Searches for Dark Forces at e^+e^- Colliders

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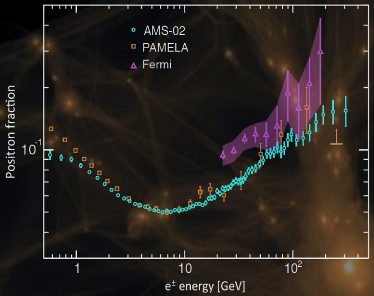
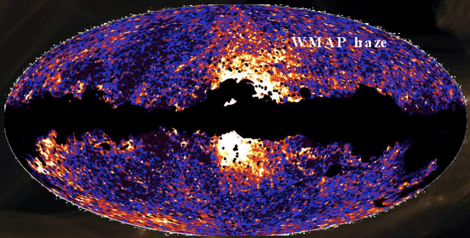
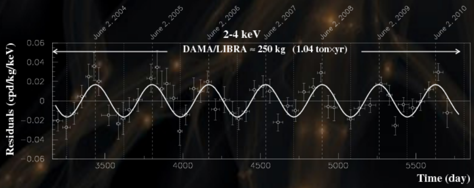
Outline

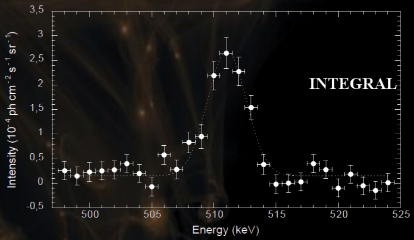
- ⋆ **Motivation to Search for Dark Forces**
- ⋆ **Dark Sector with Dark Photon**
- ⋆ e^+e^- **Collider Searches**
  - ⋆ KLOE
  - ⋆ Babar
  - ⋆ Belle
- ⋆ Conclusions

Motivations





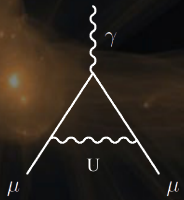




Motivations

Moreover...

- ⋆ A low mass U boson could explain the well known a_μ discrepancy with SM
  $a_\mu^{\text{dark}} \propto \frac{\alpha}{2\pi}\varepsilon^2$ for M_{U} ~10–100 MeV and $\varepsilon \sim 10^{-3}$



- ⋆ The new symmetry should be spontaneously broken by an Higgs-like mechanism, thus introducing the existence of an additional scalar particle, the dark Higgs h′.

Dark Sector

Minimal Theoretical setup:
just a gauge boson U belonging to an extra abelian gauge symmetry $U_D(1)$,
U is the lightest particle of the dark sector and can only decay into SM particles through kinetic mixing $\rightarrow$ visible decays

Dark Sector

Dark sector could be much intricate...

STANDARD MODEL
$SU(3)XSU(2)XU(1)_Y$
g, γ, $W^{\pm}$, Z^0, h

$U(1)_Y$ $U(1)_D$
X
ε

DARK SECTOR
G_D
Higgsed: W_D, h_D...
or
Confined: η_D, ω_D...

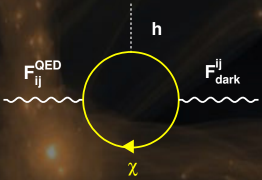
Generalised dark sector scenario:
a non-Abelian gauge group G_{D} which can be Higgsed (new gauge bosons) or confined (dark flavour mesons, glueball and baryons) at $\mathcal{O}$(MeV–10 GeV).

$G_{\mathrm{D}} \supset \mathrm{U}(1)_{\mathrm{D}}$, still mixing between photon and dark photon but U could not be the lightest particle and decay to dark particles giving rise to invisible decays

We will focus on visible and prompt U decays

The U boson

The U boson would be produced during dark matter annihilation processes and then decay to light particles, as leptons or pions: $\tilde{\chi} + \chi \rightarrow \mathrm{U} + \mathrm{U}, \mathrm{U} \rightarrow \mathrm{l}^{+}\mathrm{l}^{-}\ (\mathrm{l} = \mathrm{e}, \mu, \pi)$, if $\mathrm{m_U}$ < 1GeV



Th U couples to γ through loops of heavy dark particles charged under both QED and dark force. The mixing is described by a kinetic mixing term of the form:

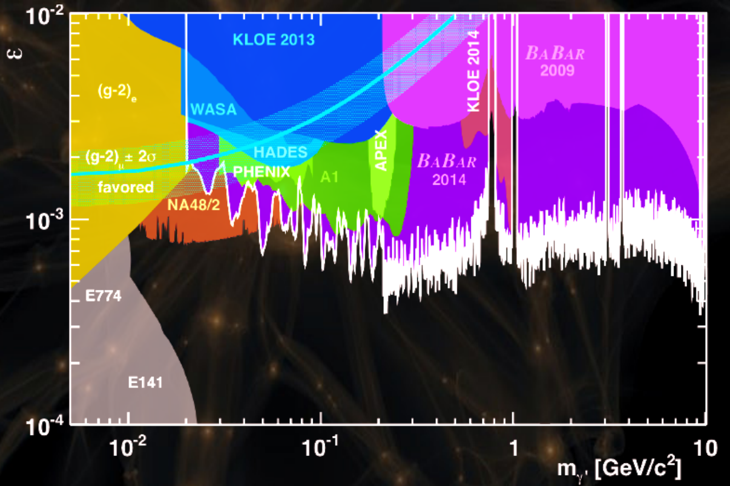
$$L = -\frac{\varepsilon}{2} F_{ij}^{\mathrm{QED}} F^{ij}_{\mathrm{dark}}$$

$\varepsilon^2 = \alpha' / \alpha_{\mathrm{em}}$ = kinetic mixing parameter $\sim 10^{-8} - 10^{-4}$

$F_{ij}^{\mathrm{em}}, F^{ij}_{\mathrm{dark}}$ = SM hypercharge gauge boson and dark photon tensors

Status of U boson Searches

Many experimental approaches... beamp dump, fixed target experiments...
we will focus on Collider Searches



U production @ e^+e^- Colliders

High luminosity electron-positron colliders have operated in the last decade all over the world, collecting unprecedented statistics at the energies of interest for dark searches. It is also planned to increase the available datasets within a few years...

- ⋆ The KLOE experiment at DAΦNE, Frascati, has accumulated about 2,5 fb^{-1} running at $\sqrt{s} \sim 1$GeV. A new run (KLOE-2) has started, taking advance of new sub-detectors and new DAΦNE interaction scheme, with the goal of reaching, within a few years, ∼5-10 fb^{-1}

- ⋆ The Belle and BaBar experiments in Japan and USA have integrated about 1 ab^{-1} each at $\sqrt{s} \sim 10$ GeV. The aim is to reach ~ 50 ab^{-1} with future generation SuperB factories

- ⋆ At $\sqrt{s} \sim 3$ GeV, the BESIII detector in Beijing aims to collect an integrated luminosity of ~ 20 fb^{-1}

U production @ e^+e^- Colliders

- $\star$ Light meson decays: $V \to P\mathrm{U}$, $\mathrm{U} \to \mathrm{l}^+\mathrm{l}^-(\mathrm{l} = \mathrm{e}, \mu, \pi)$

- $\star$ Continuum processes: $e^+e^- \to \mathrm{U}\gamma$, $\mathrm{U} \to \mathrm{l}^+\mathrm{l}^-(\mathrm{l} = \mathrm{e}, \mu, \pi)$

- $\star$ Dark Higgsstrahlung:

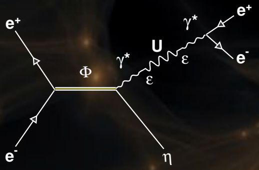
  Invisible scenario $\to m_{\mathrm{U}} > m_{h'}$, $e^+e^- \to h'\mathrm{U}\,, \mathrm{U} \to \mathrm{l}^+\mathrm{l}^-$, h' invisible because long-lived

  Visible scenario $\to m_{\mathrm{U}} < m_{h'}$, $e^+e^- \to h'\mathrm{U}\,, \mathrm{h}' \to \mathrm{UU}$, $\mathrm{U} \to \mathrm{l}^+\mathrm{l}^-(\mathrm{l} = \mathrm{e}, \mu, \pi)$

Dark Force @ KLOE-2

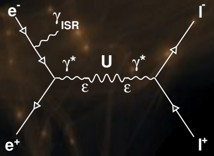
Φ Dalitz decay:

$\Phi \to \eta \mathrm{U},\ \mathrm{U} \to \mathrm{e}^+\mathrm{e}^-$
$\eta \to \pi^+\pi^-\pi^0$ (BR=22.7%)
$\eta \to \pi^0\pi^0\pi^0$ (BR=32.6%)
expected signature: peak in the dielectron inv. mass



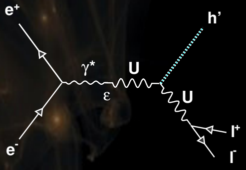
$\mathrm{U}\gamma$ events:

$e^+e^- \to \mathrm{U}\gamma,\ \mathrm{U} \to \mathrm{l}^+\mathrm{l}^-(\mathrm{l} = \mathrm{e}, \mu)$
good knowledge of bckgs
σ ~1/s: 100 times higher at DAΦNE w.r.t. B-factories
expected signature: resonance peak in the dilepton inv. mass

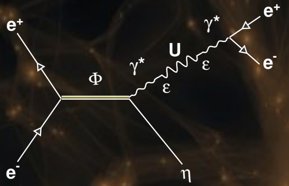


Higgsstrahlung process:

$e^+e^- \to h'\mathrm{U}$
interesting process observed at KLOE if $m_{\mathrm{U}} + m_{h'} < m_{\Phi}$
expected signature for $m_{\mathrm{h}'} < m_{\mathrm{U}}$: bump in the $M_{\mathrm{ll}} \mathrm{Vs}\ M_{miss}$ plane



Search for $e^+e^- \to \Phi \to \eta\mathrm{U}$, $\mathrm{U} \to \mathrm{e}^+\mathrm{e}^-$, $\eta \to \pi^+\pi^-\pi^0$, $\eta \to 3\pi^0$ @ KLOE-2



$\phi \to \pi^+\pi^-\pi^0 e^+e^-$ ev. sel.

- 4 tracks in a cylinder around IP + 2 photon candidates
- 495 < $M_{\pi\pi\gamma\gamma}$ < 600 MeV
- 70 < $M_{\gamma\gamma}$ < 200 MeV
- 535 < $M_{\mathrm{recoil(ee)}}$ < 560 MeV
- ToF cuts

$\phi \to \pi^0\pi^0\pi^0 e^+e^-$ ev. sel.

- 2 charged tracks in a cylinder around IP
- 6 prompt photons candidates:
  with E > 7 MeV
  not associated to any track
  in the time window expected for a photon
  $|T_\gamma - R_\gamma/c| < \mathrm{MIN}(3\sigma_t, 2\mathrm{ns})$
  acceptance: $|cos\theta_\gamma| < 0.92$
- 400 < $M_{6\gamma}$ < 700 MeV

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

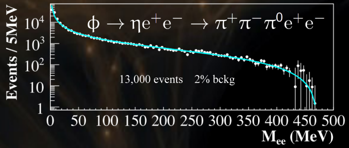
$\sigma(\phi \to \eta\mathrm{U}) \sim 40$fb for $|FF_{\phi\eta}| = 1, \ \varepsilon \sim 10^{-3}$

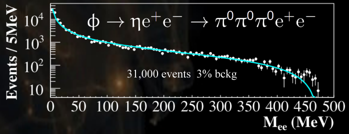
$\phi \to \pi^+\pi^-\pi^0 e^+e^-$ sample → L= 1.5fb^{-1}

$\phi \to \pi^0\pi^0\pi^0 e^+e^-$ sample → L= 1.7fb^{-1}

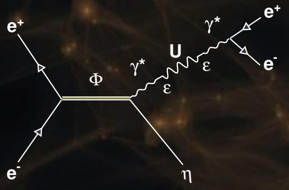
$\phi \to \eta e^+e^-$ MC simulation developed according VMD model

$\phi \to \eta\mathrm{U}$ simulation developed according to JHEP 07 051 (2009)





Search for $e^+e^- \to \Phi \to \eta \mathrm{U}$, $\mathrm{U} \to \mathrm{e}^+\mathrm{e}^-$, $\eta \to \pi^+\pi^-\pi^0$, $\eta \to 3\pi^0$ @ KLOE-2



$\phi \to \eta U$ MC sample divided in subsamples of 1 MeV width in 5 < M_{U}<470 MeV

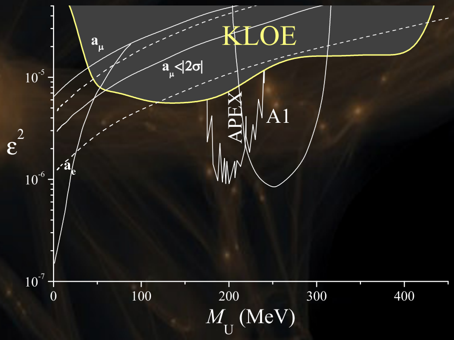
For each M_{U} sub-sample, average value of $\phi \to \eta e^+ e^-$ background from fit to M_{ee} distribution, excluding the 5 bins centred at M_U

For each M_{U} value, signal hypothesis excluded @ 90% C.L. using the $\mathrm{CL_S}$ method (error on bckg included)

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

Limit on ε $\to$ formula from Reece and Wang JHEP 07 (2009)

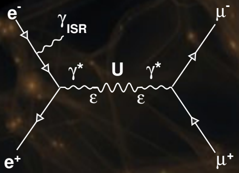
$b_{\phi\eta} \sim 1\mathrm{GeV}^{-2}$



$\varepsilon^2 = \alpha'/\alpha < 1.7 \times 10^{-5}$ @ 90% C.L. for 30 <M_{U}< 400 MeV

$\varepsilon^2 = \alpha'/\alpha < 8 \times 10^{-6}$ @ 90% C.L. for the 50 < M_{U} < 210 MeV

Search for $e^+e^- \to \mathrm{U}\gamma$, $\mathrm{U} \to \mu^+\mu^-$ @ KLOE-2



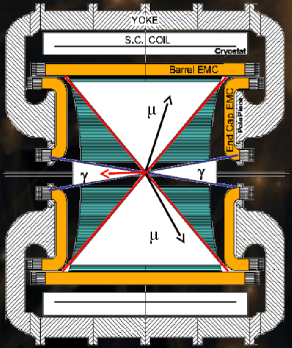
Statistics: KLOE data collected on 2002 corresponding to L= 240 pb^{-1}.

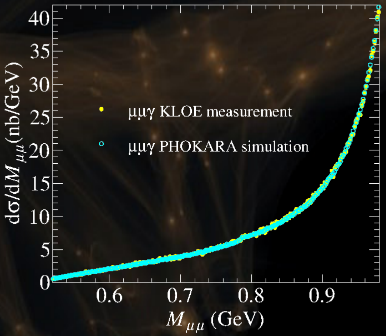
Small angle event selection
$(50^\circ < \theta_\mu < 130^\circ,\ \theta_\gamma < 15^\circ, > 165^\circ)$

High statistics ISR signal

Significant reduction of ϕ resonant and FSR bckgs

Good π/μ separation thanks to M_{trk} and $\sigma_{M_{\mathrm{trk}}}$ cuts





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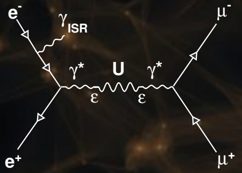
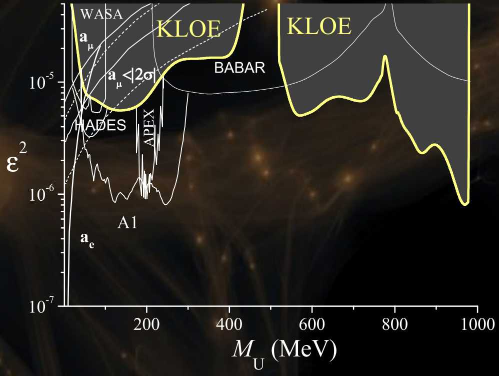


Phys. Lett. B 736 (2014) 459



$$\varepsilon^2 = \frac{N_{CL_S}/\epsilon_{\rm eff}}{H \cdot I \cdot L}$$

N$_{CL_S}$ = UL on number of U-boson candidates at 90% CL (CL$_S$ technique)

H= $\frac{\mathrm{d}\sigma_{\mu\mu\gamma}/\mathrm{dM}_{\mu\mu}}{\sigma(\mu^+\mu^-\to\mu^+\mu^-, M)}$

$I = \int \sigma^{\rm U}_{\mu\mu} \mathrm{dM}_{\mu\mu}$

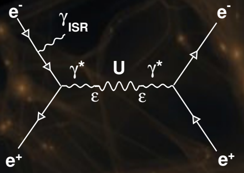
$\epsilon_{\rm eff} = 2 - 15\%$

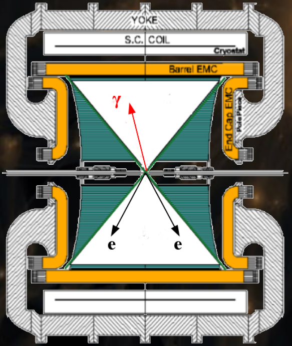
Systematic error of 1.4–1.8%

L=239.3 pb^{-1}

$\varepsilon^2 < 1.6 \times 10^{-5} - 8.7 \times 10^{-7}$ @ 90% C.L. for 520 $< M_{\rm U} <$ 980 MeV

Search for $e^+e^- \to U\gamma$, $U \to e^+e^-$ @ KLOE-2





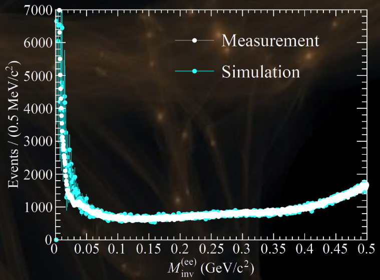
Data sample corresponding to $L = \int \mathcal{L} = 1.5\text{fb}^{-1}$

2 oppositely charged tracks ($55^\circ < \theta_e < 125^\circ$)

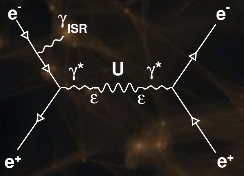
Large angle event selection ($50^\circ < \theta_\gamma < 130^\circ$)

High statistics radiative Bhabha events in KLOE data

Per mil level background contamination, or better



Search for $e^+e^- \to U\gamma$, $U \to e^+e^-$ @ KLOE-2



$$\varepsilon^2 = \frac{N_{CL_S}/\epsilon_{\rm eff}}{H \cdot I \cdot L}$$

N_{CL_S} = UL on number of U-boson candidates at 90% CL (CL_S technique)

H= $\frac{d\sigma_{ee\gamma}/dM_{ee}}{\sigma(e^+e^- \to e^+e^-, M)}$

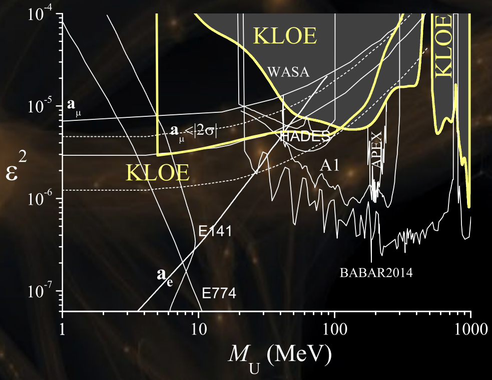
$I = \int \sigma^U_{ee} dM_{ee}$

$\epsilon_{\rm eff} = 1.5 - 2.5\%$

Systematic error < 2%

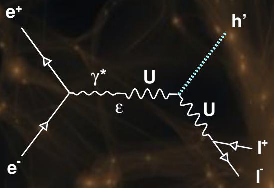
L=1.54 fb^{-1}

To be submitted



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

Dark Higgsstrahlung @ KLOE-2



Two oppositely charged tracks with vertex inside a 4×30cm cylinder around IP

EMC cluster associated to each track

Momentum direction inside the barrel: $|\cos\theta|$ < 0.75

P_{track} < 460 MeV

$|P_{\mathrm{miss}}|$ > 40 MeV

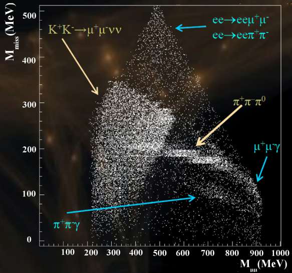
Two different scenarios:

$m_{h'} = 2m_{\mathrm{U}}$

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

$m_{h'} < m_{\mathrm{U}}$ with h' invisible

Results from on-peak sample (L=1.65fb^{-1})



Invisible scenario:

$\varepsilon \sim 10^{-3}, \alpha_D = \alpha_{em}, m_U \sim 100\mathrm{MeV} \to \tau_{h'} < 5\mu$s

$\to \beta\gamma ct < 100$m $\to$ h' invisible at KLOE up to

$\varepsilon \sim 10^{-2} - 10^{-1}$ depending on $m_{h'}$

Final state signature: 2 muons+missing energy $\to$ bump in the $M_{\mathrm{miss}} - M_{\mu\mu}$ plane

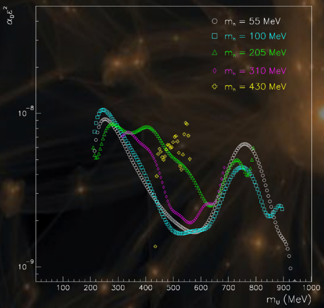
Sliding 5×5 bin matrix (excluding the central bin) for MC scale factors

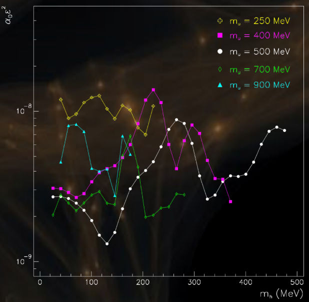
Binnig such that 90-95% of signal is in one bin

Dark Higgsstrahlung @ KLOE-2

Combined UL from on- and off-peak samples corresponding to $\varepsilon^2 \sim 10^{-6}$ to a few 10^{-8} (if $\alpha_D = \alpha_{em}$)

Accepted for publication in PLB (arXiv:1501.06795 [hep-ex])





90% CL bayesian UL on number of events converted in terms of $\alpha_D \times \varepsilon^2$ by using:

- L and signal efficiency information
- σ_{hU} and BR of the $U \to \mu^+\mu^-$
- Combined UL take into account the different L, signal efficiencies and cross sections of the two samples

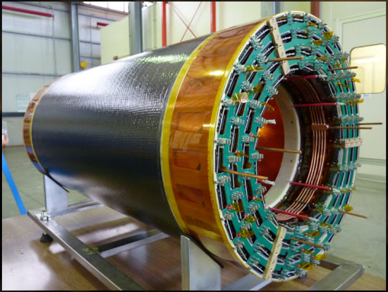
$$\alpha_D \varepsilon^2 = \frac{N_{90\%}}{\epsilon_{eff}} \frac{1}{L \cdot \sigma(\alpha_D \varepsilon^2 = 1)}$$

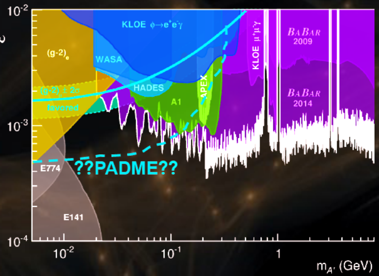
$$\sigma_{hU} \sim \frac{1}{s} \frac{1}{(1 - \frac{m_U^2}{s})^2}$$

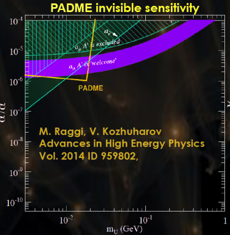
Future Dark Searches at LNF

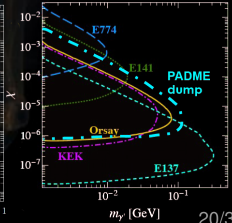
...Moreover, the PADME experiment planned at LNF will be able to perform an independent model search probing both visible and invisible U decays as well as allowing for beam dump experiments

The KLOE-2 run started. The aim is to collect about 5-10fb^{-1} in three years. In this respect the insertion of the inner tracker is expected to be particularly beneficial for dark forces searches, improving above shown limits of a factor of about 2. New analysis on KLOE full dataset are also on going...







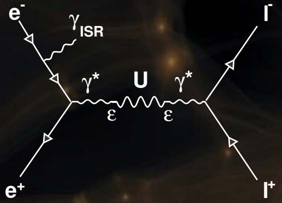


Dark Force Searches @ Babar

$\mathrm{U}\gamma$ events:

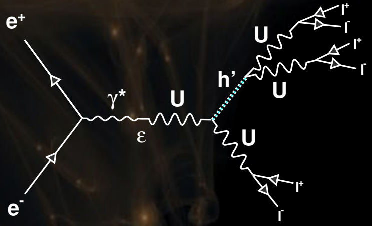
- $e^+e^- \to \mathrm{U}\gamma,\ \mathrm{U} \to \mathrm{l}^+\mathrm{l}^- (\mathrm{l} = \mathrm{e}, \mu)$
- High sensitivity
- high data statistics

- expected signature: resonance peak in the dilepton inv. mass



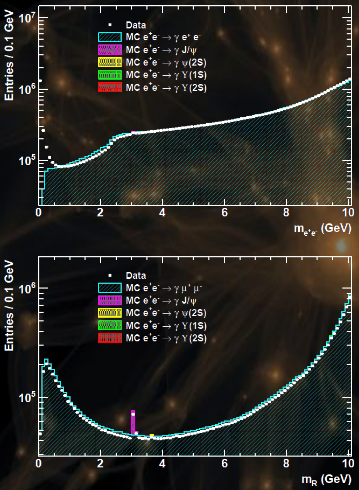
Higgsstrahlung process:

- $e^+e^- \to h'\mathrm{U},\ \mathrm{h}' \to \mathrm{UU},\ \mathrm{m}_{\mathrm{h}'} > \mathrm{m}_{\mathrm{U}}$
- suppressed by a single factor of ε
- low bckgs
- sensitive to dark coupling constant $\alpha_{\mathrm{D}} = g_{\mathrm{D}}/4\pi$
- expected signature: 6 particle final states ($4e, \mu + \pi,\ 2e, \mu + \pi ...$) or $4l + X$ (X= dark photon candidate detected via missing mass)



BaBar is also searching for dark photon invisible decays (but this search is out of the aim of this talk)

Babar Search for $e^+e^- \to U\gamma \to l^+l^-\gamma$, $l = e, \mu$



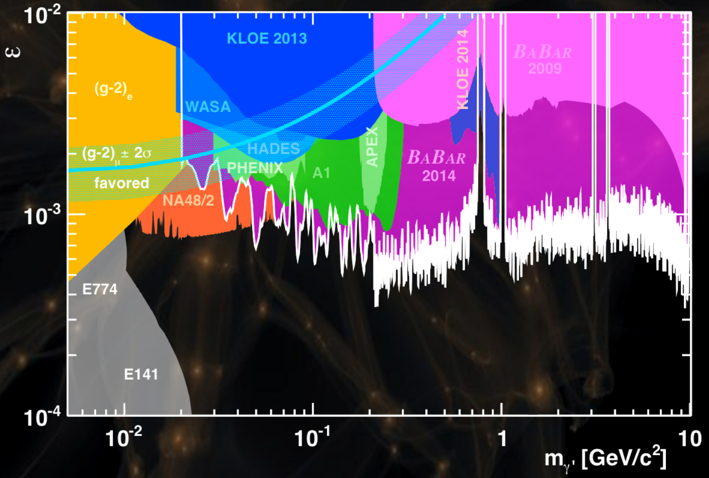
- Event selection:
  - data sample corresponding to L=514 fb $^{-1}$ collected at $\sqrt{s} \sim \Upsilon(4s)$
  - 2 tracks + 1 photon
  - Constrained fit to the beam energy and beam spot
  - Particle identification for e/μ
  - Kinematic cuts to improve purity
  - Quality cuts on tracks and photons
- Di-electron channel
  - Good agreement between data and MC (BHWIDE) above 1 GeV, low mass region affected by MC cut-off.
  - Background from photon conversions suppressed by neural network
- Di-muon channel
  - Invariant mass distribution plotted Vs $m_{\rm red} = (m^2_{\mu\mu} - 4m_\mu)^{1/2}$ (smoother near threshold)
  - Good data-MC agreement (KK)

Good data-MC agreement at the $J/\Psi, \Psi(2S), \Upsilon(1S)$ resonances

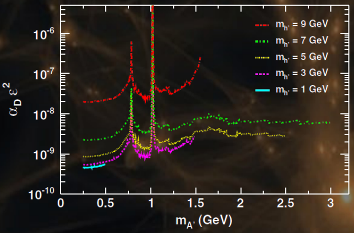
Babar Search for $e^+e^- \to \mathrm{U}\gamma \to \mathrm{l}^+\mathrm{l}^-\gamma,\ \mathrm{l} = \mathrm{e}, \mu$

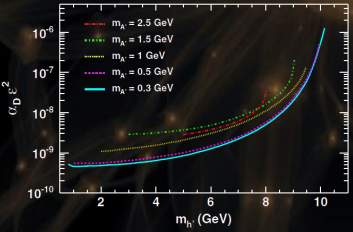
- ⋆ resonant regions excluded from extraction:
  $\pm$ 30 MeV around ω/Φ
  $\pm$ 50 MeV around $J/\Psi, \Upsilon(2\mathrm{S}), \Upsilon(1\mathrm{S}, 2\mathrm{S})$
- ⋆ largest significances: 3.4σ for electrons @ 7.02, 2.9σ for muons @ 6.09 GeV

Phys. Rev. Lett. 113 201801 (2014)



Dark Higgsstrahlung @ BaBar





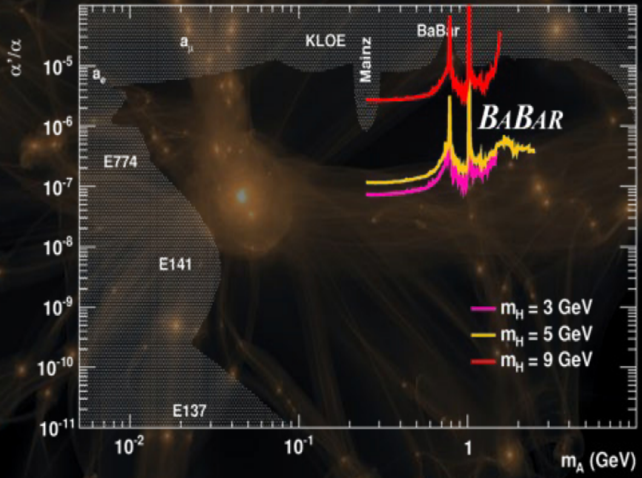
- ⋆ Prompt U and h’ decays assumed
- ⋆ Six candidates selected from the full BaBar dataset ($\sim$500 fb^{-1})

  $4\pi + 2\mathrm{l}\,(\mathrm{l} = \mathrm{e}, \mu)\,, 4\mu + 2\pi\ \ 4\mu + \mathrm{X}$
- ⋆ Three entries for each event, corresponding to the three possible assignments of the $h' \to UU$ decay
- ⋆ Estimate background from:

  wrong-sign combinations, e.g.
  $e^+e^- \to (e^+e^+)(e^-e^-)(\mu^+\mu^-)$
  sidebands from final sample
  rate for 6 leptons ~ 100 times rate for $4\pi + 2l$ above 1.5 GeV

Dark Higgsstrahlung @ BaBar

PRL 108 (2012) 211801



No events with 6 leptons

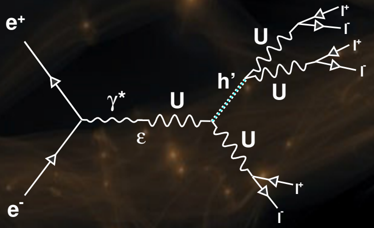
Improvement over existing limits for $m_{h'} < 5 - 7$ GeV

Dark Force Searches @ Belle

Higgsstrahlung process, visible scenario ($m_{h'} > m_{\mathrm{U}}$):

$e^+e^- \to h'\mathrm{U},\, \mathrm{h}' \to \mathrm{UU}\,, \mathrm{U} \to \mathrm{l}^+\mathrm{l}^-,\, (\mathrm{l} = \mathrm{e}, \mu, \pi)$

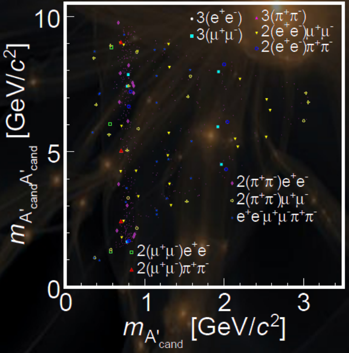
expected signature: 6 particle final states ($4e, \mu + \pi,\, 2e, \mu + \pi ...$) or $4l + X$ (X= dark photon candidate detected via missing mass)

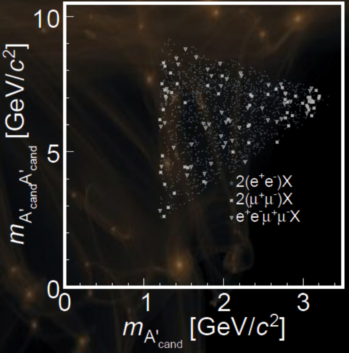


Searches on $e^+e^- \to \mathrm{U}\gamma$ events and for invisible U decays are also planned

Dark Higgsstralung @ Belle

- ⋆ U and h' assuming prompt decays
- ⋆ Full Belle statistics (977 fb^{-1})
- ⋆ $0.1 < m_{\mathrm{U}} < 3.5$ GeV and $0.2 < m_{h'} < 10.5$ GeV
- ⋆ 10 exclusive channels: $3(l^+l^-), 2(l^+l^-)(\pi^+\pi^-), 2(\pi^+\pi^-)(l^+l^-)$, and $3(\pi^+\pi^-)$, where l^+l^- is an electron or muon pair
- ⋆ 3 inclusive channels for $m_{\mathrm{U}} > 1.1$ GeV: $2(l^+l^-)X$, where X is a dark photon candidate detected via missing mass
- ⋆ Expected background estimated by a data driven method

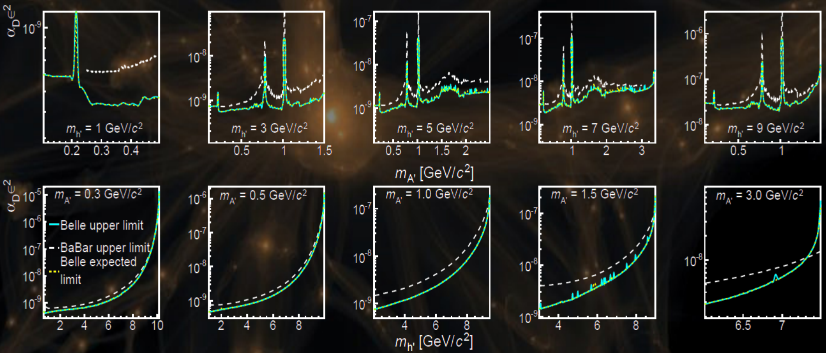




Dark Higgsstrahlung @ Belle

Belle Results compared with BaBar ones

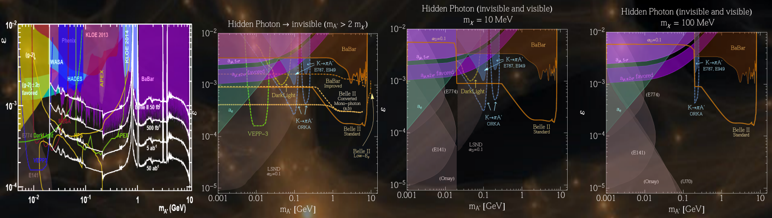
- ⋆ 90% CL upper limit on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top) and dark Higgs boson mass (bottom) by assuming branching fractions and couplings versus cross section from B. Batell et al. PRD 79 (2009) 115008
- ⋆ Limits on 3$(\pi^+\pi^-)$ and $2(e^+e^-)X$ for the first time placed by an experiment

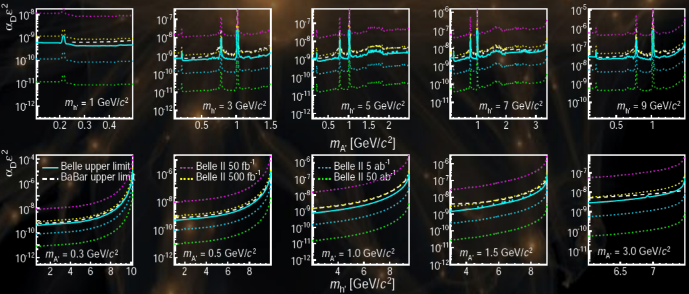


- ⋆ Belle limits for L = 977 fb^{-1} based on the Born cross section, ISR effect non negligible
- ⋆ BaBar limits for L = 520 fb^{-1} based on the visible cross section PRL 108 211801 (2012)
- ⋆ For $\alpha_D = \alpha$, $m_{h'} < 8$GeV, $m_U < 1$GeV limits on $\varepsilon^2 < 8 \times 10^{-8}$

Future Prospects @ BaBar and Belle

Babar and Belle projected sensitivities for an invisibly decaying dark photon and model independent searches (arXiv:1309.5084) $\longrightarrow$ Need for implementation of a mono-photon trigger in BelleII!

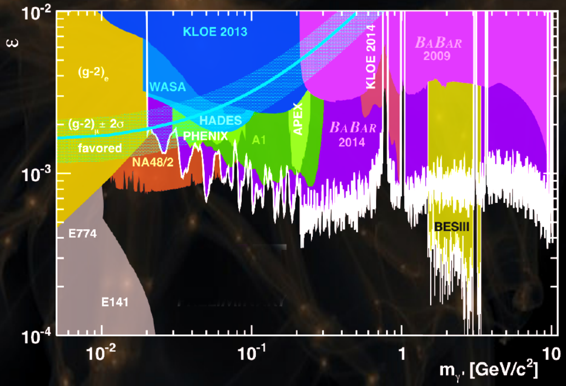




Belle projections for future DarkHiggsstrahlung searches

Conclusions: Result Summary

Process	Exp.	$\alpha_D \times \varepsilon^2$	ε^2	M_U(GeV)
$e^+e^- \to U\gamma\,,\,U \to l^-\,,\,l^+$	BaBar	-	$\sim 10^{-7}$	0.02- 10.2
$e^+e^- \to U\gamma\,,\,U \to \mu^+\,,\,\mu^-$	KLOE	-	$2.6\times10^{-5} - 8.6 \times 10^{-7}$	0.52-0.98
$e^+e^- \to U\gamma\,,\,U \to e^+\,,\,e^-$	KLOE	-	$4 \times10^{-7} - 10^{-4}$	0.005-0.52
$e^+e^- \to U\gamma\,,\,U \to l^-\,,\,l^+$	BESIII (prel.)	-	$\sim10^{-8}$	1.5-3.5
Dark Higgsstrahlung h' vis	BaBar	$\sim10^{-8} - 10^{-10}$	$\sim 10^{-6} - 10^{-8}$	0.2-3
Dark Higgsstrahlung h' inv.	KLOE	$\sim10^{-8} - 10^{-9}$	$\sim 10^{-6} - 10^{-8}$	0.2-1
Dark Higgsstrahlung h' vis.	Belle	$\sim10^{-8} - 10^{-10}$	8×10^{-8}	0.1-3.5
ϕ Dalitz decay	KLOE	-	$8.6\times10^{-6} - 1.7 \times 10^{-5}$	0.005-0.47



Conclusions

- ⋆ Electron-positron Colliders have proven to be an ideal place to search for dark forces however no signal has been observed
- ⋆ New generation machines with their high statistics datasets would play a central role in continuing these searches for dark photon masses of $\sim$1 GeV and exploring also U invisible decay hypothesis
- ⋆ Fixed target experiments will be more powerful to probe lower masses and small couplings by investigating also no prompt U decay hypothesis

Thank You!