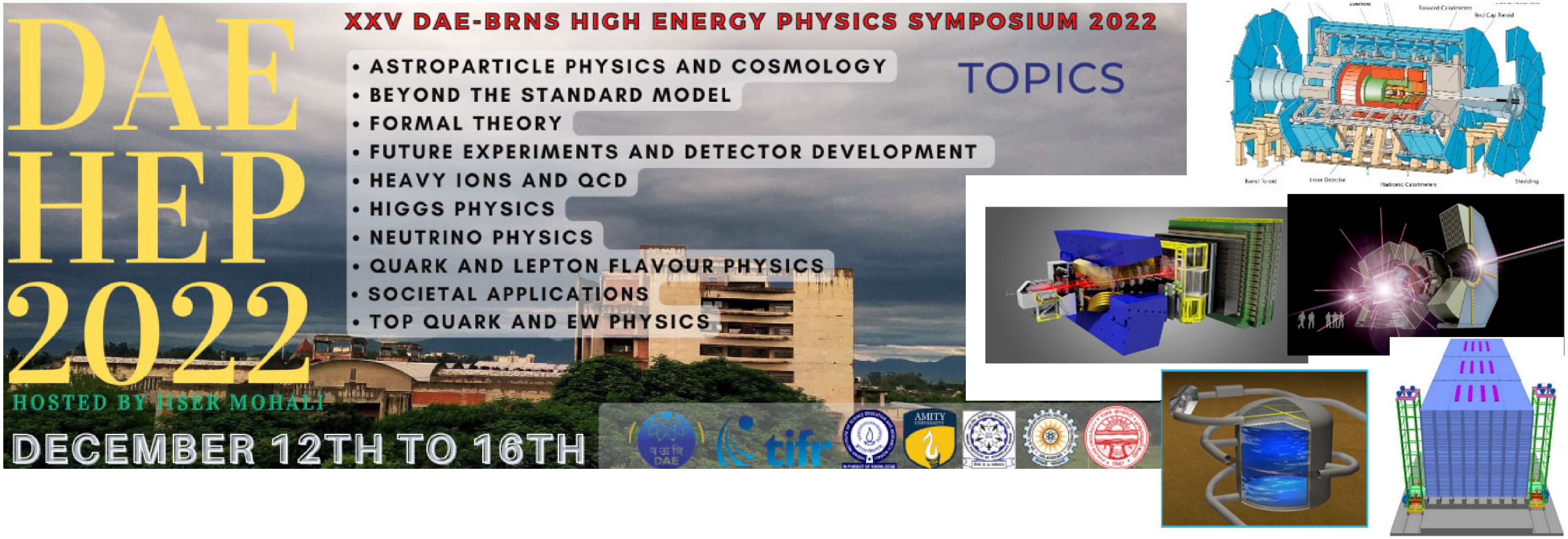


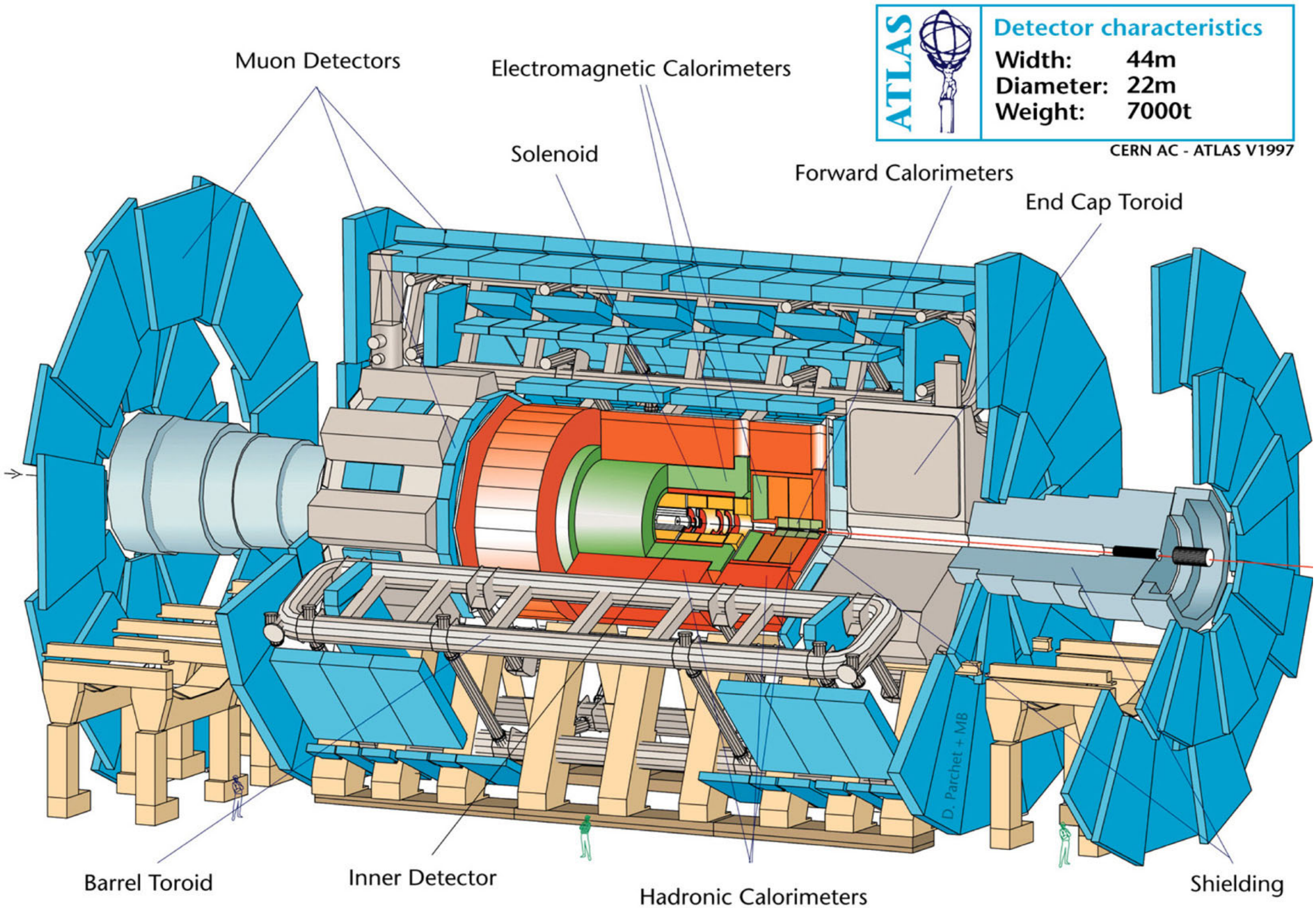
Recent advances in detectors

Univerza v Ljubljani

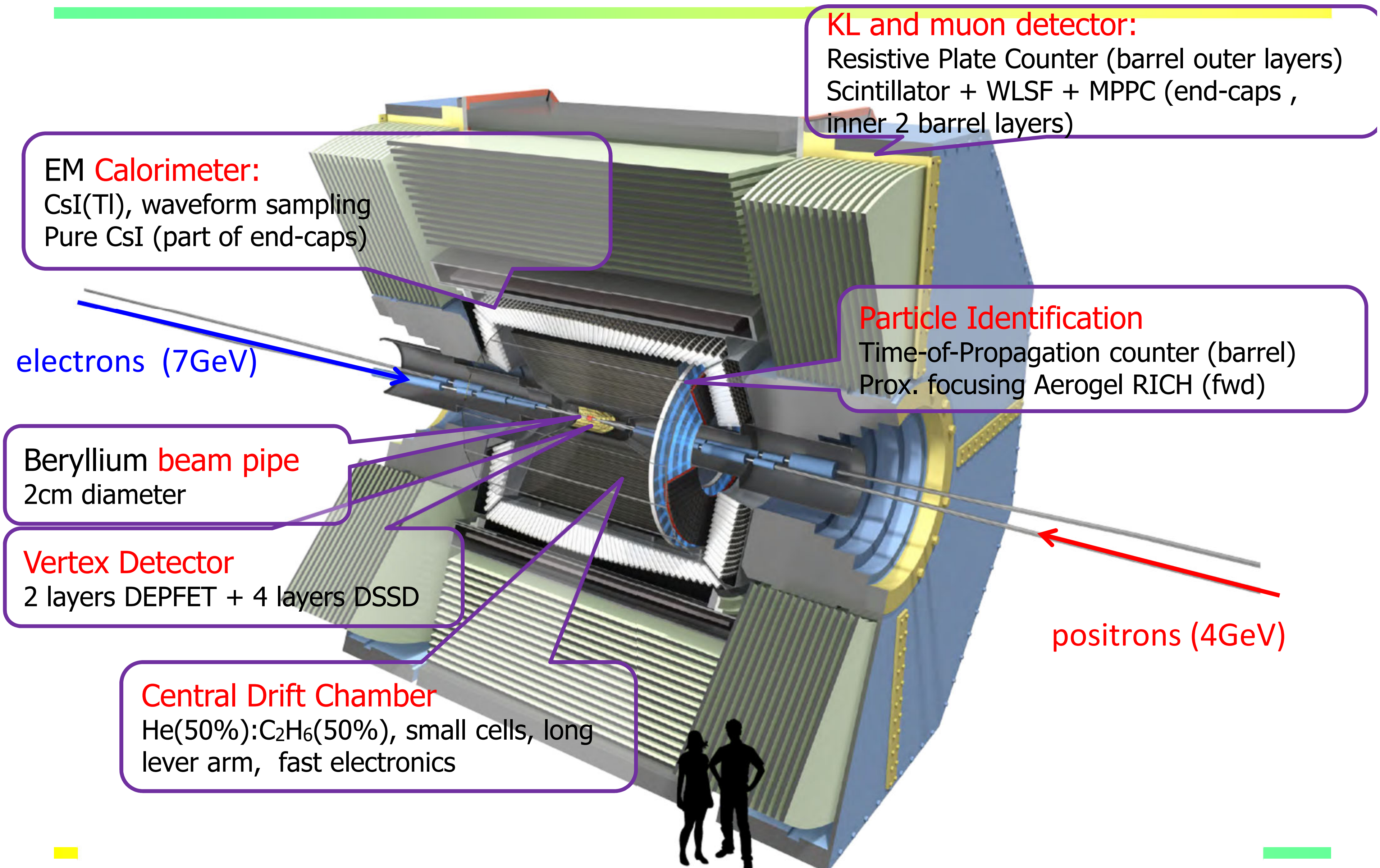
Peter Križan

University of Ljubljana and J. Stefan Institute

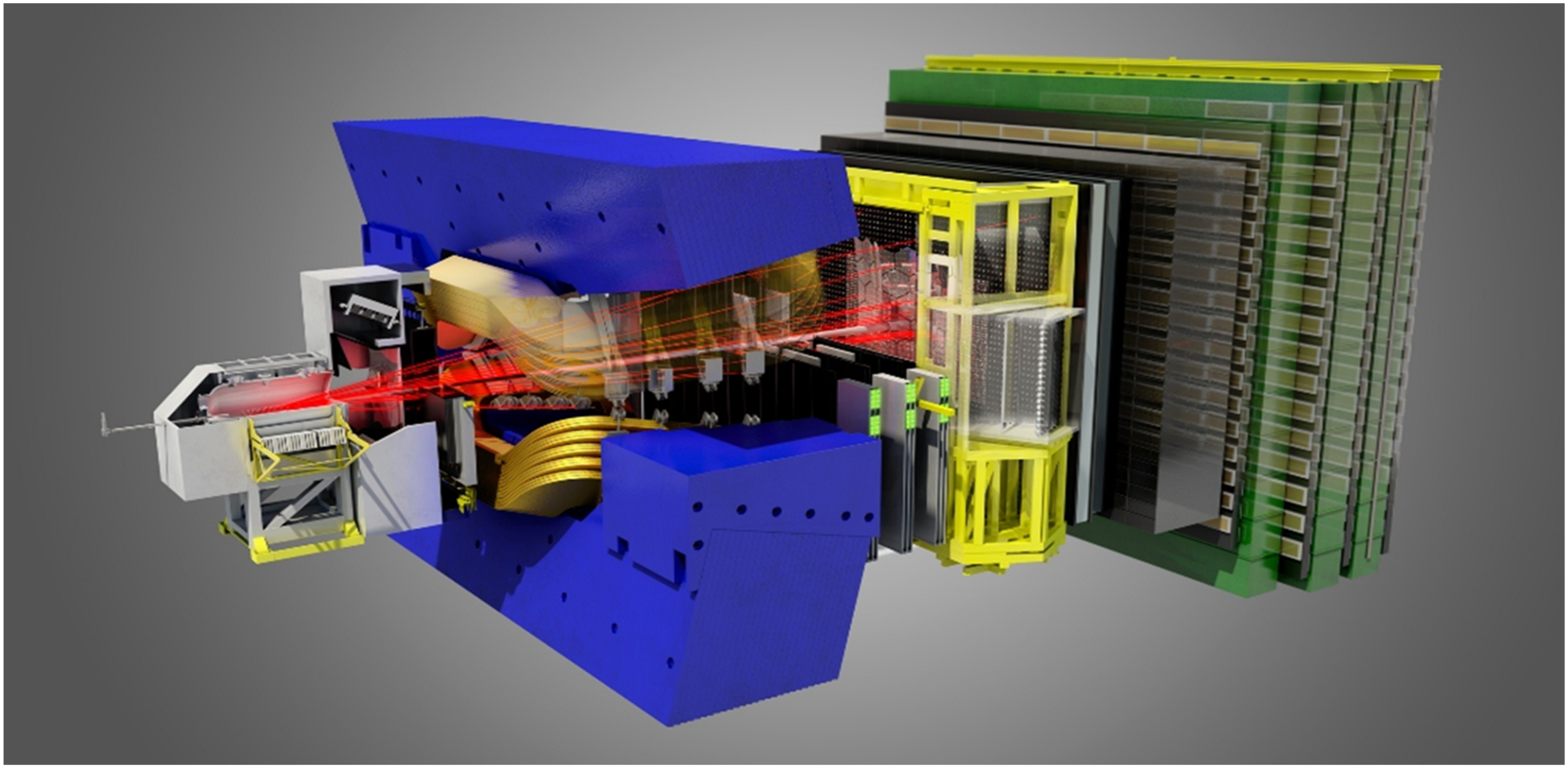
A ‘typical‘ particle physics experiment 1: ATLAS



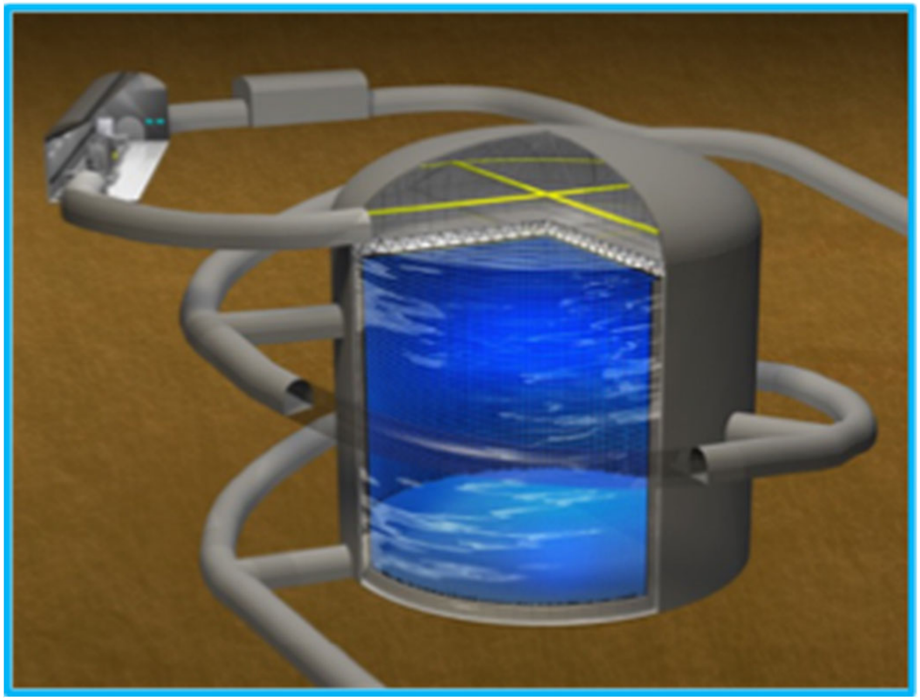
A ‘typical‘ particle physics experiment 2: Belle II



A ‘typical‘ particle physics experiment 3: LHCb



A ‘typical‘ particle physics experiment 4

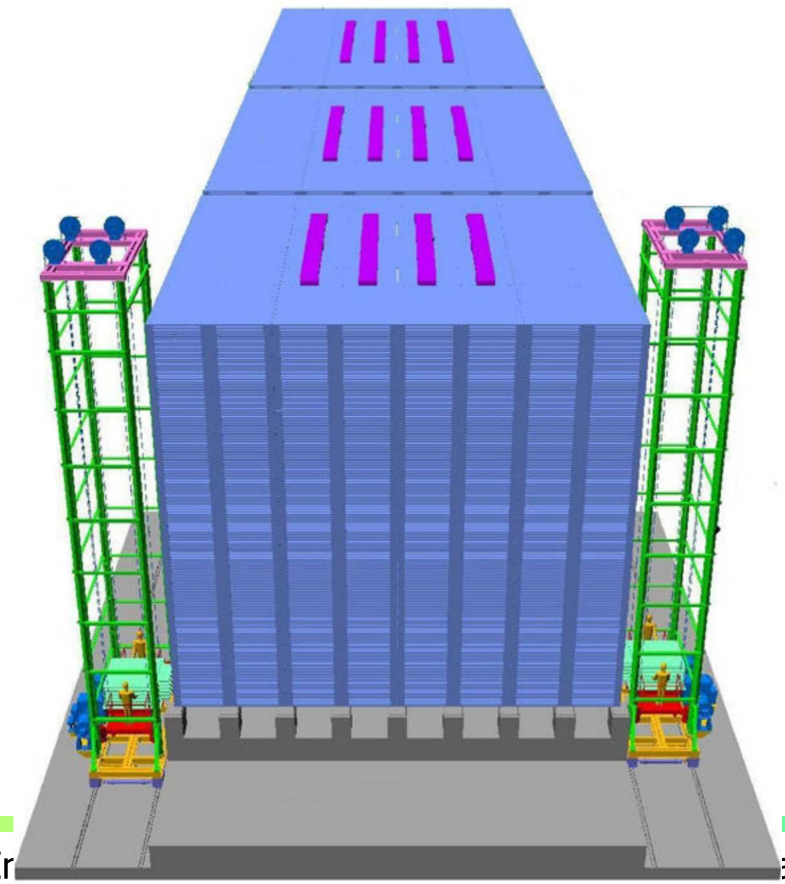


HyperKamiokande

- 260 kton ultrapure water
- 190 kton fiducial mass: 10×SK
- Innermost volume viewed by 40,000 of new 50 cm PMT

INO

- 50000 tons of magnetized iron plates
- 29000 RPCs (2m x 2m)
- 132m X 26m X 20m cavern



Contents

Introduction

New sensors for tracking

Scintillators: calorimetry and medical imaging

Particle identification (RICH, TRD)

Low level light sensors and light collection

Fiber trackers

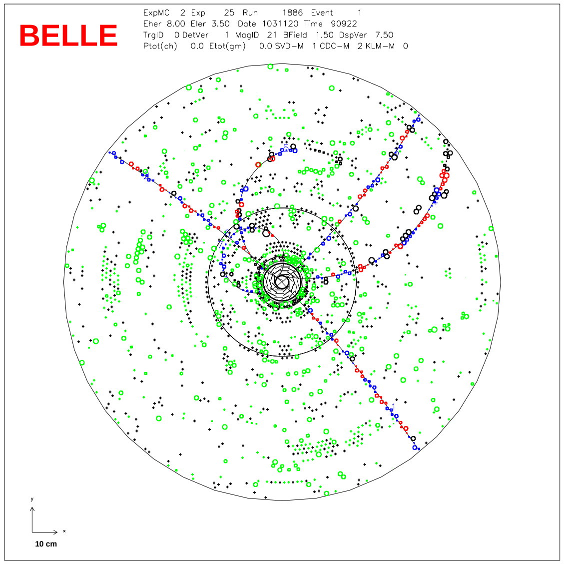
Data acquisition

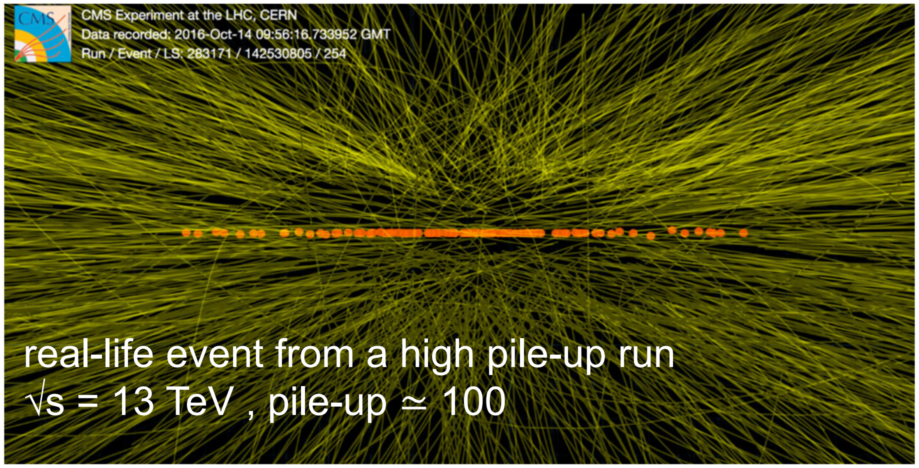
A very broad topic for a single talk – very hard to cover all interesting developments → A subsample, also partly reflecting my own interests

Tracking (and vertexing)

Various needs at present:

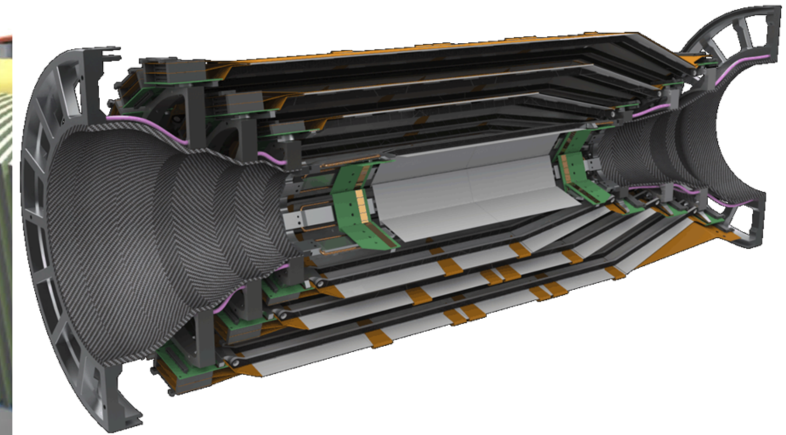
- Lower energies (Belle II): precision tracking and minimal multiple scattering, few particles in the final state, no event overlap
- LHC: precision with a high density of particles, multiple overlayed interactions within the same event, high radiation load

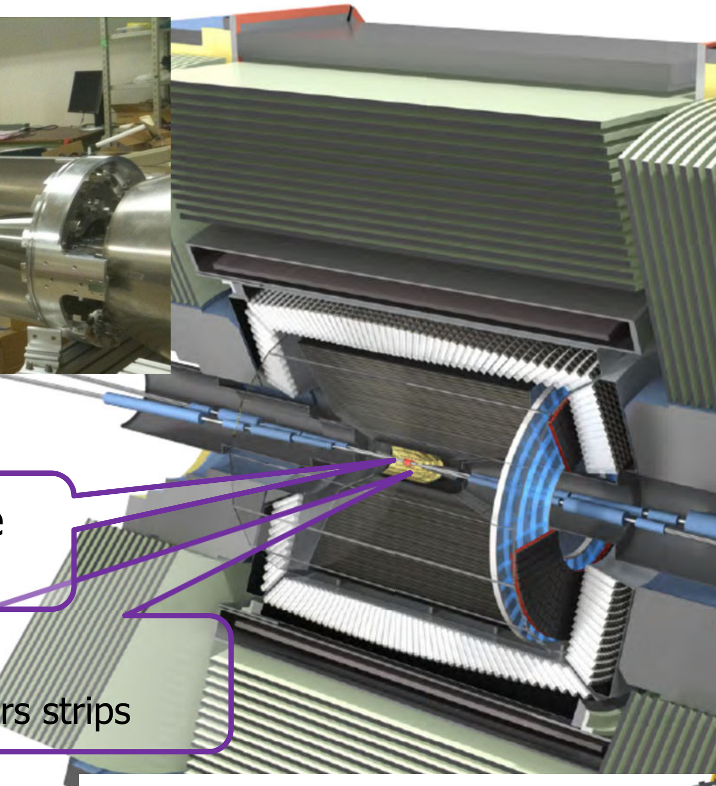


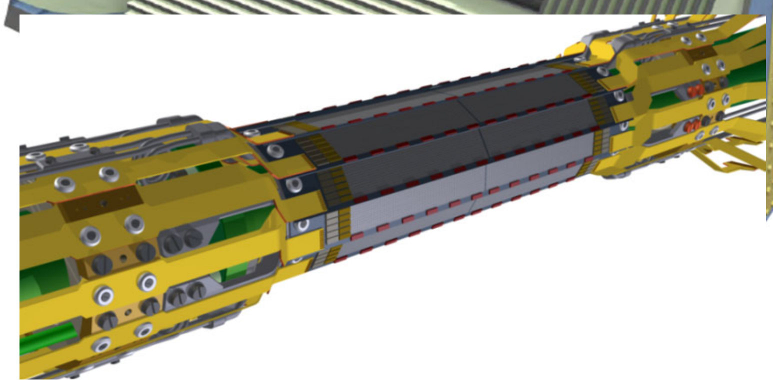


Vertexing at Belle II

Momenta of charged particles from B meson decays: p < 4 GeV/c

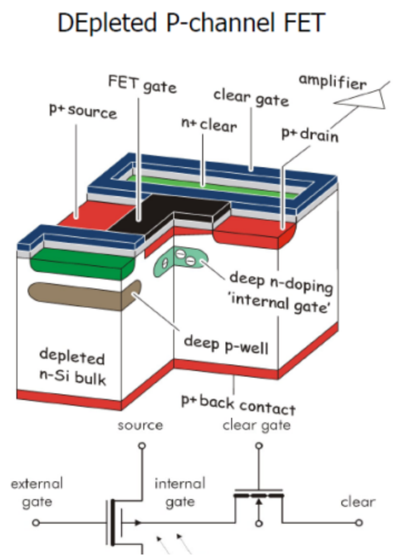




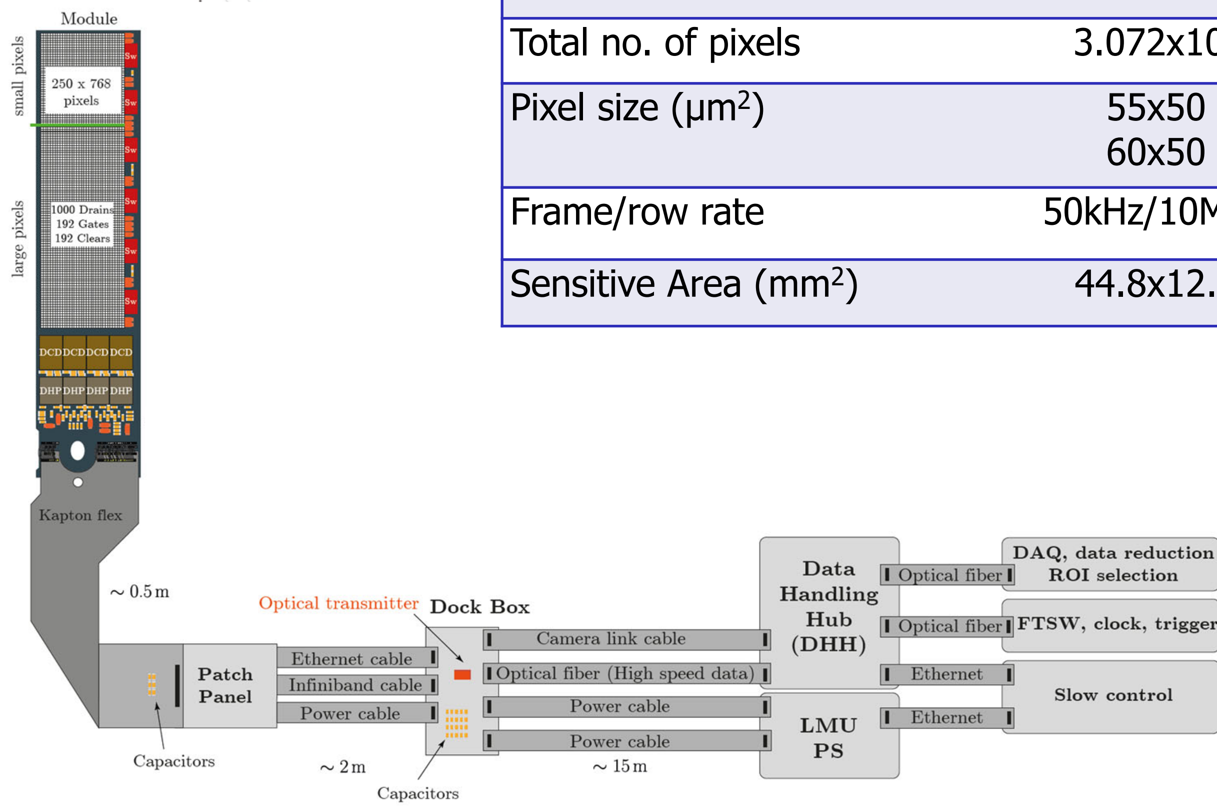


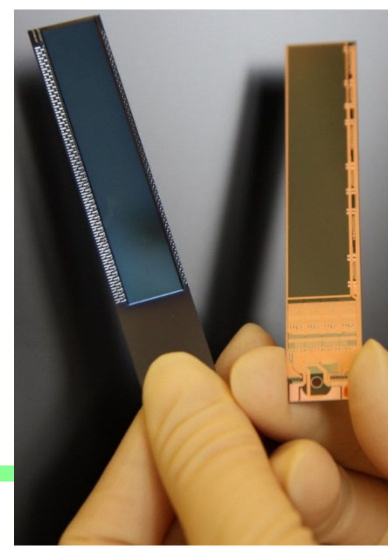
Beam Pipe		**r = 10mm**
DEPFET pixels		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD silicon strips		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 104mm**
	Layer 6	**r = 135mm**

Belle II pixel detector: 2 layers of DEPFET sensors



	L1	L2
# ladders (modules)	8 (16)	12 (24)
Distance from IP (cm)	1.4	2.2
Thickness (μm)	75	75
#pixels/module	768x250	768x250
#of address and r/o lines	192x1000	192x1000
Total no. of pixels	3.072×10^6	4.608×10^6
Pixel size (μm²)	55x50 60x50	70x50 85x50
Frame/row rate	50kHz/10MHz	50kHz/10MHz
Sensitive Area (mm²)	44.8x12.5	61.44x12.5





Belle II SVD: four layers of double-sided silicon strip detectors.

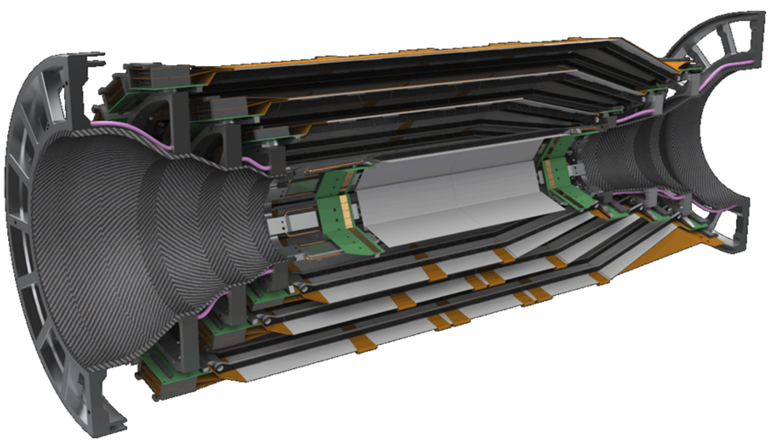
Double-sided silicon strip detectors

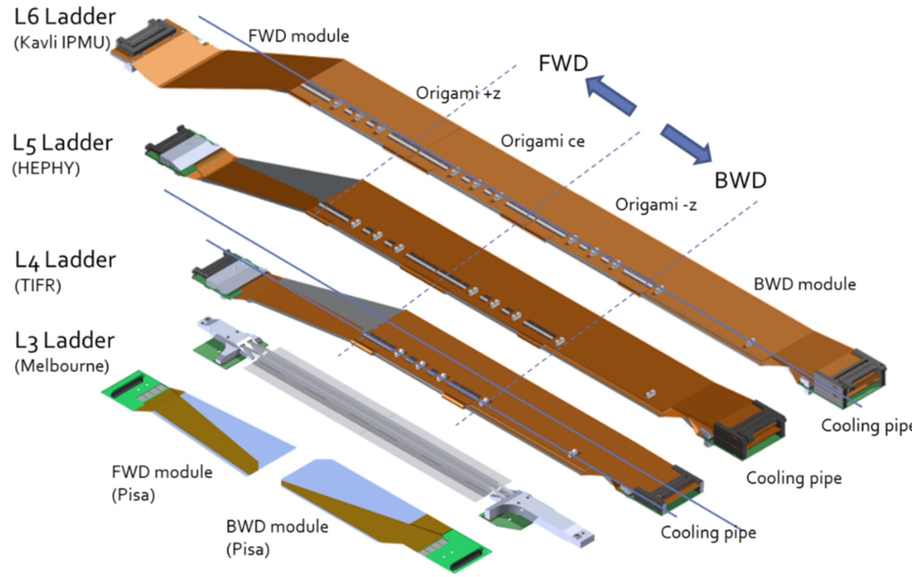
Origami chip-on-sensor concept (readout chips on top of the sensors with flex pitch adapters bent around the edge to reach the bottom sensor side) for good S/N with fast readout and moderate material budget

Excellent time resolution (~4ns) thanks to multiple recorded samples and waveform fitting

CO_2 dual-phase cooling

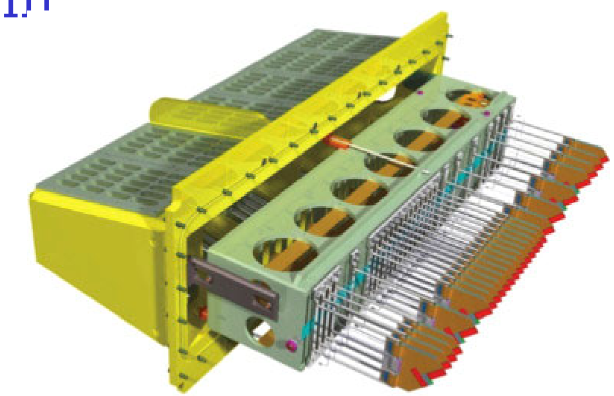
with a very strong Indian contribution

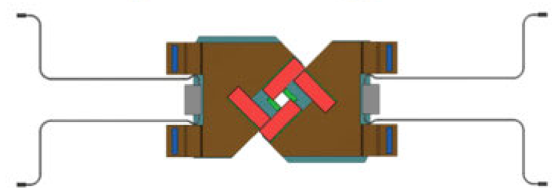


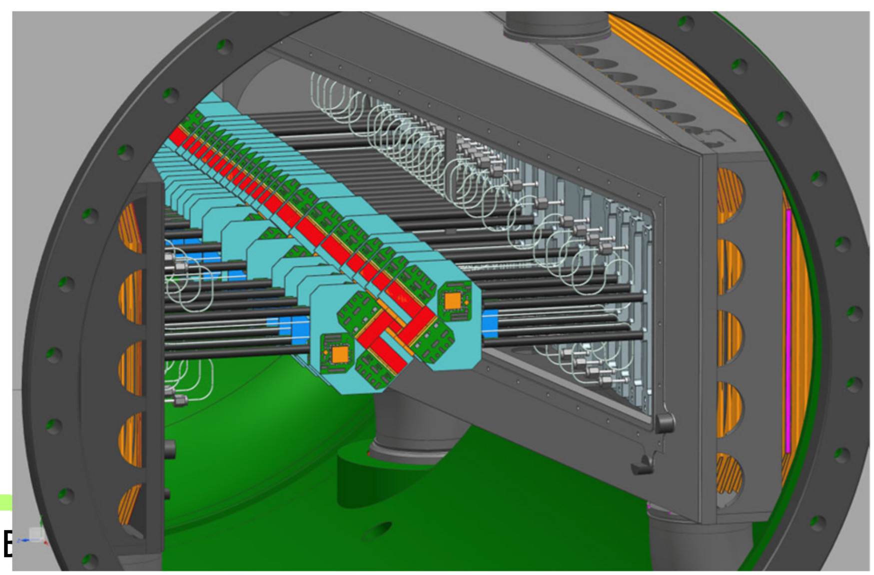


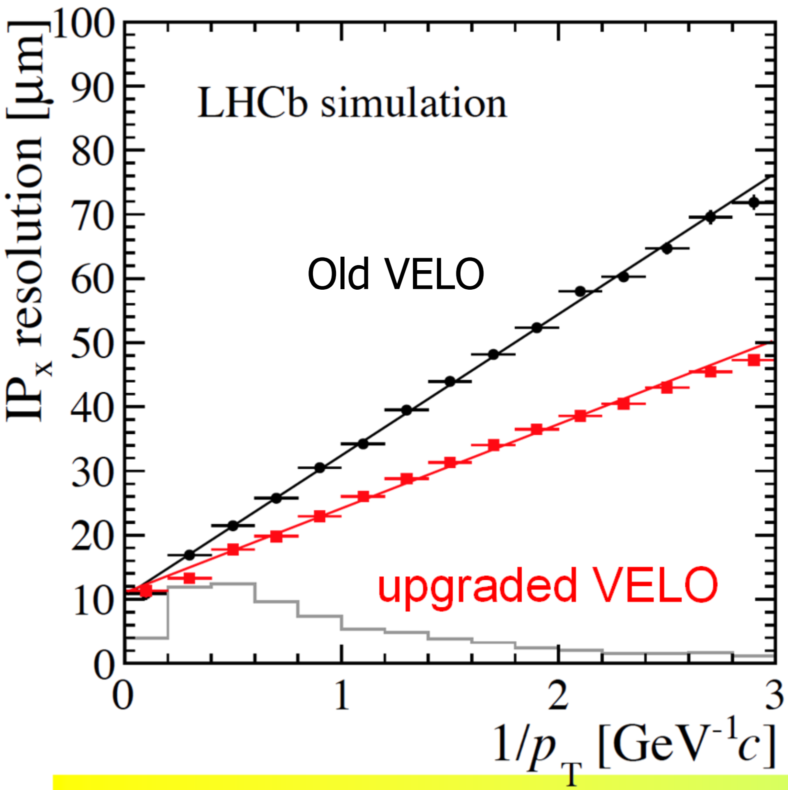
LHCb Vertex LOcator upgrade

The upgraded VELO has been installed to take data in Run III
Operation @ 40 MHz and $2x10^{33}$ $cm^{-2}s^{-1}$ and
at 3.5 mm from the beams, 2.8 Tb/s data rates,
8 x 10^{15} 1 MeV n_{eq} cm^{-2} max fluence





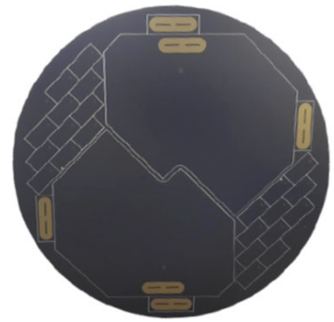


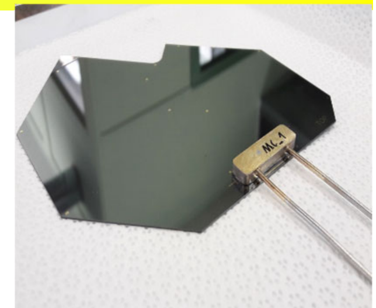


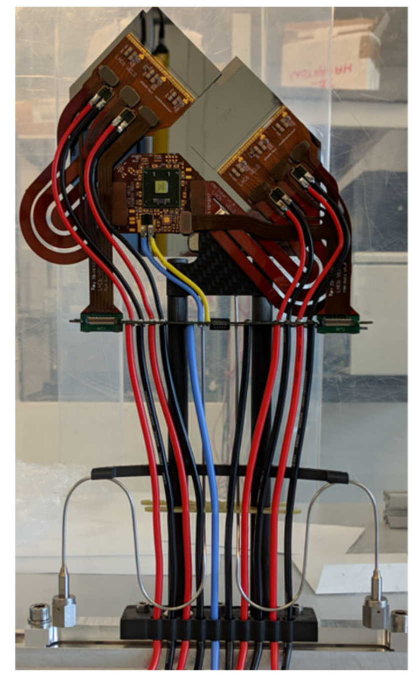
LHCb Vertex LOcator upgrade

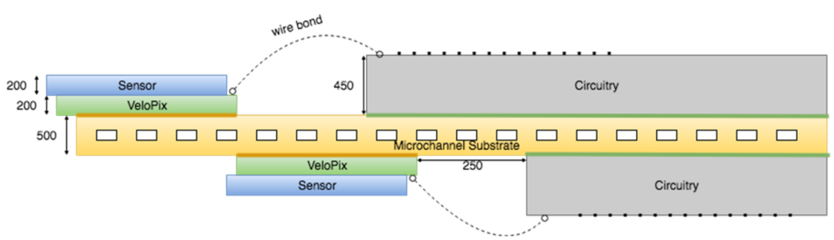
Micro-channel cooling

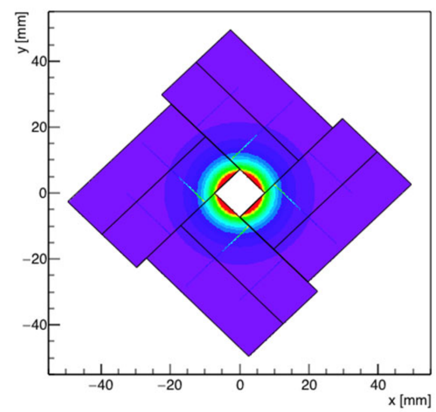
- 500 µm thick silicon substrate with integrated micro channels (70 μm x 200 μm) :
  - same thermal expansion as sensors
  - low material
  - high thermal efficiency
  - cooling power ~50 W
- pressure: 14 bar @ -30 ^{o}C, 60 bar @ 22 ^{o}C







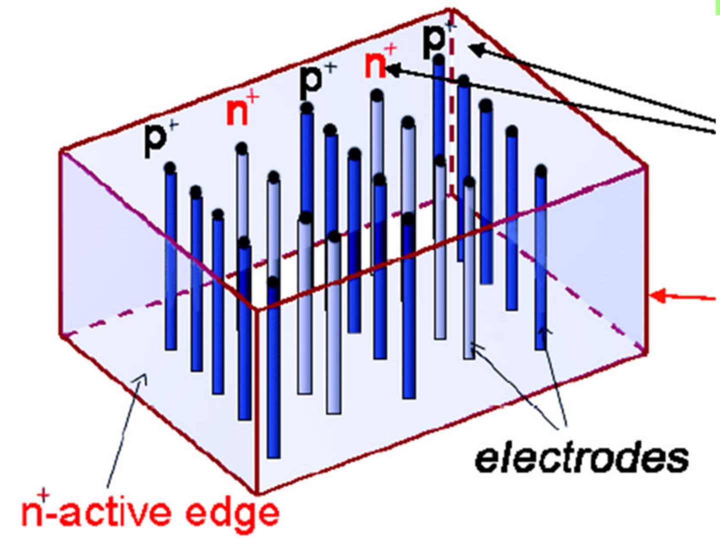




Silicon particle detectors: directions for the future

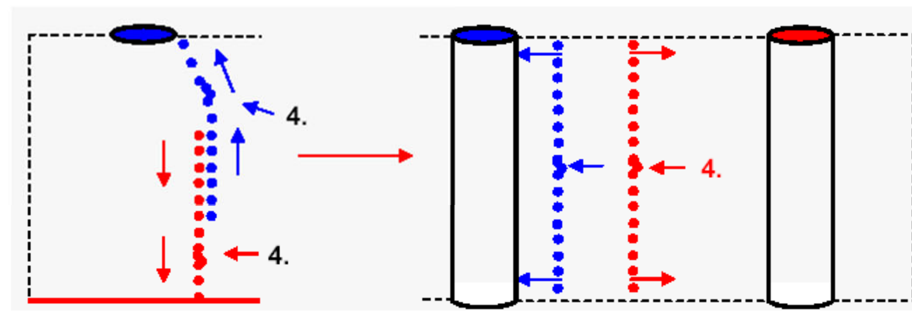
- Extreme radiation hardness – 3D detectors (hybrid technology – possibly also developments into monolitic)
- Large area coverage for position resolution (mass production) – depleted CMOS sensors (fully monolitic or hybrid ASIC)
- Timing detectors – LGAD with a possible application of 3D (hybrid technology)

3D detectors



Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.

The edge is an electrode. Dead volume at the edge < 5 μm!



Key advantages

•Better charge collection efficiency over the large fluence range (up to 3e16 cm^{-2} – close to 100%)
•Faster charge collection (depends on inter-column spacing) – very promising for timing applications
•Reduced full depletion voltage and by that the power
•Larger freedom for choosing electrode configuration
•Recent progress allowing also single sided processing

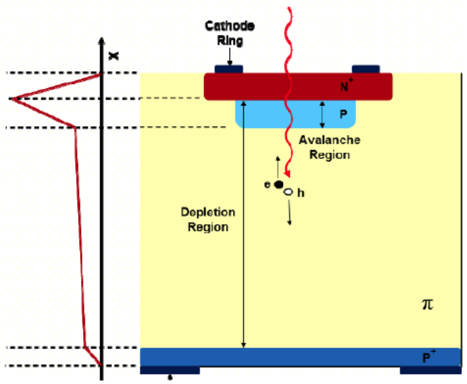
Limitations

•Columns are a dead area (aspect ratio ~30:1) - but most of the tracks are anyway inclined
•Much higher inter-electrode capacitance (hence noise), particularly if small spacing is desired
•Availability on a large scale
•Time-scale and cost

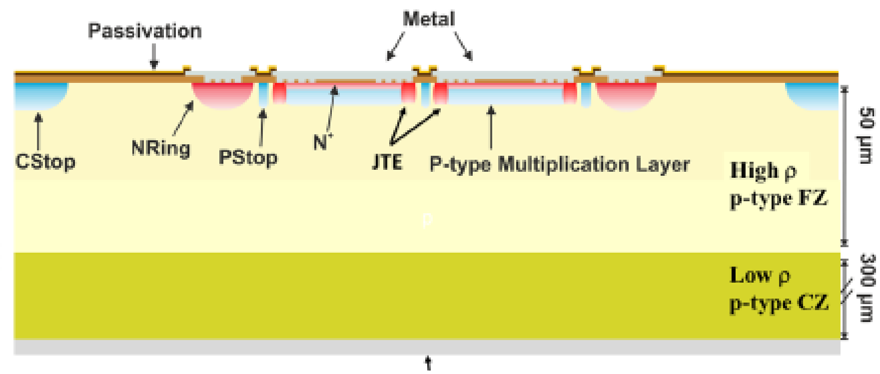
Low Gain Avalanche Detectors (LGAD)

- APD-like devices which allow segmentation and high voltage operation close to breakdown
- Pioneered by RD50 and getting more and more attention worldwide (HPK, FBK, Micron)

Schematic view of device



ATLAS High Granularity Timing Detector Test Prototype (2x2 array)



Key properties

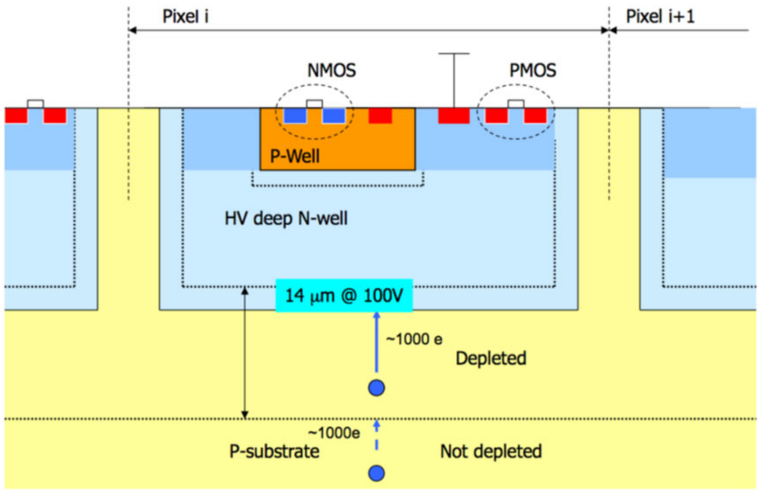
- Gain very sensitive to p+ layer doping and process parameters (~1e16 - 1e17 cm^{-3}, ~2 μm deep)
- Gains of up to 100 achieved giving excellent timing resolution of 26 ps for thin LGADs
- Currently the best technology for achieving excellent timing measurement for MIP – will be employed at ATLAS and CMS experiments after the upgrade

Limitations:

- Radiation hardness – problem of acceptor removal which decreases the gain with fluence (intensive search for solution: carbon coimplantation and understanding removal mechanism)
- Regions around the electrodes do not have gain – fill factor improvement

Depleted-CMOS detectors

- HV-CMOS process which allows monolithic detectors with application of external HV depletion
- First devices produced showing huge potential in all respects: scalability (12” wafers), cost and integration (everything integrated on chip electronics + detector)



Key properties

- Different substrates often limited by vendor – up to full depletion of 300 μm
- Excellent position resolution

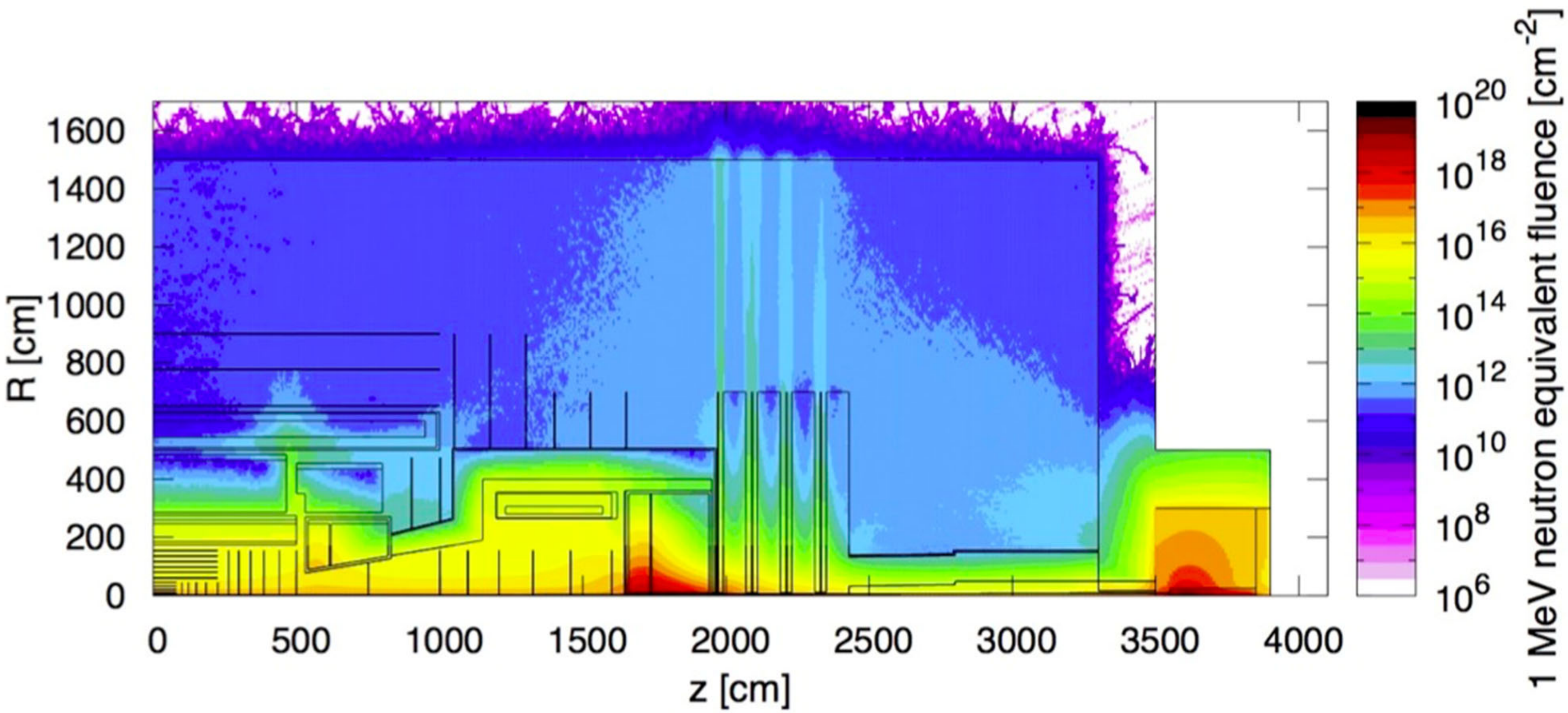
Limitations:

- Radiation hardness – problem of acceptor removal which changes detector performance
- Speed – for timing applications is not yet optimal
- SOI substrates or different other designs/processes including “Shallow Trench Isolation” affect charge collection

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 levels (~ 1e15 n/cm^2)

- examples: scaling of trapping probability with fluence (2016 JINST 11 P04023)
- electric field 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

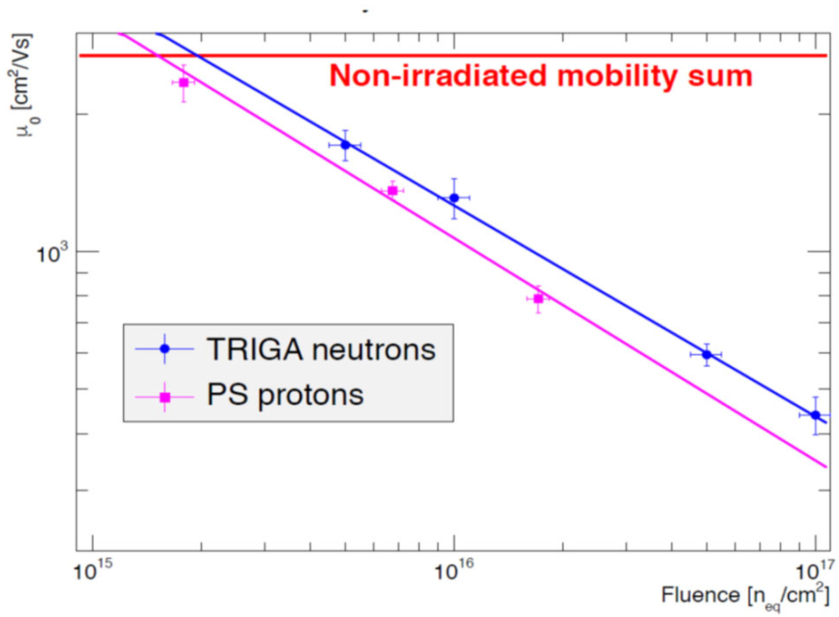
→measurements at extreme fluences are necessary!

Silicon particle detectors for the future – unexpected features

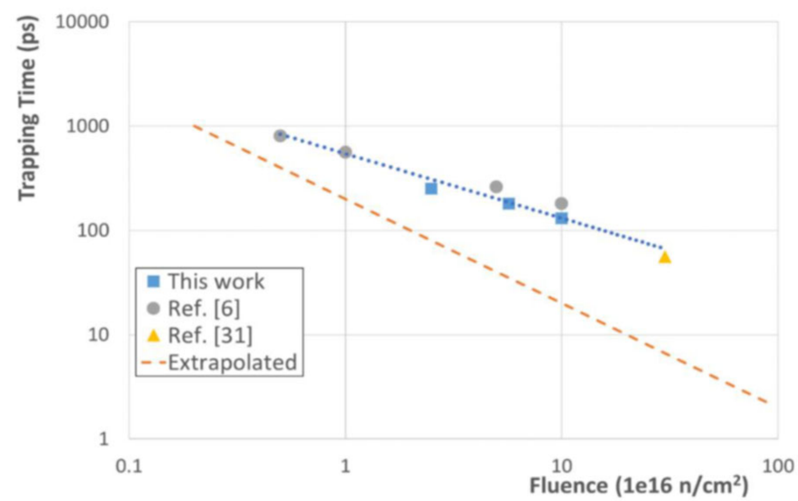
Planar silicon detectors

→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, Trento Workshop 2016



I. Mandić et al., 2020 JINST 15 P11018

Silicon particle detectors for the future – unexpected features

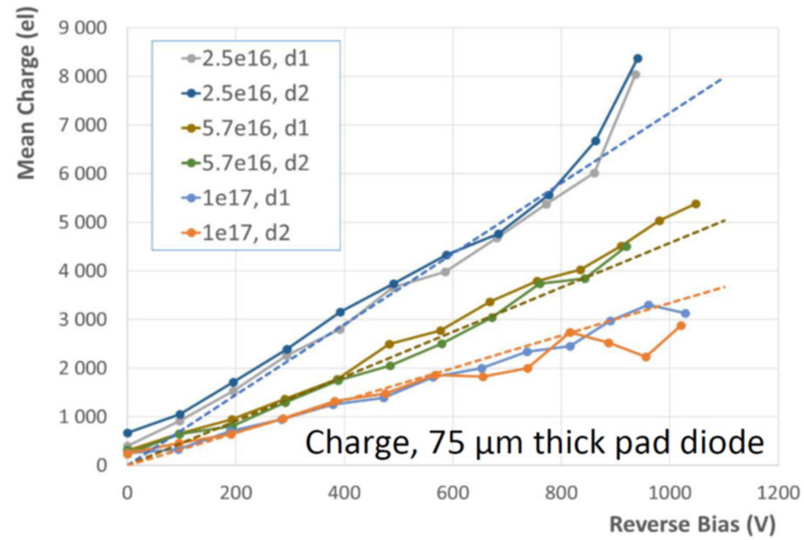
Planar silicon detectors, continued

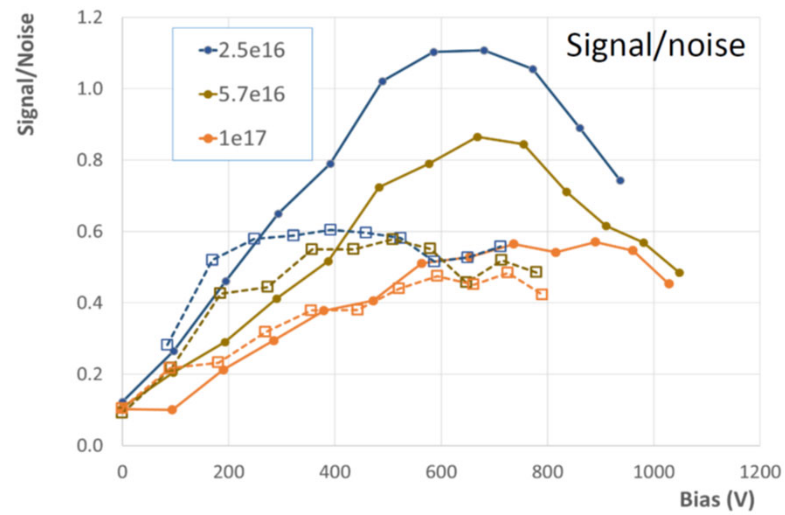
➔Collected charge increases almost linearly with bias

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:

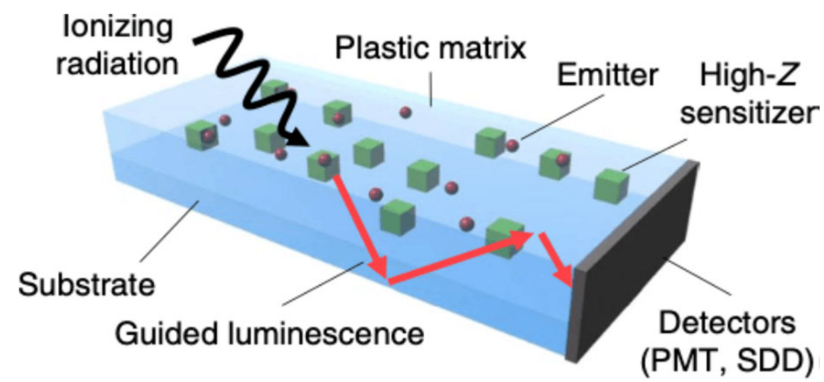
- 3D Si detectors
- Thin planar sensors with multiplication: how to make them tolerant to high irradiation levels – clever doping, inventive biasing
- Wide gap materials – SiC, diamond – also 3D

Advanced scintillators: Nanocrystal composites

EM calorimetry: Inorganic crystals vs sampling calorimeters

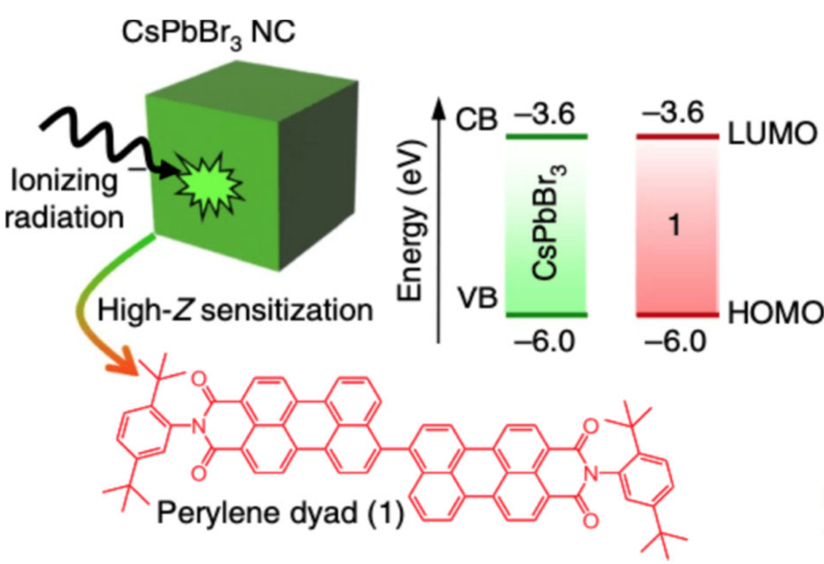
Can very fine sampling EM calorimeters be optimized to obtain performance approaching that of crystal calorimeters? PANDA/KOPIO (fine-sampling shashlyk): energy resolution $2.8\%/\sqrt{E} \oplus 1.3\%$

Could we do even 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



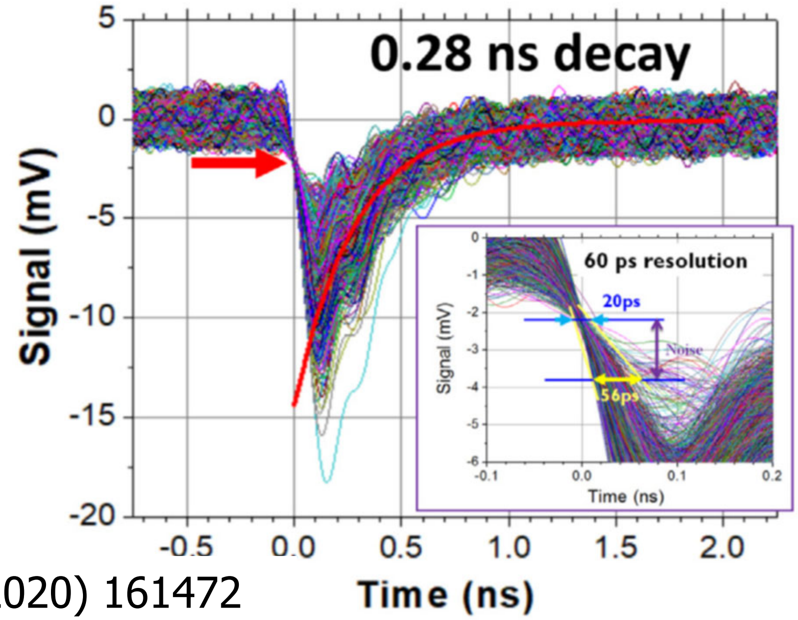
- Peak emission ~ 620 nm
- BGO-like light yield at peak
- Decay time (fast) = 3.4 ns (87%)
- Decay time (slow) = 14.1 ns (13%)
- No degradation up to 800 Gy

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 lumi-nescence centres embedded in a GaAs matrix can have uniquely fast scintillation properties with low self-absorption.

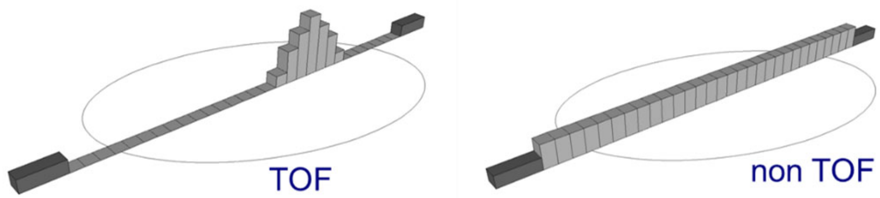


K. Dropiewski et al, NIMA 954 (2020) 161472

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

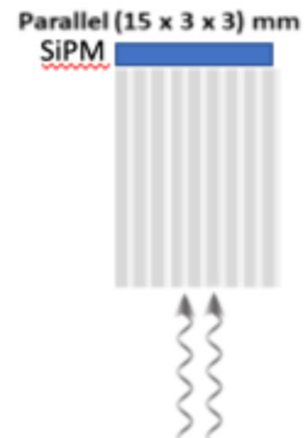
Advanced scintillators

Very fast scintillators for annihilation gamma detection in TOF-PET



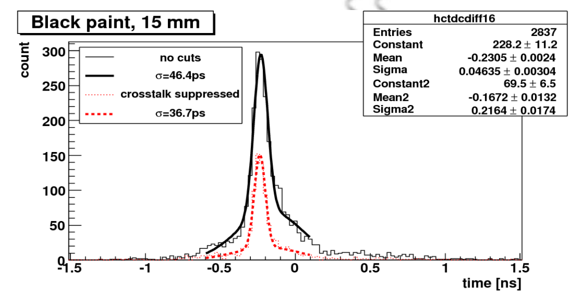
Localization of source position along the line of response:

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



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



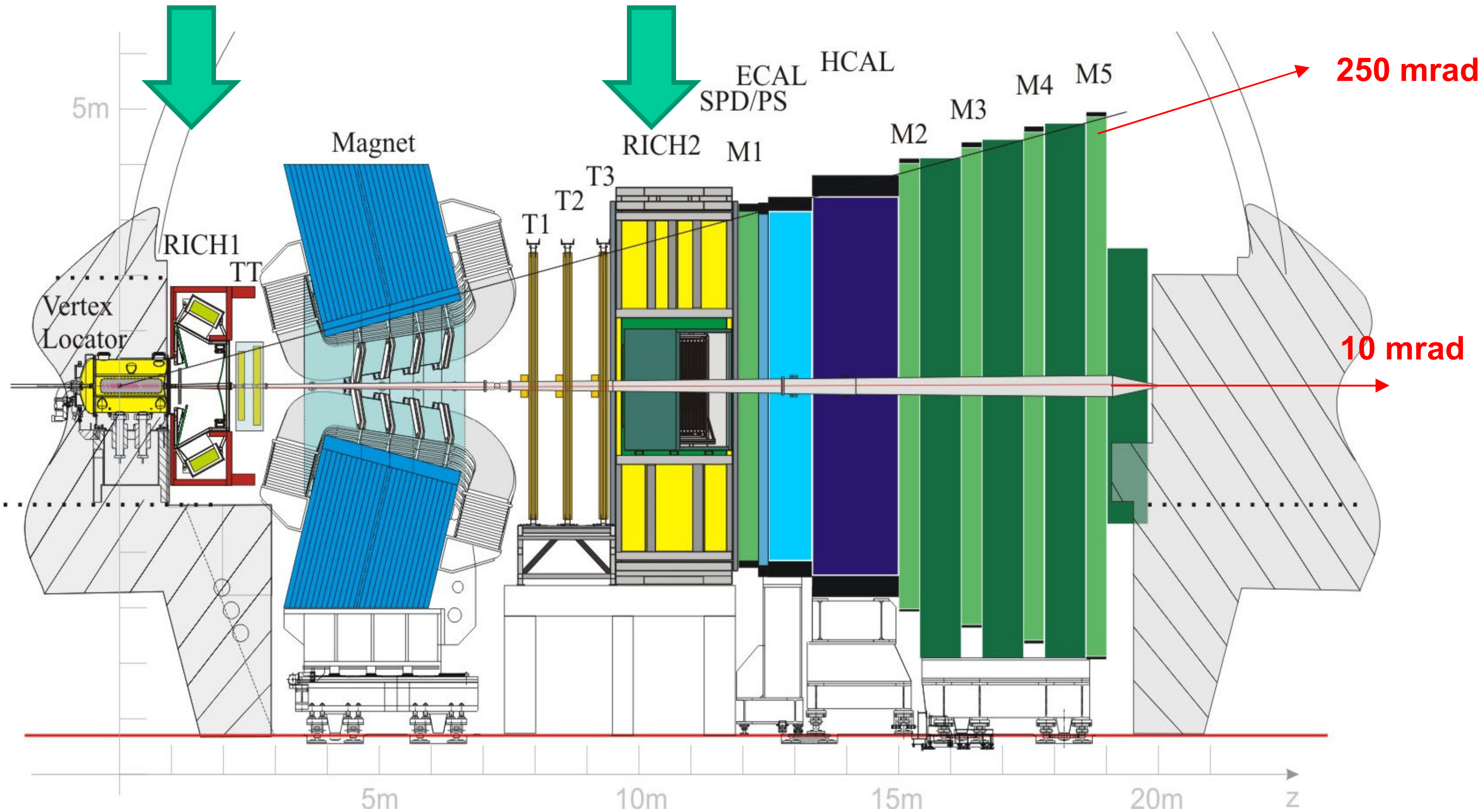
Use Cherenkov light instead of scintillations.

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: The LHCb RICH counters



Vertex reconstruction:
VELO

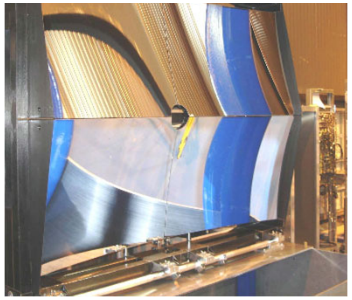
Trigger:
Muon Chambers
Calorimeters
Tracker

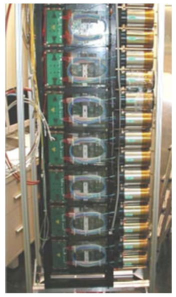
PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

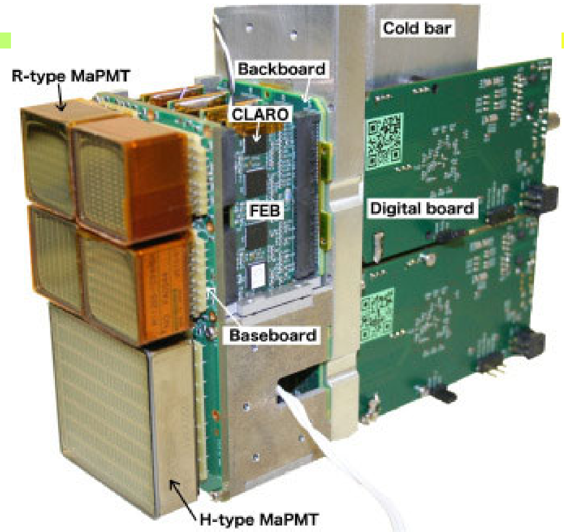
LHCb particle identification upgrade(s)

RICH Upgrade





Photosensor: Hybrid Photon Detector with 1 MHz max. readout rate

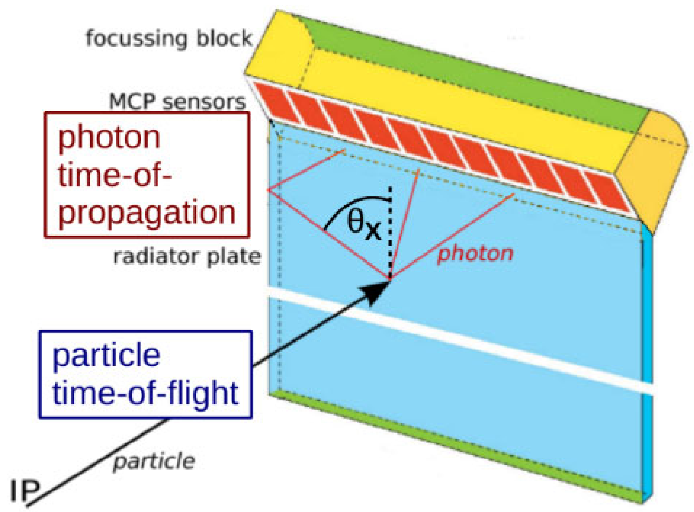


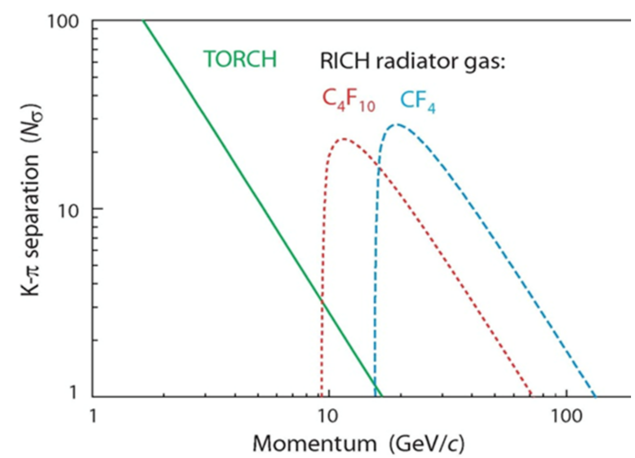
MaPMTs from Hamamatsu

Upgrade IA: New optics, photo detectors, new electronics

Next upgrades

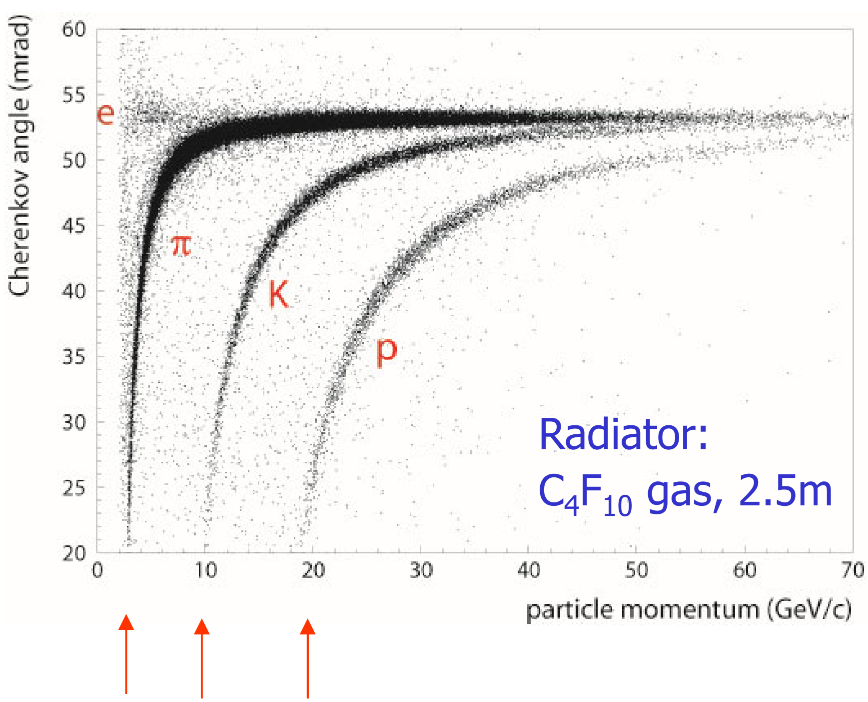
TORCH (Time Of internally Reflected CHerenkov light) ToF resolution ~10-15 ps (per track) using micro channel plate PMTs





Particle identification: novel radiators for Cherenkov detectors

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



π K p thresholds

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

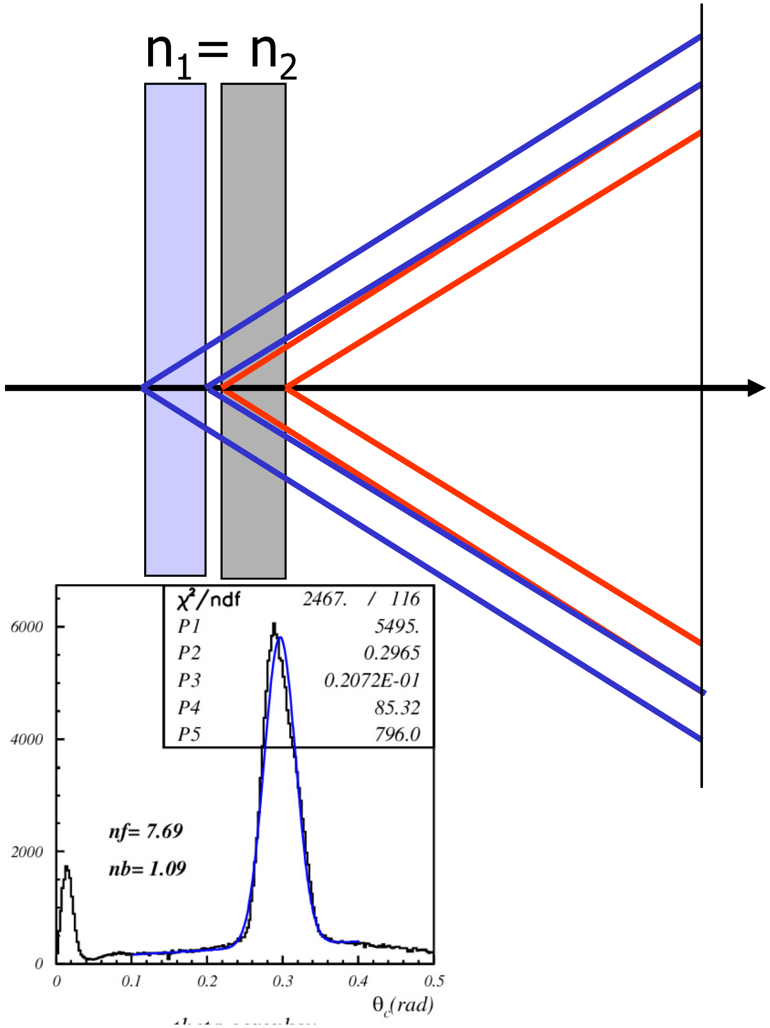
Radiator with multiple refractive indices

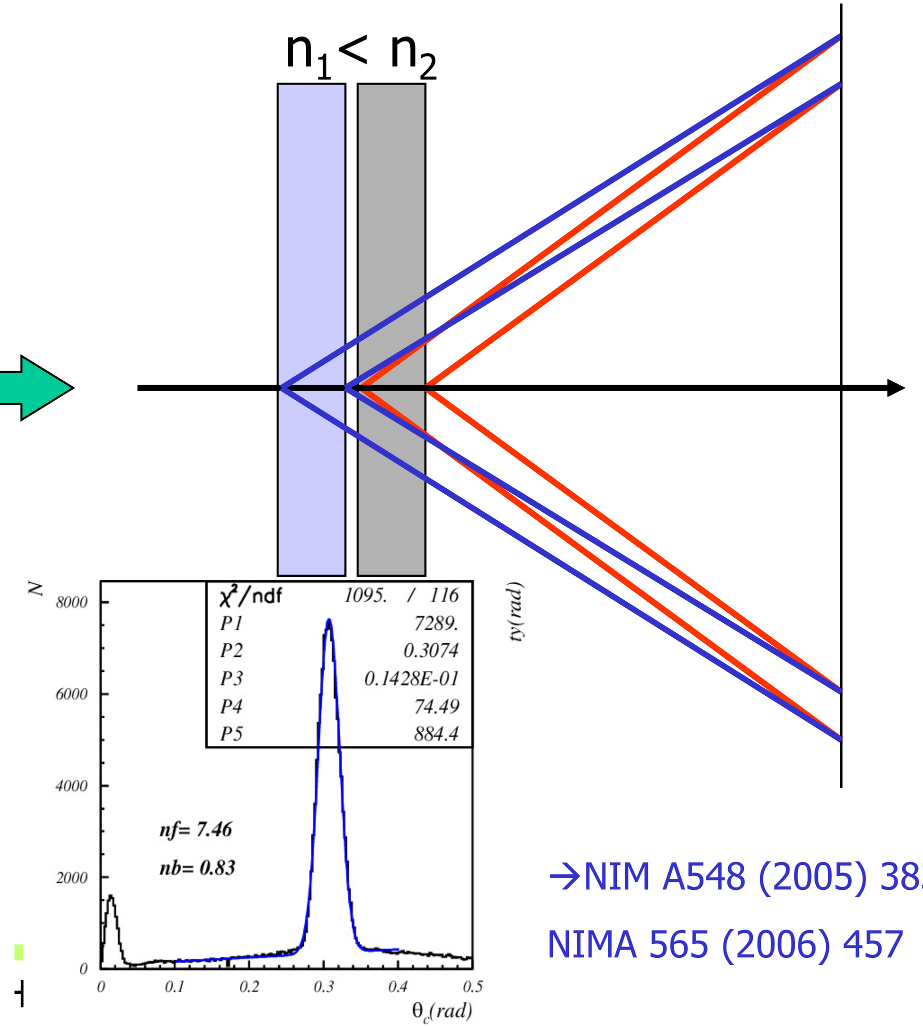
Small number of photons from aerogel → need a thick layer of aerogel.

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

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

normal

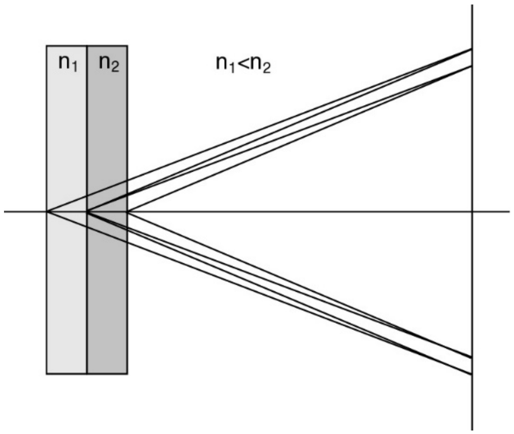


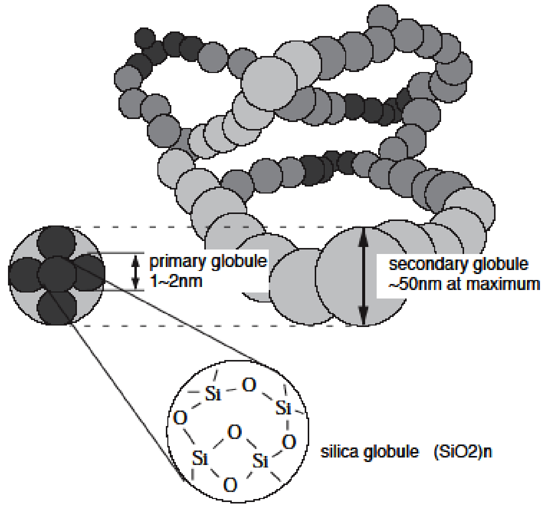


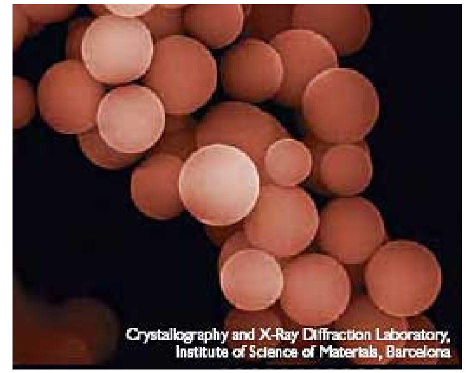
→NIM A548 (2005) 383,
NIMA 565 (2006) 457

Radiator with multiple refractive indices 2

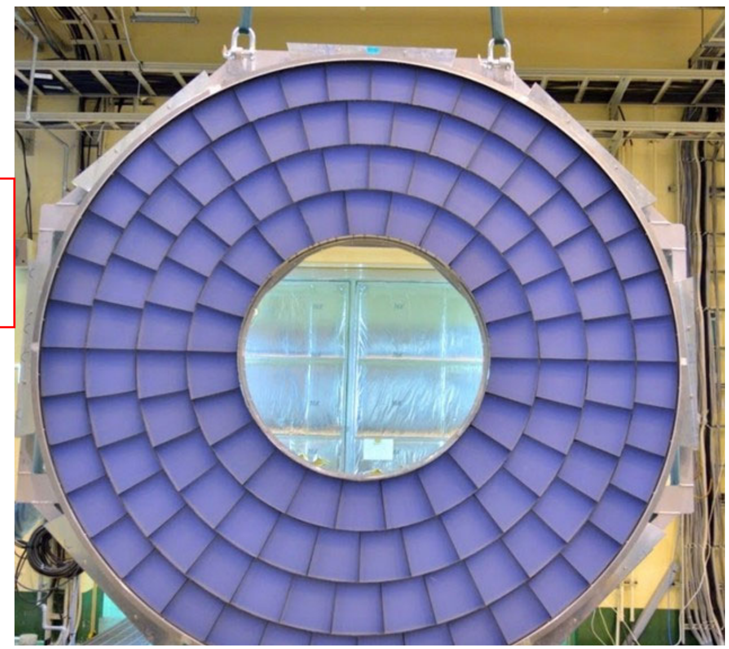
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.07.





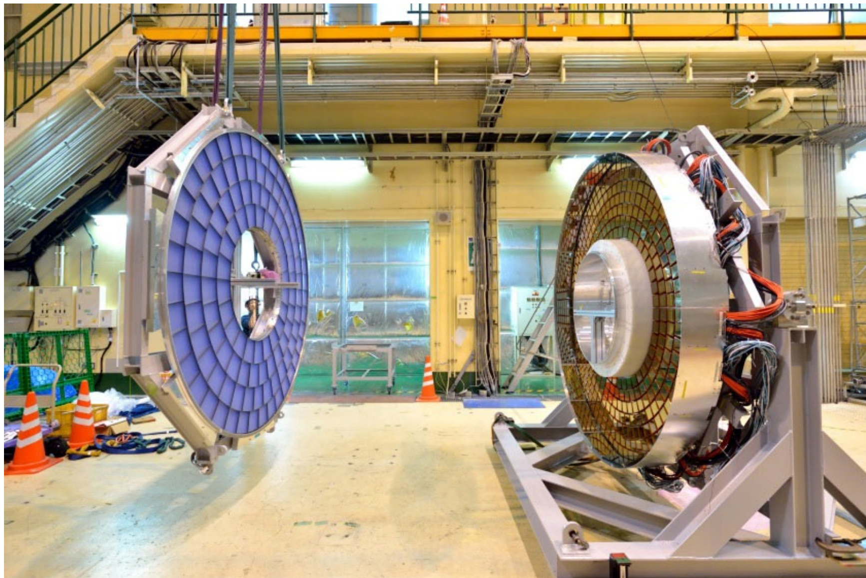


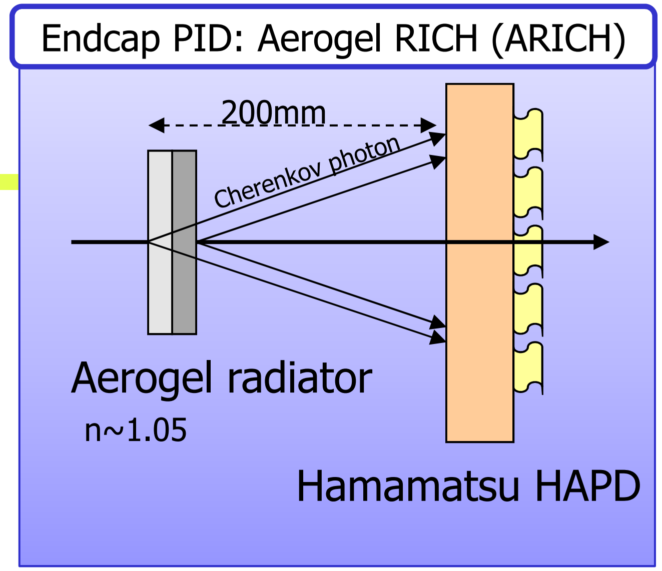
Belle II ARICH

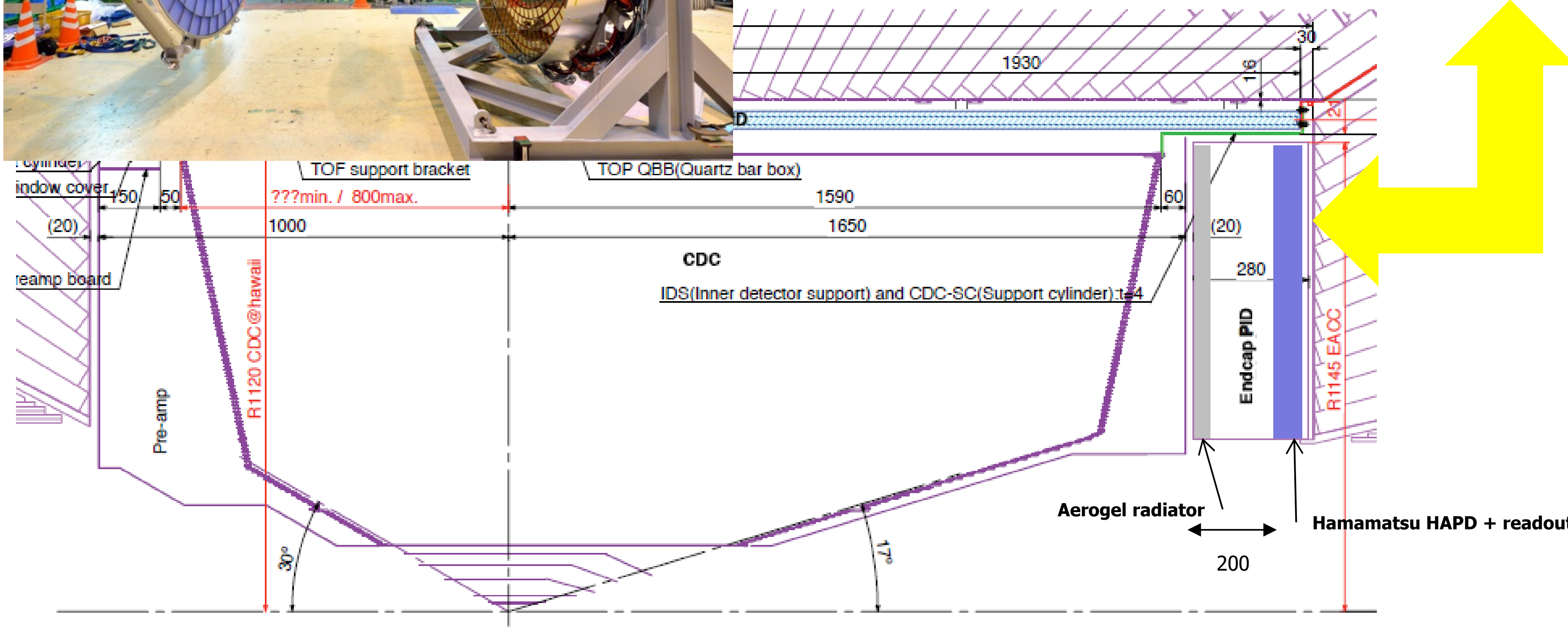


Radiator plane covered with 2 x 124 tiles water-jet cut tiles (~ 17x17cm)

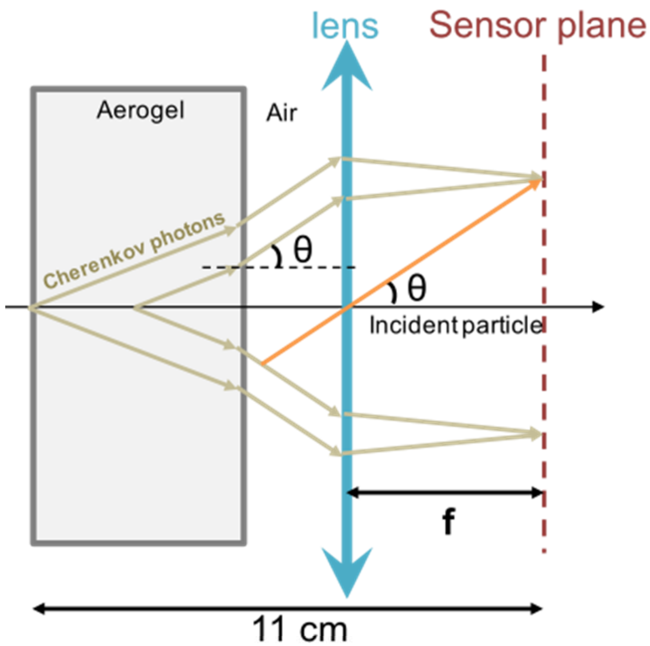
PID Devices: ARICH

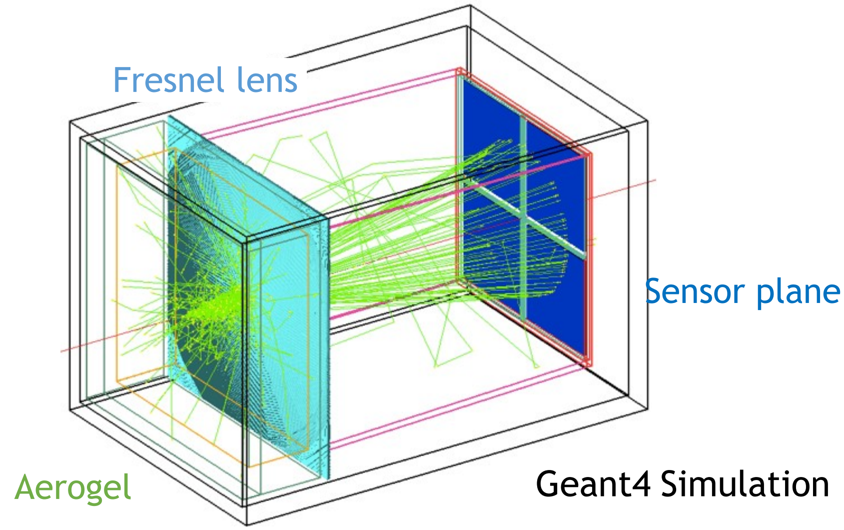




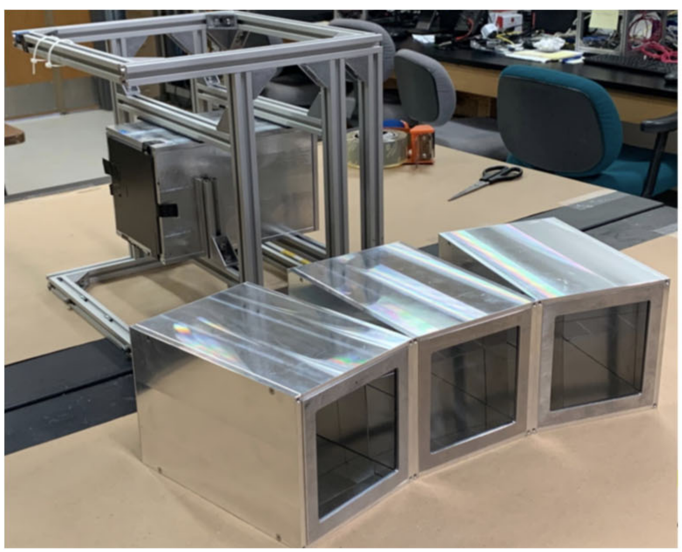


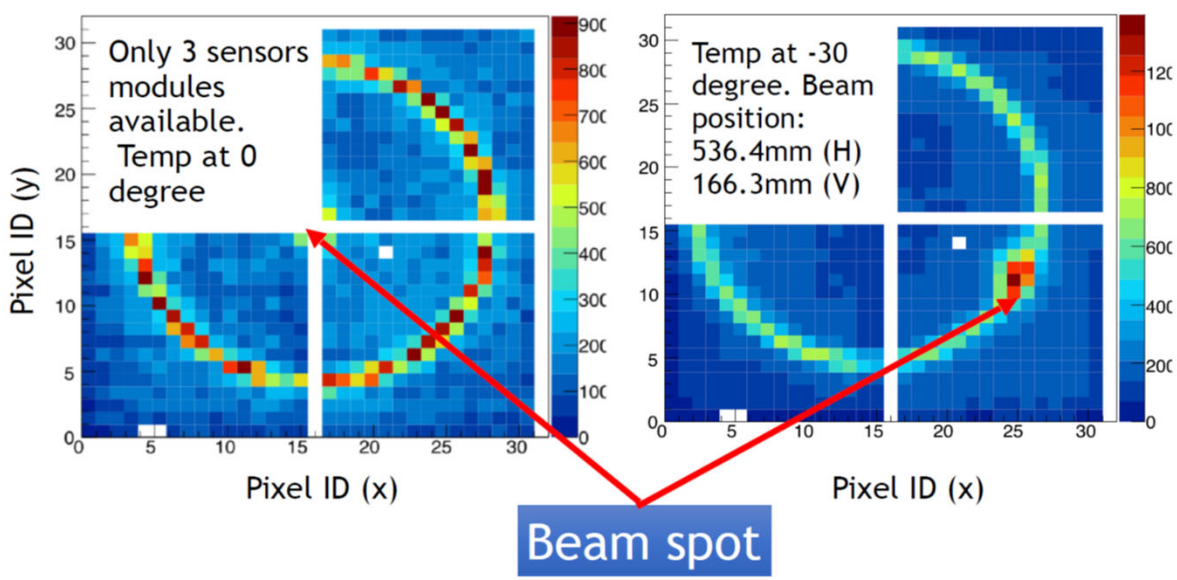
EIC detector PID: mRICH





Beam test with SiPMs as sensors





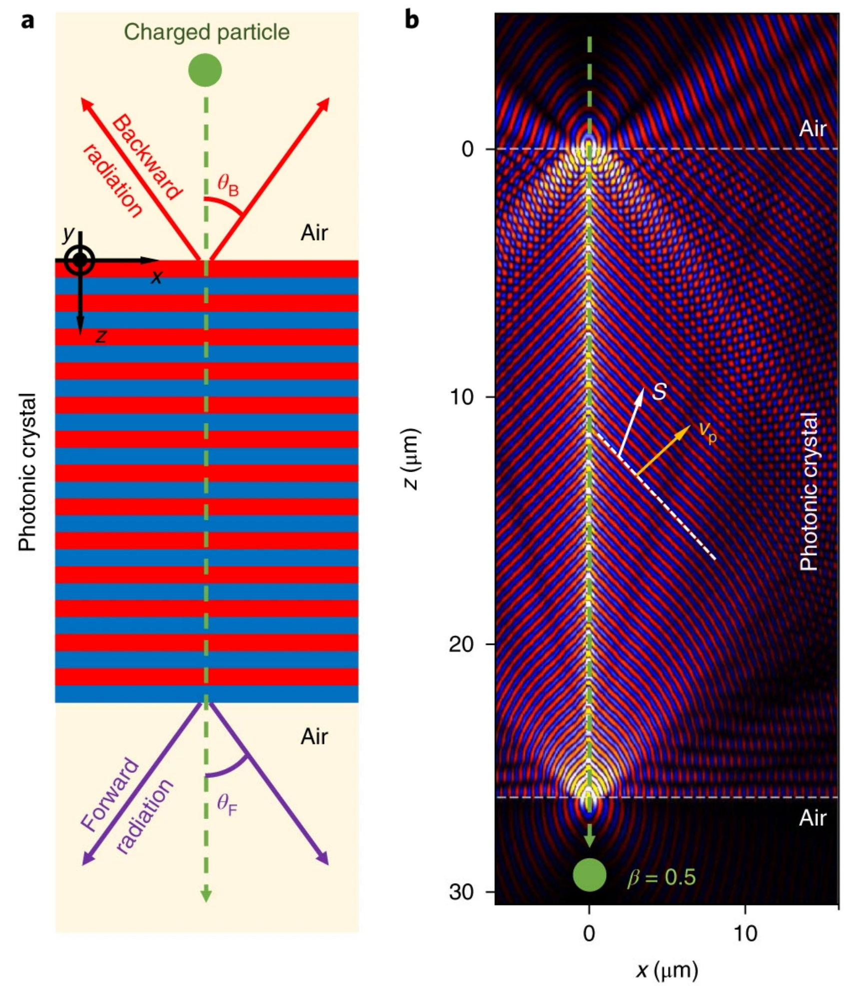
Particle identification: novel radiators for Cherenkov detectors

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!

Dark counts have single photon pulse heights (rate ~100 kHz/mm^2) – 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

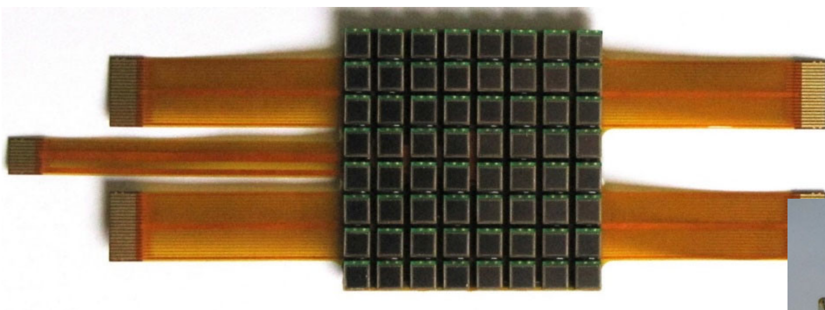
SiPM as photosensor for a RICH counter

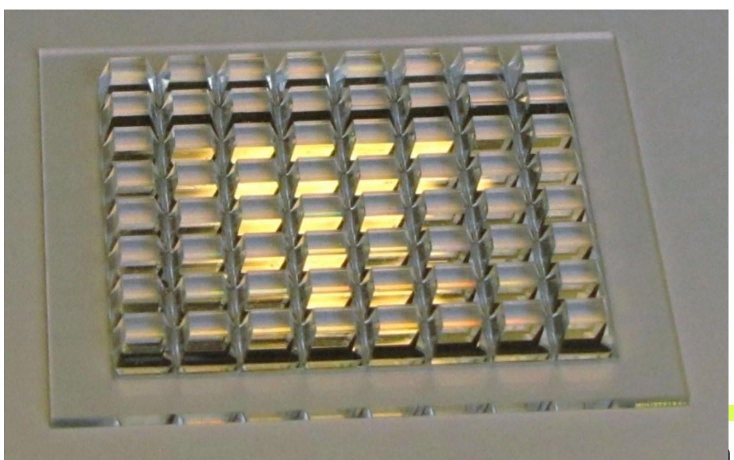
Improve the signal to noise ratio:

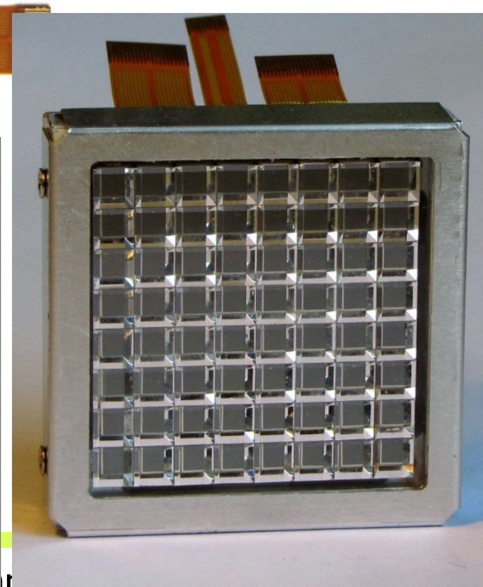
- Reduce the noise by a narrow (<10ns) time window (Cherenkov light is prompt!)
- Increase the number of signal hits per single sensor by using light collectors

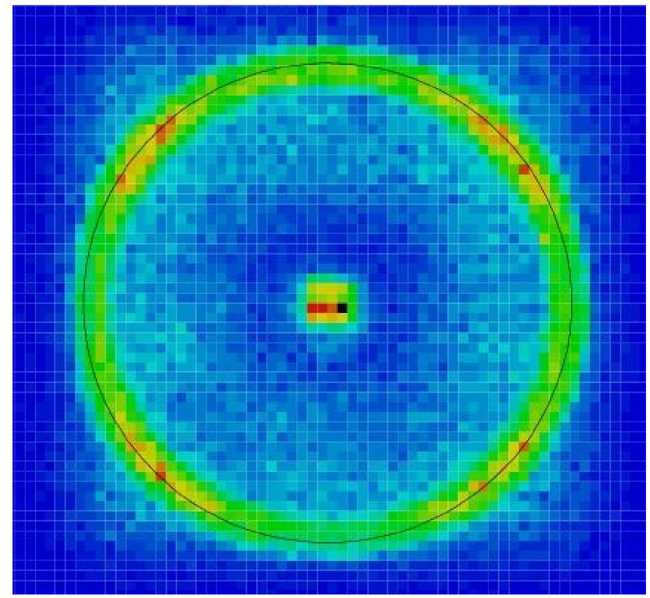
Example: Hamamatsu MPPC S11834-3388DF

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





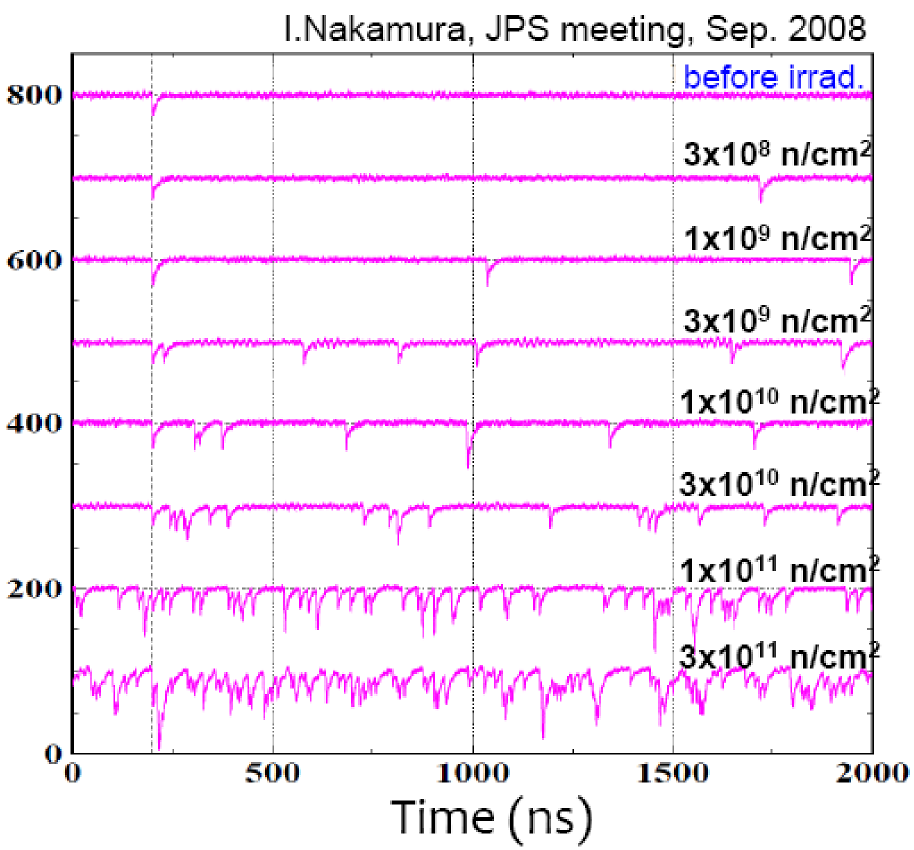




First rings with SiPMs

→ 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

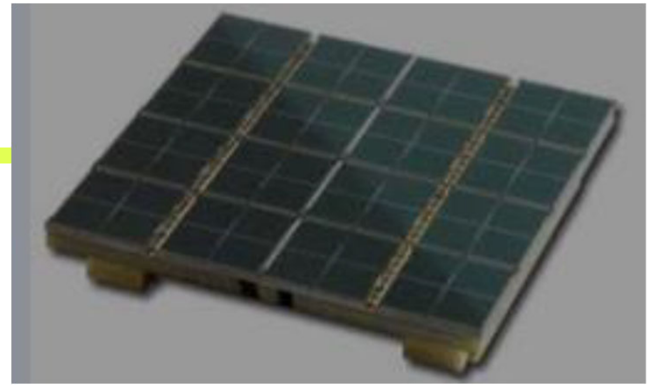
For single photon detection need

→ Cooling of sensors

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

Considered for RICHes in the EIC detector, the next LHCb upgrade and for the Belle II upgrade by the end of the decade

LAPPD Large Area Picosecond Photodetectors (MCP-PMTs)



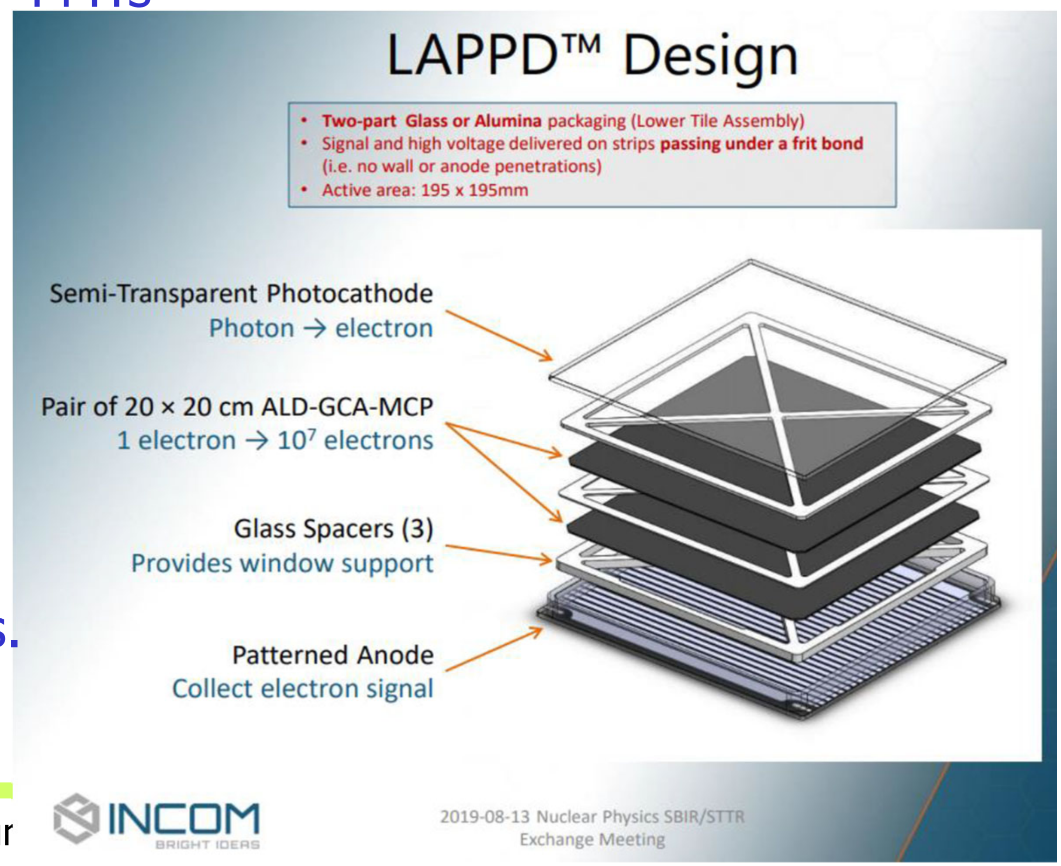
Attempt to produce less expensive large area single-photon sensitive devices

PROs:

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

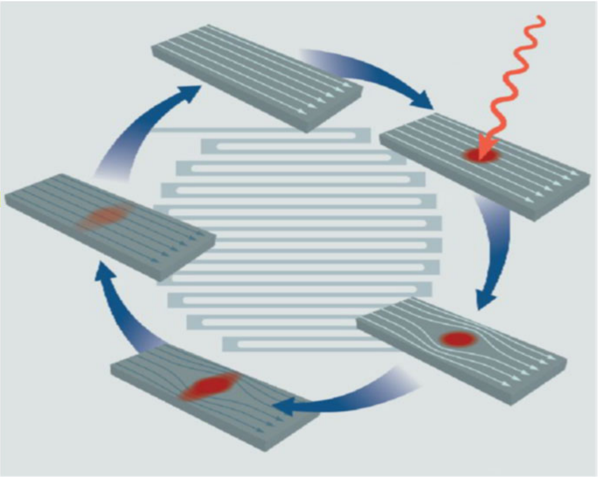
CONs:

- 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).

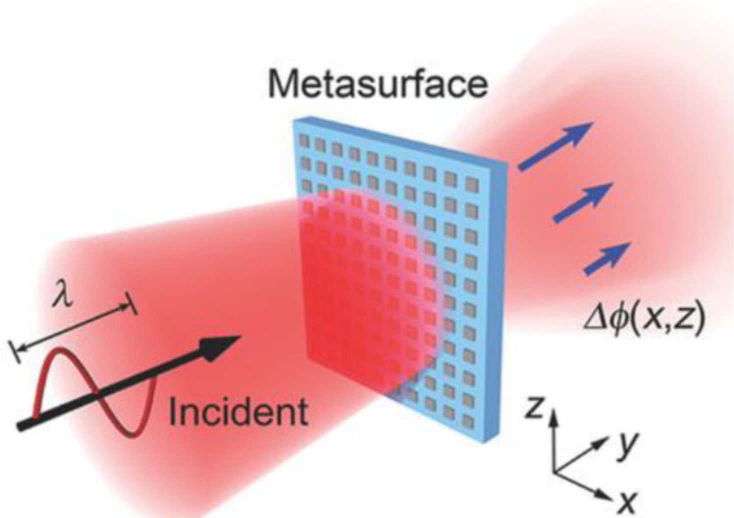
Enabling technology for quantum information science applications. Examples of SNSPDs in present use in particle physics are nanowire detectors for dark matter and dark photons.

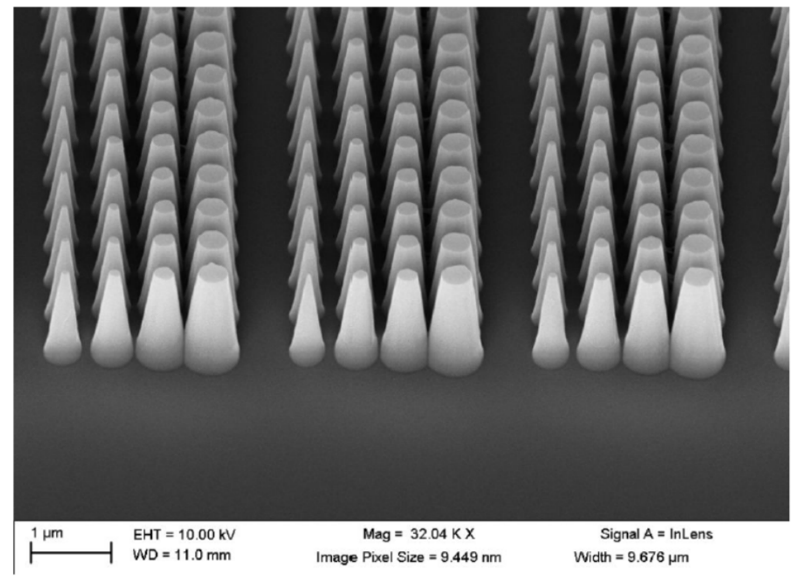
Work is in progress that could make these sensors relevant to HEP applications by lowering the energy threshold, increasing the area (using 300mm wafers and larger) and pixel size, coupling via windows to cryogenic stages, and readout of arrays (superconducting electronics for data processing).

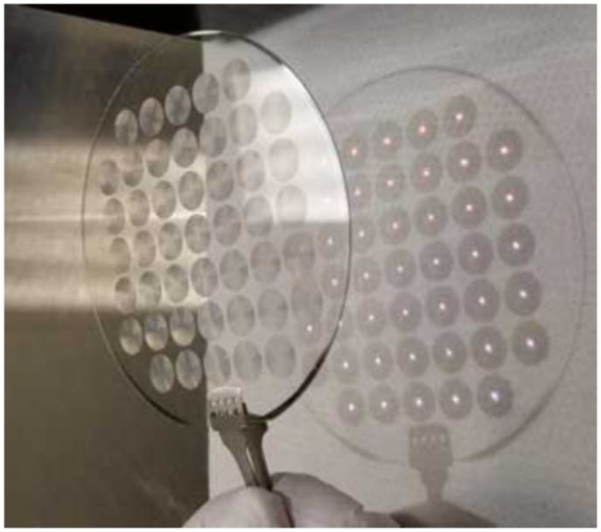
Any application of these sensors with severe cryogenic requirements in large accelerator-based detectors would require an extensive R&D program.

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

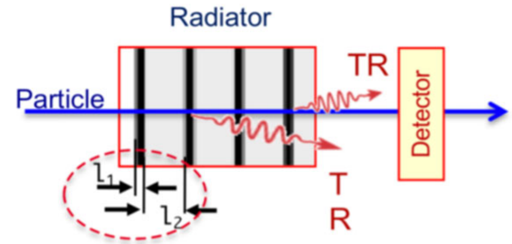
PID with TRD – new ideas

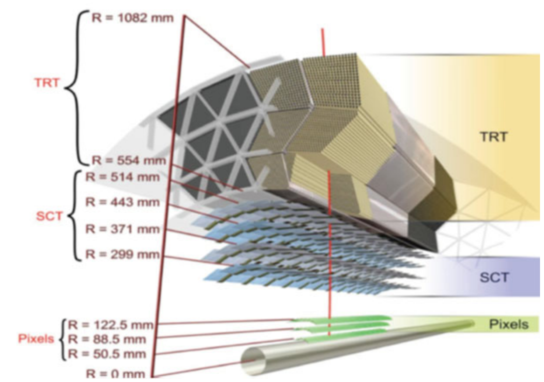
•Transition Radiation Detectors are almost everywhere: ATLAS, ALICE, AMS, CBM, EIC

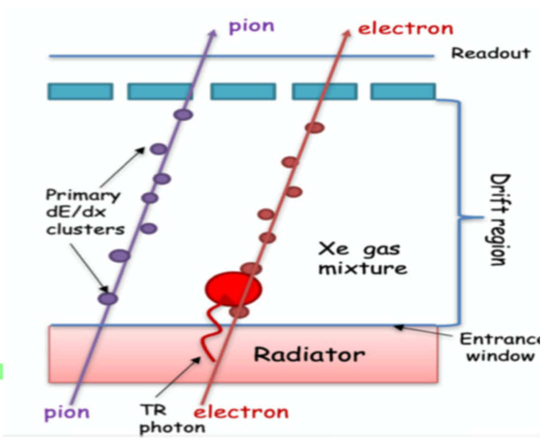
•Gas TRDs are considered a mature instrument for PID at high energies.

New ideas

- Read out with a pixel Si sensor
- TRD imaging

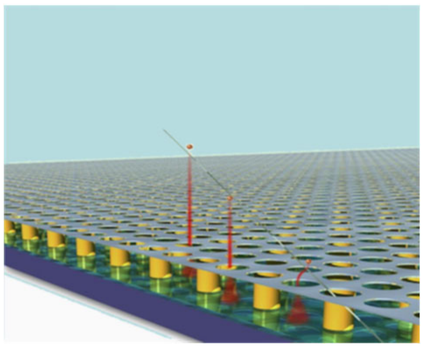


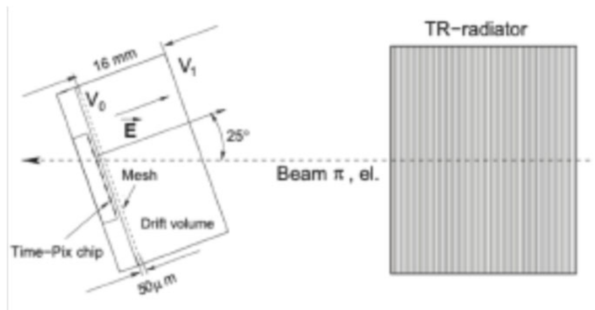


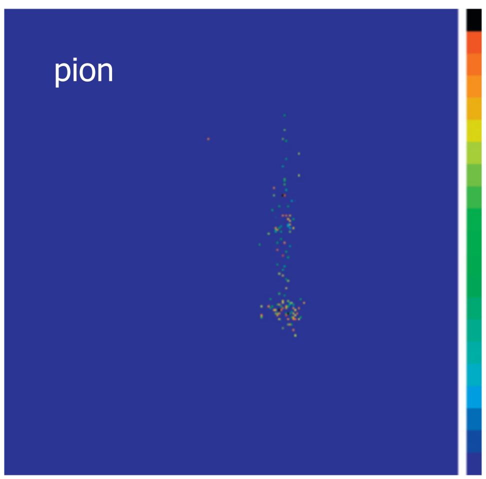


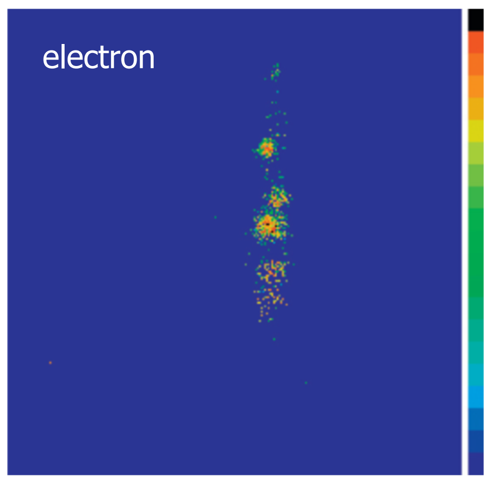
PID with TRD

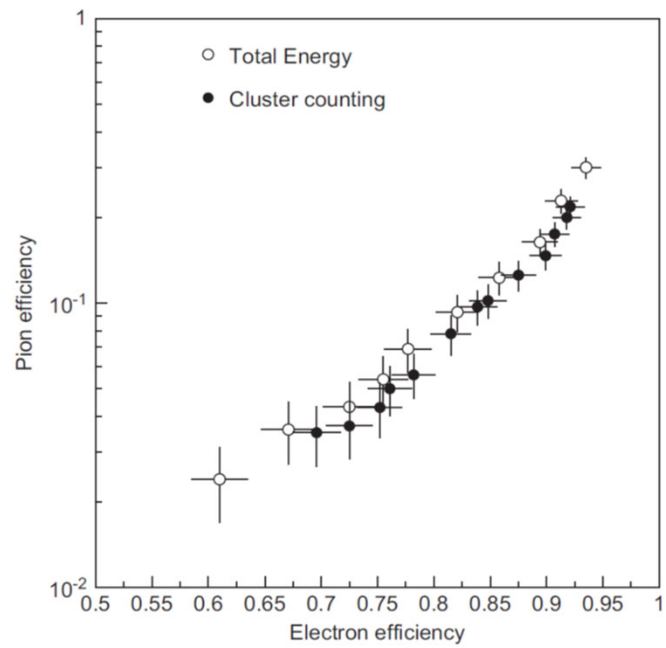
An attempt has been made to improve cluster counting by means of a GridPix.
Some improvement is possible, although not drastic. → NIM, A 706 (2013) 59







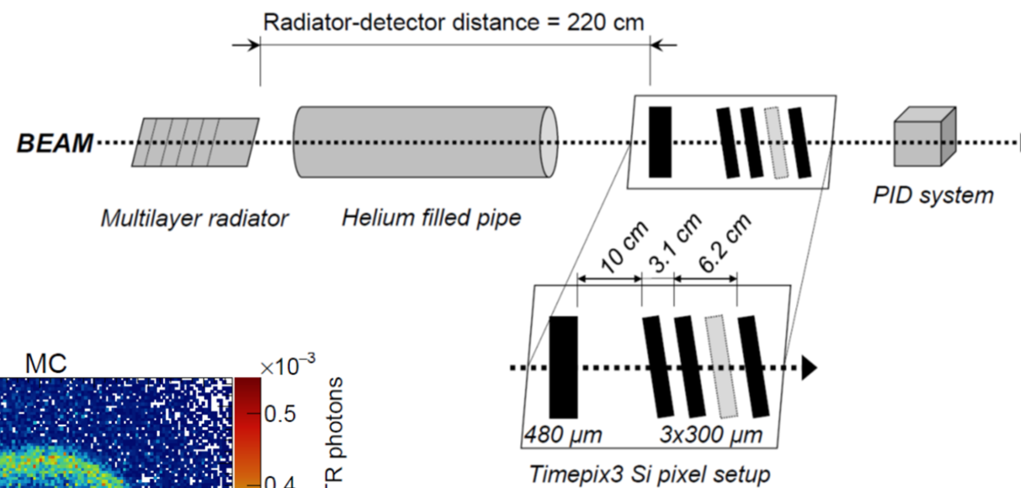




Potential improvement may be reached by differentiating the response to X-ray photons and to particle ionization → Extensive R&D required!

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

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

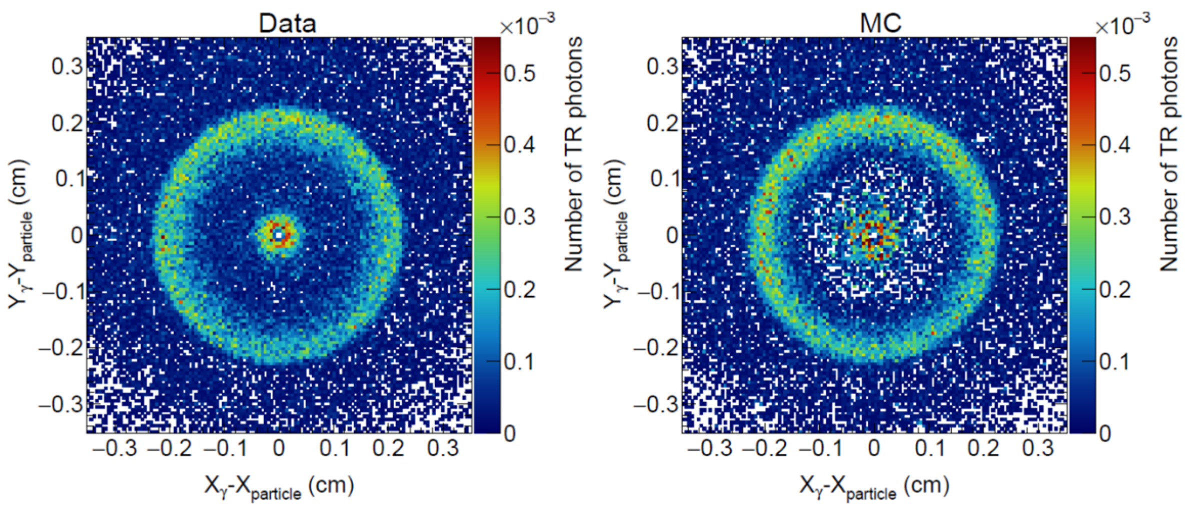
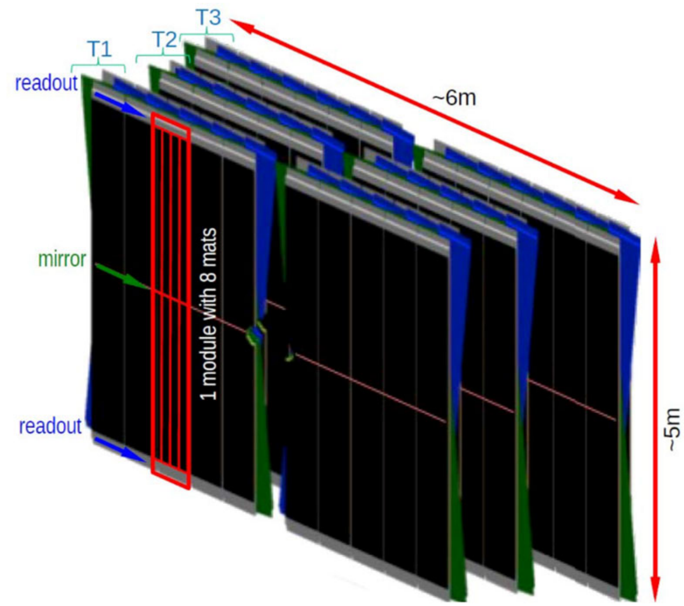


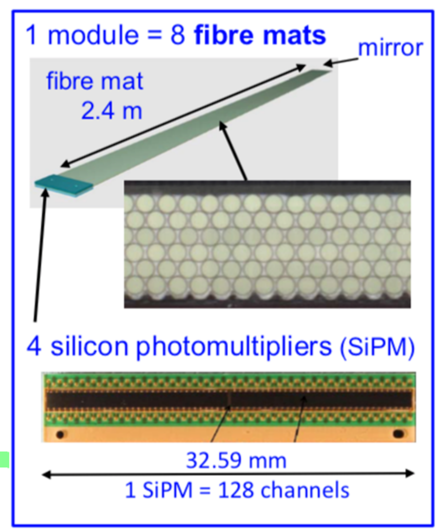
Figure 14: Relative position of identified TR photon clusters with respect to the particle clusters for 20 GeV/c electrons crossing the polypropylene radiator. Left panel: data. Right panel: MC simulation.

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.





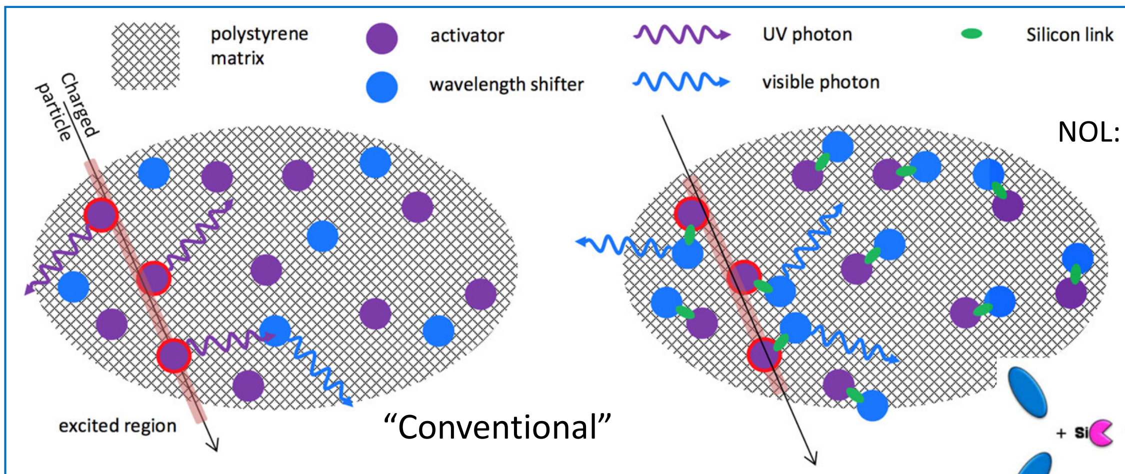
Open issues:

- Radiation tolerance
- Speed
- Emission spectrum

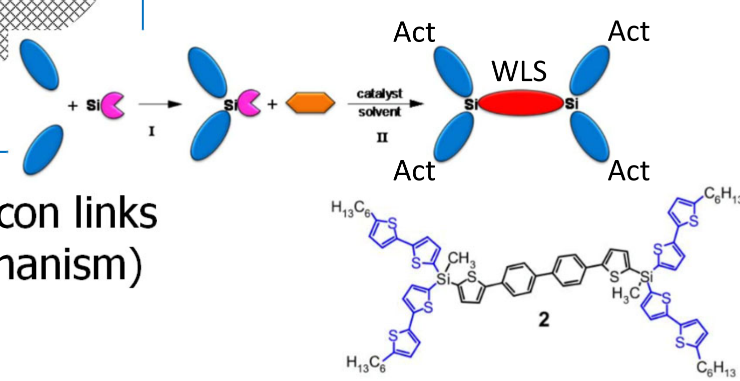
Novel optical materials for fiber trackers

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

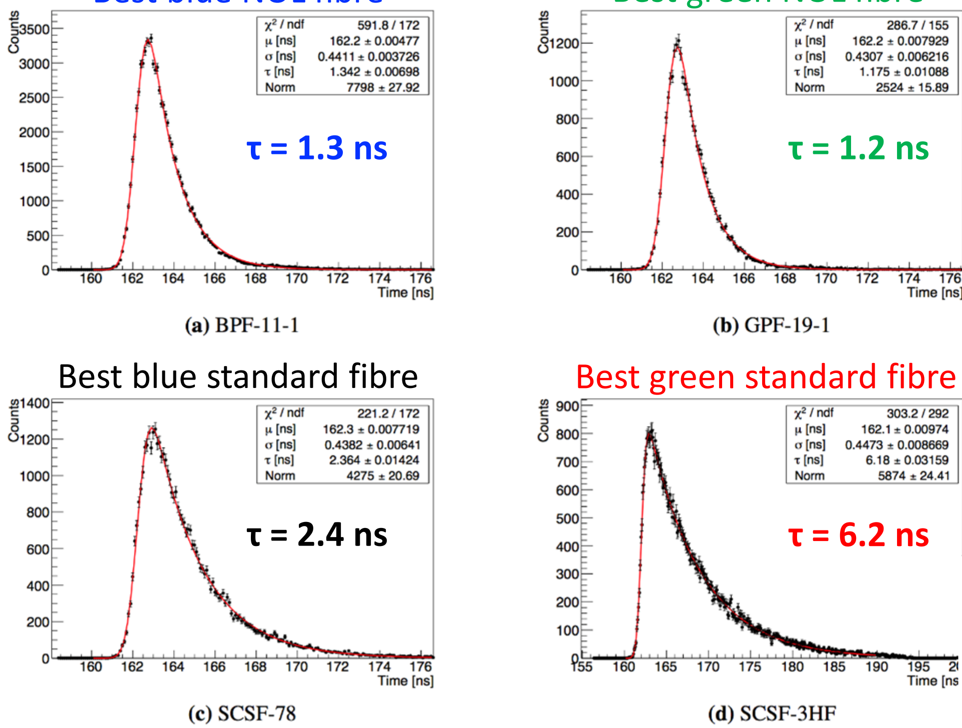
S.A. Ponomarenko et al., Nature Sci. Rep. 4 (2014) 6549

From L. Gruber, VCI 2019

NOL prototype fiber performance

O. Borshchev et al., 2017 JINST 12 P05013

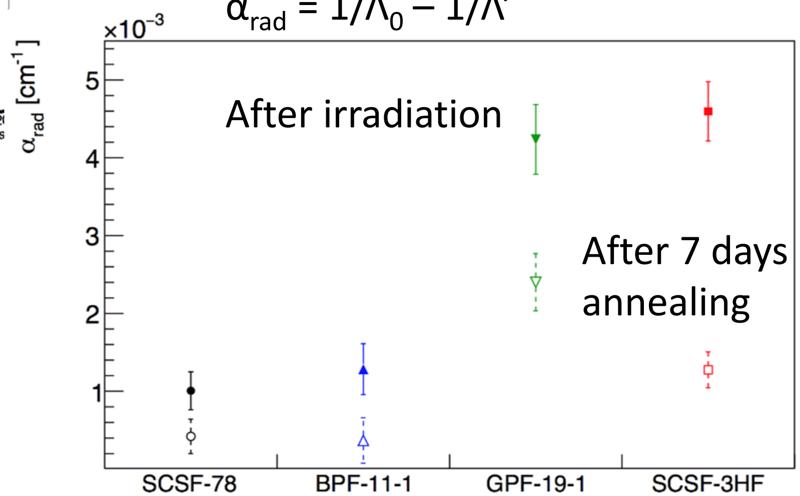
Best blue NOL fibre — Best green NOL fibre — Best blue standard fibre — Best green standard fibre



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

From L. Gruber, VCI 2019

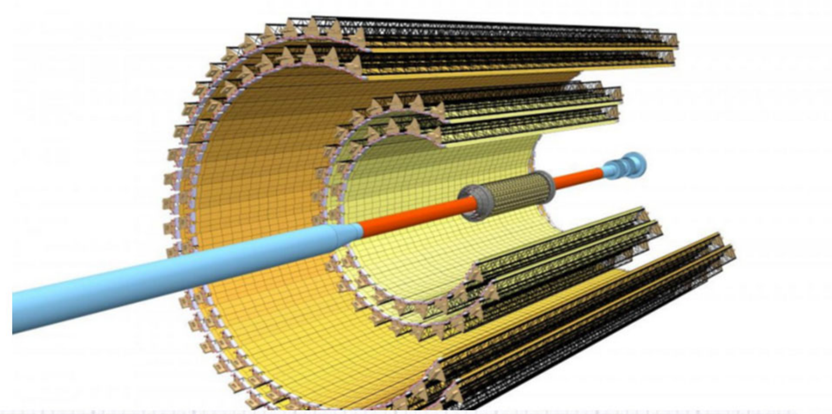
Wireless data acquisition

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

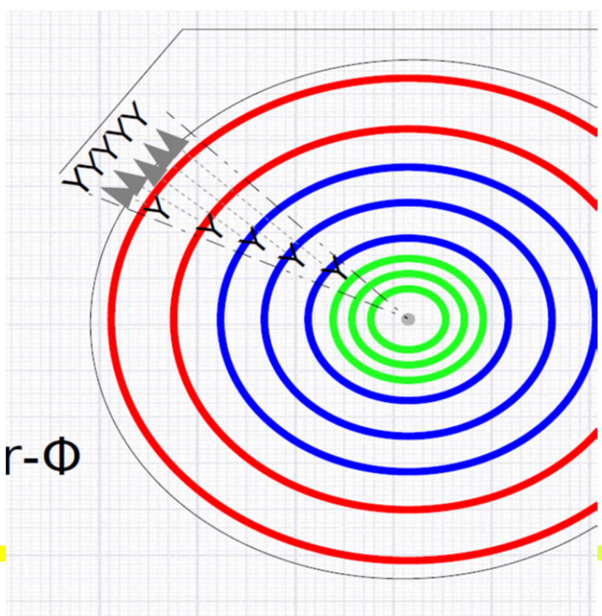
→ Not optimal for triggering

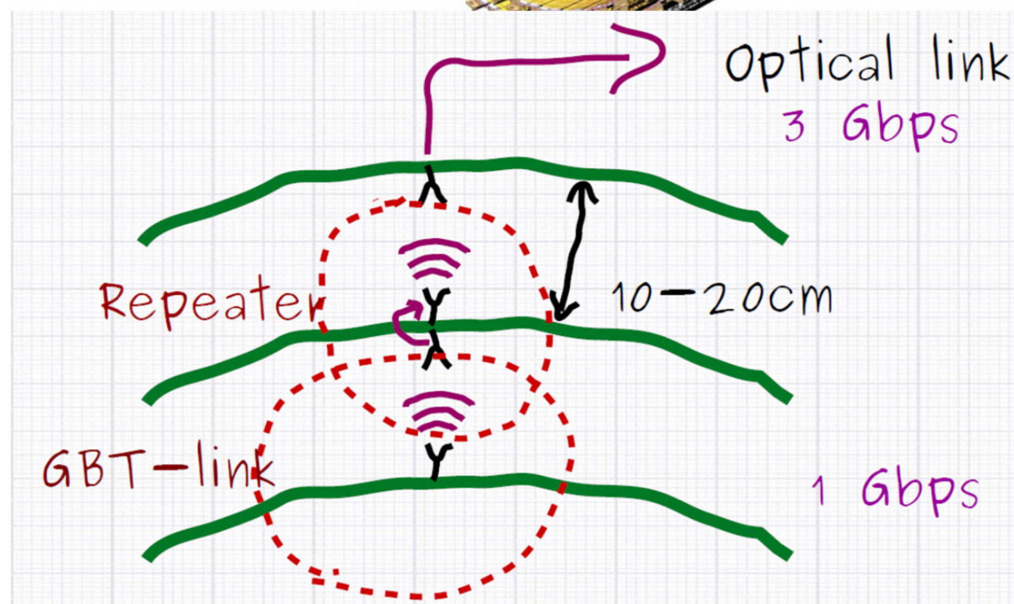
→ Not optimal for material distribution

(in particular at the barrel-endcap boundary)



Idea: read out wirelessly





Wireless data acquisition

Wifi technologies under development

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

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‘

Summary

Detectors for particle physics experiments are our discovery tools – well designed and well functioning devices have been essential for our present understanding of elementary particles and their interactions.

A very vibrant research area: a large variety of new methods and techniques has either been developed recently, or is under commissioning or early data taking.

New challenges are waiting for us when planning the next generation of experiments.

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, needs in medical imaging, innovations in the industry.

Many blue sky studies of today will become mainstream tomorrow.