LLP-BSM Searches

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A fundamental reference on LLP searches is **[1]**, the first report of the LHC LLP Community, summarizing materials discussed in meetings at CERN, ICTP (Trieste), Nikhef (Amsterdam) and Ghent University, from 2016 to 2019. See page 90-91 for "Possible improvement to LLPs searches using timing information"; In particular Fig. 1 (43) and Eq. (5.2) Ref 363:

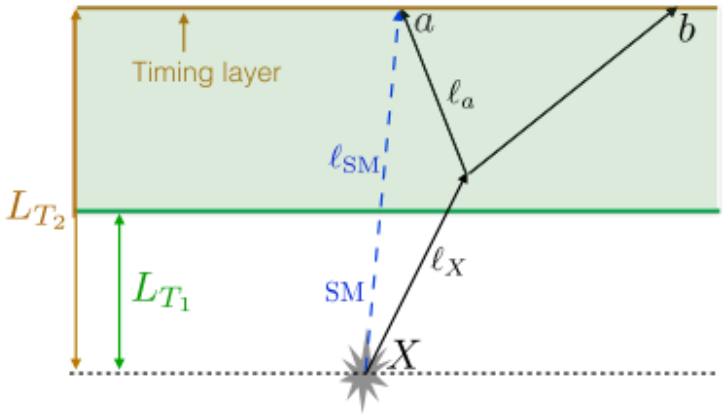

Figure 43. An event topology with an LLP X decaying to two light SM particles a and b. A timing layer, at a transverse distance L_{T_2} away from the beam axis (horizontal gray dotted line), is placed at the end of the detector volume (shaded region). The trajectory of a potential SM background particle is also shown (blue dashed line). The gray polygon indicates the primary vertex. Taken from [363].

$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}, \tag{5.2}$$

with $\beta_a \simeq \beta_{\rm SM} \simeq 1$. An ISR jet could easily be present for all processes, and can be used to 'timestamp', i.e. to derive the time of the hard collision at the PV.

For the CMS MTD located just outside the tracker volume, $\ell_{\rm SM}/\beta_{\rm SM}$ is about $O(1\text{ ns})$. As a result, with tens of picosecond (ps) timing resolution, a sensitivity to percent-level time delay caused by slow LLP motion, e.g. $1 - \beta_X > 0.01$ with boost factor $\gamma < 7$, is expected to be achieved.

Fig. 1 : From Ref. 1 and 2: A LLP X decaying to 2 light SM particles

Another fundamental reference on Forward Projects for BSM Physics is **[3]** : the FPF Collaboration is a consortium to promote the construction of an underground facility for experiments in the (very) forward direction at LHC, aiming at catching BSM signals that may escape the standard LHC experiments that have limited and non-hermetic coverage of the forward regions. While the full facility project is under scrutiny and presently ranking behind the completion of the upgrades of LHC and experiments for HL-LHC, individual small-scale

projects (FASER, SND) have been approved to start at least in part the experimental program addressed by FPF. The FACET project might join these pioneer experiments, if a scheme compatible with Run 4 configuration of LSS5 in the region 100-120m from IP5 may be found for a compact (PreFACET) spectrometer.

Up till then, other possibilities for LLP searches may be considered in the CMS forward regions ($3 \leq |\eta| \leq 5$), developing the scheme of Delayed/Displaced Jets (DDJ), following reference [2] [363 in Fig. 1] shown above, but adapted to Jet timing [4].

At CMS searches for LLP have been performed extensively (see Ref. [5]), using special triggers [6]: the timing properties of ECAL have been exploited [7] to tag non-prompt jets in a search for SUSY gluinos, which are excluded at 95% confidence level for proper decay lengths greater than 0.3m. The HGCAL excellent time resolution [8] would allow to achieve better sensitivities. DDJ triggers, for LLPs decaying into jets within the CMS HCAL [9] were introduced in Run 3 and provide a complementary sensitivity coverage to higher lifetime signal models.

HCAL Phase 1 upgrade (replacing HPDs with SiPMs and updating the QIE, including a TDC):
- improved energy resolution with SiPMs
- increased number of readout channels: depth segmentation – identify displaced jets
- precise time measurements (TDC) : identify delayed jets,
- Valuable for implementing new LLP triggers at hardware level

However, even with SiPMs, the timing properties of the barrel HCAL are not comparable with the ECAL time resolution, and show rather broad timing distributions (Fig. 2)

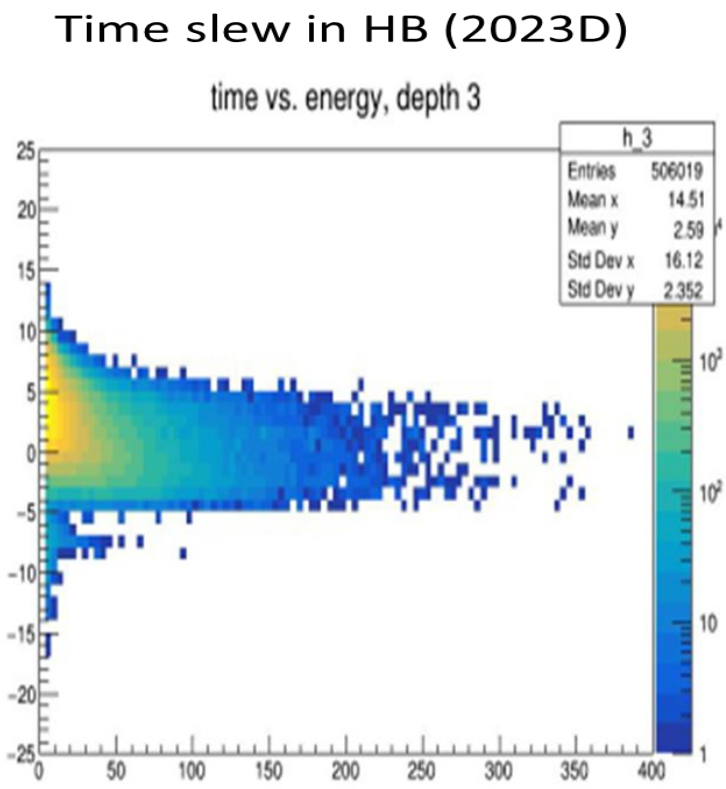

Fig. 2: The time spread of HB in 2023

Up to now little attention was addressed to HF calorimeters, which have potentially excellent intrinsic time properties (Fig. 3):

- Quartz fibers + fast PMT - - > subnanosecond time resolution
- Cherenkov Light collection
- Long baseline (11m from IP5)

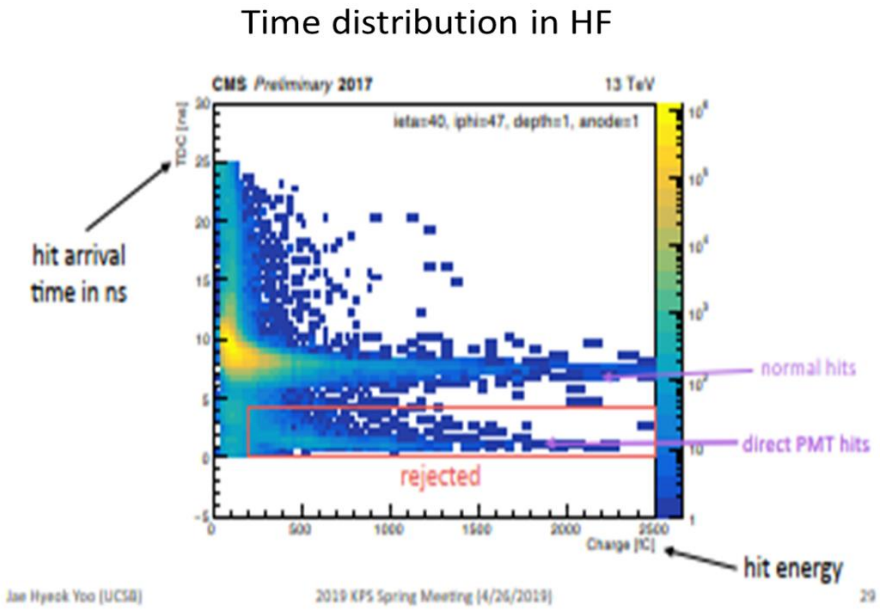

Fig. 3: HF time and charge distributions

The calorimetric study of "delayed jets" has been proposed, f.i., for the CMS barrel calorimeter, over 1.8 m inner radius, and for the end-cap calorimeter, at 7 m from CMS IP5: the HF modules are distant from the IP5 approx 11m, and cover therefore larger intervals of LLP lifetimes.

Within the many BSM signatures investigated, "Long Lived Particles" (LLP) have become a popular objective, in particular considering "non-standard" time properties, resulting from "slow", weekly interacting, particles that can travel substantial distances, before decaying. One situation of this type is shown in Fig. 4.

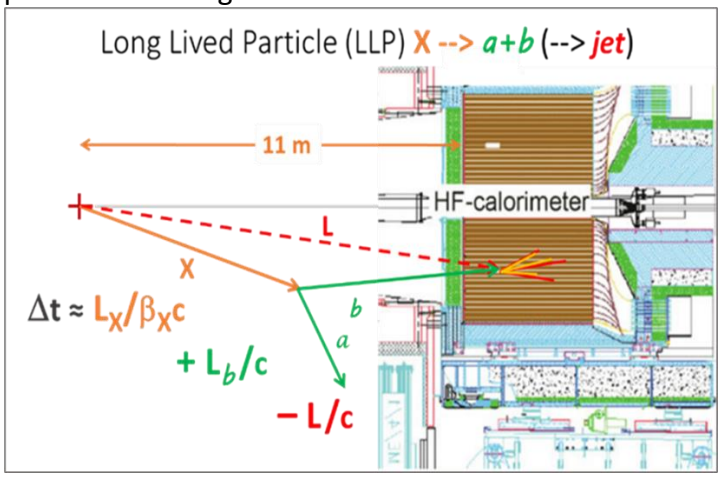

Fig 4 : A DDJ scenario for HF calorimeters

[1] Juliette Alimena et al. : Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider; J. Phys. G: Nucl. Part. Phys. 47 090501 (2020) https://iopscience.iop.org/article/10.1088/1361-6471/ab4574

[2] Liu J, Liu Z and Wang L-T : Enhancing long-lived particles searches at the LHC with precision timing information Phys. Rev. Lett. 122 131801 (2019); corresponding to [**363**]

[3] Jonathan L Feng et al.: The Forward Physics Facility at the High Luminosity LHC; J. Phys. G: Nucl. Part. Phys. 50 030501 (2023) https://iopscience.iop.org/article/10.1088/1361-6471/ac865e/pdf

[4] Wen Han Chiu, Zhen Liu, Matthew Low and Lian-Tao Wang: Jet Timing; FERMILAB-PUB-21-372-T, J. High Energy Phys. 2022, 14 (2022), https://doi.org/10.1007/JHEP01(2022)014, arXiv:2109.01682v2 [hep-ph] 7 Jan 2022 https://arxiv.org/pdf/2109.01682.pdf

[5] Claudia-Elisabeth Wulz, Techniques and Results of Neutral Long-Lived Particle Searches in ATLAS and CMS in LHC Run-2; https://arxiv.org/pdf/1907.13588.pdf

[6] CMS Collaboration: Performance of long lived particle triggers in Run 3; CMS DP-2023/043 (CMS Performance Note-17 July 2023)

[7] The CMS Collaboration: Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at √s = 13 TeV; Phys. Lett. B 797 (2019) 134876; arXiv:1906.06441; CERN-EP-2019-113 ; CMS-EXO-19-001-003 https://cds.cern.ch/record/2678845/files/scoap3-fulltext.pdf

[8] Artur Lobanov (CMS collaboration): Precision timing calorimetry with the CMS HGCAL; Proceedings of CHEF 2019, Fukuoka, Japan (25 - 29 Nov 2019); JINST 15 (2020) C07003; DOI:10.1088/1748-0221/15/07/C07003; arXiv:2005.13324v1 [physics.ins-det] 27 May 2020 https://cds.cern.ch/record/2723431/files/2005.13324.pdf

[9] Gillian Kopp et al. : Run 3 LLP Trigger with the CMS HCAL; Presented at LLP13: Searching for Long-Lived Particles at the LHC and Beyond (23 June 2023) https://indico.cern.ch/event/1216822/contributions/5451141/attachments/2672295/4632738/LLP13_HCALtrigger_GKopp.pdf

A general study on BSM physics:

[10] Tulika Bose et al.: Physics Beyond the Standard Model at Energy Frontier; Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021); arXiv:2209.13128v2 [hep-ph] 18 Oct 2022 https://www.slac.stanford.edu/econf/C210711/reports/2209.13128.pdf