Physics of Hidden Sector at ECN3

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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).

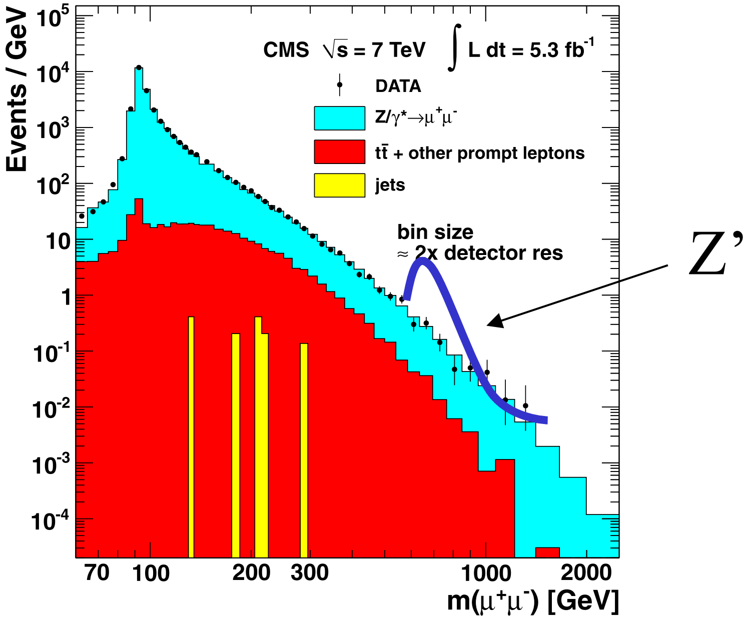
2. Motivating dark sectors and FIPs

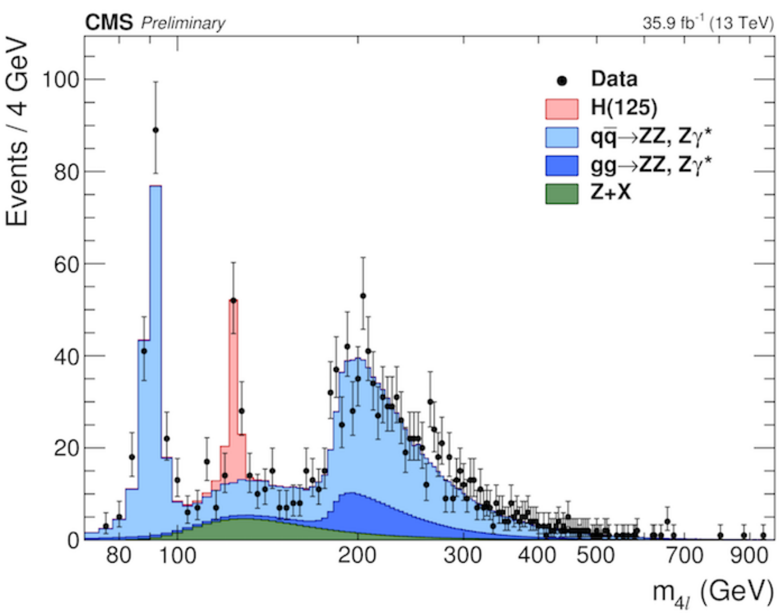
3. A multitude of ways to search for BSM physics.

4. Beam dump physics at ECN3: new level of sensitivity to all portals + unparallel sensitivity to Heavy Neutral Leptons.

5. Conclusions

LHC: Higgs, but no New Physics at high energy thus far (?!)





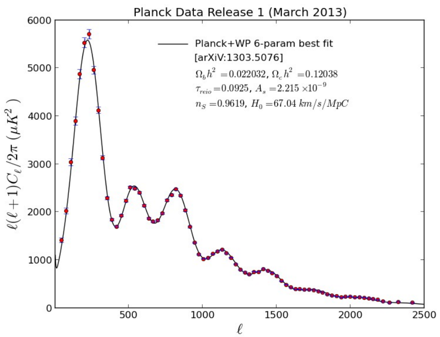
- *No hints for any kind of new physics.* Strong constraints on SUSY, extra dimensions, technicolor resonances, new Z' etc.

- There is no clear theoretical winner in the "top-down" approach. There is not a single theoretical model that has unambiguous theoretical predictions.

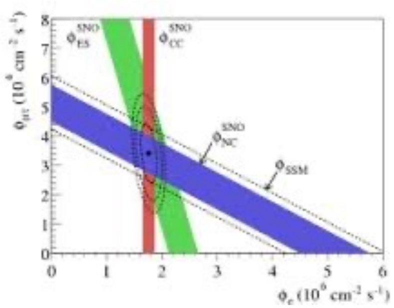
- There is no "clear practical guidance" that can be derived from the Higgs naturalness problem.

Clues for new physics

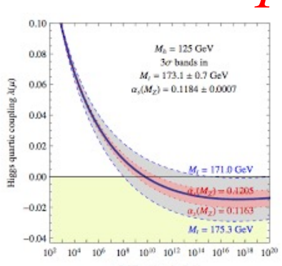
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



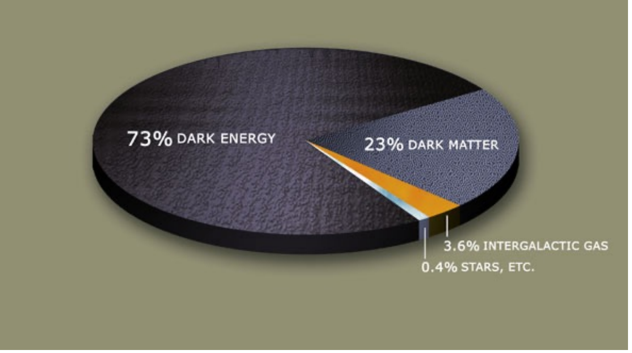
2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM.



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



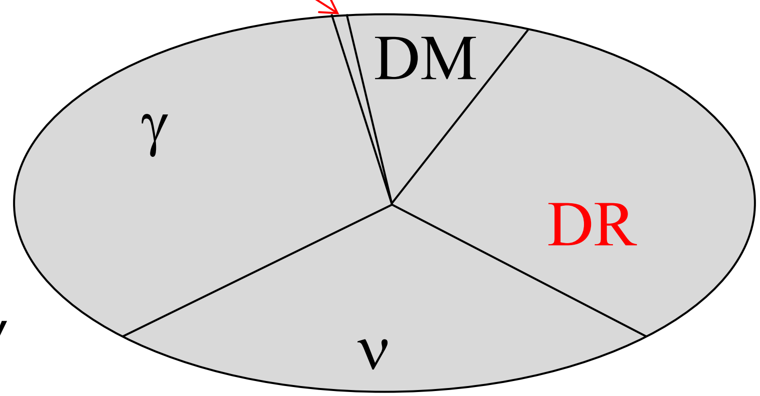
4. *"Anomalous results":* muon g-2, B-physics anomalies, SBN neutrino anomalies, Hubble constant tension etc.



Cosmology determines mass density (and sometimes spectrum/temperature) of different species

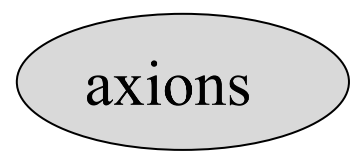
Atoms

In Energy chart they are 4%. In number density chart ~ 5×10^{-10} relative to γ



We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation, Dark Forces – Who knows!).

Number density chart for axionic universe:



Cosmological puzzles motivate terrestrial search experiments

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

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

LHN 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"

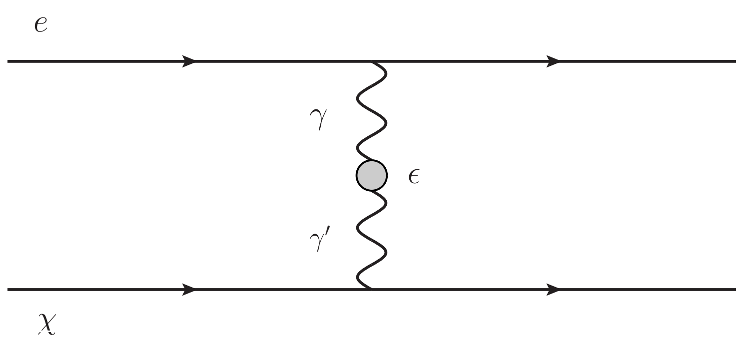
"Simplified model" for dark sector

(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*.

Motivations for Heavy Neutral Leptons

- Participates in the neutrino mass generation via see-saw

$$
\begin{aligned}
m_{\nu,\mathrm{D}}\bar{\nu}\nu &\longrightarrow y_\nu \bar{N}\nu H + (h.c.) \\
m_{\nu,\mathrm{M}}\bar{\nu}\nu &\longrightarrow (y_\nu)^2(\nu H)^c \times \frac{1}{m_N} \times (\nu H) + (h.c.)
\end{aligned}
$$

- A cornerstone/pilar for the generation of the baryon asymmetry of the Universe via leptogenesis (lepton number violation by HNL and B+L violation by SM sphalerons). *A sub-EW mass HNL version of leptogenesis is also available (ARS mechanism)*.

- Can be a "freeze-in" DM with masses in 1 keV – 100 keV range, and in the presence of other dark sector particles can easily be DM.

- Maybe contributing to the X-ray excess at ~ 3.5 keV?

Motivations for Axion-like particles

- Initially suggested (QCD axion) to solve the strong CP to problem by relaxing the effective QCD vacuum angle theta to zero.

$$\theta_{QCD} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} \longrightarrow \left(\theta_{QCD} + \frac{a}{f_a} \right) G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- Can easily constitute the entirety (or a fraction) of cold dark matter.

- More massive versions of ALPs could still provide [limited] solution to the strong CP, while being stronger coupled and amenable to beam dump searches.

- Maybe contributing to various “anomalous stellar energy loss signals”?

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).

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

- 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.)

"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.

How to look for New Physics ?

1. High energy colliders.

2. Precision measurements when symmetry is broken

3. Intensity frontier experiments where abnormal to SM appearance of FIPs (or sometimes disappearance, e.g. NA64) can be searched.

All three strategies are being actively pursued by particle physics community.

How to look for New Physics ?

1. High energy colliders.

$$\frac{1}{\Lambda^2}(\bar{e}e)(\bar{q}q) \;\to\; \sigma \propto \frac{E^2}{\Lambda^4} \;\to\; \Lambda > 10\,\mathrm{TeV}$$

2. Precision measurements when symmetry is broken

$$\frac{1}{\Lambda_{\mathrm{CP}}^2}(\bar{e}i\gamma_5 e)(\bar{q}q) \;\to\; \mathrm{EDM},\, \frac{1}{\Lambda_{\mathrm{CP}}^2} < 10^{-10}G_F \;\to\; \Lambda_{\mathrm{CP}} > 10^7\,\mathrm{GeV}$$

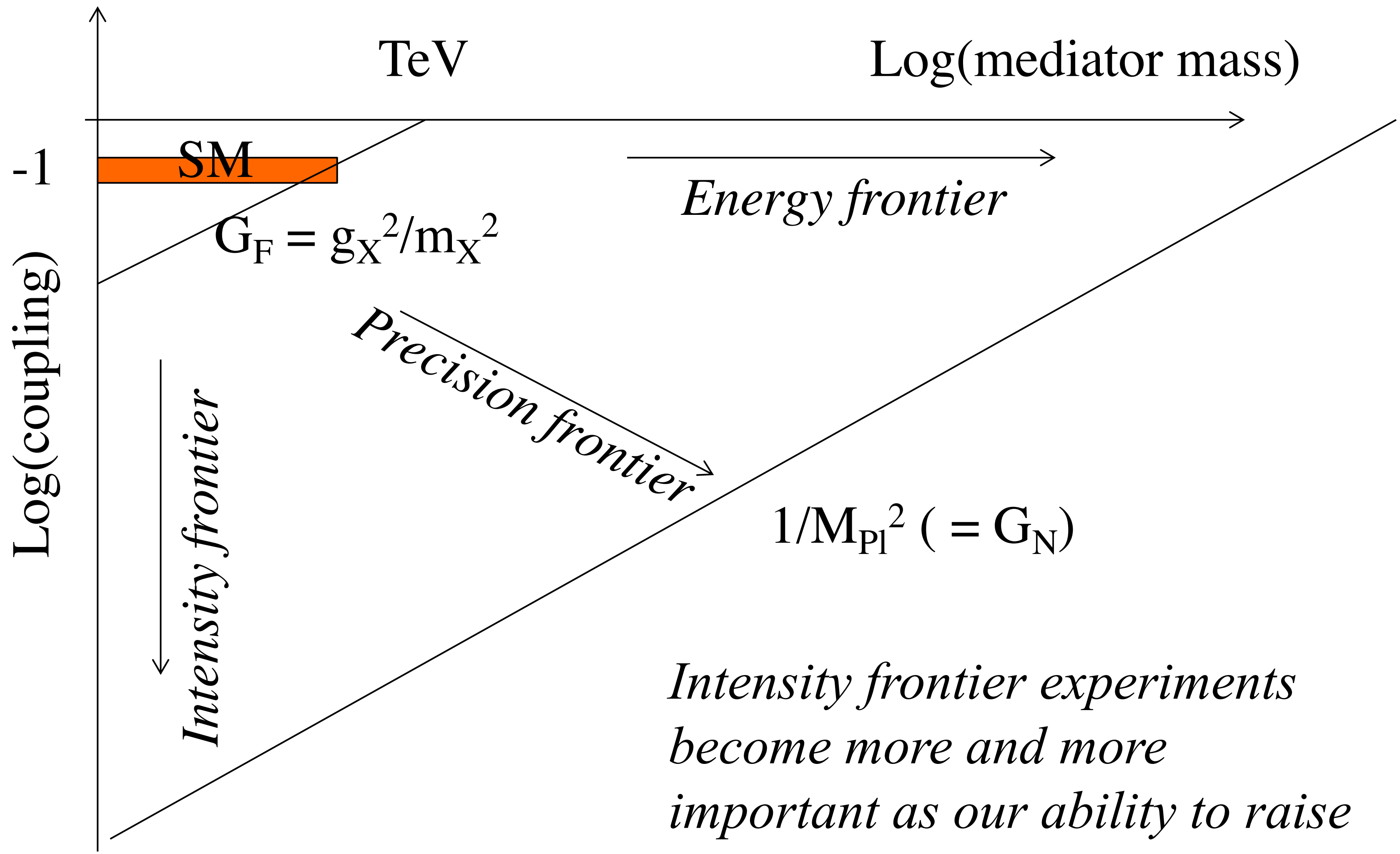
3. Intensity frontier experiments where abnormal to SM appearance of FIPs (or sometimes disappearance, e.g. NA64) can be searched.

$$pp \;\to\; \pi, K, B \;\to\; HNL + X \;\to\; HNL \text{ decay to SM}$$

All three strategies are being actively pursued by particle physics community.

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.

Future direction – new intensity experiments at CERN

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

New experimental facilities at CERN:

- Provide capability to collect over 10^{20} of 400 GeV protons on target enabling important intensity frontier experiments (SHiP) enabling best sensitivity to HNLs
- Provide new capabilities in precision studies of Kaon decays, including important "clean" modes (NA62, KLEVER): $K^+ \to \pi^+\nu\bar{\nu}$; $K_L \to \pi^0\nu\bar{\nu}$ as well as new opportunities for the short baseline beam dumps (SHADOWS)
- Provide new opportunities with studies of prompt neutrinos (including ν_τ and fixed target studies of rare decays of tau and D mesons).

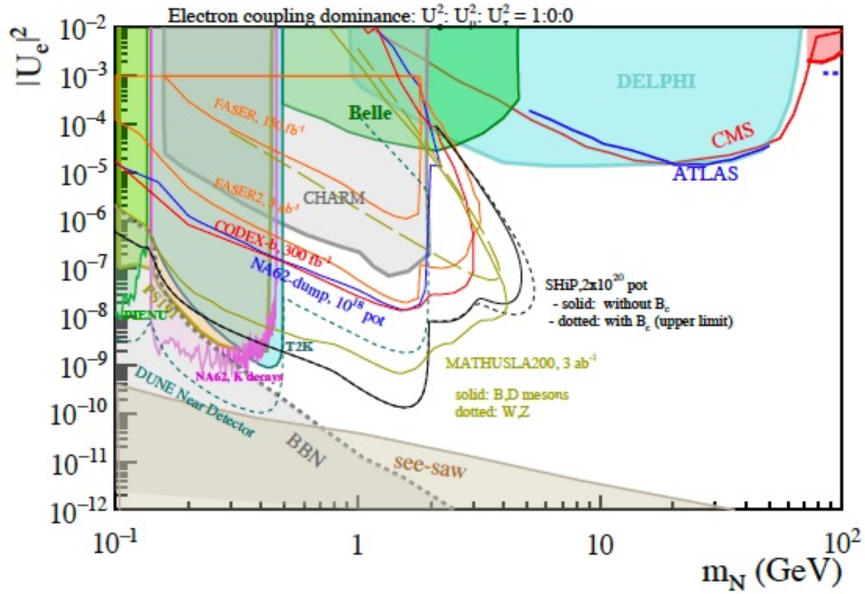
Exquisite sensitivity to New Physics can be achieved

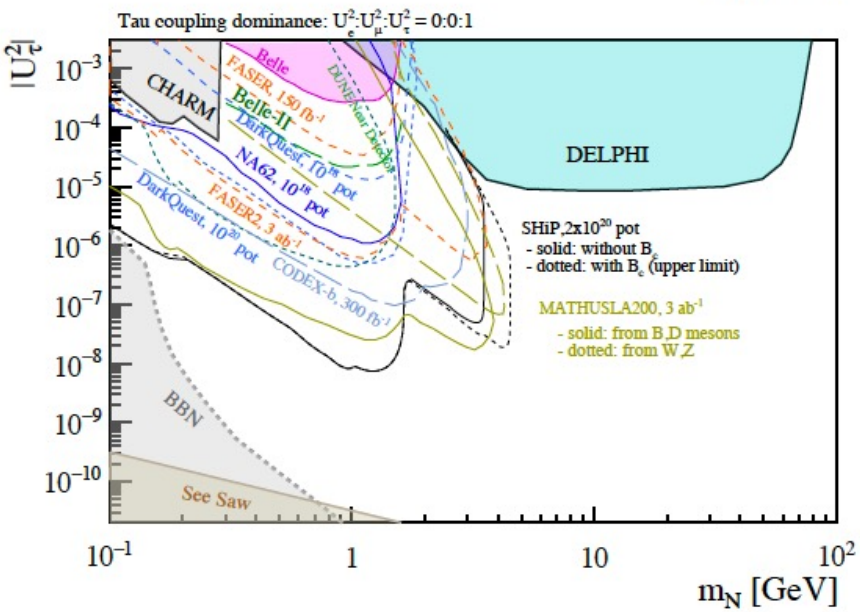
Important features of new facilities and experiments

- High intensity O(>10^{20} POT) & High energy, E=400 GeV. (Compare e.g. to 800 GeV CCFR/NuTeV where O(10^{18} POT) was collected.)
- Copious amounts of s, c, b quarks, and tau-mesons can be produced, enabling studies of their very rare decay modes.
- A much shorter baseline than before, 100 m or less (with NuTeV, CHARM~ O(km)). Enables access to much shorter-lived relics.
- Proton-nucleus collision followed by an absorber creates a "beam dump of everything". (Over 10^{21} hard gamma and positrons, over 10^{16} muons going through the absorber). *This is not yet a fully investigated advantage.*

Let us explore the sensitivity projections!

Search for Heavy Neutral Leptons



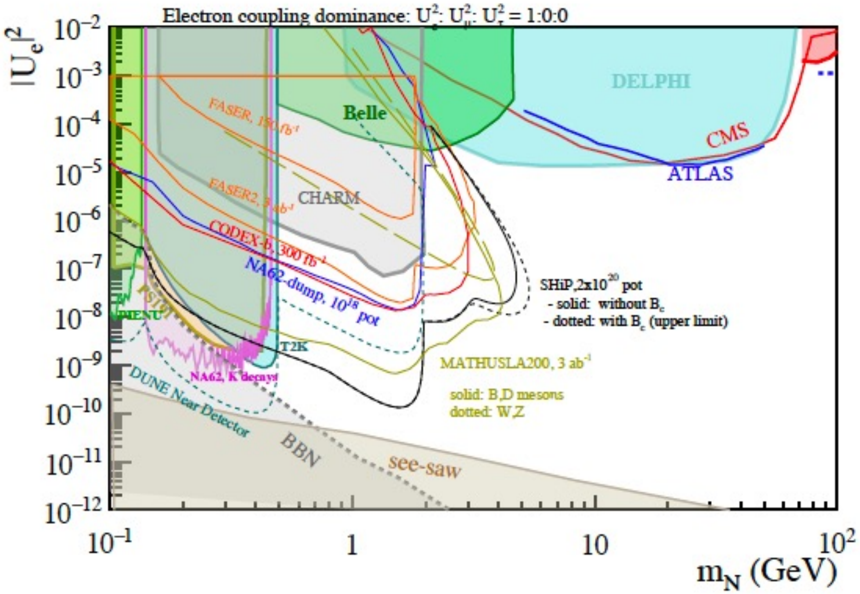


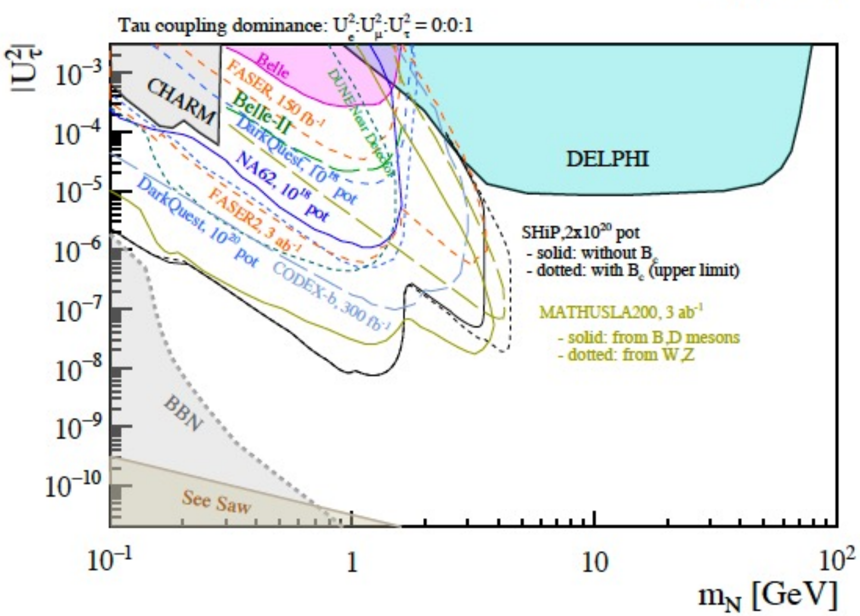
- Production channel is through prompt charm decay pp → c cbar → HNL.
- Detection is through HNL occasional decay via small mixing angle *U*, with charged states in the final state, e.g. $\pi^+\mu^-$, $\pi^-\mu^+$, etc.
- Decays are often slow, so that the sensitivity is proportional to

  (Mixing angle)^4.

  Massive improvements over old ressults possible.

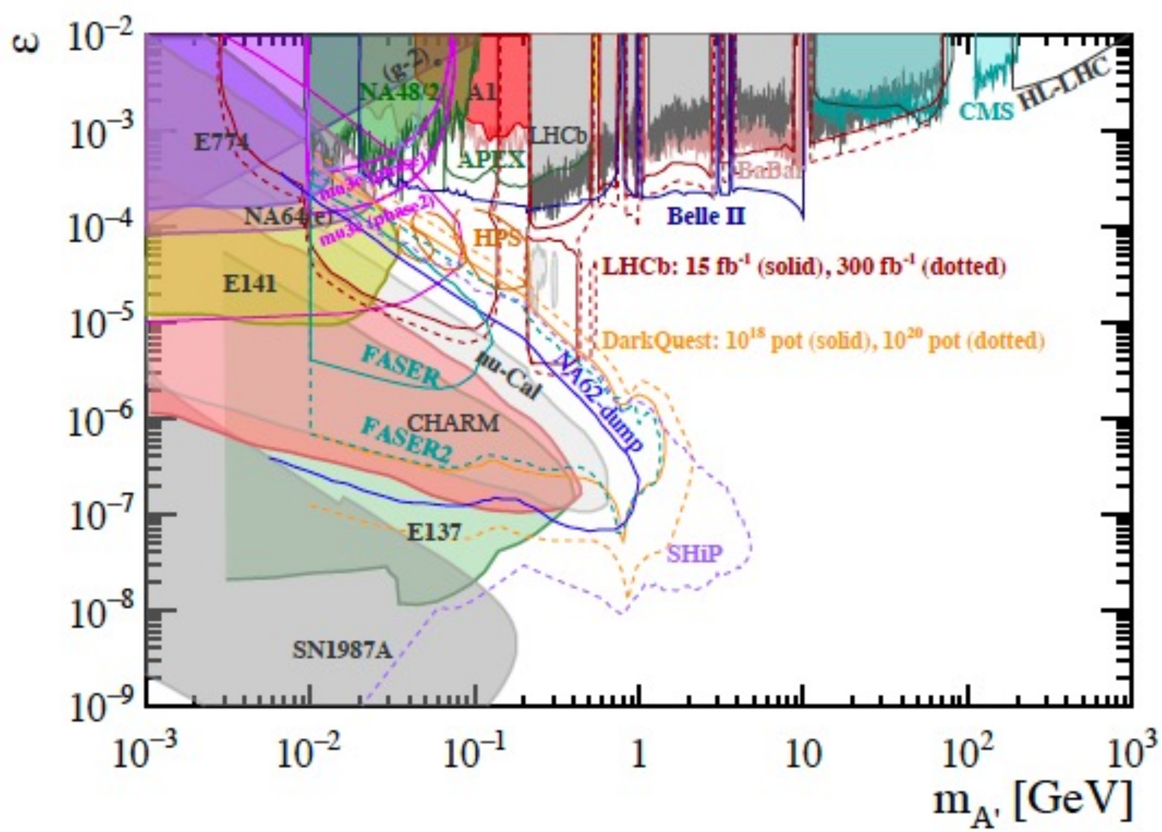
Search for Heavy Neutral Leptons





- Decay length $c\tau\beta\gamma$ scales as $(m_{HNL})^{-6}$. *One order of magnitude in mass encompasses 6 orders of magnitude of L_{decay}.*
- At above ~5 GeV there is a nice complementarity with LEP/LHC searches.
- In some DS models (e.g. with gauged B-L), even a see-saw region can be probed via Z' mediated production.
- Some models may reduce sensitivity via HNL→ dark states. In that case K →μN and eN pairs is an important tool.

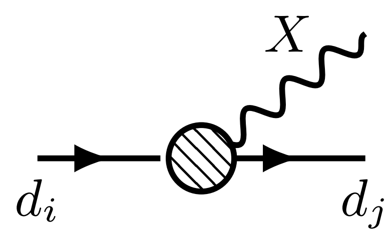
Constraints and future sensitivity to Dark Photons



O(few GeV) mass, and $\varepsilon \sim 10^{-7}$ can be probed using experiments at proposed BDF facility.

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.



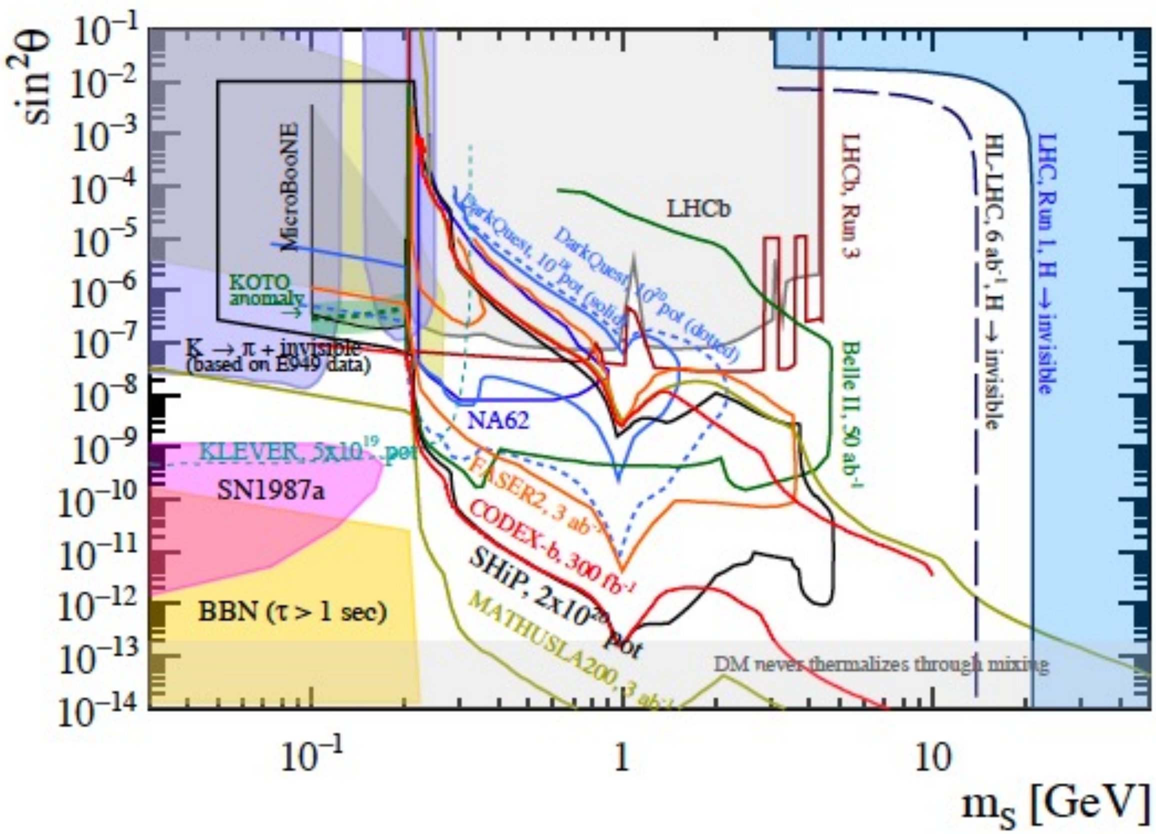
- For a fully conserved current, like couplings of dark photon,

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

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

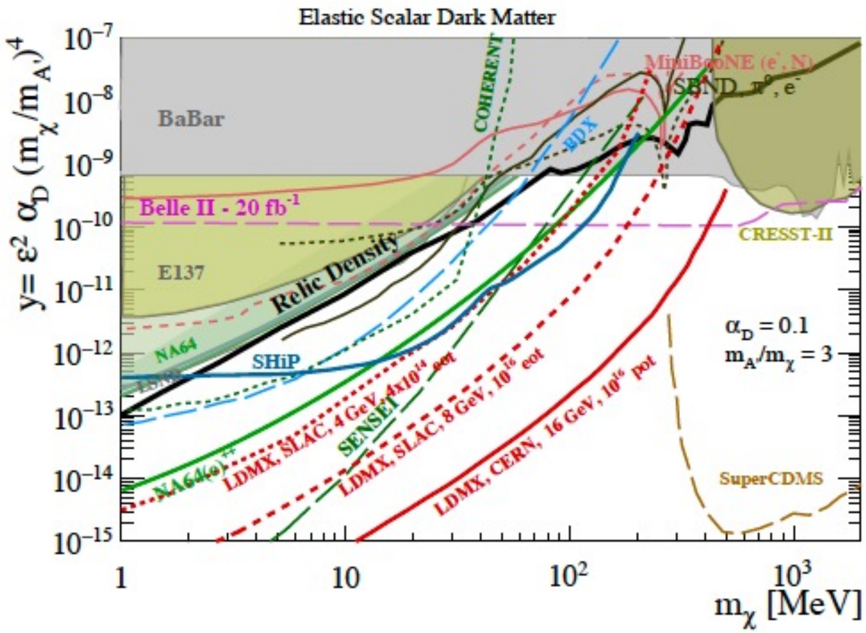
Amplitude ~ $G_F\, m^2_{top}$

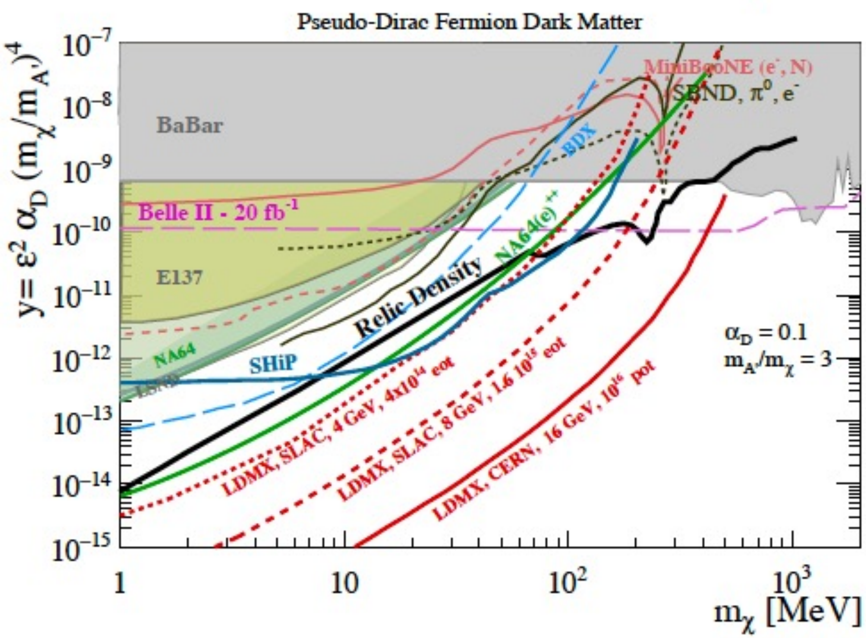
Constraints on Higgs-mixed scalars



Possible future improvements at NA62, SHiP, possibly SNB experiments, and new proposals such as MATHUSLA, CODEX-B, FASER etc. Notice the complementarity of the Kaon rare decays and beam dump 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.

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 using the CERN SPS beam enables to study dark sectors in the cutting-edge beam dump style experiments (record POT, enough energy for D, B mesons, very short baseline, "beam dump of everything"). It also enables rare K decay studies with unprecedented intensity Kaon beam.
- Breakthrough sensitivity to HNLs (perhaps best-motivated FIPs).