THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

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Experiment / Detector – Innovation in HEP Detectors and Computing

Blue Sky research for particle detectors

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New sensors for tracking

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Data acquisition

A very broad topic for a single talk – very hard to cover all interesting developments → A subsample, also partly reflecting my own interests

Why blue-sky research?

Innovative instrumentation research is one of the defining characteristics of the field of particle physics.

Blue-sky (more explorative, without addressing immediate detector specifications) R&D has often resulted in game-changing developments which could not even have been anticipated even a decade in advance.

Recent examples include micro-pattern gas detectors, SiPMs and new technologies for very fast (10 ps) timing coupled with accurate spatial information - 4D-detectors.

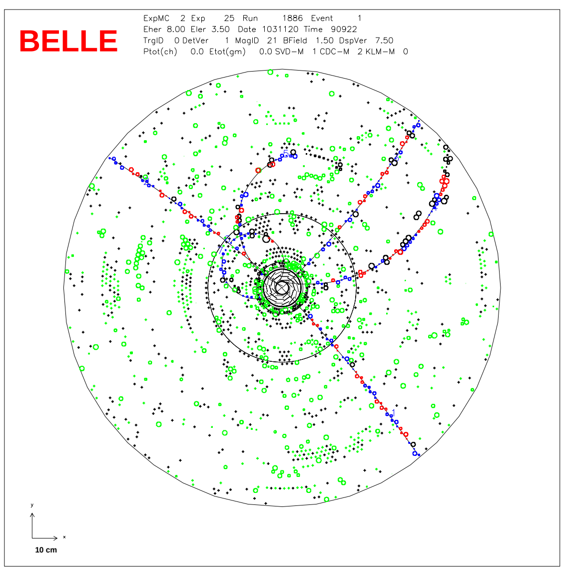
Blue-sky developments have often been of broad application and had immense societal benefit (World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science).

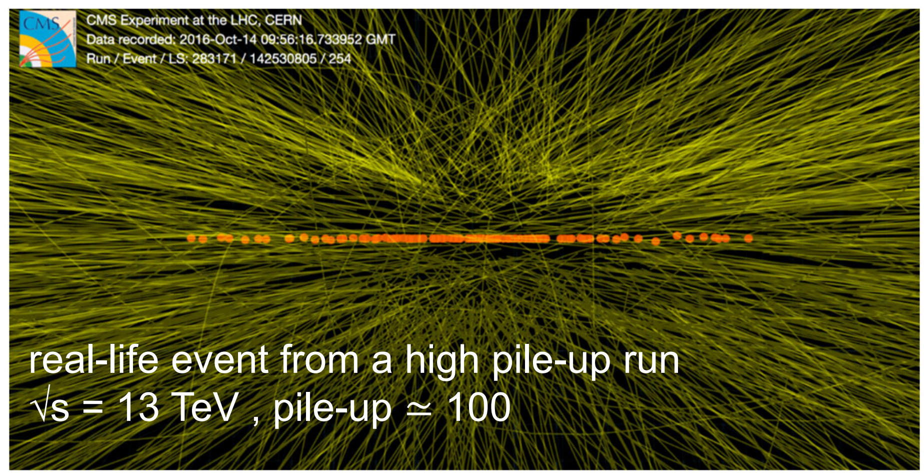
From 'The 2021 ECFA Detector Research and Development Roadmap'

Tracking (and vertexing)

Various needs at present:

- Lower energies (Belle II): precision tracking and minimal multiple scattering, few particles in the final state, no event overlap
- LHC: precision with a high density of particles, multiple overlayed interactions within the same event, high radiation load

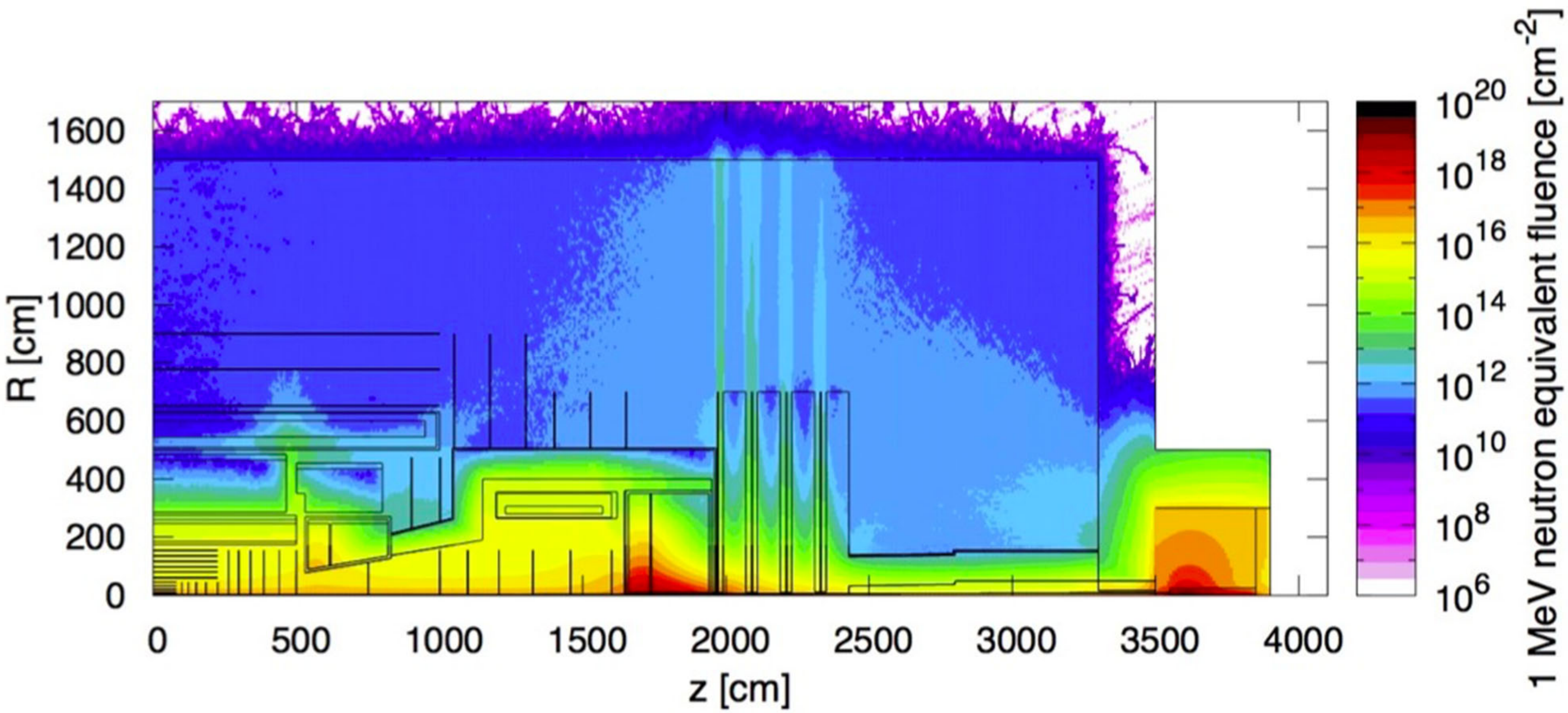




The FCC-hh environment

Radiation levels for 30/ab @100TeV up to:

- Fluence towards 10^{18} 1 MeV n_{eq}/cm^2
- Total Ionizing Dose (TID) ~ 300 MGy



Silicon particle detectors for the future

Silicon detectors very well studied up to 2e16 n/cm^2 - the maximum HL LHC level

→ but already at these fluences detectors behave differently than what would be expected from extrapolations from LHC leves (~ 1e15 n/cm^2)

- examples: scaling of trapping probability with fluence (2016 JINST 11 P04023)
- electric filed profile in irradiated detectors (double junction, field in neutral bulk)
- charge multiplication

→ based on the results of studies made up to 2e16 n/cm^2 no reliable prediction of performance at 1e17 n/cm^2 and beyond can be made

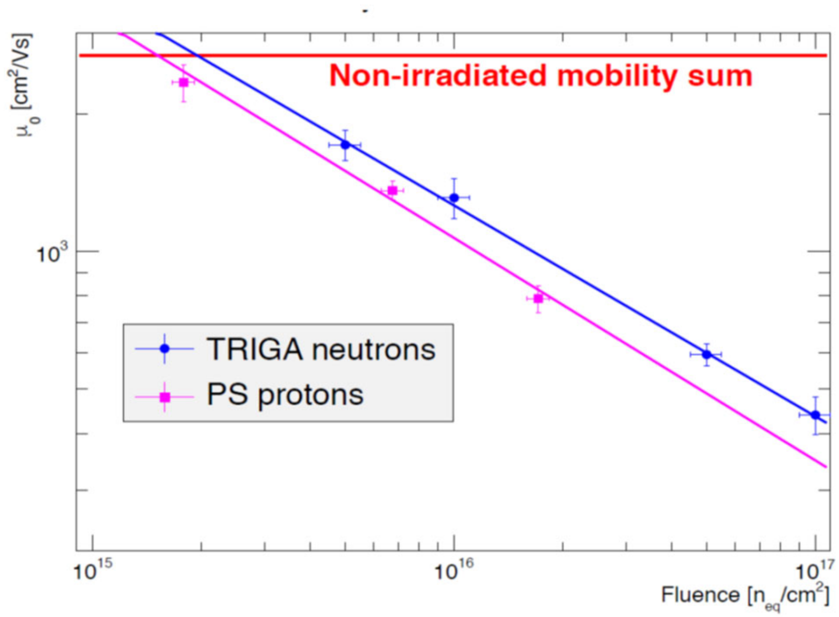
→measurements at extreme fluences are necessary!

Silicon particle detectors for the future – unexpected features

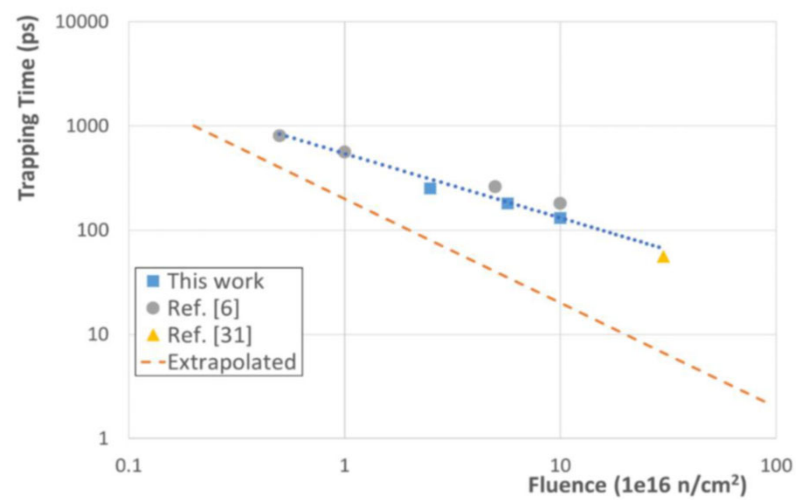
Planar silicon detectors

→mobility falls with increasing fluence
- shorter drift distance
- less multiplication
- velocity saturation at higher electric field

→effective trapping time falls with increasing fluence much slower than at low fluences
→good news! At 3e17 n/cm^2 already one order of magnitude higher than extrapolated



M. Mikuž, Treto Workshop 2016



I. Mandić et al., 2020 JINST 15 P11018

Silicon particle detectors for the future – unexpected features

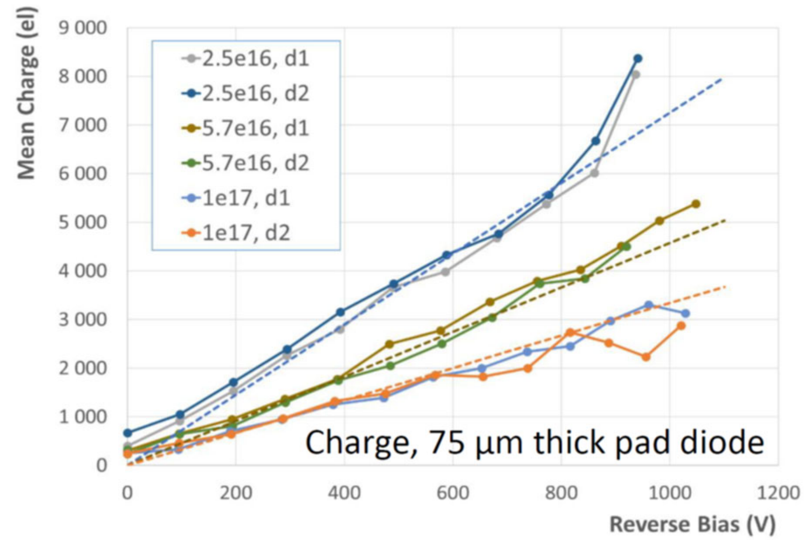
Planar silicon detectors, continued

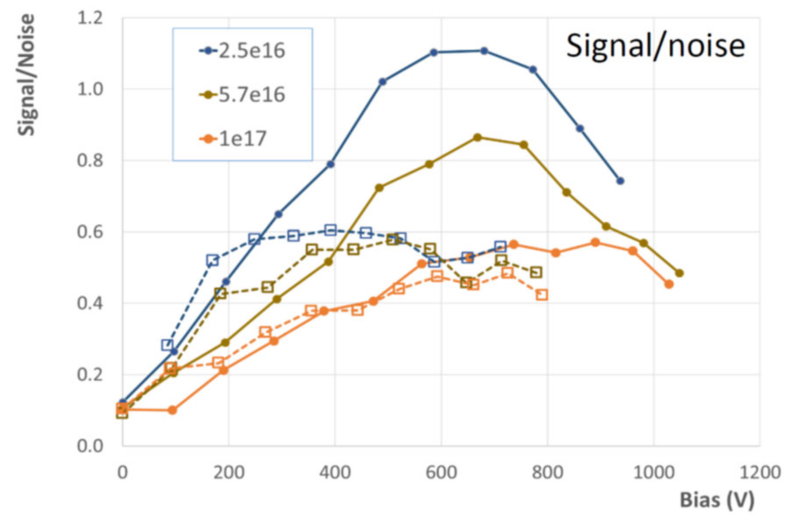
➔Collected charge increases almost linearly with bias

but

➔at high voltages S/N starts to drop

I. Mandić et al., 2020 JINST 15 P11018





→measurements at extreme fluences are necessary!

Silicon particle detectors for the future

A wide field of research – targeted + blue sky research needed

Some examples:

- 3D Si detectors
- Thin planar sensors with multiplication: how to make them tolerant to high irradiation levels – clever doping, inventive biasing
- Wide gap materials – SiC, diamond – also 3D

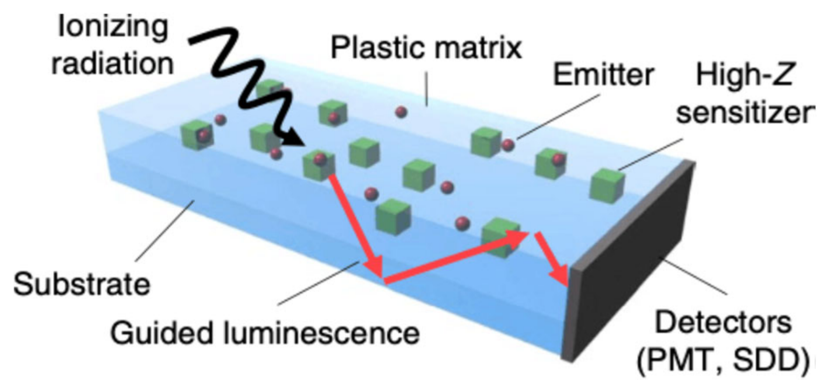
→ more in the talks by Philip Allport, Magnus Mager and Gregor Kramberger later today

Advanced scintillators: Nanocrystal composites

EM calorimetry: Inorganic crystals vs sampling calorimeters

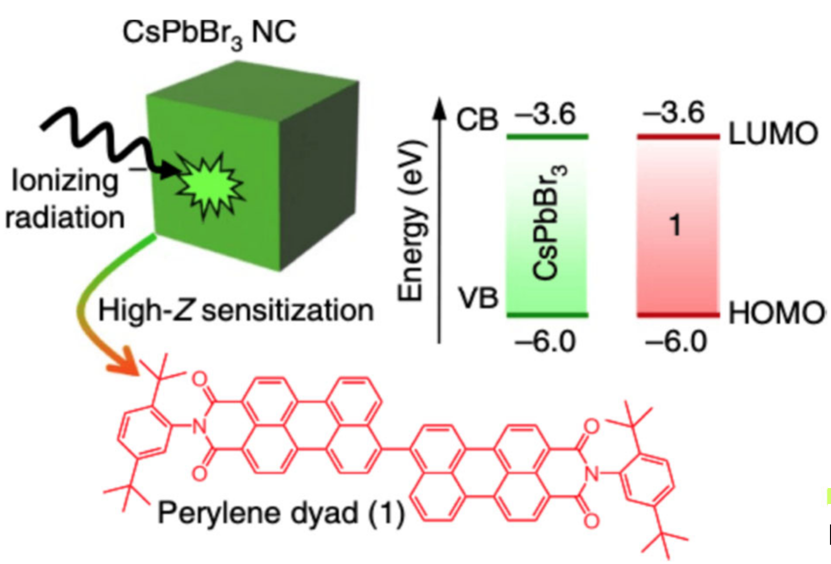
Can very fine sampling EM calorimeters be optimized to obtain performance approaching that of crystal calorimeters? PANDA/KOPIO (fine-sampling shashlyk): energy resolution $2.8\%/\sqrt{E} \oplus 1.3\%$

Could we do better than that?



Nanocrystal composites

1. Perovskite sensitizer (CsPbBr3)
2. Non-radiative transfer to fluor (perylene dyad)
3. Light propagation and readout via PMMA matrix



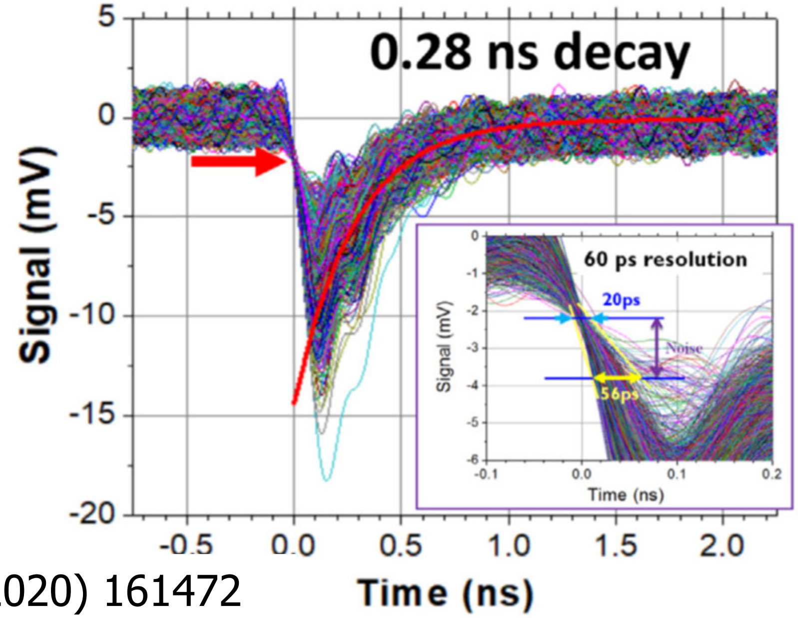
- Peak emission ~ 620 nm
- BGO-like light yield at peak
- Decay time (fast) = 3.4 ns (87%)
- Decay time (slow) = 14.1 ns (13%)
- No degradation up to 800 Gy

M. Gandini et al., Nat. Nanotechnol. 15 (2020) 462

Advanced scintillators: Fast scintillators based on quantum dots

Colloidal Quantum Dots: different sized nanoscale dots emit different colours of light due to quantum confinement.

Semiconductor scintillator based on InAs Quantum Dots functioning as luminescence centres embedded in a GaAs matrix can have uniquely fast scintillation properties with low self-absorption.

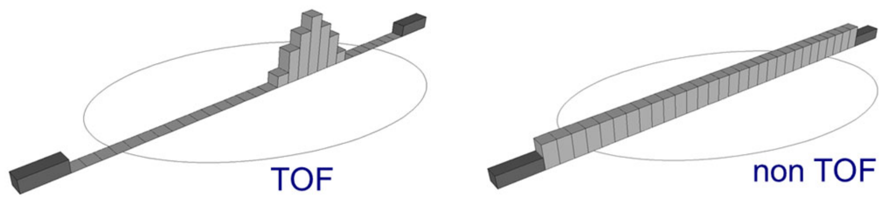


K. Dropiewski et al, NIMA 954 (2020) 161472

Related R&D pursued by RD18 (Crystal Clear): CdSe nano-platelets deposited on LYSO substrate → faster response   R. Turtos et al., JINST 11 (2016) P10015

Advanced scintillators

Very fast scintillators for annihilation gamma detection in TOFPET

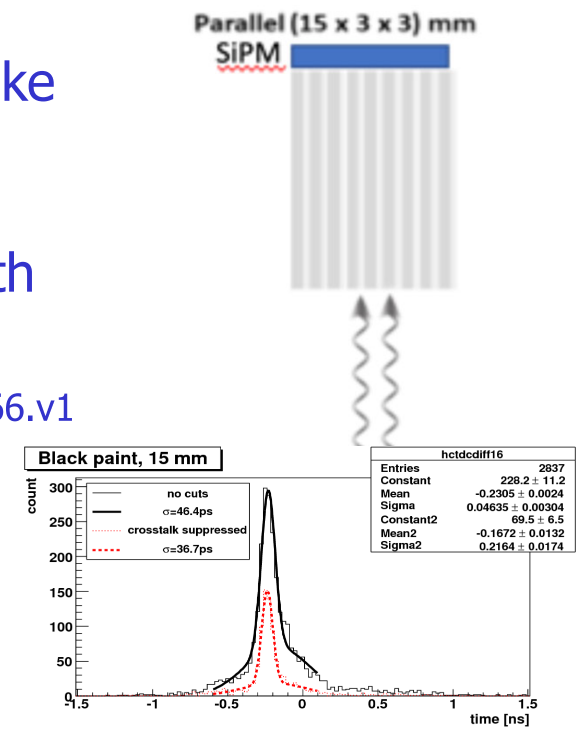


Localization of source position along the line of response:

$\Delta t \sim 66\text{ps} \rightarrow \Delta x = c_0 \Delta t/2 \sim 1\text{cm}$

Metascintillators: combine a standard high yield crystal like LYSO with a fast one; the range of the recoil electron is typically 400 to 500 microns → make sure that the photoelectron passes through both → stack layers of both materials.

P. Lecoq et al., https://doi.org/10.36227/techrxiv.17056166.v1



Use Cherenkov light instead of scintillations.

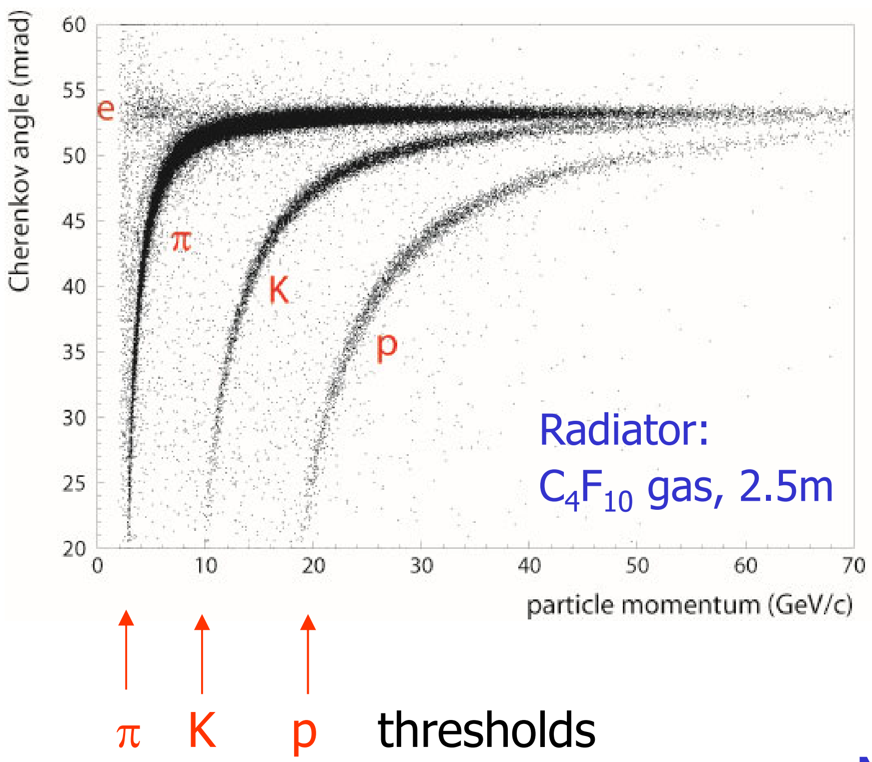
R. Dolenec et al NIMA 654 (2011) 532

Use pannels of short crystals, read-out by fast SiPMs with very fast integrated electronics (FASTiC – same as for the next LHCb RICH upgrade.)

G. Razdevšek et al, DOI 10.1109/TRPMS.2021.3115704

Particle identification: novel radiators for Cherenkov detectors

$\cos\theta = c/nv = 1/\beta n$



Challenges:

- Low number of photons
- To cover the required momentum range, need an the radiator medium with an appropriate refractive index of the radiator medium.

→Not all values of n are possible

→High momenta – low n needed → gas → very few photons, long radiator needed

Novel radiators for Cherenkov detectors

- Multiple layer radiators
- Metamaterials

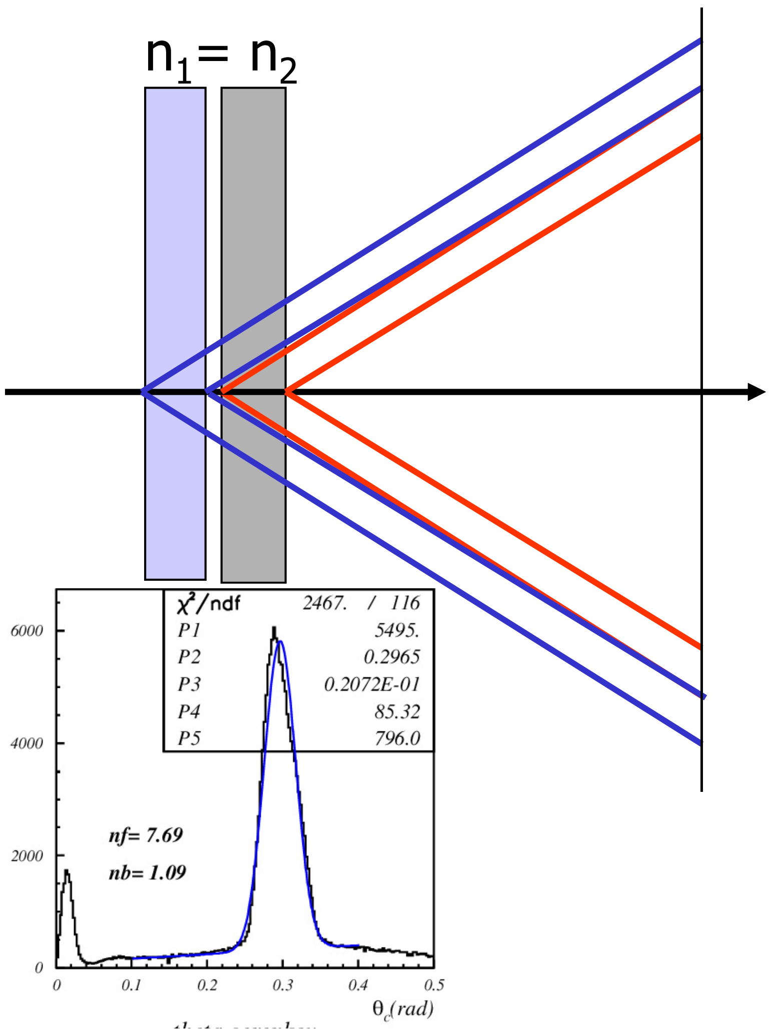
Radiator with multiple refractive indices

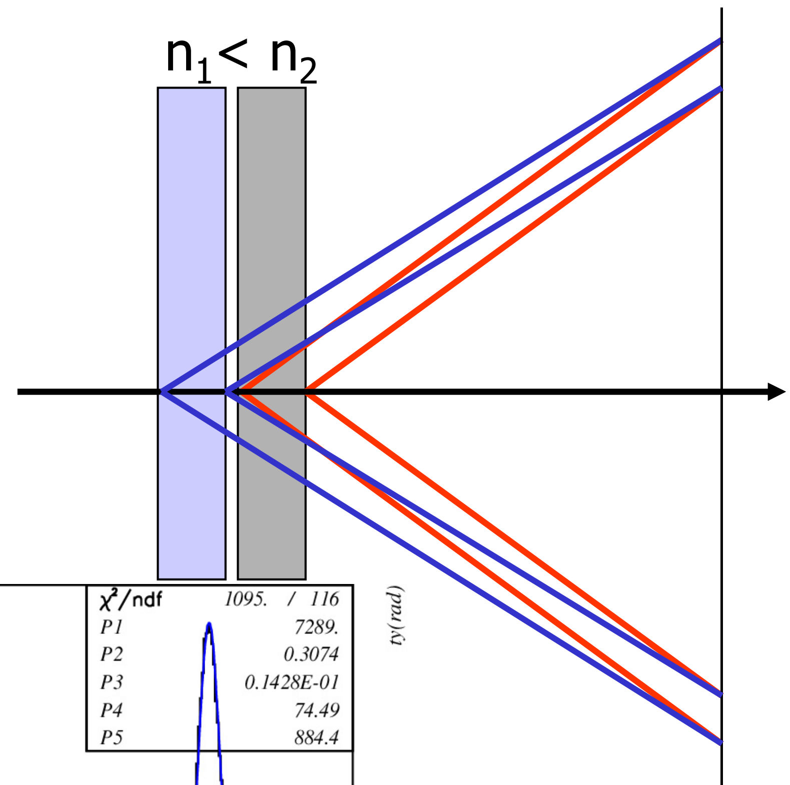
Small number of photons from aerogel → need a thick layer of aerogel.

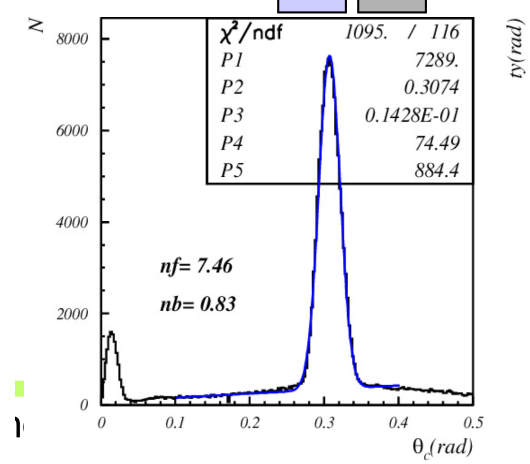
How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: "focusing" configuration → "focusing radiator"

normal





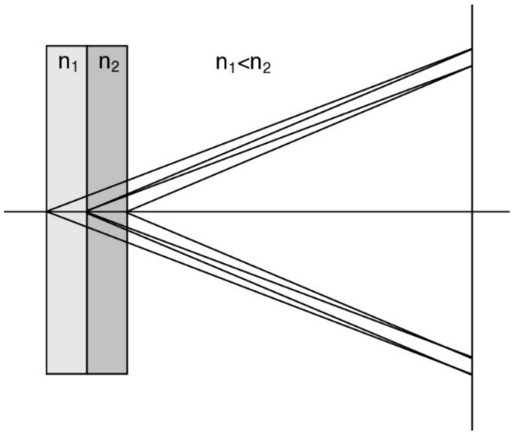


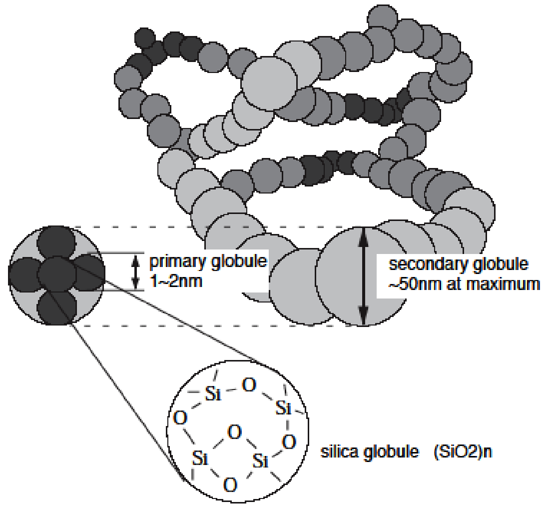
→NIM A548 (2005) 383,

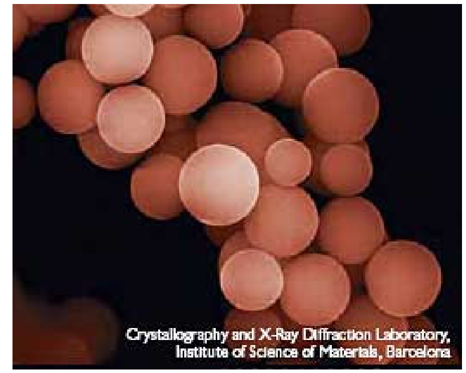
NIMA 565 (2006) 457

Radiator with multiple refractive indices 2

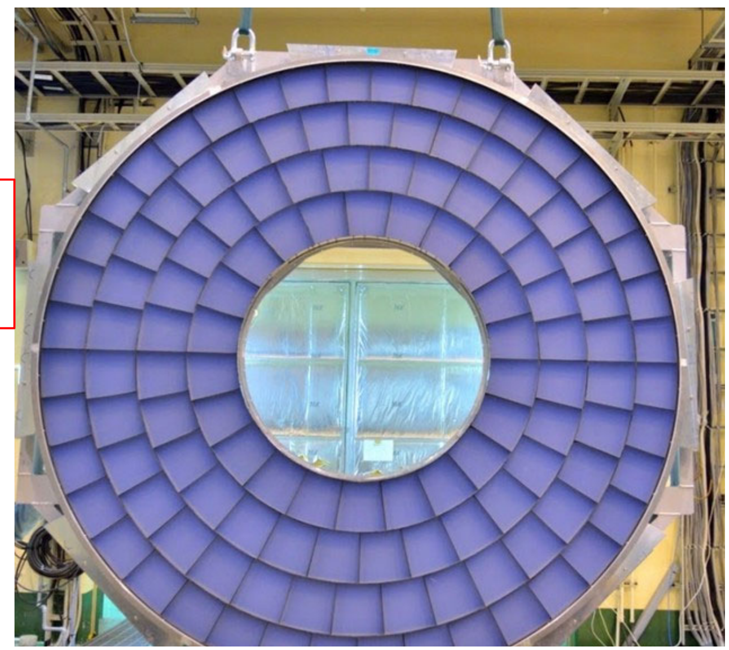
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.07.







Belle II ARICH



Radiator plane covered with 2 x 124 tiles water-jet cut tiles (~ 17x17cm)

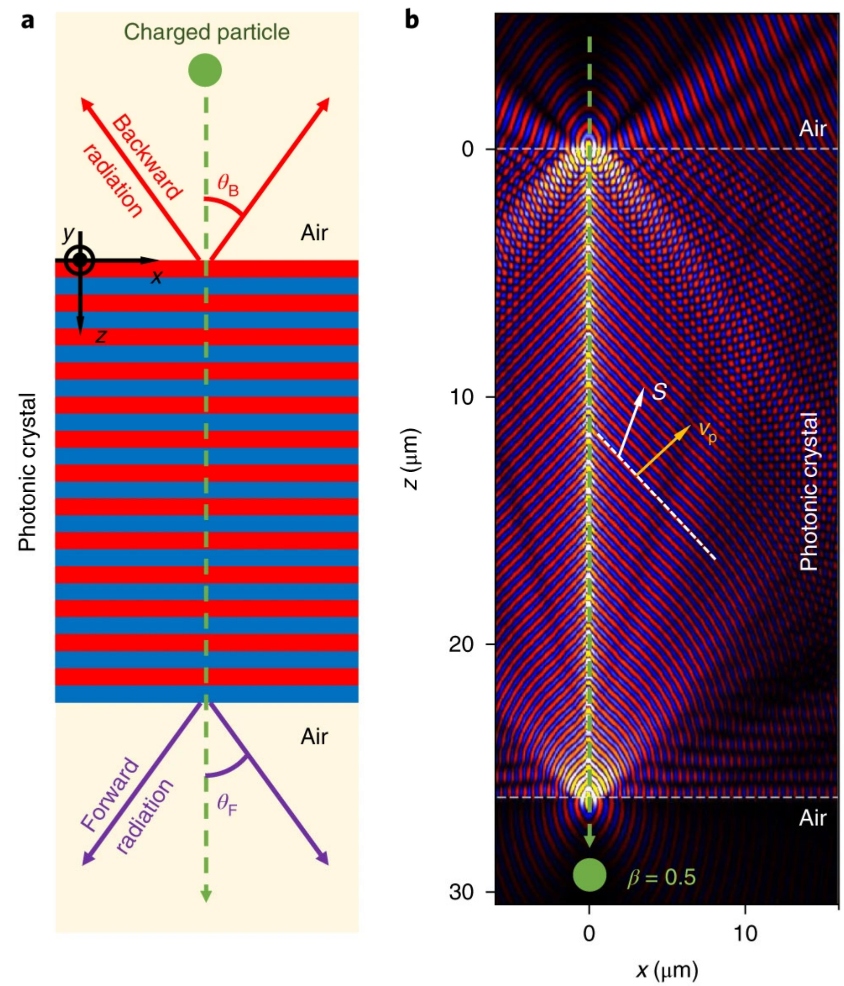
Particle identification: novel radiators for Cherenkov detectors

Metamaterials: photonic crystals, Cherenkov radiation induced by the constructive interference of resonance transition radiation

Radiation emitted in both forward and backwardd direction

Interesting concept – but still far from practical use

Lin, X., Easo, S., Shen, Y. et al.
Nature Phys 14, 816–821 (2018)



SiPMs as photon detectors for RICH detectors

SiPM: array of APDs operating in the Geiger mode. Characteristics:

- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm) PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ 10-100 kHz/mm^2
- radiation damage (p,n)

Not trivial to use in a RICH where we have to detect single photons! (=same pulse height as for the dark counts)

Dark counts have single photon pulse heights (rate 0.1-1 MHz) – and this gets worse with n irradiation…

Started as a blue sky research 15y ago – now considered for most RICH detectors planned for the future - RICHes in the EIC detector, the next LHCb upgrade and for the Belle II upgrade by the end of the decade

SiPM as photosensor for a RICH counter

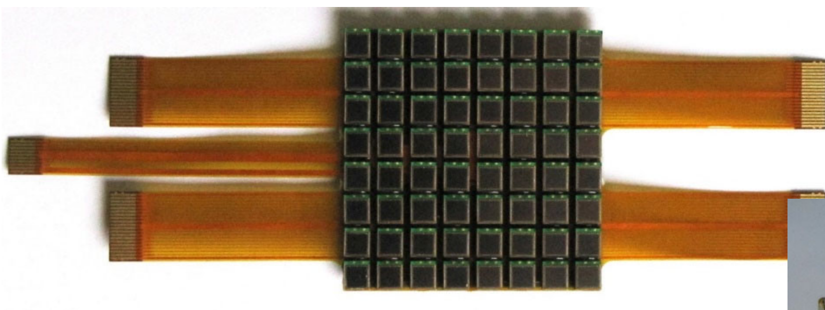
Improve the signal to noise ratio:

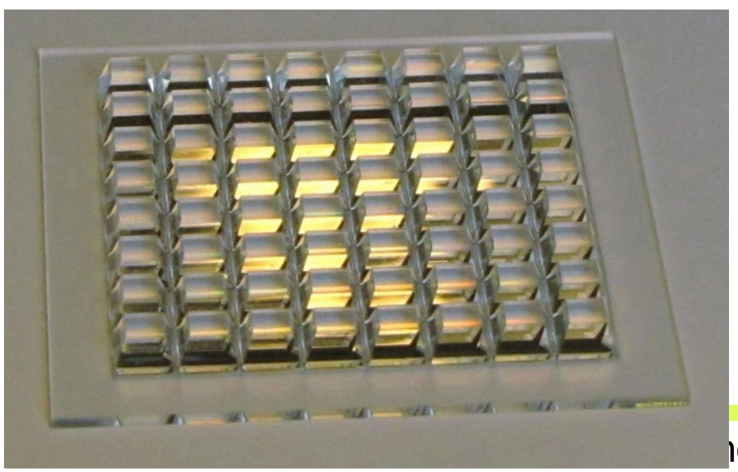
•Reduce the noise by a narrow (<10ns) time window (Cherenkov light is prompt!)

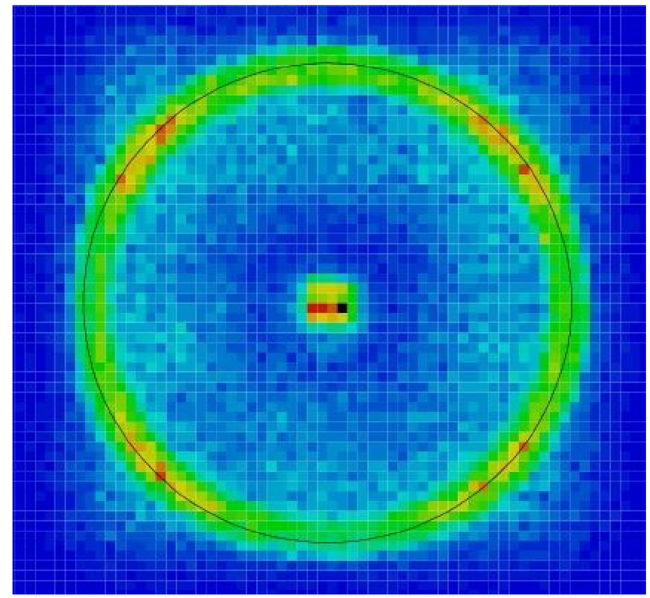
•Increase the number of signal hits per single sensor by using light collectors

Example: Hamamatsu MPPC S11834-3388DF

- 8x8 SiPM array, with 5x5 mm^2 SiPM channels
- Active area 3x3 mm^2



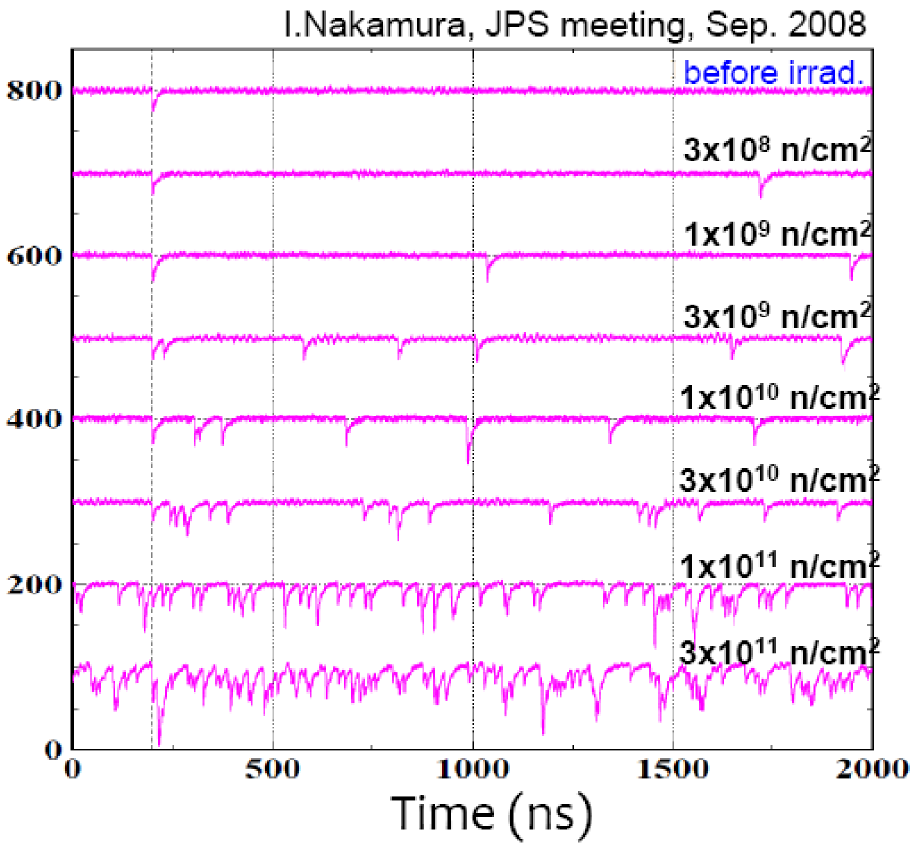




First rings with SiPMs

→ NIM A594 (2008) 13; NIM A613 (2010) 195

SiPMs: Radiation damage



Expected fluence at 50/ab at Belle II:

2-20 10^{11} n cm^{-2}

→ Worst than the lowest line

For single photon detection need

→cooling of sensors

→Some annealing method – periodical heating up, some encouraging tests

SiPMs → G-APDs with other materials?

Why GaN?

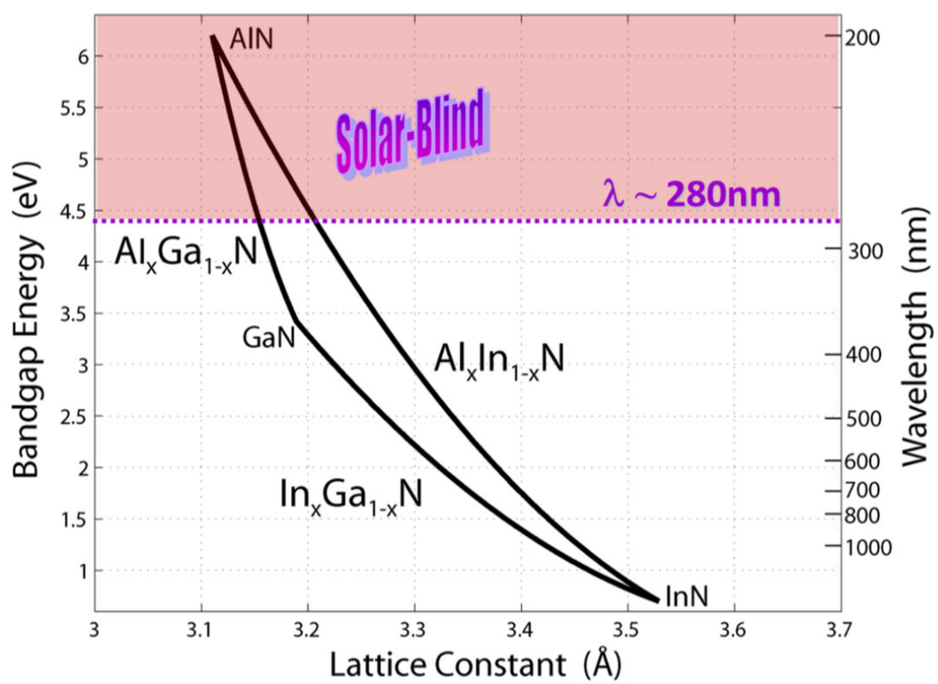
Large band-gap

- Tunable bandgap -> tunable spectral response (with In, Al)
- Potential for high UV-VUV sensitivity with little to no red sensitivity

Sufficiently clean substrates are available → Geiger-mode is possible

Increasing use of GaN in high-power electronics, LEDs, lasers

- Increasing supply of GaN-substrates
- Cleaner substrates
- Lower cost



Nepomuk Otte, talk at CPAD2021

SiPMs → G-APDs with other materials?

Geiger-mode in GaN is unexplored: Breakdown probability? Temperature dependencies? Electric field dependencies? Quenching?

Device fabrication: uniform breakdown characteristics, low dark-count rates, scalability, arrays

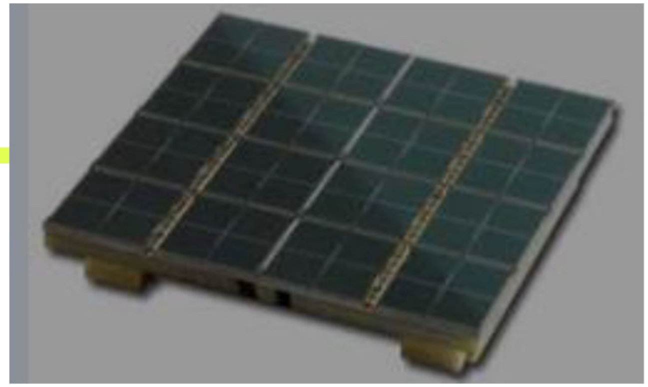
High dark-count rate prevents operation at higher overvoltages (cf. early SiPMs)

The situation is very similar to early silicon SPADs and SiPMs

- No fundamental limitations identified.
- The same methodology that improved SiPM characteristics can also improve GaN.

Nepomuk Otte, talk at CPAD2021

LAPPD Large Area Picosecond Photodetectors (MCP-PMTs)

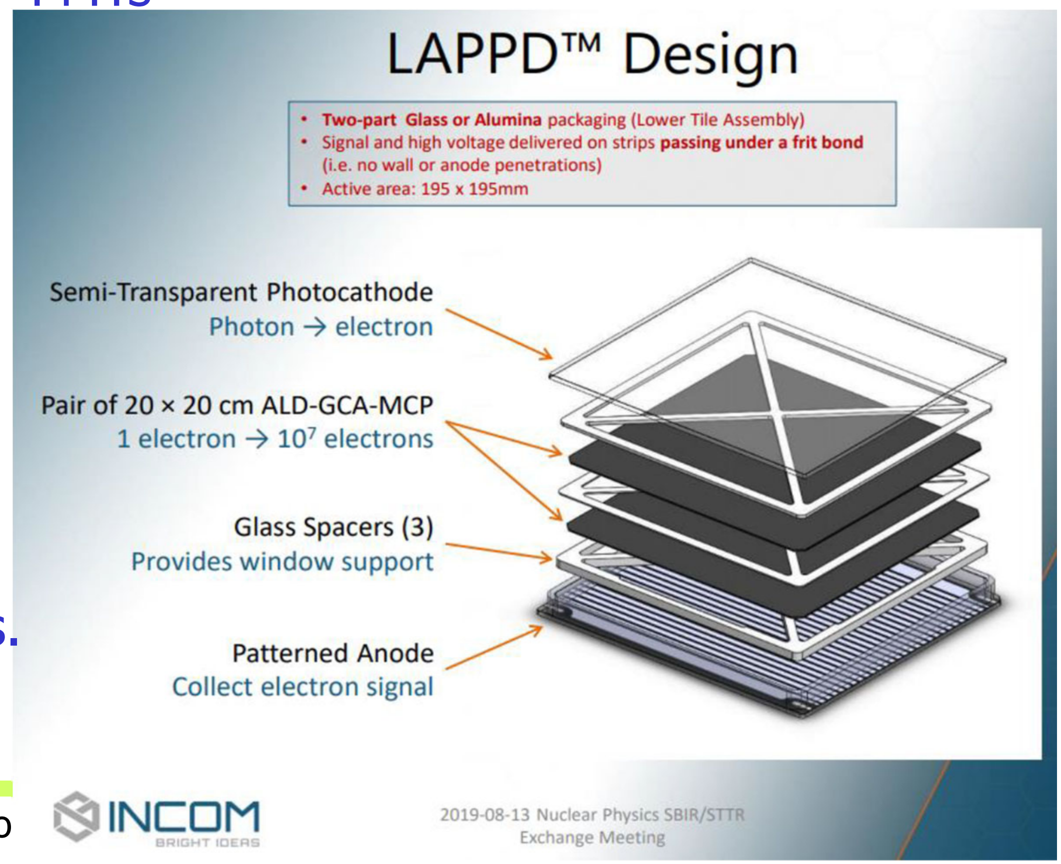


Attempt to produce less expensive large area single-photon sensitive devices

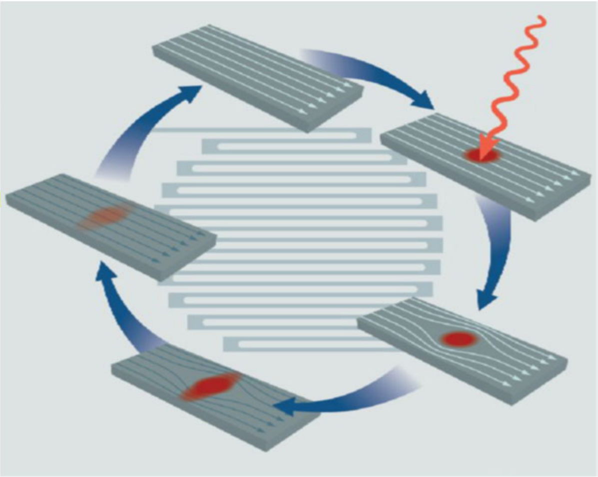
PROs:
- large area 20cm x 20cm
- cheaper than the conventional MCP PMTs

CONs:
- gain drop in magnetic field
- Small PDE compared to SiPM
- Lifetime limitation due to charge collection (for high rates)

Interesting also for large volume Cherenkov based neutrino detectors.



Superconductors for light detection



Example: superconducting nano-wire single photon detector (SNSPD): a thin (4 nm) and narrow (100-250 nm) superconducting nanostrip that is current-biased just below its critical current.

Absorption of a photon generates a resistive domain in the superconducting nanostrip, which leads to a transient voltage signal that can be detected.

A unique combination of speed, both in terms of count rate (GHz) and low timing jitter (< 3 ps), a large range of wavelength sensitivity from 120 nm to 10 μm, high detection efficiencies (approaching 100%), and low dark count rates (5-10 Hz).

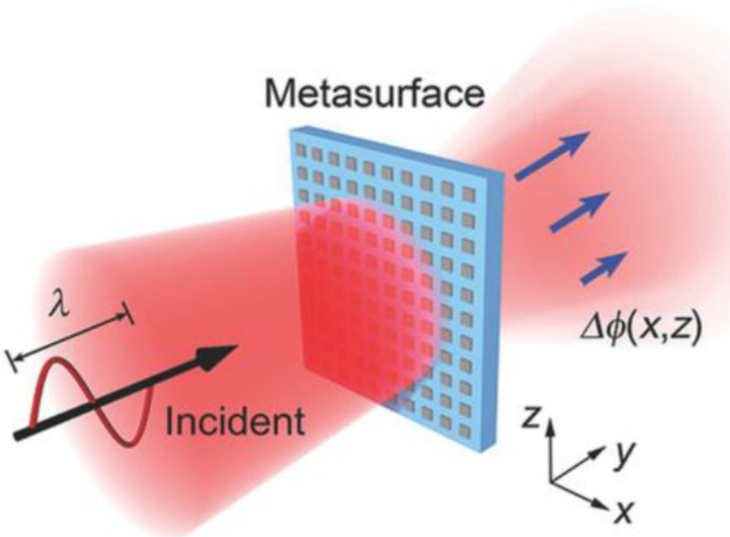
Enabling technology for quantum information science applications. Examples of SNSPDs in present use in particle physics are nanowire detectors for dark matter and dark photons.

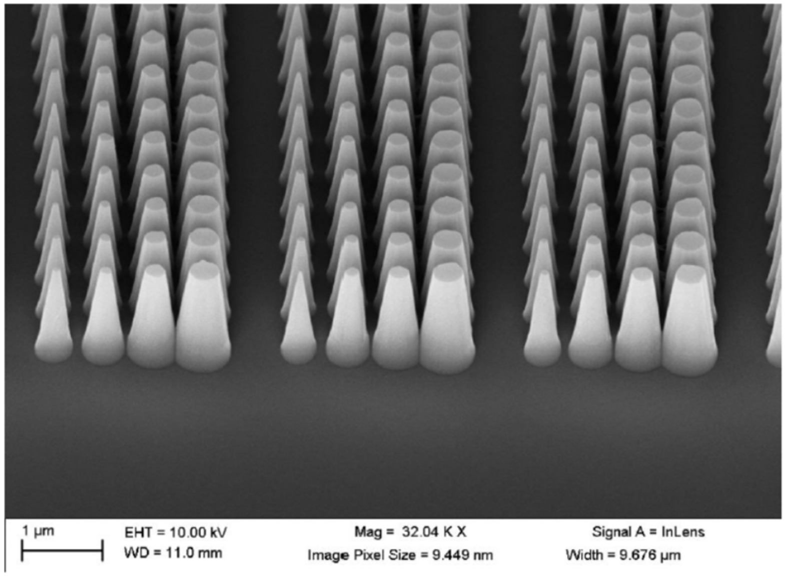
Work is in progress that could make these sensors relevant to HEP applications by lowering the energy threshold, increasing the area (using 300mm wafers and larger) and pixel size, coupling via windows to cryogenic stages, and readout of arrays (superconducting electronics for data processing).

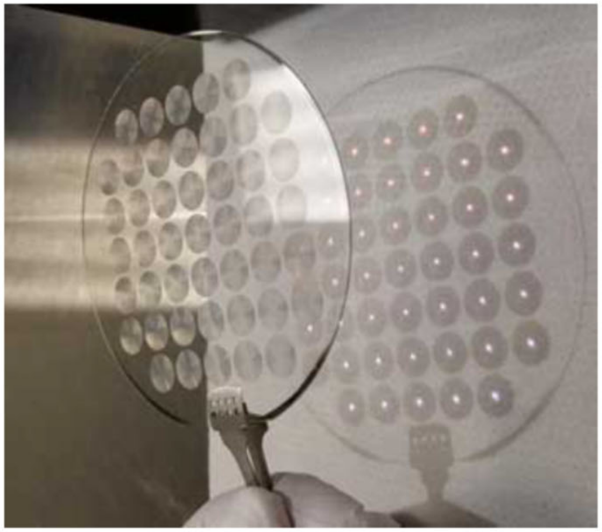
Any application of these sensors with severe cryogenic requirements in large accelerator-based detectors would require an extensive R&D program.

Sae Woo Nam @ ECFA Detector R&D TF4 Symposium

Light collection: metalenses







Capasso Group, Harvard University

Compared to ordinary lenses: thin, lightweight, cheap, more flexible.

Could be used to increase the active area of the detector (within limits given by the Louville's theorem).

Chris Stanford, talk at CPAD2021

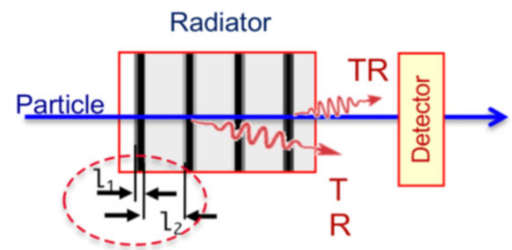
PID with TRD – new ideas

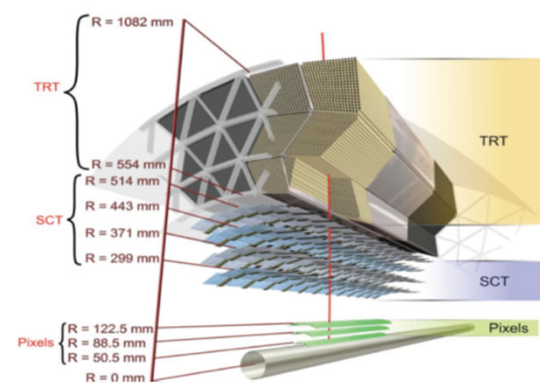
•TRDs are almost everywhere: ATLAS, ALICE, AMS, CBM, EIC

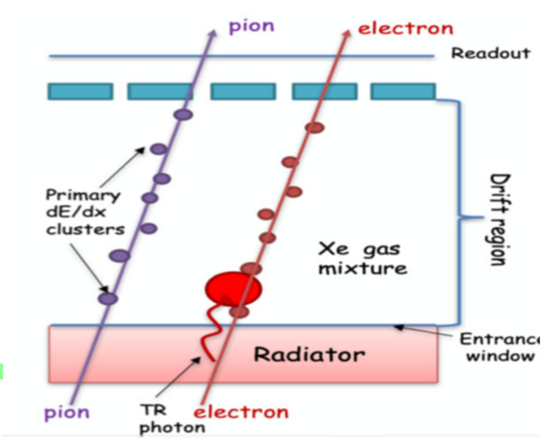
•Gas TRDs are considered a mature instrument for PID at high energies.

New ideas

- Read out with a pixel Si sensor
- TRD imaging

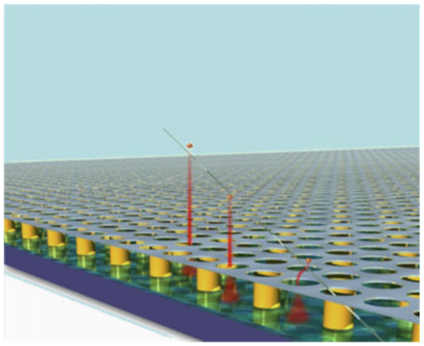


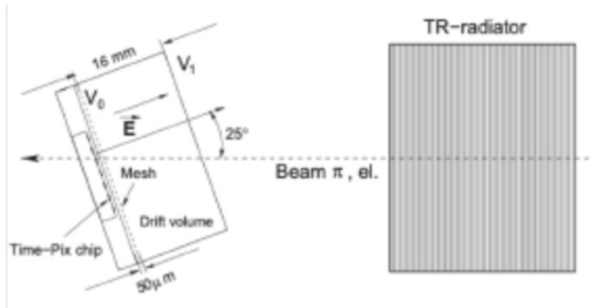


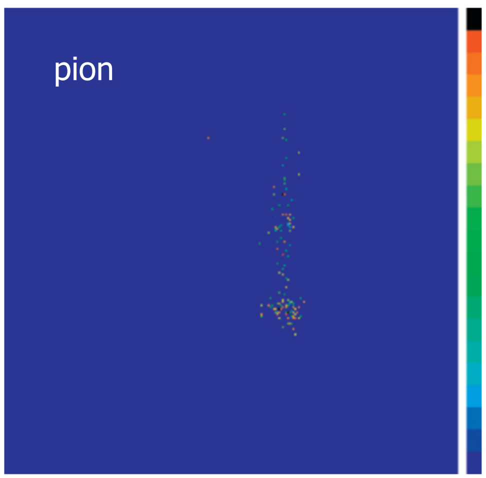


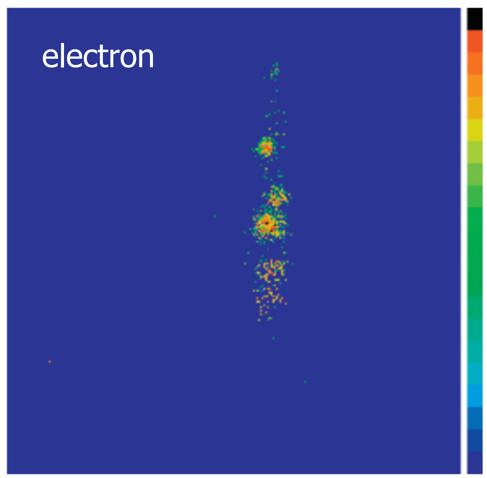
PID with TRD

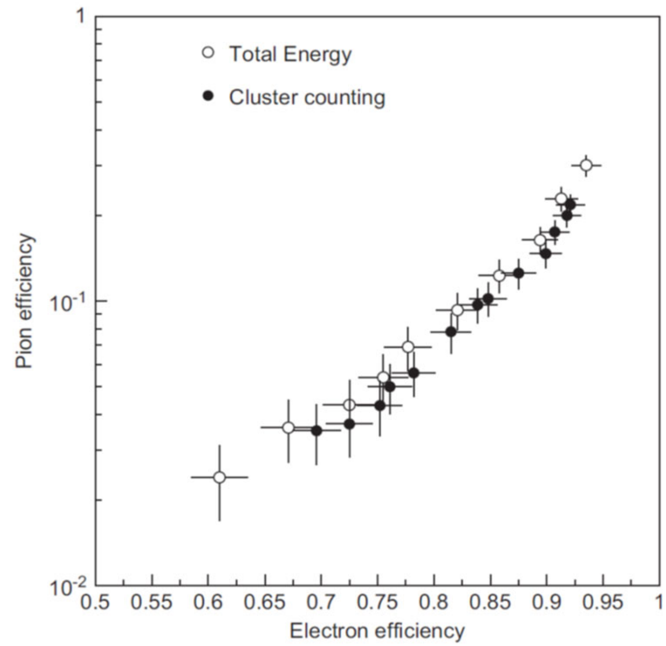
An attempt has been made to improve cluster counting by means of a GridPix.
Some improvement is possible, although not drastic. → NIM, A 706 (2013) 59







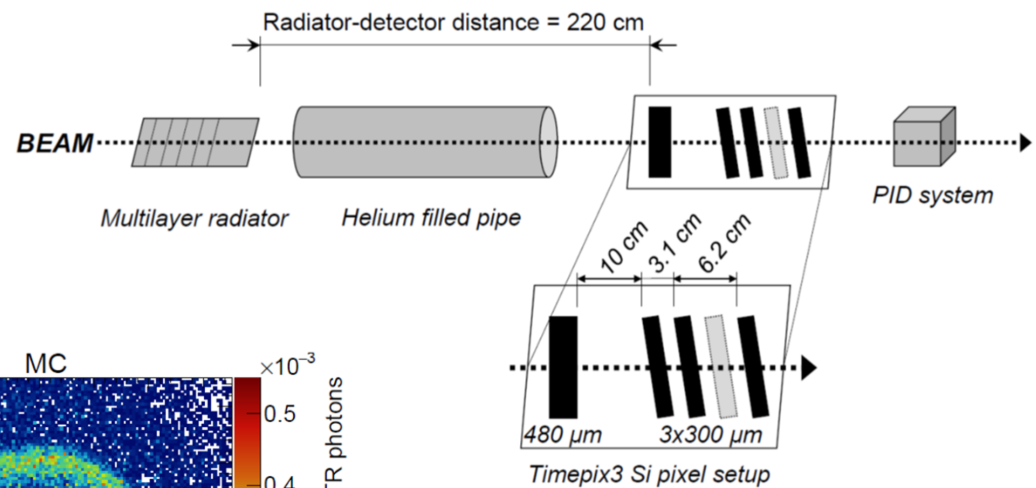




Potential improvement may be reached by differentiating the response to X-ray photons and to particle ionization → Extensive R&D required!

Transition radiation – new aspects

Extend PID beyond γ=1000? Idea: detect TRD gamma rays in a Si pixel detector, measure angle and energy. In the study by A. Romaniouk et al. it was 480μm Si bonded to the Timepix3 chip



The angle of maximum intensity depends on γ

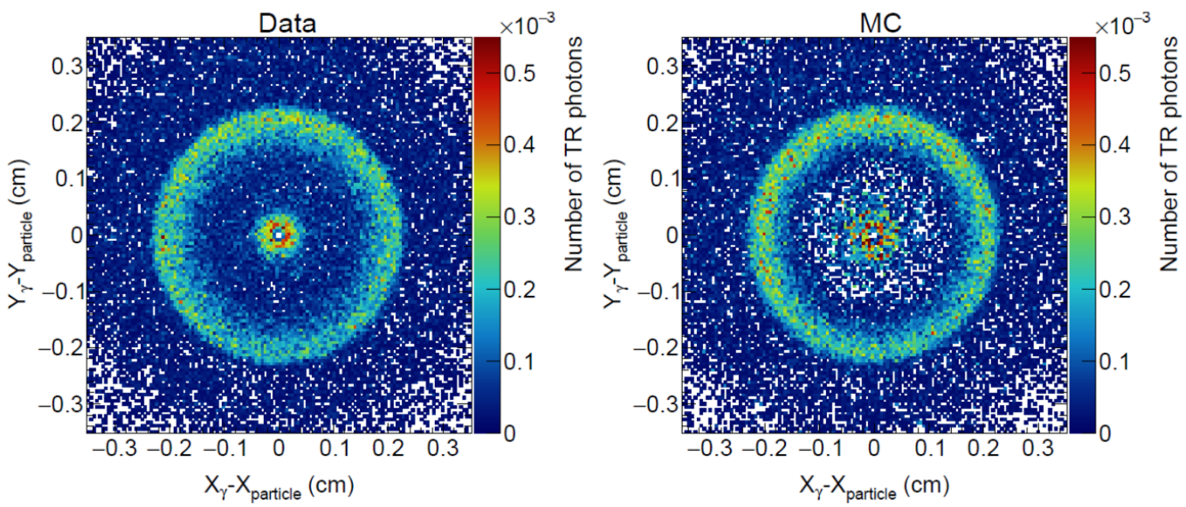


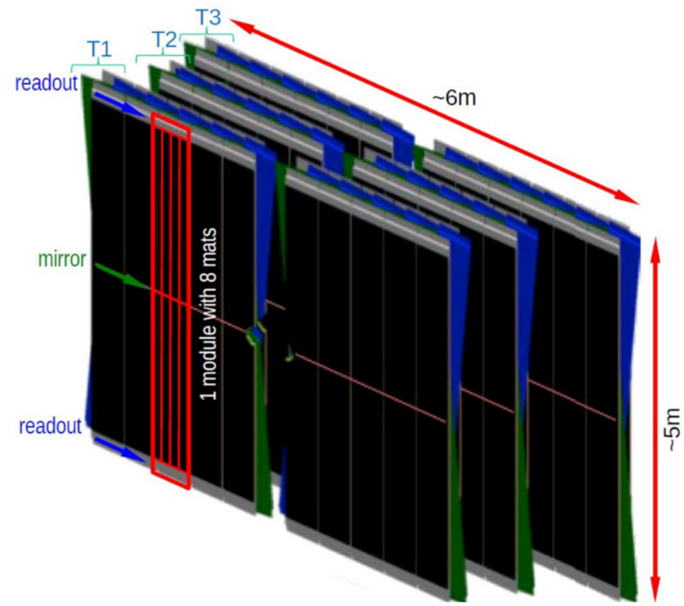
Figure 14: Relative position of identified TR photon clusters with respect to the particle clusters for 20 GeV/c electrons crossing the polypropylene radiator. Left panel: data. Right panel: MC simulation.

J. Alozy et al, NIMA 961 (2020) 163681

Novel optical materials for fiber trackers

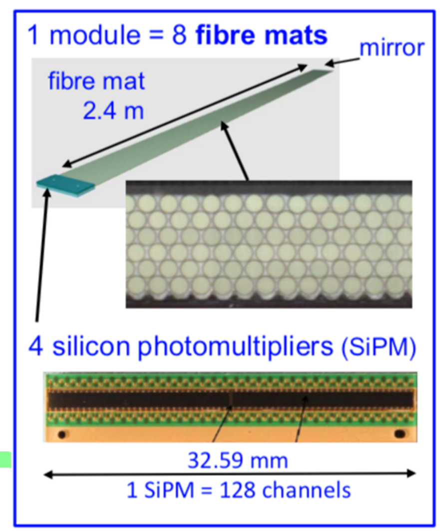
Scintillating fibres offer a cost-effective way of instrumenting large areas for charged particle tracking at relatively low material budget. With the availability of small-pitch SiPM arrays, high resolutions are possible, as shown with the LHCb SciFi tracker upgrade just being completed.

To further advance the technology, e.g. for a second upgrade of the tracker envisaged for the High-Luminosity LHC, not only the photo-sensor but also the optical fibers need to be optimised to obtain higher light yield, allowing for smaller diameters and thus higher precision and improved radiation tolerance.



Open issues:

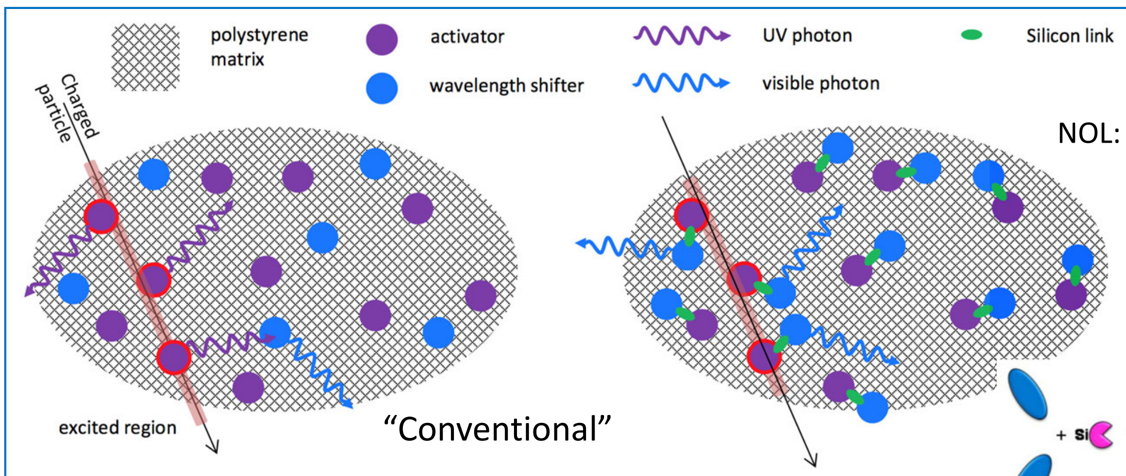
- Radiation tolerance
- Speed
- Emission spectrum



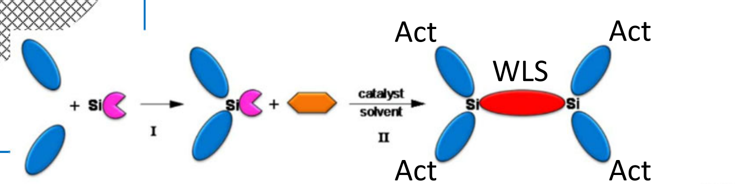
Novel optical materials for fiber trackers

Innovative materials such as Nanostructured-Organo-silicon-Luminophores (NOL) scintillators, exhibit stronger and faster light output than presently achieved.

Energy transfer from the primary excitation to the wavelength shifter is enhanced by silicon links with respect to the radiative processes in standard materials

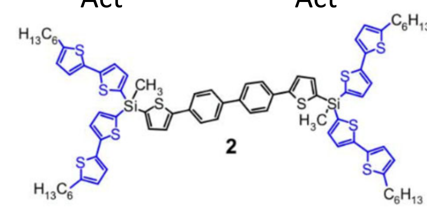


NOL: Nanostructured Organo-silicon Luminophores



Activator and WLS are chemically coupled using silicon links

- → Non radiative energy transfer (Förster mechanism)
- → Faster and more efficient
- → Higher light yield

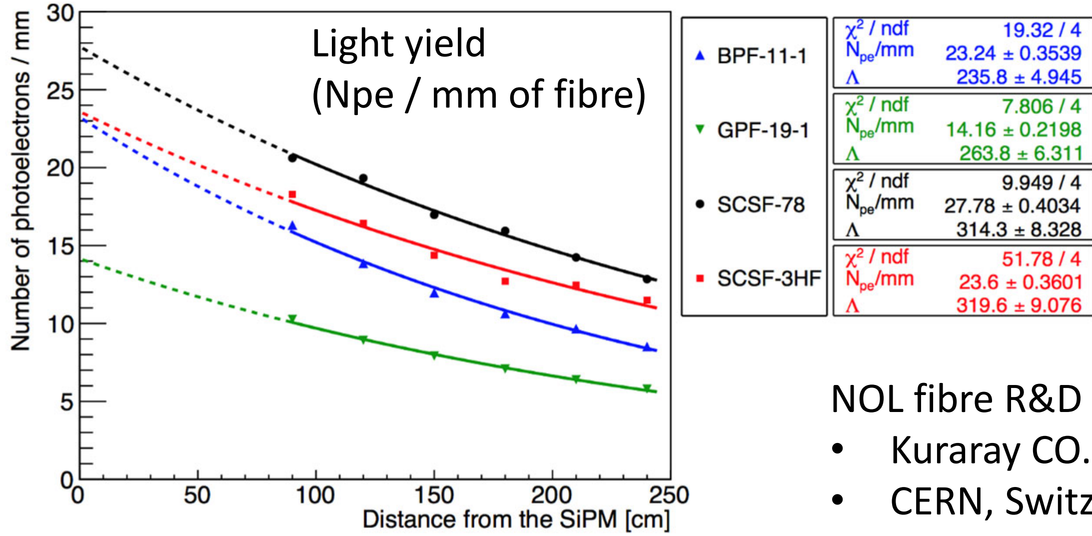


S.A. Ponomarenko et al., Nature Sci. Rep. 4 (2014) 6549

From L. Gruber, VCI 2019

NOL prototype fiber performance

O. Borshchev et al., 2017 JINST 12 P05013



Best blue NOL prototype fibre

Best green NOL prototype fibre

Best blue standard fibre

Best green standard fibre

NOL fibre R&D among 3 institutes/companies
- Kuraray CO., Japan
- CERN, Switzerland
- ISPM, Russian Academy of Sciences, Russia

- After 8 iterations NOL fibres clearly improved but still a bit behind in terms of light yield and attenuation length

Components and contents need to be carefully selected and adjusted! The used materials must be of high purity!

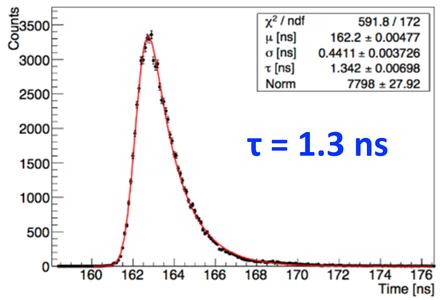
- Λ(NOL) ~ 300 cm
- Λ(standard) ~ 350 cm
- Self absorption, i.e. choice of materials, contents and purity are key issues

From L. Gruber, VCI 2019

NOL prototype fiber performance

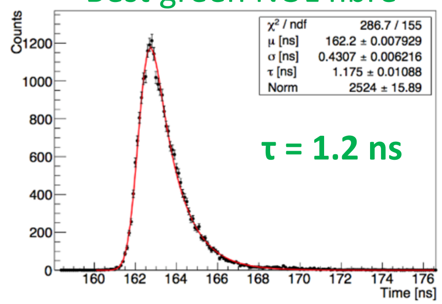
O. Borshchev et al., 2017 JINST 12 P05013

Best blue NOL fibre



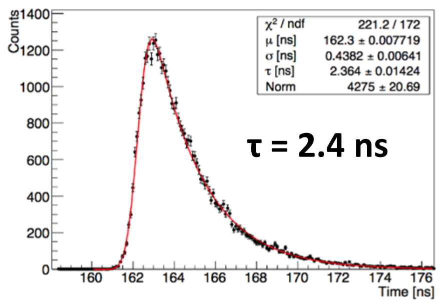
(a) BPF-11-1

Best green NOL fibre



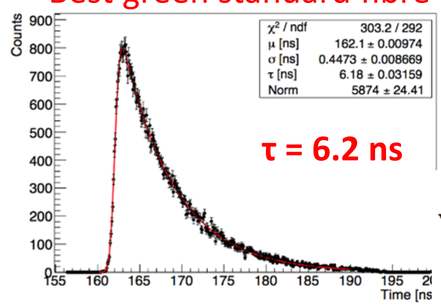
(b) GPF-19-1

Best blue standard fibre



(c) SCSF-78

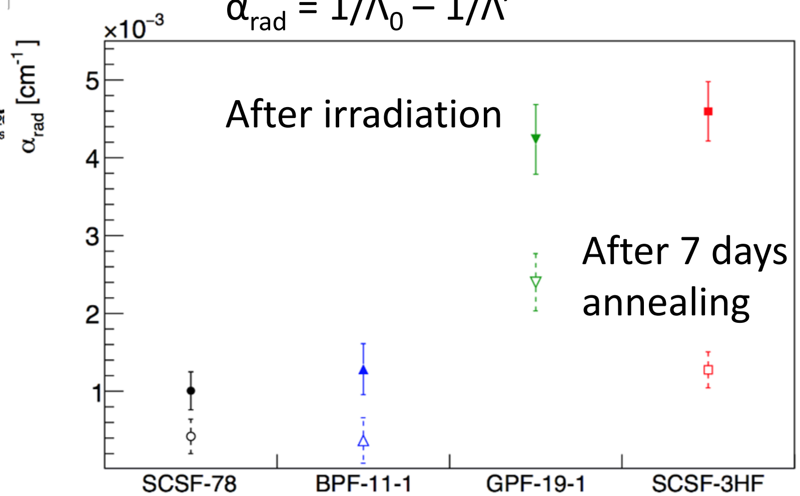
Best green standard fibre



(d) SCSF-3HF

Decay time: NOL fibres are almost a factor 2 (6) faster than the best blue (green) standard fibres, which makes them very interesting for time critical applications!

Add. attenuation coefficient
$\alpha_{rad} = 1/\Lambda_0 - 1/\Lambda'$



Radiation hardness (X-rays to a dose of 1 kGy):

- Damage is as expected on a level comparable to reference fibres

Promissing results but clearly more R+D needed

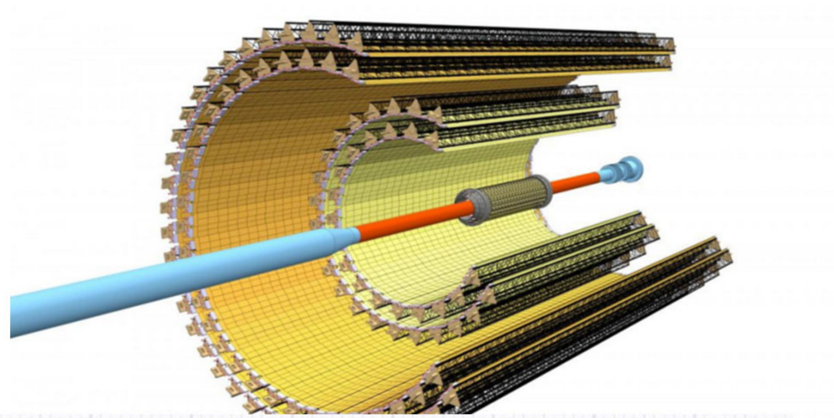
Wireless data acquisition

Physics events propagate from the collision point radially outwards – while the detectors are read our axially

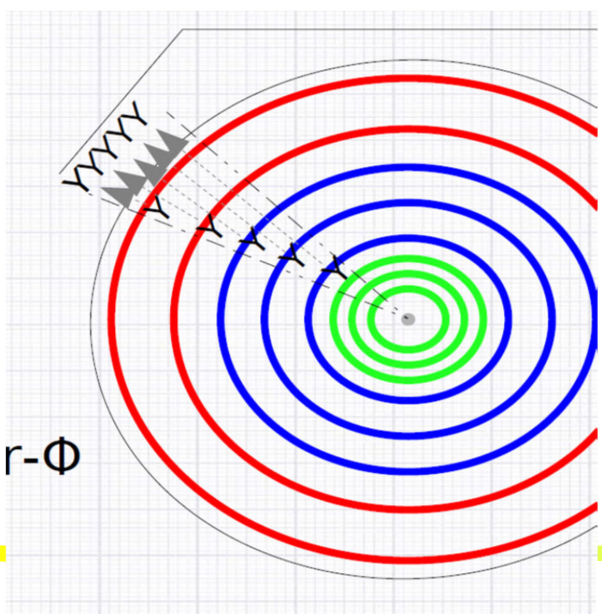
→ Not optimal for triggering

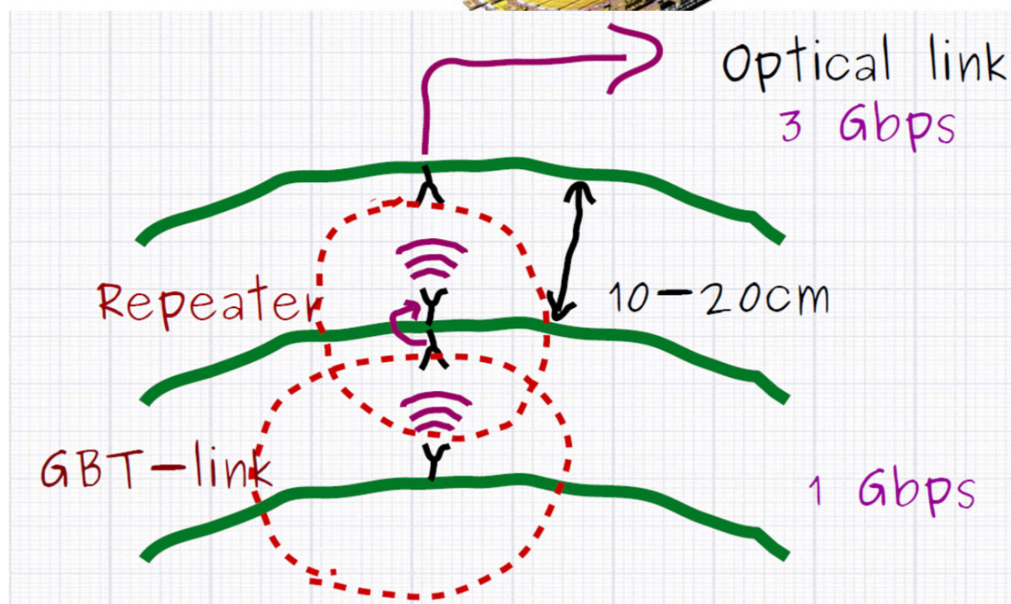
→ Not optimal for material distribution

(in particular at the barrel-endcap boundary)



Idea: read out wirelessly





Wireless data acquisition

<u>Wifi technologies under development</u>

Target short distance (10-30 cm), compact low power data links with Multi-Gbps bandwith

- Wireless transmission with mm-waves

WADAPT – Uppsala U, CERN, CEA/LETI/DTR/DACLE/LAIR, Argonne, Gangneung U, Bergen U, Heidelberg U, Tel Aviv U, Radiall

-60 GHz with commercial transceiver developed by LETI/ST in CMOS and ongoing development targeting 130 nm SiGe-Bi-CMOS

-240 GHz (IHCT Wuppertal) custom 0.13 μm SiGe HBT technology

- Wireless transmission with optical waves

INFN Pisa and Scoula Superiore Sant'Anna

Richard Brenner @ ECFA Detector R&D TF7 Symposium

Summary

Blue sky research has traditionally been an important driver of progress in particle physics – and has to be supported also in the future.

Novel ideas will also come from discoveries in condensed matter physics, advanced materials, need in medical imaging, innovations in the industry.

Many blue sky studies of today will become mainstream tomorrow.

AIDAinnova Blue Sky call

AIDAinnova is a EU funded detector R+D project hosted by CERN. Most of the effort is targeted research,but one of the work packages is devoted to blue-sky research.

In 2021, there was an open call for blue-sky research proposals.

15 proposals received: 6 on novel semiconductor detectors, 3 on radiation hard silicon, 2 on gaseous detectors, 3 on light detection and scintillators, and one on DAQ.

Selected two on novel semiconductor detectors, one on scintillators, one on DAQ.