KLOE/KLOE-2 results and perspectives on dark force search

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On behalf of the KLOE-2 collaboration

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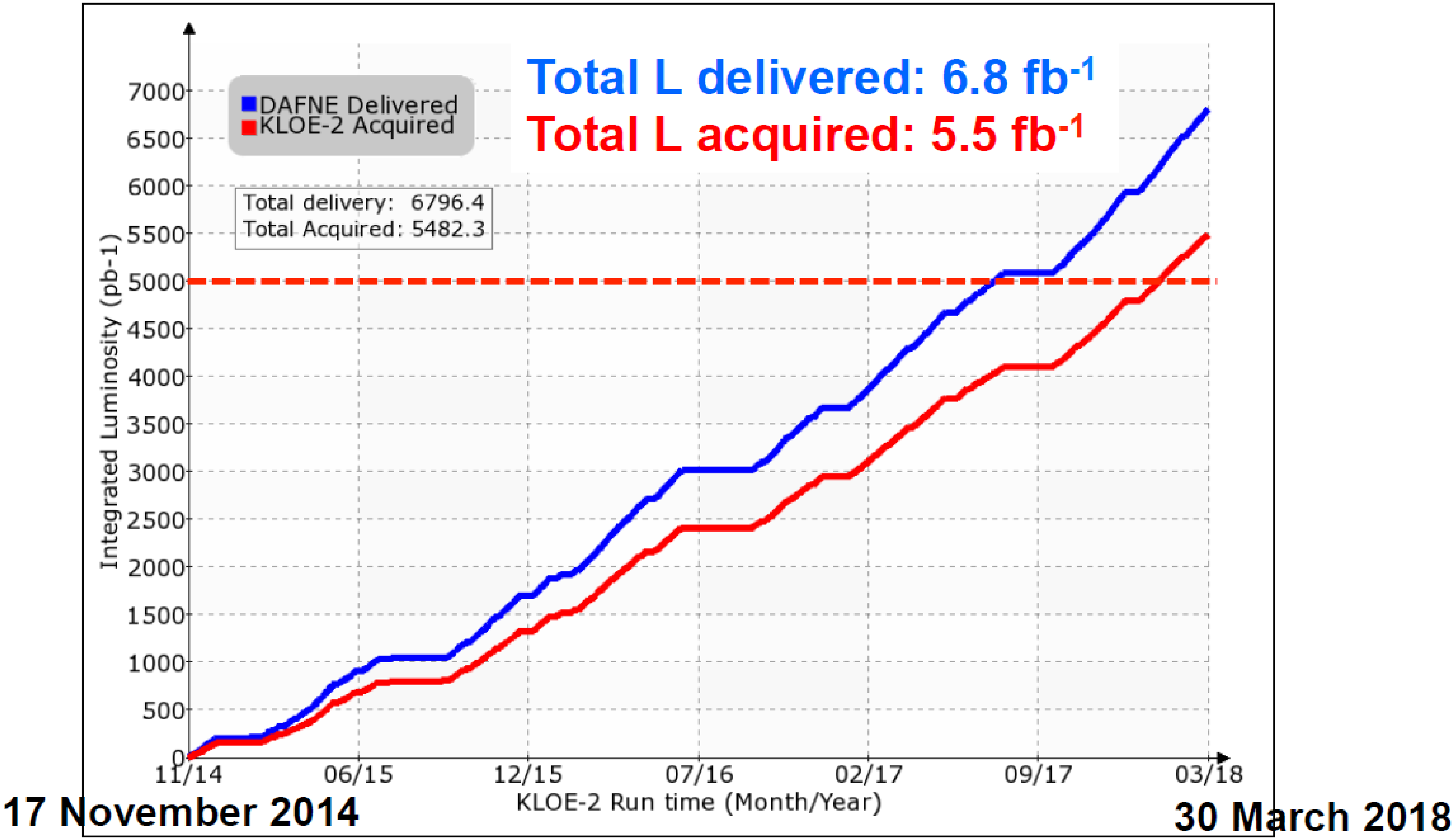
Probing the dark sector

- Experimental searches for Dark Forces can be achieved at:
  - e+e- colliders
    - Rare meson decays
    - Continuum
  - Beam dump and fixed target experiments

- KLOE/KLOE-2 is in a very good position to probe the dark sector at GeV scale:
  - It operates at DAFNE at $\sqrt{s} \sim 1$ GeV
  - Most of the interesting dark process cross sections at e+e- colliders scale with 1/s: a factor ~ 100 wrt B factories, compensating for the integrated luminosity
  - DAFNE is a Φ factory → unique environment to study rare meson decays

KLOE-2



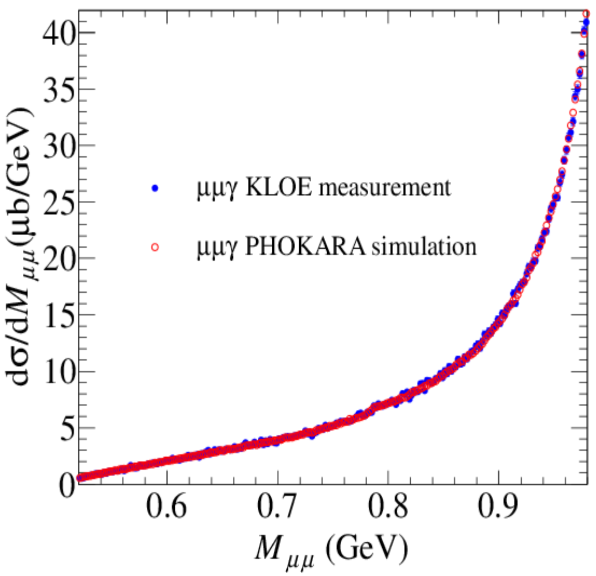
- KLOE-2 data campaign finished 31st March
- Collected 5.5 fb^{-1}
- KLOE + KLOE-2 ~8fb^{-1} → 2.4 10^{10} **Φ Largest Sample in a Φ-factory**
- Single PHoton Trigger dedicated to new DM searches

KLOE Dark Searches Summary

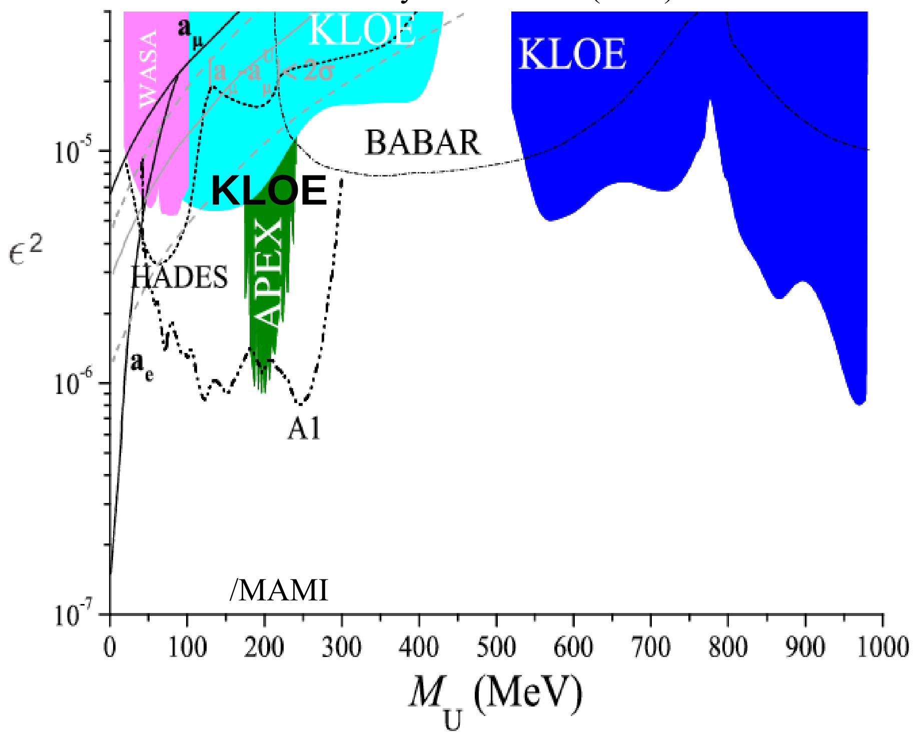
- KLOE searches:
  - Decay of the φ meson into a U boson + pseudoscalar η
    - $\varphi \to \eta U$ with $U \to e^+ e^-$ Phys. Lett B 706 (2012) 251-255; Phys. Lett B 720 (2013) 111-115
  - Associated Uγ production
    - $e^+ e^- \to U\gamma$ with $U \to \mu^+ \mu^-$ Phys. Lett B 736 (2014) 459-464
    - $e^+ e^- \to U\gamma$ with $U \to e^+ e^-$ Phys.Lett. B750 (2015) 633
    - $e^+ e^- \to U\gamma$ with $U \to \pi^+ \pi^-$ Phys.Lett. B757 (2016) 356-361
    - Combined analysis $\mu^+ \mu^-$ - $\pi^+ \pi^-$ Submmitted Phys.Lett. B
  - Higgsstrahlung process, in the m(h′)<m(U) scenario, with a dark Higgs invisible decay
    - $e^+ e^- \to Uh'$ with $h' \to$ invisible Phys.Lett. B747 (2015) 365-372

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

Di-muon mass spectrum



Phys. Lett B 736 (2014) 459-464



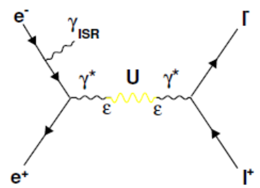
Results based on ~ 240 pb^{-1}
UL evaluated from raw spectra with CLs technique. Total sys. uncertainty approx. 2%.

Result updated with full KLOE statistics 1.93 fb^{-1} (see next slides)

A further factor of 2 in sensitivity expected from KLOE-2 experiment

- 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

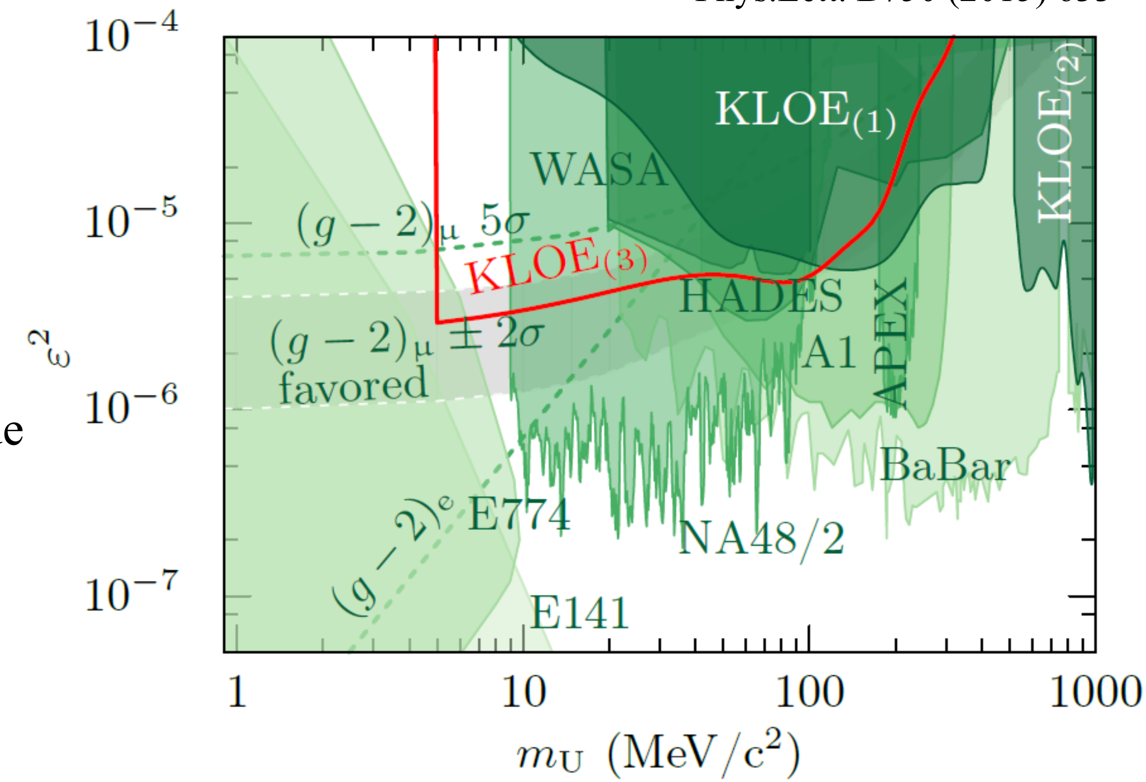


$e^+e^- \rightarrow U\gamma$ with $U \rightarrow e^+e^-$

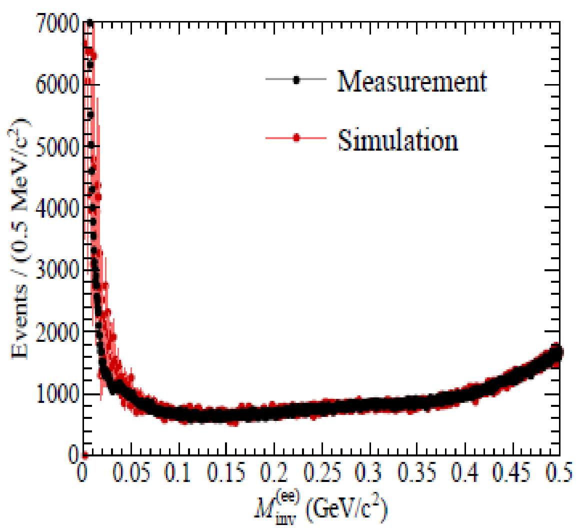
Phys.Lett. B750 (2015) 633

- High statistics radiative Bhabha in KLOE
- Approx per mil level background contamination or even better

Babayaga-NLO simulation (with weighted events)
Background estimated from data
No peak observed → UL CLs technique



Di-electron mass spectrum



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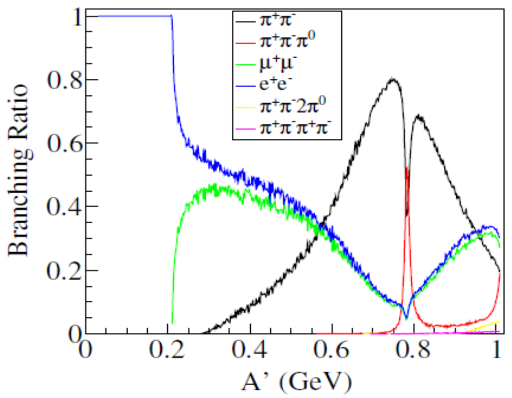
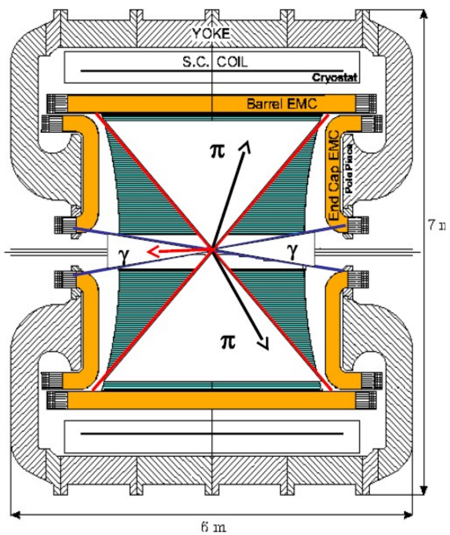
  - A1/MAMI Phys. Rev. Lett. 112 (2014)
  - NA48/2 PLB 746 (2015)

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



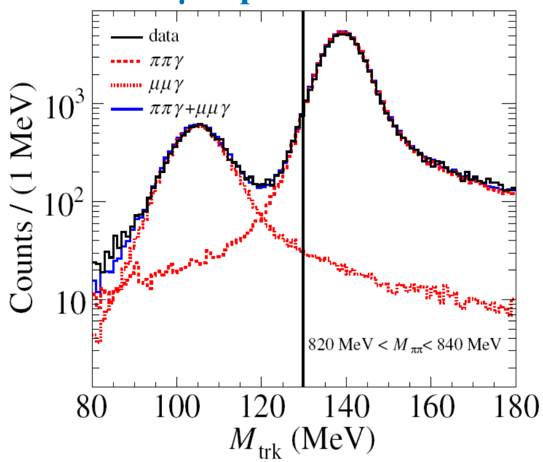
Phys.Lett. B757 (2016) 356-361



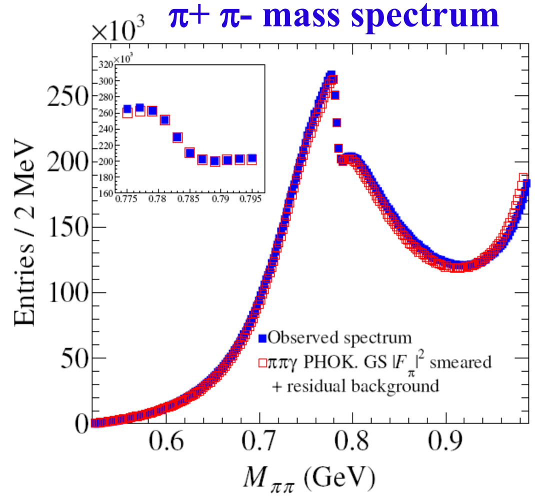
two opposite sign charged tracks $50° < \theta_\pi < 130°$

undetected small angle photon $\theta_\gamma < 15°$, $\theta_\gamma > 165°$

π/μ separation



π+ π- mass spectrum



L=1.93 fb^{-1}

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

- KLOE
  - (1) Dalitz decay *PLB 720 (2013)*
  - (2) $U \rightarrow \mu^+\mu^-$ *PLB 736 (2014)*
  - (3) $U \rightarrow e^+e^-$ *PLB 750 (2015)*
  - (4) $U \rightarrow \pi^+\pi^-$ *PLB 757 (2016)*
- BABAR *PRL 113 201801 (2014)*
- WASA *PLB 726 (2013)*
- HADES *PLB 731 (2014)*
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- NA48/2 *PLB 746 (2015)*

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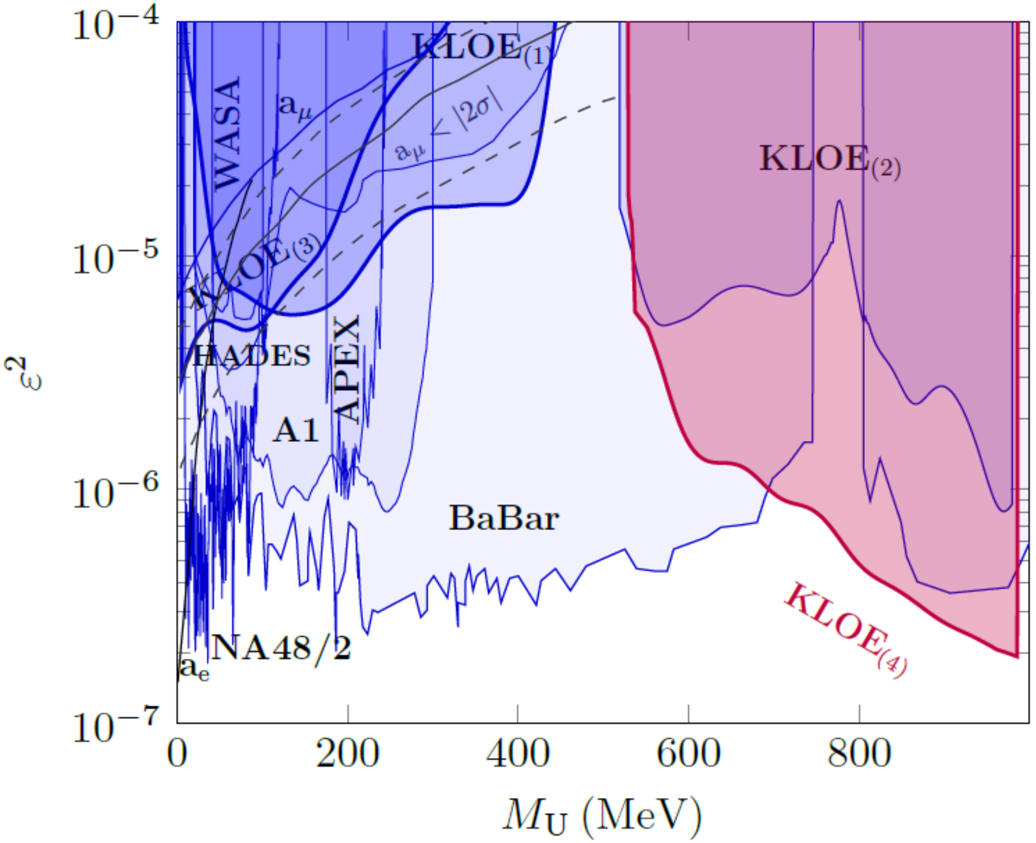
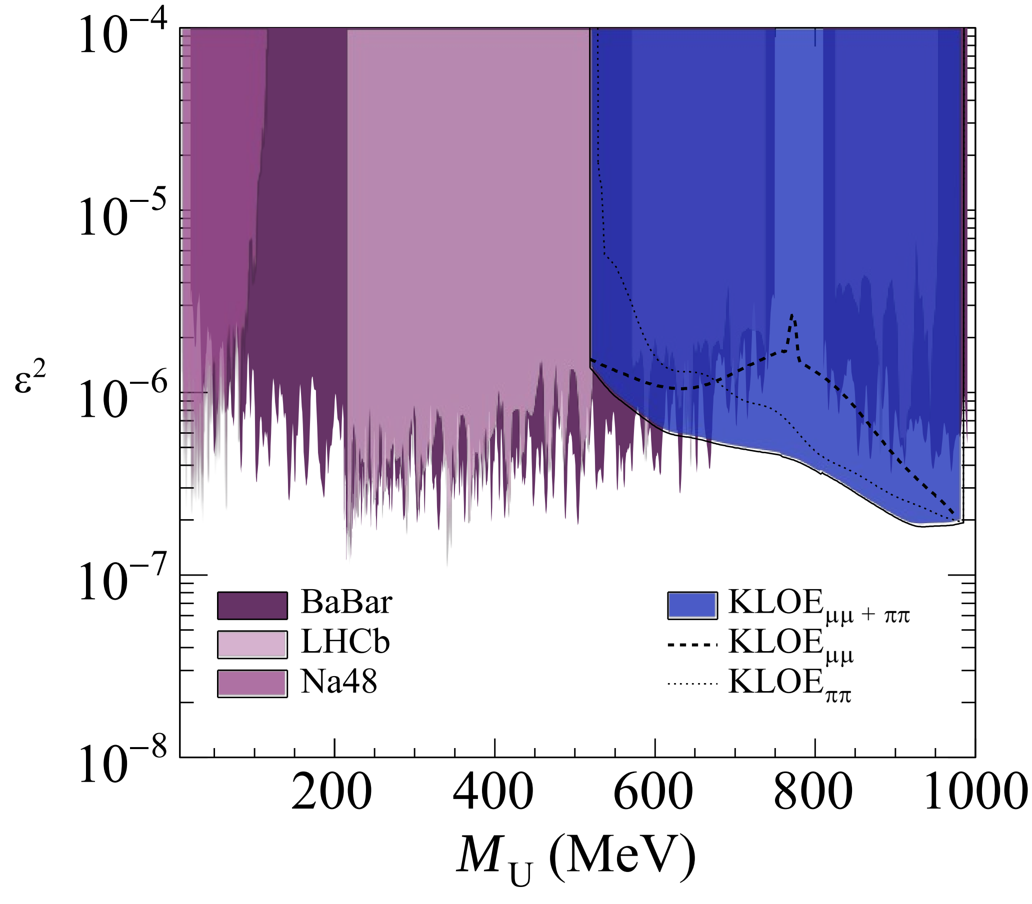


Combined $U\gamma$ with $U \to \mu^+\mu^-/\pi^+\pi^-$

- New $\mu\mu\gamma$ limit at full KLOE statistics
- $\pi\pi\gamma$ limit at the same luminosity (1.93 fb^{-1})
- Combining procedure requires:
  - Double inputs of data, expected background, U signal and systematical errors
  - Info on different efficiency and U decay branching fractions: BR($U \to \mu\mu, \pi\pi$)
- Combined limit extracted by means of CLs Technique
- The limit on ε^2 is extracted when $N^{tot}_U = N^{\mu\mu}_U + N^{\pi\pi}_U$ reaches CLs < 0.1

Best limit in the 600 MeV – 1000 MeV mass region

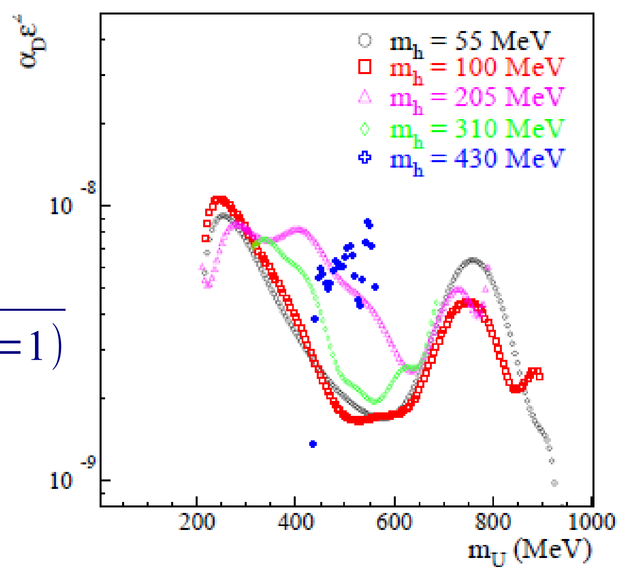


Higgsstrahlung process

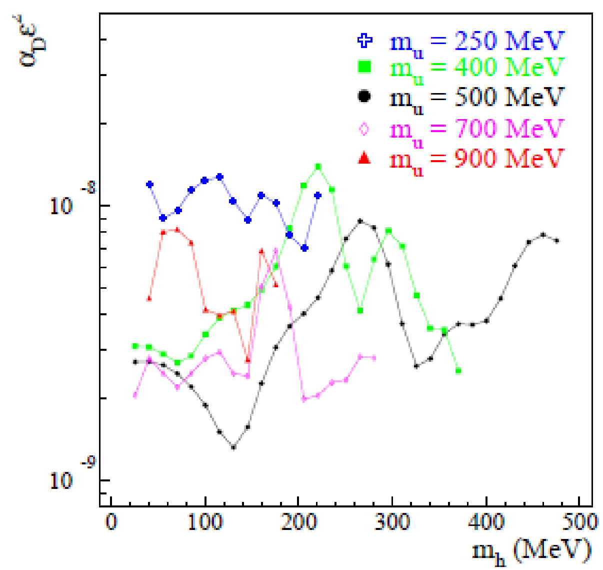
Phys.Lett. B747 (2015) 365-372

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

New GeV-scale forces

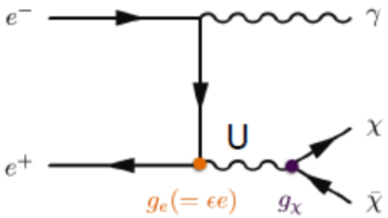
- U searches don't cover all possible scenarios
- Room for new gauge boson searches
  - Leptophobic gauge bosons
  - DM invisible decays:
    - Neutrinos
    - LDM (Light Dark Matter)
    - …
  - ...

Single Photon Trigger

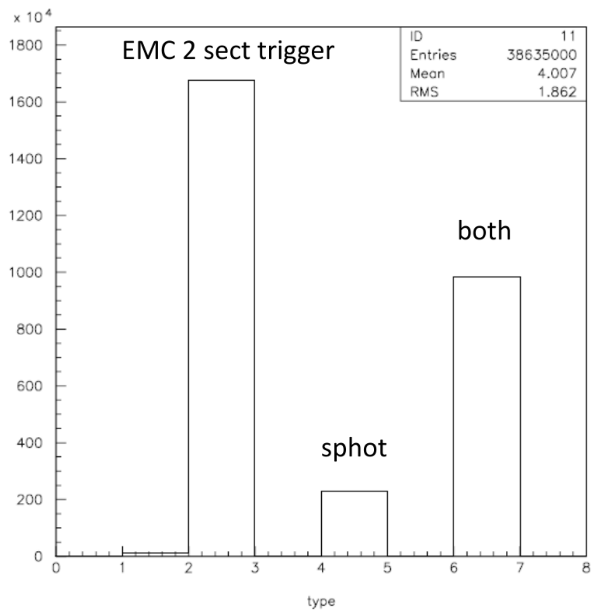
- KLOE-2 new trigger: Single Photon Trigger (SPHOT) has been implemented

- Dedicated to axion / Dark Matter forces searches in invisible decays

- Single photon trigger events:
  - One photon + missing energy

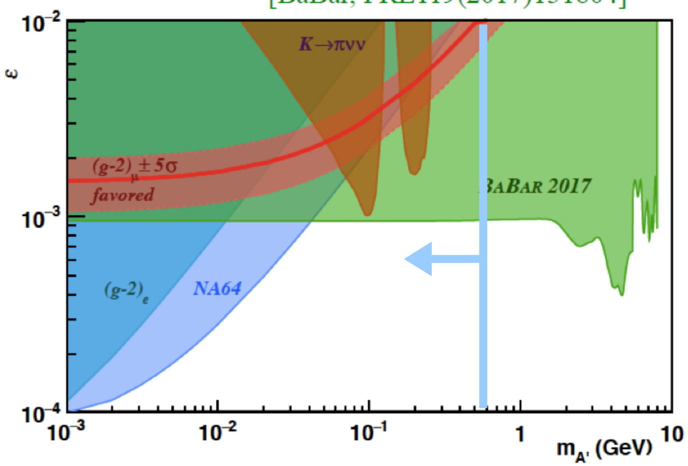


$\chi \equiv$ very light dark matter



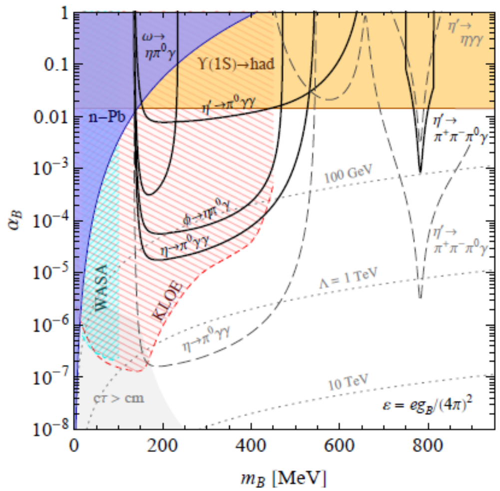
- The production mechanism (bremsstrahlung) favors low masses
  - Opens studies in lower mass region
- Opens searches for long living ALPs by looking for $1\gamma + M^2_{miss}$ final states

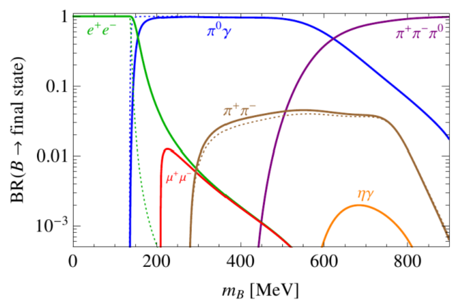
[BaBar, PRL119(2017)131804]



Leptophobic Dark Matter mediator search with KLOE-2

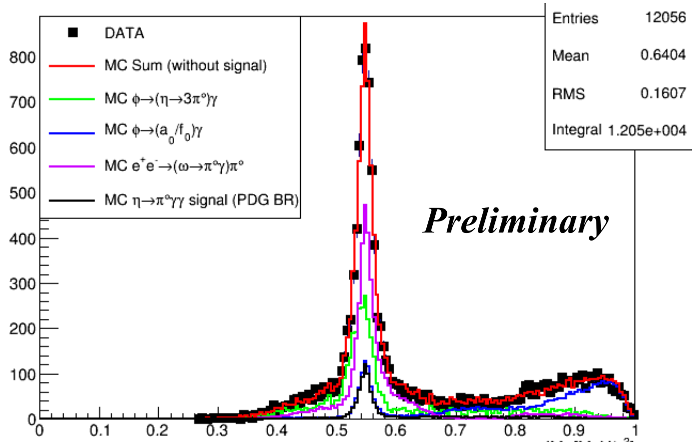
S. Tulin (Phys. Rev. D 89, 114008 (2014))





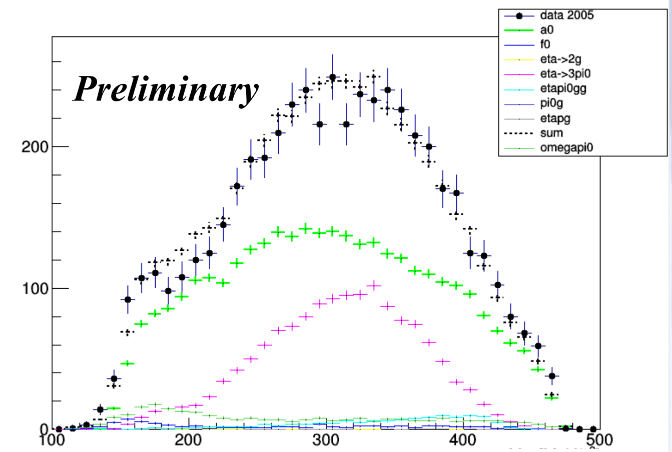
- Φ → η B with B → $\pi^0\gamma$ already under study with full KLOE statistics
  - Same final state as a0(980) scalar meson *Phys. Lett. B 681 (2009) 5-13*
  - also η→Bγ ⇒ $\pi^0\gamma\gamma$, and $e^+e^- \to \pi^0\gamma\,\gamma_{ISR}$
- Look for resonance in $\pi^0\gamma$ invariant mass
- KLOE analysis of the a0(980) meson extrapolates to a factor of ~3 improvement in $\pi^0\gamma$ invariant mass sensitivity for the upper limit calculation with the KLOE-2 data

Φ → Bγ



M(4γ) [GeV]

Φ → η B



M(3γ) [GeV]

KLOE searches

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	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	

Conclusions

- KLOE has extensively contributed to the U boson searches with (up to now) six different analysis:
  - $\varphi \rightarrow \eta U$ 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
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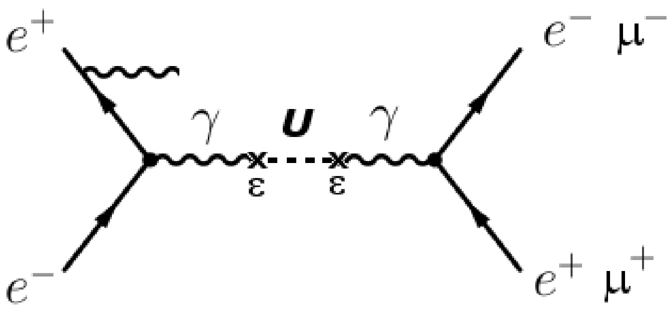
  - $e^+ e^- \rightarrow U\gamma$ with $U \rightarrow \pi^+ \pi^-$ Phys.Lett. B757 (2016) 356-361
  - Combined analysis $\mu^+ \mu^- / \pi^+ \pi^-$ with increased statistics and sensitivity on ε^2 in the mass range where the dark photon mixes with the rho meson
- Setting limits on ε^2 in the mass range $5 \text{ MeV} < m_U < 980 \text{ MeV}$
- As well as on $\alpha_D \varepsilon^2$ in the mass range $2m_\mu < m_U < 1000 \text{ MeV}$
- With the higher integrated luminosity and the presence of the new detectors in KLOE-2 it is expected to improve these limits by a factor ~2 or better.
- New searches
  - Single photon trigger.
  - Leptophobic models: B boson.

BACKUP SLIDES

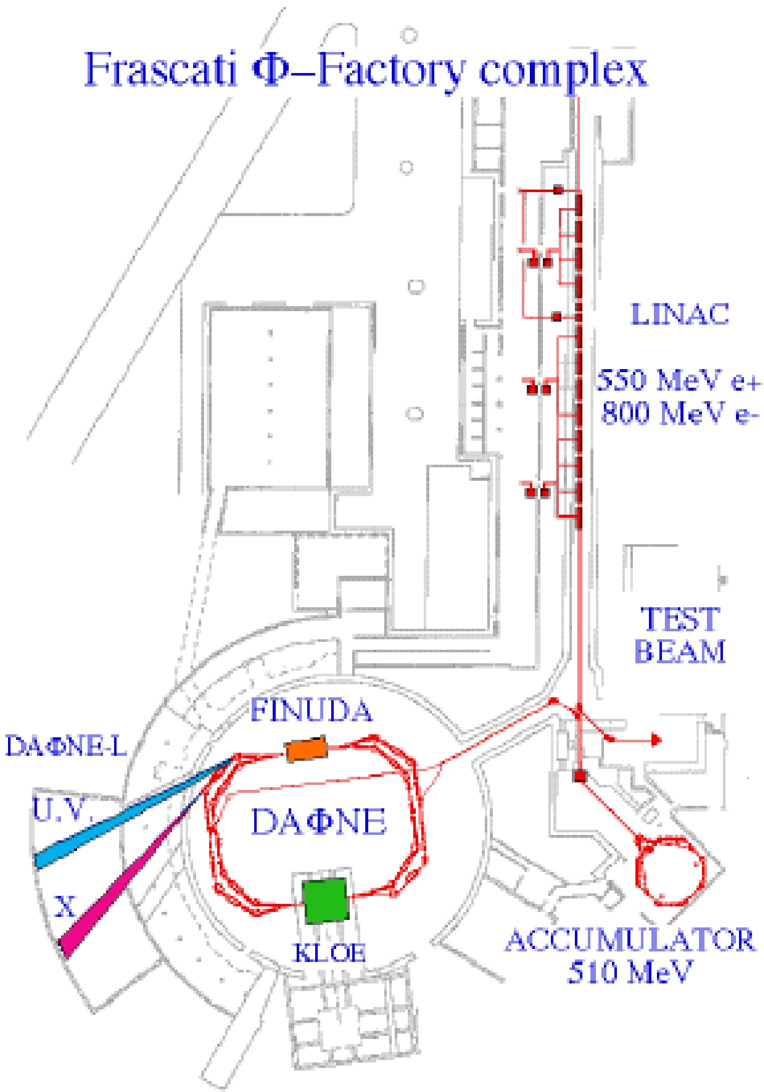
Probing the dark sector – Why?

- 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
- 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:

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

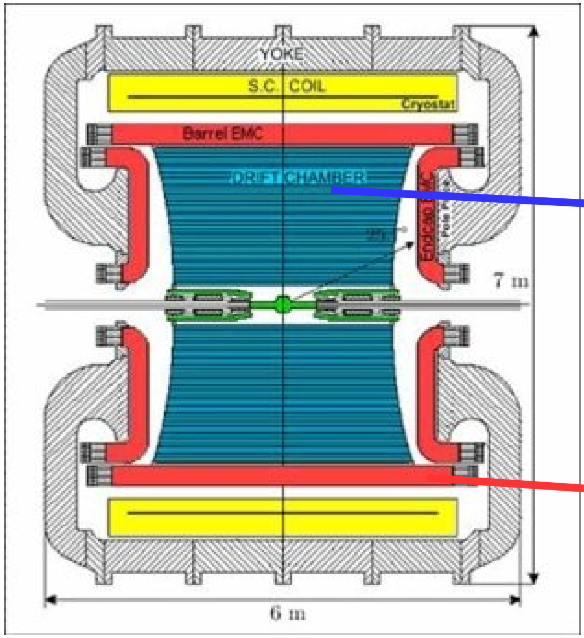


DAΦNE
(Double Annular Φ Factory for Nice Experiments)



- Running period: 1999 – 2006
- $e^+ e^-$ collider $\sqrt{s} = M_\varphi = 1019.4$ 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)

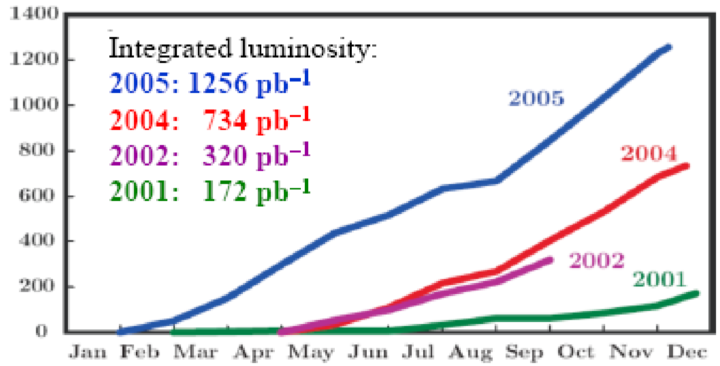


Magnetic field B = 0.52 T

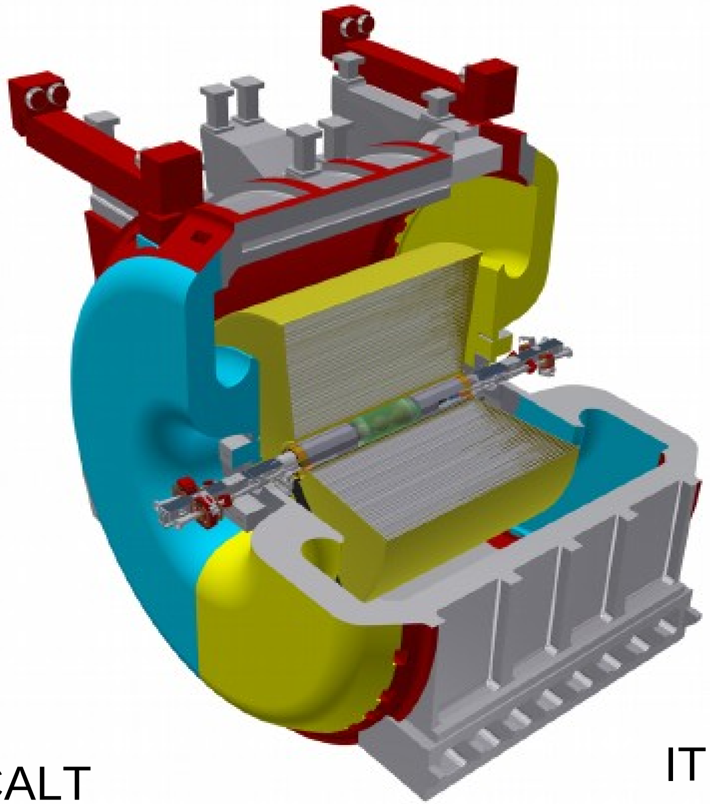
- Low-mass gas mixture 90% Helium + 10% isobutane
- $\delta p_\perp / p_\perp < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- 12582 sense wires
- Stereo geometry
- 4m diameter, 3.3m long

- 98% full solid angle coverage
- $\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_T = 57$ ps / $\sqrt{E(GeV)} \oplus 100$ ps
- Barrel + 2 end-caps:
  - Pb/scintillating fiber read out by 4880 PMTs

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



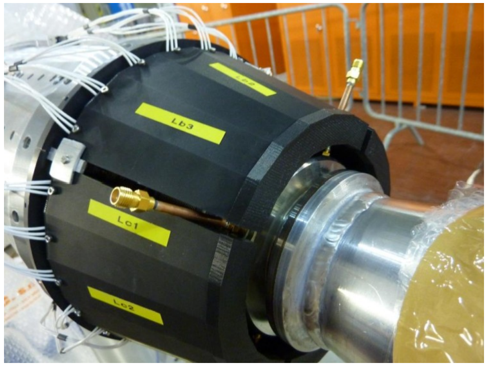
KLOE-2



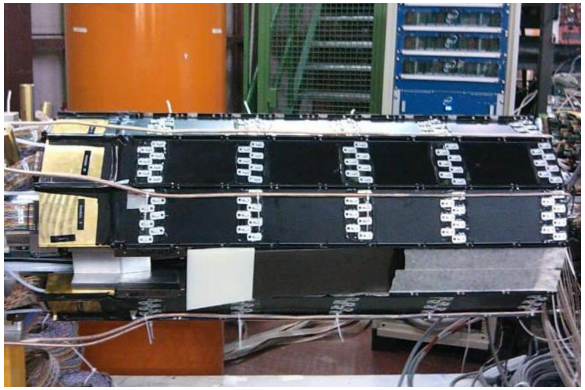
• CCALT (lyso-cristals) & QCALT (scintillator tiles and fibers with SiPM read-out)
  - 2 new calorimeters
  - Improvement acceptance at low polar angles
  - QUADS instrumentation for K_L decays

• Inner Tracker (IT)
  - 4 layers of triple Cylindrical-GEM
  - To improve vertex resolution at the IP
  - Larger acceptance for low p_t track acceptance

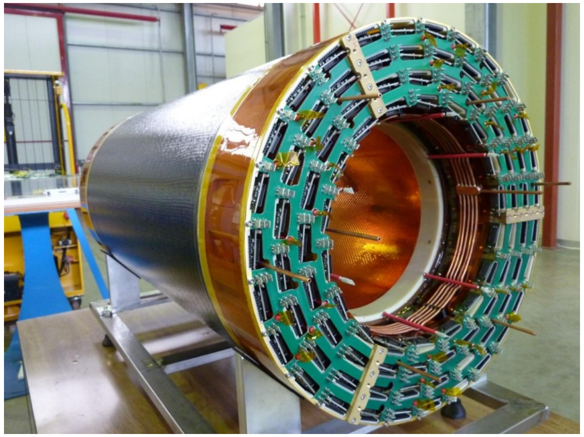
CCALT



QCALT

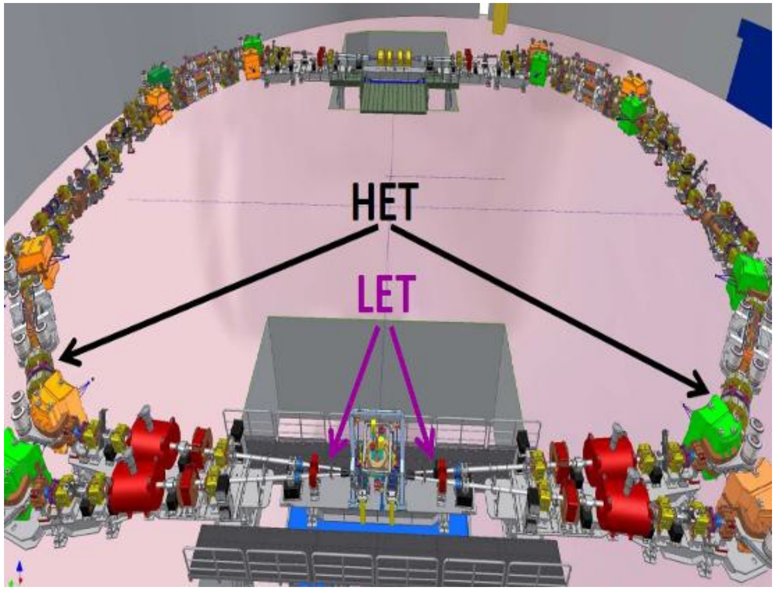


IT

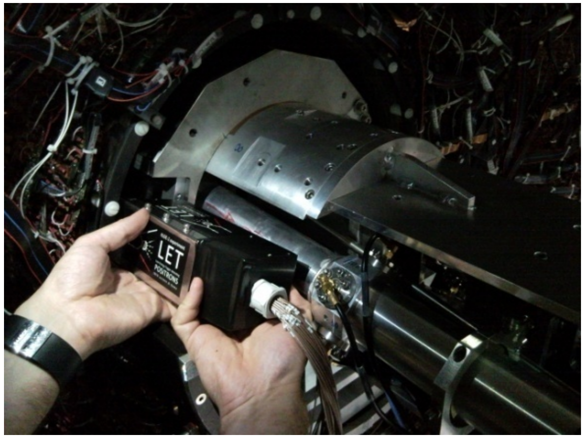


KLOE-2

- LET & HET
  - 2+2 e+e- tagger stations for γγ-physics
  - High Energy Taggers (HET)
    - Scintillator + PMT
    - 11 m from IP
    - E > 400 MeV
  - Low Energy Taggers (LET)
    - E = 160 – 230 MeV
    - Inside KLOE detector
    - LYSO with SiPM read-out



LET



HET

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)
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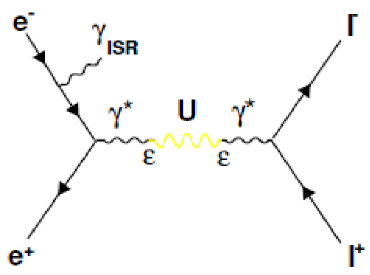


- CLs

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

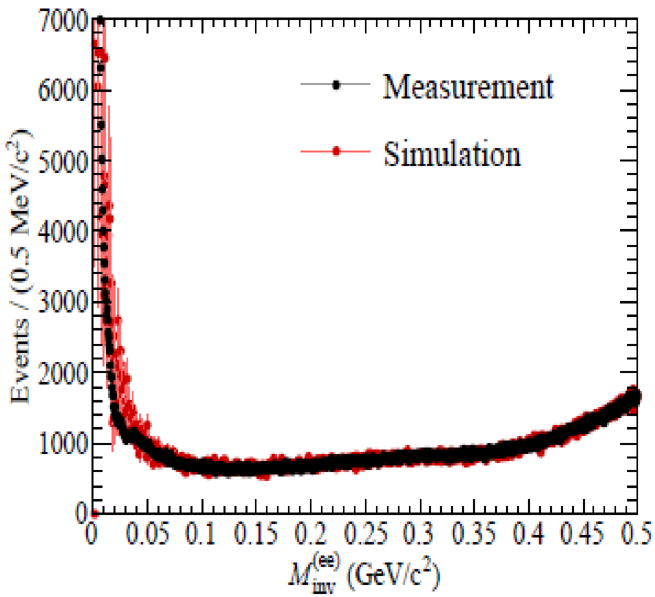
N_{CLs} = number of U boson signal events excluded at 90% C.L.

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

$$I = \int \sigma_U \, dM_U$$

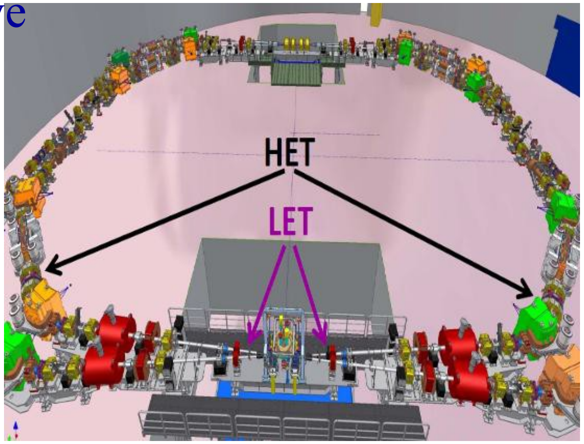
$$L_{integrated} = 1.54\ fb^{-1}$$

Di-electron mass spectrum

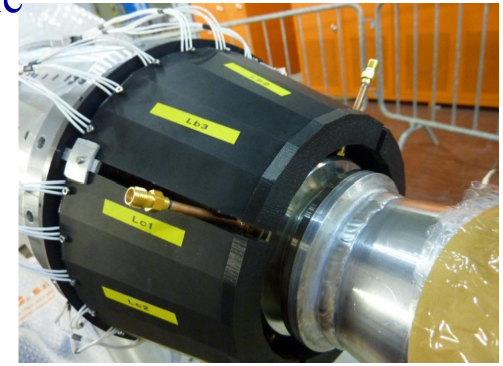


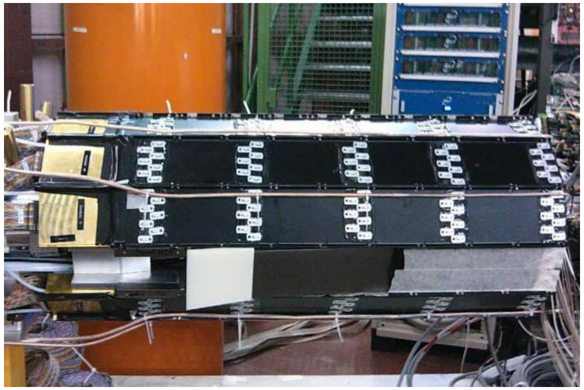
KLOE-2 Upgrade

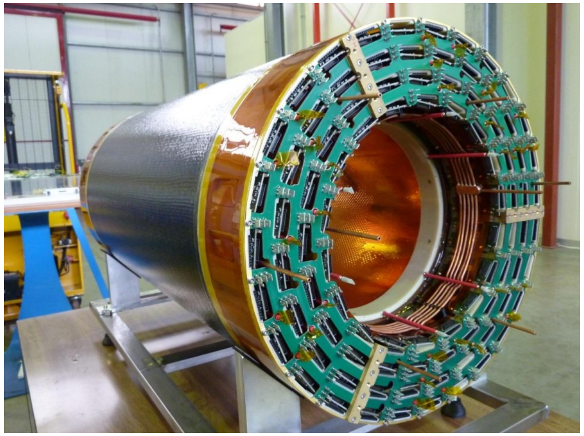
- KLOE-2 new data taking campaign started on November 2015
- It will collect more than 5 fb^{-1} within the next 3 years
- New detectors fully operative



- 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





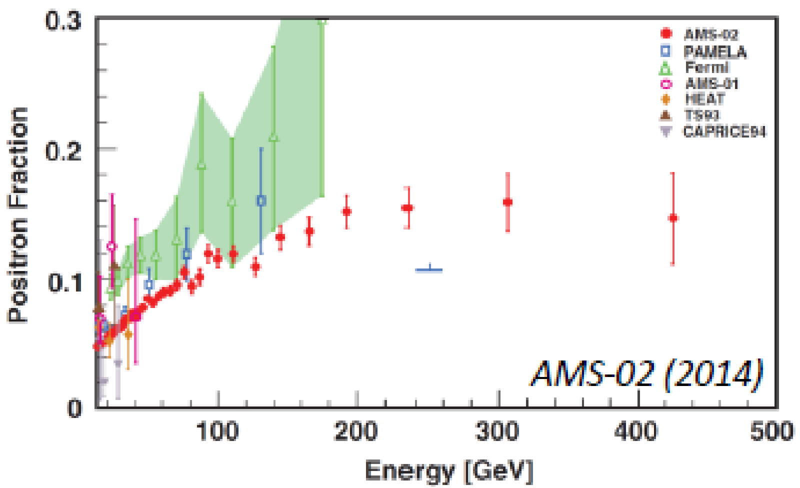


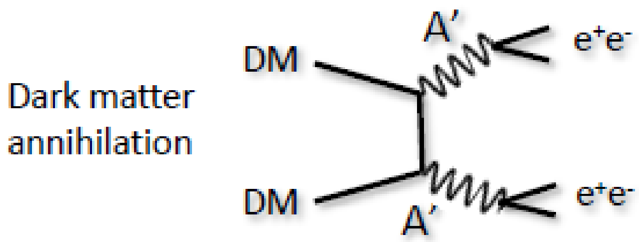
Motivations for new GeV-scale forces

Dark matter indirect detection anomalies

e.g. Pamela/AMS-02 positron excess

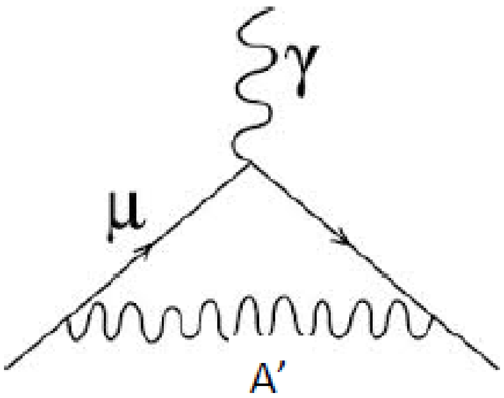
Pospelov & Ritz (2008); Arkani-Hamed et al (2008)



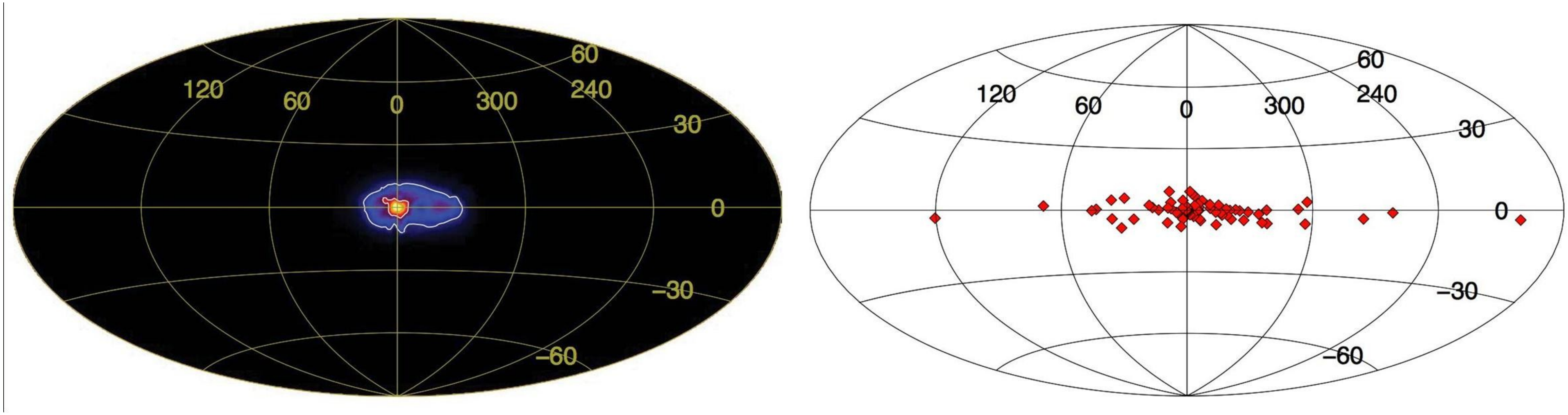


$(g\text{-}2)_\mu$ anomaly

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

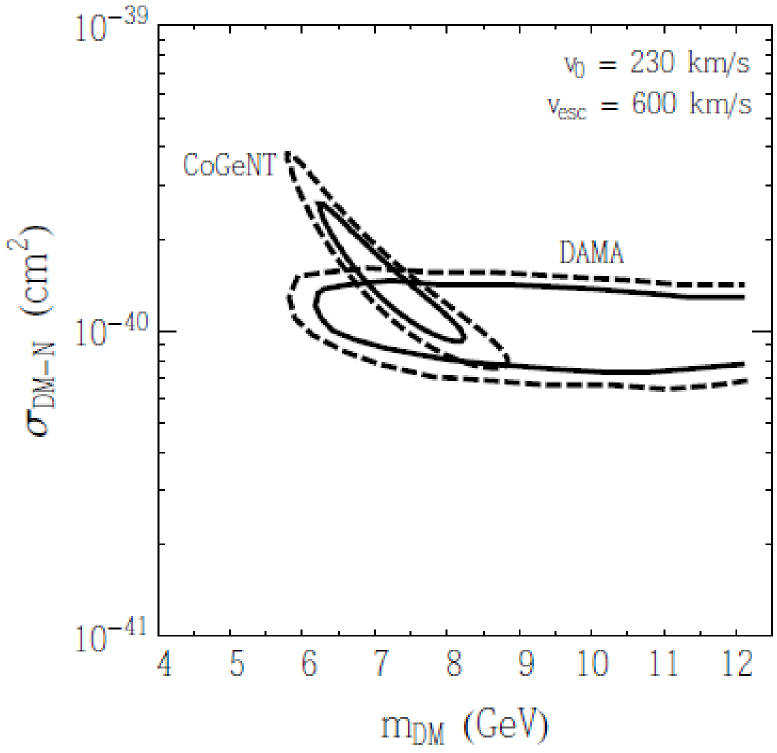
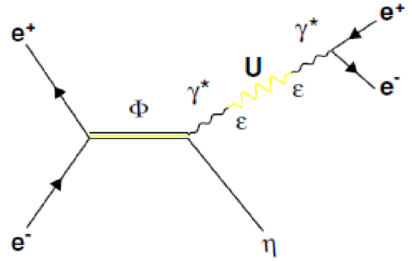


FIG. 6: A comparison of the parameter space favored by the CoGeNT spectrum with that favored by the modulation spectrum reported by DAMA/LIBRA [7]. Good agreement is found, but somewhat large quenching factors for low energy nuclear recoils on sodium are required ($Q_{Na} \sim 0.40-0.45$) [7].

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



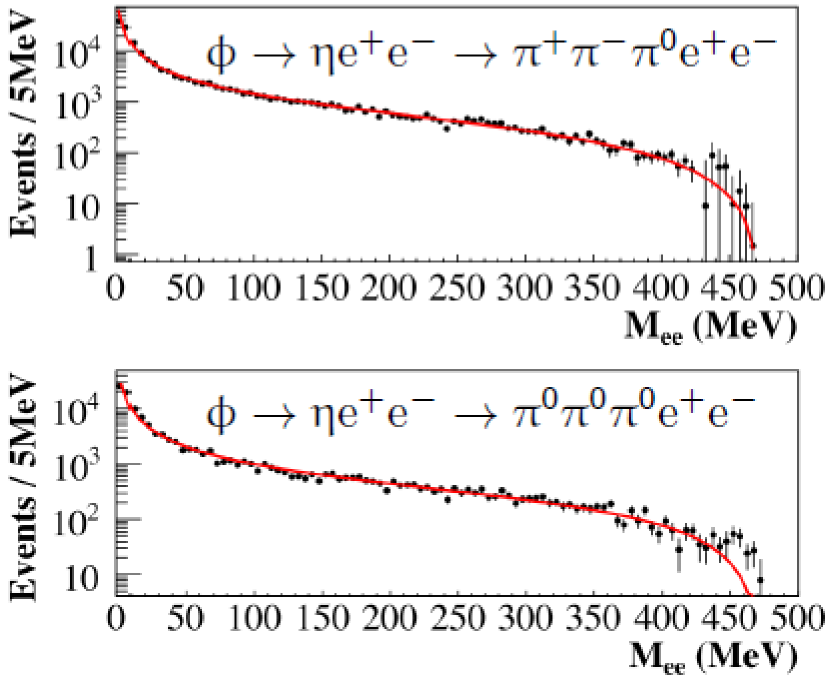
Phys. Lett B 706 (2012) 251-255
Phys. Lett B 720 (2013) 111-115

- $\varphi \to \eta e^+e^-$ irreducible background
- Simulated with a Vector Meson Dominance parameterization
- Combined analysis
  - $\eta \to \pi^+\pi^-\pi^0$
    - ~ 13000 events and 2% background
  - $\eta \to \pi^0\pi^0\pi^0$
    - ~ 31000 events and 3% background
    - Phys. Lett B 720 (2013) 111-115
- UP limit with CLs
- $\varphi \to \eta e^+e^-$ background from fit to the sidebands.
- $\varepsilon = \alpha_D/\alpha_{EM}$ derived assuming the relation:

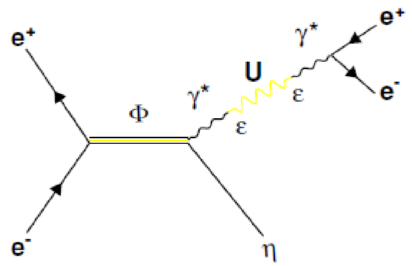
$$\sigma(\phi \to \eta U) \sim \epsilon^2 |F_{\eta\phi}(m_U^2)|^2 \sigma(\phi \to \eta\gamma)$$

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

Di-electron mass spectrum



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



Phys. Lett B 706 (2012) 251-255
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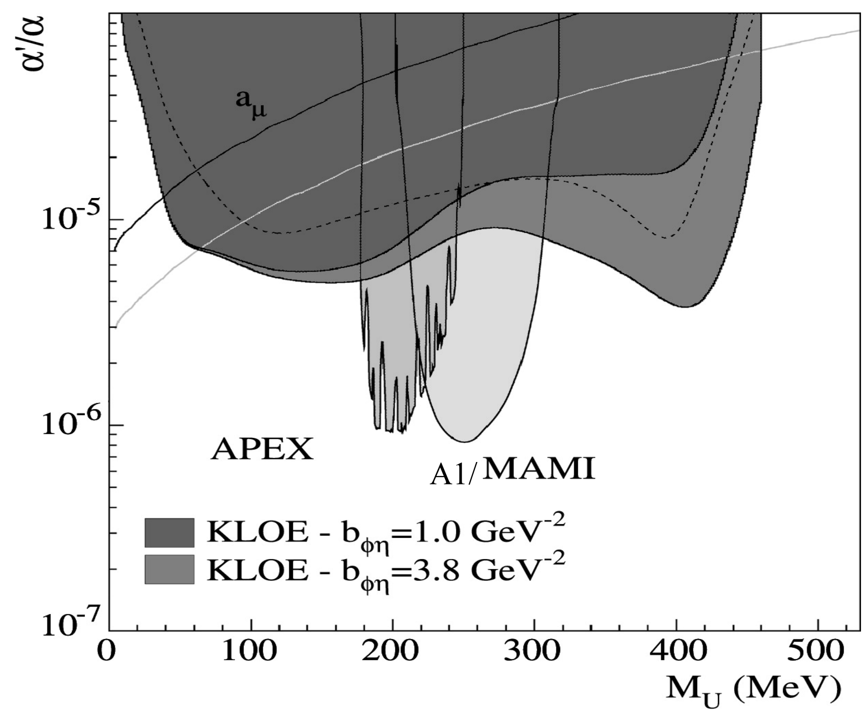


- No clear signal → Upper limit evaluation with CLs
  - $\varphi \to \eta e^+e^-$ background from fit to the sidebands.
- $\varepsilon = \alpha_D/\alpha_{EM}$ derived assuming the relation:

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

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

Higgsstrahlung process

Two different scenarios:

- $m_{h'} > 2m_U$

with decays: $e^+e^- \rightarrow Uh'$ with $h' \rightarrow UUU$ thus 6l, 2π+4l, 6π in the final state

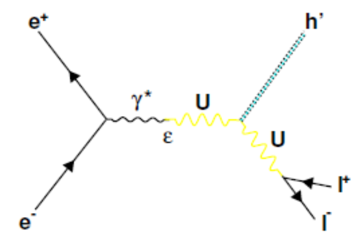
- $m_{h'} < 2m_U$

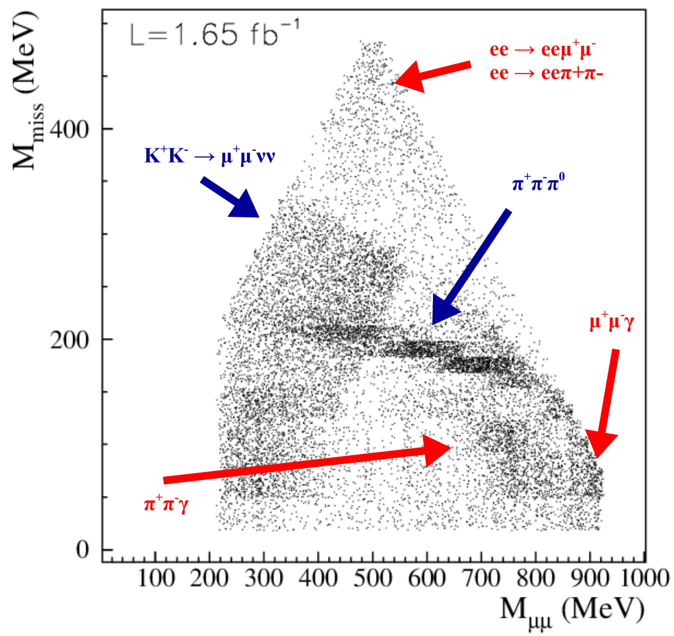
where h' is “invisible"

- Life time of the dark Higgs boson
- $\varepsilon = 10^{-3}$
- $\alpha_D = \alpha_{em}$
- $m_{h',U} \sim 100$ MeV
- $\tau > 5\ \mu s \rightarrow \beta\gamma c\tau > 100$ m $\rightarrow$ h' would be invisible up to $\varepsilon \sim 10^{-2}$ to 10^{-1} depending on $m_{h'}$

- Final state: 2 muons + missing energy $\rightarrow$ 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

Phys.Lett. B747 (2015) 365-372





Leptophobic B boson: new force coupling to quarks

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

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

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

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

- 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**

S. Tulin ArXiv:1404.4370

KLOE searches

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