Searches for Hidden Sector Particles in KLOE

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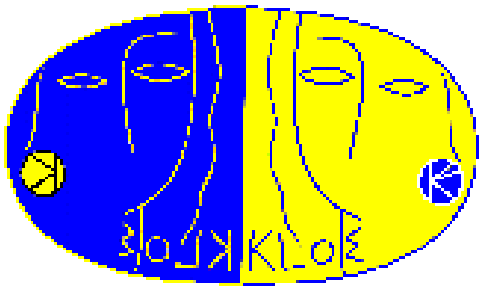


Intensity Frontier Meeting – Argonne – April 26th 2013

Outline

- DAΦNE: the Φ-Factory

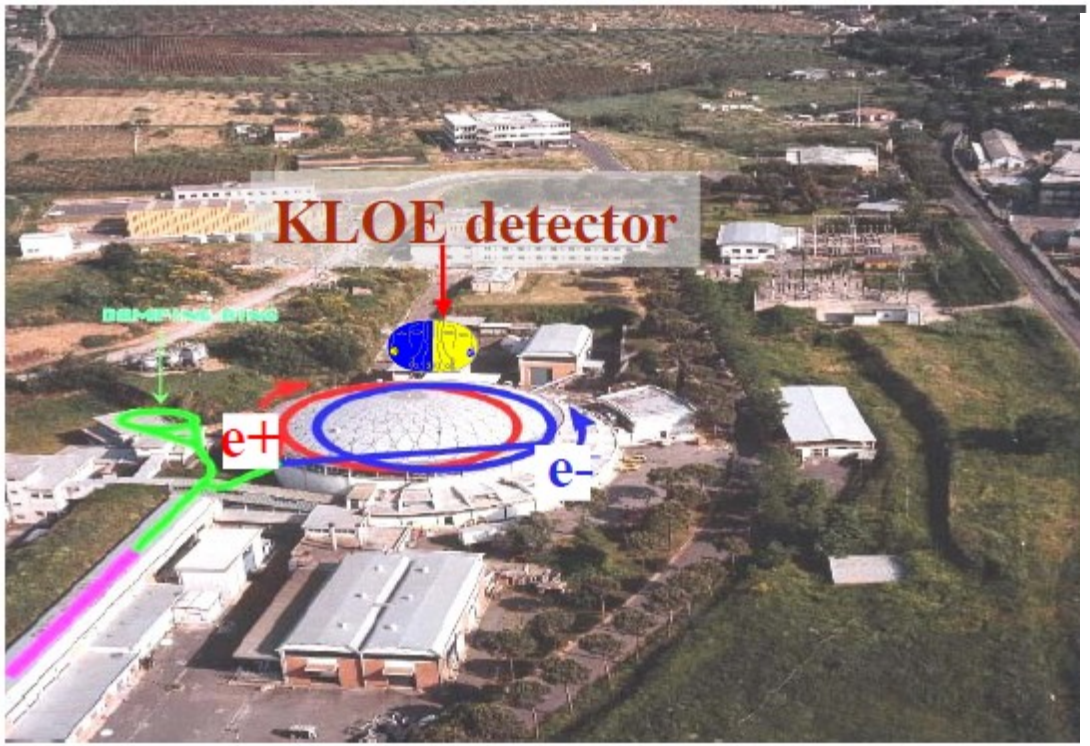
- The KLOE Detector

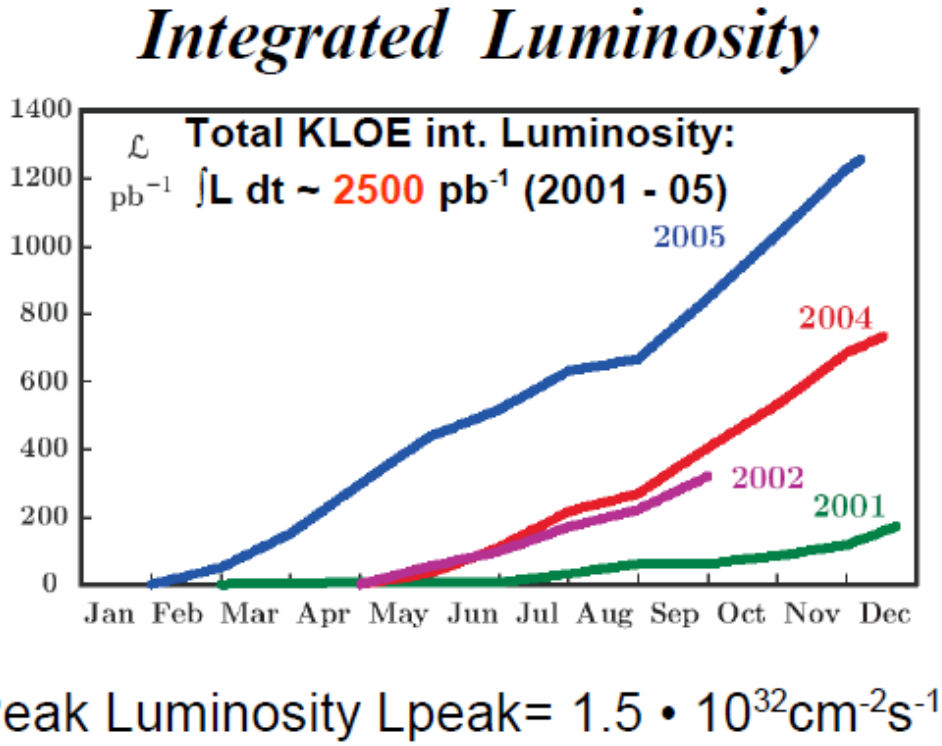
- U boson searches @ KLOE:
-Uγ events
-Φ Dalitz decay
-Higgs Strahlung

- Future Perspectives

- Conclusions

DAΦNE: the Φ-Factory



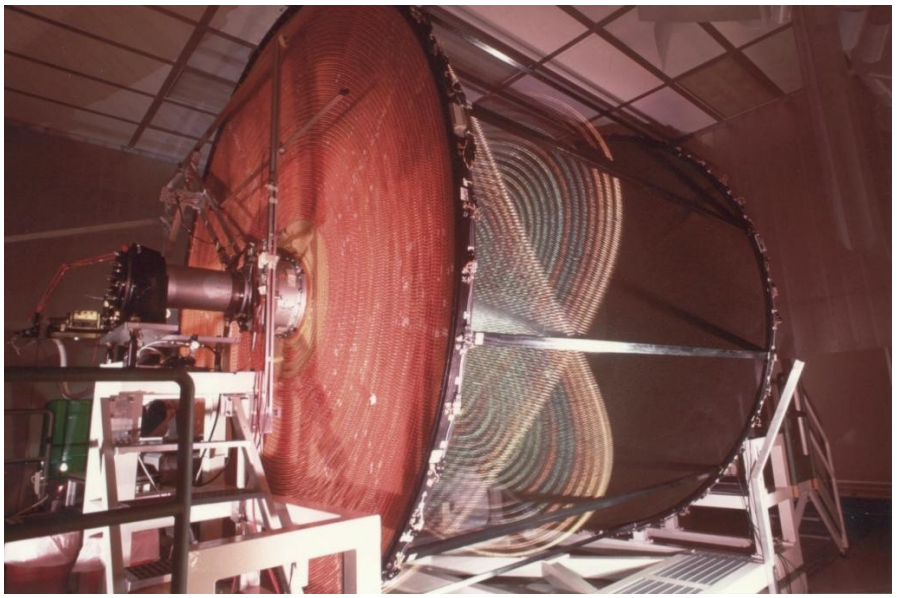


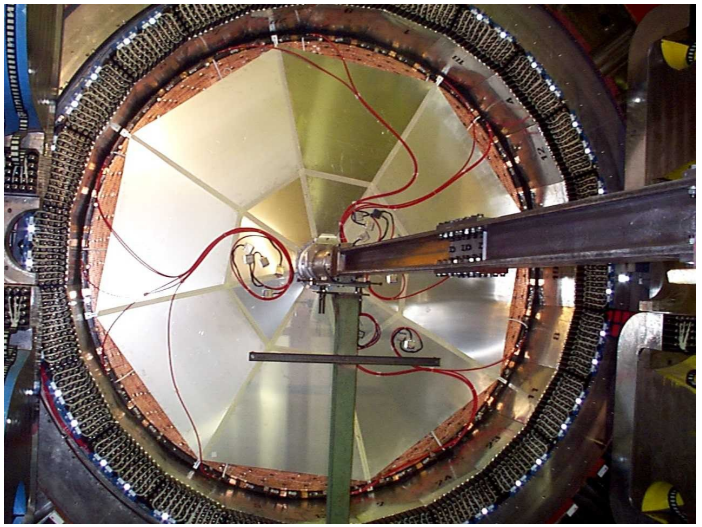
Peak Luminosity Lpeak= $1.5 \cdot 10^{32} cm^{-2} s^{-1}$

DAΦNE is a $e^+ e^-$ Colliders with a $\sqrt{s} = m_\Phi = 1.0195$ GeV, at LNF Frascati, near Rome.

The DAΦNE Accelerator Complex consists of **a linear accelerator, a damping ring**, nearly 180 m of **transfer lines**, **two storage rings** that intersect at two points, **a beam test area** (BTF) and **three synchrotron light lines.**

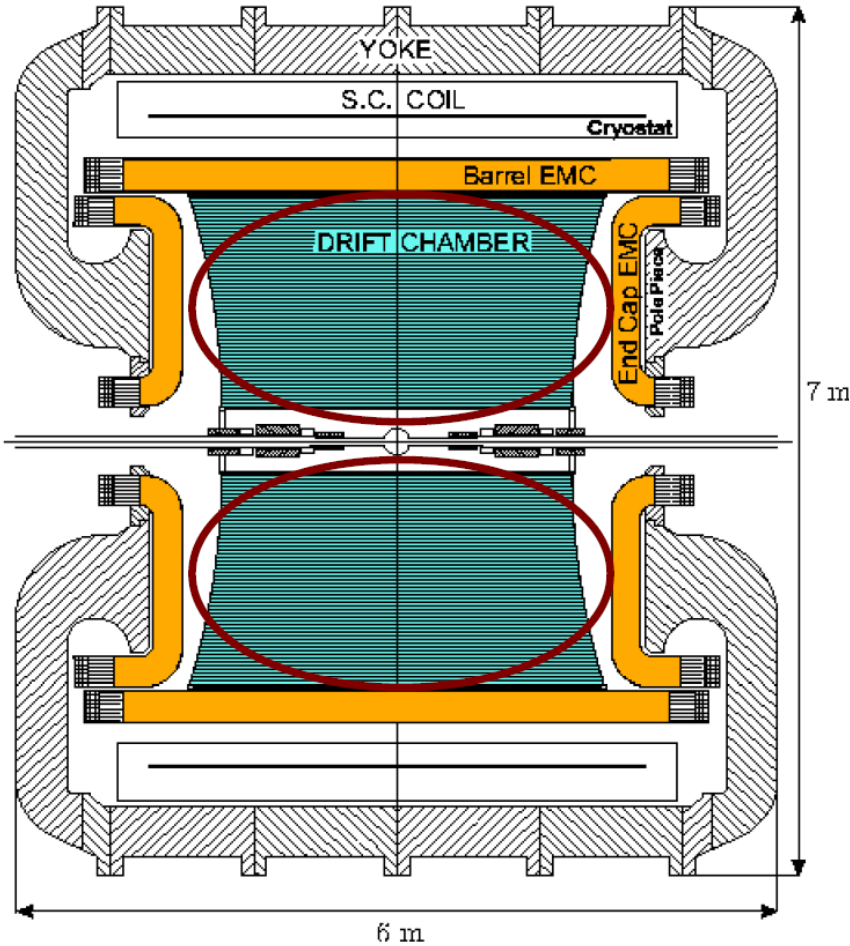
KLOE Detector: DC





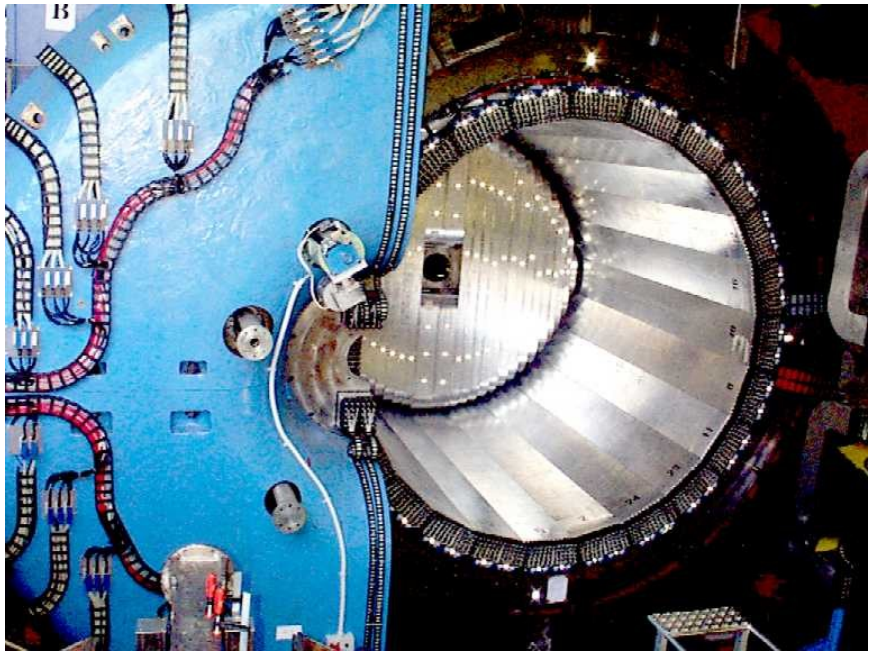
All-stereo geometry, 4m diameter, 3m long fiber epoxy composite, **12,000 sense wires**
Filled with gas mixture:90% He 10% C_4H_{10}

σ_{xy}~150μm, σ_z= 2mm
$\sigma_{p\perp}$ /$p_\perp$ better then 0.4% for large angle tracks ($40° \leq \theta \leq 140°$)
vertex resolution = ~3mm



Excellent momentum resolution

KLOE Detector : EMC



Barrel + 2 end-caps: Pb/scintillating fiber
4880 PM

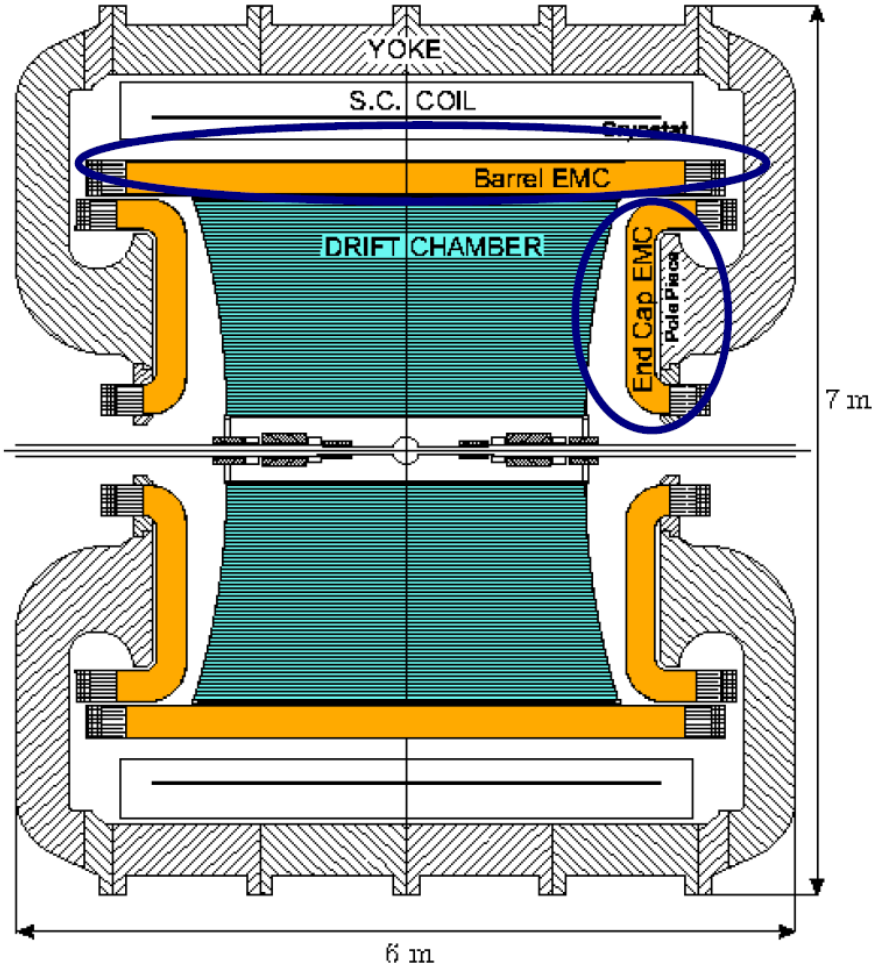
End-caps C-shaped to minimize dead zones:
98% coverage of full solid angle

$$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$$

$$\sigma_T = 54\ ps / \sqrt{E(GeV)} \oplus 100\ ps$$

(Bunch length contribution subtracted from constant term)

excellent time resolution



U boson searches @ KLOE

High luminosity $e^+ e^-$ Colliders Experiments at GeV scale like KLOE can be a direct probe of Dark Forces

- $U\gamma$ Events: $e^+ e^- \rightarrow U\,\gamma \rightarrow \mu^+ \mu^- \gamma$

Particular clean channel
$\sigma \sim 1/s$:100 times higher at DAΦNE
loss in luminosity with respect to B-factories compensated

- Φ Dalitz decay: $e^+e^- \rightarrow \Phi \rightarrow U\eta \rightarrow e^+e^- \eta$

  $\eta \rightarrow \pi^0 \pi^0 \pi^0$

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

Characteristic of light meson factory

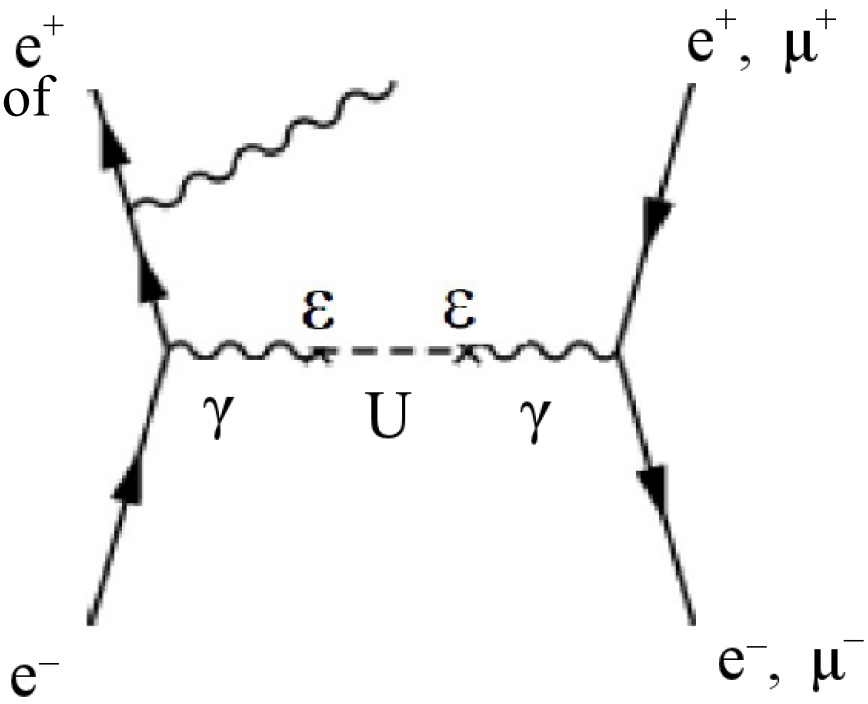
- Higgs Strahlung: $e^+e^- \rightarrow h'U \rightarrow h' \mu^+\mu^-$

Assuming the existence of a higgs' boson, a particularly interesting process is the higgs-strahlung $e^+e^- \rightarrow Uh'$, which can be observed at KLOE if $m_U + m_{h'} < m_\Phi$

U boson searches @ KLOE: $e^+ e^- \to U\gamma \to \mu^+ \mu^- \gamma$

According to several theoretical studies:
particular clean channel: $e^+ e^- \to U\gamma \to l^+ l^- \gamma$, l= e,μ

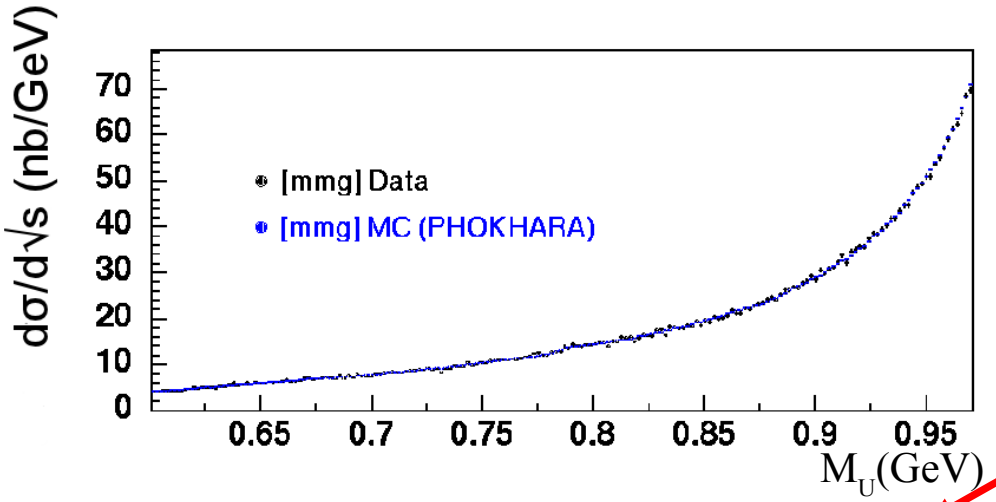
The expected U boson signal should have the shape of a **Breit-Wiegner peak in the invariant mass distribution of the lepton pair**

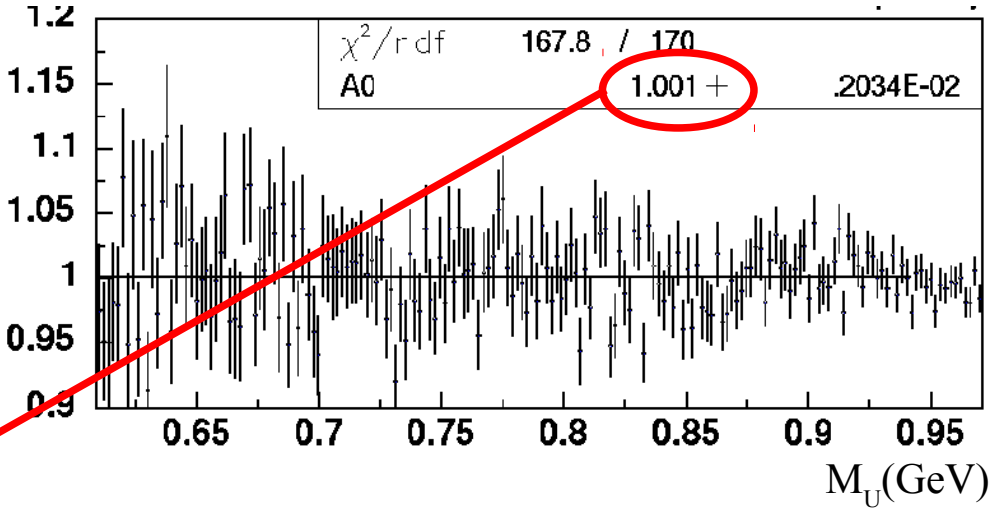


Event selection:
-Statistics: 240 pb^{-1} data taken on 2002.
-undetected photon emitted at small angle (θ_γ<15°, θ_γ>165°)
-two charged tracks with 50°<θ_μ<130° .
-high statistics signal
-significant reduction of Φ resonant and FSR radiative processes backgrounds:
$e^+ e^- \to e^+ e^- \gamma(\gamma)$
$e^+ e^- \to \pi^+ \pi^- \gamma(\gamma)$
$e^+ e^- \to \varphi \to \pi^+ \pi^- \pi^0$

U boson searches @ KLOE: $e^+ e^- \to U\gamma \to \mu^+ \mu^- \gamma$

Analysis procedure goal: **$\mu^+\mu^-\gamma$ cross section** in the 0.6 -1 GeV energy range





Excellent Data/MC agreement

UPPER LIMIT EXTRACTION at 90% CL:

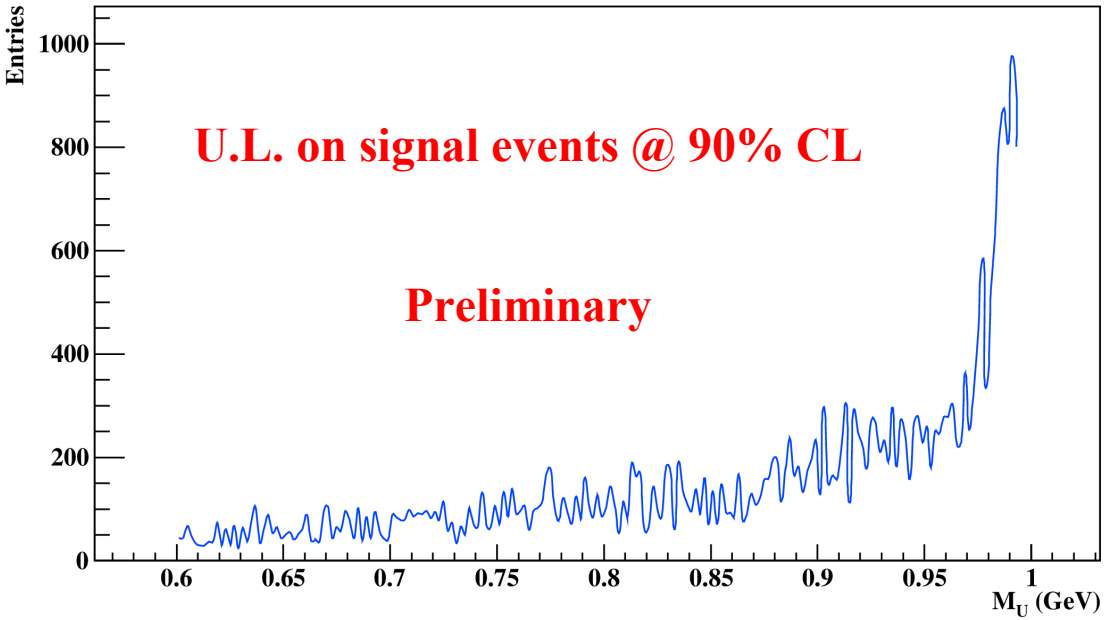
-Observed spectrum and QED NLO MC prediction by Phokara as inputs of Tlimit procedure

-each spectra divided in slices of 0.002 GeV

-each M_U sub-sample used to compute, by

Tlimit Root Class (CLS technique), the exclusion plot of number of events

Systematic error of 2% also included



U boson searches @ KLOE: $e^+e^- \to U\gamma \to \mu^+\mu^-\gamma$

UL Extraction Formula: $\varepsilon^2 = \frac{N_{CLS}/(\epsilon_{eff}\cdot L)}{H\cdot I}$

N_{CLS} = #entries of signal hypothesis of ROOT Tlimit procedure

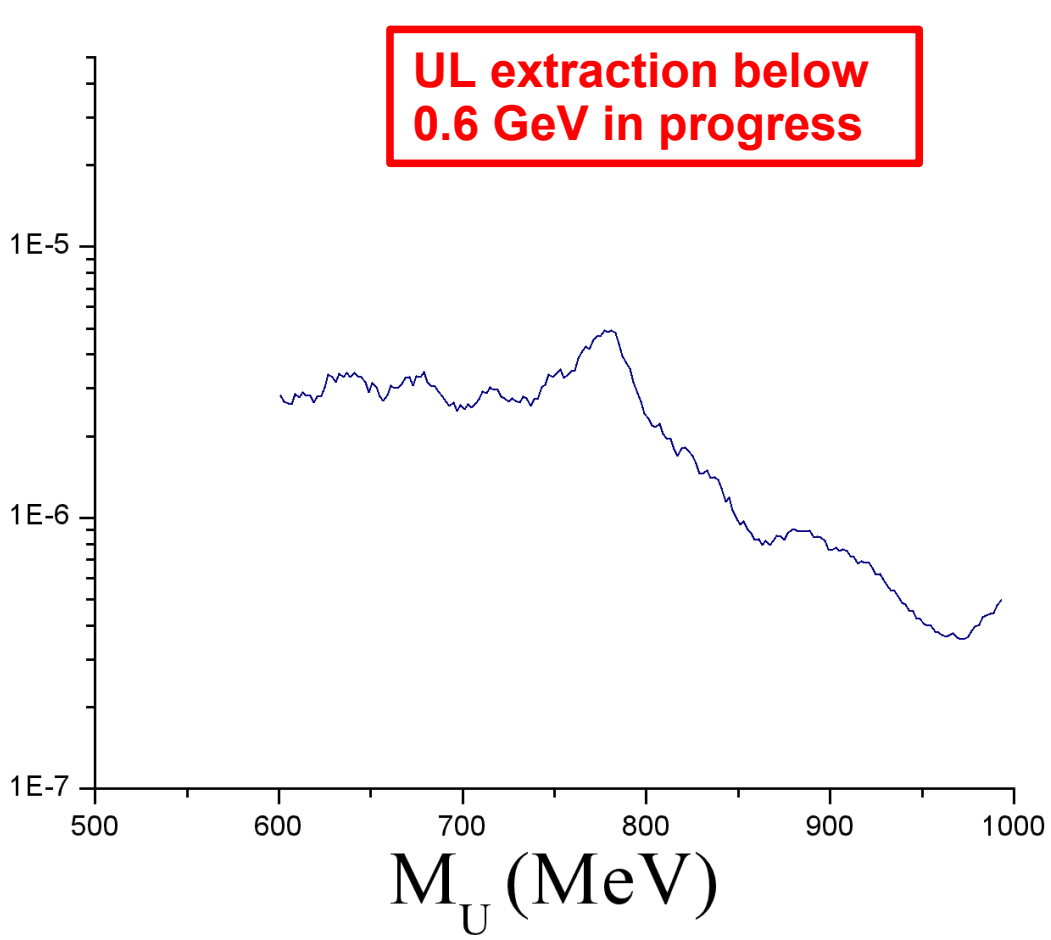
ϵ_{eff} = acceptance $(0° < \theta_\gamma < 180°\ 0° < \theta_\mu < 180°)$ + eff. corrections + FILFO + bckg subtr.

$$H = \frac{d\sigma_{\mu\mu\gamma}/d\sqrt{s_\mu}}{\sigma(e^+e^-\to\mu^+\mu^-,s)}$$

$L = 239.29\ pb^{-1}$

$$I = \int_i \sigma_U^{\mu\mu} ds_i \quad s = M_U^2 \quad s_i = \text{bin}$$

$$\sigma_U^{\mu\mu} = \sigma(e^+e^-\to U\to\mu^+\mu^-,s)$$



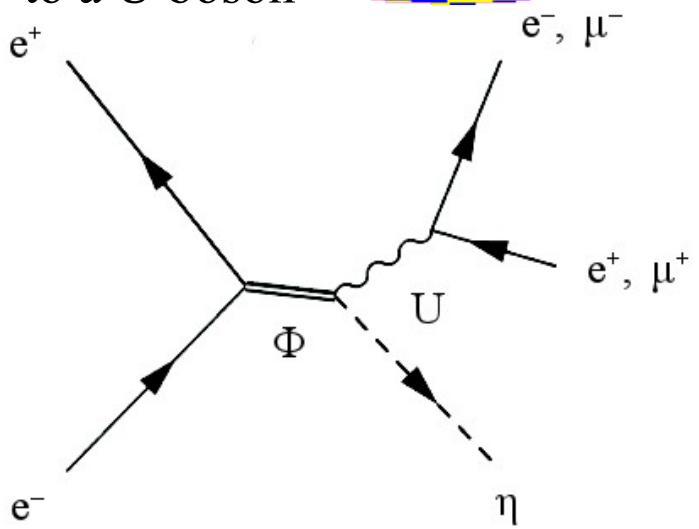
U. L. between $2.8\cdot10^{-6}$ and $4.9\cdot10^{-7}$ in the energy range 600-1000 MeV

U boson searches @ KLOE: $e^+e^- \to \Phi \to U\eta \to e^+e^-\eta$

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

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

$\sigma(\phi \to \eta U) \sim 40$ fb for $FF_{\phi\eta}=1$, $\varepsilon=10^{-3}$



Irreducible background: Φ Dalitz decay
$\Phi \to \eta\gamma^* \to \eta l^+ l^-$

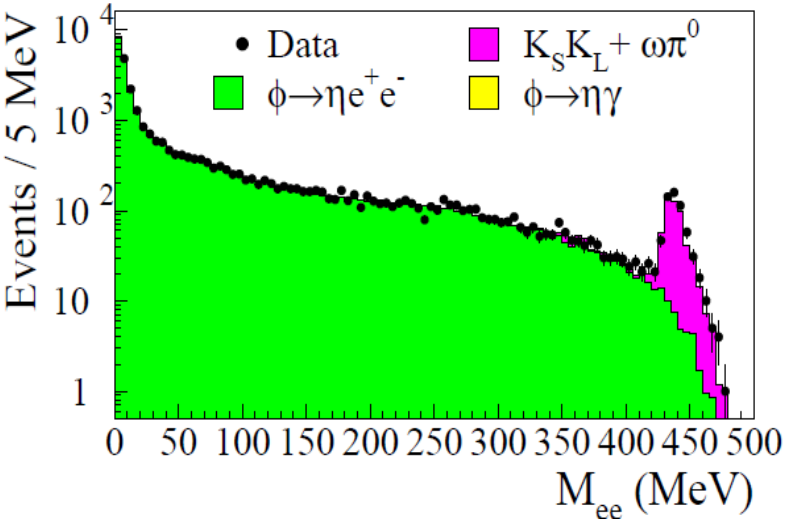
Selected decay chains:

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

$\eta \to \pi^0 \pi^0 \pi^0$ (BR=32.6%) **Phys. Lett. B720 (2013) 111-115 (arXiv:1210.39.27)**

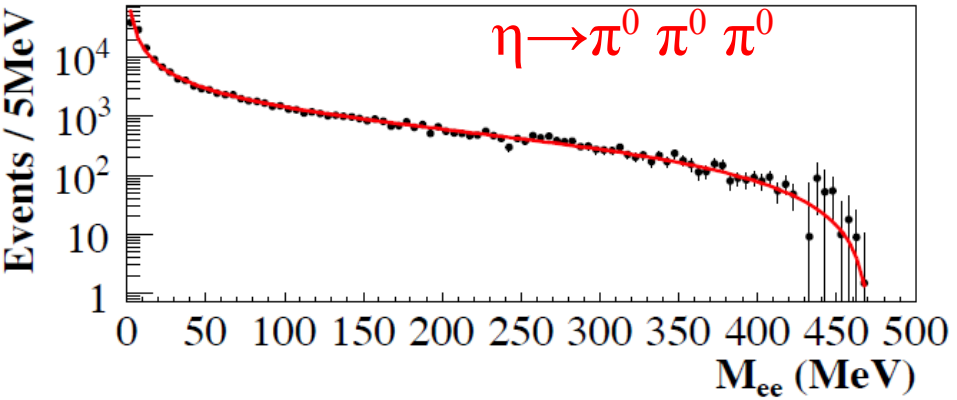
Event selection for $\eta \to \pi^0 \pi^0 \pi^0$:
- 2 tracks (1 negative and 1 positive) in a cylinder around IP
- 6 prompt photons candidates, i.e. energy clusters with E > 7 MeV not associated to any track, in an angular acceptance $|\cos\theta_\gamma| < 0.92$ and in the expected time window for a prompt photon ($|T_\gamma - R_\gamma/c| <$ MIN($3\sigma_T$, 2 ns))
- $400 < M_{6\gamma} < 700$ MeV

Event selection for $\eta \to \pi^+ \pi^- \pi^0$:
- 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

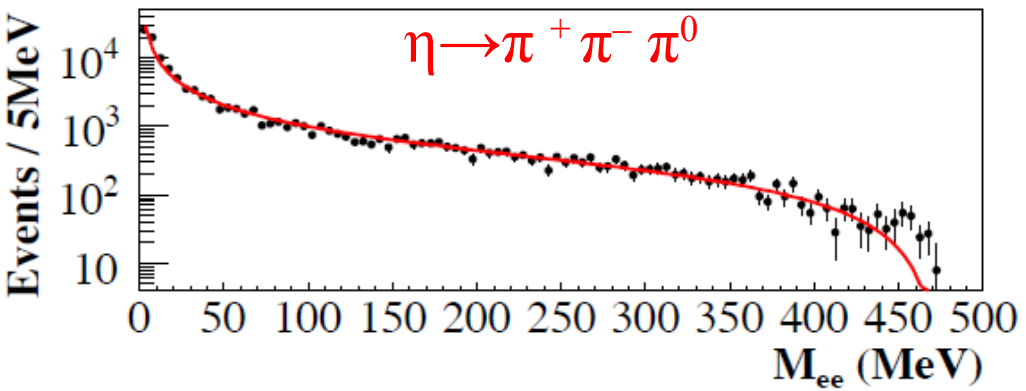


U boson searches @ KLOE: $e^+e^- \to \Phi \to U\eta \to e^+e^-\eta$

Data sample:1.7 fb^{-1}

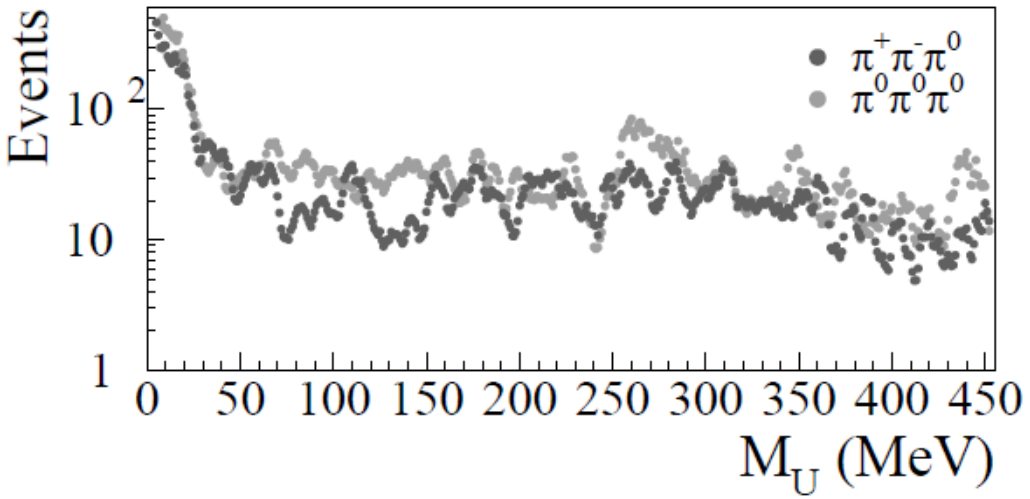


Data sample:1.5 fb^{-1}



UL Evaluation:

- $\varphi \to \eta U$ MC sample divided in sub-samples of 1 MeV width in $5 < M_U < 470$ MeV
- For each M_U sub-sample, average value of $\varphi \to \eta e^+e^-$ 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 CLS method (error on bckg included)



U boson searches @ KLOE: $e^+e^- \to \Phi \to U\eta \to e^+e^-\eta$

Exclusion plot evaluation by using the formula from Reece and Wang, JHEP 07 (2009)

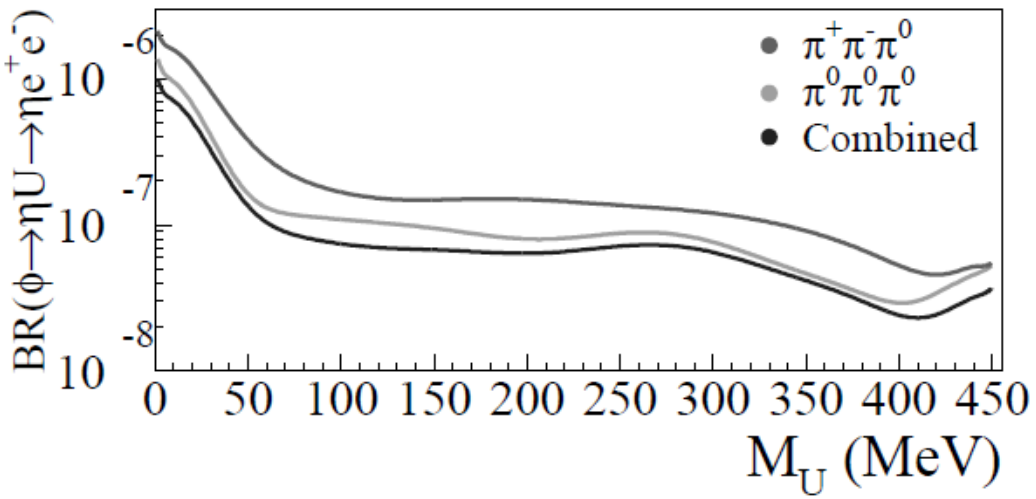
$$\sigma(e^+e^- \to \phi \to \eta U) = \epsilon^2 |F_{\phi\eta}(m_U^2)|^2 \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)} \sigma(e^+e^- \to \phi \to \eta\gamma)$$

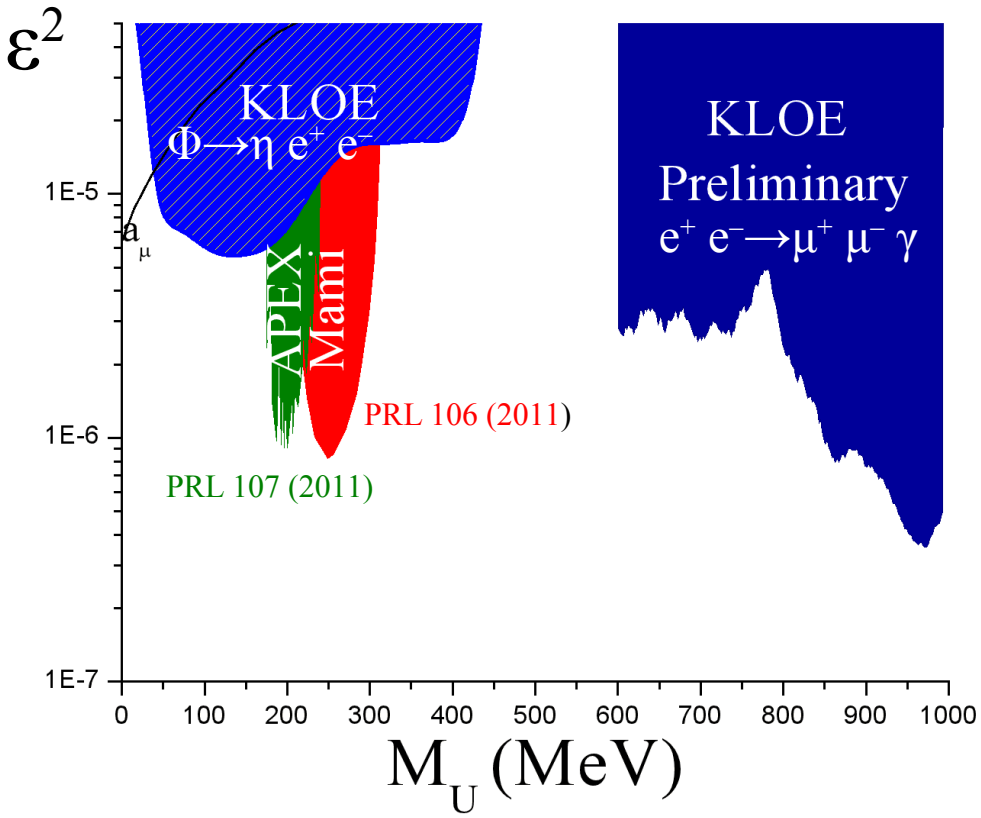
$$\lambda(m_1^2, m_2^2, m_3^2) = [1 + m_3^2/(m_1^2 - m_2^2)]^2 - 4m_1^2 m_3^2/(m_1^2 - m_2^2)^2$$

$$F_{\phi\eta}(q^2) = \frac{1}{1 - q^2/\Lambda^2} \qquad q = M_{ee}$$

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

VMD





$\alpha'/\alpha \leq 1.7\times10^{-5}$ @ 90% C.L. For 30 $< M_U <$ 400 MeV

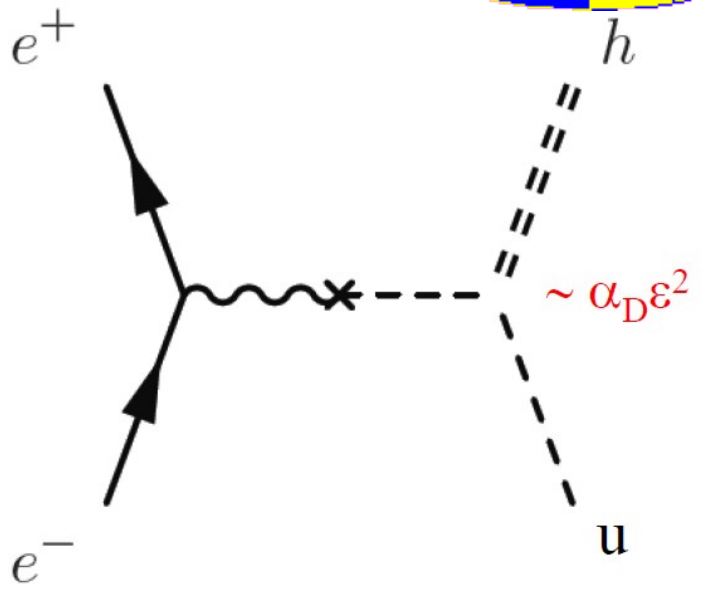
$\alpha'/\alpha \leq 8\times10^{-6}$ @ 90% C.L. for the 50 $< M_U <$ 210 MeV sub-region

U boson searches @ KLOE: $e^+e^- \to h'U \to h'\mu^+\mu^-$

Two different scenarios depending on the higgs' mass:

$m_{h'} < m_U$ ⇒ "invisible scenario"

$m_{h'} > m_U$ ⇒ $h' \to UU \to 4l, \pi+2l, \pi$



Invisible scenario:

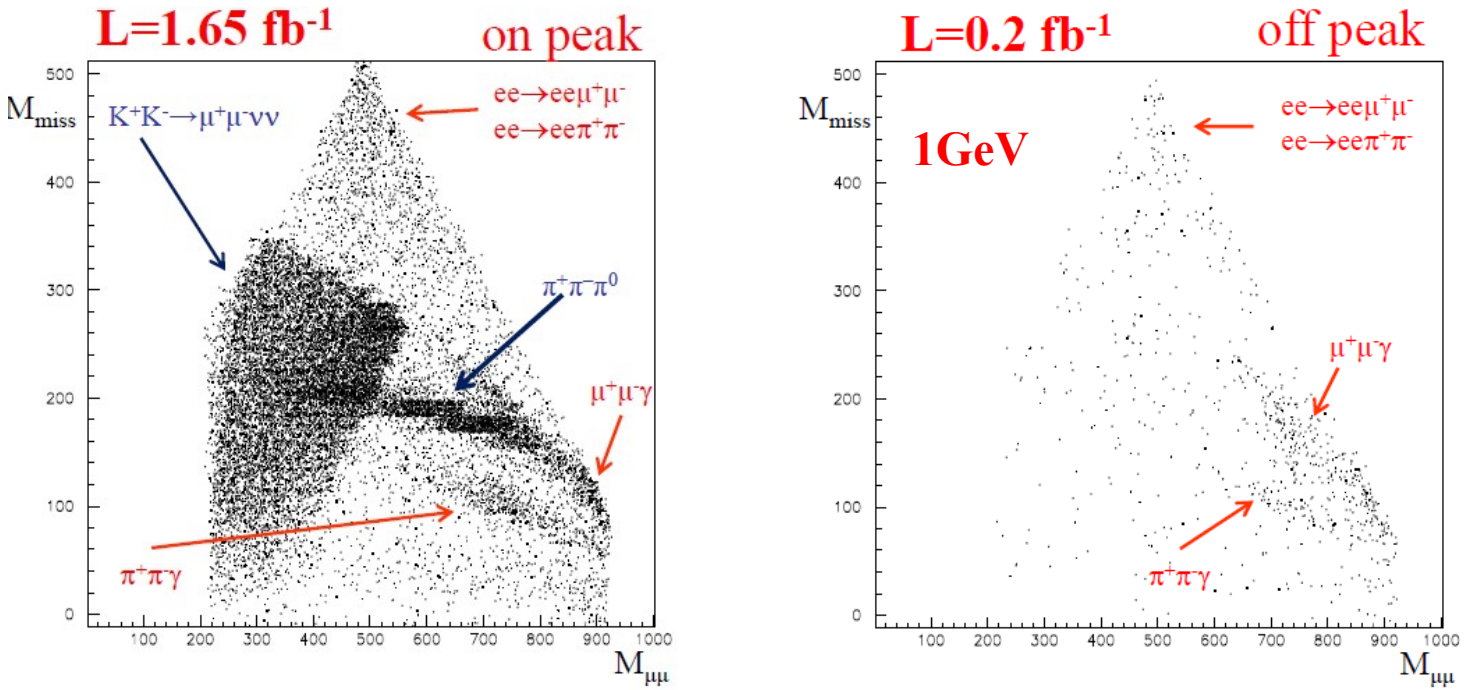
$\varepsilon \sim 10^{-3}$
$\alpha_D = \alpha_{e.m.}$
$m_{h',u} \sim 100$ MeV

⇒ $\tau_h \sim 5\mu s$

decay length > 100 m (increasing with decreasing ε)
Higgs invisible up to $\varepsilon \sim 10^{-2} - 10^{-1}$ depending on $m_{h'}$
final state signature: 2 muons+missing energy

Event selection:
events with only two opposite charge tracks, with a reconstructed vertex inside a 4×30 cm cylinder around the interaction point;
- each track must have an associated EMC cluster;
- the visible momentum direction has to be in the barrel: $|\cos\theta| < 0.75$;
- the momenta of the two tracks must be individually below 460 MeV;
- the modulus of the missing momentum must exceed 40 MeV.

U boson searches @ KLOE: $e^+e^- \to h'U \to h'\mu^+\mu^-$

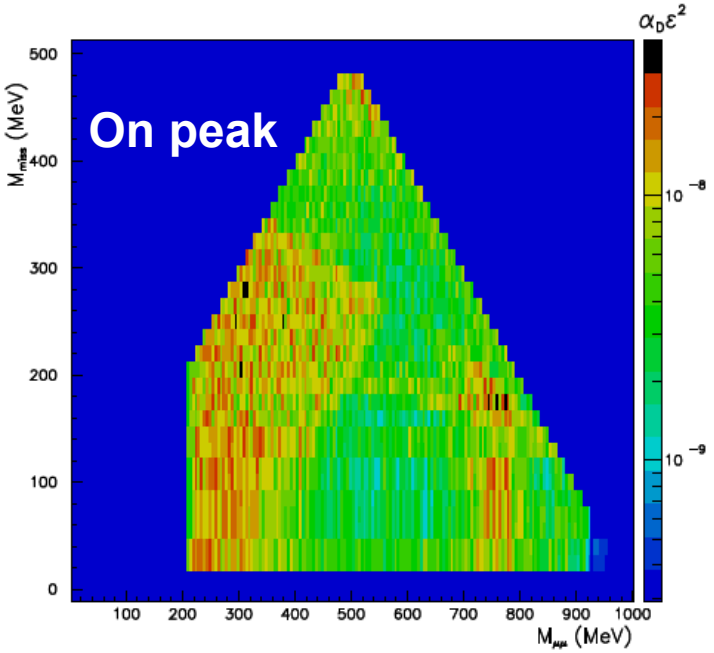


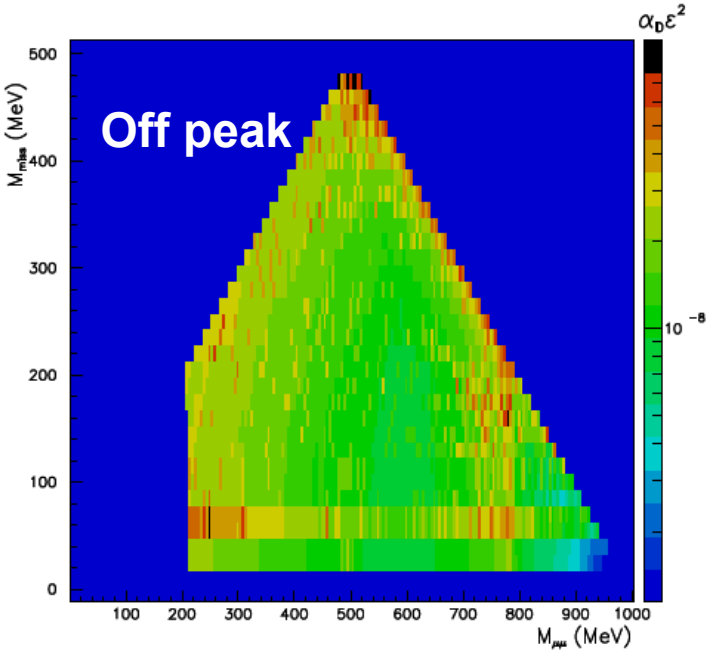
UL evaluation:

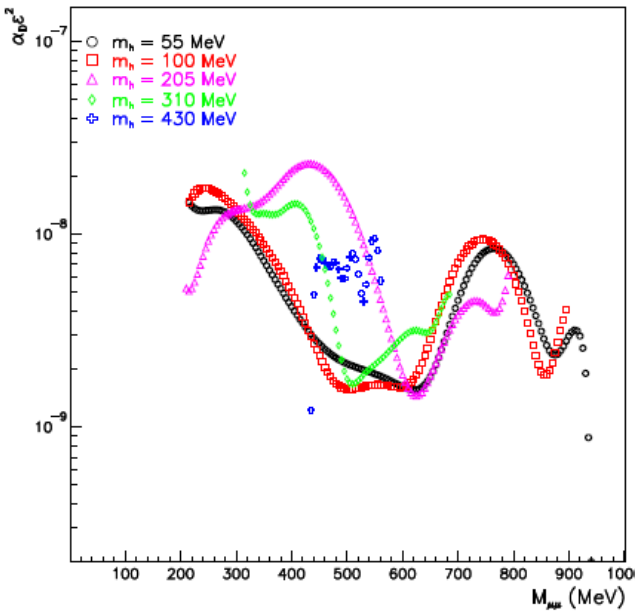
90% confidence level Bayesian upper limits on the number of events were derived bin by bin, separately for the on peak and off peak samples. Results were then converted in terms of the dark Higgstrahlung production cross section parameters, $\alpha_D \times \varepsilon^2$, by using:

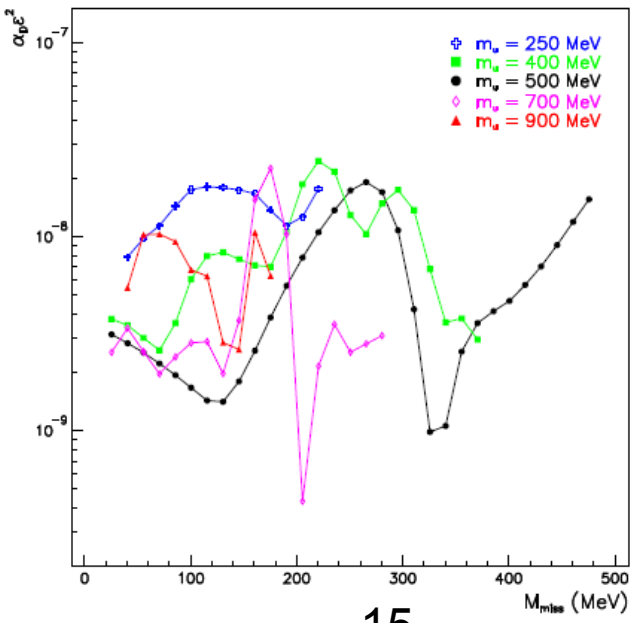
- the integrated luminosity information;
- the signal efficiency;
- the dark Higgsstralung cross section and the branching fraction of the U boson decay into muon pairs (as in B. Batell, M. Pospelov, A. Ritz Phys. Rev D, 79 (2009), p. 115008)

U boson searches @ KLOE: $e^+e^- \to h'U \to h'\mu^+\mu^-$



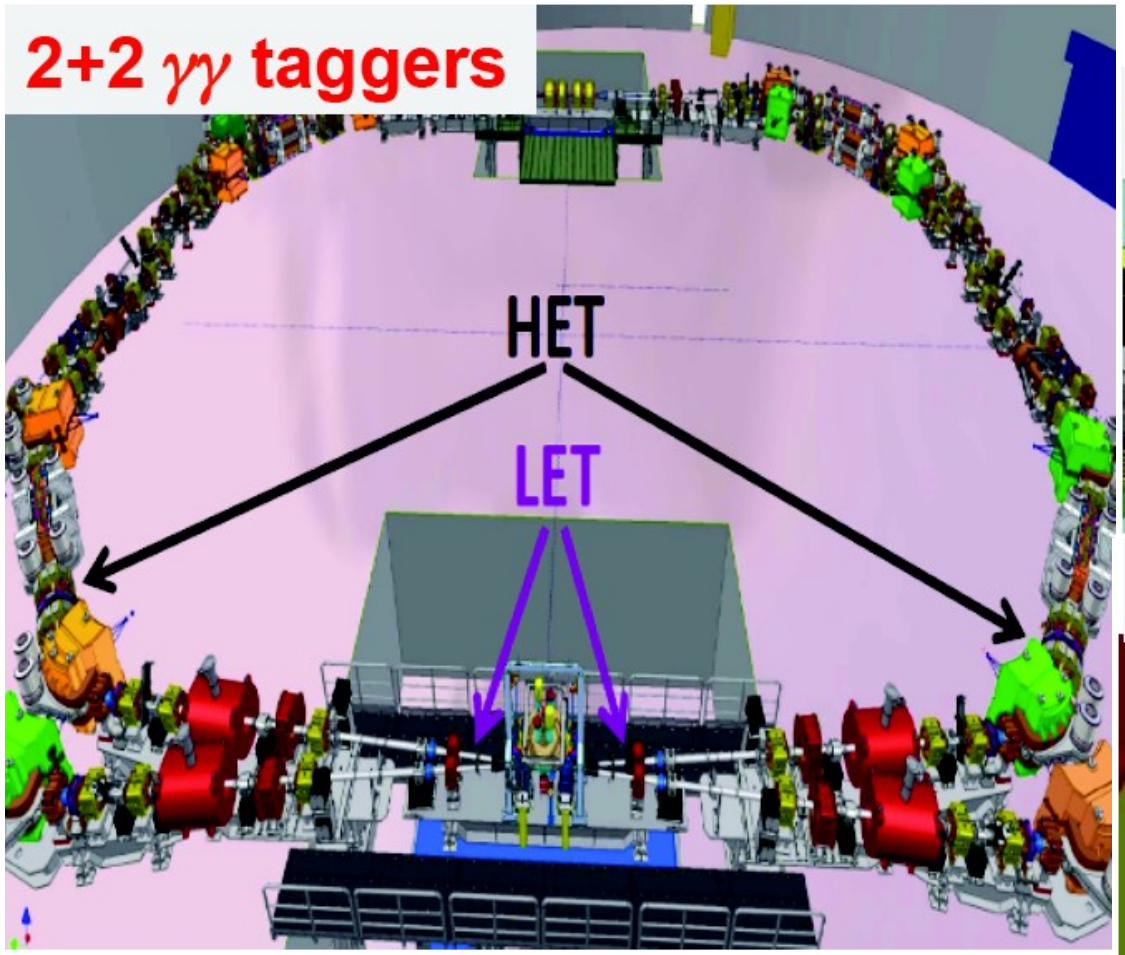


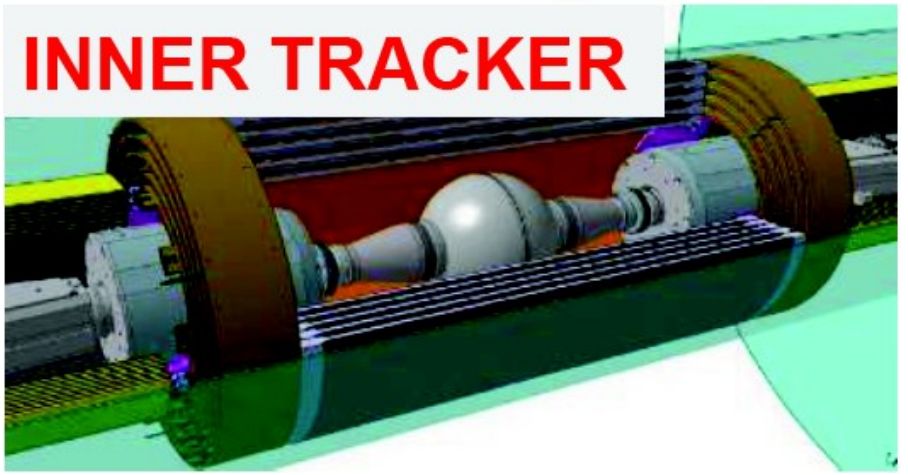


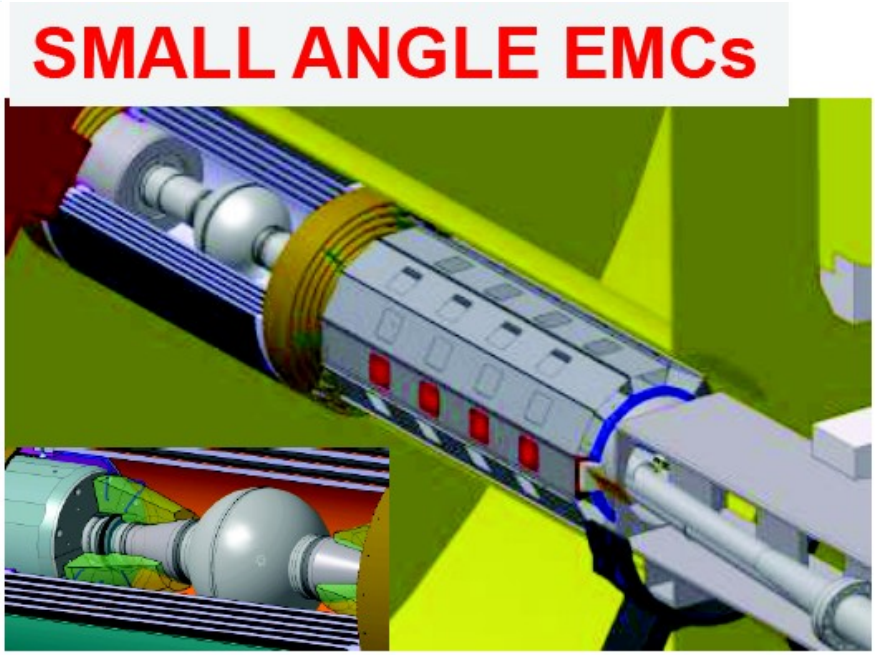


Combined UL
calculated by taking into account:
- the different integrated luminosities of the two samples
-different signal efficiencies and cross sections
Values of order of $10^{-9} \div 10^{-8}$ in $\alpha_D \times \varepsilon^2$ are excluded at 90% CL for a large range of the dark photon and dark Higgs masses.

Perspectives: from KLOE to KLOE2



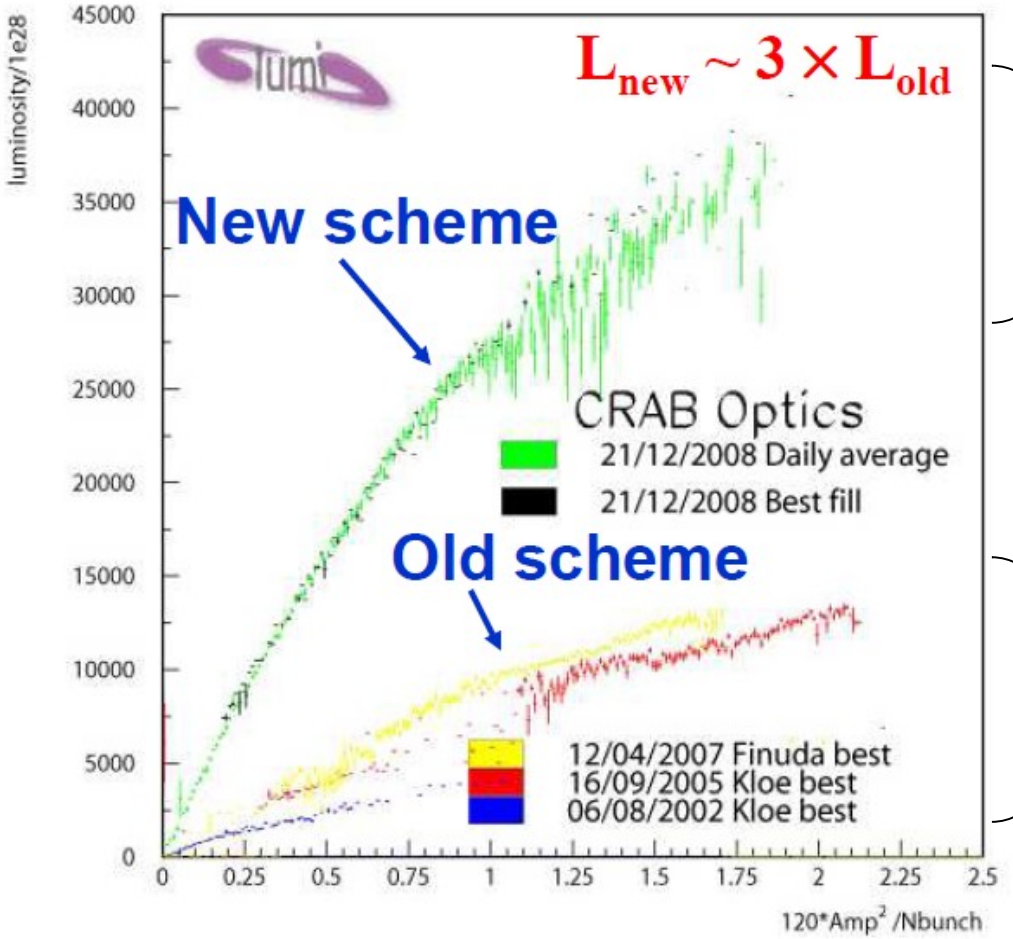




The KLOE-2 IT detector
will provide **two-track vertex position** with an
accuracy of 1-2 mm

Perspectives: DAΦNE Upgrades

DAΦNE: new interaction scheme with large beam crossing angle + sextupoles for crabbed waist optics



SIDDHARTA runs (2008-09)

KLOE runs (2002-2005)

DAΦNE run for KLOE2 scheduled for late summer

Conclusions

- KLOE/KLOE2 experiment at DAΦNE facility is well suited to the U boson search in a wide range of masses and by exploring different production mechanism (Uγ events, Φ Dalitz decay, higgs strahlung)

- No U boson evidence in the investigated mass ranges with the available luminosity was found and upper limits were set by analyzing three different U boson production processes

- All searches in an advanced status:
  - Φ Dalitz decay UL published: PLB 720 (2013) 111-115
  - $e^+e^- \rightarrow \mu^+\mu^-\gamma$ UL close to paper submission (need UL extension below 0.6 GeV)
  - Higgs strahlung UL close to paper submission (need to improve description of γγ physics background)

- KLOE2 and DAΦNE upgrades will give us the possibility to improve our upper limits

Thank you
for your attention!