Calorimeter Issues and Possible Directions for R&D

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R&D Opportunities for the LC: WS at FNAL on April 5, 2002

Outline of talk

Requirements on calorimeter

EM calorimeter

Had calorimeter

Simulations

Conclustions

This talk assumes we have a few years time for R&D

Basic Requirements on Calorimeter (I)

Hermeticity: Barrel and Endcaps

Speed of readout:

σ_{tot}(500 GeV) = 4pb

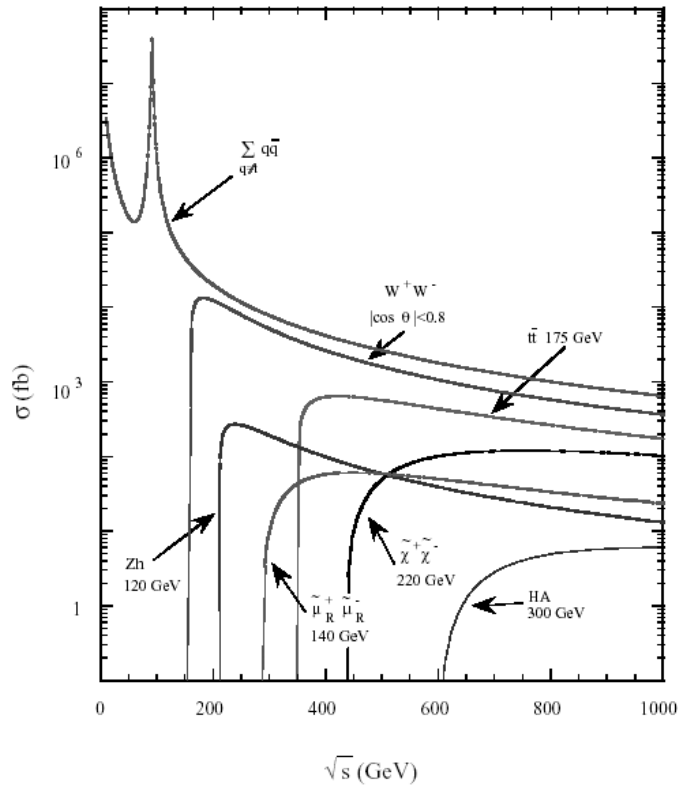
$\mathcal{L}_{NLC/TESLA}$= 0.5 10^{34}cm^{-2}s^{-1}

$\longrightarrow$ 1 event / 50 sec

Not a concern!

Unless: Surprises
Running at Z pole

Cross section versus $\sqrt{s}$



Basic Requirements on Calorimeter (II)

(Jet) Energy Resolution: Many 'interesting' final states involve 2-10 jets

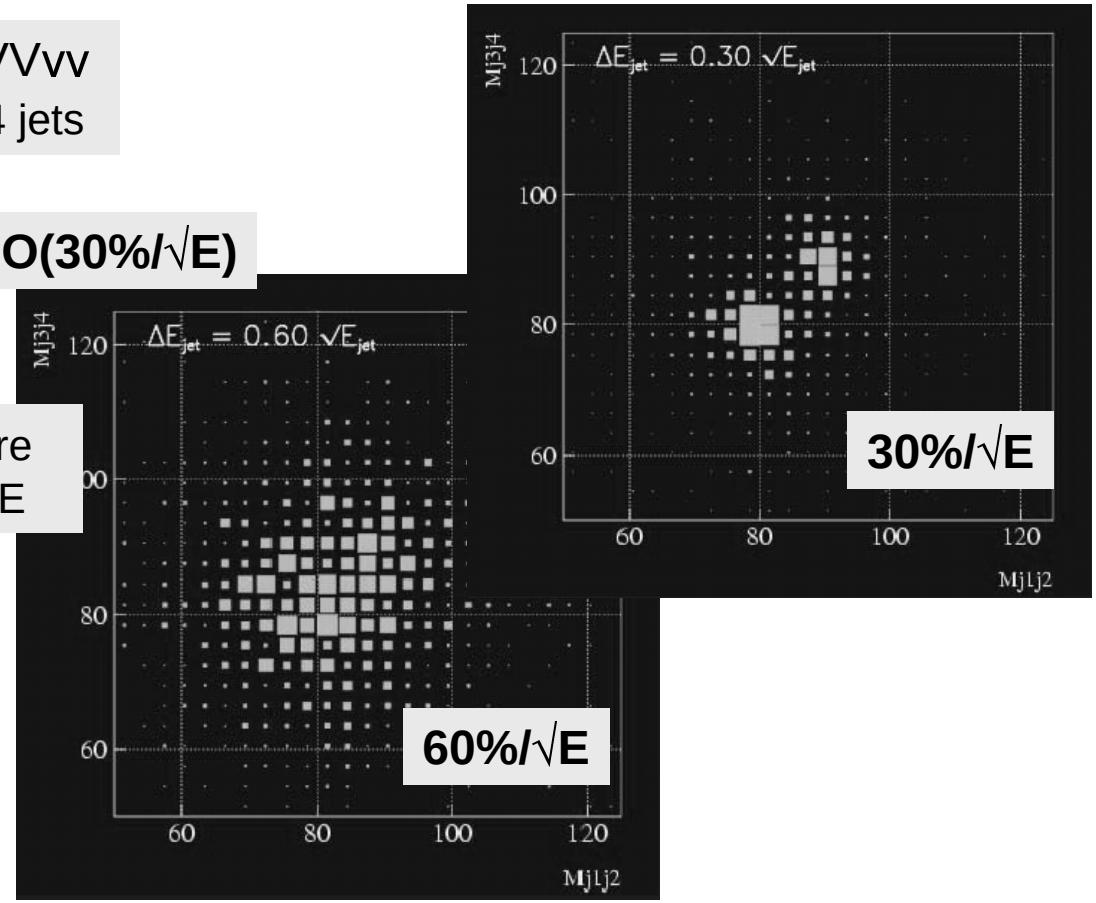
Benchmark process: $e^+e^- \rightarrow VVvv$
Separation of WW and ZZ $\longrightarrow$ 4 jets

Requires excellent resolution: O(30%/√E)

→ Has never been achieved before
→ Best so far: ZEUS with ~50%/√E

New Approach

From H.Videau



Basic Requirements on Calorimeter (IIa)

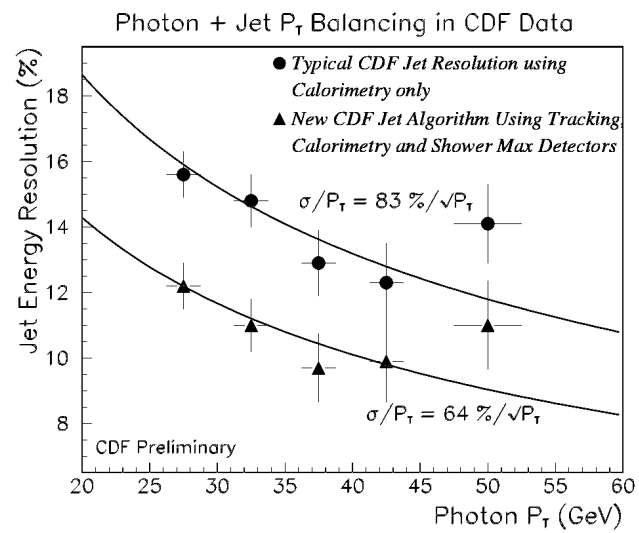
Energy Flow Algorithm EFA

Components of Jets	Fraction of Energy in %	Detector
Charged particles	60	Tracker
Photons	20	EM calorimeter
Neutral Hadrons (K^0_L,n)	10	EM and HAD calorimeter
Neutrinos	10	Lost

Requirements on Detector:

Tracker: large volume, high B-field (~4T)
E-Cal : resolution of O(10%/√E), fine segmentation
H-Cal : fine segmentation, compensation?

→ **Thick coil: calorimeter inside!**

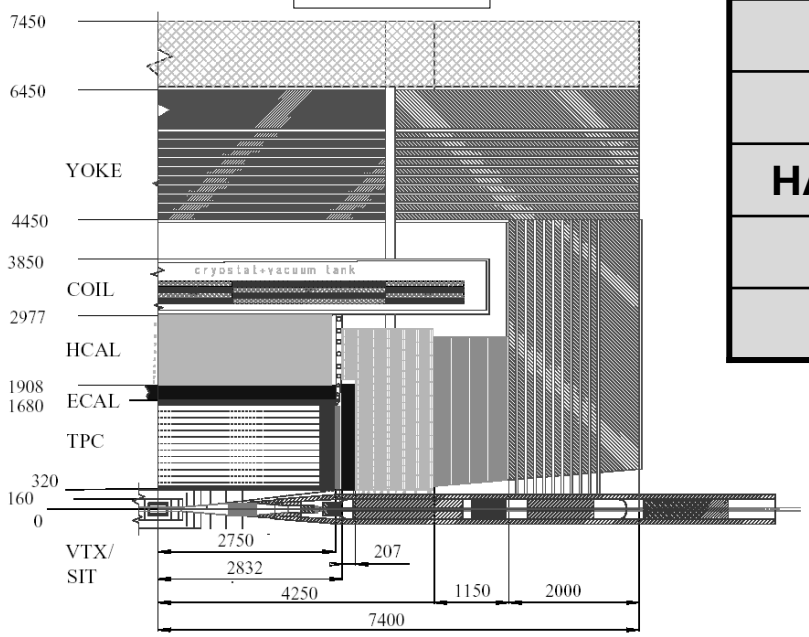


Basic Requirements on Calorimeter (III)

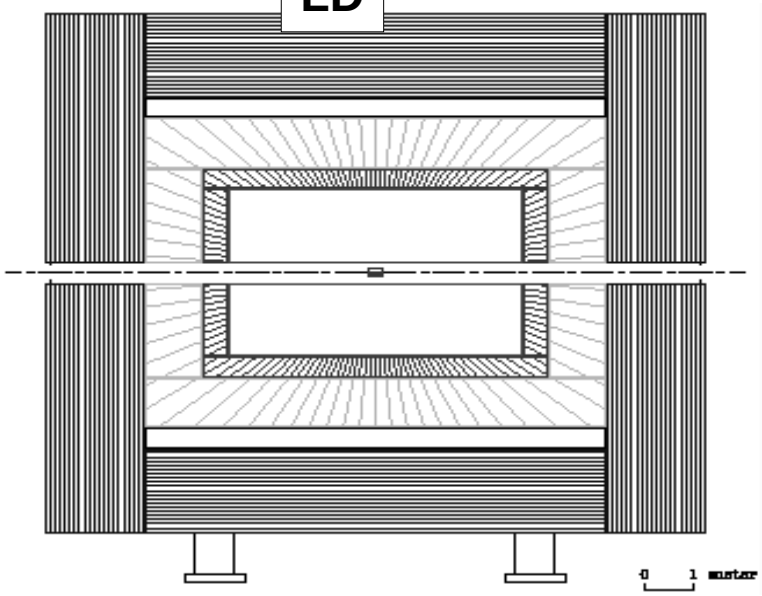
Space: current designs of LC detectors

		TESLA	SD	LD
EM	R_I	1.68	1.27	2.00
	R_O	1.90	1.43	2.50
	Δ_{EM}	0.22	0.16	0.50
HAD	R_I	1.90	1.43	2.50
	R_O	3.00	2.48	3.70
	Δ_{HAD}	1.10	1.05	1.20

TESLA



LD



Basic Requirements on Calorimeter (IV)

Cost: Not a constant with time
e.g. Price for silicon dropped significantly in past years

Affordable

EM Calorimeter (I)

Review of possible technologies

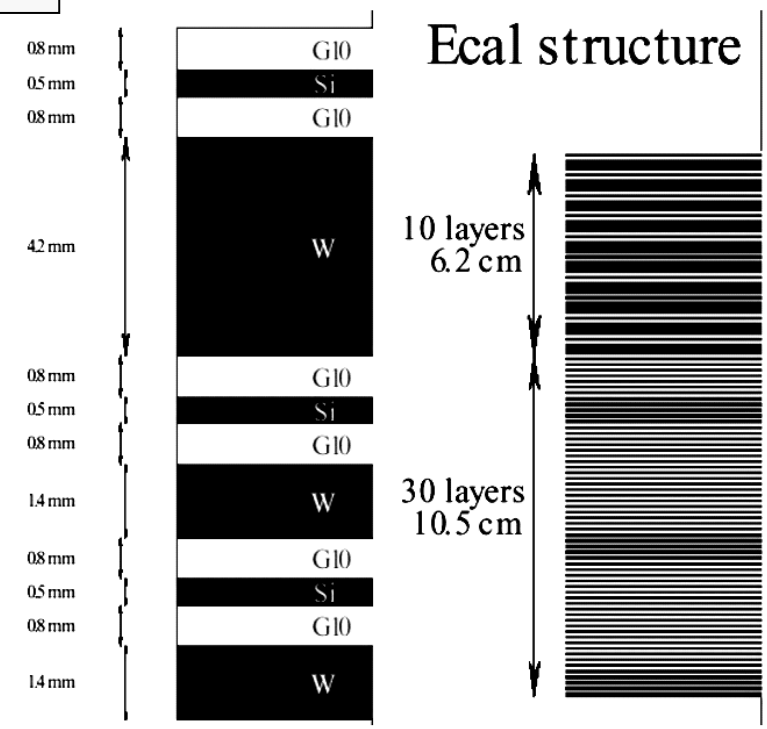
Requirements: **excellent EM Energy resolution**
fine segmentation (both laterally and longitudinally)
small Molière Radius: R_M

Silicon – Tungsten Sandwich Calorimeter

Preferred choice of

	TESLA	NLC (SD)
# of layers	40	30
Thickness of W	1.4 →4.2 mm 0.4 →1.2 X_0	2.5 mm 0.7 X_0
Thickness of EM Calorimeter	24 X_0	21 X_0
Area of silicon (barrel and endcaps)	3300 m^2	1200 m^2
Lateral segmentation	10x10 mm^2	5x5 mm^2
# of channels	$33x10^6$	$50x10^6$

TESLA TDR



EM Calorimeter (II)

Energy resolutions: EM ~ 10%/√E
(HAD: non-compensating)

Lateral density: $R_M(W) = 9$ mm
Including gap of 2.5 mm: $R_M(EM) = R_{M(W}(1+t_{gap}.t_W) \sim 18$ mm

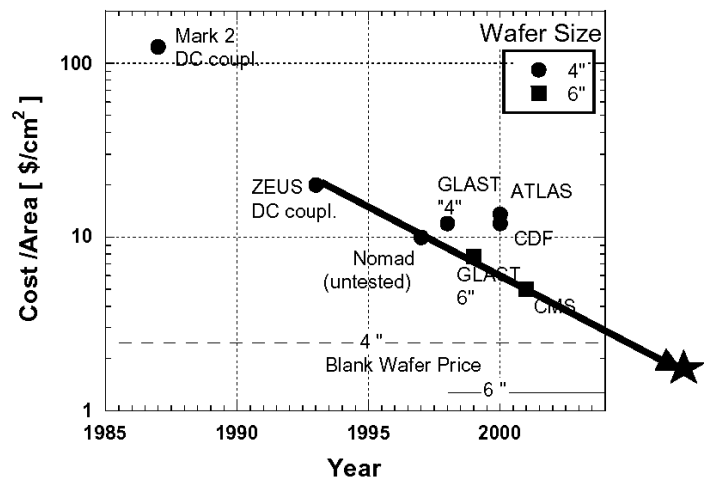
→ **Good for EFA**

Issues with Silicon/Tungsten

Cost: **Driven by Silicon wafer (~70% of cost)**
Assume $4/cm^2 → $132M (TESLA)

Gap size: **Minimize to preserve small R_M**
Possibly 2.5 mm → 1.5 mm?

Cost /Area of Single-sided Silicon Strip Detectors
(double-sided factor 2.5 higher)

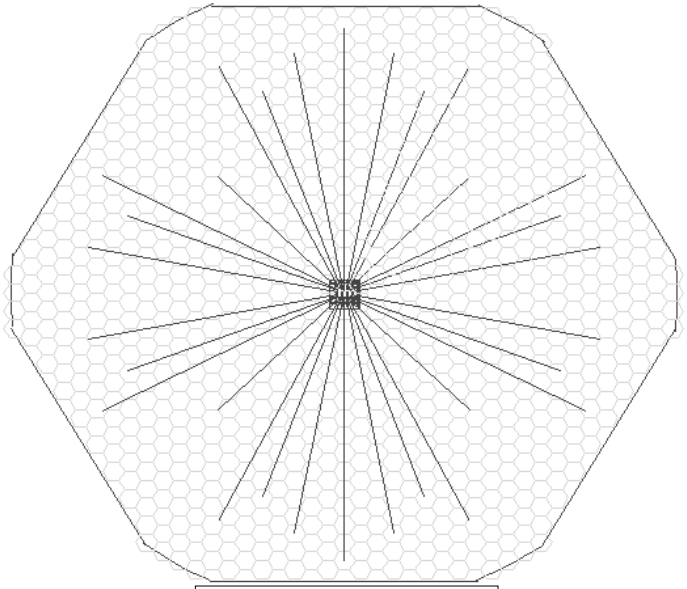


Plot by H F W Sadrozinski (Guestimates by HFWS)

EM Calorimeter (III)

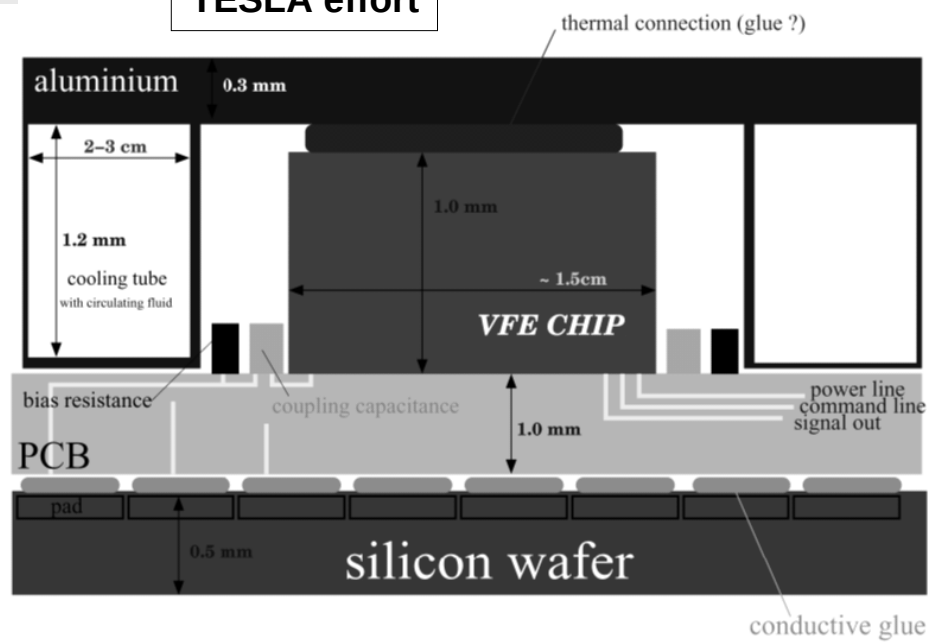
Development of readout electronics:

Full integration of readout on Silicon wafer



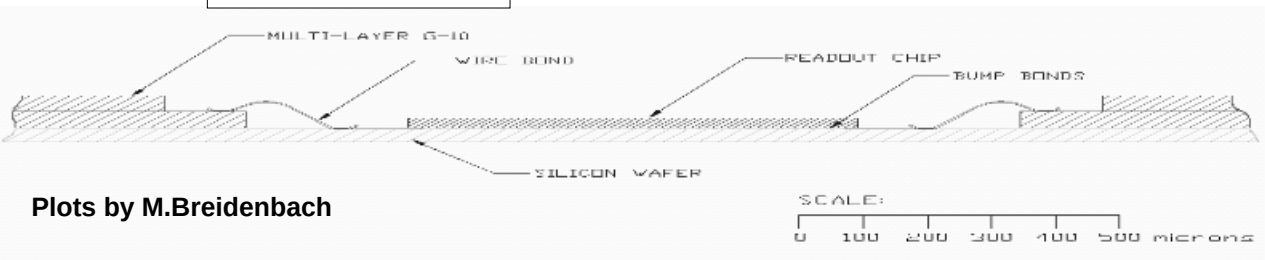
6'' Wafer
1027 (5 mm) cells

TESLA effort



ECAL – detector slab – active layer
transverse view

Note:
$t_{total} \geq 3$ mm



Plots by M.Breidenbach

EM Calorimeter (IV)

Shashlik Calorimeter

Second choice of TESLA TDR

Pb (1mm) with scintillator (1mm)

140 layers corresponding to 25 X_0

Beam tests: $\sigma_{EM}/E = 14.2\%/\sqrt{E} + 0.6\%$

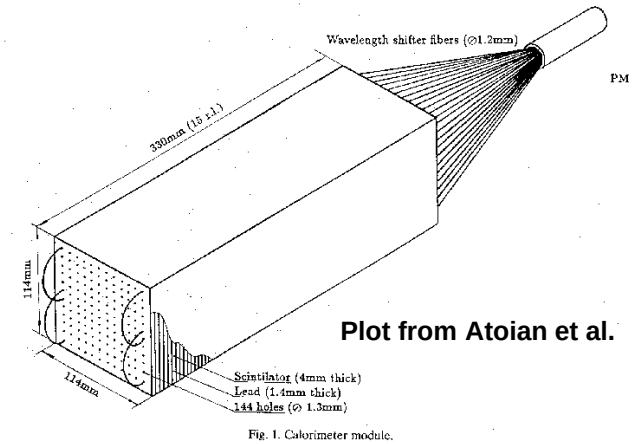
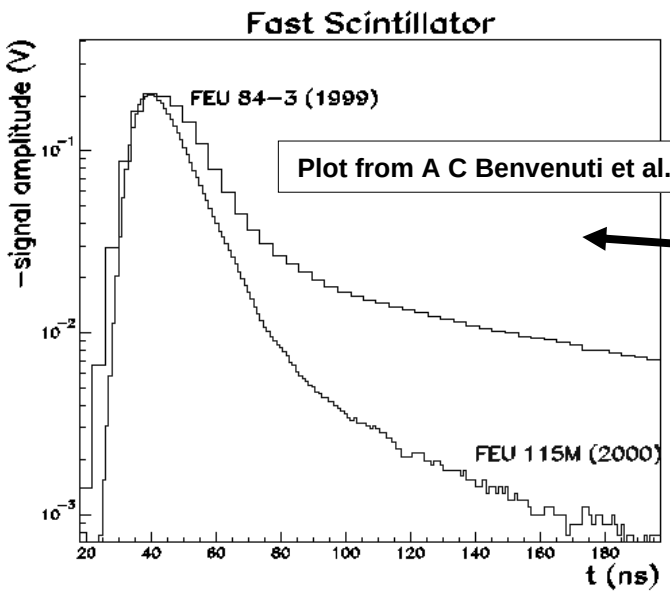


Fig. 1. Calorimeter module.

Plot from Atoian et al.



Plot from A C Benvenuti et al.

Transverse segmentation: 3x3 cm^2
use of larger scintillator pads with groves

Longitudinal segmentation: 3 ideas
Silicon pad detectors inserted at various depths
Insertion of photodiodes at various depths
Use of scintillator with different decay times

} **Max of 2-3**

Issues with Shashlik calorimeter

Lateral segmentation : enough for EFA?
Longitudinal segmentation: enough for EFA?
Cost estimate : $14M

EM Calorimeter (V)

Lead-Scintillator Sandwich Calorimeter

LD design in US, similar efforts in Europe and Japan

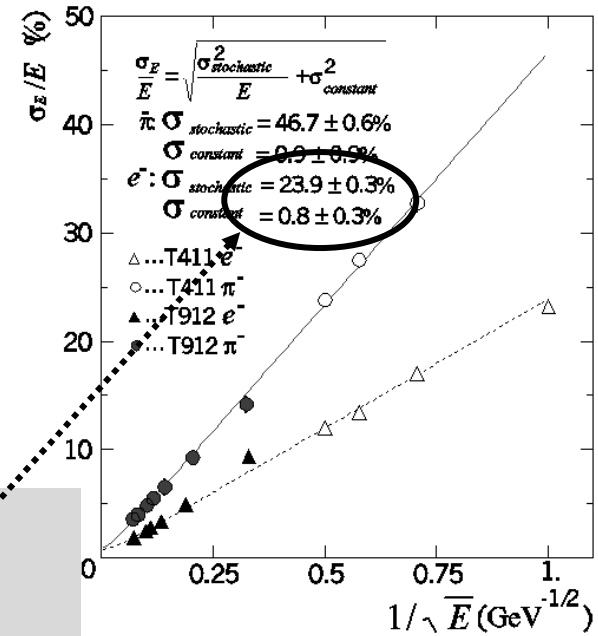
4 mm Pb with 1 mm Scintillator

40 Layers corresponding to 29 X_0

Molière Radius: R_M = 20 mm

Tiles : 50x50 mm^2

JLC Test Beam Results



Issues with Pb-scintillator

Longitudinal segmentation: None?
Good enough for EFA?
Shower maximum detectors?

Lateral segmentation : good enough for EFA?

Em resolution : good enough for EFA?
compromise other physics, e.g. $H^0 \rightarrow \gamma\gamma$

Magnetic field : readout?

EM Calorimeter (VI)

Crystal Calorimeter

Advantages: best achievable EM resolution
some crystals with short X_0, R_M
some crystals affordable

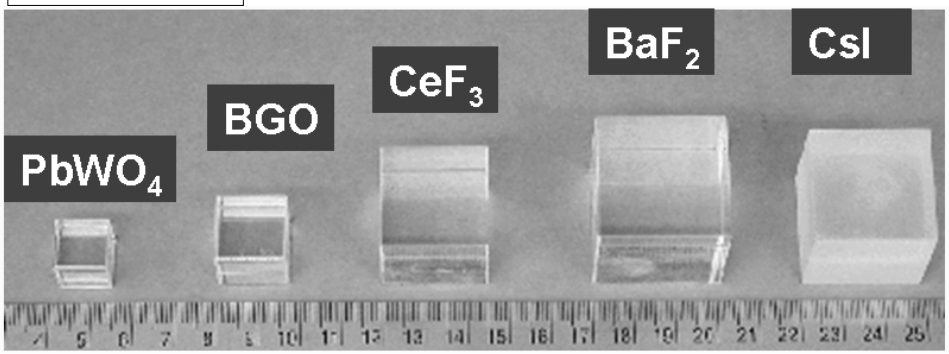
Table from R Y Zhu

	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (°C)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	0.9	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.3	2.0	2.3	2.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	18	21	22
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	2.2	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	560	420 310	300 220	480	560 420	420	440
Decay Time [b] (ns)	230	1300	35 6	630 0.9	300	50 10	40	60
Light Yield [b,c] (%)	100	45	5.6 2.3	21 2.7	9	0.1 0.6	75	30
d(LY)/dT [b] (%/ °C)	~0	0.3	-0.6	-2 ~0	-1.6	-1.9	?	?
Volume Price ($/cm^3)	1 to 2	2	2.5	2.5	7	2.5	-	-

a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.

EM Calorimeter (VII)

Plot by R Y Zhu



1.5 X_0 Cubic

Recent developments: increased light output for $PbWO_4$, PbF_2, LSO(Ce), GSO(Ce)

Issues with Crystals

Segmentation: **lateral** } compromising EFA
longitudinal
Magnetic field: **readout**
Space : **25 X_0 in say 20cm**

EM Calorimeter (VIII)

General issues for ECAL

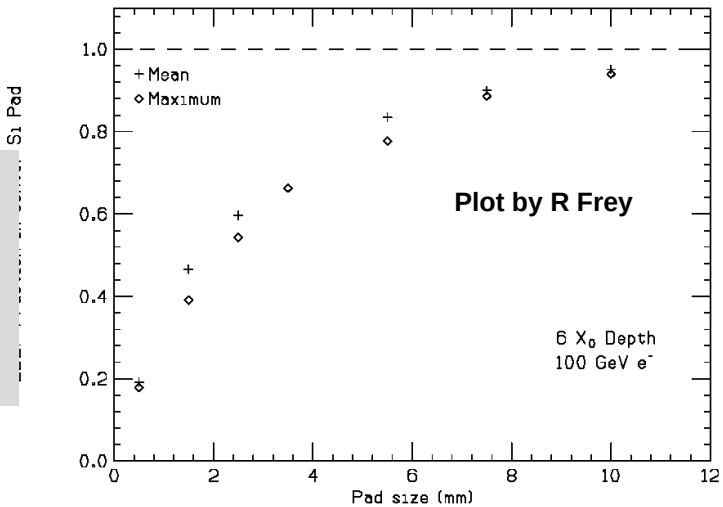
Dynamic range: Assume 1 cm^2 pads

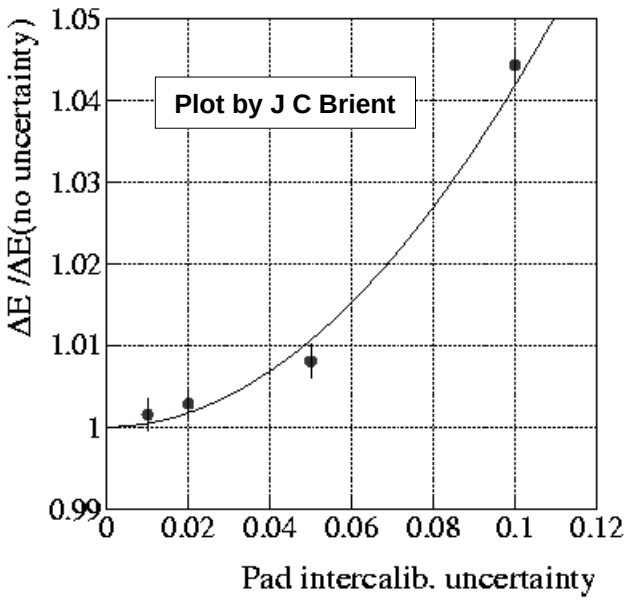
250 GeV e^+ → 340 MeV (at shower max)

MIP → 0.16 MeV

2.1×10^3 ~ 12 bits

significant reduction in pad size needed to reduce dynamic range





Calibration: absolute

intercalibration: important!

Timing information: what is needed?

HAD Calorimeter (I)

Review of possible technologies

Consensus: **sandwich calorimeter**

Requirements: **depth: $\geq 4\lambda_I$ at 90^0**
$\Delta R \leq 1.2$ m
fine segmentation
compensation?

Ratio of λ_I/X_0:

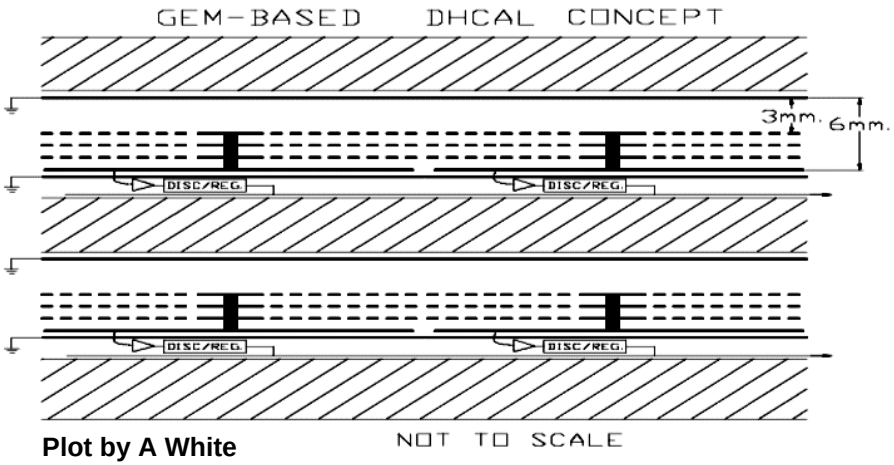
advantageous for Fe, Cu
$\rightarrow$ Active gap size ≤ 1 cm

HAD Calorimeter (II)

Gas Electron Multipliers GEM

Advantages: Low HV: few 100V/GEM layer
Thin layer: 6 mm
On-board readout possible
Flexible pad readout segmentation
Printed circuit
Either digital or semi-analog readout
Cheap

Effort: University of Texas



Plot by A White

Issues with GEMs

Effects of **stray particles**
heavily ionising particles

Long term performance

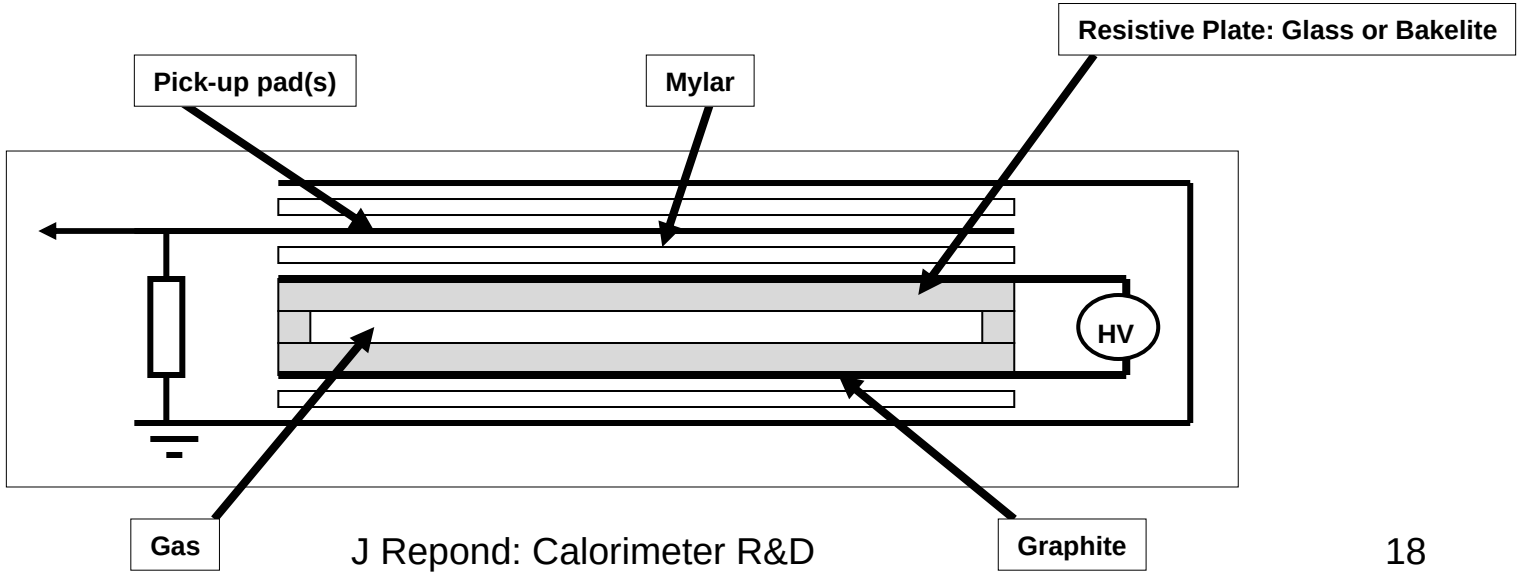
Cross talk

Calibration

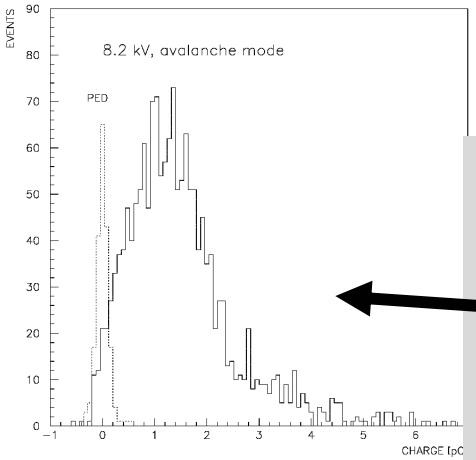
HAD Calorimeter (III)

Resistive Plate Chambers RPCs

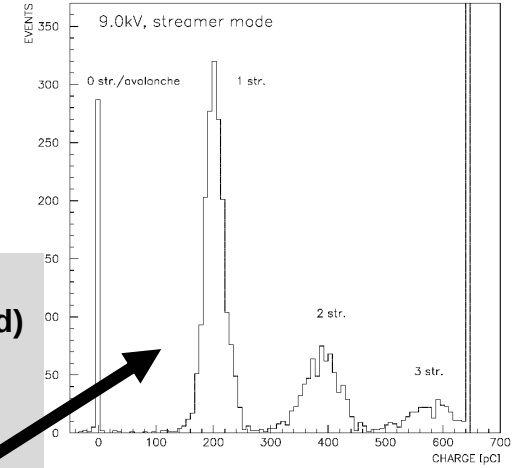
Advantages: **Thin layer**
On-board readout possible
Flexible pad readout segmentation
Printed circuit
Either analog, semi-analog, digital readout
Reliable
Underlying physics mostly understood
see http://www.coimbra.lip.pt/~rpc2001/talks.html
Cheap
Effort: **Argonne; Russia, France, Korea**

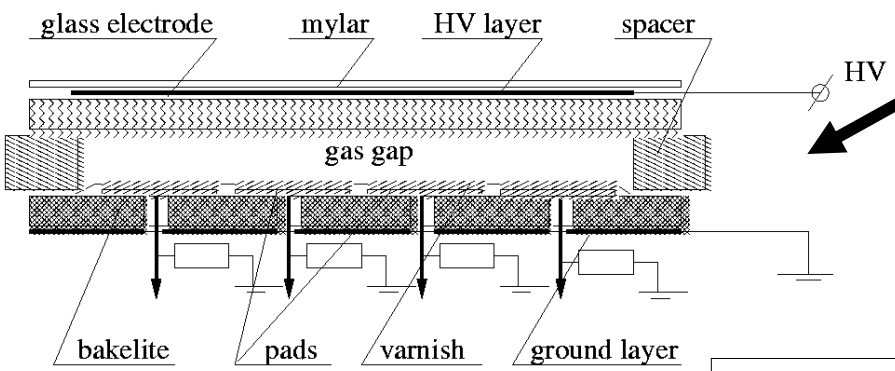


HAD Calorimeter (IV)

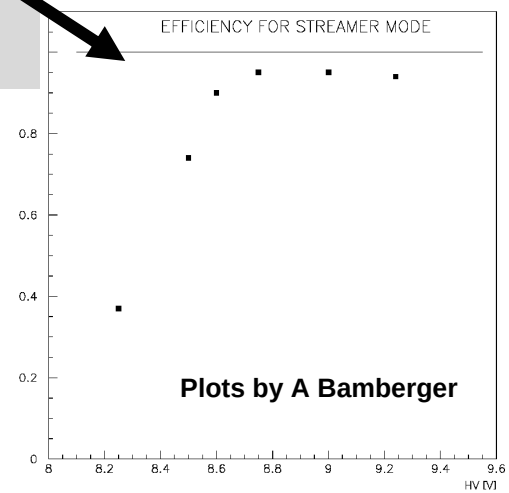


Choices: **Resistive plates: Glass (preferred)**
Bakelite (needs to be coated)
Operation: Avalanche mode
Faster
Lower HV
Smaller signal (~1pC)
Streamer mode
Slower
Higher HV
Large signals (~100pC)
Mechanical: gap size
glass thickness
number of gaps
or completely new design





Plot by V Amassov



Plots by A Bamberger

HAD Calorimeter (V)

Issues with RPCs

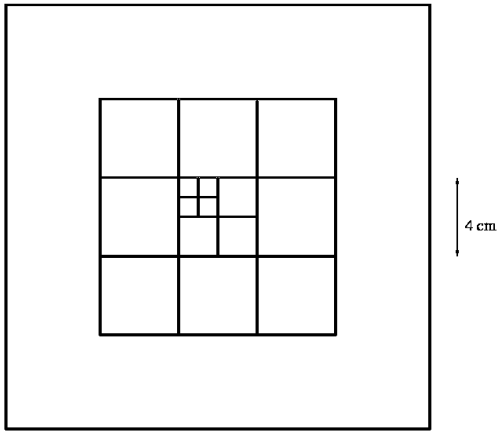
Safety with HV: **using up to 10kV**
can be reduced with smaller gaps
in avalanche mode

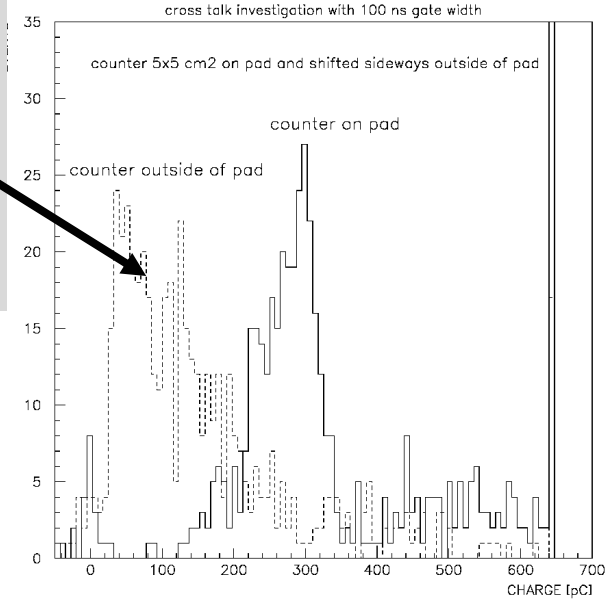
Cross talk between pads: **significant charge on neighboring pad**
reduce with higher resistivity ink
40kΩ/□ → 200kΩ/□
signal shape very different
easy to discriminate!

Long term operation: **significant experience elsewhere**

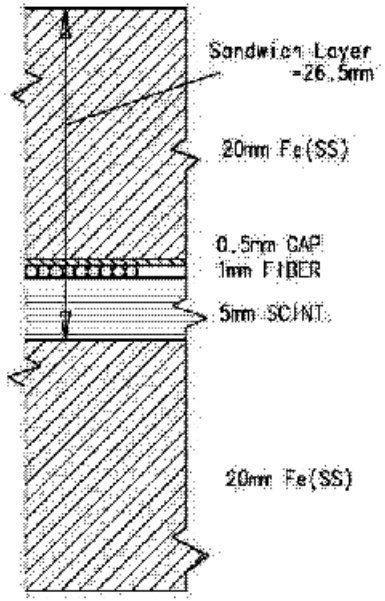
Calibration: **probably not needed in streamer mode**

Pad structure





HAD Calorimeter (VI)

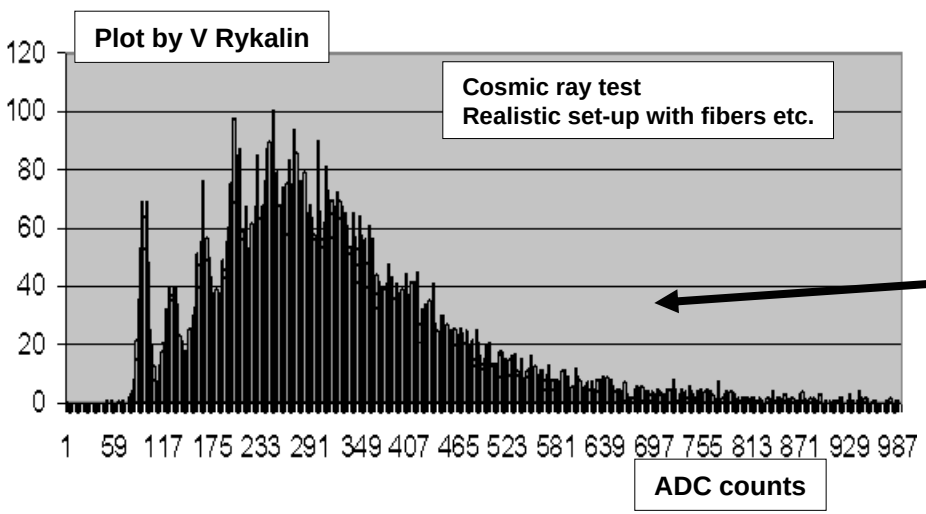


Scintillator

First choice in TESLA TDR

Lateral size : 5x5 cm² → 25x25 cm²
Longitudinally: 38 (53) layers in barrel (endcap)
9 (12) cells ganged together
gap: total t = 7.5 mm
scintillator 5.0 mm
Absorber : 20mm Fe
corresponding to 1.15 X_0

Effort : NIU-NICCAD; DESY, Russia, Prag



Readout: has to work in B-field

Avalanche photodiodes
Hybrid photodiodes
VLPC: Visual Light Photon Counters
Quantum efficiency: 60 – 80 %
Gain: 10^5 – 10^6
Operates at 7 ^{0}K
MRS: Metal Resistor Semiconductor Photodiodes
Recent development
Quantum efficiency: ~30%
Operates at room temperature

HAD Calorimeter (VII)

Issues with Scintillator

Thickness of Scintillator: **enough light for individual readout?**

Fiber routing: **light loss**

Segmentation: **readout of all tiles separately versus ganging together?**
good enough for EFA?

Choice of Photodetector

Calibration

HAD Calorimeter (VIII)

General issues for HCAL

Compensation versus EF optimization?
or can you have both?

Tail catcher?
ever used before?

Timing information?
what is needed?

Dynamic range?
analog versus hybrid versus digital

Luminosity Calorimeter

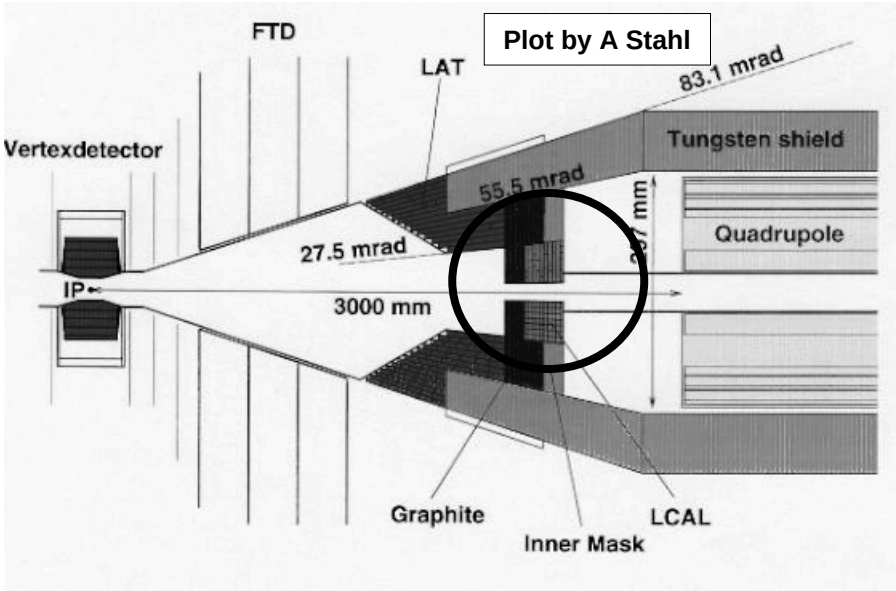
Measure: forward Bhabhas for luminosity determination
tag e^+e^- for 2-γ physics
measure beamstrahlung to optimize machine setting

Technology: $PbWO_4$ with fiber readout

Effort: no US effort; DESY, DESY-Zeuthen, Milan

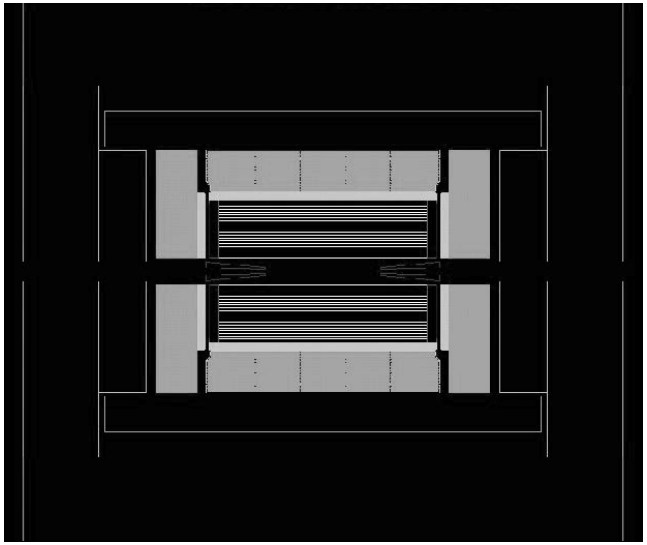
Issues with LCAL

Design of IR
Synchrotron Radiation
Radiation hardness



Simulations (I)

Overview



Europe

Simdet:

fast simulation
(realistically) parameterized detector response
should not be used to fine tune detector design

Brahms:

GEANT3 (fortran based)
full detector simulation

Mokka:

GEANT4 (C^{++} based)
flexible geometry
package ready for use

America

Fast MC:

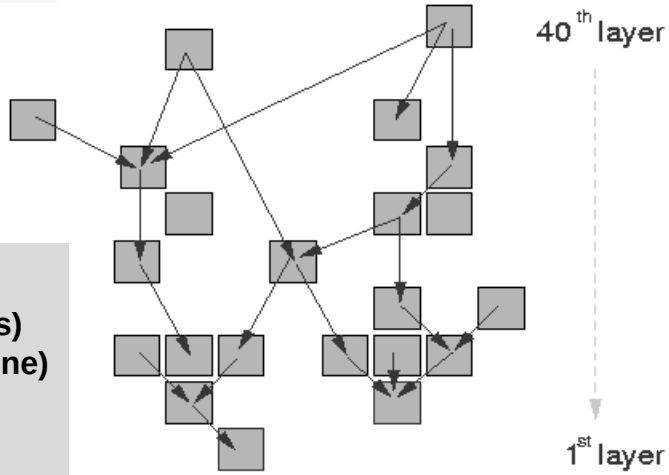
smearing/libraries
should not be used to fine tune detector design

LCD full simulation:

Gismo (EGS/Geisha)
Simulation of SD and LD designs
Transition to GEANT4 (first results available)

Simulations (II)

Tools needed for calorimeter design studies



Plot from F Badaud et al.

Clustering of CAL energies: Cluster cheater (uses 'truth')
Simple cluster builder (adjacent cells)
Radial cluster builder (1st layer → cone)

Track-cluster matching algorithm

Tracking algorithm for calorimeter: μ

Identification of γ's: ε = 85% with π = 84% (Algorithm by M Iwasaki)

Identification of neutral hadrons

Anything else?

Simulations (III)

ECAL Studies

Comparison of Si/W, Pb/scintillator, Crystal

- EM resolution
- Ability to separate different components of jets
- Jet energy resolution

HCAL Studies

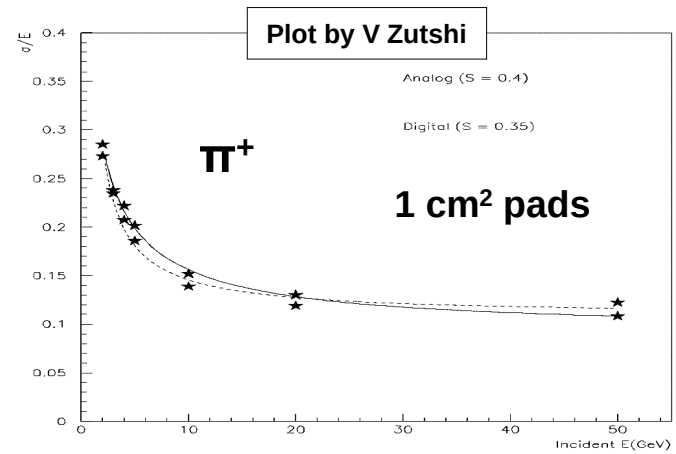
Matrix of studies for Jet Energy Resolution

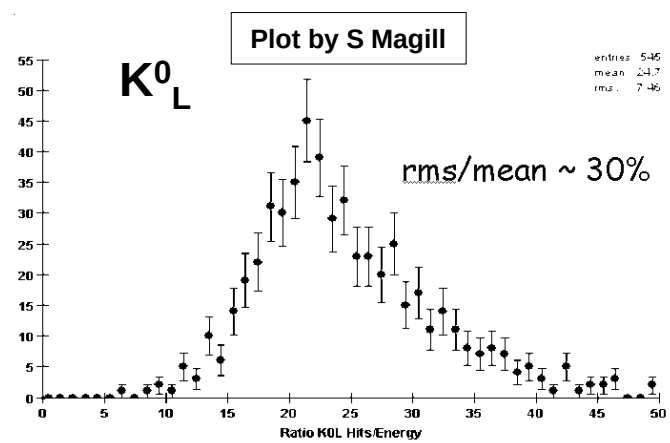
- Different absorbers
- Different segmentation: from 1 $cm^2 \rightarrow 25\ cm^2$
- Different size of active gap (R_M)
- Analog versus digital readout

Common Studies

Need for compensation

Energy flow algorithms





HCAL pad size:
Compare to analog readout: σ/E ~ 26%

Simulations (IV)

Validation of Simulations

Recently discovered bugs in Geisha package!

Large differences between Gismo and GEANT4

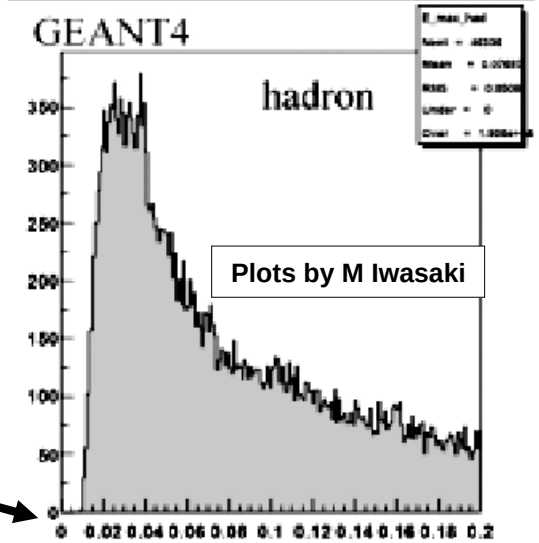
Test beams: measure single particle resolutions
shower characteristics
simulate jets with event overlays

Can't afford to design detector based on faulty simulations!!!

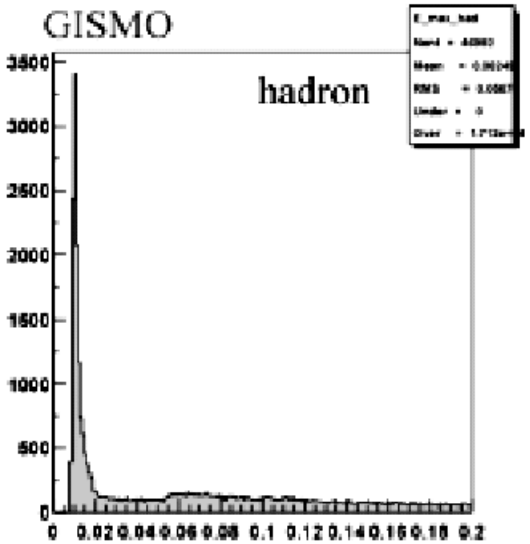
Current efforts in US

SLAC	N Graf, G Bower…
ANL	S Kuhlmann, S Magill
NIU-NICCAD	D Chakraborty, V Zutshi…
Oregon	R Frey, M Iwasaki

Maximum hit energy in a cluster



Plots by M Iwasaki



Maximum hit energy [GeV]

Conclusions

Design of calorimeter: driven by need for excellent jet energy resolution

goal: $\sigma/E \leq 30\%/\sqrt{E}$

Technologies: several choices for both ECAL and HCAL
none completely established/accepted
some technologies not (yet) pursued in US

→ **major effort needed to substantiate case for any choice**

Design issues: segmentation of readout required for optimum Energy Flow Algorithms
need for compensation

→ **major simulation effort needed to address these issues**

All listed efforts could profit from more manpower