Searching a Dark Photon with HADES

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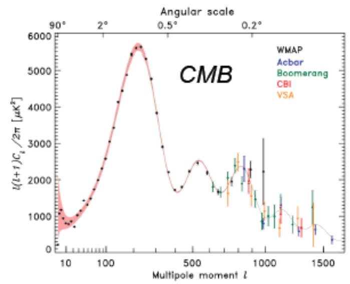
for the HADES collaboration

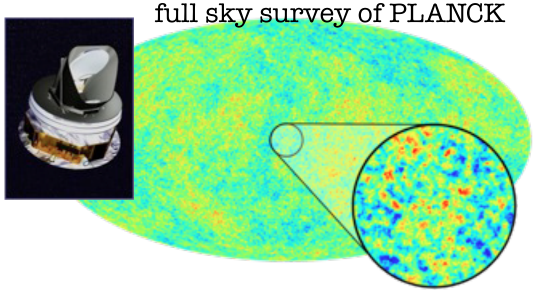
Dark Matter in the Universe : Astronomical observations

Many astronomical & astrophysical observations support the existence of a large amount of non-baryonic matter:

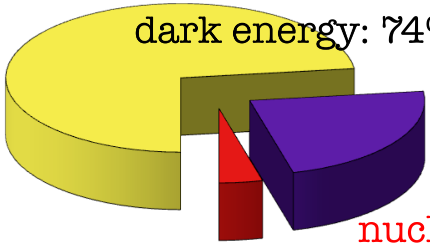


- Cosmic microwave background (CMB) anisotropies:

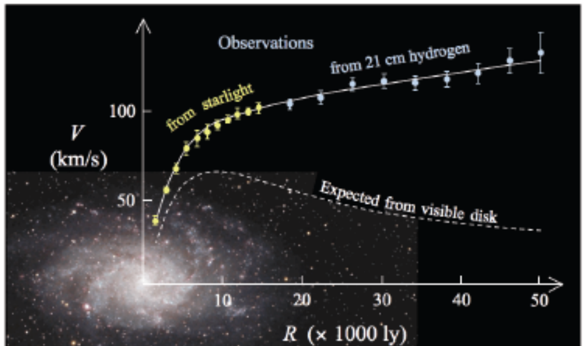
full sky survey of PLANCK



http://sci.esa.int/planck/



- Large-scale structures in the universe (galaxies, clusters of galaxies)
  In particular: **orbital velocity profiles** of galaxies



rotational speed of spiral galaxies

- Also, hints from the composition of cosmic ray spectrum (e^+/e^- excess, 511 keV line)

Recent review: Bertone, Hooper & Silk, Phys. Rept. 405 (2005) 279

(see also PDG 2012 long writeup)

Detection of dark matter particles

1. Direct observation via scattering on normal matter + recoil detection:

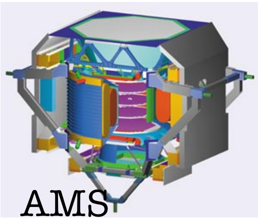
   CRESST, EDELWEISS, EURECA (sensitivity, background suppression

   → large underground detectors)

2. Annihilation of DM particles leading to observable radiation

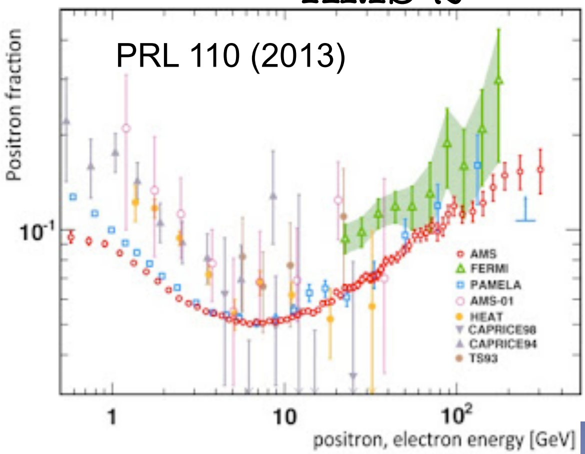
   ➢ Satellite and balloon-born experiments: (e^+/e^- excess >10 GeV)

PAMELA



- ATIC
- PAMELA
- Fermi
- AMS-01, **AMS-02** on ISS

AMS-2



➢ Gamma-ray observatories:

- H.E.S.S.
- INTEGRAL
- Fermi

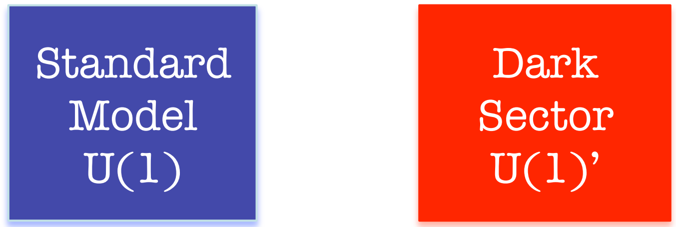
} map 511 keV annihilation line!

Standard Model and Dark Matter

- Standard model needs to be extended to accommodate DM, and to allow DM to interact with ordinary matter (beyond gravitational pull)

- One possible scenario is to add U'(1) gauge to SM: *(see e.g. P. Fayet, Phys. Lett. B 95 (1980) 285)*

  ✓ New gauge boson, the dark photon/A'/U-boson, with a MeV-GeV mass scale



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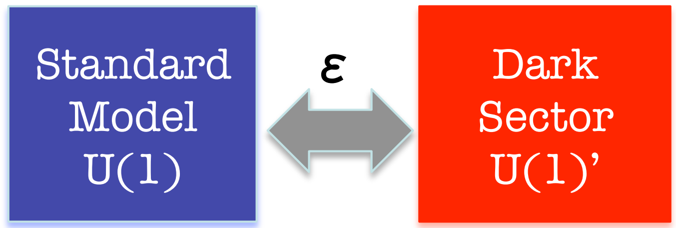
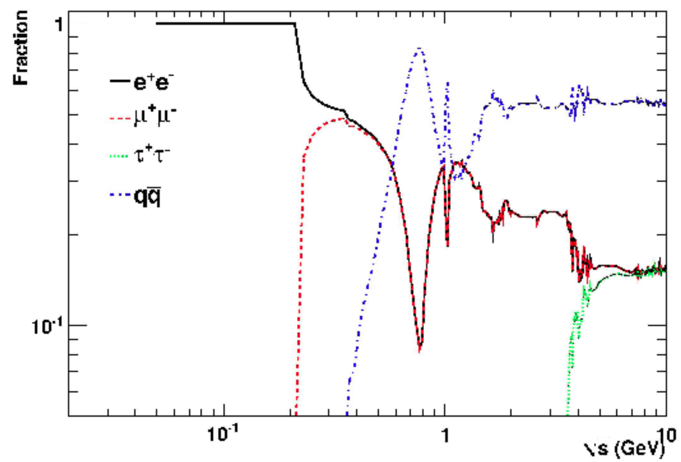


  ✓ New gauge boson, the dark photon/A'/U-boson, with a MeV-GeV mass scale

  ✓ Interaction dark sector – SM via kinetic mixing between the U(1) and U'(1) with a mixing strength $\varepsilon^2=\alpha'/\alpha$

  ✓ Mixing strength expected to be of order $\varepsilon \approx 10^{-5} - 10^{-2}$ but could be smaller even

Dark photon decay channels



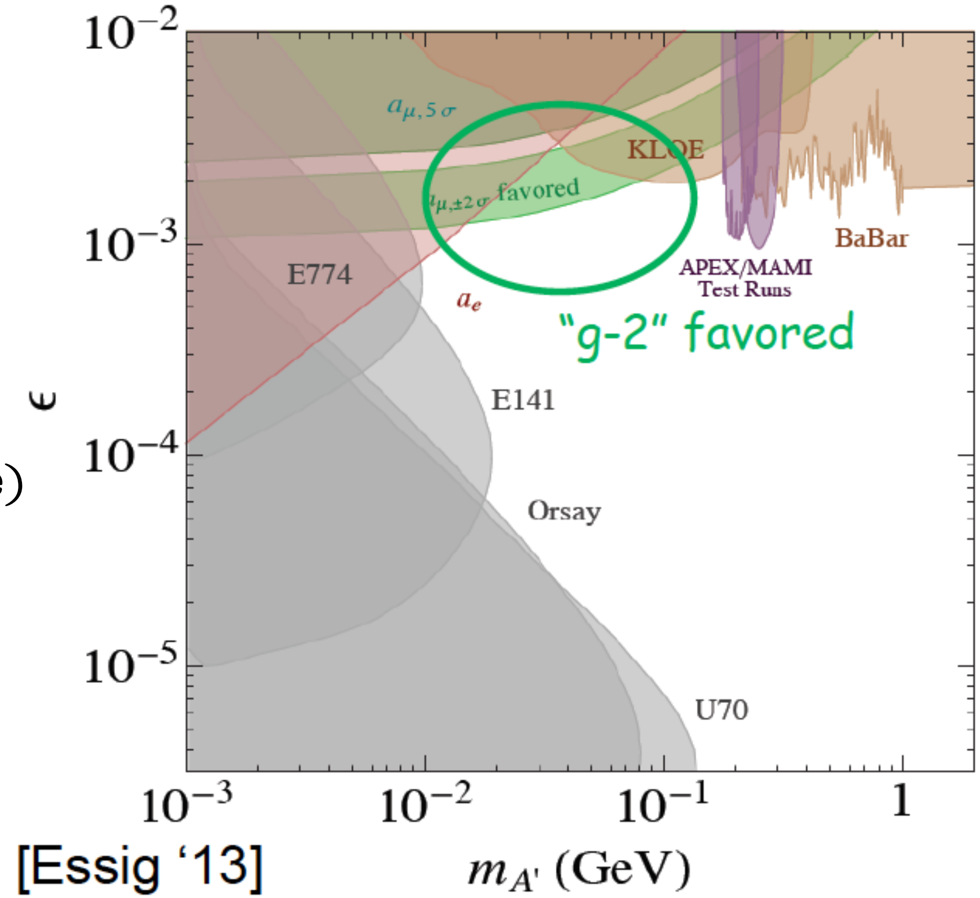
Lepton contribution dominates at low masses, and is still 30% at high masses

Particle physics implications of U boson

Particle physics experiments

- Could explain the discrepancy between the measured and calculated value of the anomalous magnetic moment of muon, a_μ = g-2,
- Can produce dark photons. In fact, photons in any process can be replaced by a dark photon (with an extra factor of e)
- Decays back to leptons/quark pairs
- Dark photon width is small (ε e) and could be long-lived

Constraints on ε vs. M_U



- Current bounds on the mixing parameter [Essig '13] ε are shown as a function of the dark photon mass. Constraints from electron/muon g-2, beam dump and fixed target experiments and e+e- collders

The Muon g-2 Anomaly

- Dirac: point-like spin ½ particle has a gyromagnetic factor g = 2
- QED high-order terms lead to g > 2 ➔ **g-2 anomaly**
- Very precisely measured **and** calculate for electron:

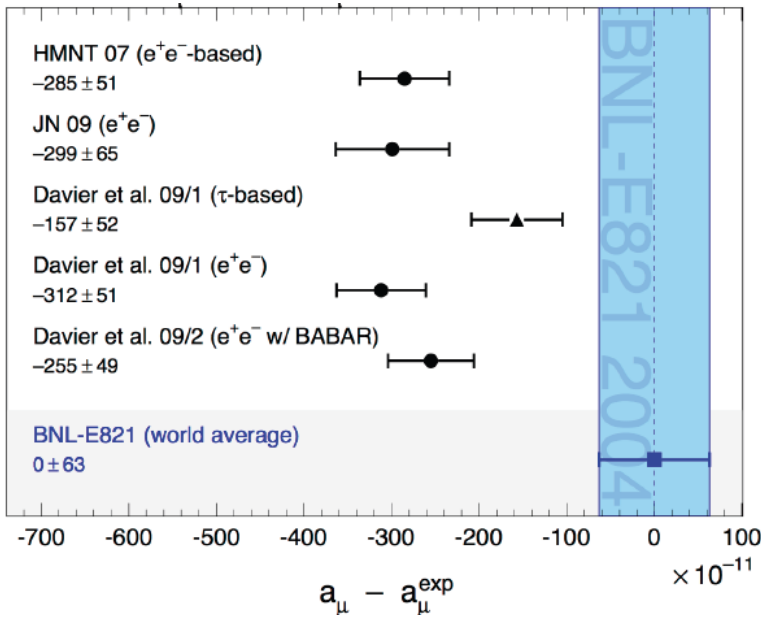
$(g_e\text{-}2)_{exp} = 0.0023193043614 6(56)$
$(g_e\text{-}2)_{theo} = 0.0023193043622 5(172)$

exp & theory agree within errors

- Remeasured recently at the Brookhaven AGS for the muon:

$(g_\mu\text{-}2)_{exp} = 0.0023318416(12)$
$(g_\mu\text{-}2)_{theo} = 0.0023318366(15)$

2.6 σ mismatch! ➔ due to new physics?
e.g. dark matter ???



Muon g-2 experiment vs. theory:
G. Bennet et al., PRD 73 (2006)

Constraints on the U boson from g-2:
M. Pospelov, PRD 80 (2009)
M. Endo et al., PRD 86 (2012)

Searching the U boson in electromagnetic processes

All EM processes can be modified by mixing the photon and dark photon, e.g.:

- $e^- + A \rightarrow e^- + X + U$ (APEX, MAMI)

  APEX: Phys. Rev. Lett. 107 (2011) 191804.
  MAMI: Phys. Rev. Lett. 106 (2011) 251802

- $\Phi \rightarrow \eta + U$ (KLOE-2)

  KLOE-2: Phys. Lett. B 720 (2013) 111

- $\pi^0 \rightarrow \gamma + U$ (WASA)

  WASA: Phys. Lett. B 726 (2013) 187

- $\eta \rightarrow \gamma + U$

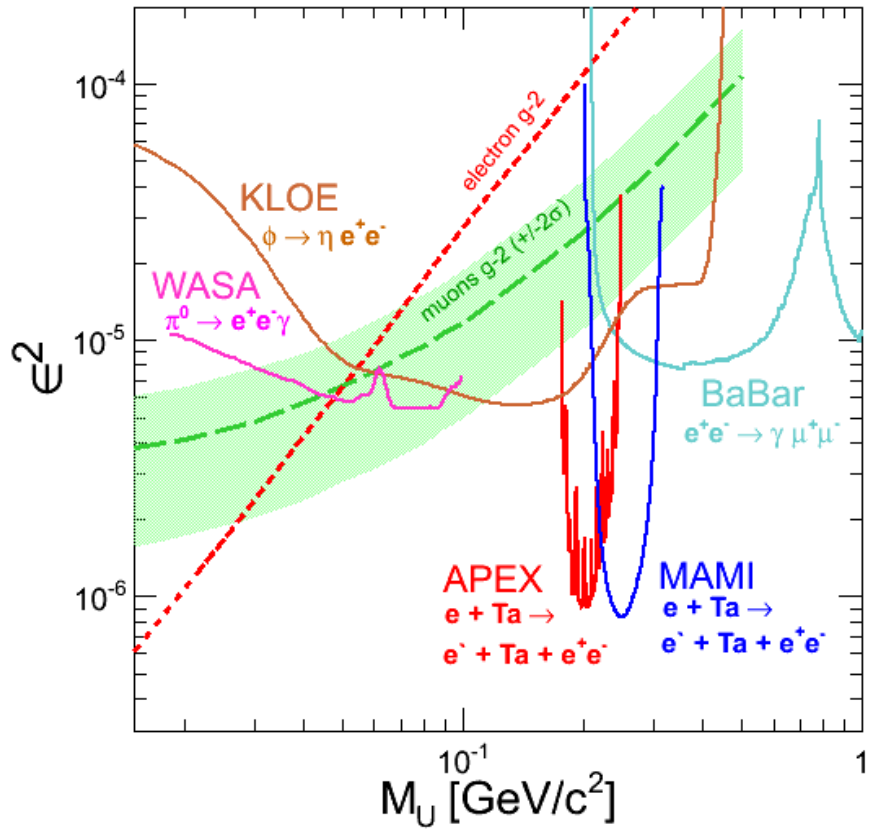
- $g - 2$ (e and μ data)

- $e^+ e^- \rightarrow \mu^+ \mu^-$ (resonance at M_u)...

Theory:

P. Fayet, PLB 95 (1980) 285 + many more papers
Pospelov et al., PLB 662 (2008) 53
Pospelov, PRD 80 (2009) 095002
Batell et al., PRD 79 (2009) 114008
Reece & Wang, JHEP 0907 (2009) 051

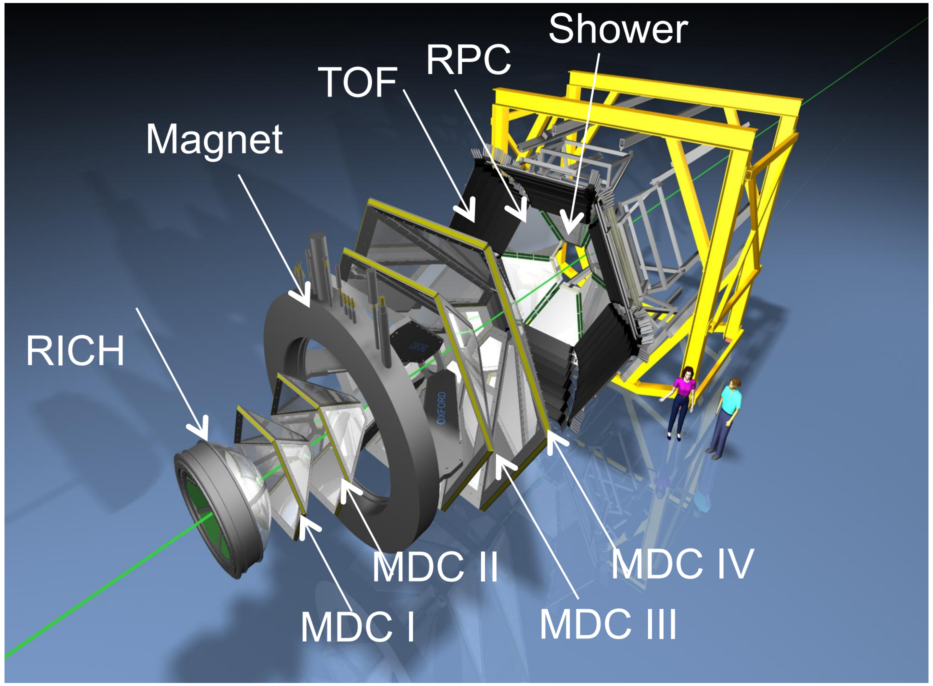
World set of U boson searches: upper limit (UL) on ε^2



The muon g-2 explainable band (90%-CL) still survives for 30-70MeV.

The HADES spectrometer at GSI

Beams from SIS18: protons, HI and secondary π-beam



The HADES spectrometer
[Eur.Phys.J. A**41** (2009) 243-277]

- Dilepton spectroscopy
- Strangeness production, e.g. K^0_s, Ξ^-, Φ, $K^{+,-}$ Λ

Acceptance:
full azimuthal angle
polar angle from 18°-85°

Time resolution:
150 ps TOF region
90 ps RPC region

Momentum resolution:
1.5% at 500MeV/c

Detector read out rate:
max. 50 kHz

Hadron PID:
β , dE/dx
additional PID for leptons:
RICH, SHOWER

Search in Dalitz decays

Measurement of $\pi^0/\eta \rightarrow \gamma\, U \rightarrow \gamma\, e^+e^-$ in Dalitz decays

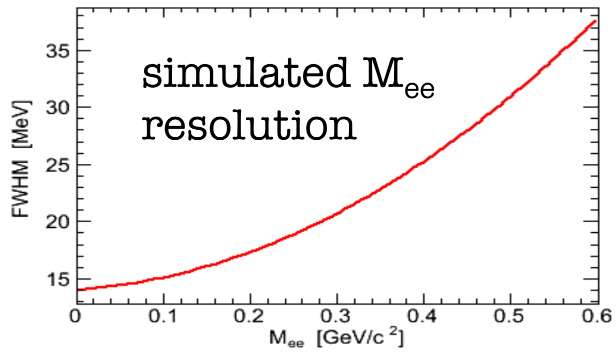
- Detection of e^+e^- pairs from the dark photons in the π^0/η Dalitz decay e+e⁻ pairs
- The dark photon exclusively decays into an e+e– pair.
- Its natural width is practically zero.
  - Expected peak width = mass resolution of spectrometer

- Important requirements for the dark photon search
  1. Large data samples of e^+e^-
  2. A very good mass resolution of e^+e^- pairs

Searching Dark Matter in HADES

A How-to-do

1. Search for a narrow peak structure in the raw dN/dM_{ee} spectrum
2. If no peak found, get an UL on peak
3. Transform this UL into an UL on the mixing parameter ε^2
4. Compare with world data

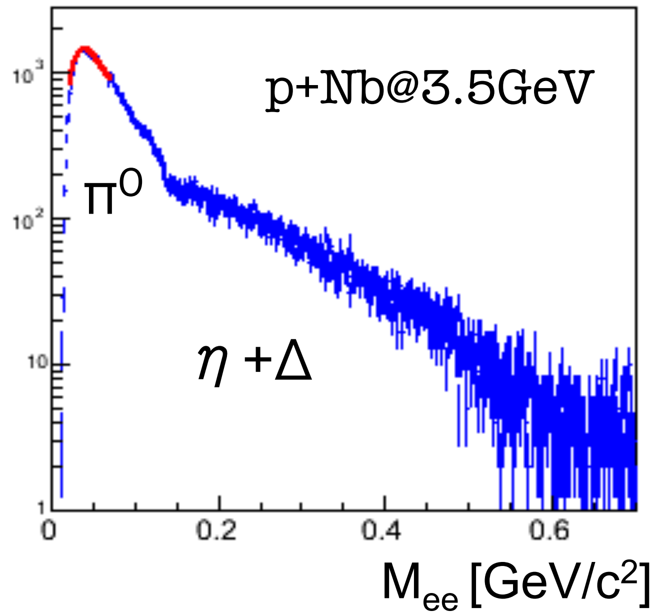


Analysis steps :

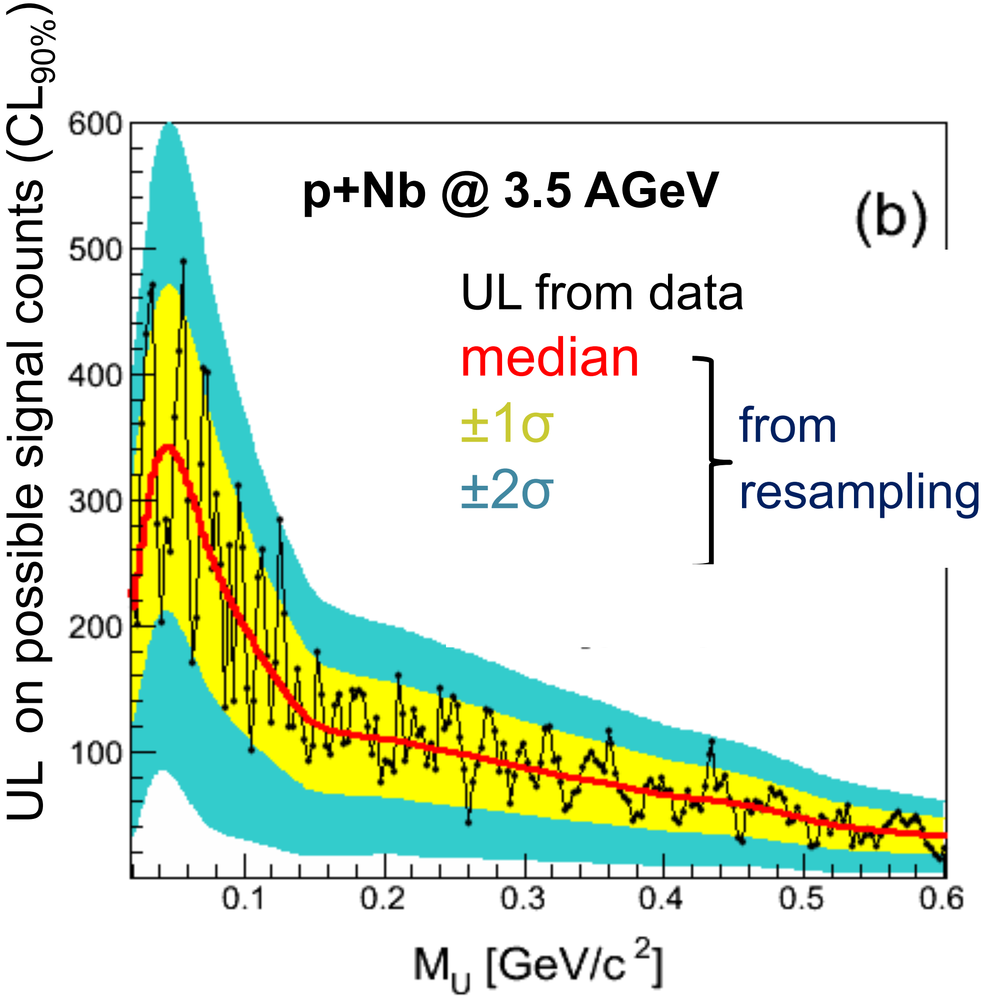
- Slide search region over M_{ee} in 3 MeV steps
- Fit inspected region using sum of a 5^{th}-order polynomial and a Gauss
- Keep position and width of Gauss fixed
- Fit window has width $M_U \pm 4\sigma$

- Use counts (total, background) to determine UL on U signal

inclusive e^+e^-



3.5 GeV p+Nb: UL at $CL_{90\%}$



Input to the UL method (maximum likelyhood)

- measured total dilepton yield
- fitted background
- error on background
- error on eff x acc 15%

W.A. Rolke et al. Nucl. Inst. Meth.Phys. Res A 551 (2005) 493.
G. Cowan et al., Eur. Phys.J. C 71 (2011) 1554.

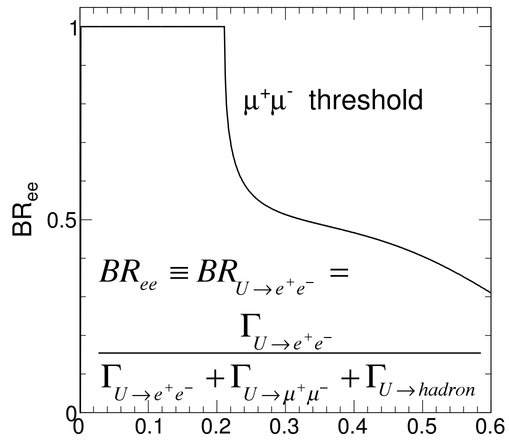
One need to correct upper limit (UL) by acceptance and efficiency in order to go from UL(raw counts) → N(U-boson) → UL(ε^2)

Upper limit of the mixing parameter

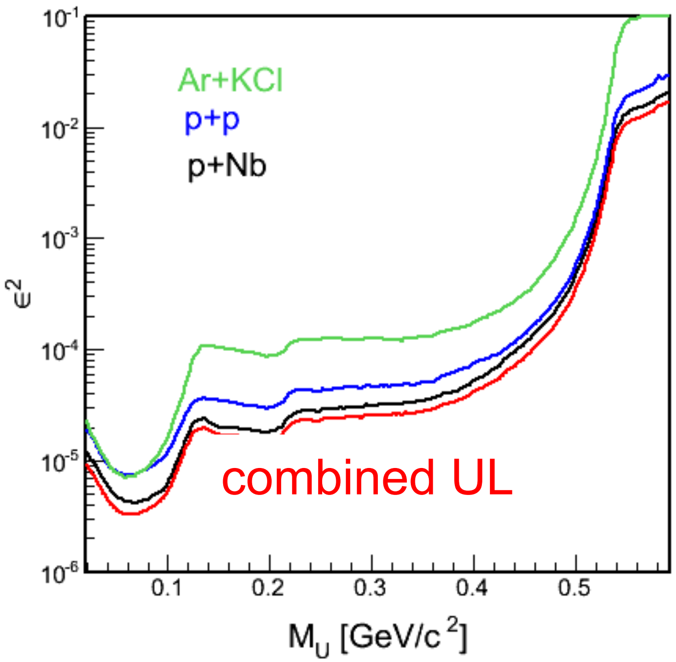
$$N_{U \to e+e-} = \varepsilon^2 BR_{U \to ee} L(M_u)$$

mixing parameter

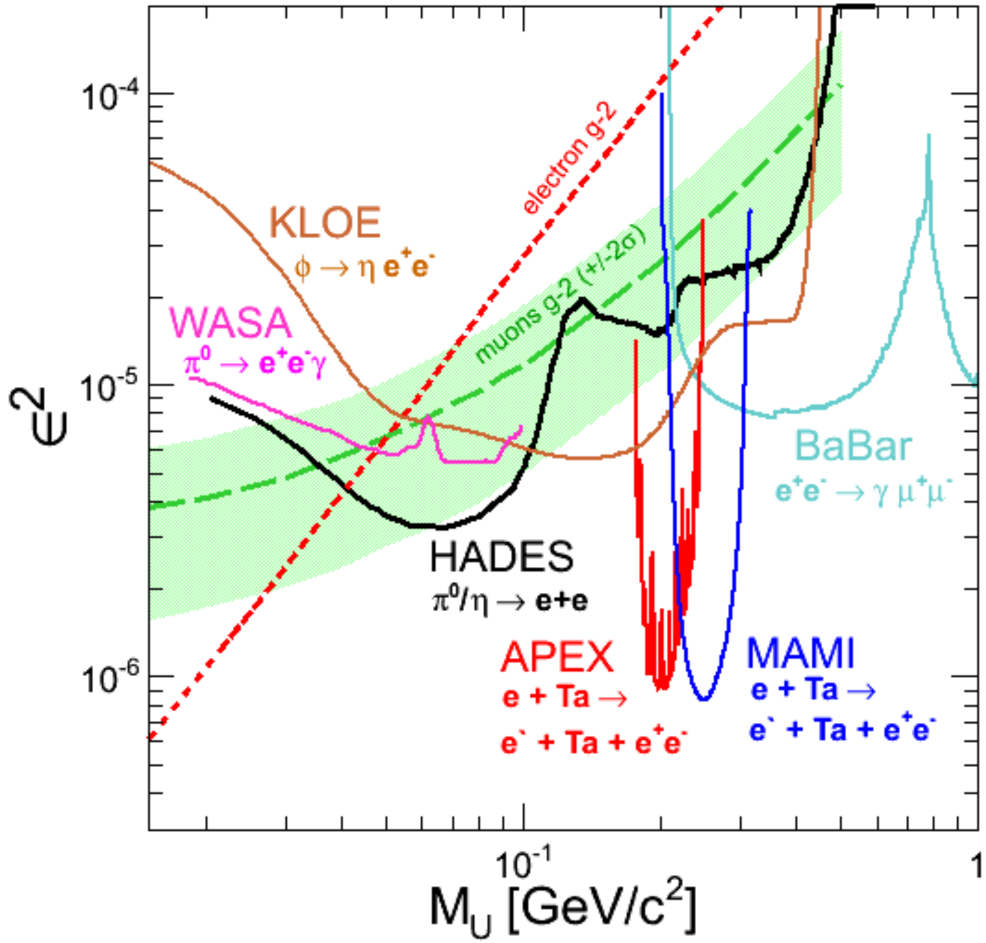
kinematic factors & source parameters



$$L(M_U) = 2N_\eta BR_{\eta \to \gamma\gamma} |F_\eta|^2 \left(1 - \frac{M_U^2}{m_\eta^2}\right)^3$$
$$+ 2N_{\pi^0} BR_{\pi^0 \to \gamma\gamma} |F_{\pi^0}|^2 \left(1 - \frac{M_U^2}{m_{\pi^0}^2}\right)^3$$
$$+ N_\Delta BR_{\Delta \to N\gamma} |F_\Delta|^2 \int A(m_\Delta) |F_\Delta|^2 \frac{\lambda^{3/2}(m_\Delta^2, m_N^2, M_U^2)}{\lambda^{3/2}(m_\Delta^2, m_N^2, 0)}$$



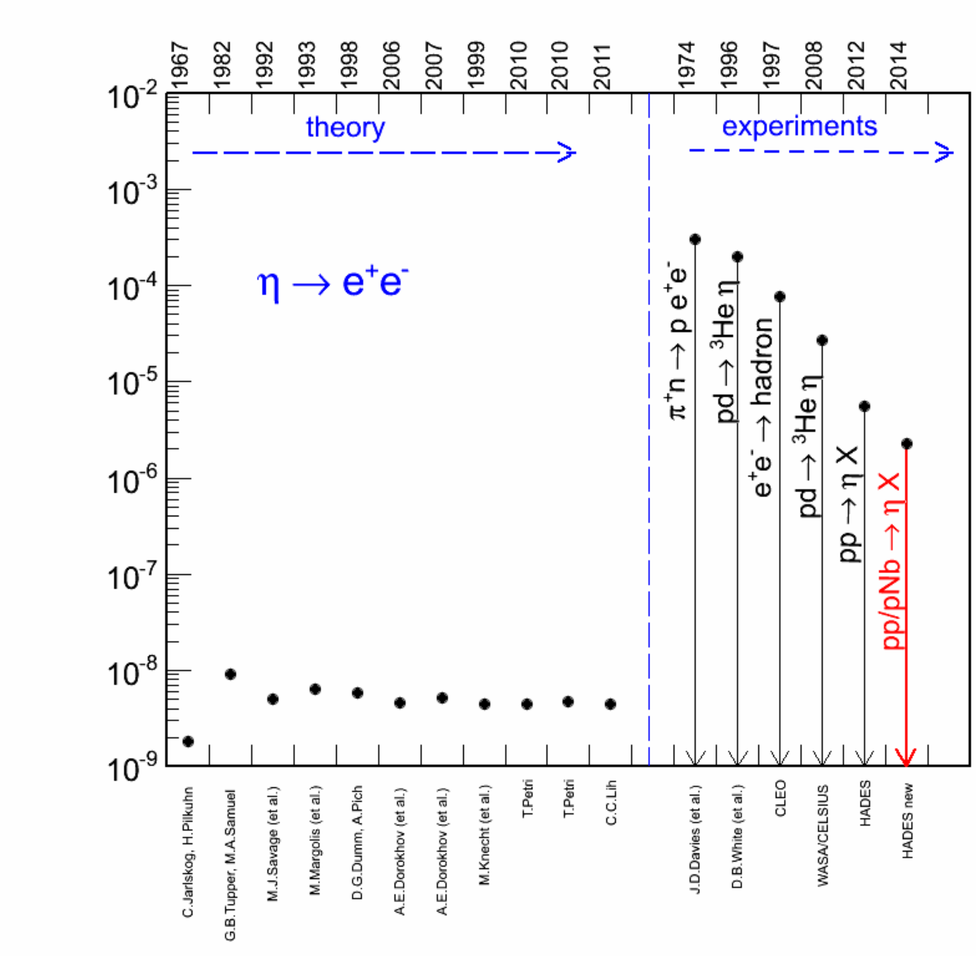
Comparison with world data set

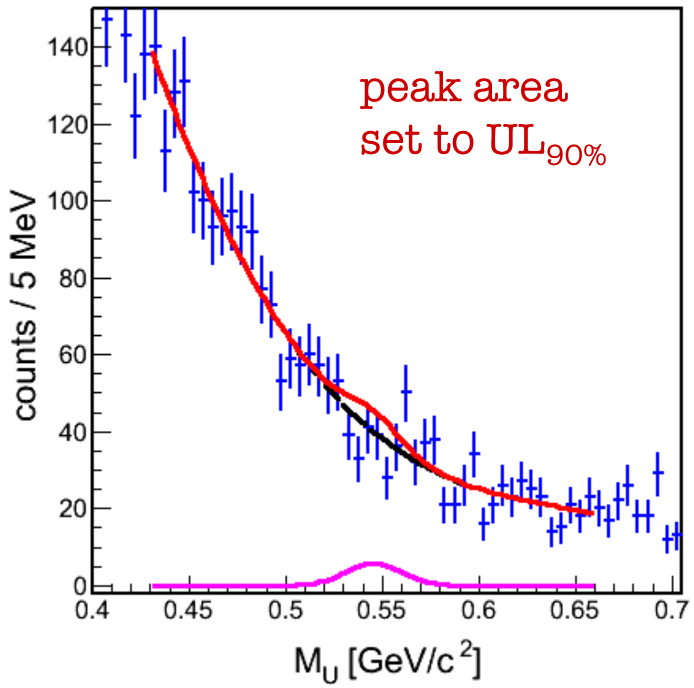


- ✓ HADES coverage : $0.02 < M_U < 0.6$ GeV/c²
- ✓ Clear improvement at low masses ($M_U < 0.1$ GeV/c²)
- ✓ Excludes to large degree the parameter range allowed by the muon g-2 anomaly
- ✓ Complementary information to the KLOE-2 results at higher masses ($M_U > 0.13$ GeV/c²)

Phys. Lett. B 731 (2014), pp. 265-271

Bonus Track: UL on $\eta \rightarrow e^+e^-$ decay





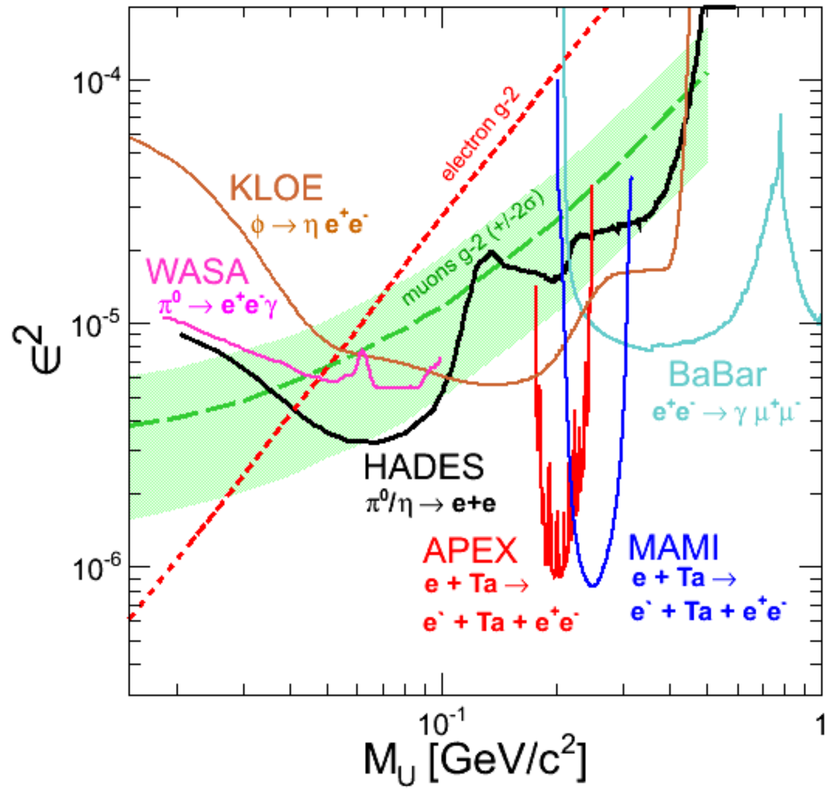
$BR_{\eta \rightarrow e^+e^-} < 2.5\times10^{-6}$ at 90% CL

Phys. Let. B 731C (2014), pp. 265-271

➔ Still far above theoretical expectations: BR≃ 5×10^{-9}

Summary and Outlook

- Dark Photon searched in a DM scenario involving an additional U'(1) force
- HADES lowered the upper limit for masses below 0.1GeV/c²
- Statistics-driven analysis
  - HADES Au+Au e^+e^- data will allow to constrain that region further



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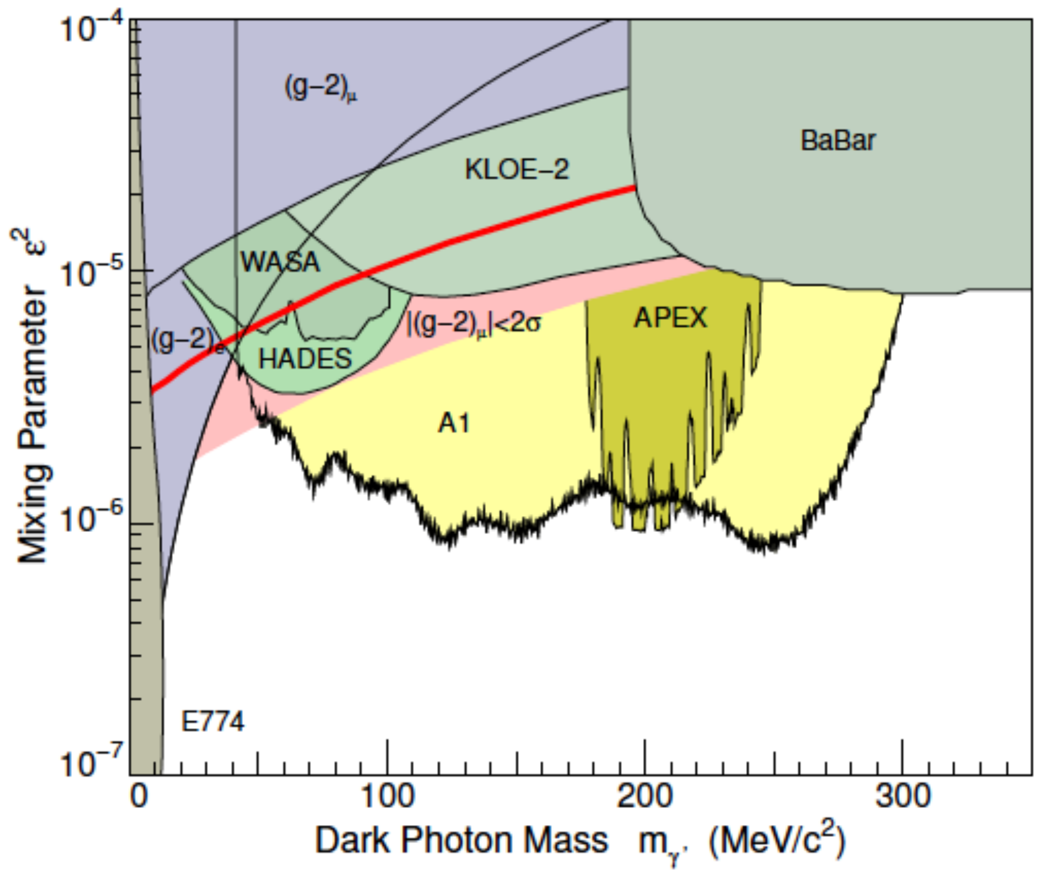

A1/MAMI : arXiv:1404:5502v1

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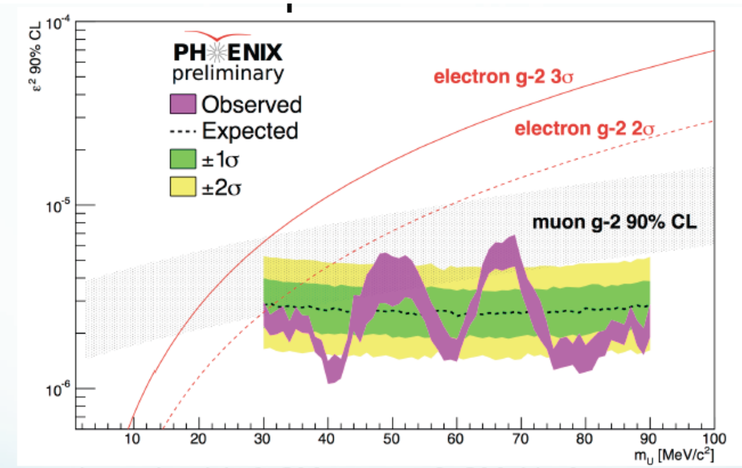

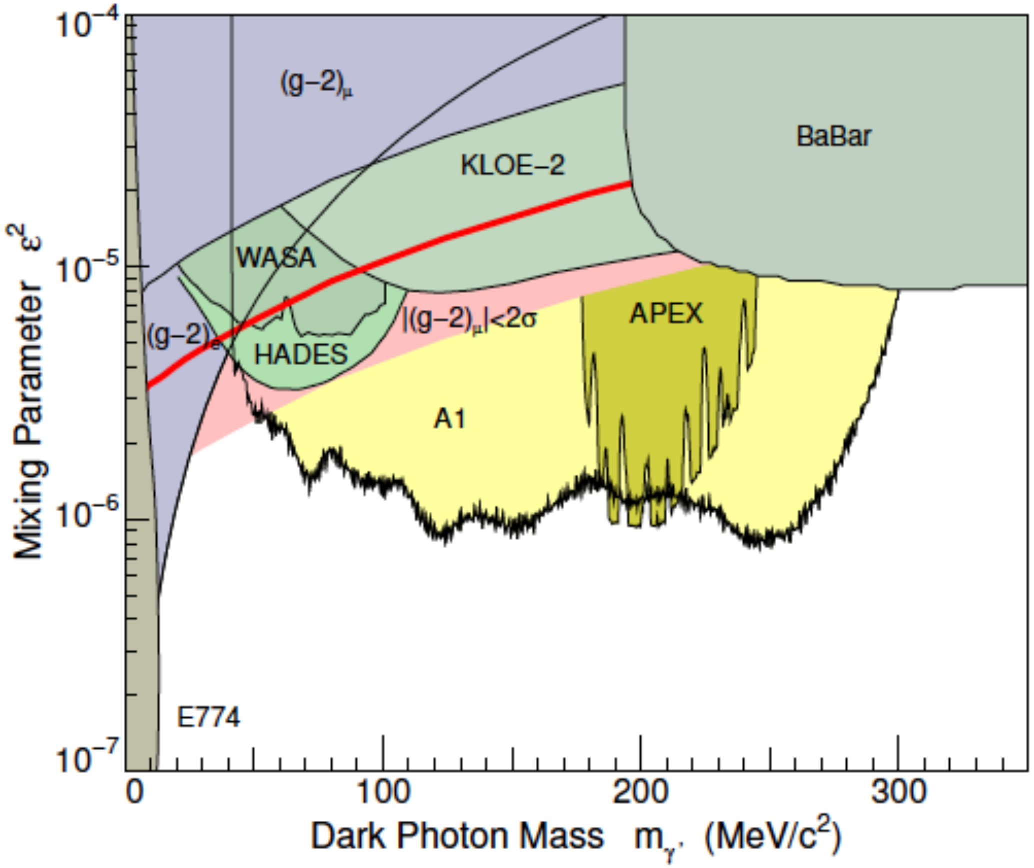

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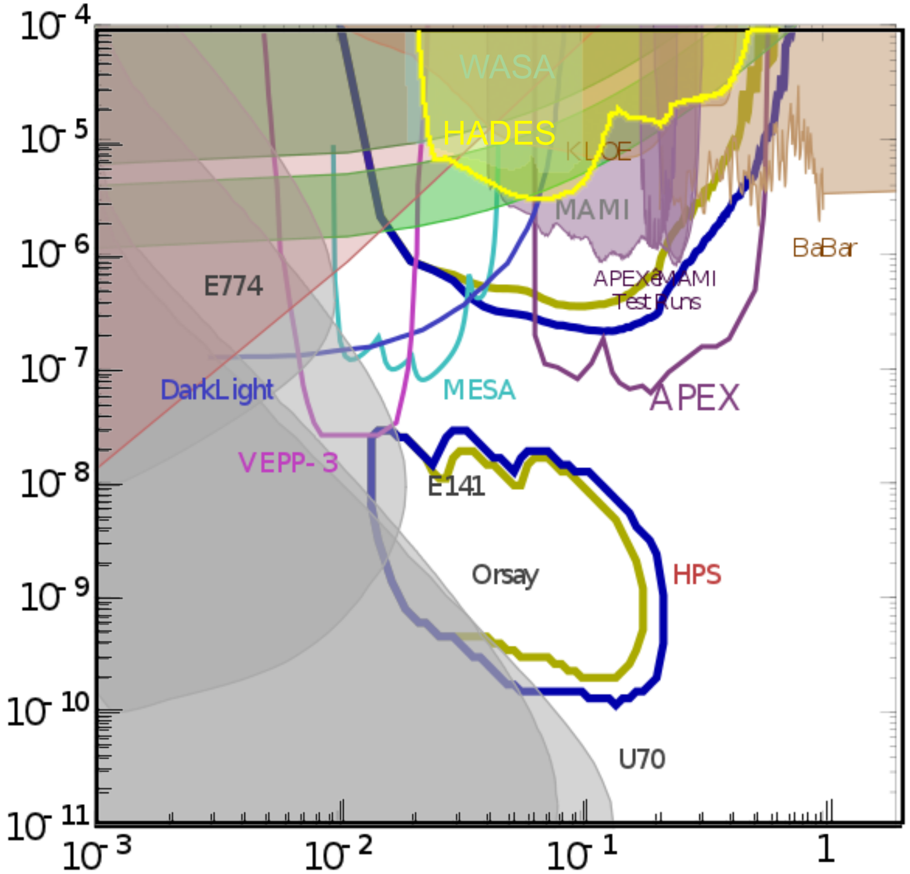
  - Dedicated experiments are planned APEX, HPS at Jefferson Lab, VEPP-3 Russia



plot adjusted from arXiv:1311:0029v1

Bonus result

- Improved upper limit on eta direct decay

$BR_{\eta \rightarrow e+e-}$ **< 2.5×10^{-6} at 90% CL**

More from the Dark Side ...

The U→e⁺e⁻ signal in Dalitz decays

for m=π^0, η: $\dfrac{\Gamma_{m\to U\gamma}}{\Gamma_{m\to\gamma\gamma}} = \dfrac{N_U^m}{N_m BR_{m\to\gamma\gamma}}$ and for Δ: $\dfrac{\Gamma_{\Delta\to NU}}{\Gamma_{\Delta\to N\gamma}} = \dfrac{N_U^\Delta}{N_\Delta BR_{\Delta\to N\gamma}}$

In analogy to the virtual photon:

$$\frac{\Gamma_{m\to U\gamma}}{\Gamma_{m\to\gamma\gamma}} = 2\varepsilon^2 \left|F_m(q^2 = M_U^2)\right|^2 \left(1 - \frac{M_U^2}{M_m^2}\right)^3$$

$$\left|F_{\pi^0}(q^2)\right| = 1 + 0.032\frac{q^2}{m_{\pi^0}^2}$$

PDG 2012

$$\left|F_\eta(q^2)\right| = \left(1 + \frac{q^2}{\Lambda^2}\right)^{-1}$$

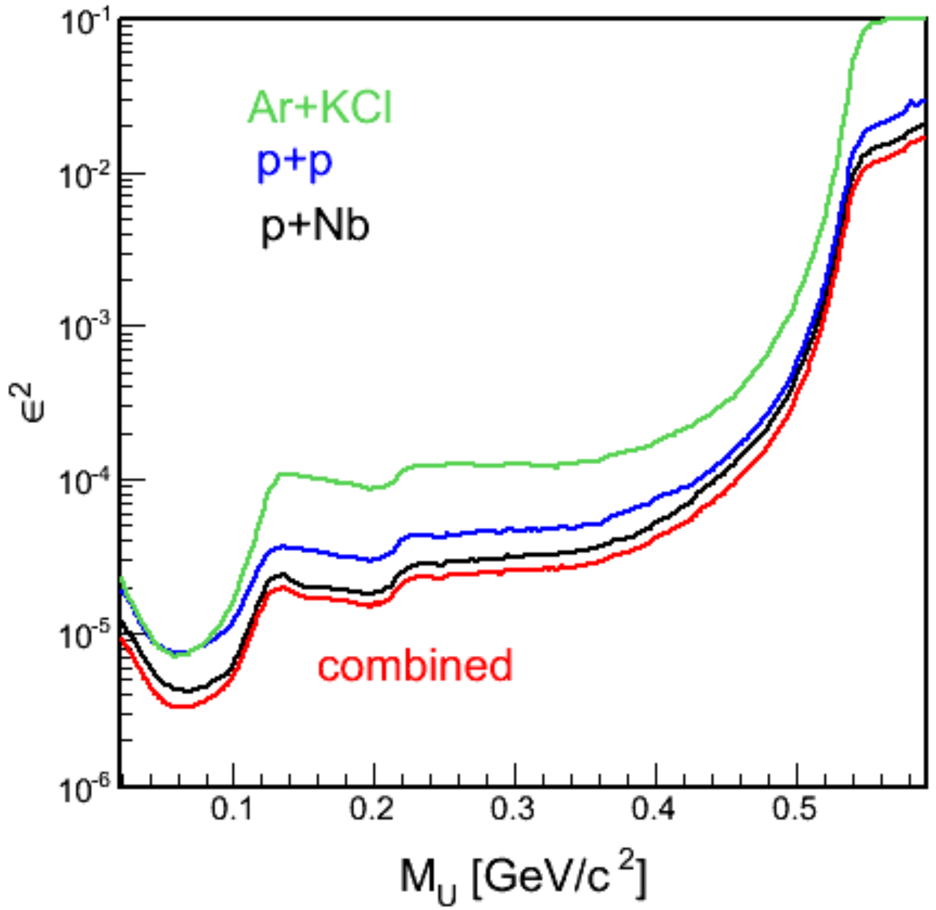
$$\Lambda = 0.72 GeV$$

H. Berghäuser et al., PLB 701,(2011) 562.
R. Arnaldi et al. PLB 677(2009) 260.

$$\frac{\Gamma_{\Delta\to NU}}{\Gamma_{\Delta\to N\gamma}} = \varepsilon^2 \int A(m_\Delta) \left|F_\Delta(M_U^2)\right| \frac{\lambda^{3/2}(m_\Delta^2, m_N^2, M_U^2)}{\lambda^{3/2}(m_\Delta^2, m_N^2, 0)} dm_\Delta$$

$$\left|F_\Delta(q^2)\right| = 1$$

Combined UL on e^2



All 3 data sets are of comparable statistical quality and ULs can be joined into one combined UL following a statistics-driven ansatz:

$$UL_{(1+2+3)} = \sqrt{(UL_{(1)}^{-2} + UL_{(2)}^{-2} + UL_{(3)}^{-2})^{-1}}$$

The combined upper limit **$UL_{(1+2+3)}$** is overall about 10-20% lower than the p+Nb value taken alone.

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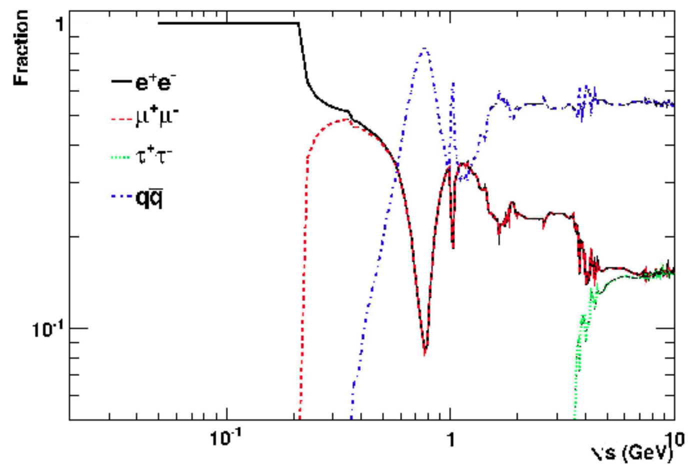
Dark photon decay channels



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  ✓ Interaction via kinetic mixing between the U(1) and U'(1)with a mixing strength $\varepsilon^2 = \alpha'/\alpha$

    ✓ Mixing strength expected to be of order $\varepsilon \approx 10^{-5} - 10^{-2}$ but could be smaller even

  ✓ Possibility to observe signal of DM via modification of well-known electromagnetic processes : e.g π^0, η, Φ decays:

$$\eta \to \gamma\gamma^* \to \gamma e^+ e^-$$

at level ε^2

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

look for modification of these well-known decays