Hidden Portals through Fixed targets (Dark Forces workshop)

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B.Batell, MP, A.Ritz, arxiv/0906.5614 – to appear in PRD

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Motivating dark forces.
2. Minimal portals: colliders vs fixed targets
3. **Production and detection of long-lived particles in proton-target collisions. Vector and Higgs portals at LSND, MiniBOONE etc**
4. **Dark forces in K and B decays**
5. Conclusions: search for dark forces/minimal portals – future direction of particle physics at the “intensity frontier”.

Intensity and Energy Frontiers

$$V(r) = \frac{\alpha}{r}\exp(-r/\lambda) = \frac{\alpha}{r}\exp(-rm)$$

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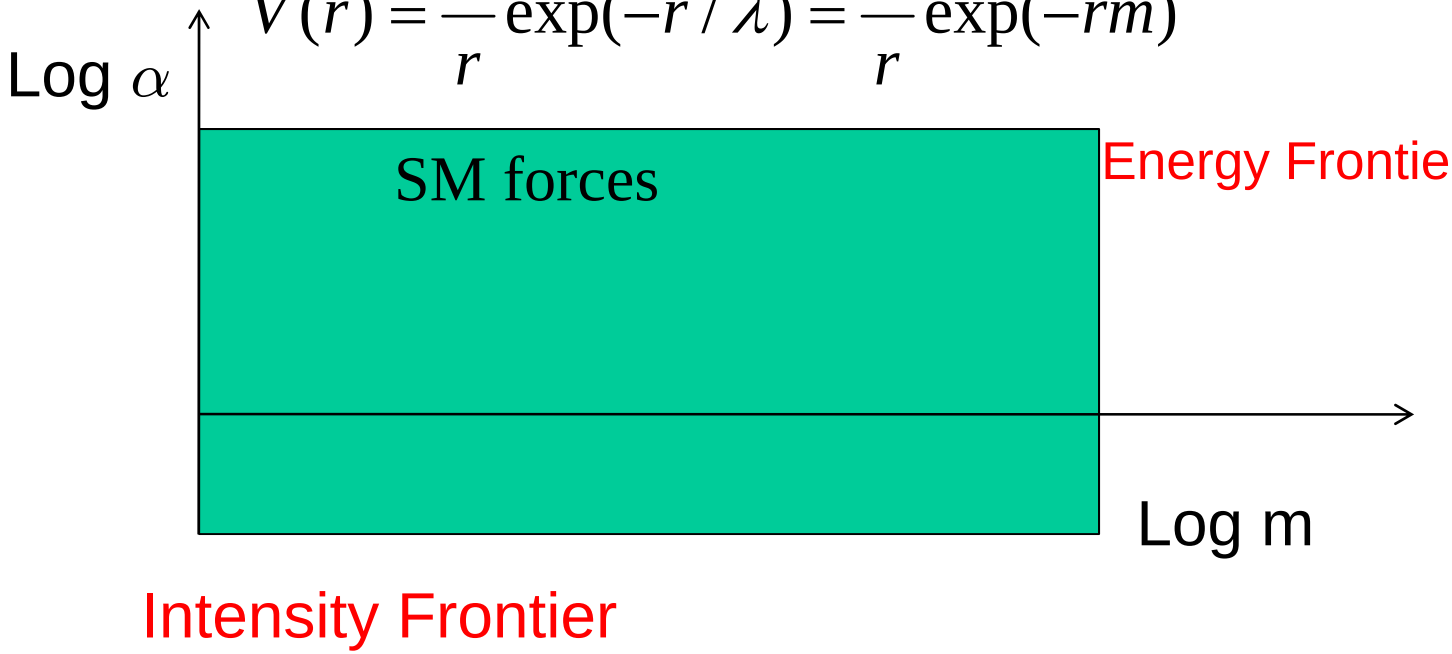
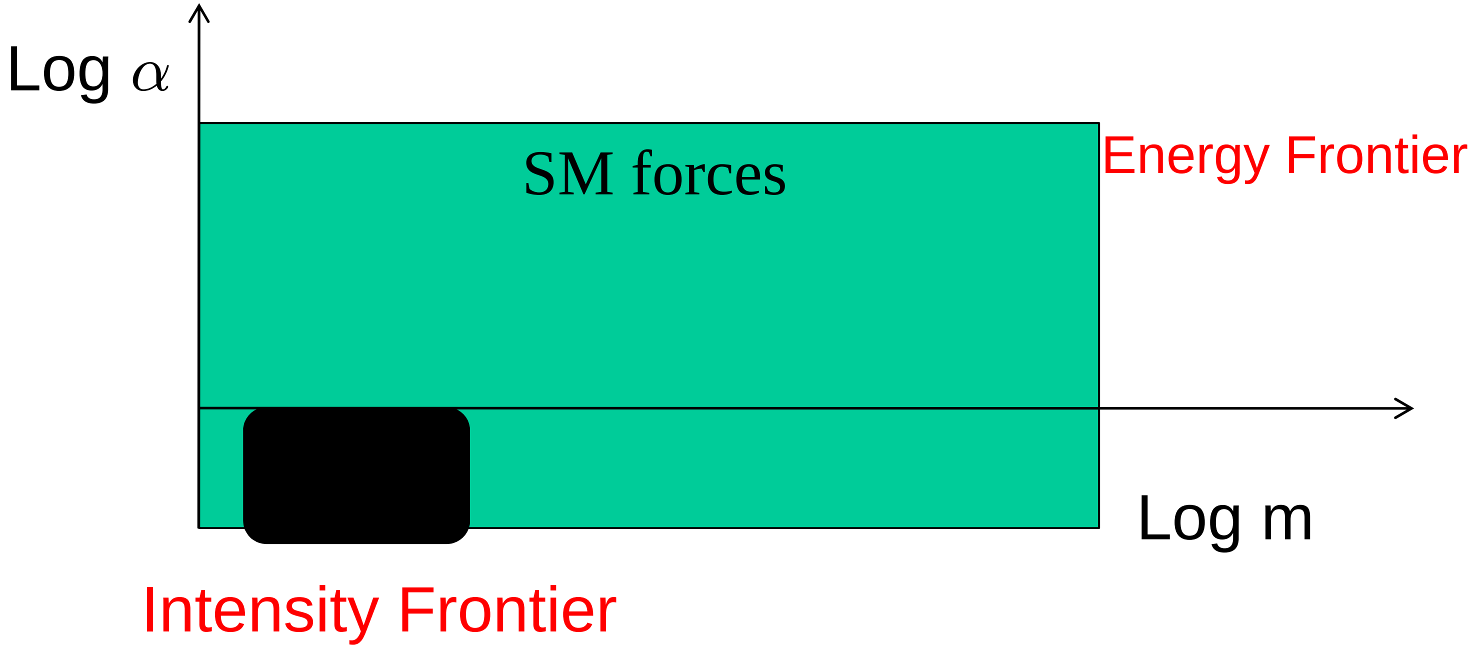


To study physics at Energy frontier and access larger and larger m one needs powerful accelerators (Tevatron, LHC...). To study very weak forces at Intensity (or luminosity) frontier one needs a lot of events (powerful beams as at T2K, NuMi, SNS etc)

Dark Forces



“Dark Forces” refer to a speculative possibility of new rather weak force with m in the interval from MeV to GeV, and log α < -4.

Motivating questions

- In nature, there is dark radiation (neutrinos +?), dark matter, dark energy. Dark forces is not a big stretch.
- Why SU(3)xSU(2)xU(1)x gravity?
- What do we know about milli-, micro-, nano- etc strength coupled and *not too heavy* particles. E.g. milli-coupled Higgs boson at a GeV, “dark” massive photon at 100 MeV etc. *There are no systematic searches of such possibilities*.
- Could any of these hypothetical states be responsible for various anomalies in particle physics: $(g-2)_\mu$, HyperCP, LSND etc?
- Some of these states “help” to explain high-energy astrophysics anomalies: PAMELA positrons, hard(er) spectrum of FGST etc.
- Secluded DM (MP, A. Ritz, M.Voloshin, 2007).

Indirect astrophysical signatures of secluded DM

Annihilation into a pair of mediators, followed by decay create boosted decay products.

If m_V is under GeV, the following consequences are generic

(**Arkani-Hamed et al, MP and Ritz, Oct 2008**)

1. The rate of annihilation in the galaxy, σ_{ann} v, is enhanced relative to the cosmological σ_{ann} v because of the long-range attractive force in the DM sector.
2. Annihilation products can be dominated by electrons and positrons, while antiprotons are kinematically not possible
3. Photon fraction might be suppressed

All this is very topical in light of much discussed Pamela results.

$$n_{e^+}/(n_{e^-} + n_{e^+}) \sim 0.1 \text{ above 10-20 GeV}$$

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Doesn’t matter

Neutral doors ["portals"] to the SM

Let us *use* these doors, and attach the Dark Matter to the SM

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

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

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

$LH\,N$ 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

$J_\mu^A\,\partial a/f$ axionic portal

……….

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

Fixed Targets or colliders? Crude comparison

If new states are light-ish (few GeV or less), they can be produced at fixed target experiments and/or colliders.

Colliders may provide cleaner environment, fixed targets win by luminosity.

Assuming very simple scaling for the production cross section

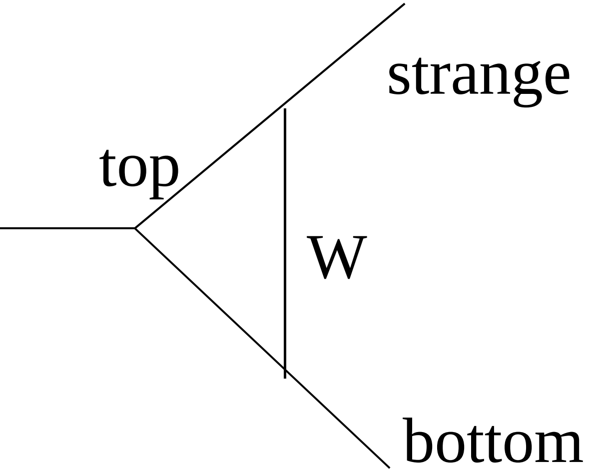
$$\sigma \sim \frac{\kappa^2}{E^2}\left(\frac{E}{\Lambda}\right)^{2n}$$

One may conclude $$\frac{N_{\rm collider}}{N_{\rm target}} \sim 10^{-6} \times \left(\frac{E_c}{E_t}\right)^{2n-2} \sim 10^{-12+6n},$$

Low dimensionality of operators favors production at fixed targets

A comment about flavour physics

Vector currents are uniquely positioned to avoid very strong flavour constraints . Axial vector portals, Higgs portals are potentially liable to very strong flavor constraints. Consider generic FCNC penguin-type loop correction.



For vector current, $G_F\, q^2$

For axial vector current, $G_F\, m_t^2$

There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in rare K and B decays.

Vector Portal Models

We will study minimal model of Holdom

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

But other modifications (multiple U(1)'s, extra nonabelian groups etc are possible)

After the breaking,

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \frac{1}{2}(\partial_\mu h')^2 - \frac{1}{2}m_{h'}^2 h'^2 + \mathcal{L}_{int},$$

With interaction terms

$$\mathcal{L}_{int} = -\frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + \frac{m_V^2}{v'}h'V_\mu^2 + \frac{m_V^2}{v'^2}h'^2V_\mu^2 - \frac{m_{h'}^2}{2v'}h'^3 - \frac{m_{h'}^2}{8v'^2}h'^4,$$

What do we know about massive SM-like photons with small kappa?

Higgs Portal Models – attaching a singlet S

Quadratic and linear coupling to Higgs is allowed

$$\mathcal{L}_{\rm int} = (H^\dagger H)(\lambda S^2 + AS) = hv(\lambda S^2 + AS) + \cdots$$

(Linear terms are forbidden if S is charged under dark group)

Integrating out heavy SM Higgs particle, we have

$$\mathcal{L}_{\rm int} = \mathcal{O}_{\rm SM}^{(h)} \frac{\lambda S^2 + AS}{m_h^2},$$

where $\mathcal{O}_{\rm SM}^{(h)} = \sum_f m_f \bar{f} f + \ldots$

Mass parameter A creates mixing between SM Higgs and S scalar, and the size of the mixing angle $\kappa' \equiv Av/m_h^2$: can be as large 0.001-0.01 without creating technical naturalness problem.

What do we know about SM Higgs like particle with milli-SM coupling?

Long-lived states in the models

1. Very small mixing, $\kappa \lesssim 10^{-7} - 10^{-6}$ will lead to the longevity of vectors, c\tau ~ several meters or more. (m_h>m_V)

2. Not too small mixing, $\kappa \sim 10^{-4} - 10^{-2}$ and $m_V > m_{h'}$

will lead to off-shell decays of the Higgs from the dark sector, and potentially very long decay lengths.

3. Milli-Higgses under 200 MeV have helicity suppression of decay width and

$$c\tau_S \simeq 1\,\mathrm{cm} \times \frac{100\ \mathrm{MeV}}{(\kappa')^2 m_S}.$$

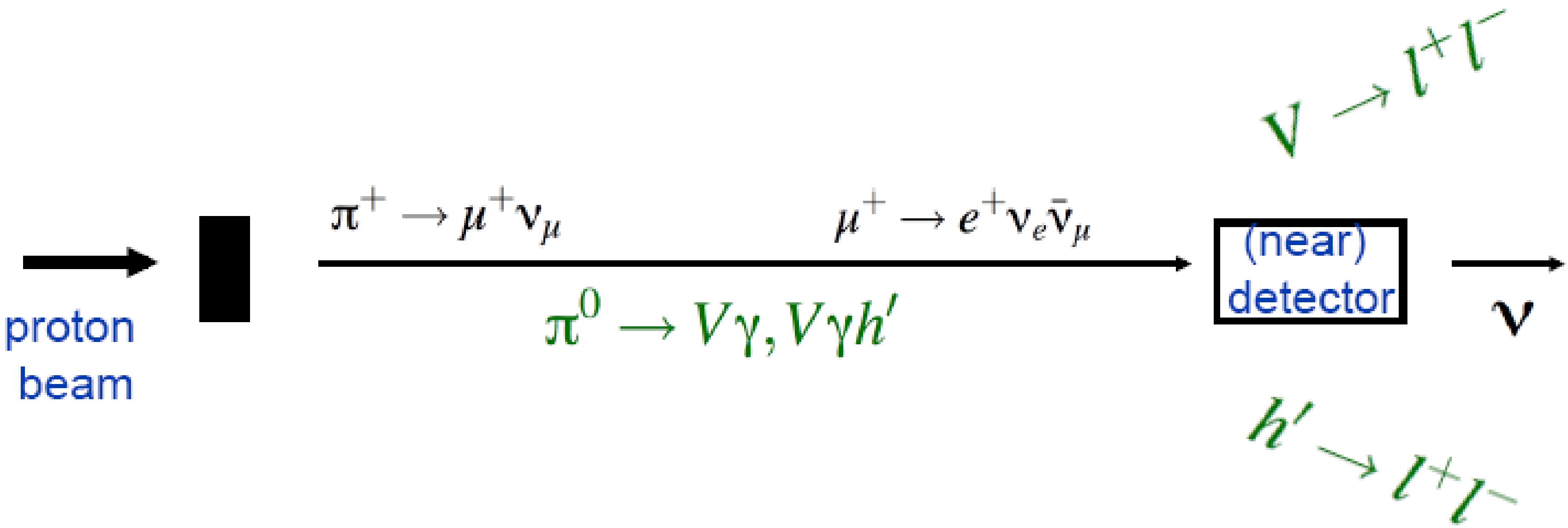
where $\kappa' \equiv Av/m_h^2;$

4. Similarly for axion portal, we have

$$c\tau_a = 5\ \mathrm{m} \times \left(\frac{f_a}{10\ \mathrm{TeV}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_a}\right).$$

Travel distance of 100m or so, problematic for colliders, is a perfect set-up for **existing** proton fixed target experiments.

Neutrino beam set up can be used for studying long-lived relics



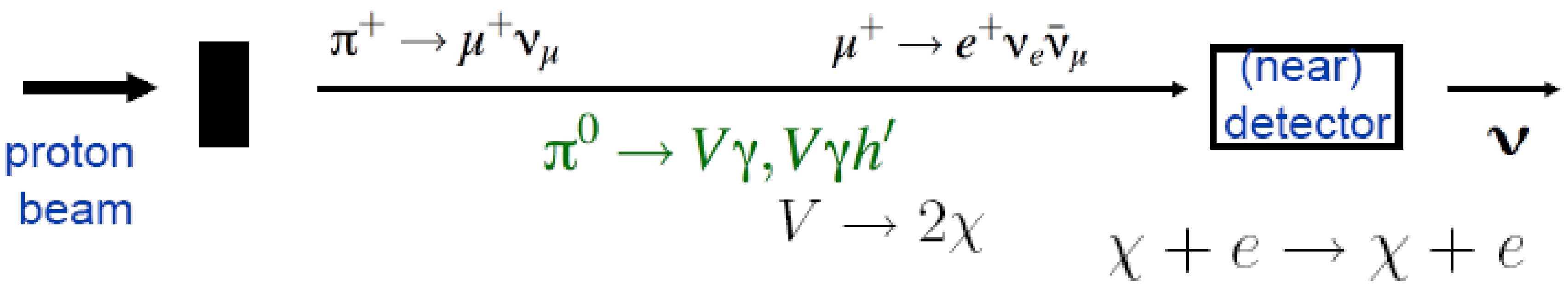
Neutrino productions are set by strong interactions,

while their detection probabilities are due to weak interactions, 10^(-14)

Exotic particle production may be small, O(kappa^2), but probability of decays inside the detector may be "geometric", as large as 10^(-4). Main

Background may come from neutrinos!

Neutrino beam set up can be accompanied by a beam of *other* light neutral states. "Dark matter beam"



Probability of prompt decay of V into new dark states χ can be sizable.

Scattering within the detector can look like neutral current events, but being mediated by light vectors could be *larger* than weak scattering rates.

Different machines, different production mechanisms

- $m_{V,h'} < 100$ MeV - LSND, SNS
- $m_{V,h'} < 1$ GeV - MiniBooNE
- $m_{V,h'} \gtrsim 1$ GeV - MINOS, (T2K, NOvA, Project X,...)

$m_{V,h'} \lesssim m_\pi$	$\pi^0 \to \gamma V, \gamma V h'$
$m_{V,h'} \lesssim 400$ MeV	$\eta \to \gamma V, \gamma V h'$
	$\Delta \to N V$
$m_{V,h'} \lesssim m_\rho$	$\rho^0, \omega, \phi \to V h', V \pi^0(\eta)$
$m_{V,h'} \gtrsim 1$ GeV	$q + \bar{q} \to V, V h', \ldots$
	$q + g \to V h', q V, \ldots$

LSND – almost 1g of protons on target

Energy ~ 800 MeV, over 10^23 POT, at least 10^21 neutral pions.

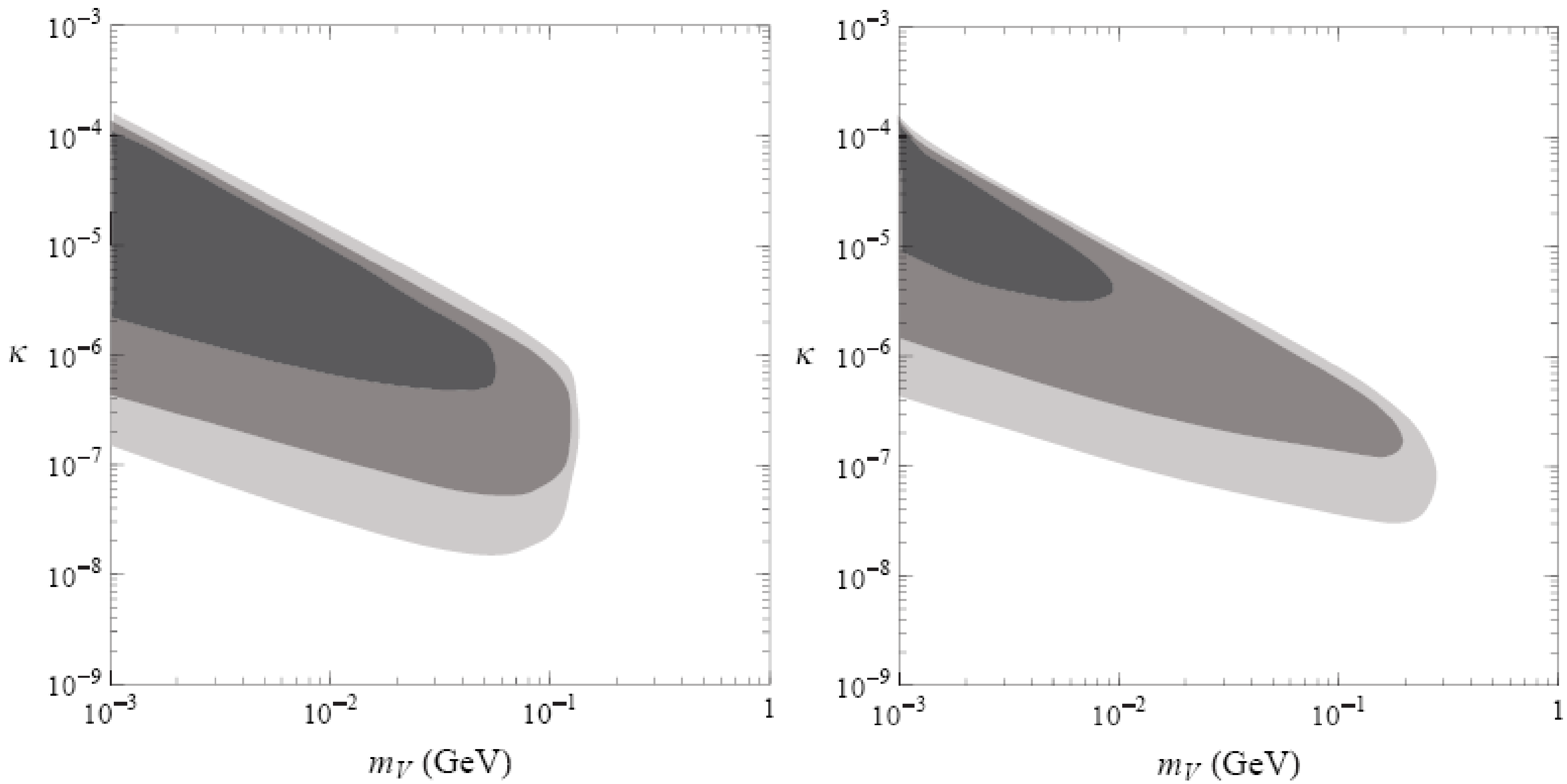


Figure 1: Sensitivity of LSND to decays $V \to e^+e^-$. The light, medium, and dark shaded regions indicate more than 10, 1000, and 10^6 expected events respectively. The left panel shows events due to vectors arising from $\pi^0 \to \gamma V$ decays, while the right panel shows events arising from $\Delta(1232) \to NV$.

Sensitivity to dark Higgs

Larger production rate (large kappa) allow to probe wider mass range

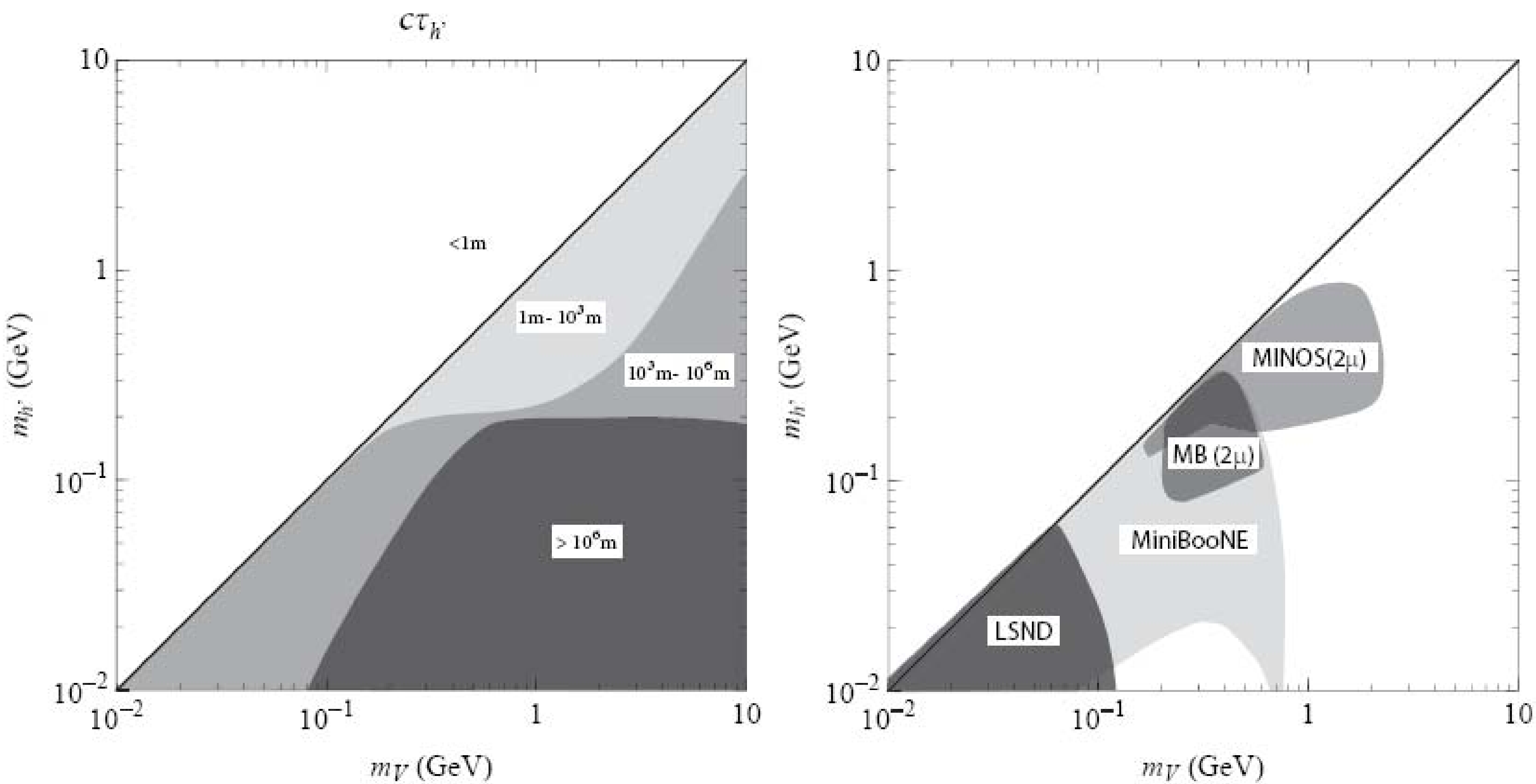


Figure 2: On the left we show the Higgs′ decay length $c\tau$ for $\kappa = 10^{-2}$ and $\alpha' = \alpha$. The regions are $c\tau < 1$m (white), 1 - 10^3m (light), $10^3 - 10^6$m (medium), and $> 10^6$m (dark). On the right, we show the sensitivity of LSND ($\pi^0 \to \gamma V h'$ - dark), MiniBooNE ($\rho, \omega \to h'V$ - light), MiniBooNE ($\rho, \omega \to h'V$, muon events only - medium), and MINOS (QCD $\to Vh'$, muon events only - medium), indicating more than 10 events expected in the detector.

Beam of MeV-dark matter

LSND provides by far the most precise test of the MeV dark matter idea of Boehm and Fayet; MP, Ritz and Voloshin. This model **kills SM modes of V decay – escapes most tests.**

1. $p + p \to X + \pi^0$
2. $\pi^0 \to \gamma V$
3. $V \to 2\chi$
4. $\chi + e \to \chi + e$

$$\frac{\alpha' \kappa^2}{\alpha} \times \left(\frac{10\ \mathrm{MeV}}{m_V}\right)^4 \times \left(\frac{m_\chi}{\mathrm{MeV}}\right)^2 \sim 10^{-6}.$$

For a "sweet spot" in parameter space (correct abundance of MeV dark matter, enough positrons for 511 keV line), the total count in the LSND detector **should exceed million events**. These type of searches can be repeated at SNS where the huge beam power at 1GeV is being used.

Search for decaying scalars and pseudoscalars

Imagine particles like pions (with similar mass) but much weaker coupled. Their production is

$$N_a \sim N_\pi \times \frac{f_\pi^2}{f_a^2} \simeq 10^{-10} \times N_\pi \times \left(\frac{10\ \mathrm{TeV}}{f_a}\right)^2,$$

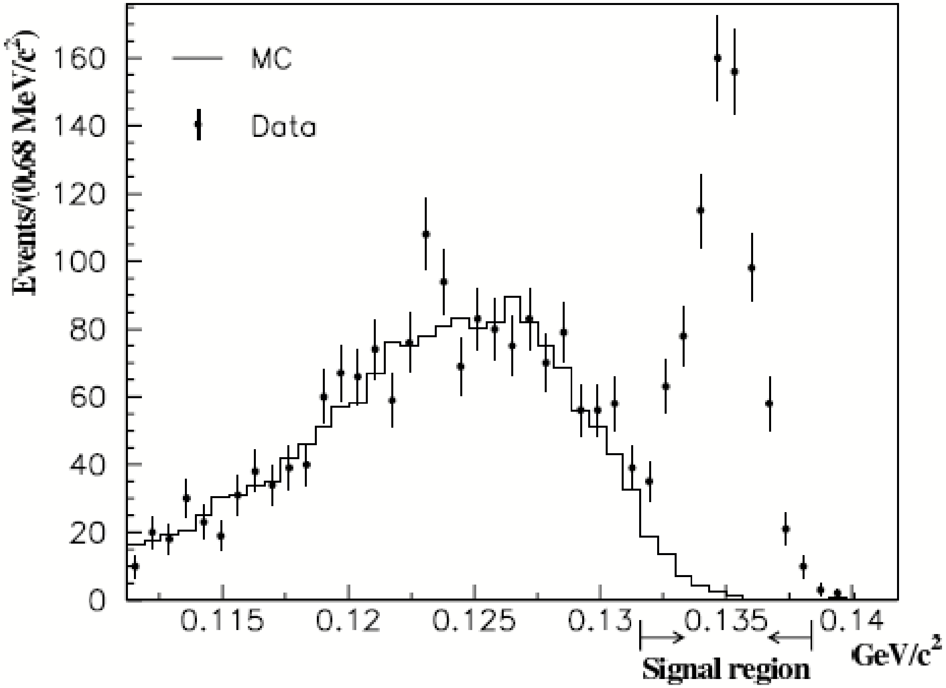
With optimized choice of travel distance (by choosing f_a), the number of decay events can be as large as

$$N_{a\ decay} \sim \Phi_\nu \times \frac{V_{det}}{\beta_a \gamma_a c \tau_a} \sim 10^9 \times \left(\frac{10\ \mathrm{TeV}}{f_a}\right)^4$$

Sensitivity to milli-Higgs is at the level of O(10^-2). Difficult to estimate because 0^+ channel is very complicated.

Precision physics with beam of K_L

Proton beams are often used as powerful sources of Kaons, and collimated beams of K_L particles can be created.



Rare decays of K_L and π_0 can be used to probe vector portals at the level of $kappa \sim 10^{-3}$. For example, about a 1000 of $\pi_0 \to ee^+$ events are seen by KTeV, with branching ration of 6×10^{-8}. Re-analysis may bring limits of $kappa$ down to 10^{-4} for $m_V < m_\pi$.

Higgs portal in K-decays

A milli-Higgs (SM Higgs-like particle with couplings scaled down by 0.001) with masses below 2m_μ can be seen in the K -> π + nothing decays. Integrating out top-W, we have

$$\mathcal{L}_{eff} = \left(\frac{\lambda_1 v^2}{m_h^2}\right) \frac{3 g_W^2 m_s m_t^2 V_{td} V_{ts}^*}{64\pi^2 m_W^2 v} \bar{d}_L s_R \phi + (h.c.),$$

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

Current experimental results on K -> π + nothing[neutrinos]

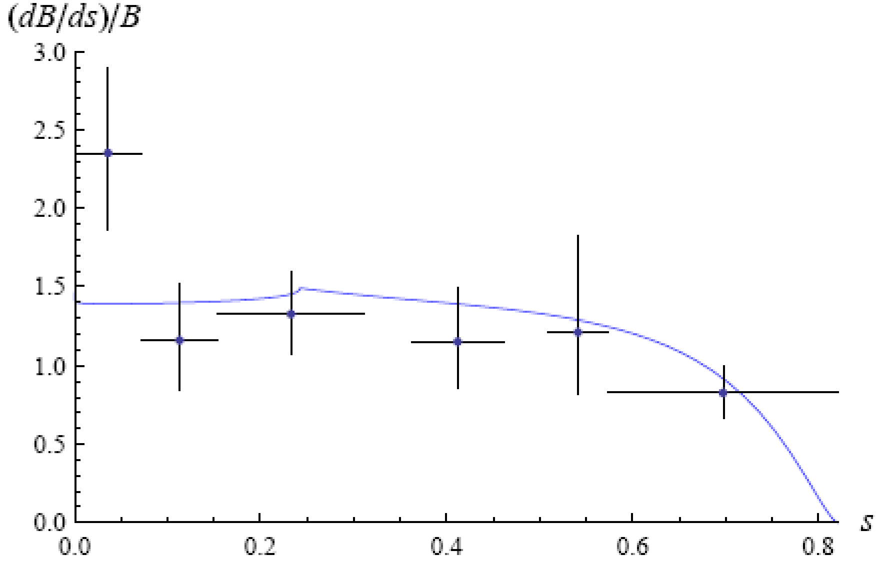
$\mathrm{Br} = 1.5^{+1.3}_{-0.9} \times 10^{-10}$ constrain (mixing angle)$^2 < 2\times 10^{-7}$ (MP,Ritz, Voloshin, 2007). Probes the couplings of hadronically coupled axions in few 100 TeV regime.

Higgs portal in B-decays

What if we have a GeV-scale milli-Higgs? The best way to probe it are B-decays, because the decays are prompt.

Some interesting modes: $\mathbf{B \to K\, ll^{+}}$; $\mathbf{B \to K^{*} ll^{+}}$. Search for peaks in the lepton inv mass distribution from underlying $\mathbf{B \to K\, S}$

Branching ~ O(1) (mix angle)^2.



The shape of the $\bar{B} \to \bar{K} l^+ l^-$ spectrum, $(dB/ds)/B$,

There is a strong sensitivity to (mix angle) ~ few 10^-4.

Other possible decay modes (missing from PDG)

$B_d \rightarrow$ **S S $\rightarrow$ 4 muons**

$B_s \rightarrow$ **S S $\rightarrow$ 4 muons**

The last decay mode can be searched for at hadronic colliders.

Conclusions

- **Search for exotic GeV sector (dark photon, milli-Higgs etc) is a legitimate goal at the intensity frontier.**
- **Particles with travel length in excess of several meters can be searched for at proton fixed targets in parallel with studying properties of neutrinos.**
- **Existing experiments (LSND, Miniboone etc) provide strong constraints on vector, Higgs and axion portal models. MeV WIMP dark matter is severely restricted.**
- **Higgs/axionic portals can be searched for with flavour changing decays. K/B decays provides strong constraints on milli-Higgs particles.**

κ-m_V parameter space