U boson search in Φ Dalitz decays with KLOE

I. Sarra

on behalf of the KLOE-2 collaboration

Dark Forces at Accelerators Workshop

INFN – Laboratori Nazionali di Frascati

16 October 2012

Outline

- U boson production mechanism
- KLOE/KLOE-2 at DAΦNE
- U boson production in ϕ decays
  - Search of $\phi \to \eta U$, $\eta \to 3\pi^0$ decay channel
  - Update of $\eta \to \pi^+\pi^-\pi^0$ decay channel
  - Combined Upper Limit
- Conclusions

Experimental motivations for U boson search

Recent astrophysical observations have shown an unclear interpretation on the Standard Model:

- PAMELA observed an excess in the positron fraction ($e^+/(e^+ + e^-)$),

- FERMI and ATIC have observed in cosmic ray data a large excess of electrons and positrons with energies between approximately 100 GeV and 1 TeV

➢ ***Dark matter*** *could possibly explain these observation:* an O(GeV) spin-1 U-boson has been proposed to mediate the interaction among ordinary and dark matter

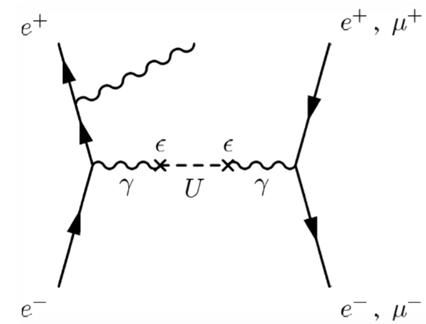
1) Since no astrophysical data involves anomalous production of antiproton, the U boson mass (m_U) should be **less than the mass of two protons**.

2) The U boson can communicate with the SM through a kinetic mixing term describing the interaction of the U boson with SM photon. In this case the parameter ε **should be less than ~ 10^{-2}** .

U boson production mechanisms at KLOE

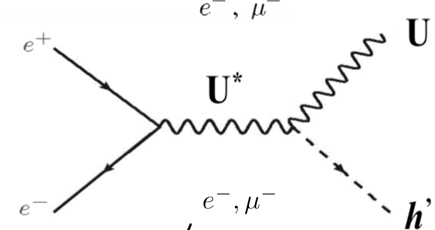
An interesting consequence of the existence of such a **light U boson** is that it can be directly produced at an accelerator, at fixed target experiments or high-luminosity $e^+ e^-$ colliders at the GeV scale. At DAΦNE the possible production mechanisms and decays are:

1) Associated Uγ production via the resonant radiative production of a U boson, followed by its decay into a lepton - anti lepton pair



F.Curciarello
Wednesday

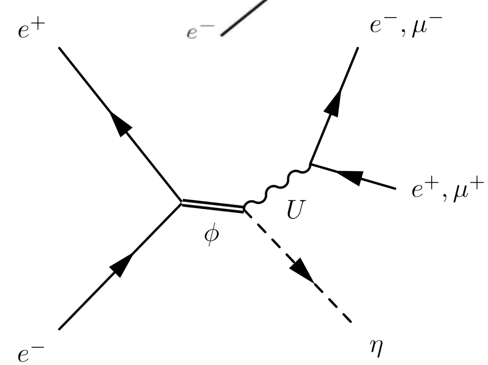
2) Higgsstrahlung production. If the hidden simmetry is spontaneously broken by a Higgs-like mechanism, the existence of at least one other scalar particle, the *h*', can be postulated



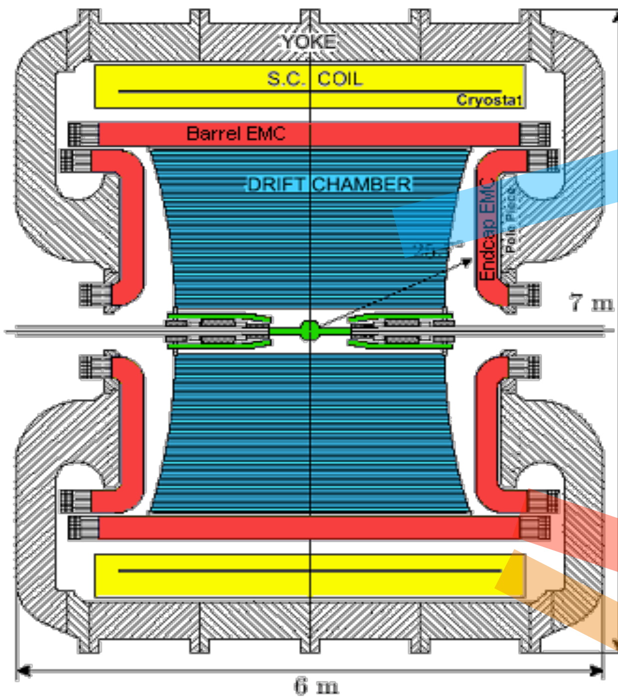
E. Graziani
Wednesday

3) Associated decay of Φ meson into a pseudoscalar and a U, as suggested by Reece and Wang.

[M.Reece and L.T.Wang, JHEP 0907:051 (2009)]



The KLOE experiment



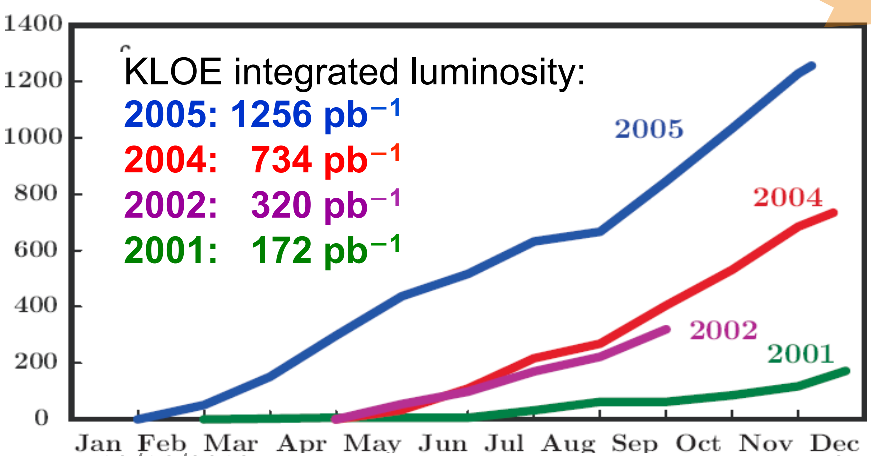
Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ (θ>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

$\sigma_{peak} \sim 3.1\ \mu b$

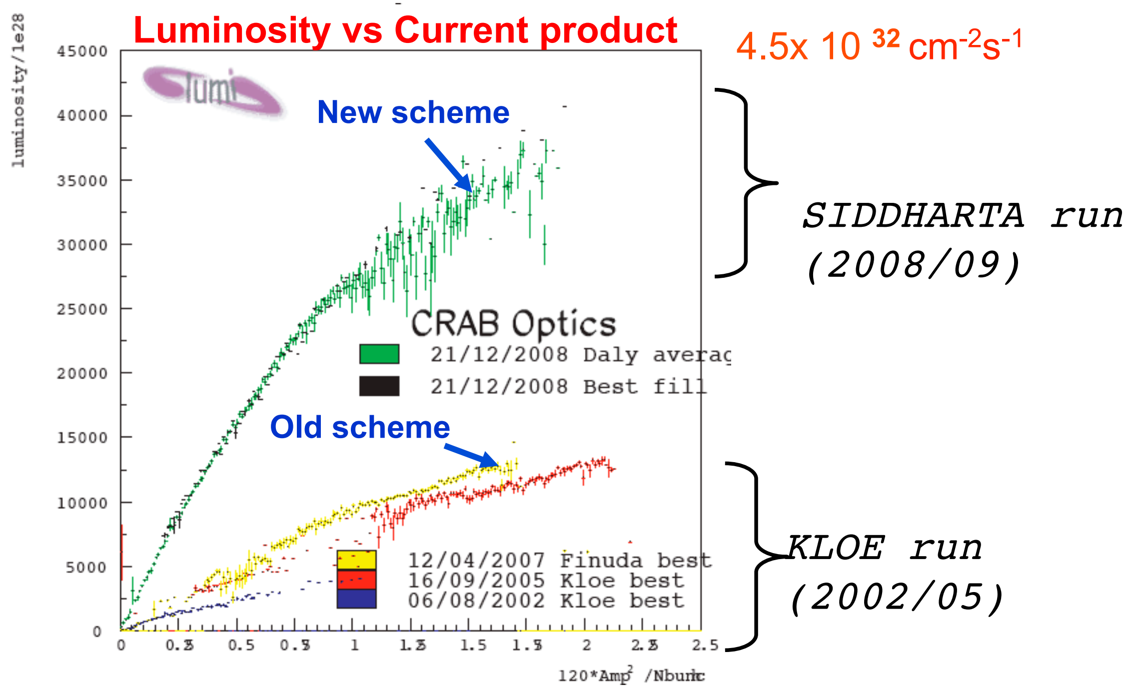
KLOE: 2.5 fb^{-1} @ $\sqrt{s} = M_\phi$ (~ 8×10^9 ϕ produced)

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

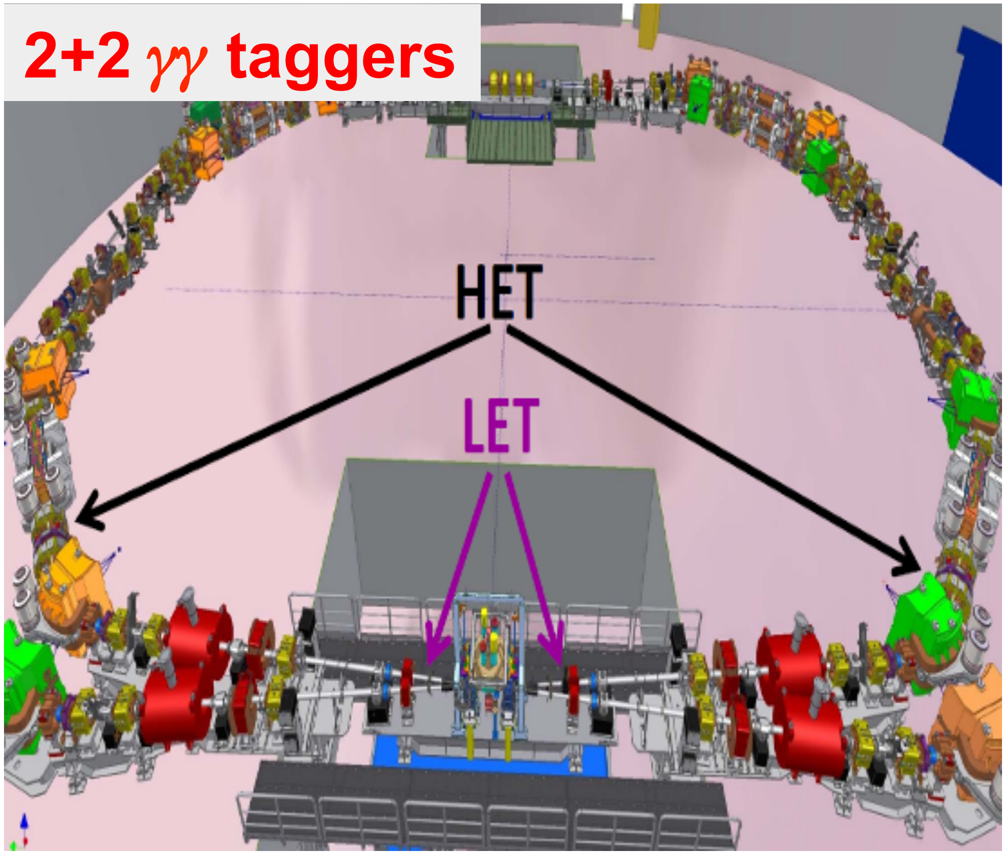
DAΦNE and KLOE-2

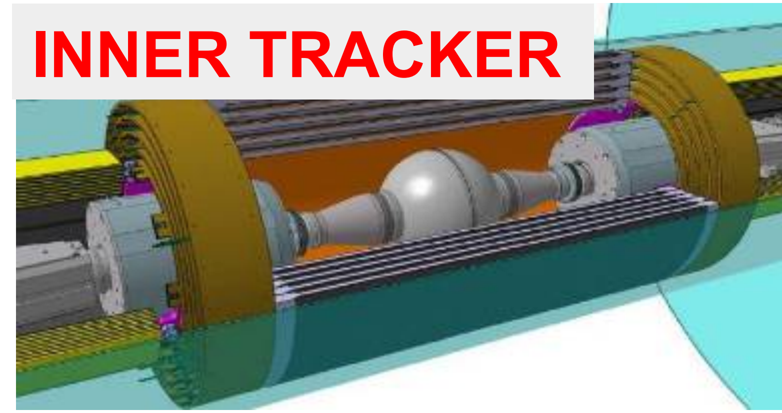
Since the beginning of 2008, DAΦNE has implemented a new interaction scheme. Results obtained during run of SIDDHARTA were very good: an increase of a peak luminosity per day by a factor of **~ 3** and of the integrated luminosity by **~ 2**.

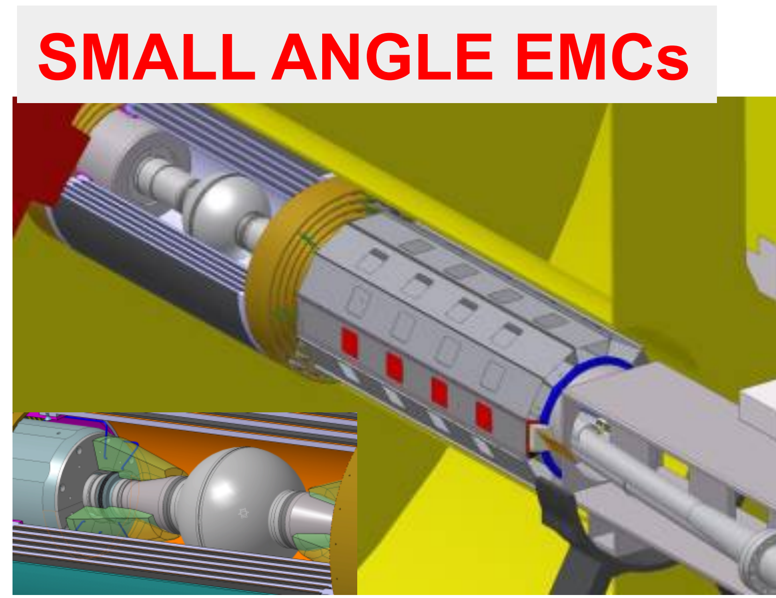
The goal is to increase the present KLOE statistics by a factor of 5 (10 fb^{-1}) within the next years.



From KLOE to KLOE-2







Searching in $\phi \to \eta l^+ l^-$ decays

- Mesons undergoing radiative decays to photons could also decay to a U boson with a branching fraction:

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

- For the $\Phi \to \eta$ U decay the estimated cross section is:

$\boldsymbol{\sigma(\Phi \to \eta U) \approx 40\ fb}$ for $FF_{\phi\eta} \approx 1$ and $\varepsilon \approx 10^{-3}$

Selected decay chain:

$U \to e^+e^-$ and $\eta \to \pi^+ \pi^- \pi^0$ (BR = 22.7%) **Phys.Lett. B706 (2012) 251-255**

$\eta \to \pi^0 \pi^0 \pi^0$ (BR = 32.6%) **Topic of this talk**

- In the present talk the combined result will be shown.

arXiv: 1210.3927, submitted to PLB

$\phi \rightarrow \eta\, e^+e^-$, $\eta \rightarrow 3\pi^0$ Dalitz decay simulation

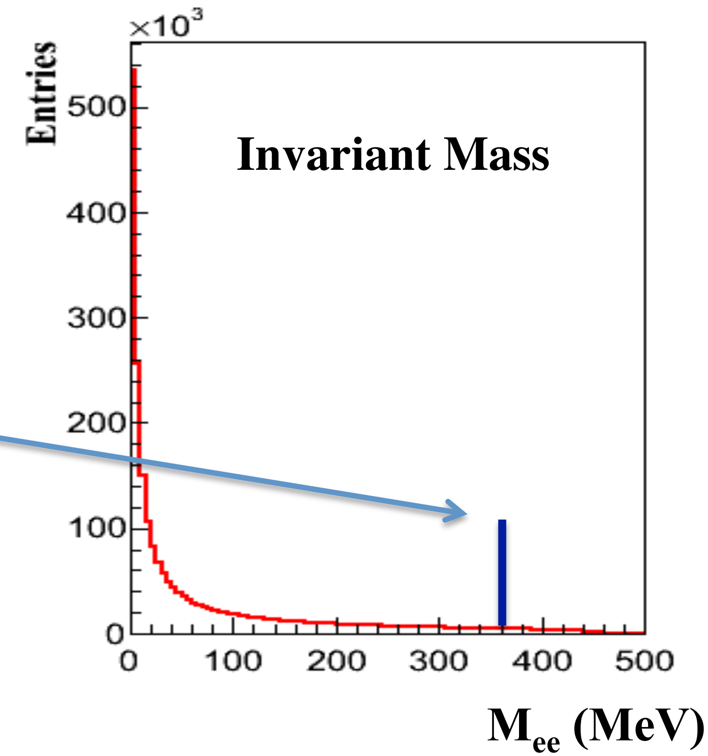
The irreducible background $\Phi \rightarrow \eta\, e^+e^-$, $\eta \rightarrow \pi\pi\pi$, has been simulated according to a Vector Meson Dominance parameterization:

$$\frac{d}{dq^2}\frac{\Gamma(\phi \to \eta\, e^+e^-)}{\Gamma(\phi \to \eta\gamma)} =$$

$$\frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\left(1+\frac{2m^2}{q^2}\right)\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2 q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

with, $\quad F(q^2_{\phi\eta}) = \dfrac{1}{1-q^2/\Lambda^2_{\phi\eta}}$

- **A distinctive feature of the expected signal is the appearance of a peak in the invariant mass distribution of the lepton pairs over the standard continuous QED background.**

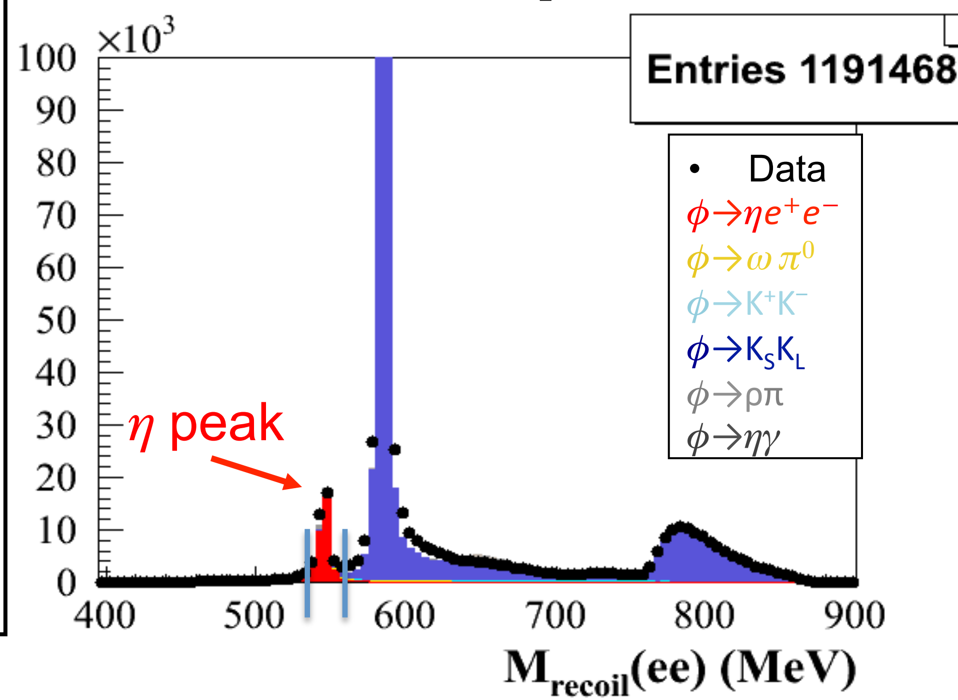


Search for $\phi \rightarrow \eta U$ Decays with $\eta \rightarrow 3\pi^0$

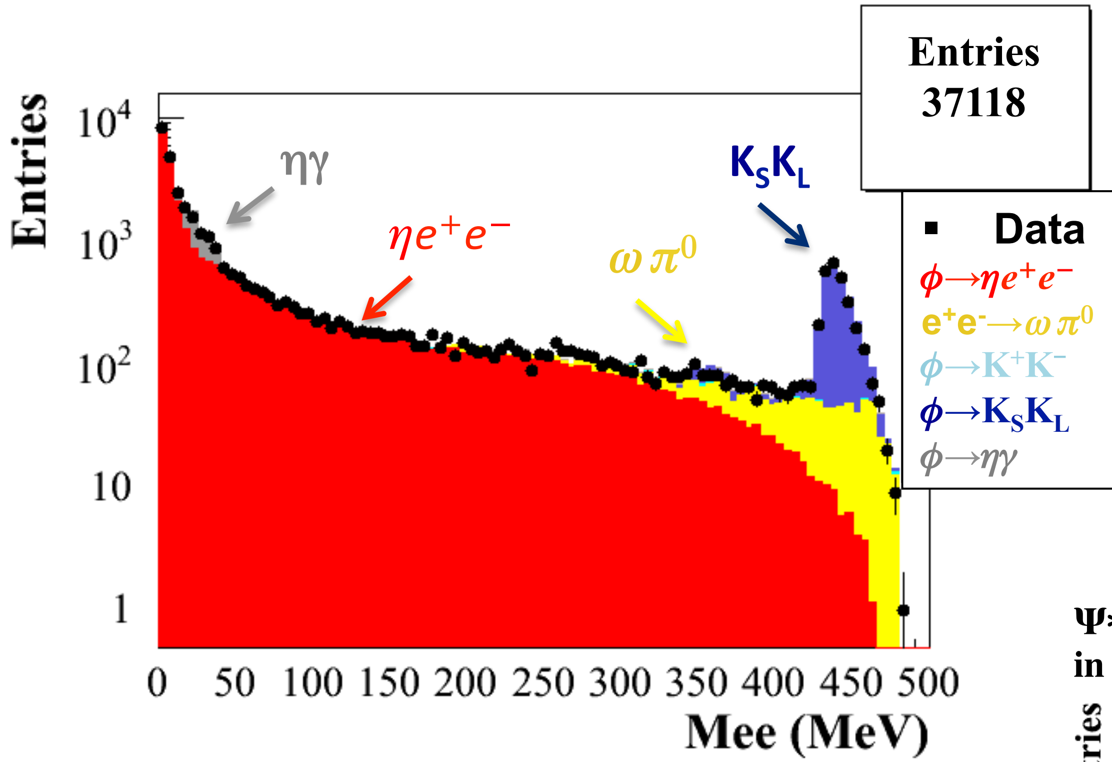
Pre-selection after triggering and streaming

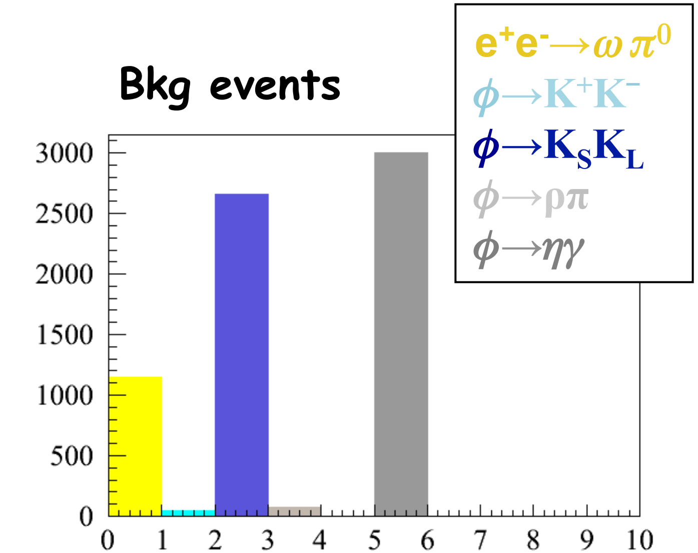
- 2 tracks (1 negative and 1 positive) in a cylinder around IP
- 6 prompt photons candidates, i.e. energy clusters with E > 7 MeV not associated to any track, in an angular acceptance | cos $\theta\gamma$| < 0.92 and in the expected time window for a prompt photon ($|T_\gamma - R_\gamma/c| < \mathrm{MIN}(\mathbf{3\sigma_T}, 2\ \mathrm{ns})$)
- **$400 < M_{6\gamma} < 700$ MeV**

Analysis performed using 1.7 fb^{-1}

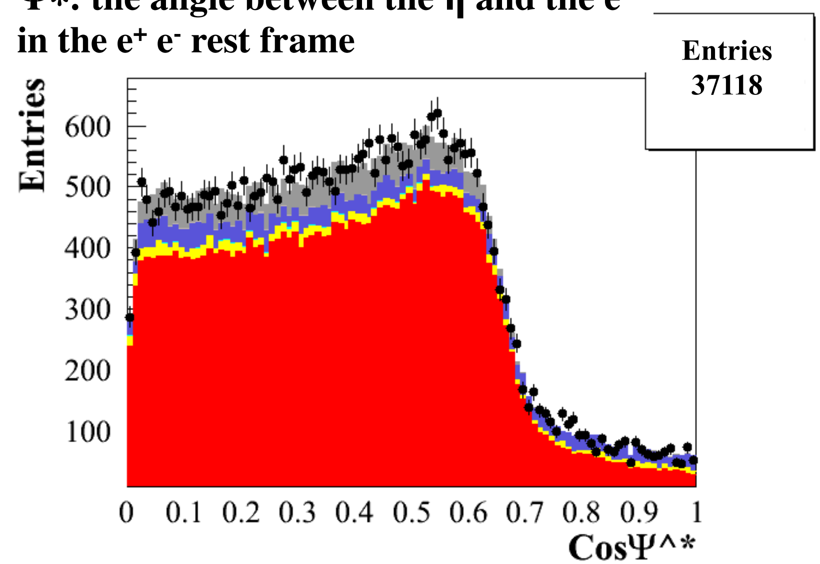


Data-MC comparison after pre-selection and cut on M_{recoil}





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



M_{recoil} cut:

$536.5 < M_{rec} < 554.5$ (3 σ around the η peak)

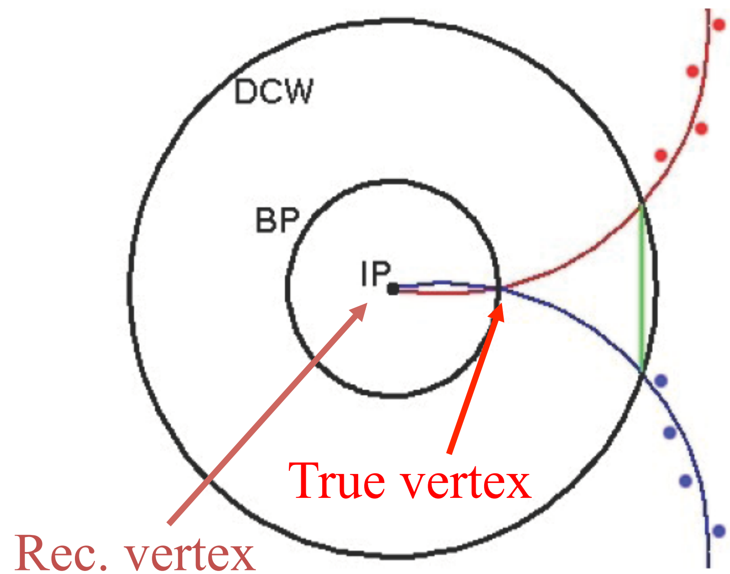
- **Background contamination ~ 20%**

Photon conversions

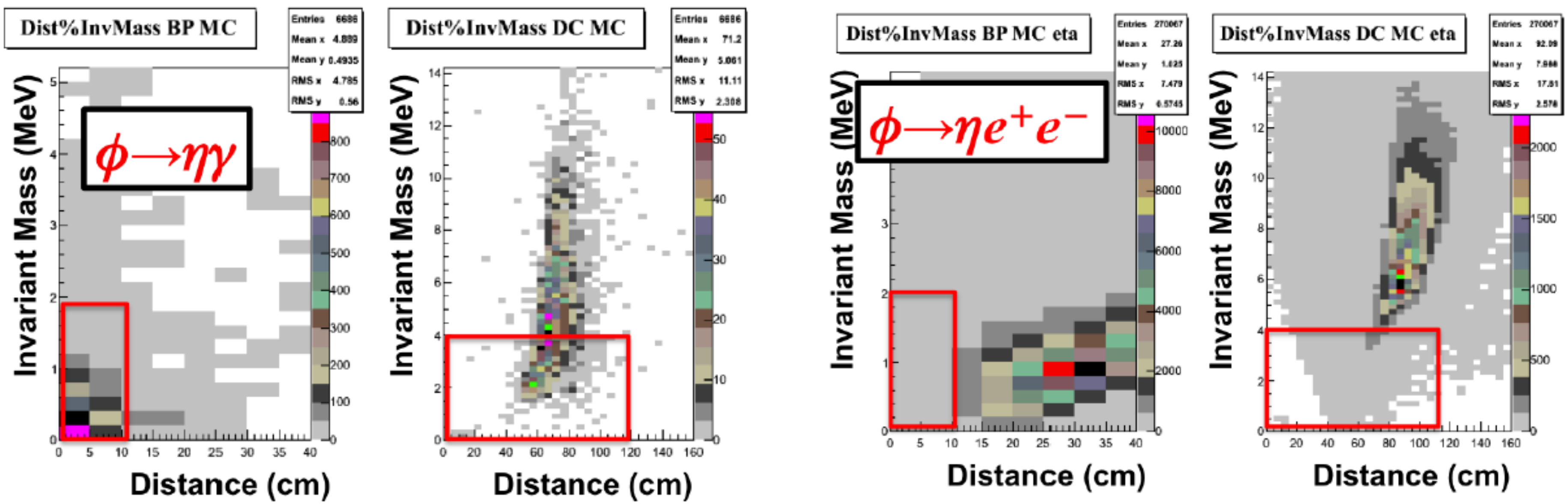
Photons produced near the interaction region, can convert on the beam pipe (BP) or on the drift chamber walls (DCW), simulating an e^+e^- pair from the interaction point

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.**



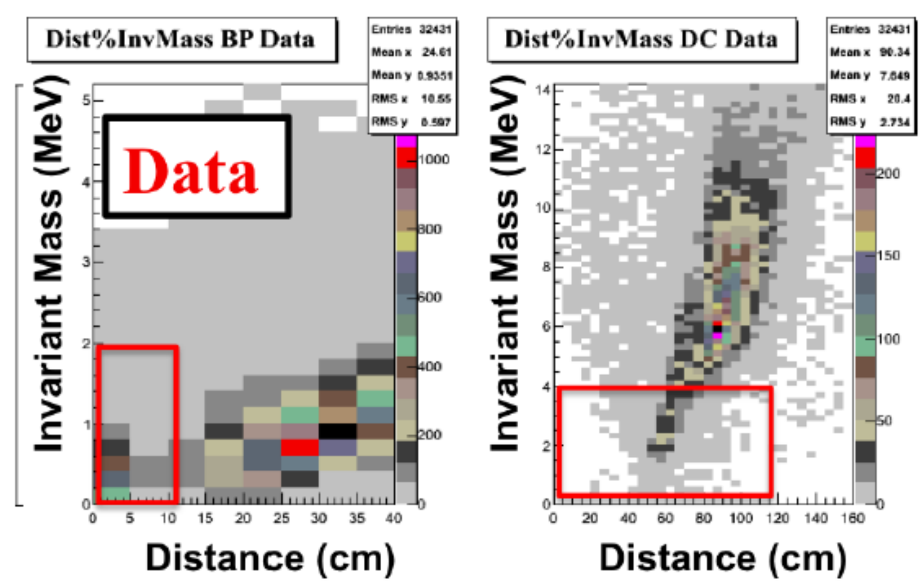
Background rejection: photon conversions



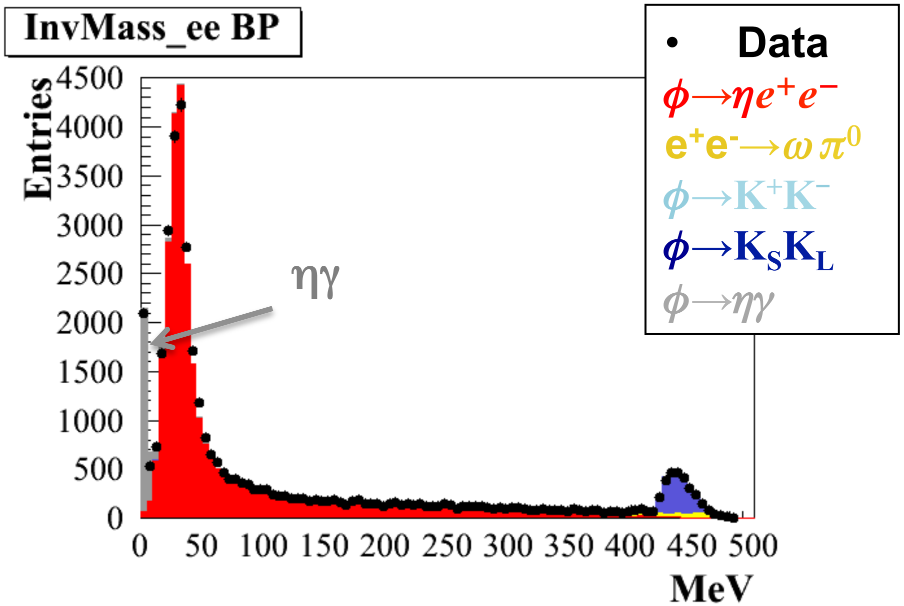
BP and DC cuts applied:

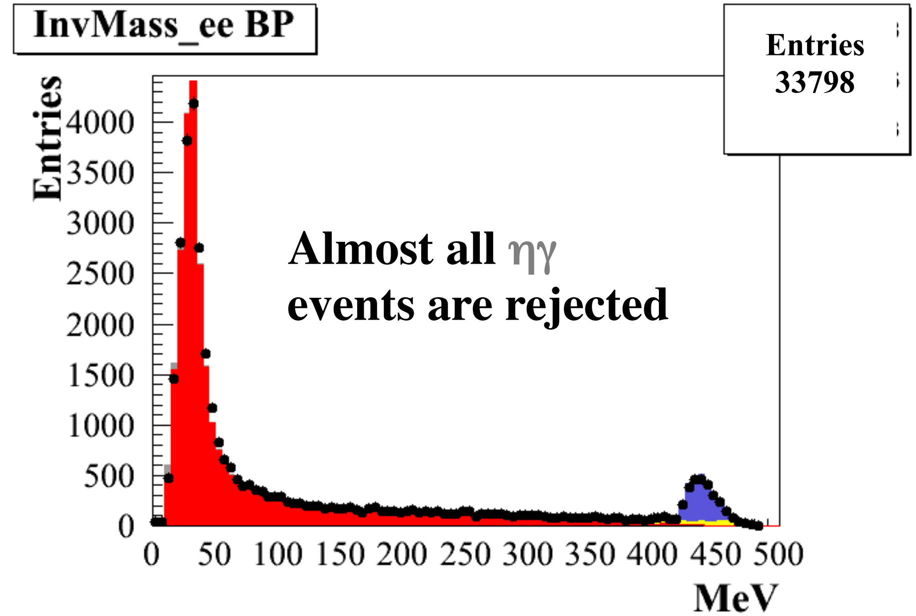
- Mee < 10 MeV && Dist < 2 cm on BP
- Mee < 120 MeV && Dist < 4 cm on DC

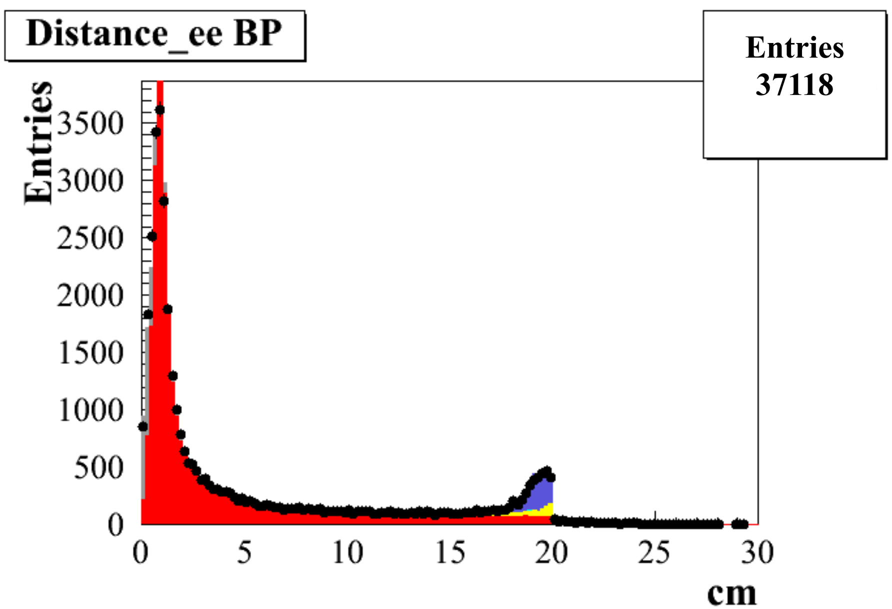
➢ **Events inside the red boxes are rejected**

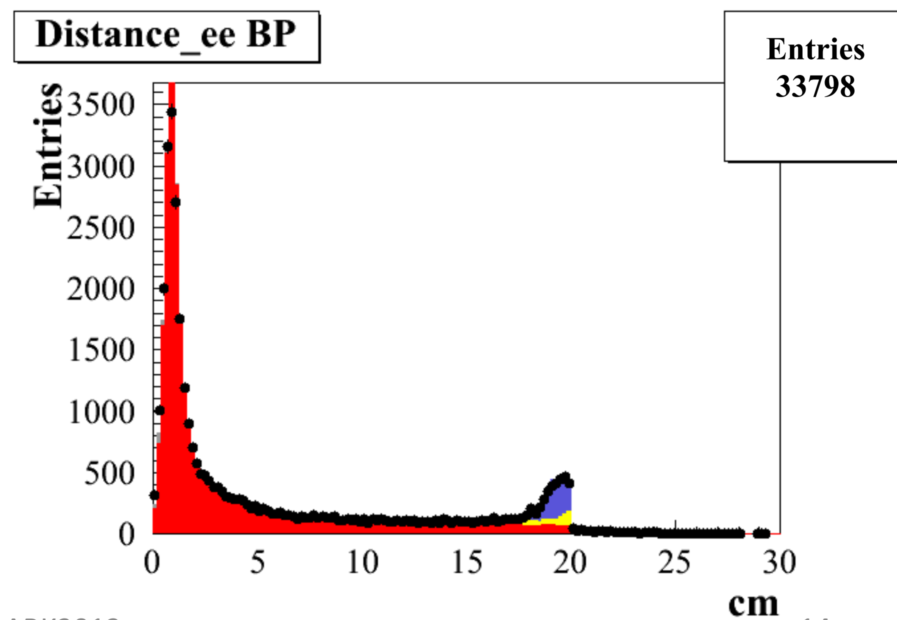


M_{ee} and D_{ee} @ BP before and after conversion cuts

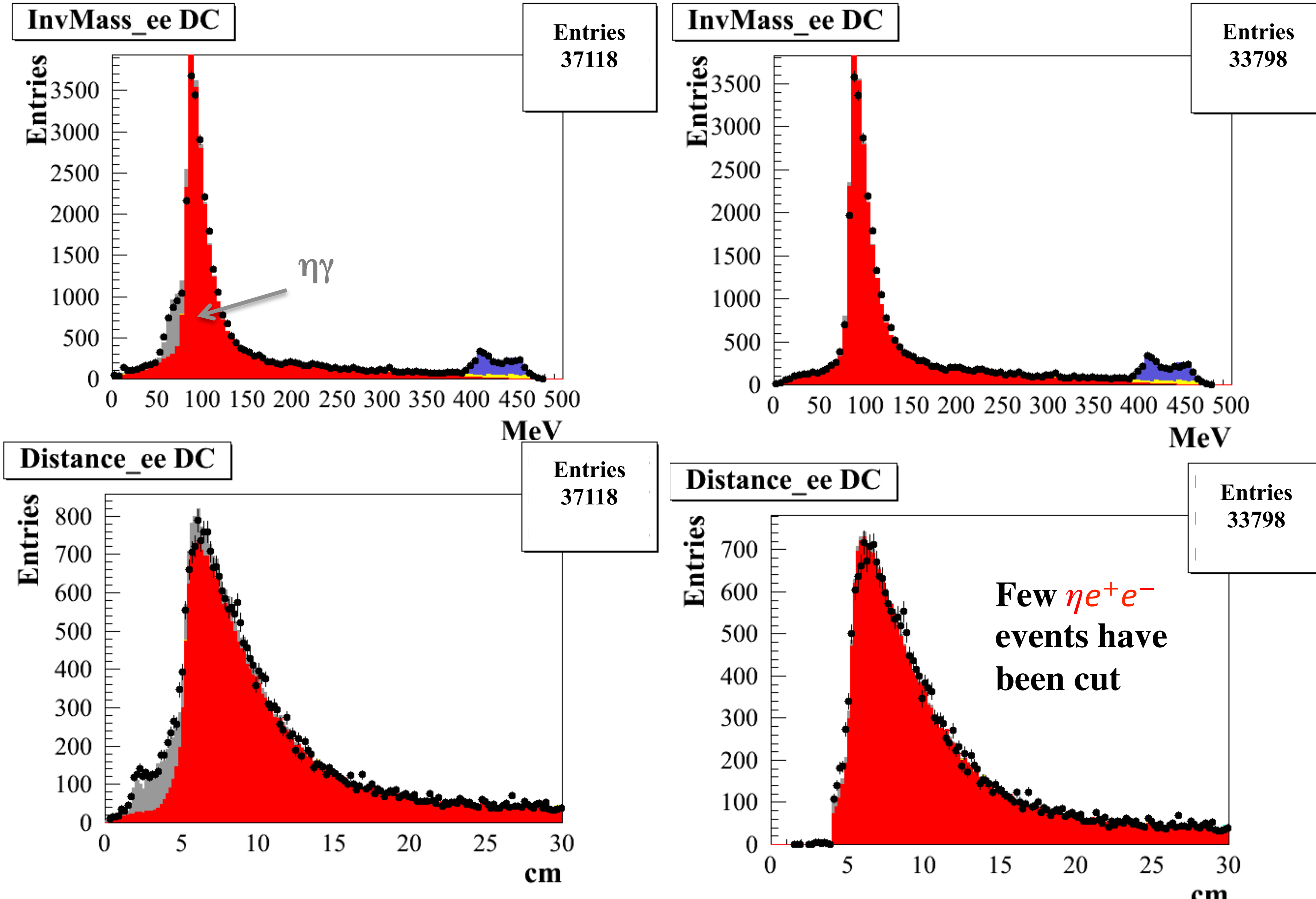




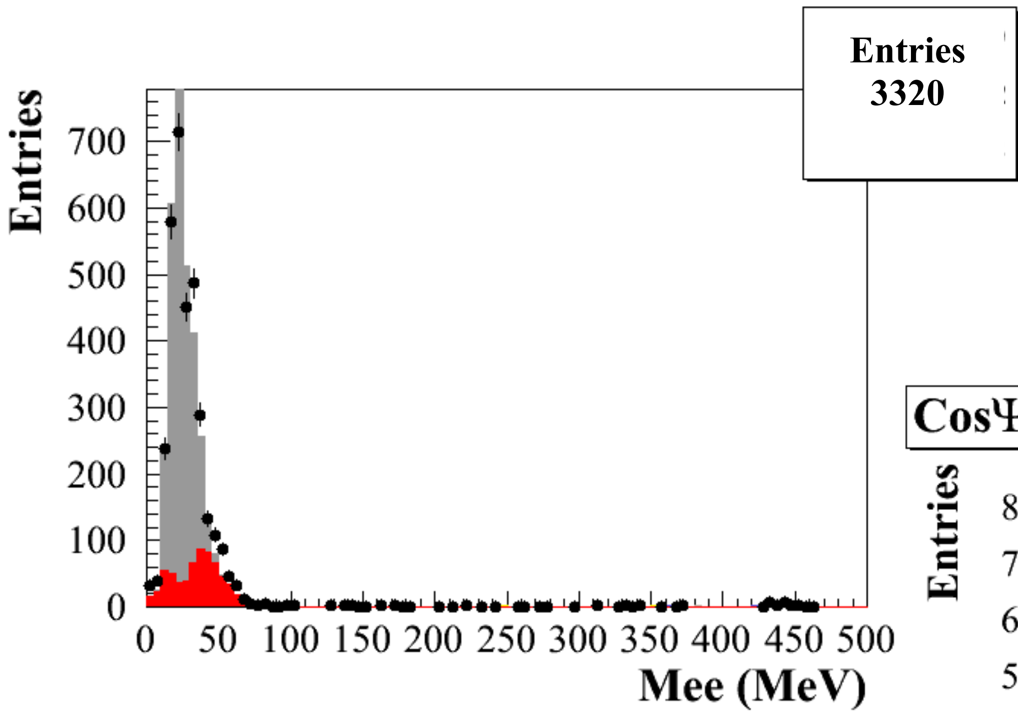




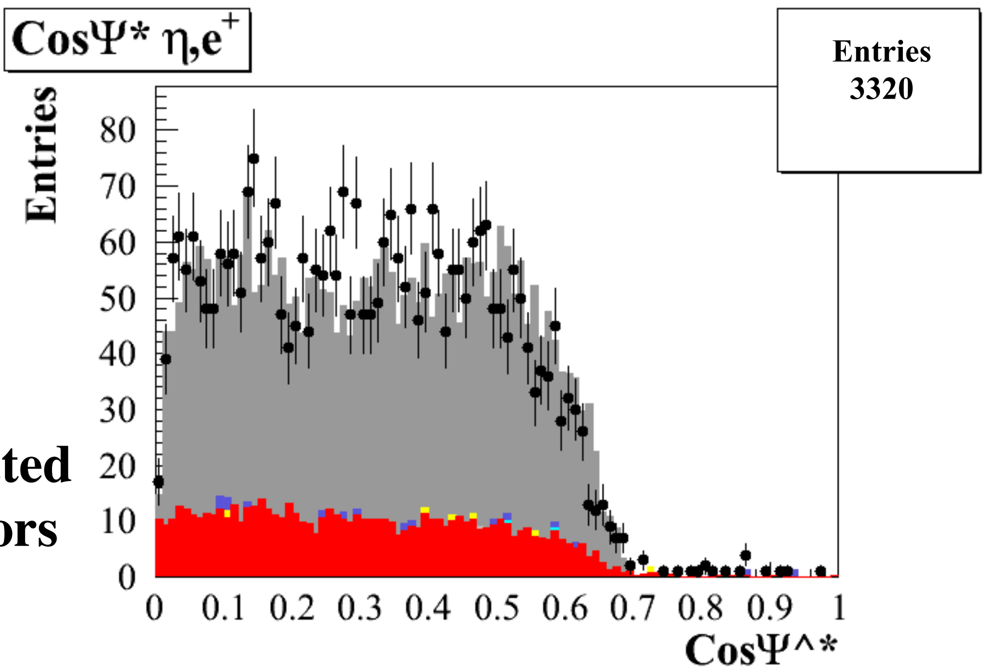
M_{ee} and D_{ee} @ DC before and after conversion cuts



Events rejected by the conversion cuts



The cuts reduce the number of bkg events by a factor of ~ 10.



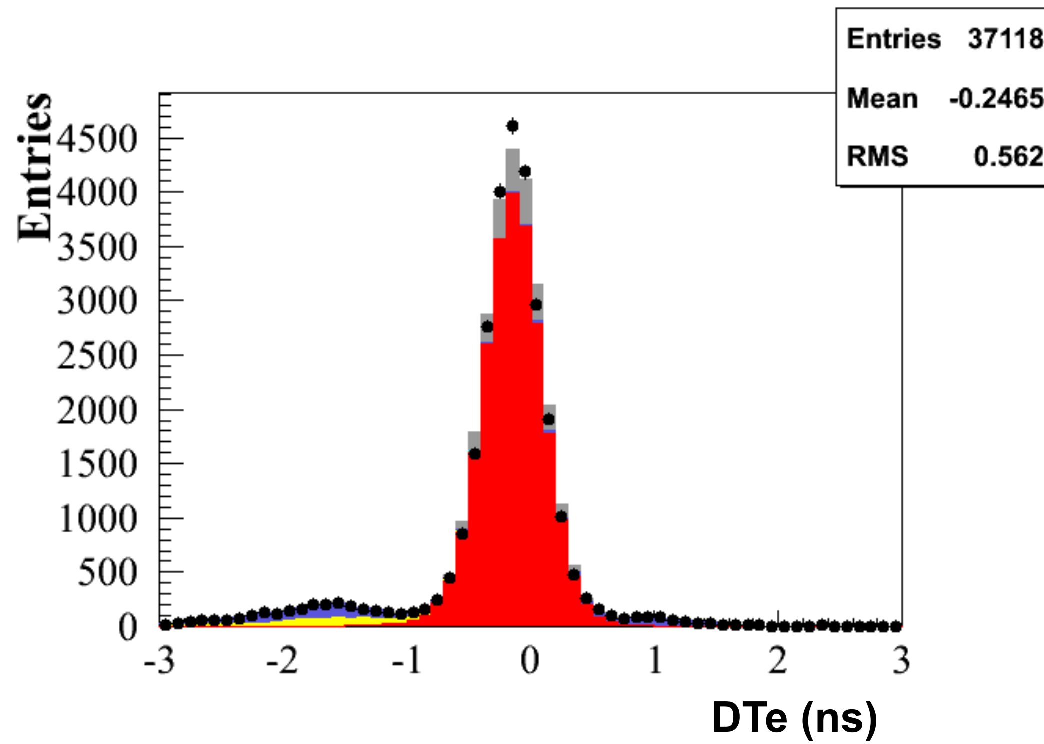
MC shapes and normalization of rejected quantity in agreement within stat. errors

Background rejection: Time Of Flight

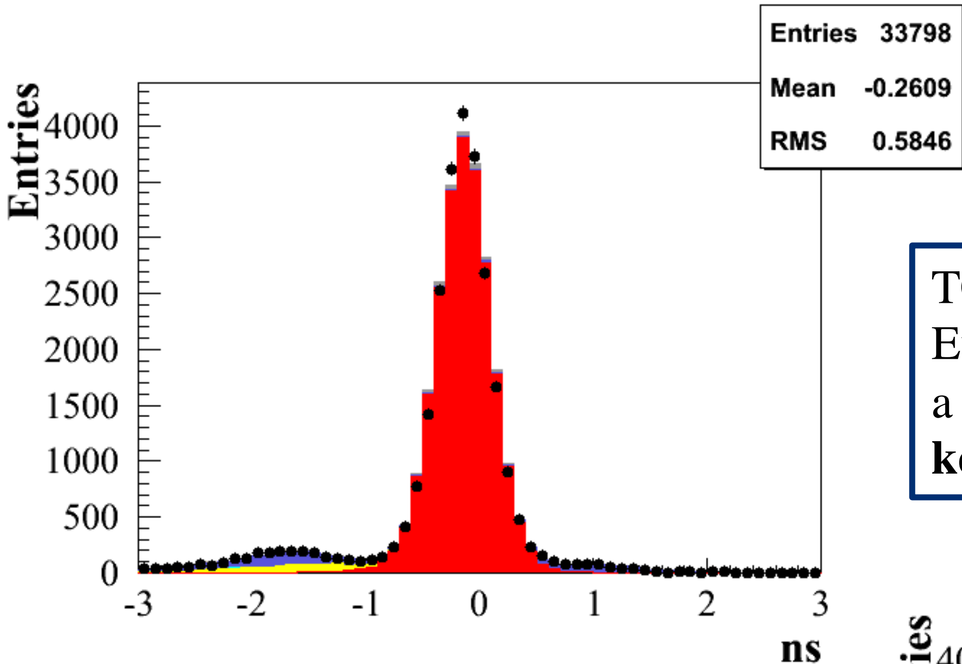
The residual background contamination, originated by $\Phi \rightarrow K_S K_L$ decays ($K_S \rightarrow \pi^+ \pi^-$ and $K_L \rightarrow 3\pi^0$) and $\omega\pi^0$ surviving the analysis cuts, has two charged pions in the final state and is suppressed using the Time of Flight of tracks to the calorimeter.

- **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 ($T_{track} = L_{track}/\beta c$).**

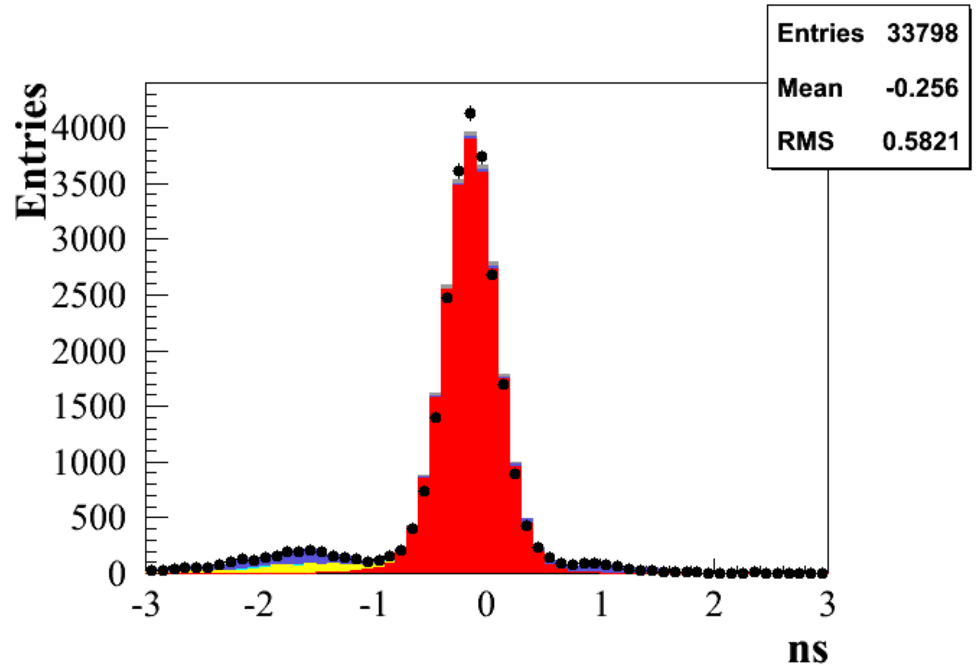
- **Dte: the difference between the measured time and the expected one in the "electron" hypothesis**



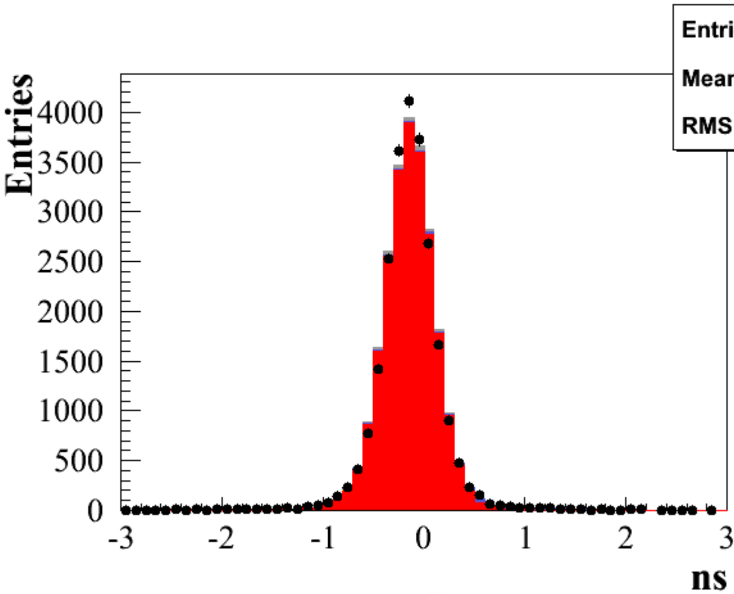
Pre-selection & M_{recoil} & Conv cuts

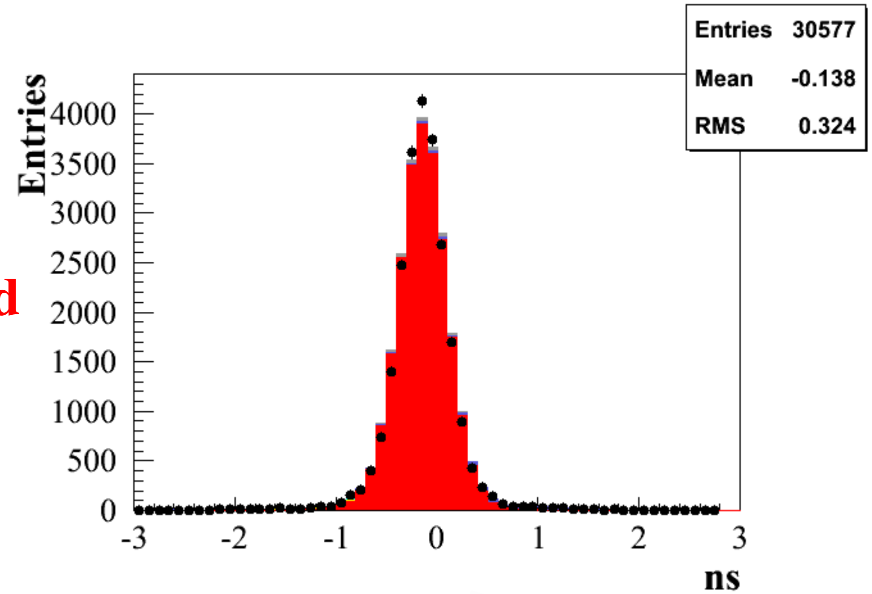


TOF procedure:
Events with an e^+ OR e^- candidate inside a 3 σ's window on the DTe variables are **kept : DTe > -0.9 ns & DTe < 0.62 ns**

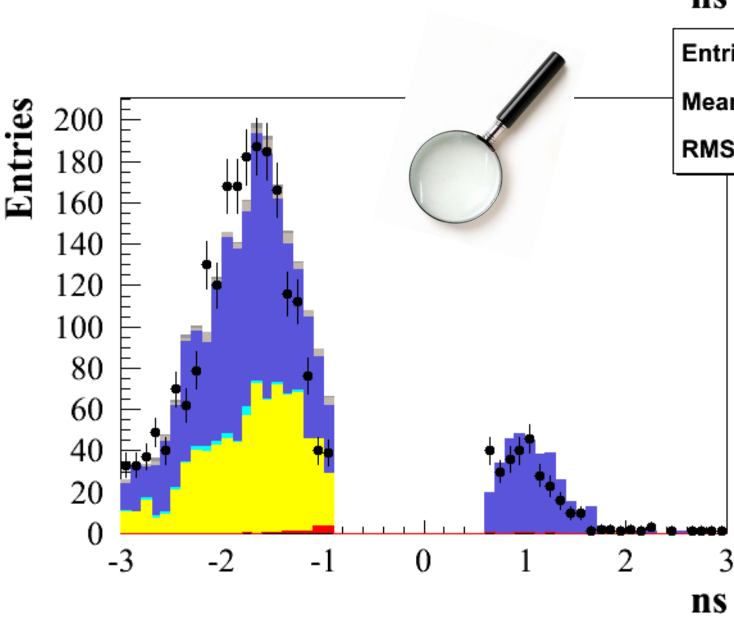


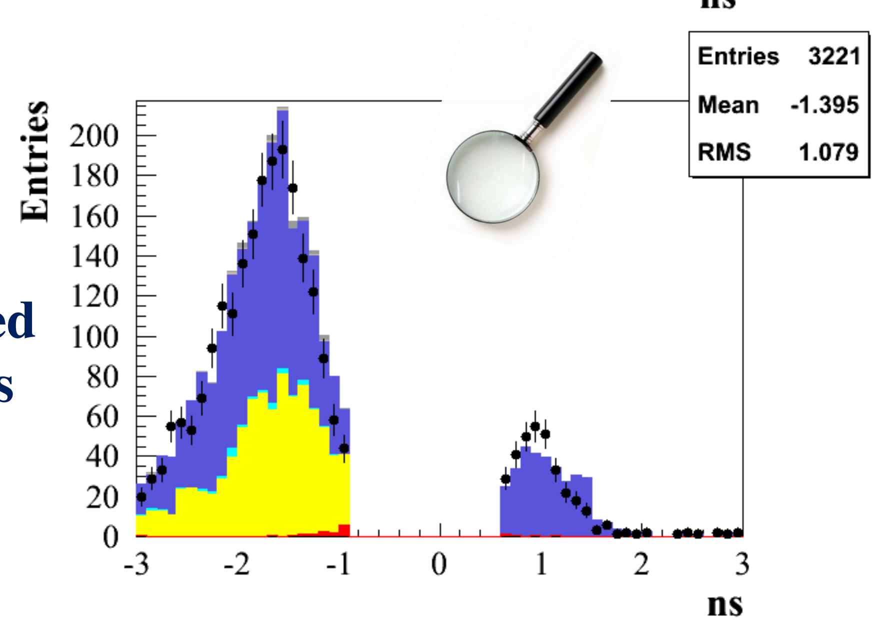
Pre-selection, M_{recoil}, Conv and TOF cuts





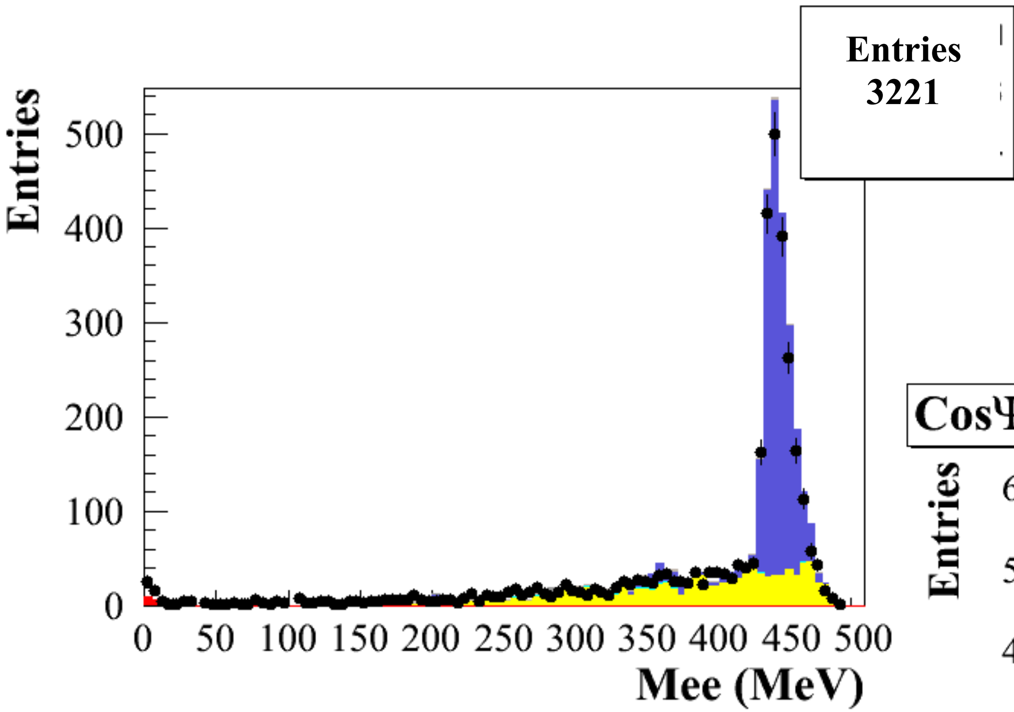
Selected events



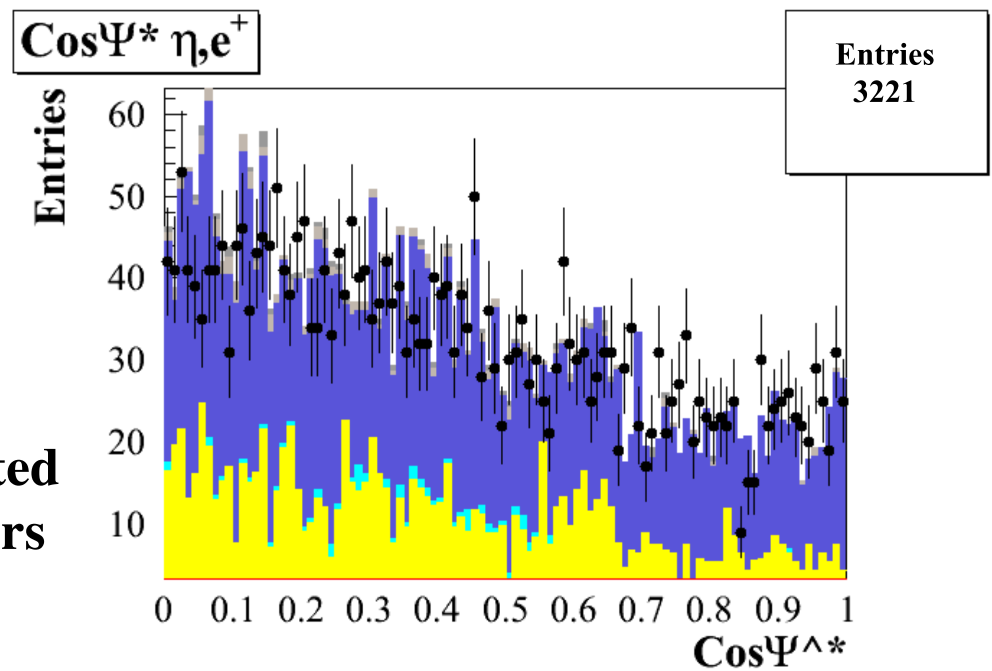


Rejected Events

Events rejected by the TOF cut

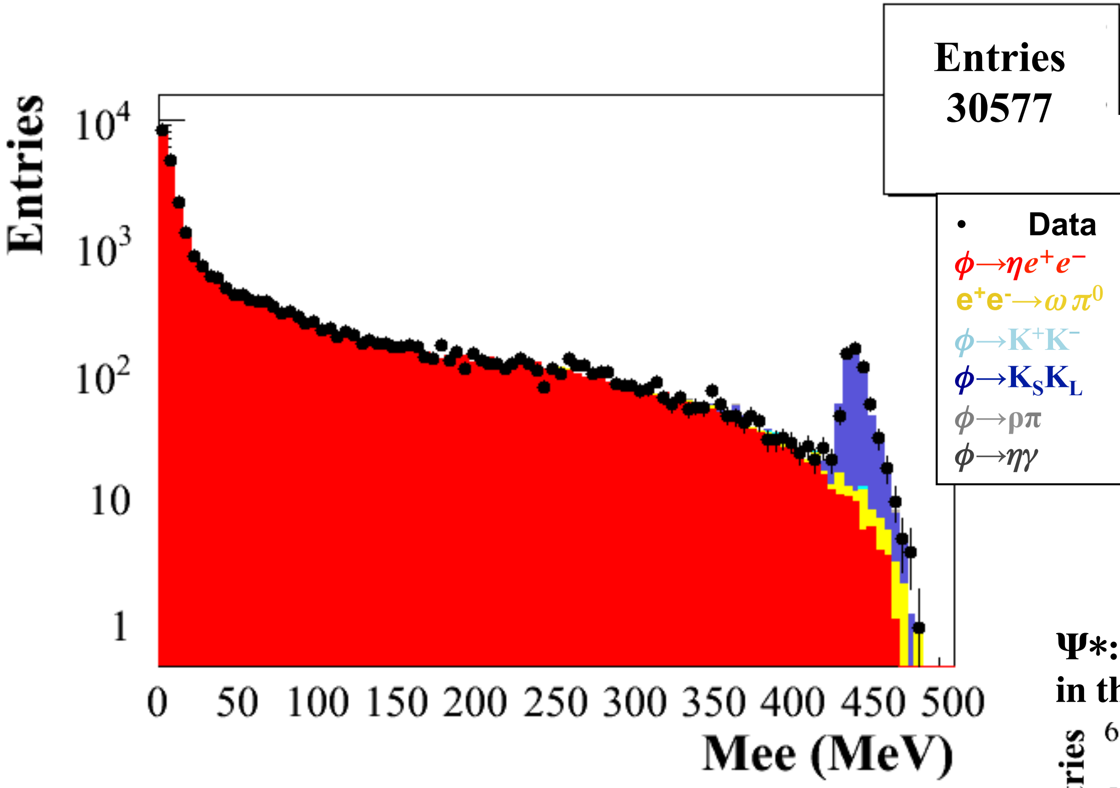


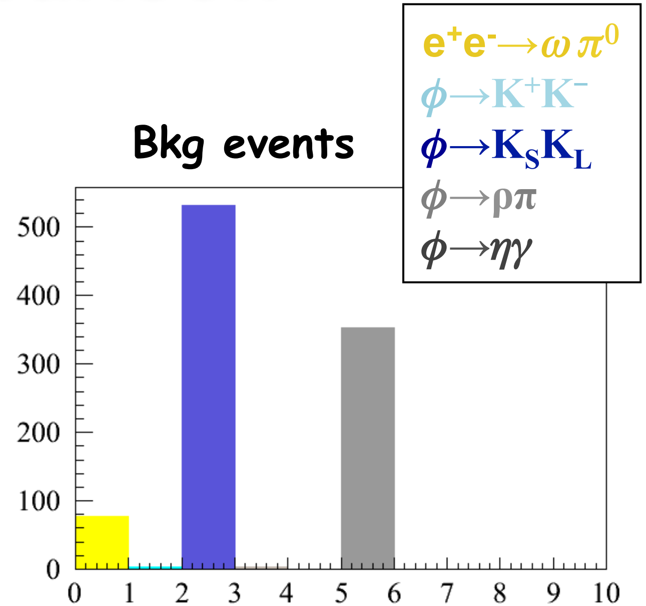
The cut reduces the number of bkg events by a factor of ~ 5.



MC shapes and normalization of rejected quantity in agreement within stat. errors

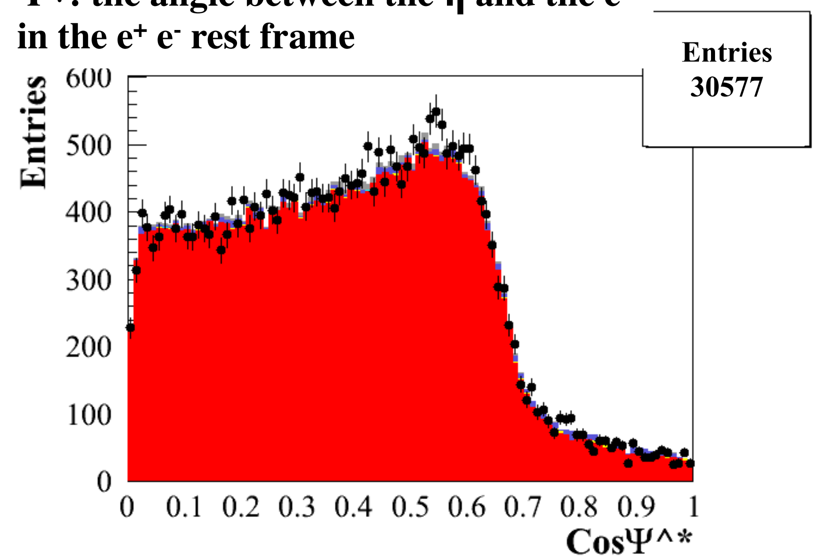
Final sample: data-MC comparison





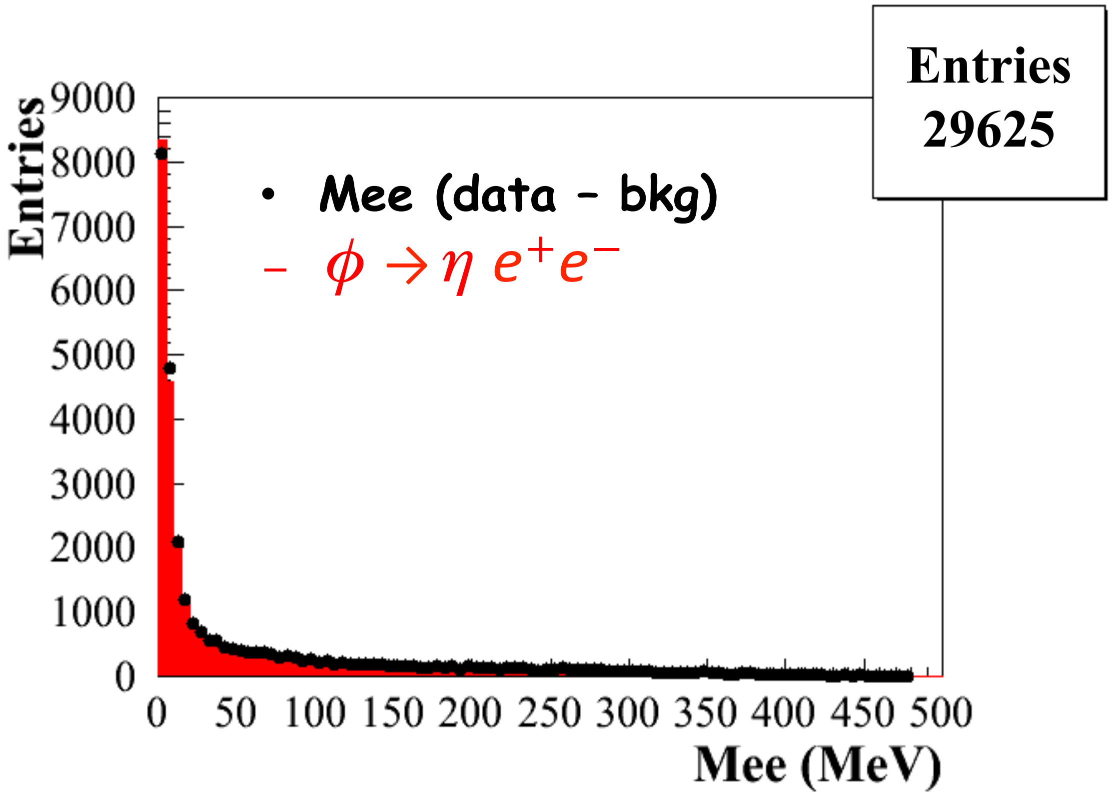
- $\sim 30500\ \phi\to\eta e^+e^-$ with $\eta\to 3\pi^0$ candidates
- Very small residual bkg contamination from $\phi\to\eta\gamma$ and $\phi\to K_SK_L$ events (<3%)

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



Final sample bkg subtracted

$\sim 29500\ \phi \rightarrow \eta e^{+}e^{-}$ with
$\eta \rightarrow 3\pi^{0}$ candidates after bkg subtraction



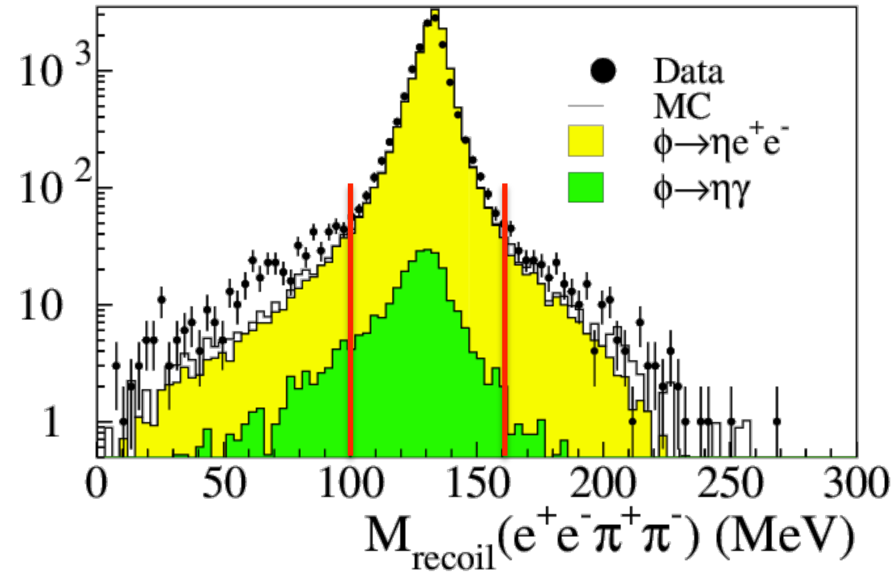
This concludes the $\eta \rightarrow 3\pi^{0}$ decay channel analysis

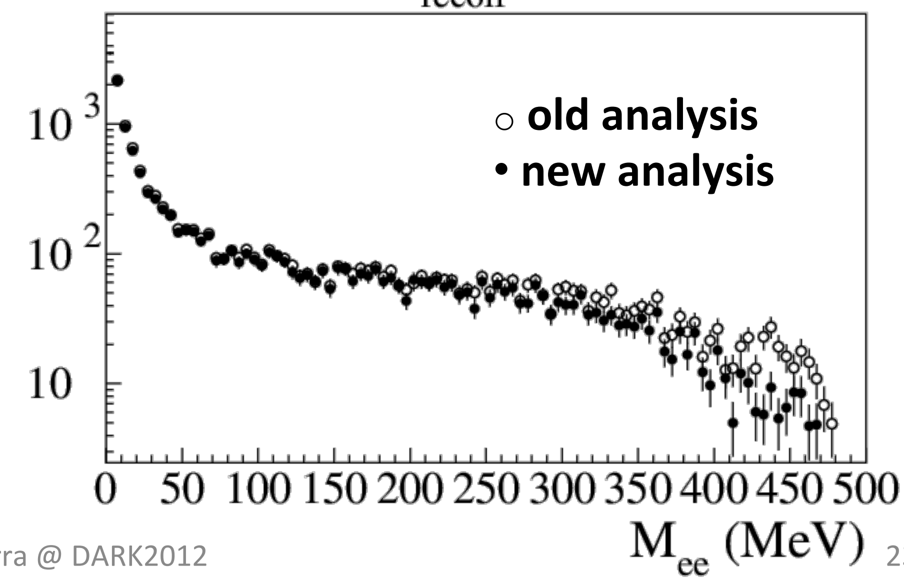
Update of the $\eta \rightarrow \pi^+\pi^-\pi^0$ channel

- We already published the search of $\phi \rightarrow \eta U$ decay, with $\eta \rightarrow \pi^+\pi^-\pi^0$ using 1.5 fb^{-1}

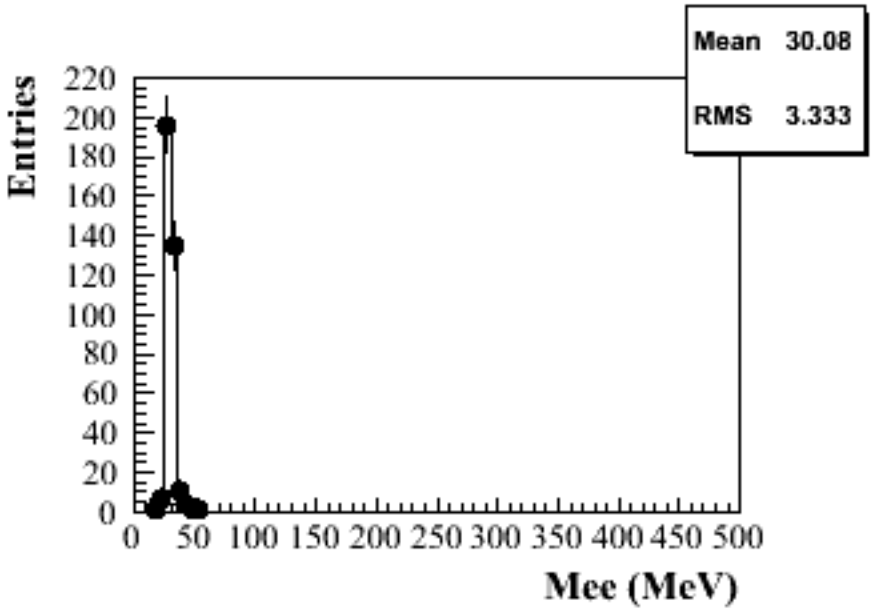
- Bkg rejection improved adding a cut on the recoil mass to the *ee*ππ system:

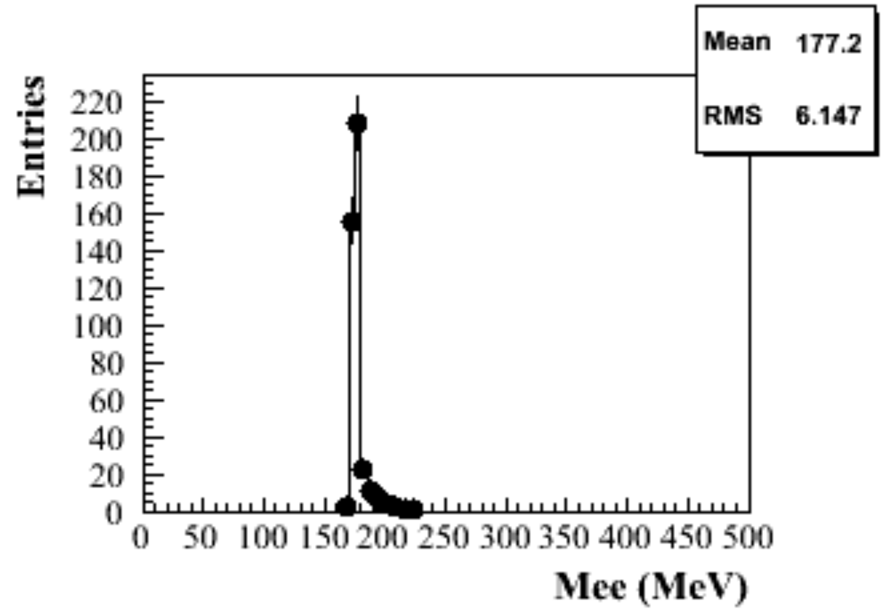
100 < $M_{recoil}(ee\pi\pi)$ < 160 MeV





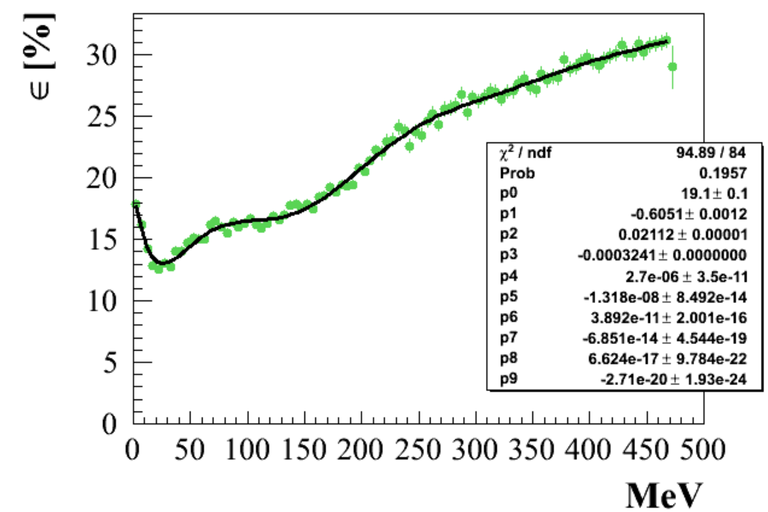
MC simulation for Φ→ηU events



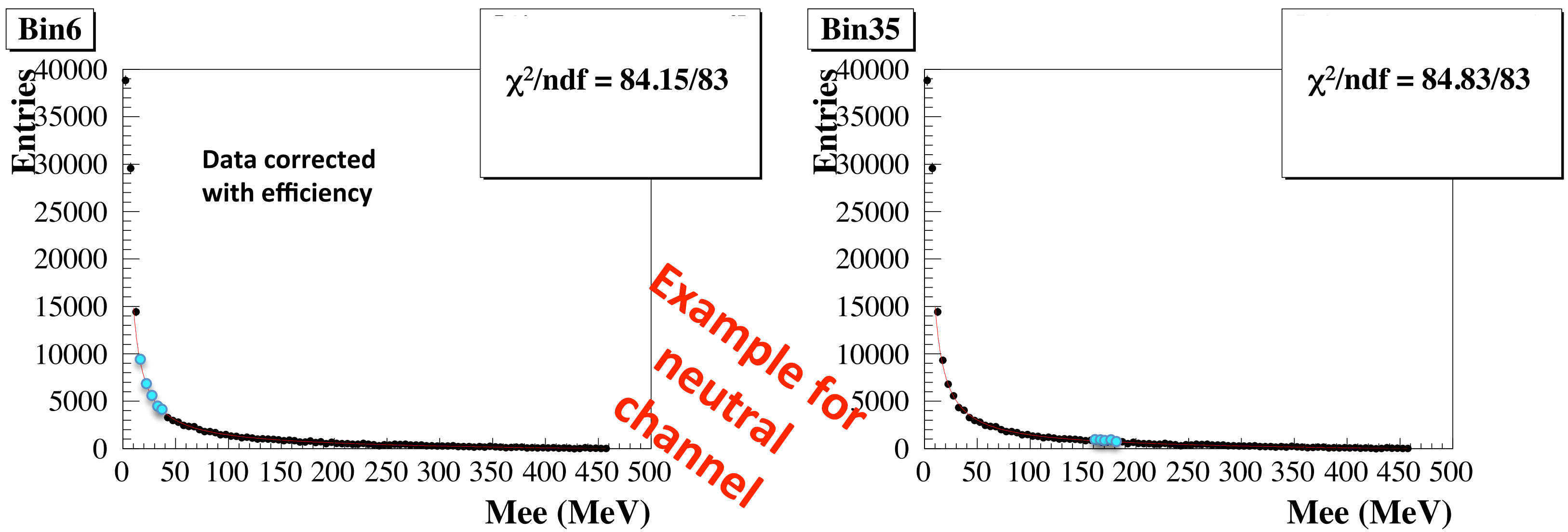


MC generation of U boson for single mass from 6 to 460 MeV carried out to:

1. **Determine the mass resolution (1< σ_{Mee}<2 MeV)**
2. **Determine the reconstruction efficiency**



Technique of bkg extraction

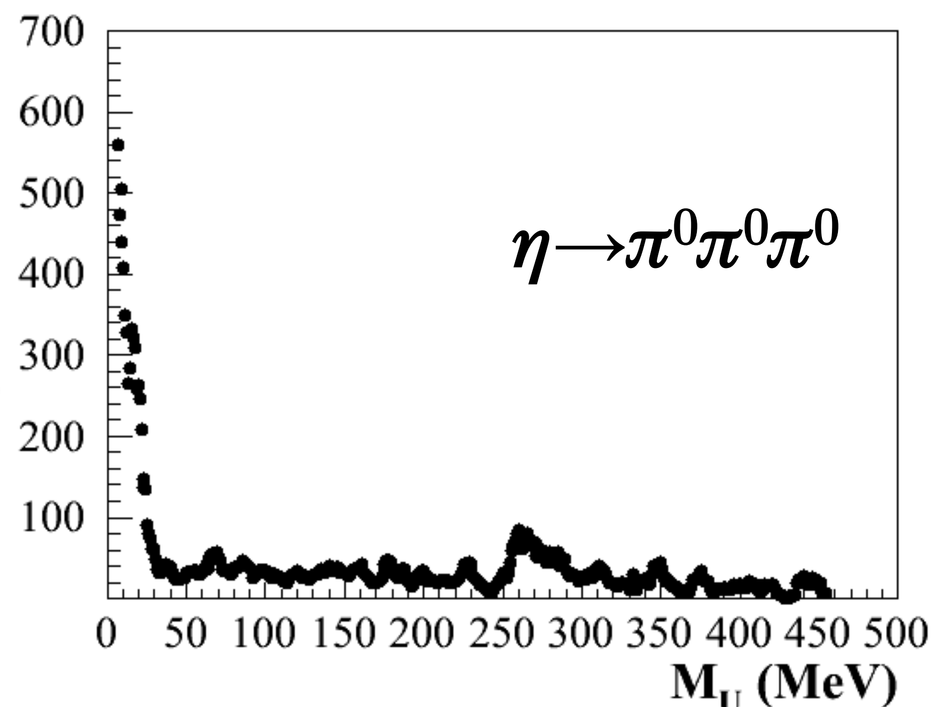


Same procedure to extract the background parameterization used for both η decay channels: for each M_U value, the expectation of $\phi \to \eta e^+e^-$ background is obtained by fitting the M_{ee} distribution, excluding 5 bins centered around M_U , used to extract U.L.

Upper limit on number of signal events

- **No clear signal structure observed above bkg – – > UL evaluation**
- $\phi \to \eta$U MC sample divided in subsamples of 1 MeV width in $5 < M_U < 456$ MeV
- For each M_U sub-sample, average value of $\phi \to \eta e^+e^-$ background from fit to M_{ee} distribution, excluding the 5 bins centered at M_U
- For each M_U value, signal hypothesis excluded **@ 90% C.L.** using the CL_S method (error on bkg included)

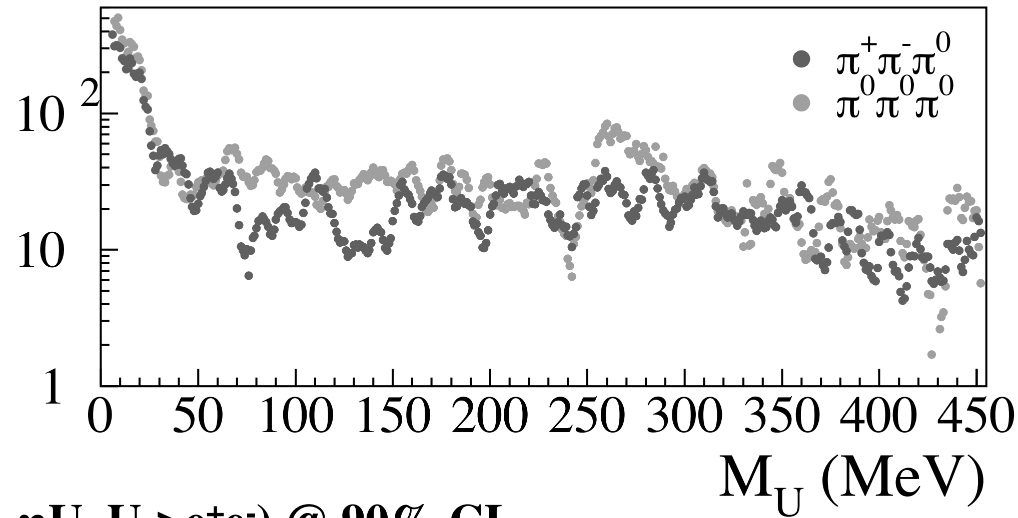
U.L. on Number of signal events for η neutral decay channel



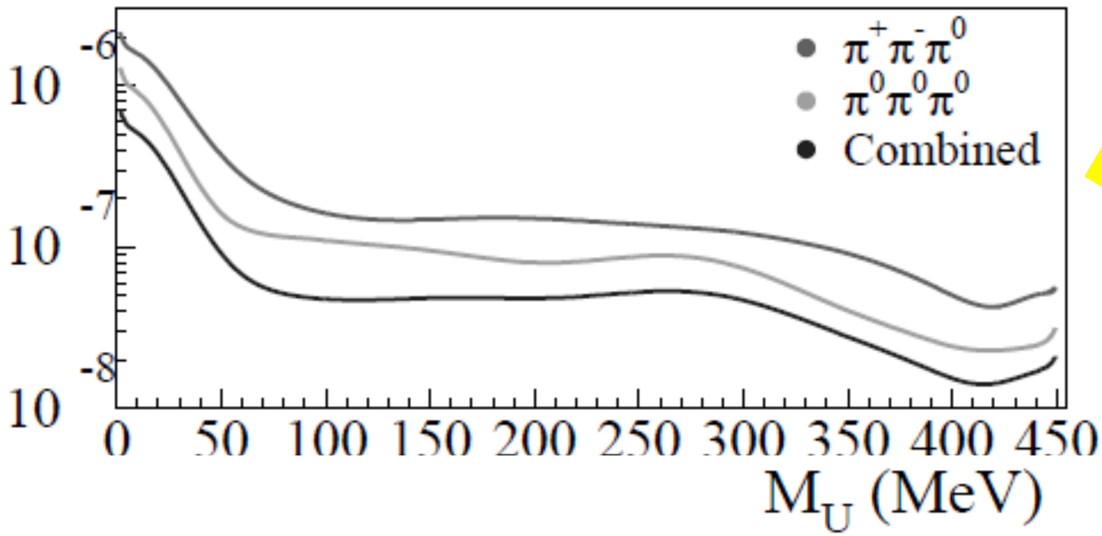
Combined exclusion plot

Combined limit use the same technique, using simultaneously the two samples, scaling them for luminosity, efficiency and relative branching ratios.

UL on Num. of ev. ($\Phi \to \eta U$, $U \to e^+e^-$) @ 90% CL



UL on BR ($\Phi \to \eta U$, $U \to e^+e^-$) @ 90% CL



arXiv: 1210.3927, submitted to PLB

Evaluation of the exclusion limit on α'/α

Exclusion plot evaluated also for $\alpha'/\alpha = \varepsilon^2$ parameter using the relation from Reece, Wang JHEP 07 (2009):

$$\sigma(\phi \to \eta U) = \epsilon^2 \, |F_{\phi\eta}(m_U^2)|^2 \, \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)} \, \sigma(\phi \to \eta\gamma) \,.$$

- We assume the the U boson decay only to leptons, with equal coupling to *ee* and $\mu\mu$

- The limit on α'/α is related to the parameterization of the form factor:

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

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

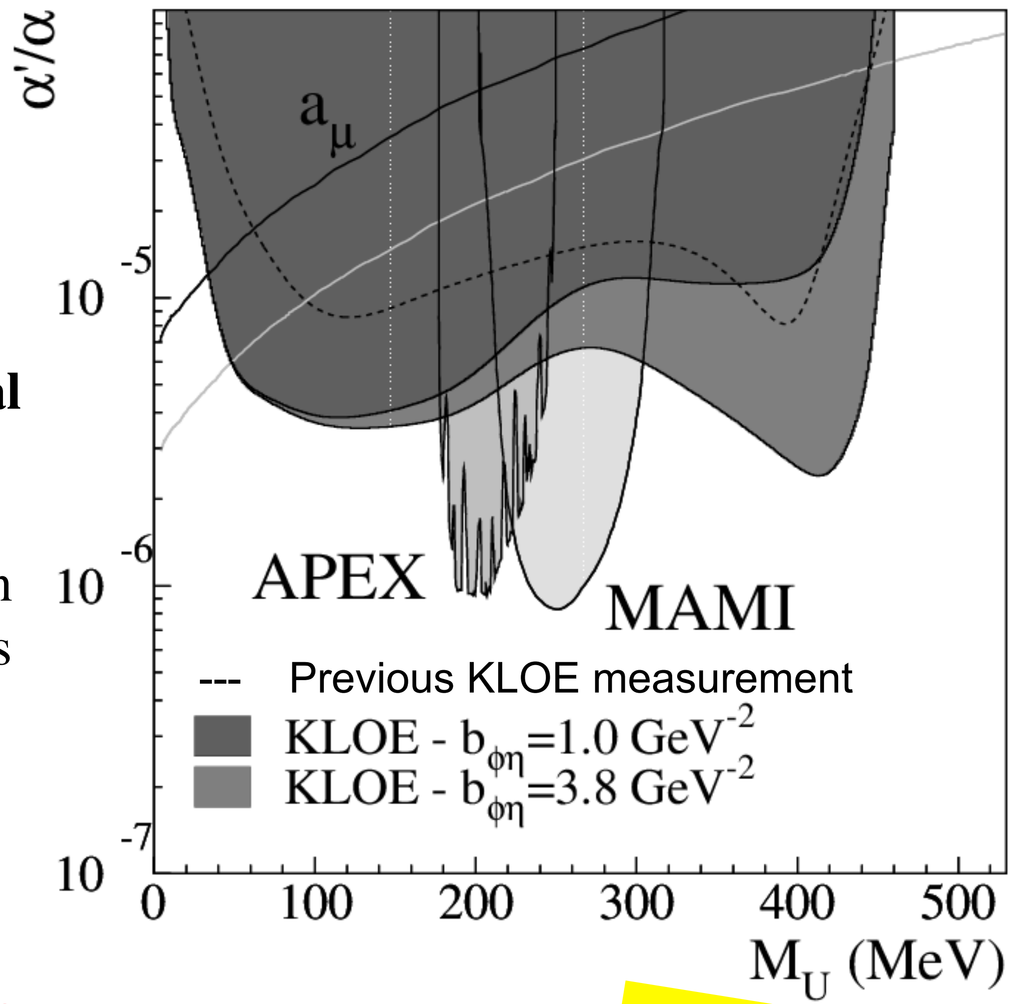
SND: $b_{\phi\eta}$= (3.8±1.8) GeV^{-2}

Combined exclusion plot on α'/α

Evaluation done with both theoretical and measured (SND) value of the FF slope

Conservatively, we use the curve obtained with theoretical prediction for the FF slope

This result enlarges the exclusion region of the U boson parameters needed to account for the observed discrepancy between measured and calculated a_μ values



$\alpha'/\alpha \leq 1.5\times10^{-5}$ @ 90% C.L. for $30<M_U<420$ MeV
$\alpha'/\alpha \leq 5.0\times10^{-6}$ @ 90% C.L. for $60<M_U<190$ MeV

arXiv: 1210.3927, submitted to PLB

Conclusions

- KLOE/KLOE-2 experiments well suited for the search of dark force mediator in a wide mass range and with different production mechanisms.
  - **New measurement of the $\phi\to\eta e^+e^-$, $\eta\to\pi^0\pi^0\pi^0$, channel completed**
  - **Refined measurement of $\phi\to\eta e^+e^-$, $\eta\to\pi^+\pi^-\pi^0$, channel**

- New exclusion plot for $\phi\to\eta U$ search obtained combining the two channels, using the curve obtained with theoretical prediction for the FF slope : **$\alpha'/\alpha \leq 1.5\times10^{-5}$ @ 90% C.L. for $30<M_U<420$ MeV**
  $\alpha'/\alpha \leq 5.0\times10^{-6}$ @ 90% C.L. for $60<M_U<190$ MeV

- A factor two enhancement in sensitivity expected from KLOE-2 experiment.

Spares

Experimental results: U boson search

Recently astrophysical observations showed a unclear interpretation on Standard Model:

- PAMELA observed an excess in the positron fraction ($e^+/(e^+ + e^-)$),
- FERMI and ATIC have observed in cosmic ray data a large excess of electrons and positrons with energies between approximately 100 GeV and 1 TeV
- The INTEGRAL satellite observes a 511 keV signal from the galactic core, which suggests the existence of an abundant positron annihilation source, far exceeding what expected from supernovae only.

PAMELA, FERMI and INTEGRAL signals require a cross section much larger than what allowed by the thermal relic abundance. Boost factors of O(100) or more above what would be expected for a thermal WIMP are required to explain these excesses. Moreover:

- **A large cross section into leptons:** typical annihilations via Z bosons produce very few hard leptons. Annihilations into W bosons produce hard leptons, but many more soft leptons through the hadronic shower.
- **A low cross section into hadrons:** even if a suitably high annihilation rate into leptons can be achieved, the annihilation rate into hadronic modes must be low. *PAMELA measurements of antiprotons tightly constrain hadronic annihilations as well*.

Low energy dark forces

The combination of these issues makes the observed high-energy anomalies difficult to explain with thermal dark matter annihilation. However, the inclusion of a new force in the dark sector simultaneously addresses all of these concerns.

- ***Dark matter** is a natural candidate for these:*

It is postulated the existence of **relatively heavy (~ 1 TeV) Weakly Interacting Massive Particles (WIMPs)** states together with at least one **relatively light (~ 1 GeV) vector boson**, mediator of a new hidden gauge symmetry.

- Although SM particles are not charged under this new symmetry they can still couple with the **"dark photon"** through the kinetic mixing mechanism with ordinary SM bosons, and specifically with the photon.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Dark} + \mathcal{L}_{mix}$$

The U boson can communicate with the SM through a kinetic mixing term describing the interaction of the U boson with SM photon. In this case the parameter ε should be less than about 10^{-2}.

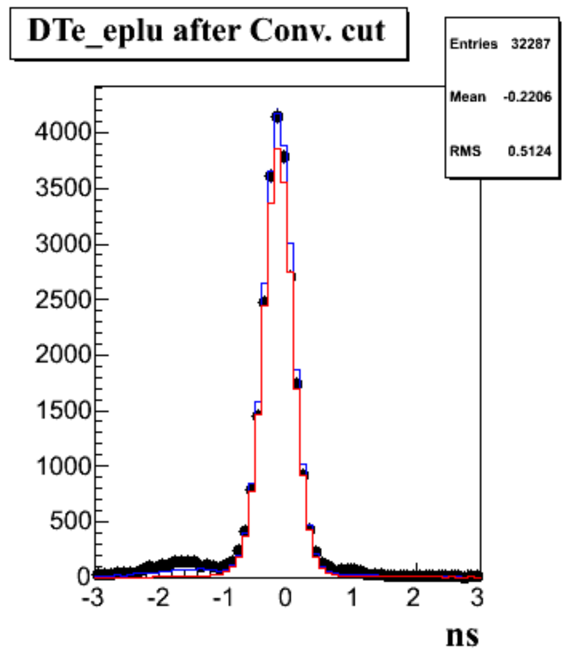
$$\begin{aligned}\mathcal{L}_{Dark} = \mathcal{L}^{F}_{Dark}(X) &\Rightarrow M_X \sim 100 - 1000\ GeV\ \ WIMP\\ + \mathcal{L}^{B}_{Dark}(U) &\Rightarrow m_U \sim GeV\ \ U\ Boson\\ + \mathcal{L}^{B}_{Dark}(h') &\Rightarrow higgs\ potential\ breaking\ U(1)_D\end{aligned}$$

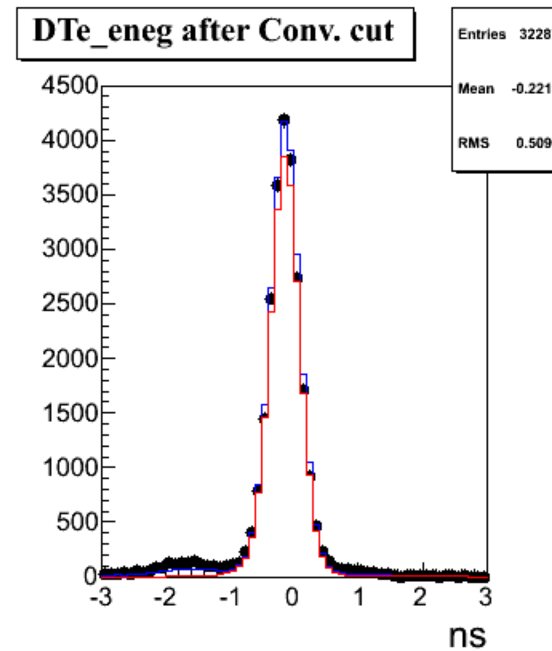
Background rejection: Time Of Flight

A relevant background, originated by $\phi \to K_S K_L$ decays ($K_S \to \pi^+ \pi^-$ and $K_L \to 3\pi^0$) surviving analysis cuts, has two charged pions in the final state and is suppressed using 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 track trajectory ($T_{track} = L_{track}/\beta c$).

- The $\Delta T = T_{track} - T_{cluster}$ variable is then evaluated in the electron (ΔTe) hypothesys



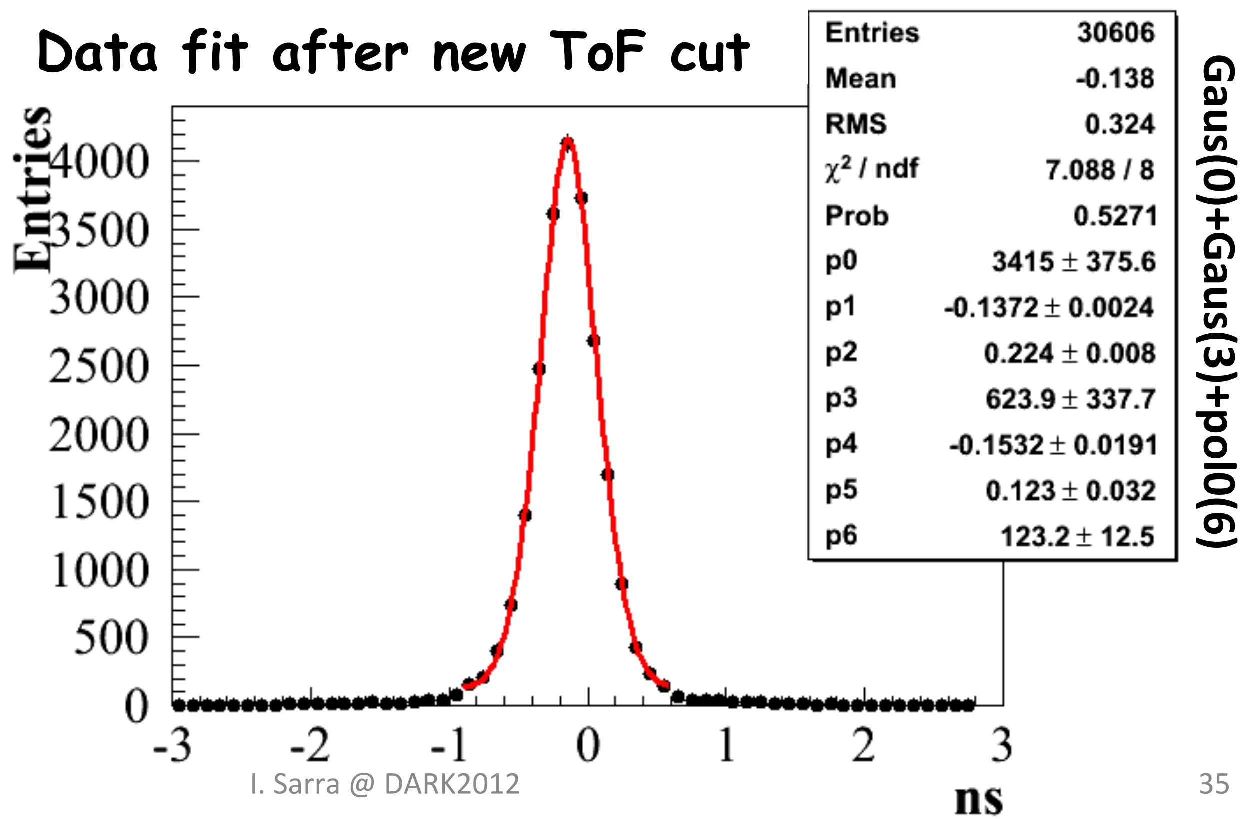


Background rejection: Time Of Flight

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

```
if( DTe_eplu != -999. &&  DTe_emin != -999.) {
  if( (DTe_eplu>=DTmin && DTe_eplu<=DTmax)  ||
      (DTe_emin>=DTmin && DTe_emin<=DTmax) ) TofFlag = 0;
}
```

Data fit after new ToF cut



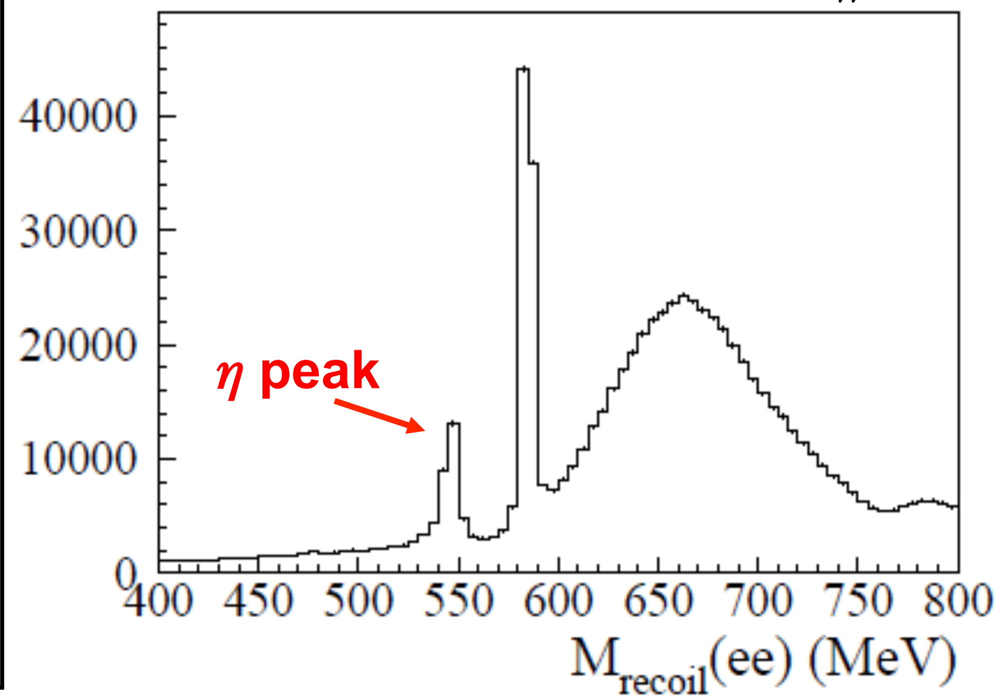
Search for $\phi \rightarrow \eta U$ Decays with $\eta \rightarrow \pi^+\pi^-\pi^0$

Pre-selection

- 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**

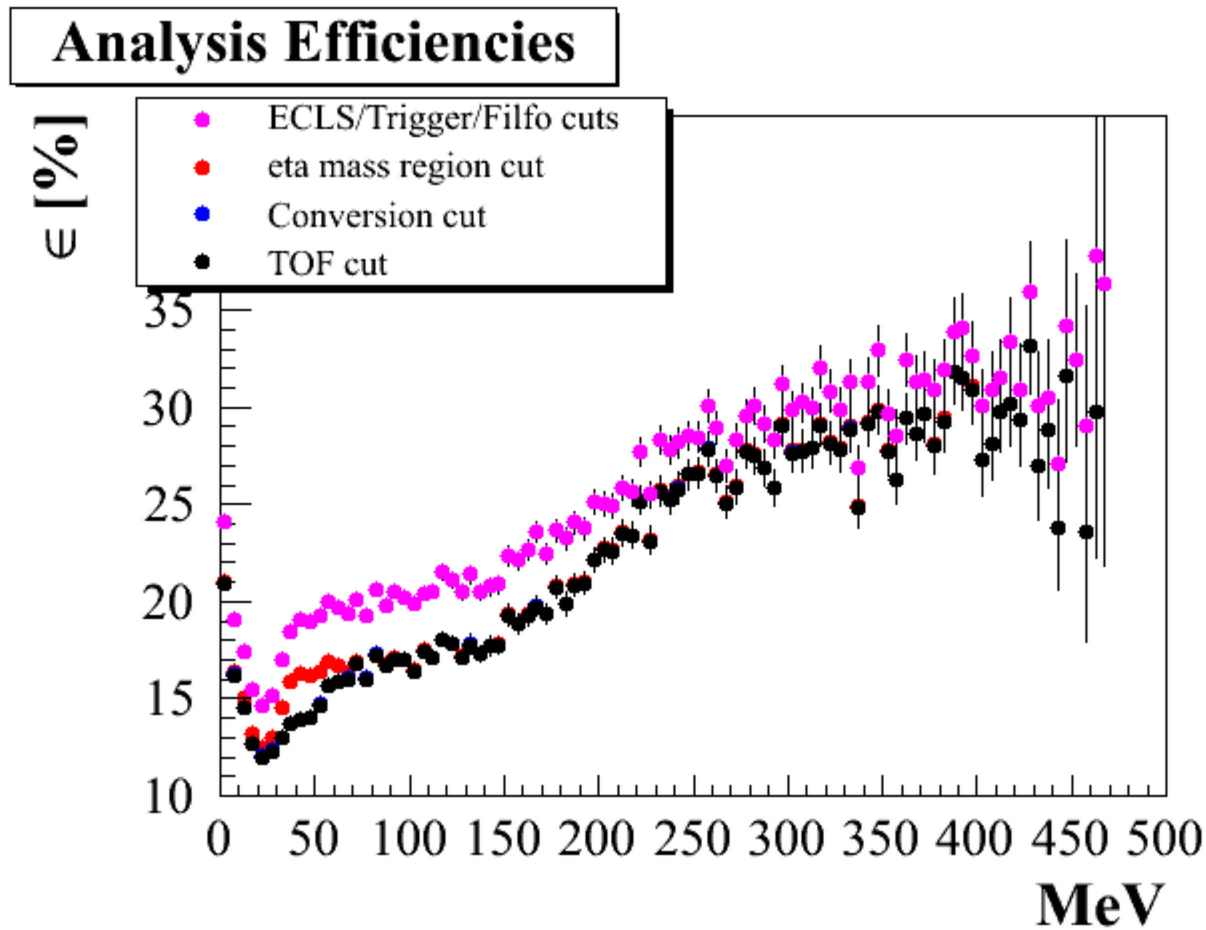
Analysis performed on **1.5 fb^{-1}**

Recoil mass to the e^+e^- pair after $M_{\gamma\gamma}$ cut



Mee Shape: Fit environment -1-

Reconstruction inputs used to perform the fit:



- **Analysis Efficiencies at different analysis steps**

- **ECLs/Trigger/Filfo**
- **Conversions on BP & DC**
- **Time of Flight of charged tracks on calorimeter**

Motivations for not including the BaBar exclusion plot

* The BaBar Collaboration never performed a direct search of the U boson. The exclusion plot is just an estimate from the search of a light, narrow scalar particle in Upsilon decays: Upsilon(3S) --> gamma A_0

* The analysis is close to the search of e+e- --> gamma U, but obviously acceptance and selection efficiency are different for scalar and vector particles

* The mu+mu- background shape from continuum production has been obtained from data taken at Upsilon(4S), with the assumption that the A_0 is produced in decays and not in QED continuum processes. This is true for the A_0, but not for the vector U boson