Particle Flow Algorithm Calorimetry

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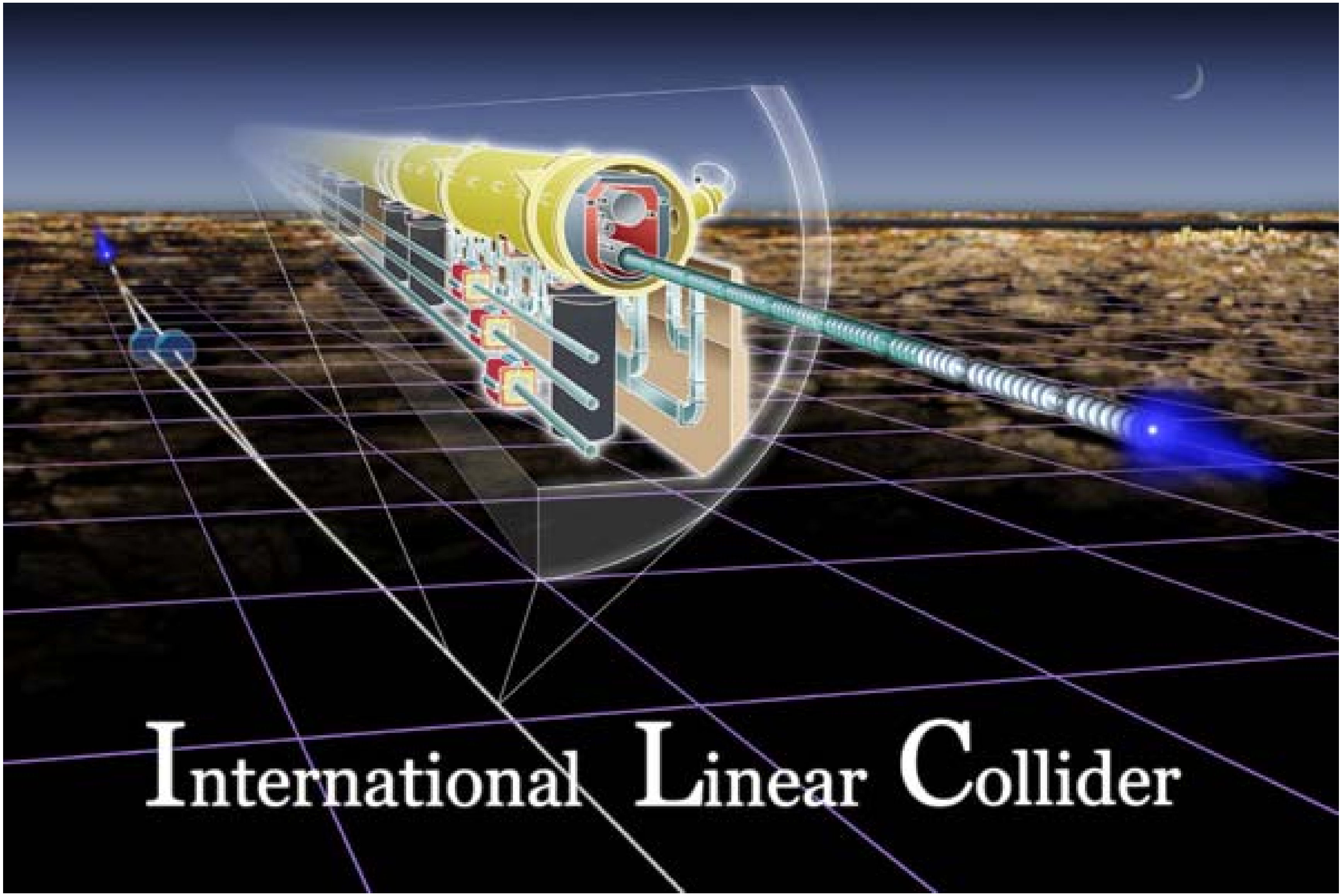
Overview – PFA Calorimetry

- The International Linear Collider.
- The Physics motivation for PFA Calorimetry.
- Required calorimeter performance.
- Traditional calorimetry – the need for Particle Flow.
- Implementation of "PFA Calorimetry", Electromagnetic and Hadronic Calorimeters.
- Particle Flow Algorithms – where we stand.
- What next?



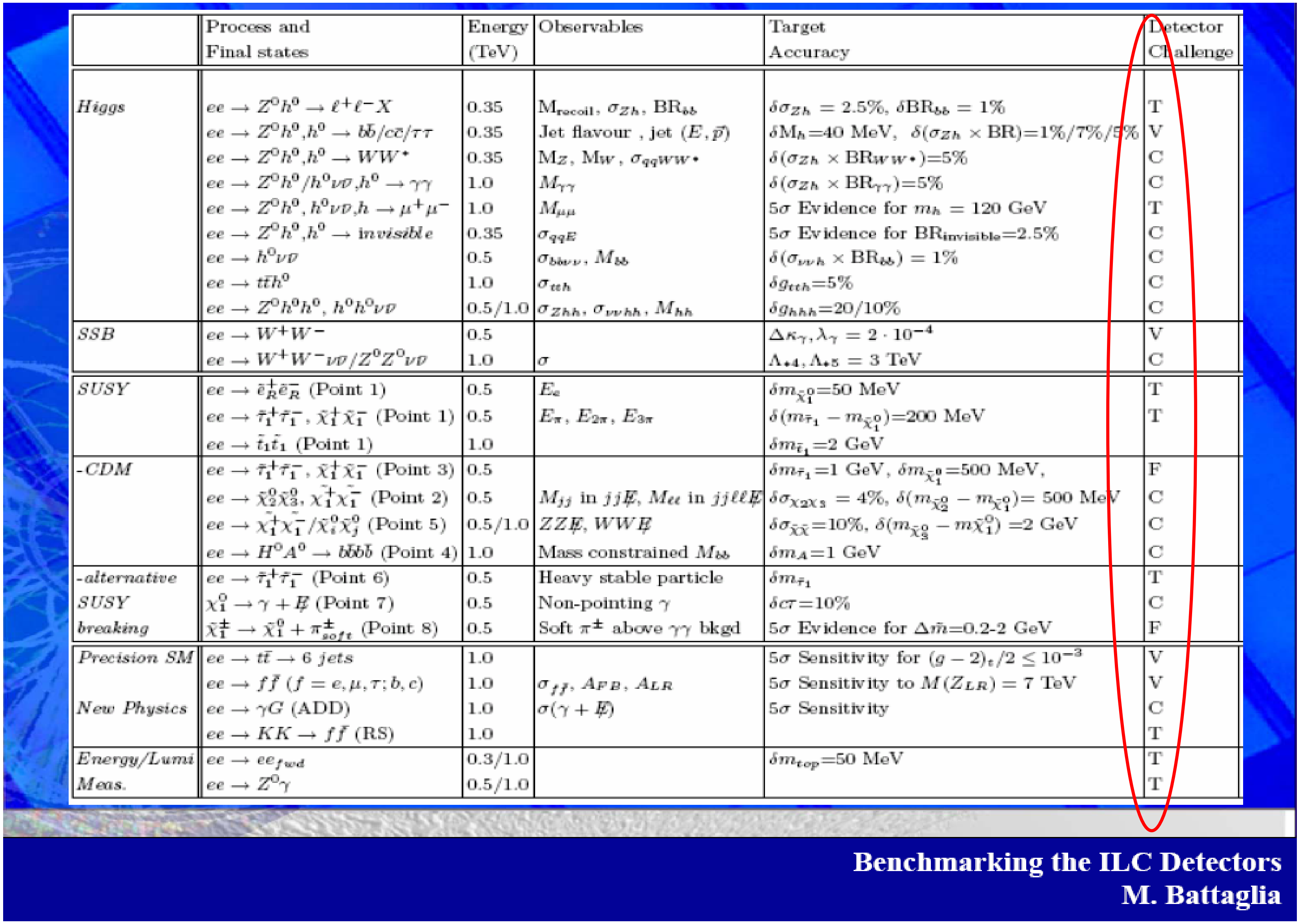
High Energy Electron-Positron Collider: 500GeV – 1 TeV

Linear Collider Physics

- A program of e^+e^- *discovery* and *precision physics* up to 1TeV
- Understanding the Electroweak sector
  - Origin of mass – Higgs physics…couplings
    e.g. g_{tth}, g_{hhh} - > separate Zh from WW, ZZ -> jets
  - EW Symmetry breaking – Supersymmetry?
- Precision studies of the massive top quark.
- Search for New Physics: W', Z', leptoquarks, ….

  …, extra dimensions
- Much of this physics program requires high precision measurements of jet energies and jet-jet invariant masses -> hence the need for a new approach to hadronic calorimetry.

ILC Calorimetry R&D - motivation



	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta\mathrm{BR}_{bb} = 1\%$	T
	$ee \to Z^0h^0, h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour , jet $(E, \vec{p})$	$\delta\mathrm{M}_h$=40 MeV, $\delta(\sigma_{Zh} \times \mathrm{BR})$=1%/7%/5%	V
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times \mathrm{BR}_{WW^*})$=5%	C
	$ee \to Z^0h^0/h^0\nu\bar{\nu}, h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times \mathrm{BR}_{\gamma\gamma})$=5%	C
	$ee \to Z^0h^0, h^0\nu\bar{\nu}, h \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $m_h = 120$ GeV	T
	$ee \to Z^0h^0, h^0 \to invisible$	0.35	σ_{qqE}	5σ Evidence for $\mathrm{BR}_{invisible}$=2.5%	C
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times \mathrm{BR}_{bb}) = 1\%$	C
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C
	$ee \to Z^0h^0h^0$, $h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C
SUSY	$ee \to \tilde{e}^+_R\tilde{e}^-_R$ (Point 1)	0.5	E_e	$\delta m_{\tilde{\chi}^0_1}$=50 MeV	T
	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$, $\tilde{\chi}^+_1\tilde{\chi}^-_1$ (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
	$ee \to \tilde{t}_1\tilde{t}_1$ (Point 1)	1.0		$\delta m_{\tilde{t}_1}$=2 GeV	
-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
	$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\chi_2\chi_3} = 4\%$, $\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1})$= 500 MeV	C
	$ee \to \tilde{\chi}^+_1\tilde{\chi}^-_1/\tilde{\chi}^0_i\tilde{\chi}^0_j$ (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
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δm_A=1 GeV	C
-alternative SUSY breaking	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6)	0.5	Heavy stable particle	$\delta m_{\tilde{\tau}_1}$	T
	$\chi^0_1 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C
	$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$ (Point 8)	0.5	Soft $\pi^\pm$ above $\gamma\gamma$ bkgd	5σ Evidence for $\Delta\tilde{m}$=0.2-2 GeV	F
Precision SM	$ee \to t\bar{t} \to 6$ *jets*	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V
	$ee \to f\bar{f}$ $(f = e, \mu, \tau; b, c)$	1.0	σ_{ff}, A_{FB}, A_{LR}	5σ Sensitivity to $M(Z_{LR}) = 7$ TeV	V
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T
Energy/Lumi Meas.	$ee \to ee_{fwd}$	0.3/1.0		δm_{top}=50 MeV	T
	$ee \to Z^0\gamma$	0.5/1.0			T

Benchmarking the ILC Detectors
M. Battaglia

Physics examples driving calorimeter design

-All of these critical physics studies involving the calorimeter demand:

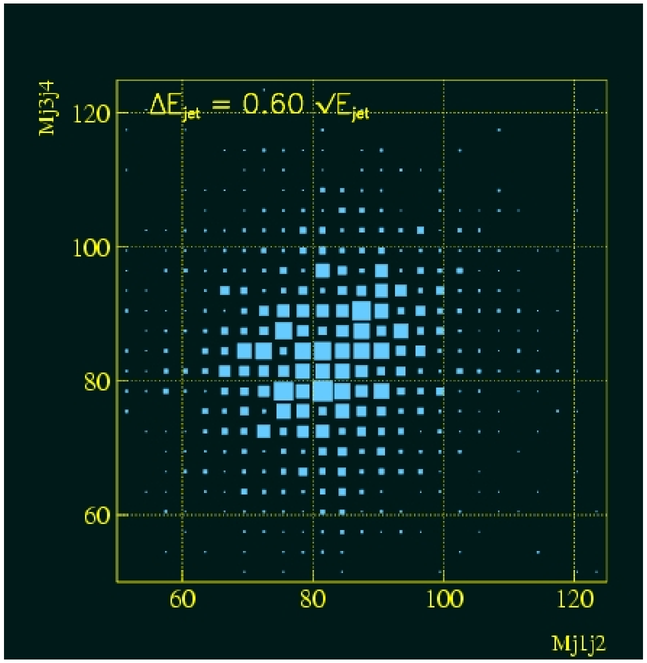
- ✧ Efficient jet separation and reconstruction
- ✧ Excellent jet energy resolution (Goal ~30%/√E)
- ✧ Excellent jet-jet mass resolution

+ jet flavor tagging

Plus… We need very good forward calorimetry for e.g. SUSY selectron studies,

and… ability to find/reconstruct photons from secondary vertices e.g. from long-lived NLSP -> γG

Importance of good jet energy resolution

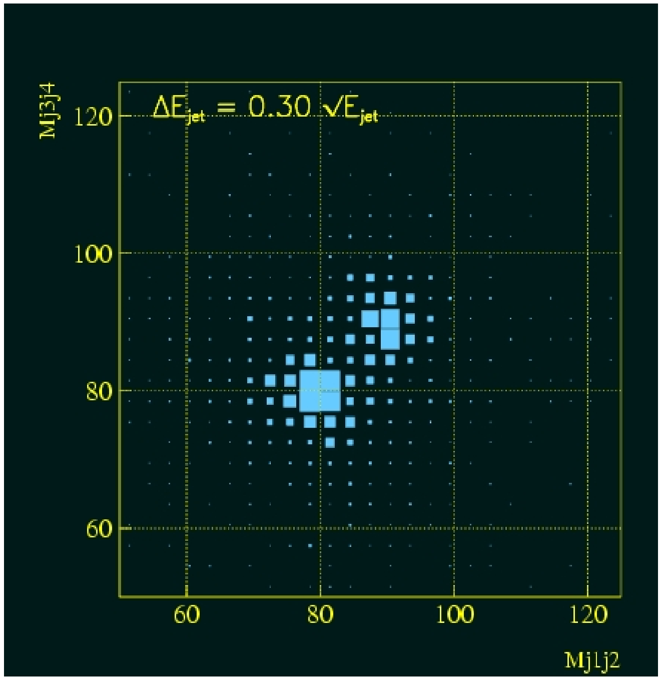


60%/√E

Simulation of W, Z reconstructed masses in hadronic mode.

Generally accepted goal for PFA's

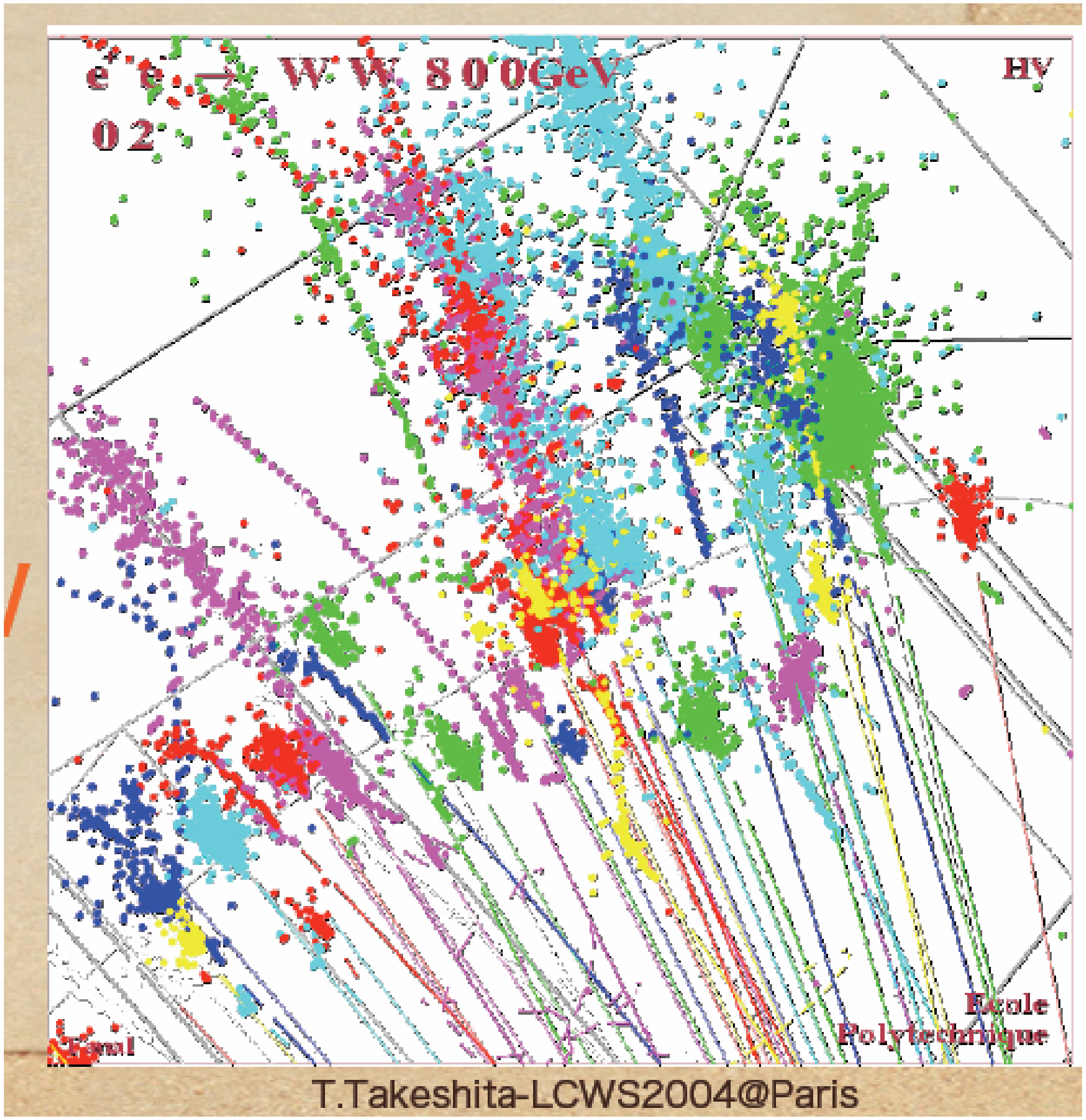
30%/√E



(from CALICE studies, H.Videau,

shown at ALCPG/Cornell: M. Schumacher)

Don't underestimate the complexity!



T.Takeshita-LCWS2004@Paris

Why not use "traditional" calorimeters?

- Equalized EM and HAD responses ("compensation")

- Optimized sampling fractions

EXAMPLES:

ZEUS - Uranium/Scintillator

Single hadrons 35%/√E ⊕ 1%

Electrons 17%/√E ⊕ 1%

Jets 50%/√E

D0 – Uranium/Liquid Argon

Single hadrons 50%/√E ⊕ 4%

Jets 80%/√E

Clearly a significant improvement is needed for LC.

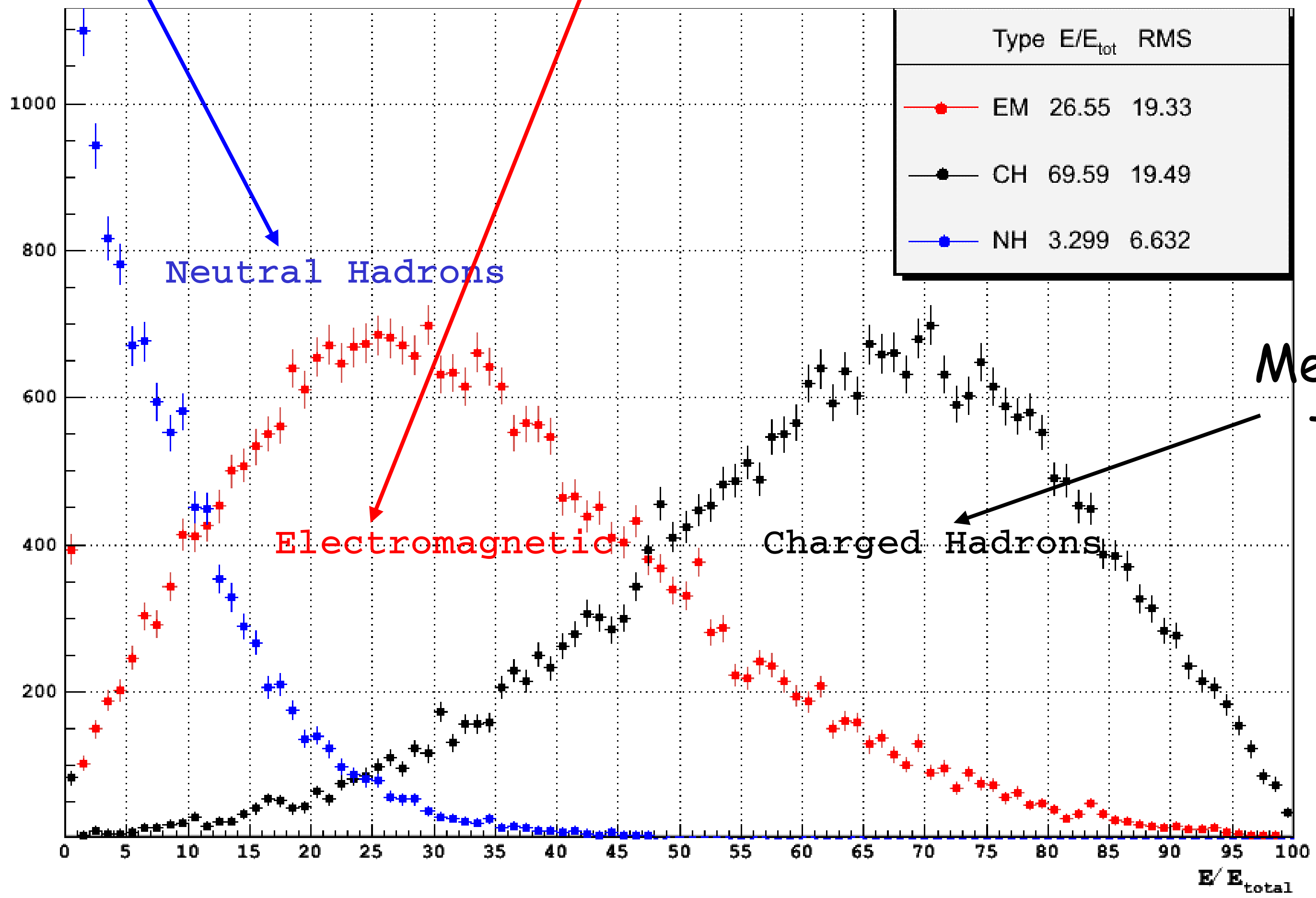
What is a jet? Component energy measurements in a PFA

Measure from hits in HCal

$e^{\pm}$ measured in tracker
γ measured in ECal

e^+e^- -> ttbar -> 6 jets

Measured in tracker



Implementation of PFA Calorimetry

Hardware components

>> Fine granularity ECal, reasonable σ(E), separate charged/gamma.

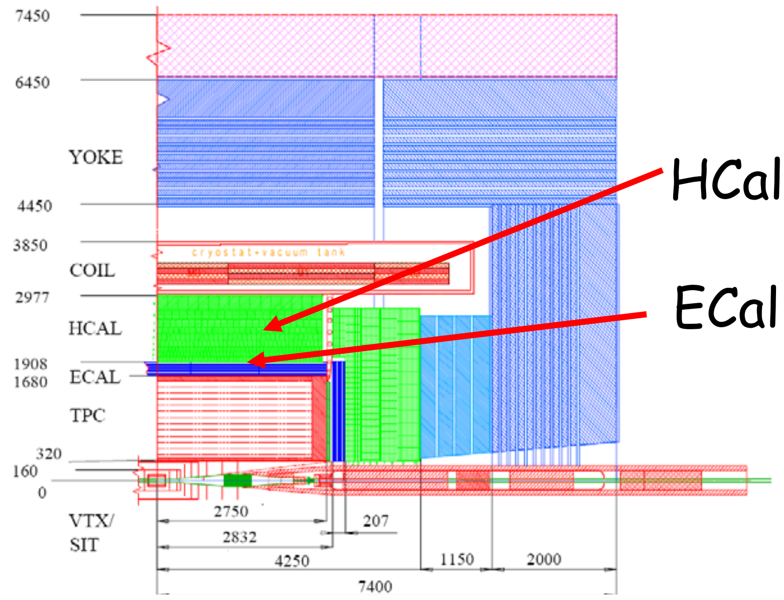
>> Fine HCal, good tracking, acceptable σ(e) for neutrals.

>> Tail-Catcher – to measure the few% of energy that may "leak" through the superconducting coil (?)

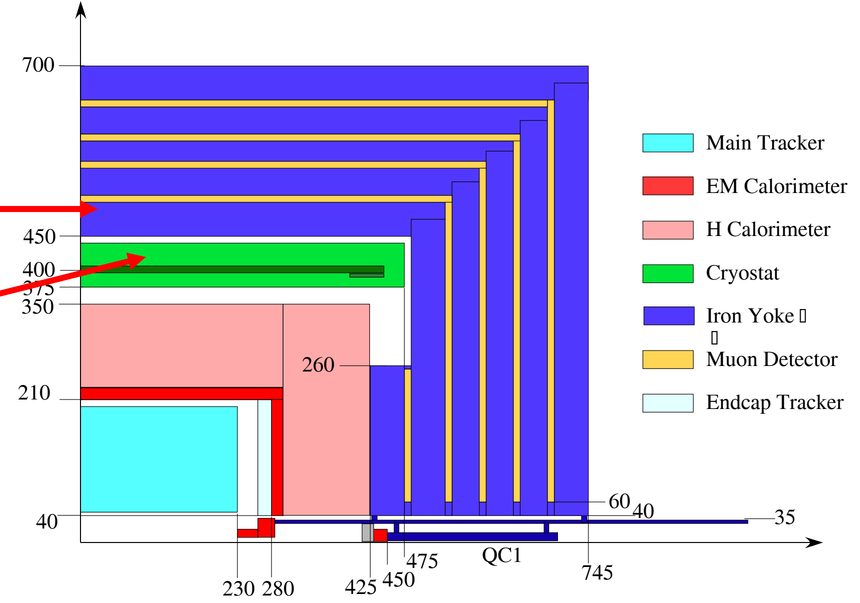
ILC Detector Design Concepts

Large Tracker

LDC

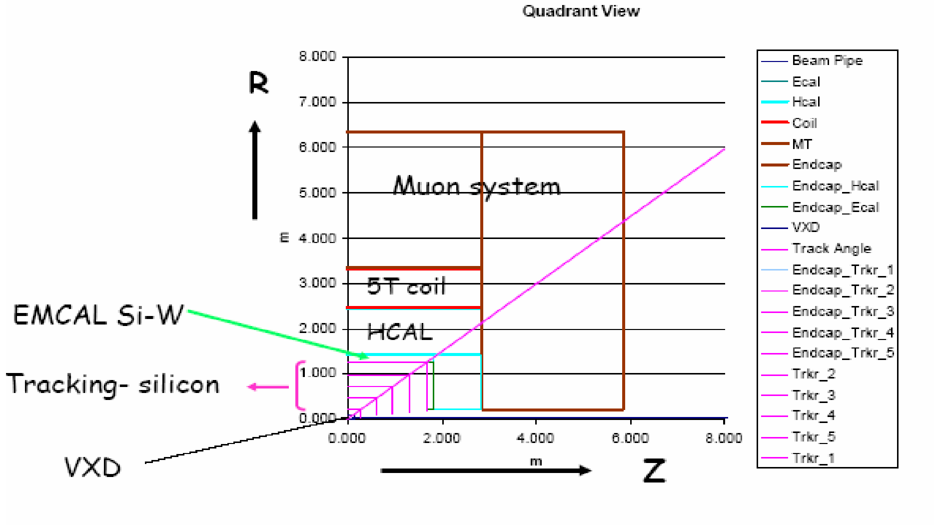


GLD

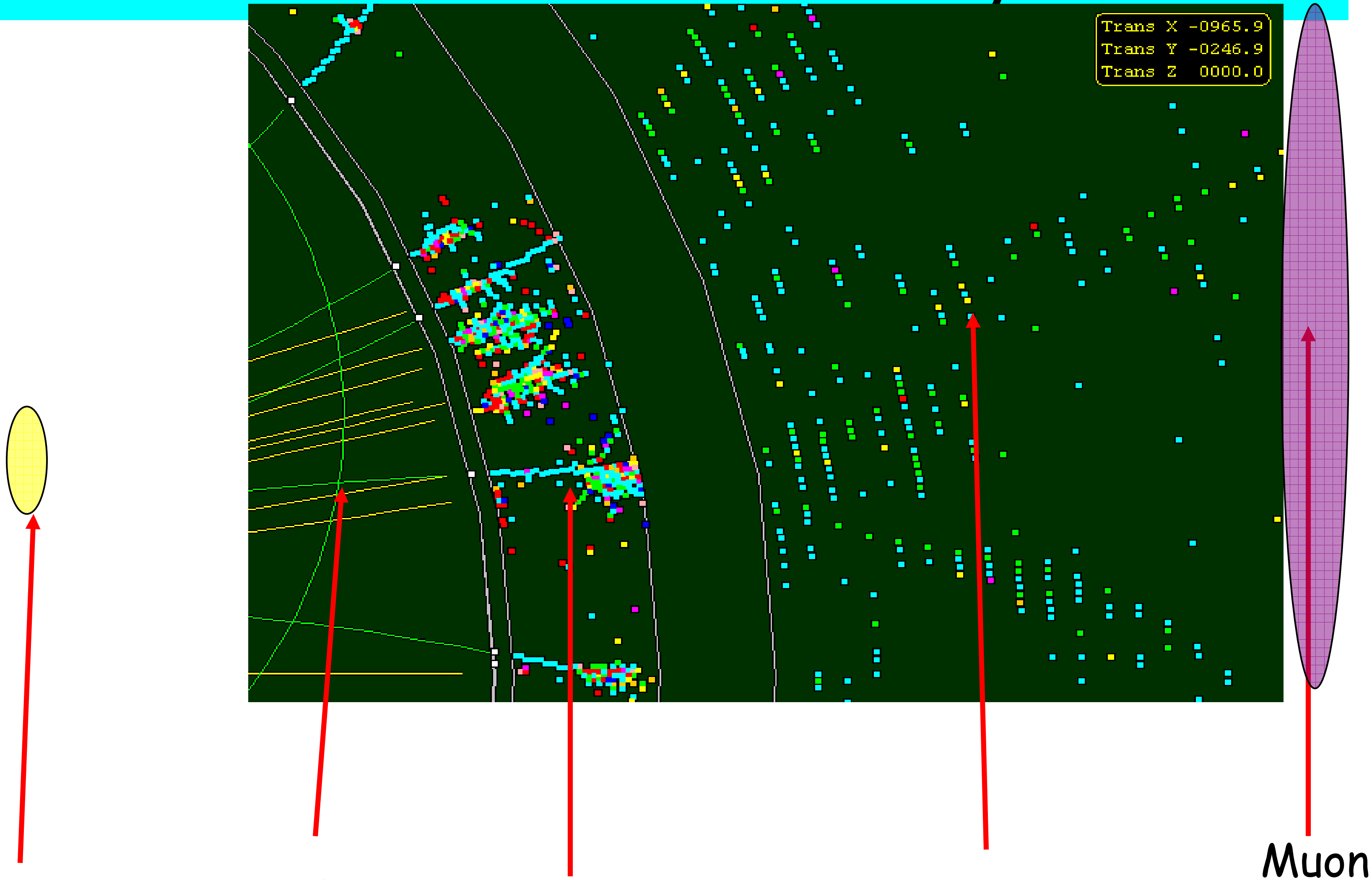


Compact tracker

SiD



Integrated Detector Design – Calorimeter is *the* critical system!



VXD
tag b,c
jets

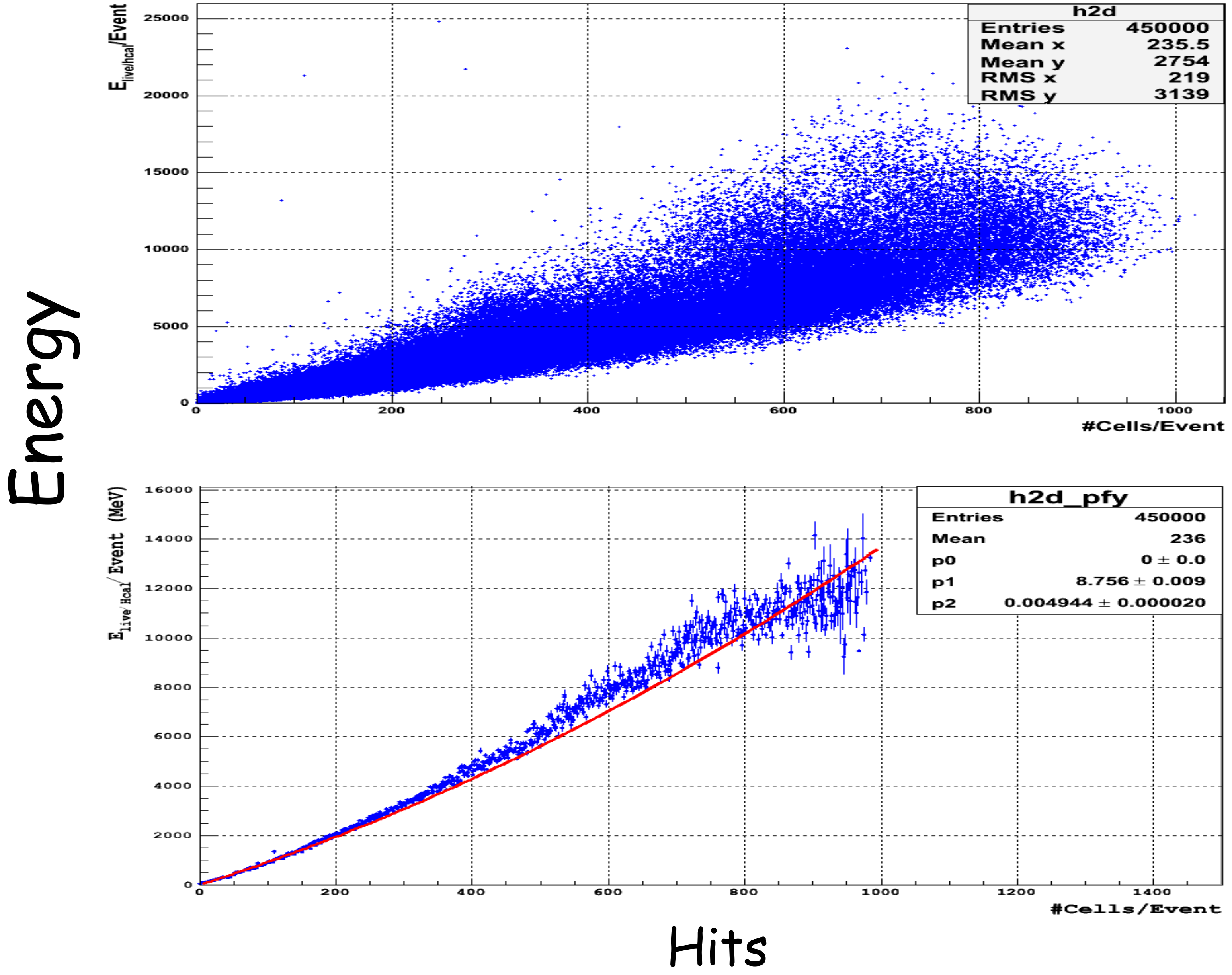
Tracking system

EM Cal

HAD Cal

Muon system/ tail catcher

Digital calorimetry - counting cells



Calorimeter Technologies

Electromagnetic Calorimeter

Physics requirements emphasize segmentation/granularity (transverse AND longitudinal) over intrinsic energy resolution.

Localization of e.m. showers and e.m./hadron separation -> dense (small X_0) ECal with fine segmentation.

Moliere radius -> O(1 cm.)

$$f_E \simeq \frac{R_{cal}}{\sqrt{R_M^2 + (4d_{pad})^2}}$$

David Strom

Transverse segmentation ≈ Moliere radius

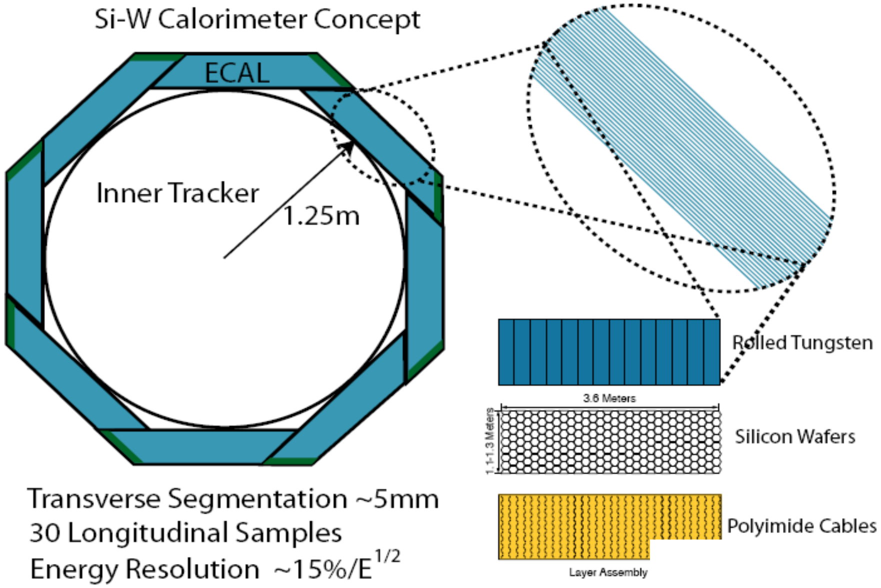
Charged/e.m. separation -> fine transverse segmentation (first layers of ECal).

Tracking charged particles through ECal -> fine longitudinal segmentation and high MIP efficiency.

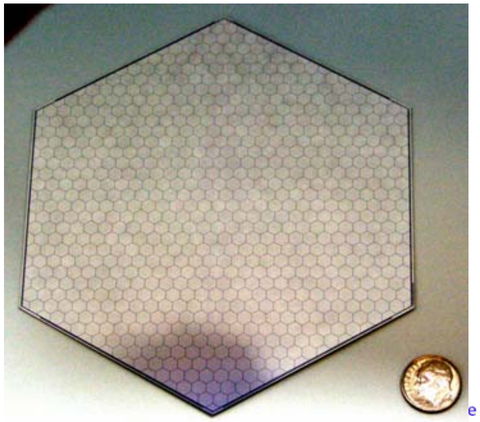
Excellent photon direction determination (e.g. GMSB)

Keep the cost (e.g. Silicon) under control!

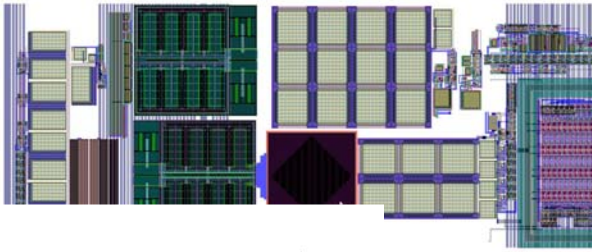
SLAC-Oregon-UC Davis-BNL
Si-W ECal R&D for SiD

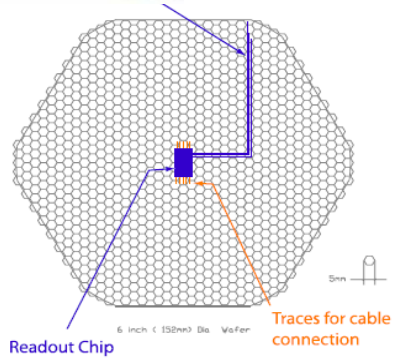


Transverse Segmentation ~5mm
30 Longitudinal Samples
Energy Resolution ~15%/$E^{1/2}$

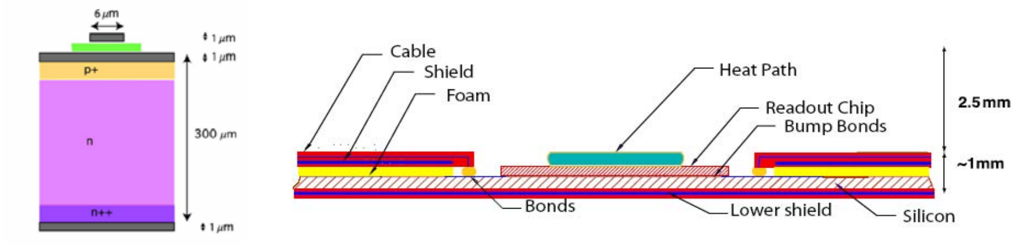


KPix Cell 1 of 1024





Effective 4 x 4 mm^2



Critical parameter: minimum space between tungsten layers.

CALICE ECal

- ➢ 130T of tungsten
- ➢ An octagonal geometry
- ➢ A high level of density

(20-40 layers, 24X0 in ~170mm)

CALICE - ECAL

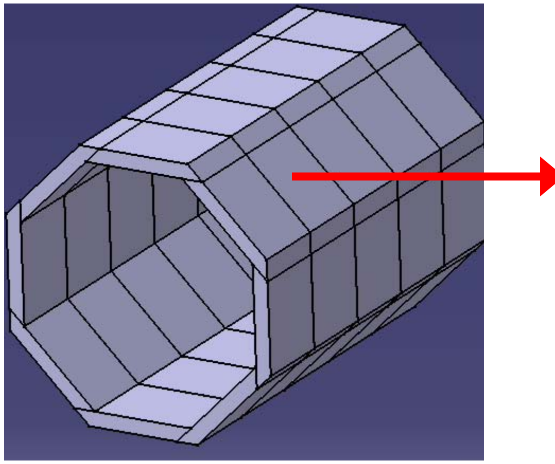
🇰🇷 Ewha Univ., Sungyunkwan Univ., Kangnung NU , Yonsei Univ.

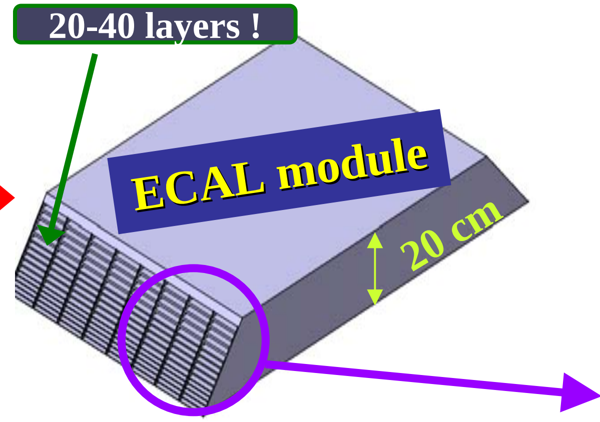
🇫🇷 LAL,LLR,LPC-Ct, LPSC, PICM

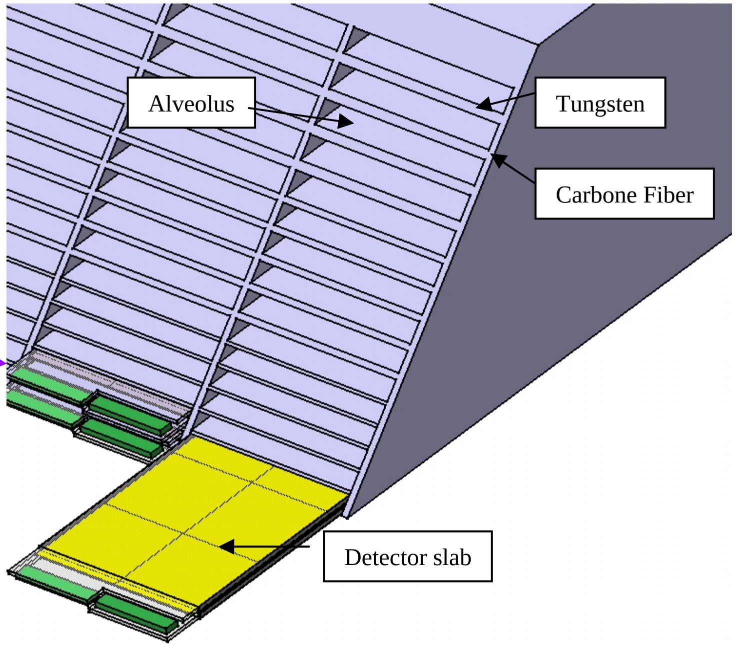
🇷🇺 ITEP,IHEP, MSU

🇨🇿 Prague (IP-ascr)

🇬🇧 Imp. Coll, UCL, Cambridge Birmingham, Manchester,RAL, RHUL

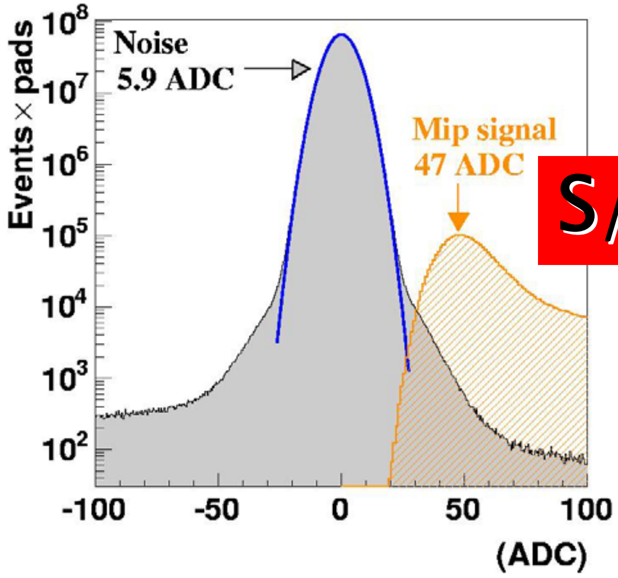






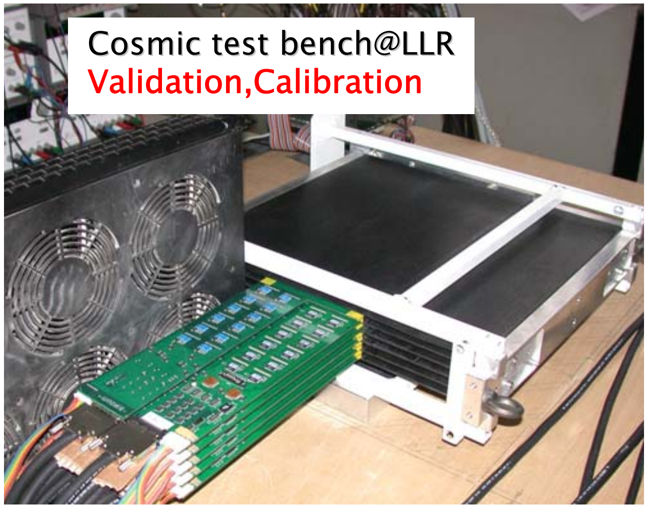
- ➢ No large area of dead zone
- ➢ All modules are identical (Tungsten wrapped by Cfi)
- ➢ The detector slabs would be tested before assembling

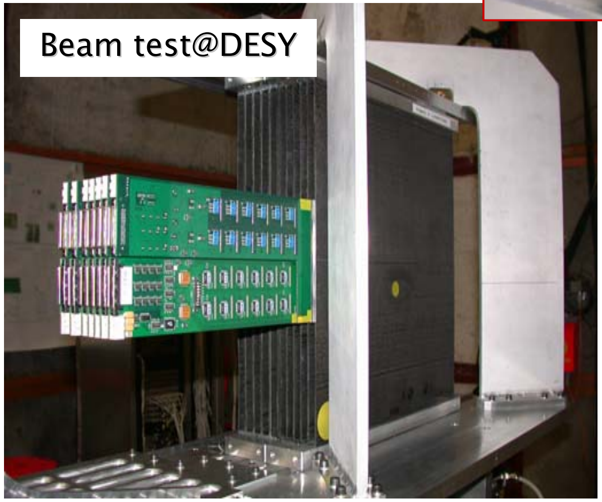
The ECAL prototype

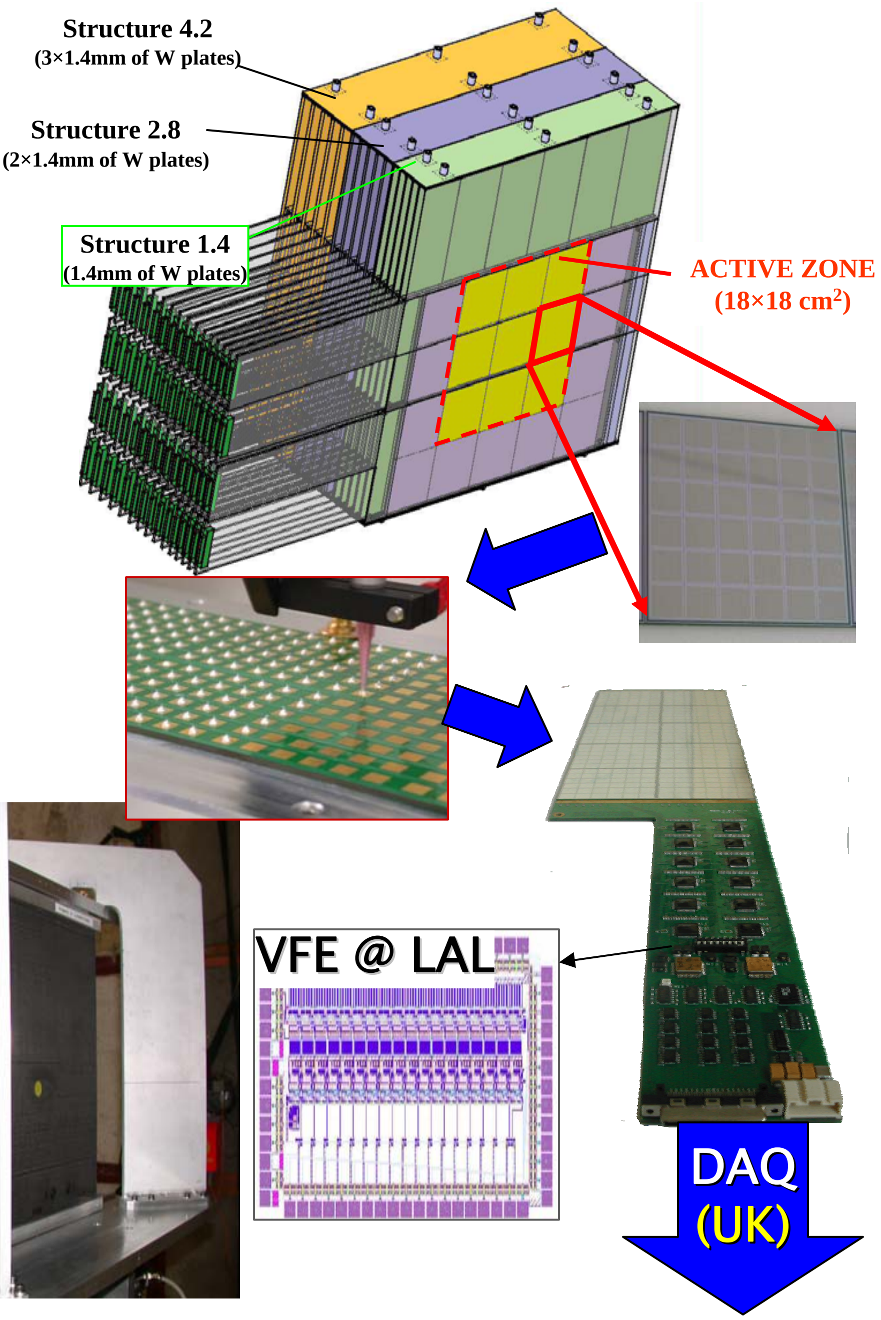


S/N ~ 8 !!

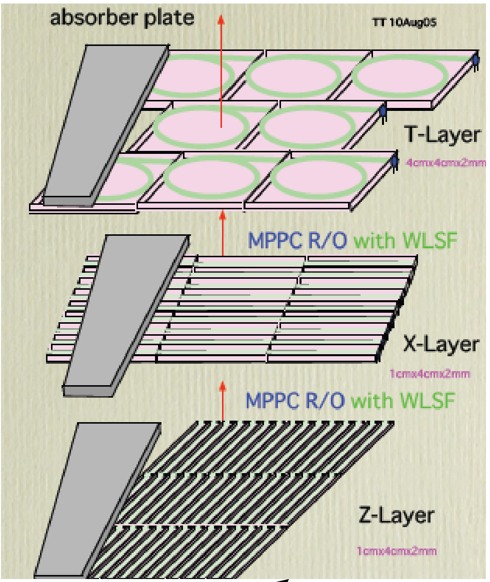
9720 channels in 18 cm^3 for this prototype

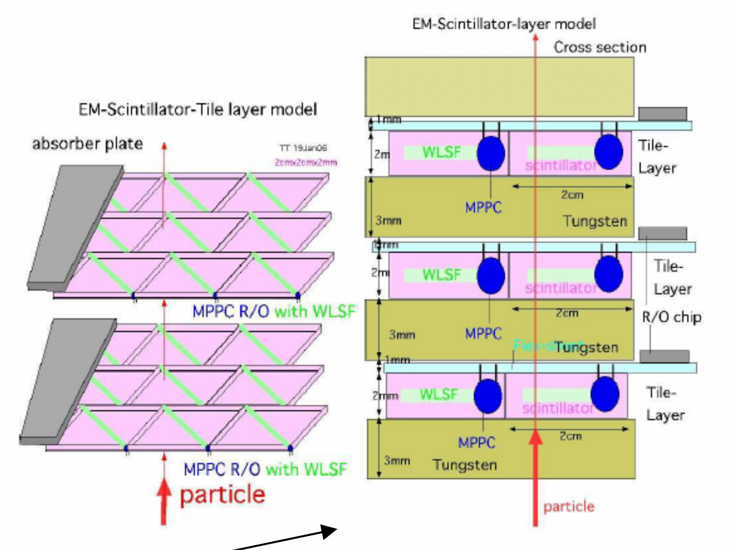

Cosmic test bench@LLR
Validation,Calibration

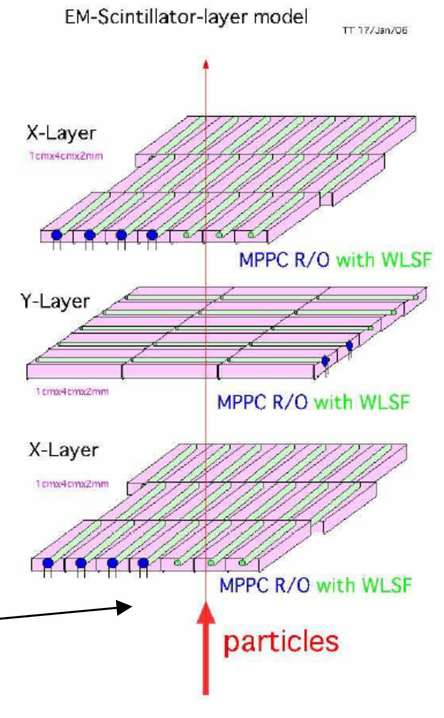

Beam test@DESY



GLD Calorimeter - design options under investigation.







ECal: Options under investigation

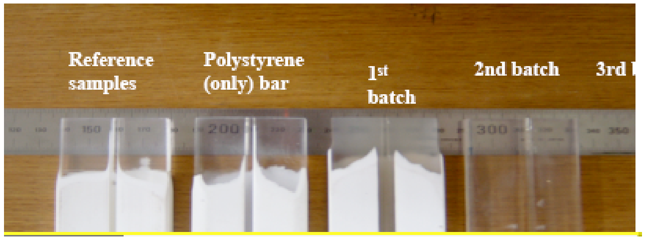
HCal: mixed tiles/strips

Use "some" silicon in ECal?

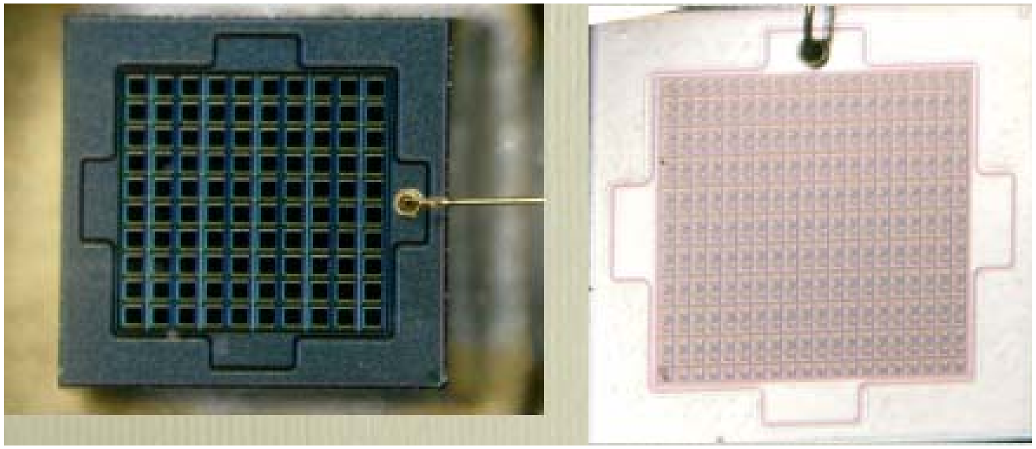
Possibly digital HCal?

Scintillator production

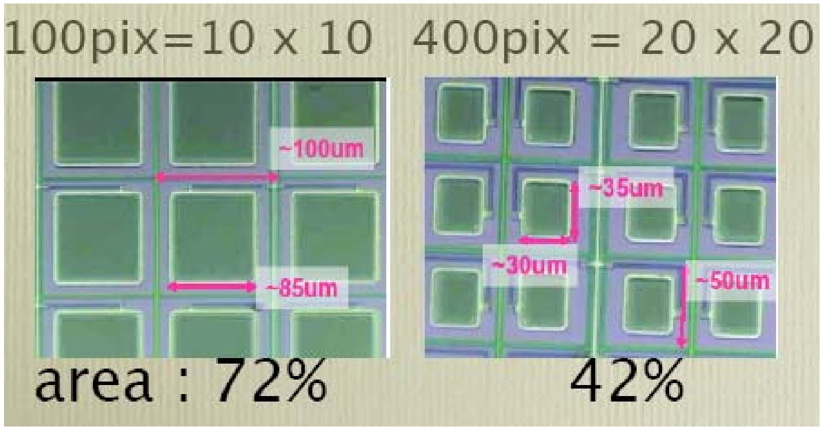
- Kyongpook Univ. (Korea)

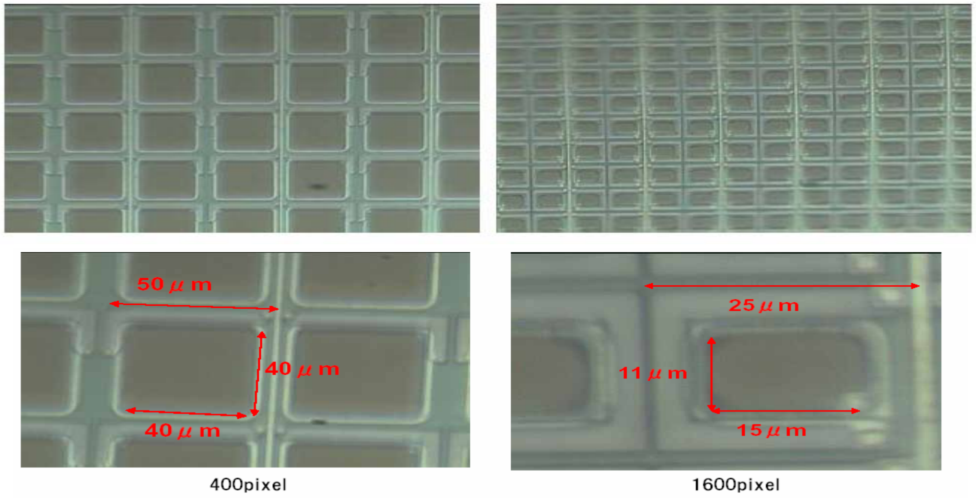


GLD Calorimeter Readout – MultiPixel Photon Counter (MPPC)



Hamamatsu





400pixel

1600pixel

Calorimeter Technologies

Hadron Calorimeter

Physics requirements emphasize segmentation/granularity (transverse AND longitudinal) over intrinsic energy resolution.

- Depth $\geq 4\lambda$ (not including ECal ~ 1λ)

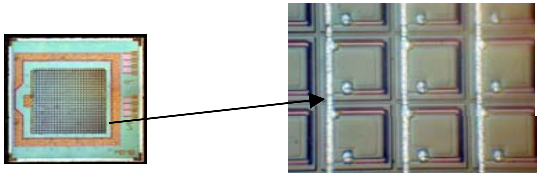
-Assuming EFlow:

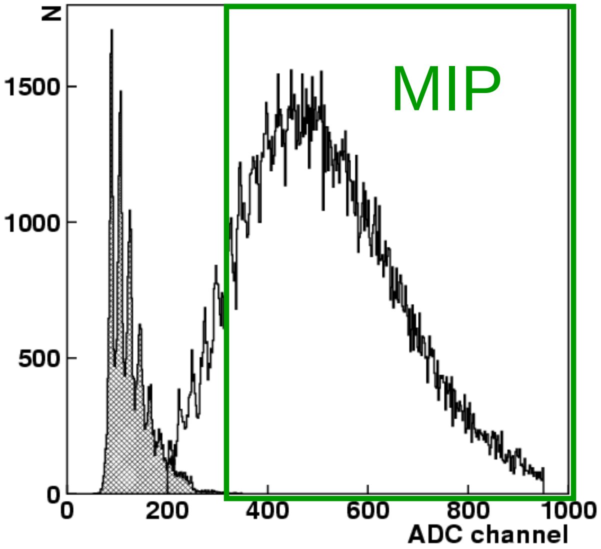
  - sufficient segmentation to allow efficient charged particle tracking.
  - for "digital" approach – sufficiently fine segmentation to give linear energy vs. hits relation
  - efficient MIP detection
  - intrinsic, single (neutral) hadron energy resolution must not degrade jet energy resolution.

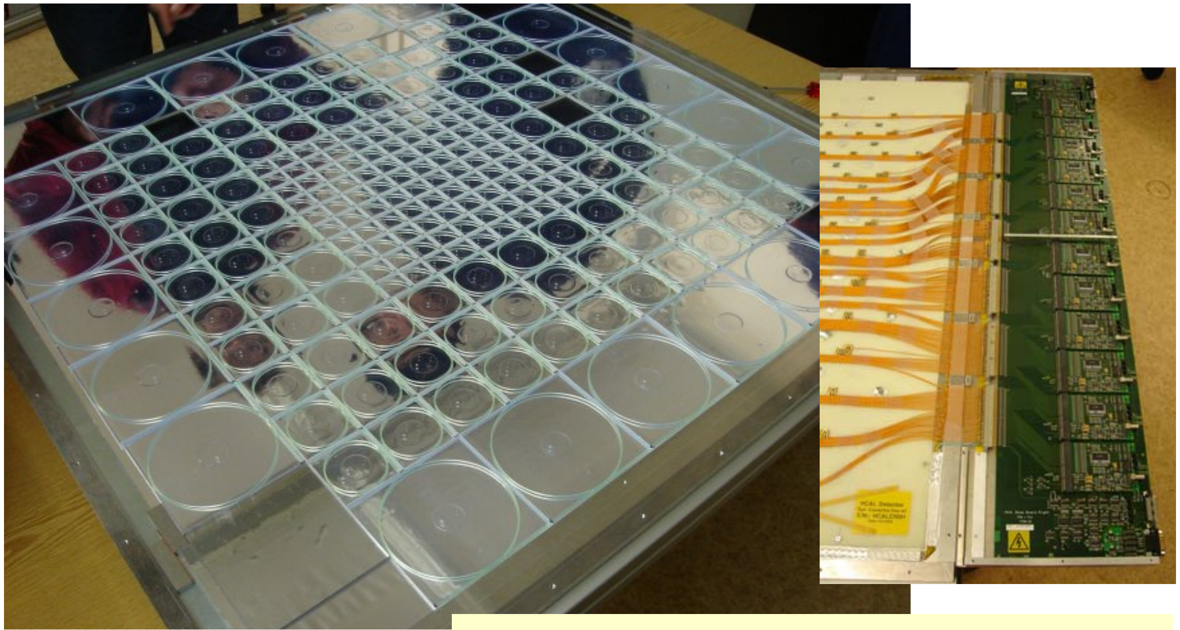
CALICE - Analog HCAL

- 1 cubic metre,
- 38 layers, 2cm steel plates
- 8000 tiles with SiPMs
- Electronics based on ECAL design

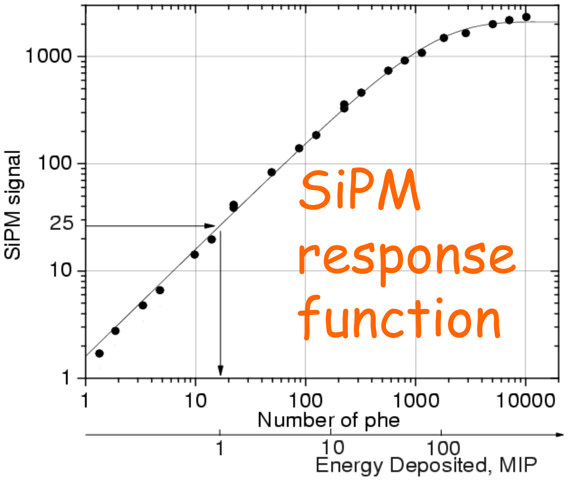
Single pixel





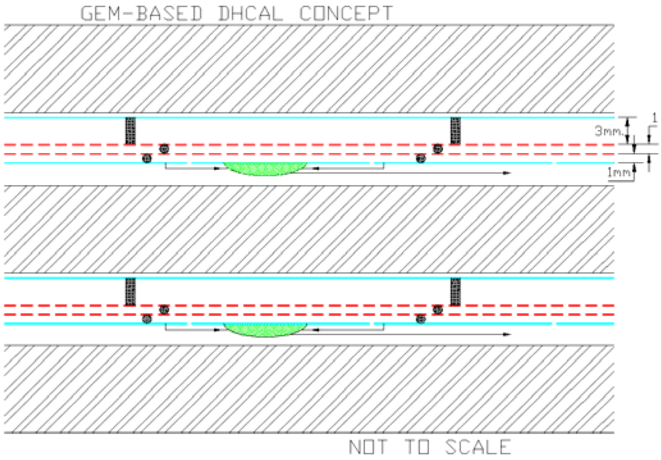


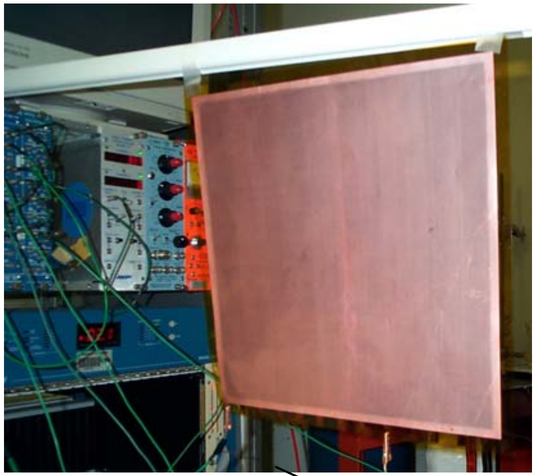
Mechanics and front end boards: DESY
Front end ASICs: LAL

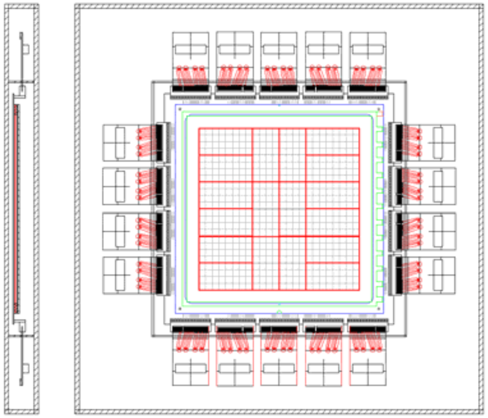


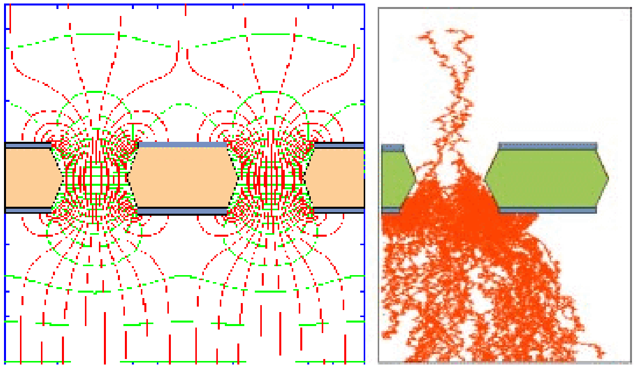
Hadron Calorimeter - CALICE/digital

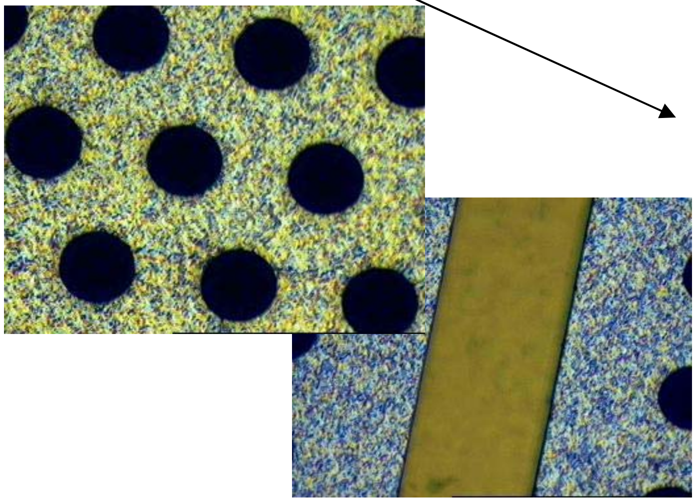
(1) Gas Electron Multiplier (GEM) - based DHCAL







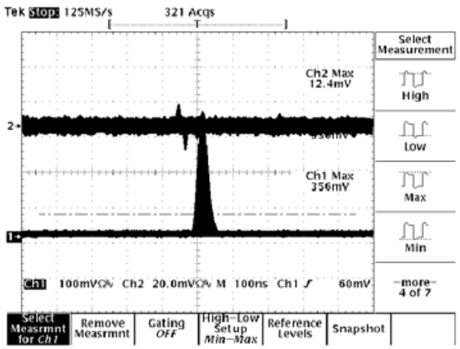


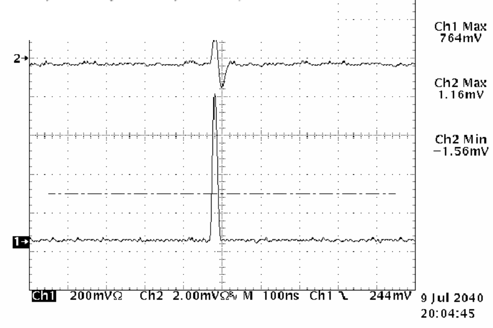


500 channel/5-layer test
30x30cm^2 foils

Details of new 30cm x 30cm foils from 3M

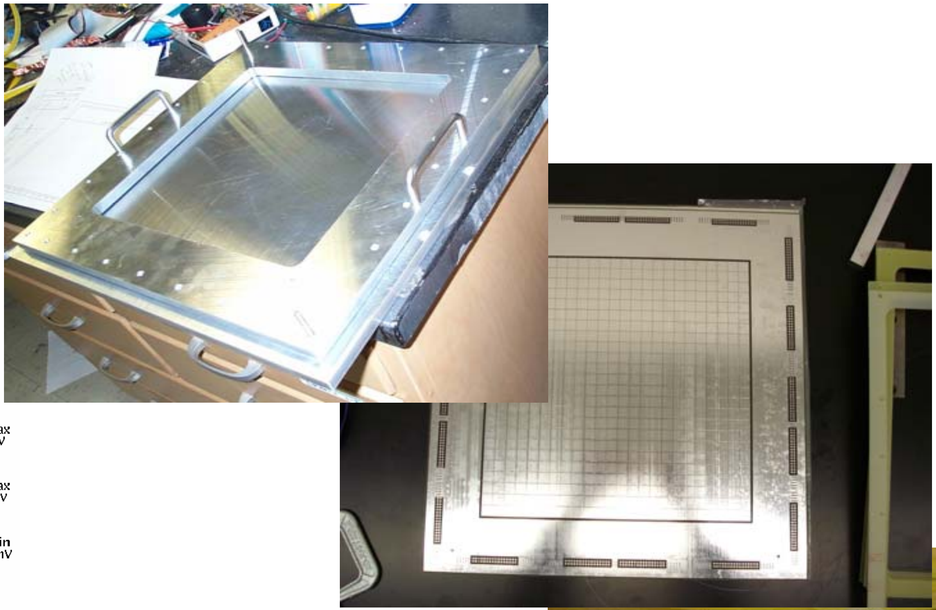
Hadron Calorimeter – CALICE/digital

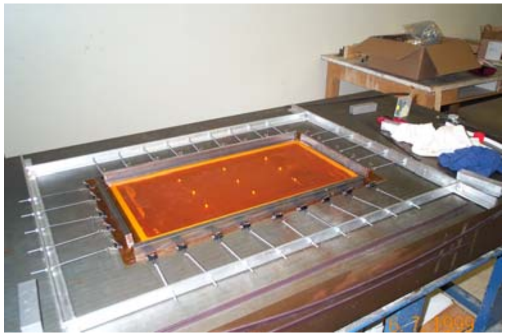


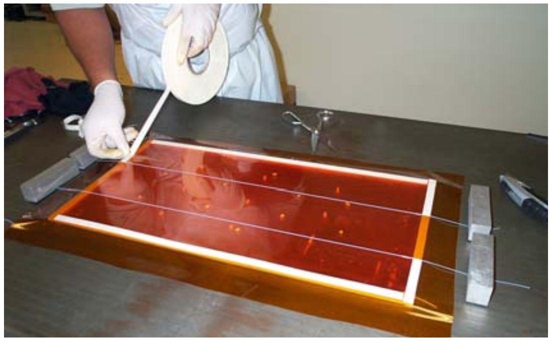


Cross talk studies

Average multiplicity = 1.27, for efficiency = 95%



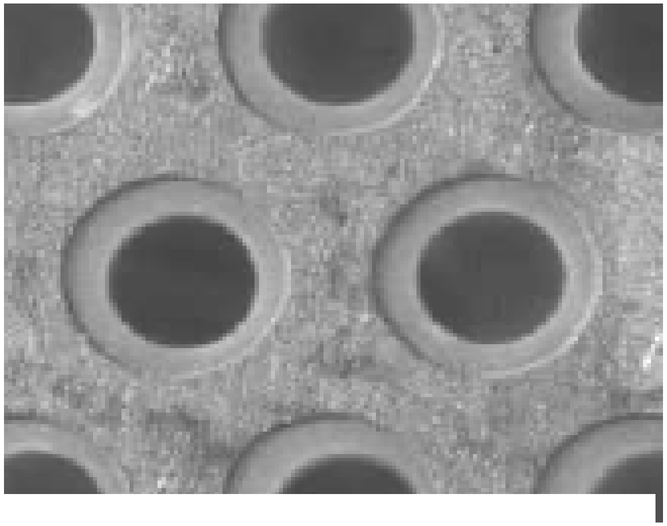


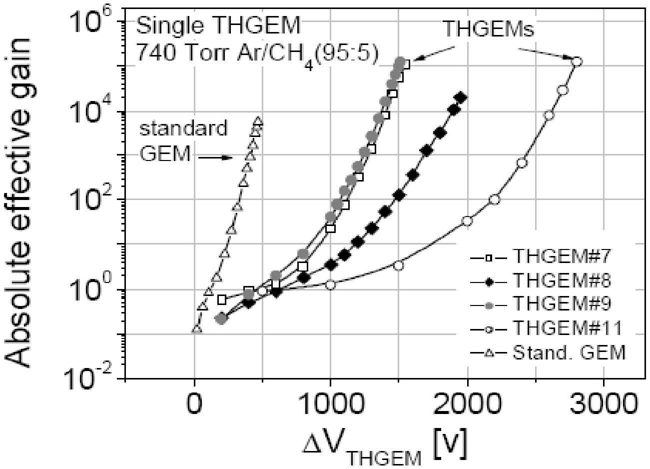


Assembly techniques for large scale GEM layers

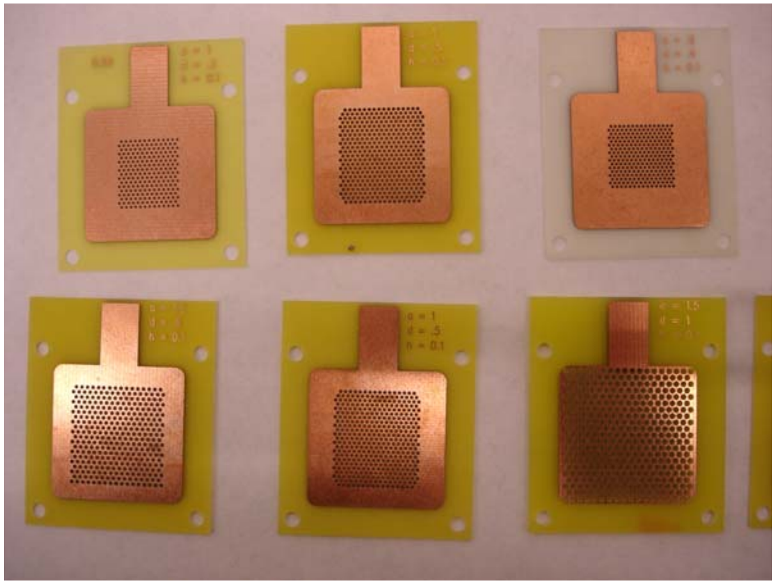
Goal: Test beam at Fermilab 2007/8

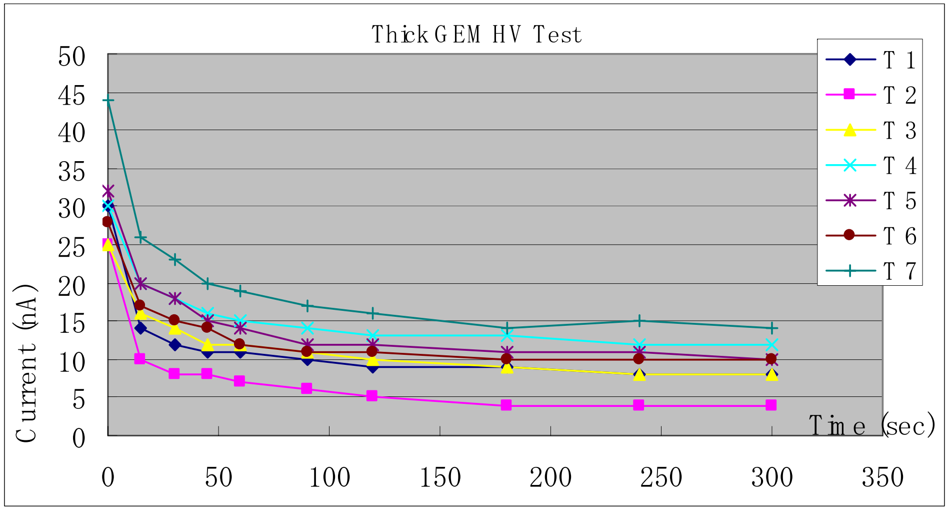
A possible alternative to thin GEM foils – thick GEM's.





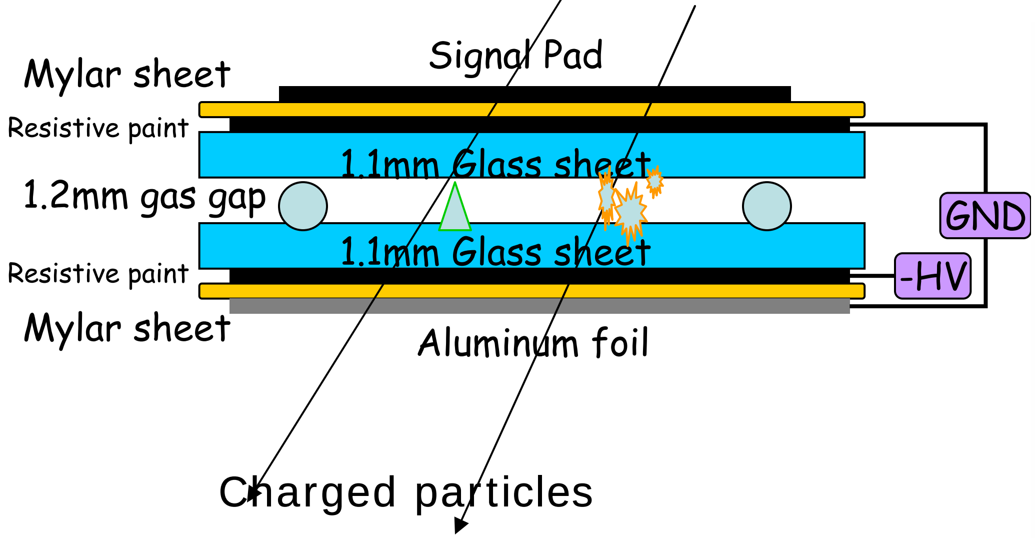
TGEM's from Weizman Inst.

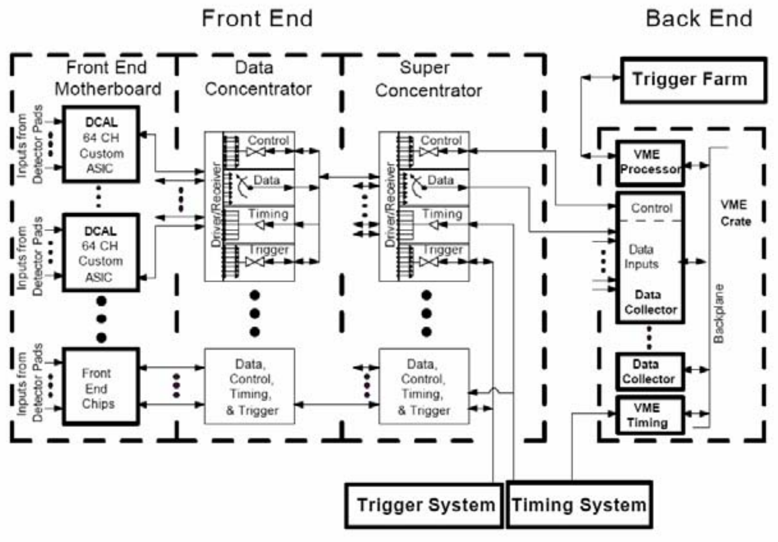


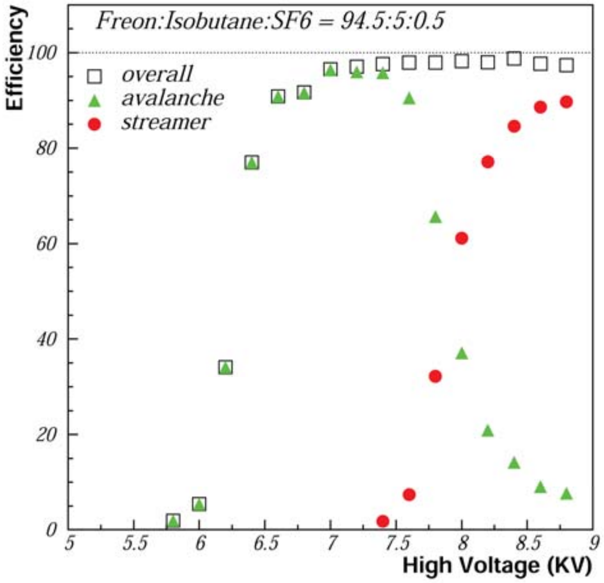


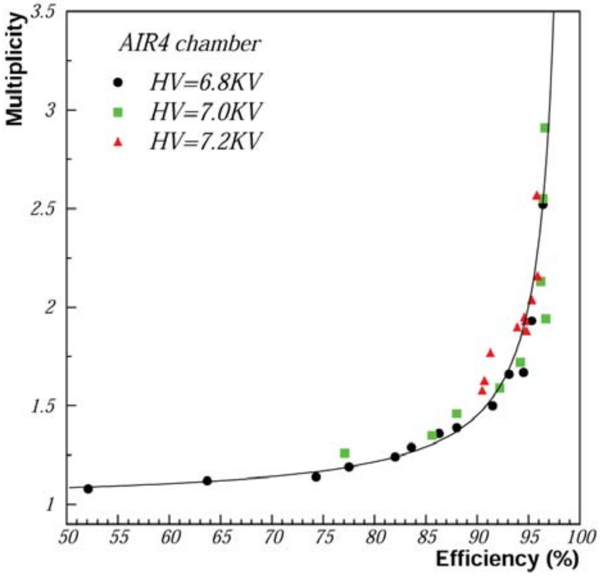
Hadron Calorimeter – CALICE/digital

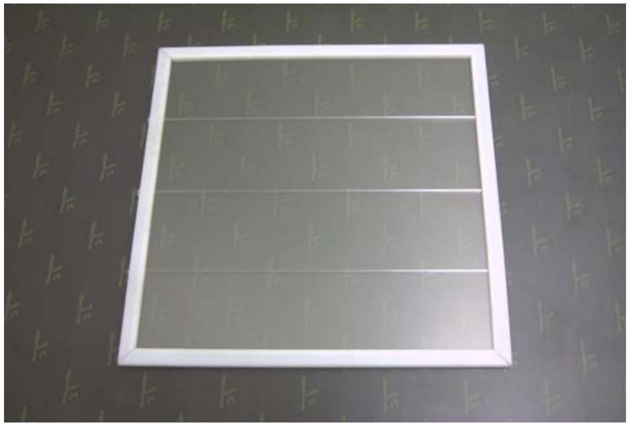
(2) Resistive Plate Chamber-based DHCAL











Using the new calorimetry –
Particle Flow Algorithms

Assuming that the various contributions to the jet energy resolution are independent, or at least the coherence can be factored into a separate term, then in general:

σ^2[E(jet)] = σ^2[Hadron(charged)] (P_t tracker – excellent)

+ σ^2[electromagnetic] ($\sim 15\%/\sqrt{E}$)

+ σ^2[Hadron(neutral)] (relies on Hits vs. Energy)

+ σ^2[“Confusion”] *(depends on PFA details!)*

Preliminaries/systematic effects for DHCAL

Ron Cassell (SLAC) has looked at various active media and absorbers, e.g.

1) Gas/scintillator active media differences

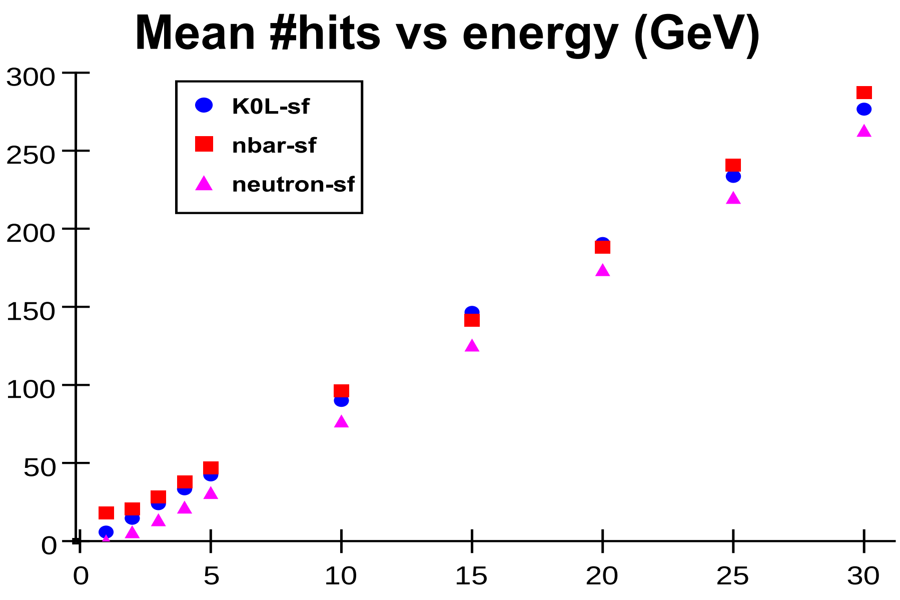
More hits /particle for scintillator – advantage??

2) Particle/Anti-particle differences: n vs. n-bar?

3) Charged vs. neutral e.g. neutron vs. proton

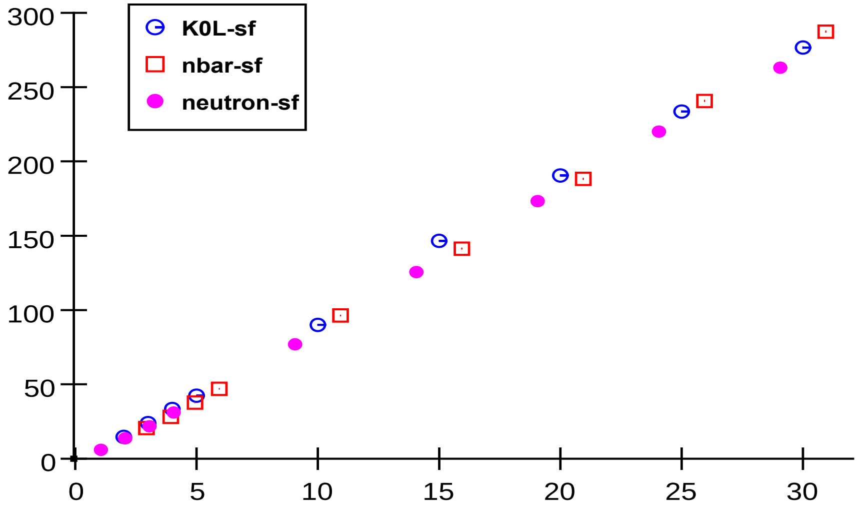
These effects in the basic response of digital calorimeters must be understood for effective PFA development.

Particle/Anti-particle differences: n vs. n-bar?



Mean #hits vs scaled E (GeV)

$E_n = E - m_n$; $E_{nbar} = E + m_{nbar}$; $E_{Klong} = E$



RPC - active medium
Stainless steel absorber

U.Malik/LCWS06 -
Ron Cassell/SLAC

Examples of PFA development

Framework PFA

- Simulated EMCAL, HCAL Hits (SLAC)
  - DigiSim (NIU) X-talk, Noise, Thresholds, Timing, etc.
- EMCAL, HCAL HitMaps
  - Track-Mip Match Algorithm (ANL)
- Modified EMCAL, HCAL HitMaps
  - MST Cluster Algorithm (Iowa)
    - H-Matrix algorithm (SLAC, Kansas) -> Photons
- Modified EMCAL, HCAL HitMaps
  - Nearest-Neighbor Cluster Algorithm (SLAC, NIU)
    - Track-Shower Match Algorithm (ANL) -> Tracks
- Modified EMCAL, HCAL HitMaps
  - Density-weighted Cluster Algorithm (NIU, ANL)
    - Neutral ID Algorithm (SLAC, ANL) -> Neutral hadrons
- Modified EMCAL, HCAL HitMaps
  - Post Hit/Cluster ID (leftover hits?)

- Tracks, Photons, Neutrals to jet algorithm

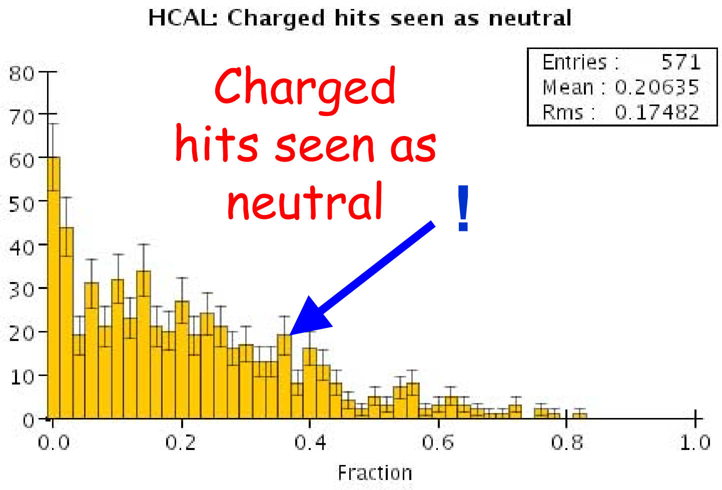
From S.Magill/Jan 2006
“Flexible PFA structure”

\+ Topologic Approach – “PandoraPFA” (Mark Thomson/U.Cambridge)

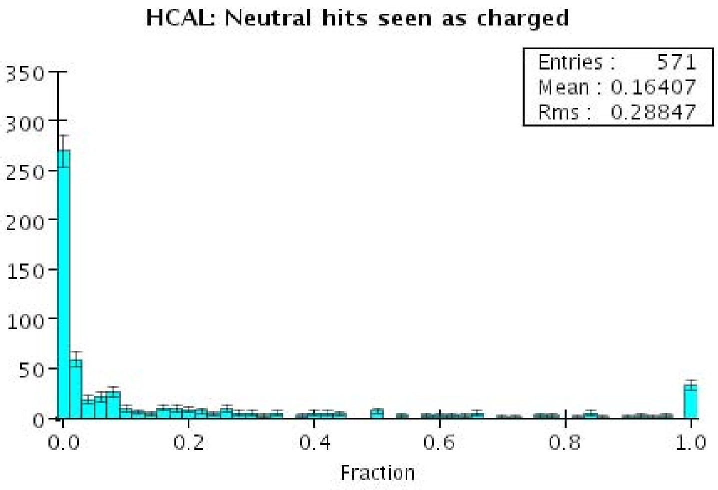
Iowa's Algorithm

- Start with finding track-segments in Ecal and/or Hcal (real MIPs and charged secondaries)
- Remove their hits
- Find EM showers and remove their hits
  - Can use various algorithms, e.g. MST, NN, Fixed Cone, …
- Find dense clumps and remove their hits
- Find large-scale hadronic showers with the MST
  - Cluster remaining hits plus track segments & clumps with MST
- Examine internal structure of hadronic showers
  - Try to link clumps & track segments together (likelihood selector)
  - Look for adjacent/overlapping clusters
- Helix extrapolation of tracks (from tracker) to Ecal to match track-segment and/or cluster.
- Identify and merge fragments (different from primary clusters)
- Get primary showering energies and id's

Example results (Iowa)


HCAL: Charged hits seen as neutral

Charged hits seen as neutral !


HCAL: Neutral hits seen as charged

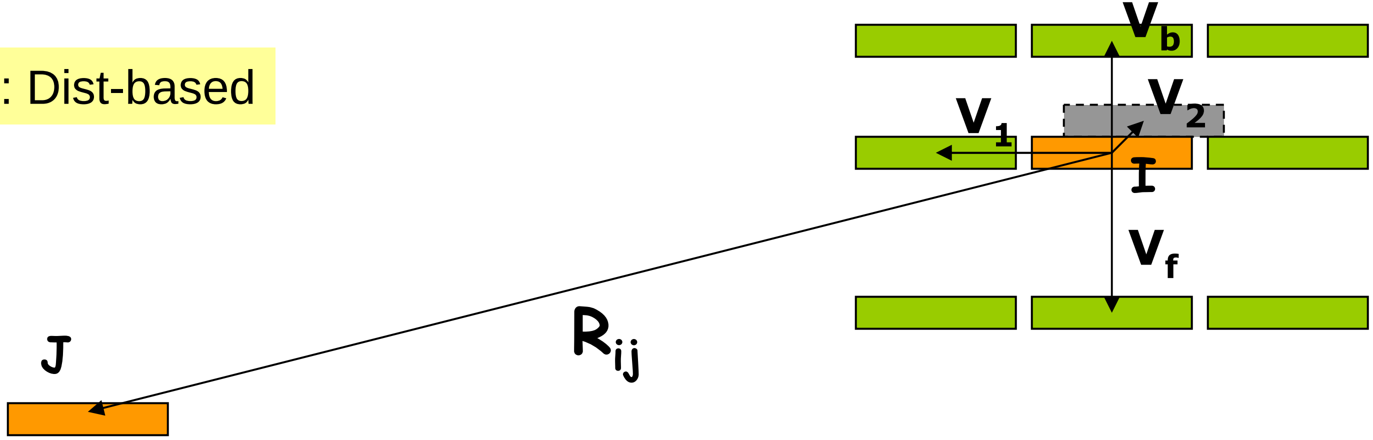
Z-pole results

Without cheating:	$\sigma/E = 49\%/\sqrt{E}$
Cheating in fragment finding:	$\sigma/E = 31\%/\sqrt{E}$
Perfect pattern recognition:	$\sigma/E = 21\%/\sqrt{E}$

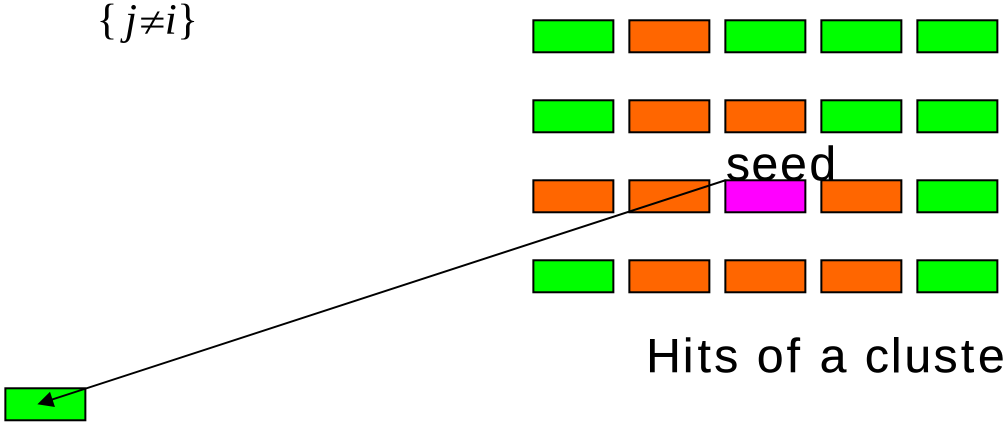
Other approaches to PFA components

V. Zutshi (NIU)

Clustering: Dist-based



$$D_i = \sum_{\{j \neq i\}} \left(e^{-(|\vec{V}_1 \bullet \vec{R}_{ij}|/|\vec{V}_1|^2)} \times e^{-(|\vec{V}_2 \bullet \vec{R}_{ij}|/|\vec{V}_2|^2)} \times e^{-(|\vec{V}_3 \bullet \vec{R}_{ij}|/|\vec{V}_3|^2)} \right)$$

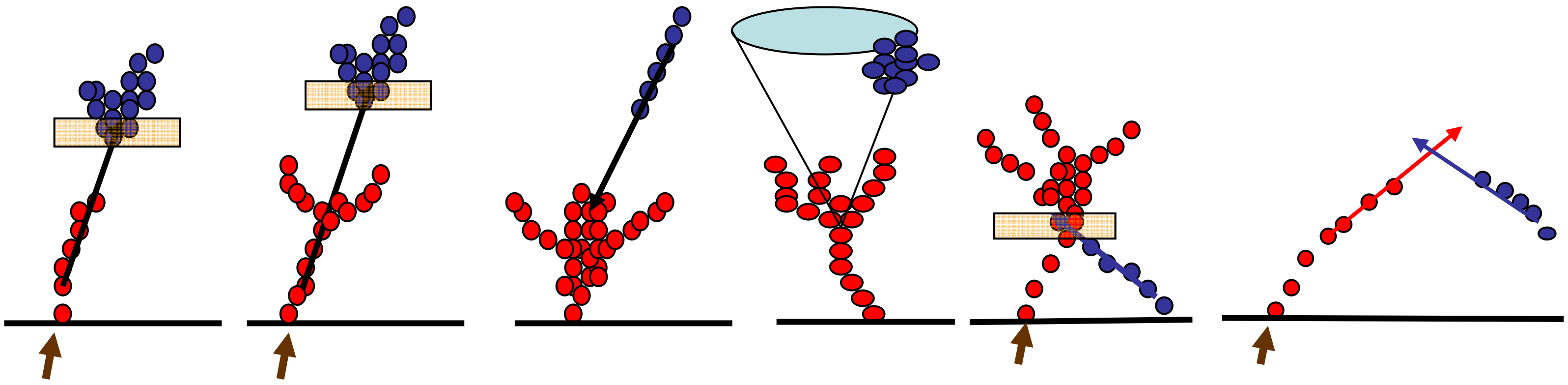


Hits of a cluster based on D_i

Hit been considered

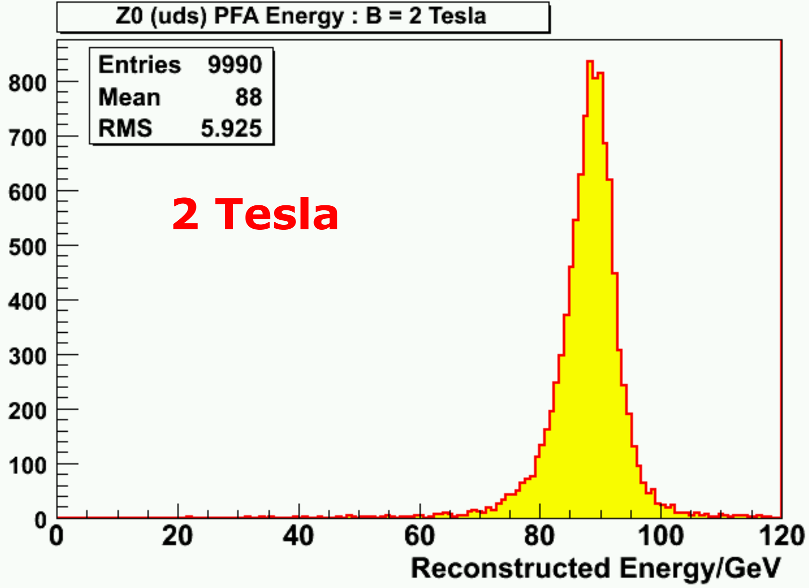
Topologic Approach – Mark Thompson

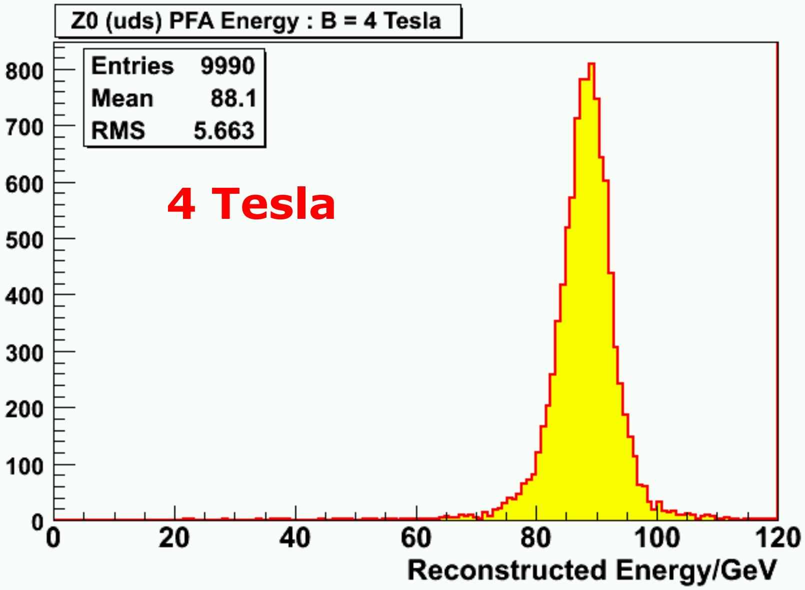
- **Preparation**
  - Isolation cuts, hit ordering, track quality
- **Initial clustering to form ProtoClusters**
  - ProtoClusters are heavyweight object:
    - collection of hits
    - +much more (not all used)…
- **Cluster association/merging**
  - Tight Topological linking of clusters
  - Looser merging of clusters
  - Track-driven merging
- **PFA**
  - Final track-cluster matching

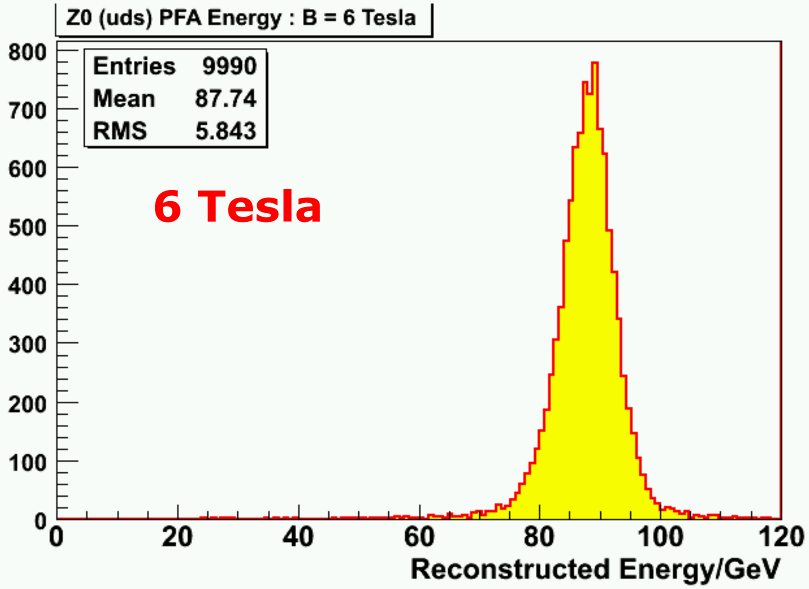


Topologic Approach – Mark Thompson

Preliminary Results : Z →uds events







- **RMS of Central 90 % of Events**

B-Field	**$\sigma_E/E = \alpha\sqrt{(E/GeV)}$**
2 Tesla	**37.8±0.4%**
4 Tesla	**35.9±0.4 %**
6 Tesla	**37.4±0.4 %**

- **only weakly depends on B**

SLAC/ANL Algorithm

1st step – Track-linked mip segments (ANL)

-> find mip hits on extrapolated tracks, determine layer of first interaction based solely on cell density

2nd step - Photon Finder (SLAC, Kansas)

-> use analytic longitudinal H-matrix fit to layer E profile with ECAL clusters as input

3rd step – Track-linked EM and HAD clusters (ANL, SLAC)

-> substitute for Cal objects (mips + ECAL shower clusters + HCAL shower clusters), reconstruct linked mip segments + clusters iterated in E/p

-> Analog or digital techniques in HCAL

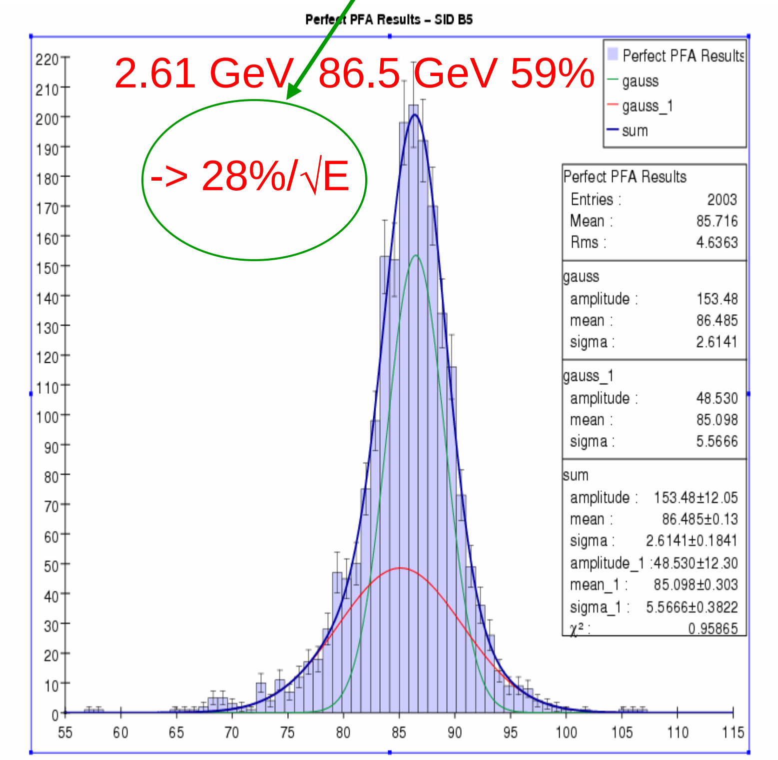
4th step – Neutral Finder algorithm (SLAC, ANL)

-> cluster remaining CAL cells, apply neural net to ID clusters

5th step – Jet algorithm

-> tracks + photons + neutral clusters used as input to jet algorithm

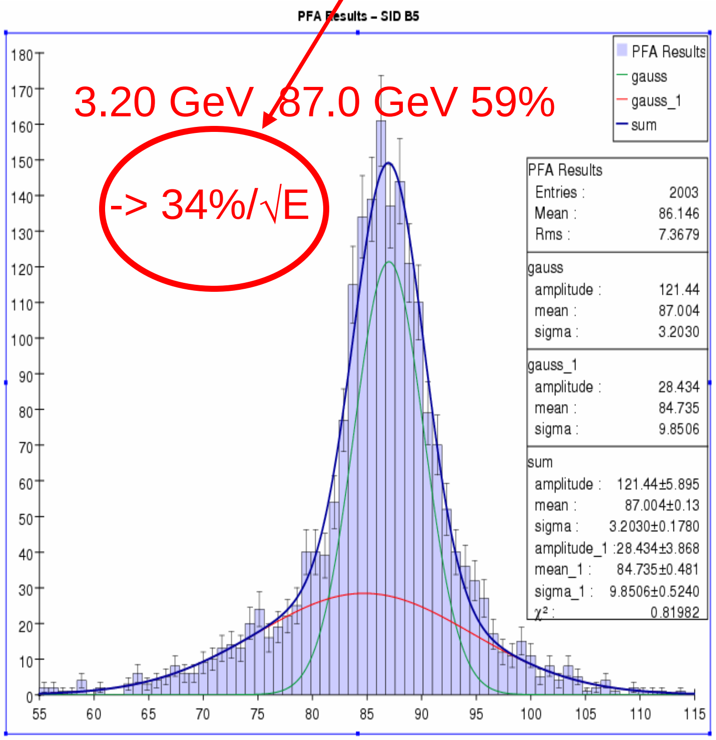
Correct track/cluster association
– perfect pattern recognition



2.61 GeV 86.5 GeV 59%

-> 28%/√E

Present status!



3.20 GeV 87.0 GeV 59%

-> 34%/√E

Average confusion contribution = 1.9 GeV <~ Neutral hadron resolution contribution of 2.2 GeV -> approaching PFA goal*

Note: Higher percentage in central region -> less overlap W/Z

The opposite correlates to an effective LOSS OF LUMINOSITY!

PFA - Issues

- Can we achieve 30%/√E for events with many high energy jets?

- Can we find an algorithm to successfully handle all the large event-to-event fluctuations and minimize the mistaken energy assignments/confusion term? …and thereby increase the fraction of events in central peak?

- Can we get agreement between test beam data and GEANT4?

- How can we best use the test beam/1m^3 setup to check inputs to PFA development and predict likely performance of future detector(s)?

Hardware/software development for ILC/PFA is a fascinating challenge – stay tuned…!!

Extra Slides

The Particle Flow Approach

Particle Flow approach holds promise of required solution – *but still remains to be proved for the Linear Collider!*

-> Use tracker to measure Pt of dominant, charged particle energy contributions in jets; photons measured in ECal.

-> Need efficient separation of different types of energy deposition throughout calorimeter system

-> Energy measurement of only the relatively small neutral hadron contribution de-emphasizes intrinsic energy resolution, but highlights need for very efficient "pattern recognition" in calorimeter.

-> Measure (or veto) energy leakage from calorimeter through coil into muon system with "tail-catcher".

Calorimeter system/overall detector design

TWO APPROACHES:

- Large inner calorimeter radius -> achieve good separation of e, γ, charged hadrons, jets,…

  Matches well with having a large tracking volume with many measurements, good momentum resolution (BR^2) with moderate magnetic field, B ~2-3T

  But… calorimeter and muon systems become large and potentially very expensive…

  However…may allow a "traditional" approach to calorimeter technology(s)??

  EXAMPLES: Large Detector, GLD,…?

Calorimeter system/overall detector design

- Compact detector – reduced inner calorimeter radius.

Use Si/W for the ECal -> excellent resolution/separation of γ/charged. Constrain the cost by limiting the size of the calorimeter (and muon) system.

This then requires a compact tracking system -> Silicon only with very precise (~10μm) point measurement.

Also demands a calorimeter technology offering fine granularity -> restriction of technology choice ??

To restore BR^2, boost B -> 5T (stored energy, forces? – looks OK in first study)

EXAMPLE: SiD

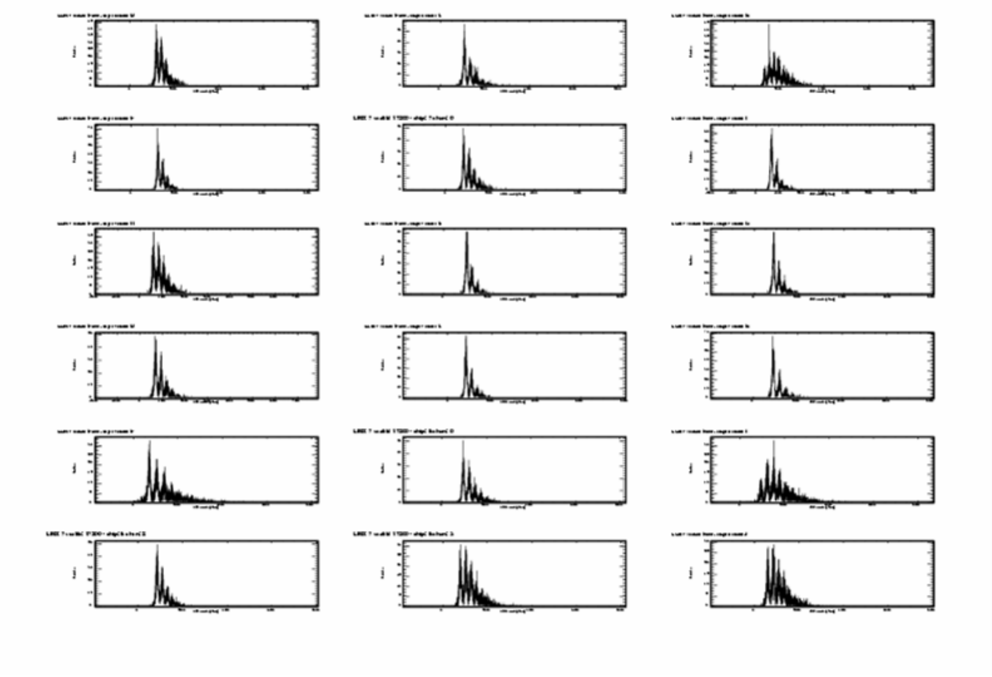
Calibration is a challenge!
…but many problems solved

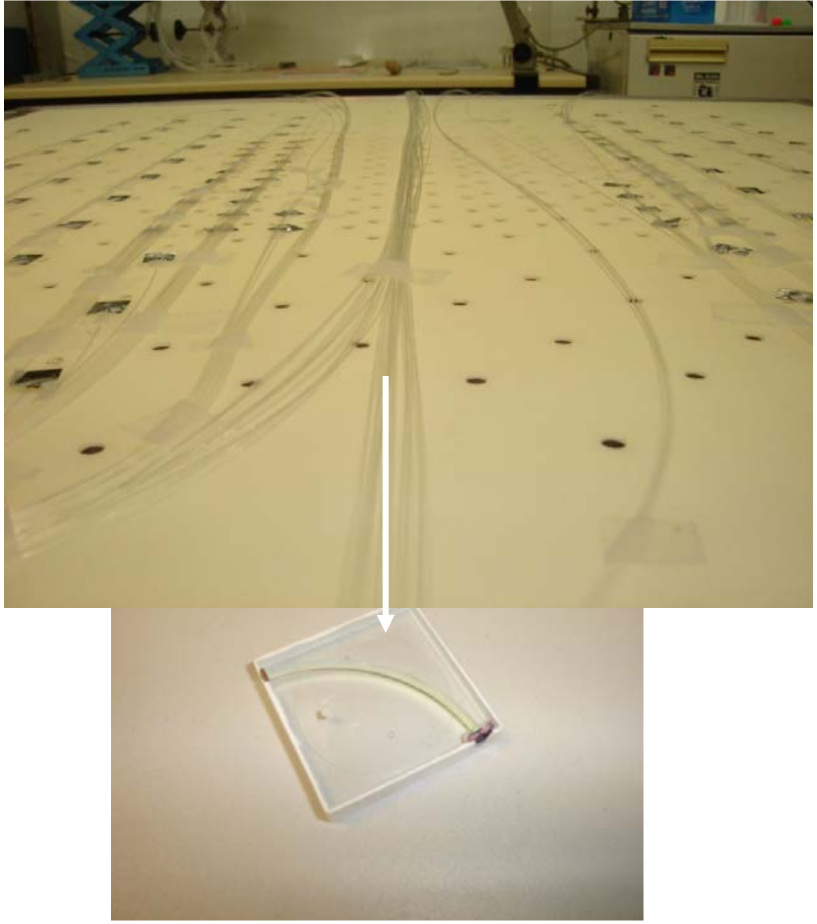
Is the level of calibration accuracy sufficient ?

How to get MIP calibration in the ILC calorimeter ?

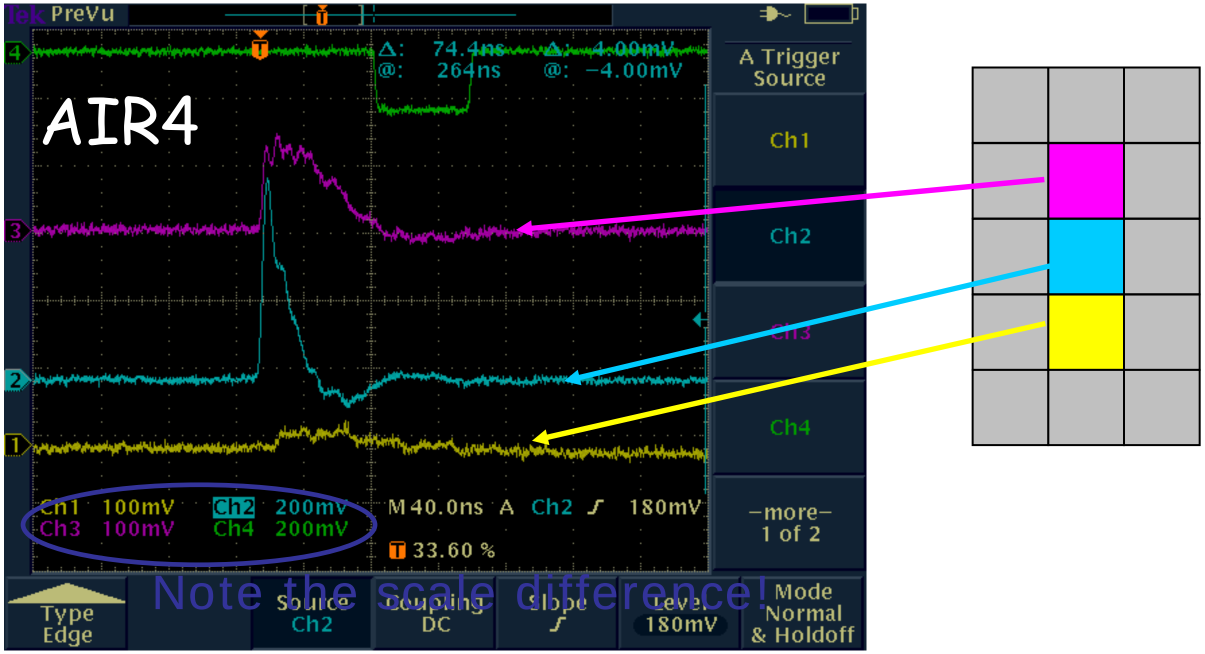
UV light 500 LED’s simultaneous flash – highly uniform

18 SiPM – one LED





Hadron Calorimeter - CALICE/digital



AIR4

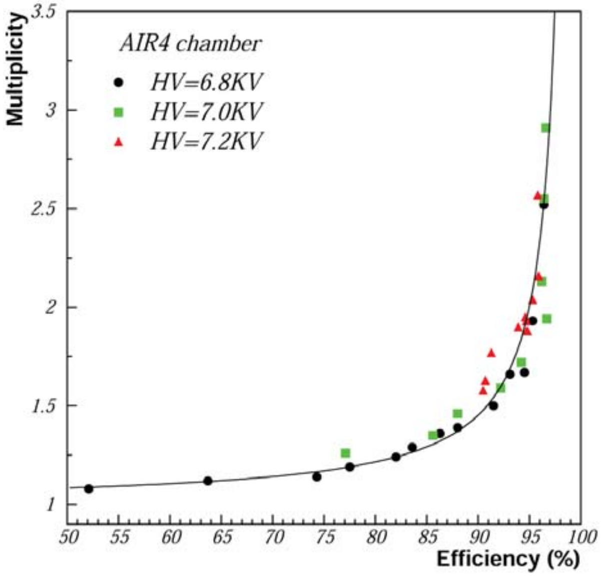
Δ: 74.4ns Δ: 4.00mV
@: 264ns @: −4.00mV

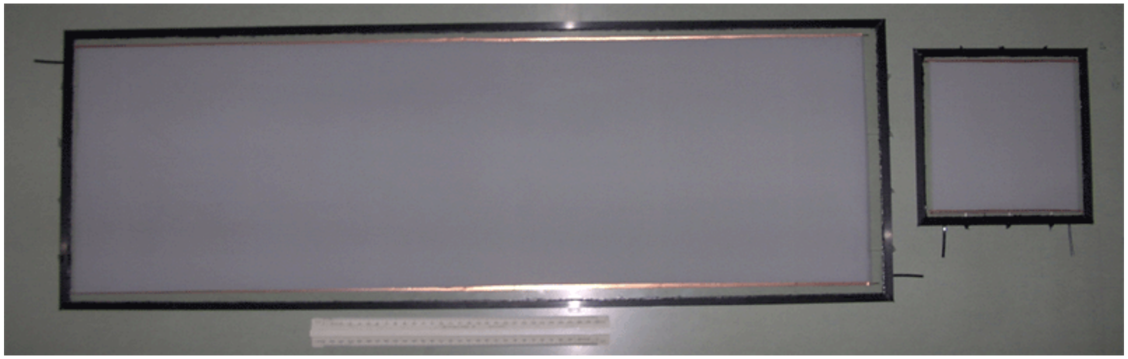
Ch1 100mV Ch2 200mV
Ch3 100mV Ch4 200mV

M 40.0ns A Ch2 ∫ 180mV

33.60 %

Note the scale difference!

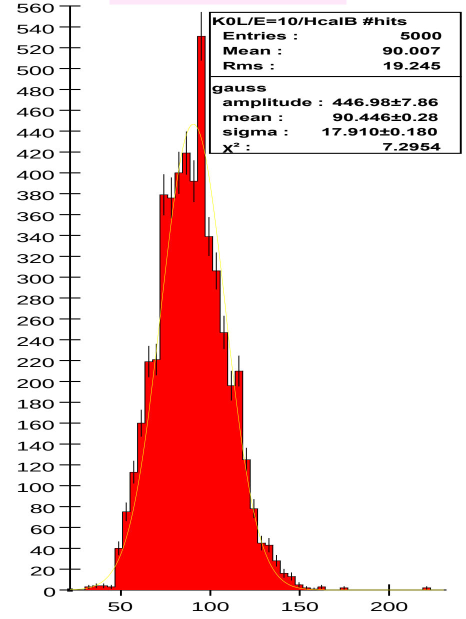




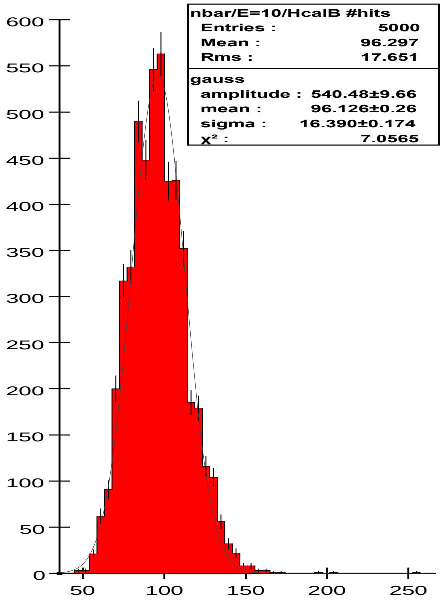
"RPC's totally understood - ready to build RPCs for the 1m3 test beam section"

Goal: Test beam at Fermilab 2007

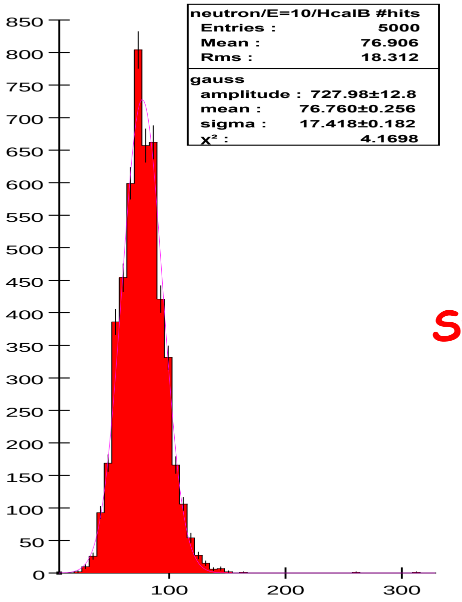
10 GeV K_L



10 GeV nbar



10 GeV n

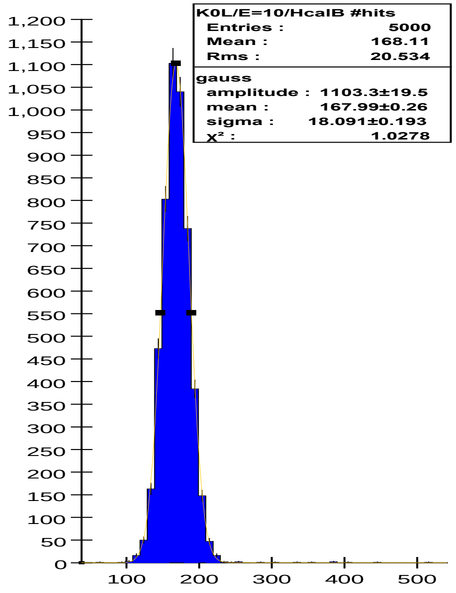


Stainless steel RPC

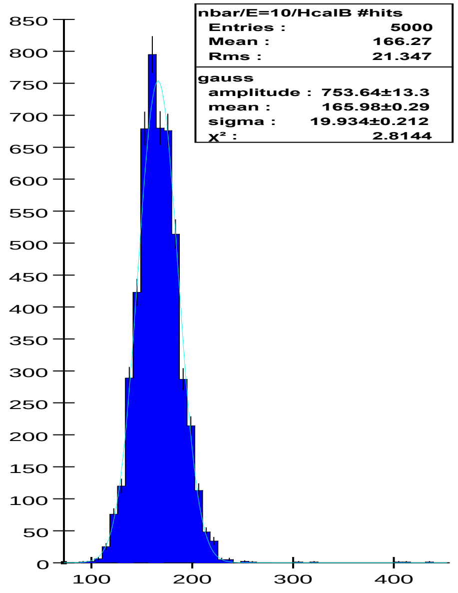
SSRPC

x-axis: # hits

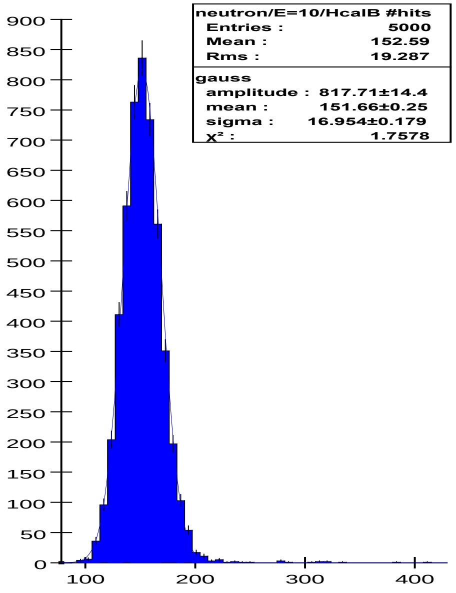
10 GeV K_L



10 GeV nbar



10 GeV n

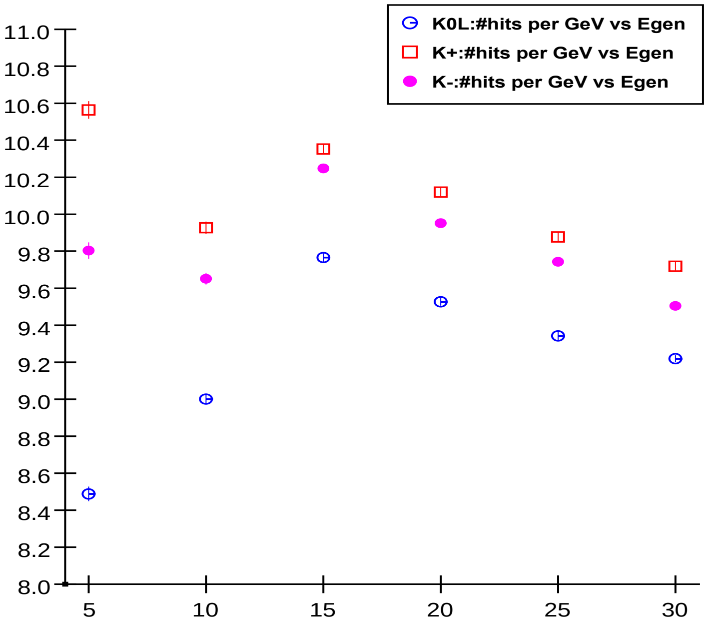


Stainless steel scintillators:

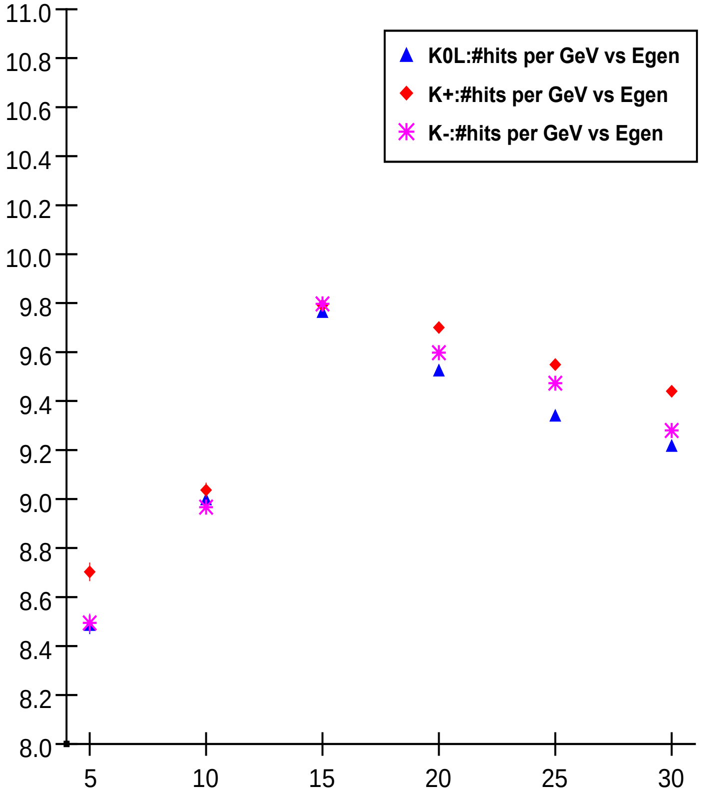
SSScint

U.Malik/LCWS06

Cal Response to Charged vs Neutral (30 m Hcal)



Allow for charged hadrons giving hits before showering



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