SiPM studies for the upgrade of the e.m. calorimeter of the Belle II detector

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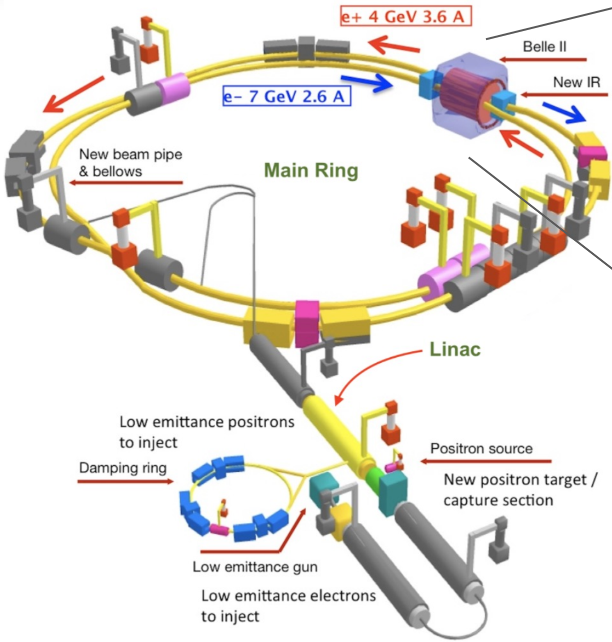
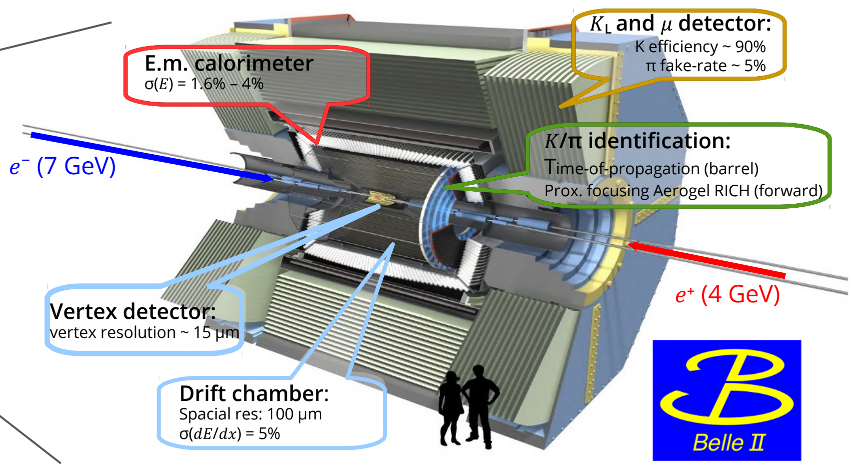
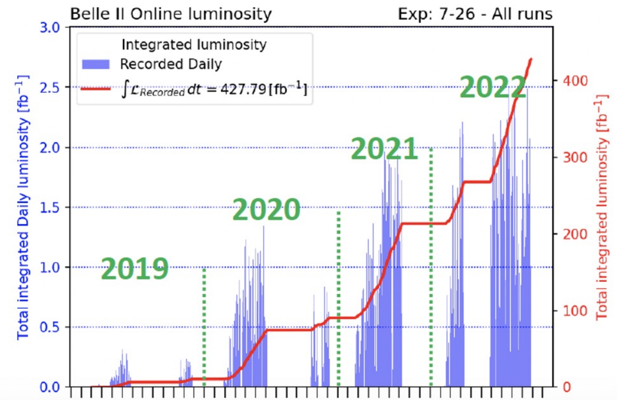
Belle II

Belle II @ SuperKEKB





- e^+e^- @10.58 GeV
- L_{peak} **= 4.7 × 10^{34} cm^{-2}s^{-1}**
  - path identified to reach 2 × 10^{35} cm^{-2}s^{-1}
- $\int L\,dt$ = 430 fb^{-1}

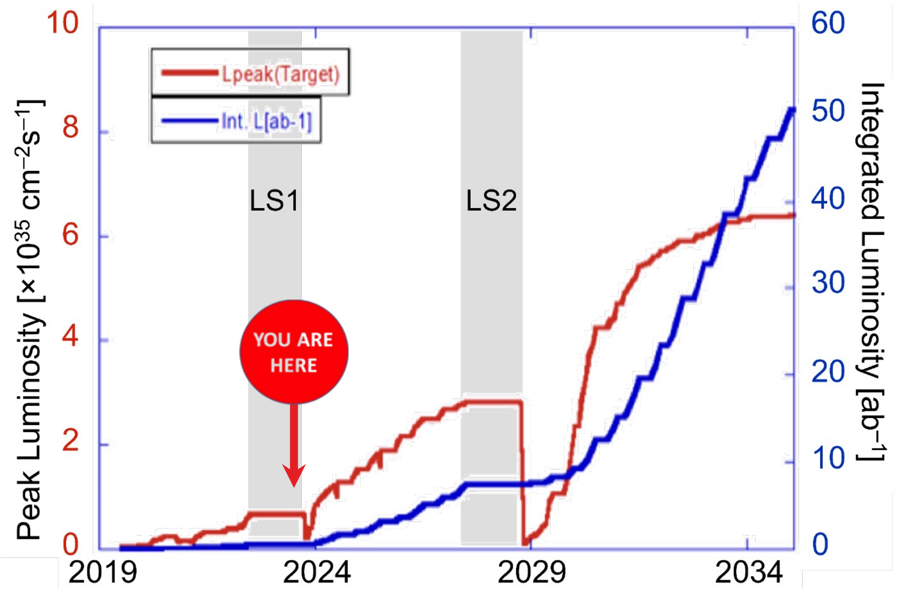


Belle II future upgrade

First long-shutdown (**LS1**) just concluded

Belle II will undergo a significant upgrade during 2027 long-shutdown (**LS2**):

- Vertexing, tracking and PID
- MDI re-design
  - Reduce machine backgrounds to cope with 6×10^{35} $cm^{-2}s^{-1}$ luminosity
- Improve electron and neutral particle reconstruction: **electromagnetic calorimeter (ECL)**
  - possible **bottleneck** at high luminosity
  - longer term timescale (> 2030)



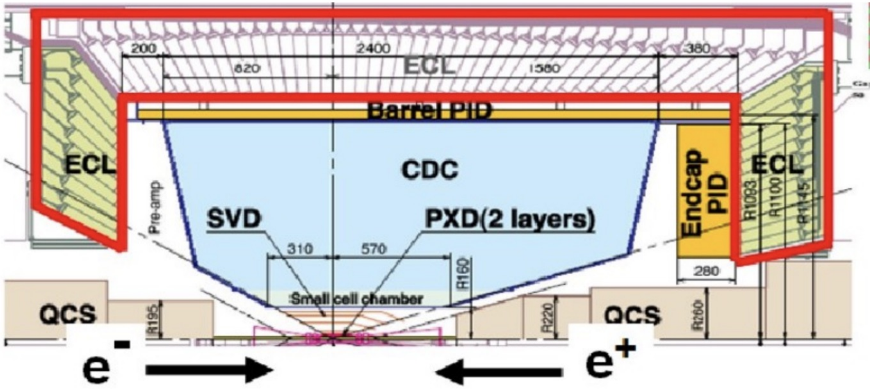
ECL @Belle II

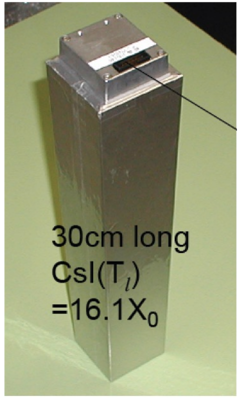
Same from Belle

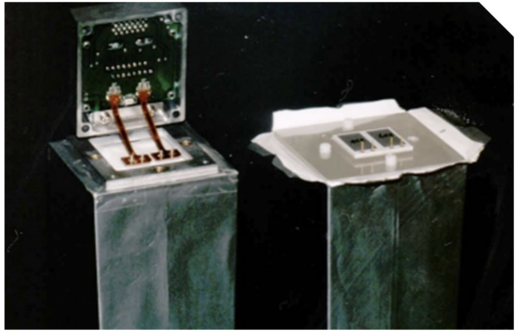
- 8736 **CsI(Tl) crystals** 30x5x5 cm^3 (~16 X_0)
- **Pin diodes** (2 x crystal)
- Charge sensitive preamplifier (**CSP**)

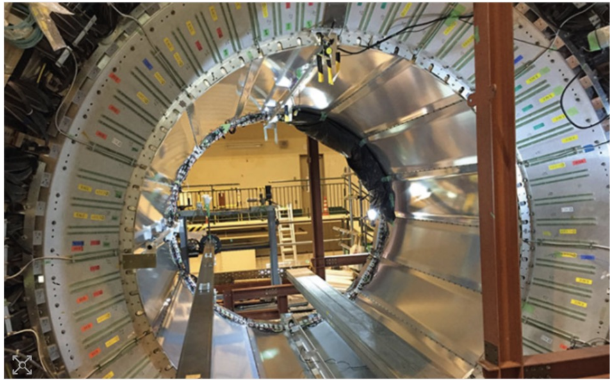
- **Shaper** (500 ns)
- **Digitizer** (1.7 MHz)
- **FPGA** to fit waveform

New for Belle II









ECL upgrade scenarios

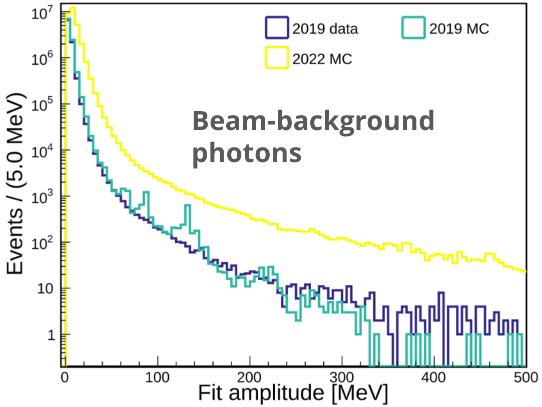
Higher rate and **occupancy** with increasing luminosity

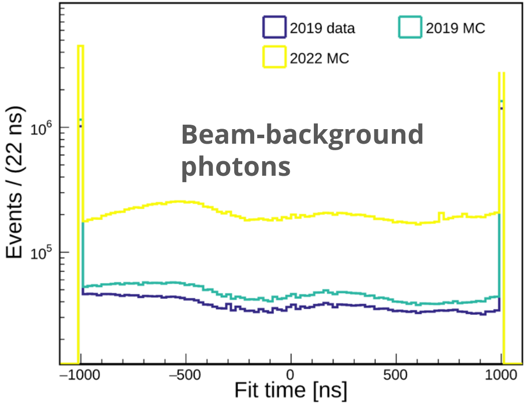
- Low energy spectrum dominated by beam-background
- Performance degradation in the low energy region: impact **soft photons** and π^0 reconstruction

Possible solutions:

a) **New crystals** with shorter decay time (pure CsI, PWO, BSO…)
   i) reject out of time beam background
   ii) **APD** readout studied in a past R&D [JINST 12 C07032]
   iii) high impact and very expensive solution

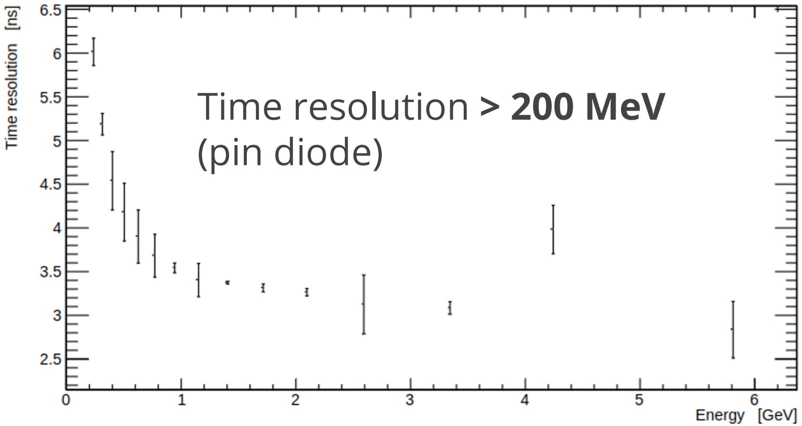
b) **New photodetector**, use same CsI(Tl) crystals
   i) fast timing for rejecting beam-background → need **internal gain**
   ii) exploit the very high LY of CsI(Tl) for the energy reconstruction
   iii) investigated APD, new R&D with **SiPM**

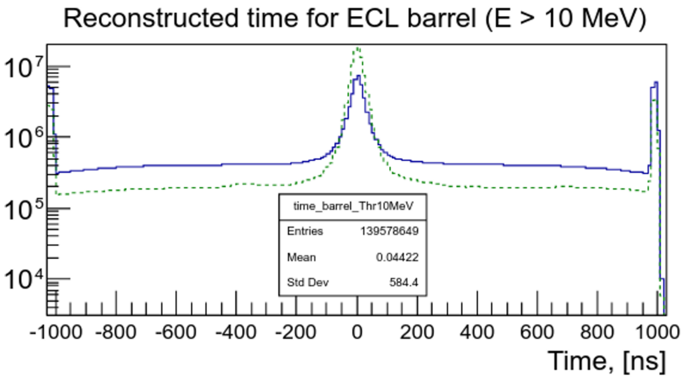




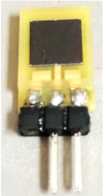
SiPM readout option

- Simpler and cheaper wrt APD
- Good solution for **timing**, even at **low energy**
    - reject beam background photons
- Not the optimal option for **amplitude measurement** (loss of linearity at high p.e. yield)
    - expected improvement with future developments
    - keep existing pin diodes for energy measurement, use SiPM for timing in the low energy region
- Beyond CsI(Tl), different crystals investigated:
    - pure CsI, LYSO, $LaBr_3$, BGO
- Possible synergy with FCC dual-readout homogeneous calorimeter R&D



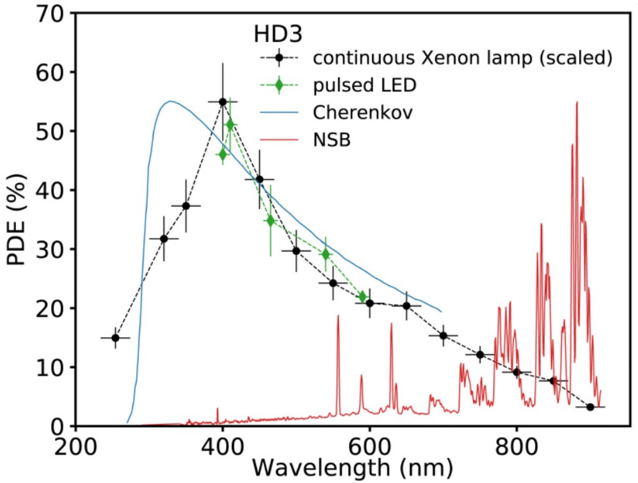


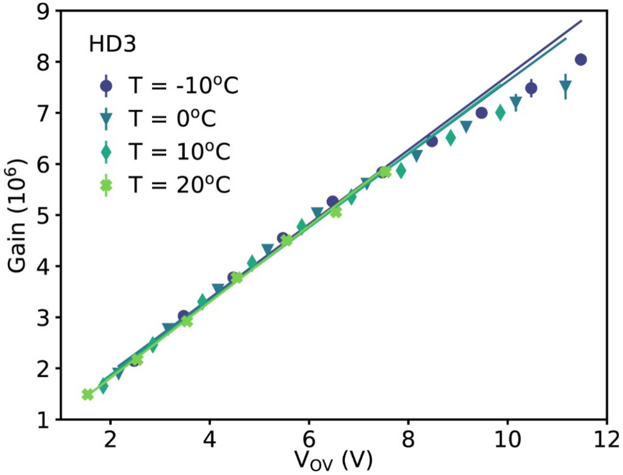
Test with SiPM prototype



Originally designed by **FBK** for CTA, characterized in [NIM A 1049, 168023 (2023)]

- **NUV-enhanced** (P.D.E. about 35% @350 nm)
  - **optimized for pure CsI** or **$LaBr_3$** emission
  - also to detect **Cherenkov light** emission in CsI(Tl)
- Area 6x6 mm^2 (effective active area ~80%, 40 μm pitch)
- Breakdown V_B ~ 26.5 V
- At O.V. +4.5 V → Gain = 3.5 x 10^6 electrons/p.e.



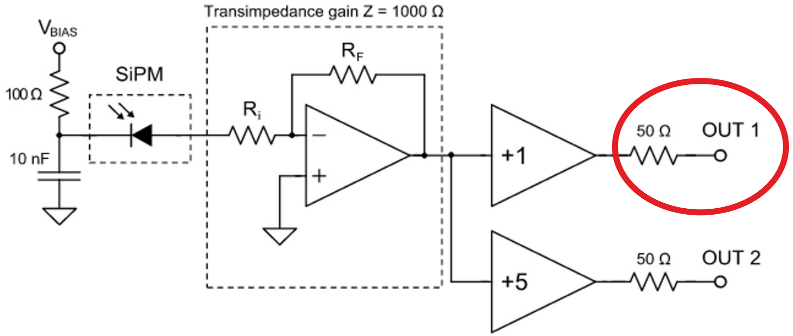


SiPM readout

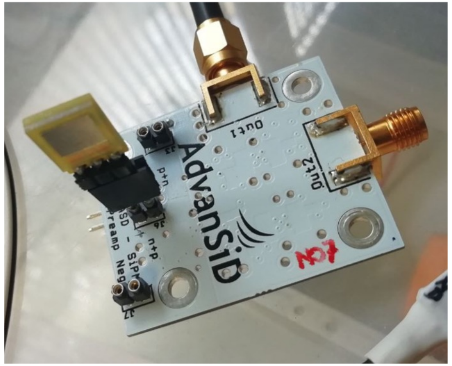
AdvanSid Board Signal amplifier

- Transimpedance amplifier: **gain** G_{out} = 500 Ω
- Takes directly the SiPM bias
- Power supply: ±5 V

Output signal amplitude is proportional to collected photo-electrons



ASD-EP-EB-N Schematic



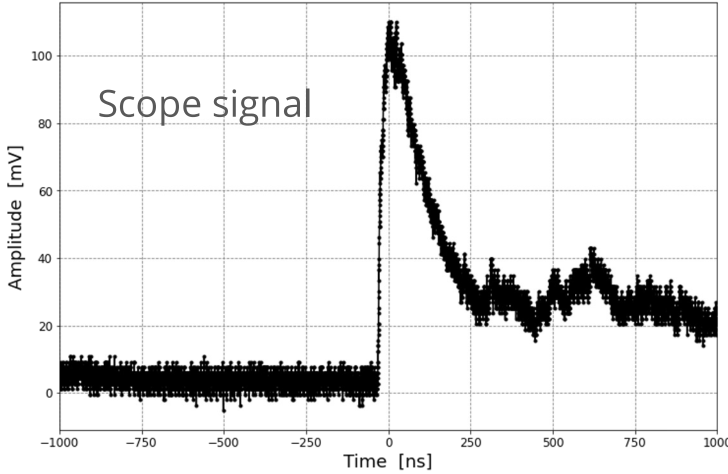
Experimental setup

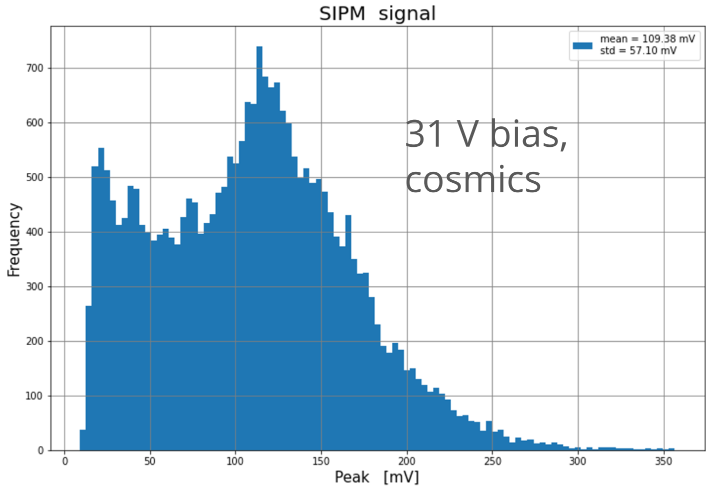
- Test **different crystals**
  - Pure CsI from Amcrys
  - CsI (Tl) from old Belle ECL
  - LYSO from SuperB
  - $LaBr_3$ from Saint Gobain
- Couple SiPM directly to crystal surface with Silicone optical grease (EJ-550)
- All crystals are wrapped with teflon + mylar foils
- Trigger cosmics with scintillator (coupled to PMT) or use radioactive source spectrum
- Save full waveforms at the scope reading the AdvanSid

Pure CsI + SiPM

- 30x6x6 cm^3
- **Low LY but short decay time (~ 10 ns)**
- SiPM discharge time dominates in the waveform
- Energy spectrum with cosmics

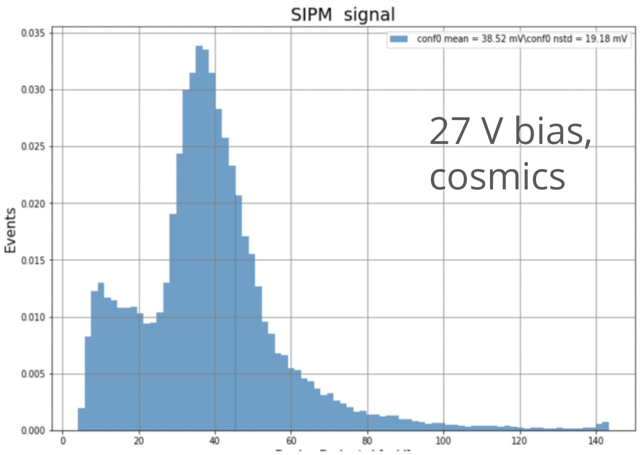
	CsI (Tl)	CsI pure
Density (g/cm^3)	4.51	4.51
λ max emission (nm)	550	310
Light yield (γ/keV)	54	2
Primary decay time (ns)	1000	10
Hygroscopic	yes	





CsI(Tl) + SiPM

- 30x6x6 cm^3
- **High LY but very long decay time (~ 1 μs)**
- Good energy resolution with cosmics
    - Compare pure CsI and CsI(Tl)



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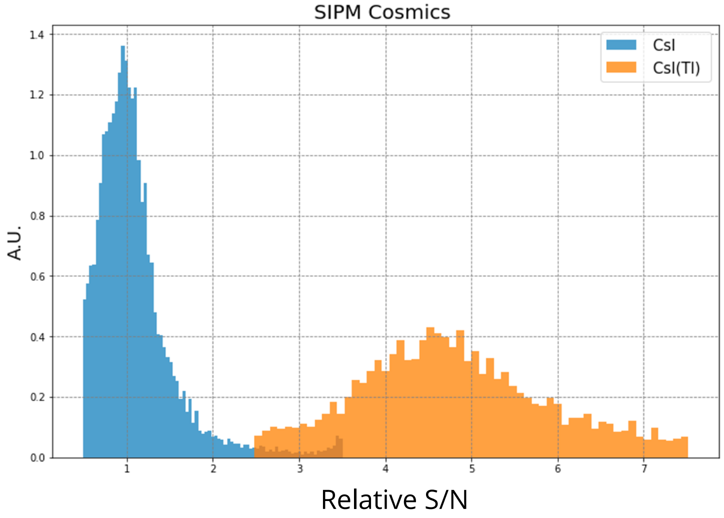
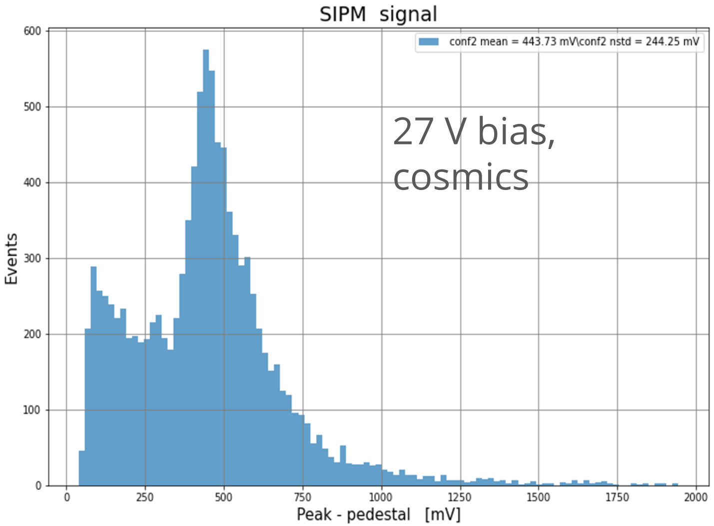


LYSO + SiPM

- $20x3x3\ cm^3$, slightly trapezoidal shape
- **High light-yield and fast decay time** (36 ns)
  - useful as a cross-check (LY ~ CsI(Tl))
- Sharp peak observed in amplitude spectrum
  - with faster emission, also energy resolution improves

Table comparing principal properties	LYSO
Density [g/cm³]	7.1
Attenuation length for 511 keV (cm)	1.2
Decay time [ns]	36
Energy resolution @ 662 keV	8.0
Light output, photons per keV	33

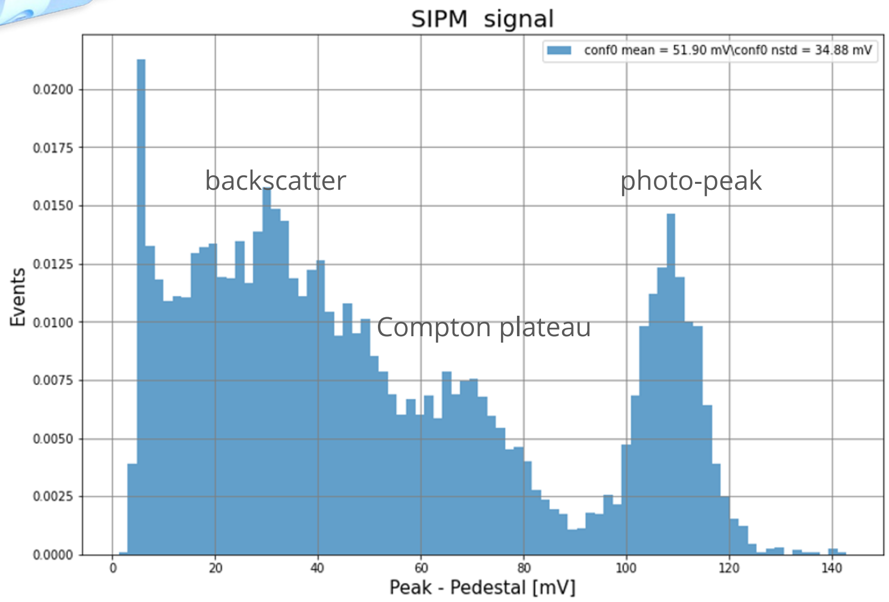


$LaBr_3$ + SiPM

One crystal from Saint-Gobain:

- Cylinder 25 mm diameter x 25 mm height
- **High light-yield and short decay time (16 ns)**
- Very good energy resolution with ^{137}Cs source

Properties	Standard $LaBr_3$(Ce)	Enhanced $LaBr_3$ (Ce+Sr)
Energy Resolution @ 662KeV	2.6%	2.2%
Photoelectron yield [% of NaI(Tl)] (for γ-rays)	165	>190
Wavelength of emission max [nm]	380	385
Primary decay time [µs]	0.016	0.025
Light yield [photons/keVγ]	63	73
Refractive index @ emission max.	~1.9	~2.0
Density [g/cm³]	5.08	
Hygroscopic	yes	

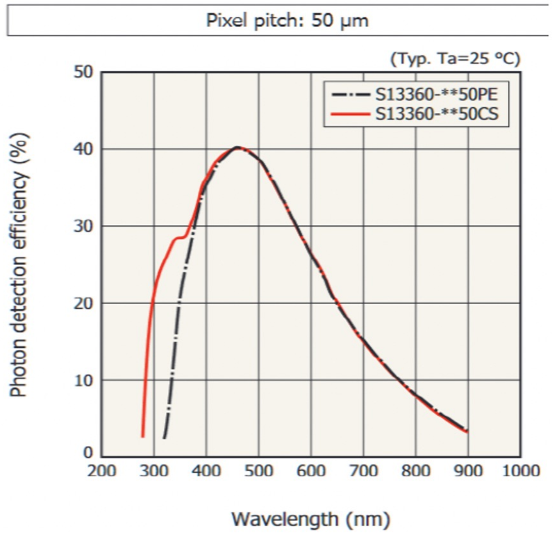


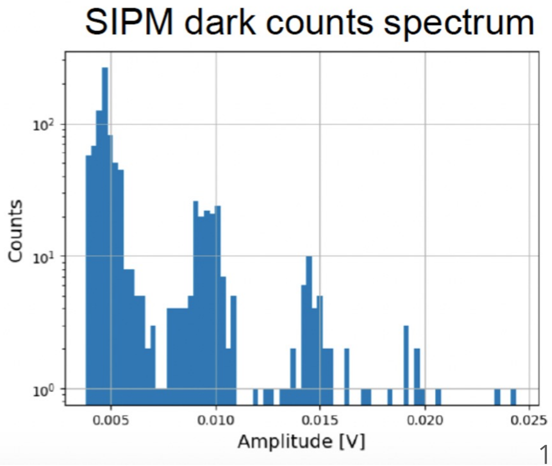
Planned tests with Hamamatsu SiPM

S13360-6050CS SiPM are going to be tested

- Non UV-enhanced → optimized for CsI(Tl) emission
- 50 μm pitch already tested @Napoli, 25 μm pitch on the pipe

Type no.	Pixel pitch (μm)	Effective photosensitive area (mm)	Number of pixels	Package	Fill factor (%)
S13360-1325PE	25	1.3 × 1.3	2668	Glass epoxy	47
S13360-3025CS		3.0 × 3.0	14400	Ceramic	
S13360-3025PE				Glass epoxy	
S13360-6025CS		6.0 × 6.0	57600	Ceramic	
S13360-6025PE				Glass epoxy	
S13360-1350PE	50	1.3 × 1.3	667	Glass epoxy	74
S13360-3050CS		3.0 × 3.0	3600	Ceramic	
S13360-3050PE				Glass epoxy	
S13360-6050CS		6.0 × 6.0	14400	Ceramic	
S13360-6050PE				Glass epoxy	
S13360-1375PE	75	1.3 × 1.3	285	Glass epoxy	82
S13360-3075CS		3.0 × 3.0	1600	Ceramic	
S13360-3075PE				Glass epoxy	
S13360-6075CS		6.0 × 6.0	6400	Ceramic	
S13360-6075PE				Glass epoxy	

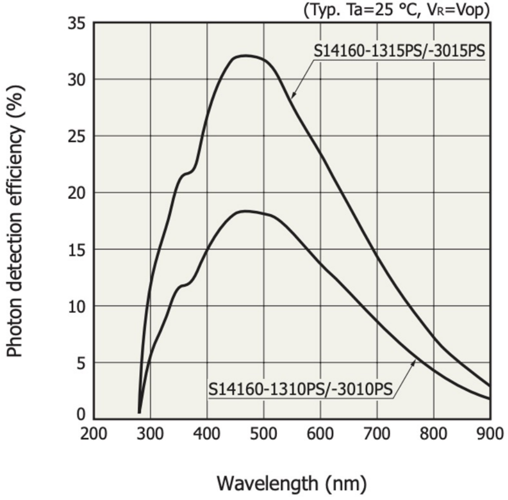




Planned tests with Hamamatsu SiPM

S14160 SiPM o be tested

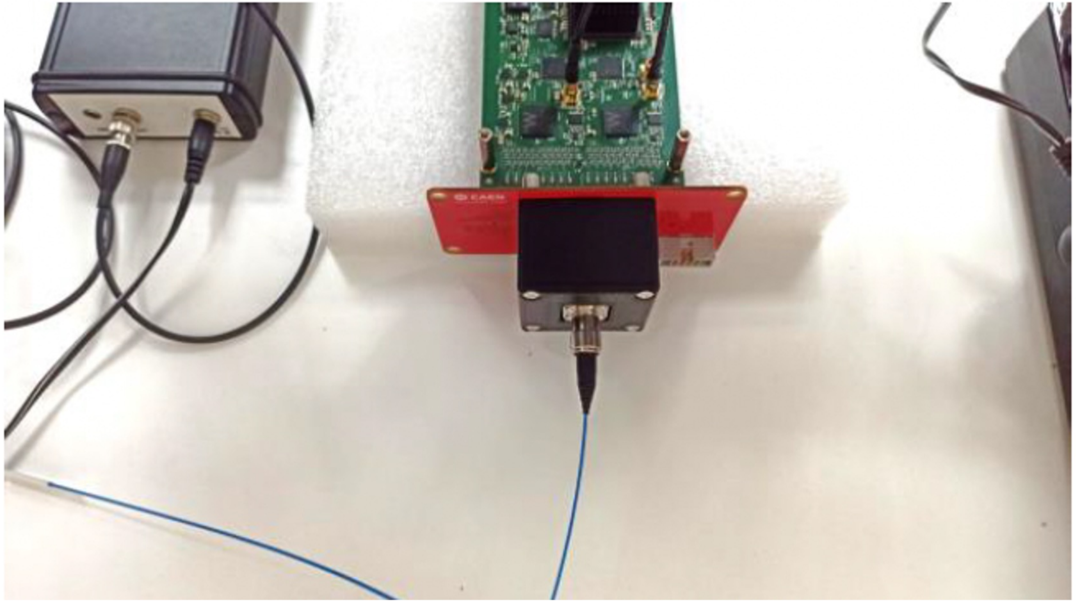
Typ. no.	Number of channels (ch)	Effective photosensitive area/channel (mm^2)	Pixel pitch (μm)	Number of pixels/channel	Package	Window	Window refractive index	Geometrical fill factor (%)
S14160-3050HS	1	3.0 × 3.0	50	3531	Surface mount type	Silicone	1.57	74
S14160-4050HS		4.0 × 4.0		6331				
S14160-6050HS		6.0 × 6.0		14331				
S14161-3050HS-04	16 (4 × 4)	3.0 × 3.0		3531				
S14161-3050HS-08	64 (8 × 8)	3.0 × 3.0		3531				
S14161-4050HS-06	36 (6 × 6)	4.0 × 4.0		6331				
S14161-6050HS-04	16 (4 × 4)	6.0 × 6.0		14331				

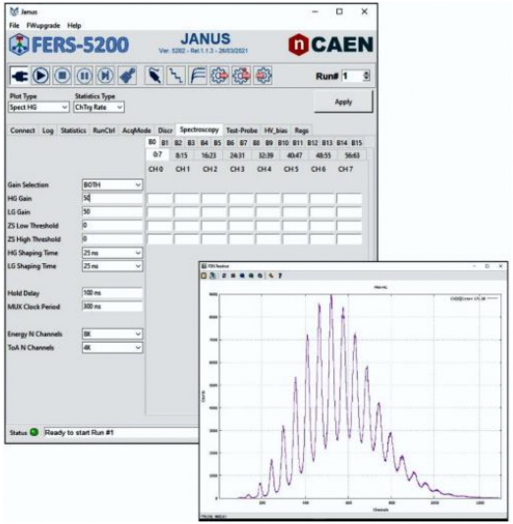


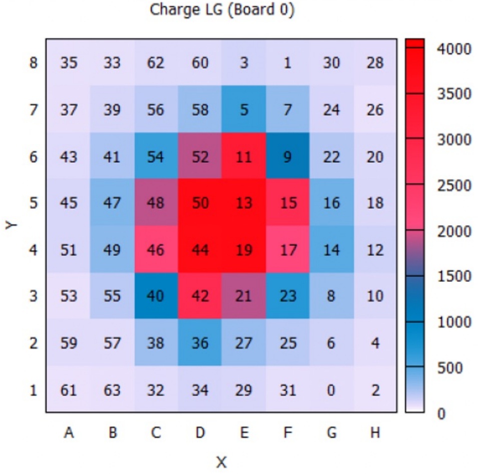
Parameter	Symbol	S14160				Unit
		-1310PS	-3010PS	-1315PS	-3015PS	
Effective photosensitive area	-	1.3 × 1.3	3 × 3	1.3 × 1.3	3 × 3	mm
Pixel pitch	-	10		15		μm
Number of pixels	-	16663	89984	7284	39984	-
Geometrical fill factor	-	31		49		%
Package	-	Surface mount type				-
Window	-	Silicone resin				-
Window refractive index	-	1.57				-

Read-out options

Test **complementary options** in Perugia and Napoli

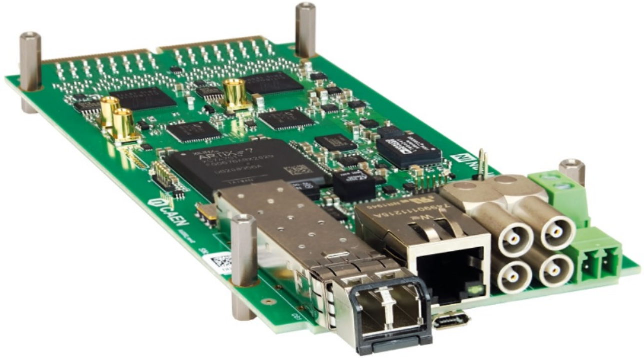






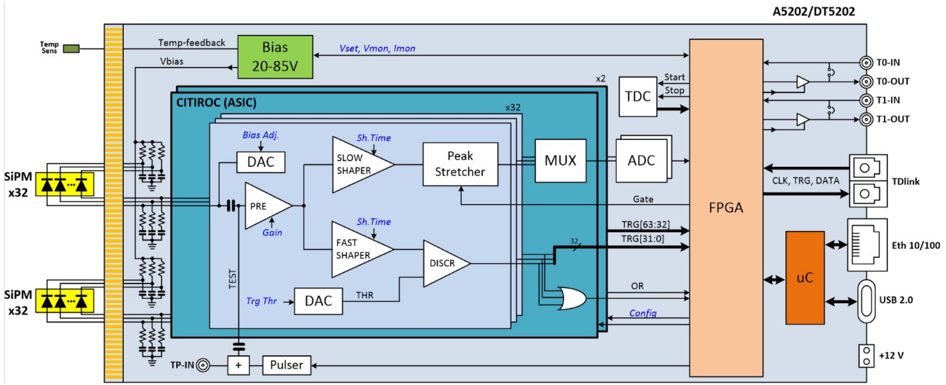
Readout option (@Napoli)

- CITIROC-1A
  - 64 ch frontend
- Onboard power supply with temperature correction



Readout scheme:

- Each channel:
  - preamplifier
  - slow shaper with peak sensing (variable shaping time)
  - fast shaper followed by a discriminator
- Output:
  - integrated charge



Analogous strategy @PG:

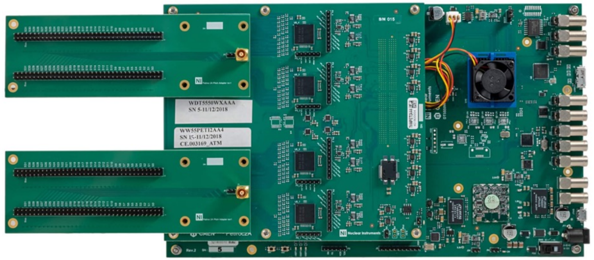
- Cremat chip with CSP + fast shaper (50 ns)
- To be integrated in custom-made board

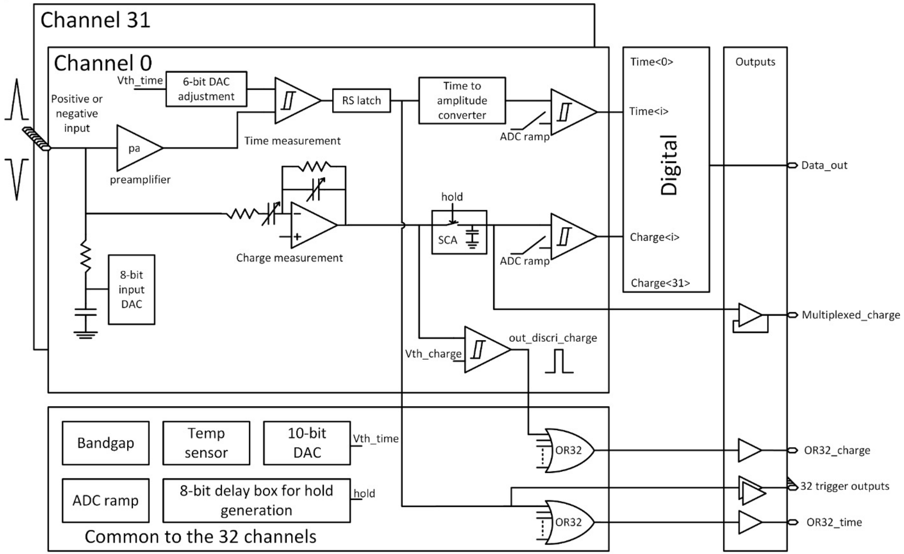
Readout option (@Perugia)

CAEN **DT5550W** with [**PETIROC-2A**]

- On-board Power Supply for SiPM Bias
- Measure both first incident photon timing and whole crystal light charge integration
- 10-bit ADC + 40 ps TDC

Ideal solution for highly accurate **SiPM timing applications**





Summary

The Belle II community will soon need to define a scenario for an upgrade of the e.m. calorimeter

- Fundamental detector for B **physics**
- The **increase in luminosity** @Belle II could lead to a significative **performance degradation**
- Full redesign of the calorimeter may not be feasible → investigate **low-impact solutions**
- A **SiPM readout** represents an interesting option
  - fully exploit the **high light-yield** of **CsI(Tl)** crystals
  - recover good **time resolution** at **low energy** deposits → reject overlapping **beam-backgrounds**
  - need to deal with **limited dynamic range**
- We are looking forward further development in the field (test of various crystals to be used in different future project like FCC)

Backup

Performance of PIN diode, APD, SiPM

	PIN [55] **(SFH2704)**	**APD** [56] **(S12053-05)**	**SiPM** [50] **(C10010)**
Gain	1	$1-50$	2×10^5
Output Type	Analogue	Analogue	Analogue or Digital
Operational Bias (V)	6	$150-200$	$24.2-24.7$
Overvoltage (V)	–	–	$1-5$
Spectral Range (nm)	400 to 1100	200 to 1000	300 to 950
Peak Sensitivity (nm)	900	620	420 *
PDE/QE (%)	–	80	18 **
Capacitance (pF)	13.4	5	50
Max Photocurrent (μA)	1.22	84	16×10^3
Dark Current (nA)	$0.1-25$	$0.2-5$	$1-10$
Area (mm^2)	3.6	21.24	2.4
Active Area (mm^2)	1.51	7.07	1
Responsivity (A/W)	0.34	21	4×10^3
Rise Time (ns)	47	0.875	0.3