

Secluded $U_S(1)$ below the weak scale (g-2, meson decays, fixed target...)

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Outline of the talk

1. Introduction. Neutral portals to the SM. Kinetic mixing portal and secluded $U_S(1)$.
2. Dark matter WIMPs via a secluded $U(1)$. (= “Dark Forces”)
3. New phenomenology below 1 GeV? $(g-2)_{e,\mu}$;
 $\Sigma^\pm \rightarrow p + V \rightarrow p + \text{lepton pair}$; K -decays.
4. Search for secluded $U(1)$ via Higgs-strahlung events at high-luminosity medium-energy lepton colliders.
 $e^+e^- \rightarrow Vh \rightarrow 6 \text{ leptons}$
5. Other methods: fixed targets, flavour physics, and much more.
6. Conclusions: lots of data are on tape waiting to be analyzed!

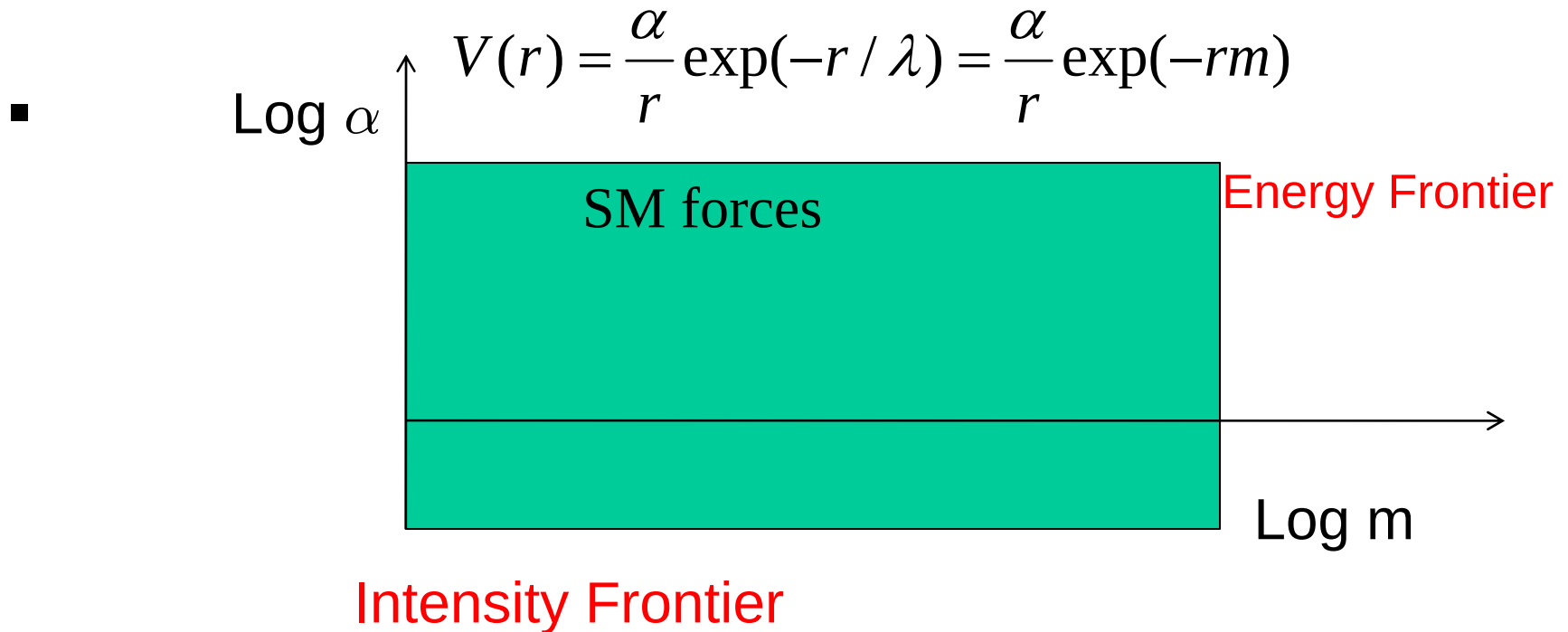
Some motivations and questions

- Why $SU(3) \times SU(2) \times U(1)$?
- What are the reasonable/minimal ways of extending the SM *below* the weak scale?
- What do we know about relatively weakly coupled (e.g. $e' \sim 10^{-3} e$) but not excessively heavy (e.g. $\text{MeV} < m_V < \text{GeV} \ll m_Z$) new physics? In particular, extra $U(1)$ groups?
- What are the implications of new “long-range” force for the direct and indirect searches of Dark Matter particles?
- Is there a decisive way of testing a secluded $U_S(1)$ below the weak scale?

Secluded (mirror, hidden etc) groups

- Suppose that the gauge group structure is richer than $SU(3) \times SU(2) \times U(1)$. For example, extra $U(1)$ factors or extra non-abelian groups. Two situations are conceivable
 1. Strength of $(\psi_{SM} \psi_{SM} V_{extra}) \sim$ Strength of $(\psi_{SM} \psi_{SM} V_{SM})$
Then inevitably, $m_V >$ weak scale. An extensive program to search for an extra “Z-prime” has been set up at Tevatron, LEP, and [I suppose] at future LHC experiments.
 2. Strength of $(\psi_{SM} \psi_{SM} V_{extra}) \ll$ Strength of $(\psi_{SM} \psi_{SM} V_{SM})$
New vector bosons, Higgs(es), etc could then *exist at or well below the weak scale*. *There are no systematic studies of their presence or absence. I hope this will change!*

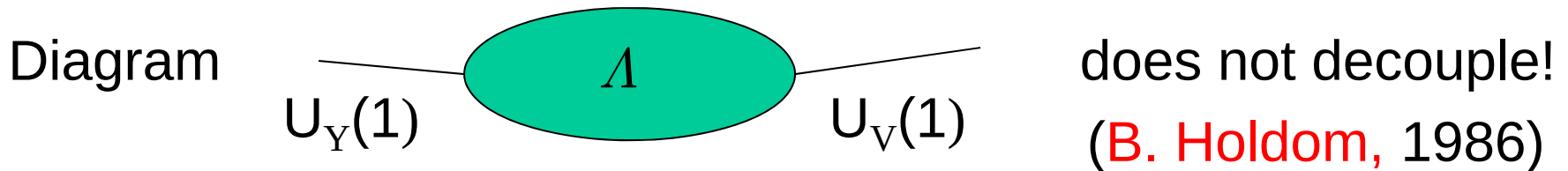
Intensity and Energy Frontiers



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)

Non-decoupling of secluded U(1)

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 $U_S(1)$



A mixing term is induced, $\kappa F_{\mu\nu}^Y F_{\mu\nu}^S$,

With κ having only the log dependence on Λ ,

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

$$M_V \sim 1/(4\pi) \kappa \times (M_Z \text{ or TeV}) \sim \text{MeV} - \text{GeV}$$

NB: should it be a new nonabelian group, the leading effect would start in Λ^{-2} order, and be extremely small

Neutral doors [“portals”] to the SM

Let us *use* these doors to attach new physics

$H^\dagger H (\lambda S^2 + m S)$ 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...

Are other portals warranted? Can they be detected? U(1) kinetic mixing portal is very unique, and $\kappa \sim 10^{-3}$, $m_\nu < \text{GeV}$ is well-motivated, or better to say, not unnatural.

This New Physics could be Dark Matter

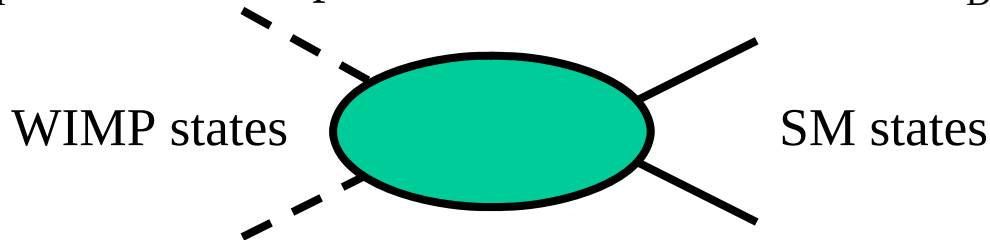
WIMPs and super-WIMP paradigms

- Weakly interacting massive particles (neutralinos, KK modes etc)

Weak-scale masses, weak-scale couplings,

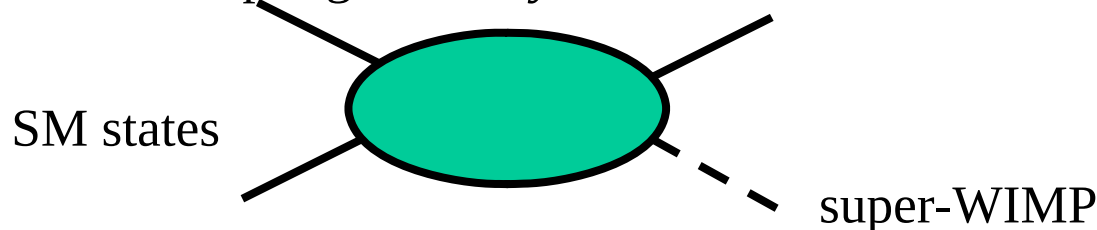
Large T ($T \gg m_{\text{DM}}$): WIMPs are in thermal/chemical equilibrium

$T \sim m_{\text{DM}}$: Period of rapid annihilation; $T < 0.05 m_{\text{DM}}$ - freeze-out



- Super-WIMPs (“sterile” neutrinos, sterile scalars etc)

Never in thermal equilibrium. Populated via SM sector “leaking” into Super-WIMPs. Couplings are *very small*



Simplest example of “vector portal” model

(MP, Ritz, Voloshin, 2007)

$$\mathcal{L}_{\text{WIMP}+\text{mediator}} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

This Lagrangian describes an extra U(1)’ group, and some matter charged under it. Mixing angle κ controls the coupling to the SM. There is no constraint from anomaly cancellation.

Below the scale of the U(1)’ breaking we have

$$\mathcal{L}_{\text{WIMP}+\text{mediator}} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu\partial_\mu B_{\mu\nu} + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi + \mathcal{L}_H,$$

Other realizations with gauged B-L or μ -e symmetries are possible

WIMP annihilation cross section

$$\frac{10^{-10} x_f}{\sqrt{g_*(T_f)} \times \langle \sigma v \rangle} \leq \Omega_{\text{DM}} h^2 \approx 0.1 \quad \Rightarrow \quad \langle \sigma v \rangle = 2.5 \times 10^{-26} \text{cm}^3 \text{s}^{-1},$$

- WIMP annihilation cross section is fixed (~ 1 pbn) by the annihilation at the freeze-out argument. This is *not* a small cross section for O(TeV) scale particles.
- If $\text{DM} + \text{DM} \rightarrow \text{SM states}$ cross section is fixed to 1 pbn, then there is some hope that $\text{SM states} \rightarrow \text{DM} + \text{DM}$, and $\text{SM} + \text{DM} \rightarrow \text{SM} + \text{DM}$ are also sizable, providing a possibility for WIMP detection at *colliders* and in *direct detection* experiments. **Not so in the secluded WIMP models.**

Secluded WIMPs charged under U(1)'

(MP, Ritz, Voloshin, 2007)

$$\mathcal{L}_{\text{WIMP}+\text{mediator}} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu B_{\mu\nu} + \bar{\psi}(iD_\mu \gamma_\mu - m_\psi)\psi + \mathcal{L}_H$$

ψ – Dirac type WIMP; V_μ – mediator

Two kinematic regimes can be readily identified:

- $m_{\text{mediator}} > m_{\text{WIMP}}$
 $\psi^+ + \psi^- \rightarrow \text{virtual } V^* \rightarrow \text{SM states}$

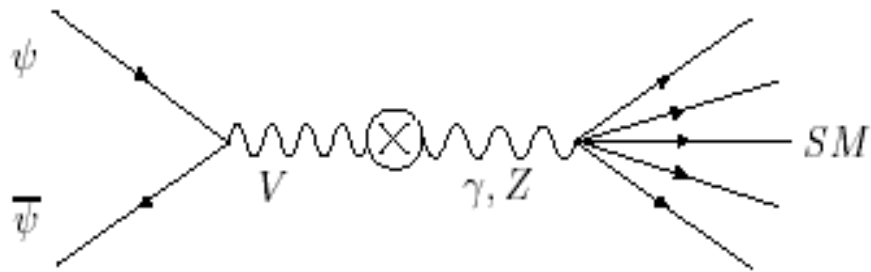
κ has to be sizable to satisfy the constraint on cross section

- 2. $m_{\text{mediator}} < m_{\text{WIMP}}$

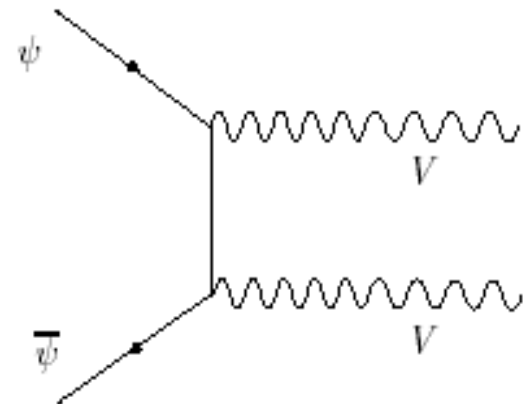
$\psi^+ + \psi^- \rightarrow \text{on-shell } V + V$, followed by $V \rightarrow \text{SM states}$

There is almost **no constraint on κ** other than it has to decay before BBN. $\kappa^2 \sim 10^{-20}$ can do the job.

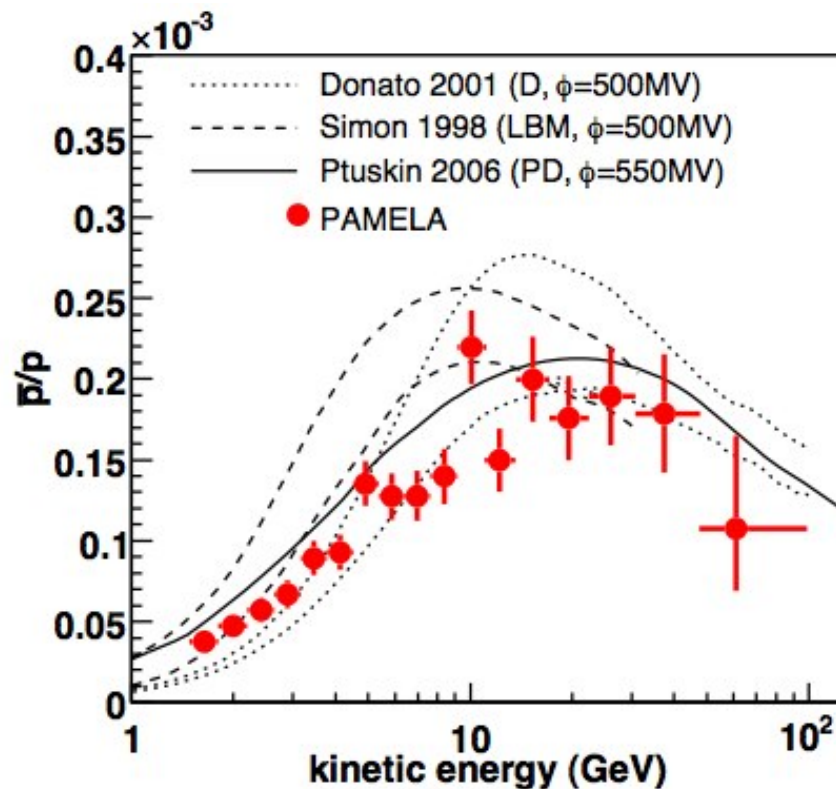
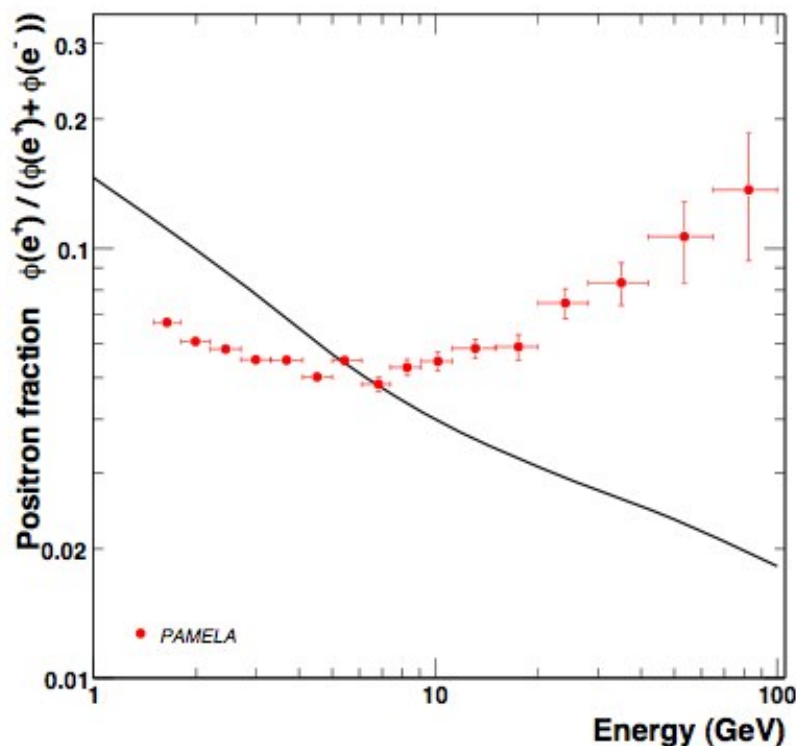
Un-secluded



Secluded



PAMELA positron fraction



No surprises with antiprotons, but there is seemingly a need for a new source of positrons!

This is a “boost” factor of 100-1000 “needed” for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work.

Indirect astrophysical signatures in secluded regime

Annihilation into a pair of V-bosons, followed by decay create boosted decay products.

If m_V is light, GeV or below, the following consequences are generic (Arkani-Hamed et al, MP and Ritz, October 2008)

1. Annihilation products are dominated by electrons and positrons
2. Anti-proton and direct photons are suppressed
3. The rate of annihilation in the galaxy, $\sigma_{\text{ann}} v$, is enhanced relative to the cosmological $\sigma_{\text{ann}} v$ because of the long-range V-exchange in the DM sector.

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

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

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,

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

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?

Experimental Sensitivity

Luminosity matters!

- Fixed targets (proton & electron beams dumps)
 - up to 10^{23} POT for modern neutrino sources
 - sensitive to long-lived states
- Medium energy colliders (BaBar, Belle)
 - large datasets $\sim O(1000) \text{ fb}^{-1}$
 - $\sqrt{s} \sim 10 \text{ GeV}$
- Rare decays
 - high statistics e.g. for kaon decays

Precision QED: g-2 constraints

1. Electron g-2 can be used as a constraint on (m_V, κ) only in conjunction with other measurements of α_{EM} .
2. The contribution to the anomaly is *positive*. Opens the door for speculation about the “anomaly” of $(g-2)_\mu$ anomaly.

$$a_f = \frac{\alpha \kappa^2}{2\pi} \int dz \frac{2m_f^2}{m_f^2(1-z)^2 + m_V^2 z} = \frac{\alpha \kappa^2}{2\pi} \begin{cases} 1 & \text{for } m_V \ll m_f \\ 2m_f^2 / 3m_V^2 & \text{for } m_V \gg m_f \end{cases}$$

For example, $m_V \sim 200 \text{ MeV}$ and $\kappa^2 = 3 \times 10^{-5}$ provide

$$\Delta a_\mu = 3 \times 10^{-9}.$$

Other QED constraints, e.g. H-Lamb shift, are not competitive

V-bosons in the decays of strange particles

V-boson will show up as a narrow very sharp resonance in the s-channel. $\Gamma_V \sim \text{eV}$. Difficult to detect.

What about rare decays of strange particles? Vector current (as opposed to e.g. axial vector current) makes V a tough object for flavor physics.

$$X_s \rightarrow Y + \gamma^* \rightarrow Y + V$$

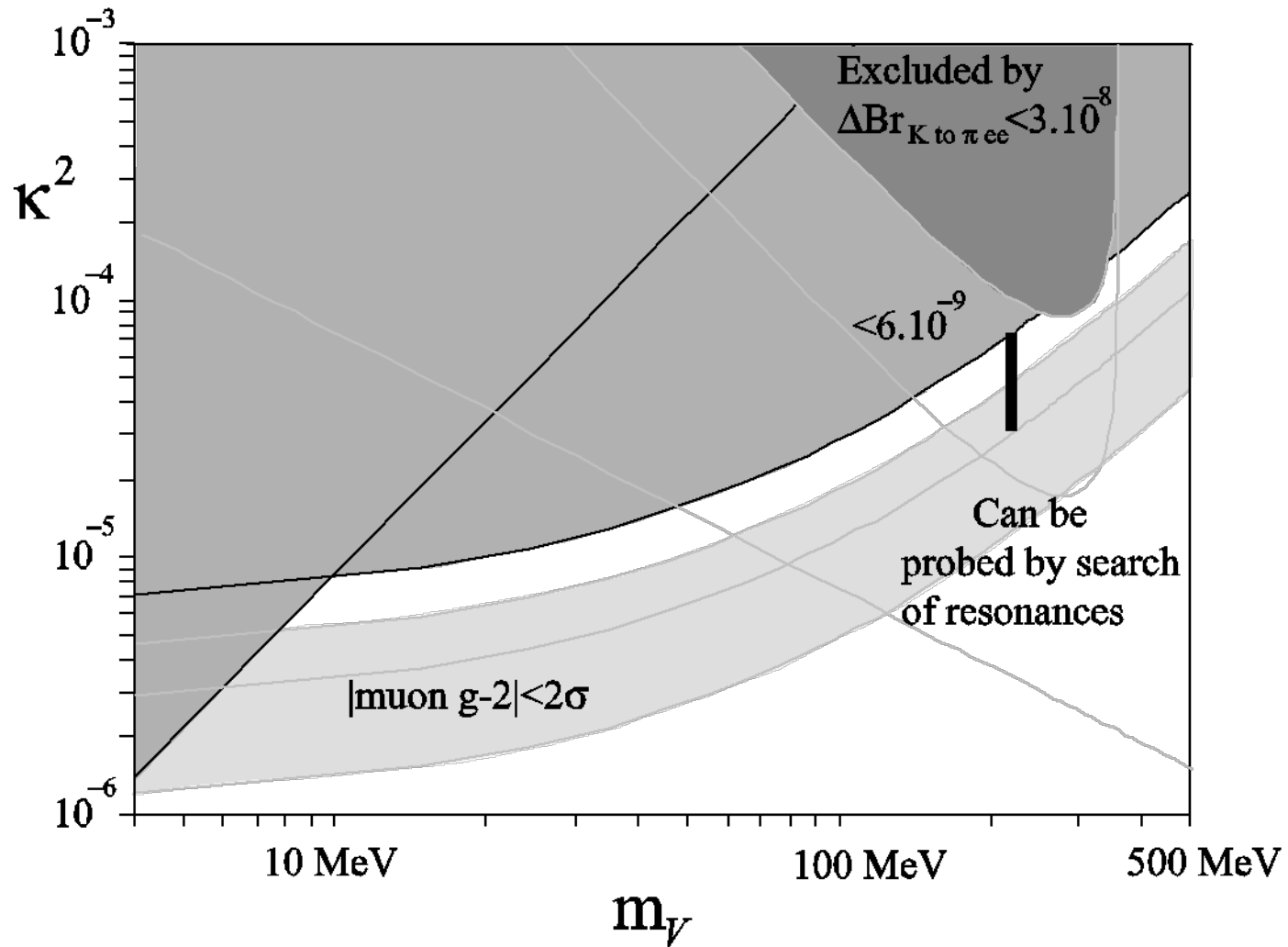
For example,

A. $K^+ \rightarrow \pi^+ + V \rightarrow \pi^+ + e^-e^+ (\mu^- \mu^+)$

B. $K^+ \rightarrow l^+ \nu + V \rightarrow l^+ \nu + e^-e^+ (\mu^- \mu^+)$ All SM decay modes

C. $\Sigma^+ \rightarrow p + V \rightarrow p + e^-e^+ (\mu^- \mu^+)$ are observed, $\text{Br} \sim 10^{-7}-10^{-8}$

κ - m_V parameter space, (MP, Nov 2008)



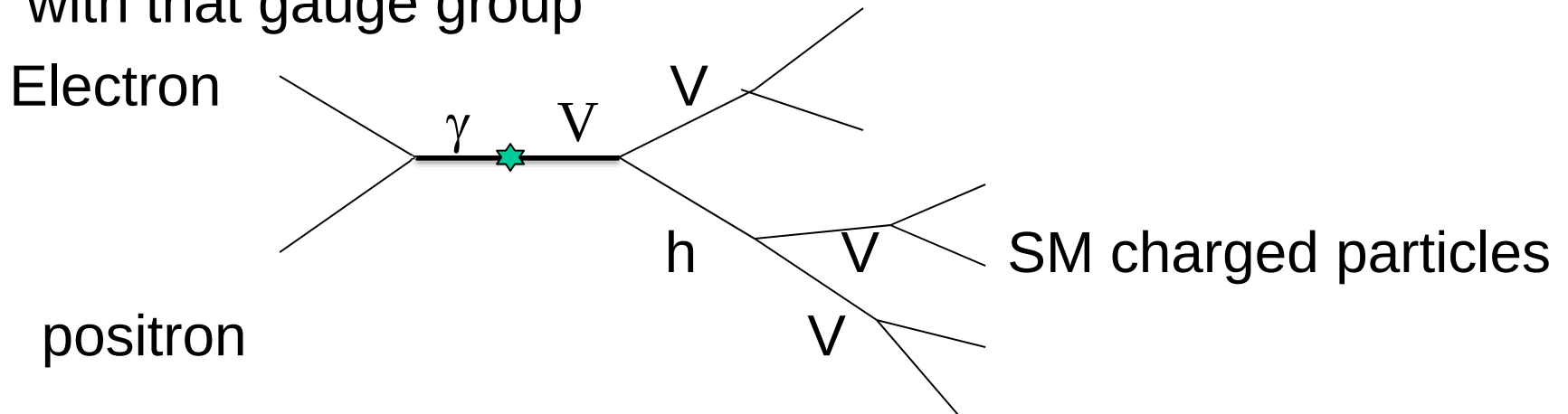
Secluded $U_S(1)$ at B-factories

(Batell, MP, Ritz, March 2009)

- To search for a milli-coupled GeV-scale particles, one does not need super-powerful machines like Tevatron or LHC.
- It is far more advantageous to use high-luminosity machines at medium energy, that provide clean environments to fish out the small signal.
- B-factories, that collected $\sim 500 \text{ fmb}^{-1}$ of data seem to be best suited for the search of the secluded gauge groups.
- Leading signatures: $e^+ + e^- \rightarrow \gamma V \rightarrow \gamma l^+ l^-$
 $e^+ + e^- \rightarrow h' V \rightarrow 3 \text{ pairs of } l^+ l^- \quad \text{or} \quad l^+ l^- + \text{missing Energy}$

Higgs'-strahlung process

- Secluded $U_S(1)$ is spontaneously broken at relatively low scales, therefore there is a not-so-heavy Higgs' associated with that gauge group



- Production of Vh comes at the cost of κ^2 in the cross section. Subsequent decay of V and h back to charged particles comes at no cost, *provided that there are no additional light states in the secluded sector*

Higgs'-strahlung

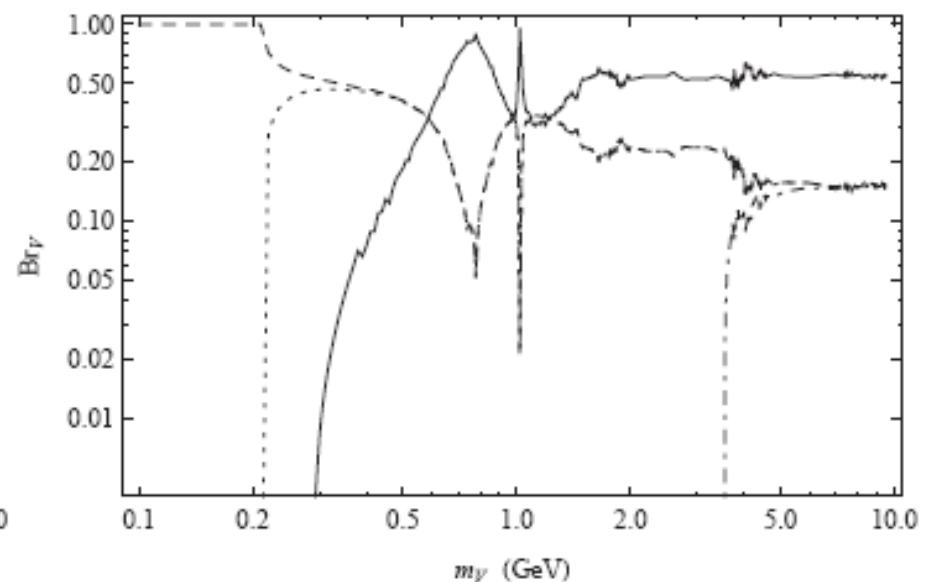
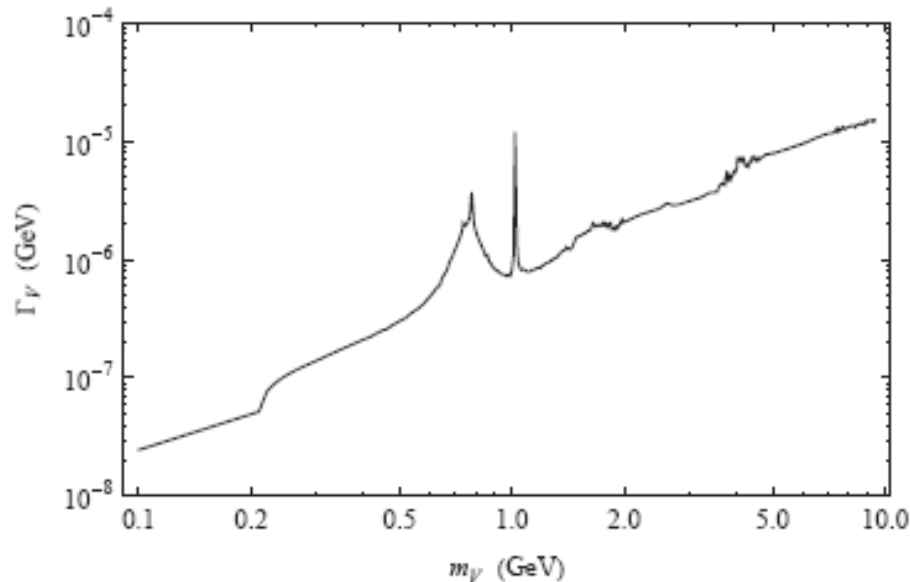
$$\begin{aligned}\sigma_{e^+e^- \rightarrow Vh'} &= \frac{\pi\alpha\alpha'\kappa^2}{3s} \left(1 - \frac{m_V^2}{s}\right)^{-2} \sqrt{\lambda\left(1, \frac{m_{h'}^2}{s}, \frac{m_V^2}{s}\right)} \left[\lambda\left(1, \frac{m_{h'}^2}{s}, \frac{m_V^2}{s}\right) + \frac{12m_V^2}{s} \right] \\ &\approx 20 \text{ fb} \times \left(\frac{\alpha'}{\alpha}\right) \left(\frac{\kappa^2}{10^{-4}}\right) \frac{(10 \text{ GeV})^2}{s},\end{aligned}$$

Up to 10000 Higgs'-strahlung events might have been produced at Babar or Belle

Subsequent fate of V and h particles

$$\Gamma_{V \rightarrow \ell\bar{\ell}} = \frac{1}{3} \alpha \kappa^2 m_V \sqrt{1 - \frac{4m_\ell^2}{m_V^2}} \left(1 + \frac{2m_\ell^2}{m_V^2} \right) .$$

$$\Gamma_{V \rightarrow \text{hadrons}} = \frac{1}{3} \alpha \kappa^2 m_V \sqrt{1 - \frac{4m_\mu^2}{m_V^2}} \left(1 + \frac{2m_\mu^2}{m_V^2} \right) R(s = m_V^2)$$

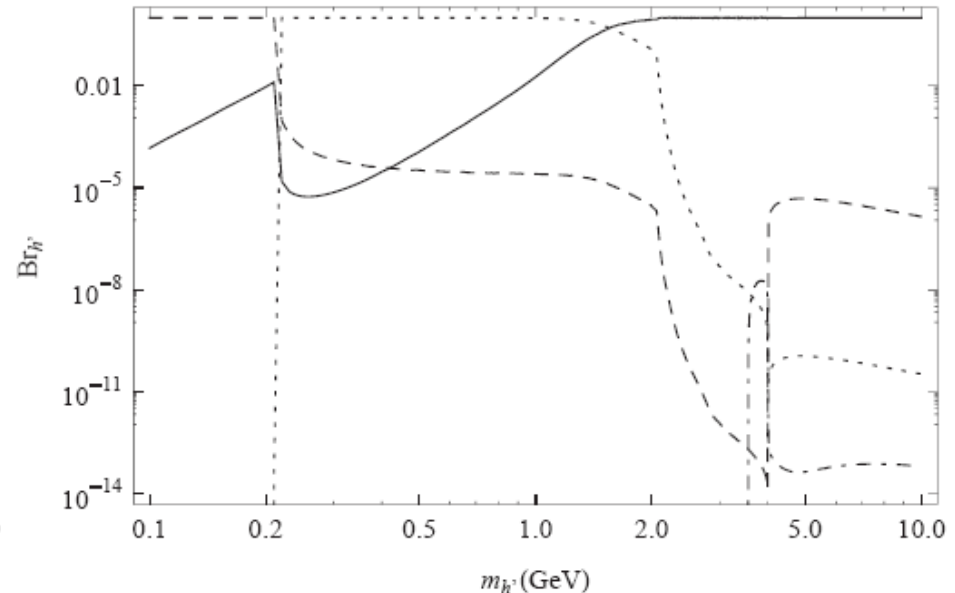
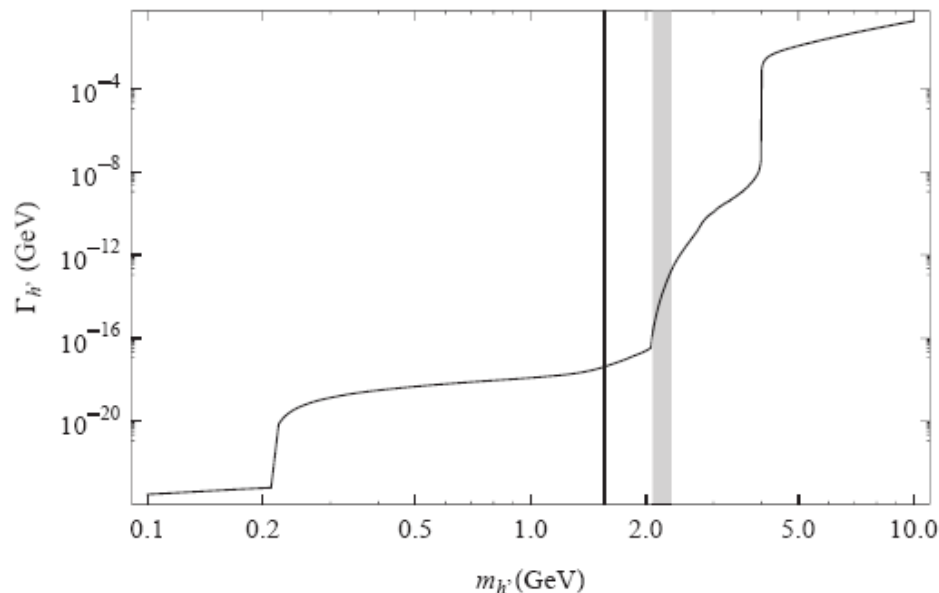


Subsequent fate of V and h particles

If $m_h > 2 m_V$, Higgs decays to two gauge bosons that subsequently decay to two charged particles each.

If $m_V < m_h < 2 m_V$, Higgs decays to two charged particles and V, again producing 4 charged particles in the final state

If $m_h < m_V$ Higgs decays mostly to two leptons via a loop-induced process



Scan of m_V - m_h parameter space (assuming >10 events)

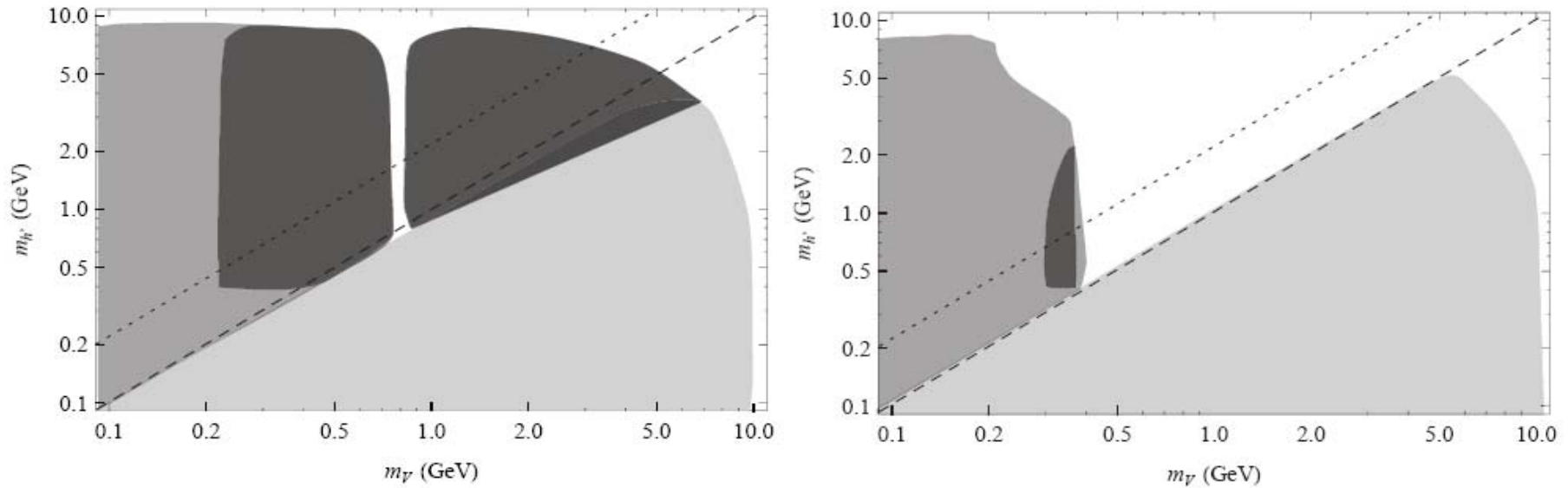
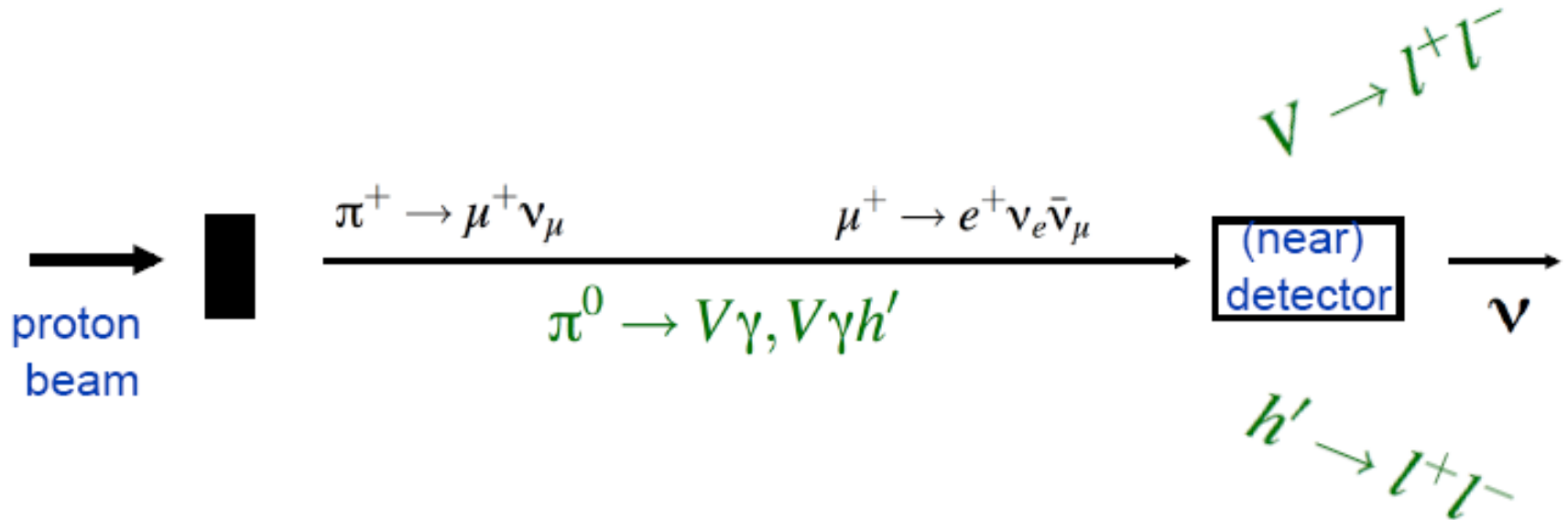


Figure 3: Sensitivity of the B -factory experiments for $\kappa = 10^{-2}$ (left) and $\kappa = 10^{-3}$ (right), with $\alpha' = \alpha$. The discovery modes are l^+l^- plus missing energy (light), $6e$ (medium), and 6μ (dark). In the region $m_{h'} > 2m_V$ ($m_{h'} > m_V$), above the dotted (dashed) line the signal contains 3 (2) leptons pairs with invariant mass $m_{l^+l^-} \simeq m_V$.

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!

Different machines, different production mechanisms

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

$$m_{V,h'} \lesssim m_\pi$$

$$m_{V,h'} \lesssim 400 \text{ MeV}$$

$$m_{V,h'} \lesssim m_\rho$$

$$m_{V,h'} \gtrsim 1 \text{ GeV}$$

$$\pi^0 \rightarrow \gamma V, \gamma V h'$$

$$\eta \rightarrow \gamma V, \gamma V h'$$

$$\Delta \rightarrow NV$$

$$\rho^0, \omega, \phi \rightarrow V h', V \pi^0(\eta)$$

$$q + \bar{q} \rightarrow V, V h', \dots$$

$$q + g \rightarrow V h', qV, \dots$$

LSND – almost 1g of protons on target

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

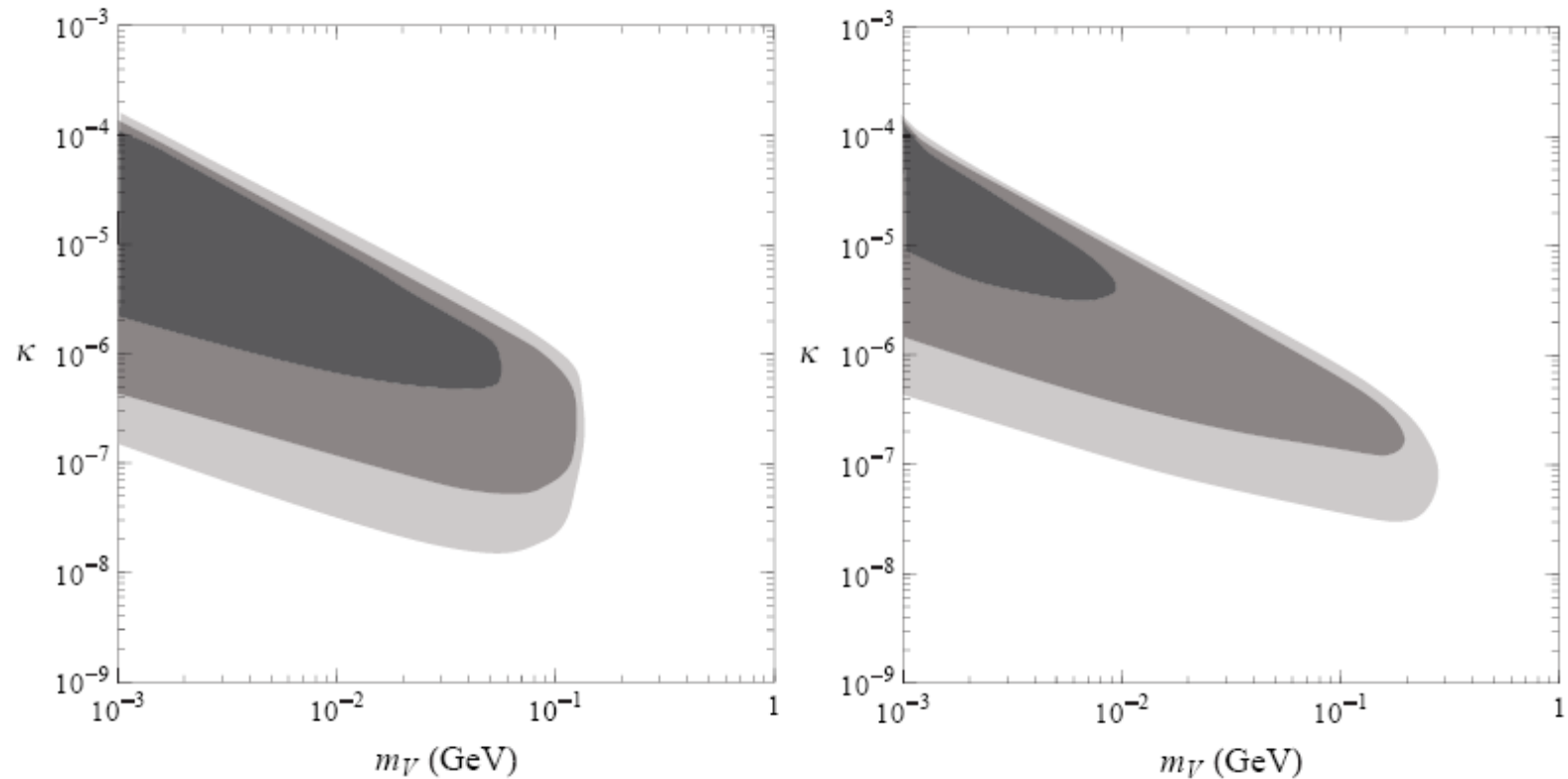


Figure 1: Sensitivity of LSND to decays $V \rightarrow e^+e^-$. The light, medium, and dark shaded regions indicate more than 10, 1000, and 10^6 expected events respectively. The left panel shows events due to vectors arising from $\pi^0 \rightarrow \gamma V$ decays, while the right panel shows events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

Sensitivity to dark Higgs

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

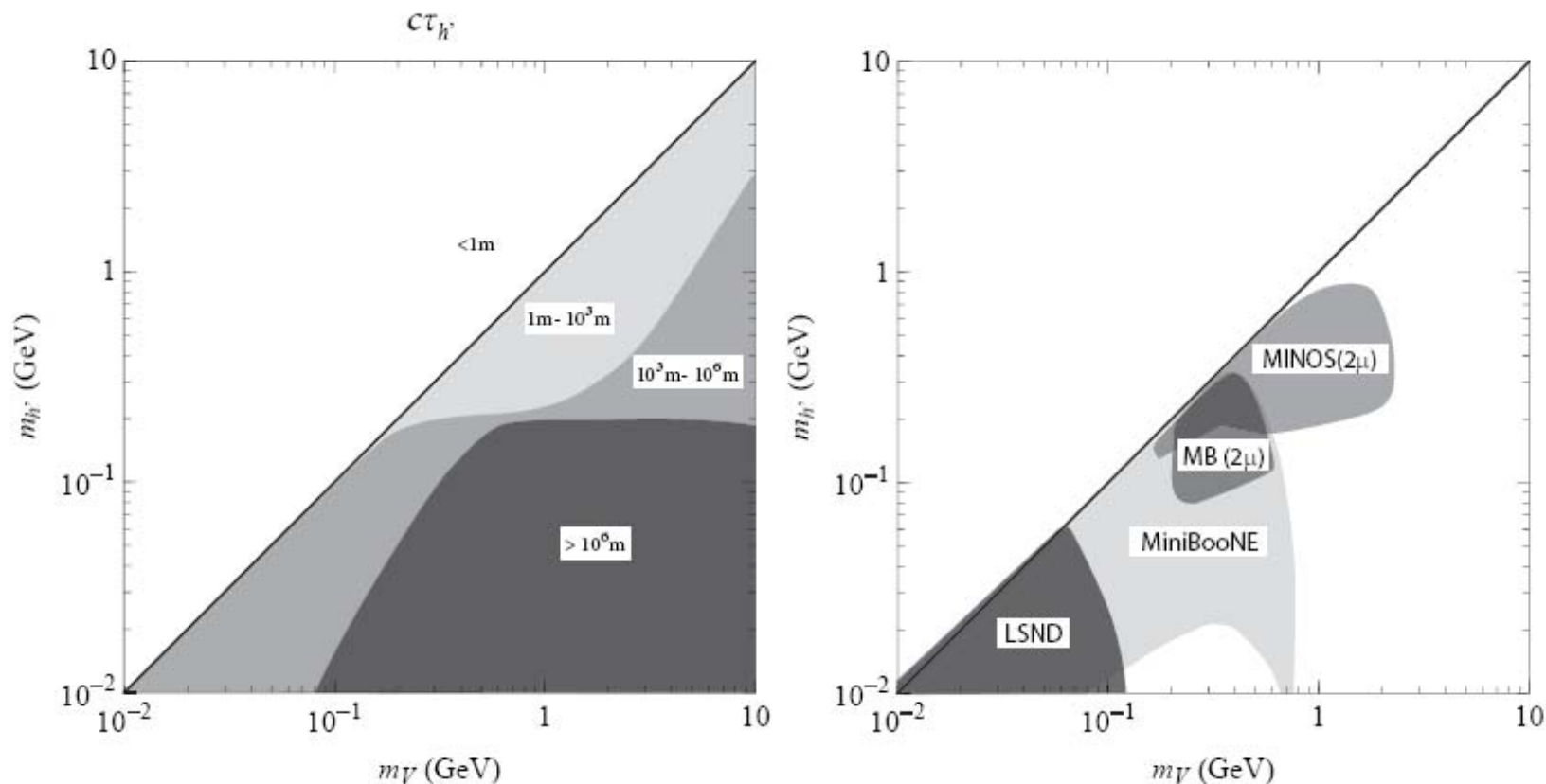
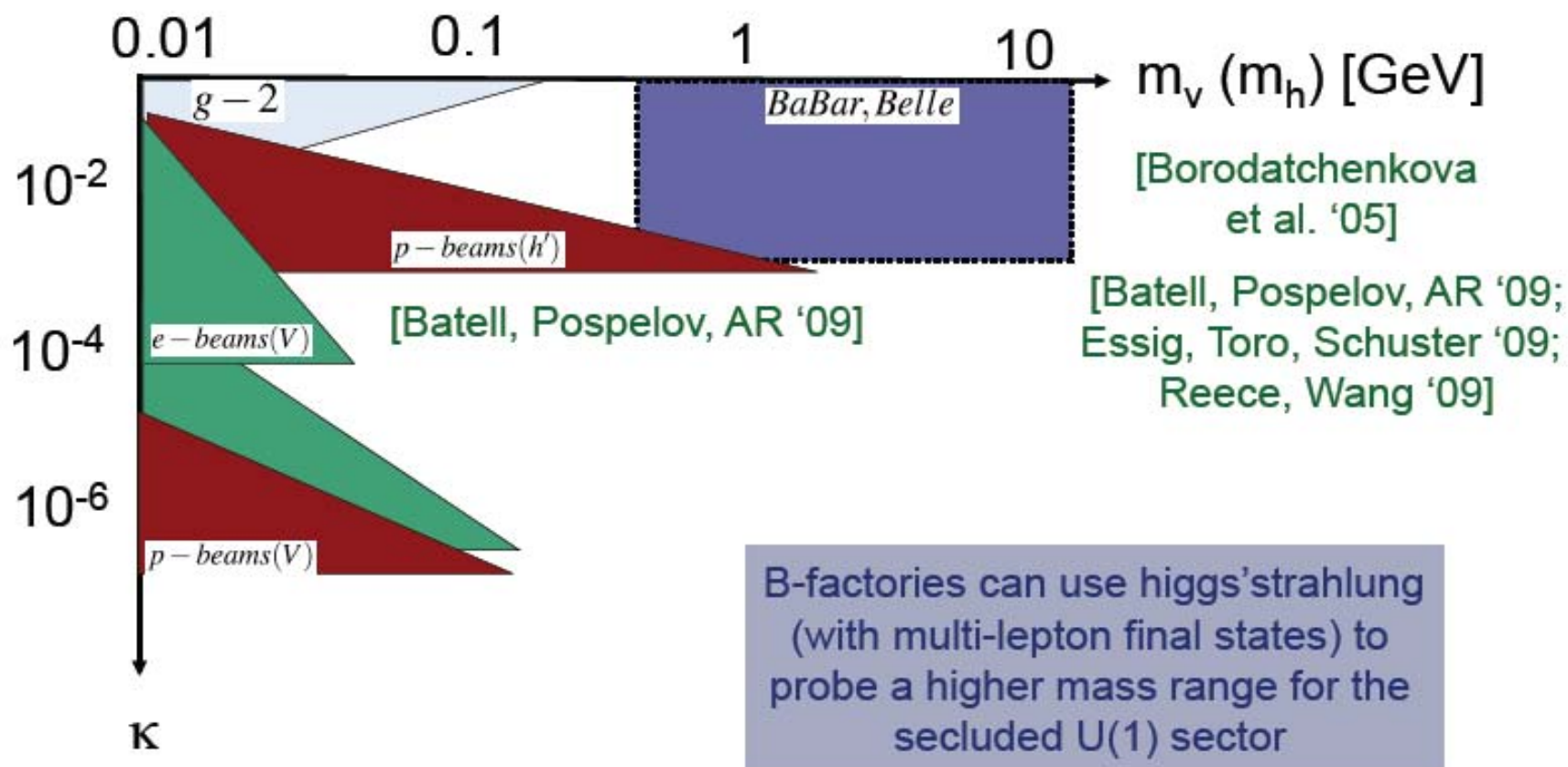


Figure 2: On the left we show the Higgs' decay length $c\tau$ for $\kappa = 10^{-2}$ and $\alpha' = \alpha$. The regions are $c\tau < 1\text{m}$ (white), $1 - 10^3\text{m}$ (light), $10^3 - 10^6\text{m}$ (medium), and $> 10^6\text{m}$ (dark). On the right, we show the sensitivity of LSND ($\pi^0 \rightarrow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

Experimental Sensitivity

In pictorial form



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.

$$\bar{t}\gamma_{\mu}t \longrightarrow (G_F q^2) \times \bar{b}_L\gamma_{\mu}S_L; \quad \bar{t}\gamma_{\mu}\gamma_5 t \longrightarrow (G_F m_t^2) \times \bar{b}_L\gamma_{\mu}S_L$$

Batell, MP, Ritz (Nov 2009) calculates the decays of B-mesons via Higgs/axion/vector portals. There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in semileptonic and fully leptonic K and B decays.

New search modes open up: $B_s \rightarrow VV \rightarrow 4 \text{ leptons}$ or $B_s \rightarrow h'h' \rightarrow 8 \text{ leptons}$.

Babar and Belle are sensitive to Higgs portal at 1 per mill level.

Conclusions

- MeV scale, $\kappa^2 \sim 10^{-4}$ - 10^{-6} type of $U(1)'$ is rather natural and broadly within reach of $g-2$ and K , hyperon decay experiments.
- For $\kappa \sim 10^{-2}$ all kinematic reach can be explored [ruled out] with the existing dataset of Babar and Belle. For $\kappa \sim 10^{-3}$, a significant portion of parameter space can be explored. Super-B can go as low as $\kappa \sim 10^{-4}$. Fixed target experiments have sensitivity to long lifetimes of new $U_S(1)$ particles.
- Rare decays of B-mesons can be used for probing the Higgs portals, and new search modes (e.g. 4lepton final states) must be pursued.

DM models with Higgs/vector/neutrino portals

Singlet scalar WIMP DM (McDonald; Burgess, MP, ter Veldhuis;...)

$$\mathcal{L} = (\partial S)^2 - V(S^2) - \lambda H^\dagger H S^2; \quad \lambda \sim O(0.1)$$

**Can lead to the “missing” Higgs decay signatures.*

Singlet scalar super-WIMP DM (McDonald)

$$\mathcal{L} = (\partial S)^2 - V(S^2) - \lambda H^\dagger H S^2; \quad \lambda \sim O(10^{-12})$$

Singlet fermion super-WIMPs = sterile neutrino DM

(Dodelson, Widrow; ...).

WIMPs and super-WIMPs in the $U(1)'$ sector:

(Holdom;; ... Fayet,...MP, Ritz, Voloshin; Arkani-Hamed et al)

Lots of other models with Z' and DM ...

Hyper-CP anomaly from $m_V = 214$ MeV

There is a published “anomaly” in the spectrum of muon pair created by the hyperon decay, $\Sigma^+ \rightarrow p \mu^- \mu^+$. All three events have the same, 214 MeV invariant mass. Branching $\sim 10^{-8}$.

Can this be caused by secluded V-boson?

This issue have been looked at by X-G He, Tandean, Valencia, who concluded that vector-like coupled new physics ($s \gamma_\mu d$) V_μ cannot fit Hyper CP (process C.) without introducing too large branchings for A. and B. *This conclusion does not apply in this case because all decays are saturated by long-distance contributions.*

My results: Model with secluded $U(1)'$, $m_V = 214$ MeV, $\kappa^2 \sim 10^{-4}$ can contribute to $\Delta Br_C = \text{few} \times 10^{-8}$, while giving $\Delta Br_{A,B} \sim 10^{-9}$. Spectrum of lepton pairs in K-decays can show the presence of V-boson.

QED background

- Naïve alpha power counting shows why Higgs strahlung is advantageous relative to $V\gamma$ process. For 6 leptons final state in the Higgs'-strahlung events the background starts at $O(\alpha^6)$, while for the other one at $O(\alpha^3)$.

- QED background from equivalent photons can be significant:

$$\begin{aligned}\sigma_{e^+e^- \rightarrow 3(e^+e^-)} &\approx \frac{\alpha^6}{\pi^3 m^2} \left(\log \frac{s}{m^2} \right)^4 \\ &\approx 10^9 \text{ fb},\end{aligned}$$

- Can be reduced by A. going to muons B. by selecting large angles for outgoing leptons C. by exploiting the kinematic relations between lepton momenta in the signal events