Master of Subatomic Physics and Astroparticles
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VERTEX DETECTOR OPTIMIZATION AT THE INTERNATIONAL LINEAR COLLIDER

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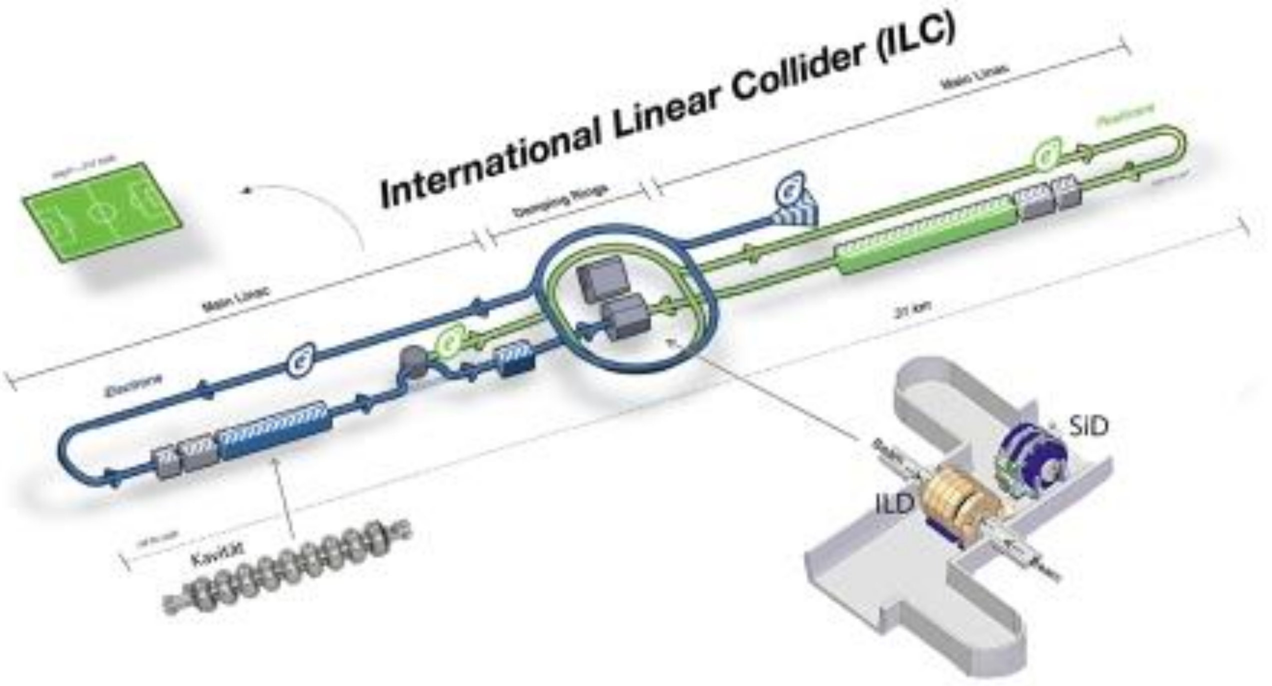
Outlines

- ILC Context
- ILC Vertex Detector Requirements
- Optimization of the ILC Vertex Detector Performance
- Summary and Outlook

International Linear Collider (ILC)

- Future $e^+ e^-$ collider (beside CLIC, FCC-ee, CEPC)
- Proposed to be built in Japan (~2030)
- 20.5 Km long.
- SC RF cavities.
- Polarised beams: e^-= 80% ; e^+= 30%.
- Luminosity:
  - Baseline: $1.35 \times 10^{34} cm^{-2} s^{-1}$ (upgradable).
- Tunable center-of-mass energy:
  - Initially: 250 GeV
  - Possible Upgrades: 350, 500, 1000 GeV
- Two detectors one IP: ILD and SiD (push-pull mode).
- Environment:
  - Clean Environment (No QCD background)
  - Fully reconstructable channels.
  - Well known initial states.



Physics at ILC

- Higgs Physics

  Mass, coupling, spin..
- BSM searches

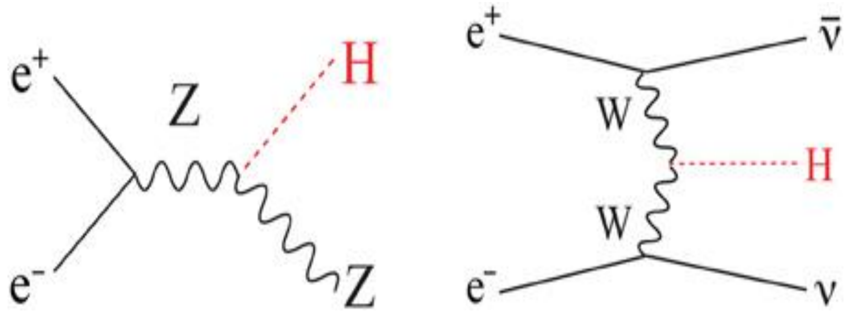
  SUSY, DM, Exotics..
- Top Quark
- E-W Precision studies
- Physics Advantages:

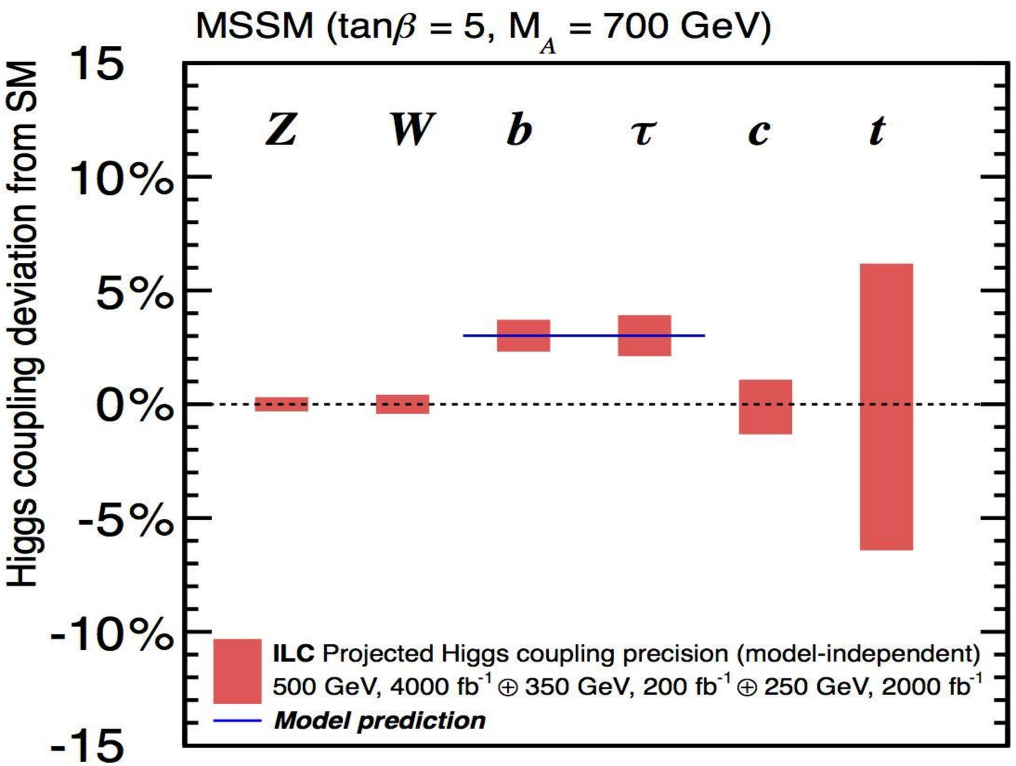
  - Precise theoretical predictions.
  - main interaction cross-sections are one to two orders of magnitude below the total cross-sections.
  - The tunable properties feature is exploited for different physics topics.

➢ Experimental conditions allow to push the detector resolution at their limits.

➢ High precision heavy flavour tagging is required for tagging most of the interesting channels.

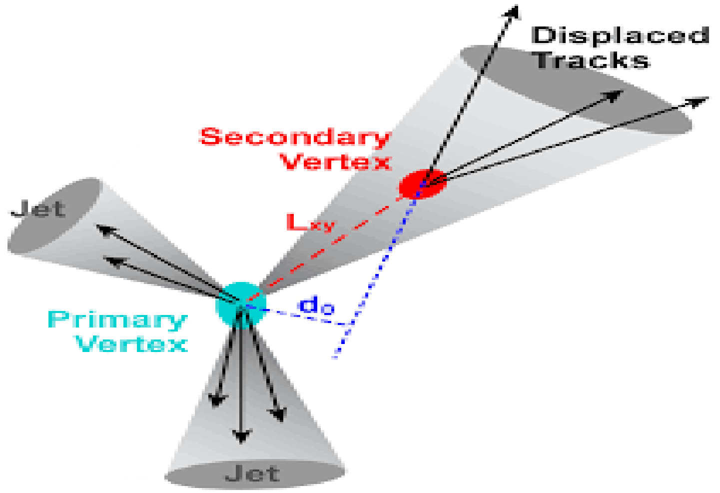
➢ High performance vertex detector is required.





few % deviation compared to the standard model values, so one needs to measure these couplings typically at the percent level.

Tracking System and Vertex Detector at ILC



- Reconstruct charged particles trajectories.
- Measuring particles momentum.
- Reconstruct Vertices:

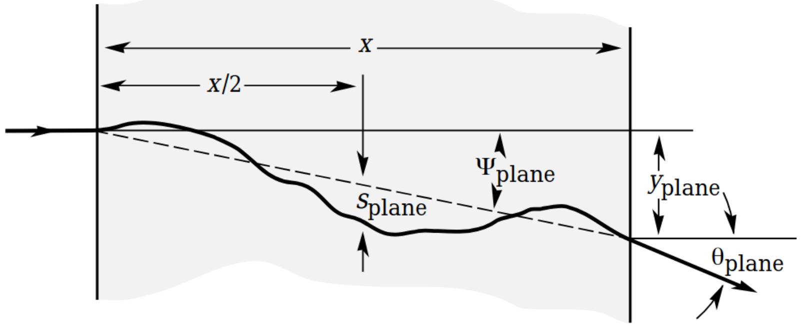
  - Primary vertex:

  IP, where particles collide.

  - Secondary vertex:

  where unstable particles decay (b, c and tau tagging).

  or particles interact with detector material.



- Impact parameter resolution:

  - $\sigma_{IP} = a \oplus b/p.\sin^{3/2}\theta$

  b depends on the material budget (related to MS formula).

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

  a depends on the spatial resolution and the geometry.

$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

- approximation

- large level arm, low inner radius ➡ very good resolution.

ILC benchmarking values:

a ≈ 5 µm; b ≈ 10 µm x GeV/c.

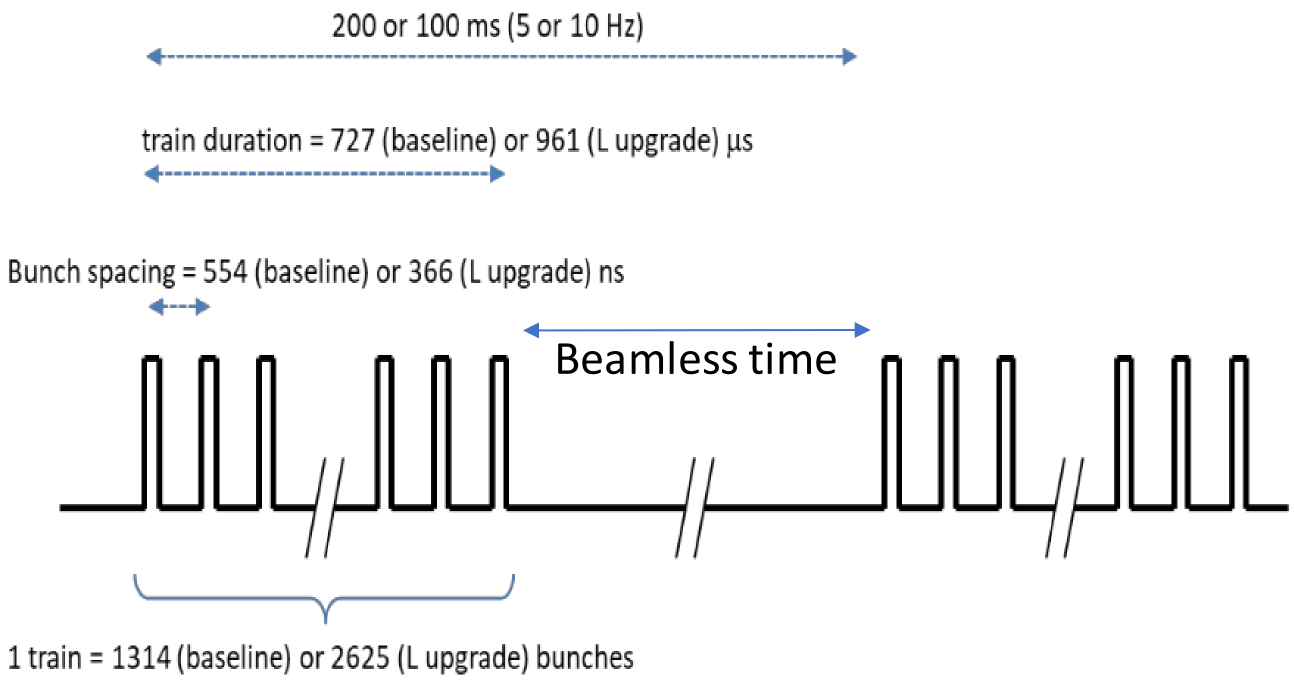
Experimental Conditions

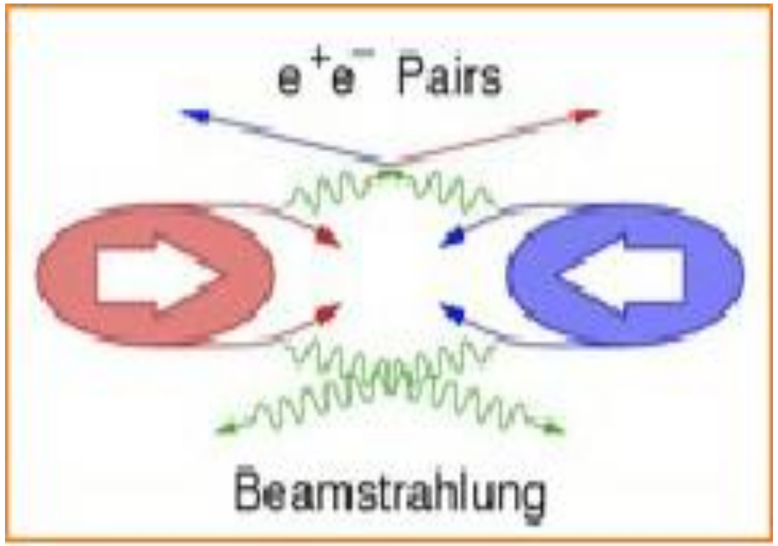
- Beam structure:
  - 5 trains per second.
  - beamless time: ~200 ms.
  - 2600 bunch per train.
  - one bunch every ~300 ns.

- Key advantages of this duty cycle:
  - No trigger system/ full readout of data.
  - decreasing the power consumption.
  - minimising the cooling system.

- Beam-Related Backgrounds:

  - Beamstrahlung $e^+ e^-$ dominating the hit density of the vertex detector.





Tracking System and Vertex Detector at ILC

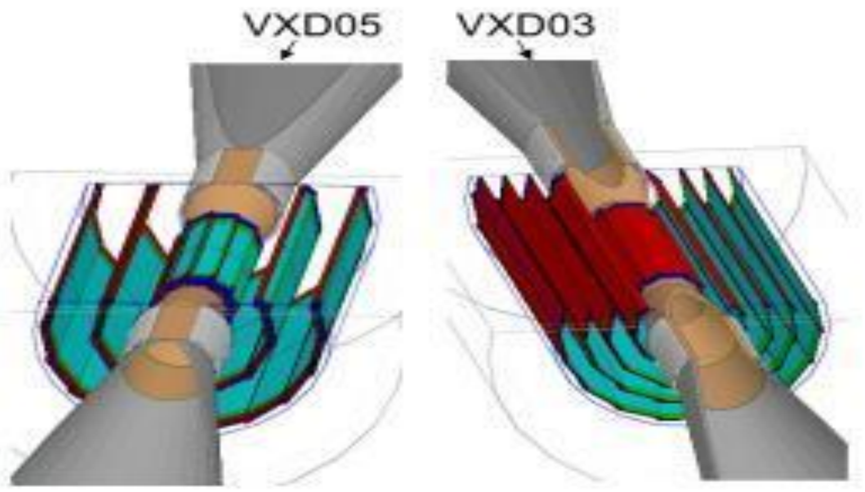
VXD Requirements:

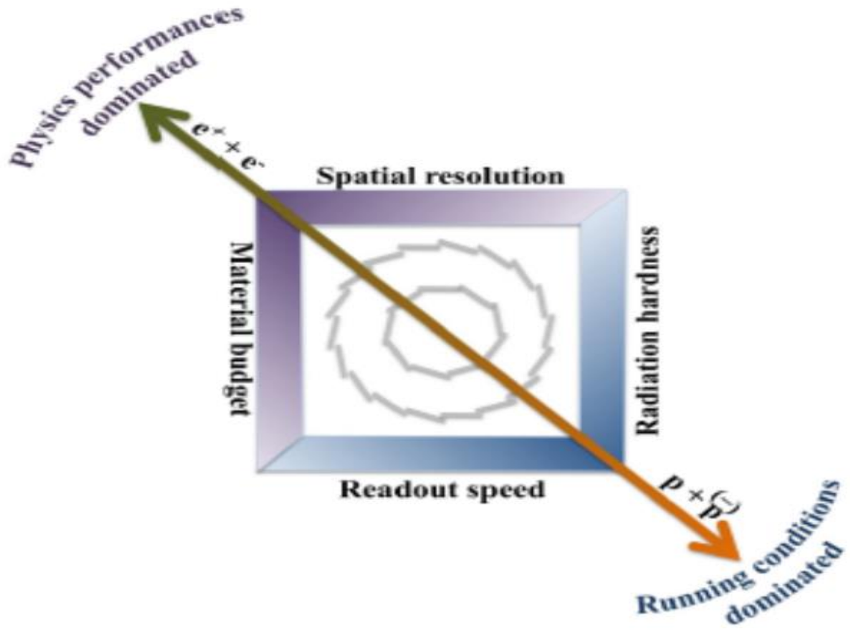
- Excellent flavour tagging.
- Low momentum tracking.
- Technology requirements:

  - Spatial resolution: ~3 µm
  - Material budget: ~0.15% X_0 per layer.
  - Adapted read out time (typically ~ µs).
  - Acceptable power consumption (~ 20 mW/cm^2

    -> VXD: ~20 W with total surface: ~0.35 m2).
  - Radiation hardness (~10^{11} neutrons equivalent

    (1MeV) (non ionising damage)
    ~ 50 kRad (ionising damage)).





Tracking System and Vertex Detector at ILC

ILD tracking system:

- Vertex Detector (VXD)

  - Inner most detector.

  - Barrel geometry.

  - 3 double-sided layers.

  - 1 mm from beampipe.

  - 2 mm in between the double layer.

- Silicon Internal Tracker (SIT)

  - 2 double-sided silicon layers.

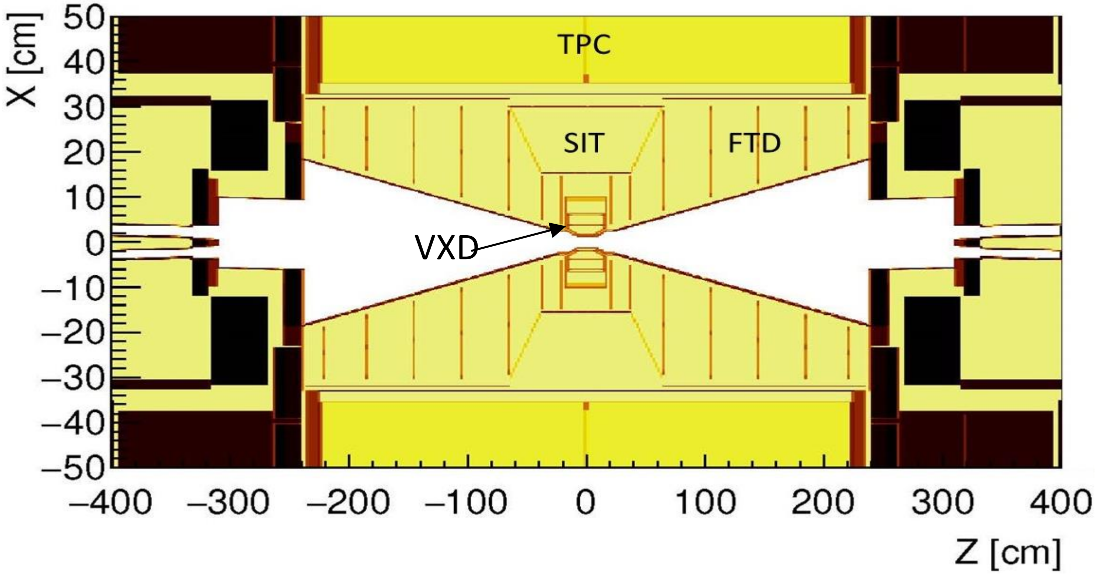
- Forward Tracking Disks (FTD)

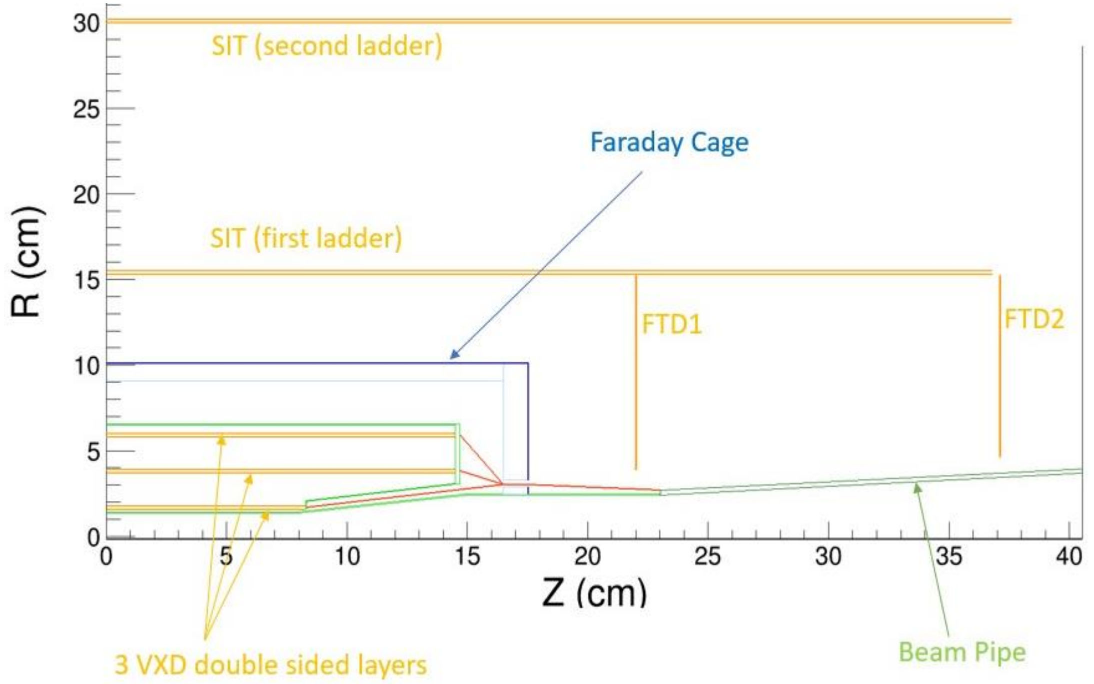
  - 7 disks in the forward region.

- Time Projection Chamber (TPC)

  - Gas-filled chamber.

  - Continuous 3-D tracking.

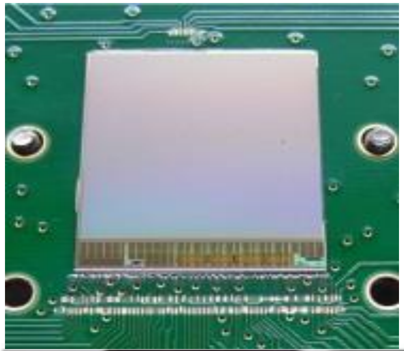


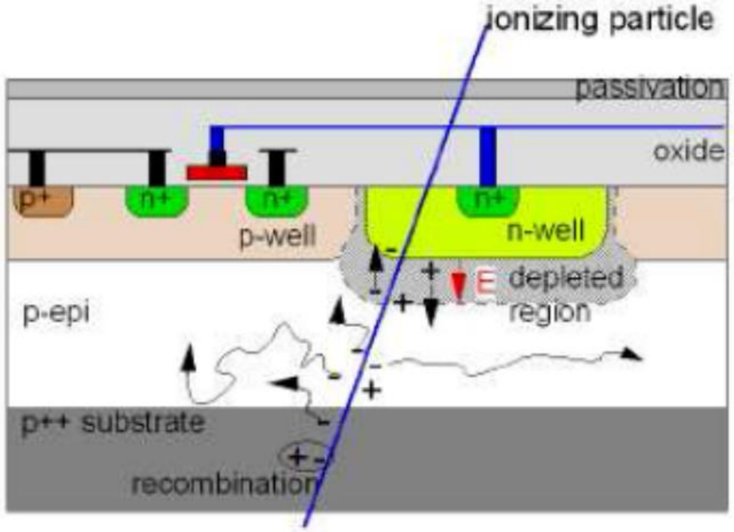


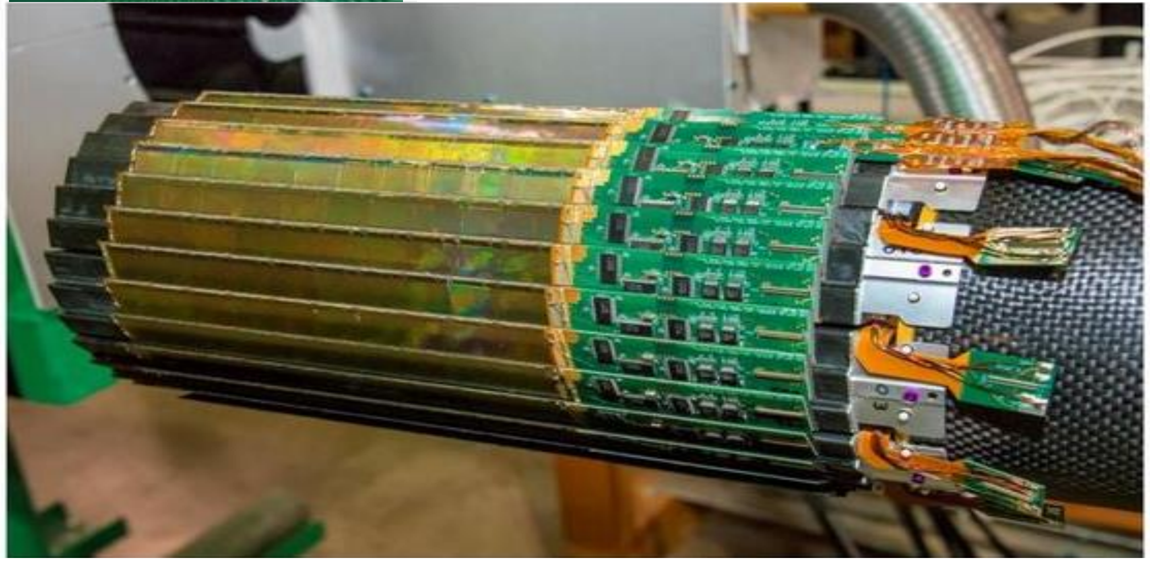
Tracking System and Vertex Detector at ILC

VXD Baseline Technology:

- CMOS Pixel Sensors:
  - Highly granular: $\sigma_{sp} \approx$ 3-5 µm (≈ 17-30µm pitch).
  - Low material budget: 50 µm.
  - Time resolution: few µs.
  - Monolithic technology.
- Applications: STAR, CBM, ALICE-ITS upgrade.
- Offers the best compromise between the different parameters contributing to the Vertex detector performance.







Optimization of the ILC Vertex Detector Performance

Guariguanchi:

- Tool:

  - Developed by A.Perez from PICSEL group at IPHC.

  - Based on ROOT framework.

  - Used for ILD tracking system optimization.

- Inputs:

  - Geometry.

  - Properties(material budget, spatial resolution, readout time).

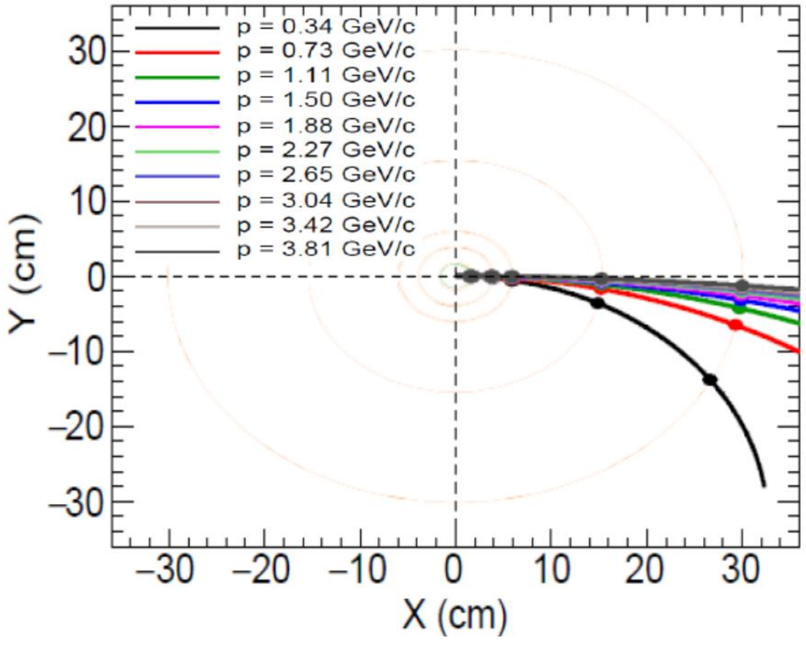
- Analyses:

  - Detector geometry visualization.

  - Impact parameter resolution as function of momentum(p, θ, ϕ).

  - Tracking efficiency analysis.

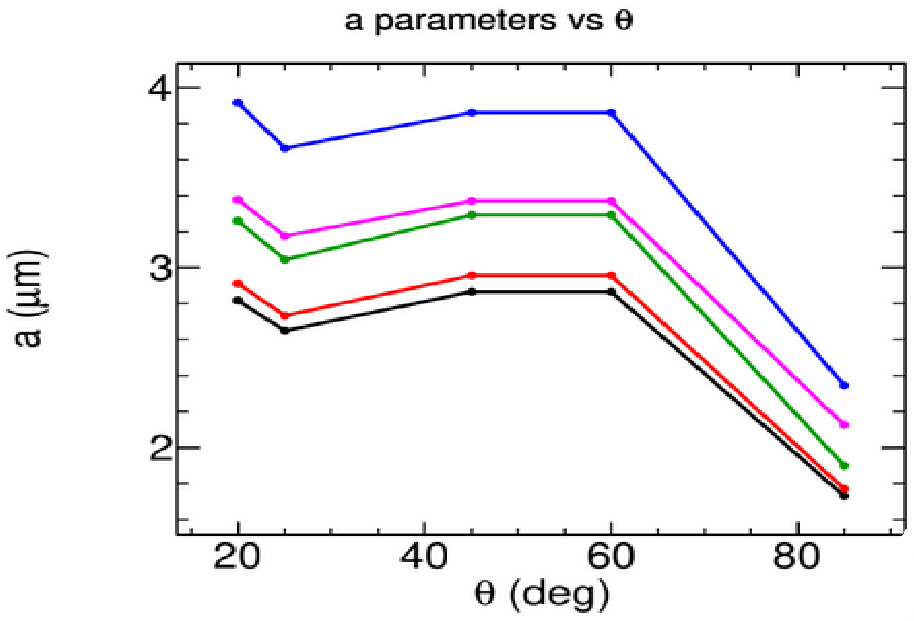
  - Material budget distribution in the detector.

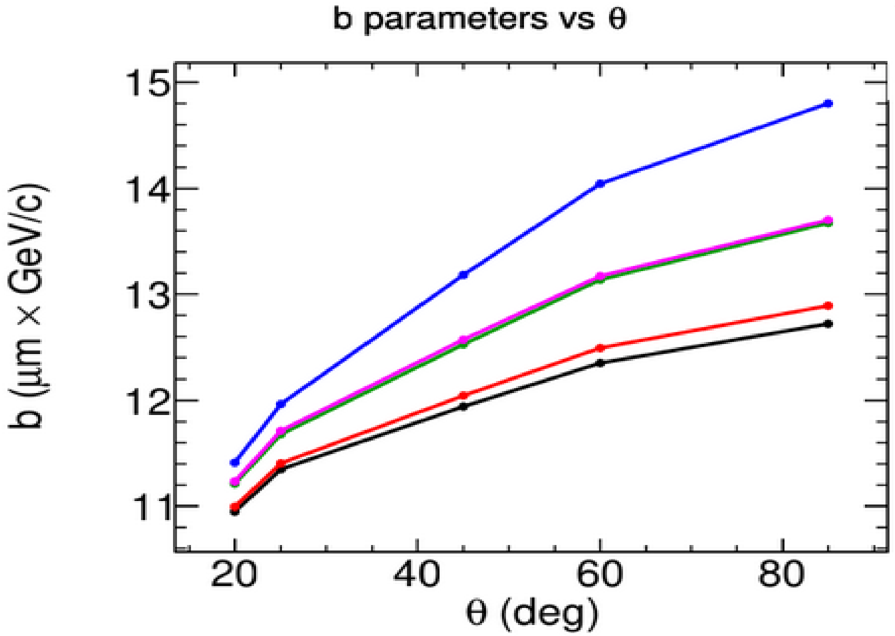


Studies on VXD:

- Spatial resolution
- Material budget
- Beam pipe
- Layers number

Optimization of the ILC Vertex Detector Performance





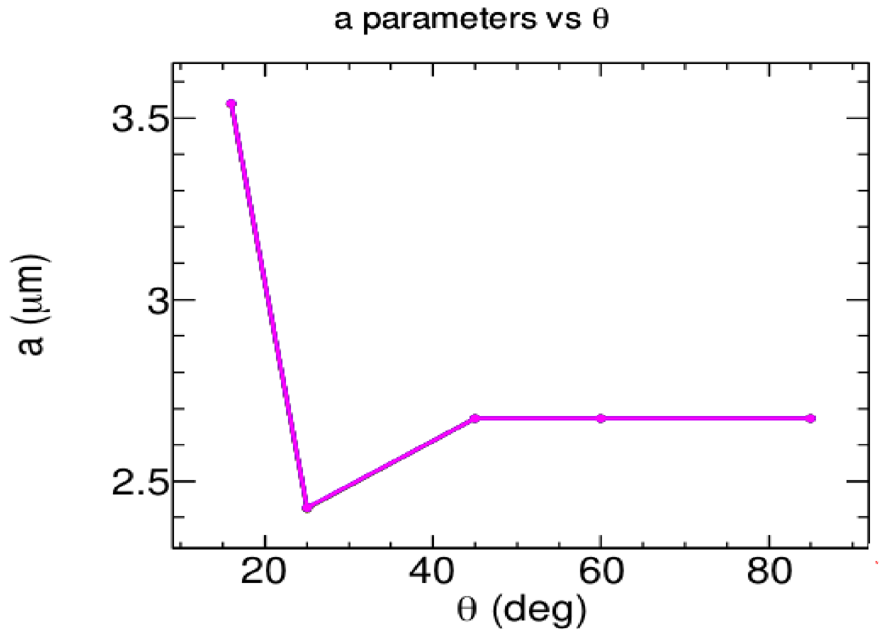
Varying the spatial resolution of the layers:

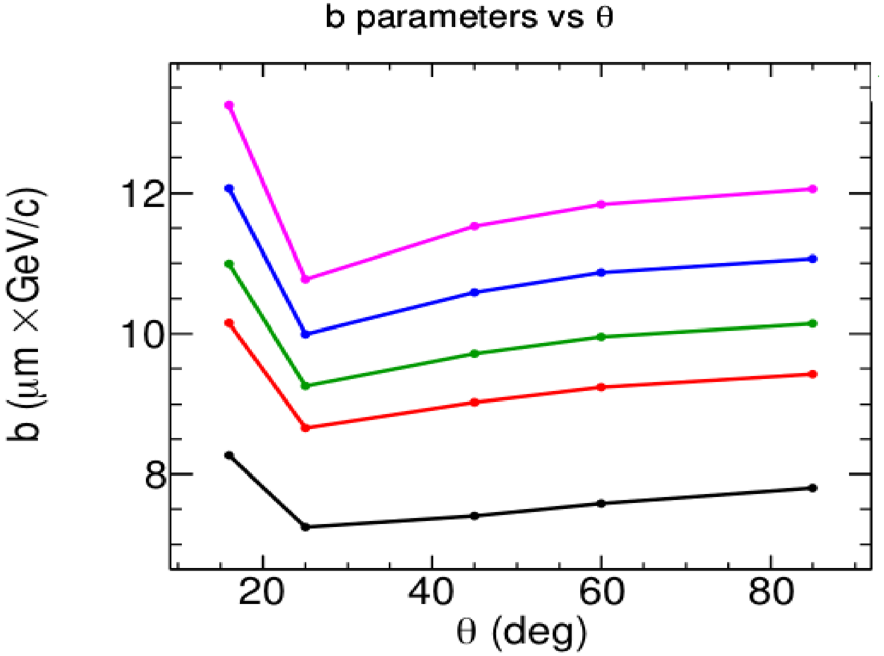
- L1/6: 2.8/4/4/4/4/4 μm
- L1/6: 3/4/4/4/4/4 μm
- L1/6: 4/4/4/4/4/4/ μm
- L1/6: 4/4/5/5/5/5 μm
- L1/6: 5/5/5/5/5/5 μm

✓ Relaxing the spatial resolution is acceptable for some range.

✓ Optimizing only the first layer didn't really worth to do.

Optimization of the ILC Vertex Detector Performance



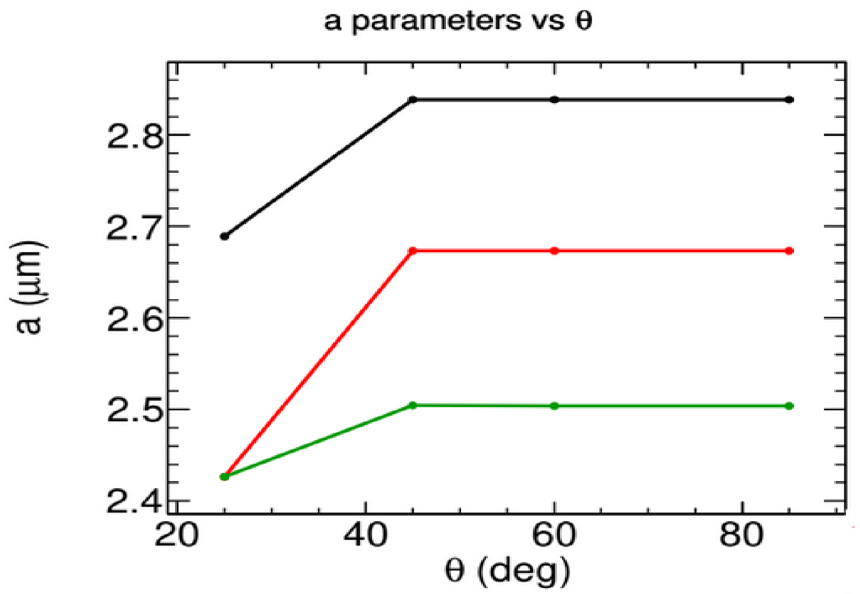


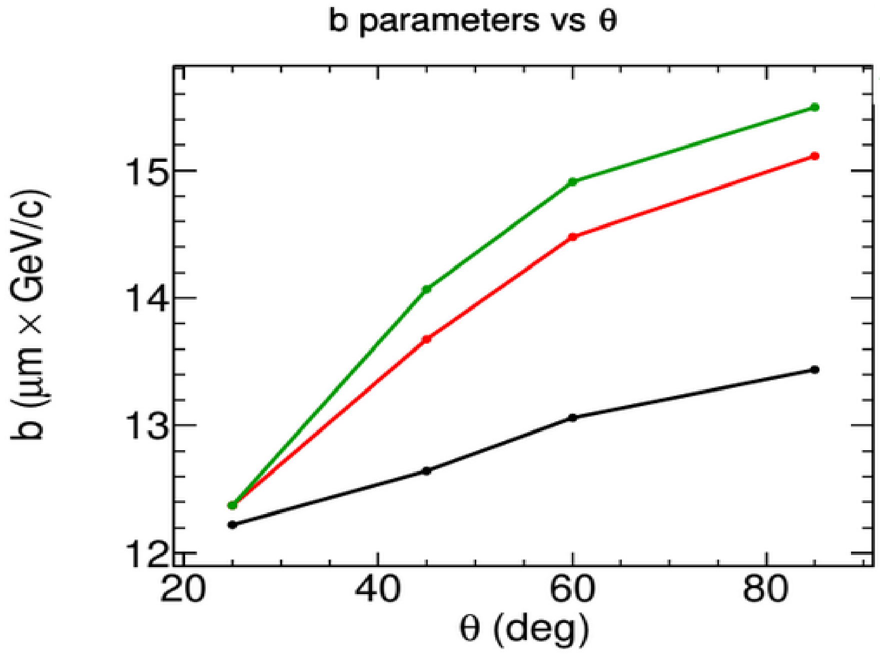
Varying the material budget of the layers:

- 0.20% X_0 per ladder
- 0.30% X_0 per ladder (baseline)
- 0.35% X_0 per ladder
- 0.40% X_0 per ladder
- 0.50% X_0 per ladder

✓ 0.30%-->0.40% X_0 is an acceptable range and we can be a little tolerant regarding the material budget target.

Optimization of the ILC Vertex Detector Performance





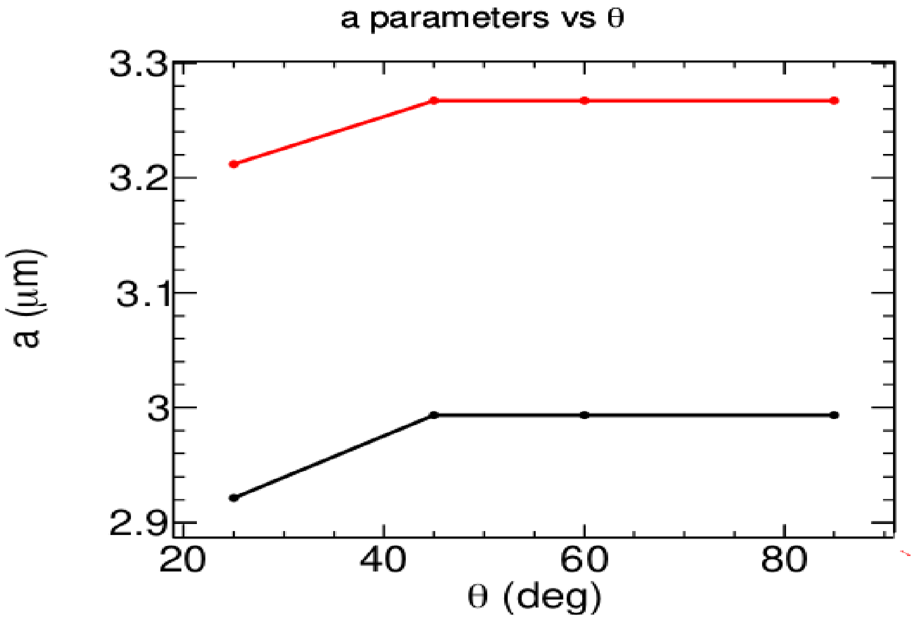
Varying the number of double layers:

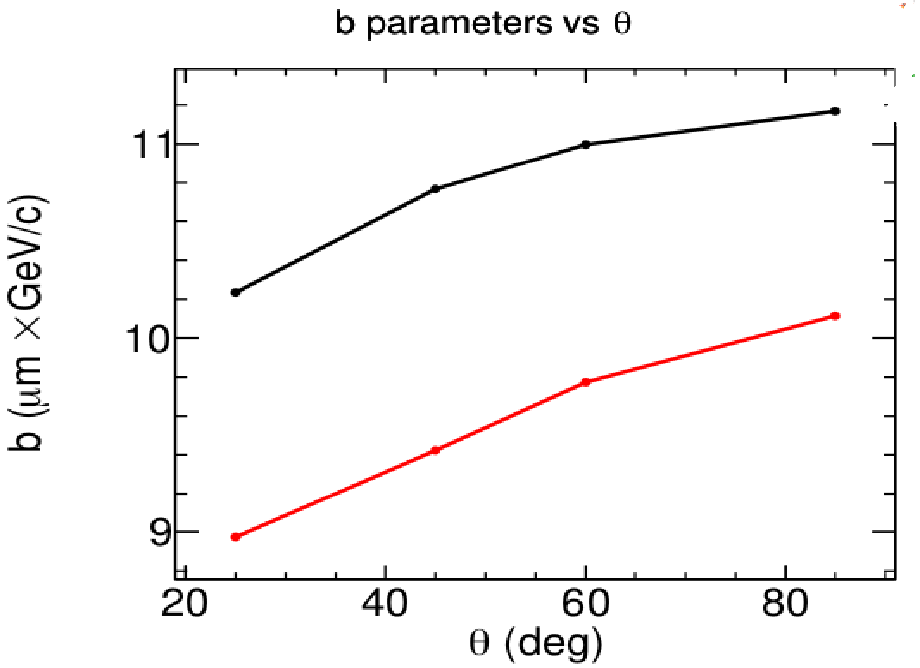
- 2 double-sided layers
- 3 double-sided layers
- 4 double-sided layers

✓ The 4 double-sided layers option is not really useful (almost the same **a** and worse **b**).

✓ The 2 double-sided layers option may seems interesting but from experience on several vertex detectors it is not really (worse tracking efficiency).

Optimization of the ILC Vertex Detector Performance



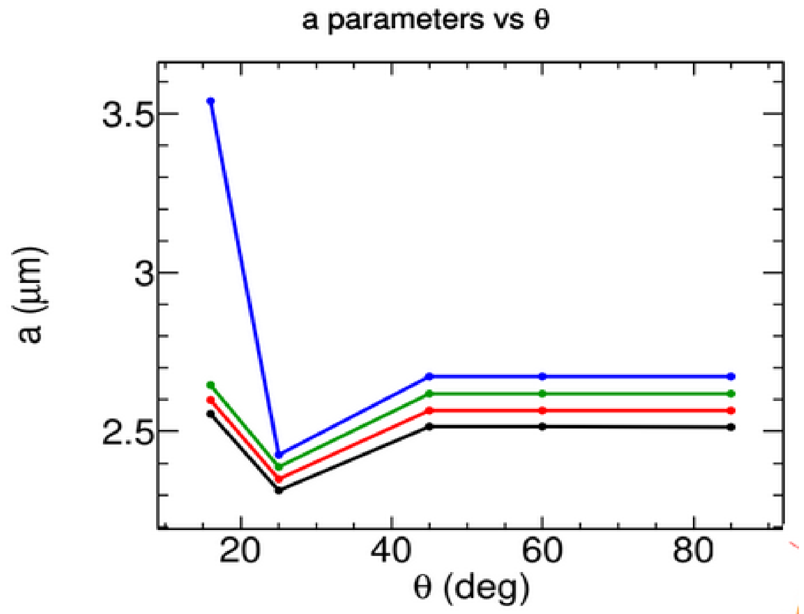


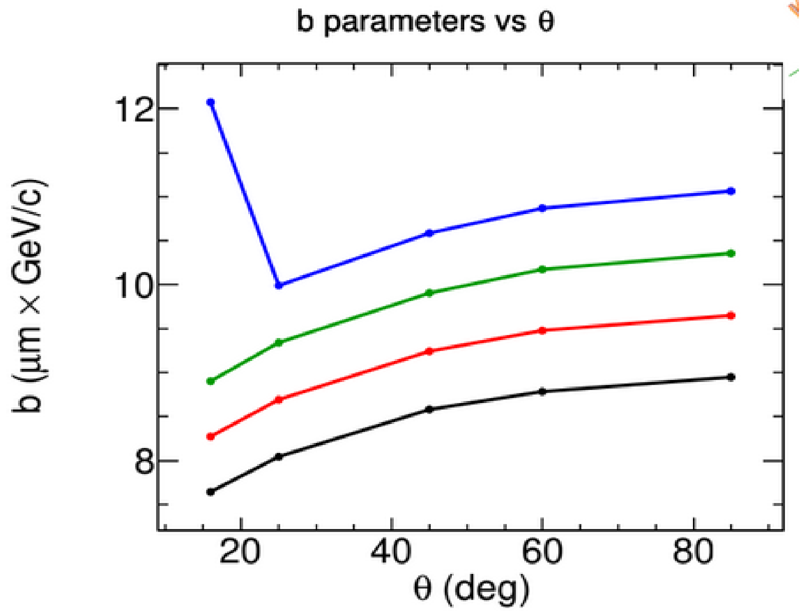
Varying the number of layers:

- 5 single layers
- 3 double-sided layers

✓ We may pay a price in degrading **b** when we choose the 3 double layers option, but it is better for the other parameters like pattern recognition.

Optimization of the ILC Vertex Detector Performance





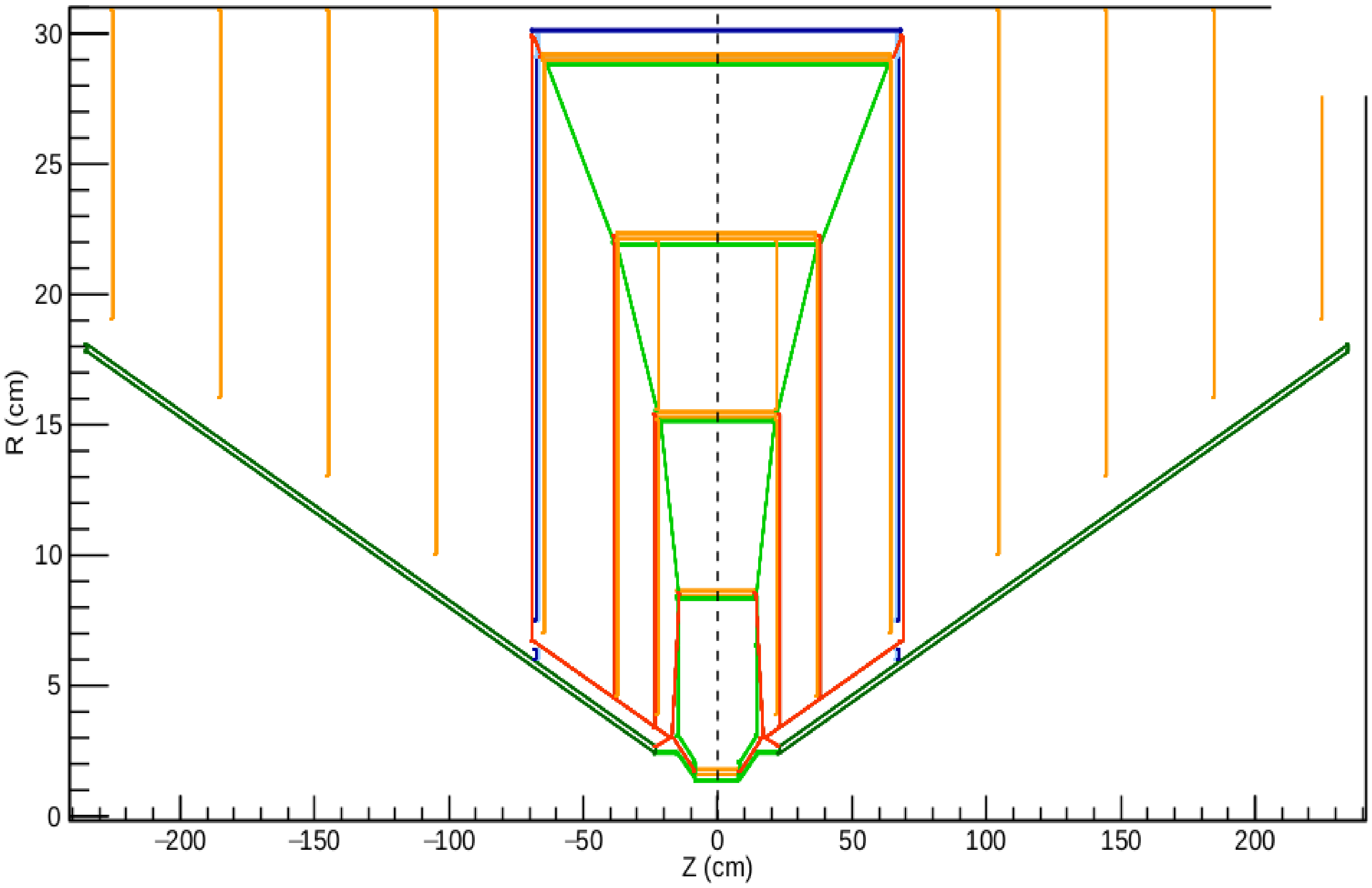
Varying the beam pipe radius:

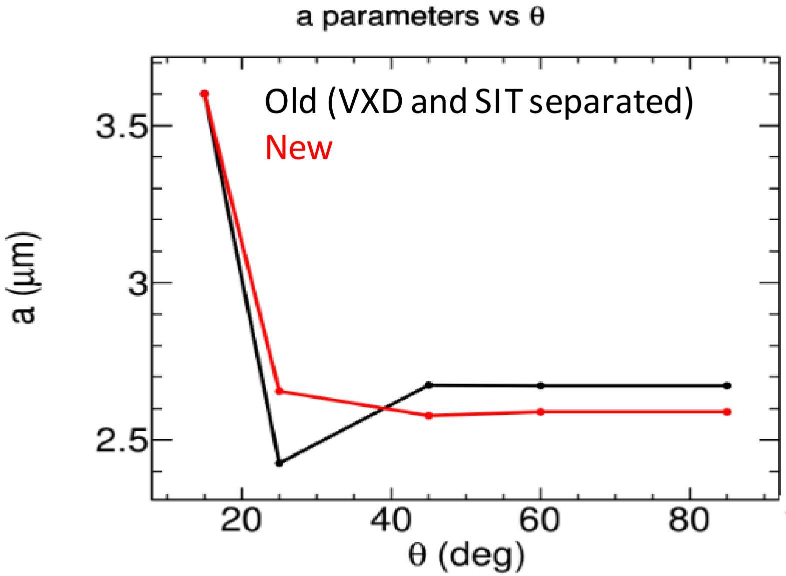
- 1.075 cm beam pipe radius
- 1.175 cm beam pipe radius
- 1.275 cm beam pipe radius
- 1.375 cm beam pipe radius (baseline)

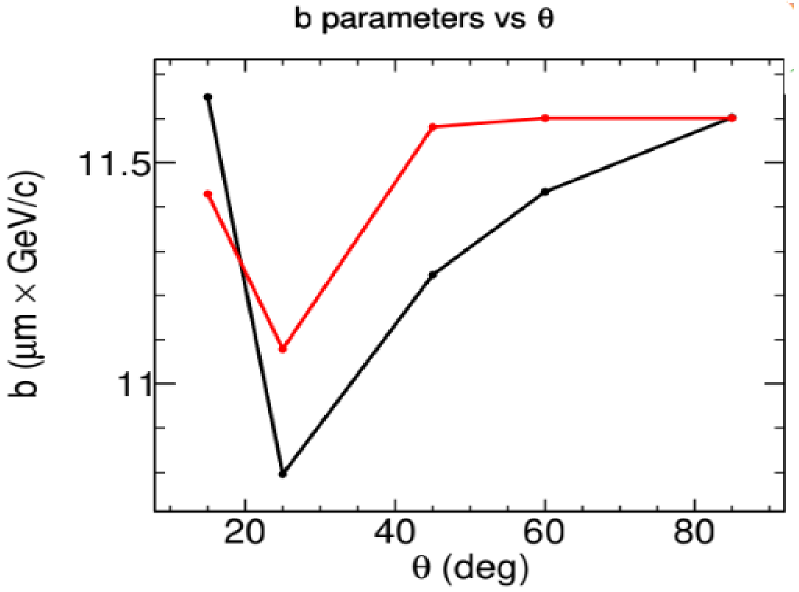
✓ Decreasing in the beam pipe radius is limited by the beam background but it seems interesting to study the impact of decreasing it down to a certain value.

Optimization of the ILC Vertex Detector Performance

First proposed geometry:

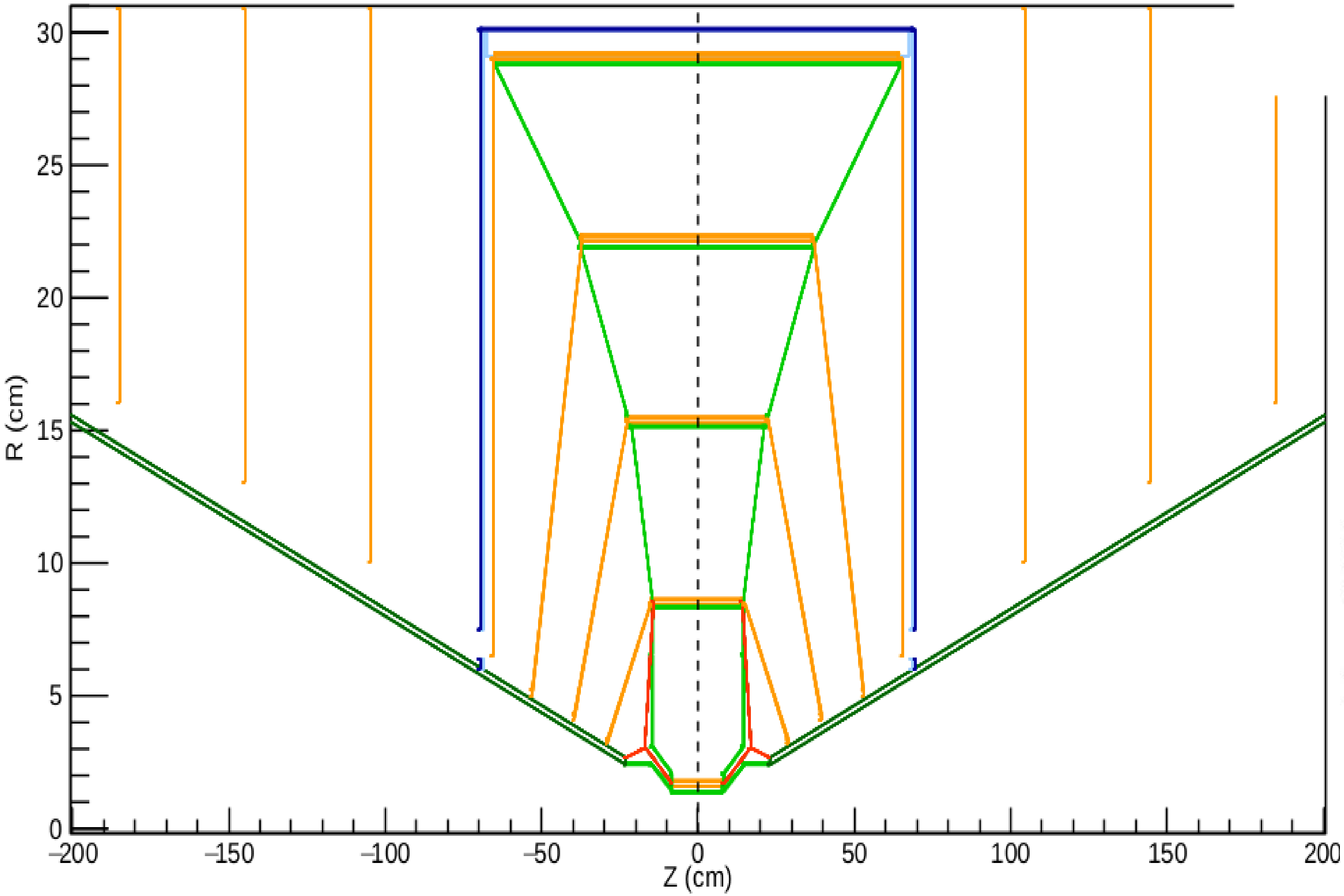


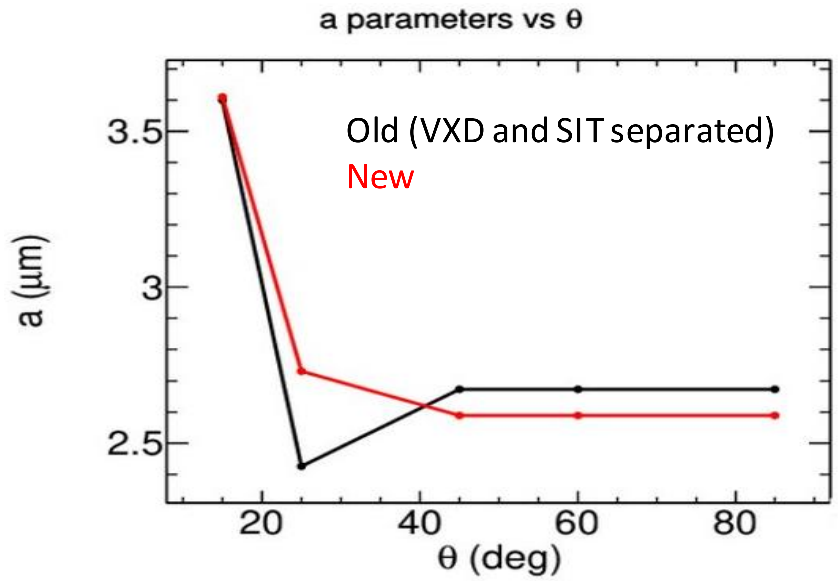


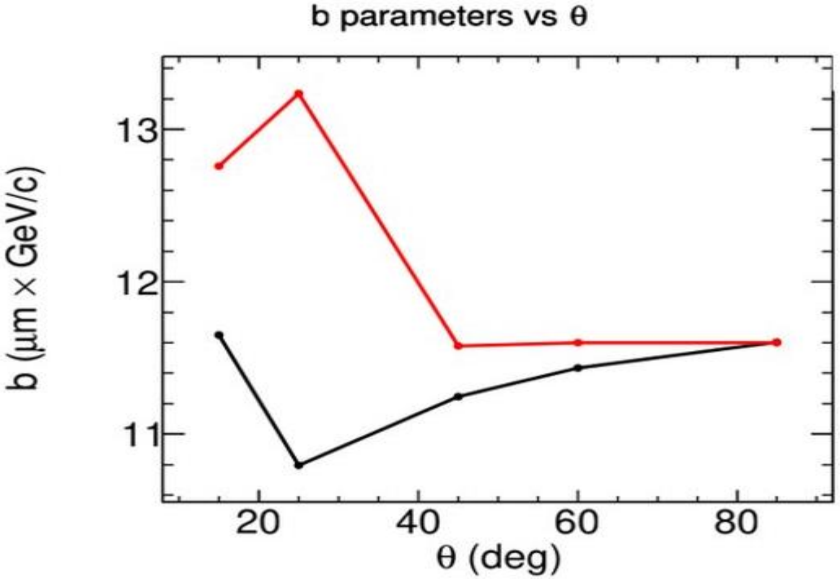


Optimization of the ILC Vertex Detector Performance

Second proposed geometry:







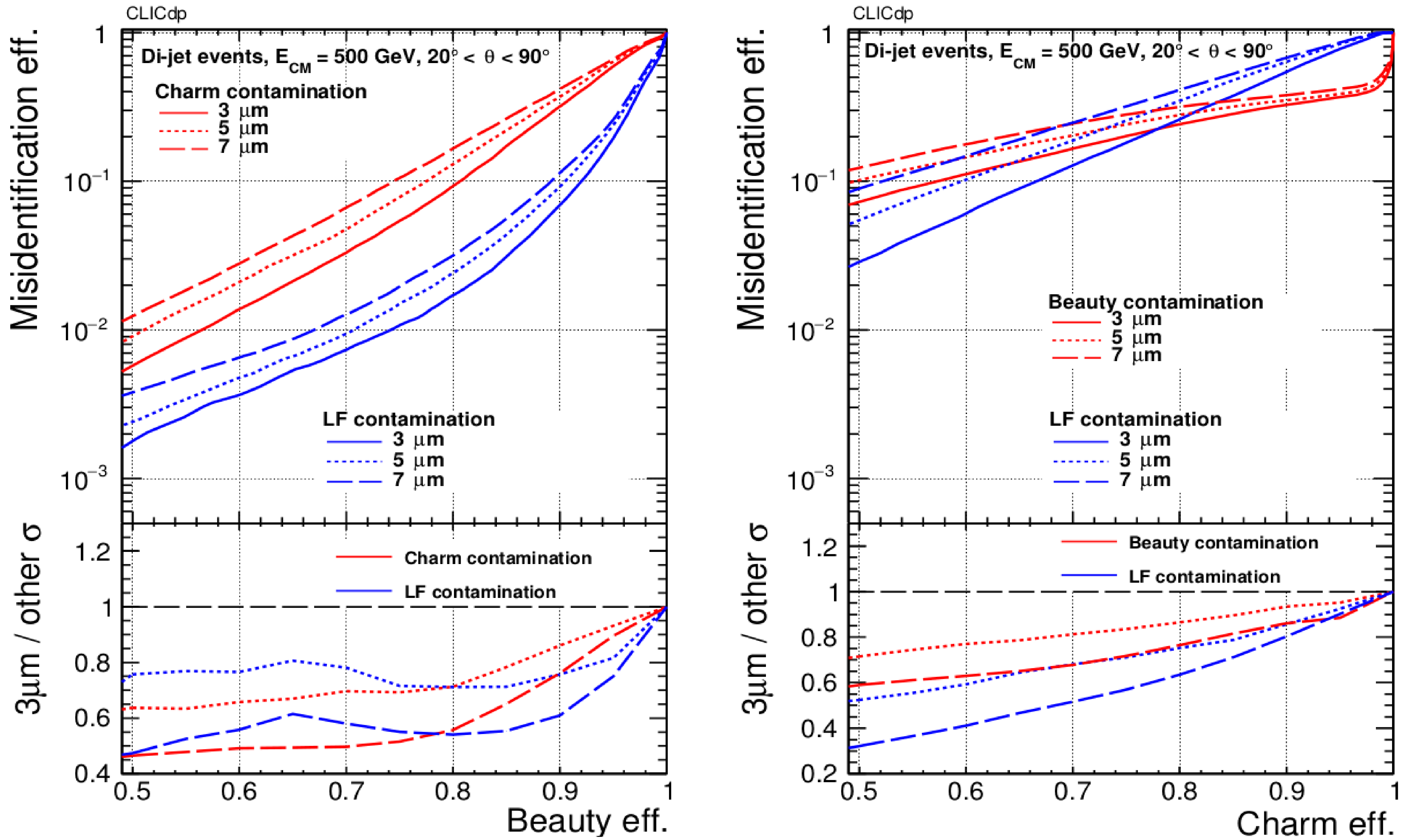
Summary and Outlook

- ✓ High challenging requirements.
- ✓ Different properties contribute and overlap.
- ✓ A compromise between the properties is needed.
- ✓ The geometry design seems to be robust against some types of changes.
- ✓ There is a degree of freedom on some of the requirements which give an insight that the goal of a very good detector can be reached.
- ✓ Progress in technology will define the limits at the end.

Next steps:

- ➢ Full simulations.
- ➢ Heavy flavour tagging performances.
- ➢ Tracking efficiency studies.
- ➢ Complete physics analysis.

Backup Slides



CLICdp
Di-jet events, E_{CM} = 500 GeV, 20° < θ < 90°
Charm contamination
3 μm
5 μm
7 μm
LF contamination
3 μm
5 μm
7 μm
Misidentification eff.
3μm / other σ
Charm contamination
LF contamination
Beauty eff.
CLICdp
Di-jet events, E_{CM} = 500 GeV, 20° < θ < 90°
Beauty contamination
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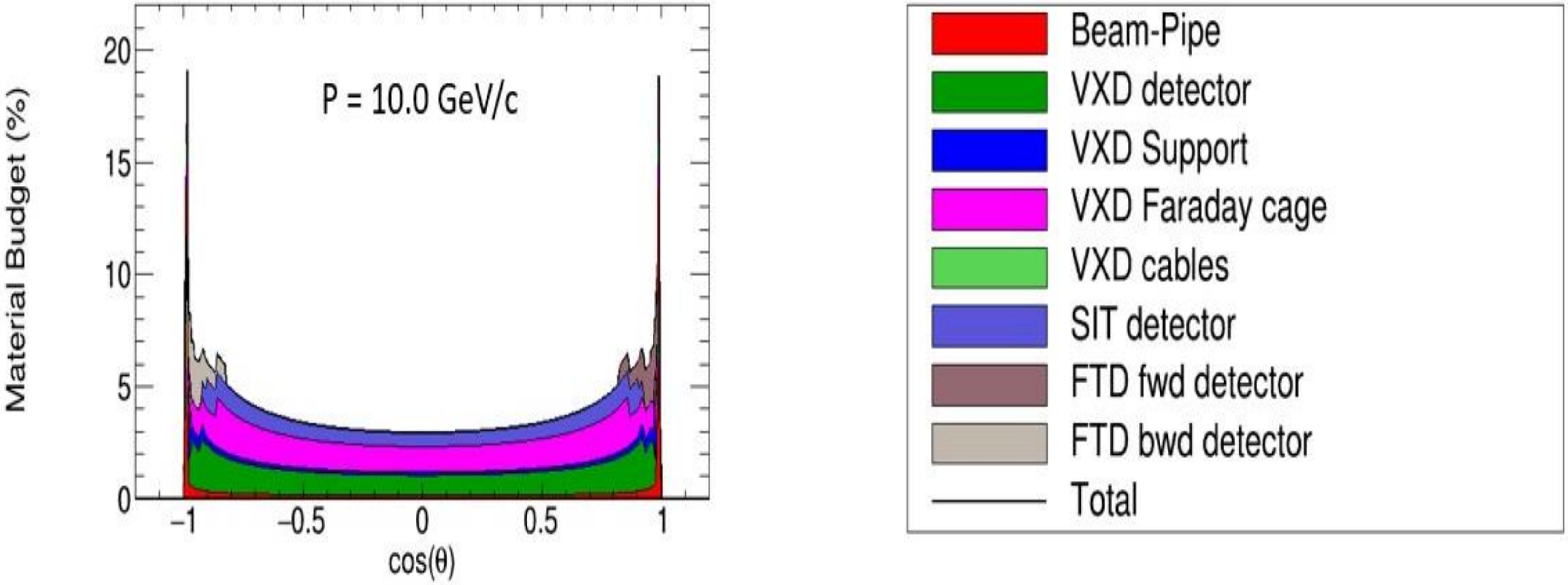
LF contamination
Charm eff.

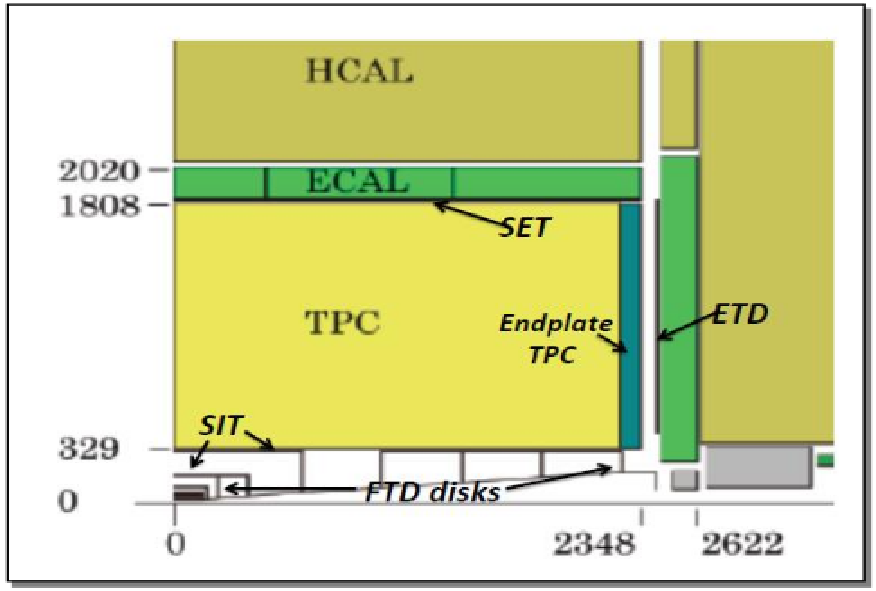

P = 10.0 GeV/c
Material Budget (%)
cos(θ)
Beam-Pipe
VXD detector
VXD Support
VXD Faraday cage
VXD cables
SIT detector
FTD fwd detector
FTD bwd detector
Total

Figures per layers						
Layer	0	1	2	3	4	5
Layer Radius (mm)	16	18	37	39	58	60
Layer $\|z\|max$ (mm)	61.9	61.9	123.8	123.8	123.8	123.8
Chip Pixel Number in X	1440	1440	1440	1440	1440	1440
Chip Pixel Number in Y	512	512	1024	1024	1024	1024
Chip Pixel PitchX (μm)	21.5	21.5	21.5	21.5	21.5	21.5
Chip Pixel PitchY (μm)	21.5	21.5	21.5	21.5	21.5	21.5
Chip Dimension X (mm) (sensitive area)	30.96	30.96	30.96	30.96	30.96	30.96
Chip Dimension Y (mm) (sensitive area)	11.01	11.01	22.02	22.02	22.02	22.02
Chip Dimension Y (mm) (non sensitive area)	2.0	2.0	2.0	2.0	2.0	2.0
Chip Surface (mm^2) (sensitive area)	341	341	682	682	682	682
Chip Surface (mm^2) (non sensitive area)	62	62	62	62	62	62
Chip Surface (mm^2) (total)	403	403	744	744	744	744
Ladder Length (mm) (sensitive area)	123.8	123.8	123.8	123.8	123.8	123.8
Ladder Width (mm) (sensitive area)	11.01	11.01	22.02	22.02	22.02	22.02
N chip per ladder on each side	4	4	4	4	4	4
Layer Surface (cm^2) (sensitive area)	136.3	136.3	599.7	599.7	926.9	926.9
N Chips Per Layer	40	40	88	88	136	136
Total surface (cm^2) (sensitive area)	3484					

Figures per double layers			
	Layer 0/1	Layer 2/3	Layer 4/5
N Chips in z	4	$4+4=8$	$4+4=8$
N Ladders	10	$2 \times 11 = 22$	$2 \times 17 = 34$
N Chips Per double Layer	80	176	272
N Chips (per architecture)	80	448	
N Total Chips	528		

Table 2: VXD dimensions

ILD dimensions



Barrel system						
System	R(in)	R(out)	z /mm	comments		
VTX	16	60	125	3 double layers	Silicon pixel sensors,	
				layer 1:	layer 2:	layer 3-6
				$\sigma < 3\mu m$	$\sigma < 6\mu m$	$\sigma < 4\mu m$
Silicon						
- SIT	153	300	644	2 silicon strip layers	$\sigma = 7\mu m$	
- SET	1811		2300	2 silicon strip layers	$\sigma = 7\mu m$	
- TPC	330	1808	2350	MPGD readout	$1 \times 6\text{mm}^2$ pads	$\sigma = 60\mu m$ at zero drift
ECAL	1843	2028	2350	W absorber	SIECAL	30 Silicon sensor layers, 5×5 mm^2 cells
					EcECAL	30 Scintillator layers, 5×45 mm^2 strips
HCAL	2058	3410	2350	Fe absorber	AHCAL	48 Scintillator layers, $3 \times 3\text{cm}^2$ cells
					SDHCAL	48 Gas RPC layers, 1×1 cm^2 cells
Coil	3440	4400	3950	3.5 T field	2λ	
Muon	4450	7755	280	14 scintillator layers		

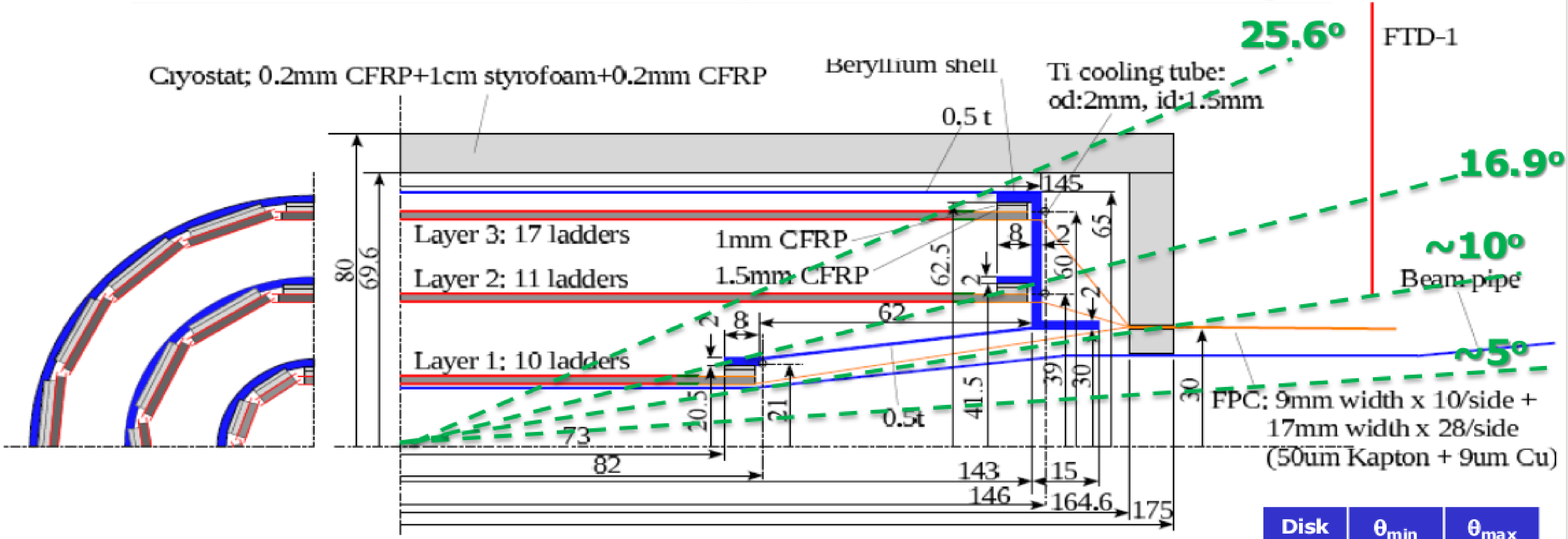
SIT characteristics (current baseline = false double-sided Si microstrips)					
Geometry			Characteristics		Material
R[mm]	Z[mm]	$\cos\theta$	Resolution R-ϕ[μm]	Time [ns]	RL[%]
153	368	0.910	R: σ=7.0,	307.7 (153.8)	0.65
300	644	0.902	z: σ=50.0	σ=80.0	0.65

SET characteristics (current baseline = false double-sided Si microstrips)					
Geometry			Characteristics		Material
R[mm]	Z[mm]	$\cos\theta$	Resolution R-ϕ[μm]	Time [ns]	RL[%]
1811	2350	0.789	R: σ=7.0,	307.7 (153.8)	0.65

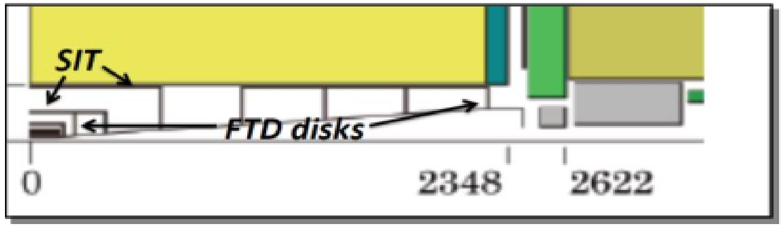
ETD characteristics (current baseline = single-sided Si micro-strips, same as SET ones)				
Geometry			Characteristics	Material
R[mm]	Z[mm]	$\cos\theta$	Resolution R-ϕ[μm]	RL[%]
419.3-1822.7	2420	0.985-0.799	x:σ=7.0	0.65

FTD characteristics (design baseline: pixels for two inner disks, microst				
Geometry			Characteristics	Material
R[mm]	Z[mm]	$\cos\theta$	Resolution R-ϕ[μm]	RL[%]
39-164	220	0.985-0.802	σ=3-6	0.25-0.5
49.6-164	371.3	0.991-0.914		0.25-0.5
70.1-308	644.9	0.994-0.902	σ=7.0	0.65
100.3-309	1046.1	0.994-0.959		0.65
130.4-309	1447.3	0.995-0.998		0.65
160.5-309	1848.5	0.996-0.986		0.65
190.5-309	2250	0.996-0.990		0.65

Reminder : Geometry in the forward region



- Different regions to consider



FTD characteristics (design baseline: pixels for two inner disks, microstrips for the rest))				
Geometry			Characteristics	Material
R[mm]	Z[mm]	$\cos\theta$	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

Disk	θ_{min}	θ_{max}
1	10.1°	36.7°
2	7.6°	23.8°
3	6.2°	25.5°
4	5.5°	16.5°
5	5.1°	12.1°
6	5.0°	9.5°
7	4.8°	7.8°

Varying in the forward disks positions: