Searches for Long-Lived Particles at High-Energy and High-Intensity Experiments

Brian Batell
University of Pittsburgh

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Motivation

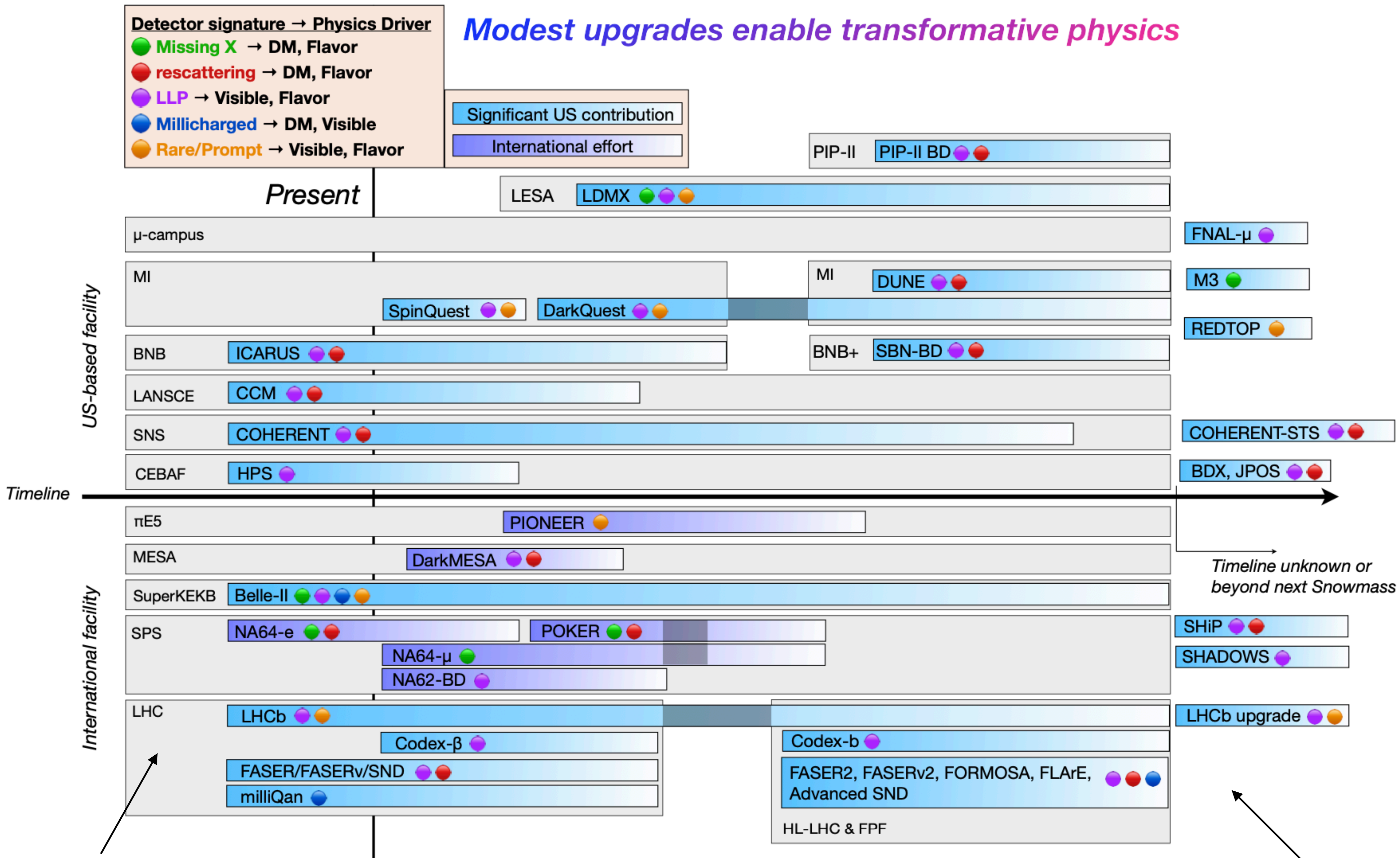
See S. Knapen's previous talk

- Long-lived particles are ubiquitous in the Standard Model and its extensions.
    - LLPs appear due to approximate symmetries, mass hierarchies, weak couplings, …
    - Arise in top-down models addressing dark matter, baryogenesis, naturalness, …
    - Light particles are necessarily weakly coupled to SM; naturally long lived

- LLPs feature a rich phenomenology, requiring multiple novel search strategies, experiments, and facilities to probe a broad range of models and signatures:
    - Calls for dedicated strategies for triggering, reconstruction, background mitigation
    - Motivates new dedicated LLP detectors at existing facilities

- There is still much work to be done and many exciting results ahead!

A Rich Experimental Landscape!



+ ATLAS and CMS

++ future high energy colliders…

Figure from RF6 Experiments & Facilities Whitepaper, 2206.04220

LLPs at the LHC: ATLAS and CMS

- Variety of signatures of LLPs (e.g., displaced and delayed leptons, photons, and jets; displaced vertices, disappearing tracks; nonstandard tracks, …)

- Striking signatures, but often require custom trigger, reconstruction, background mitigation strategies

- Substantial work needed both from the phenomenology and experimental communities to realize the full potential of LHC LLP physics program

- Unique sensitivity to heavy LLPs and low mass LLPs produced through heavy particle decays

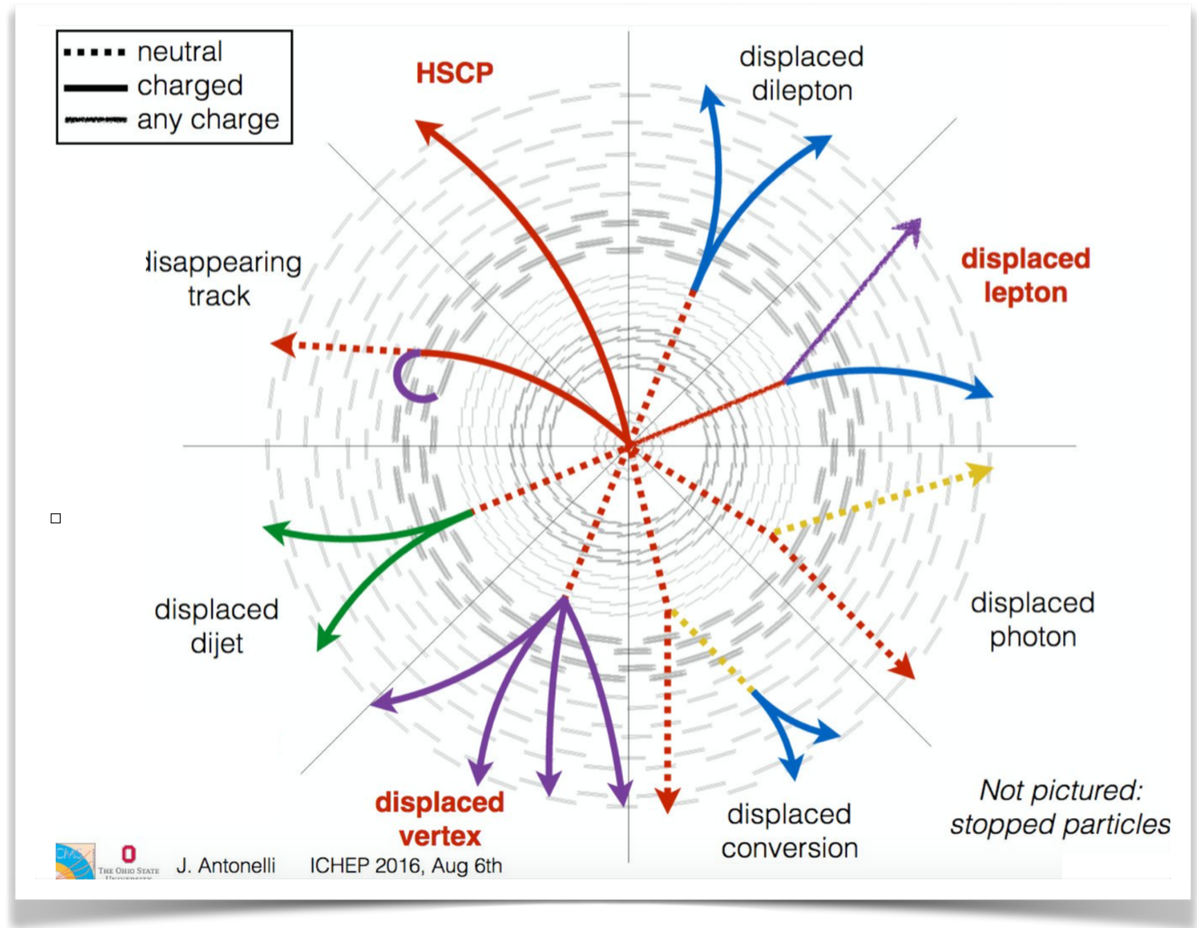
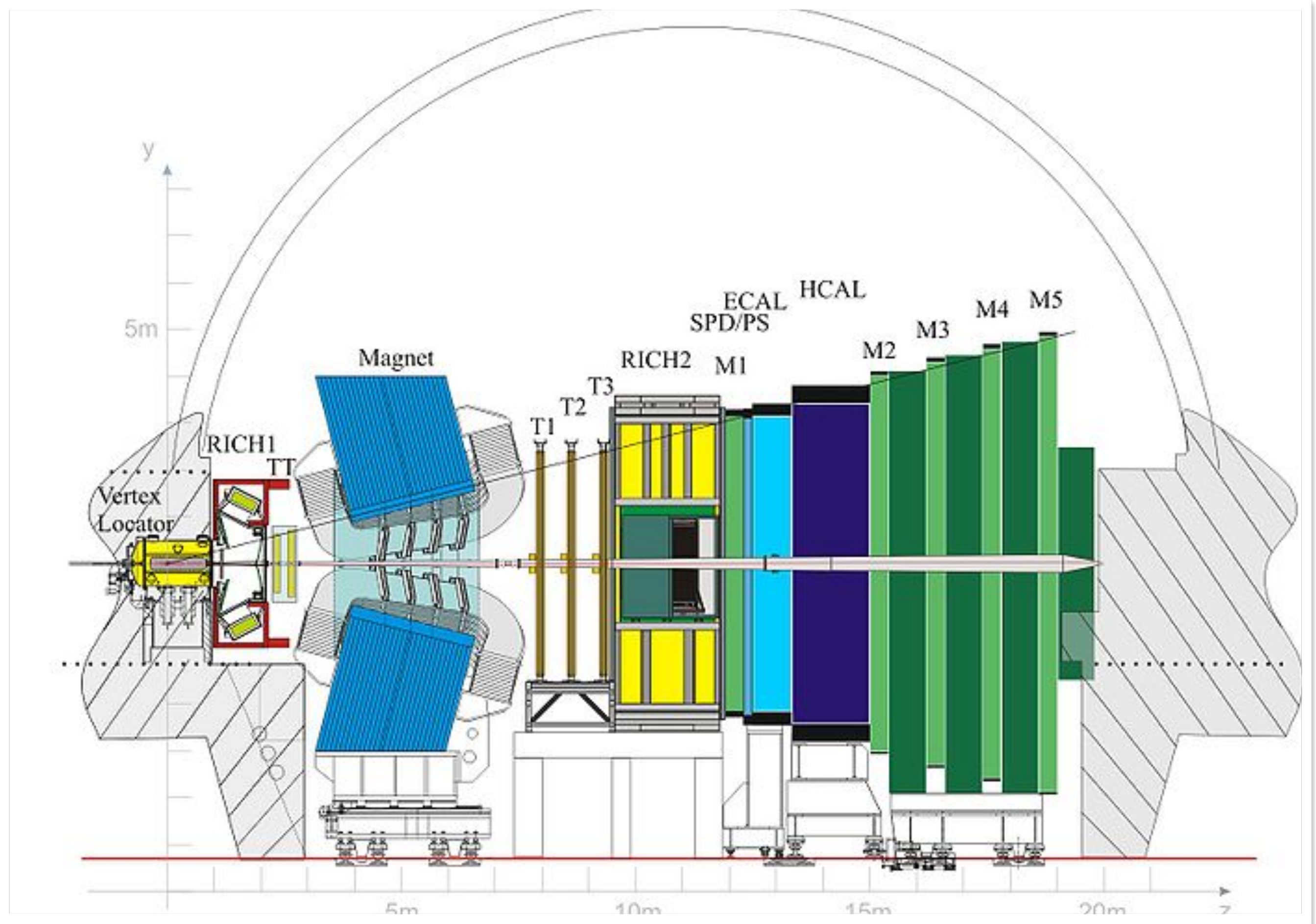


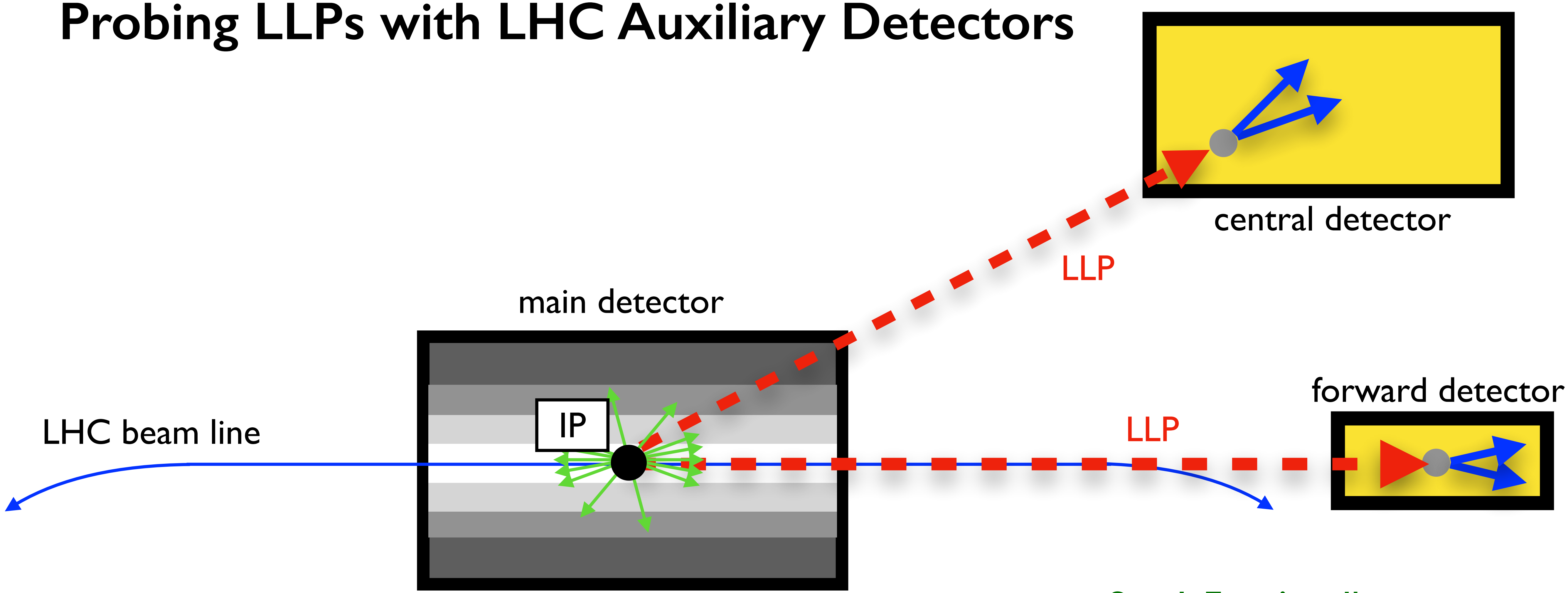
Figure from J. Antonelli

LLPs at the LHC: LHCb

- Designed to detect long lived b, c hadrons; this capability extends to BSM LLPs
- Advantages include unique forward acceptance, low pile-up, precise mass and time resolution, excellent tracking
- Powerful sensitivity to low mass LLPs with moderate lifetimes



Probing LLPs with LHC Auxiliary Detectors



See J. Feng's talk next on Forward Physics Facility

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

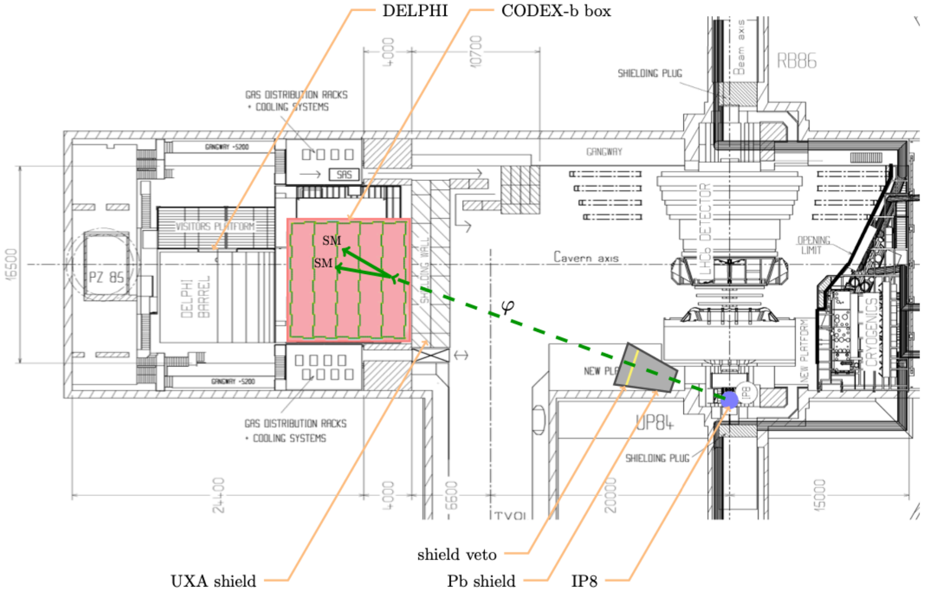
See for example:

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

Central LHC shielded detectors

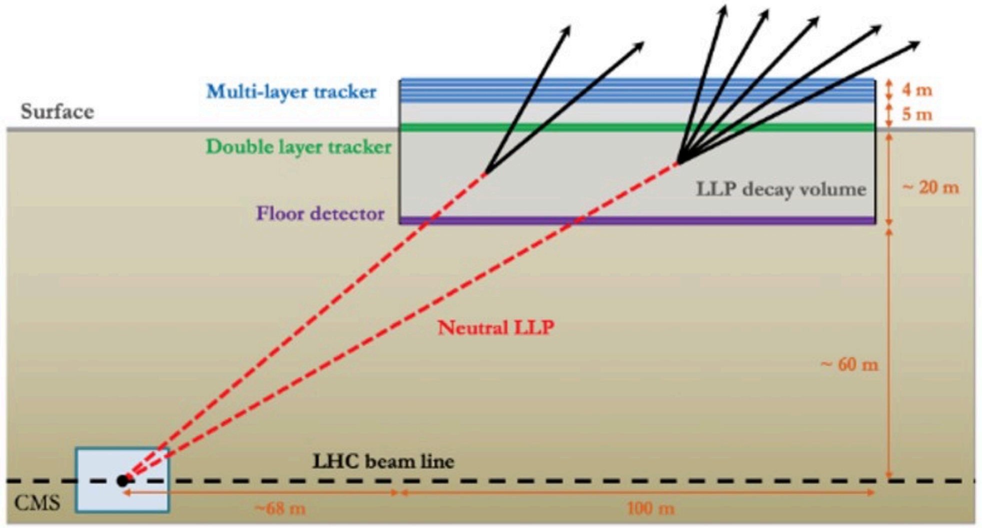
- Transverse location offers sensitivity to LLPs produced through both exotic light (e.g., meson) and heavy (e.g., Higgs) particle decays
- Backgrounds substantially mitigated by additional shielding / dirt

CODEX-b @ LHCb



- Medium-scale, modest cost detector located 25 m from LHCb IP for HL-LHC
- Smaller CODEX-β demonstrator will operate during Run 3

MATHUSLA @ CMS IP



- Large-scale surface detector near CMS for the HL-LHC era

Other proposed auxiliary detectors:

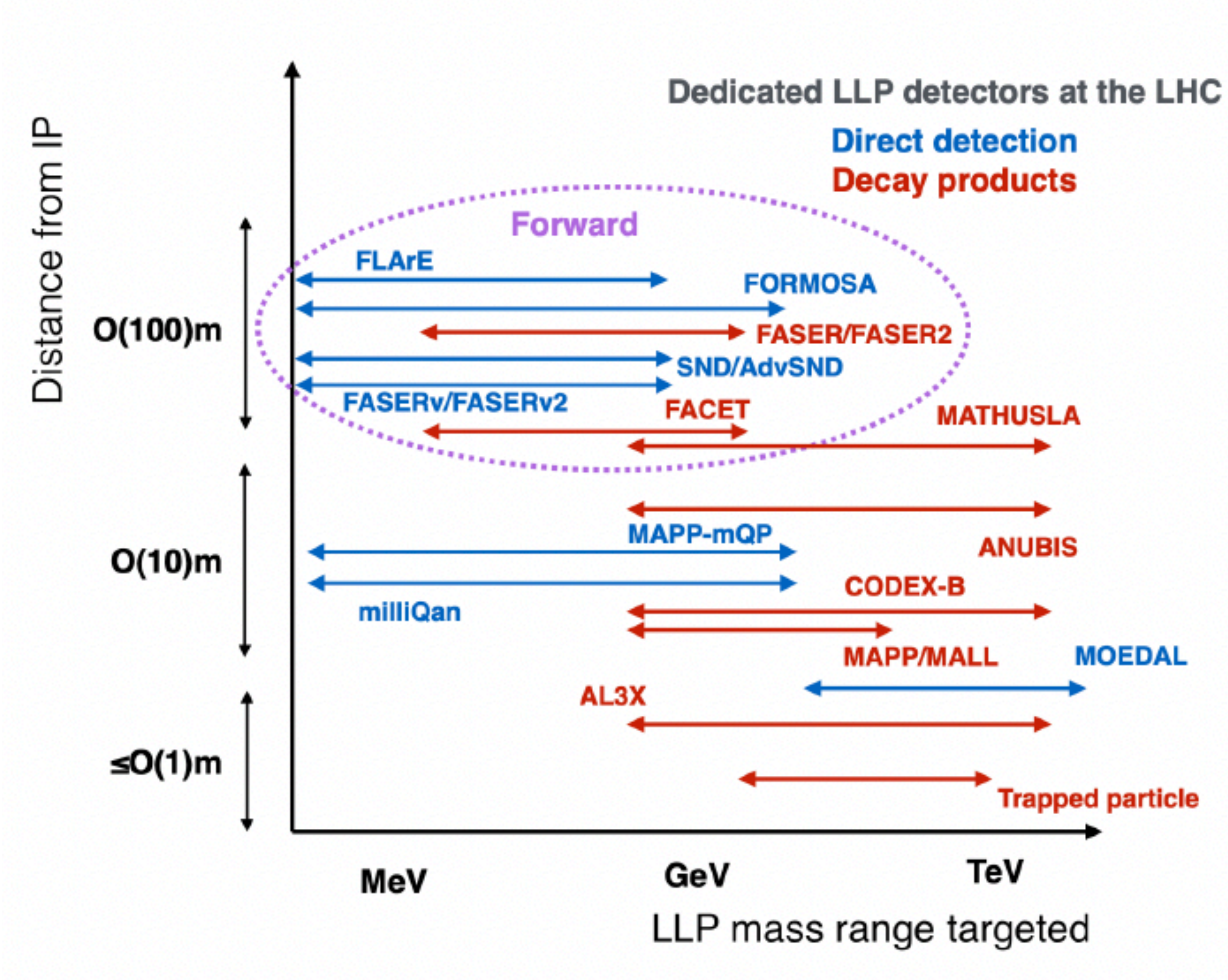
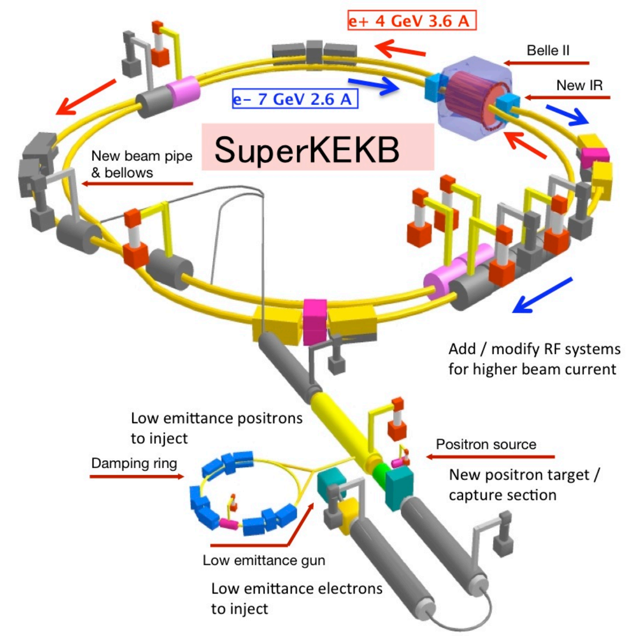
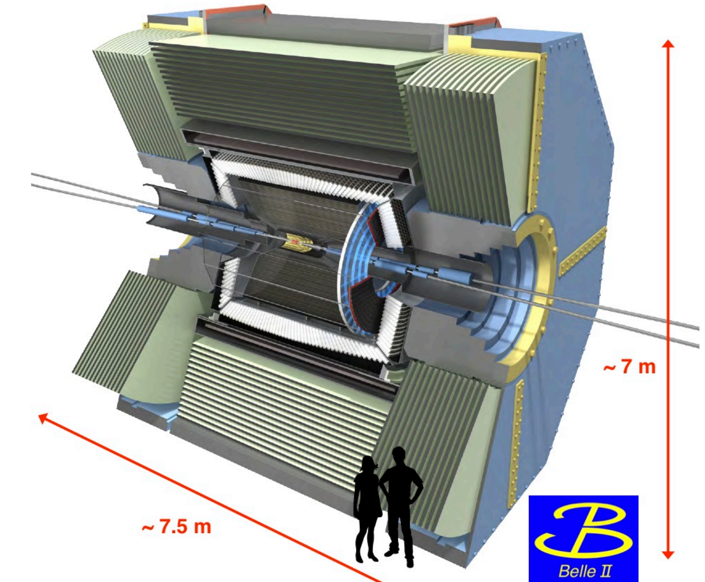


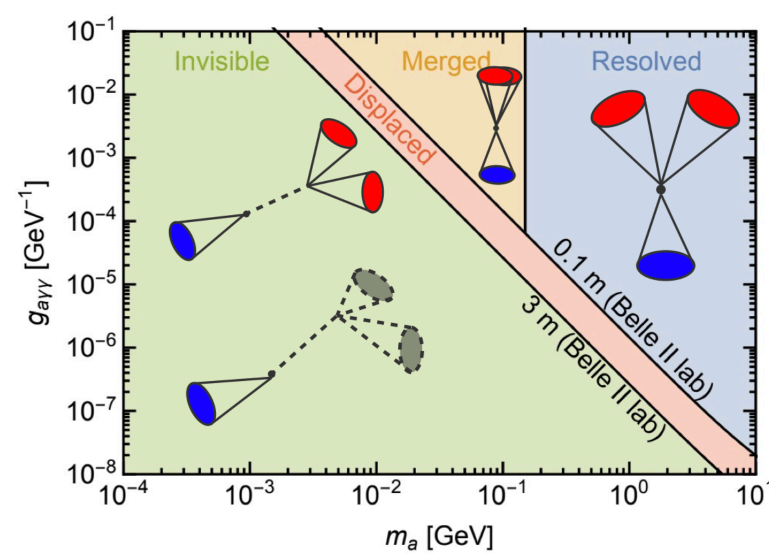
Figure from EF8,EF9,EF10 BSM draft report

B factories (Belle II)

- 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 mediator through electron, photon couplings, or through *B* meson decays
- Sensitive to a variety of signatures of prompt, displaced, and long-lived mediators







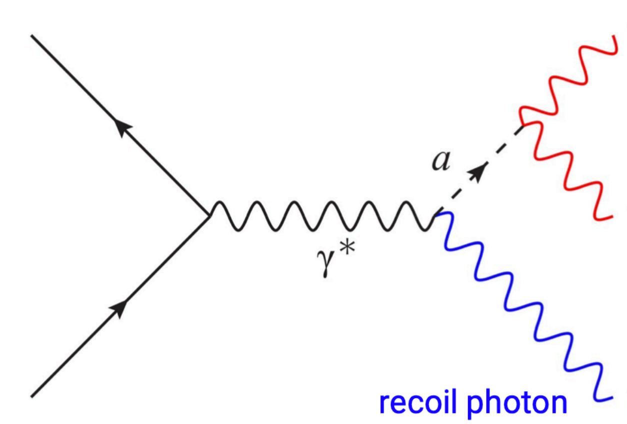
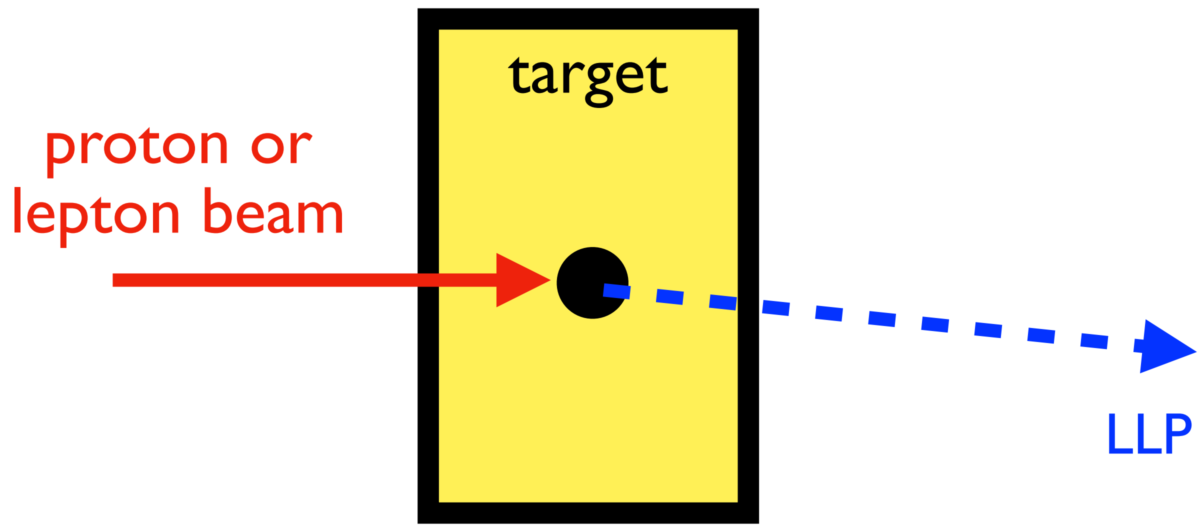


Fig from L. Corona

Probing LLPs with Fixed Target Experiments

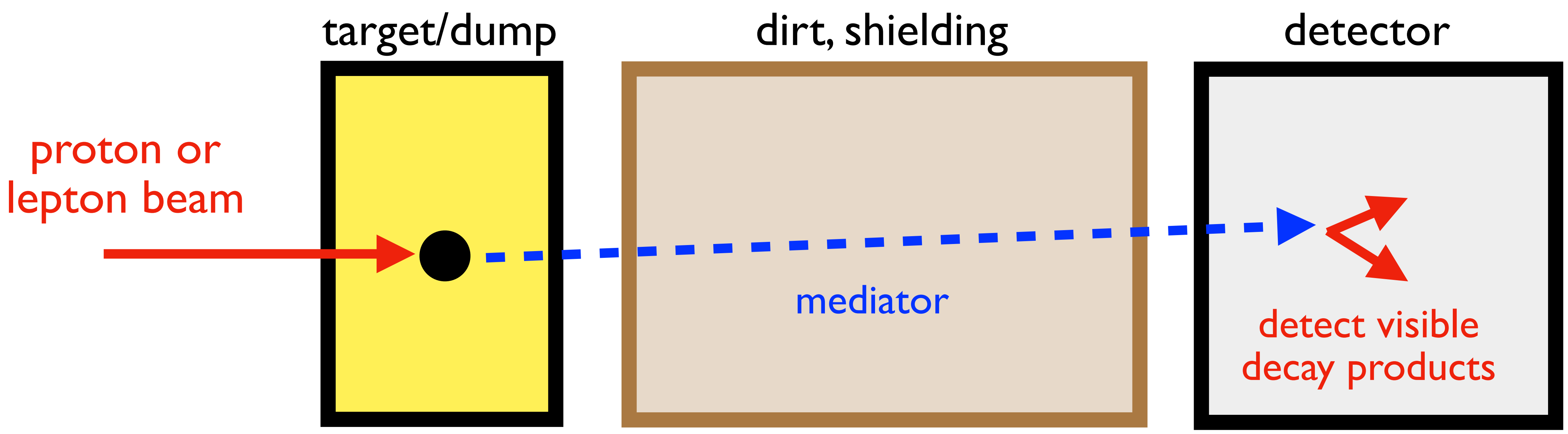


Advantages:

- high collision luminosity
- forward kinematics
- large production rates

- Basic experimental setup entails a detector located downstream of the target
- Produce LLP via rare meson decays, bremsstrahlung, secondary collisions (e.g. photon induced Primakoff process, muon induced bremsstrahlung)
- A variety of search strategies may be employed depending on the properties of the LLP:
    - mass, lifetime, couplings to SM particles, interactions with other states (e.g., dark matter, neutrinos, etc.)

Beam Dumps

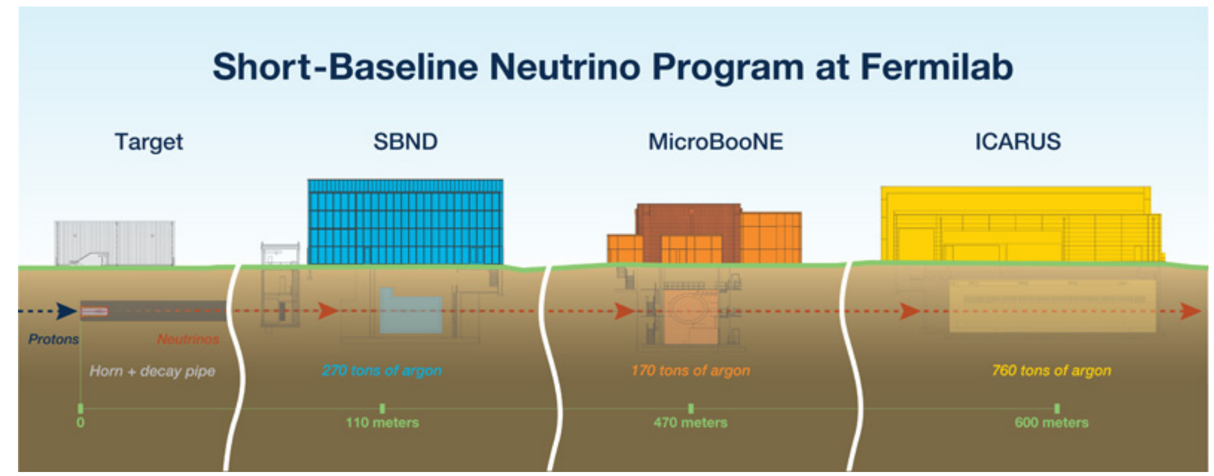


- Leverage relatively higher intensities, longer baselines to probe long mediator lifetimes, small couplings

- Experiments include MicroBooNE, ICARUS, SBND, T2K-ND280, BDX, DUNE, SBN-Beam Dump, PIP-II Beam Dump, …

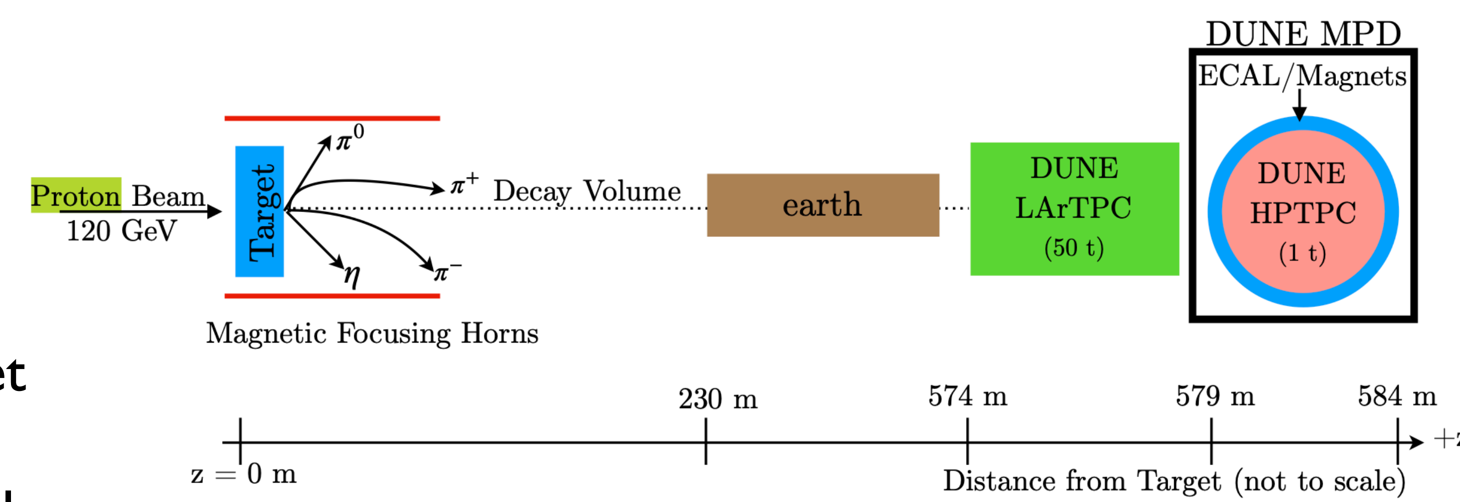
Short Baseline Neutrino Experiments @ FNAL

- 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
- LArTPC detectors have excellent particle ID, reconstruction capabilities



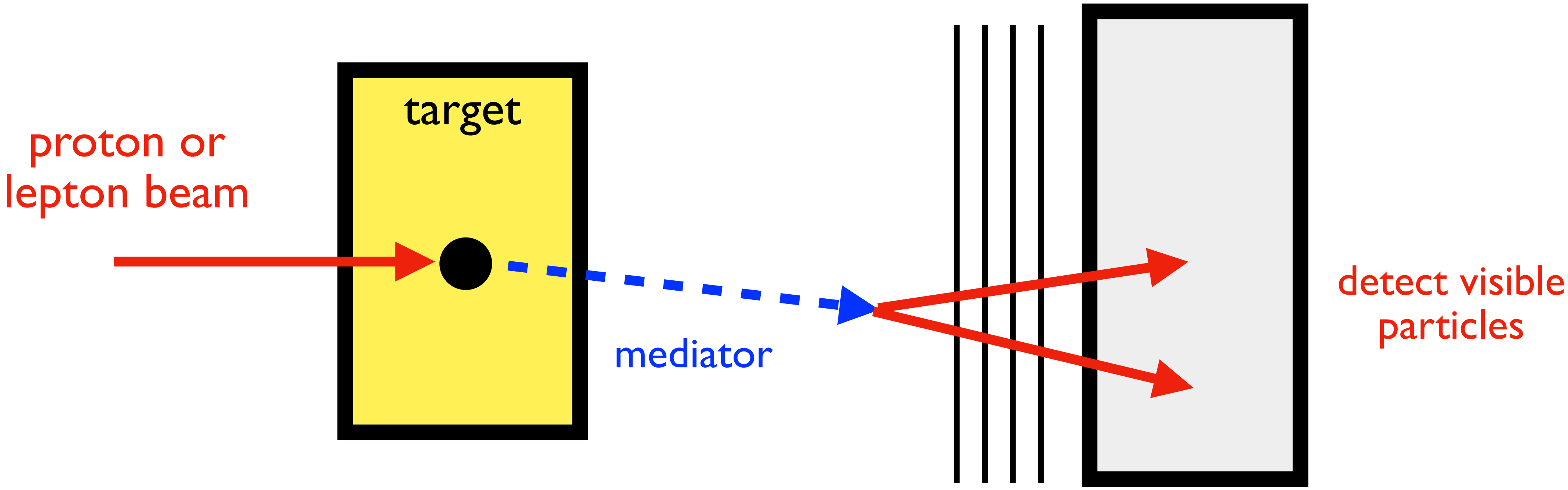
DUNE Near Detector @ FNAL

- 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
- Gaseous near detector leads to relatively low beam-related neutrino background rates



[Berryman et al.]

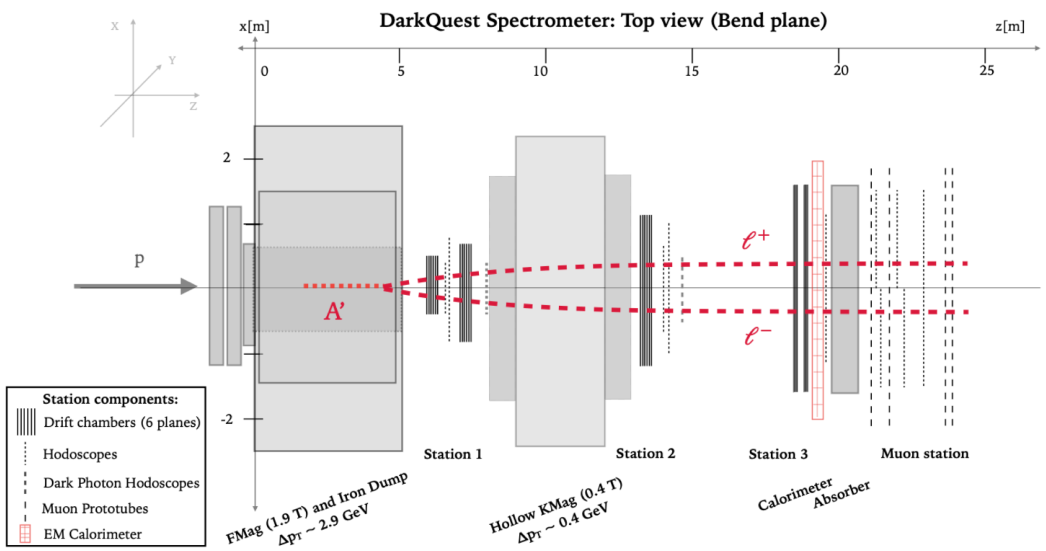
Fixed-Target / Spectrometer



- Compact detector geometry, relatively short baseline allows for sensitive probes of moderate mediator lifetimes
- Experiments include HPS, DarkQuest, …
- Dedicated missing energy/momentum experiments (NA64, LDMX,M^3) can also search for visibly decaying particles in a similar manner

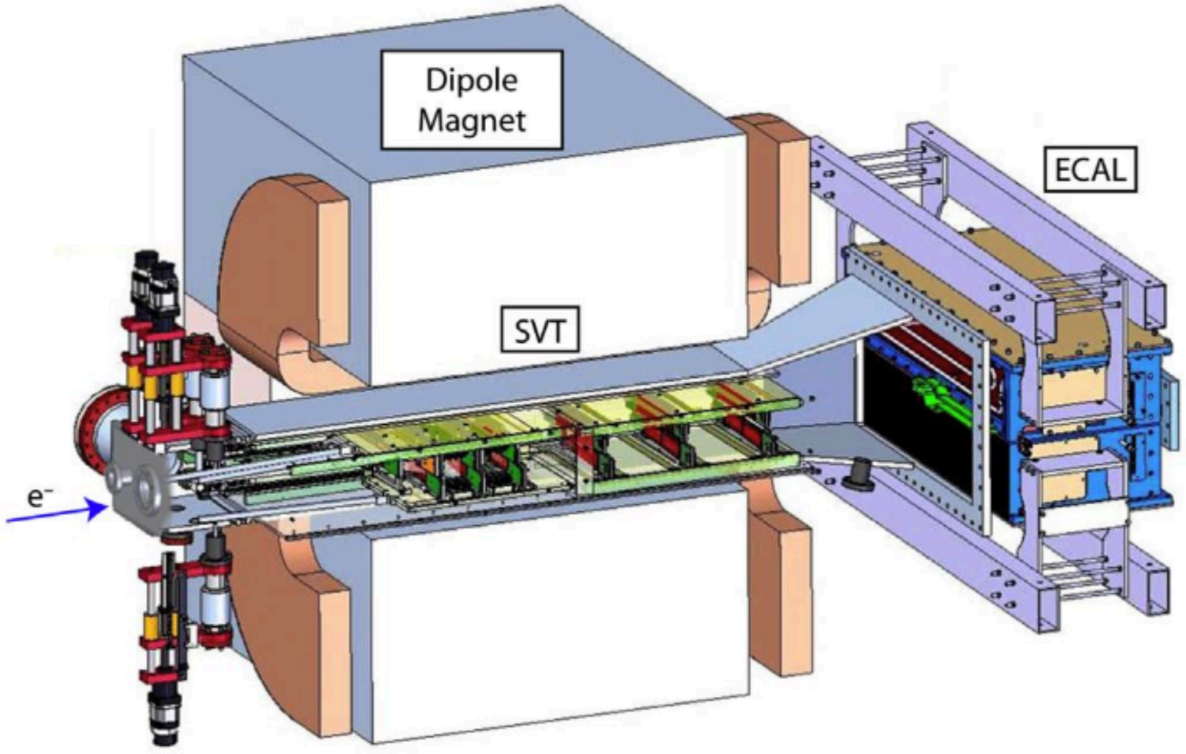
DarkQuest @ FNAL

- DarkQuest is a proposed upgrade of the SeaQuest nuclear physics experiment
- 120 GeV protons impinge on ~ 5m iron beam dump, 10^{18} - 10^{20} POT
- 4 tracking stations, muon ID system, EM calorimeter (proposed upgrade)

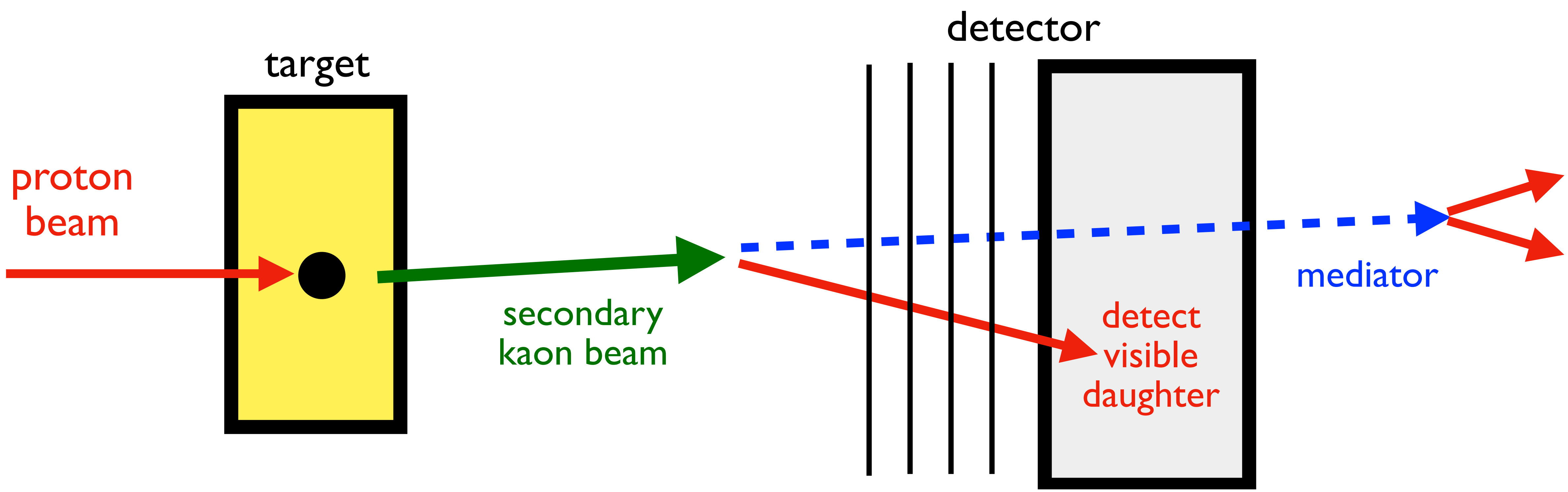


HPS @ JLAB

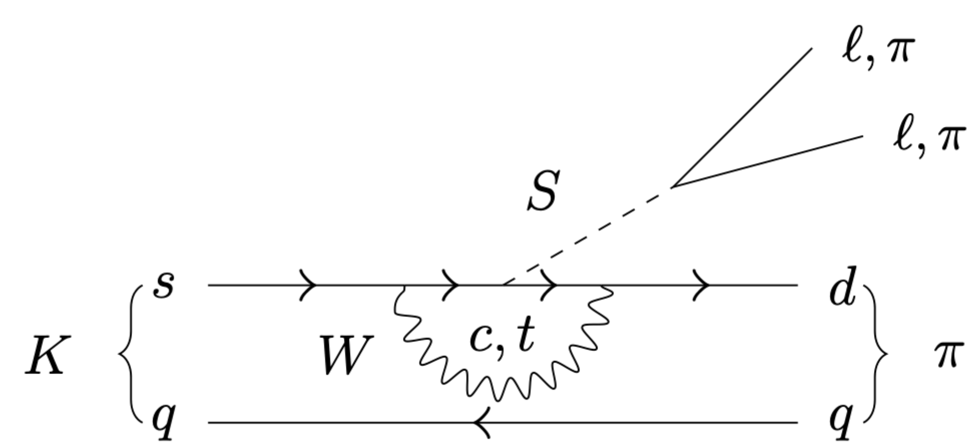
- Multi-GeV electron beam on high Z thin target
- Silicon vertex tracker + ECAL
- Both prompt and displaced dark photon searches are possible



Kaon Factories (e.g., NA62, KOTO)



- Produce mediator via rare kaon decays
- Long lived mediators detected via missing mass technique (as above)
- Short lived mediators can be searched for directly by detecting their decay products



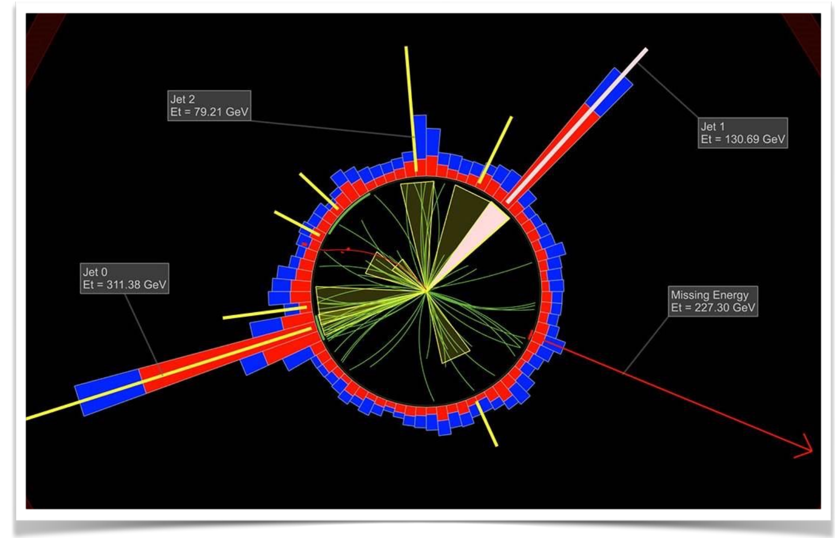
- The approach benefits from the narrowness of the Kaons, as well as large datasets

See 2201.07805 for a recent review article

- Other dedicated meson and lepton facilities can also probe LLPs (PIONEER, Mu3e, REDTOP, …)

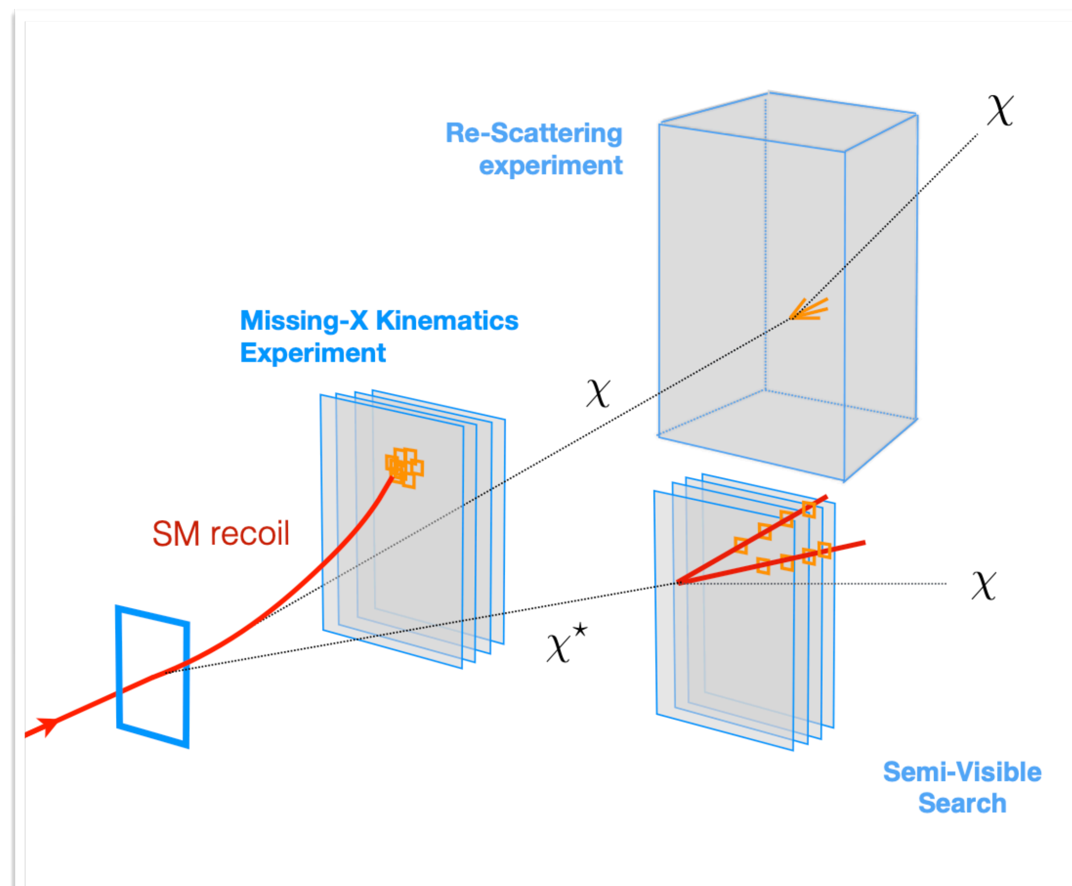
Very Long Lived / Stable Particles (e.g., Dark Matter)

- Missing pT searches at the LHC



- Fixed target missing energy / momentum (NA64, LDMX, M^3…)

- Fixed target production and re-scattering (CCM, COHERENT, BDX, DUNE, …)

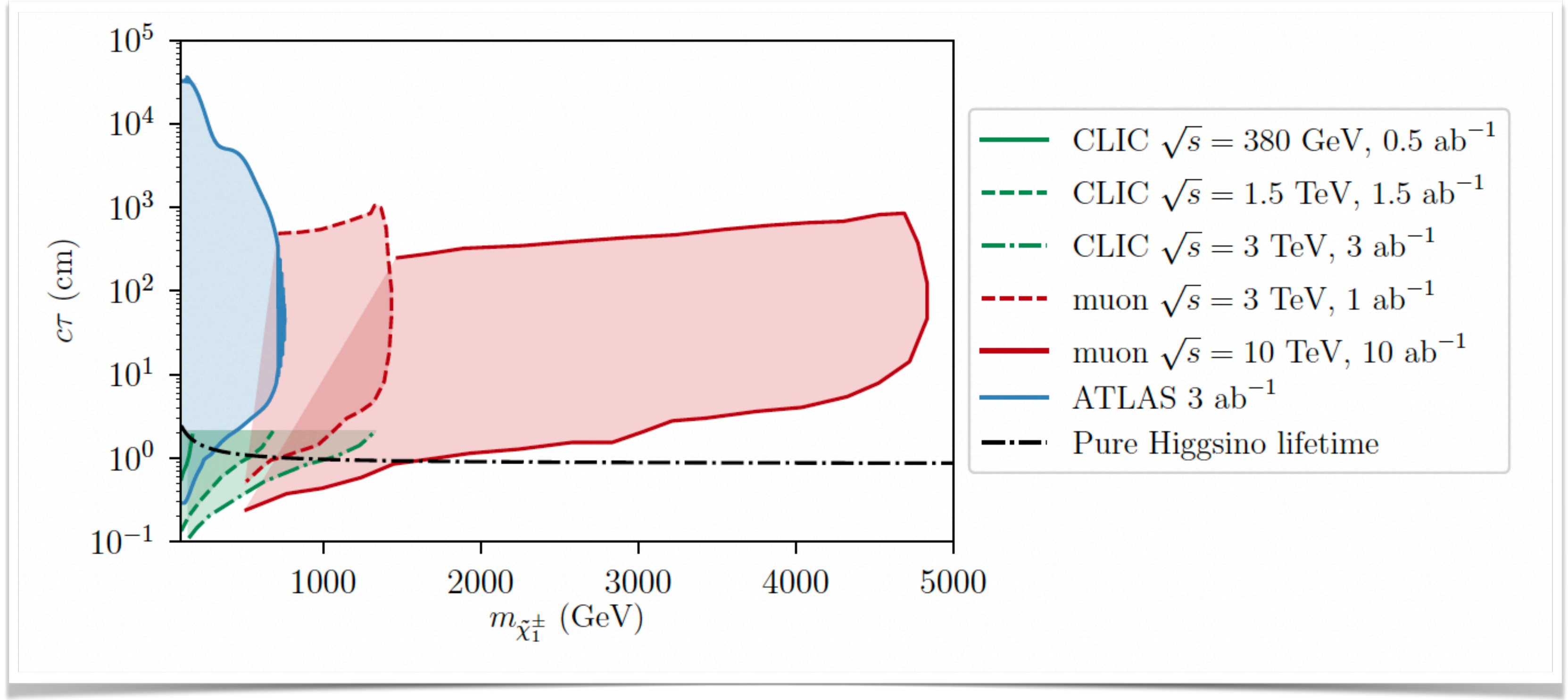


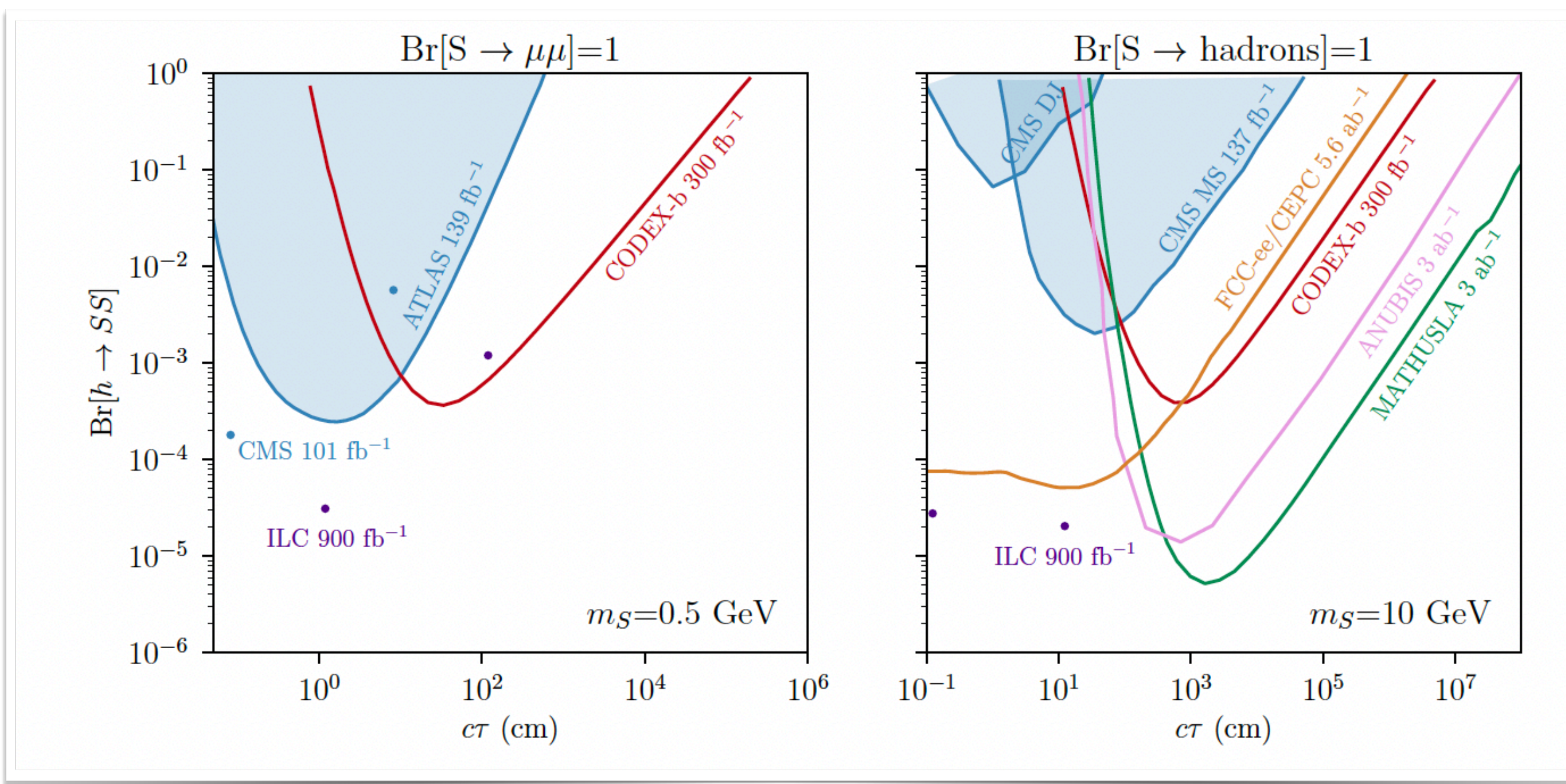
RF6 Big Idea 1 whitepaper, 2207.00597

Benchmark Studies

Long-lived chargino

(disappearing track signature)





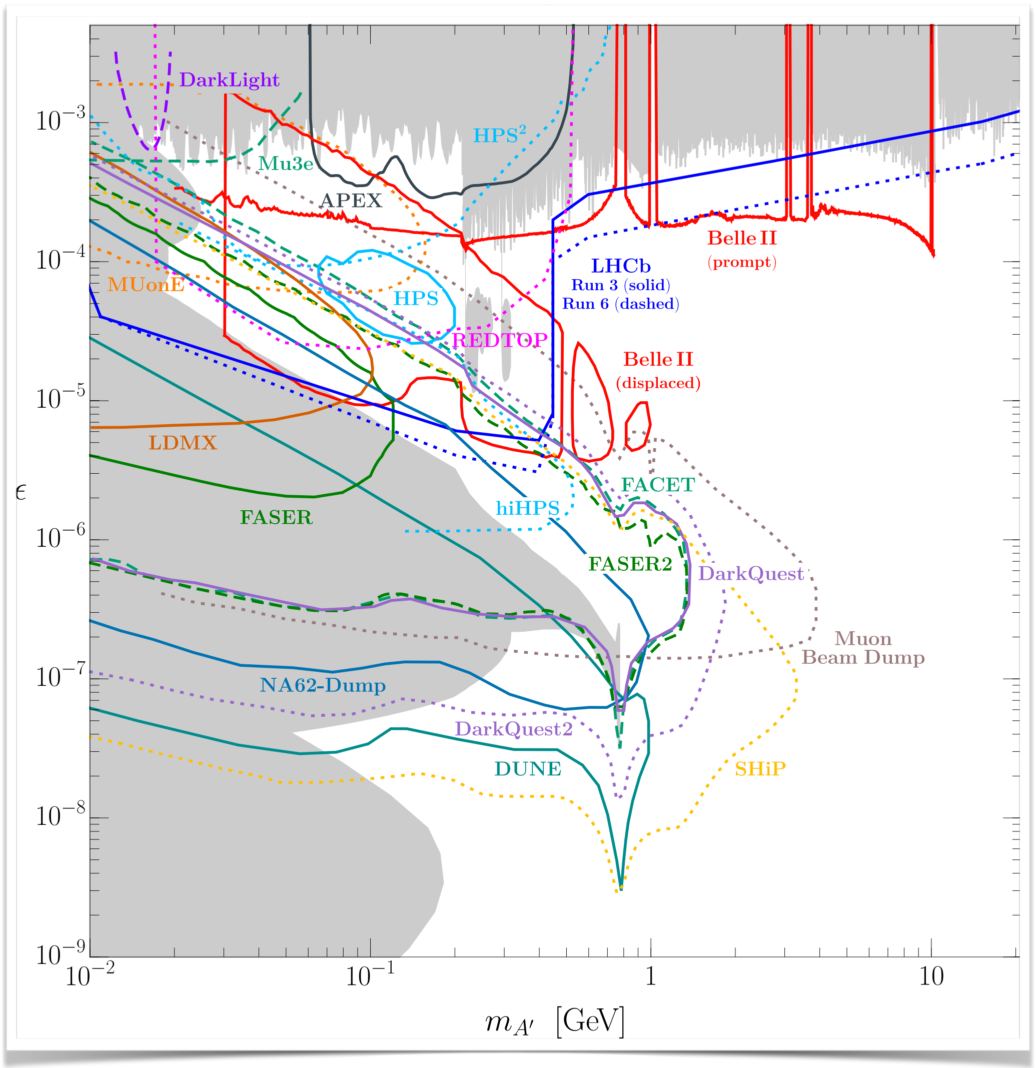
Higgs decay to LLPs

($h \to SS, S$ long lived)

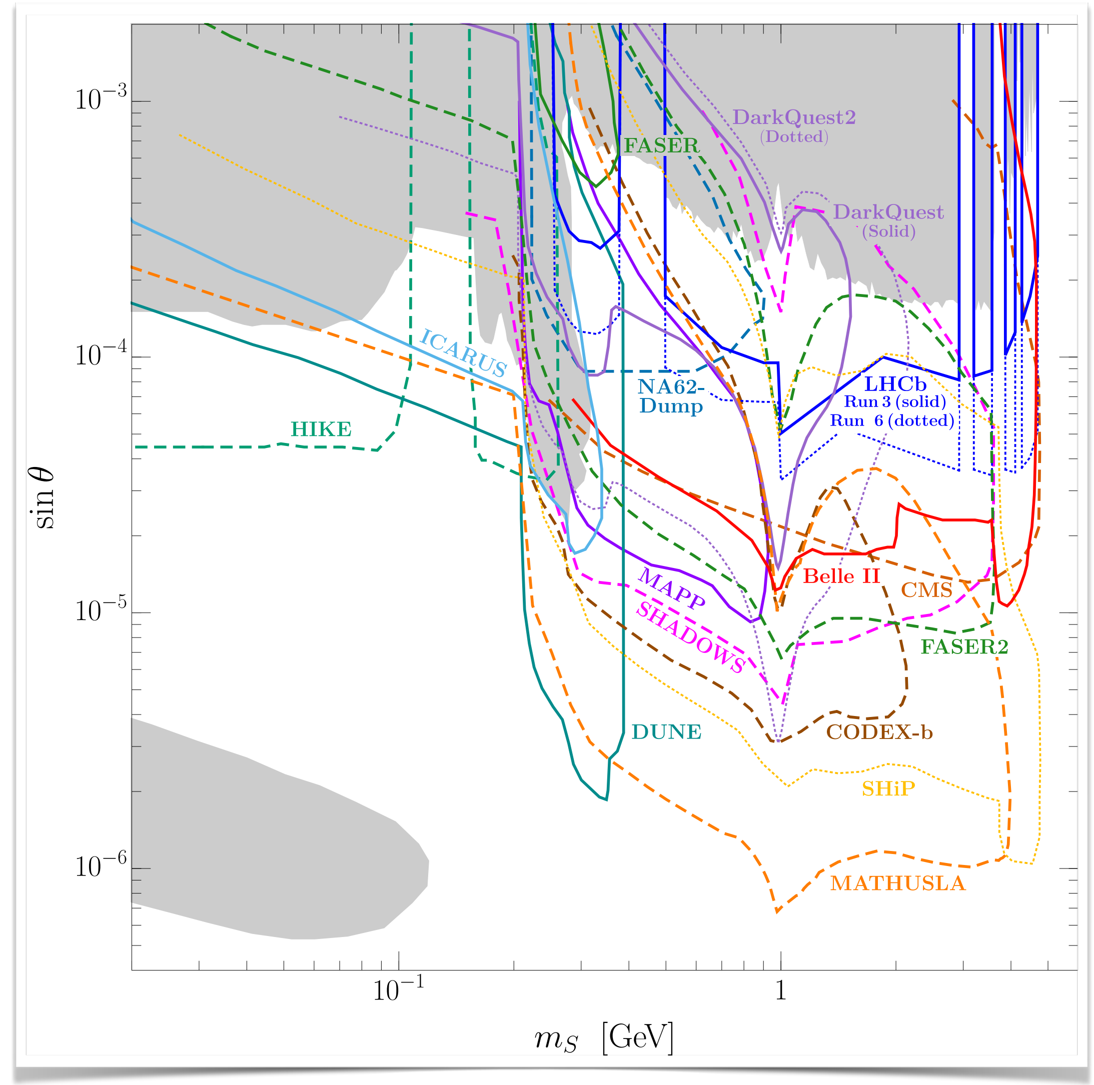
Plots from EF8,EF9,EF10 BSM draft report

Minimal Portals

Dark Photon

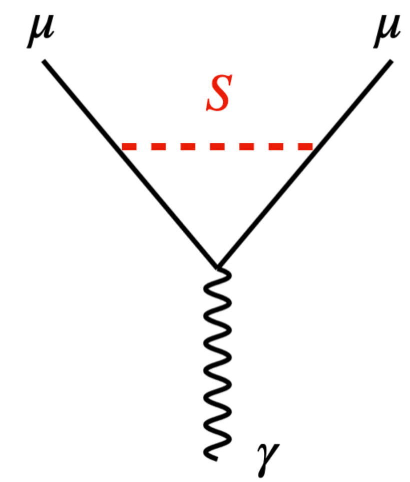


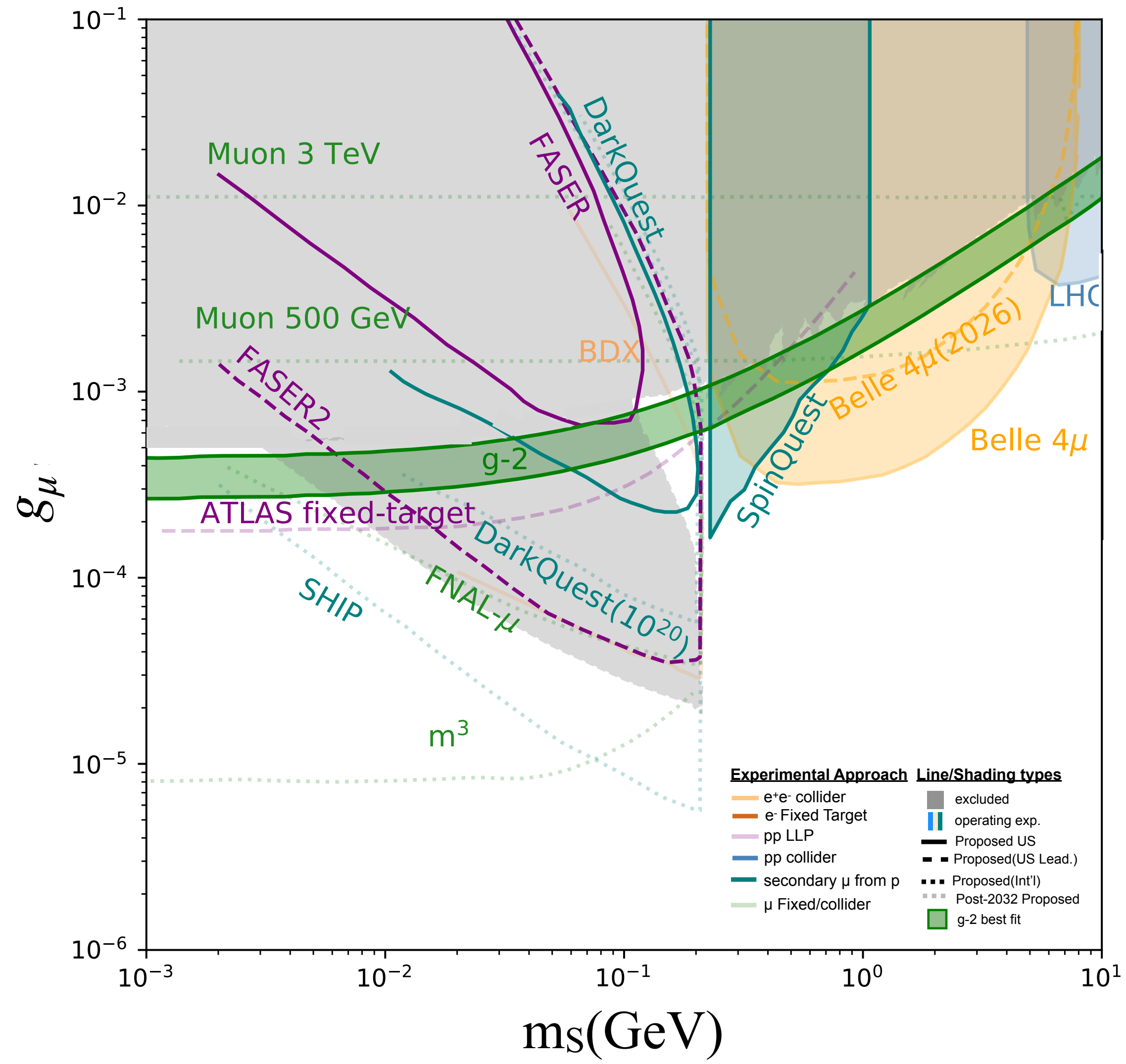
Dark Higgs



RF6 Big Idea 2 whitepaper, 2207.06905

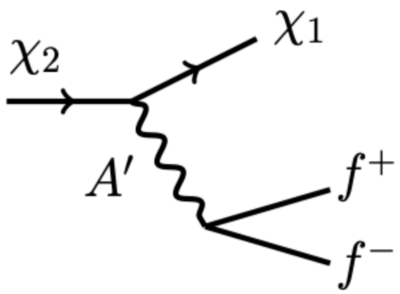
Muon-philic Scalar for $(g-2)_\mu$

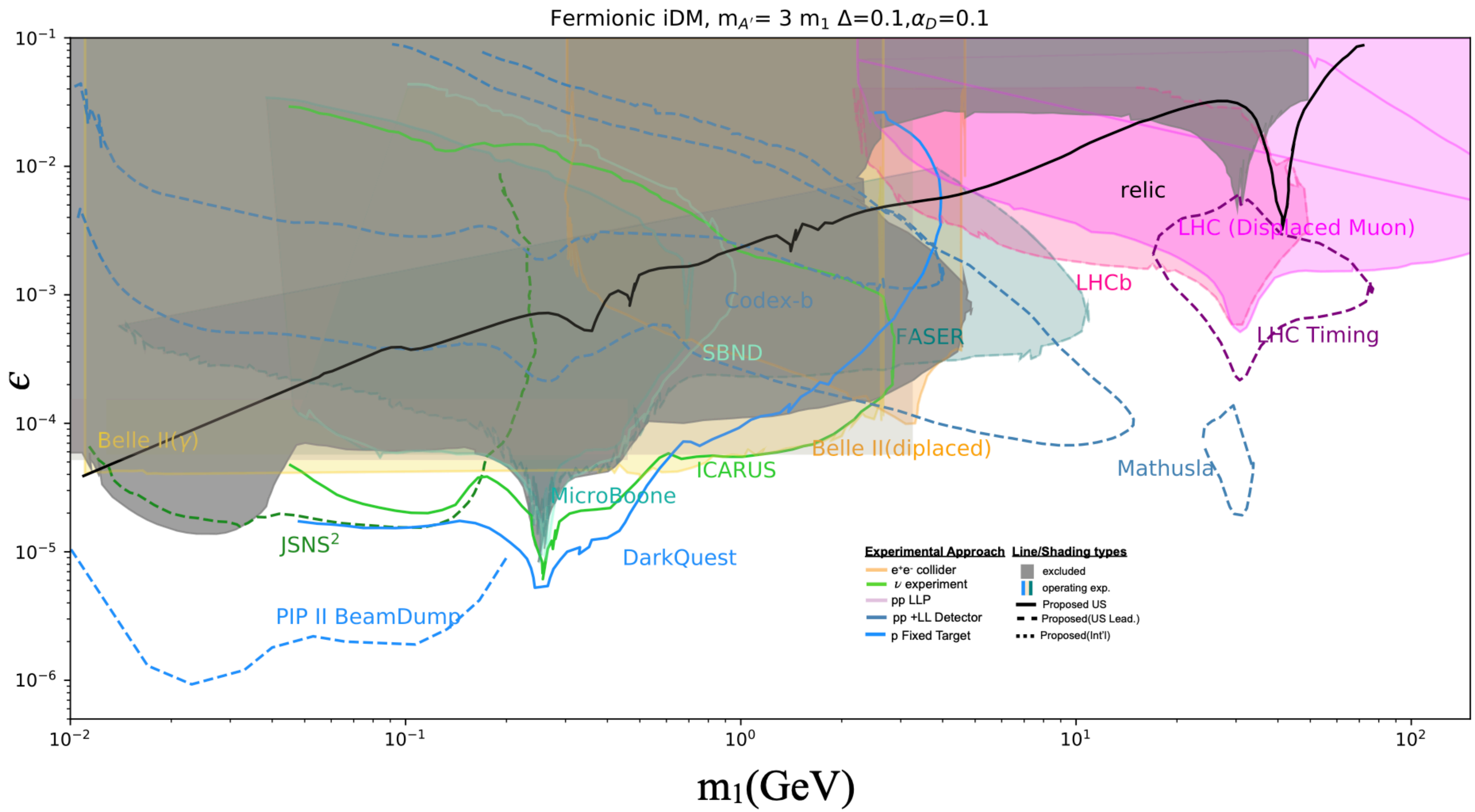




RF6 Big Idea 3 whitepaper, 2207.08990

Inelastic Dark Matter





RF6 Big Idea 3 whitepaper, 2207.00597

Summary and Outlook

- Long-lived particles are ubiquitous in nature and in BSM theories. They and appear in a variety of solutions to the outstanding puzzles in particle physics and cosmology.

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

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

- Many exciting experiments and results on the horizon!