5th Workshop on LHCb upgrade II

30 .03 - 01 .04. 2020
Barcelona

ECAL Technologies

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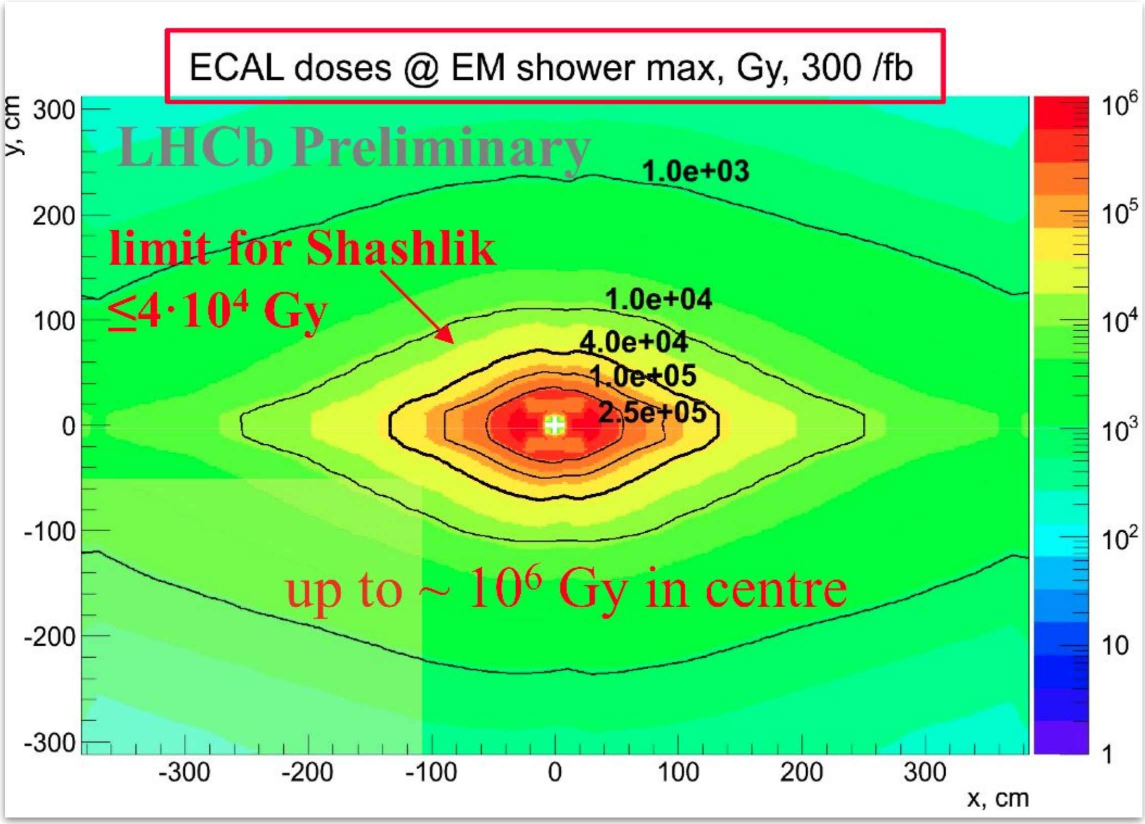
on behalf of the SPACAL R&D group
(LHCb and Crystal Clear Collaboration)

Outline

- ➔ Motivation
- ➔ Investigation on garnet-based crystal fibers
- ➔ Spacal 2018 & 2019 prototypes: beamtest results
- ➔ Shashlik beamtest results
- ➔ Photodetectors and readout electronics
- ➔ Timing plane
- ➔ Conclusions and perspectives

Motivation for ECAL upgrade

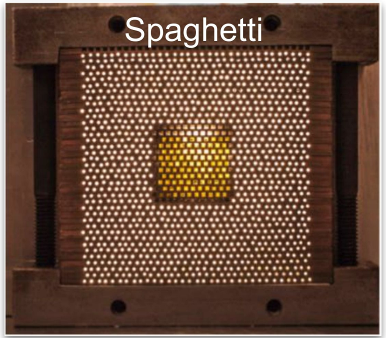


General upgrade of ECAL

- ➔ Central part (max 32 modules) needs to be replaced already during LS3
- ➔ Major upgrade foreseen for LS4 for the rest of the calorimeter, with less demanding radiation requirements

- ➔ Sustain expected **radiation dose**, up to 1MGy and ≤ 6×10^{15} cm^{-2} for 1MeV neq/cm^2 at 300 fb^{-1}
- ➔ Introduce **fast timing** resolution (few tens of ps) for pile up mitigation, and better energy reco.
- ➔ Increase **granularity** to reduce occupancy
- ➔ Keep energy resolution in the order of **$\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$**

ECAL upgrade: possible options

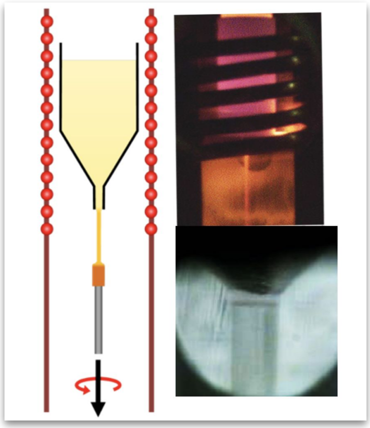


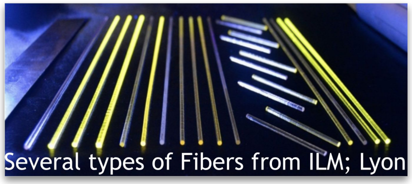
Homogeneous Crystal	Shashlik Module	Spaghetti Module
Can require long crystals (order 40 cm) to contain 25 X_0	Can be made very compact (~ 15-20 cm)	Can be made very compact (~ 15-20 cm)
Fixed Moliere Radius	Tunable Moliere Radius	Tunable Moliere Radius
Good energy resolution, few %/√E (but material budget in front of ECAL should be kept at minimum)	Good energy resolution	Challenging optimization to reach good energy resolution
Very good homogeneity	**No radiation-hard WLS fibers (yet) to transport light**	**Fibers scintillate AND transport light!**
Large volume of crystal ➡️ high cost	Some cost optimization possible	Some cost optimization possible

Started R&D on Spaghetti type module (SPACAL)

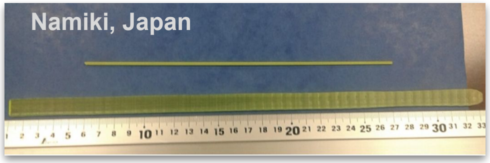
Crystal fibers production methods

μ-PullingDown

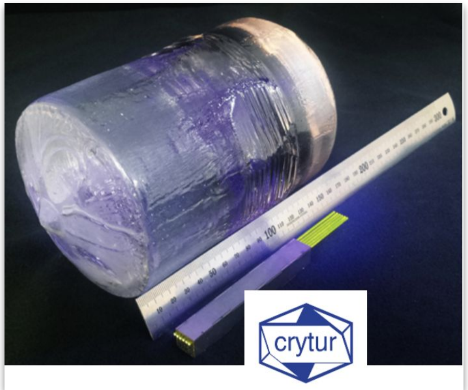


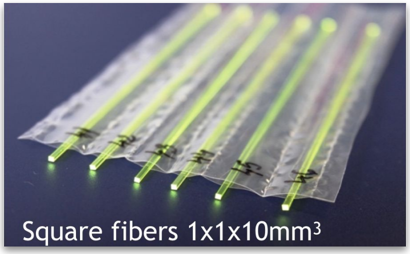


Edge-defined film-fed growth (EFG)



Czochralski

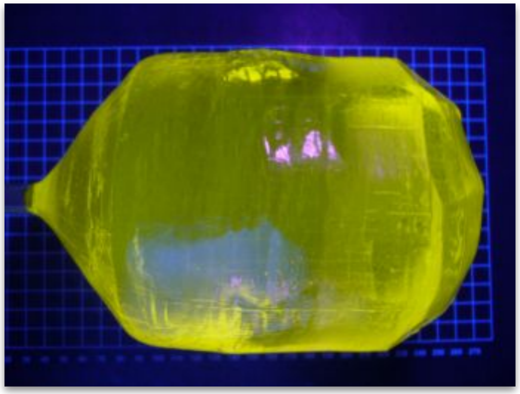


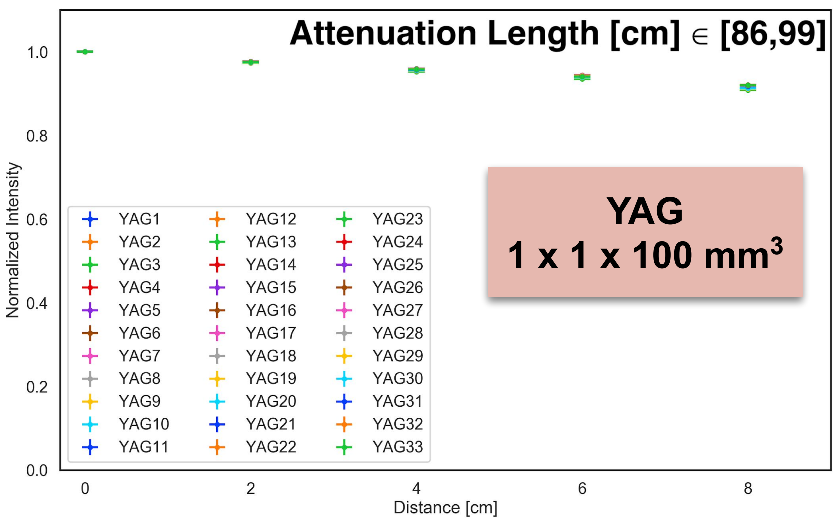


Feasibility study carried out in the frame of the **Intelum project** (EU Rise grant 644260)

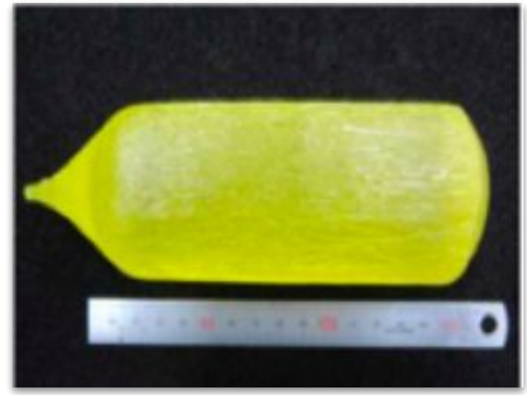
Crystal fibers for SPACAL

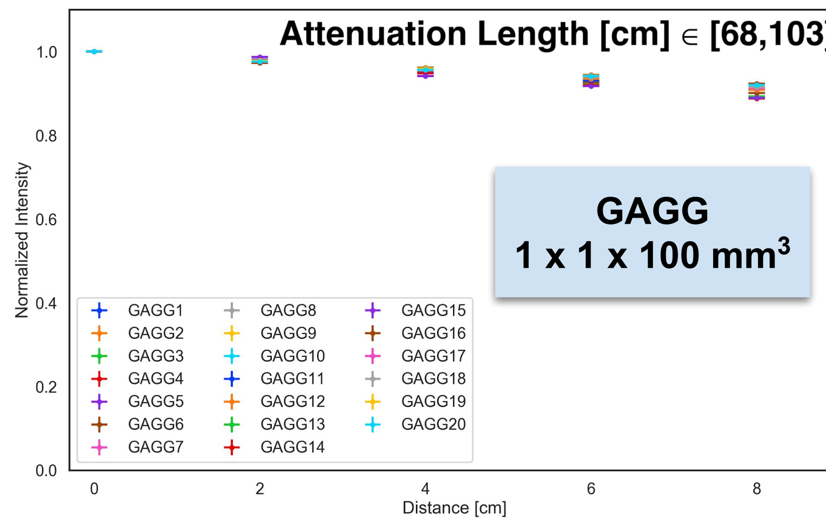
YAG (Crytur)





GAGG (FOMOS)

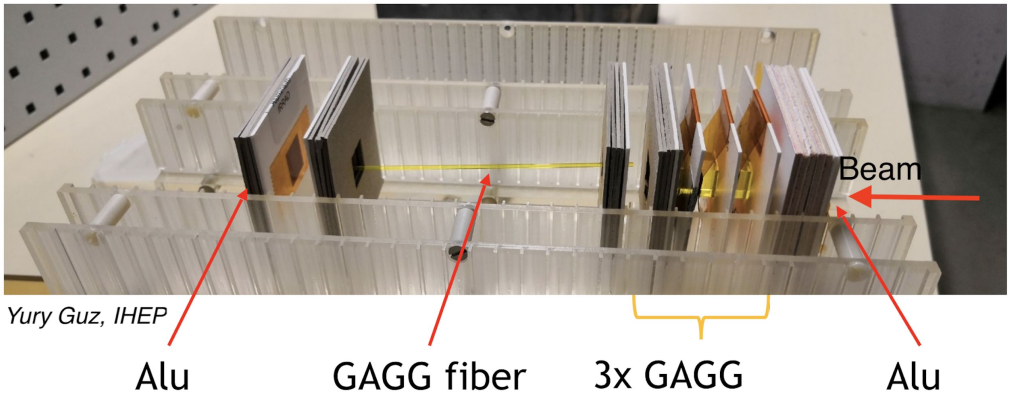


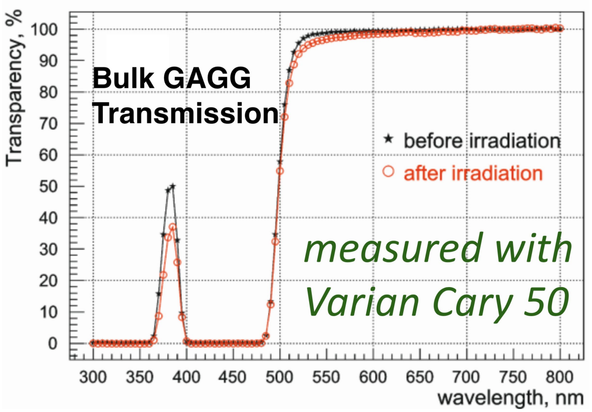


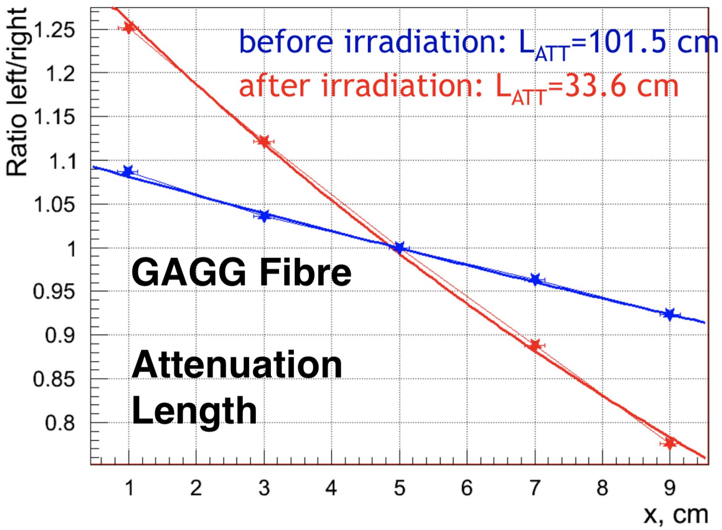
Czochralski-technique selected for SPACAL R&D activity, since currently it provides the best quality

Radiation Hardness - GAGG

GAGG samples irradiated with proton flux of 3.5 x 10^{15} p/cm^2, 24 GeV (1.03 MGy) at CERN PS



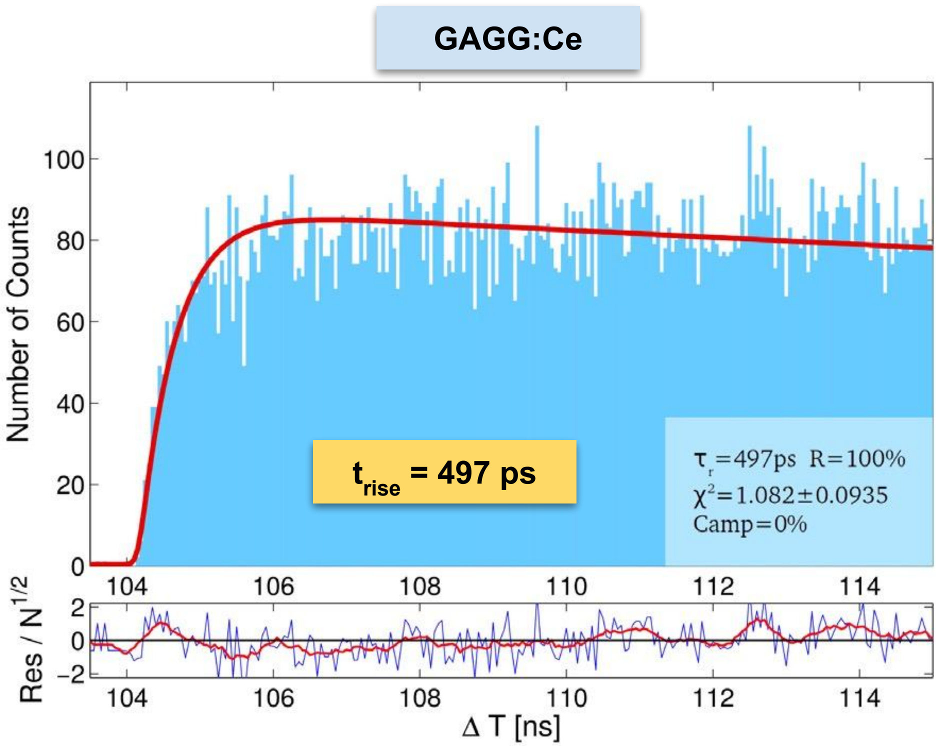


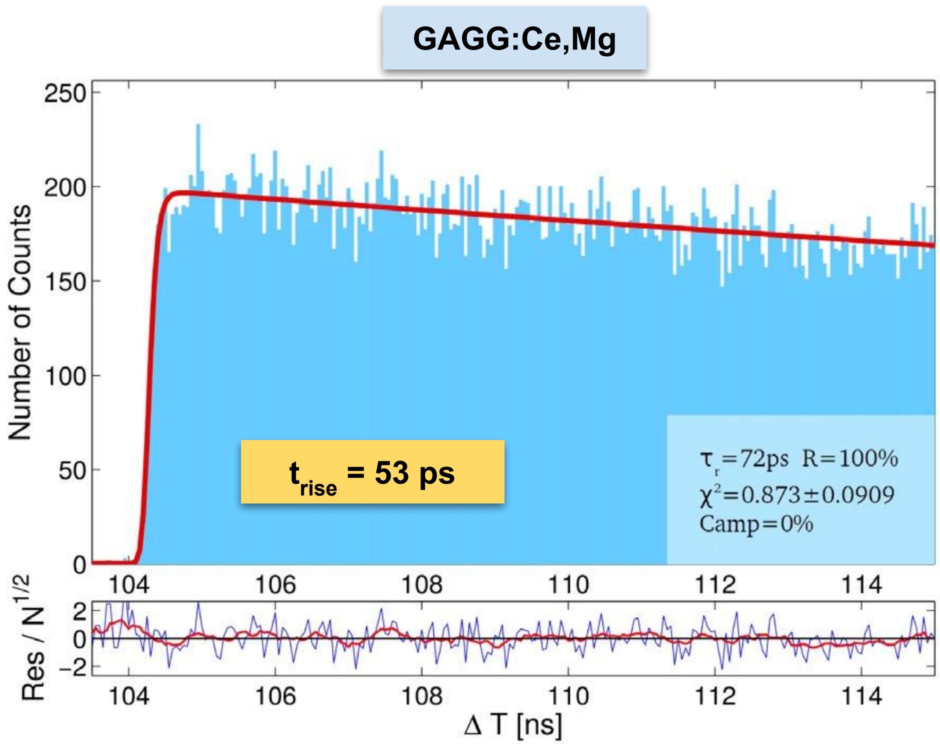


- ➔ Contribution of 2% to constant term of energy (if radiation length X_0 = 0.8 cm)
- ➔ Performance of GAGG acceptable after ~1 MGy (100 Mrad) irradiation

Time Resolution - GAGG

➔ **GAGG** samples from several producers characterized in terms of
- ➢ Coincidence timing resolution (CTR) @ 511 KeV
- ➢ Light output
- ➢ Scintillation kinematics





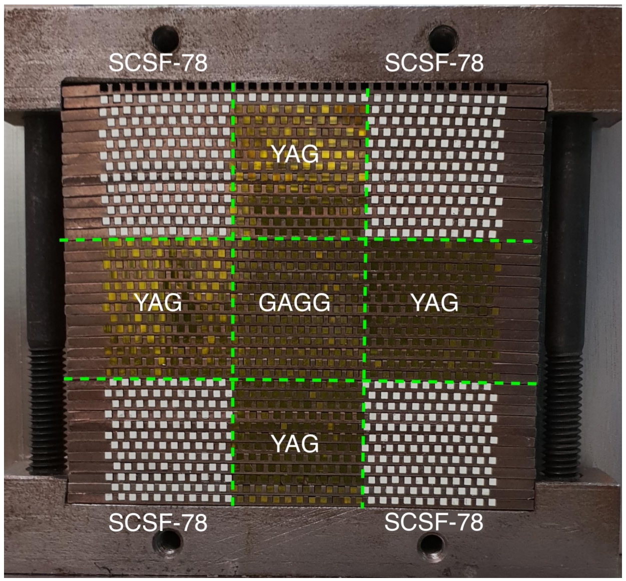
S. Gundacker et al, NIMA A 891 (2018) 42–52

➔ Aimed at producing faster crystals speeding up scintillation process

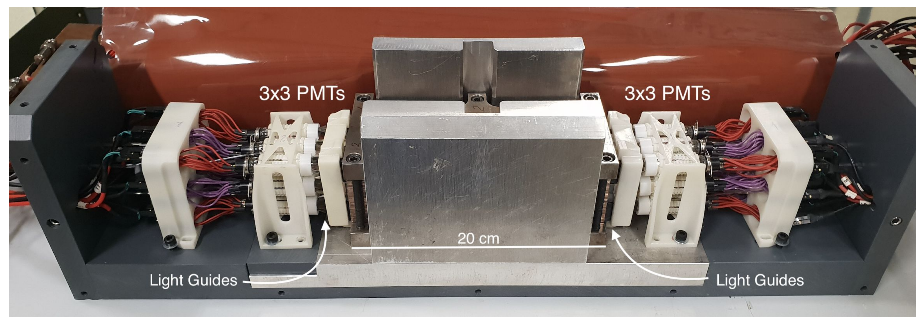
➔ Influence of co-doping on timing performance (especially on rise-time)

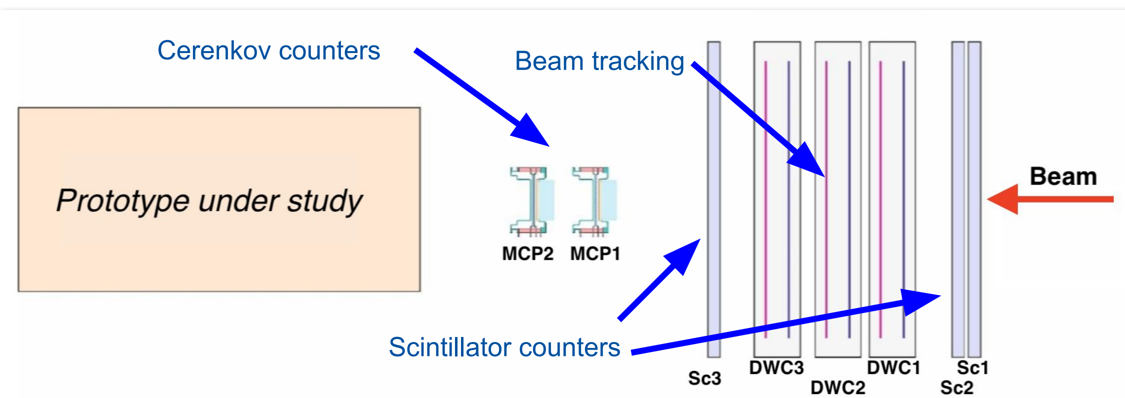
First SPACAL prototype - 2018

Performed at CERN SPS H8: **180 GeV muons** and **20 GeV electrons**



- ➔ W/Cu alloy absorber (75/25), 14.9 g/cm^3
- ➔ Module length 20 cm (25 X_0)
- ➔ Longitudinal segmentation: 10 cm + 10 cm
- ➔ 9 cells of 2 x 2 cm^2 with Moliere Radius ~1.5 cm
- ➔ 1 cell of GAGG and 4 cells of YAG
- ➔ 4 cells of SCSF-78 (KURARAY)



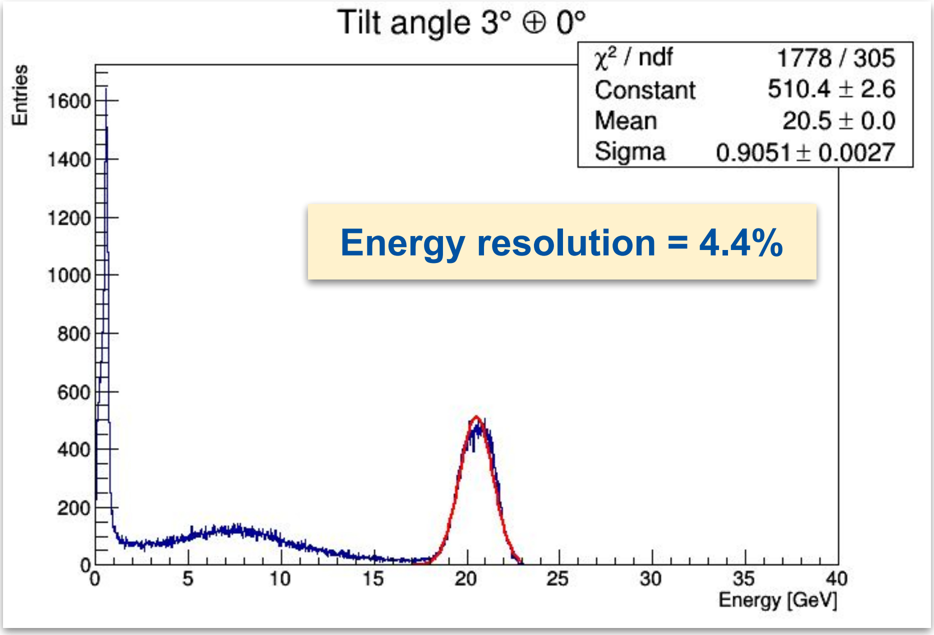


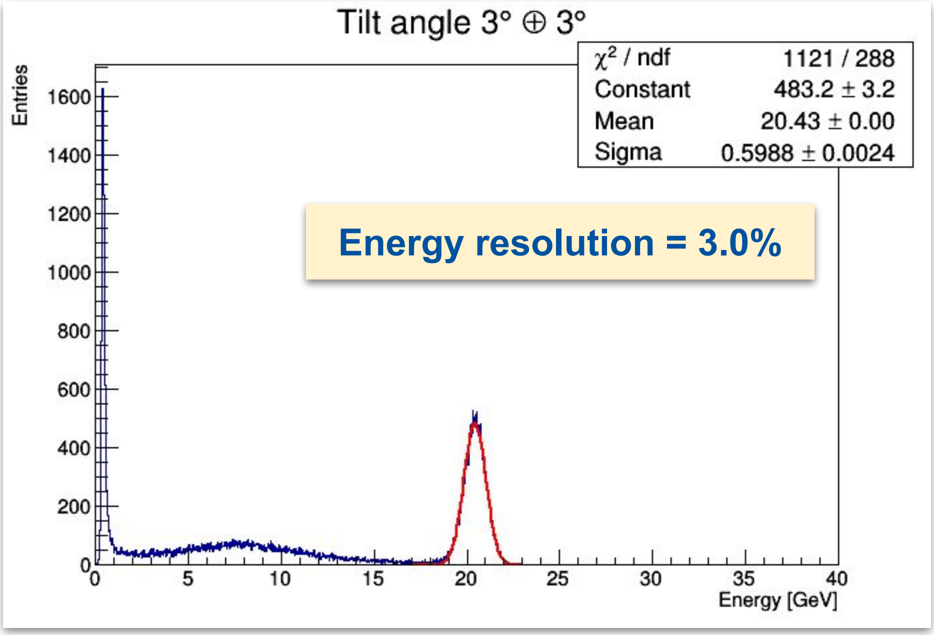
READOUT

- ➔ CAEN TDC V1290N - DWCs readout
- ➔ LeCroy ADC 1182 - Amplitude measurement
- ➔ CAEN DT5742 digitizer - Waveform recording

Energy resolution with 20 GeV e⁻

With different tilt angles, selecting events hitting a 10 x 10 mm^2 square in the center of prototype

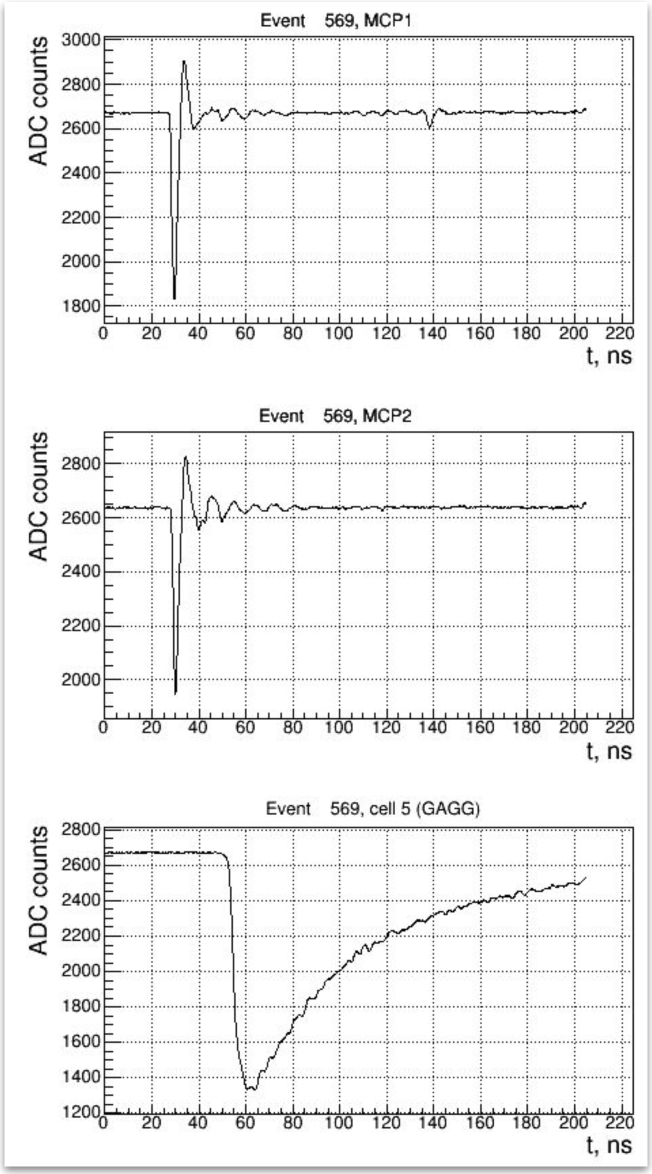


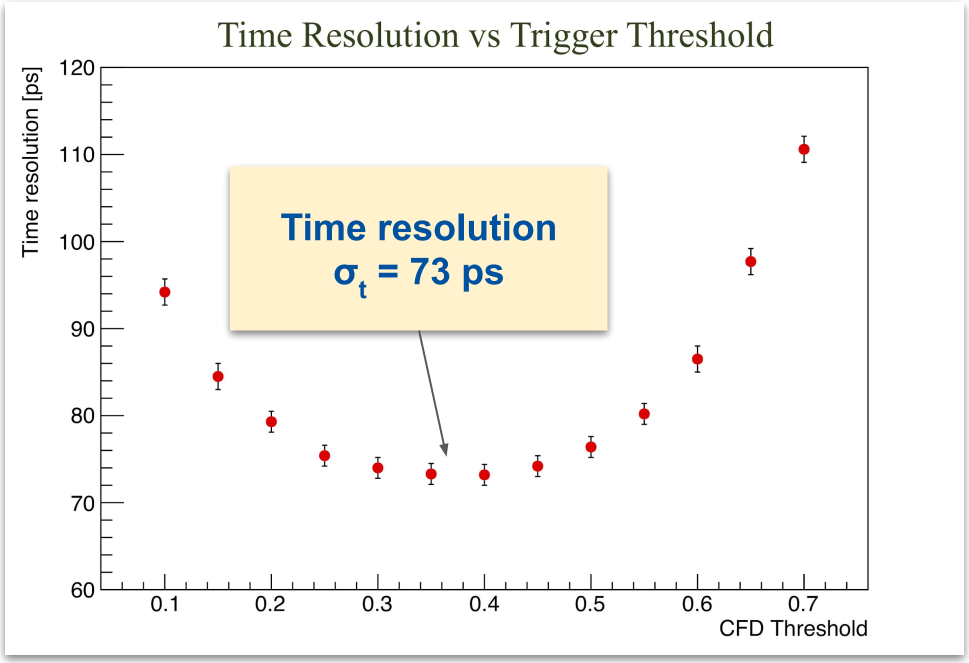


Material	Photoelectrons/MeV
GAGG	9.71 ± 0.22
YAG	6.76 ± 0.16
Plastic	1.15 ± 0.14

- ➔ GAGG/YAG ratio compatible with lab measurements
- ➔ Efforts to improve light coupling (ray-tracing simulations show factor ~4 light loss)

Timing resolution with 20 GeV e^-

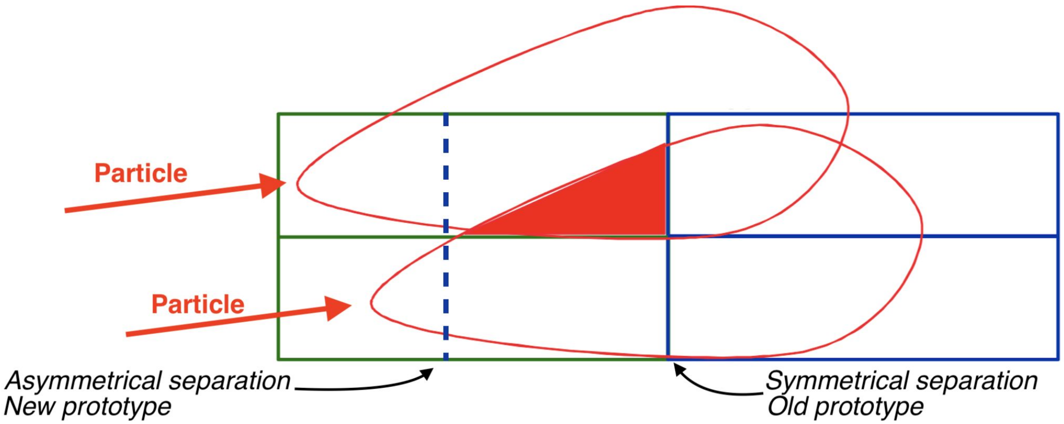


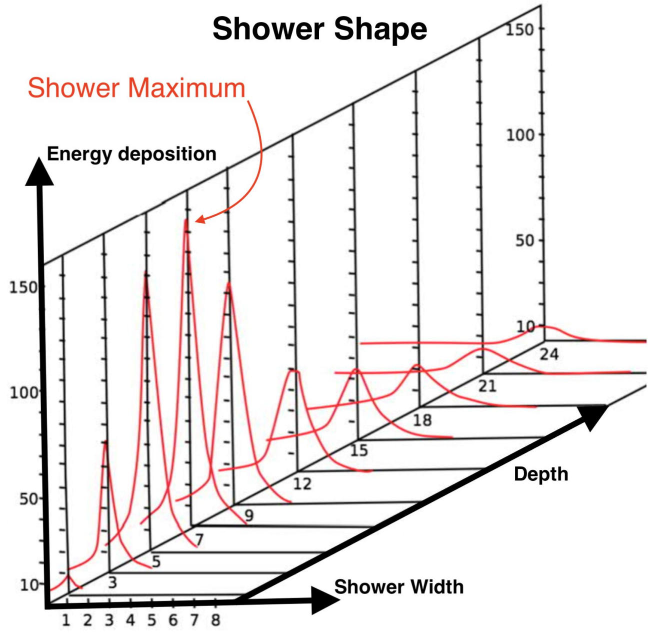


Time measurement on **GAGG** front cell:

- ➔ PMT Hamamatsu R12421
- ➔ Offline CFD technique
- ➔ Corrected for MCPs reference photodetectors resolution (σ = 21.8 ps)
- ➔ Best value σ_t = 73 ps

2019 SPACAL prototype

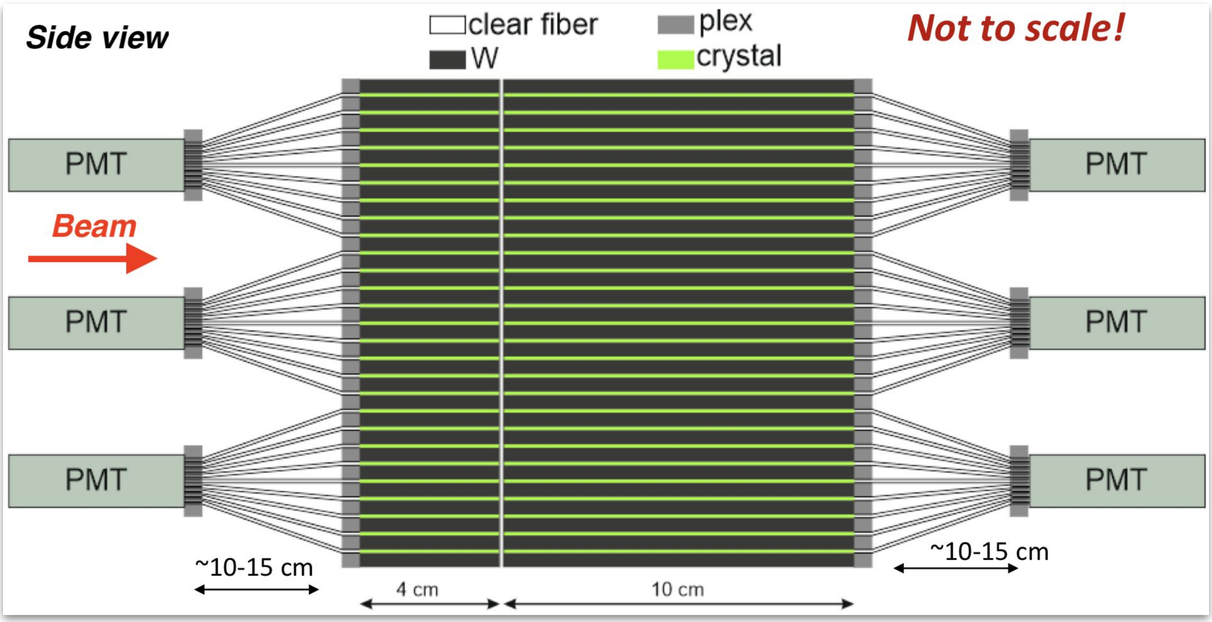


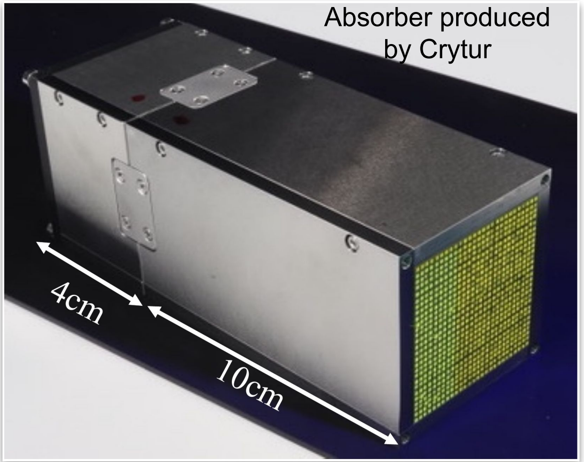


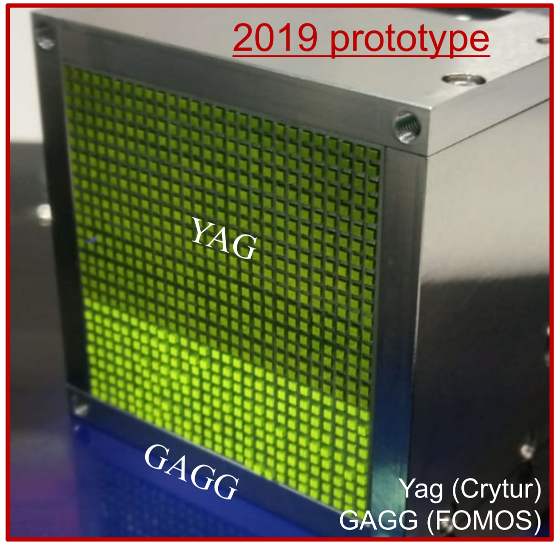
- ➔ Shorter front section to improve **time resolution**
- ➔ Shorter front section to enhance **shower separation**

2019 SPACAL prototype

Beam test at DESY: **1 to 5 GeV electrons**



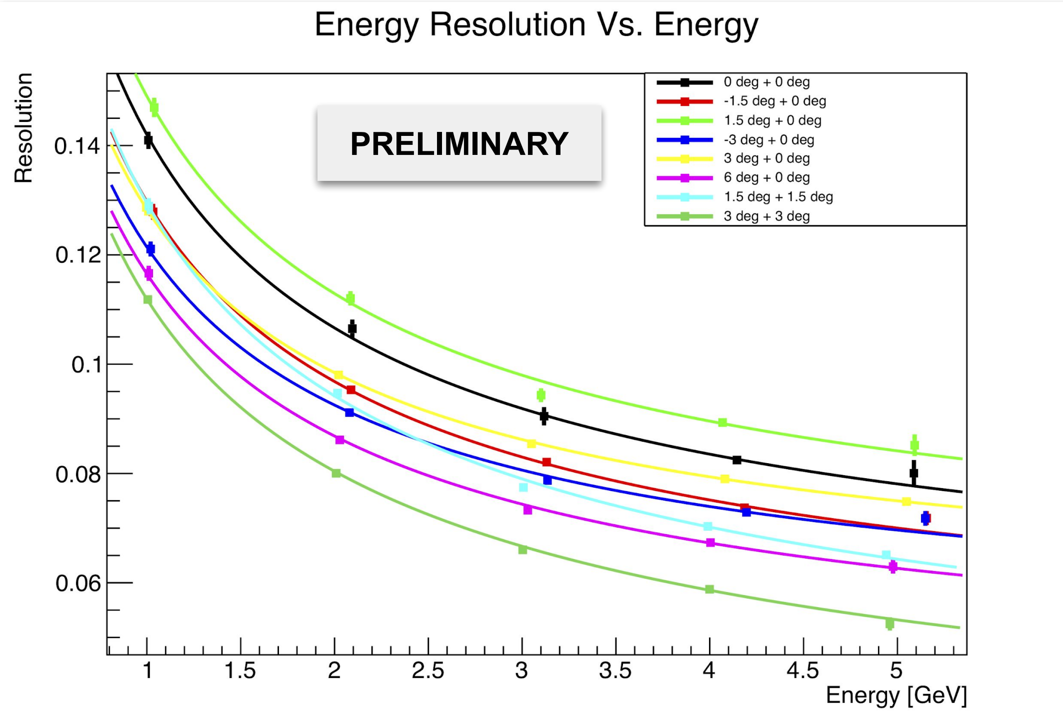




- ➔ **Pure tungsten** absorber
  - 14 cm long
  - Density 19 g/cm^3
  - 6 YAG cells
  - 3 GAGG cells
- ➔ Cell size **1.5 x 1.5 cm^2**
- ➔ Each scintillating fiber coupled to **optical fiber**
- ➔ Possibility to test with both **PMTs** and **SiPMs**

Energy resolution

Measured with electrons, for various beam angles, from 1 to 5 GeV

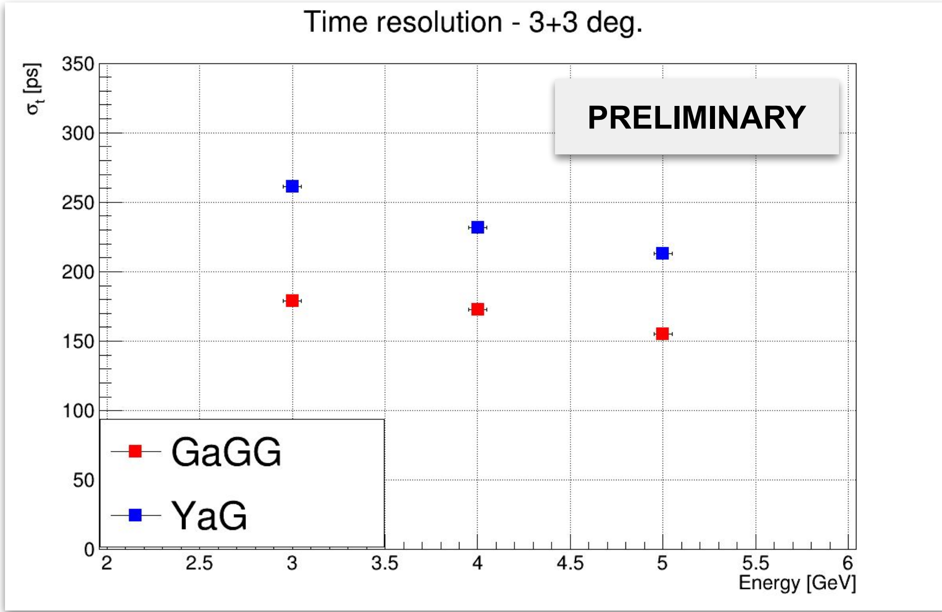


Angle [°]	Sampling term [%]	Constant term [%]
0 + 0	13.3	5.1
-1.5 + 0	12.2	4.4
1.5 + 0	13.7	5.7
-3 + 0	11.1	4.9
3 + 0	11.6	5.4
6 + 0	11.0	3.9
1.5 + 1.5	12.6	3.1
3 + 3	11.0	2.0

Material	Front [Ph.e./MeV]	Back [Ph.e./MeV]
GAGG	19 ± 2	11 ± 4
YAG	14 ± 2	10 ± 2

- ➔ Clear dependance on incident angle
- ➔ Overall higher Ph.e. values wrt TB2018
- ➔ But poor homogeneity among cells of same scintillator type (problematic coupling via clear fibers)

Timing resolution



GAGG @ 5 GeV (R7899-20 PMTs)		
Angle [°]	Front σ_t [ps]	Back σ_t [ps]
3+3	188	155

- ➔ Performance with PMTs worse than expected
- ➔ Tests with SiPMs show better results (up to **113 ps** for GAGG @ 5GeV) suggesting we are not extracting full potential
- ➔ Resolution affected by **non-uniformity of Transit Time Spread** (TTS) over PMT photocathode
  - ➢ Use of clear fibers prevents light mixing, as opposed to TB2018 configuration

- ➔ However, **plenty of useful information** gained in the dataset acquired
- ➔ Better understanding of **main factors affecting timing resolution**
  - ➢ Photo-detector TTS most likely to play dominant role (both absolute value and non-uniformity)
  - ➢ Impact of light collection/coupling
  - ➢ Useful information for tuning of MC simulations (see later)
- ➔ **Strategies already in place** to improve timing resolution in view of next test beam
  - ➢ Test faster photo-detectors (PMTs, SiPMs)
  - ➢ Mitigate impact of TTS non uniformity: light mixers, MA-PMTs, SiPMs
- ➔ Keep in mind that energy range is quite far from region of interest (> 10 Gev)

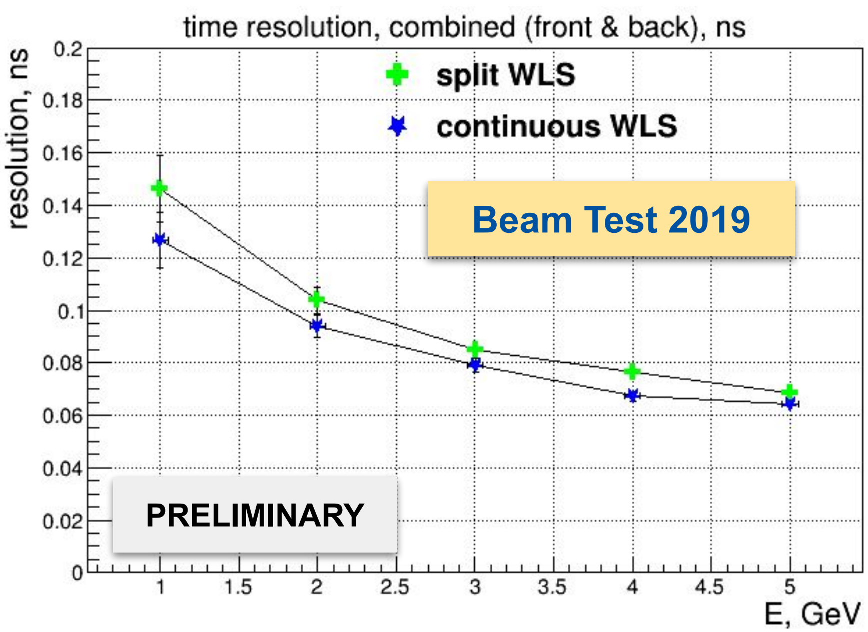
Timing resolution - shashlik modules

Shashlik technology can be used in Upgrade II in outer part of ECAL and provide timing information

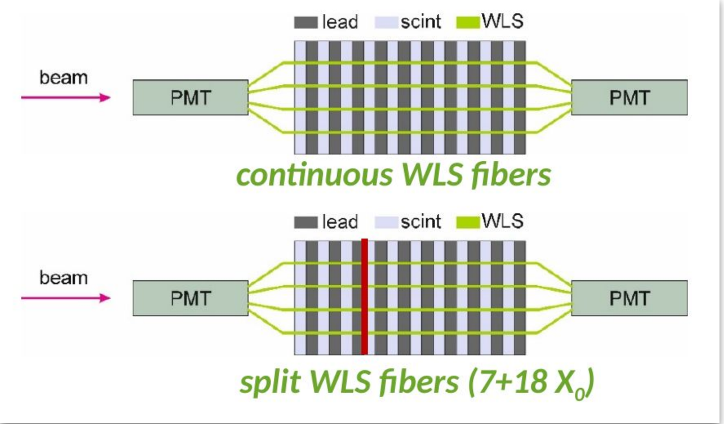
Beam Test 2018

Energy [GeV]	PMT Bias [V]	Time res. σ [ps]
20	800	69
30	800	56
30	750	57

Current ECAL modules with current PMT (R7899-20)



➔ In order to reduce effect of shower longitudinal fluctuations, two versions of shashlik were prepared for 2019 beam test
- ➢ Split WLS fibers (7+18 X0, mirrored fiber ends)
- ➢ Continuous WLS fibers



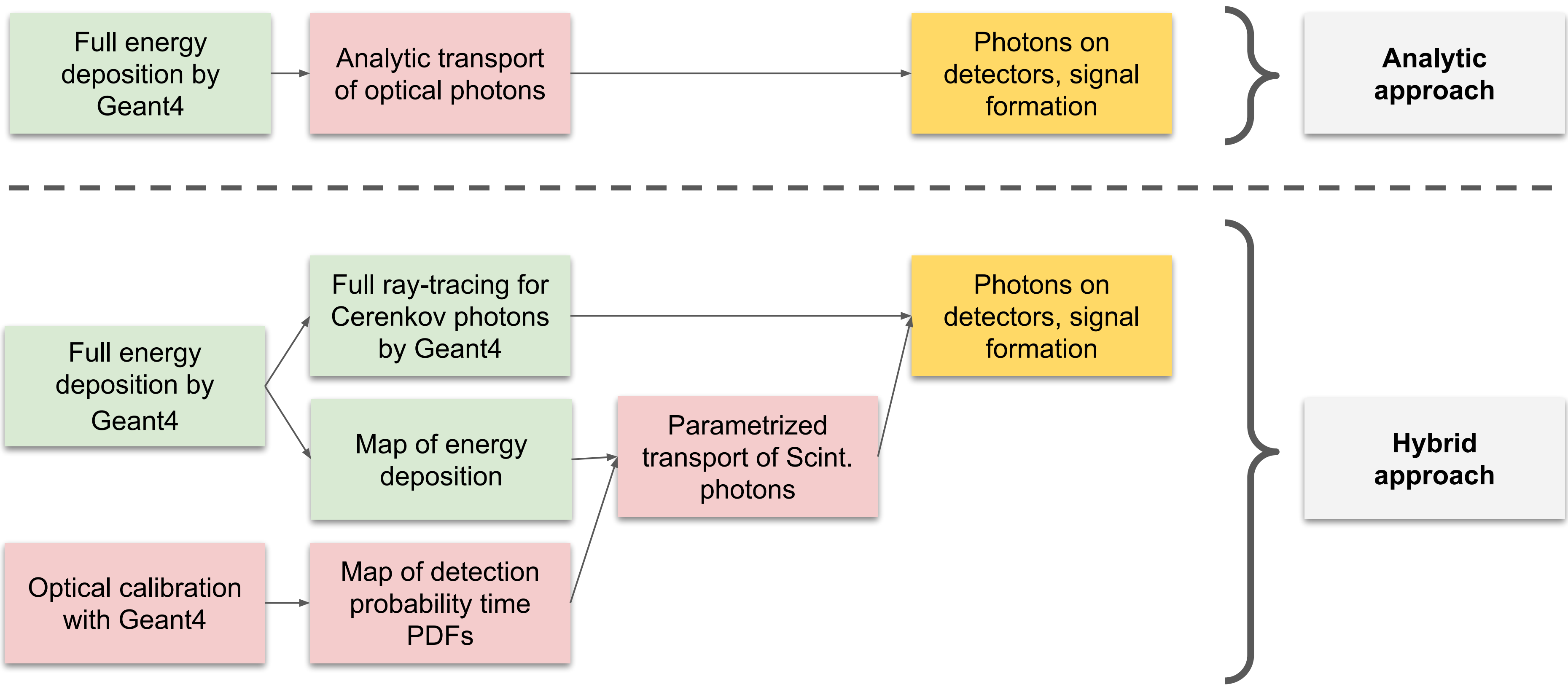
➔ Better than present ECAL modules (65-70 ps achieved at 5 GeV)

➔ Planning to try new KURARAY WLS fibers YS-2 (much faster than Y11)
- ➢ Improve time resolution
- ➢ Reduce sensitivity to spillover (shorter pulse lenght, hopefully < 25 ns)

➔ Planning to test these prototypes at higher energies (20+ GeV) at SPS, when available

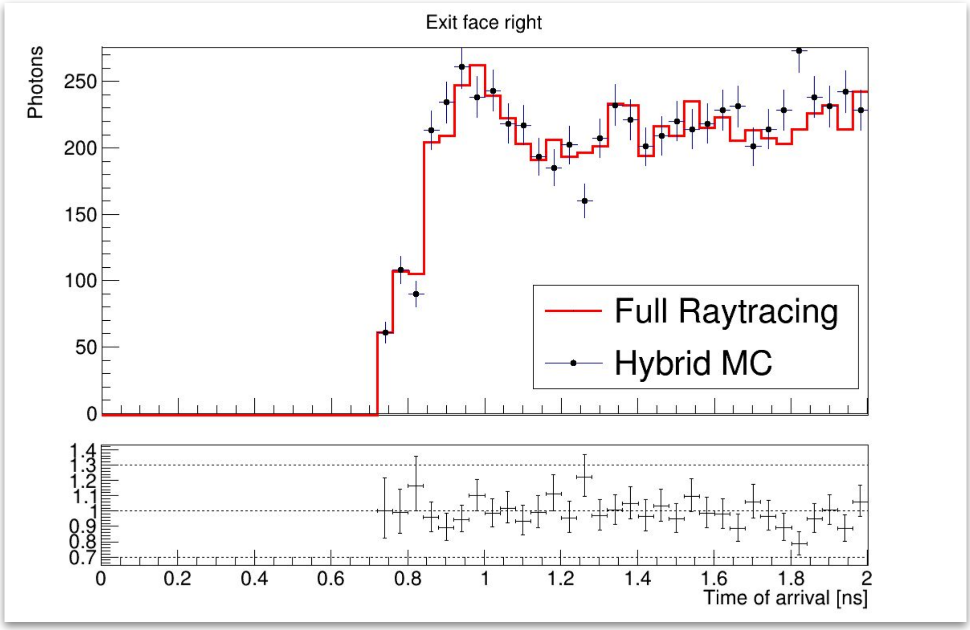
Parametrized simulations for SPACAL

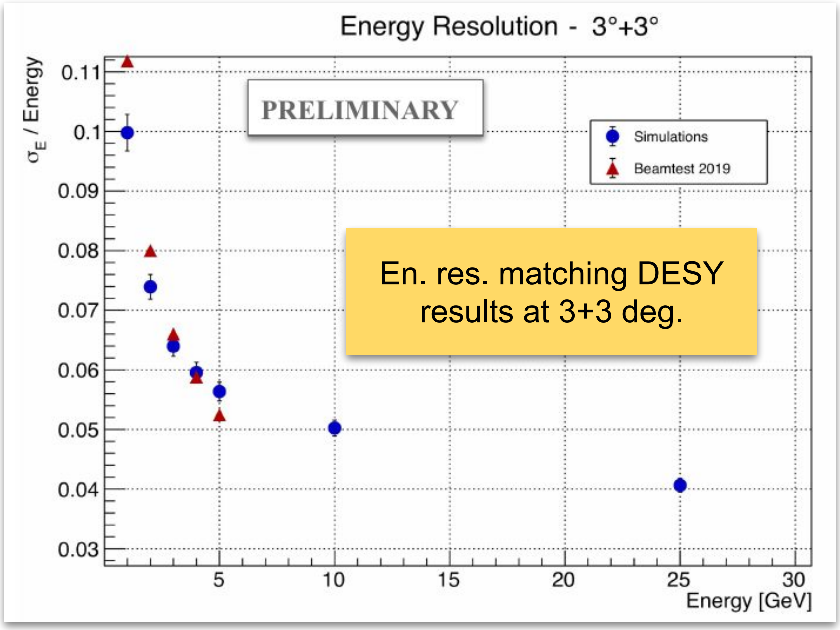
- ➔ MC required for optimization of SPACAL **geometry**, and study of factors influencing **timing resolution**
- ➔ Optical photons ray-tracing needed, but extremely CPU-consuming -> parametrization strategies developed



- ➔ **Analytic approach** valid in approximation of perfect crystal surfaces
- ➔ **Hybrid approach** allows to take into account surface imperfections
- ➔ Both approaches result in total **CPU gain** of factor between x100 and x400

Hybrid-MC - preliminary results





- ➔ Hybrid-MC **equivalent** to full ray-tracing
- ➔ Encouraging preliminary results, work in progress
- ➔ Study of time resolution with different readouts/coupling
  - ➢ PMTs, SiPMs etc
  - ➢ Clear impact of photo-detector timing resolution
- ➔ Study of faster garnets from different producers

Photodetectors and readout

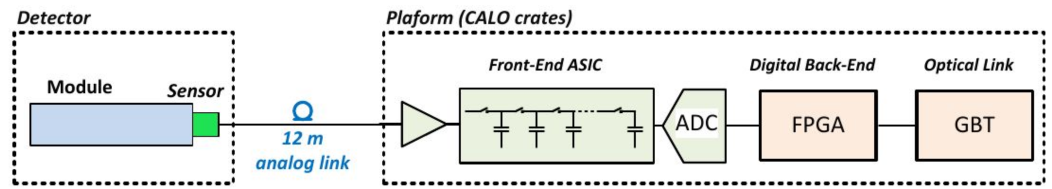
- ➔ Requirements for Phase-II ECAL **photodetector**:
  - ➢ High dynamic range
  - ➢ High timing accuracy O(20ps)
  - ➢ Radiation hardness for 300 fb^{-1} (100 Mrad)
- ➔ Candidates under study: **APDs, SiPMs, PMTs**
  - ➢ Most mature solution so far remains PMTs (rad-hardness)
- ➔ In any case, **fast waveform sampling** only choice to achieve good timing resolution with SPACAL/Shashlik
  - ➢ A dedicated ASIC will be required

- ➔ Estimate of key parameters for **electronics readout**

Number of channels	15-30k
Maximum occupancy	~10%
Dynamic range	12 bits (maybe more needed…)
Sampling	8 samples per event
Derandomized waveform (analog or digital)	
Sparsified readout	

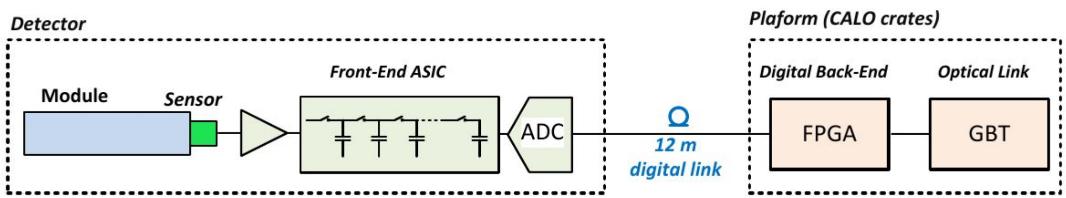
Readout Architectures

Investigations on **different readout architectures** ongoing (beam tests 2019 and 2020 can provide insight)



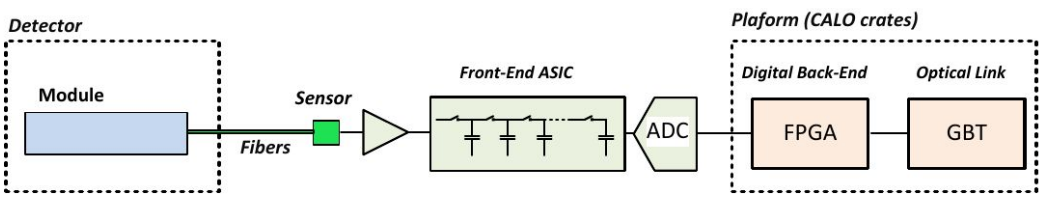
FE and readout on platform

- Main concern: jitter degradation
- Feasibility depends on SNR and losses over transmission line
- Only solution if timing wanted in LS3



On-detector FE ASIC

- Needs to be rad-hard
- High density required
- Back-end digital processing on crates



Clear Fibers

- Remove photo-sensors from hot area
- Likely timing degradation
- Maximum feasible distance?

➔ Rate of **data transmission** crucial, needs to be taken into account

➔ Different strategies for **signal processing** are also being investigated (calorimeter crates vs. online system)

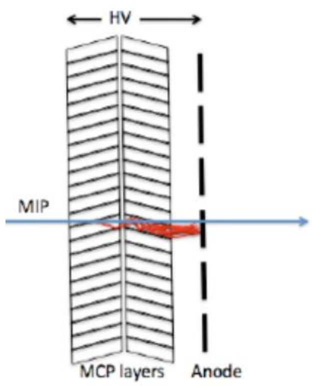
Timing plane with MCPs

Possibility to embed a timing plane based on **MCPs** in the SPACAL configuration is under investigation

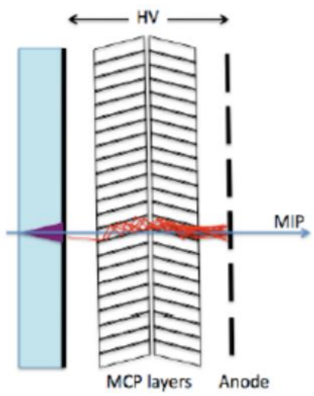
MCP-PMTs

- \+ Intrinsically very fast, O(10-20ps)
- \+ High gain stacking multiple layers
- − Typically small-sized, very expensive
- − Not radiation-hard

i-MCP



MCP-PMT

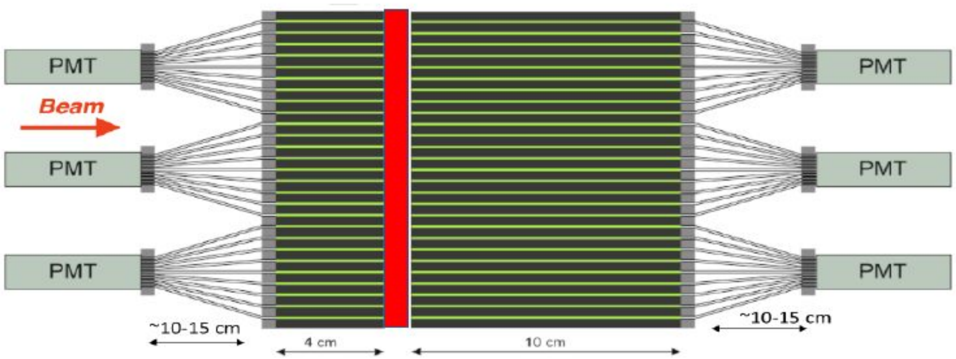


➔ The **photocathode** of MCP-PMTs is needed if high efficiency on single electrons is required

➔ If several charged particles are available (after a few X_0 in an electromagnetic shower) 100% efficiency can be achieved even if photocathode is removed -> **iMCPs** (ionization-mode MCPs)

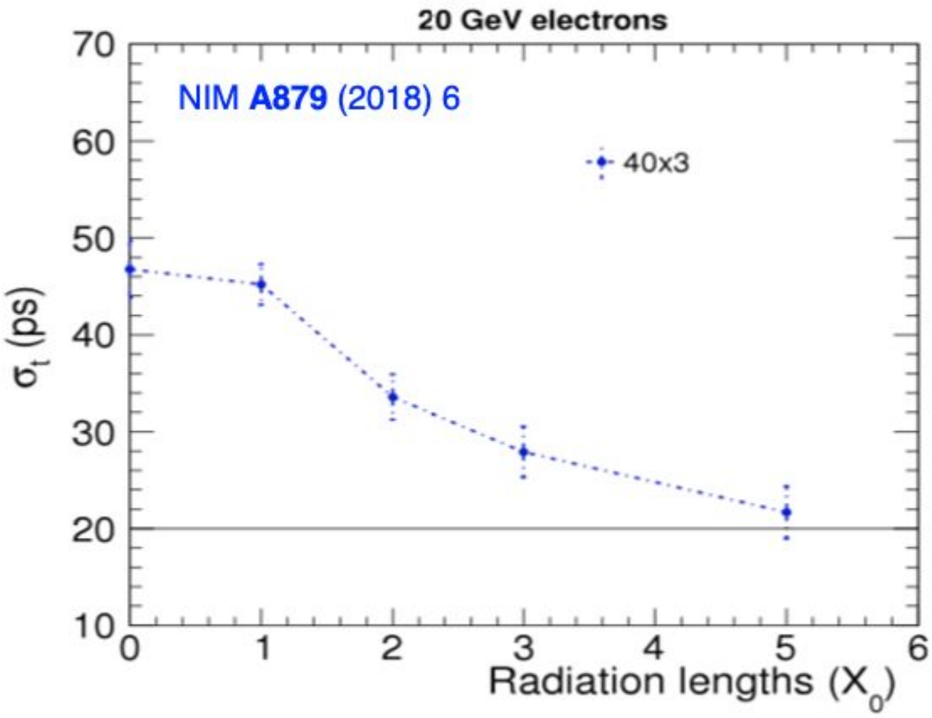
➔ Good timing precision can be obtained independently of shower depth (temporal coherence)

➔ Embedding a ~1 cm **i-MCP layer** in the SPACAL, placed around the shower maximum, can fit the dual readout, asymmetric configuration and provide fast timing information



Timing resolution, i-MCPs

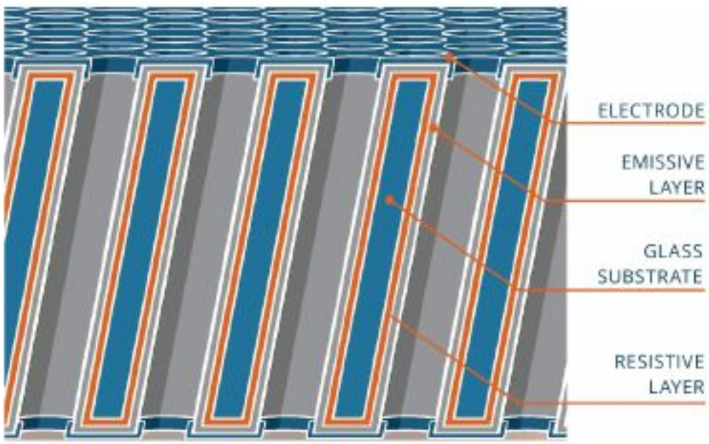
Timing resolution of **i-MCPs** improves after a few radiation lengths

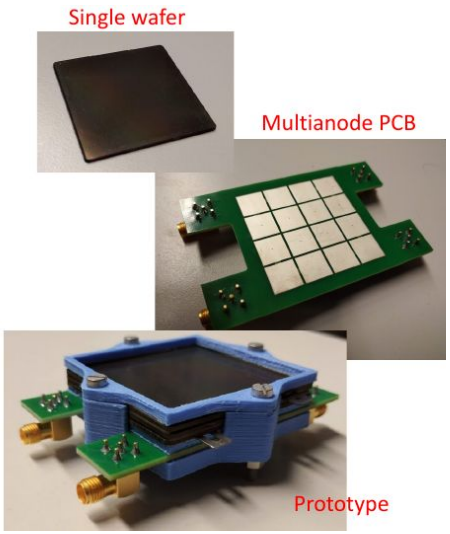


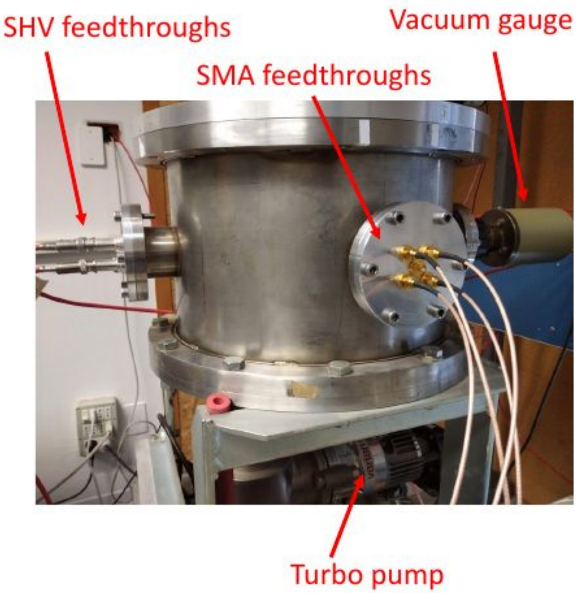
- ➔ In this example, timing resolution of one i-MPC layer placed after an absorber with variable radiation lengths
- ➔ Around **20 ps** obtained after **5X_0** on beam test with 20 GeV electrons
- ➔ With some R&D efforts, this resolution could be further improved

R&D efforts with i-MCPs

To explore feasibility of this approach, it is mandatory to **reduce costs** and **improve radiation tolerance**







➔ Exploring feasibility of technologies developed in recent years based on **atomic layer deposition** (ALD) of resistive and emissive layers on borosilicate glass
  - Wafer size up to 20x20 cm^2
  - Enhanced secondary electron emission
  - Prolonged device lifetime is predicted

➔ **First tests** on ALD MPCs ongoing at INFN MiB and BO laboratories

➔ Keeping open mind to other production methods under development by several producers

➔ **Strong R&D needed** to answer many open questions

Conclusions

- ➔ SPACAL configuration can represent a viable solution for the innermost part of ECAL
  - ➢ Allows tuning of cell size, enabling reduction of occupancy
  - ➢ Can provide radiation hardness with appropriate crystal materials
  - ➢ R&D effort initiated by the collaboration

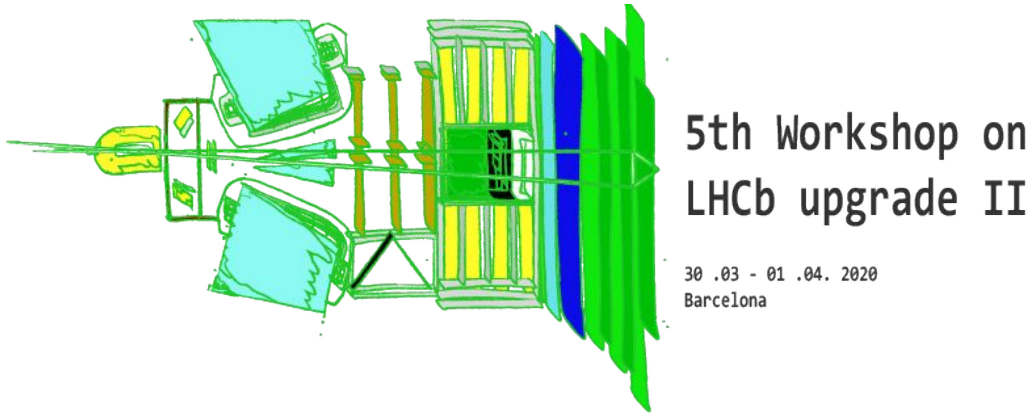
- ➔ Beam tests on first SPACAL prototypes carried out in 2018 and 2019
  - ➢ Energy resolution in the right ballpark
  - ➢ Timing resolution in 2019 configuration worse than expected. Sources of degradation identified, mitigation strategies defined for next prototypes

- ➔ Based on the knowledge acquired in beam tests, investigation continues on different
  - ➢ Crystal scintillators
  - ➢ Photo-detectors
  - ➢ Readout architectures

- ➔ The possibility of developing a timing plane based on i-MCPs is under study

- ➔ Strategies in place to improve timing resolution for SPACAL configuration for future beam tests

- ➔ For the moment, given current situation, concentrating on MC-simulation efforts



Thank you for your attention!