Forward Tracking;
physics case, challenges and detector design

Today:

emphasis on forward vertexing

ILC workshop of the Americas,

Albuquerque (NM), USA

September 29-October 3 2009

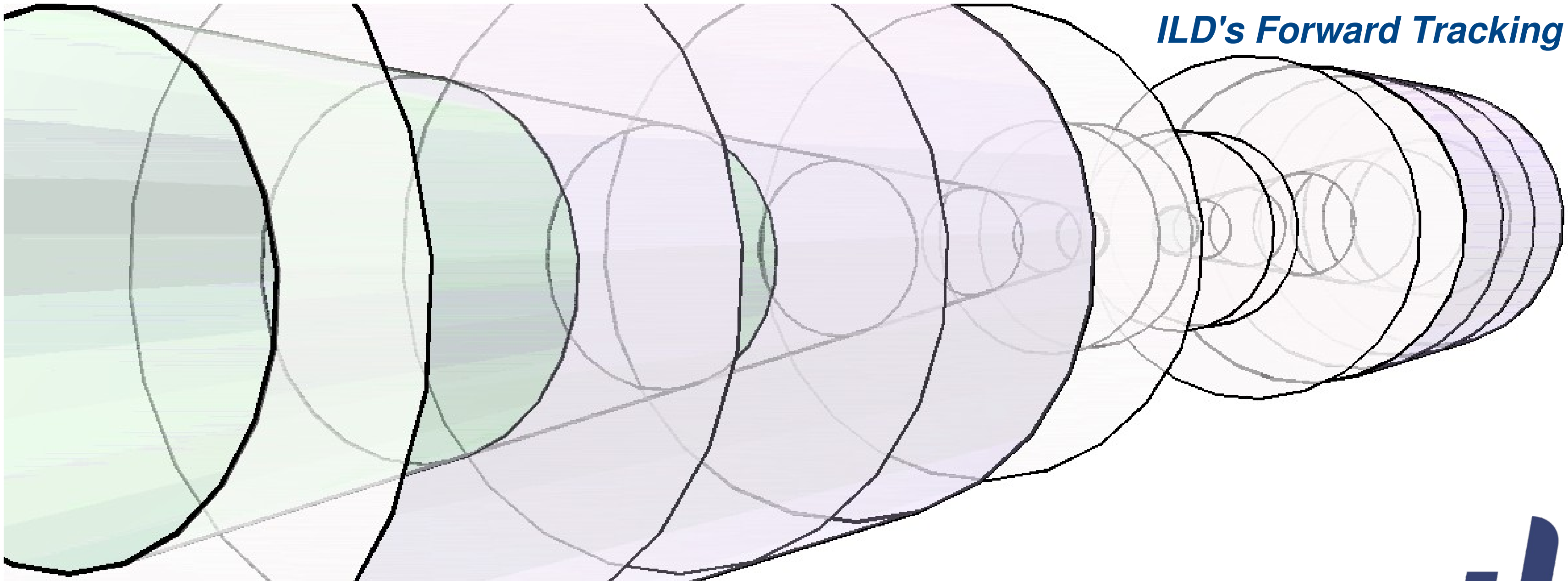
Marcel Vos (IFIC – U. Valencia/CSIC)

Alberto Ruiz (IFCA)

Thanks to the Spanish network for “future colliders”

The scope of this talk

ILD's Forward Tracking Disks



The forward region = *$6^o < \theta < 30^o$*

(0.1 rad $< \theta <$ 0.45 rad, 0.9 $< \cos\theta <$ 0.995, 1.5 $< |\eta| <$ 3)

in future e^+e^- colliders

Why is forward tracking performance important?

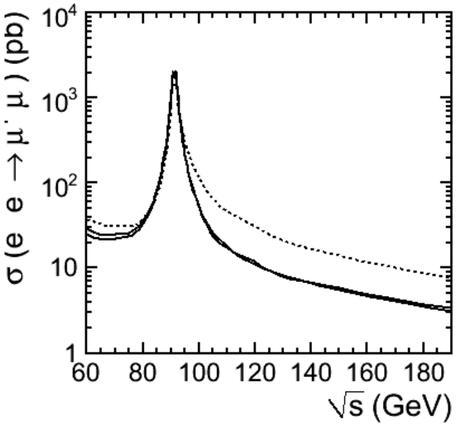
There is a series of very relevant physics processes where final state particles are predominantly emitted at small polar angle

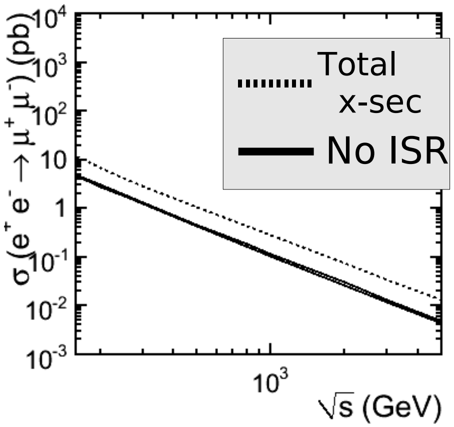
Mostly electrons, but also muons, t, b- and c-jets

From LEP-I to the ILC (to CLIC)

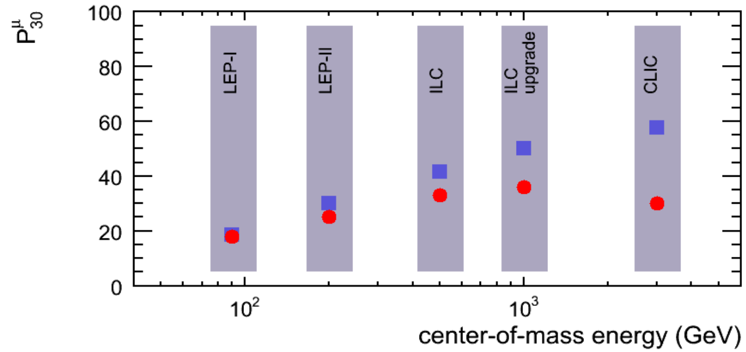
$e^+e^- \rightarrow Z/\gamma* \rightarrow \mu^+\mu^-$

with(----)/without(- - -) ISR

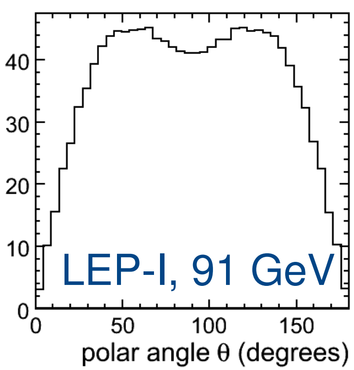


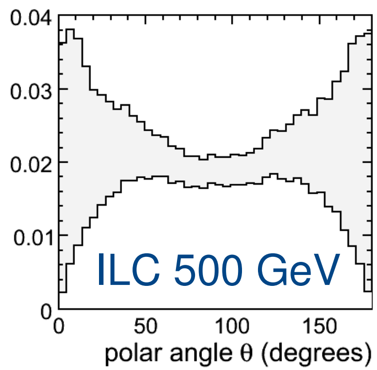


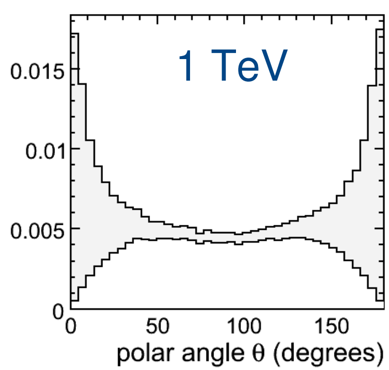
P^X_{30}: Probability that final state product X is emitted at a polar angle $5 < \theta < 30°$

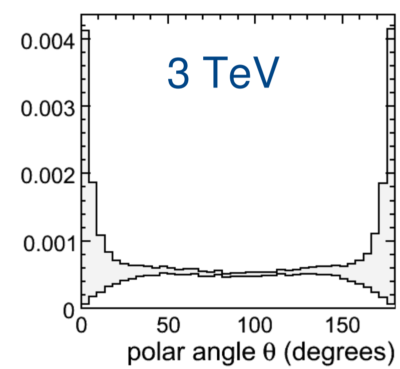


Determine the relevance of the forward region in several key processes for a number of scenarios increasing center-of-mass energy







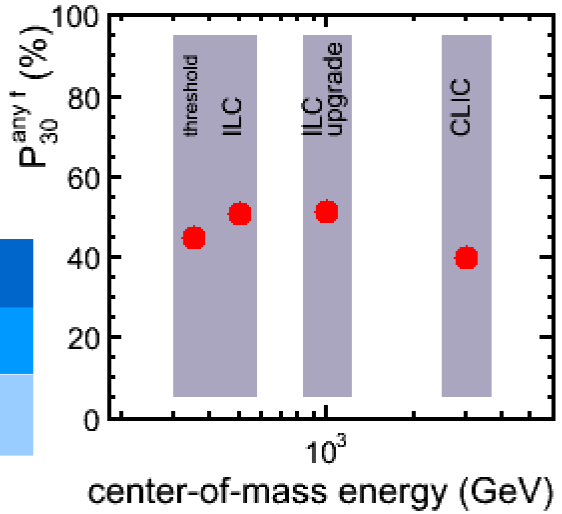


Multi-fermion final states

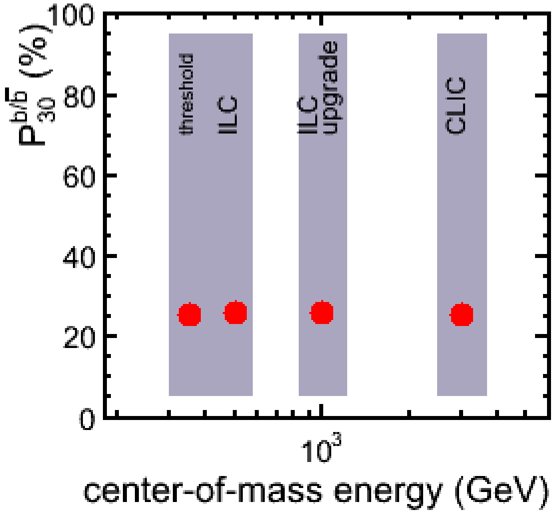
- **2 → 2 processes dominated LEP-I physics**
- **At larger √s, 2 → N, with N=4,6,8,... becomes more relevant**

√s	91 GeV	500 GeV	3 TeV
machine	LEP-I	ILC	CLIC
$\langle N_{jets} \rangle$	<3	5	6.4

At least 1 (of 6) fermions



At least 1 (of 2) b-quarks



As an example look at $e^+e^- \to Z \to tt$, no ISR

√s	500 GeV	1 TeV	3 TeV
at least one top	0.15	0.17	0.22
at least one b	0.22	0.25	0.25
any fermion	0.59	0.51	0.4

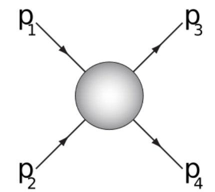
Final states with many fermions (like ordinary SM tt-events) are hardly ever fully contained in the central detector
Tag a forward b-jet in 1 out of 4 events: requires vertexing

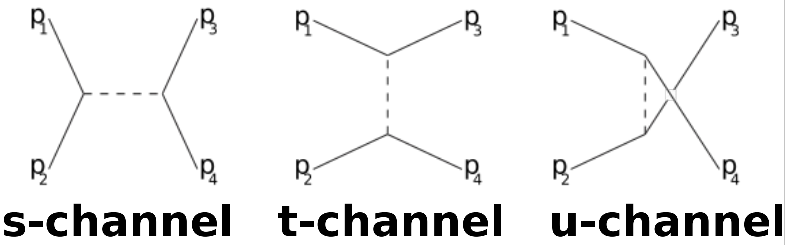
The importance of the t-channel

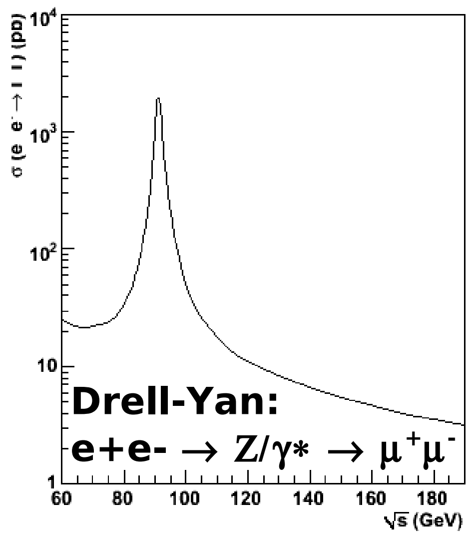
With increasing center-of-mass energy
(from LEP-I to to LEP-II to ILC to CLIC)
the importance of the t-channel increases

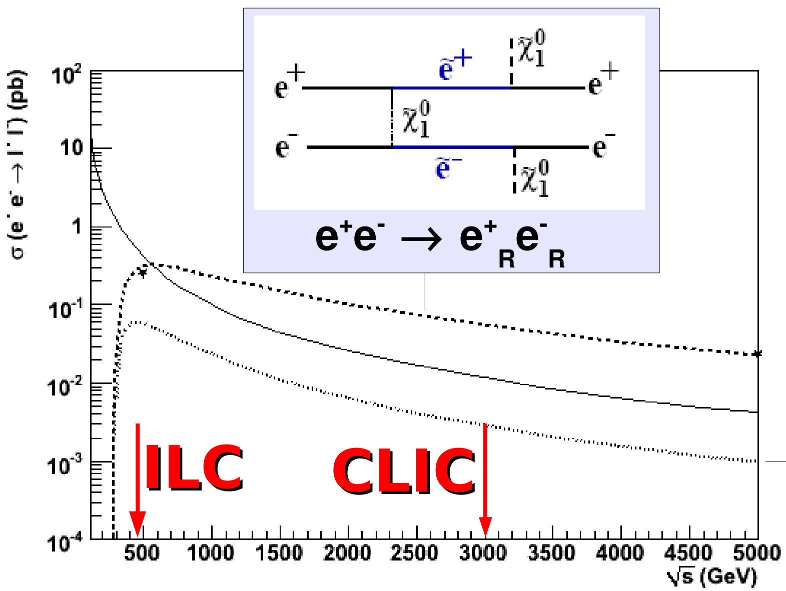
Example: scalar lepton production in SUSY (SPS benchmark point 1a)

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

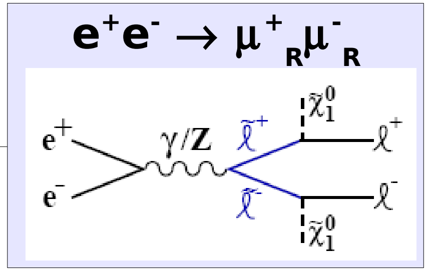






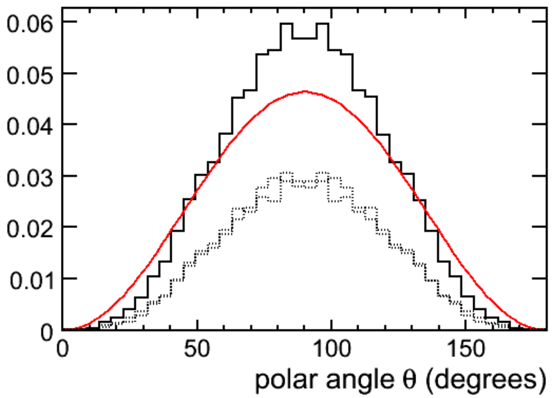


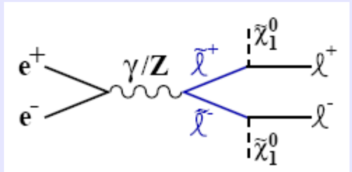
MadGraph/MadEvent (hep-ph/0208156)



The importance of the t-channel

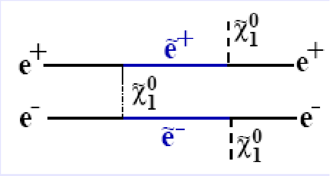
polar angle distribution for s-lepton production

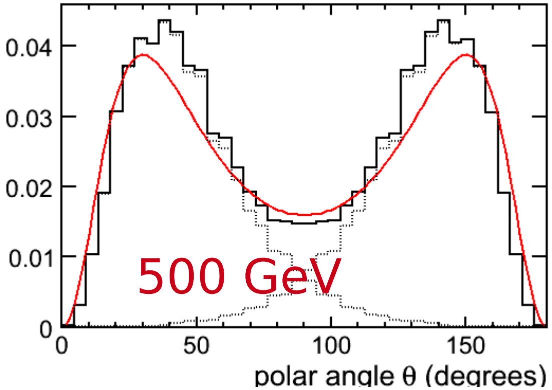


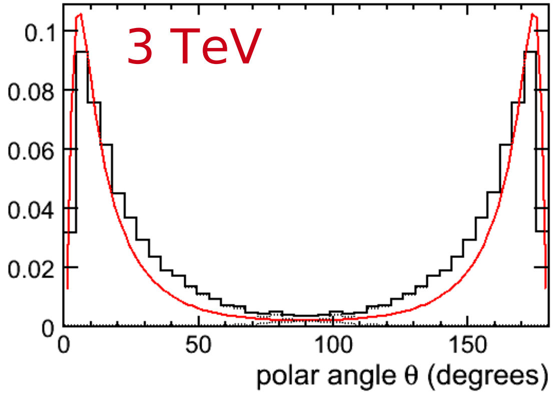


scalar muons

s-electro







Products from t-channel prefer the forward region, and this feature becomes more pronounced at CLIC energies

Fraction of forward s-electrons ($\theta < 30^o$) for s-electron pair production in SPS1a

@ 500 GeV **24 %** **@ 1 TeV** **50 %**

Scan SUSY space (analytical expression for polar angle distribution)

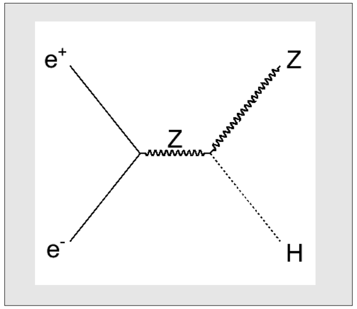
t-channel

Table: $P_{e\sim}^{30}$ for scalar electron production in different machines and for different points of the Snowmass benchmark set

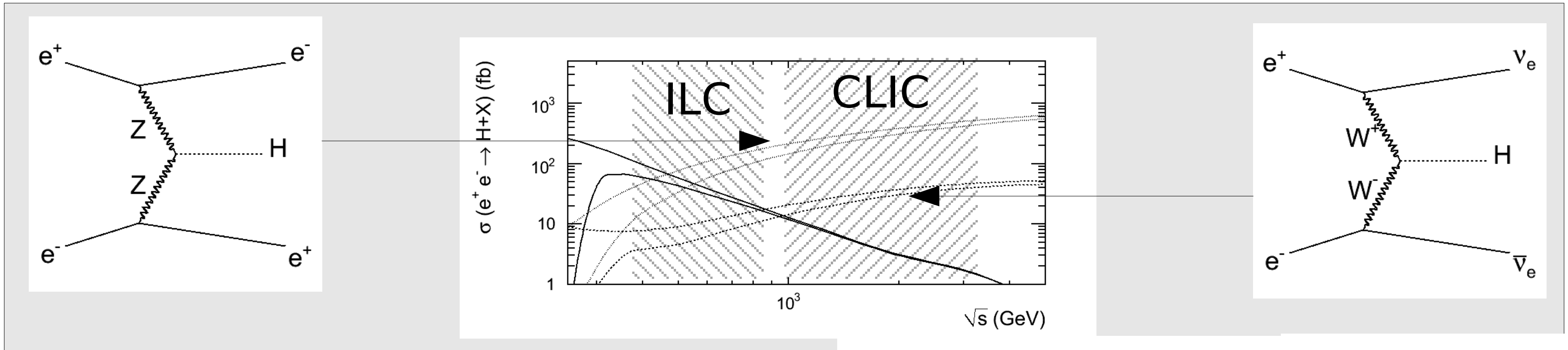
	$m(e_R)$	$m(\chi^0)$	500 GeV	800 GeV	1 TeV	2 TeV	3 TeV
SPS1a	135	99	30	46	54	70	73
SPS2	1451	79	-	-	-	-	10
SPS3	178	160	20	38	48	63	70
SPS4	416	118	-	-	21	65	72
SPS5	192	119	21	47	57	70	71
SPS6	236	189	8	27	38	64	73
SPS7	127	161	25	35	43	65	73
SPS8	176	137	24	44	47	66	72
SPS9	303	175	-	26	42	61	67

Scalar electron production is extremely peaked in the forward direction whenever the center-of-machine exceeds the masses of the s-electron and neutralino significantly. For $CLIC^{3TeV}$ this is the case for all points but one.

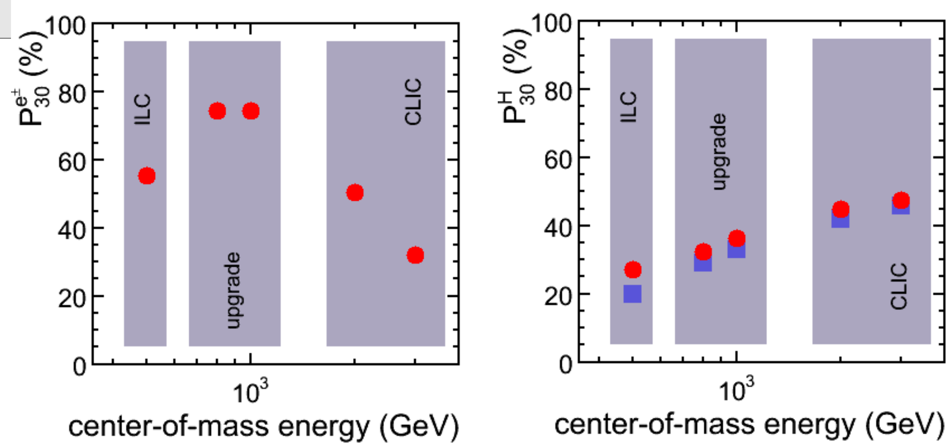
Higgs production



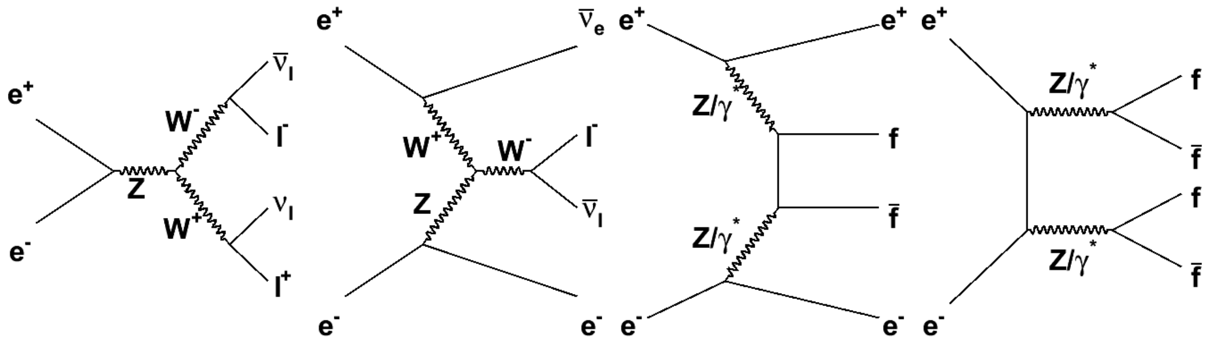
- Higgs-strahlung is the dominant Higgs production process for a low-mass at small √s
- Recoil-mass reconstruction is the tracking benchmark analysis par excellence
- A very central signature



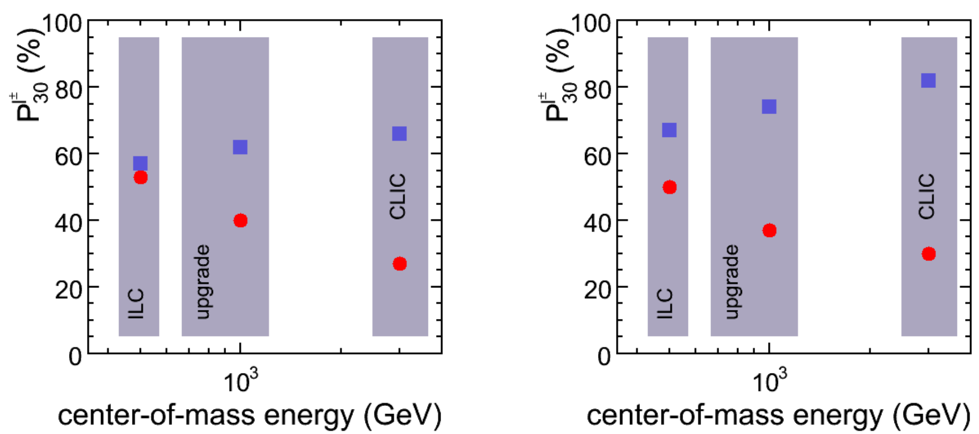
Vector boson fusion processes are much more interesting at CLIC
ZZH can be reconstructed using the recoil-mass analysis on extremely forward electrons



Di-boson production



The last example: di-boson production.



The polar angle distribution of electrons is extremely peaked in forward direction

Forward tracking physics case

Forward tracking requirements at the next e^+e^- collider
part I: the physics case for forward tracking

J. Fuster [v], S. Heinemeyer [s], C. Lacasta [v], C. Mariñas [v], A. Ruiz [s], M. Vos [v*]

[s] IFCA Santander

[v] IFIC Valencia

February 12, 2009

Abstract

In this note we explore the detector requirements of the forward tracking region for a future e^+e^- collider with a center-of-mass energy in the range from 500 GeV to 3 TeV. The relevance of the forward region is explored for a wide range of physics processes.

Little guidance for forward detector design from standard benchmark reactions (cos $\theta < 0.95$)

Together with many other analyses and channels that we didn't discuss:

- A_{FB} in the bb and cc system
- Degenerate staus and neutralino
- center-of-mass energy determination using $\mu\mu\gamma$ events

These examples make the physics case for orward tracking:

At a high-energy e^+e^- collider several potentially very interesting physics analyses require excellent tracking and vertexing performance. These arguments become more urgent as the center-of-mass energy increases. Precise electron reconstruction is of particular importance.

Why is forward tracking challenging?

The material!
Hermetic coverage
Significant background at smallest radii
The unfavorable orientation of the magnetic field
Abundant low momentum tracks – pattern recognition

Today: forward vertexing – interplay VXD and forward tracker

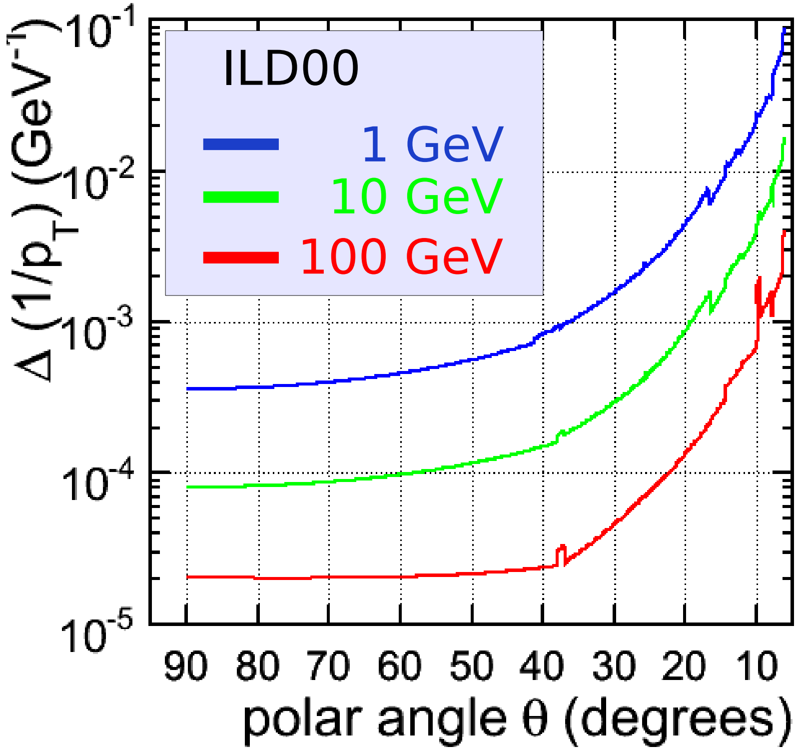
Momentum resolution

ILC tracking specification: momentum resolution $\Delta(1/p_T) < 5 \times 10^{-5}$ (GeV^{-1})

Precision required to reconstruct the Higgs boson using the recoil method, and to reconstruct SUSY end-points

ILD00 momentum resolution single muons

- ✔ Performance ~ stable down to 36°
- ✔ Steep loss between 6-36°



worse forward performance is the result of a combination of

(a) magnetic field orientation (inevitable within 4π detector geometry)

(b) loss of # of measurements in TPC

Momentum resolution

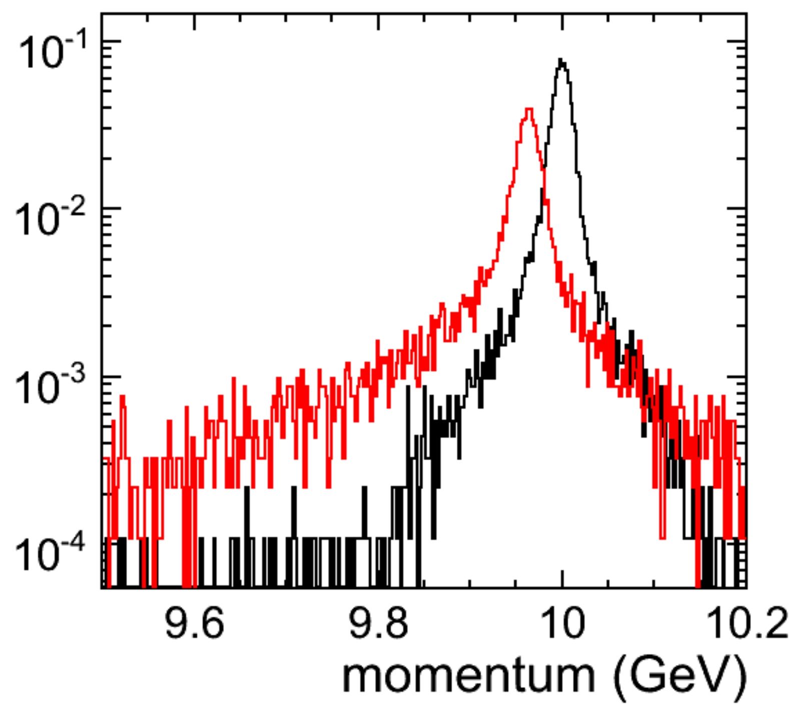
Momentum resolution for electrons (remember t-channel!!)

- ✔ Ongoing study (Jordi Duarte, IFCA): generate single-electron samples (private, but available for those interested)
- ✔ compare tracker-only momentum resolution of single electrons with the LOI results for muons
- ✔ Understand tracker-parameter dependence
  - ➔ material!

ILD00 full simulation

— 10 GeV μ^-

— 10 GeV e^-



Ongoing study by Jordi Duarte

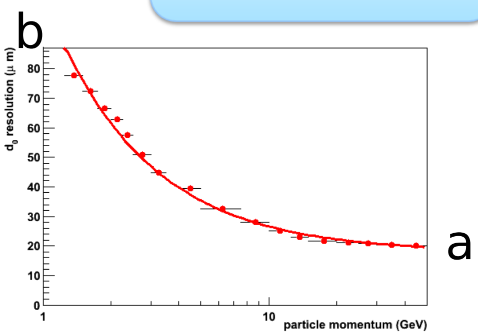
Impact parameter resolution

VXD: impact parameter resolution 5 – 10 μm.

This precision is required to achieve excellent heavy flavour tagging, particularly for couplings of the Higgs boson to charm (cτ ~150 μm) and bottom (cτ ~ 450 μm)

	a (μm)	b (μm GeV)
LEP	25	70
SLD	8	33
LHC	12	70
ILC	5	10

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



Unprecedented precision
(small pixels, 20x20 μm^2)

Strongly reduce the multiple Coulomb scattering term
(material: 0.1 % X_0 / layer ~ 100 μm Si)

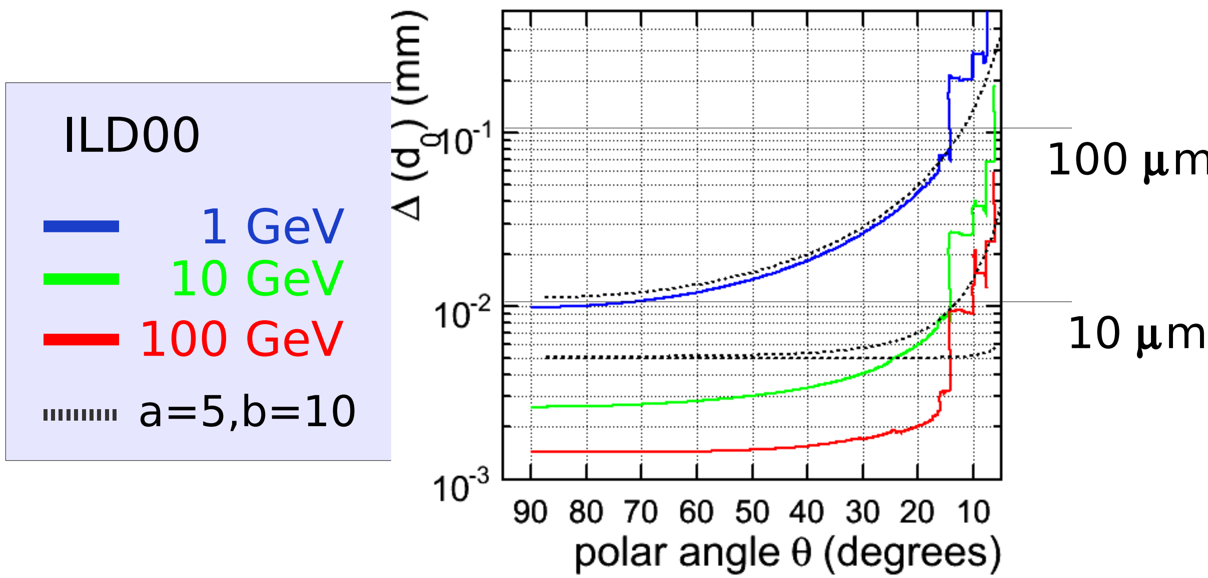
ILD vertexing performance

central:

a~1.7 μm

forward:

performance significantly worse than extrapolation of barrel formula with a=5,b=10



Vertex-Forward Tracking

SiD (barrel+end-cap) and ILD (long barrel + FTD) have chosen very different layouts for the vertex detector and innermost forward tracking system

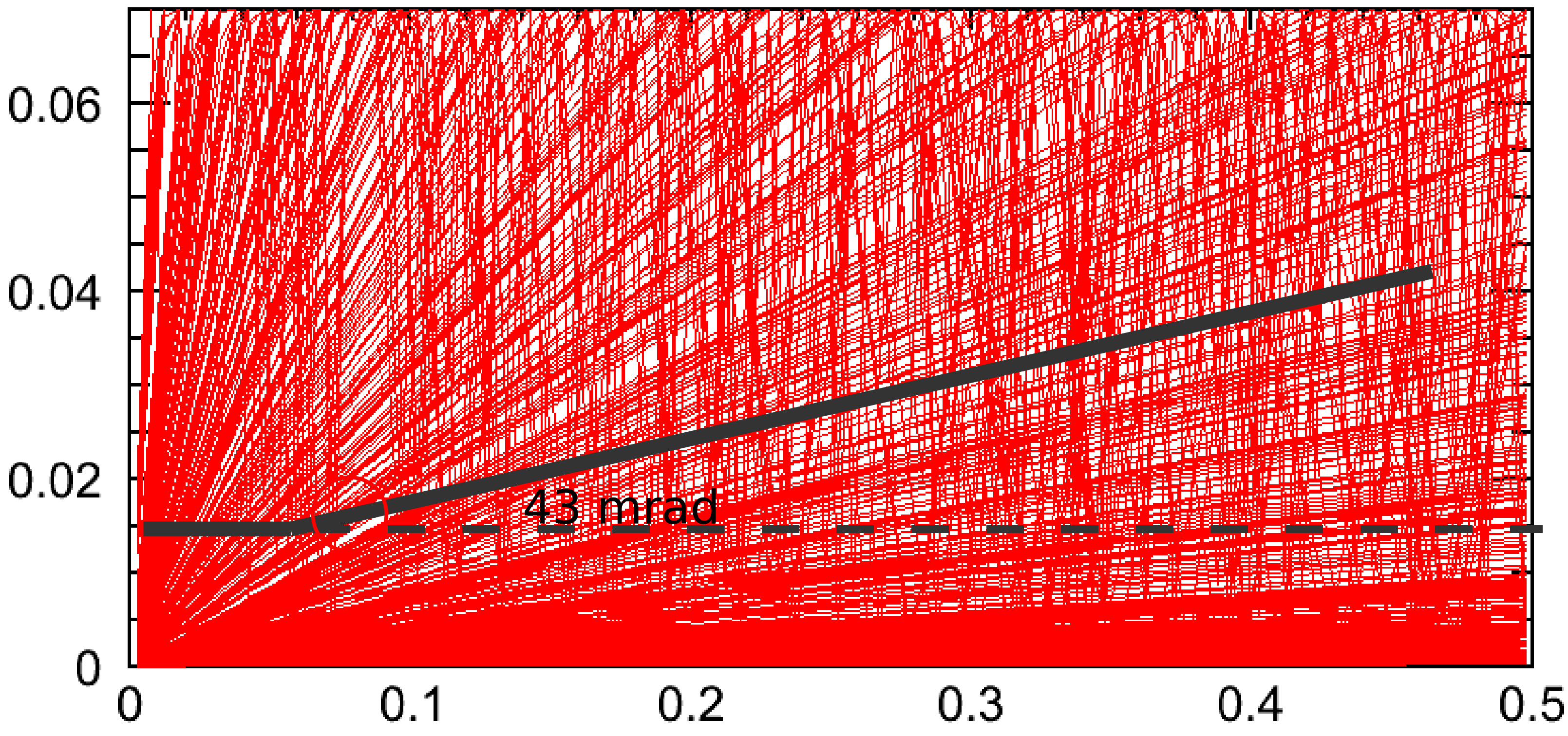
Establish strengths and weaknesses of different solutions by comparing the impact parameter resolution of toy geometries

CAVEAT: We're not comparing SiD and ILD (too many differences)

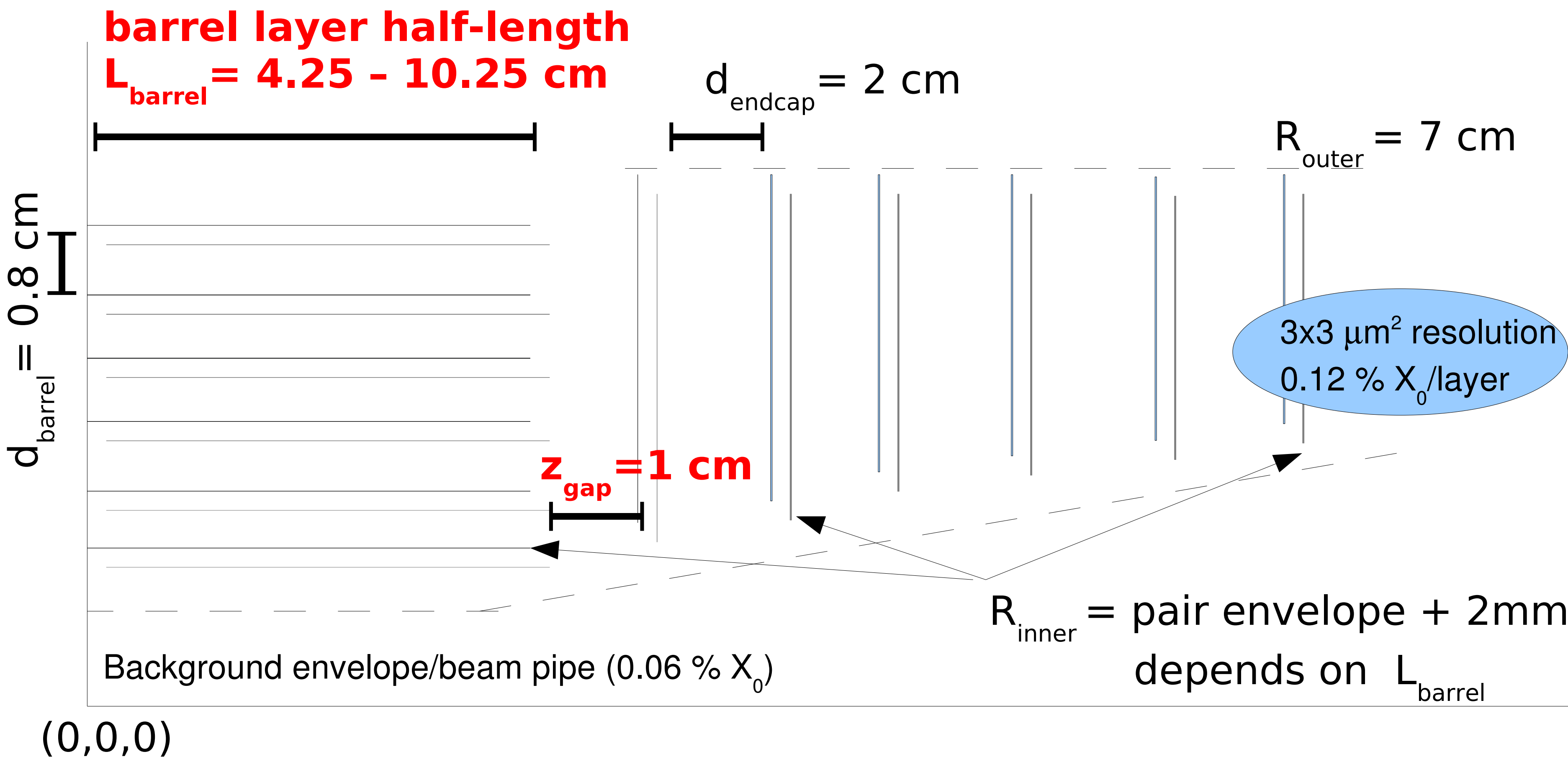
- Simplify the problem, reduce the number of observables
  - Vertexing is more than just flavour tagging.
  - Flavour tagging is more than just impact parameter resolution
- Simplify the problem, reduce the number of degrees of freedom
  - Uncertainty in the material budget (services!)
  - Uncertainty in the envelope of the pair background (B-field, machine parameters)
- Simplify the problem, software limitations
  - conical beam pipe (with thicker conical sections) not yet implemented

Choosing the background envelope

Use SiD beam pipe as starting point (implicitly assumes 5 Tesla field)
6.25 cm straight section, 43 mrad opening angle
2 mm margin for all silicon elements (cylinders and disks)



Choosing a toy geometry



SiD: L_{barrel} ~ 6.25 cm, z_{gap} ~ 1 cm

ILD: L_{barrel} ~ 12.5 cm, z_{gap} ~ 10 cm

Tools – track fitting

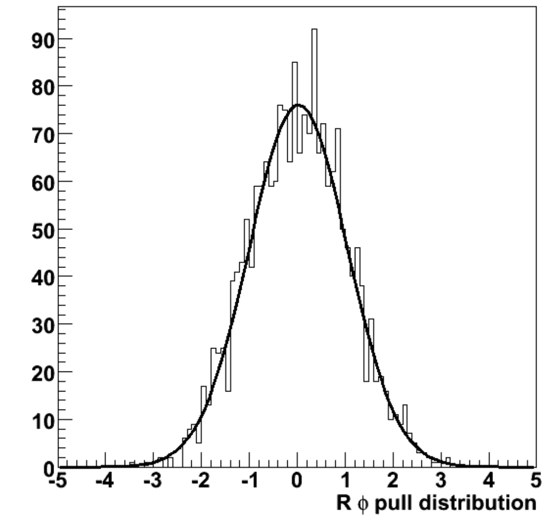
CMS Kalman filter tool-kit.

The result of years of work by a lot of people. Validated in large-scale MC productions.

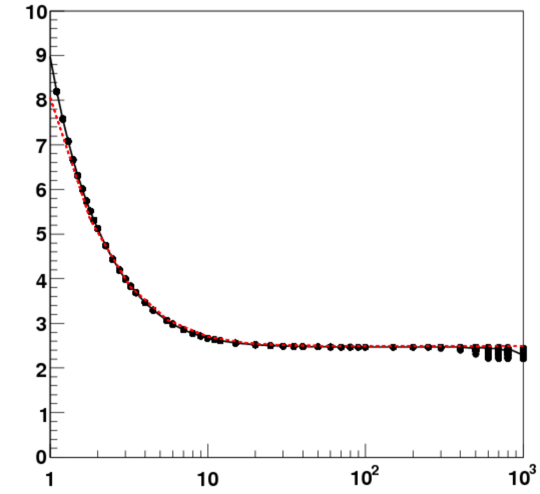
Extracted all relevant code in a series of libraries with limited external dependencies (CLHEP, ROOT).

Interfaced to toy geometries in standalone programme. Tested results for internal consistency and against existing fast-simulation packages.

Interfaced to MarlinReco (GEAR geometry, LCIO hits)



pull distribution R ϕ coordenate at last measurement plane



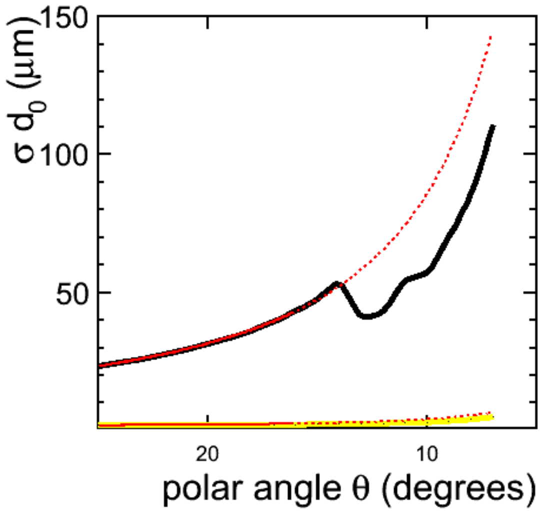
LCDTRK vs. KF: Transverse impact parameter resolution vs p_T

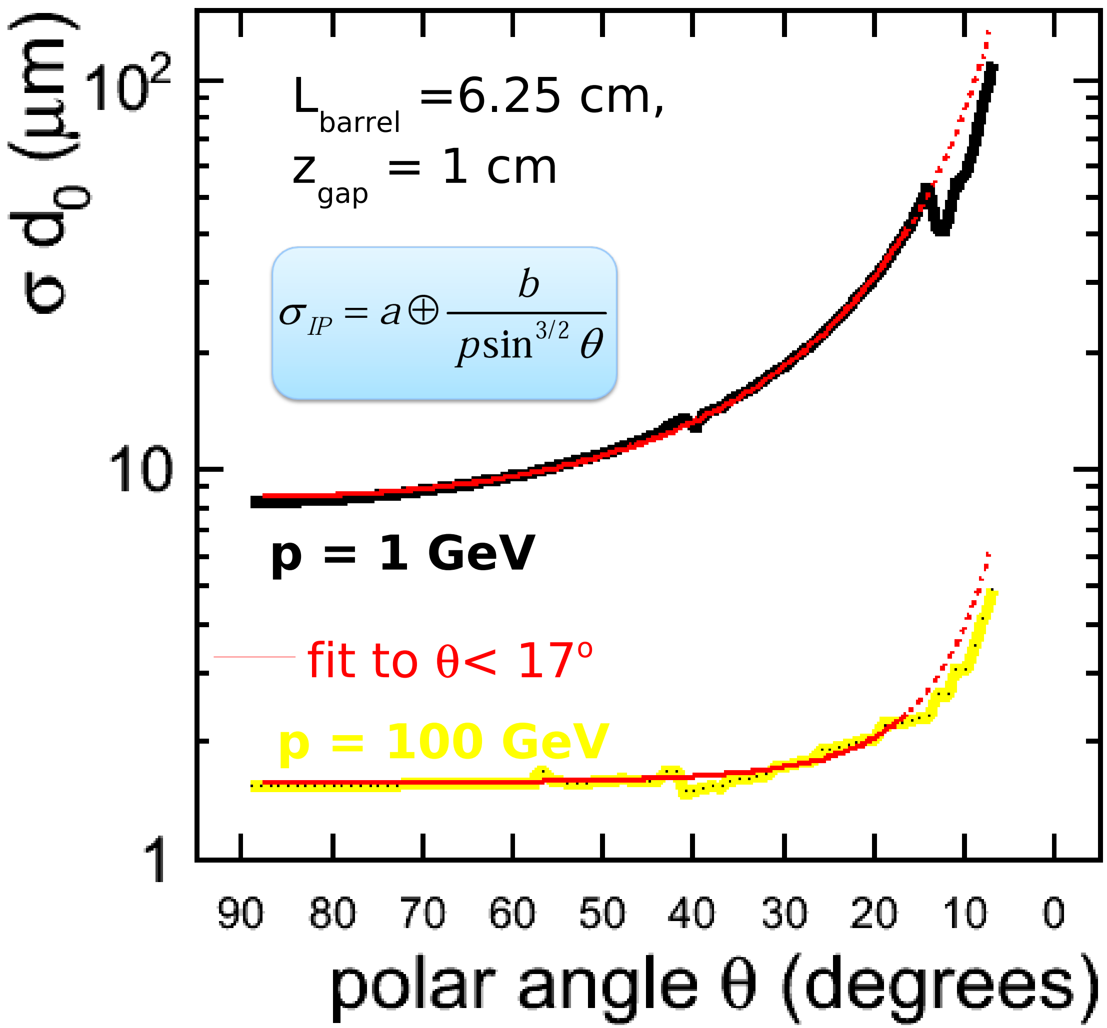
Transverse impact parameter resolution

Transverse impact parameter resolution vs. polar angle

Barrel-dominated part well-described by the standard formula.

Deviations in the very forward region (as expected)

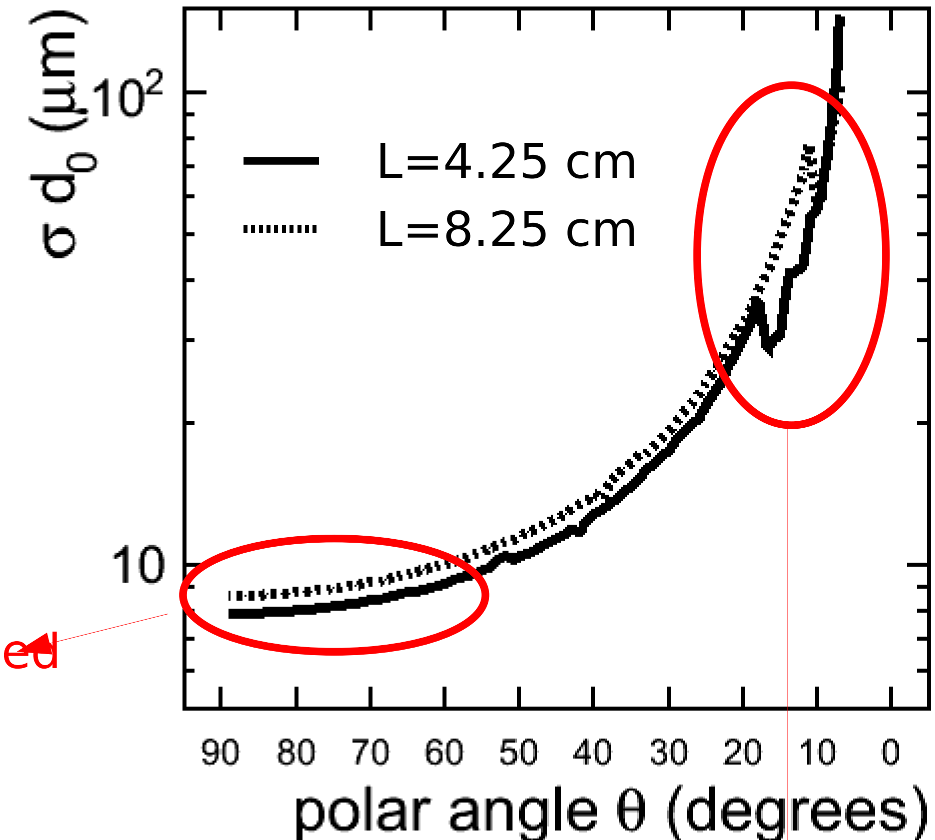




Comparison of different layouts

Longer barrel
→ worse performance

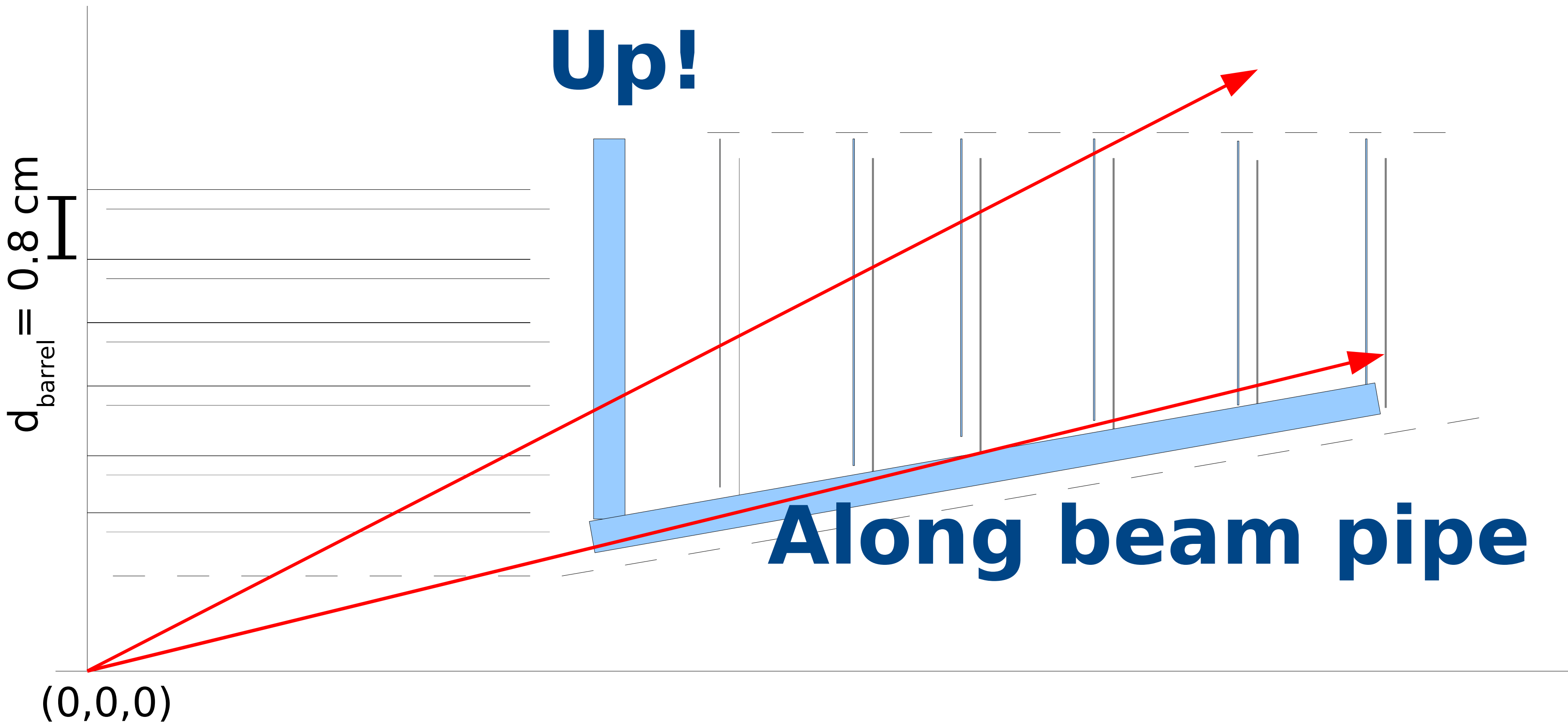
But, let's repeat with material for barrel services



Central performance degraded due to larger radius

Barrel-endcap transition moved to smaller angle

Choosing a toy geometry



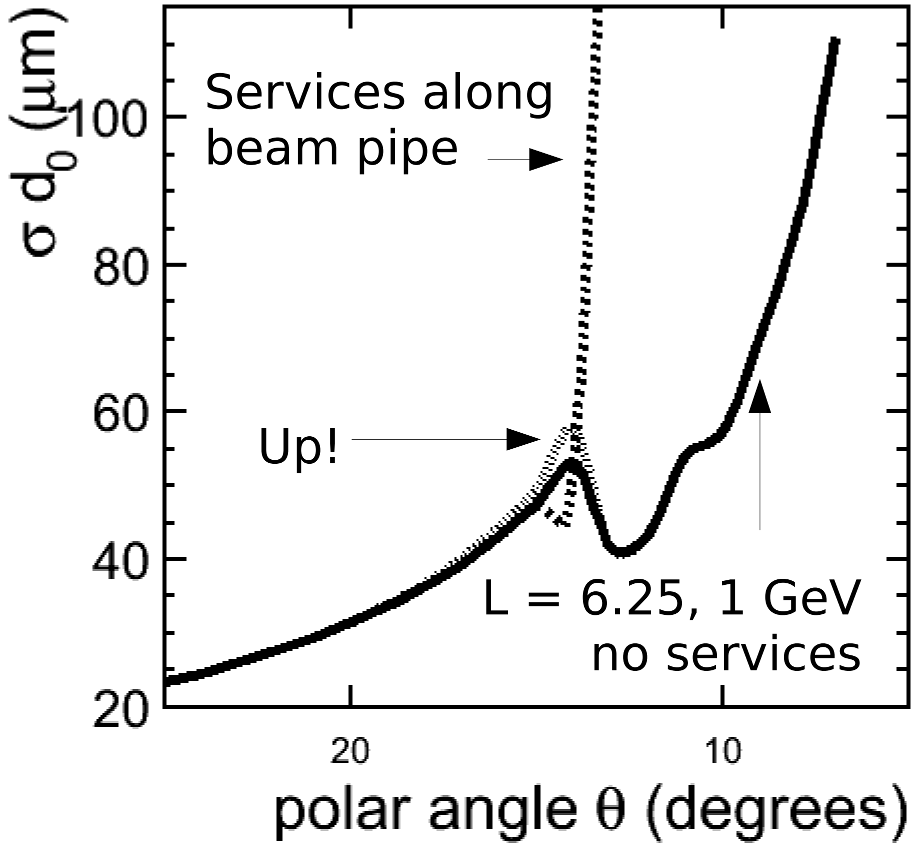
Add 3 % X_0 (on perpendicular crossing) of barrel VXD services

Two routing options

Up! or along beam pipe?

The forward region clearly does NOT like the services routed along the beam pipe

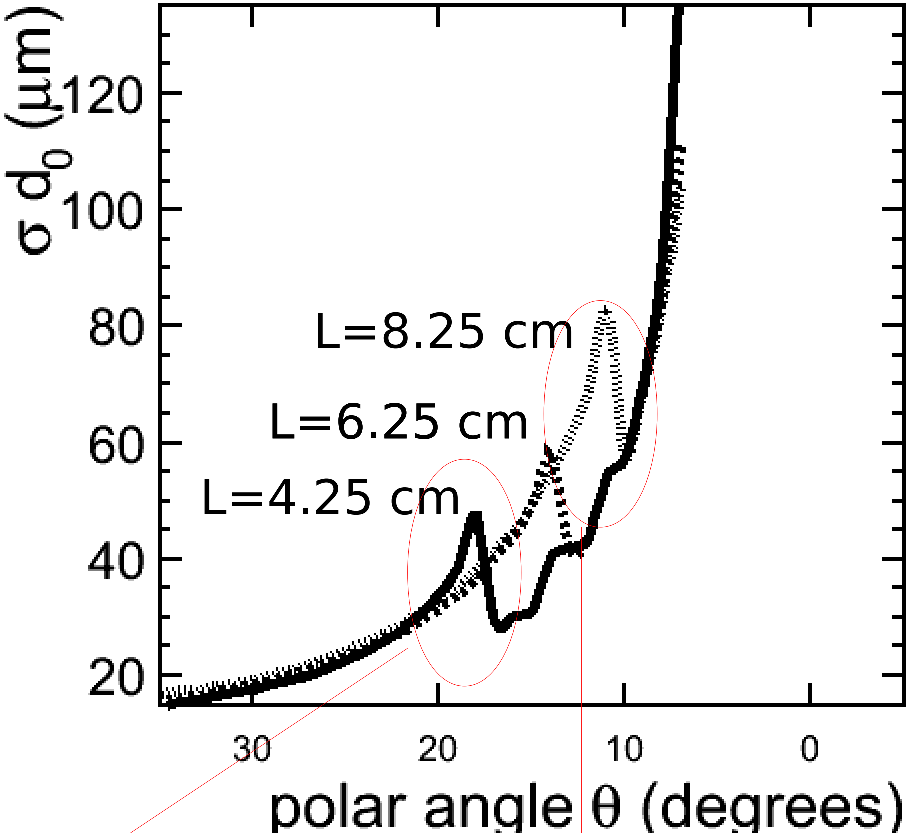
If anything close to a few radiation lengths comes in the way between endcap and interaction point we can forget about forward vertexing



Comparison L_{barrel}

A longer barrel removes the "material bump" from the central region...

Of course, the material comes back - with a vengeance – at smaller angle



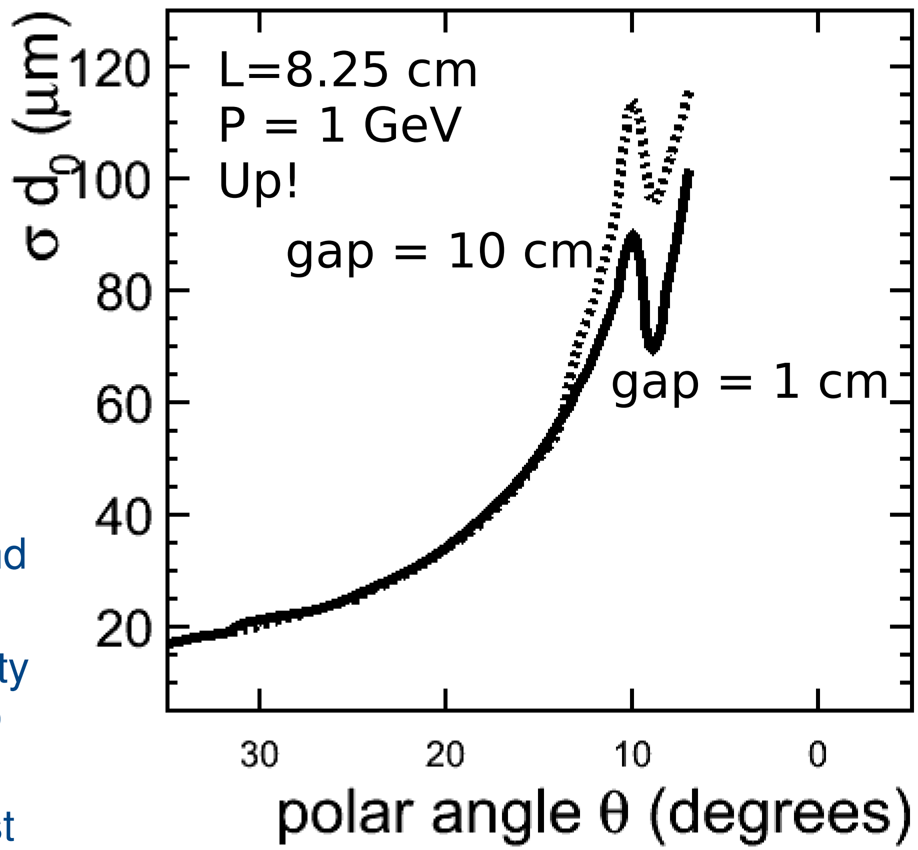
Save a little here....

Large distance, shallow angle

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.

Conclusions

There is significant physics to be gained (or lost) in the forward region (6-30º)

If the central vertexing performance is somewhat of a challenge, maintaining good performance at small polar angle is close to impossible

A simple-minded layout optimization (see caveats) of the VXD-FTD layout for forward vertexing performance yields:

- Minimize z_{gap}

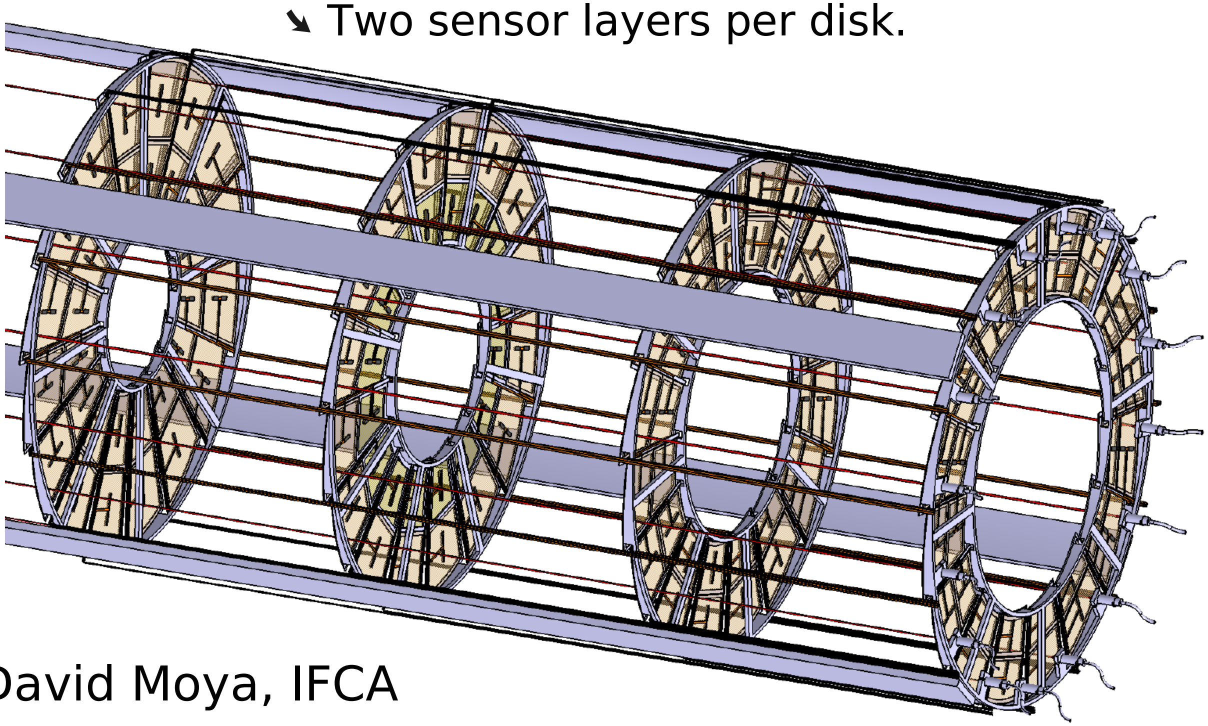
Service routing/material is essential in choosing optimal geometry:

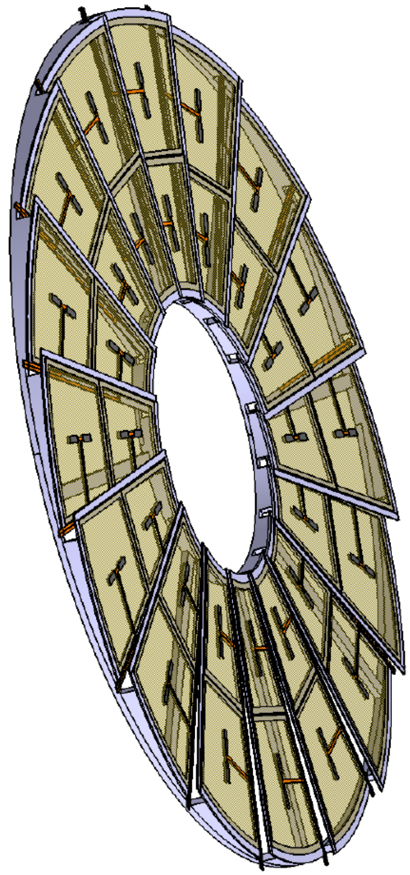
- Upward ⇔ very short barrel + closely packed end-cap:
  + works well even at low angle
  - any material (beam pipe) in front of the disks will destroy the performance
- Along beam pipe ⇔ very long barrel
  + no “material bump” due to services down to ~15º
  - limited vertexing beyond first barrel layer coverage

Backup slides

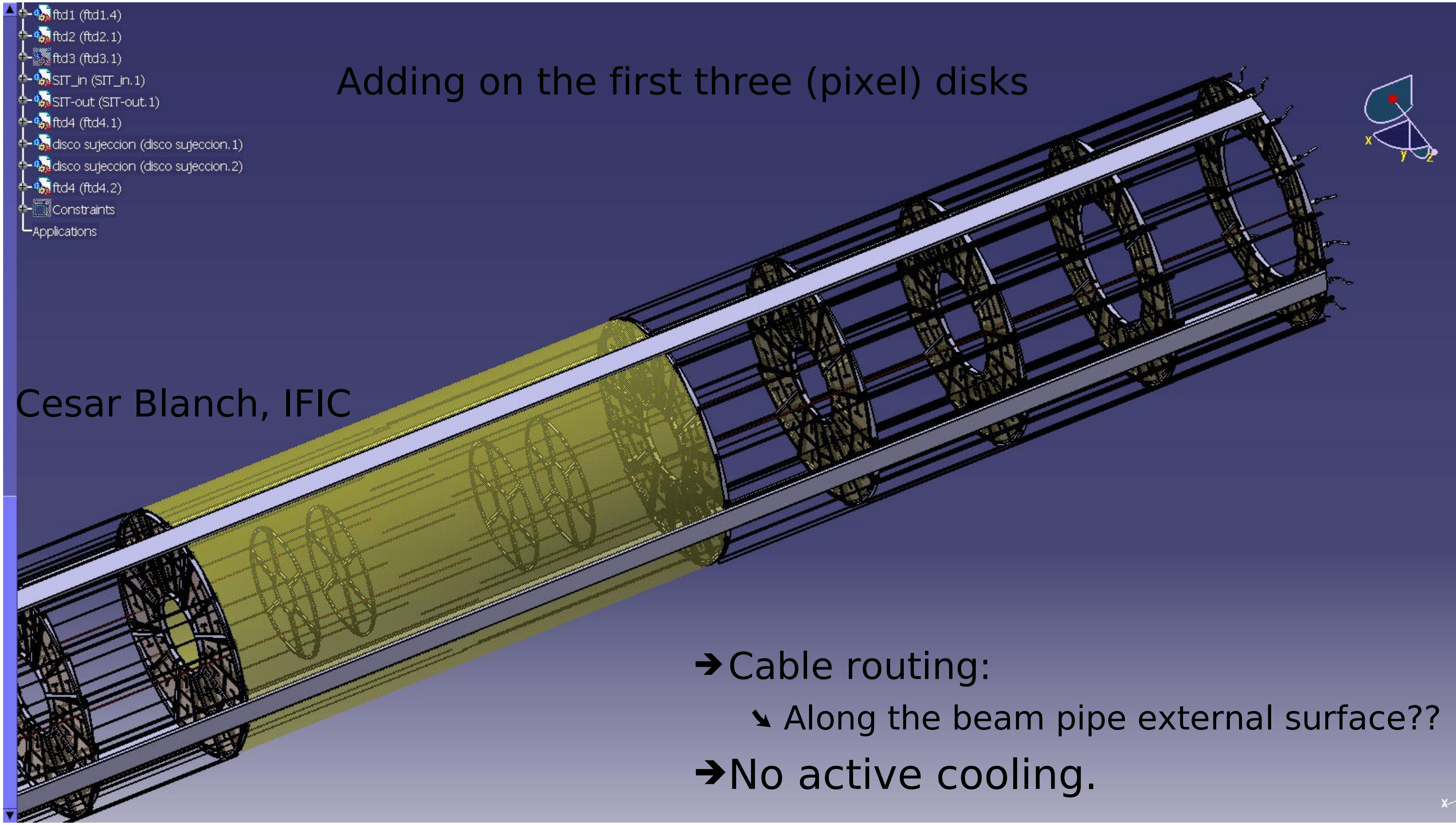
Towards an FTD design

- ➔ Micro-strip module guidelines:
  - ROC on sensor
  - ROC thinned to 50-100 um
  - 6” wafers (approx 10 cm x 10 cm sensors)
  - 150 μ m thickness
    - Two sensor layers per disk.





David Moya, IFCA



Adding on the first three (pixel) disks

Cesar Blanch, IFIC

- ➔ Cable routing:
  - ➘ Along the beam pipe external surface??
- ➔ No active cooling.

Conclusions

Interest of the forward region:

in several interesting physics cases the final state products have a strong preference for the forward region

Specific challenges:

momentum resolution under unfavorable field orientation
impact parameter measurement for very forward tracks
non-negligible background level (read-out speed)
standalone pattern recognition (background, low p tracks)
minimal distortion of particles/global performance

Requirements:

granularity @ reasonable speed staying within the power budget

Laser alignment:

the only “many-layer” silicon system in ILD

Towards a design:

engineering studies of FTD

More information on
http://ific.uv.es/~vos/ilc

REFERENCES

A. Savoy Navarro et al. (the SiLC collaboration), PRC review, DESY, 2008

A. Savoy Navarro et al. (the SiLC collaboration), ILC tracking review, Beijing 2007

The challenges of forward tracking, *invited talk*, IEEE NSS&MIC, Dresden, Germany, 2008

Forward tracking, TILC08 (ACFA/EDG) Sendai, Japan, 2008

The silicon tracker elements, ILD meeting, Sendai, Japan, 2008

Forward Tracking, SiD meeting, Oxford, UK, 2008

The silicon tracker, First ILD workshop, Desy Zeuthen, Germany, 2008

Tracking and alignment at the ILC, *invited talk*, 2nd alignment workshop for the LHC, CERN, Ginebra, Switzerland, 2007

Tracking at the ILC,invited talk, 8th International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, published Nucl. Instr. Meth.,

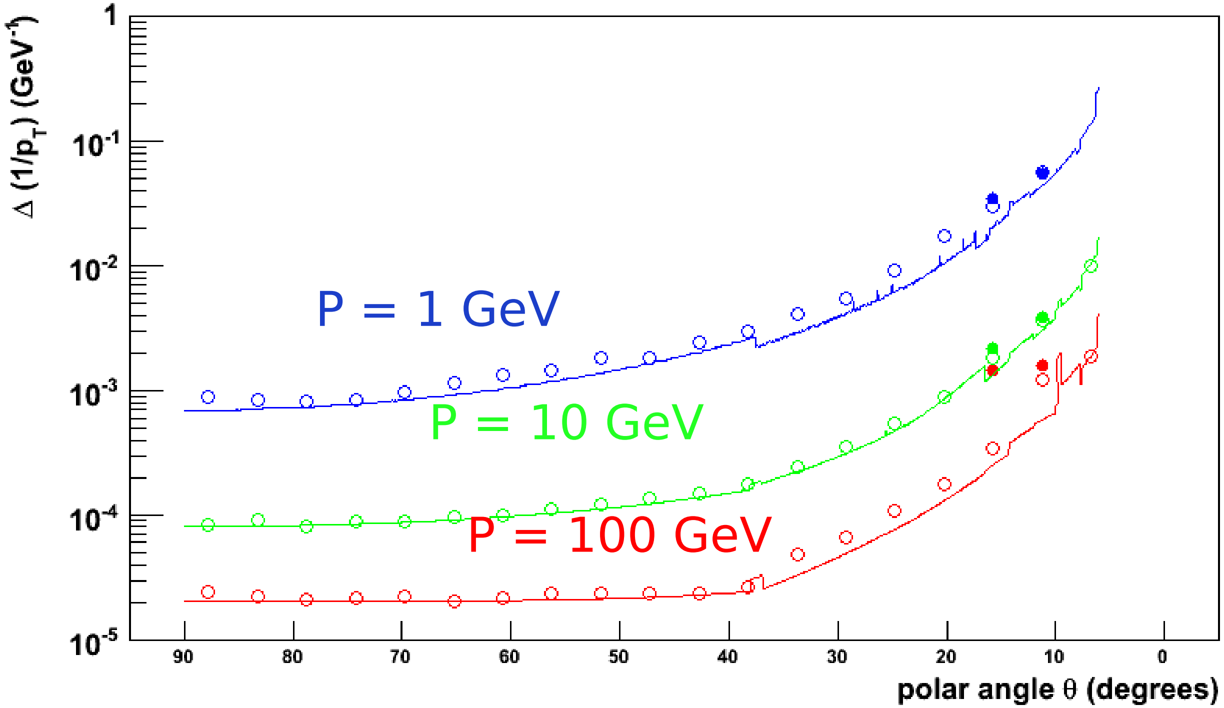
Overview of SiLC simulation, Linear Collider Workshop (LCWS07), *DESY (Germany), 2007,* arXiv:0801.4509

The SiLC simulation task force, ILC software workshop, Orsay, France, 2007

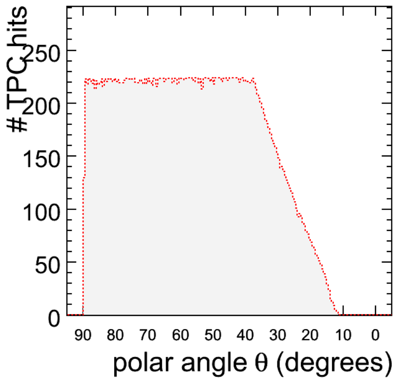
The SiLC simulation task force, Tracking review, "the SiLC collaboration",, Beijing, China, 2007

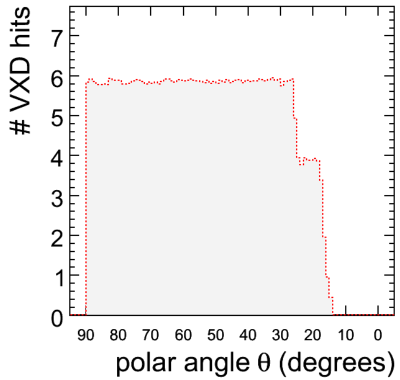
Transverse momentum resolution versus polar angle
Measured on three single-muon samples with fixed |p|

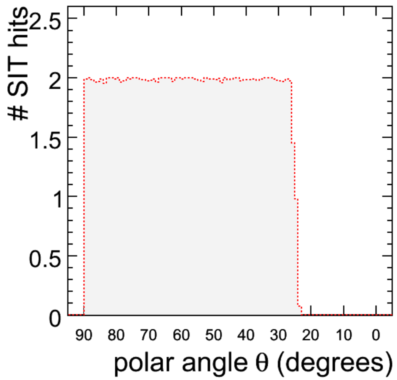
- LiCToy on ILD00 (full KF fit), *M. Valentan, HEPHY Vienna*
- FullLDCTracking on ILD00 (Mokka/MarlinReco) *Vos/Duarte/Iglesias*
- CMS KF Track Fit on standalone FTD *Vos/Duarte/Iglesias*



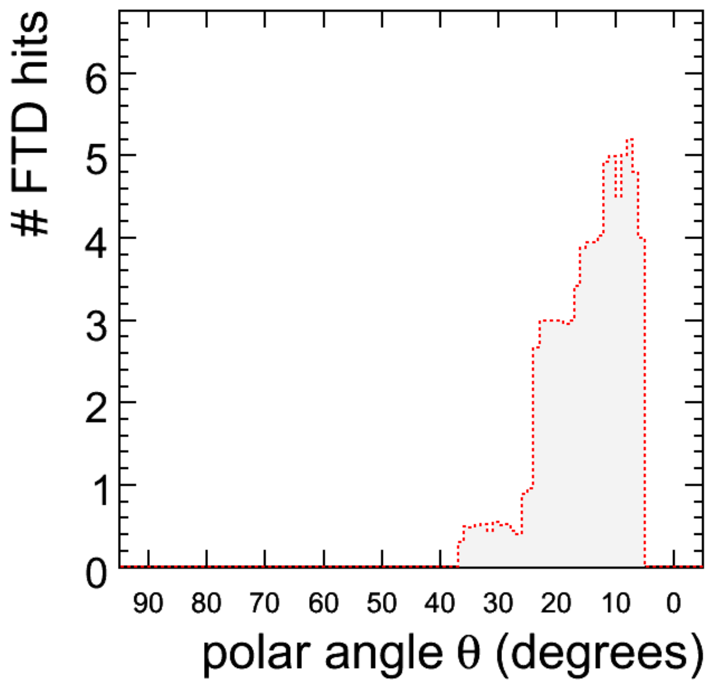
Coverage



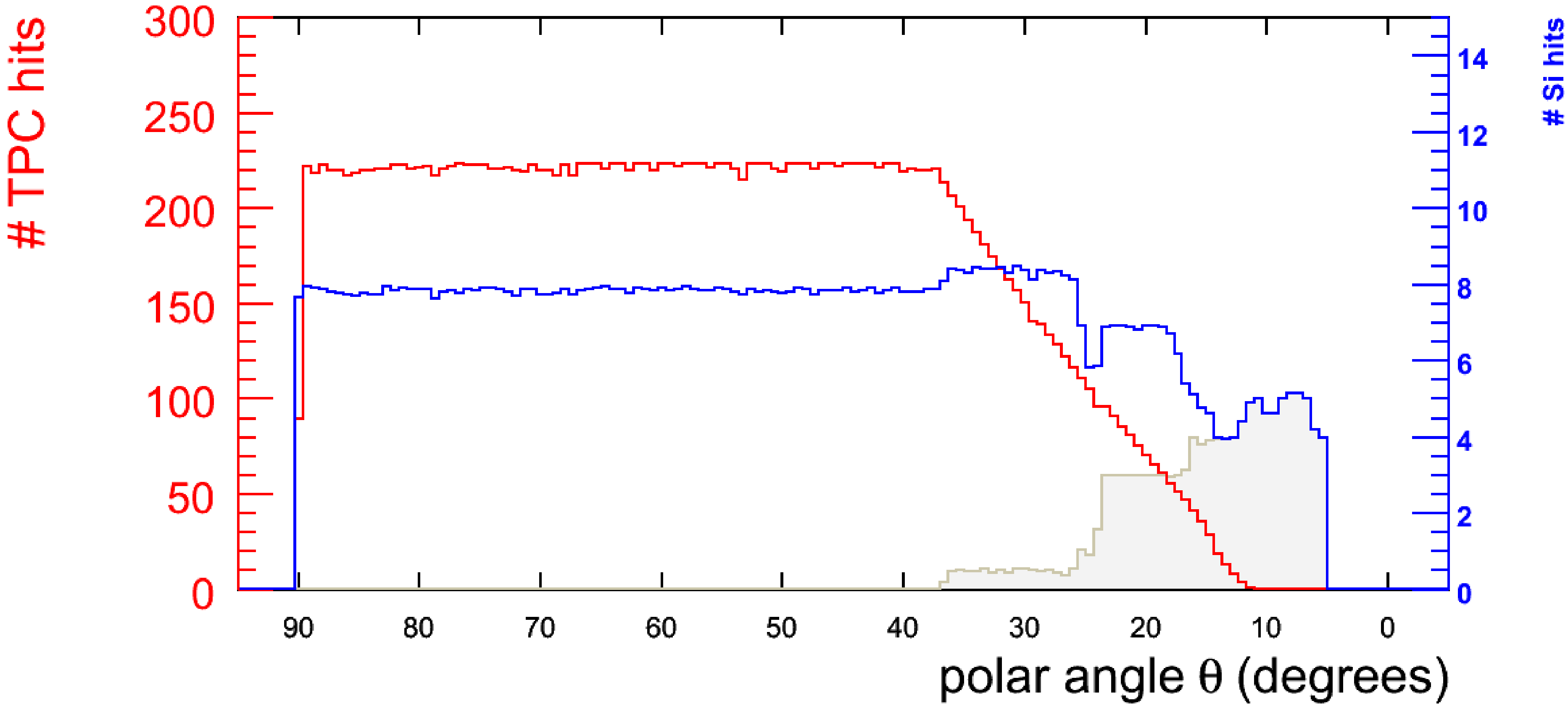




Concept	Magnetic Field	Angular 5-point	Coverage 3-point
SiD	5 T	12.5 (43 barrel)	9
LDC	4 T	26	19
GLD	3T	26 (6 points)	18 (4 barrel + 2 disk)
ILD	3.5 T	26 (6 points)	17



Coverage



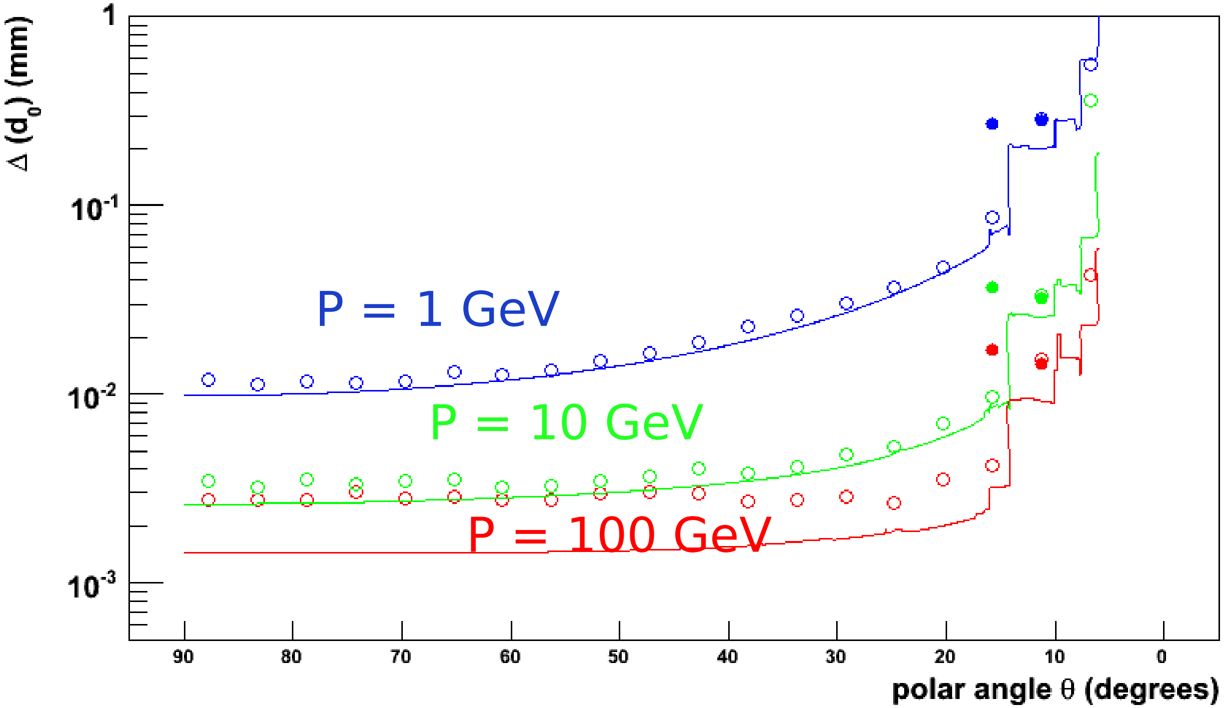
TPC hits
300
250
200
150
100
50
0
14
12
10
8
6
4
2
0
Si hits
90
80
70
60
50
40
30
20
10
0
polar angle θ (degrees)

Transverse impact parameter resolution versus polar angle
Measured on three single-muon samples with fixed |p|

— LiCToy on ILD00 (full KF fit), *M. Valentan, HEPHY Vienna*

○ FullLDCTracking on ILD00 (Mokka/MarlinReco) *Vos/Duarte/Iglesias*

● CMS KF Track Fit on standalone FTD *Vos/Duarte/Iglesias*



Coordinated ILC effort in Spain

Strong Spanish participation in DEPFET
IFIC (since 2005)
USC, UB, URL, CNM (since 2008)

Silicon for Large Colliders

IFIC, IFCA, UB, CNM, USC
one EUDET member, several associates

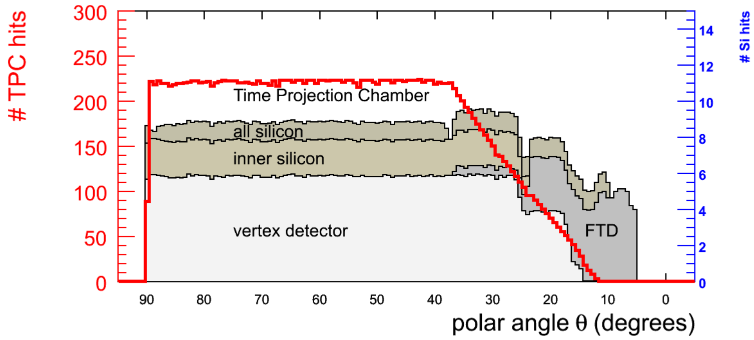
CALICE

CIEMAT Madrid

Coordinated effort (led by A. Ruiz):

- regular meetings
- funding/projects
- R&D interests
- the forward tracker

Pattern recognition



Clearly, 6-15 degrees is weakest region in ILD in terms of number of measurements. And remember:

- non-negligible pair background
- First disks close to interaction point (jets!)
- Abundant low-momentum tracks (loopers)

Ongoing study (Carmen Iglesias) Evaluate hit densities in tt events per disk and per petal (subdividing disks in 8,20 or 16 single-wafer segments)

- Average #hits/disk falls by a factor 3 due to reduced angular coverage of outermost disks
- Average #hits/petal falls even faster (outermost disks divided in 16 segments)

It is important to evaluate the hit density locally (jets)

- A significant probability to receive several hits/petal remains even in the outermost disk

	#hits/disk		#hits/petal	
disk	avg.	peak	avg.	peak
FTD1	9	37	1.1	12
FTD2	5	27	0.6	10
FTD3	8	36	0.4	10
FTD4	6	29	0.3	9
FTD5	5	25	0.3	10
FTD6	4	23	0.2	5
FTD7	3	28	0.2	4

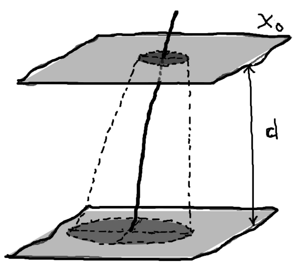
Pattern recognition - tools

Combinatorial algorithm based on KF kit

The track finder of the ATLAS (arXiv:0707:3071) and CMS (NIM A 559 143) experiments

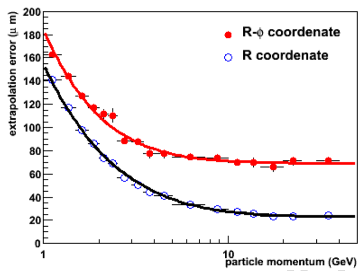
Run standalone FTD reconstruction implemented in MarlinReco processor on tt events with superposed pair background.

- Reference FTD (TESLA layout)
- 10 μm R-ϕ resolution
- 1.2 % X_0/disk (1-3) and 0.8 % X_0/disk (4-7).
- Several scenarios for R-resolution, from pixel to single-sided strip.

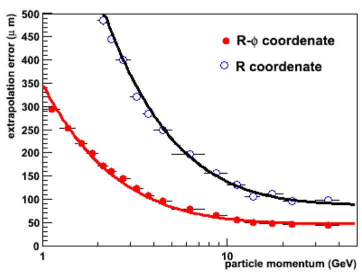


Extrapolation precision

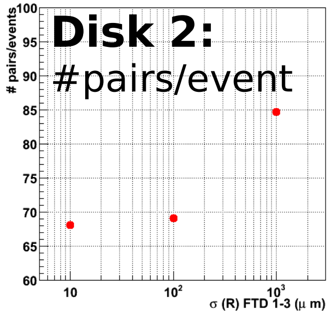
Innermost disks

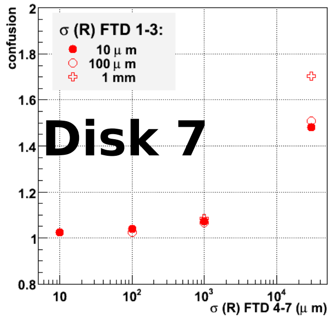


Outermost disks



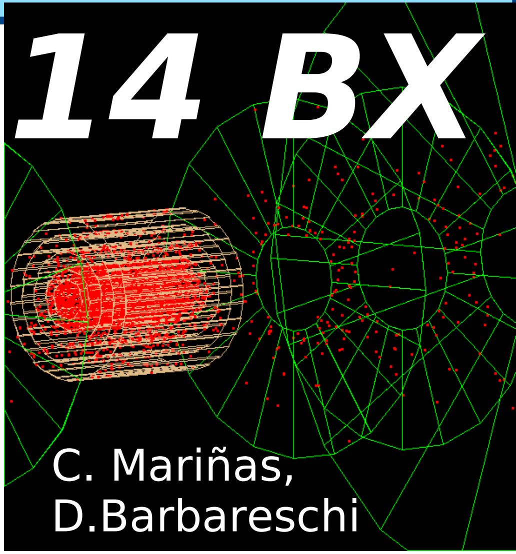
Confusion



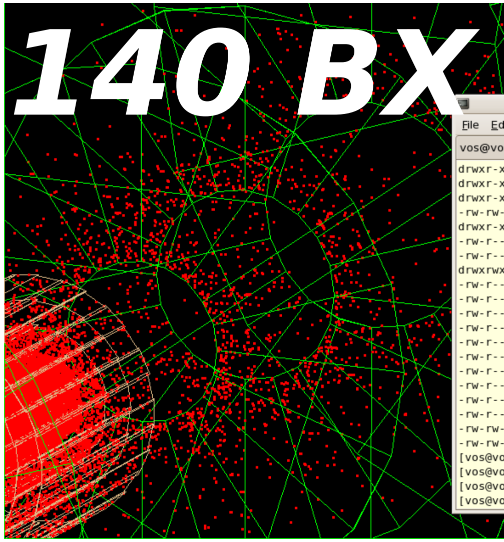


Pattern recognition

The combinatorial algorithm on stand-alone FTD is able to efficiently and cleanly reconstruct tracks down to a p_T of 100 MeV, provided:



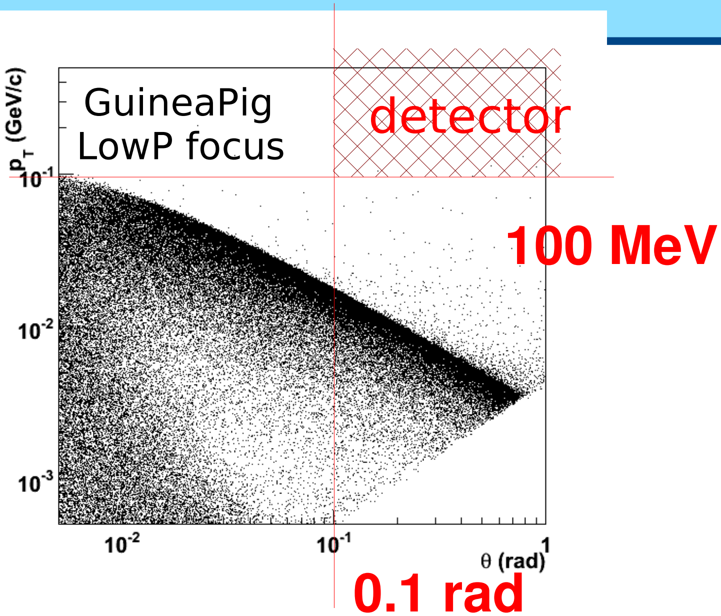
R-segmentation: in innermost disks 500 μm required, in outermost disks O (1cm)

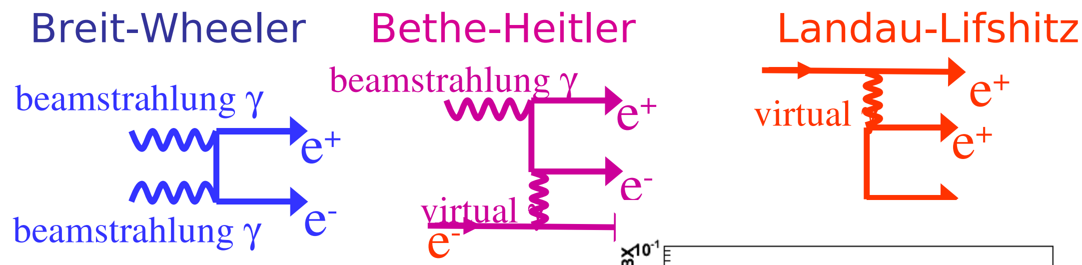


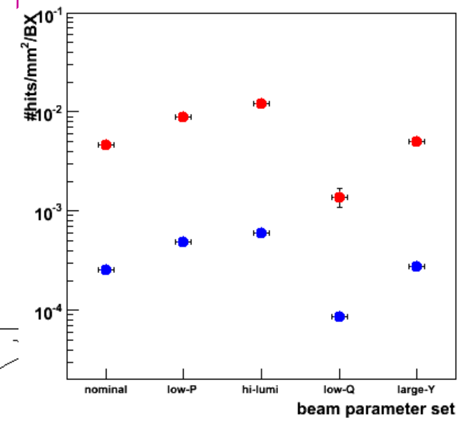
Read-out speed: beyond several 10s of integrated bunch crossings the density of low momentum tracks prevents algorithm convergence

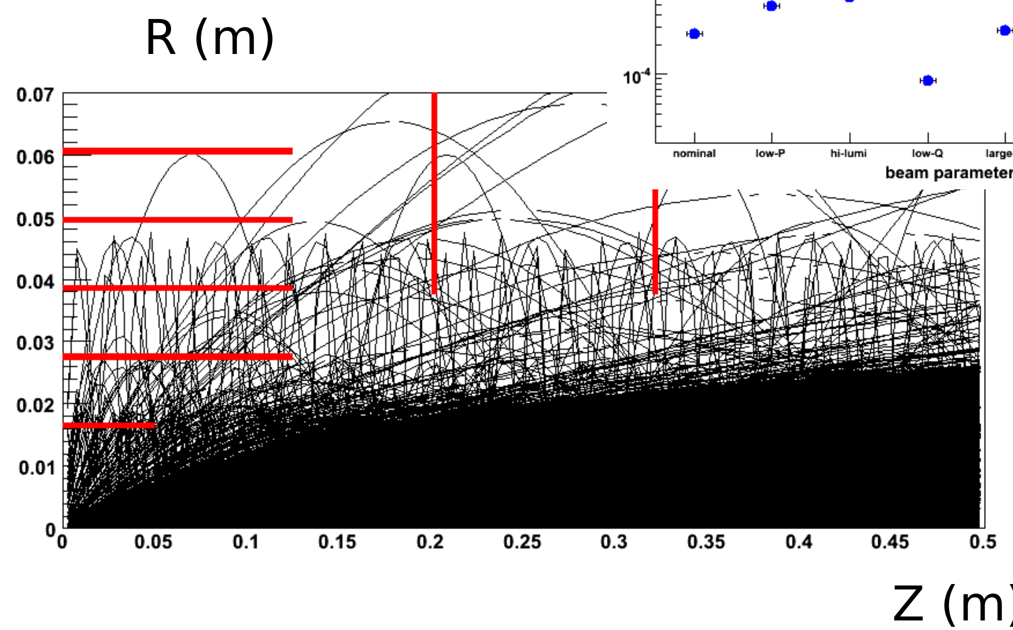
Material: an increase of the material beyond 1%/disk has dramatic consequences on pattern recognition

Environment: background level



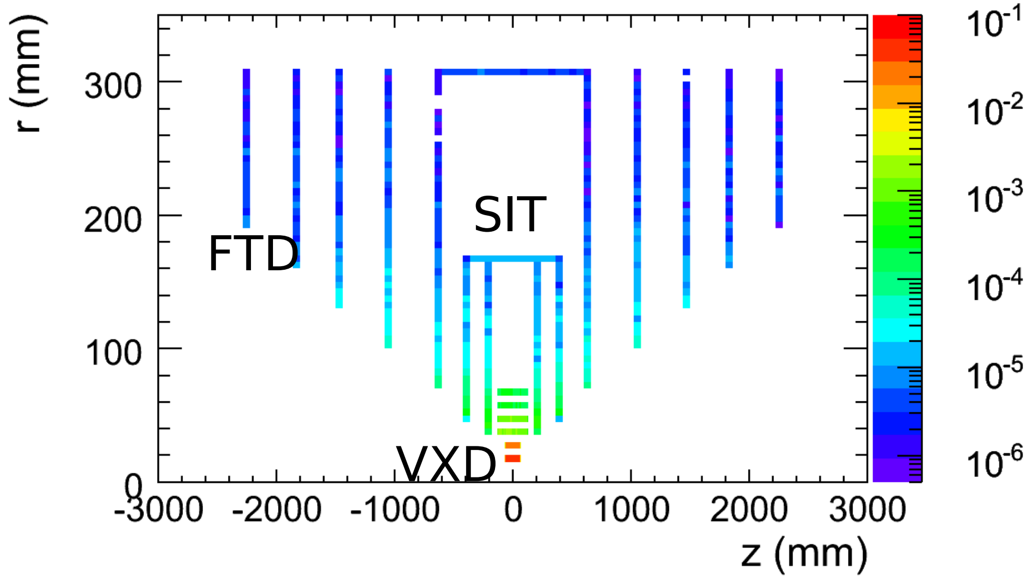






Incoherent e^+e^- pair produc off beamstrahlung photons produces a very large num of electrons and positrons each BX. The large majorit soft and/or emitted at low angle and are trapped in th "accumulation zone"

Pair background



GEANT4 simulation of GUINEA-PIG events by Toni Harlin
(thanks also to A. Vogel and Katarzyna Wichman)

Hit density
(#/mm²/BX)

detector	min	typical	max
VXD 1		4×10^{-2}	
VXD 6		3×10^{-4}	
FTD1	$<10^{-5}$	1×10^{-4}	2×10^{-3}
FTD7	5×10^{-6}	7×10^{-6}	9×10^{-6}
SIT 1		3×10^{-5}	
SIT 2		3×10^{-6}	

Hit density = number of GEANT4 energy deposits per unit area per ILC bunch crossing
Does not take into account the number of channels fired by a single hit

	Typical area sensitive elements	time resolution:
pixel:	$25 \times 25\ \mu m^2 = 6.25 \times 10^{-4}\ mm^2$	100 BX
strips:	$50\ \mu m \times 10\ cm = 0.5\ mm^2$	1 BX