New Physics with neutrino near detectors

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Perimeter Institute, Waterloo/University of Victoria, Victoria/CERH TH

Neutrino platform meeting

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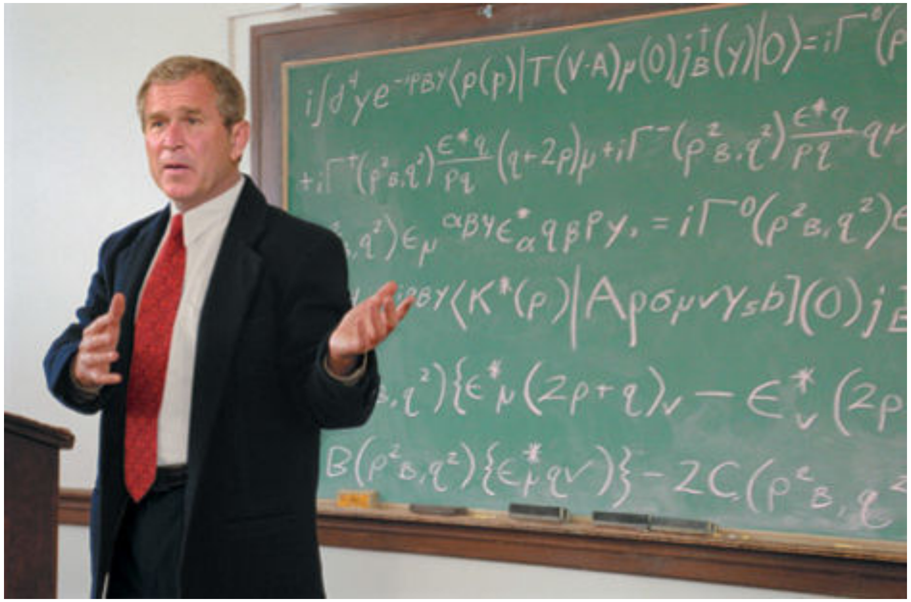
New Physics with DUNE near detector



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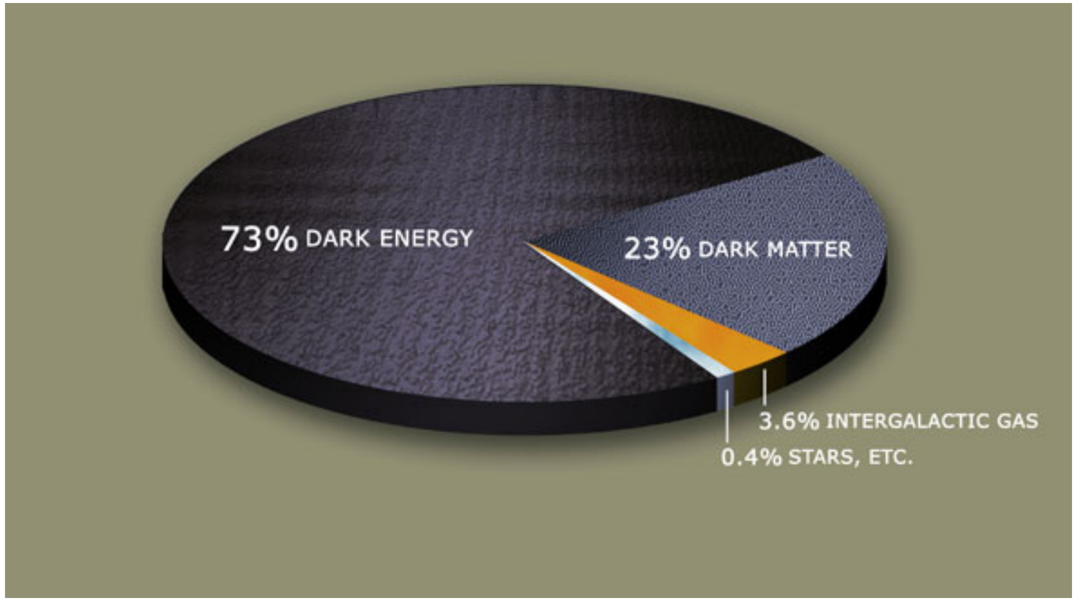
Big Questions in Physics

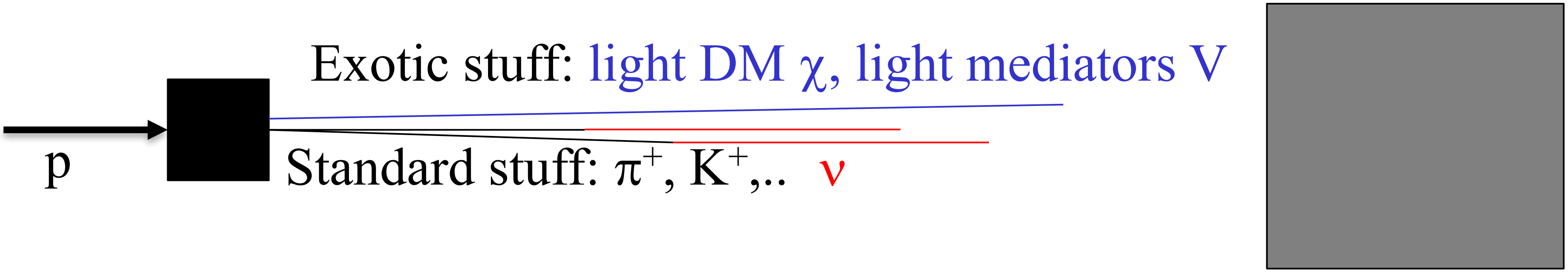


“Missing mass” – what is it?

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

Challenges ?? Too many options for DM. In “direct detection” or collider experiments there is an extrapolations from ~ kpc scale (~ 10^{21} cm) down to 10^2 cm scale.

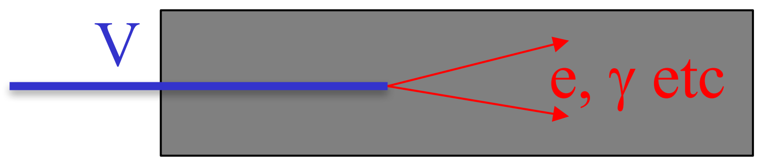
Types of New Physics to be explored



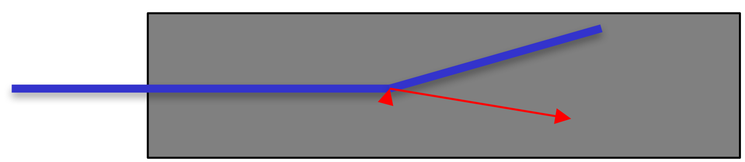
Neutrino detector

Options:

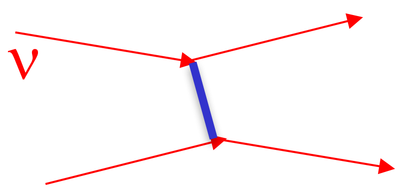
1. Exotic stuff is "metastable", decays to SM inside the detector



2. Exotic stuff is "stable", but can scatter on SM particles



3. Exotic particles can modify neutrino scattering itself.



Types of new physics

4. There is of course also a possibility of active-sterile oscillation

5. Combination of all of the above: e.g. Sterile neutrinos can have ”secret interactions”, and also scatter off SM particles.

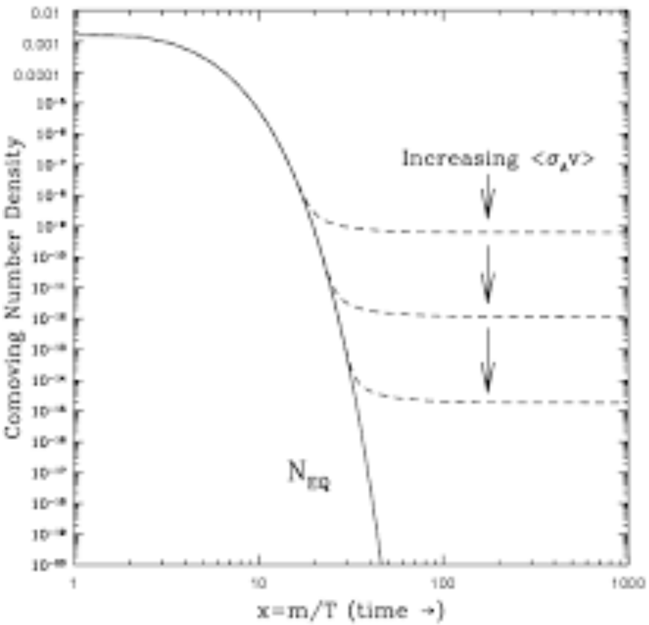
New neutrino efforts (DUNE, SNB experiments at Fermilab, neutrino detector at SHiP, etc) offer possibilities for new physics searches. *My talk is aimed at raising awareness of these possibilities*

Outline of the talk

1. *Introduction.*
2. Light dark matter and light mediators.
3. Dark sector searches at short baseline neutrino experiments.
4. Probing new forces in neutrino scattering.
5. Search for HNLs in non-minimal setups (examples with B-L, and dipole portal)
6. Conclusions.

Weakly interacting massive particles

Imagine a stable particle "X" with small-ish annihilation cross section, X + X → SM states.

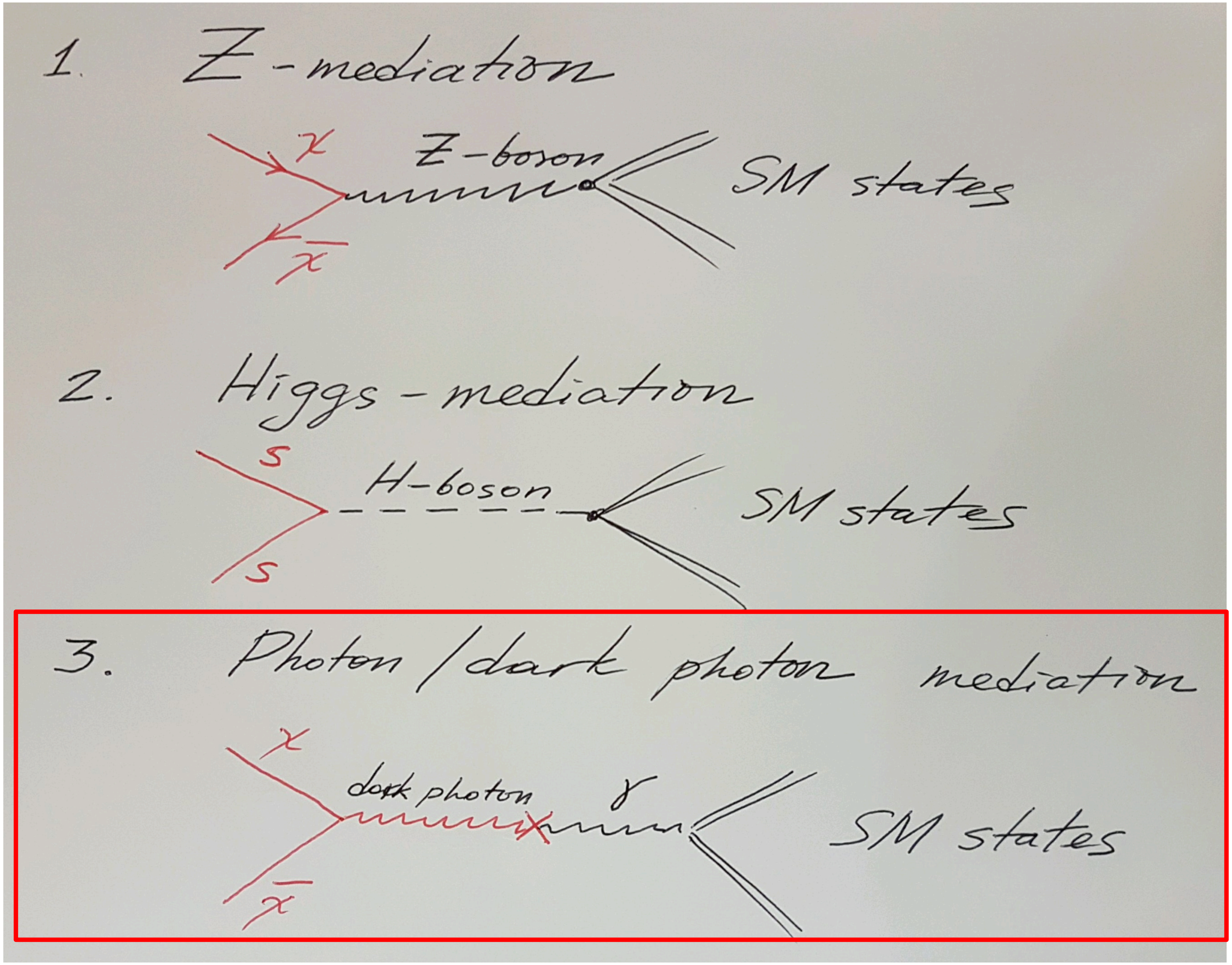


Honest solution of Boltzmann equation gives a remarkably simple result. $\Omega_X = \Omega_{DM}$, observed if the annihilation rate is

10^{-36} cm^2 = α^2/Λ^2 → Λ = 140 GeV. **Λ ~ weak scale (!)** First implementations by (Lee, Weinberg; Dolgov, Zeldovich,….)

$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

Examples of DM-SM mediation

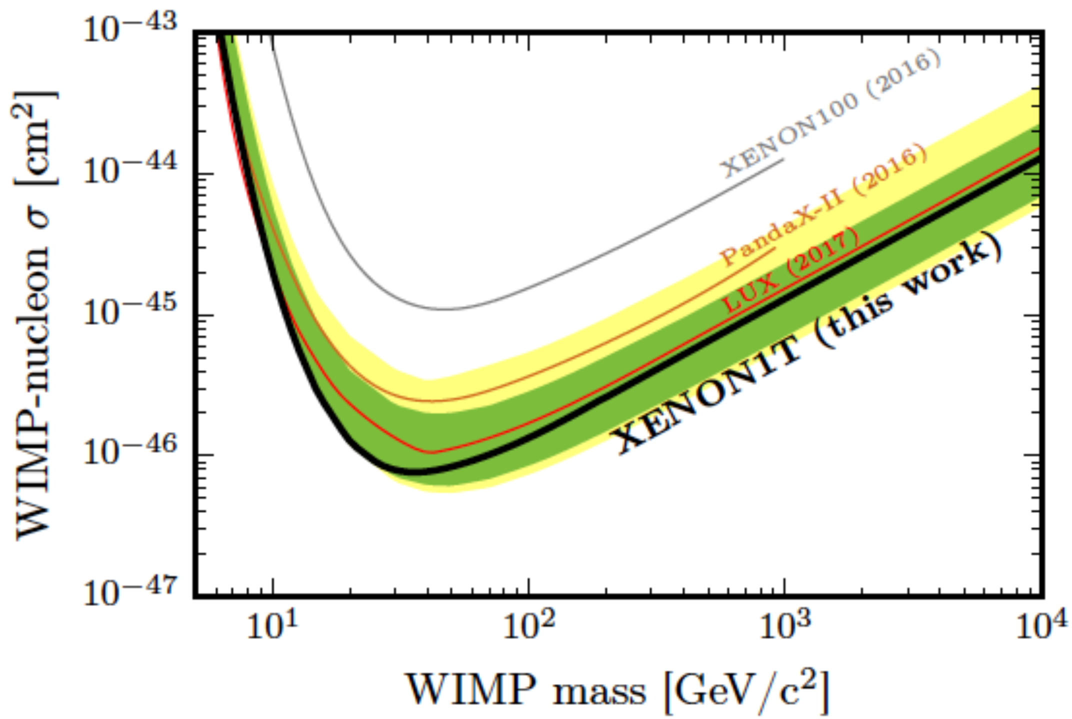


Very economical extensions of the SM.

DM particles themselves + may be extra mediator force. Can be very predictive.

Search for WIMP-nucleus scattering
(latest LUX, XENON 1T and PANDA-X results)

What about MeV mass range ?



- Optimum sensitivity, $m_{WIMP} \sim m_{Nucleus}$ (a little lighter because of nuclear form factor).
- No sensitivity below $m_{WIMP} \sim$ few GeV, due to exceedingly small recoil that does not give much light or scintillation. *But do we really need to look below $M_{WIMP} <$ GeV, given Lee-Weinberg window?*

Light WIMPs are facilitated by light mediators

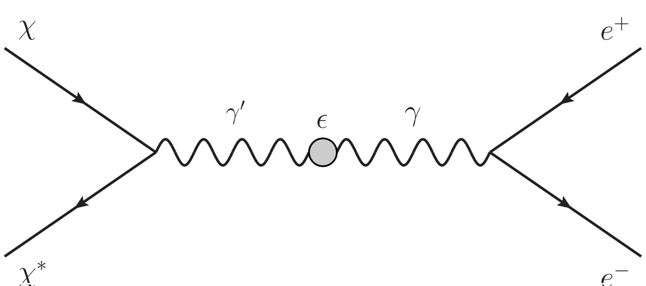
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\rm annih}(v/c) \sim 1 \text{ pbn} \implies \Omega_{\rm DM} \simeq 0.25,$

Electroweak mediators lead to the so-called Lee-Weinberg window,

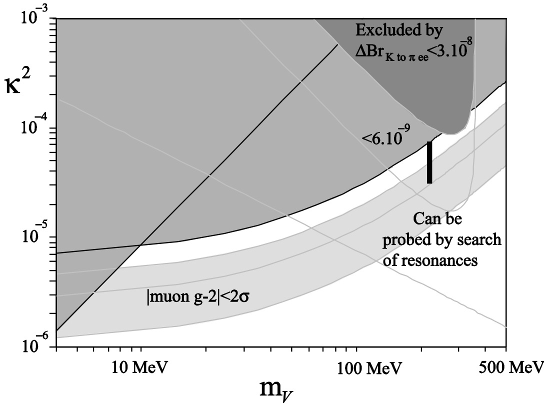
$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for } m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for } m_\chi \gg m_W. \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

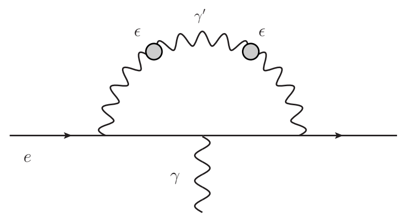
If instead the annihilation occurs via a force carrier with light mass, DM can be as light as ~ MeV (and not ruled out by the CMB if it is a scalar).



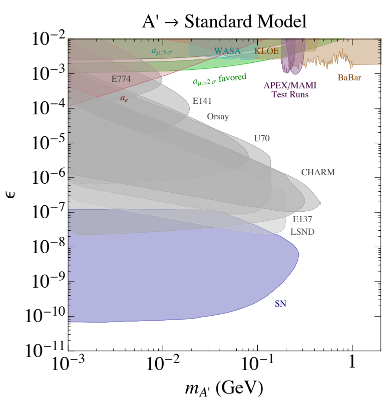
$$\sigma_{\rm annih}(v/c) \simeq \frac{8\pi\alpha\alpha_D\epsilon^2(m_\chi^2+2m_e^2)v^2}{3(m_{A'}^2-4m_\chi^2)^2}\sqrt{1-m_e^2/m_\chi^2}.$$

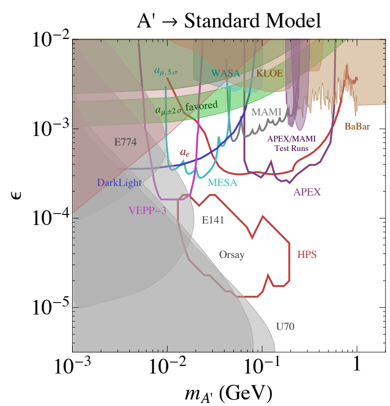
Search for dark photons



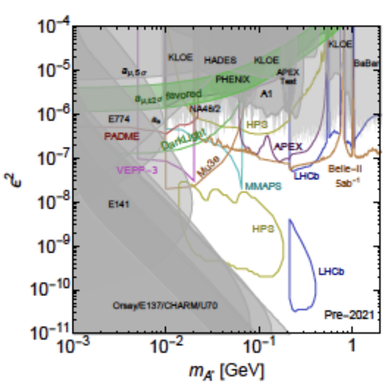


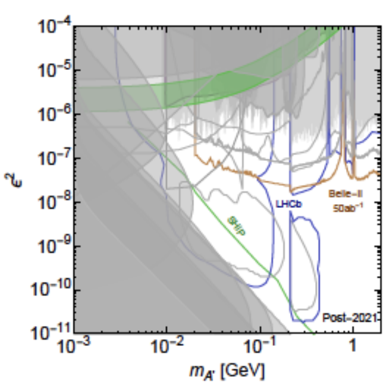
Dark photon with kinetic mixing ~ 10^{-3} is the simplest model that can account for anomalous $\Delta a_\mu \sim 3\ 10^{-9}$, MP, 2008





Search for dark photons (A' → e^+e^-) has become an important part of the intensity frontier program, Snowmass exercise, Minneapolis, 2013





By 2018, there is a large community in place ("Cosmic Vision" summary, 100s of authors, 2017), where the search for dark photon is one of the priorities.

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)

$LH\,N$ 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

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

……….

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

“Simplified models” for light DM

some examples

- Scalar dark matter talking to the SM via a dark photon (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

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

- Fermionic dark matter talking to the SM via a “dark scalar” that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

After EW symmetry breaking S mixes with physical h, and can be light and weakly coupled provided that coupling A is small. Let’s call it dark Higgs. (Possibilities for SHiP and LArND (?))

How to look for light WIMP DM ?

1. Detect missing energy associated with DM produced in collisions of ordinary particles

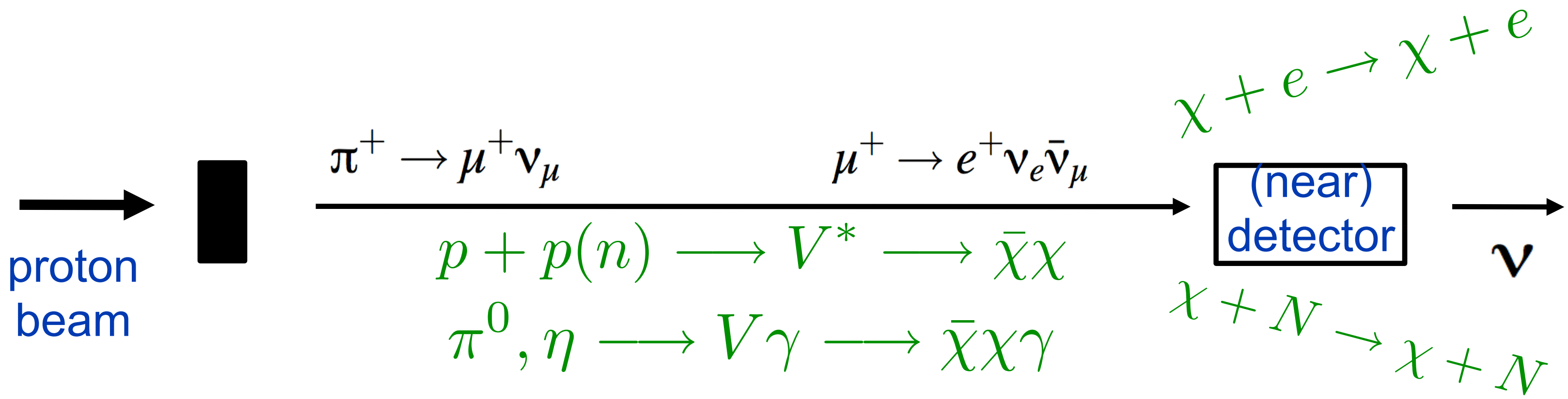
2. Produce light dark matter in a beam dump experiment, and detect its subsequent scattering in a large [neutrino] detector

3. Detect scattering of light ambient DM on electrons, and keep lowering the thresholds in energy deposition.

All three strategies are being actively worked on, and pursued by several ongoing and planned experiments.

Fixed target probes - Neutrino Beams

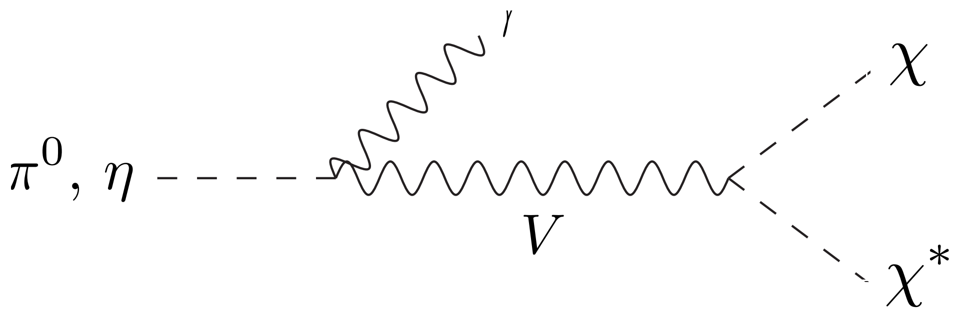
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

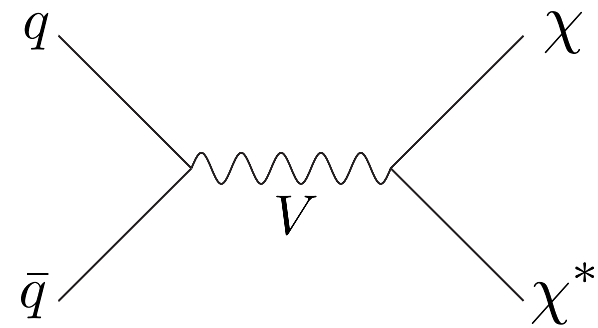


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

T2K	MINOS	MiniBooNE
30 GeV protons	120 GeV protons	8.9 GeV protons
(➠ ~5x10^{21} POT)	10^{21} POT	10^{21} POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

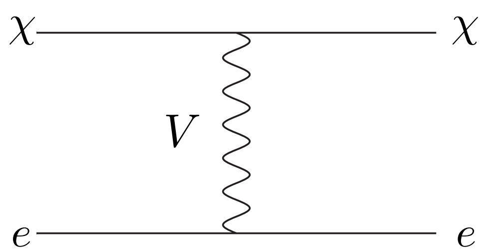
Light DM - trying to see production + scattering



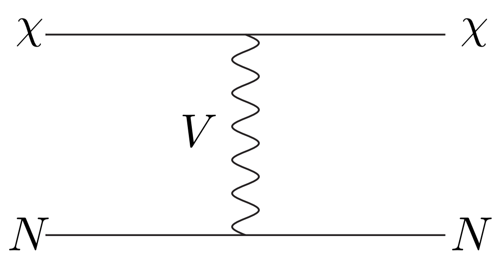


In the detector:

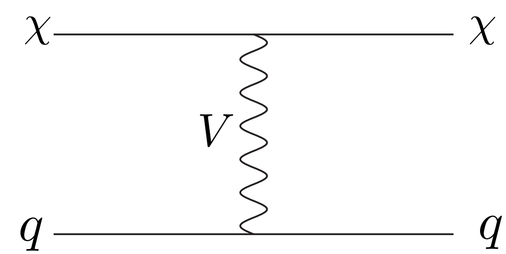
Elastic scattering on electrons



Elastic scattering on nucleons



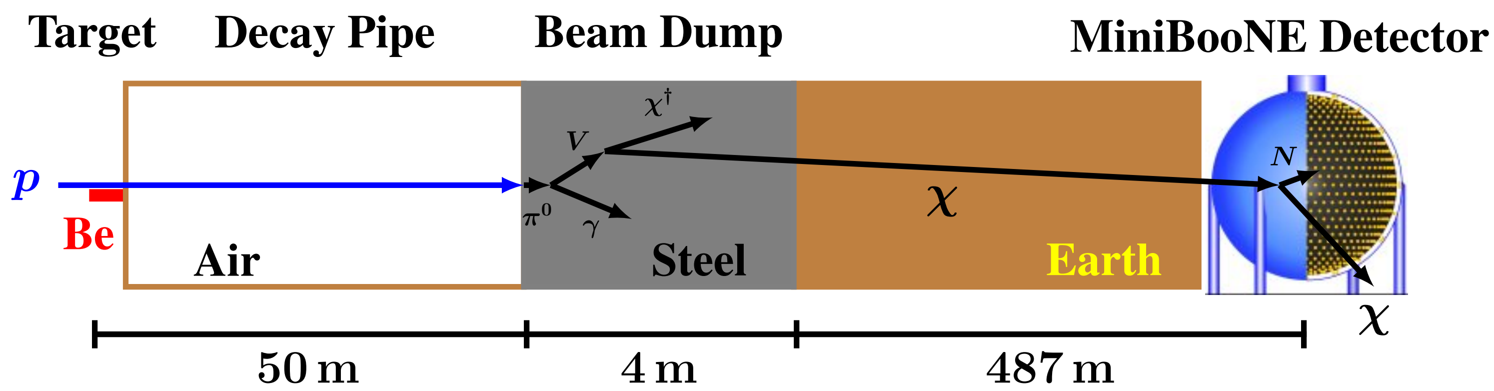
Deep inelastic scattering



Same force that is responsible for depletion of χ to acceptable levels in the early Universe will be responsible for it production at the collision point and subsequent scattering in the detector.

Signal scales as (mixing angle)^4.

MiniBooNE search for light DM



MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

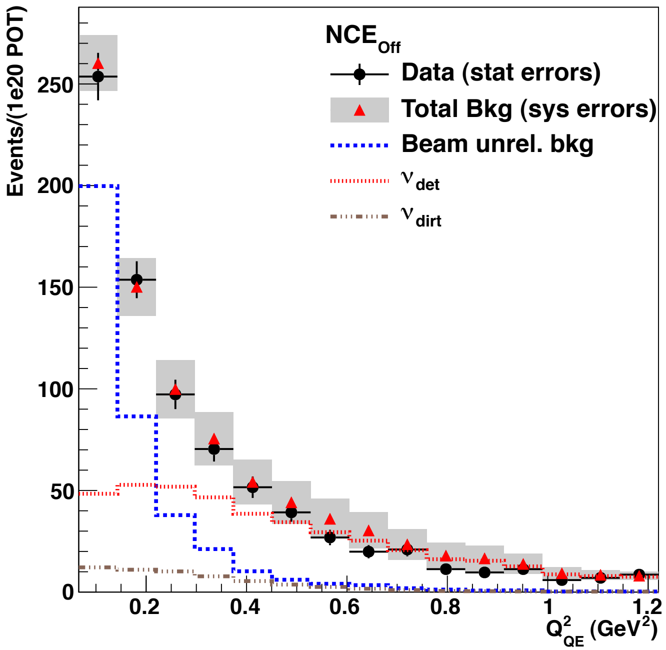
By-passing Be target is crucial for reducing the neutrino background (Richard van de Water et al. …) . Currently, suppression of ν flux ~50.

Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – 2016, 2017

Important contribution from P deNiverville, B Batell.

MiniBoone results

Results of the "neutrino-less" run are now published

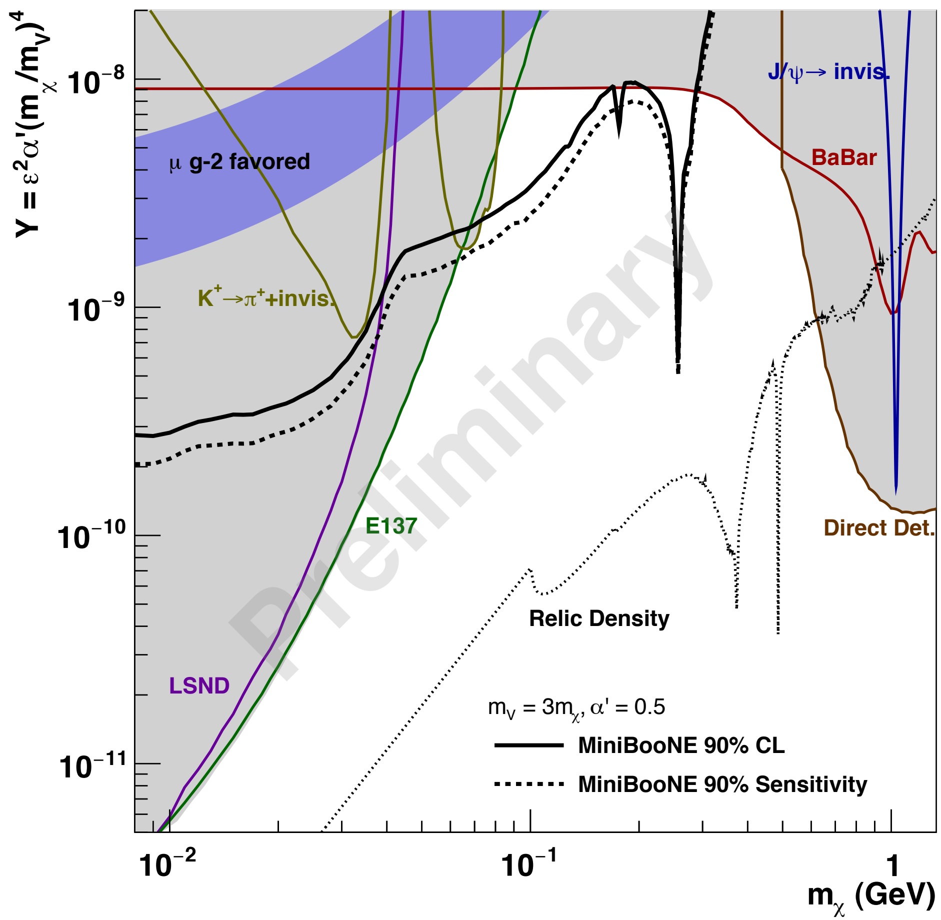


	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

The off-target run of MiniBoone is a success (despite the absence of DM signal!):

- Neutrino background from the beam is brought down to be comparable from cosmics
- Data are well described by MC

New parts of the parameter space get excluded



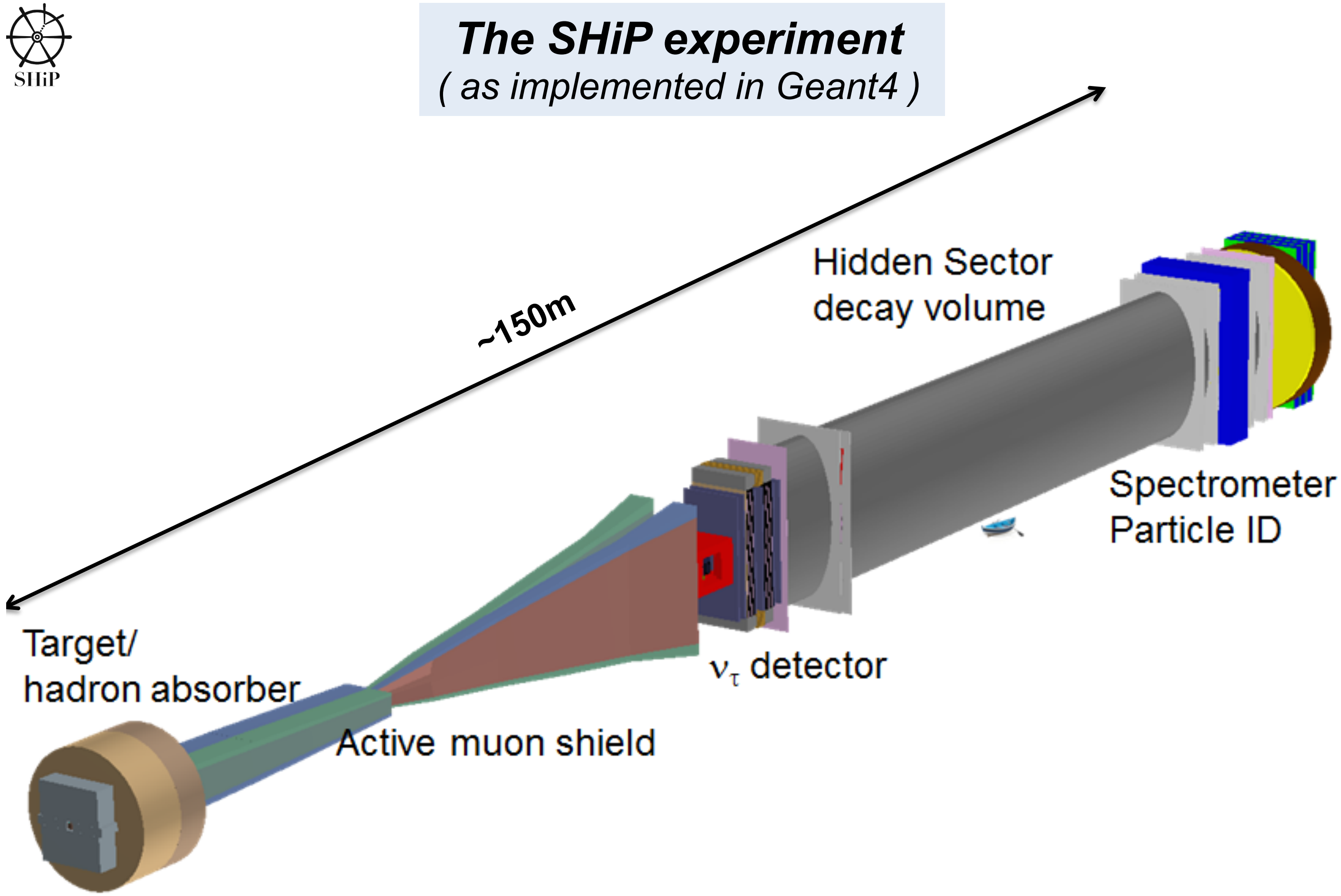
Improves over LSND, SLAC experiments, and Kaon decays in the range of the mediator mass from ~ 100 to few 100 MeV. Details can be found in 1702.02688, PRL 2017. *Are there ways to improve with LArND ?*

Future directions for light dark matter in collisions

To improve on sensitivity to light dark matter in beam dump/fixed target experiments:

- Coherent neutrino scattering experiments
- **SHiP**
- NA64 with more intensity (LDMX)
- More experiments at short neutrino baseline program and DUNE near detector
- ….
- Ultimate beam dump experiment looking for light DM in scattering = powerful accelerator next to large neutrino detectors deep underground for least background.

Future: SHiP project at CERN



A proposal for a large experiment at CERN SPS to look for all types of hidden particles: sterile neutrinos, axion-like particles, dark photons, dark Higgses. Can also be used to study scattering signature of light DM

SHiP sensitivity to light DM

- Estimated in deNiverville et al.

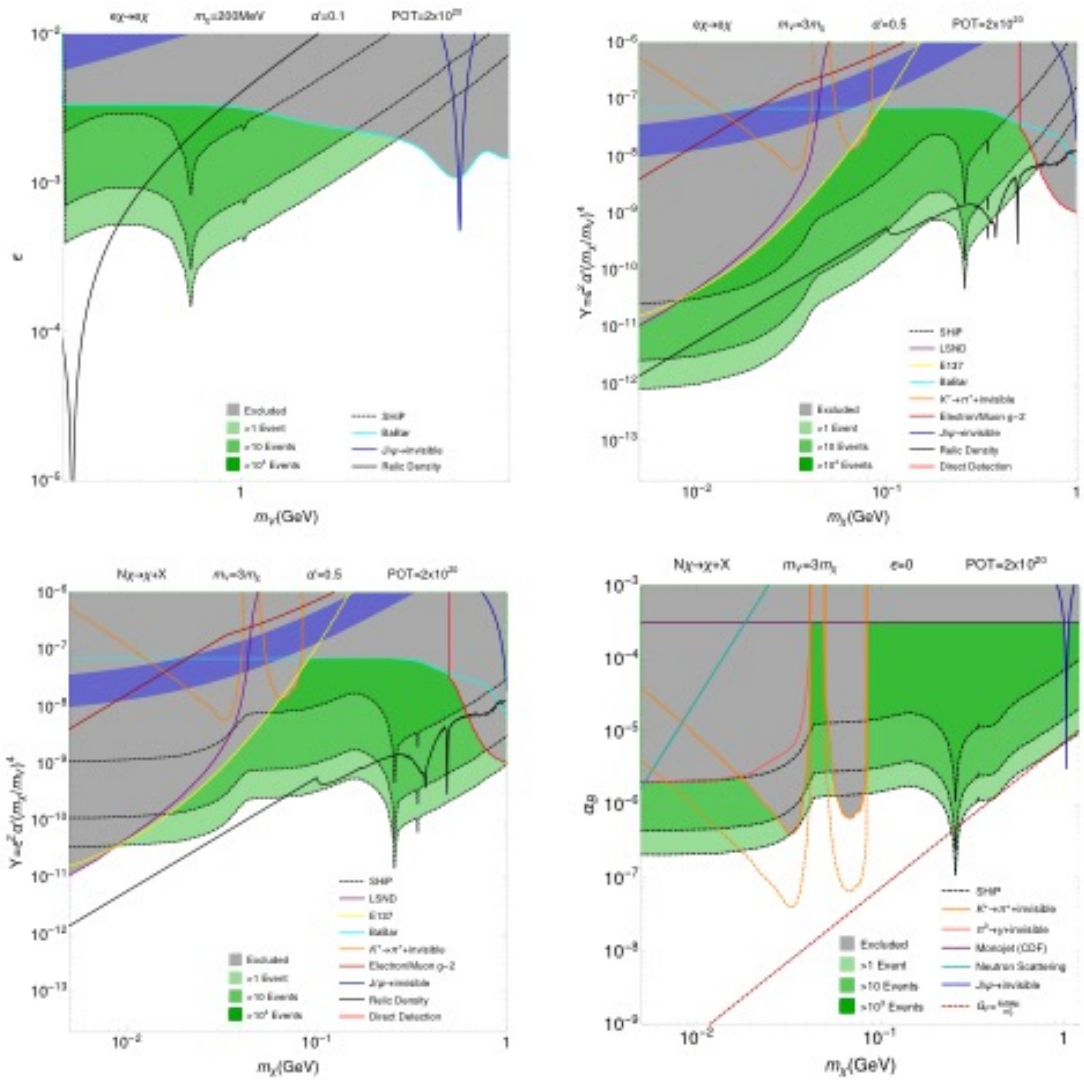
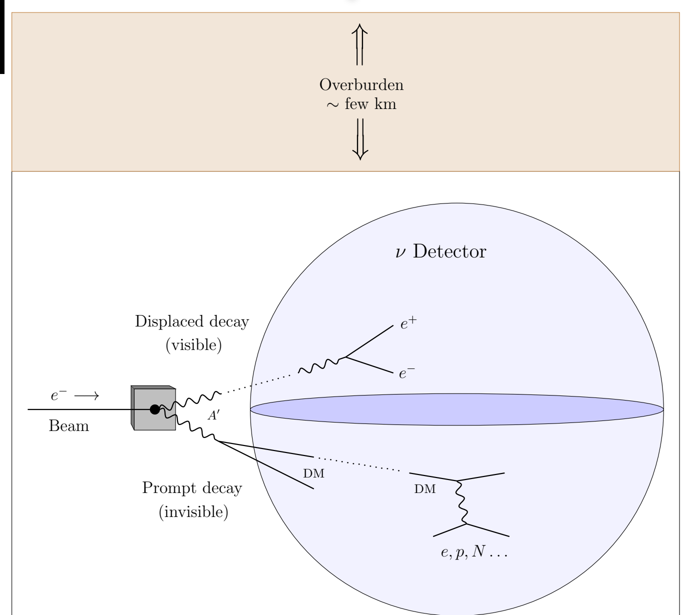


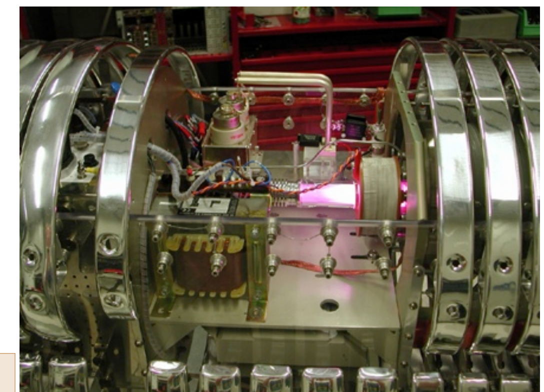
FIG. 11. Plots showing the SHiP yield of light dark matter scattering events in various channels.

More coverage of dark sector using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2014, 2015

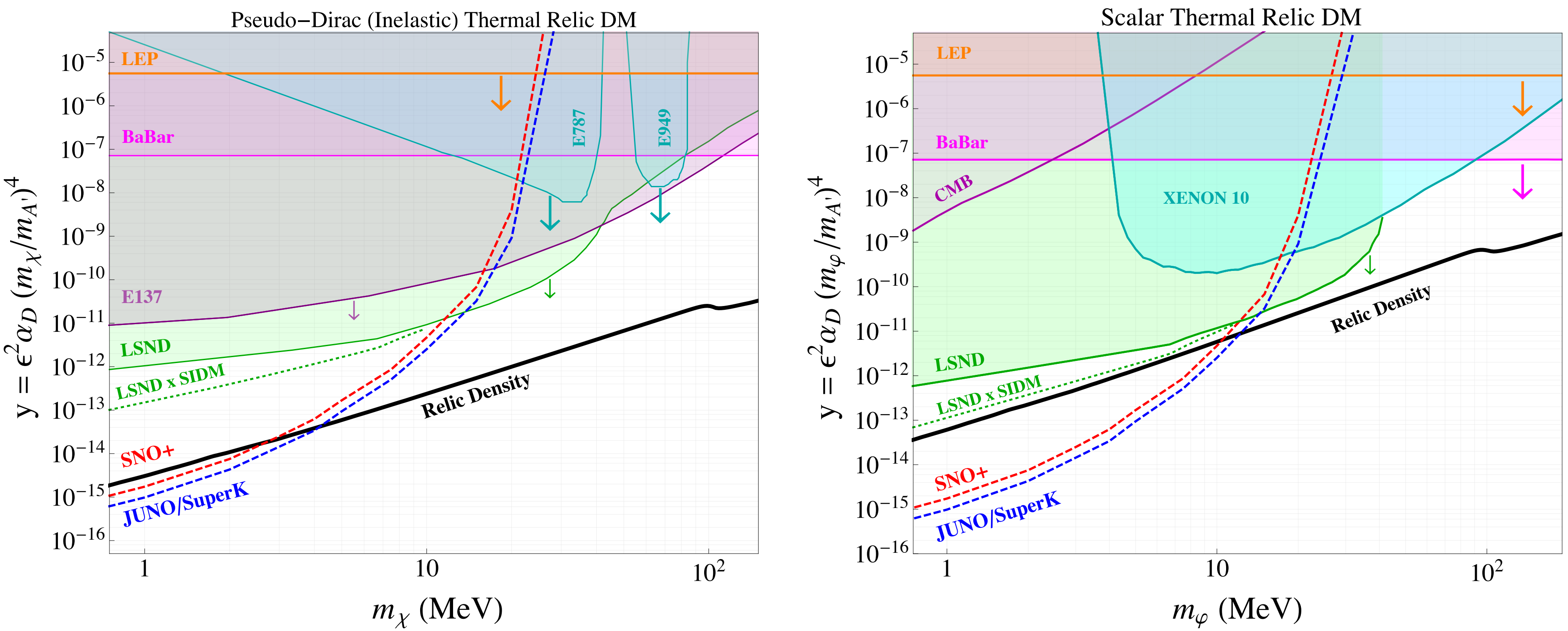
Borexino, Kamland, SNO+, SuperK, Hyper-K (?) …





LUNA, DIANA,…, 1 e-linac for calibration

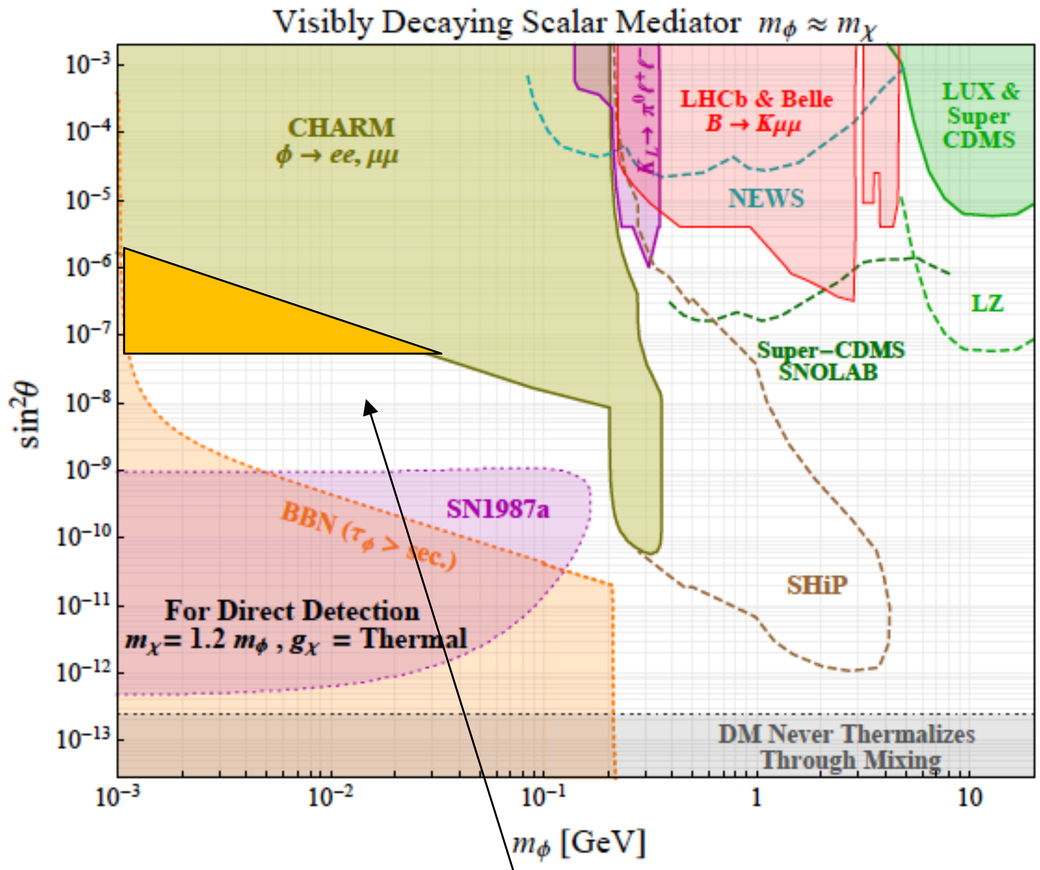
Sensitivity to light DM



One will significantly advance sensitivity to light DM in the sub-100 MeV mass range. Assuming 10^{24} 100 MeV electrons on target

Izaguirre, Krnjaic, MP, 1507.02681, PRD

Constraints on Higgs-like mediators



From Krnjaic 2015 (certain curves need to be revised) See also G Perez talk yesterday.

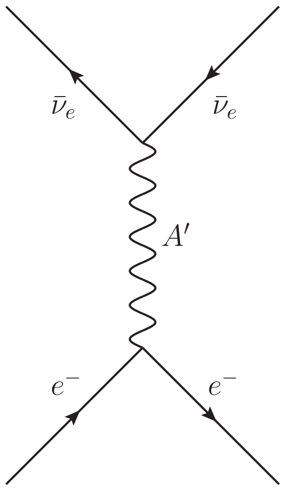
Question: Is there a further sensitivity to *S* from K→π *S* followed by *S* decay in the LArND detector at SNB ? DUNE?

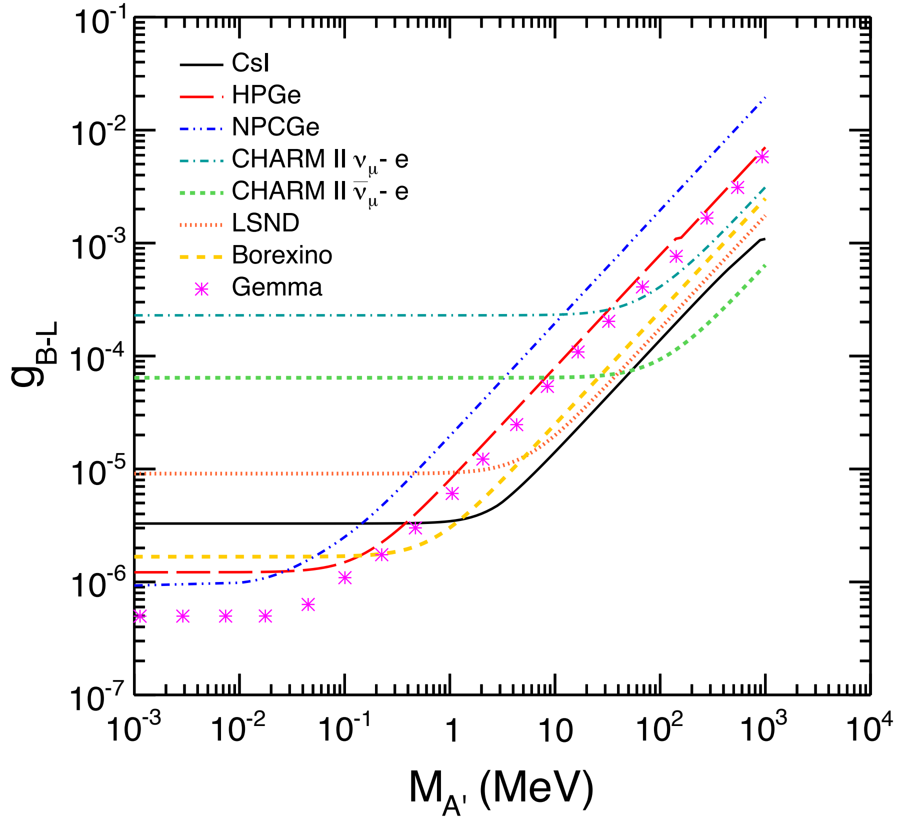
Z’ in neutrino scattering

1. Neutrino scattering itself can be sensitive to “mediators”, if they have sizeable couplings to them.
2. [Dark photon cannot be probed efficiently, as its coupling to neutrinos is additionally suppressed.]
3. Neutrino scattering provides best constraints on such a well-motivated model as Z’ of $U(1)_{B\text{-}L}$
4. Muon neutrino initiated lepton pair-production (aka “trident”) can also be sensitive to models where Z’ does not couple to light quarks and electrons.

Z' of gauged *B-L* number

Constraints can be derived from a variety of neutrino-electron scattering, from large (LSND) and small (e.g. Texono) experiments





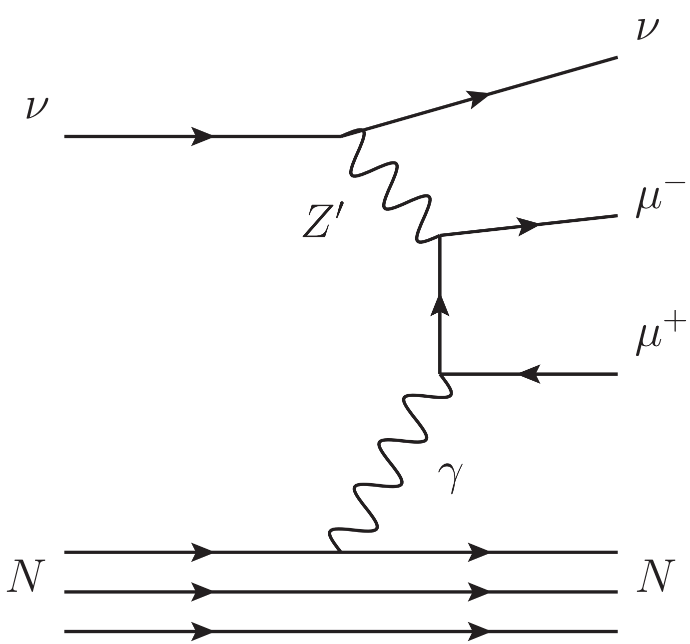
Aliev et al, 2015. Constraints follow from consistency of the SM calculations with the observed e ν → e ν scattering.

Constraints on Z' of L_μ - L_τ

Experimental results

$$\sigma_{\rm CHARM-II}/\sigma_{\rm SM} = 1.58 \pm 0.57 \ ,$$
$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28 \ ,$$
$$\sigma_{\rm NuTeV}/\sigma_{\rm SM} = 0.67 \pm 0.27 \ .$$

Hypothetical Z' (any Z' coupled to L_μ) contributes constructively to cross section.



In the heavy Z' limit the effect simply renormalizes SM answer:

$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1 + \left(1 + 4s_W^2 + 2v^2/v_\phi^2\right)^2}{1 + (1 + 4s_W^2)^2}$$

~8-fold enhancement of cross section for muon g-2 relevant paremeters

Muon pair-production by neutrinos

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

Neutrino Tridents and *W*-*Z* Interference

S. R. Mishra,[a] S. A. Rabinowitz, C. Arroyo, K. T. Bachmann,[b] R. E. Blair,[c] C. Foudas,[d] B. J. King,

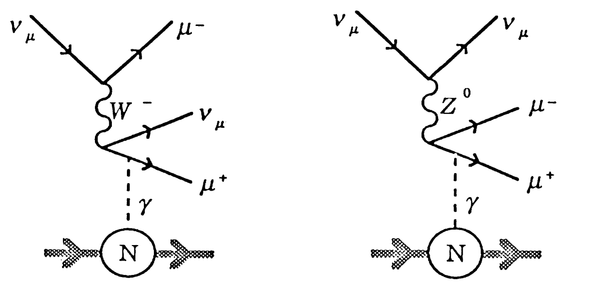


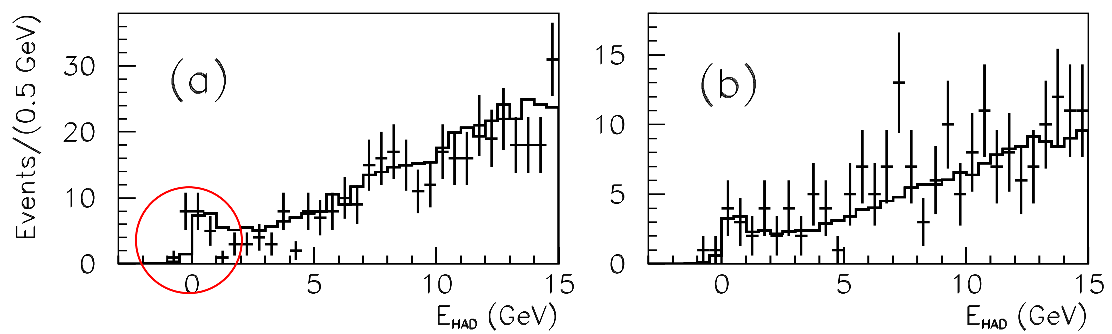
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

$$\sigma_{\nu N}(\mathrm{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\ ,$$

$$\sigma(\nu\ \mathrm{trident}) = (4.7 \pm 1.6) E_\nu \times 10^{-42}\ \frac{\mathrm{cm}^2}{\mathrm{Fe\ nucleus}}$$

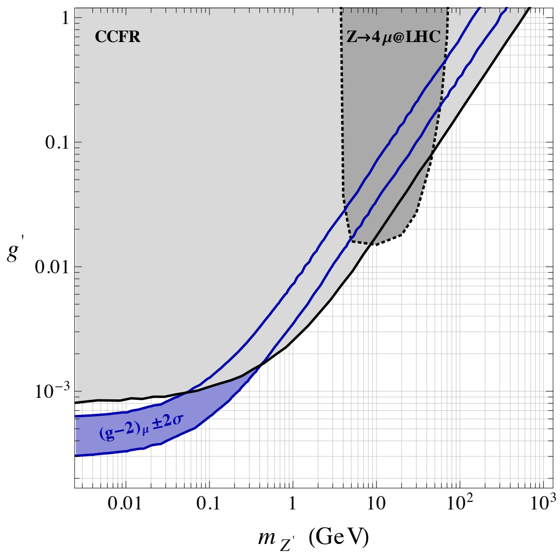
$$\text{at } \langle E_\nu \rangle = 160\ \mathrm{GeV}\ .$$

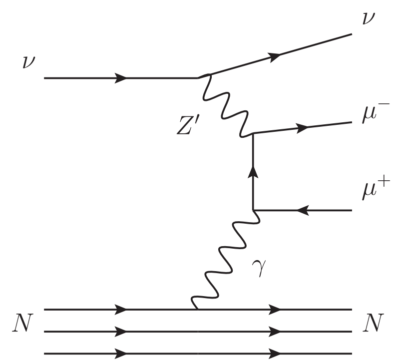
- NuTeV results:

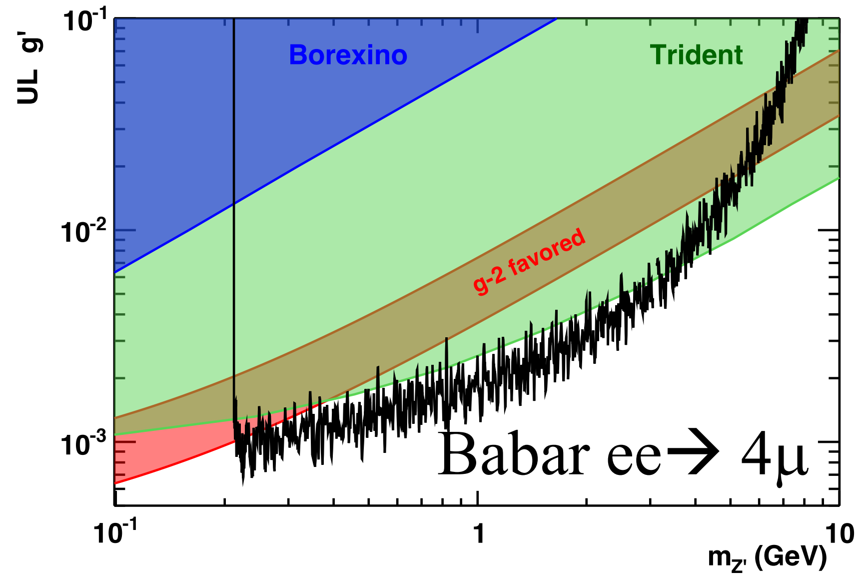


Trident production was seeing with O(20) events, and is fully consistent with the SM destructive W-Z interference.

Constraints on L_μ-L_τ $M_{Z'}$ - g' parameter space







Muon pair production process excludes solutions to muon g-2 discrepancy via gauged muon number in the whole range of

$M_{Z'} > 400$ MeV

In the "contact" regime of heavy Z'>5 GeV, the best resolution to g-2 overpredicts muon trident cross section by a factor of ~ 8.

Altmannshofer, Gori, MP, Yavin, 2014

See the improved analysis by Magill and Plestid, 2016.

Limits on $(g')^2/(m_Z')^2$ are better than G_{Fermi}.

Possibility for improvement

From Altmannshoffer et al, 2014

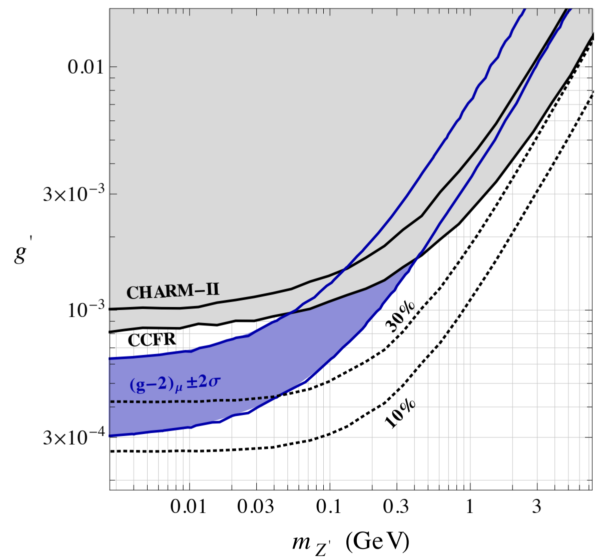


FIG. 3. Same as Fig. 2 but focusing on the low mass region. Constraints from CHARM-II and CCFR, Eqs. (15) and (16) are shown separately. We do not attempt a statistical combination of the results. The dashed lines show the expected limit if the trident cross-section could be measured with 10% or 30% accuracy using 5 GeV neutrinos scattering on Argon.

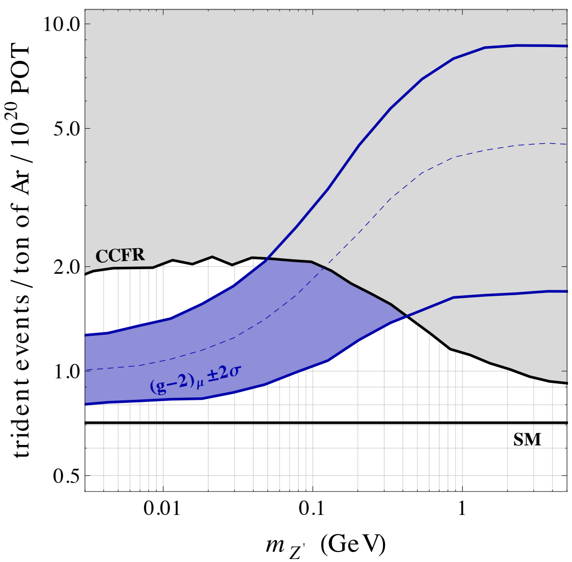


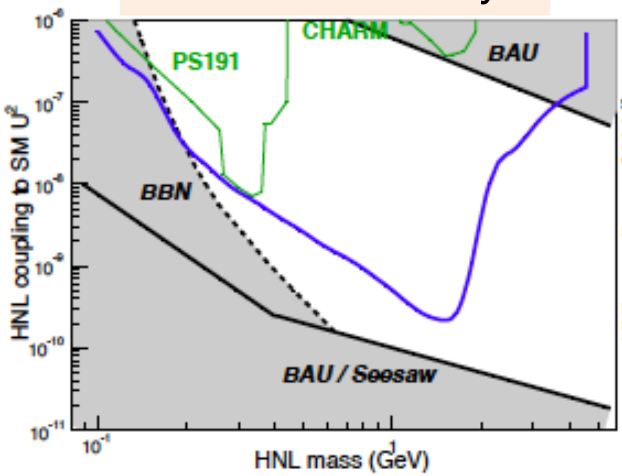
FIG. 4. Expected number of trident events per ton of Argon and per 10^{20} POT at the LBNE near detector for a neutrino energy of $E_\nu = 5$ GeV as a function of the Z' mass. The horizontal line shows the SM prediction. The purple (dark grey) region corresponds to Z' masses and couplings that yield a contribution to the muon g-2 in the range $\Delta a_\mu = (2.9 \pm 1.8) \times 10^{-9}$. The light grey region is excluded by CCFR.

- 10% accuracy measurement of muonic trident at DUNE may probe the remainder of the parameter space. DUNE studies needed.
- NA 64 in the muon mode would be the best way to go (Gninenko)

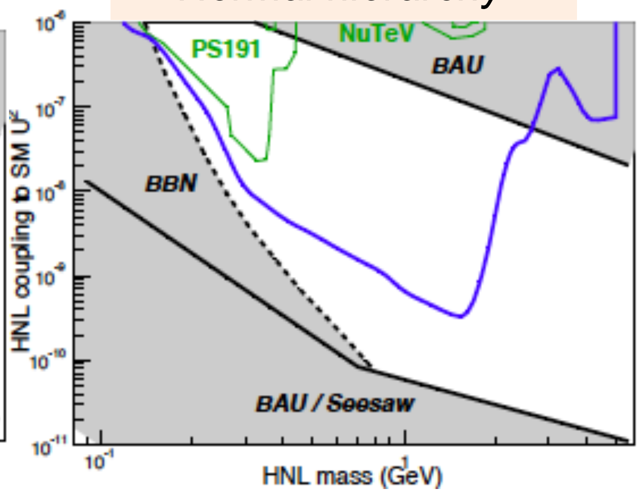
Search for Heavy Neutral Leptons

- Production channel is through charm pp → c cbar → N_R. (N_R are often called Heavy Neutral Leptons, or HNL)
- Detection is through their occasional decay via small mixing angle *U*, with charged states in the final state, e.g. $\pi^+\mu^-$, $\pi^-\mu^+$, etc.
- Decays are slow, so that the sensitivity is proportional to (Mixing angle)^4. *Production is very inefficient*.

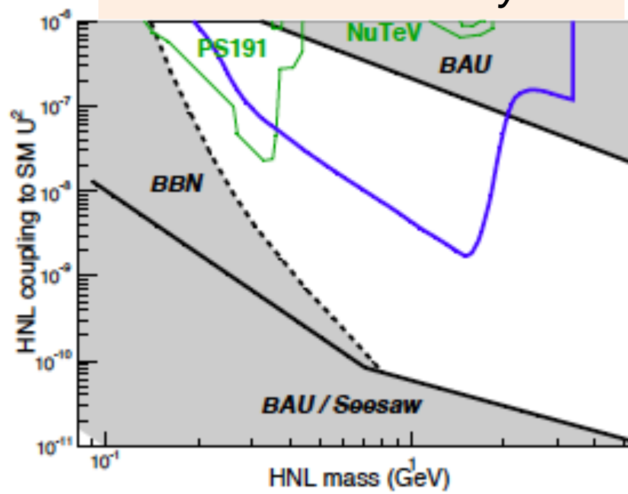
U^2_e: U^2_μ: U^2_τ~52:1:1
Inverted hierarchy



U^2_e: U^2_μ: U^2_τ~1:16:3.8
Normal hierarchy



U^2_e: U^2_μ: U^2_τ~0.061:1:4.3
Normal hierarchy



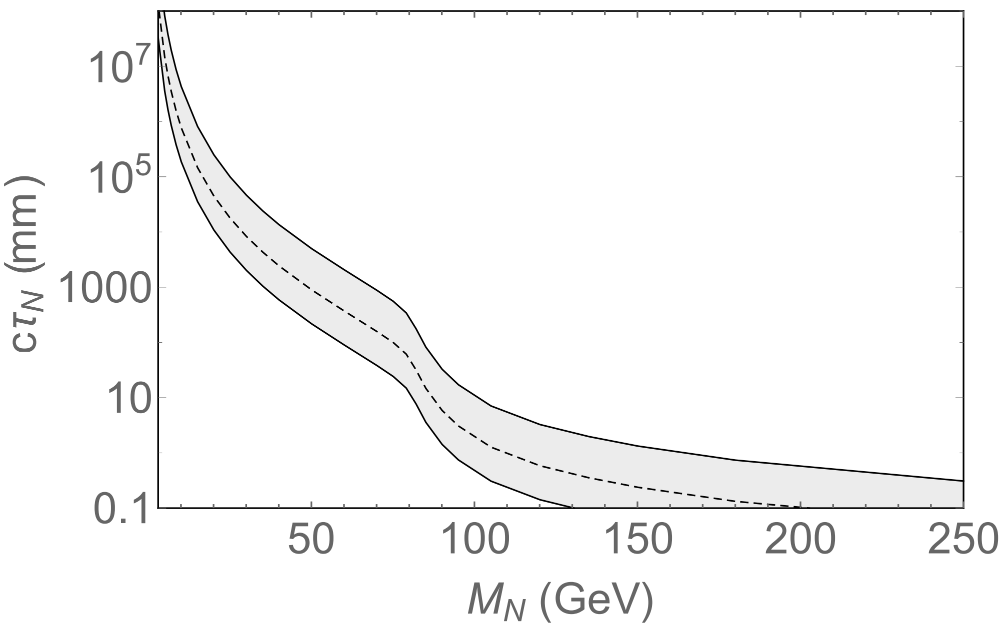
HNL production can be enhanced in non-minimal models, Batell et al.

Lifetimes and decay channels of RH neutrinos

$$\Gamma_{N\to\mu\ell_\alpha\nu_\alpha} = \frac{G_F^2 M_N^5 |\theta_{\mu N}|^2}{192\pi^3} \quad (\alpha \neq \mu),$$

$$\Gamma_{N\to\mu\mu\nu_\mu} = \frac{G_F^2 M_N^5 |\theta_{\mu N}|^2}{192\pi^3}(1 + 4\mathrm{s_W}^2 + 8\mathrm{s_W}^4),$$

$$\Gamma_{N\to\mu\ell\nu} \simeq 10^{-15}\ \mathrm{eV} \times \frac{|\theta_{\mu N}|^2}{\theta_{\mathrm{s-s}}^2}\left(\frac{M_N}{1\ \mathrm{GeV}}\right)^4$$



Lifetime with seesaw input.

Lifetime is a very sensitive function of mass. 1 GeV: cτ > 1 km

100 GeV: cτ = 1 mm

Complicating the picture: combination of vector and neutrino portal

B. Batell, MP, B. Shuve, 1604.0699, PRD 2016 – in depth study of the sensitivity reach of LHC experiments and SHiP to the right-handed neutrinos + additional B-L interaction.

Reason? We want to find a modification of the minimal model where LHC and/or SHiP will be sensitive to the RH neutrinos with seesaw size mixing angles…

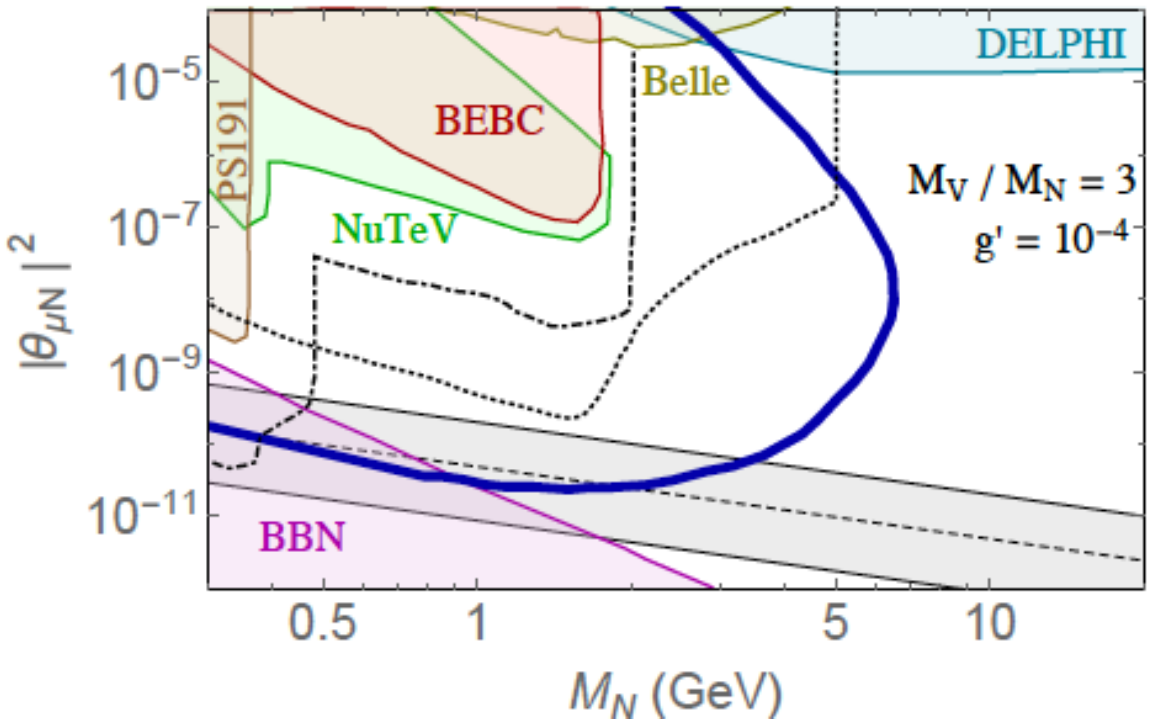
The Majorana mass of RH neutrinos can be consistent with the B-L gauge symmetry, if the mass term is generated via a charge 2 Higgs type interaction, $y_N \Phi N N/2 + \text{h.c.}$

Different production mechanism

- *Standard scenario:* production rate ~ θ^2. Very inefficient!
- *Our modified scenario*: $pp \to X + V_{B-L} \to X + NN$, production rate is controlled by $(g_{B-L})^2$.
- Decay rates are proportional to θ^2 in both cases.
- Since $(g_{B-L})^2$ can be $\gg \theta^2$, the RH neutrino pair-production rate is strongly enhanced.

Reaching the "seesaw mixings" with SHiP

SHiP sensitivity scales now as $\sim (g_{B\text{-}L})^2 \times \theta^2$. We have fixed $M_V = 3M_N$ for concreteness.



Gray band – the seesaw band. SHiP will probe inside the seesaw range of mixing angles. Reason – more efficient production.

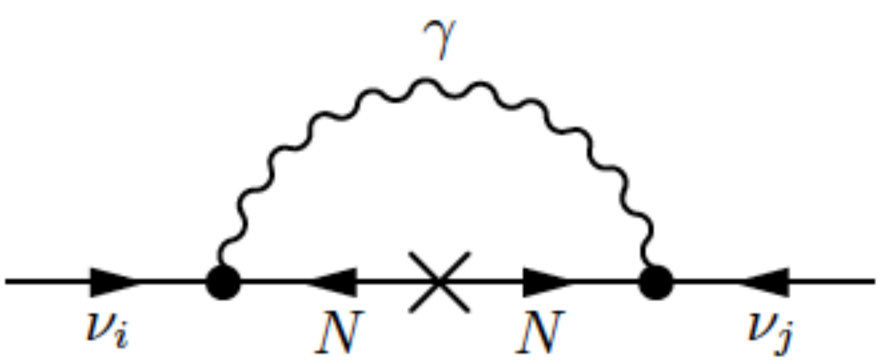
Models with HNL and a dipole coupling

- Magill, Plestid, MP, Tsai, to be submitted. Consider a heavy neutral lepton with dim=5 couplings to photons and neutrinos:

$$\mathcal{L}_d = i\bar{N}_D \partial\!\!\!/ N_D + (d_\gamma \bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} P_R N_D + h.c.) - m\bar{N}_D N_D$$

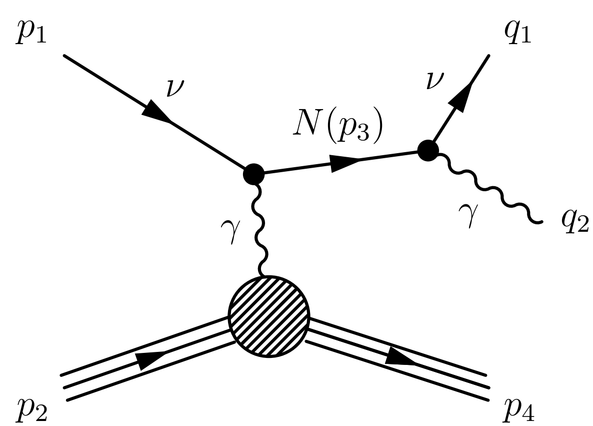
- This model has two free parameters, m_D and d_γ, and the dipole coupling gamma has a dimension of inverse mass.

- The heavy *N* has to be Dirac to avoid strong feedback to active neutrino masses



Main signatures: up-scattering + decay

- The dominant production mode is the EM-induced upscattering of the active neutrino species.



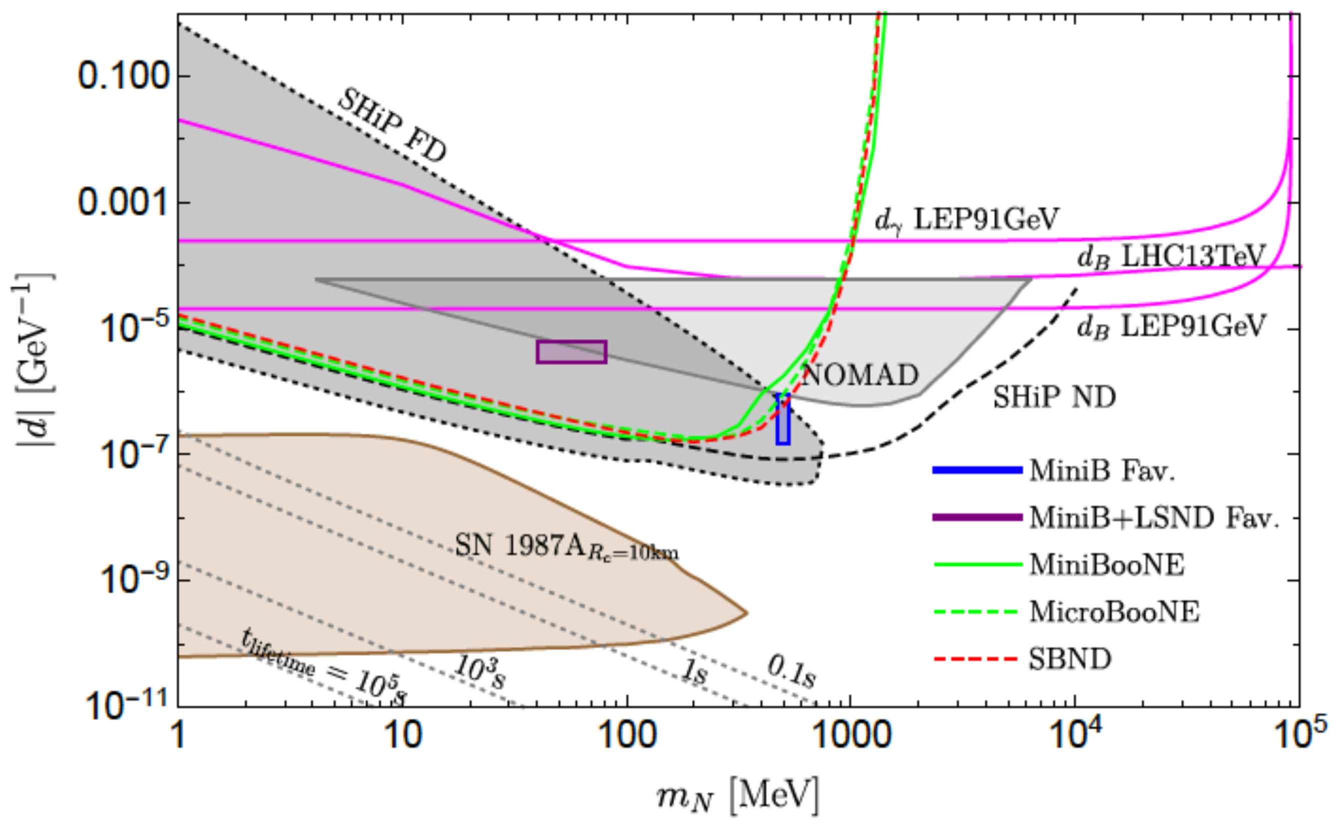
$$t_{\rm dec} = \tau\gamma = 6.6 \times 10^{-7}{\rm s}\left(\frac{50\ {\rm MeV}}{m_N}\right)^4\left(\frac{10^{-6}\ {\rm GeV}^{-1}}{d}\right)^2$$

$$L_{\rm dec} = c\tau\beta\gamma \approx 200{\rm m}\left(\frac{50\ {\rm MeV}}{m_N}\right)^4\left(\frac{10^{-6}\ {\rm GeV}^{-1}}{d}\right)^2$$

$$\sigma_{\rm per\ nucleus} = 4.5 \times \left(\frac{Z}{18}\right)^2\left(\frac{d}{10^{-6}\ {\rm GeV}^{-1}}\right)^2 \times 10^{-38}\ {\rm cm}^2$$

Both the production and decay are in “convenient” range for realistic values of d

Sensitivity to dipole coupling



- MiniBoone and future LAr1-ND have sensitivity to d^{-1} ~ 1000 TeV scale!
- CERN experiment SHiP will also have a strong sensitivity, both through the neutrino and "far" detectors
- Because the leading coupling is dim=5, many different energy scale experiments are sensitive to the same parameter range
- LSND curve to be added; Low mass region suggested by Gninenko is excluded

Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (e.g. dark photon or dark Higgs-mediated models) are quite minimal yet UV complete, and have diverse DM phenomenology.
2. Sub-GeV WIMP dark matter can be searched for via production & scattering or missing energy. Neutrino experiments are sensitive to light dark matter through its production and scattering (LSND, MiniBoone etc.) SHiP will improve on that.
3. Search for mediators (diversifying away from dark photon) benefit significantly from neutrino scattering. Trident production can limit even the most "hidden" possibilities such as gauged L_μ-L_τ.
4. Sensitivity to HNL can be improved – especially if there are new production modes, as in the examples given with the B-L mediated model, and with EM dipole portal to HNLs.
5. More theory and experimental studies of sensitivity to NP are needed. [E.g. how to efficiently combine ν and ν-less modes?]