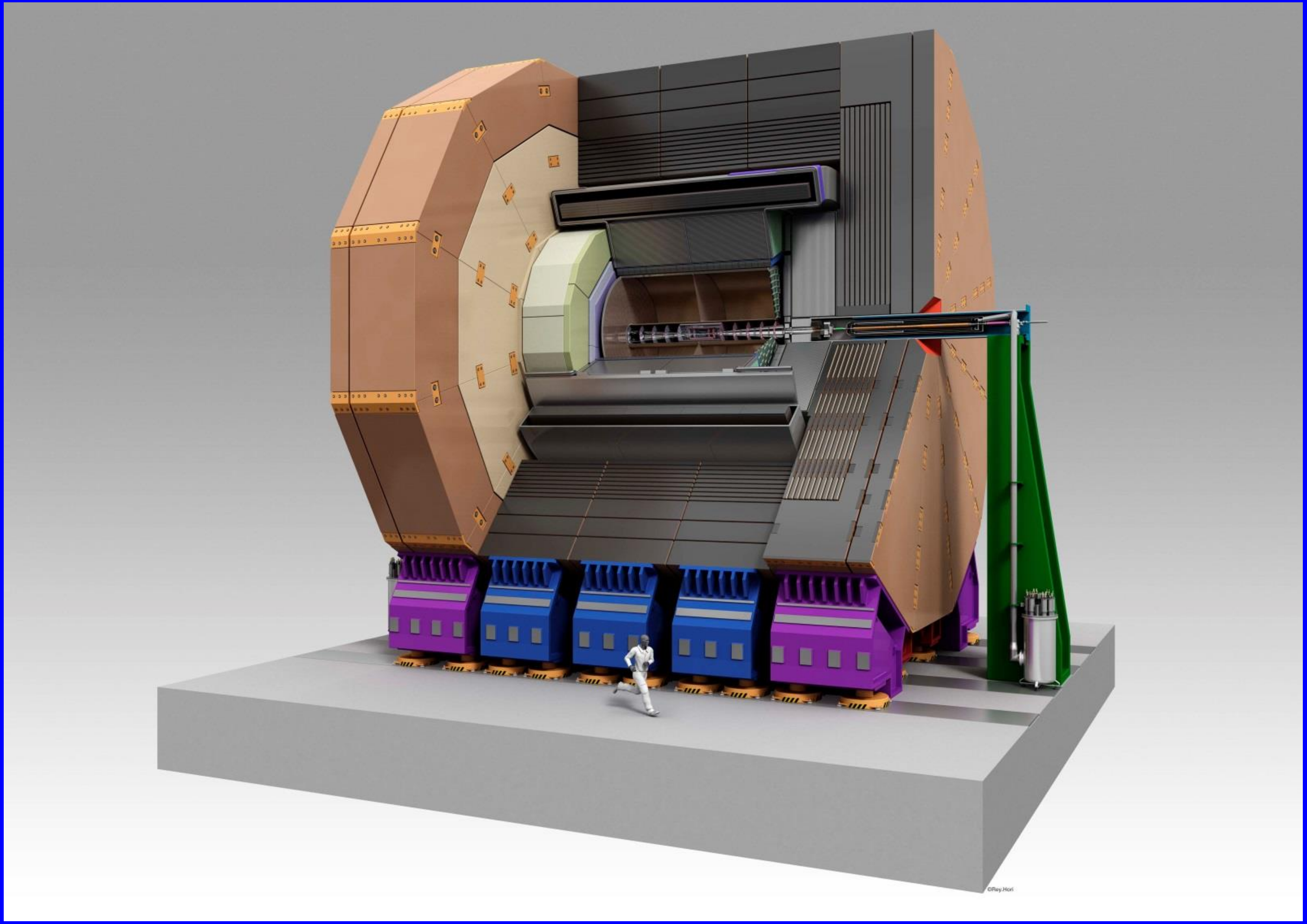
ILD: Detector Performance



Graham W. Wilson

University of Kansas

Como Workshop, May 17th 2013

Outline

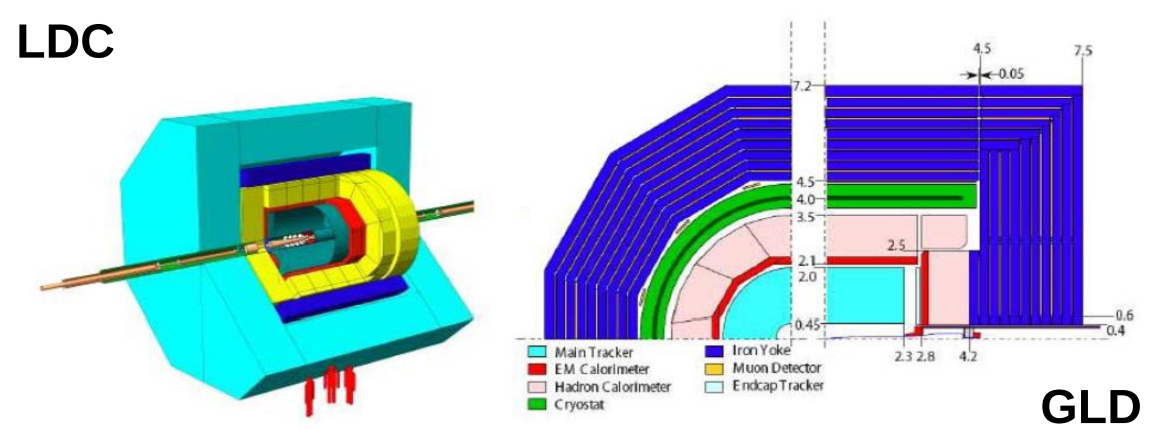
- Introduction
  - ILD evolution
- ILD
  - Detector Concept
  - Detector Sub-systems
  - Detector Performance Studies
  - Physics Benchmark Performance
  - (More detailed engineering and detector integration)
    - push-pull, power-pulsing, assembly, calibration, alignment …

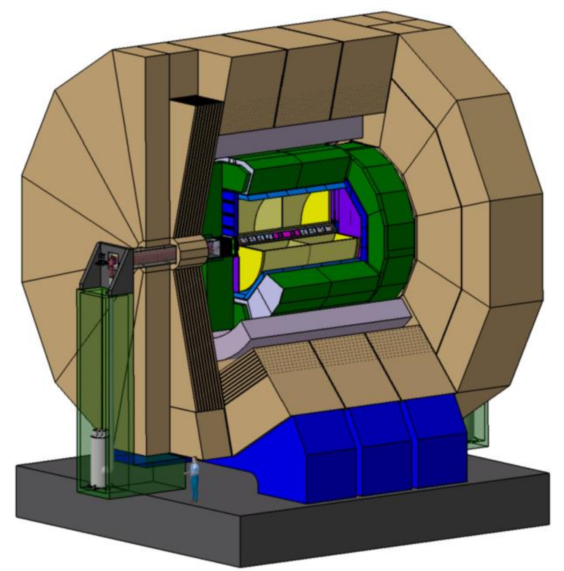
The ILD Detector Baseline Document (DBD) will be in one of the volumes of the ILC TDR that will be released on June 12th 2013
(Accelerator, Physics, ILD, SiD)

See DBD and LOI for more details.

ILD

- Origins in the TESLA, JLC and LD detector concepts.
- First conceptual reports in the mid 90s.
- ILC Reference Design Report (RDR) 2007
  - GLD Detector Outline Document (DOD) arXiv:physics/0607154
  - LDC DOD

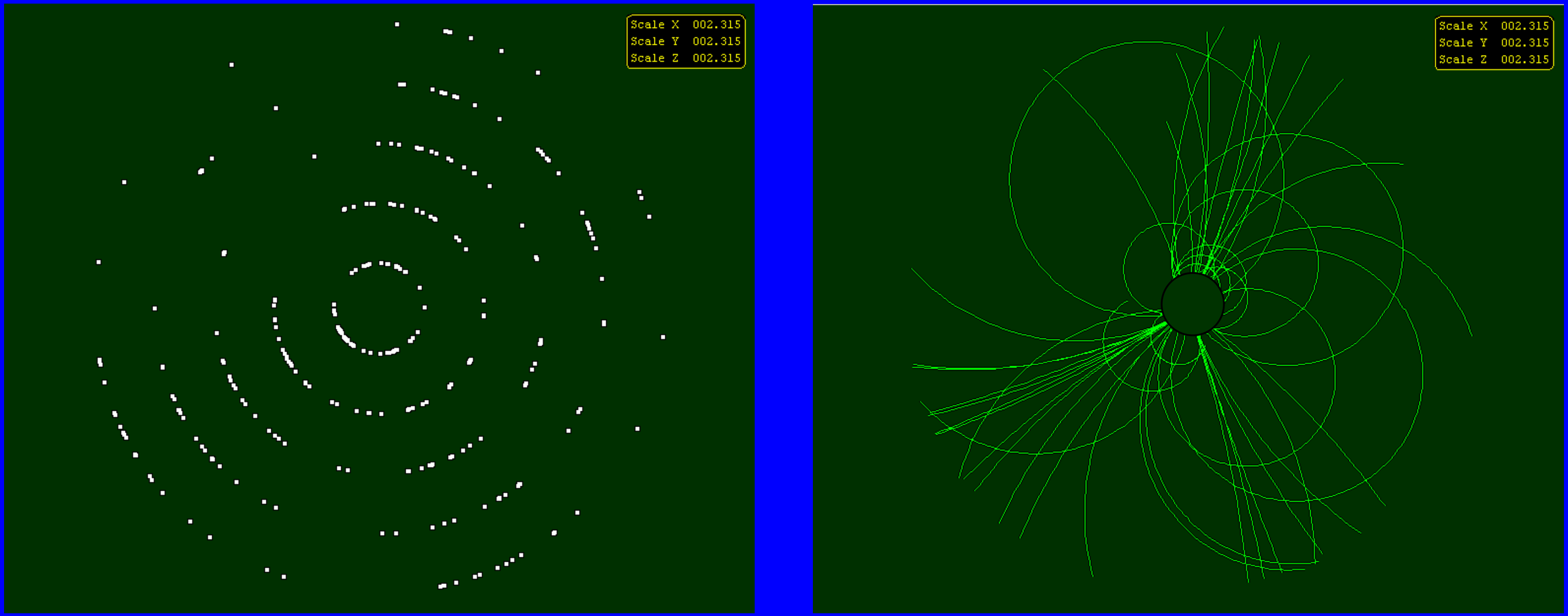




ILD

- LDC + GLD => ILD (2007)
- ILD Letter of Intent – 2009 (695 signatories)
- LoI validated by IDAG (link)

Silicon or Gaseous Central Tracking Detector?



silicon

gaseous

same event

The detector we are planning to build is more akin to an electronic bubble chamber than an LHC detector but with true 3D volume pixels and exquisite calorimetry too.

ILD Detector Concept

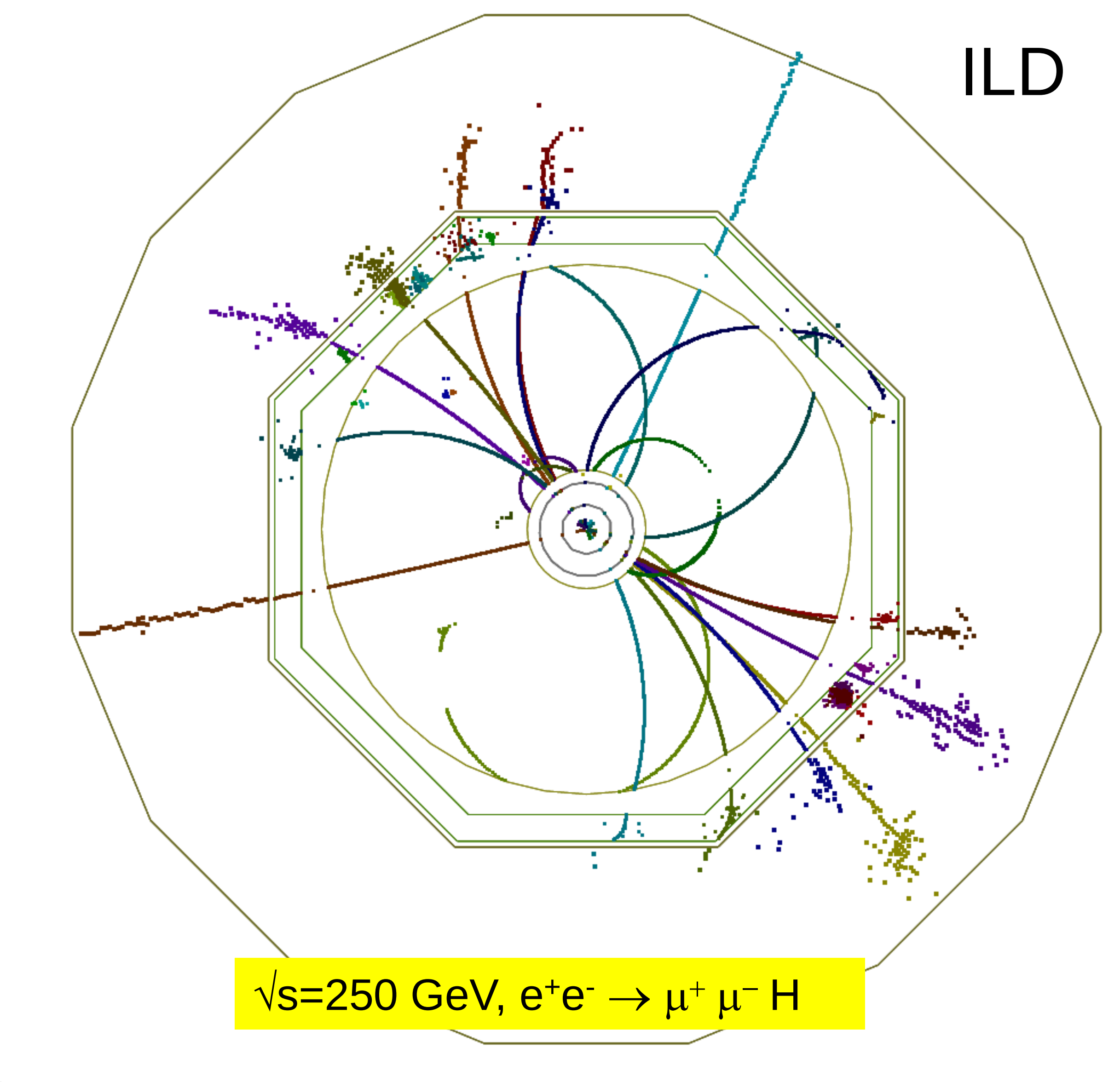
- Physics needs drive the detector design
- Experience, particularly from LEP, points towards:
  - **Particle-flow** for complete event reconstruction
  - A highly redundant and reliable TPC-centered tracking design emphasizing pattern recognition capabilities and low mass tracking
    - "dE/dx for free", and V^0 reconstruction (K_S, Λ, γ conversion)
  - A fine granularity calorimeter capable of particle-flow
  - Ultra-hermetic
- Accelerator and tracking system designed with sufficient safety margin to operate reliably.

Event Reconstruction

The Vision: Do the best possible physics at the linear collider. Reconstruct as far as possible every single piece of each event.

Like bubble chamber reconstruction.

But with full efficiency for photons and neutral hadrons in a high multiplicity environment at high luminosity.



$\sqrt{s}$=250 GeV, $e^+e^- \rightarrow \mu^+ \mu^- H$

What kind of physics ?

- Processes central to the perceived physics program :
  - 2f at highest energy, W, Z
  - Zh
  - ννh
  - tt, tth
  - Zhh, ννhh
  - Charginos, neutralinos, sleptons if kinematically accessible
- These emphasize:
  - Jet energy resolution (assumed to be done with particle flow) aiming for W/Z separation
  - Hermeticity
  - Granularity
  - Leptons, taus, b, c tagging
  - Control of initial-state parameters (L, E, P, dL/dE)

Detector design requirements

- Detector design should be able to do excellent physics in a cost effective way.

  : the physics we know is there, may be there, and new unexpected physics

- Very good **vertexing** and **momentum** measurements

$\sigma_b = 5 \oplus 10/(\, p\, \beta \sin^{3/2}\theta)\ \mu\text{m}$ $\sigma(1/p_T) \leq 2 \times 10^{-5}\ \text{GeV}^{-1}$

- Good **electromagnetic energy** measurement.

$$\sigma_E/E \approx 15\%/\sqrt{E}\ (\text{GeV}) \oplus 1\%$$

- The physics demands hermeticity and the physics reach will be significantly greater with state-of-the art **particle flow**
  - Close to 4π steradians.
  - Bubble chamber like track reconstruction.
  - An integrated detector design.
  - Calorimetry designed for resolving individual particles.

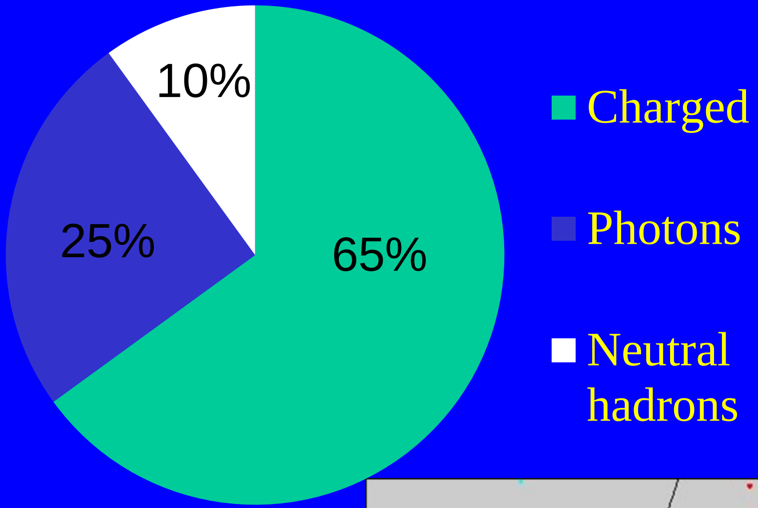
$\sigma_{E_{jet}}/E_{jet} \approx 3 – 4\%$ (W, Z separation)

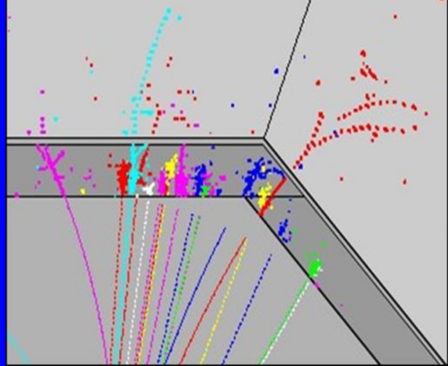
Particle-Flow in a Nut-Shell

E(jet) = E(charged) + E(photons) + E(neutral hadrons)

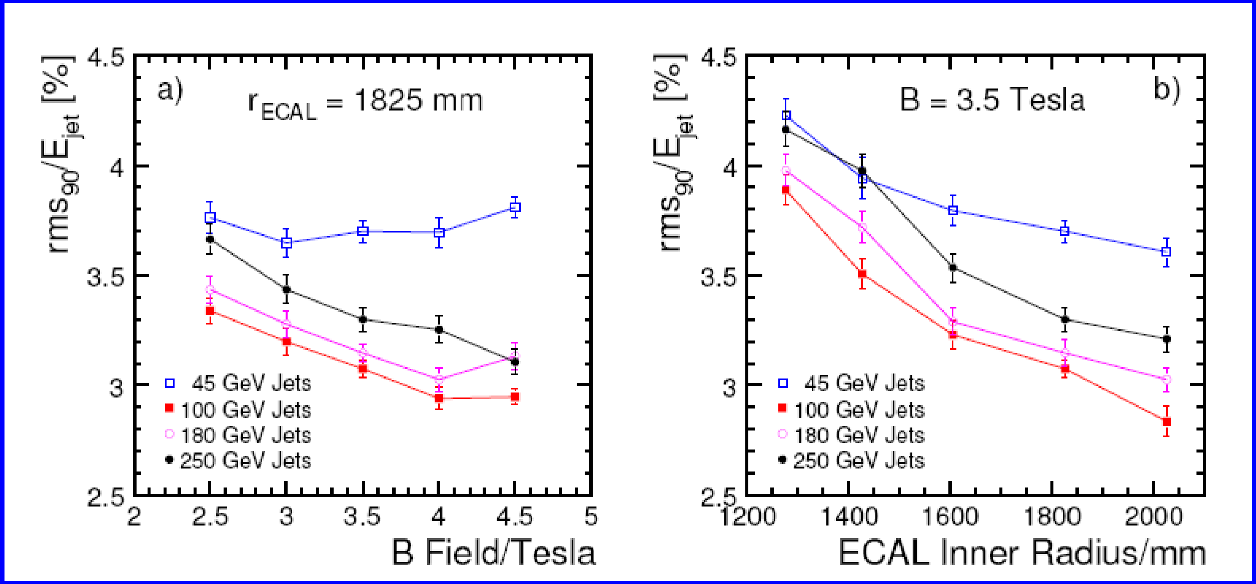
- Basics
  - Outsource **65%** of the event-energy measurement responsibility from the calorimeter to the tracker
    - Emphasize particle separability (large R) and tracking
    - Leading to better jet energy precision
  - Reduce importance of hadronic leakage
    - Now only 10% instead of 75% of the average jet energy is susceptible
    - Detector designs suited to wide energy range
  - Maximize event information
    - Aim for full reconstruction of each particle including V^0s, kinks, π^0 etc.
    - Facilitates software compensation and application of multi-variate techniques

Particle AVERAGEs





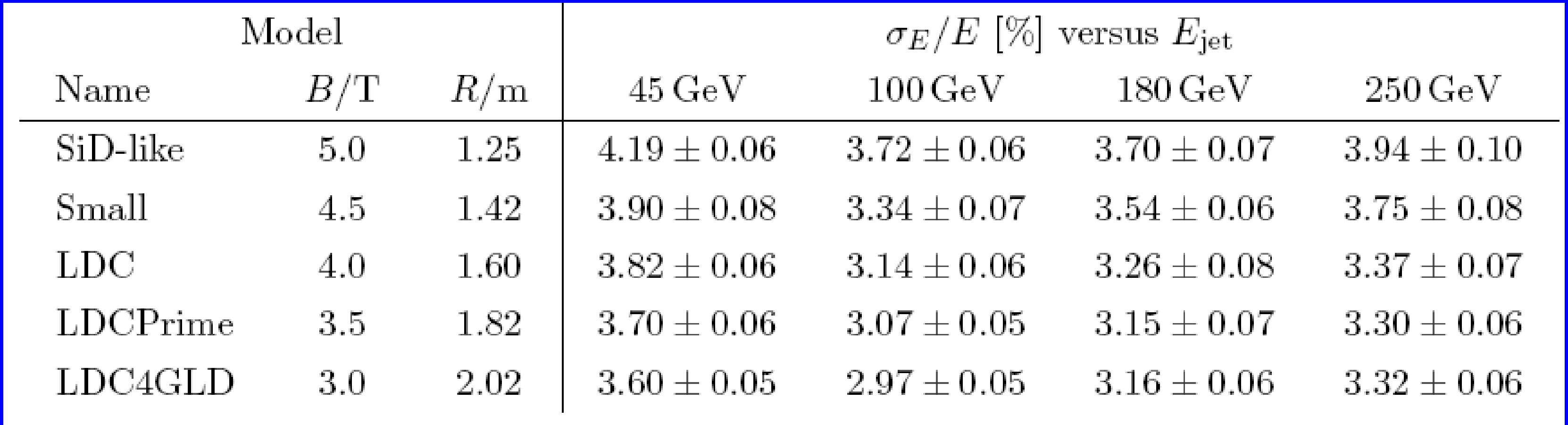
LOI Global Detector Optimization



R is more important than B.

Empirically confusion error scales as $(B^{0.3} R)^{-1}$

Also high-p tracking error scales as $(BR^2)^{-1}$



Model			σ_E/E [%] versus E_{jet}			
Name	B/T	R/m	45 GeV	100 GeV	180 GeV	250 GeV
SiD-like	5.0	1.25	4.19 ± 0.06	3.72 ± 0.06	3.70 ± 0.07	3.94 ± 0.10
Small	4.5	1.42	3.90 ± 0.08	3.34 ± 0.07	3.54 ± 0.06	3.75 ± 0.08
LDC	4.0	1.60	3.82 ± 0.06	3.14 ± 0.06	3.26 ± 0.08	3.37 ± 0.07
LDCPrime	3.5	1.82	3.70 ± 0.06	3.07 ± 0.05	3.15 ± 0.07	3.30 ± 0.06
LDC4GLD	3.0	2.02	3.60 ± 0.05	2.97 ± 0.05	3.16 ± 0.06	3.32 ± 0.06

$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{R}{1825\,\mathrm{mm}}\right)^{-1.0} \left(\frac{B}{3.5\,\mathrm{T}}\right)^{-0.3} \left(\frac{E}{100\,\mathrm{GeV}}\right)^{0.3} \%.$$

intrinsic tracking leakage confusion

Choices

- Based on the optimization studies, we came to a consensus in Fall 2008 for a detector with B= 3.5 T (nominal) and R_{ECAL}= 1.85 m for the LoI.
- Arguments for Larger
  - Particle-flow performance
  - High p_T muon momentum resolution
  - π^0 reconstruction (τ)
- Arguments for Smaller / Higher Field
  - Background sensitivity of VTX. Inner hit density ~ $1/\sqrt{B}$
  - Impact parameter at low p_T
  - Cost
- For the DBD process, the global detector parameters have stayed the same.
  - Should be re-quantified with current understanding and technological options.

Designing a Detector with Margin

- Primary concern was to make sure the performance of the designed detector met or exceeded those envisaged for the physics
  - Design philosophy is cost-conscious, but meeting the required performance/physics goals is the main design criterion
- Kept a solenoid engineered for 4T with nominal field of 3.5T
- Increased the depth of the HCAL(6.8 λ_I incl. ECAL)
  - More margin for higher energy jets / higher √s
- Chose an ECAL effective cell size of 5mm × 5mm.
- Studying the merits of the additional tracking sub-detectors
  - Increased precision, redundancy, alignment capabilities, time-stamping, more material

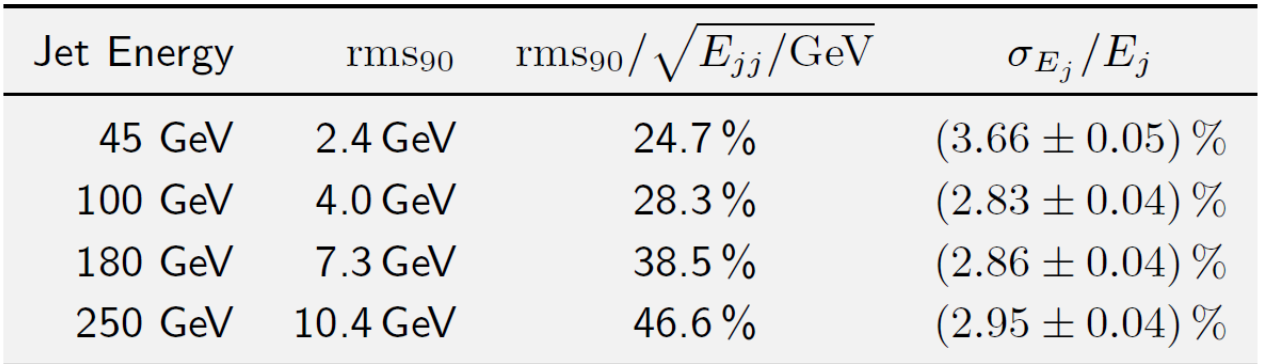
The ILD design also serves as a good starting point for a CLIC detector.
See Philipp Roloff's talk and CLIC_ILD.

Current Particle Flow Performance

(ILD_o1_v5)

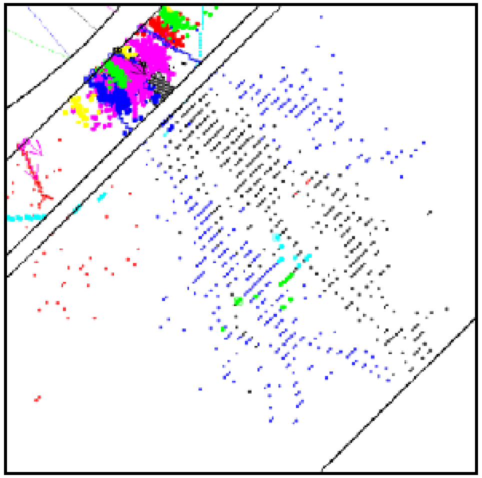
★ Benchmarked using:

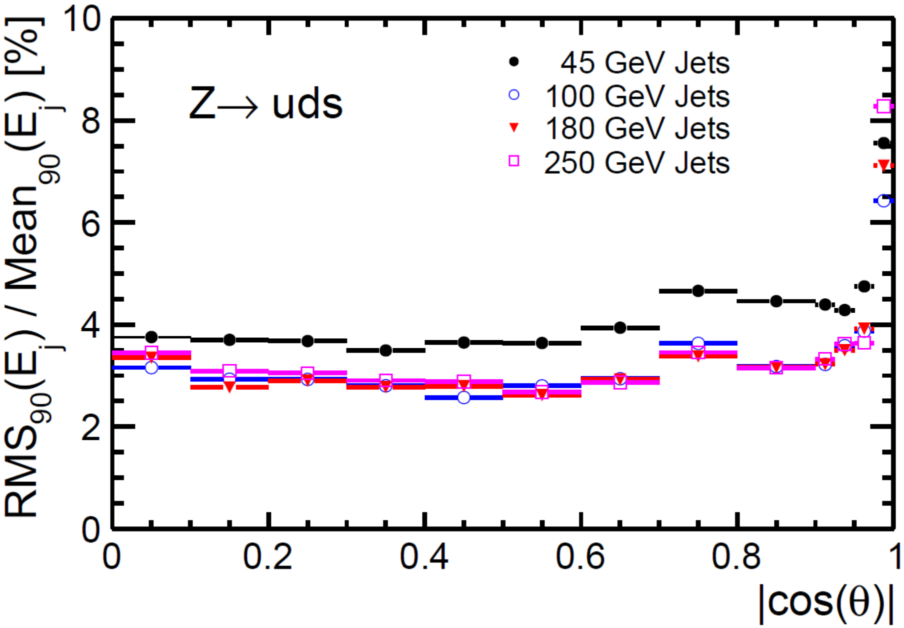
- $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ decays at rest
- $|\cos\theta|<0.7$



Jet Energy	rms_{90}	$\mathrm{rms}_{90}/\sqrt{E_{jj}/\mathrm{GeV}}$	σ_{E_j}/E_j
45 GeV	2.4 GeV	24.7 %	$(3.66 \pm 0.05)\ \%$
100 GeV	4.0 GeV	28.3 %	$(2.83 \pm 0.04)\ \%$
180 GeV	7.3 GeV	38.5 %	$(2.86 \pm 0.04)\ \%$
250 GeV	10.4 GeV	46.6 %	$(2.95 \pm 0.04)\ \%$

di-jet **jet**

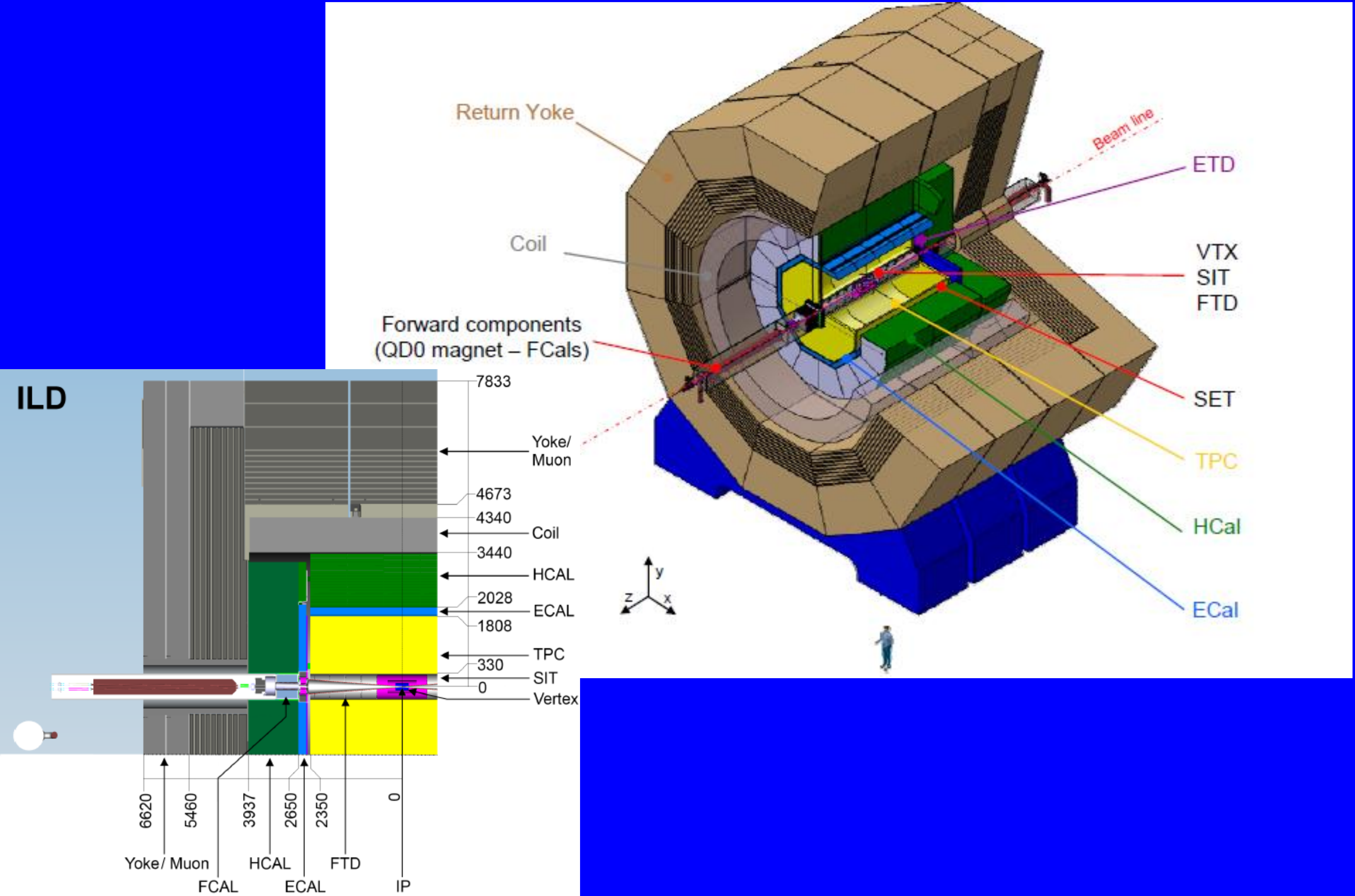




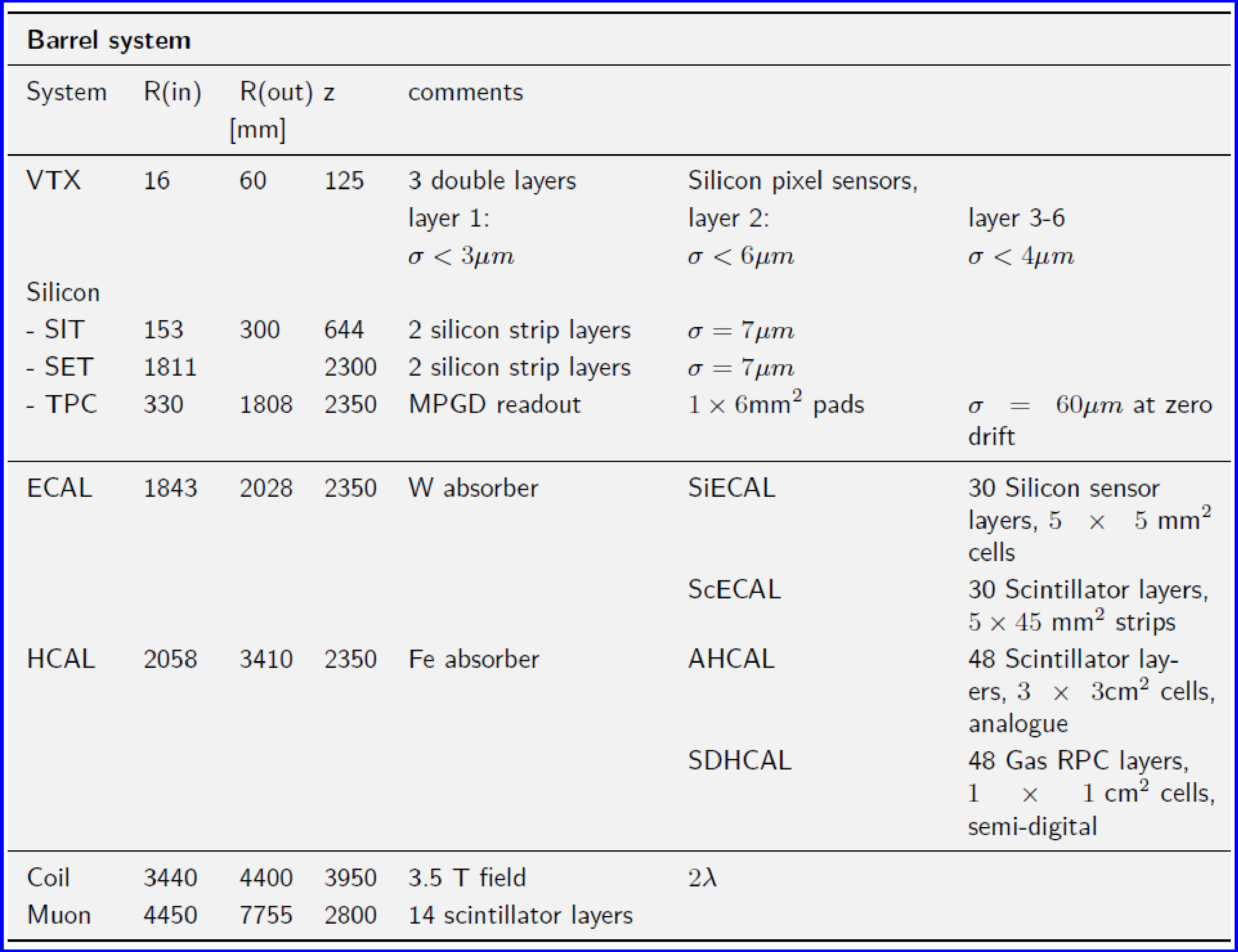
NOTE:

- $\sigma_E = \mathrm{rms}_{90}$
- In terms of statistical power $\mathrm{rms}_{90} \times 1.1 \approx$ Gaussian equiv.
- No strong angular dependence down to cosθ~0.975

ILD Detector Sub-systems



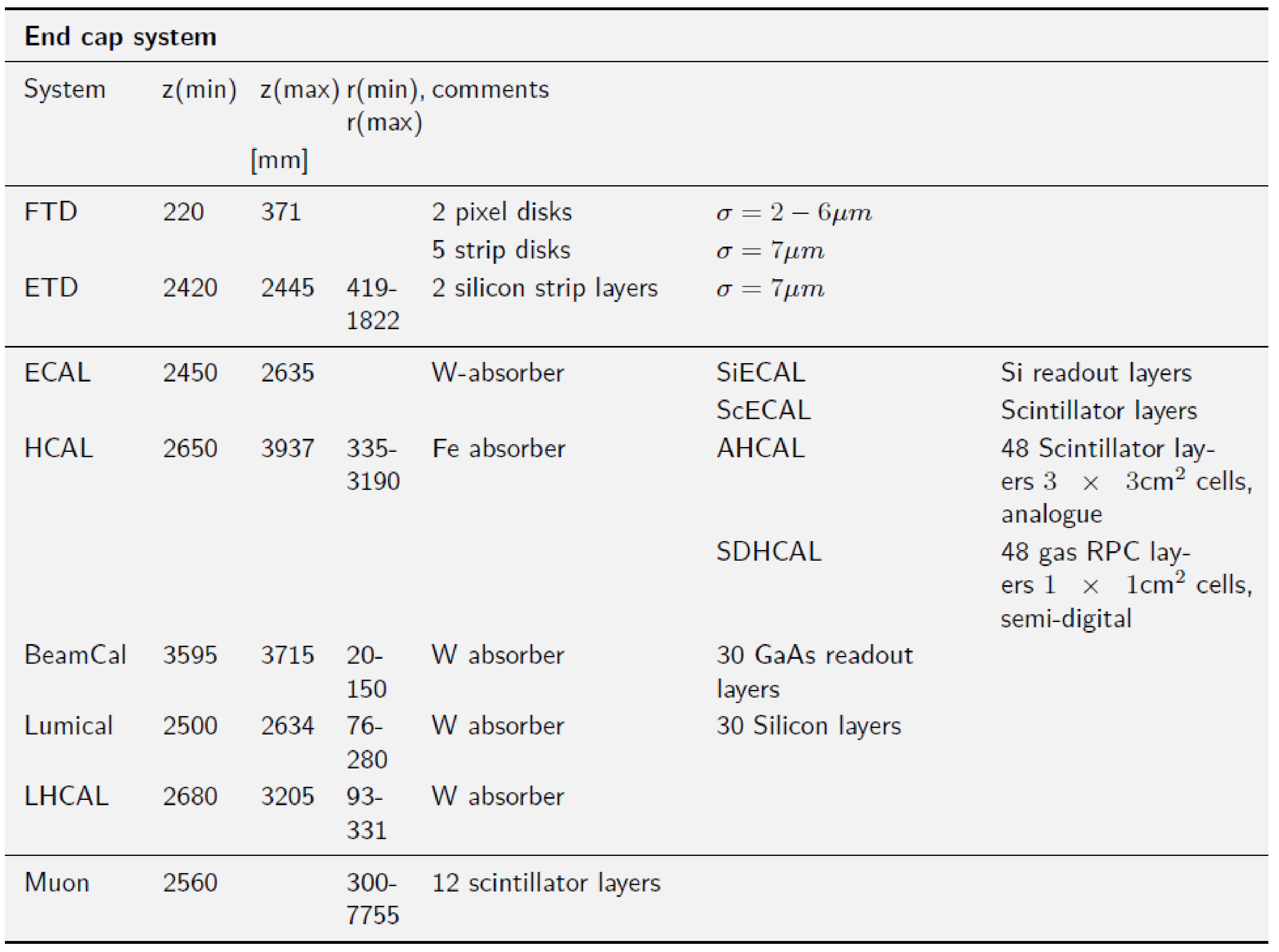
Barrel Detector Parameters



Barrel system

System	R(in)	R(out) [mm]	z	comments		
VTX	16	60	125	3 double layers layer 1: $\sigma < 3\mu m$	Silicon pixel sensors, layer 2: $\sigma < 6\mu m$	layer 3-6 $\sigma < 4\mu m$
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	1×6mm^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
					ScECAL	30 Scintillator layers, 5×45 mm^2 strips
HCAL	2058	3410	2350	Fe absorber	AHCAL	48 Scintillator layers, 3×3cm^2 cells, analogue
					SDHCAL	48 Gas RPC layers, 1×1 cm^2 cells, semi-digital
Coil	3440	4400	3950	3.5 T field	2λ	
Muon	4450	7755	2800	14 scintillator layers		

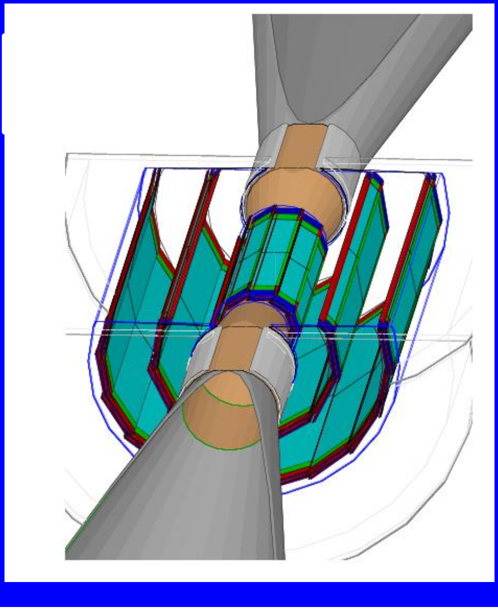
Endcap Detector Parameters



End cap system

System	z(min)	z(max)	r(min), r(max)	comments		
	[mm]					
FTD	220	371		2 pixel disks	$\sigma = 2 - 6\mu m$	
				5 strip disks	$\sigma = 7\mu m$	
ETD	2420	2445	419-1822	2 silicon strip layers	$\sigma = 7\mu m$	
ECAL	2450	2635		W-absorber	SiECAL	Si readout layers
					ScECAL	Scintillator layers
HCAL	2650	3937	335-3190	Fe absorber	AHCAL	48 Scintillator layers 3×3cm^2 cells, analogue
					SDHCAL	48 gas RPC layers 1×1cm^2 cells, semi-digital
BeamCal	3595	3715	20-150	W absorber	30 GaAs readout layers	
Lumical	2500	2634	76-280	W absorber	30 Silicon layers	
LHCAL	2680	3205	93-331	W absorber		
Muon	2560		300-7755	12 scintillator layers		

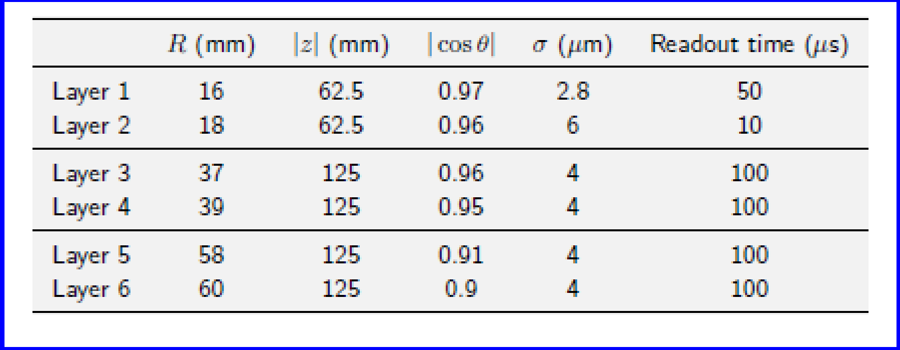
Vertex Detector



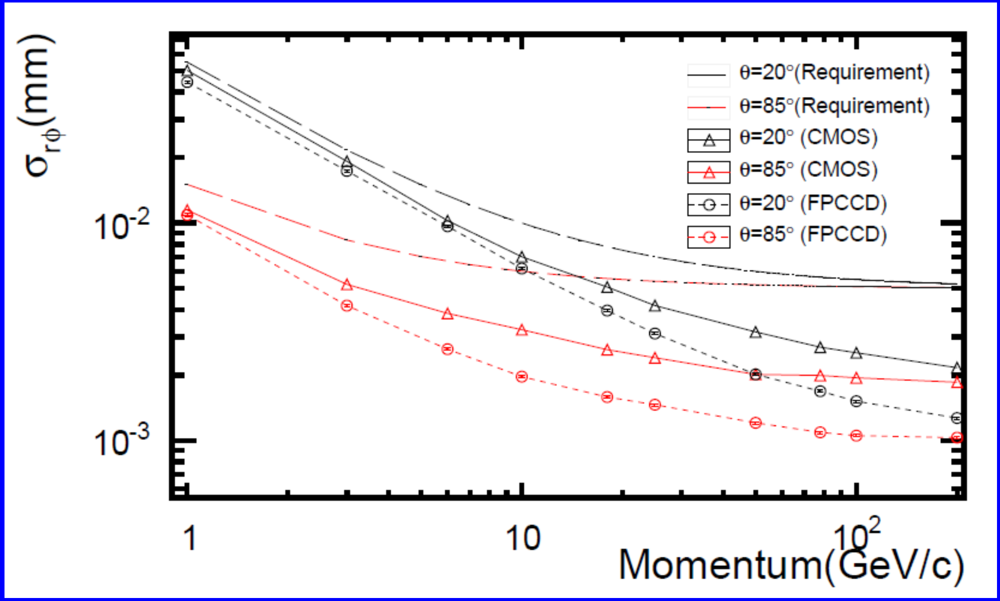
Several different technologies: pixel sensors, readout scheme, material budget. CMOS, FPCCD, DEPFET.

Pairs background => Inner radius ~ $1/\sqrt{B}$

Baseline geometry: 3 double-layers.



	R (mm)	$\lvert z\rvert$ (mm)	$\lvert\cos\theta\rvert$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100

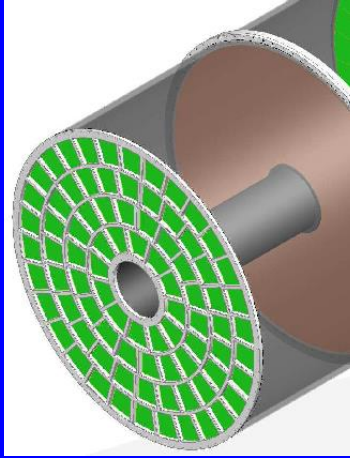


CMOS and FPCCD solutions meet the design requirement of

$$\sigma_b=5 \oplus 10/(p\,\beta\,\sin^{3/2}\theta)\ \mu\text{m}$$

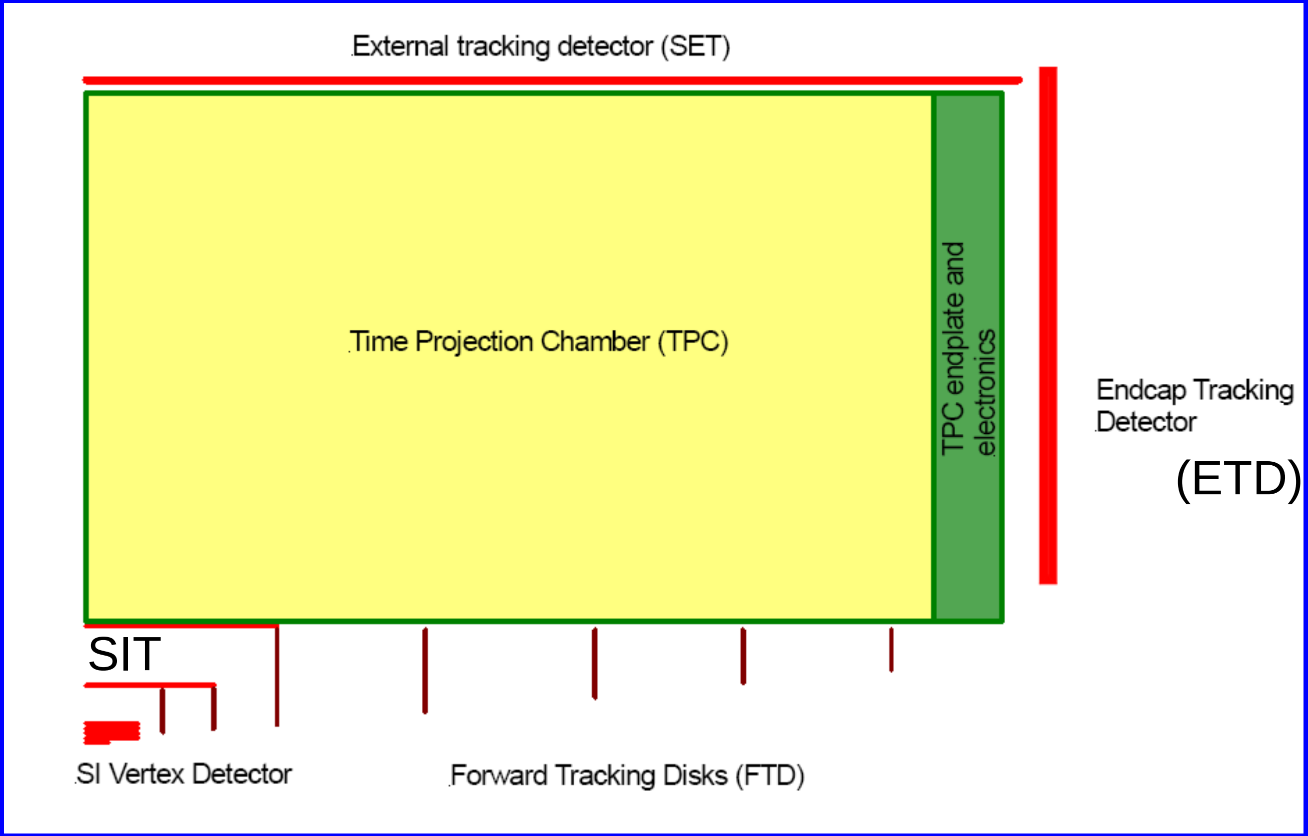
See Marc Winter's talk

Main Tracker: TPC



Supplemented by stand-alone VTX tracking, SIT + Forward tracking disks.

SET and ETD provide precise external space-point.



3 10^9 volume pixels.

224 points per track.

Single-point resolution

50 - 100 μm r-ϕ,

400 μm r-z

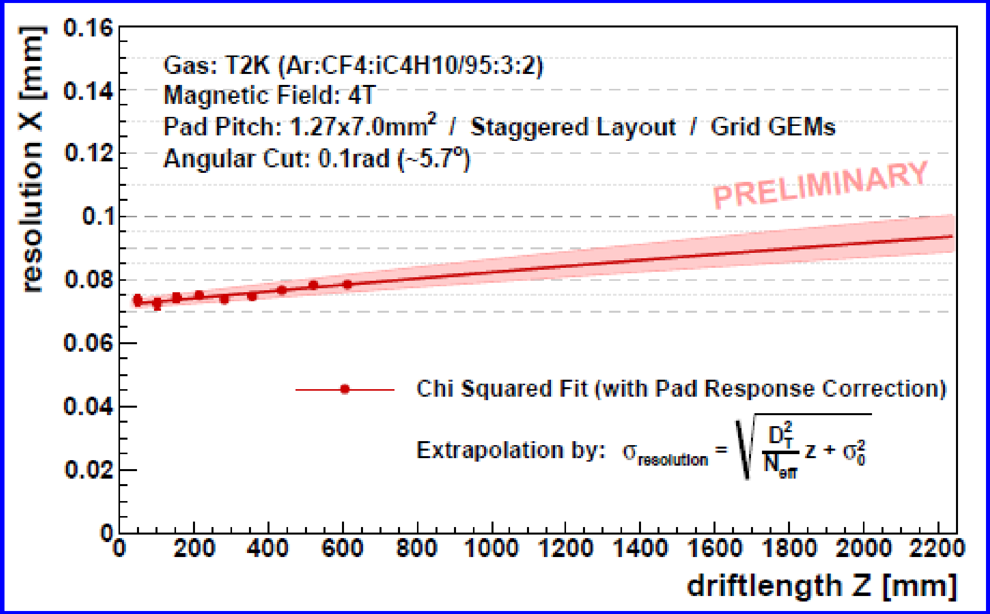
|cosθ| < 0.985 (TPC)

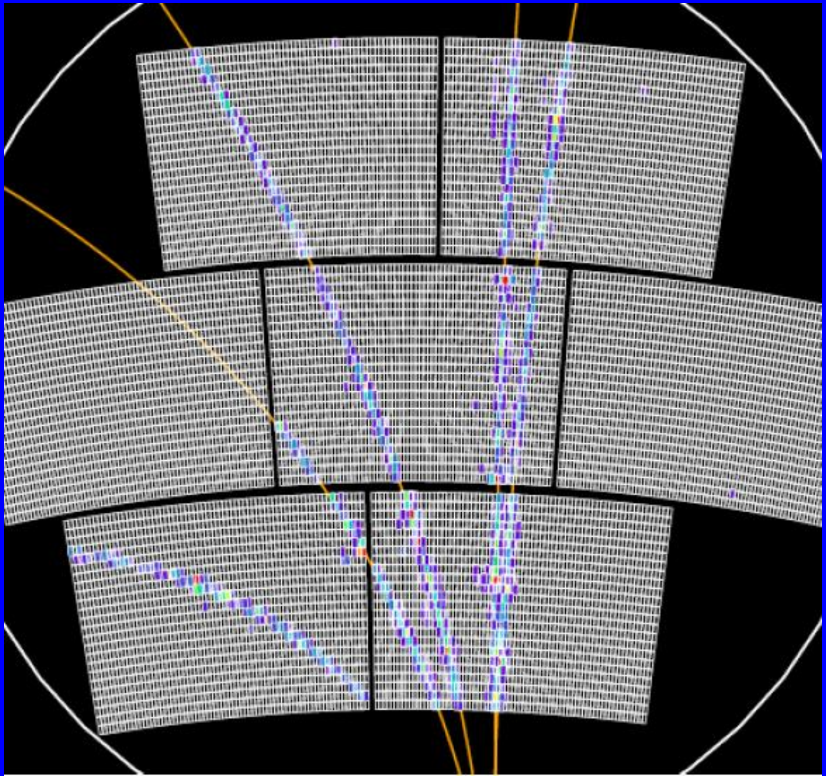
|cosθ| < 0.996 (FTD)

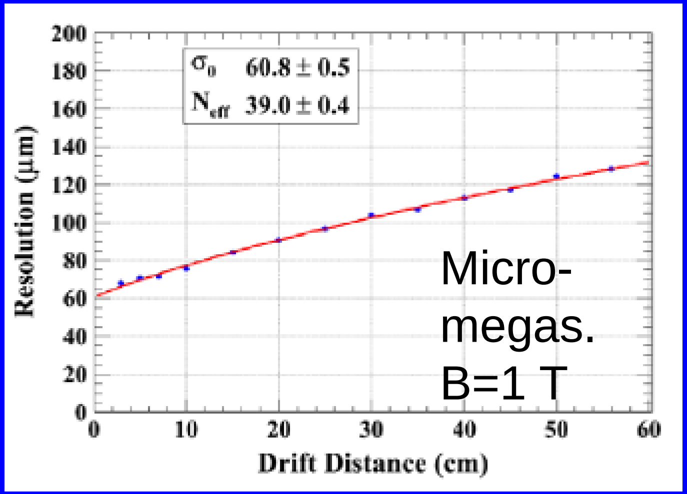
Readout options: GEM, Micromegas. Alternative: Si Pixel

SIT and FTD are essential elements of an integrated design.

TPC Performance Prospects





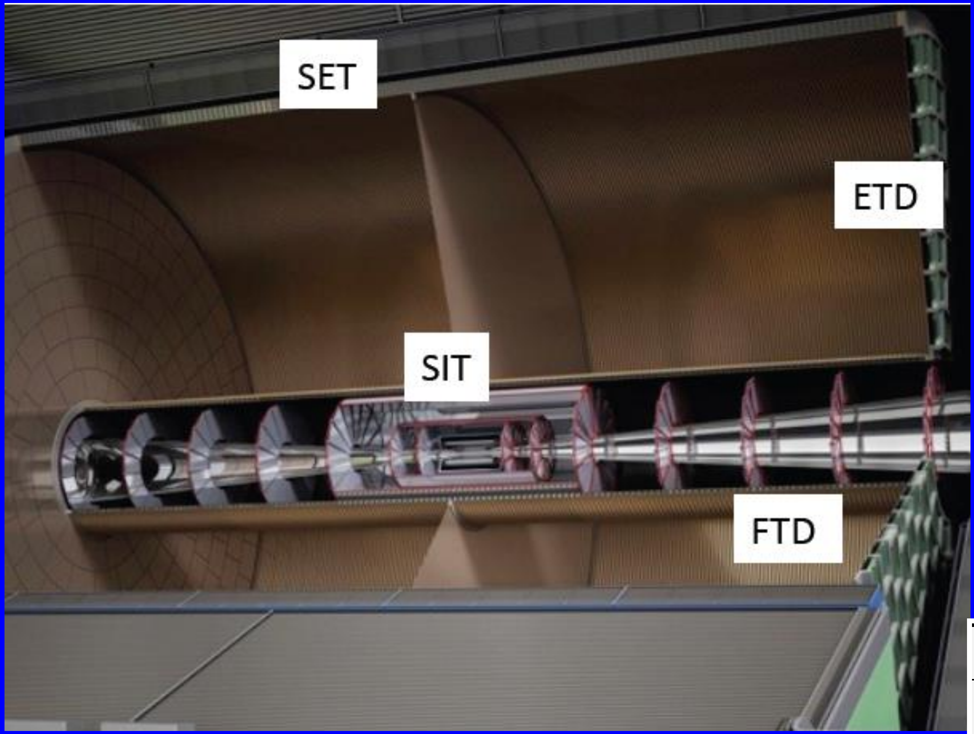


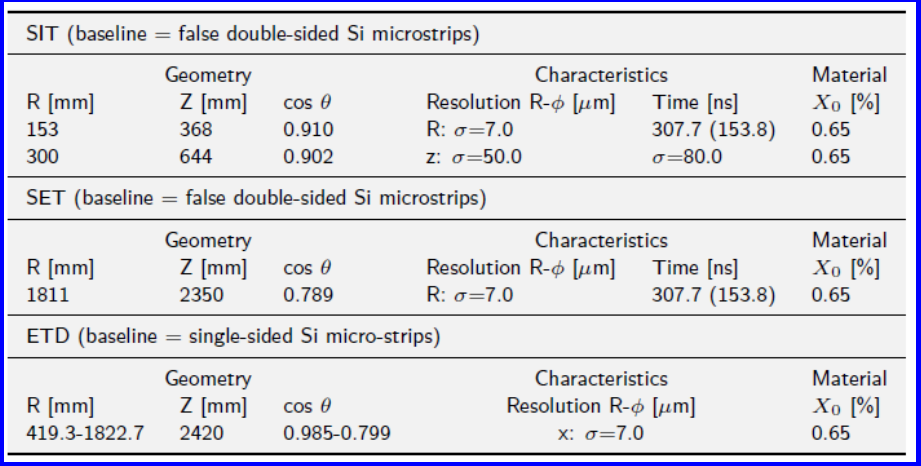
Point resolution requirements achieved.

Integrated system performance and 2-track separation under study.

See Astrid Muennich’s talk for more details

Silicon Tracking Components





SIT (baseline = false double-sided Si microstrips)

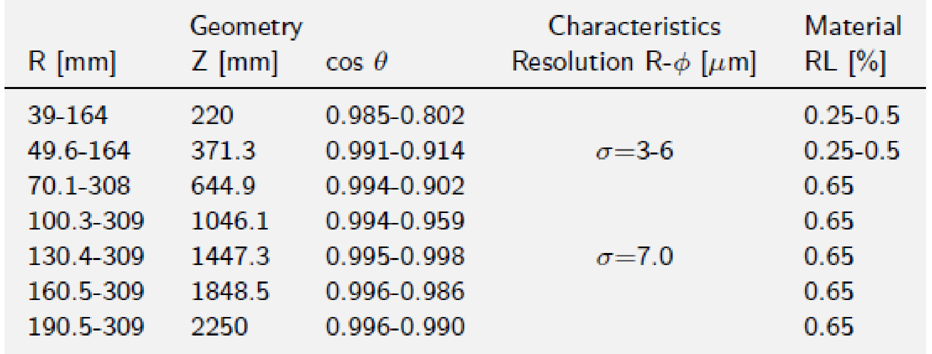
Geometry			Characteristics		Material
R [mm]	Z [mm]	cos θ	Resolution R-ϕ [μm]	Time [ns]	X_0 [%]
153	368	0.910	R: σ=7.0	307.7 (153.8)	0.65
300	644	0.902	z: σ=50.0	σ=80.0	0.65

SET (baseline = false double-sided Si microstrips)

Geometry			Characteristics		Material
R [mm]	Z [mm]	cos θ	Resolution R-ϕ [μm]	Time [ns]	X_0 [%]
1811	2350	0.789	R: σ=7.0	307.7 (153.8)	0.65

ETD (baseline = single-sided Si micro-strips)

Geometry			Characteristics	Material
R [mm]	Z [mm]	cos θ	Resolution R-ϕ [μm]	X_0 [%]
419.3-1822.7	2420	0.985-0.799	x: σ=7.0	0.65



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

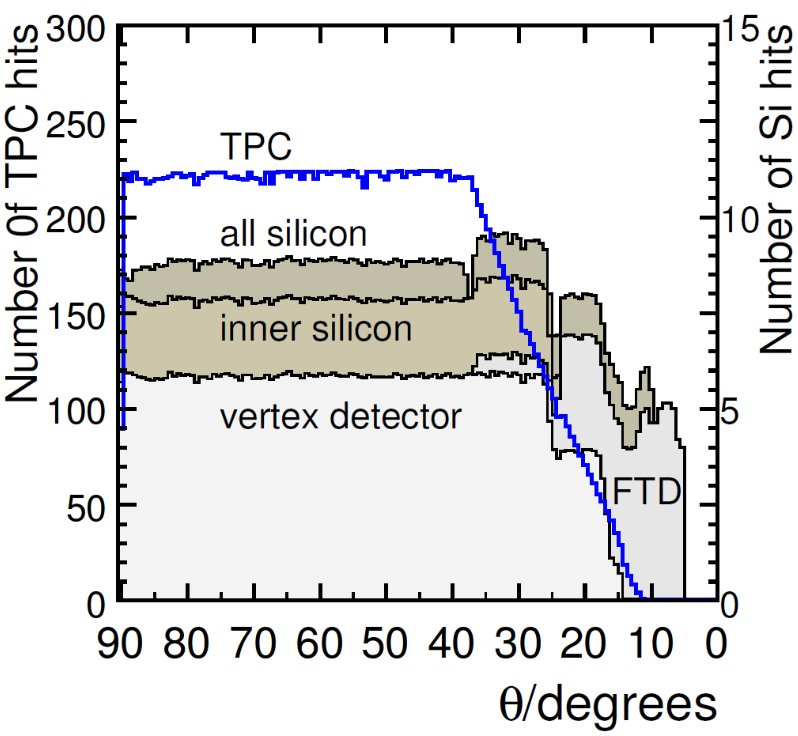
Geometry			Characteristics	Material
R [mm]	Z [mm]	cos θ	Resolution R-ϕ [μm]	RL [%]
39-164	220	0.985-0.802		0.25-0.5
49.6-164	371.3	0.991-0.914	σ=3-6	0.25-0.5
70.1-308	644.9	0.994-0.902		0.65
100.3-309	1046.1	0.994-0.959		0.65
130.4-309	1447.3	0.995-0.998	σ=7.0	0.65
160.5-309	1848.5	0.996-0.986		0.65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

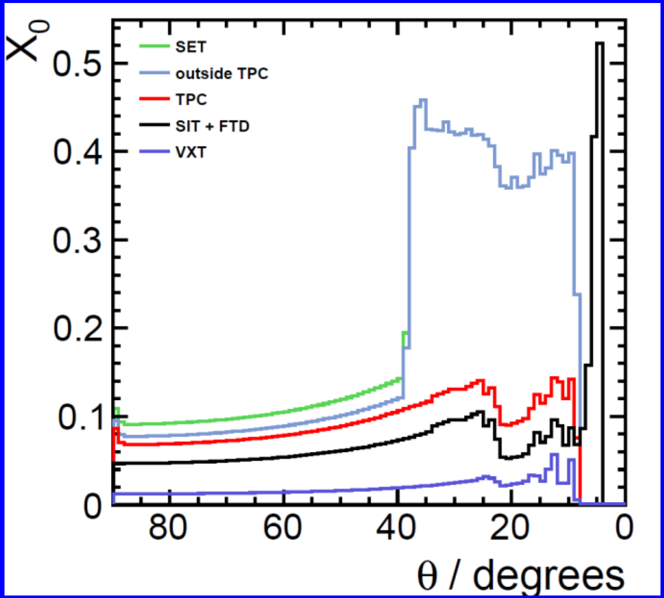
SIT = 2 space points

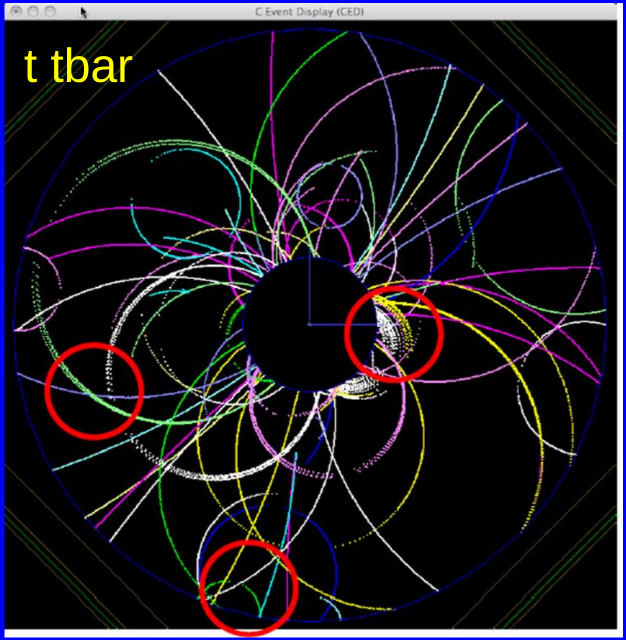
SET, ETD = 1 space point

FTD = 9 space points

Tracking System



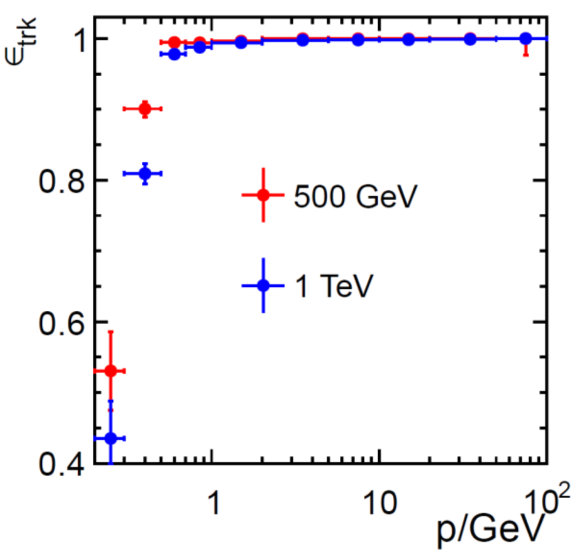


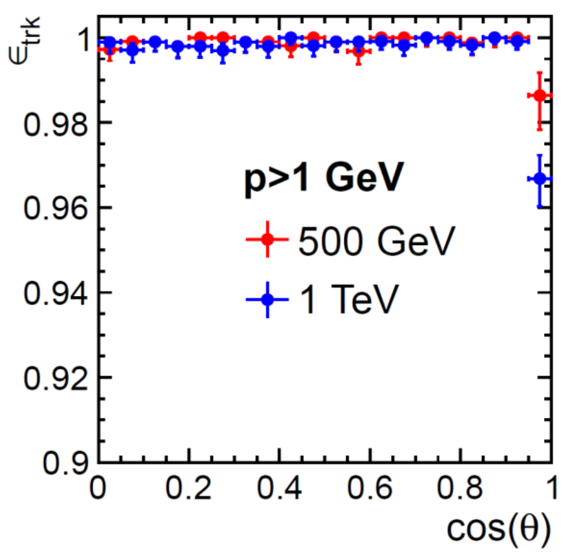


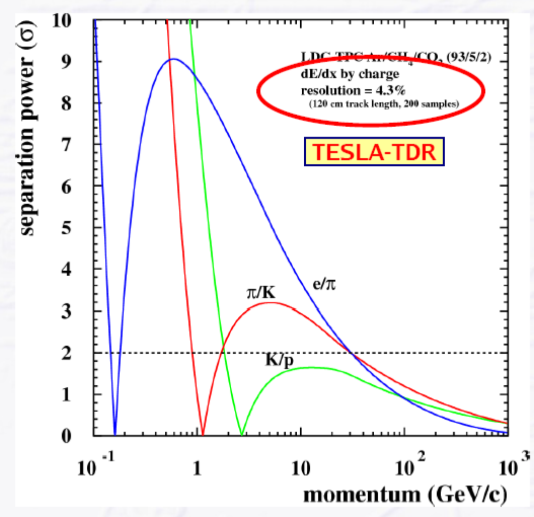
Complete TPC coverage to 37°
VTX + SIT + FTD + SET + ETD =>
precision, redundancy and coverage to
|cosθ| = 0.996.

Tracking Performance

$e^+e^- \rightarrow t\,\bar{t} \rightarrow$ 6 jets with machine backgrounds







dE/dx performance similar to ALEPH, OPAL

Straightforward V^0 reconstruction

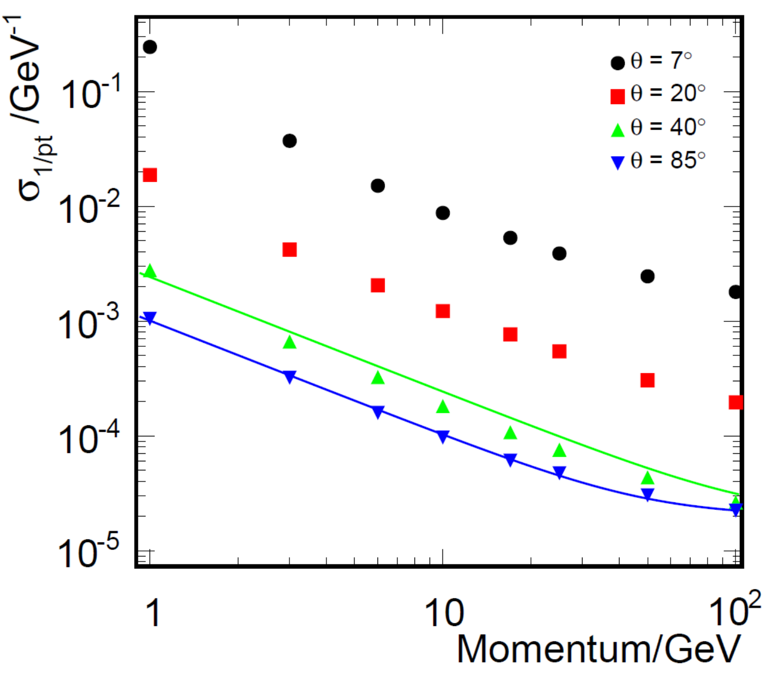
Highly efficient tracking.

Central component of particle-flow performance.

Expected occupancy < 0.5%

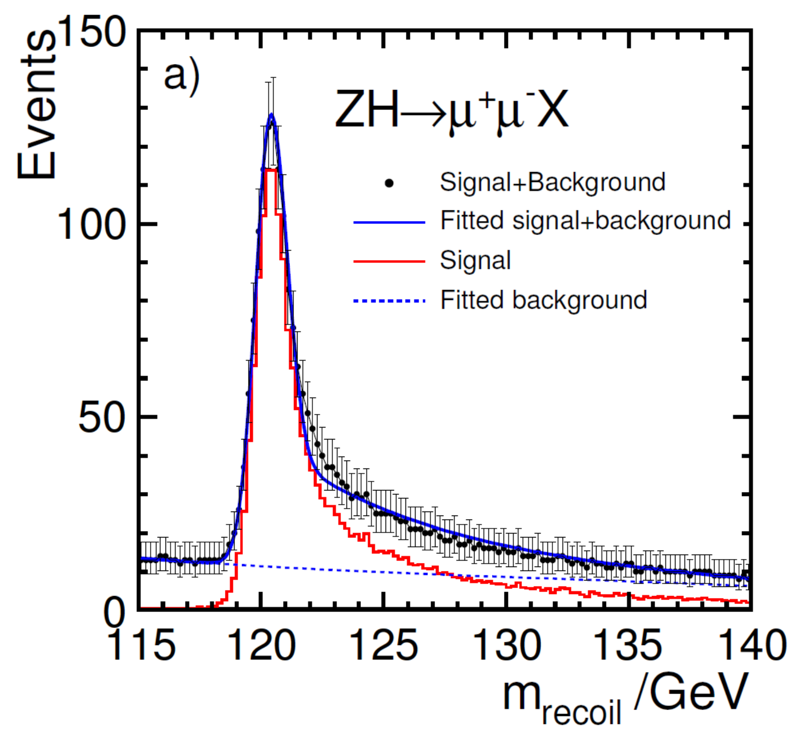
TPC tracking should be robust to ×20

Momentum Resolution

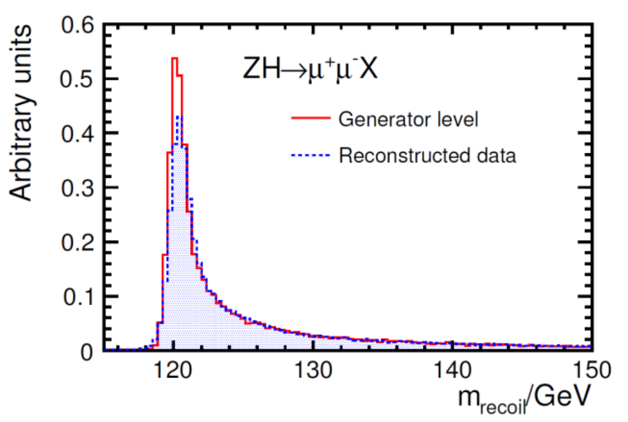


$$\sigma_{1/p_T} = a \oplus b/(p_T \sin\theta)$$

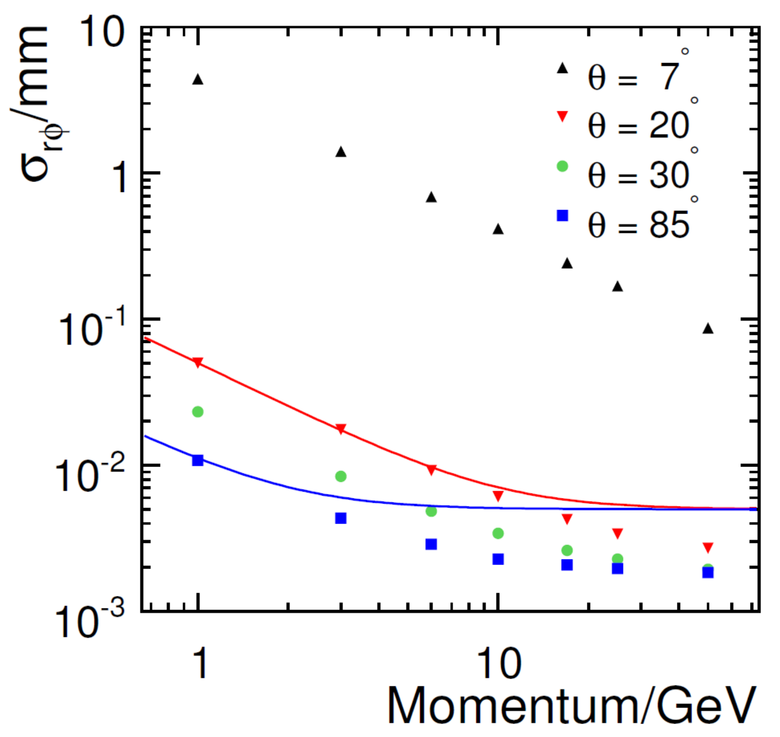
$$a = 2 \times 10^{-5}\,\mathrm{GeV}^{-1} \quad \text{and} \quad b = 1 \times 10^{-3}$$

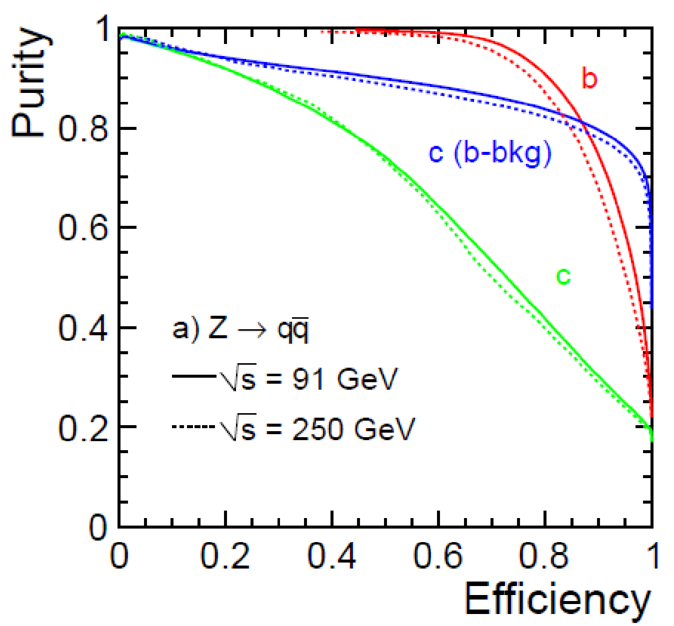


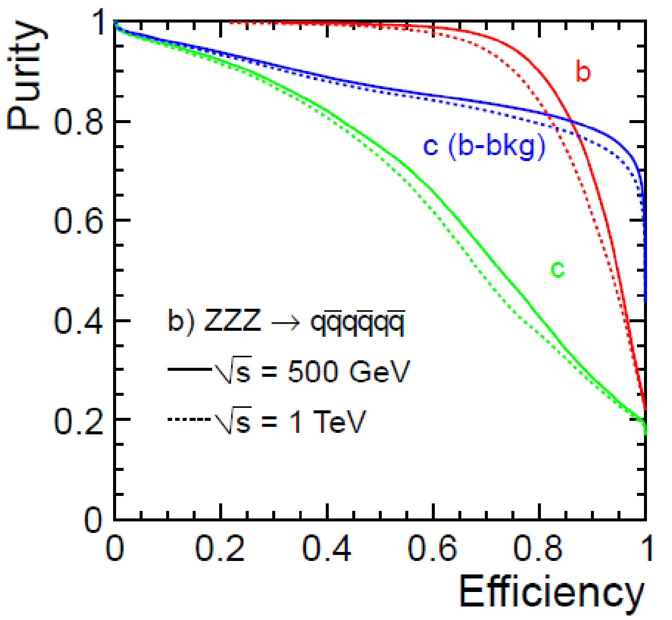
Matches well requirements from Higgs recoil measurement.



Vertexing Performance







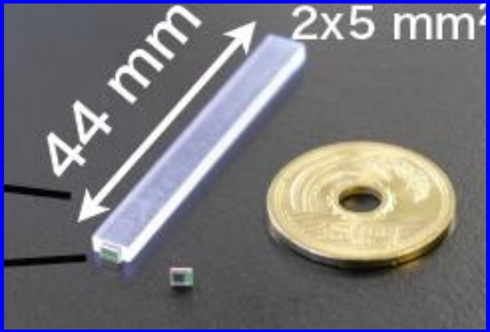
Curves are:

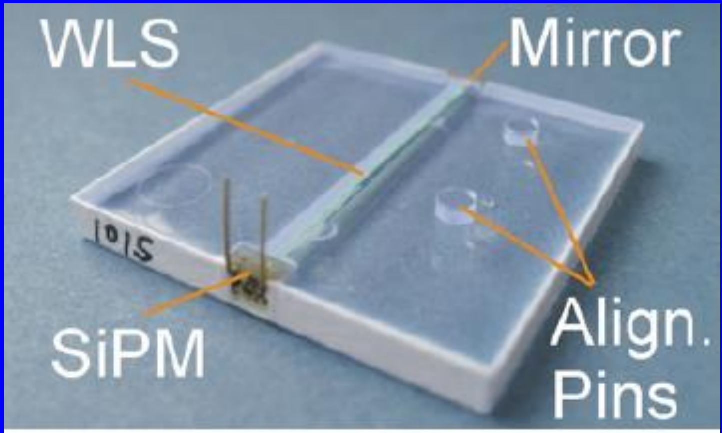
$$\sigma_b = 5 \oplus 10/(\,p\,\beta\,\sin^{3/2}\theta)\ \mu\text{m}$$

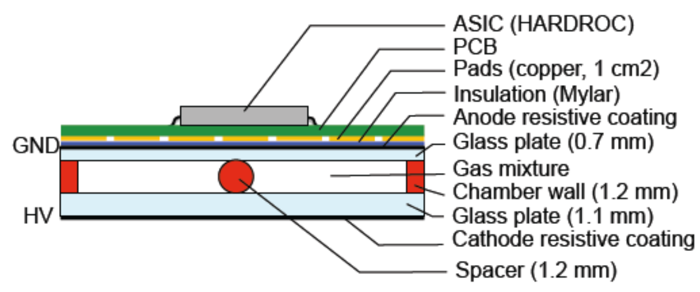
Calorimetry Technologies

All are studied by CALICE

- ECAL (23 X_0 : 20 x 0.6 X_0 + 9 x 1.2 X_0)
  - Silicon-W
    - transverse cell-size 5mm X 5mm
  - Scintillator-W with MPPC readout
    - 5mm X 45 mm X 2mm strips
  - (Digital: MAPS)
- HCAL
  - Analog : Scintillator + Stainless Steel.
    - Tiles with Si-PM readout
    - 3mm Sc, 3cm X 3cm.
  - Digital/Semi-Digital : Gas + Stainless Steel.
    - Glass RPCs or MPGDs, 1cm X 1cm

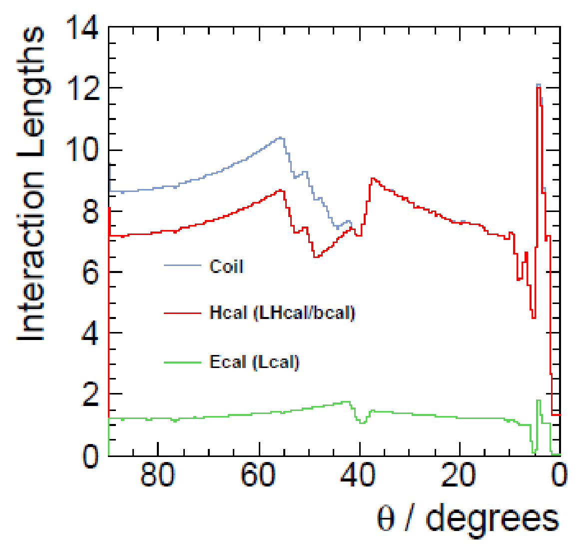


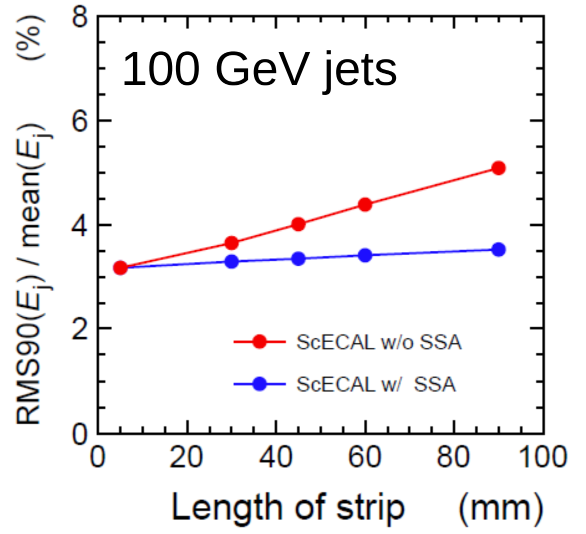




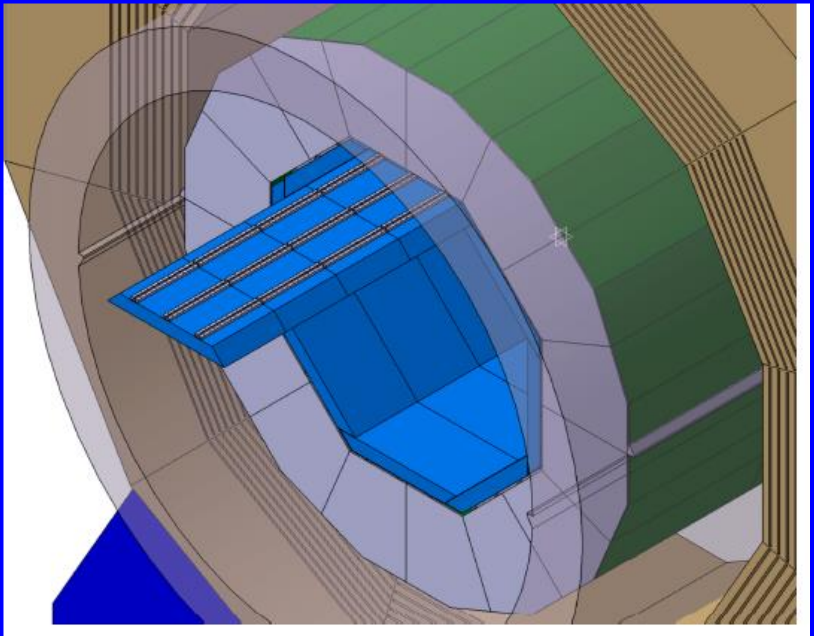
Calorimetry Options Studied

- ILD_o1: Si-W ECAL, Analog HCAL (Scint-Fe).
- ILD_o2: Scint-W ECAL, Analog HCAL (Scint-Fe)
- ILD_o3: Si-W ECAL, Semi-digital HCAL (Gas-Fe)
- Ongoing work looking at hybrid Si/Scint with W ECAL designs (cost awareness).

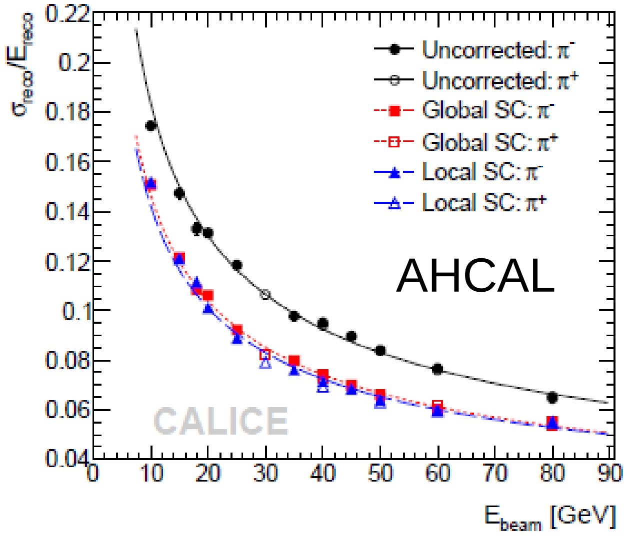


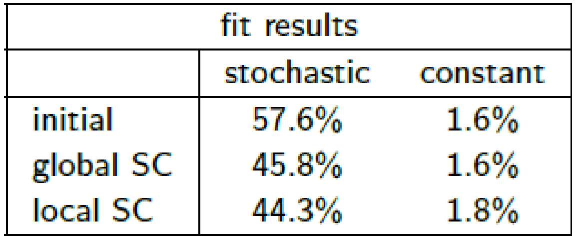


The Calorimeter ?

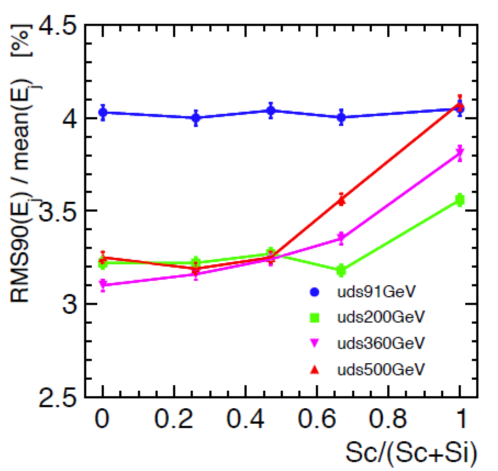


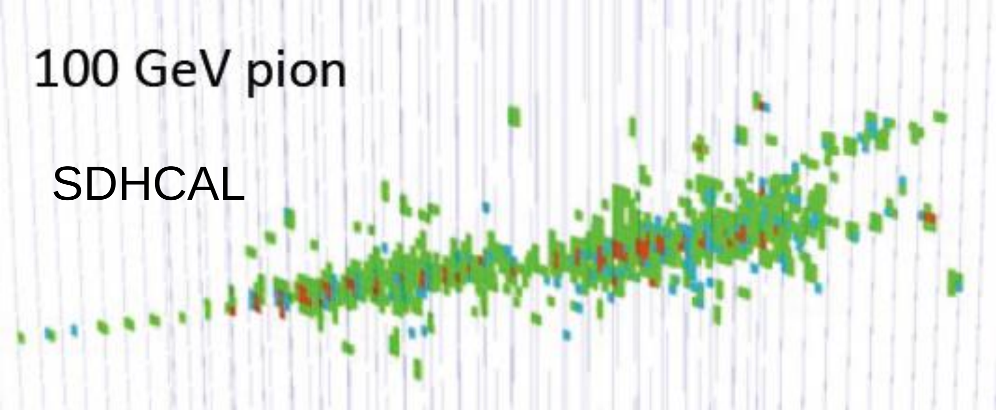
Many options under study (see Felix Sefkow talk)





fit results		
	stochastic	constant
initial	57.6%	1.6%
global SC	45.8%	1.6%
local SC	44.3%	1.8%

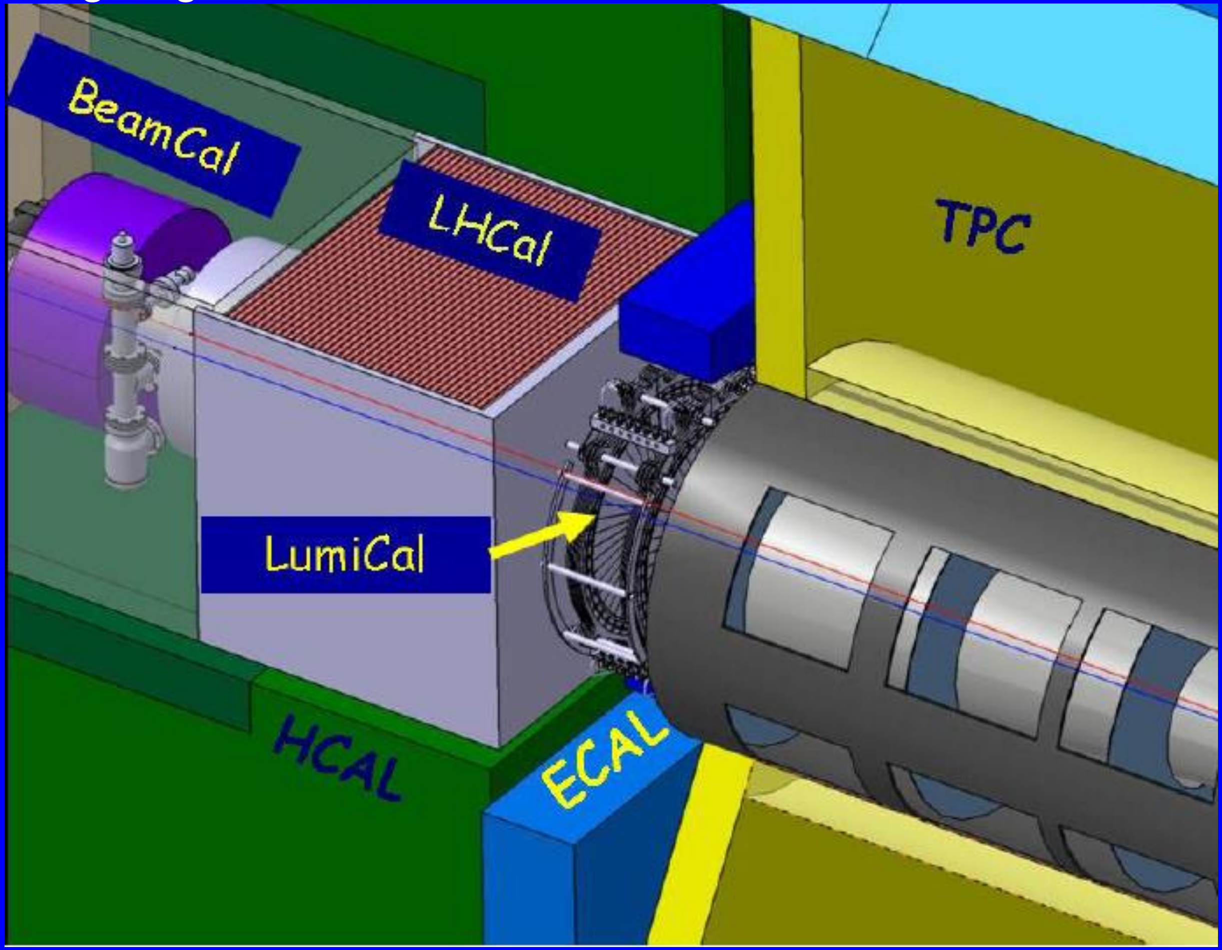




NB Performance = mix of hardware + software algorithms. Room for further improvement in each.

Forward Region

Goals: Measure precision luminosity (with Bhabhas) and provide hermeticity down to around 5 mrad. Accommodate ±7 mrad crossing angle.



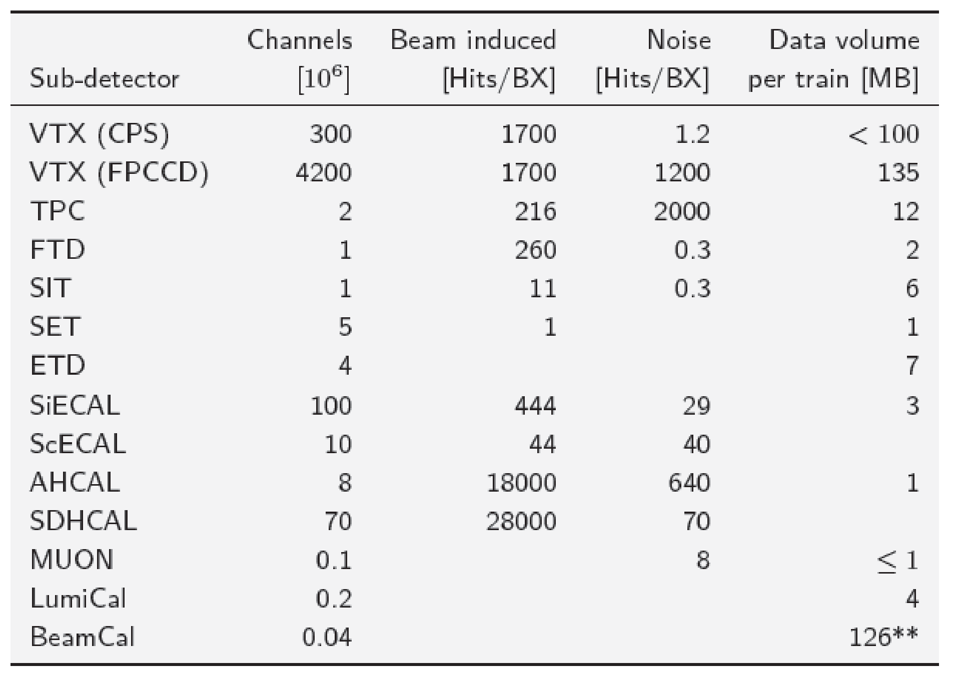
LumiCal (32-74 mr)

LHCal (4λ plug)

BeamCal (5-40 mr)

Worth noting

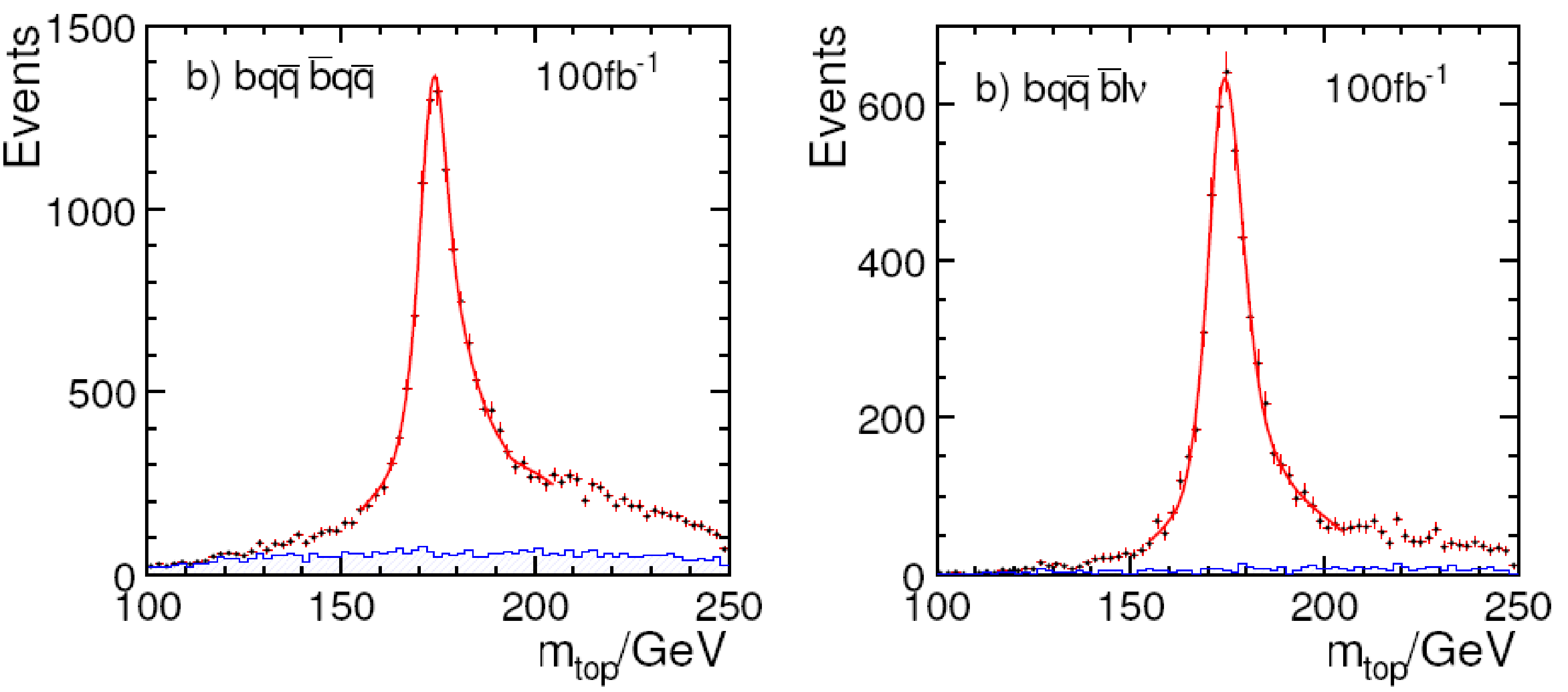
- Instrumented Yoke
  - Straightforward
- Trigger
  - No Hardware trigger
- Data Acquisition
  - Expected data volume – OK



Sub-detector	Channels [10^6]	Beam induced [Hits/BX]	Noise [Hits/BX]	Data volume per train [MB]
VTX (CPS)	300	1700	1.2	< 100
VTX (FPCCD)	4200	1700	1200	135
TPC	2	216	2000	12
FTD	1	260	0.3	2
SIT	1	11	0.3	6
SET	5	1		1
ETD	4			7
SiECAL	100	444	29	3
ScECAL	10	44	40	
AHCAL	8	18000	640	1
SDHCAL	70	28000	70	
MUON	0.1		8	≤ 1
LumiCal	0.2			4
BeamCal	0.04			126**

Top pair production

$\sqrt{s}$ = 500 GeV. Full simulation



Analysis uses particle-flow reconstruction, b-tagging, and kinematic fit.

Result: statistical error of 30 MeV for 500 fb^{-1}

(Factor of 2.5 improvement in sensitivity over hadronic-only study of PRD 67, 074011 (2003).

(4) Jets + Missing Energy

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow qq\tilde{\chi}_1^0qq\tilde{\chi}_1^0$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow qq\tilde{\chi}_1^0qq\tilde{\chi}_1^0$$

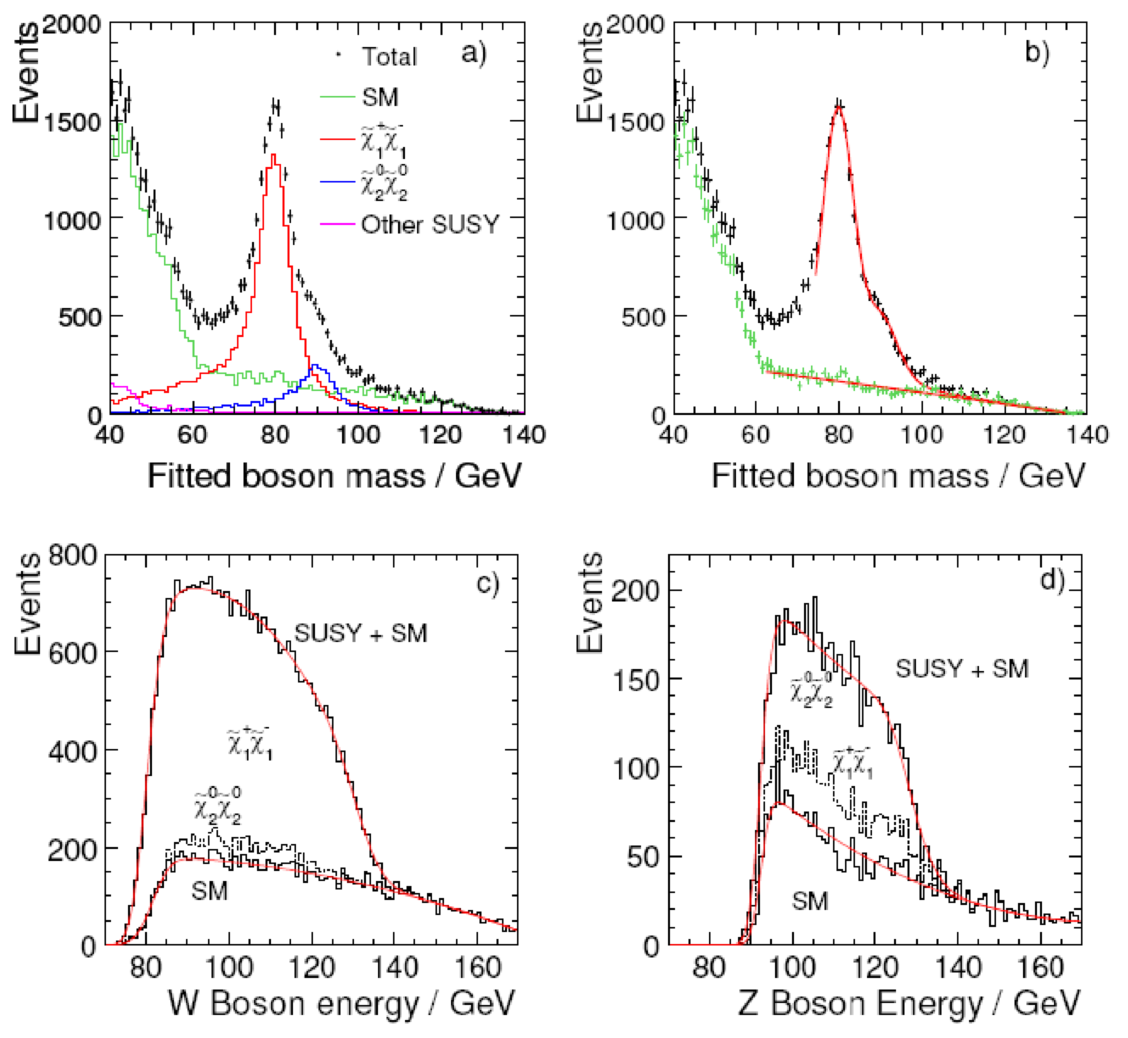
Full simulation

√s=500 GeV

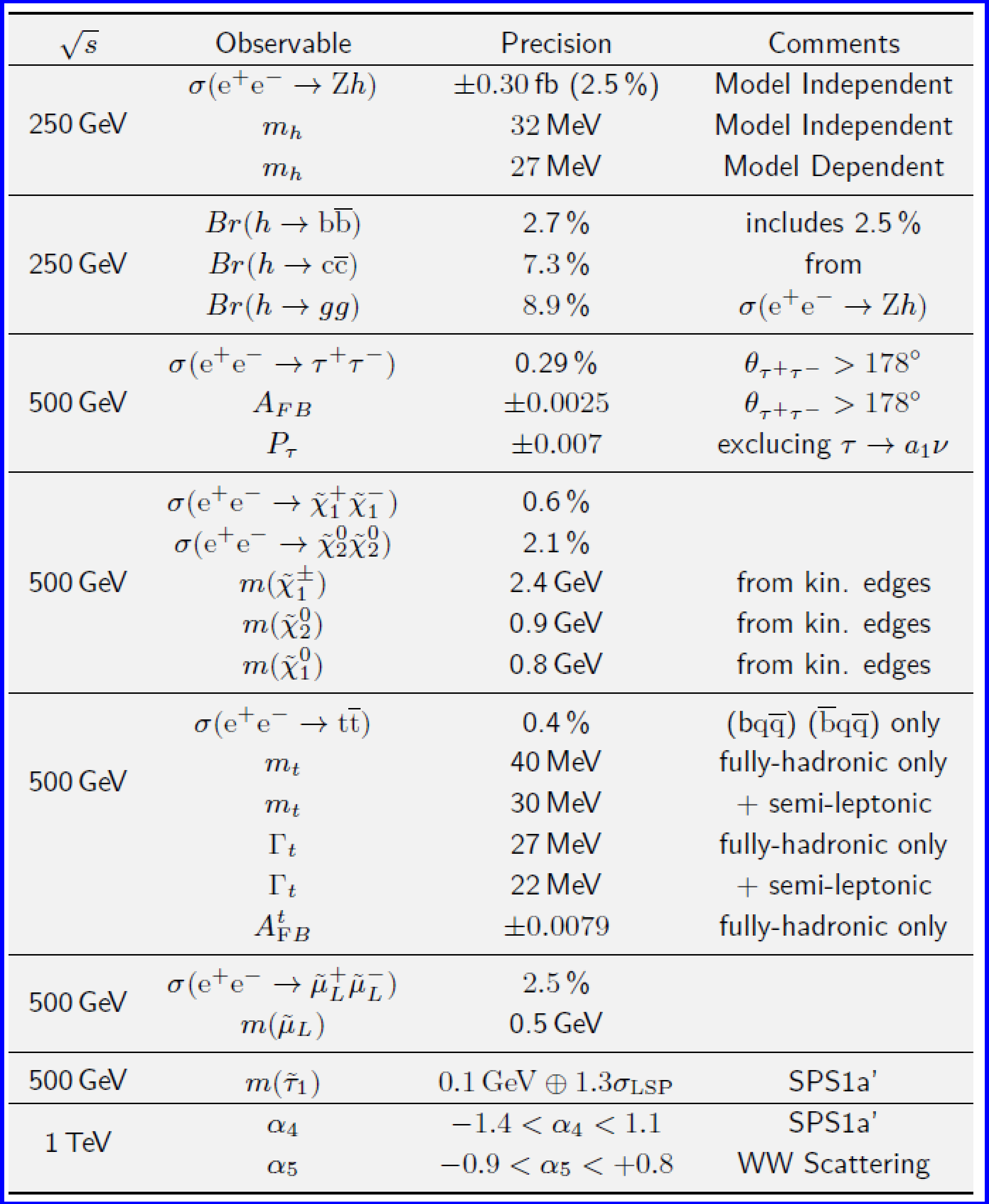
m(C$_1$,N$_2$) ≈ 210 GeV

m(N$_1$) = 117 GeV

Spectroscopy in complicated final state feasible

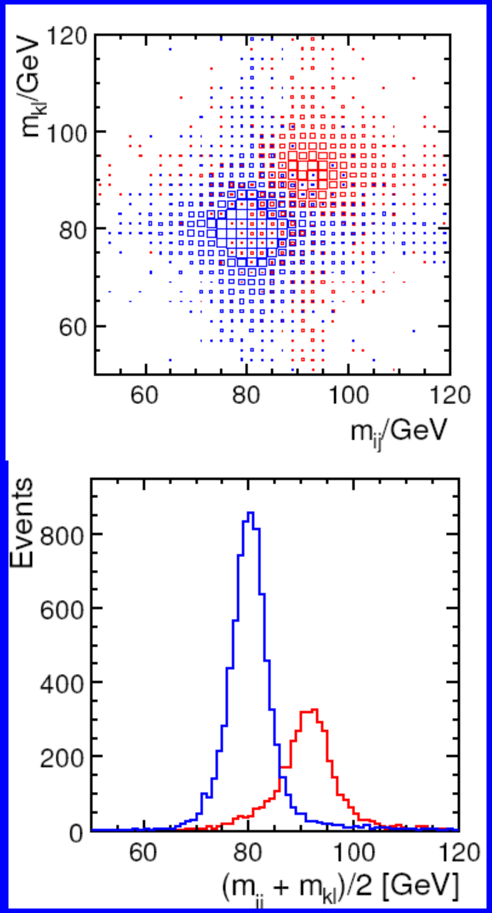


Physics Benchmark Performance Summary



$\sqrt{s}$	Observable	Precision	Comments
250 GeV	$\sigma(e^+e^- \to Zh)$	± 0.30 fb (2.5 %)	Model Independent
	m_h	32 MeV	Model Independent
	m_h	27 MeV	Model Dependent
250 GeV	$Br(h \to b\bar{b})$	2.7 %	includes 2.5 %
	$Br(h \to c\bar{c})$	7.3 %	from
	$Br(h \to gg)$	8.9 %	$\sigma(e^+e^- \to Zh)$
500 GeV	$\sigma(e^+e^- \to \tau^+\tau^-)$	0.29 %	$\theta_{\tau^+\tau^-} > 178°$
	A_{FB}	± 0.0025	$\theta_{\tau^+\tau^-} > 178°$
	P_τ	± 0.007	exclucing $\tau \to a_1\nu$
500 GeV	$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	0.6 %	
	$\sigma(e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0)$	2.1 %	
	$m(\tilde{\chi}_1^\pm)$	2.4 GeV	from kin. edges
	$m(\tilde{\chi}_2^0)$	0.9 GeV	from kin. edges
	$m(\tilde{\chi}_1^0)$	0.8 GeV	from kin. edges
500 GeV	$\sigma(e^+e^- \to t\bar{t})$	0.4 %	$(bq\bar{q})$ $(\bar{b}q\bar{q})$ only
	m_t	40 MeV	fully-hadronic only
	m_t	30 MeV	+ semi-leptonic
	Γ_t	27 MeV	fully-hadronic only
	Γ_t	22 MeV	+ semi-leptonic
	A^t_{FB}	± 0.0079	fully-hadronic only
500 GeV	$\sigma(e^+e^- \to \tilde{\mu}_L^+\tilde{\mu}_L^-)$	2.5 %	
	$m(\tilde{\mu}_L)$	0.5 GeV	
500 GeV	$m(\tilde{\tau}_1)$	$0.1\,\mathrm{GeV} \oplus 1.3\sigma_{\mathrm{LSP}}$	SPS1a'
1 TeV	α_4	$-1.4 < \alpha_4 < 1.1$	SPS1a'
	α_5	$-0.9 < \alpha_5 < +0.8$	WW Scattering

WW Scattering



Studies done with full simulation including SM physics backgrounds

Concluding Remarks

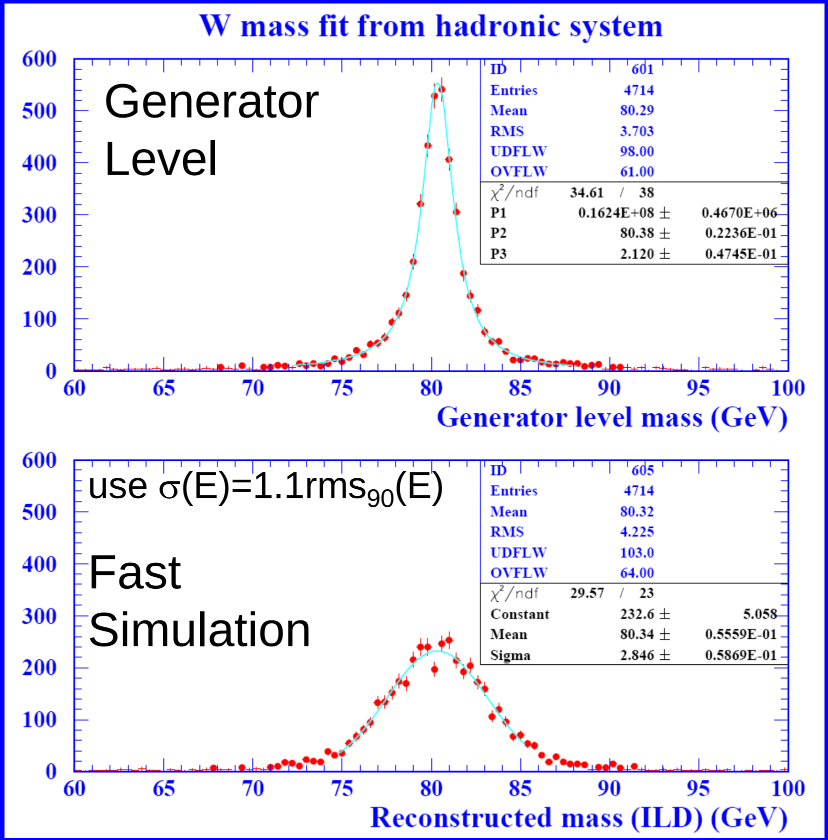
- ILD is a mature detector concept well suited to ILC physics requirements.
- ILD is keeping its options open in terms of technological solutions for detector subsystems.
    - Together with the detector R&D collaborations we have developed many of the tools needed to make informed choices.
- Still lots of room for innovation and new ideas.
- ILD welcomes new and returning members.
- ILD is taking steps towards more formal membership and governance in anticipation of becoming a real collaboration with an actual project.

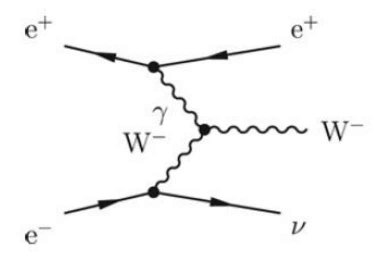
- Upcoming meetings of relevance
    - ECFA LC2013, DESY, Hamburg, May 27-31.
    - Dedicated ILD Workshop, September? Likely in Europe.

Backup Slides

Is ILD jet energy resolution “good enough” ?

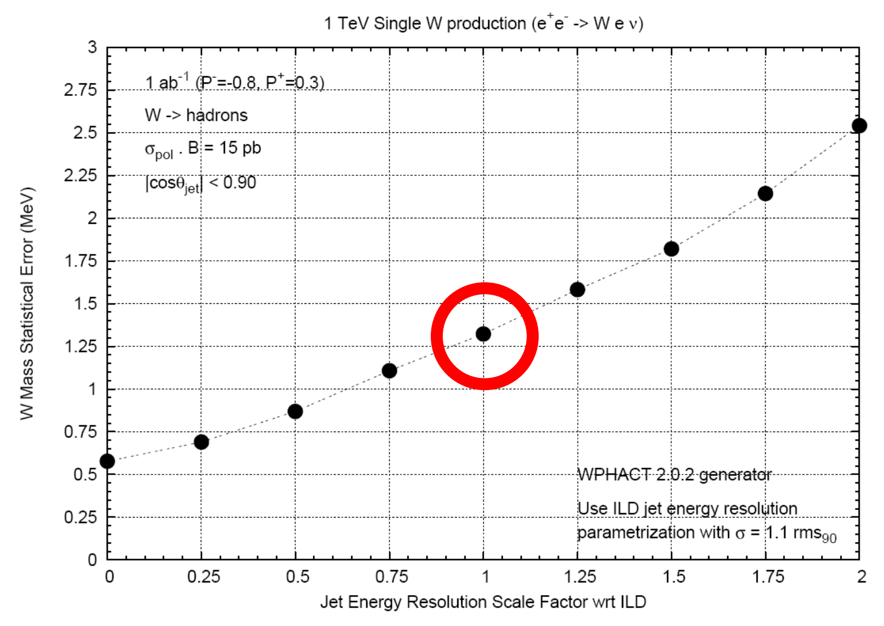
Single W study at √s = 1TeV





W → q q
(jets are not so energetic)

Is this useful for physics ? Example m_W.

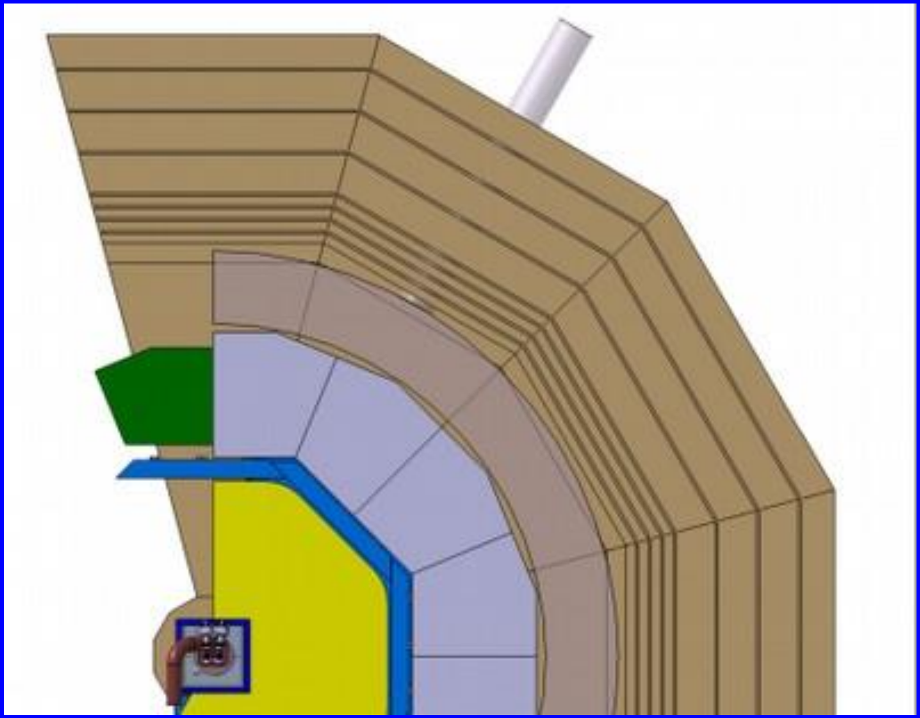


=> Further E_{jet} resolution improvement very desirable

Very useful ! (Especially, if the really challenging requirements on jet energy scale and calibration can be met !)

MDI / Detector Integration

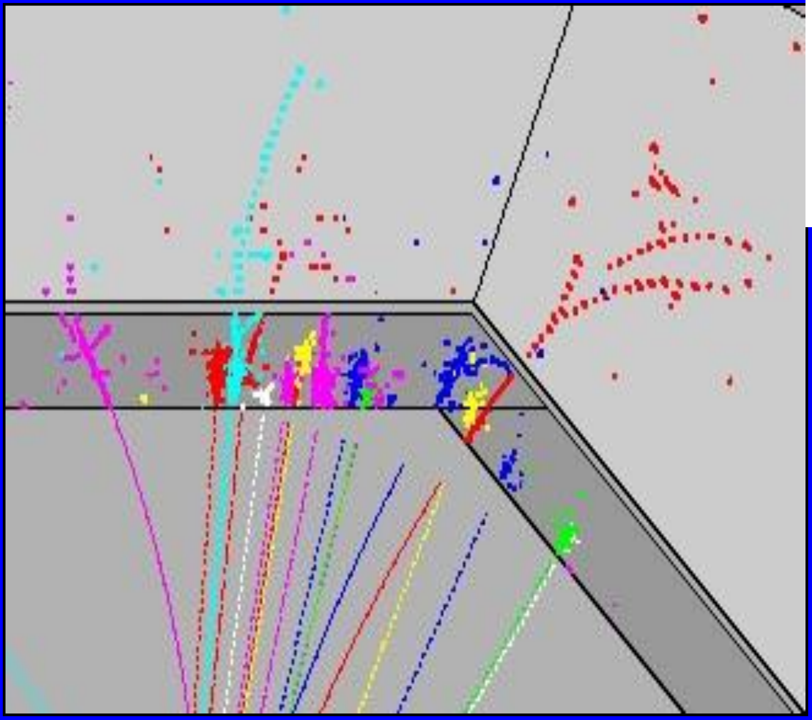
- Real-world engineering and design issues investigated
  - Detector assembly and maintenance
  - Push-pull
  - Backgrounds
  - Alignment, power, cooling, cables
  - Etc/etc
- So far no show stoppers
- Will need extensive engineering support as we move forward

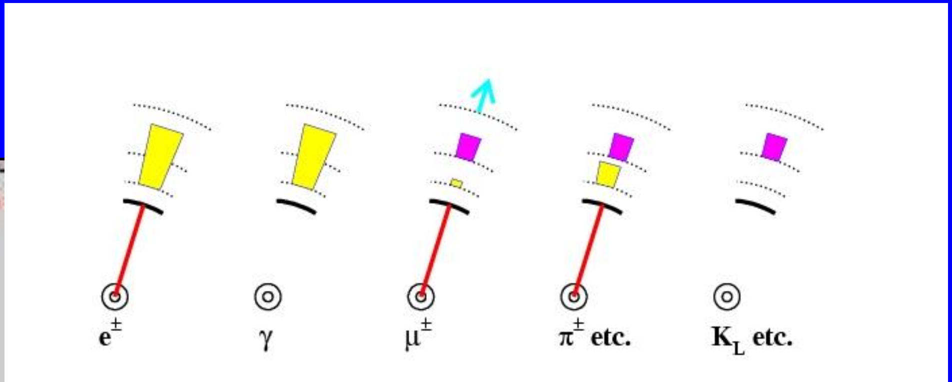


What is particle flow ?

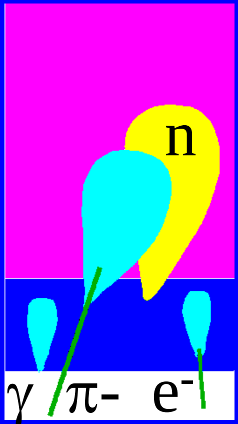
$$E_{jet} = E_{ch} + E_{\gamma} + E_{NH}$$

Particle-by-particle event reconstruction





T E T T H

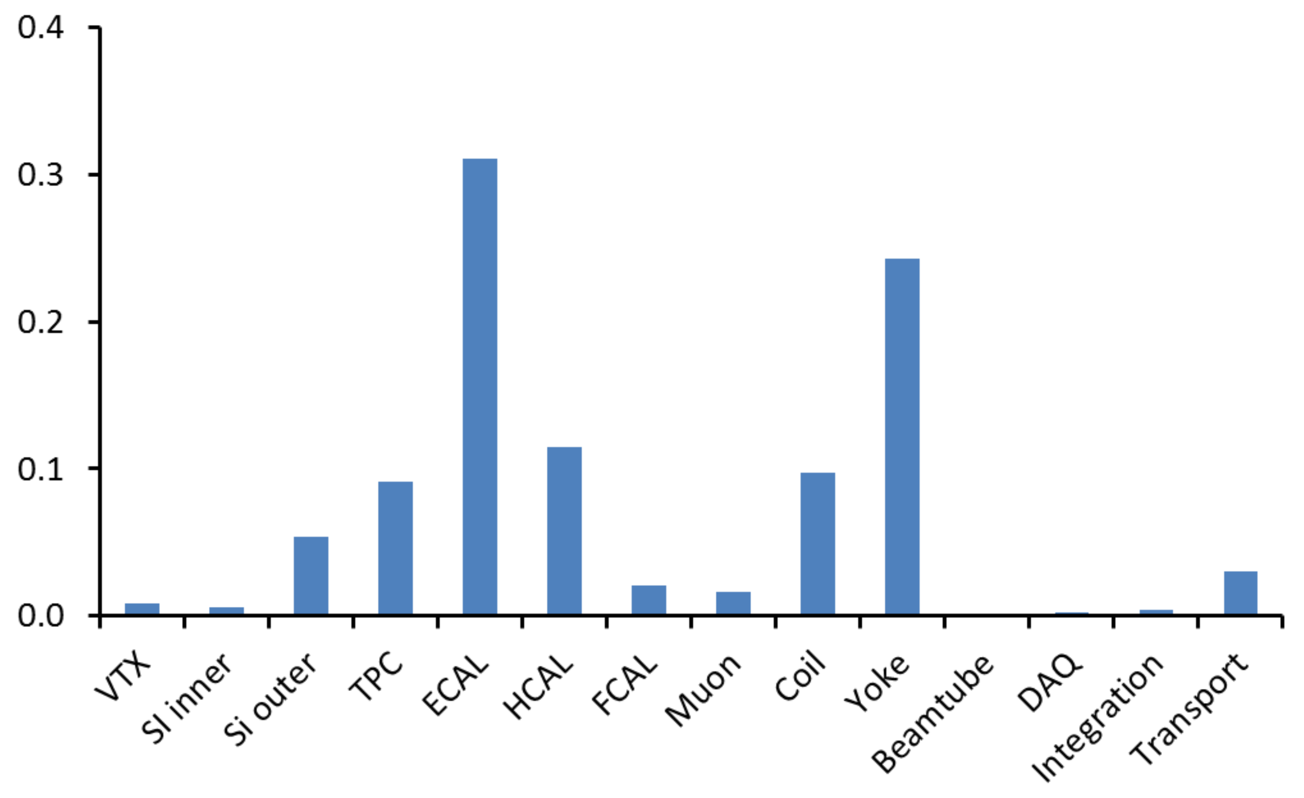


HCAL

ECAL

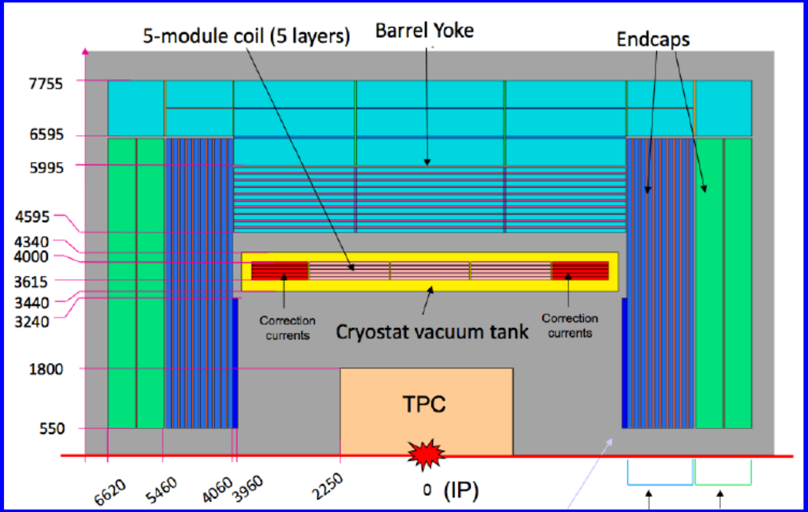
Emphasizes particle separability → large R

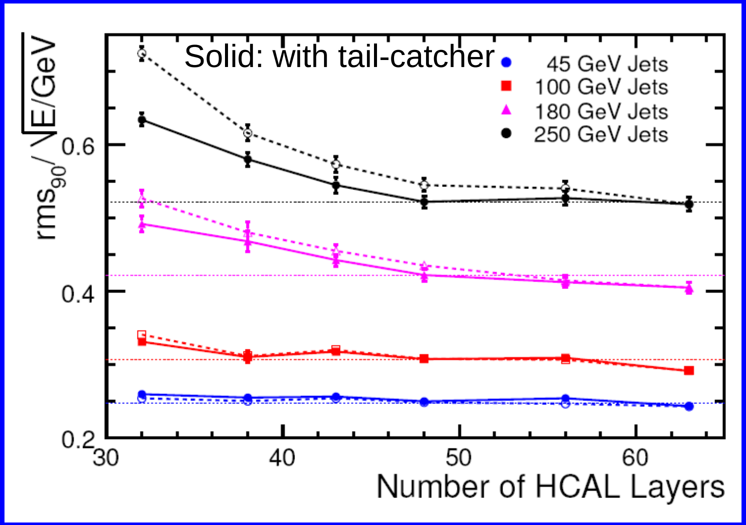
Estimated Relative Costs



Total about 400 MILCU. Comparable to an LHC detector.

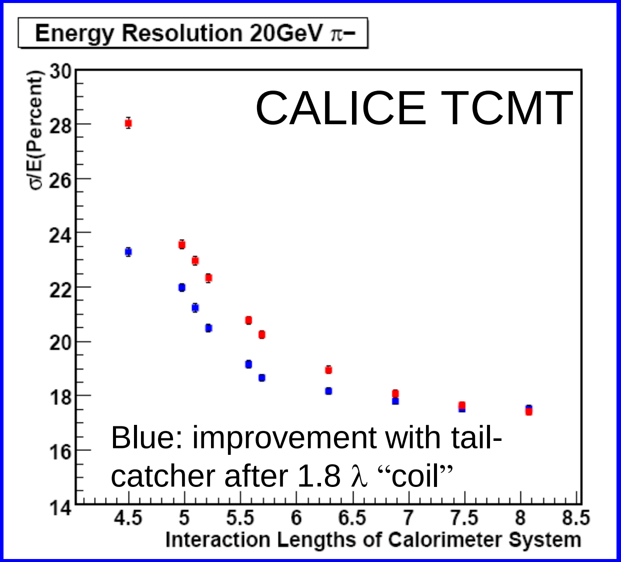
Instrumented Return Yoke





Yoke is large. It will be instrumented for muon detection: scintillator strips, RPCs considered.

Instrumented gaps can serve as a tail-catcher. More important at high energy, or if CAL system is thinner than current 6.8 λ (48 HCAL layers).



ILC Accelerator Parameters

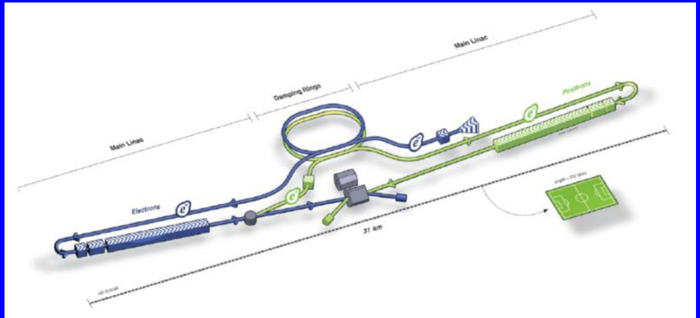
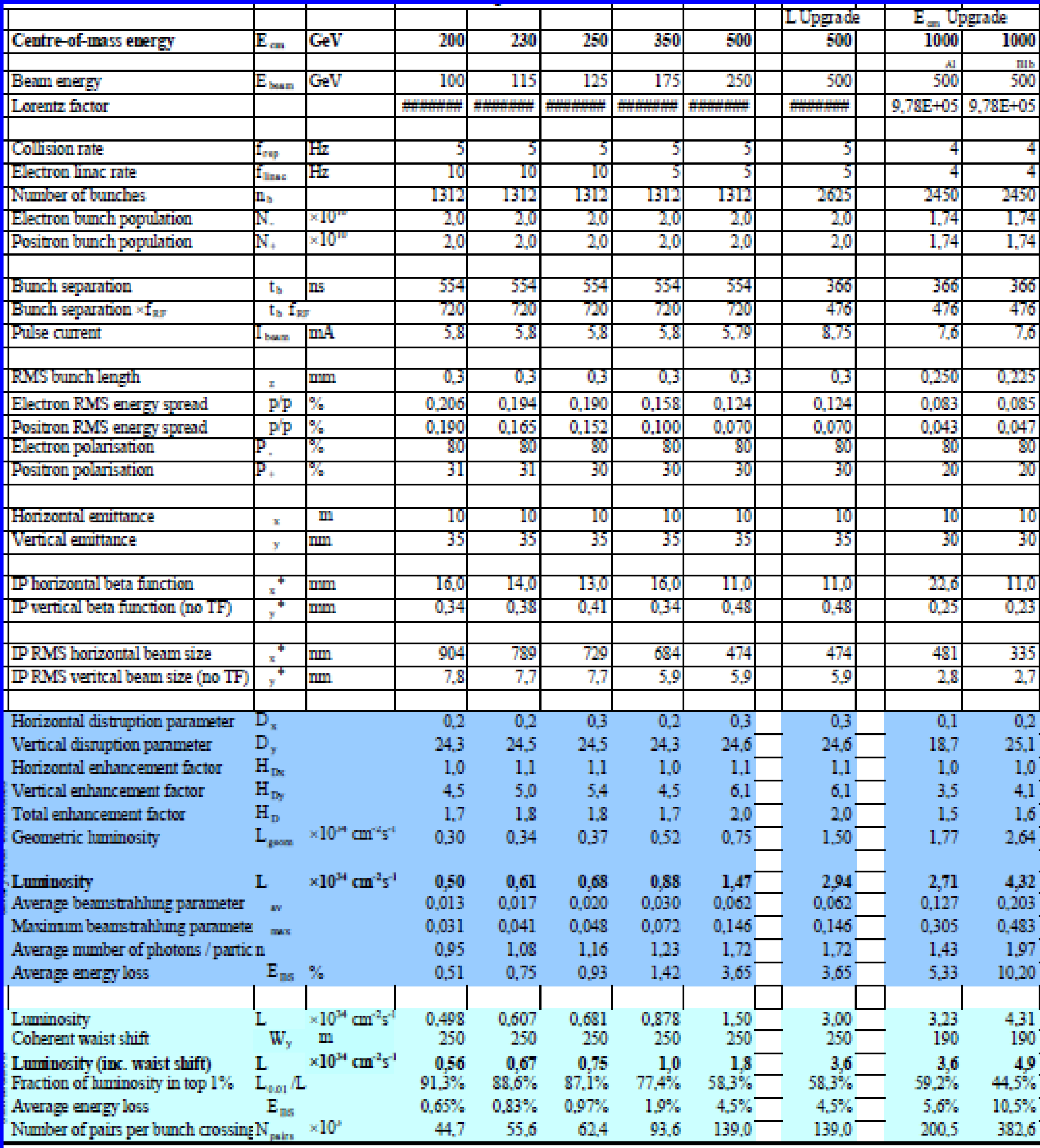


Figure 2: Layout of the ILC accelerator systems.

Parameters of interest for precision measurements:

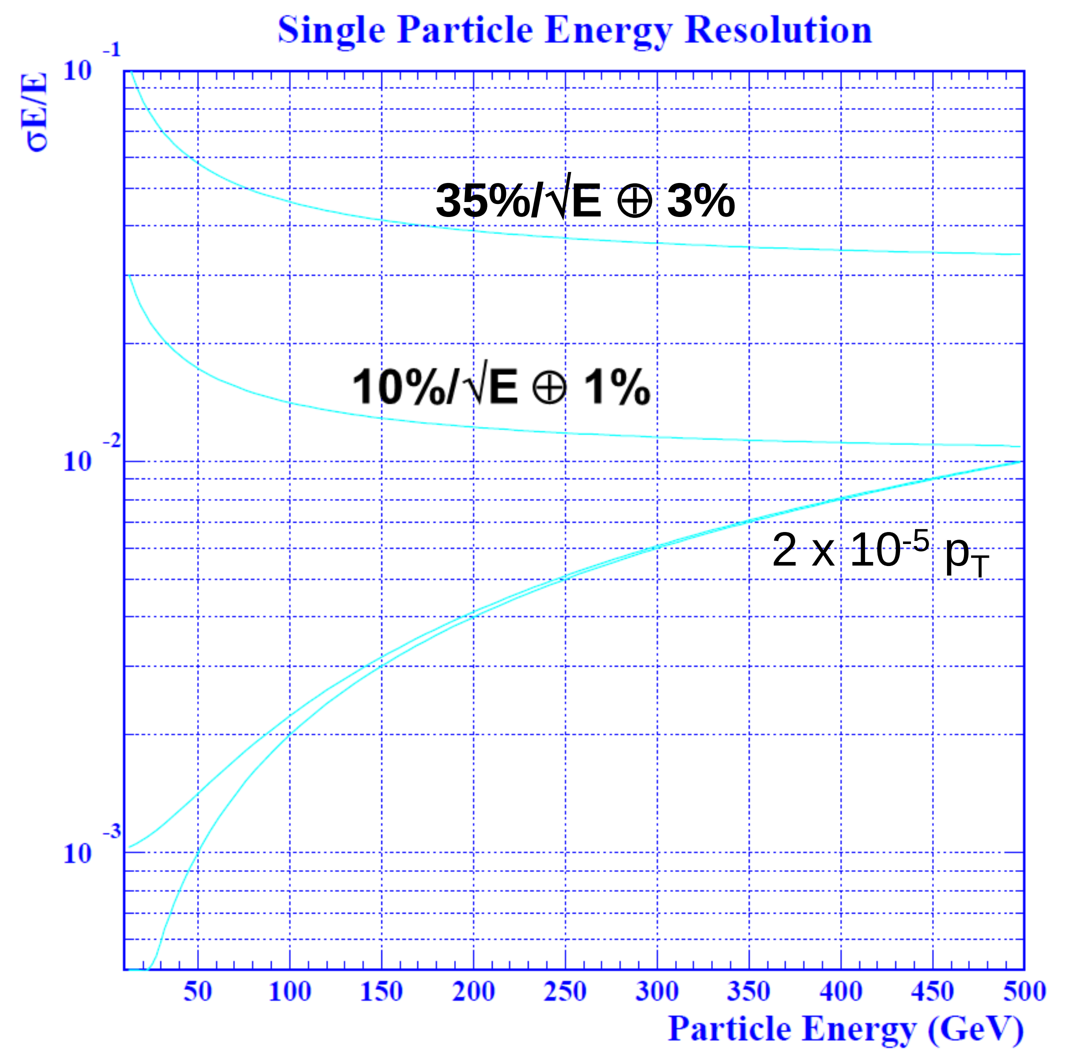
Beam energy spread,
Bunch separation,
Bunch length,
e^- Polarization / e^+ Polarization,
dL/d$\sqrt{s}$,
Average energy loss,
Pair backgrounds,
Beamstrahlung characteristics,

and of course **luminosity**.



								L Upgrade	E_{cm} Upgrade	
Centre-of-mass energy	E_{cm}	GeV	200	230	250	350	500	500	1000	1000
									A1	B1b
Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
Lorentz factor			#######	#######	#######	#######	#######	#######	9,78E+05	9,78E+05
Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
Electron bunch population	N_-	$\times10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Positron bunch population	N_+	$\times10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Bunch separation	t_b	ns	554	554	554	554	554	366	366	366
Bunch separation $\times f_{RF}$	$t_b\ f_{RF}$		720	720	720	720	720	476	476	476
Pulse current	I_{beam}	mA	5,8	5,8	5,8	5,8	5,79	8,75	7,6	7,6
RMS bunch length	$_z$	mm	0,3	0,3	0,3	0,3	0,3	0,3	0,250	0,225
Electron RMS energy spread	p/p	%	0,206	0,194	0,190	0,158	0,124	0,124	0,083	0,085
Positron RMS energy spread	p/p	%	0,190	0,165	0,152	0,100	0,070	0,070	0,043	0,047
Electron polarisation	P_-	%	80	80	80	80	80	80	80	80
Positron polarisation	P_+	%	31	31	30	30	30	30	20	20
Horizontal emittance	$_x$	m	10	10	10	10	10	10	10	10
Vertical emittance	$_y$	nm	35	35	35	35	35	35	30	30
IP horizontal beta function	$_x^*$	mm	16,0	14,0	13,0	16,0	11,0	11,0	22,6	11,0
IP vertical beta function (no TF)	$_y^*$	mm	0,34	0,38	0,41	0,34	0,48	0,48	0,25	0,23
IP RMS horizontal beam size	$_x^*$	nm	904	789	729	684	474	474	481	335
IP RMS veritcal beam size (no TF)	$_y^*$	nm	7,8	7,7	7,7	5,9	5,9	5,9	2,8	2,7
Horizontal distruption parameter	D_x		0,2	0,2	0,3	0,2	0,3	0,3	0,1	0,2
Vertical disruption parameter	D_y		24,3	24,5	24,5	24,3	24,6	24,6	18,7	25,1
Horizontal enhancement factor	H_{Dx}		1,0	1,1	1,1	1,0	1,1	1,1	1,0	1,0
Vertical enhancement factor	H_{Dy}		4,5	5,0	5,4	4,5	6,1	6,1	3,5	4,1
Total enhancement factor	H_D		1,7	1,8	1,8	1,7	2,0	2,0	1,5	1,6
Geometric luminosity	L_{geom}	$\times10^{34}$ cm^{-2}s^{-1}	0,30	0,34	0,37	0,52	0,75	1,50	1,77	2,64
Luminosity	**L**	**$\times10^{34}$ cm^{-2}s^{-1}**	**0,50**	**0,61**	**0,68**	**0,88**	**1,47**	**2,94**	**2,71**	**4,32**
Average beamstrahlung parameter	$_{av}$		0,013	0,017	0,020	0,030	0,062	0,062	0,127	0,203
Maximum beamstrahlung paramete	$_{max}$		0,031	0,041	0,048	0,072	0,146	0,146	0,305	0,483
Average number of photons / partic n			0,95	1,08	1,16	1,23	1,72	1,72	1,43	1,97
Average energy loss	E_{BS}	%	0,51	0,75	0,93	1,42	3,65	3,65	5,33	10,20
Luminosity	L	$\times10^{34}$ cm^{-2}s^{-1}	0,498	0,607	0,681	0,878	1,50	3,00	3,23	4,31
Coherent waist shift	W_y	m	250	250	250	250	250	250	190	190
Luminosity (inc. waist shift)	**L**	**$\times10^{34}$ cm^{-2}s^{-1}**	**0,56**	**0,67**	**0,75**	**1,0**	**1,8**	**3,6**	**3,6**	**4,9**
Fraction of luminosity in top 1%	$L_{0.01}/L$		91,3%	88,6%	87,1%	77,4%	58,3%	58,3%	59,2%	44,5%
Average energy loss	E_{BS}		0,65%	0,83%	0,97%	1,9%	4,5%	4,5%	5,6%	10,5%
Number of pairs per bunch crossing	N_{pairs}	$\times10^{3}$	44,7	55,6	62,4	93,6	139,0	139,0	200,5	382,6

Comparison of Tracker Resolution with Calorimetric Resolution



- ECAL and HCAL based energy measurements for charged particles are not competitive with design momentum resolution over the complete ILC envisaged energy range.