Timing in calorimeters

Due to the lack of funding everything shown today has been stolen elsewhere

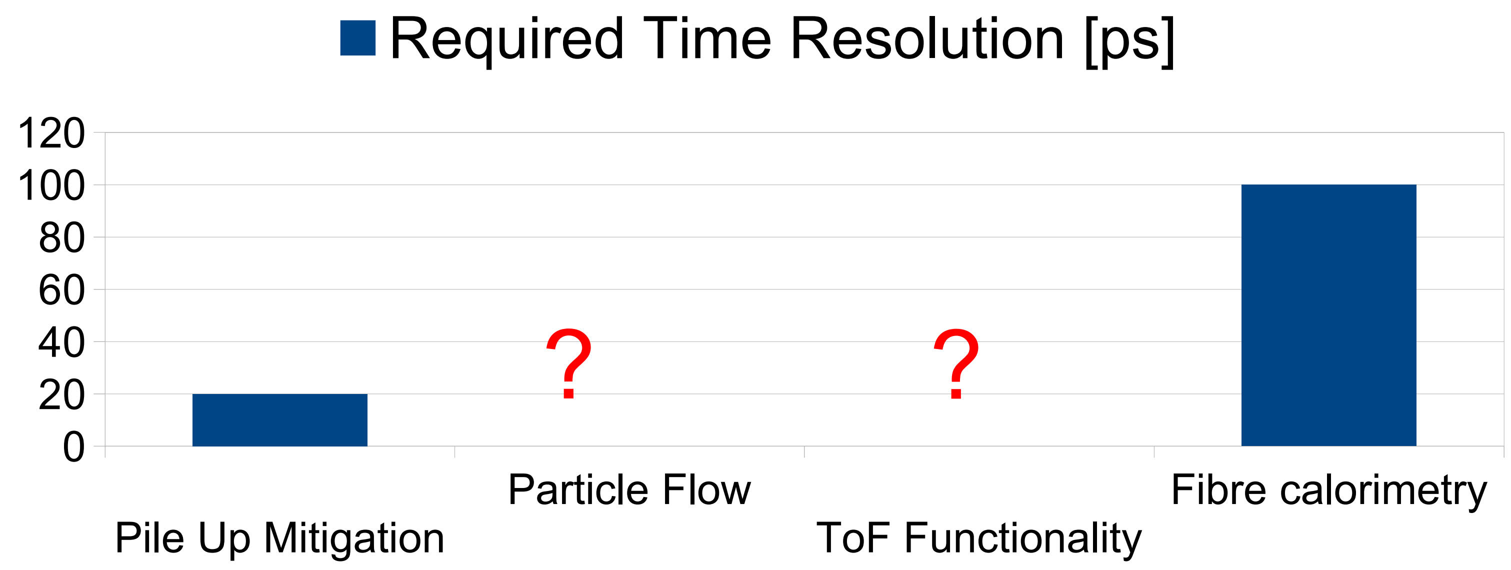
Roman Pöschl

FCC France – December 2021

This talk benefits a lot from the discussion during the preparation of the ECFA Detector R&D Roadmap

Requirement on timing

- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters



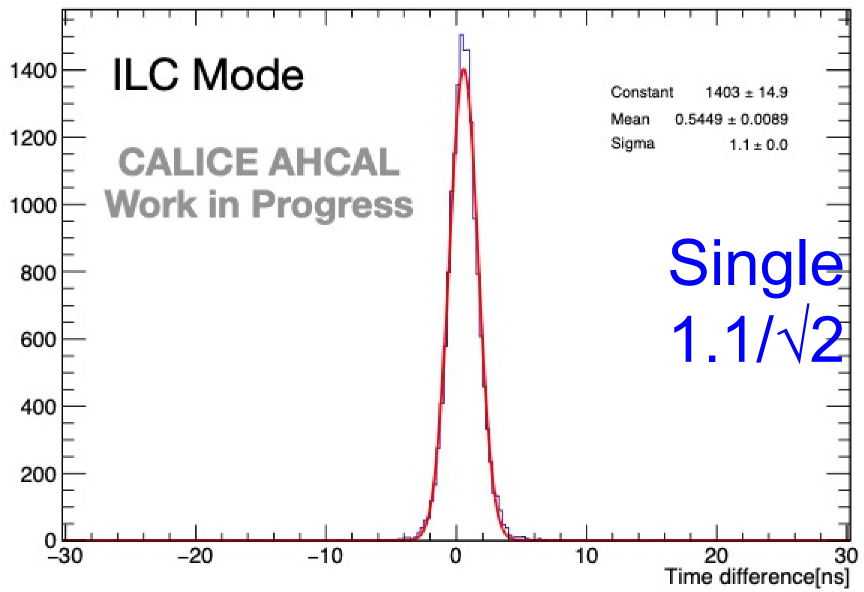
- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels
- See also talk by Nural

The next decade – ps timing in calorimeters

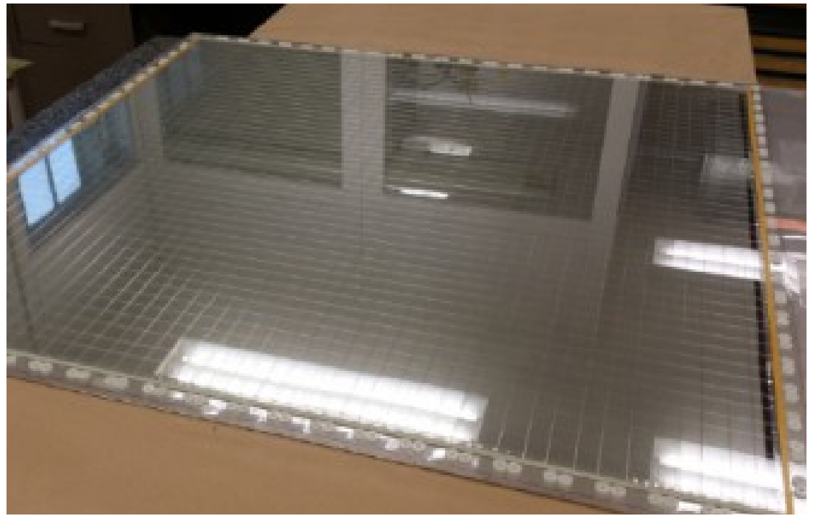
Pioneered by LHC Experiments, timing detectors are/will be also under scrutiny by CALICE Groups

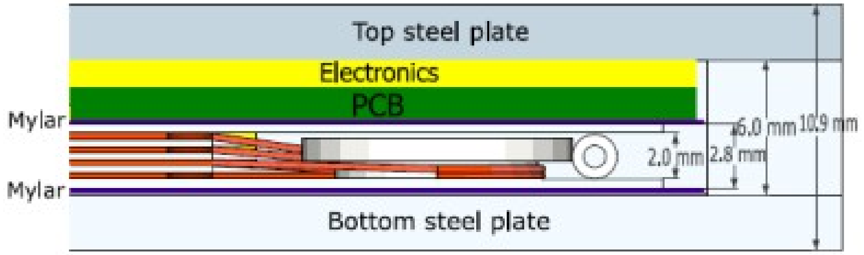
Hit time resolution:
Results from 2018 beam test of AHCAL with muons

Clock frequency 5 MHz, Powering pulsing



Single channel resolution
$1.1/\sqrt{2} = 0.78$ns

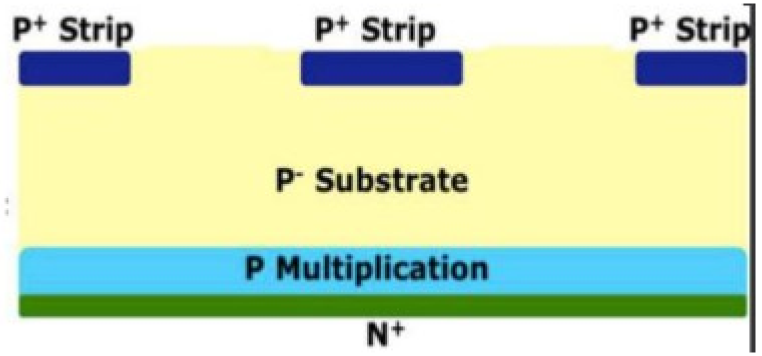




Under development:
GRPC with PETIROC
- < 20ps time jitter
- Developed for CMS Muon upgrade

- We need to understand <u>quickly</u> how much “timing” is really needed
  - Average timing O(100ps) in all layers
  - Excellent timing O(30ps) or better in a few layers
- This drives the hardware development

Inverse APD as LGAD?

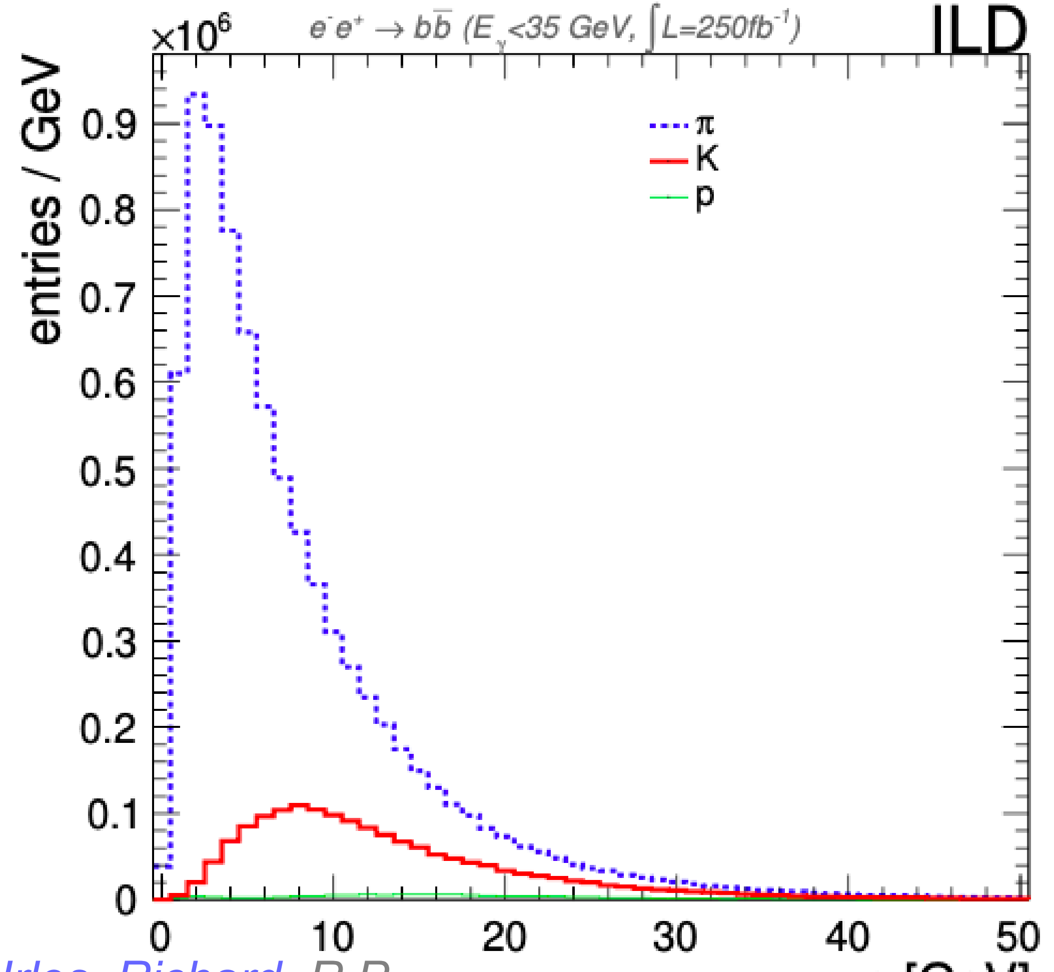


Inverse APD
by Hamamatsu

Gain ~ 50

Calorimeters with ToF Functionality?

Momenta and abundance of pi/K/p in ee->bb @ 250 GeV



ILD: Irles, Richard, R.P.

Available time resolution with calos

Difference in ToA at ILD Calos

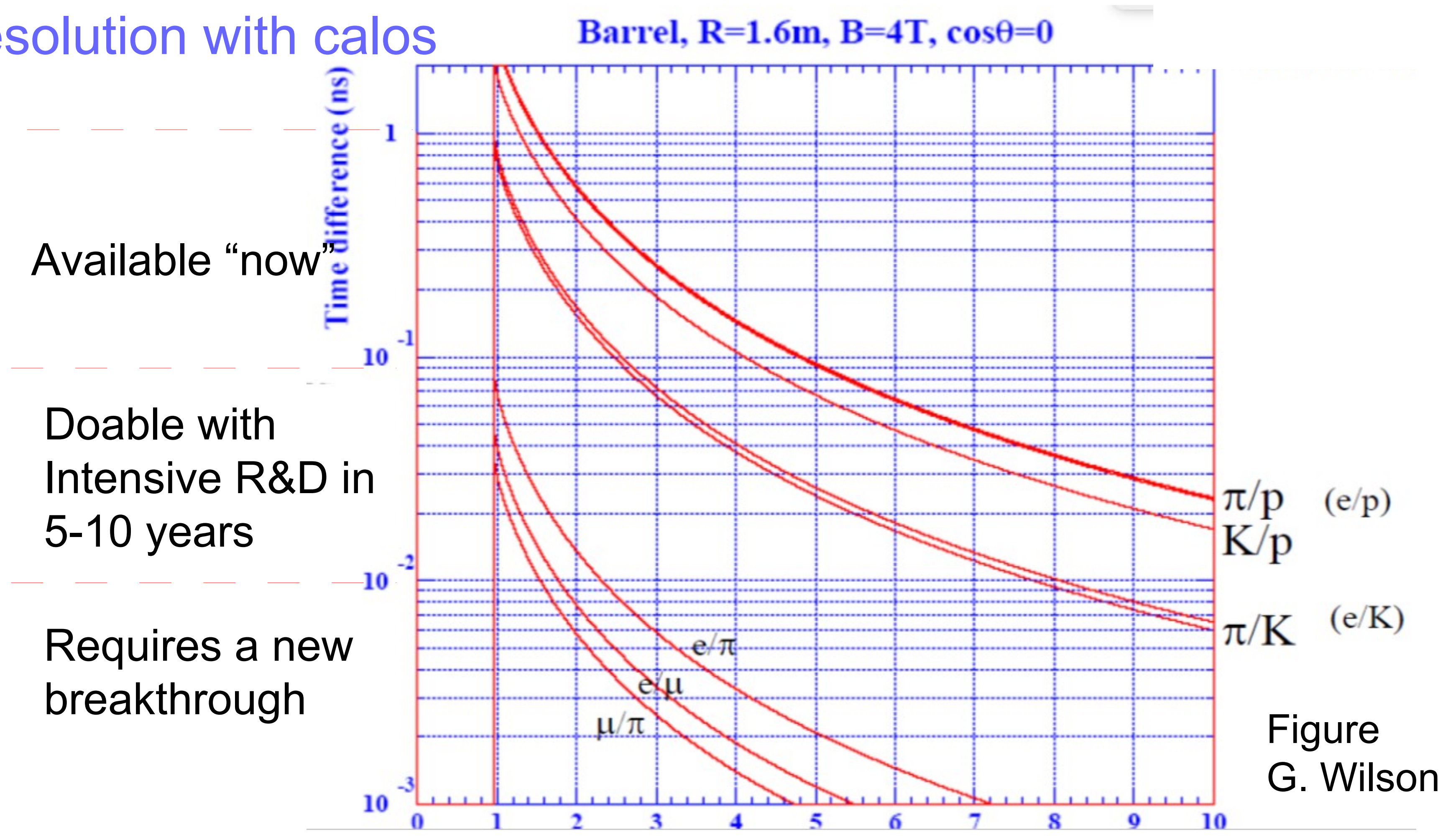
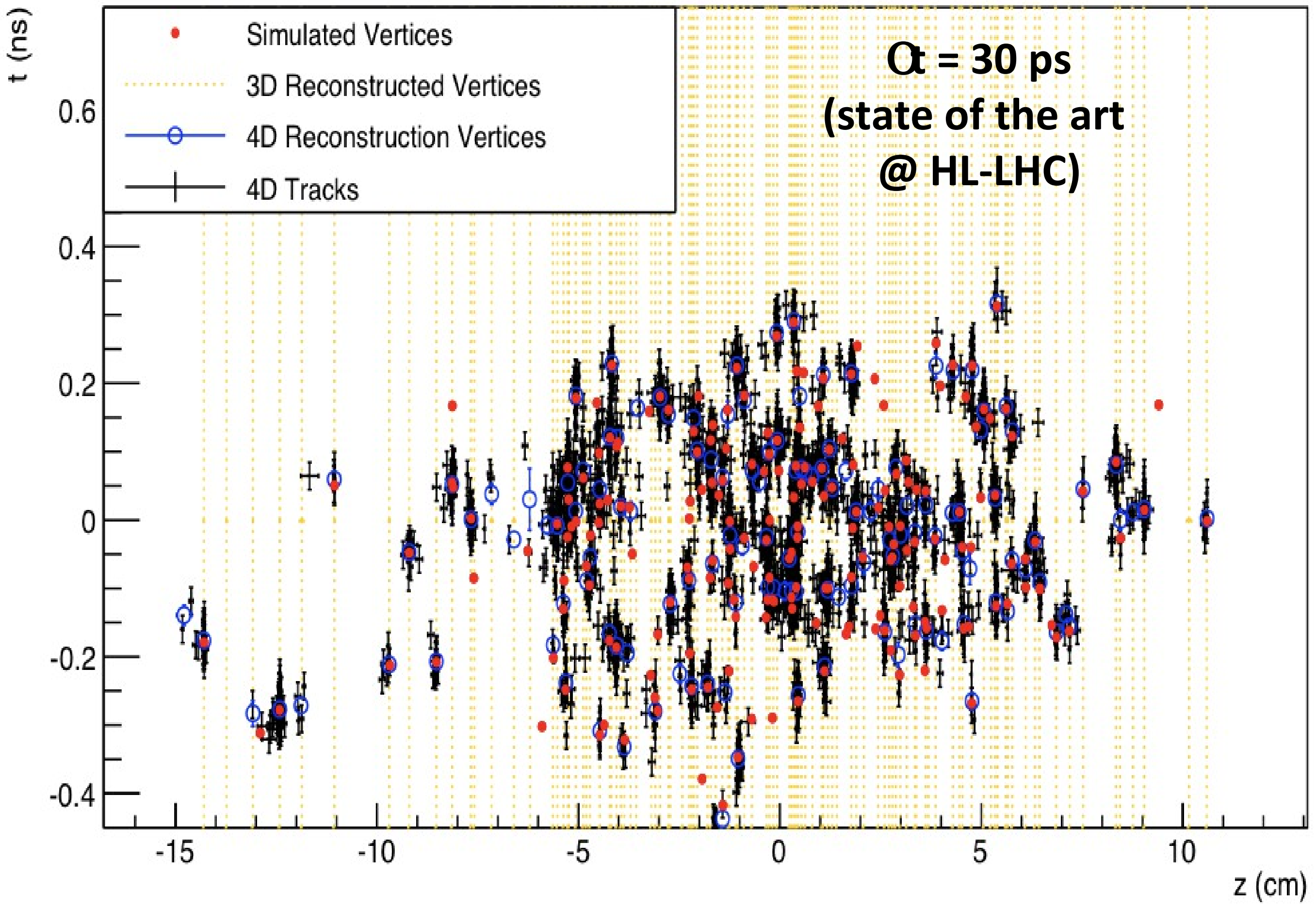


Figure G. Wilson

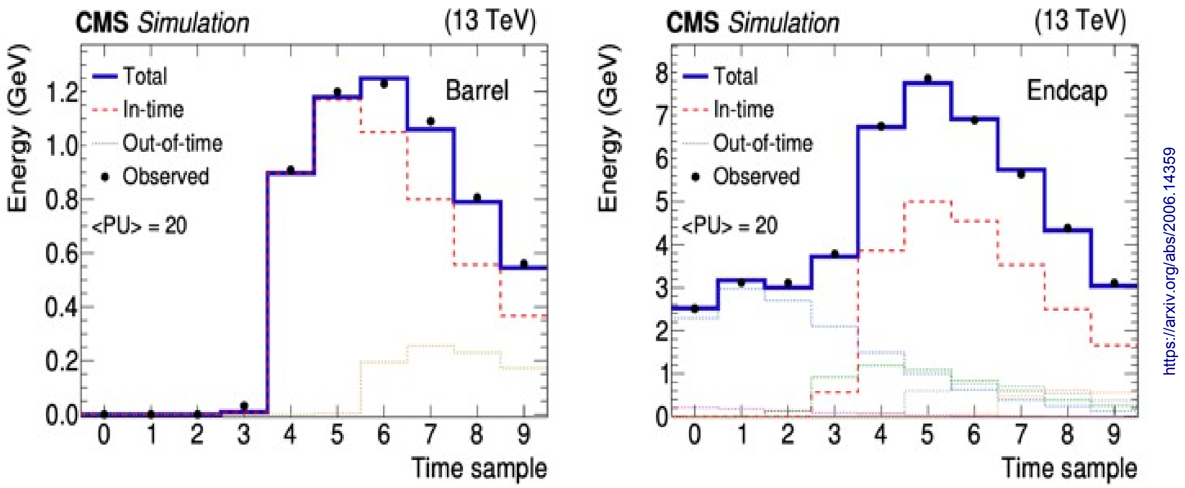
- Particle momenta (at 250 GeV) have peak below 10 GeV but long tail to higher energies
- Realistically ToF measurements will be (in foreseeable future) limited to particles below 10 GeV
  - Note that, apart from power consumption, in a final experiment one needs to control full system
- Momenta above 10 GeV require a real breakthrough and maybe even radically new approaches
  - Mandatory if ToF should work at and well above 250 GeV i.e. at Linear Collider energies

Timing in calorimeters I

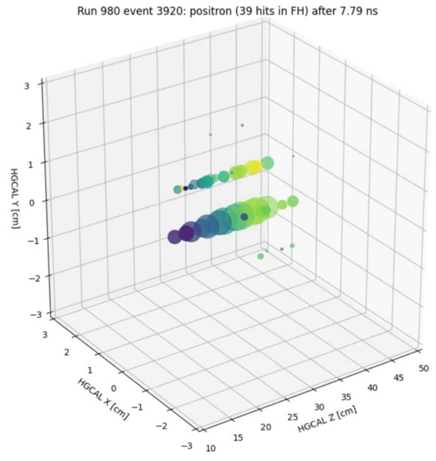


Red dots: 200 simulated vertices
Vertical yellow lines: 3D-reconstructed vertices (*i.e.* no timing info.) **Black crosses** and **blue open circles:** **4D-reco inc. time information**

Many vertices that appear to be merged in the spatial dimension are clearly separated when time information (~30ps accuracy) is available



CMS ECAL uses template fits to in-time signal plus out-of-time signals to extract the best energy measurement

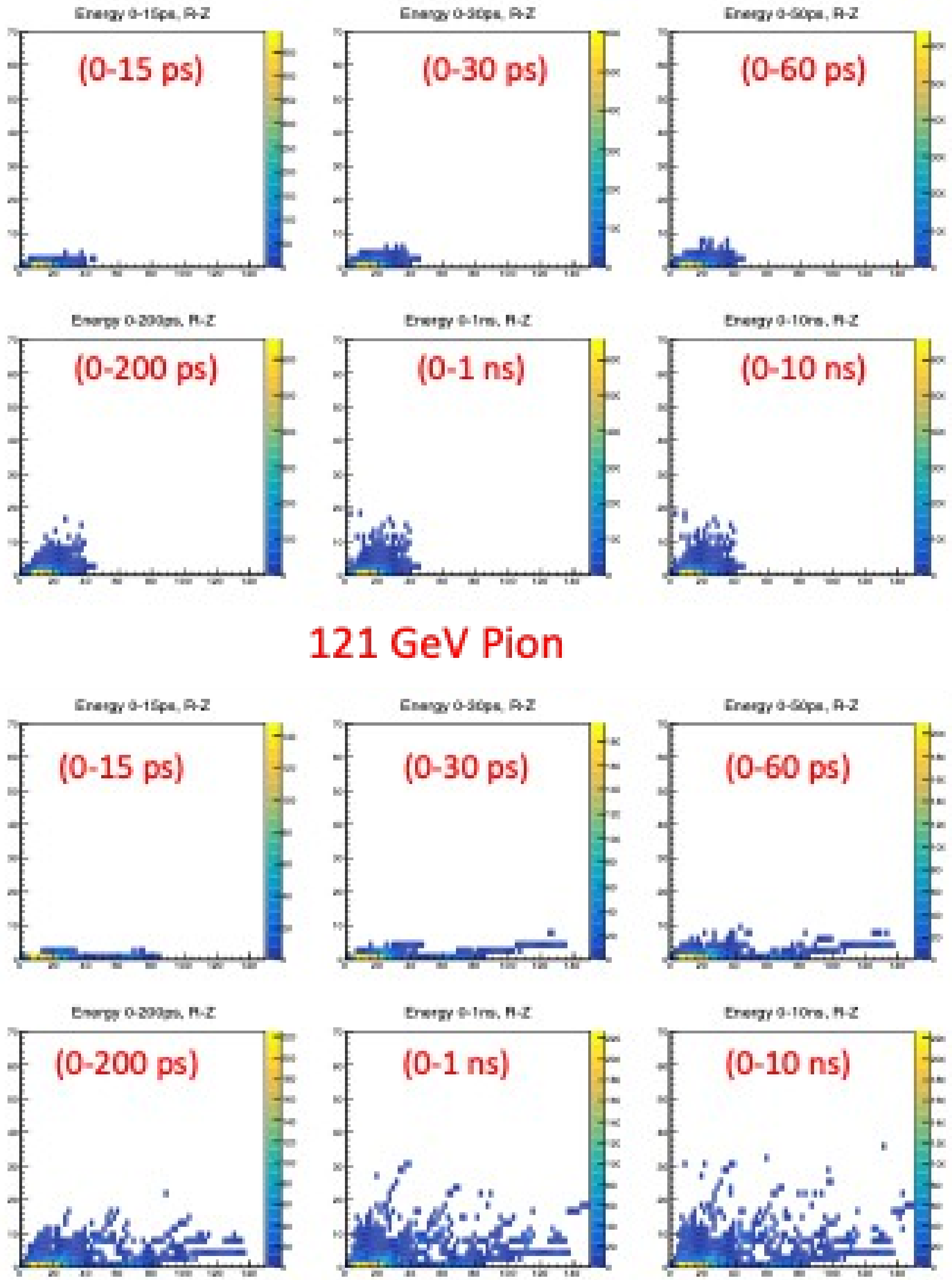


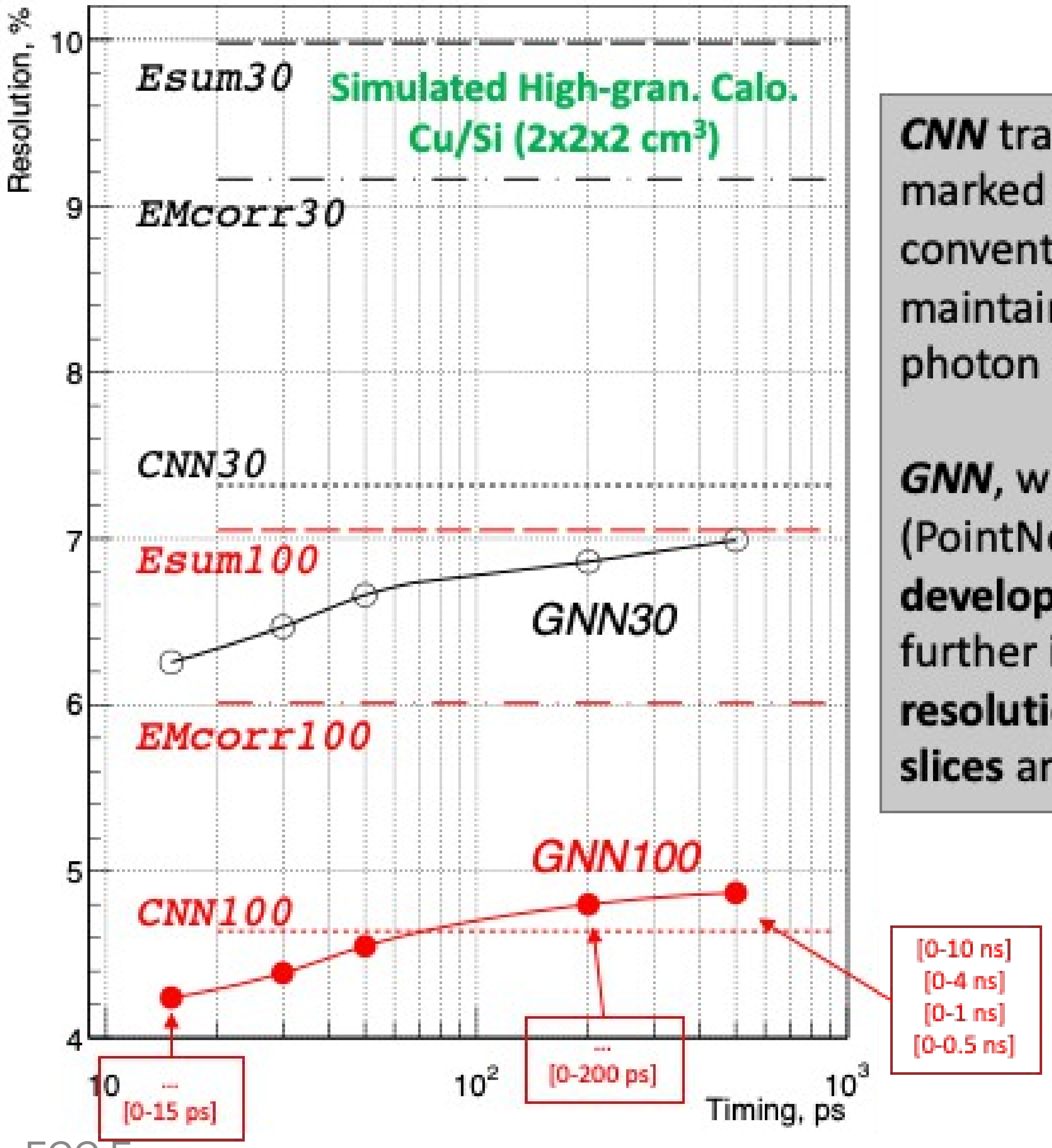
CMS HGCAL has measured **evolution of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

ECFA Roadmap TF6,
Summary of calorimeter symposium

Timing in calorimeters II

Features that emerge in the time domain can help distinguish particle types and, with GNNs, enhance σ(E)/E





CNN trained on pions achieves marked improvement over the conventional approache while maintaining performance for photon reconstruction

GNN, with edge convolution (PointNet), **with shower development timing information** further **improves energy resolution** when **shorter time slices** are included

arxiv:2108.10963

Novel optical materials

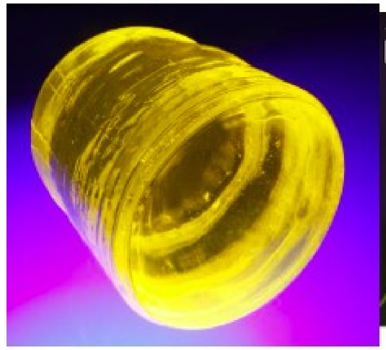
- Radiation hard optical materials with ultrafast timing response are required for new detectors in HEP, nuclear medicine and industry

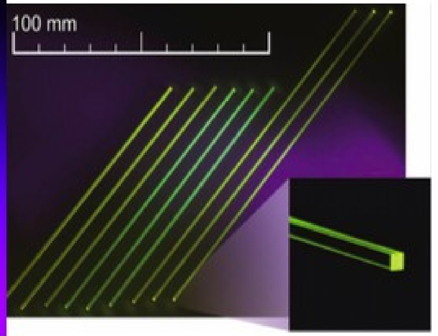
- A time resolution below 30 ps or even in the sub ps domain requires a better understanding of the fast signal production mechanisms in detection materials

- Innovative test suites required for the combination of fast timing and radiation tolerance will be developed for the characterisation and classification of materials

- Scalable and cost effective production techniques for the novel materials have to be explored together with the industrial partners

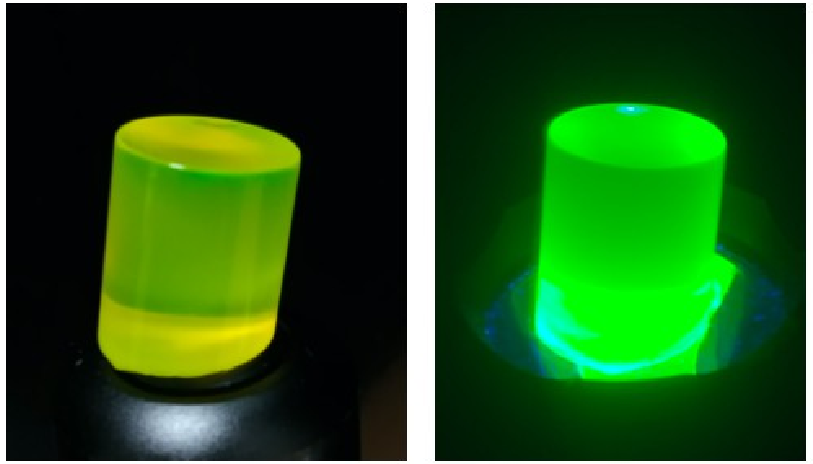
Crytur YAG ingots => fibers

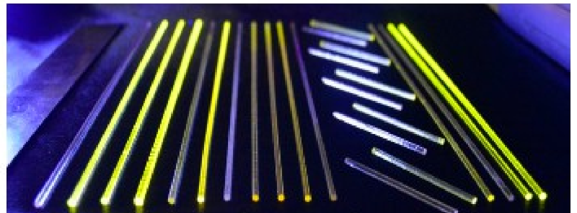




Crytur PWO crystals

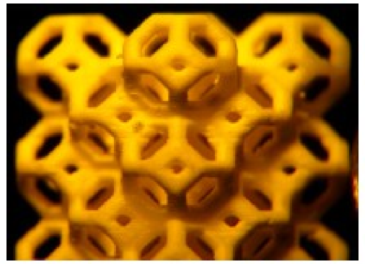
GlasstoPower development on quantum materials





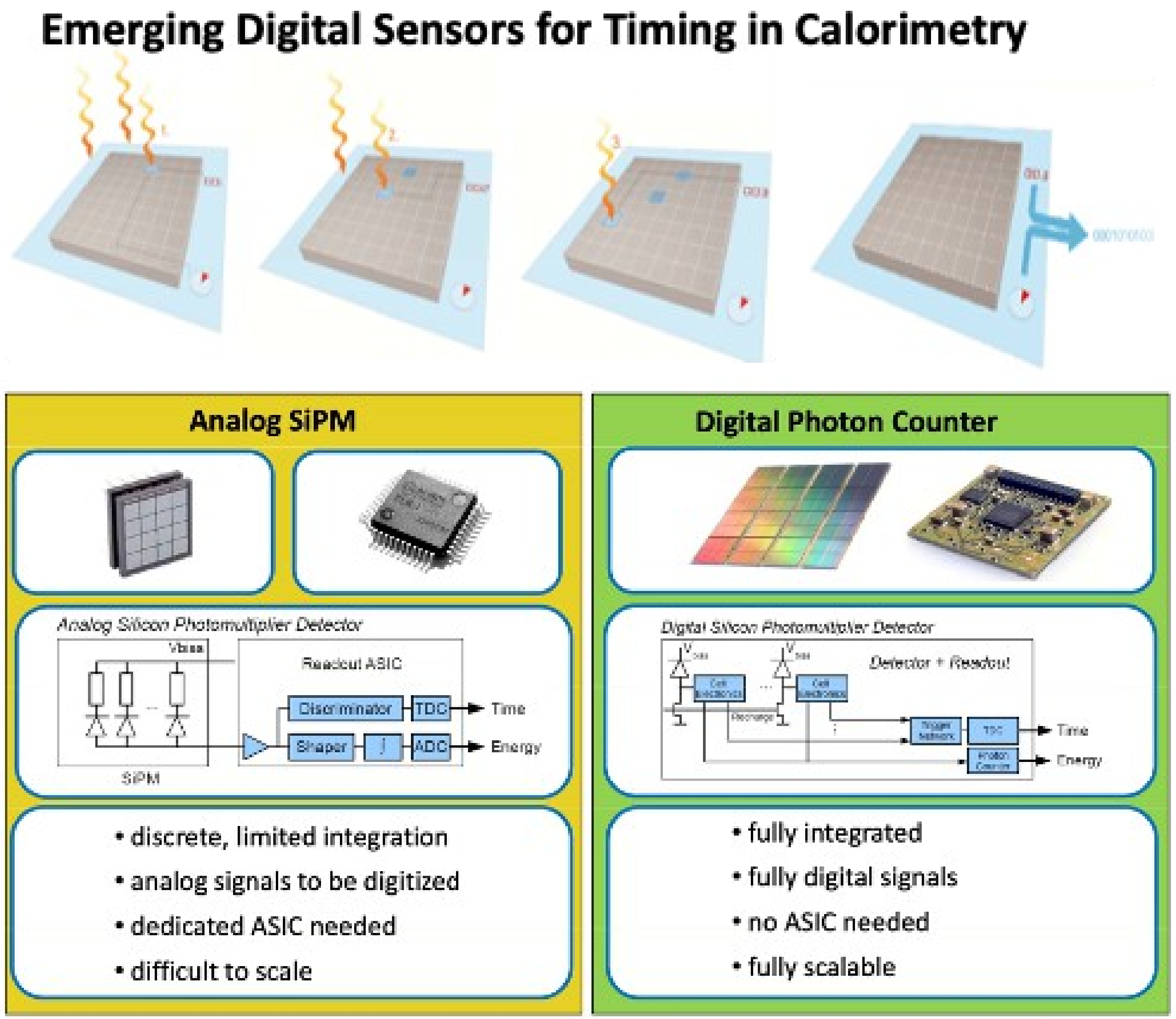
Several types of Fibers from ILM; Lyon

3 D printed garnet Crystals



Courtesy G. Dosovitskyi, Kurchatov Institute

R&D needs for precision timing in calorimeters



Signal-producing materials

- Optimization of properties e.g. fast rise/fall times; suppression (through doping) of slower components
- Industrialization of cost-effective mass production

Electronics

- Low-power high-precision TDCs & PLLs in ASICs
- Highly-performant low-power on-detector digitizers

Light-detection devices

- Ultra-fast light detectors (e.g. SiPMs) inc. digital varieties

Detectors

- High-precision timing over very large areas
- Use of dedicated embedded timing layers e.g. shower-max timing with RADiCAL, or LGAD layers etc.

Software/firmware

- Use of RNN, GNN etc. for single-photon detection, pileup mitigation, energy measurements, particle ID

General

- Prototyping & beam tests – critical for progress & training
- Close partnerships with industry for materials, sensors, electronics etc.

Shower development in CALICE type calorimeters I

Shower reconstruction

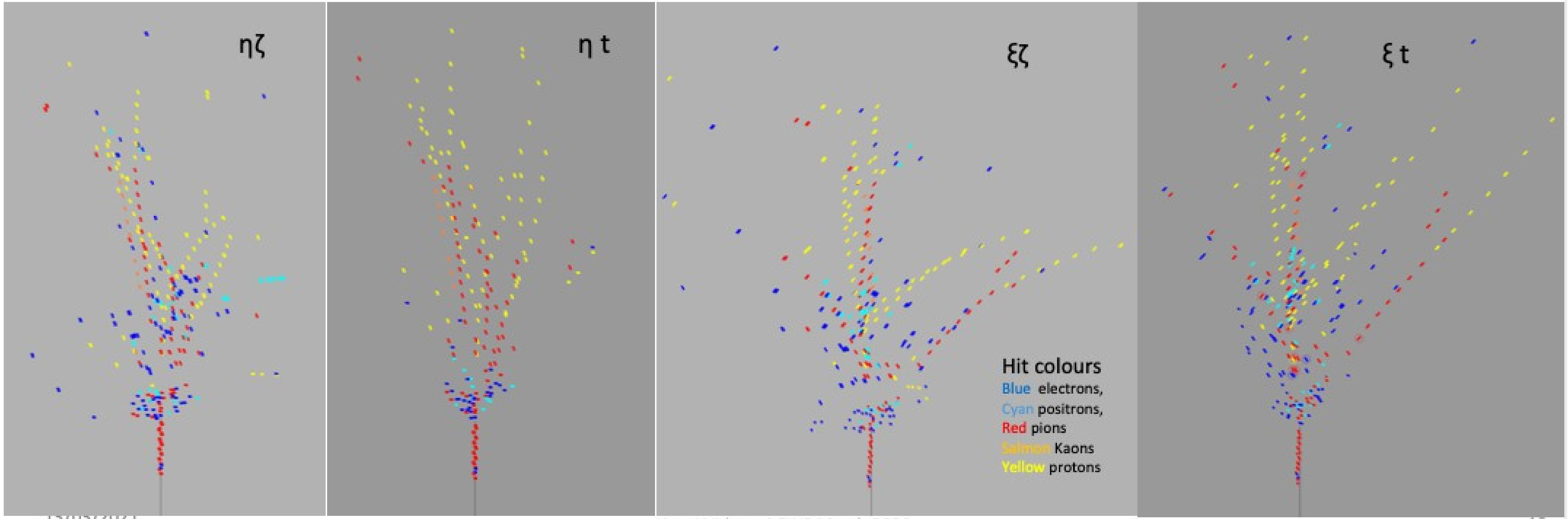
It is known that the more dimensions, the easiest to reconstruct patterns

Using the time-space

To figure out the pattern of a shower developed by a charged track or a neutral
We assume that the main direction of the shower, called ζ, is
- along the flight line from interaction to the earliest hit in the Ecal (or globally) for a neutral
- along the track direction at the position of the earliest hit for a charged track

Two perpendicular coordinates, ξ and η, are chosen to optimise the match with the detector axes, mostly for visualisation.
Then t which is much correlated to ζ.

You see immediately
the role of the β
and how the protons slow down
when the pions do not



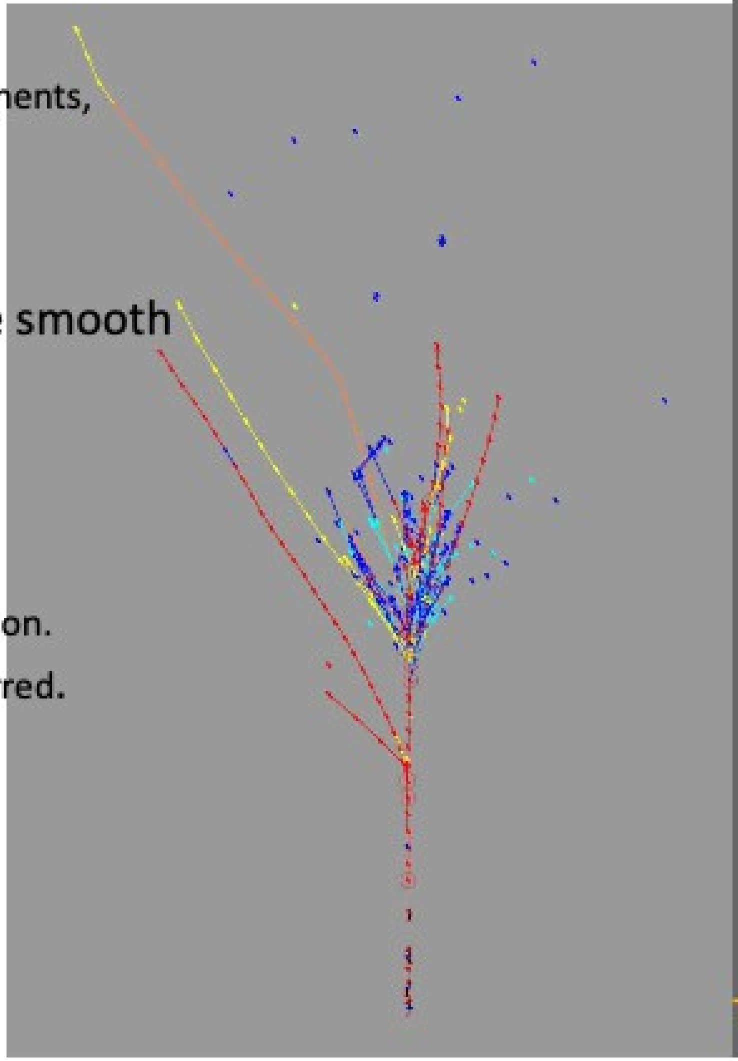
15/03/2021 Henri Videau LCWS March 2021 12

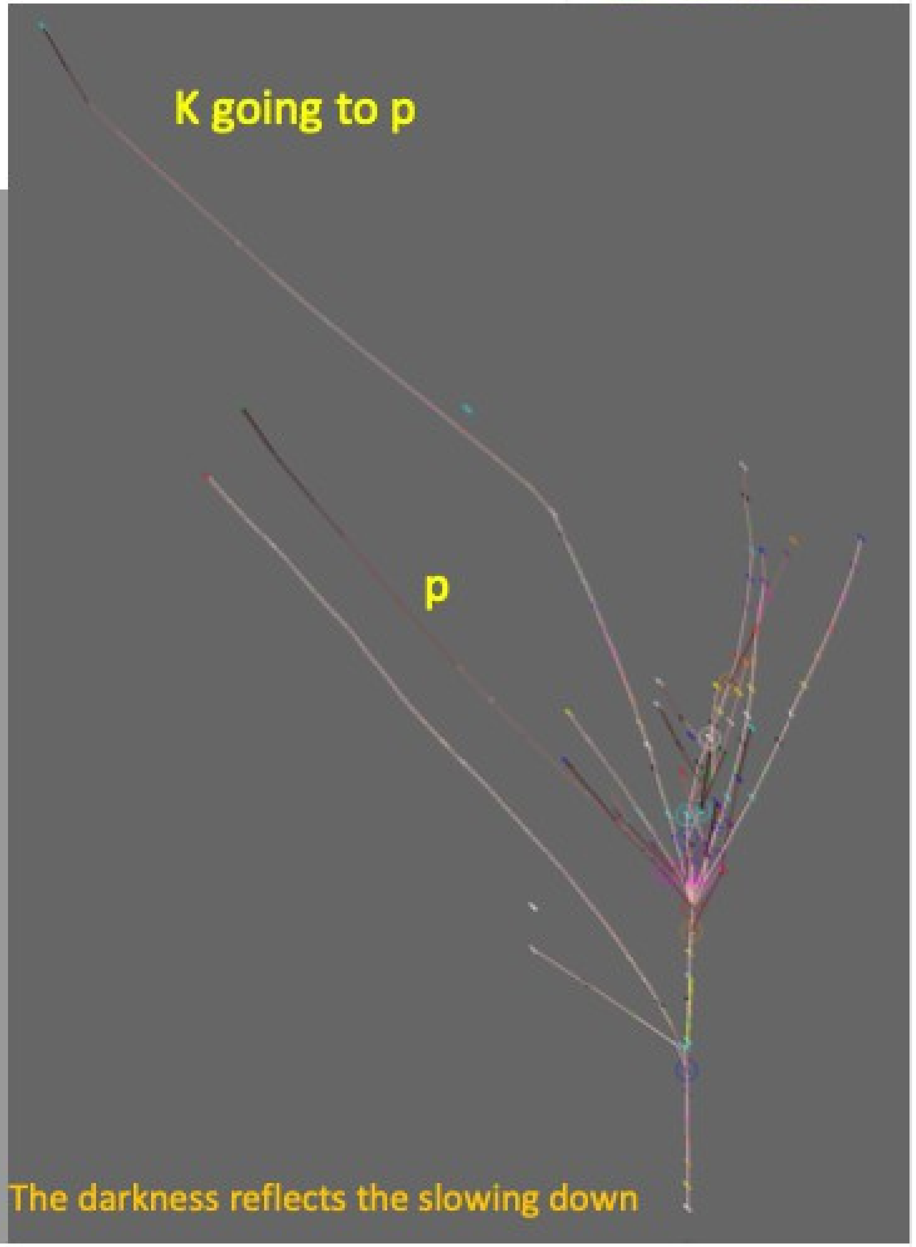
H.Videau et al., LCWS2021

Shower reconstruction

The constraint from a smooth β, within the errors, and the identification of decays
β can more or less be measured on each connector joigning two successive hits,
a change of β along a track.

A hadronic shower as seen in previous figures shows two components,
the hadronic tracks, the electromagnetic parts,
the hadrons fly a measurable time&distance
with a β uncertainty of 10% per step.
Successive βs measured along the track have to be smooth
and the energy loss on a certain length provides
an ID and an estimate of the momentum,
watch protons versus pions
Better, if the track comes to a stop,
its ID and energy are then measured by range with good precision.
The energy of a track sailing through the calorimeter can be inferred.





> A precise measurement of the time provides
> a strong tool to reconstruct tracks in a shower,
> to identify them,
> to measure their energy, to identify a decay
> as a spatial kink and a β step (space-time kink).

H.Videau et al., LCWS2021

Summary and Conclusion

- Optimal use of timing is the challenge for the next decade to come

- Need to specify what we mean with time resolution
  - Timing of high energetic shower with O(100MIPS) in a cell is “easy”
  - Timing at MIP level is much more challengng, O(10ps) for each cell!!!!

- Need to understand soon very well what we need
  - Can build up on LHC but future calorimeters man need to go further

- Imaging calorimeters will transit from highly pixelised snapshot cameras to film cameras
  - Rich fileld for application of modern algorithms
  - Attractiveness for next generation of scientists?

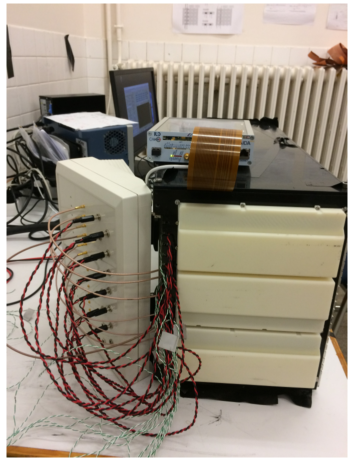
Backup

Timing – Key questions

- Particle flow is driving concept for most of the detector designs for Higgs factories
- Introducing timing for Higgs factories may assist PFA but has implications for detector design
- What is better?
  - Excellent timing of the order of 10-30ps in a few layers at e.g. the beginning of a calorimeter or
  - Average timing of the order of 100-200ps in the entire detector
- Guidance has to come from GEANT4 simulations that implement properly the time structure of hadronic showers
- The specific needs for timing would trigger dedicated hardware developments
- Given current hardware constraints CALICE will be able to validate G4 physics list at the 500ps - 1ns level
  - With large prototypes
  - Maybe better with smaller dedicated setups

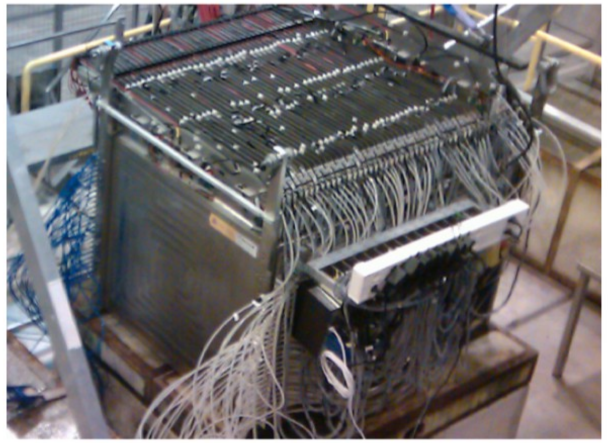
(Main) Technological prototypes

ScECAL



SiECAL

AHCAL



SDHCAL

Name	Sensitive Material	Absorber Material	Resolution	Pixel size/mm^3	~Layer size**/cm^3	~Layer depth/X_0	~Layer depth/λ_I	# of Pixels/ layer	# of layers	Comment
ScECAL	Scintillator	W-Cu Alloy	Analogue, 12bit	5x45x2	23x22x0.5	0.73	0.03	210	32	2x16 x and y strips
SiECAL	Si	W	Analogue, 12bit	5.5x5.5x 0.3 (0.5, 0.65)	18x18x 0.24 (- 0.63)	0.6-1.6	0.02-0.06	1024	≥22	Can be run in different configs.
AHCAL	Scintillator	Fe*/W	Analogue, 12bit	30x30x3	72x72x2/ 1.4	1/2.9	0.11	576	38	Running with Fe and W
SDHCAL	Gas	Fe*	Semi-digital 2bit	10x10x6	100x100x 2.6	1.1	0.12	9216	48	

*Stainless Steel

**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)