Feebly Interacting Particles review

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Feebly Interacting Particles: FIPs 2022 workshop report

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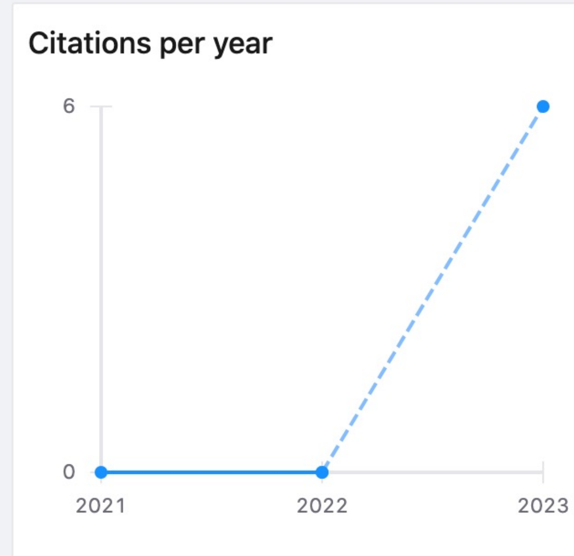

The Search for Feebly Interacting Particles

Gaia Lanfranchi, Maxim Pospelov, Philip Schuster

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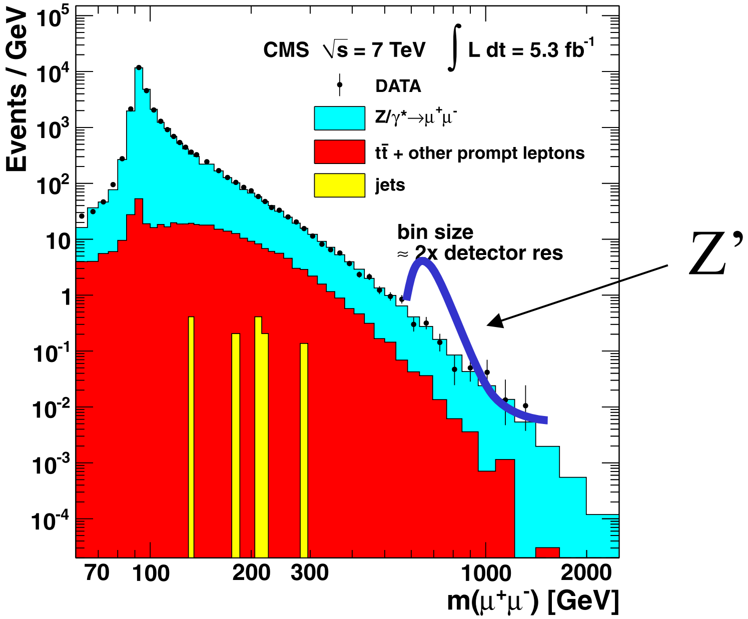
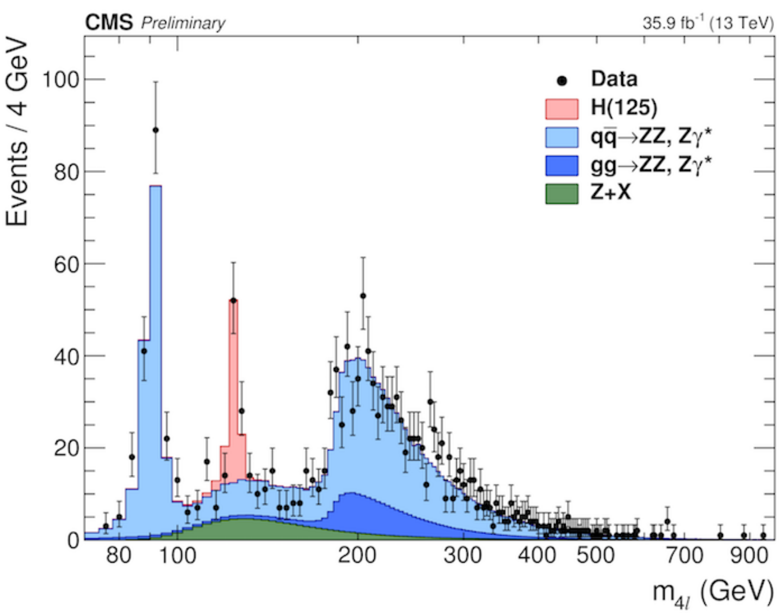
LHC: Higgs, but no New Physics at high energy thus far (?!)





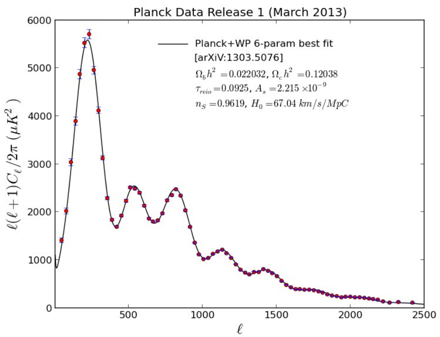
- *No hints for any kind of new physics.* Strong constraints on SUSY, extra dimensions, technicolor resonances, new Z' etc.

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

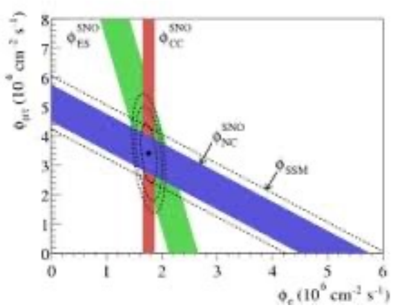
- There is no "clear practical guidance" that can be derived from the Higgs naturalness problem.

Clues for new physics

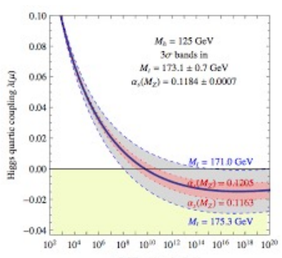
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



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.



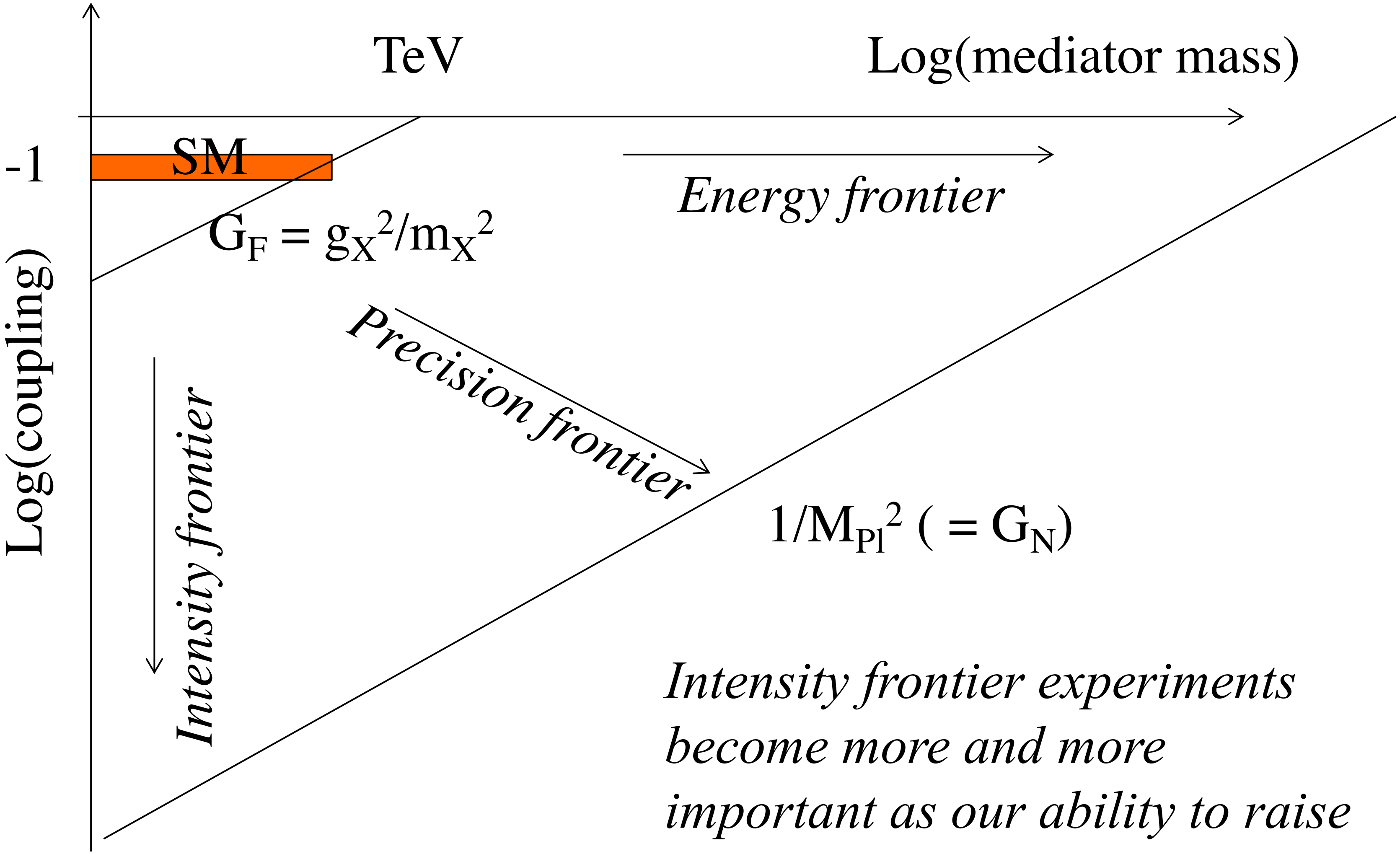
3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



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

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 ?

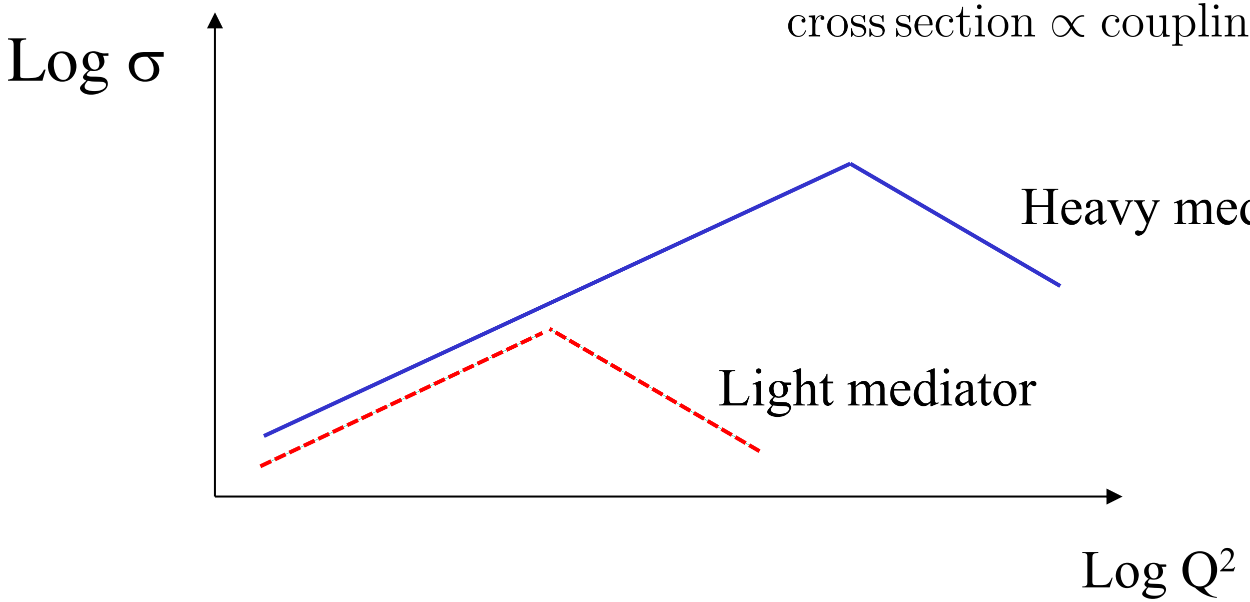


Intensity frontier experiments become more and more important as our ability to raise energy becomes limited.

Light particles change σ(E)

Light particles induced interactions do not benefit from going to large energies the same way as e.g. interactions from heavy particles

$$\text{cross section} \propto \text{couplings} \times \frac{Q^2}{(Q^2+M^2)^2}$$



High intensity is a key to probe light particles with small couplings (FIPs)

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. /Λ^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)

$LH\,N$ 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"

Motivations for Heavy Neutral Leptons

- Participates in the neutrino mass generation via see-saw

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

- 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).

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

- 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.

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*

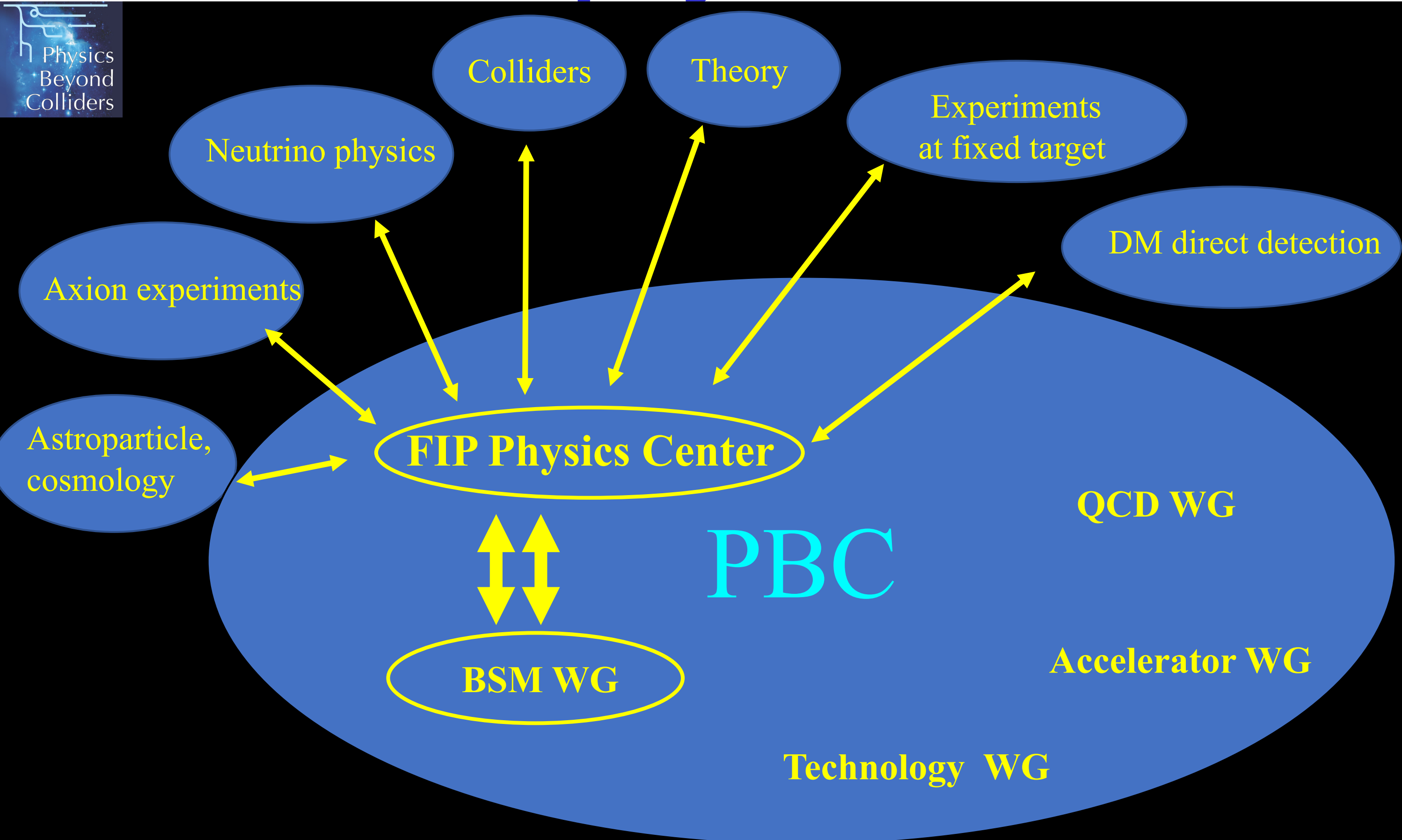
Vector | scalar | HNL | ALPs

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

FIP physics center idea



- The “FIP Physics Center” is the place in PBC where FIP physics is discussed (BSM-WG mostly focused to discuss experimental issues)
- The FPC is the natural portal to external FIP-related activities

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Slides from G. Lanfranchi

FPC steering group

- **Martin Bauer** (Durham U., UK) theorist, main interest: axions/ultra light bosons
- **James Beacham** (Duke U., US) experimentalist, ATLAS, convener LLP@LHC WG, connection to the LHC
- **Albert De Roeck** (CERN) experimentalist, CMS, convener LLP@LHC WG, connection to LHC &US neutrino community
- **Marco Drewes** (Louvain U., B) theorist, main interest: HNLs
- **Maurizio Giannotti** (Barry U., US) theorist, main interest: FIPs in stellar evolution.
- **Gian Francesco Giudice** (CERN) head of CERN Theory department and CERN representative for EuCAPT;
- **Stefania Gori:** (California U.) theorist, Convener of the RF6 (Dark sector at high intensity) Snowmass WG;
- **Pilar Hernandez** (Valencia, ES): theorist, main field: heavy neutral leptons, but she is very broad;
- **Igor Irastorza** (Zaragoza, ES) experimentalist, IAXO spokesperson, connection to axion experiments
- **Joerg Jaeckel** (Heidelberg, D) theorist, main interest: axions. Convener of CF2 in Snowmass (wavelike DM)
- **Felix Kahlhoefer** (Aachen U., D) theorist, main interest: axions/ALPs
- **Gordan Krnjaic** (FNAL & Chicago U., US): theorist, FNAL: main interest: light DM and related models.
- **Gaia Lanfranchi** (INFN, IT): experimentalist, FIPs @ extracted beam lines
- **Jacobo Lopez-Pavon** (Valencia U., ES) theorist, main interest: HNLs
- **Jocelyn Monroe** (Royal Halloway U, London, UK) experimentalist, connection to DM direct detection community.
- **Silvia Pascoli** (Bologna U., IT) theorist, main interest: neutrinos & HNLs. APPEC deputy chair and EuCAPT.
- **Maxim Pospelov** (Minneapolis U. & Perimeter I.): theorist: wide range of FIPs
- **Joshua Ruderman** (NYU, US) theorist, main interest: astroparticle
- **Philip Schuster** (SLAC, US) theorist. Main interest: light DM and related mediators, connection to US extracted beams
- **Mikhail Shaposhnikov** (EPFL, CH) theorist: worldwide reference for HNLs.
- **Jessie Shelton** (Urbana U., US): theorist, main interest: astroparticle.
- **Yevgeni Stadnik** (Tokyo U., JP) theorist, main interest: ultra-light FIPs
- **Stefan Ulmer** (Riken, JP), experimentalist (AD), connection to ultra-low FIPs

+ representatives of PBC experiments related to FIP physics

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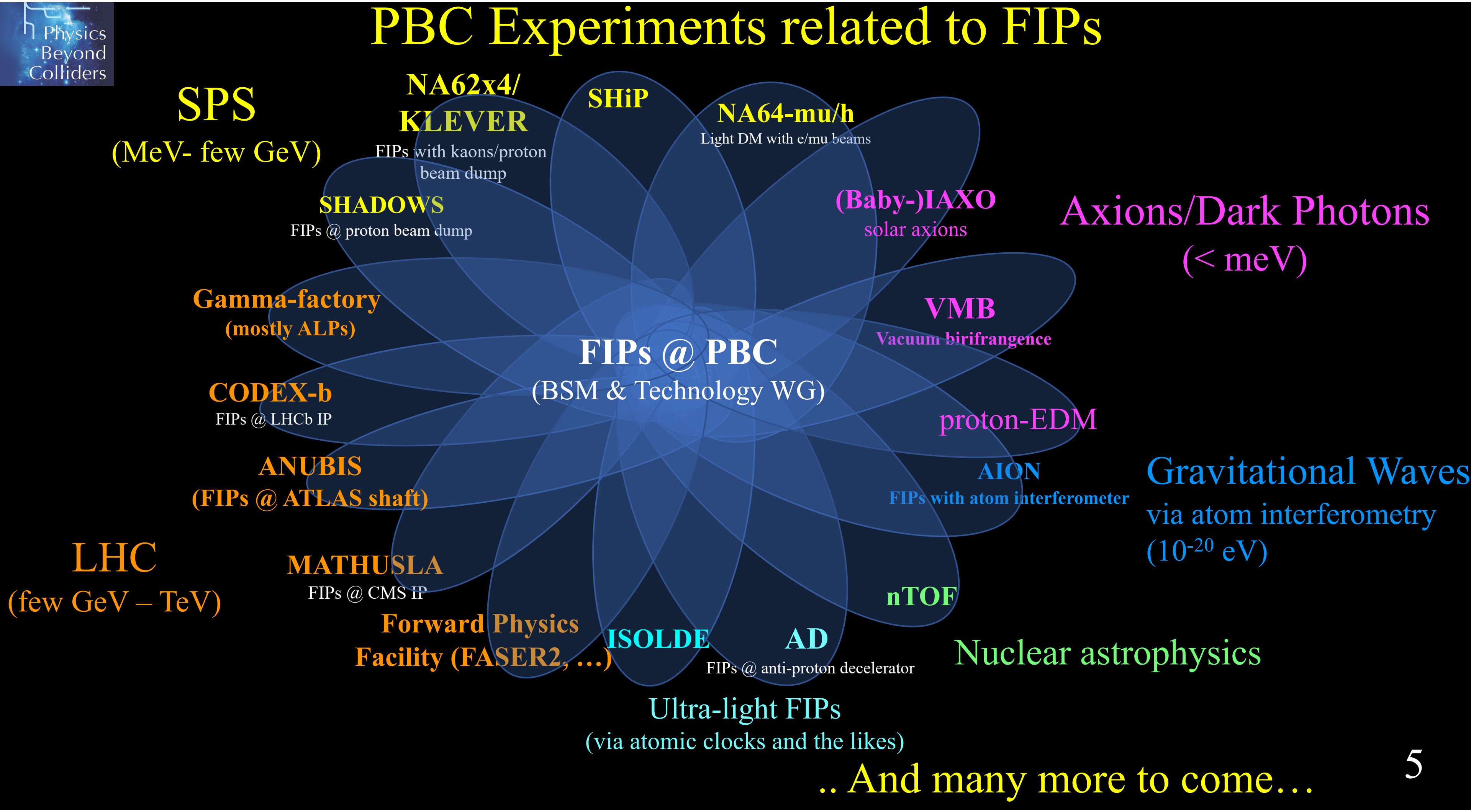
Several *more participants have been added: M. Hostert, J. Klaric, ...*

Connection to experiments



Future direction – new intensity experiments at CERN

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

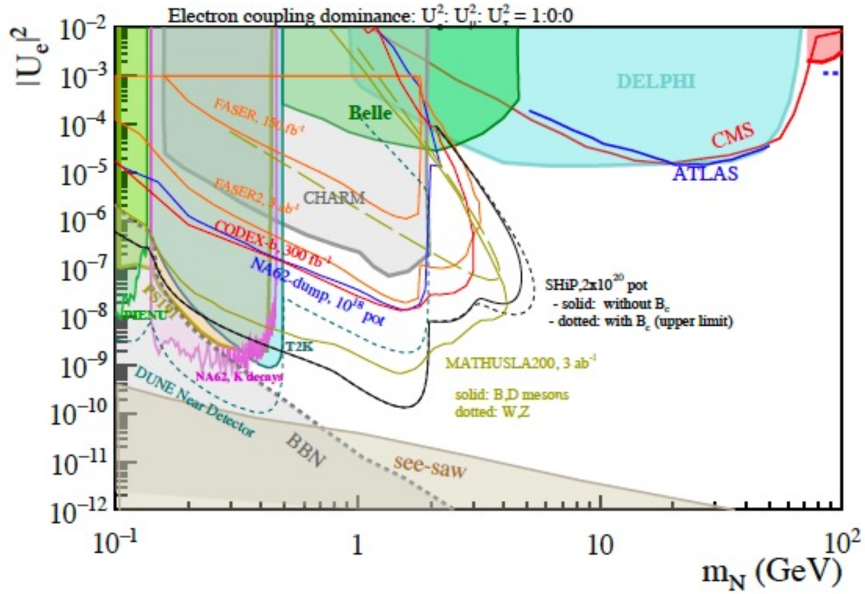
New experimental facilities at CERN:

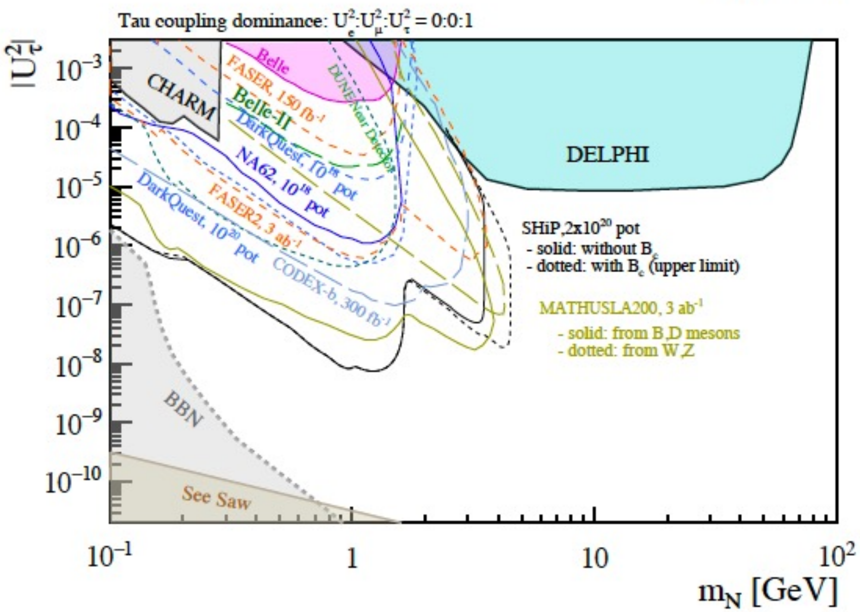
- Provide capability to collect over 10^{20} of 400 GeV protons on target enabling important intensity frontier experiments (SHiP) enabling best sensitivity to HNLs
- Provide new capabilities in precision studies of Kaon decays, including important "clean" modes (NA62, HIKE): $K^+ \to \pi^+ \nu \bar{\nu}$; $K_L \to \pi^0 \nu \bar{\nu}$ 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).

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.*

Search for Heavy Neutral Leptons



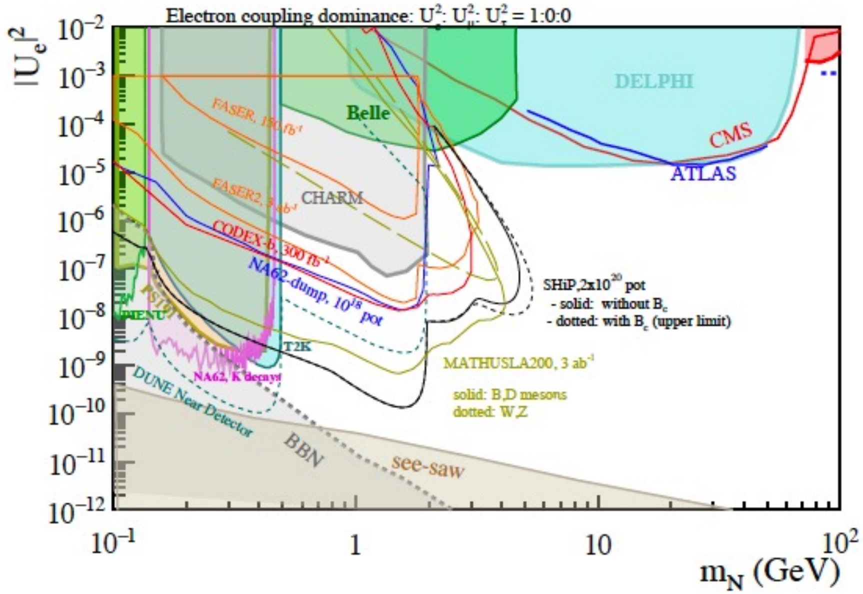


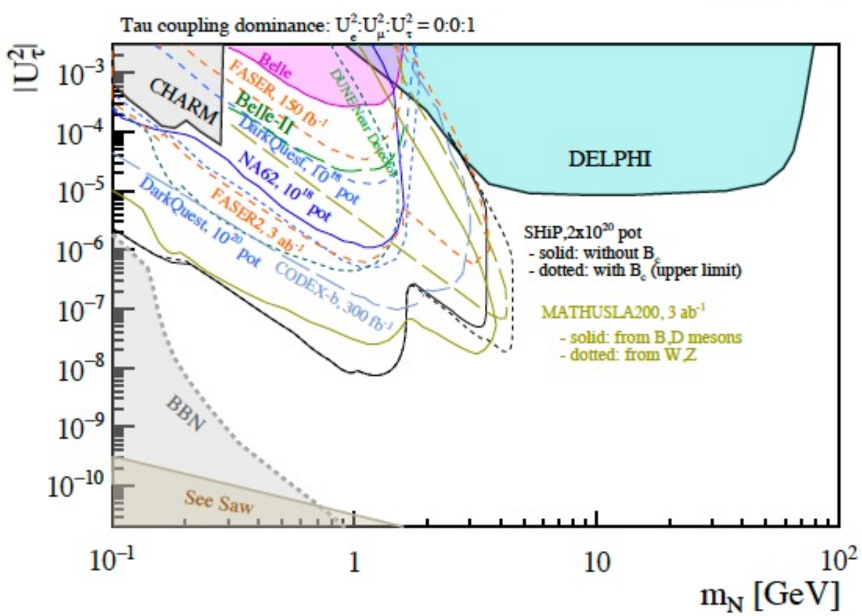
- Production channel is through prompt charm decay pp → c cbar → HNL.
- Detection is through HNL occasional decay via small mixing angle *U*, with charged states in the final state, e.g. $\pi^+\mu^-$, $\pi^-\mu^+$, etc.
- Decays are often slow, so that the sensitivity is proportional to

  (Mixing angle)^4.

  Massive improvements over old ressults possible.

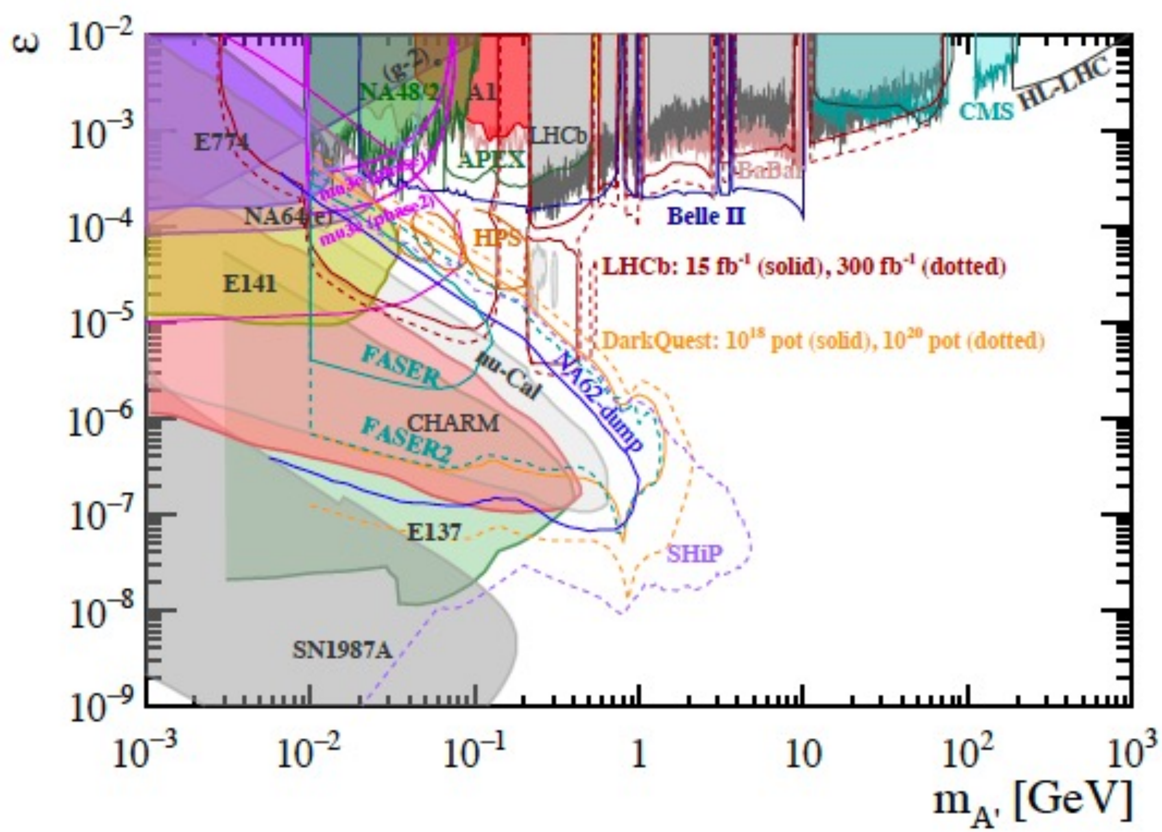
Search for Heavy Neutral Leptons





- 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.

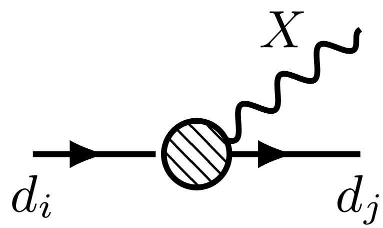
Constraints and future sensitivity to Dark Photons



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.



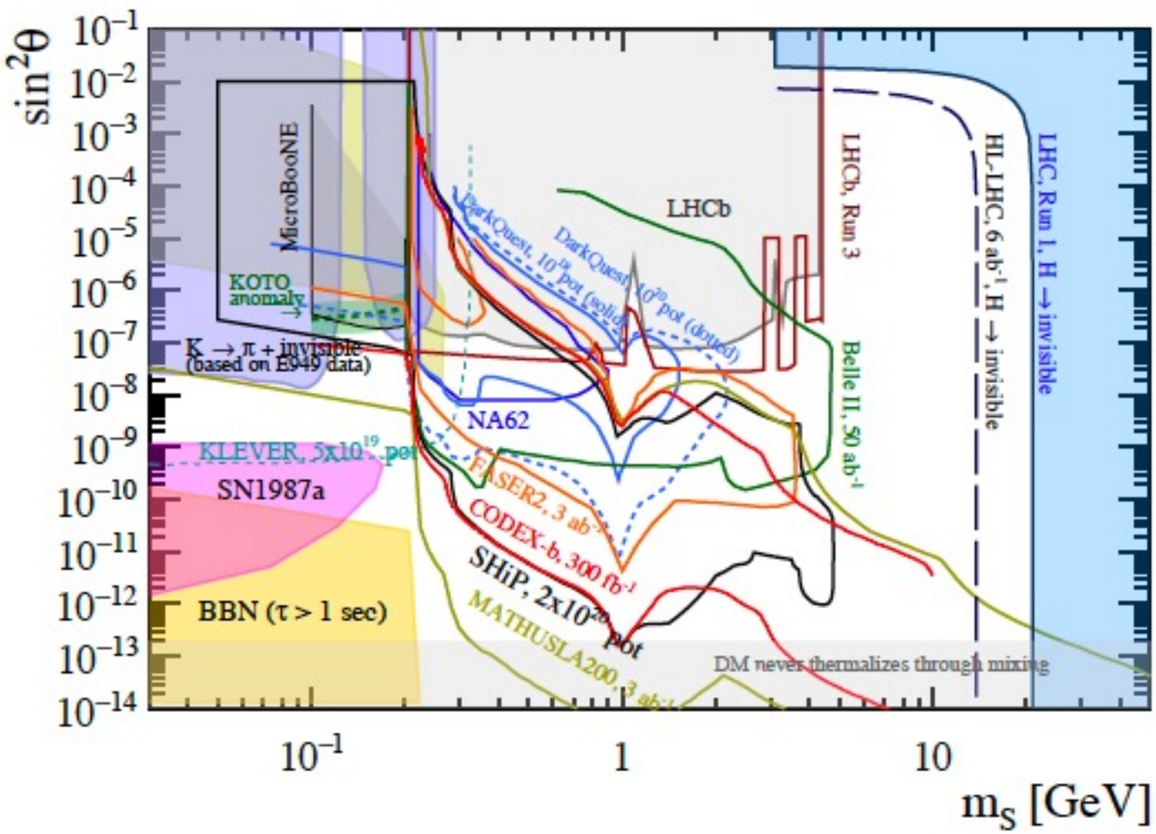
- For a fully conserved current, like couplings of dark photon,

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

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

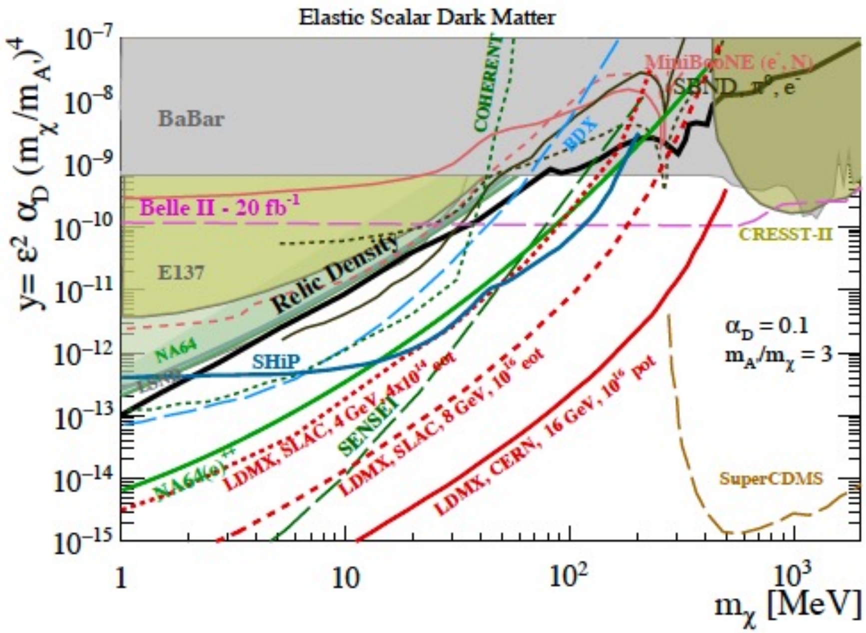
Amplitude ~ $G_F\, m^2_{top}$

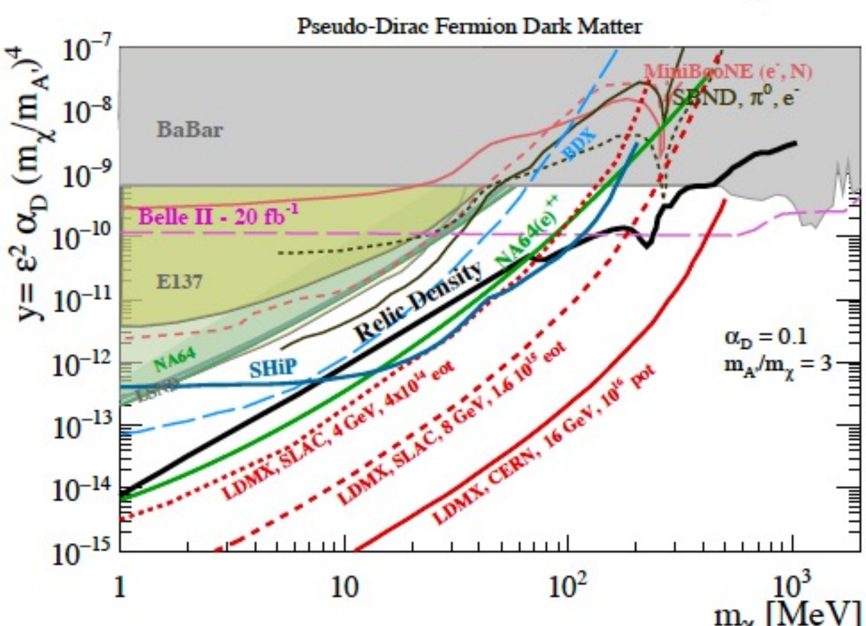
Constraints on Higgs-mixed scalars



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.

Physics "benefits" of FIP searches

- New dedicated/novel experiments are designed, new run modes for existing experiments are implemented (NA64, LDMX, light dark matter direct detection, Miniboone beam dump mode run)

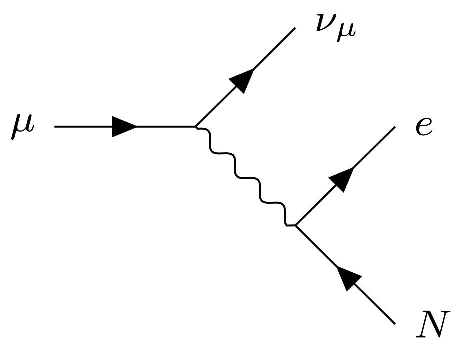
- Old data from past experiments are being re-analyzed.

- New FIP-motivated signatures in existing experiments are being explored (Here the list is enormous. E.g. latest from NA62: search for $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$ decay)

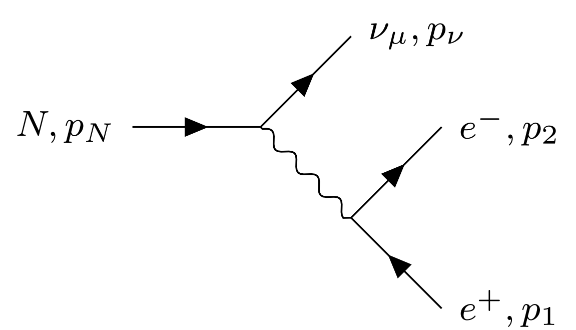
- Benchmark/portal framework provided some insurance that no interesting physics is missed. (It would be nice to expand it to the sub-eV new physics and formulate a new set of benchmarks there.)

New HNL constraints from old LSND

- With Y. Ema, Z. Liu and K. Lyu, e-Print: 2306.07315 [hep-ph]

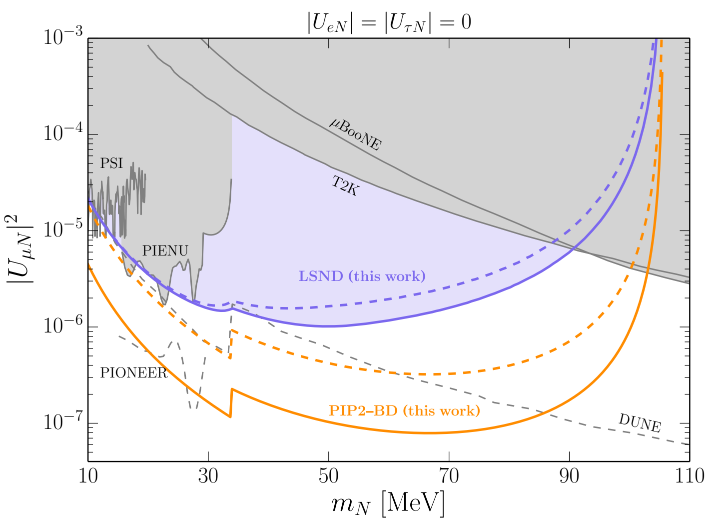


Production



Detection

- Sometimes a pair will look like a single electron → contributes to ν–e scattering sample at LSND. Strong acceptance penalty.



- Even with the penalty, LSND provides novel constraints due to enormous POT.
- PIP2 beam dump could improve on these constraints.

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.

- *New HNL limits from old experiment (LSND) are presented. More can be done at PiP-II.