An alternative determination of the LEP beam energy
&
Calorimetry for the ILC

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Part 1: An alternative determination of the LEP beam energy

- Why verify the beam energy?
- The standard approach.
- The alternative approach:
  - method;
  - systematic errors;
  - results;
  - conclusions.

Why determine the beam energy accurately?

- Accurate knowledge of beam energy (E_b) important for many precision measurements at LEP.
- Relevant for measurement of $\int \mathcal{L}dt$ via Bhabha cross-section $\propto 1/E_b^2 \Rightarrow$ fundamental to all cross-section determinations:

$$\frac{\Delta\sigma}{\sigma} = \frac{2\Delta E_b}{E_b} .$$

- Vital for accuracy of m_W measurement—a main objective of LEP II program → resolution improved through kinematic fit constraints:

$$\frac{\Delta m_W}{m_W} = \frac{\Delta E_b}{E_b} .$$

The standard LEP energy calibration

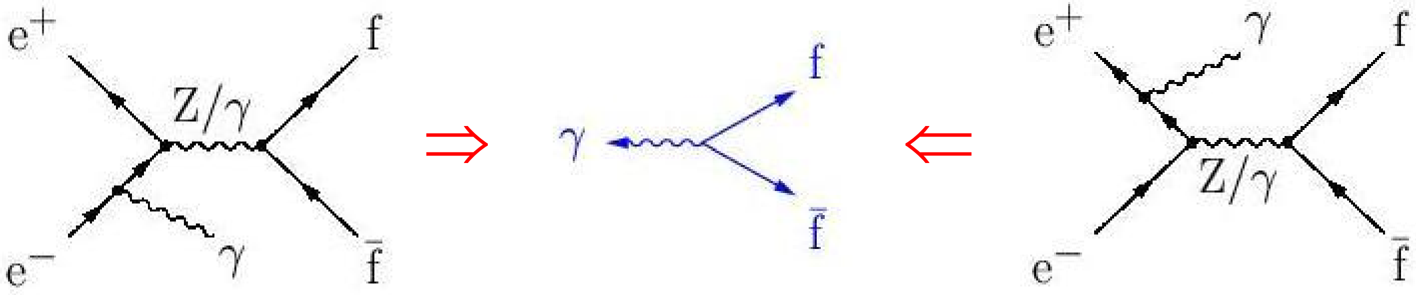
- Measured at LEP I energies (E_b ~ 45 GeV) by resonant depolarization (RDP).
- Relies on ability to generate LEP beams with detectable spin polarizations.
- Polarization can be destroyed by oscillating B-field when in phase with spin precession.
- At resonance, can infer the "spin-tune", ν:

$$\nu = \frac{f_{\mathrm{prec}}}{f_{\mathrm{rev}}} = \frac{g_e - 2}{2} \cdot \frac{E_b}{m_e c^2}$$

- RDP works up to E_b ~ 60 GeV, but fails at LEP II energies (E_b ~ 100 GeV).
- At LEP II, fit lower energy RDP measurements with $E_b = a + bB$; deduce E_b from B-field (using NMR probes) at physics energies → magnetic extrapolation.
- Yearly uncertainty on E_b ~ 20 MeV; is this reliable?

The radiative return approach

- Select fermion-pair events which exhibit "radiative return to the Z" (resonant enhancement)…



…and construct:

$\sqrt{s'}$ = $f\bar{f}$ invariant mass ($f = q, e^-, \mu^-, \tau^-$)
= Z/γ propagator mass
= centre-of-mass energy after initial-state radiation (ISR).

- $\sqrt{s'}$ sensitive to E_b through energy and momentum constraints in kinematic fits.
- Use events with $\sqrt{s'} \sim m_Z$ to reconstruct 'pseudo'-Z peak in MC (E_b known exactly) and in data (E_b inferred by measurement).
- Attribute any relative shift between peaks to a discrepancy in the measurement of the beam energy: ΔE_b.

$\sqrt{s'}$ reconstruction

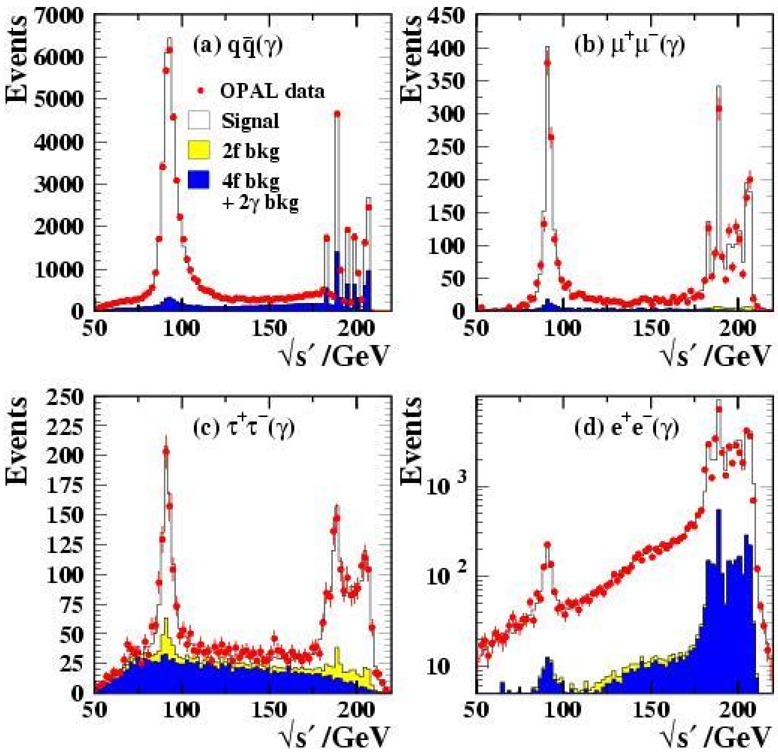
- Hadronic channel:
  - Invoke standard hadronic selection.
  - Identify all isolated photons.
  - Force remaining system into jets (Durham scheme).
  - Apply kinematic fit without/ with unseen photon(s) along ±z, using jet energies and angles, and $(E, \vec{p})$ conservation.
  - Retain events with exactly one reconstructed photon (either in Ecal or along ±z).
  - Compute $\sqrt{s'}$ from jet energies and momenta:

    $\sqrt{s'} = m_{\text{jet-jet}}$.
- Leptonic channels:
  - Invoke standard leptonic selection.
  - Identify highest energy isolated photon; if no photons found, assume one along ±z.
  - Treat event as having 3 final-state particles: $\ell^+\ell^-\gamma$.
  - Compute $\sqrt{s'}$ from angles alone, imposing $(E, \vec{p})$ conservation:

$$\frac{s'}{s} = \frac{\sin\chi_1 + \sin\chi_2 - |\sin(\chi_1+\chi_2)|}{\sin\chi_1 + \sin\chi_2 + |\sin(\chi_1+\chi_2)|}.$$

Reconstructed $\sqrt{s'}$ distributions

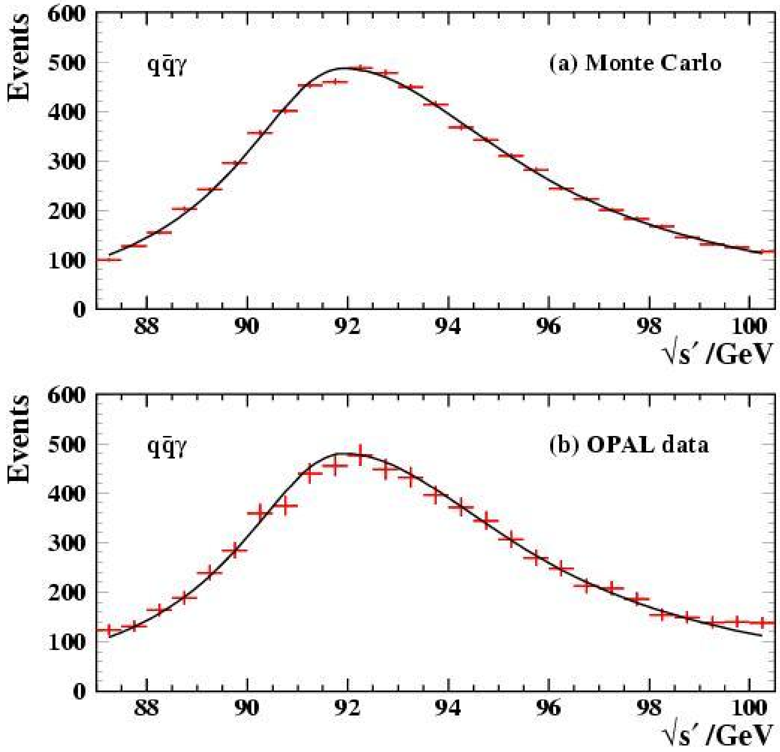
- 1997–2000 OPAL data:

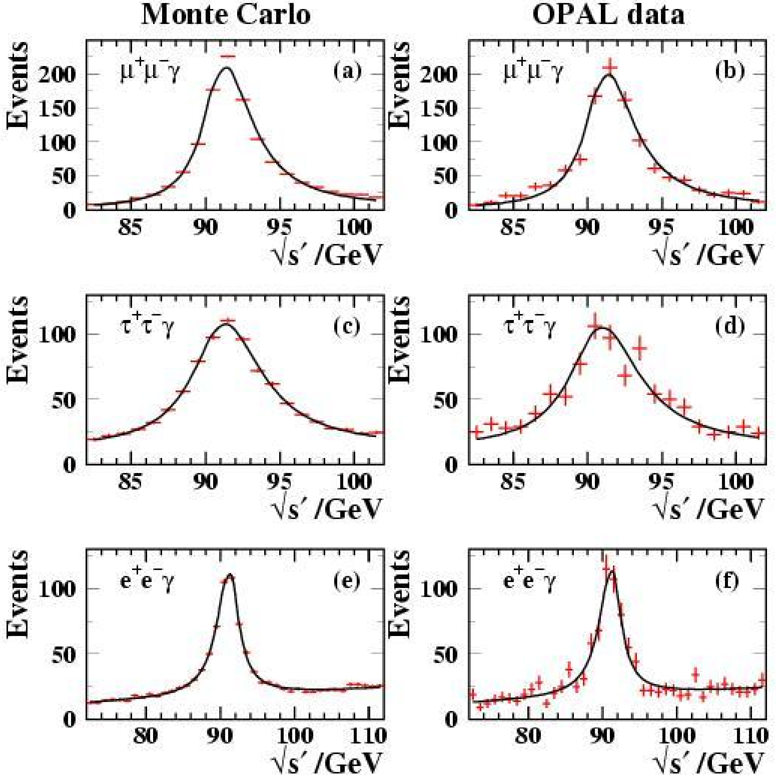


- Dominated by radiative-return and full-energy events.
- (a) $q\bar{q}\gamma$: high statistics, b/g ~ 4 % under peak → mainly $q\bar{q}e^+e^-$ (resonant); $\sqrt{s'}$ resolution ~ 2 GeV.
- (b) $\mu^+\mu^-\gamma$: lower statistics, but very low b/g and excellent angular resolution.
- (c) $\tau^+\tau^-\gamma$: low efficiency, worse resolution and larger b/g.
- (d) $e^+e^-\gamma$: small signal, dwarfed by *t*-channel contribution.

Fitting the peak

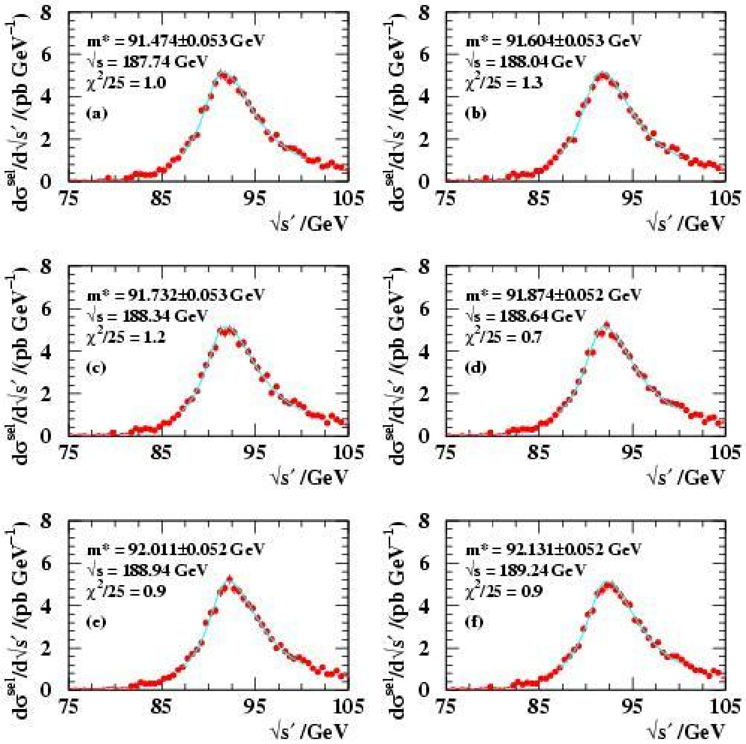
- Analytic function fitted to reconstructed $\sqrt{s'}$ distribution in MC at known $E_b = E_b^{MC}$ around ‘pseudo’-Z peak.
- Same function fitted to reconstructed $\sqrt{s'}$ distribution in data, assuming $E_b = E_b^{LEP}$ (normalization/peak position free to vary).

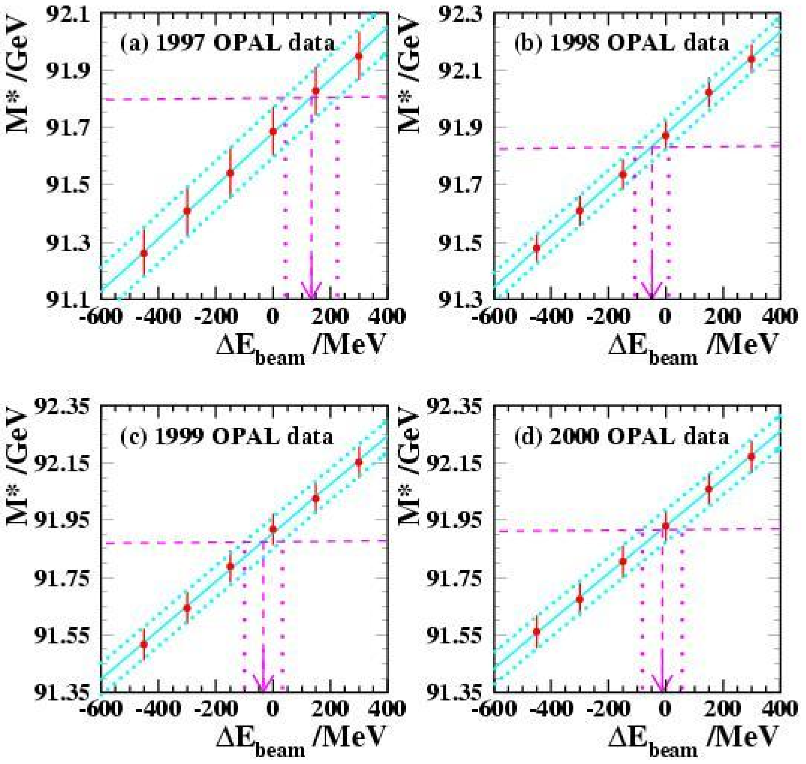




Extraction of beam energy (e.g. $q\bar{q}\gamma$ channel)

- Repeat function fitting in data as a function of assumed discrepancy, $\Delta E_b = E_b^{OPAL} - E_b^{LEP}$ (= −450, −300, −150, 0,+150,+300 MeV); use peak position (M^*) to characterize overall √s′ energy scale. E.g. 1998 data:





- Extract optimum value of ΔE_b where M^* in data matches MC expectation.

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Dominant systematic errors

- Hadronic channel:

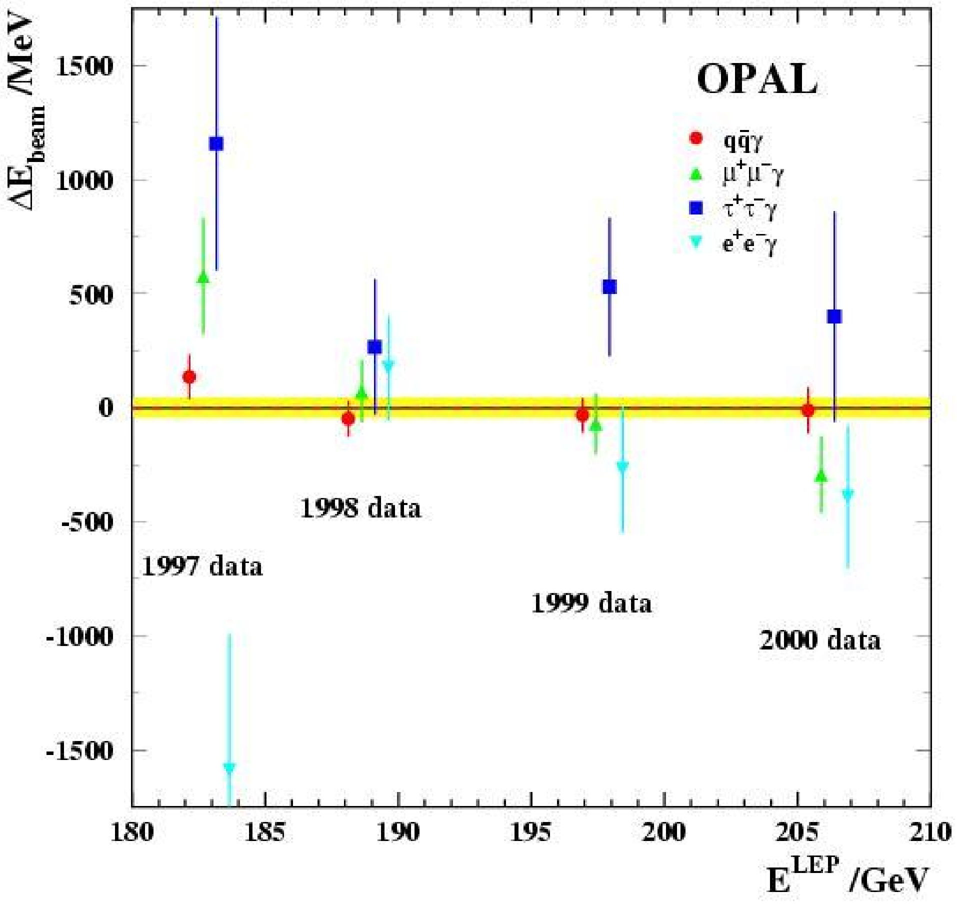
Effect	**Error /MeV**
Detector modelling	34
(jet mass scale	25)
(jet energy scale	17)
(photon energy scale	12)
(jet angular scale	9)
(other	7)
Fragmentation/hadronization	16
Fit parameters	3
ISR modelling	3
Backgrounds	1
I/FSR interference	1
Beam energy spread/boost	1
Total	**38**
Monte Carlo statistics	5
LEP calibration	11
Full Total	**40**

- Leptonic channels:

Effect	**Error /MeV**		
	$\mu^+\mu^-\gamma$	$\tau^+\tau^-\gamma$	$e^+e^-\gamma$
Lepton angular scale	21	66	24
Lepton angular resolution	2	4	7
Fit parameters	1	4	10
ISR modelling	1	7	10
Non-resonant background	< 1	6	4
Bhabha/*t*-channel	< 1	3	5
Beam energy spread/boost	2	5	6
Total	**21**	**67**	**30**
Monte Carlo statistics	9	34	34
LEP calibration	11	11	11
Full Total	**25**	**76**	**46**

Beam energy measurements

- 1997–2000 OPAL data:



- All $q\bar{q}\gamma$ data:
  $\Delta E_b = +1 \pm 38 \pm 40$ MeV.
- All $\ell^+\ell^-\gamma$ data:
  $\Delta E_b = -2 \pm 62 \pm 24$ MeV.
  - all $\mu^+\mu^-\gamma$ data:
    $\Delta E_b = -32 \pm 75 \pm 25$ MeV.
  - all $\tau^+\tau^-\gamma$ data:
    $\Delta E_b = +313 \pm 175 \pm 76$ MeV.
  - all $e^+e^-\gamma$ data:
    $\Delta E_b = -88 \pm 146 \pm 46$ MeV.
- All $f\bar{f}\gamma$ data combined:
  $\Delta E_b = 0 \pm 34 \pm 27$ MeV.

Conclusions

- Beam energy from radiative fermion-pairs consistent with standard LEP calibration

  ⇒ vindication for magnetic extrapolation procedure;

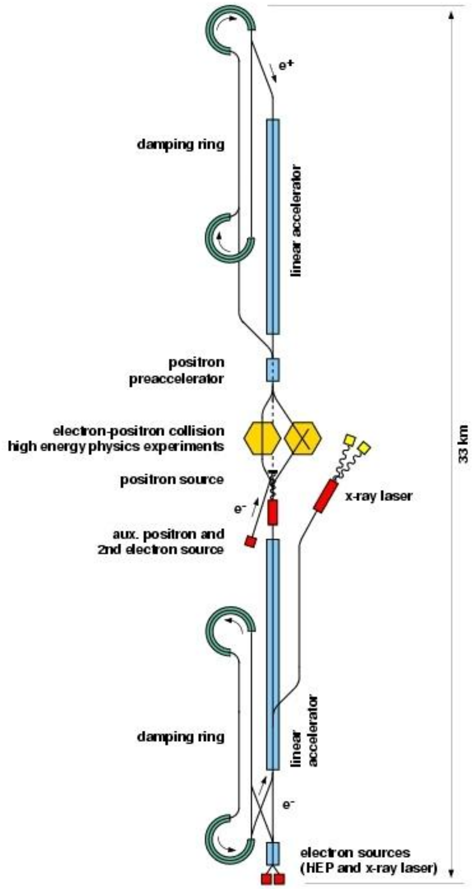
  ⇒ good news for m_W determination.
- Systematic uncertainties 38 ($q\bar{q}\gamma$), 21 ($\mu^+\mu^-\gamma$), 67 ($\tau^+\tau^-\gamma$), 30 ($e^+e^-\gamma$) MeV; cf. ~ 20 MeV error on magnetic extrapolation.
- For more info, see **Phys. Lett. B 604, 31 (2004)**.
- Standard LEP approach requires circulating beams; not appropriate for a linear collider.
- Radiative return approach independent of accelerator specs → potential method for measuring E_b at a high-statistics future linear collider: the ILC.
- Possibility under investigation…

Part 2: Calorimetry for the ILC

- Why do we need the ILC?
- The physics objectives.
- The calorimeter requirements & how to achieve them.
- The CALICE program:
    - overview;
    - prototypes & test beams;
    - simulation;
    - reconstruction.

The International Linear Collider (ILC)

- Widespread worldwide support for an e^+e^- linear collider operating at $\sqrt{s}$ = 0.5–1 TeV.
- August '04: International Technology Review Panel recommended adoption of superconducting (TESLA-like) technology for the accelerator.
- Asia, Europe and North America lined up behind decision; agreed to collaborate on technical design.
- Timescale for physics set by ILC Steering Group
  - first collisions ~ 2015;
  - detector TDRs in 2009;
  - formation of experimental collaborations in 2008.
- Much to be done in next 3 years!



ILC/LHC synergy

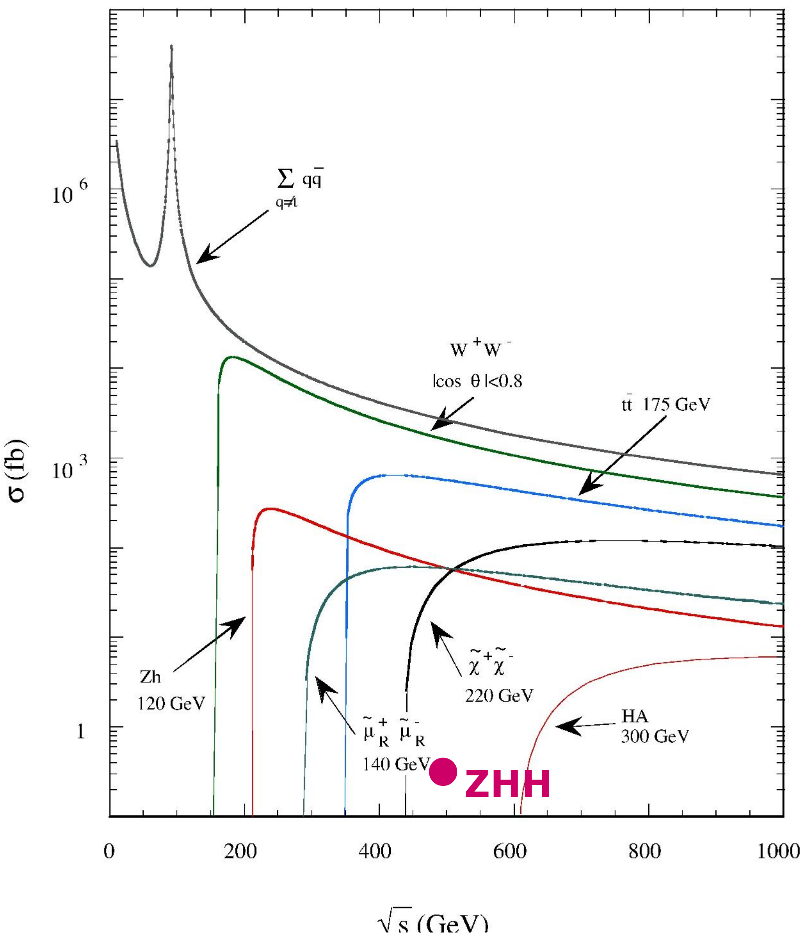
- ILC will provide precision measurements (masses, branching fractions, *etc.*) of physics revealed by LHC:
  - properties of Higgs boson(s);
  - characterization of SUSY spectrum;
  - precision measurements of the top quark;
  - strong electroweak symmetry breaking;
  - much, much more…
- Overlapping running of LHC/ILC beneficial to physics capabilities of both machines (⇒ aim for collisions in 2015).
- Dedicated study group investigating synergy between ILC and LHC [see **LHC-LC Study Group**, **hep-ph/0410364** ~ 500 pages!]

ILC physics objectives

- Many of the "interesting" processes involve multi-jet (6/8 jets) final states, as well as leptons and missing energy.
- Accurate reconstruction of jets key to disentangling these processes.
- Small signals, e.g. $\sigma(e^+e^- \to ZHH) \sim 0.3$ pb at 500 GeV.

  ⇒ require high luminosity.

  ⇒ need detector optimized for precision measurements in a difficult environment.

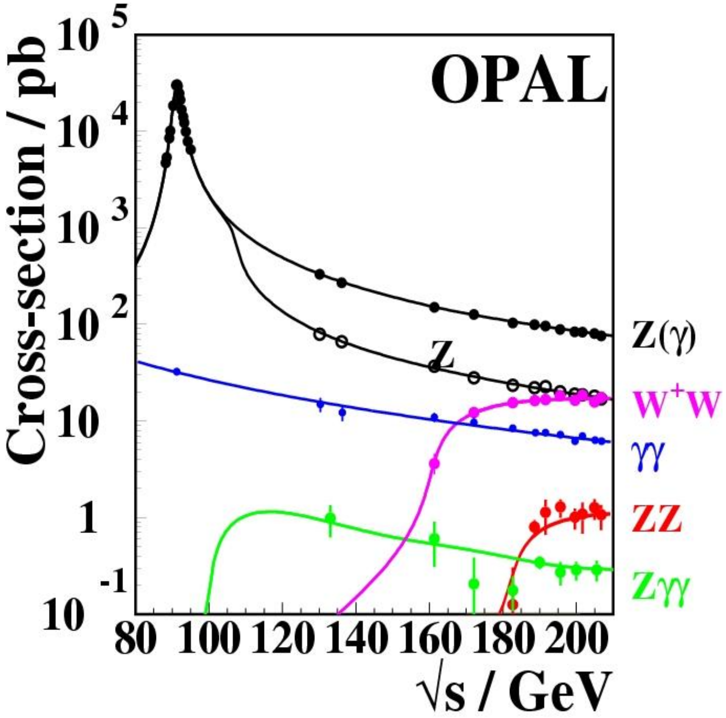


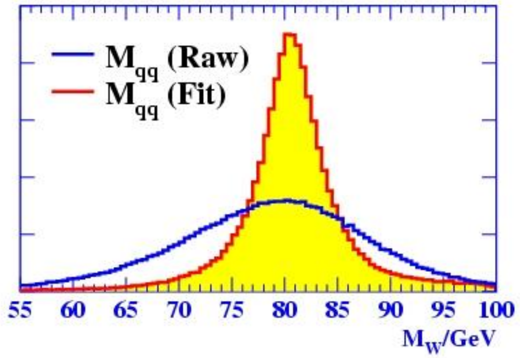
Comparison with LEP

- Physics at LEP dominated by $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$; backgrounds not too problematic.
- Kinematic fits used for mass (*e.g.* m_W) reconstruction ⇒ shortcomings of jet energy resolution surmountable.
- Physics at ILC dominated by backgrounds.
- Beamstrahlung, multi-ν final states, SUSY(?)

  ⇒ missing energy (unknown);

  ⇒ kinematic fitting less applicable.
- Physics performance of ILC depends critically on detector performance (unlike at LEP).
- Stringent requirements on ILC detector, especially the calorimetry.
- Excellent jet energy resolution a must!





$W^\pm/Z$ separation at the ILC

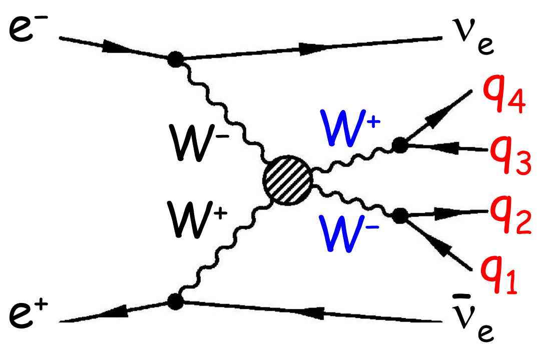
- Jet energy resolution impacts directly on physics sensitivity.
- If Higgs mechanism not realized in nature, then QGC processes become important:

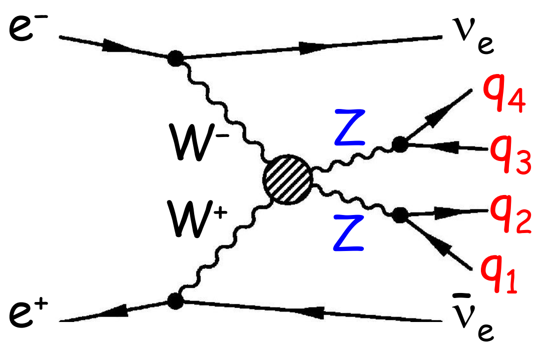
  $e^+e^- \to \nu_e\bar{\nu}_e W^+W^- \to \nu_e\bar{\nu}_e q_1q_2q_3q_4$;

  $e^+e^- \to \nu_e\bar{\nu}_e ZZ \to \nu_e\bar{\nu}_e q_1q_2q_3q_4$.
- To differentiate, need to distinguish $W^\pm \to qq$, from $Z \to qq$.
- Requires unprecented jet energy resolution:

  $\sigma_E/E \sim 30\%/\surd(E/\mathrm{GeV})$.
- Best acheived at LEP (ALEPH):

  $\sigma_E/E \sim 60\%/\surd(E/\mathrm{GeV})$.





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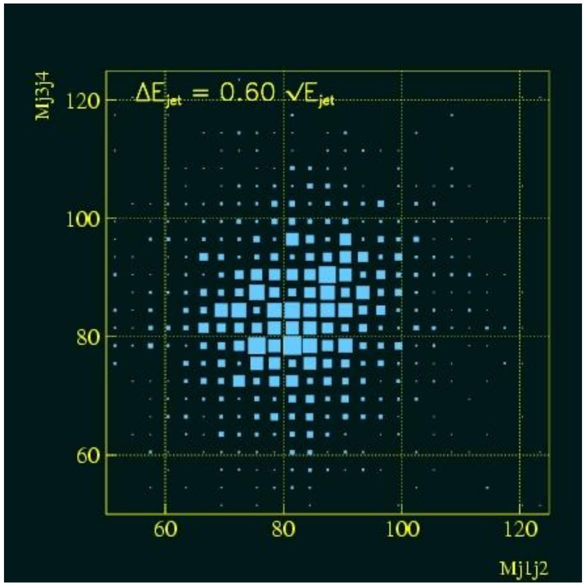
$W^\pm/Z$ separation at the ILC

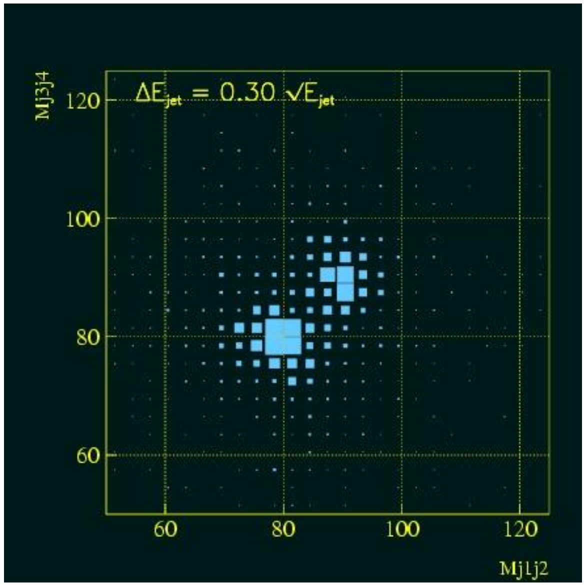
- Plot jet_1-jet_2 invariant mass vs jet_3-jet_4 invariant mass:

LEP detector



$\sigma_E/E \sim 60\%/\sqrt{(E/GeV)}$

ILC detector



$\sigma_E/E \sim 30\%/\sqrt{(E/GeV)}$

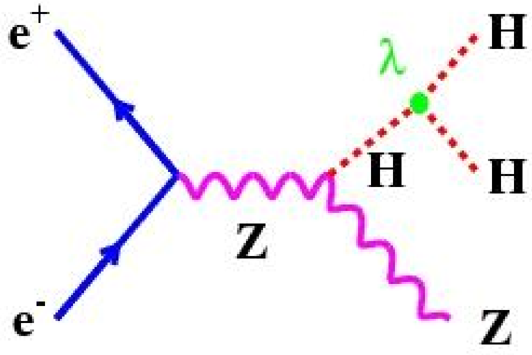
- Discrimination between W^+W^- and ZZ final states achievable at ILC.

Higgs potential at the ILC

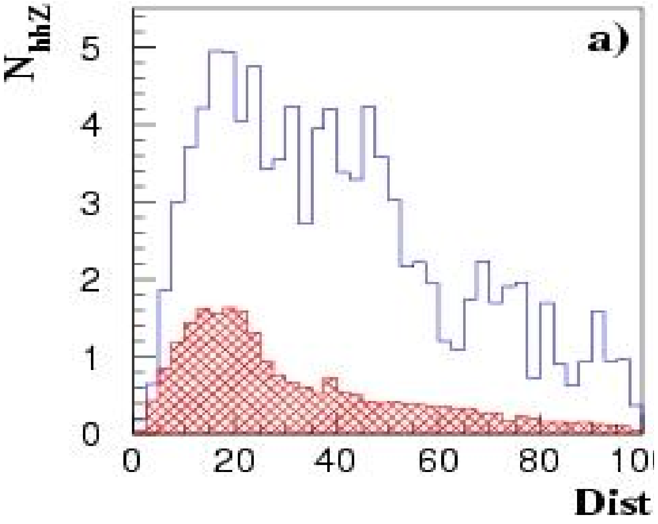
- If Higgs does exist, probe potential via trilinear HHH coupling in:

  $e^+e^- \rightarrow ZHH \rightarrow qqbbbb$.
- Signal cross-section small; combinatoric background large (6 jets).
- Use discriminator:

  $Dist = ((M_H - M_{12})^2 + (M_z - M_{34})^2 + (M_H - M_{56})^2)^{1/2}$.

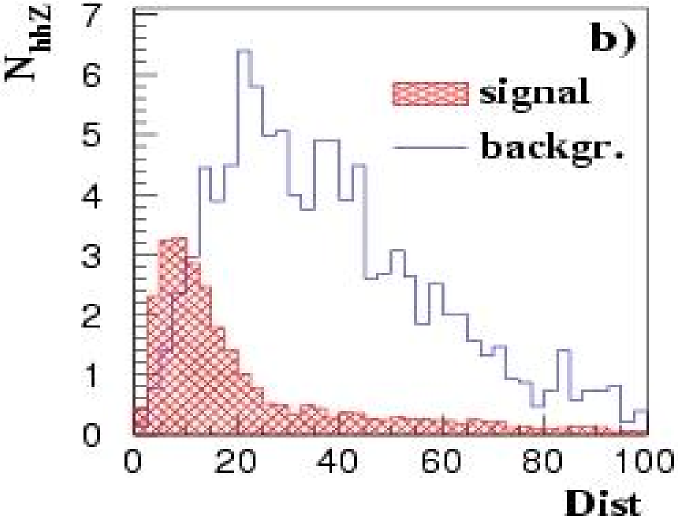


LEP detector



$\sigma_E/E \sim 60\%/\surd(E/GeV)$

ILC detector

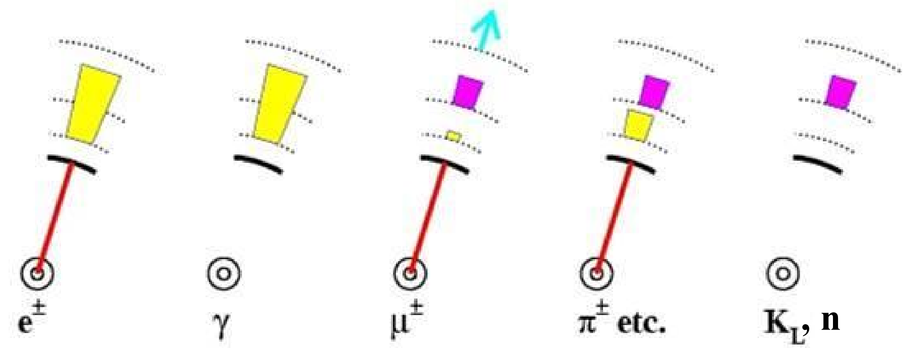


$\sigma_E/E \sim 30\%/\surd(E/GeV)$

- Measurement possible at ILC with targeted jet energy resolution.
- How can this goal actually be achieved?

The particle flow paradigm

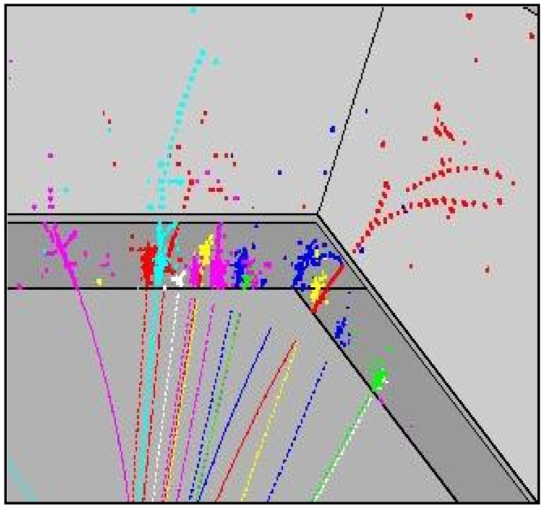
- LEP/SLD ⇒ optimal jet energy resolution achieved through particle flow paradigm.
- Reconstruct 4-momentum of each and every particle in the event using the best-suited detector:
  - charged particles (~ 65 % of jet energy) → tracker;
  - photons (~ 25 %) → Ecal;
  - neutral hadrons (~ 10 %) → (mainly) Hcal.
- Replace poor calorimeter measurements with good tracker measurements ⇒ explicit track-cluster associations; avoiding double counting.

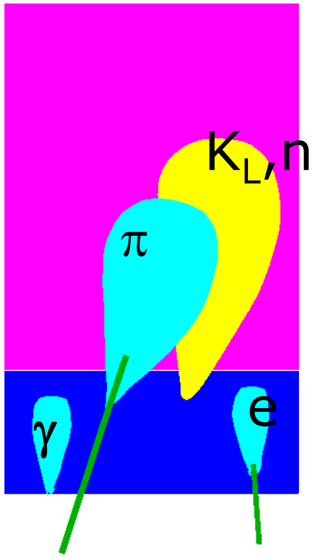


- Need to efficiently separate energy deposits from different particles in a dense environment.

The particle flow paradigm

- Jet energy resolution:
  $\sigma^2(E_{jet}) = \sigma^2(E_{ch.}) + \sigma^2(E_\gamma) + \sigma^2(E_{h0}) + \sigma^2(E_{confusion})$.
- Excellent tracker ⇒ $\sigma^2(E_{ch.})$ negligible.
- Other terms calorimeter-dependent.
- Expect $\sigma(E_i) = A_i \surd E_i$ for $i=\gamma,h0$ (≈ intrinsic energy resolution of Ecal, Hcal, respectively: $A_\gamma \sim 11\ \%$, $A_{h0} \sim 50\ \%$).
- Since $E_i = f_i E_{jet}$ ($f_\gamma \sim 25\ \%$, $f_{h0} \sim 10\ \%$):
  $\sigma(E_{jet}) = \surd\{(17\ \%)^2 E_{jet} + \sigma^2(E_{confusion})\}$.
- Ideal case, $\sigma(E_{confusion}) = 0$
  ⇒ $\sigma(E_{jet}) = 17\ \% \surd E_{jet}$;
  ⇒ desired resolution attainable (in principle).
- Reality dictated by wrongly assigned energy.
- Ability to separate E/M showers from charged hadron showers from neutral hadron showers is **critical**.
- Granularity (*i.e.* spatial resolution) more important than intrinsic energy resolution.





Calorimeter requirements

- Implications of particle flow on calorimeter design:
  - excellent energy resolution for jets;
  - excellent energy/angular resolution for photons;
  - ability to reconstruct non-pointing photons;
  - hermeticity.
- Need to separate energy deposits from individual particles

  $\Rightarrow$ compact, narrow showers;

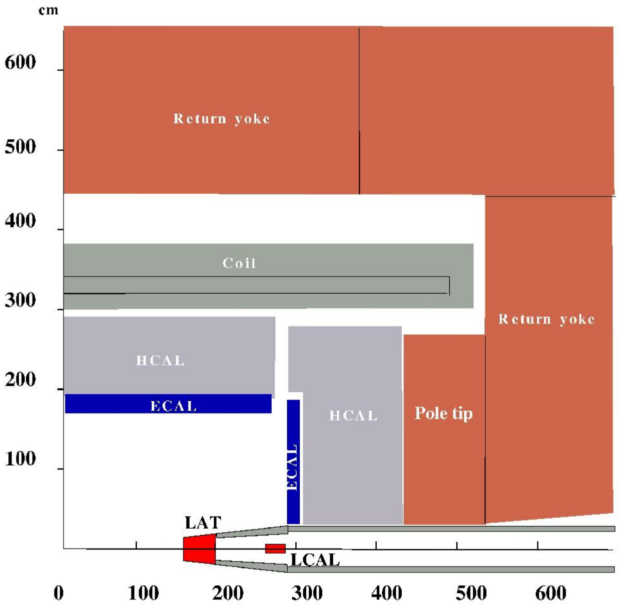
  $\Rightarrow$ small X_0 and $R_{\text{Molière}}$ and high lateral granularity ~ $O(R_{\text{Molière}})$.
- Need to discriminate between E/M and hadronic showers

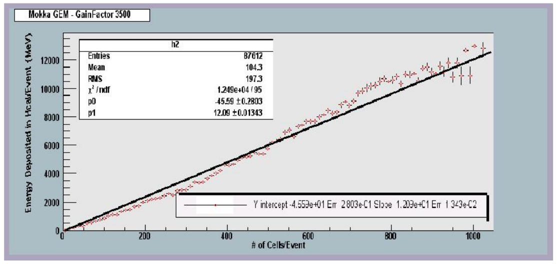
  $\Rightarrow$ force E/M showers early, hadronic showers late;

  $\Rightarrow$ small $X_0 : \lambda_{\text{had}}$ absorber and high degree of longitudinal segmentation.
- Need to separate hadronic showers from charged and neutral particles
- $\Rightarrow$ strong B-field (also good for retention of background within beampipe).
- Need minimal material in front of calorimeters
- $\Rightarrow$ put the Ecal and Hcal inside coil (at what cost?).

Calorimeter requirements

- Ecal and Hcal inside coil ⇒ better performance, but impacts on cost.
- Ecal → silicon-tungsten (Si/W) sandwich:
  - Si → pixelated readout, compact, stable.
  - W → $X_0:\lambda_{had}$ ~ 1:25;
  - $R_{Molière}$ ~ 9 mm (effective $R_{Molière}$ increased by inter-W gaps) ⇒ 1×1 cm^2 lateral granularity for Si pads;
  - longitudinal segmentation: 40 layers ($24X_0$, $0.9\lambda_{had}$).
- Hcal → ??/steel (??/Fe) sandwich (?? is a major open question):
  - ?? = scintillator ⇒ analog readout (AHcal), lower granularity (~ 5×5 cm^2) → electronics cost.
  - ?? = RPCs, GEMs, … ⇒ digital readout (DHcal), high granularity (1×1 cm^2) → count cells hit ∝ energy (if 1 hit per cell).



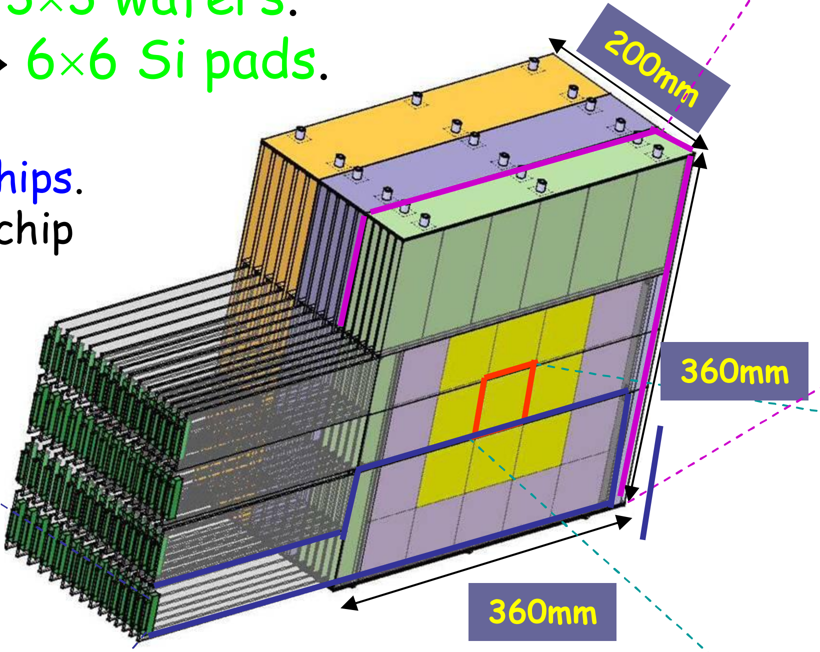


CALICE

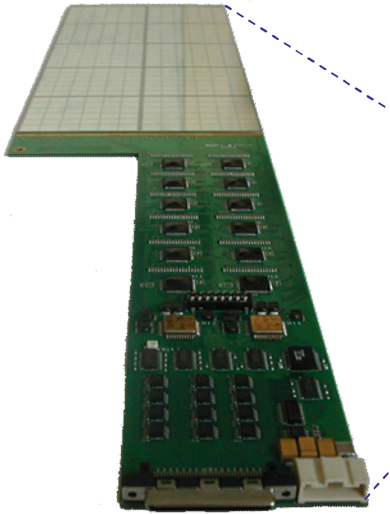
- CAlorimeter for the LInear Collider Experiment → collaboration of 190 members, 32 institutes (Asia, Europe & North America).
- R&D on calorimetry; working towards beam tests of prototypes in a common hardware+software framework.
- Focus on high granularity, fine segmentation.
- Aims to:
  - test technical feasibility of hardware;
  - compare alternative concepts (e.g. AHcal vs DHcal);
  - validate simulation tools (especially modelling of hadronic showers);
  - prove (or disprove) the viability of a particle flow detector;
  - justify cost for high granularity.
- Pre-prototype Ecal already (mostly) built; part-tested with cosmic rays (Paris, DESY) and low energy (1–6 GeV) e^- beam (DESY).

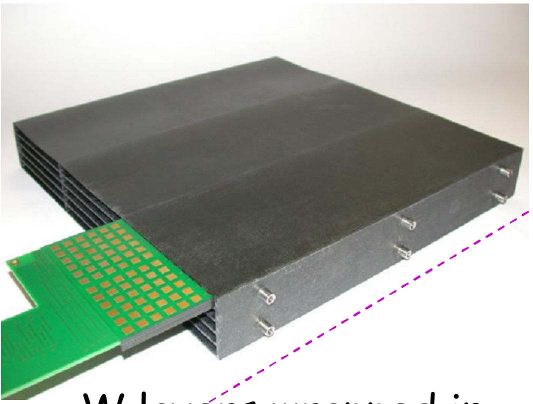
ECAL prototype overview

- Si/W 3×10 layers; W thickness 1.4, 2.8, 4.2 mm ($0.4X_0$, $0.8X_0$, $1.2X_0$).
- Each layer → 3×3 wafers.
- Each wafer → 6×6 Si pads.



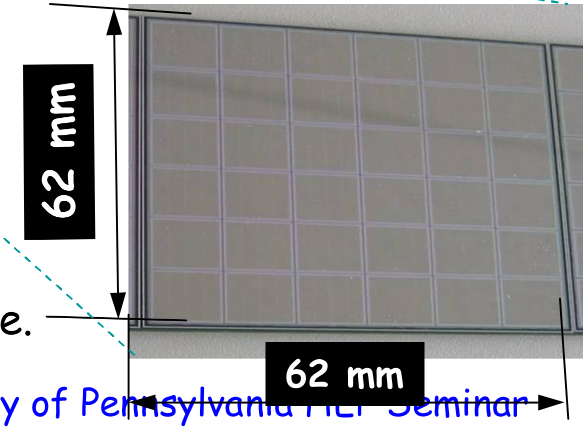
- PCB houses 12 VFE chips.
- 18 channels input to chip
  ⇒ 2 chips/wafer.
- 1 multiplexed output.





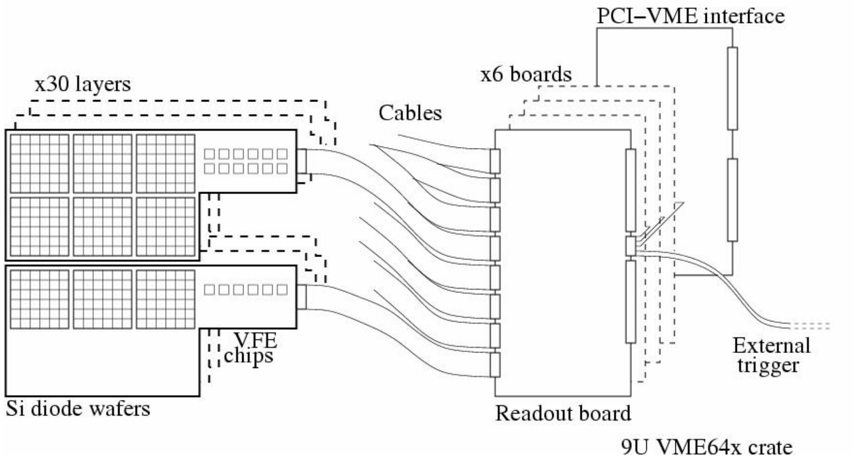
- W layers wrapped in carbon fiber.
- Si/W/Si sandwich slots into 8.5 mm alveolus.

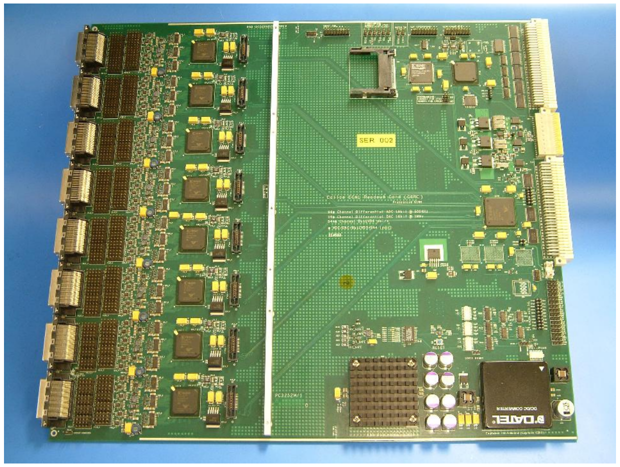
- 6x6 1x1 cm^2 (x0.5 mm) Si pads.
- Analog signal; 16-bit dynamic range.



Ecal prototype electronics

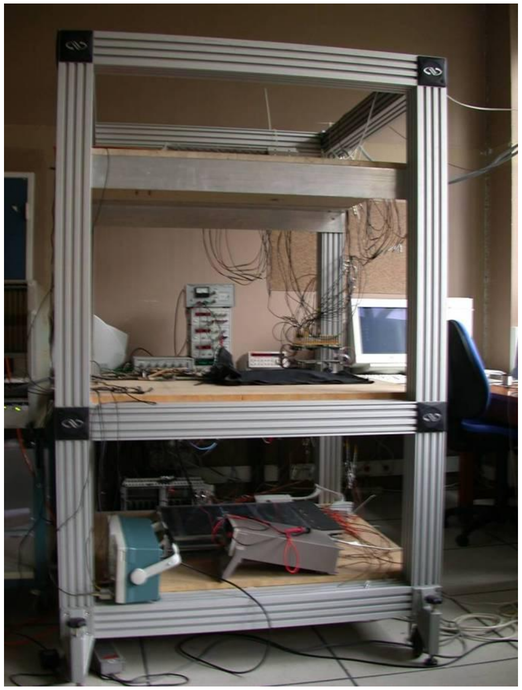
- CALICE readout card (CRC) based on CMS tracker FE driver board (saved time!).
- Designed/built by UK institutes (Imperial, RAL, UCL).
- Receives 18-fold multiplexed analog data from up to 96 VFE chips (= 1728 channels $\Rightarrow$ 6 cards required for full prototype).
- Digitizes; on-board memory to buffer ~ 2000 events during spill.
- AHcal plan to use same CRCs.

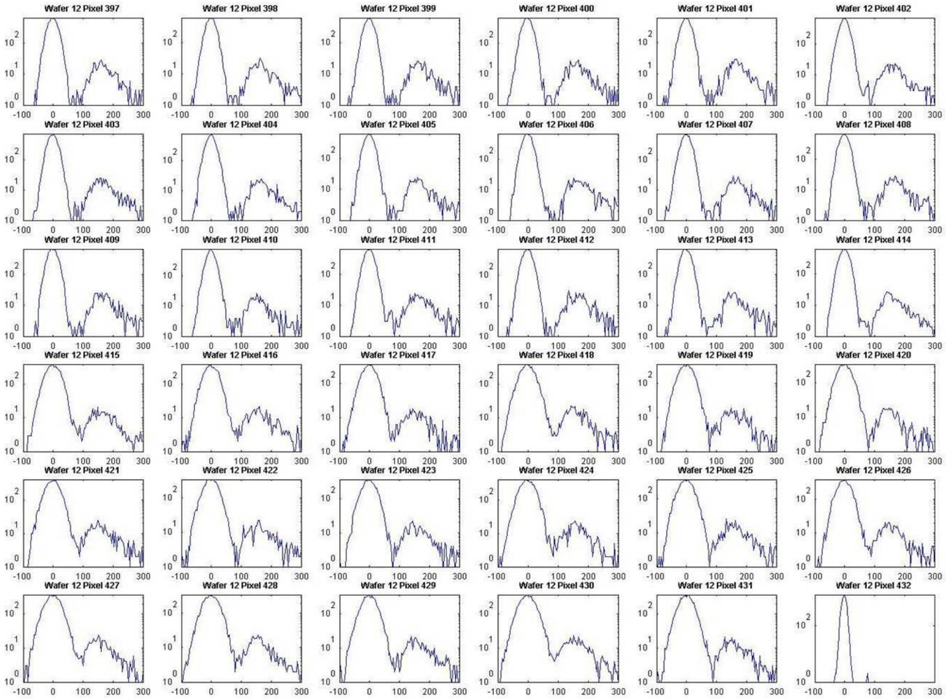




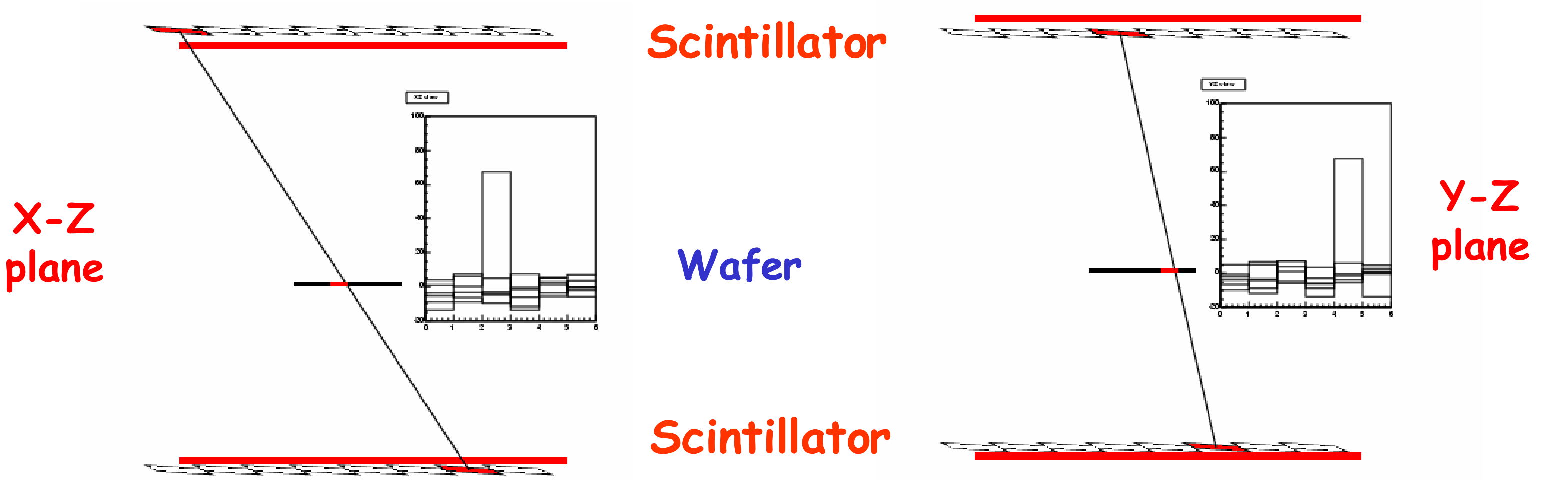
Cosmic ray tests

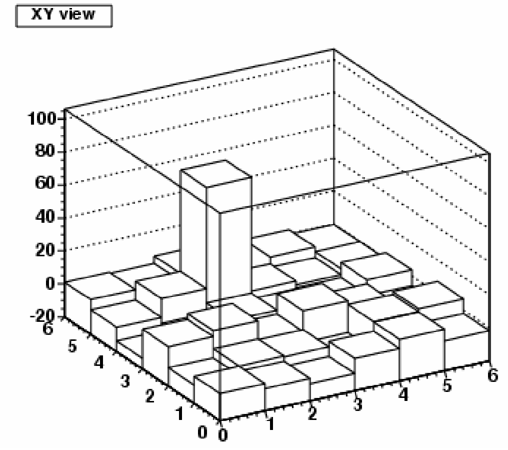
- Cosmic calibration, Dec. 2004 (LLR, Paris).
- E.g. of response vs ADC value for 6×6 cm^2 wafer (36 1×1 cm^2 Si pads) → Gaussian noise; Landau signal (mip):





Cosmic ray tests



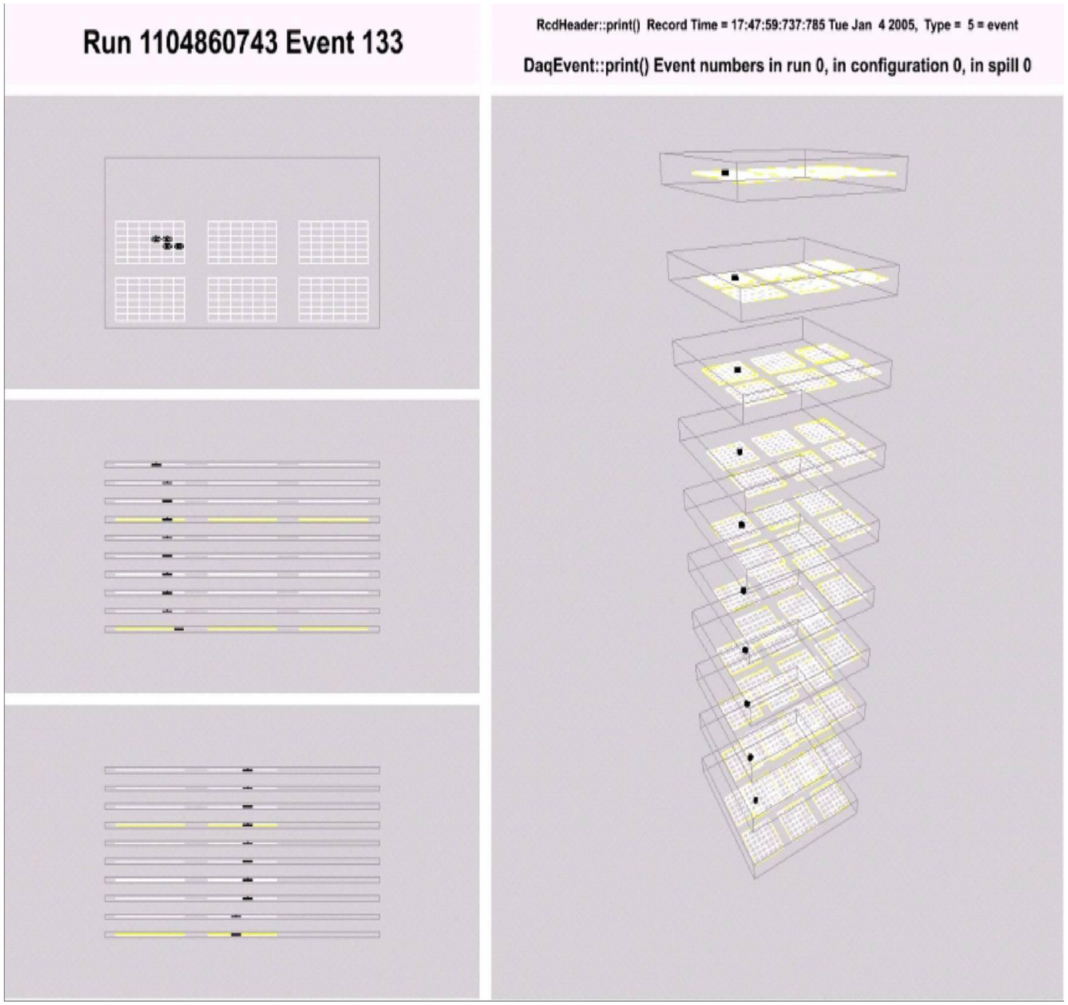


- E.g. of cosmic ray event.
- Single Si wafer; full read-out chain.
- Triggered by coincidence in scintillators.
- Track extrapolated through Si wafer.
- See clear signal over background.

Chris Ainsley
<ainsley@hep.phy.cam.ac.uk>

Cosmic ray tests

- 10 layers assembled, Dec. 2004 (LLR, Paris).
- > 10^6 events recorded over Xmas (unmanned).
- Signal/noise ~ 9.
- This event: Jan 4, 2005.



Run 1104860743 Event 133

```
RcdHeader::print()  Record Time = 17:47:59:737:785 Tue Jan  4 2005,  Type =  5 = event
DaqEvent::print() Event numbers in run 0, in configuration 0, in spill 0
```

Beam tests

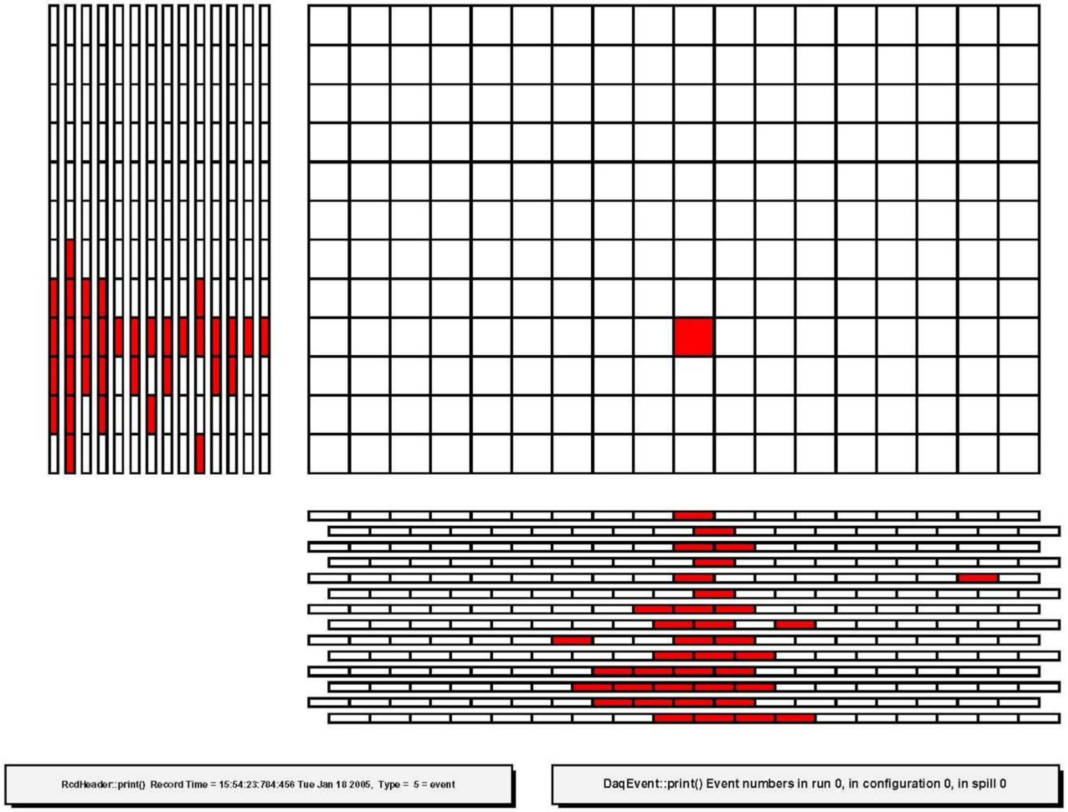
- Jan. 12, '05

  Ecal hardware moved to DESY.
- Jan. 13–14

  14 layers, 2×3 wafers/layer assembled ⇒ 84 wafers total ⇒ 3024 Si pixels (1/3 complete).
- Jan. 17

  First e^- beam recorded, triggered by drift chamber (200 μm resolution).
- Jan. 18

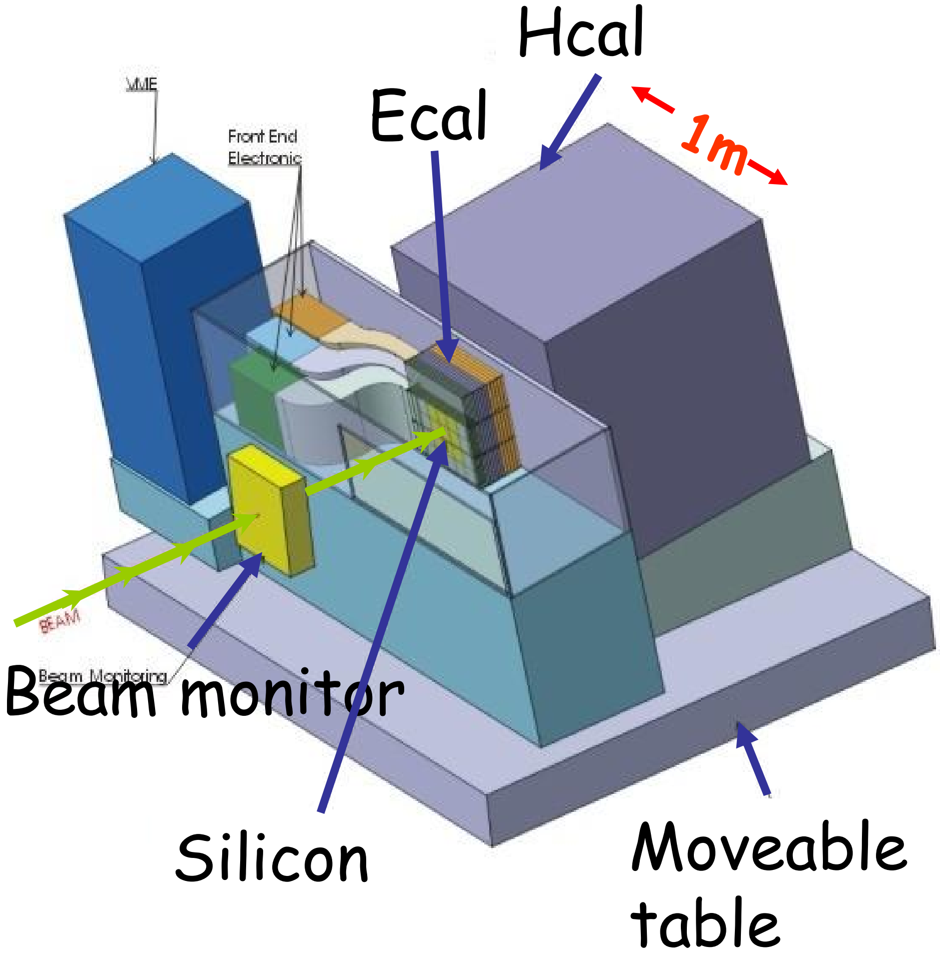
  This event (6 GeV e^-):



```
RcdHeader::print()  Record Time = 15:54:23:784:456 Tue Jan 18 2005,  Type =  5 = event
```

```
DaqEvent::print() Event numbers in run 0, in configuration 0, in spill 0
```

CALICE test beam schedule

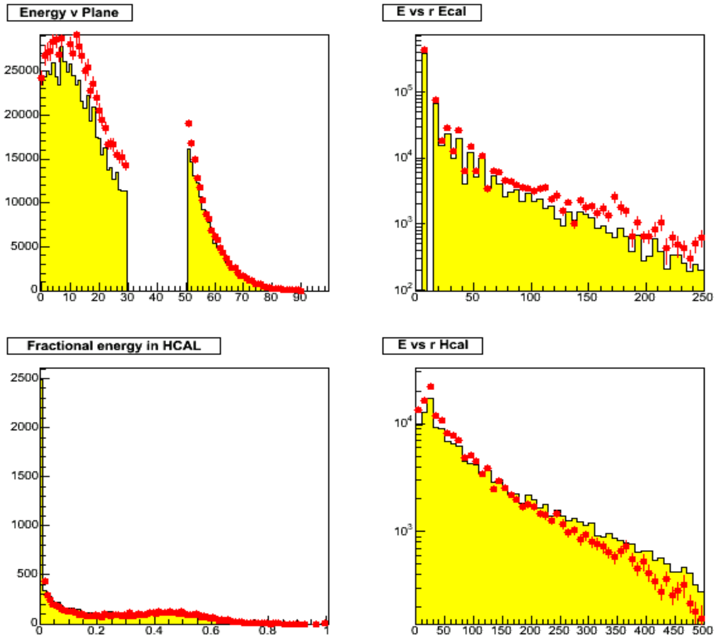


- 10-12/2005
  ECAL only, cosmics, DESY.
- 1-3/2006
  6 GeV e^- beam, DESY (complete ECAL: 9720 channels).
- 9-11/2006
  Physics run at CERN, with AHcal.
- mid-2007
  To FNAL MTBF.
- ECAL: 30 layers W+Si.
- HCAL: 40 layers Fe +
  - "analogue" tiles:
    - scintillator tiles;
    - 8k, 3x3 cm^2 –12x12 cm^2.
  - "digital" pads:
    - RPCs, GEMs;
    - 350k, 1x1 cm^2.

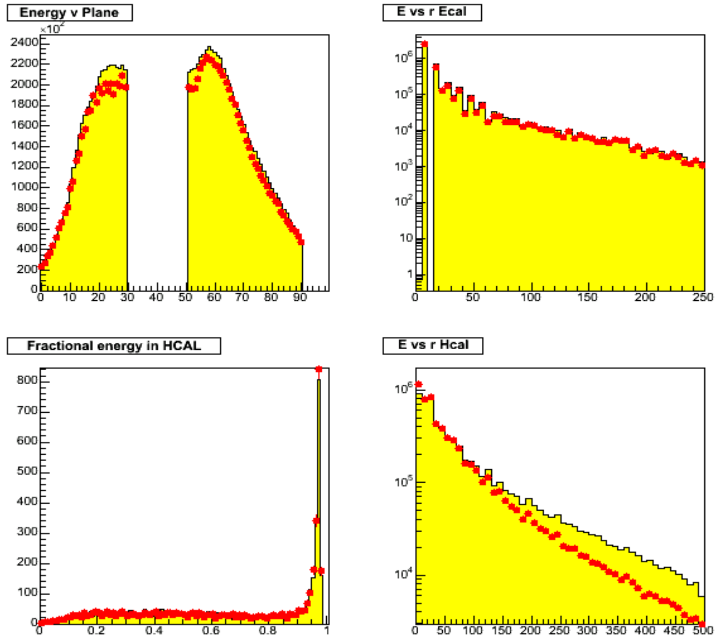
Simulation

- Hadronic shower development poorly understood in simulation.
- Geant3 (histo) and Geant4 (points) show basic differences.

1 GeV π^+



50 GeV π^+

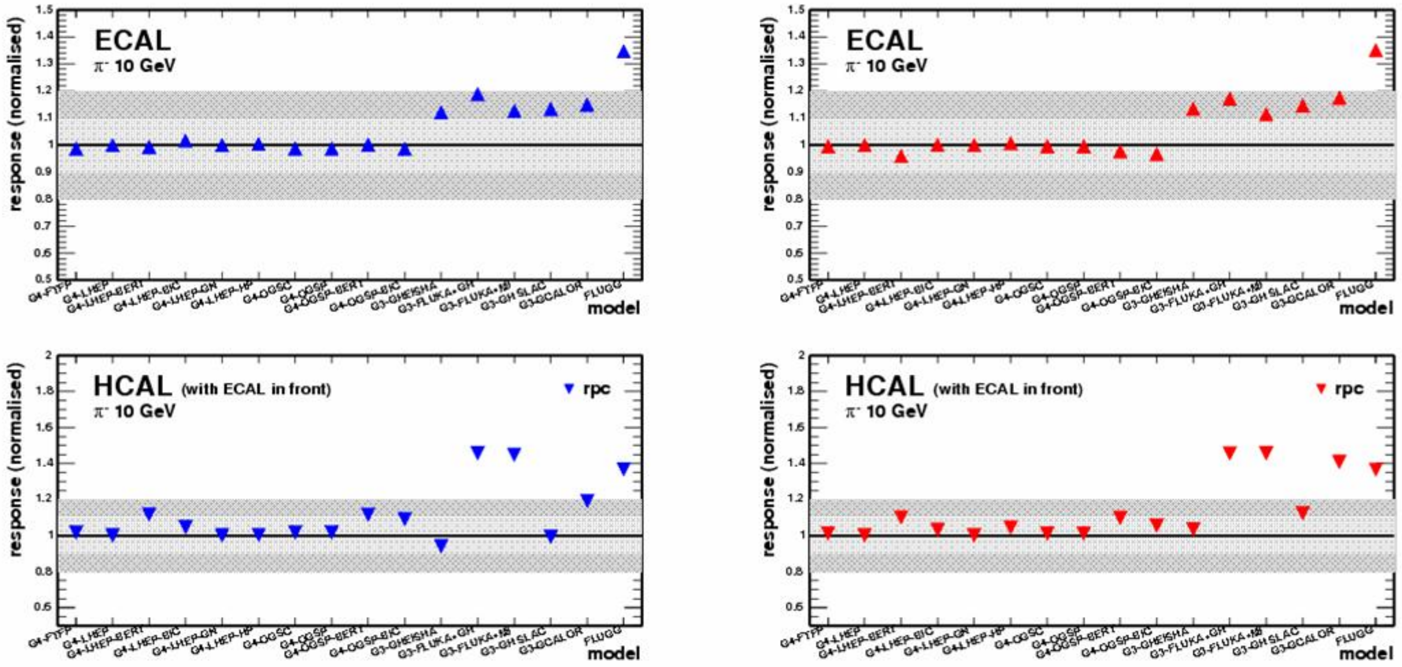


- Need reliable simulation to optimize proposed detector for ILC.
- Use test beam data to critically compare different models.

Comparing the models

- Compare G3 and G4 (and Fluka) with different hadronic shower models.
- E.g. **10 GeV** π^-; Si/W Ecal, RPC/Fe Hcal:

cells hit (normalized) Energy deposited (normalized)

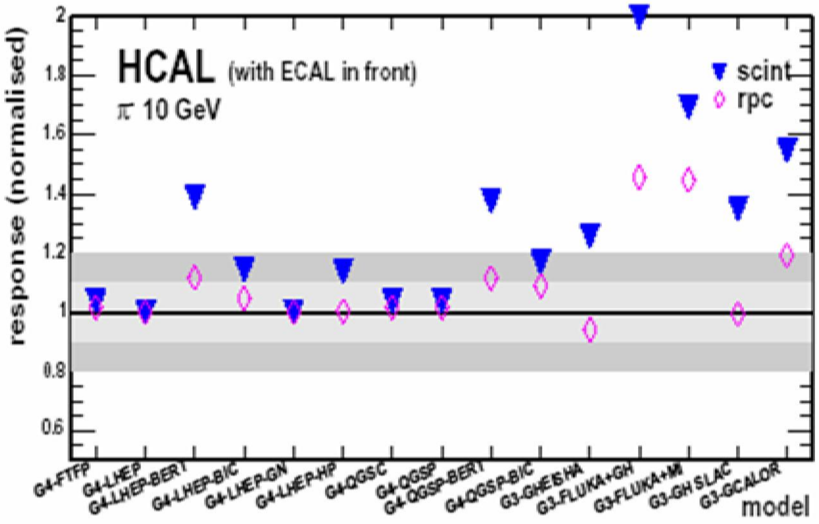


- Ecal shows some E/M discrepancies, but general consistent behavior.
- Hcal variation much more worrisome.

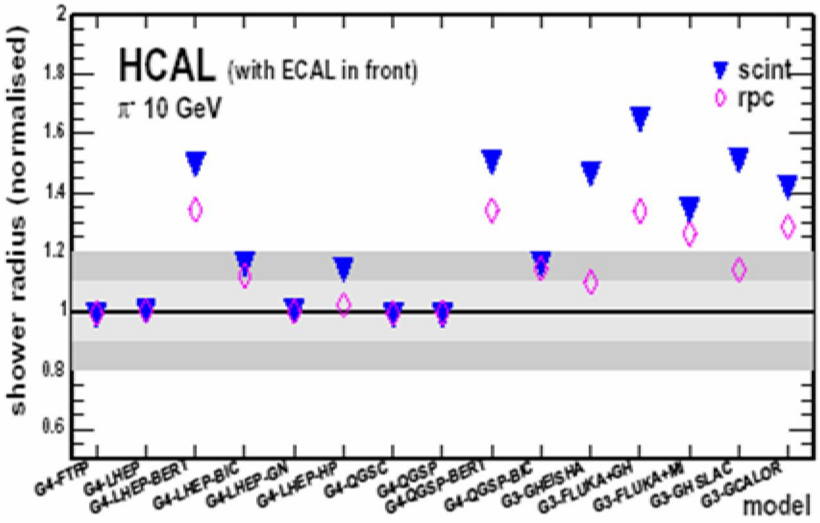
Comparing the models

- Extend to comparison between RPC and scintillator Hcal alternatives.

\# cells hit (normalized)



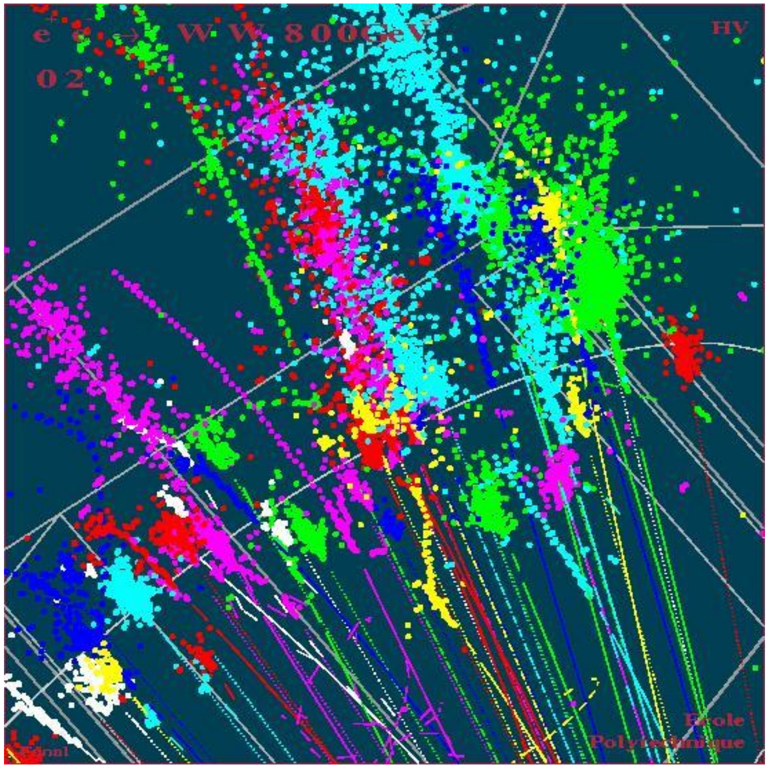
Shower width (normalized)



- RPC Hcal less sensitive to low energy neutrons than scintillator Hcal.
- Enforces need for test beam data.
- Guides test beam strategy (energies, statistics, *etc.*).

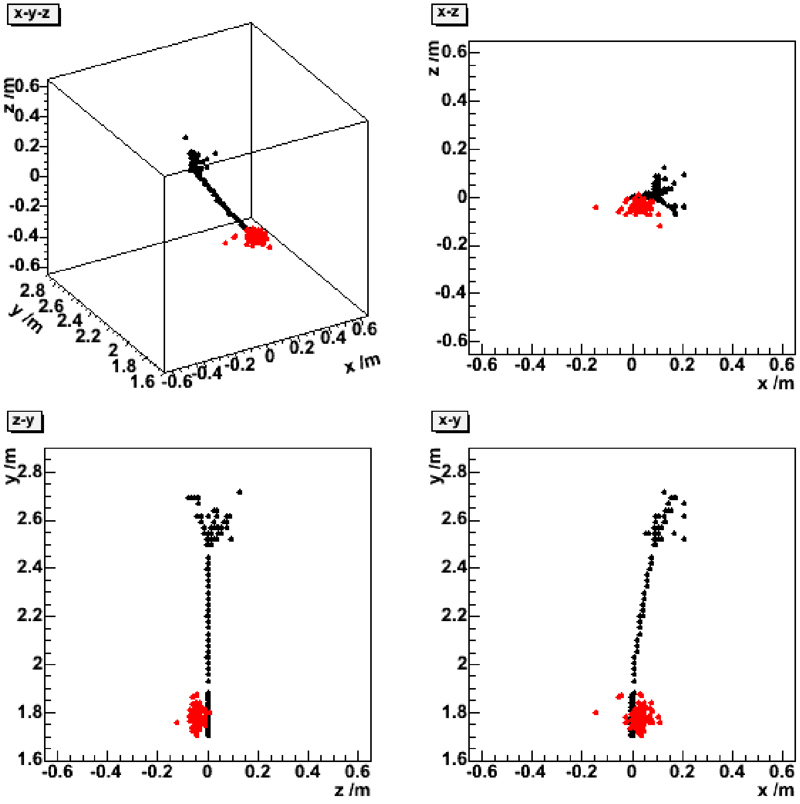
Calorimeter cluster reconstruction

- Reconstruction software development heavily reliant on simulation.
- Essential for detector optimization studies.
- Highly granular calorimeter → **very different** from previous detectors.
- Shower-imaging capability.
- Requires **new approaches** to cluster reconstruction.
- Must have minimal ties to geometry.
- Ingenuity will dictate success of particle flow.



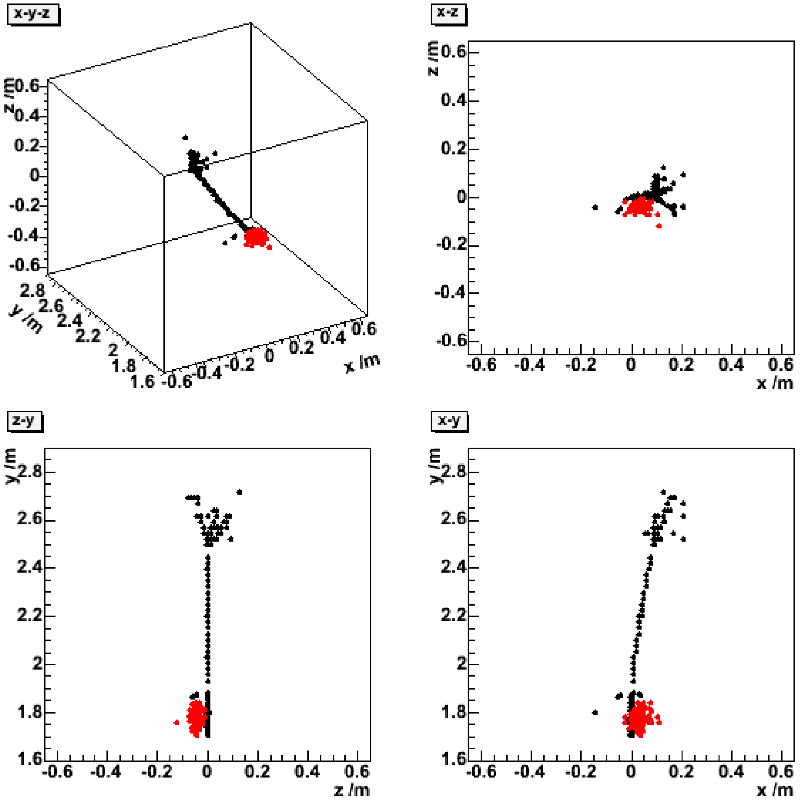
π^+/γ: Si/W Ecal + RPC/Fe DHcal

True clusters



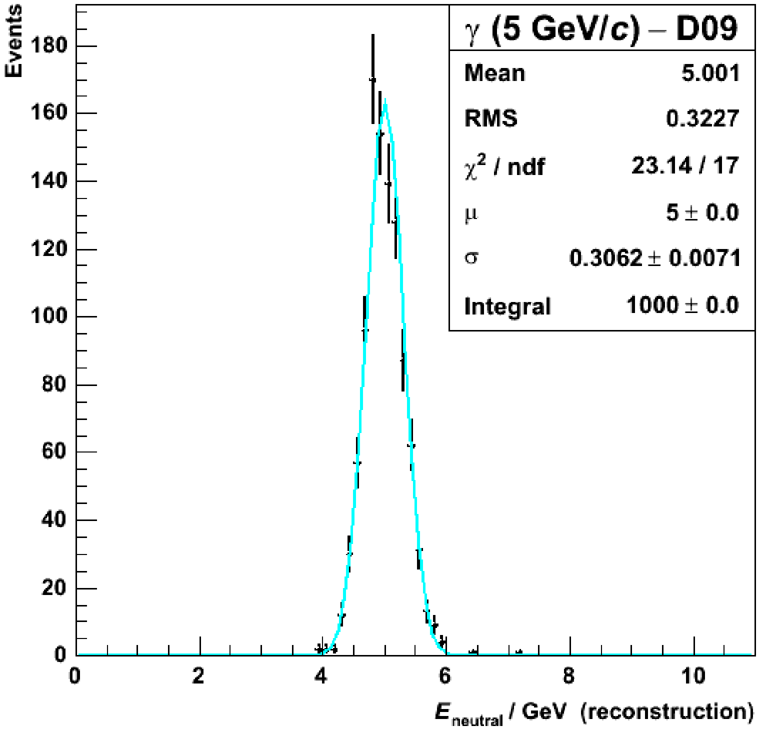
- **Black** cluster = 5 GeV/*c* π^+.
- **Red** cluster = 5 GeV/*c* γ.

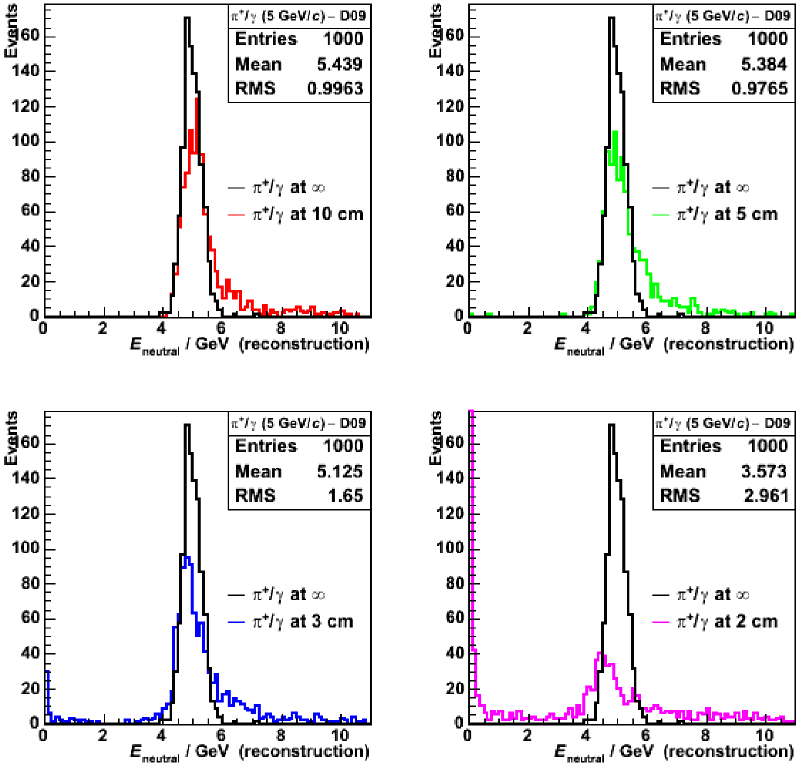
Reconstructed clusters



- **Black** cluster matched to charged track.
- **Red** cluster left over as neutral $\Rightarrow \gamma$ energy well reconstructed.

π^+/γ: Si/W Ecal + RPC/Fe DHcal



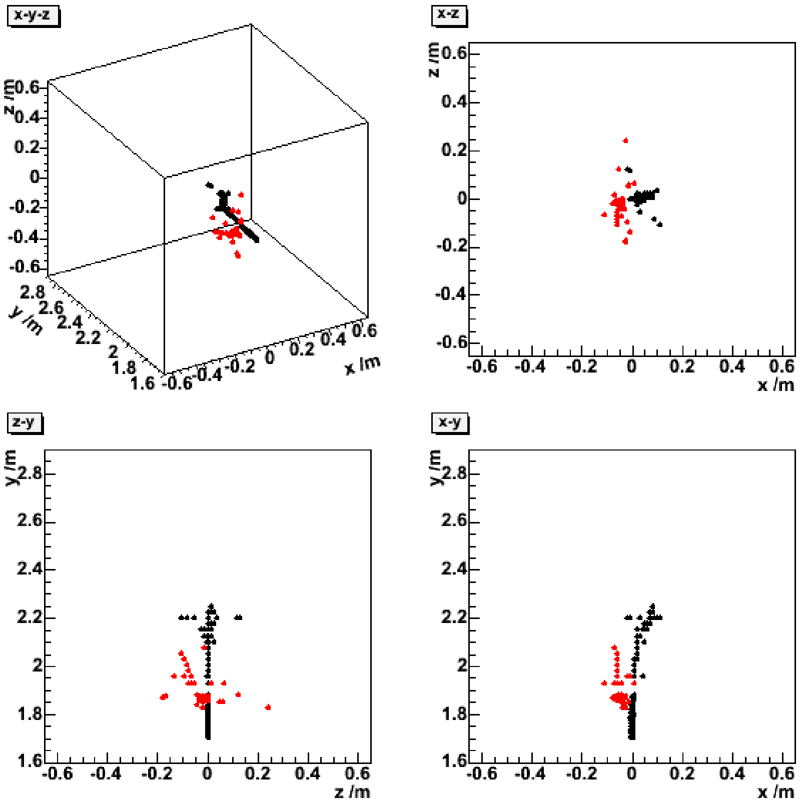


- **1k single γ at 5 GeV/c.**
- Fit Gaussian to energy distribution, calibrated according to:
  $E = \alpha[(E_{\text{Ecal; 1-30}} + 3E_{\text{Ecal; 31-40}})/E_{\text{Ecal mip}} + 20N_{\text{Hcal}}]$.
- Fix factors α, 20 by minimising χ^2/dof.
- $\sigma/\sqrt{\mu} \sim 14\% \sqrt{\text{GeV}}$.

- **1k γ with nearby π^+ (10, 5, 3, 2 cm from γ).**
- Peak of photon energy spectrum well reconstructed; improves with separation.
- Tail at higher E → inefficiency in π^+ reconstruction.
- Spike at $E = 0$ below 3 cm → clusters not distinguished.

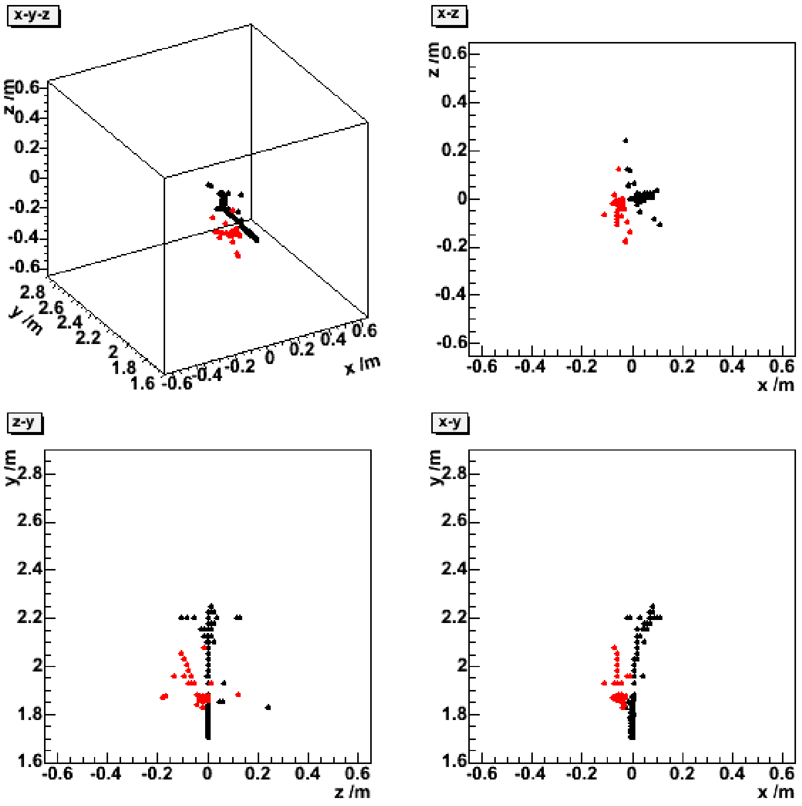
π^+/n: Si/W Ecal, RPC/Fe DHcal

True clusters



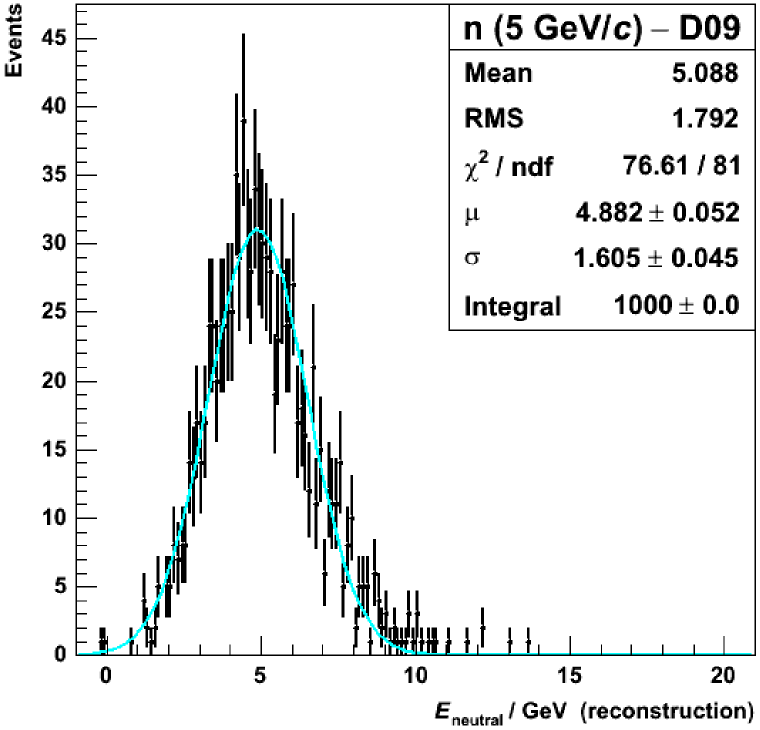
- **Black** cluster = 5 GeV/*c* π^+.
- **Red** cluster = 5 GeV/*c* **n**.

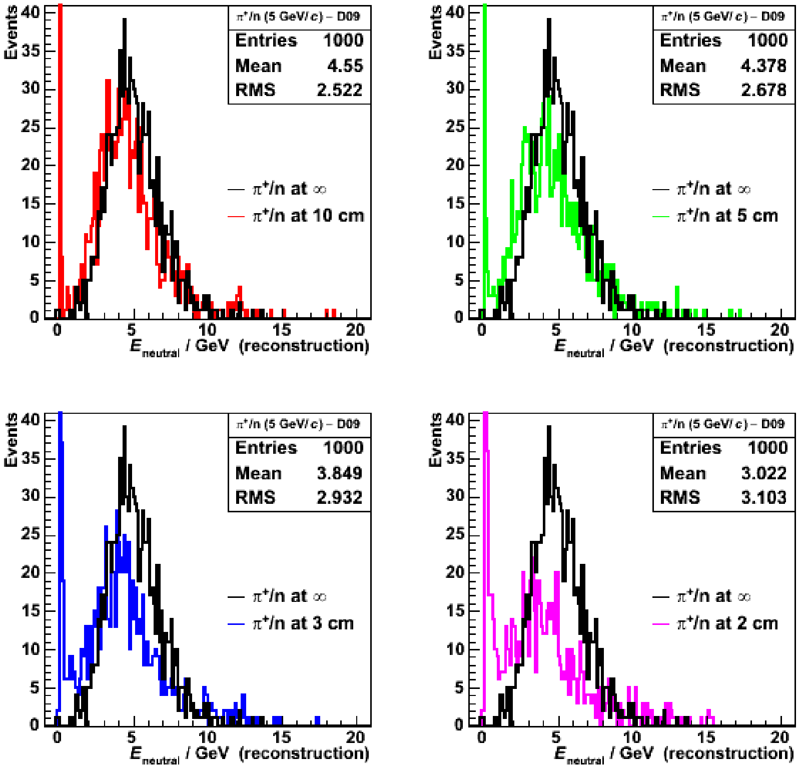
Reconstructed clusters



- **Black** cluster matched to charged track.
- **Red** cluster left over as neutral ⇒ n energy well reconstructed.

π^+/n: Si/W Ecal, RPC/Fe DHcal



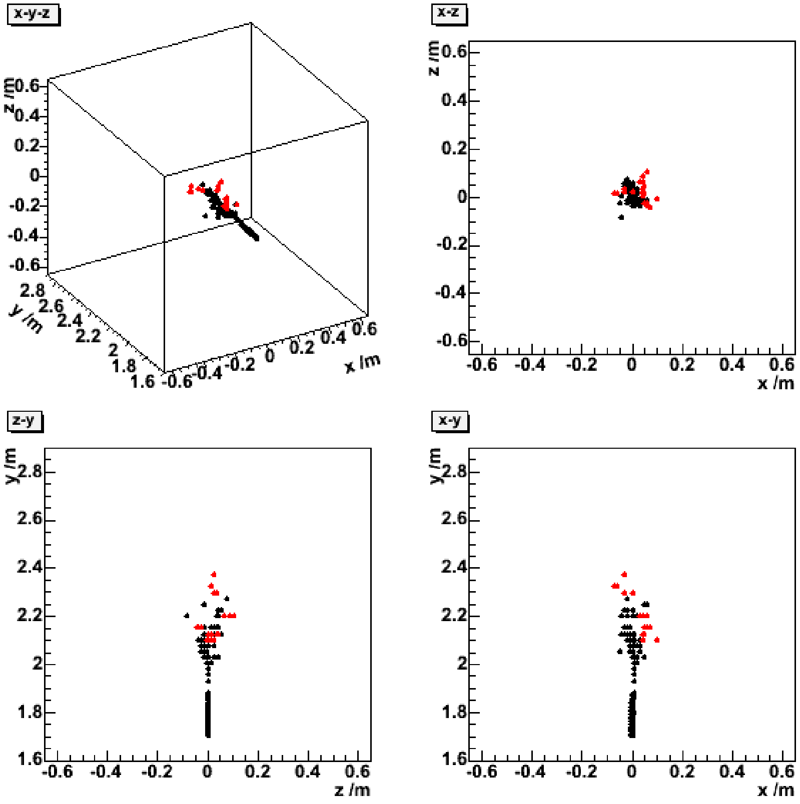


- **1k single n at 5 GeV/c.**
- Fit Gaussian to energy distribution, calibrated according to:
  $E = \alpha[(E_{\mathrm{Ecal;\,1\text{-}30}} + 3E_{\mathrm{Ecal;\,31\text{-}40}})/E_{\mathrm{Ecal\ mip}} + 20N_{\mathrm{Hcal}}]$.
- Fix factors α, 20 by minimising χ^2/dof.
- $\sigma/\sqrt{\mu} \sim 73\% \sqrt{\mathrm{GeV}}$.

- **1k n with nearby π^+ (10, 5, 3, 2 cm from n).**
- Peak of neutron energy spectrum well reconstructed; improves with separation.
- Spike at $E = 0$ even at 10 cm → clusters not distinguished.

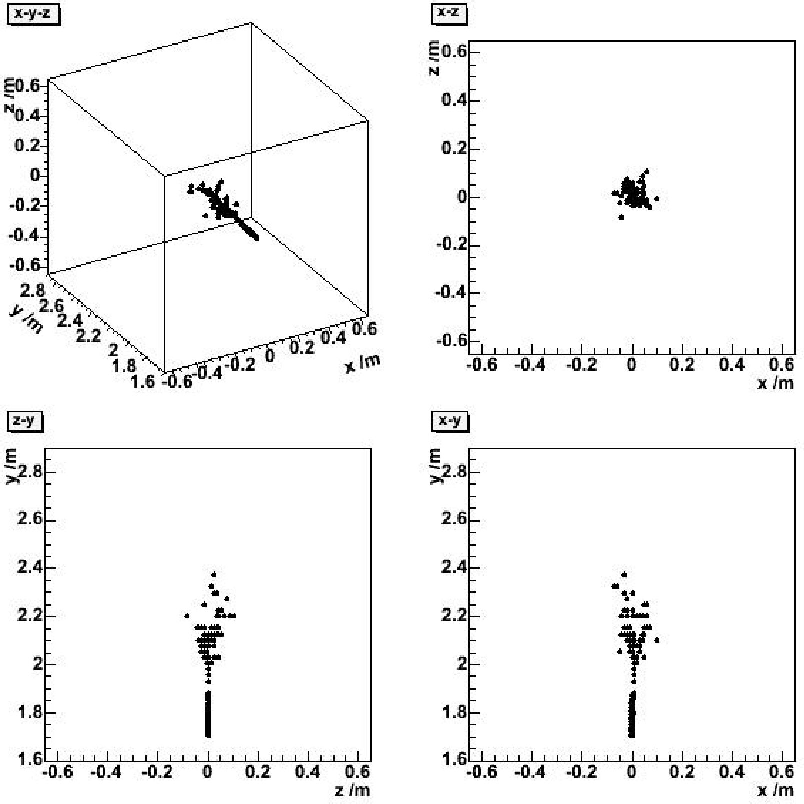
π^+/n: Si/W Ecal, RPC/Fe Hcal

True clusters



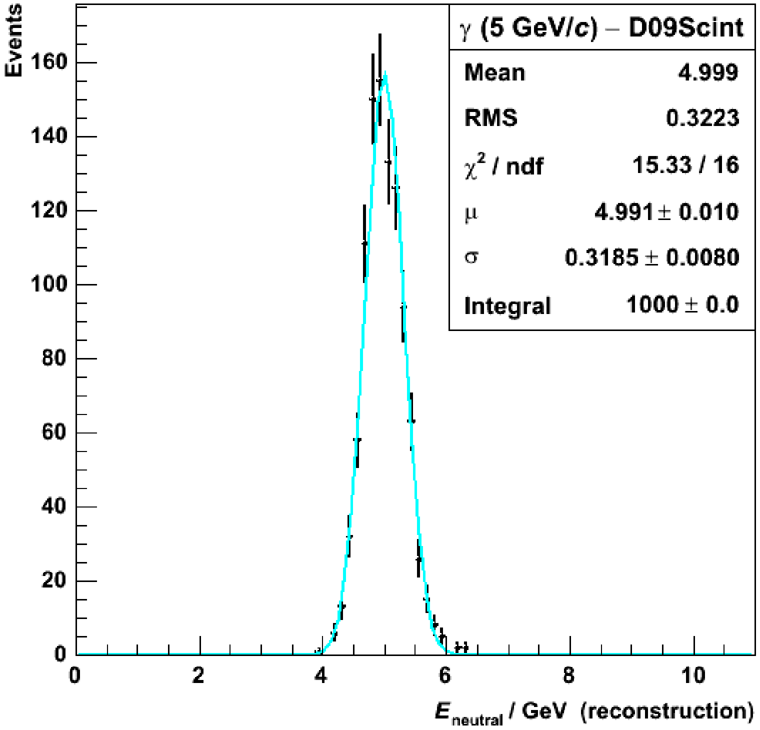
- **Black** cluster = 5 GeV/*c* π^+.
- **Red** cluster = 5 GeV/*c* **n**.

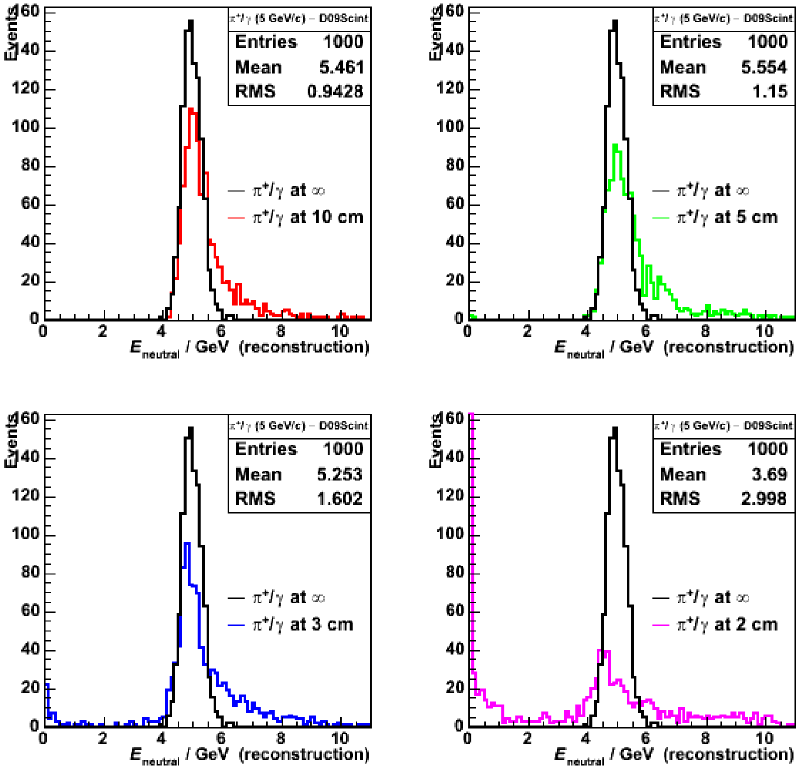
Reconstructed clusters



- **Black** cluster matched to charged track.
- Nothing left over as neutral ⇒ n not reconstructed (*i.e.* $E = 0$).

π^+/γ: Si/W Ecal + scintillator/Fe AHcal

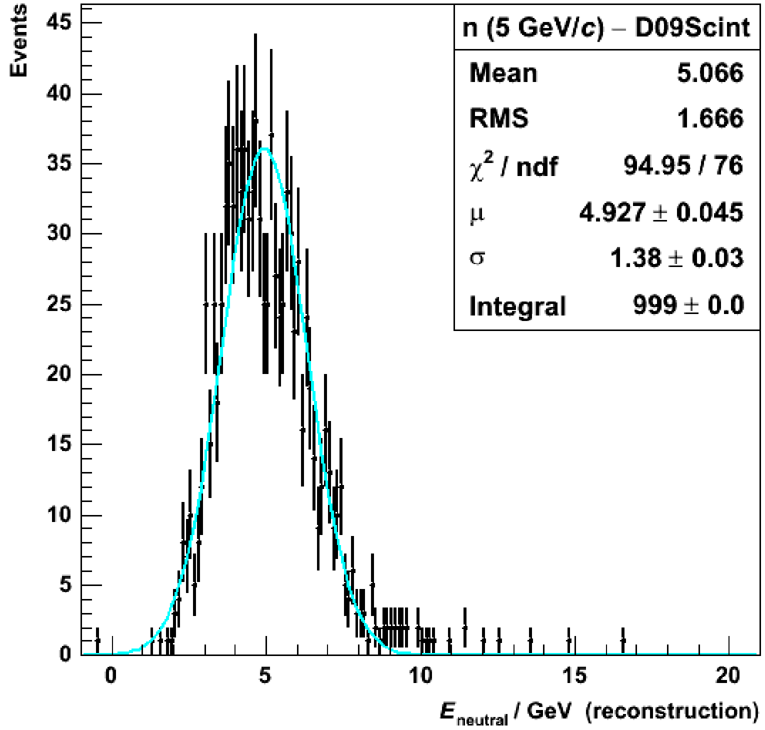


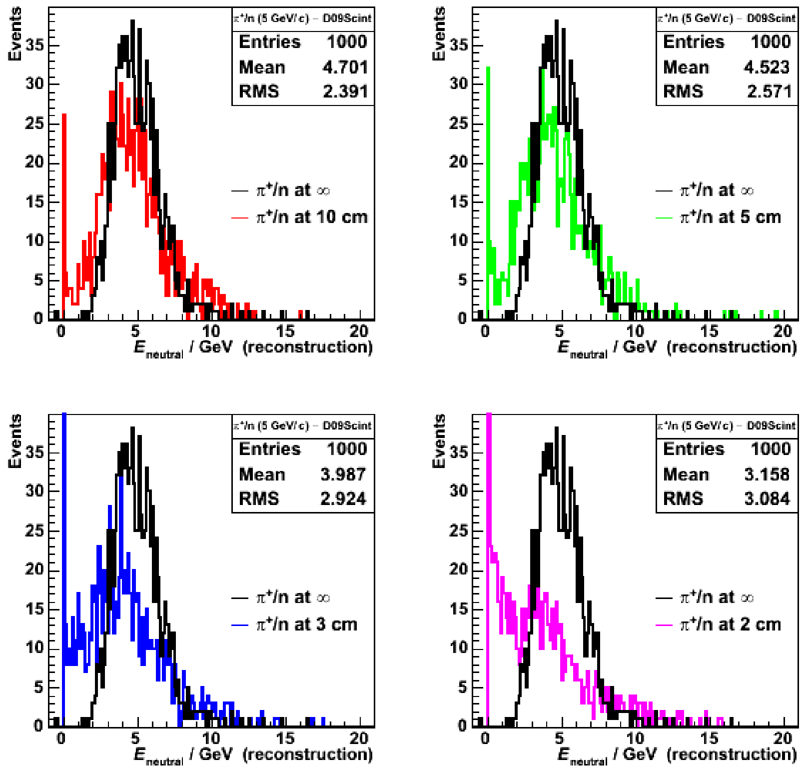


- 1k single γ at 5 GeV/c.
- Fit Gaussian to energy distribution, calibrated according to:
  $E = \alpha[(E_{\text{Ecal; 1-30}} + 3E_{\text{Ecal; 31-40}})/E_{\text{Ecal mip}} + 5E_{\text{Hcal}}/E_{\text{Hcal mip}}]$.
- Fix factors α, 5 by minimising χ^2/dof.
- $\sigma/\sqrt{\mu} \sim 14\% \sqrt{\text{GeV}}$ (as for DHcal).

- **1k γ with nearby π^+ (10, 5, 3, 2 cm from γ).**
- General trends much as for DHcal.

π^+/n: Si/W Ecal + scintillator/Fe AHcal

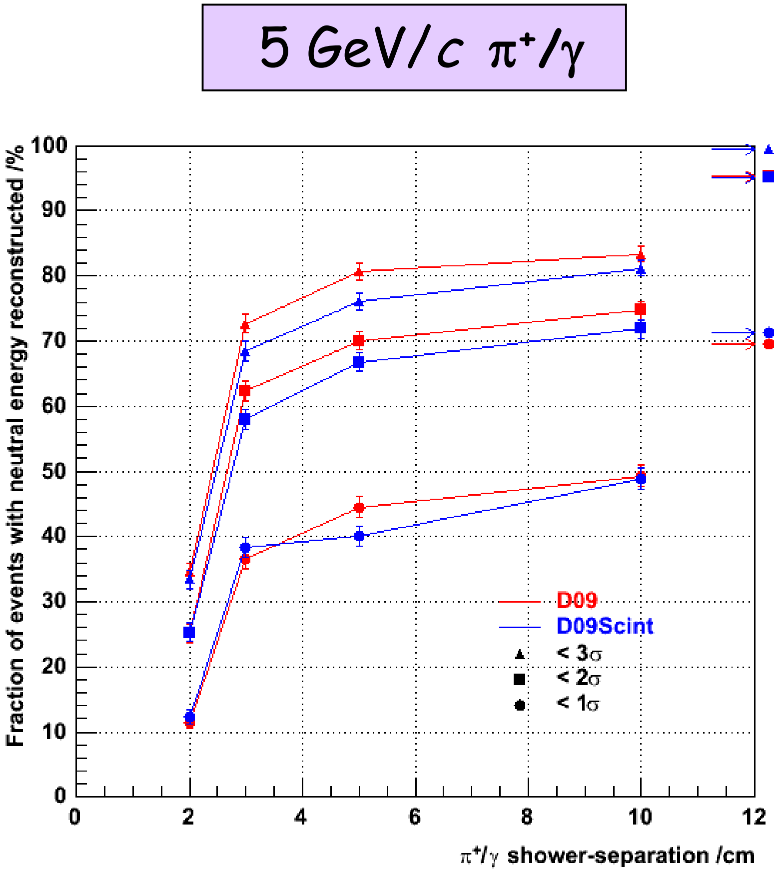


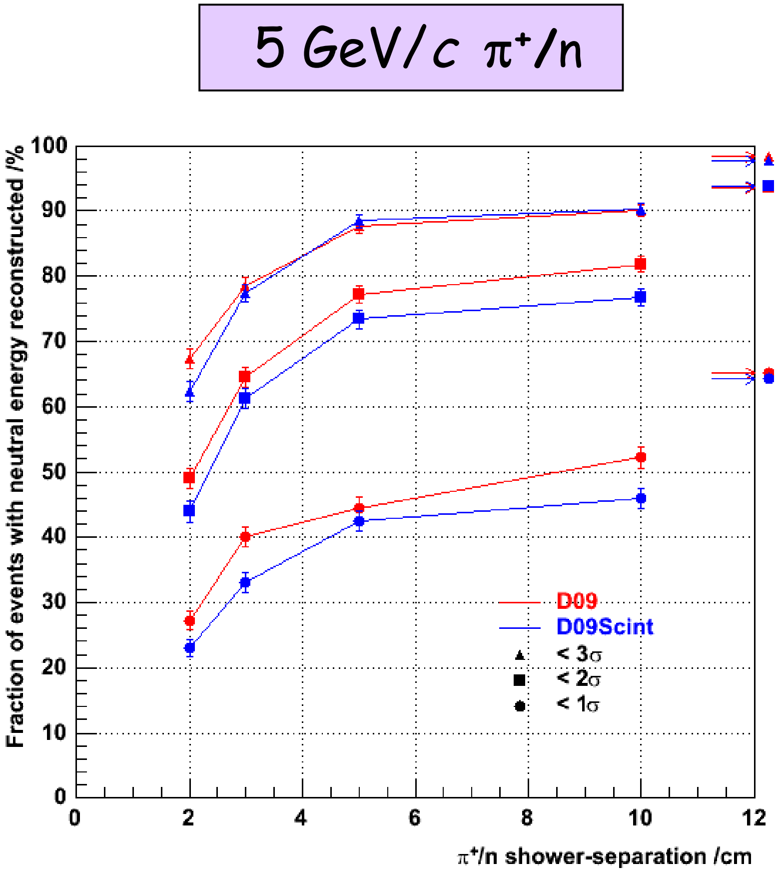


- 1k single **n** at 5 GeV/*c*.
- Fit Gaussian to energy distribution, calibrated according to:
  $E = \alpha[(E_{\text{Ecal; 1-30}} + 3E_{\text{Ecal; 31-40}})/E_{\text{Ecal mip}} + 5E_{\text{Hcal}}/E_{\text{Hcal mip}}]$.
- Fix factors α, **5** by minimising χ^2/dof.
- $\sigma/\sqrt{\mu}$ ~ 62% √GeV (cf. 73% √GeV for DHcal).

- **1k n with nearby π^+ (10, 5, 3, 2 cm from n).**
- General trends much as for DHcal.

π^+/neutral cluster separability vs separation





- Fraction of events with photon energy reconstructed within 1,2,3σ generally higher for DHcal ("D09") than for AHcal ("D09Scint").

- Similar conclusion for neutrons.
- RPC DHcal favored over scintillator AHcal?
- Needs further investigation…

Conclusions

- ILC: an e^+e^- linear collider operating in the range 0.5–1 TeV.
- Will complement LHC's discovery potential by providing precision measurements.
- Requires unprecedented jet energy resolution.
- Achieved through combination of highly granular calorimetry and particle flow.
- Detector optimization relies on realistic simulation (especially of hadronic showers).
- Needs test beam data for verification.
- CALICE collaboration leading the way.
- For more info, go to **http//:www.hep.phy.cam.ac.uk/calice/**