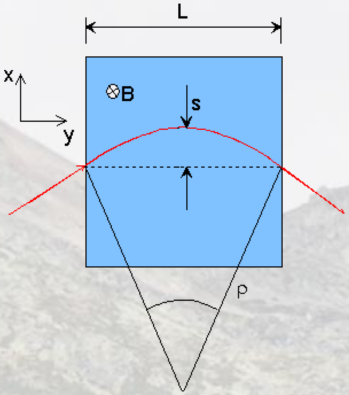
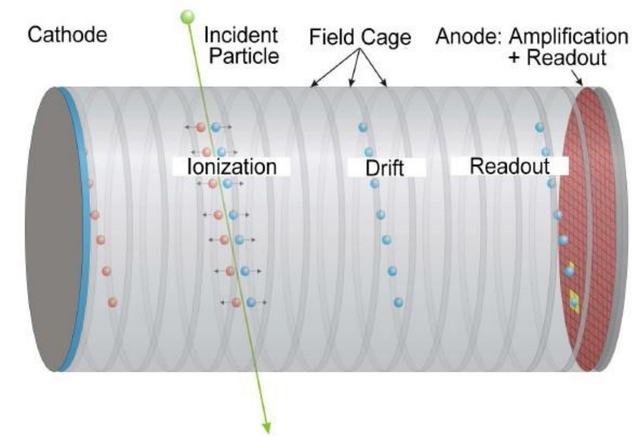
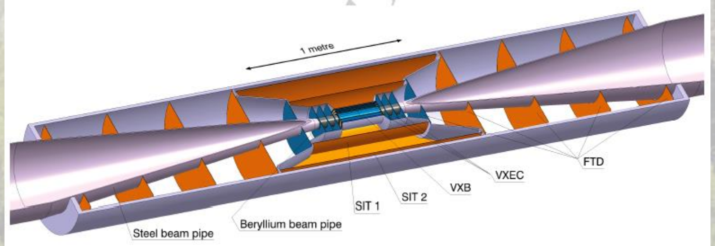
FORWARD TRACKING AT CLIC







A. Ruiz-Jimeno,CLIC-CERN_1Oct2013

Outline

Requirements

Detector concepts layout

Environment background

Momentum Resolution

Impact parameter precision

Pattern recognition

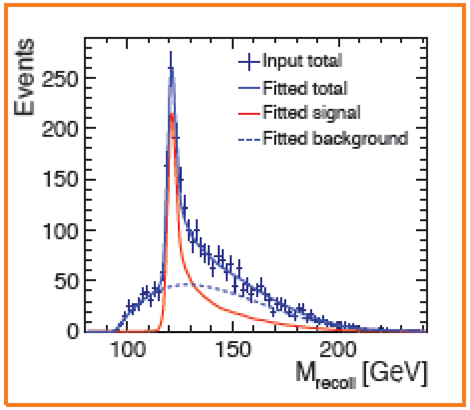
*More details on JINST **8** T06001 2013*

Thanks to D. Dannheim, M. Vos et al.

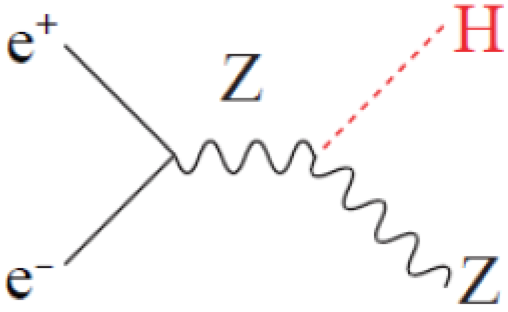
Requirements at CLIC

Good momentum resolution

$$\sigma_{p_T}/p_T^2 \sim 2\times 10^{-5}\,\mathrm{GeV}^{-1}$$



350 GeV



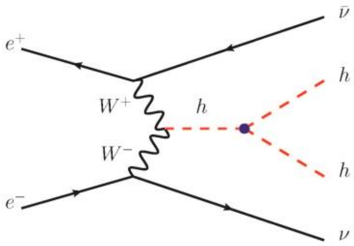
Good impact parameter precision

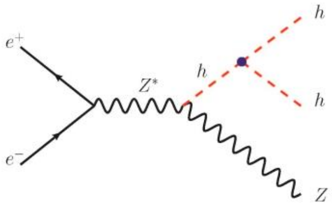
b,c,τ tagging

$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

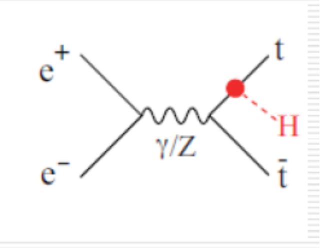
barrel

Good pattern recognition



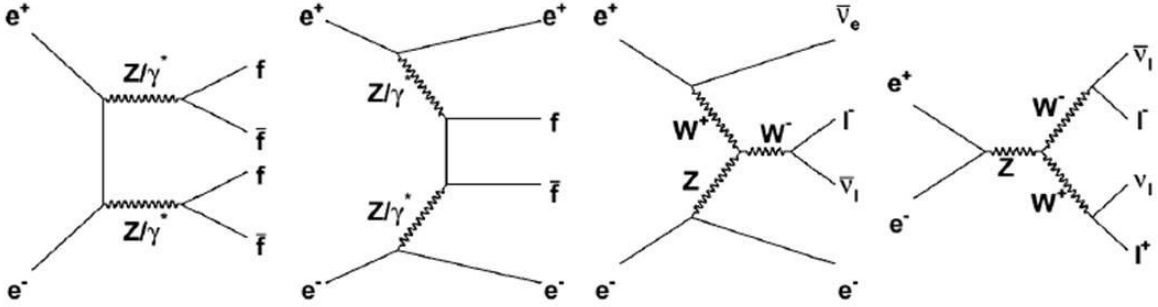


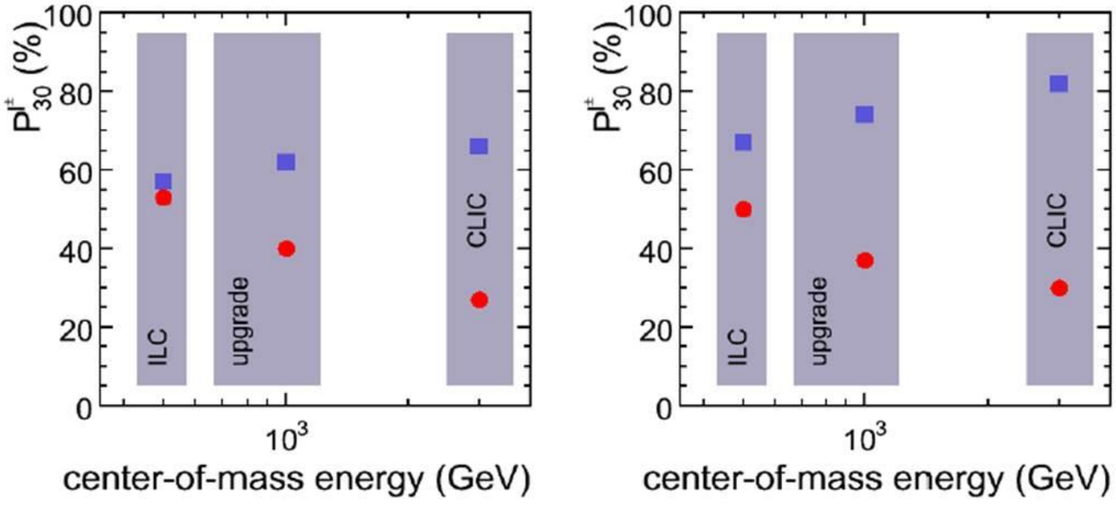
Full angular acceptance



High jet multiplicity

Full angular acceptance





(a) $l^+l^-\nu\bar{\nu}$

(b) $l^+l^-l^+l^-$

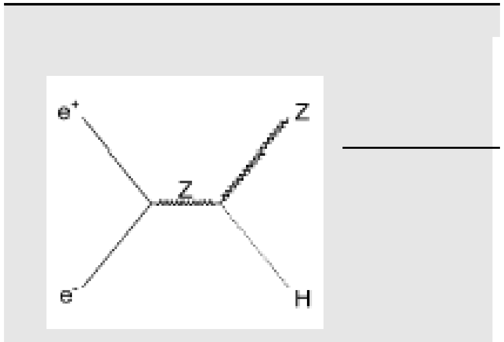
Figure 11. MadGraph [13] prediction for the fraction of charged leptons emitted in the forward direction in $l^+l^-\nu\bar{\nu}$ and $l^+l^-l^+l^-$ events. The round markers represent $P_{30}^{l\pm}$, while the squared markers correspond to the total fraction of forward charged leptons ($\theta < 30^\circ$).

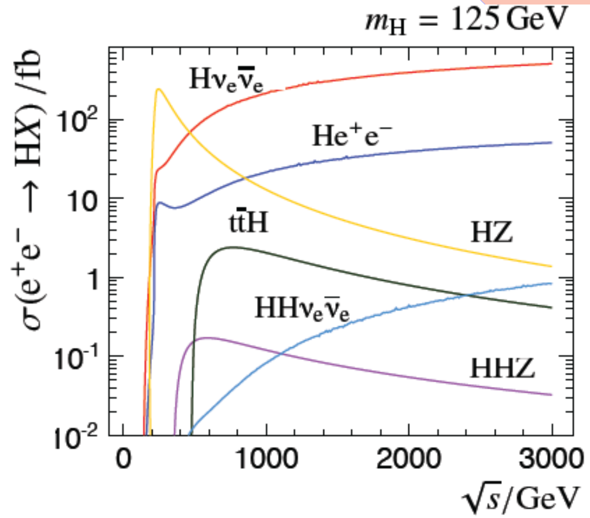
Forward tracking increasingly important with higher c.m.s. energy

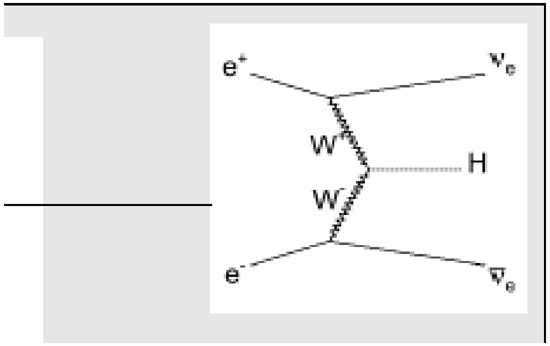
2009 JINST4 P08002

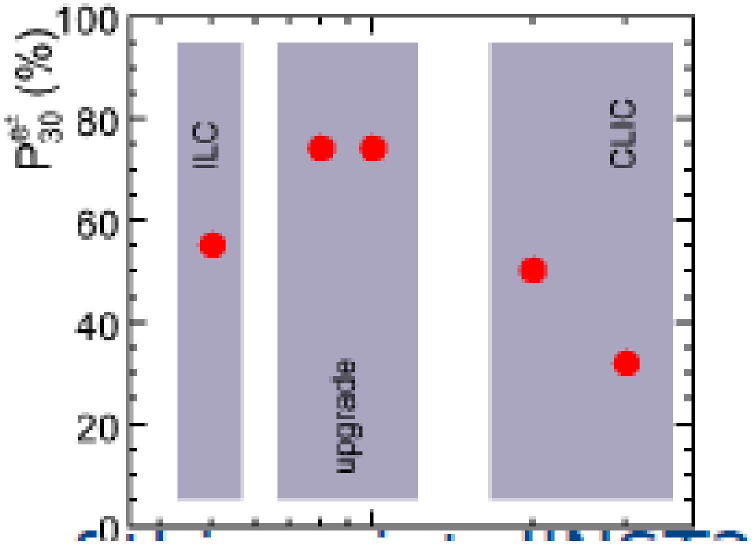
Full angular acceptance

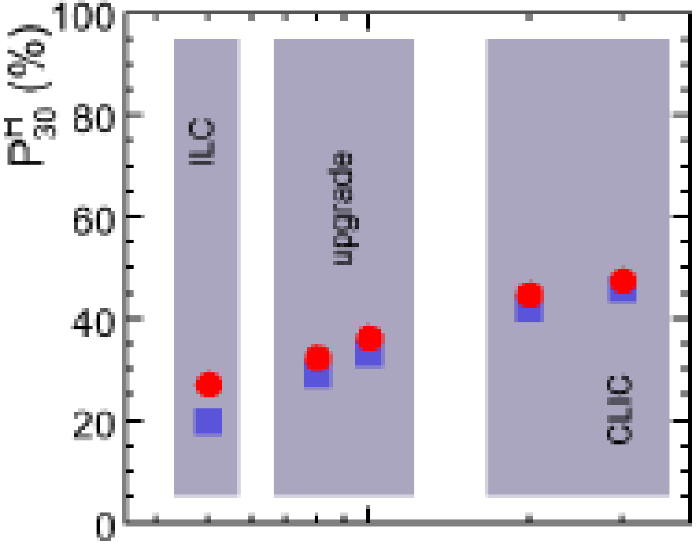
Forward tracking increasingly important with higher c.m.s. energy







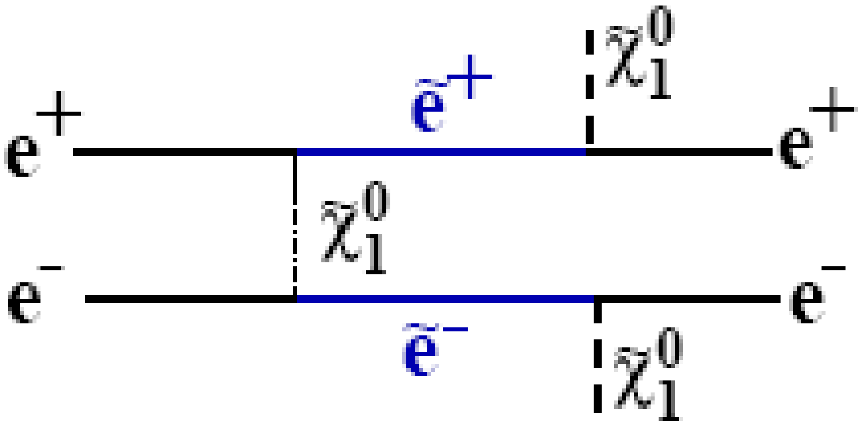


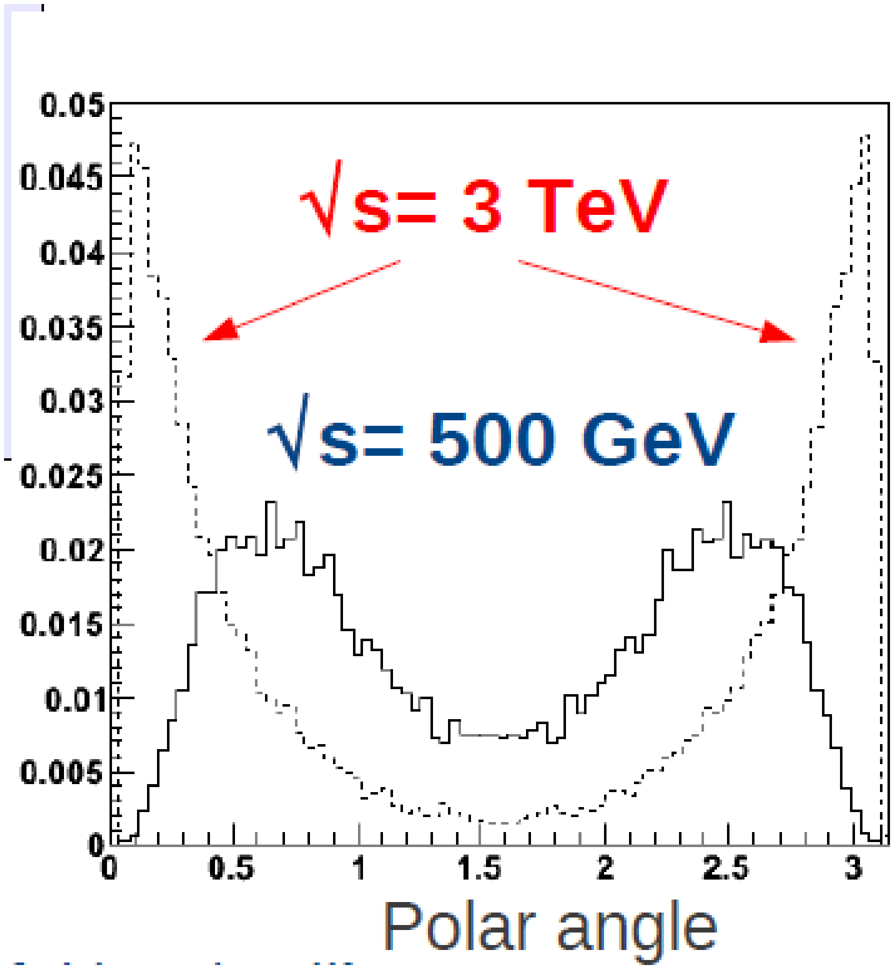


2009 JINST4 P08002

Full angular acceptance

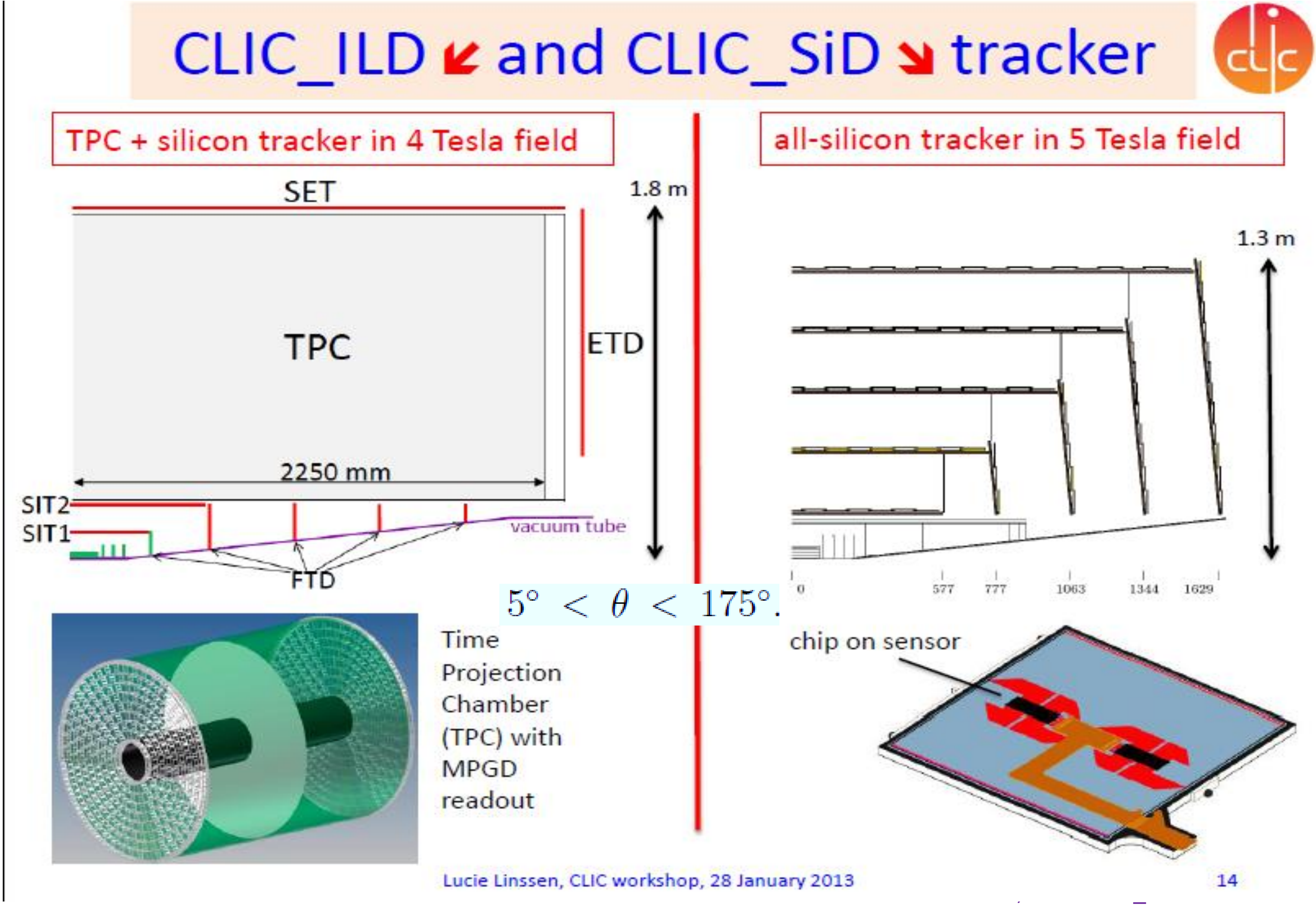
Forward tracking increasingly important with higher c.m.s. energy





2009 JINST4 P08002

Two detector concepts .



CLIC_ILD ↙ and CLIC_SiD ↘ tracker

TPC + silicon tracker in 4 Tesla field

all-silicon tracker in 5 Tesla field

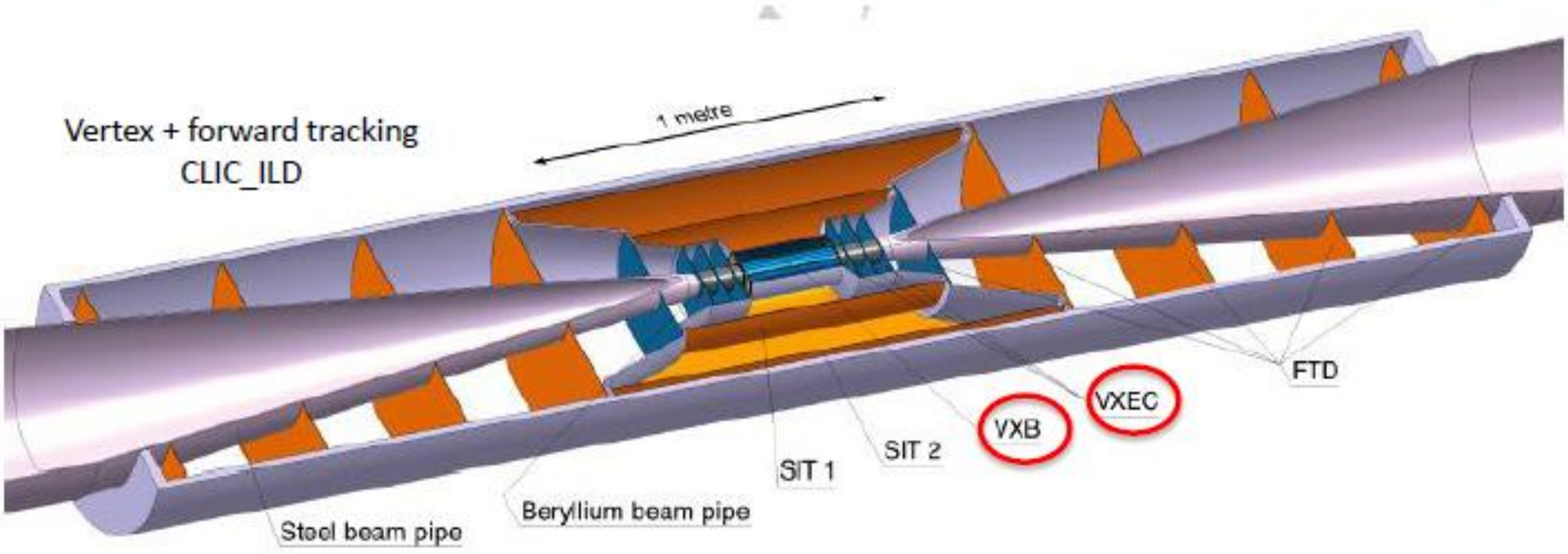
$5° < \theta < 175°.$

Time Projection Chamber (TPC) with MPGD readout

chip on sensor

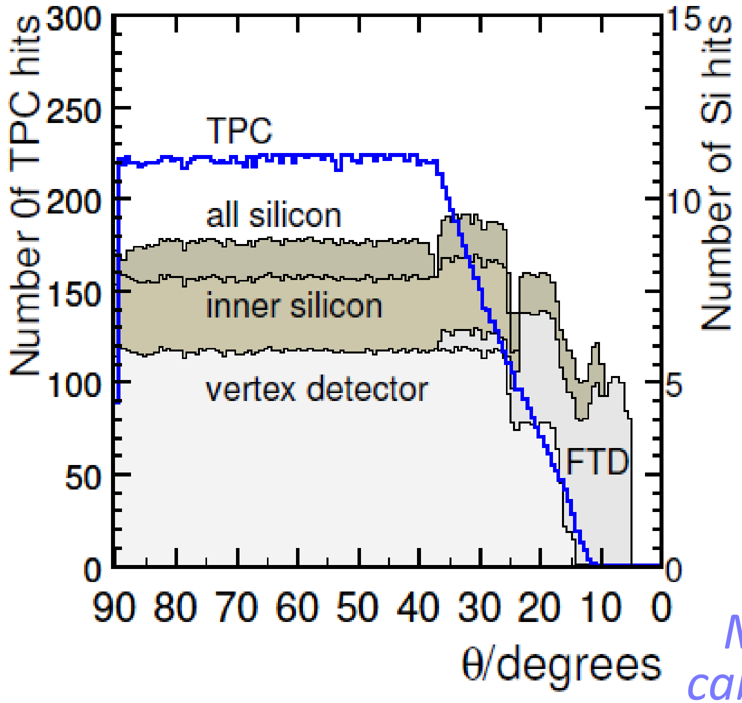
Lucie Linssen, CLIC workshop, 28 January 2013

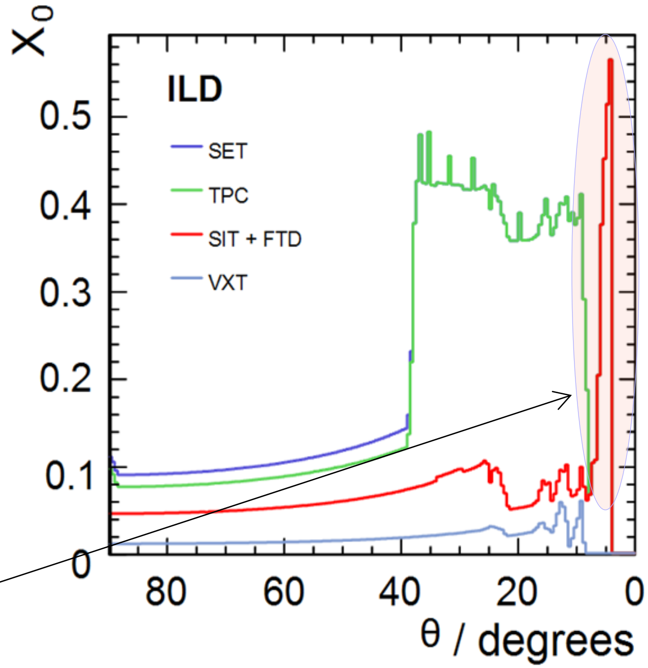
CLIC vertex detector



- ~25×25 µm pixel size => ~2 Giga-pixels
- 0.2% X_0 material par layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
  - Aim: 0.2 µW/channel
- Time stamping 10 ns
- Radiation level <10^{11} $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

Very challenging R&D project !





Mainly vertex cables, services… (not FTD)

ILD design for ILC

*For **CLIC**, the innermost vertex detector layer radius is increased from1.5 cm. to 2.6 cm or 3.1 cm (in both concepts), and the FTD pixel part is modified to recover the coverage lost for the increase of the inner radius of the barrel*

To increase the pattern recognition robustness of the forward system the innermost forward tracking system is formed by six closely spaced and highly granular disks

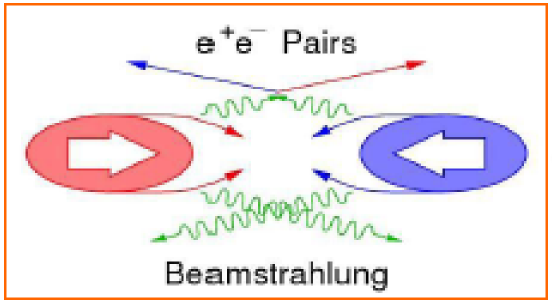
(Berilium pipe at 5º, of 0.07% X0)

CLIC machine environment (1)

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (µm)	44

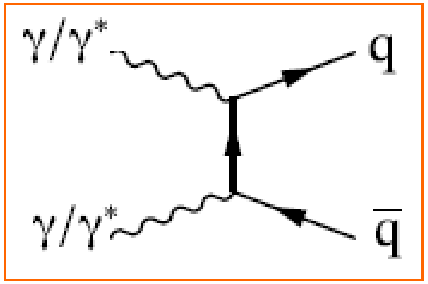
Drives timing requirements for CLIC detector

very small beam size



Beam related background:

- Small beam profile at IP leads very high E-field
  - **Beamstrahlung**
    - Pair-background
    - γγ to hadrons



CLIC machine environment (2)

Coherent e^+e^- pairs
- 7×10^8 per BX, very forward

Incoherent e^+e^- pairs
- 3×10^5 per BX, rather forward

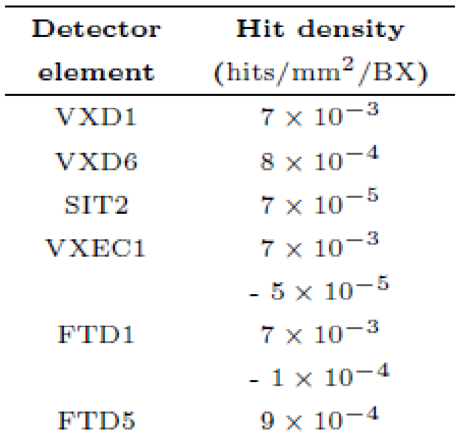
$\gamma\gamma \rightarrow$ hadrons
- 3.2 events per BX
- main background in calorimeters
  - ~19 TeV in HCAL per bunch train

→

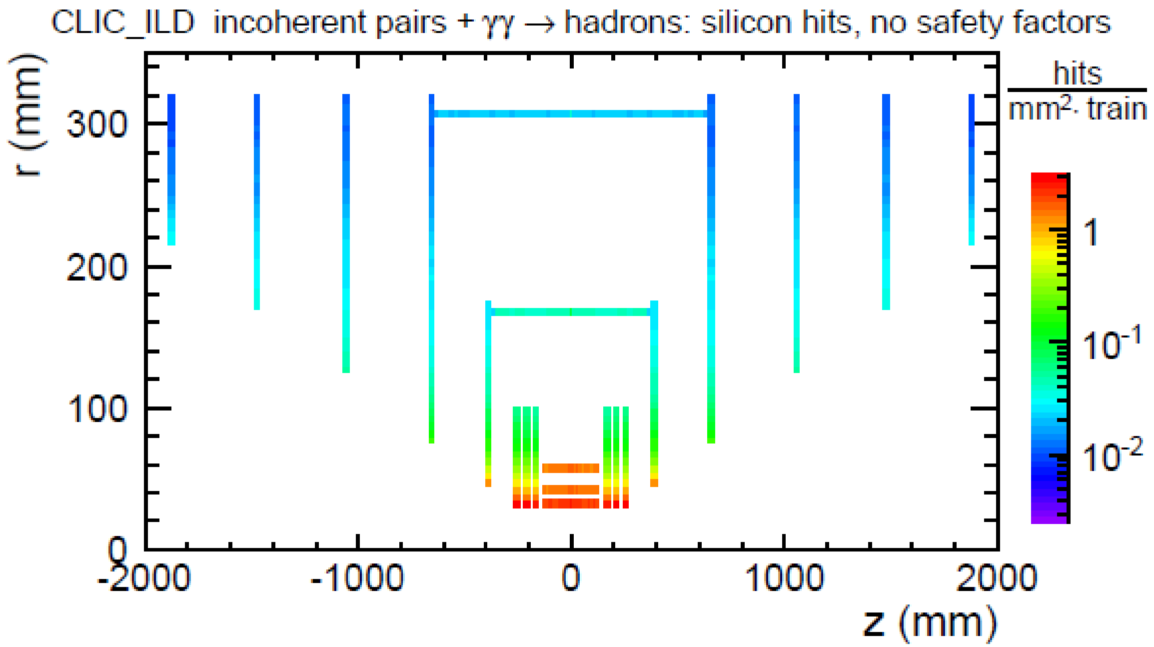
Simplified view:

Pair background
- Design issue (high occupancies)

$\gamma\gamma \rightarrow$ hadrons
- Impacts on the physics
- Needs suppression in data



Detector element	Hit density (hits/mm^2/BX)
VXD1	7×10^{-3}
VXD6	8×10^{-4}
SIT2	7×10^{-5}
VXEC1	7×10^{-3} $- 5 \times 10^{-5}$
FTD1	7×10^{-3} $- 1 \times 10^{-4}$
FTD5	9×10^{-4}



hits/mm^2/BX). The table shows average densities over the detector surface, except for the innermost vertex detector disk (VXEC1) and the innermost forward tracking disk (FTD1), where the densities at the innermost and outermost radius

Good momentum resolution

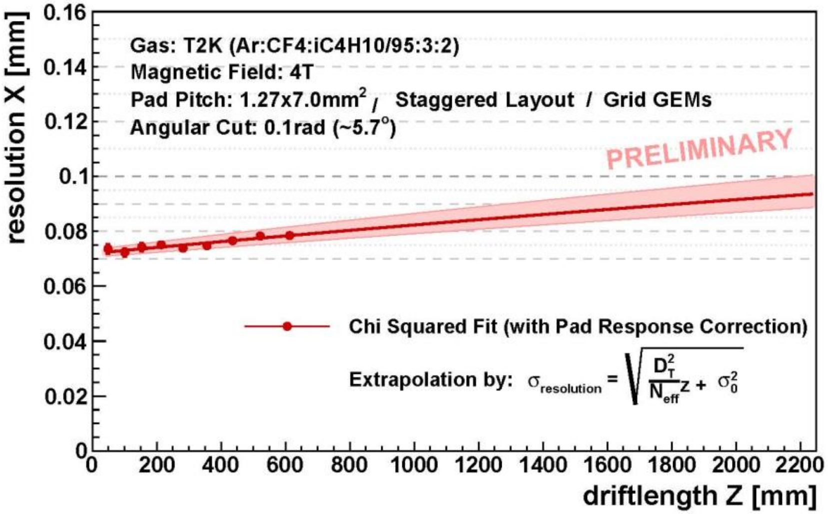
$$\sigma_{1/p_T} \approx \sqrt{\left(\frac{2\times 10^{-5}}{\mathrm{GeV}^{-1}}\right)^2 + \left(\frac{10^{-3}}{p_T\,[\mathrm{GeV}]\sin\theta}\right)^2} \quad \rightarrow$$

Goal ILD

Gluckstern formula for N equally spaced layers
(N>10, no Multiple Scattering)
Lever arm L perpendicular to magnetic field B

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{720}{N+4}}\,\sigma_{r\phi}\,\frac{p_T}{0.3BL^2},$$

Degradation at small angle due to the reduction of L

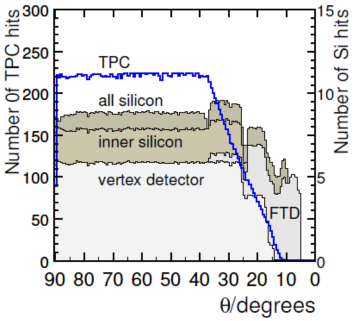


TPC resolution is dependent of drift length

Complex tracking system ILD:

- $\sigma_{r\phi}$ *not uniform*
- *at angles<40º, N decreases, added to shorter L*
- *forward tracking, N<10,* $\sigma_{r\phi} \sim 7\mu m$

Note also that $\Delta(1/p) \sim \Delta(1/p_t) * \sin\theta$*, important in the forward tracks*
(the total momentum is the relevant quantity for most physics analysis)

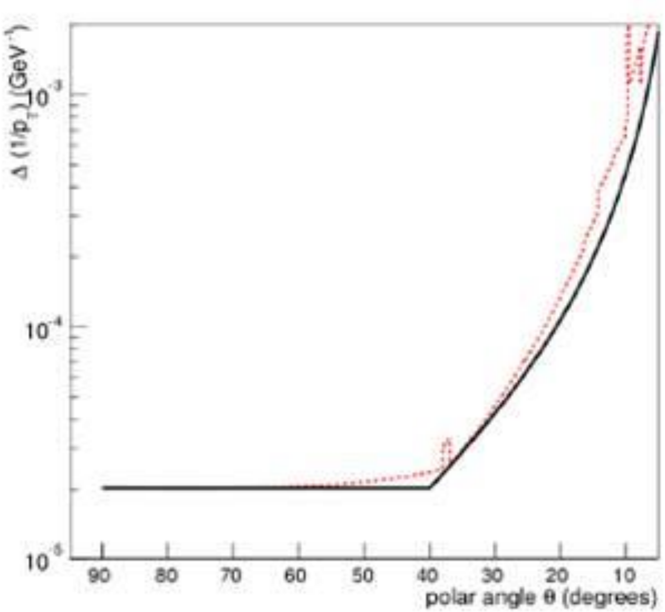


Good momentum resolution

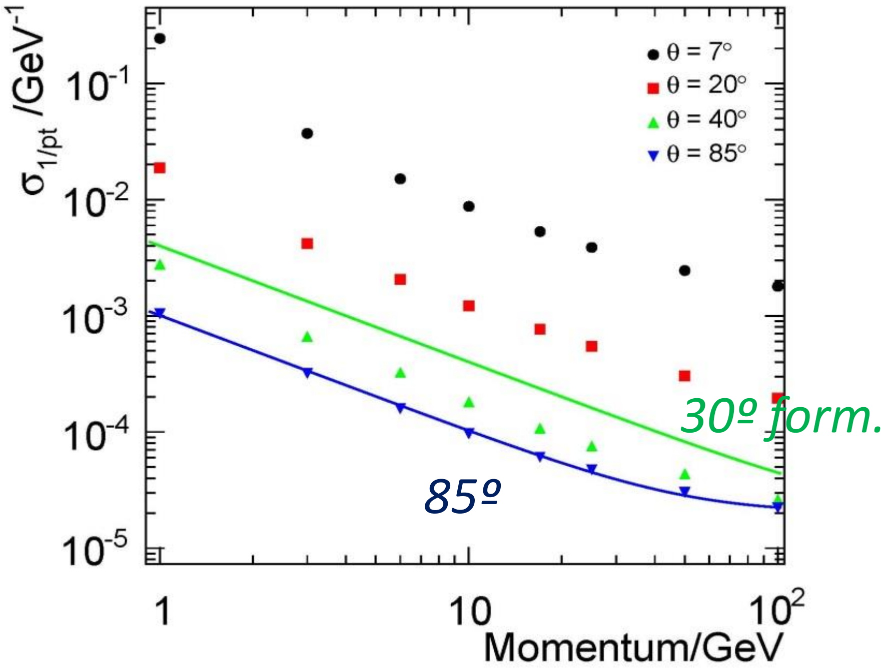
$$\sigma_{1/p_T} \approx \sqrt{\left(\frac{2\times10^{-5}}{\mathrm{GeV}^{-1}}\right)^2 + \left(\frac{10^{-3}}{p_T\,[\mathrm{GeV}]\sin\theta}\right)^2}$$

→ Goal ILD

Multiple scattering contribution depends on the material budget. Equals the other term at p~50GeV, at large angle



ILD 100GeV muons
(dashed line: fast simulation;
continuous line:Gluckstern)



ILD-ILC

Good impact parameter precision

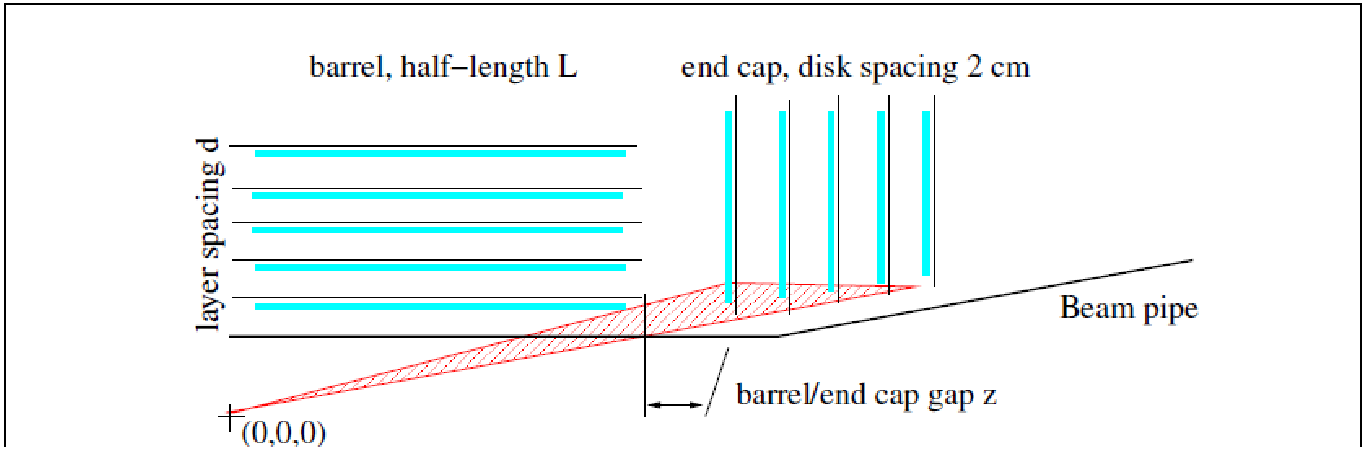
$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\text{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\text{m}}$$

barrel

Forward- backward

$$\Delta d_0 = a[\mu\text{m}] \oplus \frac{b \times \frac{L}{R}[\mu\text{m}]}{p[GeV]\cos^{3/2}\theta}.$$

- *The distance to the interaction point (IP) of the innermost hit goes as (sin$^{-1}\theta$, cos$^{-1}\theta$) in the (barrel, forward) tracking*
- *Multiple scattering is proportional to square root of material thickness in X_0*
- *Finally, b is multiplied, in the forward tracker, by the ratio of the IP distance along z (L) of the first disk to the inner radius of the barrel tracker (R)*

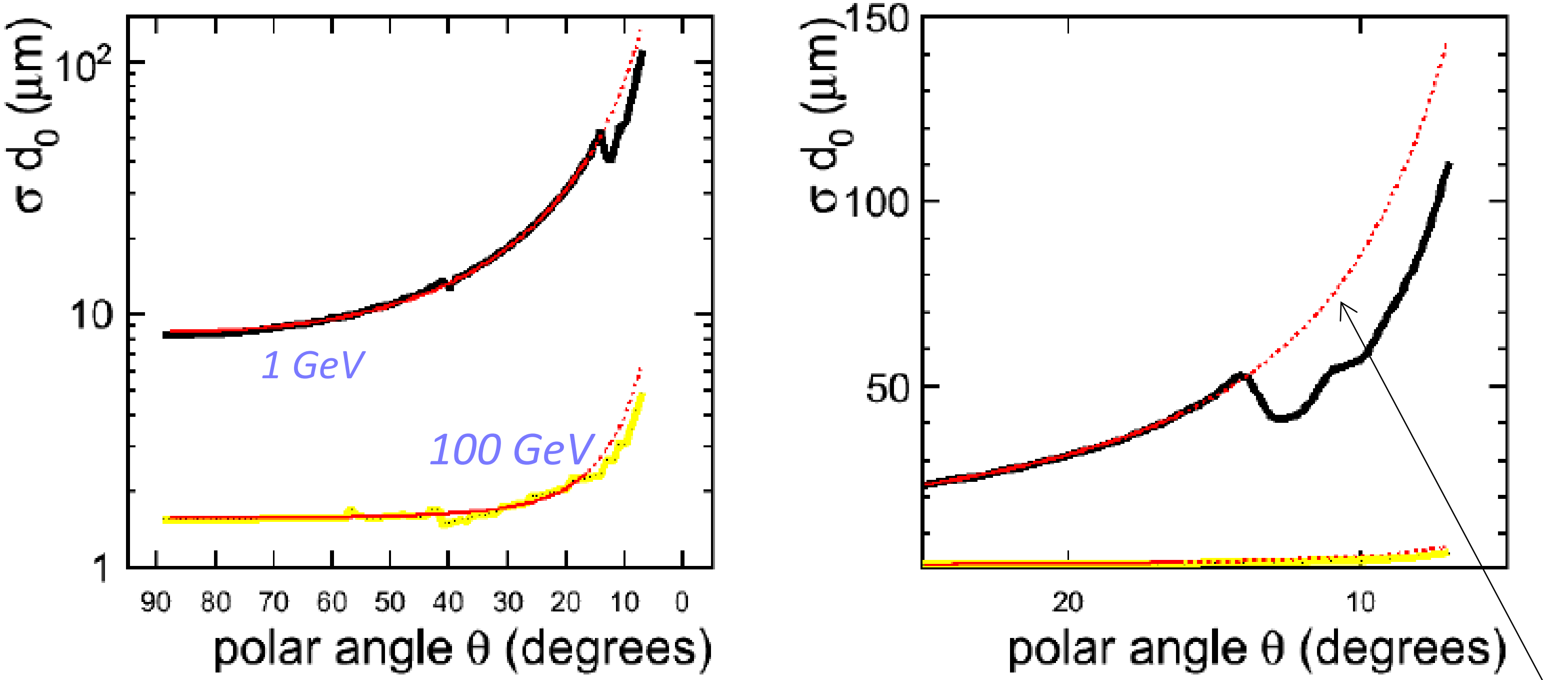


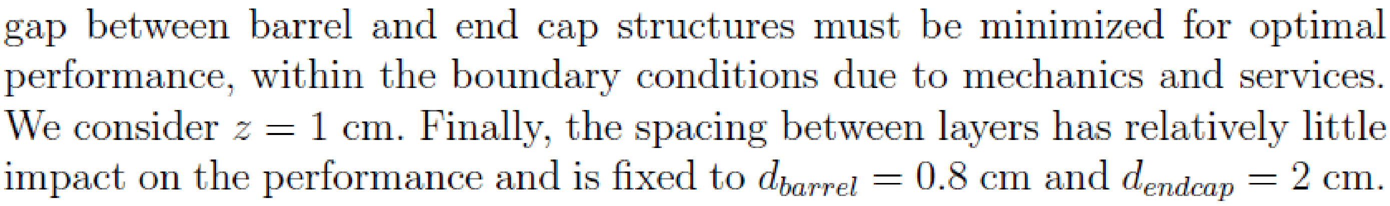
The generic vertex detector layout.

Limited by the background near IP

The gap between barrel and end cap limited by mechanics and services

Good impact parameter precision




gap between barrel and end cap structures must be minimized for optimal performance, within the boundary conditions due to mechanics and services. We consider $z = 1$ cm. Finally, the spacing between layers has relatively little impact on the performance and is fixed to $d_{barrel} = 0.8$ cm and $d_{endcap} = 2$ cm.

Functional form, toy detector with 0,12% X_0 per layer, 3 μ spatial resolution in $r\phi$ and z and internal radius=1.5 cm.

Realistic material budget can degrade notoriously the impact parameter resolution

Engineering challenges:

Beam pipe as thin as possible

Careful optimization of the services and support structures of the barrel vertex detector to avoid a.m.a.p. the line of sight between the IP and the innermost disk

Routing of the barrel vertex detector cables and services over the end-cap

Good pattern recognition

Particle flow requires excellent pattern recognition
Needed to keep to the *minimum fakes tracks*, due to

- inefficiency reconstruction
- accidental combinations of hits

Forward region is challenging:

- Beam induced background increases seriously for the zone close to the beam pipe

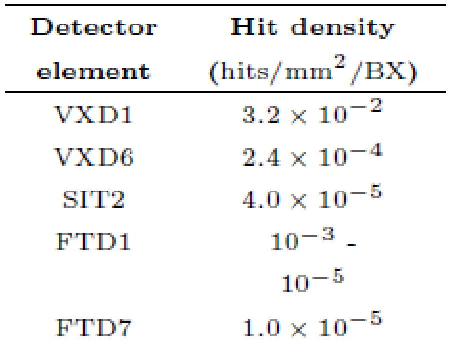
- This is amplified for other background processes as γγ→hadrons

- Abundance of low momentum particles curling through the forward tracking region due to the strong magnetic field

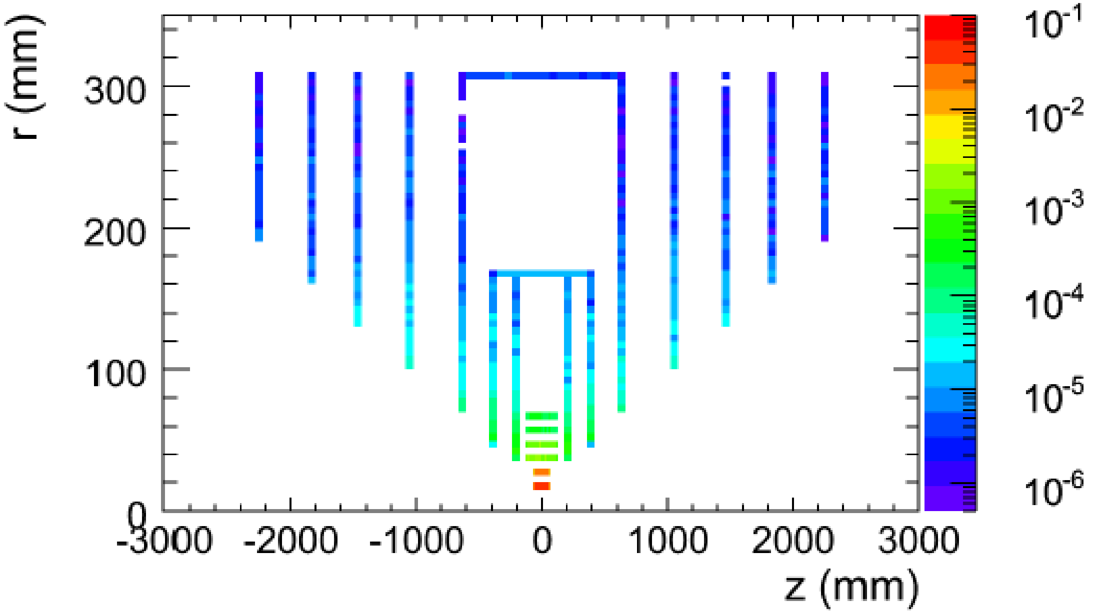
- Larger distance between layers (compared to the barrel) driving larger uncertainty on the extrapolation of the position between layers

Good pattern recognition

OCCUPANCY AT ILD-ILC (500 GeV operation, LoI results)



Detector element	Hit density (hits/mm^2/BX)
VXD1	3.2×10^{-2}
VXD6	2.4×10^{-4}
SIT2	4.0×10^{-5}
FTD1	10^{-3} - 10^{-5}
FTD7	1.0×10^{-5}



Physics + background

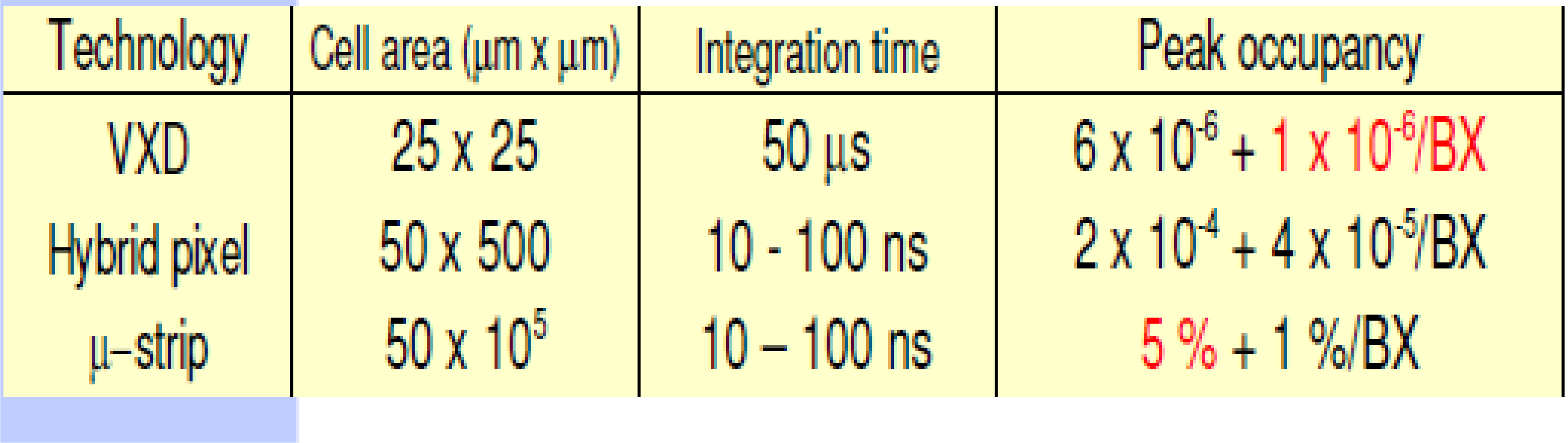
FTD1 (ee →tt) average

$$1 \times 10^{-4} \frac{\text{hits}}{\text{mm}^2} + 1.6 \times 10^{-4} \frac{\text{hits}}{\text{mm}^2\text{BX}}.$$

FTD1 (ee →tt) peak

$$1 \times 10^{-2} \frac{\text{hits}}{\text{mm}^2} + 1.6 \times 10^{-3} \frac{\text{hits}}{\text{mm}^2\text{BX}}.$$

OCCUPANCY AT ILD-ILC (500 GeV operation, LoI results)



Technology	Cell area (μm x μm)	Integration time	Peak occupancy
VXD	25 x 25	50 μs	$6 \times 10^{-6} + 1 \times 10^{-6}$/BX
Hybrid pixel	50 x 500	10 - 100 ns	$2 \times 10^{-4} + 4 \times 10^{-5}$/BX
μ–strip	50×10^{5}	10 – 100 ns	5 % + 1 %/BX

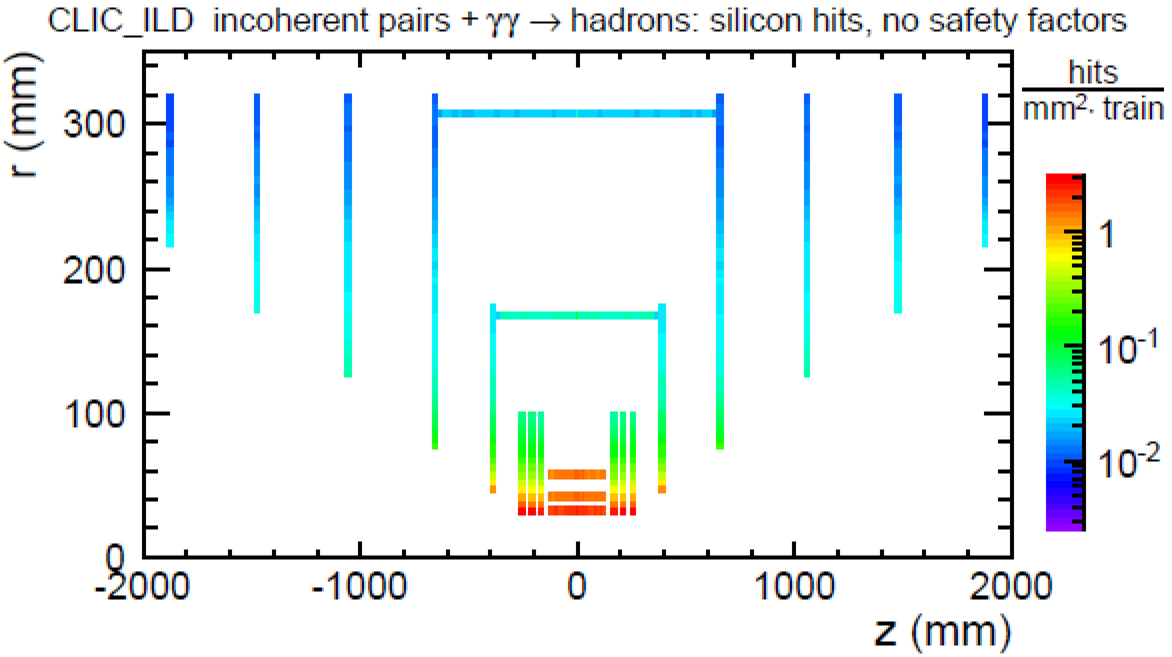
10 cm long, 50 μm wide strips → peak occupancy of 6%/BX, too high

Pixels of 25*25 μm^2 in the most inner region allows robust pattern recognition for a readout time of 50 μsec (about 100 BX)
→occupancy at peak about 10^{-4}, comfortable

Also acceptable pixel CCD detectors 10*10 μm^2 integrating 1312 BX

OCCUPANCY AT CLIC

Detector element	Hit density (hits/mm^2/BX)
VXD1	7×10^{-3}
VXD6	8×10^{-4}
SIT2	7×10^{-5}
VXEC1	7×10^{-3} - 5×10^{-5}
FTD1	7×10^{-3} - 1×10^{-4}
FTD5	9×10^{-4}



BX separated 0.5 nsec, tracking and vertex detector integrating over the train duration of 156 nsec.

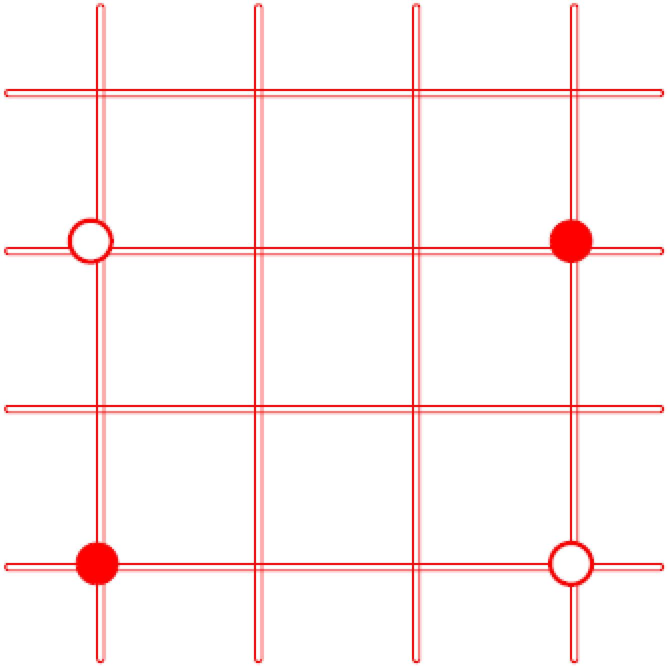
To maintain comfortable level of occupancy, time stamping with 10 nsec. precision is sufficient

Low-mass and low-power hybrid pixel detectors with a pitch of aprox.25*25 μm^2 and readout architecture based on TimePix are foreseen

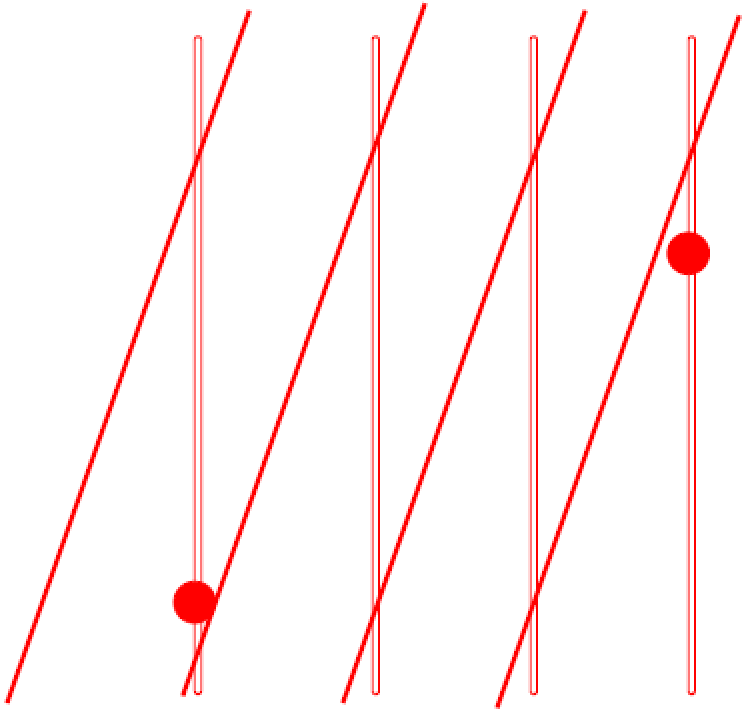
Ultra-fast detectors with Time stamping at the level of 1 BX in study

Good pattern recognition

Microstrip detectors in the forward tracker have radially oriented strips. To constraint the second coordinate with a low proportion of ghost hits, an stereo angle α of about 100 mrad will be used



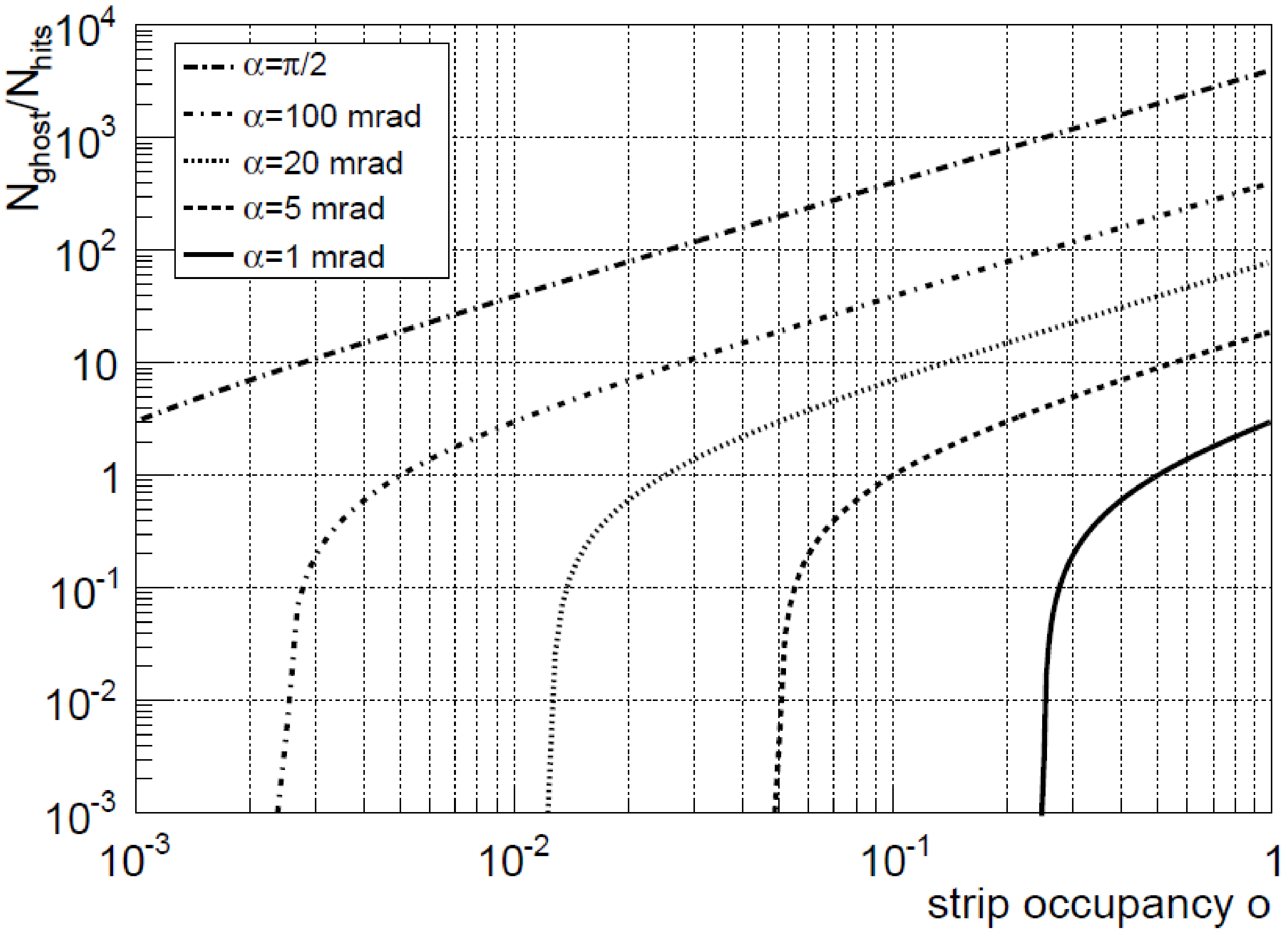
The total number of "ghost" hits increases as N^2, where N is the number of real hits



Using an small stereo angle between strips helps to reduce the number of "ghost" hits

Good pattern recognition

The ghost hit rate depends on the hit density , the pitch and the sensor dimensions



*100*100 mm^2 sensors with 25 μm pitch*

Microstrip detectors are very much limited to very low occupancy (lower than 1%), in practice. ***For the innermost disks in the LC it is needed pixelated devices.***

Good pattern recognition. R-measurement precision

$$\sigma(r\phi) = \frac{\sigma}{\sqrt{2}\cos(\alpha/2)},$$

$$\sigma(r) = \frac{\sigma}{\sqrt{2}\sin(\alpha/2)}$$

pitch p

$$\sigma = p/\sqrt{12}$$

α= 100 mrad → $\sigma(r) = 20\,\sigma(r\phi)$

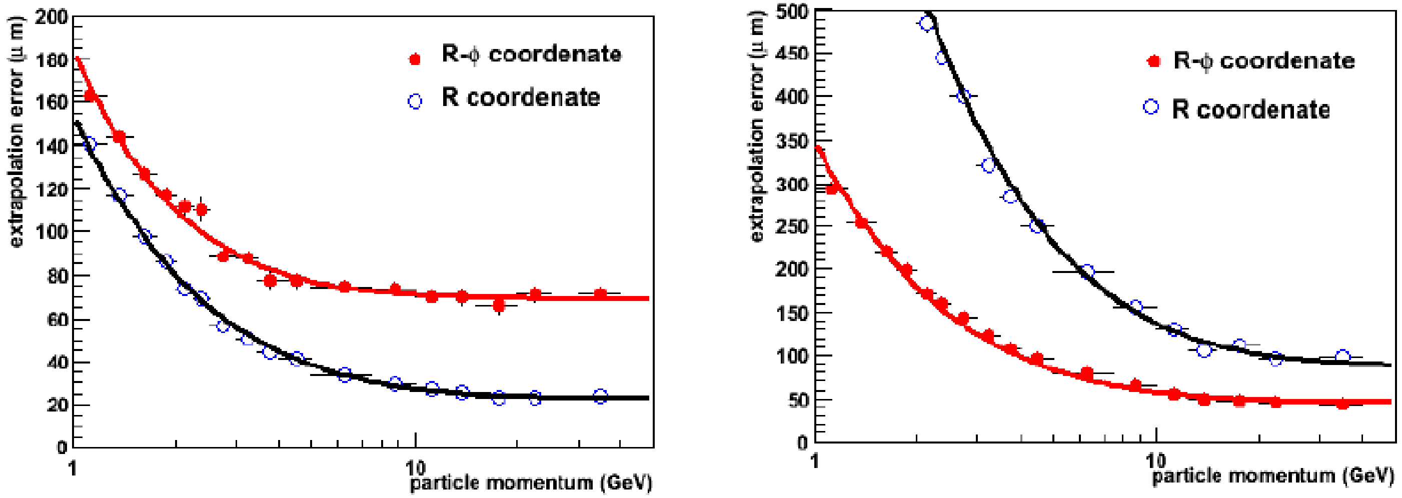


Fig. 11. The uncertainty on the extrapolated $r\phi$- (closed markers) and r-coordinate (open markers). The leftmost panel corresponds to the extrapolation of a pixel triplet to the fourth disk. The rightmost panel corresponds to the extrapolation from the 5th to the 6th disk.

Example with 11 cm distance between disks 1,2,3, and 25 cm there on.
$\sigma(r\phi)$=10μm ; $\sigma(r)$ = 10μm in pixels, no constraints in microstrips

Good pattern recognition. Confusion analysis

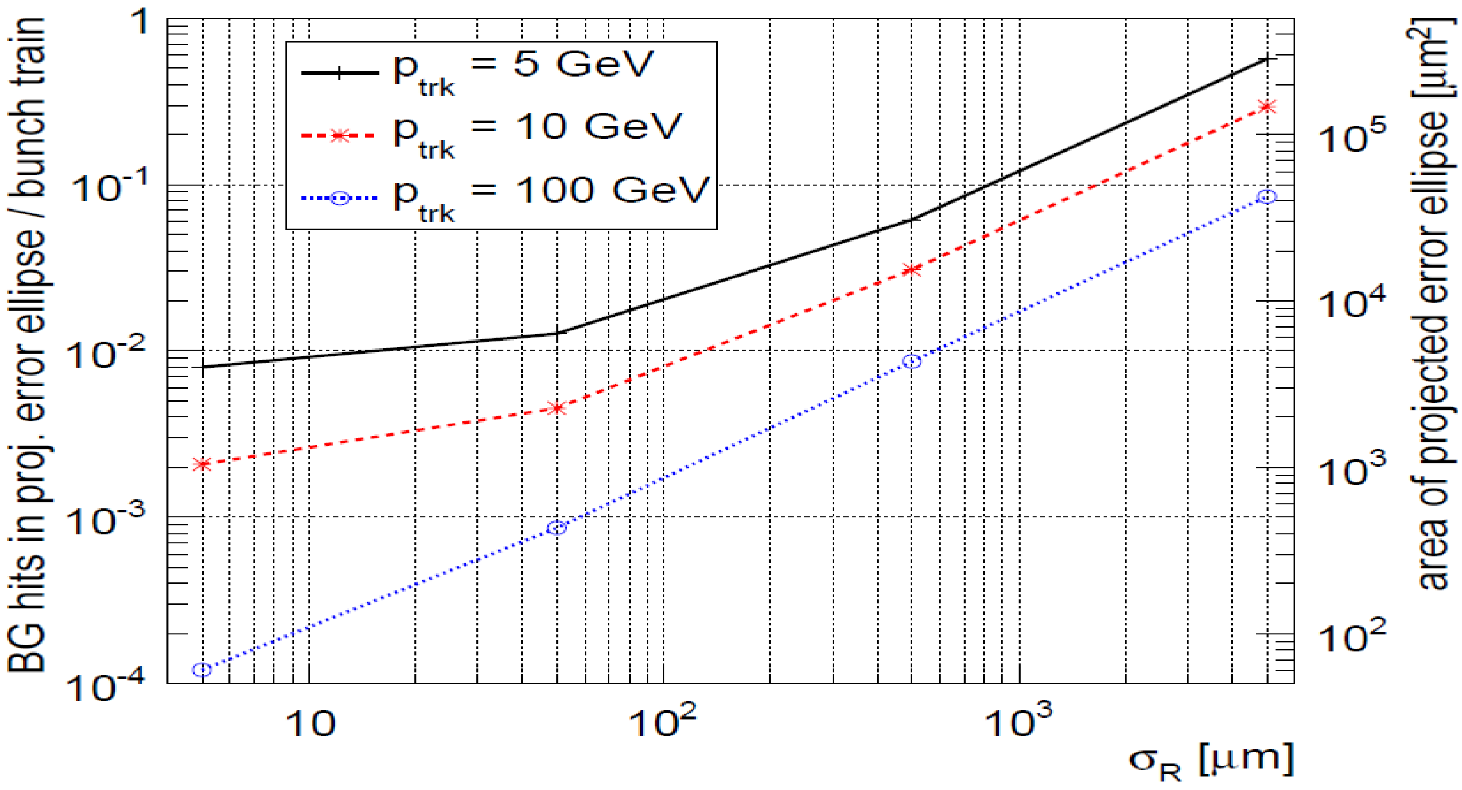


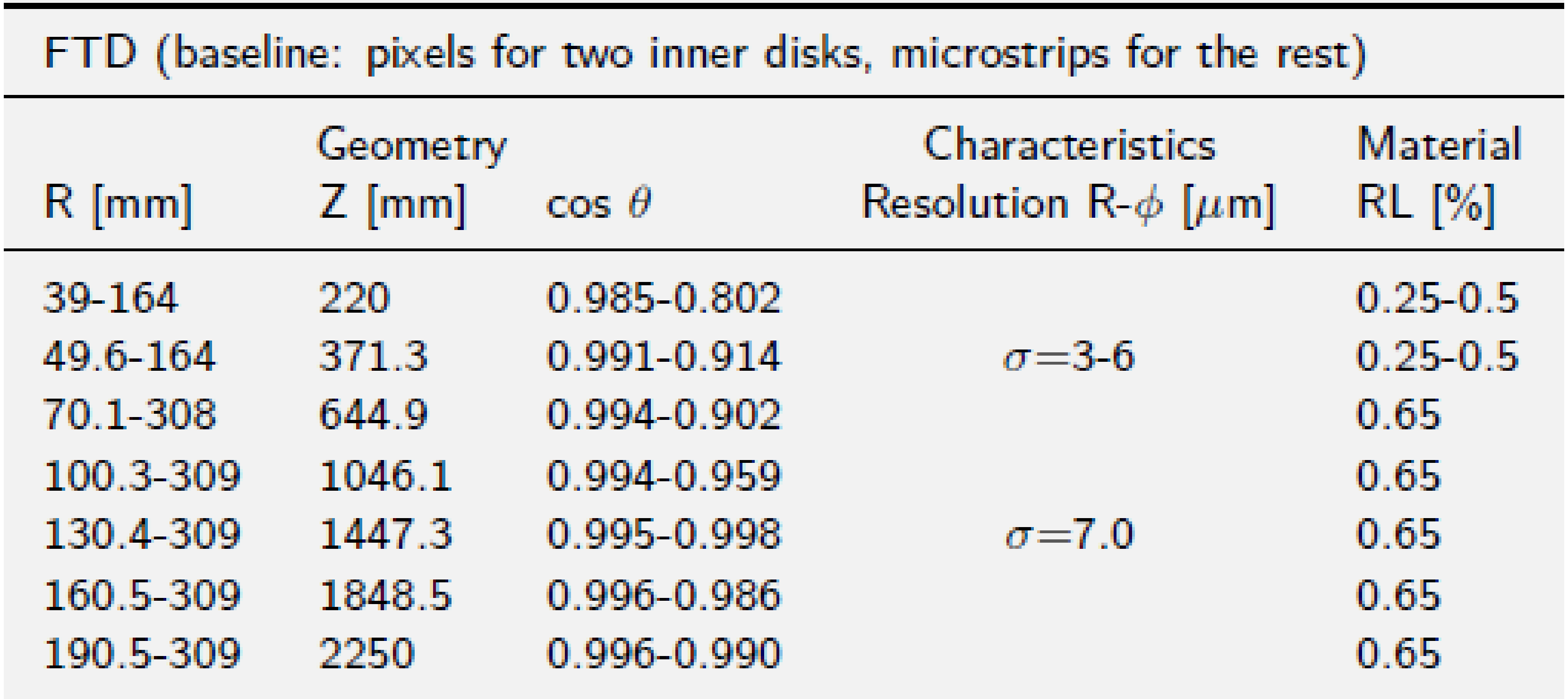
Fig. 13. Expected background hit rates inside track-extrapolation error ellipses projected from a track stub formed by measurements on six μ-strip disks onto the outermost forward pixel layers. The $r\phi$-resolution is fixed at 5 μm and the resolution in r is varied between 5 μm and 5 mm. The scale on the right axis gives the are of the respective error ellipses. The background occupancy is assumed to be 2 hits per mm^2 and bunch train.

Moderately precise r-measurements should be needed in all the forward tracking layers to have a robust pattern recognition

SUMMARY

- The main challenges of the forward tracking system have been identified
- The transverse momentum resolution is degraded in the forward region, approximately as 1/ $\sin^{3/2}\theta$, due to the not favorable orientation of the magnetic field. To maintain good performance for tracks emitted at small polar angle, emphasis should be given to the development of detectors with excellent spatial resolution for the r-coordinate, while maintaining the strict material budget.
- The vertex reconstruction performance for charged particles emitted at small polar angle is also degraded. An end cap detector equipped with precise and thin pixel detectors can check the 1/ $\sin^{3/2}\theta$ growth of the impact parameter resolution, but this requires a very strict control of the material in the beam pipe and the services and support in the barrel-end cap transition.
- Efficient and clean track reconstruction demands highly granular devices in the innermost regions of the detector, where the background density is highest.
- Robust pattern recognition moreover requires the determination with moderate precision of the r-coordinate of hits in all forward tracking layers.

BACKUP



FTD (baseline: pixels for two inner disks, microstrips for the rest)

Geometry			Characteristics	Material
R [mm]	Z [mm]	cos θ	Resolution R-ϕ [μm]	RL [%]
39-164	220	0.985-0.802		0.25-0.5
49.6-164	371.3	0.991-0.914	σ=3-6	0.25-0.5
70.1-308	644.9	0.994-0.902		0.65
100.3-309	1046.1	0.994-0.959		0.65
130.4-309	1447.3	0.995-0.998	σ=7.0	0.65
160.5-309	1848.5	0.996-0.986		0.65
190.5-309	2250	0.996-0.990		0.65

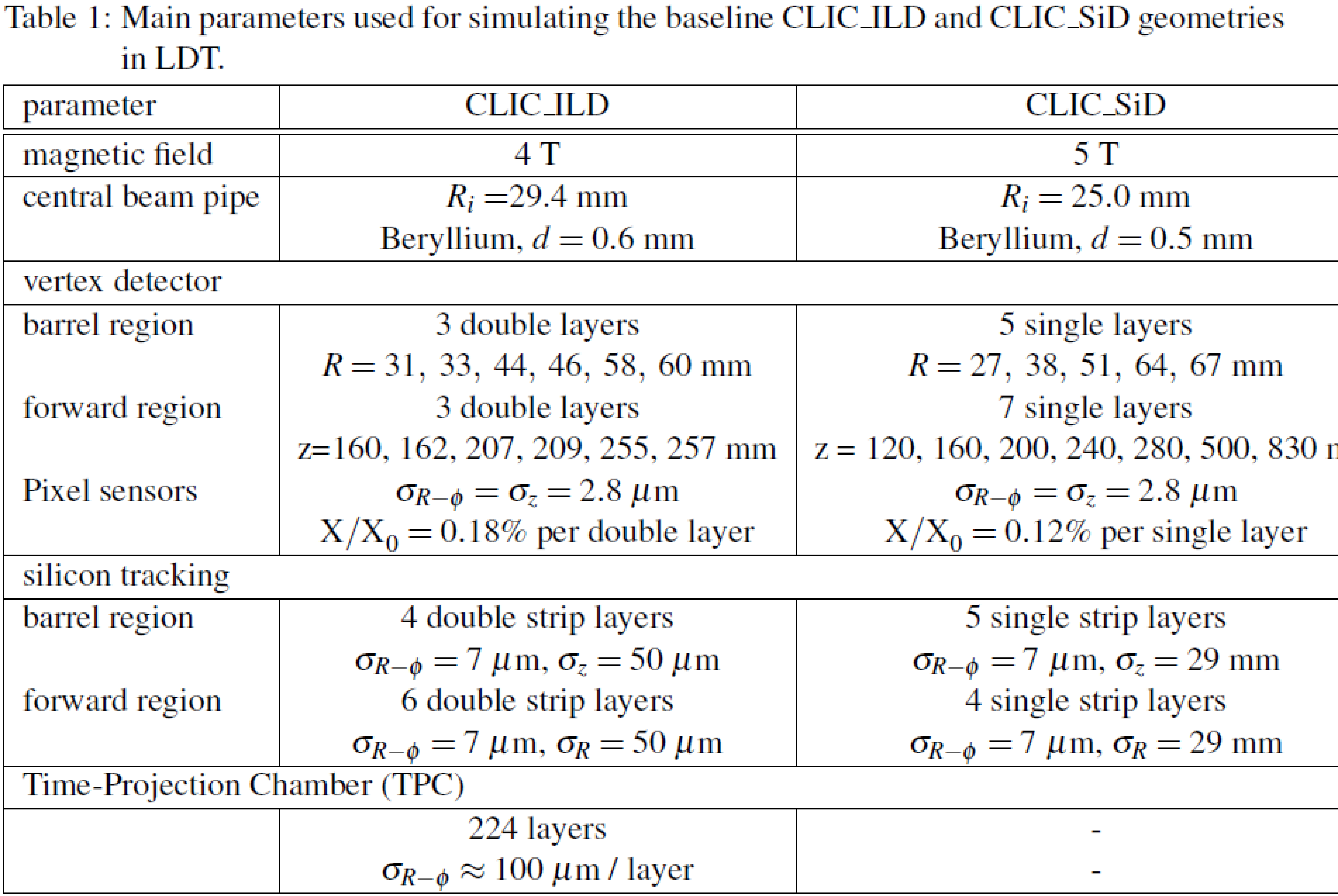


Table 1: Main parameters used for simulating the baseline CLIC_ILD and CLIC_SiD geometries in LDT.

parameter	CLIC_ILD	CLIC_SiD
magnetic field	4 T	5 T
central beam pipe	R_i =29.4 mm Beryllium, $d = 0.6$ mm	$R_i = 25.0$ mm Beryllium, $d = 0.5$ mm
vertex detector		
barrel region	3 double layers $R = 31,\ 33,\ 44,\ 46,\ 58,\ 60$ mm	5 single layers $R = 27,\ 38,\ 51,\ 64,\ 67$ mm
forward region	3 double layers z=160, 162, 207, 209, 255, 257 mm	7 single layers z = 120, 160, 200, 240, 280, 500, 830
Pixel sensors	$\sigma_{R-\phi} = \sigma_z = 2.8\ \mu$m $X/X_0 = 0.18\%$ per double layer	$\sigma_{R-\phi} = \sigma_z = 2.8\ \mu$m $X/X_0 = 0.12\%$ per single layer
silicon tracking		
barrel region	4 double strip layers $\sigma_{R-\phi} = 7\ \mu$m, $\sigma_z = 50\ \mu$m	5 single strip layers $\sigma_{R-\phi} = 7\ \mu$m, $\sigma_z = 29$ mm
forward region	6 double strip layers $\sigma_{R-\phi} = 7\ \mu$m, $\sigma_R = 50\ \mu$m	4 single strip layers $\sigma_{R-\phi} = 7\ \mu$m, $\sigma_R = 29$ mm
Time-Projection Chamber (TPC)		
	224 layers $\sigma_{R-\phi} \approx 100\ \mu$m / layer	- -

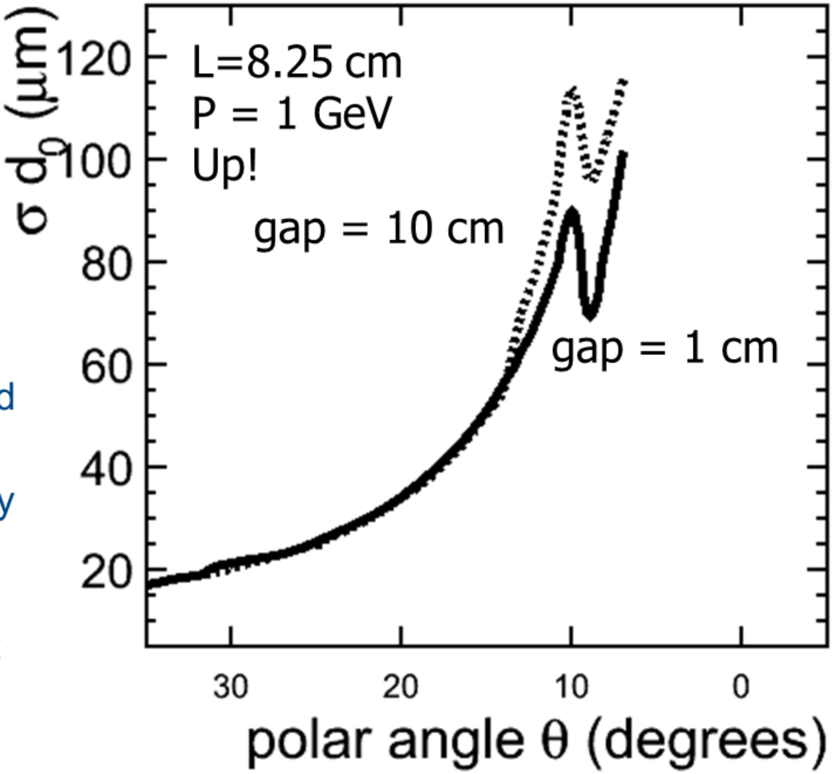
Zgap between the FTD1 and VTX

Comparison z_{gap}

Minimize the gap! *

But: if we route the services along the beam pipe, the forward vertexing performance is terrible and essentially insensitive to z_{gap}

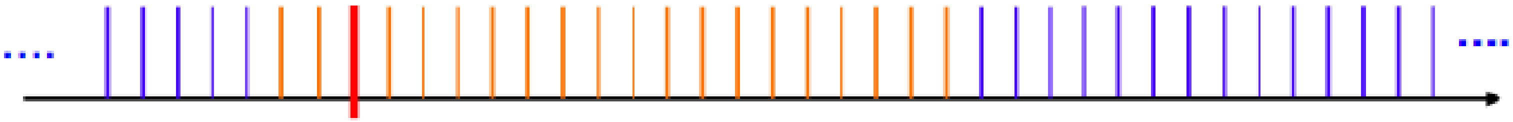
* In ILD the distance between VXD and innermost FTD is close to 10 cm. This clearance is motivated by the possibility to fit in a VXD cryostat. If a “cold” VXD technology is chosen, a short gap implies one has to install the innermost disks inside the cryostat.



time window / time resolution

The event reconstruction software uses:

Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a

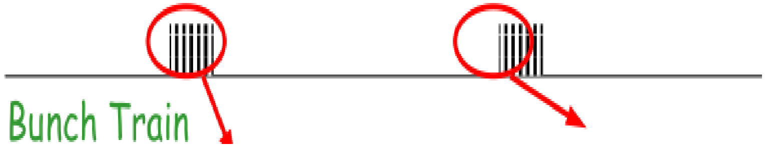


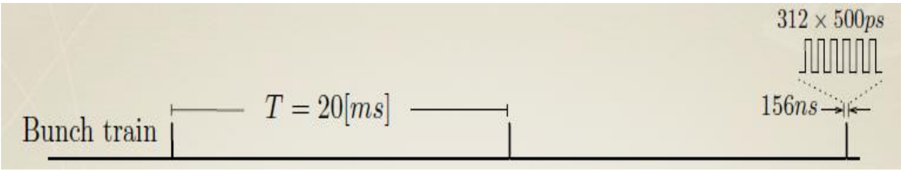
t_0 physics event (offline)

Translates in precise **timing requirements** of the sub-detectors

1.Power

- The ILC and CLIC accelerator has a non continuous operation mode:





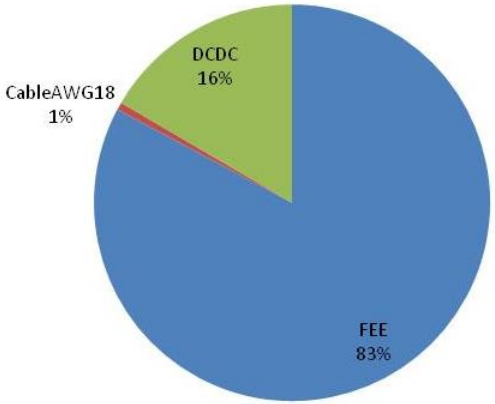
- If the power demanded by the FEE is synchronized to the bunch train, it helps to save energy
- Several solutions may possible to power the detectors
  - DC-DC-based power distribution
  - Super-capacitor based power distribution
  - Silicon based capacitors based power distributions.
- Each of them has advantages and disadvantages.
  - Material / Performance / Power dissipation /EMI
- Power solutions should be optimized to ILC and CLIC
  - Big difference in terms of duty cycle.

1. Power summary

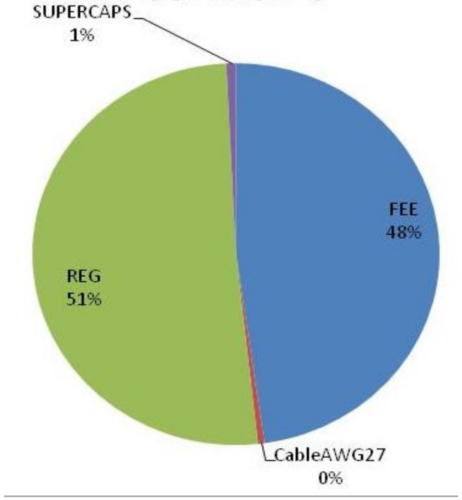
– Example at ILC-FTD

	DC-DC	**Super-caps**
Power dissipation	228 W	395 W
EMI phenomena	Yes	No*
RAD tolerant	Yes	**?**
Material budget	(240 DC-DC) ?	(80 SC) ?
Reliability	?	?
Power pulse applications	Not frequent	Yes
Installed power	1.4 kW	0.48 kW
Primary PS	≈ 36 W	≈ 15 W
Mains protection (UPS effect)	No	Yes

DC-DC

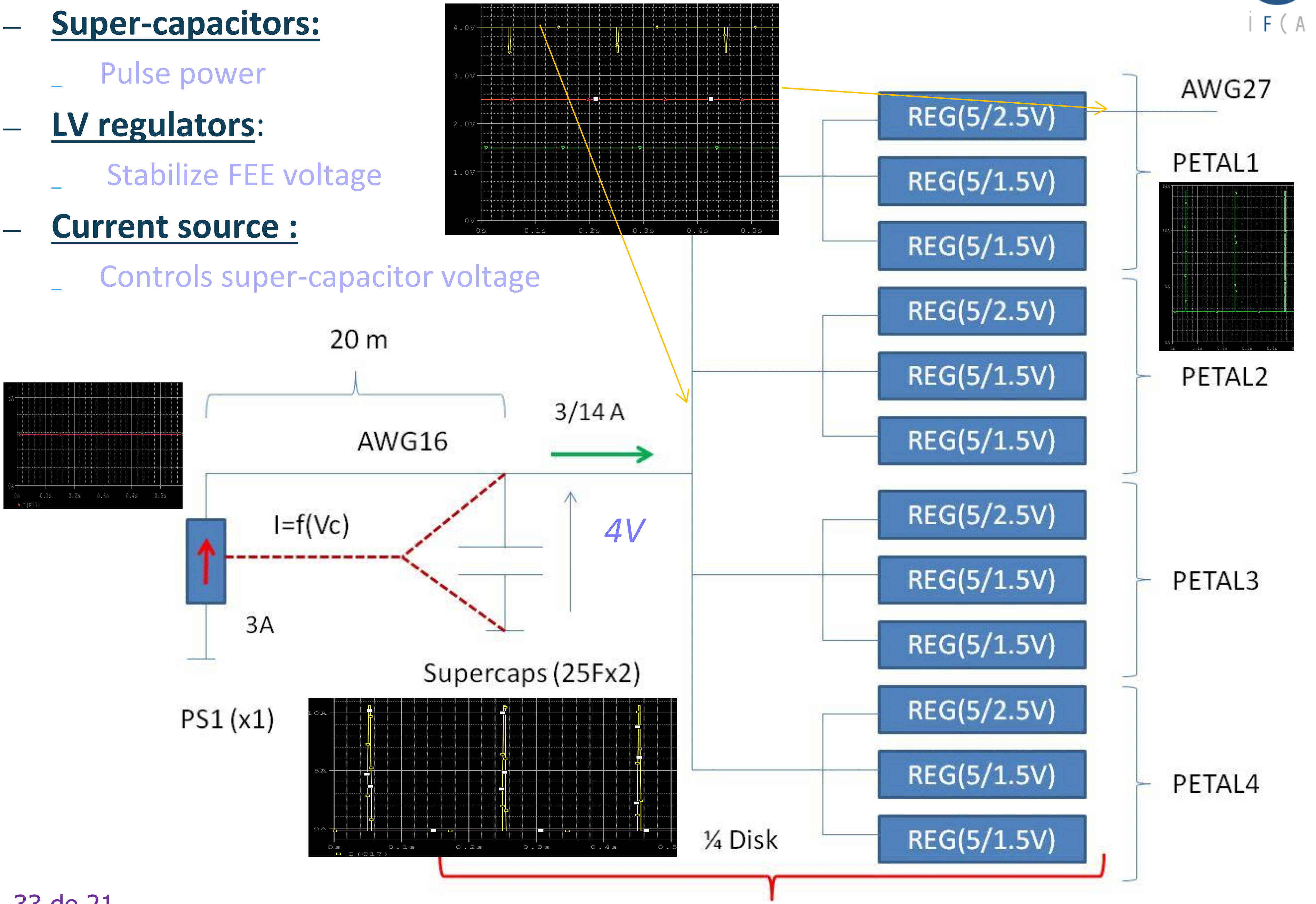


SUPERCAPS



Powering schemes: Super-capacitor based PS

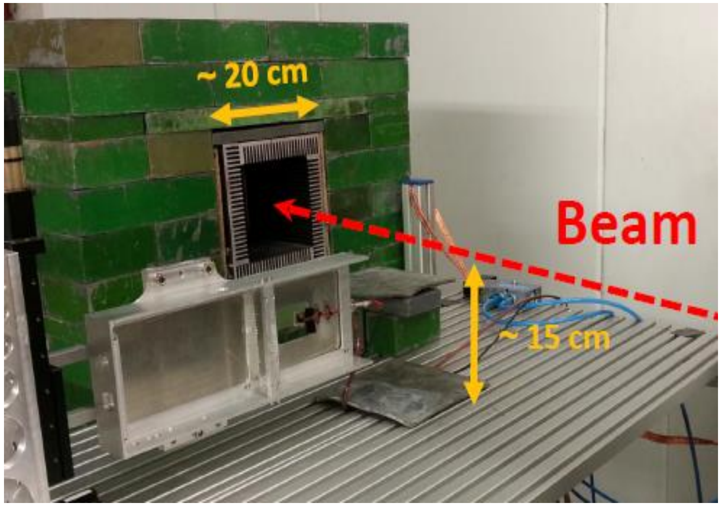
- **Super-capacitors:**
  - Pulse power
- **LV regulators**:
  - Stabilize FEE voltage
- **Current source :**
  - Controls super-capacitor voltage

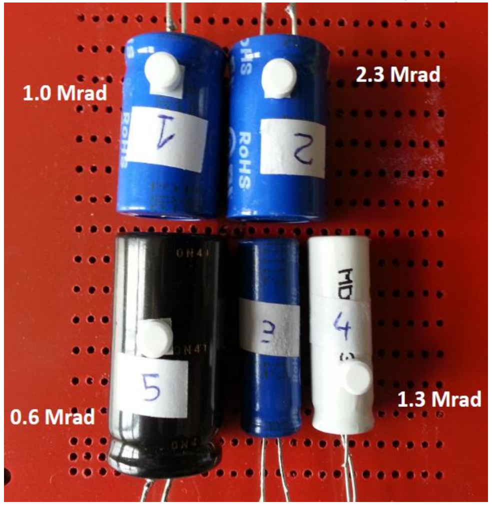


Radiation test for Super-capacitors

Radiation test has been performed at Electron Stretcher Accelerator

(ELSA, Bonn)





- Electrons at 20 MEV
- Beam spot – 3x3 cm2
- 4 hours of irradiation.
- Total dose :
  - 0.6 Mrad -2.3 Mrad (3%)
- C and ESR were measured
  - 5 capacitors