TIMING LAYERS FOR CLIC

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CLIC ANALYSIS MEETING

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(submitted as Snowmass21 LOI & JHEP)

High granularity analog calorimetry

- All future HEP detectors will use “5D” design (position, energy, time)
- Baseline for ILC, CLIC, FCC-ee is ***analog high-granularity*** calorimeter
  - $5x5\ mm^2$ cells ECAL (Si/W), $3x3\ cm^2$ HCAL with SiPMT/scintillators
- FCC-hh/HE-LHC baseline is also ***analog high-granularity*** calorimeter:
  - large dynamic range MeV – TeV per channel (10^4 range)
  - up to 50 M channels assuming $5x5\ cm^2$ HCAL cells (baseline)
- High-precision timing with tens-of-ps resolution for time-of-flight (TOF) ?

Benefits of using timing layers

- **All experiments:**
  - Particle ID from TOF
  - PFO reconstruction: Reducing confusion term (mis-matching of energy depositions and particles)
  - Identification of BSM long-lived particle for new physics
  - Physics objects reconstruction, lepton isolation, b-tagging, etc.
- **CLIC:**
  - Background rejection (coherent and coherence e+e- production)
  - ~500 ps
- **FCC, HE-LHC**
  - Pileup rejection → significant impact when using ~20 ps

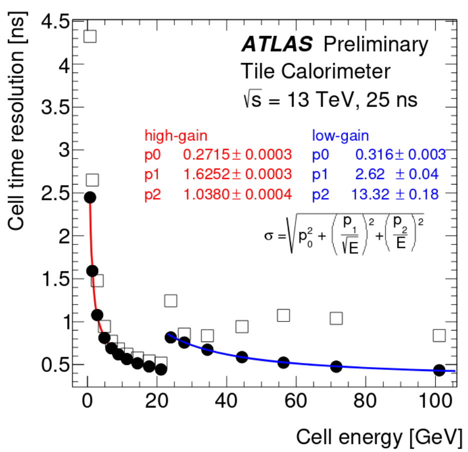
From the CPAD report: https://arxiv.org/pdf/1908.00194.pdf

Section: 4.1.5 Critical Needs

- Picosecond time resolution **???!**
- Modern image processing technology, both hardware (GPUs) and software (image processing and deep learning)
- Low-cost, high-light-yield, fast and radiation-tolerant .. scintillators
- Advances in Silicon Photomultiplier (SiPM) technology. Improved UV detection, larger dynamic range though smaller pixels, direct coupling to, or integration with readout electronics
- Low-cost radiation-tolerant electro-optical transceivers at ~10 Gbps or more.
- Continued development of GEANT..

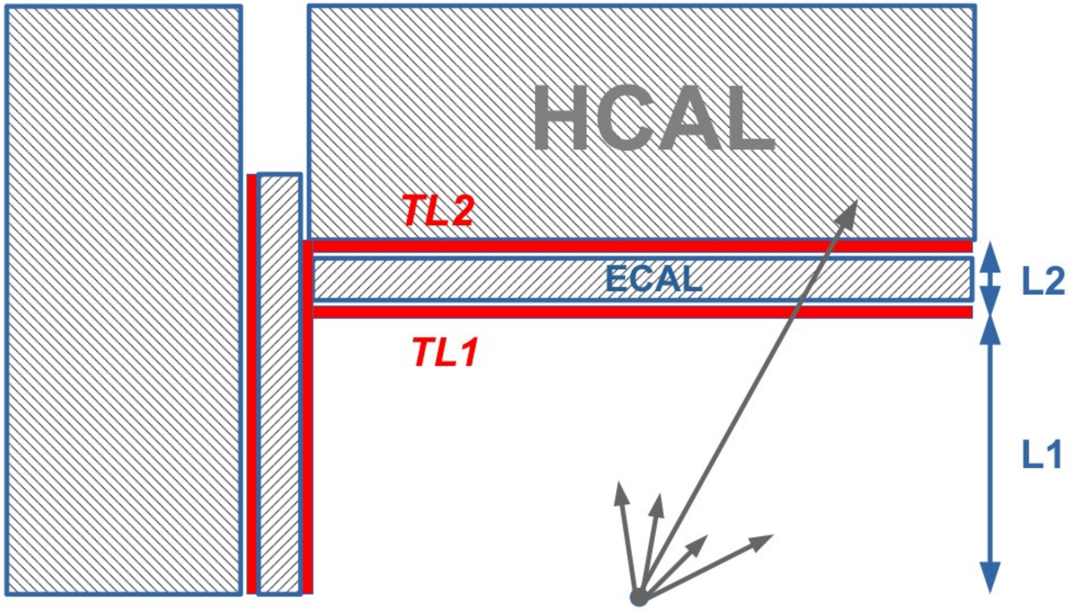
~1 ns is baseline for CLIC/FCC calorimeters (technology / price)

1 ns is NOT a technological challenge:
Time resolution for TileCal (ATLAS) is already ~0.4 - 2 ns (jets) → designed 20 years ago



Timing layers (generic design)

Instead of designing ECAL/HCAL with ~10 ps capabilities for all cells, add **timing layers (TL)** for high-precision timing measurement



Timing layers is not a new idea in general considering the High-Granularity Timing Detector HGTD project in ATLAS with 30 ps resolution.

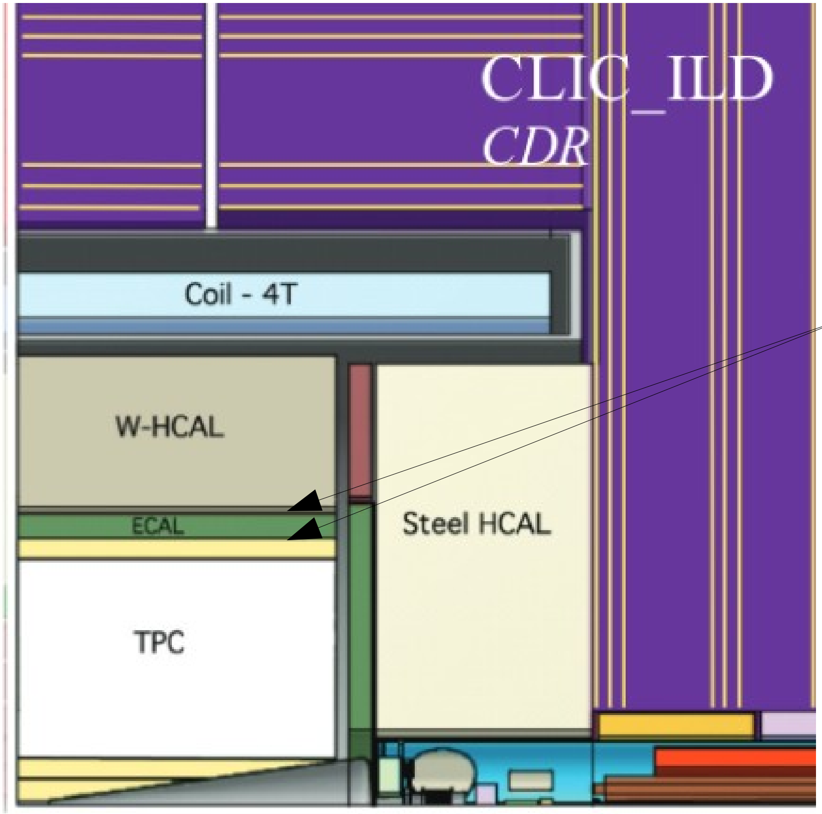
Future detectors can extend it to the full coverage (including the barrel region)

Position of TL1 is similar to "preshower" detectors for CDF, ATLAS and ZEUS but without ps timing..
TL2 can added to measure TOF without known vertex position? (see the discussion)

Timing detector (TLs) for post-LHC experiments (HE-LHC, CLIC, FCC-ee, FCC-hh, ILC etc)

- TLs can drastically reduce the price of future detectors keeping ECAL/HCAL with the standard (~ 1 ns) time resolution
- May have a different granularity and readout than ECAL/HCAL
- Pick a technology best optimized for timing measurements, but not necessary energy measurements

CLIC example (can be FCC-ee, ILD, FCC-hh..)

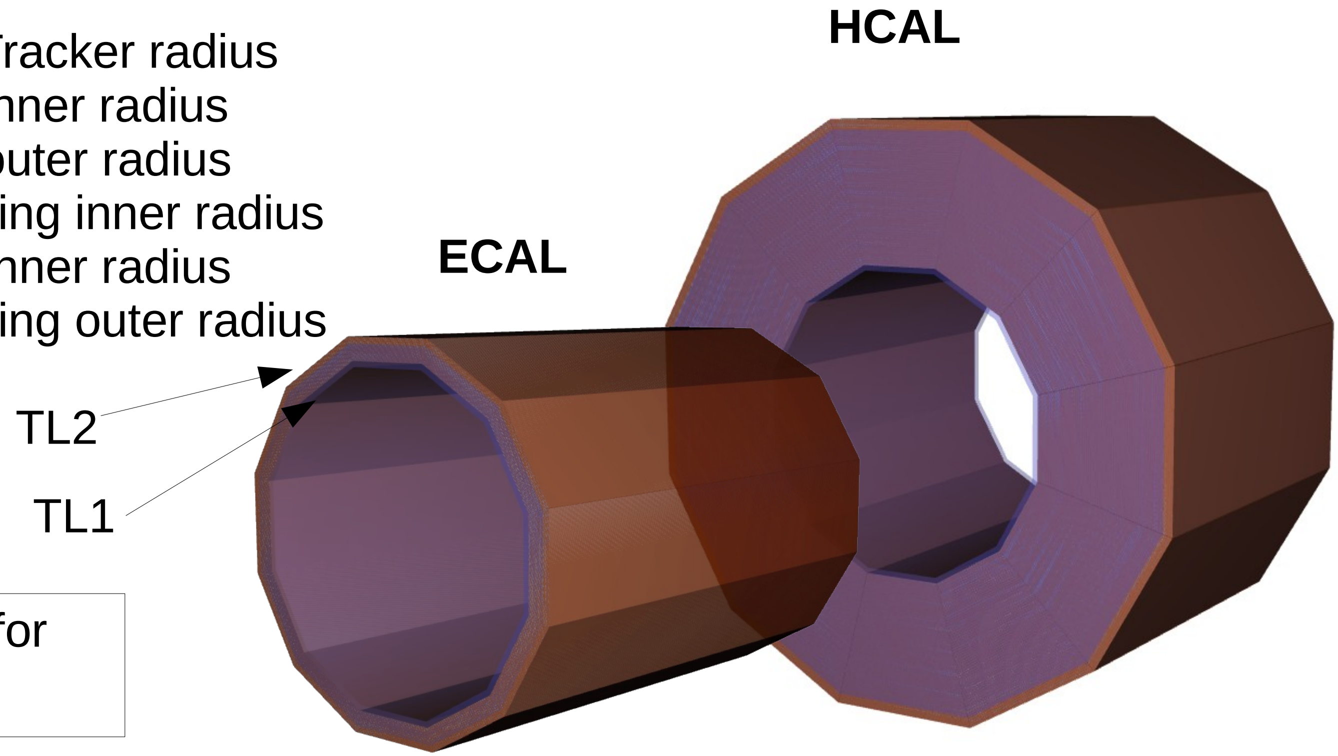


Add a dedicated TL with ~10-20 ps resolution before and after ECAL

TL1 - for 1st Silicon layer of ECAL
TL2 - for last Silicon layer of ECAL

The idea applied to CLIC o3 v13

1499*mm - Outer Tracker radius
1500*mm - ECAL inner radius
1702*mm - ECAL outer radius
1738*mm - HCAL ring inner radius
1740*mm - HCAL inner radius
3330*mm - HCAL ring outer radius



Time-of-flight (TOF) for L=0.2 m is **667 ps**

Notes:

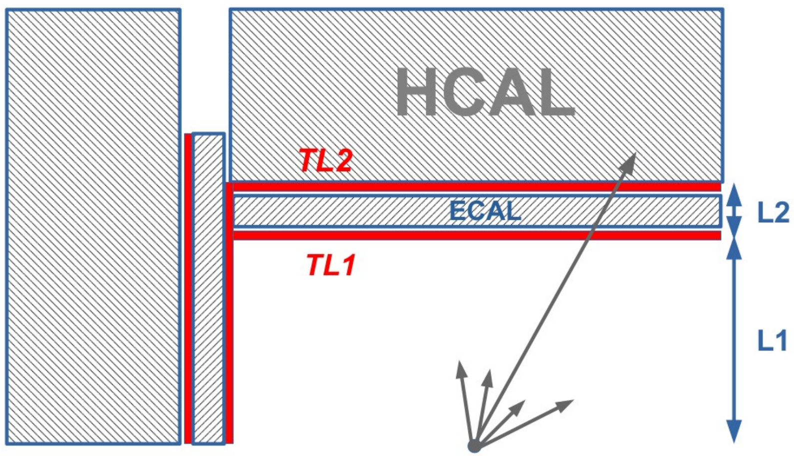
- Calorimeter with ~1 ns readout resolution is not sufficient to measure TOF between TL2 and TL1. Need ~ 10-20 ps
- CLIC tolerance range is not large enough to fit TLs assuming the LHC style technology based on ultra fast LGAD
  - > 10 cm width per timing detector + cooling, readout

Solutions

- The timing detector should have ~10 ps resolution to measure TOF to take advantage of 2 timing layers
- Dedicated detector should have ~1 cm width to avoid major changes in the CLIC geometry (ECAL can be moved closer to the HCAL outer ring)
- When using the current LGAD technology, changes in CLIC geometry are required
- If no dedicated timing layer is used, first and layers ECAL layers should have ~10 ps timing

Do you need 2nd TL?

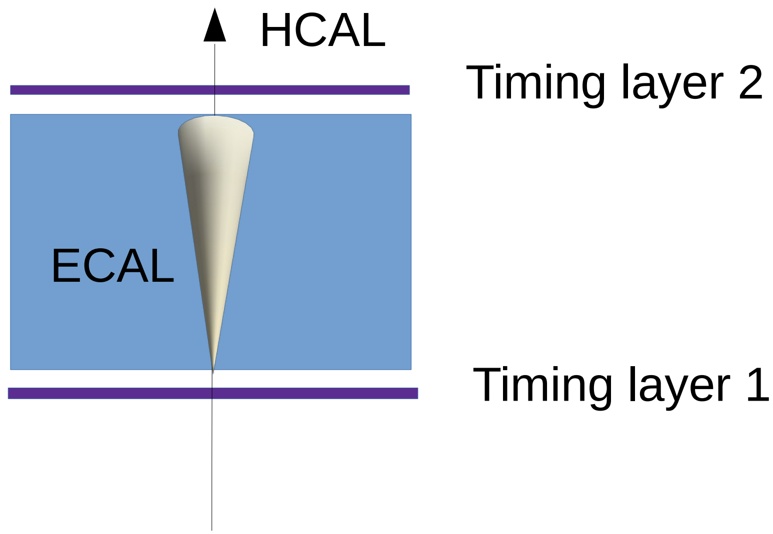
- Directional capability that will allow correlated hits with calorimeter
- Redundancy
- TOF between TL2 and TL1 (without vertex)
  - Provides acceptance to LLP that also decays to LLP → unique!
  - Standard TOF measurement when production vertex is unknown or have large uncertainty (pileup etc.).
    - Some experiments have ~200 ps uncertainty.



Can it work?

- only if EM shower propagates through ECAL with small RMS and time delays

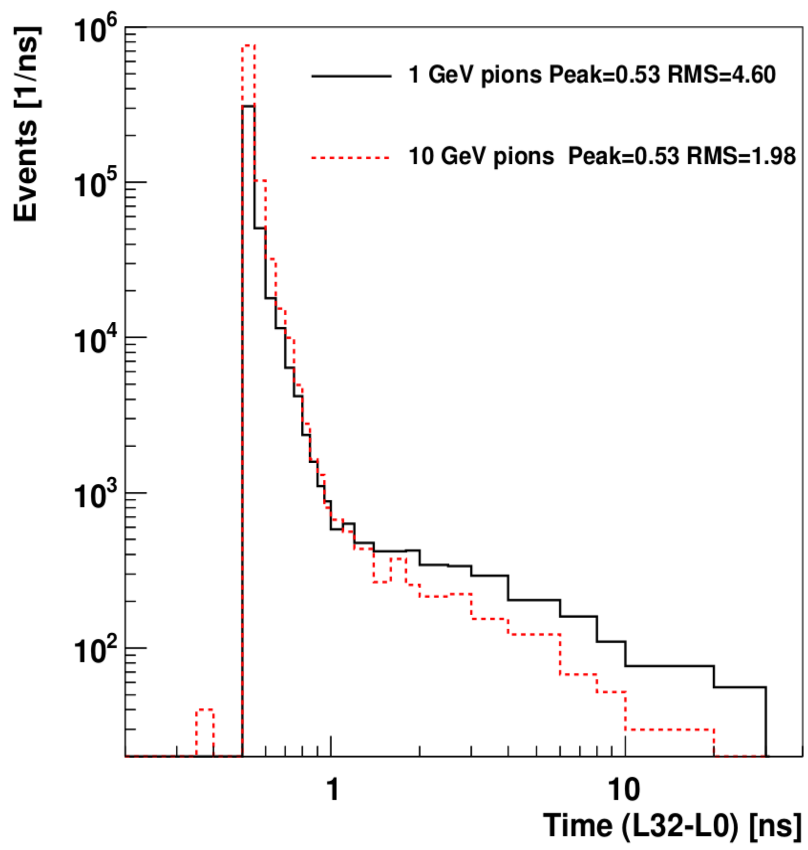
  - Need full Geant4 simulations



Full simulation studies using Geant4 (from HepSim)

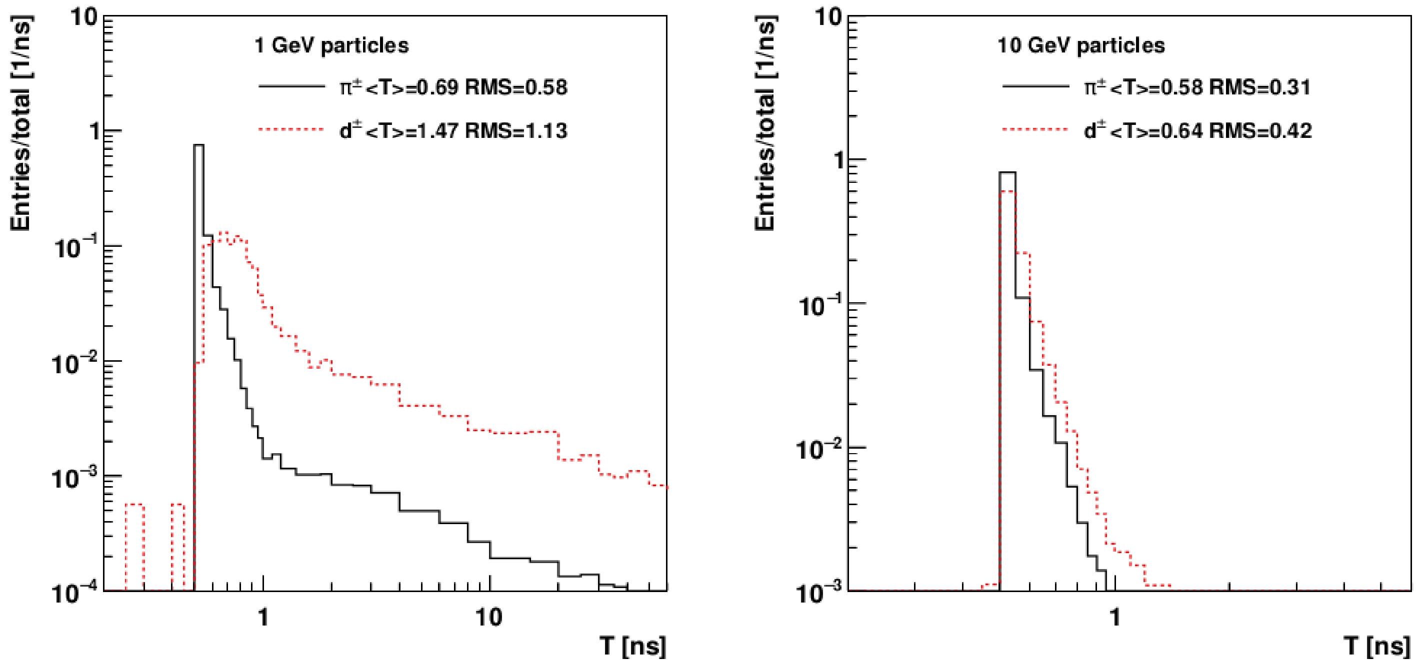
- Use Geant4 and FCC-like geometry with 32 Si/W layers:
  - 20 cm distance between TL2 and TL1
  - similar to CLIC
- Use single pion "guns" with 1 and 10 GeV
- Calculate time difference between TL2 and TL1 for first arriving hits in Si
- On average, time required for hits to propagate through ~20 cm of ECAL cells is ~0.6 ns, with RMS < 5 ns
- For standard 1 ns detector TL1 and TL2 signals is seen as instantaneous hit in both layers

TOF for pions traveling a distance between TL2 and TL1 (~0.2 m)



Can time difference between TL2 and TL1 be used for physics measurements assuming ~10 ps readout?

TOF for TL2-TL1 for deuterons. Geant4 simulations



Deuterons (m=2.04 GeV) for a proof-of-concept test:

- Heavy, well understood simulations of interaction with material
- Can be produced in e+e- interactions (coalescence models)

- TOF difference between deuterons and pions is ~200-700 ps for p~1 GeV
- Can be measured by ~ 20 ps detector

→ For BSM search:
Particles heavier than d± can be separated for p > 1 GeV

Showcase

Semi-analytical approach for TOF

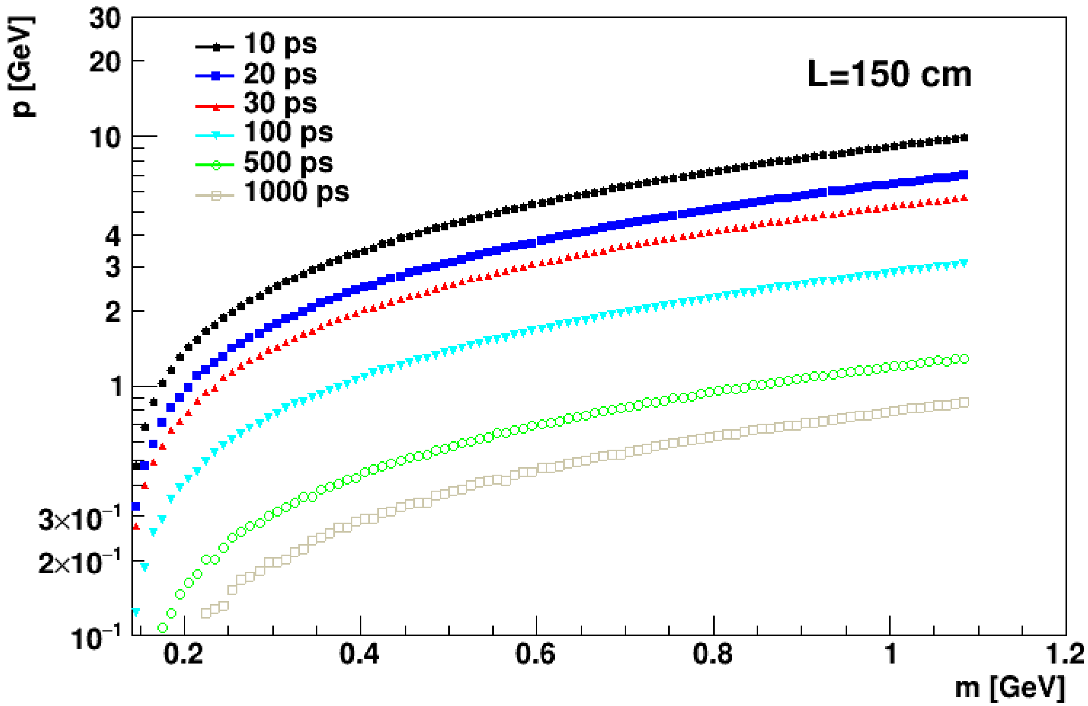
- If we know the exact position / time of the primary vertex, time of flight (TOF) can be used to identify particles (light and heavy)
- See, for example, https://arxiv.org/abs/1807.05453

3 σ separation of a particle (with mass “m” and momenta “p” traveling the distance L) from a particle with the mass m_F hypothesis using σ_{TOF} resolution of a timing detector

$$\frac{L}{c\sigma_{\mathrm{TOF}}}\left|\sqrt{1+\frac{m^2}{p^2}}-\sqrt{1+\frac{m_F^2}{p^2}}\right| > 3$$

Example: single-particle separations

- ECAL inner radius R=1.5 m (CLIC_o3_v13)
- 3 σ separation of a particle with "m" from the pion hypothesis

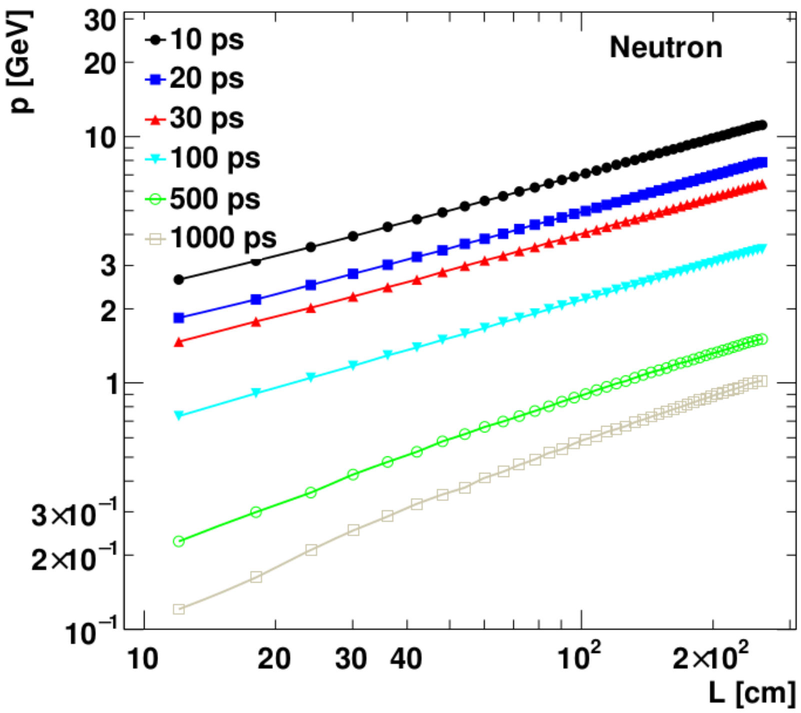


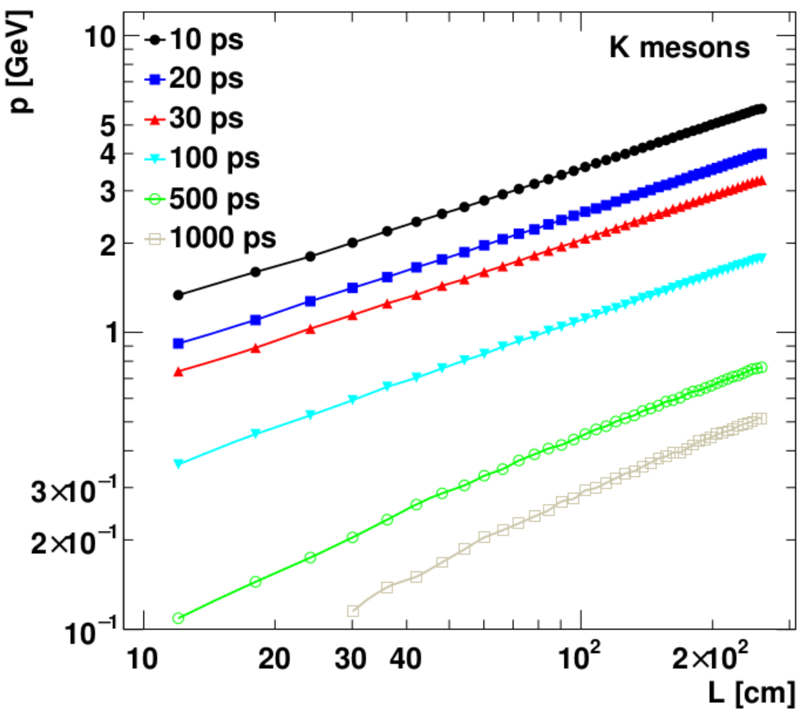
Assuming a 20 ps detector:

- K0L can be separated from pions up to p~3 GeV
- p/n can be separated from pions up to p~7 GeV

Arbitrary L but fixed mass hypothesis

- 3 σ separation of p/K from the pion hypothesis





Can be used by any detector with different distance L from the vertex

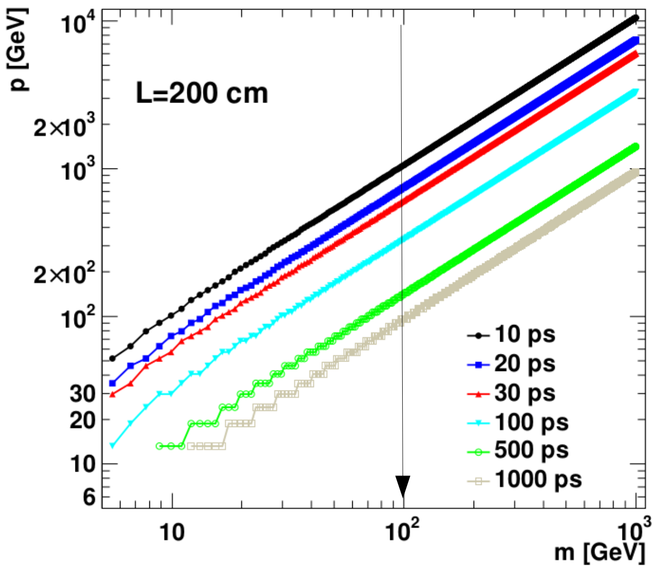
Reconstruction of stable massive particles

- Studies of heavy long-lived (or quasi-stable) particles is one of the main goals of many searches
- For studies of stable massive particles pions cannot be a good reference for semi-analytical calculations
  - Reference can be rather arbitrary for particles with masses > 10 GeV
- Heaviest stable particle is α particle (two protons and two neutrons)
  - Can be easily stopped by material, but we do not know exact origins in the material, nor remaining flux after they stopped
  - Use α particle as a reference (m_F=3.72 GeV) and calculate 3σ separation above this mass (but any choice > 2 GeV can be used too)

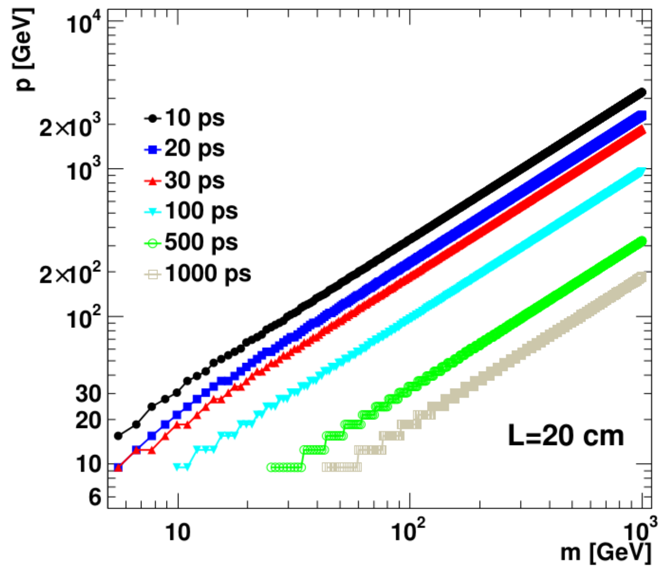
$$\frac{L}{c\sigma_{\mathrm{TOF}}}\left|\sqrt{1+\frac{m^2}{p^2}}-\sqrt{1+\frac{m_F^2}{p^2}}\right|>3$$

Reconstruction of stable massive particles

- 3σ separation of a particle with a mass "m" from the α particle hypothesis
- Use ~ FCC L=2 m (from vertex to TL1) and 0.2 m distances (TL2-TL1)



(a) for $L = 2$ m



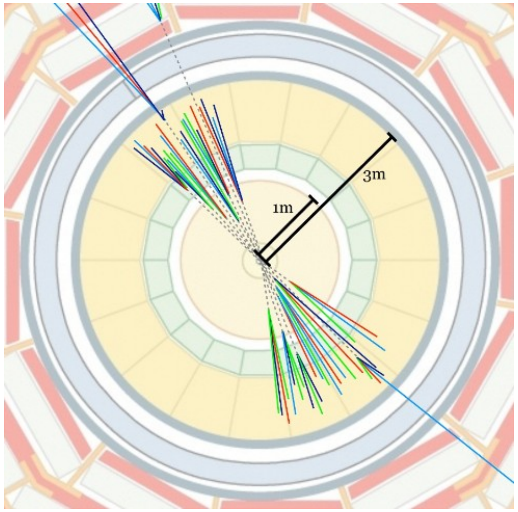
(b) for $L = 0.2$ m

Benchmark: BSM particle with M=100 GeV can be identified

- up to 700 GeV in momentum for σ_{TOF}=20 ps
- up to 90 GeV using 1 ns

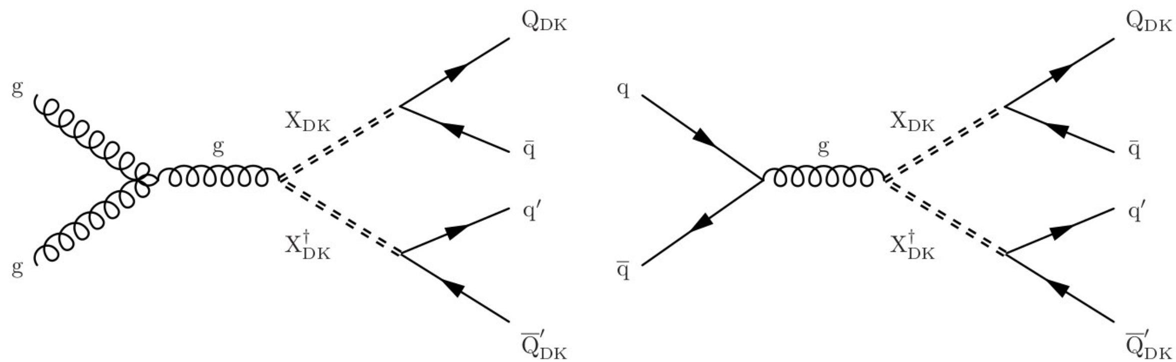
For TL2-TL1 measurements (without collision vertex information), 100 GeV particles can also be identified up to 200 GeV

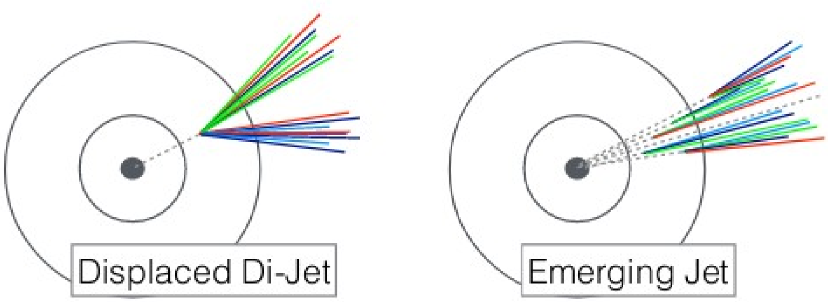
Emerging jets



Y. Bai and P. Schwaller, “Scale of dark QCD”, Phys. Rev. D 89 (2014) 063522,
doi:10.1103/PhysRevD.89.063522, arXiv:1306.4676.
P. Schwaller, D. Stolarski, and A. Weiler, “Emerging jets”, JHEP 05 (2015) 59,
doi:10.1007/JHEP05(2015)059, arXiv:1502.05409.

CMS publication: arXiv:1810.10069v2



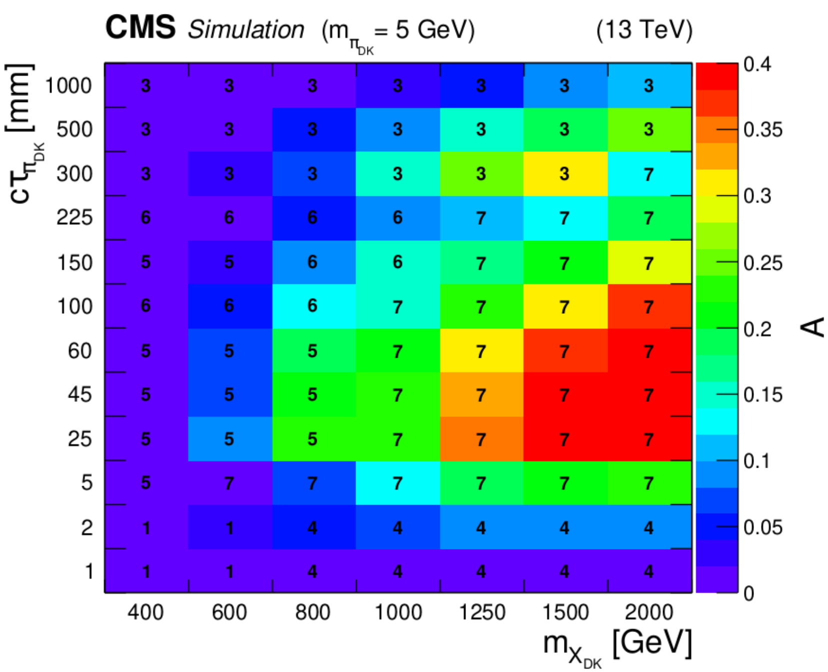


- Dealing with tracks for emerging jets is complicated
- One way to fight background is to veto prompt (and secondary) tracks

MC samples created for HepSim with the help of the authors (URL link)

CMS track acceptance vs CAL timing-layers

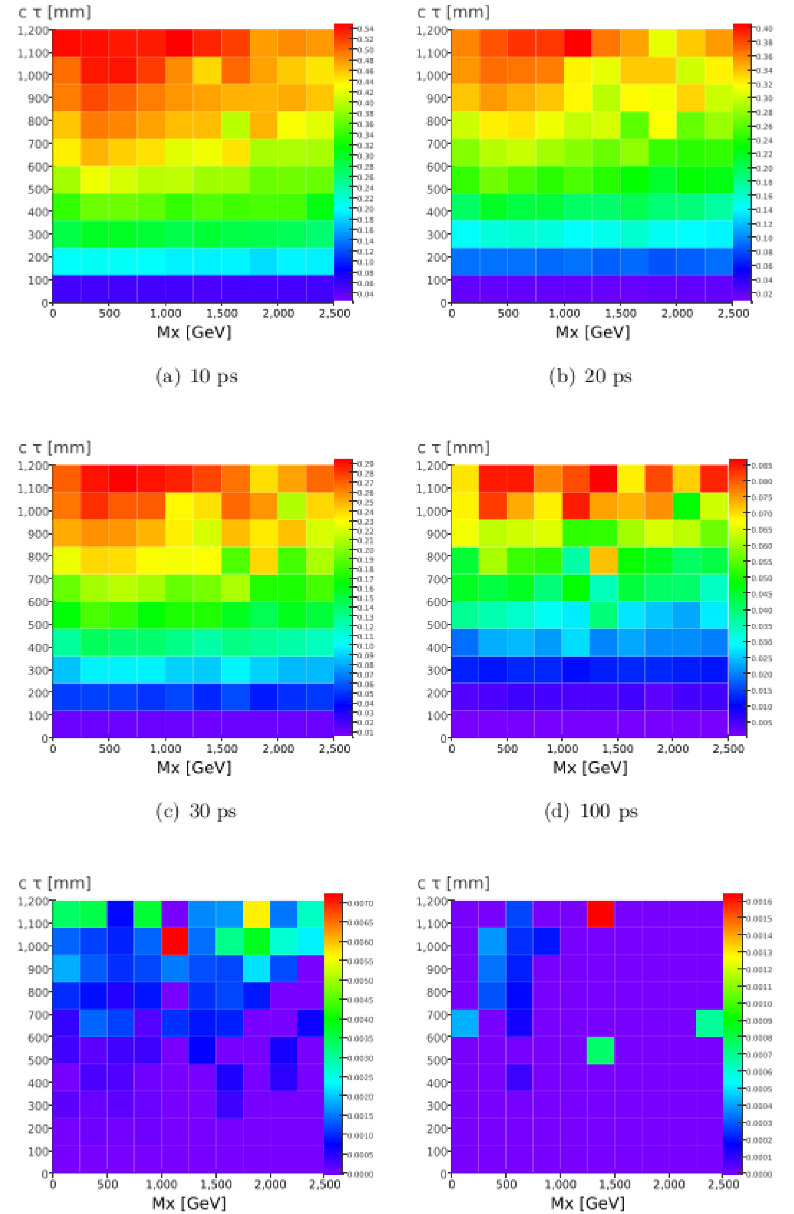
Acceptance as a function of decay length (mm) and mass of the mediator that decay to dark pions



Pythia8 simulations from HepSim using TOF and timing layers →

Timing Layers show large acceptance for small Mx

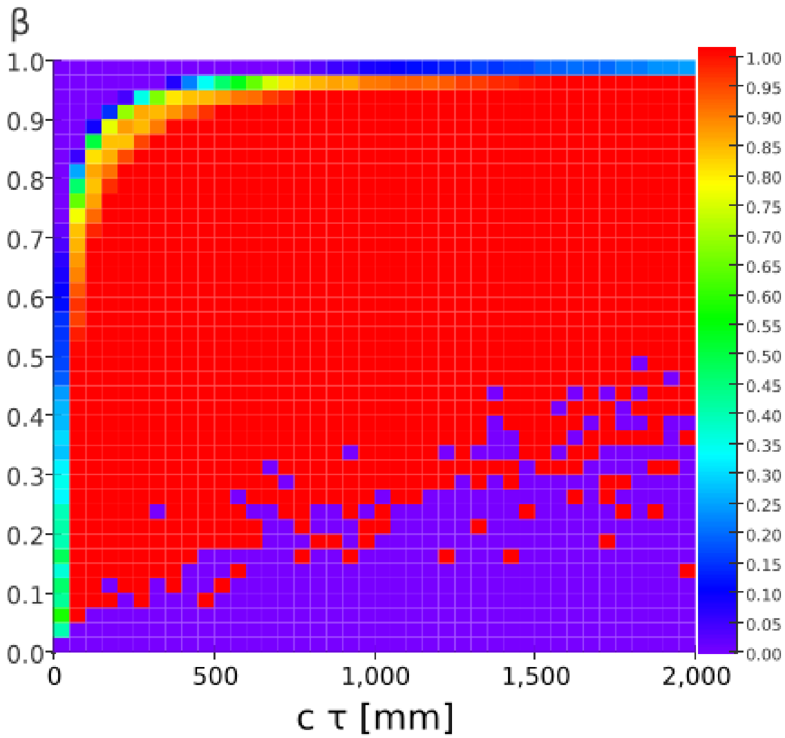
Calorimeters with TL1



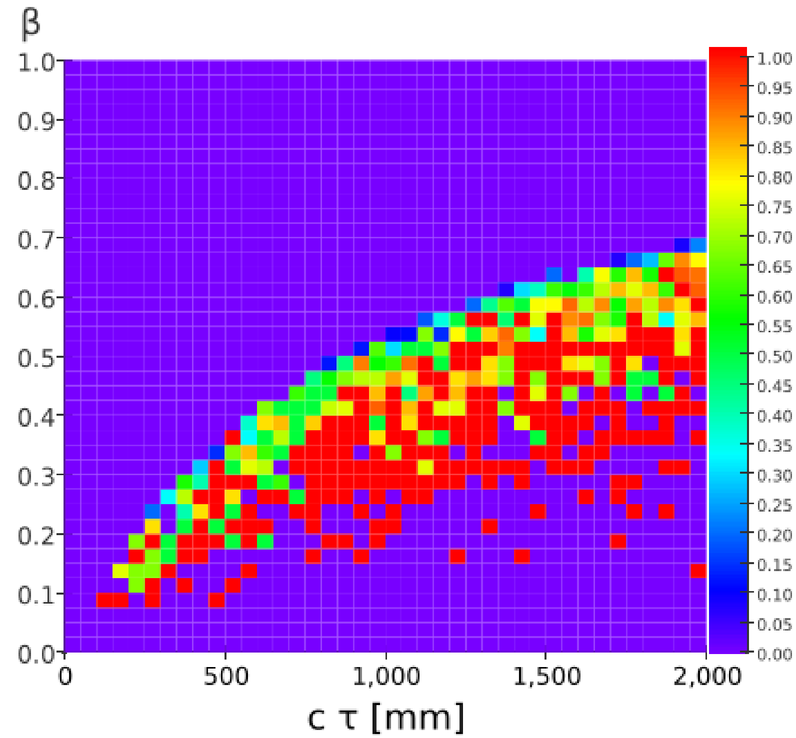
(a) 10 ps (b) 20 ps (c) 30 ps (d) 100 ps (e) 500 ps (f) 1000 ps

Emerging jets for HE-LHC (27 GeV)

- Create HepSim Pythia8 simulations for pp 27 TeV using emerging jets model
- Ntot - events as a function of beta(dark pion) vs c*tau(dark pion) without cuts
- Then apply “3*sigma” requirement for different timing-layers resolutions
- Calculate acceptance Nacc/Ntot for different resolutions



(a) 20 ps



(b) 1000 ps

Emerging jets for HE-LHC (27 TeV)

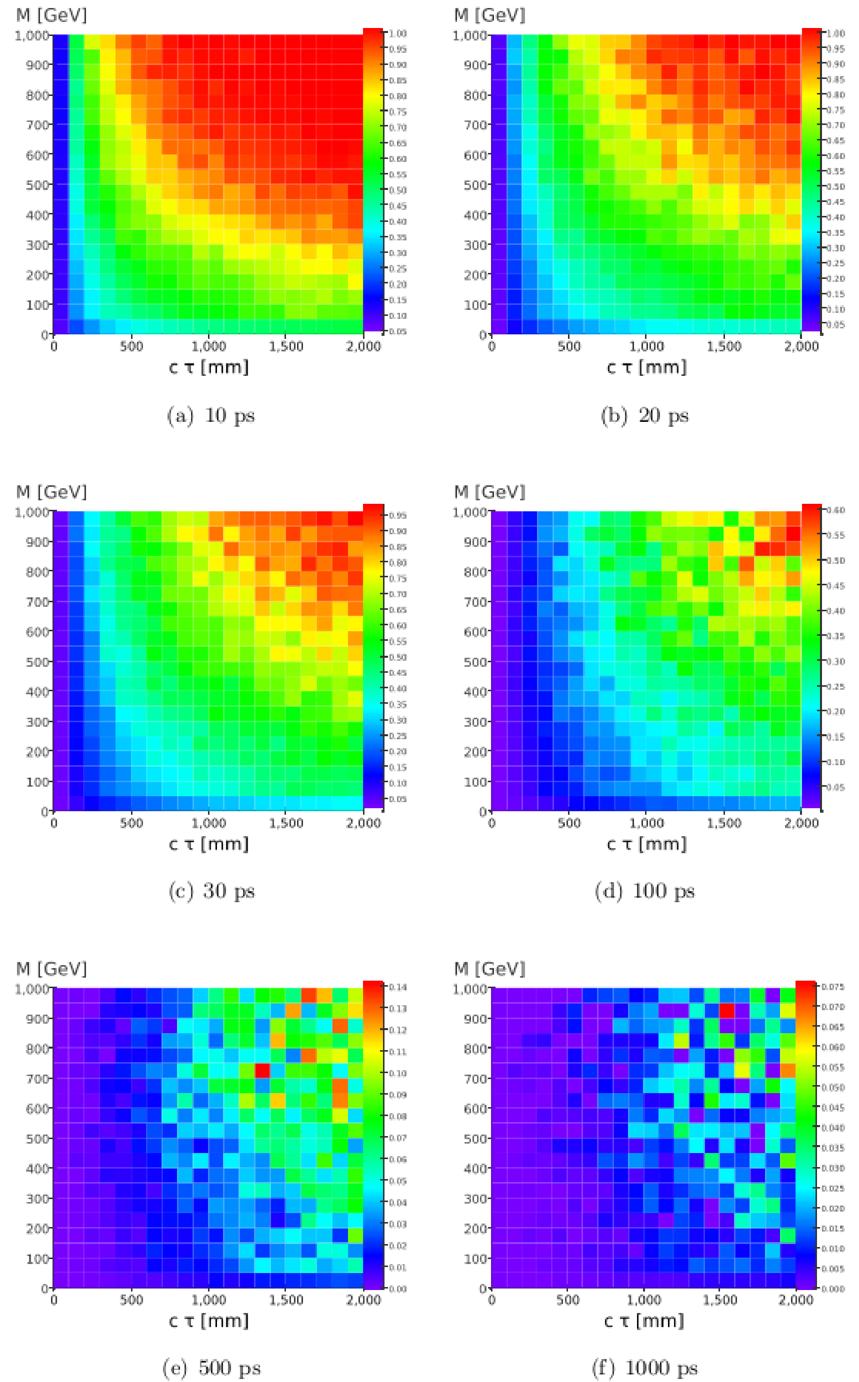
Calculate acceptance as a function of dark pion mass and c*tau

Timing layers acceptance to detect merging jets from dark pion as a function of mass of dark pions and c*tau

Timing layers give large acceptance for large c*tau and mass of dark pions

Notes:

- no information used on detect designs
- acceptances can equally be applied to CLIC (or any other experiment)



(a) 10 ps (b) 20 ps (c) 30 ps (d) 100 ps (e) 500 ps (f) 1000 ps

Summary

- Timing layers with tens of picosecond capabilities complement calorimeters with the standard ~0.5 - 1 ns readout
- Overwhelming benefits for BSM long-lived particles
- Other expected benefits:
  - Particle identification (baryons vs pions vs kaons etc.)
  - Reducing confusion terms in PFA → improvements for jets etc.
  - b-tagging, etc.
- To be quantified using realistic Monte Carlo simulations
  - Implemented in CLIC simulations?
  - Studied during Snowmass21?
- Survey for best technology for timing layers is ongoing