DRD4 kick-off meeting
16 May 2023

A compact RICH for a Higgs Factory

Roger Forty (CERN)
on behalf of those working on the ARC detector

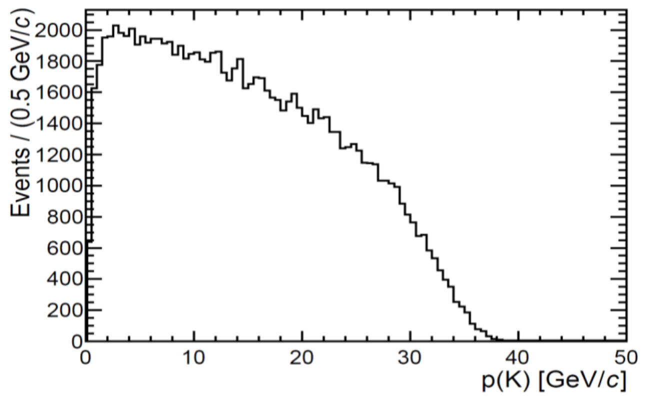
Increasing interest in charged hadron ID for experiments at a future e^+e^- Higgs Factory
A compact RICH has been designed for such experiments: **ARC** (Array of RICH Cells)
Uses dual radiators (aerogel + unpressurised C_4F_{10} gas) and would profit from R&D on:

- **Photon sensors:** high efficiency, mm-scale pixels, compact
- **Radiator gas:** environmentally-friendly alternatives to fluorocarbons
- **Aerogel:** large-area, high clarity tiles
- **Lightweight construction:** vessel and spherical mirrors

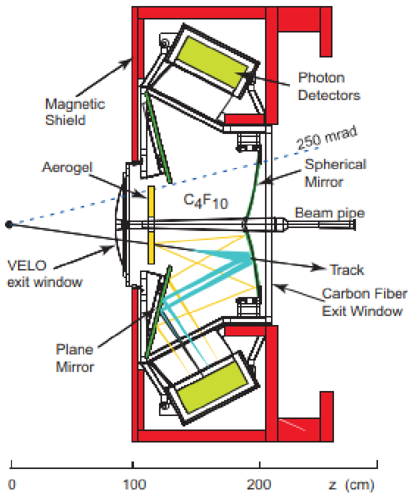
Motivation

- From the latest update of the European Strategy, an e^+e^- Higgs Factory is the highest priority future collider to follow the LHC
- Experiments designed for such colliders traditionally concentrate on precision tracking + particle-flow calorimetry, however recent increase in interest for adding **charged-hadron ID**
  → identify H and W decays + exploit world-class flavour physics enabled by huge Z statistics (at least for the circular options)
- Momentum range of interest = 1– 40 GeV/*c*
  → RICH technique is most suited, in particular for those experiments with silicon trackers
  (cluster counting in gaseous trackers → DRD1)
- Timescale of e^+e^- Higgs Factory experiments: earliest implementation in mid-2040s
  → well adapted to a phase of strategic R&D
- How can adapt LHCb-like RICH for a 4π experiment?
  (or **dRICH** of EIC: similar concept, but 120-cm thick)

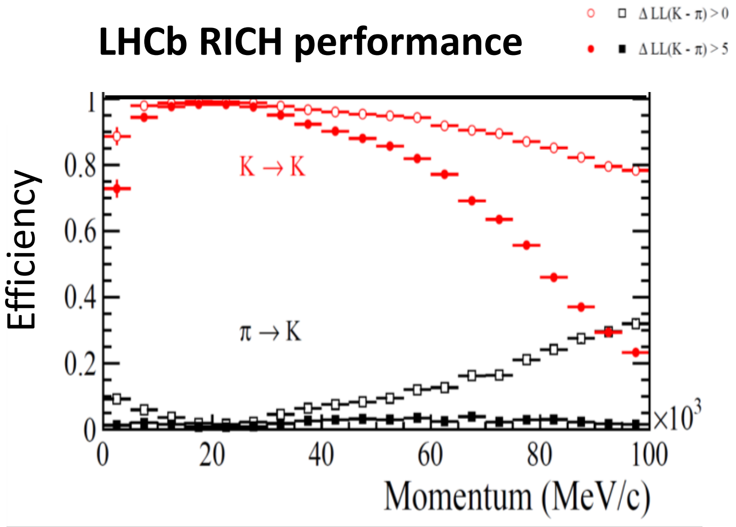
$B_s \to D_sK$ simulation in Z events



LHCb RICH1



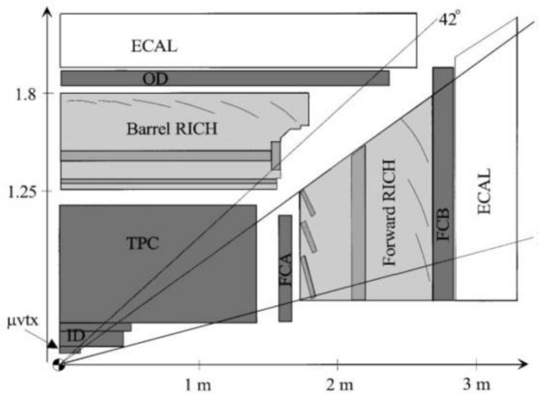
LHCb RICH performance



Collider RICH detector

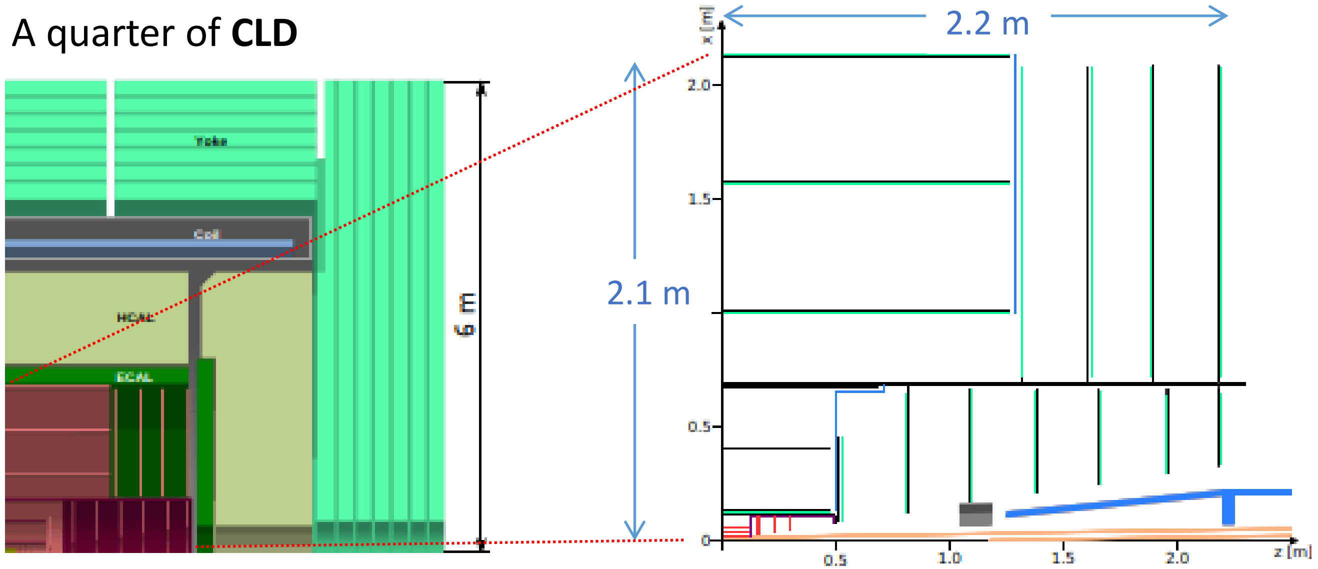
- Earlier examples of RICH detectors at e^+e^- colliders include those of DELPHI and SLD: large radial dimensions, challenging photosensors
- To be concrete, new proposed design is based on the current **CLD** experiment concept for FCC-ee N. Bacchetta *et al.*, arXiv:1911.12230
- Target a radial depth of **20 cm**, and material budget of **few % X_0**
  Such aggressive parameters will be necessary for it to be accepted…

DELPHI RICH

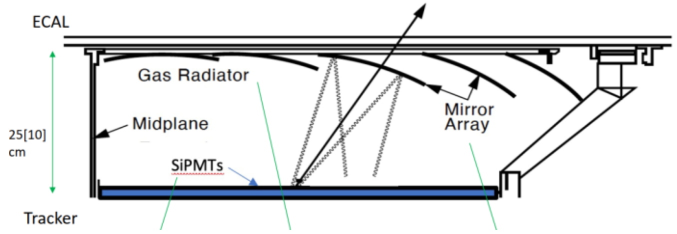


A quarter of **CLD**

Zoom on tracker



Adapted version of **SLD CRID** V. Cairo *et al.*



→ CLD tracker would need to be re-optimized using 10% less radial space
Already studied in Appendix B of note (to reduce cost of calorimeter)

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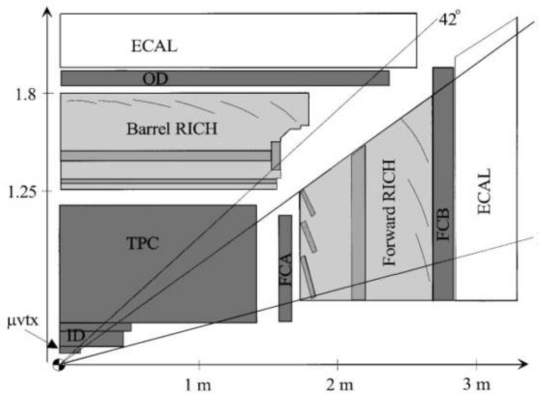
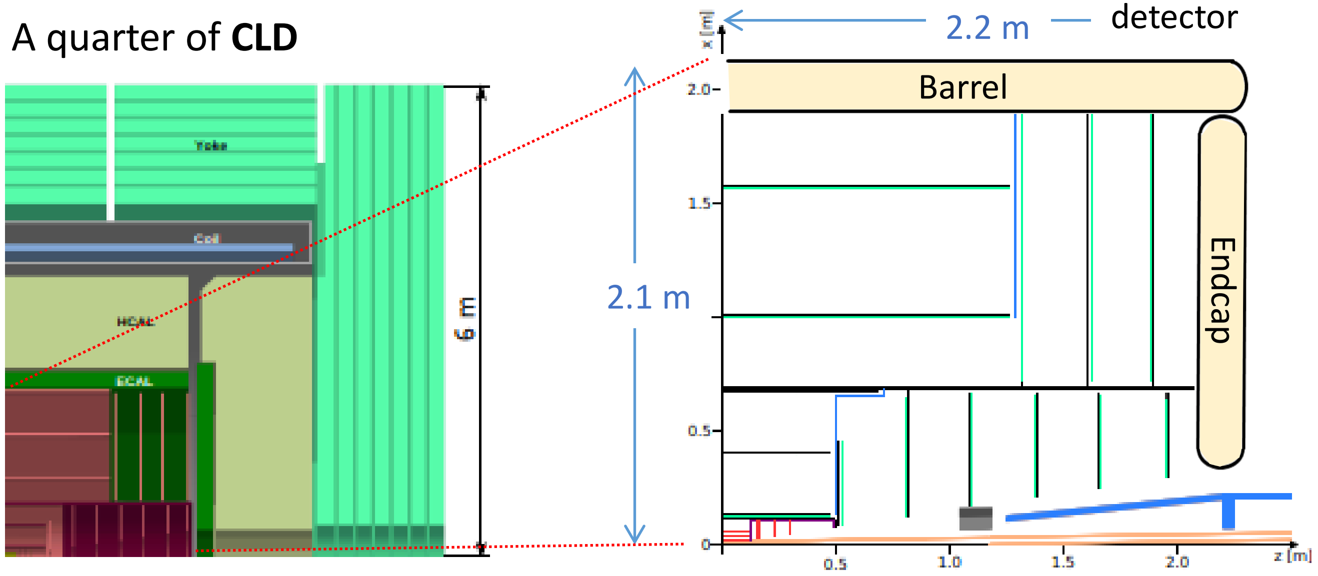


A quarter of **CLD**

Zoom on tracker

Proposed **ARC** detector



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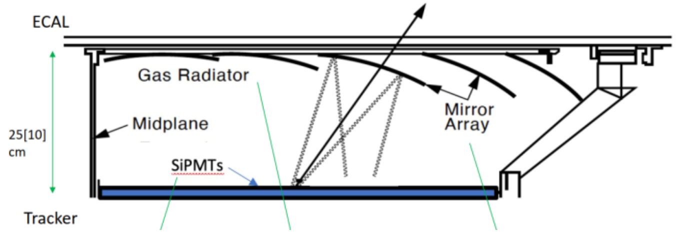

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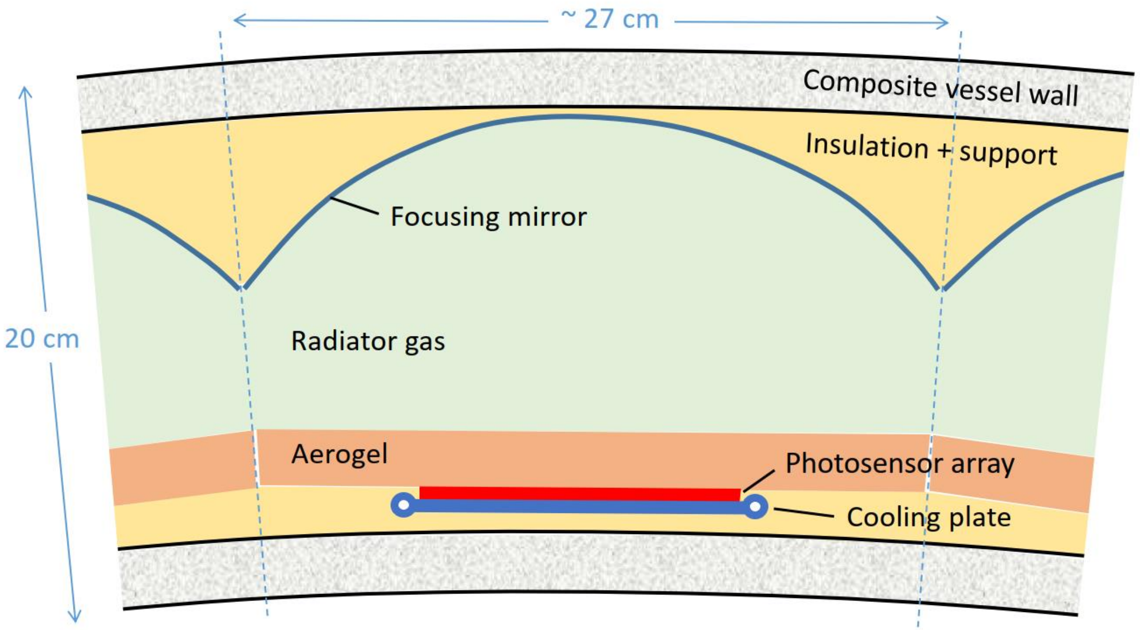
RICH cellular layout

- Challenge to arrange optical elements so that Cherenkov light focused onto a single sensor plane, as the detector radial thickness is reduced
- Concept inspired by the compound-eye of an insect: tile the plane with many separate cells, each with its own mirror and sensor array
- Use spherical focusing mirrors: focal length = radius-of-curvature/2
  → select radius-of-curvature $R \approx 30$ cm for radiator thickness of 15 cm

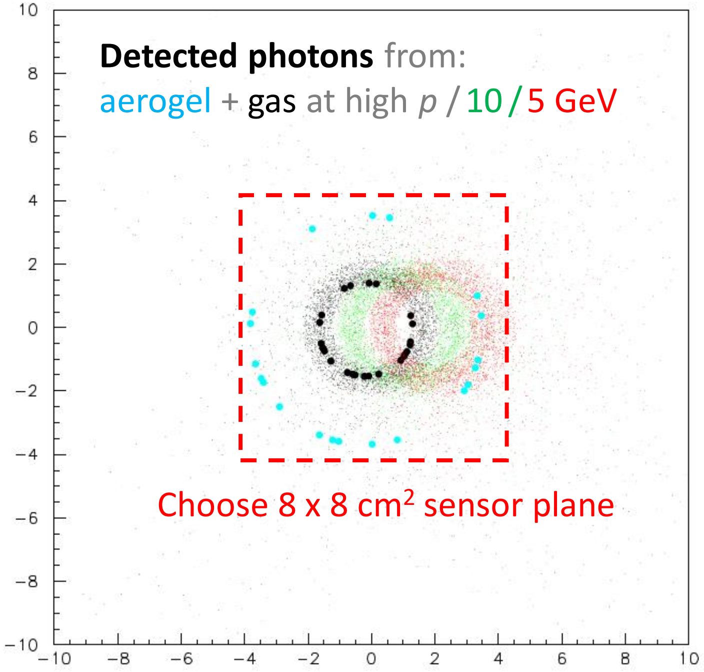
https://www.findlight.net/blog/2019/01/23/artificial-compound-eyes/



ARC detector (one cell)

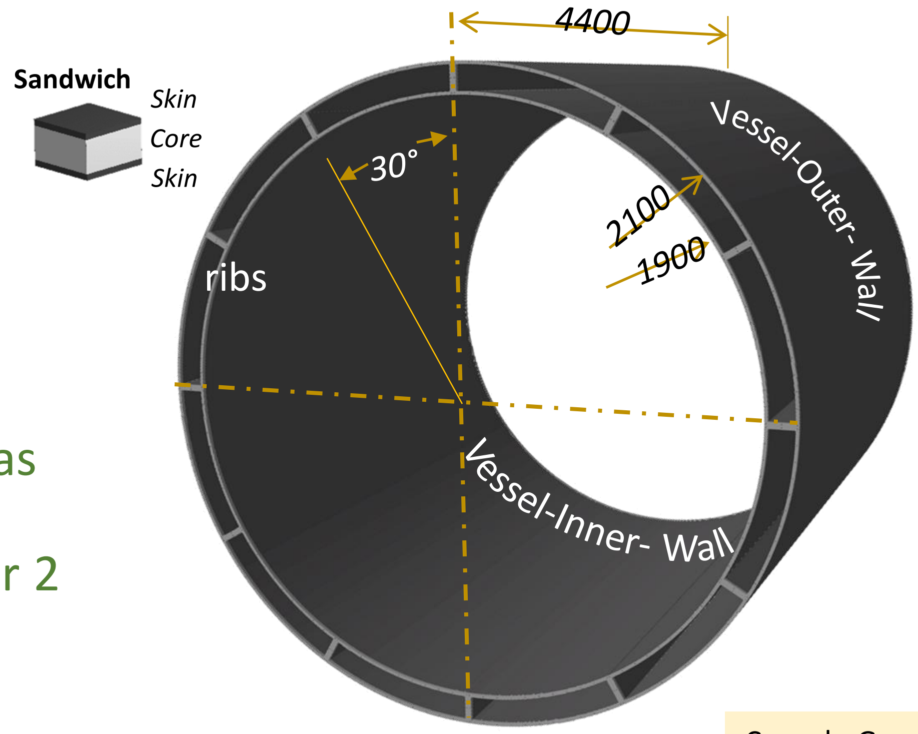
Simulate tracks from IP crossing detector uniformly over acceptance and ray trace Cherenkov photons to sensor plane:

Ring radii = $R \cdot \theta_C / 2$
≈ 1 cm (3.6 cm)
for gas (aerogel)

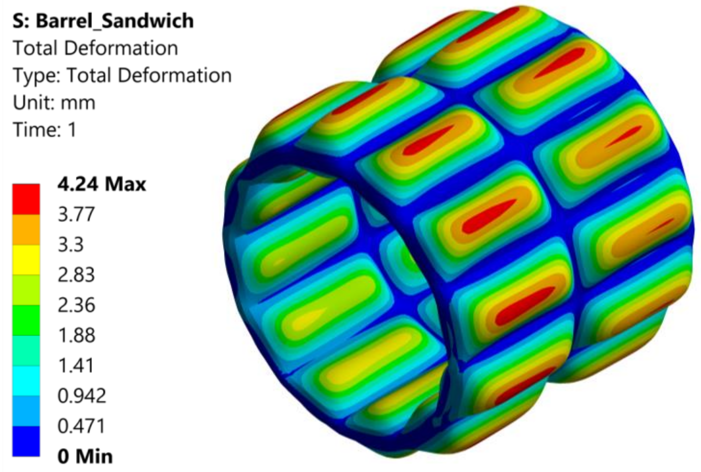


Vessel

- Should be as lightweight as possible: propose to use carbon-fibre composite sandwich with foam core
- Initial concept was for pressurized radiator gas up to 4 bar Related R&D already underway for lightweight cryostats
- Finite-element analysis made for 4 bar pressure, over the gas volume of ~ 10 m^3 → maximum deflection of walls under pressure: 4 mm (barrel), 7 mm (endcap) with a safety factor 2
- Achieved with 20 mm-thick walls, for a remarkably low material budget: 2.7% X_0 (per wall)
- Subsequent studies indicated that an *unpressurized* radiator may be sufficient (depending on the sensor PDE) → material can be further reduced, currently assume 10 mm-thick walls
- **R&D** needed to ensure leak tightness of CF walls (liner-less), out-of-autoclave curing to avoid need of large autoclave, etc. Also, to develop suitable lightweight spherical mirrors

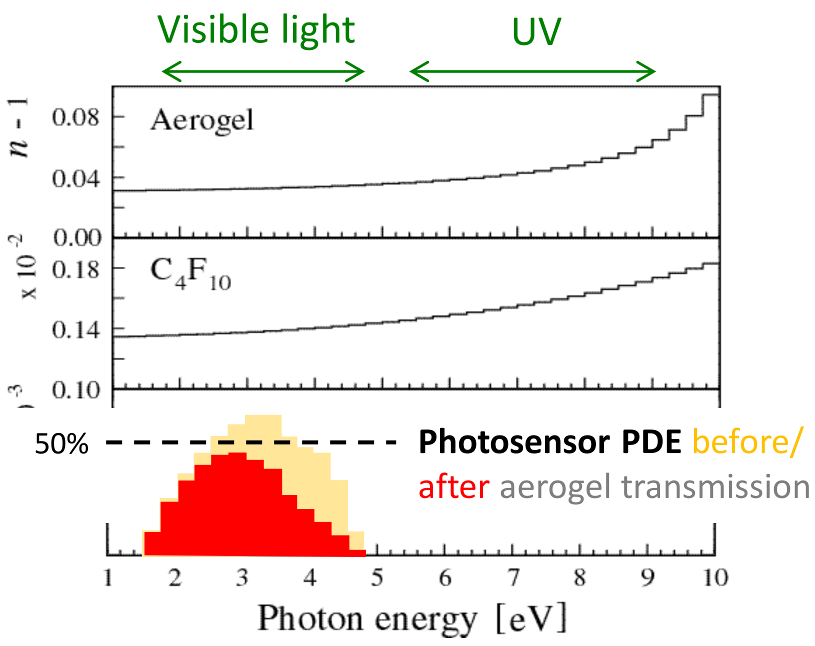


Corrado Gargiulo



Radiator gas R&D

- Baseline choice is **C_4F_{10}** due to its excellent chromatic properties → optimizes resolution (~ 1 mrad is the target)
- However, fluorocarbons have high global warming potential, (GWP ≈ 9000 for C_4F_{10}) and despite aiming for a leak-less system, may be required to explore alternatives
- Replacing the gas radiators with a mixture of $C_5F_{10}0$ and N_2 can allow refractive index to be tuned to that of C_4F_{10} Greg Hallewell
  $C_5F_{10}0$ is one of the Novec family of gases (#5510), GWP < 1
  However, long term Novec supply is also in question…
- **Xenon** is not a greenhouse gas, and stays in gas phase at room temperature up to over 20 bar
  However, lower refractive index (n = 1.0007) so would need higher pressure than C_4F_{10}, and somewhat worse dispersion
  Pressurized **argon** is also discussed as an option (e.g. at EIC)
- For such new gas choices, **R&D** needed to ensure suitability e.g. level of scintillation, compatibility with materials, etc.

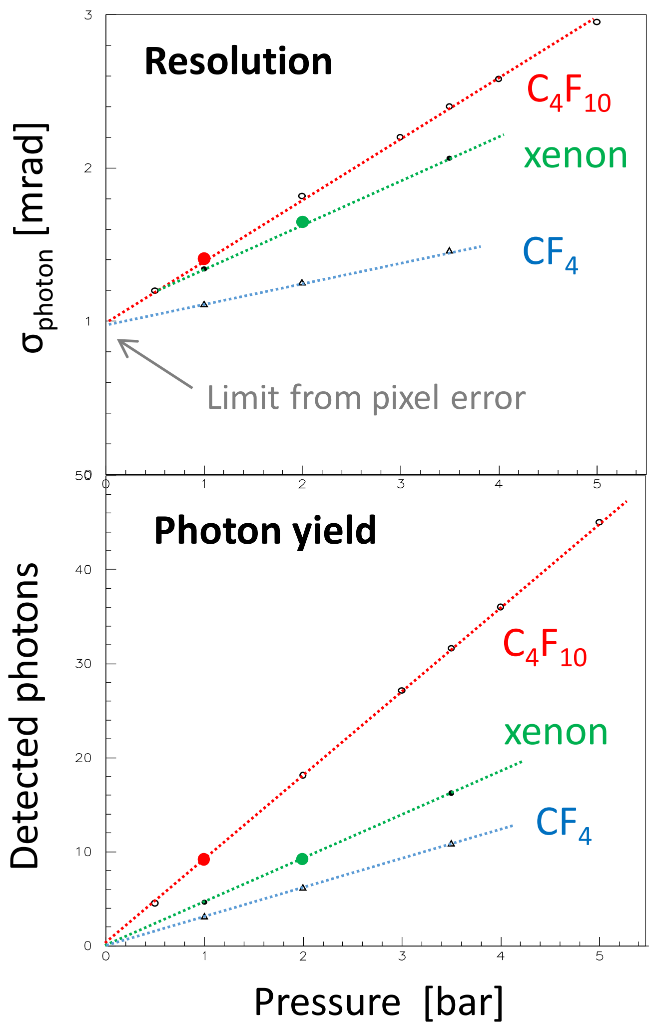


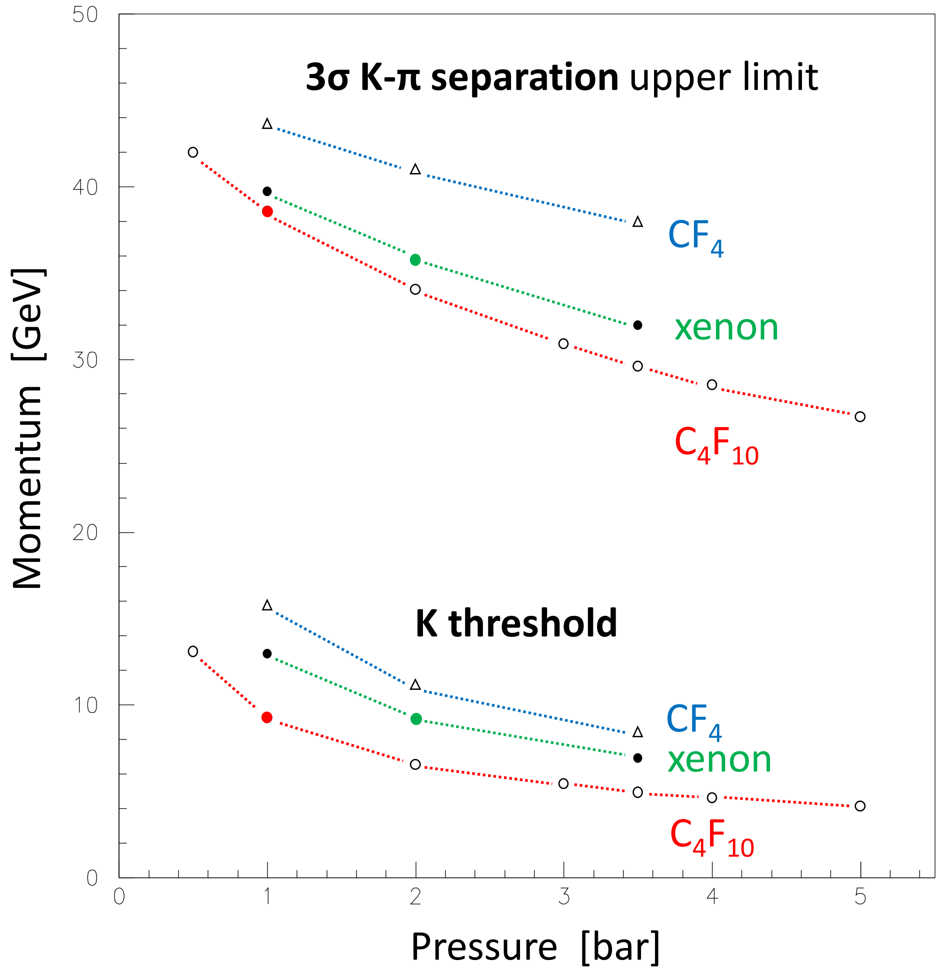
Dispersion is also reduced if photosensor is sensitive to lower (visible) wavelengths

Use of aerogel as a "filter" in front of the photosensor works in this direction

Radiator gas parameter scan

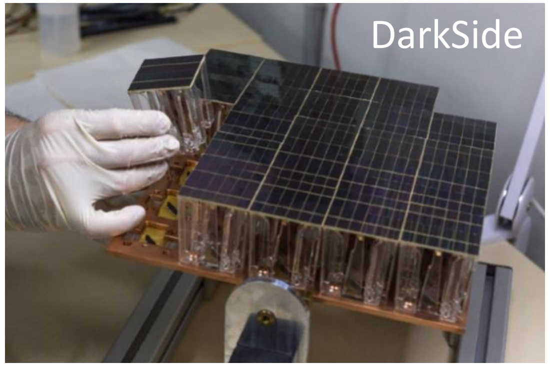
- Performance studied varying systematically the gas type and pressure
- Two possible choices of working point indicated:
- C_4F_{10} at atmospheric pressure gives good momentum range for K-π separation, with acceptable photon yield for the parameters assumed
- **Xenon** at 2 bar may provide similar performance, if fluorocarbons unacceptable
- Optimal point may be expected to change in the presence of background



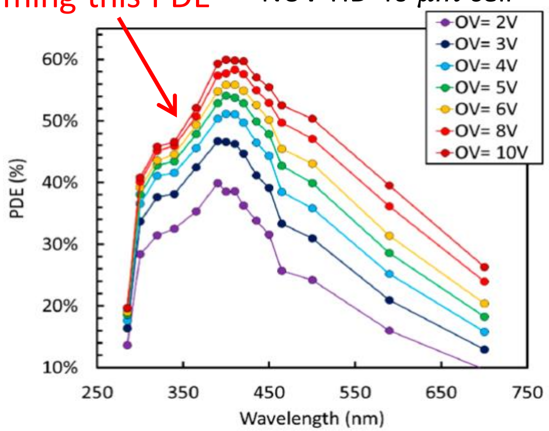


Sensor R&D

- Photosensor performance is crucial for this concept: they need to be compact, low material budget, high efficiency, mm-scale pixellization, cheap (~ 8m^2 active area, 8M pixels)
- **SiPM**s appear to be the ideal candidate, but not yet widespread in RICH detector instrumentation (single-photon detection)
- Level of acceptable dark-count rate to be established, probably requires cooling → potential issue with liquefying radiator gas
  Note that radiation dose expected is low at a Higgs Factory, so major concern at hadron machines of increase of DCR with irradiation should *not* be an issue – annealing not required?
- Nevertheless, assume that cooling will be required → sensors + electronics mounted on cooling plate with CO_2 circulation
  Need to insulate from gas volume, while allowing Cherenkov light through: use **aerogel** as an excellent thermal insulator
- Other **R&D** aspects: optimizing efficiency, active-area coverage, potential use of fast timing to reduce background

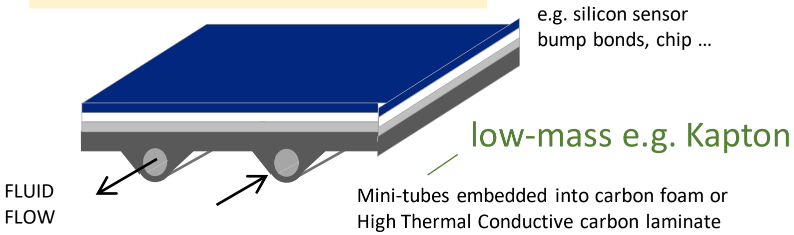


Assuming this PDE



A. Gola et al, Sensors 19 (2019) 308

D. Hellenschmidt, CERN-EP R&D



Aerogel

- Silica aerogel can withstand high pressure, has tunable refractive index n = 1.01–1.10, v. low **thermal conductivity**: ~ 0.015 W/m·K

  For 1 cm thickness, assuming ΔT = 70 K, heat transmitted through a 25 x 25 cm^2 tile is only a few watts < heat from the electronics

- Propose use both as a secondary Cherenkov radiator (suitable for low momentum tracks) *and* as thermal insulation around sensors

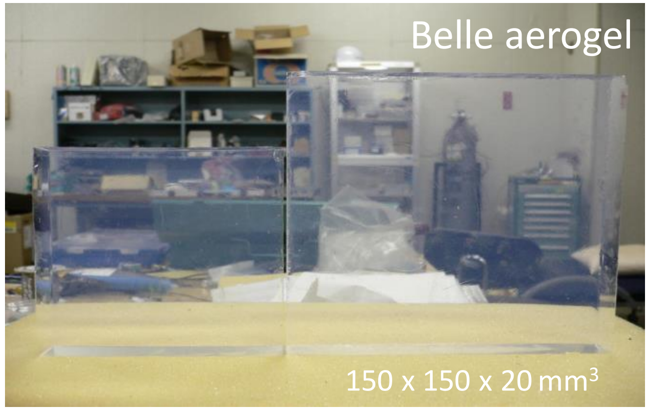
  Photons from the gas radiator have to pass through aerogel → some loss from scattering, but also shifts towards visible

- High clarity, large area aerogel tiles developed by Belle for ARICH (other recipes also available): assume clarity C = 0.005 μm^4/cm

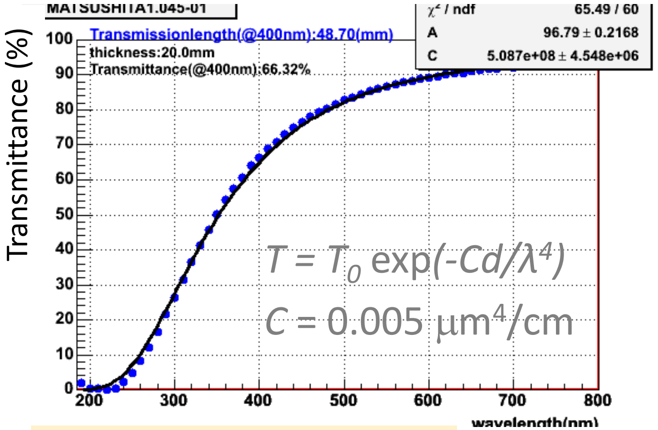
  n = 1.03 → $\theta_C \approx$ 240 mrad

- Aerogel photons focused by same mirror as those from gas onto same sensor plane → concentric rings if track above both thresholds

- **R&D** issues: developing larger, thinner tiles, testing use as thermal insulator (suitable mounting, joints, etc.), compatibility with gas, etc.



Transmittance *vs* wavelength

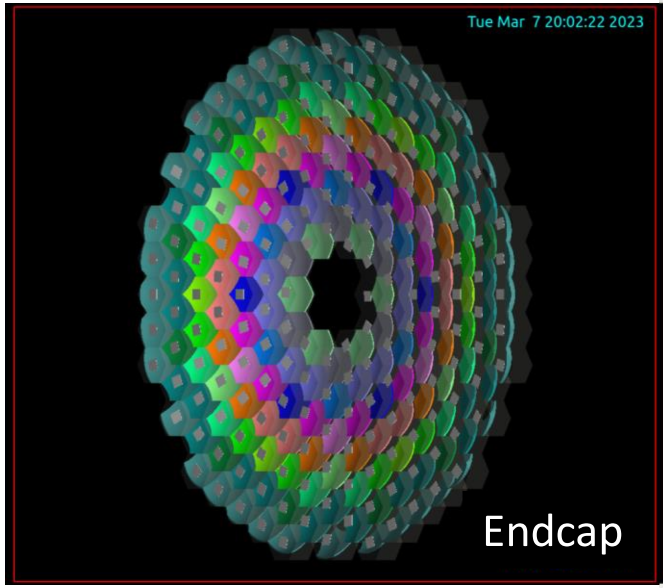


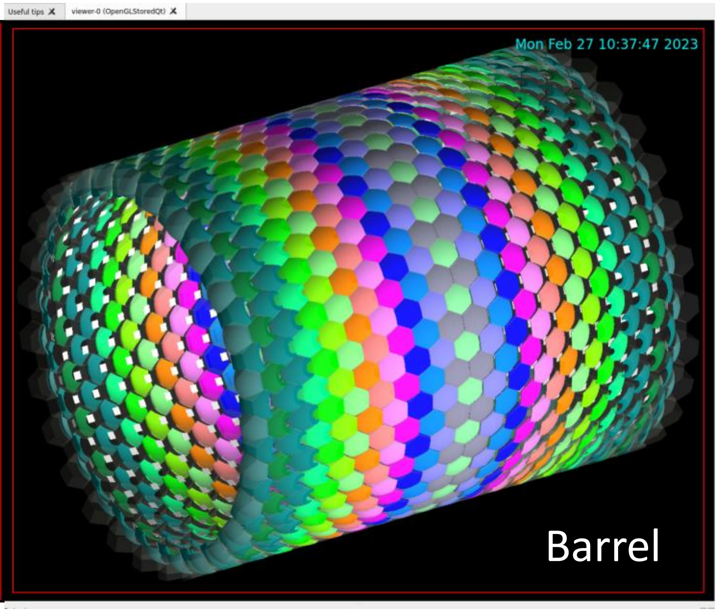
I. Adachi, ECFA TF4, 6/5/2021

Simulation

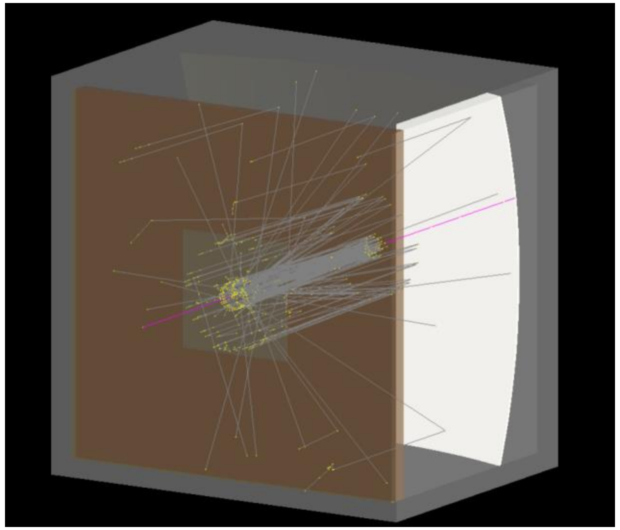
- Resolution optimized using similar hexagonal cells, ~ 1300 in total
- Optimization of optical layout has been performed using a standalone ray-tracing study: adjusting the position, curvature and tilt of mirrors and sensors for each of the 39 unique cells Martin Tat
- Geometry has been described in DD4HEP in collaboration with the FCC software group

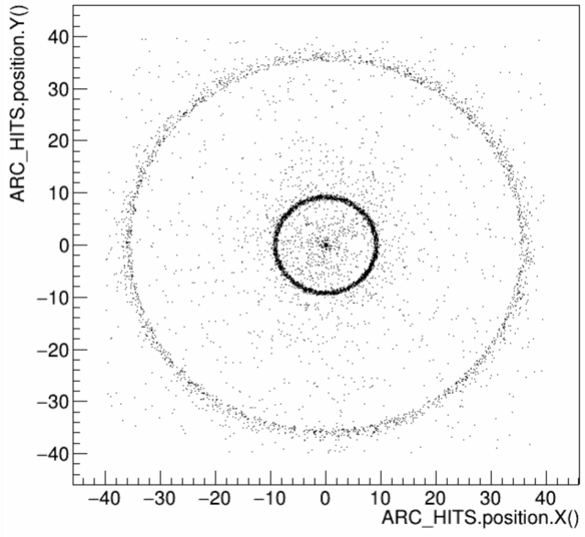
  Alvaro Tolosa Delgado *et al.*
- First studies made of full simulation of tracks passing through an ARC cell with Geant4 (detector efficiency not included yet)





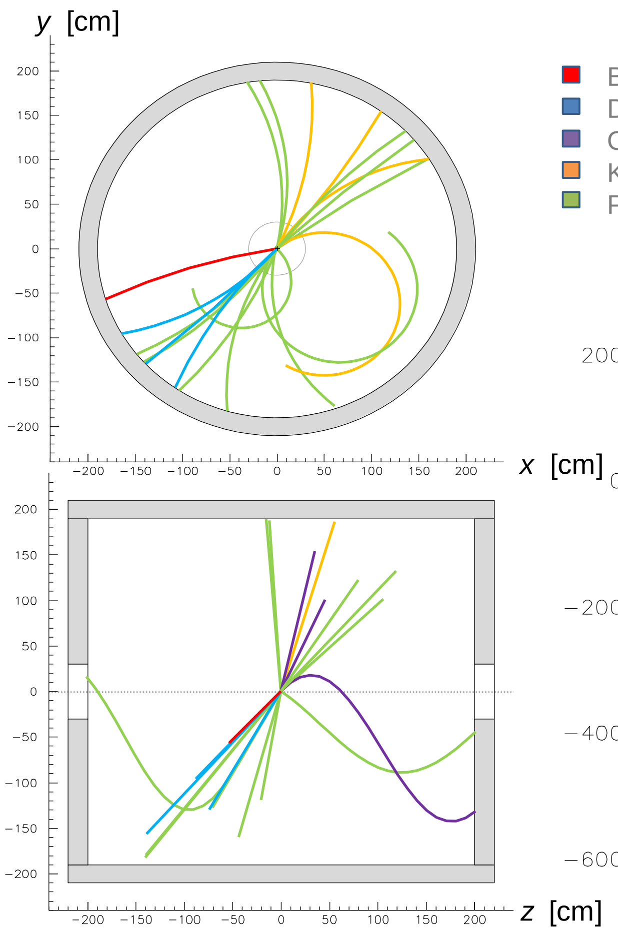
Alvaro Tolosa Delgado

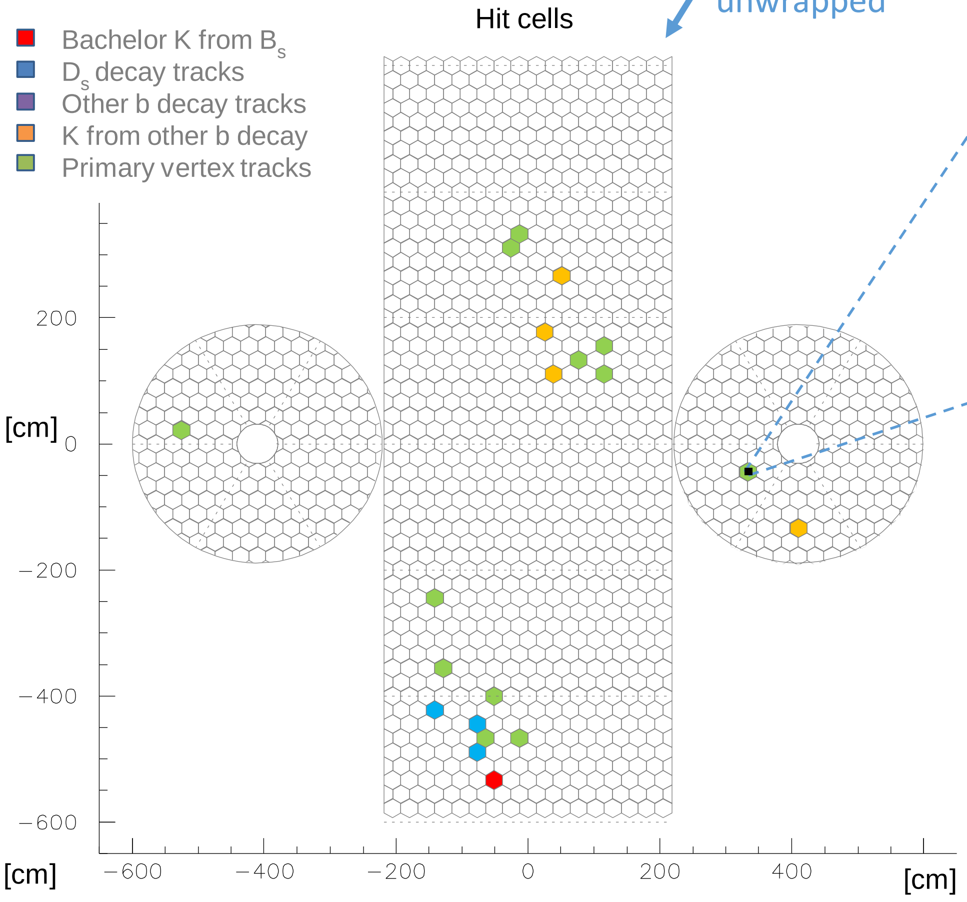


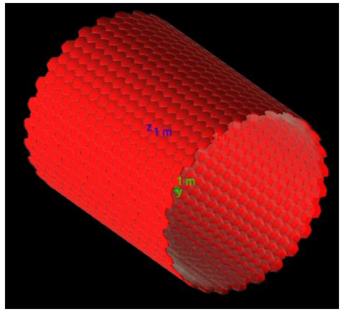


Performance

Event display of $B_s \rightarrow D_s K$ in Z event in ARC

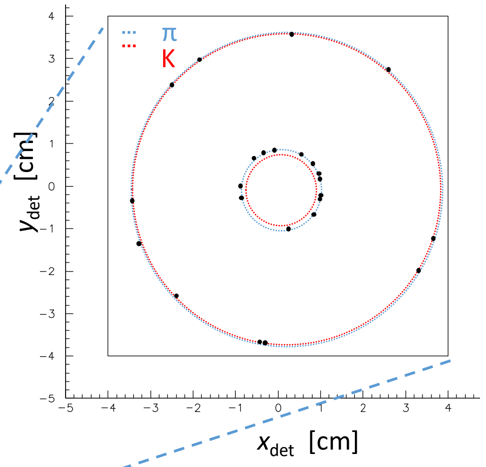






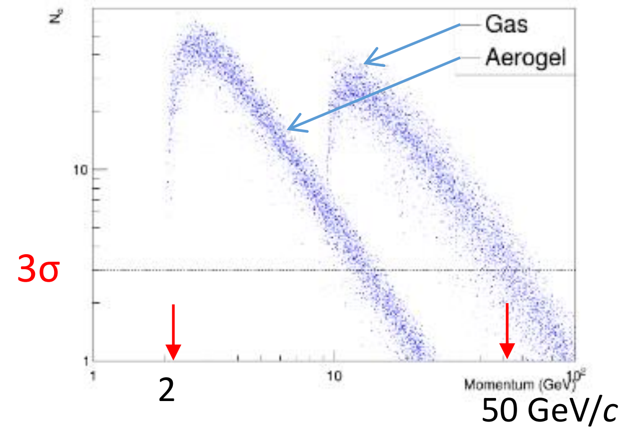
unwrapped

Zoom on hits in sensor of one cell



K-π separation

Martin Tat



From standalone simulation, including 2T B-field (to be followed up with full Geant4 simulation)

→ Excellent K-π separation from 2–50 GeV/c

Conclusions

- A **compact RICH detector** (ARC) is proposed to fit the geometry of a 4π collider experiment, with barrel and endcaps, suitable for FCC-ee (or other Higgs Factory)
- Previous detectors of this type were too bulky to be easily integrated – novel aspects of current concept should allow both radial depth (20 cm) and material budget (few % X_0) to be minimized:
  - **Aerogel** has dual use both as secondary radiator and as thermal screen for the sensors: Assuming SiPMs are used, they can be cooled to limit noise, isolated from gaseous radiator
  - **RICH vessel** uses a lightweight design of carbon-composite construction: few-mm wall displacement acceptable up to 4 bar pressurization (although current preference is for unpressurized gas to minimize the material budget)
  - **Cellular** optical layout is used to squeeze the detector into the limited radial space
- Detailed study in progress via simulation: high resolution (~ 1 mrad) achieved over full acceptance → excellent particle ID performance predicted, satisfying the requirements
- An extensive programme of **R&D** would be interesting to validate the concept: for the lightweight construction, for the gaseous and aerogel radiators, and in particular for the SiPM photosensors

  Collaboration with other groups working on related applications within DRD4 would be welcome

Z-Factories are great Flavour Factories

See S. Monteil, FCC CDR overview '19

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	1000	500

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^{\pm}K^{\mp}$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

out of reach
at LHCb/Belle

boosted b's/τ's
at FCC-ee