Broadening the search for new physics at the intensity frontier experiments

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(thank you Brian, Roni, Paddy for putting together a wonderful workshop ! Workshop addressed issues of light dark matter and "dark forces" –possible new interactions of dark sector *)*

38 years rule = new forces of nature are discovered every 38 years for the last 150 yrs

1. 1860s – first papers of Maxwell on EM. Light is EM excitation. E & M unification.
2. 1897 – Becquerel discovers radioactivity – first evidence of weak charged currents (in retrospect).
3. 1935 – Chadwick gets NP for his discovery of neutron with subsequent checks that there exists strong n-p interaction. Strong force is established.
4. 1973 – Gargamelle experiment sees the evidence for weak neutral currents in nu-N scattering
5. 2011/2012 Discovery of the Higgs, i.e. new Yukawa force.
6. *Prediction: Discovery of a new dark force – 2050?*

(+/- 2 years or so).

Outline of the talk

1. Energy and Intensity Frontiers. Portals to SM. Implications of the LHC results.
2. "Anomalies" and various rationales for dark forces at low energy. Secluded U(1) (= dark photon) model. Possible connection to dark matter. Main features and signatures.
3. *Selected new results/ideas for secluded sectors:*

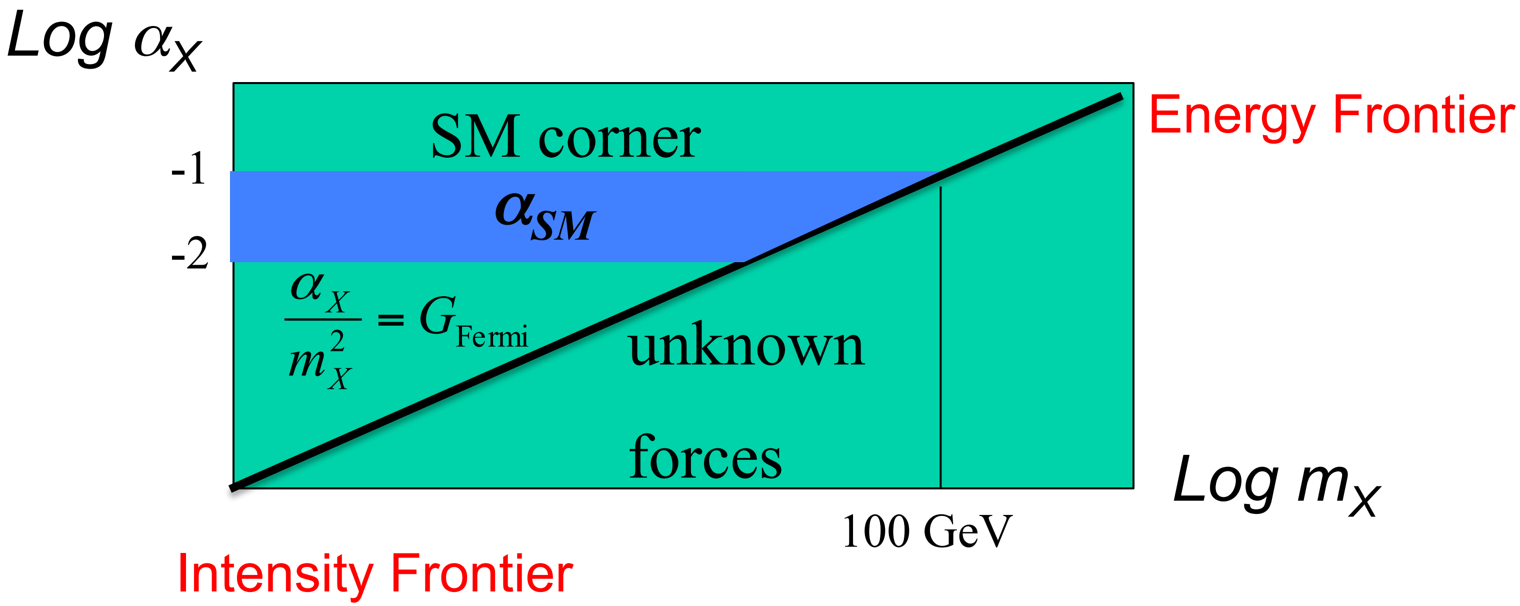
    3a. Fixed target searches of dark photons and light (MeV scale) dark matter

    3b. Constraints on leptophilic dark forces from neutrino trident production.

    3c. New physics coupled to muons? New opportunities for the future Fermilab experiments?

4. Conclusions.

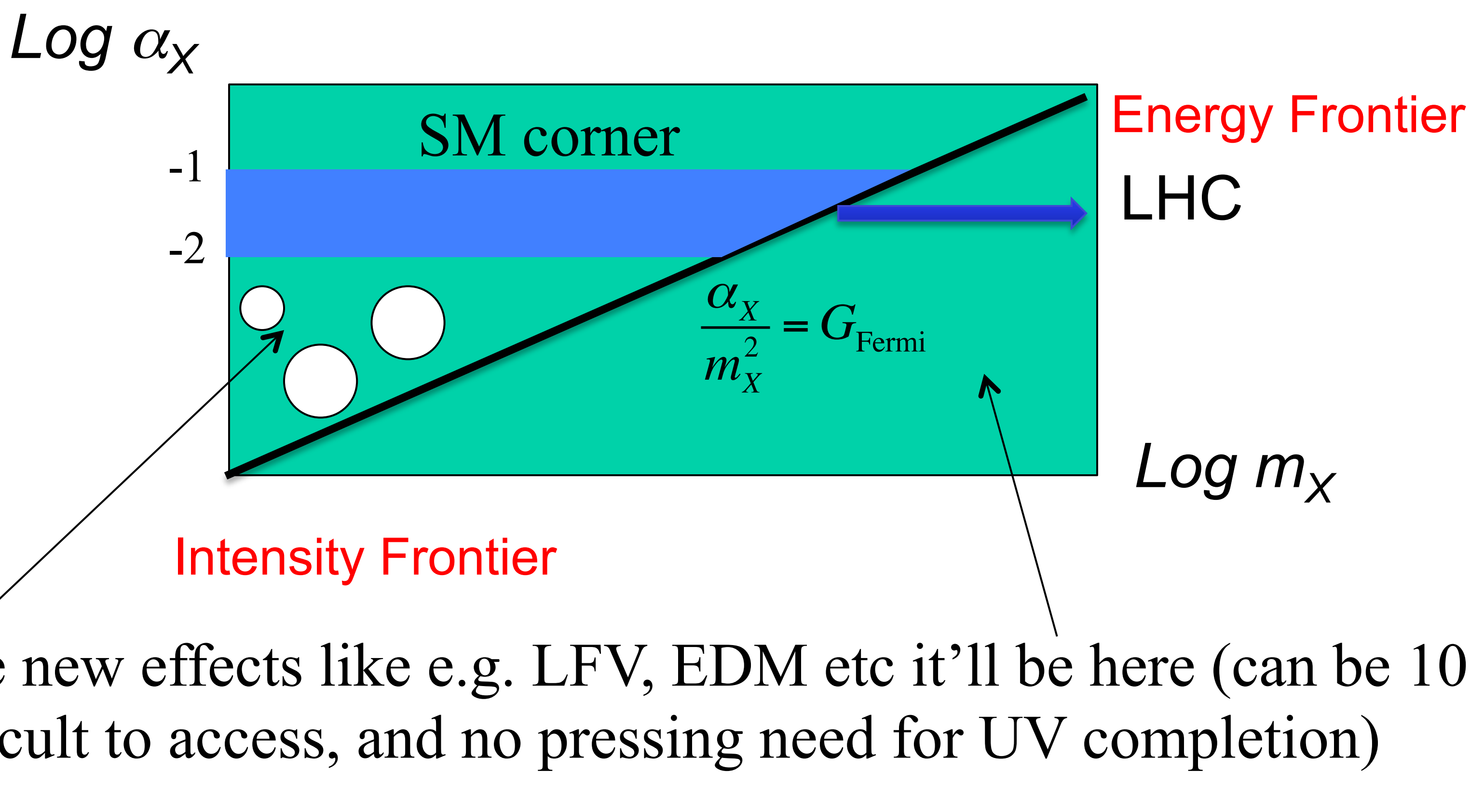
Intensity and Energy Frontiers



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

LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, while having no success with $\alpha_X < 10^{-6}$, and $m_X \sim$ GeV.

"Stronger than weak" New Physics



If you see new effects like e.g. LFV, EDM etc it'll be here (can be 1000 TeV, difficult to access, and no pressing need for UV completion)

There is a lot of "untouched" territory even for interactions that are "stronger than weak". Examples: dark photon; baryonic dark vector; gauged flavor symmetries such as L_μ-L_τ

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

$B_{\mu\nu} V_{\mu\nu}$ "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

……….

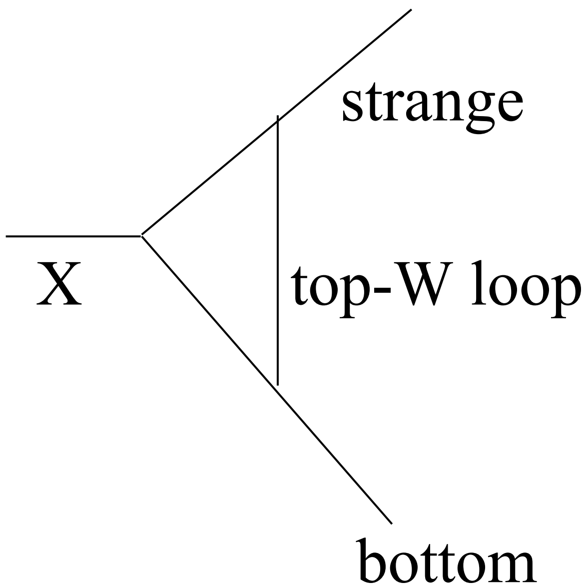
$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}^{(k)}_{\rm med}\mathcal{O}^{(l)}_{\rm SM}}{\Lambda^n},$$

Systematic searches of light new physics?

1. Broad classes of New Physics models should be investigated. These include new neutrino states (sterile or "semi-sterile"); new gauge bosons (dark photons, dark baryonic vectors, gauged lepton symmetries); new light stable particles (e.g. MeV-scale "dark matter"); new light scalars mixing with the Higgs.
2. Places such as FermiLab provide ample opportunities for such searches ← *but many possibilities remain untouched*.
3. In a systematic search the results many old experimental results can get repurposed for the new needs.
4. There are many reasonable physics searches where quick progress is possible ("low-hanging fruits").
5. Anomalies – either in particle physics, or more indirectly in astrophysics – can become the guiding principle of *where to look first*.

Why EM or baryonic 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 a conserved 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.

Recent motivations for new states/new forces below GeV

1. Theoretical motivation to look for an extra U(1) gauge group.
2. Recent intriguing results in astrophysics. 511 keV line, PAMELA positron rise, ...
3. More than a decade old discrepancy of the muon g-2.
4. New discrepancy of the muonic hydrogen Lamb shift.
5. Long-standing puzzles in neutrino experiments (LSND, MiniBooNe, …)
6. Other motivations.

….

Simplest example of a dark vector force

(Holdom 1986; earlier paper 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) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

In this talk κ = ε

Low-energy content: Additional massive photon-like vector V, and a new light Higgs h', both with small couplings.

Well over several hundred theory papers have been written with the use of this model in some form in the last four years.

"Non-decoupling" of secluded U(1)
Theoretical expectations for masses and mixing

Suppose that the SM particles are not charged under new $U_S(1)$, and communicate with it only via extremely heavy particles of mass scale Λ (however heavy!, e.g. 100000 TeV) charged under the SM $U_Y(1)$ and $U_S(1)$ (B. Holdom, 1986)

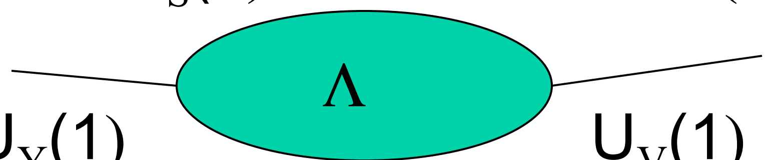


Diagram $U_Y(1)$ $U_V(1)$ does not decouple!

A mixing term is induced, $\kappa\, F^Y_{\mu\nu} F^S_{\mu\nu}$,

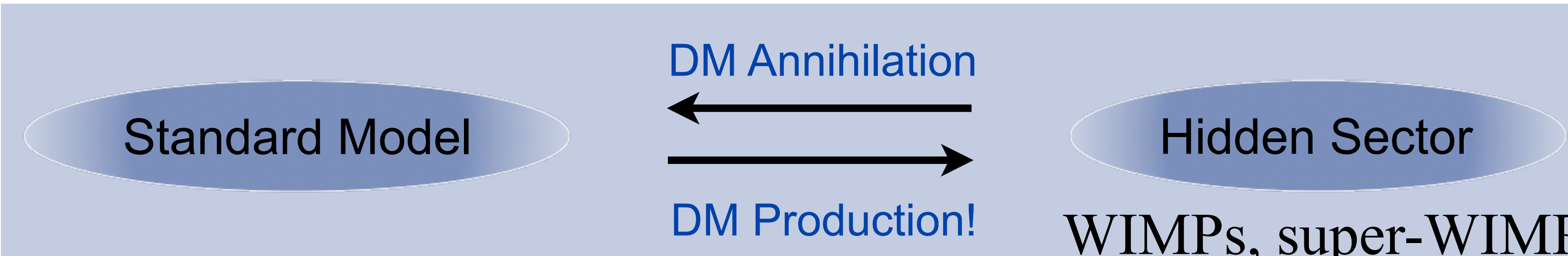
With κ having only the log dependence on mass scale Λ

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

$M_V \sim e'\kappa M_{EW}$ (M_Z or TeV) ~ MeV – GeV

This is very "realistic" in terms of experimental sensitivity range of parameters.

Possible connection to WIMP-y dark matter



WIMPs, super-WIMPs

Mediators (SM Z, h etc or dark force)

Heavy WIMP/heavy mediators: - "mainstream" literature

Light WIMPs/light mediators: Boehm et al; Fayet; MP, Ritz, Voloshin; Hooper, Zurek; others

Heavy WIMPs/light mediators: Finkbeiner, Weiner; Pospelov, Ritz, Voloshin (secluded DM); Arkani-Hamed et al., many others

Light WIMPs/heavy mediators: does not work. (Except for super-WIMPs; or non-standard thermal history)

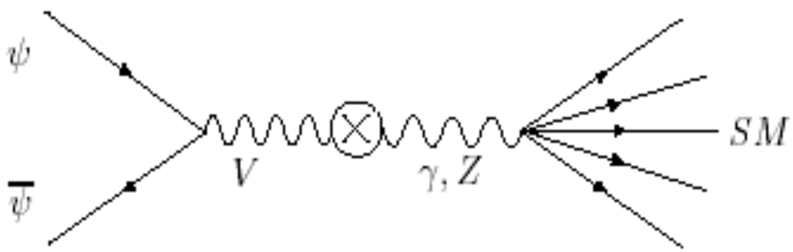
Light mediators allow to speculatively tie several anomalies to the possible effects of WIMP dark matter.

Secluded WIMP idea – heavy WIMPs, light mediators

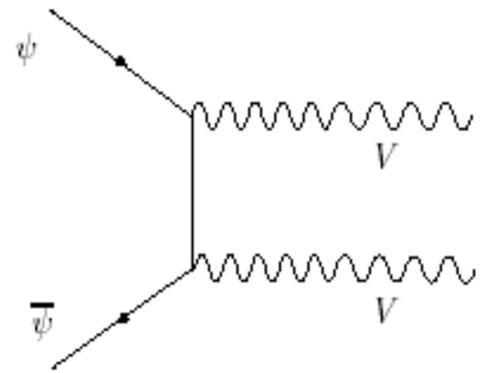
$$\mathcal{L}_{\text{WIMP+mediator}} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

ψ – weak scale Dark Matter; V –mediator particle.

$m_{mediator} > m_{WIMP}$



$m_{mediator} < m_{WIMP}$



Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle κ.

It turns out *this helps* to tie PAMELA positron rise and WIMP idea together. Can be successfully used to model recent galactic γ-excess.

Astrophysical motivations: 511 keV line

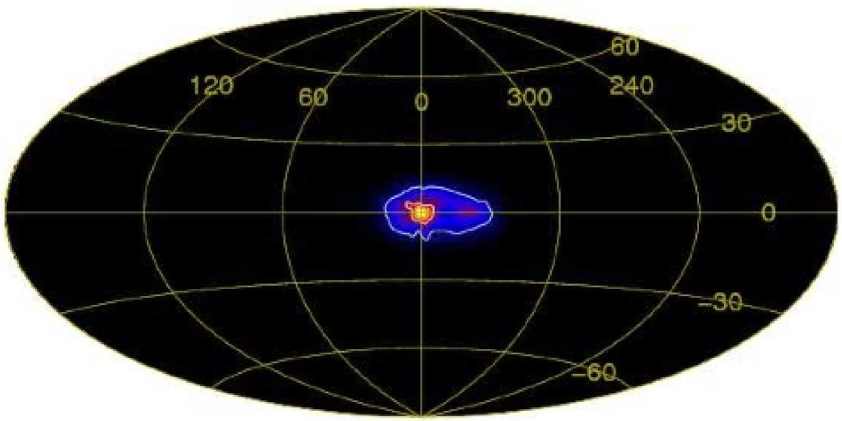


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

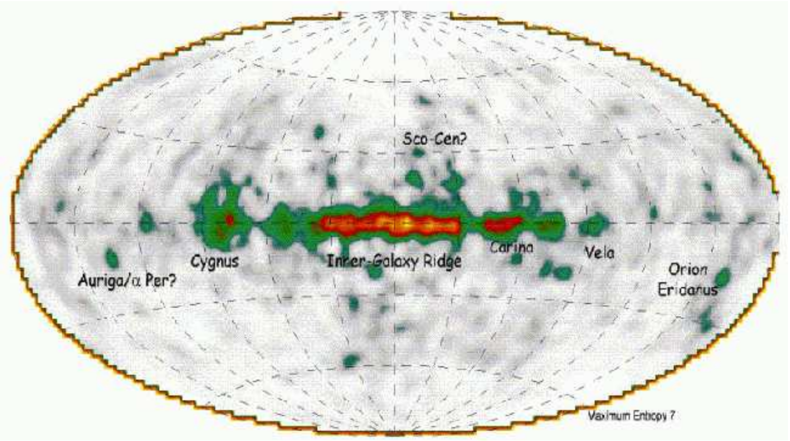
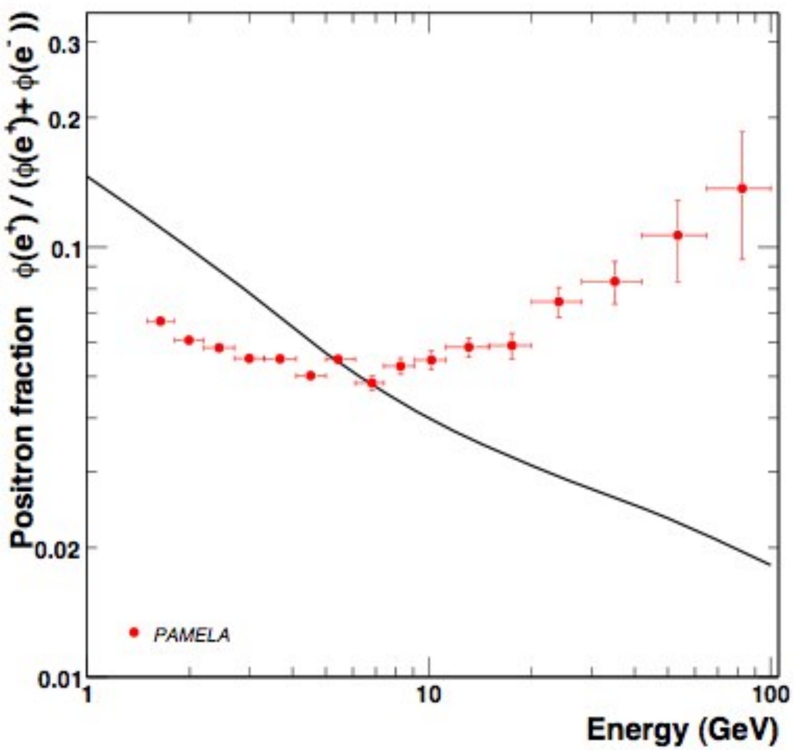


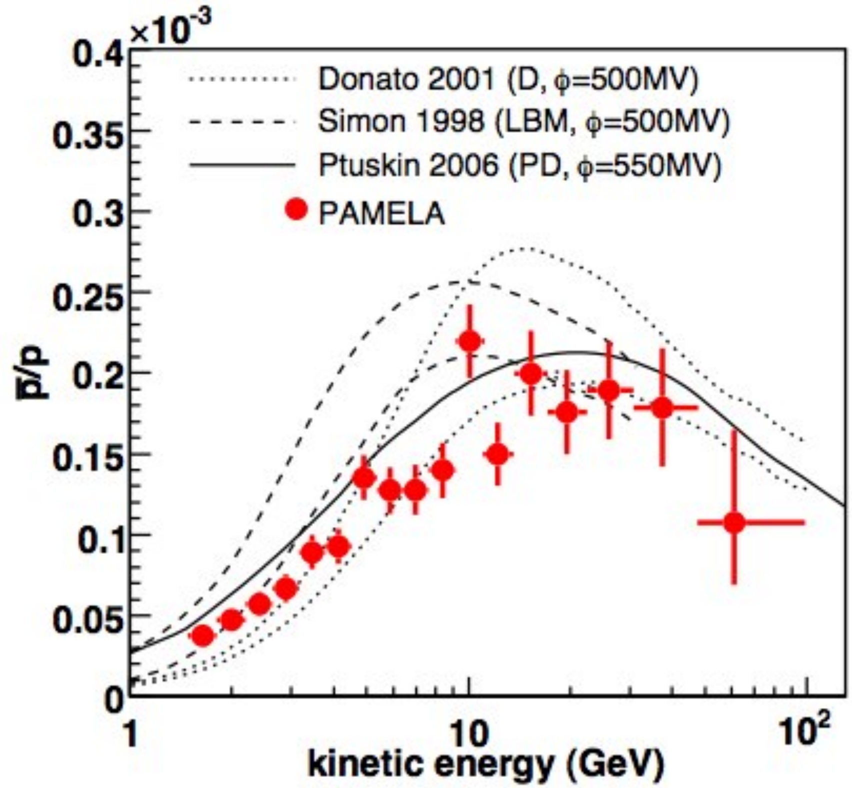
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

There is a lot more positrons coming from the Galactic Center and the bulge that expected. The emission seems to be diffuse.

1. Positrons transported into GC by B-fields?
2. Positrons are created by episodic violent events near central BH?
3. Positrons being produced by DM? Either annihilation or decay?

PAMELA positron fraction

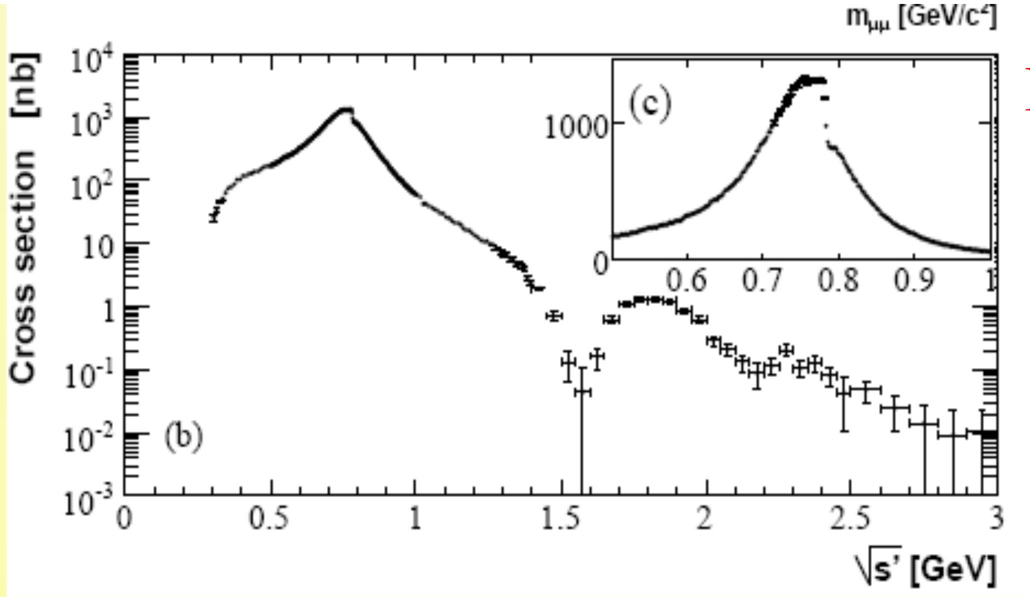




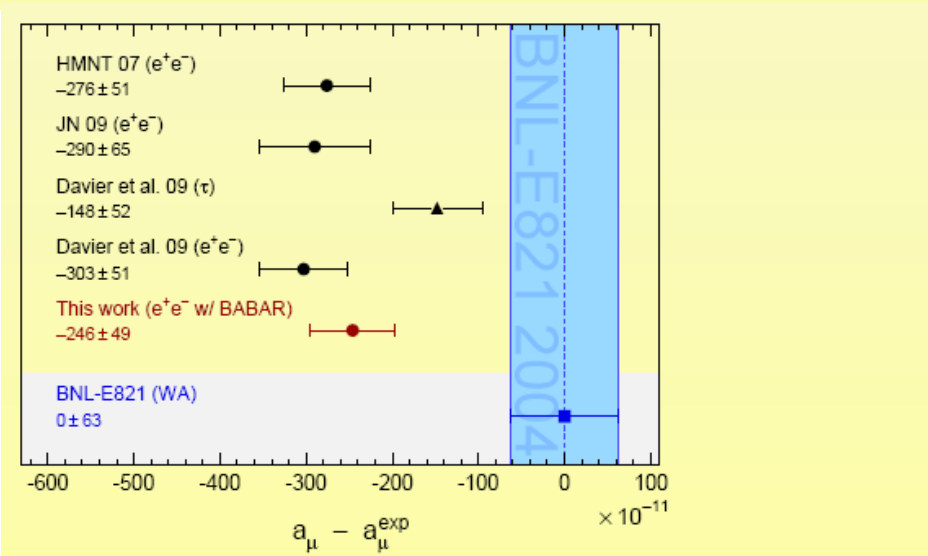
No surprises with antiprotons, but there is seemingly a need for a new source of positrons!

This is a "boost" factor of 100-1000 "needed" for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because <σv > is too small. Enhancing it "by hand" does not work because WIMP abundance goes down. Dark forces allow bridging this gap due to the late time enhancement by Coulomb (Sommerfeld).

g-2 of muon



More than 3 sigma discrepancy for most of the analyses. Possibly a sign of new physics, but some complicated strong interaction dynamics could still be at play.

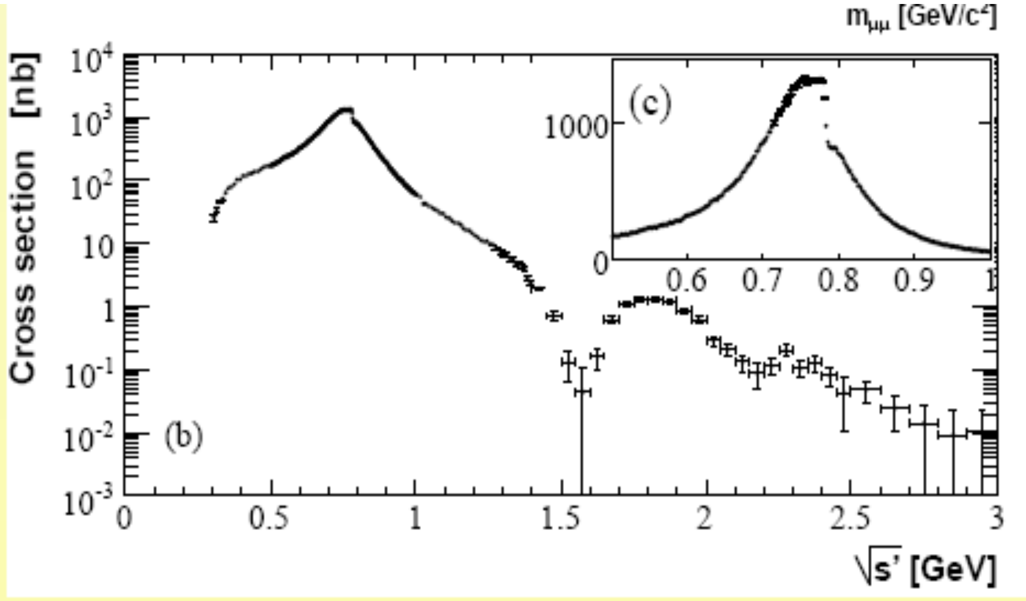


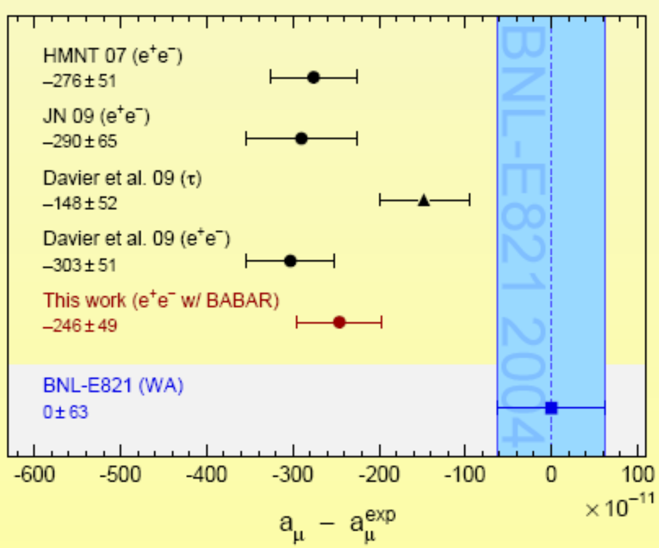
✱ Davier et al. arXiv:0906-5443

Supersymmetric models with large-ish *tanβ*; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

Sub-GeV scale vectors/scalars can also be at play.

g-2 of muon





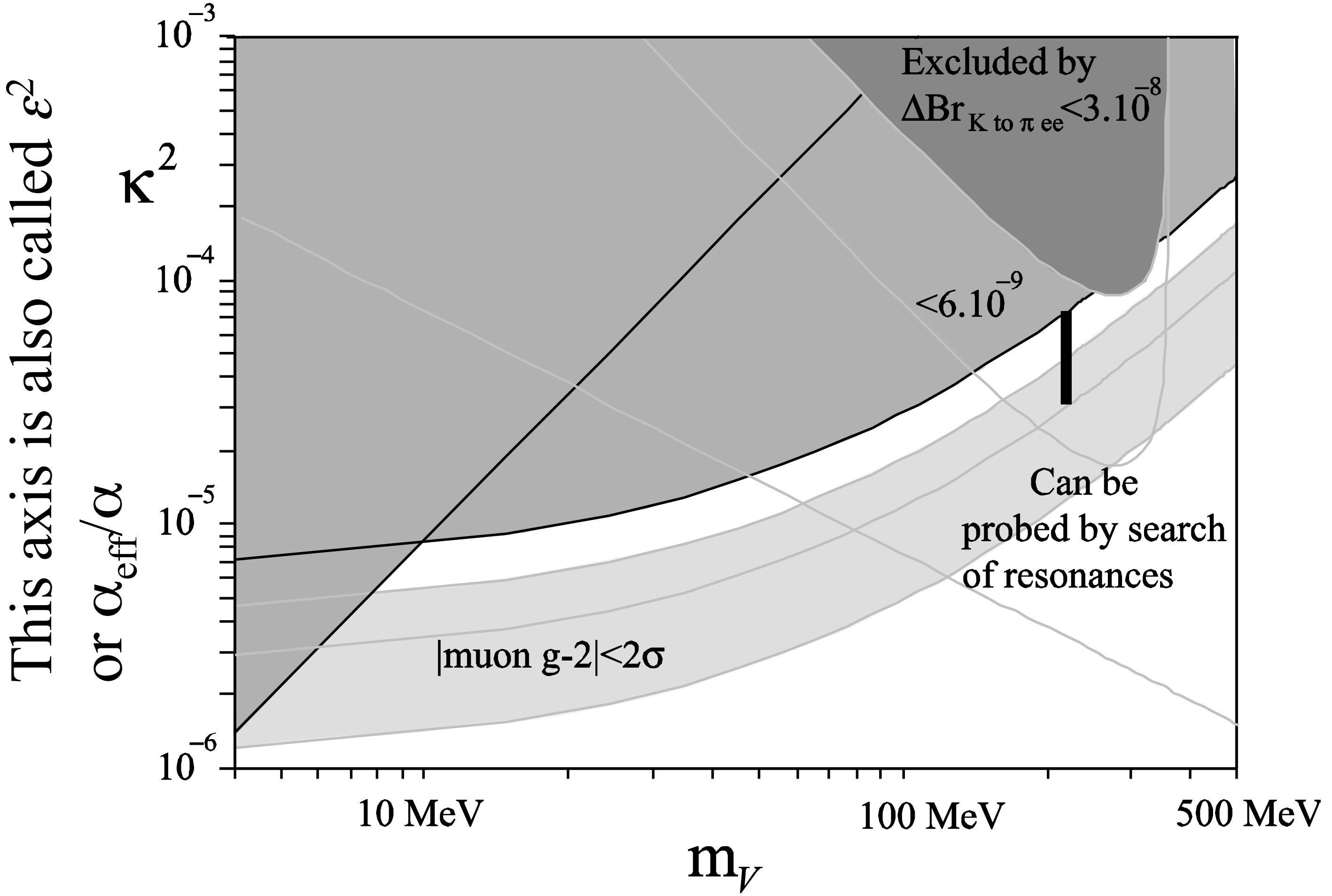
✱ Davier et al. arXiv:0906-5443

Upcoming Fermilab muon g-2 experiment aims at shrinking the experimental error bar by a factor of ~ 4.

κ-m_V parameter space

If g-2 discrepancy taken seriously, a new vector force can account for deficit. (Krasnikov, Gninenko; Fayet; Pospelov)

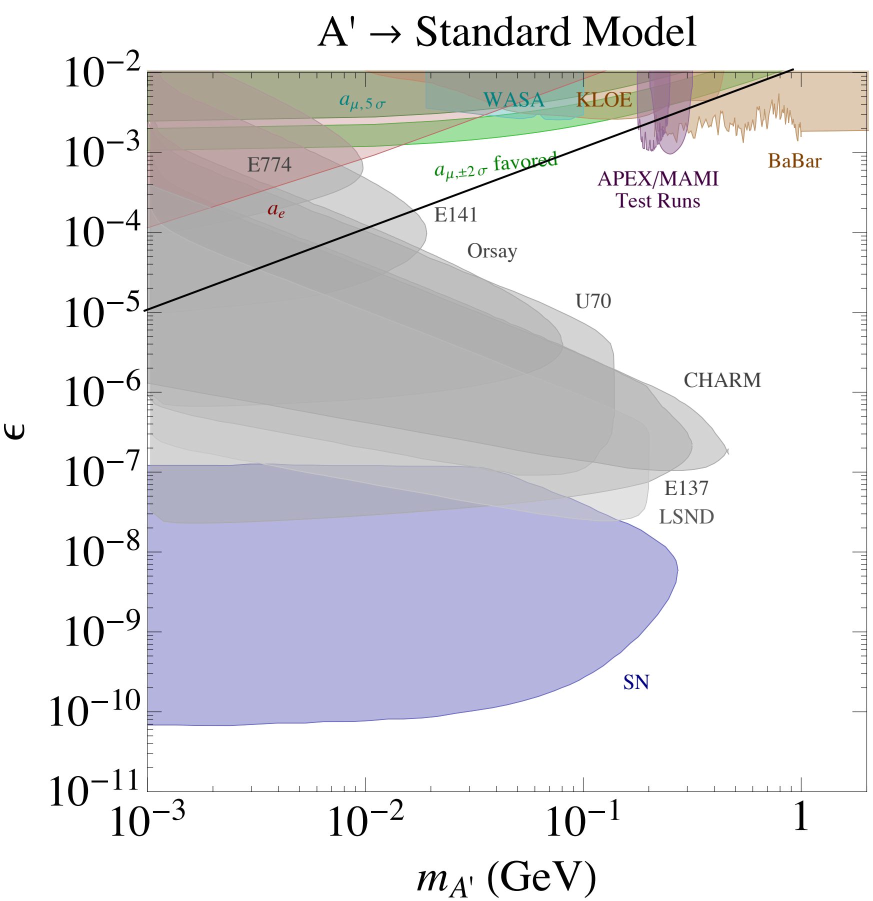
E.g. mixing of order few 0.001 and mass $m_V \sim m_\mu$

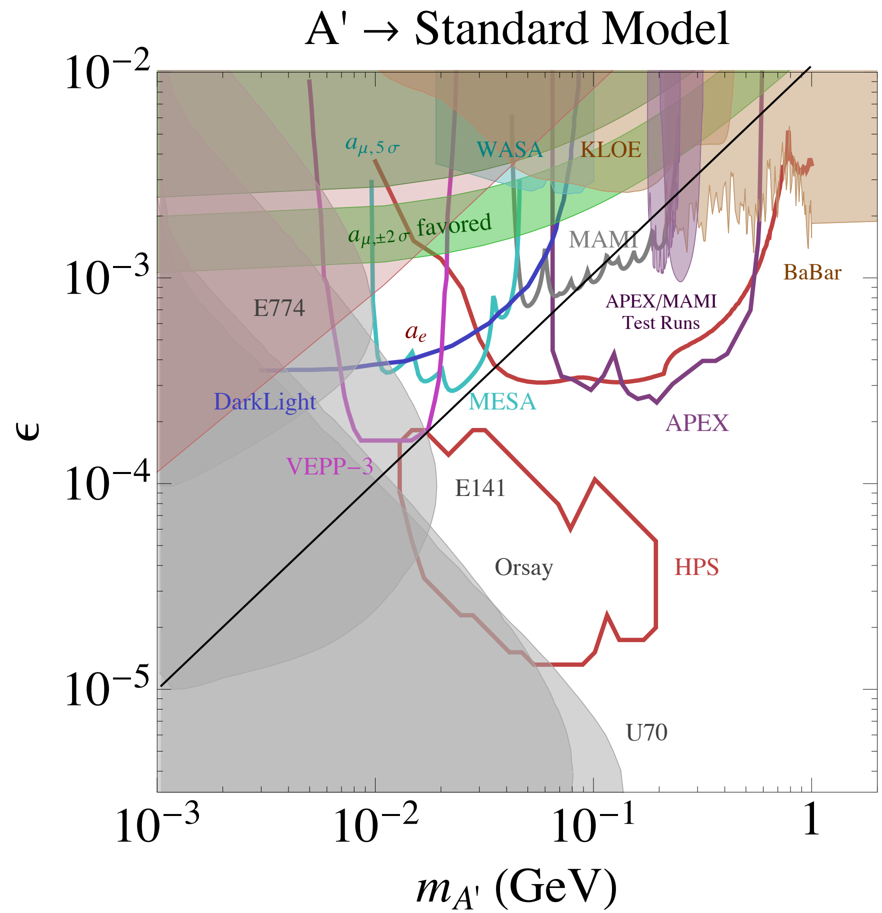


MP, 2008

Since 2008 a lot more of parameter space got constrained

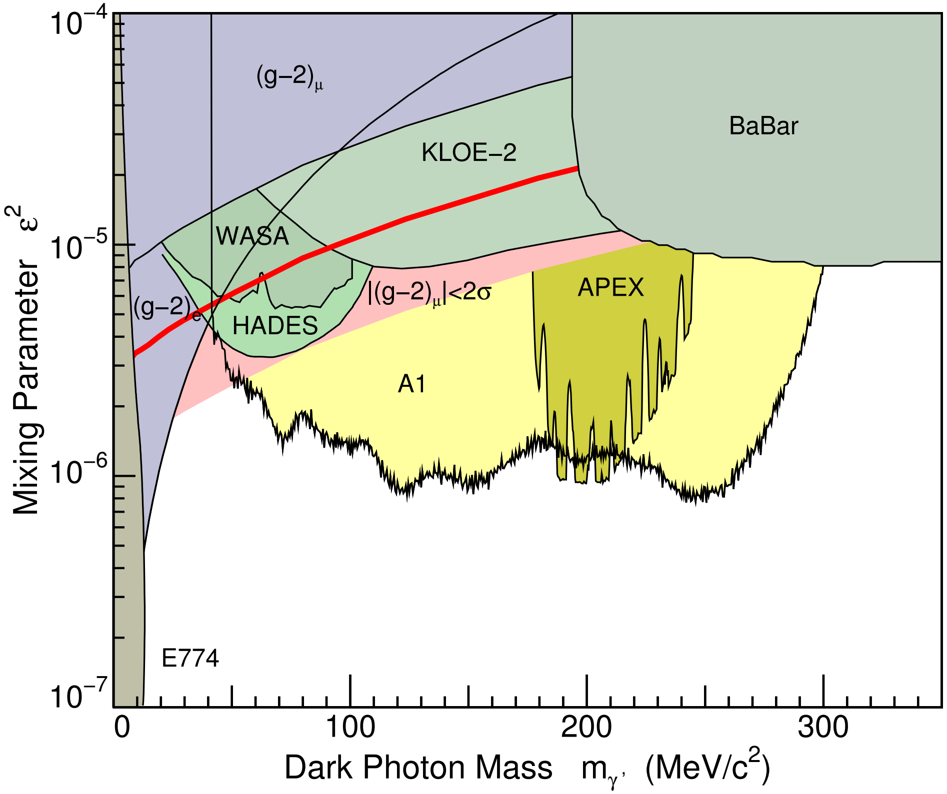
κ-m_V parameter space, Essig et al 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, and soon the g - 2 ROI will be completely covered. *Gradually, all parameter space in the "SM corner" gets probed/excluded.*

Newest results from Mainz A1



H. Merkel et al., April 2014.

Gradually all g-2 ROI gets excluded in this minimal model.

New Babar results are expected any time now: M.Graham, this meeting

Other reasonable scenarios of dark vector force?

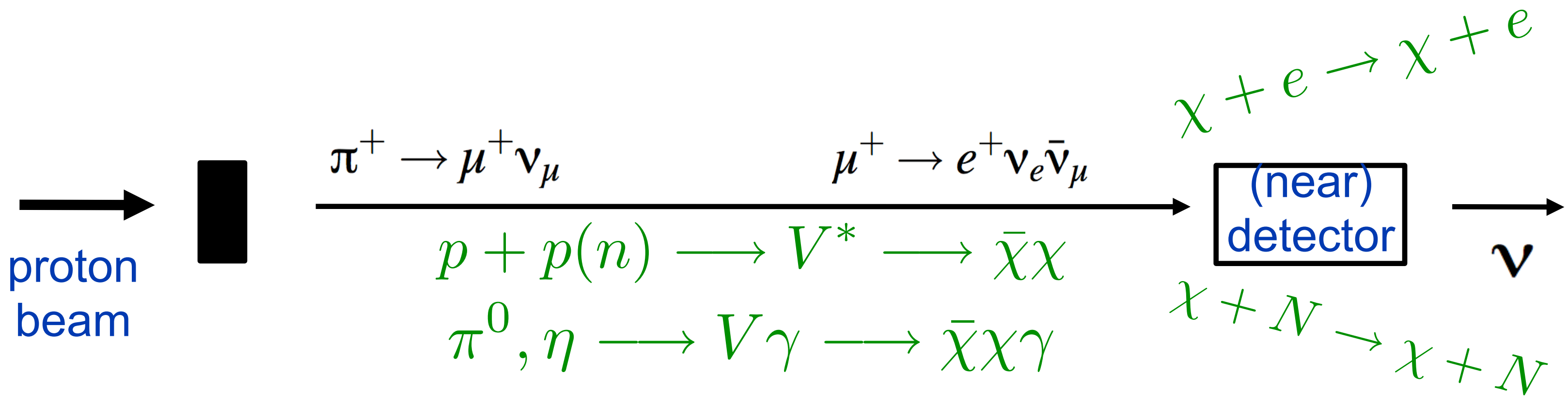
1. Many of the existing bounds will not apply if the "dark photon" is even more "dark": once produced it can decay to V → 2 DM particles, depleting visible modes. We can turn it around and use as an opportunity to search for light DM (which is e.g. being suggested in connection with 511 keV excess, Boehm et al, 2003).

2. There are other reasonable examples of "*leptophilic*" dark forces that can be easily lead to the deviation of muon g-2, such as gauged lepton number L_μ-L_τ etc. In this case, one should expect extra effects for *neutrinos*. (…, Glashow et al, …)

3. There is also a very reasonable example of "leptophobic" portal, $V_\mu q \gamma_\mu q$, very poorly constrained by direct experiments (McKeen; Frugiuele, this meeting), where Fermilab is uniquely positioned to make progress.

Fixed target probes - Neutrino Beams

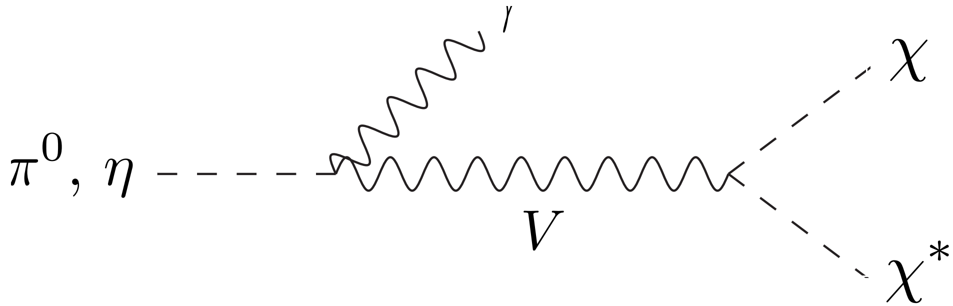
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

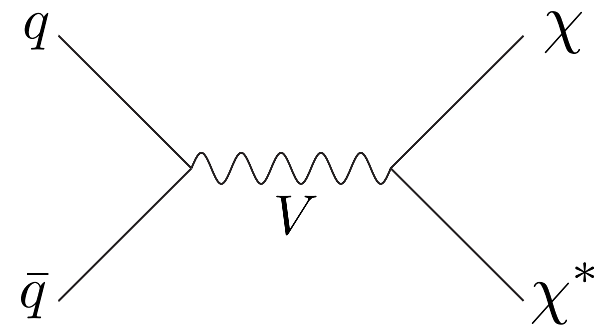


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

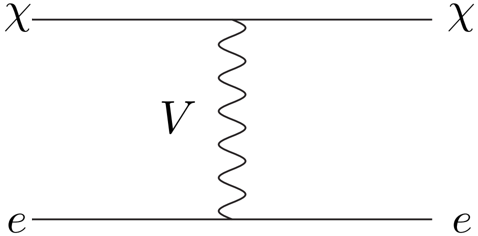
Illustration of the main idea



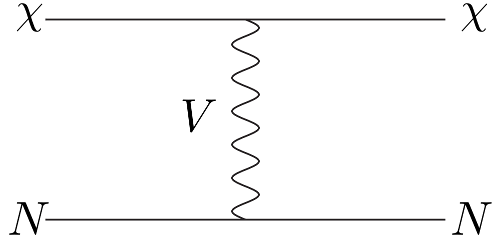


In the detector:

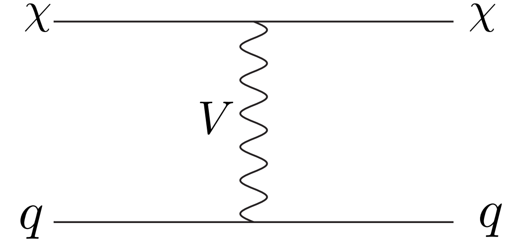
Elastic scattering on electrons



Elastic scattering on nucleons



Deep inelastic scattering



From D. McKeen talk.

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.

Comparison of Neutrino and light DM

Neutrinos:

Production:

Strong scale $\sigma \sim 100$ mbn

Detection:

Weak scale $\sigma \sim G_F^2 E_{cm}^2$

Light WIMPs:

Production:

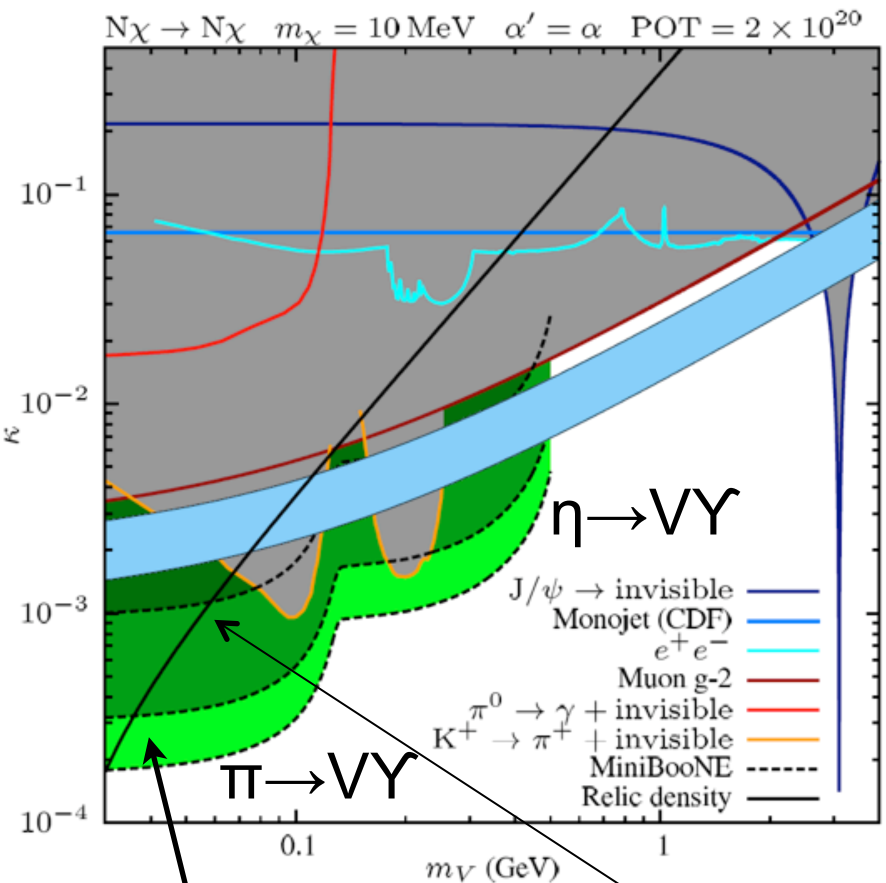
$\sigma \sim \sigma_{\text{strong}} \times \varepsilon^2$

Detection:

Larger than weak scale!

Signals $\sim \sigma_{\text{production}} \times \sigma_{\text{detection}}$ can be of comparable strength

The reason for "stronger-than-weak" force for light dark matter comes from the Lee-Weinberg argument. (The weak-scale force will be *insufficient* in depleting WIMP DM abundance to observable levels if m_{DM}< few GeV. Therefore, stronger-than-weak force and therefore relatively light mediator is needed for sub-GeV WIMP dark matter).



10, 10^3, 10^6 events

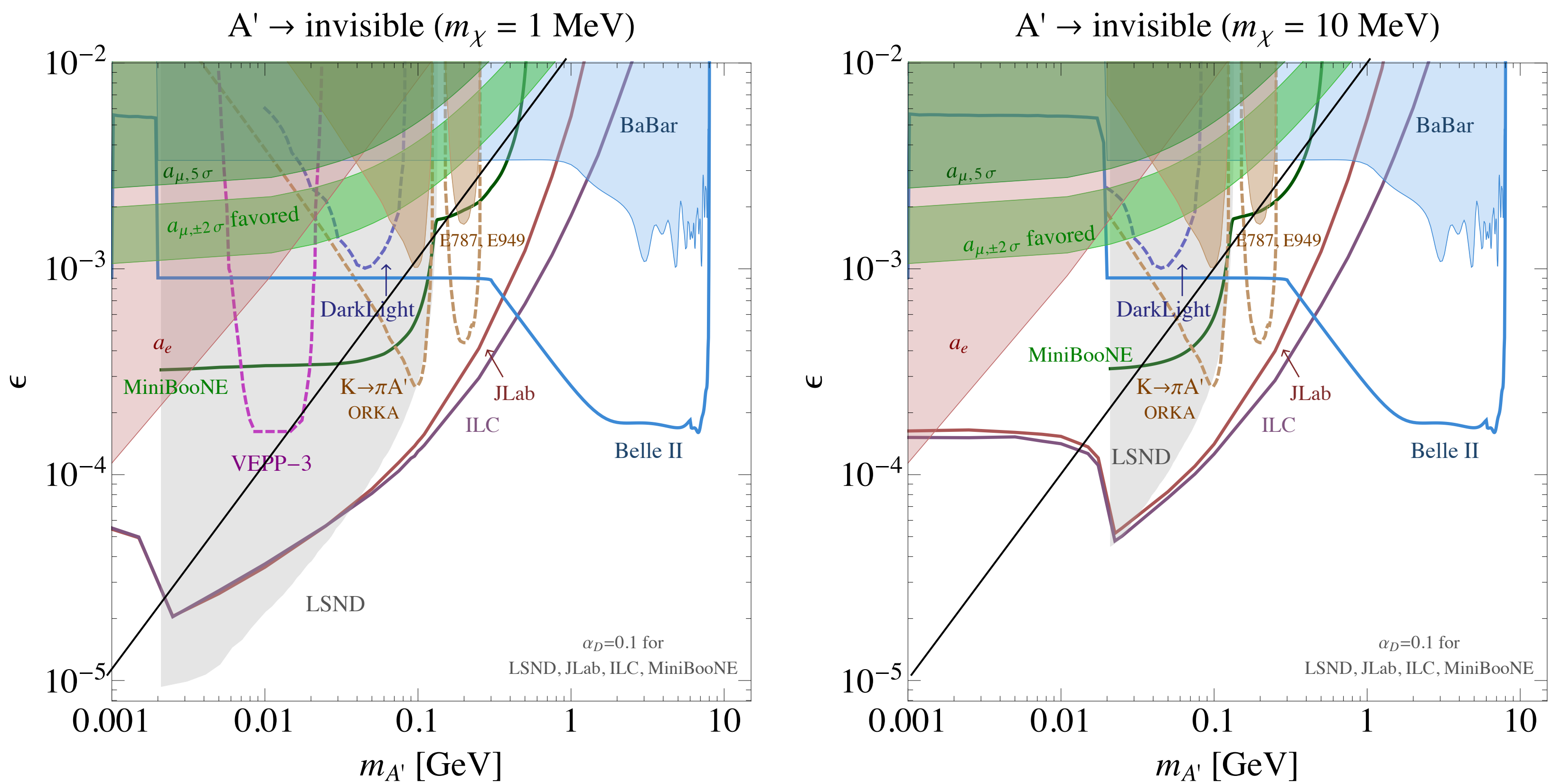
Batell, deNiverville, McKeen, MP, Ritz

MiniBooNE sensitivity – quite a bit of new ground can be covered.

There is an on-going run by the experiment in the off-target mode to reduce the neutrino background

(In the simplest model, existing searches do cover the region of parameter space compatible with the correct relic abundance)

Compilation of current constraints on dark photons decaying to light DM



The sensitivity of electron beam dump experiments to light DM is investigated in Izaguirre, Krnjaic, Schuster, Toro 2013; Surujon et al.

Looking into the future…

- Future Fermilab experiments **MicroBooNE, Nova, LBNE** (may be *new* beam dump experiments) will all have decent sensitivity to studies of light new states (either pair-produced in the target/beam dump and scattering in the near detector, or singly produced with subsequent decay.)
- Some thoughts should be invested into determining what the best strategy is too achieve the main goals of the experiments aimed at neutrino physics, and at the same time extracting maximum sensitivity to the new light states beyond SM. (New ideas at the workshop, J. Yu; R. van de Water)
- Further theoretical efforts should be spent onto diversifying away from the simplest model (e.g. dark photon) as it may not capture all the interesting physics that can be studied in these experiments.

Leptonic dark force

New theoretical angle ("dark force" at the intensity frontier) often brings back to focus some old experimental results that at the time nobody considered as "probes" of new physics.

Altmannshofer, Gori, MP, Yavin, 2014.

There are some flavor symmetries in the SM that can be gauged without much problem: L_μ-L_τ, $B - 3L_\mu$,… Some of these combinations have no gauge anomalies, and so are UV safe. These symmetries could

- Also be responsible for the muon g-2 "anomaly-of-the-anomaly"
- Lead to interesting collider signatures
- Be phrased as "non-standard neutrino interactions", leading to $(q\gamma_\mu q)\times(\nu\gamma_\mu\nu)$ etc.

Evidently, there is much less room for the "stronger-than-weak" forces.

Example: gauged L_μ - L_τ symmetry

Altmannshofer, Gori, MP, Yavin, 2014.

- This is the *least constrained* possibility because neither electrons nor nucleons have extra interactions with neutrinos.
- However, g-2 is corrected in the "right direction" and to make connection with previous plots, one should take $e \times \kappa \rightarrow g'$.
- LHC provides decent sensitivity to the model with sizable g' and $m_{Z'}$ > few GeV via Z → 4 muons. Excludes g-2 solution for $m_{Z'} > 30$ GeV.
- Rather old but remarkable results on neutrino trident production (CHARM-II, CCFR, NuTeV) provide the strongest constraint on this model.

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,

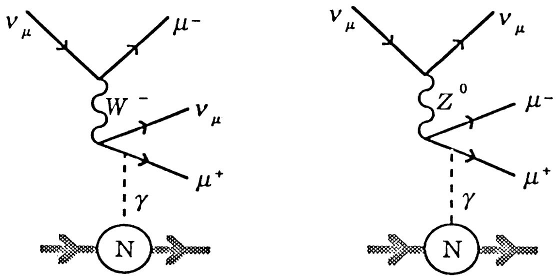


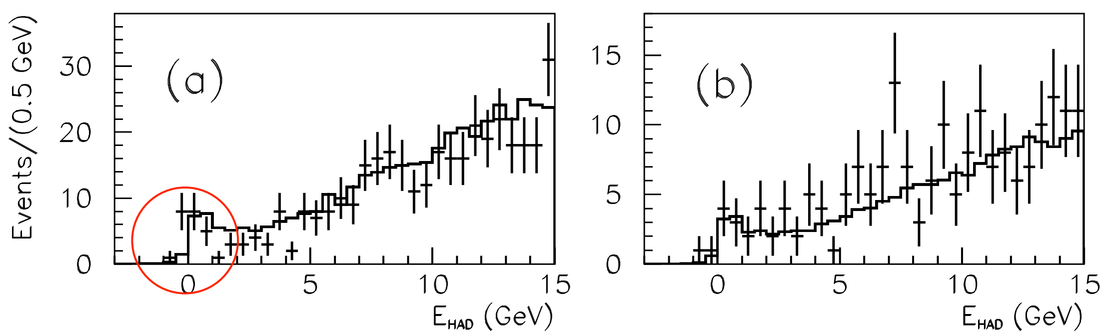
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

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

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

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

- NuTeV results:



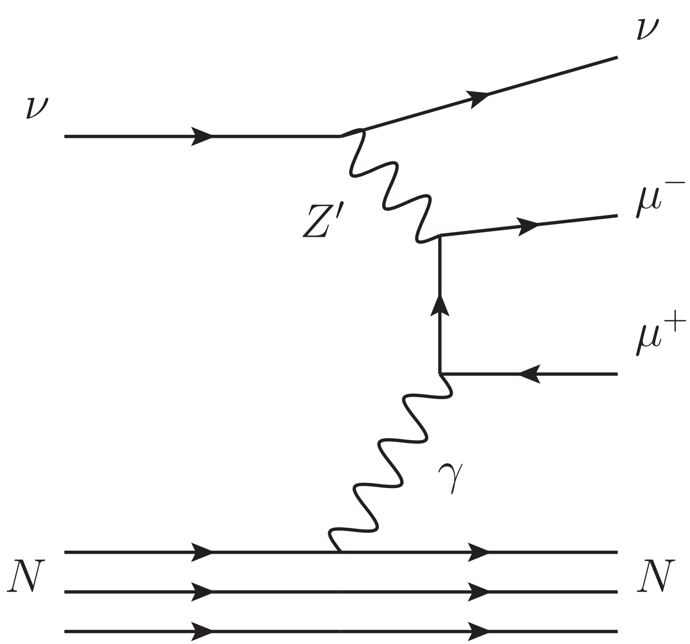
Trident production was seeing with O(20) events, and is fully consistent with the SM destructive W-Z interference.

Additional contribution from Z' of L_μ - L_τ

Experimental results

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

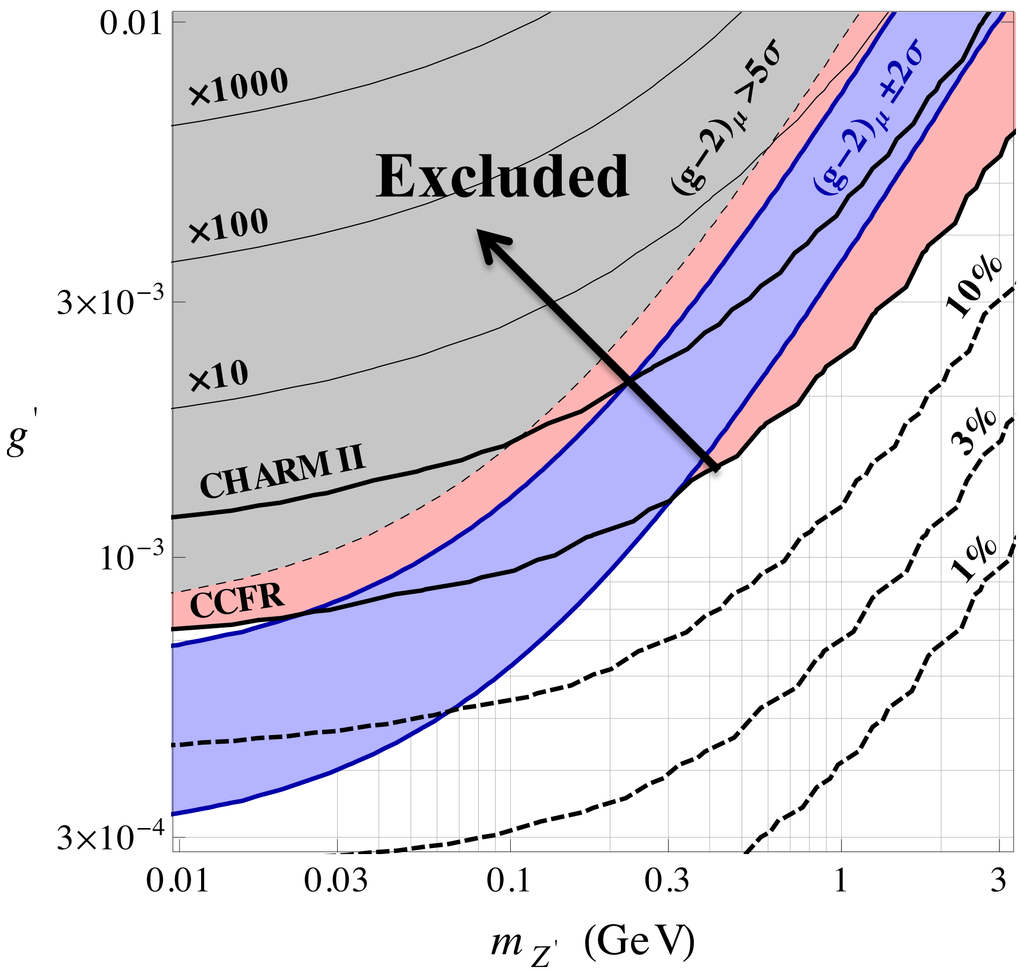
Hypothetical Z' (any Z' coupled to L_μ) contributes constructively to cross section.



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

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

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

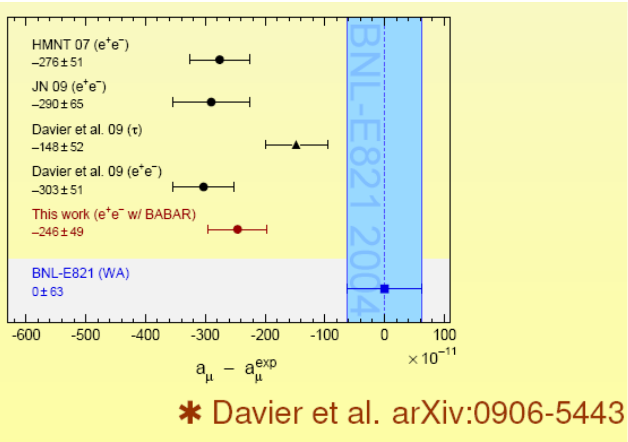
$M_{Z'} > 300$ MeV

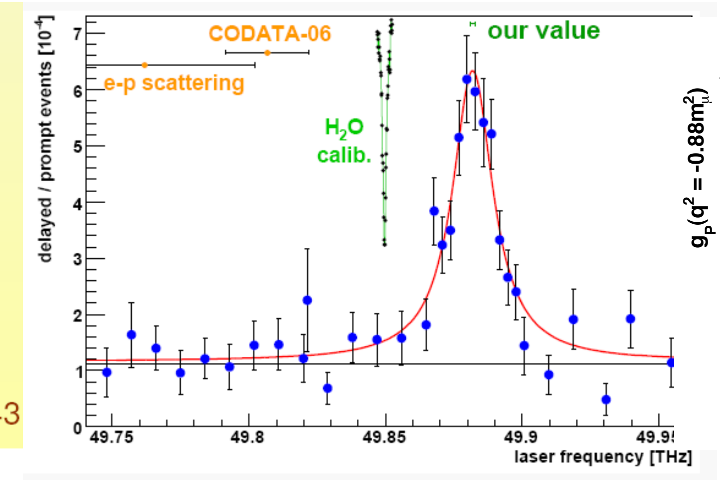
In the "contact" regime of heavy Z'>5 GeV, the best resolution to g-2 overpredicts muon trident cross section by a factor of ~ 8.

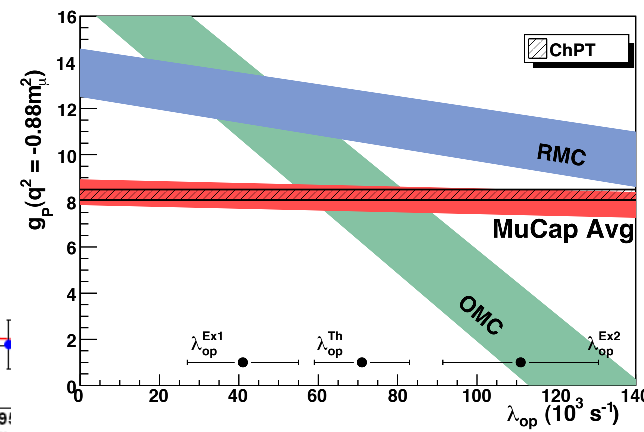
*** This is the prime example of an old measurement "reprocessed" to kill a significant part of the "dark force" parameter space ***

Can it be improved in the future ???

Muons are misbehaving; have we tested them enough?







May be something happens with muonic "neutral" channels at low energy. We do not know – therefore it would be quite foolish not to explore additional possibilities of testing "NC-like" signatures in muons at low energy.

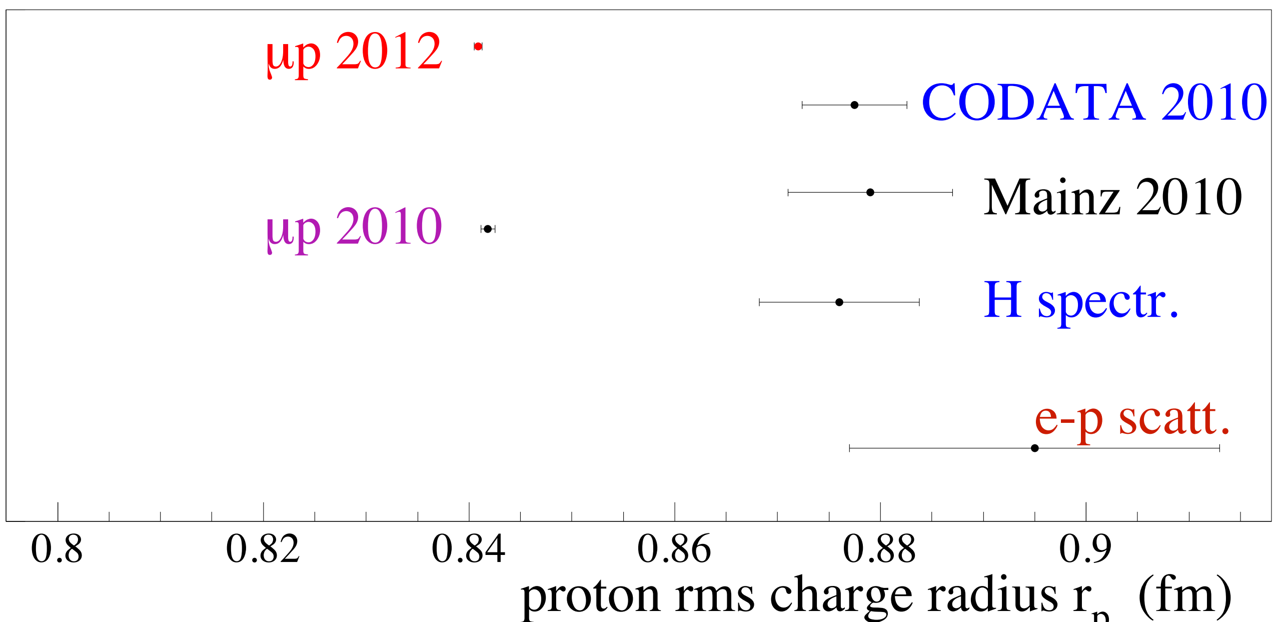
Resolution of current puzzles (r_p, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches *of new phenomena* associated with muons.

Recent excitement in precision QED

New measurements of the Lamb shift in muonic hydrogen allow for the best ever extraction of the proton charge radius. Famously, there is a large discrepancy with the e – p results.

Proton charge radius: r_{p} = 0.84089 (26)$_{\mathrm{exp}}$ (29)$_{\mathrm{th}}$ = 0.84089 (39) fm (prel.)

μp theory: A. Antogini *et al.*, arXiv :1208.2637 (atom-ph)



1. Experiments wrong? 2. Theory wrong? 3. Two-photon strong interaction “box” is anomalously large? 4. New physics with O(MeV) scale particles?....

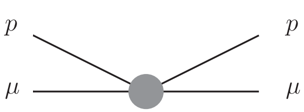
Why should we care about r_p problem?

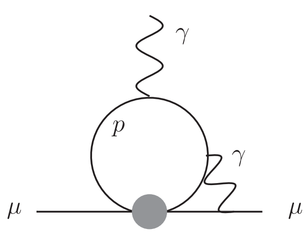
G-2 experiment "migrated" from BNL to Fermilab.

r_p problem is a huge challenge: if by any chance the muon-proton interaction is "large": either the two-photon strong interaction diagram or "light new physics", then g-2 is not really calculable with required precision!

$$\Delta\mathcal{L} \simeq C(\bar{\psi}_\mu \psi_\mu)(\bar{\psi}_p \psi_p),$$

$$C \text{ needs to be } \sim (4\pi\alpha) \times 0.01 \text{ fm}^2$$





$$\Delta(a_\mu) \sim -C \times \frac{\alpha m_\mu m_p}{8\pi^3} \times \begin{cases} 1.7; & \Lambda_{\text{had}} \sim m_p \\ 0.08; & \Lambda_{\text{had}} \sim m_\pi \end{cases}$$

$$5 \times 10^{-9} \lesssim |\Delta(a_\mu)| \lesssim 10^{-7}.$$

Shift is much larger than hadronic LBL error! Larger than discrepancy…

New physics with muons at Fermilab

- Brand new g – 2 experiment
- μ2e experiment
- Possible muon EDM experiment

In μ2e experiment 10^{10} muon captures per second with [hopefully] no beam-related backgrounds in the ~ microsecond intervals between proton bunches.

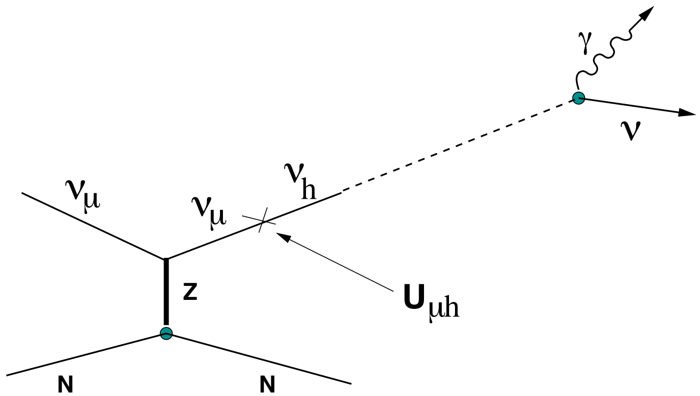
- This can be used for searching for light weakly coupled new physics

  new bosons radiated off muon lines in the capture process

  new sterile-type neutrinos emitted in the capture process

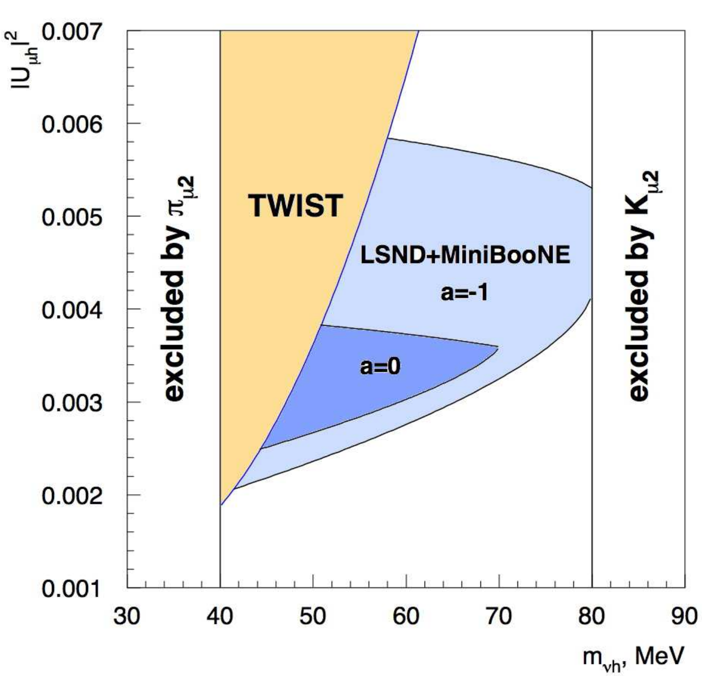
With subsequent decays outside the detector shielding

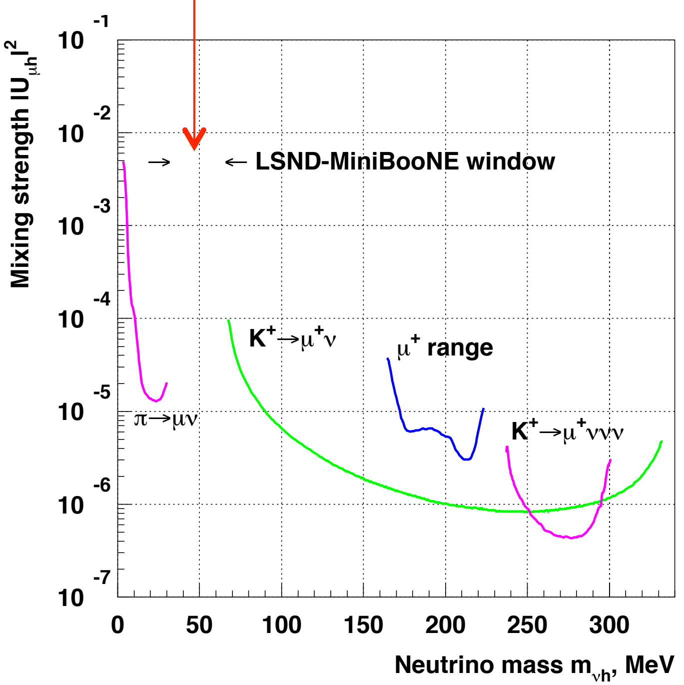
Example: ~ 50 MeV sterile neutrino model



S Gninenko (2010): a metastable neutrino model with possible "fix" to LSND/MiniBooNe excess

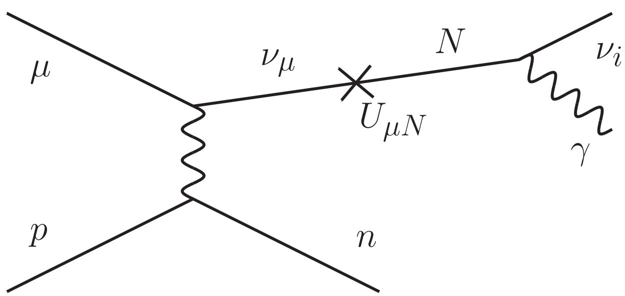
Very relaxed bounds with mixing angle^2 up to 10^{-2}.

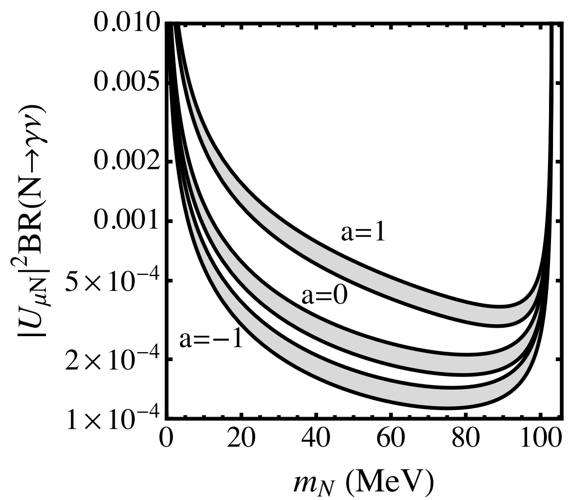




Sterile neutrino via muon capture

- McKeen, MP : new contribution to the radiative photon capture





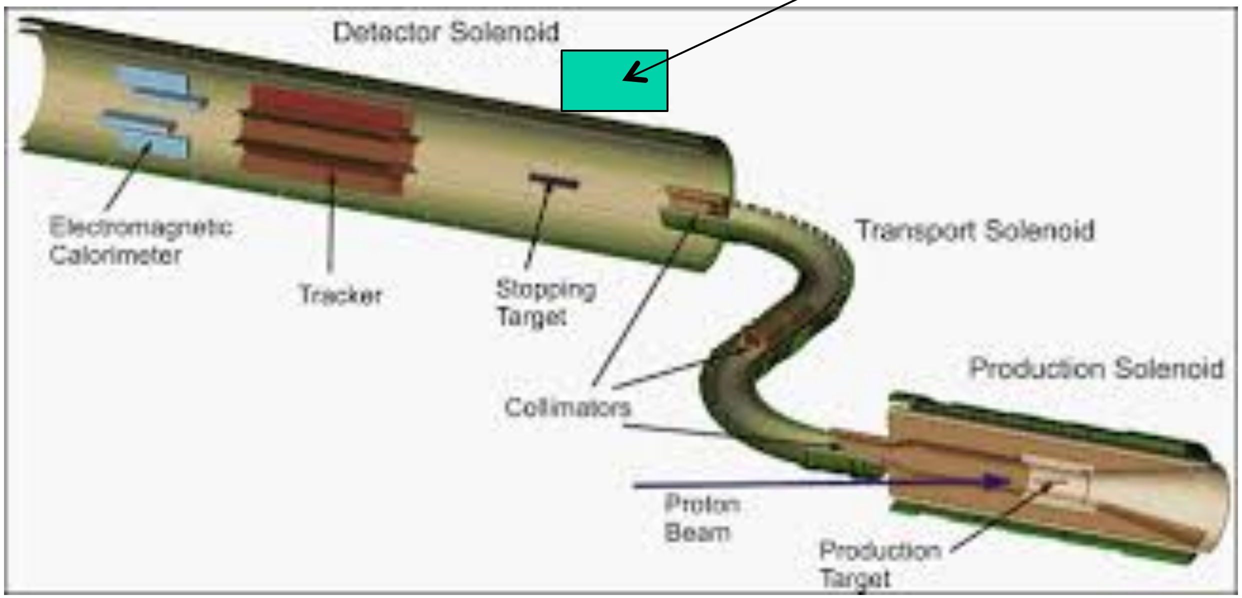
Current constraints: (mixing angle)^2 < 10^{-3}, (but there is an excess in radiative muon capture on protons!) will lead to maximum of

10^7 ~ 50 MeV gammas per second generated at μ2e due to Al capture.

Significant fraction of events will be outside of the shield. One can significantly improve bounds on sterile neutrinos in the 50 MeV range.

Adding a detector outside μ2e ?

New detector outside main shield



With a detector (registering γ, electrons, positrons) in a reasonable proximity to the capture target, one can significantly improve bounds on sterile neutrinos in the 50 MeV range [and e.g. decisively test the suggested explanation of the neutrino anomalies.]

Conclusions

- **Fermilab experiments**

MiniBooNe, MicroBooNE

Nova, LBNE

Muon g-2

Muon capture μ2e

ORKA

- **Light New Physics**

Dark photons

Light (MeV-scale) dark matter

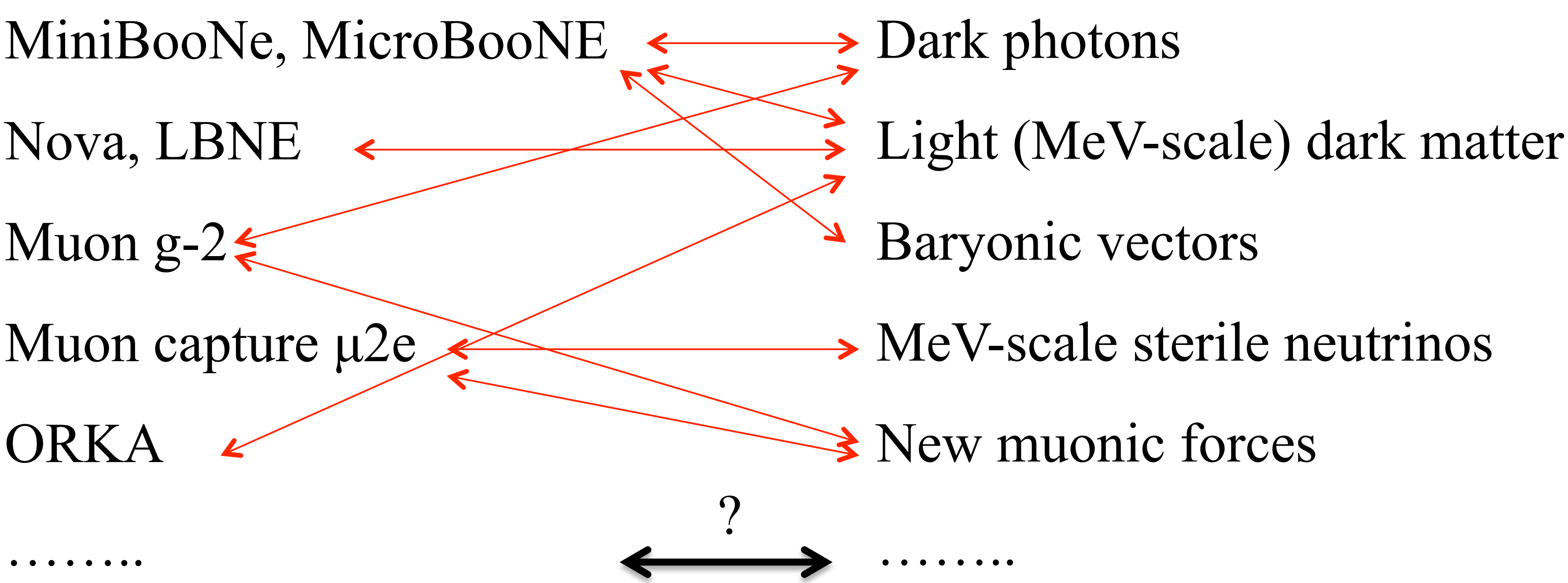
Baryonic vectors

MeV-scale sterile neutrinos

New muonic forces

Conclusions

- **Fermilab experiments**
- **Light New Physics**



Fermilab is a unique place for making decisive progress in searching for New Physics in form of the light weakly coupled particles.