Cleaning the SM backyard – looking for GeV-scale new physics

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Based mainly on:
2009 paper, with Brian Batell, Adam Ritz
2011 paper: last week

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Introduction. Which portals allow for “stronger-than-weak” forces? Kinetic mixing and baryon current portals.
2. Mini-review of kinetic mixing phenomenology.
3. New signatures of baryonic portal. WIMP-like recoil signal.
4. Conclusions

Intensity and Energy Frontiers

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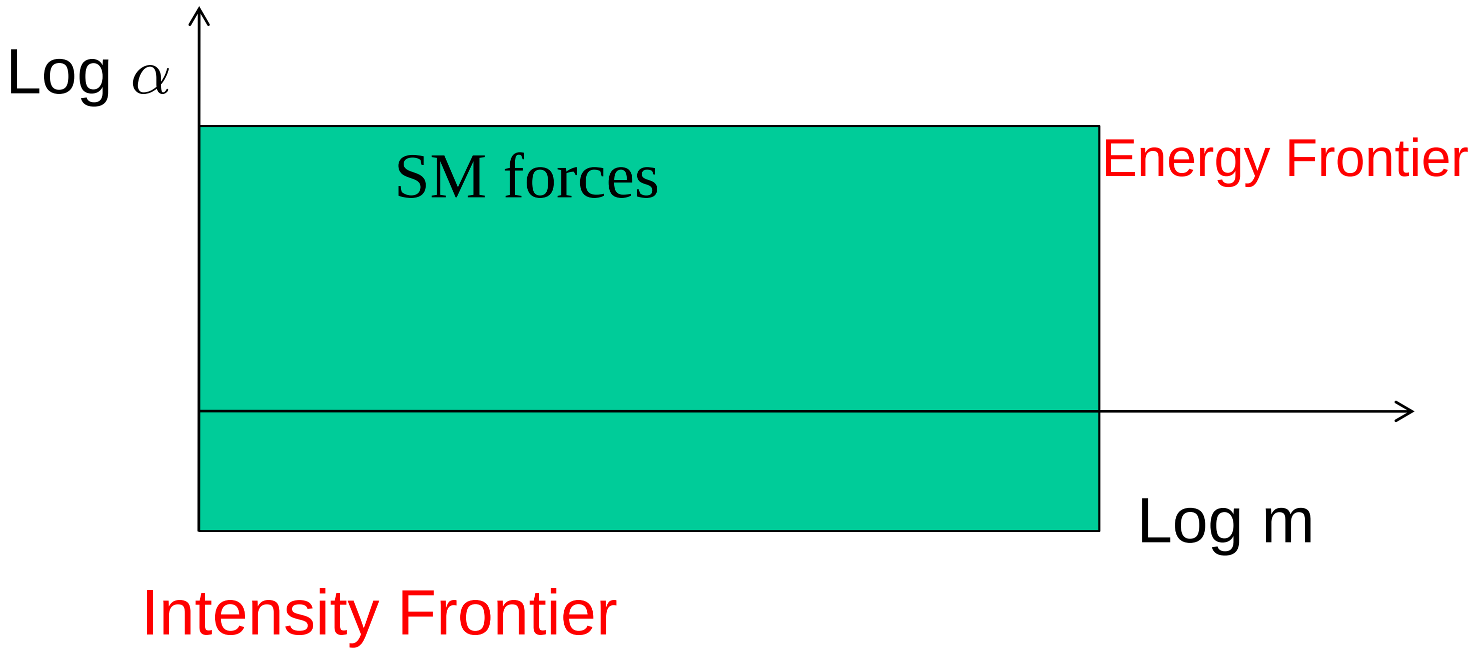
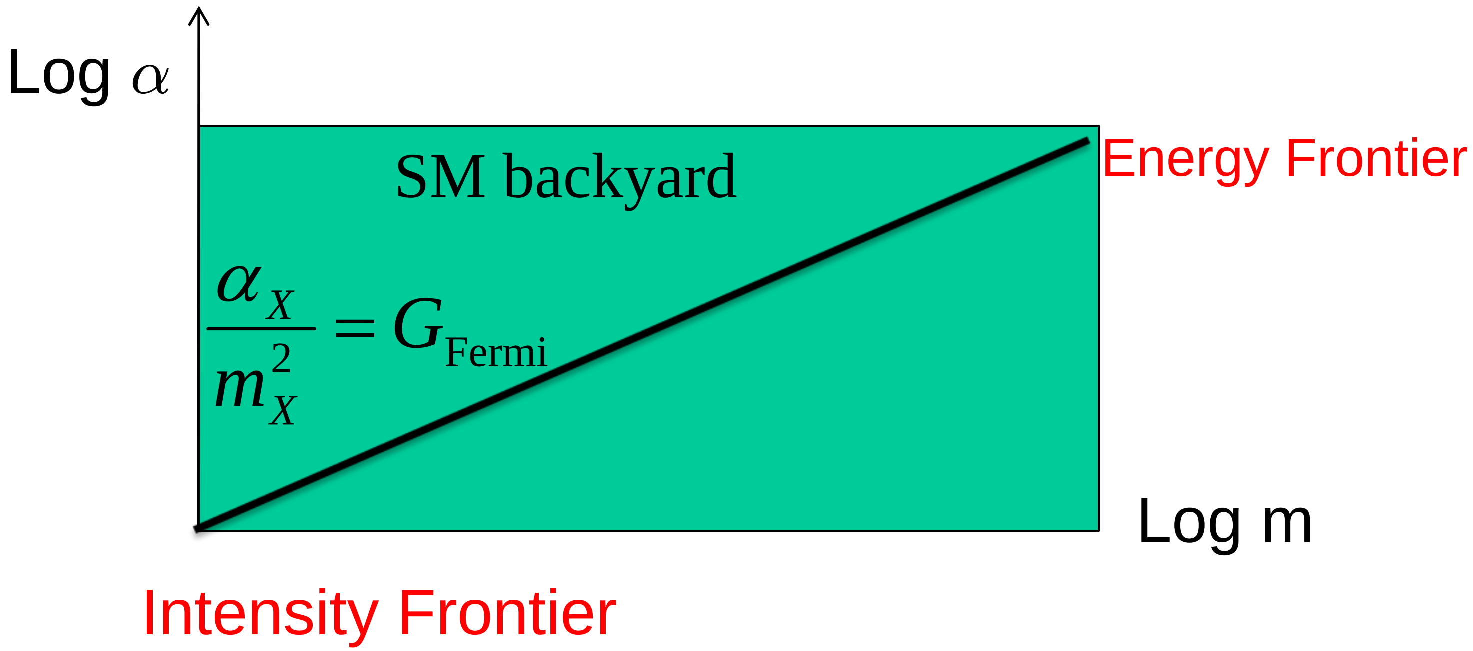


$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow$$

$$\text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

Intensity and Energy Frontiers

(for this talk I will limit the mass of the mediator m_X >MeV)

- 

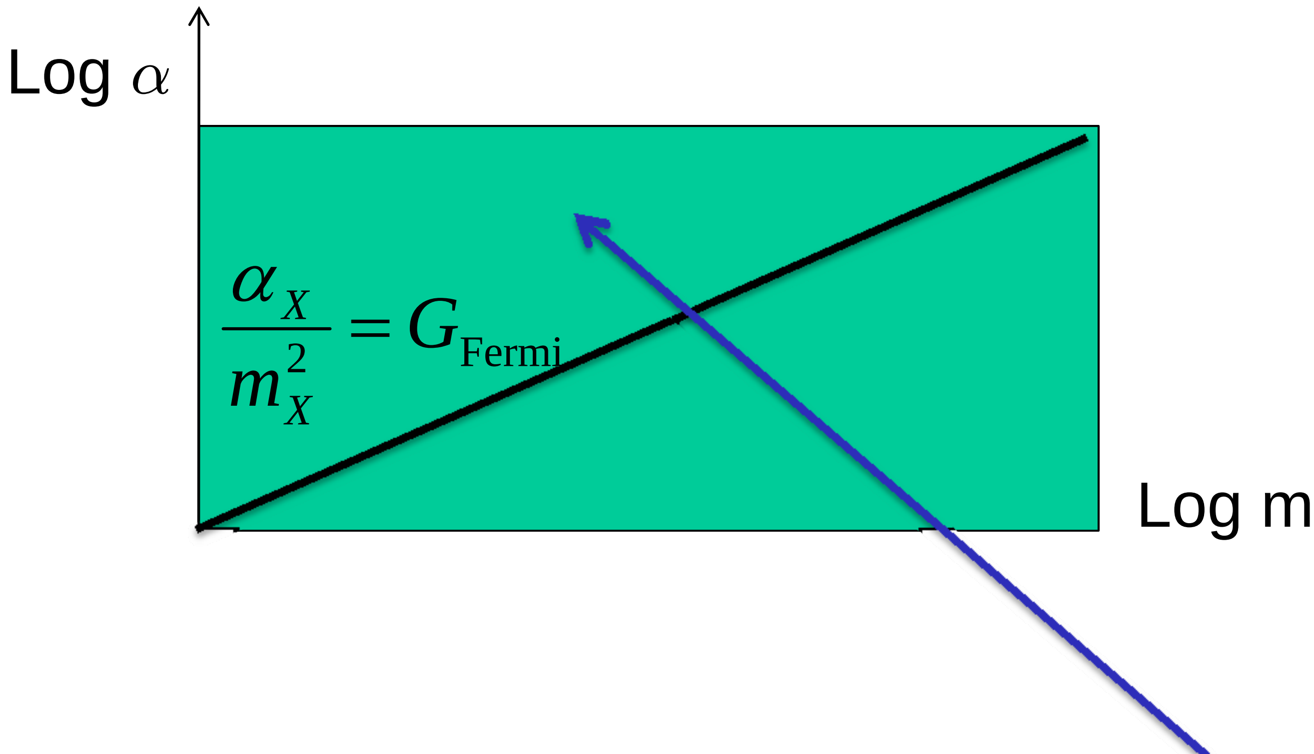
To study physics at Energy frontier and access larger and larger m one needs powerful accelerators (Tevatron, LHC...). To study very weak forces at Intensity (or luminosity) frontier one needs a lot of events (powerful beams as at T2K, NuMi, SNS etc)


Beautiful TeV frontier – lots of energy required
05/04/2009

Ugly backyard – some determination needed

What if you clear garbage and see something extraordinary …

Well-posed theory question

- 

What kind of reasonable "New Physics" force could hide in this corner? What are the candidates for "stronger-than-weak" new forces?

Answer

(technical naturalness assumed, no excessive fine-tuning of physical amplitudes etc.)

1. **“Kinetically mixed” vector force**

2. **Vector forces coupled to baryonic current.**

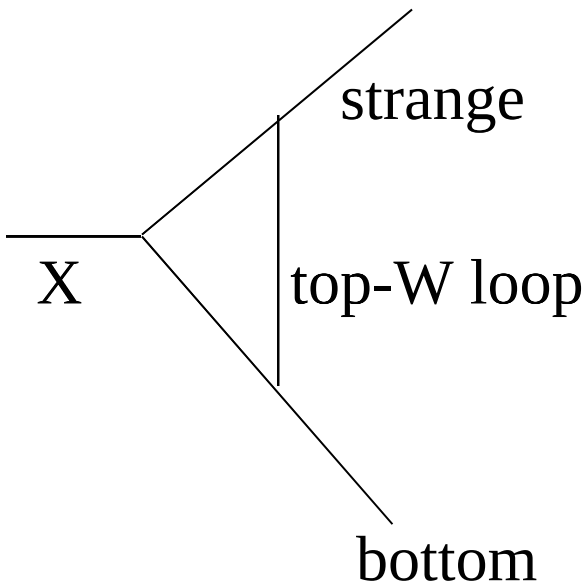
3. **Some exceptional lepton forces such as gauged L_μ-L_τ, gauged τ_R or μ_R.**

I do not know of any other examples (if you do, please tell me). I will share my thoughts on cases 1 and 2.

There are no systematic searches of these portals.

Why baryonic or EM currents are "safe" from flavor constraints

Conserved vector currents are uniquely positioned to avoid very strong flavor 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.There is no room for stronger-than-weak forces in these channels.

Simplest example of additional U(1) model

(Holdom 1986; earlier papers by Okun')

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

This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ϵ, η, χ) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

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Why searching for new gauge boson(s) at low and medium energies is important

1. Standard Model is built on SU(3)xSU(2)xU(1) interactions. *Testing for existence of additional gauge groups is needed.*
2. Hints for new sub-GeV gauge bosons might be given to us by *several particle physics anomalies*, most importantly g-2 of the muon.
3. New U(1) groups can serve as mediators of connection between SM and particle dark matter. *Speculative but interesting*.
4. Additional U(1) with kinetic mixing to photons is a very “natural” possibility of new light physics. *It is very simple – even elegant – and extremely predictive.*
5. Significant advances can be achieved using fixed target setups. Only a very small subset of experiments done at low energy can be sensitive to physics beyond SM.

WIMP paradigm

$$\frac{10^{-10}x_f}{\sqrt{g_*(T_f)}\times\langle\sigma v\rangle} \leq \Omega_{\rm DM}h^2 \approx 0.1 \quad \Longrightarrow \quad \langle\sigma v\rangle = 2.5\times10^{-26}{\rm cm}^3{\rm s}^{-1},$$

Main property of WIMPs is the weak-scale annihilation cross section to the SM states. Does the scattering of WIMPs on SM or SM->DM is of the same size?

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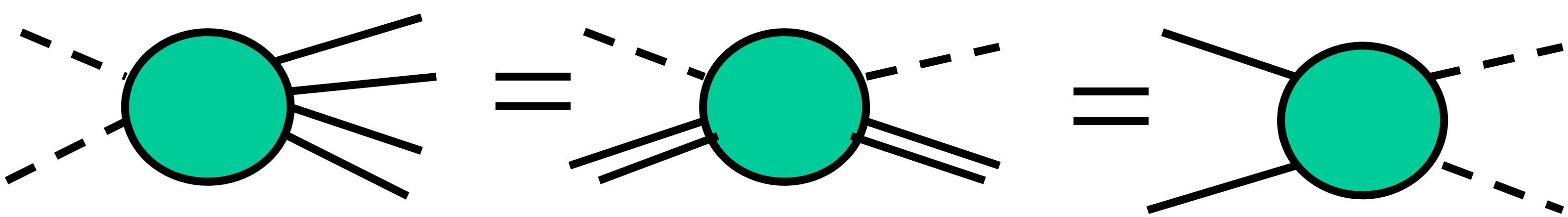


Simplest example of "vector portal" mediation between SM and DM

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

This Lagrangian describes an extra U(1)' group (**dark force**), and some matter charged under it. Mixing angle κ controls the coupling to the SM.

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

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

Now we have 3 parameters, m_V, κ, m_{WIMP}

This class of WIMP models was introduced and partially analyzed in MP, Ritz, Voloshin, 2007. Earlier specific example appeared in Finkbeiner and Weiner, 2007.

The existence of dark forces changes standard WIMP paradigm

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

ψ – Dirac type WIMP; V_μ – mediator particle.

Two kinematic regimes can be readily identified:

- $m_{mediator} > m_{WIMP}$

  $\psi^+ + \psi^- \to$ virtual $V^* \to$ SM states

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

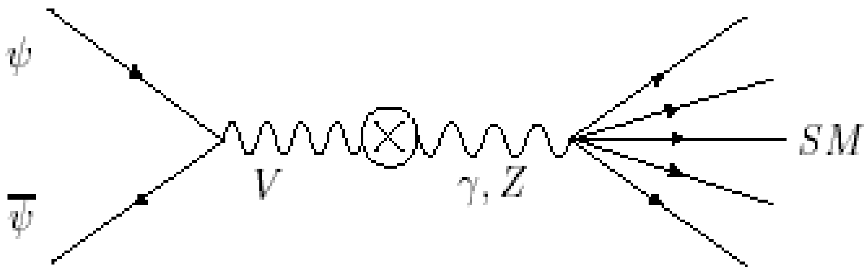
2. $m_{mediator} < m_{WIMP}$

   $\psi^+ + \psi^- \to$ on-shell $V + V$, followed by $V \to$ SM states

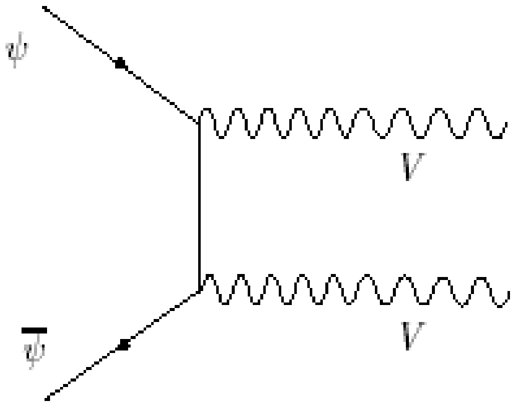
There is almost no constraint on κ other than it has to decay before BBN. $\kappa^2 \sim 10^{-20}$ can do the job.

Two types of WIMPs

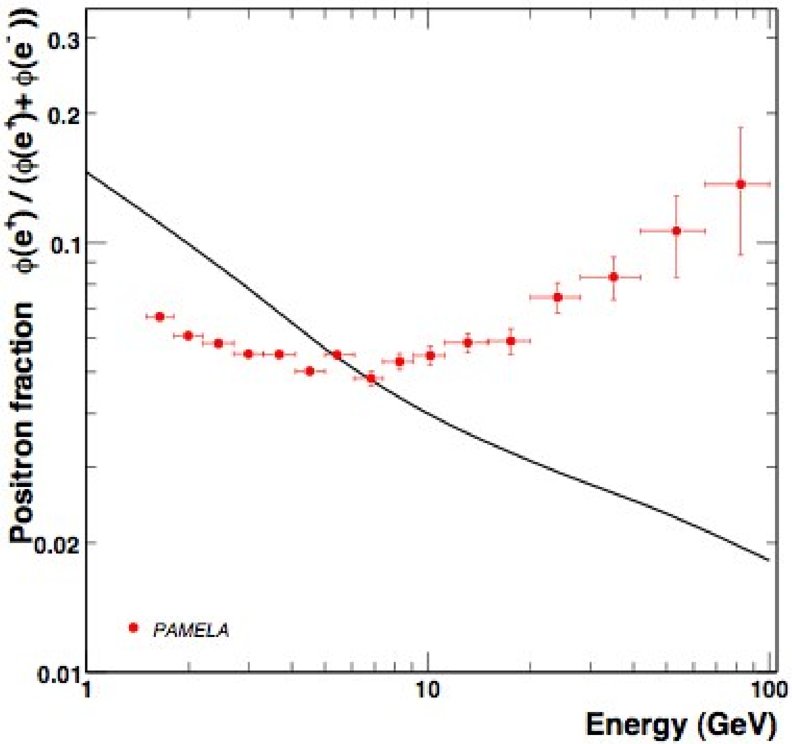
Un-secluded

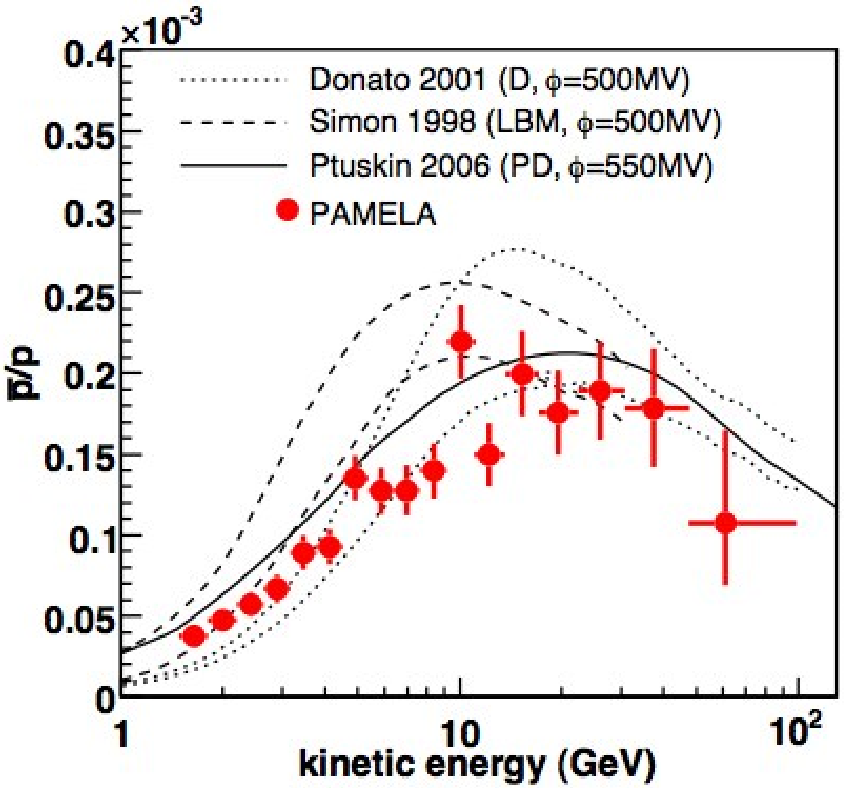


Secluded



PAMELA positron fraction (700 citations in SPIRES)





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, because <σ v > is too small.

Indirect astrophysical signatures in secluded regime

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

If m_V is under $m_{DM} v_{DM}$ **~ GeV, the following consequences are generic**

(Arkani-Hamed, Finkbeiner, Slatyer Weiner; MP and Ritz, Oct 2008)

1. Annihilation products are dominated by electrons and positrons
2. Antiprotons are absent and monochromatic photon fraction is suppressed
3. 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* V-mediated force in the DM sector.

Fits the PAMELA result. (but then again many things may cause positron rise, not just DM)

Search for the Dark Force

- However suggestive the PAMELA hints may look like, no conclusive proof of the existence of dark force may ever come from indirect astrophysical signatures. Even the connection to DM may be a wishful thinking...
- Only reproducible terrestrial experiments might convince anyone in the existence of dark forces.
- We come back to the “intensity frontier” picture. ***Huge luminosities are required.***

Most important aspects of extra U(1) phenomenology

1. *Whether or not there are new light states* (other than SM) charged under U(1):

U-boson$_{\text{Fayet}}$ $\rightarrow$ DM; V-boson$_{\text{our model}}$ $\rightarrow$ SM charged particles.

It seems that chances to detect V-boson are much higher.

2. *Possibility of long-lived states*. Vectors are long-lived if mixing angles are small $\kappa \lesssim 10^{-7} - 10^{-6}$. Higgs' particles are very long-lived even if the mixing angles are sizable, provided that

$$\kappa \sim 10^{-4} - 10^{-2} \text{ and } m_V > m_{h'}$$

3. *Possibility of increased lepton multiplicities at no cost* (e.g. in the decay chain of Higgs')

4. *New vector states couple to the SM via a conserved current* (EM current). No $(m_t/m_K)^2$ enhancement of FCNC as it would have been for (pseudo)scalar or axial-vector portals. Moderate flavor constraints

I shall now go over novel signatures of extra sub-GeV scale U(1)

Precision QED: new force provide correction to anomalous magnetic moments of leptons

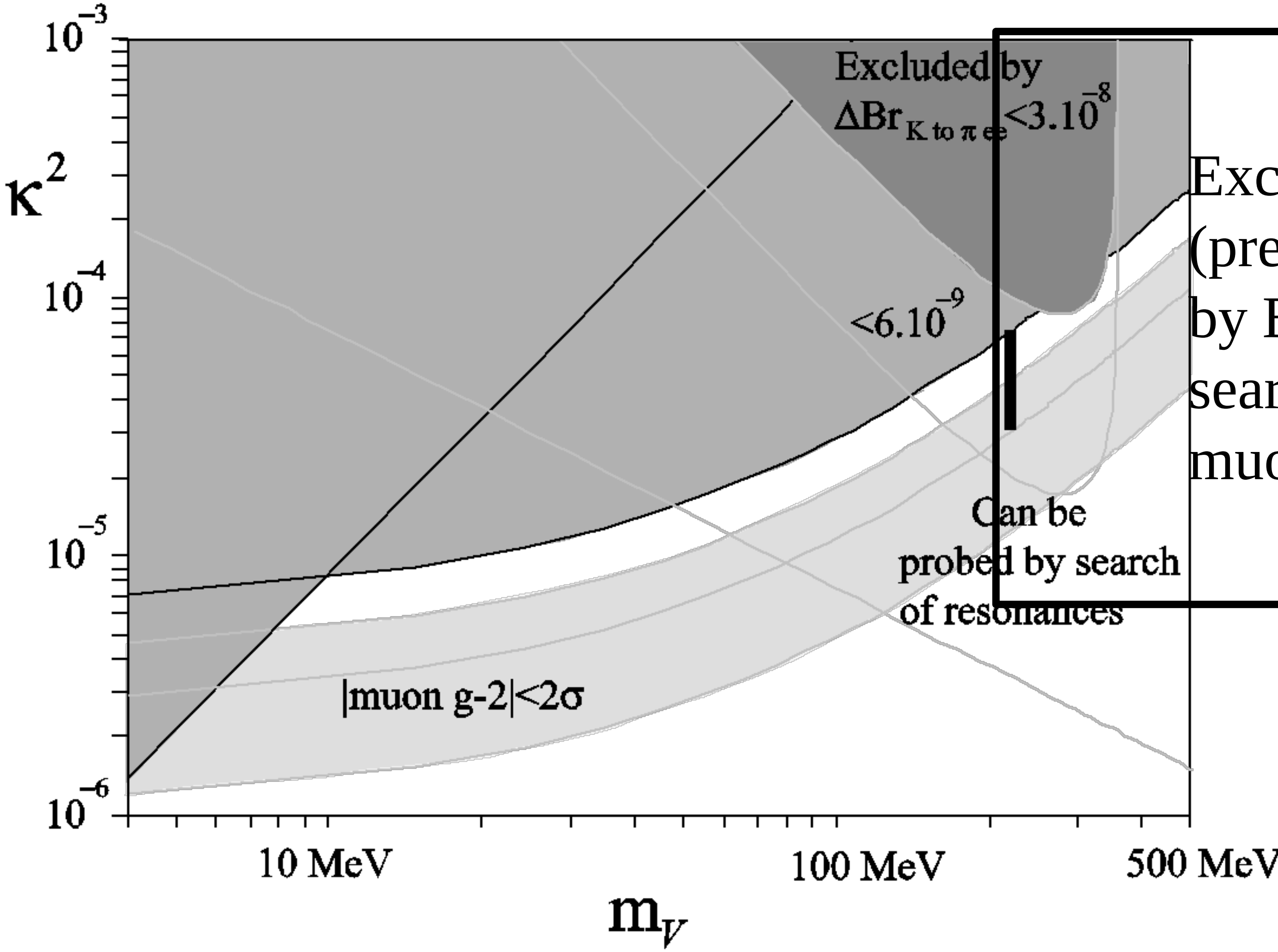
1. Electron g-2 can be used as a constraint on (m_V, κ) only in conjunction with other measurements of α_{EM}.
2. The contribution to the anomaly is *positive*. Opens the door for speculation about the "anomaly" of $(g\text{-}2)_\mu$ anomaly.

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

For example, $m_V \sim 200$ MeV and $\kappa^2 = 3 \times 10^{-5}$ provide $\Delta a_\mu = 3 \times 10^{-9}$.

κ-m_V parameter space

If g-2 discrepancy taken seriously, mixing of order few 0.001 and mass $m_V \sim m_\mu$ helps to resolve it (MP, 2008)



Excluded (preliminary) by BaBar search of di-muon peaks

Intensity Frontier: e+e- machines

(Batell, MP, Ritz; Essig, Schuster, Toro; Reece and Wang, 2009)

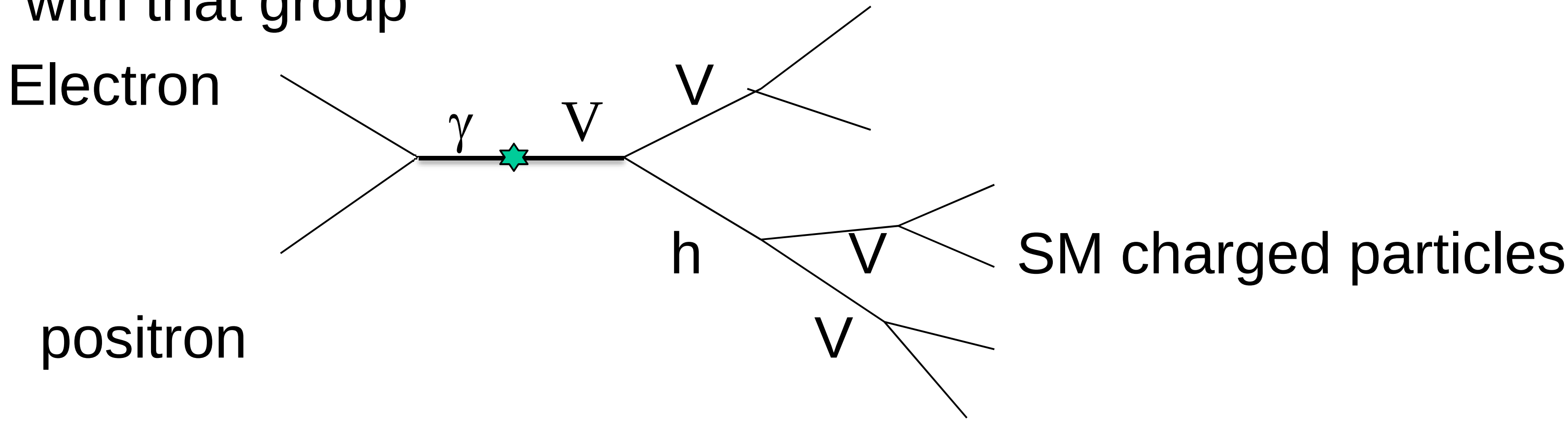
- To search for a milli-coupled GeV-scale particles, one does not need super-powerful machines like Tevatron or LHC.
- It is far more advantageous to use high-luminosity machines at medium energy, that provide clean environments to fish out the small signal.
- B-factories, that collected up to 1500 fmb^{-1} of data seem to be best suited for the search of the secluded gauge groups.
- Leading signatures:

Single vector production: $e^+ + e^- \to \gamma\, V \to \gamma\, l^+ l^-$

Higgs'-strahlung: $e^+ + e^- \to h'\, V \to$ 3 pairs of $l^+ l^-$ or $l^+ l^-$ + missing Energy

Higgs'-strahlung process

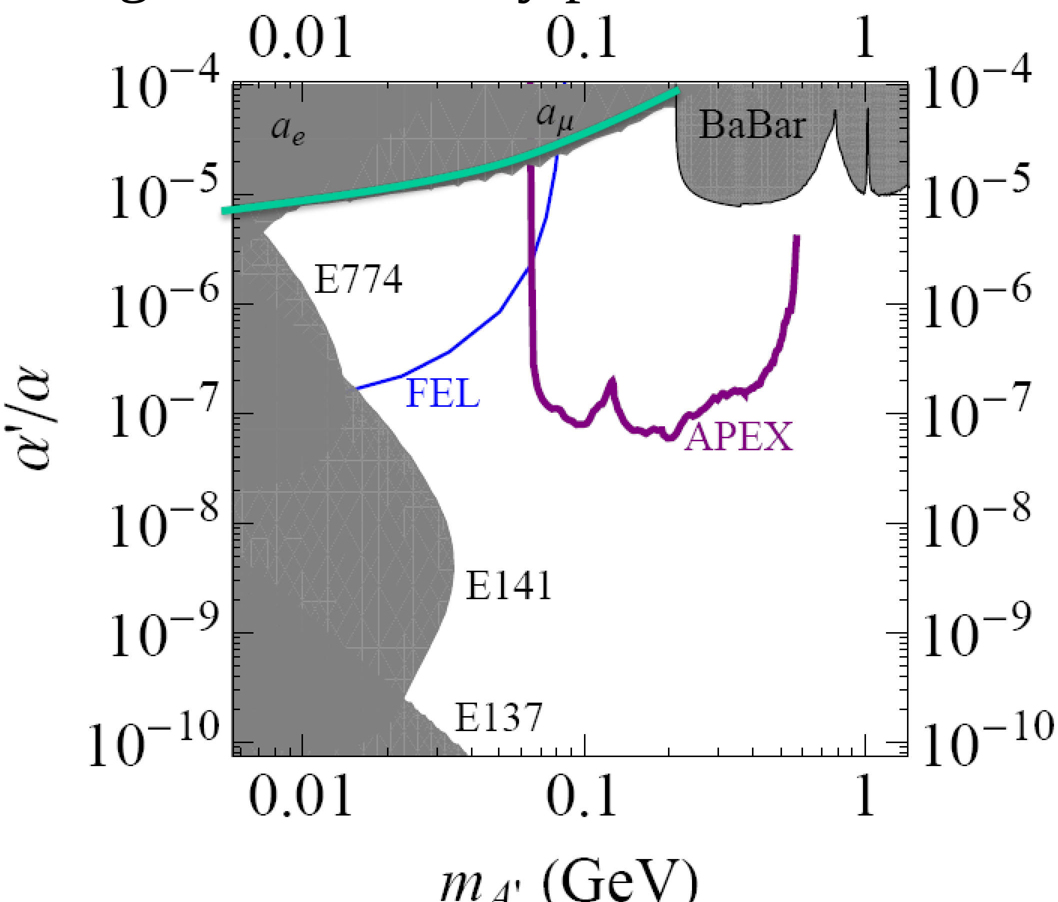
- Secluded $U_S(1)$ is spontaneously broken at relatively low scales, therefore there is a not-so-heavy Higgs' associated with that group



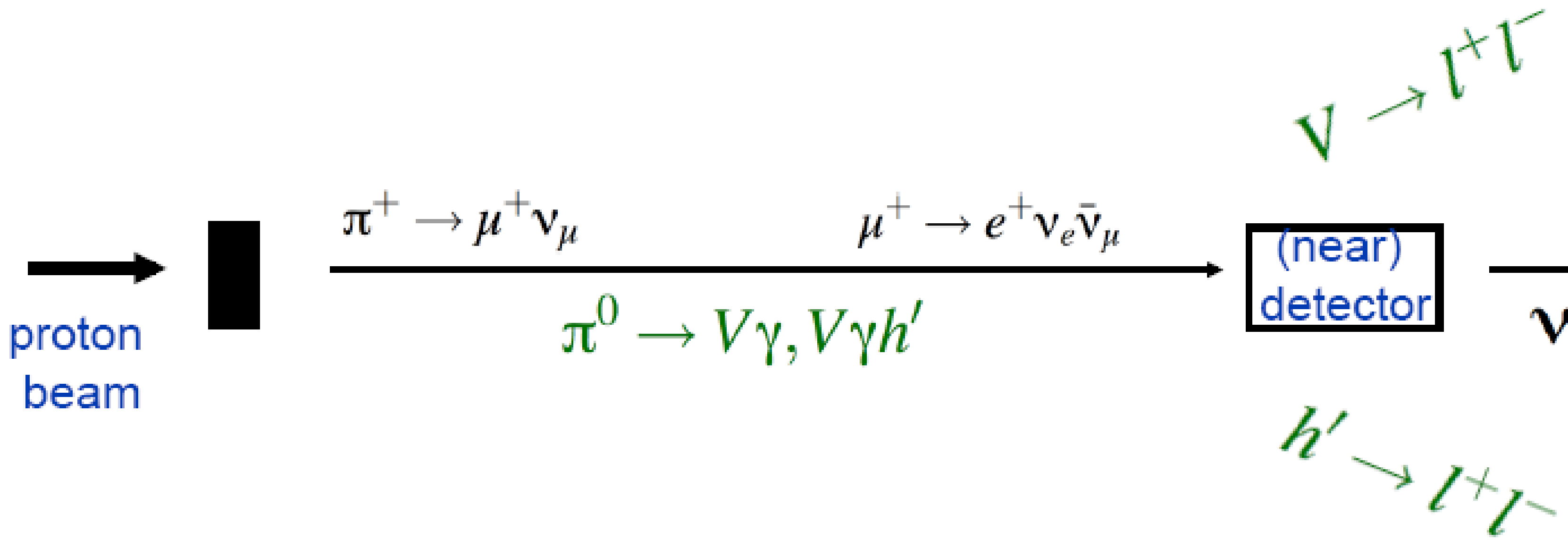
- Production of Vh comes at the cost of $(\kappa)^2$ in the cross section. Subsequent decay of V and h back to charged particles comes at no cost, *provided that there are no additional light states in the secluded sector.*
- *Both BaBar and Belle (?) are planning to do a multi-lepton search.*

Intensity Frontier: Electron beam on target

- Bjorken et al., 2009; Fisher and Thaler, 2009; Essig et al. 2010; Denig et al. 2010…
- Advance by several orders of magnitude in terms of kappa can be made. g-2 region can be fully probed!



Neutrino beam setup can be used for studying long-lived relics (Batell et al., 2009; Harnik et al. 2010)



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!

LSND – almost 1g of protons on target

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

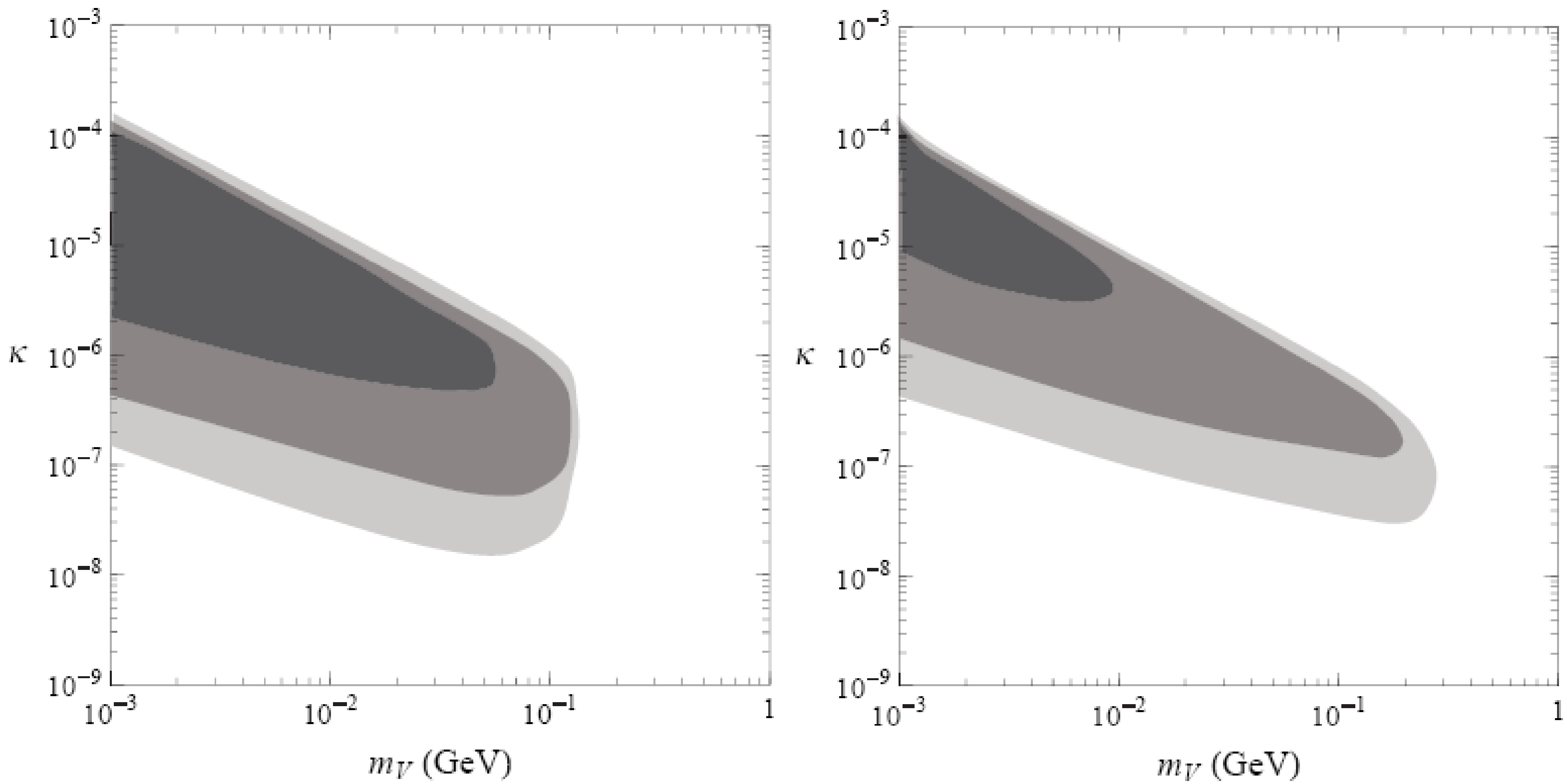
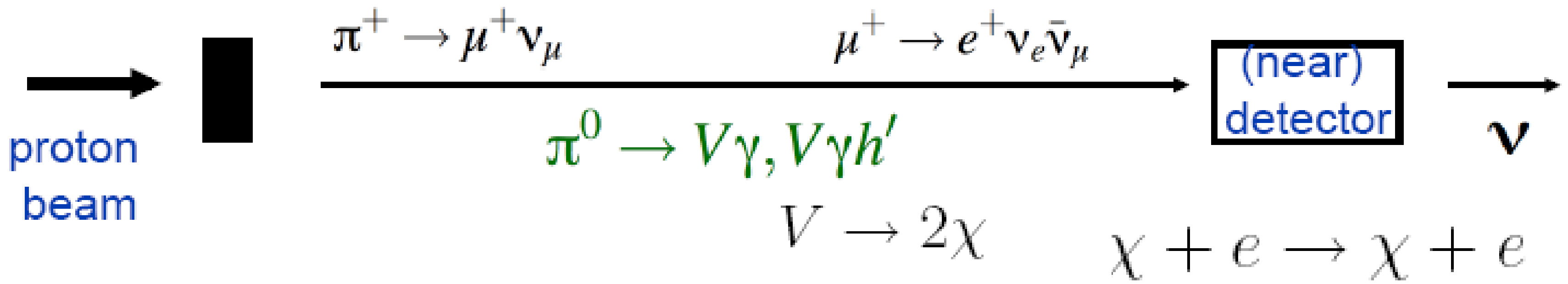


Figure 1: Sensitivity of LSND to decays $V \to e^+e^-$. The light, medium, and dark shaded regions indicate more than 10, 1000, and 10^6 expected events respectively. The left panel shows events due to vectors arising from $\pi^0 \to \gamma V$ decays, while the right panel shows events arising from $\Delta(1232)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

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

(MeV DM a la Fayet, Boehm)



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. E.g. LSND provides best constraints on MeV WIMPs

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.

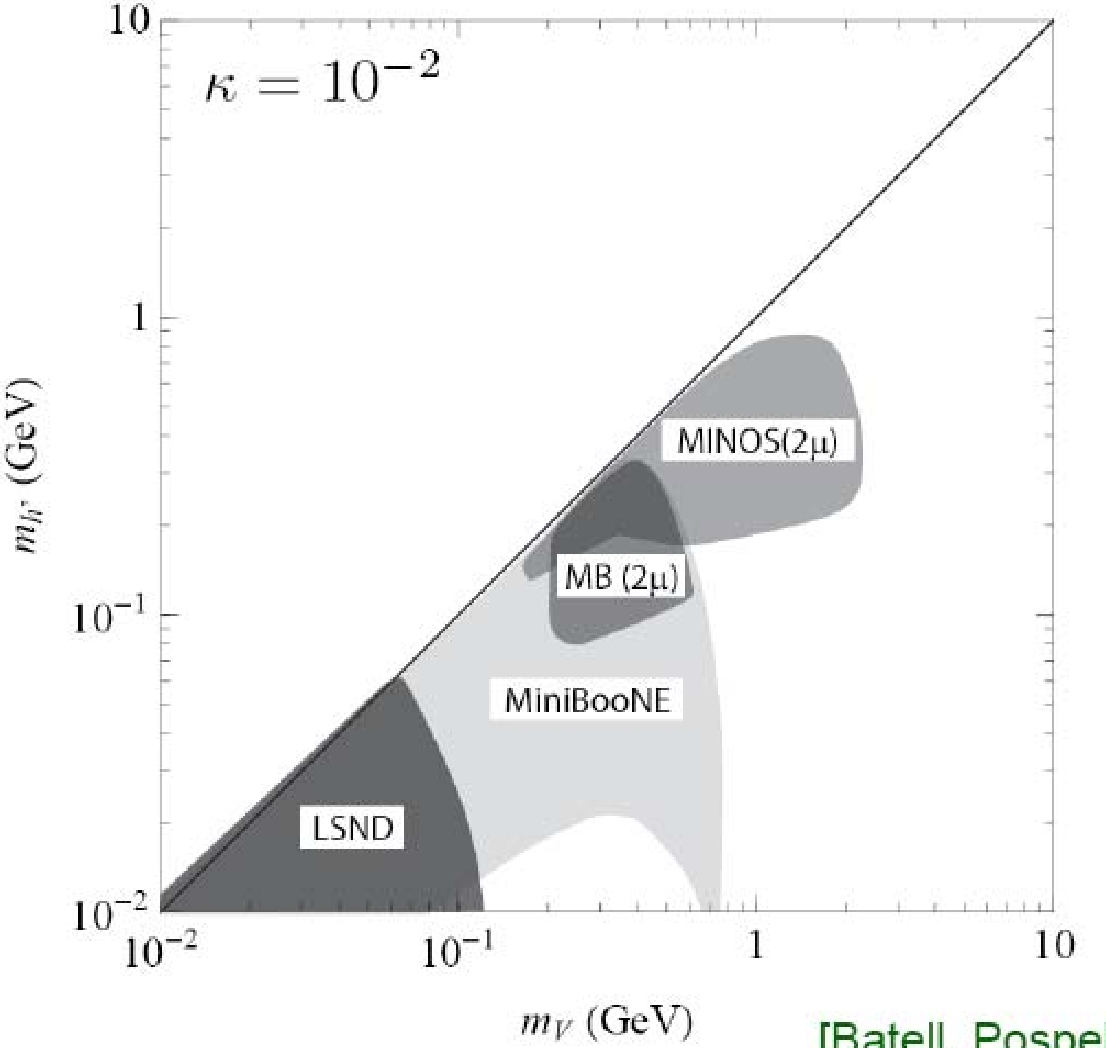
1. $p + p \to X + \pi^0$
2. $\pi^0 \to \gamma V$
3. $V \to 2\chi$
4. $\chi + e \to \chi + e$

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

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. **New proposal (CLEAR) to measure elastic neutrino-N scattering at SNS can be used to kill MeV DM.**

Sensitivity to Higgs'

From LSND, MiniBooNE, NuMI/MINOS, …



[Batell, Pospelov, AR '09]

Mini-conclusion

1. **If the massive photon decays back to the SM (to pairs of leptons, pions etc), electrons on fixed targets is probably the best chance on detecting its prsence (e.g. APEX etc).**

2. **If the massive photon decays to some light sterile under the SM states, its search signal at electron facilities via “bump hunt” is compromised, but there will be a very strong signal at neutrino beam facilities (e.g. example of MeV-scale dark matter).**

Dark forces? Really?
Is it too speculative?

- Let us have an “ignorant history lesson”, and look at the discovery of weak neutral currents around mid-70s.

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(co-)Discovery of Neutral Currents by GARGAMELLE experiments and its scientific objectives

(as viewed by next generation of ignorant theorists like myself)

- Objective 1: nobody remembers/cares what it was
- Objective 2: nobody remembers/cares what it was
- Objective 3: nobody remembers/cares what it was
- Objective 4: nobody remembers/cares what it was
- Objective 5: nobody remembers/cares what it was
- Objective 6: nobody remembers/cares what it was
- Objective 7: **Search for possible existence of neutral currents**
- Objective 8: nobody remembers/cares what it was
- Objective 9: nobody remembers/cares what it was
- Objective 10: nobody remembers/cares what it was
- Objective 11: nobody remembers/cares what it was
- Objective 12: nobody remembers/cares what it was

New Baryonic Currents and "Semi-sterile" neutrinos

- If there is a 4th neutrino, sterile under standard EW interactions, but very interactive via new baryonic currents new phenomenological consequences open up:

1. Signals at direct Dark Matter detectors at low recoil
2. New "neutral-current-like" events at fixed targets/neutrino beams
3. New signatures at neutrino detectors
4. ….

The model

- Consider a new “neutrino-like” particle coupled to baryonic currents:

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \bar{\nu}_b\gamma_\mu(i\partial_\mu + g_l V_\mu)\ \nu_b + \sum_q \bar{q}(i\not{D}_{SM} + \frac{1}{3}g_b\gamma_\mu V_\mu)q + \mathcal{L}_m.$$

At the nucleon level we have a isosinglet vector current:

$$\frac{1}{3}V_\mu g_b \sum_q \bar{q}\gamma_\mu q \ \rightarrow \ g_b V_\mu(\bar{p}\gamma_\mu p + \bar{n}\gamma_\mu n) + \ldots$$

These properties *suppress* standard neutrino signals and *enhance* the elastic recoil. Let us introduce an analogue of Fermi constant:

$$\mathcal{L}_{NCB} = G_B \times \bar{\nu}_b\gamma_\mu\nu_b J_\mu^{(0)}; \quad G_B = \frac{g_l g_b}{m_V^2} \equiv \mathcal{N} \times \frac{10^{-5}}{\mathrm{GeV}^2}.$$

Oscillation of Solar neutrinos into neutrino$_b$

- Suppose the mass matrix is such that some part of the solar neutrinos oscillate into neutrino$_b$.

At the Sun location we have ("+" is an appropriate mu-tau neutrino combination that participates in solar neutrino oscillations)

$$P_e(\mathrm{Sun}) \simeq \frac{1}{3}; \quad P_+(\mathrm{Sun}) \simeq \frac{2}{3}; \quad P_b(\mathrm{Sun}) = 0.$$

- At Earth's location one can easily have a more complicated mix:

$$P_b(\mathrm{Earth}) \simeq \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]$$

$$P_e(\mathrm{Earth}) \simeq \frac{1}{3}\left(1 - \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]\right)$$

$$P_+(\mathrm{Earth}) \simeq \frac{2}{3}\left(1 - \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]\right),$$

Effective interaction and enhancement of elastic channels

How much signal you would have is given by

Probability of oscillation * interaction strength

$$\mathcal{N}_{\text{eff}}^2 = \mathcal{N}^2 \times \frac{1}{2} \times \sin^2(2\theta_b),$$

Despite *N* being very large, say a 100 or a 1000, standard neutrino detectors will have hard time detecting neutrino$_b$ because

$$\frac{\sigma_{\nu_b-\text{Nucl}}(\text{elastic})}{\sigma_{\nu_b-\text{Nucl}}(\text{inelastic})} \sim \frac{A^2}{E_\nu^4 R_N^4} \sim 10^8,$$

Elastic scattering signal

- There can be a considerable recoil signal from neutrino_b due to the coherent enhancement, and interaction strength that I took stronger-than-weak:

$$\frac{dR}{dE_r} \simeq \frac{A^2 m_N}{2\pi} \times \frac{1}{2}\sin^2(2\theta_b) G_B^2 \Phi_{^8\mathrm{B}} \times I(E_r, E_0)$$

$$\simeq 85 \,\frac{\text{recoils}}{\text{day} \times \text{kg} \times \text{KeV}} \times \left(\frac{A}{70}\right)^3 \times \frac{N_{\text{eff}}^2}{10^4} \times I(E_r, E_0).$$

Here I(E_r) is the recoil integral given by

$$I(E_r, E_0) = \int_{E^{\min}(E_r)}^{\infty} dE \,\left(1 - \frac{(E^{\min})^2}{E^2}\right) \times f_{^8\mathrm{B}}(E) \times 2\sin^2\left[\frac{\pi E_0}{E}\right]$$

Recoil in Germanium detectors a-la CoGeNT

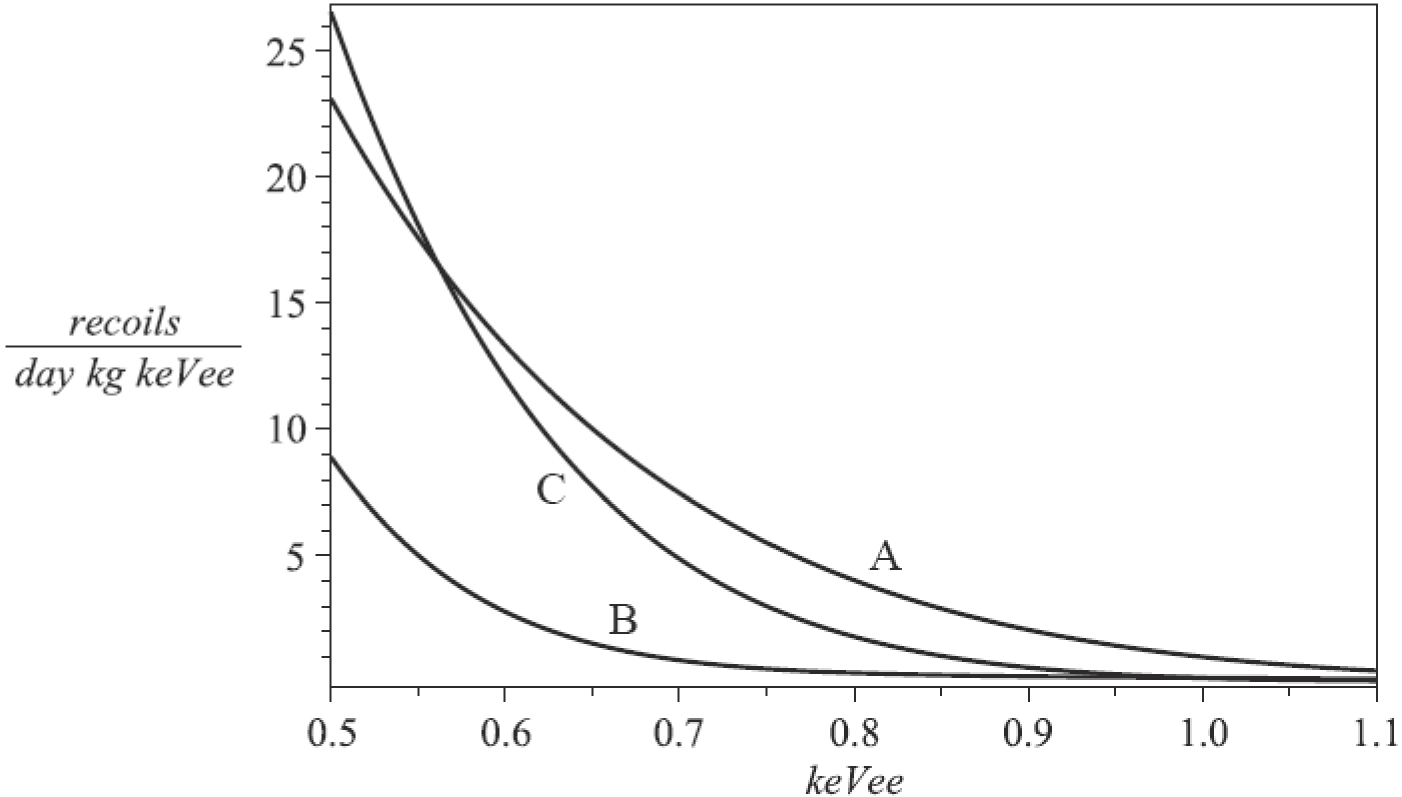


Figure 1: Expected recoil event rate in Germanium in units of recoils/day/kg/keVee as the function of E_r in keVee. The NCB enhancement factor, $\mathcal{N}_{\text{eff}} = 100$. A, B and C lines correspond to $E_0 = \infty$, $E_0 = 12$ MeV and $E_0 = 14$ MeV.

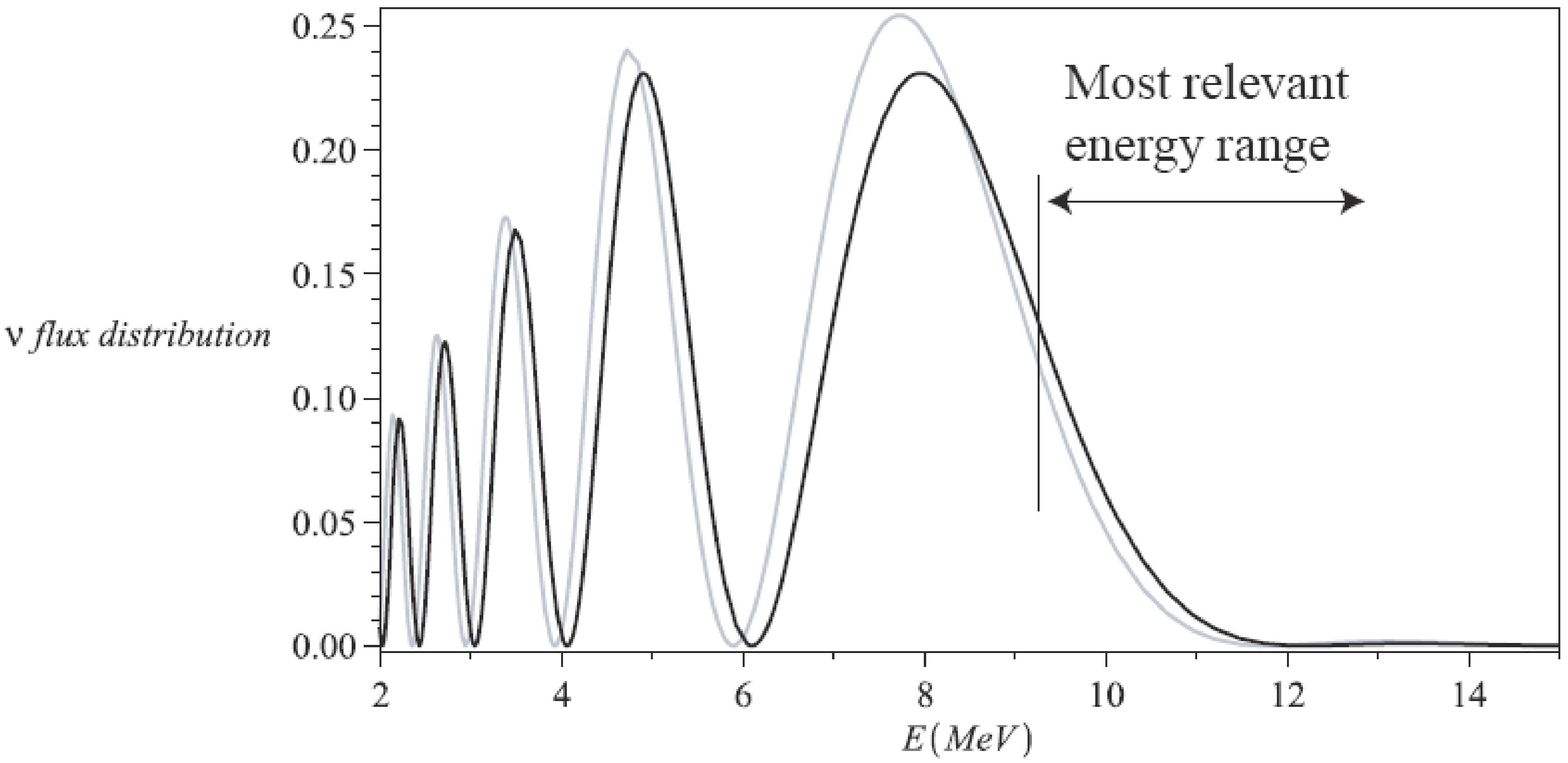
Morphology of the signal

- Very similar to sub-10 GeV scale WIMPs.
- Somewhat softer at the highest recoil, hence "safer" from strong Xe, Ge CDMS etc constraints where threshold is higher
- Has a chance of "explaining CoGeNT and/or CRESST signals". Can be a correct magnitude and not too bad a spectral shape.
- Will show difference with the low-mass WIMPs if a lighter target (e.g. He) is used. Neutrinos will give more recoil on He, while WIMPs will give less.

- What about "DAMA modulation signal"? Last time we checked the Sun was closer to Earth in January – hence anti-modulation compared to DAMA

“Just-so” phase reversal

- If oscillation length is comparable to the Earth-Sun distance, the phase can be reversed, and more neutrinos will arrive in July



Modulation in NaI for different oscillation lengths

(DAMA can be accommodate if one tolerates ~ 1 month phase shift)

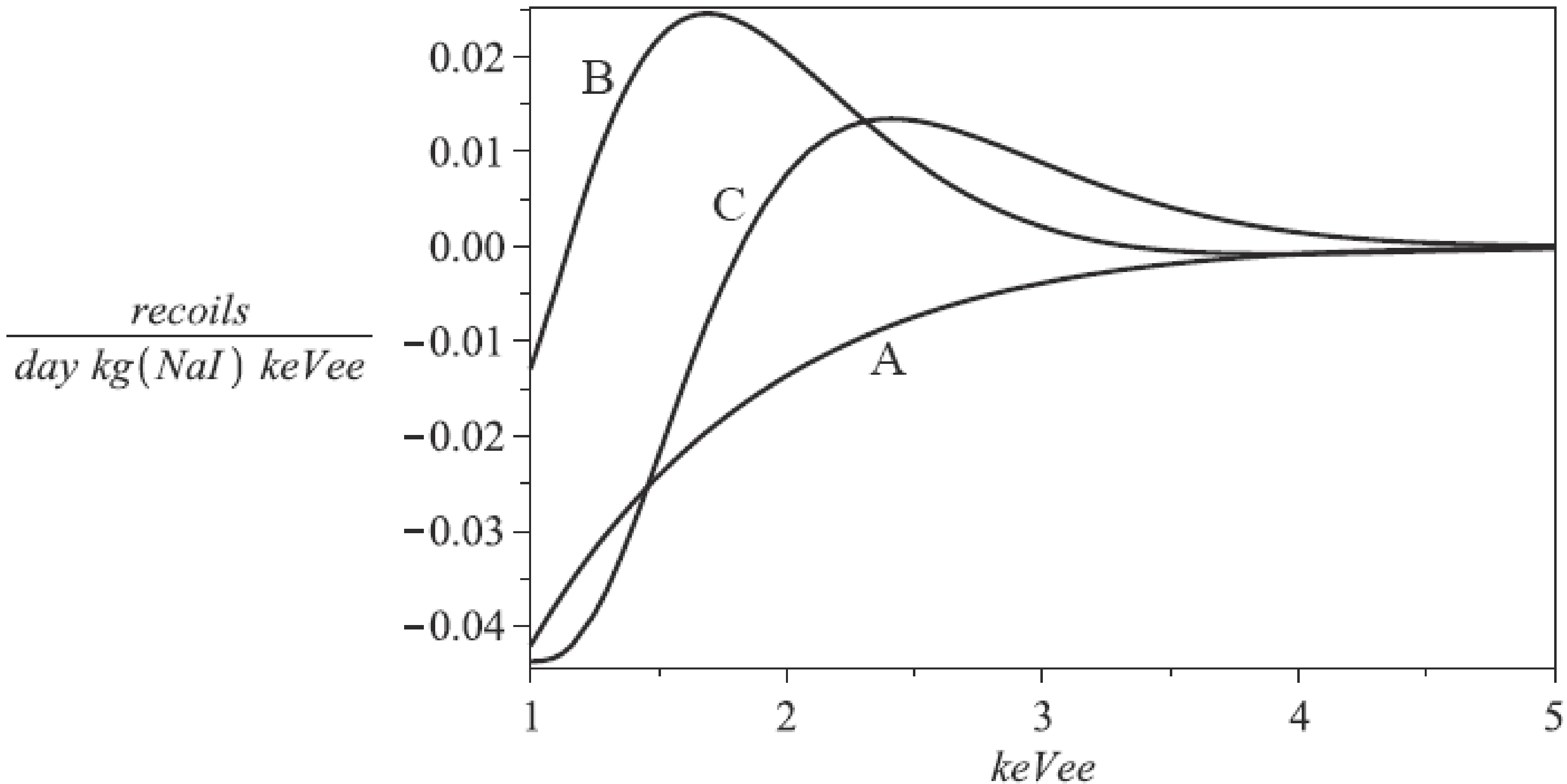


Figure 4: Modulation of the counting rate in recoils/kg(NaI)/keVee for ν_b-scattering on Na. As before, A curve is for large E_0, B is for $E_0 = 12$ MeV and C is for $E_0 = 14$ MeV while $\mathcal{N}_{\rm eff}^2 = 10^4$. Both signs of modulation are possible.

What about "conventional" neutrino signals?

- Consider for example the deuteron breakup reaction, or Carbon excitation with subsequent energy release:

$$\begin{aligned} d + \nu_b &\rightarrow \nu_b + n + p \\ {}^{12}\mathrm{C} + \nu_b &\rightarrow \nu_b + {}^{12}\mathrm{C}^*(4.44\ \mathrm{MeV}) \rightarrow \nu_b + {}^{12}\mathrm{C} + \gamma \end{aligned}$$

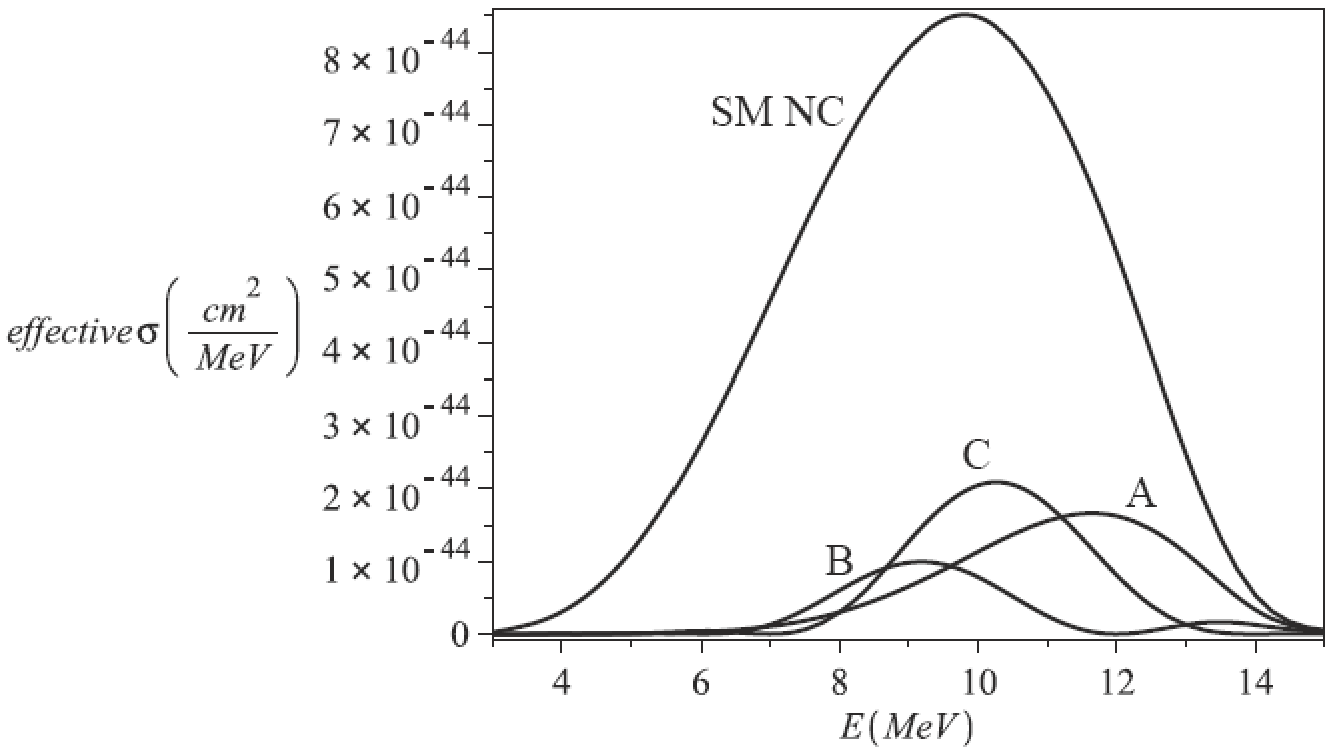
Because of the properties of baryonic currents the hadronic amplitude is quadratic in neutrino energy, and the signal is quartic:

$$\langle d|\exp(i\mathbf{q}\mathbf{r}^{(n)}) + \exp(i\mathbf{q}\mathbf{r}^{(p)})|np\rangle$$

$$= 2\langle d|np\rangle + i\mathbf{q}\cdot\langle d|\mathbf{r}^{(n)} + \mathbf{r}^{(p)}|np\rangle - \frac{q_k q_l}{2}\langle d|r_k^{(n)} r_l^{(n)} + r_k^{(p)} r_l^{(p)}|np\rangle = -\frac{q_k q_l}{4}\langle d|r_k r_l|np\rangle$$

Inelastic processes are suppressed

- Even if coupling^2 is enhanced by 10000, the NCB process is just about 10% of the SM NC process at SNO:



Counting rate at BOREXINO

Counting rate at BOREXINO is not going to be very large either

$$R(4.4\ \mathrm{MeV}) \sim (0.05-0.15)\times\frac{\gamma\ \mathrm{injections}}{100\ \mathrm{tonne}\times\mathrm{day}}\times\frac{\mathcal{N}_{\mathrm{eff}}^2}{10^4}.$$

Small signal but comparable to Boron8 SM neutrino ES.

P.S. to my paper

Is the elastic recoil on hydrogen visible at BOREXINO?

Most of it is buried under the C14 background below 200 keV.

However, it makes sense to analyze BOREXINO signal for annual modulations in the energy range of 200-300 keV.

Possible avenues to search for neutrino_b and new baryonic currents

- *Hadron colliders*: If G_B / G_F is fixed at a 100 or so, Tevatron experiments will produce an *upper* bound on vector mass.
- *Neutrino oscillations*: Matter effects for (anti)neutrino_b can be significant. In light of latest developments in neutrino physics, the 4^{th} one may not be an unwelcome addition.
- *Neutrino beams*: Ample opportunities to produce neutrino_b in hadronic cascades and detect them using the "NC-like" scattering on nucleons.
- *Cosmology*: a departure from N_neutrino = 3 is expected. Better CMB probes are forthcoming.
- *Rare decays*: New precision tests of K-> pi nu nu may detect extra energy sinks.

Conclusions

- Extra U(1)'s below the weak scale is a natural theoretical possibility. WIMP physics combined with the GeV-scale dark force idea provide nice interpretation to the PAMELA positron anomaly.
- Gauge bosons/Higgses of Dark Forces can be searched for at the precision and intensity frontiers. High-luminosity medium-energy colliders or fixed targets + powerful beams probe a wide range of masses and mixing angles.
- There can exist new neutrino states, sterile under SM interactions and very much interactive via new baryonic force, with interaction strength well above G_Fermi. It turns out that these types of neutrinos and new forces are actually best probed with DM detectors. With a force 100-1000 times stronger than weak force, one can generate observable signals at low recoil, not unlike those of DAMA and CoGeNT.