Comments on Linear Collider Calorimetry

Case for Precision ECAL?

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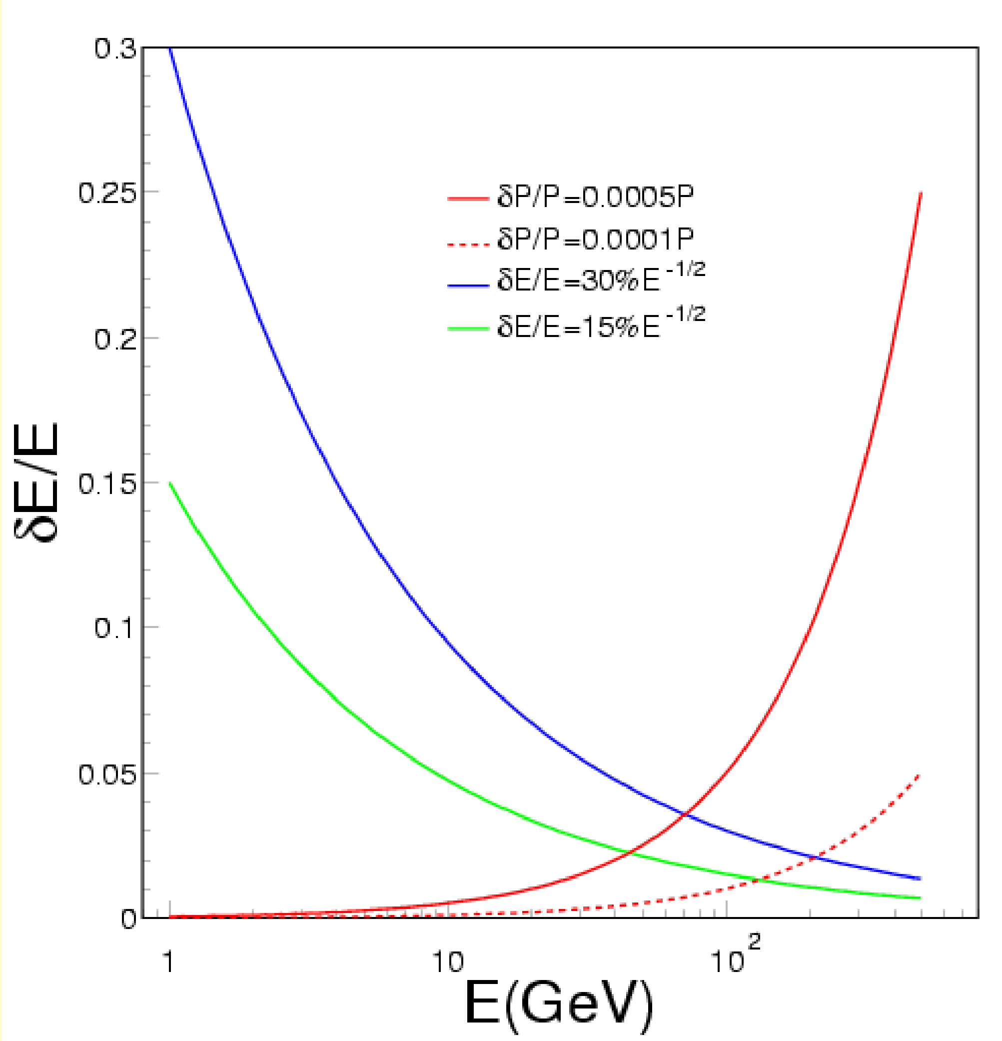
Introduction

- 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.

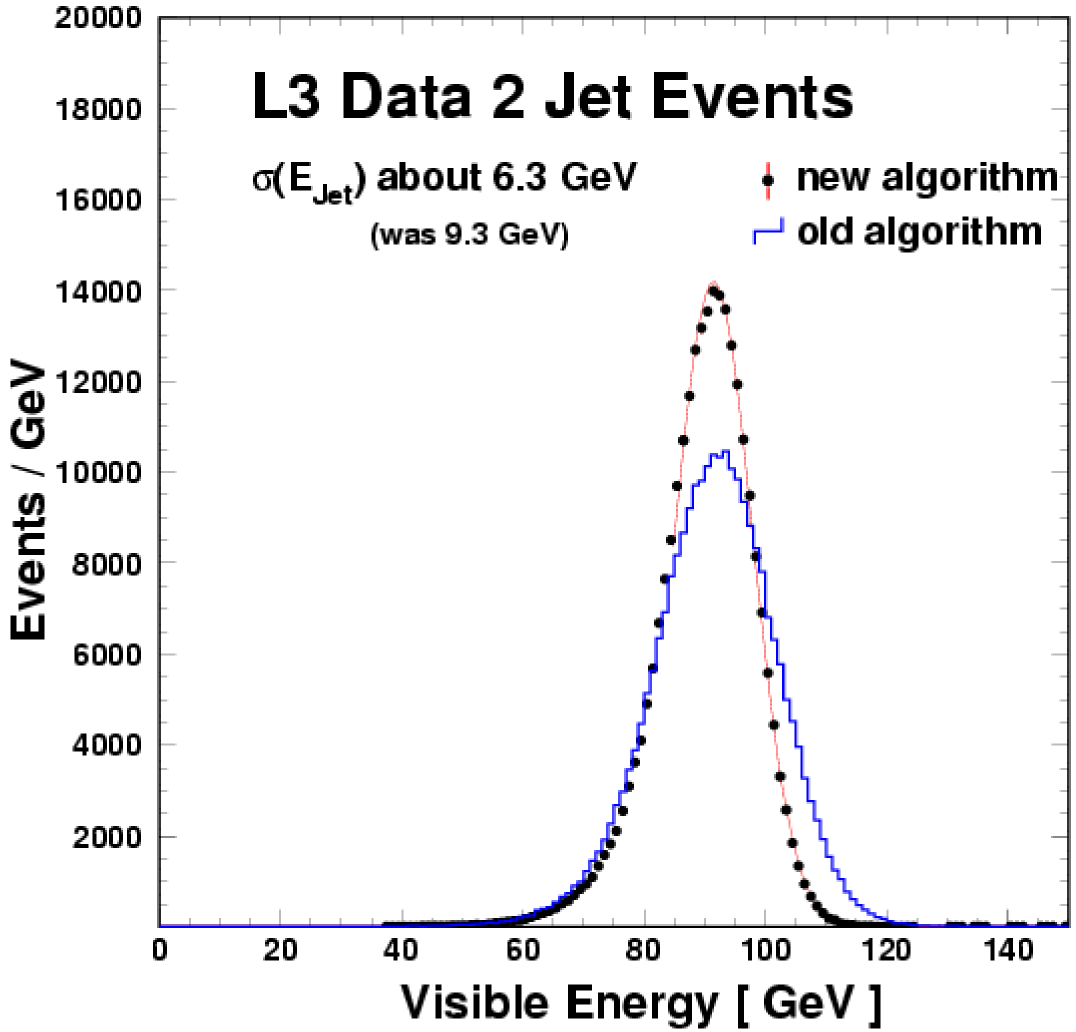
What is Energy Flow



- 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.

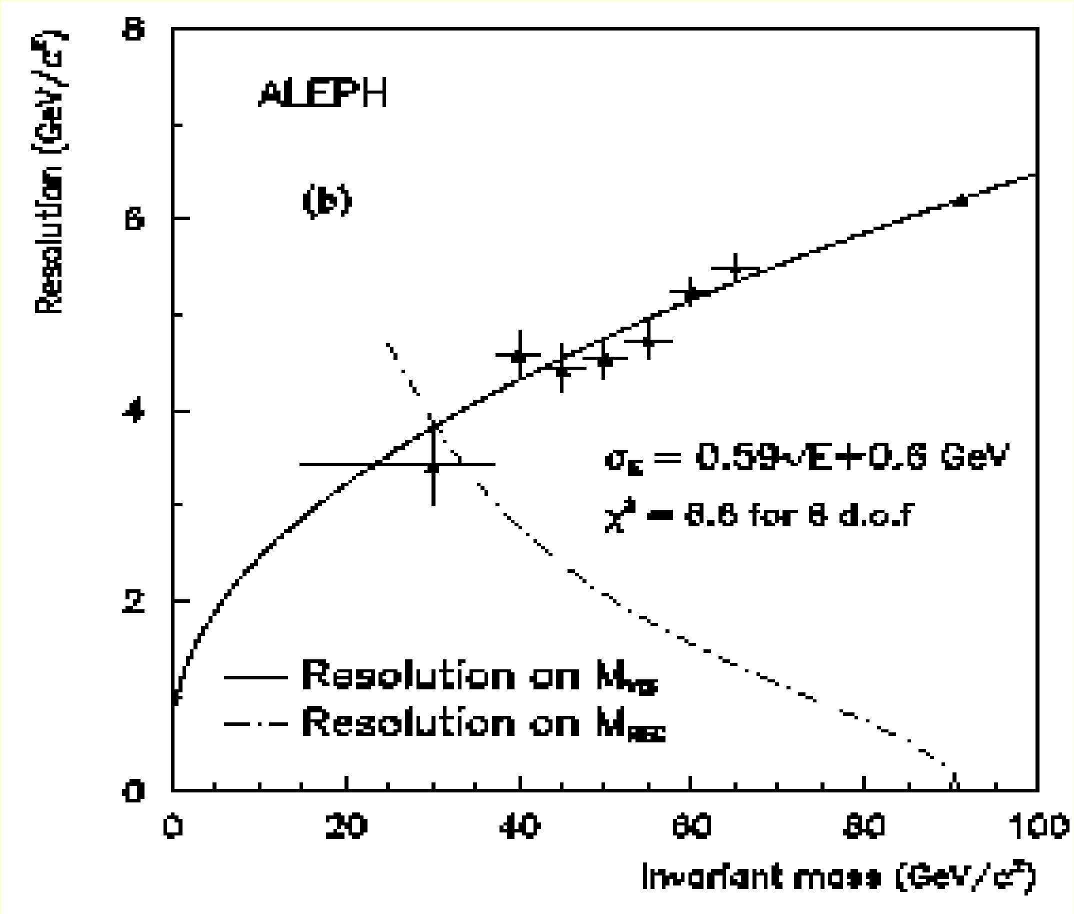
Energy Flow at L3: *Z->qq* at LEP I

Proceedings of Sitges Workshop, p.1058, 1999

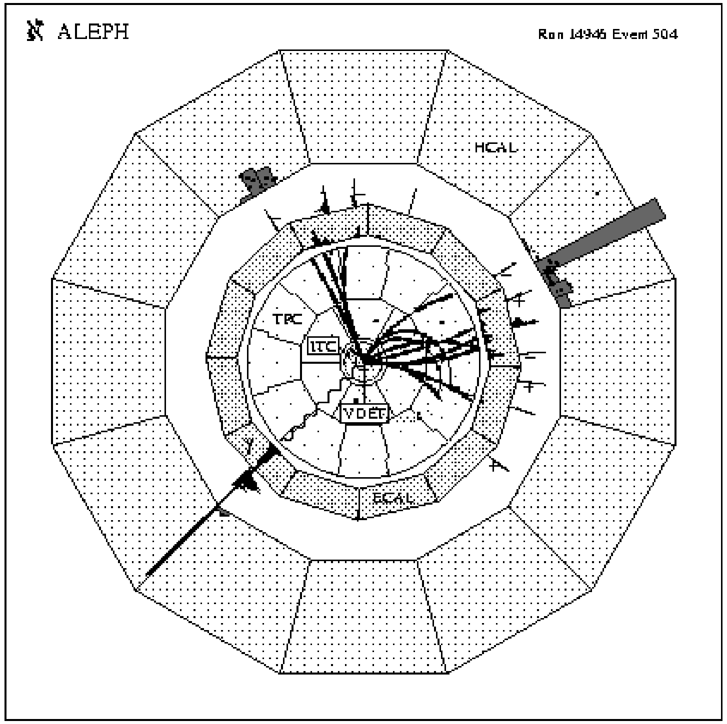


- Classical energy flow improves Z mass resolution by 30%.
- Similar improvement observed in all 4 LEP experiments. See papers in Calor2002 Proceedings.
- This distribution shows only effect of detector, not QCD physics and jet definition algorithm.

Energy Flow in ALEPH: $Z \to q q \gamma$



M. Minard, Calor2002



$\sigma(E)=(0.59+-0.03)\sqrt{E}+(0.6+-0.3)$ GeV: 6.3 GeV @ Z

CDF Energy Flow: Jet Energy

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

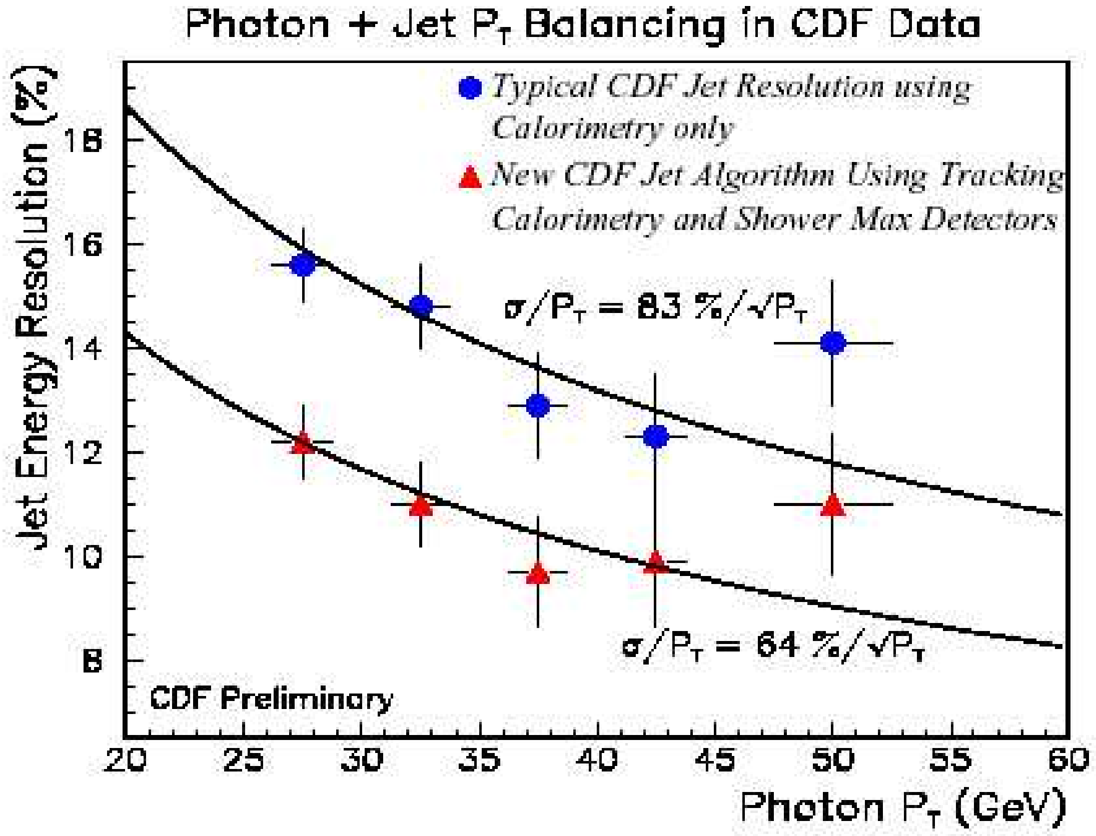


Figure 4: *The central detector resolution σ_D is plotted as a function of P_T^γ for the two methods.*

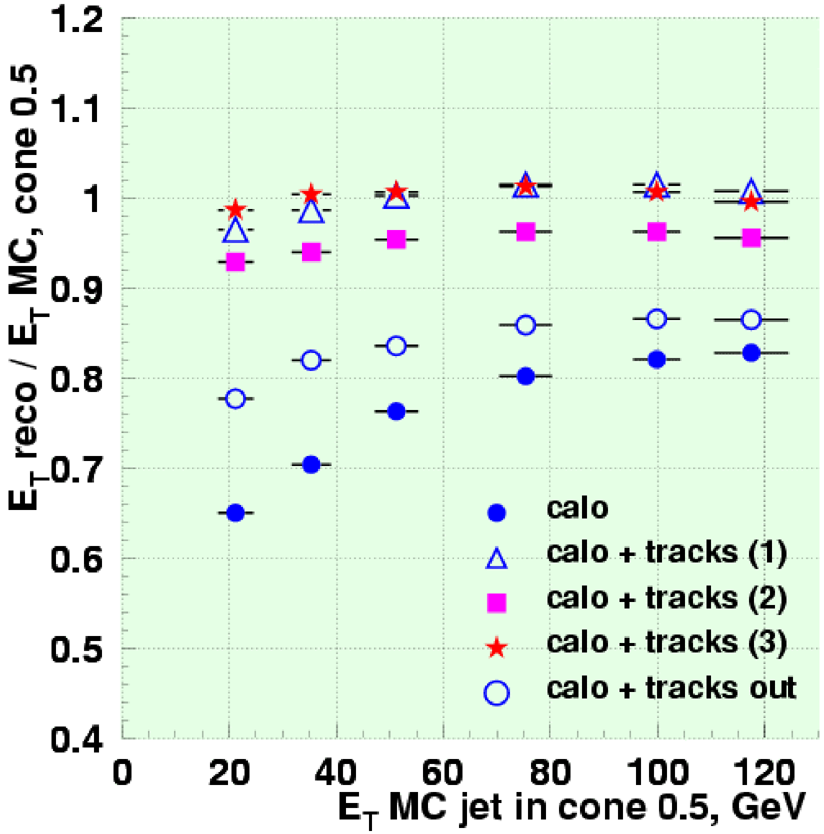
U. Baur et al., Fermilab-Pub-001297, 2000.

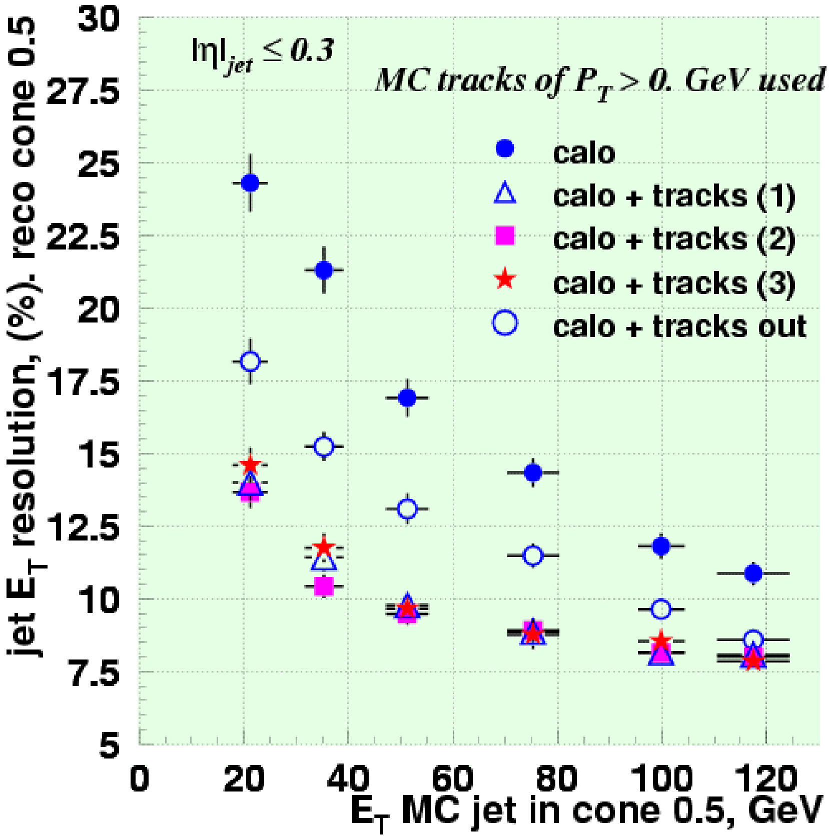
CMS Energy Flow: Jet Energy

S. Kunori, Talk in Calor2002

E_T Scale: < 2% in 20 — 120 GeV

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

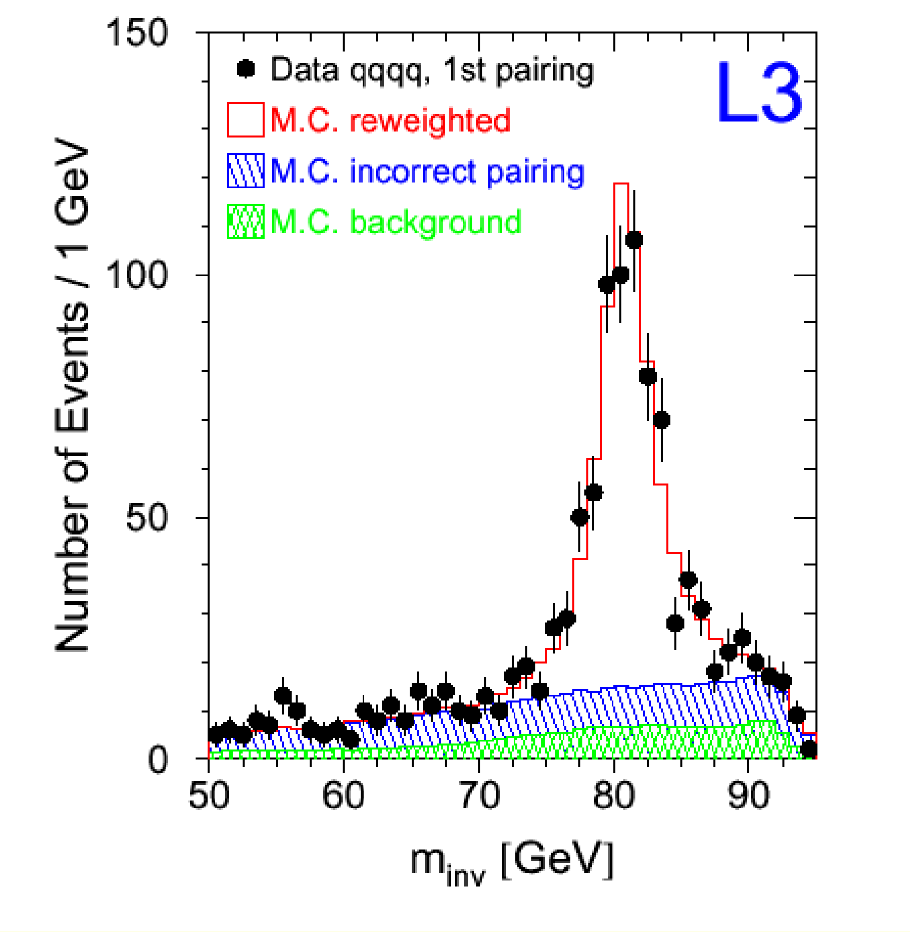




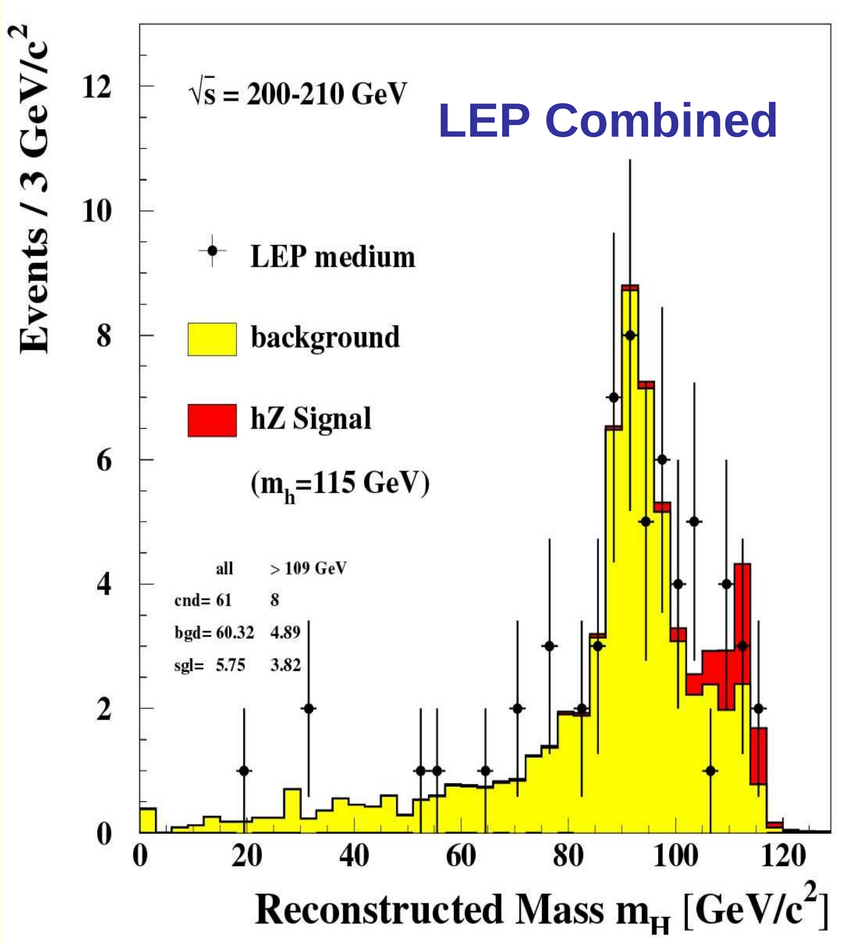
Calo: no corrections; 1: simple average; 2: shower library;
3: library, track-cluster match, out cone track; 4: out cone track only.

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: Free from QCD, Algorithm & Cal. resolution.

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

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

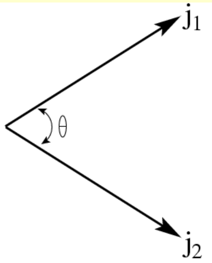
Assuming calorimeter resolution:

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

Neglecting the constant term b,

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

Jet-Jet Mass Measurement



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

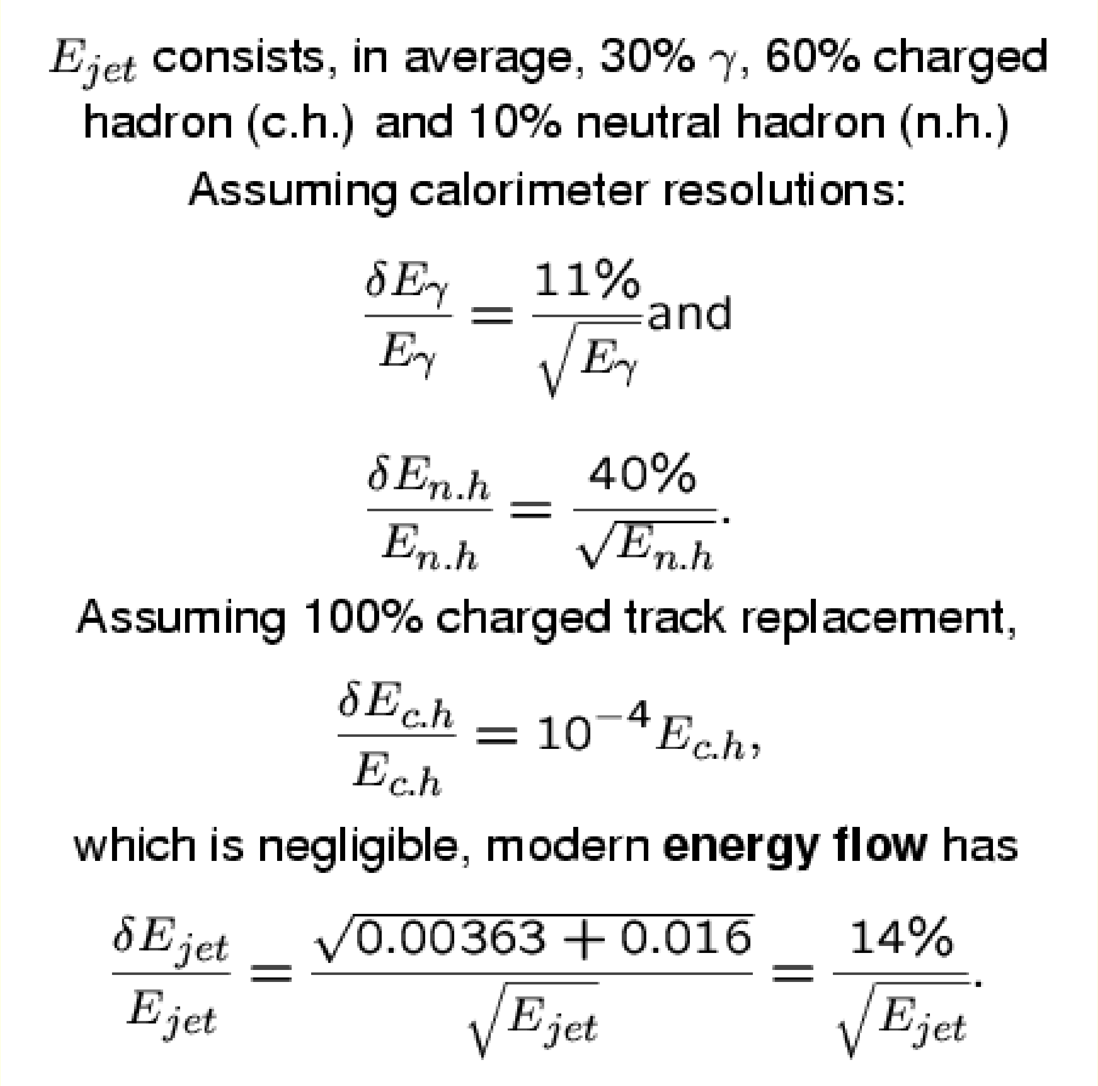
$$\frac{\delta M}{M} = \frac{1}{2}\sqrt{(\frac{\delta E_1}{E_1})^2 + (\frac{\delta E_2}{E_2})^2 + (ctg\frac{\theta}{2}\delta\theta)^2}$$

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

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

“Theoretical Limit” of Energy Flow?

V. Morgunov, Paper in Calor2002 Proceedings



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

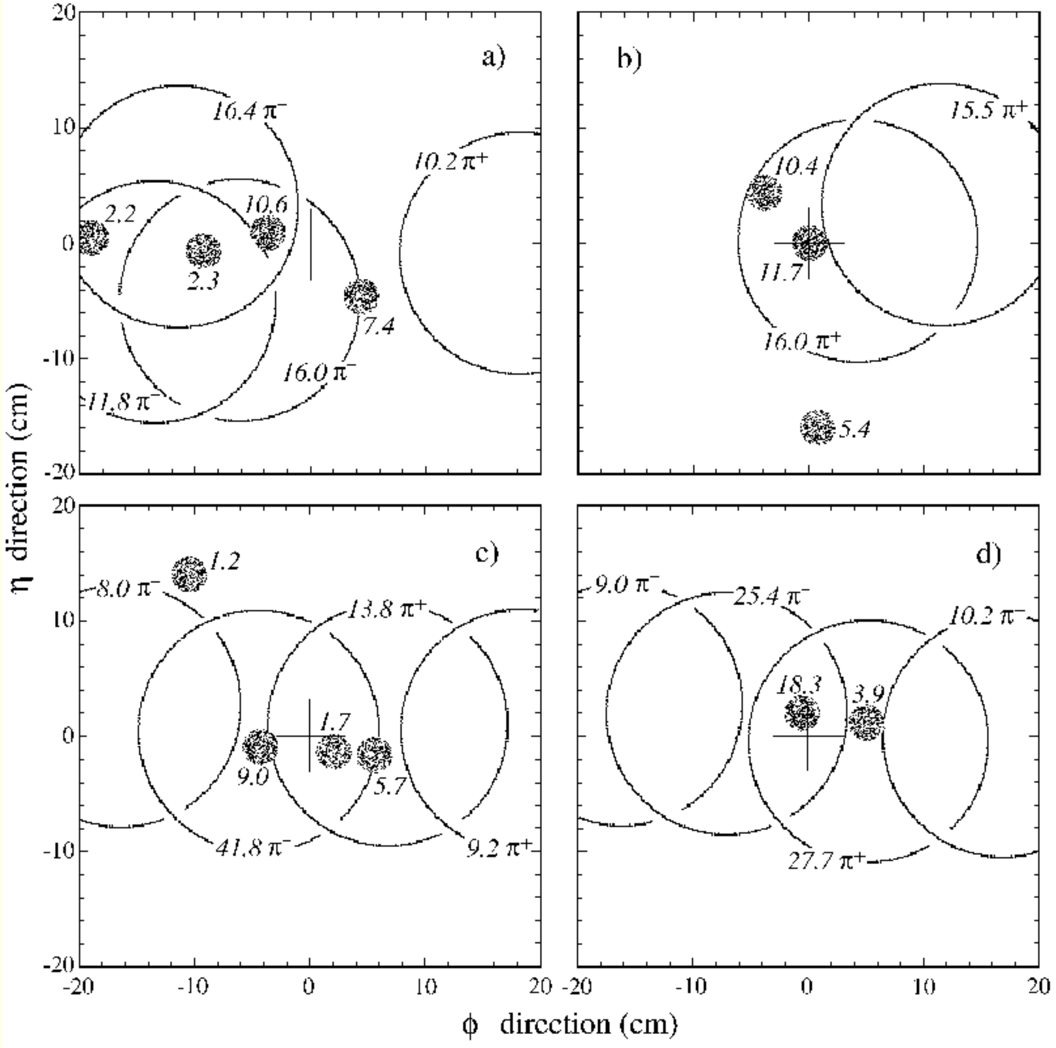
$$\frac{\delta E_{jet}}{E_{jet}} = \frac{\sqrt{0.00363 + 0.016}}{\sqrt{E_{jet}}} = \frac{14\%}{\sqrt{E_{jet}}}.$$

Comments:

- 100% charged track replacement is impossible because of shower overlap.
- Additional uncertainty due to QCD physics and jet definition.

Shower Overlap is Unavoidable

R. Wigmans, Paper in Calor2002 Proceedings



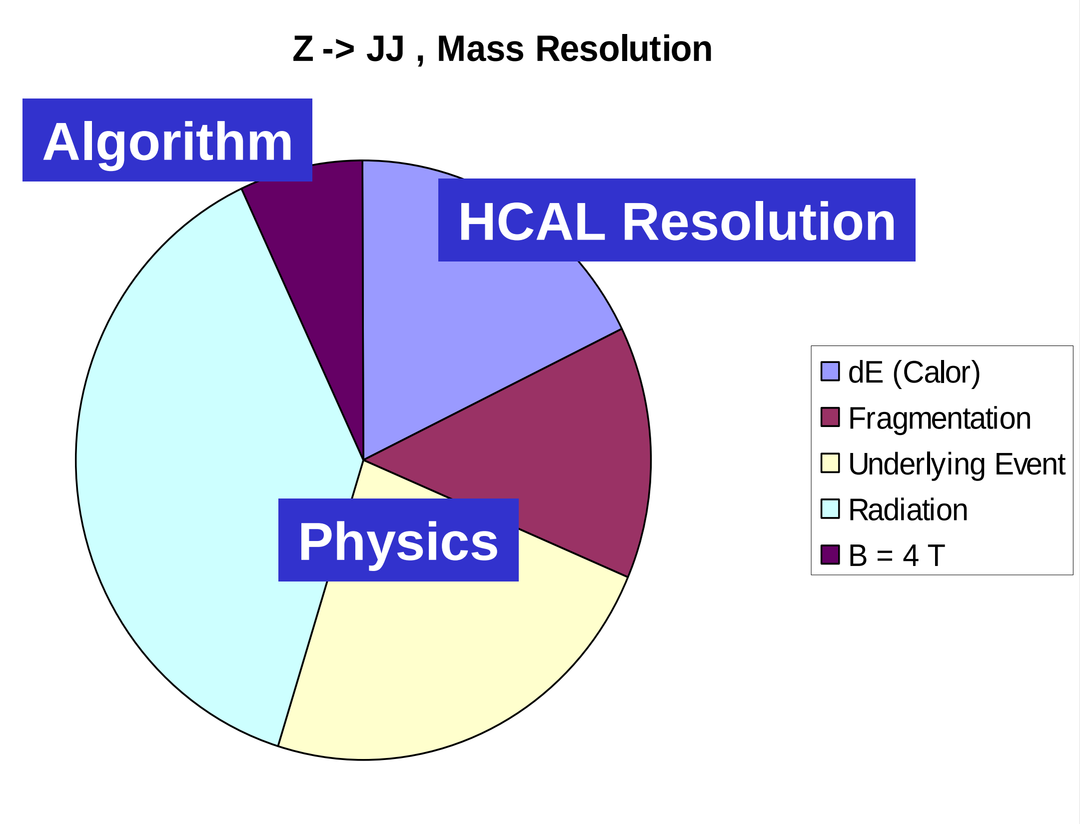
4 typical 100 GeV quark jets in “Tesla” detector. Dark dots are EM shower with Moliere radius of 1 cm. Open circles are hadron showers with interaction length of 10 cm.

Attempt by CDF and CMS indicates that shower library and particle ID with shower maximum does not help.

Jet Mass Resolution in Hadron Collider

D. Green, Paper in Calor2002 Proceedings

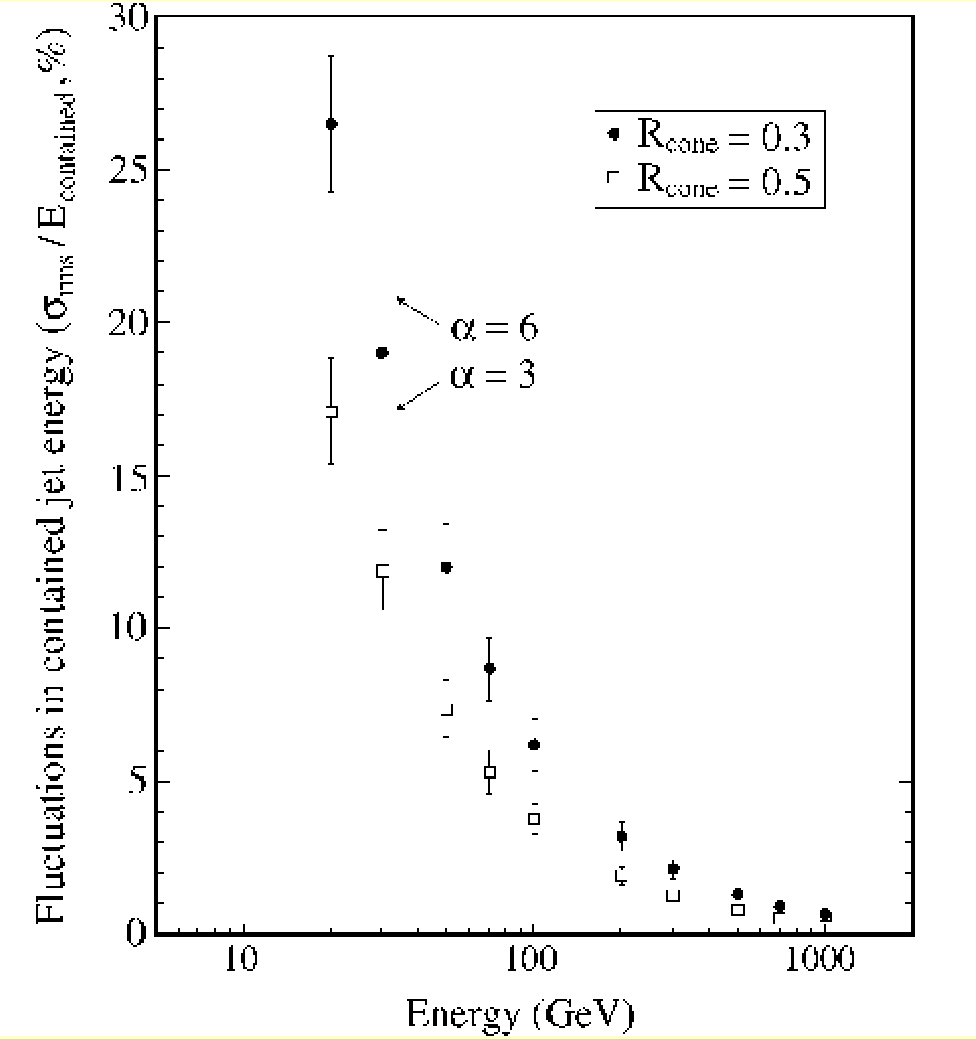
- Monte Carlo studies identify the elements contributing to the mass error. Quote low P_T, Z -> JJ. dM/M ~ 13% without FSR.



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

Partial Effect of Fragmentation & Algorithm

R. Wigmans, Paper in Calor2002 Proceedings



Jet energy fluctuation in a cone of R= 0.3 and 0.5: 5% at 100 GeV.

Comments:

- Fragmentation effect is underestimated because of the independent jet fragmentation model used.
- QCD effect of FSR, i.e. gluon bremsstrahlung, is not included in simulation.
- Lower limit of jet energy resolution: “a” = 50%!!

Energy Flow Summary

- **Classical energy flow** improves jet energy resolution by 30%, to ~60% stochastic term. Further improvement must also address the physics limitations.
- **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

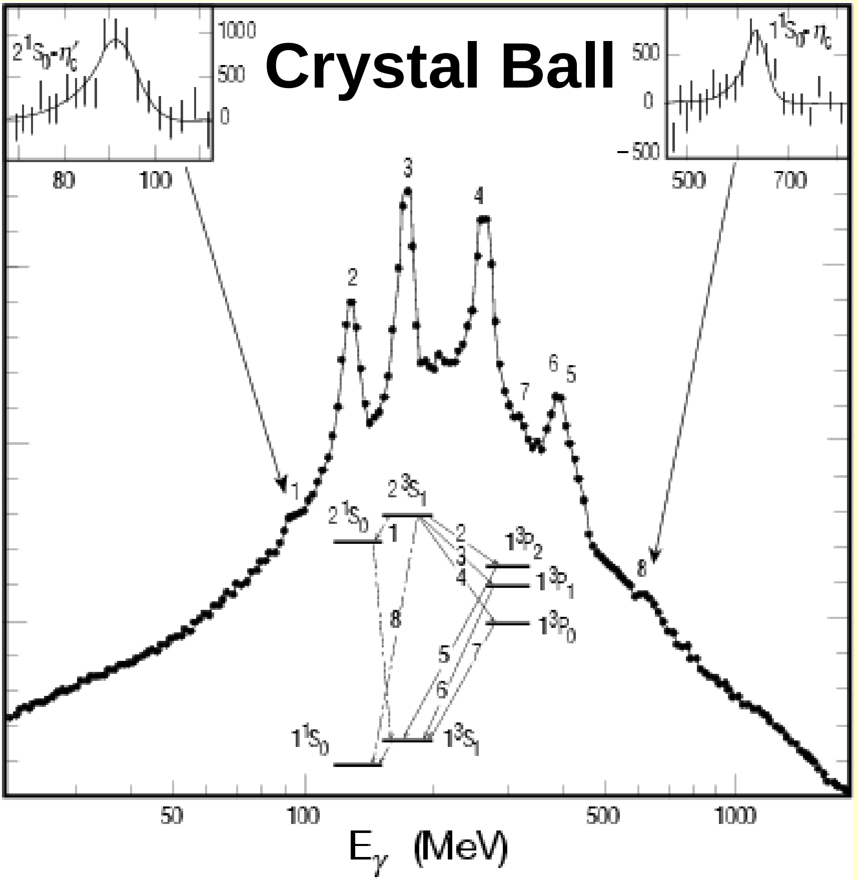
- Photons and electrons are fundamental particles for SM and new physics.
- Performance of precision ECAL, such as crystals, well understood:
  - Good energy, position and photon angular resolution;
  - Good e/photon identification and reconstruction efficiency;
  - Good missing energy resolutions;
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

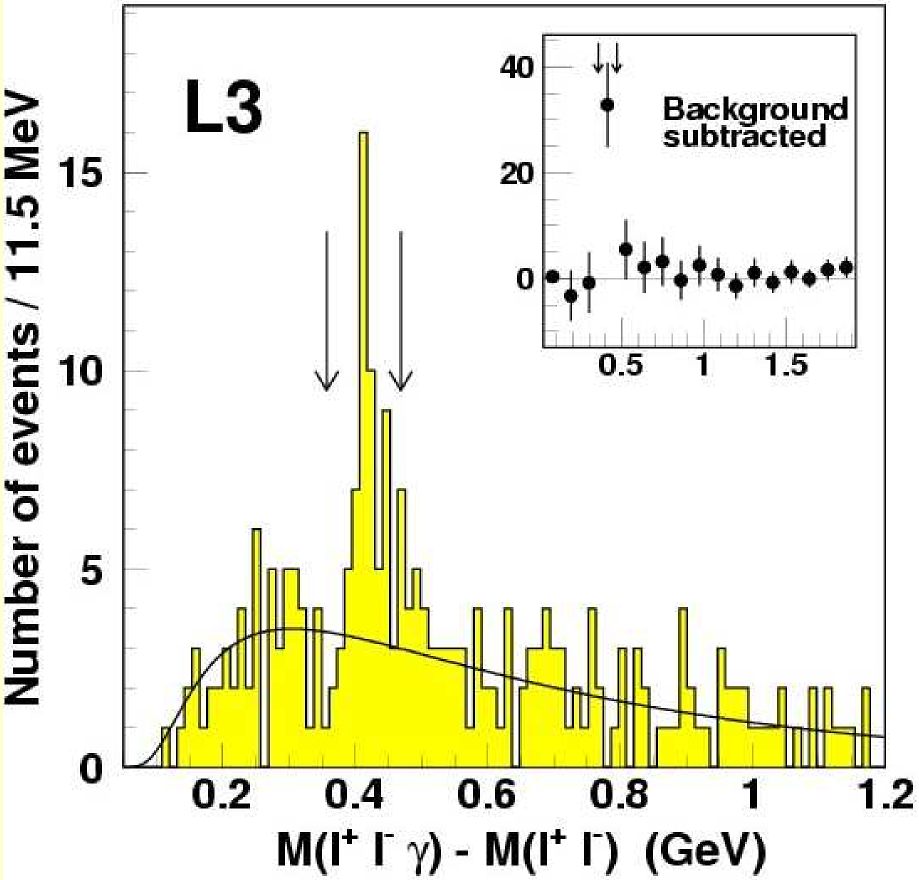
SM Physics in Precision ECAL

Charmonium System Observed Through Inclusive Photons

Charmed Meson in Z Decay

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





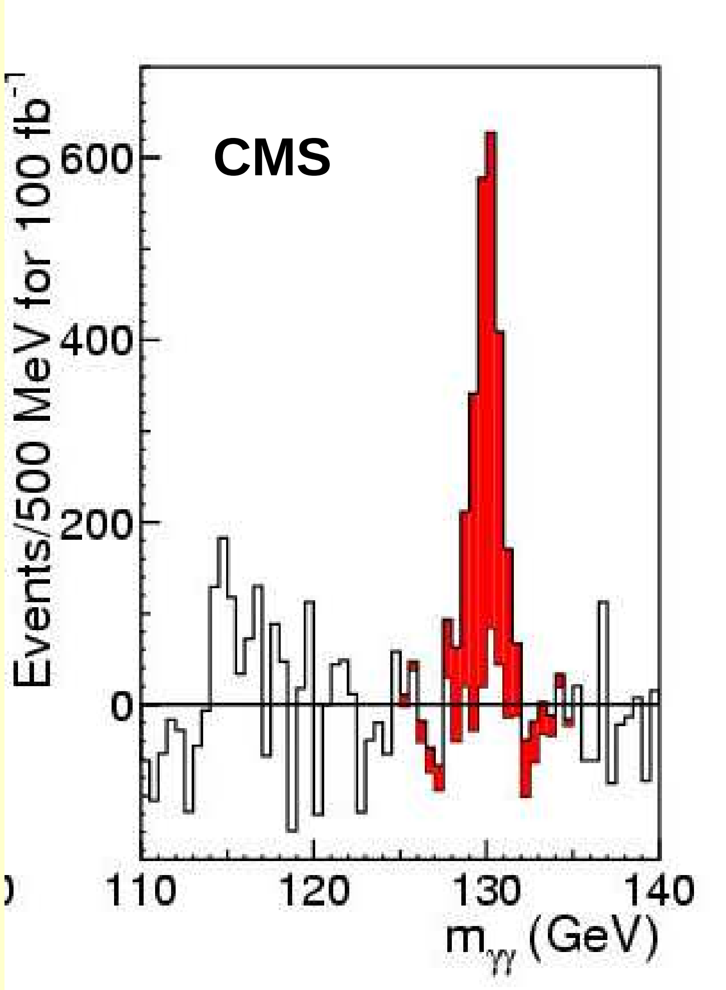
New Physics in Precision ECAL

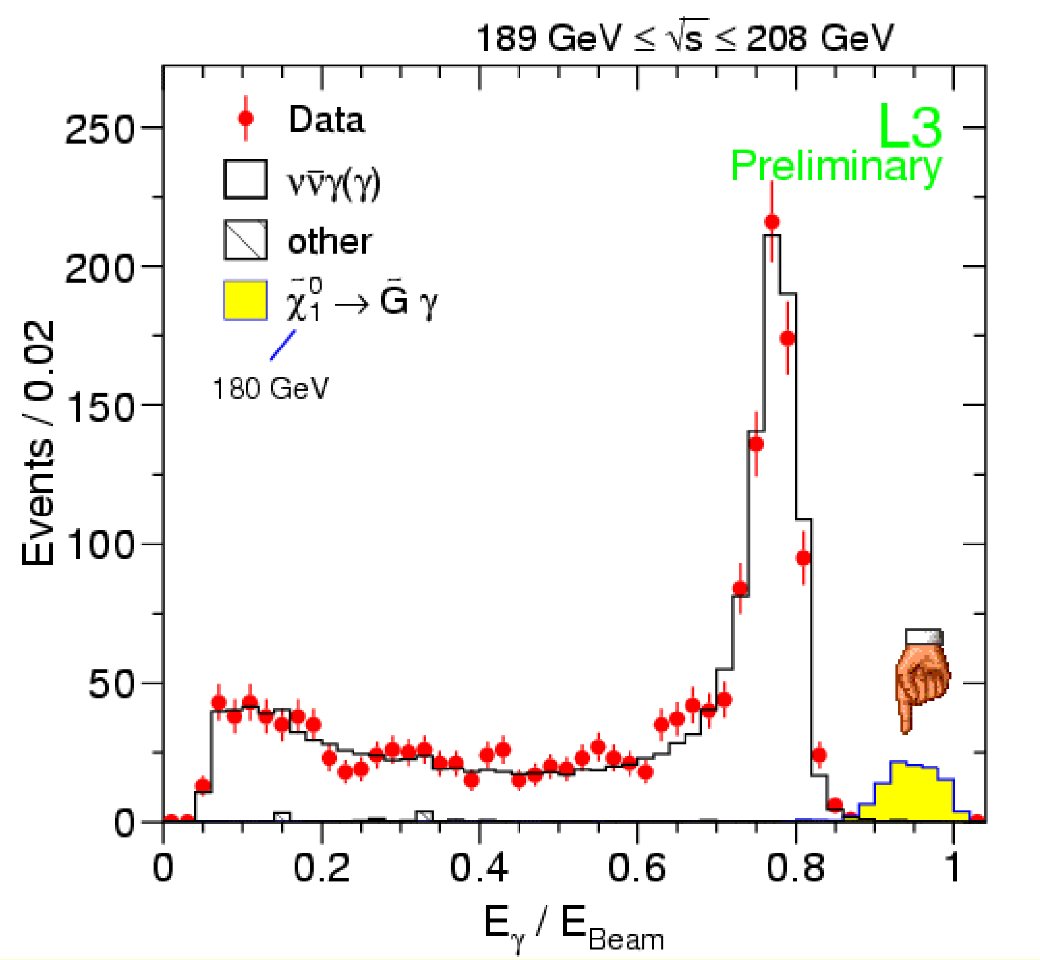
J. Gunion, in Snowmass

$$H \to \gamma\gamma$$

SUSY Breaking with Gravitino

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





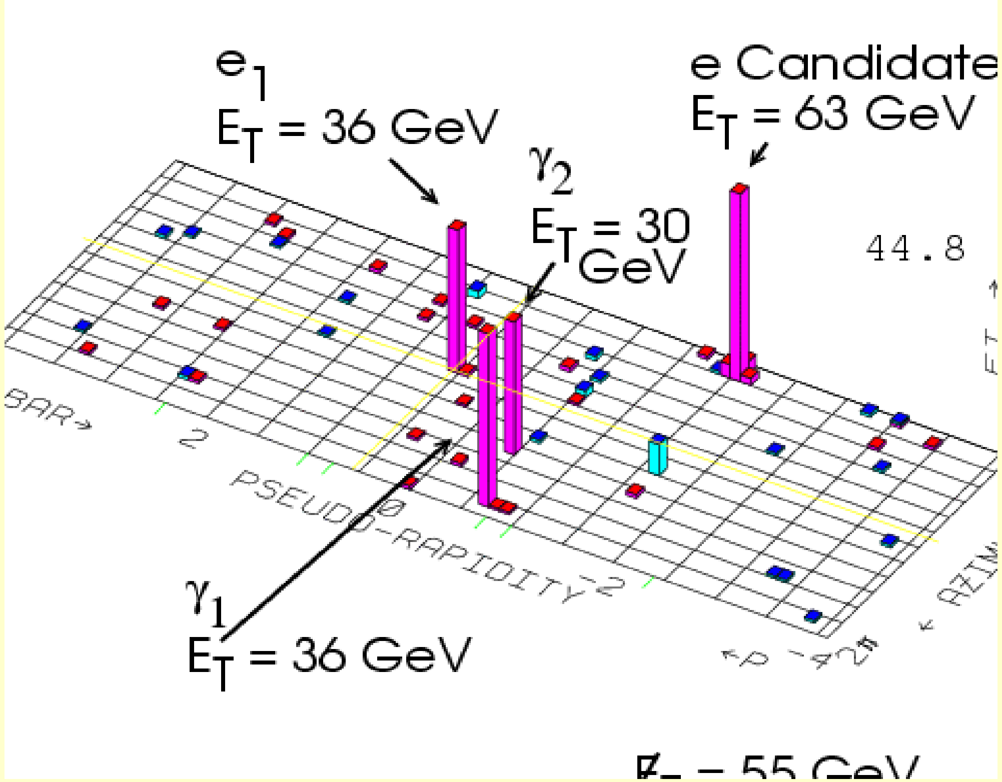
New Physics in Precision ECAL (Cont.)

The CDF event: 2 e + 2 γ + E_T^{miss}

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

Possible SUSY explanation

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

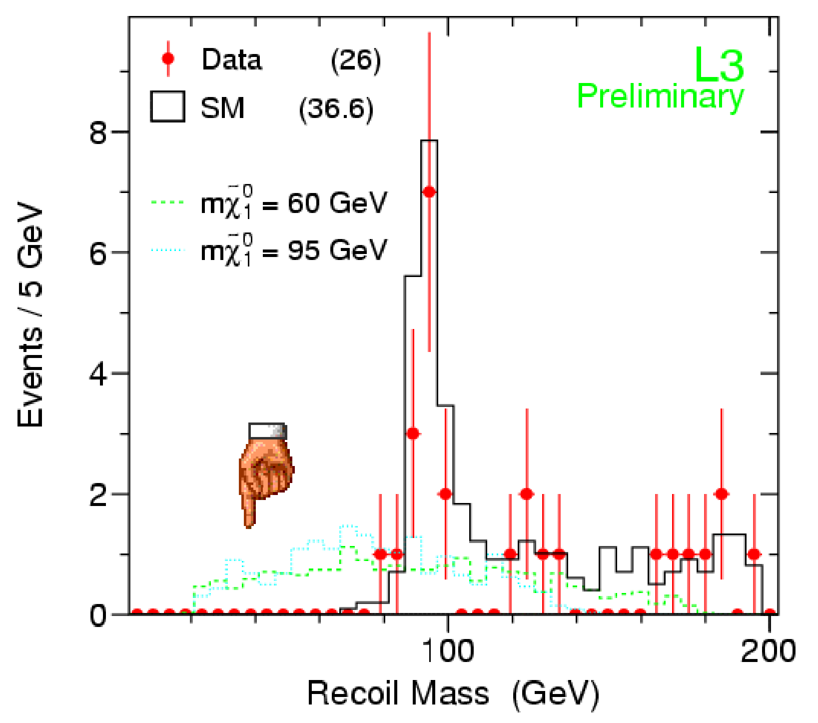


L3 should be able to observe

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

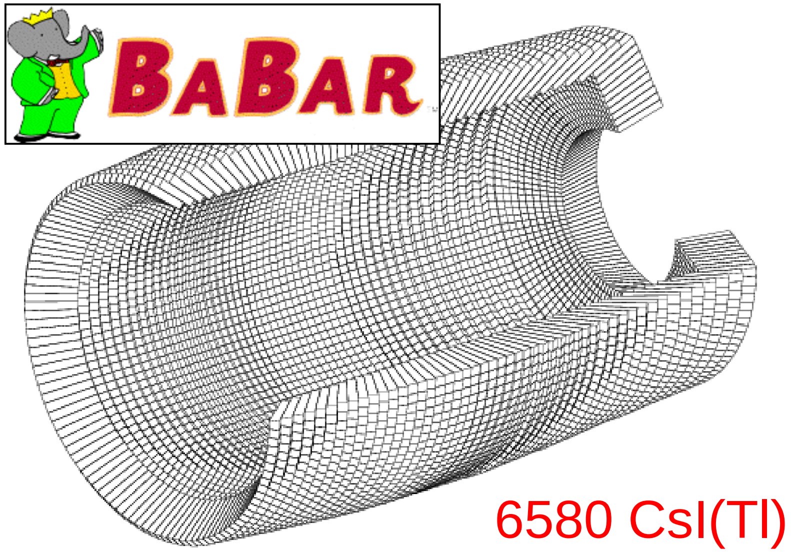
Another possible channel

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



BaBar CsI(Tl) Resolution

Crystal Calorimetry at Low Energies

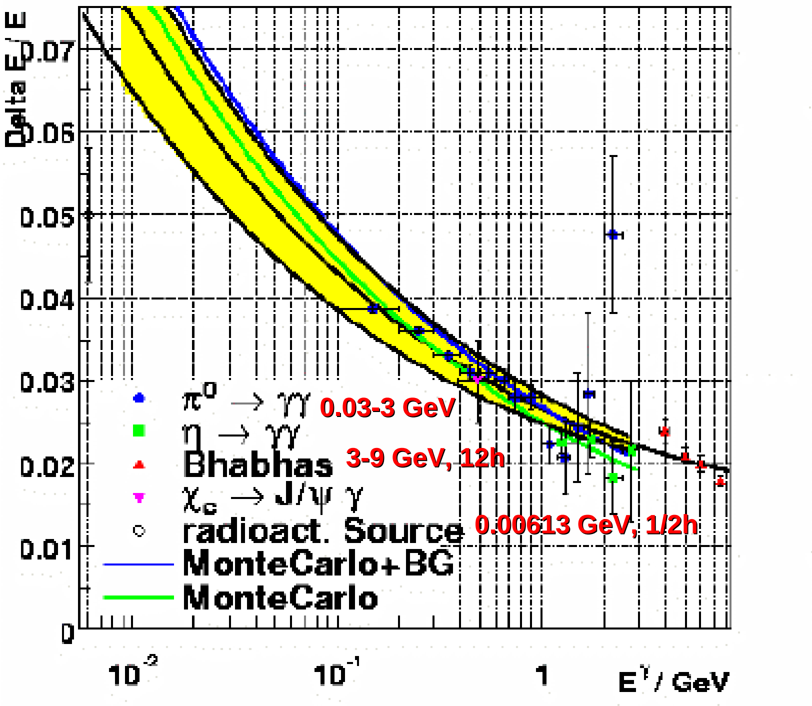


6580 CsI(Tl)

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

Energy resolution

M. Kocian, SLAC, CALOR2002



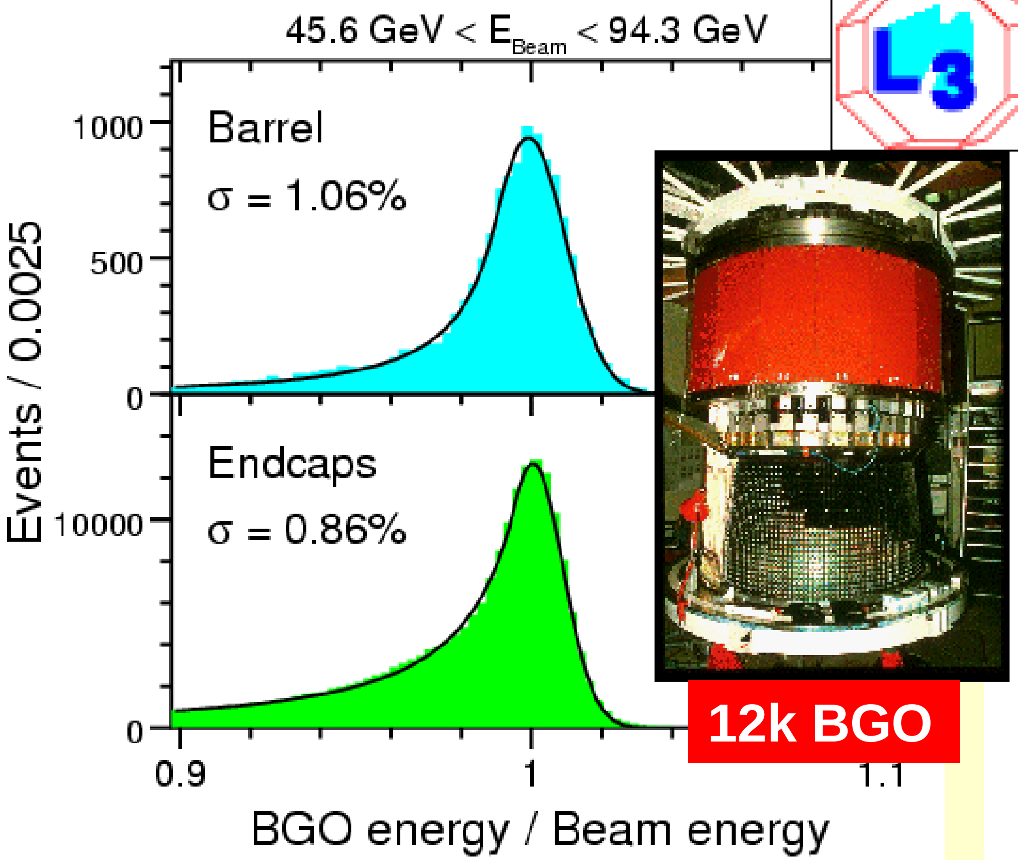
$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

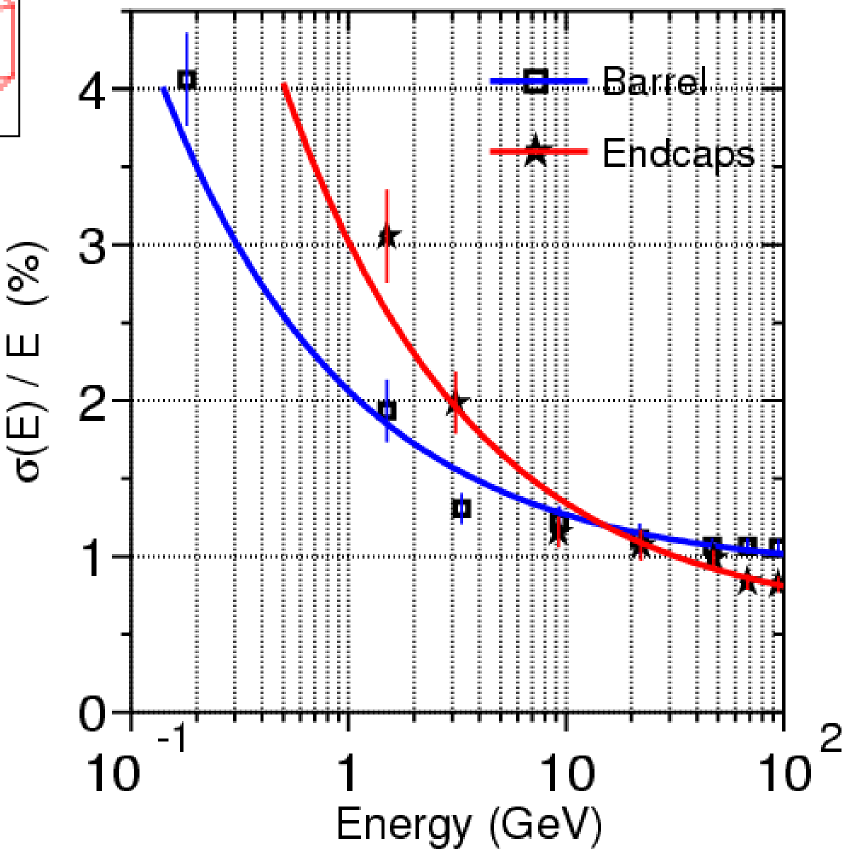
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

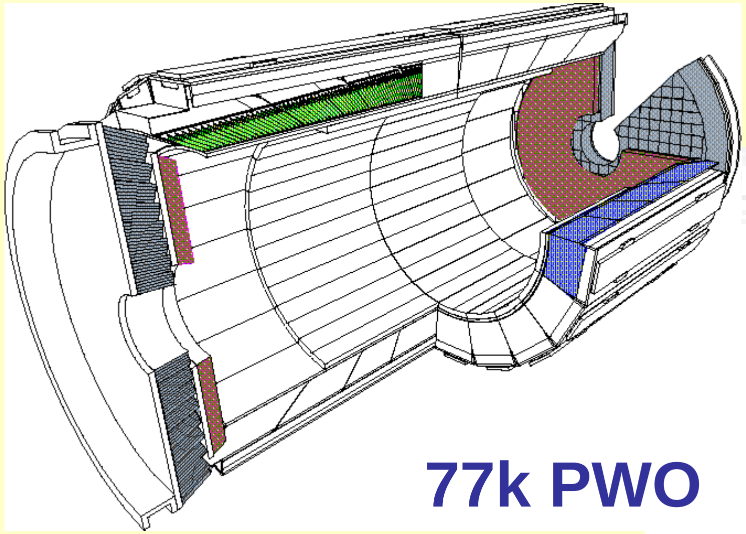
L3 BGO Resolution

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

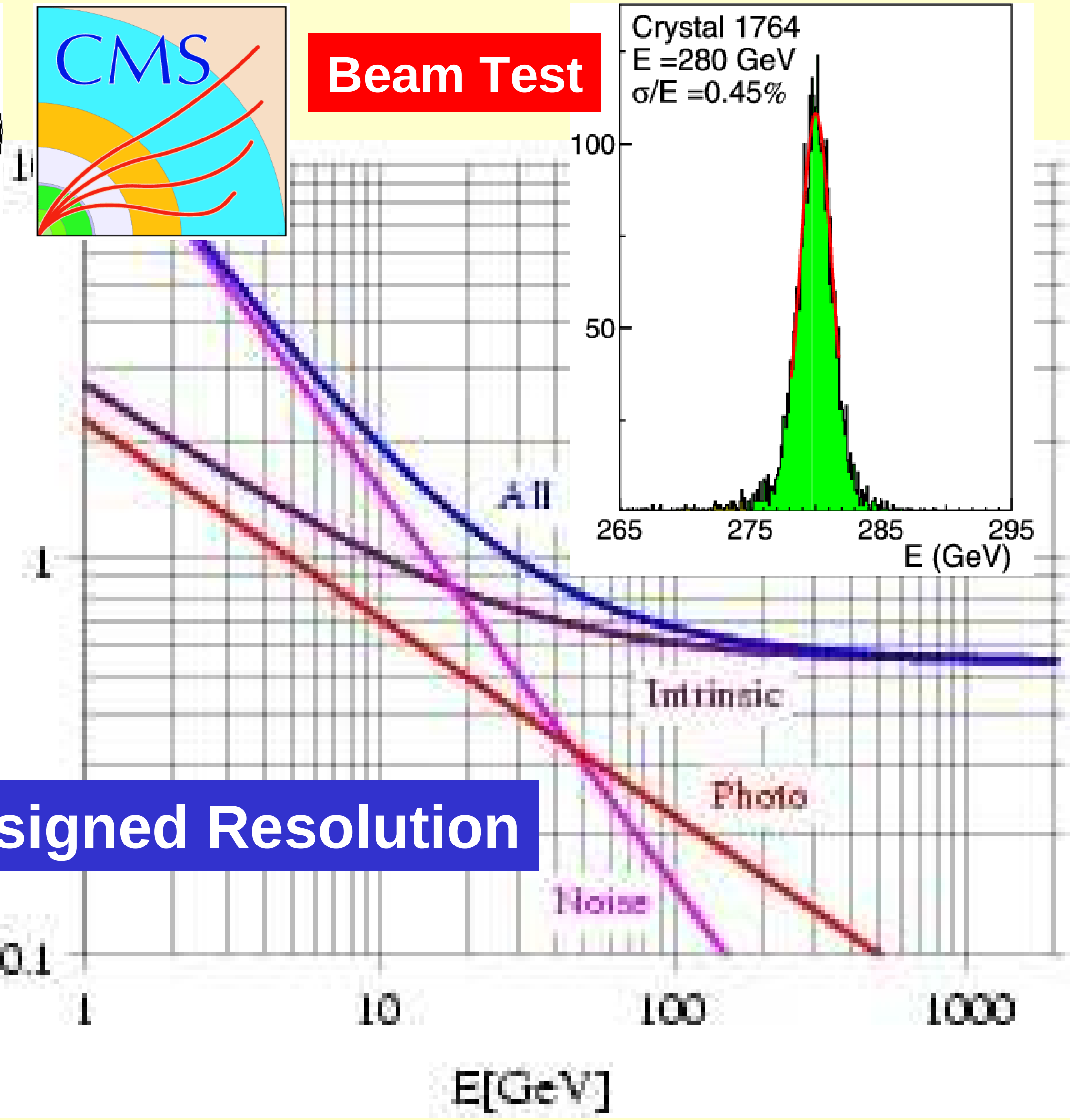




CMS PWO Resolution



77k PWO

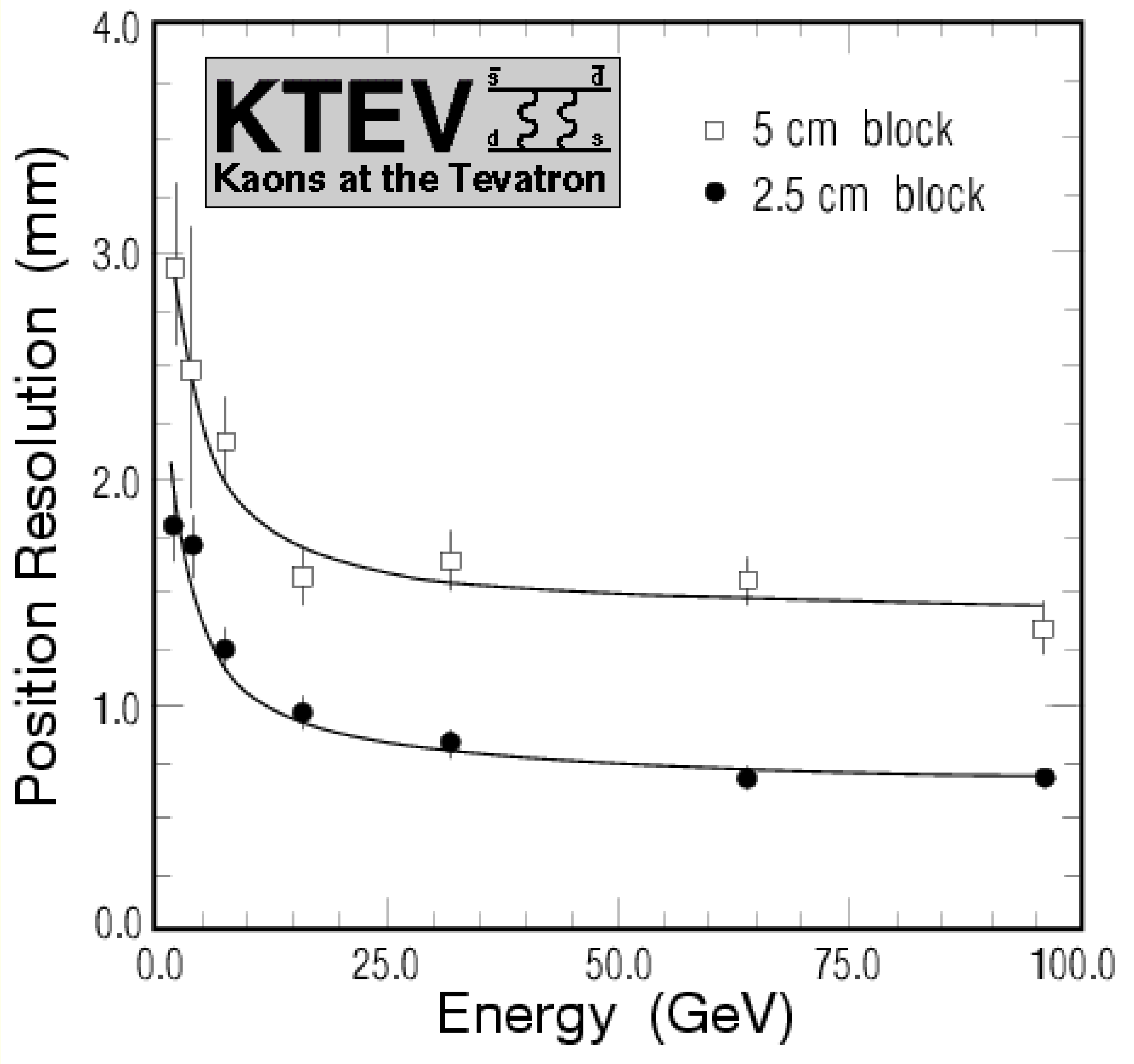


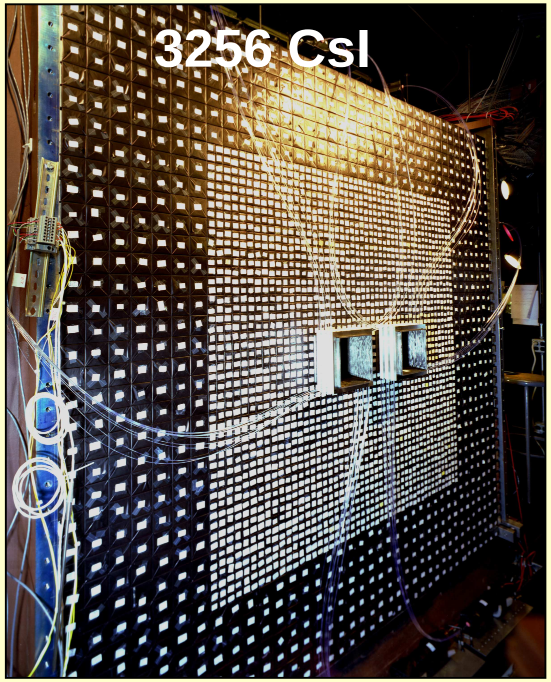
Beam Test

Designed Resolution

Crystal Calorimetry at High Energies

KTeV CsI Position Resolution





Sub mm position resolution is achievable.

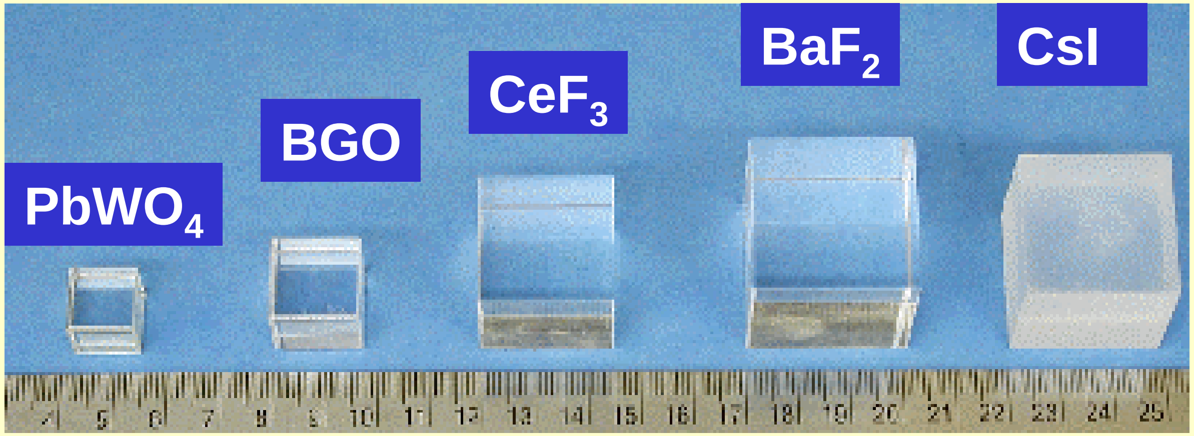
L3 BGO & CMS PWO: 0.3 mm at high energies.

Properties of Crystal Scintillators

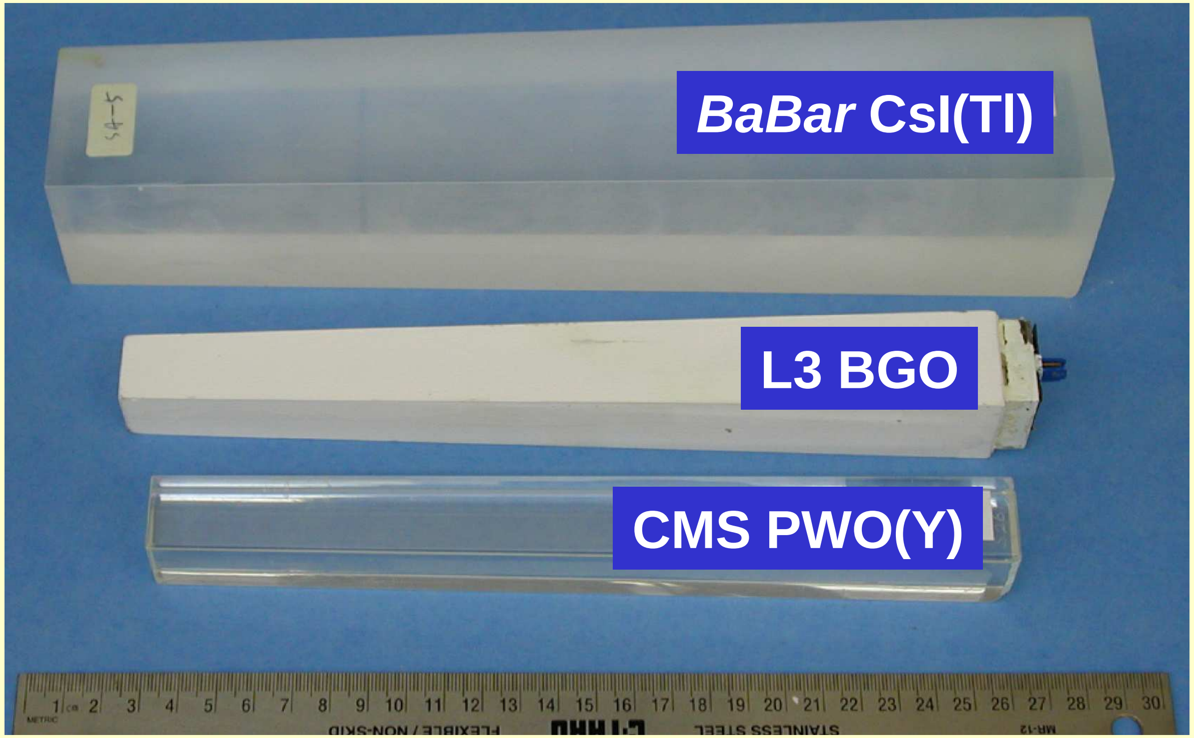
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF$_2$	BGO	PbWO$_4$	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (ºC)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	0.9	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.3	2.0	2.3	2.37
Interaction 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	?	?
Experiment	Crystal Ball	CLEO BaBar BELLE	KTeV	(L*) (GEM) TAPS	L3 BELLE	CMS ALICE BTeV…	-	-

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

Samples of Crystal Scintillators



1.5 X_0 Cubic



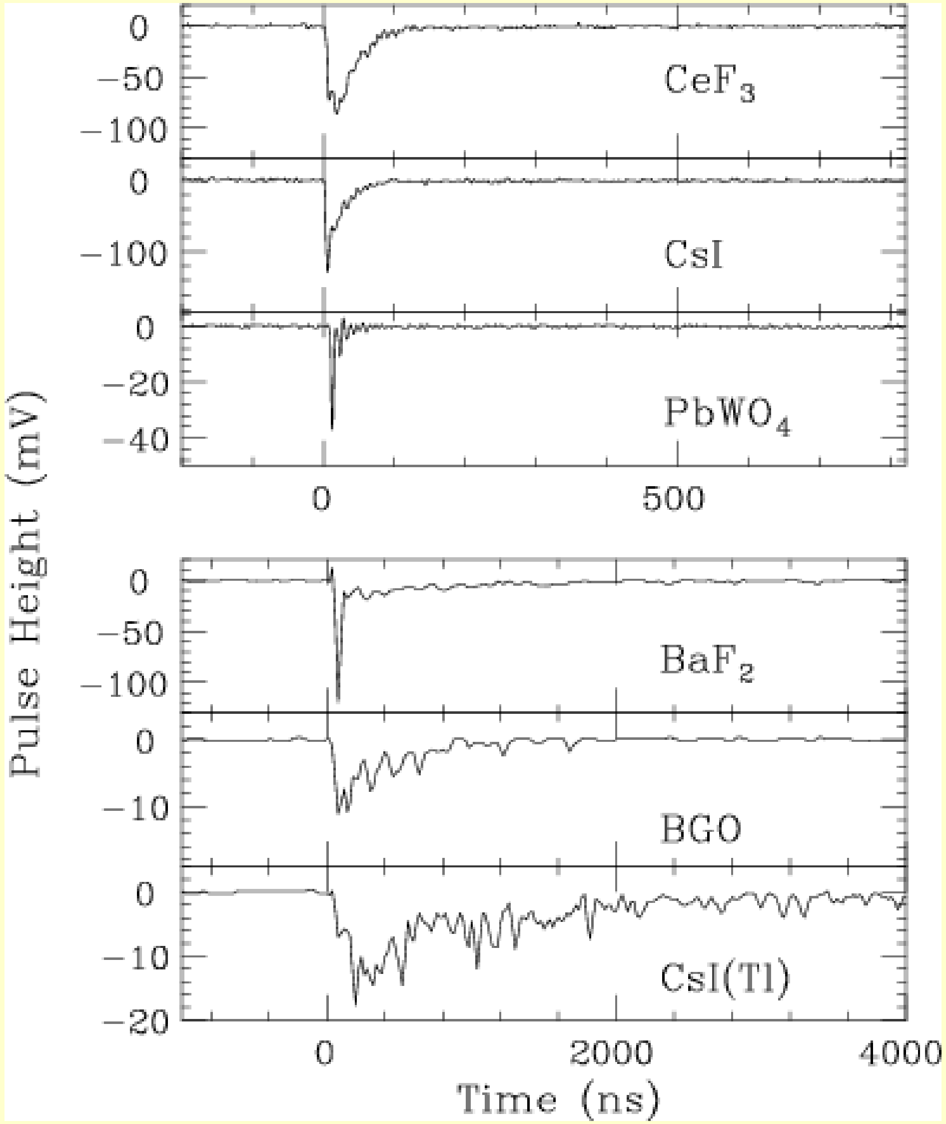
Full Size Samples

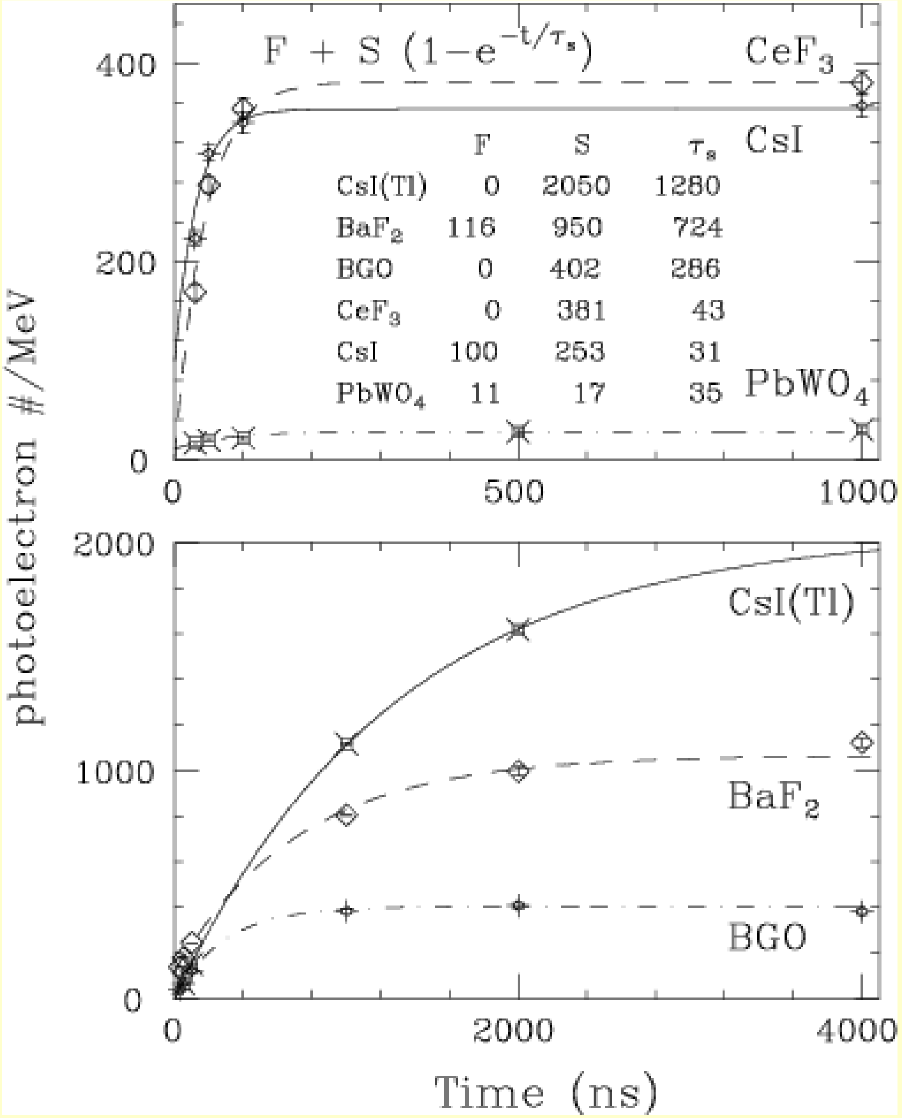
BaBar **CsI(Tl): 16 X_0**

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

Scintillation Light of 6 Samples

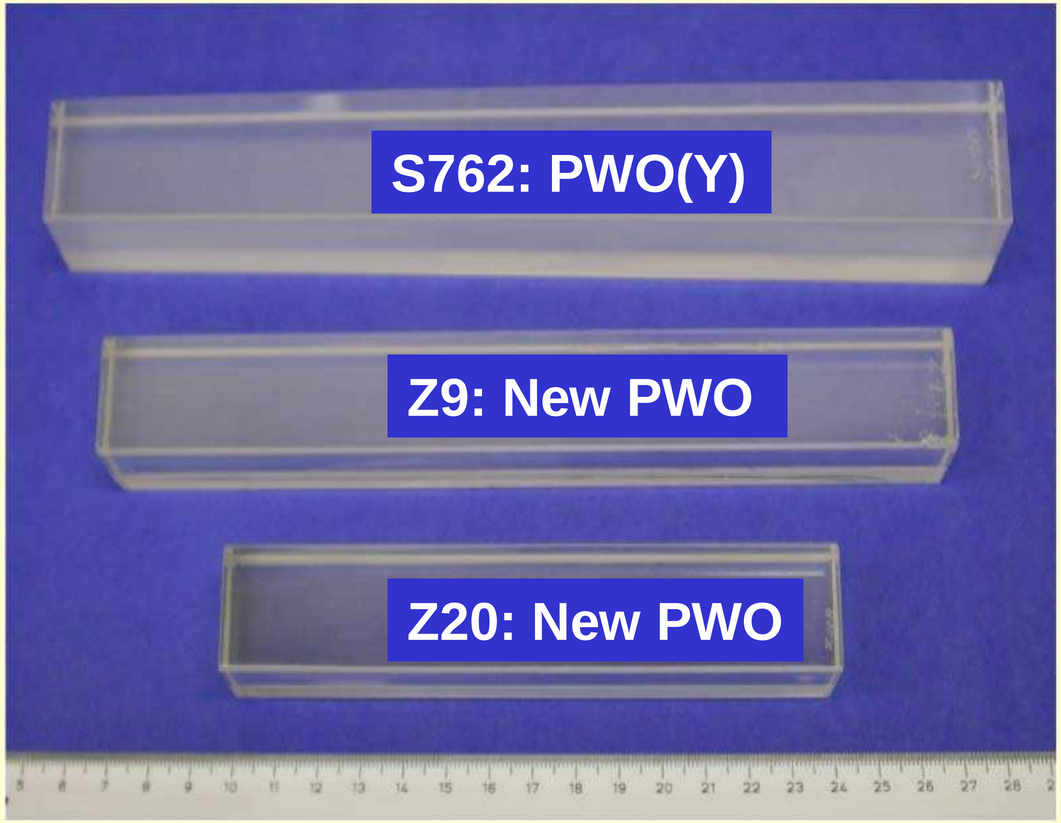




	F	S	τ_s
CsI(Tl)	0	2050	1280
BaF$_2$	116	950	724
BGO	0	402	286
CeF$_3$	0	381	43
CsI	100	253	31
PbWO$_4$	11	17	35

New Type PWO Crystal Samples

PWO Samples from SIC

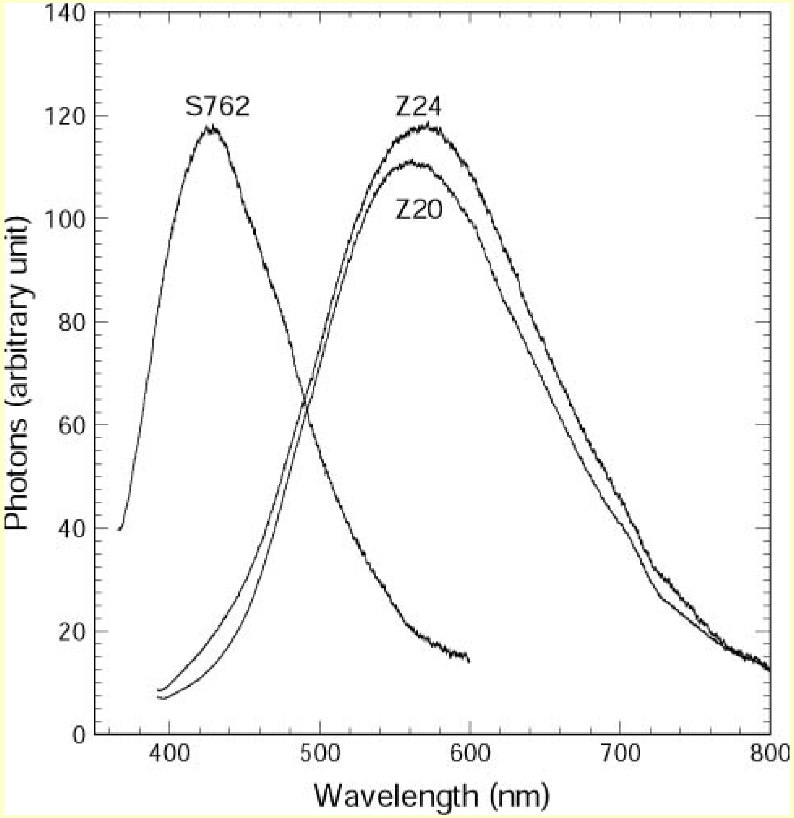


S762: PWO(Y)

Z9: New PWO

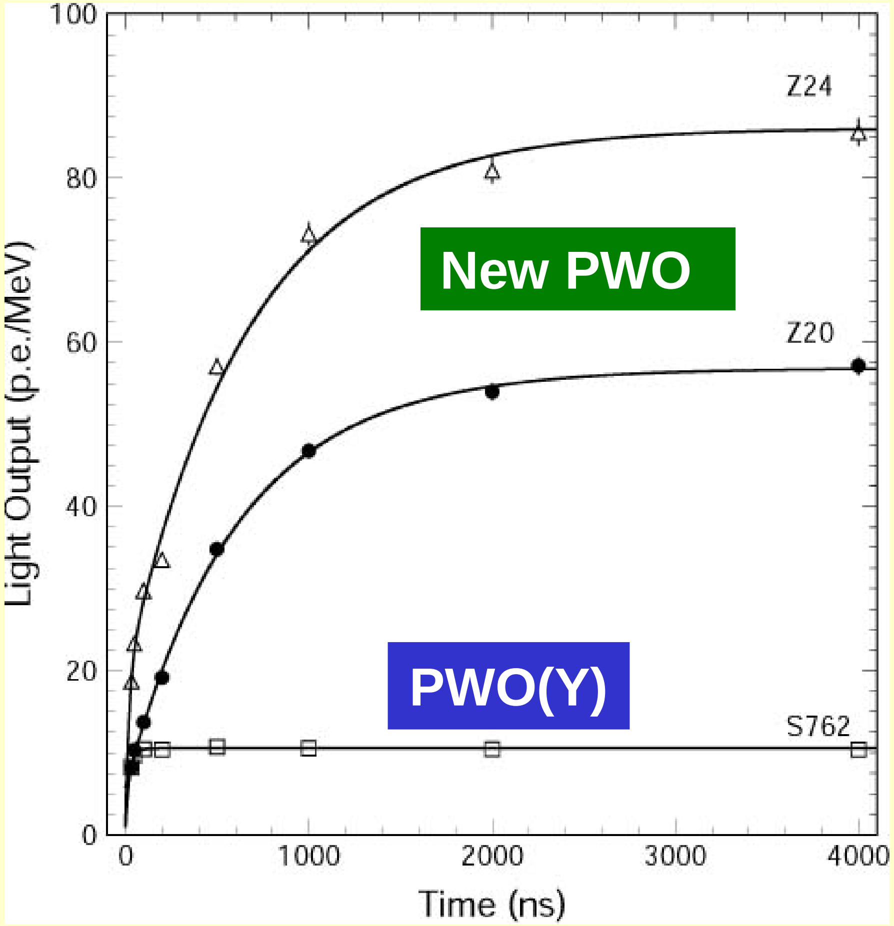
Z20: New PWO

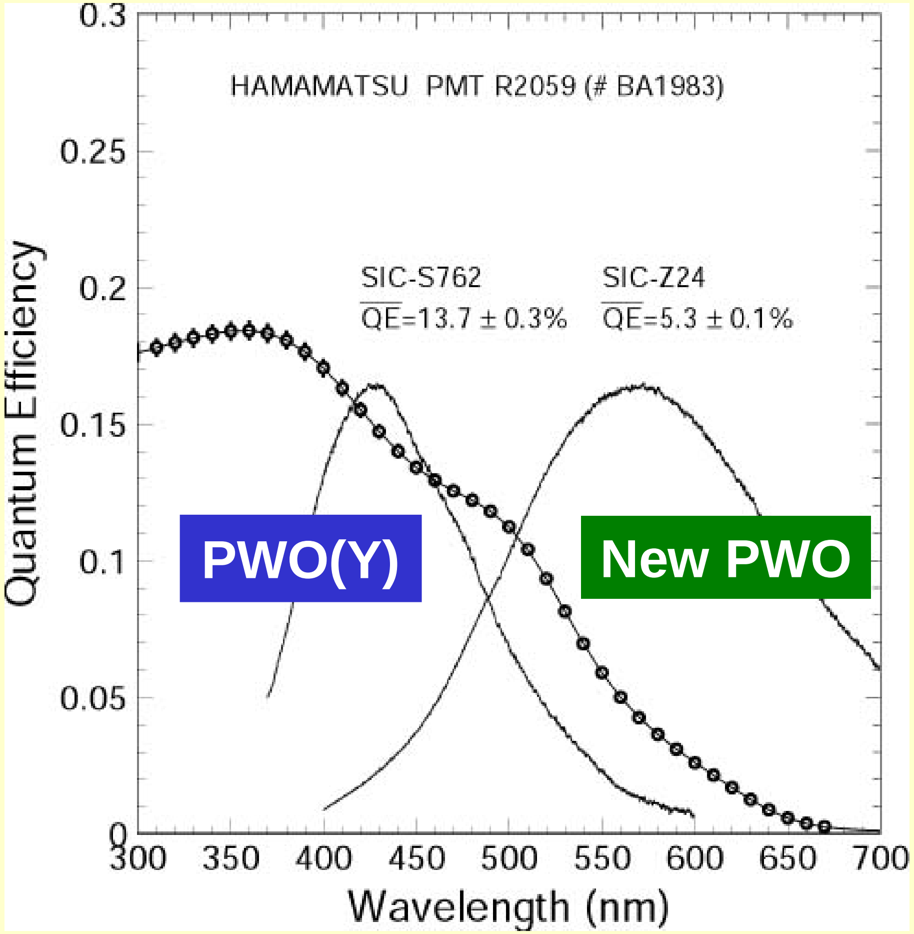
Emission Spectra



New PWO has green emission peaked at 560 nm

PWO Crystal with High Light Yield


Decay Kinetics


QE of PMT and Emission

Taking into account of PMT QE, new PWO has 10 X LY

Summary: Crystal Calorimetry for LC

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