A New Experimental Perspective on Long-Lived Particles and Beam Backgrounds

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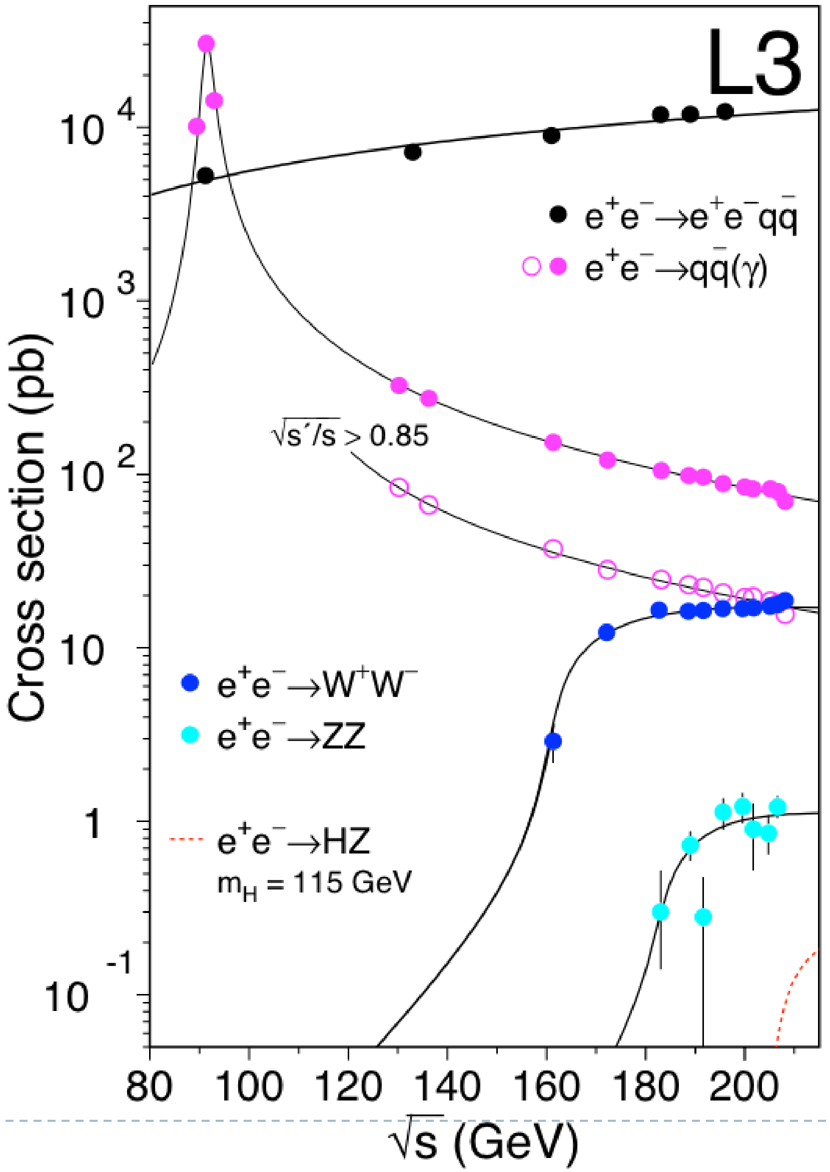
Bunch Trains at LEP (1995)

- **My first experience w/ (circular) collider detector timing within a bunch crossing:**
  - Four bunch trains (spacing 247.5ns, $87\lambda_{RF}$)
  - Needed phase lock for synchronous BGO calorimeter readout gate (5μs)
  - Offline analysis tagged which bunch within a train the signal event originated from (has some impact on integrated signal)
  - Luminal region
    - Transverse spread smaller than experimental resolution (5μm – vertical, 140μm - horizontal)
    - Longitudinal spread substantial (~7mm)
    - Less than one event per crossing?

Two-Photon Physics/Beam Background

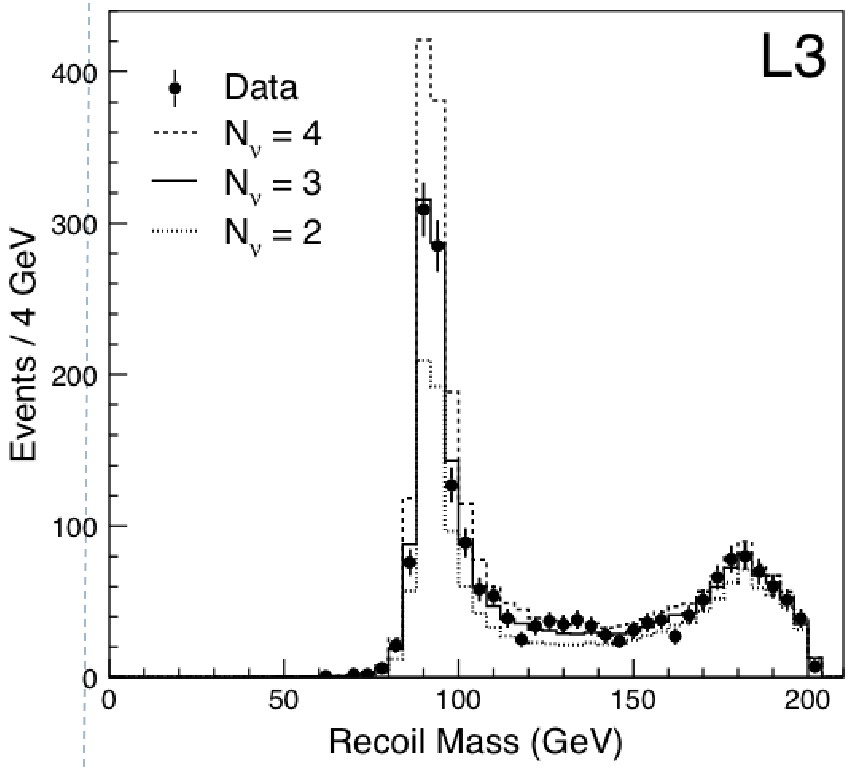
- **Not completely clean**
  - Two-photon physics
  - Bhabha scattering (lumi)
  - Off-momentum electrons
  - Beam gas
- **Two-photon grows w/ beam energy**
  - More difficult to veto on very forward energy deposits

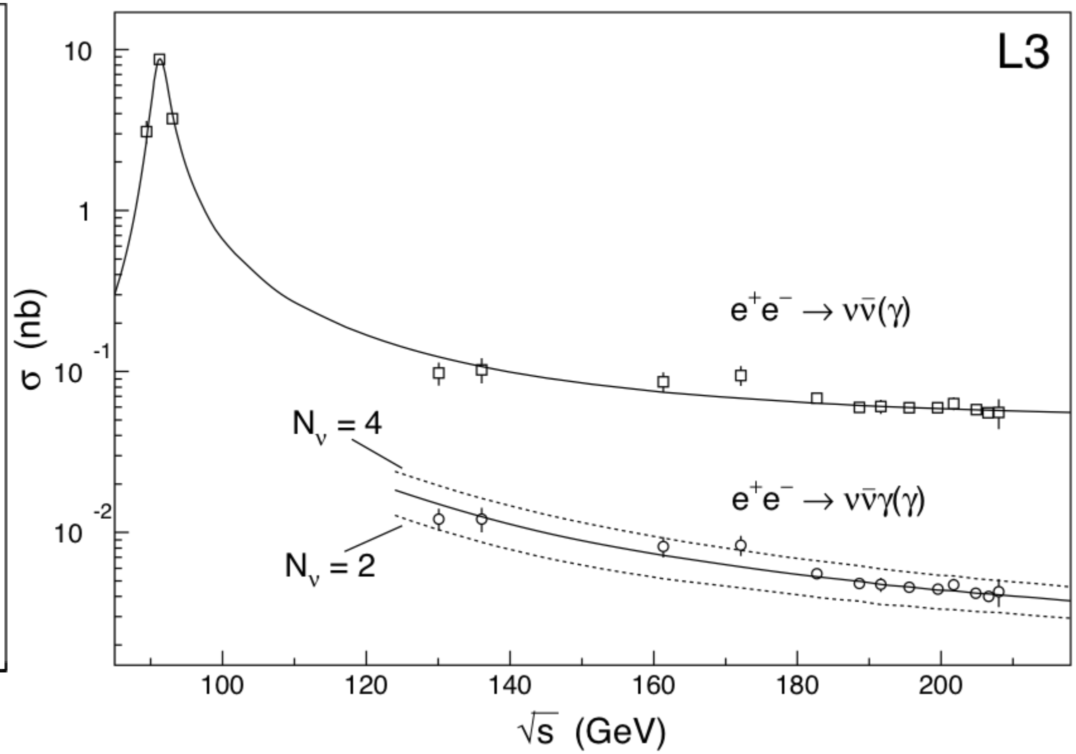


Starting Point:
Should not assume that are particles are coming from signal vertex

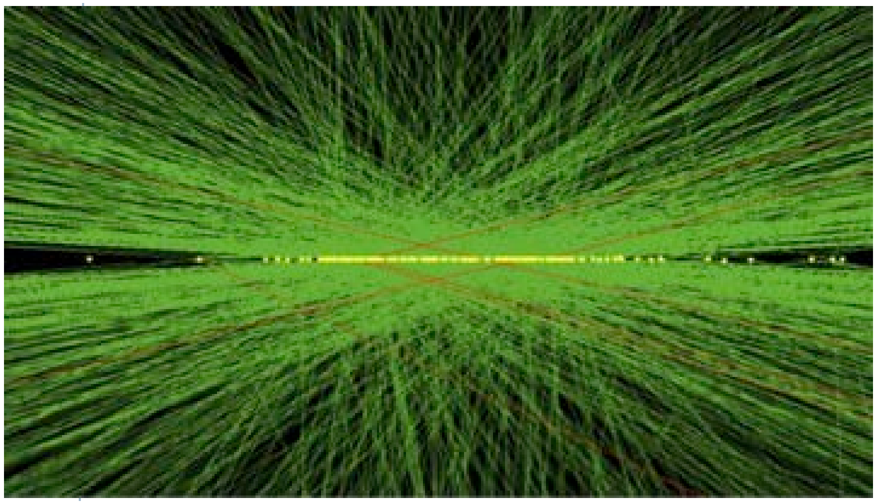
Single Photon Trigger

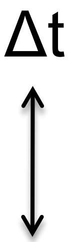
- **How clean did we want it?**
  - Recoil photons (~8% of full √s collision rate)
    - New Physics Searches and Neutrino Counting

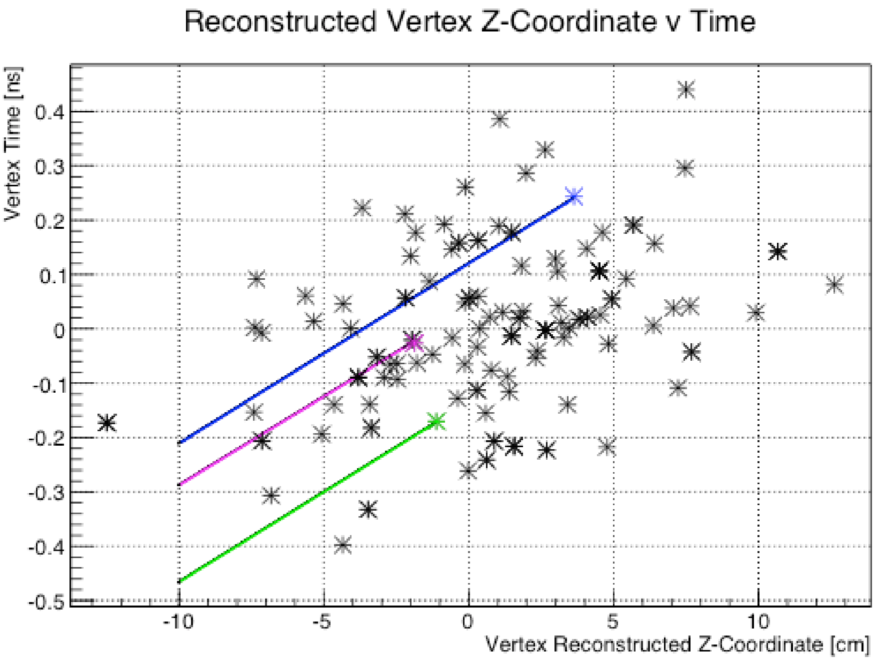




HL-LHC Pileup







+ Neutrals into Calorimeters!

- **Current detectors separate vertices within a bunch crossing purely on z-vertex location (3D w/ beamspot)**
  - Vertex merging sets in at ~0.3mm spacing
  - HL-LHC is ~0.6mm spacing on average
- **In ~25-50ps time exposures, the z-vertex beamspot is similar while the pileup returns to Run 1 LHC levels**
  - 4D vertex algorithms (neutrals associated to a band of vertices)

Why do we need help w/signal vertex location?

- **Higgs to di-photons (or a 750 GeV resonance) invariant mass resolution**
  - Need vertex to better than 1cm (typically)
- **B-tagging and forward jets**
  - z-coordinate resolution degrades at high pseudo-rapidity
  - secondary vertices (more longitudinal than transverse) are impaled by pileup tracks (top quark centrality ~0.2)
  - Higgs production mechanism or other forward jet production (including gluon ISR) need correct vertex assignment for p_T-balance, H_T and MET
- **Long-lived particles and delayed signatures**
  - At high mass, a significant fraction of decays are simply delayed - low velocity
  - Displaced vertices are typically ~4 times more forward (along luminal region) than transverse

Anything new from detector designers?

- **Fast-timing (20-30ps) is one of the rapidly growing fields within detector R&D**
  - Several clever ideas are making fast-timing a practical reality for collider detector
    - Calorimeter-based: Photons/EM showers can be tapped at shower max or multiple times along the longitudinal shower ($1/\sqrt{N}$ w/ a good clock)
    - Track-based: MIP-sensitive timing layers augment static 3D tracking and can also benefit from multiple sampling with low mass detectors
    - Hermetic timing (MIPs + Photons/EM showers) – determine (all) vertex t_0's and reduce photon combinatorial vertex association by factor 5-6

Calorimeter timing

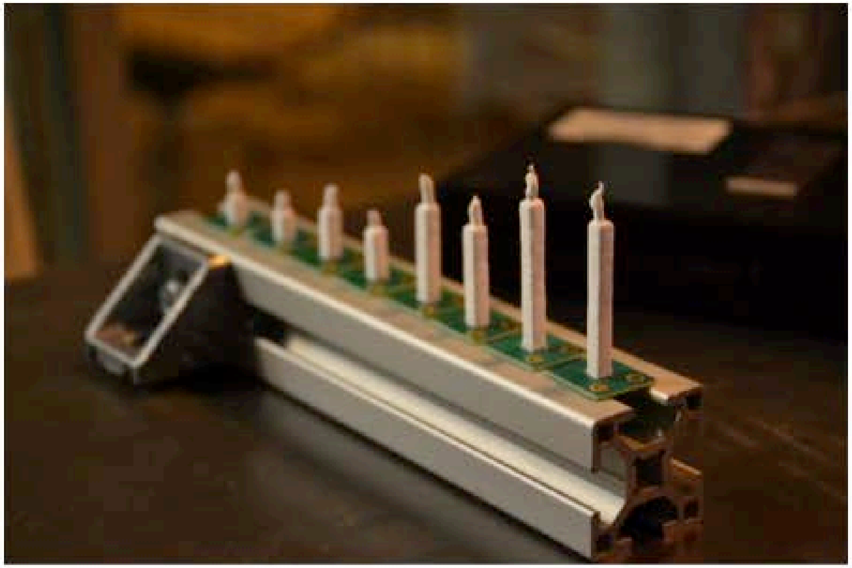
- High energy EM timing can achieve better than 10ps. Limits of long-crystal timing versus E are not completely known. A resolution of 30ps has been achieved with 20cm LYSO crystals with front/back MCP readout. Similar performance (11ps) has been achieved with MIPs using 5mm LSO crystals and SiPMs. With enough signal ~10-30ps possible over the entire range. New development with UV photo-sensitive APD with interference-filtered (0.9ps comp) BaF_2 look promising.
- SiPAD sampling calorimeter with EM core multiplicities of ~100 for thresholds of 20-30 MIP make this an effective timing device (even with 50ps per cell timing). Uses full pulse width Time-Over-Threshold – I give a new proposal for a readout scheme later in the talk.
- Shower max pixelated MCP w/ photocathode also demonstrated to ~30ps with 4 or more lateral hits

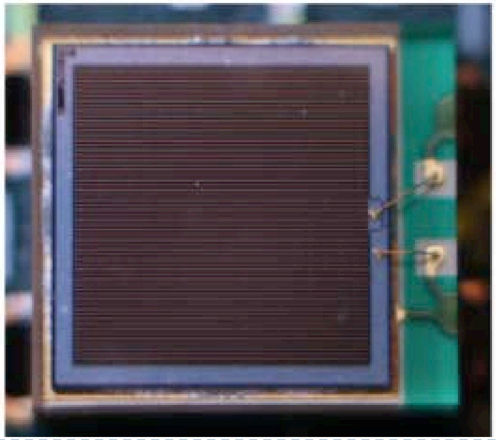
Dedicated fast timing layer for MIPs

- Ionization-MCPs (based on secondary emission) achieve approximately ~35ps with 70% MIP efficiency (triple layer) and with a photocathode give ~15ps and ~100% MIP efficiency.
- Hyperfast Silicon APDs (“Deep depletion”) have 100% MIP efficiency and achieve ~15ps for an equivalent MIP pulse (fast IR pulse) w/ high gain and S/N~100. Time structure in leading edge of MIP data being studied (may be limited by Landau fluctuations).
- Ultrafast Silicon (“Reach-through”) hope to achieve ~50ps per layer operating at gain~10, and would use 4 or more layers to achieve 20-30ps MIP timing (mini-tracking detector).
- Short (5mm) crystal scintillators with SiPMs boost MIP signal to avoid Landau fluctuations and achieve 11ps for 5mm LSO crystals and FBK SiPMs.
- Micro-Pattern Gas Detectors with Photocathode achieve ~20ps (diffusion limited) time resolution.

Crystals and photodetectors

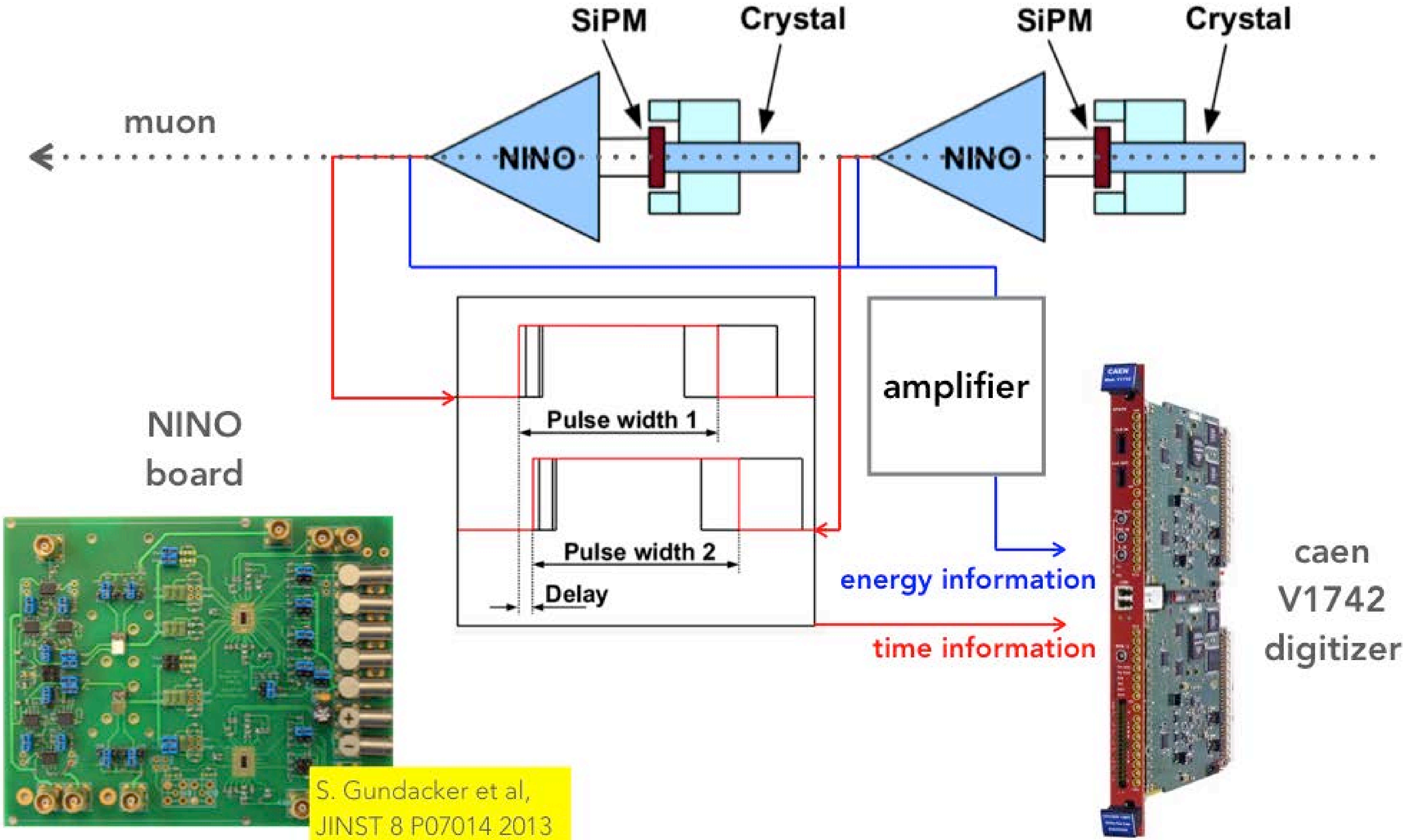
- 1^{st} configuration:
  - couples of **LYSO:Ce crystals** (*CPI*), dimensions **3×3×L mm^3**, **L=5,10,20,30 mm**
  - Crystals coupled to 3×3 mm^2 SiPM (Hamamatsu TSV MPPC), 50 µm SPAD (3600 SPADs)
  - SiPMs connected to the board through ~5 cm long wires



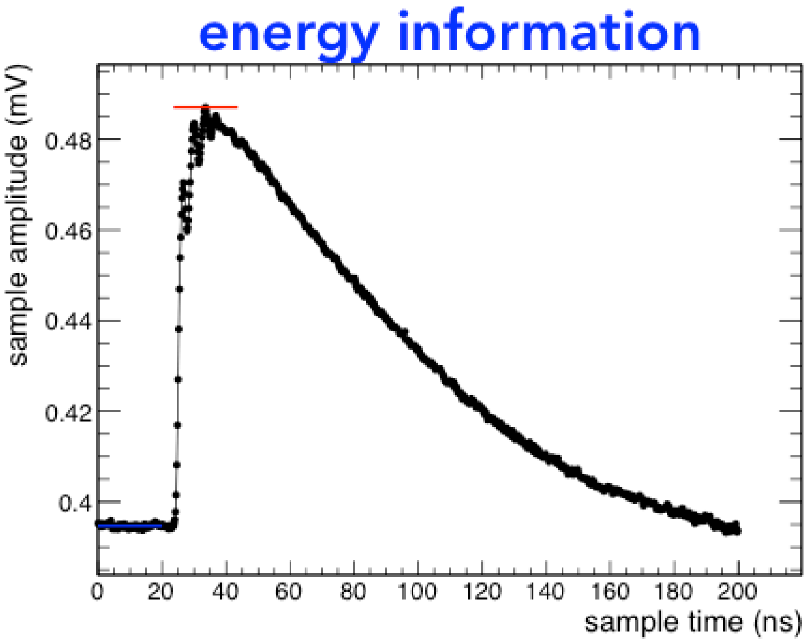


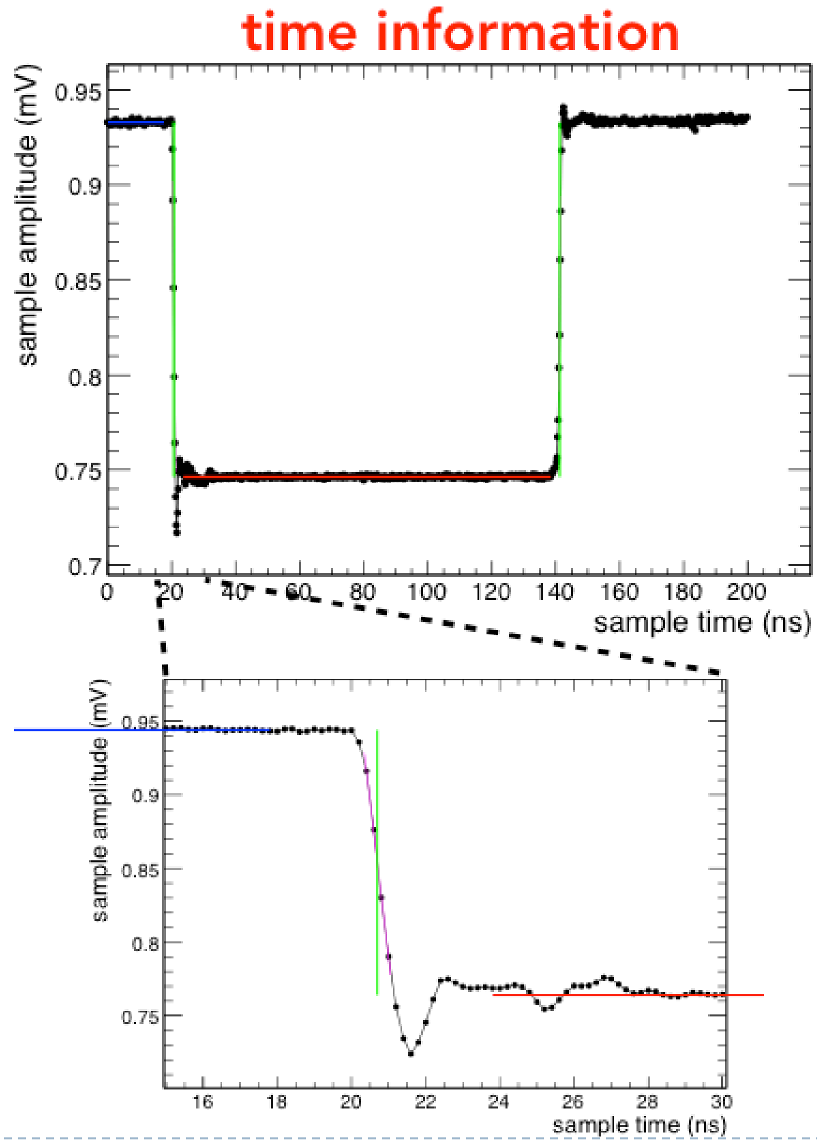
- 2^{nd} configuration:
  - couples of **LSO:Ce:Ca crystals** (*Agile*), dimensions **2×2×5 mm^3**
  - Crystals coupled to 4×4 mm^2 SiPM (FBK NUV-HD), 25 µm SPAD (6400 eff. SPADs)
  - SiPMs directly connected to the board

Measurement setup



Crystal pulse reconstruction

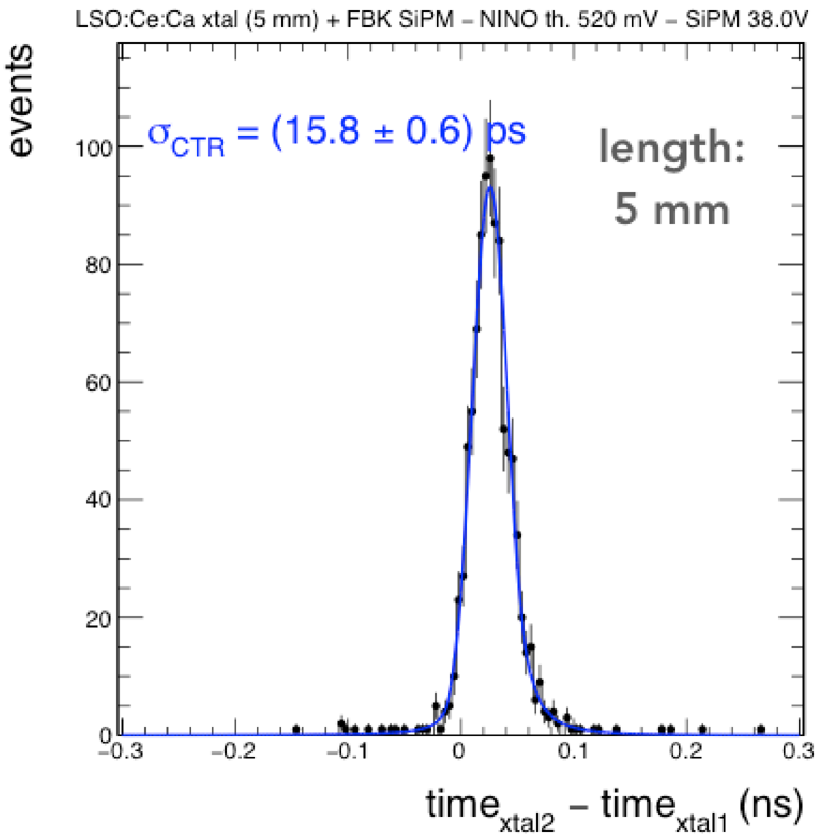




LSO:Ce:Ca + FBK NUV SiPM timing measurements - **Amplitude walk correction**

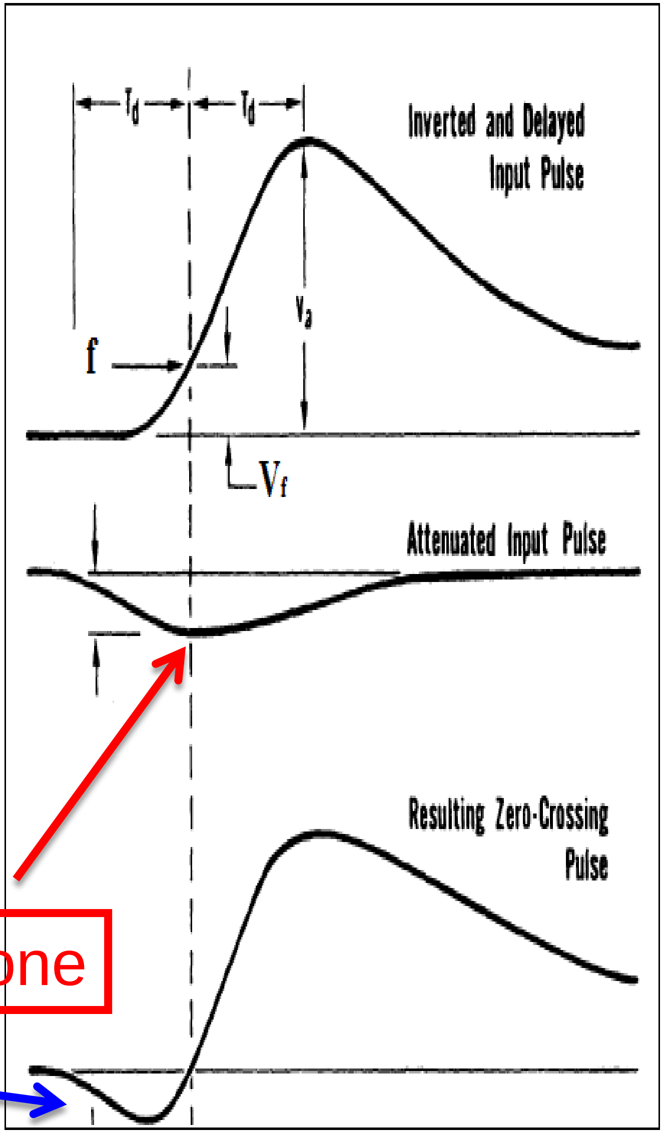
- We measure
  σ_{CTR} ~ 16 ps for 5 mm crystals

- This means (assuming the two crystals are the same)
  σ_{single} ~ 11 ps



New Analog Electronics Approach

- **New Timing-Amplitude Concept: CFToT – Constant Fraction Time-Over-Threshold**
  - Method for replacing dynamic range constraints with precision timing electronics and precision timing references for start and stop signals
  - Benefit for readout/DRS-type is that digitization is “on demand” per edge



Measure this pulse width

Not this one

New Perspective

- **We have the opportunity to create tighter interface between the machine and detectors**
  - The burden of creating "ideal conditions" for physics has for the most part been placed on the machine groups – and at the same time, max. lumi
  - Hermetic timing (MIPs and photons/EM shower cores) offers the opportunity to dissect the self-consistency of our precision spatial, energy and momentum measurements and to assess the self-consistency with the collision vertex – this capability with further our sensitivity to the smallest signal of interest (for example, single photon trigger) and expand sensitivity to long-lived particles from both delayed and displaced vertices
  - R&D concepts are rich – but need a path into the detector designs