Probing New Physics in Neutrino experiments (other than ν masses)

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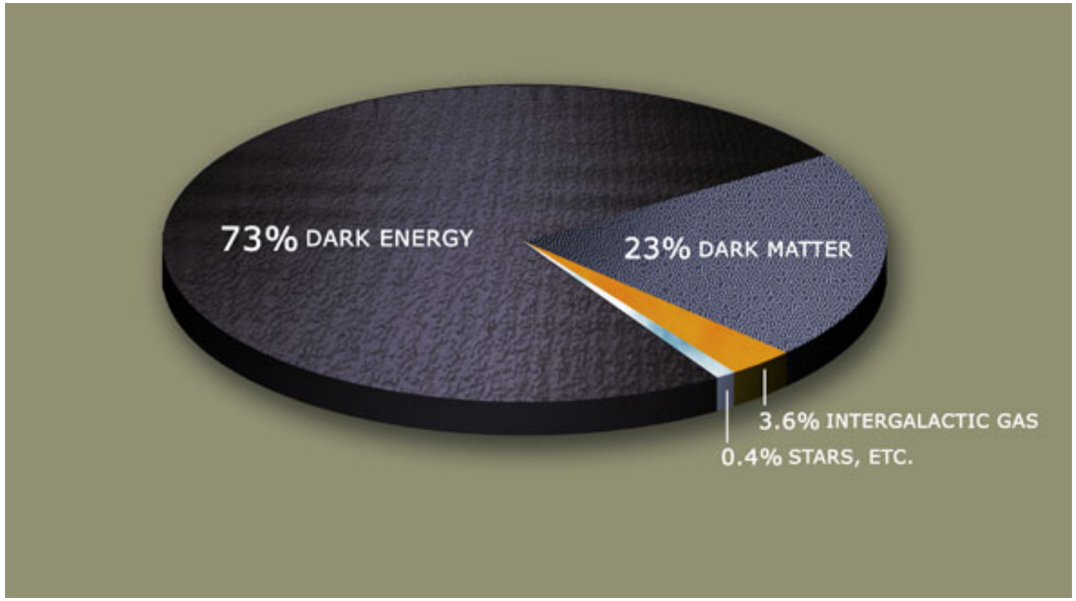
Nu-Int 2017 meeting

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Big Questions in Physics

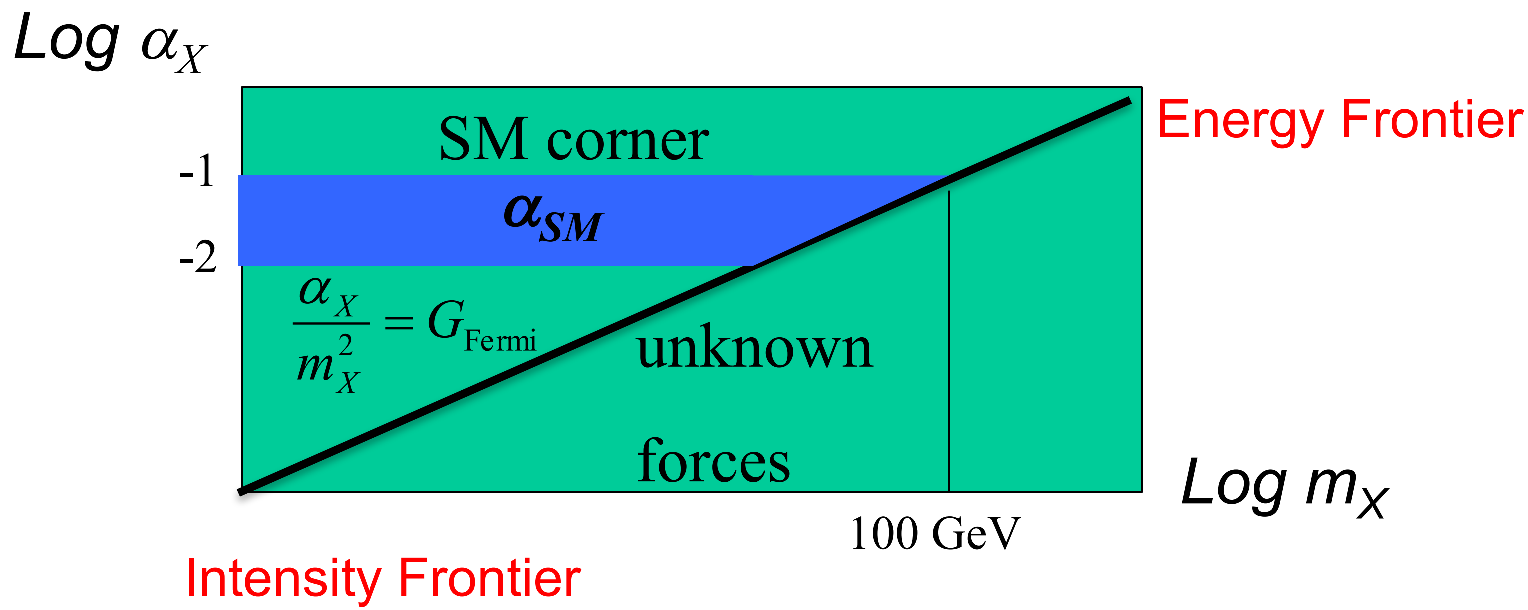


"Missing mass" – what is it?

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.

Intensity and Energy Frontiers



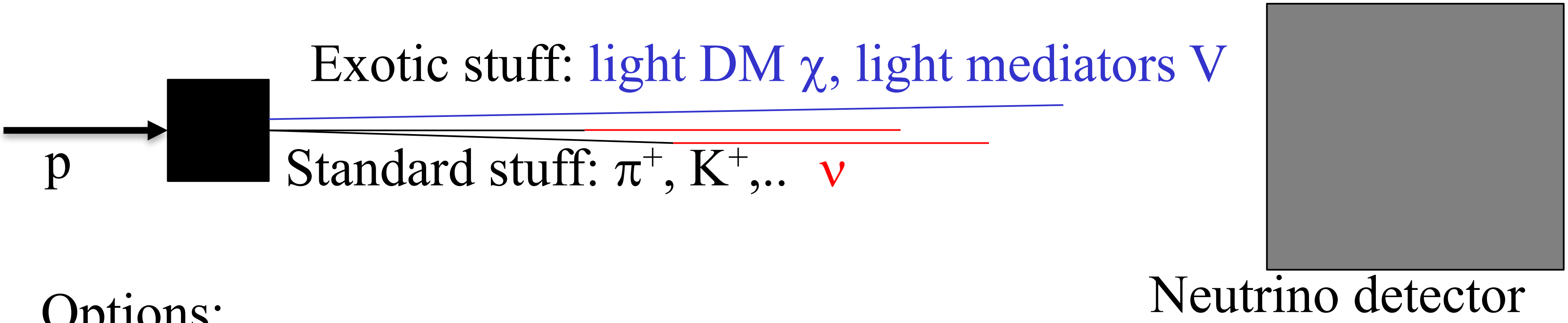
$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, but may have little success with $\alpha_X \sim 10^{-6}$, and $m_X \sim$ GeV.

Outline of the talk

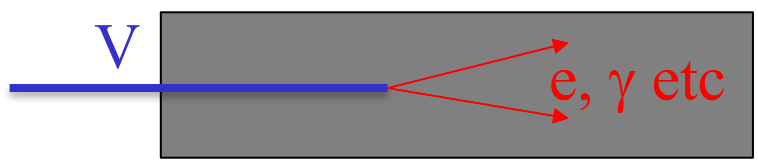
1. *Introduction. New physics at the energy and intensity frontier.*
2. Light dark matter and light mediators.
3. Searches at short baseline neutrino experiments.
4. Probing new forces in neutrino scattering.
5. Conclusions.

Types of New Physics to be explored

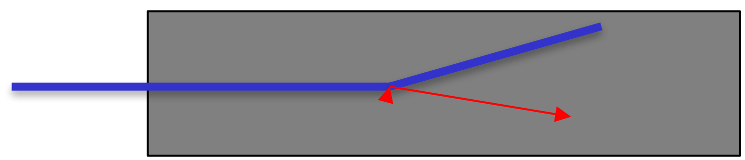


Options:

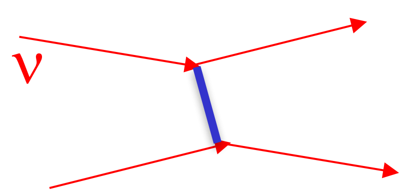
1. Exotic stuff is "metastable", decays to SM inside the detector



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



3. Exotic particles can modify neutrino scattering itself.



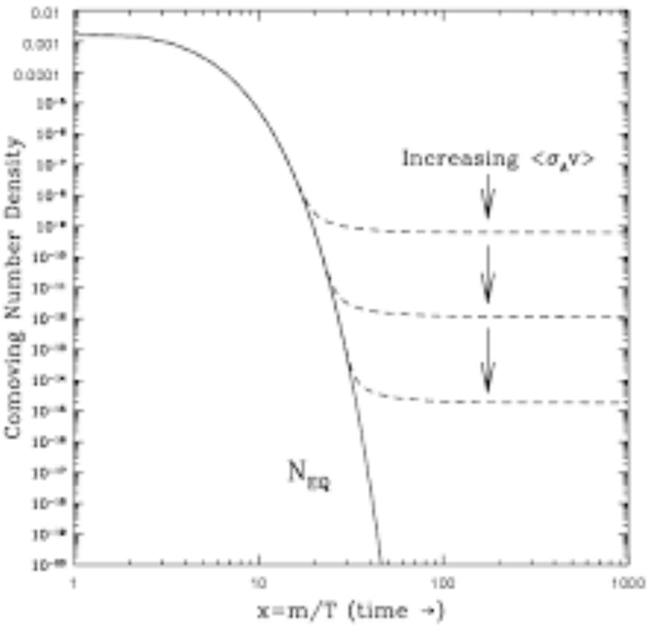
Types of new physics

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.

Weakly interacting massive particles

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

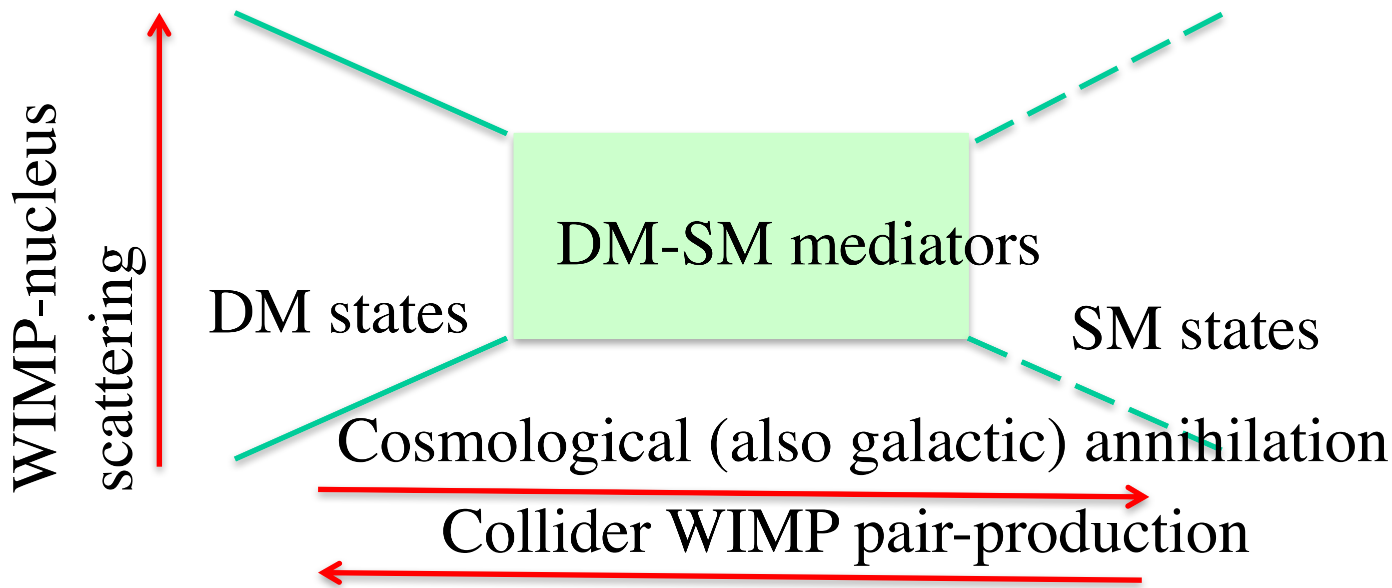


Honest solution of Boltzmann equation gives a remarkably simple result. $\Omega_X = \Omega_{DM}$, observed if the annihilation rate is

$10^{-36}\ \mathrm{cm}^2 = \alpha^2/\Lambda^2 \rightarrow \Lambda = 140$ GeV. **Λ ~ weak scale (!)** First implementations by (Lee, Weinberg; Dolgov, Zeldovich,….)

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

WIMP paradigm, some highlights

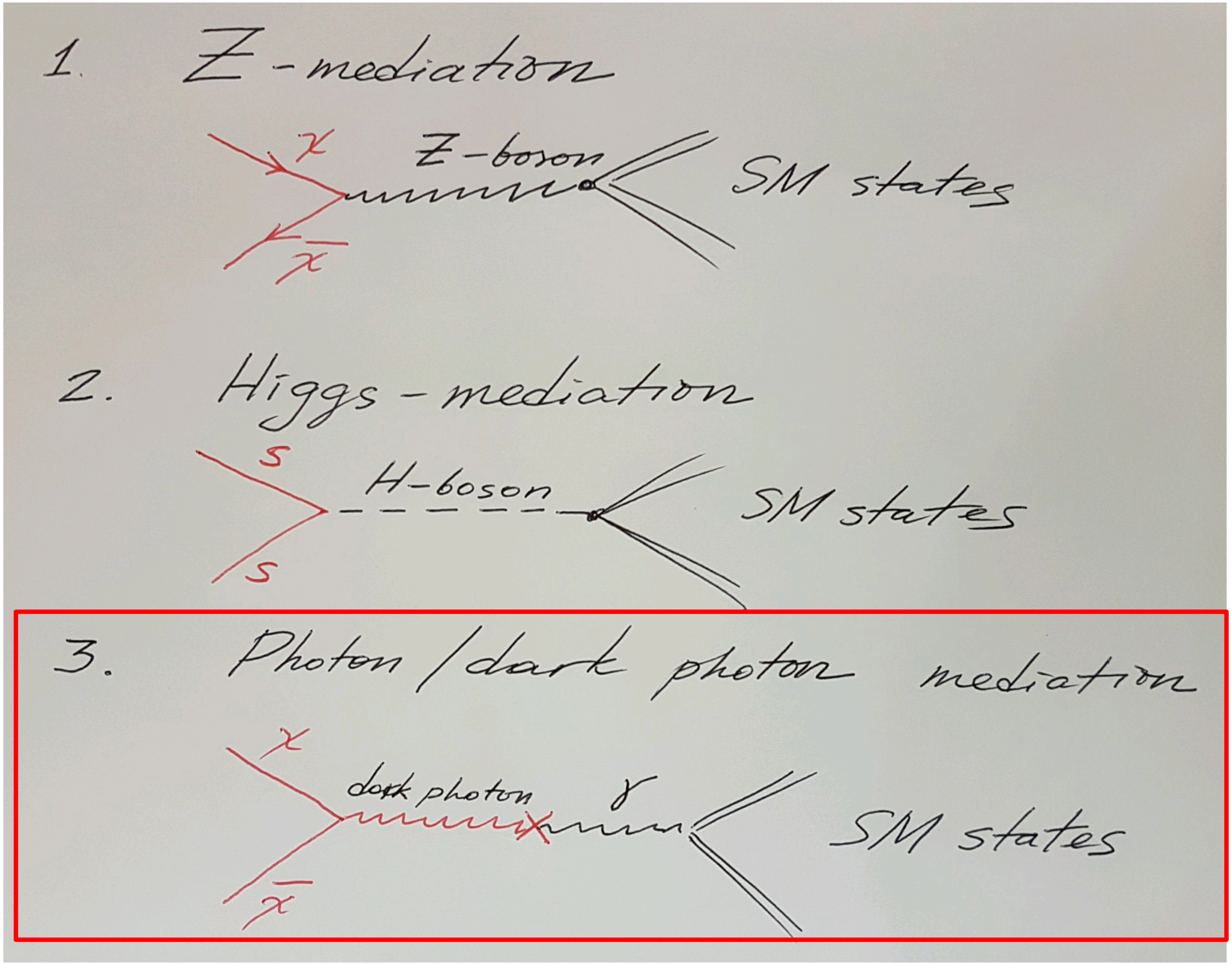


$$\langle \sigma_{ann} v \rangle \approx 1\mathrm{pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production? (What is the mass range?)

Examples of DM-SM mediation

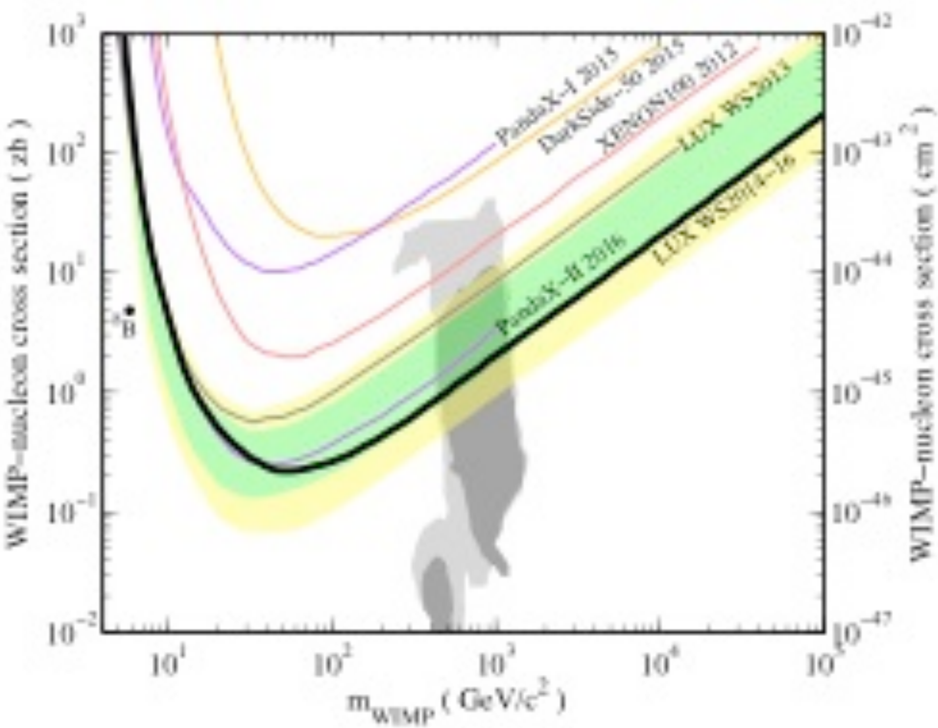


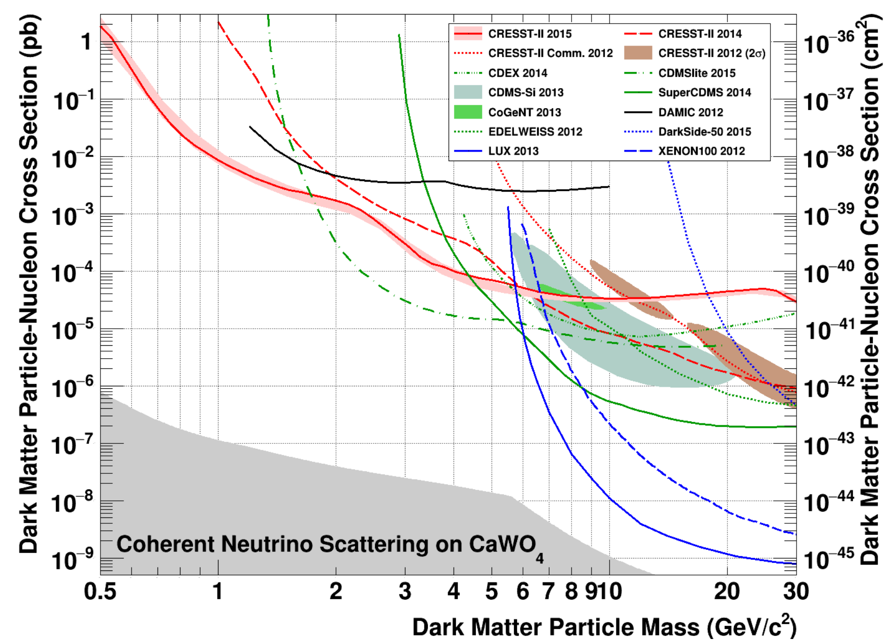
Very economical extensions of the SM.

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

Progress in direct detection of WIMPs

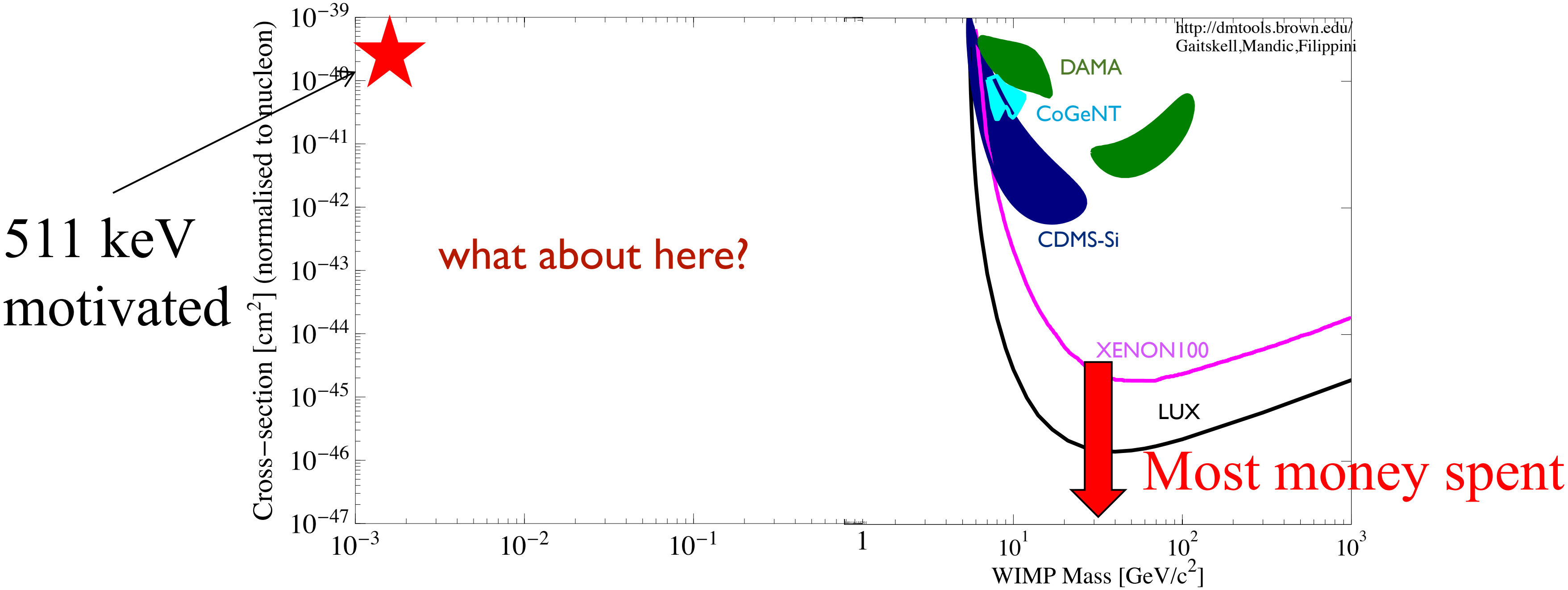
(latest 2016 LUX and CRESST results)





Spin-independent Z-boson mediated scattering of a Dirac WIMP is excluded from ~ 1 GeV to 100 TeV – i.e. over the entire WIMP mass range. EW scale Higgs mediated models are heavily constrained (but there are exceptions). Next generation noble-liquid-based experiments will begin probing EW loop level cross sections.

Light DM – difficult to detect via nuclear recoil



- There is a large, potentially interesting part of WIMP DM parameter space that escapes constraints from DM-nuclear scattering, but is potentially within reach of other probes

- Viable models imply *the dark sector*, or accompanying particles facilitating the DM → SM annihilation. Can create additional signatures worth exploring.

Light WIMPs are facilitated by light mediators

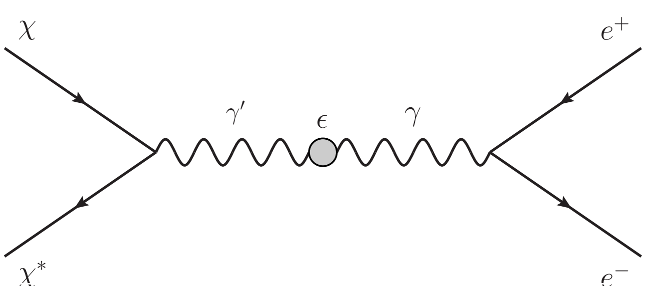
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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

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

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

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).



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

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…

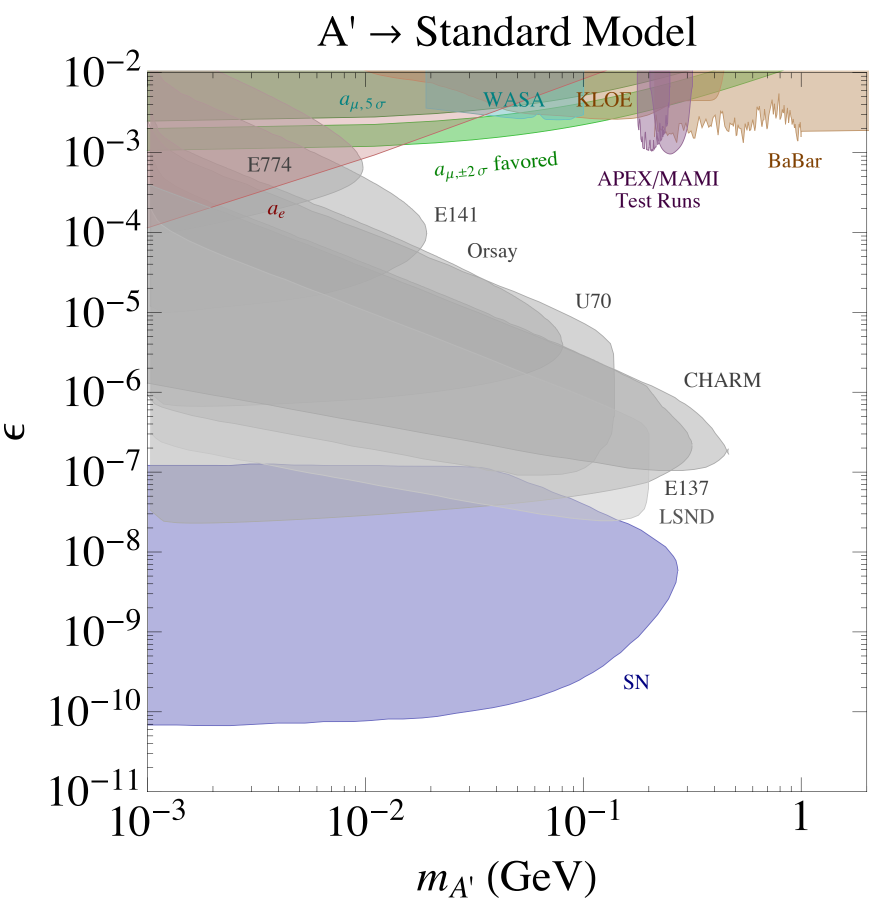
Dim>4

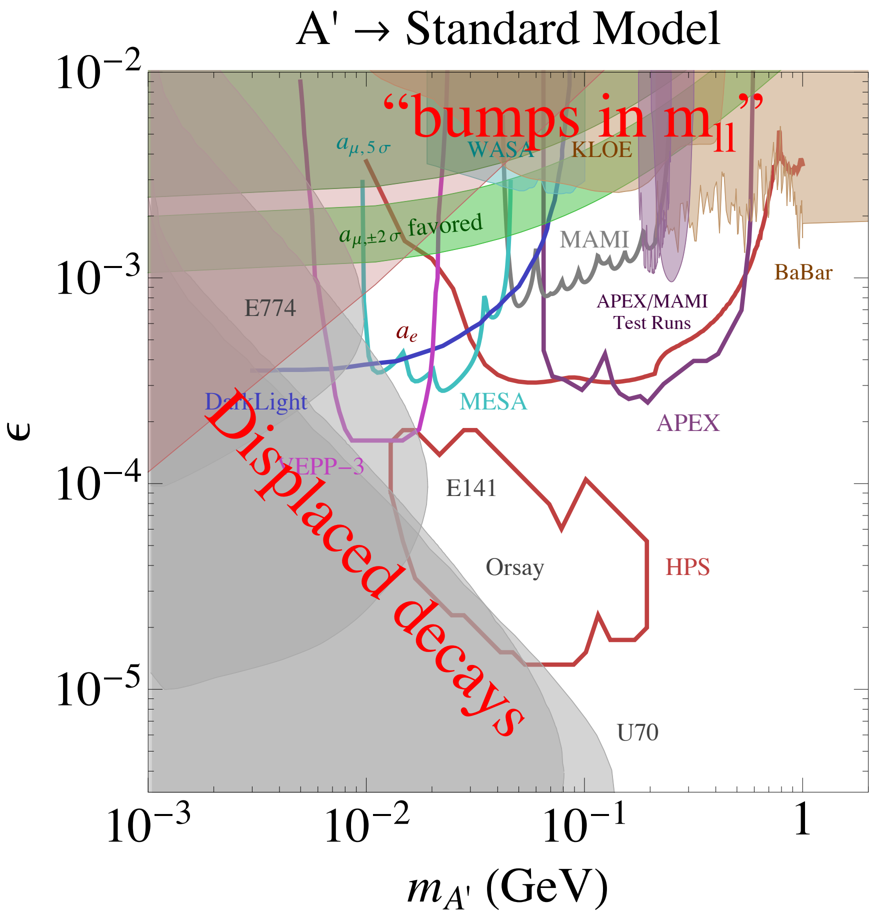
$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

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

Search for dark photons, Snowmass study, 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, not least because of the tantalizing positive ~ $(\alpha/\pi)\varepsilon^2$ correction to the muon g - 2.

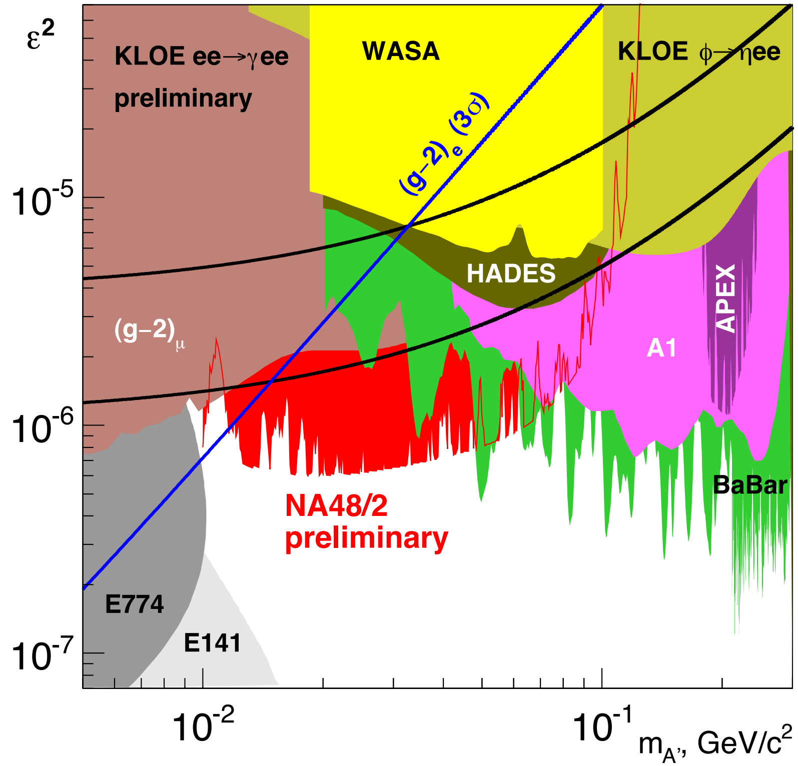
Zooming in: A1, Babar, NA48

Signature: "bump" at invariant mass of e^+e^- pairs = $m_{A'}$

Babar: $e^+e^- \rightarrow \gamma V \rightarrow \gamma l^+l^-$

A1(+ APEX): $Z e^- \rightarrow Z e^- V \rightarrow Z e^- e^+e^-$

NA48: $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$



Latest results by NA48 exclude the remainder of parameter space relevant for g-2 discrepancy.

Only more contrived options for muon g-2 explanation remain, e.g. $L_\mu - L_\tau$, or ~~dark photons~~ ~~*decaying to light dark matter.*~~

"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.

Anomalies? A simple concept of dark matter + mediator allows [speculatively] connecting DM to some on-going puzzles

1. Unexpectedly strong and uniform 511 keV emission from galactic bulge could be fit by annihilation of a few MeV galactic WIMPs.
2. If DM is heavy and mediator is light, one can fit its annihilation to the famous positron-to-electron ratio rise (thanks to Sommerfeld enhancement at low velocity, bound states effects, as well as lepto-phylic composition of the final states)
3. Inner density profiles of galaxies can smoothed out by the self-scattering WIMPs with 10^{-24}cm^2/GeV. For EW scale WIMPs, light mediators can easily provide such cross section.
4. ….

These connections are all rather interesting but not necessarily compelling. We'd like a laboratory probe (Exclusion or confirmation).

How to look for light WIMP DM ?

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

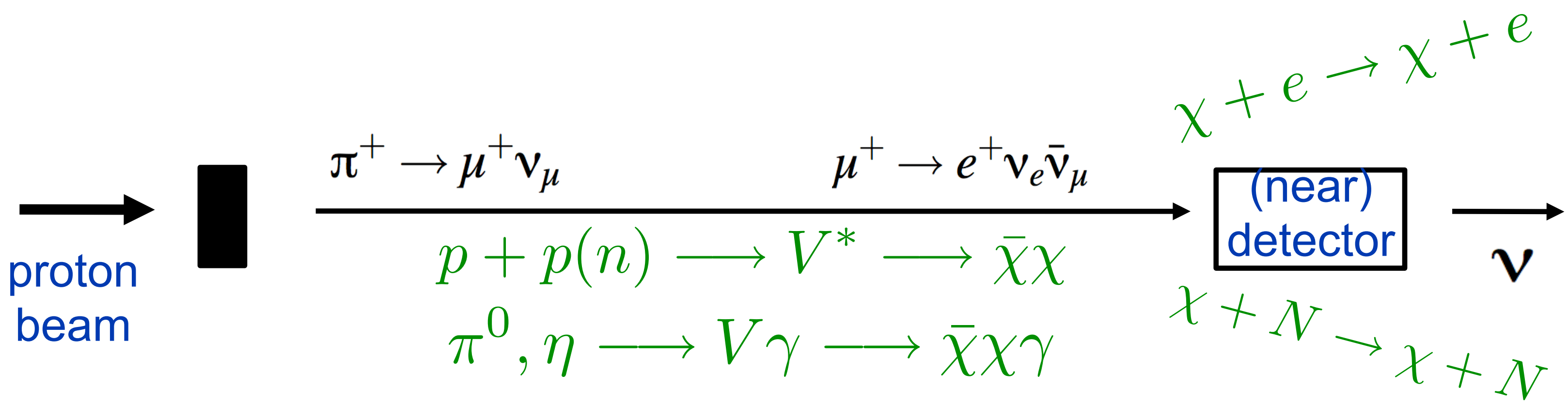
2. Produce light dark matter in a beam dump experiment, and detect its subsequent scattering in a large [neutrino] detector

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

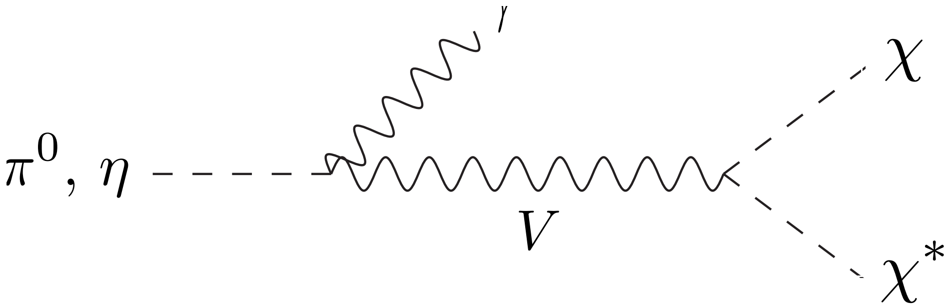
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

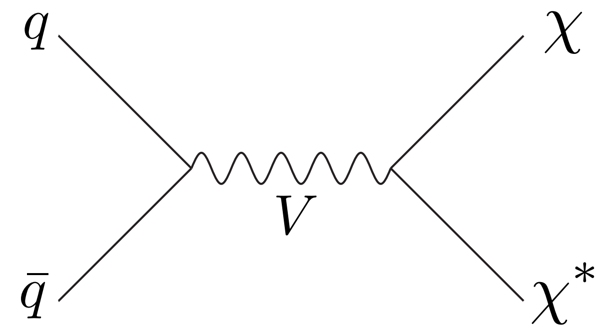


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

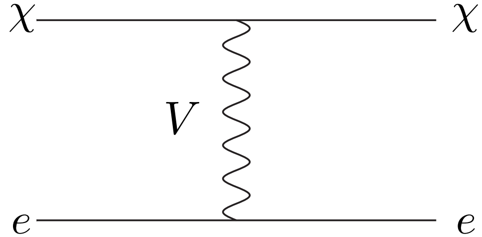
Light DM - trying to see production + scattering



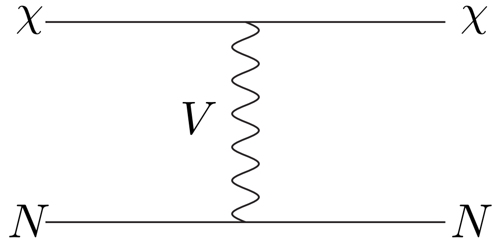


In the detector:

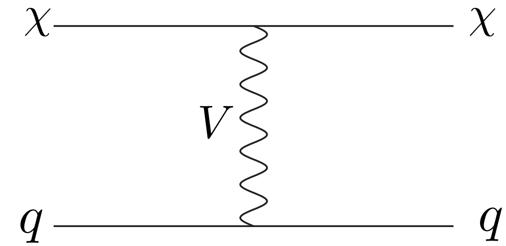
Elastic scattering on electrons



Elastic scattering on nucleons



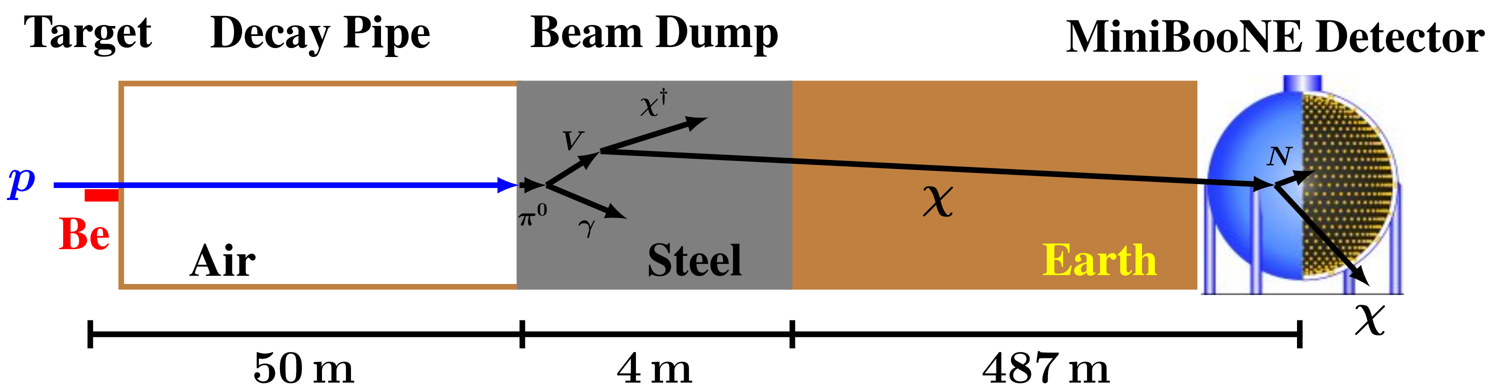
Deep inelastic scattering



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]

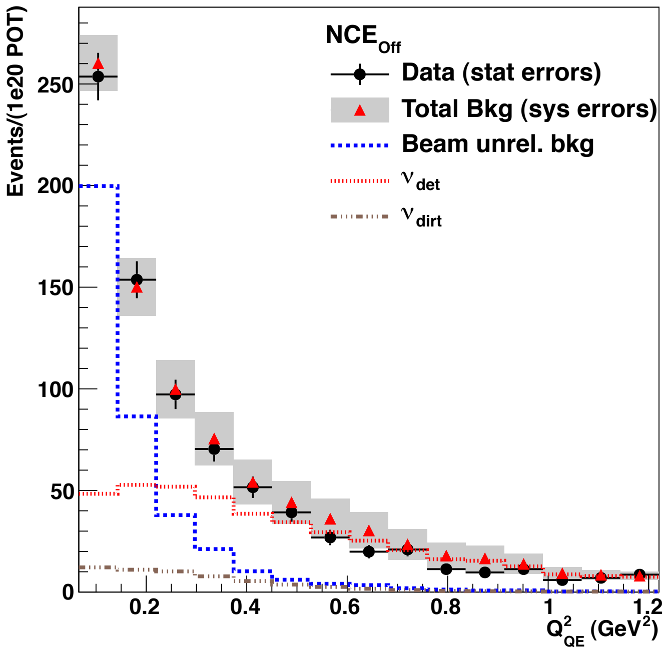
By-passing Be target is crucial for reducing the neutrino background (Richard van de Water et al. …) . Currently, suppression of ν flux ~50.

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.

On-going and future projects

From the W & C talk by Thornton, and a new paper

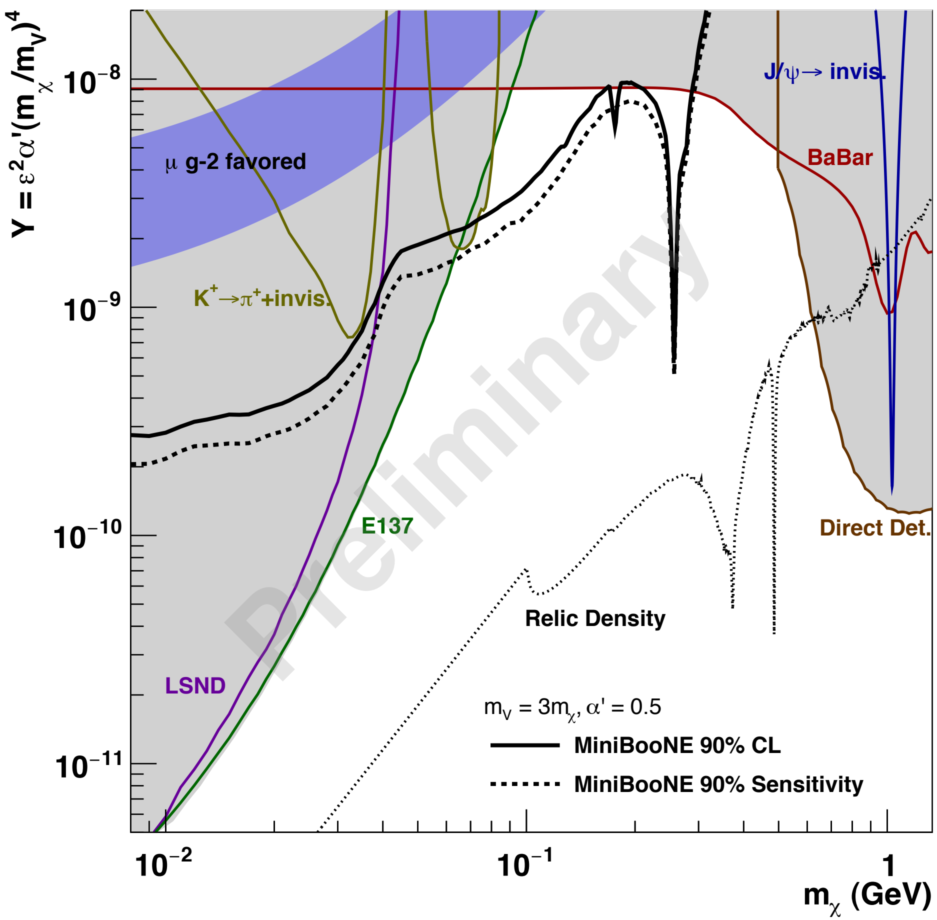


	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

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.

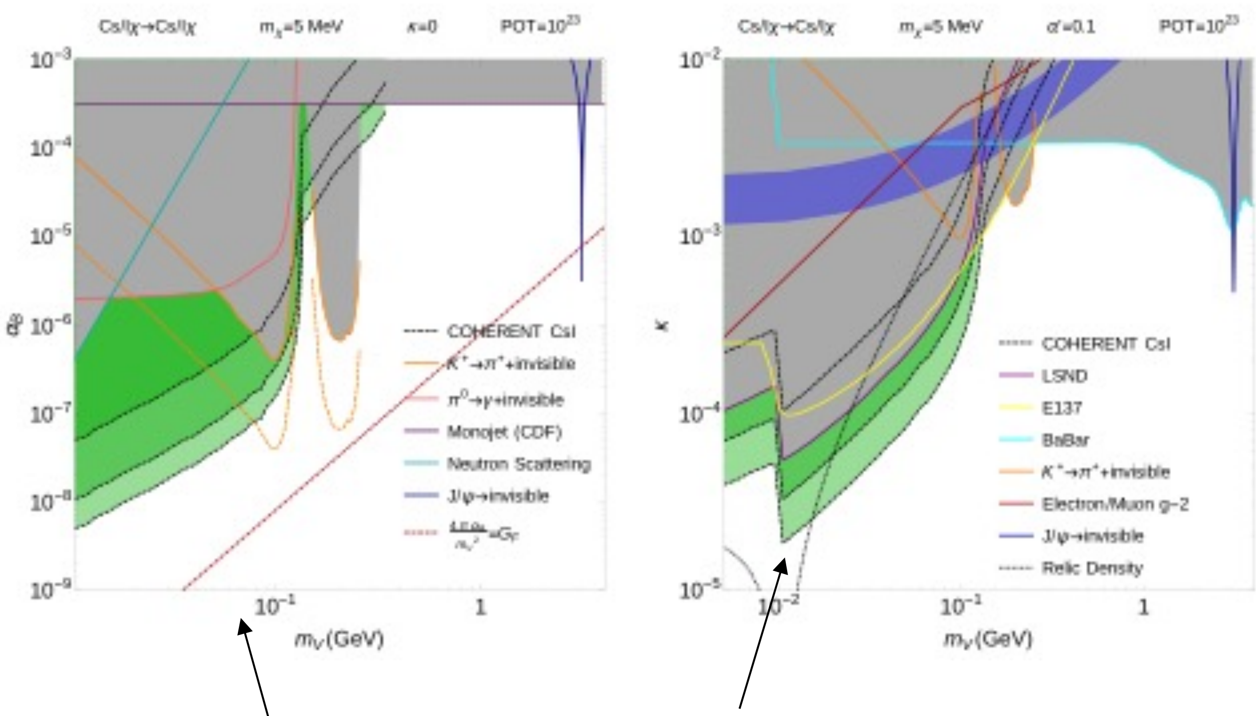
Future directions for light dark matter in collisions

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.

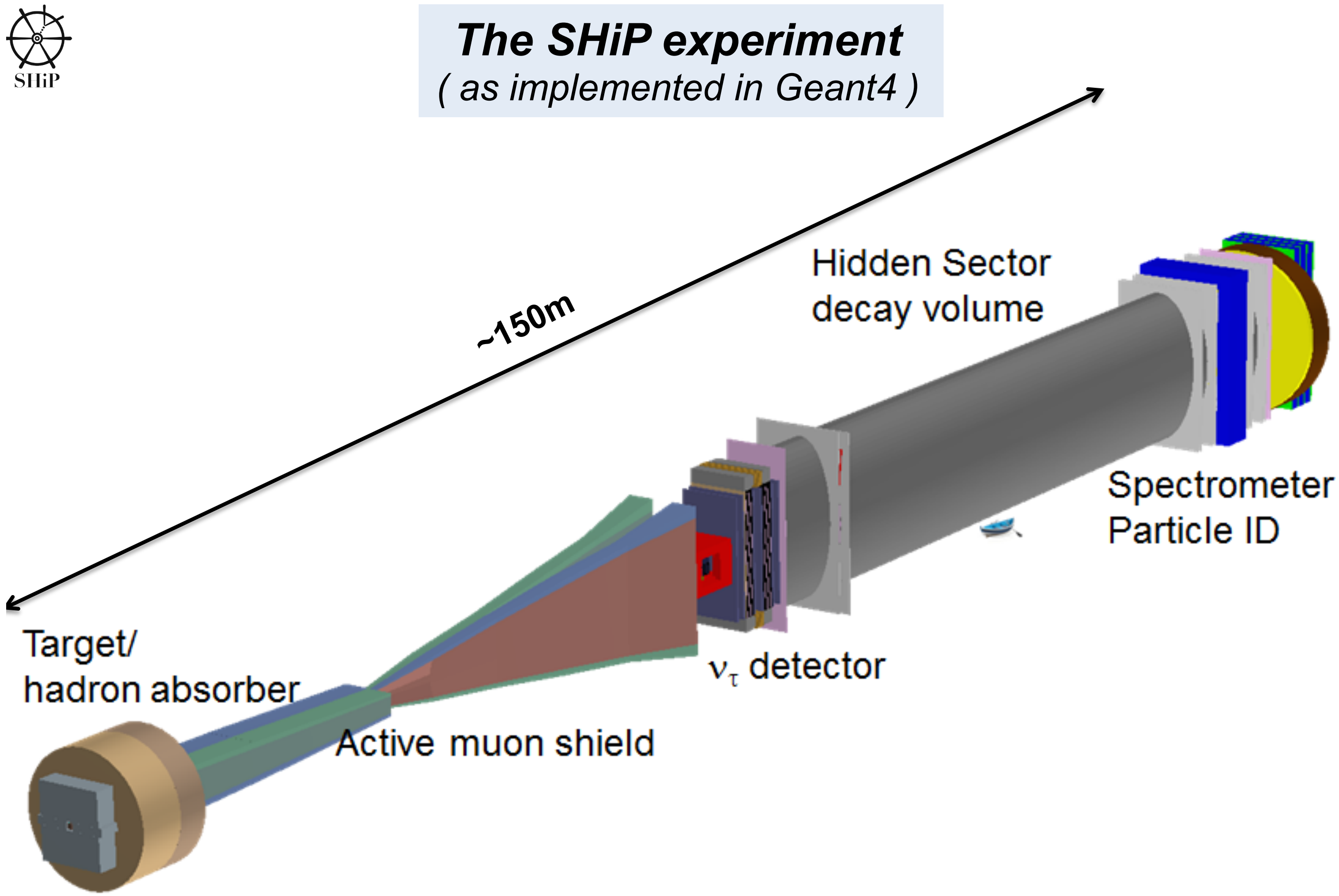
Sensitivity to light Dark Matter at COHERENT

- COHERENT will look for a coherent elastic – nucleus scattering
- It will also be sensitive to light dark matter scattering produced in the decays of π^0 to light mediators. deNiverville, MP, Ritz, 2015



Dark U(1)B and dark photons mediators

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.

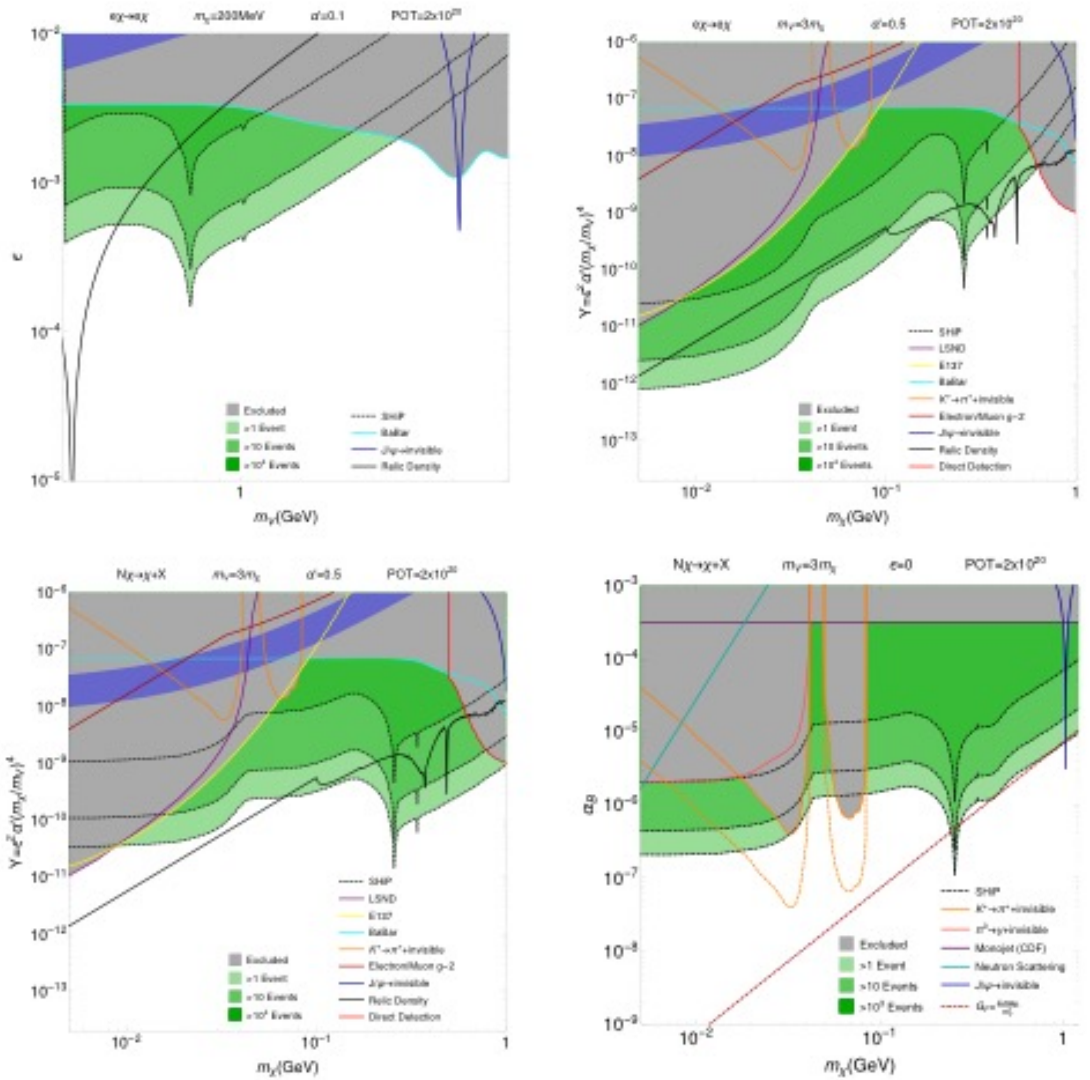


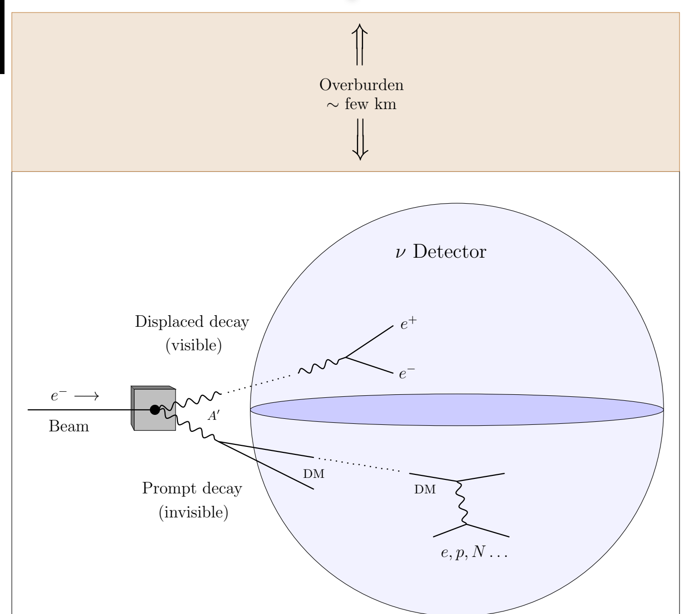
FIG. 11. Plots showing the SHiP yield of light dark matter scattering events in various channels.

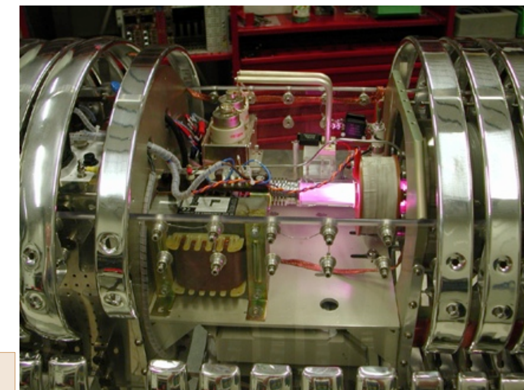
More coverage of dark sector using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2014, 2015

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

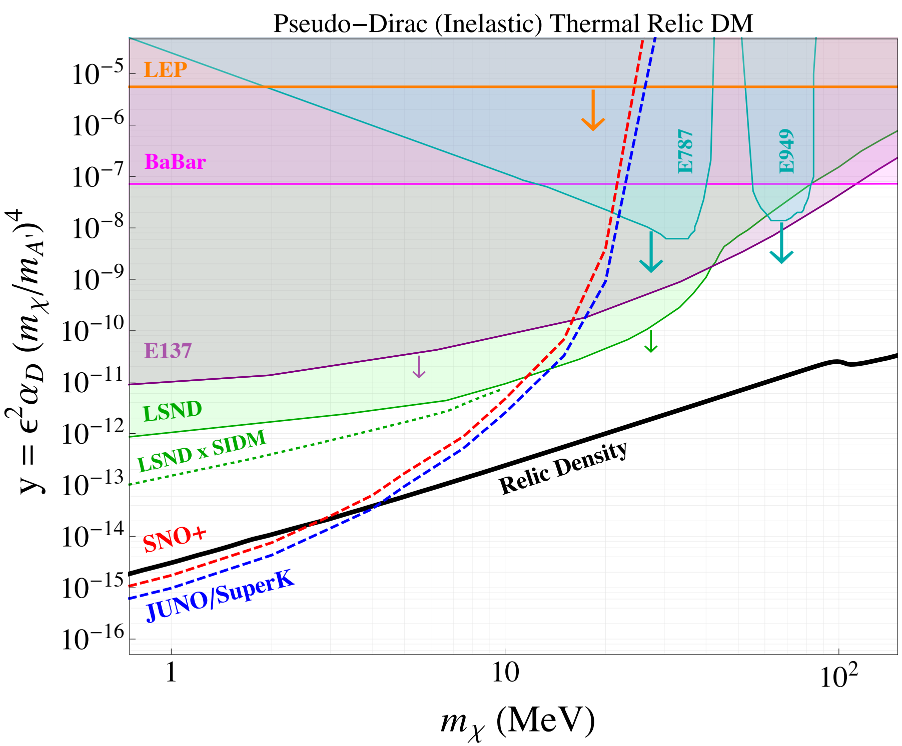
+

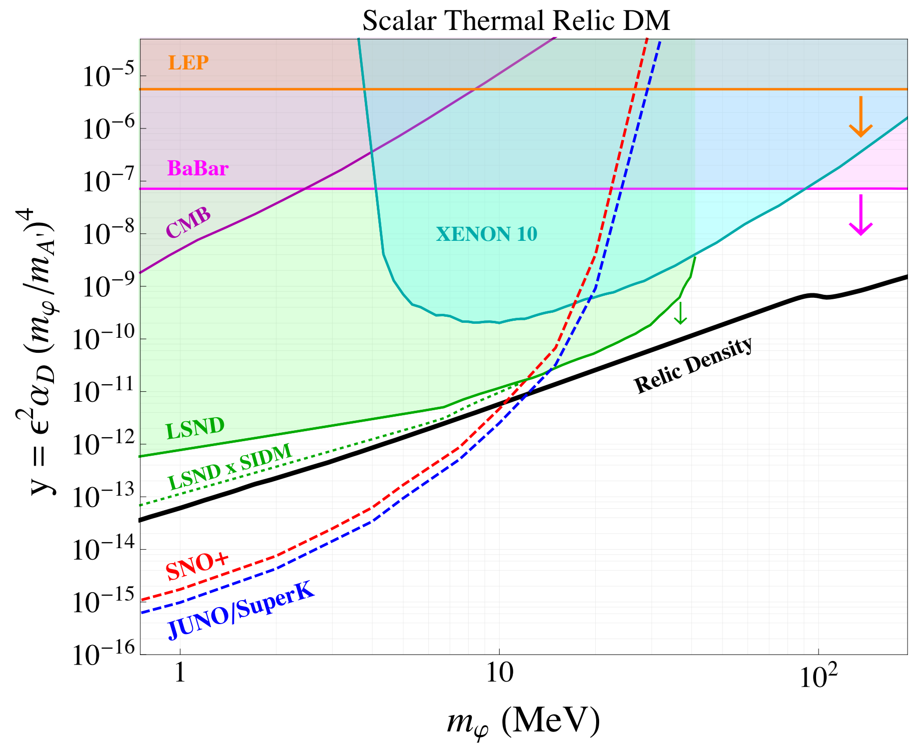




LUNA, DIANA,…, 1 e-linac for calibration

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

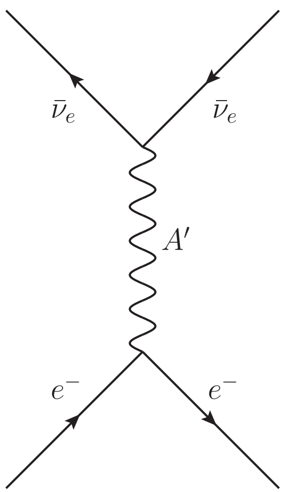
One of the topics to be discussed at a pre-TAUP meeting at PI, Jul20-22

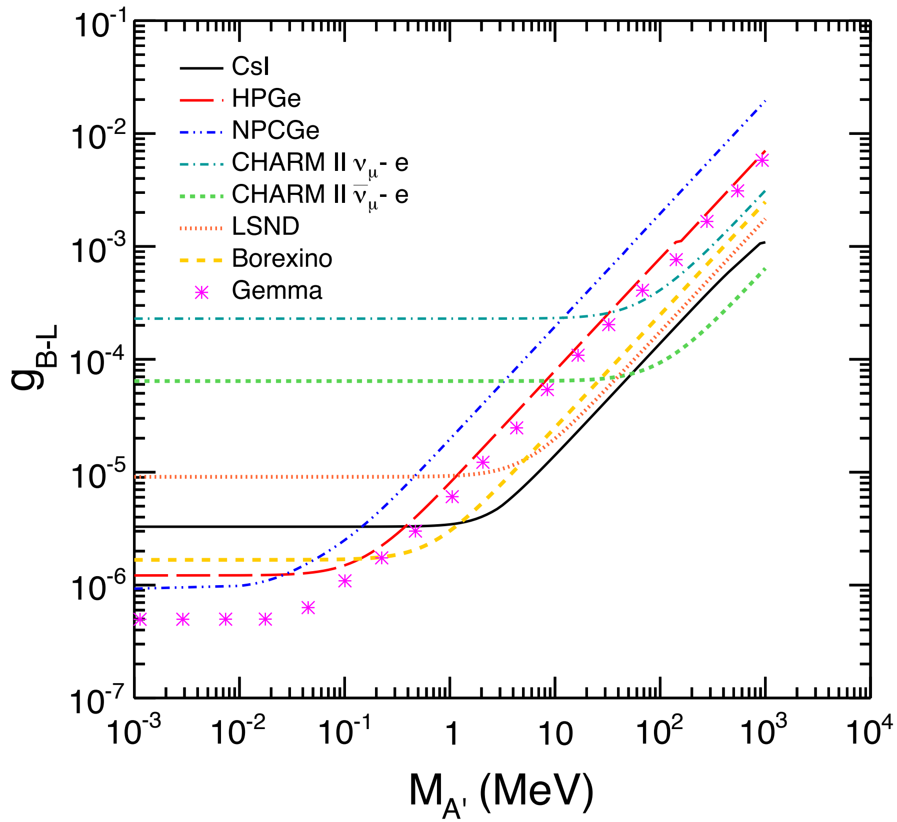
Z' in neutrino scattering

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 $U(1)_{B-L}$
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





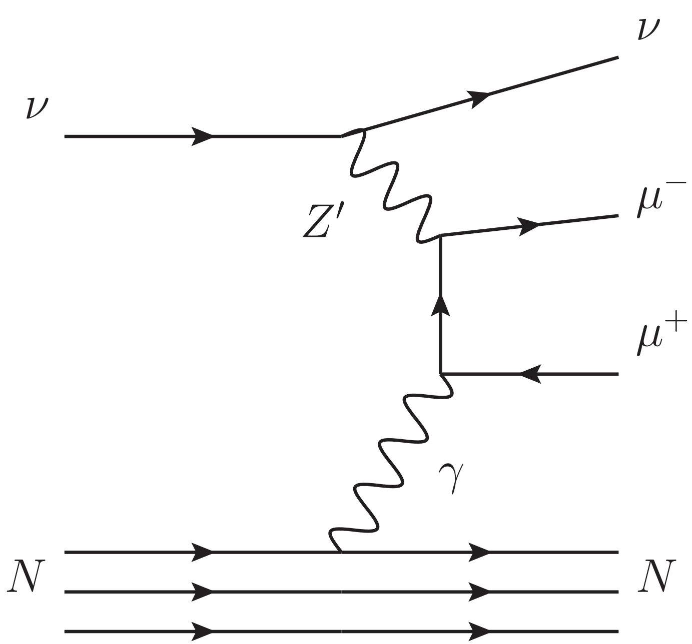
Aliev et al, 2015. Constraints follow from consistency of the SM calculations with the observed e ν → e ν scattering.

Constraints on Z' of L_μ - L_τ

Experimental results

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

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



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

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

~8-fold enhancement of cross section

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,

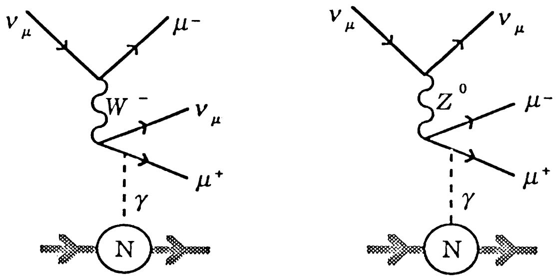


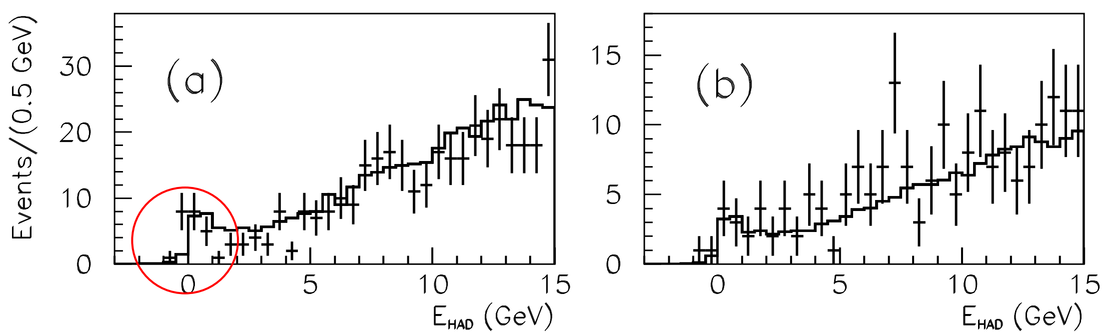
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

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

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

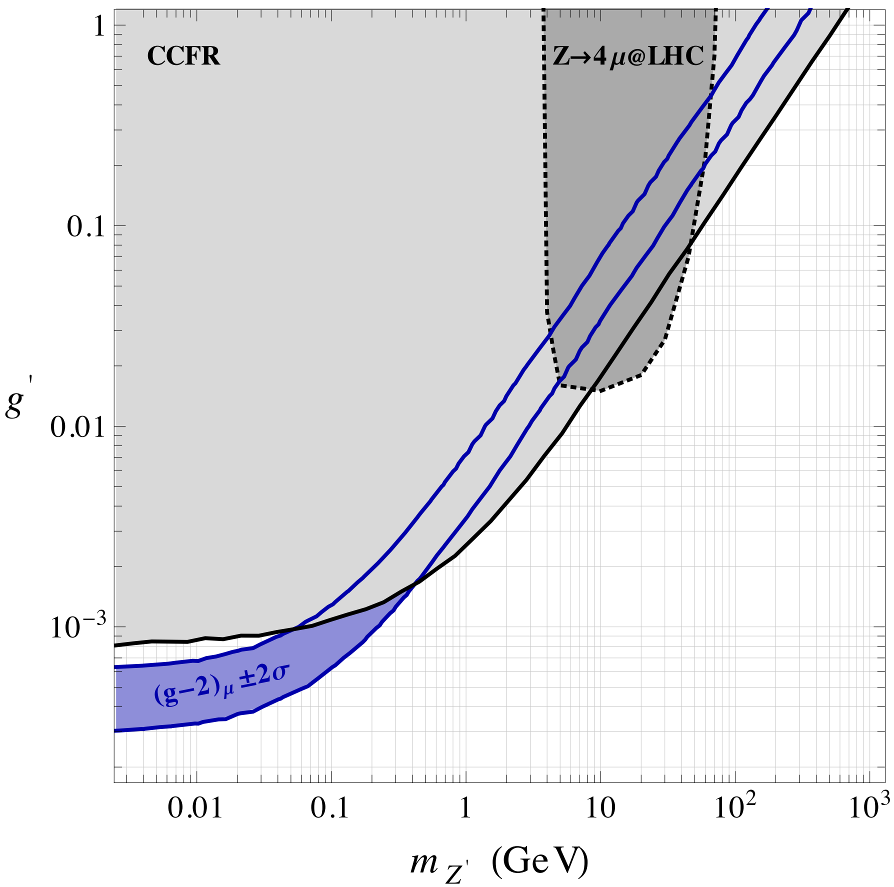
$$\text{at } \langle E_\nu \rangle = 160\ \mathrm{GeV}\,.$$

- NuTeV results:



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

Full result on $M_{Z'}$ - 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.

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. Visible displaced decays of mediators – probably – is the field where future gains in sensitivity can occur with the several liquid Ar detectors coming on-line.