Search for dark forces with KLOE

MESON 2016

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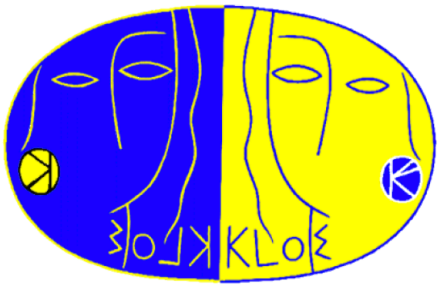

on behalf of the KLOE and KLOE-2 Collaborations

NATIONAL SCIENCE CENTRE
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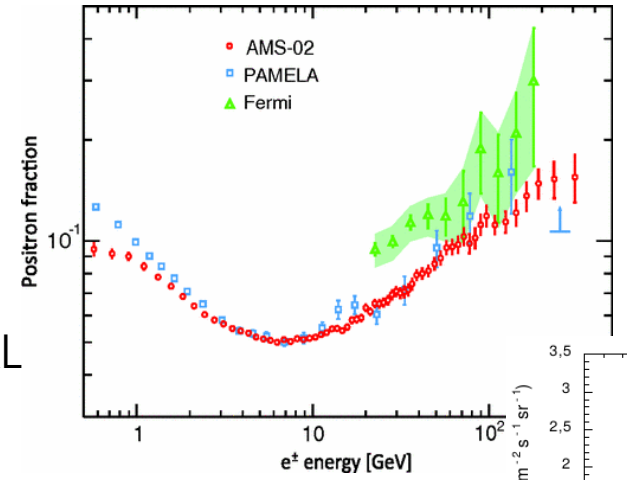
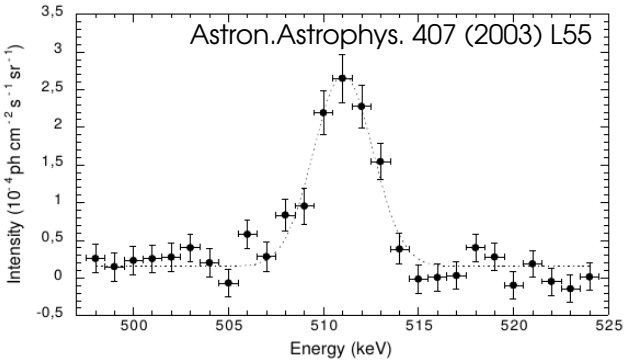
Motivation for dark forces' searches

Astronomy:

- positron excess in the cosmic ray flux
  - no similar effect for antiprotons
- 511 keV gamma ray signal from the galactic center seen by the INTEGRAL satellite
- the annual modulation measured by DAMA/LIBRA

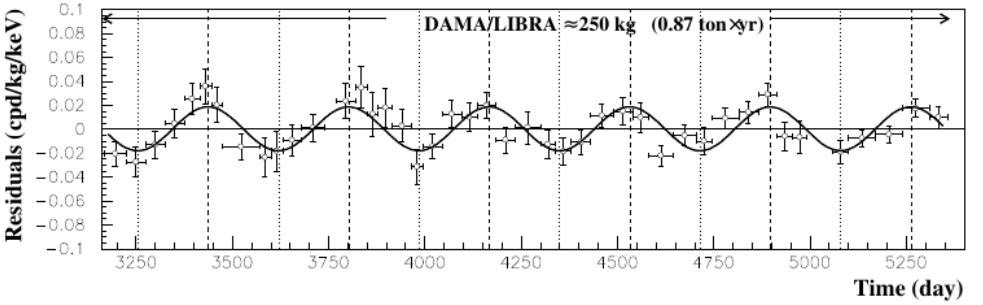


Phys.Rev.Lett 110 (2013) 141102



Particle physics:

- muon magnetic moment anomaly



Eur. Phys. J. C (2010) 67, 39-49

Proposed explanation:

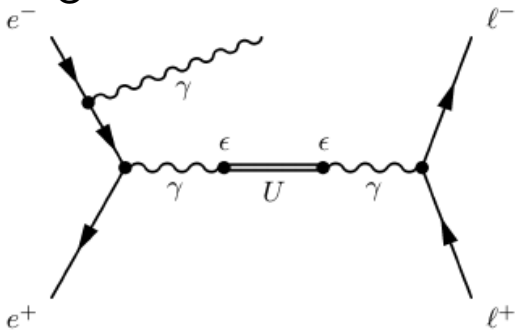
- Weakly Interacting Massive Particles charged under new type of inteaction
- new gauge interaction mediated by a new boson:

  the U boson (also known as dark photon)

The U boson (dark photon) and its searches

- gauge boson of the dark forces
- light vector boson
- could be produced in WIMP annihilations
- couples to an ordinary photon through small kinetic mixing

$$\mathcal{L} = -\frac{\varepsilon}{2} F_{ij}^{QED} F_{dark}^{ij}$$



$\varepsilon^2 = \alpha' / \alpha_{EM}$ – kinetic mixing parameter

$\varepsilon^2 \sim 10^{-8} - 10^{-3}$

=> effects observable in O(GeV) energy scale colliders!

Analogously to the SM:
Spontaneous breaking of the $U(1)_D$ symmetry

=> introduction of **dark Higgs (h')**

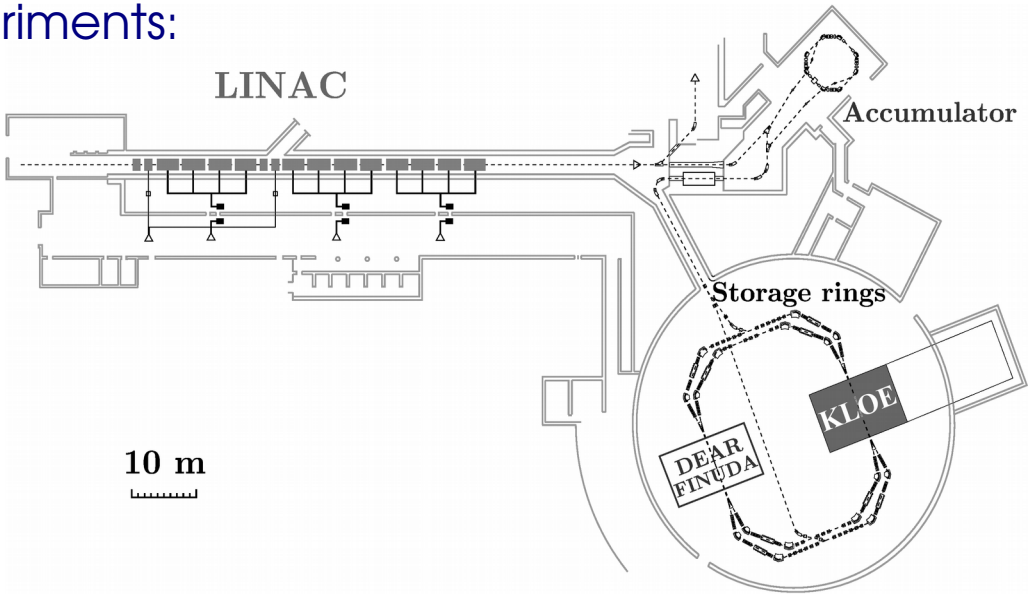
U boson searches at KLOE:

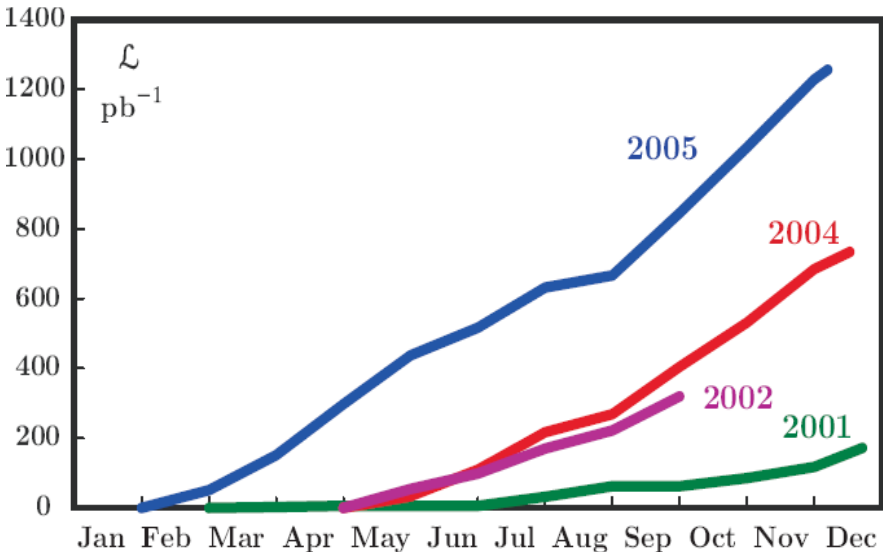
- Dalitz decays of Φ:
  - $e^+e^- \to \Phi \to \eta U$, $U \to e^+e^-$
    - $\eta \to \pi^+\pi^-\pi^0$
    - $\eta \to \pi^0\pi^0\pi^0$
- Continuum processes:
  - $e^+e^- \to U\gamma$
    - $U \to \mu^+\mu^-$
    - $U \to e^+e^-$
    - $U \to \pi^+\pi^-$
- Higgsstrahlung process:
  - $e^+e^- \to Uh'$

The DAΦNE Φ-factory

Double Annular Φ-factory for Nice Experiments:

- e^+e^- collider
- fixed energy $\sqrt{s} = M_\phi \approx 1020$ MeV
  - off-peak operation possible
- separate storage rings for e^+ and e^- to reduce beam-beam interaction
- 2 interaction regions





DAΦNE operations (KLOE run):

- peak luminosity of $1.4 \cdot 10^{32}$ $cm^{-2}s^{-1}$
- best daily perfomance: 8.5 pb^{-1}/day

Data collected by KLOE:

- at Φ peak:
  - 2001-2 ~0.5 fb^{-1}
  - 2004-5: ~1.9 fb^{-1}
- 260 pb^{-1} off-peak

For more details, see M. Silarski's talk on Monday, high noon

The KLOE Detector

Large Drift Chamber

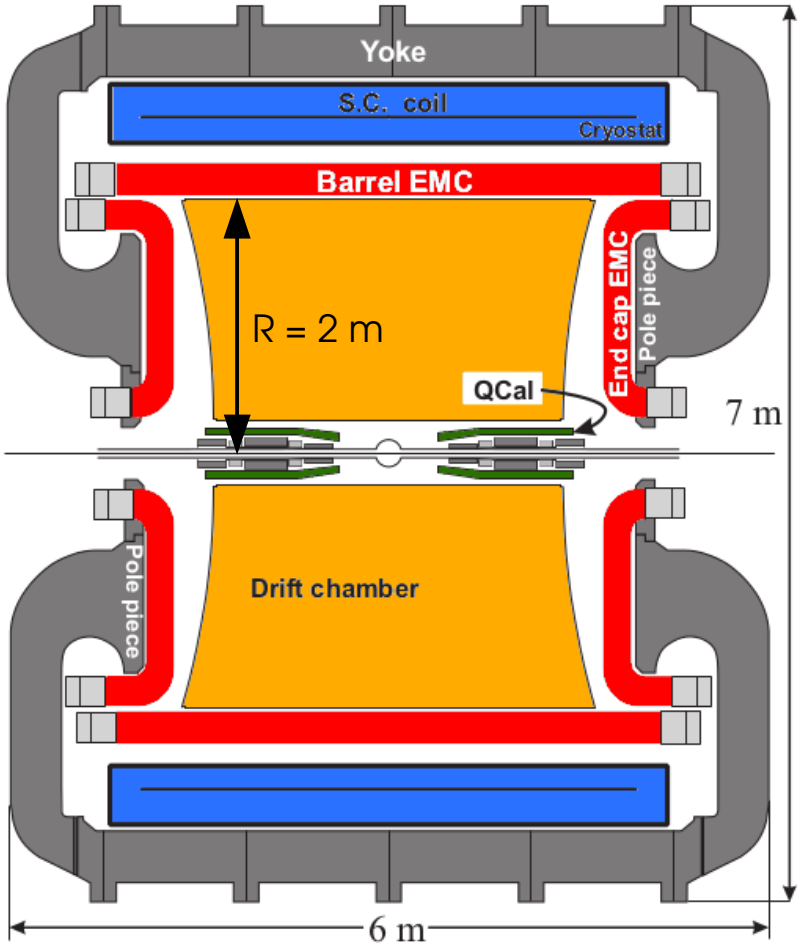
- gas: 90% He + 10% C_4H_{10}
- R_{inner} = 25 cm,
  R_{outer} = 2 m
- $\sigma_{xy} \approx 150$ μm, $\sigma_z \approx 2$ mm
- $\sigma(p_T)/p_T = 0.4\%$

KLOE-2 upgrade

- new detectors in the interaction region

- will collect ~5fb^{-1} in the next 2 years

For more details, see M. Silarski's talk on Monday, high noon



Electromangnetic Calorimeter

- lead and scintillating fibers
- hermetic coverage (98% 4π)
- barrel with C-shaped endcaps

$$\sigma_t = \frac{54\ ps}{\sqrt{E[GeV]}} \oplus 140ps$$

$$\sigma_E = \frac{5.7\%E}{\sqrt{E[GeV]}}$$

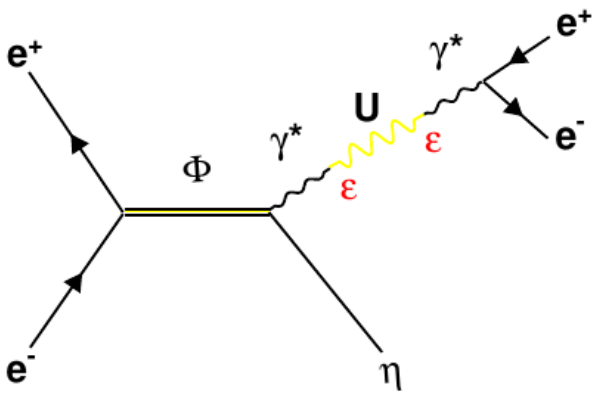
$$\sigma_x = \sigma_y = 1\ cm$$

$$\sigma_z = \frac{1.2\ cm}{\sqrt{E[GeV]}}$$

Superconducting coil

- B = 0.52 T

$\Phi \to \eta U, U \to e^+e^-$, $\eta \to \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$

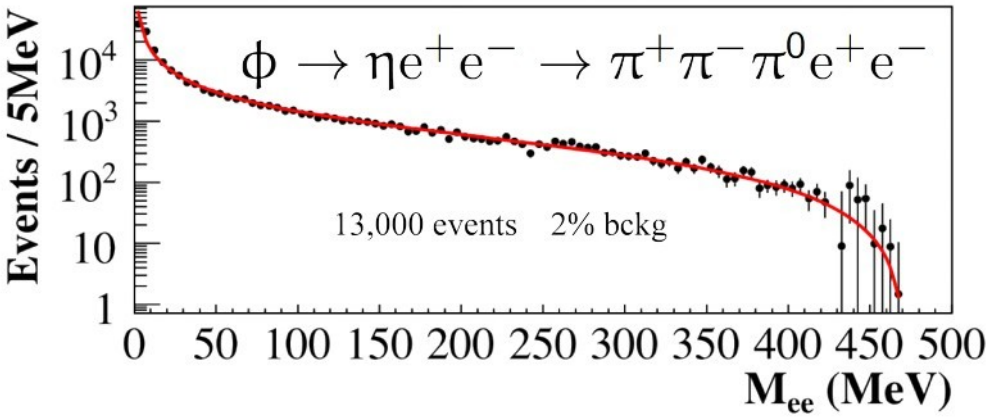


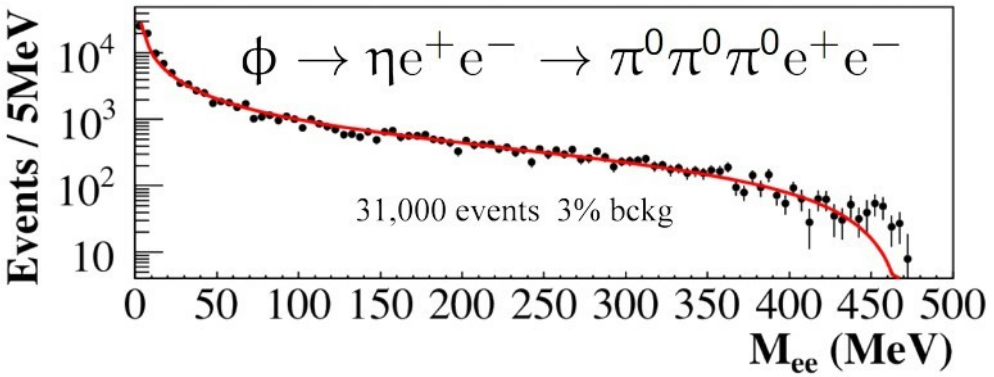
$\Phi \to \eta U, U \to \pi^+\pi^-\pi^0\ e^+e^-$

- 4 tracks, 2 photon candidates
- $495 < M_{\pi\pi\gamma\gamma} < 600$ MeV
- $70 < M_{\gamma\gamma} < 200$ MeV
- $535 < M_{recoil(ee)} < 560$ MeV
- ToF cuts
- background contamination 2%

$\Phi \to \eta U, U \to \pi^0\pi^0\pi^0\ e^+e^-$

- 2 charged tracks
- 6 prompt photons candidates, E>7 MeV not associated to track
- $|T_\gamma - R_\gamma/c| < \min(3\sigma(t), 2ns)$
- acceptance: $|\cos(\theta_\gamma)| < 0.92$
- $400 < M_{6\gamma} < 700$ MeV
- background contamination 3%





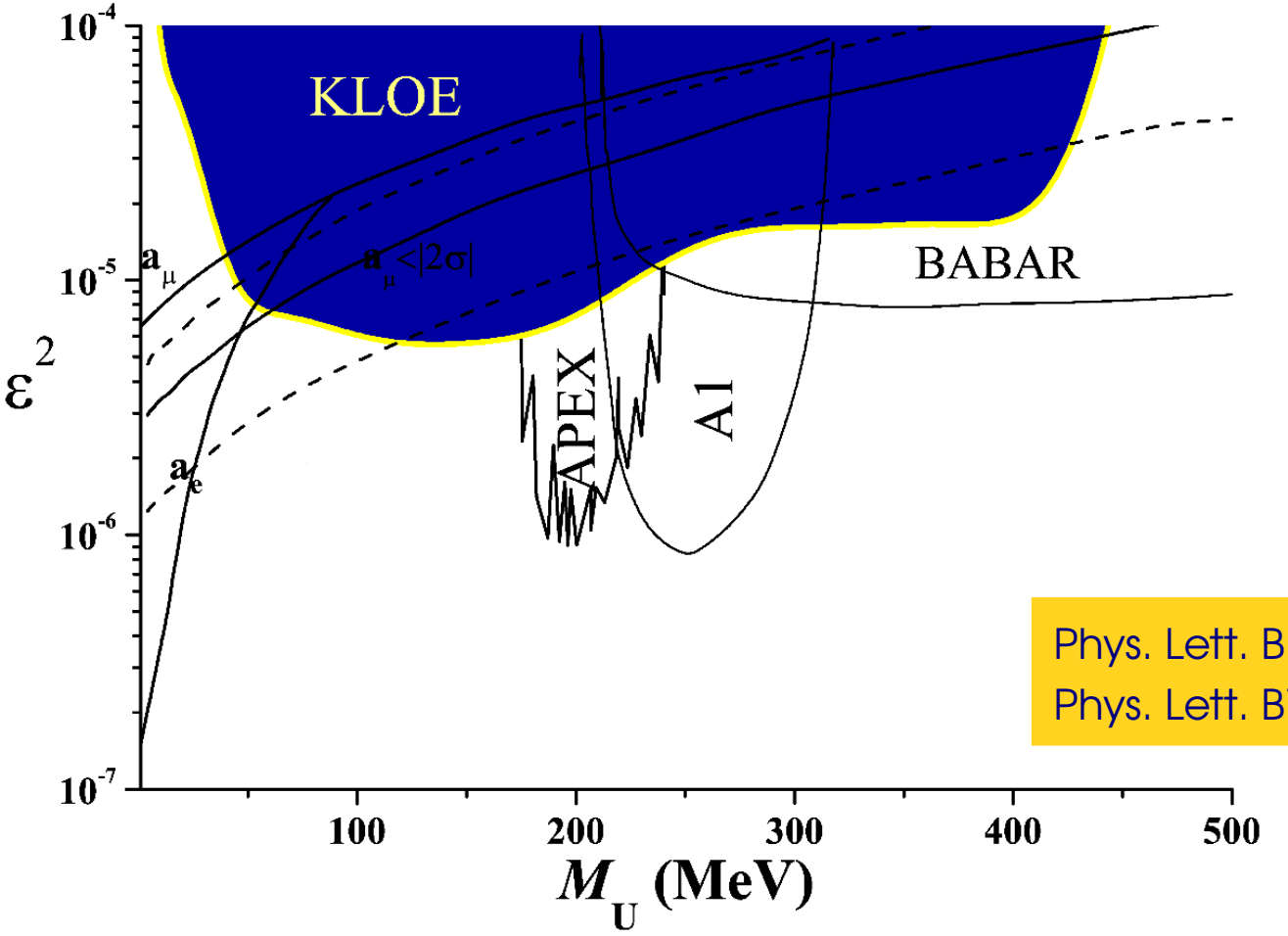
- $\Phi \to \eta e^+e^-$ bcg extracted by a fit parametrised by the VMD model
- signal expected as a peak above continuum background in M_{ee}
- no signal observed
- CLs technique used to estimate the upper limit

Phys. Lett. B 706 (2012) 251
Phys. Lett. B720 (2013) 111

$\Phi \to \eta U,\ U \to e^+e^-\ ,\ \eta \to \pi^+\pi^-\pi^0\ /\ \pi^0\pi^0\pi^0$

90% C.L. upper limit on ε^2 obtained assuming the relation:

$\sigma(\varphi \to \eta U) \sim \varepsilon^2 |F_{\eta\varphi}(m_U^2)| \sigma(\varphi \to \eta\gamma)$ (Reece-Wang, JHEP0907:051 (2009))

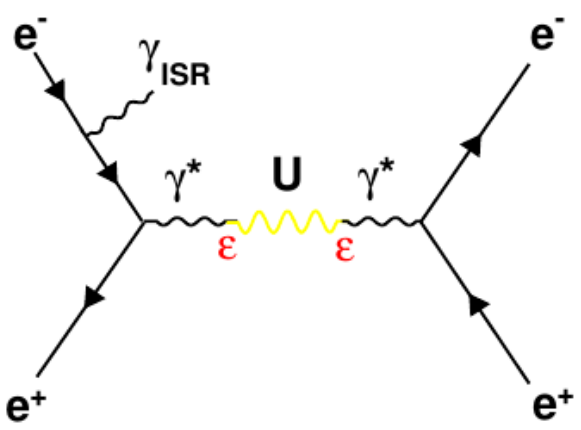


Phys. Lett. B 706 (2012) 251
Phys. Lett. B720 (2013) 111

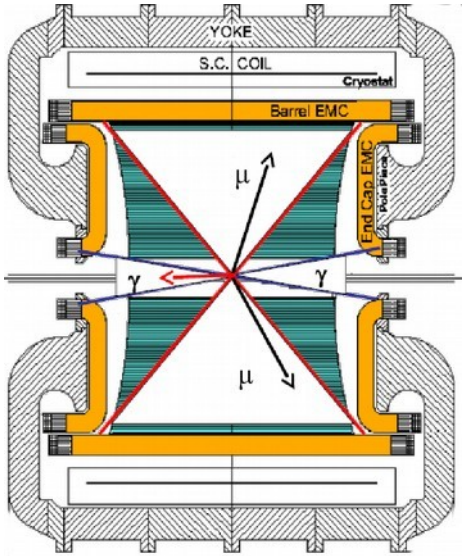
$\varepsilon^2 < 1.7\times10^{-5}$ @ 90% C.L. for $30<M_U<400$ MeV

$\varepsilon^2 < 8\times10^{-6}$ @ 90% C.L. for $50<M_U<210$ MeV

$e^+e^- \to U\gamma$ with $U \to \mu^+\mu^-$

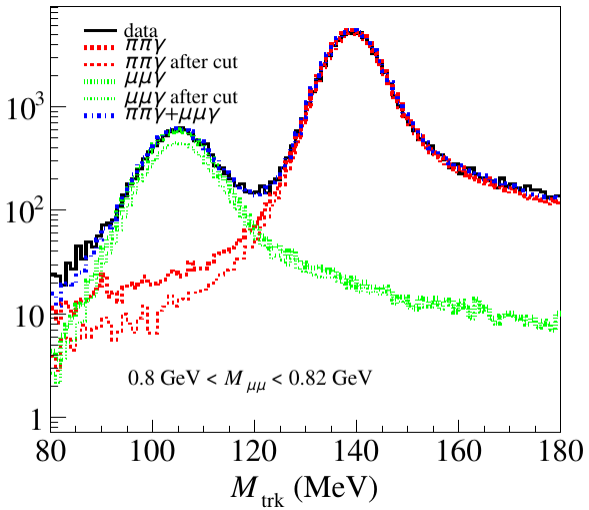


- data sample luminosity 240 pb^{-1}
- ISR events for a continuum of dimuon mass
- 2 tracks ($50^\circ < \theta_\mu < 130^\circ$)
- Undetected γ ($\theta_\gamma < 15^\circ$ or $\theta_\gamma > 165^\circ$)
- High statistics ISR signal
- Strong suppression of FSR and $\Phi \to \pi^+\pi^-\pi^0$

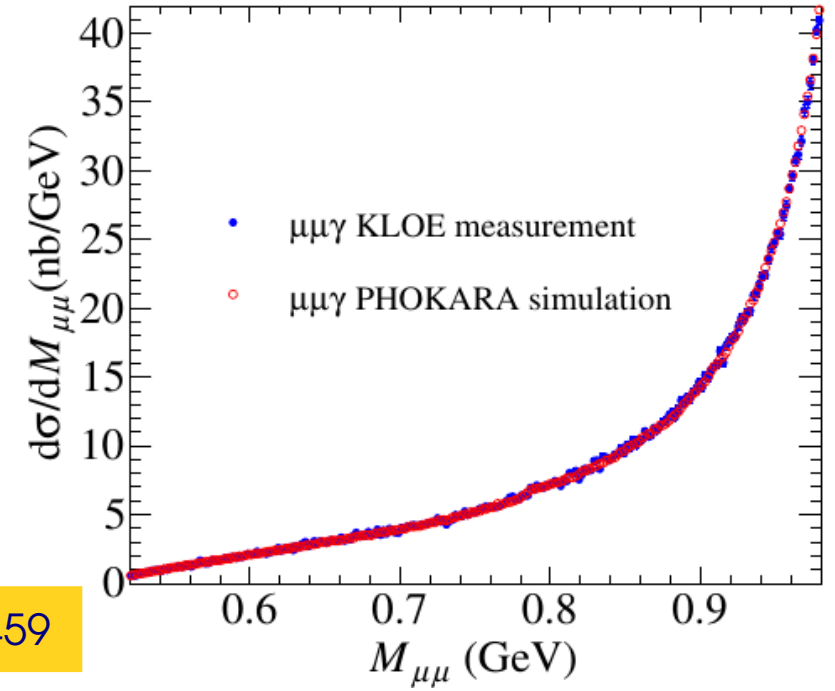


- Good π/μ separation with M_{trk} and σ_{Mtrk} cuts

  M_{trk} - "track mass" assuming 2 equal mass particles and 1 photon



Phys. Lett. B 736 (2014) 459



$e^+e^- \to U\gamma$ with $U \to \mu^+\mu^-$

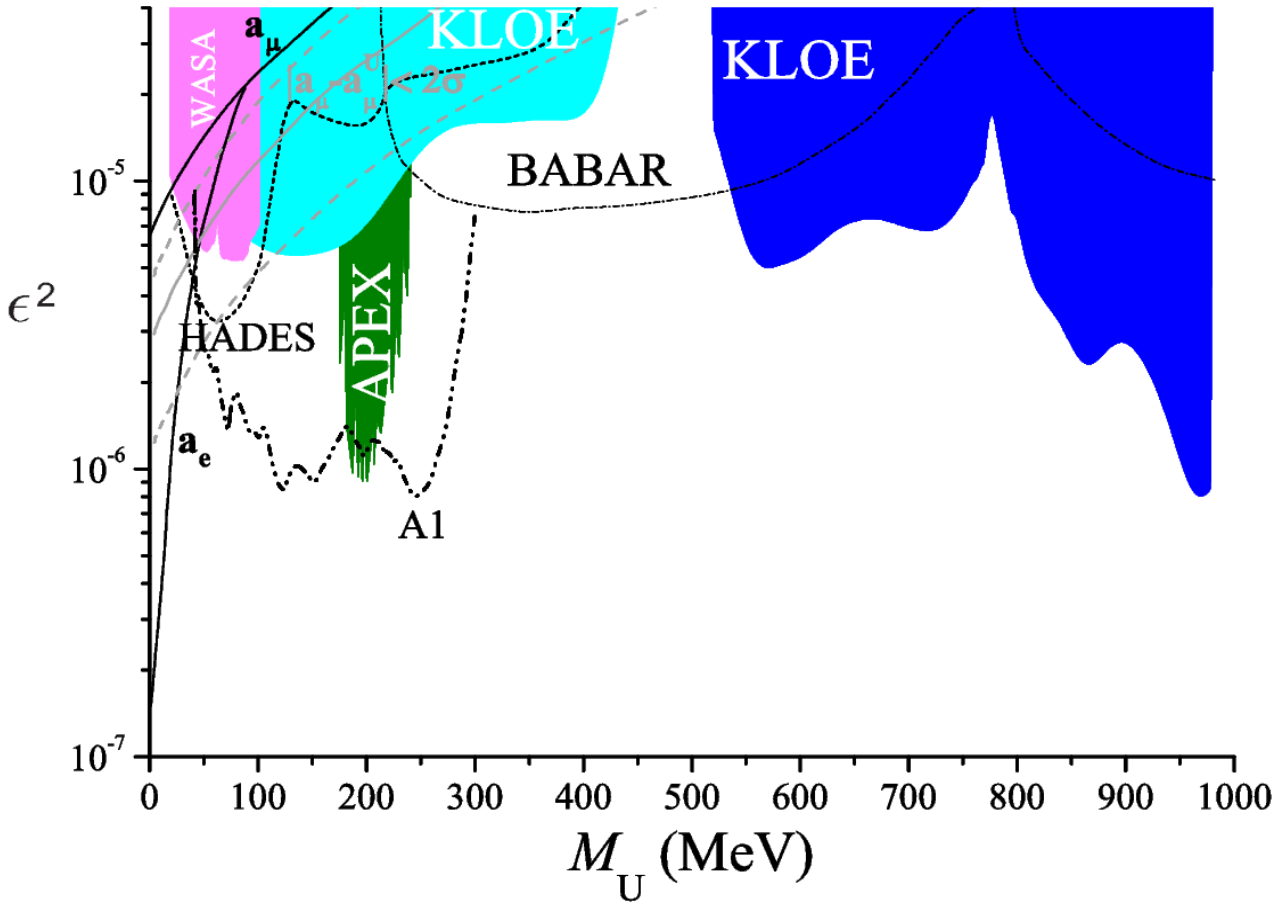
- 90% C.L. upper limit on number of U candidates obtained using the CLs technique
- $\varepsilon^2 = \frac{N_{CLS}/\epsilon_{eff}}{H \cdot I \cdot L}$

  I – eff. cross section

  L – integrated luminosity

  H – radiator function extracted from $\frac{d\sigma_{\mu\mu\gamma}}{dM_{\mu\mu}}$

Phys. Lett. B 736 (2014) 459

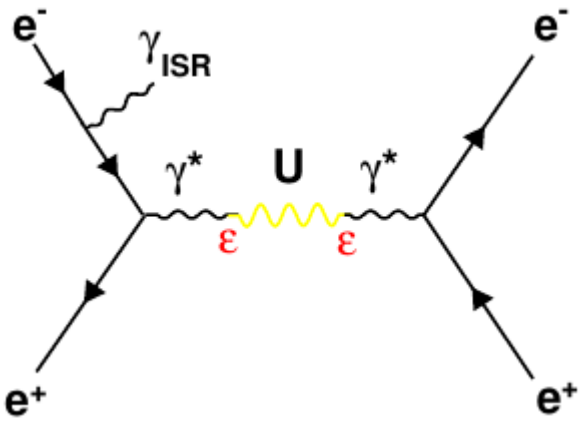


$\varepsilon^2 < 1.6\times10^{-5} - 8.7\times10^{-7}$ @ 90% C.L. for $520 < M_U < 980$ MeV

KLOE Dalitz $\Phi \to \eta e^+e^-$

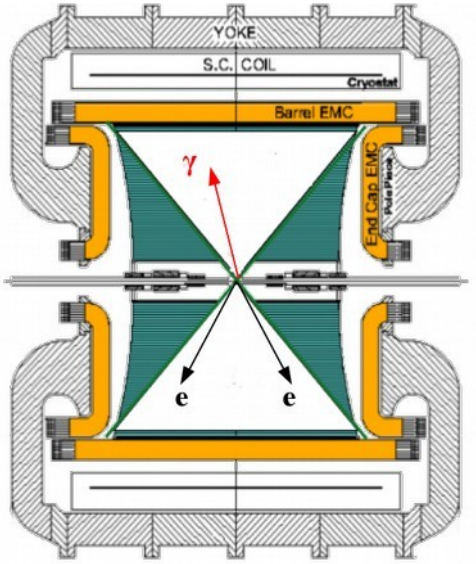
KLOE $e^+e^- \to \mu^+\mu^-\gamma$

$e^+e^- \to U\gamma$ with $U \to e^+e^-$

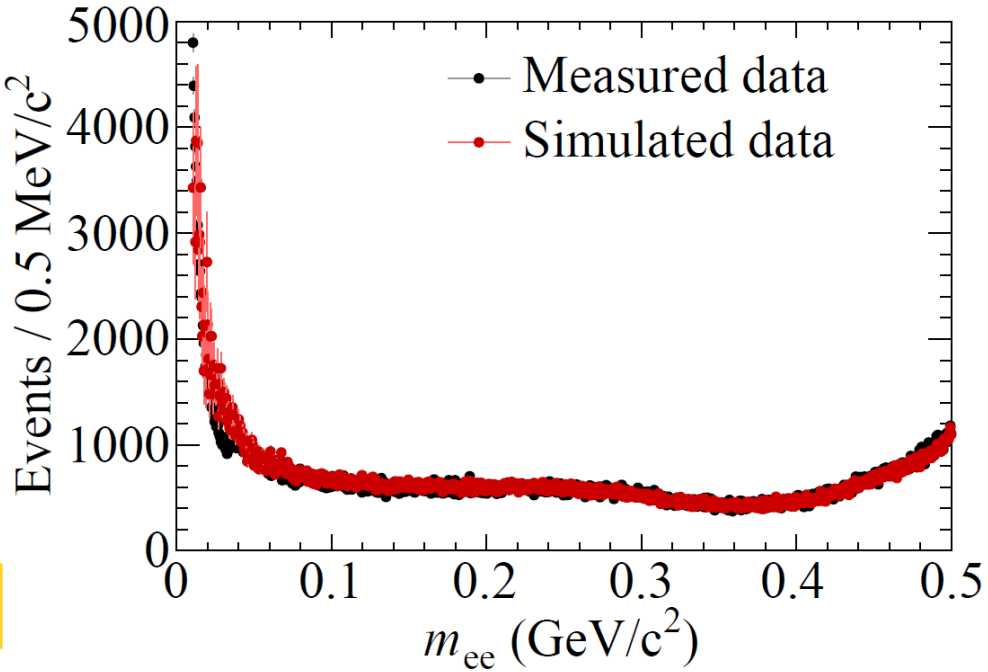


Motivation:

Access to U boson masses as low as $2m_e$



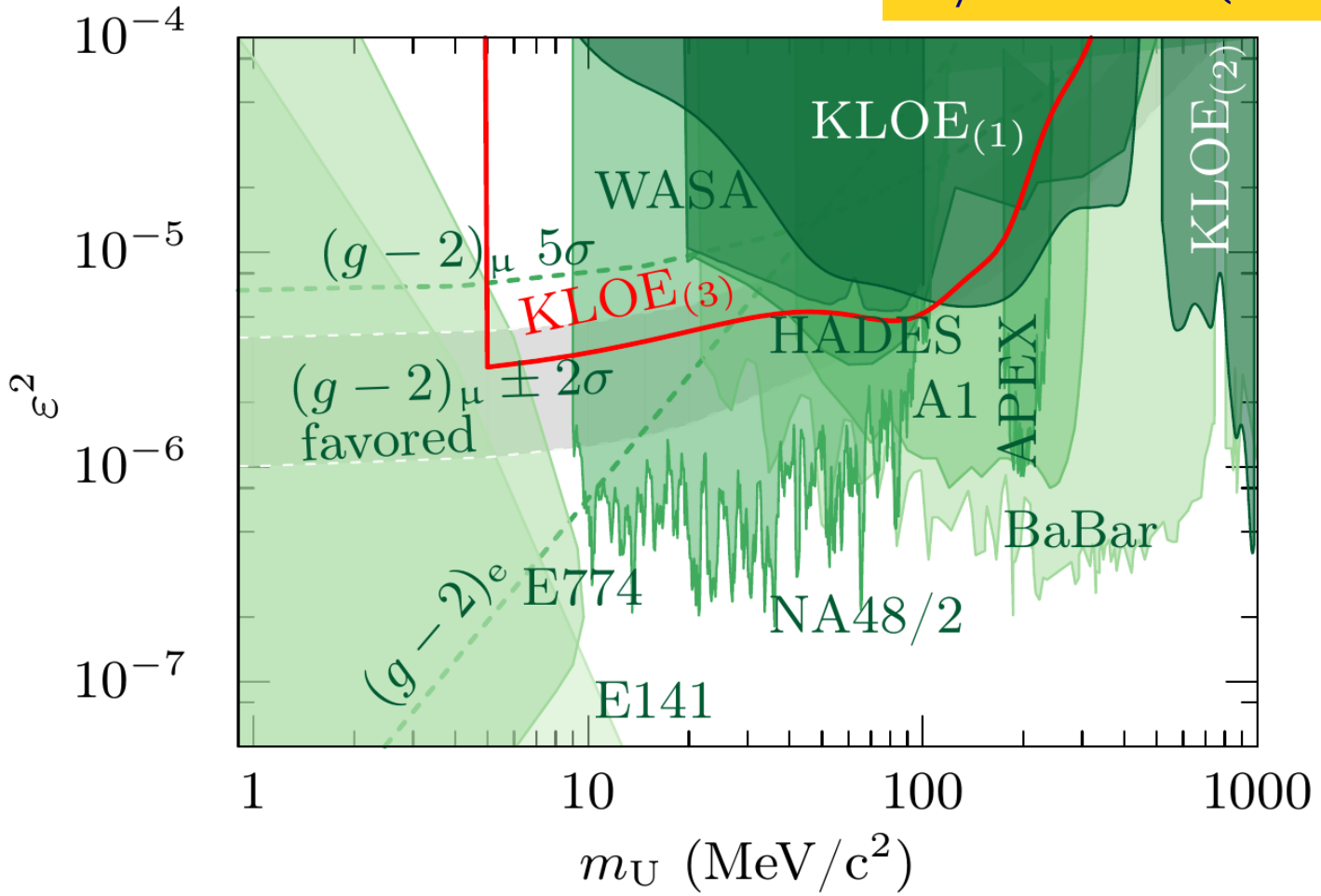
- data sample luminosity 1.5 fb^{-1}
- 2 tracks ($55° < \theta_e < 125°$) of opposite charge
- detected photon ($50° < \theta_\gamma < 130°$)
- high statistics radiative Bhabha events in KLOE data
- background contamination at per mil level or better



Phys. Lett. B750 (2015) 633-637

$e^+e^- \to U\gamma$ with $U \to e^+e^-$

Phys. Lett. B750 (2015) 633-637



KLOE(1) – Dalitz $\Phi \to \eta e^+e^-$

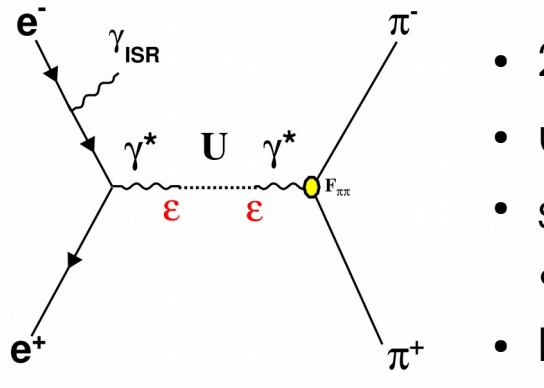
KLOE(2) – $e^+e^- \to \mu^+\mu^-\gamma$

KLOE(3) – $e^+e^- \to e^+e^-\gamma$

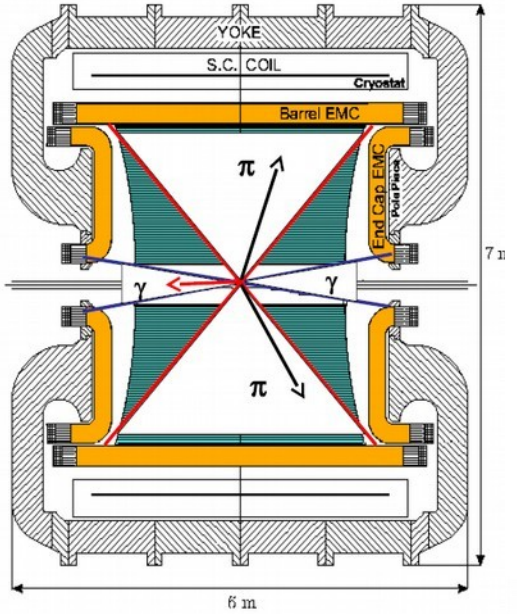
$\varepsilon^2 < 10^{-6} - 10^{-4}$ @ 90% C.L. for $5 < M_U < 520$ MeV

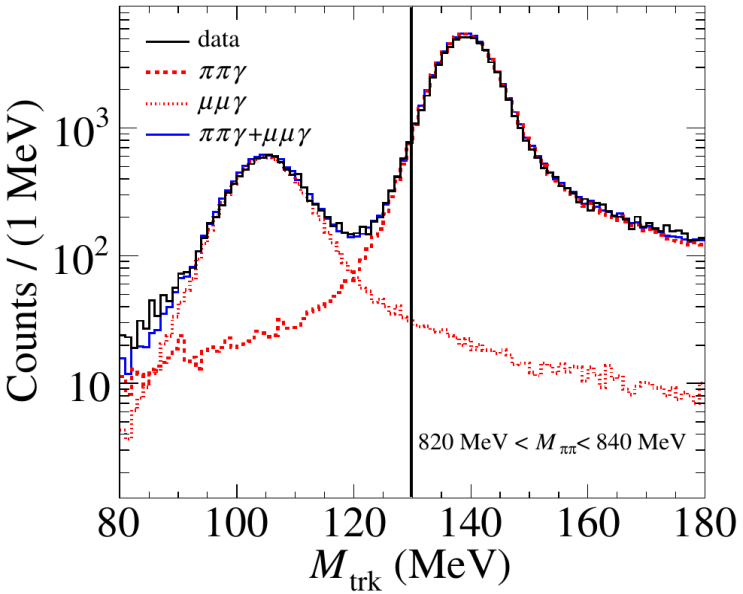
$e^+e^- \to U\gamma$ with $U \to \pi^+\pi^-$

Motivation: In the ρ-ω region dominant branching fraction into hadrons limits sensitivity of leptonic channels

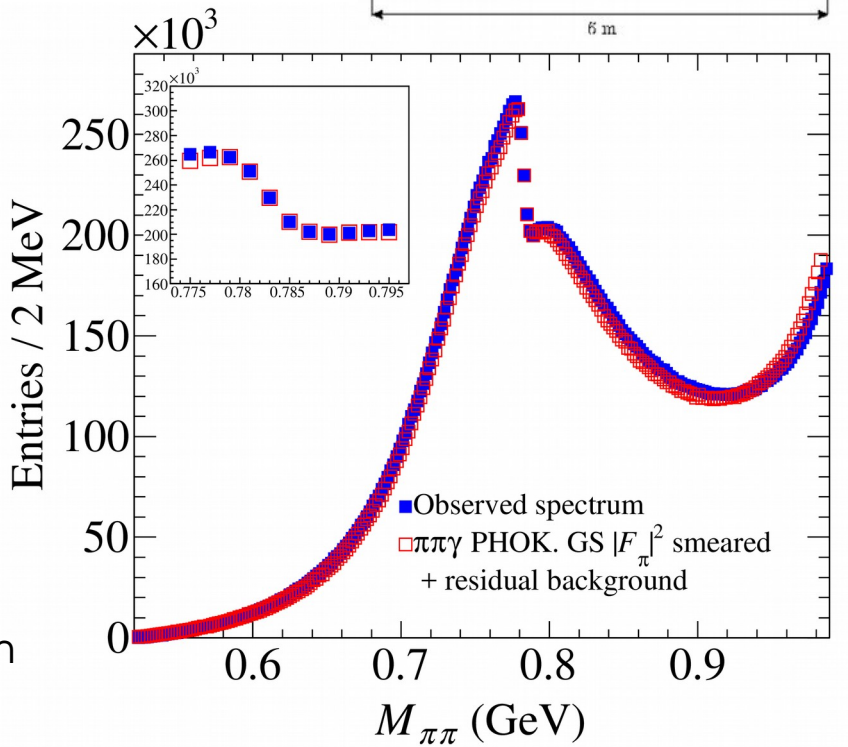


- 2 tracks ($50° < \theta_\mu < 130°$)
- undetected ISR γ ($\theta_\gamma < 15°$ or $\theta_\gamma > 165°$)
- strong suppression of FSR and $\Phi \to \pi^+\pi^-\pi^0$
- kinematic cuts on M_{trk} and $M_{\pi\pi}$





Phys. Lett. B757 (2016) 356

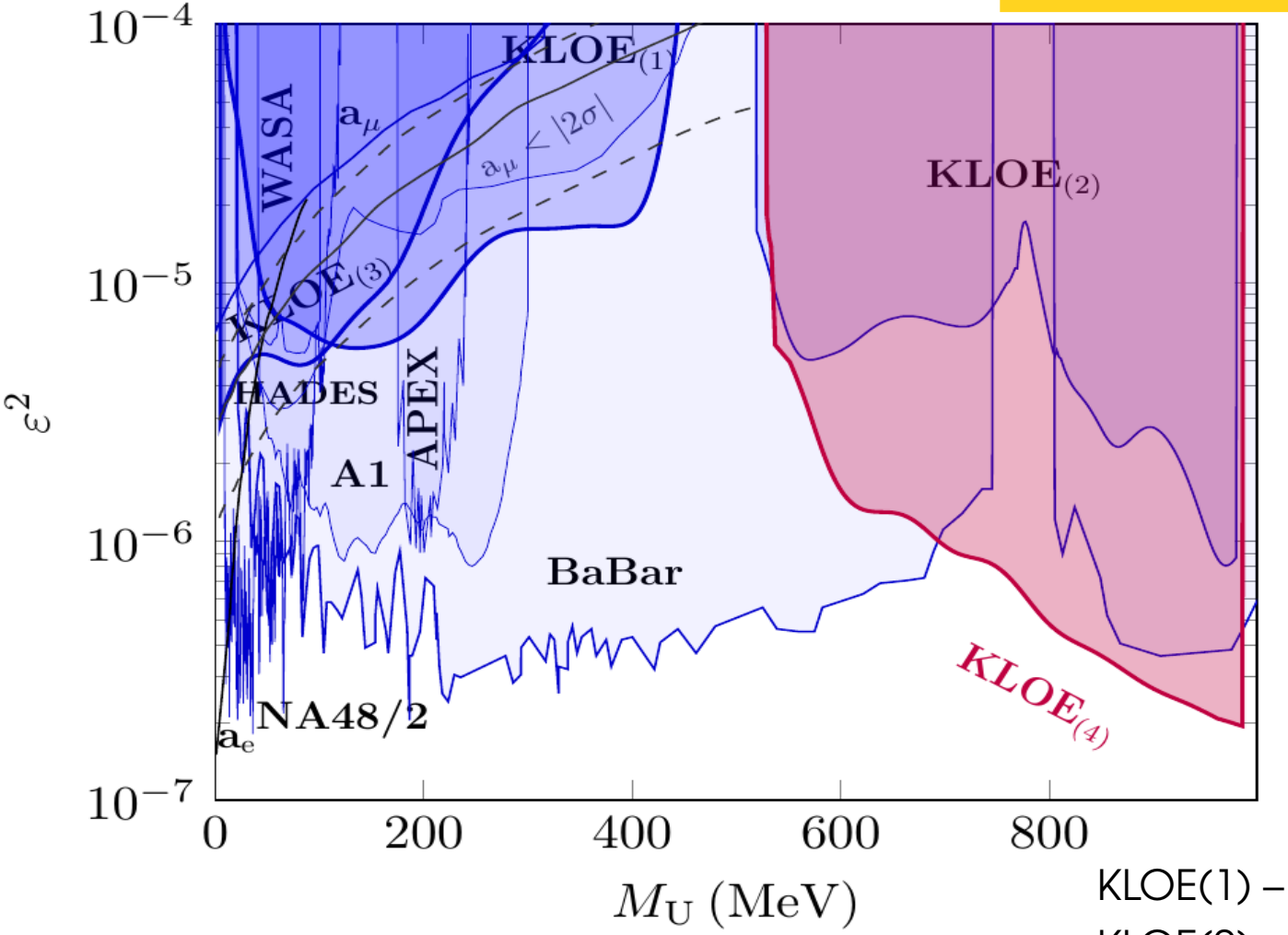


- dedicated simulation with PHOKHARA + GS pion form factor parametrisation to describe the ρ-ω region

$e^+e^- \to U\gamma$ with $U \to \pi^+\pi^-$

90% C.L. upper limit on ε^2

Phys. Lett. B757 (2016) 356



KLOE(1) – Dalitz $\Phi \to \eta e^+e^-$

KLOE(2) – $e^+e^- \to \mu^+\mu^-\gamma$

KLOE(3) – $e^+e^- \to e^+e^-\gamma$

KLOE(4) – $e^+e^- \to \pi^+\pi^-\gamma$

Search for dark Higgsstrahlung

2 possible scenarios:

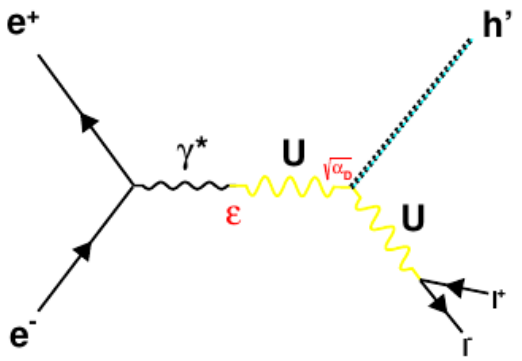
- $m_{h'} > 2m_U$

  => $h' \to UU \to 4l,\ \pi + 4l,\ \pi$

- $m_{h'} < m_U$

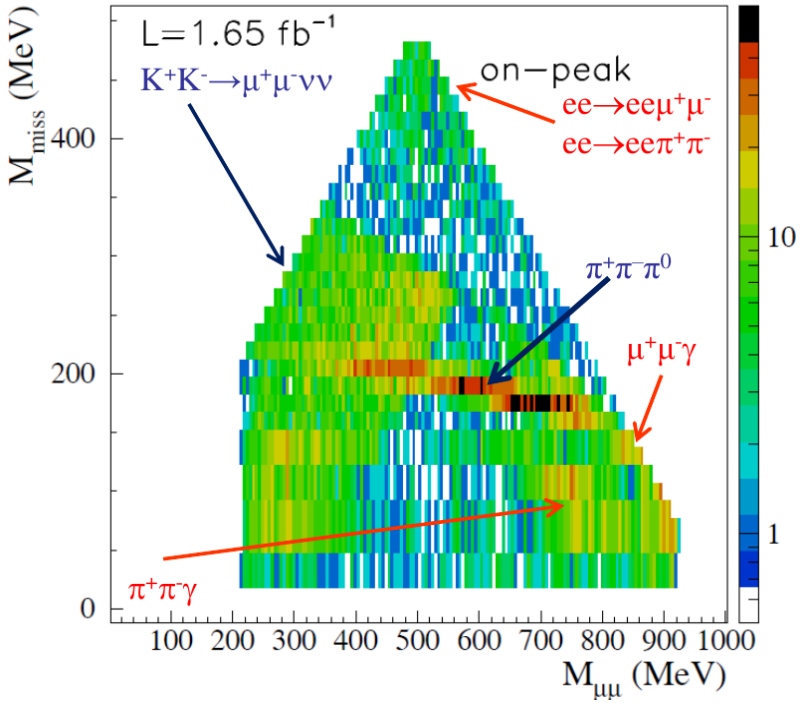
  => h' escapes detection

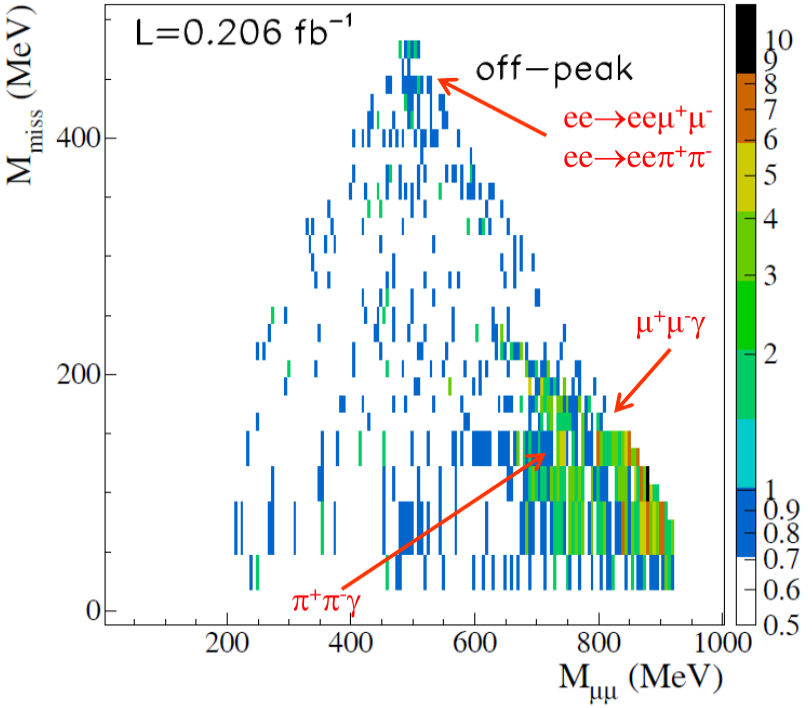
  ("invisible dark Higgs")



- data used:
  - 1.65 fb^{-1} at Φ peak
  - 206 pb^{-1} off-peak (1000 MeV)
- selecting 2 muon tracks and missing mass
- searching for a peak in the M_{miss} vs. $M_{\mu\mu}$ distribution

Phys. Lett. B 747 (2015) 365





Search for dark Higgsstrahlung

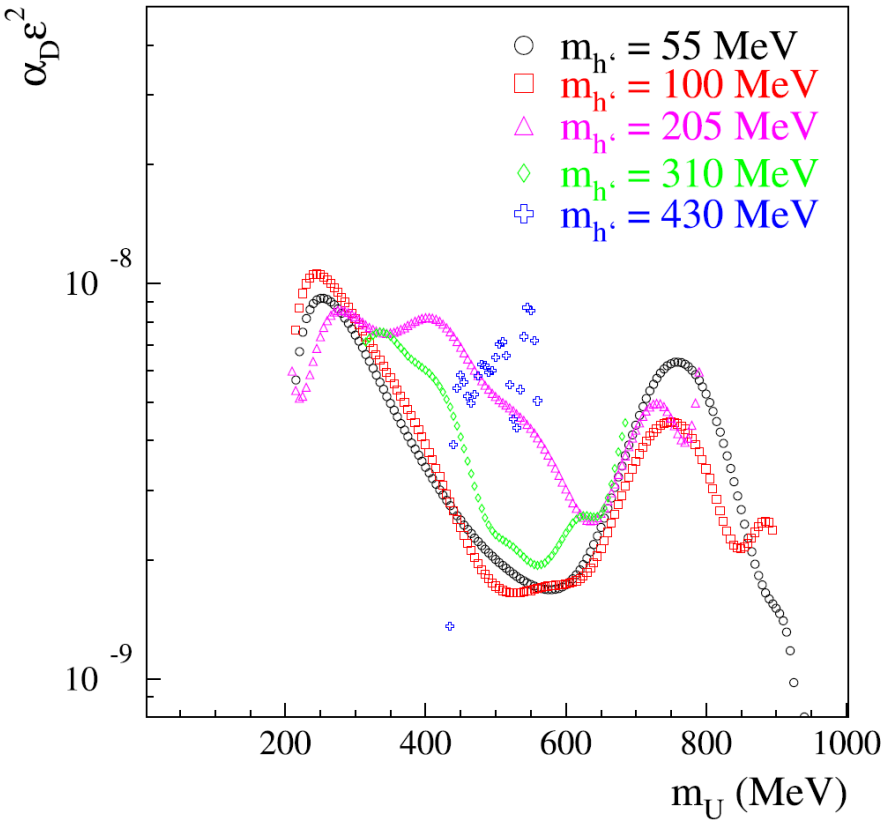
- bayesian limit was set on the number of signal events at 90% C.L. ($N_{CL=90\%}$)
- $\alpha_D \varepsilon^2 = \frac{N_{CL=90\%}}{\epsilon_{eff}} \frac{1}{L \cdot \sigma(\alpha_D \varepsilon^2 = 1)}$

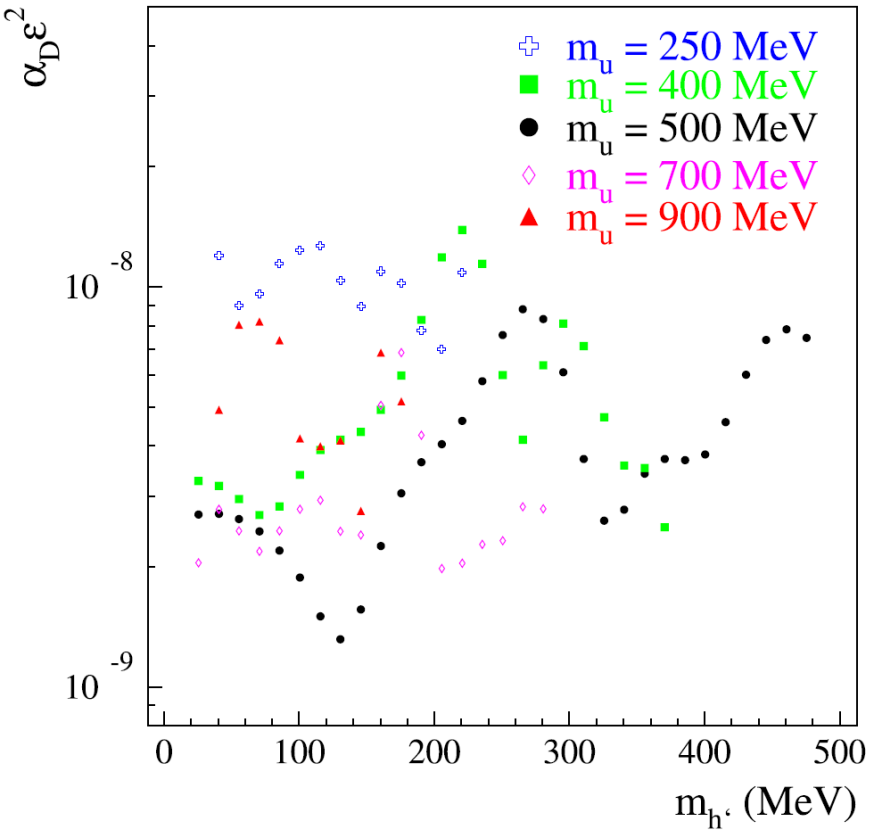
L – integrated luminosity

σ(αε²=1) – dark Higgsstrahlung cross section for αε²=1

90% C.L. upper limits combined for on and off-peak samples

Phys. Lett. B 747 (2015) 365





The limits 10^{-9}-10^{-8} on $\alpha_D\varepsilon^2$ translate to $\varepsilon < 10^{-4}$-10^{-3} if $\alpha_D = \alpha_{em}$

Summary

- The KLOE experiment has contributed to the U boson searches with five measurements, exploiting three processes:
  - $\Phi \to \eta U$ with $U \to e^+e^-$ and $\eta \to \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$ — Phys. Lett. B720 (2013) 111
  - $e^+e^- \to U\gamma$ with:
    - $U \to \mu^+\mu^-$ — Phys. Lett. B 736 (2014) 459
    - $U \to e^+e^-$ — Phys. Lett. B750 (2015) 633
    - $U \to \pi^+\pi^-$ — Phys. Lett. B757 (2016) 356
  - $e^+e^- \to Uh'$ with h' invisible — Phys. Lett. B 747 (2015) 365

- No U boson signal was observed
- Upper limits on ε^2 were set in U boson mass range 5 – 980 MeV
  - Present results limited by statistics

- KLOE-2 started taking data with a view to collecting 5 pb^{-1} of data
  - **We expect to improve the sensitivity twice with KLOE-2**


BAR
Thank you
for your attention!

Backup Slides

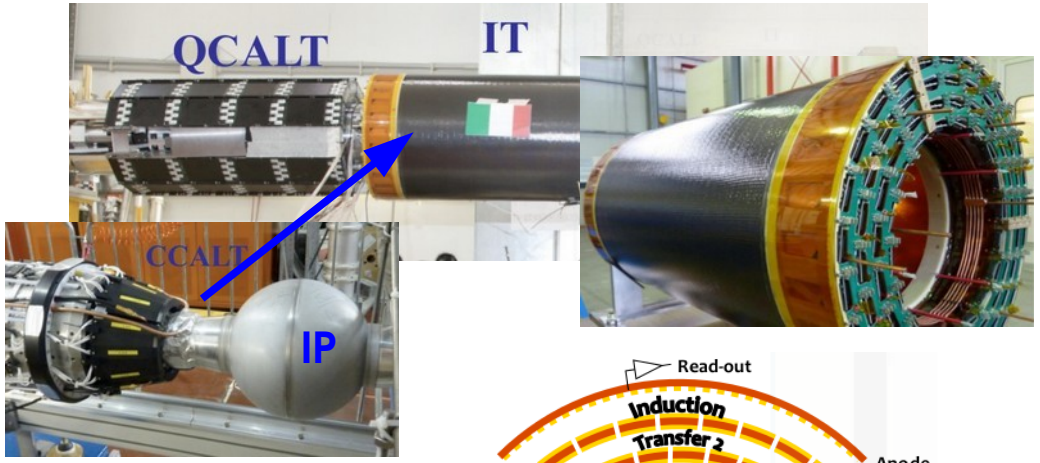
KLOE upgrade to KLOE-2

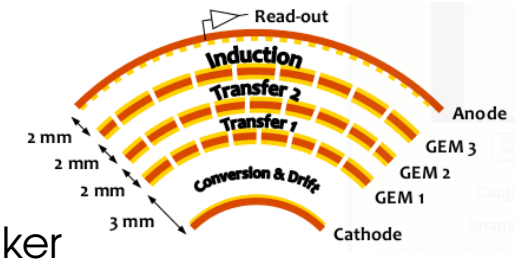
Detector upgrades:

NIMA 617 (2010),105

- QCALT – sampling calorimeter to instrument the final focusing region
- CCALT – LYSO calorimeter to increase acceptance for γ-s from IP

NPB 197 (2009), 215



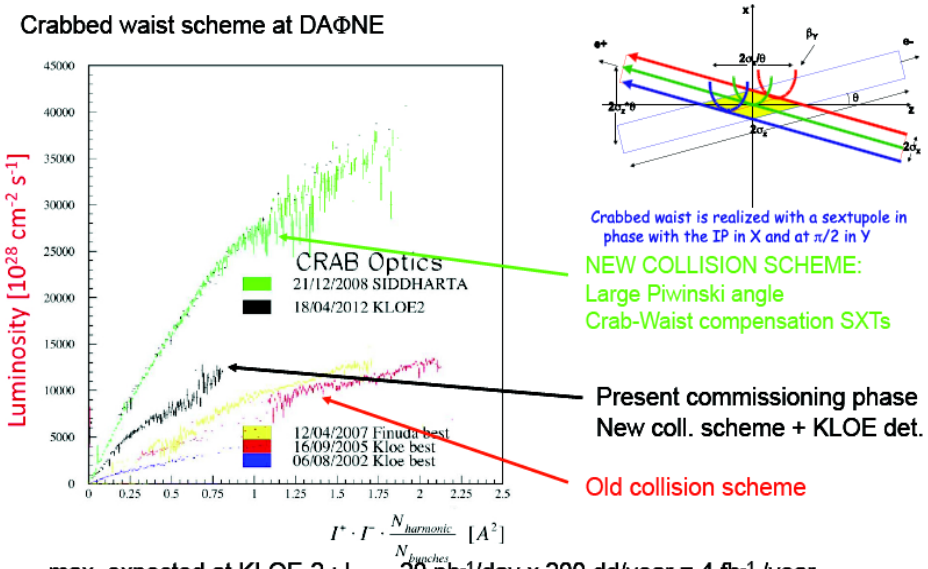


- new Inner Tracker
  - first cylindrical GEM detector ever built
  - 4 layers of triple GEM
  - increased acceptance for low-p_T tracks
  - Improved vertexing resolution near the IP

NIMA 628 (2011),194

DAΦNE upgrade:

- crabbed waist collision scheme
- 2-3x higher luminosity



max. expected at KLOE-2 : L_{int} ~ 20 pb^{-1}/day x 200 dd/year = 4 fb^{-1} /year

KLOE-2 is starting operation with the goal to collect ~5 fb^{-1} in 2-3 years