Searching for Light Dark Matter with Proton-Beam Fixed Target Experiments

Patrick deNiverville

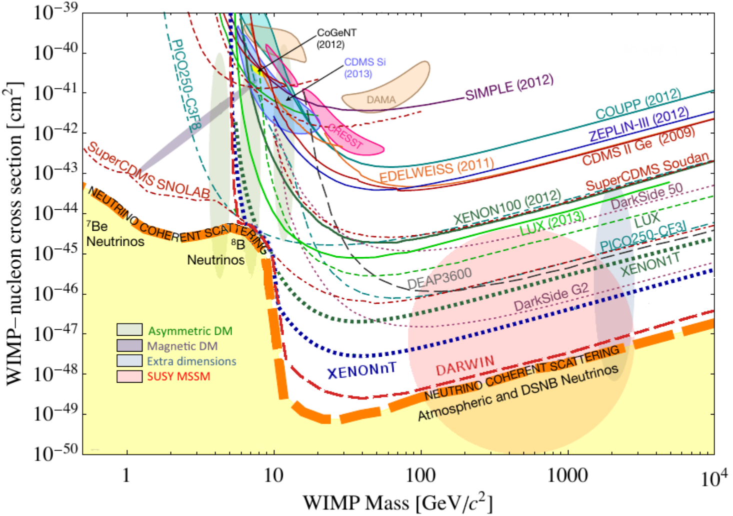
University of Victoria

July 15, 2016

[PdN, M. Pospelov, A. Ritz 2011, arXiv:1107.4580 [hep-ph]]
[PdN, D. McKeen, A. Ritz 2012, arXiv:1205.3499 [hep-ph]]
[B. Batell, PdN, D. McKeen, M. Pospelov, A. Ritz 2014, arXiv:1405.7049 [hep-ph]]
[PdN, M. Pospelov, A. Ritz 2015, arXiv:1505.07805 [hep-ph]]
[C. Chen, PdN, M. Pospelov, A. Ritz, In Preparation]

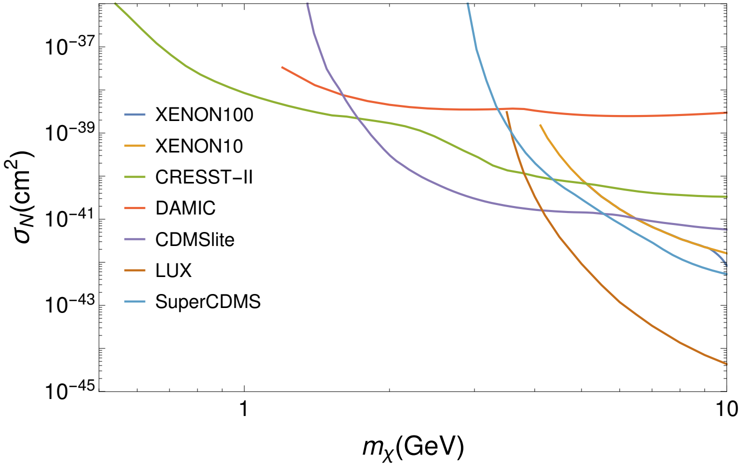
Direct Searches

Experimental limits for WIMP-Nucleon cross section



[L. Baudis 2014, arXiv:1408.4371 [astro-ph.IM]]

Direct Searches



Thermal Relic Dark Matter

One of the simplest WIMP dark matter production mechanisms is that of the thermal relic. Dark matter is a relic left over from early universe, before BBN.

- While $T \gg m_{\rm DM}$, dark matter in thermal equilibrium with early universe.
- As T decreases, production becomes less efficient, and $n_{\rm DM}$ declines.
- Annihilation rate is suppressed, as it is proportional to $n_{\rm DM}^2$. Dark matter is further diluted by the expansion of the universe.
- Annihilation ceases to have a major effect on the number density, and the dark matter freezes out.

Scenario is insensitive to initial conditions of the universe. We can relate the annihilation cross section to the observed dark matter abundance

$$\frac{\Omega_{DM}}{\Omega_{\rm matter}} \sim \frac{1{\rm pbn}}{\langle \sigma v \rangle_{\rm fo}}$$

Lee-Weinberg Bound and Thermal Relics

The Lee-Weinberg bound tells us that for $m_{\rm DM} <$ few GeV that annihilates via SM mediators with weak scale mass, the dark matter annihilation rate is too small and a thermal relic is overproduced in the early universe,

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm matter}} > 1.$$

This bound can be circumvented by introducing new light mediators that allow new dark matter annihilation channels.

Dark matter candidates in these scenarios could potentially be created at low energies. We will be particularly interested in the regime where $m_{\rm DM} < m_{\rm Mediator}$.

Dark Matter Scenario with Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V^2 V_\mu^2 + \epsilon V_\nu \partial_\mu F_{\mu\nu} + |(\partial_\mu - e' V_\mu)\chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'}$$

- Scalar DM candidate χ charged under $U(1)'$. V is the gauge boson of $U(1)'$ symmetry.
- Four model parameters:
  - m_V, m_χ, ϵ and α'
- V can be produced through kinetic mixing with γ at $\mathcal{O}(\epsilon^2)$.
- χ couples to SM through the V.
  - For $2m_\chi < m_V$, $\mathrm{Br}(V \to \chi\bar{\chi}) \sim 1$ and V decay is prompt. For $2m_\chi > m_V$, $\mathrm{Br}(V \to \mathrm{SM}) \sim 1$.
- The $U(1)'$ coupling strength α' must be kept small to maintain perturbativity.
  - We set $\alpha' = 0.1$ or 0.5, but it can be varied quite widely.

Dark Matter Scenario with Baryonic Coupling

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + g_B V_\mu J_B^\mu - \frac{\epsilon}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

$$D_\mu = \partial_\mu - i g_B q_B V_\mu = \partial_\mu - i e' V_\mu$$

- Alternative to the kinetic mixing model, with V coupling directly to the baryon current.
- I will set $\epsilon = 0$ when discussing this model, and focus on the baryonic coupling.
  - Leptophobic scenario.
  - One can include kinetic mixing by allowing $\epsilon \neq 0$, but for most choices of parameters one coupling will dominate over the other.
- Escapes many of the constraints on kinetic mixing models.
- Requires a more complicated dark sector to serve as good thermal relic DM candidate.

Experimental Constraints - Kinetic Mixing

Cosmological:

- Big Bang Nucleosynthesis - So long as $m_{\rm DM} > 1 - 2$ MeV, freeze-out occurs before BBN [Serpico & Raffelt '04, Jedamzik & Pospelov '09] .
- Cosmic Microwave Background - Annihilation through p-wave, has little effect [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08] .

Particle Physics:

- Lepton $g-2$ - Affects the value of $g-2$. Quite strong at low mass, but weakens with increasing mass [Fayet; Pospelov '08] .
  - Can also bring theoretical value of muon $g-2$ into closer agreement with experimental value.
- $V \to l^+ l^-$ - Weak so long as $BR(V \to 2\chi) \sim 1$, holds for most of parameter space of interest. [Bjorken et al. '09; Batell et al '09; Reece & Wang '09; MAMI '11, APEX '11, BaBar'12, ...]
- Missing energy in rare decays.
  - Sensitivity to low m_V provided by π, K decays. [E949]
  - Need to use J/ψ, $\Upsilon(1S)$ decays for higher masses of m_V. [BESII'08, BaBar'09, Fayet'09]

Experimental Constraints - Kinetic Mixing

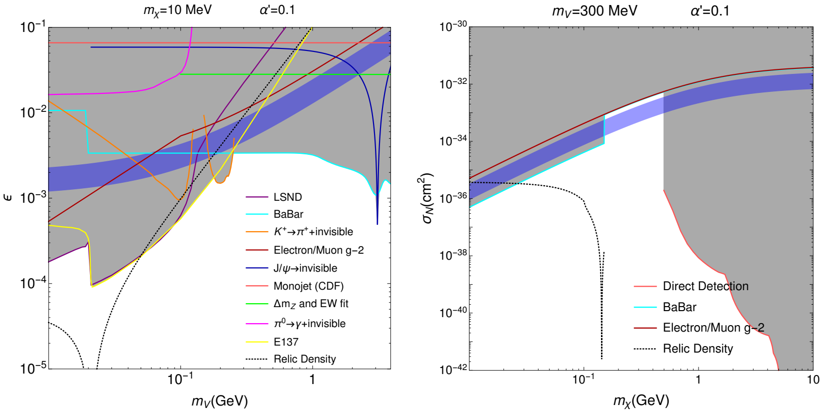
More Particle Physics:

- Monophoton search at BaBar, provides strongest constraint at high masses [Essig '13 arXiv:1309.5084, BaBar '08 arXiv:0808.0017] .
  - This could be improved dramatically by future e^+e^- colliders.
- Electron beam dump experiments, provides some of the strongest limits at low energies.
  - E137 [Batell '14 arXiv:1406.2698] .
- Proton Beam Dumps and Fixed Target Experiments.
  - Neutral current elastic scattering at LSND [PdN '11, LSND Collaboration '01 arXiv:hep-ex/0101039, Y. Kahn 2014, arXiv:1411.1055]

Direct Dark Matter Detection:

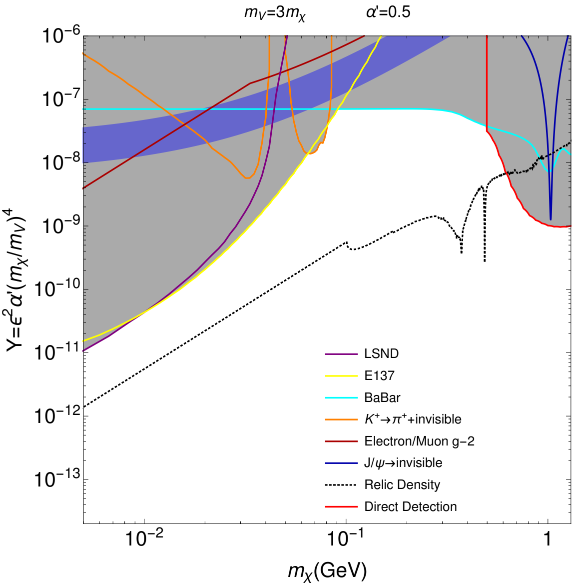
- DAMIC, LUX, CDMS(lite), XENON10, CRESST-II, (XENON100 soon?)...

Kinetic Mixing Parameter Space

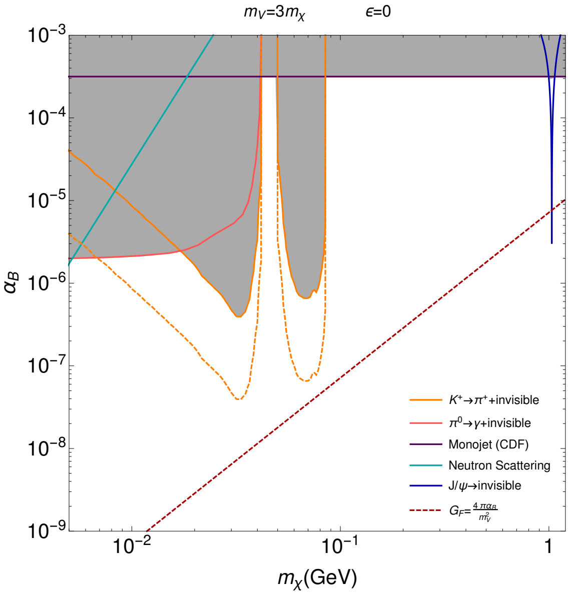


- Dashed Relic Density line indicates parameters which reproduce observed dark matter relic density.
- $\sigma_{N\chi \to N\chi} \propto \epsilon^2 \alpha' \frac{\mu(m_p, m_\chi)^2}{m_V^4}$.

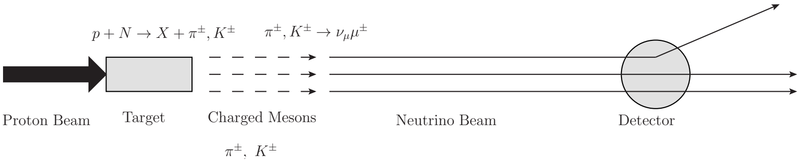
Kinetic Mixing Parameter Space



Leptophobic Parameter Space



Fixed Target Neutrino Experiments

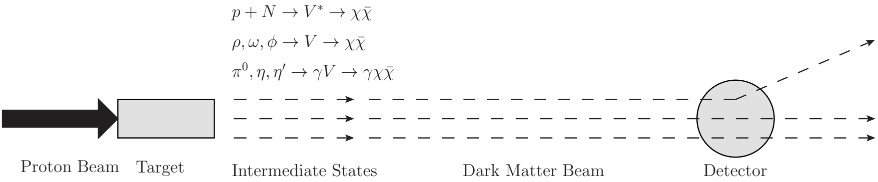


- Experiments involve impacting a target with $\sim 10^{20} - 10^{22}$ protons to produce a high intensity neutrino beam.
  - Neutrinos produced from decays of charged mesons.
  - Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.
- Non-neutrinos are removed from the beam before it reaches the target to reduce background.

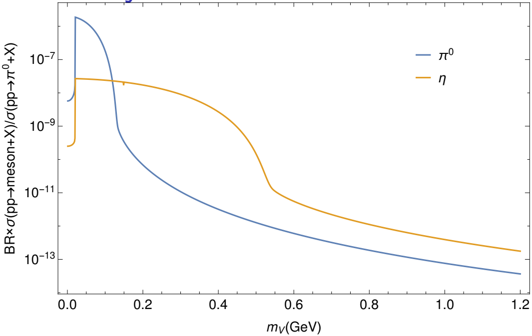
Production of a Dark Matter Beam

Production of a dark matter beam could occur through many channels:

- Radiative decays of pseudoscalar mesons: π^0, η, η'.
- Coupling to vector mesons: ρ, ω, ϕ. [D. Morrissey & A. Spray 2014, arXiv:1402.4817 [hep-ph]]
- Radiative π^- capture: $p + N \to \pi^-, \pi^- + p \to n + V^*$. Very relevant for low energy experiments.
- Direct parton-level production: $p + N \to V^* \to \chi\bar{\chi}$. Most relevant for high energy experiments.
- Bremsstrahlung: $p \to p + V^*$.



Neutral Meson Decay



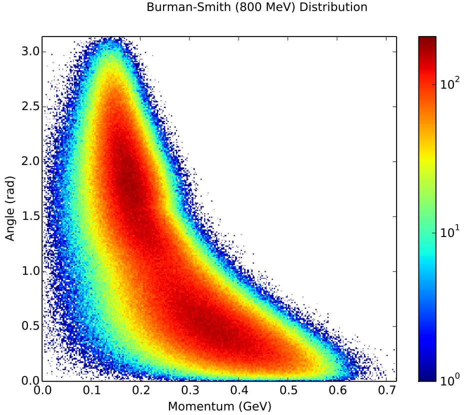
$p + N \to \pi^0, \eta \to V\gamma$

- π^0's are produced alongside $\pi^{\pm}$'s, and in similar quantities.
  - η's are produced at a rate 20-30 times lower than that of π^0's, but with a similar momentum distribution.
- Analysis of this production channel at LSND placed best limits on 1 MeV to $\mathcal{O}$(10 MeV) dark matter for $m_V < m_{\pi^0}$. [Batell '09] .
- Requires a parameterization of the π^0 distribution for each experiment.

π^0 production distributions

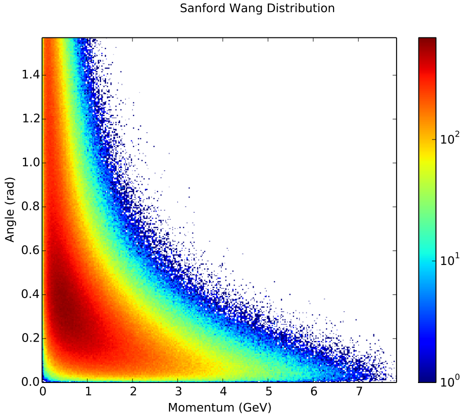
- Fitting to the average of a π^+ and π^- distribution provides a reasonable approximation of the observed production rate and distribution.
- These distributions were fitted with data from a limited set of angles, may not be as reliable at large angles.
- Distributions were calibrated on relatively thin targets, do they still hold for beam dumps?

Burman-Smith Distribution



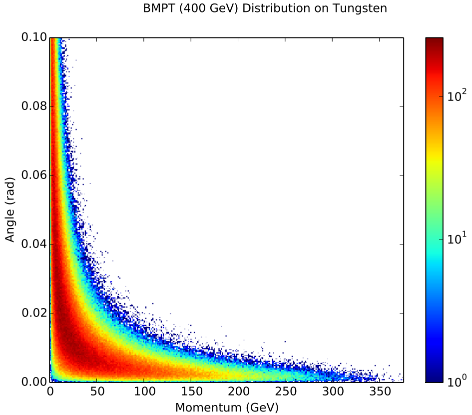
- Burman Smith distribution is suitable for beam energies of $\mathcal{O}(1\,\mathrm{GeV})$ and a variety of materials [Burman '89] .
- Used for LSND and COHERENT.
- While parameterization does extend to angles larger that 90°, it may not be reliable in this regime.

Sanford Wang Distribution



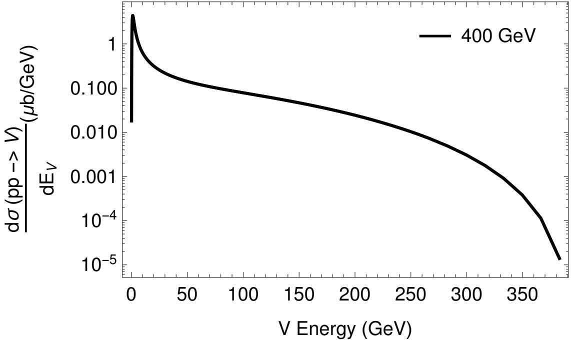
- Fitted for BNB energies and the MiniBooNE target. [Aguilar-Arevalo [MiniBooNE collaboration]] '09]
- Used for MiniBooNE Beam Dump Run and CENNS.
- Fit performed with thin target, limited angular sampling.

BMPT Distribution



- BMPT distribution fitted for higher energy beams, can be scaled to multiple energies and materials [Bonesini et. al. '01] .
- Used for SHiP and T2K.
- Not very different from Sanford-Wang when scaled to 8.9 GeV.

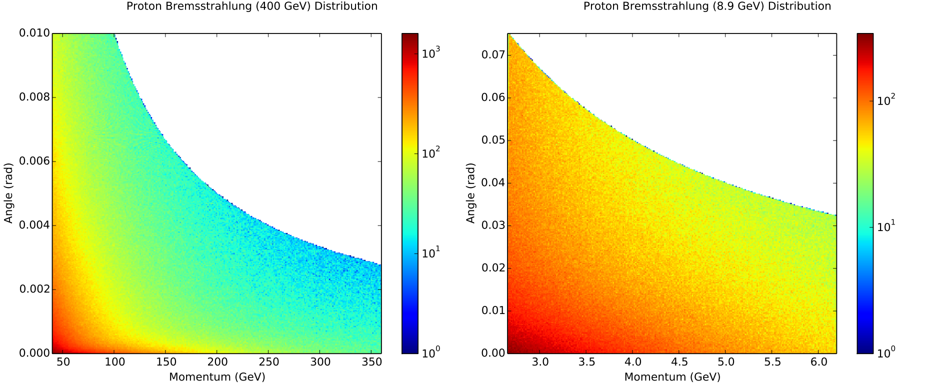
Direct Production



$p + N \to V^* \to \chi\bar{\chi}$

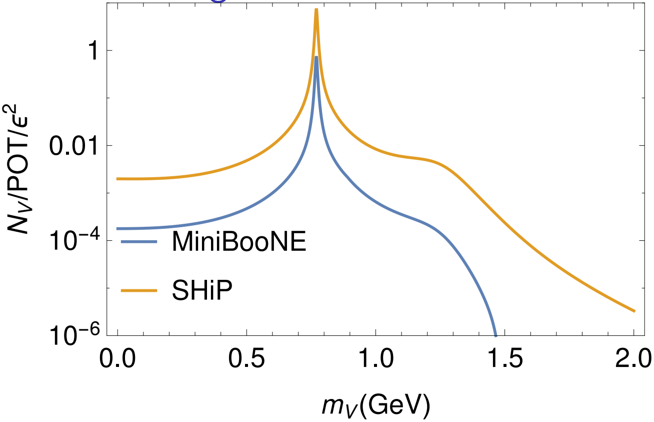
- Production channel for V's with $m_V \geq 1\,\mathrm{GeV}$.
  - Calculation becomes increasingly unreliable at smaller masses.
  - Turned on at m_ρ, where it is subleading.
- V production rate drops off rapidly with increasing V mass.
- Process is helicity suppressed in the forward direction, can obtain a larger event rate from this production channel with a slightly off-axis detector.

Proton Bremsstrahlung



- Following the treatment by [Blümlein and Brunner '13] and [Gorbunov et al '14] .
- Actual V production rate is down from η by a factor of ~ 100, but far more forward focused.
- Calculation performed using analogue of Weizacker-Williams approximation, limits regime of kinematic validity (cuts on transverse momentum and energy of V).

Proton Bremsstrahlung



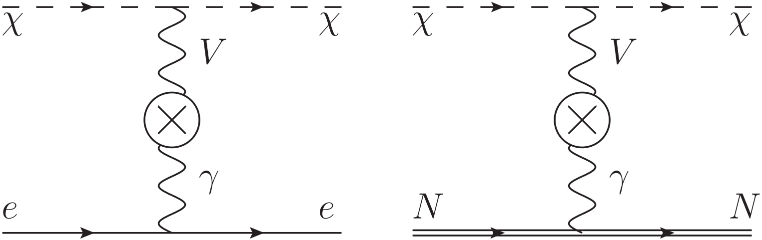
- Difference in production comes from cuts on fraction of beam energy carried by the V (z) and transverse momentum (p_t).
- Using time-like form factor from [Faessler et. al. 2009, arXiv:0910.5589] .
- MiniBooNE: $z \in [0.3, 0.7]$, $p_t < 0.2$ GeV.
- SHiP: $z \in [0.1, 0.9]$, $p_t < 1$ GeV.

π^- Capture

$p + N \rightarrow \pi^-, \pi^- + p \rightarrow n + V$

- Majority of π^- which are stopped in the target are absorbed by protons.
- Approximately 50% of these absorption events results in isotropic photon emission.
  - Photon has energy of $\sim 129\ \mathrm{MeV}$. [R. MacDonald '76]
  - Other 50% of events result in π^0 emission, should be accounted for by previously mentioned distributions.
- Distribution of dark matter is isotropic, which is a large advantage for very off-axis experiments
- Dark matter production in this channel is suppressed by smaller number of π^-'s produced at lower energies.
- This channel was only considered for COHERENT and CENNS.

Detecting Low Mass Dark Matter - Elastic Scattering



- We can search for hidden sector dark matter through its interactions with nucleons or electrons.
- Dark matter scattering signature resembles NCE (neutral current elastic) ν Nucleon scattering.
- A simple counting experiment is possible, but may fail to generate a significant signal above the neutrino signal and other backgrounds without very large POT.
  - Dark matter production is prompt, so it can benefit from any timing structure in the beam.
  - Dark matter propagation may be delayed relative to that of neutrinos, and could appear as out-of-time events.
- $\sigma_{\chi N,e \to \chi N,e} \propto \epsilon^2 \alpha' \alpha$

Detecting Low Mass Dark Matter - Elastic Scattering

Electron Scattering

- Electron scattering can be very peaked in the forward direction, angle cuts can dramatically reduce background.

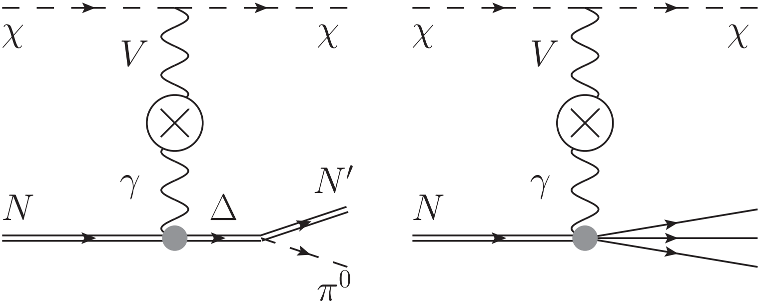
Baryonic Vector

- We only consider scattering off Nuclei.
- $\sigma_{\chi N \to \chi N} \propto \alpha_B^2$.

Coherent scattering

- We consider both the Baryonic V and Kinetic mixing scenarios.
- For Kinetic mixing: $\sigma_{\chi Z \to \chi Z} \propto Z^2 F_{\mathrm{Helm}}(q^2)$.
- For the Baryonic V: $\sigma_{\chi A \to \chi A} \propto A^2 F_{\mathrm{Helm}}(q^2)$.
- In both cases, we switch to incoherent scattering for $q^2 > (50\ \mathrm{MeV})^2$.

Detecting Low Mass Dark Matter - Inelastic Scattering



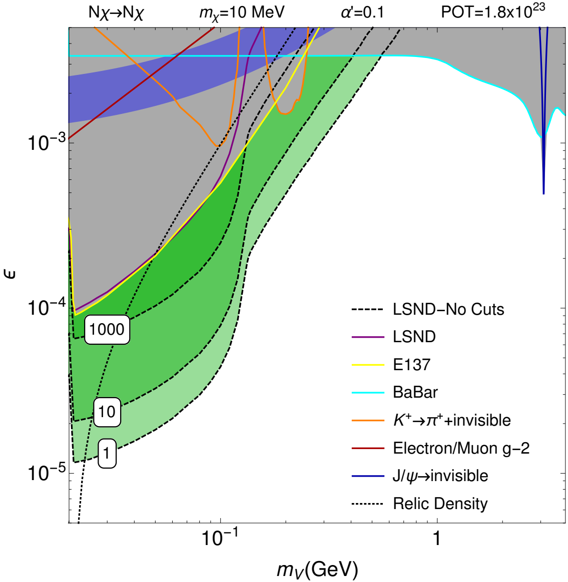
DM induced inelastic π^0 production

- Smaller cross section than NCE Nucleon-DM scattering, but expect lower backgrounds.
- Energy distribution very similar to neutrino induced production. Angular distribution may differ?

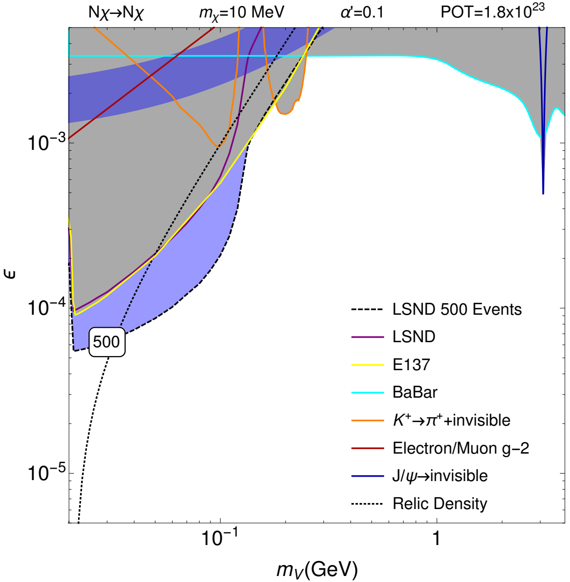
Deep Inelastic Scattering

- Fairly basic treatment, no modeling of end state.

Interpreting the Plots



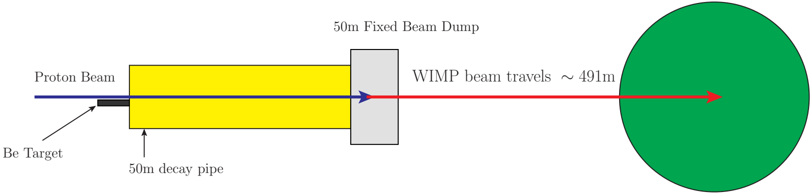
Interpreting the Plots



MiniBooNE Neutrino Run

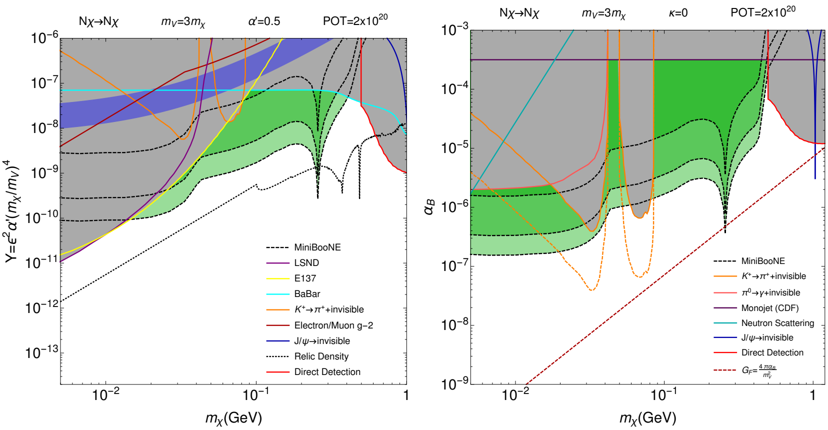
- Collected $\sim 10^{21}$ POT with 8.9 GeV energy.
- 650 ton mineral oil Detector located 541 meters from a beryllium production target.
- Charged pions decay into neutrinos in a 50 meter decay volume following the target.
- Magnetic focusing horns select for neutrino or antineutrinos.
- Likely to be large neutrino backgrounds $\mathcal{O}(1000)$ without harsh cuts to discriminate between dark matter and neutrino scattering events.

MiniBooNE Beam Dump Run



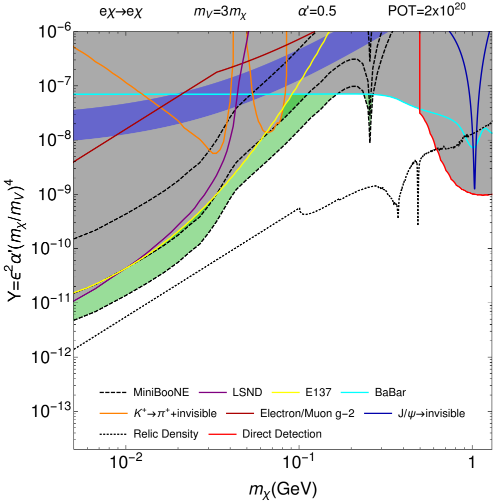
- Rather than using the target, direct beam into 50m steel beam absorber.
  - Reduce background by reducing total number of neutrinos produced.
  - Neutrino background should drop by factor of 50.
- Collected 2×10^{20} POT with 8.9 GeV energy.
- Full analysis of nucleon and electron dark matter scattering signal underway.

MiniBooNE



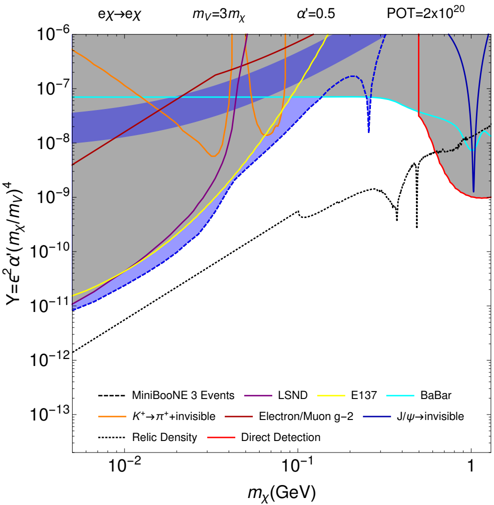
- Nucleon Recoil Kinetic Energy $\in [0.35, 1]\,\mathrm{GeV}$.

MiniBooNE



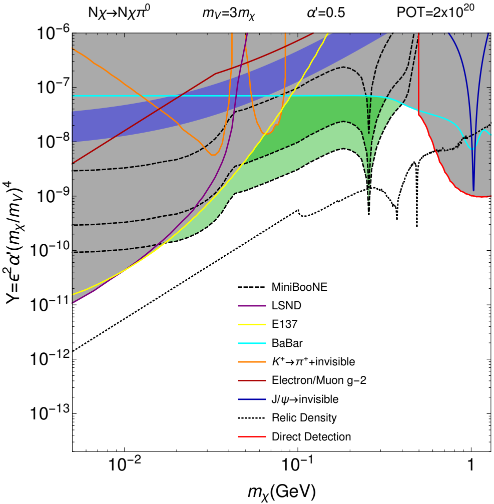
- Cut on $\cos(\theta) > 0.99$, expect almost no background.

MiniBooNE



- Cut on $\cos(\theta) > 0.99$, expect almost no background.
- Place exclusion on 3 events.

MiniBooNE

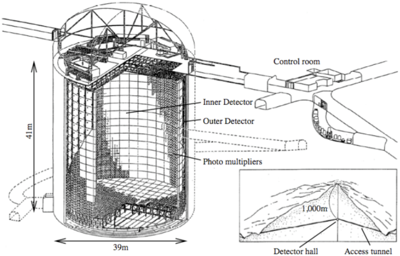


- No energy cuts, π^0 energy distribution of dark matter very similar to that of neutrinos.
- Angular distribution shows some differences, may be worthwhile cutting on angle.

T2K

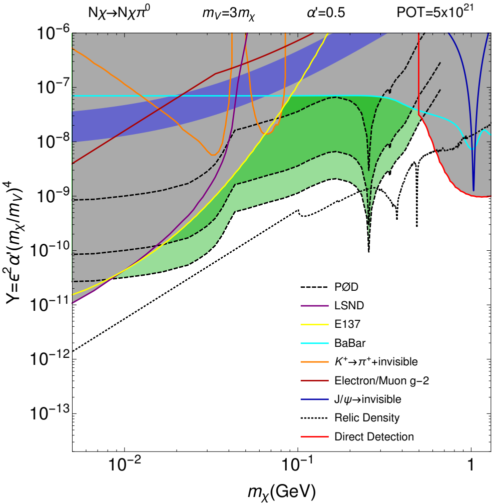
- Two detectors, ND280 and Super-K 2.5°off axis.
- 5×10^{21} POT at 30 GeV
- ND280 is a multicomponent detector 280 meters from the target.
  - We are most interested in $\chi N \to \chi N \pi^0$ in the PØD.
  - Assumed fiducial mass of 6.1 tonnes.
- Super-K is a 50 kilotonne cylindrical water Cerenkov detector 295 km from the target.
  - Low geometrical acceptance is somewhat mitigated by low backgrounds.

Super-K



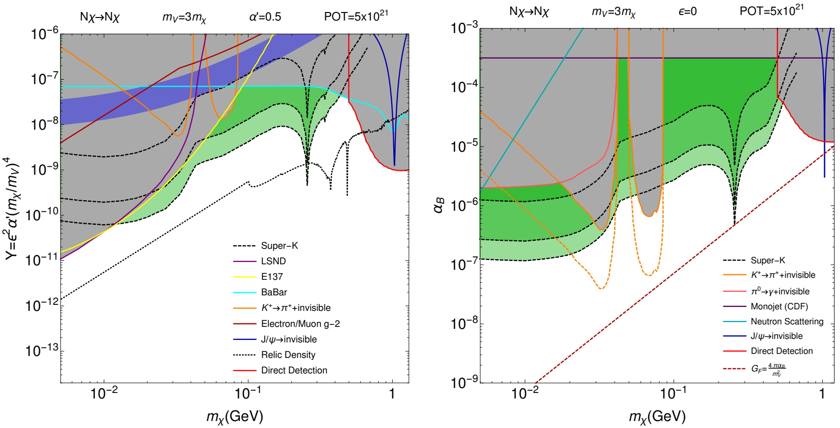
[T2K Collaboration 2011 arXiv:1106.1238]

T2K - PØD



Backgrounds could be large.

T2K - Super-K



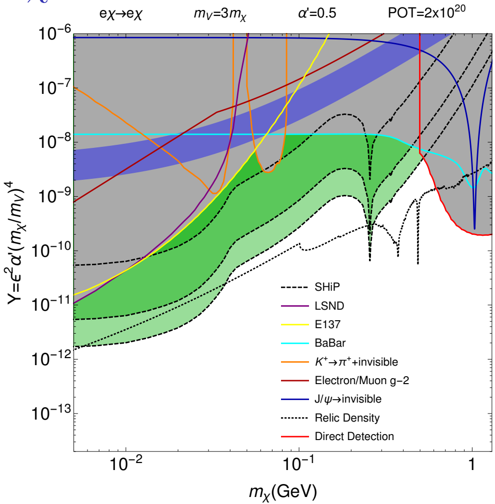
- Cut on time delay relative to neutrino arrival of 50 ns removes beam related backgrounds.
- $Q^2 > 0.05\,\mathrm{GeV}^2$.
- Thanks to Akira Konaka for these cuts.

SHiP

Search for Hidden Particles

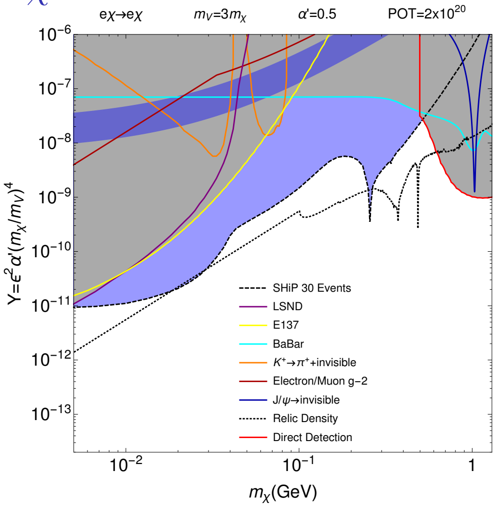
- Proposed beam dump experiment with sensitivity to a wide variety of hidden sector scenarios.
- 400 GeV proton beam from the SPS.
- Projections made for 2×10^{20} POT with 2.5 ton neutrino detector located 100 m from the target.
- Neutral Current DM-electron scattering is highly peaked in the forward direction. Cutting on very forward scattering can remove most other projected backgrounds.
- Thanks to Walter Bonivento for background estimates.

SHiP - $e\chi \to e\chi$



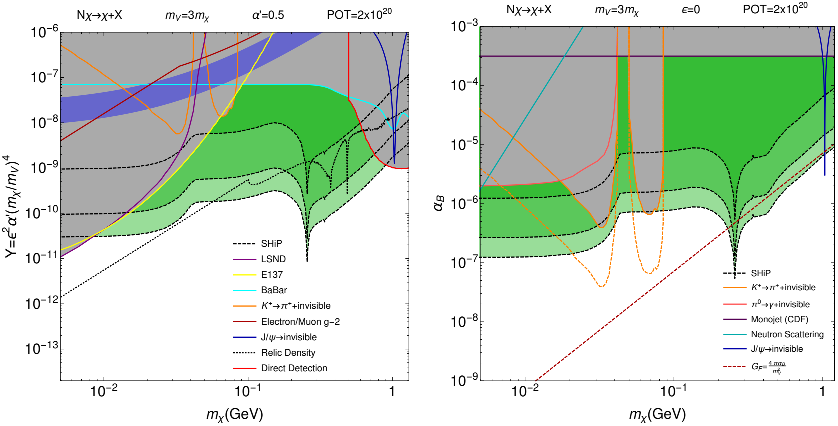
- Electron Energy $\in [2, 20]$ GeV.
- Electron Scattering Angle $\in [10, 20]$ mrad.
- ~ 300 background events expected in this energy and angle window.

SHiP - $e\chi \to e\chi$



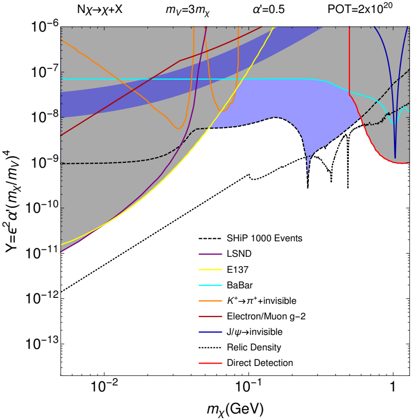
- Electron Energy $\in [2, 20]$ GeV.
- Electron Scattering Angle $\in [10, 20]$ mrad.
- ~ 300 background events expected in this energy and angle window.
- Could make exclusion with $2 \times \sqrt{300} \approx 30$ events

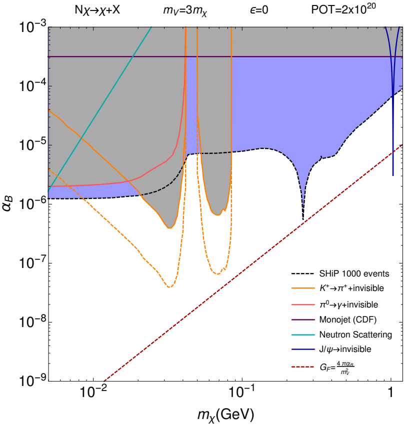
SHiP - Deep Inelastic Scattering



- Very large neutrino backgrounds expected, few $\times\ 10^5$.

SHiP - Deep Inelastic Scattering





- Very large neutrino backgrounds expected, few $\times\ 10^5$.
- Exclusion contour at $\approx 10^3$ events.
- Could be dramatically improved by differentiation between neutrino and DM induced DIS scattering.

Fixed Target Neutrino Experiments - CEνNS

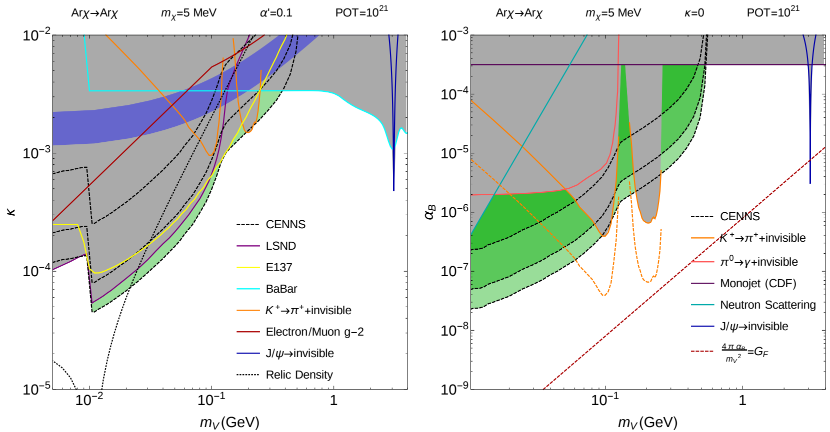
Proposed experiments that impact a low energy proton beam to study Coherent Elastic Neutrino Nucleus Scattering (CEνNS) by studying neutrinos produced from at-rest decays of charged pions. We are interested in the applications of two proposed CEνNS experiments: COHERENT (SNS):

- Phase III experiment calls for a ton-scale detector.
- We consider 1 ton of CsI[Na] located 30 meters from the target, 90° relative to the beamline.
- $\sim 10^{23}$ POT (protons on target) per year with 1 GeV kinetic energy.

CENNS (BNB):

- Ton-scale liquid argon detector.
- We consider 1-ton of LAr located 20 meters from the target, 90° relative to the beamline.
- Projections made for $\sim 10^{21}$ 8.9 GeV POT (approximately five years of running with BNB).

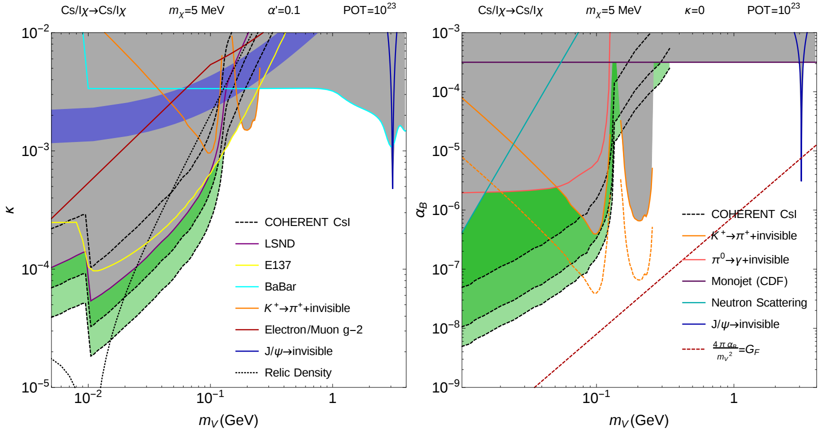
CENNS



$E_{\text{recoil}} > 50\text{keV}$ to remove prompt neutrinos.

Incoherent scattering makes a sizeable contribution for $m_V > m_\pi^0$

COHERENT

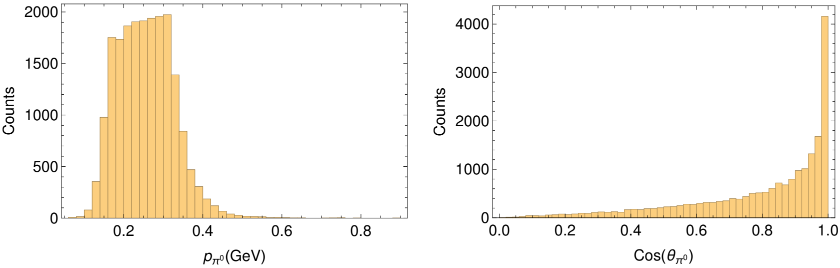


$E_{\text{recoil}} > 16\text{keV}$ to remove prompt neutrinos.

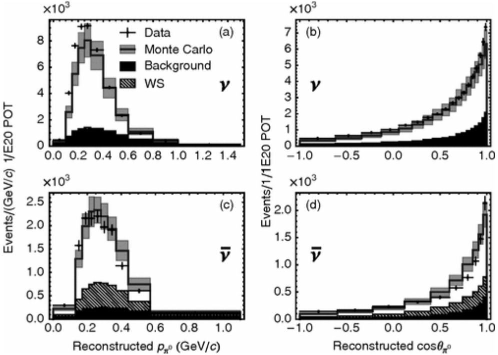
Summary

- Thermal relic particles with a sub-GeV mass and interactions mediated by a light $U(1)'$ vector boson provides a viable dark matter candidate.
- This candidate escapes many of the best limits imposed by standard direct, indirect and collider searches.
- Proposed CEνNS experiments like COHERENT and CENNS, and beam dump experiments like SHiP and MiniBooNE during its off-target run possess novel sensitivity to light dark matter scenarios, and can search the parameter space during regular operations.
- While new limits are being placed on the kinetic mixing parameter space, a great deal of viable parameter space remains unconstrained.
- Simple variations on the benchmark scenario, such as a baryonically coupled V mediator, possess very different sets of constraints, and can also be targeted by hadron experiments.

BACKUP

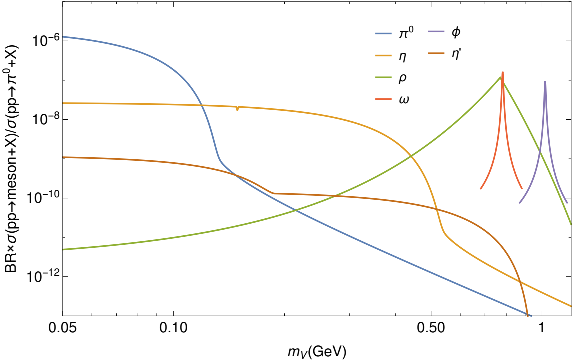


Counts
p_{π^0}(GeV)
Counts
Cos(θ_{π^0})



Data
Monte Carlo
Background
WS
(a)
(b)
(c)
(d)
Events/(GeV/c) 1/E20 POT
Events/1/1E20 POT
Reconstructed p_{π^0} (GeV/c)
Reconstructed $\cos\theta_{\pi^0}$

Vector Meson Mixing

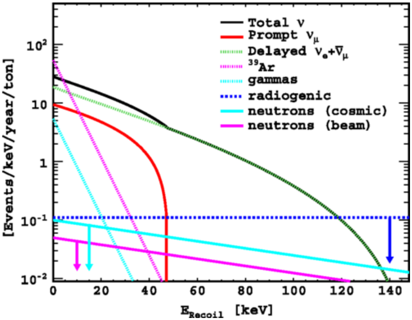


$p + N \to \rho, \omega, \phi \to V$

- Mixing between the V and vector mesons.
- No ρ, ω, ϕ production distributions available.
  - Use π^0 distribution for lack of a better alternative.
- ρ does not mix with the Baryonic V.
- $\eta' \to V + X$ was also considered, but is subleading in every part of the parameter space.

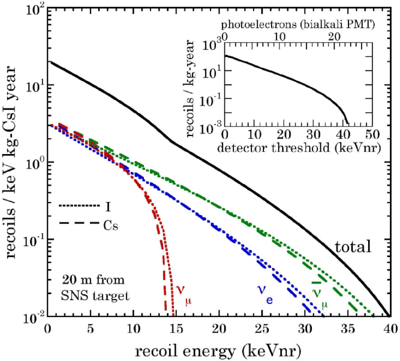
Nucleon Recoils from CEνNS events

c



CENNS

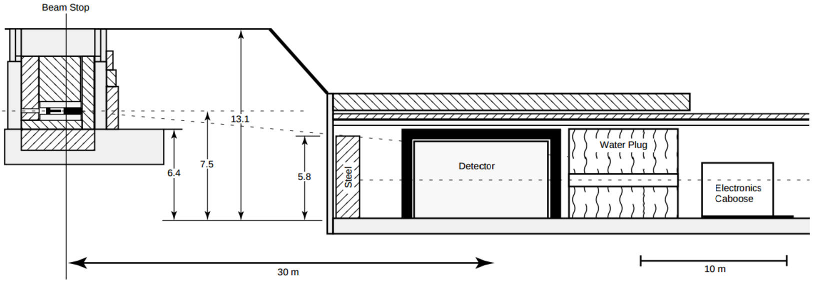
[Brice, S. J. et. al. 2014, arXiv:1311.5958]



COHERENT

[Collar et. al. 2014, arXiv:1407.7524]

Fixed Target Neutrino Experiments - LSND



[Athanassopoulos, C. arXiv:nucl-ex/9605002]

- 10^{23} POT with 800 MeV beam, operating from 1993 to 1998.
- Signal from $\pi^0 \to V^{(*)}\gamma \to \gamma\chi\bar{\chi}$.
- Burman-Smith π^+ distribution used to estimate π^0 distribution [LA-11502-MS http://www.osti.gov/scitech/servlets/purl/6167579]
- Limit with a counting experiment: Observed 55 non-standard scattering events [[LSND Collaboration] 2001, arXiv:hep-ex/0101039] . We cut on 110, to account for uncertainties in π^0 production.
- Off-shell calculation performed by [Y. Kahn, G. Krnjaic, J. Thaler, and M. Toups 2014, arXiv:1411.1055 [hep-ph]]