A Long-Lived Particle and Dark Matter Search at the LHC at z = 80 - 127 m.
(Expression of Interest: Snowmass EF08+09+10)

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Abstract

We intend to develop a proposal to search for BSM long-lived particles (LLPs), such as dark photons with $m_{A'} \lesssim 20$ GeV, in the forward direction of IR5 (CMS), penetrating 35 m – 50 m of steel in the Q1 – Q3 quadrupoles and D1 dipole, and either decaying in a large vacuum pipe or interacting in an imaging calorimeter. Neutral LLPs with $|\eta| > 8$ decaying after traversing 83 m of vacuum may also be detected if their mass is several GeV.

BSM long-lived particles with lifetimes $c\tau \sim 10$ cm — 100 m at the LHC may be detected with a new forward spectrometer downsteam of IR5 as an extension of CMS. A 20 m long section of beam pipe with diameter $\sim$ 100 cm with a thin back window can replace the standard $\sim$ 20 cm diameter pipe, providing a large volume of high vacuum for LLP decays. The 35 Tm D1 dipole acts as a sweeping magnet, deflecting charged particles that exit Q1 – Q3 to the left and right of the outgoing beam [1]. The quadrants above and below the beams are swept clear of charged particles, and at R > 12.5 cm at z = 116 m are not in a direct line from the collision point for neutral particles. The number of interaction lengths of steel traversed ranges between $190\lambda_{int}$ and $320\lambda_{int}$ (50 m Fe). Precision tracking, timing, imaging calorimetry and muon detectors between z = 116 m and 126 m can measure $\gamma\gamma, e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, h^+h^-, \tau^+\tau^-, c\bar{c}$, $b\bar{b}$ and jets from LLPs with mass $\lesssim$ 20 GeV[2] decaying in the vacuum. Such a system has sensitivity to LLPs with (unboosted) lifetimes $c\tau$ from $\sim$10 cm to $\sim$ 100 m in 3 ab^{-1}, see Fig. 1.

The possibility of detecting semi-strongly interacting (but penetrating) dark matter particles in the calorimeter will also be studied. Background from high energy hadrons emerging from the steel can be mitigated by precision ToF and the depth of first interaction.

We present this Forward Multiparticle Spectrometer (FMS) as a possible new subsystem for CMS. It should operate at full luminosity in Run 4. Fig. 2 shows a schematic arrangement; dimensions are provisional and subject to optimization.

As presently planned the straight beam pipe (for both incoming and outgoing beams) has a radius increasing from R = 7.5 cm at the exit of D1 (z = 82 m) to R = 12.5 cm at the entrance to the TAXN (z = 127 m). We propose installing over at least 20 m of this section a larger beam pipe $\sim$ 100 cm in diameter, followed at z = 116 m by a thin perpendicular steel (or beryllium) window and a spectrometer. The spectrometer should have excellent tracking to reconstruct tracks from a vertex in the vacuum, imaging electromagnetic and hadronic calorimetry to measure not only the energy but direction, time and start position of showers, followed by muon chambers with a steel toroid for momentum measurement. All these detectors can have the same technology as the planned endcap upgrades for CMS, but over an area only 0.35 m^2, of order 1% of the two CE-H endcap modules.

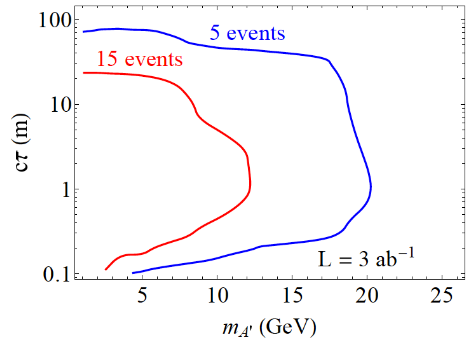

Figure 1: Numbers of events expected in the 20 m-long FMS pipe in 3 ab^{-1} in the $c\tau, m(A')$ plane. For the model see Ref.[2].

Neutral LLPs with $|\eta| > 8$ pass through the D1 aperture and if they then decay with opening angle $\theta \gtrsim 8$ mrad may be detected, backgrounds from K^0 and Λ^0 notwithstanding. Charged particles with momenta $p_z > 3$ TeV stay inside the pipe entering the TAXN.

After the D1 magnet there is LHC equipment (DFX and cold diode) limiting installation of a wider beam pipe until $z \sim 90$ m. Before the transition of the pipe to the enlarged pipe an iron toroid surrounds the pipe, with a circular field $1.5 - 2.0$ Tesla, deflecting muons that emerge from the back of D1 to smaller and larger radii, reducing background at the downstream detectors. In front of and behind this toroid a pair of track chambers measure muons. Any that reach the spectrometer 20 m further downstream (a field-free region) can be matched and such muons eliminated from the data. Immediately at the back of the toroid a counter hodoscope, e.g. quartz Cherenkov bars with precision timing, can give a fast signal for trigger purposes and to confirm that a neutral particle entered the pipe. It could also provide a trigger on penetrating particles with very low electric charge (mCP?).

At $z = 116$ m the transition from the new large pipe to the standard pipe, $R = 12.5$ cm, is made with a thin steel (or beryllium) window where the particles emerge from the LHC vacuum into air, into the detectors covering UP+DOWN quadrants over 10 m in length[1]. Precision vertexing of tracks to ensure they came from a vertex in the vacuum requires that this window be as few radiation lengths as possible and perpendicular to the beam; it may include a strengthening grid covering a small fraction of the area. The effect of the change in the pipe diameter on the beams may be mitigated by an internal thin screen; such issues need studying by LHC experts.

The main set of detectors are behind the window at $z = 116$ m. Tracking, calorimetry and muon chambers can use identical technology to the planned CMS endcap. They measure the decay products of any neutral LLPs that penetrate the steel in the Q1 - Q3 and D1 magnets and then decay in the 20 m long, 100 cm diameter volume, and of non-penetrating particles with mass a few GeV/c^2 and $\eta > 8$. This includes final states $\gamma\gamma$, e^+e^-, $\mu^+\mu^-, e^\pm\mu^\mp, \tau^+\tau^-$, $c\bar{c}, b\bar{b}$ as well as hadron pairs and jets. The FMS is especially well suited for detecting decaying LLPs with $M(X) \lesssim 20$ GeV and (boosted) lifetimes $\gamma c\tau$ from tens of meters to many km. Precision timing on the tracks and/or calorimeter showers not only helps with vertexing in 4-dimensions, but the time-of-flight over 120 m together with the energy gives additional information on $M_X (= E/\gamma)$.

The FMS also may have the potential to discover stable dark matter particles as distinct from decaying portals, if they interact in the calorimeter. To have a probability exceeding 1% of penetrating the steel absorber and then interacting in the calorimeter their nuclear interaction length should be in the range $(10^2 \lesssim \lambda_{LLP} \lesssim 10^4) \times \lambda_{int}$, i.e. semi-strong. A conserved quantum number could allow them to be produced semi-strongly in pairs, but unable to decay. The background from high momentum neutral Standard Model particles ($\gamma, n, K^0, \Lambda^0$ and their antiparticles) *may* be overwhelming, but can be reduced by the powerful features of the HGCAL technology, especially shower imaging, pointing, and timing. For example a particle with mass $M(X) = 10$ GeV/c and momentum $p_z = 200$ GeV/c arrives at $z = 125$ m 375 ps later than a neutron, assuming a straight path from the collision region. From the energy of contained showers and the time-of-flight a mass

[1]The LEFT+RIGHT quadrants have very high fluxes of charged particles with momenta $1 < p < 3$ TeV deflected sideways by the quadrupoles Q1 – Q3 and D1. These may be measured in low pileup runs with a differently optimized set of detectors including hadron identification. This is the subject of a separate Snowmass LoI.

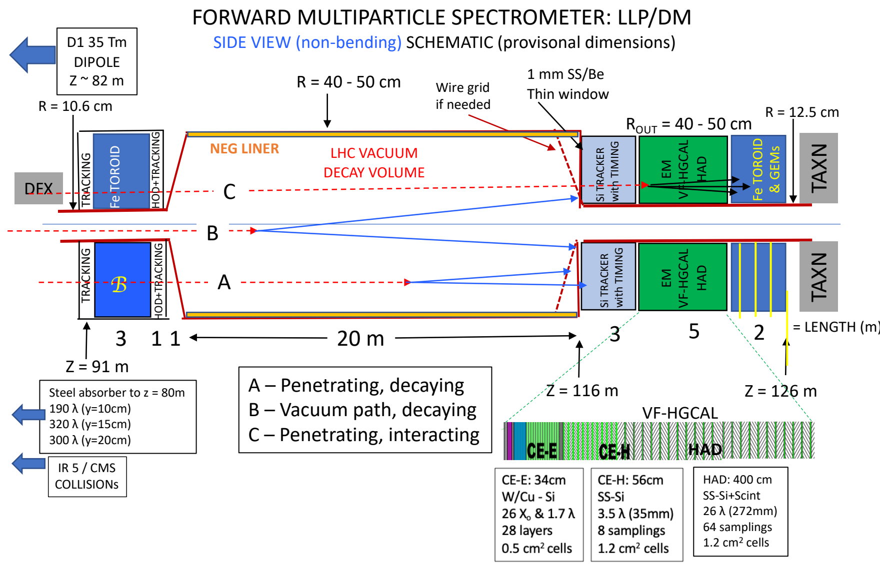

Figure 2: Schematic layout of proposed FMS spectrometer (side view). Three classes of LLP are shown (red dashed lines). A: Penetrating $>$ 35 m of steel and decaying in the large decay volume. B: Traversing $>$ 83 m of vacuum and then decaying. C: Penetrating $>$ 35 m of steel and then interacting in the calorimeter.

can be calculated. The main background will be neutrons that have scattered, having a longer path length. This background is mitigated by the shower direction measurement and the position in z of the starting point of the shower (essentially uniform for an LLP, but with the characteristic λ_{int} = 16 cm for hadrons in steel). The calorimeter can be as much as 30 λ_{int} long.

In principle the FMS could be added as a new subsystem of CMS for Run 4, HL-LHC. LLPs with $M \lesssim 20$ GeV decaying in the vacuum can be observed. The long flight path, precise timing, energy and shower-shape measurement also gives the FMS a unique capability of discovering semi-strongly interacting dark matter particles.

We invite interested experimenters and theorists to help develop this idea into a Snowmass White Paper and a proposal to CMS.

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References

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[2] M.Du, Z.Liu, and V.Tran, JHEP **05**, 055 (2020) [arXiv:1912.00422 [hep-ph], and Internal Note on FMS Aug. 2020.

[3] Snowmass EOI for a Forward Detector Facility, EFxx.