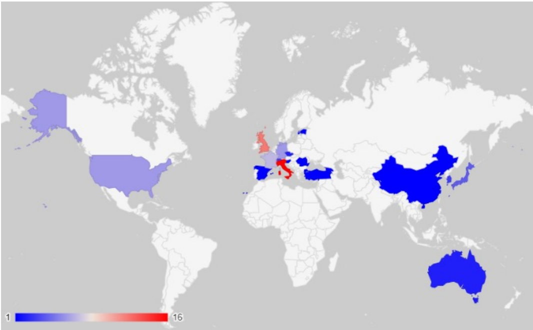
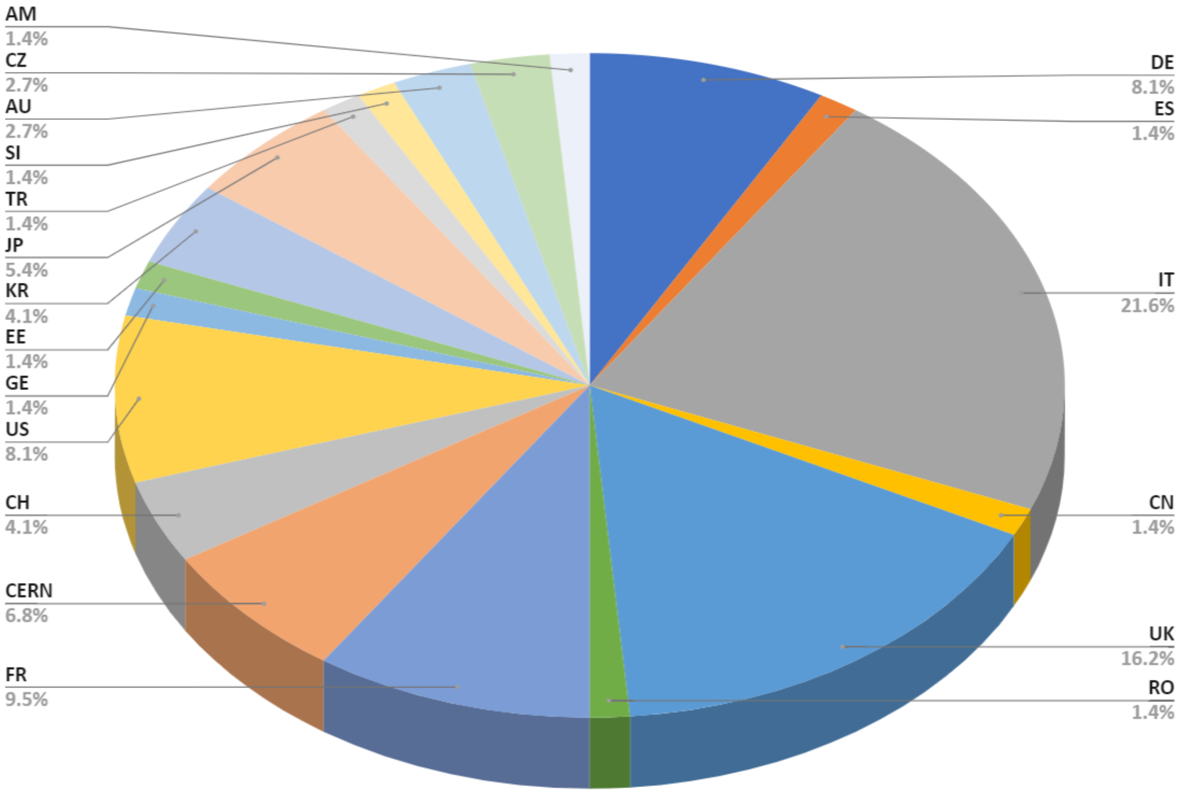
ECFA DRD4 - R&D Collaboration for Photon Detectors and Particle identification Techniques

- Proposal preparation: lead by P. Križan and C. Joram, approved by CERN Research Council
  - https://cds.cern.ch/record/2884872
- Constitution Jan 23-24, 2024 @ CERN

The DRD4 collaboration

- 74 institutes
- 19 nationalities





DRD4

Scope

DRD4 is a collaboration covering a variety of topics

- Photodetectors (vacuum, solid state, hybrid), single photon sensitive
- Particle Identification (PID) techniques (Cherenkov based, Time of Flight)
- Scintillating Fibre (SciFi) tracking
- Transition Radiation (TR) using solid state X-ray detectors

Outside Scope

DRD4 does not perform active R&D but follows with interest

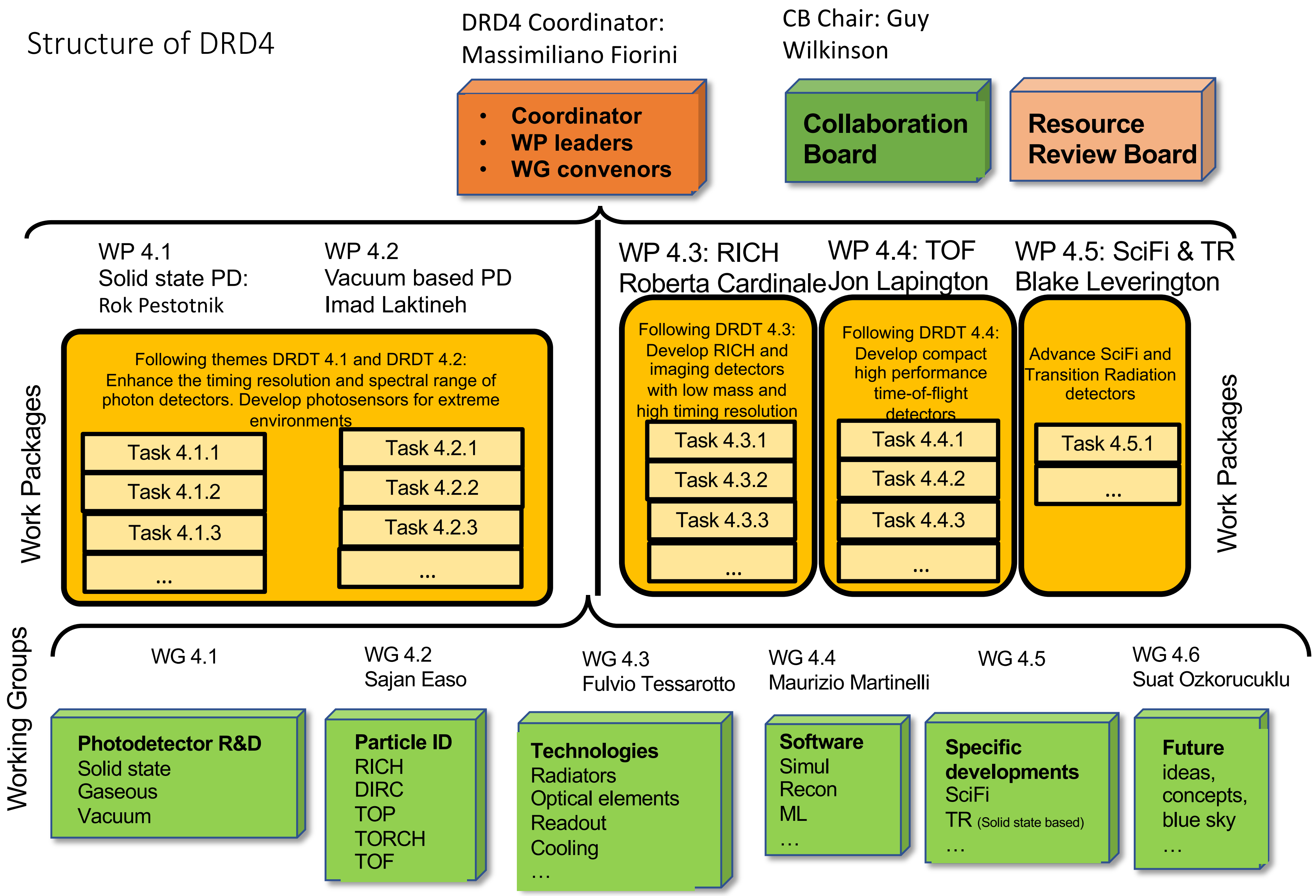
- Gas based photodetectors → DRD1, e.g. Picosec
- Gas based PID, e.g. dE/dx, TR → DRD1
- SiPM for cryogenic noble gas temperatures → DRD2
- LGAD R&D for TOF → DRD3

DRD4

DRD4 physics case

- Particle ID is an important ingredient of modern particle physics experiments
- Coverage of momentum range may require combination of techniques
- (Far) future projects are e.g. LHCb RICH upgrade, BELLE II, ALICE-3, EIC, FCC-ee,…
- Domains of application and PID performance is growing with the available photodetectors. SiPM may revolutionise the field. As for other detectors, the inclusion of precise time information may bring a break through in performance.

Structure of DRD4



Belle II groups + Japanese companies participation

Short name	Official group name	Principal investigator		WP1	WP2	WP3	WP4	WP5
KEK	High Energy Accelerator Research Organization	Nishida Shohei	JP	x		x		
Ljubljana	Jožef Stefan Institute	Rok Pestotnik	SI	x	x	x		
Nagoya	Nagoya university	Kenji Inami	JP	x	x			
Padova B2	INFN Padova B2	Ezio Torassa	IT	x				
Tokyo	Tokyo Metropolitan University	Hidekazu Kakuno	JP	x				
Napoli	University of Napoly	Raffale Giordano	IT					
HPK	Hamamatsu Photonics	Mauro Bombonatti	JP					

DRD4


RADIOACTIVE
DON'T Expose to radiation
Expensive
This side UP
This side UP
FRAGILE
No shock !!!
WORK PACKAGES

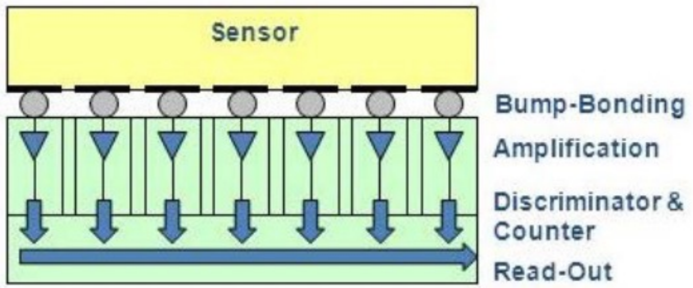
WP 4.1 Solid-State Photodetectors – 3 tasks

Each WP has several task, where specific objectives are addressed:
Many groups (good!) with heterogenous background

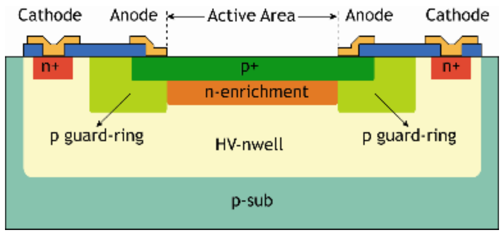
DRD4

Task 4.1.1 - SSPD w new configurations and modes (16 groups)

- **Backside illuminated** (BSI) SiPMs: potential for an enhanced PDE and a better radiation tolerance.
- **Vacuum ultraviolet (VUV) or near-infrared (NIR)** sensitive SiPMs: design, fabrication, and characterisation
- **Developing ultra-granular SiPM that integrates with the readout electronics** by using 2.5D or 3D interconnection techniques.
- **CMOS-SPAD light sensors**: co-integration of SPADs and electronics, digitized output signals with low power consumption and fast read-out.
- **New materials for light detection**, e.g., SiC, GeC, InGaAs, GaAs technology: possible advantages in SSPDs.



Ultra graniular SiPMs



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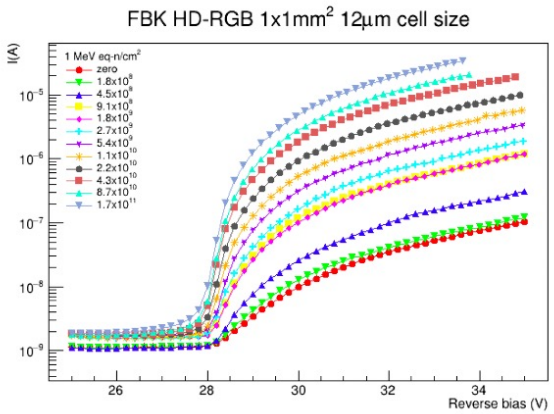
BSI SiPMs

Task 4.1.2 - Fast radiation hard SiPMs (17 groups)

- **Standardize procedures for quantification** of radiation effects.
- **Characterize the irradiated SiPMs** in a wide range of temperatures down to -200 deg..
- **Study of annealing**.
- **Study and quantify other measures** enabling the use of SiPM in highly irradiated areas:
  - smaller SiPMs
  - macro- and micro-light collectors



Bias current increase after the irradiation

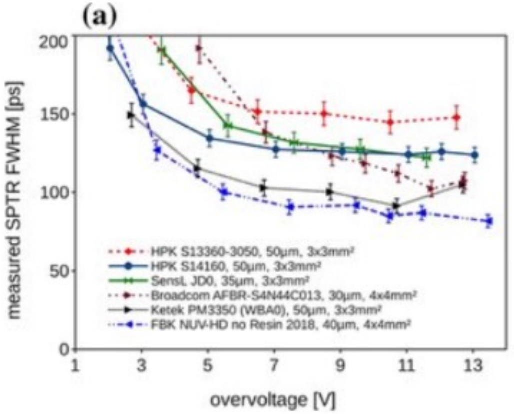
WP 4.1 Solid-State Photodetectors ...

DRD4

Task 4.1.3 **Timing of SSPD + Readout electronics** (**16 groups**)

RO electronics - transversal activity for all WPs

- Study and **improve the timing of SiPMs**.
- **Co-design of a multi-ch. readout** ASIC exploiting the timing potential.
- **Optimized, reliable, cost-effective integration** and packaging with integrated cooling.
- **Vertical integration of SiPM arrays to FEE:** optimize timing by reducing the interconnections' parasitic inductances and capacitances.



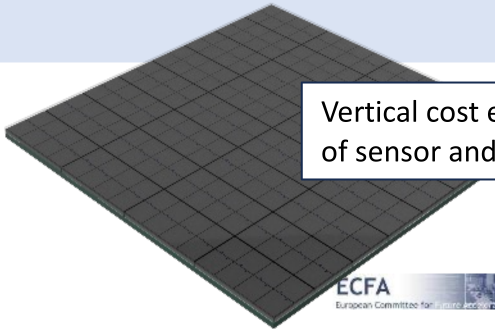
SPTR of the current sensors

Milestones:

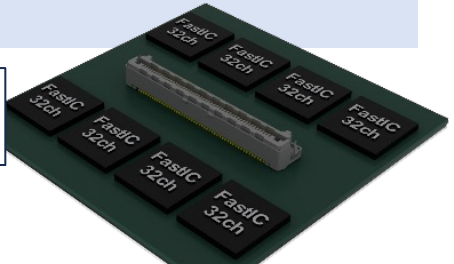
- M4.1.1.1 Tested Back-side illuminated SiPM samples (M24)
- M4.1.1.2 Tested CMOS-SPAD samples (M24)
- M4.1.2 Standardization of characterization procedures and standards to measure SiPM performance after irradiation (M18)
- M4.1.3 Demonstrated high-performance readout electronics for solid-state photon detectors (M24)

Deliverables:

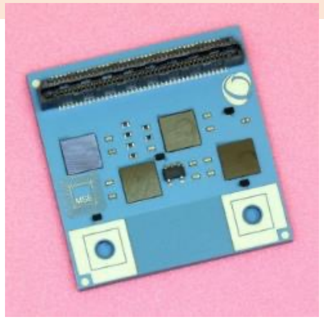
- D4.1.1.1 Demonstrator of BSI SiPM array (M36)
- D4.1.1.2 Demonstrator of CMOS-SPAD monolithic sensor (M36)
- D4.1.2 Report on achieved state-of-the-art fast and radiation hard SiPMs and analysis of prospects (M36)
- D4.1.3 Demonstrator of the ultra-fast SiPM with optimized readout electronics (M36)



Vertical cost effective integration of sensor and readout electronics



Integrated cooling: SUBLIMA



WP 4.2 Vacuum-based Photon Detectors – 3 tasks

DRD4

- 90 years after their invention - still the primary technology choice for many applications
- Goal: **Develop a new generation of VPDs** in partnership with international companies to fully exploit their performance
  *includes the development of read-out electronics

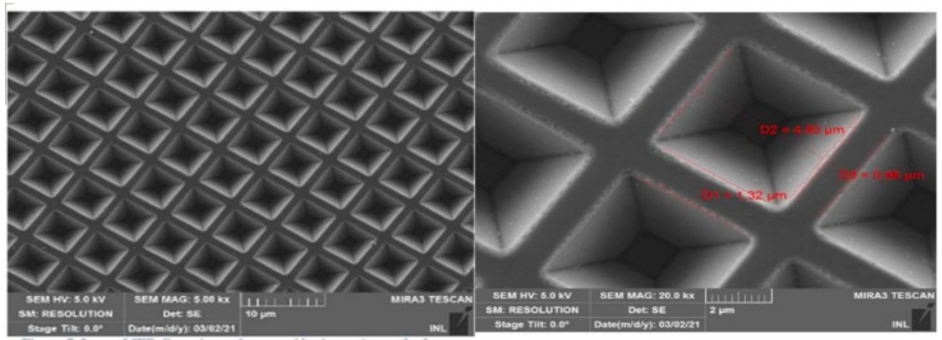
Task 4.2.1 - New materials, new coatings, longevity and rate capability studies (14 groups)

Develop new materials and techniques

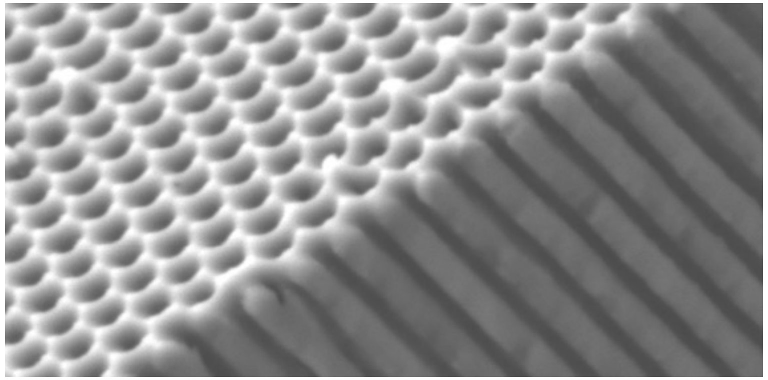
- prolong the lifetime of a MCP-PMT tube,
- Improve time rate capabilities

Use new techniques with new materials to achieve high aspect ratio with small diameter

- better gain, time, and spatial resolution



A new structure to produce photocathode with high granular structure produced using electrochemical etching on Silicon wafer (IP2I, INL)



NanoChannel Plate (NCP) based on Anode Aluminum Oxide (AAO) structure using ALD and other coating techniques (IP2I,IMP) with .400 nm holes

Task 4.2.2 - New photocathode materials, structure and high quantum efficiency VPD (4 groups)

- Search for new materials with the required characteristics to be used as photocathodes
- Develop photocathodes with new structures

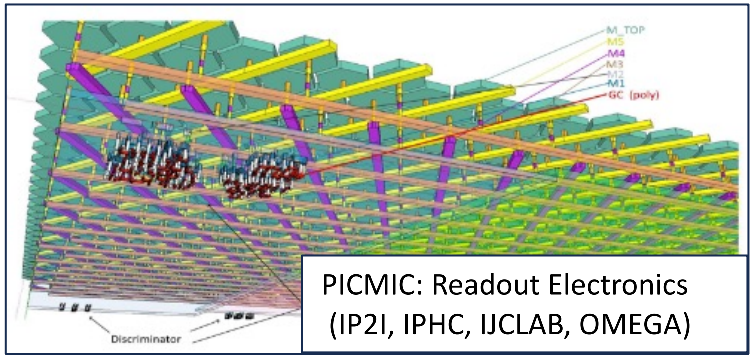
WP 4.2 Vacuum-based Photon Detectors …

DRD4

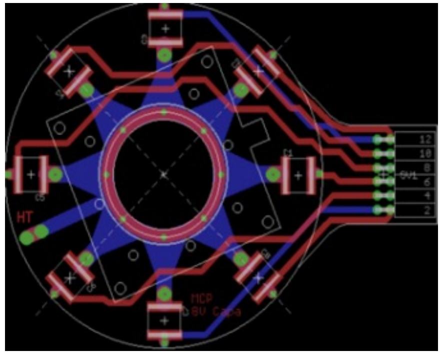
Task 4.2.3 - VPD time and spatial resolution (21 groups)
- Development of large area photodetector
  - excellent timing and position resolution

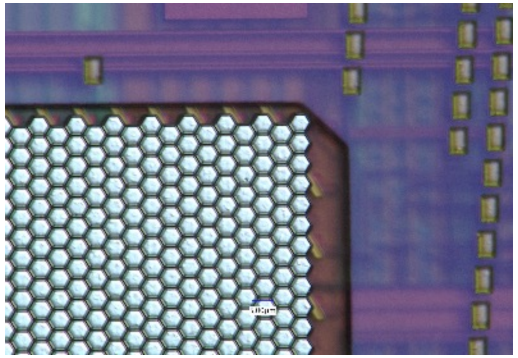
PICMICO (position): pixels sensors (5 µm-pixels), 180 nm TJ

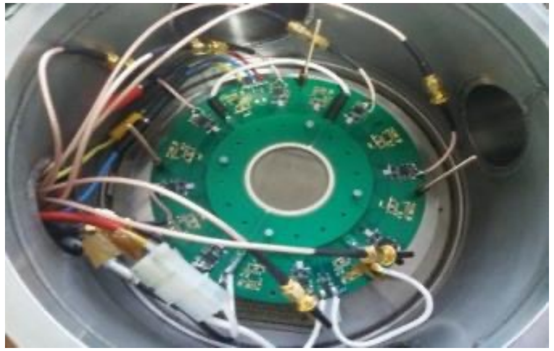
PICMIC0 (timing): new scheme for measuring arrival time using waveform catcher



PICMIC: Readout Electronics (IP2I, IPHC, IJCLAB, OMEGA)







Milestones:

- **M4.2.1.1 T**echnologies to produce electron multipliers with excellent timing and spatial resolutions **(M18)**
- **M4.2.1.2** Long lifetime and high-rate capability VPD **(M24)**
- **M4.2.2**. Reflective photocathode with granular structure of a few microns pitch **(M24)**
- **M4.2.3** Design of read-out electronics capable to reach O(10 ps) timing resolution (**M24)**

Deliverables:

- **D4.2.1** Prototype production of a new generation of MCP-PMT using innovative techniques (**M36**)
- **D4.2.2** Production of photocathodes made of different materials using either granular structure or different structure **(M36)**
- **D4.2.3** & Production of a read-out system demonstrator able to fully exploit timing and spatial resolution of MCPs **(M36)**

WP 4.3 RICH and other imaging detectors for future experiments – 5 tasks

DRD4

Task 4.3.1 New materials radiators and components (11 groups):

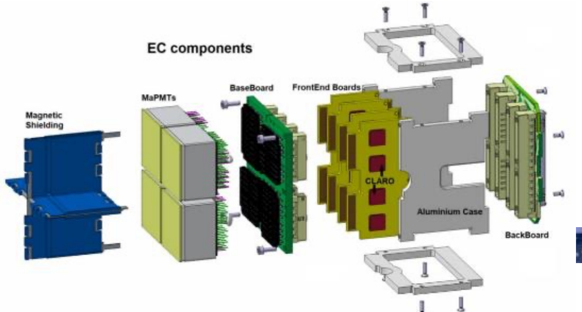
- including **gas alternatives**,
- optimized **aerogel modules**,
- precise interferometric **measurement of refractive index**.

Task 4.3.2 Development of new RICH detector concepts for improved performance: (6 groups)

- including high-pressure gas radiator,
- fast timing, combined RICH/TOF;
- Goal: **technological demonstrators & proof of concepts**.

Task 4.3.3 Single-Photon Sensitive Module for Imaging Arrays from sensor to DAQ and self-calibration systems (12 groups):

- fully functional autonomous modules (SiPM and LAPPD):
  - scalable RO electronics,
  - integration to arrays w cooling,
  - on-detector calibration/alignment/monitoring.

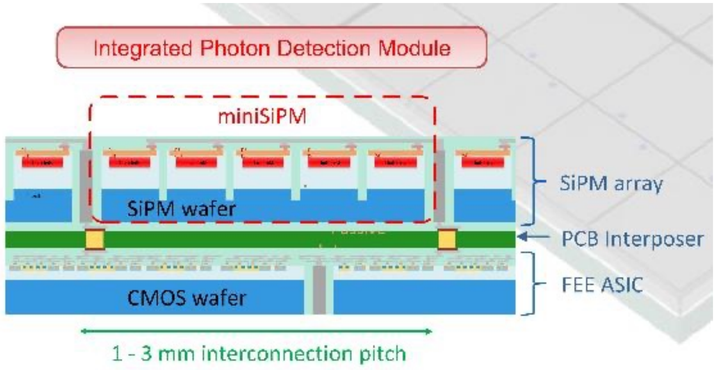


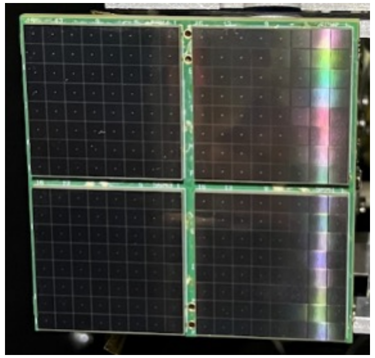
Task 4.3.4 Study of RICH detectors for future electron-positron colliders (3 groups):

- prototype a cell for the ARC concept

Task 4.3.5 Software and Performance (11 groups)::

- simulation (fast, tiny systematic effects)
- Reconstruction algorithms
  - for high occupancy,
  - large background/noise,
  - large events/hits rate,
  - large amount of data

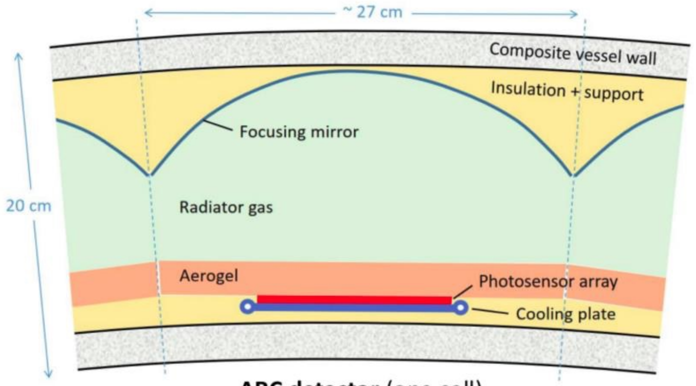




WP 4.3 RICH …

DRD4

- Complex systems: should satisfy the requirements for future experiments
  - better control of systematics, timing, higher PDE and low noise, cope with large occupancy, radiation hardness.
- Strong interaction with WP 4.1&2: **specifications & feedback**
- flexible readout system (sensor → DAQ) for imaging arrays.
- Key topic - **Thermo-mechanical engineering**
- Activities parallel with WP 4.4 : similar requirements for photo-detector arrays:
  - optimize resources: **efficient coordination and information exchange needed**.



ARC detector (one cell)

Milestones:

- M4.3.1 Specifications of requirements for future detectors (**M12**)
- M4.3.2 Report on technological challenges (**M12)**
- M4.3.3. Report - survey of possible solutions and specifications for the prototype(s), based on physics (**M12)**
- M4.3.4 Full conceptual design for ARC detector (**M12**)
- M4.3.5 Survey of existing software and techniques and definition of requirements and solutions for the future challenges (**M12**)

Deliverables:

- D4.3.1 Performance of radiator gas alternatives to per-fluorocarbons (**M36**)
- D4.3.2. Feasibility study for new RICH detector concepts - (**M36**)
- D4.3.3. Prototype of Autonomous Cluster of Imaging Arrays (**M36**)
- D4.3.4. Evaluation of a prototype ARC cell (**M36**)
- D4.3.5. Framework for (fast) tracing of Cherenkov photons (**M36**)

WP 4.4 Time Of Flight – 4 tasks

DRD4

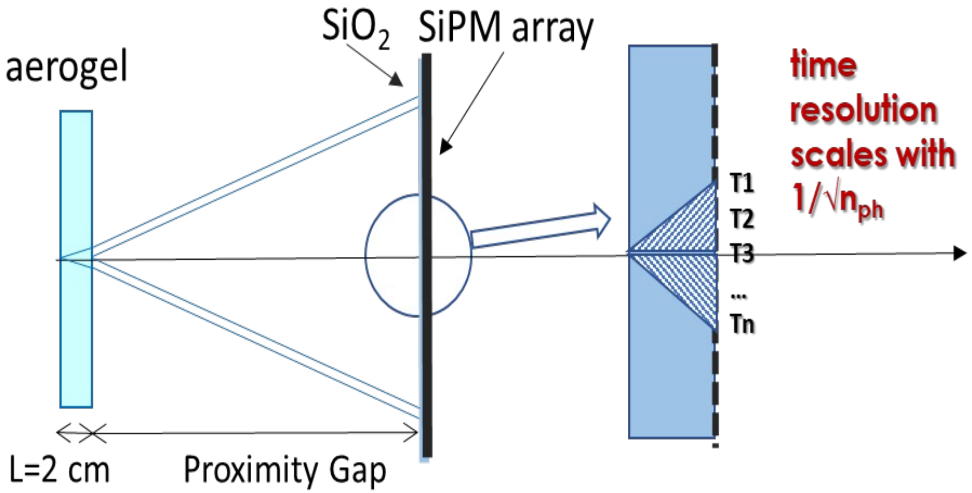
Task 4.4.1 - Study the coupling of a thin Cherenkov radiator to a single-photon detector array, for TOF of charged particles (5 groups):

- Prompt Cherenkov light ideal for fast timing.
- Cherenkov light yield is small compared with scintillation light; such limitation can be overcome by using sensors capable of detecting single Cherenkov photons.
- Goal: high precision timing ($\sigma_t \sim$10-15 ps)
- Principle: high refractive index solid Cherenkov radiators coupled to arrays of silicon photomultipliers or multichannel plates.

Task 4.4.2 - Develop a SiPM array for single-photon detection, with mm-scale pixelation, suitable for use in TOF prototypes (6 groups):

- SiPM detectors and electronics to provide mm-scale position sensitivity and fast timing of Cherenkov light at the very high rates expected with HL-LHC and future colliders.
- System aspects of combining SiPM arrays with radiation hardness, mm-scale pixelation, and cooling,
- Integration with multichannel readout electronics such as the FastIC ASIC family
- Goal: achieving the best possible time resolution.

A thin slab of SiO_2 added in front of the SiPM array acts as a Cherenkov radiator providing about a hundred photons per charged particle



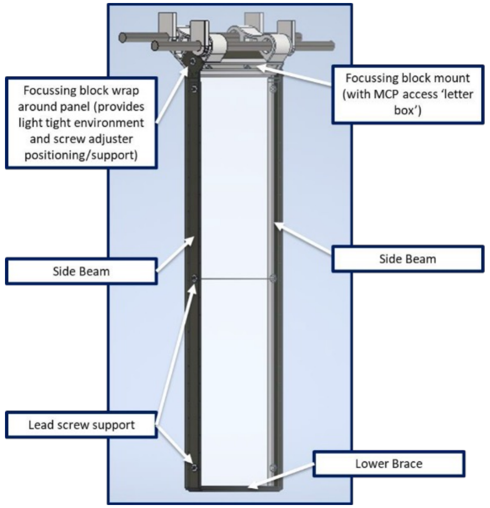
time resolution scales with $1/\sqrt{n_{ph}}$

WP 4.4 TOF

Task 4.4.3 - Develop lightweight mechanical supports for DIRC-type TOF detectors (3 groups):

- Cherenkov radiators large, heavy quartz plates.
- high geometrical precision.
- Prototype support developed using lightweight materials.
  - Adjustable and accurate positioning required.
  - Minimize distortion + support quartz, detectors, electronics.

- Prototype for performance verification.



Proposed quartz Cherenkov radiators and lightweight support structure For TORCH

Task 4.4.4 - Develop techniques for measuring the optical properties of optical components for TOF detectors (6 groups):

- Characterization of the quartz Cherenkov radiators
  - Radiator optical specification is demanding.
  - Challenging to manufacture and difficult to measure.
  - Develop Precision measurement
- Share existing Facilities

Milestones:

- M4.4.1 Selection of suitable material for the Cherenkov radiator and its coupling to the sensor (M18)
- M4.4.2 Demonstration of single-photon detection with SiPM arrays with FastIC readout **(M18)**
- M4.4.3 Design of a lightweight TOF module **(M18)**
- M4.4.4 Report on progress in setting up optical laboratory for characterizing TOF radiator **(M18)**

Deliverables:

- D4.4.1 Prototype TOF detector **(M36)**
- D4.4.2 Prototype of array of cooled, mm-scale segmented SiPMs with integrated readout **(M36)**
- D4.4.3 Prototype of a lightweight mechanical support for a DIRC-type TOF detector **(M36)**
- D4.4.4 Optical laboratory for characterizing the performance of a DIRC-style quartz radiator plate **(M36)**

WP 4.5 SciFi and TR – 1 task

DRD4

Task 4.5.1 (only 1 task): (**6 groups**):

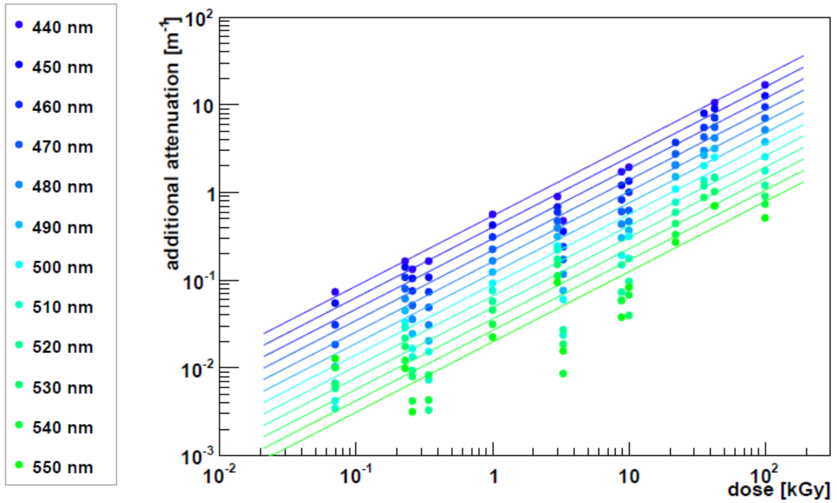
Develop an improved radiation hard scintillating fibre with a fluorescence decay time less than 4 ns.

The standard fast fibre is over 25 years old (SCSF-78M and -78MJ from Kuraray)

- Peaks at 450nm, 3.5m attenuation length, 2.8ns decay time

Goal: A new fibre with larger Stoke's Shift (to >500nm) would improve the transmission after irradiation of the fibre

- Should have same or better light yield, attenuation, decay time, and stable in time.



From the thesis of R. Ekelhof, 2016. TU Dortmund

Milestones:

- **M.4.5.1.1** Pre-Selection of suitable scintillators or cladding modification (**M12-M18**)
  - Obtain samples and characterize the bulk scintillator material
  - → the hardest part. We can't produce our own.
- **M.4.5.1.2** Radiation hardness, timing, wavelength **M18-M24**
- **M4.5.1.3** Production of fibre samples (a few km) with Kuraray (**M24-M30**)
  - In contact with positive response. Production facility closed until mid-2024.
- **M4.5.1.4** Testing and qualification of prototype fibre samples
  - Light yield, attenuation length, timing, radiation hardness **M36**

Deliverables:

Report on candidates M26

Report on any produced prototype (M28)

Not guaranteed to find any

WORKING GROUPS

DRD4

Progress & Innovation →

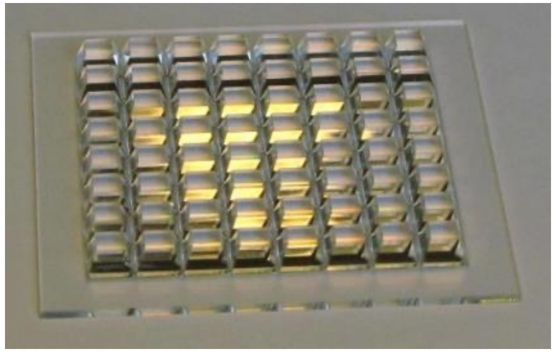
WG 4.1 Forum to discuss advances in photo-detectors

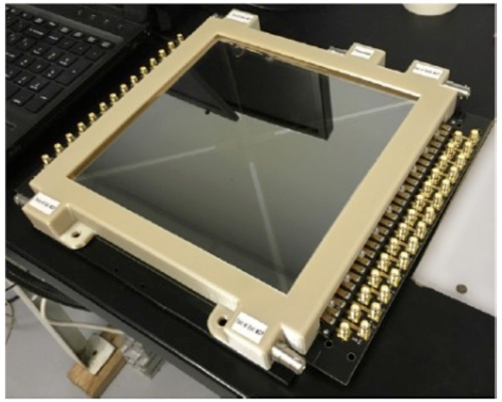
59 groups!

- ❑ solid-state (SiPM)
- ❑ vacuum-based (MCP-PMT) photo sensors

Topics:

- Radiation tolerance
- Longevity
- extreme conditions: e.g., cryogenic and high magnetic field
- SiPM timing;
- Large-area SiPMs;
- Large-area vacuum photo sensors, e.g., LAPPDs;
- Fine granularity detectors for future high-rate experiments;
- highly segmented photocathode structures and NanoChannel Plate (NCP)
- New technologies: CMOS-SPADs, new SiPM structures, BSI SiPMs
- Novel materials for photon detection: e.g., Ge-on-Si APDs;
- Hybrid photon sensors: Timepix-HPDs and MCP-HPDs , ...
- PICMIC readout concept
- Read-out electronics for extreme environments
- Optimal sensors and readout electronics integration;
- Simulations of photo-detector response.





- ❑ Standardization of procedures for the characterization of photon detectors.
- ❑ Regular knowledge exchange with
  - DRD1 - gas-based photodetectors
  - DRD2 - photosensors for cryogenic detectors
  - DRD6 - calorimeters
  - DRD7 - novel concepts in read-out electronics.

WG 4.2 Particle ID: RICH, DIRC, TOF, TOP, TORCH

39 groups!

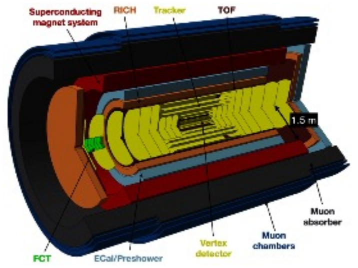
DRD4

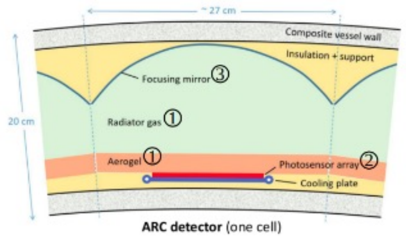
- Choice of PID method depends on numerous parameters, e.g. p-range, tolerable mass, available space and budget
- Over the past 5 decades several new principles have emerged, optimising performance while reducing space and mass. Border between Cherenkov imaging and TOF detectors has almost disappeared
- SiPMs, if sufficiently noise less, may allow for new concepts

- Different PID methods still share many challenges, e.g.
    - optical concepts
    - single photon detection
    - radiator technology (and operation)
    - mechanical integration
    - fast timing
    - software (simulation)

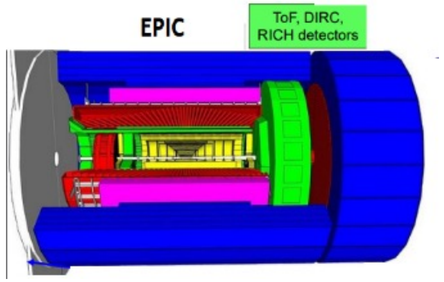
\+ Help new members to gain experience in detector design and software.

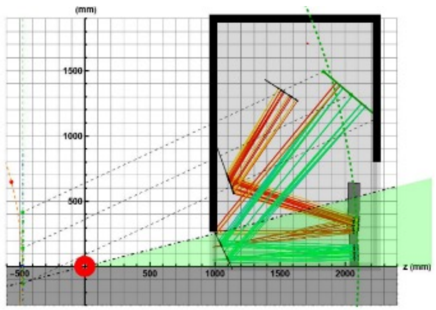
-- There are only very few people with the relevant expertise on various PID techniques. It may be difficult for them to provide voluntary support over extended periods of time to train new members in the WG.

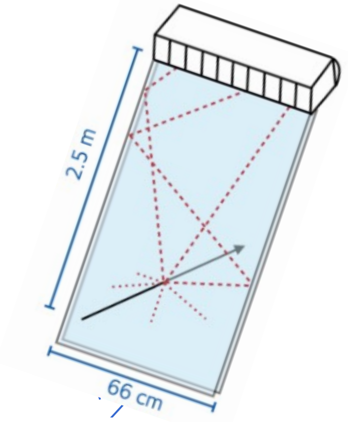




ECFA
European Committee for Future Accelerators







WG 4.3 Technologies and Tools

33 groups!

DRD4

Key technologies:

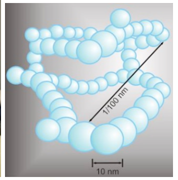
- Radiators (gas, aerogel, …) characterization, purity, fluid circulation, monitoring, …
- Optical technologies (mirrors, lenses, …) coatings, aspherical elements, q.a., …
- Thermo-mechanical engineering design light materials, pressurized, coolants,…
- Ancillary instrumentation (calibration, alignment, monitoring), PDE, (n-1), safety, …

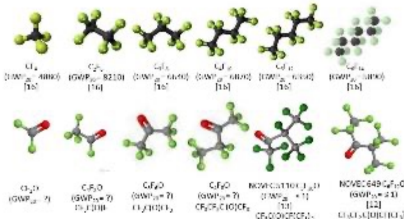
Readout electronics:

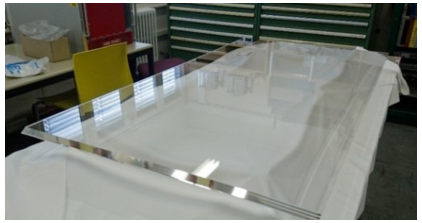
- Integrated electronics for fast low-noise full readout chain of PMT/MCP/SiPM. FE/BE, high-rate/high-bandwidth DAQ, trigger/self-trigger; low-consumption; rad-hard components; wide temperature range.

Develop full readout system chain for fast, low noise, highly pixelated single photon counters, using existing or soon-to be ready ASICs.

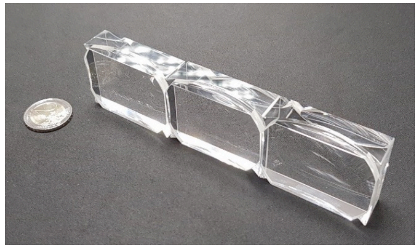
Aerogel
Samples and structure



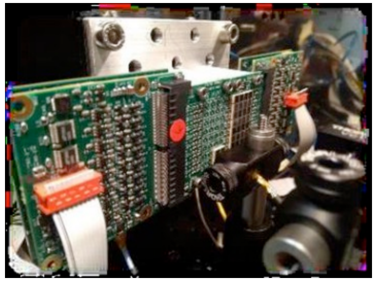


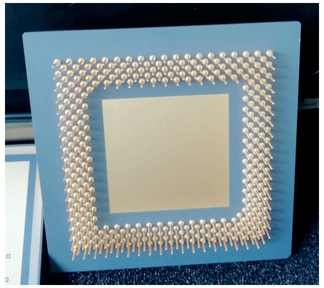


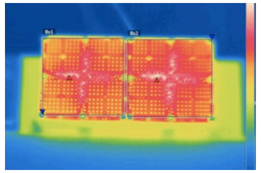
Quartz bar (TORCH)



Compound lenses (PANDA)

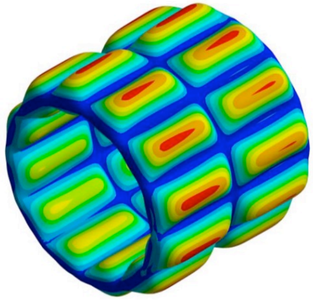






thermal simulation of MAPMTs

Deformation of Pressurised ARC vessel



WG 4.4 **Software:** Simul, Recon, ML, …

11 groups

DRD4

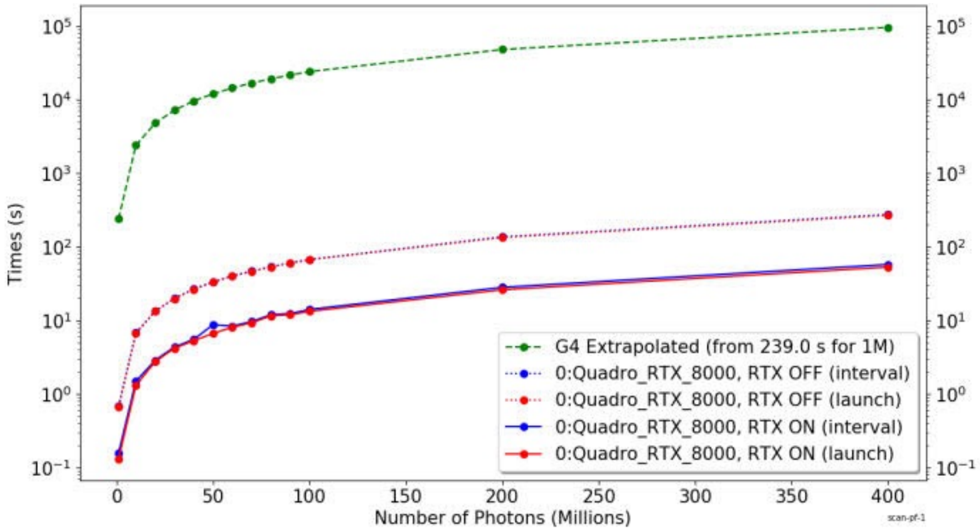
Some of the topics that are being considered:

- Explore the use of the machine learning techniques to improve PID algorithms
- Develop software that runs on hardware such as GPUs to speed up simulation and reconstruction.
  This would be useful for Cherenkov detector projects that will simulate and reconstruct billions of events.
- Simulate the next generation of photon detectors and their readout.
- Create a framework to evaluate the new algorithms that will be developed on different software platforms.

- Example of the speed-up in CPU time achieved in optical photon simulation using GPUs for a Cherenkov detector.

- Advantages of having this WG:
  - Facilitate the exchange of new ideas on software.
  - Develop common solutions across projects.

- Issues for the WG:
  - Some topics may need significant investment in time. The relevant experts may not always be available to develop the software for this.



Simulation time vs number of photons

Green: GEANT4 alone
Solid Red: GPU with RTX
Dotted Red :GPU without RTX

Speedup factor above 1600 obtained with GPU usage

Ref: S.Blyth, EPJ Web Conf, 251 (03009) , 2021 From JUNO experiment

WG 4.5 Specific developments: SciFi tracking …

17 groups

DRD4

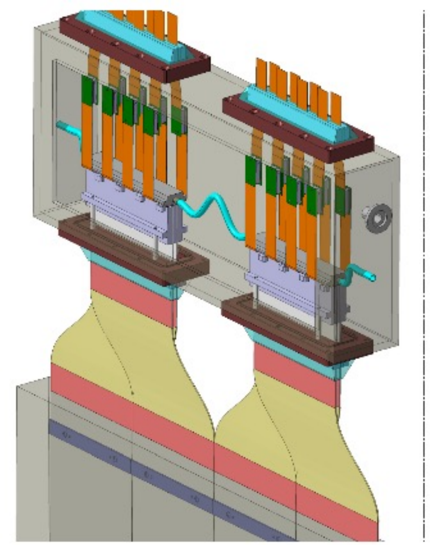
Scintillating Fibre tracking and Transition Radiation trackers are two relatively small and unrelated activities.
Still, they fit in DRD4, probably better than anywhere else in the DRD network.

A. "Improvement of the performance SciFi trackers in high rate and high radiation environments"

- SciFi with SiPM readout is an elegant way of tracking particles, however the limited radiation tolerance of the fibres and SiPMs leads to a chain of technological challenges such as fading signal amplitude and noisy SiPMs that need to be addressed by low temperature operation, multi-layer fibre mats, replacement strategies, etc.
  Some of these problems are similar to those occurred to RICH detectors in harsh radiation environments (e.g LHCb-II).

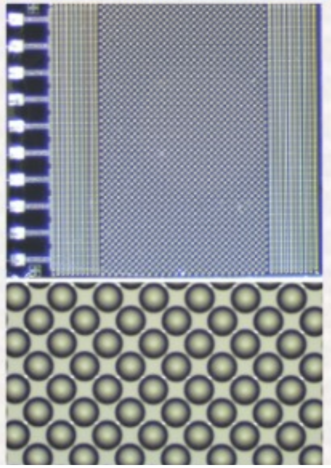
WG4.5.A is the forum where people meet developing SciFi trackers / upgrades.

- novel fast & radiation-hard scintillating fibres
- Tracking with photon timing information in high occupancy environments
- Micro-lenses on SiPMs
- fibre ribbon and detector plane production techniques (flexible ribbons)
- Cryogenic cooling of SiPMs




Laterally-flexible fibre mat with feed-through into a vacuum box for LHCb Upgrade 2, which may use cryogenically cooled SiPMs.
[Source: Guido Haefeli EPFL]

μ-Lens implemented on 10ch custom device



[Source: Guido Haefeli EPFL]

Specific developments: … and TR (Solid state based)

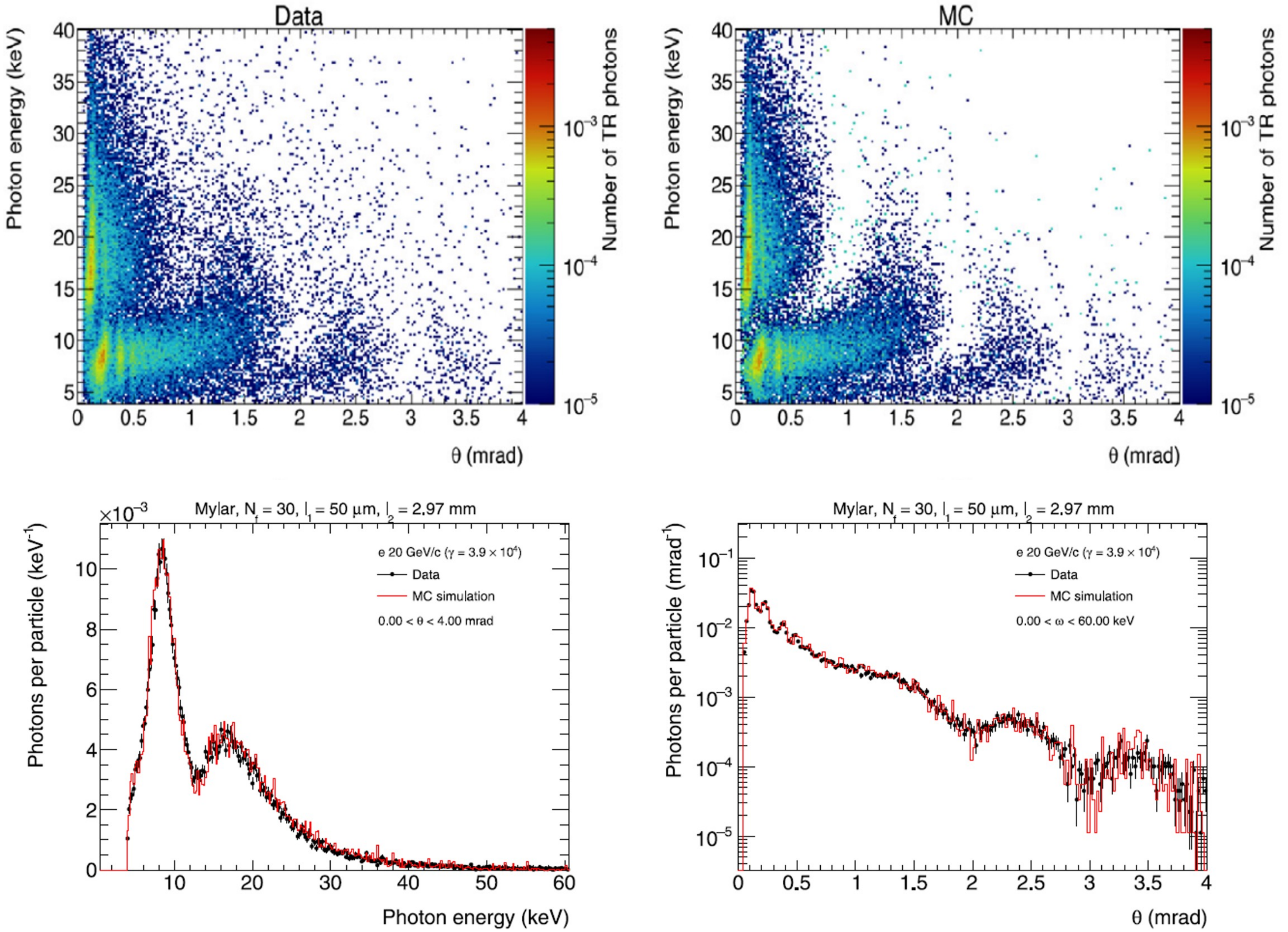
17 groups!

DRD4

Plots taken from: J. Alozy et al., NIMA961 (2020), 163681

B. Transition Radiation Detectors

- **Goal:** development of a novel TRD based on highly segmented pixel semiconductor detectors, for measuring both the energies and the emission angles of TR X-rays
- **Applications:** hadron ID in the TeV range
- **Activities:**
    - analysis of existing data
    - development of MC simulations
    - development and optimization of new radiators
    - development of highly pixelated detectors based on Si, GaAs and CdTe
    - development of readout chips associated to the detectors
    - beam test studies



WG 4.6

12 groups

DRD4

Future ideas, concepts, blue sky …

This WG will act as the DRD4 collaboration's gate for novel ideas and revolutionary concepts

- New ideas shall find in WG4.6 the right environment to prosper
- Help the new concepts to reach the required level of maturity
- Hope to transform some of these ideas into breakthroughs in the field, impact the future of photon detection

Some vague ideas, e.g. nano channel plates, using ALD and other coating techniques.

Strong connections with the other WGs

CAVEAT: not many groups proposed activities so far

DRD4

Summary and conclusions

- Particle ID remains a key component in modern high energy physics experiments. Often, PID is achieved with Cherenkov and TOF detectors, that in turn often rely on photodetection.
- Photodetection is undergoing a strong transformation. SiPMs invade in fields of applications that were occupied since decades by vacuum and gas based devices.
- The DRD4 proto-collaboration has formed to propose a broad but focused R&D program on photodetectors and particle ID devices.
- Since RD26 (1992) "Development of a Large Area Advanced Fast RICH Detector for Particle Identification at the Large Hadron Collider Operated with Heavy Ions" this is the first international R&D collaboration in this field.
- The scope of DRD4 includes also SciFi tracking and Transition Radiation detectors. They fit well into DRD4.
- 74 groups from 19 countries, with a lot of relevant background, are prepared to become collaboration members.
- Their small average group size and scarce resources are a concern.
- The success of DRD4 will also depend on the ability of the groups to grow and to find additional resources.