RICH Technology Requirements & Optical Elements

Carmelo D’Ambrosio (CERN)

- Introduction
- Examples of close/far future PID/RICH detectors environments, requirements and designs:
  - LHC-Upgrades/EIC/Future Colliders
- Technology requirements are driven by performance requirements in a defined environment
- Main quantities affecting system performance
- A simple example of the evolution of the LHCb RICH system (spanning more than 20 years)
  - Technological challenges
- Conclusions
- Spares

RICH Technology Requirements & Optical Elements

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- RICH detectors for “big” experiments; today challenges for tomorrow detectors;
- No Astro-Particles examples, although the field becomes very relevant for Cherenkov detectors and they use mirrors and photodetector arrays (like us);
- No pretense to give a consistent review of what the R&D on the field presents, rather will stay on existing working detectors and their future developments;
- Most of the slides have been produced by using material from the LHCb RICH Collaboration and the ECFA Input Session of Future Facilities. Thank you very much for the help.
- I’ll discuss about Technology requirements as driven by Performance;
- I’ll limit it to RICHes with VIS/NUV photodetection systems;
- I’ll not discuss about DAQ, data rates handling, pattern recognition and simulation techniques/technologies, specific for RICH detectors;
- I apologize if you will hear a lot about the LHCb RICH.
- Apologies if I forgot to mention something or someone.

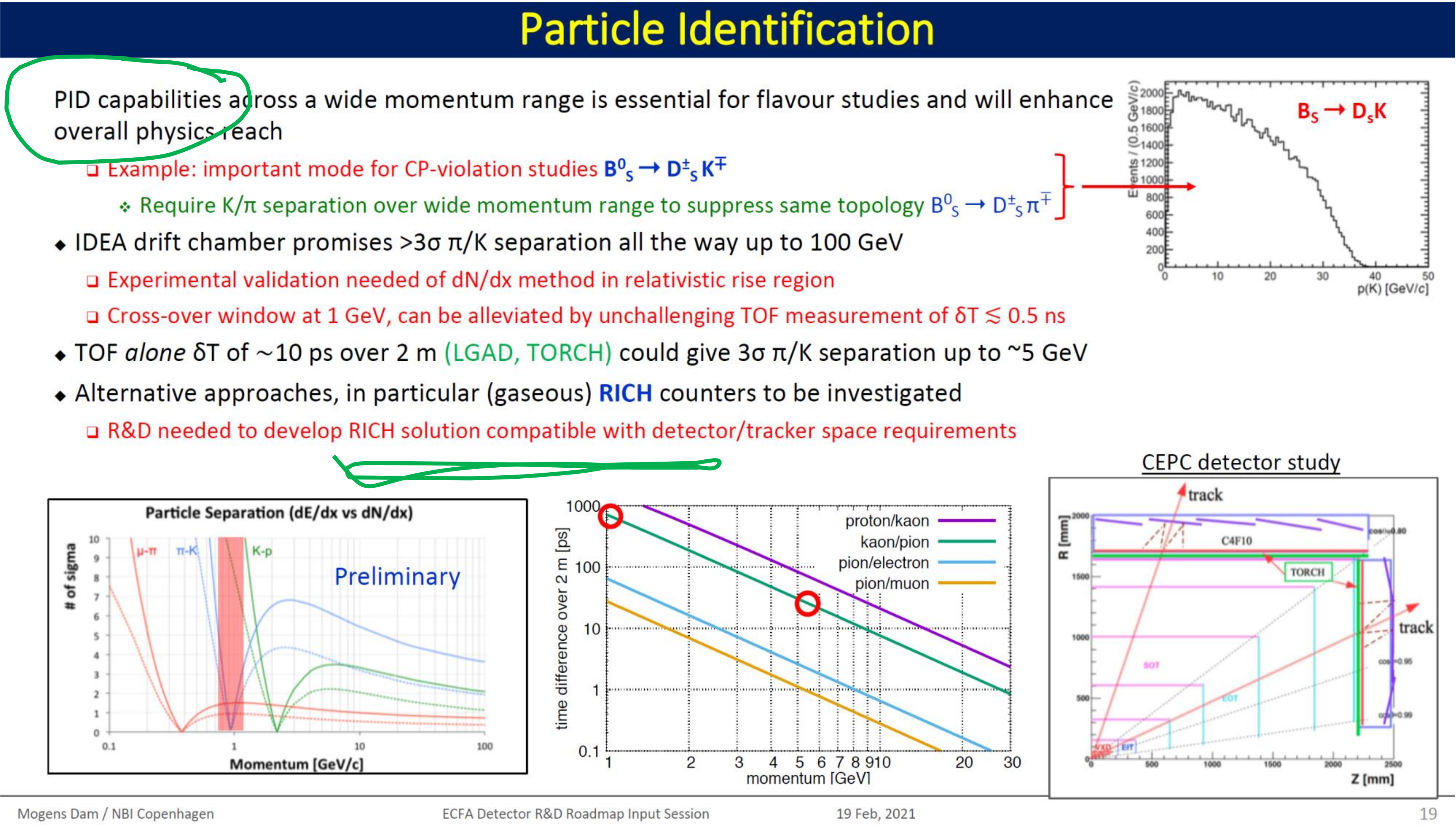
Do RICH Detectors have a bleak future in front of them?

Present requirements for future detectors

Following is a number of slides taken from https://indico.cern.ch/event/994685/ ,

ECFA Detector Roadmap Input, Feb 2021.

CERN/FCC-ee



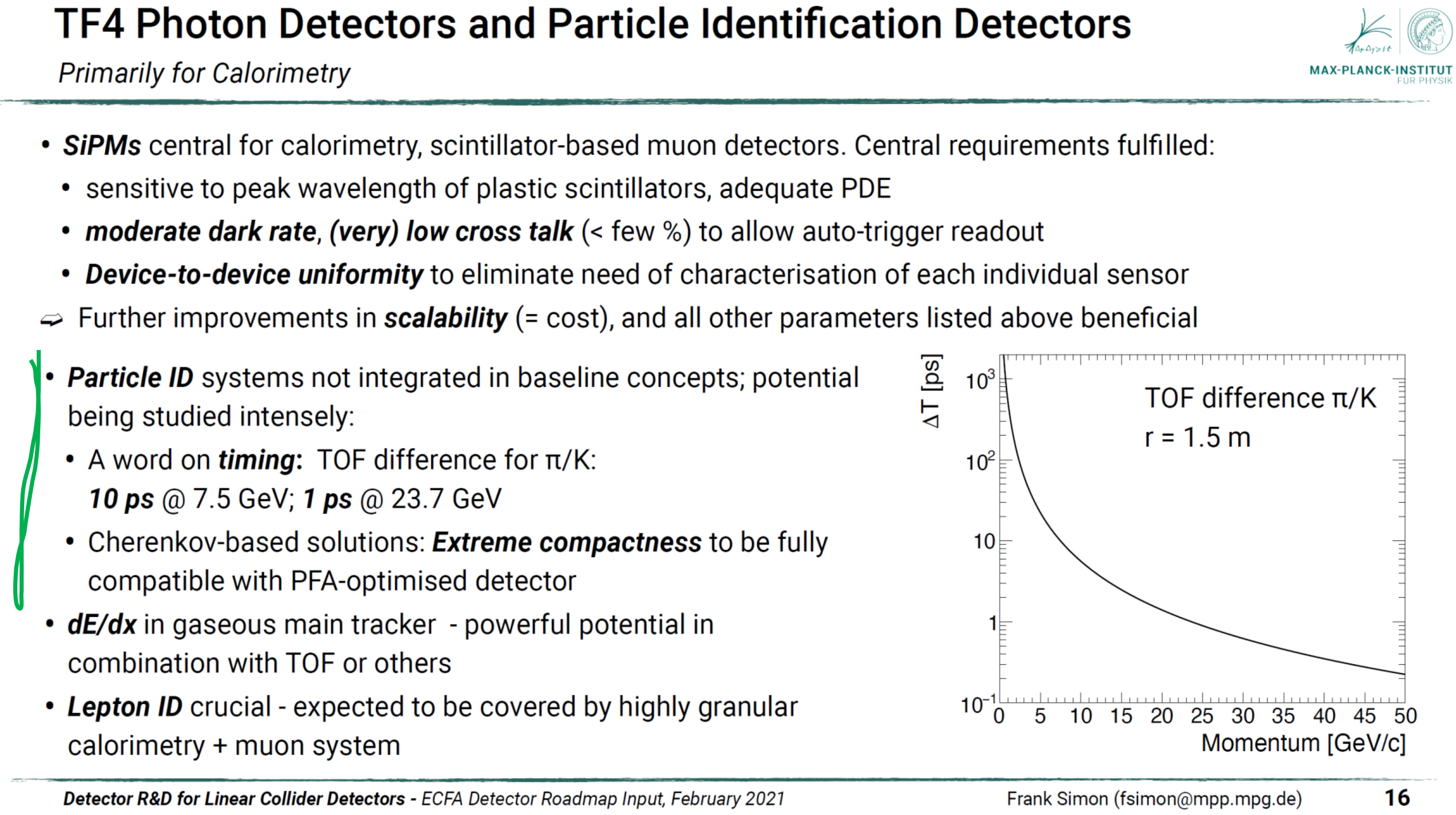
Particle Identification

- PID capabilities across a wide momentum range is essential for flavour studies and will enhance overall physics reach
  - ❑ Example: important mode for CP-violation studies $B^0_s \to D^\pm_s K^\mp$
    - ❖ Require K/π separation over wide momentum range to suppress same topology $B^0_s \to D^\pm_s \pi^\mp$
- IDEA drift chamber promises >3σ π/K separation all the way up to 100 GeV
  - ❑ Experimental validation needed of dN/dx method in relativistic rise region
  - ❑ Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of $\delta T \lesssim 0.5$ ns
- TOF *alone* δT of ~10 ps over 2 m (LGAD, TORCH) could give 3σ π/K separation up to ~5 GeV
- Alternative approaches, in particular (gaseous) **RICH** counters to be investigated
  - ❑ R&D needed to develop RICH solution compatible with detector/tracker space requirements

Mogens Dam / NBI Copenhagen ECFA Detector R&D Roadmap Input Session 19 Feb, 2021 19

https://indico.cern.ch/event/994685/

Electron Linear Collider



TF4 Photon Detectors and Particle Identification Detectors

Primarily for Calorimetry

MAX-PLANCK-INSTITUT FÜR PHYSIK

- ***SiPMs*** central for calorimetry, scintillator-based muon detectors. Central requirements fulfilled:
  - sensitive to peak wavelength of plastic scintillators, adequate PDE
  - ***moderate dark rate***, ***(very) low cross talk*** (< few %) to allow auto-trigger readout
  - ***Device-to-device uniformity*** to eliminate need of characterisation of each individual sensor

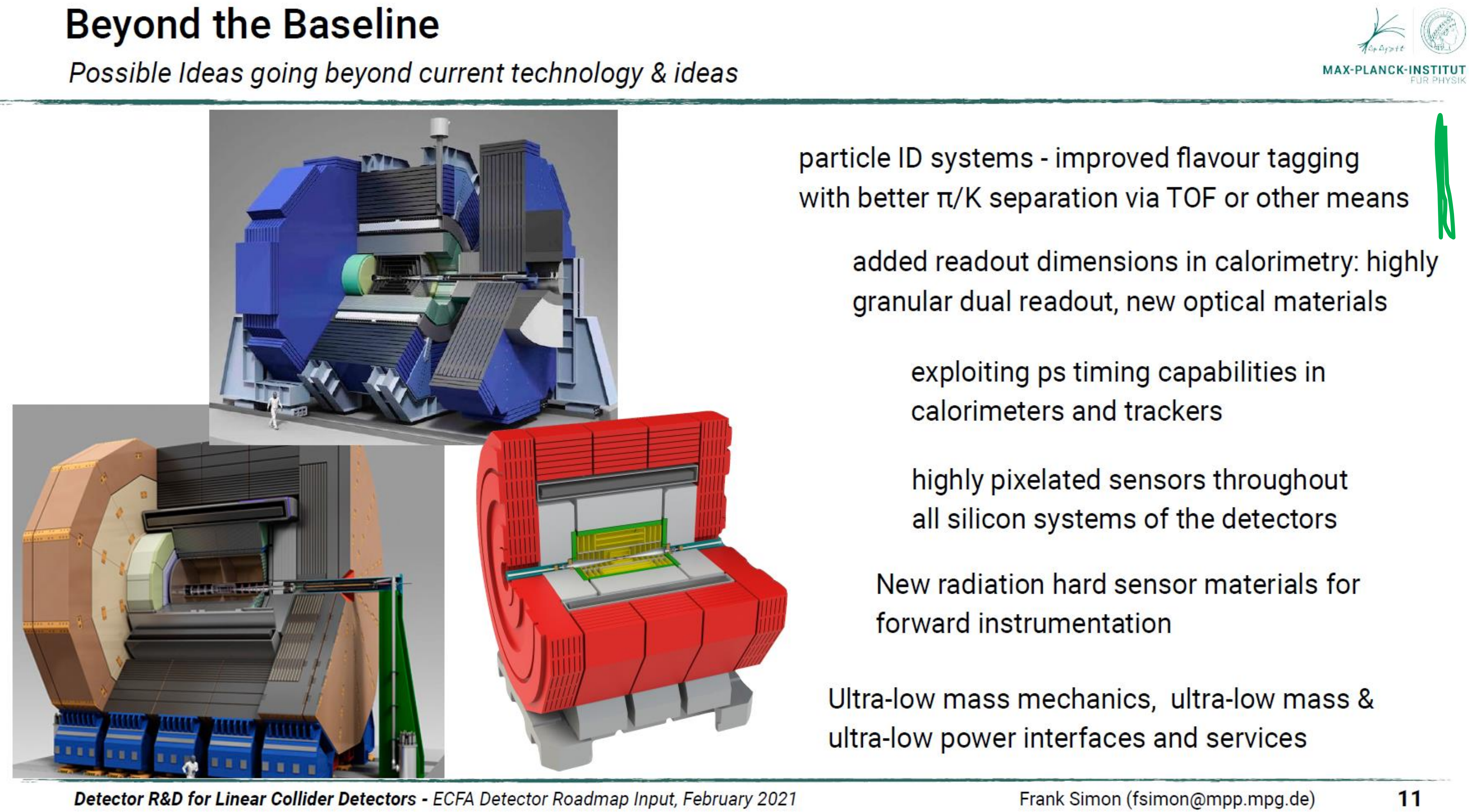
⇨ Further improvements in ***scalability*** (= cost), and all other parameters listed above beneficial

- ***Particle ID*** systems not integrated in baseline concepts; potential being studied intensely:
  - A word on ***timing***: TOF difference for π/K: ***10 ps*** @ 7.5 GeV; ***1 ps*** @ 23.7 GeV
  - Cherenkov-based solutions: ***Extreme compactness*** to be fully compatible with PFA-optimised detector
- ***dE/dx*** in gaseous main tracker - powerful potential in combination with TOF or others
- ***Lepton ID*** crucial - expected to be covered by highly granular calorimetry + muon system

***Detector R&D for Linear Collider Detectors** - ECFA Detector Roadmap Input, February 2021*   Frank Simon (fsimon@mpp.mpg.de)   **16**

https://indico.cern.ch/event/994685/

Linear Collider



Beyond the Baseline

Possible Ideas going beyond current technology & ideas

particle ID systems - improved flavour tagging with better π/K separation via TOF or other means

added readout dimensions in calorimetry: highly granular dual readout, new optical materials

exploiting ps timing capabilities in calorimeters and trackers

highly pixelated sensors throughout all silicon systems of the detectors

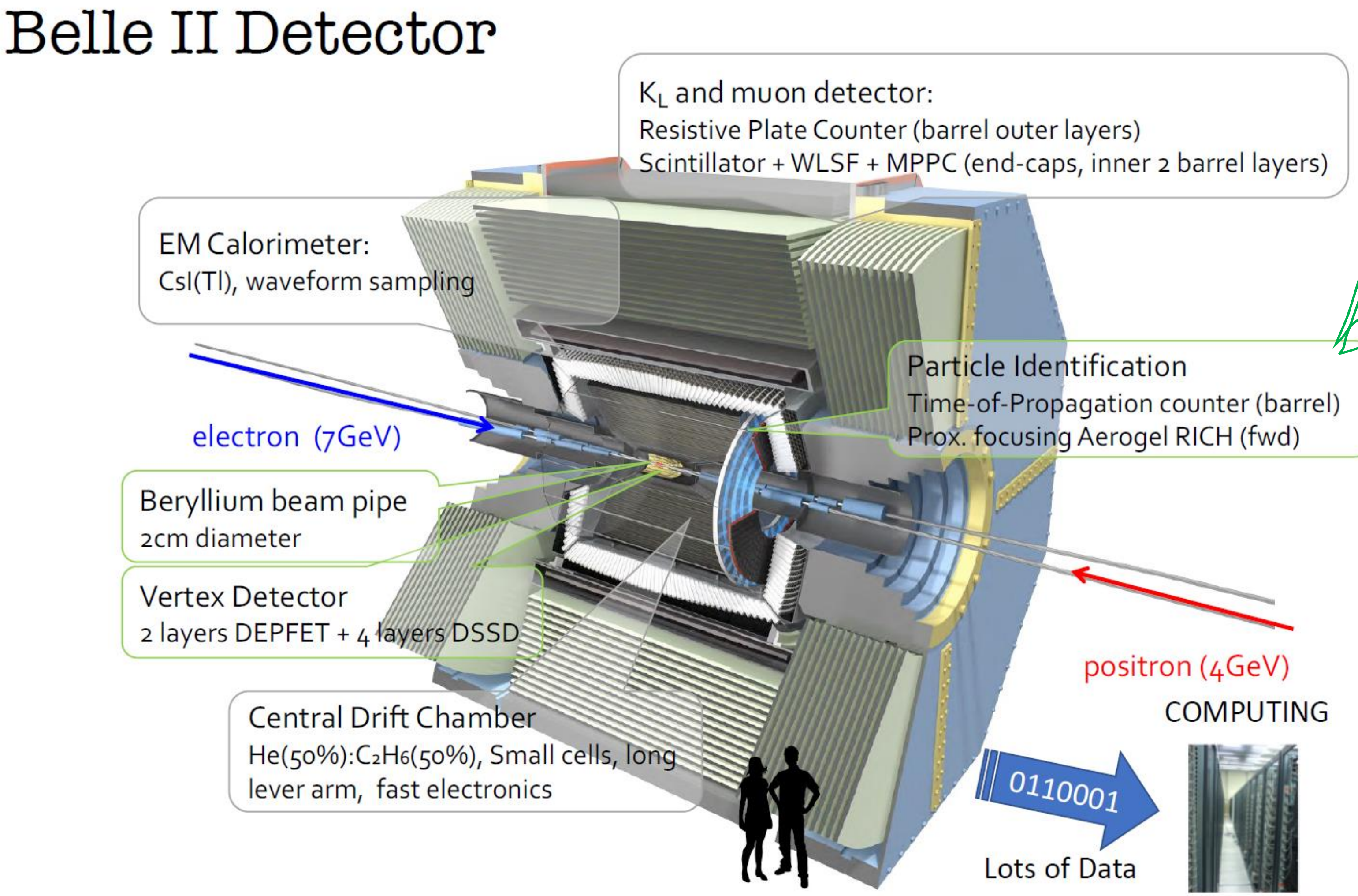
New radiation hard sensor materials for forward instrumentation

Ultra-low mass mechanics, ultra-low mass & ultra-low power interfaces and services

***Detector R&D for Linear Collider Detectors** - ECFA Detector Roadmap Input, February 2021*

Frank Simon (fsimon@mpp.mpg.de) **11**

Belle II Upgrades for High Luminosity



Belle II Detector

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

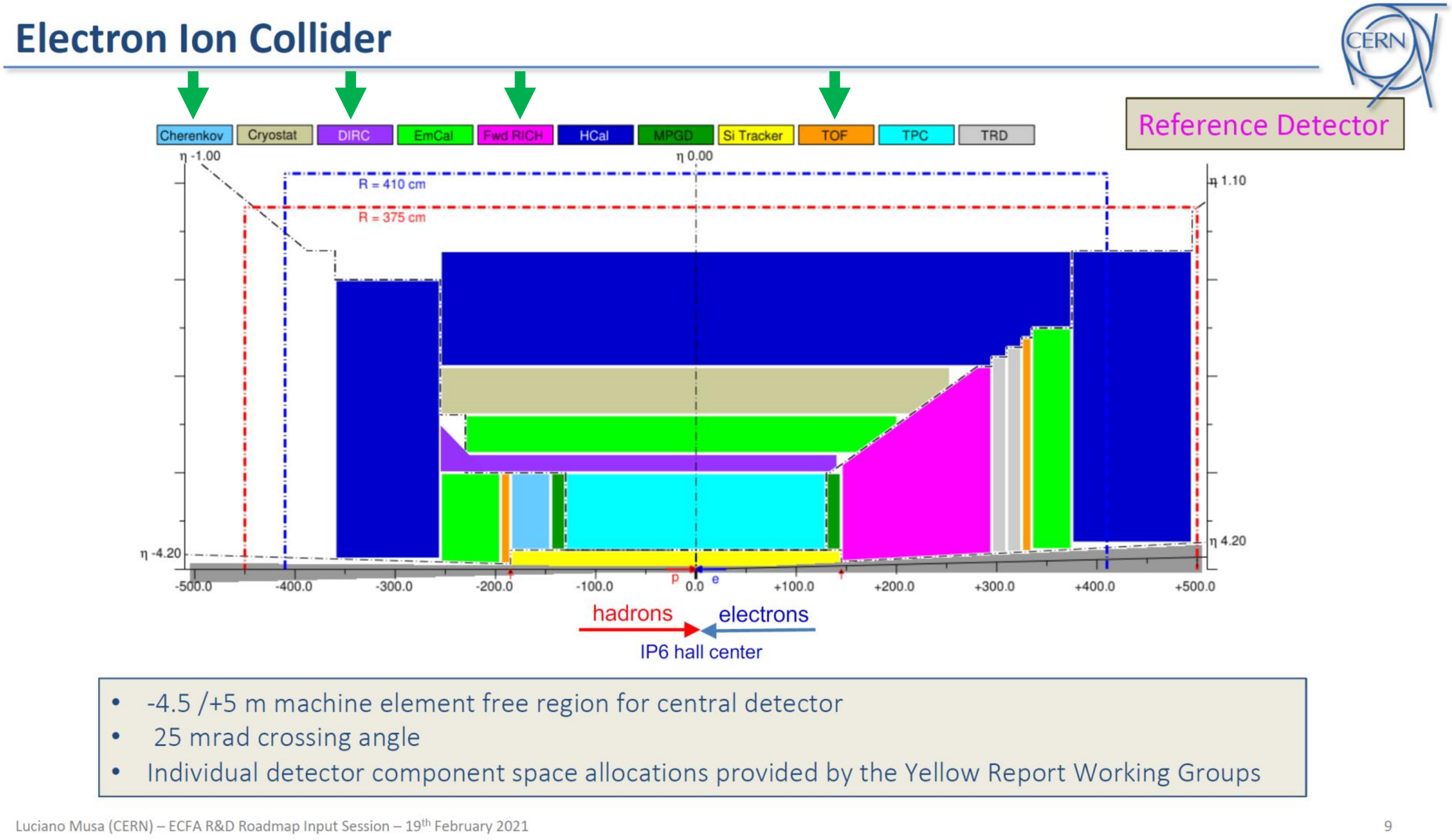
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

https://indico.cern.ch/event/994685/ Slides prepared by Francesco Forti (presented by Mogens Dam)

Electron Ion Collider



Electron Ion Collider

Reference Detector

- -4.5 /+5 m machine element free region for central detector
- 25 mrad crossing angle
- Individual detector component space allocations provided by the Yellow Report Working Groups

Luciano Musa (CERN) – ECFA R&D Roadmap Input Session – 19th February 2021

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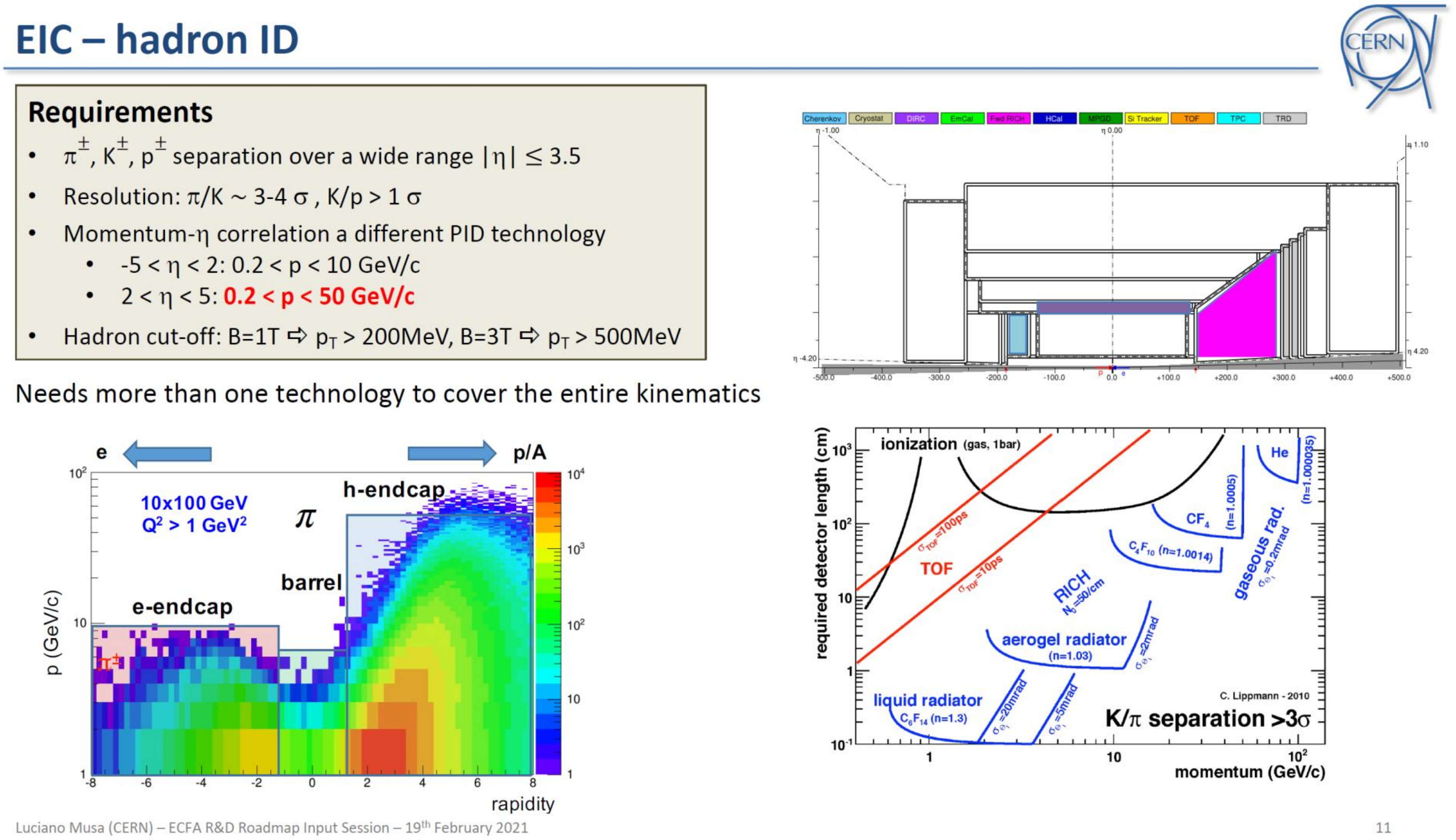
Electron Ion Collider



EIC – hadron ID

Requirements

- $\pi^\pm$, $K^\pm$, $p^\pm$ separation over a wide range $|\eta| \leq 3.5$
- Resolution: π/K ~ 3-4 σ , K/p > 1 σ
- Momentum-η correlation a different PID technology
  - $-5 < \eta < 2$: $0.2 < p < 10$ GeV/c
  - $2 < \eta < 5$: **$0.2 < p < 50$ GeV/c**
- Hadron cut-off: B=1T ⇨ $p_T > 200$MeV, B=3T ⇨ $p_T > 500$MeV

Needs more than one technology to cover the entire kinematics

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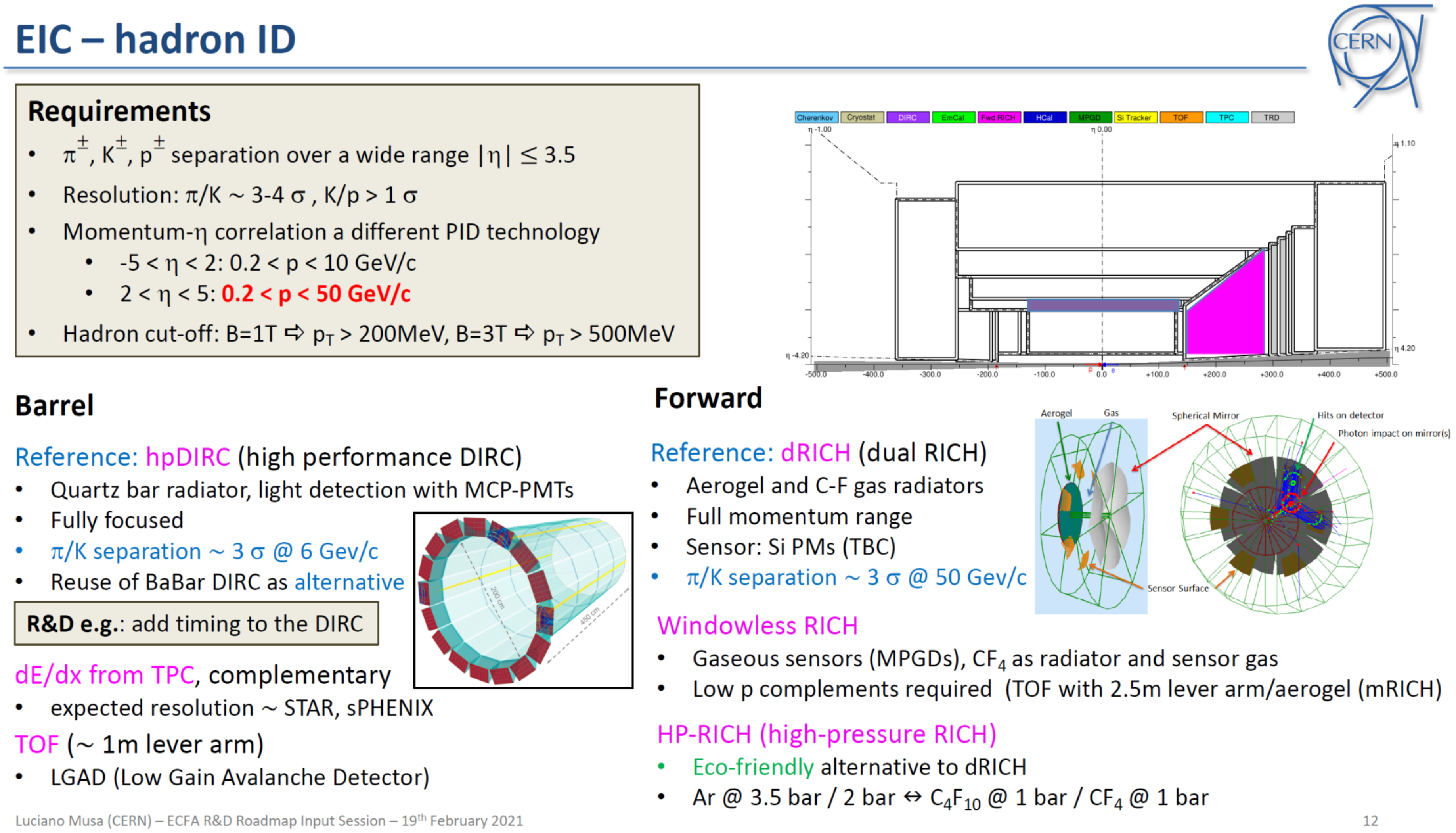
Electron Ion Collider



EIC – hadron ID

Requirements

- $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
- Resolution: $\pi/K \sim 3\text{-}4\ \sigma$, $K/p > 1\ \sigma$
- Momentum-η correlation a different PID technology
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- Hadron cut-off: B=1T ⇨ $p_T > 200$MeV, B=3T ⇨ $p_T > 500$MeV

Barrel

Reference: hpDIRC (high performance DIRC)

- Quartz bar radiator, light detection with MCP-PMTs
- Fully focused
- π/K separation ~ 3 σ @ 6 Gev/c
- Reuse of BaBar DIRC as alternative

R&D e.g.: add timing to the DIRC

dE/dx from TPC, complementary

- expected resolution ~ STAR, sPHENIX

TOF (~ 1m lever arm)

- LGAD (Low Gain Avalanche Detector)

Forward

Reference: dRICH (dual RICH)

- Aerogel and C-F gas radiators
- Full momentum range
- Sensor: Si PMs (TBC)
- π/K separation ~ 3 σ @ 50 Gev/c

Windowless RICH

- Gaseous sensors (MPGDs), CF_4 as radiator and sensor gas
- Low p complements required (TOF with 2.5m lever arm/aerogel (mRICH)

HP-RICH (high-pressure RICH)

- Eco-friendly alternative to dRICH
- Ar @ 3.5 bar / 2 bar ⇔ C_4F_{10} @ 1 bar / CF_4 @ 1 bar

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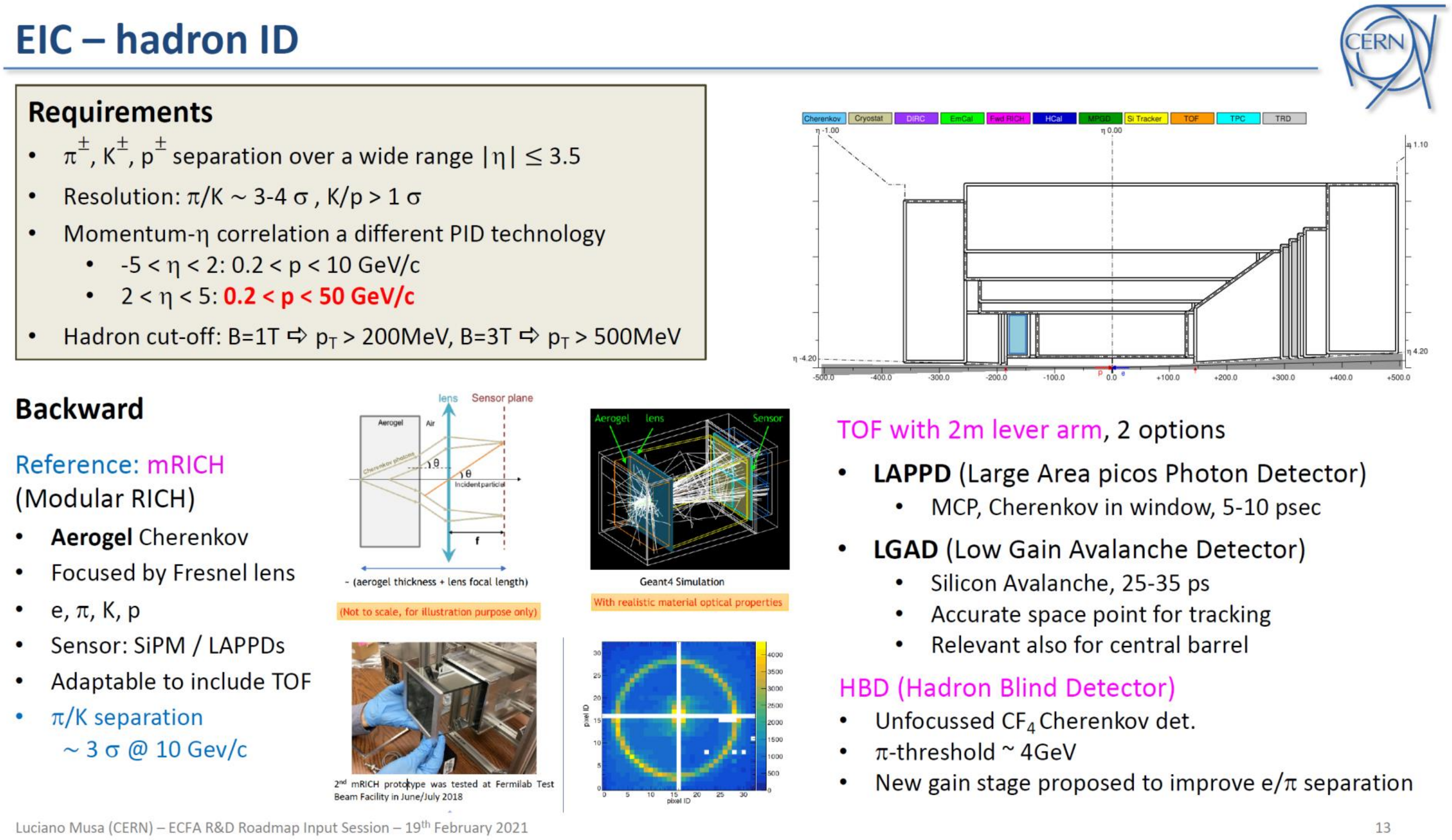
Electron Ion Collider



EIC – hadron ID

Requirements

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Backward

Reference: mRICH
(Modular RICH)

- **Aerogel** Cherenkov
- Focused by Fresnel lens
- e, π, K, p
- Sensor: SiPM / LAPPDs
- Adaptable to include TOF
- π/K separation
  ~ 3 σ @ 10 Gev/c

~ (aerogel thickness + lens focal length)

(Not to scale, for illustration purpose only)

Geant4 Simulation

With realistic material optical properties

2nd mRICH prototype was tested at Fermilab Test Beam Facility in June/July 2018

TOF with 2m lever arm, 2 options

- **LAPPD** (Large Area picos Photon Detector)
  - MCP, Cherenkov in window, 5-10 psec
- **LGAD** (Low Gain Avalanche Detector)
  - Silicon Avalanche, 25-35 ps
  - Accurate space point for tracking
  - Relevant also for central barrel

HBD (Hadron Blind Detector)

- Unfocussed CF_4 Cherenkov det.
- π-threshold ~ 4GeV
- New gain stage proposed to improve e/π separation

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CERN/Fixed Target

Contact: S. Levorato, INFN Trieste; J. Friedrich, TU München; V. Andrieux, U of Illinois; O. Denisov, INFN Torino

AMBER / CERN

Technologies candidates under investigation

The Intermediate momenta (3 to 20 GeV/c) range particle identification requires high quality new Aerogel Materials

The size issue

M.Tabata et al., The Journal of Supercritical Fluids, Vol.110, April 2016, Pages 183-192

The uniformity control

The transparency issue

Key issues

Tile size and uniformity
Duration of production

Technologies candidates under investigation

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon		
		Second assessment report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Perfluorinated compounds				
Sulfur hexafluoride	SF_6	23,900	22,800	23,500
Nitrogen trifluoride	NF_3		17,200	16,100
PFC-14	CF_4	6,500	7,390	6,630
PFC-116	C_2F_6	9,200	12,200	11,100
PFC-218	C_3F_8	7,000	8,830	8,900
PFC-318	$c\text{-}C_4F_8$	8,700	10,300	9,540
PFC-31-10	C_4F_{10}	7,000	8,860	9,200
PFC-41-12	C_5F_{12}	7,500	9,160	8,550
PFC-51-14	C_6F_{14}	7,400	9,300	7,910
PCF-91-18	$C_{10}F_{18}$		>7,500	7,190
Trifluoromethyl sulfur pentafluoride	SF_5CF_3		17,700	17,400
Perfluorocyclopropane	$c\text{-}C_3F_6$			9,200

~ 90 m^3 C4F10 gaseous radiator,
Gas recovery at the end of operation (once per year) in closed loop mode
Unavoidable losses (3%) determined by the achievable P (7 bar) and T (-32 C) of the liquefier system. Vapor pressure at -32 C is 0.2 bar

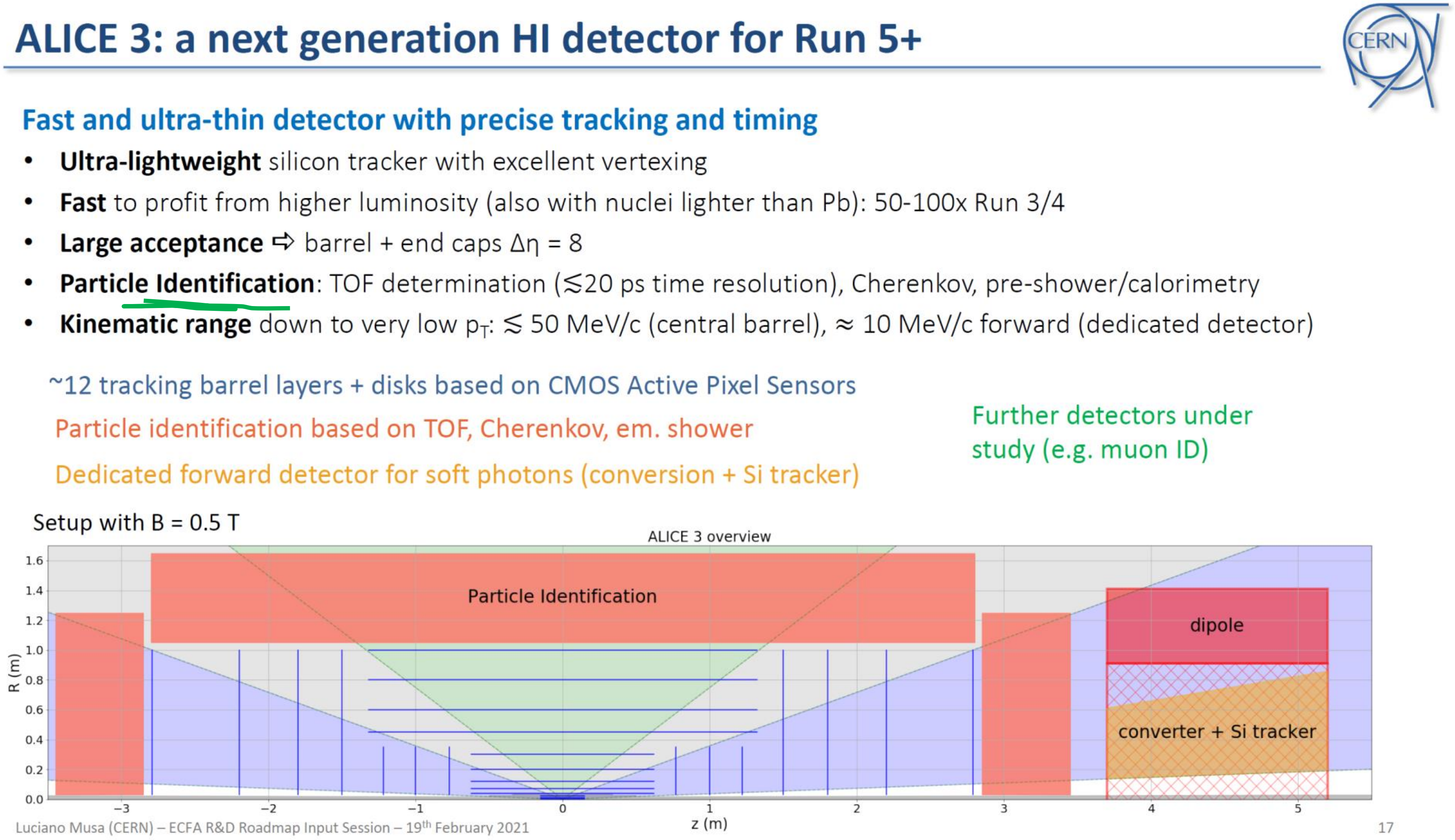
→ Improving the Gas recovery system efficiency or use new technology approach: molecular membranes
→ Search for Green gas alternatives

TF1, TF4, TF7

19.02.2021 R&D | Strong Interaction | Fixed Target | J. Bernhard 18

https://indico.cern.ch/event/994685/ , also presentation from Fulvio Tessarotto and others in this session

CERN/HL-LHC



ALICE 3: a next generation HI detector for Run 5+

Fast and ultra-thin detector with precise tracking and timing

- **Ultra-lightweight** silicon tracker with excellent vertexing
- **Fast** to profit from higher luminosity (also with nuclei lighter than Pb): 50-100x Run 3/4
- **Large acceptance** ⇨ barrel + end caps $\Delta\eta = 8$
- **Particle Identification**: TOF determination ($\lesssim$20 ps time resolution), Cherenkov, pre-shower/calorimetry
- **Kinematic range** down to very low p_T: $\lesssim$ 50 MeV/c (central barrel), $\approx$ 10 MeV/c forward (dedicated detector)

~12 tracking barrel layers + disks based on CMOS Active Pixel Sensors

Particle identification based on TOF, Cherenkov, em. shower

Dedicated forward detector for soft photons (conversion + Si tracker)

Further detectors under study (e.g. muon ID)

Setup with B = 0.5 T

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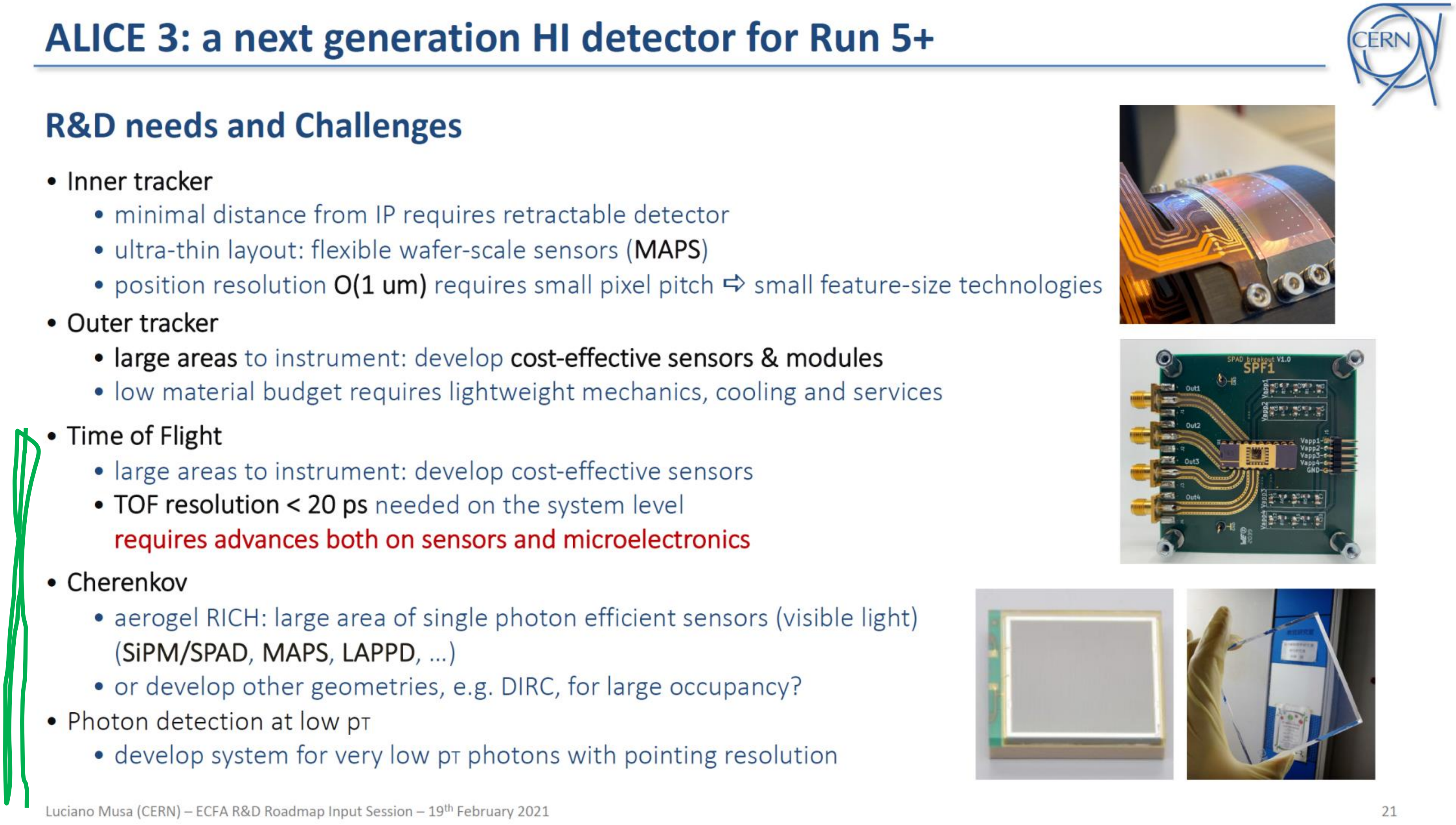
CERN/HL-LHC



ALICE 3: a next generation HI detector for Run 5+

R&D needs and Challenges

- Inner tracker
  - minimal distance from IP requires retractable detector
  - ultra-thin layout: flexible wafer-scale sensors (**MAPS**)
  - position resolution **O(1 um)** requires small pixel pitch ⇨ small feature-size technologies
- Outer tracker
  - **large areas** to instrument: develop **cost-effective sensors & modules**
  - low material budget requires lightweight mechanics, cooling and services
- Time of Flight
  - large areas to instrument: develop cost-effective sensors
  - **TOF resolution < 20 ps** needed on the system level
    requires advances both on sensors and microelectronics
- Cherenkov
  - aerogel RICH: large area of single photon efficient sensors (visible light) (**SiPM/SPAD, MAPS, LAPPD, …**)
  - or develop other geometries, e.g. DIRC, for large occupancy?
- Photon detection at low p_T
  - develop system for very low p_T photons with pointing resolution

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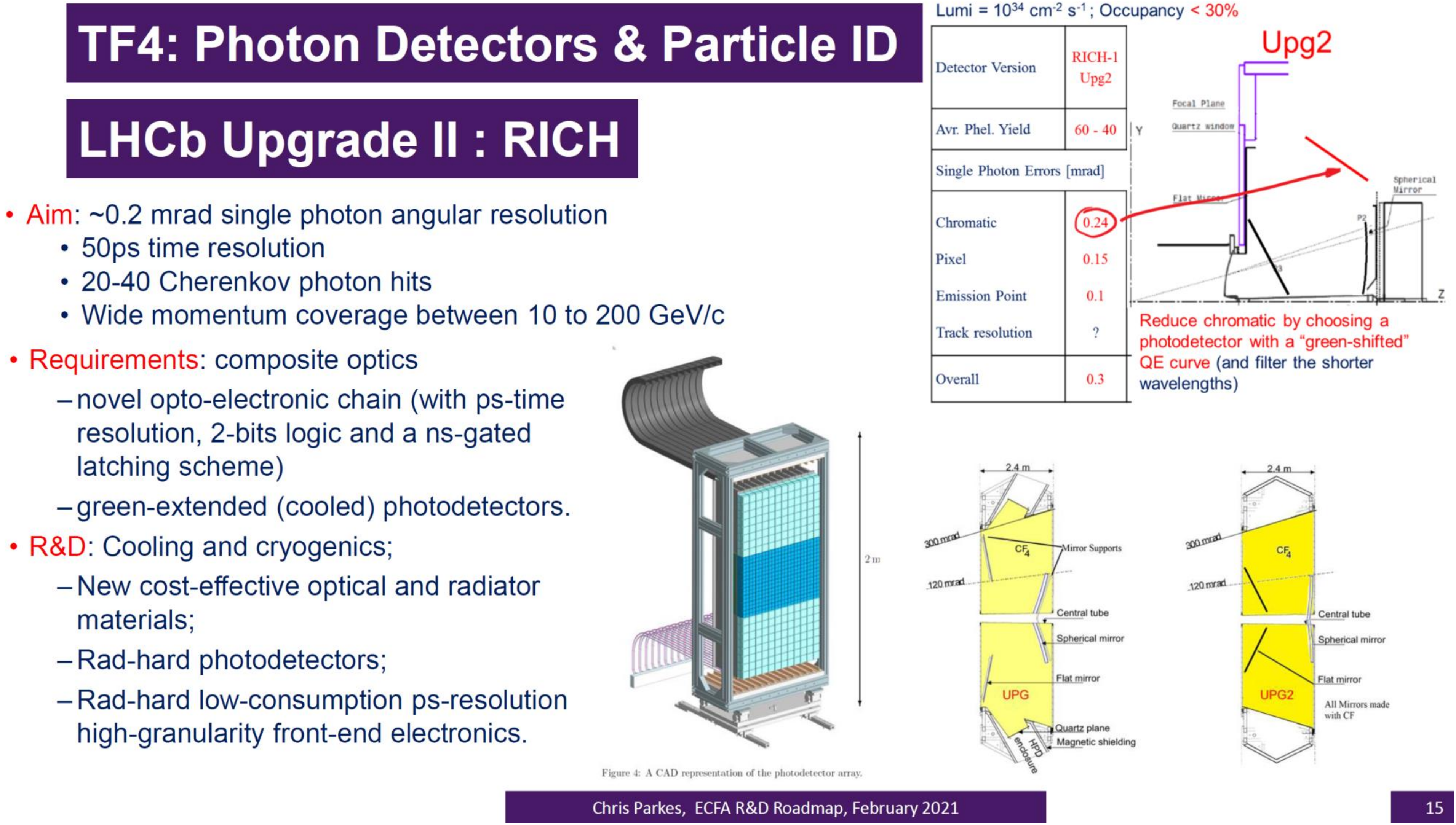
CERN/HL-LHC



TF4: Photon Detectors & Particle ID

LHCb Upgrade II : RICH

- Aim: ~0.2 mrad single photon angular resolution
  - 50ps time resolution
  - 20-40 Cherenkov photon hits
  - Wide momentum coverage between 10 to 200 GeV/c
- Requirements: composite optics
  - novel opto-electronic chain (with ps-time resolution, 2-bits logic and a ns-gated latching scheme)
  - green-extended (cooled) photodetectors.
- R&D: Cooling and cryogenics;
  - New cost-effective optical and radiator materials;
  - Rad-hard photodetectors;
  - Rad-hard low-consumption ps-resolution high-granularity front-end electronics.

Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	60 - 40
Single Photon Errors [mrad]	
Chromatic	0.24
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.3

Reduce chromatic by choosing a photodetector with a "green-shifted" QE curve (and filter the shorter wavelengths)

Figure 4: A CAD representation of the photodetector array.

Chris Parkes, ECFA R&D Roadmap, February 2021

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Performance

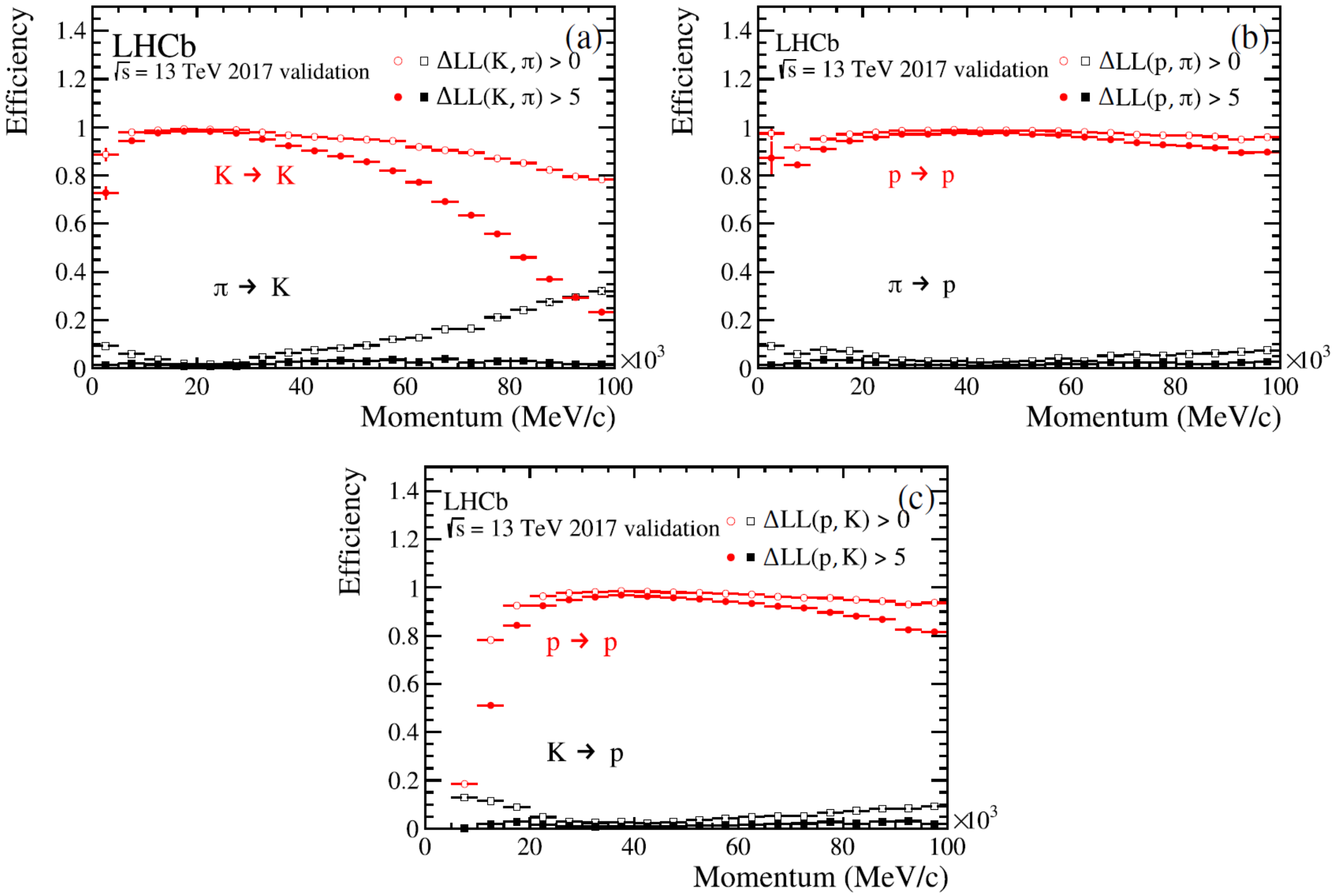


Figure 20. The efficiency of selecting kaons (a), protons (b and c), with the associate leakage from misidentifying pions (a and b) and kaons (c) as a function of momentum. Two selections are made, a loose section (hollow circles) and a tight selection (solid circles).

Figure of merit

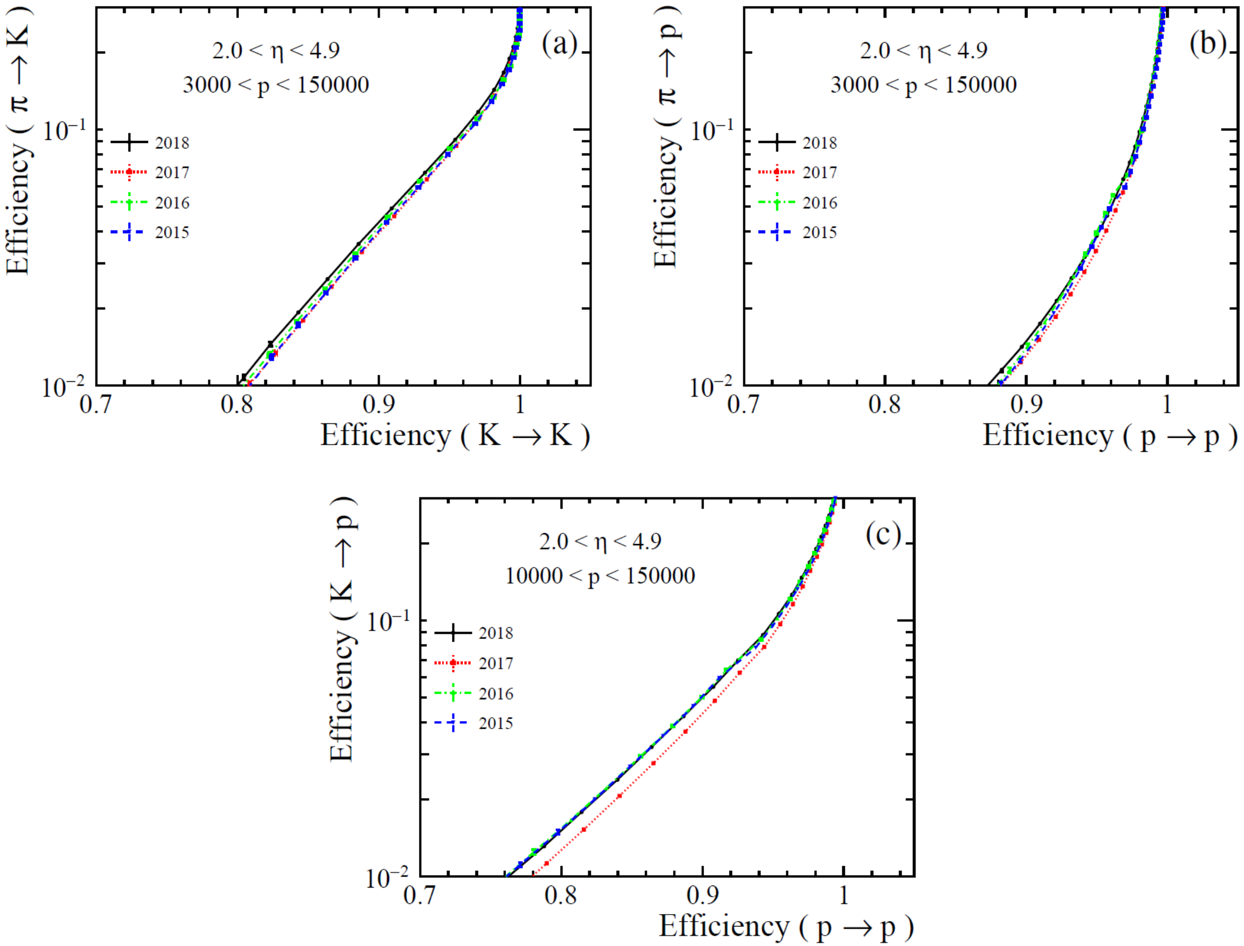
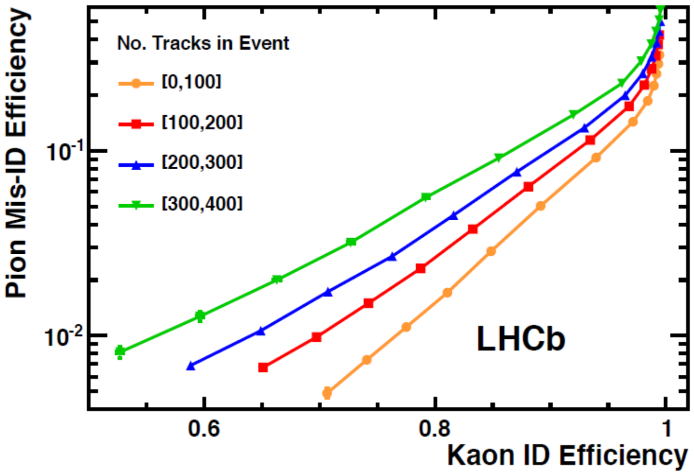
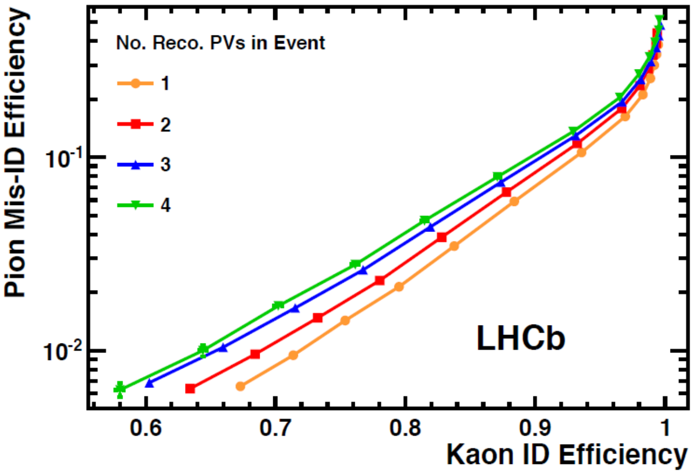


Figure 19. The efficiency of selecting kaons (a), protons (b and c), with the associate leakage from misidentifying pions (a and b) and kaons (c). The efficiency curves are shown for 2015 (blue, dashed), 2016 (green, dash-dotted), 2017 (red, dotted), 2018 (black solid). Uncertainties are statistical only, and are highly correlated between points on the same curve.

Performance depends on event multiplicities

Degradation of performance at higher occupancy (tracks/PVs)





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Main quantities affecting system performance

- Number of detected photons
- Occupancy
- Pattern Recognition strategy
- Uncertainties on the Cherenkov angle measurement $\sigma_{space}/\sqrt{N}$:
  - Chromatic;
  - Emission;
  - Pixel;
  - Trackers;
- Uncertainties on the photon time measurement (new) σ_{time} :
  - Sensor + electronics time resolution;
- Uncertainties on the “ring/track” time measurement (new) $\sigma_{time}/\sqrt{N}$:
  - Chromatic;
  - t_0.

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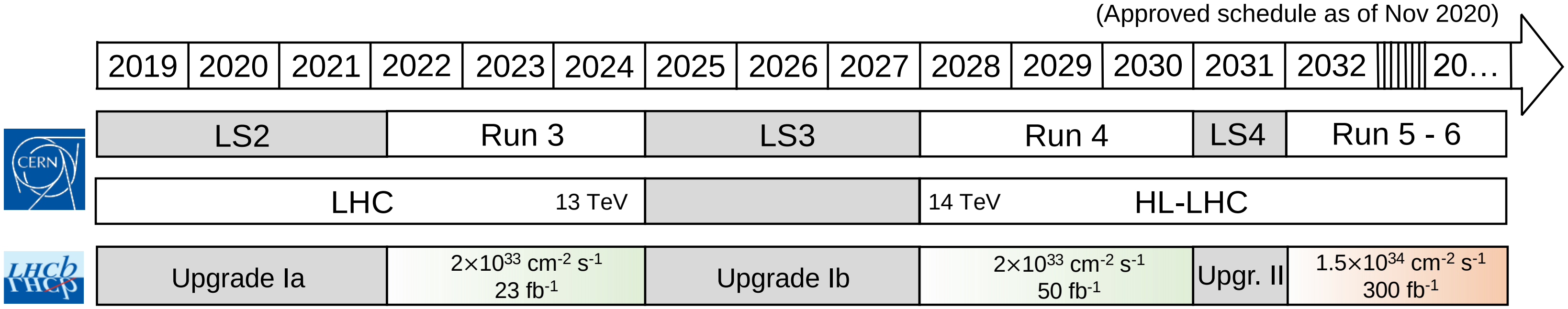
Evolution of the LHCb RICH System



(Approved schedule as of Nov 2020)

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 20…

LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 - 6

LHC 13 TeV | 14 TeV HL-LHC

Upgrade Ia | 2×10^{33} cm^{-2} s^{-1} 23 fb^{-1} | Upgrade Ib | 2×10^{33} cm^{-2} s^{-1} 50 fb^{-1} | Upgr. II | 1.5×10^{34} cm^{-2} s^{-1} 300 fb^{-1}

The LHCb roadmap … :

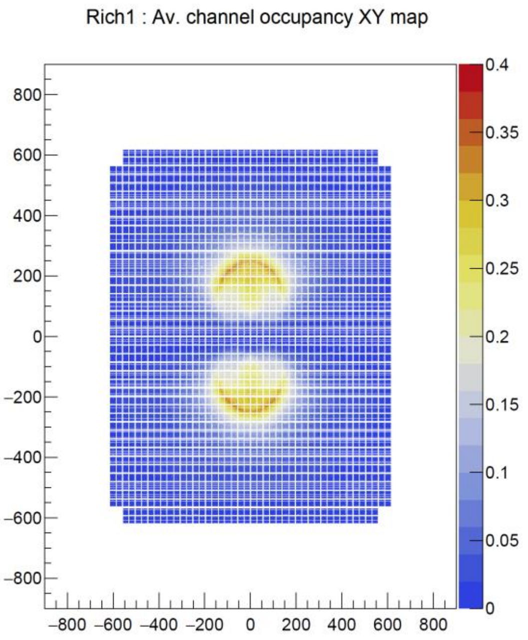
Original	in 2008 LHCb is born (x2 10^{32} Lumi, Run 1 and 2);
Upg Ia	2022, the first upgrade (x20 10^{32} Lumi);
Upg Ib	(LS3, between 2025 – 2027* included) 2028, possibly a limited upgrade for the RICHes;
Upg II	(LS4, 2031) 2032, a major foreseen upgrade (HL-LHC, x150 10^{32} Lumi).

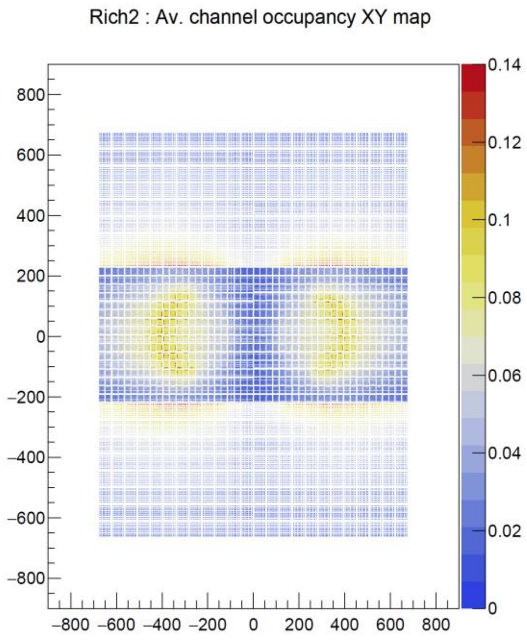
Keep same performance as in Run 2 for future systems

* This corresponds in time to ATLAS and CMS Phase II upgrade

Strategy I

- Keep peak Occupancies (time and space) < 30%
- Improve Single Photon Cherenkov Angle precision to < 0.5 mrad





Radiator	C_4F_{10}	
Detector Version	RICH-1 Old (HPD)	RICH-1 Upg2
Avr. Ph.Electron Yield	25 (30)*	40 - 30
Single Photon Uncertainties [mrad]		
Chromatic	0.84	0.24 – 0.18
Pixel	0.9	0.15
Emission Point	0.8	0.1
Track resolution	0.4	?0.4?
Overall	1.52	0.5 (0.3 – 0.2)

How is this achieved?*

- New optical system sitting in the detector acceptance to reduce aberrations;
- Higher granularities (achievable with a longer focal mirror or/and a smaller sensor pixel size);
- New photodetectors with green-enhanced high QE.

* See also spare slides

Optical system challenge

In order to improve photon emission uncertainties in space and time (ex.: a flat focal surface),

optics will have to be placed in the experimental acceptance, which implies:

Low fraction of material budget, $\lesssim 1\%\ X_0$, $\lesssim 1\%\cdot\lambda_I$, $\lesssim 5\ \mathrm{Kg/m^2}$;

Very high radiation resistance;

Long life, stability;

Excellent optical quality;

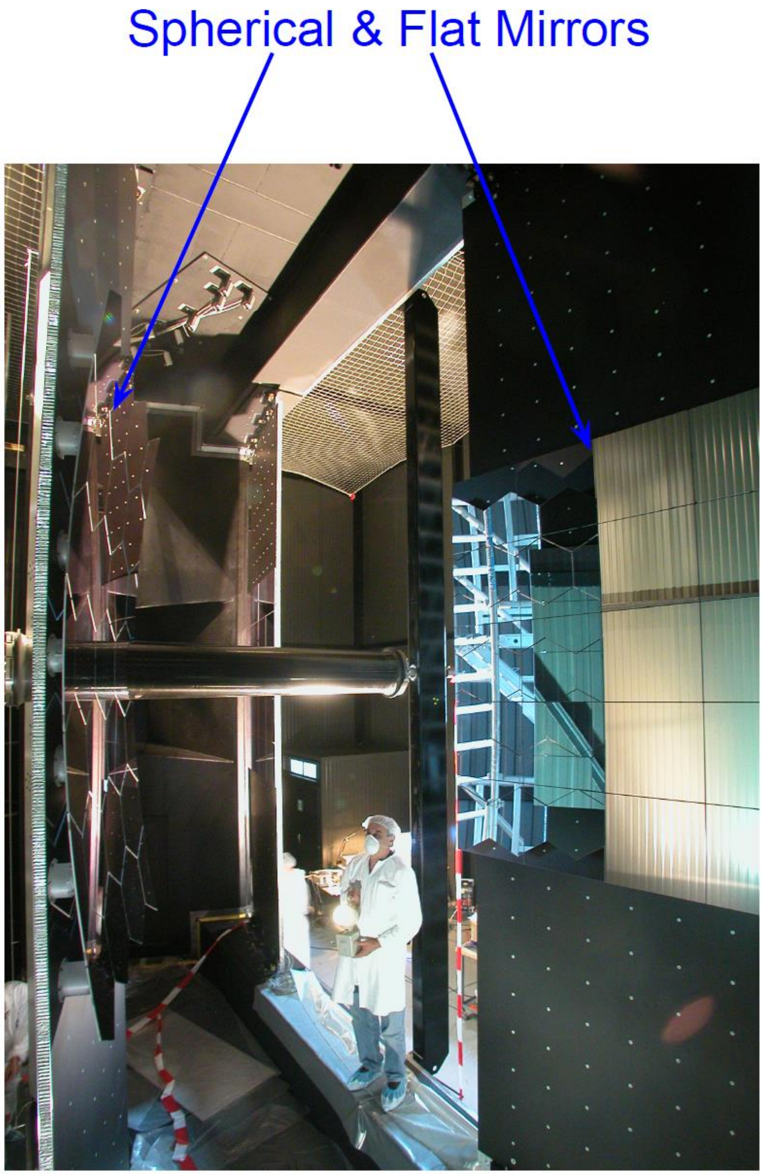
Supports placed in out-of-acceptance regions;

Reflective coatings tuned to the specific application.

Today, all (or most of) these qualities are present in light-weight composite mirrors.

New optical designs, which address the Occupancy dis-uniformity and try to compensate it.

Composite/glass mirrors for RICH1 and 6 mm thin glass mirrors for RICH2


Spherical & Flat Mirrors

Light-weight composite mirrors and supports

In RICH1 we already have Carbon Fibre-based Spherical Mirrors and support structure developed and produced by CMA (AZ, USA).

However, R&D is still needed:

- To develop flat mirrors;
- Further improve quality;
- Further reduce the %Xo;
- Reduce price.

New development:

Si-Carbide mirrors

(up to 1.5 m and ~5 Kg/m^2)

Light-weight composite mirrors and supports :

CF spherical mirrors and supports already in the old RICH1 (~1.3% X_0, produced by CMA, USA);
First CF flat mirror prototype for RICH1 produced;

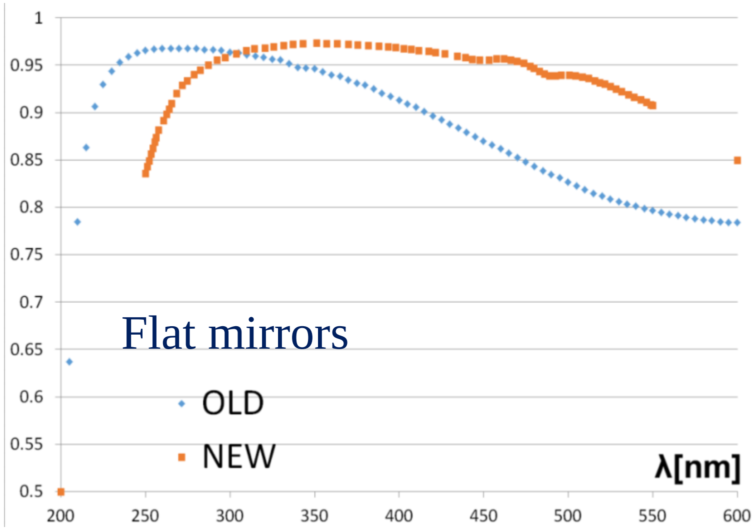
The present RICH1 spherical mirrors have an improved backside to reach ~1% X_0 and the same precision.

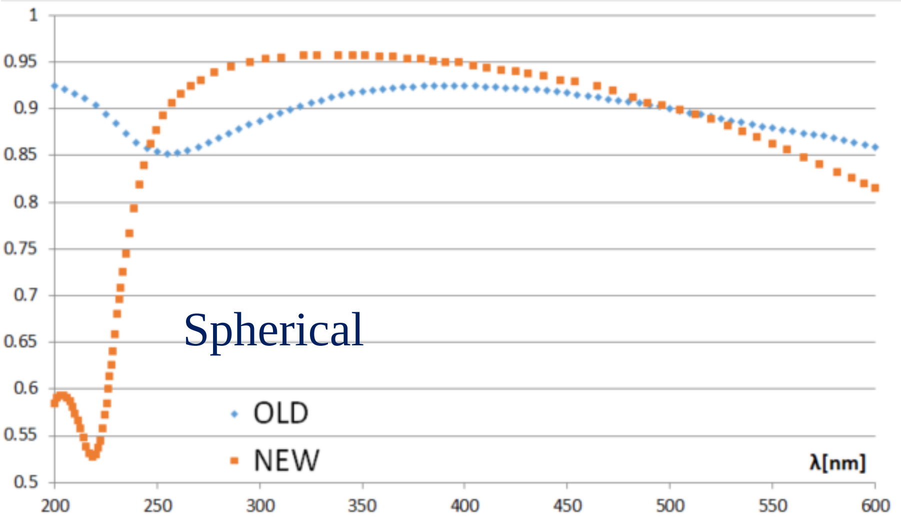
Very light structures, placed outside the exp. acceptance, must be used to support them (see previous slide photograph).

Cost is an issue!

All marked in red needs R&D!

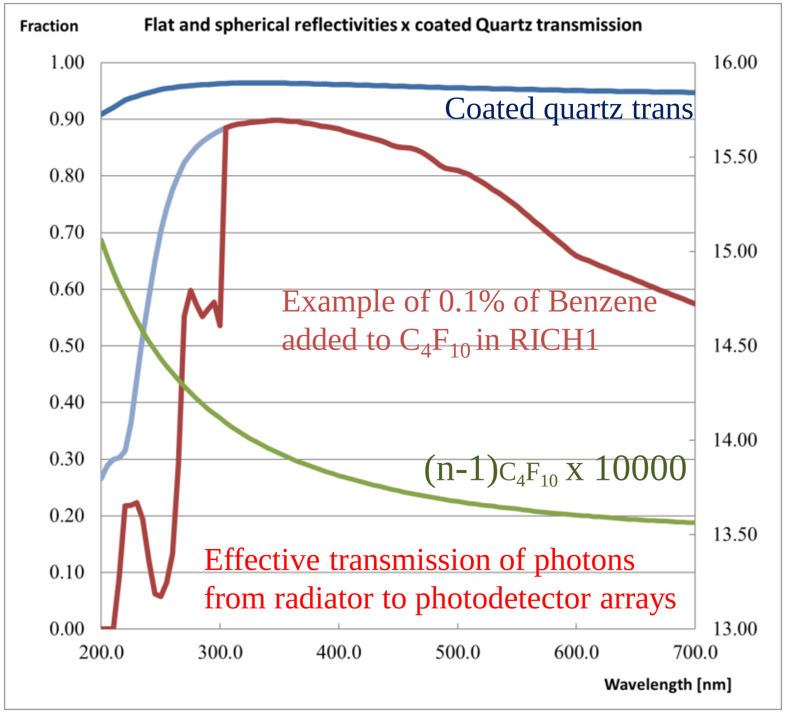
Reflective coatings tuned to the specific application





Reflectivities for the old and the new RICH1 optical system: coatings (Cr, Al, MgF_2, SiO_2+HfO_2)* are tuned to match their photodetector arrays properties and eventually suppress unwanted photons in the UV.

Flat and spherical reflectivities x coated Quartz transmission



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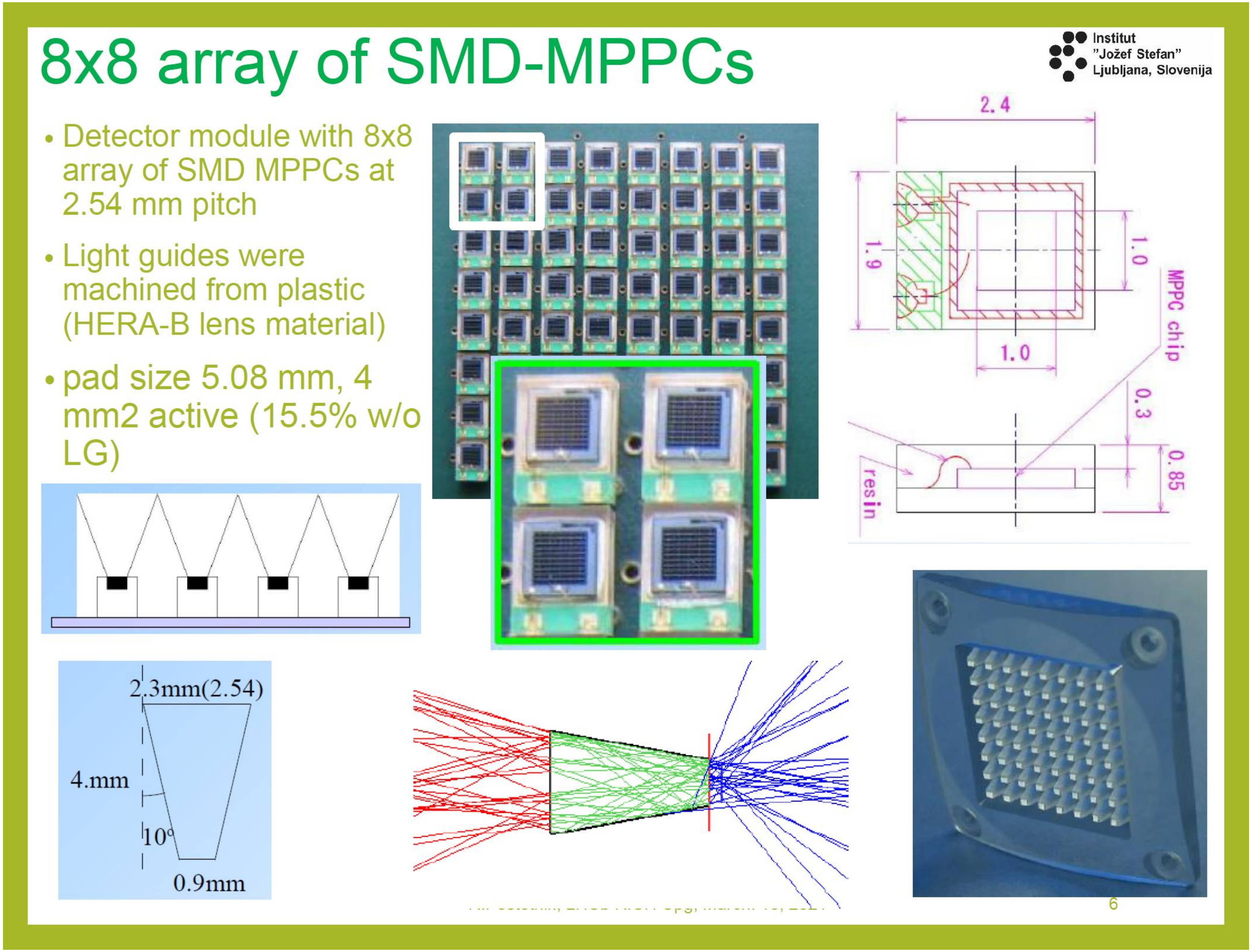
*CERN/EP-DT Coating Lab

Lenses: arrays of light guides



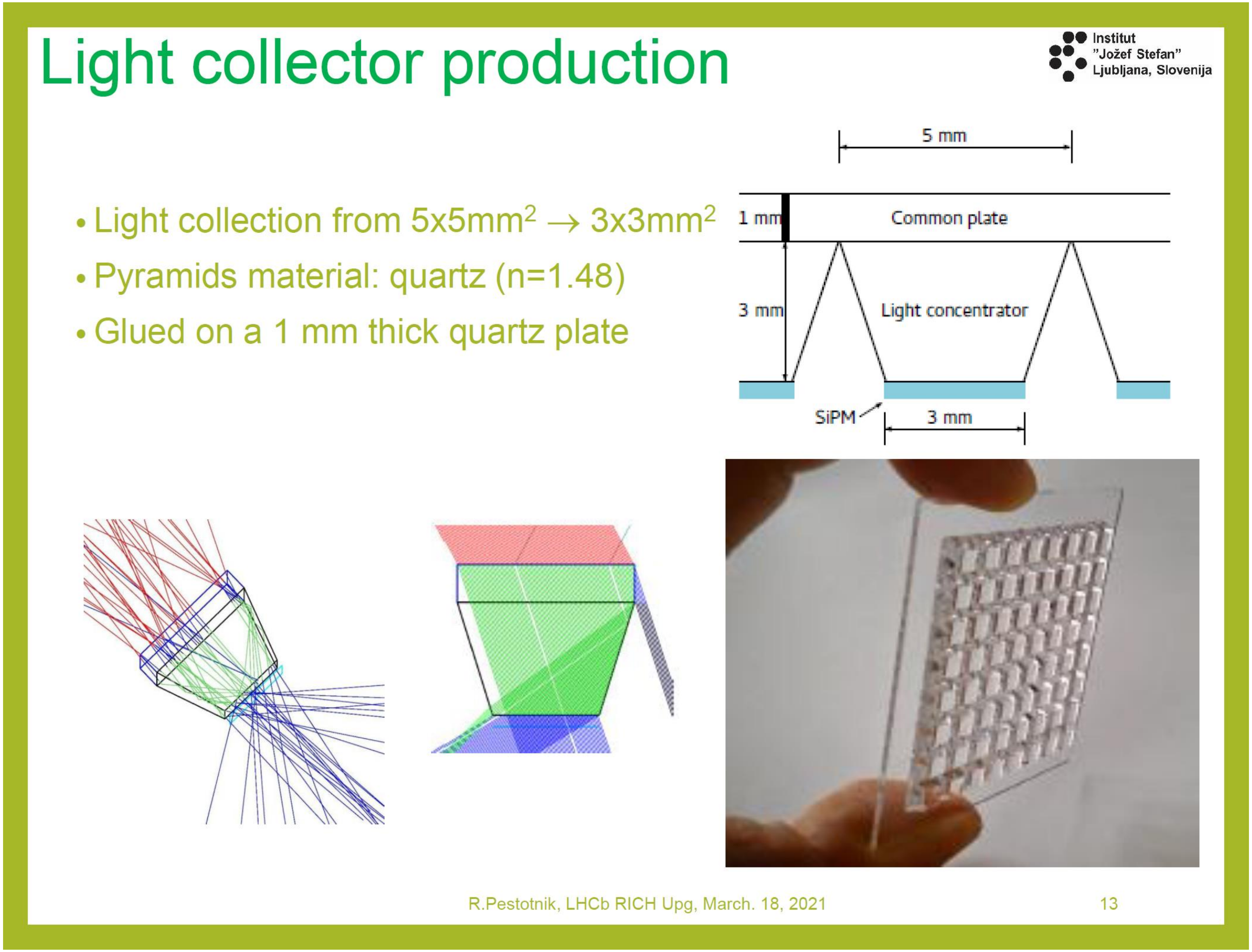
8x8 array of SMD-MPPCs

Institut
"Jožef Stefan"
Ljubljana, Slovenija

- Detector module with 8x8 array of SMD MPPCs at 2.54 mm pitch
- Light guides were machined from plastic (HERA-B lens material)
- pad size 5.08 mm, 4 mm2 active (15.5% w/o LG)

6

Lenses: arrays of light guides



Light collector production

Institut
"Jožef Stefan"
Ljubljana, Slovenija

- Light collection from 5x5mm^2 → 3x3mm^2
- Pyramids material: quartz ($n=1.48$)
- Glued on a 1 mm thick quartz plate

R.Pestotnik, LHCb RICH Upg, March. 18, 2021

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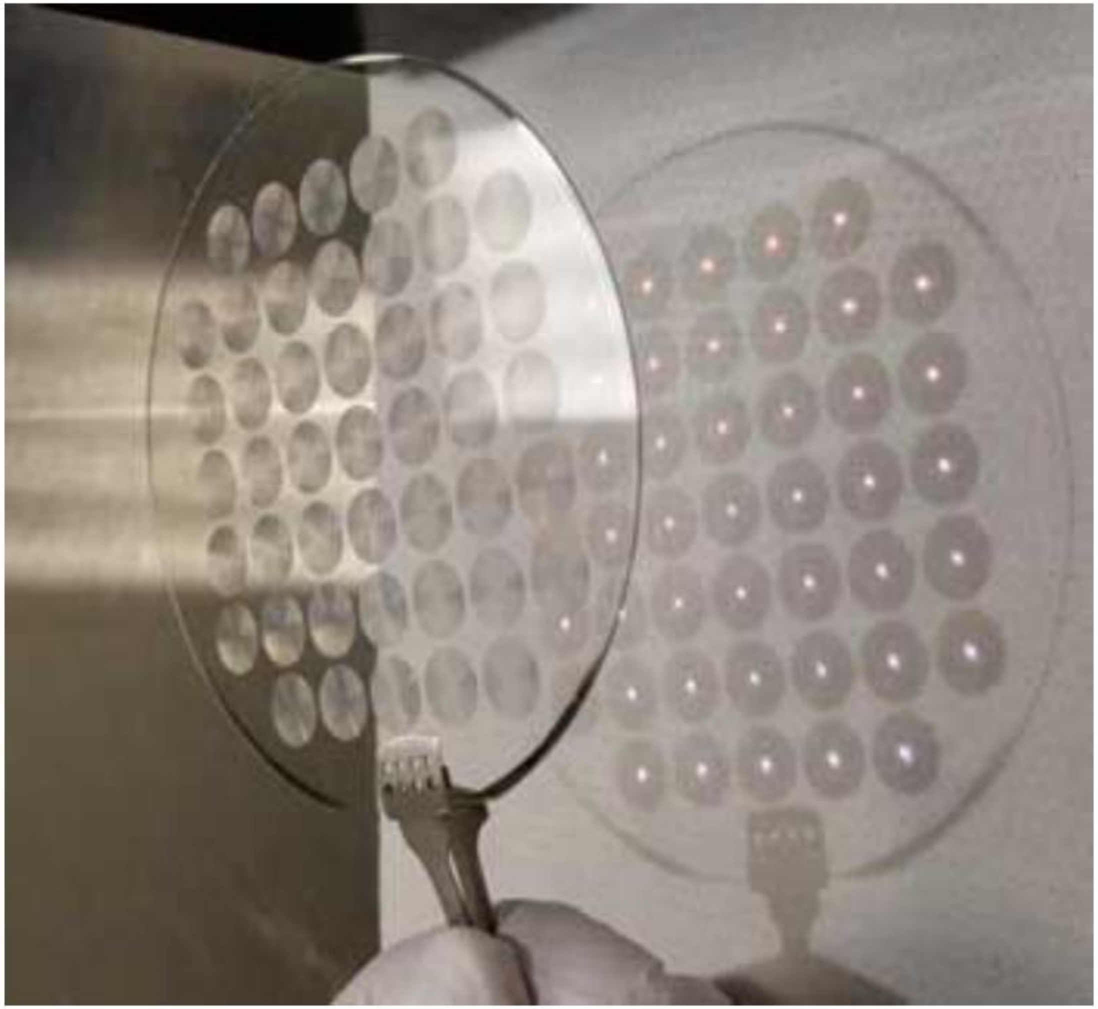
Lenses: meta-lenses and lenslet arrays



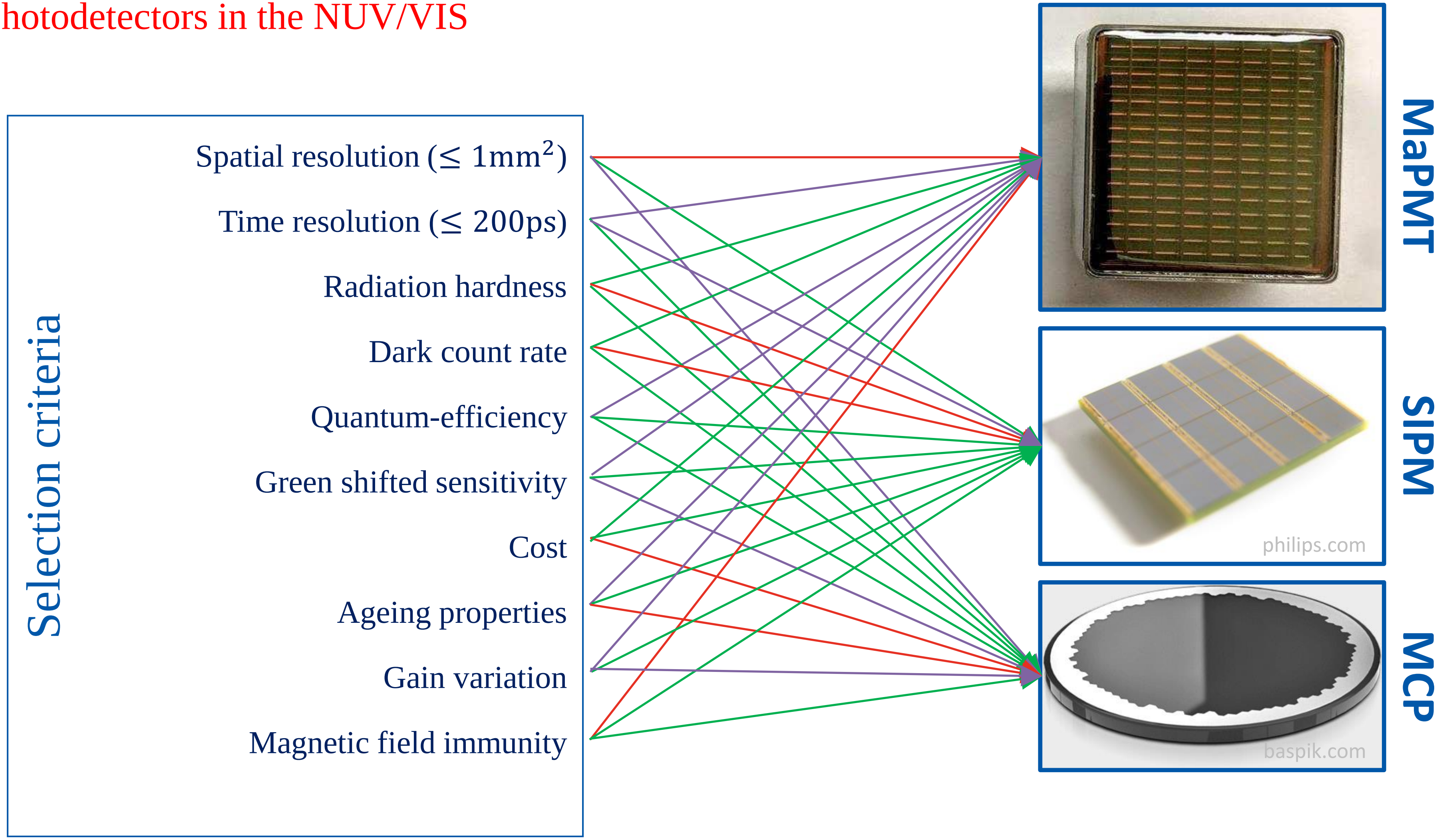
Capasso Group, Harvard University

Transmission
Time resolution
Focal distance
Cost
etc

Chris Stanford
Harvard University
Guenette Group

CPAD – 3/18/2021

Photodetectors in the NUV/VIS



Selection criteria

- Spatial resolution ($\leq 1\text{mm}^2$)
- Time resolution ($\leq$ 200ps)
- Radiation hardness
- Dark count rate
- Quantum-efficiency
- Green shifted sensitivity
- Cost
- Ageing properties
- Gain variation
- Magnetic field immunity

R&D is very strong in this field, with a lot of variants, based on these concepts: HPDs, LAAPDs, Silicon Hybrids, etc. (see next contributions).

However, at present none of these satisfies yet the harsh requirements of a high-precision RICH system (in LHCb or in future collider experiments). Go cryogenic with SiPMs!

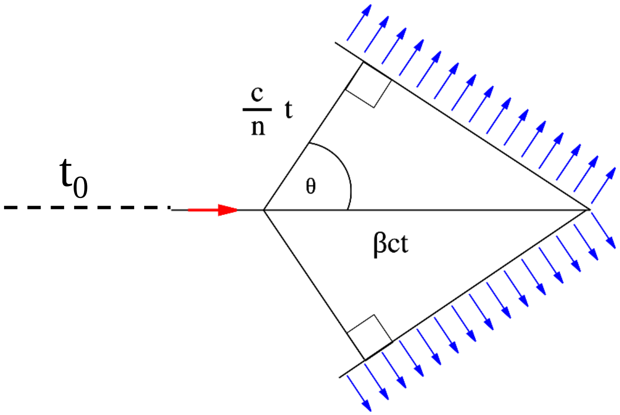
Strategy II

- Profit as much as possible from the unique property of a RICH detector, that is, the common arrival time of photons
- Provide the system with timing capabilities (event gating and photon ToD*)
- Possibly provide the frontend electronics with a 2-bits-like logic

*ToD = Time of Detection

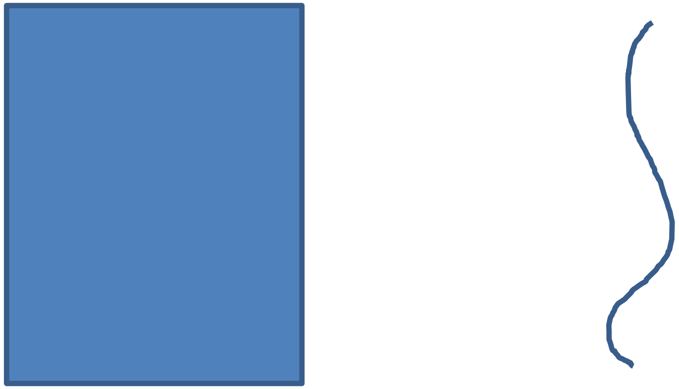
Time in a gaseous RICH Detector

By definition all the point on the wavefront have the same $\Delta t = t - t_0$



https://commons.wikimedia.org/w/index.php?curid=637092

Whatever the black box and the resulting wavefront, the previous is obviously still true



This means, the variation of Δt is minimal (for a given WL, zero) anywhere over the focal surface

By reducing:

optical aberrations (resulting in an exploitable focal surface)

and chromatic dispersion (same condition true for the full range of detected wavelengths).

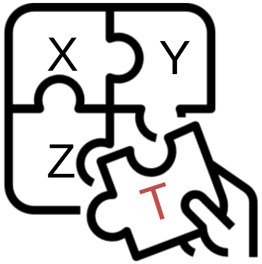
It follows that:

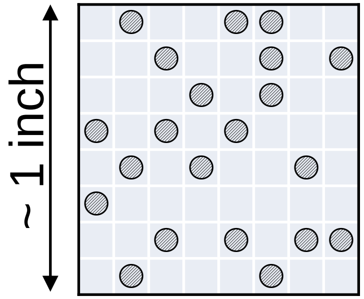
all the Cherenkov photons produced along a particle track are detected at the same time

Addition of time: n-bits ‘colour’ picture

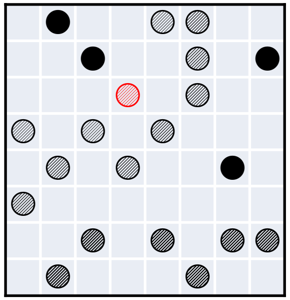
Visualisation of RICH hit maps

(not representing actual patterns)

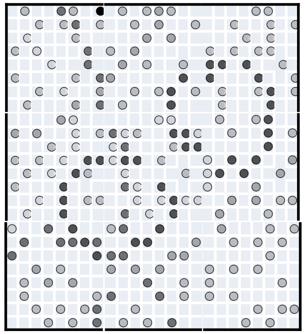




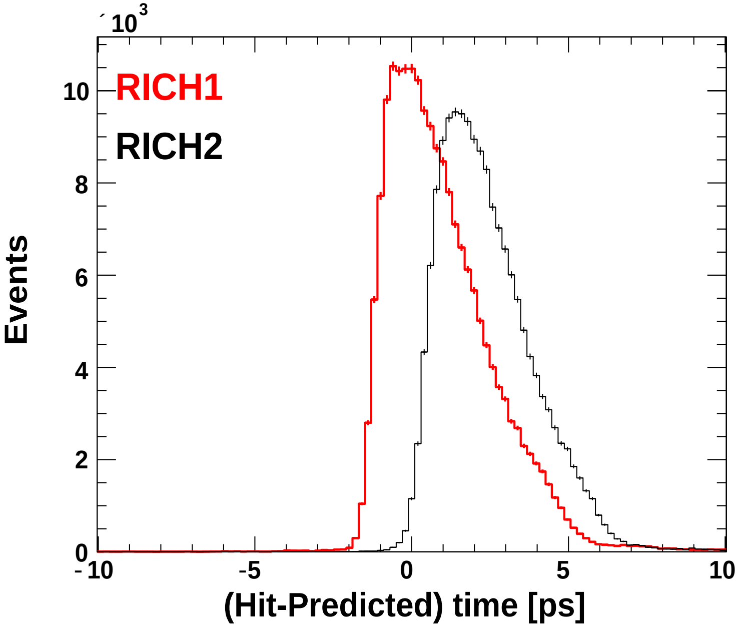
Run 3:
MAPMTs ($\sigma \sim$150 ps)
and 3.125 ns readout bin.



Run 4:
MAPMTs ($\sigma \sim$150 ps)
and $\lesssim$ 100 ps readout bin.



Run 5:
SiPM ($\sigma \lesssim$ 100 ps possible)
and $\lesssim$ 100 ps readout bin.



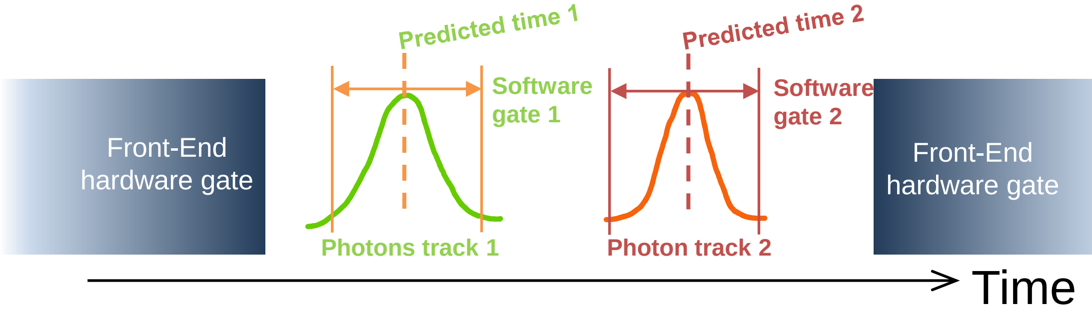
Taking all contributions into account, obtain a prediction of better than 10 ps.

- Faster detectors are better, as in practice the photodetector resolution will dominate the width of the time gate.
- Negligible tail from photon dispersion, which would become smaller with green-shifted QE.

(software) gate around predicted time reduces combinatorics

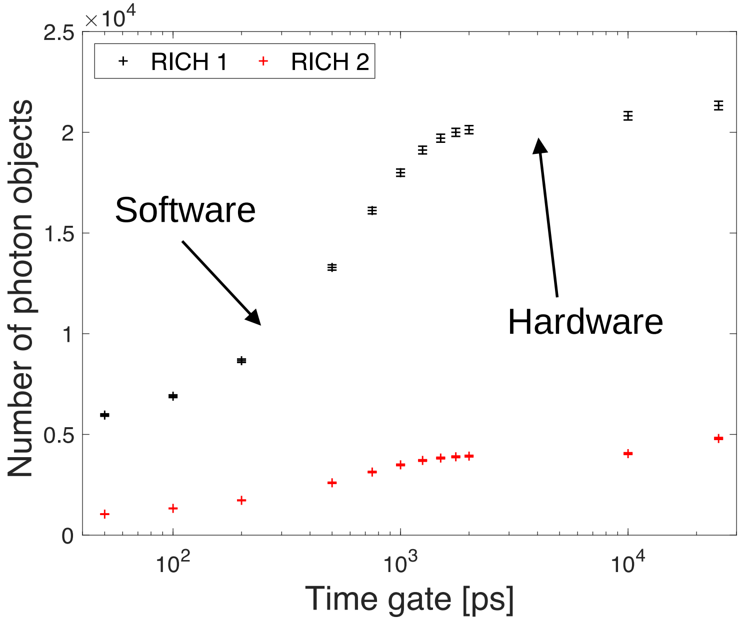
The high potential of RICH timing is gradually ‘unlocked’ as more information about the event becomes available from the front-end to High-Level Trigger.

- **Nanosecond** scale at the front-end readout (hardware gate).
- **Picosecond** scale at the event reconstruction algorithms.



Application of a **sub-ns software time gate around the predicted hit time** reduces combinatorial background.

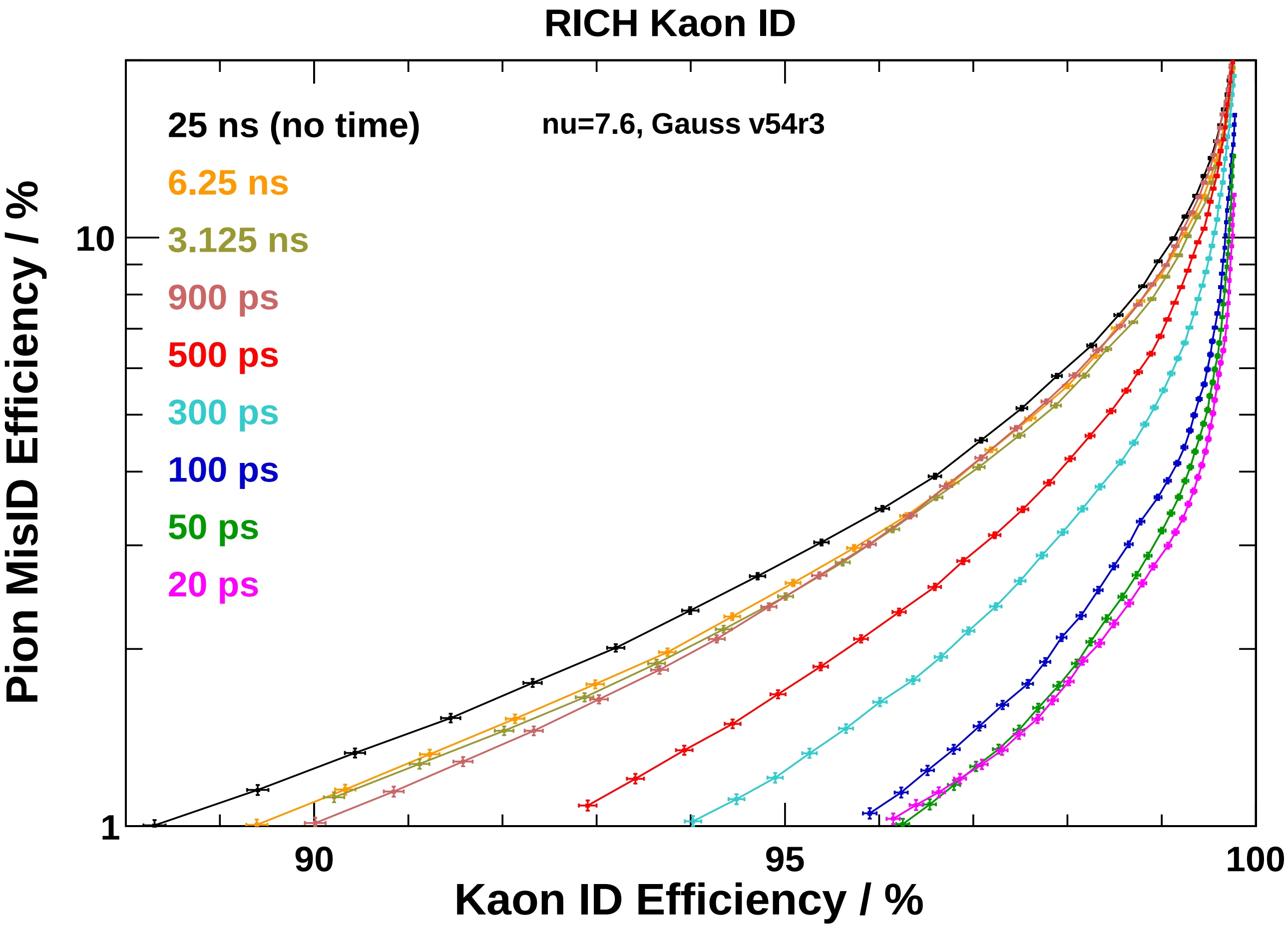
- Improves PID performance.
- Reduces CPU resources in reconstruction.



Do we gain in Performance?

Curves show clear trend: smaller time gates improve PID by reducing combinatorics.

- Sensor jitter and primary vertex timestamp resolution are not included, in order to show the high potential of faster photon sensors and electronics.
- Full LHCb simulation.



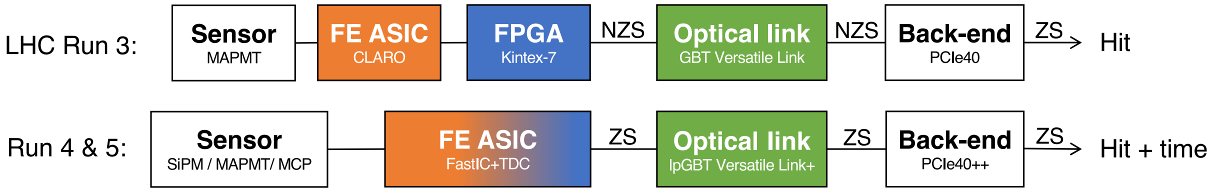
Front-end electronics for timing

A front-end ASIC followed by time-digital conversion (TDC) is a classic scheme, which should work well, provided it is well matched to the photosensor.

Quite known (by me) are the NINO + HRTDC (used in the TOF of ALICE) and more recently the FASTIC and Pico-TDC (one in its prototype and the other quite established versions) and finally the FASTIC+TDC (single ASIC, being designed). Several ASICs are being produced by our HEP community for the LHC Exp.

There are also tests with "soft-TDC" (TDC programmed FPGA) and a new scheme recently proposed of a "sampling" ASIC, based on a high frequency clock, which following the analog front-end could sample the 25ns (LHC clock) in multiples of 40 MHz (for example 2.56 GHz internal clock would result in 64 sampling slots per clock cycle).

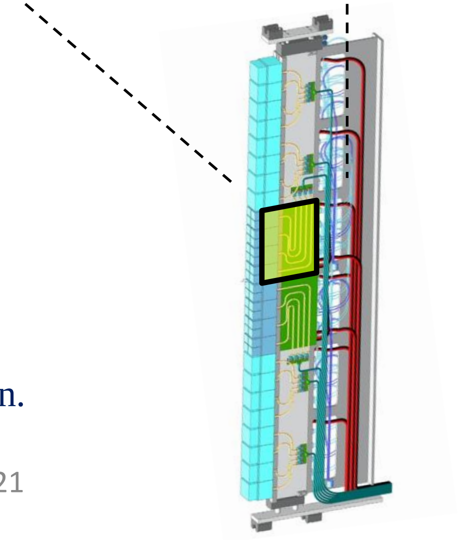
A Constant Fraction Discriminator seem to be a desirable inclusion in the front-end ASIC, especially to limit the number of bits to be moved by the DAQ. Compactness of full chain critical for future applications.



LHC Run 3: **Sensor** MAPMT — **FE ASIC** CLARO — **FPGA** Kintex-7 — NZS — **Optical link** GBT Versatile Link — NZS — **Back-end** PCIe40 — ZS → Hit

Run 4 & 5: **Sensor** SiPM / MAPMT/ MCP — **FE ASIC** FastIC+TDC — ZS — **Optical link** lpGBT Versatile Link+ — ZS — **Back-end** PCIe40++ — ZS → Hit + time

Run 3 readout electronics



LHCb RICH Upgrade II

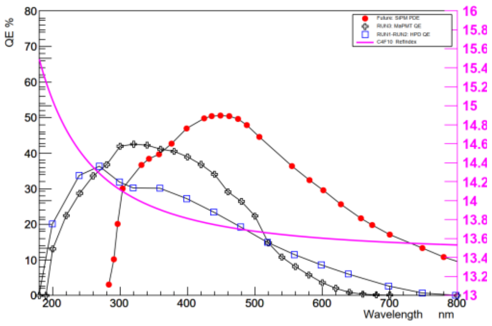
- Novel opto-electronic chain with SiPM as baseline sensor.
- FastIC+TDC readout in packaged or pixel format.
- Smaller pixels require compact electronics with high density / low power consumption.
- Luminosity factor 7.5 requires significant improvement in bandwidth capabilities.

Strategy III

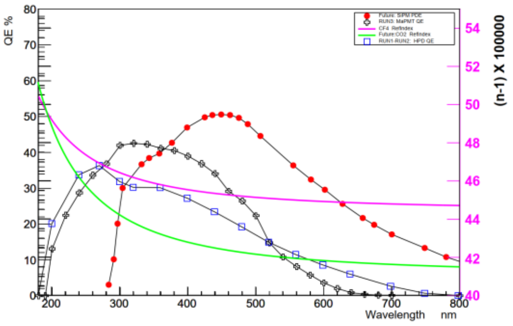
- Provide RICH1 and RICH2 with green gases (whenever possible) or with a leak-less system. This is becoming an extremely important issue. Fluoro-carbon gases have been and still are the basis of low chromaticity machines. However, new options open up when the wavelength range of operation is shifted towards the green spectrum.

Gas systems

RICH1



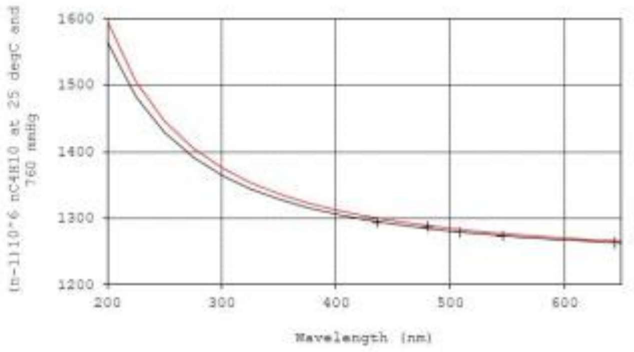
RICH2



RICH2: Preliminary

Resolution (in mrad)	MaPMT : CF_4	MaPMT: CO_2
Chromatic	0.34	0.53
Overall	0.50	0.66
Yield	34	33

C_4F_{10} vs C_4H_{10} : RICH1



Gas	GWP (20 year)
C_4F_{10}	6870
C_4H_{10}	3.3
CF_4	4880
CO_2	1.0

Investigating the use of alternative gases which have similar ref. index, but lower global warming potential (GWP).

C_4H_{10}

(isobutane)

!!! ☹

Critical is further improving gas tightness, and build a “leakless vessel”.

Do RICH Detectors have a bleak future in front of them?

- RICH detectors have to evolve with time, as the whole experiments do.
- Environments ahead are given by high luminosities and radiation levels, high event rates, by wide momenta and acceptance coverages, by compact central and high rapidity geometries.
- The challenge is to maintain high performance and full efficiencies in such environments.
- Technologies (whether existing or to be developed) will have to assure the compliance of the detector to the needed specifications and resulting performance.
- New optical components and designs, new materials, vessels, radiators, electronics, photosensors: all needs to be re-visited in the light of the future challenges and eventually re-developed. Number of detected photons and space are critical parameters.

- The push for the future will consist in developing RICH detectors with very high angular precision, with unique time properties and … as compact as possible.

Acknowledgements

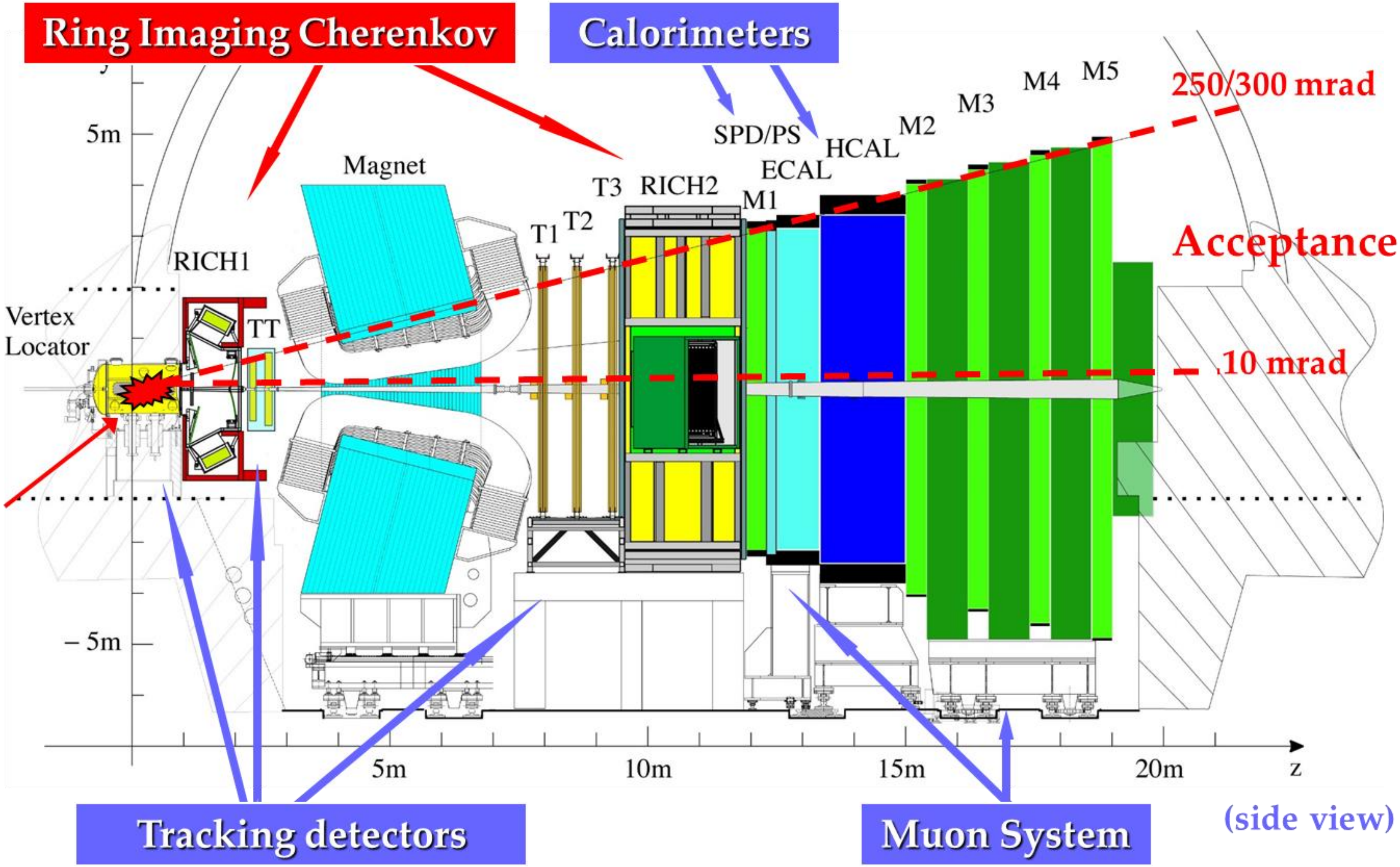
Most of the slides have been produced by using material from the LHCb RICH Collaboration and the ECFA Input Session of Future Facilities.

Thank you very much for the help.

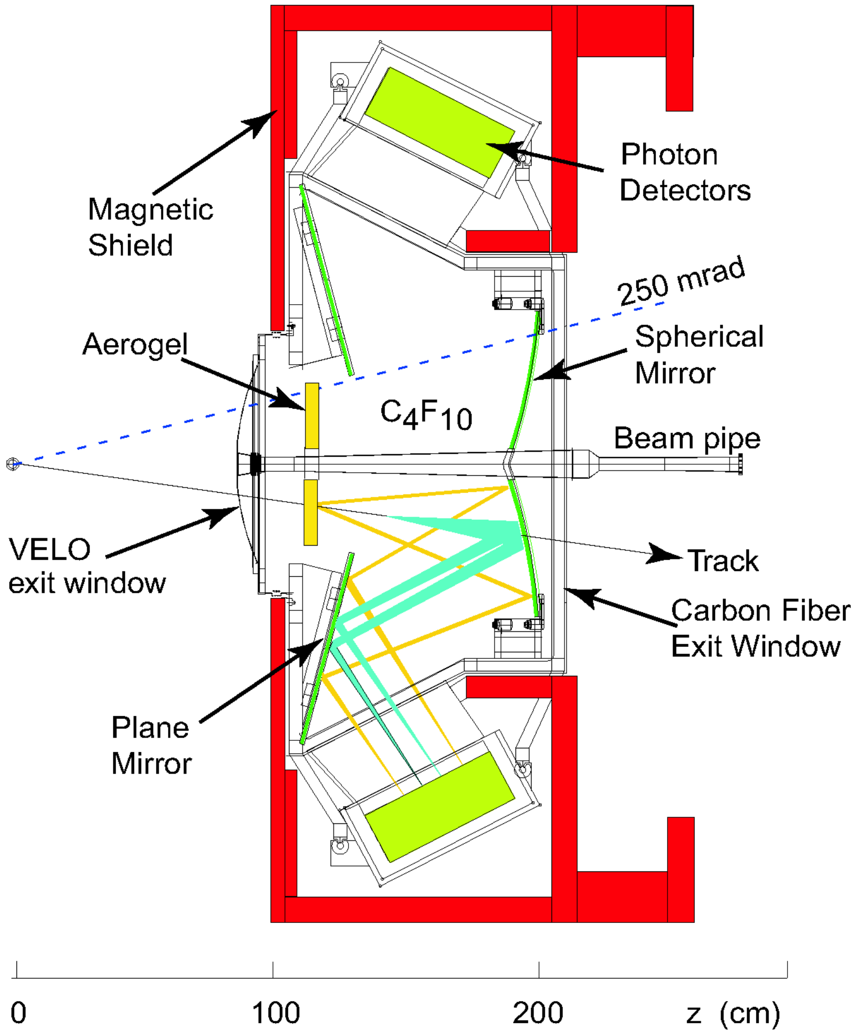
Spares

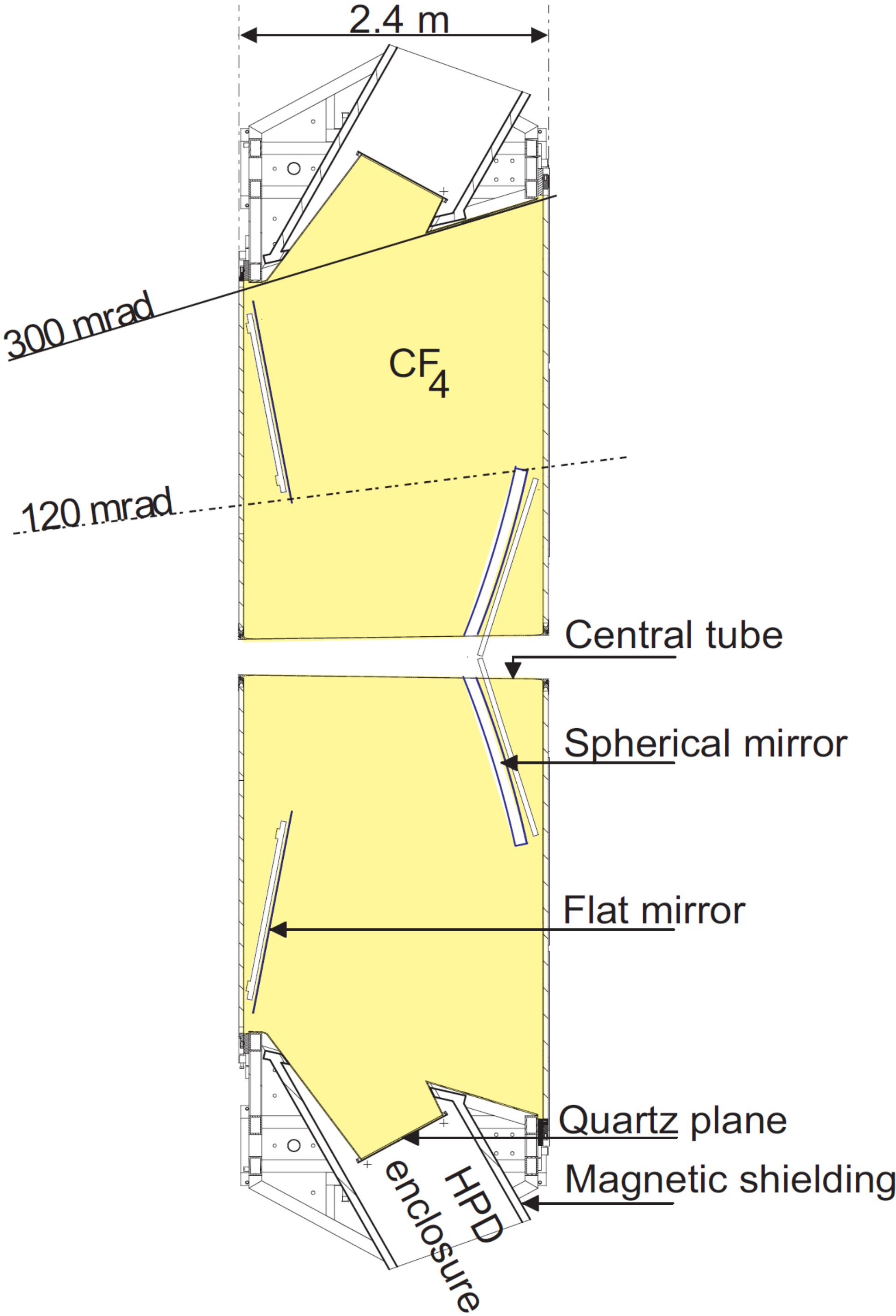
Let me start with a simple example: the LHCb RICH Detector System

LHCb single-arm spectrometer, dedicated to precision studies of CP asymmetries and of rare decays in the B-meson system

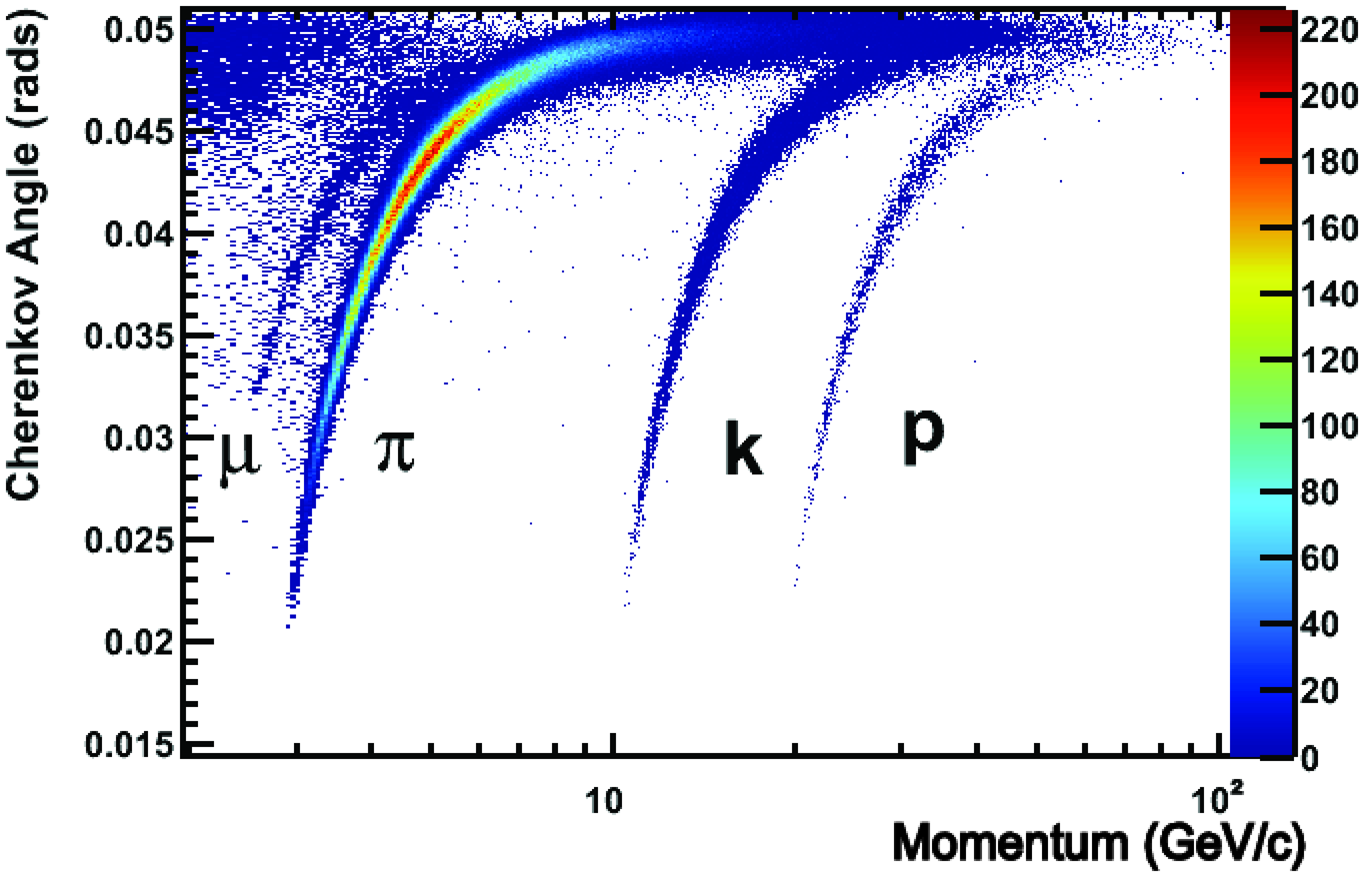


RICH1 and RICH2





RICH1 first signals



Eur. Phys. J. C (2013)

How is this achieved?

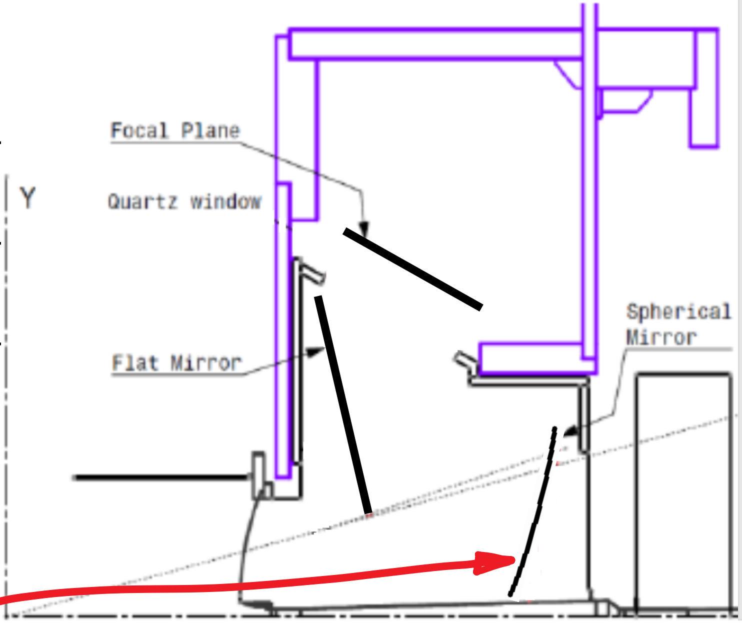
- New optical system sitting in the detector acceptance to reduce aberrations;
- Higher granularities (achievable with a longer focal mirror or/and a smaller sensor pixel size);
- New photodetectors with green-enhanced high QE.

Optical Performance and Photon Yields

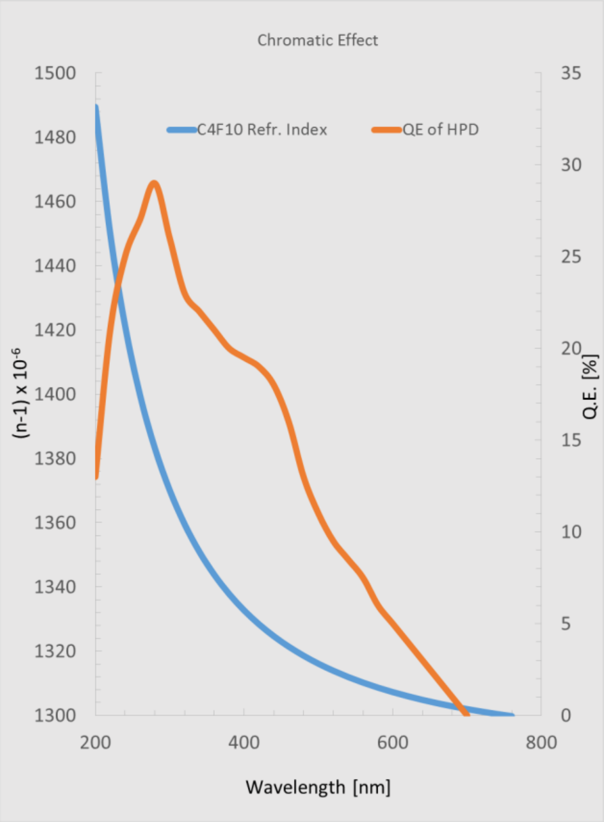
Lumi = 2×10^{32} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Old (HPD)
Avr. Phel. Yield	30
Single Photon Errors [mrad]	
Chromatic Pixel Emission Point Track resolution	0.84 0.9 0.8 0.4
Overall	1.52

Old



depends on spherical mirror tilt and focal length



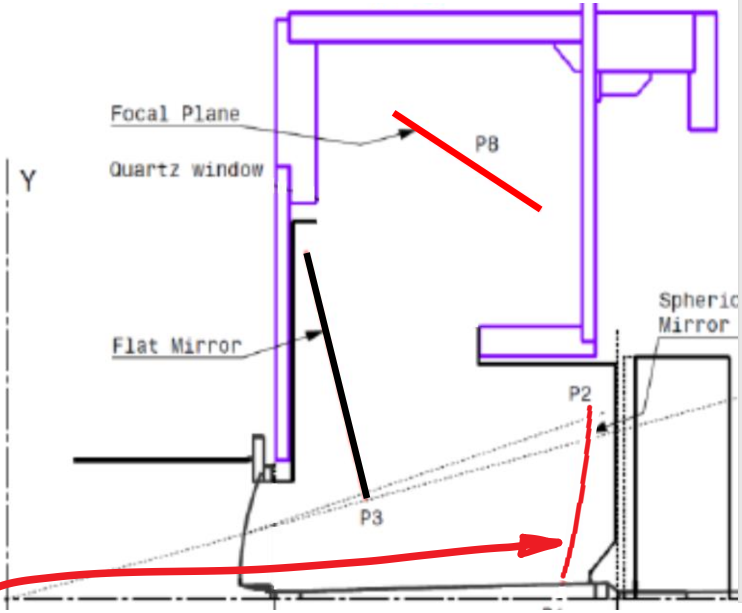
Chromatic depends on the overlap between dispersion and photodetector QE

Optical Performance and Photon Yields

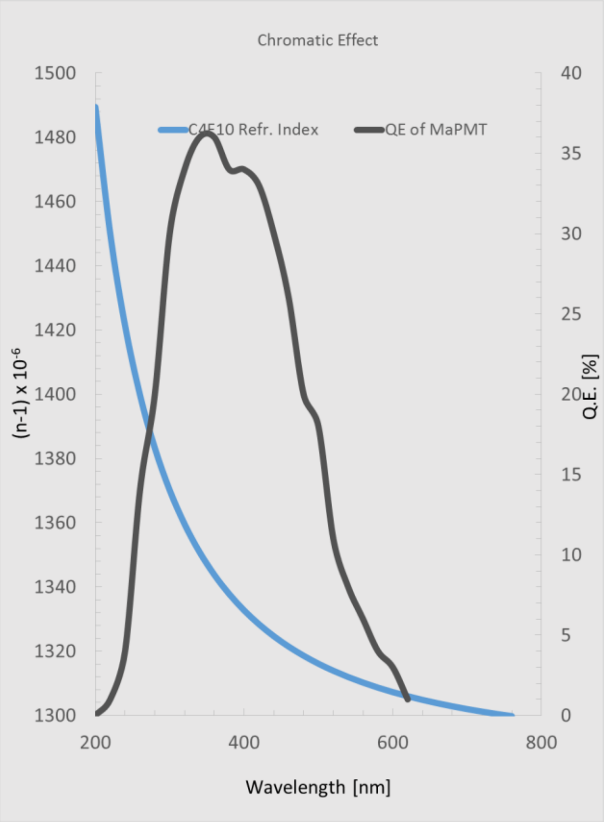
Lumi $\leq 2 \times 10^{33}$ cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg1
Avr. Phel. Yield	40
Single Photon Errors [mrad]	
Chromatic	0.58
Pixel	0.44
Emission Point	0.37
Track resolution	0.4
Overall	0.9

Upg1



depends on spherical mirror tilt and focal length

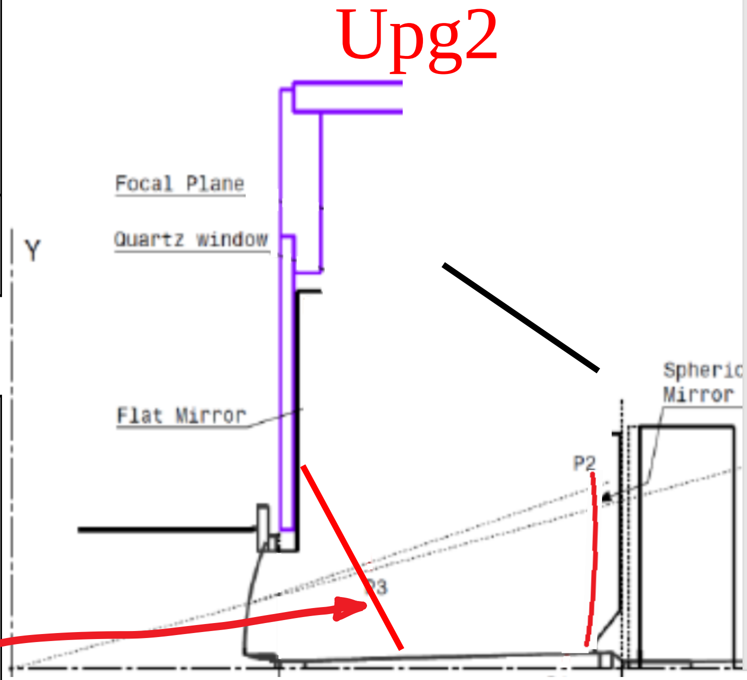


Chromatic depends on the overlap between dispersion and photodet. QE

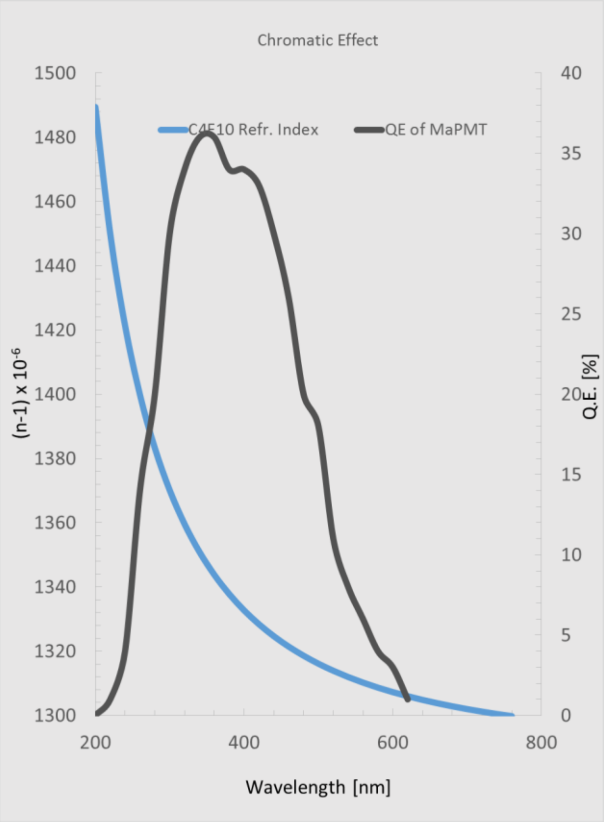
Optical Performance and Photon Yields

Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy > 100%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	
Single Photon Errors [mrad]	
Chromatic Pixel Emission Point Track resolution	0.58 0.44 0.1 ?
Overall	0.7



Use lightweight flat mirror in the acceptance (reduce aberrations)

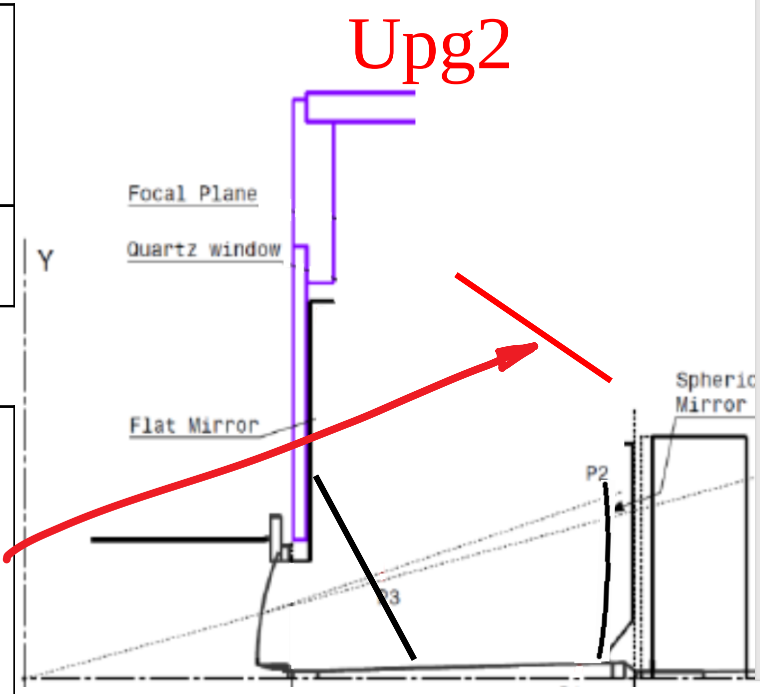


Chromatic depends on the overlap between dispersion and photodet. QE

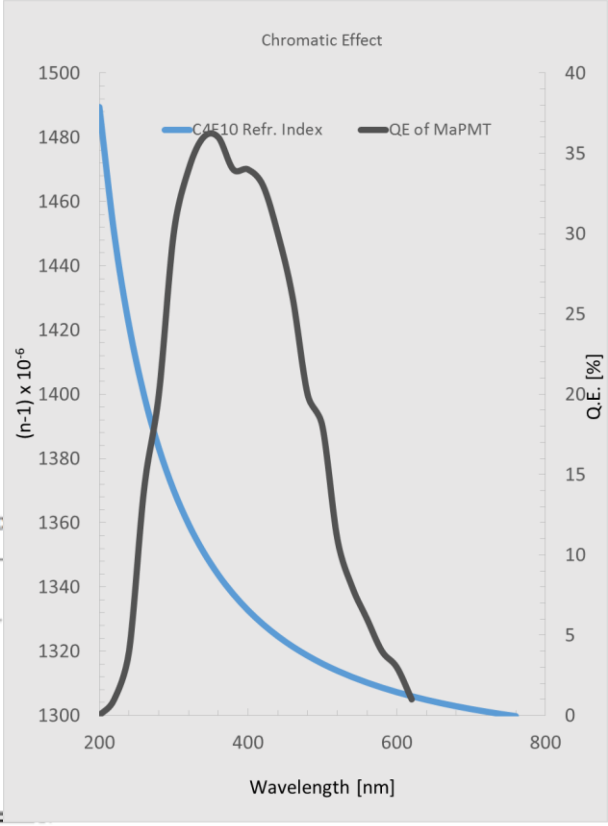
Optical Performance and Photon Yields

Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	
Single Photon Errors [mrad]	
Chromatic	0.58
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.6



Reduce pixel size to ~1mm



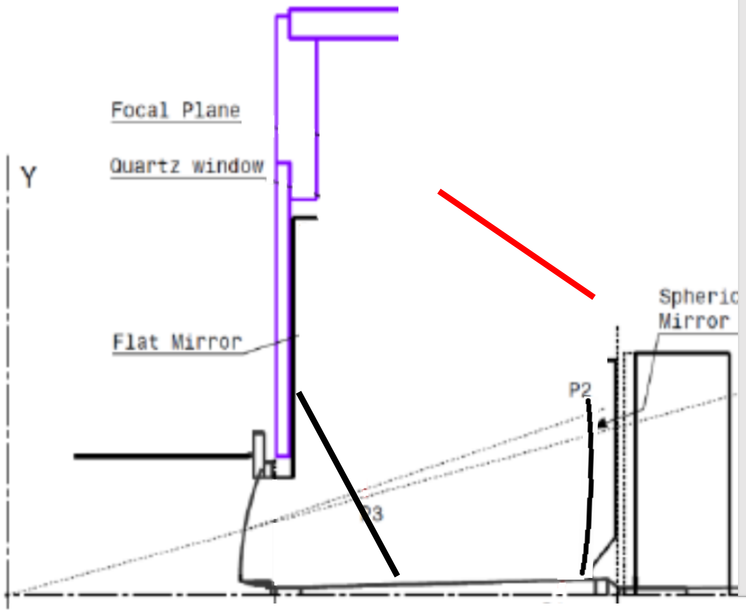
Chromatic depends on the overlap between dispersion and photodet. QE

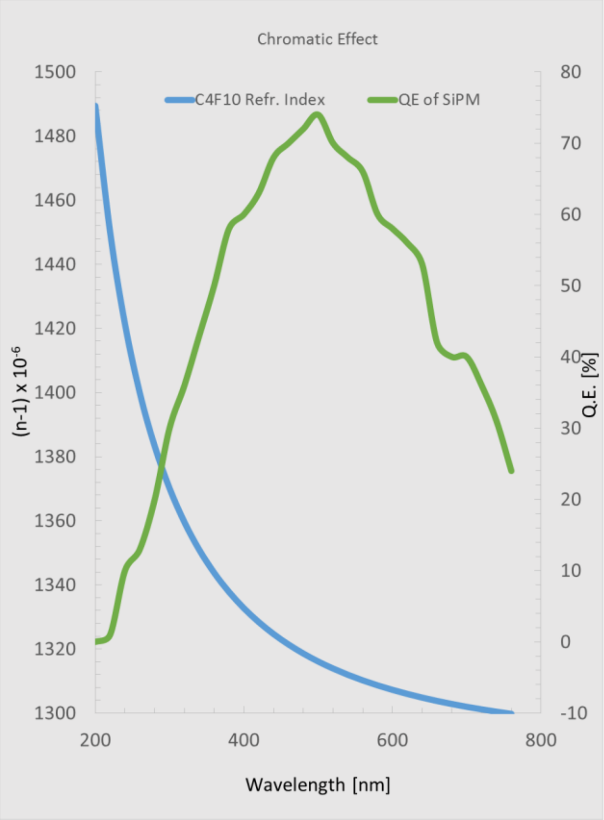
Optical Performance and Photon Yields

Lumi = 10^{34} cm^{-2} s^{-1} ; Occupancy < 30%

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	60 - 40
Single Photon Errors [mrad]	
Chromatic	0.24
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.3

Upg2

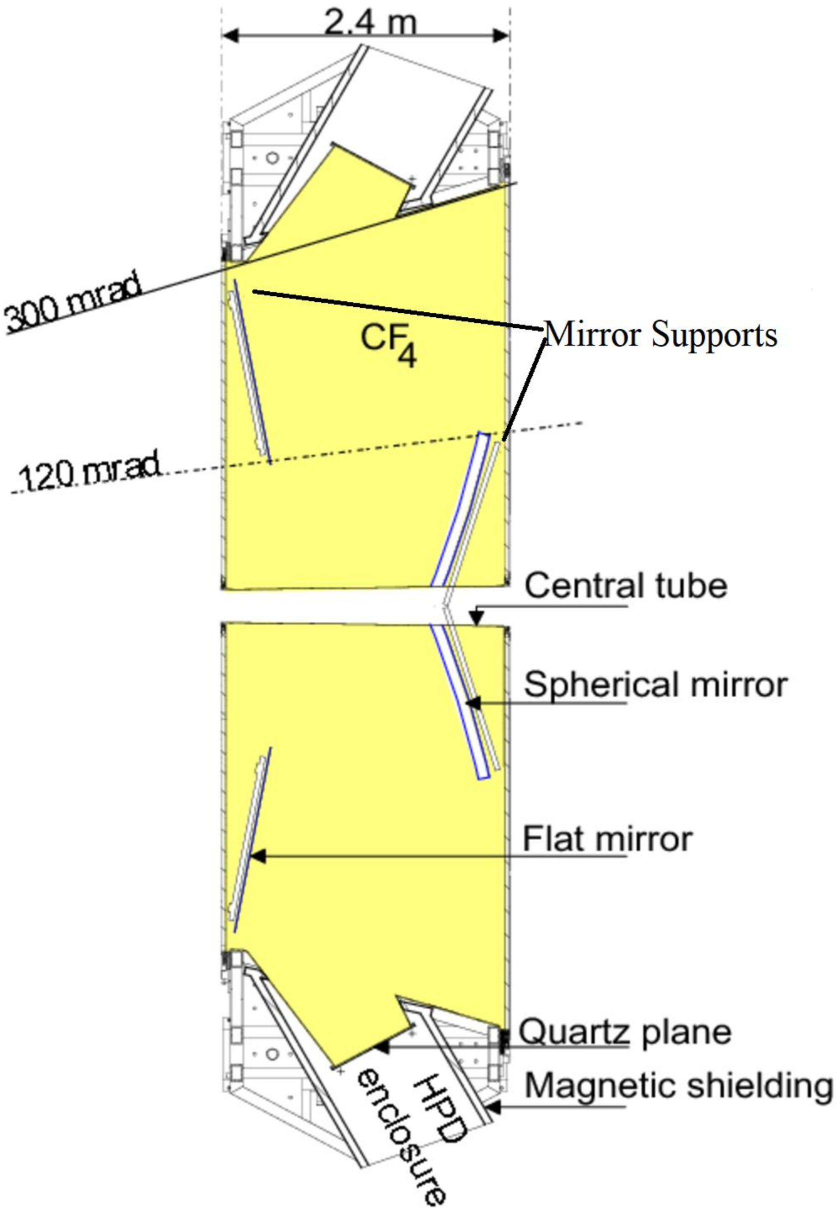


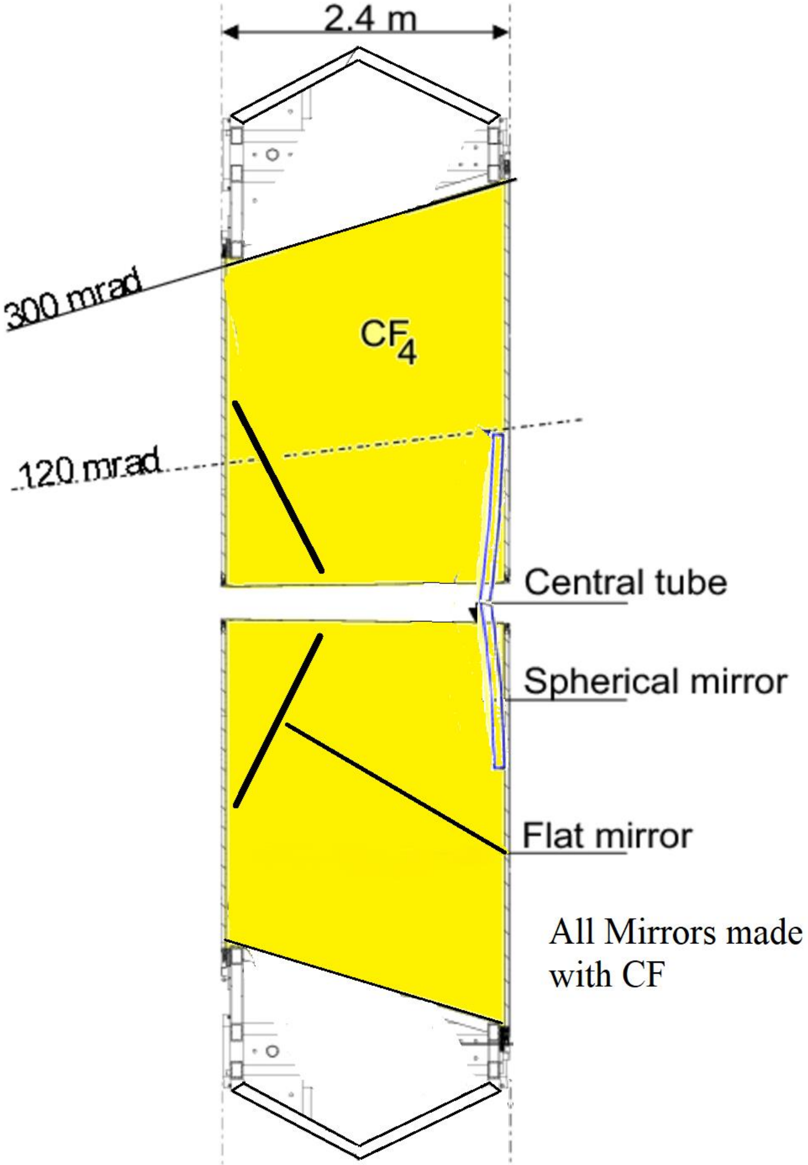


Reduce chromatic by choosing a photodetector with a "green-shifted" QE curve (and filter the shorter wavelengths)

Chromatic depends on the overlap between dispersion and photodet. QE (this example of a SiPM QE is rather from literature than realistic, QE between 50% and 60% would be closer to reality)

RICH 2 would also evolve …





All Mirrors made
with CF

Simulated Optical Performance and Photon Yields

For Upg2, $\sigma_{\vartheta} \lesssim 0.5 mrad$ (old RICH-1 ~1.6 mrad)

Radiator	C_4F_{10}			CF_4	
Detector Version	RICH-1 Old (HPD)	RICH-1 Upg1	RICH-1 Upg2	RICH-2 Upg1	RICH-2 Upg2
Avr. Ph.Electron Yield	25 (30)*	40 (rms=8)	40 - 30	22 (rms=5)	30 - 20
Single Photon Errors [mrad]					
Chromatic	0.84	0.58	0.24 – 0.18	0.31	~0.1
Pixel	0.9	0.44	0.15	0.20	0.07
Emission Point	0.8	0.37	0.1	0.27	0.05
Track resolution	0.4	?0.4?	?0.4?	?0.4?	?0.4?
Overall	1.52	0.9	0.5 (0.3 – 0.2)	0.60	0.42 (0.13)

0.7 – 0.8** 0.4 – 0.5**

*Value from data (expected); ** updated overall, see https://indico.cern.ch/event/982426/

Back-on-the-envelope performance improvement @ high momenta (RICH-2)

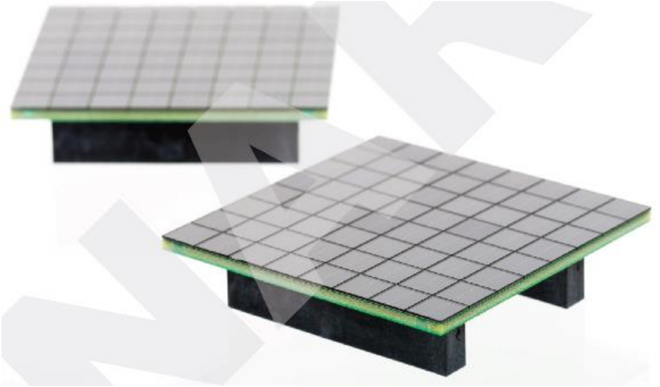
	OLD	UPGRADE Ia	UPGRADE Ib	UPGRADE II	UPGRADE II
p_{max} [GeV/c]	HPD, N_{phel}=17, CF_4, σ=0.67	MaPMT, N_{phel}=25, CF_4, σ=0.50	MaPMT, N_{phel}=22, CO_2, σ=0.50	SiPM, N_{phel}=25, CO_2, σ=0.2	SiPM, N_{phel}=25, CO_2, σ=0.13
$n_{3\sigma k\pi}$	85	109	108	177	235
$n_{3\sigma kp}$	144	183	182	297	396
$n_{3\sigma\pi p}$	167	213	212	346	460

A word about SiPMs

\+ High QE in the green, good single photon sensitivity, becoming cheap and easy to produce arrays with punchthrough technologies, insensitive to magn. field, etc

– Very sensitive to neutrons and ionizing particles;

– High dark count rates (DCR), depend on:
  - Temperature, a factor ~2 every 10 ^{o}C,
  - Surface, ~linear,
  - Structure,
  - Operational electric conditions.



1. Cool down (develop cryo/cooling - down to liquid N_2 - and vacuum systems to host the array);
2. Use microlenses to decrease diode surface: optimize diode shape, increase array active surface and improve time resolution;
3. Gate inside the 25 ns LHC clock (1 ns or less);
4. Implement neutron plastic shields, wherever possible.