Crystal Technologies for LC

Ren-yuan Zhu
Caltech

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- Design Considerations for Calorimeter at LC.

- What Can Crystal Calorimetry Offer?

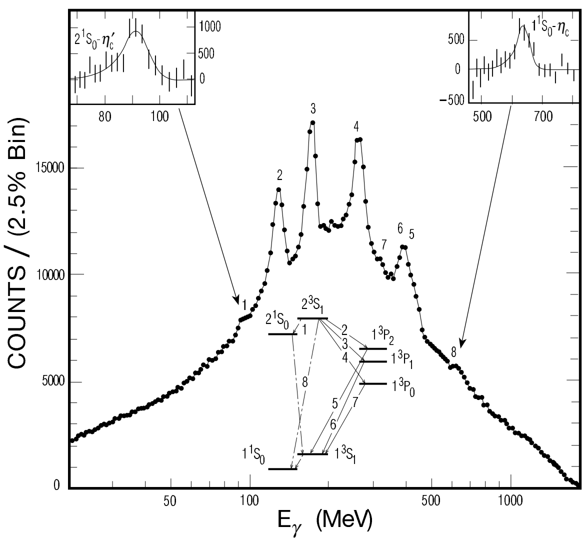
- Possible Crystal Technologies for LC:
  - Oxides: from BGO to $PbWO_4$;
  - Halides: from CsI to PbF_2.

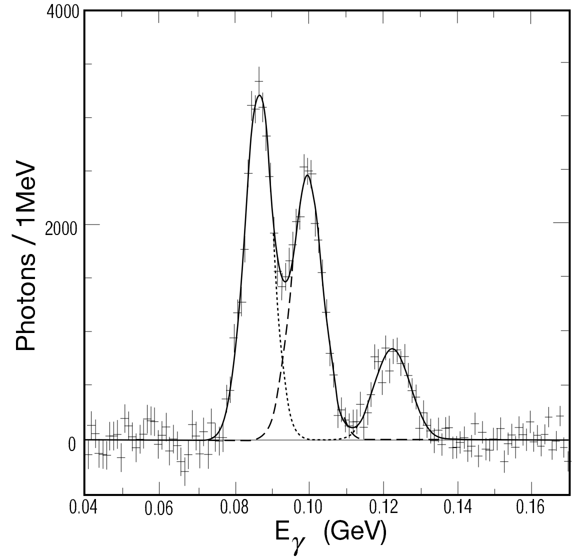
Design Considerations for Calorimetry at LC

- Precision measurement of electrons and photons: e/γ related physics.
  - Electromagnetic energy resolutions;
  - Position and photon angular resolutions;
  - e/γ identification and reconstruction efficiency.
- Good missing energy resolutions: ν/SUSY related physics.
  - Hermeticity.
- Good jet energy resolution: jet related physics.
  - Achievable jet resolution and intrinsic limitation;
  - Dead material (coil?) in the middle of a calorimeter;
  - Jet resolution improvement by using other detector components;
  - Jet resolution improvement by using kinetic constraints: Z mass and center of mass.
- Dense absorber: a compact and cost effective calorimeter.

Discovery Power of Precision e & γ

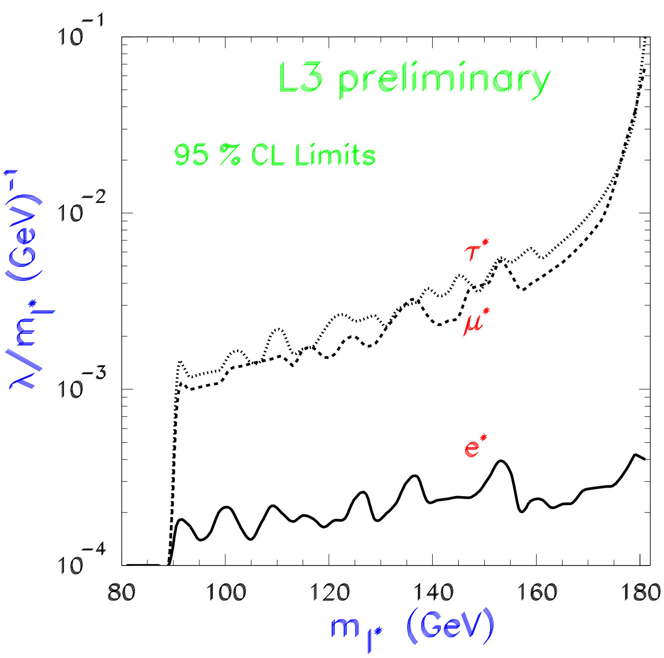
- Study quarkonium system through inclusive photons by Crystal Ball and CLEO.

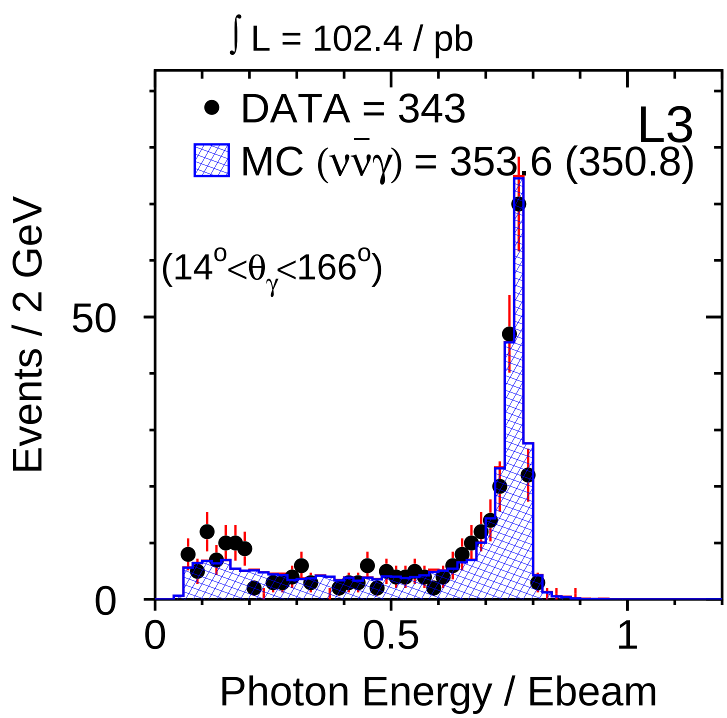




- Searches for excited leptons in composite models and a SUSY breaking model with gravitino $\tilde{G}$ as LSP at LEP II.

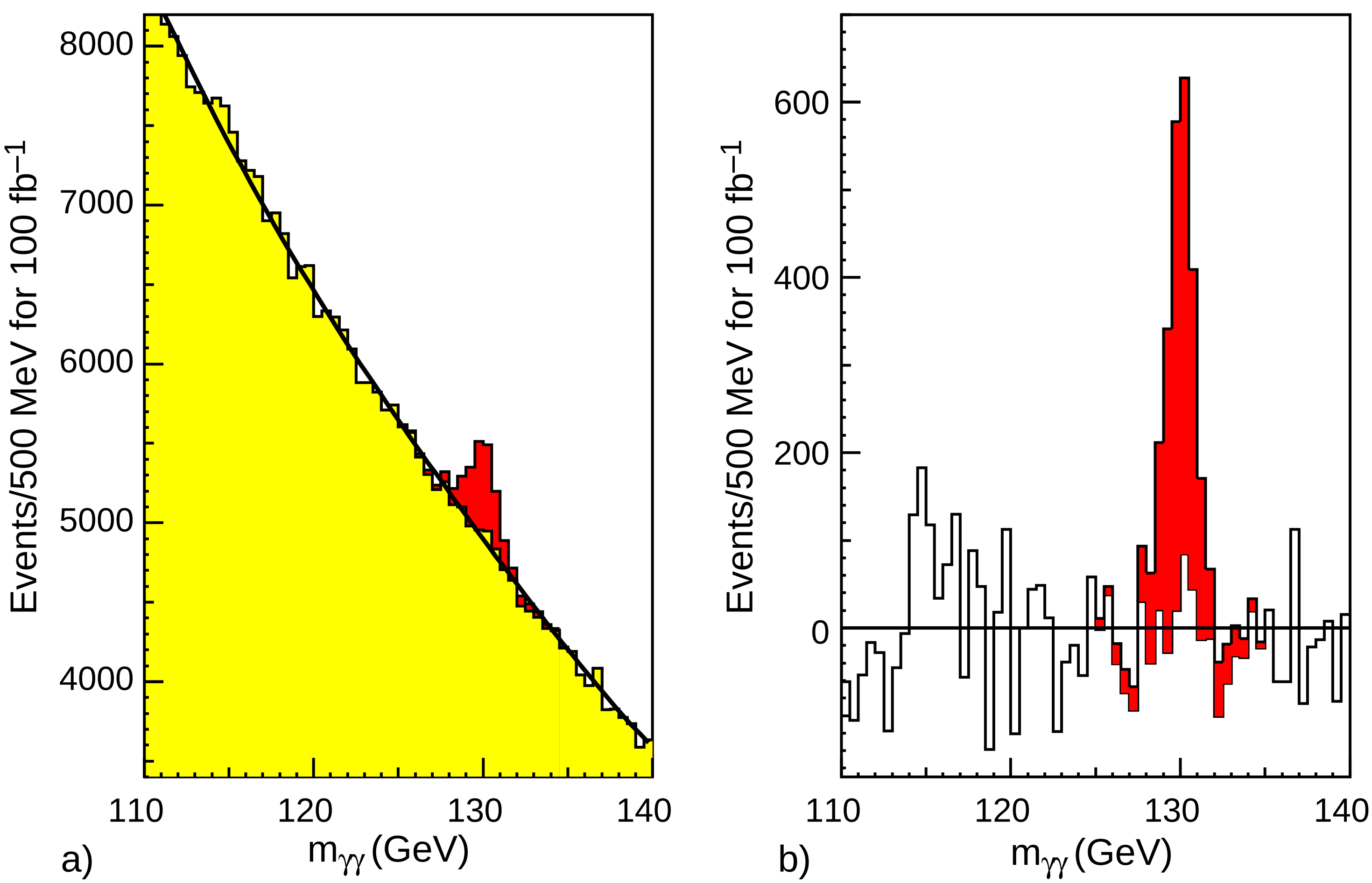
$$\mathrm{e}^+\mathrm{e}^- \to \ell^*\ell^*\ or\ \ell^*\ell,\ \ell^* \to \ell\gamma, \quad \mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ or\ \tilde{\chi}_1^0\tilde{G},\ \tilde{\chi}_1^0 \to \tilde{G}\gamma$$





Discovery Power of Precision Photons

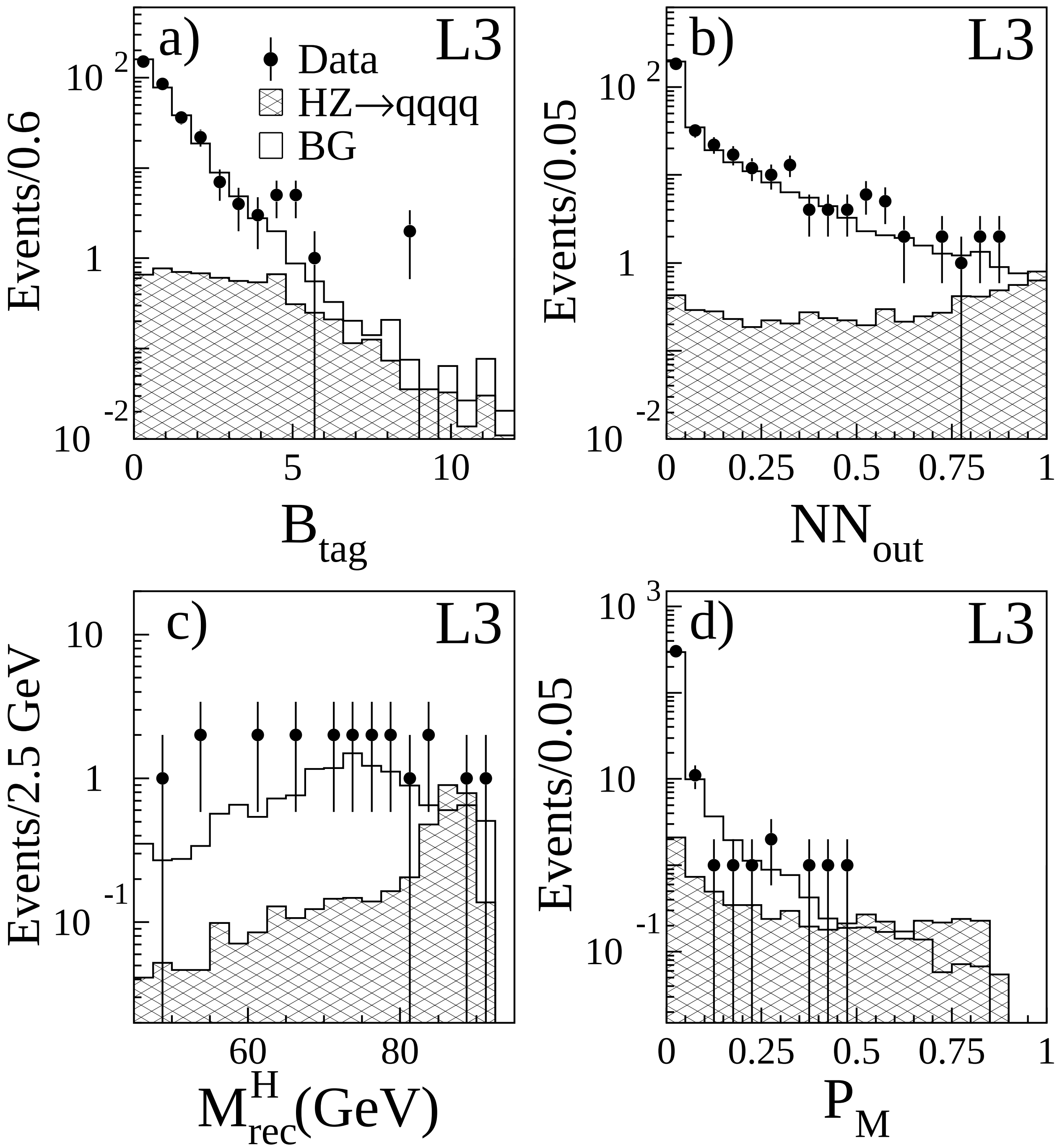
H$\rightarrow\gamma\gamma$ Searches with PWO ECAL by CMS at LHC



Higgs Searches by L3 at LEP II

The Higgs background is suppressed by b-tagging and neural network analysis. Kinetic constraints improve mass resolution to ∼3% for 87 GeV Higgs.

$$e^+e^- \to H^0 Z,\ H^0 \to b\bar{b}\ and\ Z^0 \to q\bar{q}$$



What Can Crystal Calorimetry Offer?

- Good **electromagnetic energy resolution** because of total absorption: 0.6% is achievable for isolated e or γ, $\sigma = 2\%/\sqrt{E} \oplus 0.5\% \oplus c/E$.

- Good **position resolution** because of its fine segmentation: 0.3 mm is achievable for cell size and Molière radius of 2 cm, $\sigma = 2/\sqrt{E} \oplus 0.29$ mm.

- Good **photon angular resolution** because of no ambiguity in primary event vertex in LC — bunch length 0.2 mm.

- Good **e and γ identification and reconstruction efficiency** because of fine granularity and pointing geometry: e/π discrimination better than 10^{-3} is achievable for e ID efficiency of 95%.

- Good **missing energy resolution** together with HCAL because of hermeticity.

- Good **jet energy resolution** by using information from other detector components: L3 achieved 7% for hadronic Z decays.

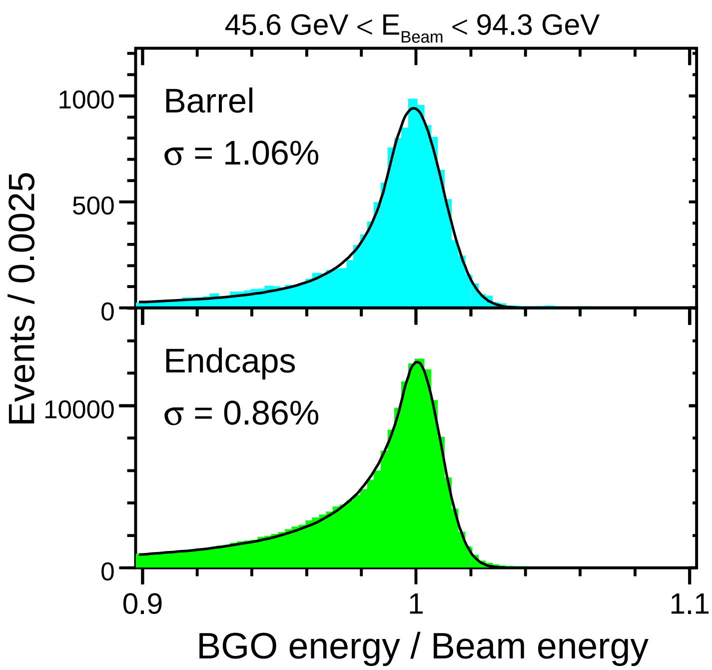
- Can be rather **compact** by using heavy crystals of less than 1 cm radiation length ($PbWO_4$ and PbF_2).

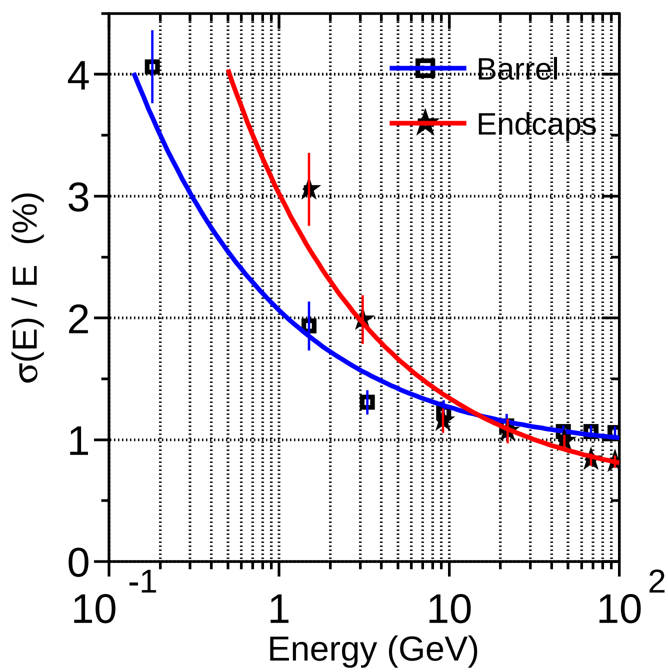
KTeV CsI Calorimeter & Measured Resolution

Bhabha Electron Energy Resolution with L3 BGO

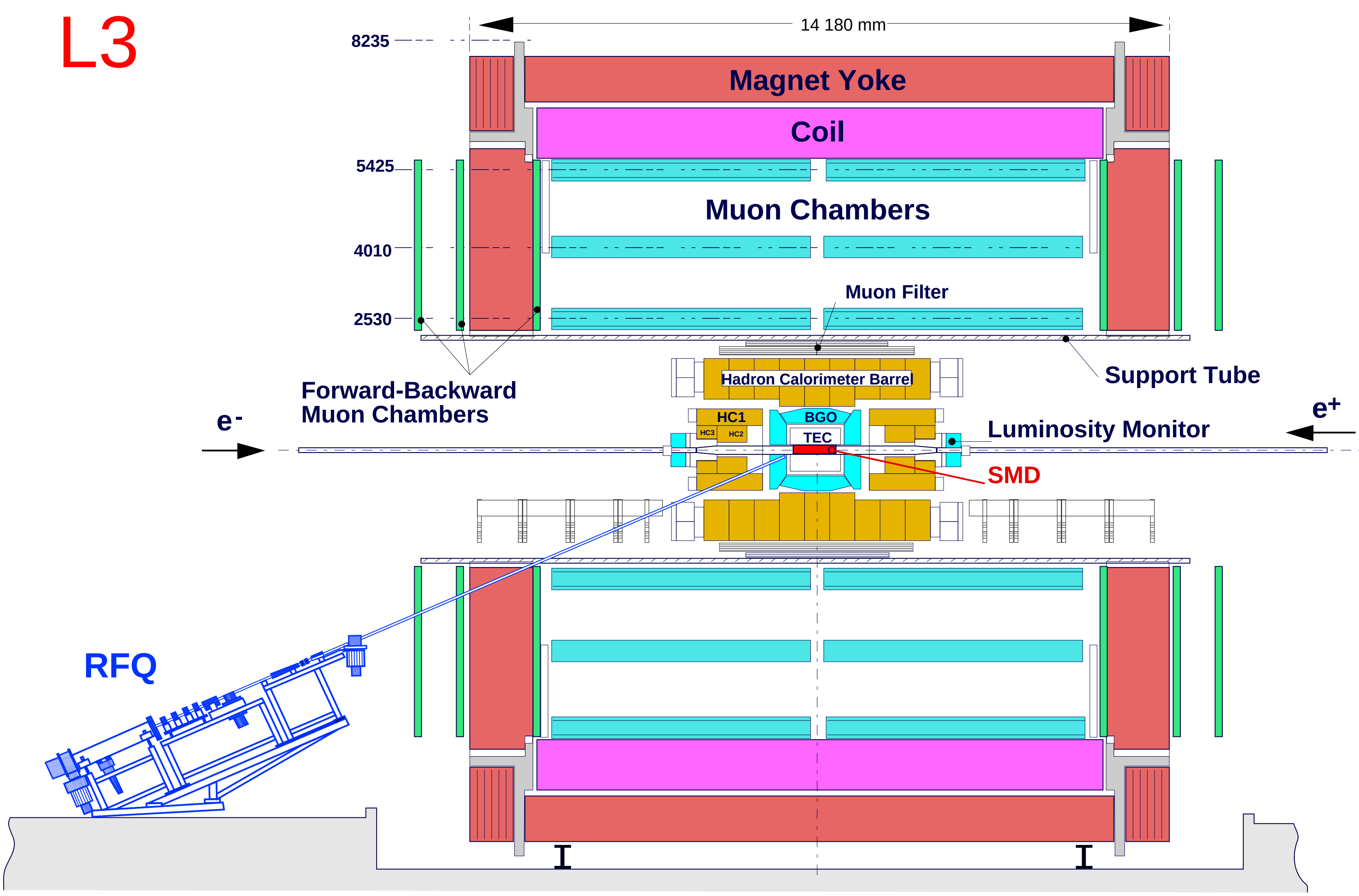
0.5% Calibration Achieved *in situ* with RFQ

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





RFQ Installation in L3 Experiment



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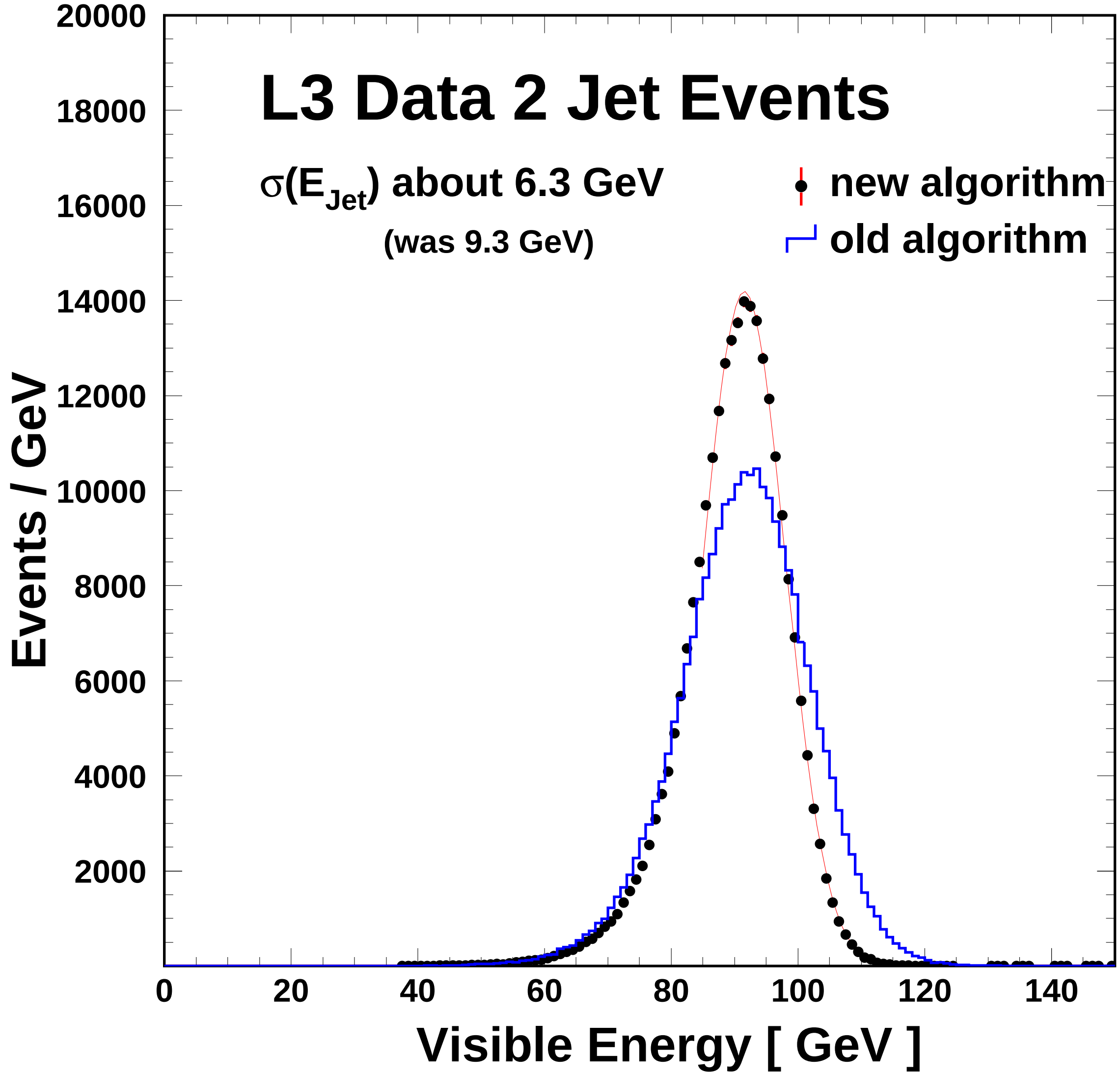
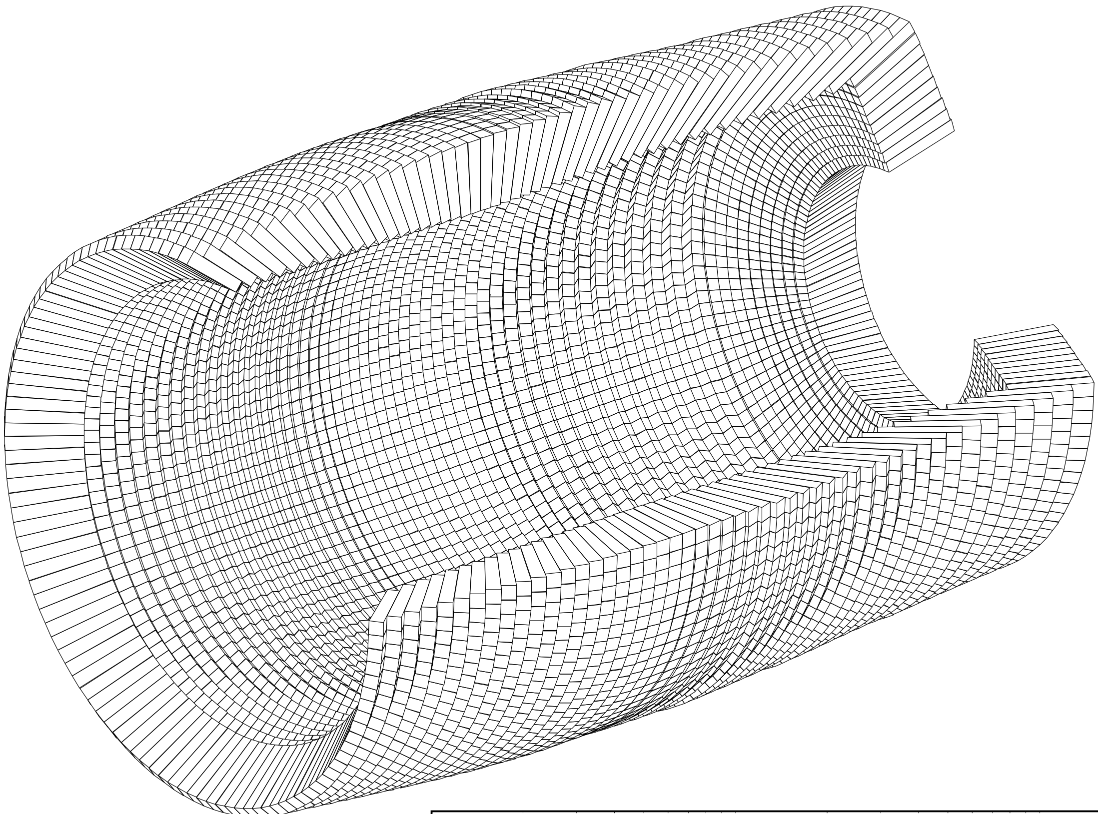
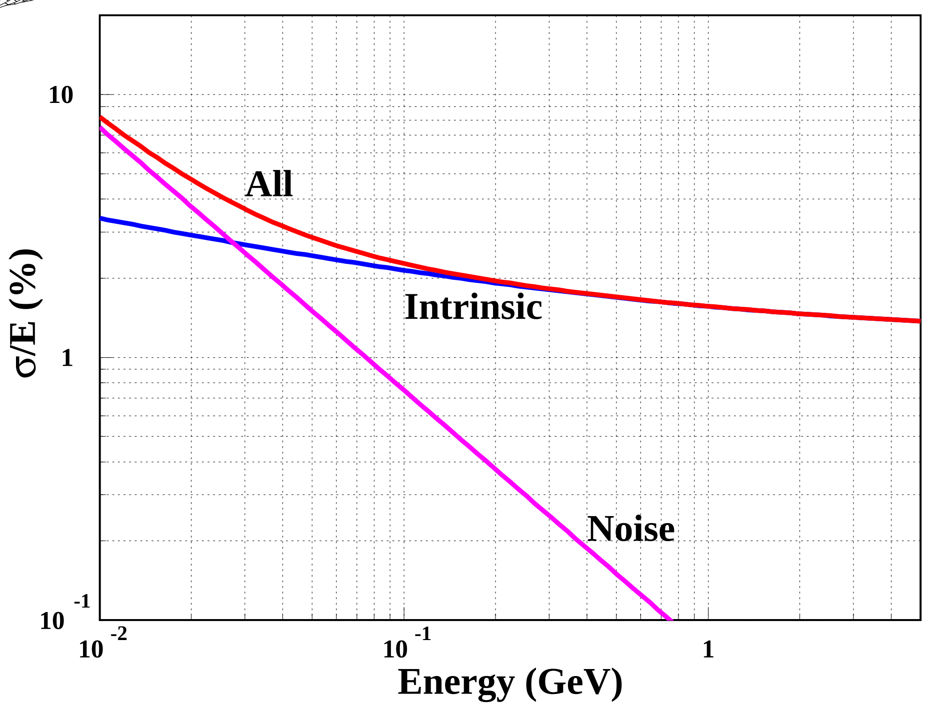
Improvement of L3 Jet Mass Resolution

Using Information from other Detector Components

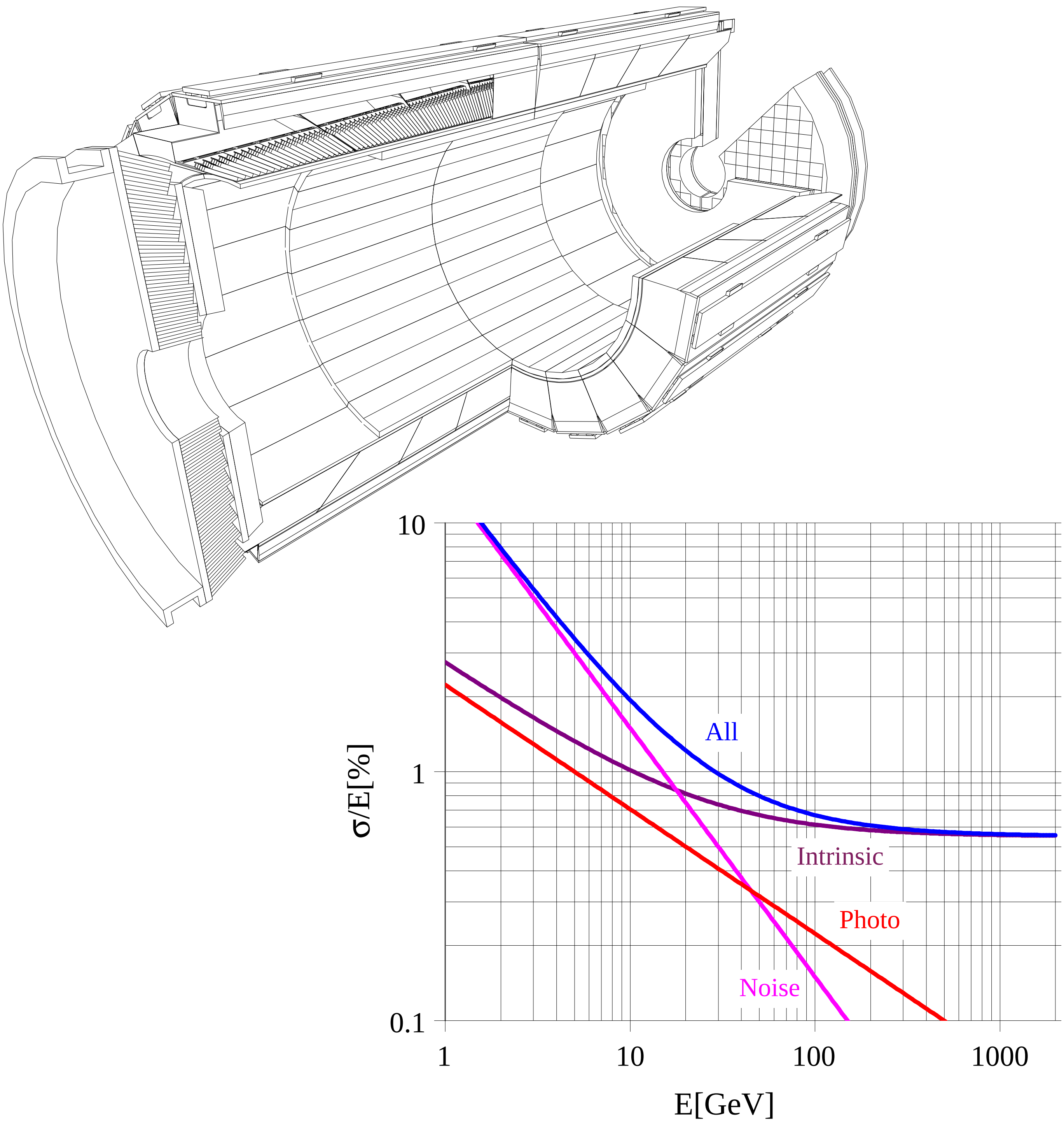


$BaBar$ CsI(Tl) ECAL and Resolution



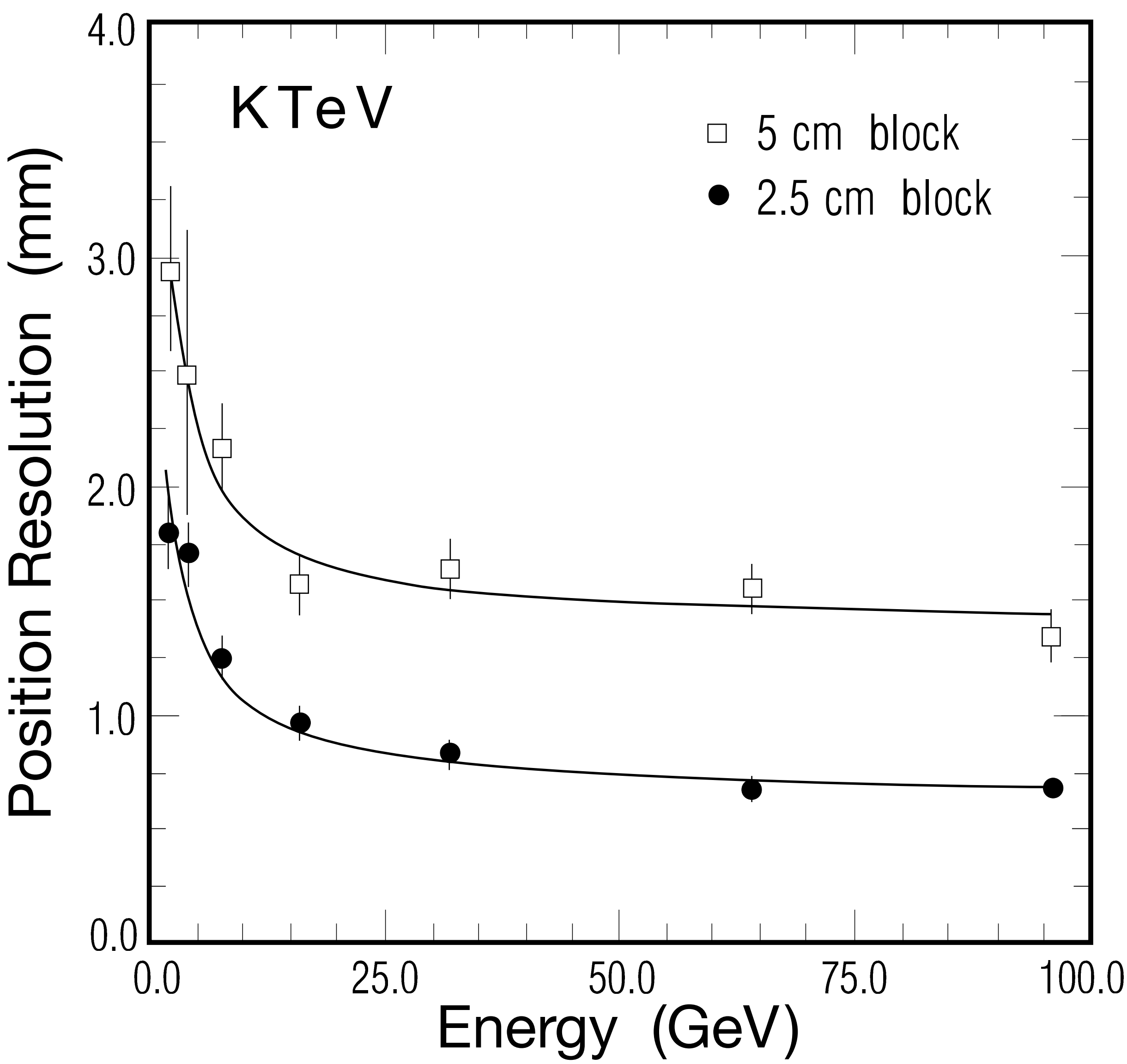


CMS $PbWO_4$ ECAL and Resolution



Crystal Position Resolution

$2/\sqrt{E} \oplus 0.29$ mm for $R_{Moliere}$ = 2 cm



Possible Choices of Crystal Technology

- Oxides:
  - BGO is a mature and dense crystal (ρ = 7.13 g/cc, X_0 = 1.12 cm, $R_{Moli\grave{e}re}$ = 2.3 cm), but has a slow scintillation (300 ns) and not cost effective ($7/cc) due to expensive raw material (GeO_2).
  - $PbWO_4$ is a mature and dense crystal (ρ = 8.28 g/cc, X_0 = 0.89 cm, $R_{Moli\grave{e}re}$ = 2.0 cm). It is a fast and cost effective crystal ($2.5/cc). Its low light yield is overcome by using Si avalanche photodiode. $\sigma = 4.1\%/\sqrt{E} \oplus 0.37\% \oplus 0.15/E$ has been achieved with 25 mm^2 APD readout in beam test. It is possible to develop a brighter $PbWO_4$ crystal.
- Halides:
  - CsI is a mature and cost effective crystal ($2/cc), but has low density (ρ = 4.5 g/cc, X_0 = 1.85 cm, $R_{Moli\grave{e}re}$ = 3.5 cm). In addition, CsI(Tl or Na) is too slow ($\sim$1 μs) and CsI is less bright.
  - PbF_2 is a mature and dense crystal (ρ = 7.77 g/cc, X_0 = 0.93 cm, $R_{Moli\grave{e}re}$ = 2.1 cm). It is also cost effective (less than $PbWO_4$). However, it is not yet a scintillator, but being used as a Čerenkov radiator. A scintillating PbF_2 crystal may be developed by selected doping.

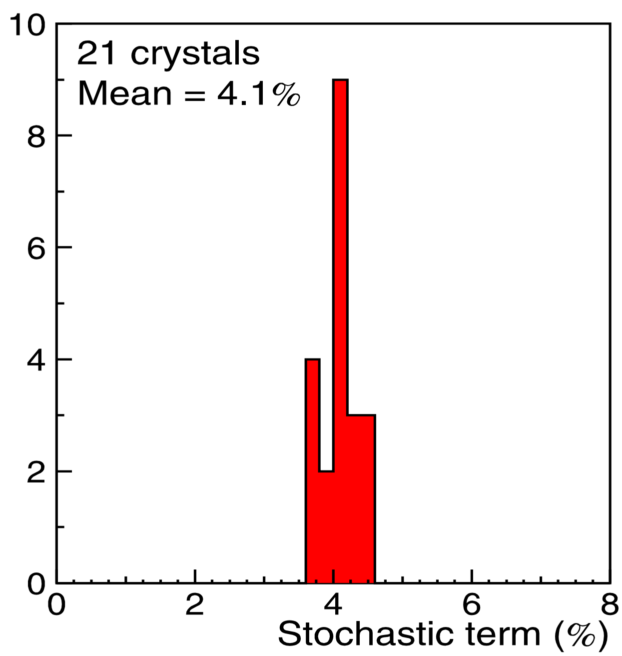
CMS $PbWO_4$ Energy Resolution in Beam Test

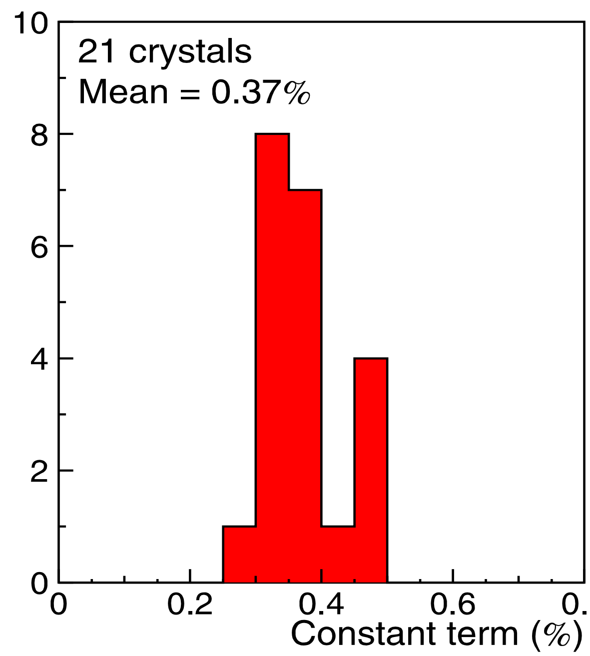
Stochastic & Constant Terms

$$\frac{\delta E}{E} = \frac{\mathbf{a}\%}{\sqrt{E}} \oplus \mathbf{b}\% \oplus 0.15/E$$

- $\bar{\mathbf{a}}$ = 4.1% ⇐ 1.7 p.e./MeV in 25 mm^2 APD.
  CMS ECAL TDR uses **50 mm**^{2} APD ⇒ $\bar{\mathbf{a}}$ = 2.9%.

- $\bar{\mathbf{b}}$ = 0.37% ⇐ a better understanding of the consequence of light response uniformity.

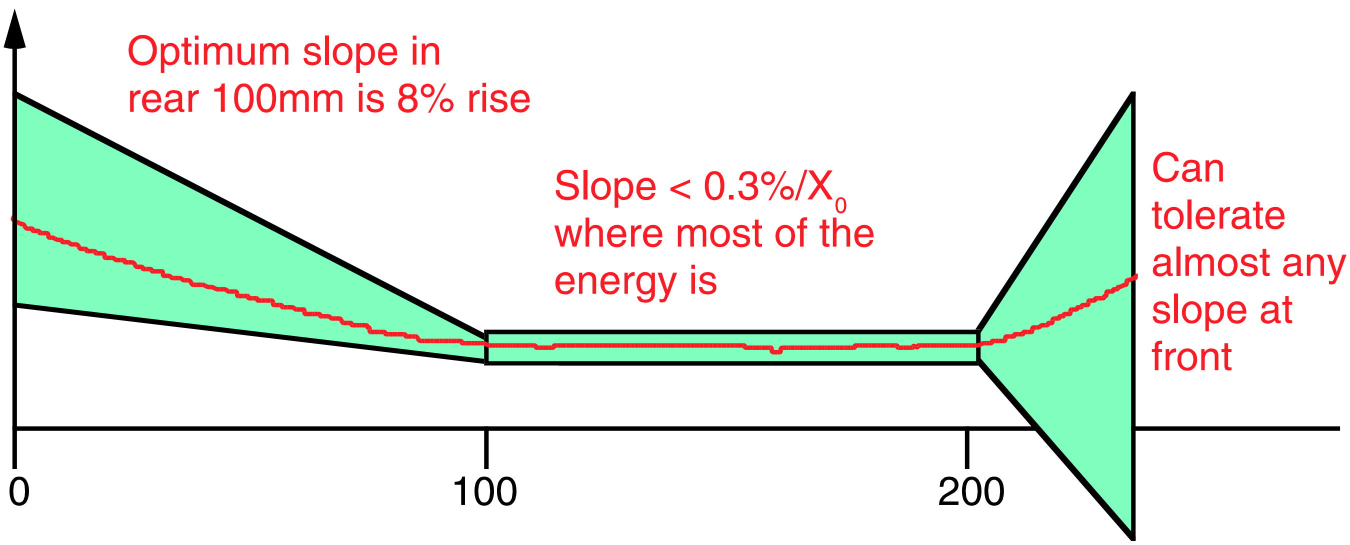


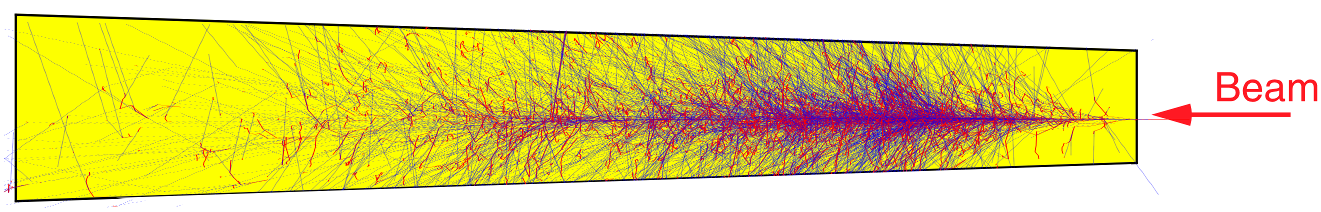


Effect of Light Response Uniformity

D. Graham & C. Seez, CMS Note 1996-002

- Minimize contributions to the constant term of energy resolution, caused by light response non-uniformity.

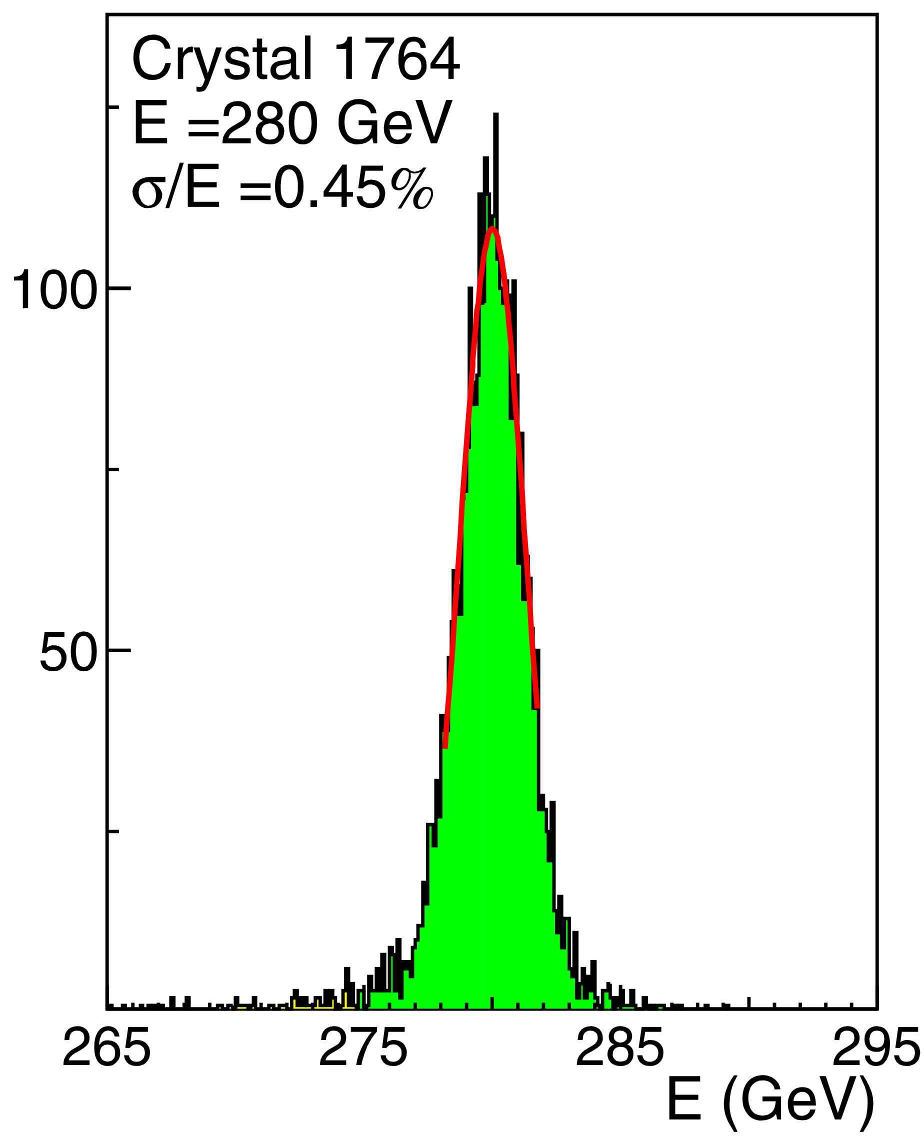


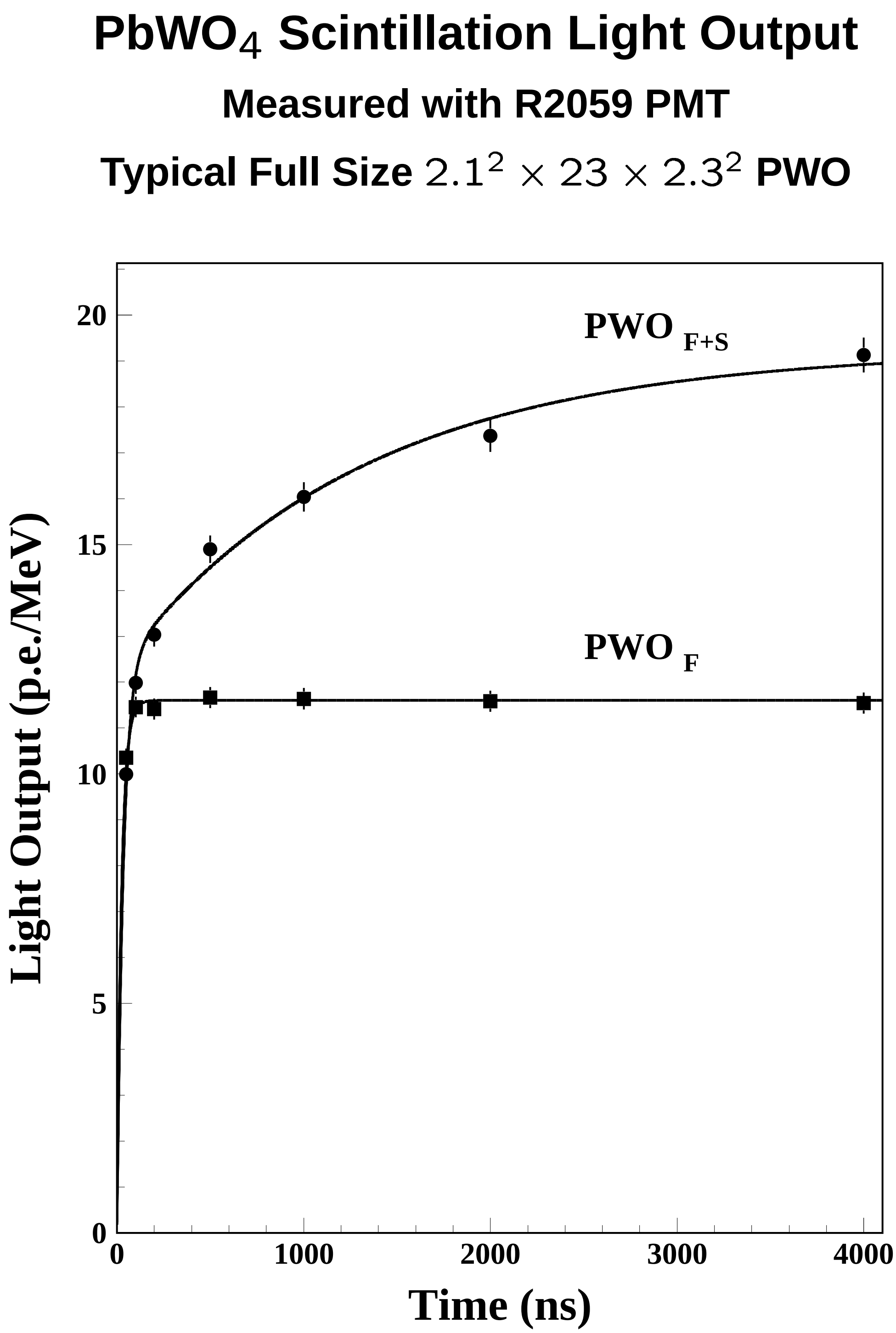


CMS $PbWO_4$ ECAL Beam Test

Resolution of 280 GeV Electrons

$$\frac{\delta E}{E} = \frac{4.1\%}{\sqrt{E}} \oplus 0.37\% \oplus 0.15/E = 0.45\%$$

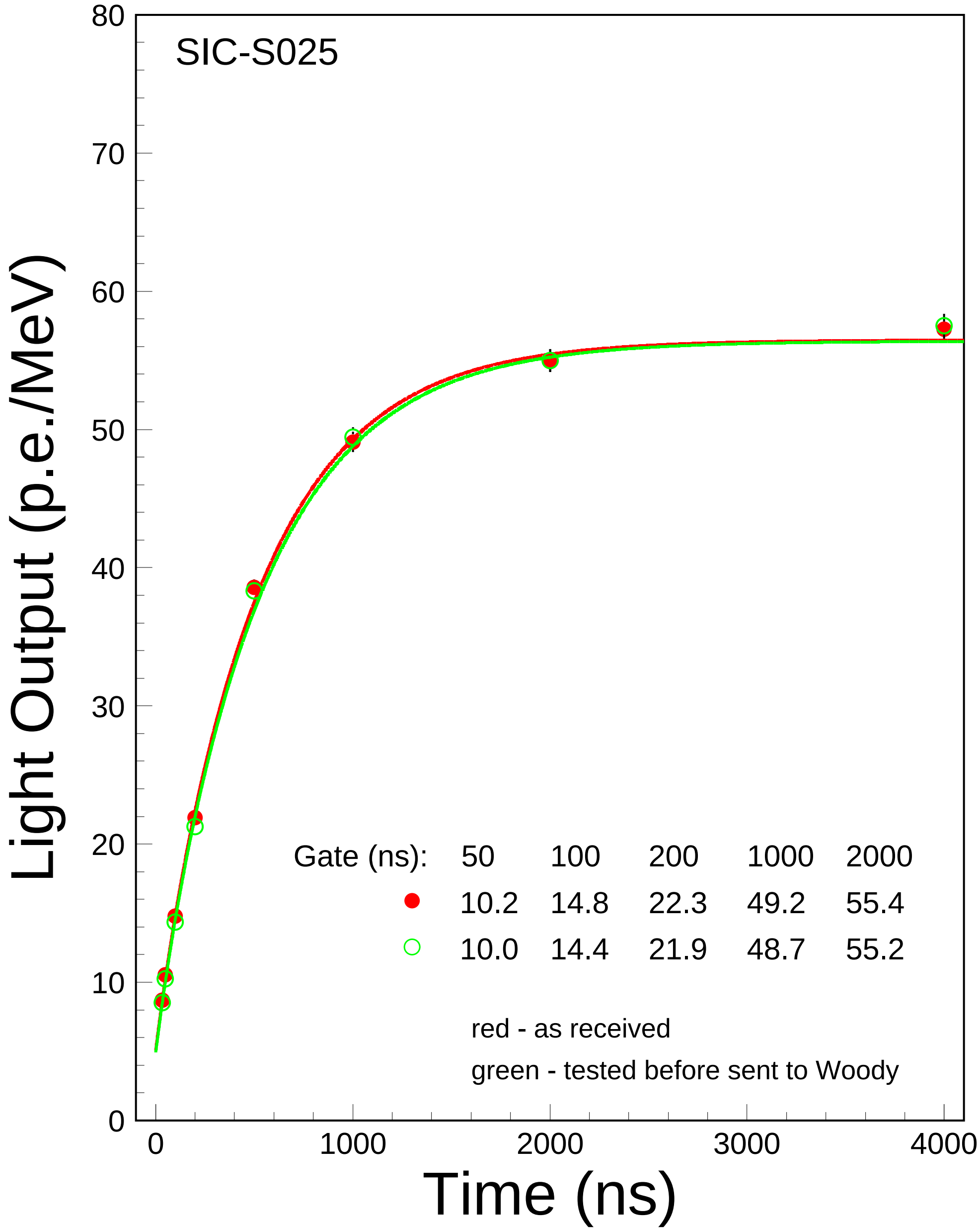



PbWO4 Scintillation Light Output
Measured with R2059 PMT
Typical Full Size 2.1² × 23 × 2.3² PWO
PWO F+S
PWO F
Light Output (p.e./MeV)
Time (ns)
0
5
10
15
20
0
1000
2000
3000
4000

$PbWO_4$ Scintillation Light Output

Size $2.1^2 \times 10 \times 2.1^2$ PWO

56 p.e./MeV Measured with with R2059 PMT



Status of PbF_2 Crystal as a Scintillator

- PbF_2 has been studied in details as a Čerenkov material by D. Anderson and C. Woody *et al.*, *NIM* **A290** (1990) 385 and *IEEE Trans. Nucl. Sci.* **NS-40** (1993) 546.

- Attempt has been made to produce scintillating PbF_2 through phase transition (cubic to orthorhomic). Positive result reported by N. Klassen *et al.* in *Crystal 2000* (1992) 587 does not agree with observations by S. Derenzo *et al. IEEE Trans. Nucl.Sci.* **NS-37** (1990) 206 and D. Anderson *et al. NIM* **A342** (1994) 473.

- Observation of fast scintillation in PbF_2(Gd) and PbF_2(Eu) was reported by D. Shen *et al.* (SIC) *Jour. Inor. Mater.* Vol **10**1 (1995) 11. The scintillation emission of PbF_2(Gd) was confirmed by C. Woody *et al.* in *Delft Conference* (1995), and **6.5 p.e./MeV** was observed for a PbF_2(Gd) sample of $\phi 2.1 \times 2.2$ cm from SIC by using R2059 PMT.

- About 1,000 PbF_2 crystals of $3 \times 3 \times 18.6$ cm (a total of 0.167 m^3) are being produced by SIC in 1998 for an experiment at Mainzer Microtron, Germany. They are used as Čerenkov radiator.

X-ray Excited Emission Spectra of PbF_2(Gd)

D. Shen *et al.*, *Jour. Inor. Mater.* **Vol 101 (1995) 11.**

X-ray Excited Emission Spectra of PbF_2(Eu)

D. Shen *et al.*, *Jour. Inor. Mater.* **Vol 101 (1995) 11.**

γ-ray Excited Emission Spectra of PbF_2(Gd)

C. Woody *et al.*, *Delft Conference* **(1995)**

PbF_2(Gd) ($\phi 2.1 \times 2.2$ cm) Pulse Height

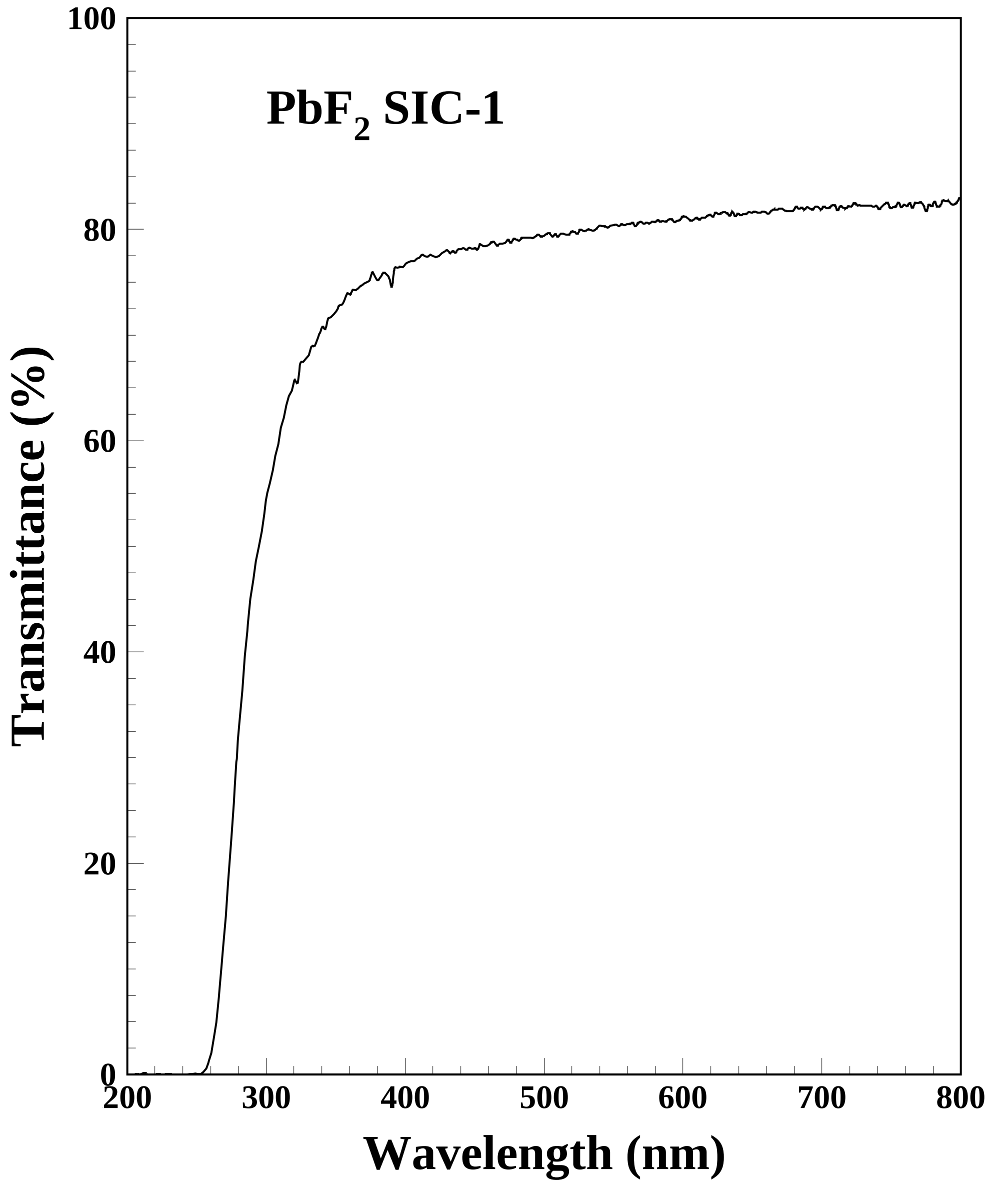
Measured at AGS with 1 GeV/c MIPS by C. Woody *et al.*

6.5 p.e./MeV Observed by R2059 PMT

Longitudinal Transmittance of PbF_2

Measured with Hitachi U-3210 Photospectrometer

$3 \times 3 \times 18.6$ cm Sample from SIC



Radiation Damage (10 krad) and Annealing

$3 \times 3 \times 18.6$ cm PbF_2 Sample from SIC

Measured by F. Maas

Summary

- To maximize physics reach, calorimetry for LC should have good measurement on electrons, photons and jets.

- A crystal calorimeter provides the best achievable resolutions for electrons and photons, a good missing energy resolution and an adequate jet resolution.

- Recently developed low cost, heavy crystals offers a cost effective crystal calorimeter solution.

- Feasible crystal technologies:
  - A $PbWO_4$ calorimeter;
  - A PbF_2 calorimeter following successful R&D.