New Physics in the MeV-GeV window

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The Search for Feebly Interacting Particles

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Plan

1. *Introduction.*

A. Is there a BSM physics and where it may hide?

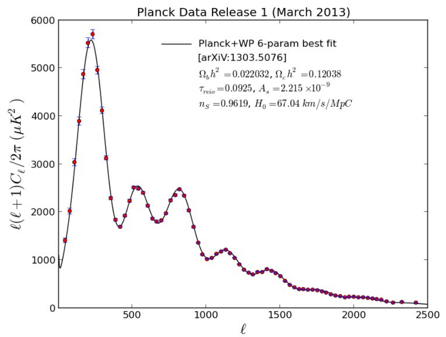
B. The notion of dark sectors/feebly interacting particles (FIPs).

2. A closer look at dark photon, and related models.

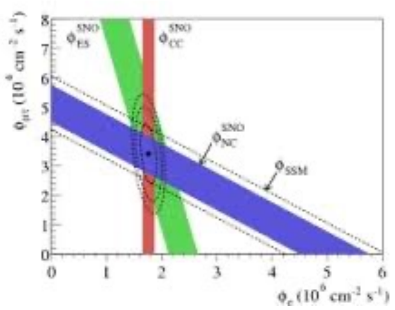
3. Conclusions

Clues for new physics

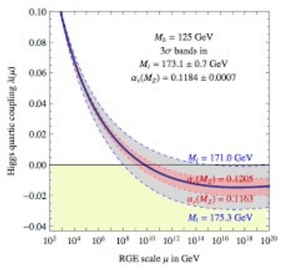
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM.



3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



4. *"Anomalous results":* muon g-2, B-physics anomalies, SBN neutrino anomalies, Hubble constant tension etc.

SM as an Effective Field Theory

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out

$L_{SM+BSM} = -\, m_H^2\, (H^+_{SM} H_{SM})$ + all dim 4 terms $(A_{SM},\ \psi_{SM},\ H_{SM})$ +

(Wilson coeff. $/\Lambda^2$) $\times$ Dim 6 etc $(A_{SM},\ \psi_{SM},\ H_{SM})$ + …

For example: $$\frac{1}{\Lambda^2}(\bar{e}e)(\bar{q}q)$$

But is this framework really all-inclusive? – it is motivated by new heavy states often with sizeable couplings. The alternative possibility for New Physics – weakly coupled light new physics - is equally viable

SM as an Effective Field Theory in the presence of FIPs

Typical BSM model-independent approach is to include all possible BSM operators + light new states explicitly.

$L_{SM+BSM} = - m_H^2\, (H^+_{SM} H_{SM}) +$ all dim 4 terms $(A_{SM},\ \psi_{SM},\ H_{SM}) +$

(W.coeff. $/\Lambda^2) \times$ Dim 6 etc $(A_{SM},\ \psi_{SM},\ H_{SM})\ + \ldots$

all lowest dimension portals $(A_{SM},\ \psi_{SM},\ H,\ A_{DS},\ \psi_{DS},\ H_{DS}) \times$ portal couplings

\+ dark sector interactions $(A_{DS},\ \psi_{DS},\ H_{DS})$

SM = Standard Model

DS – Dark Sector

Minimal portal interactions

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

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

……….

Owing to small couplings, such particles represent "dark sector"

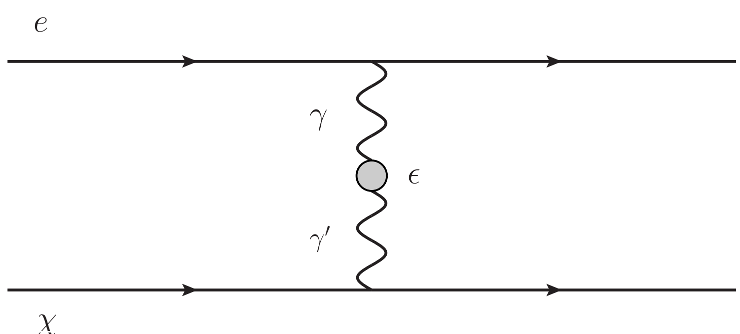
“Simplified model” for dark sector

(Okun’, Holdom,…)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g'A'_\mu) - m_\chi]\chi,$$

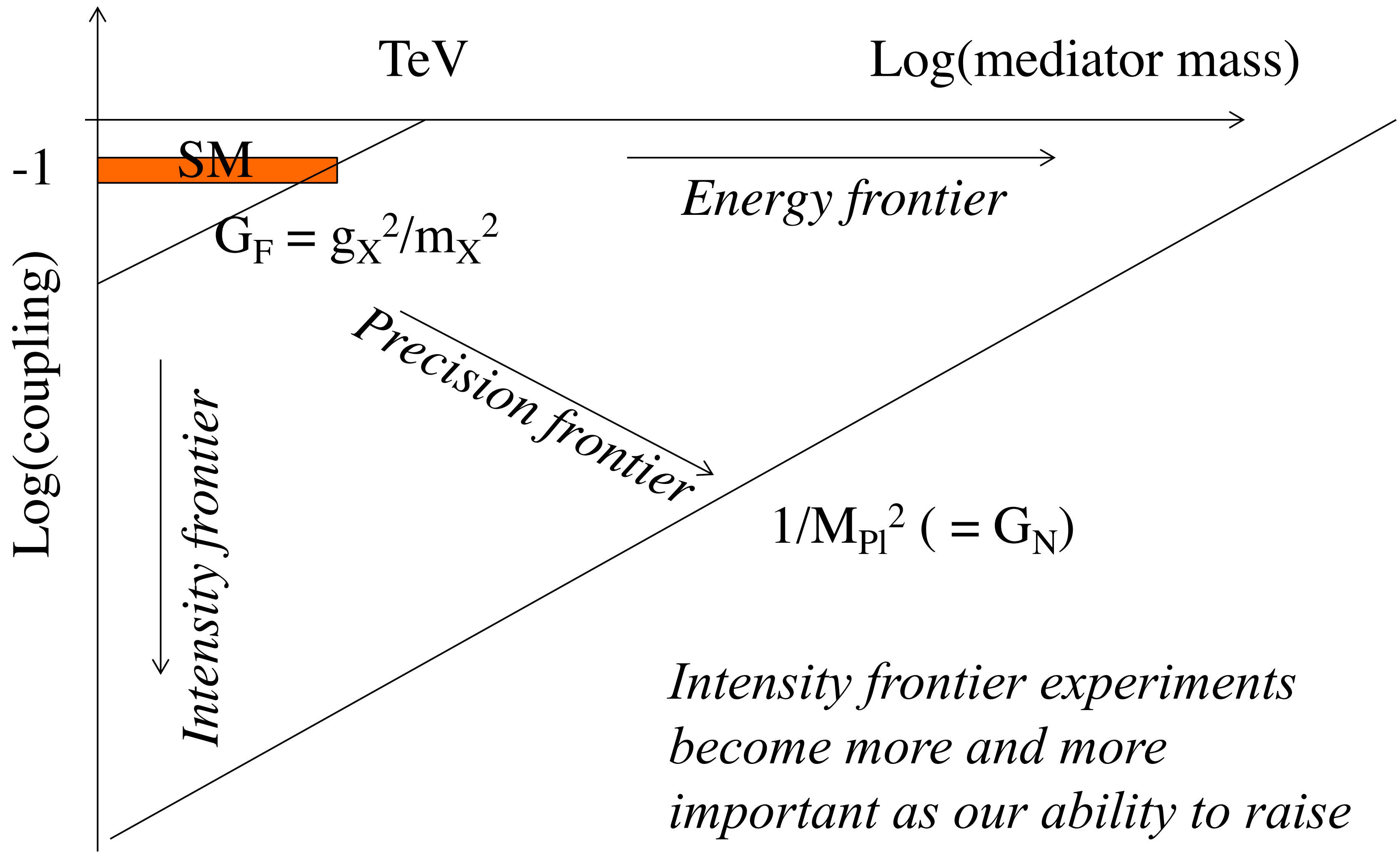


A – photon, *A’* – “dark photon”, ψ - an electron, χ - a DM state, *g’* – a “dark” charge

- “Effective” charge of the “dark sector” particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can “communicate” interaction between SM and dark matter. *It represents a simple example of BSM physics*.

Search for New Physics

In 2012-2013 LHC experiments discovered a new particle (Higgs boson) and a new force (Yukawa force). What do we know about forces in nature ?



Intensity frontier experiments become more and more important as our ability to raise energy becomes limited.

Motivations for dark vectors and dark scalars

- Dark scalar is the only object that can have a super-renormalizable portal dim=3 to the Higgs boson. Can be connected to the Higgs mass naturalness via the so-called relaxion mechanism (self-organized criticality).

$$(H^\dagger H) \times m_H^2 \longrightarrow (H^\dagger H) \times (m_H^2 + c_1 S + c_2 S^2 + ...)$$

- Dark scalar can help develop the 1st order EW phase transition and with extra CP-violation (provided e.g. by additional Higgs doublet) can lead to successful EW baryogenesis.
- Light dark photons can result from "neutral naturalness" approach
- Dark vectors/scalars can be DM themselves – either freeze-in or oscillate like axion. Can be mediators for light WIMP models.
- Maybe behind certain anomalies (e.g. $L_{mu} - L_{tau}$ dark vector can "correct" muon g-2.)

Models vs Experiments

Benchmark Cases (MP and PBC, 2018)

1. *Dark photon*
2. *Dark photon + light dark matter*
3. *Millicharged particles*
4. *Singlet scalar mixed with Higgs*
5. *Quartic-dominated singlet scalar*
6. *HNL, e-flavour dominance*
7. *HNL, μ-flavour dominance*
8. *HNL, τ-flavour dominance*
9. *ALPs, coupling to photons*
10. *ALPs, coupling to fermion*
11. *ALPs, coupling to gluons*

Vector

scalar

HNL

ALPs

Experimental proposals, mostly CERN

- *SHiP* — *Beam Dump*
- *NA62+* — *Flavour, possible BD*
- *FASER* — *LHC add-on*
- *MATHUSLA* — *large LHC add-on*
- *Codex-B* — *LHC add-on*
- *MilliQan* — *LHC add-on*
- *NA64* — *missing momentum*
- *KLEVER* — *flavour*
- *REDTOP* — *fixed target*
- *IAXO* — *axion exp*
- *ALPs-II* — *axion exp*
- ……..

I hope that in the end, a clear strategy for building up CERN intensity frontier program will emerge, with new sensitivity to sub-EW scales

"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 $2m_{DM} < m_{mediator}$.

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

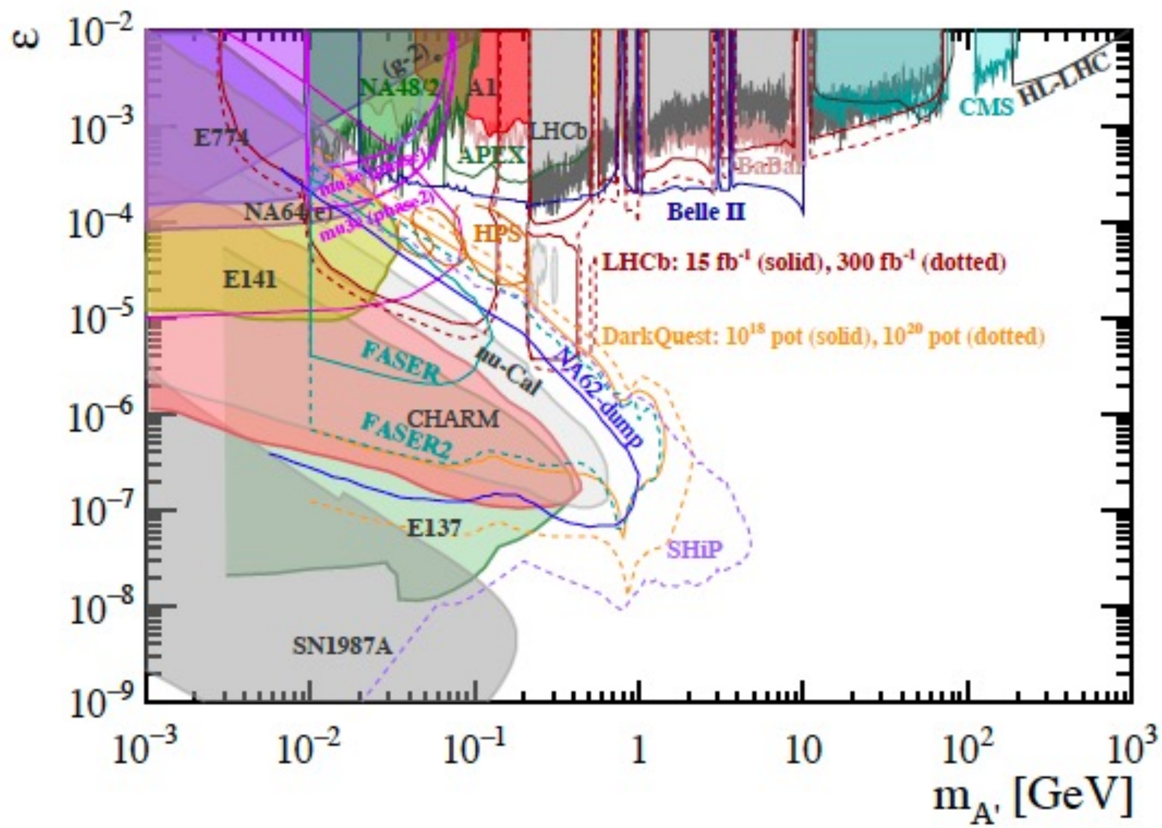
- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

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

After EW symmetry breaking *S* ("dark Higgs") mixes with physical *h* and can be light and weakly coupled provided that coupling A is small.

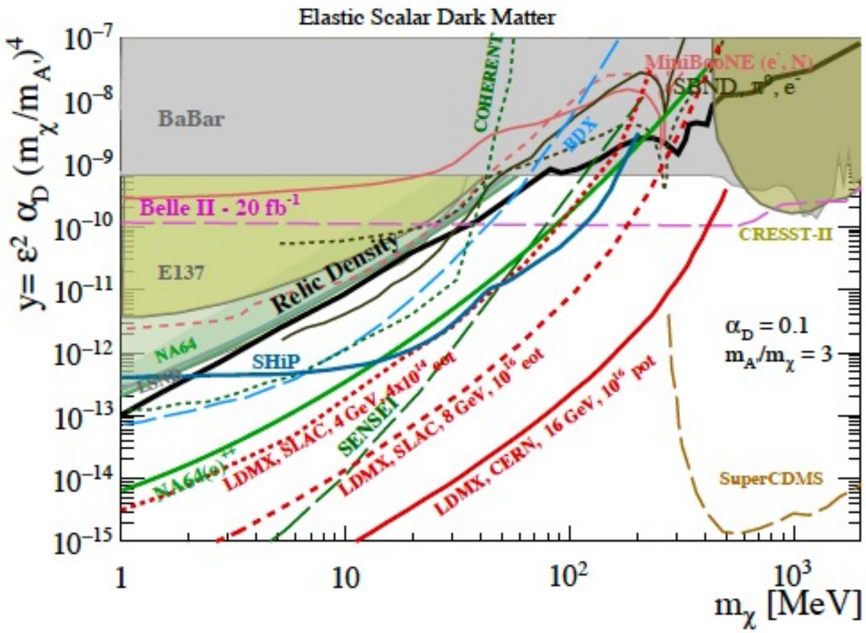
Take away point: these models have both stable (DM) and unstable (mediator) light weakly coupled particles.

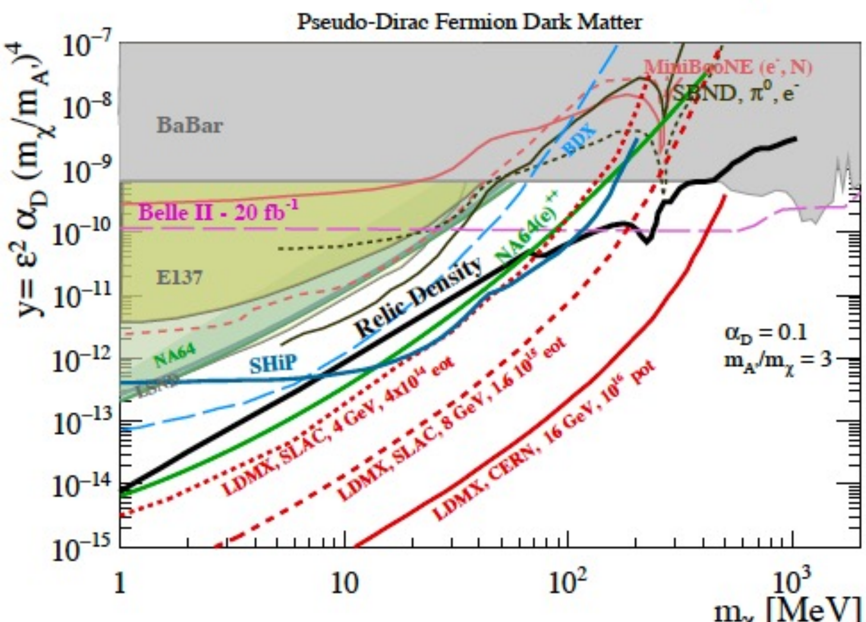
Constraints and future sensitivity to Dark Photons



O(few GeV) mass, and ε ~ 10^{-4} can be probed using experiments at JLab. (Plot from recent PBC studies)

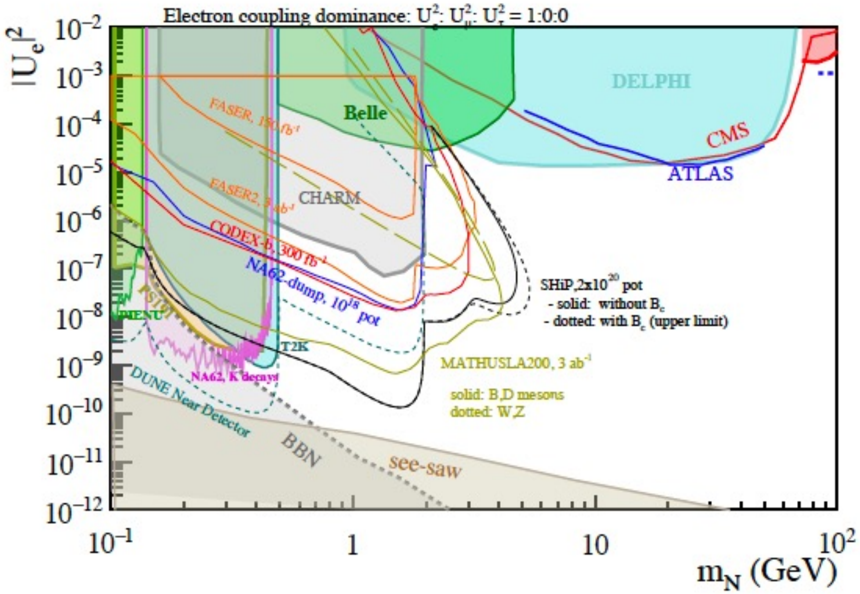
Dark Matter through Dark Photon portal

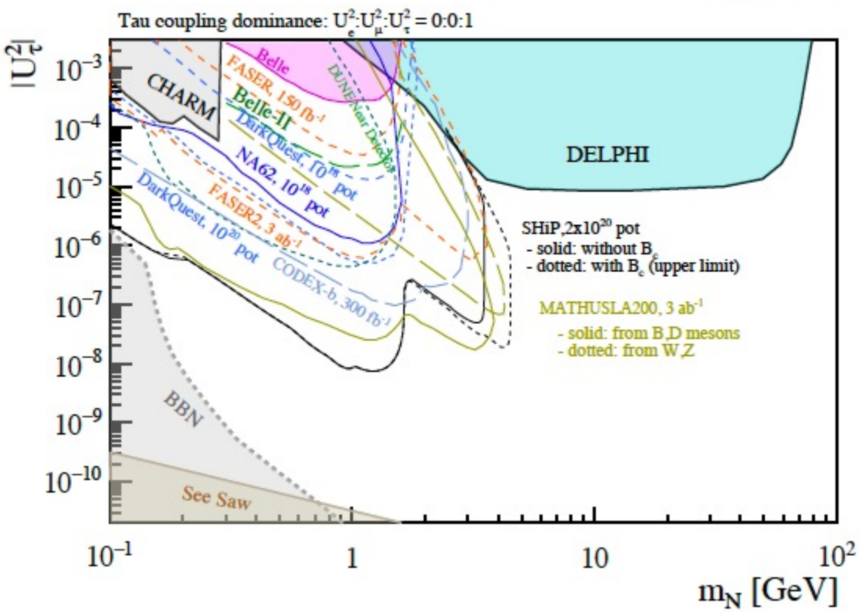




- At the moment, neutrino and beam dump experiments provide best sensitivity in the light mass range.
- Beam dump scaling, ε^4, is eventually to be overtaken by missing energy/momentum experiments with ε^2 scaling. (Newer NA64 results cross into relic density motivated territory)
- There is a nice complementarity with direct detection experiments that have a low detection threshold.

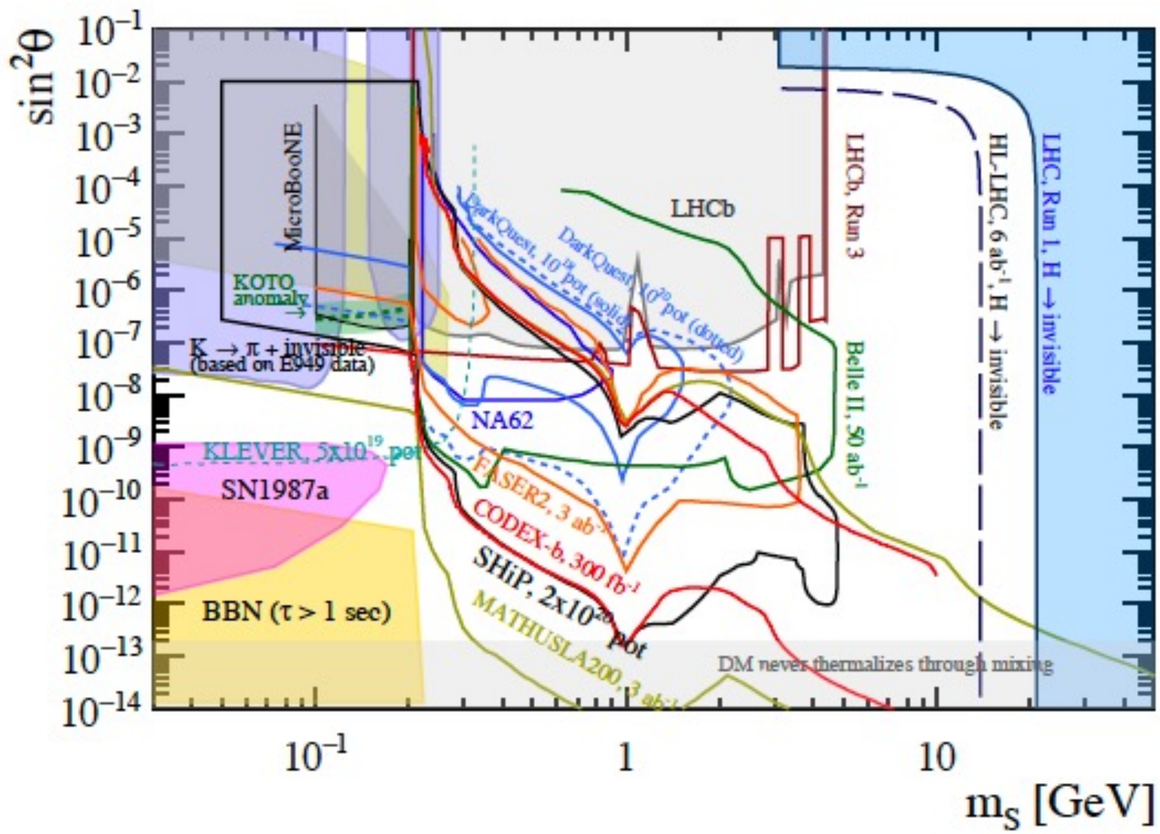
Search for Heavy Neutral Leptons





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

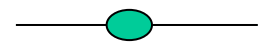
Constraints on Higgs-mixed scalars



Possible future improvements at NA62, SHiP, possibly SNB experiments, and new proposals such as MATHUSLA, CODEX-B, FASER etc.

Dark photons ++

Let’s classify them into several cartegories

1. *Dark photon: technically natural, UV complete, couple to a conserved current.* $\varepsilon =$ 
2. *B-L, L_μ-L_τ, and other anomaly free combinations: all of the above, but coupling constant g_X is small – somewhat unusual. Strong constraints from neutrino physics.*
3. *Models coupled to the tree-level conserved current broken by anomalies. E.g. gauged baryon number, or lepton number. Presumes cancellation of anomalies at high-energy. Nice low energy behaviour, weak constraints on gauged baryon number?*
4. *Models coupled to a non-conserved current. (e.g. vector particle coupled to an axial-vector current)*

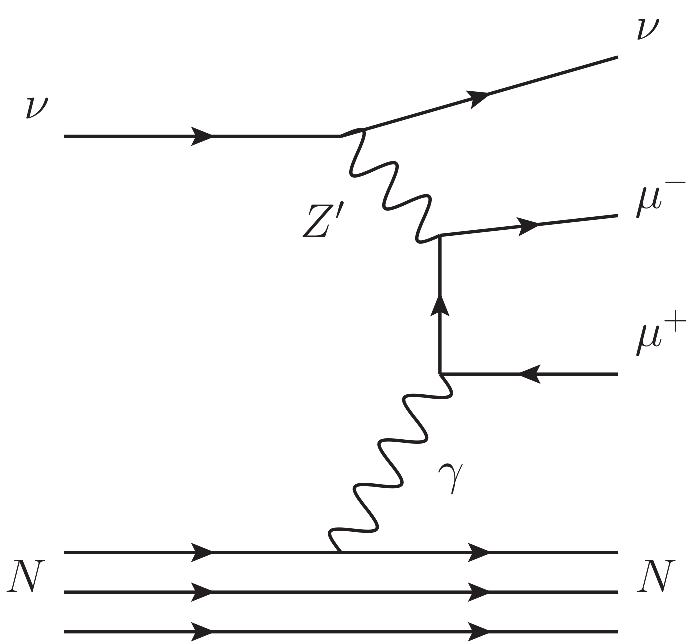
- Phenomenology-driven demand often force speculators to consider 3 and 4. (proton charge radius, ”X17” anomaly)

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:

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

~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,

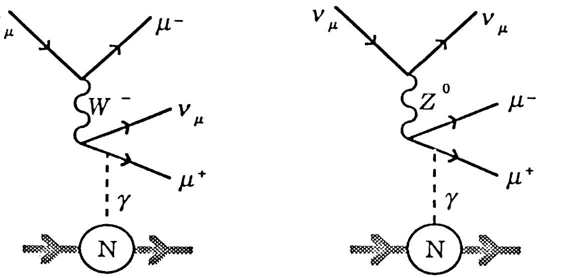


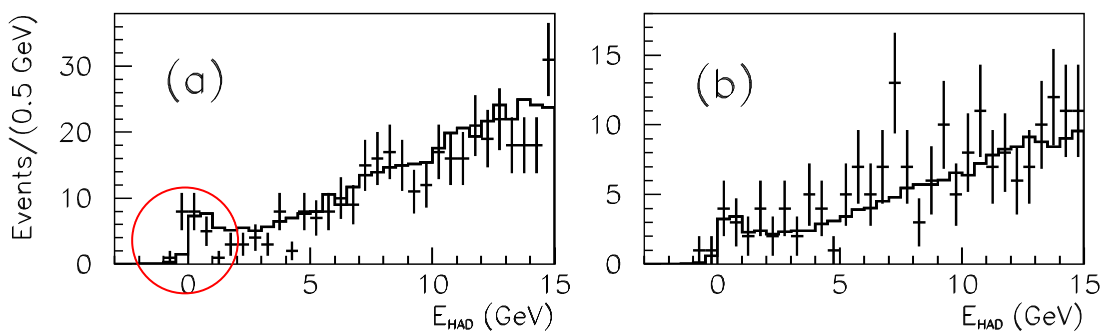
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

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

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

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

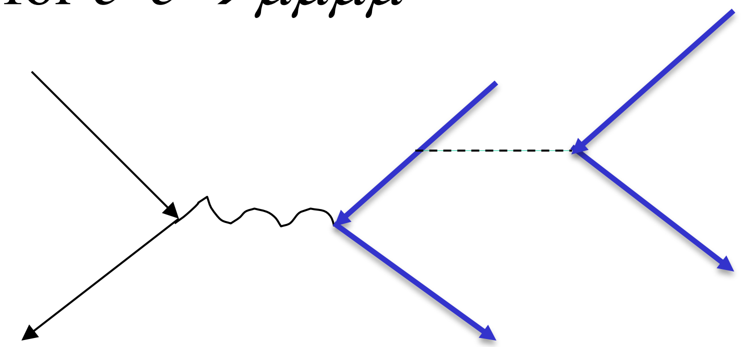
- NuTeV results:

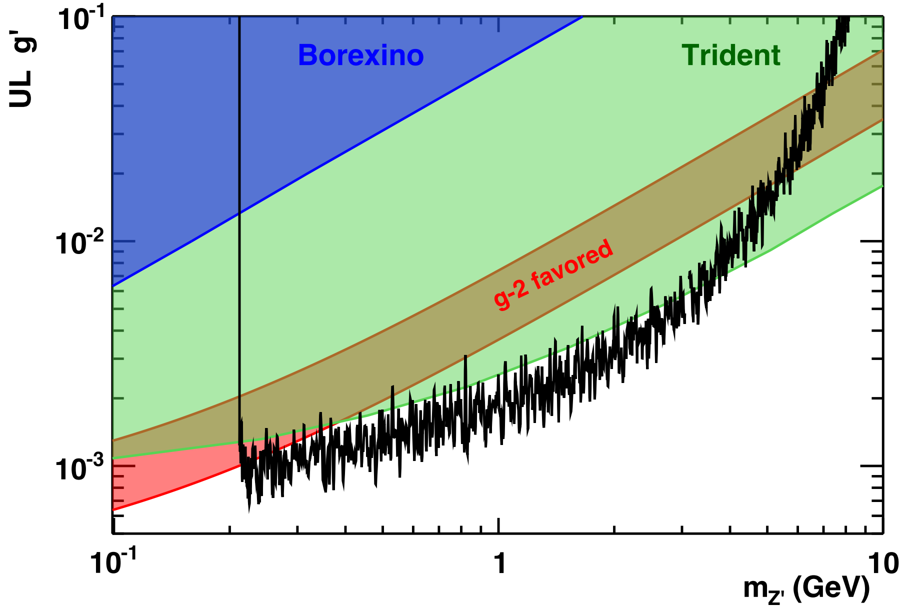


Trident production was seeing with O(20) events, and is fully consistent with the SM destructive W-Z interference.

Recent constraint from BaBar on L_μ-L_τ

Babar + B. Shuve have looked for $e^+e^- \rightarrow \mu\mu\mu\mu$

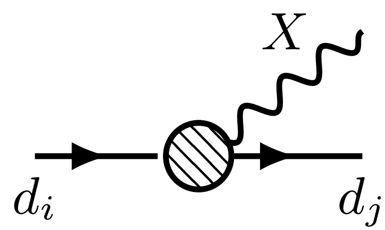




- Absence of peaks in invariant mass improves constraints in 210 MeV – 4 GeV window.
- Below 2muon threshold, L_μ-L_τ model is the most difficult: Z'→neutrinos. NA64 with muons, or LDMX?

Non-conserved currents will be sensitive to high-mass scales through loops

- It is well known that there is an enhancement of non-conserved currents inside loops leading to FCNC. The key – access to momenta ~ m_W and m_t.



- For a fully conserved current, like couplings of dark photon,

Amplitude ~ $G_F\, m^2_{meson}$

For a non-conserved current, such as Higgs-mixed scalar

Amplitude ~ $G_F\, m^2_{top}$

Gauge symmetry broken by anomalies

- Consider $L = g_X X_\mu \, \Sigma(\bar{q} \, \gamma_\mu \, q)$ which is the coupling of a vector particle "X" to a baryon current. If we stay at the tree level, then the current is exactly conserved, and nothing would be wrong with such a $U(1)_{\text{baryon}}$.

- However [and famously], this symmetry is broken by the triangle chiral anomaly (Adler++):

$$\partial^\mu J_\mu^{\text{baryon}} = \frac{\mathcal{A}}{16\pi^2}\left(g^2 W^a_{\mu\nu}(\tilde{W}^a)^{\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- The vector X cannot stay massless, and a strong interaction will develop at scales $\lesssim \frac{4\pi m_X}{g_X} / \left(\frac{3g^2}{16\pi^2}\right)$ (Preskill) unless such theory is UV completed, and anomaly is cancelled in full theory

$Z \rightarrow \gamma X$ decay

- At one loop, Z boson will decay to γ X final state, and the emission of longitudinal scalar is m_Z^2/m_X^2 enhanced. (A=3/2 for the baryonic X).

$$\Gamma_{Z\to\gamma X} \simeq \frac{\mathcal{A}^2}{384\pi^5} g_X^2 g^2 g'^2 \frac{m_Z^3}{m_X^2}$$

This corresponds to

$$\frac{\Gamma_{Z\to\gamma X}}{\Gamma_Z} \simeq 10^{-7}\mathcal{A}^2 \left(\frac{\mathrm{TeV}}{m_X/g_X}\right)^2$$

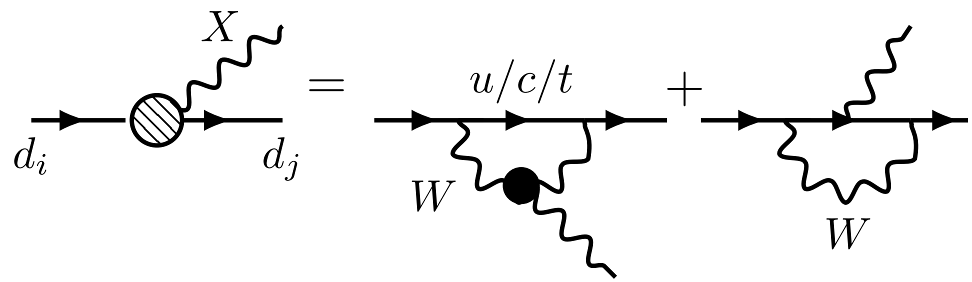
- One can use previous LEP measurements for Z→ gamma + invisible, as well as Tevatron Z→ gamma + pi0.

- LHC will have huge sensitivity through studies of $l^- l^+ \gamma$ final states.

FCNC amplitudes at two loop

- Anomalous [two-loop] contributions to FCNC amplitudes are important

$$\mathcal{L} \supset g_{X d_i d_j} X_\mu \bar{d}_j \gamma^\mu \mathcal{P}_L d_i + \text{h.c.} + \ldots$$



$$g_{X d_i d_j} = -\frac{3g^4\mathcal{A}}{(16\pi^2)^2} g_X \sum_{\alpha\in\{u,c,t\}} V_{\alpha i} V^*_{\alpha j} F\left(\frac{m_\alpha^2}{m_W^2}\right)$$

$$\simeq -\frac{3g^4\mathcal{A}}{(16\pi^2)^2} g_X V_{ti} V^*_{tj} F\left(\frac{m_t^2}{m_W^2}\right) + \ldots,$$

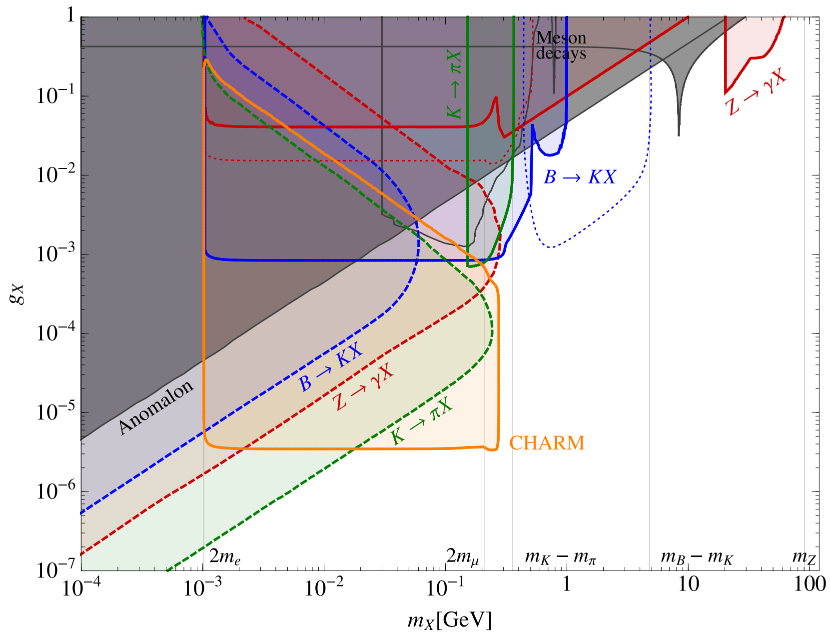
where

$$F(x) \equiv \frac{x(1 + x(\log x - 1))}{(1-x)^2} \simeq x \quad (\text{for } x \ll 1)$$

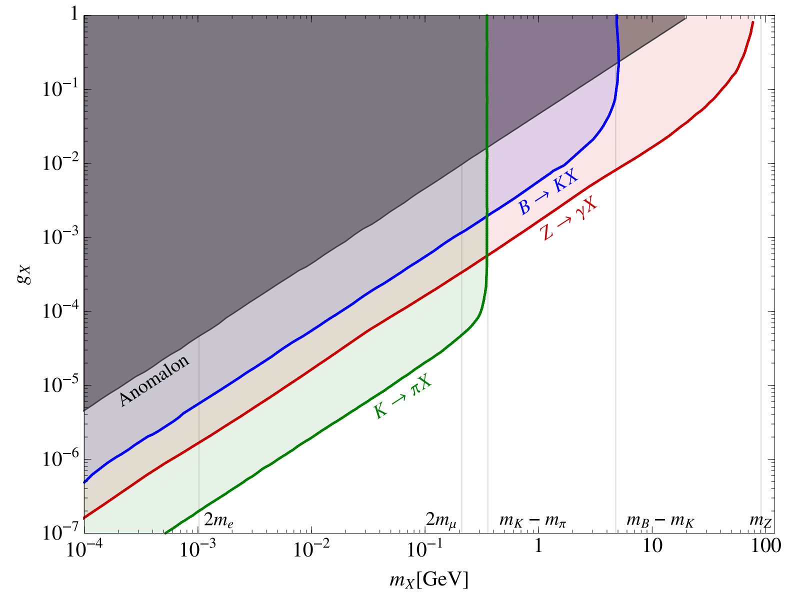
- $$\mathcal{M}^{2-\text{loop}}/\mathcal{M}^{1-\text{loop}} \propto g^2/(16\pi^2) \times (m_t/m_X)^2$$

Resulting constraints on gauged baryon or lepton number

- No additional X→ invisible channels.



gauged B number



gauged L number

- The baryonic(leptonic) force in this case is limited to be below weak interaction strength, $(g_X^2/m_X^2) < G_F$.
- Constraints are very strong, put in doubt some models for X17.

Opportunities with 22 GeV beam?

- Search of FIPs in photoproduction. Real and quasi-real photons can produce scalars/pseudoscalars on a target, $Z + \gamma \rightarrow Z + a$. Subsequent decay of *a* can be searched for. This benefits from energy.

- More exotic parity violation: in the 1980s at CERN parity violation in $(\text{Vector})_{\text{muon}}\,(\text{Axial})_{\text{quark}}$ has been observed. The other combination $(\text{Axial})_{\text{muon}}\,(\text{Vector})_{\text{quark}}$ has not been seen at low energies. Since the parity asymmetry grows with Q^2, $(G_F\, Q^2/\alpha)$, one can try to see P-violation in muon pair production, $ep \rightarrow ep + \mu^+ \mu^-$. A detector with muon capabilities (Solid) would be required.

- Beam dump, fixed targets (HPS, BDX etc). Displaced decays benefit from higher energy.

Conclusions

- Dark Sectors / FIPs represent a well-motivated strategic direction in New Physics studies at the intensity frontier experiments.

- There is an elaborate theoretical and experimental effort to study “most reasonable” models of dark sector/FIPs, systematized in e.g. PBC working group.

- New physics opportunities at Jlab can be considered: search of new particles in the photoproduction; fixed target experiments, and beam dumps. Higher-energy polarized beam (22 GeV) may enable studies of parity violation in muon pair production.