Detector Challenges for Lepton Colliders

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Detector Challenges for Lepton Colliders

- The prospective Lepton Colliders and Detectors

- Detector requirements and challenges

- Current R&D … Next steps…future possibilities

- Ideas for the future

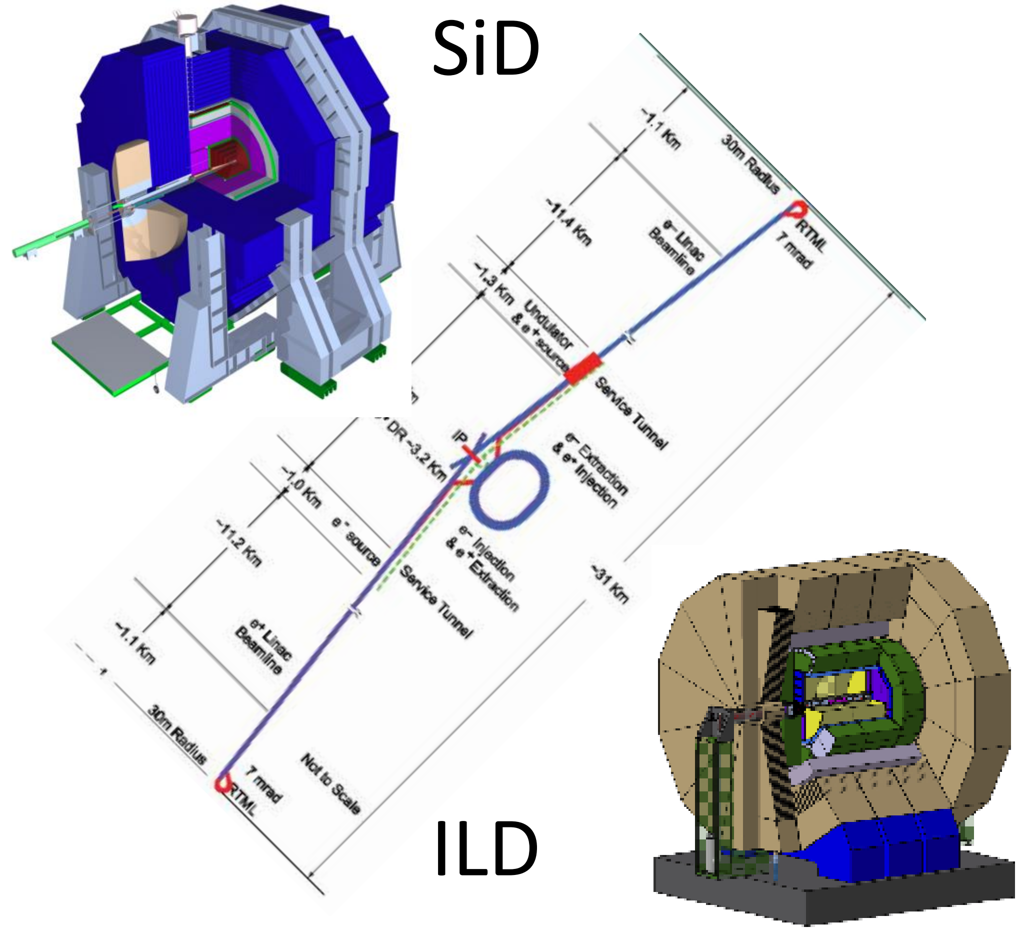
With thanks for input from Jim Brau, Ron Lipton, and several unknowing donors

Colliders and Detectors

ILC

500 GeV – 1 TeV

$e^+ e^-$

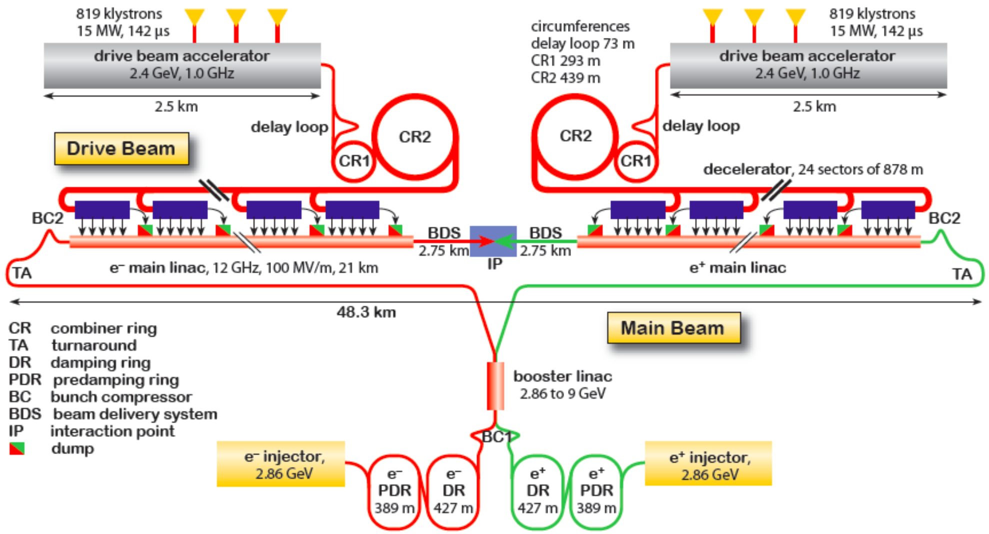


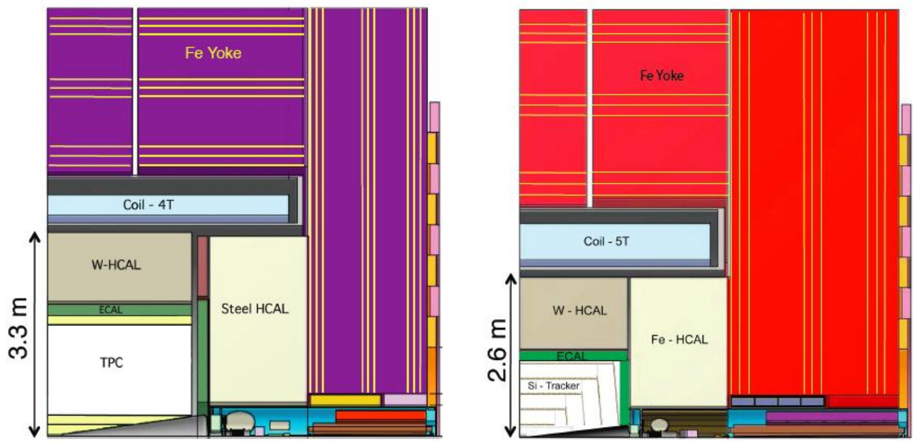
Detector Detailed Baseline Designs and Accelerator TDR -> Completion in 2012

Colliders and Detectors

≤ 3 TeV

$e^+ e^-$





Detector and Accelerator CDR completed in 2011

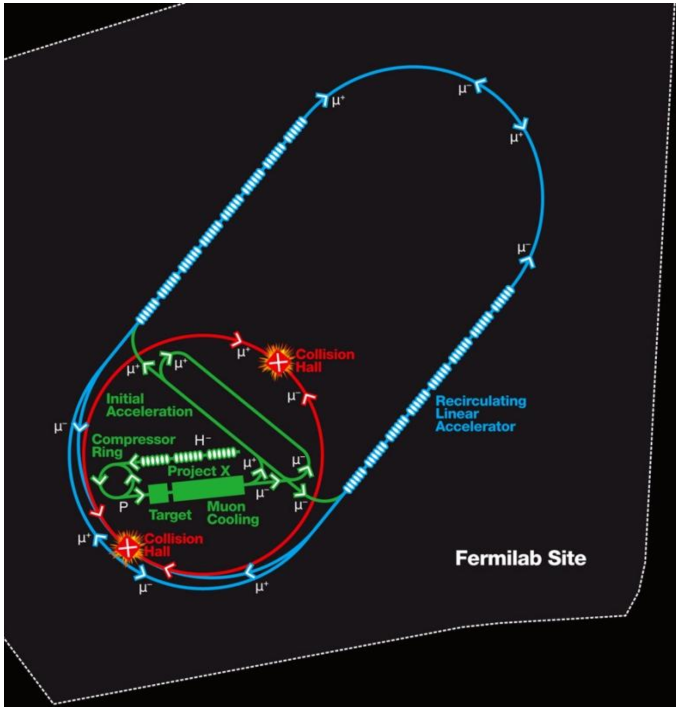
Prepare full TDR 2017-2022

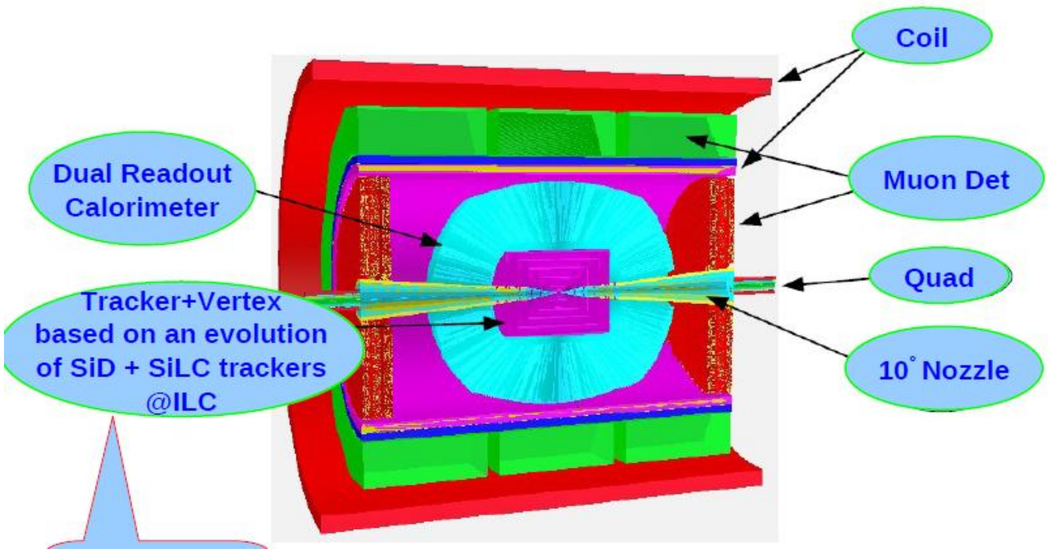
ILD’ and SiD’

Colliders and Detectors

Muon Collider

$\leq$ 4 TeV

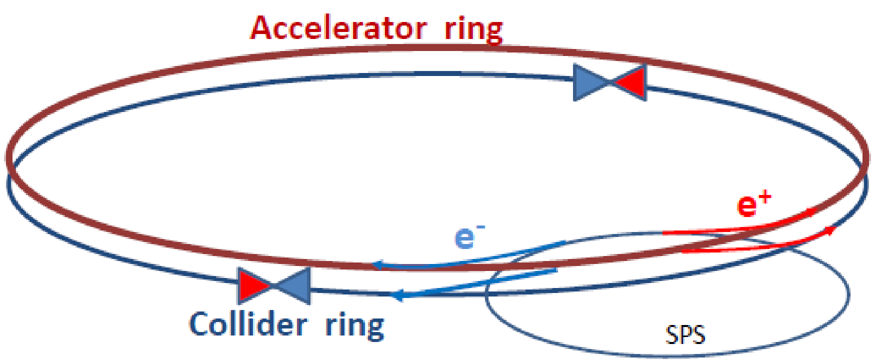


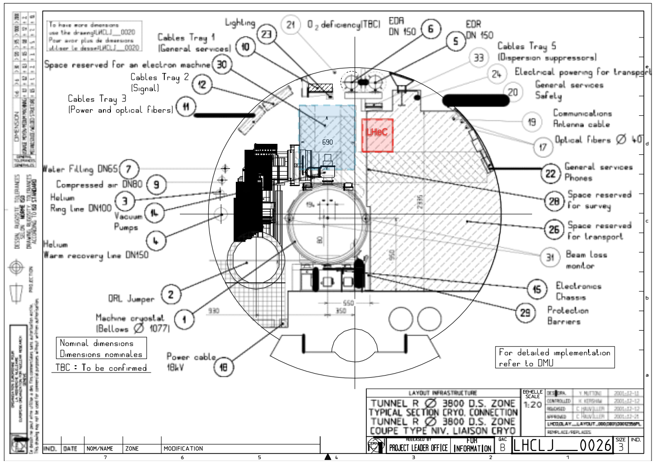


Muon Accelerator Proposal: studying design/feasibility

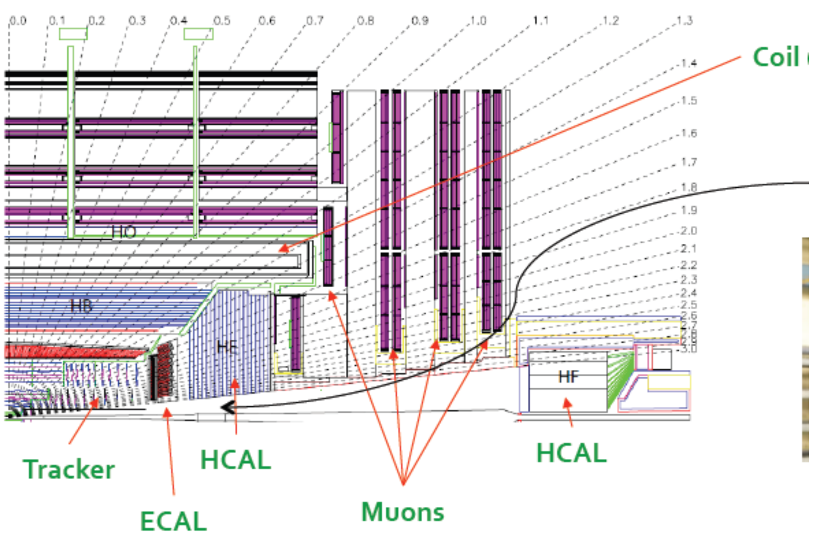
Colliders and Detectors

LEP3: A high Luminosity e^+e^- Collider in the LHC tunnel





A new proposal to use LEP3 with the CMS (+ATLAS?) detector as a Higgs factory



Detector(s) – CMS? ATLAS, SiD, ILD…?

Detector Requirements -> Challenges

– Vertexing: heavy quark flavor identification, charge measurement

- Tracking: momentum resolution, track separation, efficiency

  $\delta(1/p_T) \sim 2\text{-}5 \times 10^{-5}$ /GeV
- Calorimetry: jet energy measurement, jet-jet mass resolution

  Jet energy resolution 3% or better
- Overall: full angular coverage, minimize dead regions, dead materials, alignment, calibration,…

- General: robustness against backgrounds, survivability

Detector R&D perspective

- A large body of R&D exists for ILC detectors, developed over more than a decade and solutions exist that can deliver required physics performance – to be presented in Detailed Baseline Designs.

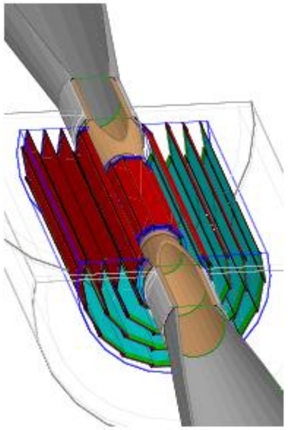
- Much of this R&D is applicable to the CLIC detectors, but higher backgrounds, more demanding timing, higher energies,…

- For the Muon Collider the backgrounds are severe and additional R&D is needed to address occupancies, energy deposition, and radiation hardness.

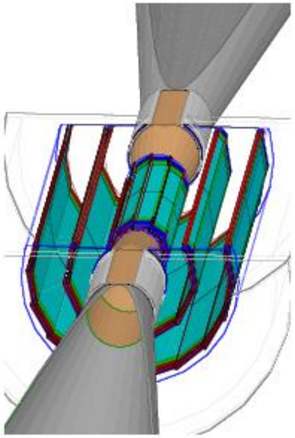
- For LEP3 initial studies have used the present CMS detector – special case and for Higgs factory only.

Vertexing – designs - ILC

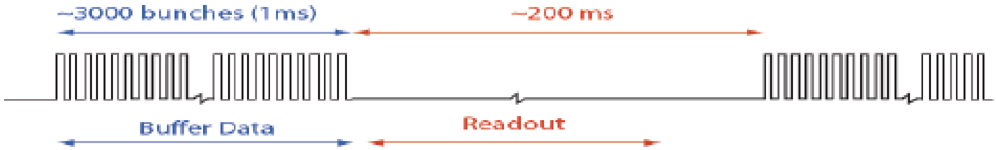
ILD

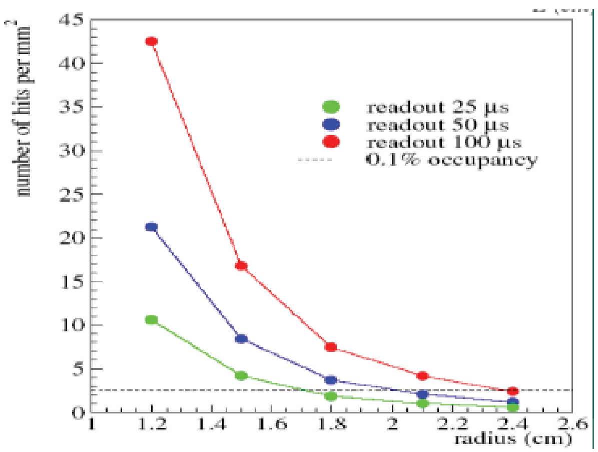


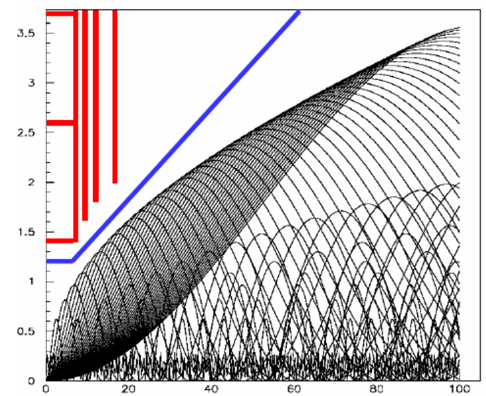
5 x single sided



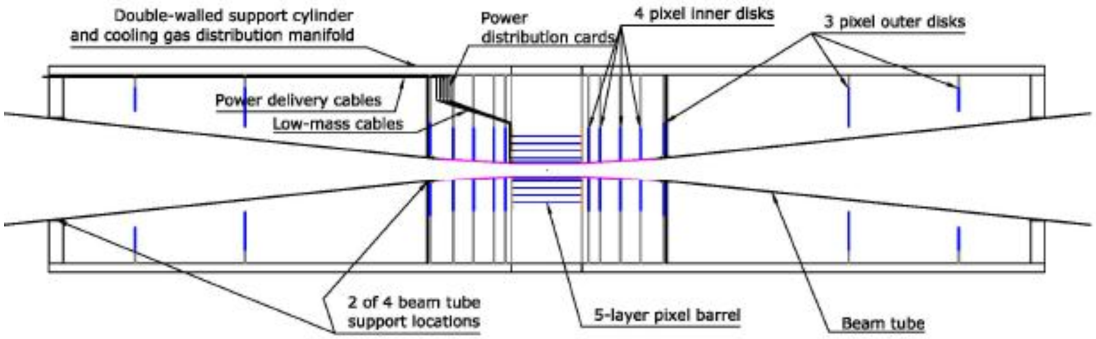
Double-sided

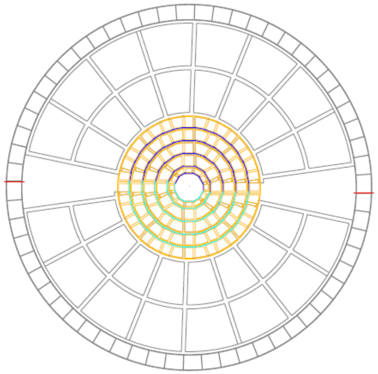






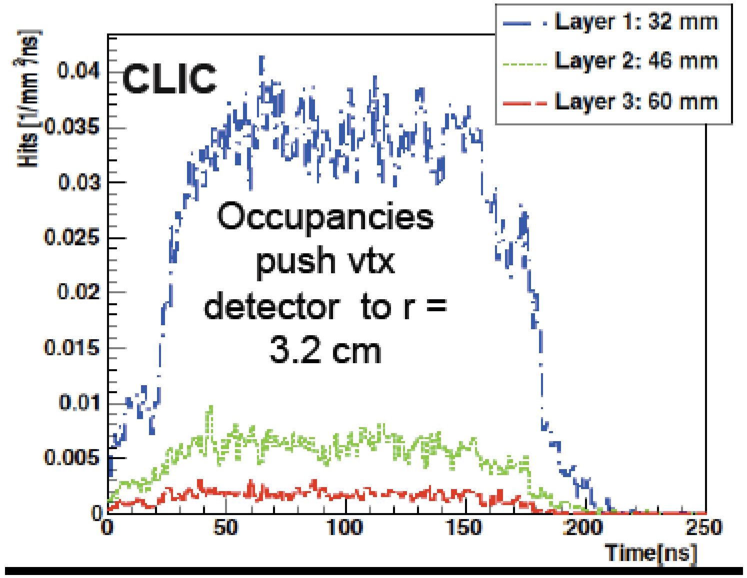
SiD



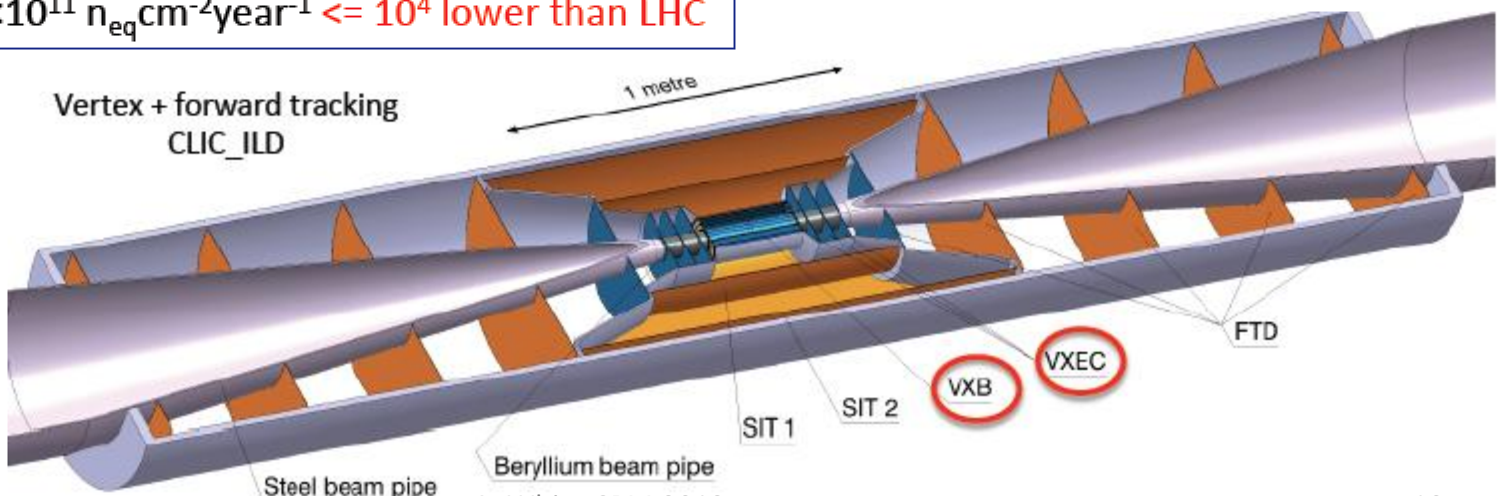


Vertexing – designs - CLIC

CLIC bunch separation 0.5ns !
CLIC beams are 25 nm in both x and y
-> higher level of beamstrahlung (vs. ILC)

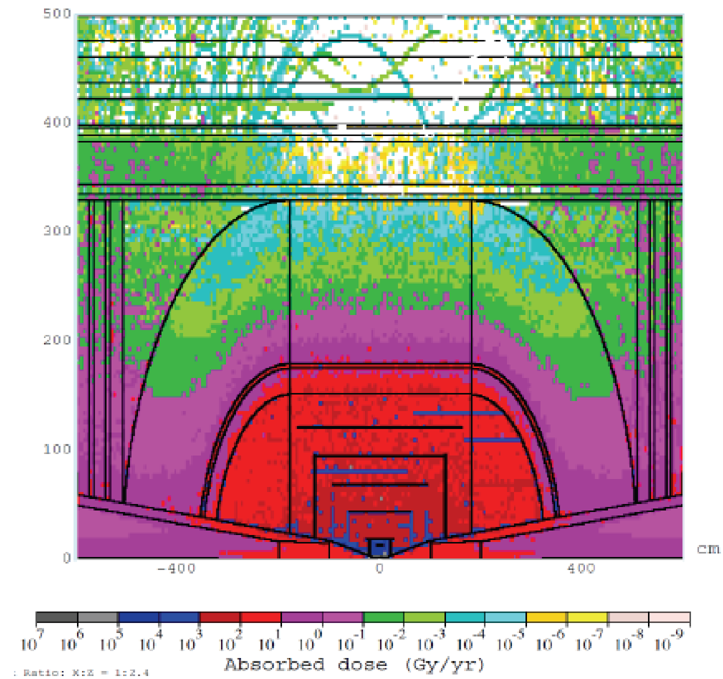


- 20×20 μm pixel size
- 0.2% X_0 material par layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
- Time stamping 10 ns
- Triggerless readout for 156 ns bunch train
- Radiation level $<10^{11}\ n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC



Vertexing – issues for Muon Collider

The muon collider detector environment is challenging:



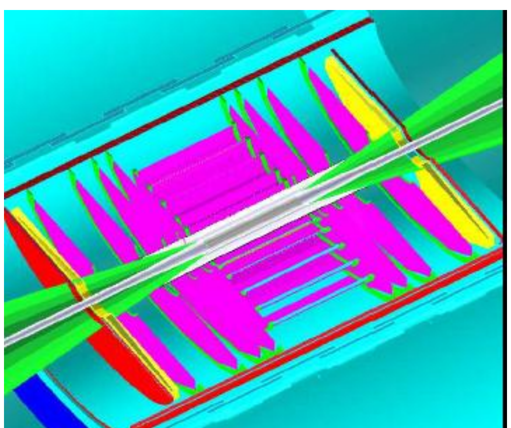
3×10^4 pairs/bunch xing

Beam halo issues

Muon beam decays: 1.3×10^{10}/m/s for two beams of 0.75 TeV

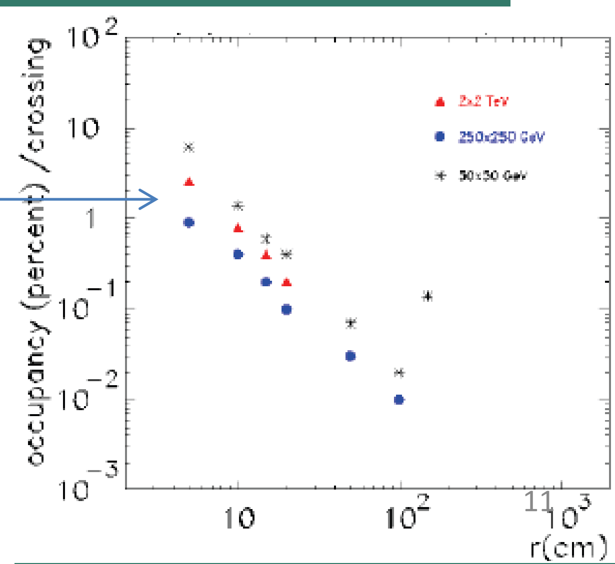
-> high radiation dose – survivability?

-> high vertex detector occupancy



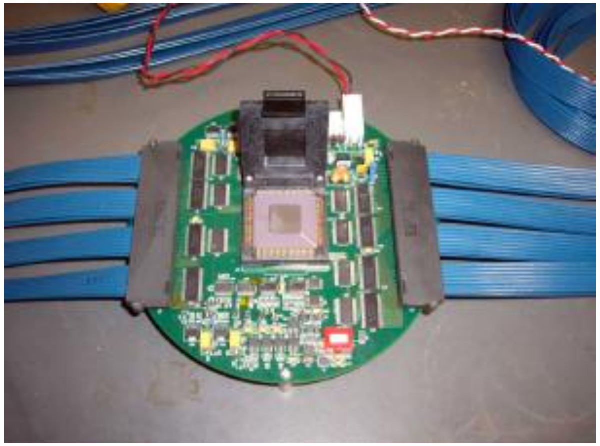
Occupancy drives vertex inner radius to ≥ 5 cm.

Modified SiD design

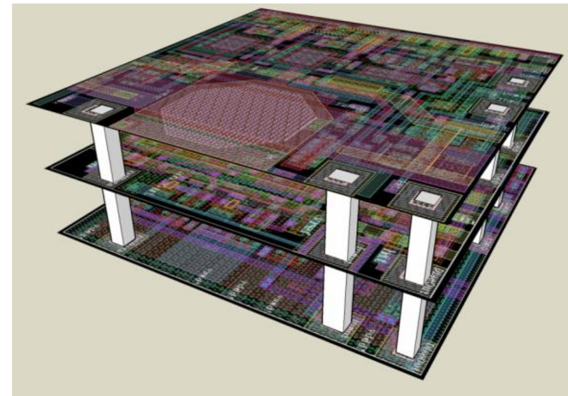


Vertexing - technologies

Examples

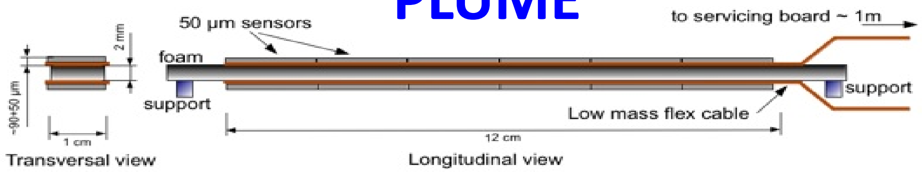


Chronopix
10 x 10 μm²

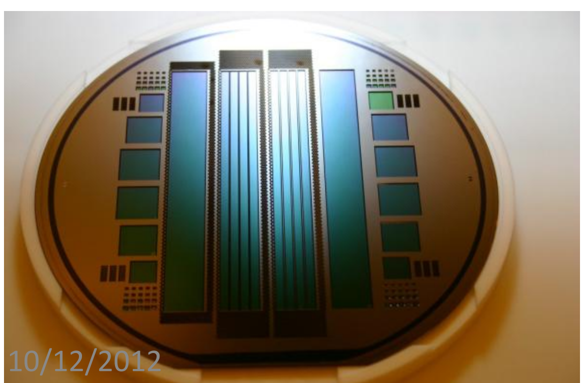


3-D

PLUME



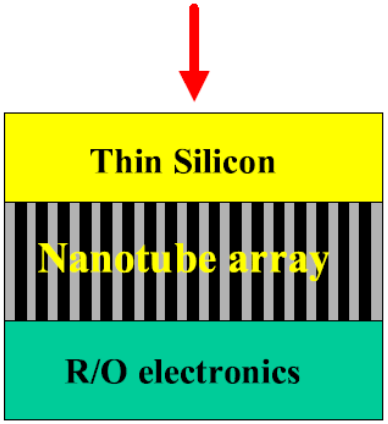
Fully equipped ladder with 50 μm sensors
by 2012 ~ 0.3% X_0

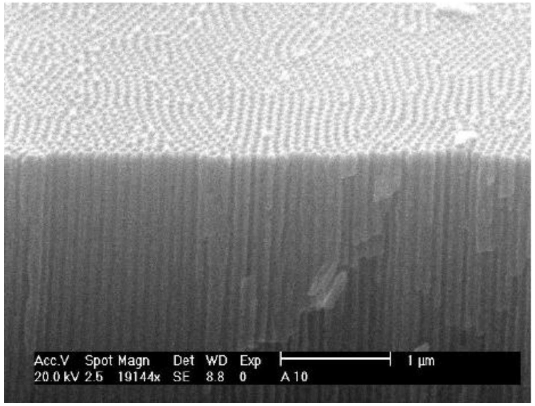


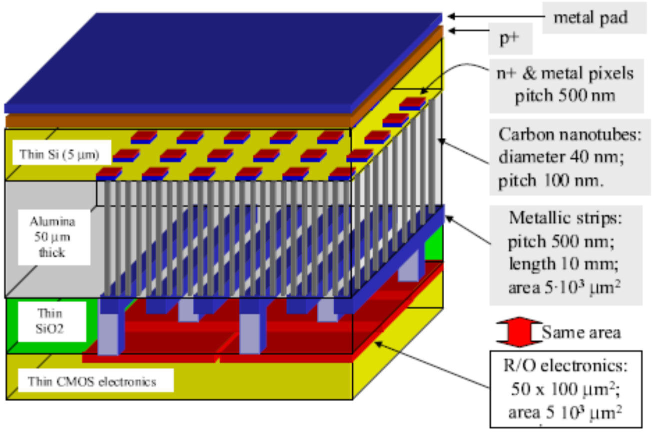
	ILC	*Belle 2*
occupancy	0.13 hits/μm²/s	0.4 hits/μm²/s
Frame time	25-100 μs	10 μs
Duty cycle	1/200	1
	Excellent spatial resolution (3- 5 μm) AND material budget (0.12 % X_0/layer)	Lowest possible material budget (0.15 % X_0/layer) Moderate pixel size (50 x 75 μm²)

Vertexing – challenges - ideas

- Too early to decide on any given technology
- Examples are what can be achieved in short term – assuming successful R&D
- Where will we stand when we come to build a lepton collider detector?
- => Follow electronics/sensor developments, try new ideas
- Can we learn from other areas e.g. nanotechnology:
  Ordered arrays of carbon nanotubes ?



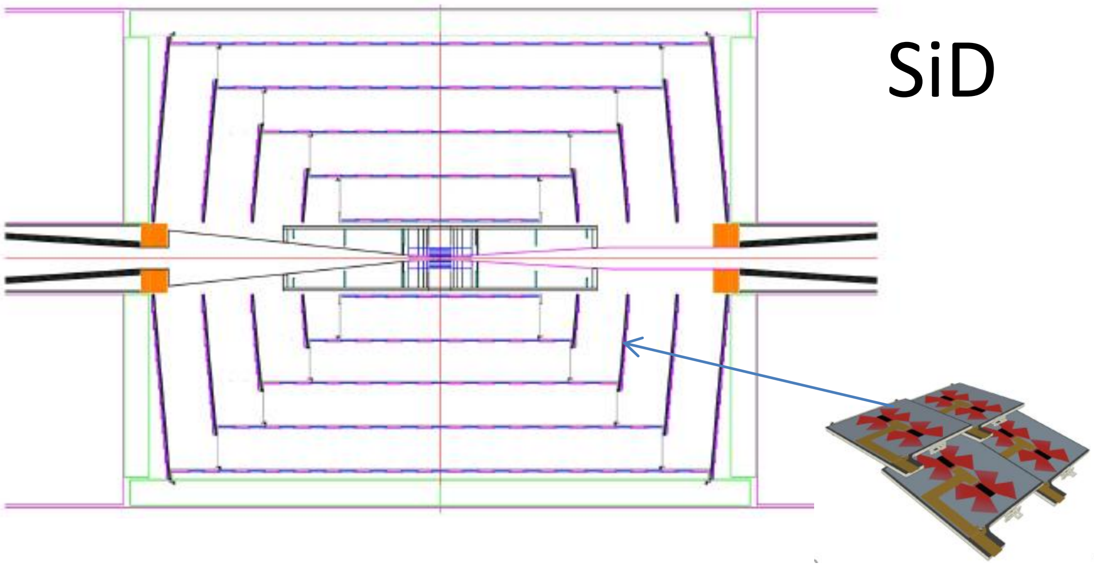




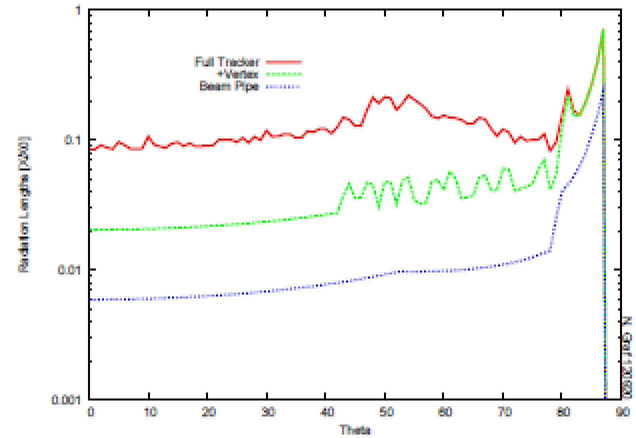
R. Angelucci et al (2002)

Tracking - designs

SiD



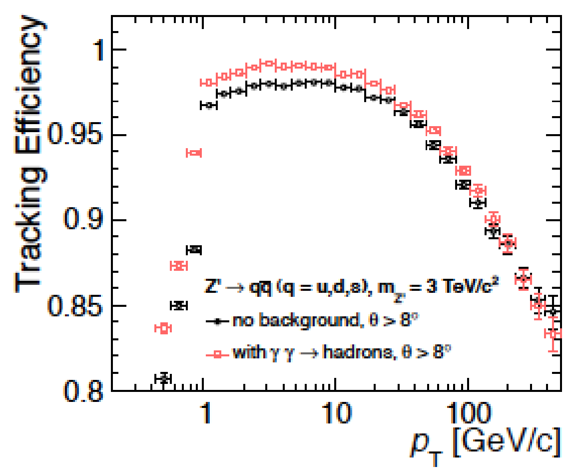
Low material budget

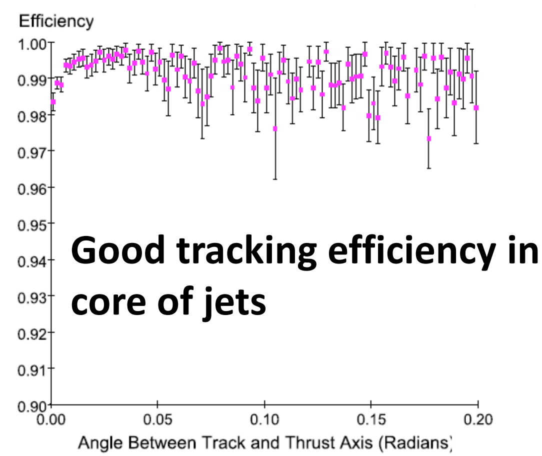


CLIC

SiD

- Optimized tracking algorithms for CLIC_SiD and studies at 3 TeV
  - Silicon tracking performs very well under severe conditions: Z’ → qqbar @ 3 TeV



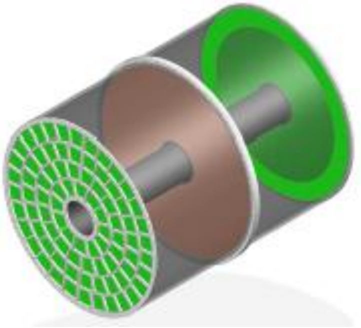


Good tracking efficiency in core of jets

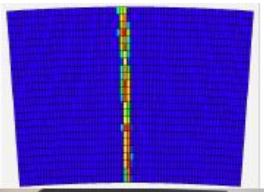
Tracking - designs

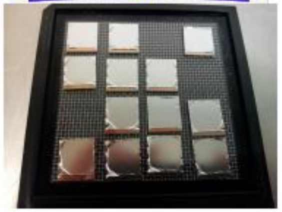
- σ(r, φ) ≤ 100 μm
- σ(z) ≈ 500 μm
- 2 hit resolution
  ≈ 2mm in (r,φ)
  ≈ 6 mm in z
- dE/dx ~ 5%

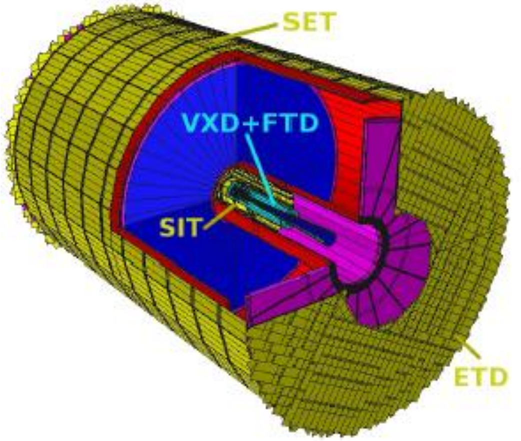
ILD

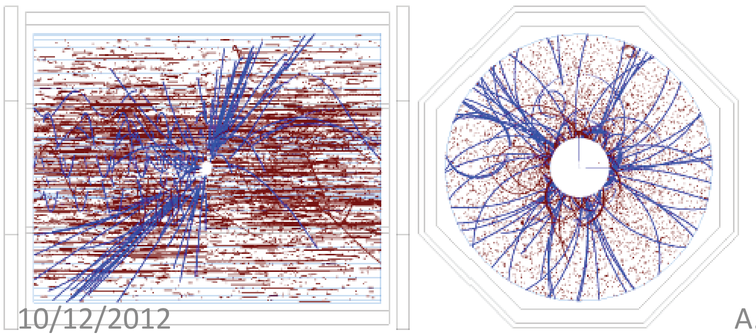


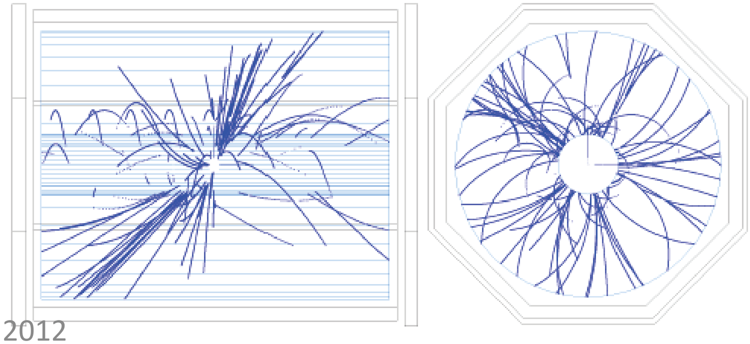
Silicon layers around a TPC





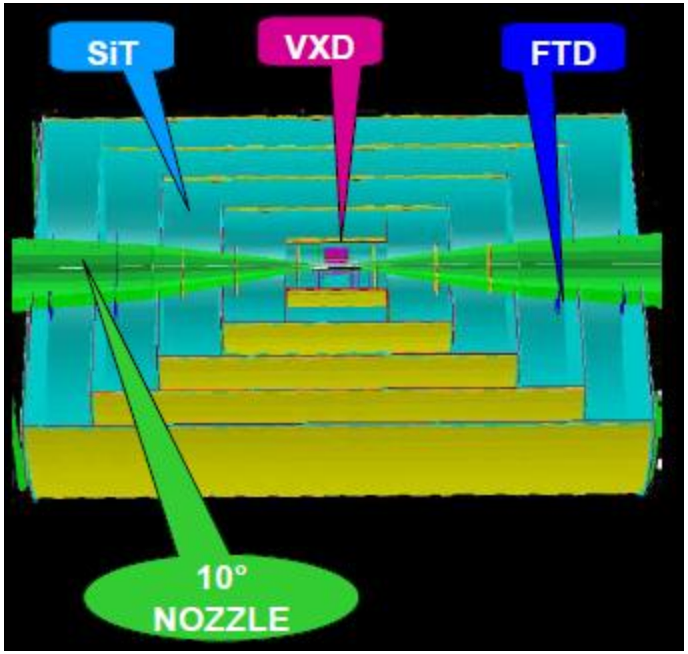






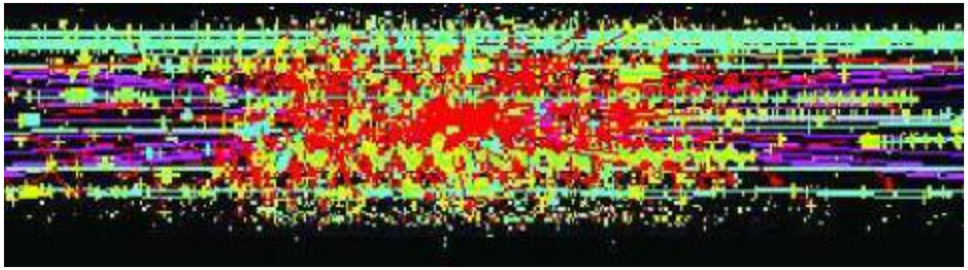
Tracking - challenges

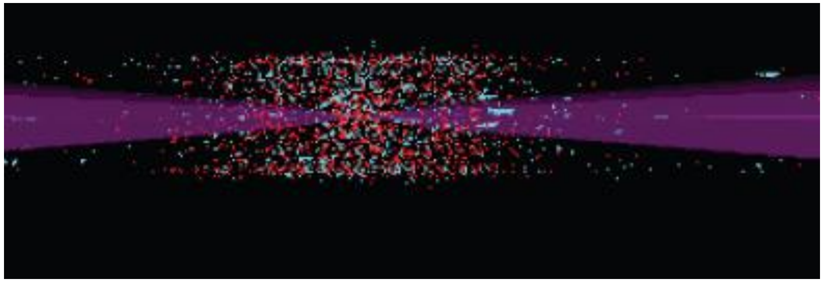
Muon Collider



Backgrounds very large!
-> need radiation hard devices

Use "traveling trigger" idea (as for calorimetry – see later)?





EM hits in time with traveling trigger

ILC Physics and Detector Challenges

TABLE II: Benchmark reactions for the evaluation of ILC detectors

	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge	Notes
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta BR_{bb} = 1\%$	T	{1}
	$ee \to Z^0h^0,\ h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour , jet $(E, \vec{p})$	δM_h=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5%	V	{2}
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times BR_{WW^*})$=5%	C	{3}
	$ee \to Z^0h^0/h^0\nu\bar{\nu},\ h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5%	C	{4}
	$ee \to Z^0h^0/h^0\nu\bar{\nu},\ h^0 \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $M_h = 120$ GeV	T	{5}
	$ee \to Z^0h^0, h^0 \to invisible$	0.35	σ_{qqE}	5σ Evidence for $BR_{invisible}$=2.5%	C	{6}
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$	C	{7}
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C	{8}
	$ee \to Z^0h^0h^0,\ h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C	{9}
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V	{10}
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C	{11}
SUSY	$ee \to \tilde{e}^+_R\tilde{e}^-_R$ (Point 1)	0.5	E_e	$\delta M_{\tilde{\chi}^0_1}$=50 MeV	T	{12}
	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 1)	0.5	E_π, $E_{2\pi}$, $E_{3\pi}$	$\delta(M_{\tilde{\tau}_1} - M_{\tilde{\chi}^0_1})$=200 MeV	T	{13}
	$ee \to \tilde{t}_1\bar{\tilde{t}}_1$ (Point 1)	1.0		$\delta M_{\tilde{t}_1}$=2 GeV		{14}
-CDM	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 3)	0.5		$\delta M_{\tilde{\tau}_1}$=1 GeV, $\delta M_{\tilde{\chi}^0_1}$=500 MeV,	F	{15}
	$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3,\ \chi^+_1\chi^-_1$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\tilde{\chi}_2\tilde{\chi}_3} = 4\%$, $\delta(M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1})$= 500 MeV	C	{16}
	$ee \to \chi^+_1\chi^-_1/\tilde{\chi}^0_i\tilde{\chi}^0_j$ (Point 5)	0.5/1.0	$ZZ\not{E}$, $WW\not{E}$	$\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta(M_{\tilde{\chi}^0_3} - M_{\tilde{\chi}^0_1})$ =2 GeV	C	{17}
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δM_A=1 GeV	C	{18}
-alternative	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6)	0.5	Heavy stable particle	$\delta M_{\tilde{\tau}_1}$	T	{19}
SUSY	$\tilde{\chi}^0_1 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C	{20}
breaking	$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$ (Point 8)	0.5	Soft $\pi^\pm$ above $\gamma\gamma$ bkgd	5σ Evidence for $\Delta\tilde{m}$=0.2-2 GeV	F	{21}
Precision SM	$ee \to t\bar{t} \to 6\ jets$	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V	{22}
	$ee \to f\bar{f}\ (f = e, \mu, \tau; b, c)$	1.0	σ_{ff}, A_{FB}, A_{LR}	5σ Sensitivity to $M_{Z_{LR}} = 7$ TeV	V	{23}
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C	{24}
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T	{25}
Energy/Lumi	$ee \to ee_{fwd}$	0.3/1.0		δM_{top}=50 MeV	T	{26}
Meas.	$ee \to Z^0\gamma$	0.5/1.0			T	{27}

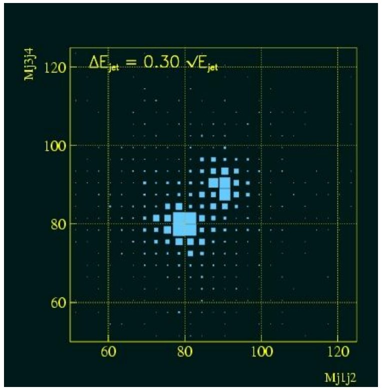
From M. Battaglia etc al. SLAC-PUB-11877

Calorimetry - goal

- Many physics processes for future linear colliders involve jets
- For precision studies, require excellent jet energy and jet-jet mass resolutions.

- The goal is 3% $\Delta E_{jet}/E_{jet}$ (set at $M_{W/Z}$ scale by requirement to separate W and Z bosons):

- Take 3% $\Delta E_{jet}/E_{jet}$ as a general goal for all jet energies



30%/√E

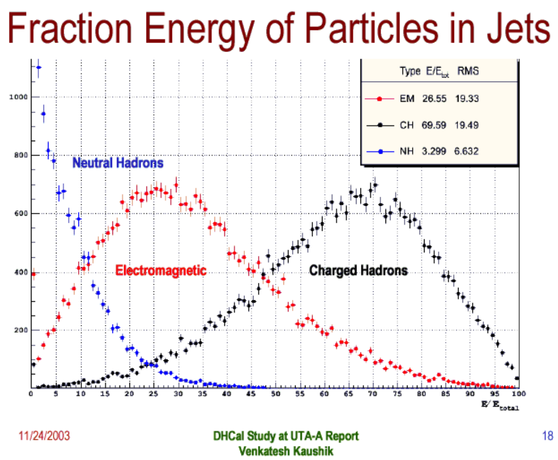
- The issue is then – how to achieve this goal

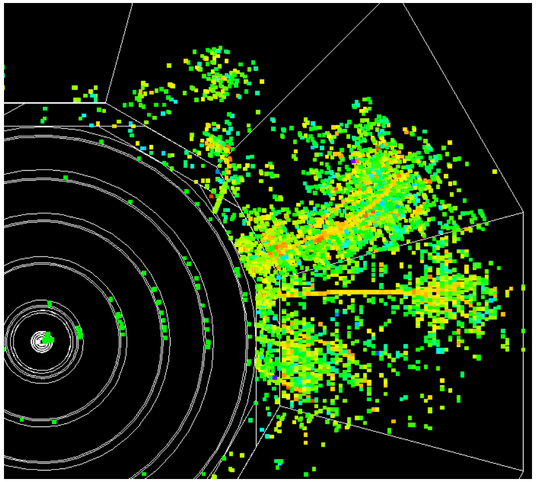
- Two basically different approaches:

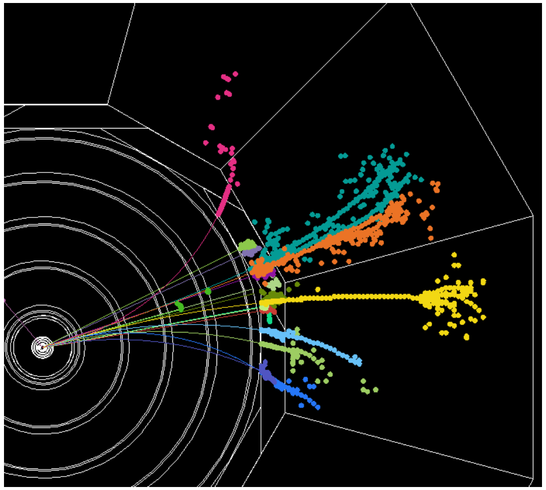
Calorimetry - designs

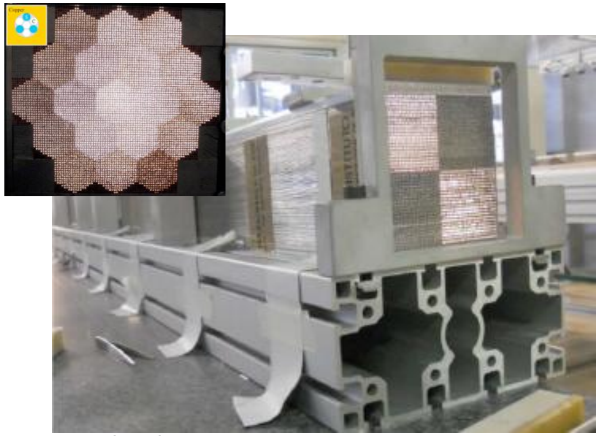
Achieving excellent jet energy resolution:

Particle flow



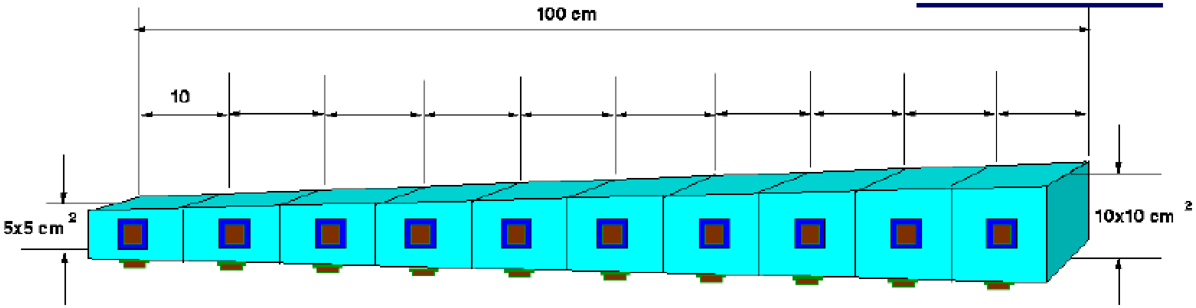






DREAM

Dual readout



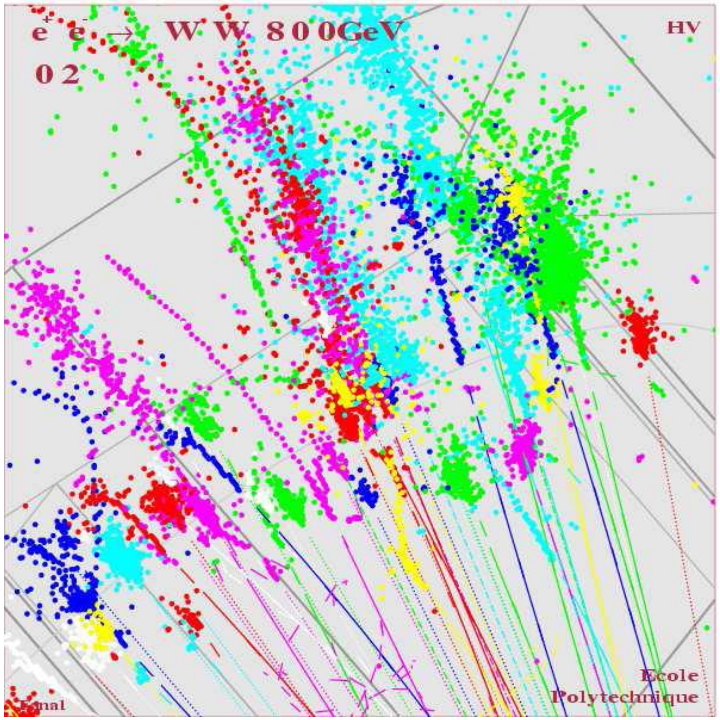
HOMOGENEOUS

Calorimetry - challenges

Implementing a successful PFA system is both a hardware and a software challenge

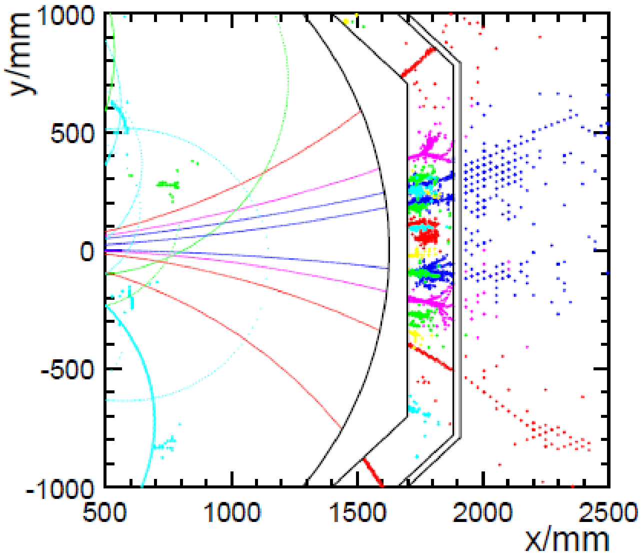
Requires an integrated approach to detector design: tracking ⊕ calorimetry

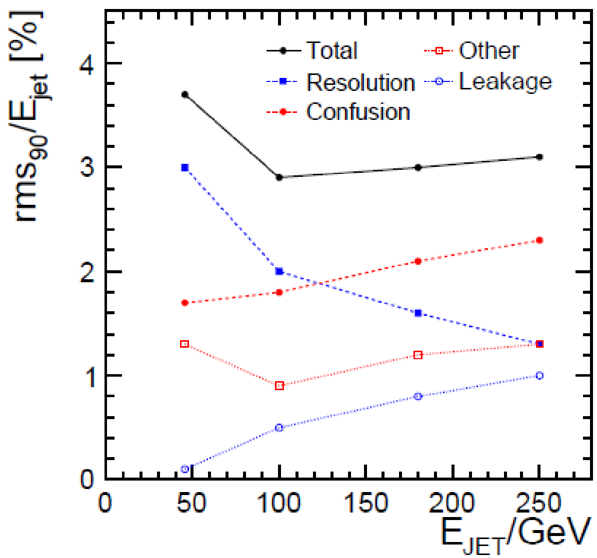
-> Requires "tracking calorimeters" – follow charged particles and associate with energy depositions
-> Requires high degrees of transverse and longitudinal segmentation – reduce "confusion" term especially for high energy jets
-> Requires thin active layers – contain ~40 layers inside magnet and contain cost
-> Requires sufficient depth to restrict losses due to leakage
+ timing for bunch resolution, stability, survivability, calibration, …



Calorimetry – challenge met

PANDORA/PFA   M. Thompson



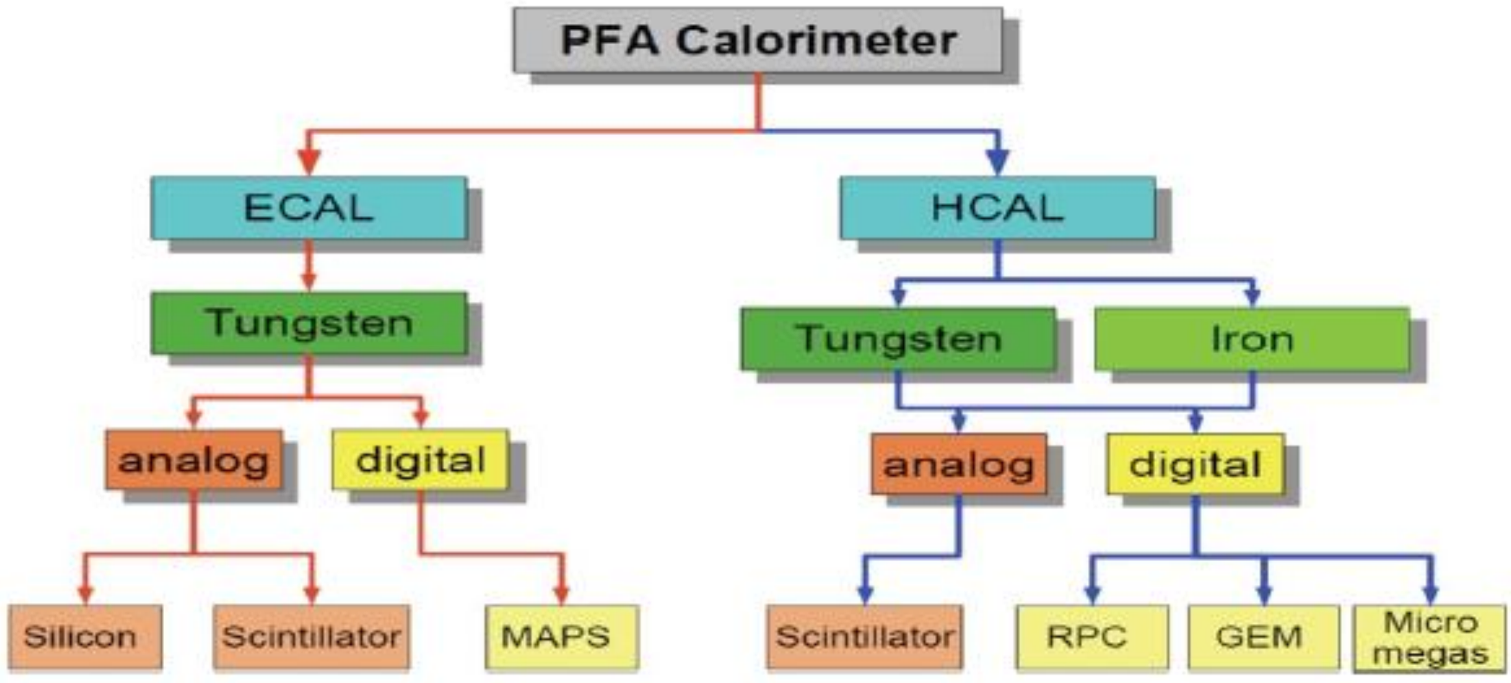


Alternative PFA developed by U. Iowa
- Being used in a SiD DBD process

Jet Energy	rms	$rms_{90}(E_{jj})$	$rms_{90}(E_{jj})/\sqrt{E_{jj}}$	$rms_{90}(E_j)/E_j$
45 GeV	3.4 GeV	2.4 GeV	25.2 %	(3.74 ± 0.05) %
100 GeV	5.8 GeV	4.1 GeV	29.2 %	(2.92 ± 0.04) %
180 GeV	11.6 GeV	7.6 GeV	40.3 %	(3.00 ± 0.04) %
250 GeV	16.4 GeV	11.0 GeV	49.3 %	(3.11 ± 0.05) %
375 GeV	29.1 GeV	19.2 GeV	81.4 %	(3.64 ± 0.05) %
500 GeV	43.3 GeV	28.6 GeV	91.6 %	(4.09 ± 0.07) %

Table 3: Jet energy resolution for $Z \rightarrow uds$ events with $|\cos\theta_{q\bar{q}}| < 0.7$, expressed as: i) the rms of the reconstructed di-jet energy distribution, E_{jj}; ii) rms_{90} for E_{jj}; iii) the effective constant α in $rms_{90}(E_{jj})/E_{jj} = \alpha(E_{jj})/\sqrt{E_{jj}(\mathrm{GeV})}$; and iv) the fractional jet energy resolution for a single jet where $rms_{90}(E_j) = rms_{90}(E_{jj})/\sqrt{2}$.

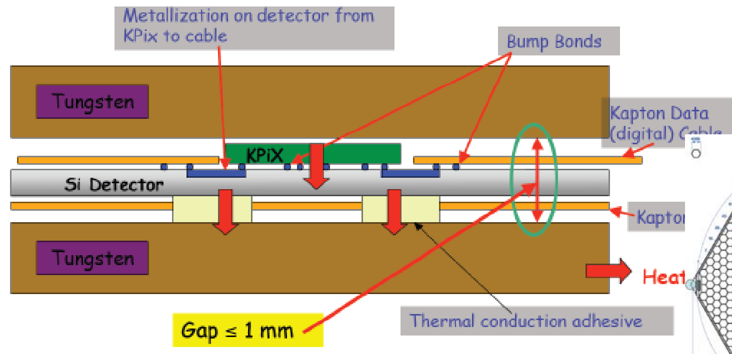
We have risen to the challenge
– no shortage of ways to implement PFA !

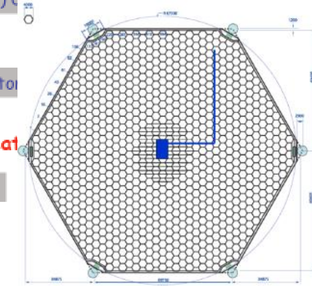


Calorimetry – challenges being met

ECAL

CALICE Si/W ECal

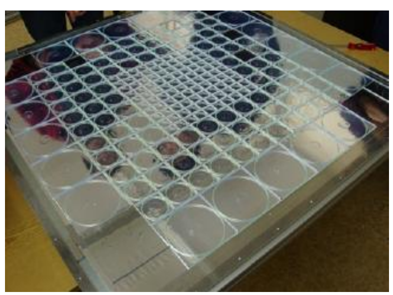




SiD Si/W ECal

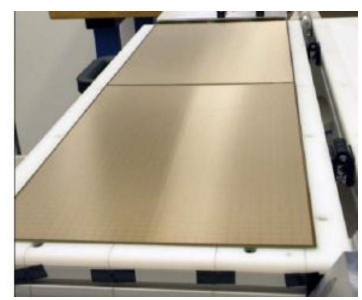
HCAL

Glass RPC

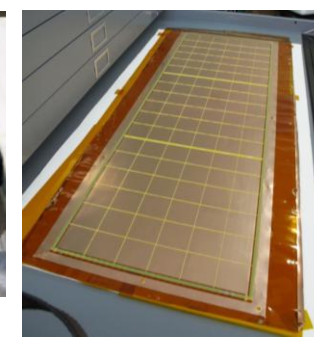


Scintillator AHCAL

SDHCAL

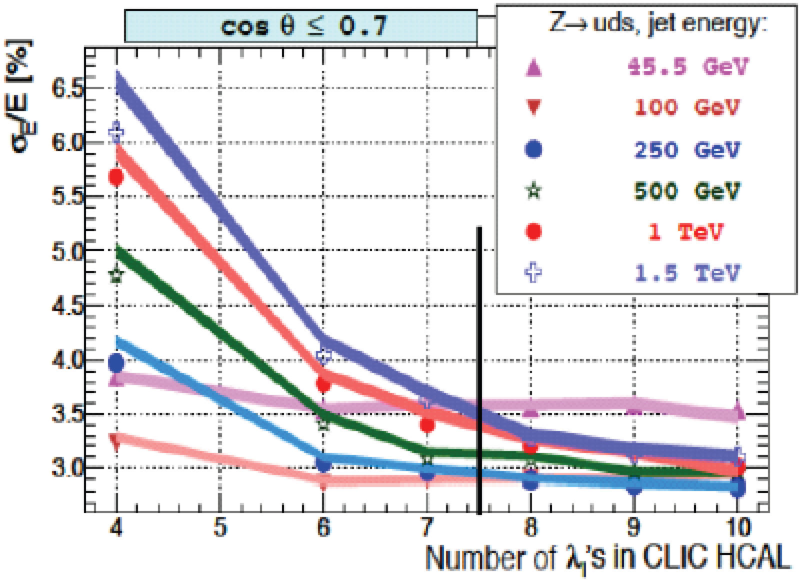


Micromegas DHCAL

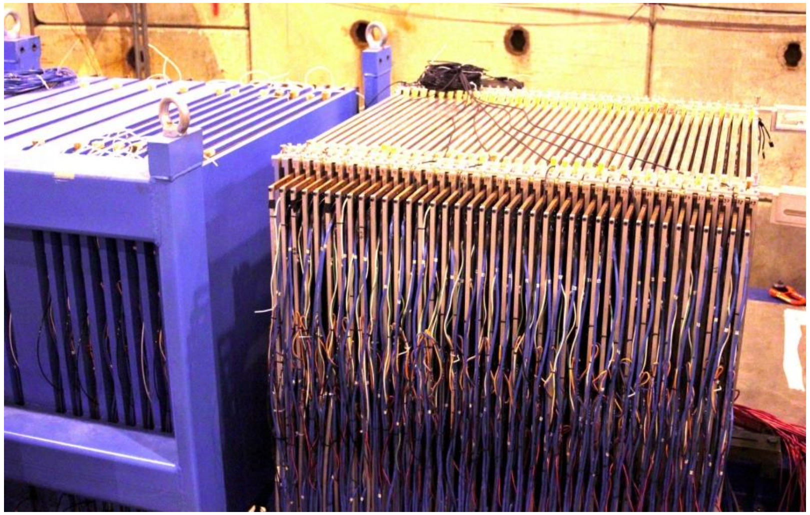


GEM DHCAL

Calorimetry – challenges being met



CLIC

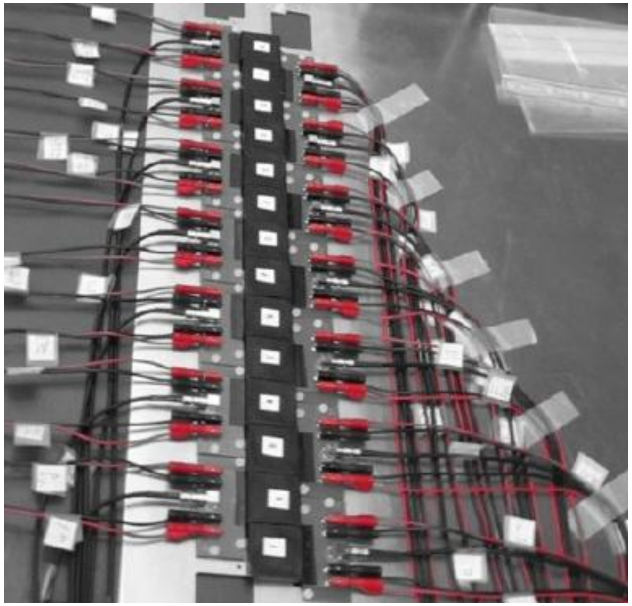


CERN test beam – RPC/Tungsten plates

Jet Energy	$\mathrm{rms}_{90}(E_{jj})/\sqrt{E_{jj}}$		$\mathrm{rms}_{90}(E_j)/E_j$	
	3.5 T & 6 λ_I	4 T & 8 λ_I	3.5 T & 6 λ_I	4 T & 8 λ_I
45 GeV	25.2 %	25.2 %	(3.74 ± 0.05) %	(3.74 ± 0.05) %
100 GeV	29.2 %	28.7 %	(2.92 ± 0.04) %	(2.87 ± 0.04) %
180 GeV	40.3 %	37.5 %	(3.00 ± 0.04) %	(2.80 ± 0.04) %
250 GeV	49.3 %	44.7 %	(3.11 ± 0.05) %	(2.83 ± 0.05) %
375 GeV	81.4 %	71.7 %	(3.64 ± 0.05) %	(3.21 ± 0.05) %
500 GeV	91.6 %	78.0 %	(4.09 ± 0.07) %	(3.49 ± 0.07) %

Calorimetry – challenges being met

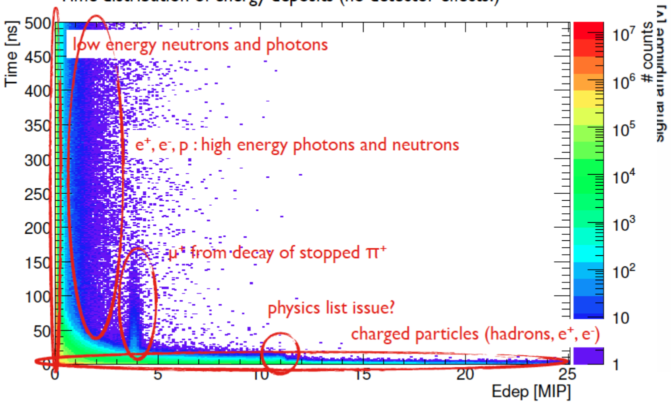
Frank Simon – TIPP2011

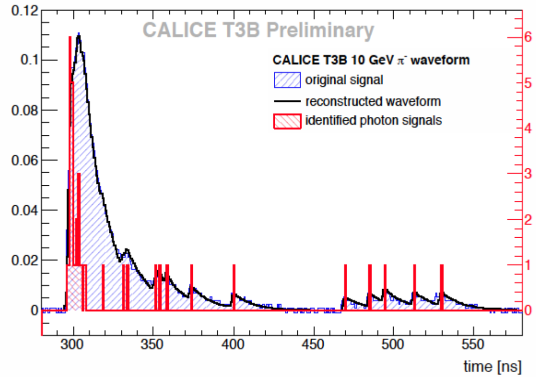


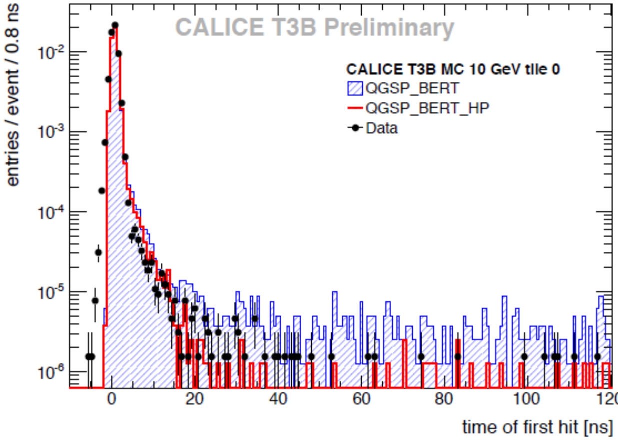
- $\gamma\gamma \rightarrow$ hadrons substantial:
  ~ 12 hadrons/bunch crossing in the barrel region (4 GeV / bunch crossing) [up to 50 hadrons / 50 - 60 GeV barrel + endcap + plug calorimeters]
- extreme bunch crossing rate: every 0.5 ns

⇨ Very good time resolution in all detectors important to limit impact of background!

- Geant4 simulation of a 30 layer Scintillator-W calorimeter (QGSP_BERT)
  - Time distribution of energy deposits (no detector effects!)







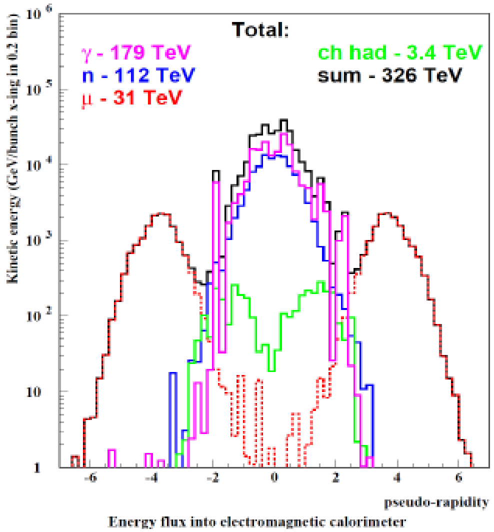
Calorimetry - challenges

Muon Collider

~100 TeV in HCAL for each bunch crossing !

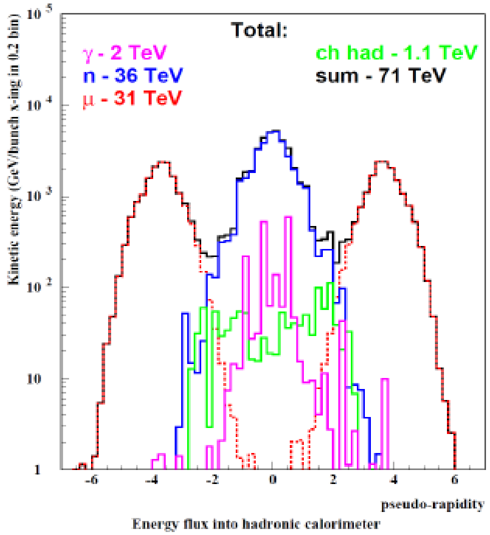
MARS Particles in Detector Volume		
Particle Type	Total Number	Total Kinetic Energy (TeV)
EM	1.785E8	169.9
MUONS	8021.	184.4
MESONS	17589.	6.8
BARYONS	0.409E8	177.4

Energy Flow into Ecal



Peak: ~1 GeV / 2x2 cm^2 cell with $\sigma_E \sim 30$ MeV

Energy Flow into Hcal



Peak: ~1.5 GeV / 5x5 cm^2 cell with $\sigma_E \sim 80$ MeV

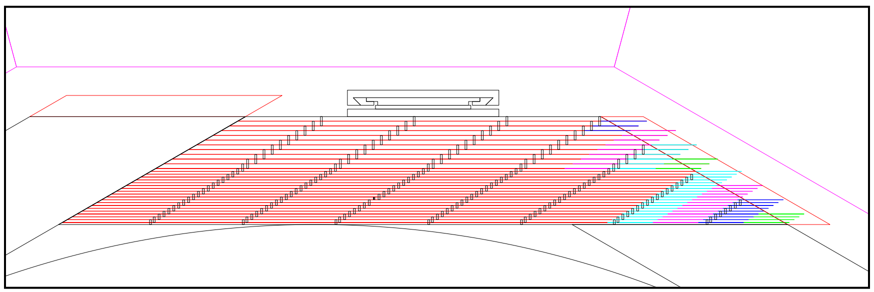
"Traveling gate trigger" idea (R. Raja) with pixel (200μm) calorimeter

- Trigger for every crossing – timing "travels out" at v = c through calorimeter and gates each pixel
- Separate EM/Hadronic energy depositions via pattern recognition + use "compensation".

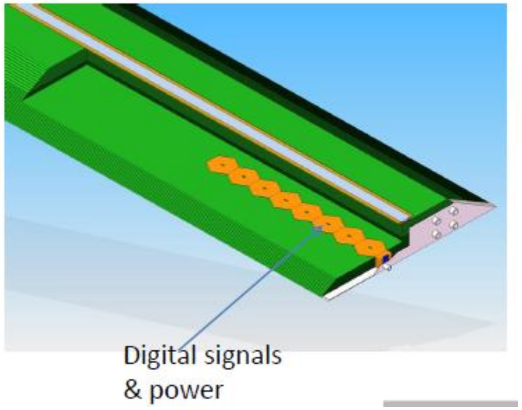
Particle Type	Total Number	$\delta_t < 2$ns	Surviving fraction
EM	1.79E+08	2.17E+06	1.21E-02
MUONS	8.02E+03	1.83E+03	2.28E-01
MESONS	1.76E+04	2.66E+03	1.51E-01
BARYONS	4.09E+07	3.93E+05	9.62E-03

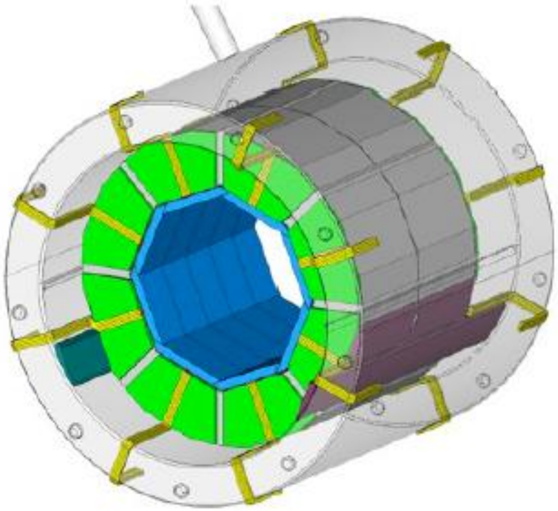
Calorimetry – current challenges

- Design of a fully realizable calorimeter module with full services as part of a complete calorimeter system design.

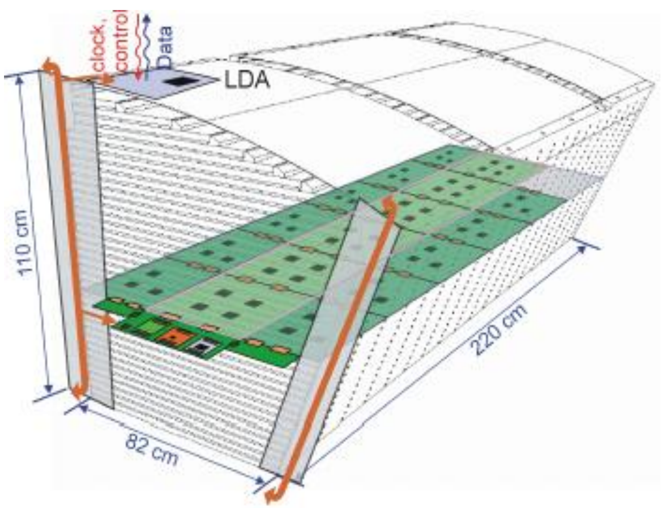


SiD
ECAL





ILD AHCAL



Calorimetry – next challenges

Many other areas that are being addressed for ILC/CLIC and need to be addressed for other colliders:

e.g. Power pulsing, Cooling,…

Also room for other ideas:

e.g. could be move some PFA functions into hardware? Local track/cluster associations, using double-layer vectors?

For Dual readout – fiber or homogeneous – need a specific design for a lepton collider detector – then show its physics performance.

The story continues

New physics may well present new detector challenges!
Remain open to new technologies
Be prepared to adapt designs
Follow new materials development
Use new techniques (3D printing?)

A large body of generic and concept specific R&D has been carried out
- essential to keep up the developments
- new CPAD in U.S. to promote instrumentation
- ECFA detector panel in Europe…

Detector R&D is the essential enabler of experiments!