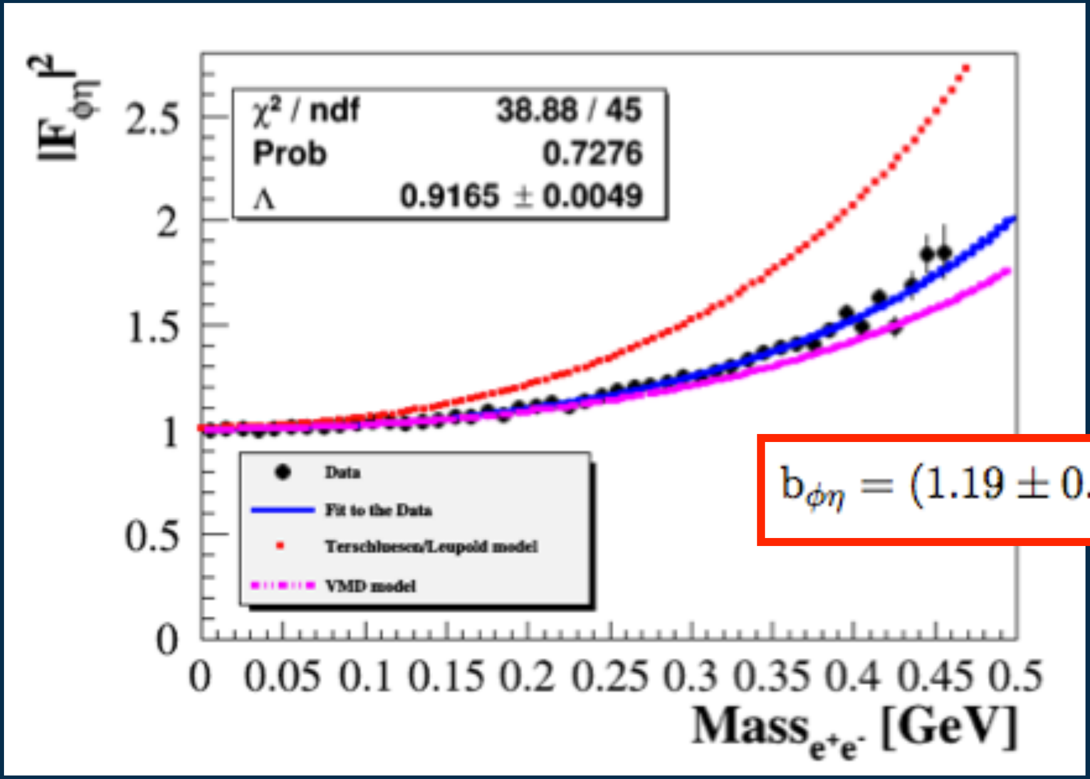
CUT	b Value	χ^2/NDF
fit 1-82	1.25±0.10	110.58/80=1.38
fit 10-92	1.17±0.12	88.45/80=1.11
fit 10-82	1.18±0.12	79.71/70=1.14
fit 2-92	1.14±0.10	103.69/88=1.18
fit 3-92	1.25±0.11	97.65/87=1.12
fit 4-92	1.12±0.11	94.24/86=1.10
fit 5-92	1.12±0.11	94.05/85=1.11

- The total systematic error is the sum in quadrature of all contributions

CUT	$b_{\phi\eta}$ Variation
$M_{REC.} + 1\sigma$ -1σ	+3/3% -4.6%
$TOF + 1\sigma$ -1σ	-2.5% 1.5%
$Conv.(small\ box)$ $(large\ box)$	-5.9% +1.7%
Fit	± 4.4%
	-9.0% **6.0%**

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

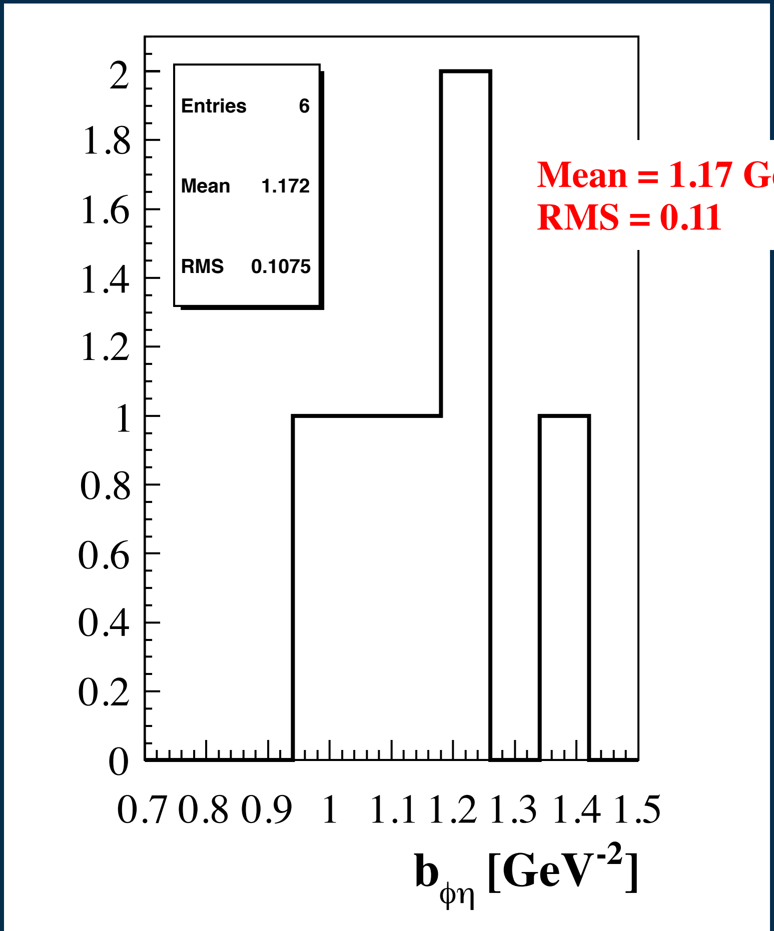
As a cross check, we also fitted the TFF obtained using MC signal events, generated with $b_{\phi\eta}$=1.2 GeV^{-2}, in place of data



$$b_{\phi\eta} = (1.19 \pm 0.01)\ \ GeV^{-2}$$

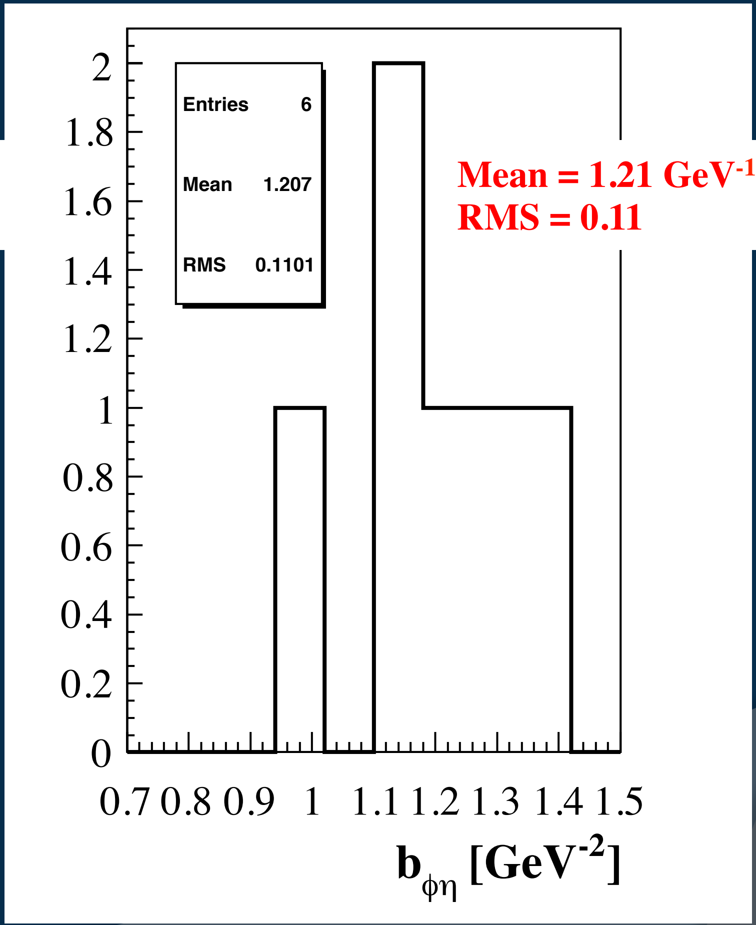
We performed the fit to the MC distribution also using the same data statistics → 1% of MC statistics ~ Data statistics

5 MeV binning



Mean = 1.17 GeV^{-1}
RMS = 0.11

10 MeV binning



Mean = 1.21 GeV^{-1}
RMS = 0.11