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Comments on Linear Collider Calorimetry

Case for Precision ECAL?

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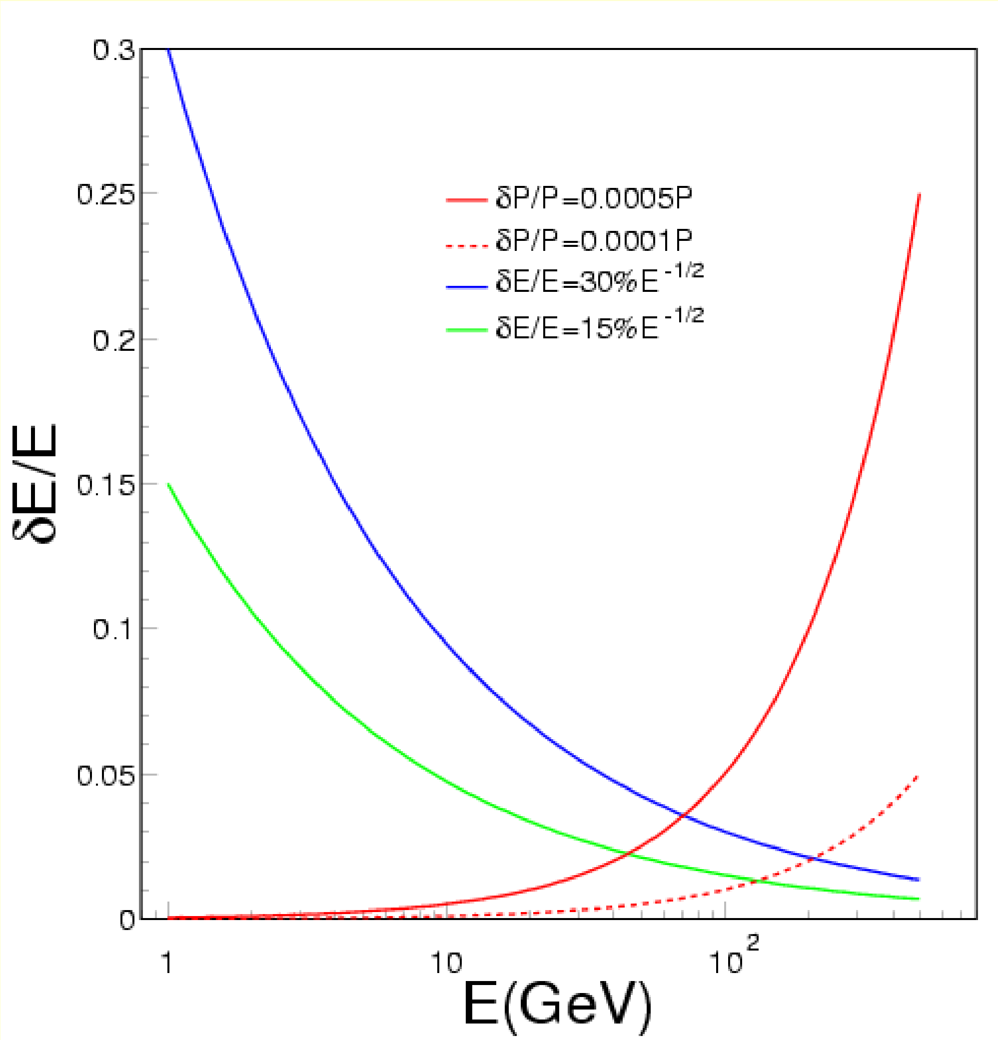
Introduction

- While all recent built HEP detectors have precision ECAL, LC calorimetry community pursues precision jet calorimetry. A sexy solution is the **energy flow**, which requires "particle reconstruction in jets" and thus calorimeter with fine segmentations.
- Jet and jet-jet mass measurements suffer from systematic uncertainties from physics (QCD and fragmentation), algorithm (jet definition) and detector (resolution and leakage).
- While the limit to the precision ECAL is well understood the limit to the jet measurement at LC is yet to be fully investigated.

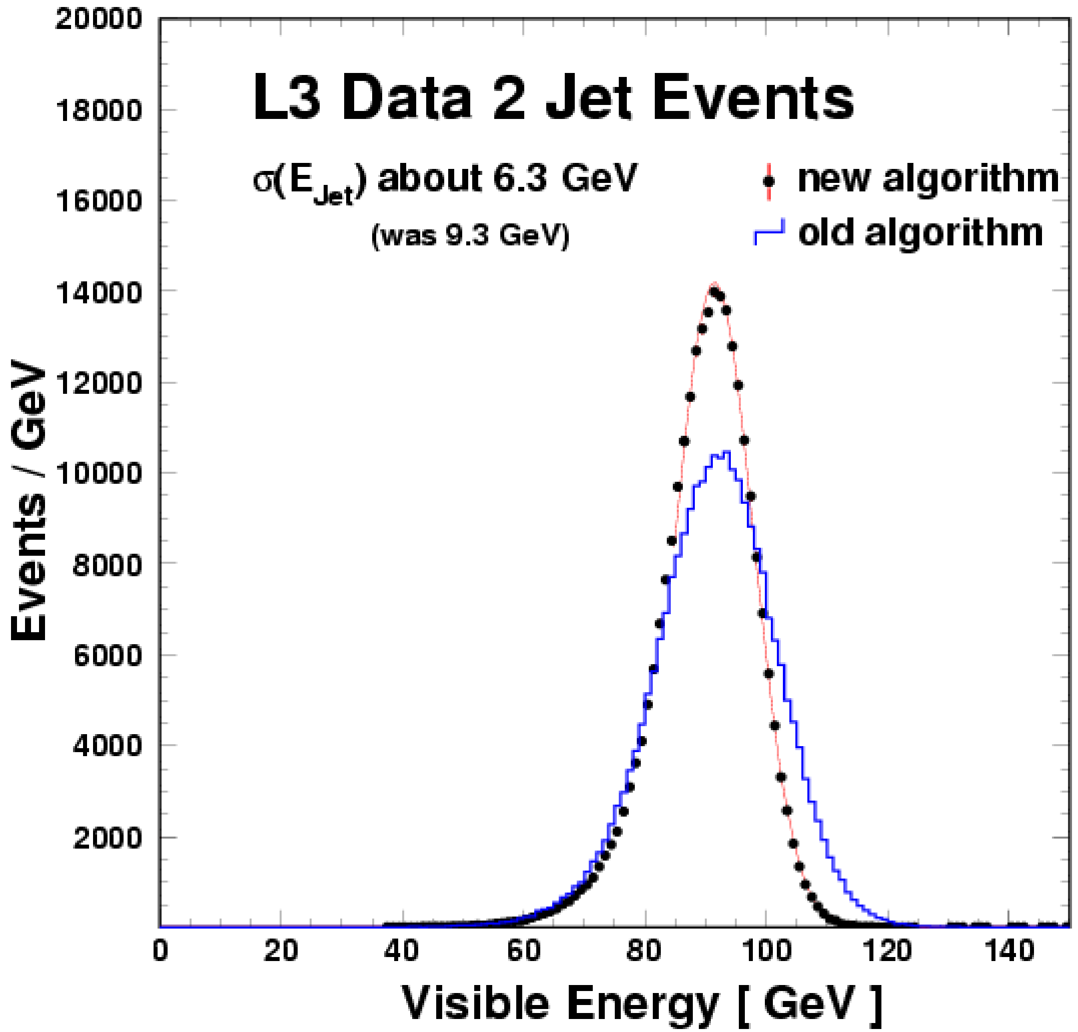
What is Energy Flow



- Jet energy is not well measured by calorimeter.
- At LC energies, energy of isolated charged calorimeter cluster may be replaced by better measured matching tracker momentum.
- For overlapping clusters, classical energy flow subtracts average response: 30% improvement.
- Modern energy flow tries to subtract exact deposition.

Energy Flow at L3: Z Mass at LEP I

Proceedings of Sitges Workshop, p.1058, 1999



- Classical energy flow improves Z mass resolution from 10 to 7%: 30% improvement
- Similar improvement observed in all 4 LEP experiments. See presentations in Calor2002.

CDF Energy Flow: Jet Energy

Photon + Jets by CDF, using shower maximum (particle ID) and tracker: 24% improvement.

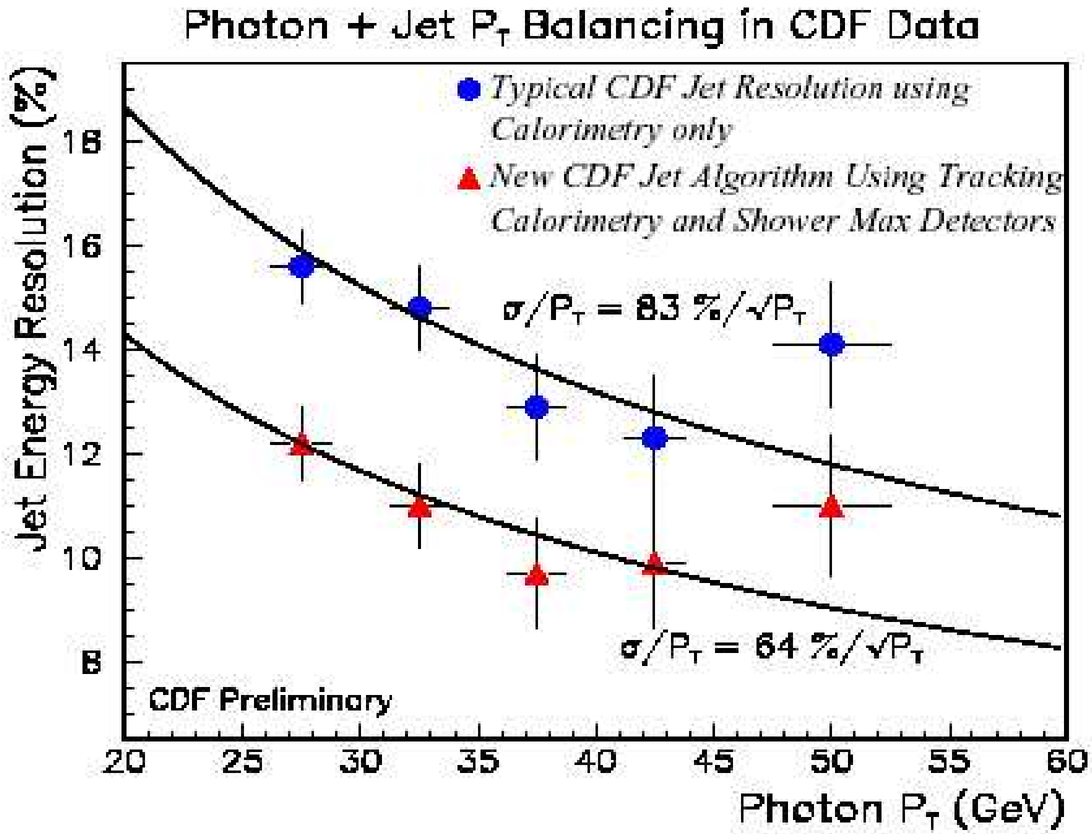


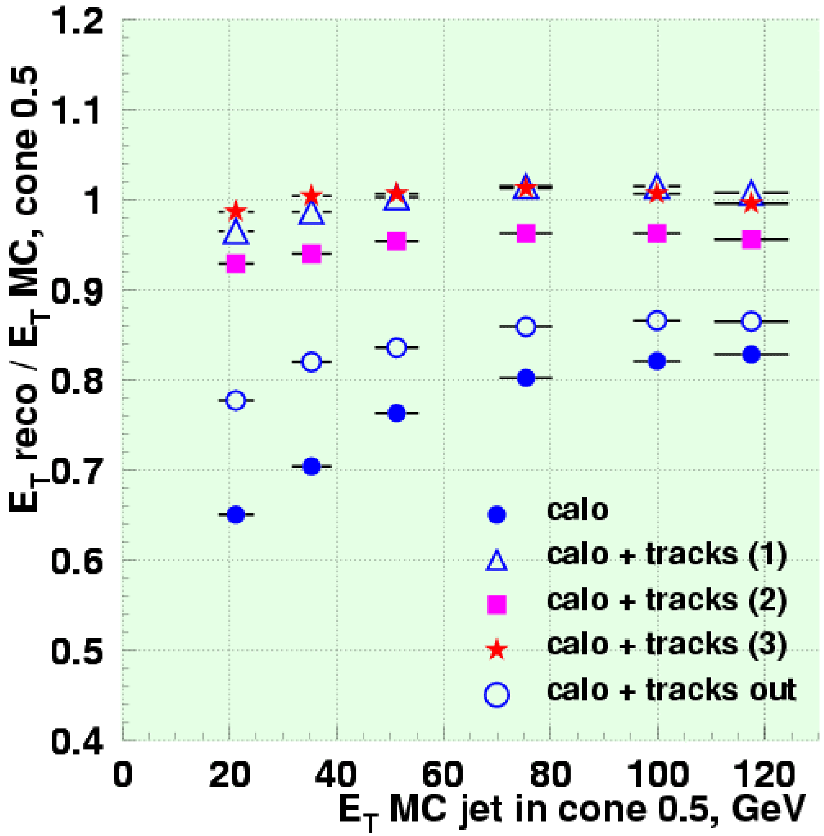
Figure 4: *The central detector resolution σ_D is plotted as a function of P_T^γ for the two methods.*

U. Baur et al., Fermilab-Pub-001297, 2000.

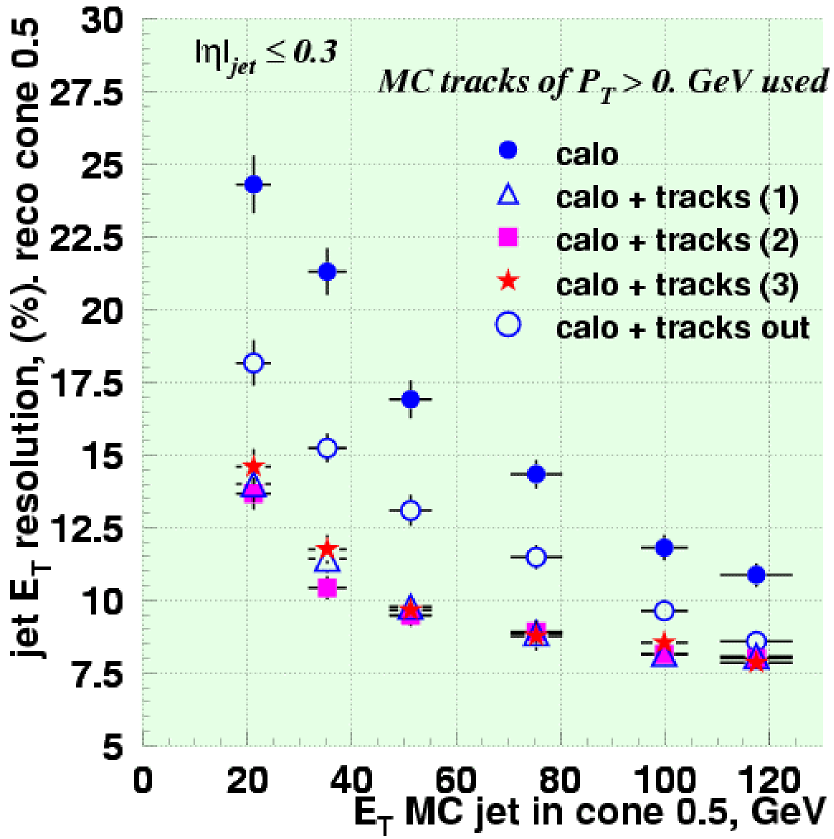
CMS Energy Flow: Jet Energy

S. Kunori, Talk in Calor2002

E_T Scale: < 2% in 20 — 120 GeV



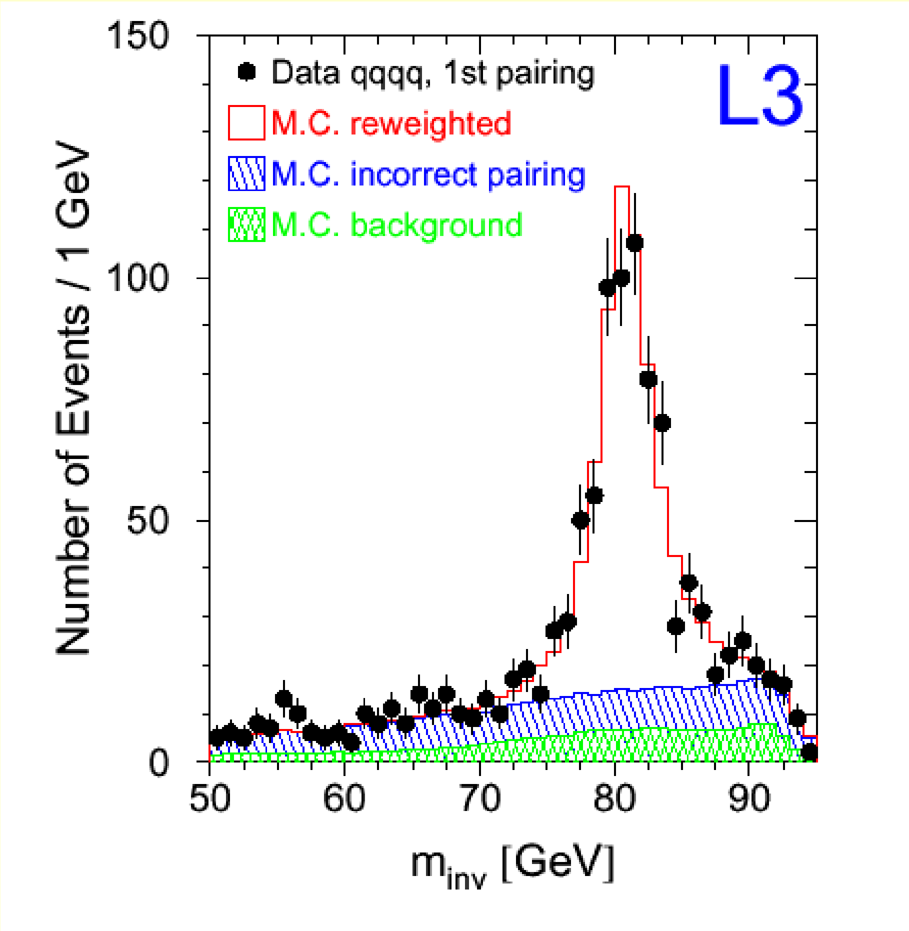
Res.: 24 to 14% @ 20 GeV, 12 to 8% @ 100 GeV



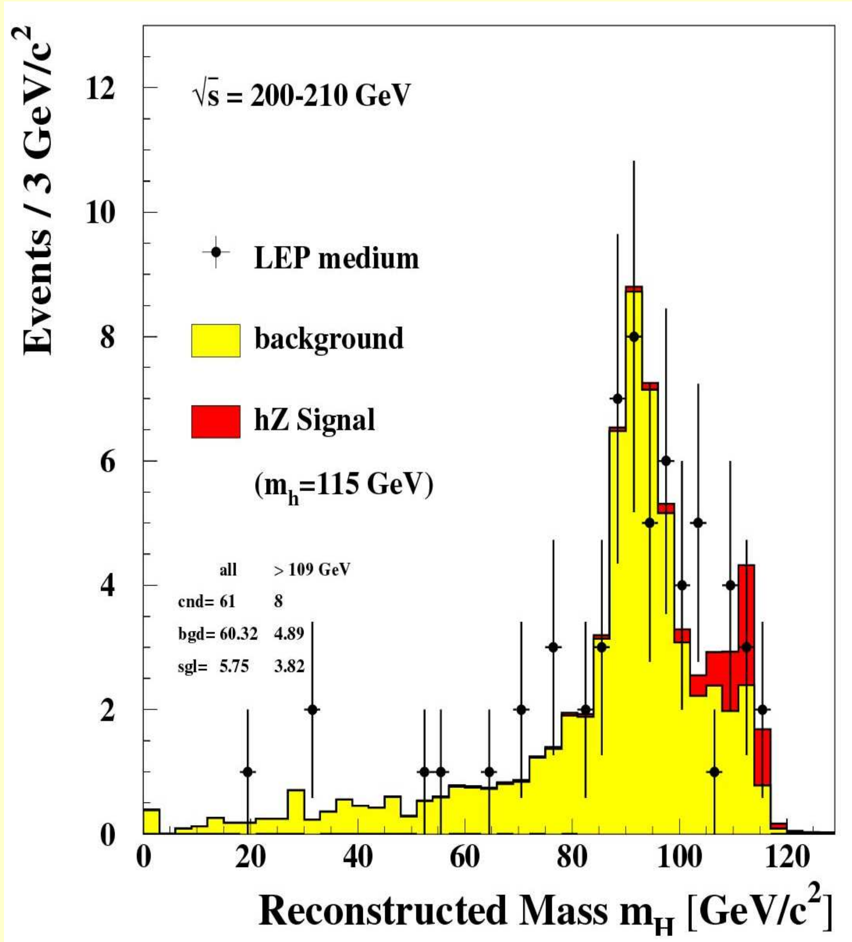
Calo: no corrections; 1: simple average; 2: shower library;
3: library, track-cluster match, out cone track; 4: out cone track only.

Best Jet Mass Resolution at LEP II

W Mass with 2 jets by L3: 3%



Higgs with 2 jets at LEP: 3%



4C Fit using Jet direction: calorimetry resolution irrelevant.

Comparison of Stochastic Term a

	L3	CDF	CMS
Calorimeter	97%	83%	107-120%
Energy Flow	65%	64%	63-80%
4C Fit	26%		

Jet Energy Measurement

$$E_{jet} = \sum_{i=1}^{n} E_i$$

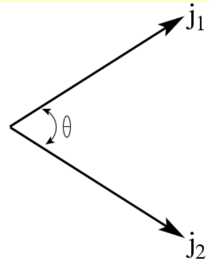
Assuming calorimeter resolution:

$$\frac{\delta E_i}{E_i} = \frac{a}{\sqrt{E_i}} \oplus b$$

Neglecting the constant term b,

$$\frac{\delta E_{jet}}{E_{jet}} = \frac{a}{\sqrt{E_{jet}}}$$

Jet-Jet Mass Measurement



$$M = 2\sqrt{E_1 E_2}\, sin\frac{\theta}{2}$$

$$\frac{\delta M}{M} = \frac{1}{2}\sqrt{(\frac{\delta E_1}{E_1})^2 + (\frac{\delta E_2}{E_2})^2 + (ctg\frac{\theta}{2}\delta\theta)^2}$$

If $\theta = \pi$ and $E_1 = E_2$,

$$\frac{\delta M}{M} = \frac{a}{\sqrt{M}}$$

"Theoretical Limit" of Energy Flow

V. Morgunov, Talk in Calor2002

E_{jet} consists, in average, 30% γ, 60% charged hadron (c.h.) and 10% neutral hadron (n.h.)

Assuming calorimeter resolutions:

$$\frac{\delta E_\gamma}{E_\gamma} = \frac{11\%}{\sqrt{E_\gamma}} \text{and}$$

$$\frac{\delta E_{n.h}}{E_{n.h}} = \frac{40\%}{\sqrt{E_{n.h}}}.$$

Assuming 100% charged track replacement,

$$\frac{\delta E_{c.h}}{E_{c.h}} = 10^{-4} E_{c.h},$$

which is negligible, modern **energy flow** has

$$\frac{\delta E_{jet}}{E_{jet}} = \frac{\sqrt{0.00363 + 0.016}}{\sqrt{E_{jet}}} = \frac{14\%}{\sqrt{E_{jet}}}.$$

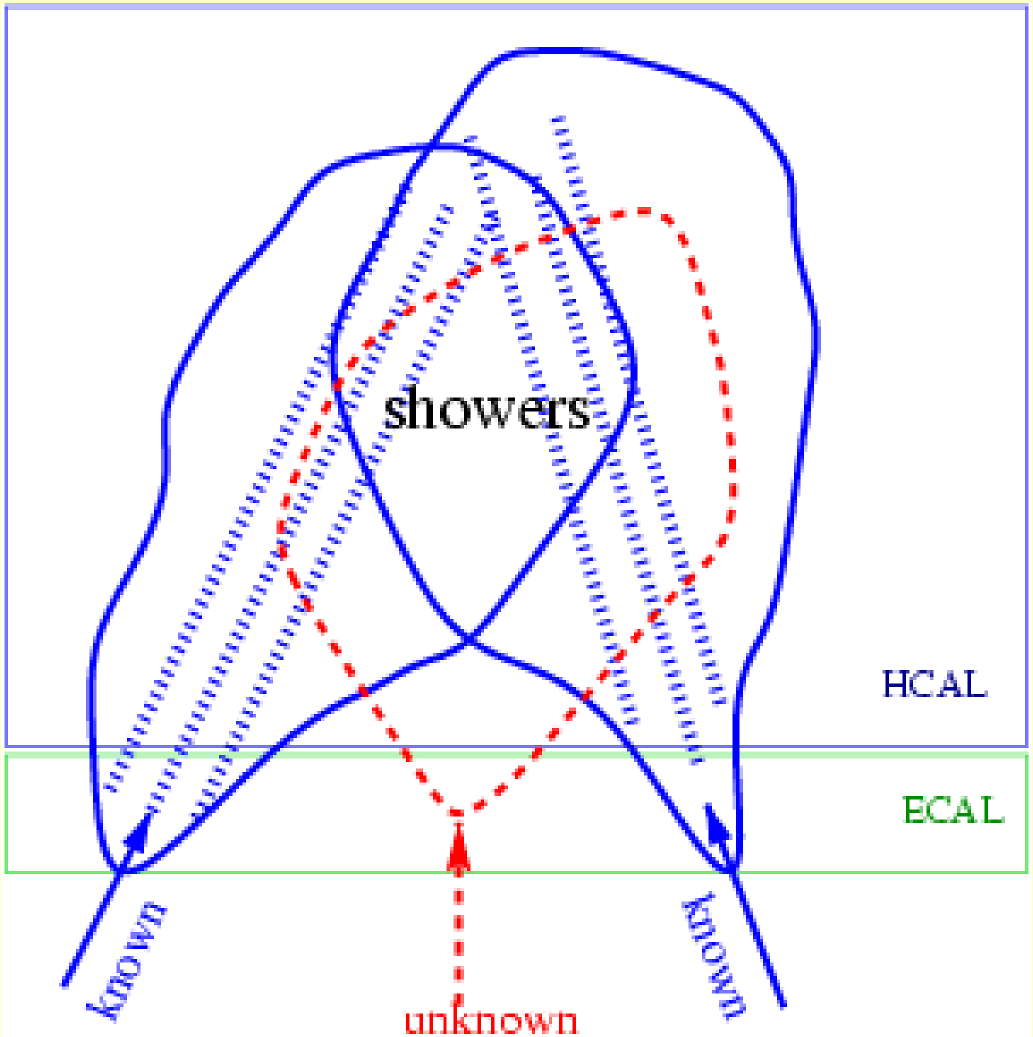
100% charged track replacement is impossible because of shower overlap.

Additional uncertainty due to physics and jet definition.

Optimization of detector design must be done after full investigation of all contributions.

Solution for Shower Overlap?

V. Morgunov, Talk in Calor2002



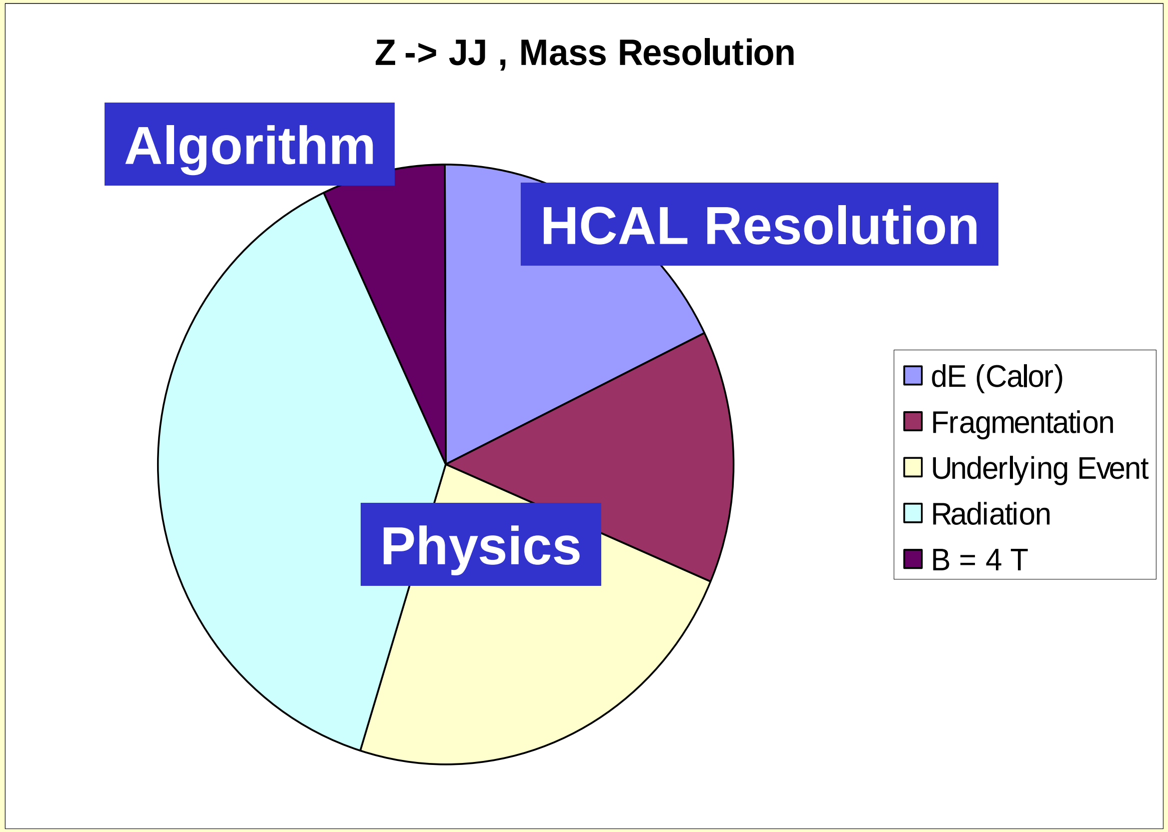
R. Wigmans: Shower overlap is unavoidable, and fine segmentation does not help.

Attempt by CDF and CMS indicates that shower library and particle ID with shower maximum detector for overlap shower do not help.

Jet Mass Resolution in Hadron Collider

D. Green, Talk in Calor2002

- Monte Carlo studies identify the elements contributing to the mass error. Quote low P_T, Z -> JJ. dM/M ~ 13% without FSR.



FSR is the biggest effect. The underlying event is the second largest error (if cone R ~ 0.7). Calorimeter resolution is a minor effect.

Energy Flow Summary

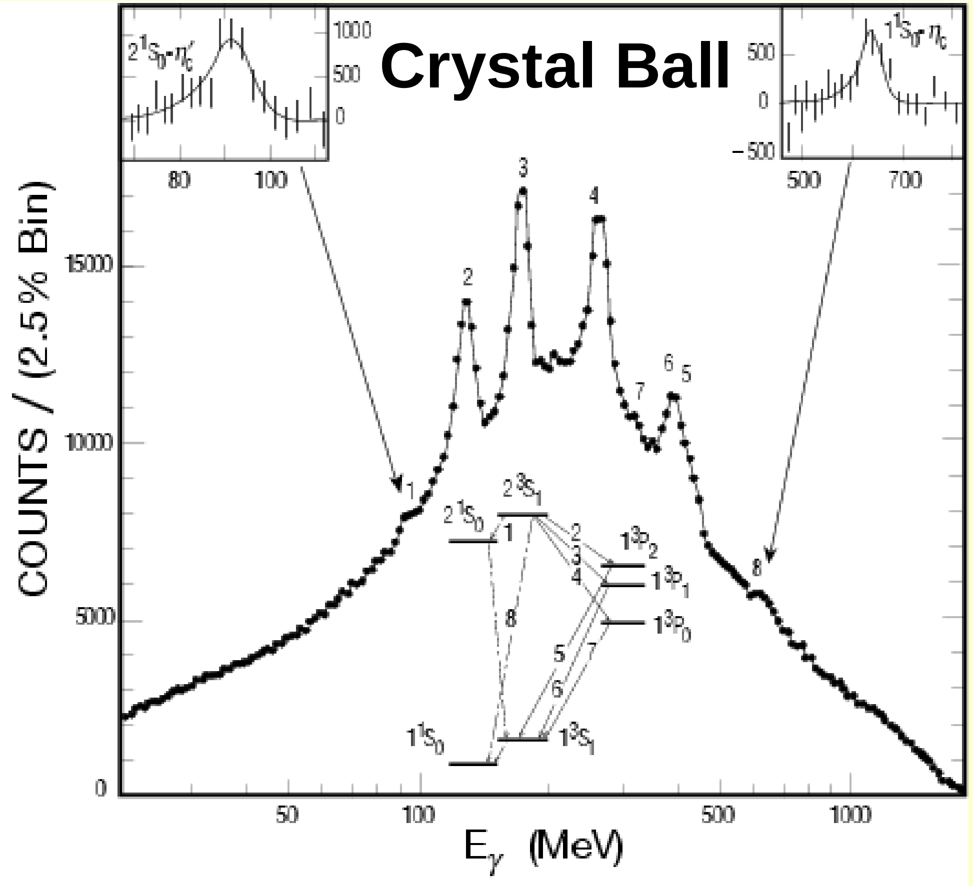
- Classical **energy flow** improves jet energy resolution by 30%, to 60% stochastic term. Any further improvement must also address the physics limitations.
- The **energy flow** is less effective at high energies: tracker resolution & shower overlap.
- Jet direction is better measured. Less than 30% stochastic term is already achieved by using 4C fit, which is also available **free** at LC.
- Before spending tax payer's money in calorimeter segmentation, full simulation and verification with test beam are required to understand limitations to the jet measurement.

Why Precision ECAL at LC

- Photons and electrons are fundamental particles for SM and new physics.
- Performance of precision ECAL, such as crystals, well understood:
  - Good energy, position and photon angular resolution;
  - Good e/photon identification and reconstruction efficiency;
  - Good missing energy resolutions;
  - Good jet energy resolution with energy flow.

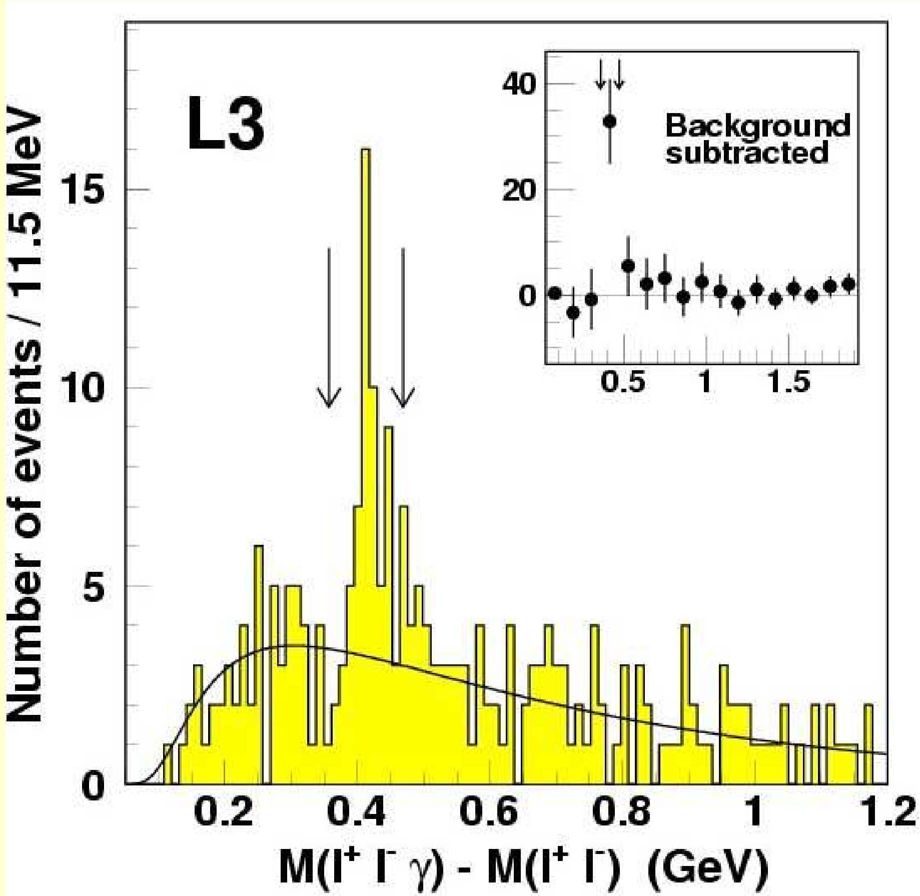
SM Physics in Precision ECAL

Charmonium System Observed Through Inclusive Photons



Charmed Meson in Z Decay

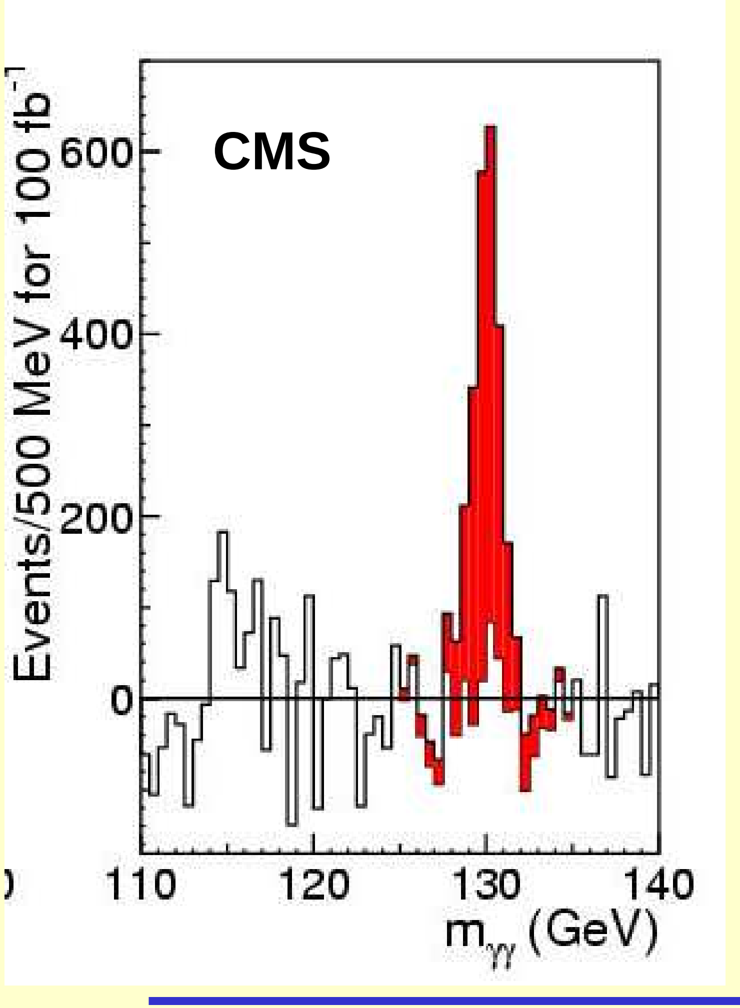
$$\chi_{c1} \to J/\psi\gamma$$



New Physics in Precision ECAL

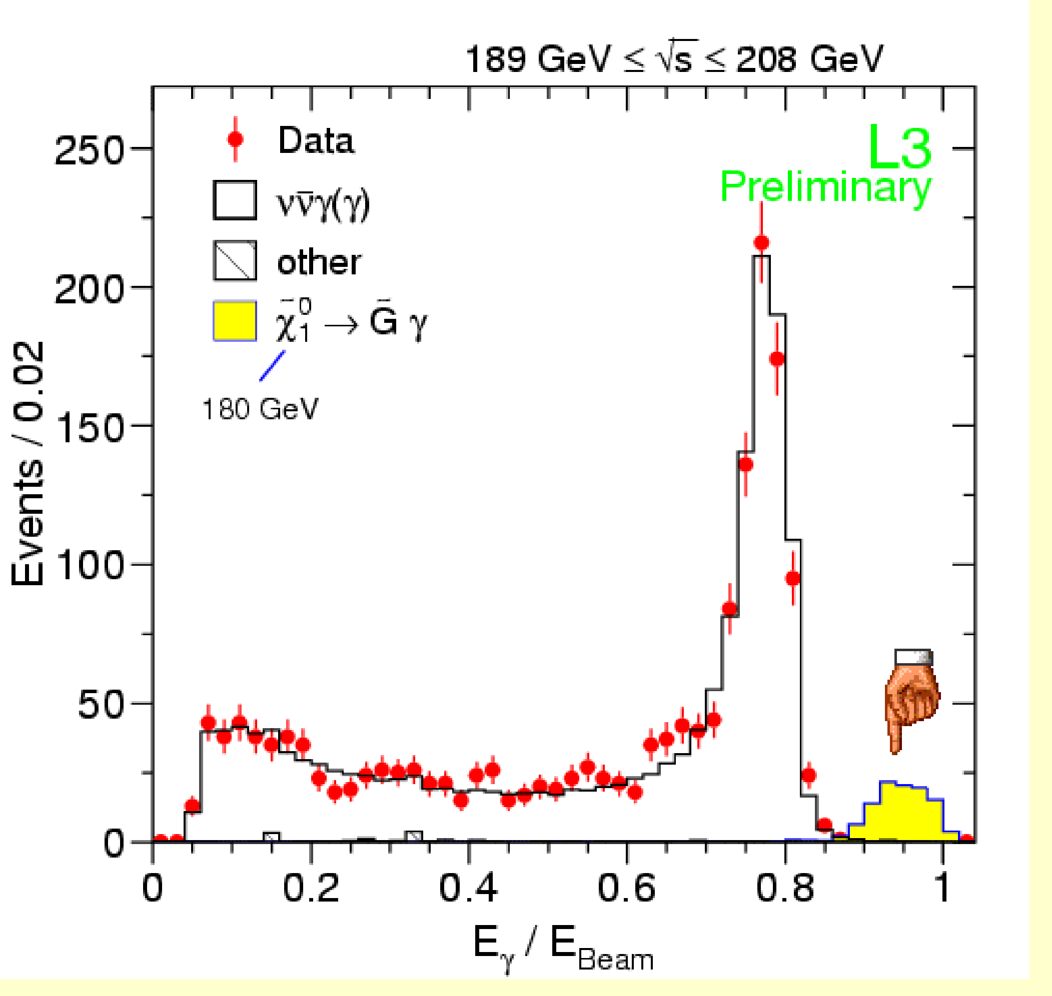
J. Gunion, in Snowmass

$$H \rightarrow \gamma\gamma$$



SUSY Breaking with Gravitino

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



New Physics in Precision ECAL (Cont.)

The CDF event: **2 e + 2 γ + E_T^{miss}**

SM expectation (WW$\gamma\gamma$) ~ 10^{-6} (PR D59 1999)

Possible SUSY explanation

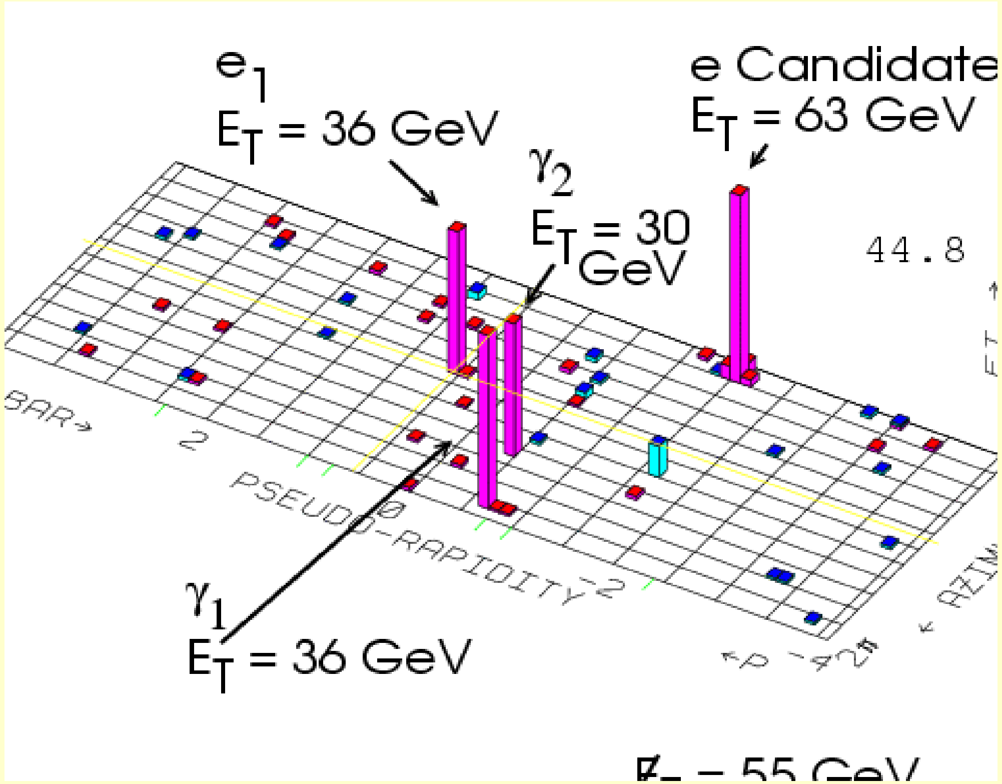
$$q\bar{q} \to \tilde{e}^+\tilde{e}^- \to ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ee\gamma\gamma\tilde{G}\tilde{G}$$

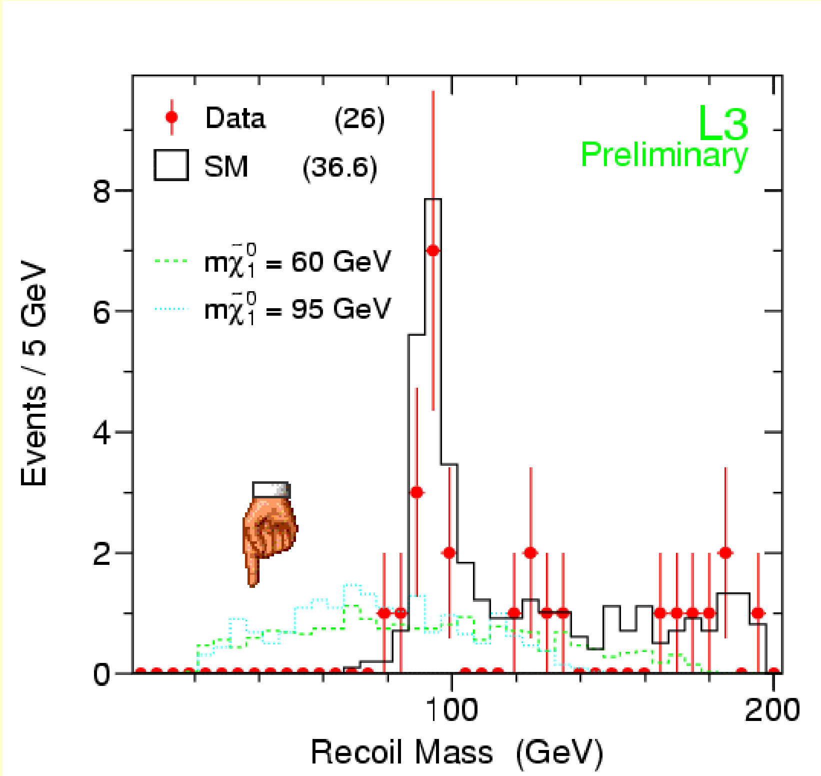
L3 should be able to observe

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$$

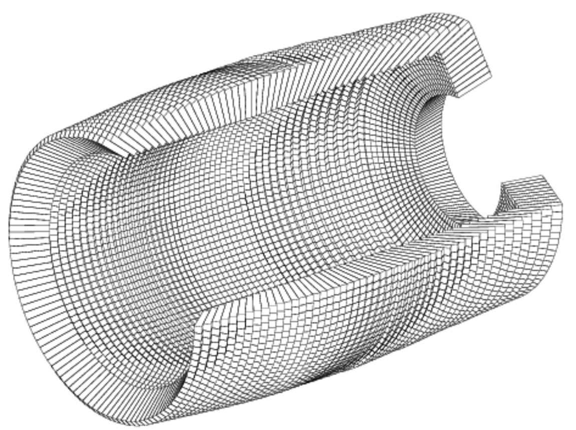
Another possible channel

$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \gamma\gamma\tilde{\chi}_1^0\tilde{\chi}_1^0$$

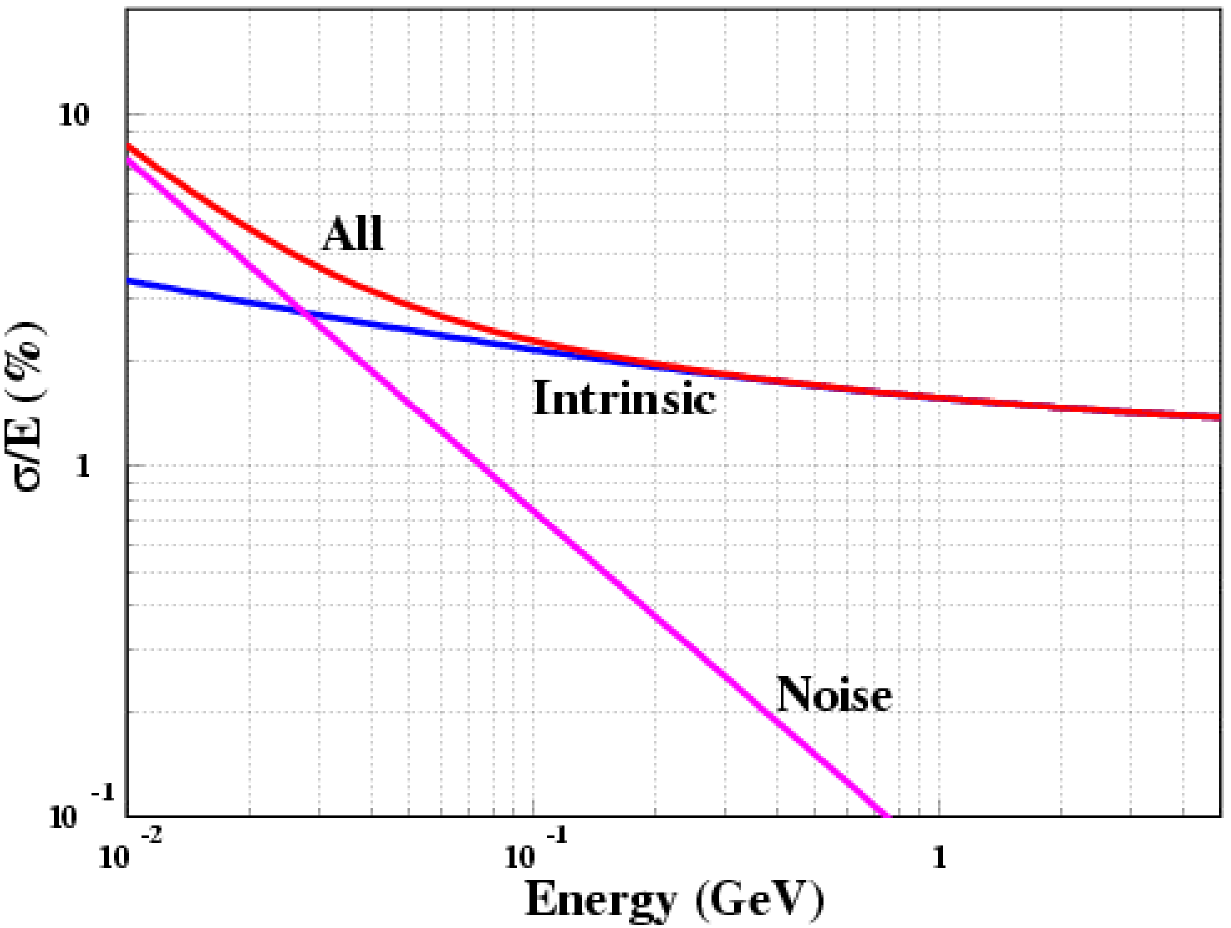




BaBar CsI(Tl) Resolution



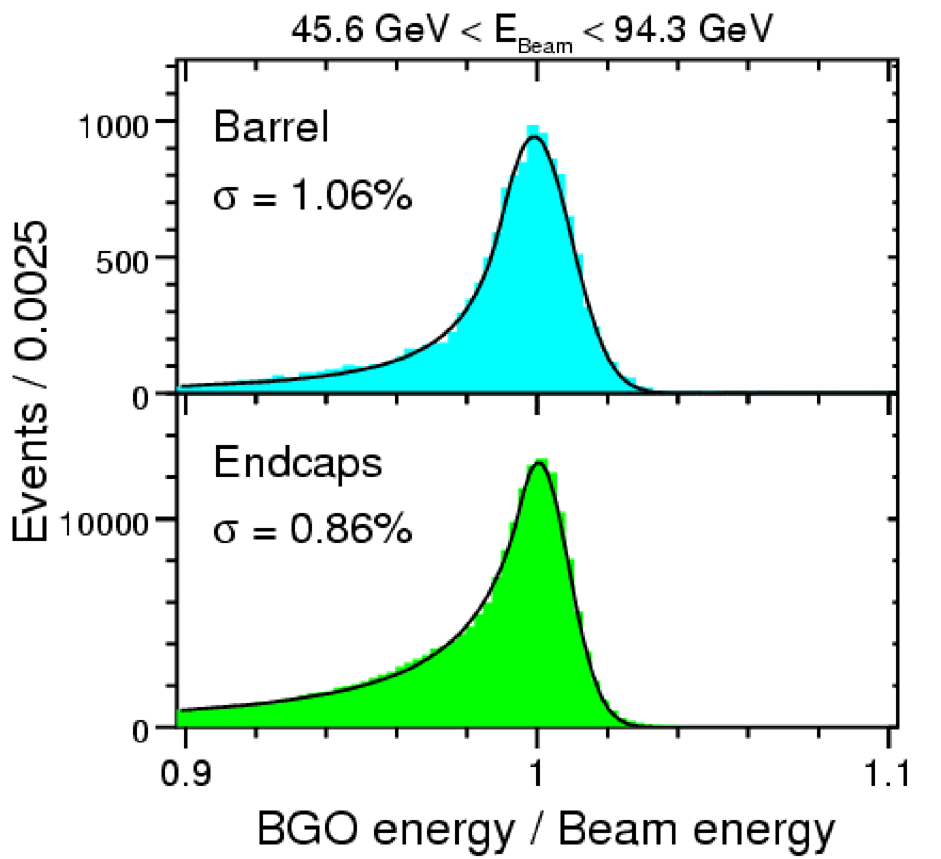
Crystal Calorimetry at Low Energies

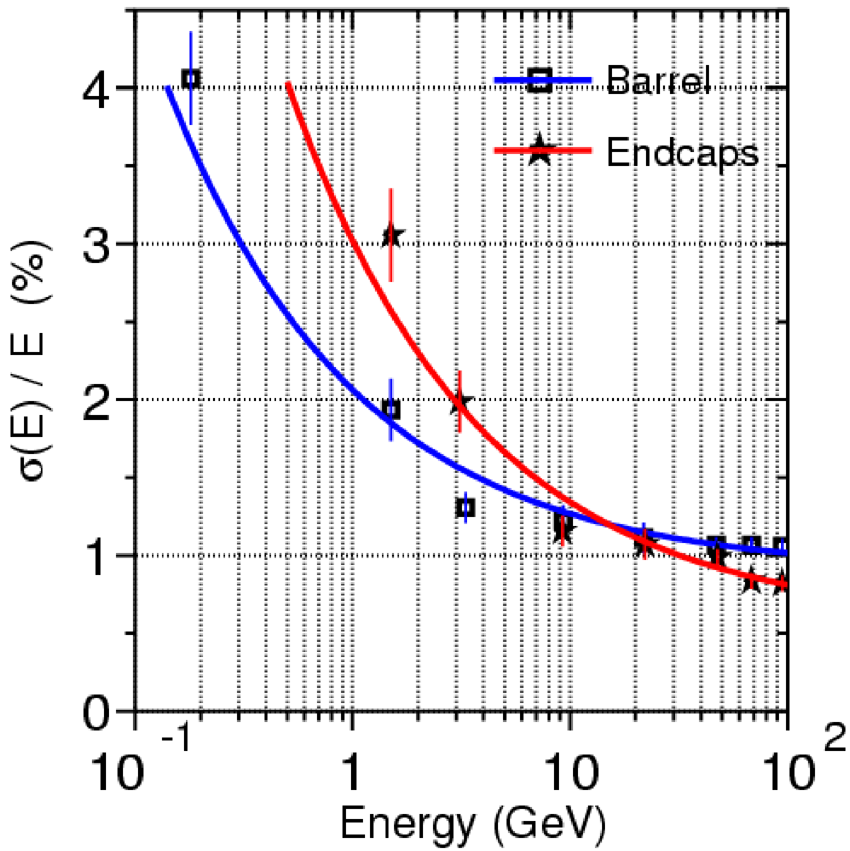


Good light yield of CsI(Tl) provides excellent energy resolution at B factory energies

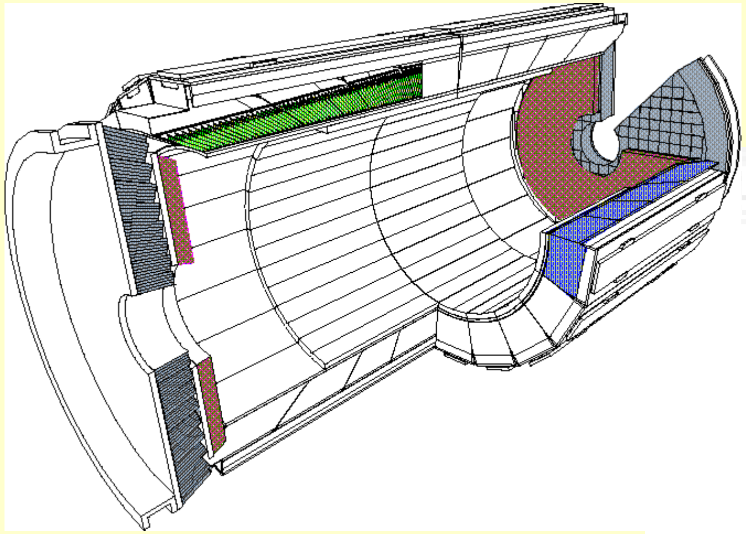
L3 BGO Resolution

Contribution	“Radiative”+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%





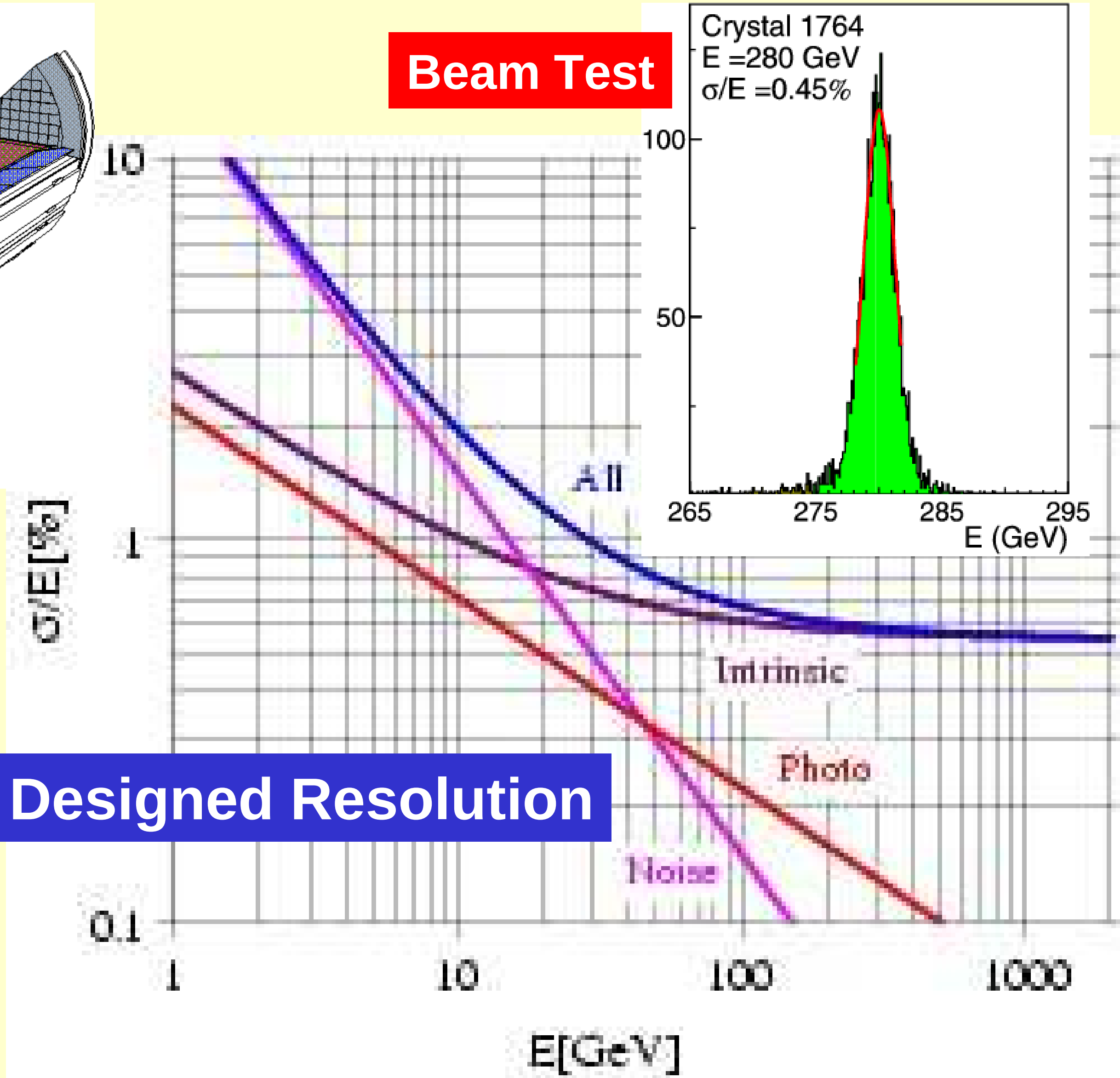
CMS PWO Resolution



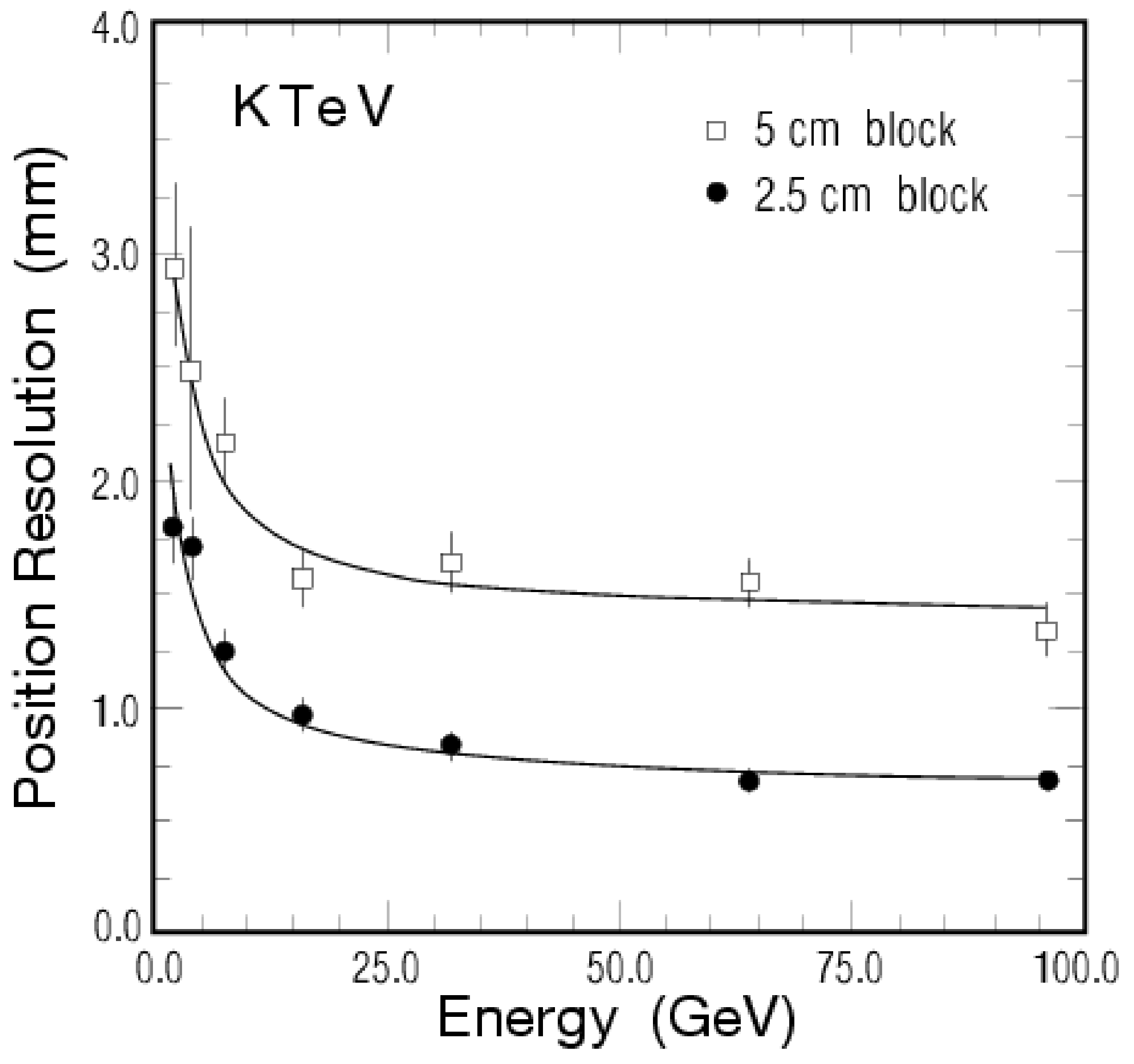
Crystal Calorimetry at High Energies

Beam Test

Designed Resolution



KTeV CsI Position Resolution



Sub mm position resolution is achievable.

L3 BGO & CMS PWO: 0.3 mm at high energies.

Properties of Crystal Scintillators

Crystal	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 (ºC)	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] (%/ ºC)	~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.

Summary: Crystal Calorimetry for LC

- To maximize physics reach, calorimetry for LC should have precision measurement on electrons, photons and jets.
- The crystal calorimetry provides the best achievable EM resolution, good missing energy and jet resolution.
- Some heavy crystal scintillators may provide a cost effective precision EM calorimeter solution.