Feebly Interacting Particles at Non-Conventional Experiments

Brian Batell
University of Pittsburgh

LHCP 2022
May 16-20, 2022

Theoretical motivation for Feebly Interacting Particles (FIPs)

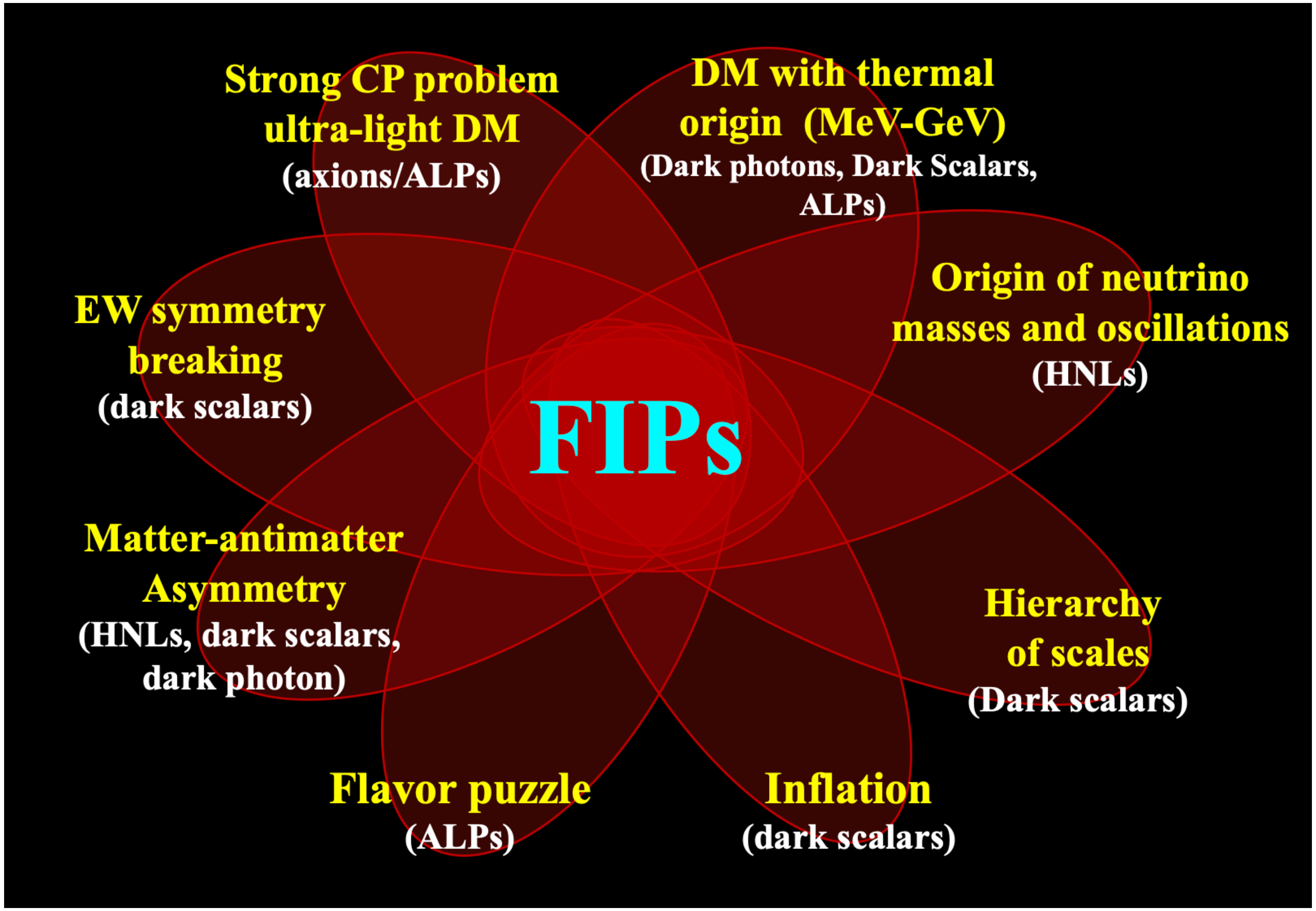


Figure from G. Lanfranchi

See earlier talk by A. Thamm

Worldwide experimental effort to search for FIPs

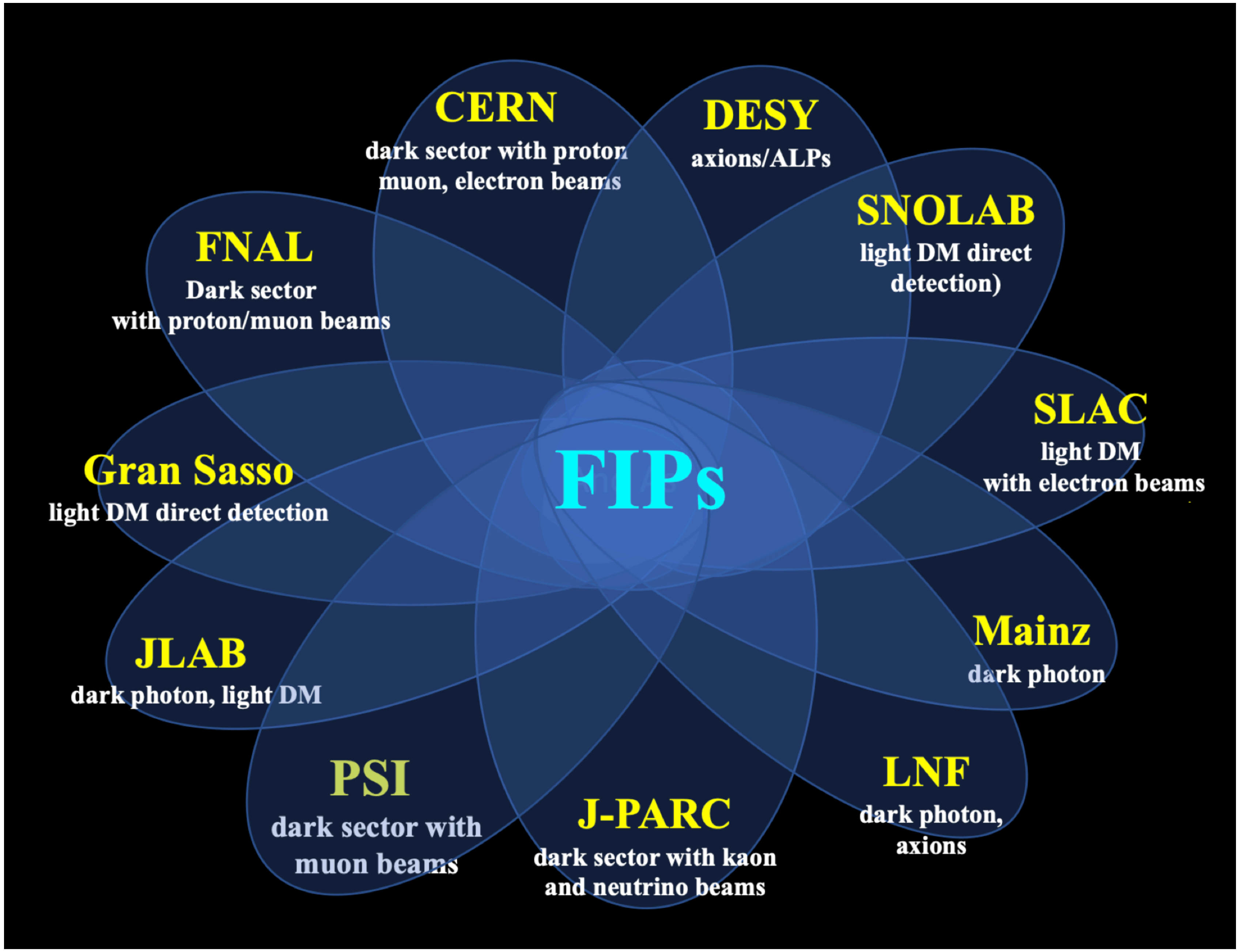


Figure from G. Lanfranchi

FIPs and Portals

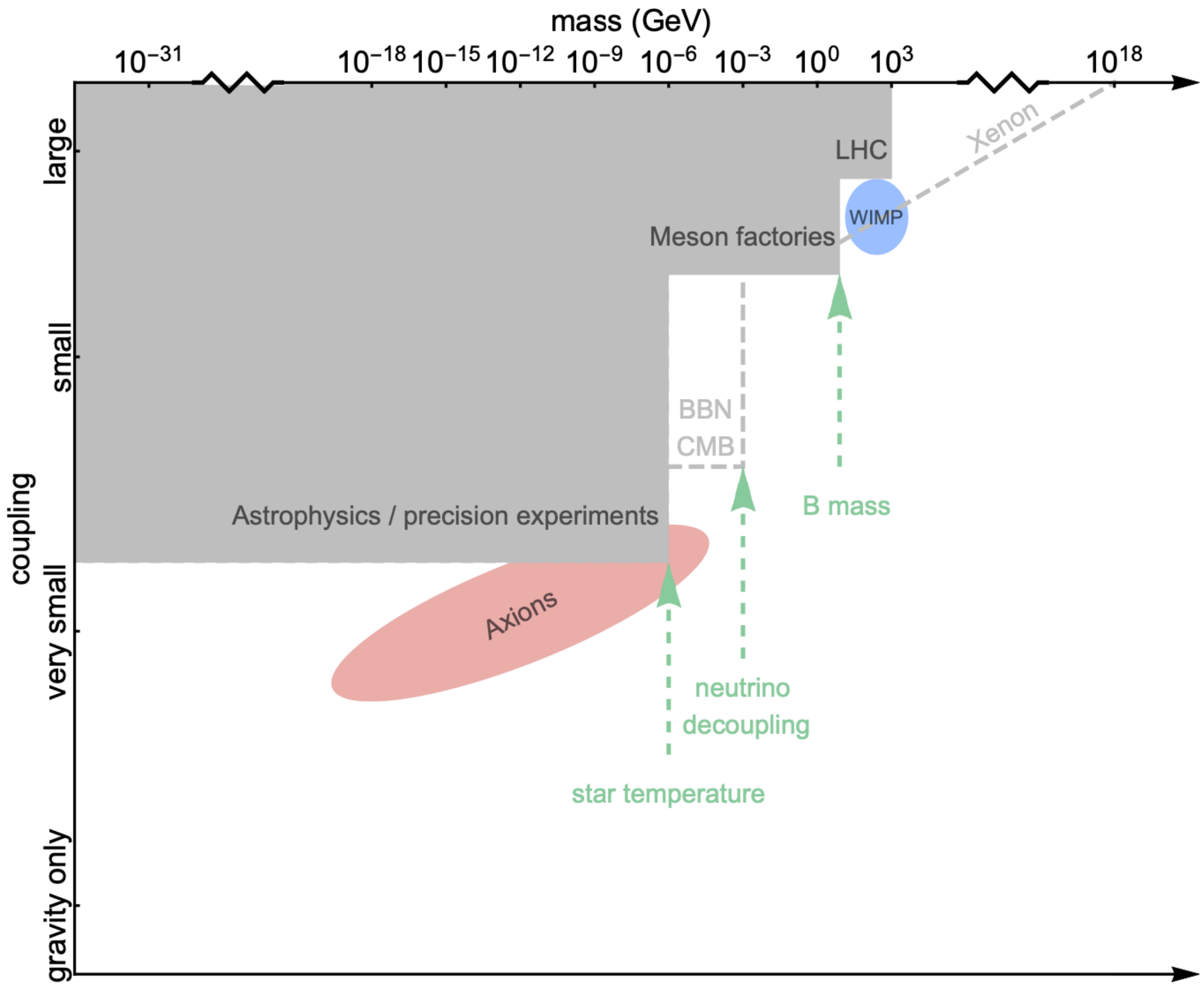
- Renormalizable portals:

$\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	Vector Portal
$(A\,S + \lambda\,S^2)\,H^\dagger H$	Higgs Portal
$yNLH$	Neutrino portal

- Many other possibilities:
  - Higher dimension portals, e.g. axion-like particle, flavor-specific scalar, …
  - Anomaly free (e.g., $B - L, L_\mu - L_\tau$ …) and anomalous (B, …) gauge bosons

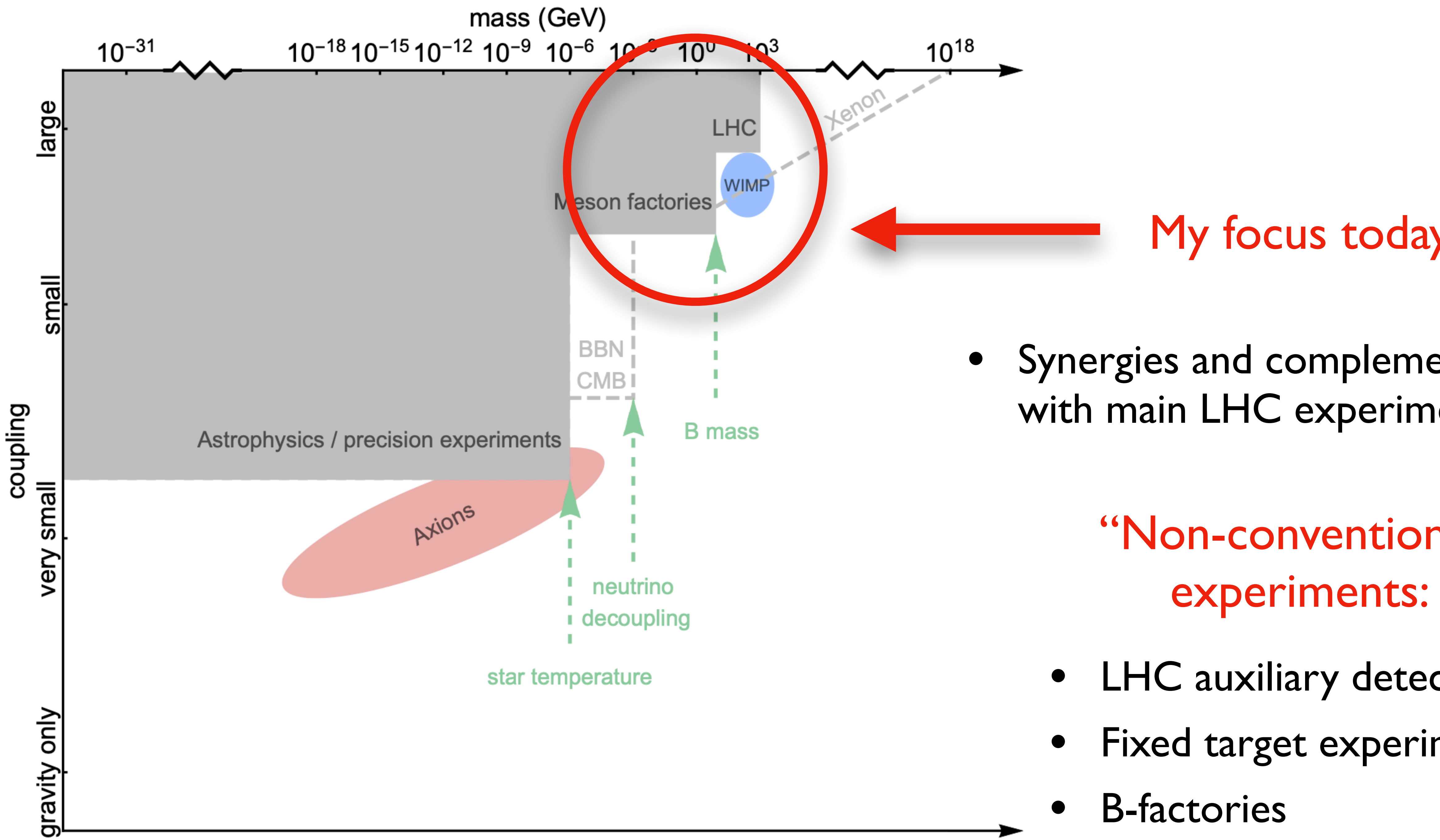
- FIPs often come with additional structure and states (e.g., dark matter, dark Higgs, new electroweak scale states,…)

The FIP Landscape



FIPs 2020 Workshop Report
Figure from S. Knapen

The FIP Landscape



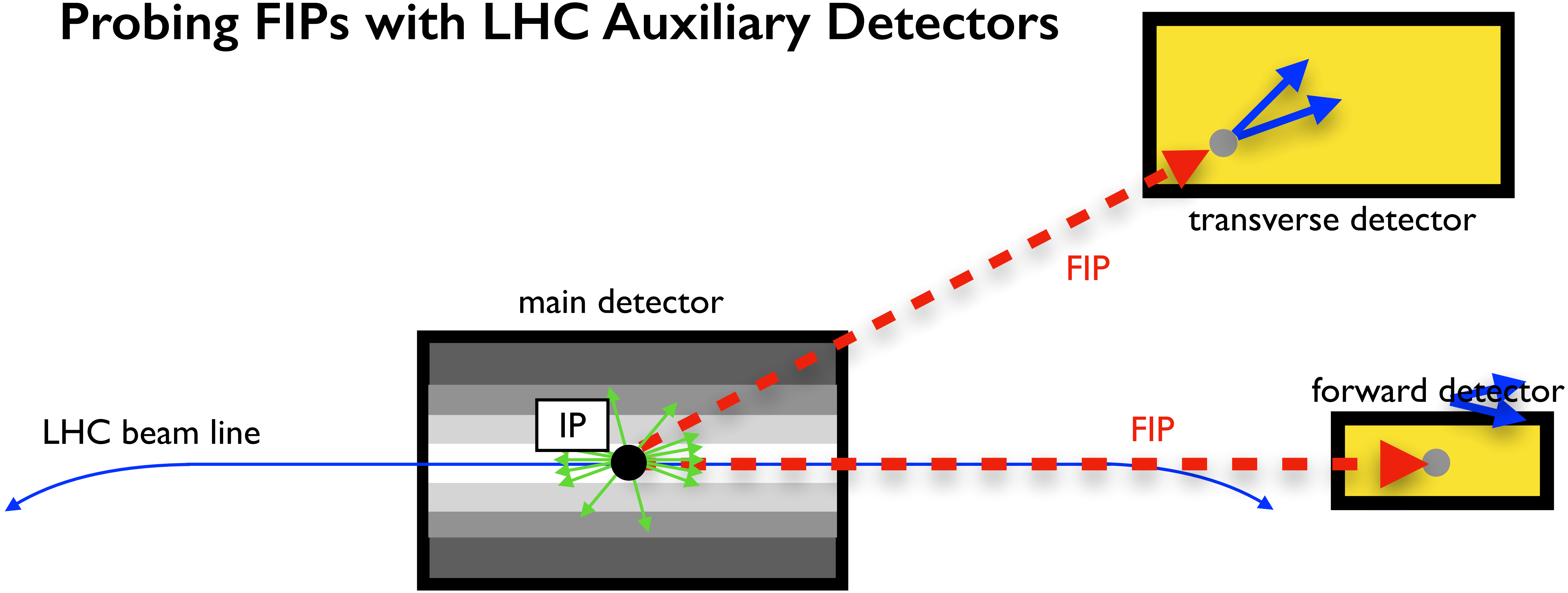
- Synergies and complementarity with main LHC experiments

"Non-conventional" experiments:

- LHC auxiliary detectors
- Fixed target experiments
- B-factories

FIPs 2020 Workshop Report
Figure from S. Knapen

Probing FIPs with LHC Auxiliary Detectors



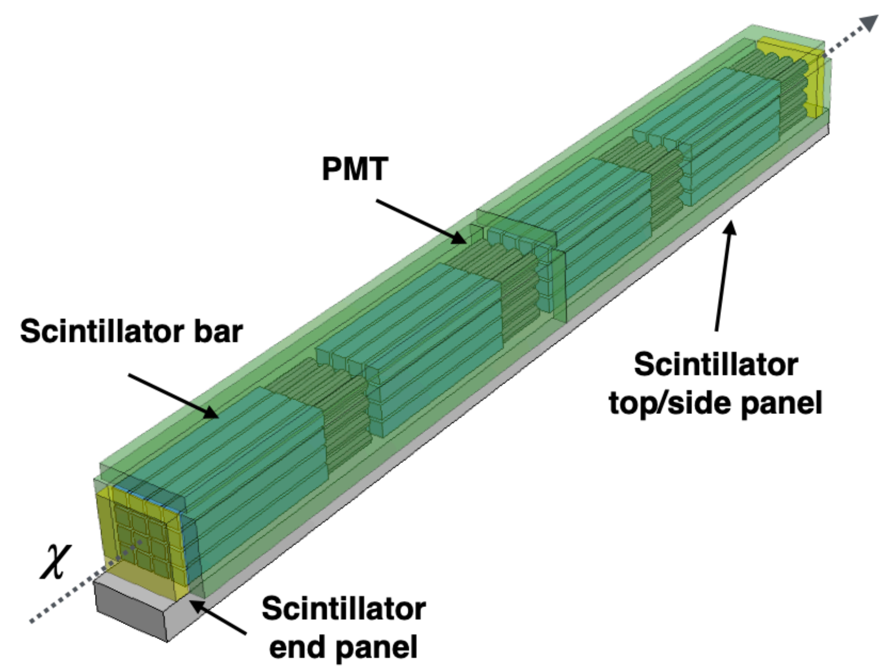
- ***Basic idea:*** use primary high energy LHC *pp* collisions as the production source of FIPs, and place a detector nearby to the interaction point to detect them

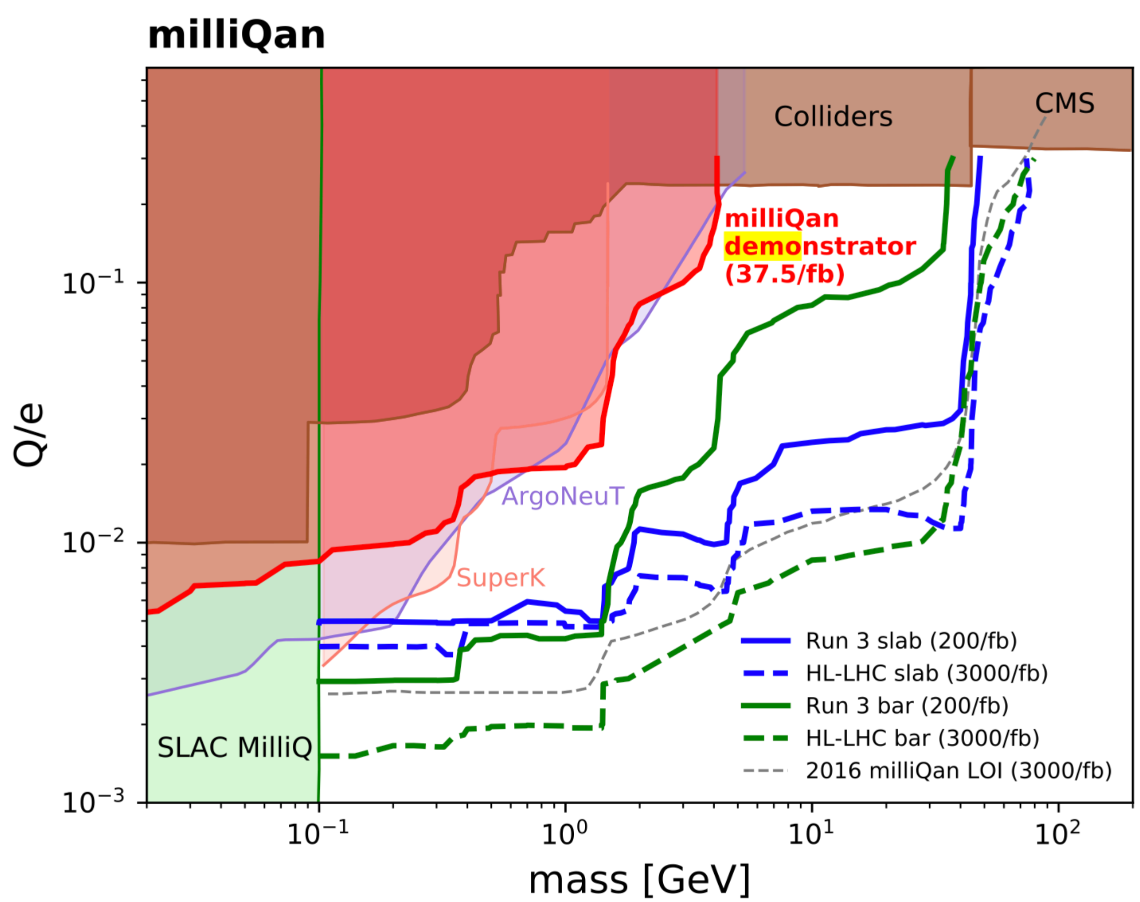
See for example:

[Haas, Hill, Izaguirre, Yavin]
[Feng, Galon, Kling, Trojanowski]
[Chou, Curtin, Lubatti]
[Gligorov, Knapen, Papucci, Robinson]
…

milliQan @ CMS

- Meter-scale scintillator detector located 33 m from CMS IP
- Signature consists of few photo-electrons from ionization by mCP
- Sensitivity of mCP with charges $\sim 10^{-3}e - 10^{-2}e$ and masses between $\sim 1 - 100\text{GeV}$
- milliQan demonstrator (~1% scale prototype) operated successfully during Run 2 - new limits!
- Expanded milliQan detector will collect data during LHC Run 3



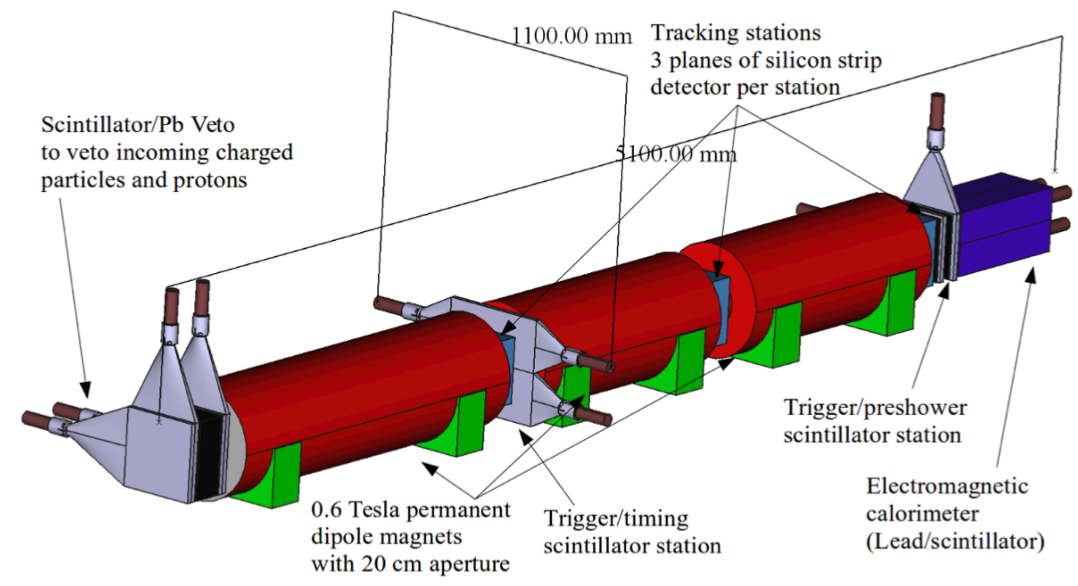


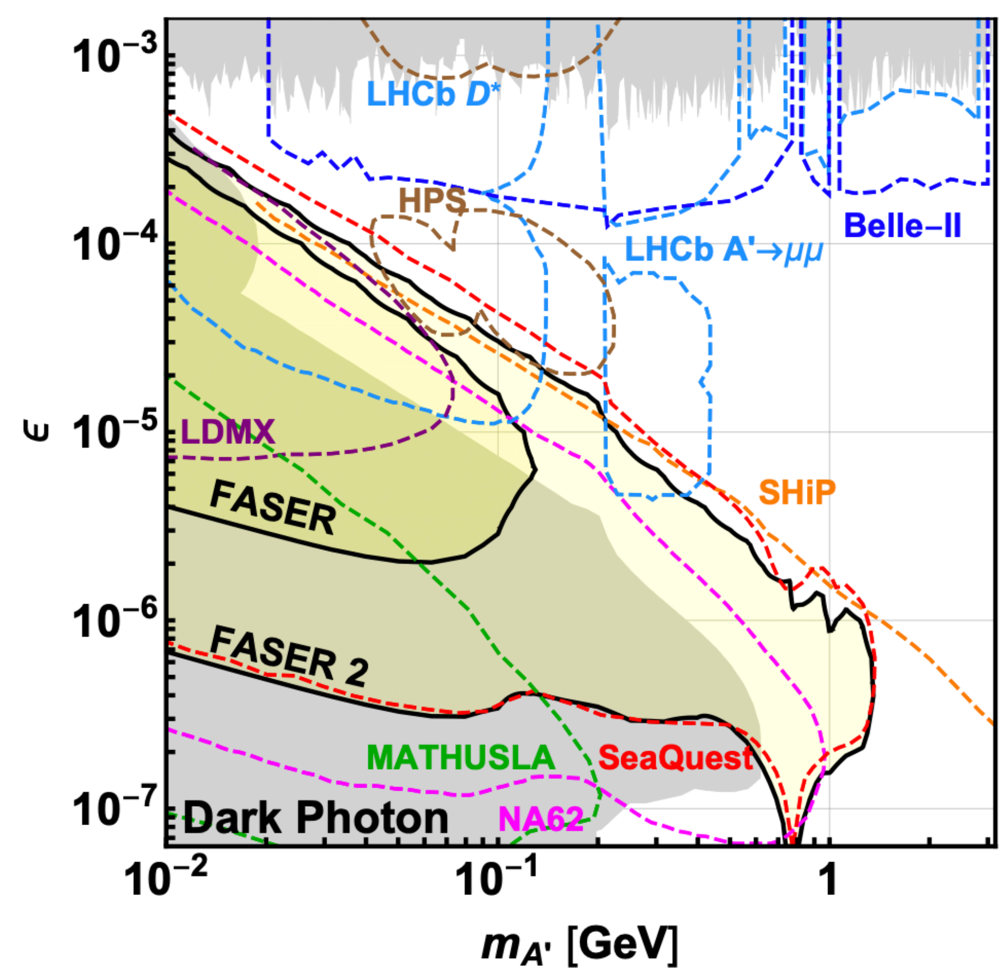
[milliQan Collaboration, 2104.07151]

See talks by Y.-D. Tsai and M. Carrigan

FASER @ ATLAS

- Meter-scale length LLP detector located 480 m downstream of ATLAS IP
- Active decay volume, spectrometer, and electromagnetic calorimeter detector
- Signature is visible SM particles from LLP decays
- Sensitive to visibly decaying dark photons, dark scalars, HNLs, ALPs, etc. in the MeV-GeV mass range
- FASER is installed and collecting data during LHC Run 3
- FASER2, a larger successor to FASER, is envisioned for the HL-LHC era



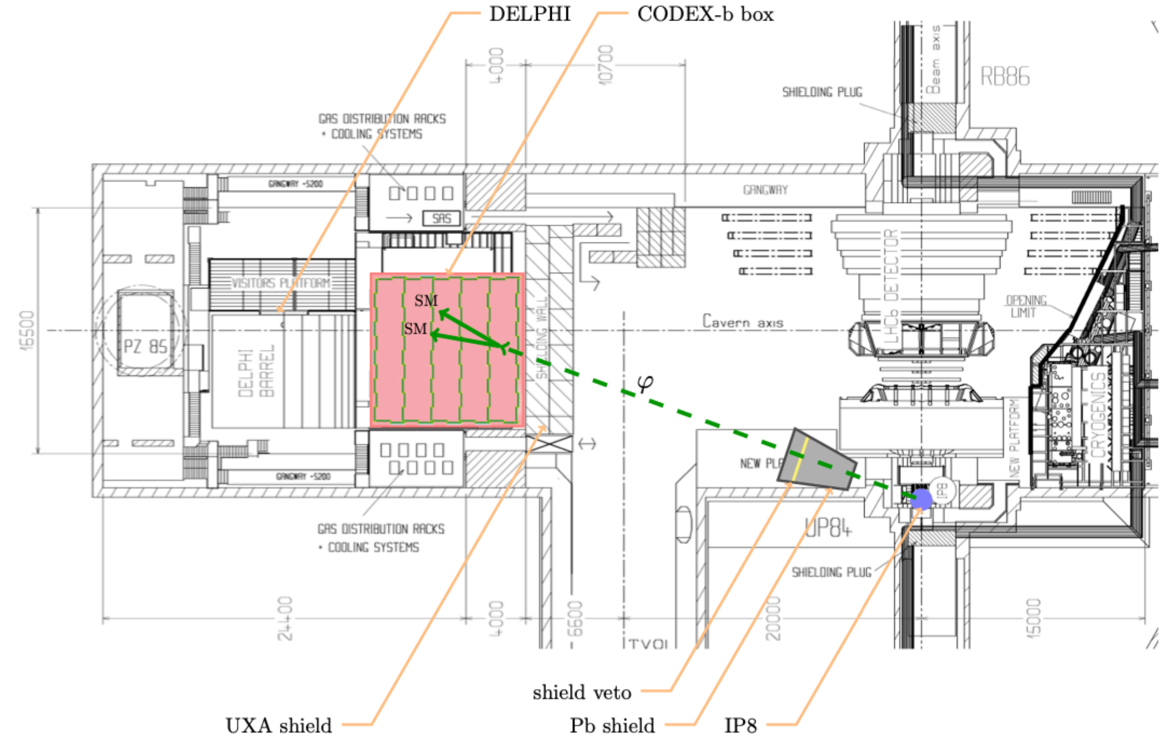


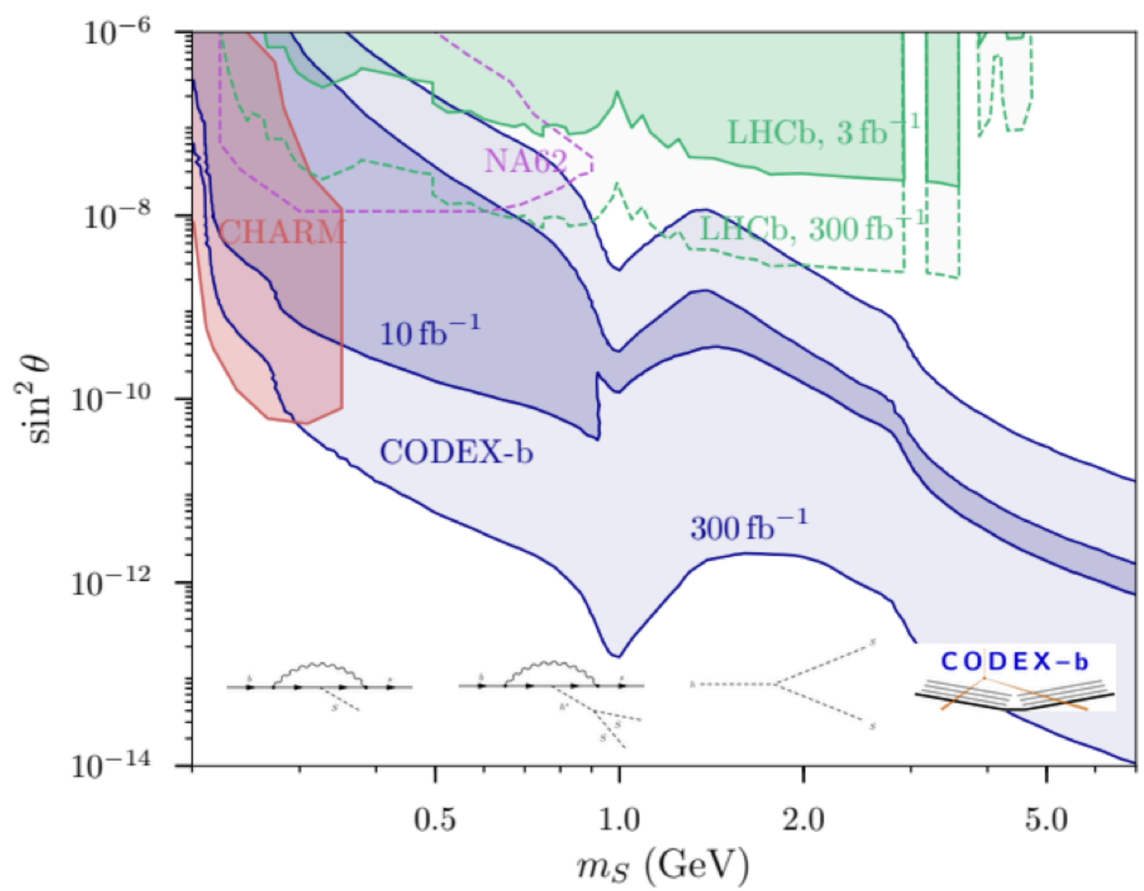
[FASER Collaboration, 1901.04468]

See talk by K. Li

CODEX-b @ LHCb

- Medium-scale, modest cost LLP detector located 25 m from LHCb IP
- Resistive Plate Chamber detector provides timing, position, vertexing. Passive shielding and active vetos to mitigate backgrounds
- Signature is visible SM particles from LLP decays
- Transverse location offers sensitivity to LLPs produced through both exotic light (e.g., meson) and heavy (e.g., Higgs) particle decays
- Smaller CODEX-β demonstrator will operate during Run 3, while CODEX-b will run during HL-LHC



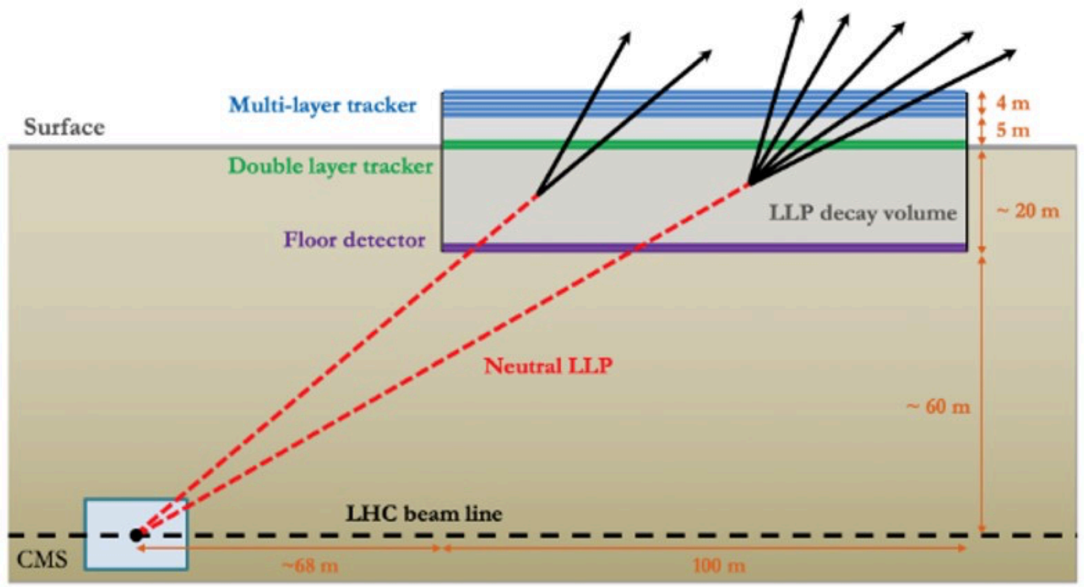


[CODEX-b Collaboration, 2203.07316]

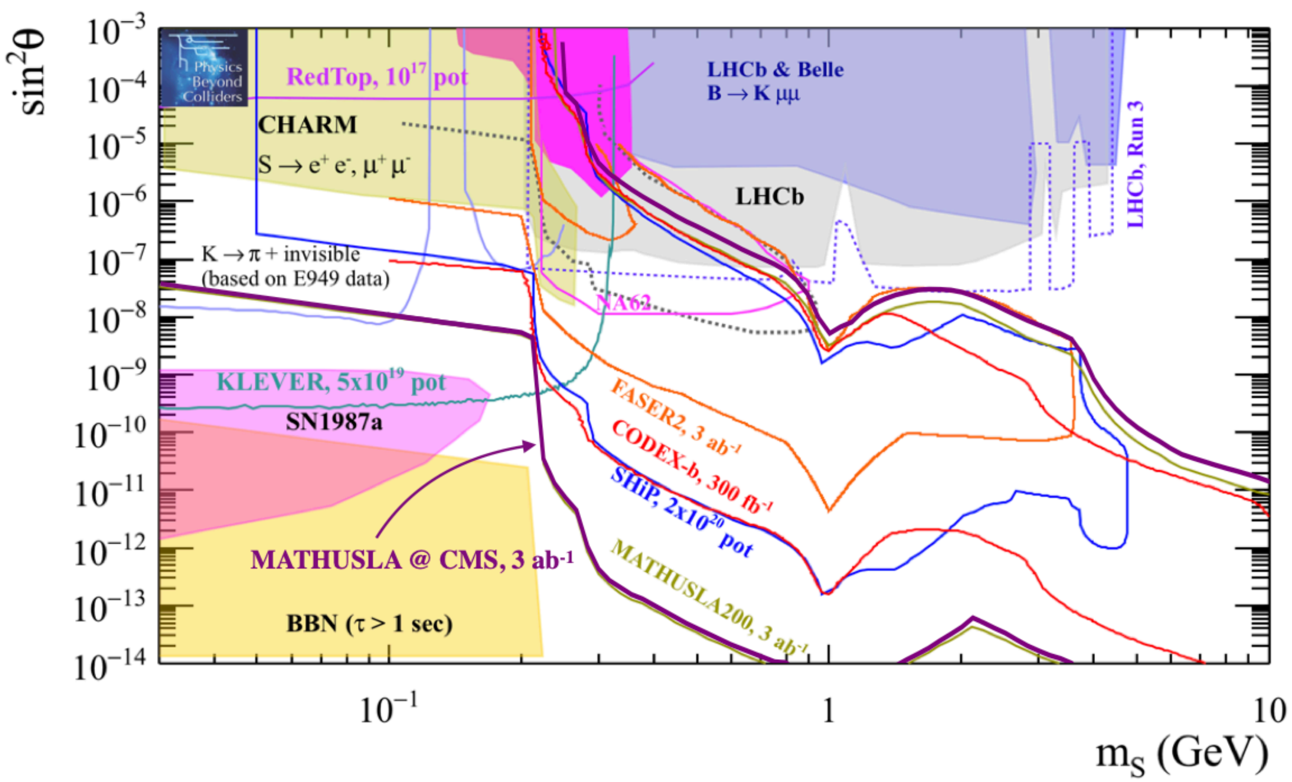
See talk by L. Henry

MATHUSLA @ CMS IP

[MATHUSLA Collaboration, 2203.08126]



- Large-scale LLP detector located on surface near CMS proposed for the HL-LHC era
- Multiple scintillator detector planes allow timing, spatial, vertexing measurements
- Signature is visible SM particles from LLP decays
- Transverse location offers sensitivity to LLPs produced through both exotic light (e.g., meson) and heavy (e.g., Higgs) particle decays

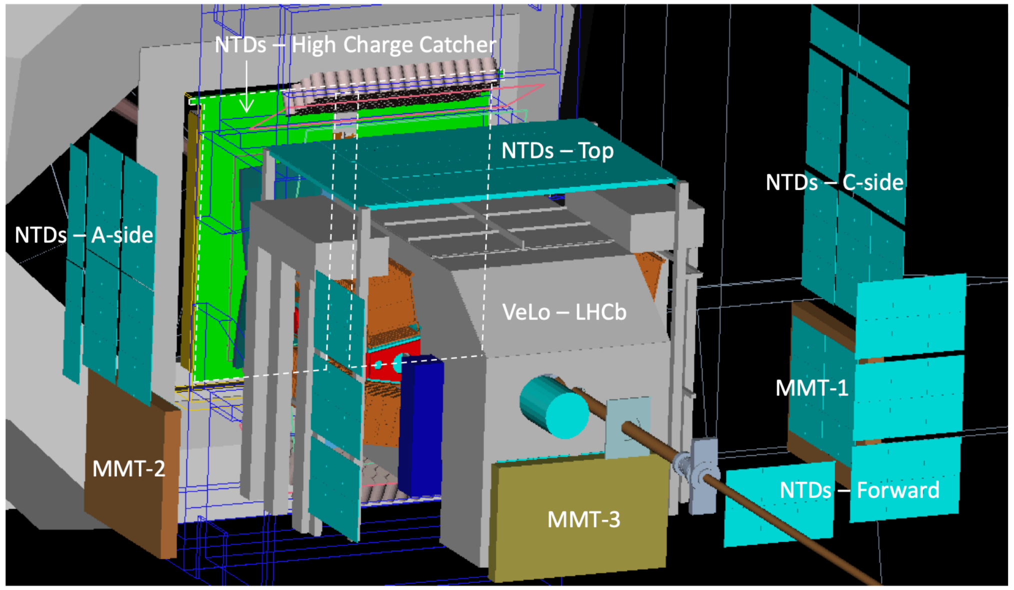


[CERN PBC Report, 1901.09966]

See talk by L. Henry

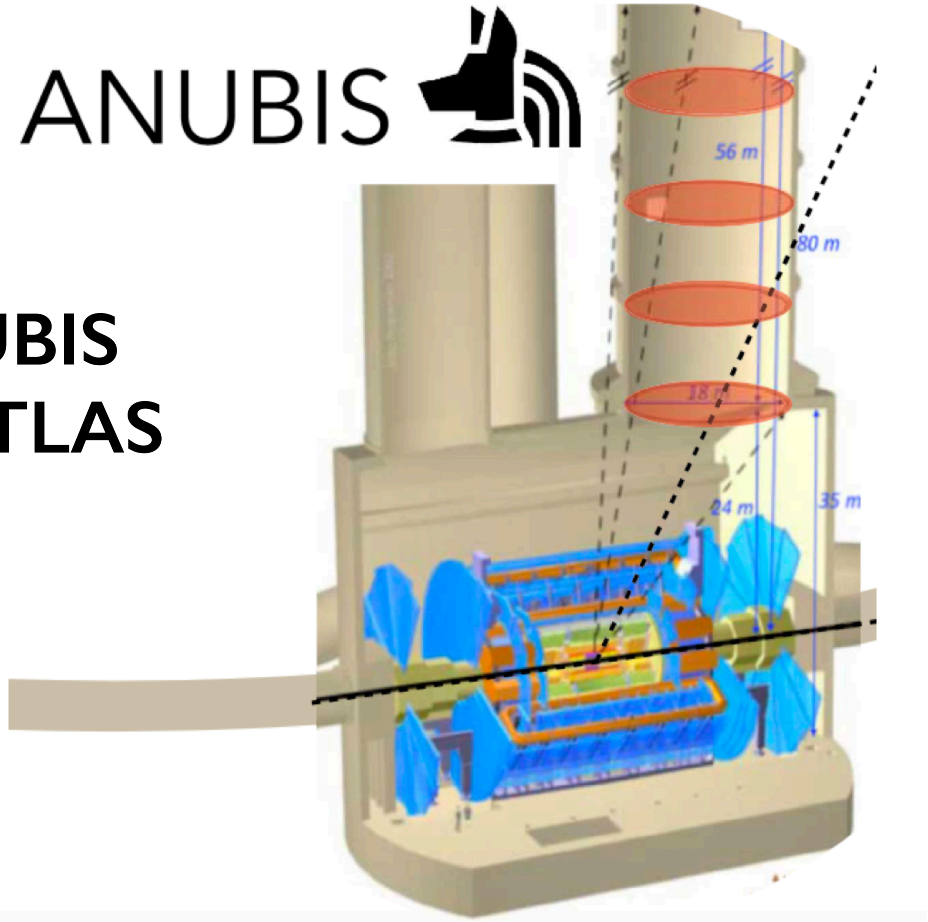
Other LHC auxiliary detectors

MOEDAL-MAPP @ LHCb



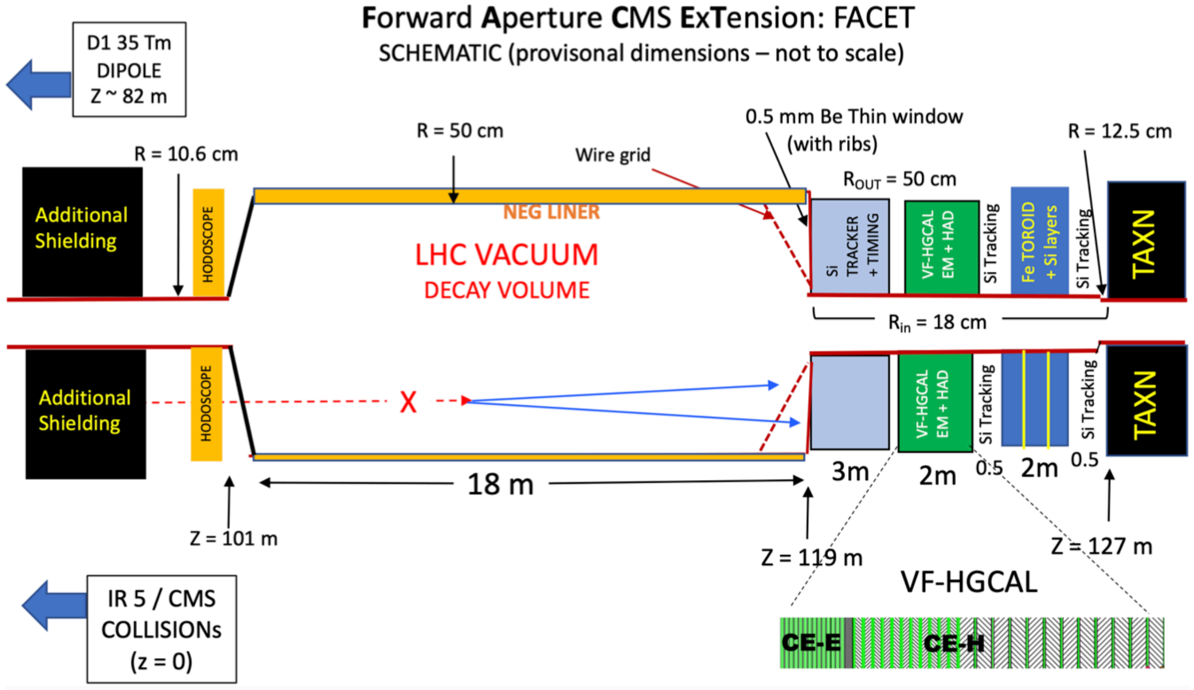
See talk by M. Carrigan

ANUBIS @ ATLAS



See talk by L. Henry

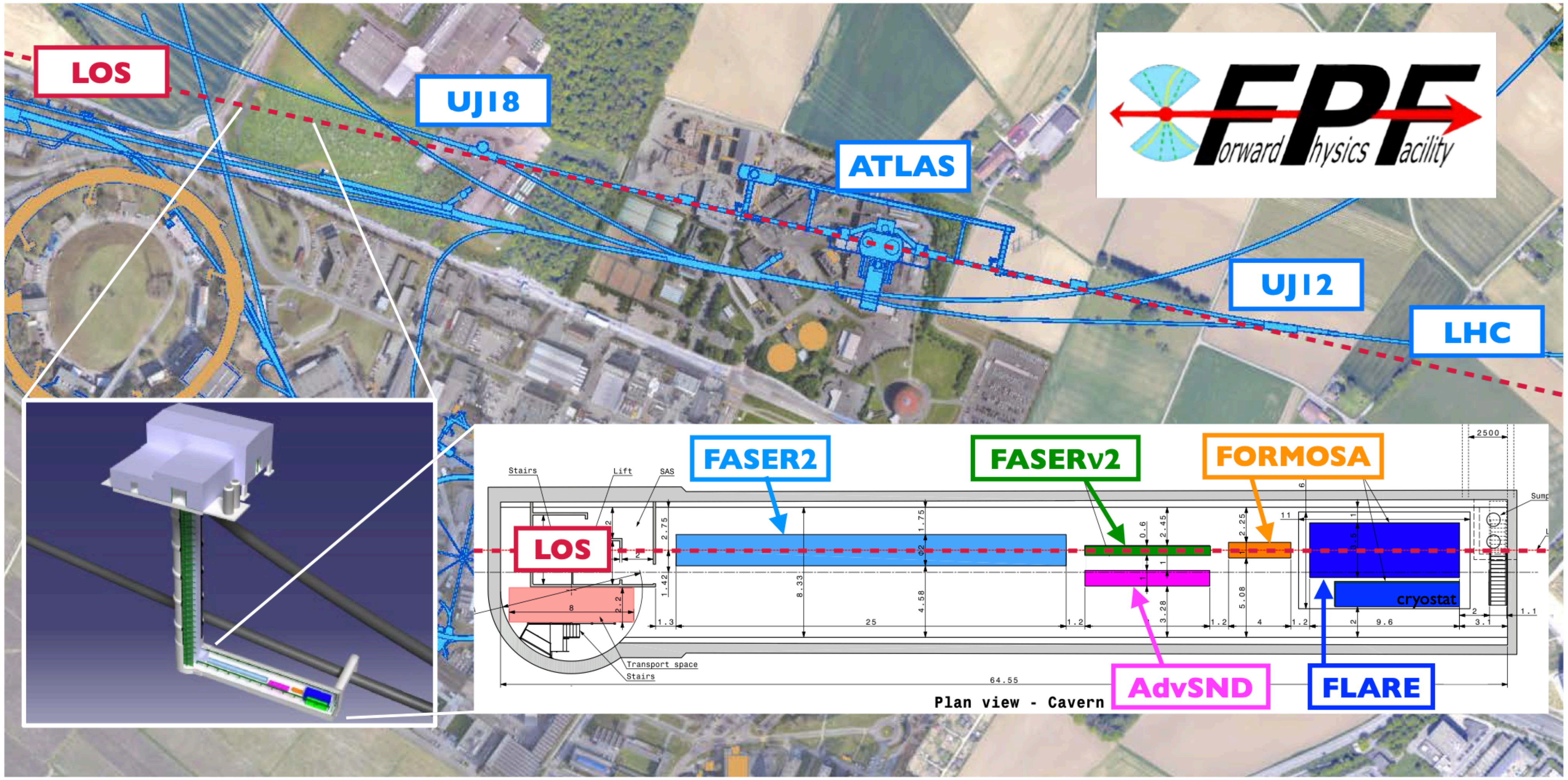
FACET @ CMS



…

The Forward Physics Facility

- Proposal to create a facility to host a suite of forward physics experiments which will operate during the HL-LHC era
- Physics studies include BSM, neutrinos, QCD, astroparticle physics, …



FPF Report, 2109.10905

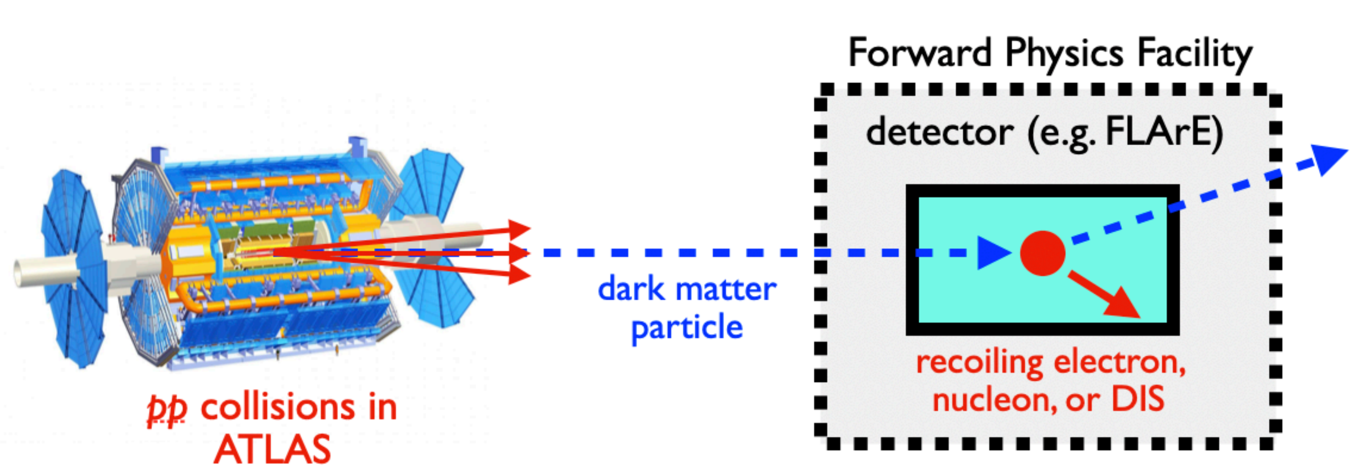
Snowmass whitepaper, 2203.05090

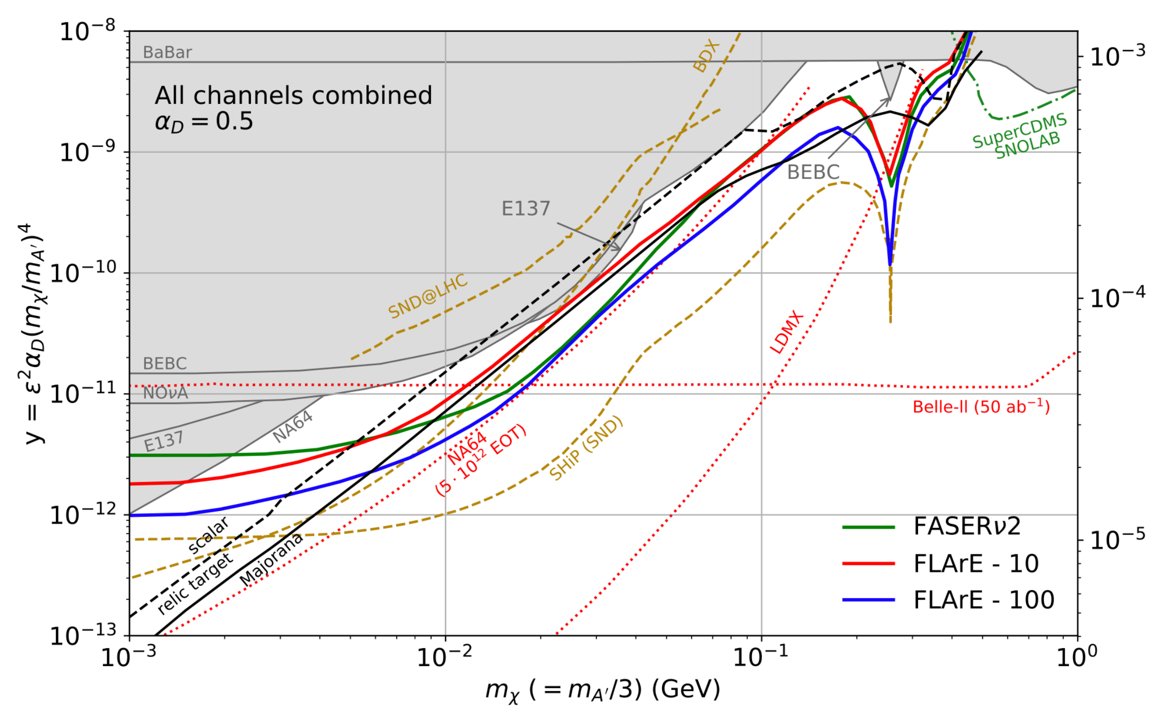
Forward LHC Neutrino Experiments

- The LHC produces a TeV-energy neutrino beam TeV in the forward direction
- The first collider produced neutrinos have been detected by FASERν

[FASERν Collaboration: 2105.06197]

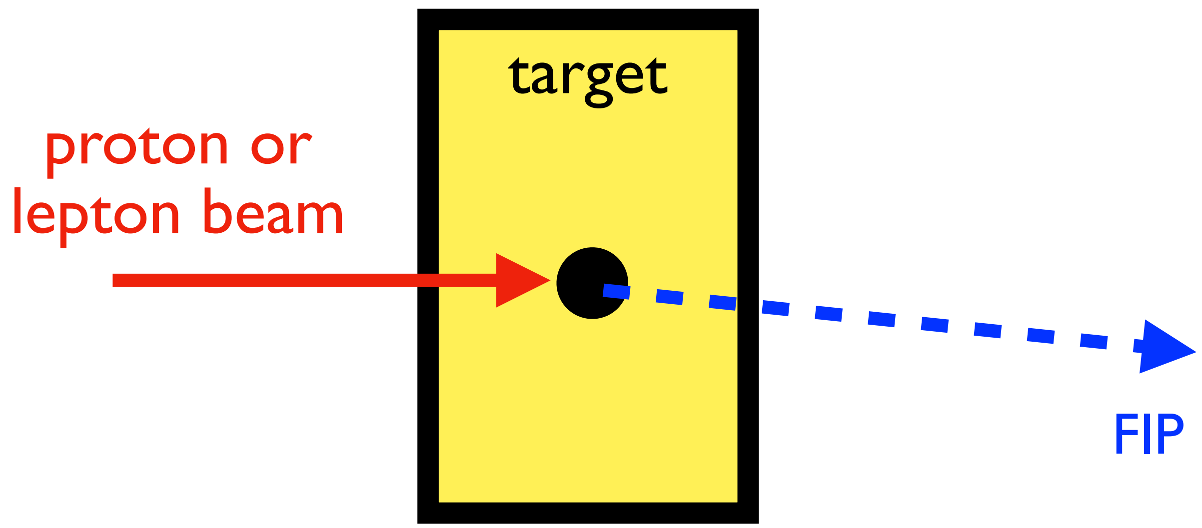
- Exciting prospects for neutrino physics at FASERν, SND@LHC (Run 3) and FASERν2, FLArE, FORMOSA (HL-LHC)
- FIPs can also be explored with forward LHC neutrino detectors
- Example: vector portal dark matter





[BB, Feng, Feig, Ismail, Kling, Abraham, Trojanowski]
[2101.10338, 2107.00666, 2111.10343]

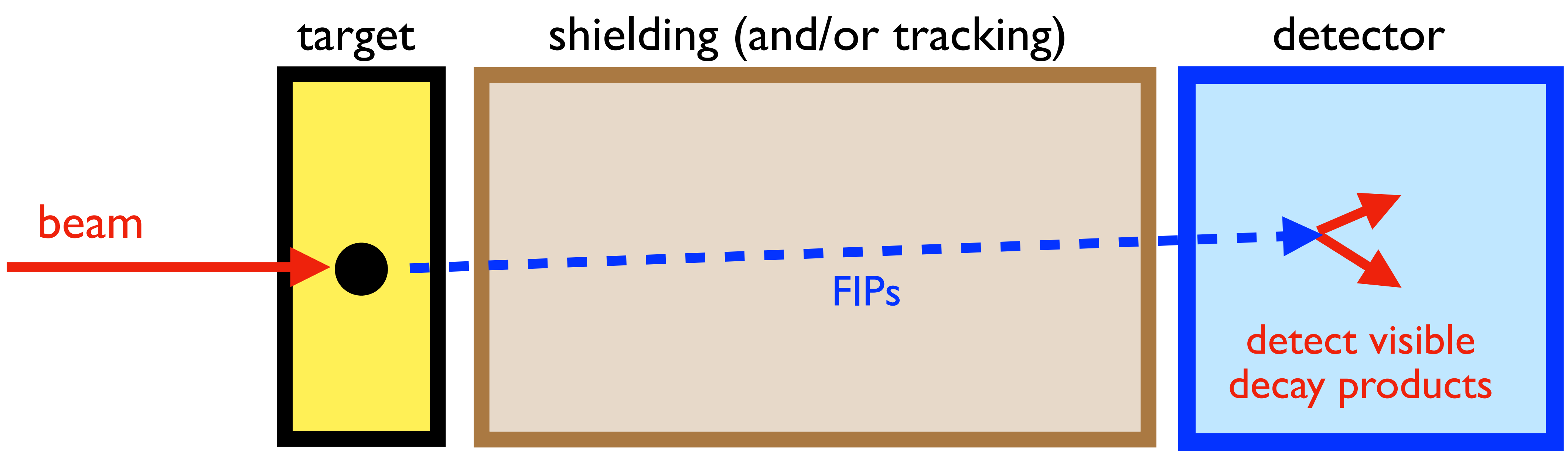
Probing FIPs with Fixed Target Experiments



Advantages:
- high collision luminosity
- forward kinematics
- large production rates

- Basic experimental setup entails a detector located downstream of the target
- A variety of search strategies may be employed depending on the properties of the FIP:
  - mass, lifetime, couplings to SM particles, interactions with other FIPs, etc.

Visibly decaying FIPs at fixed target experiments



See for example:

[Gorbunov, Shaposhnikov] (HNLs)

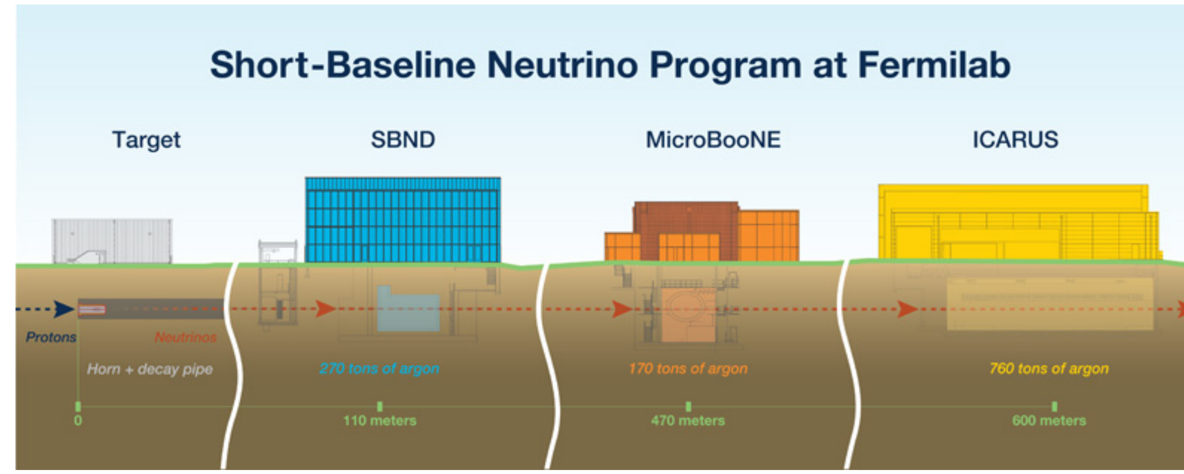
[Essig, Kaplan, Harnik, Toro] (ALPs, Dark Photons)

…

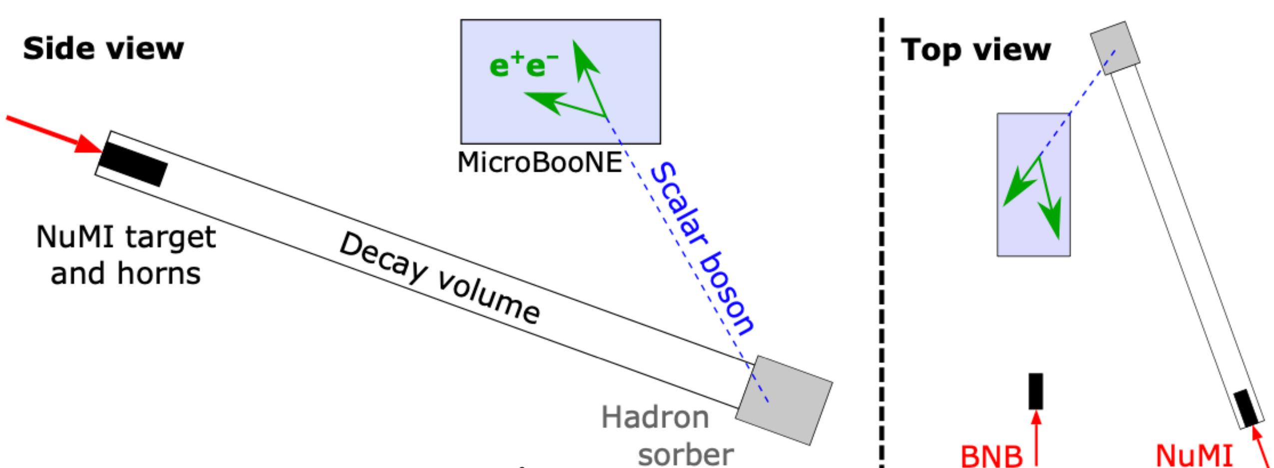
- Experiments include SHiP, SHADOWS, MicroBooNE, ICARUS, SBND, DUNE, HPS, APEX, DarkQuest …

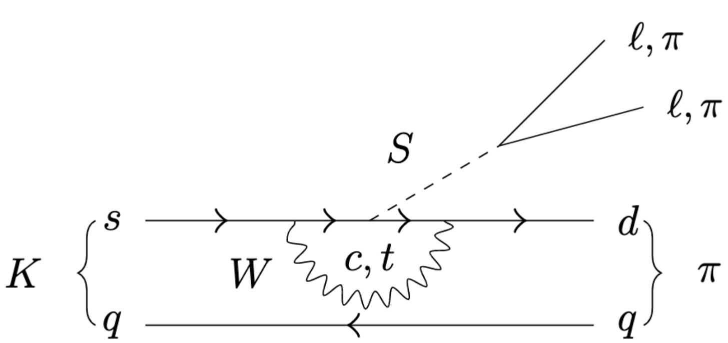
Short Baseline ν-Experiments @ FNAL

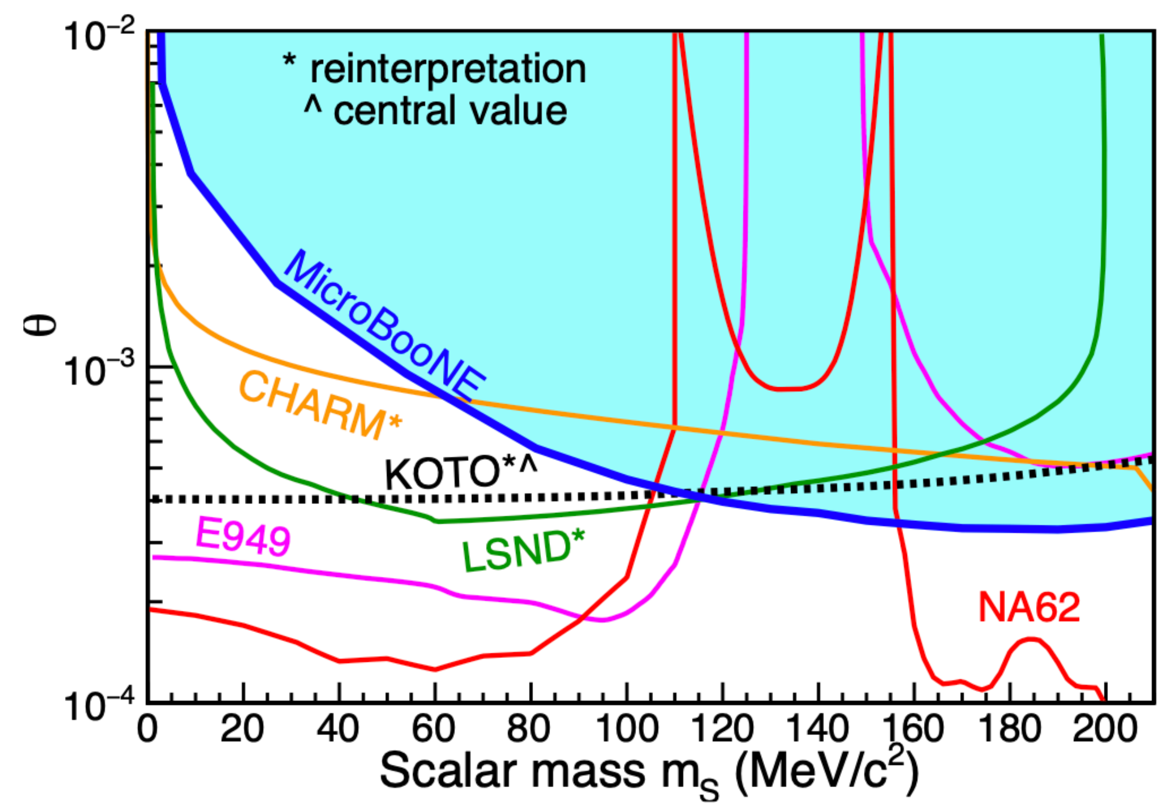
- MicroBooNE, SBND, ICARUS LArTPC detectors
- Situated along 8 GeV Booster beam line and slightly off axis from 120 GeV NuMi beam line
- Will collect ~ 10^{21} POT over next several years



- These experiments have sensitivity to a variety of FIP models
- Example: MicroBooNE search for Higgs portal scalar





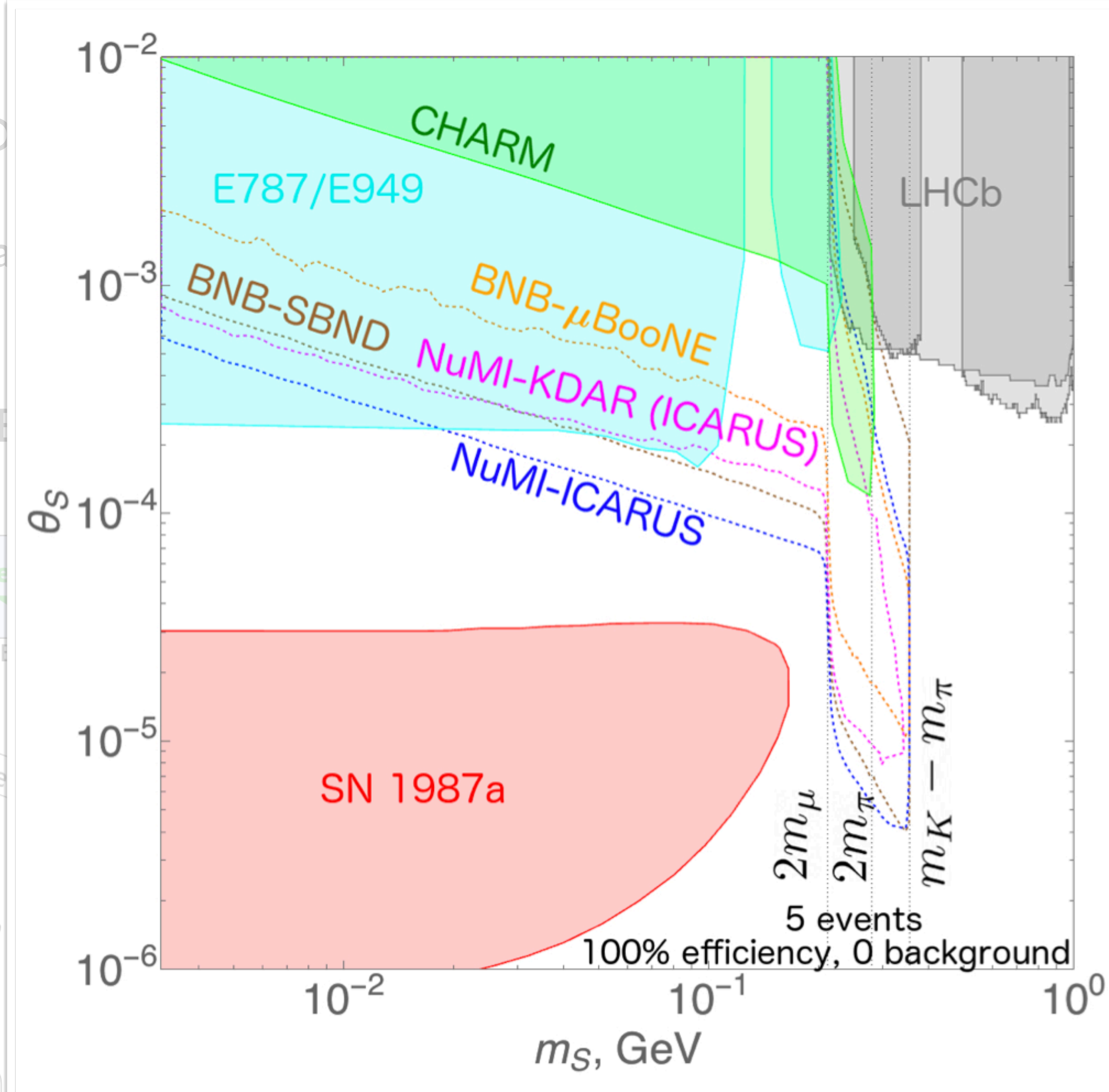


[MicroBooNE, Phys. Rev. Lett 127 (2021) 15, 151803]

Short Baseline ν-Experiments @ FNAL

- MicroBooNE, SBND, ICARUS LArTPC detectors
- Situated along 8 GeV
  slightly off axis from I
- Will collect ~ 10^{21} PO
- These experiments ha
  dark sector models
- Example: MicroBooNE

Future prospects for ICARUS and SBND

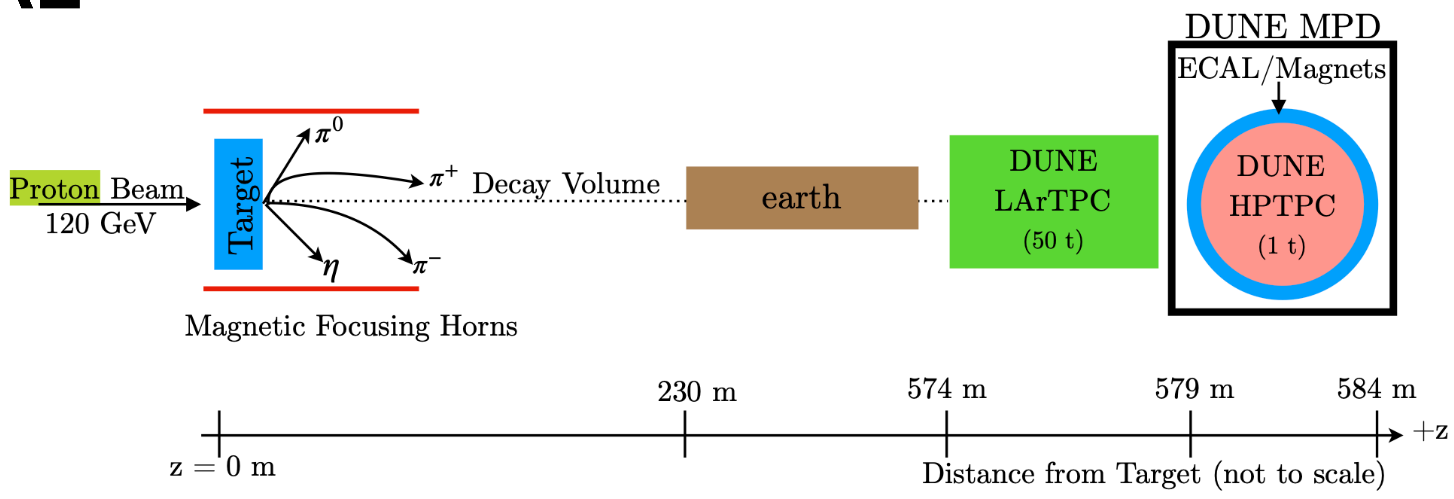


[...v. Lett 127 (2021) 15, 151803]

[BB, Berger, Ismail]

DUNE Near Detector @ FNAL

- 120 GeV proton beam, ~10^{22} POT
- Multi-Purpose Near Detector (MPD): 1 ton gaseous Argon TPC, surrounded by ECAL, located 574m downstream of target

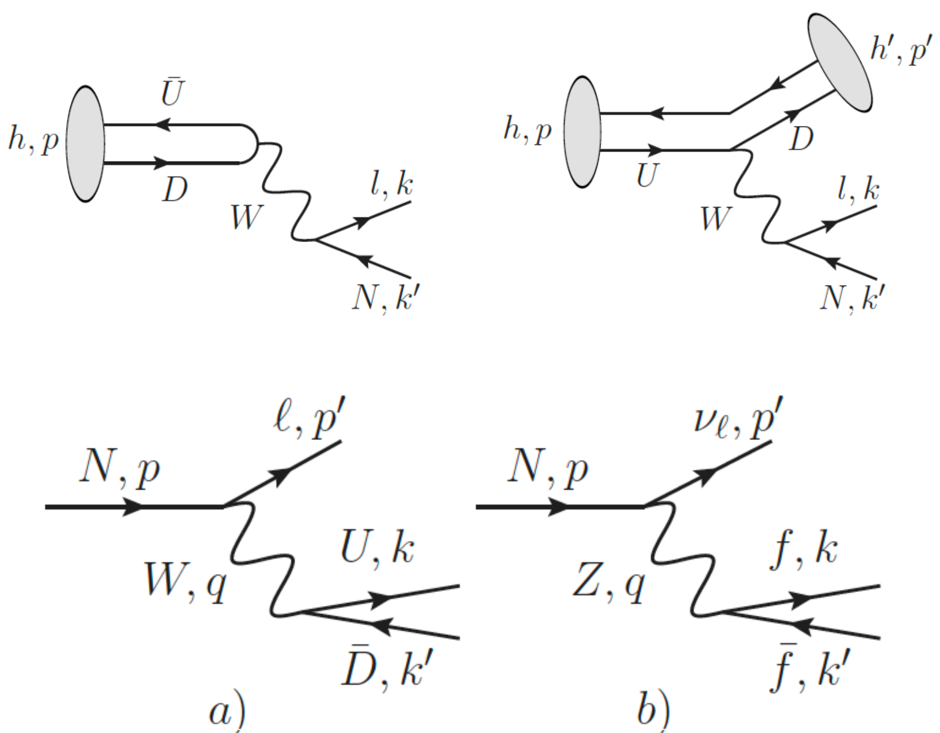


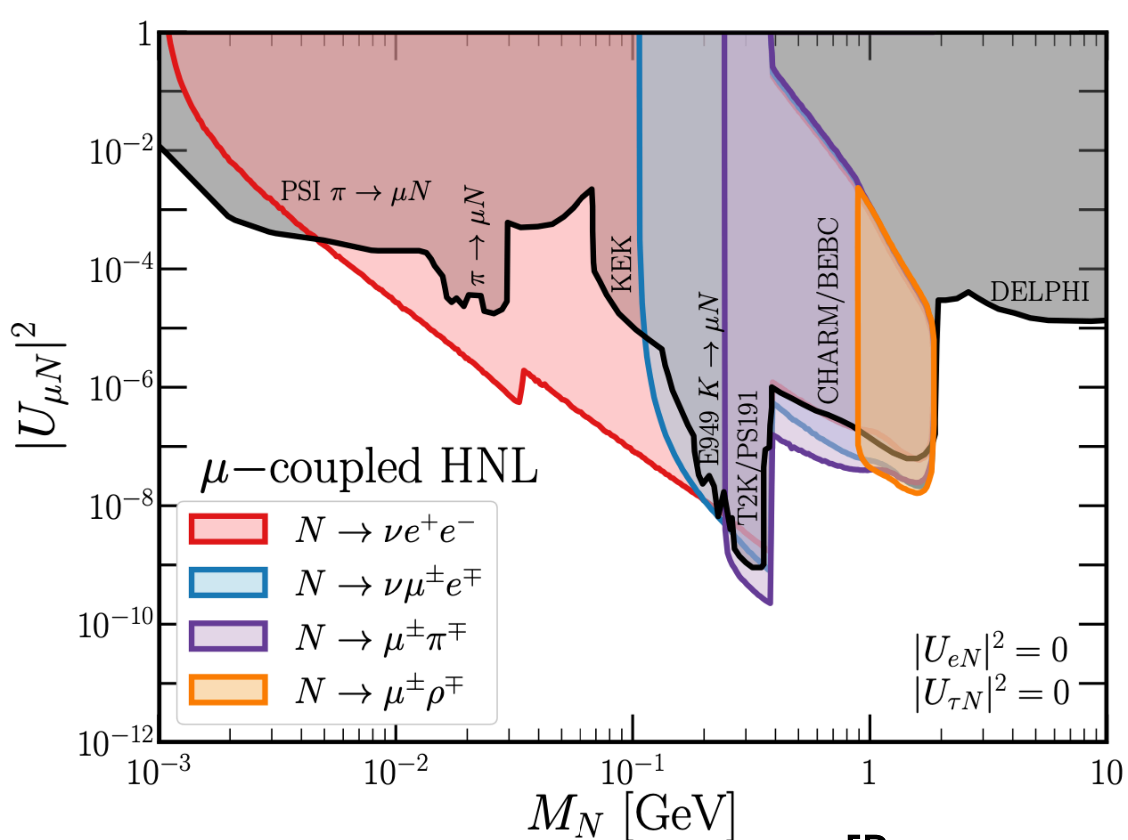
- Sensitivity to a variety of FIP models
- Example : Heavy Neutral Leptons at DUNE MPD

[Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf]
[Ballett, Boschia, Pascoli]
[Coloma, Fernandez-Martınez, Gonzalez-Lopez, Hernandez-Garcia, Pavlovic]

HNL production

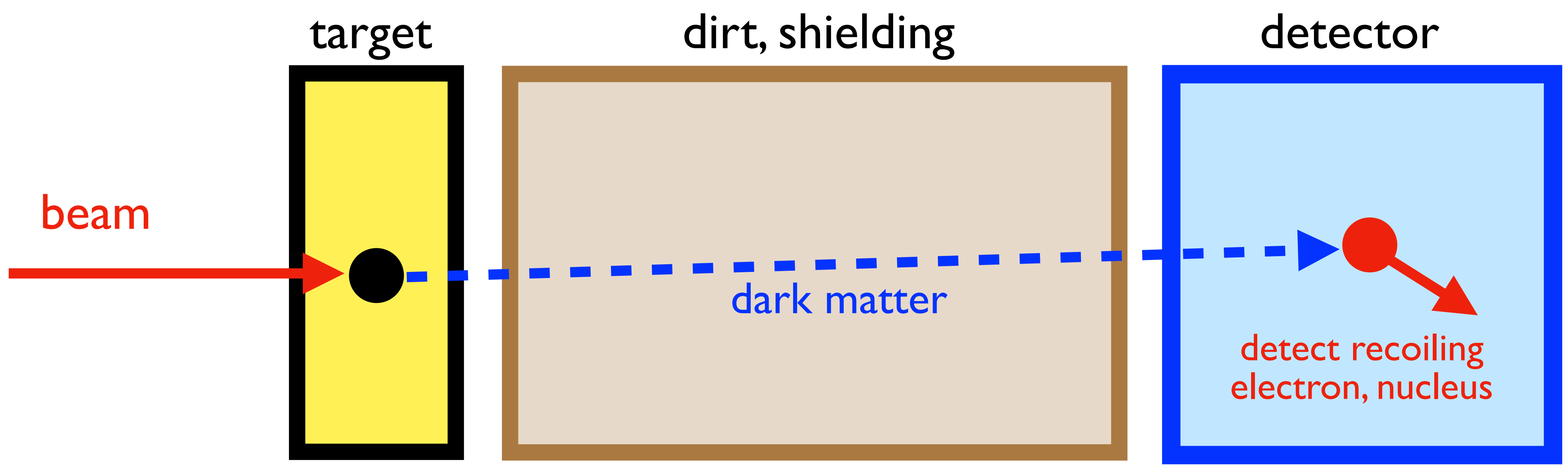
HNL decay





[Berryman et al.]

Dark matter scattering at fixed target experiments



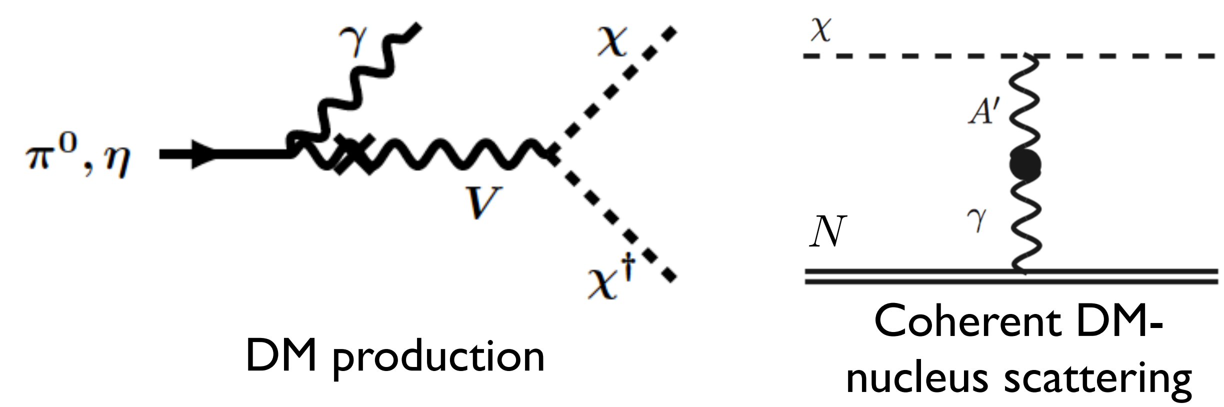
See for example:

[BB, Pospelov Ritz]
[deNiverville, Pospelov Ritz]
[Coloma, Dobrescu, Frugiuele, Harnik]
[Kahn, Krnjaic, Thaler, Toups]
[Izaguirre, Krnjaic, Schuster, Toro]
[de Romeri, Kelly, Machado, Krnjaic]
…

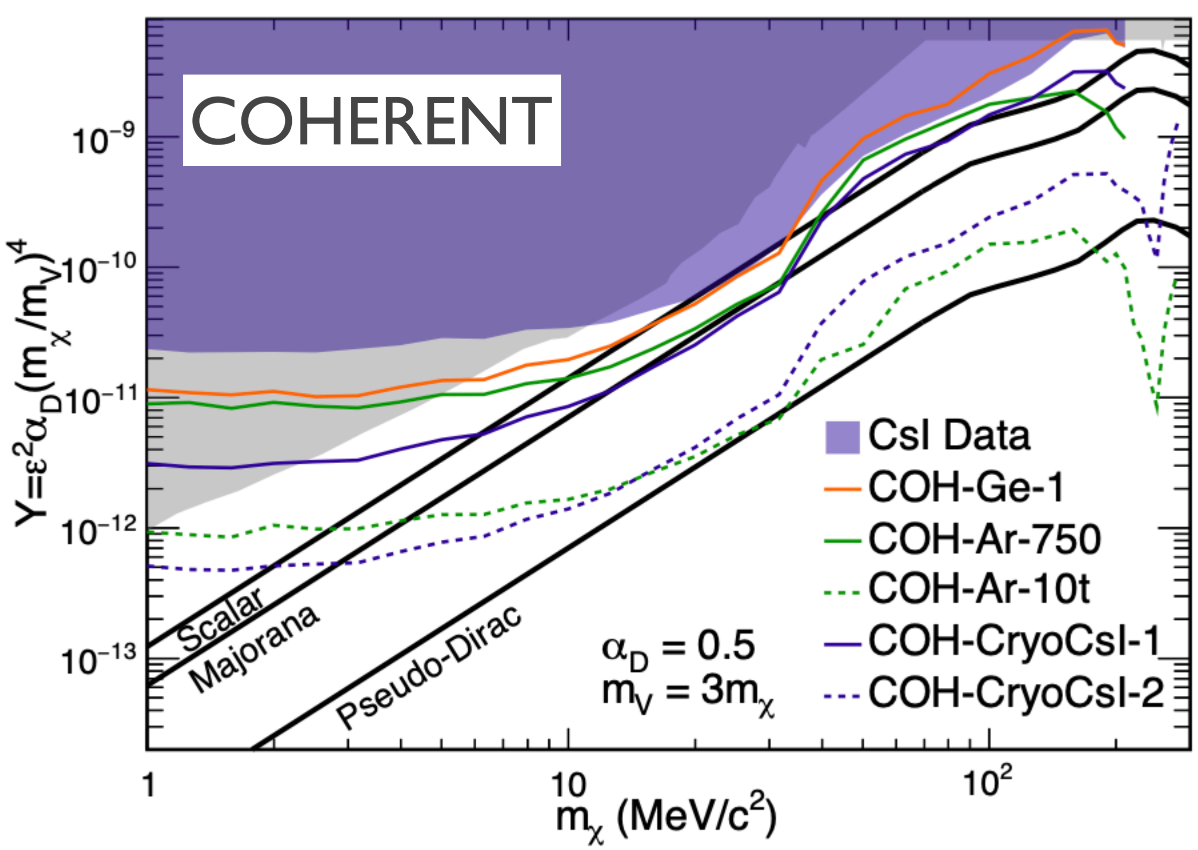
- Experiments include COHERENT, CCM, MicroBooNE, ICARUS, SBND, JSNS^2, DUNE, BDX, …

GeV-scale CEνNS Experiments

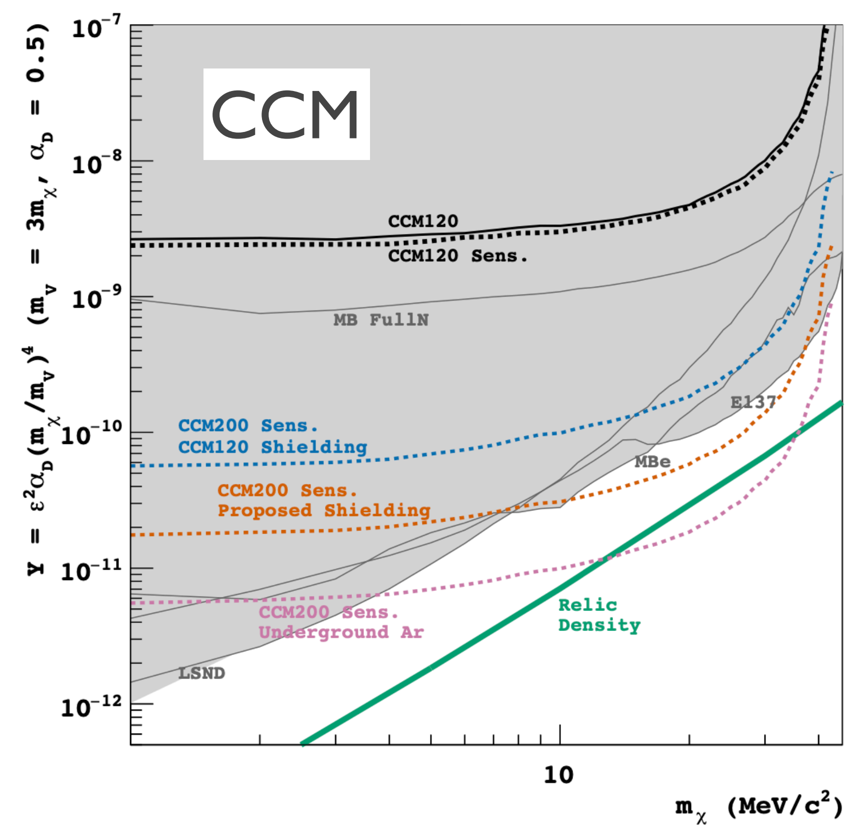
- First observation of Coherent Elastic Neutrino Nucleus Scattering (CEvNS) by COHERENT! [Science 357 (2017) no.6356, 1123-1126]
- CEνNS experiments can probe light dark matter: [deNiverville, Pospelov, Ritz] [Ge, Shoemaker]



- Example: COHERENT@ORNL and CCM@LANL sensitivity to vector portal DM

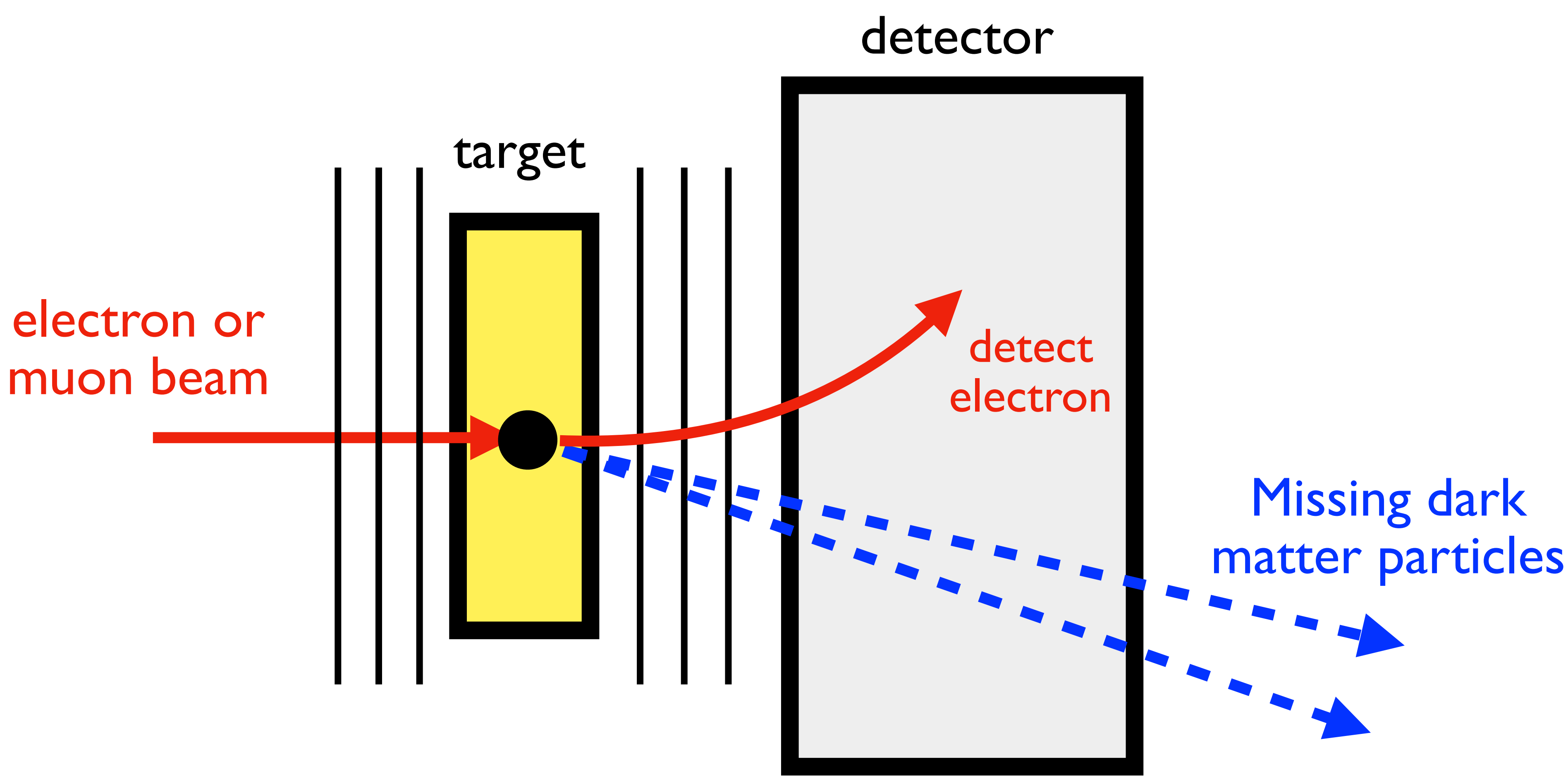


[COHERENT Collaboration, 2110.11453]



[CCM Collaboration, 2105.14020]

Missing energy / momentum searches for dark matter



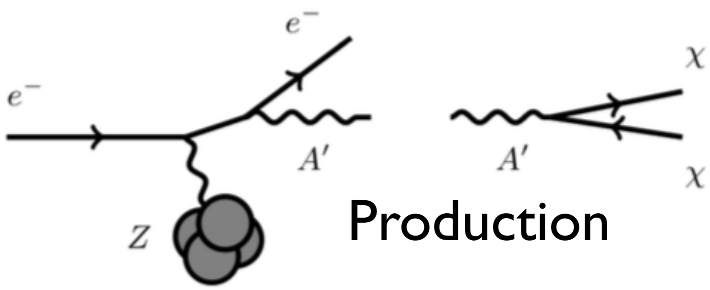
[Andreas. et al]
[Izaguirre, Krnjaic, Schuster, Toro]
[Kahn, Krnjaic, Tran, Whitbeck]

- Experiments include NA64, LDMX, M^3, …

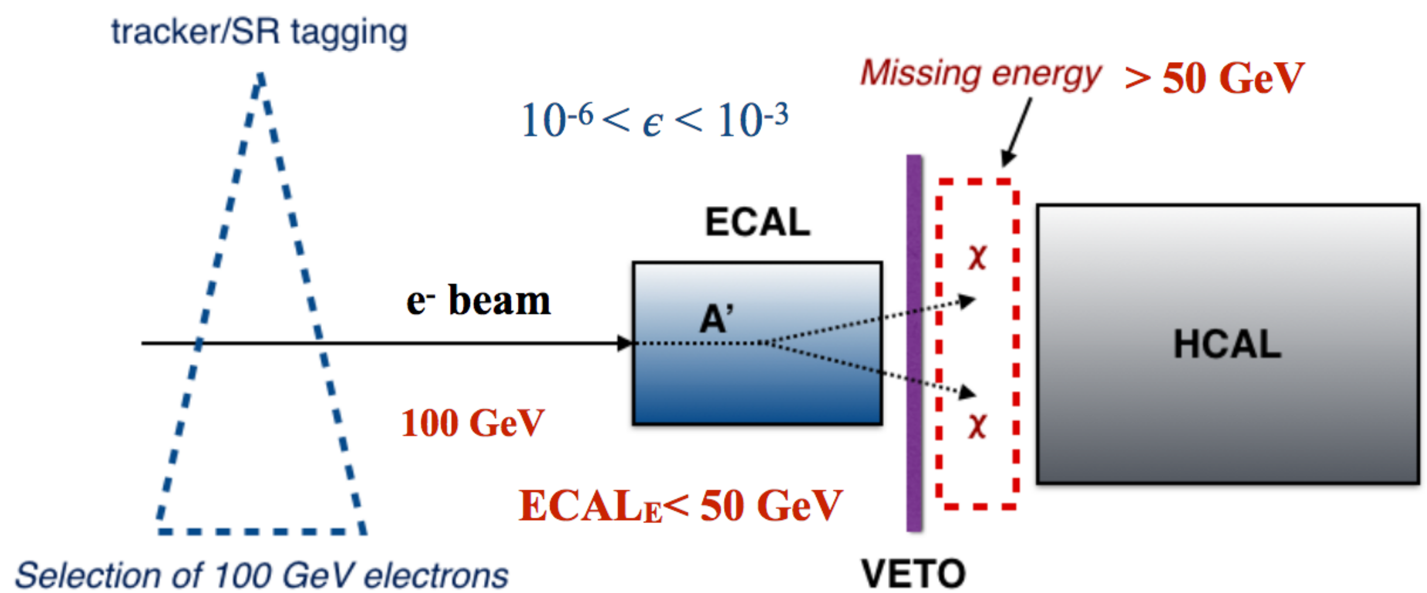
NA64 @ CERN

- 100 GeV electron beam incident on ECAL

- Dark matter produced in ECAL and carries most of the beam energy



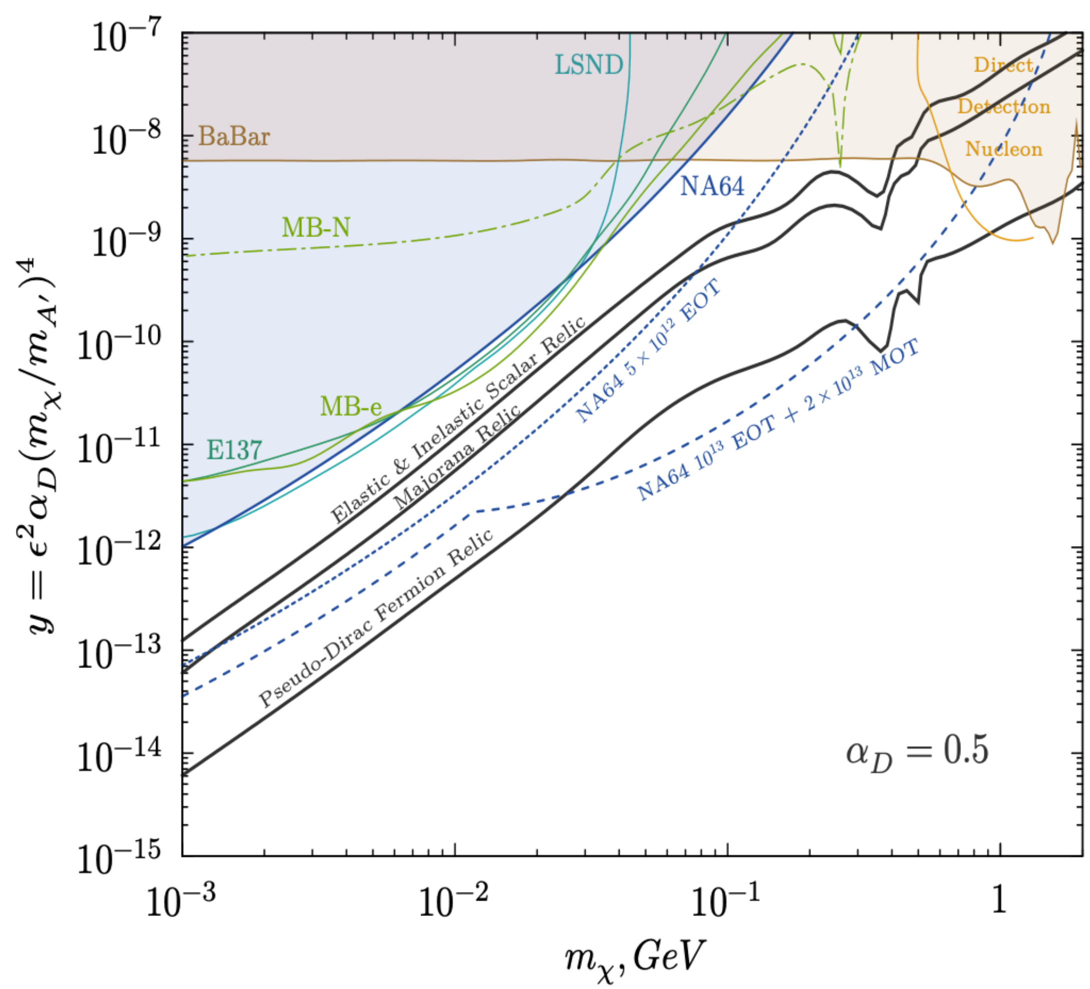
Production



- Large missing energy signature (small energy deposition in ECAL, no energy deposition in HCAL)

- 2.84 x 10^{11} EOT - best limits on invisibly decaying dark photon below 300 MeV

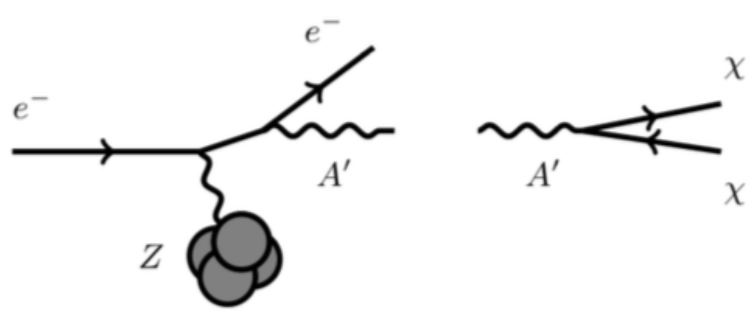
- Future datasets with electron and muon beams can probe a significant parts of the thermal relic targets

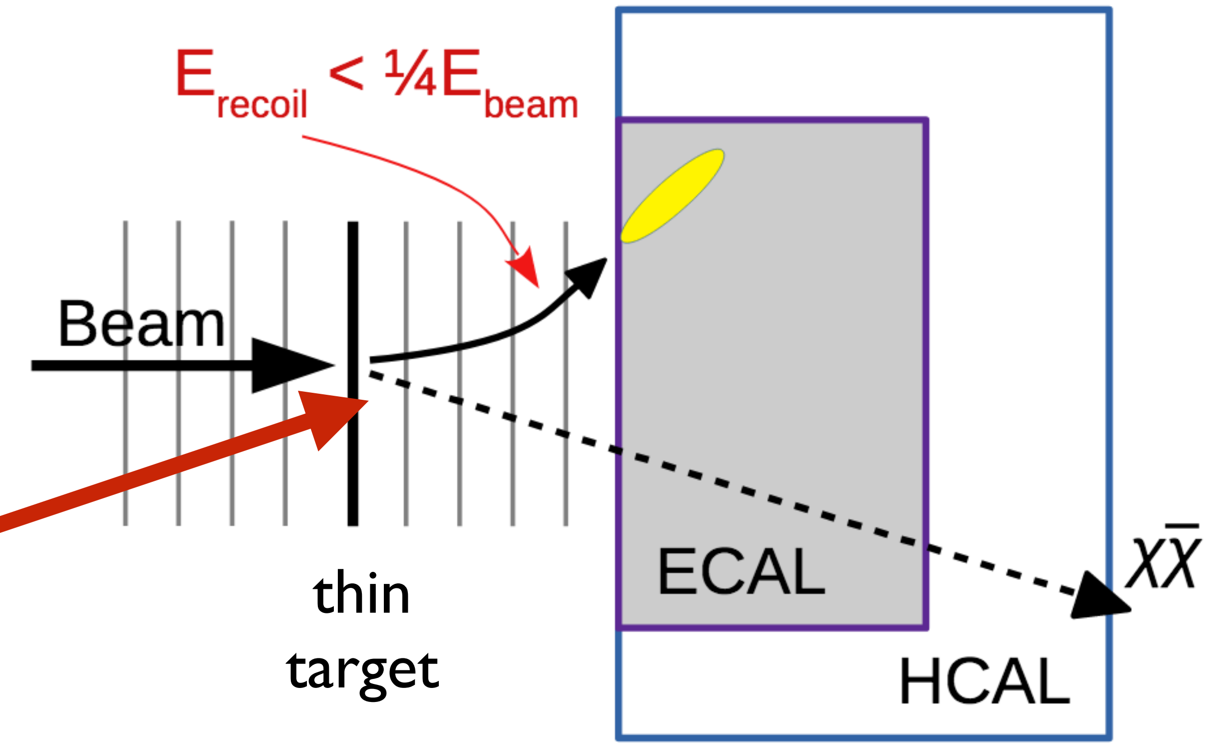


NA64 Collaboration 1903.07899

LDMX @ SLAC

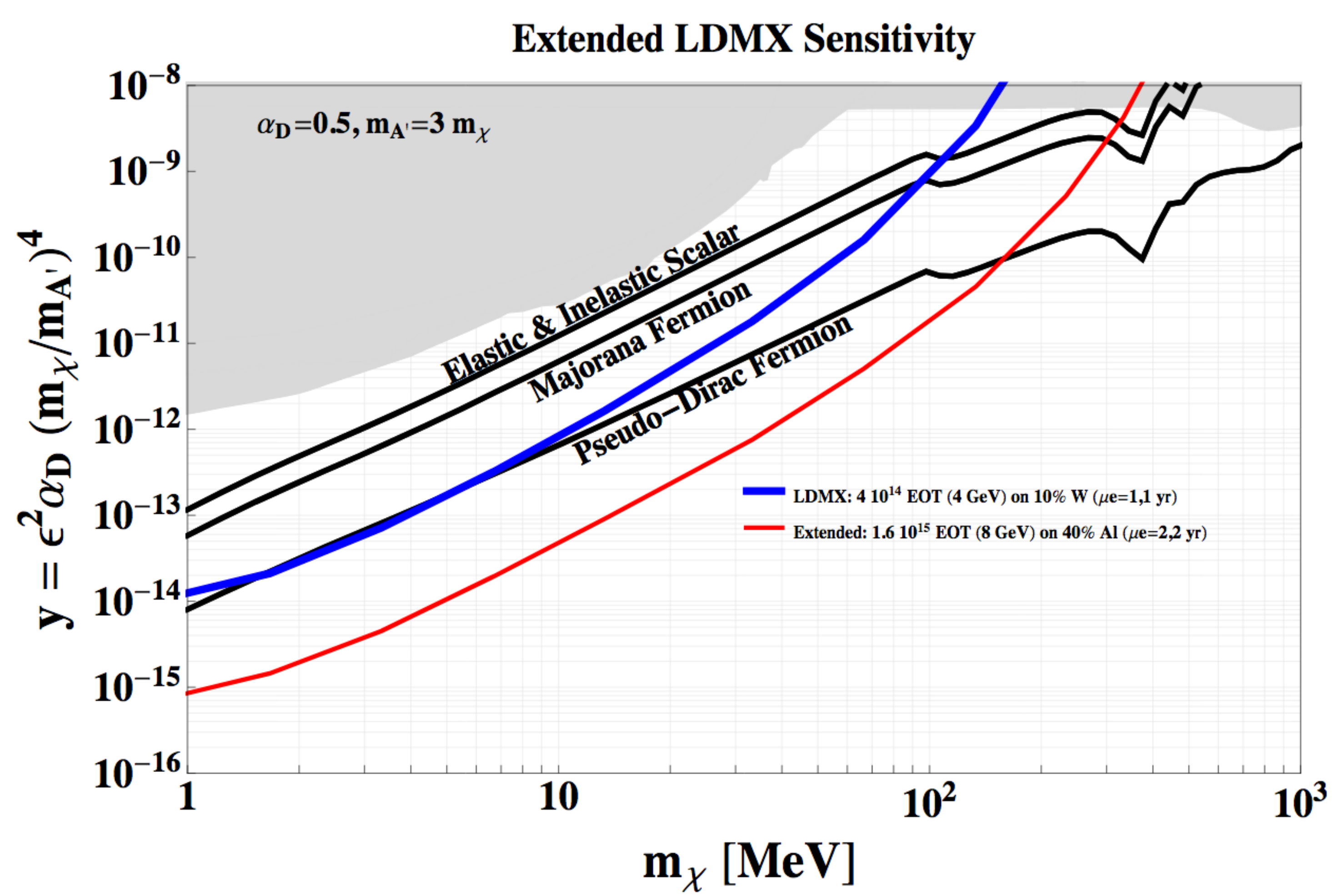
- Proposed electron beam experiment utilizing missing momentum technique





- More kinematic handles to reject backgrounds, discriminate final state electrons from photons

- Excellent sensitivity to dark matter, including relic density targets



LDMX design study, 1808.05219

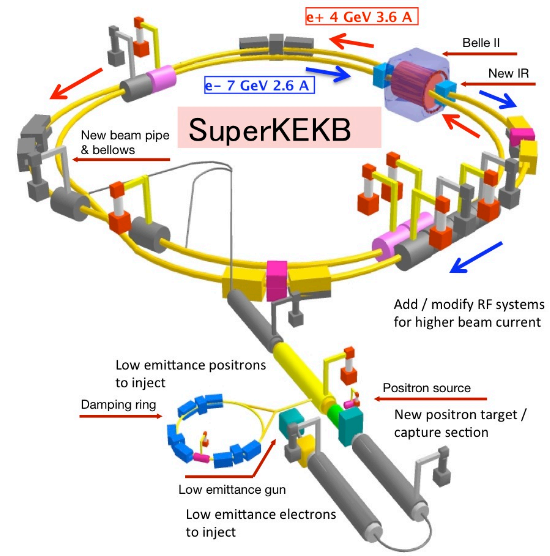
Belle II @ KEK

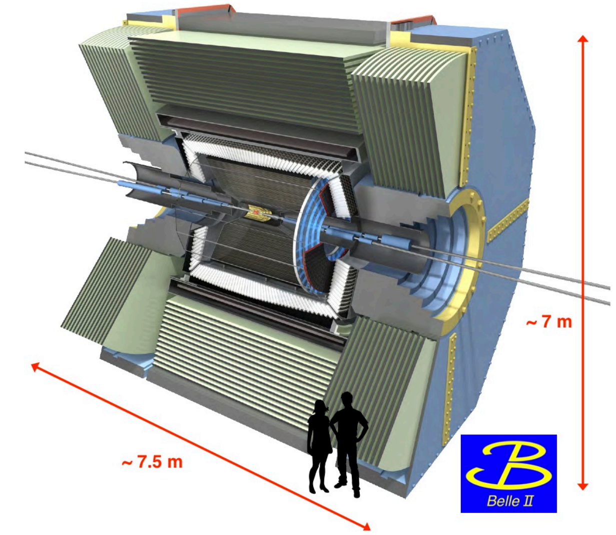
- Medium energy ($E_{\mathrm{CM}} \sim 10.5\,\mathrm{GeV}$), high luminosity e^+e^- collider

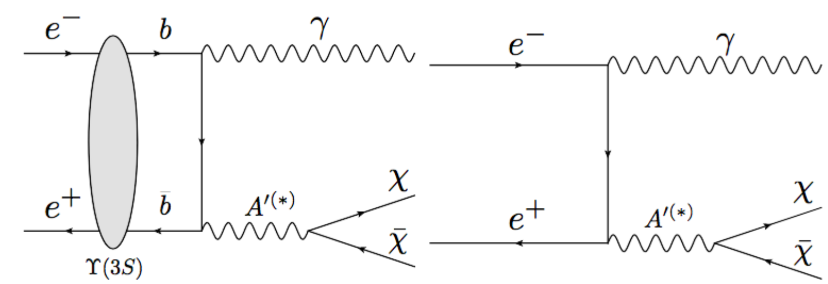
- Hermetic detector, full reconstruction of event kinematics

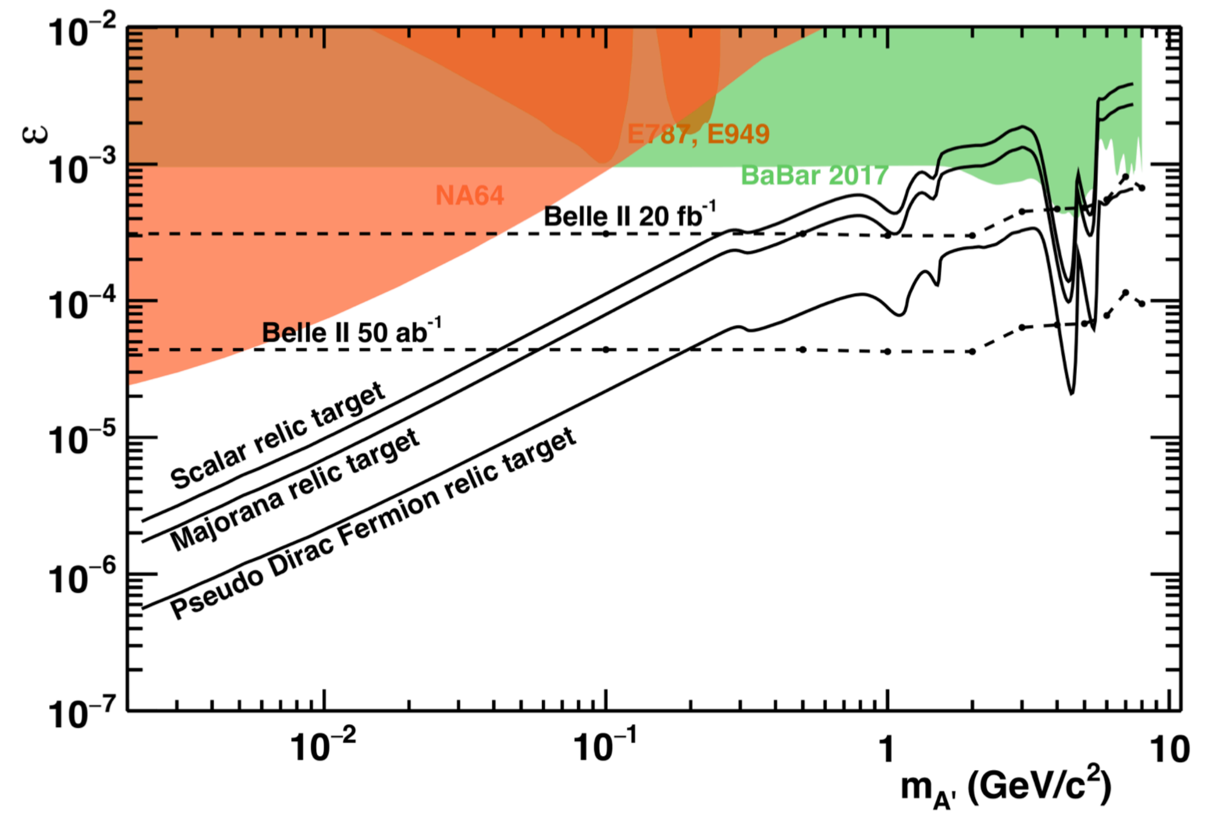
- Direct production of FIP through electron, photon couplings, or through B meson decays

- Sensitive to a variety of signatures of prompt, displaced, and long-lived mediators





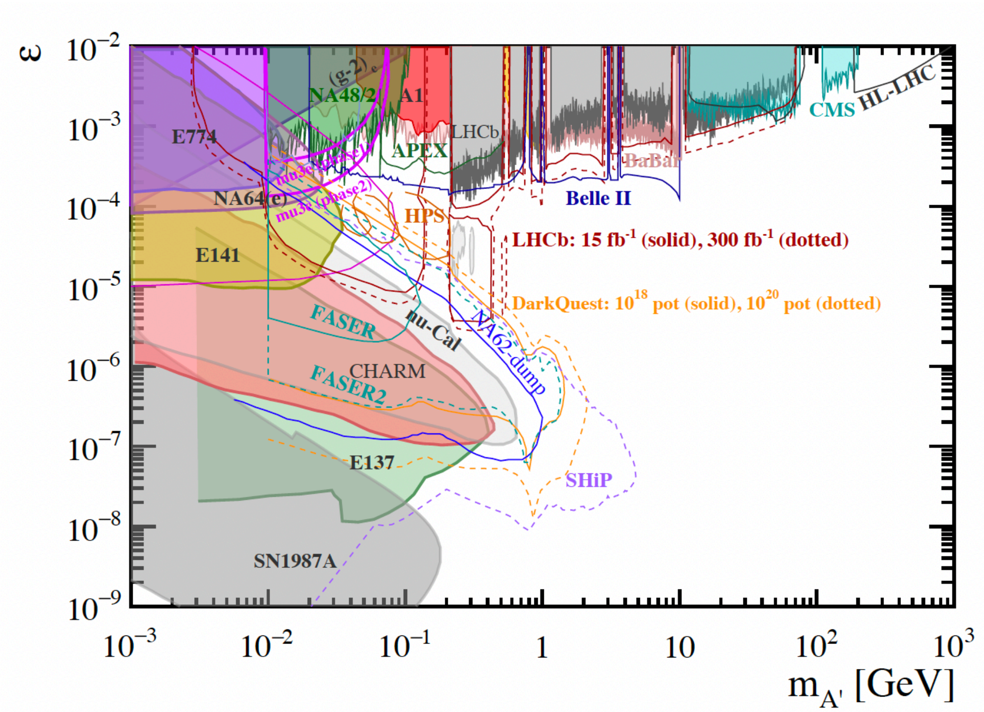




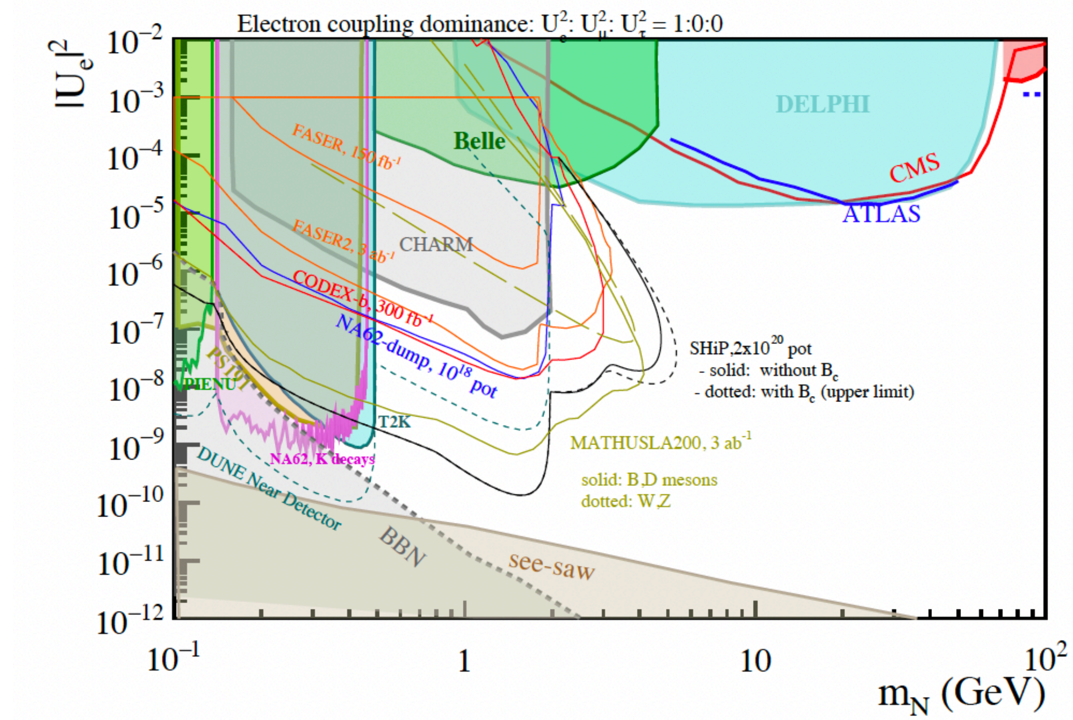
Belle II Physics Book, 1808.10567

A rich experimental program lies ahead!

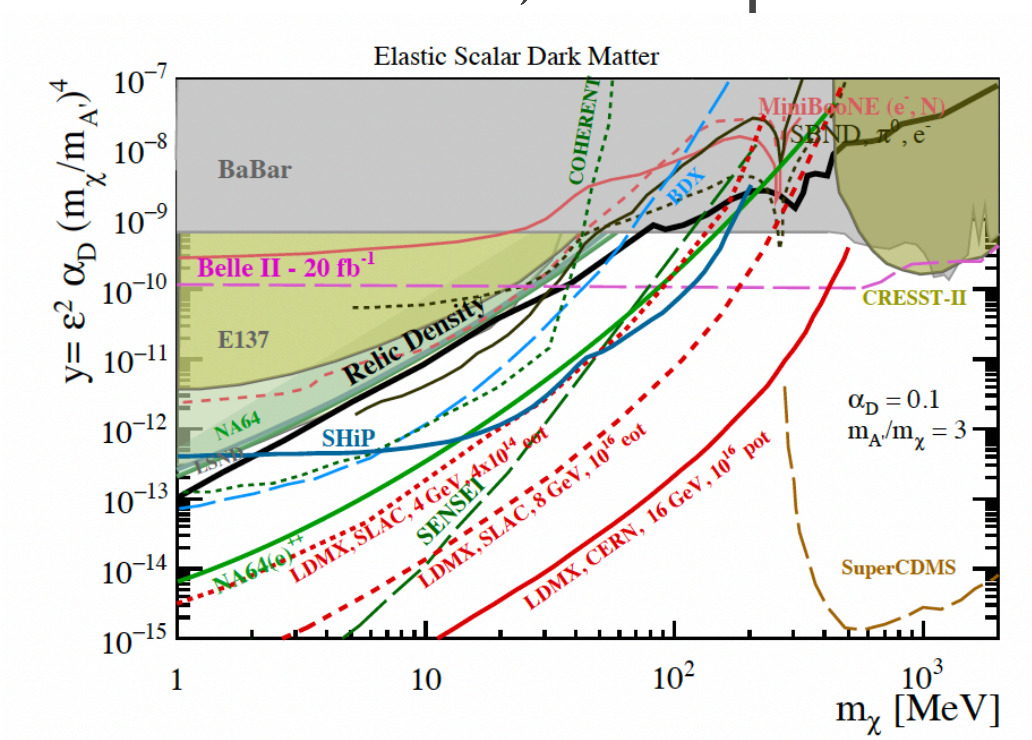
Dark photon, vector portal



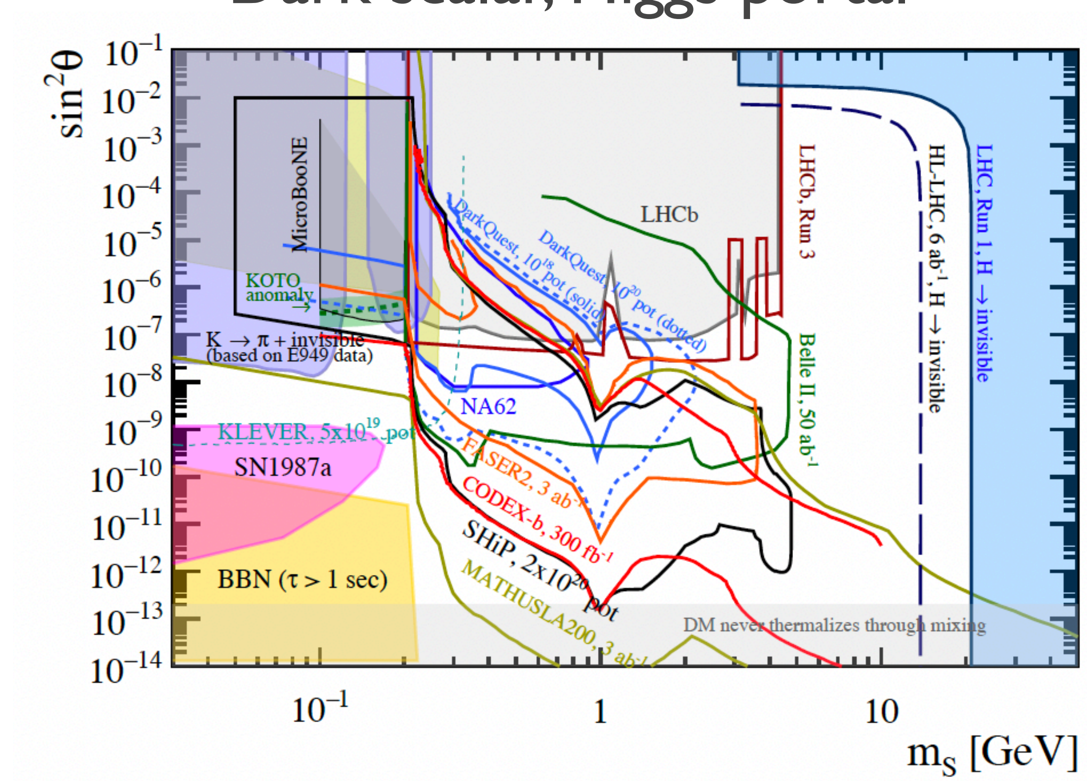
Heavy neutral lepton, neutrino portal



Dark matter, vector portal



Dark scalar, Higgs portal



[FIP review, Lanfranchi, Pospelov, Schuster, 2011.02157]

Summary and Outlook

- Feebly interacting particles (FIPs) may play a role in addressing several outstanding puzzles in particle physics and cosmology.

- And expansive worldwide program of experiments will provide a fertile ground for FIP searches in the coming years.

- New auxiliary detector at the LHC as well as intensity frontier experiments provide powerful sensitivity to a variety of FIPs, complementing searches at the main LHC experiments.

- Many exciting experiments and results on the horizon!