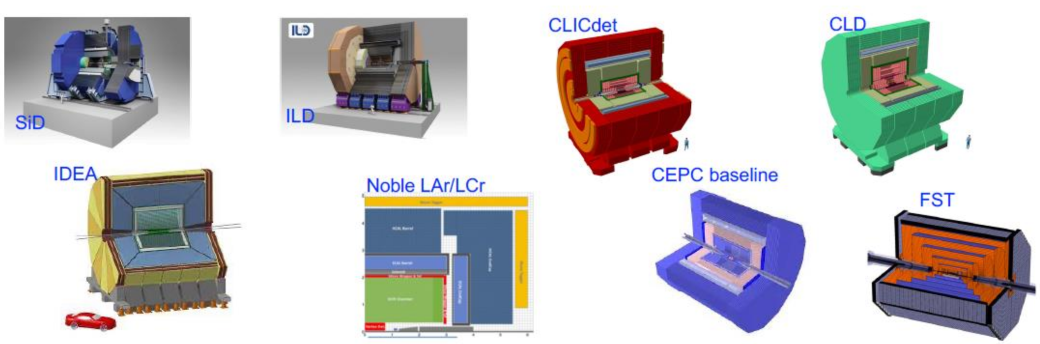
Introduction: a reminder of the possible tracking concepts and technologies

Tracking vertexing requirements

Technologies

Tracking/vertexing detectors in future e^+e^- colliders

Collider	ILC		CLIC	FCCee			CEPC	
Bunch separation (ns)	330/550		0.5	20/990/3000			25/680	
Power Pulsing	yes		yes	no			no	
beamstrahlung	high		high	low			low	
Detector concept	SiD	ILD	CLICdet	CLD	IDEA	Lar	Baseline	IDEA
B Field (T)	5	3.5	4	2	2	2	3	2
Vertex	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel
Vertex Rmin (mm)	16	16	31	12	12	12	16	16
Tracker	Si-strips	TPC	Si-Pixel	Si-Pixel (+RICH ?)	DC/Si-strips	DC/Si-strips or Si-Pixels	TPC or Strips	DC/Si-strips
Tracker Rmax (m)	1.25	1.8	1.5	2.2	2.0	2.0	1.8	2.1
Disks layers	4 + 4	2 + 5	6 + 7	3 + 7	3 (150 mrad)		2+6	

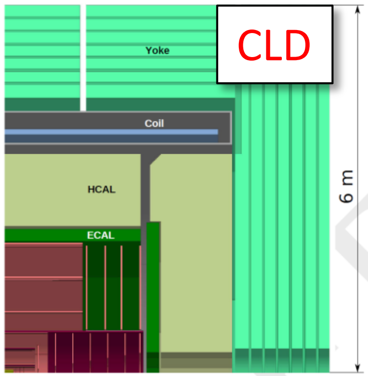


(From D. Dannheim)

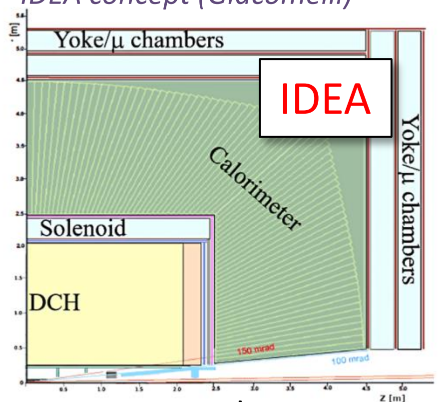
Large similarities between the concepts but also significant differences

Detector concept & tracking

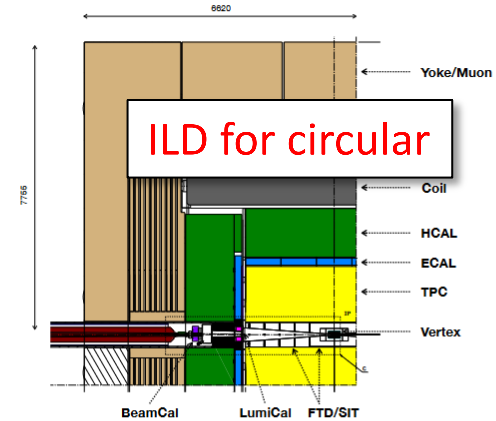
ILD & CLD concepts (Poeschl)



IDEA concept (Giacomelli)



ALLEGRO concept (Aleksa)



- Inspired from CLICdet
- « Full Silicon »
- Possibly + RICH
- Calo. inside coil

- VTX 3 layers
- Calo. outside coil
- Drift Chamber
- Si wrapper

IDEA drift chamber (Filippis)

- VTX: 3 double layers
- Calo. inside coil
- TPC ?

FCC & TPC (D. Jeans)

- VTX ⇨ Silicon pixels (CMOS-MAPS)
- Added dedicated timing layer ?
- Shared concerns: MDI, beam background, integration, cooling, etc.

Wireless (Rarbi)

Defining the figure of merits

Physics program priorities
√s

Cooling (Winter)

Vertexing
Tagging capabilities (b,c, τ, s)
Impact parameter resolution
Standalone tracking capabilities
Low pT tracking
Vertex charge determination
Hit/track separation
Displaced vertex (LLP, etc.)
Acceptance

65nm CMOS (Besson)

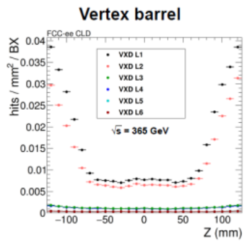
Tracking
Tracking efficiency/fake tracks
Momentum resolution
Charge determination
Robustness/redundancy
Association with calo. clusters

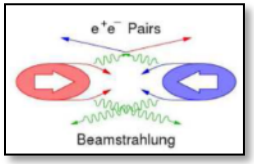
Particle ID
dEdx
Timing measurement
RICH

MPGD (Jeanneau)

Timing CMOS (Schwemling)

Picosec / micromegas (Kallitsopoulou)



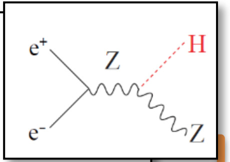


Vertex detector requirements (ILC/FCCee)

Physics O(Hz/cm²)

Beam background O(10-50 MHz/cm²)

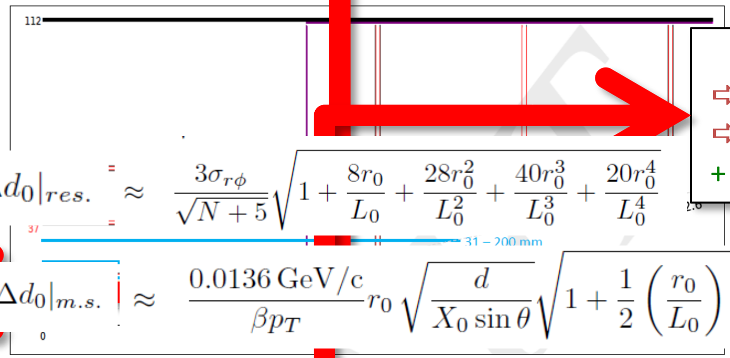
Physics
- ⇨ Flavour tagging
- ⇨ Low pT tracks
- ⇨ Vertex/Jet charge determination
- ⇨ Track seeding



Vertex reconstruction
- ⇨ granularity
- ⇨ Pitch ~17-20 μm
- ⇨ (σ_{sp} ~3-4 um)

CLD and IDEA Vertex Detectors designs (superimposed)

MAPS with $\sigma_{hit} \simeq 3$ μm and $X/X_0 \simeq 0.3\%$ / layer of Si
- CLD concept: double layers Barrel/Endcap configuration
- IDEA concept: single closer layers in Long Barrel configuration



$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV}/c}{\beta p_T} r_0 \sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

(Figure: D. Contardo)

Material Budget
- ⇨ ~ 0.15% X_0 / layer
- ⇨ < 1% X_0 for the whole VTX
- + ~0.4-0.6 % X_0 for the beam pipe

Beam background

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Rad.Tol. devices

Time resolution
O(100ns-1 μs)

O(10ns)@CLIC

Power consumption
~< 50mW/cm²

Fast read-out & low Power Architectures (~ 20-50 mW/cm²)

No Power pulsing @FCCee

Cooling
Stiffness / Alignment

Low material detectors & supports structures

$$\sigma_{d_0} = a \oplus \frac{b}{p\sin^{3/2}\theta}$$

$a \simeq 5\,\mu m$ b~10 − 15 $\mu m.GeV$

- Design: 5 single layers or 3 double layers ? Inner and outer radius ? Etc.
- R&D: ⇨Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution (BX)

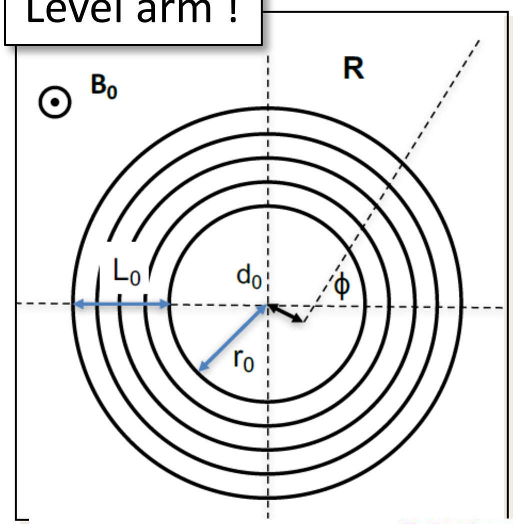
Ju

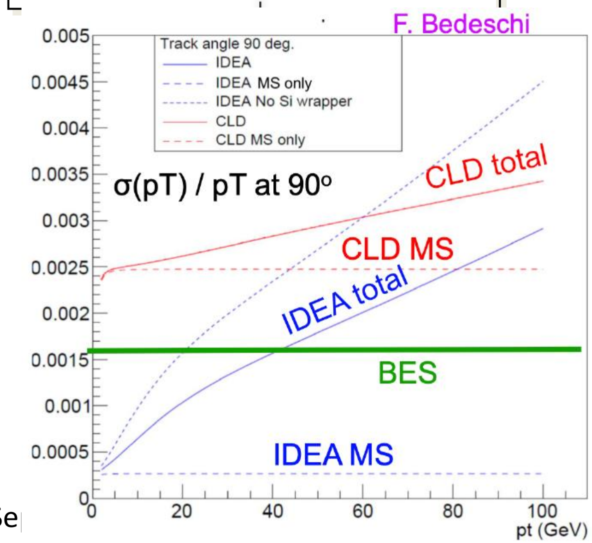
Tracker requirements

Expected performances

$$\frac{\sigma_{p_T}}{{p_T}^2} \sim 2 \times 10^{-5} GeV^{-1}$$

Level arm !





Physics
- ➪ Momentum resolution
- ➪ Tracking efficiency
- ➪ Track separation, low fake tracks
- ➪ Etc.

- Material budget vs intrinsic resolution
  - ✓ Typically σ_{sp} ~5-10 μm/layer ; material ~1-2% X_0/layer ; Power ~< 100 mW/cm^2
  - ✓ Low momentum vs high momentum ⇦ physics input
- 2 main options:
  - ✓ All silicon (CLD, CLICdet, SiD)
    - Few high resolution layers
    - Possibly timing capabilities
  - ✓ Silicon + Gazeous detector
    - TPC (ILD) / Drift Chamber (IDEA) / RICH (CLD ?)
    - dEdx/dNdx capabilities,
    - More hits, overall less materials
    - TPC: Ion back flow issue for circular colliders
- PID Strategy to be included (RICH, timing, dEdx, etc.)

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

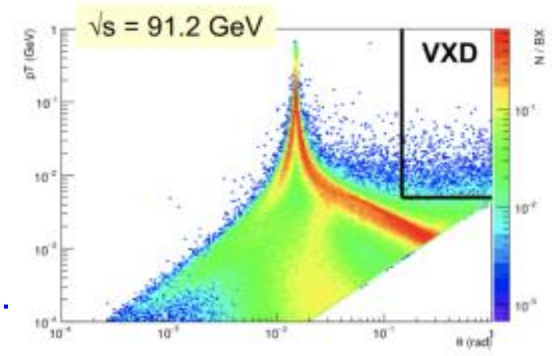
$$d_{tot}/X_0 = (N+1)d/X_0.$$ d = layer thickness, N = # layers

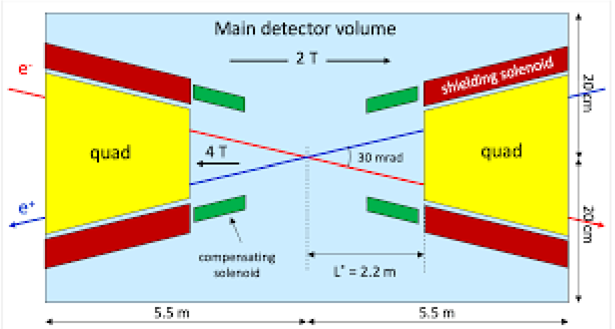
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\text{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}} \qquad \frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

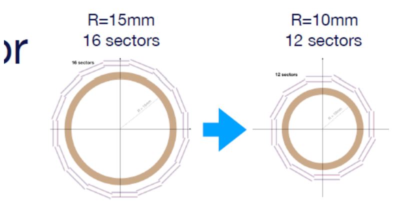
m.s. term dominates for pT ~< O(100) GeV/c

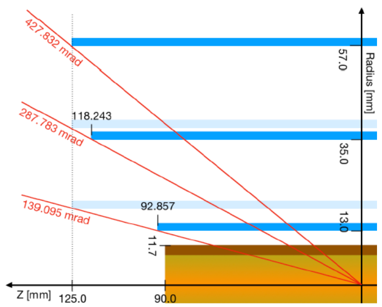
Vertex/tracking detector comments

- Particle ID has to be included in the tracker concept
  - ✓ dEdx and/or dNdx and/or fast timing
  - ✓ RICH ⇨ reduced outer radius
- Inner and outer radius are key factors
- Forward acceptance (e.g. asymmetry measurements)
  - ✓ Limited by MDI constraints, beam pipe, luminosity measurements, etc.
    - 30 mrad crossing angle (FCCee) ⇨ ~150 mrad acceptance
- B-field
  - ✓ Limited to 2 T in circular machine (@ Z-pole)
  - ✓ Calo inside coil ?
- Beam time structure
  - ✓ Power pulsing only for linears
- Beam related Background
  - ✓ Beamstrahlung (incoherent e^+e^- pairs)
    - Occupancy driver for linears
    - Less severe for circular (⇨Rmin reduction ~10mm))
  - ✓ Synchrotron radiation (mainly circulars)
    - Possible shielding (increase beampipe material budget)
- VTX Geometry
  - ✓ Probably 5-6 layers VTX (R < 60 mm)
    - Robustness (standalone tracking)
    - low momentum tracking
    - Track seeding @ different radii
    - e.g. FIPs, highly ionizining particles, LLPs, etc.









VTX/Tracking detector is highly connected to the MDI and the whole detector concept

J. Andrea, G. Sadowski, Z El Bitar

Beam pipe discussion

- V05 = new beam pipe radius & material budget
  - ✓ 5 µm Au + 2 x 350 µm layers of BeAl + liquid parafin ~ 0.6 % X_0 ⇨ mat. Budget +33%
  - ✓ Inner radius: 15 mm ⇨ 10mm

D0 resolution – single μ^- – CLD_o1_v04

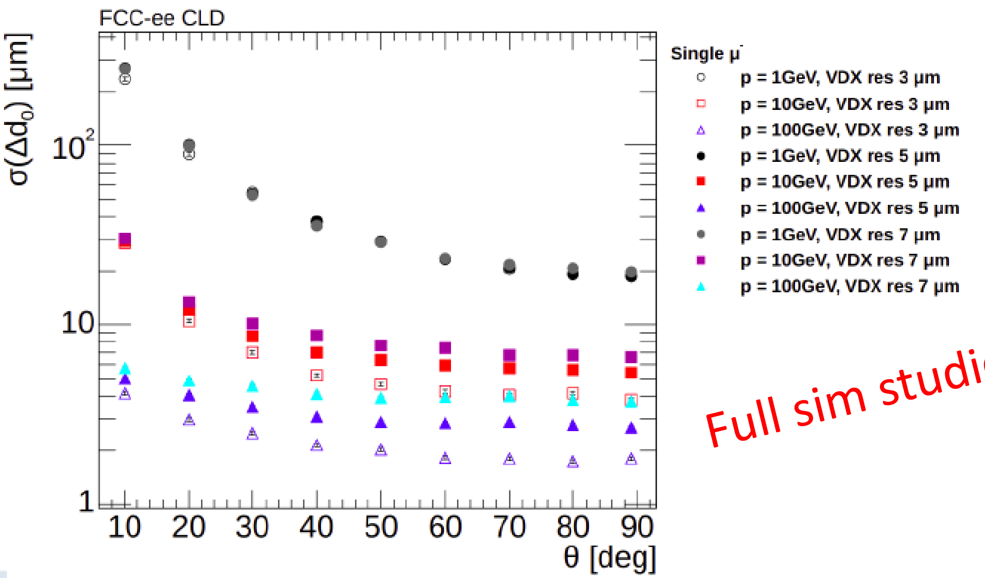


Figure: D0 resolution (10k events)

Full sim studies !

D0 & pT resolution – single μ^- – CLD_o2_v05 (10k events)

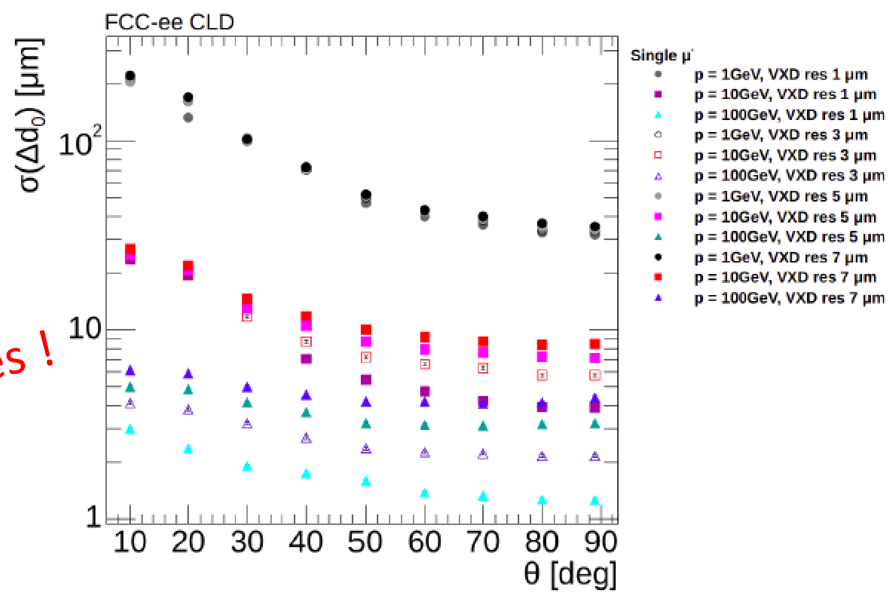


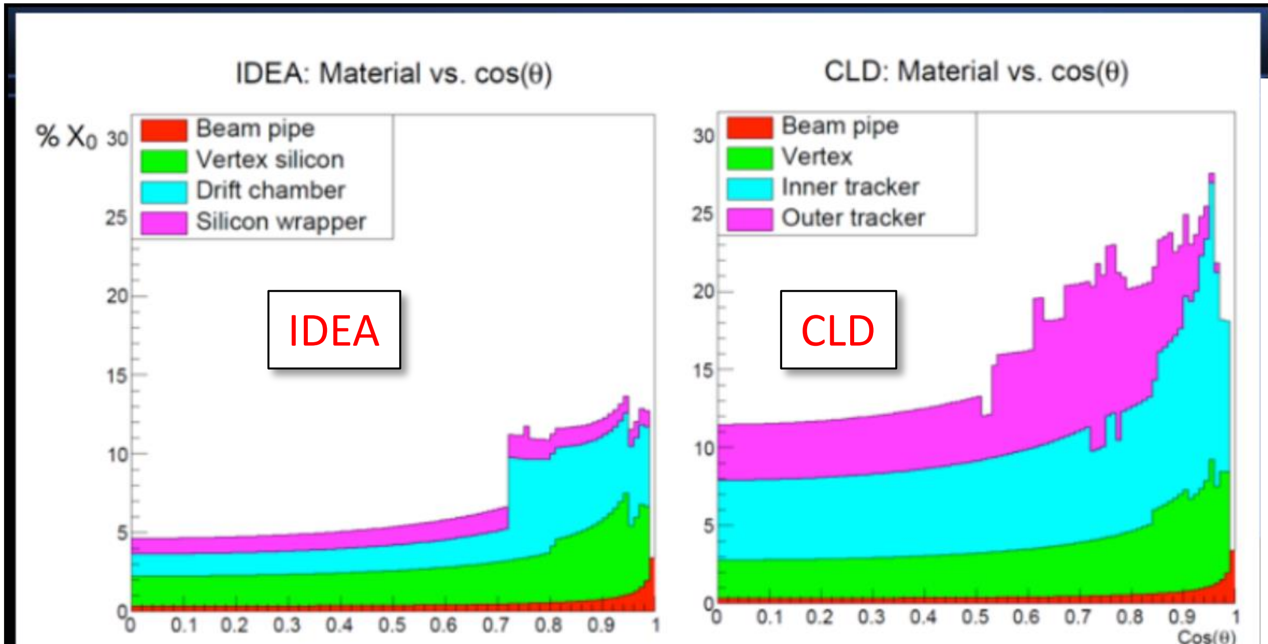
Figure: D0 resolution

V04 geom; sp. resolution = 3 um; p = 10 GeV, θ = 90 deg ⇨ $\sigma(\Delta d_0) = 3.8 \pm 0.1 \mu m$
V05 geom; sp. resolution = 3 um; p = 10 GeV, θ = 90 deg ⇨ $\sigma(\Delta d_0) = 5.7 \pm 0.1\ \mu m$
V04 geom; sp. resolution = 5 um; p = 10 GeV, θ = 90 deg ⇨ $\sigma(\Delta d_0) = 5.4 \pm 0.1 \mu m$
V05 geom; sp. resolution = 5 um; p = 10 GeV, θ = 90 deg ⇨ $\sigma(\Delta d_0) = 7.1 \pm 0.1\ \mu m$

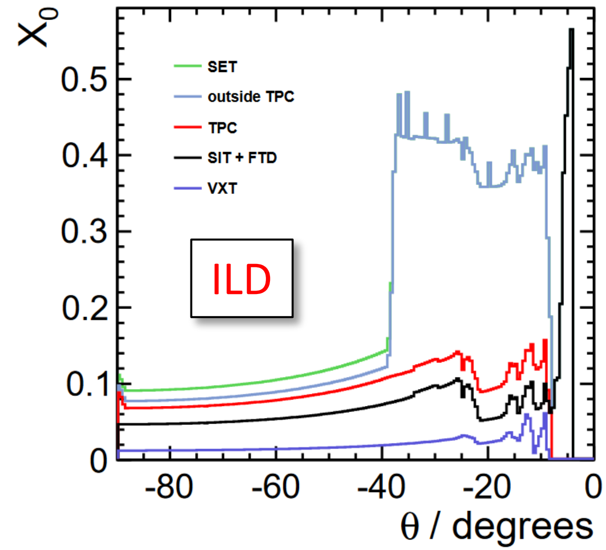
+42%

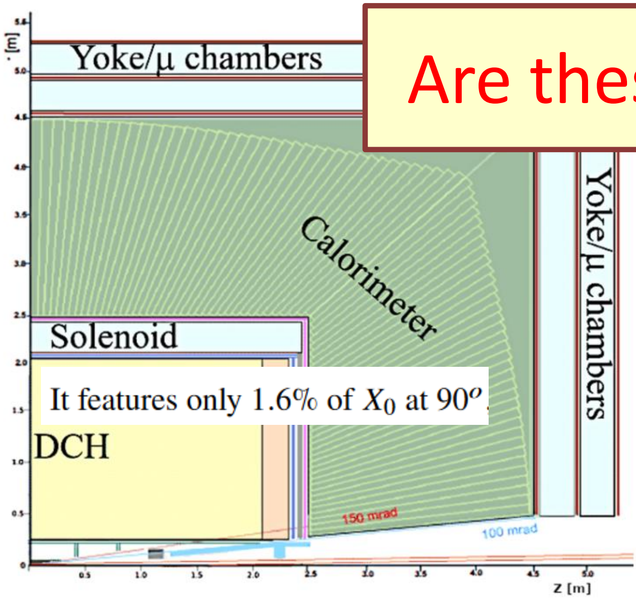
+24%

Material budget discussion

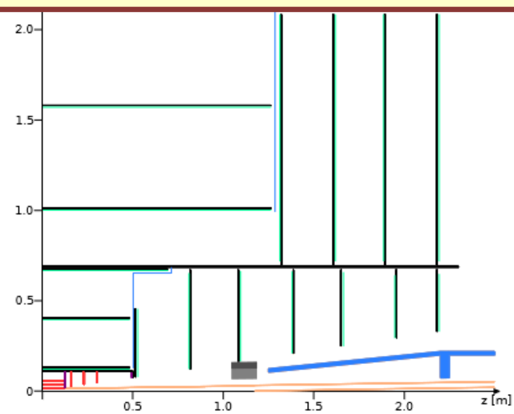


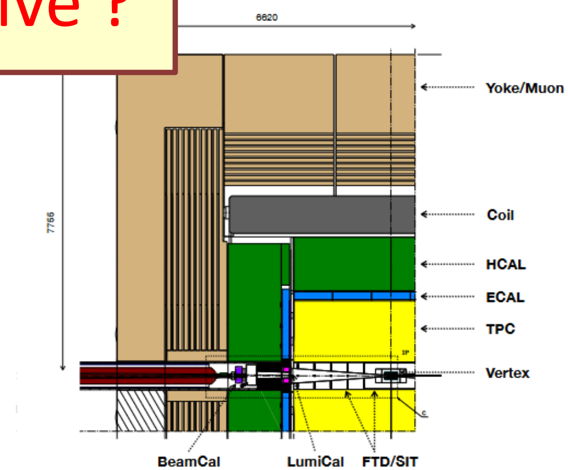
ILD material





Are these estimates conservative ?

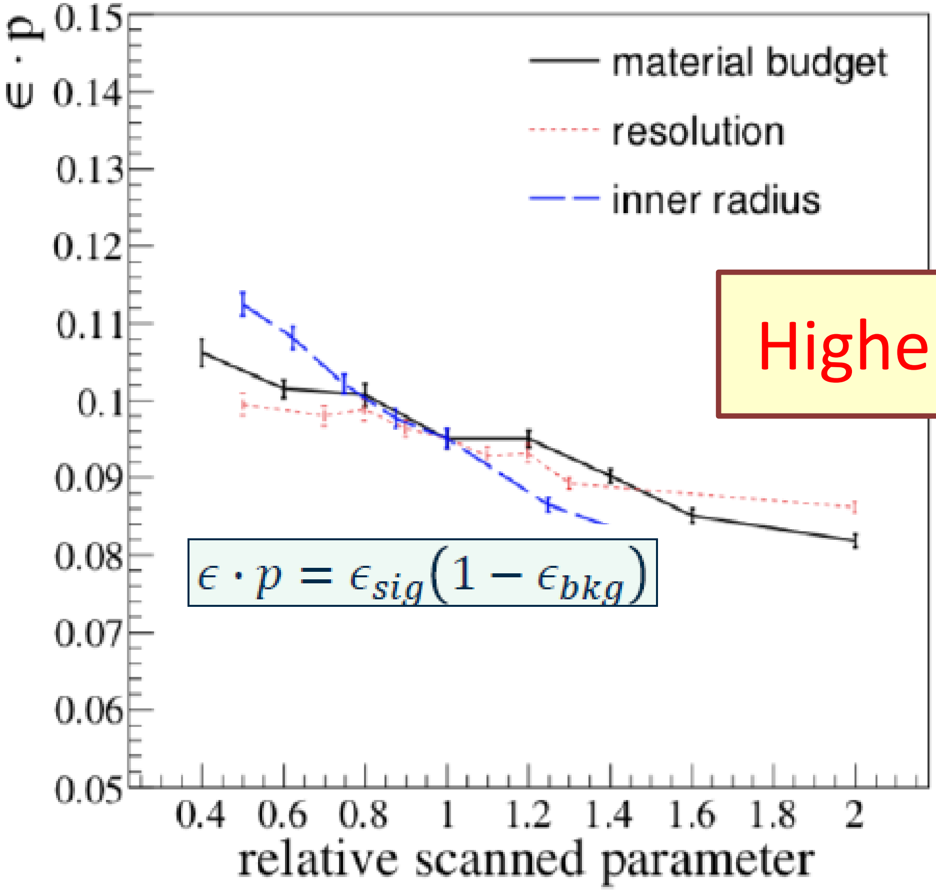




https://pos.sissa.it/414/337/pdf

CEPC vertex detector optimization

c-tagging: Detector optimization for CEPC



$\epsilon \cdot p = \epsilon_{sig}(1 - \epsilon_{bkg})$

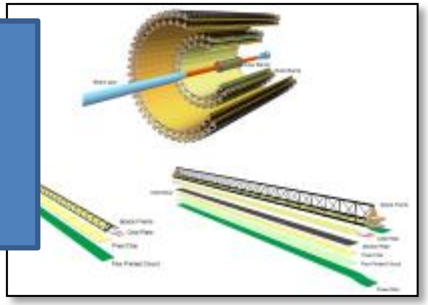
Higher dependance to mat. budget

M. Ruan, **ECFA WG3: Topical workshop on tracking and vertexing**

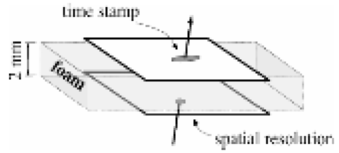
https://indico.cern.ch/event/1264807/contributions/5344222/attachments/2655752/4599314/ECFA-2.pdf

Material budget: starting from the layers

Classical single sided layers (e.g. ALICE ITS-2)



Double sided layers



PLUME

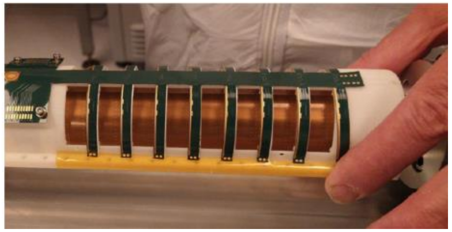
(Bristol, DESY, IPHC)

Double sided ladders with minimized material budget

0.35% X_0 reached ⇨ ~0.3 X_0 doable (with air flow cooling)

Pseudo stitching + bent sensors (superALPIDE)

- 1 silicon piece cut from one ALPIDE wafer (9x2 dies, ~1/2 of layer 0)



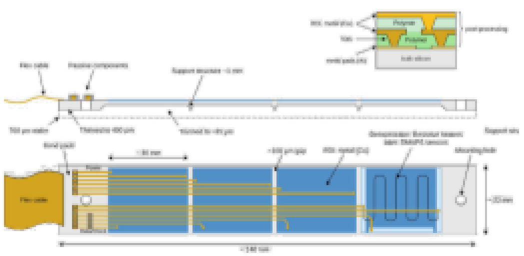
Integration !

Self supported silicon (Belle-2 upgrade)

7.1x1.5 cm²

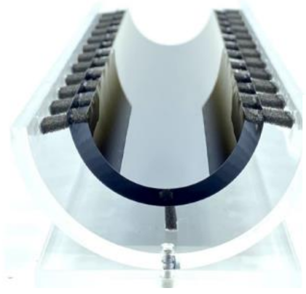
Thickness (edge/center) 430/90 µm

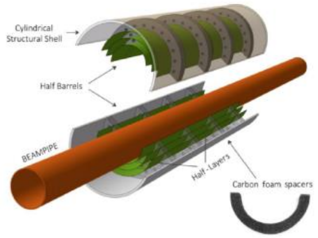
Planarity ~17 µm



Stitching + bent sensors ALICE-ITS3

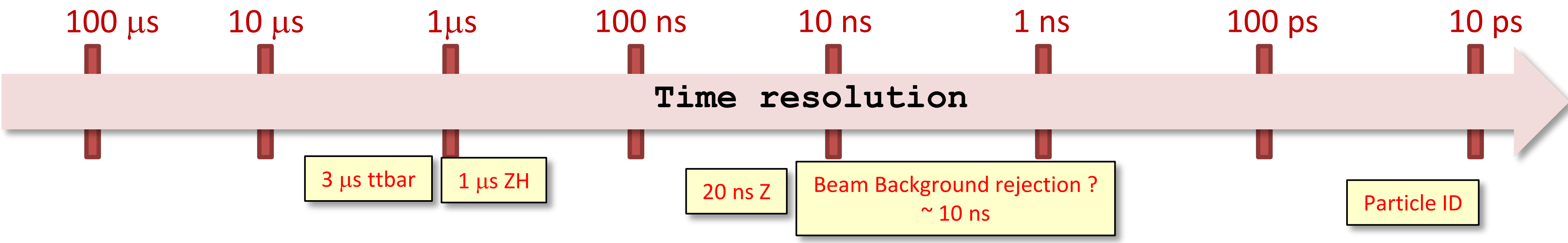
Layers 2+1





Inputs for engineering studies

Timing & 4-D tracking



- Time resolution Δt
  - ✓ Bunch separation (3 μs / 1 μs / 20 ns @ FCCee)
  - ✓ Background rejection ? (1-10 ns range)
  - ✓ Particle ID (10-100 ps)
- Usual drawbacks to go faster
  - ✓ Power consumption
  - ✓ Active Cooling & geometrical acceptance due to services
  - ✓ In pixel circuitry ⇨ larger pixels (or multipixels)
  - ✓ Fill factor, dead time
  - ✓ PID Restricted to low momentum particles (~< few GeV/c)
- Still
  - ✓ Forward region not covered by a central gazeous detector (TPC)
  - ✓ Added value for intermediate radii (e.g. LLPs ?)
- Specialized layers
  - ✓ Doesn't compromise the other requirements (material budget and granularity)
    - Probably not in the most inner layers

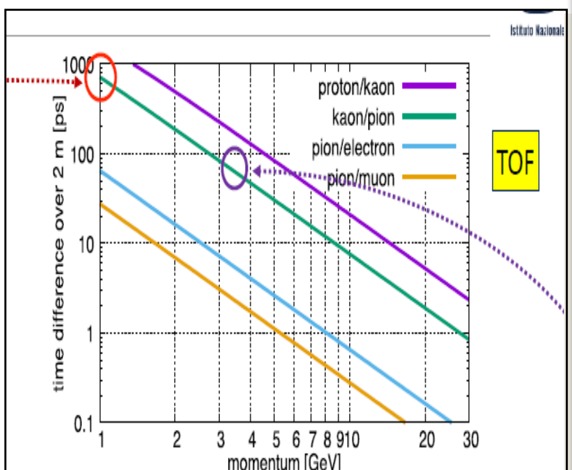
Particle ID and time resolution DRD4 & 1/3

More details here: https://indico.cern.ch/event/1202105/contributions/5402790/attachments/2662086/4612032/FCC-DRD4.pdf

- Goal:
  - ✓ K/π, π/e^- separation, etc. ⇨ Interest to push beyond 10 ps resolution
  - ✓ Even more important for the physics program @ Z peak

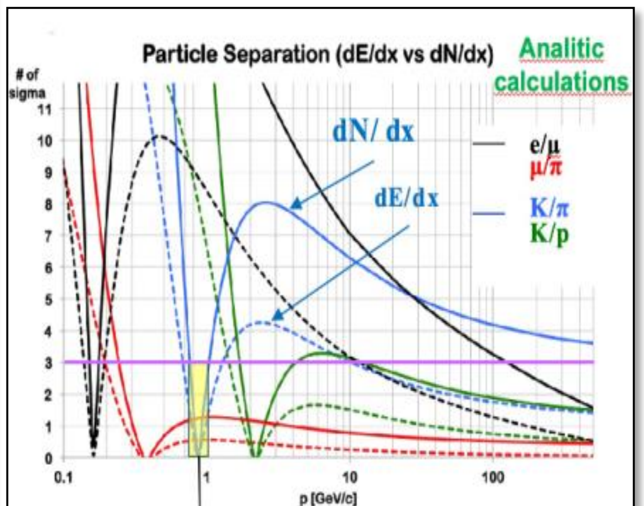
Fast timing (<100 ps) Solid state (pixelated) detector (DRD3)	dE/dx + dN/dx Mainly gazeous detector, e.g. TPC, DC, RICH (DRD1)

Time difference (ps)



Time of Flight

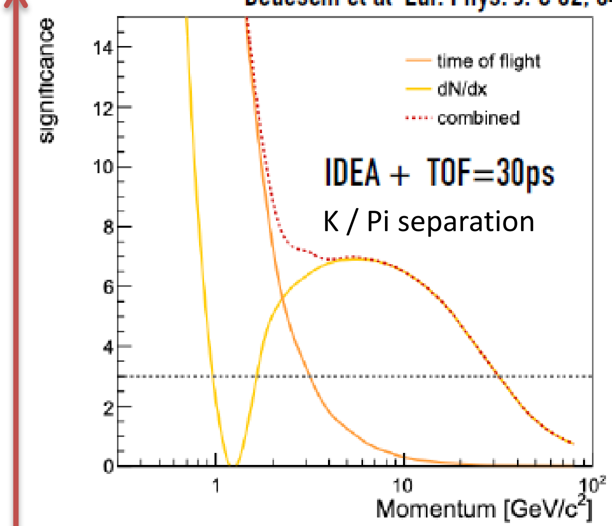
Separation Power (significance)



dE/dx – dN/dx

Separation Power

Bedeschi et al Eur. Phys. J. C 82, 646



Combined measurement

Momentum (GeV/c)

Particle ID and time resolution DRD4 & 1/3

TF#1 Gaseous Detectors — Anna Colaleo, Leszek Ropelewski
TF#2 Liquid Detectors — Roxanne Guenette, Jocelyn Monroe
TF#3 Solid State Detectors — Nicolo' Cartiglia, Giulio Pellegrini
TF#4 Photon Detectors & PID — Neville Harnew, Peter Krizan
TF#5 Quantum & Emerging Technologies — Marcel Demarteau, Michael Doser
TF#6 Calorimetry — Roberto Ferrari, Roman Poeschl

More details here: https://indico.cern.ch/event/1202105/contributions/5402790/attachments/2662086/4612032/FCC-DRD4.pdf

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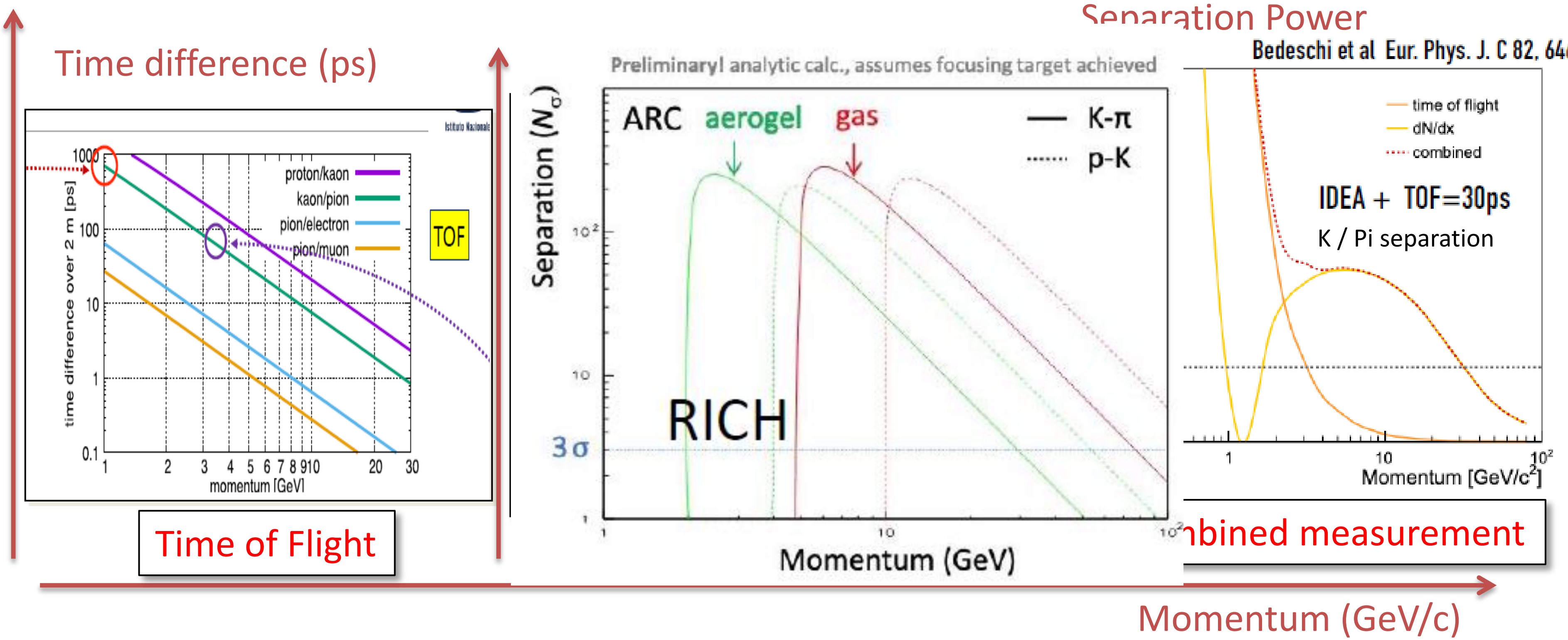


Agenda

CMOS-MAPS, Timing, gazeous detectors (TPC, Drift), wireless, Cooling

1st tracking session

09:00	Introduction: a reminder of the possible tracking concepts and technologies	*auguste besson*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	09:00 - 09:15
	MCMOS TPSco 65nm and electronics	*auguste besson*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	09:20 - 09:40
	Timing with MCMOS + potential application to FCC	*Philippe schwemling*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	09:45 - 10:00
10:00	picosec-Micromegas	*Alexandra Kallitsopoulou*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	10:05 - 10:20
	TPC in an FCC environment	*Daniel Jeans*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	10:25 - 10:40
	IDEA Drift Chamber	*Nicola De Filippis*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	10:45 - 10:55

Software session

Status of the Key4HEP Ecosystem	*Ziad El Bitar*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	14:30 - 14:45
Summary of software development in AIDAINNOVA	*Gérald Grenier*		
A preliminary estimation of the fluxes in calorimeters at t...	*Vincent BOUDRY*		
Detailed simulation in LAr Calorimetry	*Tong LI*		
Detailed simulation for Tracking	*Gaëlle Sadowski*		
R&D projects / parallel session (if needed)		*Piet Mondrian, Bâtiment 25*	15:00 - 16:00

Detector concept session

	ALLEGRO concept (presentation and discussion)	*Martin Aleksa*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	16:30 - 17:00
17:00	ILD' and CLD concept (presentation and discussion)		*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	17:00 - 17:30
	IDEA concept (presentation and discussion)	*Paolo Giacomelli*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	17:30 - 18:00
18:00	Possible sub-detectors EoI (presentations and discussions)		*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	18:00 - 18:30
	Global discussion (including "next steps in tracking R&D")		*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	18:30 - 19:00
19:00				

WADAPT : Wireless Allowing Data and Power Transfer	*Dr Fairouz MALEK et al.*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	10:30 - 10:45

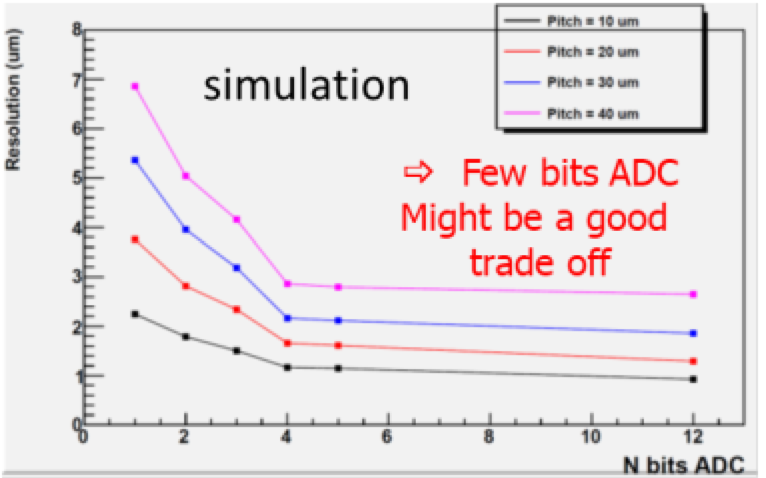
2nd tracking session

MPGD	*Fabien Jeanneau*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	11:00 - 11:15
A light Vertex detector cooling system for the ultimate Super KeKb luminosity	*Marc WINTER et al.*	*Bâtiment 25, Amphi Grünewald, Institut Pluridisciplinaire Hubert Curien, 23 rue du Loess, 67037 Strasbourg*	11:20 - 11:35

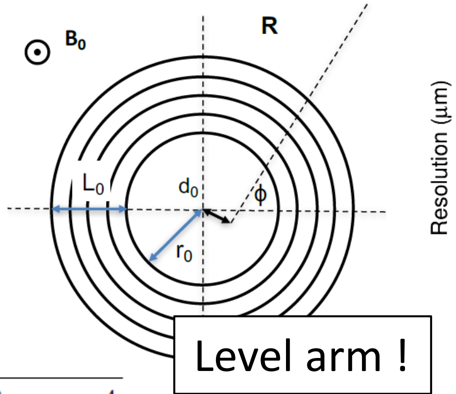
backup

Spatial resolution in Higgs factories

- Typical targets:
  - ✓ σ_{sp}~3 µm for the vertex layers
  - ✓ σ_{sp}~5-10 µm for the outer tracker layers
- Resolution in each layer depends on
  - ✓ Pitch
    - In conflict with the functionnalities inside the pixel
    - Favored by small feature size technology
  - ✓ Charge deposition
    - Sensitive layer thickness
  - ✓ Charge sharing (SNR vs resolution)
    - Depletion:
    - Staggered pixels
  - ✓ Charge encoding
    - Binary output / ADC / Tot / etc.



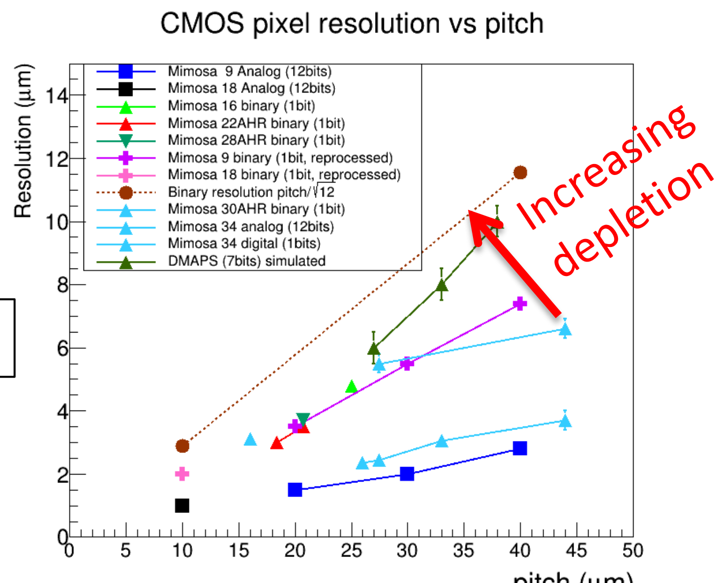
$$\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\,sin^{3/2}\theta}\right)^2$$



$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

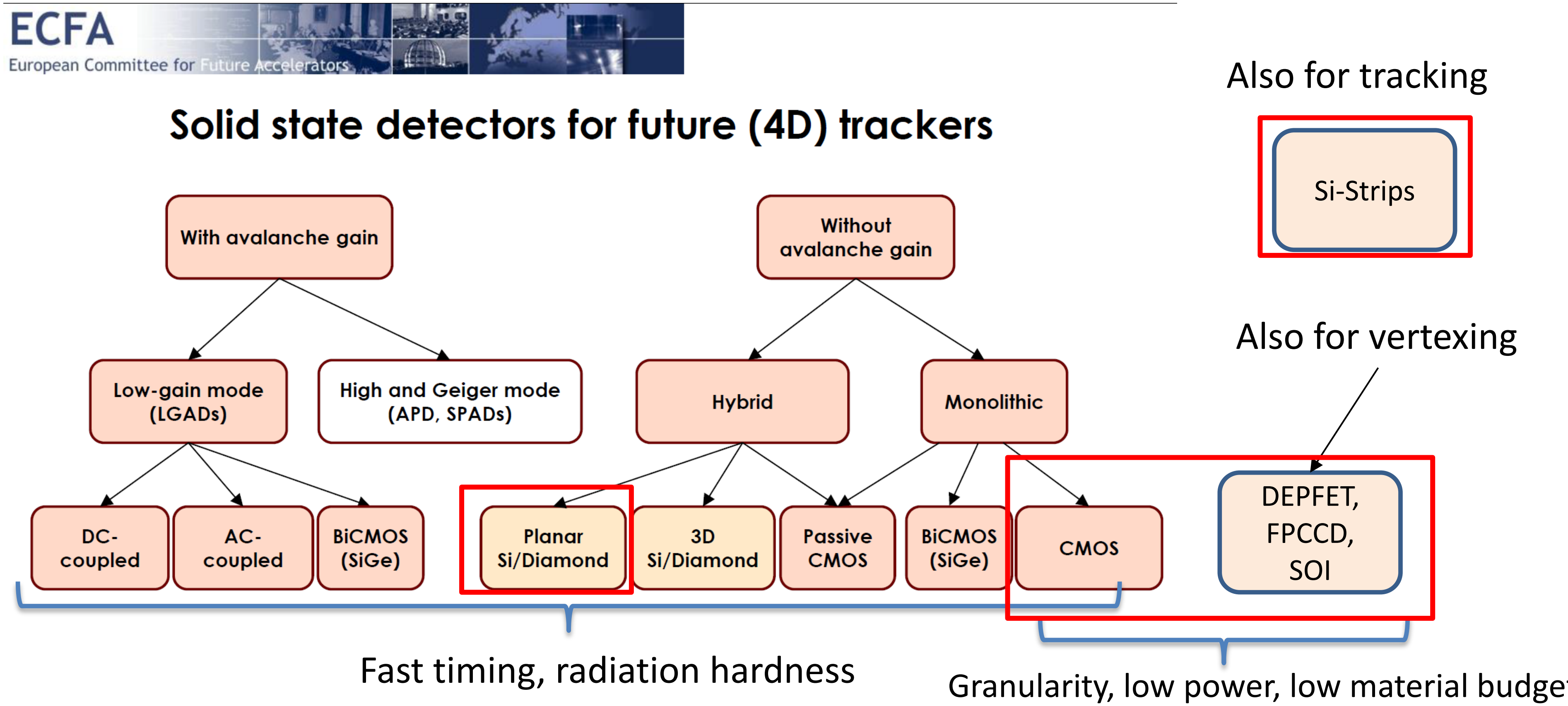
$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

d = layer thickness, N = # layers



⇨ σ_{sp} ~ 3 µm ⇦⇨ pitch ~ 15-20 µm
(assuming binary output, ~20 µm epi.thickness & large depletion in 180nm tech.)

Pixel detectors landscape for FCCee detectors



- VTX hierarchy of the driving parameters
  - ✓ Granularity & material budget > Power > time resolution > Radiation hardness
- Outer tracker
  - ✓ Material budget still a must. Relaxed granularity ⇨ possible focus on Power, time resolution
- Specialized timing layers
  - ✓ Timing layer ⇨ Price to pay: granularity and/or Power
- R&D needed to improve the parameter space

Power vs fast timing vs pixel size

Brief considerations about electronics: power

Name	Sensor	node	Pixel size	Temporal precision [ps]	Power [W/cm²]
ETROC	LGAD	65	1.3 x 1.3 mm²	~ 40	0.3
ALTIROC	LGAD	130	1.3 x 1.3 mm²	~ 40	0.4
TDCpic	PiN	130	300 x 300 μm²	~ 120	0.45 (matrix) + 2 (periphery
TIMEPIX4	PIN, 3D	65	55 x 55 μm²	~ 200	0.8
TimeSpot1	3D	28	55 x 55 μm²	~ 30 ps	5-10
FASTPIX	monolithic	180	20 x 20 μm²	~ 130	40
miniCACTUS	monolithic	150	0.5 x 1 mm²	~ 90	0.15 – 0.3
MonPicoAD	monolithic	130 SiGe	25 x 25 μm²	~ 36	40
Monolith	LGAD monolithic	130 SiGe	25 x 25 μm²	~ 25	40

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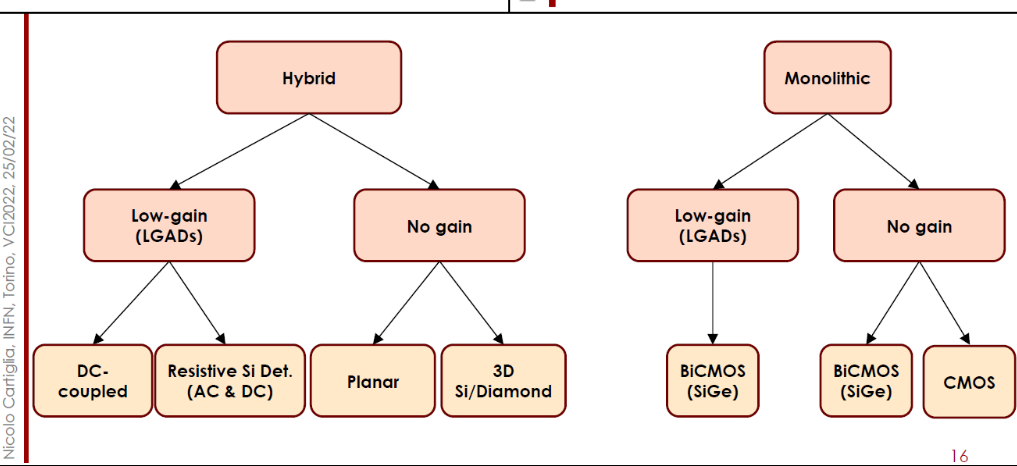
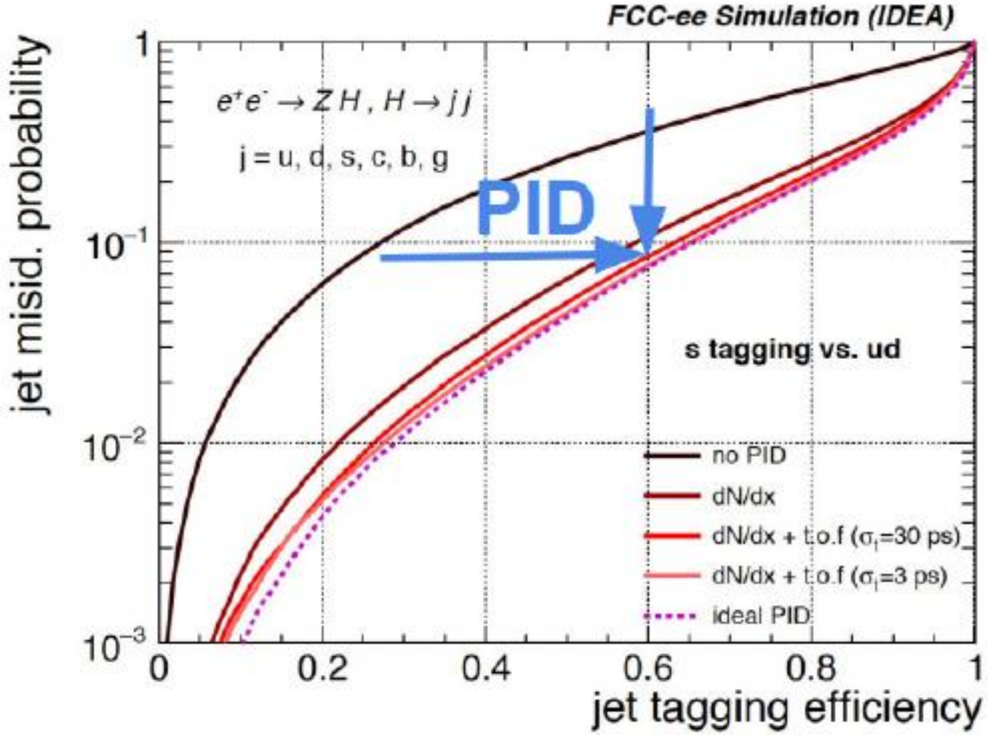


Price to pay: additionnal cooling system (addtionnal material)

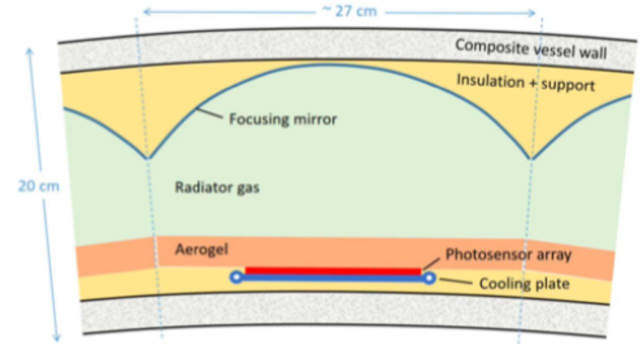
s-tagging



FCC-ee Simulation (IDEA)
$e^+e^- \to ZH, H \to jj$
j = u, d, s, c, b, g
PID
s tagging vs. ud
no PID
dN/dx
dN/dx + t.o.f (σ_t=30 ps)
dN/dx + t.o.f (σ_t=3 ps)
ideal PID
jet misid. probability
jet tagging efficiency
1
10^{-1}
10^{-2}
10^{-3}
0
0.2
0.4
0.6
0.8
1

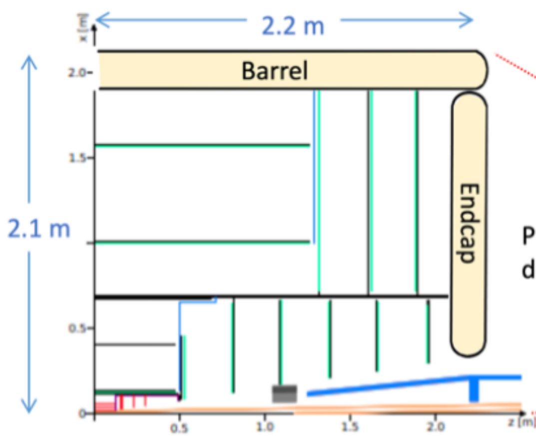
Compact RICH detector for FCC-ee

- Design goal: Compact design, max 20 cm depth, few % X_0
- Use spherical focussing mirrors, *r* = 30 cm, for radiator thickness of 15 cm
- Two radiators
  - Aerogel
  - Gas
    - Unpressurised C_4F_{10} gives good momentum range for K-π separation, with acceptable photon yield
    - Pressurised Xenon may provide similar performance if fluorocarbons unacceptable



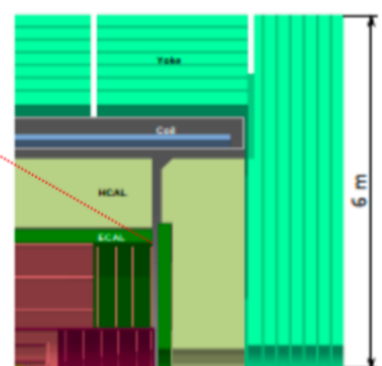
ARC detector (one cell)

Zoom on tracker

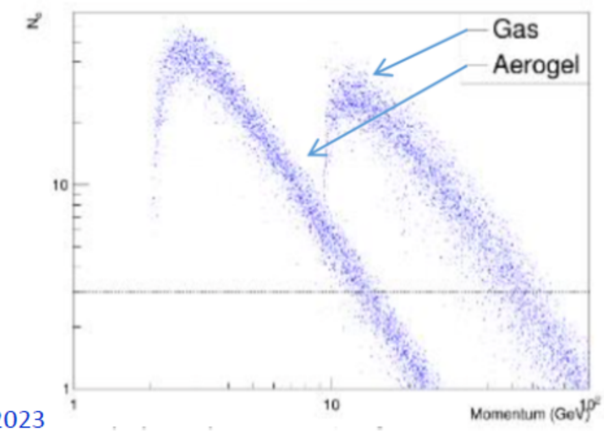


Proposed **ARC** detector

A quarter of **CLD**



K-π separation



R.Forty, 9th FCC Week, 2023

Mogens Dam / NBI Copenhagen CERN EP Seminar on Future Colliders 20.06.2023 19