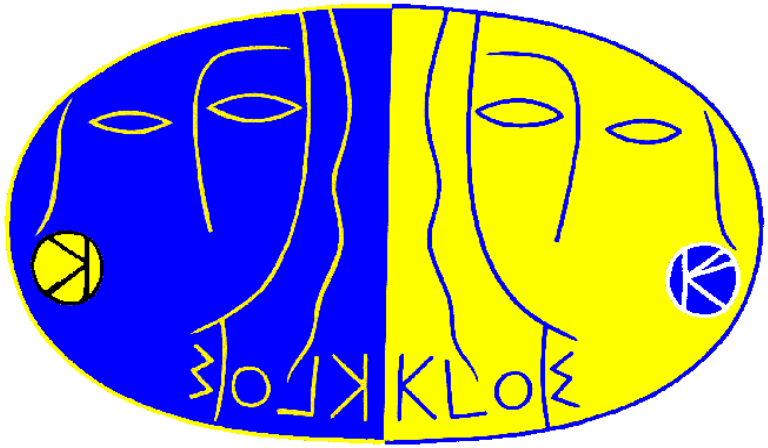
Dark Forces searches with KLOE



Elena Perez del Rio
on behalf of the KLOE-2 Collaboration

Jagiellonian Symposium of Fundamental
and Applied Subatomic Physics
Krakow
7-13 June 2015

New hidden-forces

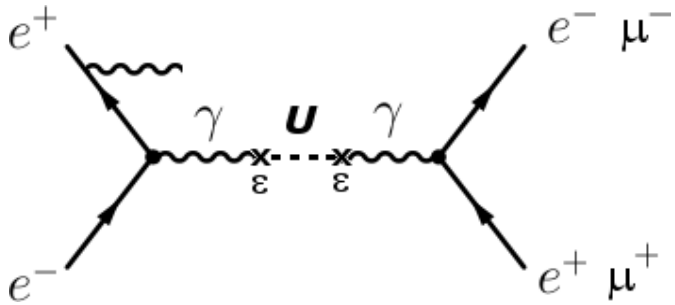
- Astrophysical observations
  - e^+/e^- excess in cosmic ray flux (PAMELA)
  - Total e^+/e^- flux (ATIC, Hess, Fermi)
  - Positron spectrum in primary cosmic rays (AMS)
  - 511 keV gamma ray signal from the galactic center (INTEGRAL)
  - DAMA/LIBRA annual modulation
  - Low energy spectrum of nuclear recoil dark matter candidate (CoGeNT)
- Particle physics puzzles
  - g-2 muon anomaly
- WIMPs belonging to a secluded gauge sector

  → New GeV-scale forces beyond SM
- Experimental searches:
  - e+e- colliders
    - Rare meson decays
    - Continuum
  - Beam dump and fixed target experiments

New GeV-scale forces: Dark Photon

- A new low energy gauge interaction mediated by a neutral light mass vector particle, usually named the U boson, with a small kinetic mixing ε ($<10^{-3}$) with SM
- Dark vector boson U which mixes with photon:

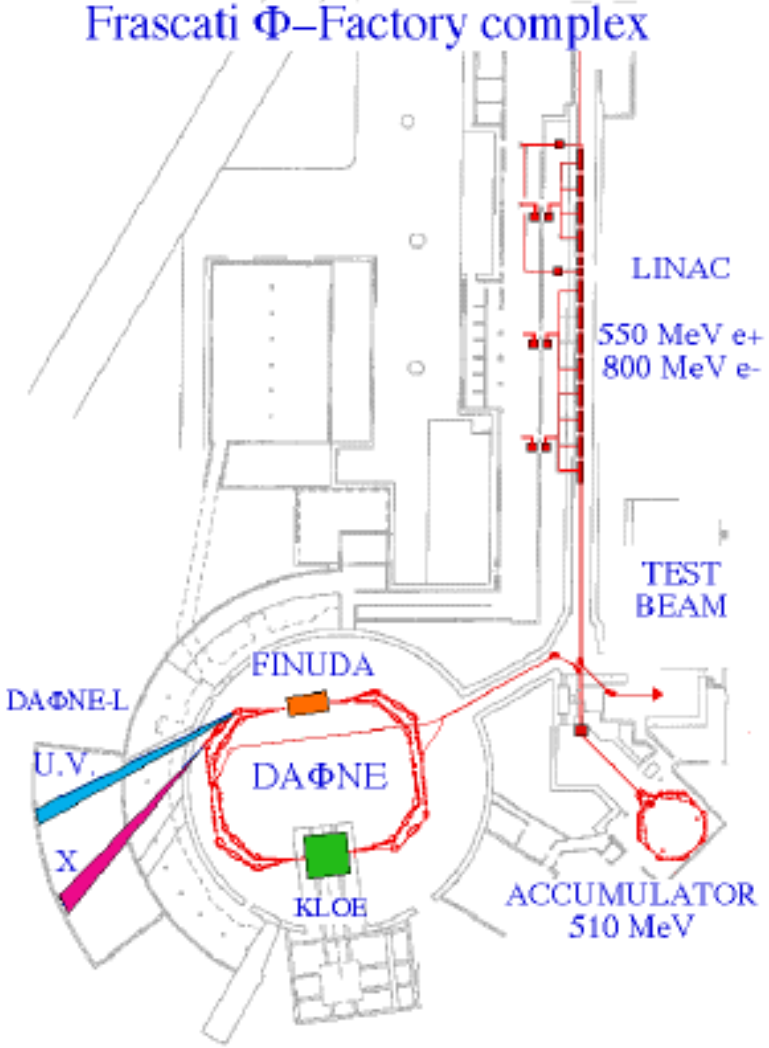
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$



- Many searches in the recent years
- KLOE:
  - $\Phi \rightarrow \eta U$ with $U \rightarrow e^+ e^-$ — Phys. Lett B 706 (2012) 251-255, Phys. Lett B 720 (2013) 111-115
  - $e^+ e^- \rightarrow U\gamma$ with $U \rightarrow \mu^+ \mu^-$ — Phys. Lett B 736 (2014) 459-464
  - $e^+ e^- \rightarrow Uh'$ with $h' \rightarrow$ invisible — Phys. Lett B accepted
  - $e^+ e^- \rightarrow U\gamma$ with $U \rightarrow e^+ e^-$ — Draft Paper
- Search for dilepton resonances

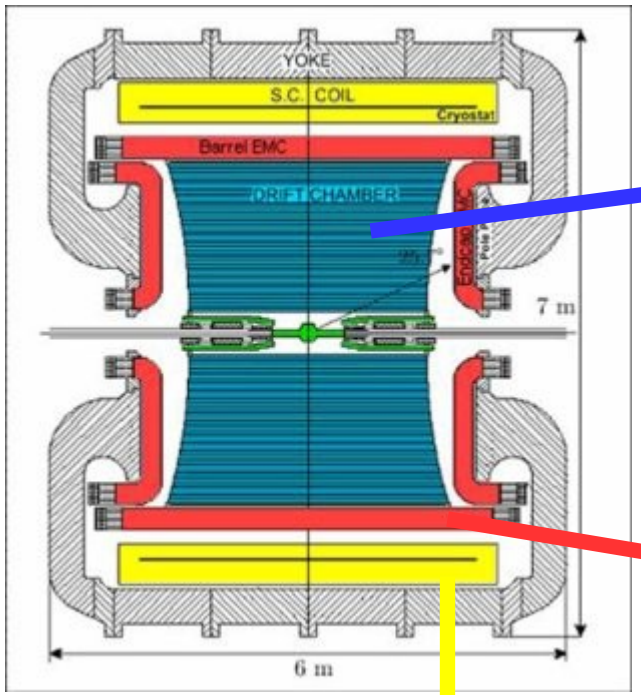
DAΦNE

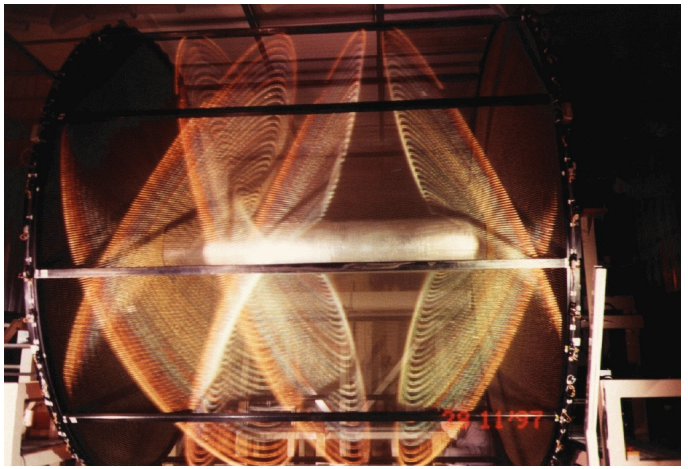
(Double Annular Φ Factory for Nice Experiments)



- Running period: 1999 – 2006
- $e^+ e^-$ collider $\sqrt{s} = M_\Phi = 1019.4$ MeV
- 2 interaction regions
- $e^+ e^-$ separated rings
- 105 + 105 bunches spaced by 2.7 ns
- $I^-_{peak} \sim 2.4$ A and $I^+_{peak} \sim 1.5$ A

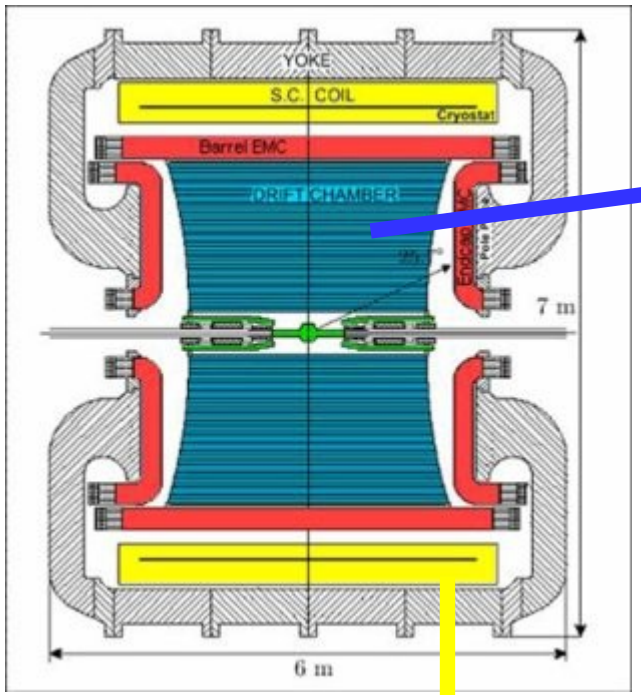
KLOE
(K LOng Experiment)



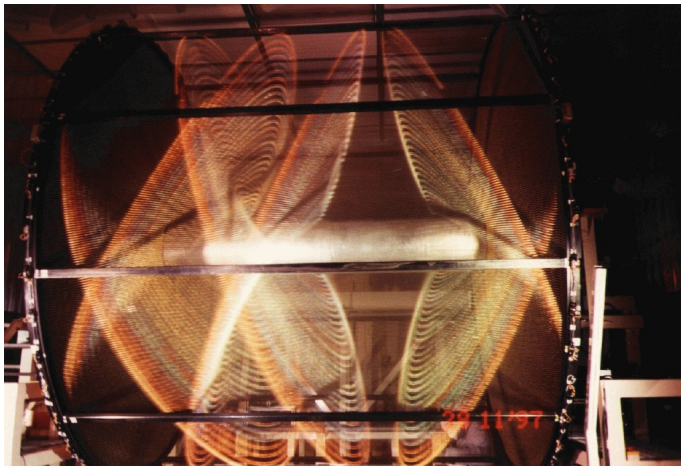


Magnetic field B = 0.52 T

KLOE
(K LOng Experiment)

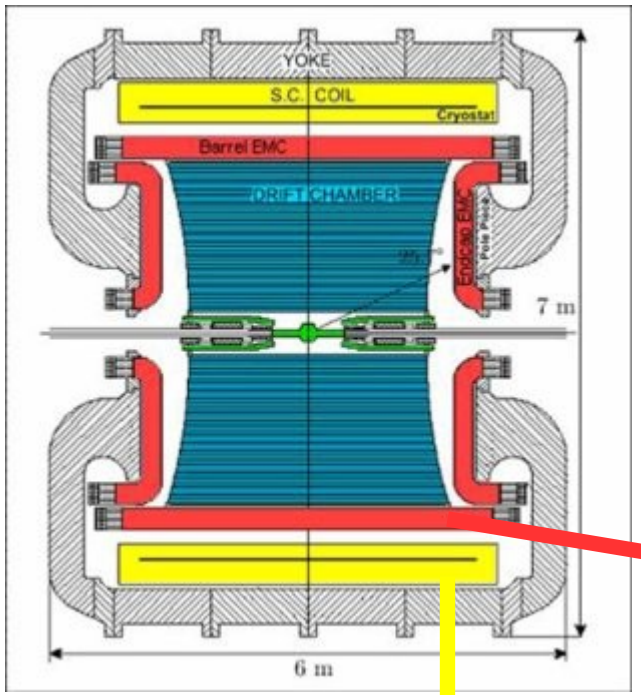


Magnetic field B = 0.52 T



- Low-mass gas mixture 90% Helium + 10% isobutane
- $\delta p_\perp / p_\perp < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- 12582 sense wires
- Stereo geometry
- 4m diameter, 3.3m long

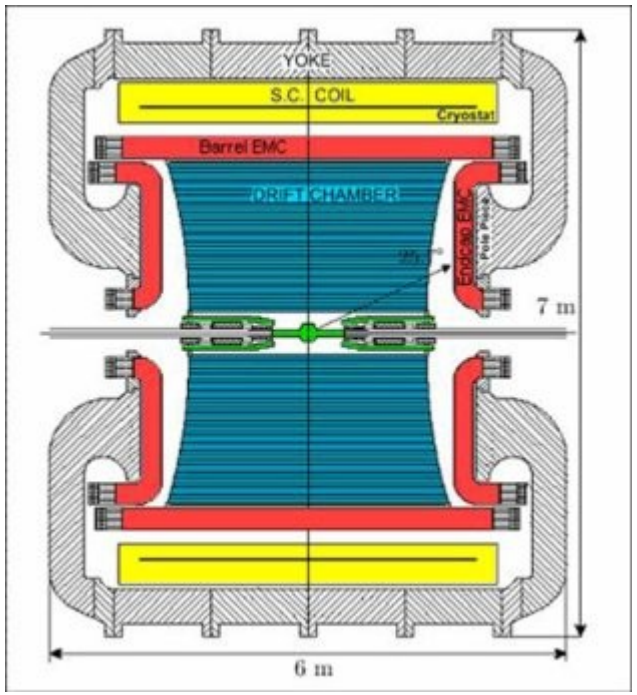
KLOE
(K LOng Experiment)

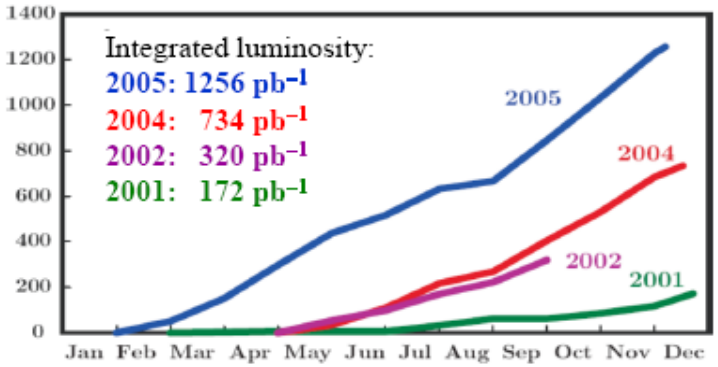


Magnetic field B = 0.52 T

- 98% coverage full solid angle
- $\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$
- $\sigma_T = 57 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 140 \text{ ps}$
- Barrel + 2 end-caps:
  - Pb/scintillating fiber read out by 4880 PMTs

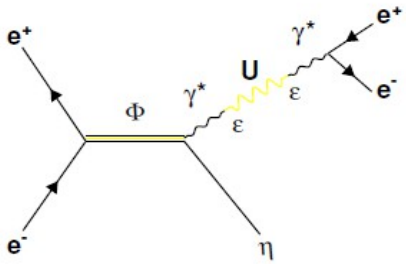
KLOE
(K LOng Experiment)





- KLOE data taking campaign ended in 2006
- 2.5 fb^{-1} acquired at $\sqrt{s}=M_{\Phi}$
- ~ 260 pb^{-1} off-peak

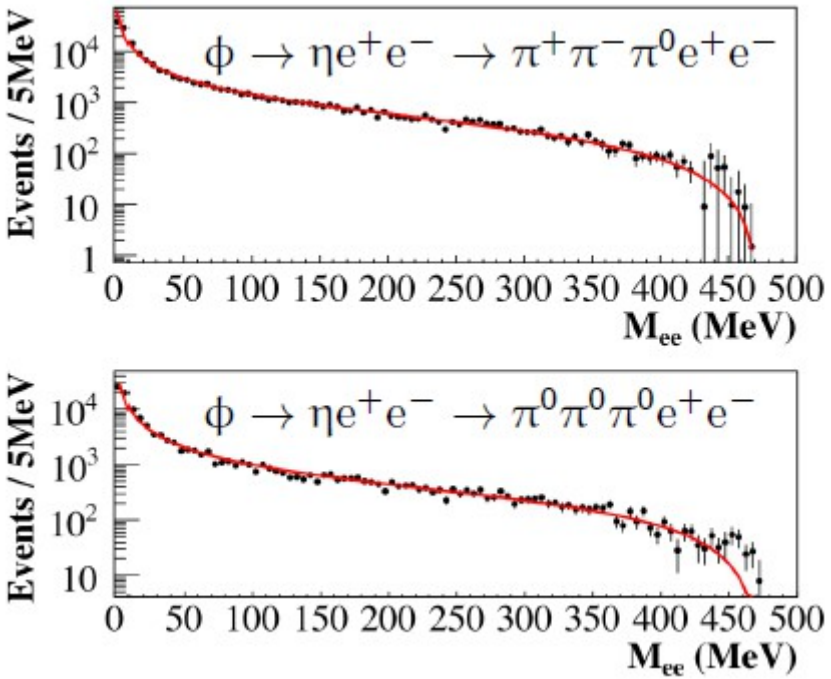
$\Phi \rightarrow \eta U$ with $U \rightarrow e^+e^-$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$



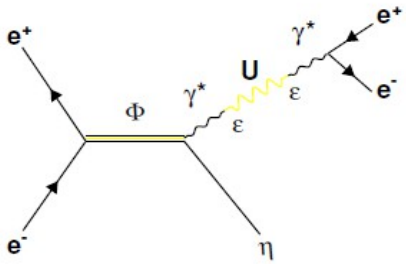
Phys. Lett B 706 (2012) 251-255
Phys. Lett B 720 (2013) 111-115

- No peak observed in M_{ee} distribution
- $\Phi \rightarrow \eta e^+e^-$ irreducible background
- $\eta \rightarrow \pi^+\pi^-\pi^0$
  - ~ 13000 events and 2% background
- $\eta \rightarrow \pi^0\pi^0\pi^0$
  - ~ 31000 events and 3% background

Di-electron mass spectrum



$\Phi \rightarrow \eta U$ with $U \rightarrow e^+e^-$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$



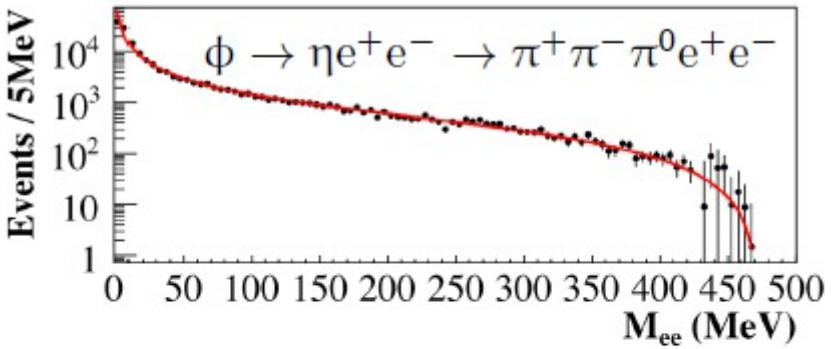
Phys. Lett B 706 (2012) 251-255
Phys. Lett B 720 (2013) 111-115

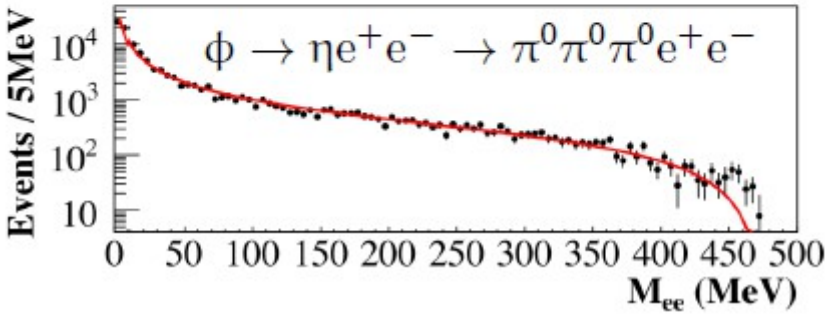
- UP limit with CLs
- $\Phi \rightarrow \eta e^+e^-$ background from fit to the sidebands.
- $\varepsilon = \alpha_D/\alpha_{EM}$ derived assuming the relation:

$$\sigma(\Phi \rightarrow \eta U) \sim \epsilon^2 |F_{\eta\Phi}(m_U^2)|^2 \sigma(\Phi \rightarrow \eta\gamma)$$

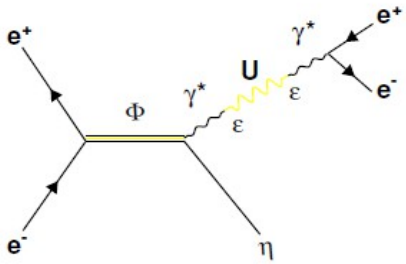
from *[Reece-Wang, JHEP0907:051 (2009)]*

Di-electron mass spectrum





$\Phi \rightarrow \eta U$ with $U \rightarrow e^+e^-$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$



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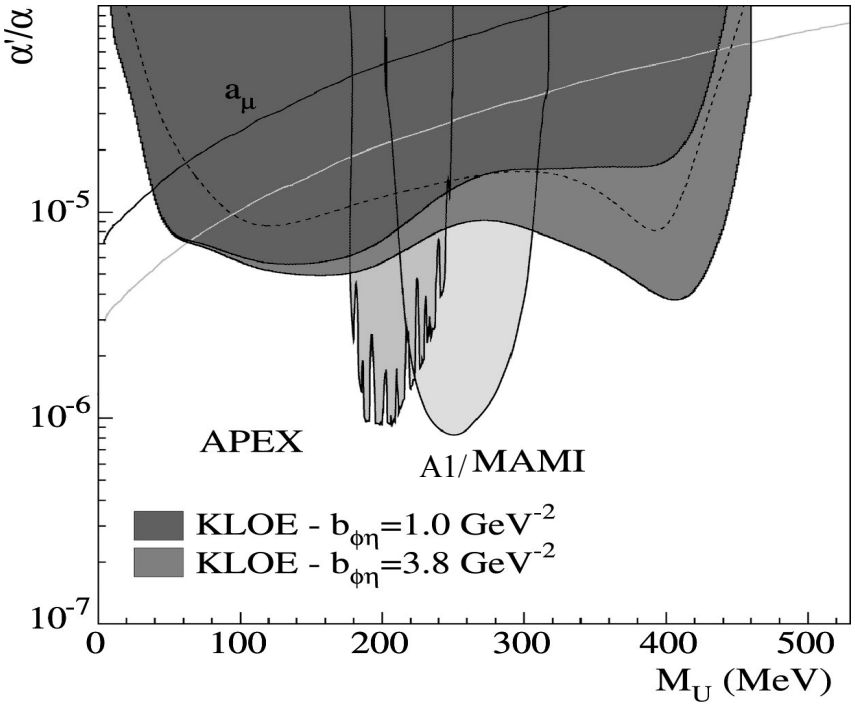

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$$\sigma(\Phi \rightarrow \eta U) \sim \epsilon^2 |F_{\eta\Phi}(m_U^2)|^2 \sigma(\Phi \rightarrow \eta\gamma)$$

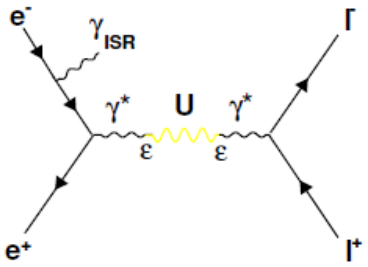
from *[Reece-Wang, JHEP0907:051 (2009)]*

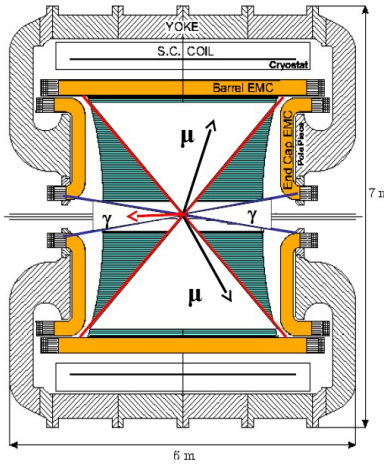
Slope factor from KLOE $b_{\Phi\eta} \sim 1.28$ GeV^{-2} *PLB 742(2015)*

Exclusion limit compared with:
- APEX *PRL 107 (2011)*
- A1/MAMI *PRL 106 (2011)*

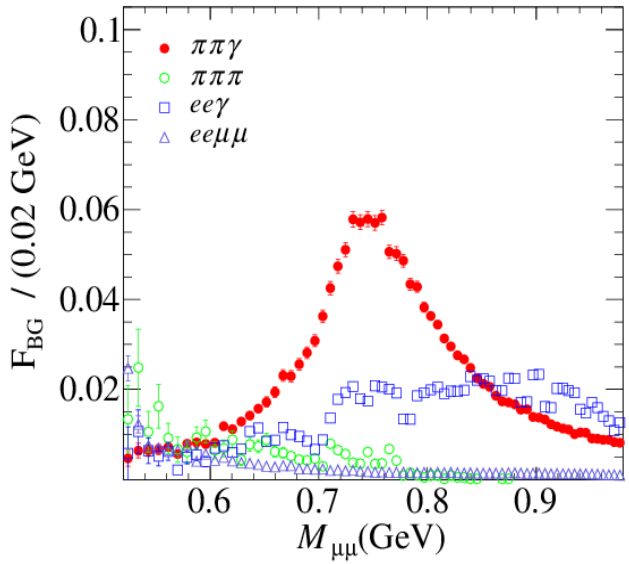
at the moment of the KLOE publication

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

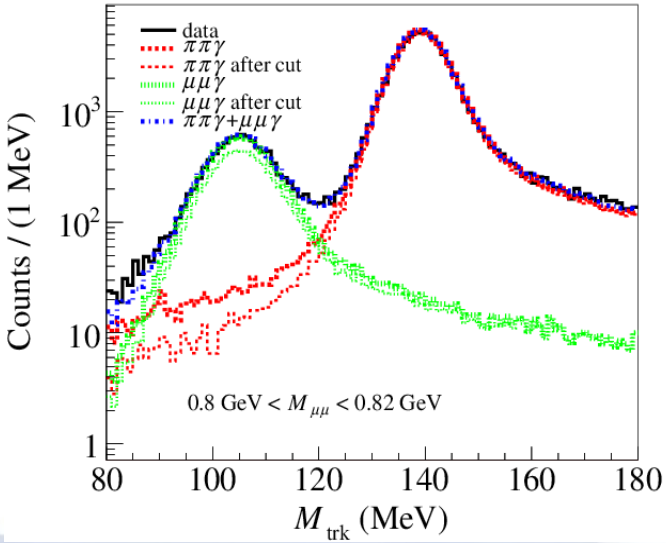




Phys. Lett B 736 (2014) 459-464



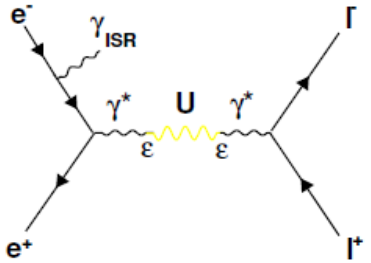
- Two opposite charged tracks within a cylind around IP
- $50º < \theta\mu < 130º$
- Undetected photon $\theta\gamma < 15º, >165º$
- High statistics ISR
- Strong suppression of FSR and $\Phi \rightarrow \pi^+\pi^-\pi^0$
- Good μ / π separation with M_{trk} and σ_{Mtrk}
  - M_{trk} = track mass assuming two equal mass charged particles and 1 γ in the final state



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

Phys. Lett B 736 (2014) 459-464

- Main sources of background
  - e+ e- $\rightarrow \pi^+ \pi^- \gamma(\gamma)$
  - e+ e- $\rightarrow e^+ e^- \gamma(\gamma)$
  - $\phi \rightarrow \pi^+ \pi^- \pi^0$
- UL evaluated from raw spectra. Total sys. uncertainty approx. 2%.
- CLs



Di-muon mass spectrum

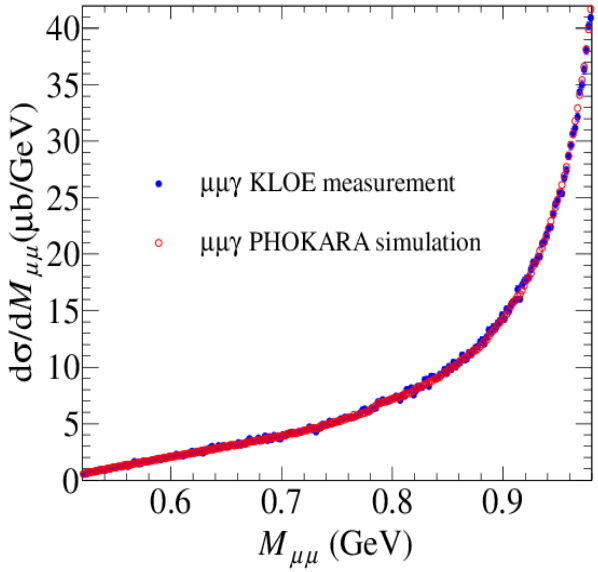
$$\epsilon^2 = \frac{\alpha'}{\alpha} = \frac{N_{CLs}}{\epsilon_{eff}} \frac{1}{H \cdot I \cdot L_{integrated}}$$

N_{CLs} = number of U boson signal events excluded at 90% C.L.

$$H = \frac{d\sigma_{\mu\mu\gamma}/dM_{\mu\mu}}{\sigma(ee \rightarrow \mu\mu, M)}$$

$$I = \int \sigma_U dM_U$$

$$L_{integrated} = 293.3\ pb^{-1}$$

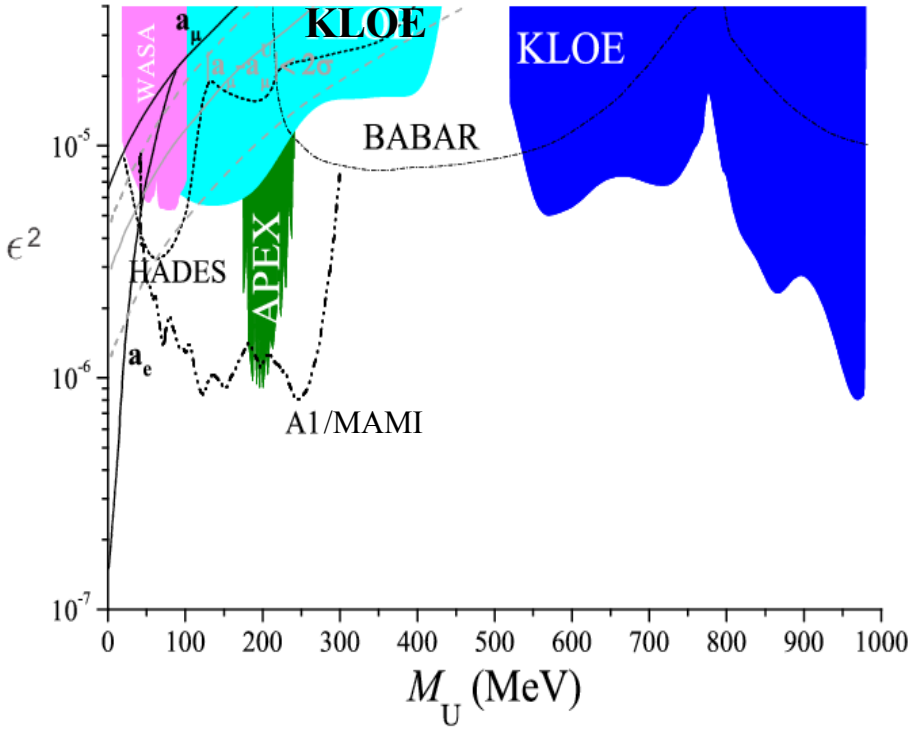


$e^+e^- \rightarrow U\gamma$ with $U \rightarrow \mu^+\mu^-$

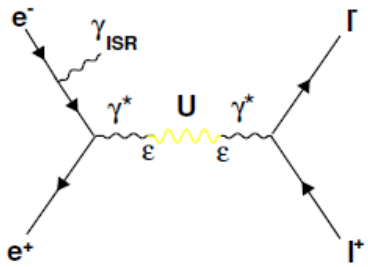
Phys. Lett B 736 (2014) 459-464

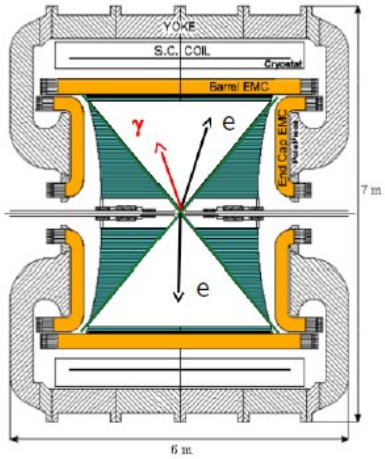
- UL on ε^2 compared to
  - BABAR Phys. Rev. Lett. 113 201801 (2014)
  - WASA PLB 726 (2013)
  - HADES PLB 731 (2014)
  - APEX PRL 107 (2011)
  - A1/MAMI Phys. Rev. Lett. 112 (2014)

At the moment of the KLOE publication



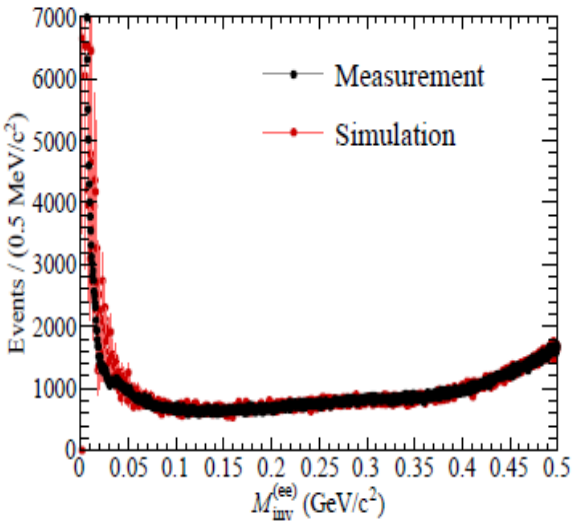
$e^+e^- \rightarrow U\gamma$ with $U \rightarrow e^+e^-$





- Two opposite charged tracks within a cylinder around IP
- $55^\circ < \theta_e < 125^\circ$
- detected photon $50^\circ < \theta_\gamma < 130^\circ$
- M_{trk} variable to separate electrons from muons and pions
- High statistics radiative Bhabha in KLOE
- Approx per mil level background contamination or even better

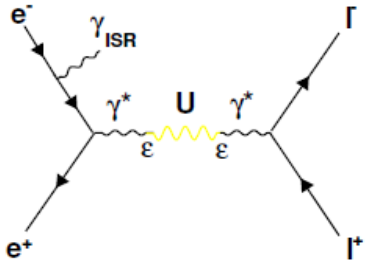
Di-electron mass spectrum



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

- CLs

$$\epsilon^2 = \frac{\alpha'}{\alpha} = \frac{N_{CLs}}{\epsilon_{eff}} \frac{1}{H \cdot I \cdot L_{integrated}}$$



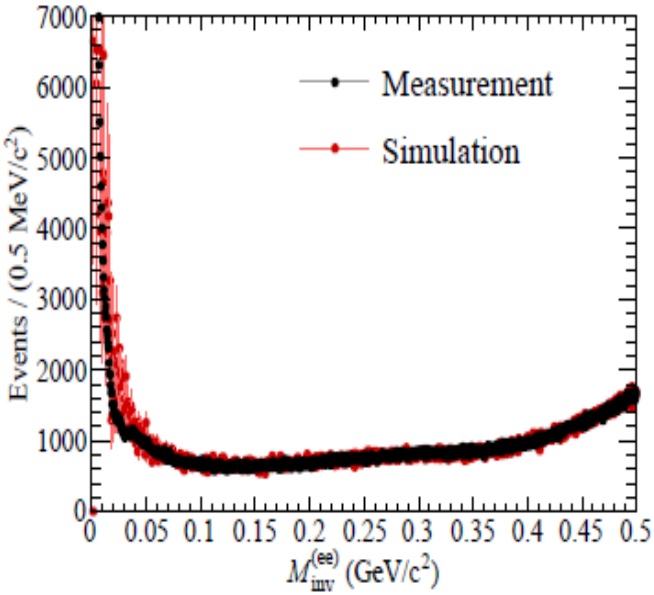
N_{CLs} = number of U boson signal events excluded at 90% C.L.

$$H = \frac{d\sigma_{ee\gamma}/dM_{ee}}{\sigma(ee \rightarrow ee, M)}$$

$$I = \int \sigma_U dM_U$$

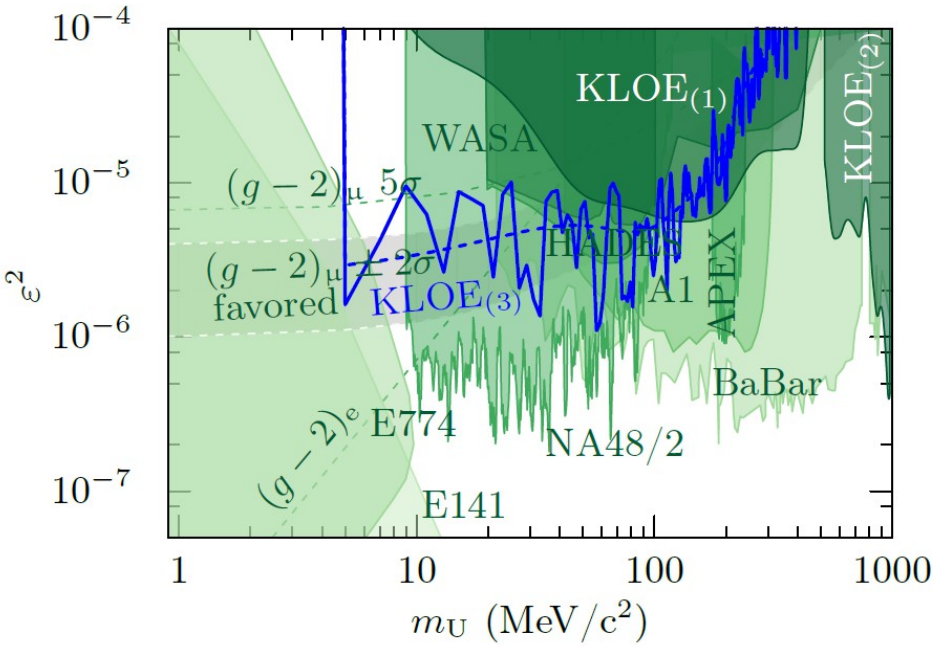
$$L_{integrated} = 1.54\ fb^{-1}$$

Di-electron mass spectrum



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

- UL on ε2 compared to
-
  - KLOE
  - BABAR *Phys. Rev. Lett. 113 201801 (2014)*
  - WASA *PLB 726 (2013)*
  - HADES *PLB 731 (2014)*
  - APEX *PRL 107 (2011)*
  - A1/MAMI *Phys. Rev. Lett. 112 (2014)*
  - NA48/2 *PLB 746 (2015)*



Higgsstrahlung process

Phys. Lett B accepted

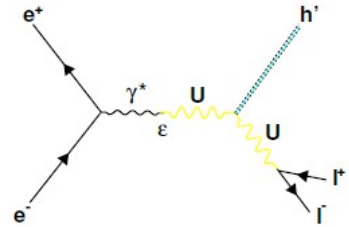
Two different scenarios:

- $m_{h'} > 2m_U$

with decays: $h' \rightarrow UU \rightarrow 4l, \pi+2l, \pi$

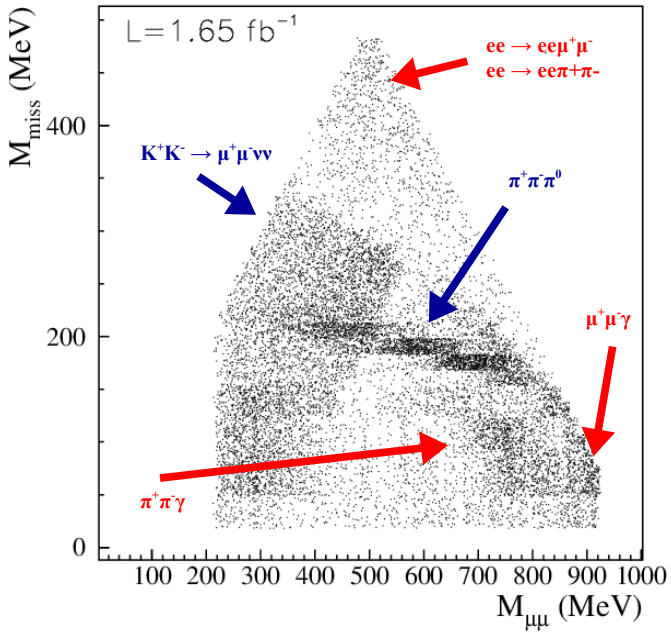
- $m_{h'} < 2m_U$

where h' is "invisible"



- Life time of the dark Higgs boson
- $\varepsilon = 10\text{-}3$
- $\alpha_D = \alpha_{em}$
- $m_{h',U} \sim 100$ MeV

- $\tau > 5\ \mu s \rightarrow \beta\gamma c\tau > 100$ m → h' would be invisible up to $\varepsilon \sim 10^{-2} \div 10^{-1}$ depending on $m_{h'}$

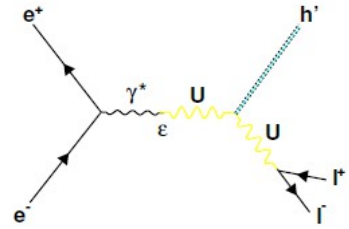


Final state: 2 muons + missing energy → enhancement in the M_{miss} vs $M_{\mu\mu}$ distribution

Higgsstrahlung process

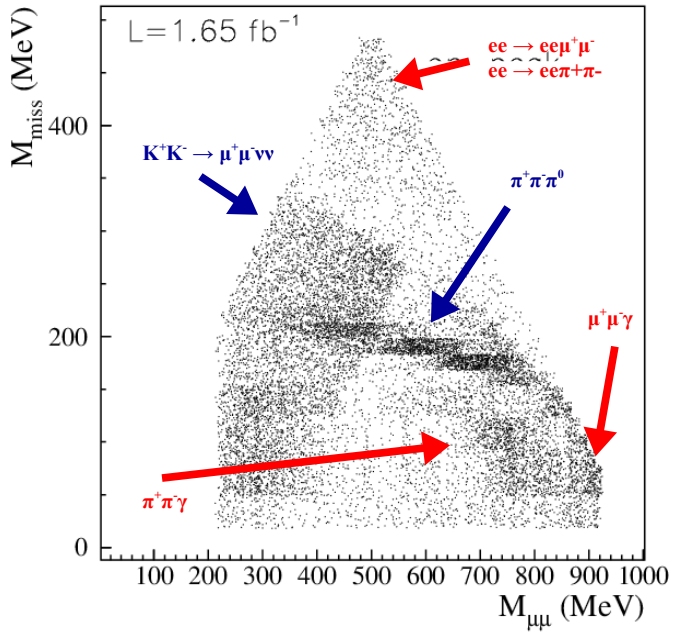
Phys. Lett B accepted

Final state: 2 muons + missing energy → enhancement in the M_{miss} vs $M_{\mu\mu}$ distribution



• Binning chosen such that 90-95% of signal would be in one bin

• Sliding 5x5 bin matrix (excluding the central bin used to checked the presence of a possible signal) used to determine background MC scale factors

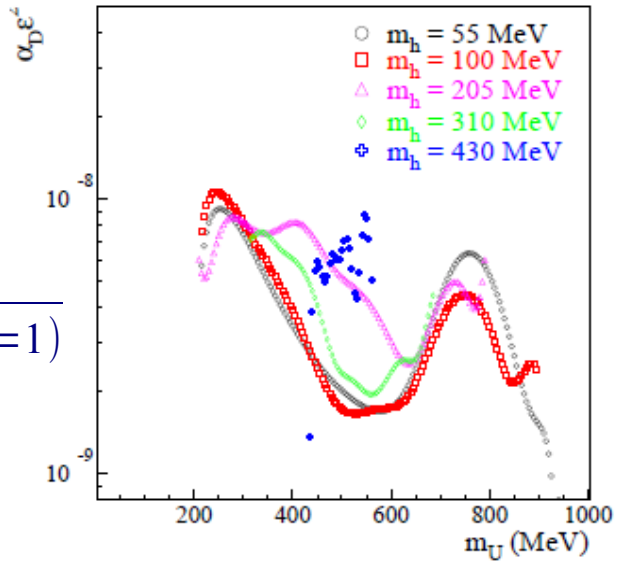


Higgsstrahlung process

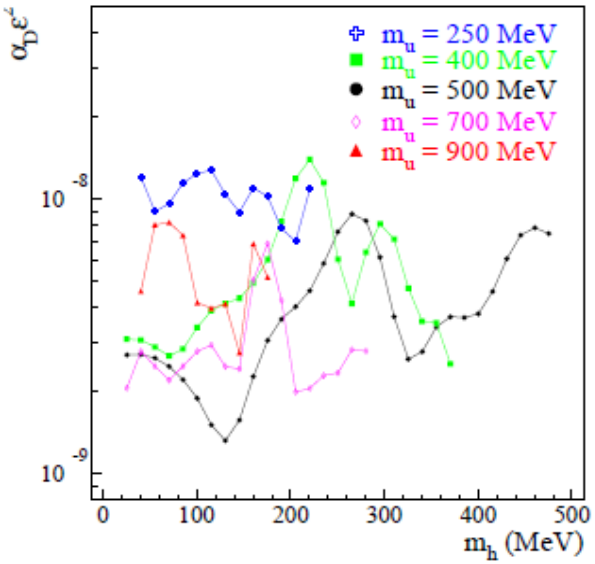
Phys. Lett B accepted

Combined results on- and off- peak data

$$\alpha_D \epsilon^2 = \frac{N_{90}}{\epsilon_{eff}} \frac{1}{L_{integrated} \cdot \sigma(\alpha_D \epsilon^2 = 1)}$$



Limit on $\alpha_D\varepsilon^2$ vs m_U at 90% CL



Limit on $\alpha_D\varepsilon^2$ vs $m_{h'}$ at 90% CL

Limits ~ $10^{-8} \div 10^{-9}$ in $\alpha_D\varepsilon^2$ (translate in $10^{-3} \div$ some 10^{-4} in ε if $\alpha_D = \alpha_{em}$)

Conclusions

- KLOE has extensively contributed to the U boson searches with (up to now) four different measurements:
  - $\Phi \rightarrow \eta U$ with $U \rightarrow e^+ e^-$ — Phys. Lett B 706 (2012) 251-255; Phys. Lett B 720 (2013) 111-115
  - $e^+ e^- \rightarrow U\gamma$ with $U \rightarrow \mu^+ \mu^-$ — Phys. Lett B 736 (2014) 459-464
  - $e^+ e^- \rightarrow Uh'$ with $h' \rightarrow$ invisible — Phys. Lett B submitted
  - $e^+ e^- \rightarrow U\gamma$ with $U \rightarrow e^+ e^-$ — Draft Paper

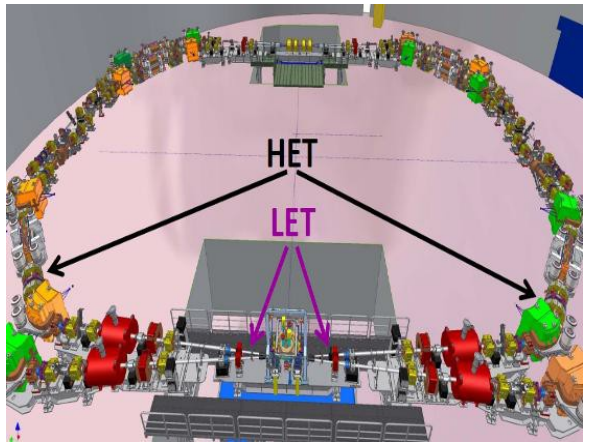
- Setting limits on ε^2 in the mass range $5\ \text{MeV} < m_U < 980\ \text{MeV}$
- As well as on $\alpha_D \varepsilon^2$ in the mass range $2m_\mu < m_U < 1000\ \text{MeV}$
- KLOE-2 has started a new data campaign in November 2014
  - It will collect more than 5 fb^{-1} within the next 3 years

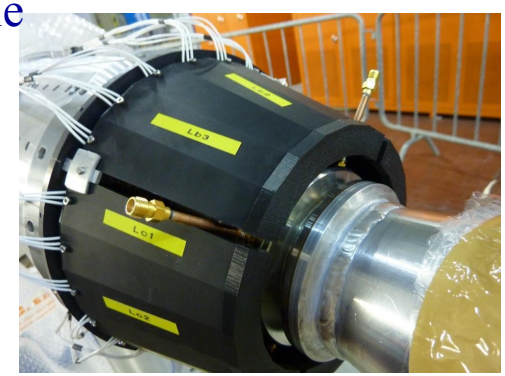
BACKUP SLIDES

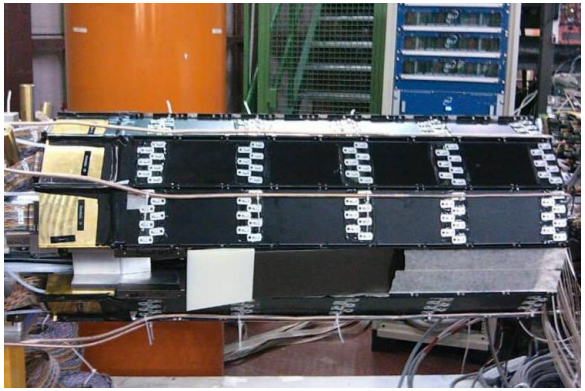
KLOE-2 Upgrade

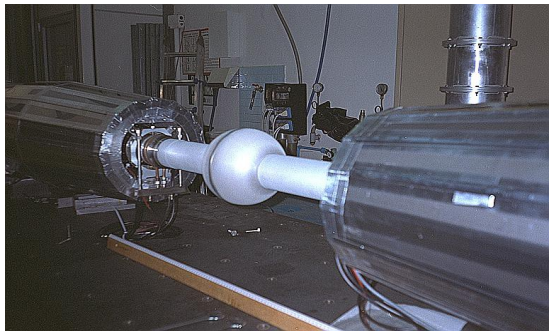
- KLOE-2 new data taking campaign started on November 2015
- It will collect more than 5 fb^{-1} within the next 3 years
- New detectors fully operative

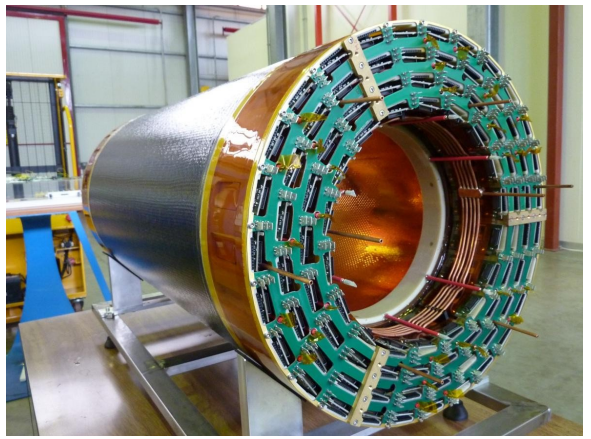
- LET & HET
  - e+e--taggers for γγ-physics
- CCALT & QCALT
  - 2 new calorimeters (for low angle γs & s from K_L decays)
- IT
  - 4 layers of C-GEM
  - better vertex reconstruction and larger low p_t track acceptance









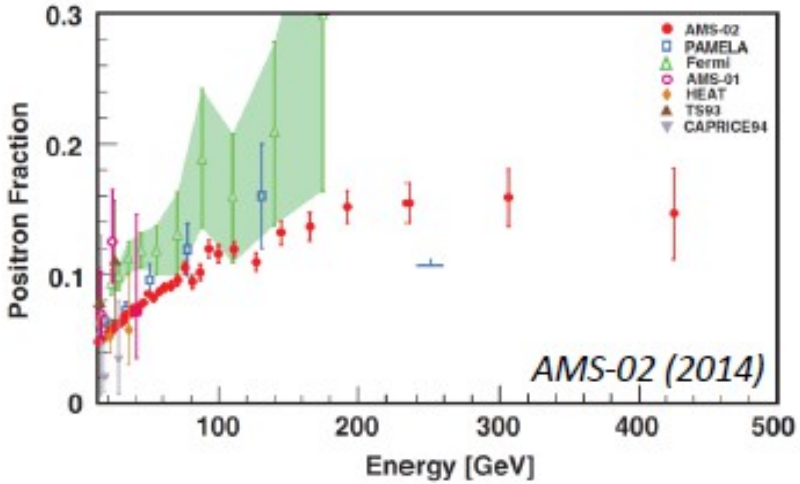


Motivations for new GeV-scale forces

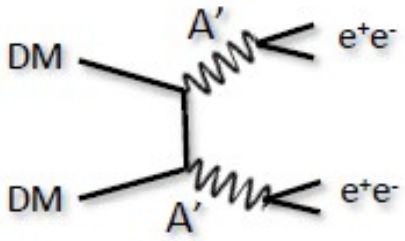
Dark matter indirect detection anomalies

e.g. Pamela/AMS-02 positron excess

Pospelov & Ritz (2008); Arkani-Hamed et al (2008)

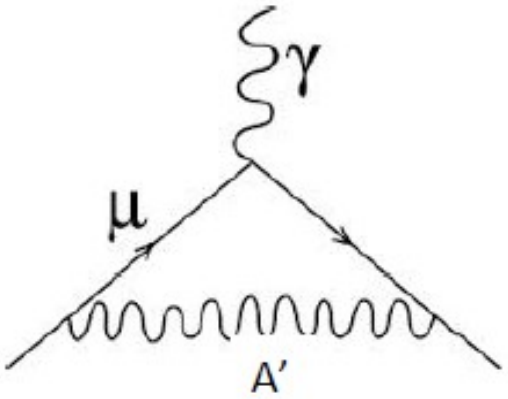


Dark matter annihilation

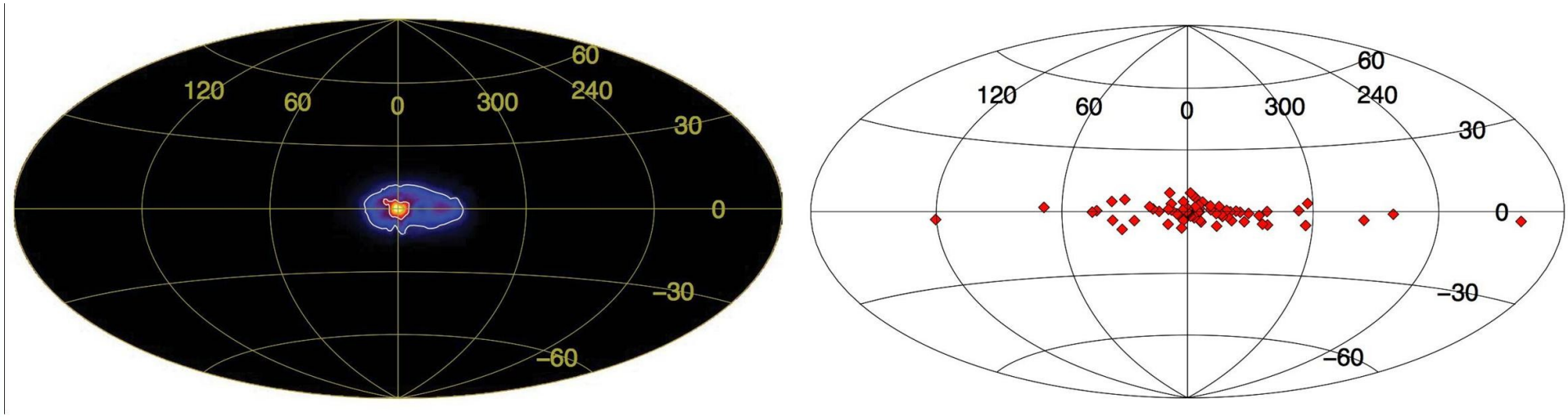


$(g-2)_\mu$ anomaly

Pospelov (2008)



Motivations for new GeV-scale forces



The left-hand panel shows the glow of 511 keV gamma rays coming from the annihilation of electrons by their antimatter counterparts, the positrons of the Milky Way observed by SPI. The map shows the entire sky, with the galactic centre at the middle. The emission can be seen extending towards the right-hand side of the map. The color code shows the intensity of the signal (white more intense). The right-hand panel shows the distribution of hard low mass X-ray binary stars detected by IBIS/ISGRI telescope on board INTEGRAL satellite. This stellar population has a distribution that matches the extent of the 511 keV map.
(Credits: Integral CEA and CESR team)

Motivations for new GeV-scale forces

CoGeNT scattering cross sections with nucleus

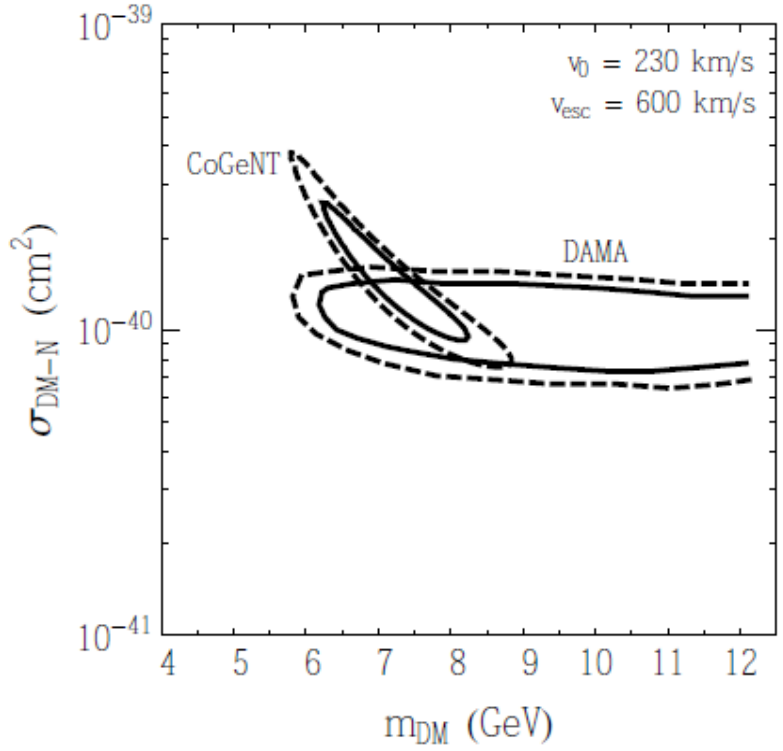
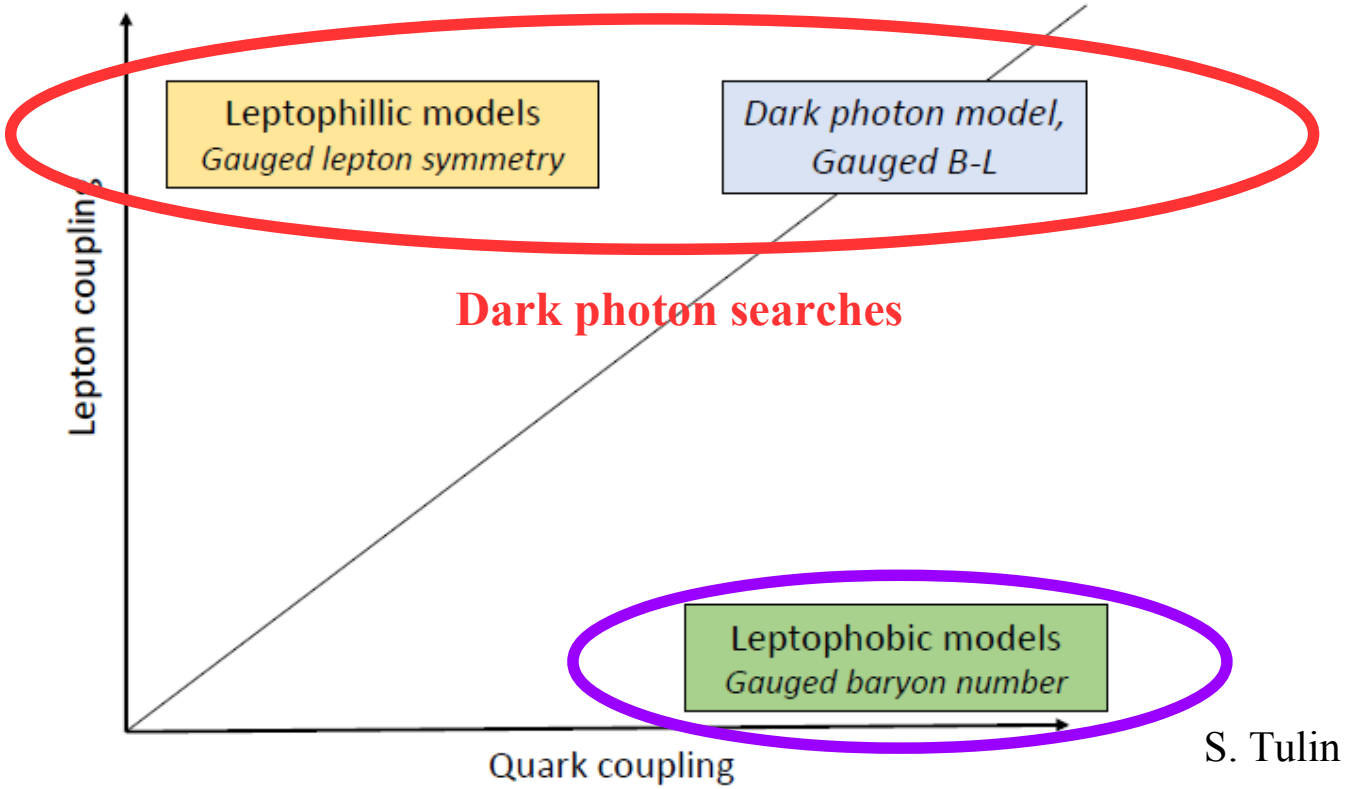


FIG. 6: A comparison of the parameter space favored by the CoGeNT spectrum with that favored by the modulation spectrum reported by DAMA/LIBRA [7]. Good agreement is found, but somewhat large quenching factors for low energy nuclear recoils on sodium are required ($Q_{Na} \sim 0.40-0.45$) [7].

New GeV-scale forces

- U searches don't cover all possible scenarios
- Room for new gauge boson searches



S. Tulin

Also a 3rd axis with invisible decays (neutrinos, light dark matter)

Leptophobic B boson: new force coupling to quarks

- B boson couples mainly to quarks
- Most basic model → coupling to baryon number

$$\mathscr{L} = \frac{g_B}{3}\,\bar{q}\gamma^\mu q B_\mu$$

$$g_B \lesssim 10^{-2} \times (m_B/100\ \mathrm{MeV})$$

$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\,\mathrm{MeV})^2$$

- Literature:
  - Radjoot (1989), Foot et al (1989), Nelson & Tetradis (1989), He & Rajpoot (1995), Bairley & Davidson (1995), Aranda & Carone (1998), Fileviez Perez & Wise (2010), Graesser et all (2011),Dobrescu & Frugiule (2014), Batell et all (2014), **S. Tulin (Phys. Rev. D 89, 114008 (2014))**
- Discovery signal depends on mass m_B

Leptophobic B boson

- **B boson decays**

KLOE searches

S. Tulin ArXiv:1404.4370

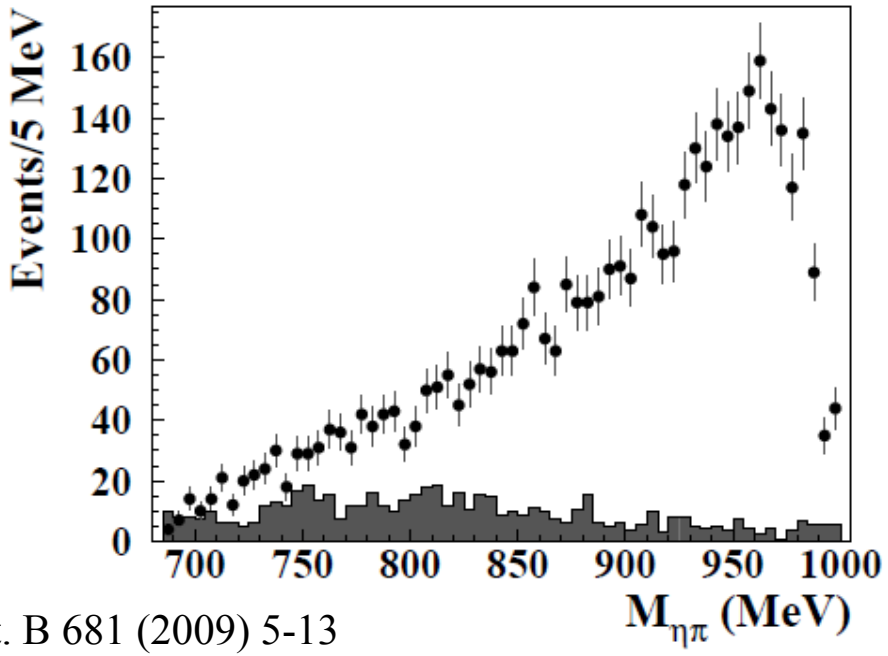
Decay → Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	

Covered by dark photon searches

New signals

B boson search at KLOE

- $\Phi \rightarrow \eta B$ with $B \rightarrow \pi^0\gamma$
  - Channel used for a0(980) scalar meson
- Look for resonance in $\pi^0\gamma$ invariant mass
- 2001/2002 data analysis
  - ~ 13000 Φ events after background subtraction



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