



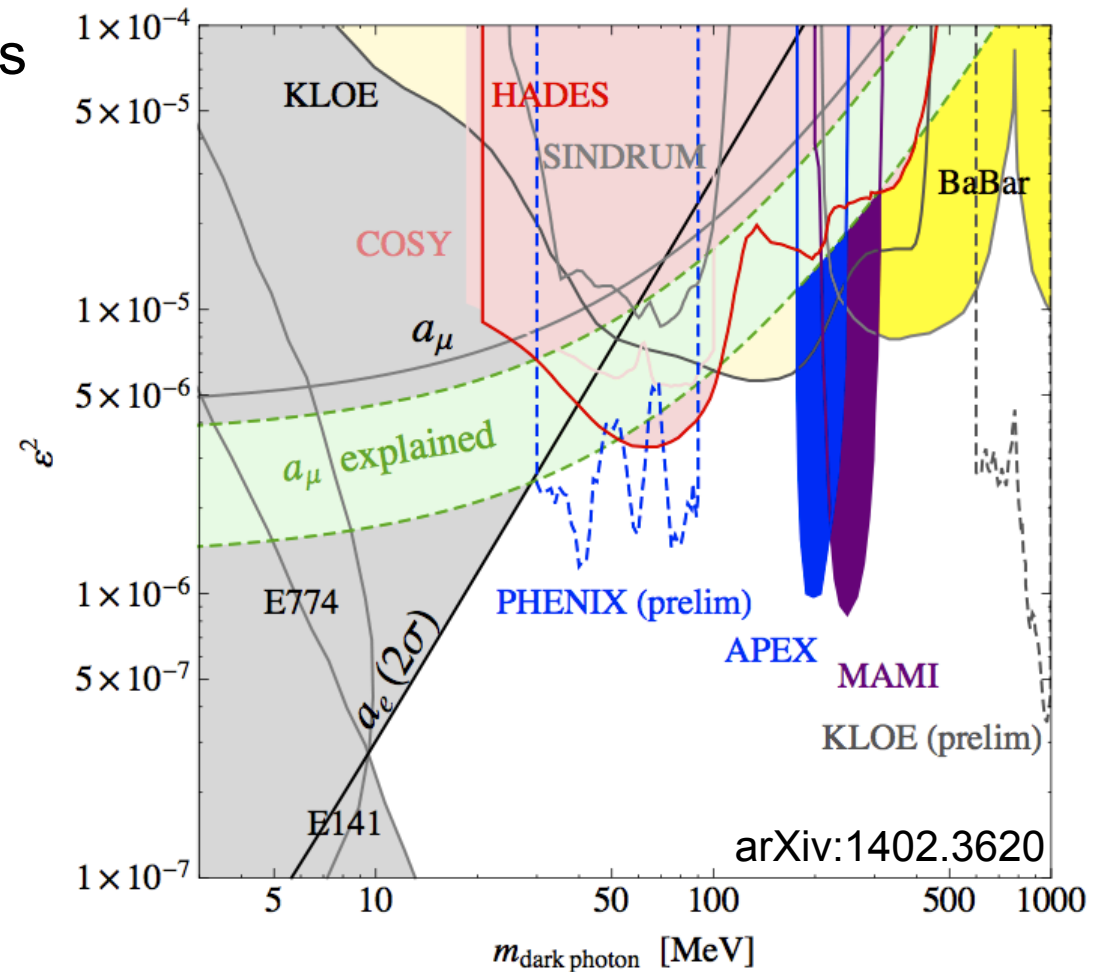
DARK PHOTON SEARCHES IN MESON- DECAY EXPERIMENTS

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Dark Interactions Workshop
Brookhaven National Laboratory
June 11, 2014

Overview

- Meson-decay experiments are well-suited to explore the mass region $\sim(10-1000) \text{ MeV}/c^2$
- Experiments:
 - SINDRUM
 - π^0 decay
 - WASA-at-COSY
 - π^0 decay
 - KLOE
 - ϕ decay
 - e^+e^- annihilation
 - NA48/2, NA62
 - π^0 decay
 - K^+ decay
 - E787/E949
 - K^+ decay



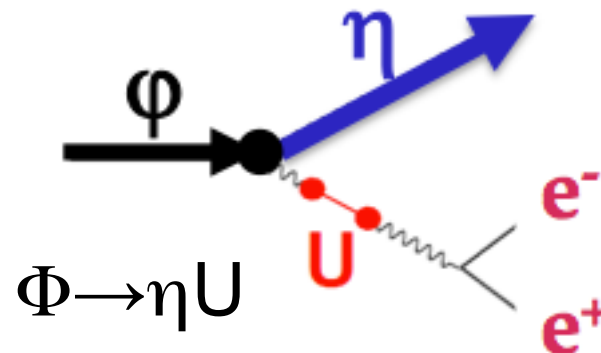
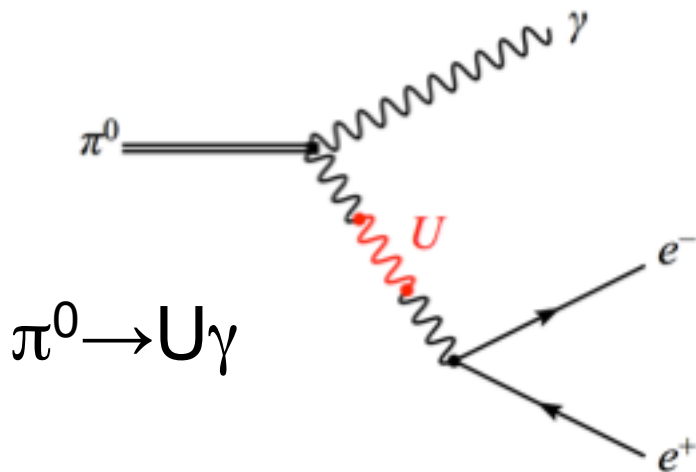
Processes

- Mesons decay to dark photon via kinetic mixing between SM photon and dark photon:

$$L_{\text{int}} = -\frac{1}{2} \epsilon F_{\mu\nu}^{QED} F_{Dark}^{\prime\mu\nu}$$

- Most analyses assume:
 - $\text{BR}(U \rightarrow e^+e^-) + \text{BR}(U \rightarrow \mu^+\mu^-) = 1$
 - $\text{BR}(U \rightarrow e^+e^-) = 1$ when $M_U < 2M_\mu$

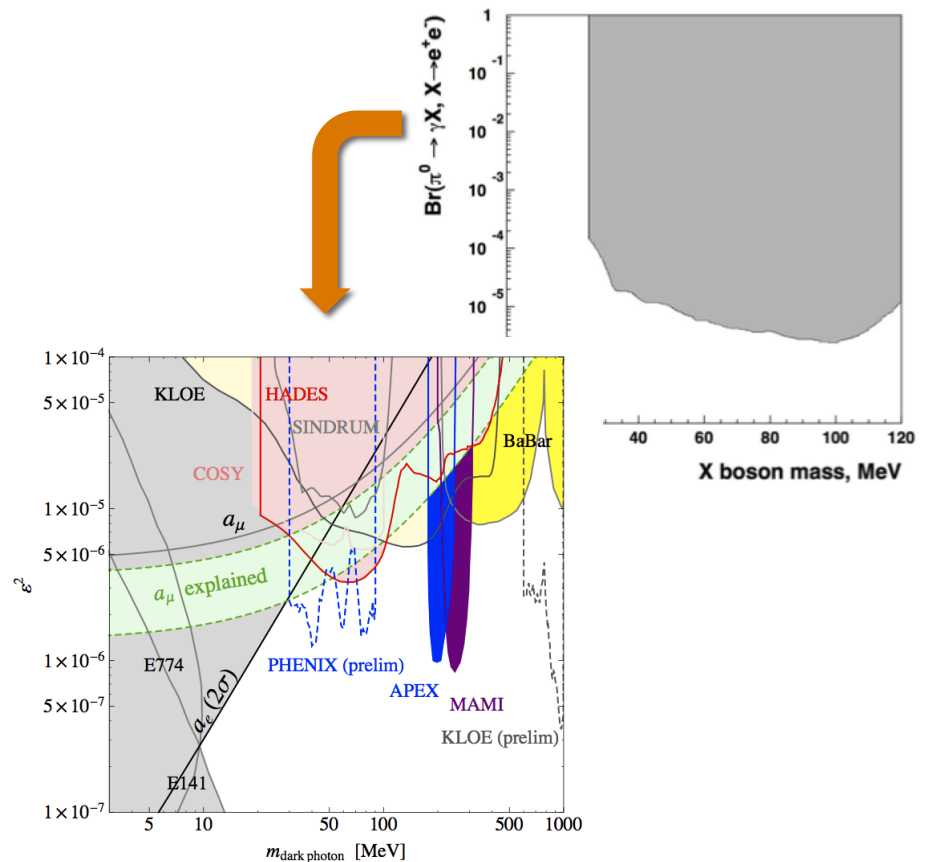
BR upper limit \sim
 $(\text{Flux})^{-1/2} \times$
 $(\text{Acceptance})^{-1/2} \times$
 $(M_{ee} \text{ resolution})^{1/2}$



SINDRUM Limit: $\pi^0 \rightarrow U\gamma, U \rightarrow e^+e^-$

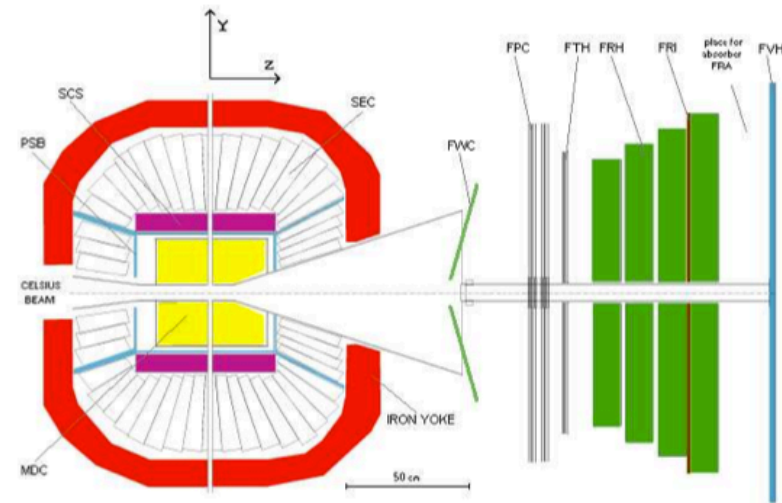
- SINDRUM search for $\pi^0 \rightarrow \gamma X$ (PSI, 1992)
 - 95-MeV/c π^- beam incident on liquid hydrogen target producing at-rest pions: $\pi^- p \rightarrow \pi^0 n$
 - $\sim 10^5$ $\pi^0 \rightarrow e^+e^-\gamma$ decays
 - BG: $\pi^- p \rightarrow ne^+e^-\gamma$
 - Magnetic spectrometer: $\sigma_p/p \sim 2\%$
 - Search for peak in e^+e^- invariant mass distribution
 - Branching ratio upper limit for $25 < M_X < 120$ MeV/c²
- Result analyzed in terms of dark photon by Gninenko in 2013

R. Meijer Drees et al.,
Phys.Rev.Lett. 68
(1992) 3845

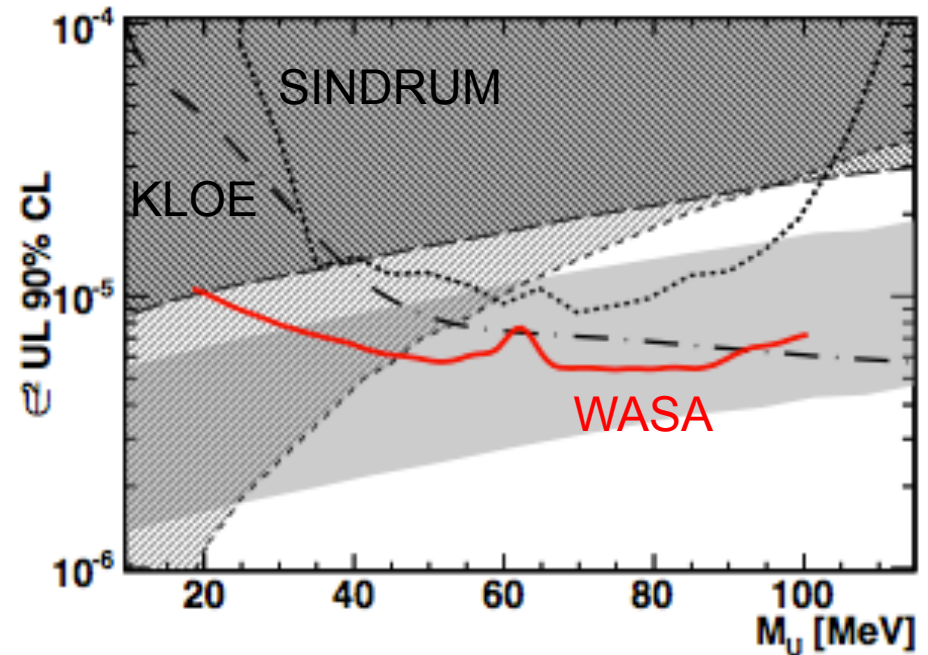
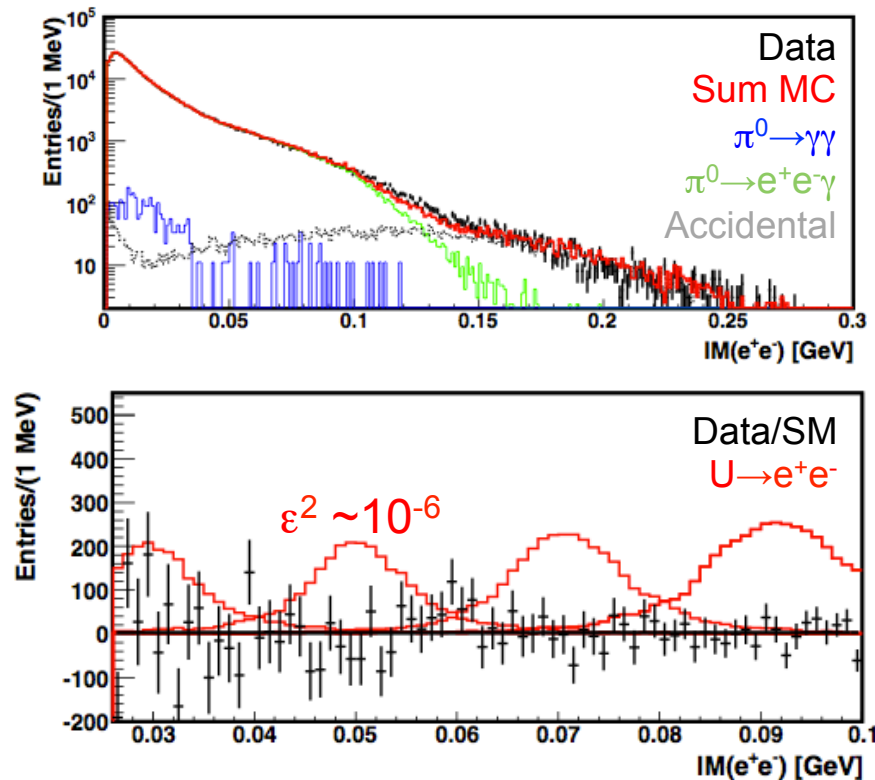


WASA-at-COSY Experiment

- Detector designed for study of rare π^0 decay using $pp \rightarrow pp\pi^0$
- Dark photon search uses COSY proton beam energy of 550 MeV
 - C.O.M. excess energy of 122 MeV w.r.t. $pp \rightarrow pp\pi^0$ threshold (below two pion production threshold)
- Forward Detector: reconstruction of protons
- Central Detector: reconstruction of photons/electrons
 - $\sigma_p/p < 2\%$



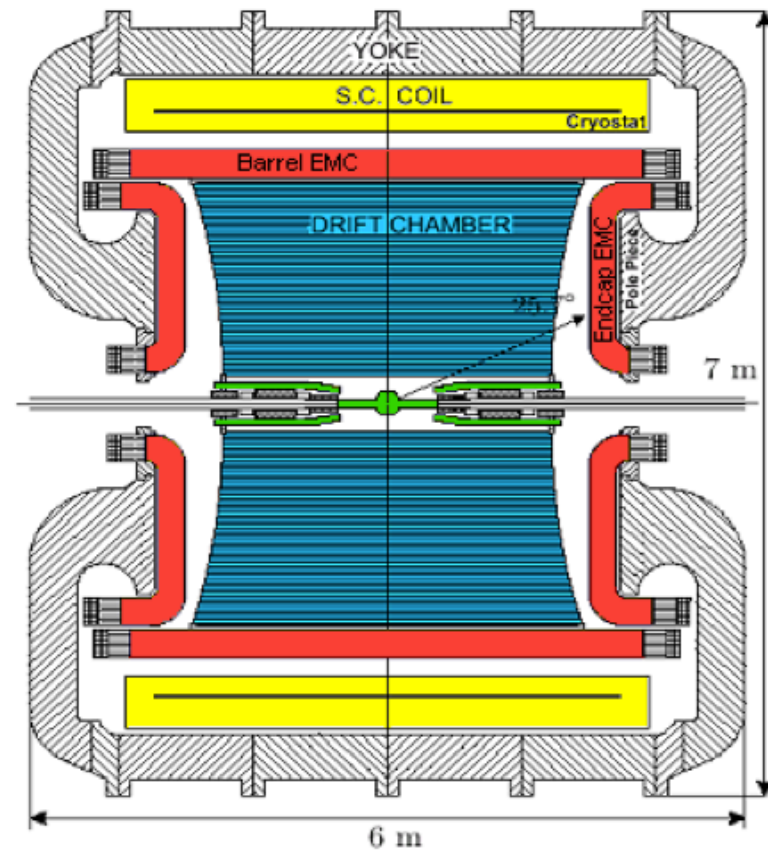
WASA-at-COSY Search: $\pi^0 \rightarrow U\gamma$, $U \rightarrow e^+e^-$



- $5 \times 10^5 \pi^0 \rightarrow e^+e^-\gamma$ decays
- Search for peak in e^+e^- invariant mass distribution

KLOE Experiment

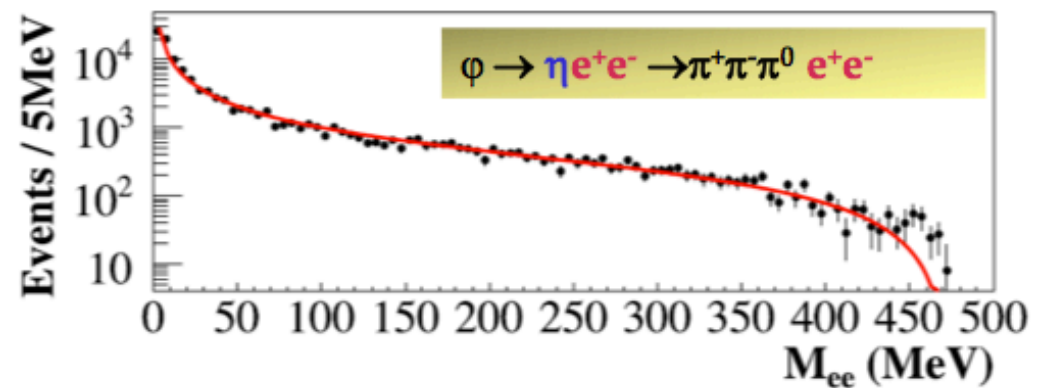
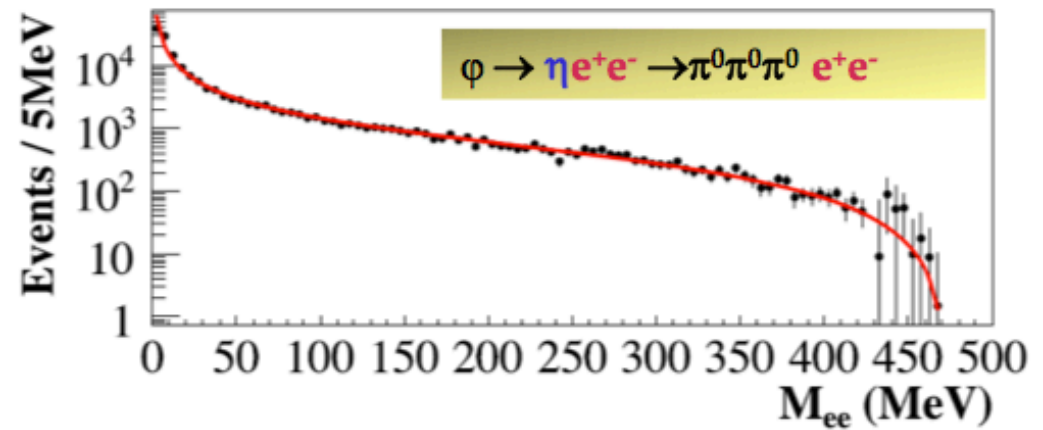
- DAΦNE: e^+e^- Φ factory
 - $\Phi \rightarrow K^+K^-$ ($\sim 49\%$)
 - $\Phi \rightarrow K_S K_L$ ($\sim 34\%$)
 - $\Phi \rightarrow \rho\pi + \pi^+\pi^-\pi^0$ ($\sim 15\%$)
 - $\Phi \rightarrow \eta\gamma$ ($\sim 1\%$)
- Drift chamber
 - $\sigma_p/p < 0.4\%$
- Lead/scintillating fiber EM calorimeter
 - $\sigma_E/E \sim 5.7\%/\sqrt{E}$ [GeV]
- Data collected:
 - 2.5 fb^{-1}
 - $\sim 8 \times 10^9$ Φ decays



KLOE Search: $\Phi \rightarrow \eta U, U \rightarrow e^+ e^-$

- Search for excess in M_{ee} distribution of irreducible $\Phi \rightarrow \eta e^+ e^-$ background
- $\eta \rightarrow \pi^0 \pi^0 \pi^0$
 - 30577 events
 - ~3% background
- $\eta \rightarrow \pi^+ \pi^- \pi^0$
 - 13254 events
 - ~2% background
- $\sigma(M_{ee}) < 2 \text{ MeV}$

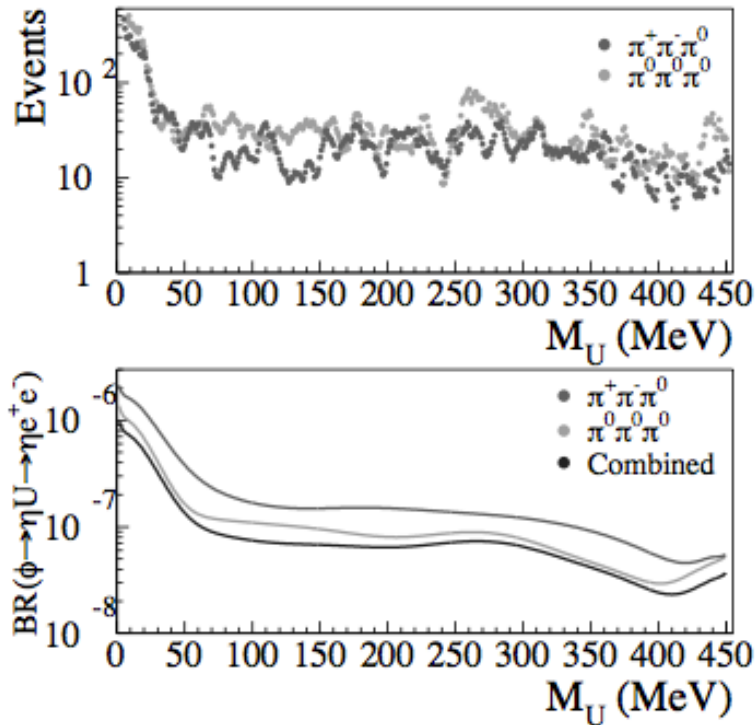
Fit to irreducible background:



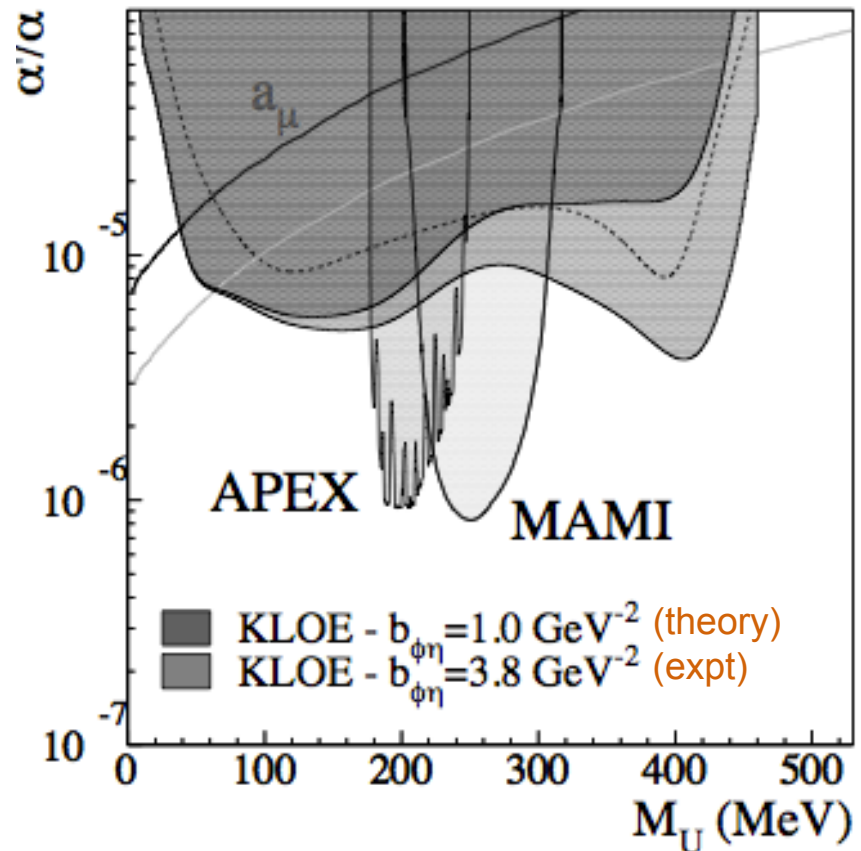
KLOE $\Phi \rightarrow \eta U$ Limit

90% CL upper limit on:

- number of observed events (top)
- branching ratio (bottom)



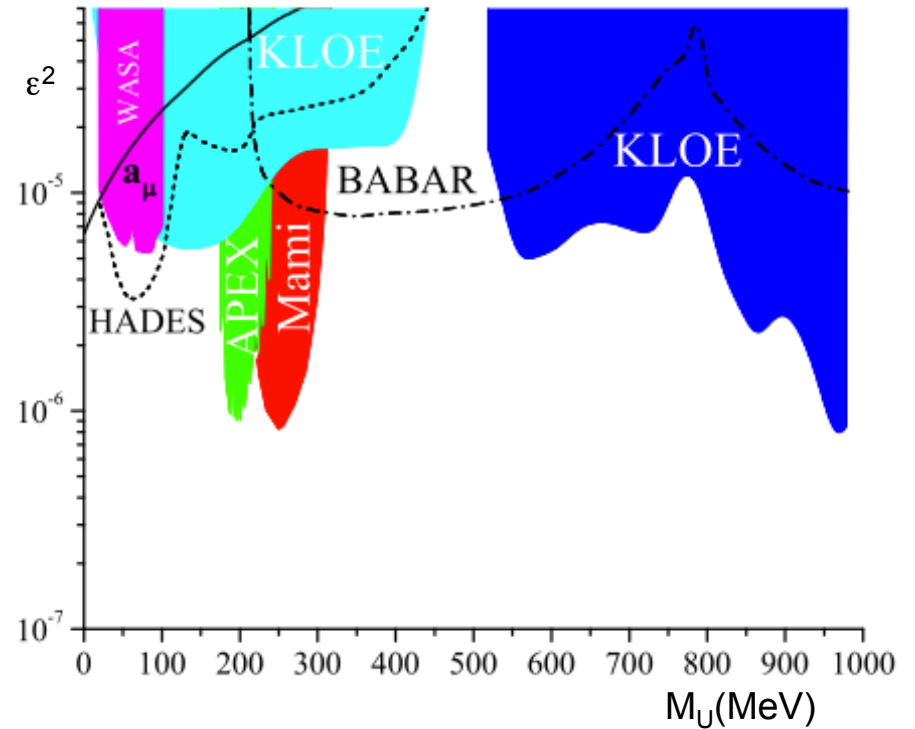
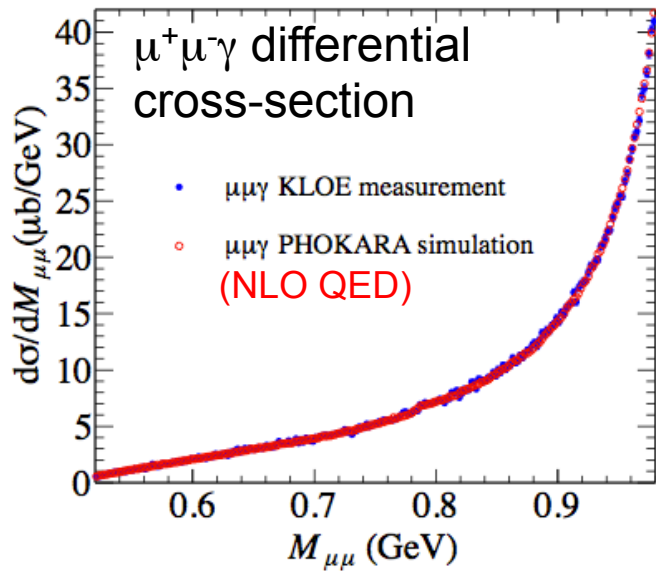
Exclusion plot:



Note that limit depends on the form factor $F_{\phi\eta}(q^2)$: $b_{\phi\eta} = dF/dq^2(0)$

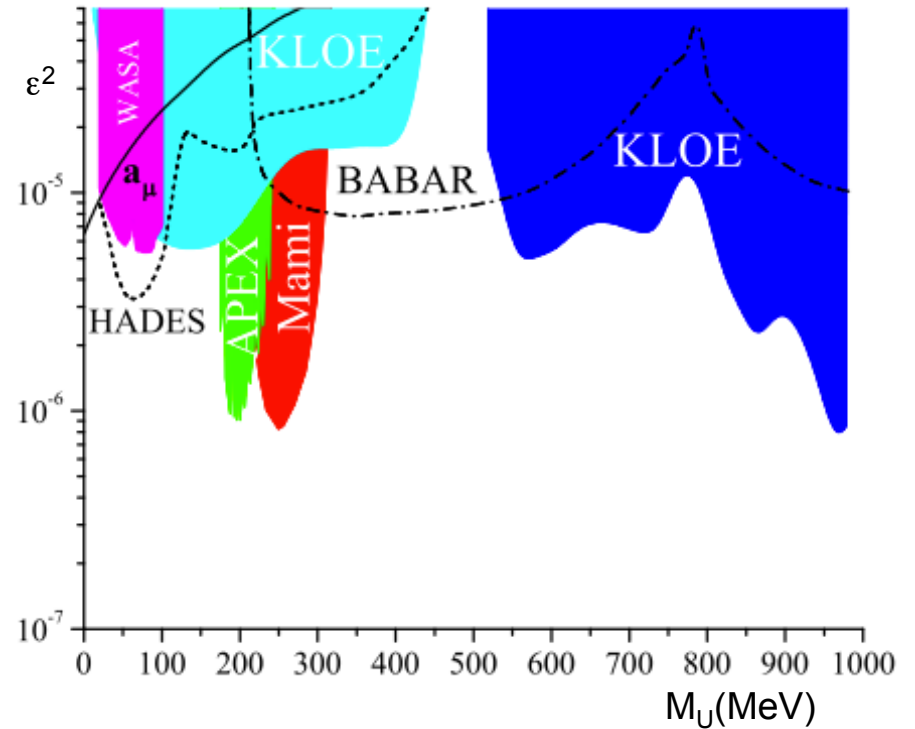
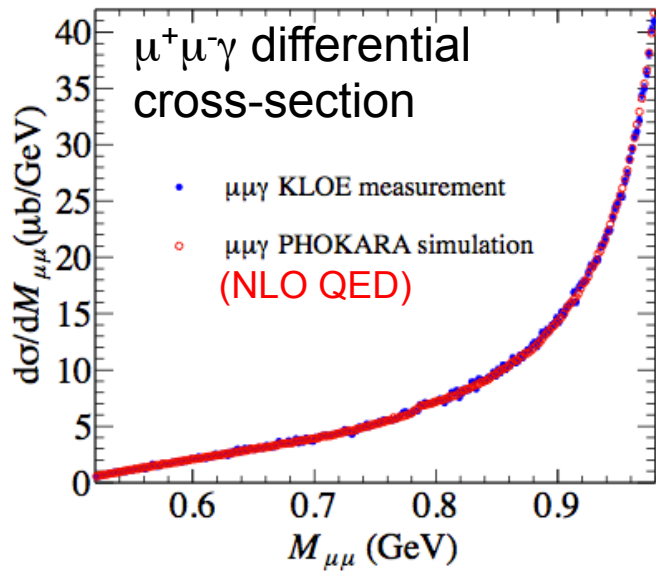
KLOE Search: $e^+e^- \rightarrow U\gamma, U \rightarrow \mu^+\mu^-$

- Production of dark photon in e^+e^- annihilation
- Search for peak in $\mu^+\mu^-$ invariant mass distribution
- $\sim 5 \times 10^5 \mu^+\mu^- \gamma$ events
- Backgrounds: $\pi\pi\gamma, \pi\pi\pi, ee\gamma, ee\mu\mu$



KLOE Search: $e^+e^- \rightarrow U\gamma, U \rightarrow \mu^+\mu^-$

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New result expected at ICHEP'14:

- $e^+e^- \rightarrow U\gamma, U \rightarrow e^+e^-$
- $35 \text{ MeV}/c^2 < M_U < 520 \text{ MeV}/c^2$
- Expected sensitivity: $\epsilon^2 \sim 10^{-6}$

NA48/2 Experiment

Ancestor: NA31		
1997	ϵ'/ϵ run	$K_L + K_S$
1998	ϵ'/ϵ run	$K_L + K_S$
NA48	ϵ'/ϵ run	K_S
	$K_L + K_S$	Hi. Int.
2000	K_L only	K_S High Intensity
NO Spectrometer		
2001	ϵ'/ϵ run	K_S High Int.
NA48/1	K_S High Intensity	
	2003 K^\pm High Intensity	
NA48/2	2004 K^\pm High Intensity	
NA62 (Rk phase)	2007/08: $K_{e2}^+ / K_{\pi 2}^+$ runs	
NA62	2007-2013: R&D	
	2012: Start $K^+ \rightarrow \pi^+ \nu \bar{\nu}$	

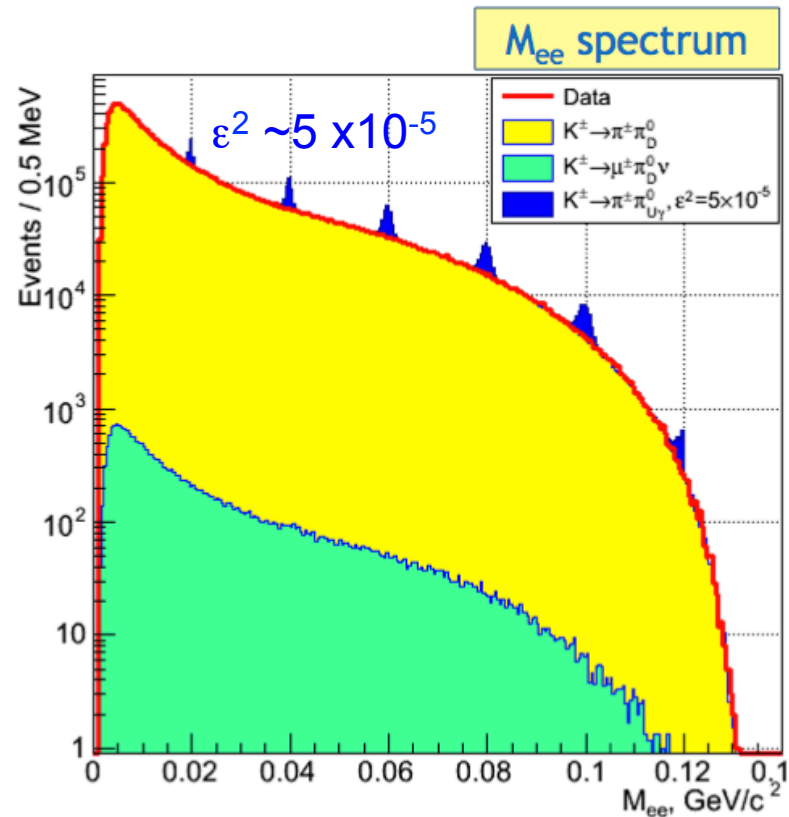
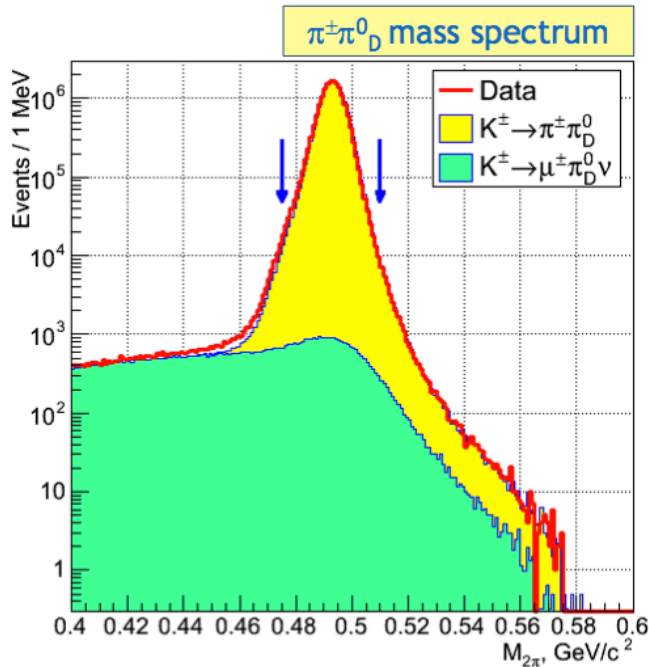
- 4 drift chambers
 - $\sigma_p/p \sim 1\% \oplus 0.044\% \times p$ [GeV/c]
- Liquid Krypton EM Calorimeter
 - $\sigma_E/E \sim 3.2\%/\sqrt{E} \oplus 9\%/\sqrt{E} \oplus 0.42\%$ [GeV]

Improved to 0.48% \oplus 0.009% in 2007

NA48/2 Search: $\pi^0 \rightarrow U\gamma, U \rightarrow e^+e^-$

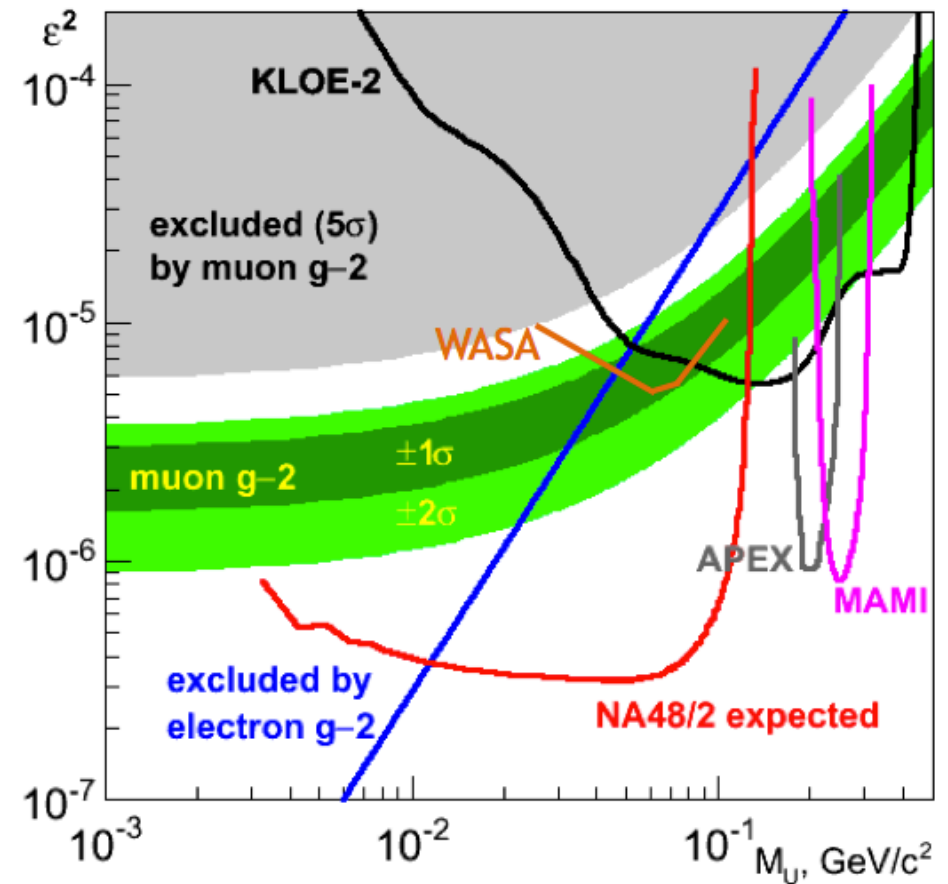
- Large sample of tagged π^0_D decays ($\sim 2 \times 10^7$) from $K^\pm \rightarrow \pi^\pm \pi^0_D$
 - Kaon flux: $\sim 2 \times 10^{11}$
 - Acceptance: $\sim 5\%$
 - M_{ee} resolution: $\sim 1.2\%$

- Search for peak in e^+e^- invariant mass distribution



NA48/2 Expected Sensitivity

- Analysis in progress
- For $\text{BR}(U \rightarrow e^+e^-) = 1$ ($M_U < 2M_\mu$)
- Measurement of π^0 EM form factor to characterize SM background in progress



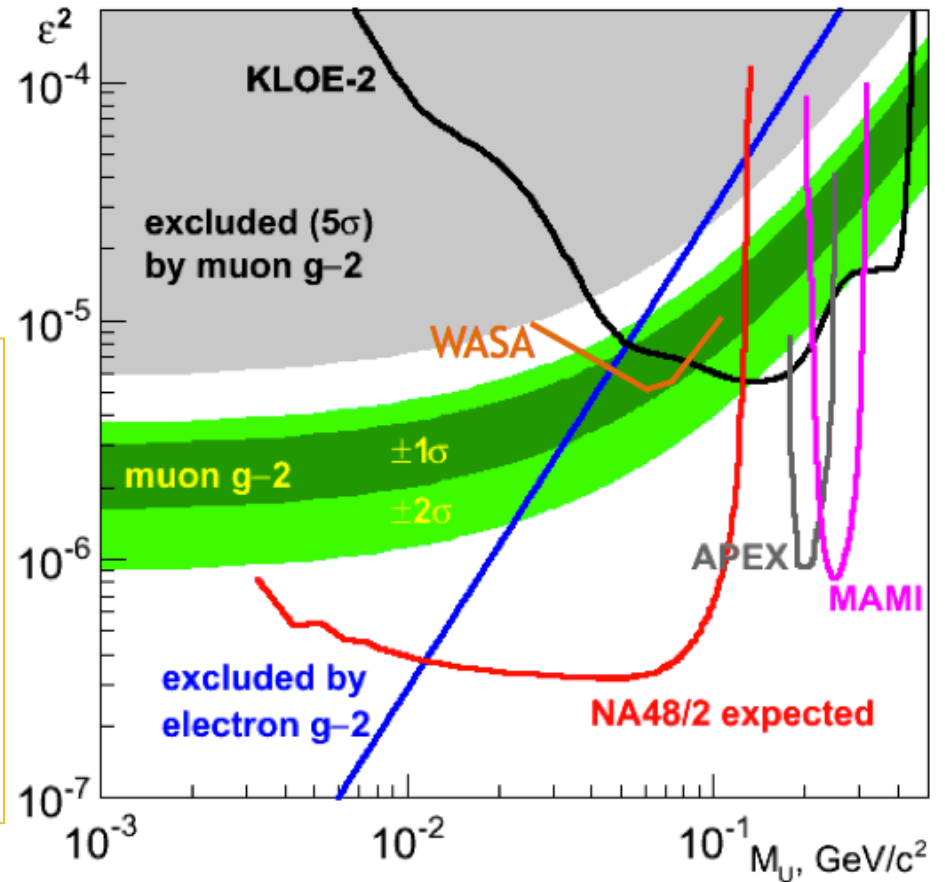
NA48/2 Expected Sensitivity

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- Measurement of π^0 EM form factor to characterize SM background in progress

KTeV search?

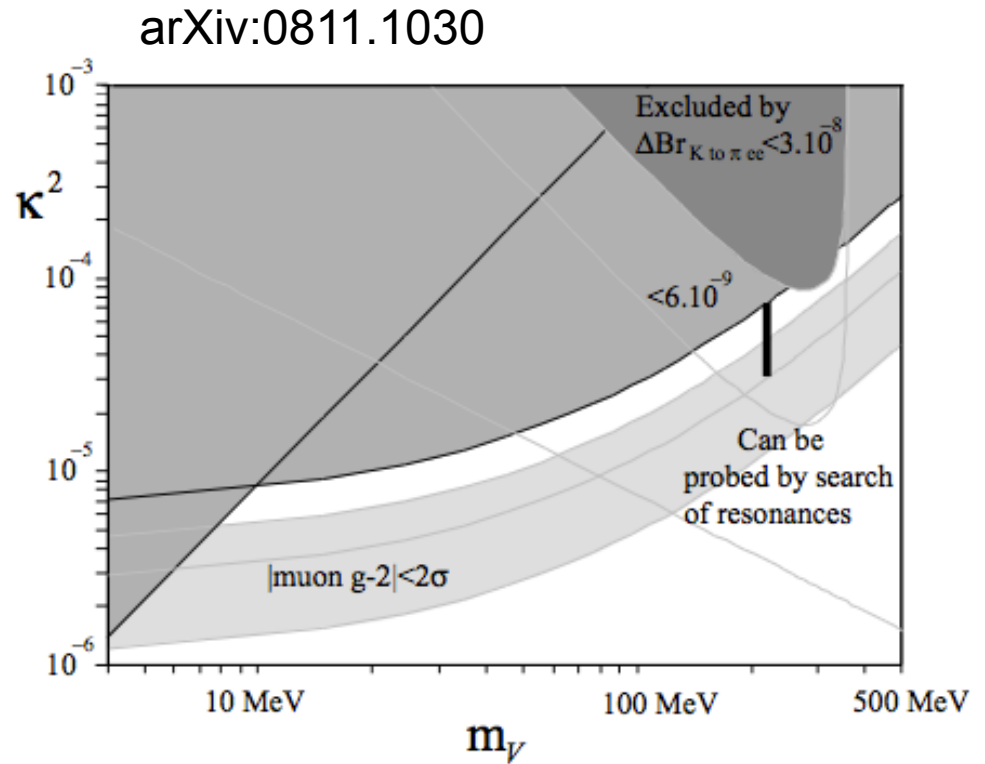
Existing π^0_D analysis:

- $\sim 2 \times 10^6 \pi^0_D$ decays from $K_L \rightarrow \pi^0 \pi^0 \pi^0_D$ (arXiv:hep-ex/0610072)
- M_{ee} : 70-100 MeV/c²
- Unlikely to be pursued given NA48 stats & difficulties with access to KTeV data.



NA48/2 Search: $K^+ \rightarrow \pi^+ U$, $U \rightarrow \ell^+ \ell^-$

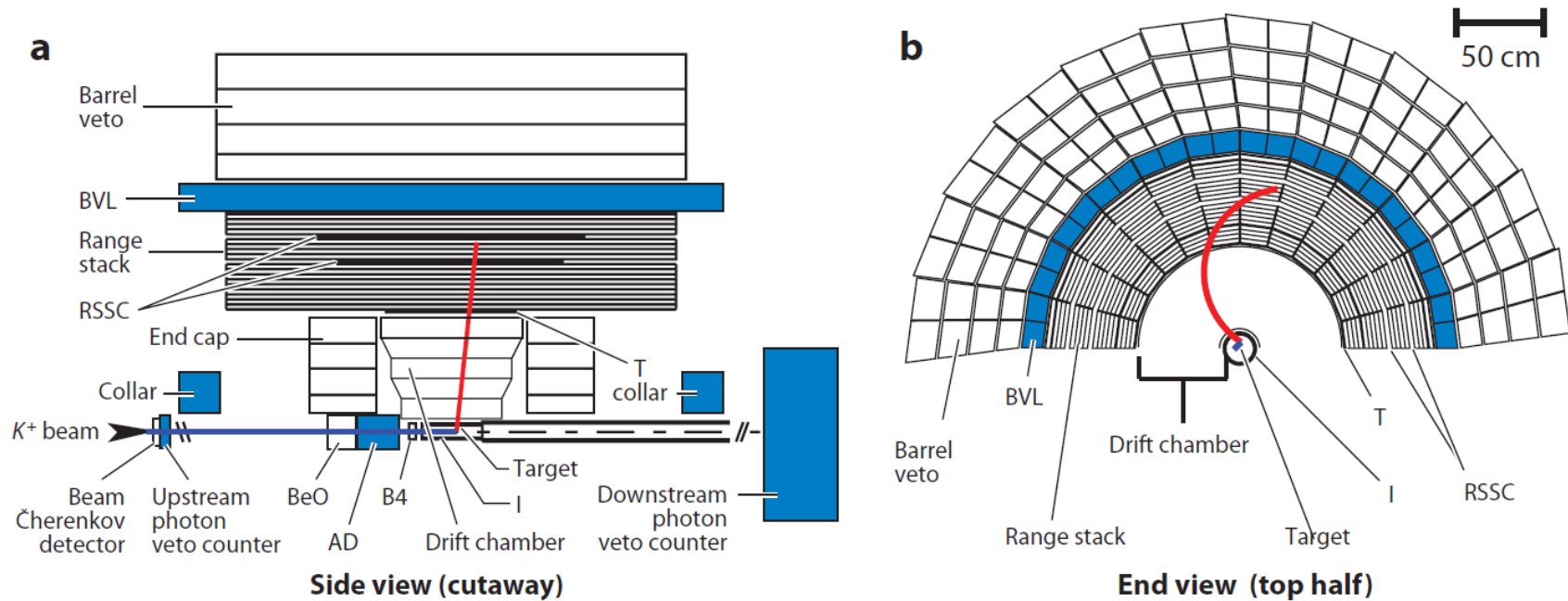
- Search for resonance in $M_{ee,\mu\mu}$ distribution for SM $K^+ \rightarrow \pi^+ \ell^+ \ell^-$ decay
- Pospelov: Possible that up to 10% of $K^+ \rightarrow \pi^+ e^+ e^-$ “SM” branching ratio is from U resonance
 - $BR(K^+ \rightarrow \pi^+ e^+ e^-) = 3 \times 10^{-7}$
 - Requiring $BR(K^+ \rightarrow \pi^+ U) < 3 \times 10^{-8}$ produces exclusion plot shown here
- NA48/2 plans to reanalyze existing data: $K^+ \rightarrow \pi^+ e^+ e^-$ (7253 events*) & $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ (3120 events*) to set an experimental limit



* arXiv:0903.3130

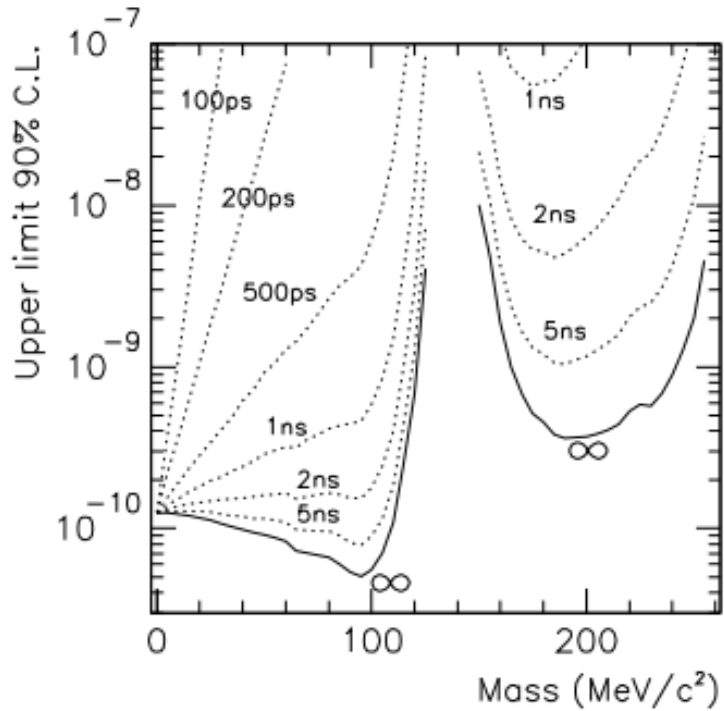
* arXiv:1011.4817

E787/949 Experiment



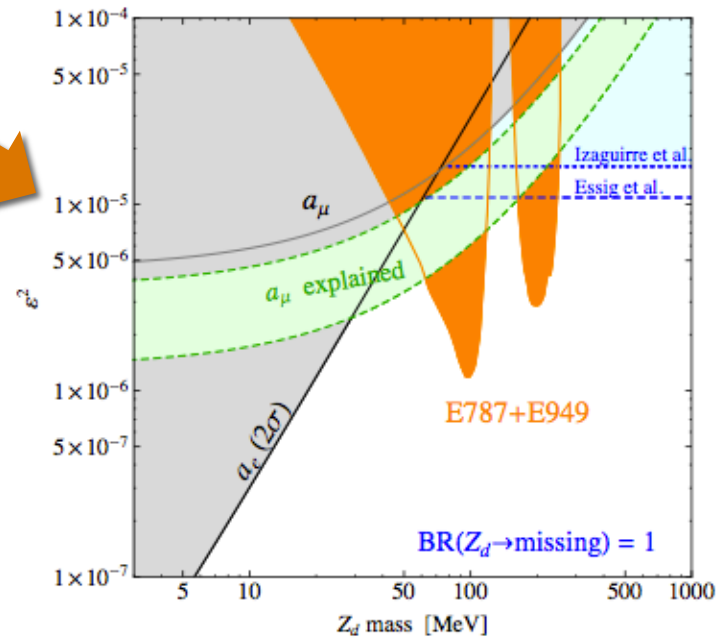
- Primary physics: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- K^+ decays at rest in the stopping target
- Decay π^+ track momentum analyzed in drift chamber
 - $\sigma_p/p \sim 1\%$
- Decay π^+ stops in range stack, range and energy are measured
- Barrel veto + End caps + Collar provide 4π photon veto coverage

E787/949 Search: $K^+ \rightarrow \pi^+ X^0$



- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data interpreted as limit on $BR(K^+ \rightarrow \pi^+ X^0)$, assuming X^0 is non-interacting, and either X^0 is stable or X^0 decay products are detected and vetoed

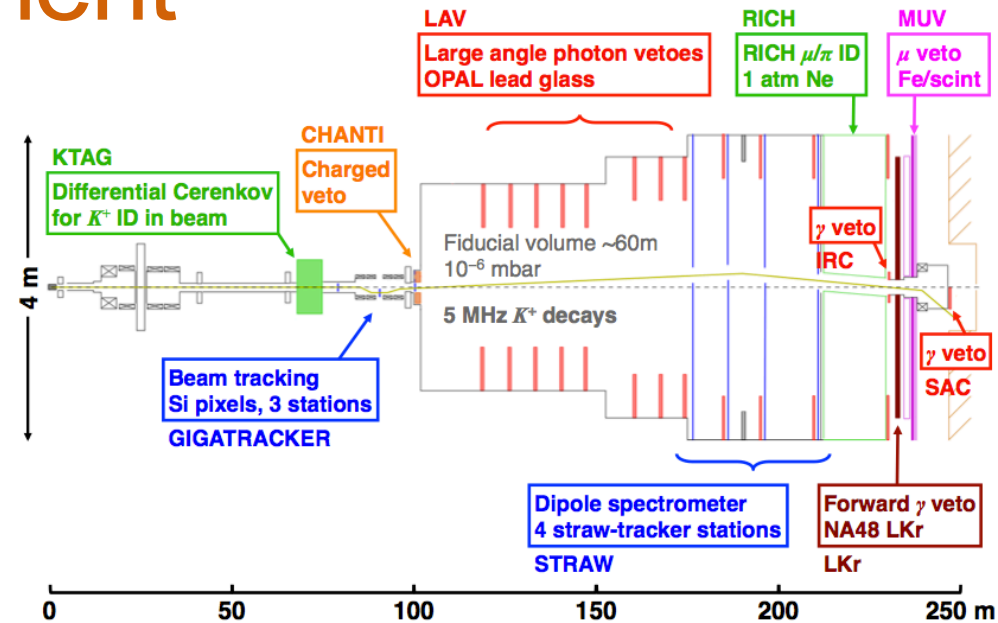
- Davoudiasl, Lee, Marciano:
 - If light dark particles exist, $U \rightarrow$ invisible will dominate, so that limits set using $BR(U \rightarrow l^+ l^-) = 1$ are lifted
 - In this case, $K^+ \rightarrow \pi^+ X^0$ limit applies:



NA62 Experiment

Ancestor: NA31

NA48	1997	ϵ'/ϵ run	$K_L + K_S$
	1998	ϵ'/ϵ run	$K_L + K_S$
	1999	ϵ'/ϵ run $K_L + K_S$	K_S Hi. Int.
	2000	K_L only K_S High Intensity NO Spectrometer	
NA48/1	2001	ϵ'/ϵ run $K_L + K_S$	K_S High Int.
	2002	K_S High Intensity	
	2003	K^\pm High Intensity	
NA48/2	2004	K^\pm High Intensity	
	2007/08	$K_{\pi 2}^+ / K_{\pi 2}^+$ runs	
NA62 (Rk phase)	2007-2013	R&D	
NA62	2012	Start $K^+ \rightarrow \pi^+ \nu \bar{\nu}$	



- Primary physics goal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- $\sigma_p/p \sim 0.3\% \oplus 0.008\% p$ [GeV]
 - $\sigma(M_{ee}) \sim 1$ MeV
- 4.5×10^{12} K^+ decays/year
 - x45 more than NA48/2
 - $\sim 10^8 \pi^0_D$ decays/year
- Expect increase in statistics in $\pi^0 \rightarrow U\gamma$, $K^+ \rightarrow \pi^+ U$, $K^+ \rightarrow \pi^+ X^0$ searches
 - Searches are background limited
 - Limited analysis effort

Summary

- Meson-decay experiments have excellent sensitivity for dark photon searches in an interesting region of parameter space
 - Large sample sizes
 - High-resolution detectors
- Expect sensitivity to $\varepsilon^2 \leq 10^{-6}$ in upcoming results from:
 - KLOE ($35 \text{ MeV}/c^2 < M_U < 520 \text{ MeV}/c^2$)
 - NA48/2 ($3 \text{ MeV}/c^2 < M_U < 100 \text{ MeV}/c^2$)
- Future meson-decay experiments:
 - NA62: 4.5×10^{12} K^+ decays/year, $\sim 10^8$ π^0_D decays/year
 - KOTO: $\sim 1 \times 10^{12}$ K^0_L flux in upcoming first full run