Search of Dark Photons in KLOE

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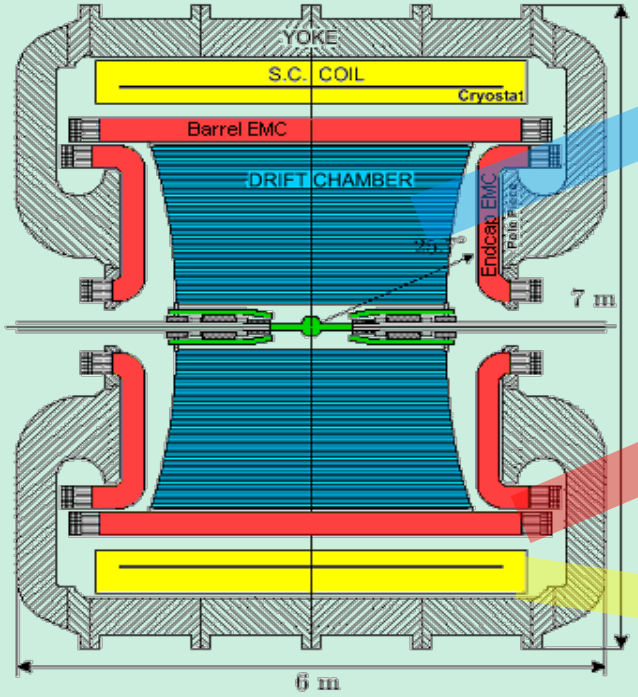
on behalf of the KLOE-2 Collaboration

Light Dark Matter @ Accelerators
La Biodola, 24 – 28 May 2017

Outline

- KLOE and KLOE-2
- Dark photon searches at KLOE
  - ϕ meson decays
  - associated $e^+e^- \rightarrow U\gamma$ production
  - Higgs-strahlung
- Perspectives @ KLOE-2
- Conclusions

The KLOE experiment



Drift chamber

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

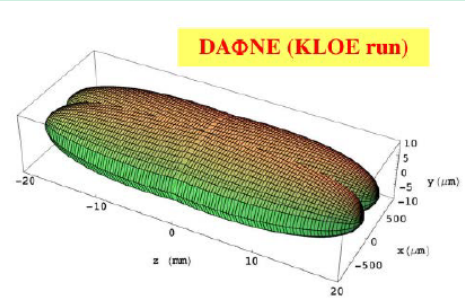
- The KLOE experiment at the DAΦNE ϕ-factory took data in 2001-2006
- 2.5 fb^{-1} integrated @ 1.02 GeV, 250 pb^{-1} @ 1 GeV
- Excellent quality data set for precision measurements on:
  - ✓ Kaon physics
  - ✓ Light meson spectroscopy
  - ✓ Hadron production in $\gamma\gamma$ collisions
  - ✓ Search for dark force mediator
  - ✓ $\pi^+\pi^-$ contribution to $(g-2)_\mu$

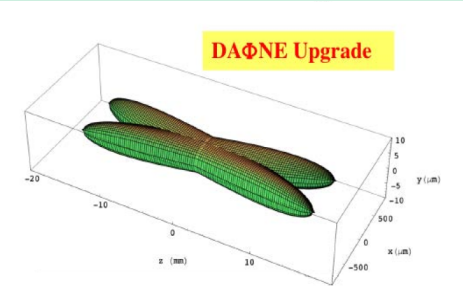
ϕ decay	Events/fb^{-1}
K^+K^-	1.5×10^9
K_LK_S	1.0×10^9
η	5×10^7
η′	2×10^5

KLOE-2 run

DAΦNE: new interaction scheme

- Large angle beam crossing
- Crabbed waist sextupoles





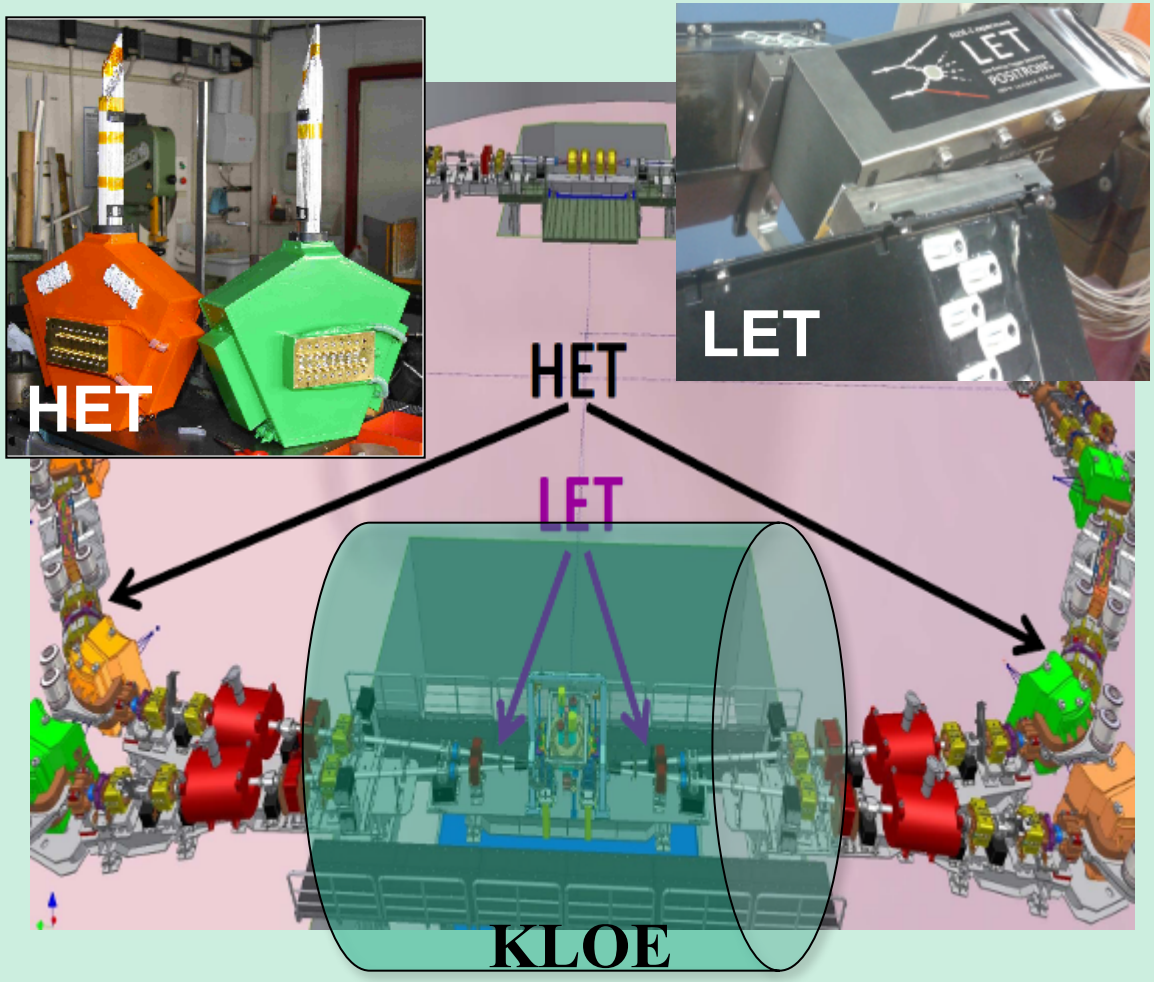
KLOE-2:

- Detector upgrade ($\gamma\gamma$ taggers + GEM inner tracker + low-θ EMCs)
- Extension of the KLOE physics program [Eur. Phys. J. C 68 (2010), 619]

- **KLOE-2 run since November 2014**
- **Expected $\geq$ 5 fb^{-1} by the end of March 2018**
- **DAΦNE performances: L_{ave} ~ 1.5 × 10^{32} cm^{-2}s^{-1}, L_{int} ~ 10 pb^{-1}/day**
- **Background levels much higher than in the past**
- **KLOE-2 detectors operational**
- **More than 3.7 fb^{-1} data collected**

The KLOE-2 upgrade: γγ taggers

2+2 γγ taggers installed inside/outside the detector
Measurement of lepton momenta in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$



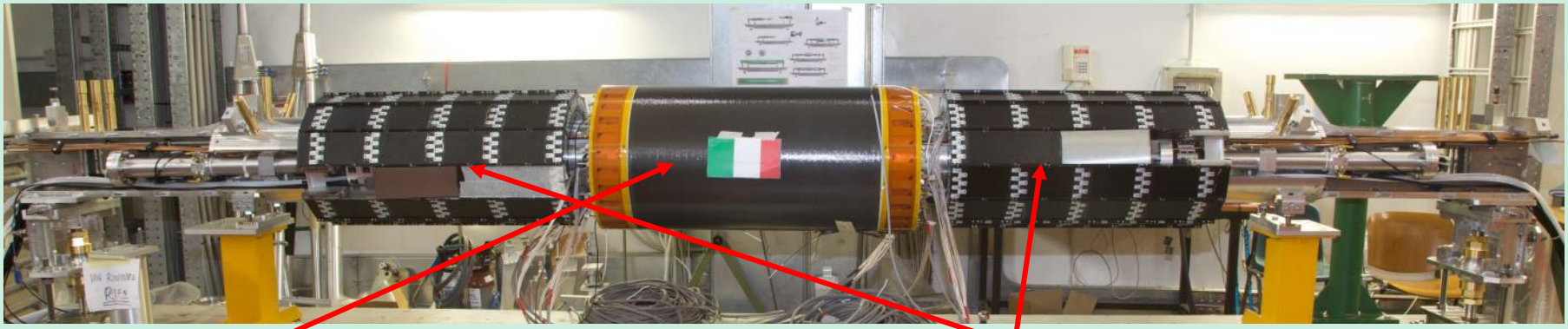
LET : E=160–230 MeV

- Inside KLOE detector
- LYSO+SiPM
- σ_E<10% for E>150 MeV

HET : E > 400 MeV

- 11 m from IP
- Scintillator hodoscopes
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps

The KLOE-2 upgrade: IR region



INNER TRACKER

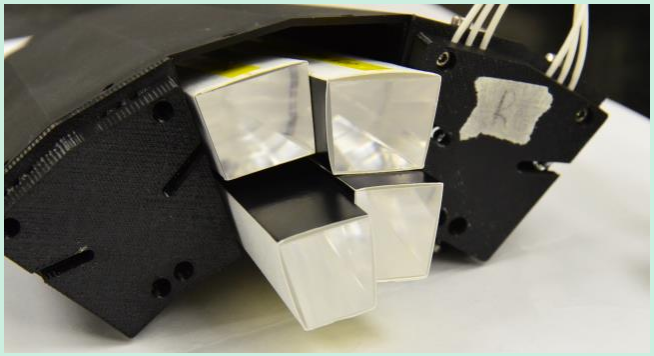
- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

QCALT

- W + scintillator tiles + WLS/SiPM
- QUADS coverage for K_L decays

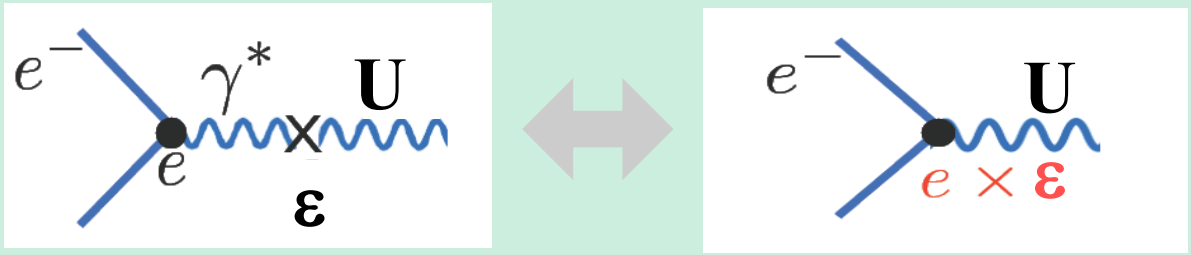
CCALT

- LYSO + SiPM
- Increase acceptance for γ's from IP ($21^o \rightarrow 10^o$)



Low energy dark forces

Hidden gauge sector weakly coupled with SM through a mixing mechanism of a new **gauge boson (U, A', V…)** with the photon:



$$\varepsilon^2 = \frac{\alpha'}{\alpha_{em}}$$

$$\mathcal{L}_{mix} = \frac{\varepsilon}{2} F^{e.m.}_{\mu\nu} F^{\mu\nu}_{dark}$$

- ✗ U mass range: **1 MeV – few GeV**
- ✗ Coupling constant of electric charge to U: $\varepsilon \leq 10^{-3}$
- ✗ U production through photon mixing
- ✗ U decay modes:
  - visible decays (U → e^+e^- / $\mu^+\mu^-$ / $\pi^+\pi^-$ / …) through another photon mixing
  - invisible decays (U → $\chi\chi$)

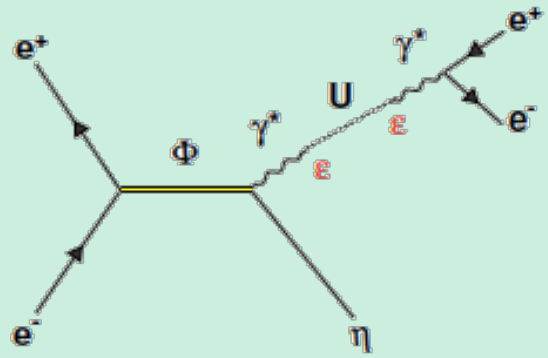
Observable @ low energy colliders

Dark Photon @ KLOE

Minimal hypothesis: visible and prompt U decays

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

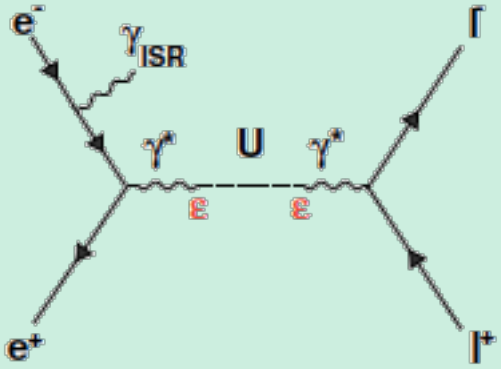
  Peculiar of a light meson factory



- **e^+e^- collisions**: $e^+e^- \to U\gamma \to \ell^+\ell^-\gamma/\pi^+\pi^-\gamma$

  x-sec ∝ 1/s

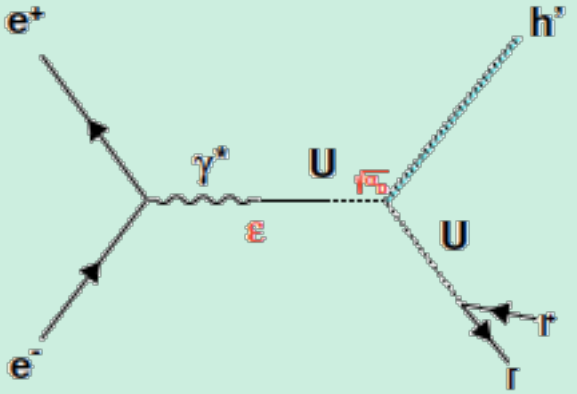
  100 times higher at DAΦNE w.r.t. b-factories
  Compensate lower luminosities



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

  If the hidden symmetry is spontaneously broken by a Higgs-like mechanism, the existence of at least one other scalar particle, the *h′*, can be postulated

  Can be observed @ KLOE if $m_U + m_h < m_\phi$



Dark Photon @ KLOE: $\phi \to \eta U$

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

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

Irreducible background: ϕ Dalitz decay $\phi \to \eta\gamma^* \to \eta l^+ l^-$ ($\sigma = 0.7$ nb)

$X \to YU$	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}

VMD

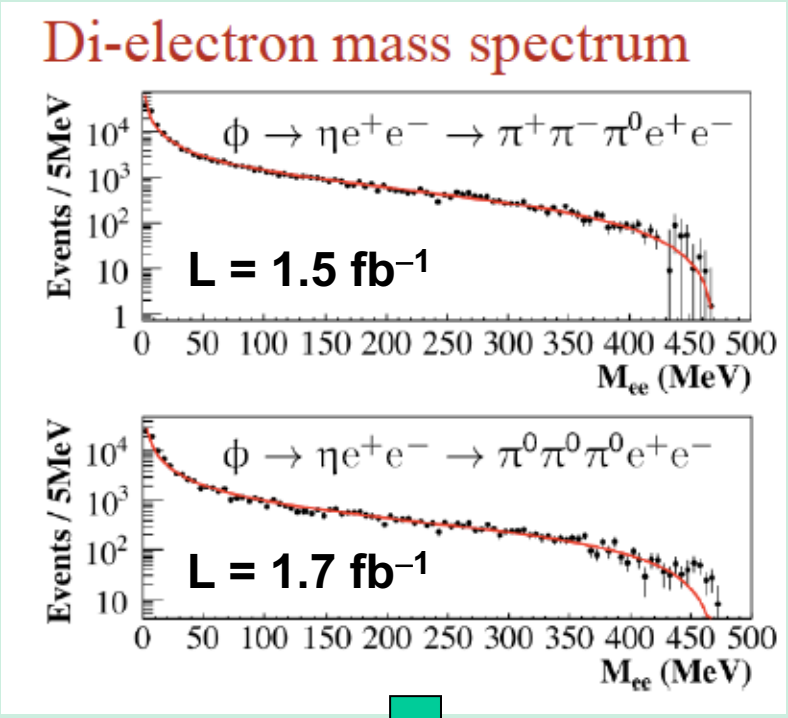
All KLOE stat.
All decay chains

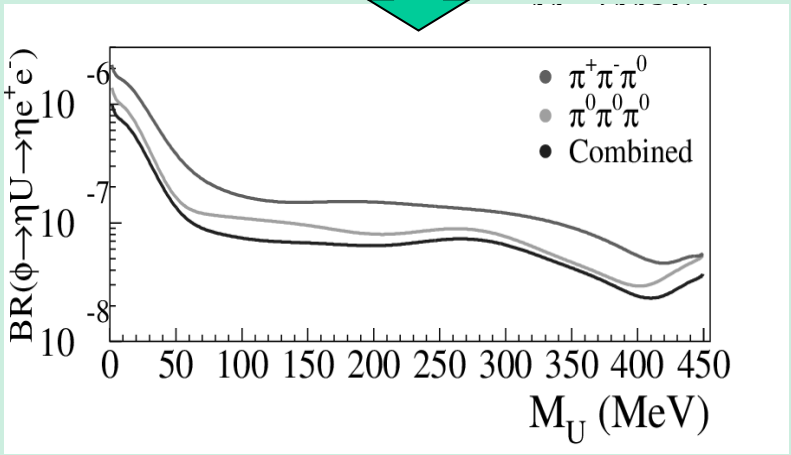
[M.Reece and L.T.Wang, JHEP 0907:051 (2009)]

Selected decay chains: $U \to e^+e^-$ + $\eta \to \pi^+\pi^-\pi^0$ (BR = 22.7%) PLB 706 (2012) 251

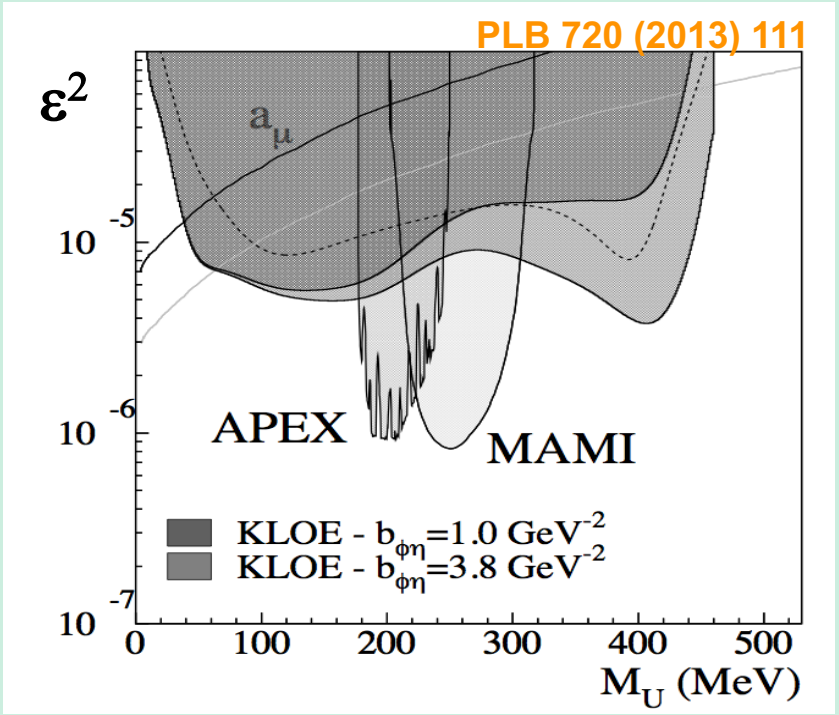
$\eta \to \pi^0\pi^0\pi^0$ (BR = 32.6%) PLB 720 (2013) 111

$\phi \to \eta U$ search: $U \to e^+e^-$, $\eta \to \pi\pi\pi$





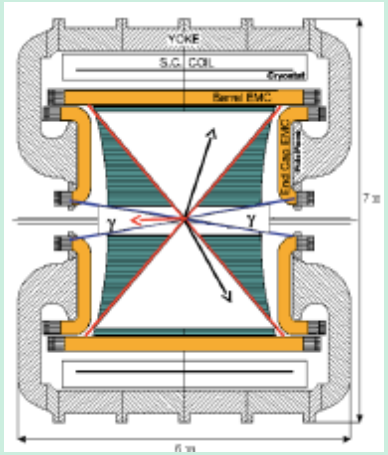
- ✗ No clear signal above background ➪ UL
- ✗ $\phi \to \eta e^+e^-$ bckg from fit to M_{ee} sidebands
- ✗ For each M_U value, 1 MeV step, signal hypothesis excluded @ 90% C.L. using CL_S method (bckg error included)

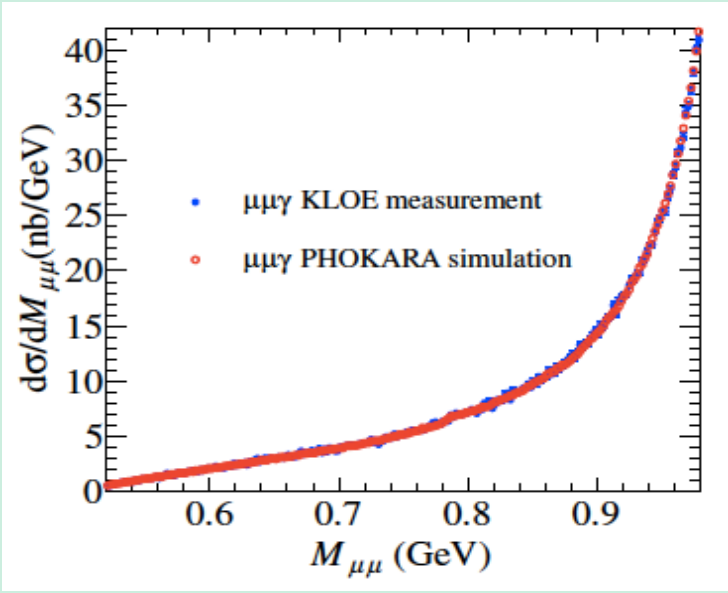


ε^2 **<1.5×10^{-5} ÷ 5.0×10^{-6}** @ 90% C.L. for 30<M_U<420 MeV

U boson search in $e^+e^- \to \mu^+\mu^-\gamma$

- ✗ Results based on 240 pb^{-1}
- ✗ Undetected small angle photon (θ_γ<15°, θ_γ>165°)
- ✗ Two opposite sign charged tracks (50°<θ_μ<130°)
  - significant reduction of ϕ resonant and FSR bckg
  - high statistics ISR signal
- ✗ Good π/μ separation from kin. cuts
- ✗ Bckg. from PHOKHARA NLO QED





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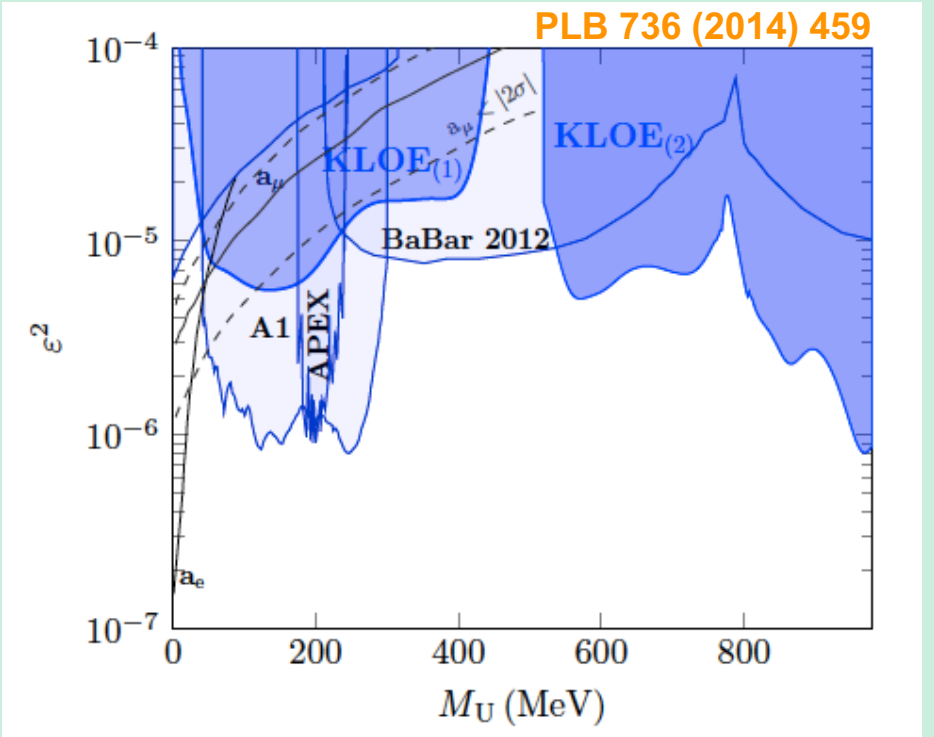
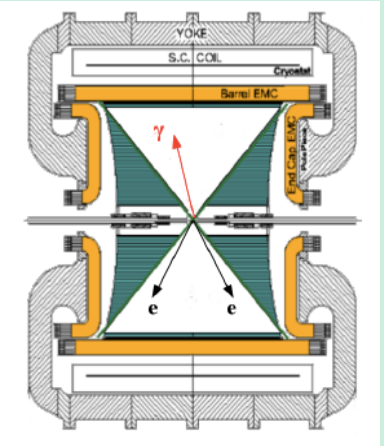
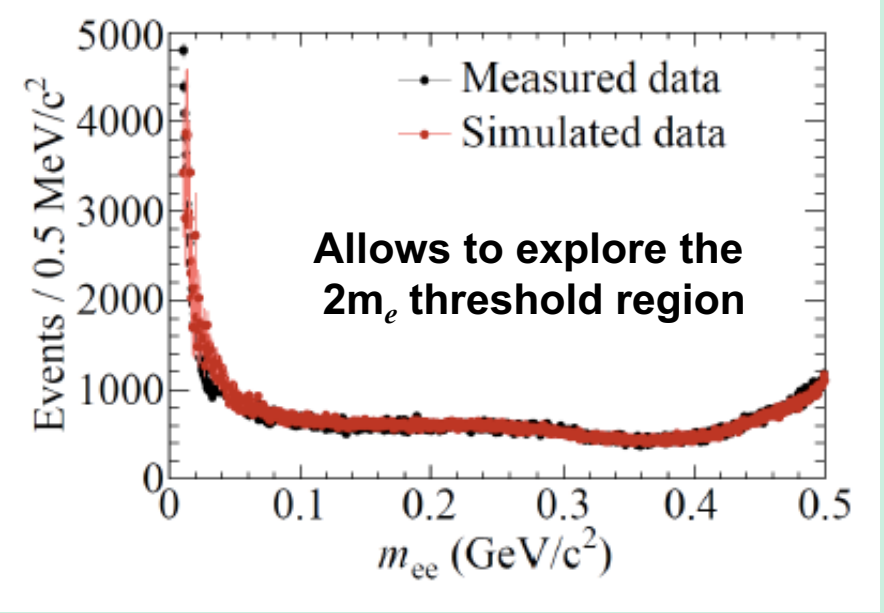


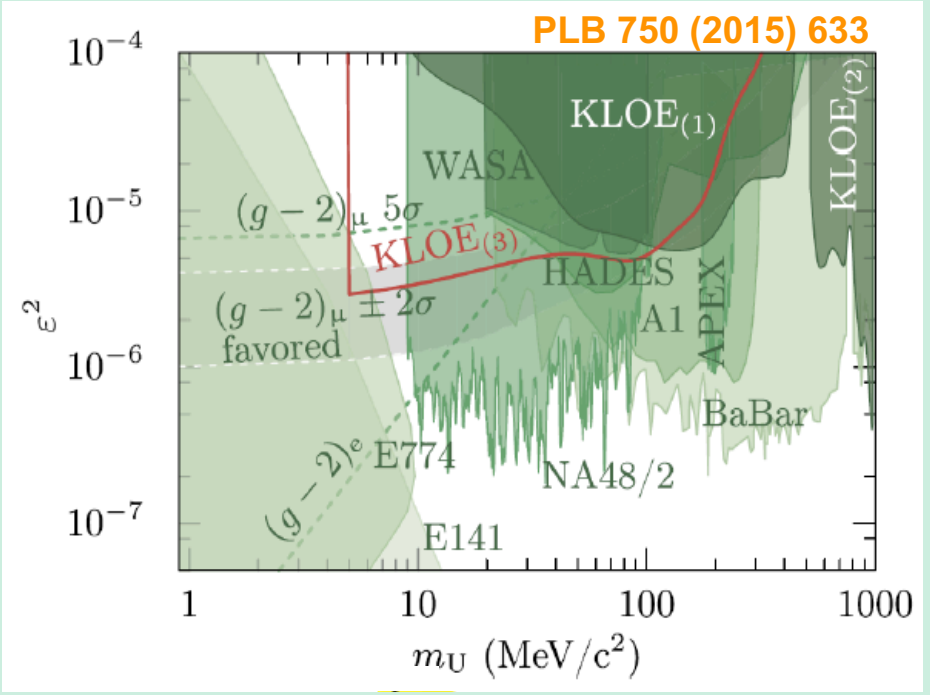
$\varepsilon^2 < 1.6\times10^{-5} \div 8.7\times10^{-7}$ @ 90% C.L. for $520 < M_U < 980$ MeV

U boson search in $e^+e^- \to e^+e^-\gamma$

- ✗ Results based on 1.54 fb^{-1}
- ✗ Detected large angle photon ($50° < \theta_\gamma < 130°$)
- ✗ Two opposite sign charged tracks ($55° < \theta_\mu < 125°$)
  - high statistics radiative Bhabha events (bckg<1%)
- ✗ High π/μ rejection from kin. cuts
- ✗ Bckg. from data sidebands



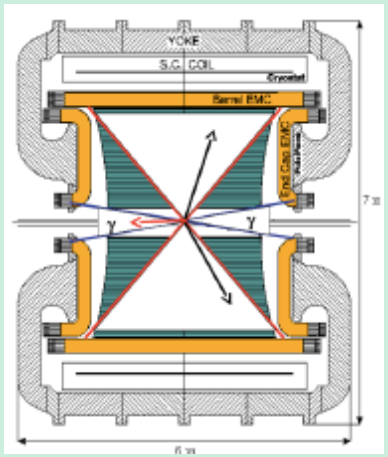


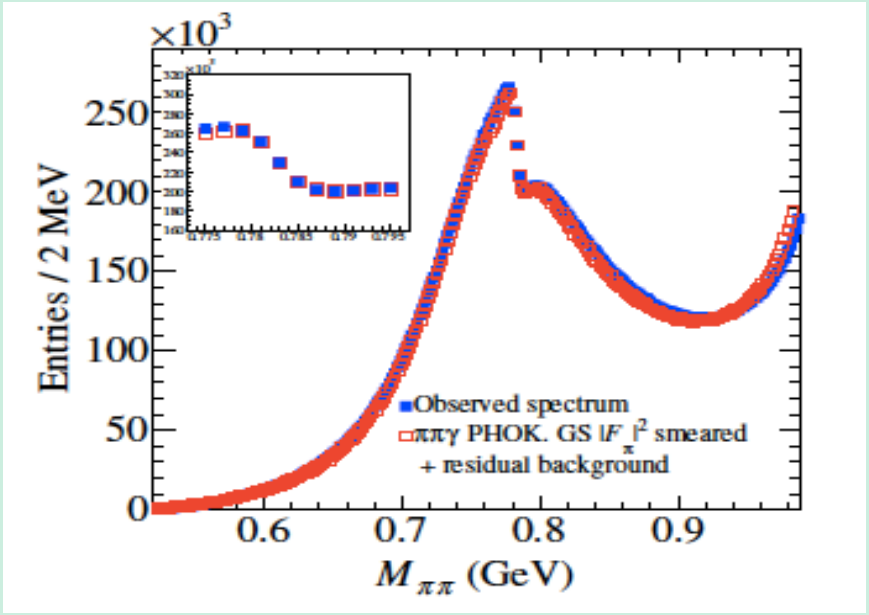


$\varepsilon^2 < 10^{-4} \div 4\times10^{-6}$ @ 90% C.L. for
$5 < M_U < 520$ MeV

U boson search in $e^+e^- \to \pi^+\pi^-\gamma$

- ✗ Results based on 1.93 fb^{-1}
- ✗ Undetected small angle photon (θ_γ<15°, θ_γ>165°)
- ✗ Two opposite sign charged tracks (50°<θ_μ<130°)
  - significant reduction of ϕ resonant and FSR bckg
  - high statistics ISR signal
- ✗ Good π/μ separation from kin. cuts
- ✗ Bckg. from sidebands





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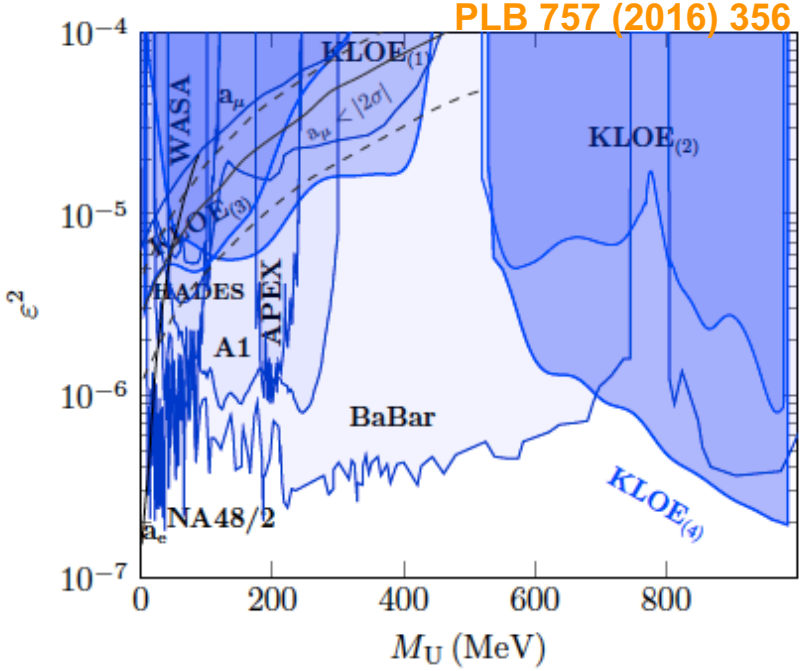
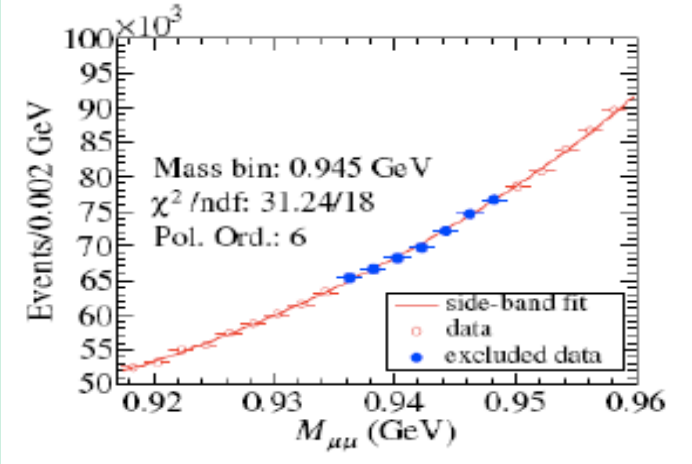
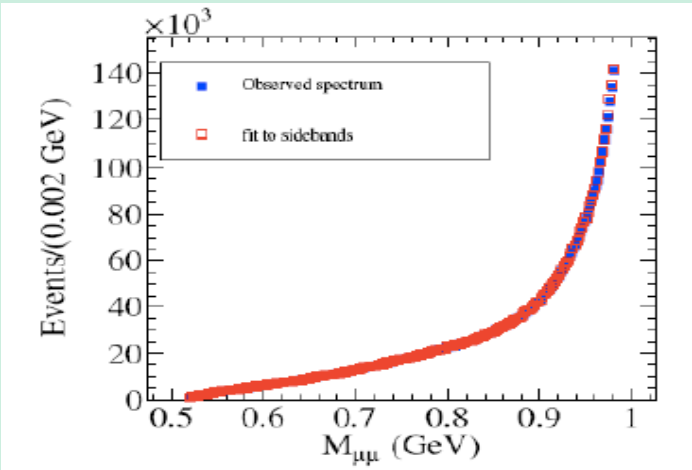


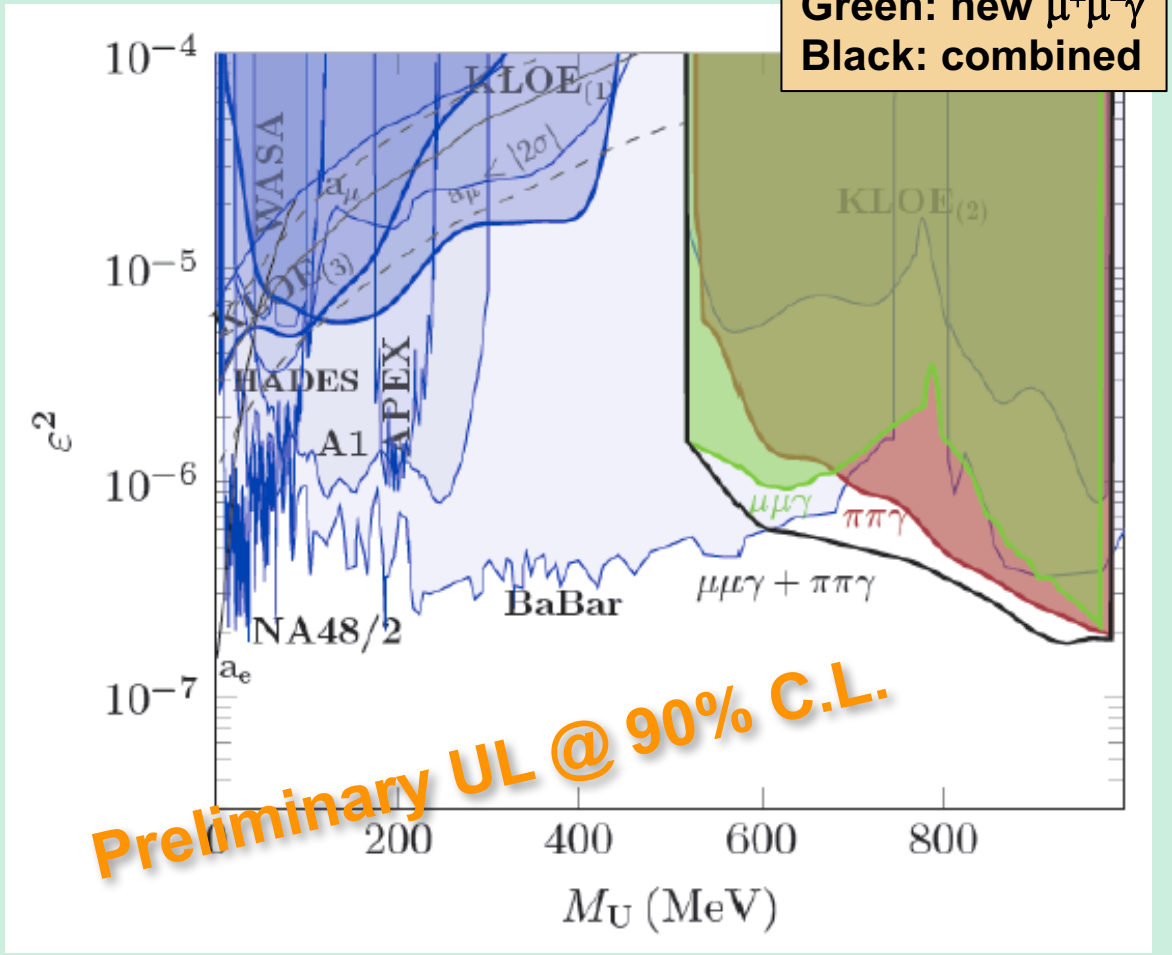
$\varepsilon^2 < 1.8\times10^{-5} \div 1.9\times10^{-7}$ @ 90% C.L. for $527 < M_U < 987$ MeV

Combined search: $e^+e^- \to \mu^+\mu^-\gamma/\pi^+\pi^-\gamma$

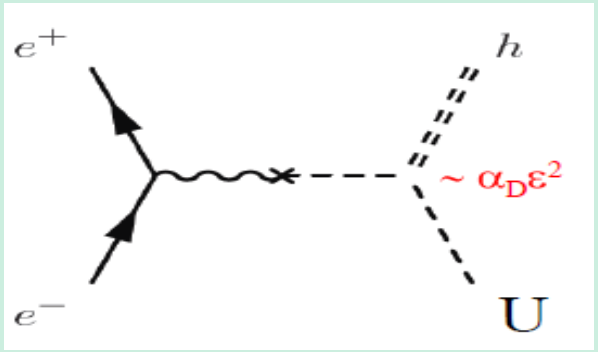
- ✗ $U \to \mu^+\mu^-$ search extended to the whole KLOE data set (1.93 fb^{-1})
- ✗ Analysis similar to $e^+e^- \to \pi^+\pi^-\gamma$ (bckg fitting sidebands of the observed spectrum)







Dark photon @ KLOE: *h′*-strahlung



$$m_h > 2\,m_U : h' \rightarrow UU \rightarrow 4l/\ldots$$

$$m_h < 2\,m_U : h' \rightarrow \text{“invisible”}$$

$\varepsilon = 10^{-3}$
$\alpha_D = \alpha$
$m_{U,h} \sim 100$ MeV

$\tau_h \sim 5\ \mu s$

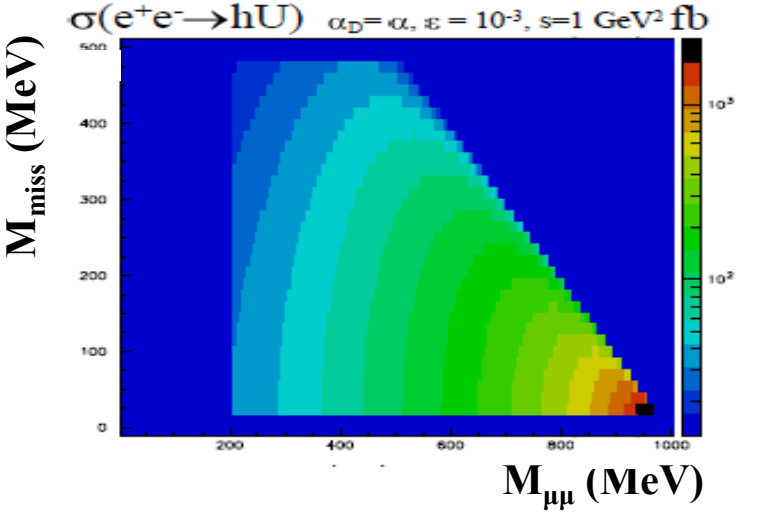
$$\sigma \approx 20\,fb \times \left(\frac{\alpha_D}{\alpha}\right)\left(\frac{\varepsilon^2}{10^{-4}}\right)\frac{10^2\,GeV^2}{s}$$

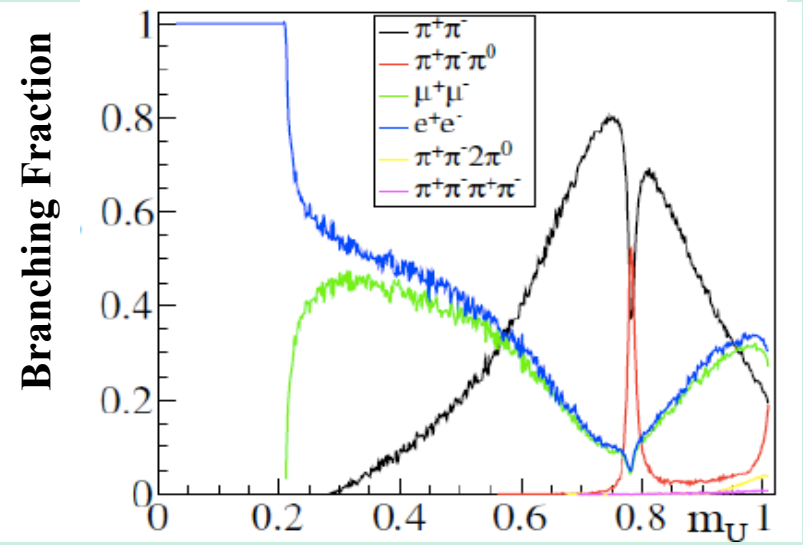
[B. Batell, M. Pospelov, A. Ritz: PRD79 (2009) 115008]

L_h > 100 m, increasing with decreasing ε

Higgs invisible up to $\varepsilon \sim 10^{-2} - 10^{-1}$, depending on m_h

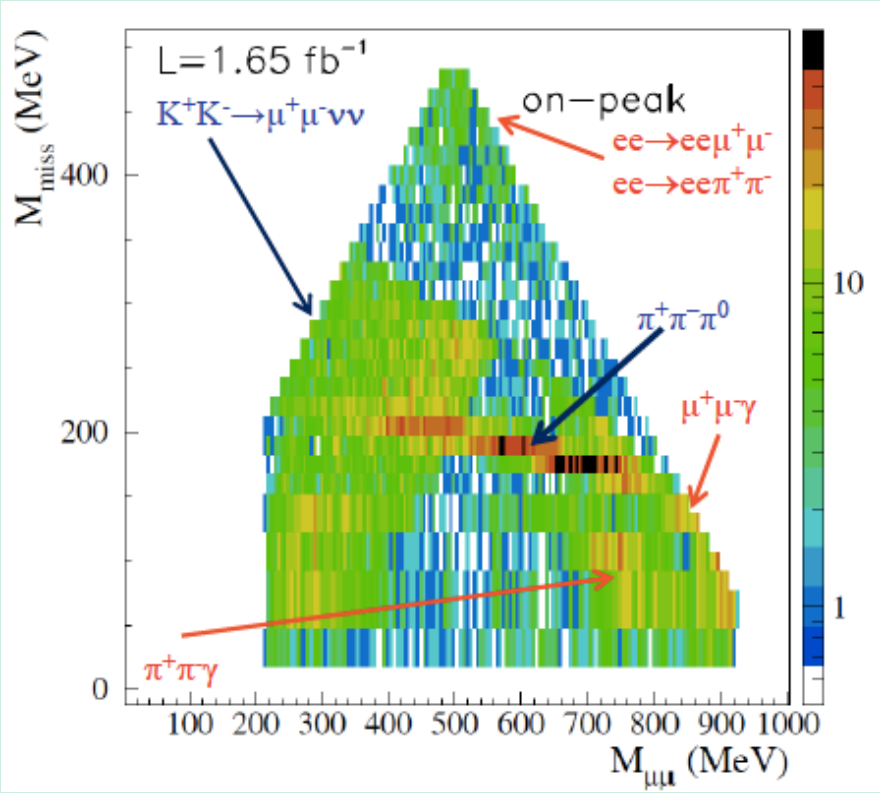
Signature: **U decay + missing energy**

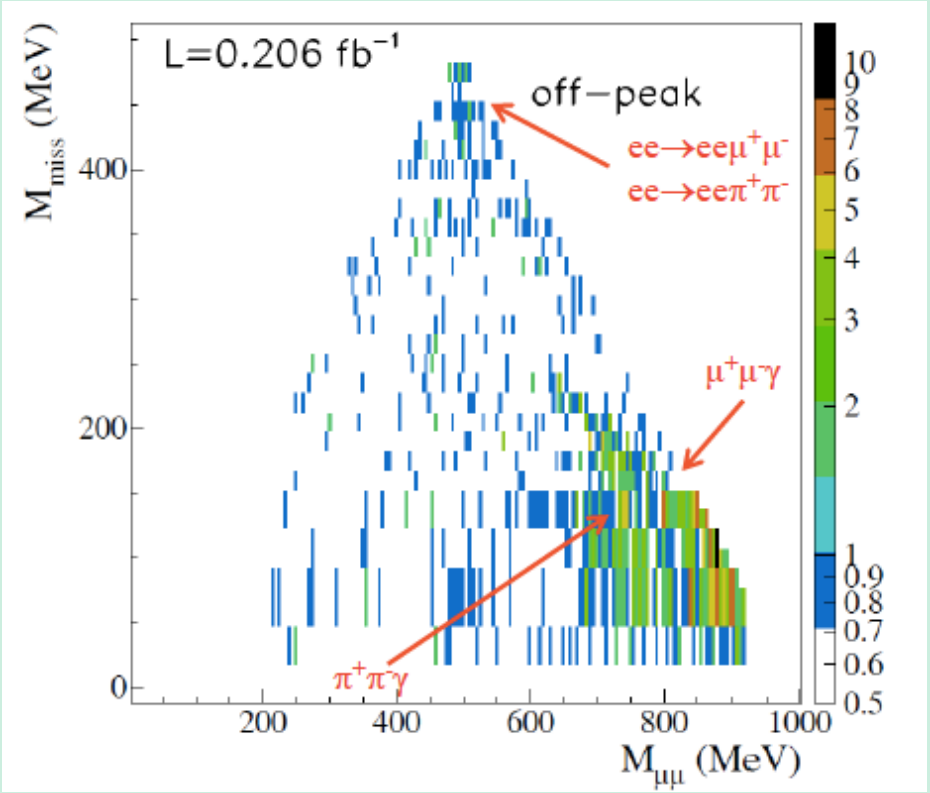




Dark photon @ KLOE: U → $\mu^+\mu^-$ + invisible

- Selected final state for $m_h < m_U$: $e^+e^- \rightarrow U(\rightarrow \mu^+\mu^-)$ + missing energy
- Analysis both on on-peak (1.65 fb^{-1}) and off-peak (0.2 fb^{-1}) data





Binning such as to keep 90-95% of the signal in one bin:

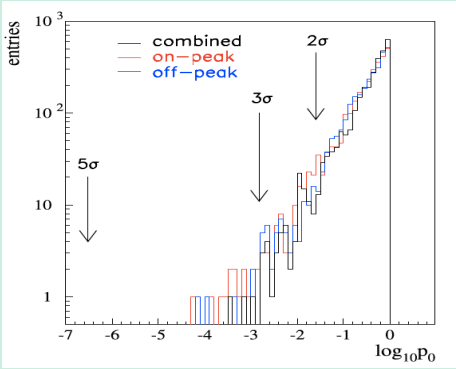
✗ 5 MeV bin in M_U

✗ 15 ÷ 50 MeV bin in M_h

Dark photon @ KLOE: U → $\mu^+\mu^-$ + invisible

Combined result from on peak and off peak data:
90% C.L. bayesian UL in the coupling-mass planes

p_0 value distributions show no significant excess



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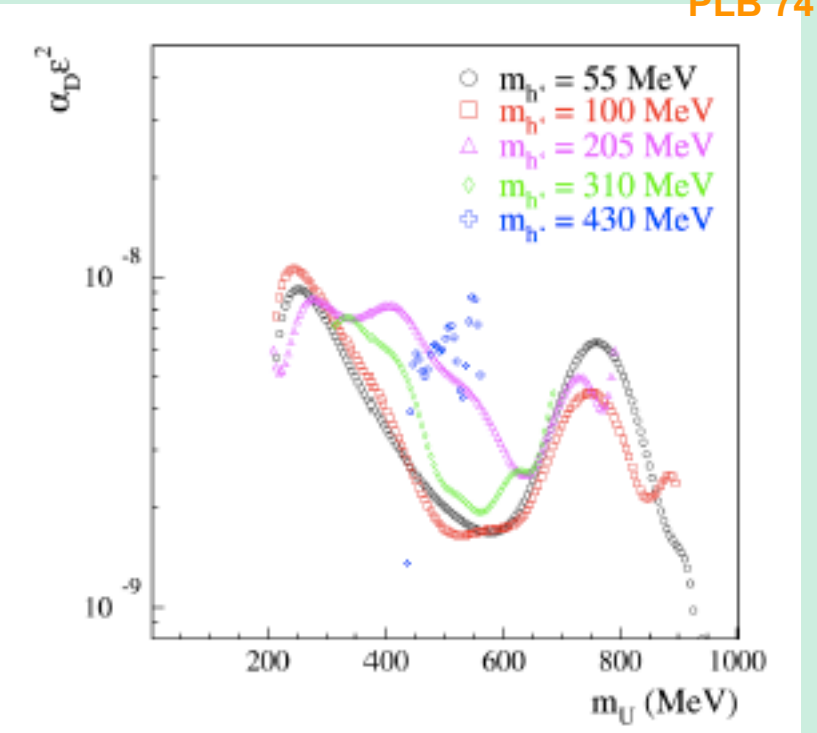
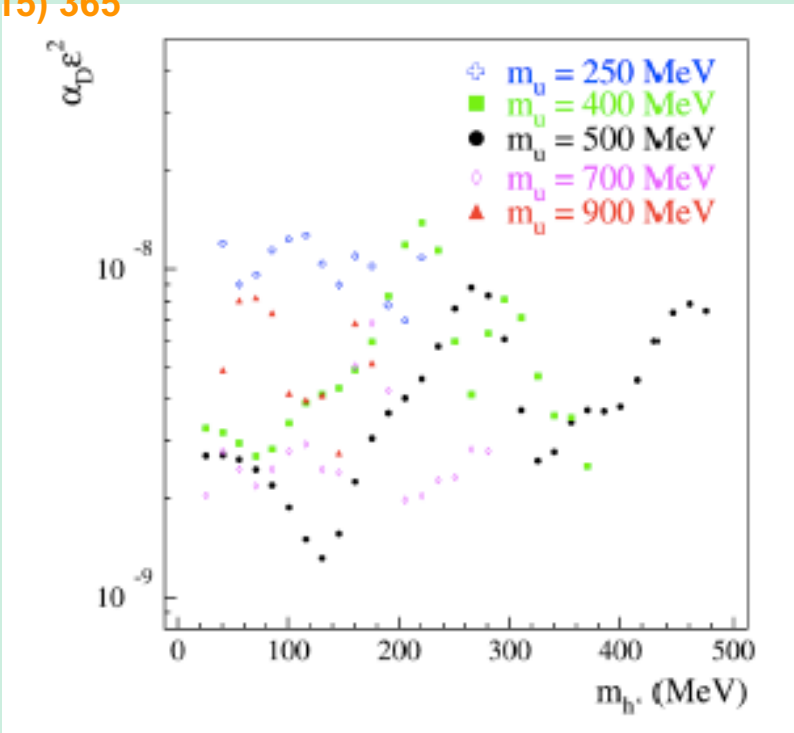


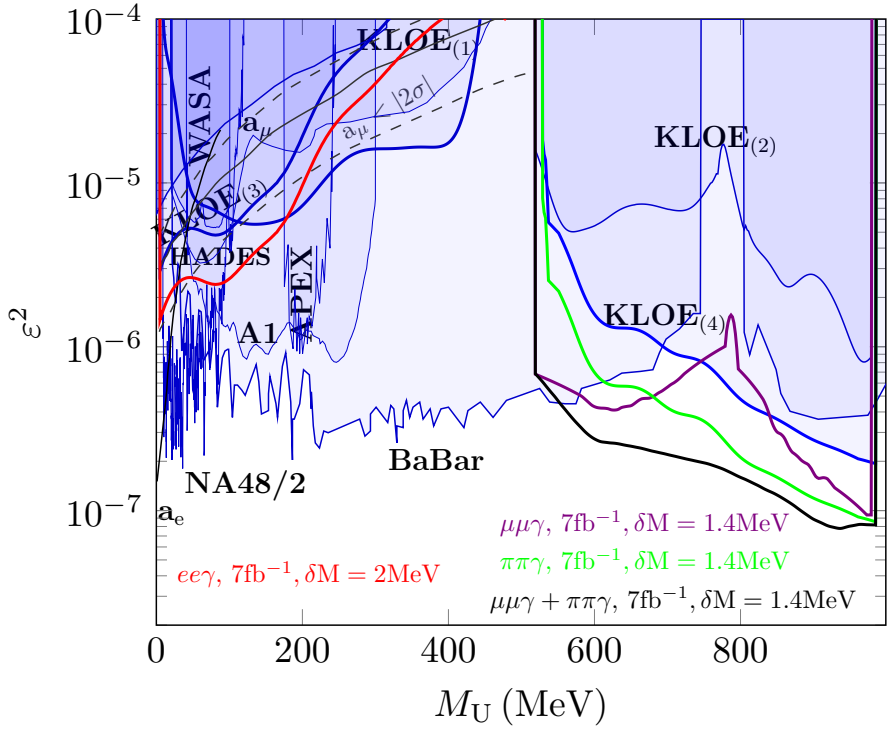


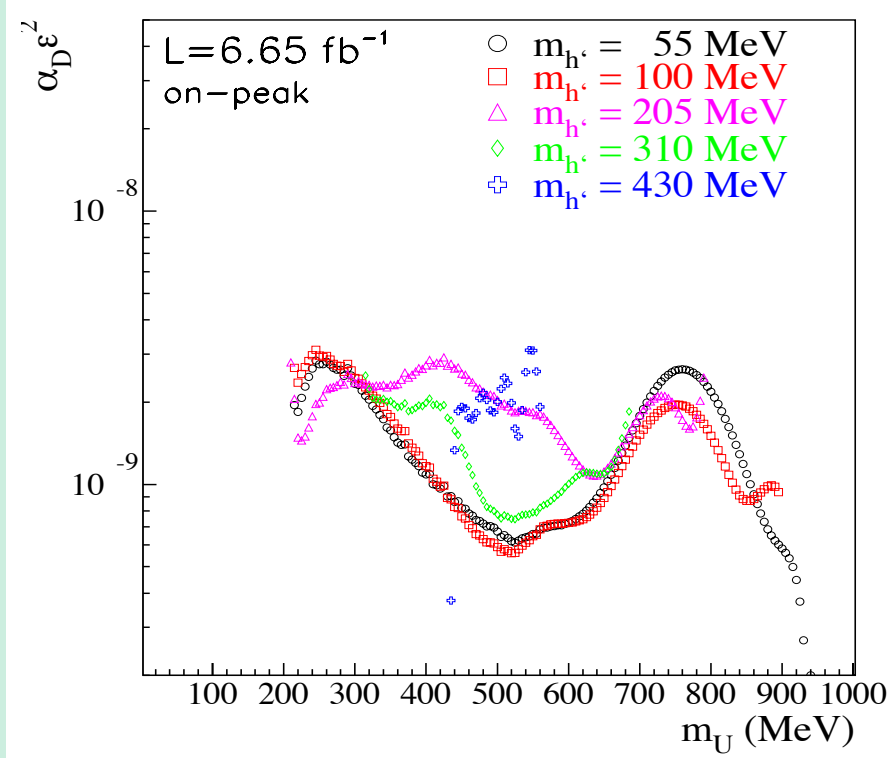
$\varepsilon^2 < 10^{-6} \div$ few 10^{-8} @ 90% C.L. if $\alpha_D=\alpha_{em}$

Dark photon @ KLOE-2

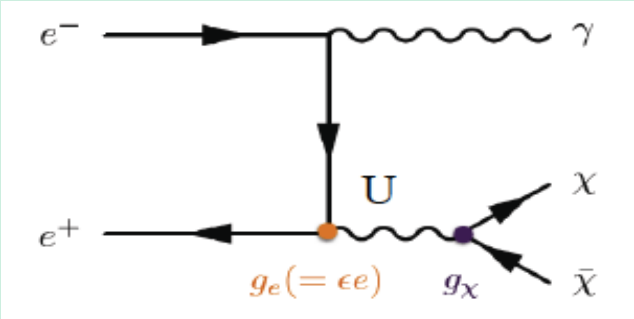
Projections for KLOE-2 assumes:

- ✓ L = 5 fb^{-1} fully available for analyses
- ✓ 30% improvement in mass resolution (S/B ratio)
- ✓ 2-3 improvement in vertex position ($K^{\pm}$ rejection)

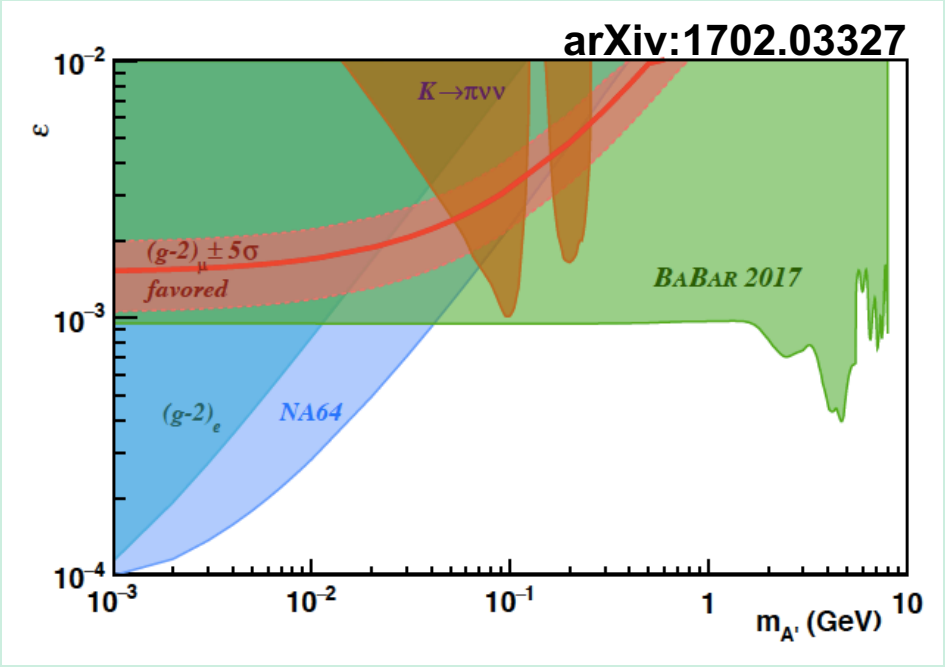




Dark photon @ KLOE-2: invisible decays



χ: very light dark matter



- ✗ Signature: monochromatic photon with $E_\gamma = (s\text{-}M_U^2) / 2\sqrt{s}$
- ✗ Single photon trigger (SPT) since end 2016, with a threshold of $E_\gamma \sim 350$ MeV (~ 570 MeV in M_U)
- ✗ L~2 fb^{-1} with SPT expected at the end of data taking
- ✗ The 100 times higher x-sec w.r.t. b-factories makes this search still interesting at KLOE-2
- ✗ Currently work in progress to reduce Touschek background

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Conclusion

- **KLOE search for dark gauge boson U exploits different channels**
  - ✓ $\phi \to \eta U$, with $\eta \to \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$ — PLB 706 (2012) 251 / PLB 720 (2013) 111
  - ✓ $e^+e^- \to U\gamma \to e^+e^-\gamma$ / $\mu^+\mu^-\gamma$ / $\pi^+\pi^-\gamma$ — PLB 736 (2014) 459 / PLB 750 (2015) 633, PLB 757 (2016) 356
  - ✓ $e^+e^- \to Uh' \to \mu^+\mu^-\gamma + E_{miss}$ — PLB 747 (2015) 365

  UL on the mixing parameter ε^2 ($\alpha_D\varepsilon^2$) in the range $10^{-5} \div 10^{-7}$, depending on the process and on the U (U/h′) mass

  - ➢ All measurements statistically dominated

- **KLOE-2 run in progress, 5 fb^{-1} of new data + improved tracking performances**
  - ✓ current limits will be improved by a factor 2 ÷ 3
  - ✓ Single Photon Trigger implemented for U → invisible search
  - ✓ search of leptophobic B boson in $\phi \to \eta B$, $B \to \pi^0\gamma$ and $\eta \to B\gamma$, $B \to \pi^0\gamma$ channels