HEP Detectors:

Requirements from Long-Lived Particle Searches

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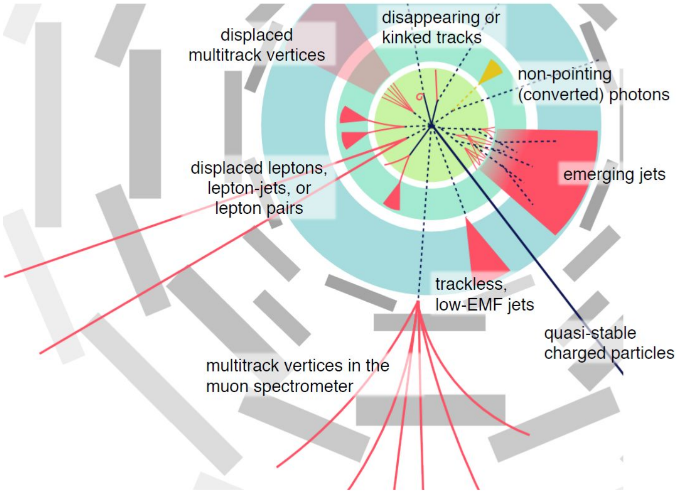
Introduction

- New detector (and collider) designs need to explicitly take into account the many, varied LLP signatures from their inception
  - Ignoring LLPs at this stage can easily **preclude future searches**
- We've brainstormed a list of some key topics for discussion
- Goals:
  - Spark discussion (minimal discussion slide-by-slide, larger discussion at end)
  - Outline major detector topics relevant for LLP searches
  - Frame which studies should be prioritized by the community over the year

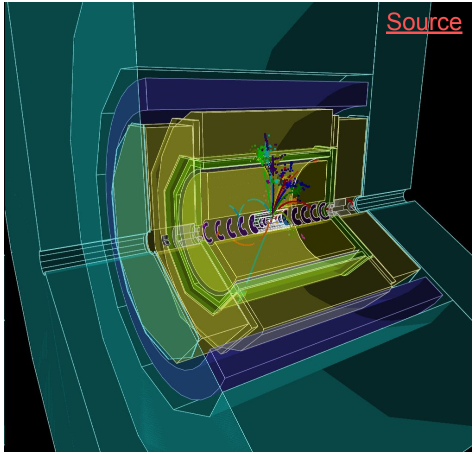


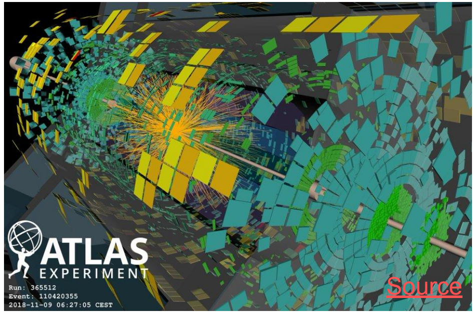
H. Russell

Please use the **Raise Hand** feature or chat (Zoom or #cpm_topic_131) to comment.

Aside: Collider Environments (ee, μμ, pp, AA, Ap, ep, ...)

- Properties of the collider itself can play a role in LLP sensitivity
    - Achievable integrated luminosity / Achievable hard scatter energy
    - Need to reduce detector occupancy / particle multiplicity
    - Levels of beam-induced backgrounds
    - Beam-spot size
    - Time between collisions (and status of detector readout)
    - Differences in radiation hardness requirements among colliders
- Many of the topics discussed today need to be studied explicitly considering the **collider environment** the detector sits in!





General Requirements

- Hermiticity
  - Different geometry choices that provide similar hermeticity for prompt particles can differ drastically in their coverage of particles not originating at the interaction point
- Geometry
  - Interplay of geometry choice with hermeticity, trigger-capabilities, and even data-rate reduction need to keep in mind LLP needs
- High granularity at large radius
  - Identifying decays of LLP in various sub-systems away from the interaction point and distinguish them from detector-specific backgrounds (including beam-induced backgrounds)
- Particle ID
  - Measurement of ionization energy loss and timing can boost particle ID capabilities and offer unique handles for LLP direct identification
- Timing (more later)
- Dataflow/software must be defined to not prevent LLP searches
  - Inclusive initial reconstruction and/or nimble re-reconstruction

Inner Tracker

- Particle ID (ToF, dE/dx, etc)
  - Need concrete statements on requirements for future detectors
- Large radius pixels
  - Or, more generally, ability for precision-tracking at outer radii
- Minimum radius of first layer(s)
  - “Short”-lived BSM particles, interplay with MET (and missing mass) analyses
- Depending on environment, one can also explore the advantages of TPCs or a mixed TPC+Si system to allow identification of LLP-specific signatures
  - E.g. kinked track, or good measurement of ionization energy loss
  - What are the trade-offs depending on the split in radius between Si and TPC?

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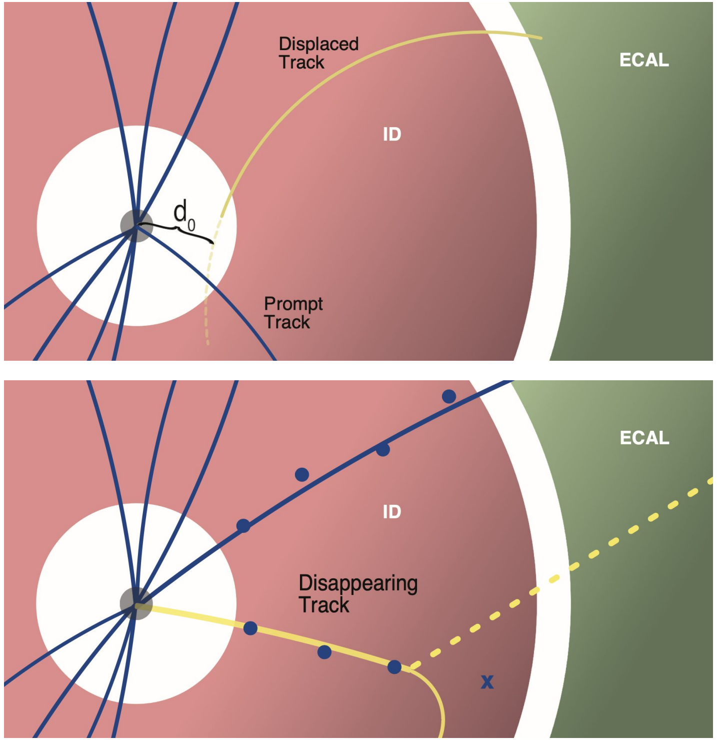

Calorimeters

- Segmentation / Geometry
- Stopping power for stopped particle searches
- Sensitivity to delayed particles' decay
  - e.g. readout and powering during non-colliding bunches)
- Ability to convert photons for sensitivity to displacement
- Pileup/BIB suppression

Muon Spectrometers

- Non-pointing reconstruction capabilities
- High granularity for vertexing
- Detector volume / extent
- Cosmic ray efficiency for vetoes

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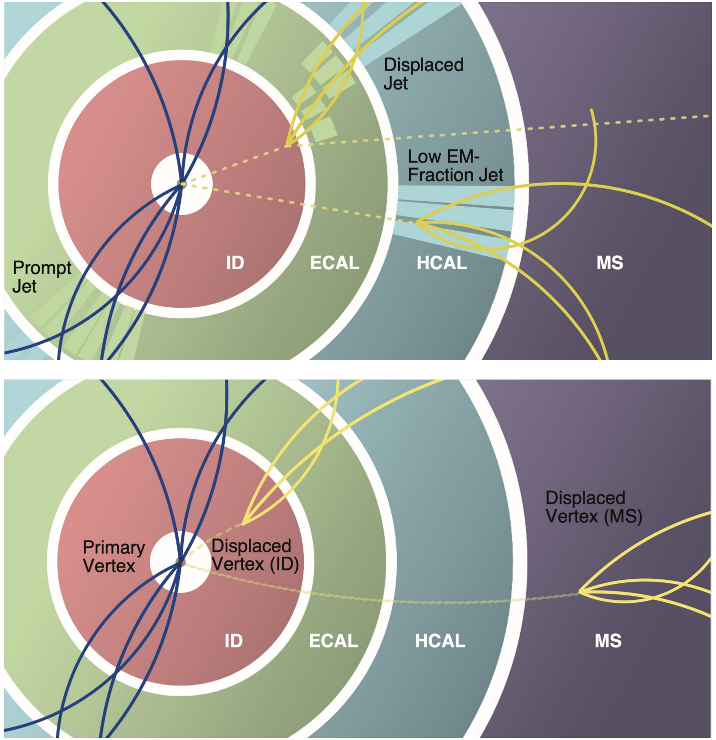
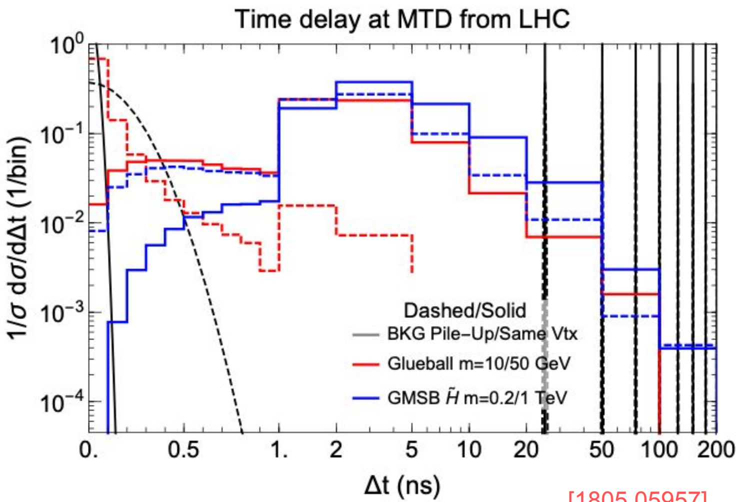


Timing information

- Sub-detector timing resolution
- Out-of-time acceptance
  - Extend readout window without accepting too much e.g. BIB
- Limitations from shaper response times
- Shower evolution and time-based pointing info
  - “Backwards-going” particle sensitivity
- Dedicated timing detectors
  - Pileup suppression, Slow ToF, 4D displaced vertexing



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Trigger (when relevant)

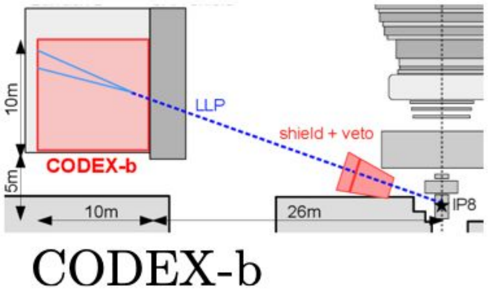
- Late triggers
  - Slight delays, beta ~ O(0.1)
  - Very out of time, apparent beta << 0.1
- Displaced object triggers
  - Hardware tracking abilities
  - Trade-off between simplifications and loss of coverage for LLPs (e.g. Looser trigger roads)
- Direct detection triggers
  - SMP/HSCP/CLLP triggering, large ionization
- Interplay between HW and SW triggering
- Latency for far detector triggering
- Detector geometry to enable smart triggering

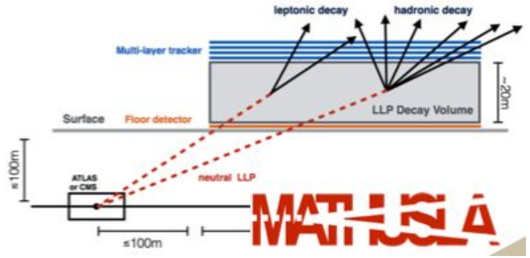
Far detectors

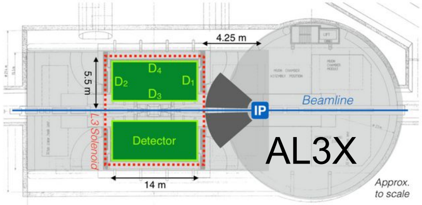
- Proposals for add-ons to existing detectors such as CODEX-b, MATHUSLA, …
- Future colliders could have pre-excavated, shielded experimental halls
  - In forward and central regions

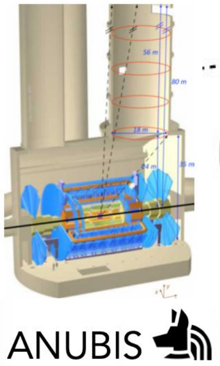
- Integration with trigger and DAQ system for combined analyses vs continuous data-taking for maximum acceptance
- Pointing capabilities towards the IP
- Particle ID?

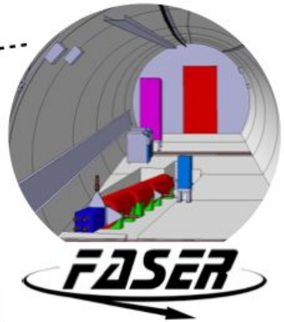
- Quite a few slides/LoIs on this











Snowmass exercise wish-list

From BRN for HEP R&D

- How BRN Higgs requirements compared
  to LLP needs?
    - Most of what discussed above fits or extends these requirements
    - Any non-trivial conflict / compromise?

- Even few basic studies could help translate features discussed today into "proto-"requirements as done in the table here

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and 8×10^{17} n_{eq}/cm^2 TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) n_{eq}/cm^2 in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and 8×10^{17} n_{eq}/cm^2 TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

List of (potentially) relevant LoIs
[Very quick assessment by authors, apologies for omissions]

Including LLP in their scope:

TRACK-BASED TRIGGERS FOR EXOTIC SIGNATURES
Recent Progress and Next Steps for the MATHUSLA LLP Detector
4-Dimensional Trackers
Triggering on charged particles using silicon pixel detectors
The road ahead for CODEX-b
FASERν 2: A Forward Neutrino Experiment at the HL LHC
Scintillator Extrusions for Mega-detectors: MATHUSLA Letter of Interest for Snowmass 2021

General

Muon Collider solidifying the physics case
Muon Collider experiment: requirements for new detector R&D and reconstruction tools
A selection of benchmark studies at FCC-ee
From FCC Physics and Experiments Design Study
CEPC Detectors
Belle II Detector Upgrades
Silicon Vertex Detector for circular electron positron collider
Time of Flight Detector for circular electron positron collider
Detector optimisation and detector technology R&D for the CLIC detector and for the CLD detector of FCC-ee
PRECISION TIMING DETECTORS FOR FUTURE COLLIDERS
Large area CMOS monolithic active pixel sensors for future colliders
SiD LOI Snowmass 2021
IDEA detector Letter of Intent

Could be relevant if extended to LLP (small effort req.)

Identification of TeV hadrons: Transition Radiation Detectors
Time Projection Chamber R&D Letter of Intent
28nm CMOS for 4D Tracker Readout Chips
High Precision Timing and High Rate Detectors
Self-driving data trigger, filtering, and acquisition systems for high-throughput physics facilities
Physics potential of timing layers in future collider detectors
Towards ultra-high granularity calorimetry
Particle Flow Calorimeters for the Circular Electron Positron Collider
τ reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e+e− colliders

BACKUP