International Union of Pure and Applied Physics
C11 Young Scientist Prize 2020

Precision timing with fast crystals at collider experiments (from a biased perspective)

ICHEP 2020 | PRAGUE

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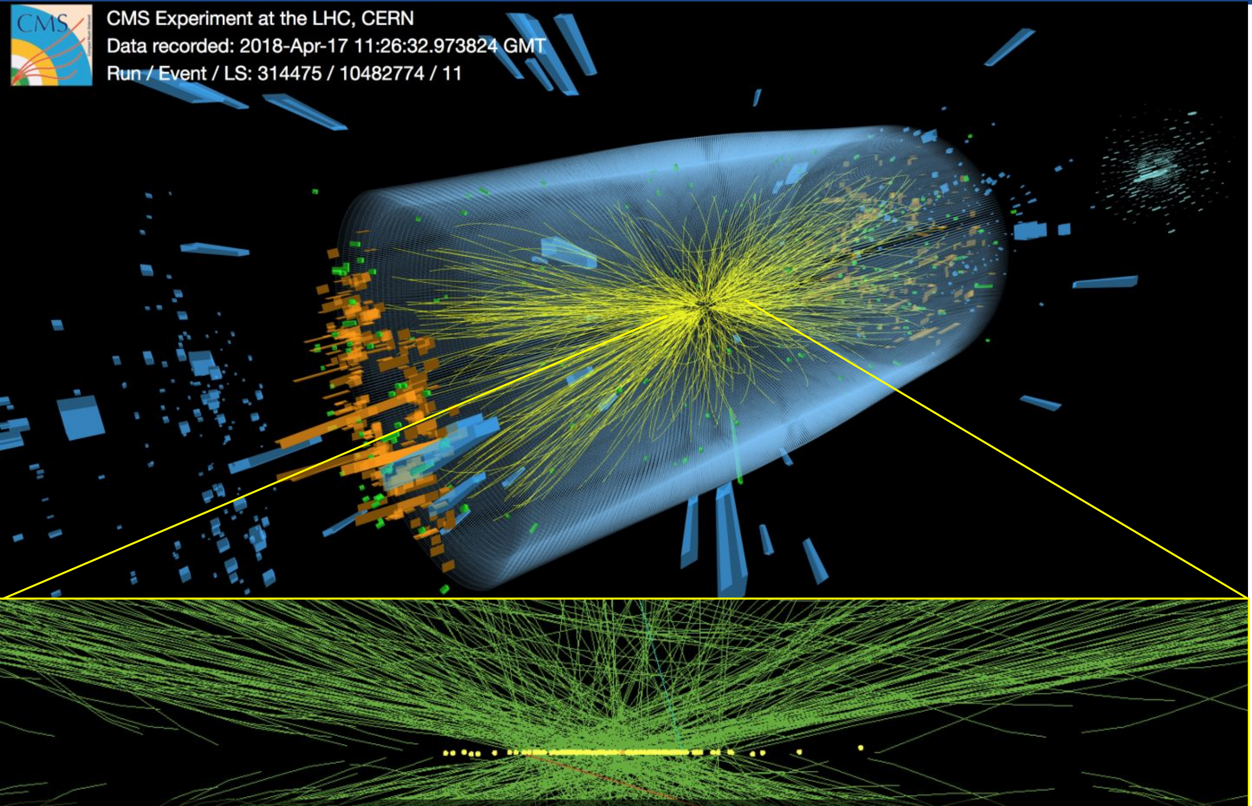
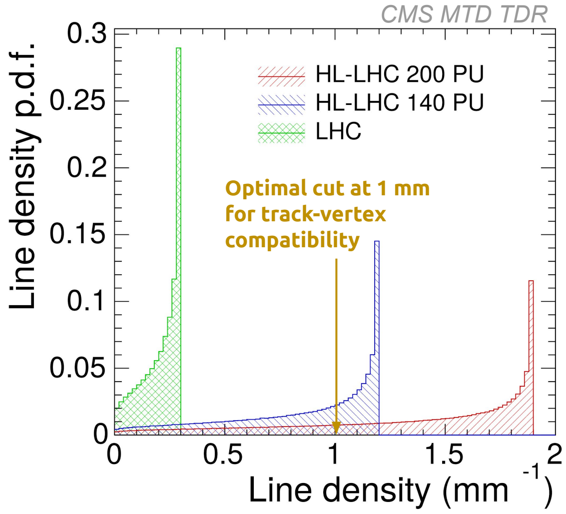
A **challenge** of high luminosity colliders (**HL-LHC**)



Number of collisions per bunch crossing (**pile-up**):

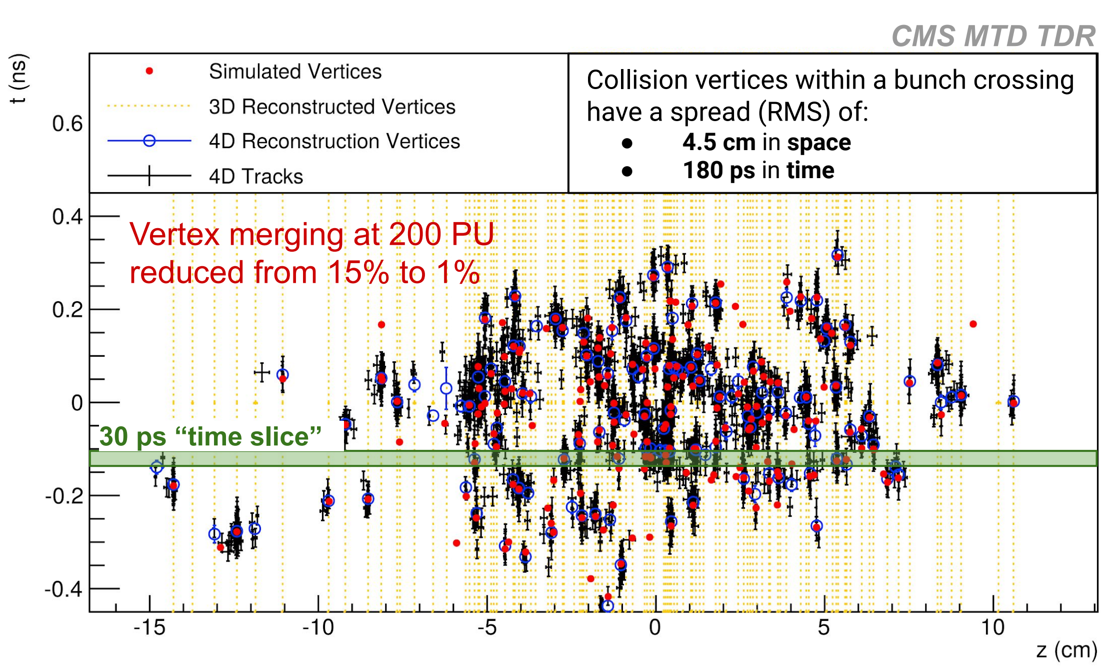
- Phase I LHC: ~40-50 collisions
- High Luminosity LHC: 140-200 collisions

- At HL-LHC, up to **5x higher vertex density** (than LHC)
- Challenging for algorithms based on spatial information only
  → **non-negligible impact of pile-up on physics quantities**



Extend our vision with **timing detectors**

Many presentations at ICHEP 2020 (e.g. ATLAS [C.Rizzi] and CMS [K.F.DiPetrillo, N.Lu])

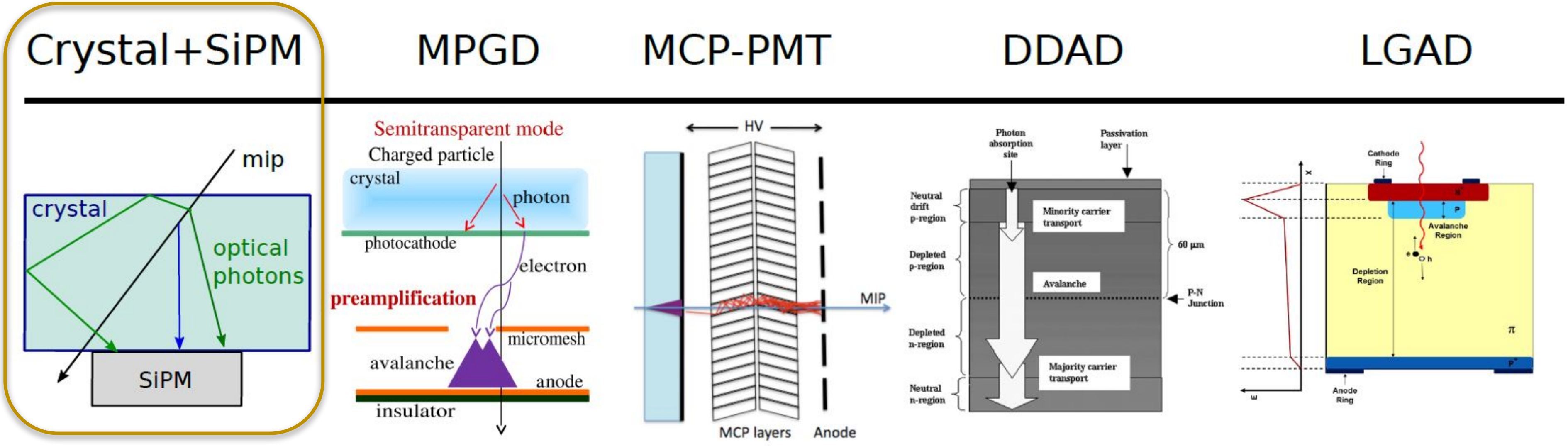


- Timing of charged particles helps with one of the major challenges of high luminosity colliders: **pile-up**
- It also enables new physics studies:
  - New reach for **Heavy ion physics** at CMS by discriminating low p_T hadrons (p,K,π) based on TOF
  - Searches for **long lived particles** by reconstructing secondary vertices through TOF

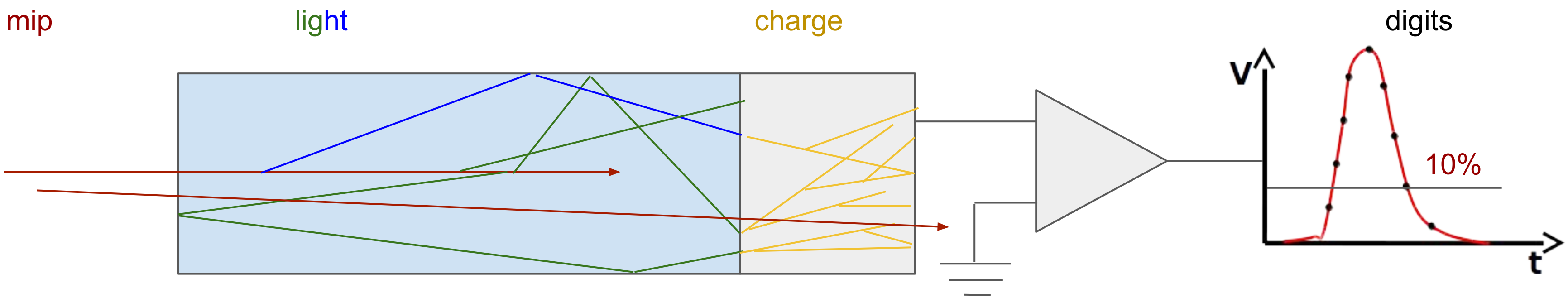
The number of use cases for high time resolutions at colliders grows the more we think about it!

Trending precision timing **technologies**

- Many technologies have been recently demonstrated capable to achieve O(30) ps time resolution for minimum ionizing particles
- **Fast scintillating crystals** read out with silicon photomultipliers are a robust, radiation tolerant and flexible option with advantages for scalability to large area detectors



Precision timing with **crystal based detectors**



SCINTILLATOR

1. Primary particle deposits energy in the scintillator volume (**dE/dx**, Bethe-Block) and a finite number of **e-h pairs** from ionization are created along the track

2. Generation of a **finite number of photons** (LY) following the time distribution of the scintillation process (rise+decay time)

3. **Travel time** of photons to reach the photodetector (absorption, surface losses/reflections, scattering)

PHOTODETECTOR

1. Photons are detected with limited efficiency (**PDE**) at the photocathode (generation of photoelectrons)

2. Photoelectrons are amplified via a multiplication process (**gain**)

3. A single photoelectron is detected with limited time resolution (**SPTR**) related to the detection and avalanche mechanisms

4. Charge is collected at the anode

ELECTRONICS

1. Signal is shaped and amplified (electronic **noise** is present)

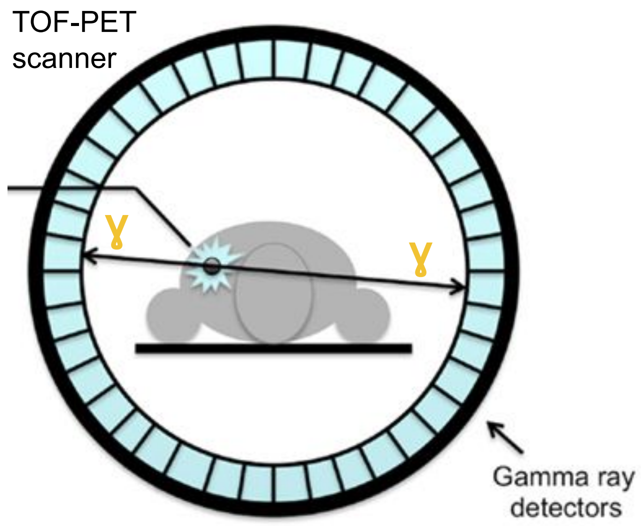
2. Time information must be extracted from the electric signal:
- leading edge **discrimination**
- constant fraction discrimination
- fine waveform sampling

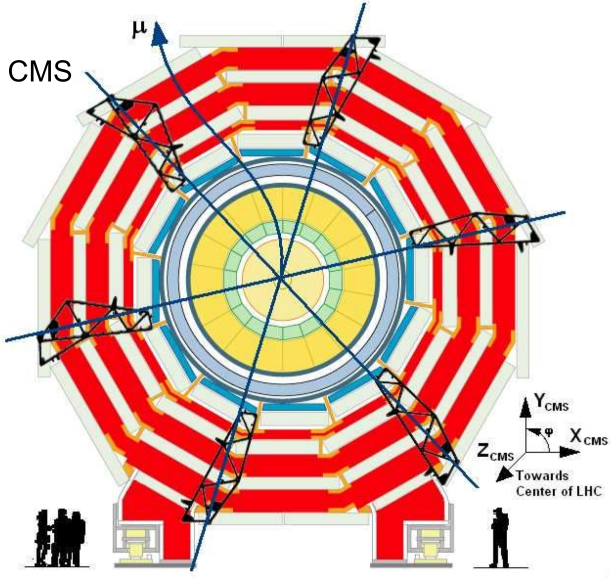
2. Time stamp from the discrimination is with respect to an internal **clock** of the instrument (which may jitter)

Several steps in the overall detection chain need to be optimized to achieve picosecond-level timing!

Synergies with medical imaging applications

- Crystals and SiPMs are of great interest also for **t**ime-**o**f-**f**light **p**ositron **e**mission **t**omography
- Both fields are targeting unprecedented time resolution to enable new detector features
- *Personal experience: **synergies and knowledge transfer between the medical imaging and HEP fields** boosted the development of crystal+SiPM technologies for timing applications*





- **Similar challenges:**
  - Hunt for fast, bright,
  - and dense crystals
  - SiPMs with high PDE and good single photon time resolution
- **More HEP challenges:**
  - Larger areas
  - Radiation tolerance
  - Higher rate

Understanding and optimizing **scintillating crystal properties**

- Working closely with crystal manufacturers to **enhance scintillation properties for timing applications**

- Key factors are:
  - High light yield and density
  - Short rise and decay times

$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{dep} \cdot LY \cdot LCE \cdot PDE}}$$

Scintillation rise and decay time constants

SiPM Photon Detection Efficiency

Energy deposit in the crystal

Crystal Light Yield

Light Collection Efficiency

Nuclear Instruments and Methods in Physics Research A 852 (2017) 1–9

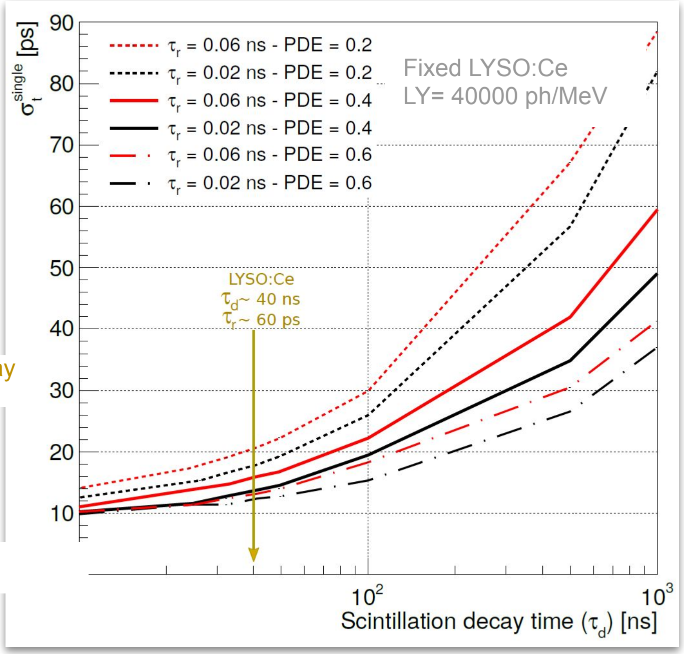
Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

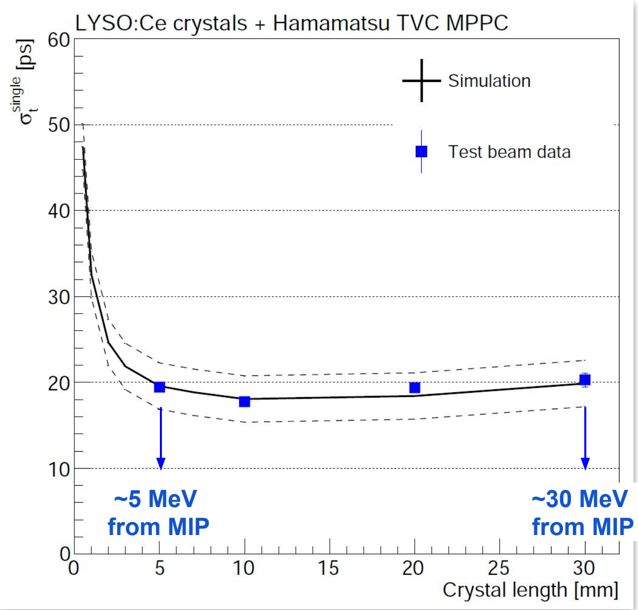
Timing capabilities of garnet crystals for detection of high energy charged particles

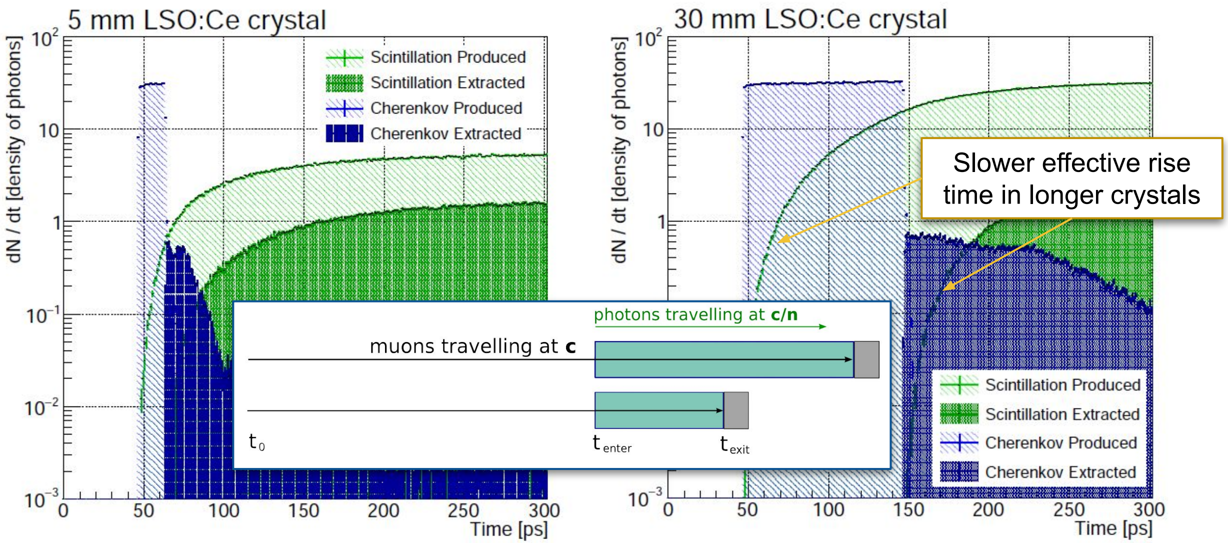
M.T. Lucchini[a,*], S. Gundacker[a], P. Lecoq[a], A. Benaglia[b], M. Nikl[c], K. Kamada[d,f], A. Yoshikawa[d,e,f], E. Auffray[a]



The impact of **light transit time**

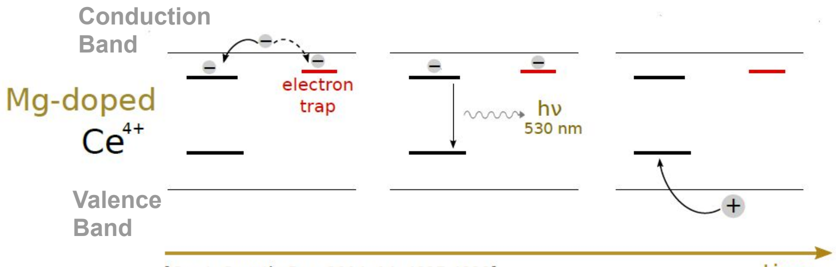
Despite the larger light signal in longer crystals the improvement in time resolution is small since light is produced over a larger time interval





Crystal **band-gap engineering**

- **Co-doping of crystals with divalent ions** (e.g. Mg^{2+}, Ca^{2+}) a viable path **to achieve:**
  - faster scintillation kinetics
  - better radiation tolerance



[Cryst. Growth. Des. 2014, 14, 4827-4833]

Nuclear Instruments and Methods in Physics Research A 816 (2016) 176–183

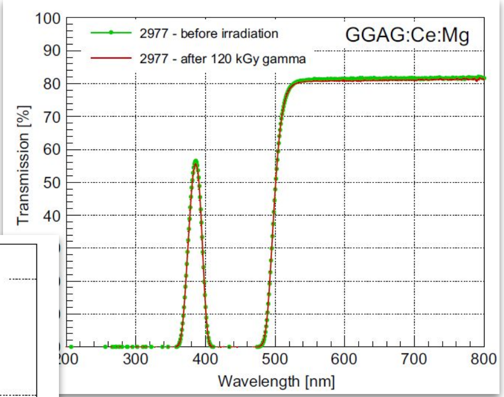
Contents lists available at ScienceDirect

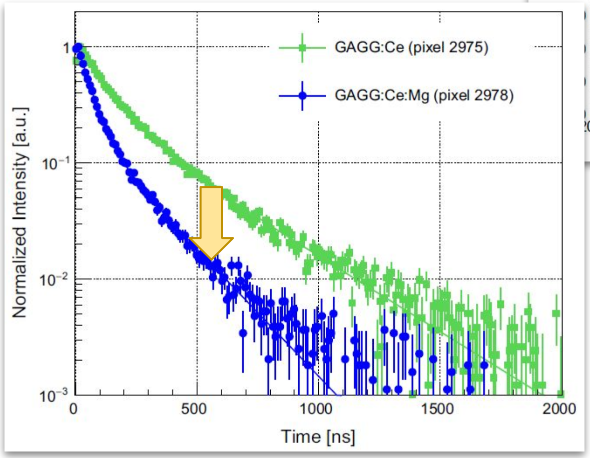
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Effect of Mg^{2+} ions co-doping on timing performance and radiation tolerance of Cerium doped $Gd_3Al_2Ga_3O_{12}$ crystals

M.T. Lucchini [a,*], V. Babin [c], P. Bohacek [c], S. Gundacker [a], K. Kamada [d,f], M. Nikl [c], A. Petrosyan [b], A. Yoshikawa [d,e,f], E. Auffray [a]





Proof-of-concept:
10 ps time resolution achieved!

- Proof-of-principle that an optimized (small and fast) crystal+SiPM sensor can achieve **10 ps time resolution** for detection of a single MIP
- **Test beam results** obtained with muon beam at the CERN SPS, using NINO ASIC-based electronics for SiPM readout

Nuclear Instruments and Methods in Physics Research A 830 (2016) 30–35

ELSEVIER

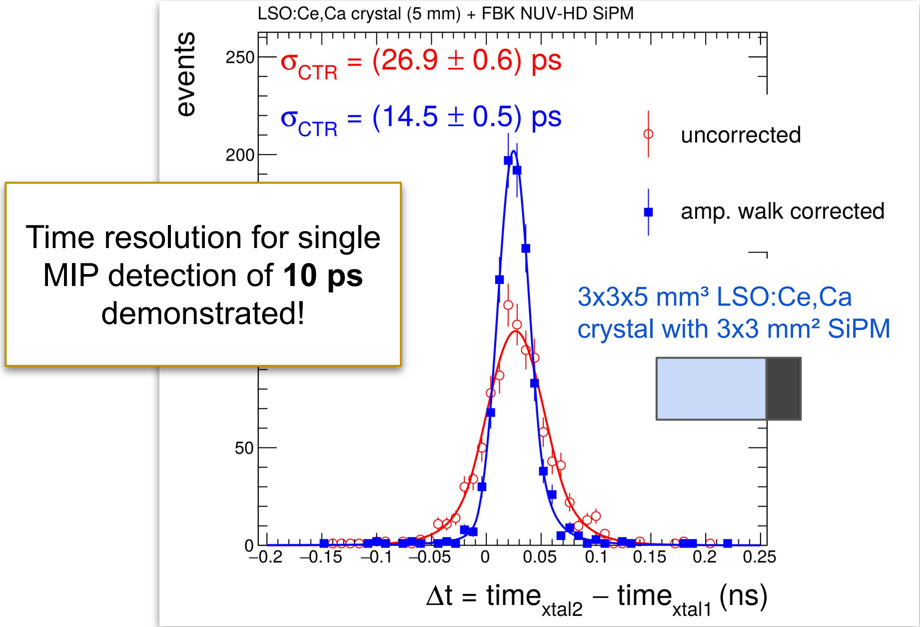
Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

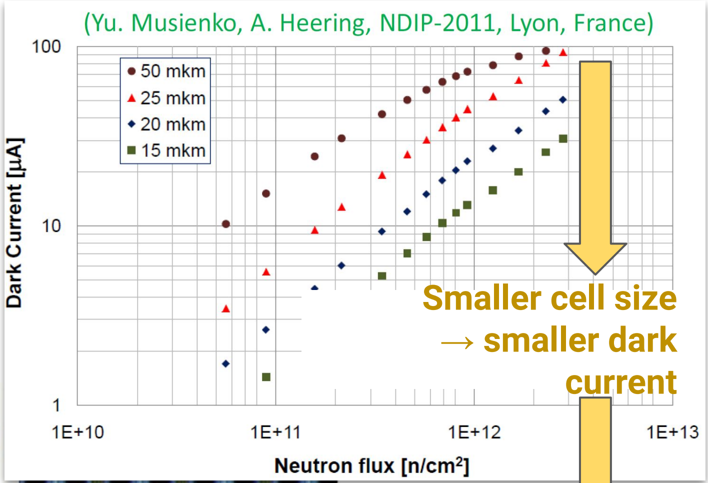
Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout

A. Benaglia [a,*], S. Gundacker [a], P. Lecoq [a], M.T. Lucchini [a], A. Para [b], K. Pauwels [a], E. Auffray [a]

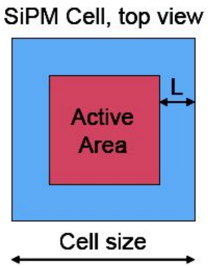


Silicon Photomultipliers for timing

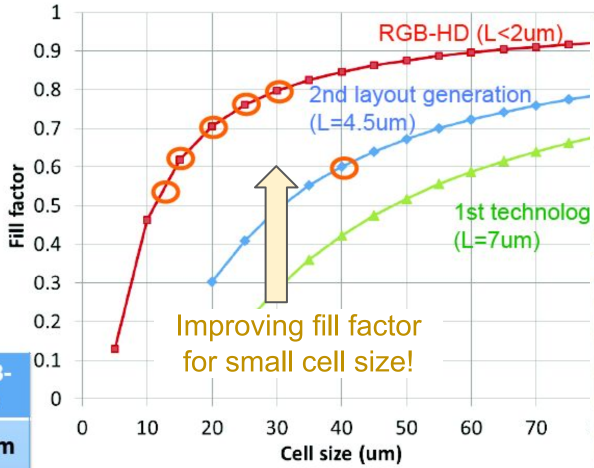
- Key SiPM properties for timing applications:
  - High **PDE** (photon detection efficiency)
  - Good **SPTR** (single photon time resolution)
- **Radiation tolerance**, an additional challenge
  - Huge improvements over the past years driven by HEP applications! (e.g. CMS Upgrades)



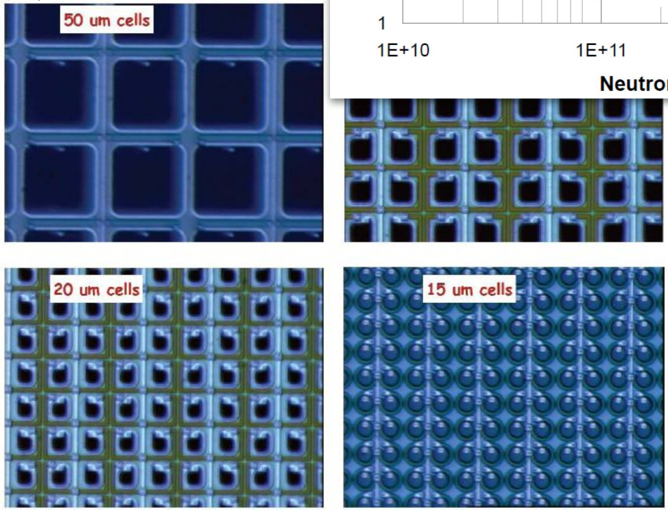
Smaller cell size → smaller dark current



	Std. SiPM RBG	RGB-HD
CS	40 μm	15 μm
FF	60 %	62 %



Courtesy of FBK



Smaller cell occupancy

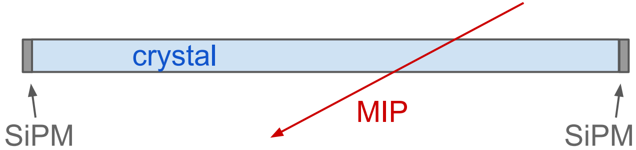
Less self-heating effects

Challenges of **large area detectors**

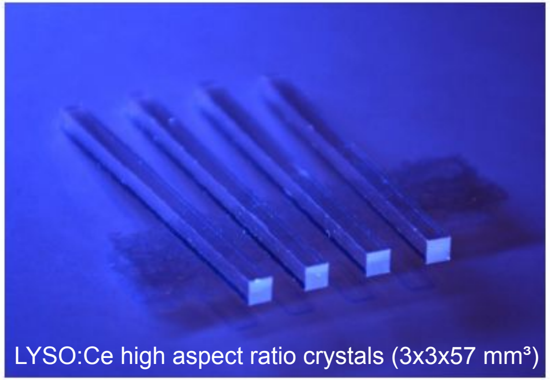
Scaling up a proof-of-concept detector technology to instrument large areas typical of collider experiments while maintaining excellent time resolution poses new challenges

- **Cost**
- **Power consumption**
- **Channel count**
- **Uniformity**

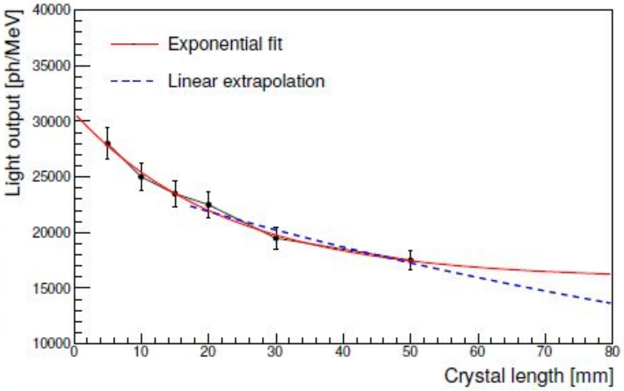
One way to reduce channel count is to exploit total internal reflection of light in high aspect ratio crystals



Pictures from CMS MTD TDR



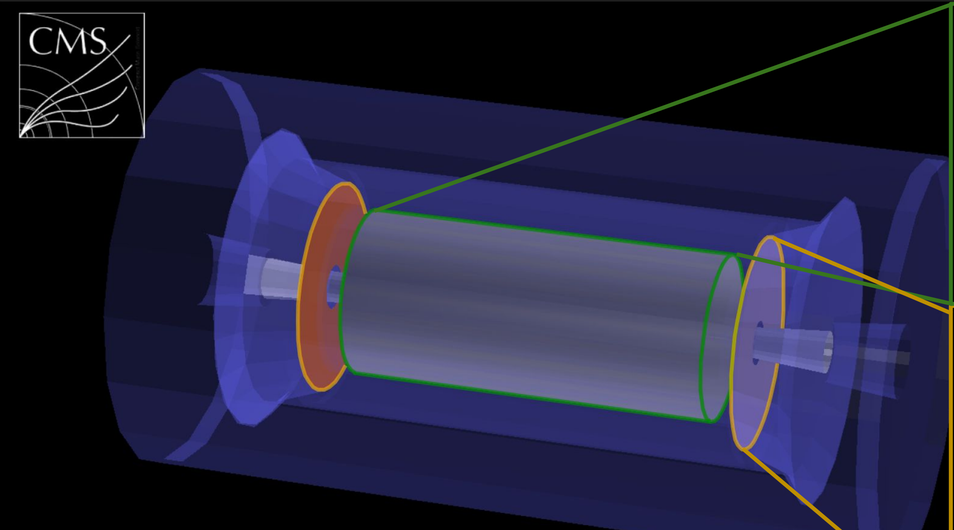
LYSO:Ce high aspect ratio crystals (3x3x57 mm^3)



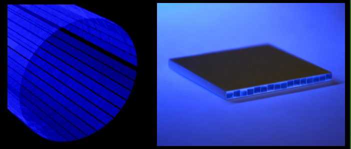
An **example**: the CMS MIP Timing Detector

- R&D on precision timing with fast crystals converged on a concrete proposal for a large area timing detector
- Global **detector optimization exploits different technologies** in different regions of the detector

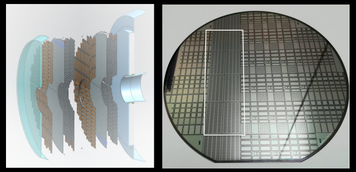
https://cds.cern.ch/record/2667167



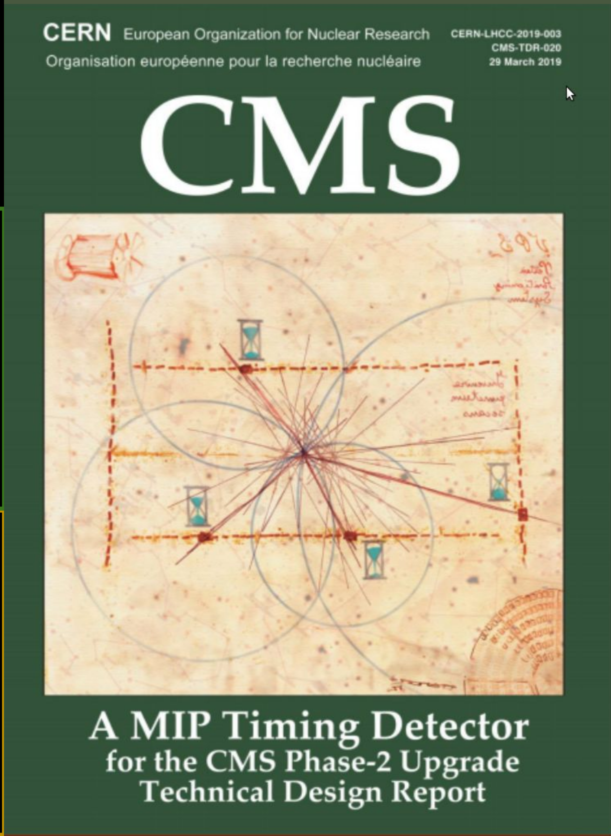
BARREL
Surface ~ **38 m²**
Number of channels ~ **332k**
Radiation level ~ **2×10^{14} n_{eq}/cm²**
Sensors: LYSO crystals + SiPMs



ENDCAPS
Surface ~ **14 m²**
Number of channels ~ **8500k**
Radiation level ~ **2×10^{15} n_{eq}/cm²**
Sensors: Low gain avalanche detectors



- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for $|\eta|<3.0$


CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire
CERN-LHCC-2019-003
CMS-TDR-020
29 March 2019

CMS

A MIP Timing Detector
for the CMS Phase-2 Upgrade
Technical Design Report

Many thanks

Princeton and CERN-Lab27 groups

CMS colleagues

ICHEP 2020 conference organizers

IUPAP committee