Triggering long-lived particles: challenges and perspective for the HL-LHC at ATLAS and CMS

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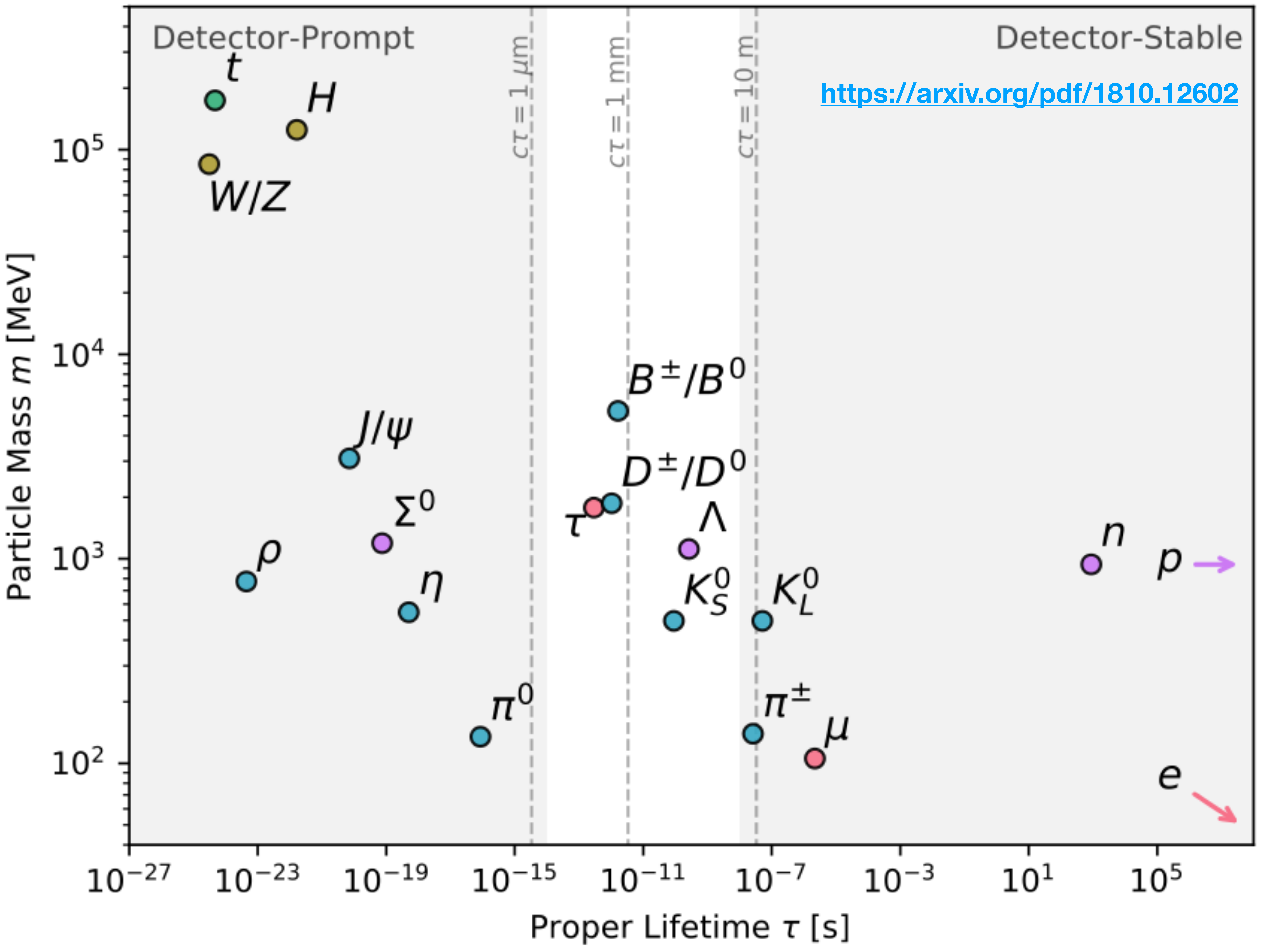
Long-lived particles

Standard Model particles exist over a great range of proper lifetimes… and also BSM particles can be long-lived!

A variety of mechanisms can control a particle's lifetime:

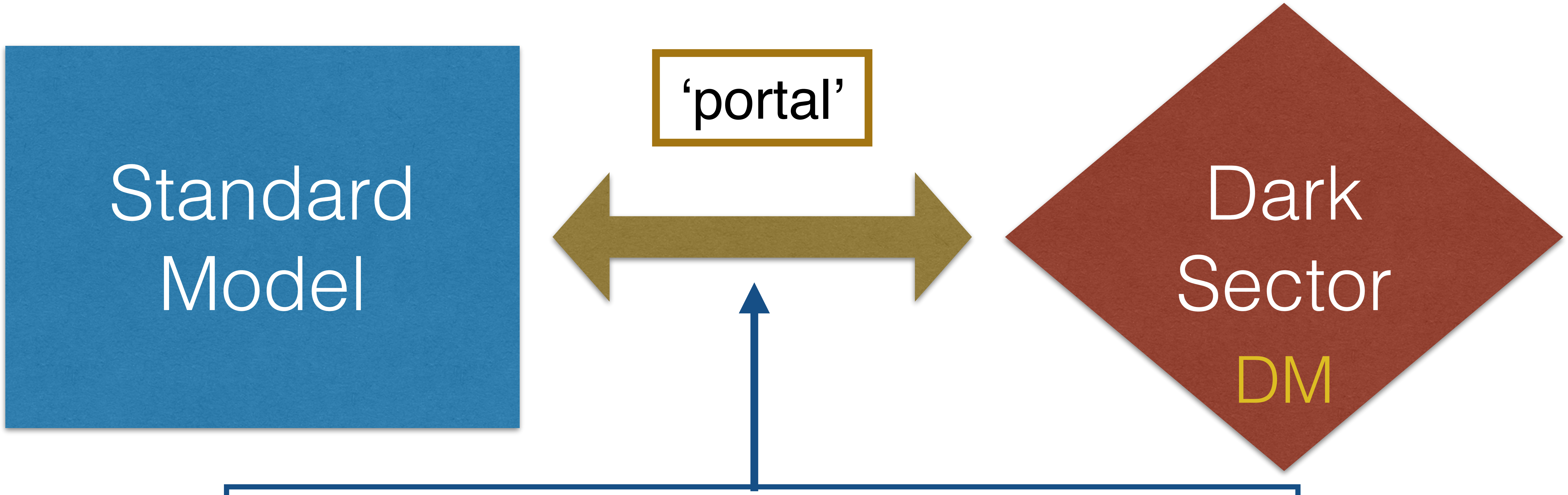
- Decays via heavy particles
- Limited phase space (small mass splittings)
- Small couplings

ATLAS and CMS are not optimised for BSM LLP signals
Without dedicated searches, we are missing large corners of potential BSM physics



Dark Sectors

New Physics can be decoupled from electroweak scale in Dark Sector models, requiring additional low-mass mediators to explain the observed relic density with light DM (sub-GeV)



Shift the focus from the Dark Matter sector composition to the new mediator itself

Dark Sector portals

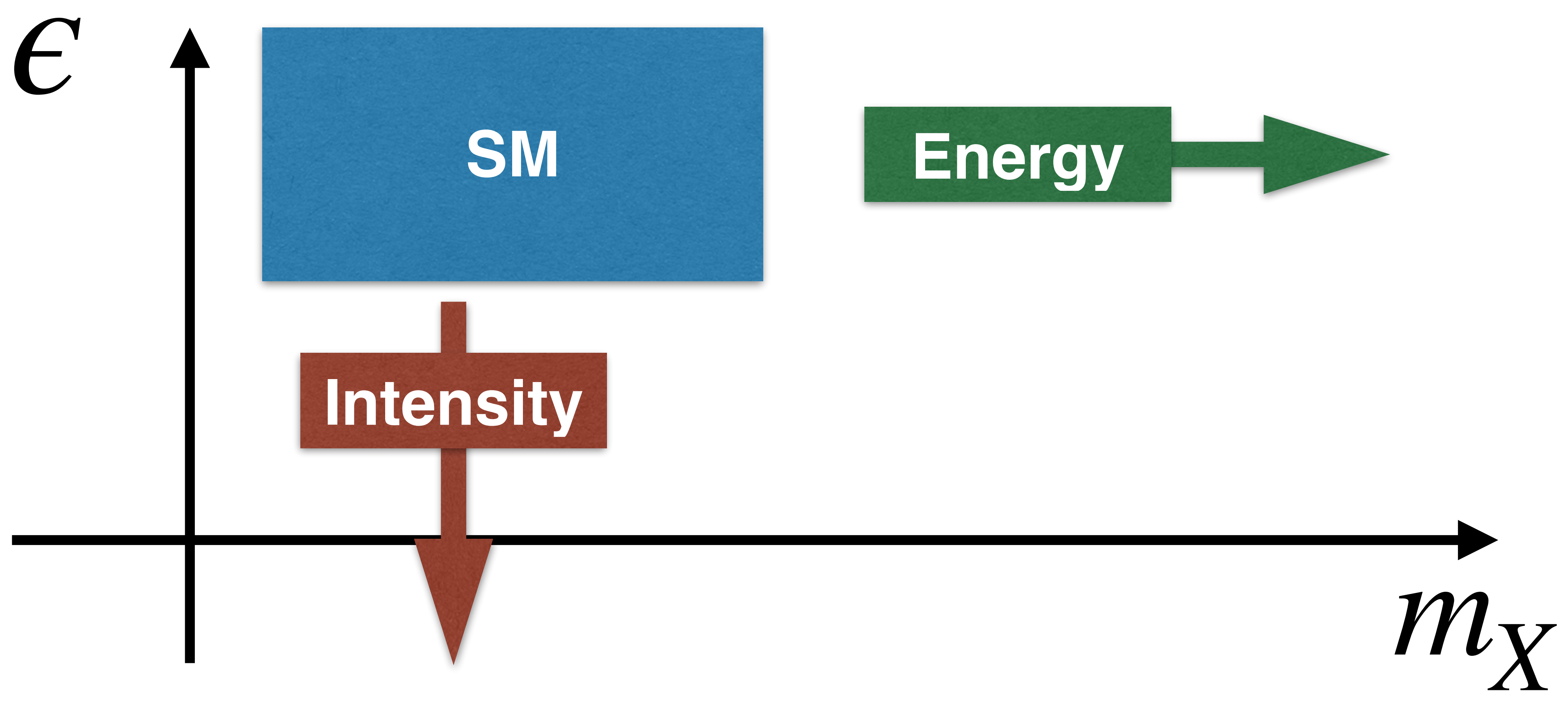
Light mediators, HNL and ALPs must be SM singlets: options limited by SM gauge invariance

Pseudoscalar portal: $C_W F'_{\mu\nu} \tilde{F}^{\mu\nu} \frac{a}{f_a}$ **axions/ALPs**

Vector portal: $\epsilon F^{\mu\nu} F'_{\mu\nu}$ **'dark' vector boson (A', γ_d, Z_d) which mixes with SM photon**

Scalar portal: $\kappa H^2 S^2 + \mu H^2 S$ **'dark' scalar boson (S) —> exotic Higgs decays**

Neutrino portal: $\kappa(HL)N$ **no more sterile neutrino**



Feebly interacting particles are well motivated but their mass scale is unknown and are very difficult to probe at particle colliders, often lead to unconventional signatures!

Dark Sector portals

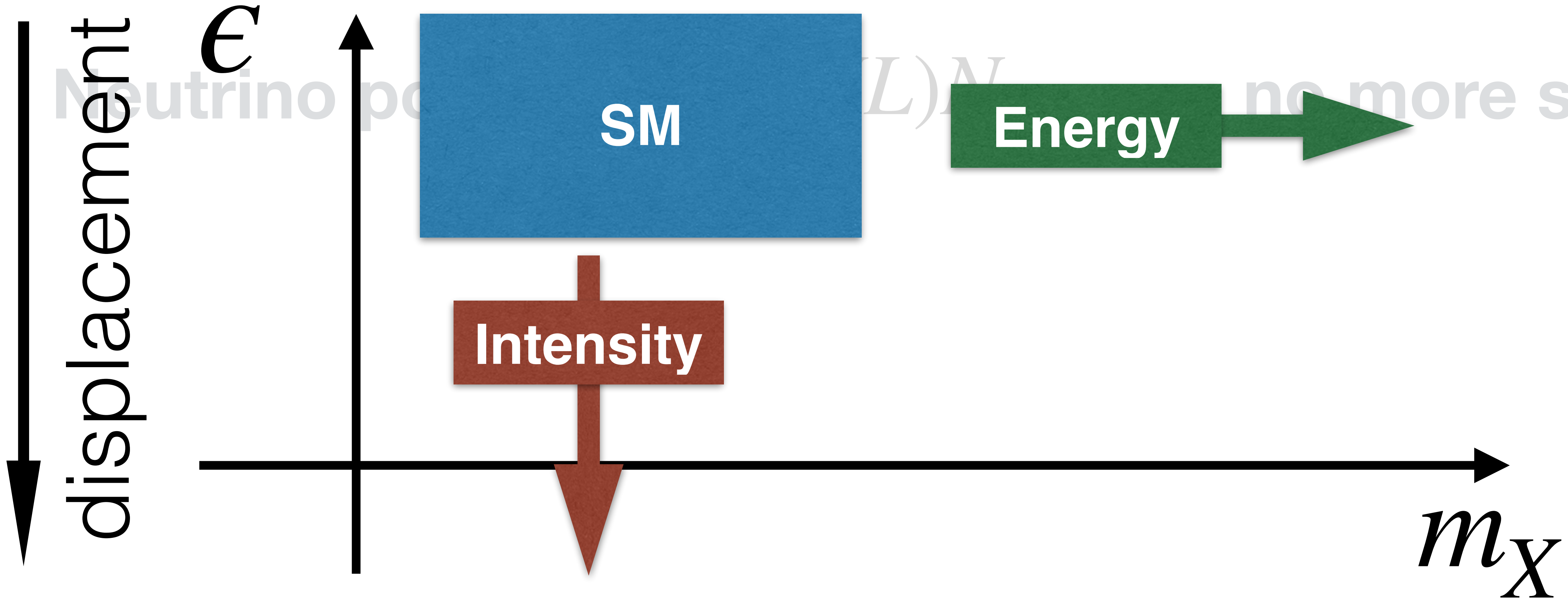
Light mediators, HNL and ALPs must be SM singlets: options limited by SM gauge invariance

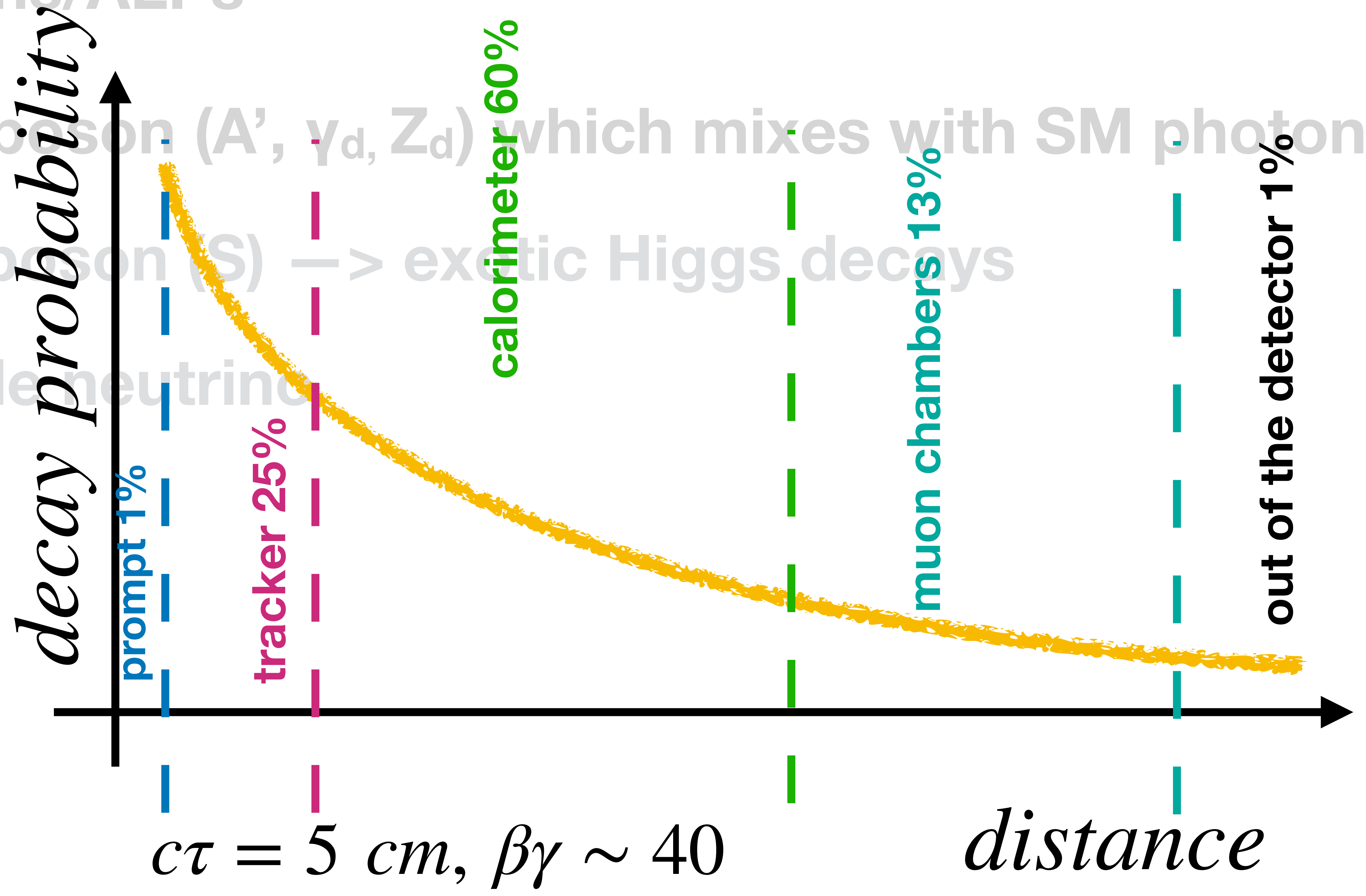
Pseudoscalar portal: $\delta_\mu \bar{\psi}\gamma^\mu\gamma^5\psi$, $\frac{a}{f_a} F'_{\mu\nu}\tilde{F}^{\mu\nu}$ axions/ALPs

Vector portal: $\epsilon F^{\mu\nu}F'_{\mu\nu}$ 'dark' vector boson (A', γ_d, Z_d) which mixes with SM photon

Higgs portal: $\kappa H^2 S^2 + \mu H^2 S$ 'dark' scalar boson (S) —> exotic Higgs decays

Neutrino po... $(L)N$ no more sterile neutrino...



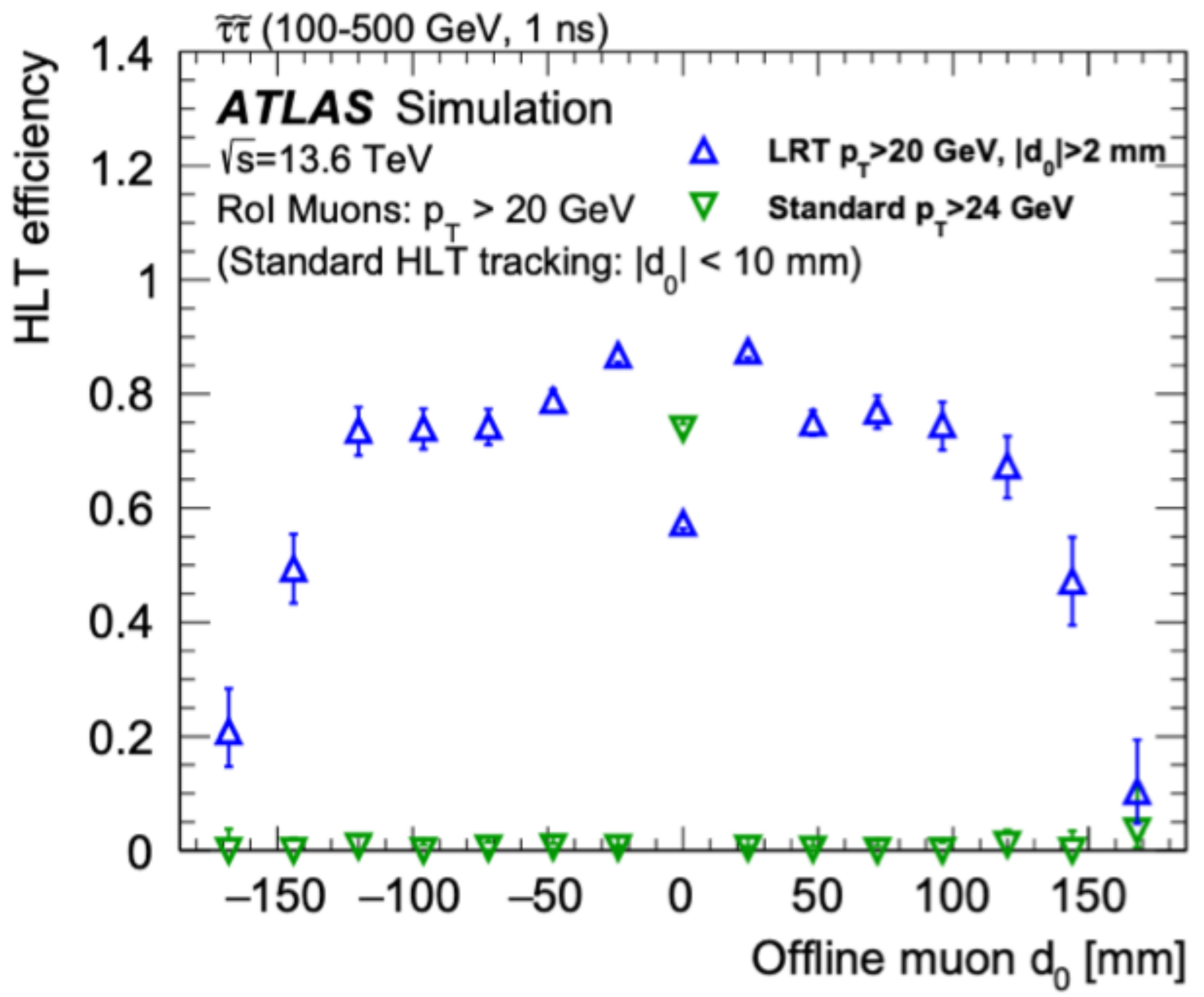


Triggering LLP

LLPs follow an exponential decay —> important to use all sub-detectors

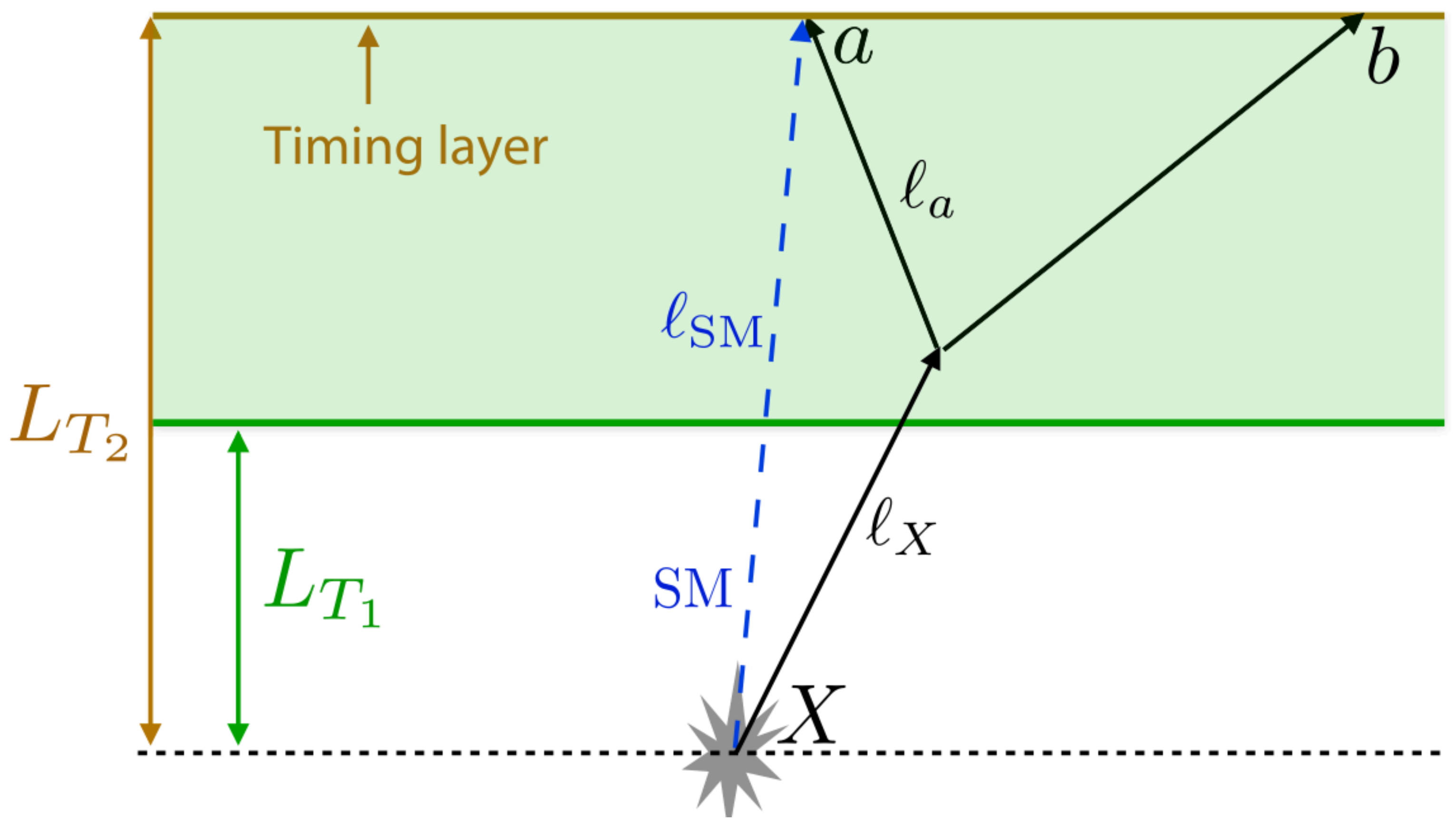
Tracker

- Tricky! Dense environment with little information at trigger level…
- ID vertexing with leftover tracks (e.g. Large Radius Tracking@HLT)
- Rely on triggers that don't use ID track: MS-only triggers or photon triggers



Calorimeter

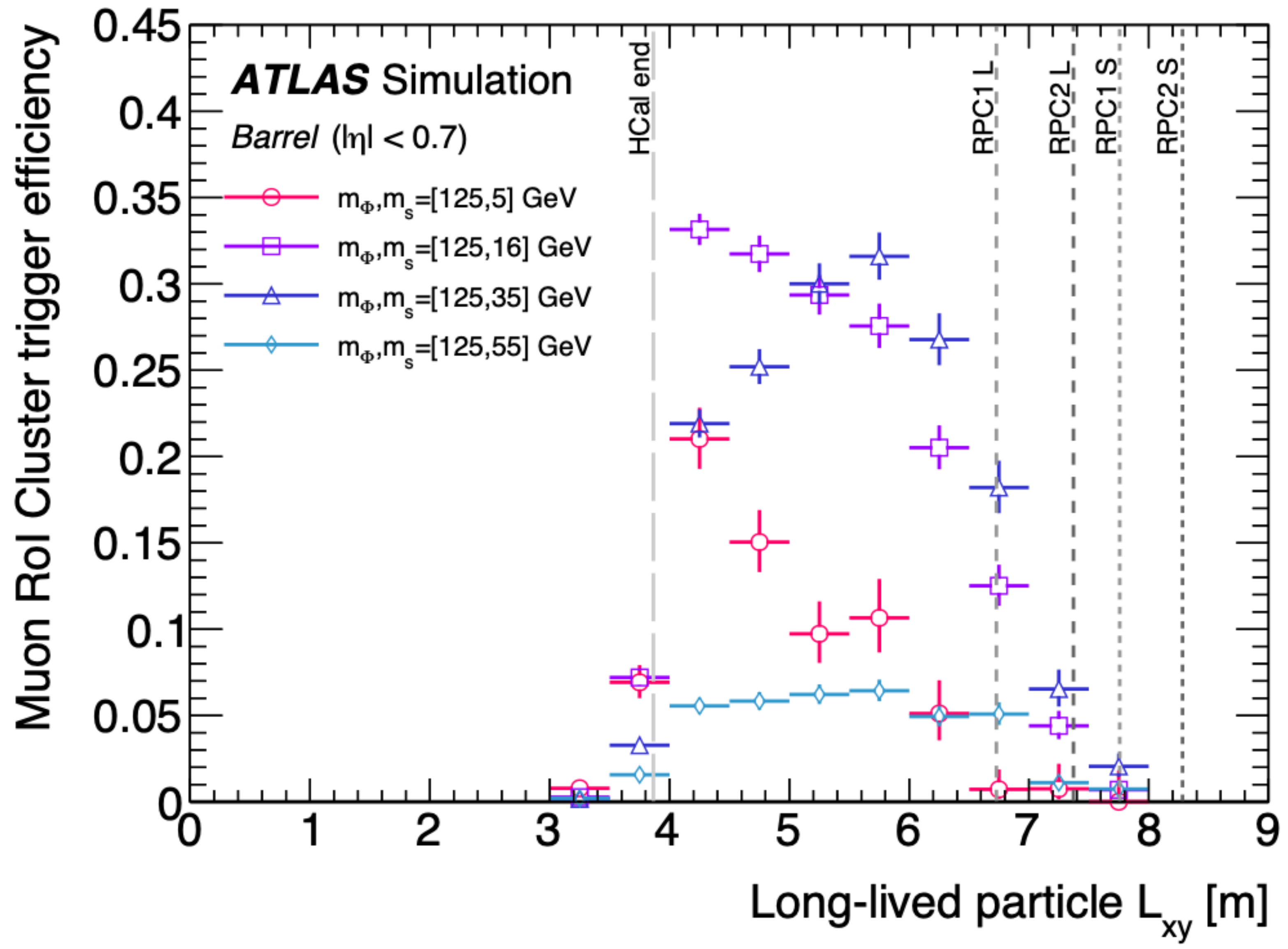
- Anomalous shower shapes
- Large HCal to ECal energy ratio
- Calo timing



$$\Delta t^{i}_{\mathrm{delay}} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\mathrm{SM}}}{\beta_{\mathrm{SM}}}$$

Muon system

- Large muon cluster multiplicity from showers
- Displaced vertex with muon tracks
- Very close-by muons

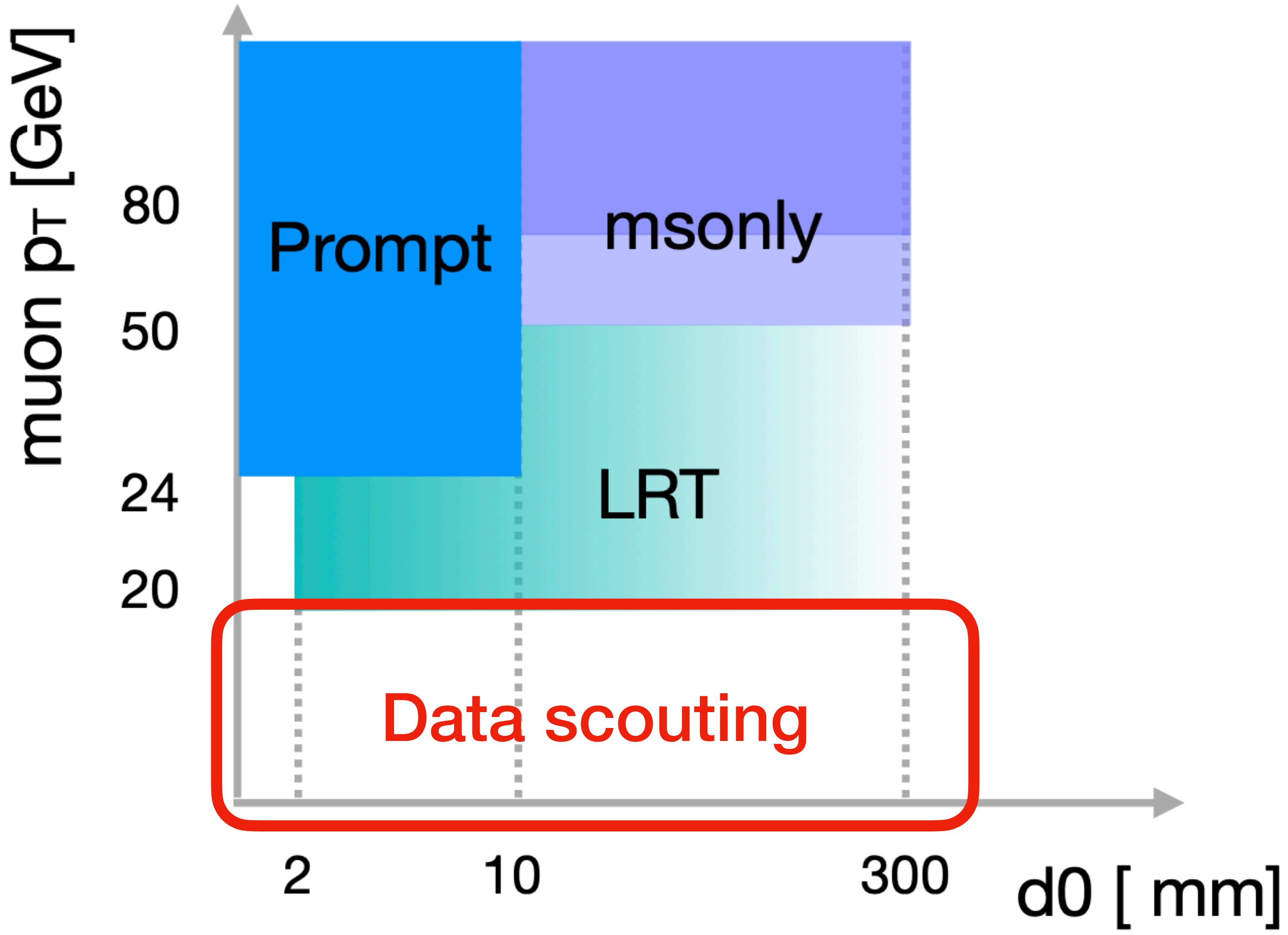


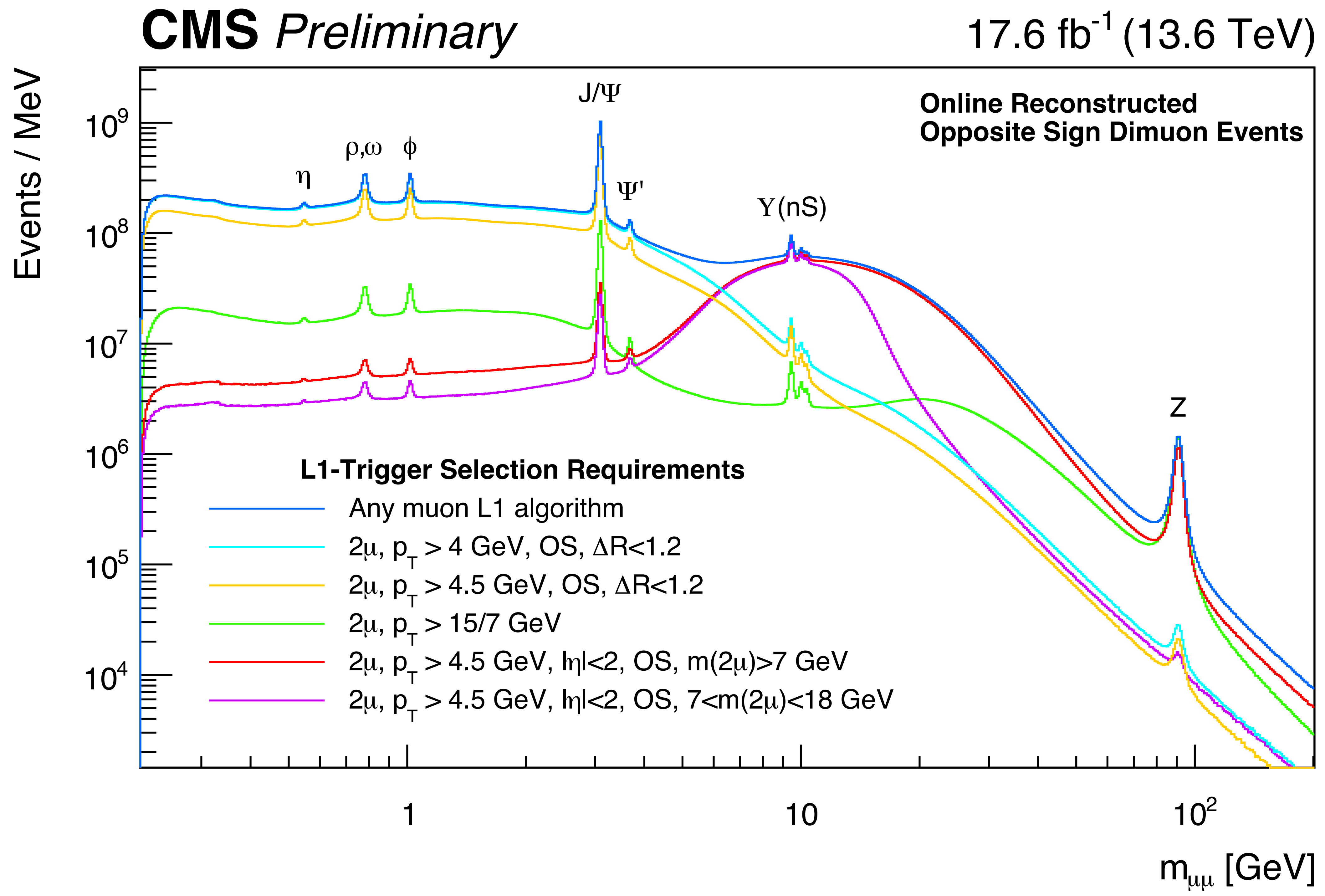
TLA and Data scouting

Events must be **reconstructed by the trigger** before being discarded for further analysis
… rather than throw away the event, save the trigger reconstructed information!

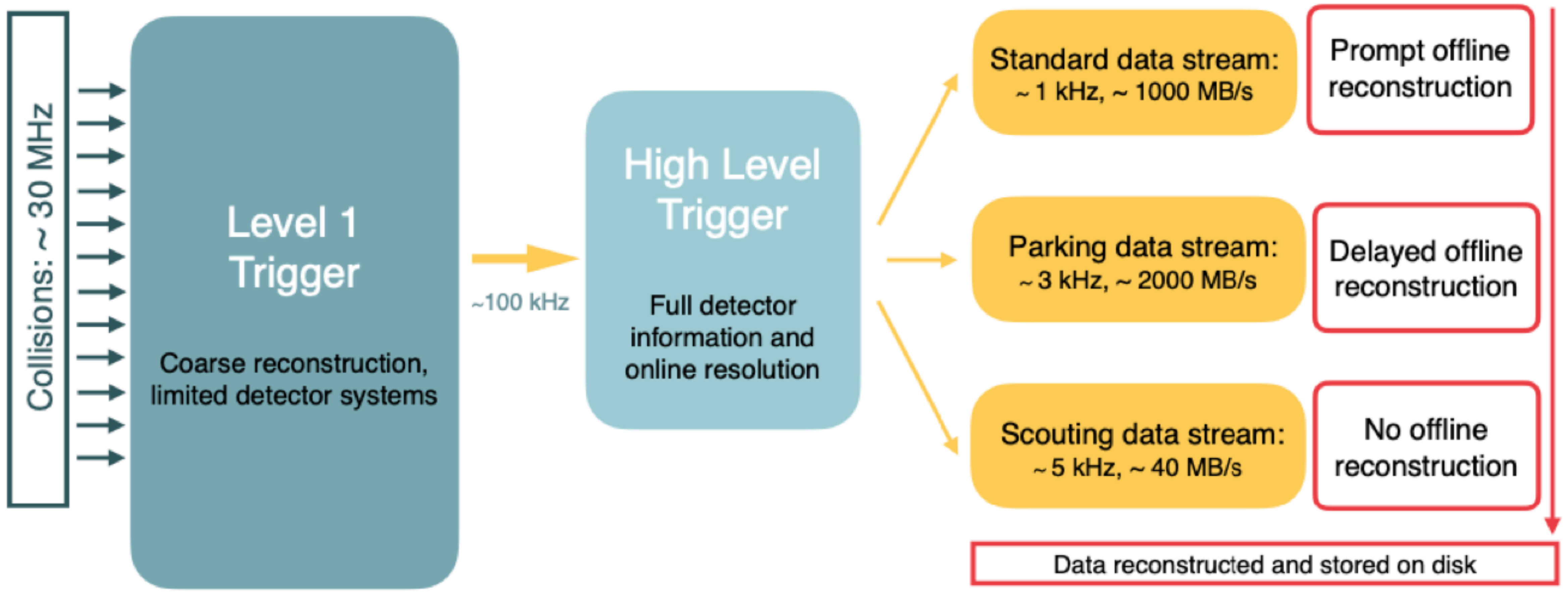
- Collection of limited resolution events at significantly higher rates than the standard L0/L1 —> reduce trigger bias enhancing sensitivity for new physics

Extremely effective for Dark Sector searchers with reduced pT thresholds and looser constraints

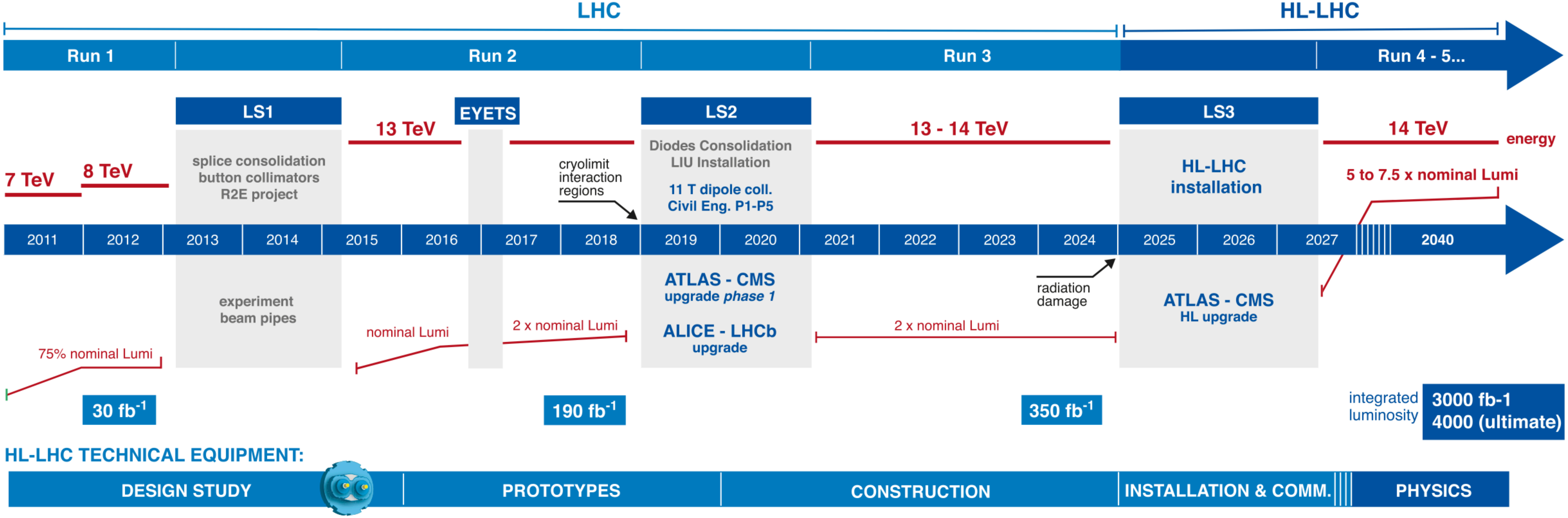




At least two muons with pt > 4 GeV and no mass requirement



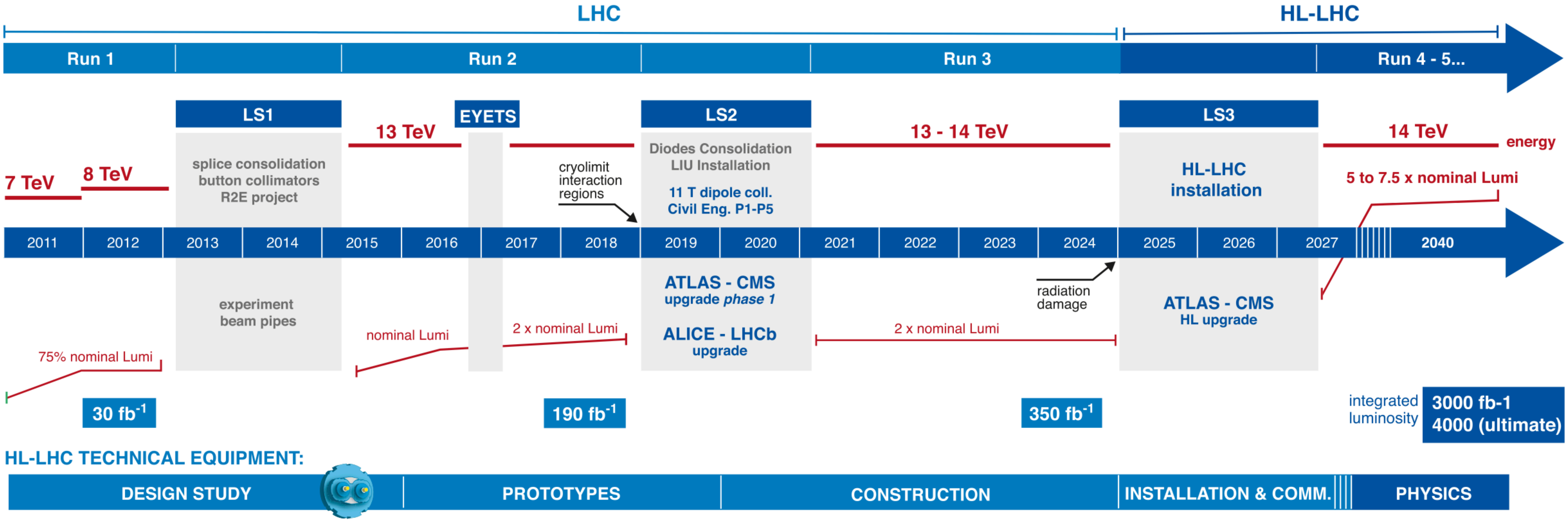
Road to HL-LHC



High-Luminosity LHC: 2029 and beyond

- Deliver up to 4000 fb^{-1} integrated luminosity at 14 TeV
- Increase in instantaneous luminosities up to $L \simeq 7.5\times10^{34}$ cm^{-2} s^{-1} (Run-2 ~ $2x10^{34}$)
- Pile-up $<\mu>$ = 200 interactions per bunch crossing (Run-2 ~ 20-60)

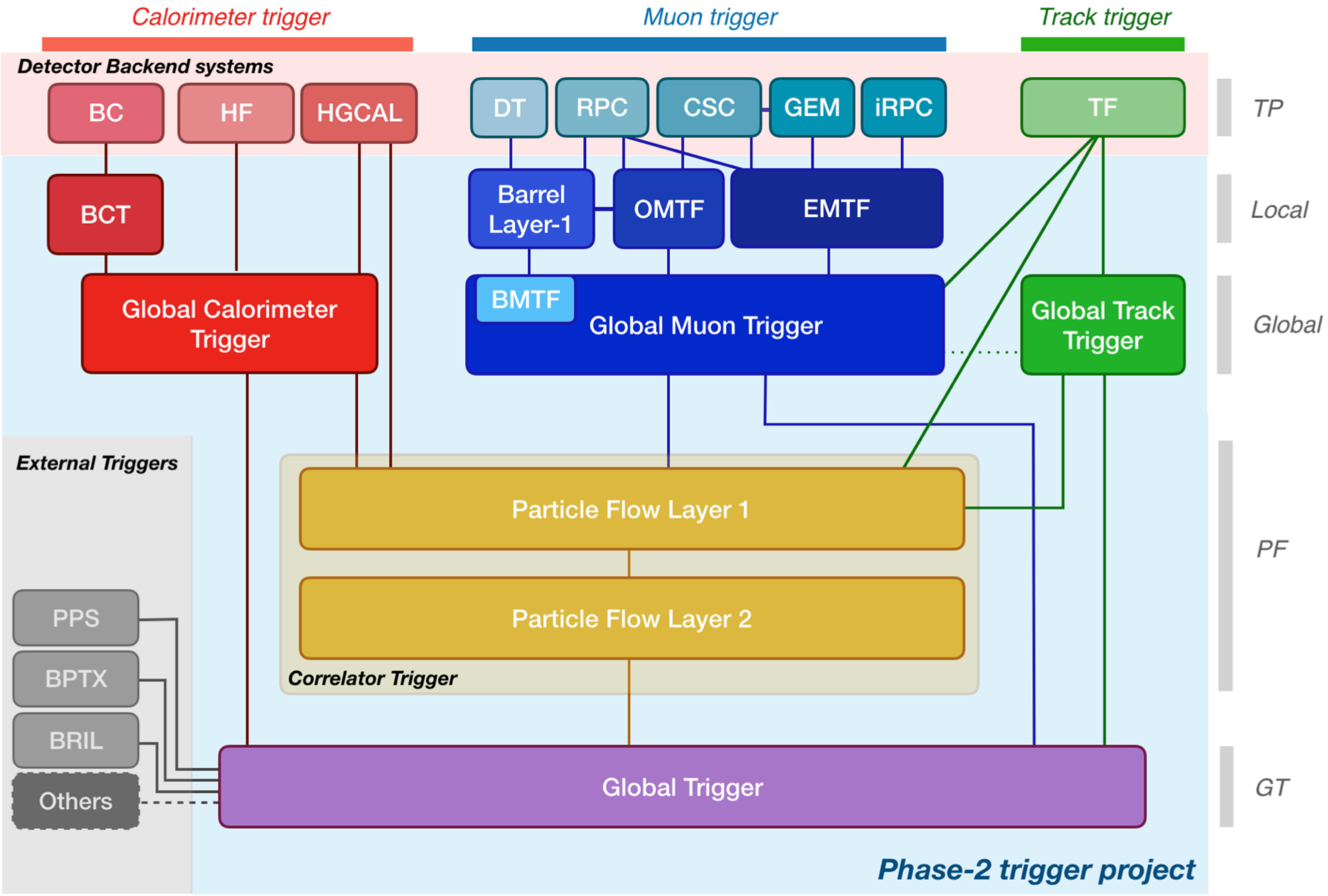
Road to HL-LHC



What does a **μ ~ 200** mean in terms of a detector requirement in HL-LHC to maintain similar performance:

- Larger event sizes —> more collisions per bunch crossing, many more tracks, …
- Higher detector occupancy —> need a detector with higher granularity
- Higher trigger rates —> redesign of our trigger architecture and readout system
- Increasing reconstruction complexity —> Run more complex software online
- High radiation environment —> need silicon with higher tolerances

CMS TDAQ@HL-LHC



L1:

- Custom FPGA hardware
- All detectors (but silicon-pixel) provide inputs: **tracks!**
- Data reduction **40 MHz —> 750 kHz** (100 kHz@Run3) w/ 12.5 us (3.8 us@Run3) latency

Correlator trigger:

- Information from subsystems combined in an offline-like fashion
- **Particle Flow**, PU mitigation; ubiquitous usage of ML

HLT:

- Farm of servers with CPUs and GPUs
- Data reduction **750 kHz —> 7.5 kHz** (1 kHz@Run3)

ATLAS TDAQ@HL-LHC

Hardware based L0 trigger:

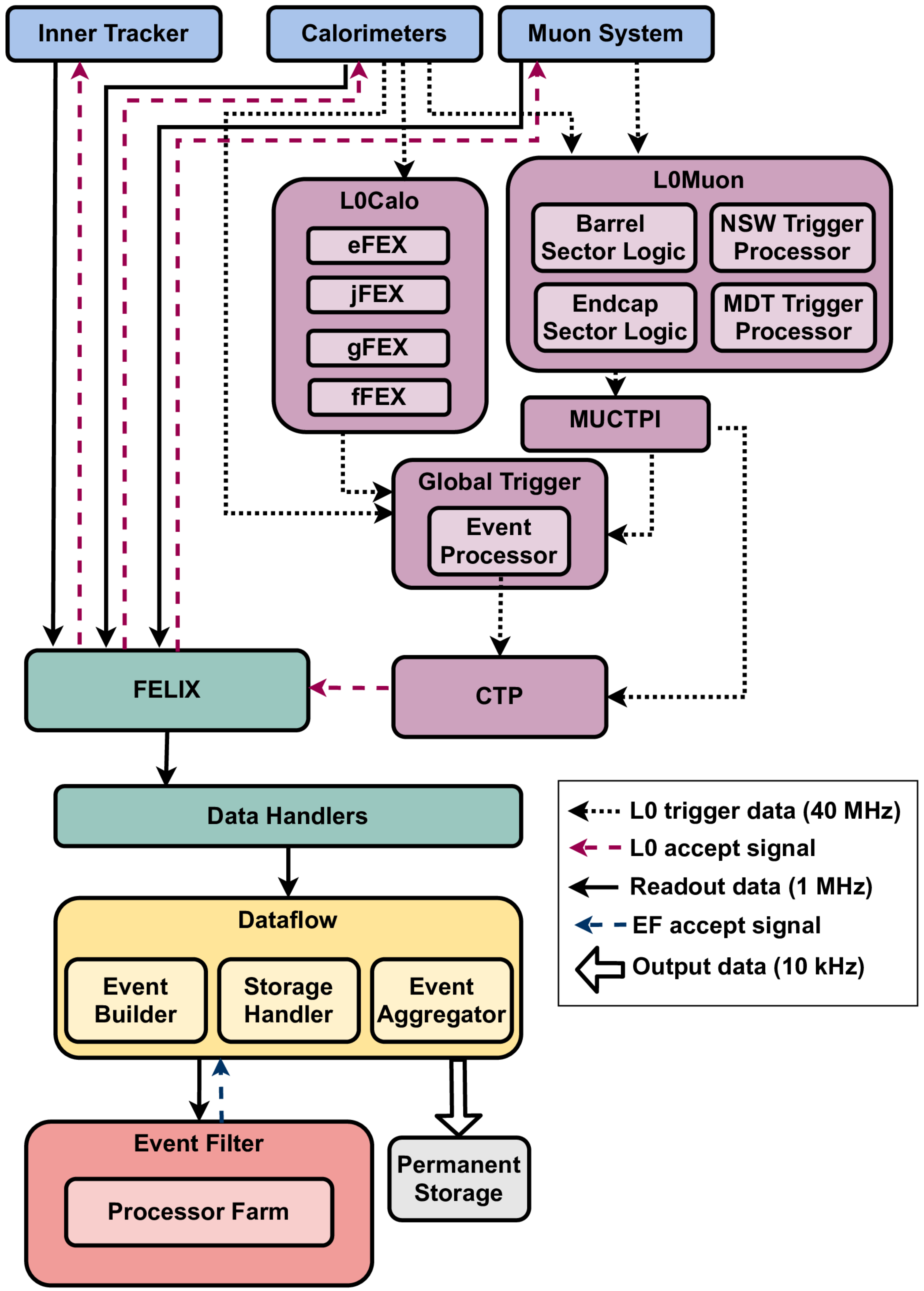
- Inputs from Calo and Muon
- Identifies physics object and calculates event-level quantities: L0 accept decision
- Data reduction **40 MHz —> 1 MHz** (100 kHz@Run3) w/ 10 us (2.4 us@Run3) latency

DAQ:

- Readout and **dataflow with full granularity** (offline-like reconstruction) @**1 MHz**

Software Based Event Filter:

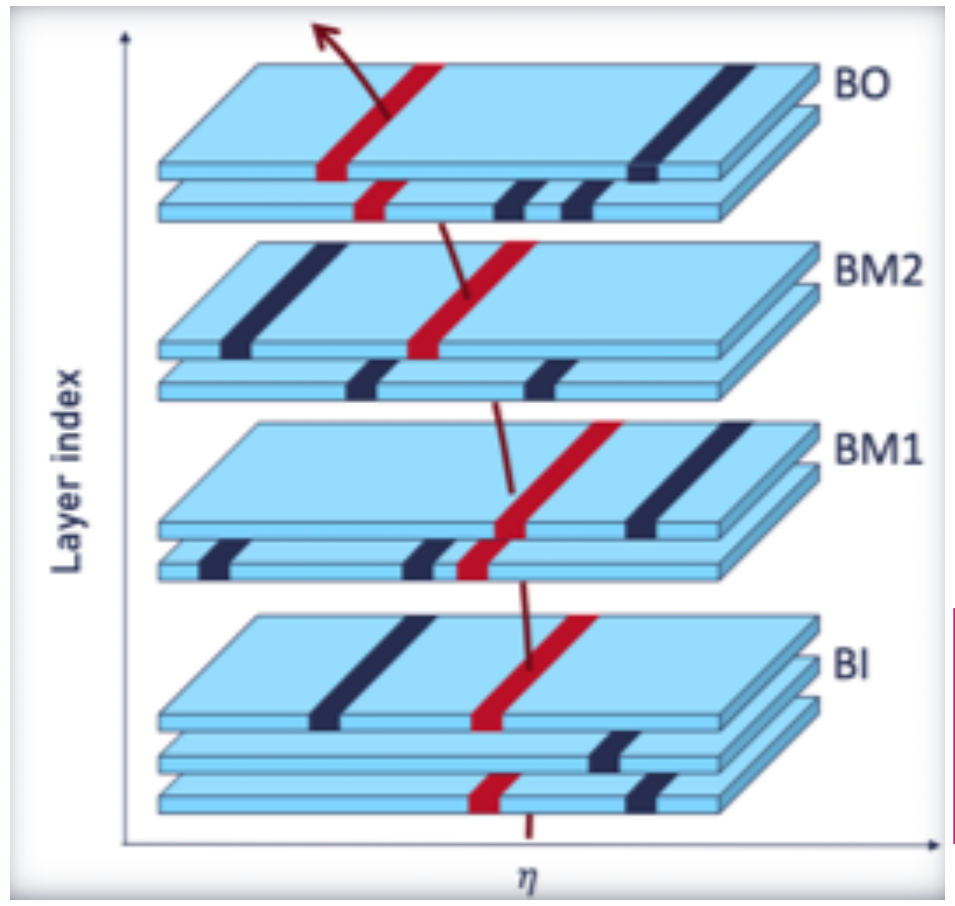
- Data reduction **1 MHz —> 10 kHz** (3 kHz@Run3)
- Multiple types of computational units CPU+GPU/FPGA
- Running event reconstruction algorithm



MS pattern recognition

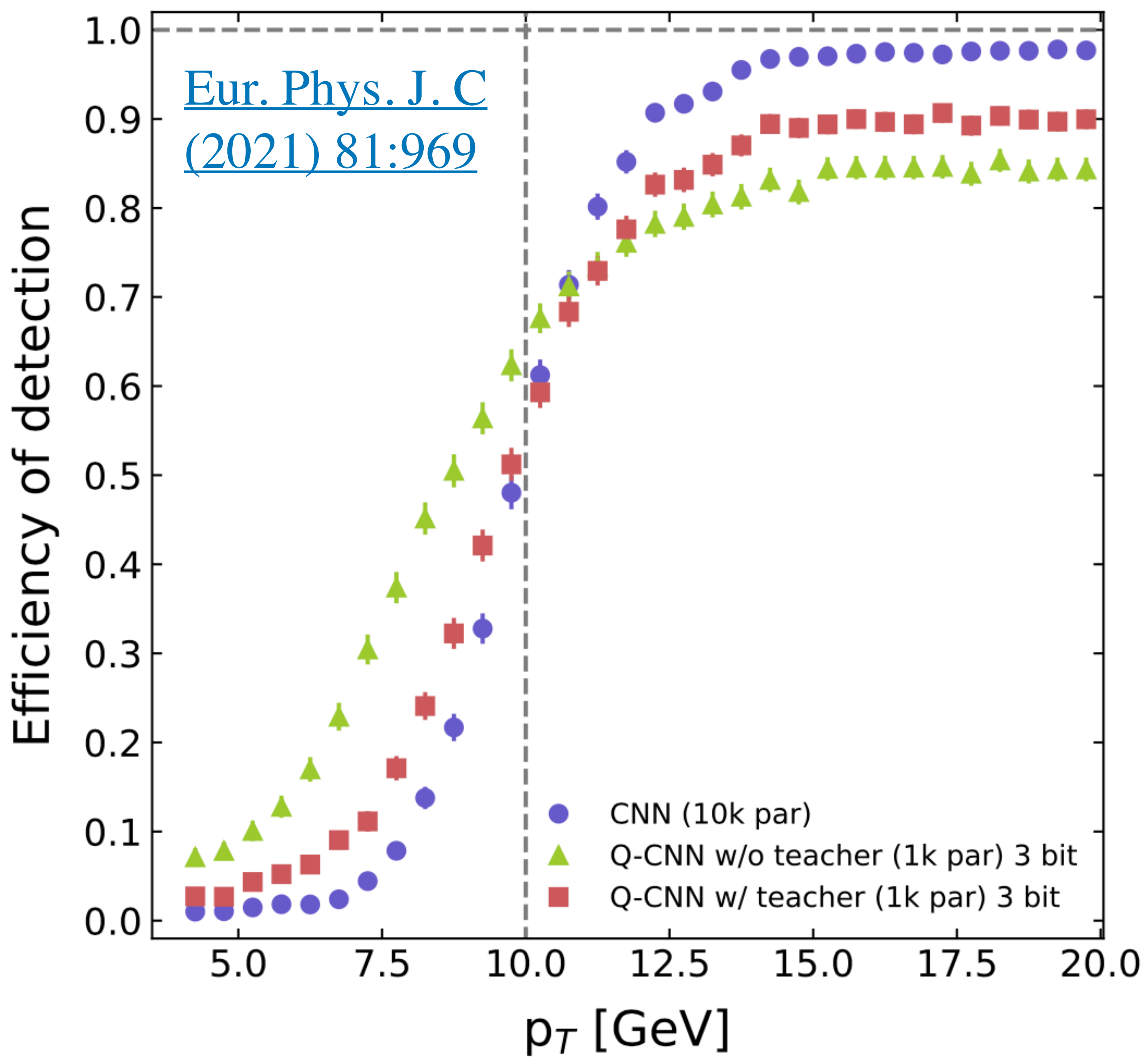
A ultra-fast (<**400ns/inference**) NN for identification of muonic particles in the muon spectrometer of the ATLAS detector at the LHC

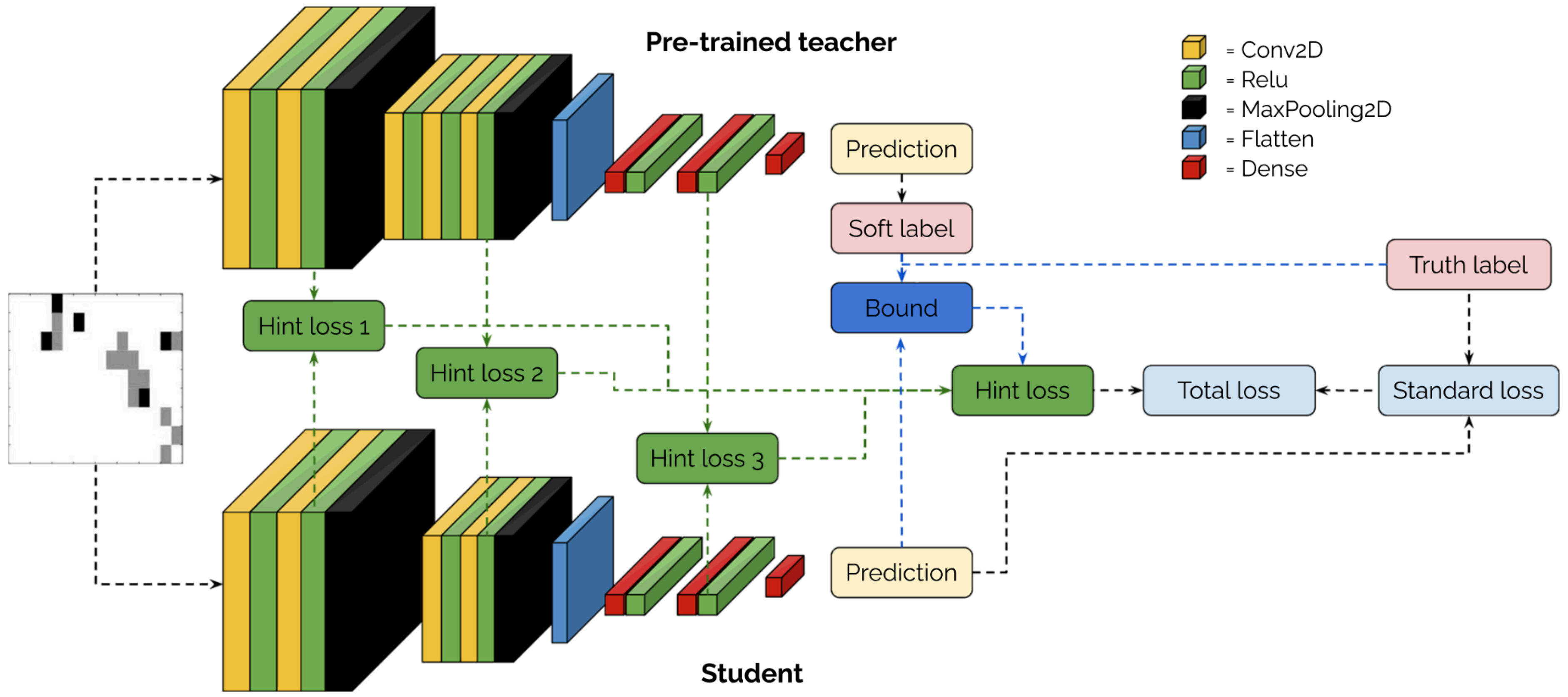
- Precise pT measurement and secondary vertexing already at L0
- Multi-stage **CNN model compression** and simplification based on **aggressive quantisation** and **knowledge transfer techniques** to avoid degradation of physics performances

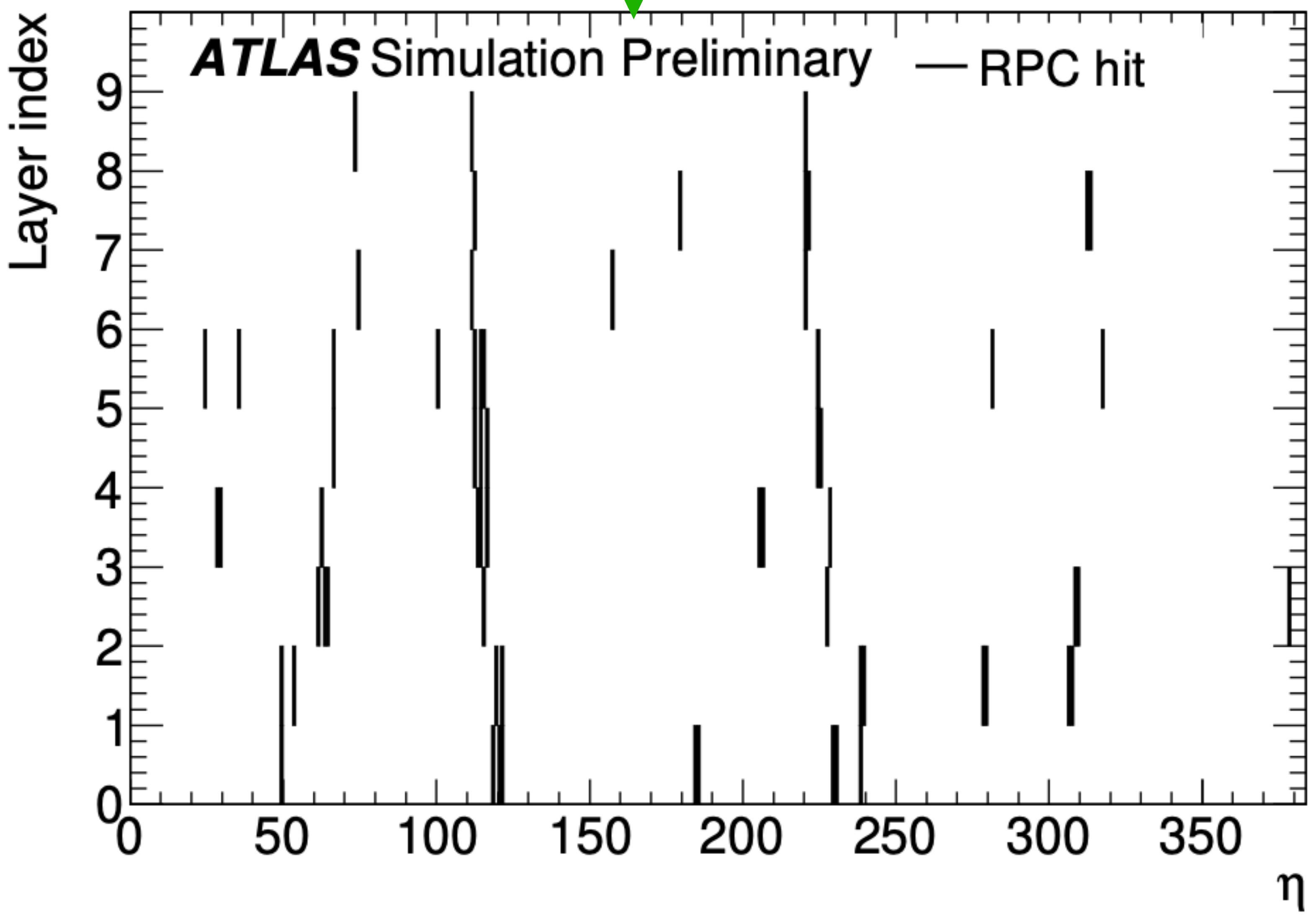


new 'BI' RPC trigger planes

Signals from RPC mapped to images, which can be processed by a CNN





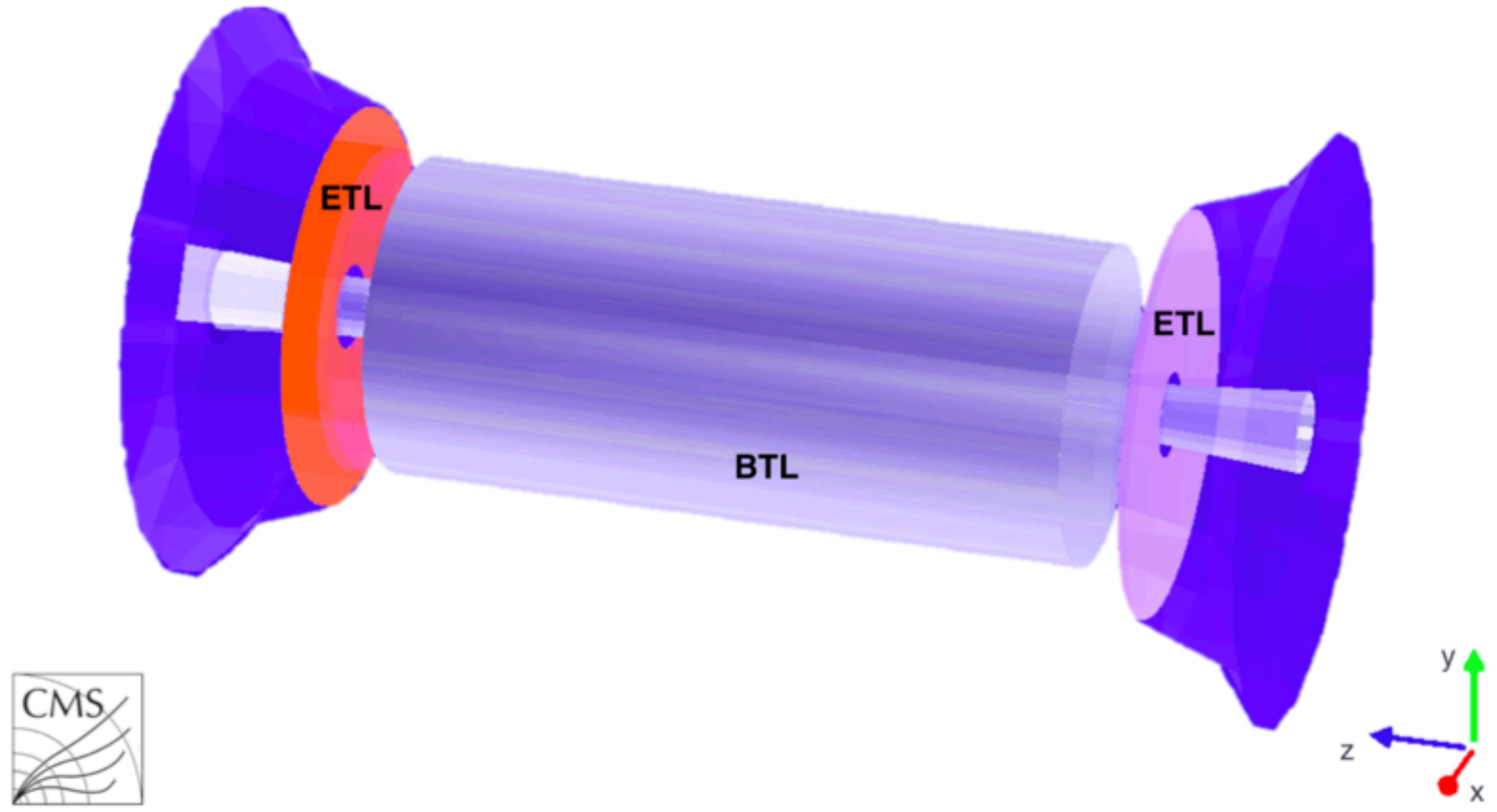


Precision Timing

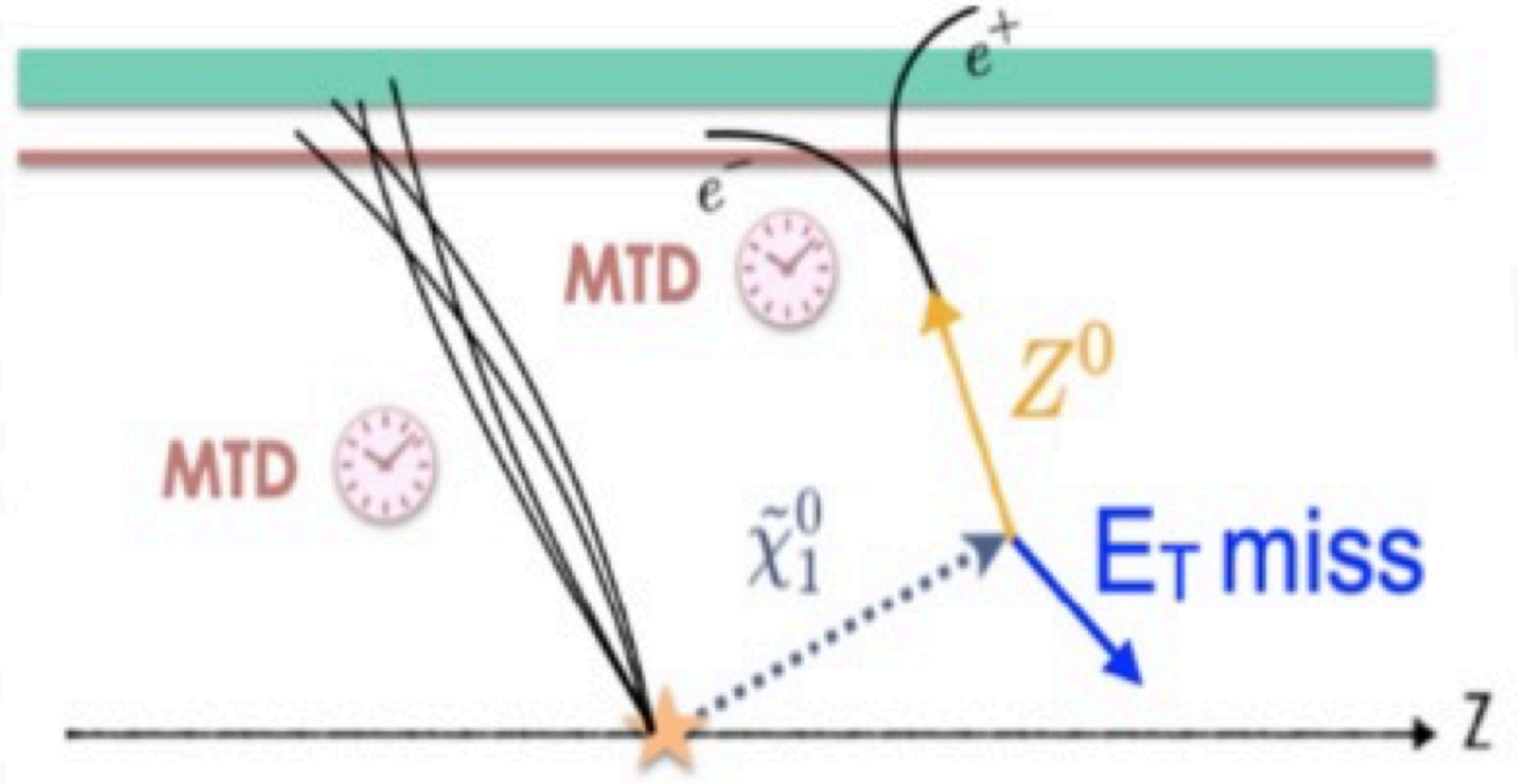
If one can trigger on a delayed signature, the efficiency could be improved by more than an order of magnitude

Exploit timing at trigger level:

- particle ID and combine with dE/dx to help improve Heavy Stable Charged Particles searches
- Look for mismatch between time-based and momentum-based mass reconstruction
- Delayed jets and delayed photons



Per-particle timing —> 4D tracking



Thin layers between tracker and calorimeters:

- MIP sensitivity with 30ps time resolution
- Hermetic coverage for $|\eta|<3.0$

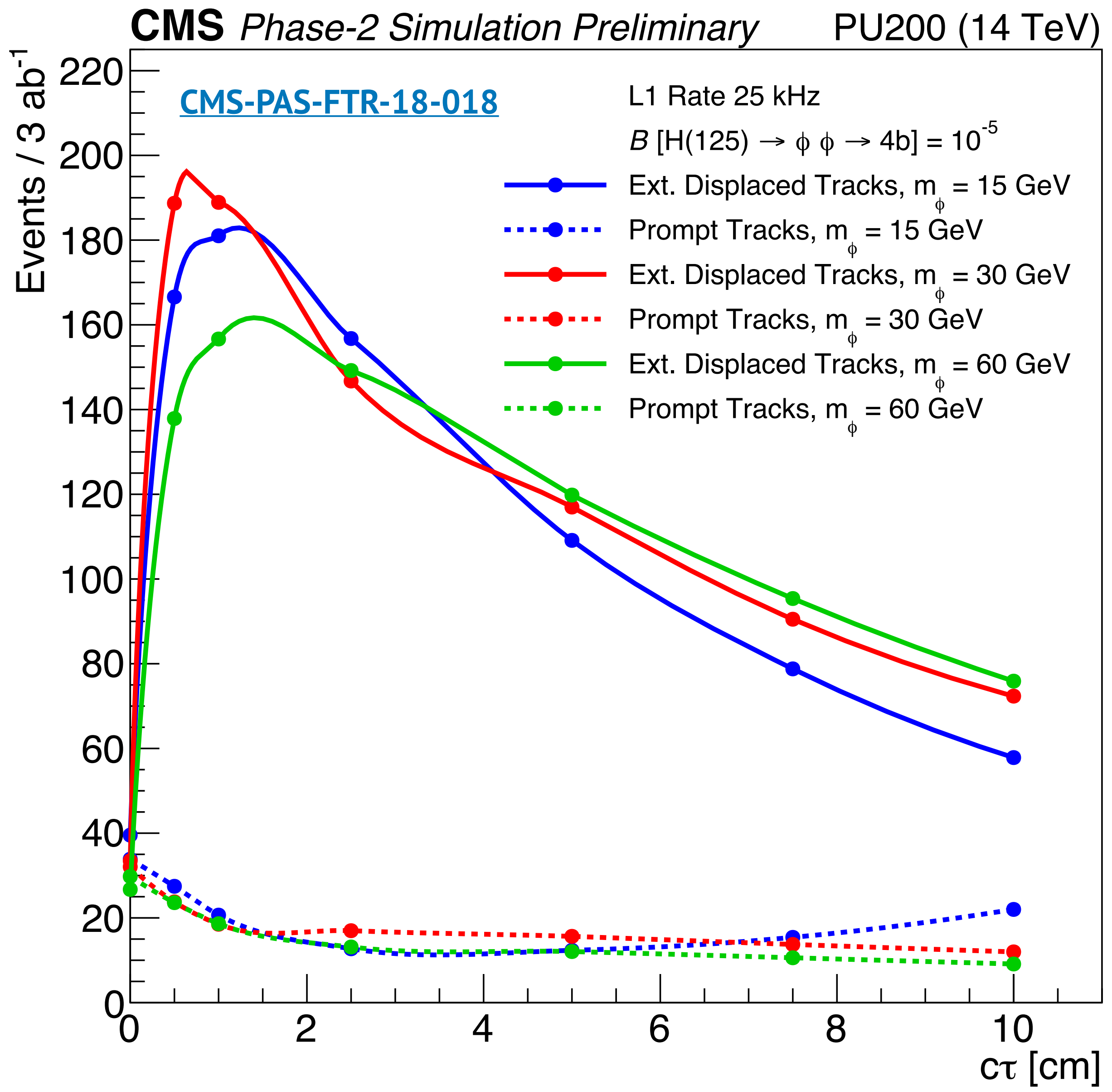
Great benefit for displaced vertex reconstruction and LLP tagging

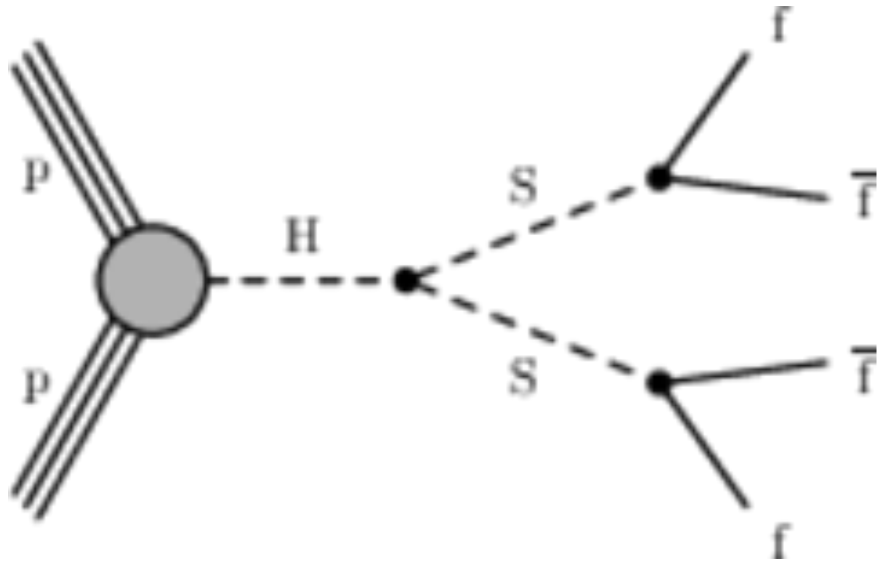
L0/L1 Tracks

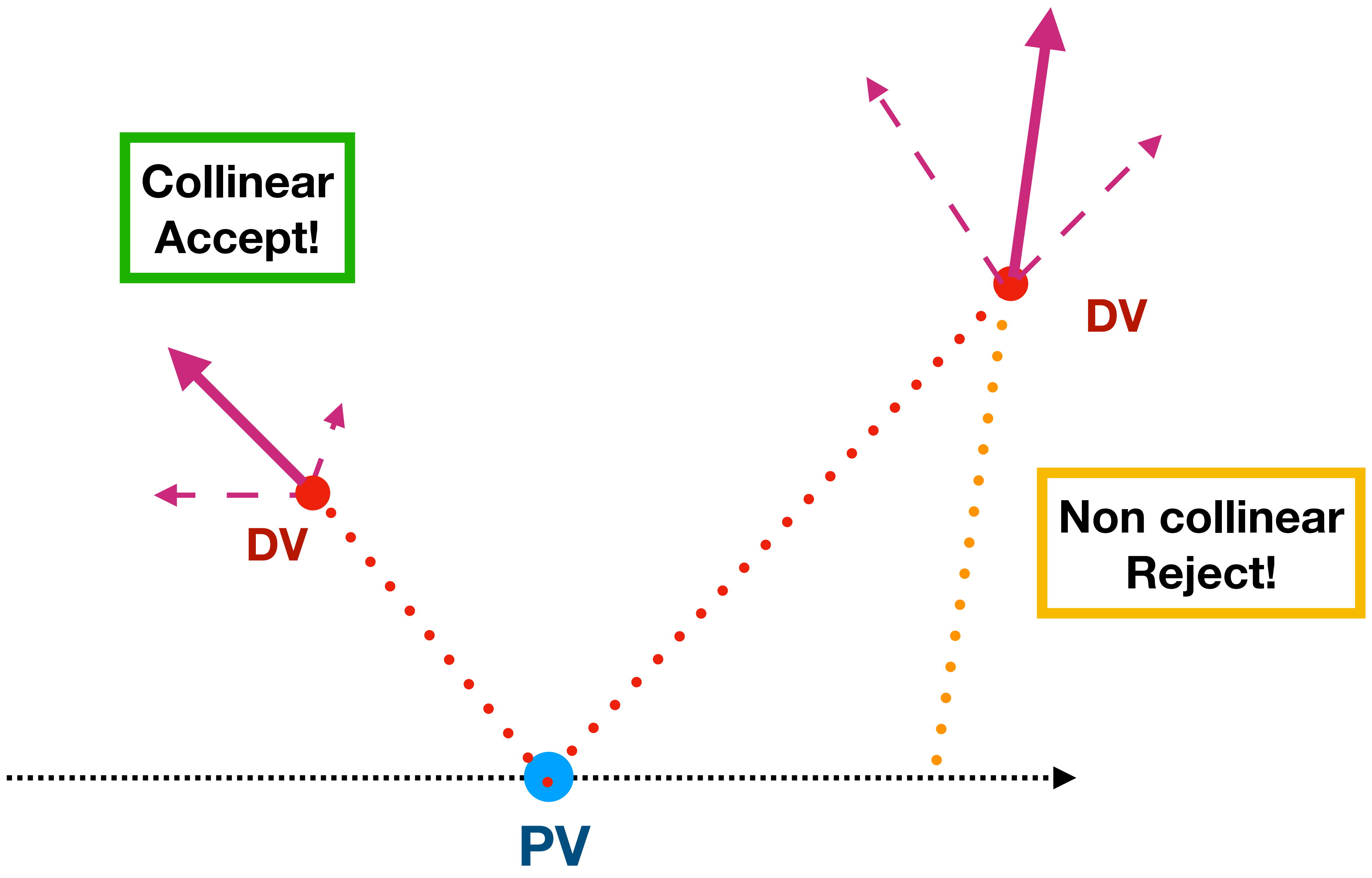
Maintain high efficiency and keep rates under control for L1 objects —> L1 track finding and fitting perfect for LLP

Build track objects from full tracker system: jets, PV, vertices, H_T

- **2-track vertexing** to get a rough idea of where the secondary vertex is from the track parameters: is it a good vertex? If it's close to each track's d0 & z0: keep the vertex, else discard it.
- **Track Jet** Trigger for Displaced Jets





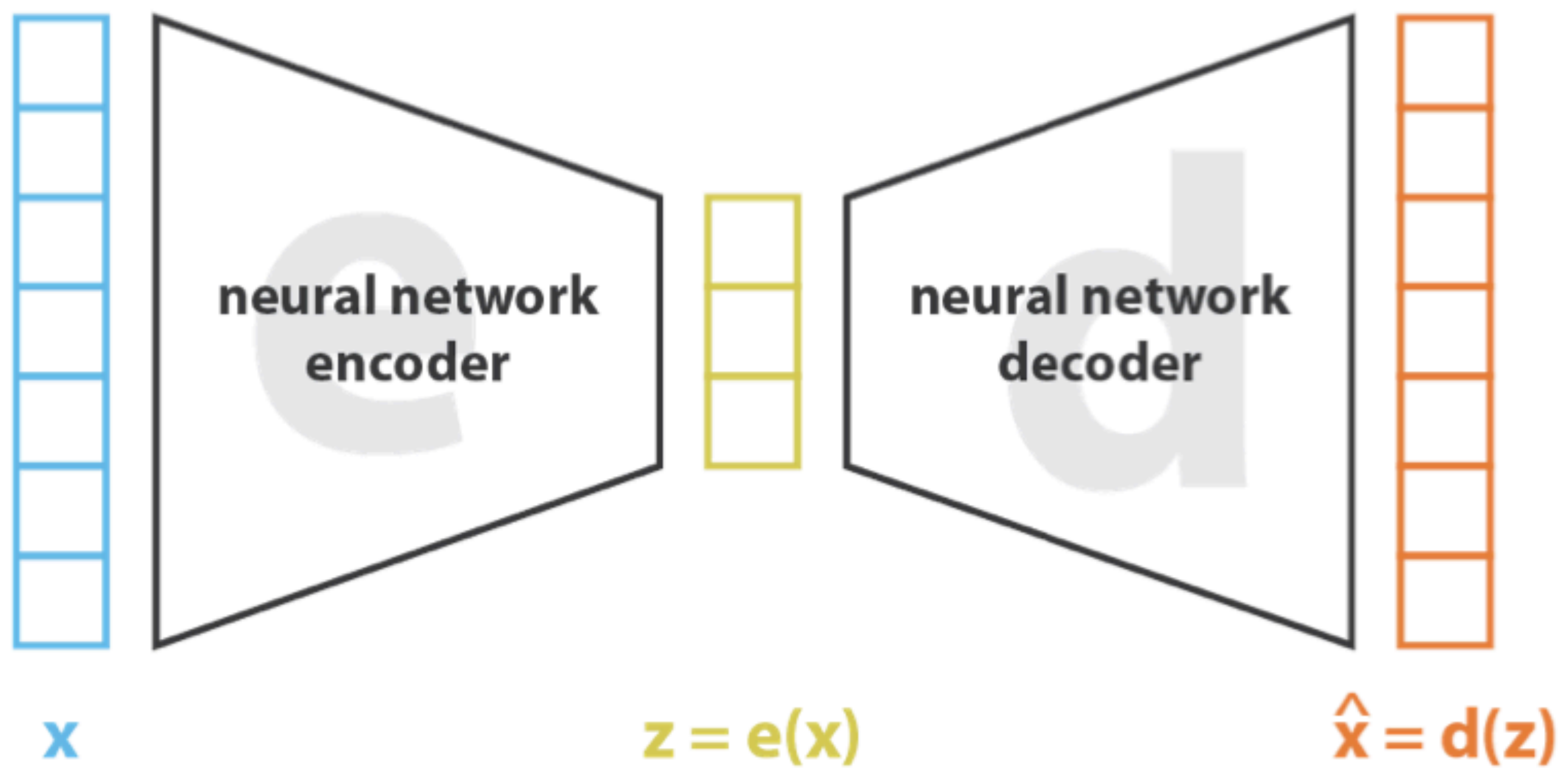


is the vector pointing from the PV to the DV parallel to the vector sum of the decay-particle's momentum?

AD triggers

Normal trigger selections compare the event particles to a table of rules —> Could these selections reject the New Physics we'd like to see?

- Exploit autoencoders on FPGAs for microsecond period inferencing
- Isolate any type of anomalous event
- Motivate new searches with low or zero trigger acceptance
- Variational autoencoders for dark jets using track information



Process each collision every 25 ns with an AD algorithm

Is it anomalous?

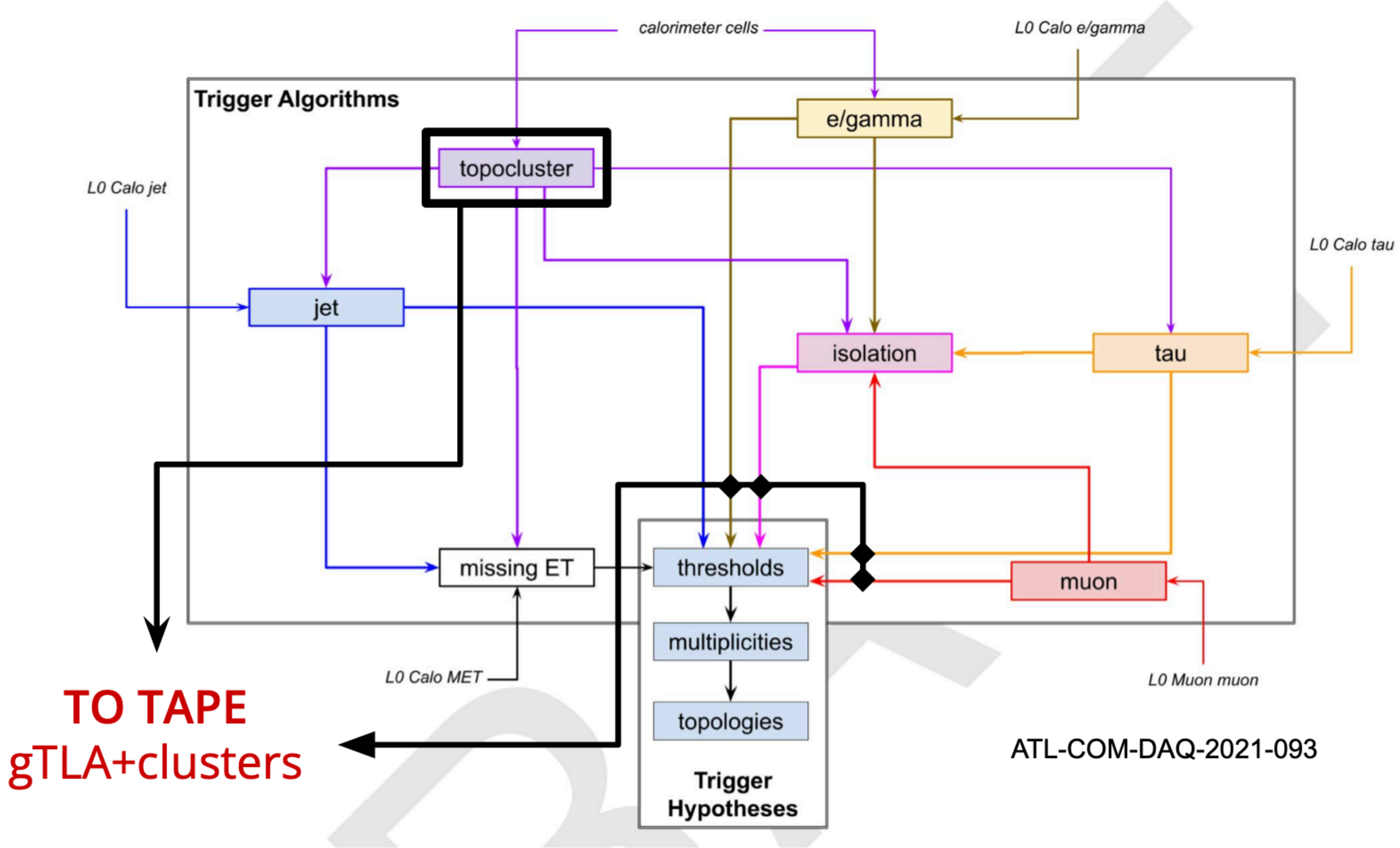
YES!
Could be a hint of a so far unimagined process

Real time analysis

(aka how to take decision fast and efficiently)

ATLAS/CMS produce more data than we can handle: trigger's challenge is to keep interesting physics

- Real-time decisions for what to keep built on FPGA —> microsecond latency constraints @ 40 MHz
- Enables searches that would otherwise have been impossible due to trigger constraints
- Develop AI based event selection for ultra-fast inference with extreme sparse data and heavily compressed and quantised neural network models
- **Ideal Scenario:** Stream global trigger reco to tape
    - if clusters can be saved for every event, a true Trigger-Less Analysis in the Calorimeter becomes possible



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Conclusions

LLPs are an exciting avenue to search for BSM physics and vital to have triggers that are sensitive to these unique decays :

- The HL-LHC will increase the statistics for all physics searches, but also produce more complicated events due to increased pileup
- Upgrades allow reconstruction of more sophisticated, offline-like, objects to improve triggering
- Track trigger and precision timing are game changers, with large gains in acceptance at light LLPs
- Need to anticipate challenges: let’s prepare well for the next Run and design new amazing triggers

Let’s make Run-4 LLP friendly!

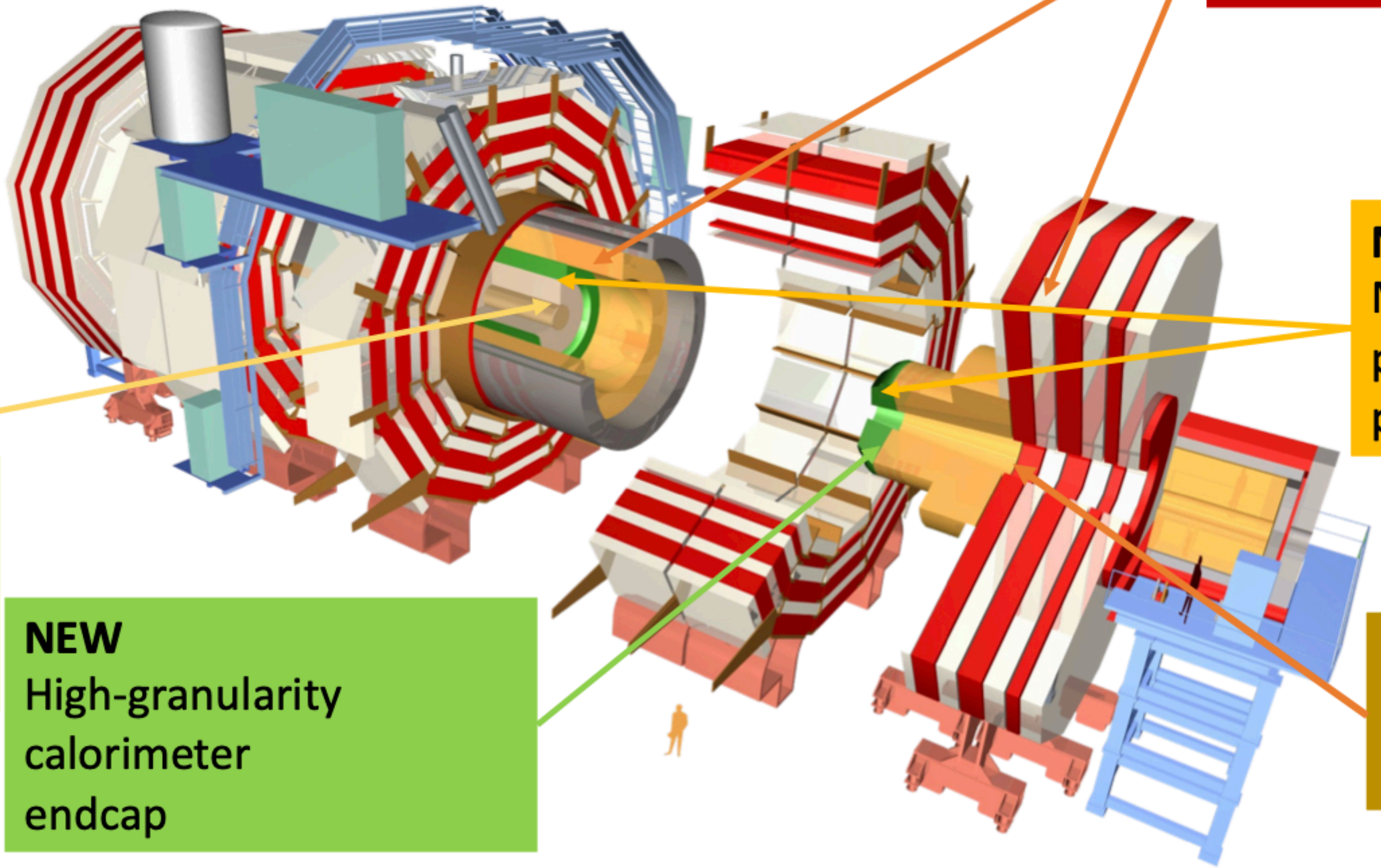
CMS upgrade in a nutshell

Trigger requirements are driving most of the electronics upgrades

Upgraded Trigger and Data Acquisition system:

- Tracking in L1 at 40 MHz. Output rate 750 kHz.
- Latency 12.5 μs, longer pipelines.
- High Level Trigger output 7.5 kHz

Electronics upgrade: Barrel Calorimeter and muon system



NEW
MIP Timing detector precision timing for pileup mitigation

NEW
Inner Tracker, coverage up to |η|= 3.8, reduced material

NEW
High-granularity calorimeter endcap

NEW
Muon detector
GEM/RPC 1.6<η<2.4

Challenge: **cold operation**
→ bi-phase CO_2 cooling at −35° C

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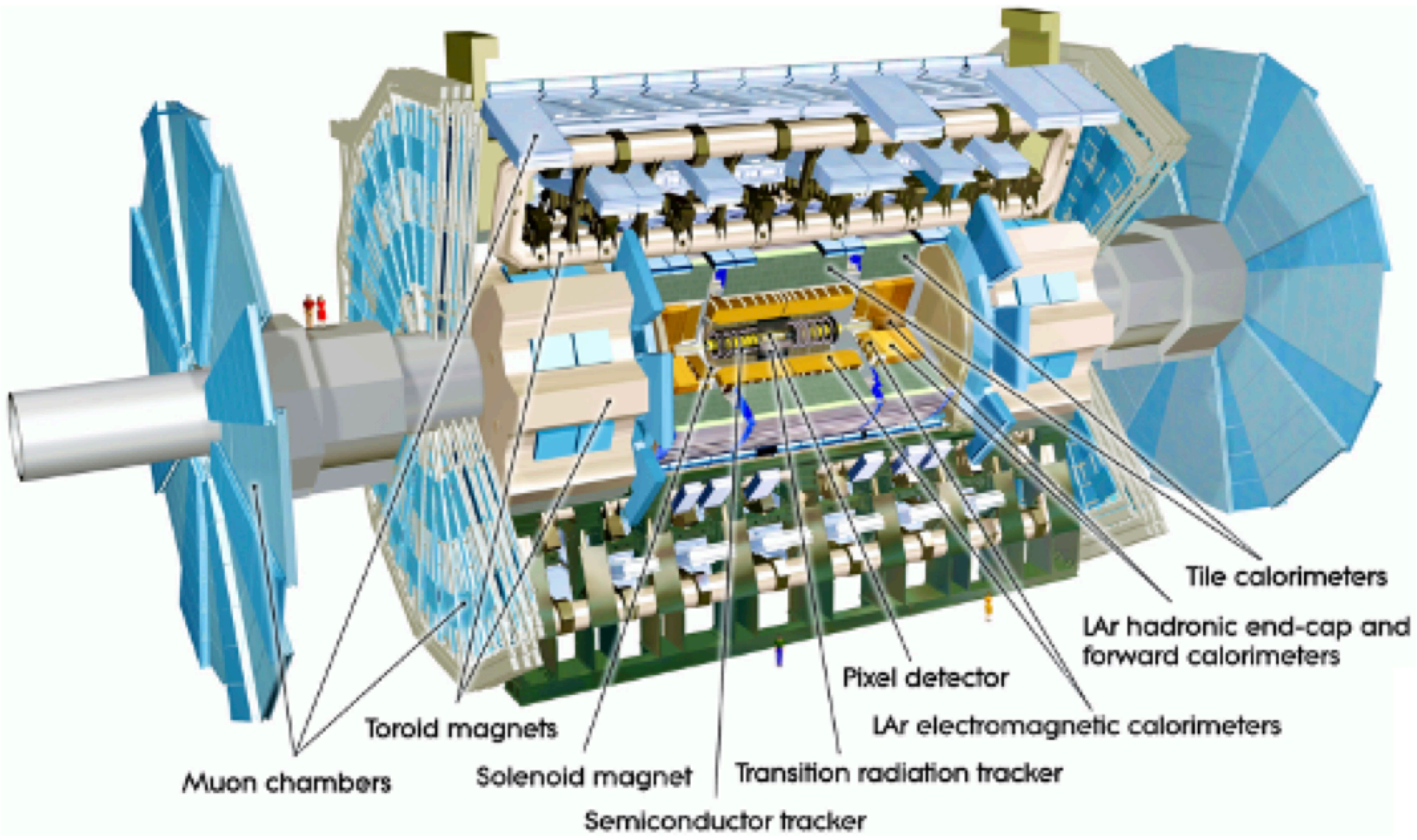
ATLAS upgrade in a nutshell



- **Upgraded Trigger and Data Acquisition system**
  - Improved Level-0 Trigger (1 MHz)
  - Improved High-Level Trigger

- **Electronics Upgrades**
  - LAr Calorimeter
  - Tile Calorimeter
  - Muon system

New High Granularity Timing Detector (HGTD)

- Forward region ($2.4 < |\eta| < 4.0$)
- Low-Gain Avalanche Detectors (LGAD) with 30 ps time resolution
- Luminosity measurement

- **New Muon Chambers**
  - Inner barrel region with new RPC (trigger) and sMDT (precision) detectors

- **New Inner Tracking Detector (ITk)**
  - All silicon, up to $|\eta| = 4$
  - Two subsystems: Pixel (inner layers) and Strip
  - Higher granularity for pileup rejection: 50x50 μm^2 pixels

Additional small upgrades

- Luminosity detectors (1% precision goal)
- HL-ZDC