Ricerca di “Dark Forces” @ KLOE

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Outline

- U boson production mechanisms
- Possible collider signatures
- U boson production in ϕ decays: KLOE-2 limit

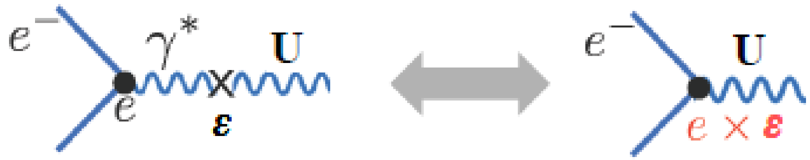
Experimental results: U boson search

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 10 and 100 GeV

➢ ***Dark matter** is a natural candidate for these:* 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** [1].
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 about 10^{-2}** .



U boson: possible production mechanisms

- 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.

- At flavor factories, e.g. at DAΦNE, and present and future B-factories, a particularly clean and simple channel via the radiative reaction $e^+e^- \rightarrow U\gamma$, with subsequent decay of the U into a lepton pair.

- A further line of research also available at e^+e^- colliders is the **study of the decays of a vector meson into a pseudoscalar and a U**, as suggested by Reece and Wang [2]. In particular Reece andWang have focused their attention on the channel $\phi(1020) \rightarrow U\eta$.

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

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

- Meson having radiative decay to one photon can decay to a U boson with $BR(X \to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times BR(X \to Y\gamma)$

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$BR(X \to Y + \gamma)$	$BR(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

All KLOE stat.
All decay chains

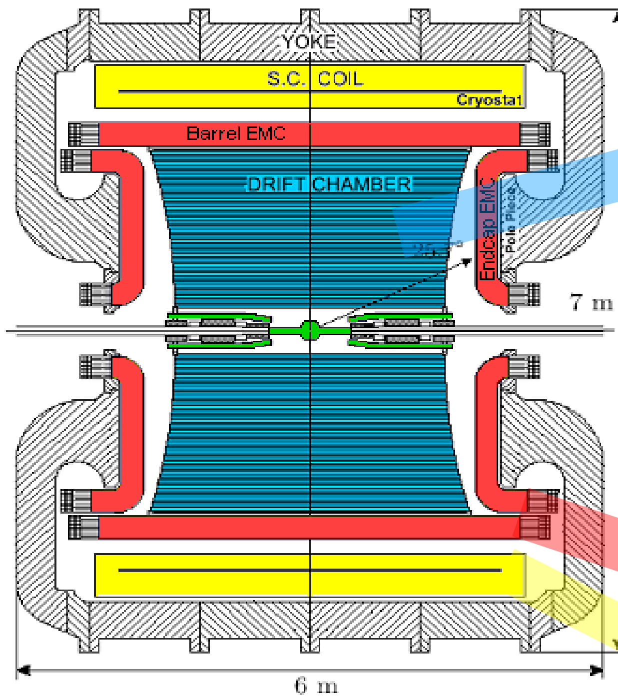
[M.Reece and L.T.Wang, JHEP 0907:051 (2009)]

➡ ***$\sigma(\Phi \to \eta U) \approx 40$ 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%) **Published**

$\eta \to \gamma\gamma / \pi^0 \pi^0 \pi^0$ (BR = 39.3/32.6%) **In Progress**

The KLOE experiment



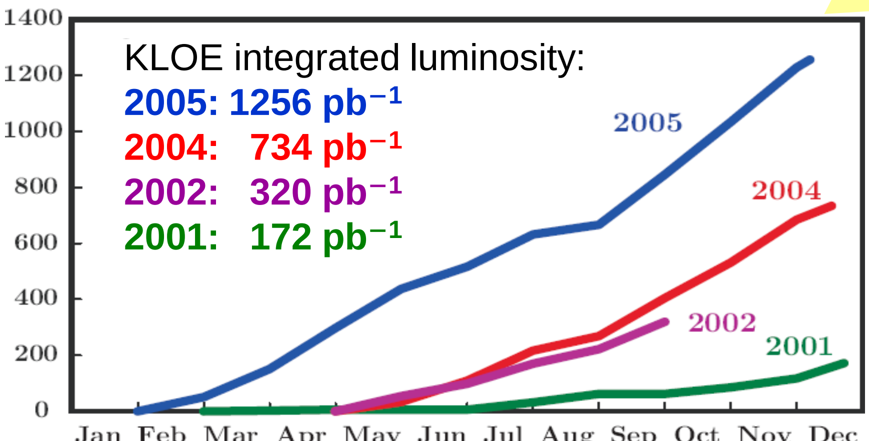
Drift chamber

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



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)

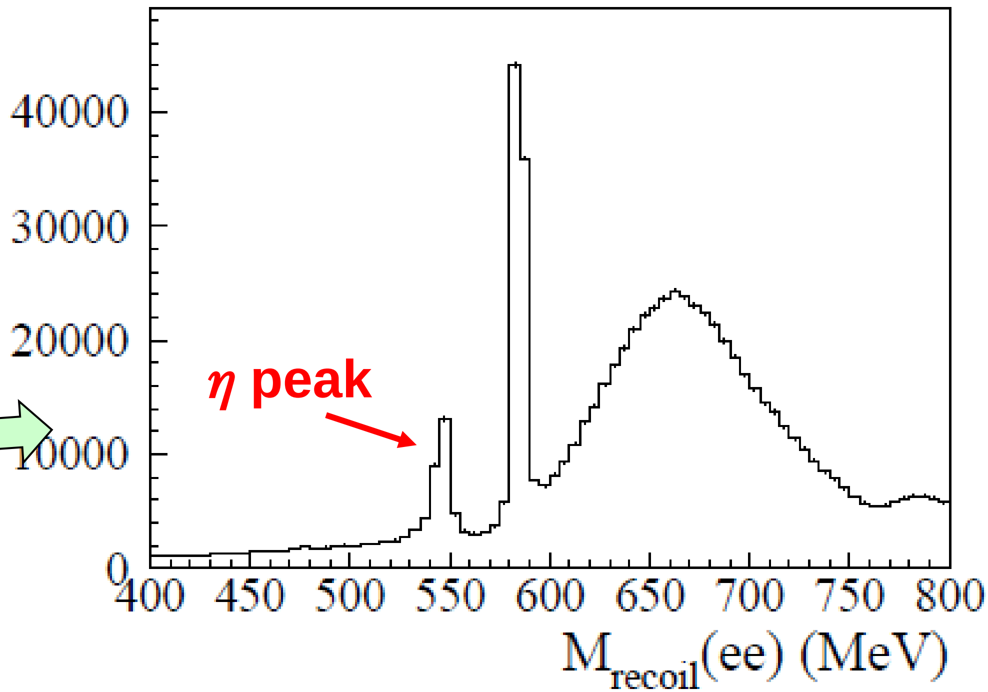
+ 250 pb^{-1} @ 1000 MeV (off-peak data)

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

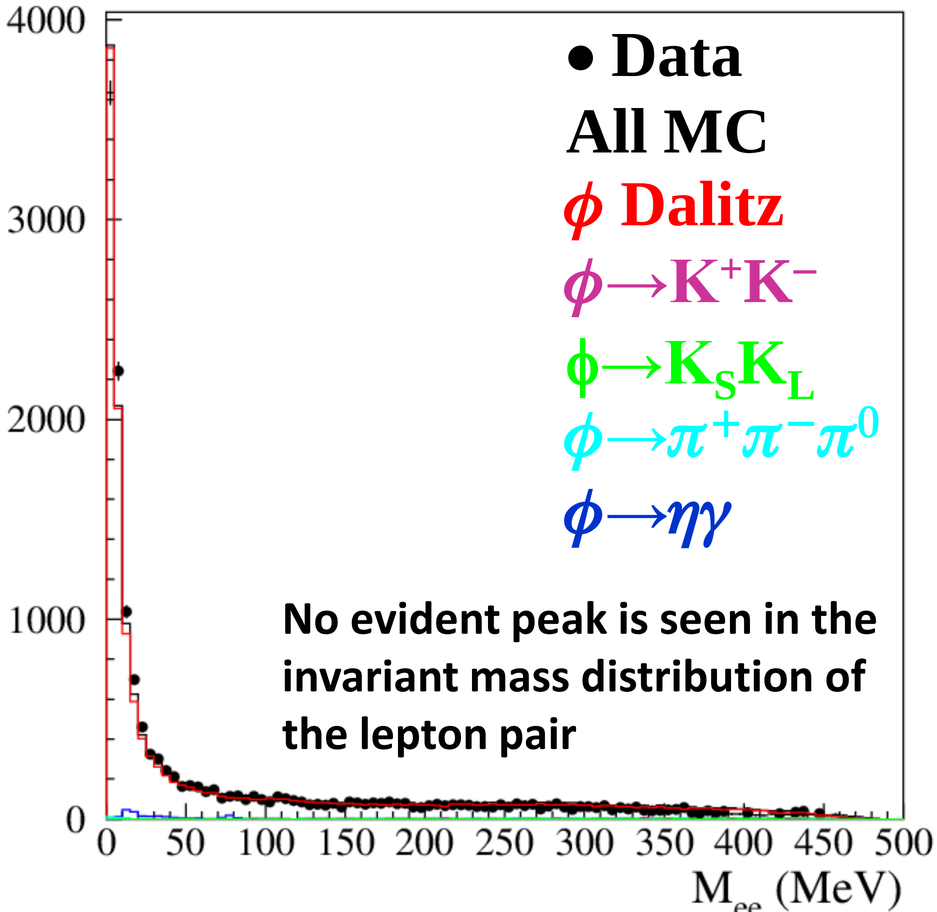
Analysis performed on **1.5 fb^{-1}**

- 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**

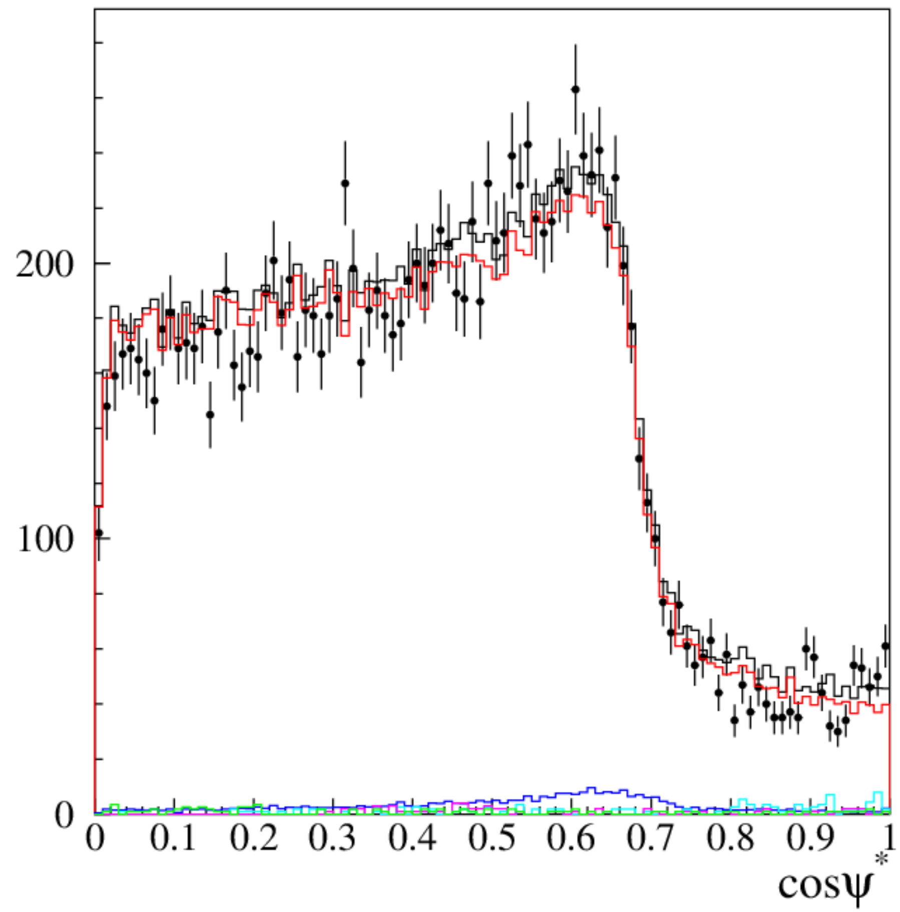
Recoil mass to the e^+e^- pair after $M_{\gamma\gamma}$ cut



Data-MC comparison



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

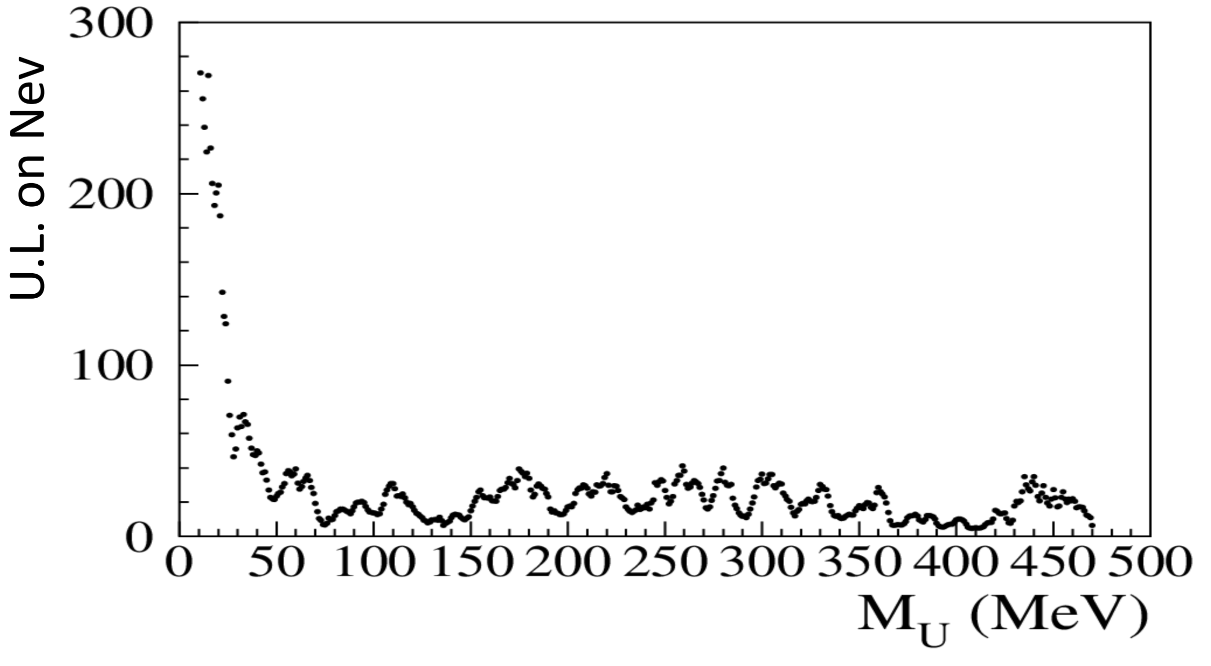


- **~14000 $\phi \to \eta e^+ e^-$ with $\eta \to \pi^+\pi^-\pi^0$ candidates**
- **Very small residual contamination from $\phi \to \eta\gamma$ events**
- **MC M_{ee} shape from VMD with FF slope from SND (213 events)** [PLB504(2001) 275]

  ➡ **Extract directly from our data!**

Exclusion plot for number of events

- $\phi \rightarrow \eta U$ MC sample [M.Reece and L.T.Wang, JHEP 0907:051 (2009)] divided in subsamples of 1 MeV width in 5< M_U<470 MeV
- For each M_U sub-sample, average value of $\phi \rightarrow \eta e^+ e^-$ 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 bckg included)



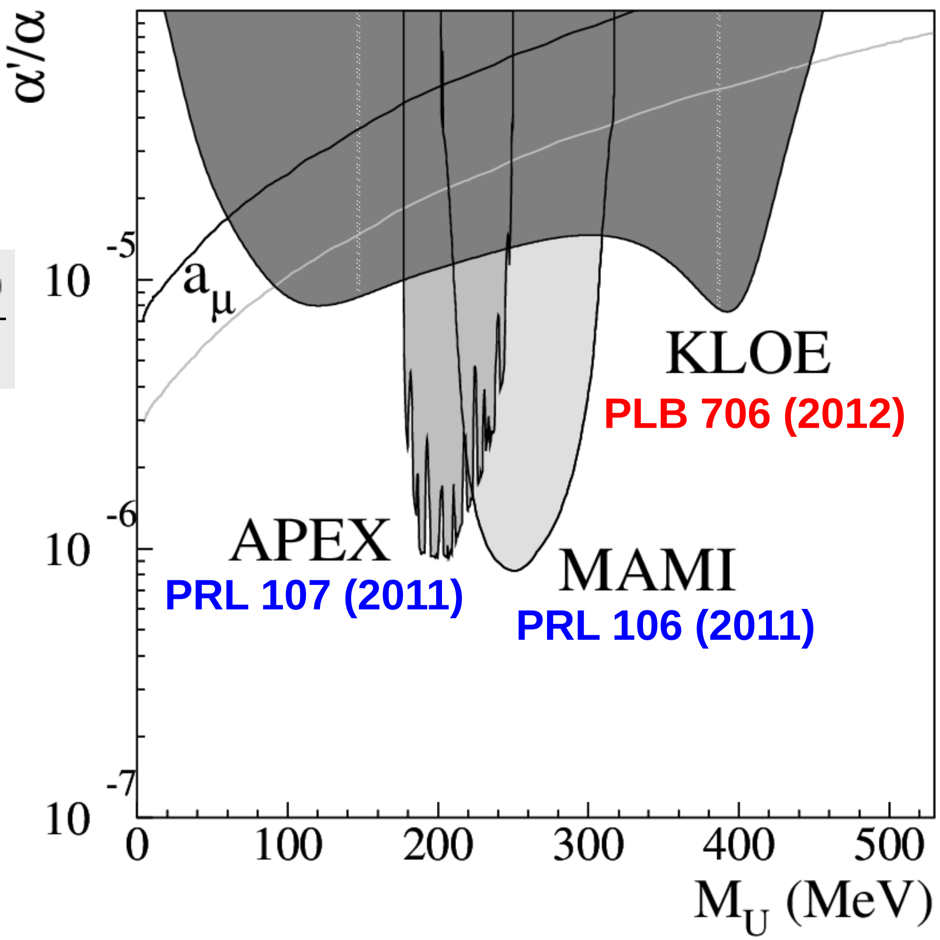
Exclusion plot for α' / α

UL on $\alpha'/\alpha = \varepsilon^2$ takes into account:

➢the kinematic factors

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

[Reece-Wang, JHEP0907:051 (2009)]



$\alpha'/\alpha \leq 2 \times 10^{-5}$ @ 90% C.L. for 50<M_U<420 MeV

Searching in $\phi \rightarrow \eta\gamma^*$ Decays with $\eta \rightarrow 3\pi^0$

PRELIMINARY

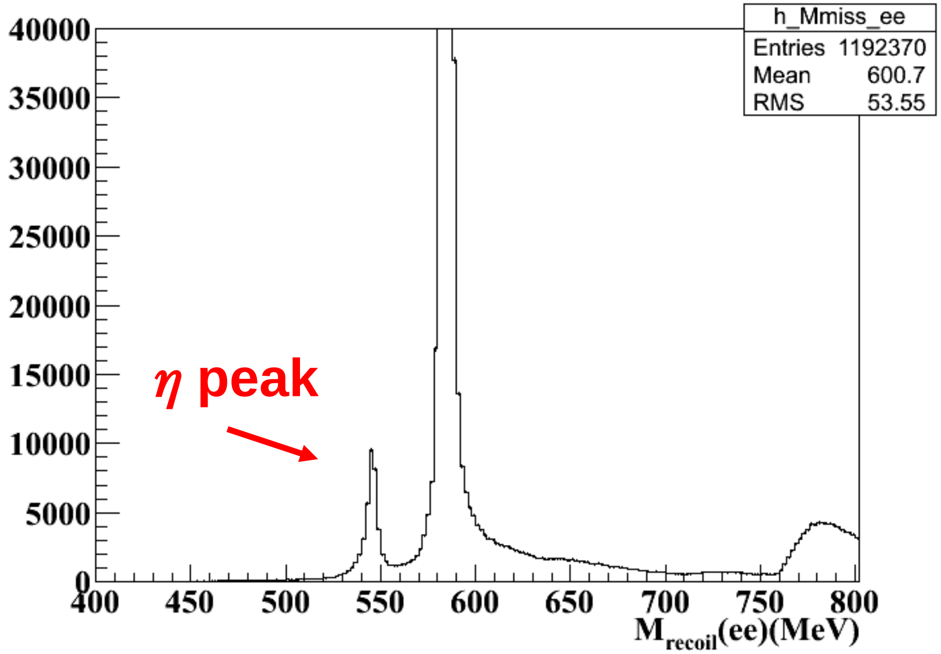
Analysis performed on 1.7 fb^{-1}

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

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

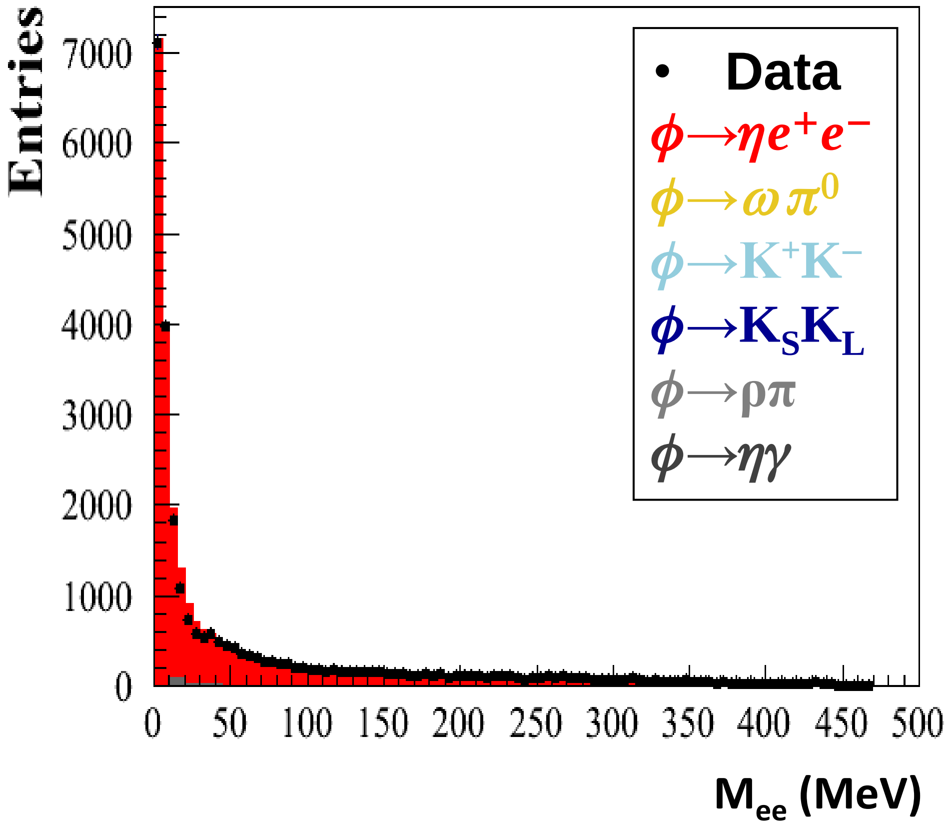
- **Photon conversion + ToF cuts**

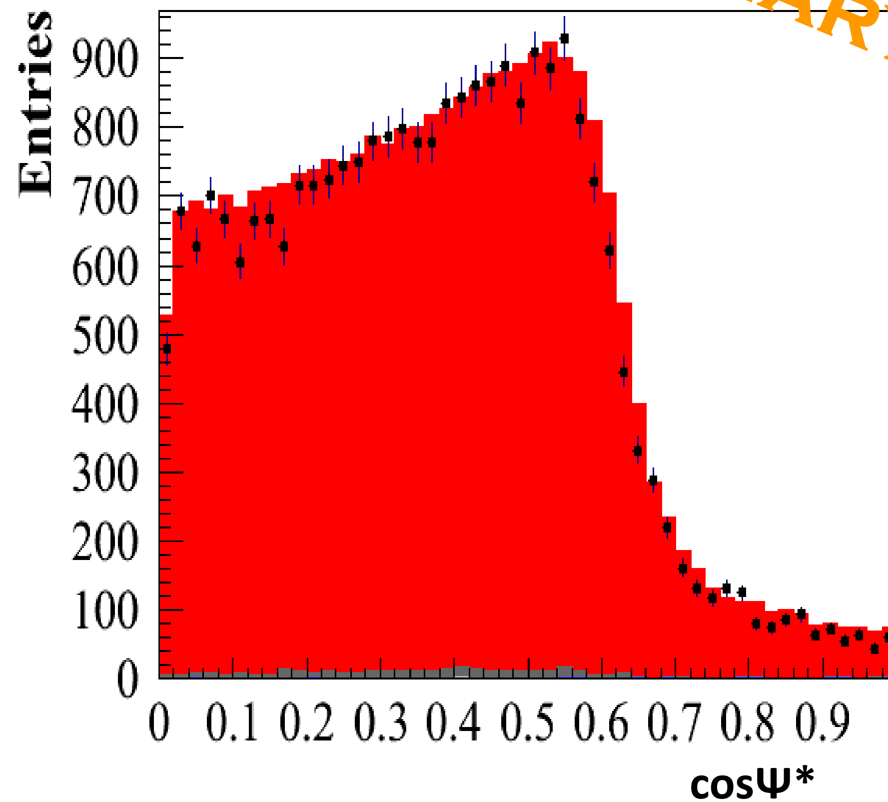
Recoil mass to the e^+e^- pair



$\phi \to \eta$U: other ongoing studies

PRELIMINARY





- ~26000 $\phi \to \eta e^+e^-$ with $\eta \to 3\pi^0$ candidates (~2 times $\eta \to \pi^+\pi^-\pi^0$)
- Small residual contamination from $\phi \to \eta\gamma$ and $\phi \to K_S K_L$ events

Possibility to compare the Mee shape and to extend/combine the upper limit.

Conclusions

- Several intriguing experimental hints suggest that a ‘secluded world’, with manifestation at low energies, could explain the puzzle of the dark matter

- KLOE/KLOE-2 experiments well suited for the search of the boson mediator of this dark force in a wide mass range and with different production mechanisms

- The present KLOE result is through the $\phi \to \eta U$, $\eta \to \pi^+\pi^-\pi^0$, decay, which allowed us to set a limit of:

$\alpha' / \alpha \leq 2 \times 10^{-5}$ @ 90% C.L. for $50 < M_U < 420$ MeV

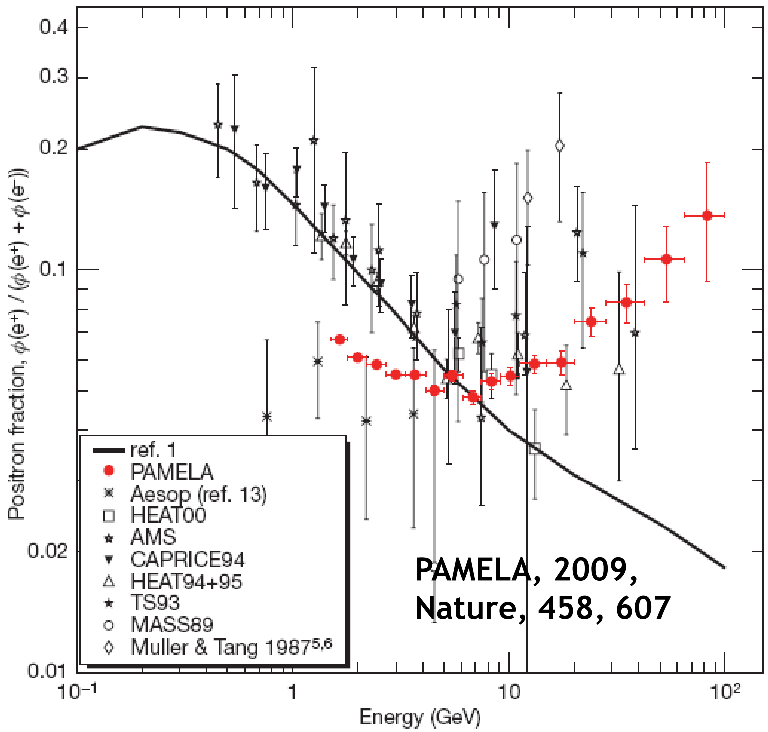
- Progresses in other η decay channels show a large reconstruction analysis efficiency and a reduced background → possibility to extend/combine the upper limit.

References

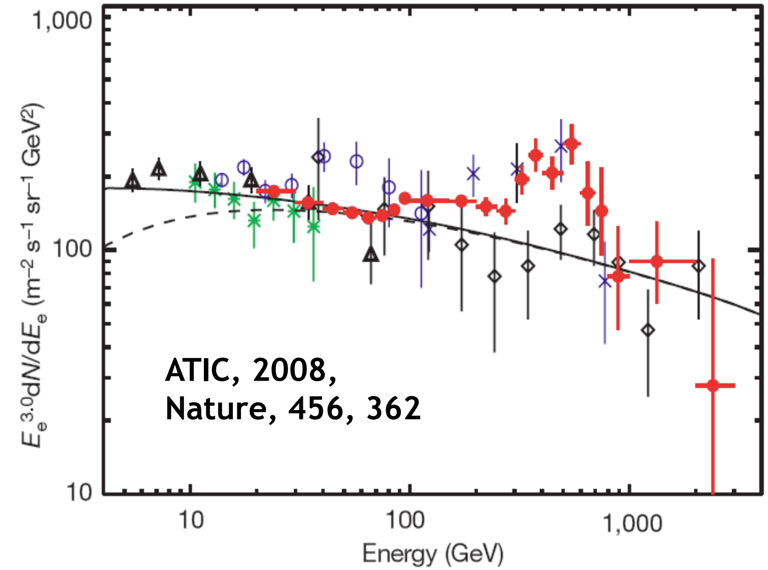
- [1] L. Barzè, *Light dark forces at flavor factories*, 2011 J. Phys.: Conf. Ser. 335 012077 , URL http://iopscience.iop.org/1742-6596/335/1/012077
- [2] M. Reece, L.T. Wang, JHEP 07, 051 (2009).

Spares

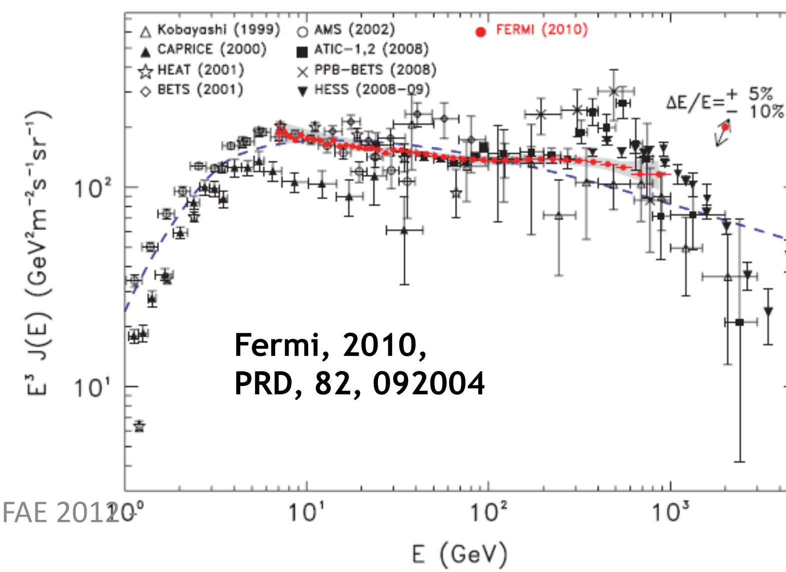
PAMELA
discovery of the positron excess



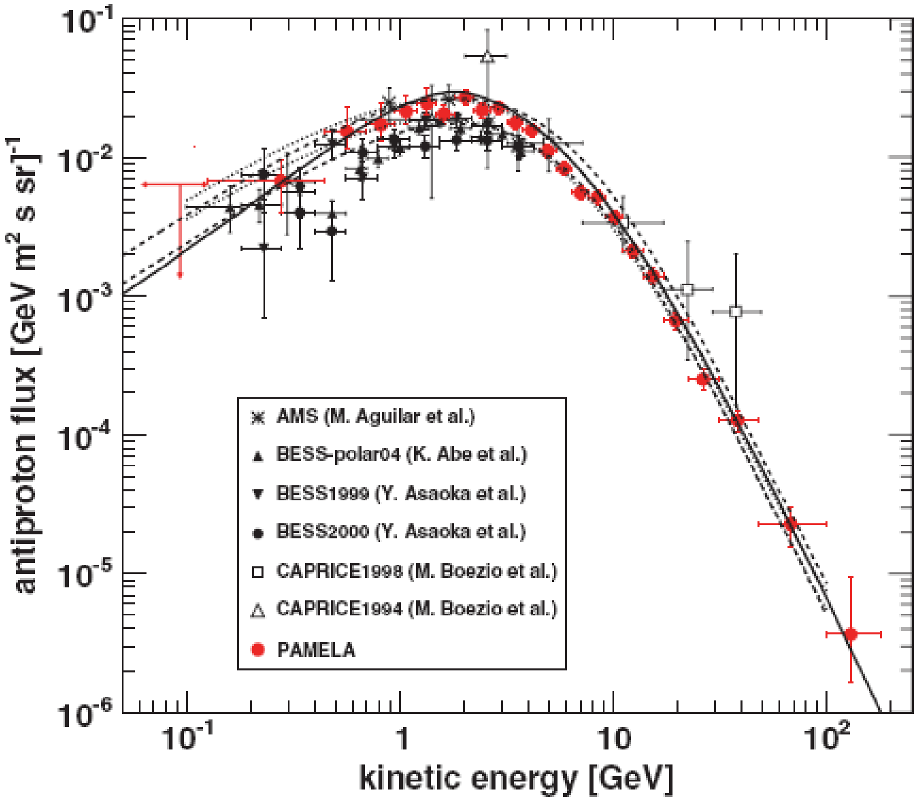
ATIC
observation of the electron+positron spectra

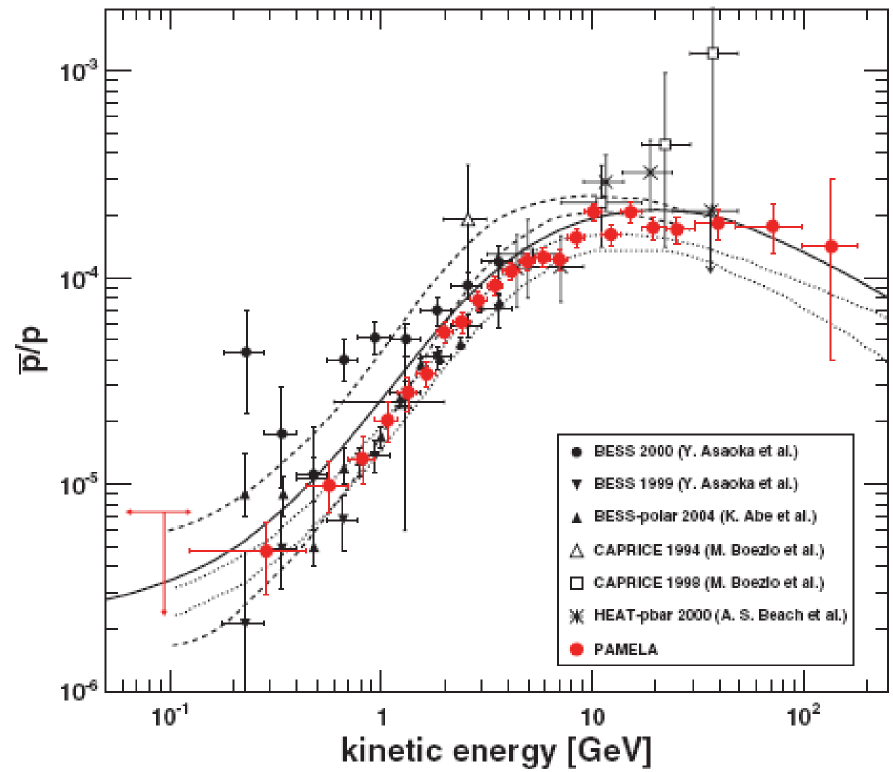


Fermi
observation of the electron+positron spectra

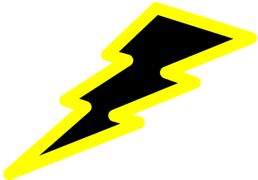


PAMELA
observation of the antiproton flux



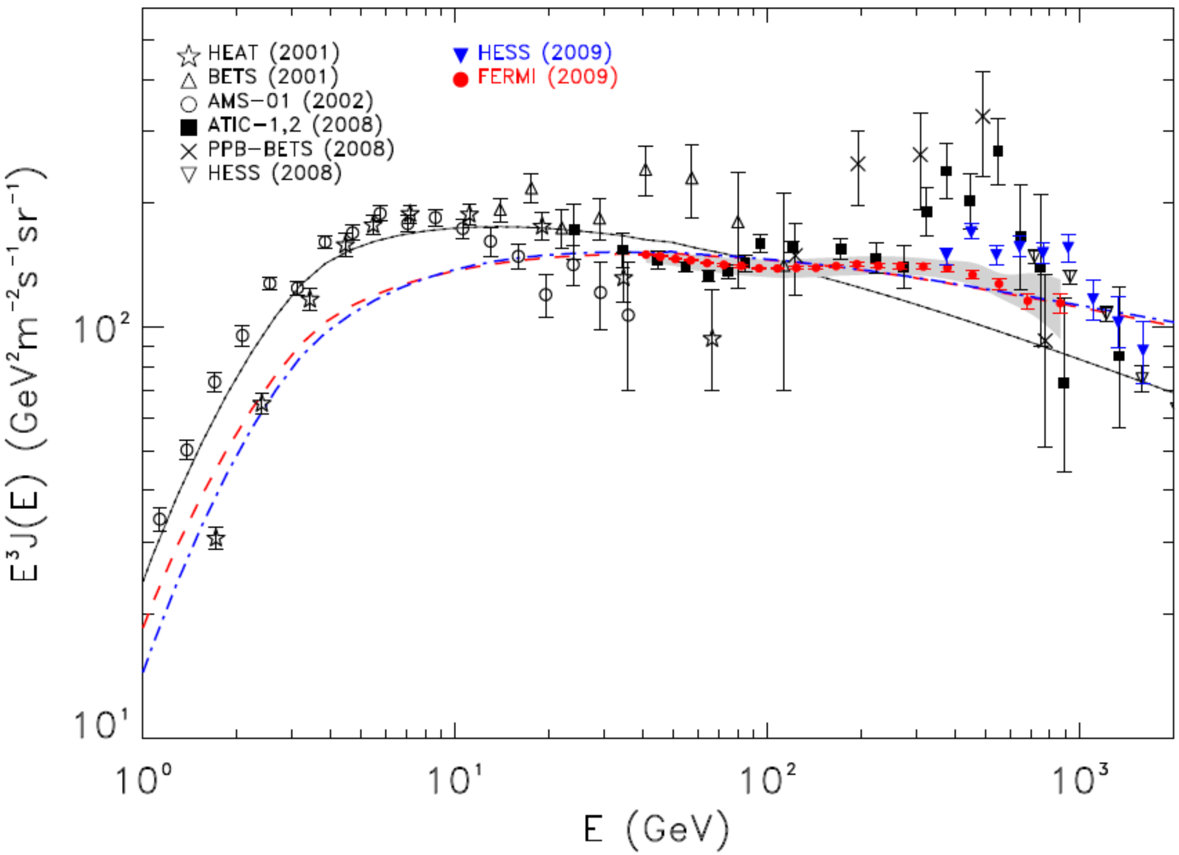


PAMELA, 2010, PRL, 105, 121101



Electrons+positrons from Fermi/LAT (Abdo et al., PRL102,181101)

- ATIC peak not confirmed
- spectrum compatible to E^{-3} with **mild** excess @ same energy of ATIC



- Flatness of spectrum disfavours interpretations of PAMELA in terms of a light Dark Matter particle (m≲450 GeV)

…their possible explanation

- All these observations do not have easy interpretations in terms of standard astrophysical and/or particle physics processes
- The simplest assumption [11] is to **add an extra U(1) symmetry to SM** symmetry group which describes a new dark force and suppose this force as carried by a new vector boson.
- Although SM particles are not charged under this new symmetry they can still couple with the “dark photon" (dubbed as A’, or U in the literature) through the kinetic mixing mechanism with ordinary SM bosons, and specifically with the photon.
- **With reactions involving WIMPs in the initial state and standard particles as positrons in the final state and supposing these reactions mediated by the U boson it would be possible to explain the experimental signals described.**

U boson

- Since no astrophysical data involves anomalous production of antiproton, **it is necessary to require the U boson mass (m_U) to be lower than the mass of two protons** [10].

- It is possible to suppose also that U boson can communicate with the SM through a kinetic mixing term of the form [10]

$$L_{mix} = \frac{\varepsilon}{2} F^{em}_{\mu\nu} F^{\mu\nu}_{dark}$$

describing the interaction of the U boson with SM photon.

- In this case the parameter ε should be lower than about $10^{-2} - 10^{-3}$.

Search for dark forces @ KLOE

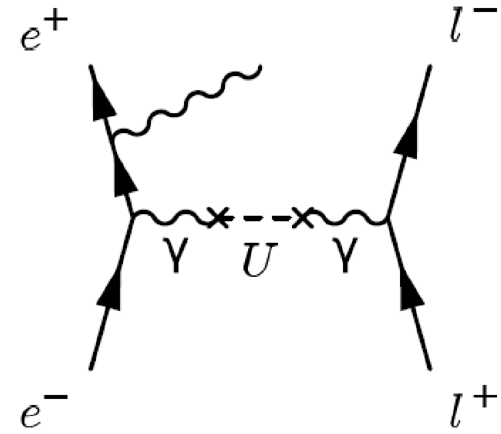
- **Meson decays**: $\phi \rightarrow \eta$U, $\eta/\pi^0 \rightarrow$Uγ ...

  Peculiar of a light meson factory

- $\boldsymbol{e^+e^-}$ **collisions**: $e^+e^- \rightarrow$U$\gamma \rightarrow \ell^+\ell^-\gamma$

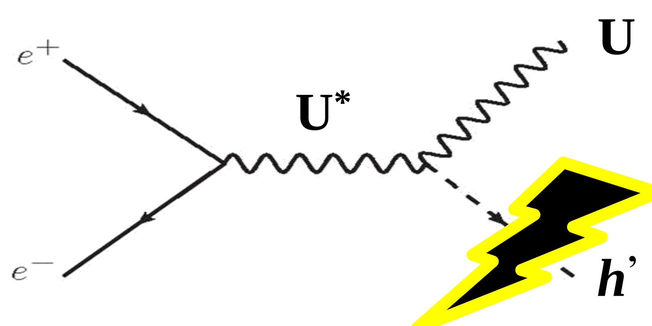
  x-sec ∝ 1/s

  100 times higher at DAΦNE w.r.t. b-factories
  Compensate lower luminosities



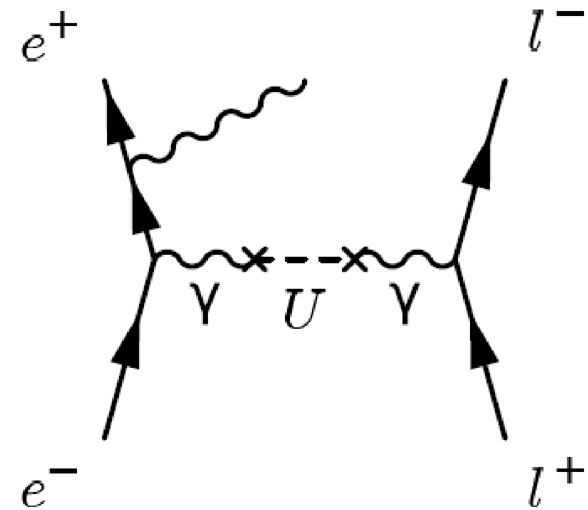
- ***h'*** **-strahlung**: $e^+e^- \rightarrow$U*$\rightarrow$Uh'

  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



U boson production mechanisms

1. The U boson can be produced in **e+e-** collisions via the radiative reaction **e+e-→Uγ**, with subsequent decay of the U into a lepton pair.



If the two leptons are charged, it can be observed as a resonant peak of the lepton pair invariant mass distribution over the standard continuous QED background.

2. U bosons can be produced in electron collisions on a fixed target in a process analogous to ordinary bremsstrahlung.

In this case, production cross sections are much higher with respect to e+e- processes. However backgrounds, both from ordinary QED reactions and from possible beam related sources are also higher.

Analysis Performed

- Analysis performed on 1.7 fb^{-1} (2004-2005 Data Taking)
- Comparison with MC:

  1) **Jaroslaw** production (10 times the Data ~17 fb^{-1}) for the irreducible background:

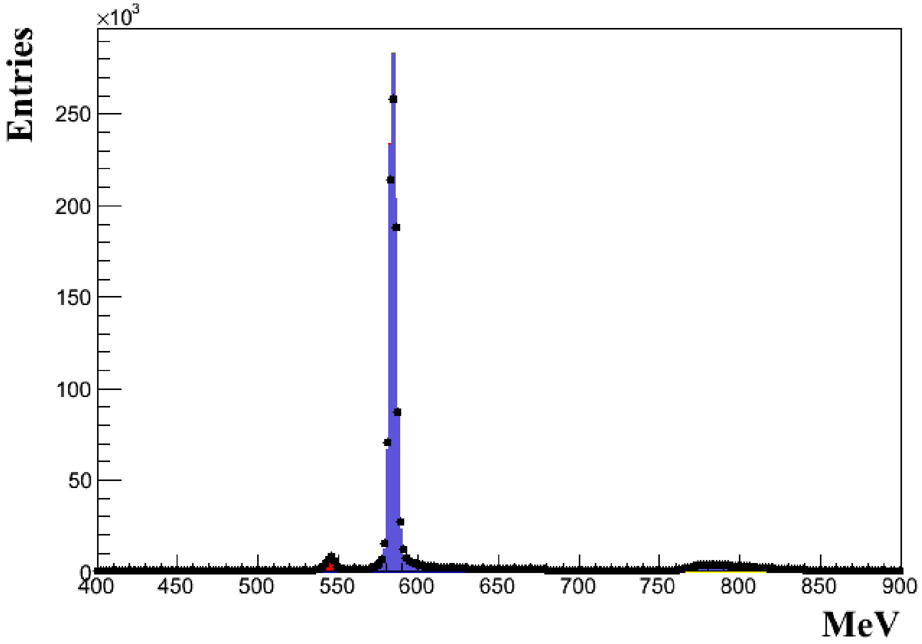
  Dalitz decay $\Phi \rightarrow \eta\gamma^{*} \rightarrow \eta e^{+}e^{-}$, $\eta \rightarrow$ **$3\pi^{0}$**

  2) all_phys production to estimate Bkg from"standard" Φ decays (3.2 fb^{-1})

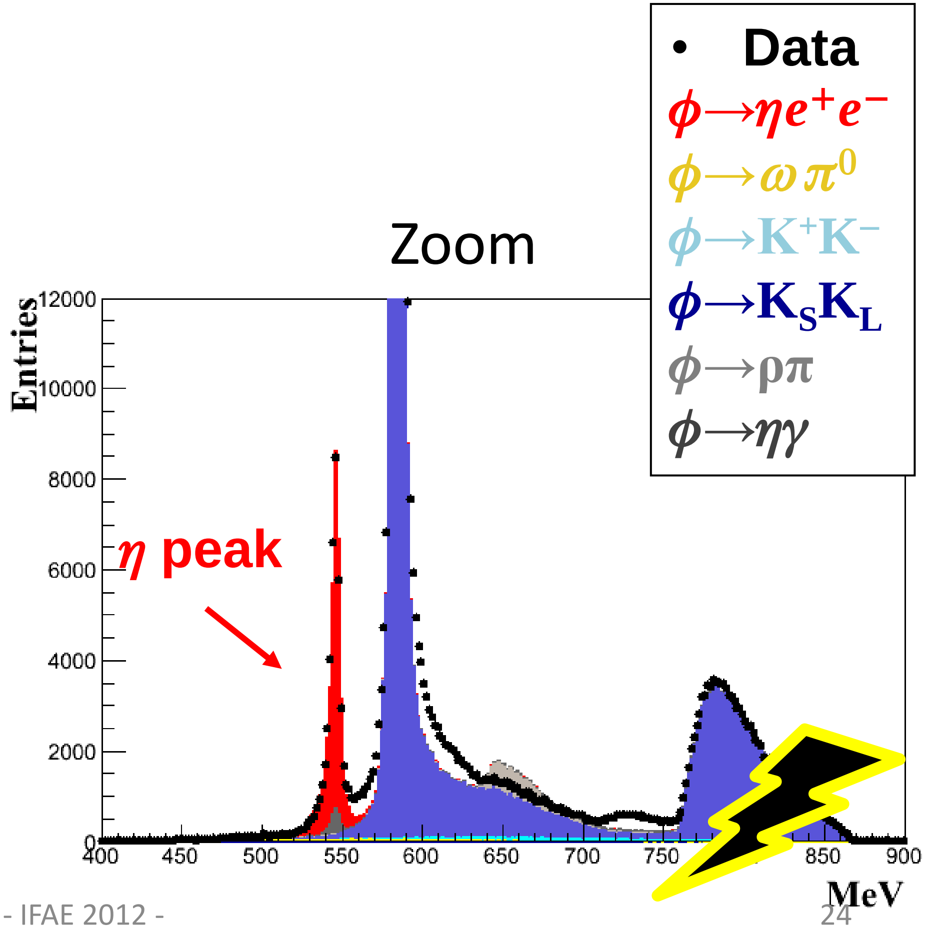
- Hit or Miss applied to **JJ/Simona** production according to the CosΨ* using the form factor parametrization from the SND experiment

Searching in ϕ –>ηl+l– Decays with η -> $3\pi^0$

Recoil Mass (e^+e^-)



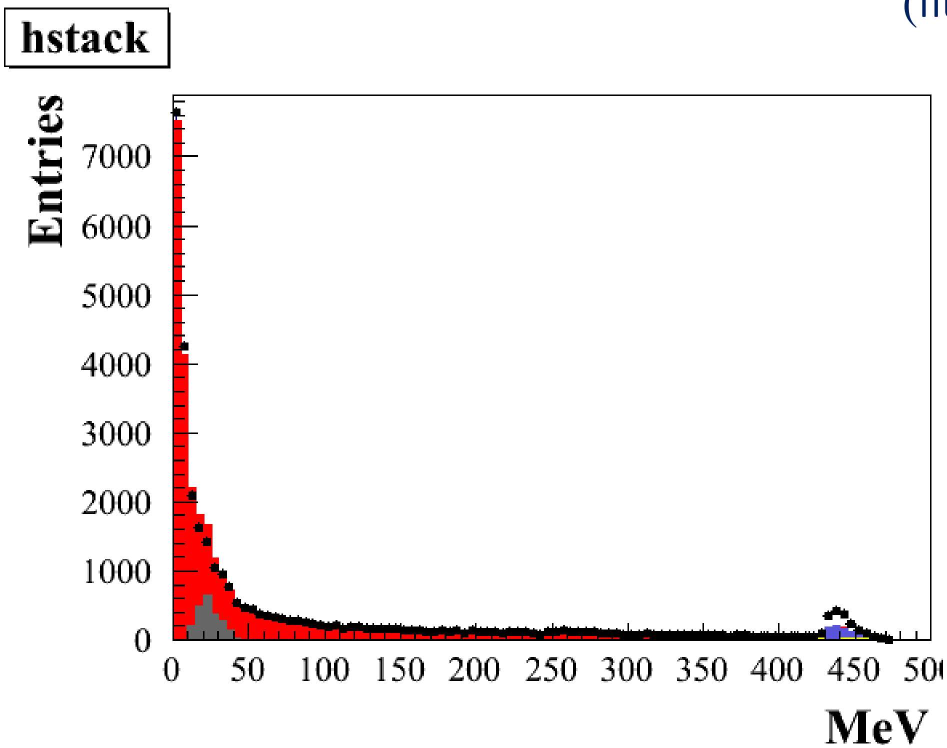
Zoom

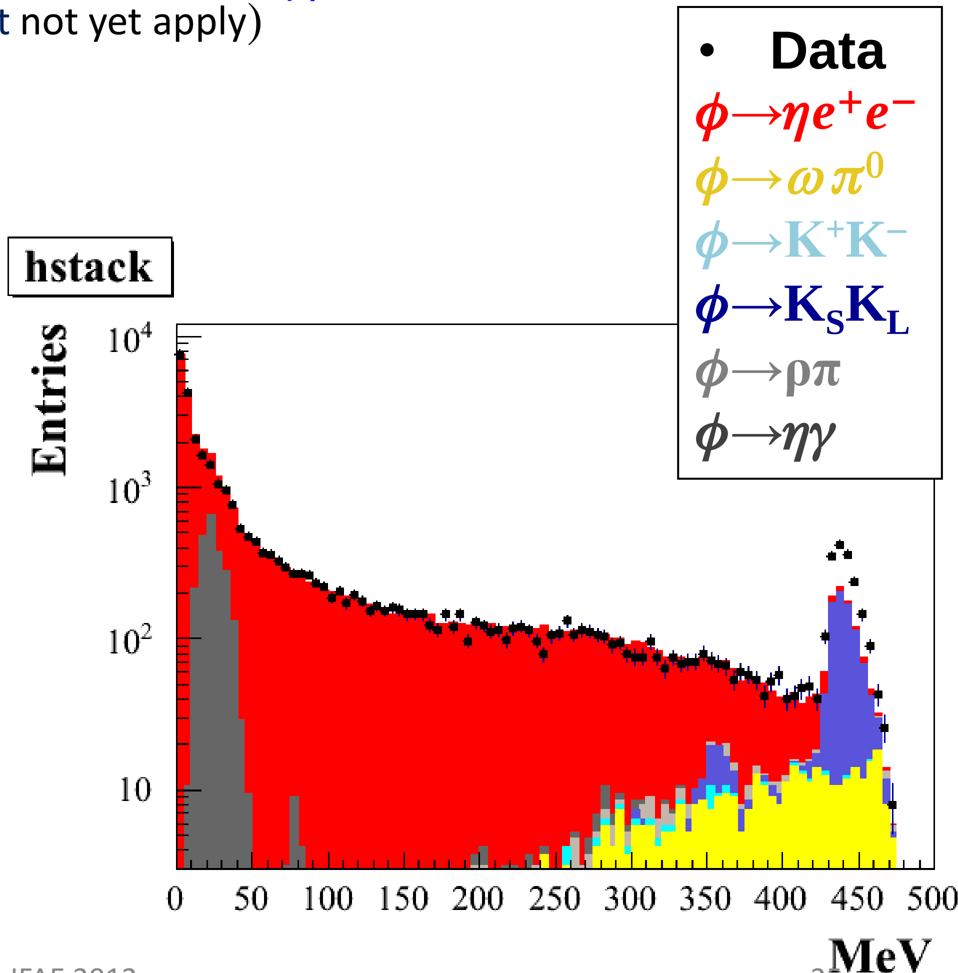


- Events selected in a ~**2σ (6 MeV)** window of the **recoil mass,** around the peak corresponding to η

- **Invariant Mass for e^+e^- pair:**

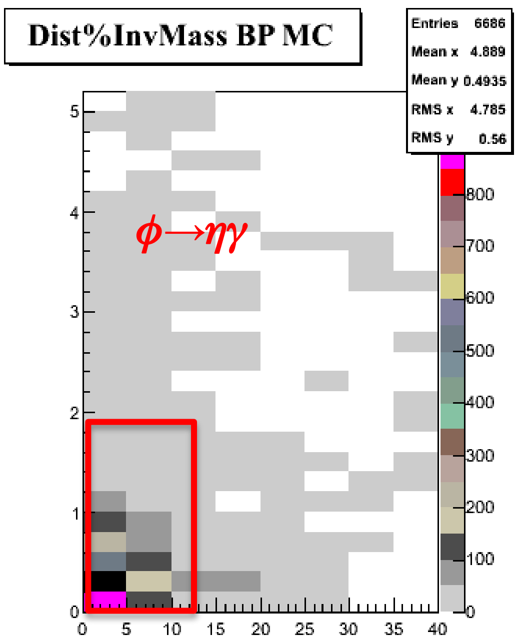
Hit or Miss on MC M_{ee} shape applied:
Corrected with $\mathbf{B}_{\phi\eta} \sim 2$ GeV^{-2}
(fit not yet apply)

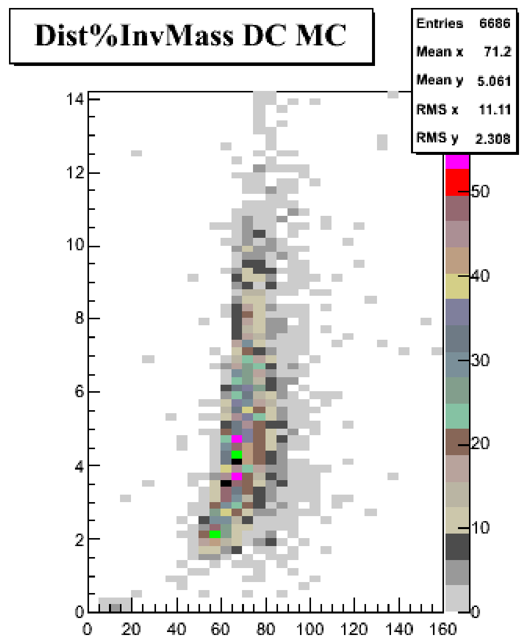


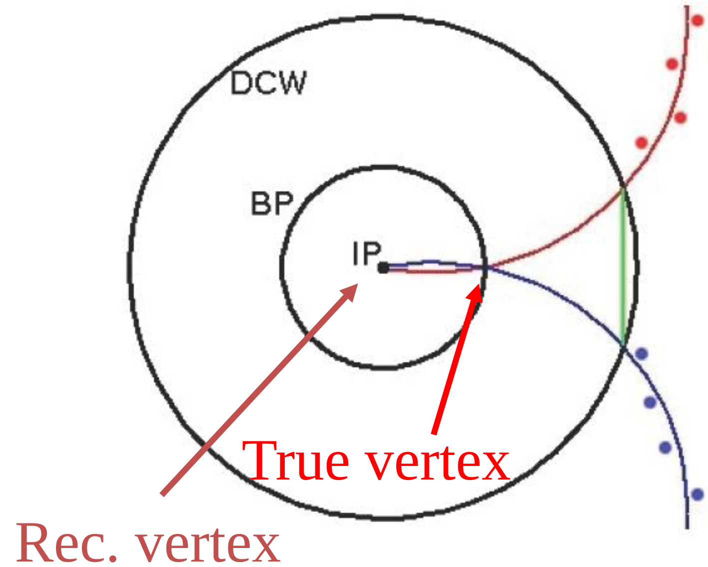


Background rejection: photon conversions

Photon conversions on beam pipe (BP) or drift chamber walls (DCW), are rejected by tracing back the tracks of the two $e^+ e^-$ candidates and reconstructing their invariant mass (Mee) and distance (Dee) at the BP/DCW surfaces

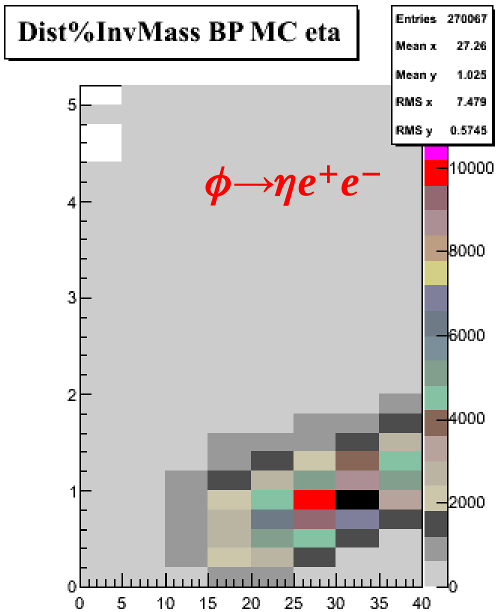


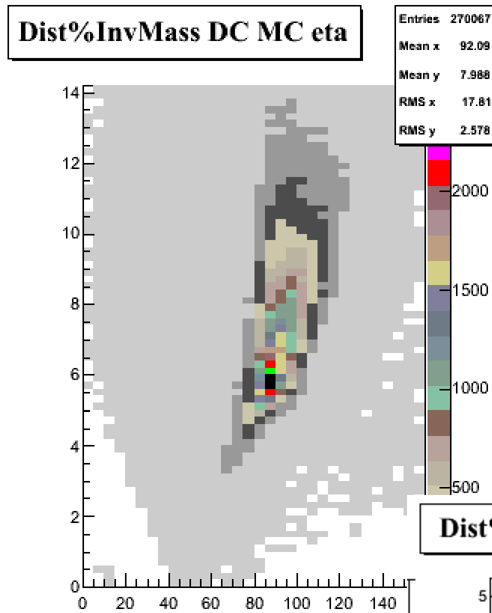


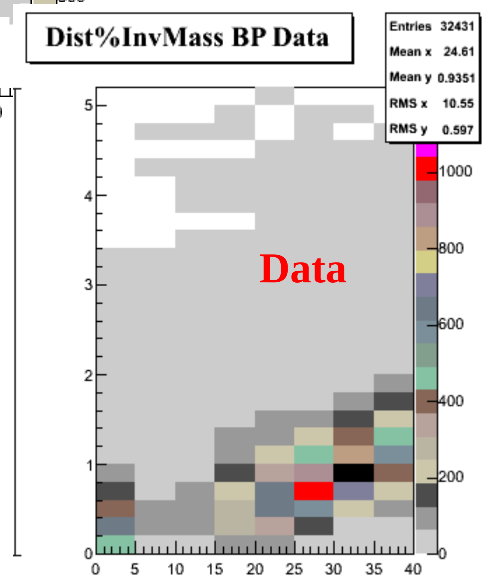


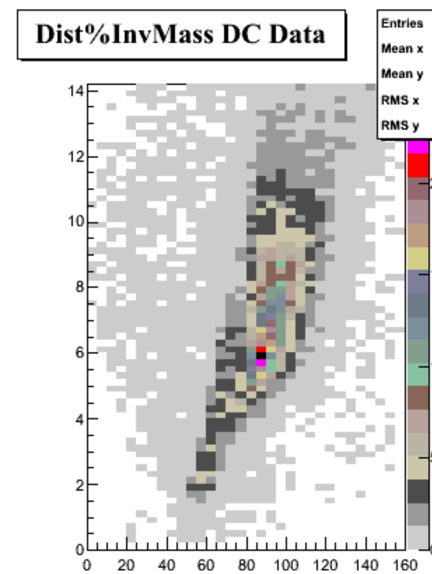
Only BP cut is applied
(Mee < 10 MeV && Dist BP < 2 cm)

Background rejection: photon conversions



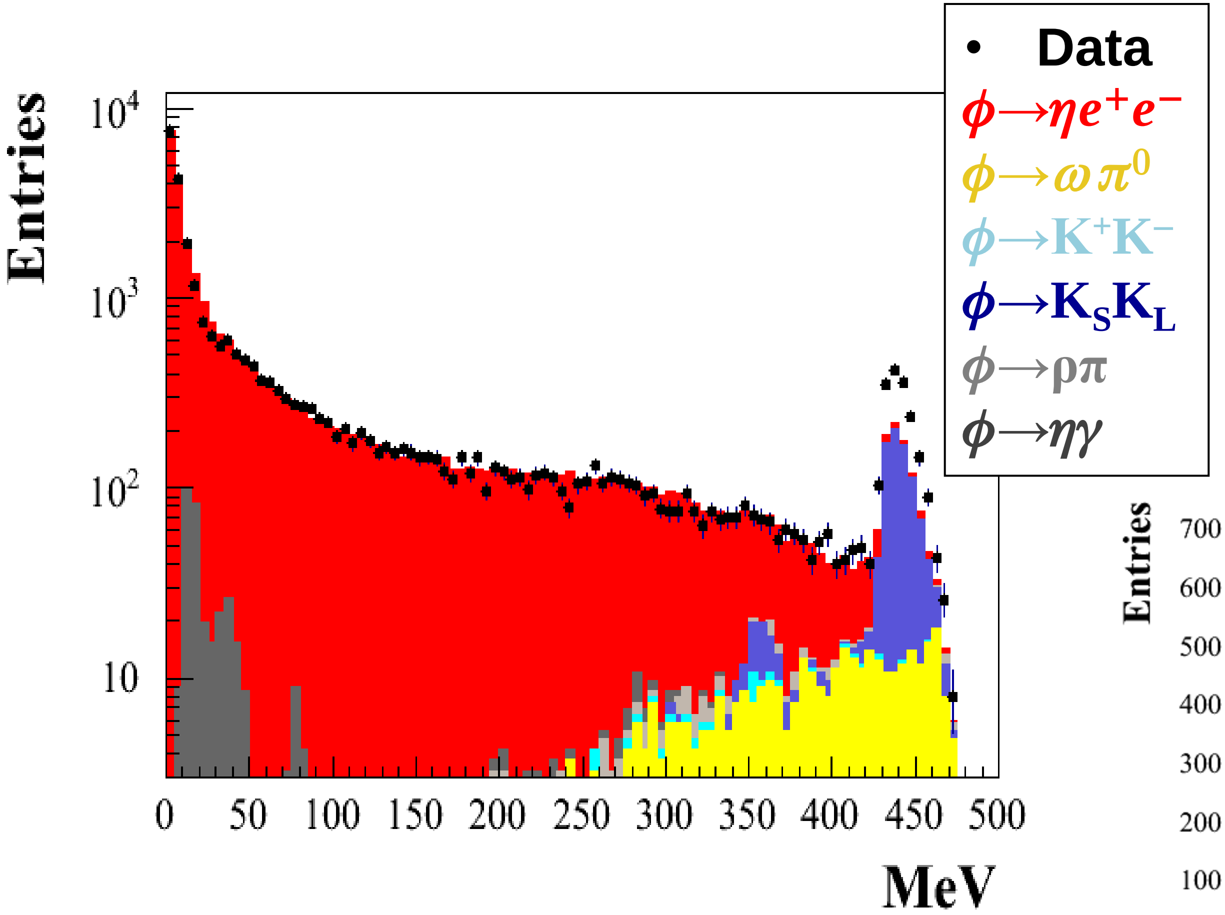




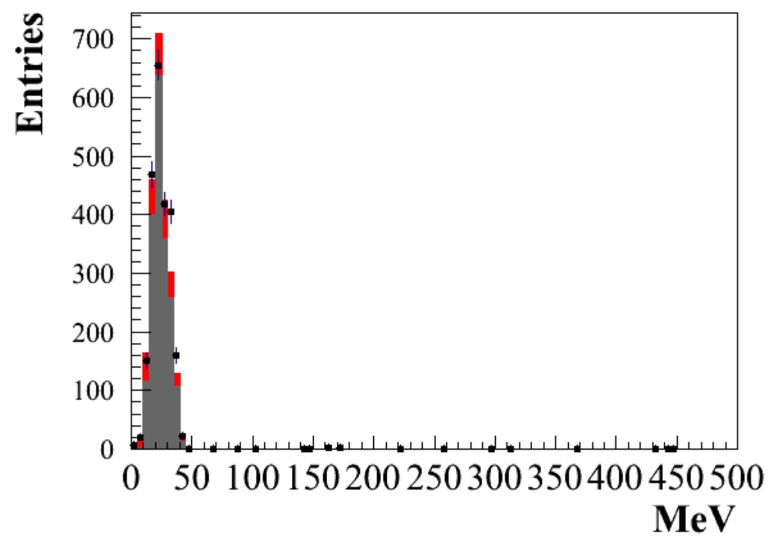


Only BP cut is applied
(Mee < 10 MeV && Dist BP < 2 cm)

Invariant Mass (e^+e^-): after conversions cut



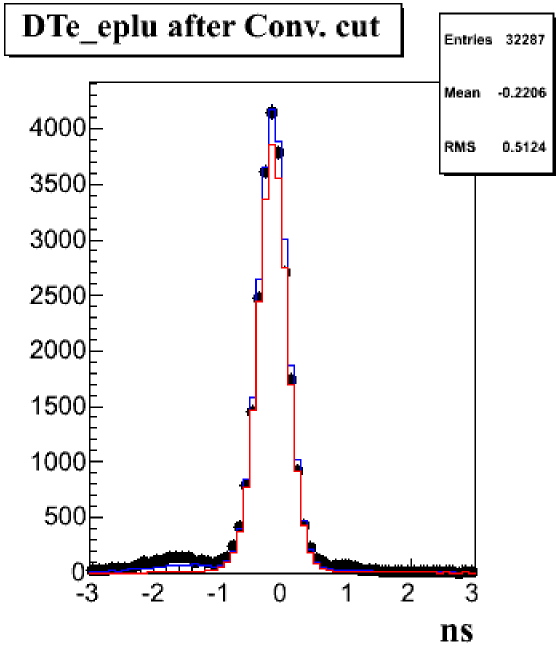
events rejected

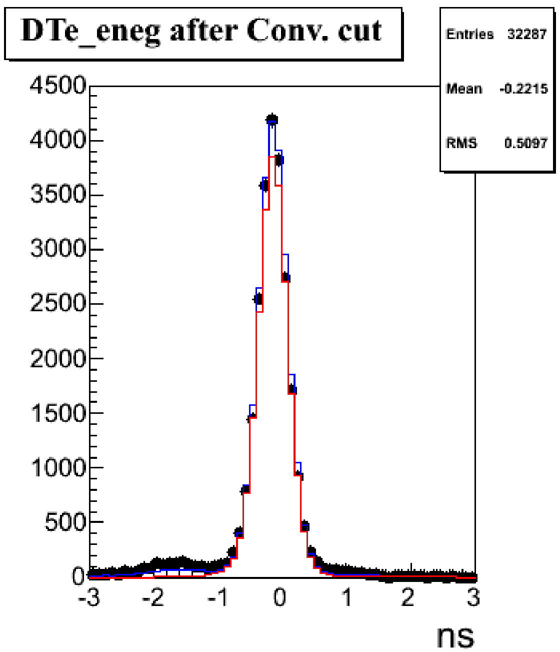


Background rejection: Time Of Flight

A relevant background, originated by $\phi \rightarrow K_S K_L$ decays ($K_S \rightarrow \pi^+ \pi^-$ and $K_L \rightarrow 3\pi^0$) surviving analysis cuts, has more than two charged pions in the final state and is suppressed using time-of-flight of tracks to the calorimeter.

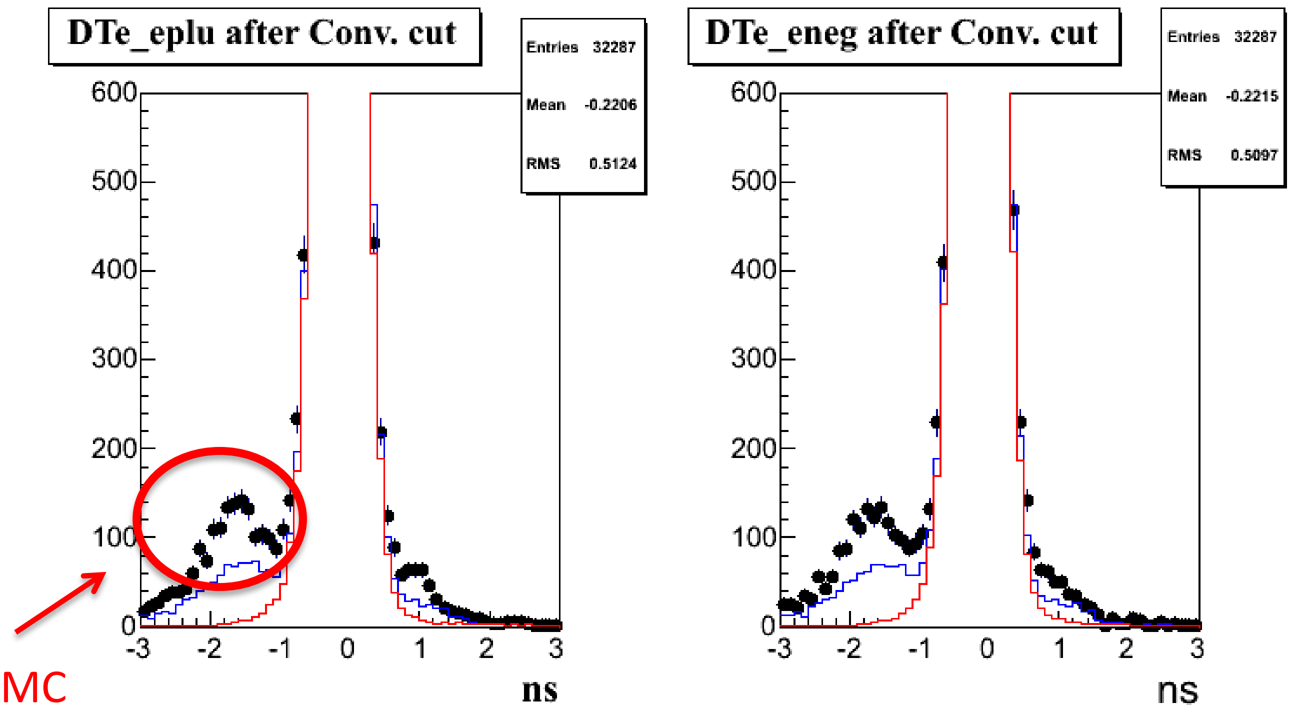
- When an energy cluster is connected to a track, the arrival time to the calorimeter is evaluated both using the calorimeter timing ($T_{cluster}$) and the track trajectory ($T_{track} = L_{track}/\beta c$). The $\Delta T = T_{track} - T_{cluster}$ variable is then evaluated in the electron (ΔTe) hypothesys





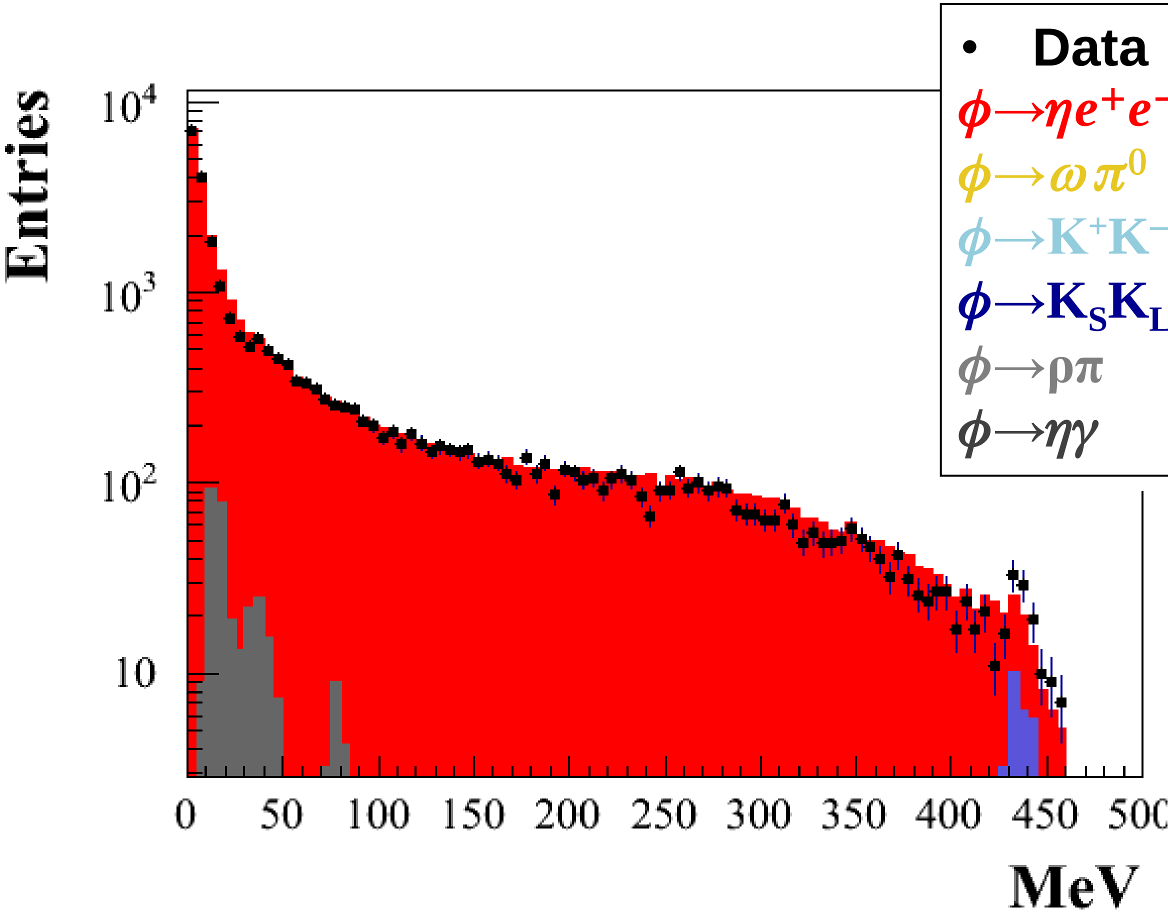
Background rejection: Time Of Flight -2-

Events with an e^+ and e^- candidate outside a 3 σ's window on the ΔTe variables are **rejected** **(ΔTe < -0.8 && ΔTe > 0.6)**

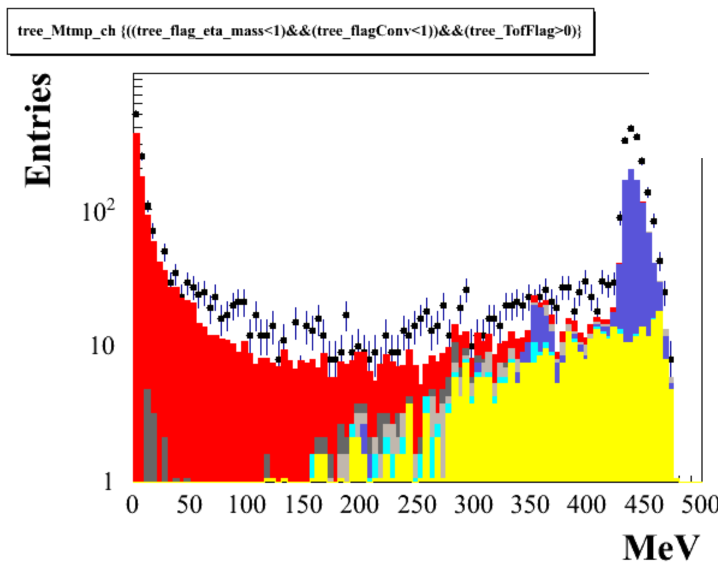


Most of Data-MC disagreements are rejected by TOF cut

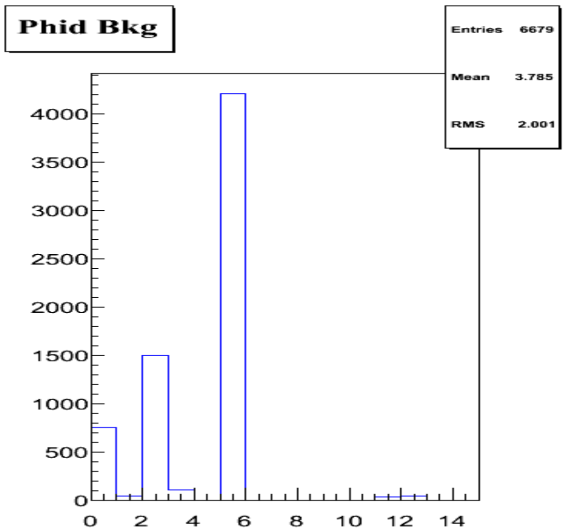
Invariant Mass (e^+e^-):
after conversions & TOF cuts

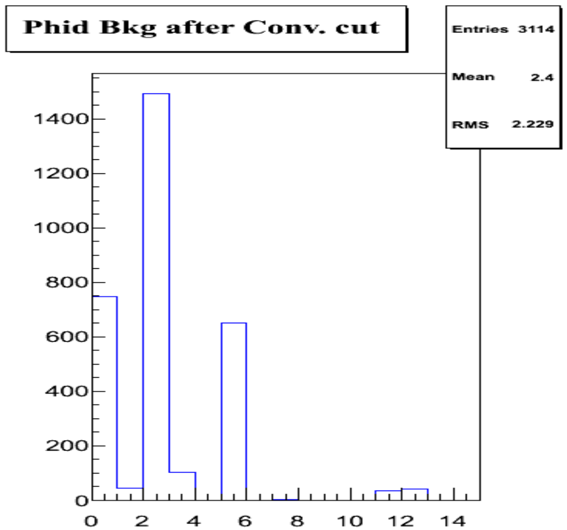


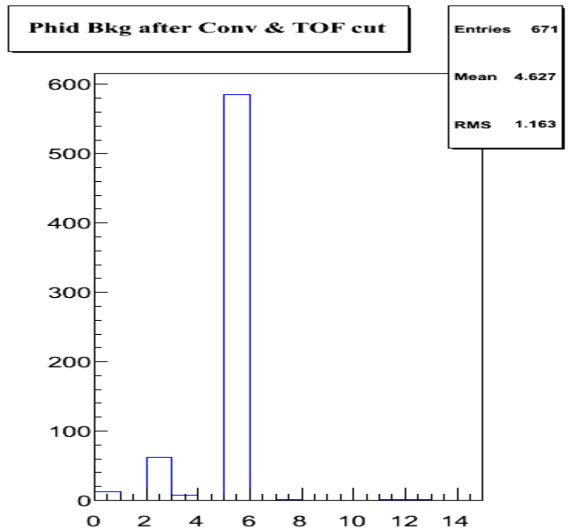
events rejected

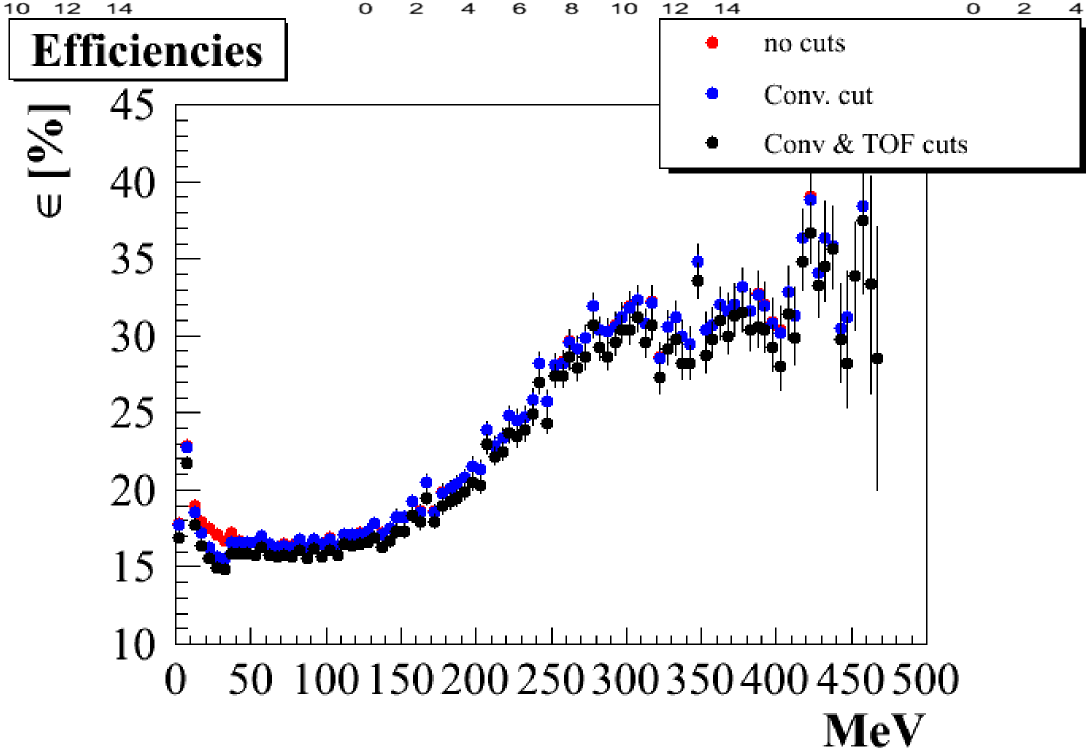


Cuts summary and Efficiencies









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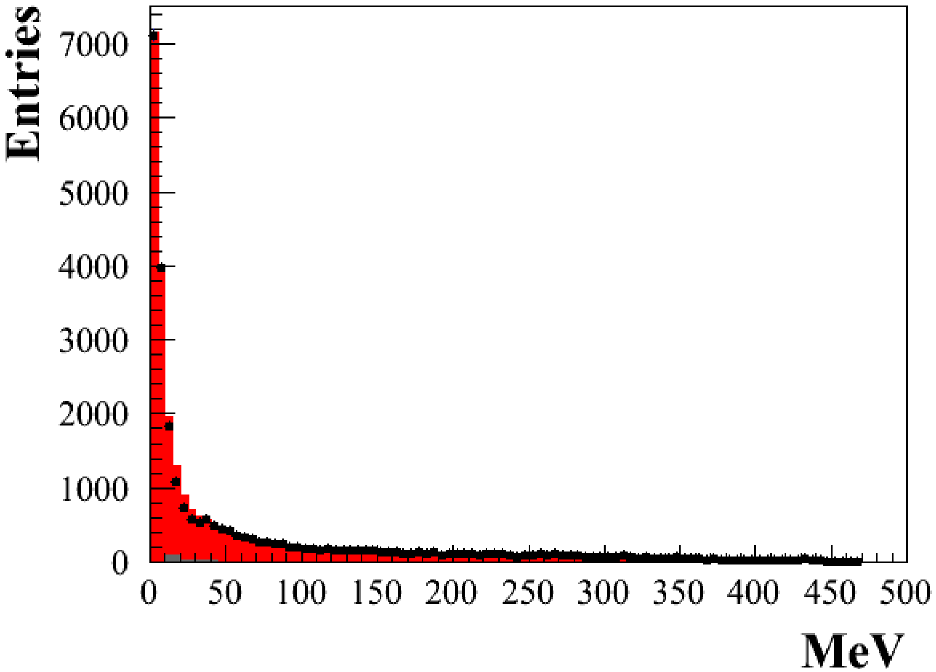
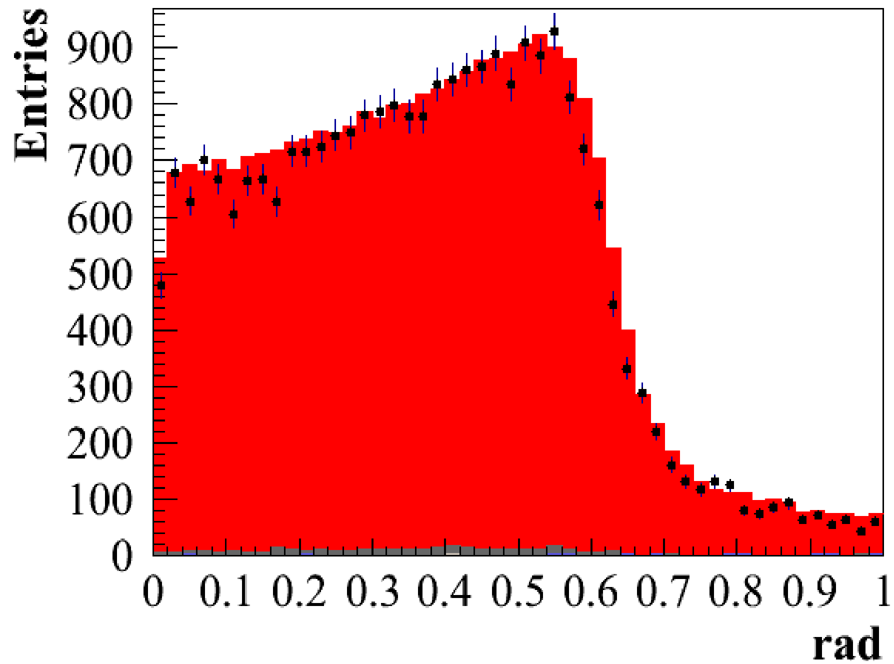
Data-MC comparison summary



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



- **~26000 $\phi \to \eta e^+ e^-$ with $\eta \to 3\pi^0$ candidates** (~2 times $\eta \to \pi^+ \pi^- \pi^0$)
- **Small residual contamination from $\phi \to \eta\gamma$ and $\phi \to K_S K_L$ events**
- **MC M_{ee} shape with FF slope from SND (213 events)** [PLB504(2001) 275]

Extract it directly from our data!

Fit to the M_{ee} shape

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

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

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

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

FF slope:

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