Dark Sectors and Kaon physics

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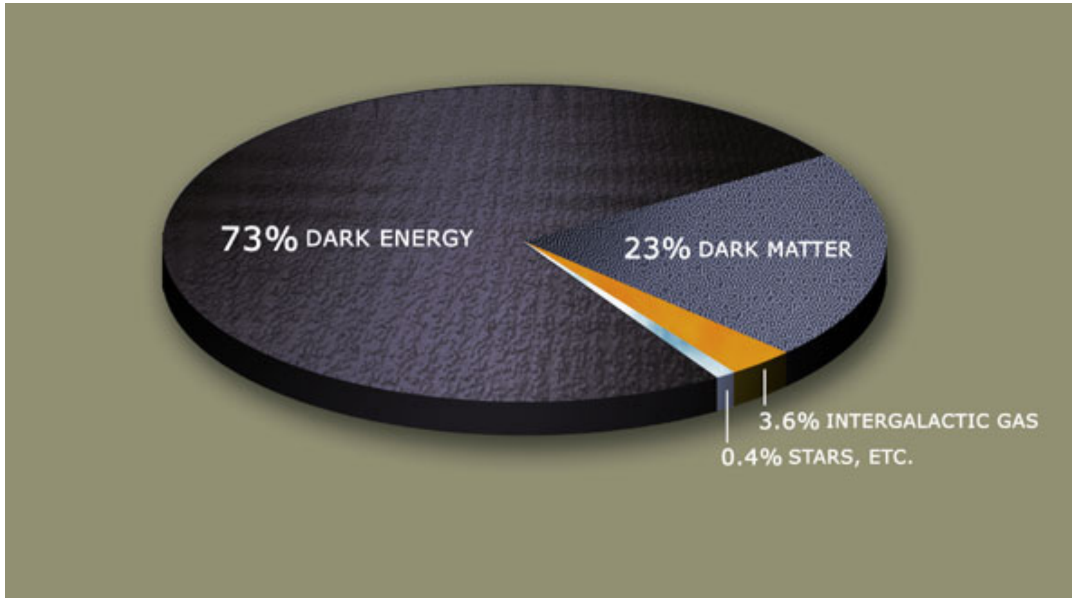
Outline of the talk

1. Introduction. Intensity Frontier. Portals to light new physics.
2. "Golden mode" of NA62, $K \to \pi$ + *missing energy* – a potential for future discovery. Dark photons + light dark matter, Higgs portal scalar.
3. Radiative decays of Kaons, and sensitivity to new physics:

   $K \to \mu\nu\ l^+l^-$; $K \to \pi^+\pi^0\ e^+e^-$
4. Beam dump mode ?
5. Conclusions

Big Questions in Physics



"Missing mass" – what is it?

New particle, new force, …? *Both*? How to find out?

(History lesson: first "dark matter" problem occurred at the nuclear level, and eventually new particles, neutrons, were identified as a source of a "hidden mass" – and of course immediately with the new force of nature, the strong interaction force.)

Neutral "portals" to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

LHN neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a/f$ axionic portal

……….

$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\rm med}^{(k)} \mathcal{O}_{\rm SM}^{(l)}}{\Lambda^n},$$

On-going and future projects

Fixed Target/beam dump experiments sensitive to

- Dark Photons: HPS, DarkLight, APEX, Mainz, SHiP…
- Light dark matter production + scattering: MiniBoNE, BDX, SHiP…
- Right-handed neutrinos: SHiP
- Missing energy via DM production: NA62 ($K \rightarrow \pi\nu\nu$ mode), positron beam dumps…
- Extra Z' in neutrino scattering: DUNE near detector (?)

New physics: UV or IR? (let's say IR/UV boundary ~ EW scale)

Neutrino oscillations: We know that new phenomenon exists, and if interpreted as neutrino masses and mixing, is it coming from deep UV, via e. .g Weinberg's operator

$$\mathcal{L}_{\rm NP} \propto (HL)(HL)/\Lambda_{\rm UV} \text{ with } \Lambda_{\rm UV} \gg \langle H\rangle$$

or it is generated by *new IR field*, such as RH component of Dirac neutrinos?

Dark matter: 25% of Universe's energy balance is in dark matter: we can set constraints on both. If it is embedded in particle physics, then e.g. neutralinos or axions imply new UV scales.

However, *there are models of DM where NP lives completely in the IR, and no new scales are necessary*.

Both options deserve a close look. In particular, *light and very weakly coupled states are often overlooked, but deserve attention*.

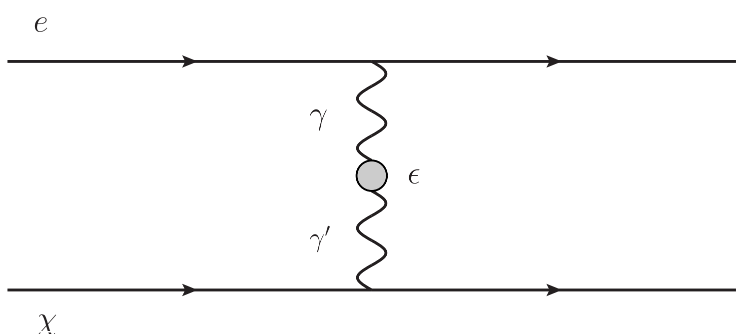
"Simplified model" for dark sector

(Okun', Holdom,…)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F^2_{\mu\nu} + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g'A'_\mu) - m_\chi]\chi,$$



A – photon, *A'* – "dark photon", ψ - an electron, χ - a DM state, *g'* – a "dark" charge

- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r^2_\chi \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. *It represents a simple example of BSM physics*.

“Non-decoupling” of secluded U(1)
Theoretical expectations for masses and mixing

Suppose that the SM particles are not charged under new $U_S(1)$, and communicate with it only via extremely heavy particles of mass scale Λ (however heavy!, e.g. 100000 TeV) charged under the SM $U_Y(1)$ and $U_S(1)$ (B. Holdom, 1986)

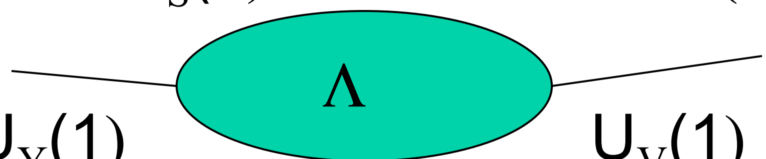


Diagram $U_Y(1)$ $U_V(1)$ does not decouple!

A mixing term is induced, $\kappa F^Y_{\mu\nu} F^S_{\mu\nu}$,

With κ having only the log dependence on mass scale Λ

$\kappa \sim (\alpha\alpha')^{1/2} (3\pi)^{-1} \log(\Lambda_{UV}/\Lambda) \sim 10^{-3}$

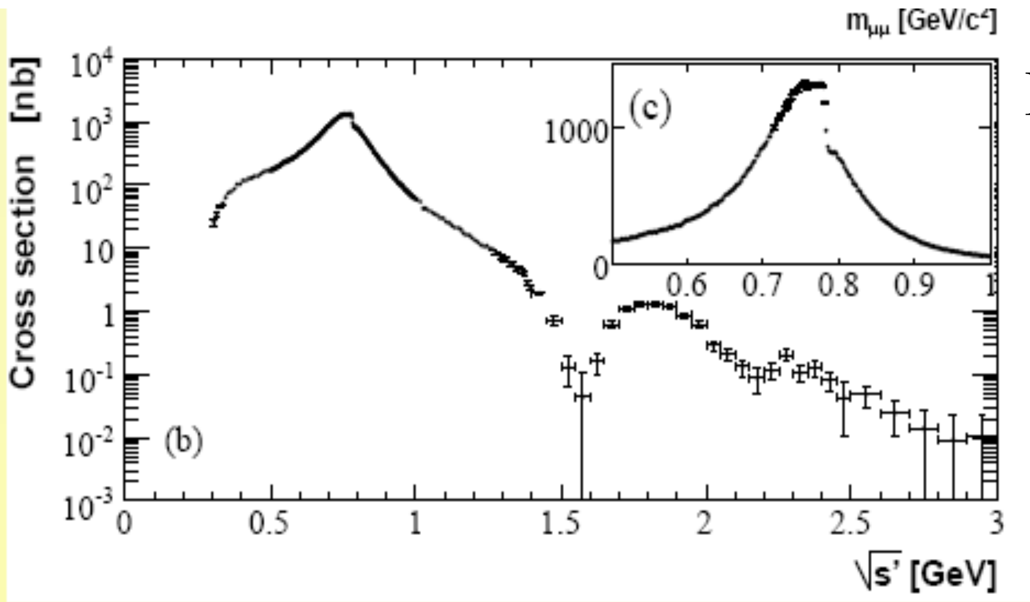
$M_V \sim e'\kappa M_{EW}$ (M_Z or TeV) ~ MeV – GeV

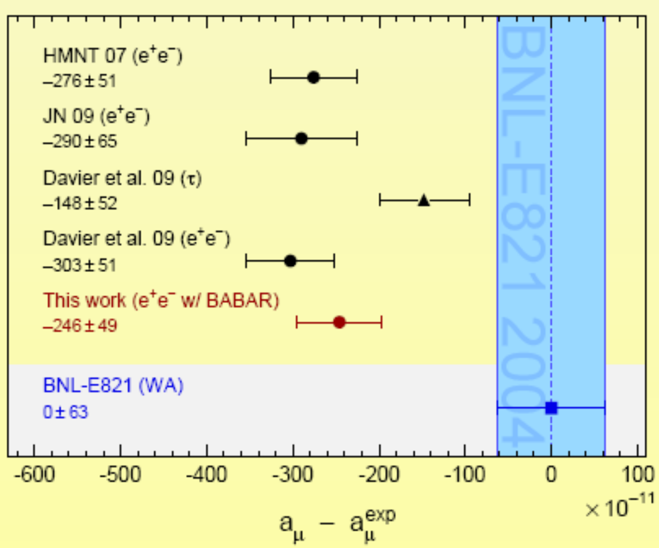
This is very “realistic” in terms of experimental sensitivity range of parameters.

Some specific motivations for new states/ new forces below GeV

1. A 1.5 decade old discrepancy of the muon g-2.
2. Discrepancy of the muonic hydrogen Lamb shift.
3. Theoretical motivation to look for an extra U(1) gauge group.
4. Recent intriguing results in astrophysics. 511 keV line, PAMELA (+Fermi, AMS2) positron rise.
5. Too-big-to-fail etc problems of CDM + solution via a DM re-scattering with a light mediator.
6. Other motivations (most recently, a claim of new particles in the decay of the 18.15 MeV state in ^{8}Be).

g-2 of muon





✱ Davier et al. arXiv:0906-5443

More than 3 sigma discrepancy for most of the analyses. Possibly a sign of new physics, but some complicated strong interaction dynamics could still be at play.

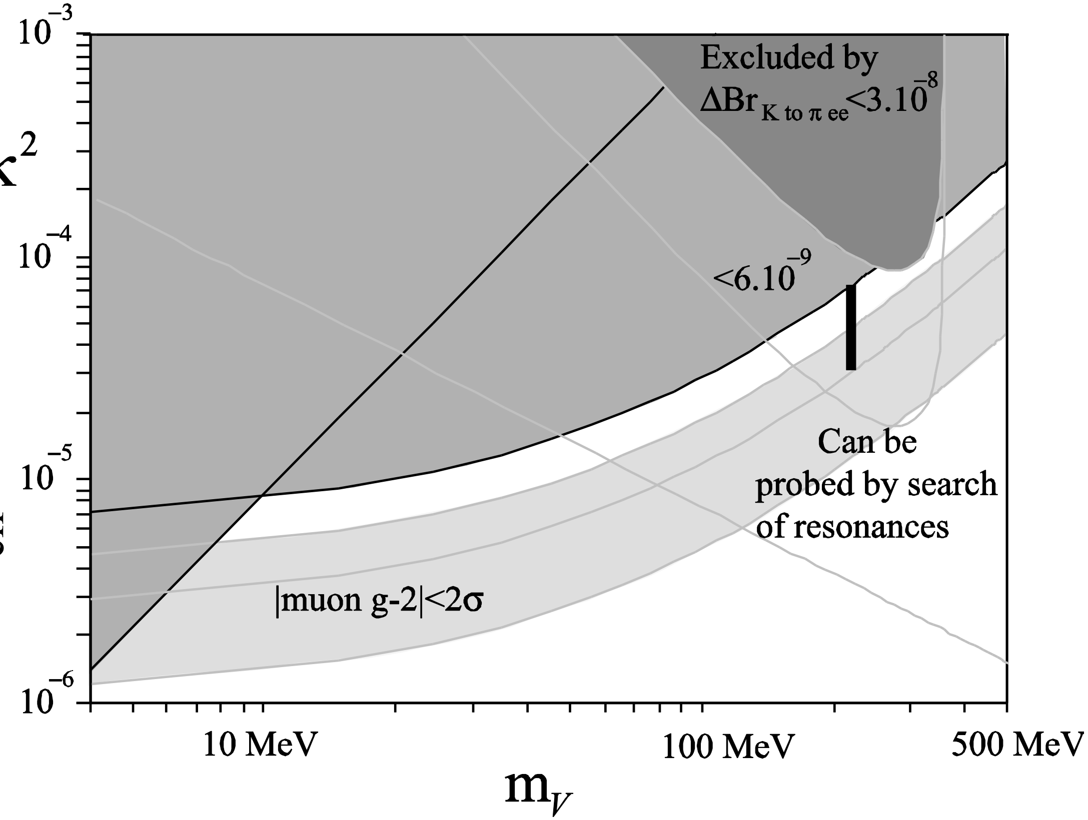
Supersymmetric models with large-ish *tanβ*; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

Sub-GeV scale vectors/scalars can also be at play.

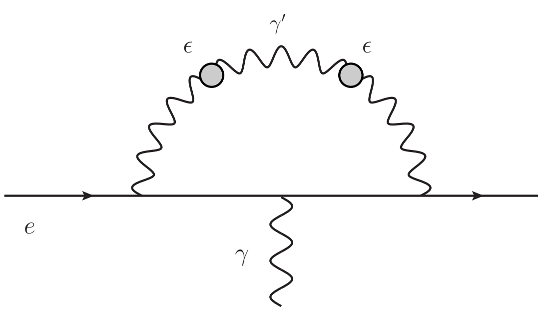
κ-m_V parameter space

If g-2 discrepancy taken seriously, a new vector force can account for deficit. (Krasnikov, Gninenko; Fayet; Pospelov)
E.g. mixing of order few 0.001 and mass $m_V \sim m_\mu$

This axis is also called ε^2 or α_{eff}/α

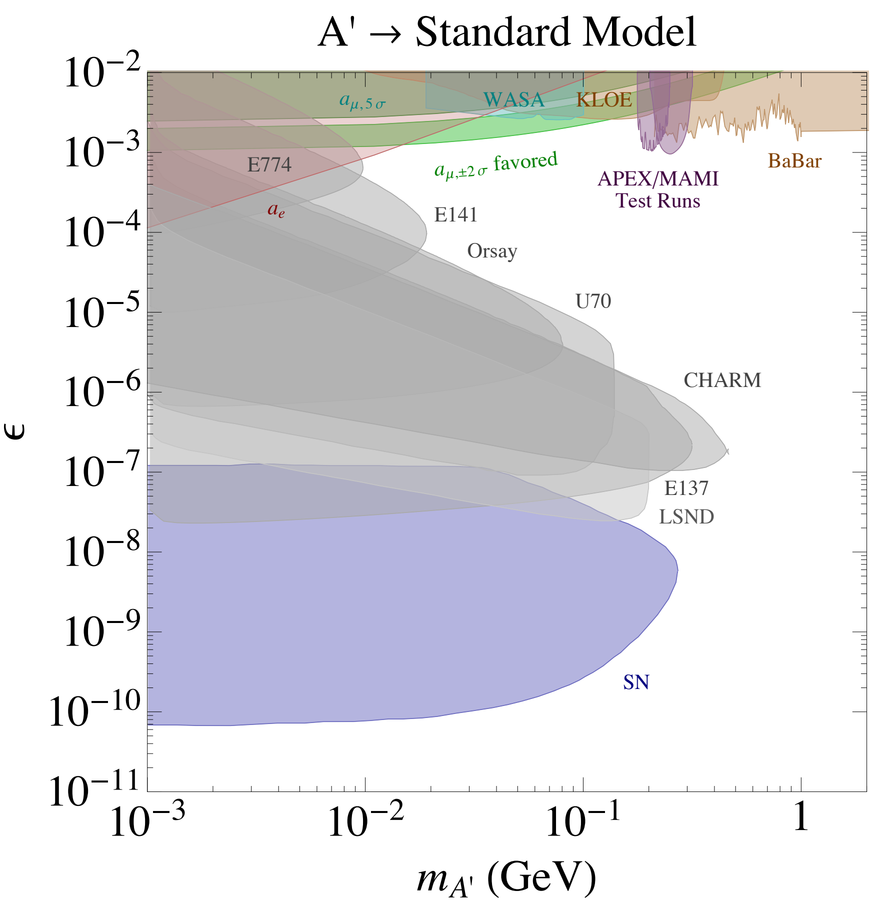


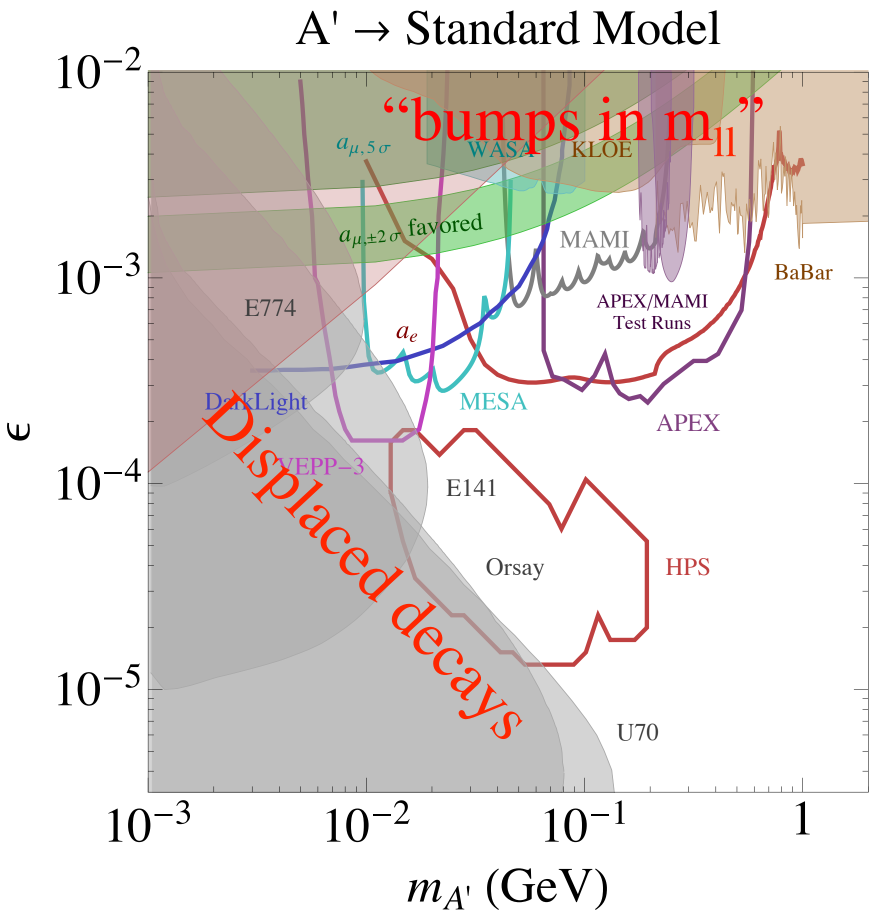
MP, 2008



Since 2008 a lot more of parameter space got constrained

Search for dark photons, Snowmass study, 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, not least because of the tantalizing positive ~ $(\alpha/\pi)\varepsilon^2$ correction to the muon g - 2.

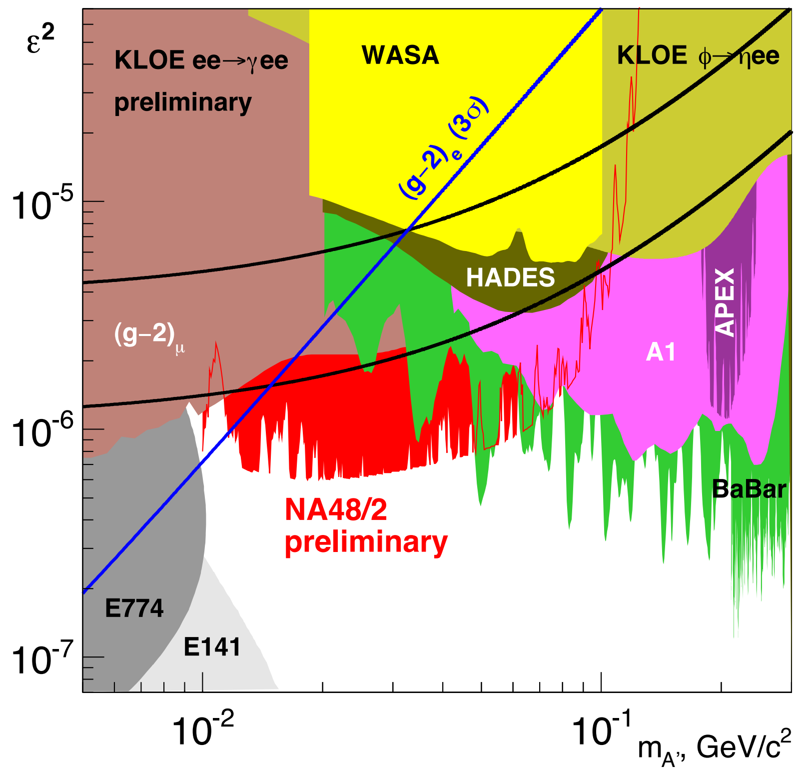
Latest results: A1, Babar, NA48

Signature: "bump" at invariant mass of e^+e^- pairs = $m_{A'}$

Babar: $e^+e^- \rightarrow \gamma V \rightarrow \gamma l^+l^-$

A1(+ APEX): $Z e^- \rightarrow Z e^- V \rightarrow Z e^- e^+e^-$

NA48: $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$



Latest results by NA48 exclude the remainder of parameter space relevant for g-2 discrepancy.

Only more contrived options for muon g-2 explanation remain, e.g. $L_\mu - L_\tau$, or dark photons *decaying to light dark matter.*

Sensitivity to a light Higgs-mixed scalar

Example: new particle admixed with a Higgs.

$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

After (Higgs Field = vev + fluctuation h), the actual Higgs boson mixes with S.

Mixing angle: $$\theta = \frac{Av}{m_h^2}$$

The model is technically natural as long as A not much larger than m_S
Low energy: new particle with Higgs couplings multiplied by θ

New effects in Kaon and B-decays.

Sensitivity to a light Higgs-mixed scalar

K → *π* + *missing energy* – a potential for future discovery.

- Underlying quark-W loop for *s* → *d* + *Scalar* is enhanced by m_t^2/m_W^2 factor.
- Above di-muon threshold, recent LHCb searches of B → K + muon pair of fixed invariant mass provide a dominant constraint.
- Below mS = 210 MeV, the decays are displaced – in fact very long outside of the NA62 detector, because of the small Yukawa for electrons. $\Gamma_S = \theta^2 (m_e/v)^2/(8\pi)\, m_S$.

Result (see e.g. MP, Ritz, Voloshin, 2007)

$$\Gamma_{K\to\pi+\phi-\text{mediator}} \simeq \left(\frac{\lambda_1 v^2}{m_h^2}\right)^2 \left(\frac{3m_t^2 V_{td}V_{ts}^*}{16\pi^2 v^2}\right)^2 \frac{m_K^3}{64\pi v^2}.$$

Constraint: (mixing angle)$^2 < 2\times10^{-7}$, in the technically natural range of mixings.

Sensitivity to a light vector decaying invisibly

$K^+ \rightarrow \pi^+ +$ *missing energy* – a potential for future discovery of dark photon decaying to light dark matter.

$K^+ \rightarrow \pi^+ +$ *dark photon* $\rightarrow \pi^+ + \chi\chi$

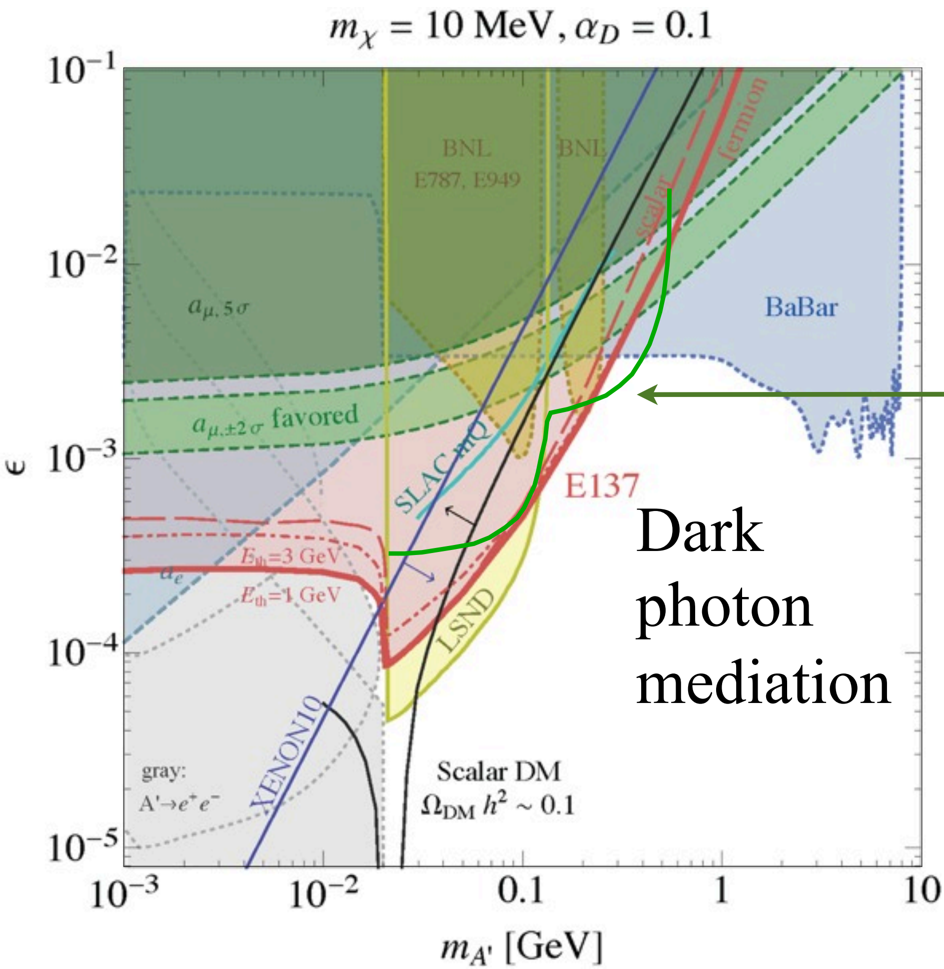
The rate for decay to a dark photon (MP, 2008):

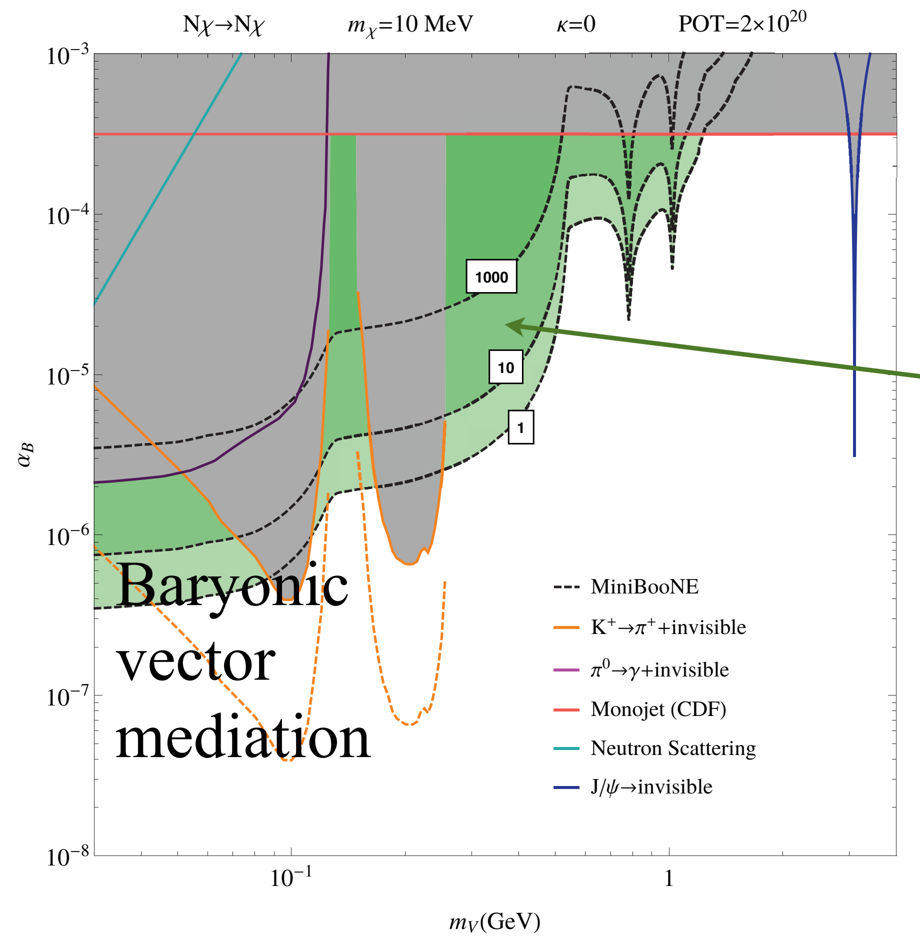
$$\Gamma_{K\to\pi V} = \frac{\alpha\kappa^2}{2^{10}\pi^4}\frac{m_V^2 W^2}{m_K} f(m_V, m_K, m_\pi) \implies \mathrm{Br}_{K\to\pi V} \simeq 8\times 10^{-5}\times\kappa^2\left(\frac{m_V}{100\ \mathrm{MeV}}\right)^2.$$

Decouples as $m_V \rightarrow 0$.

Sensitive probes of mixing angles down to 10^{-3}.

Constraints on invisibly decaying dark photons





BNL results can be significantly improved by NA62

Radiative decays

New particles could be coupled only to leptons proportionally to their mass. Or they can couple to quarks in such a way to prevent $\pi^0 \rightarrow V + \gamma$. *(Irvine group idea in connection with Be8 anomaly).*

In that case studies of

$K \rightarrow \mu\nu\ l^+l^-$

$K \rightarrow \pi^+\pi^0\ e^+e^-$

can shed light on these type of models.

Leptonic 2HDM + singlet scalar

Consider 2HDM where one of the Higgses (Φ_1) will mostly couple to leptons, and also mixes with a singlet that is "light" relative to EW scale.

$$V = V_{2\mathrm{HDM}} + V_S + V_{\mathrm{portal}}$$

$$V_{2\mathrm{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_2\right)^2\right]$$

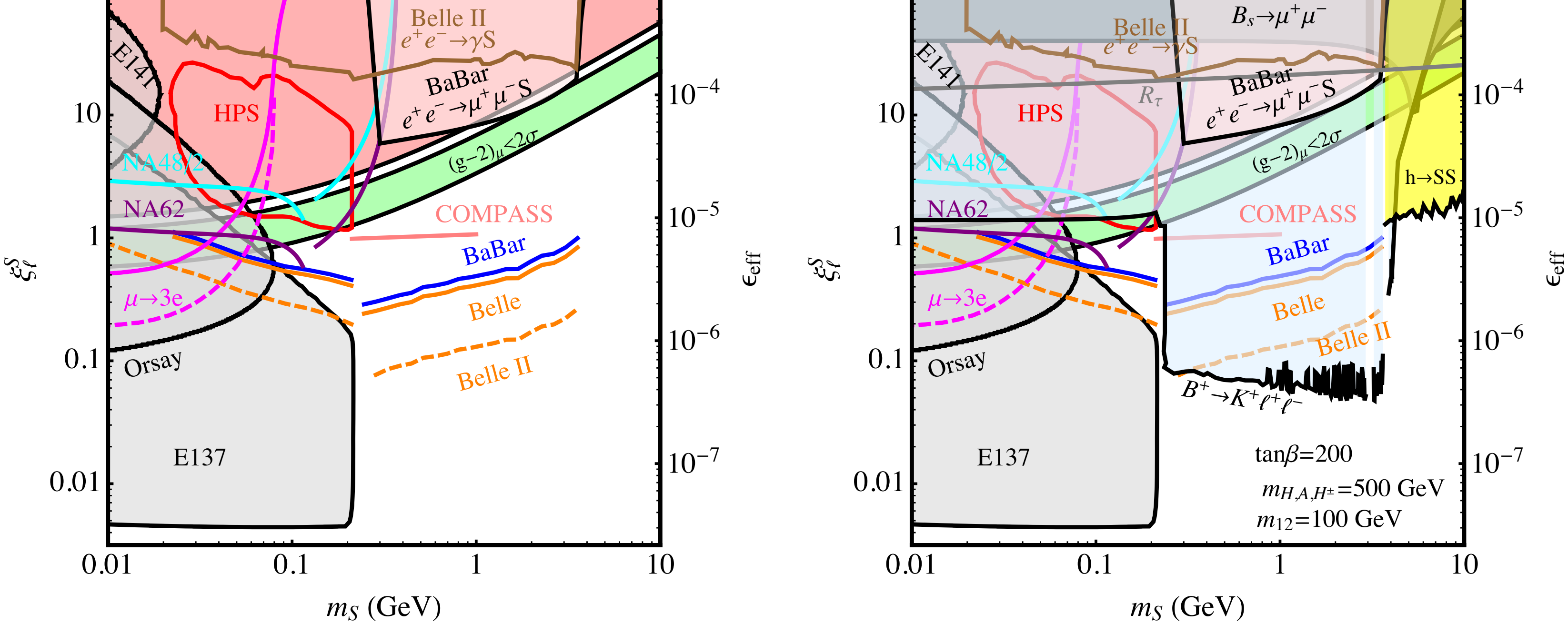
$$V_S = BS + \frac{1}{2} m_0^2 S^2 + \frac{A_S}{2} S^3 + \frac{\lambda_S}{4} S^4$$

$$V_{\mathrm{portal}} = S\left[A_{11}\Phi_1^\dagger \Phi_1 + A_{22}\Phi_2^\dagger \Phi_2 + A_{12}\left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)\right]$$

Calling the the lightest scalar particle *S*, one takes a large tan beta regime, and considers an effective low-energy Lagrangian

$$\mathcal{L}_{\mathrm{eff}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 + \sum_{l=e,\mu,\tau} g_\ell S \bar{\ell}\ell, \qquad g_\ell = \xi_\ell^S m_\ell / v$$

where it is important that 1. S can be light, 2. couples mostly to leptons, proportionally to their masses. This leads to an effective "reweighting" of the traditional e-mV parameter space for all effect involving leptons.



"Effective" mixing angle for electrons

$$\kappa_{\rm eff} \equiv m_e \xi_{\ell\ell}/ev$$

One can still "fix" the g-2 discrepancy with such scalar.

Batell, Lange, McKeen, Pospelov, Ritz, *2016*.

B-factory signal from the associated $\tau^+\tau^-$ + *Scalar* → $\tau^+\tau^-$ $\mu^+\mu^-$ production will test the model below $m_S \sim 3.5$GeV. Kaon decay studies are also warranted ($K \to \mu\nu\ l^+l^-$ including low m_{ee})

Beam dump mode

Running the NA62 in the beam dump mode is also a good idea:

- *Unparallel (among existing experiments) sensitivity to the displaced decays of light particles.*
- *Proton beam dump is also automatically a photon, electron and muon beam dump.*
- *Sensitivity to models of light New Physics where g-2 of the muon is corrected via series of light "overlapping" new resonances, where search for a bump is not possible. (Chen, MP, Zhong in progress)*

Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (dark photon, scalar coupled Higgs portal) are quite natural, and *helpful* in explaining a number of puzzles in particle physics and astrophysics.

2. There is a strong sensitivity of NA62 to all underlying 2-body decay modes that give K→ p + missing energy. Models with very light scalars mixed via the Higgs portal. Models with dark photon decaying invisibly.

3. New radiative decay mode studies ($K \rightarrow \mu\nu\ l^+l^-$) could constrain lepton-specific Higgs models with light particles. The observed $K \rightarrow \pi^+\pi^0\, e^+e^-$ spectrum can be analyzed for presence of anomalies.

4. Beam dump run is a good idea (possible pre-amble for SHiP)