State-of-the-art of Shashlik calorimeters

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Outline

1. Calorimetry
2. Types of calorimeters
3. Electromagnetic calorimetry
4. Shashlik calorimeter
5. Shashlik calorimeter - properties
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Calorimetry

One of the most important and powerful detector techniques in experimental physics

Two main categories of calorimeter:

Electromagnetic calorimeters - detection of electron/positron and photons

Hadron calorimeters - detection of particles that interact via strong nuclear force

Both can be either homogeneous or sampling

Sampling - the material that produces the particle shower is distinct from the material that measures the deposited energy

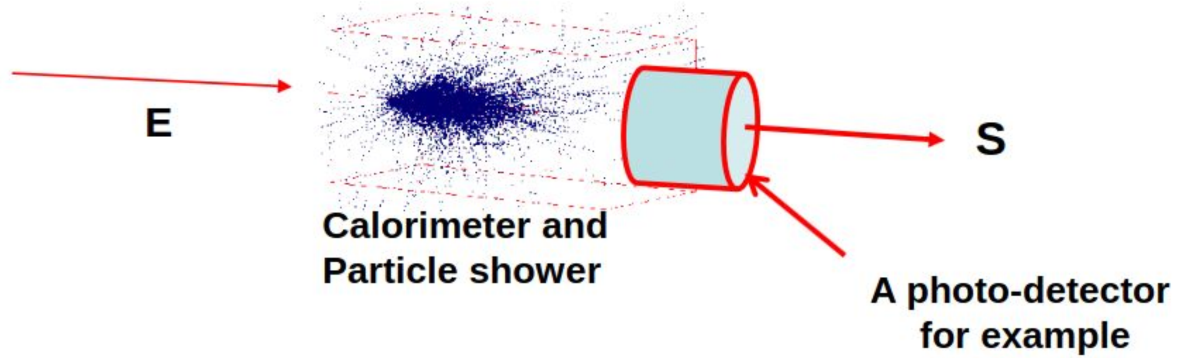
Homogeneous - entire volume is sensitive and contributes to the signal

Calorimetry

Calorimeters are designed to stop and fully contain their respective particles

Measure - energy of incoming particle(s) by total absorption in the calorimeter
- spatial location of the energy deposit
- direction of the incoming particle (not always)

Detector response $S \propto E$



Calorimetry

Basic mechanism:

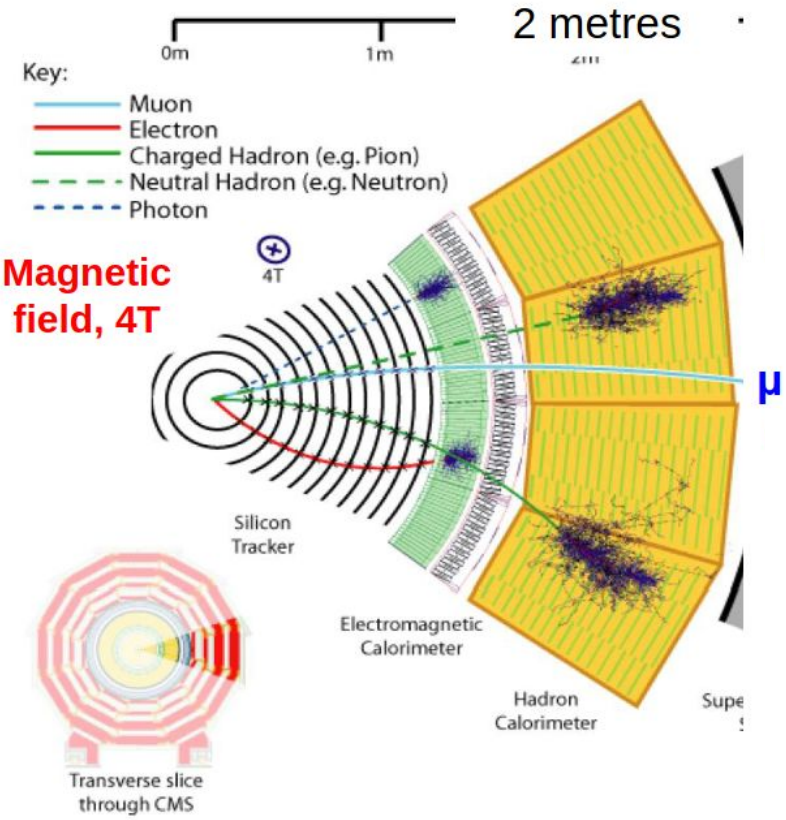
- Energy lost by the formation of electromagnetic or hadronic cascades/showers in the material of the calorimeter

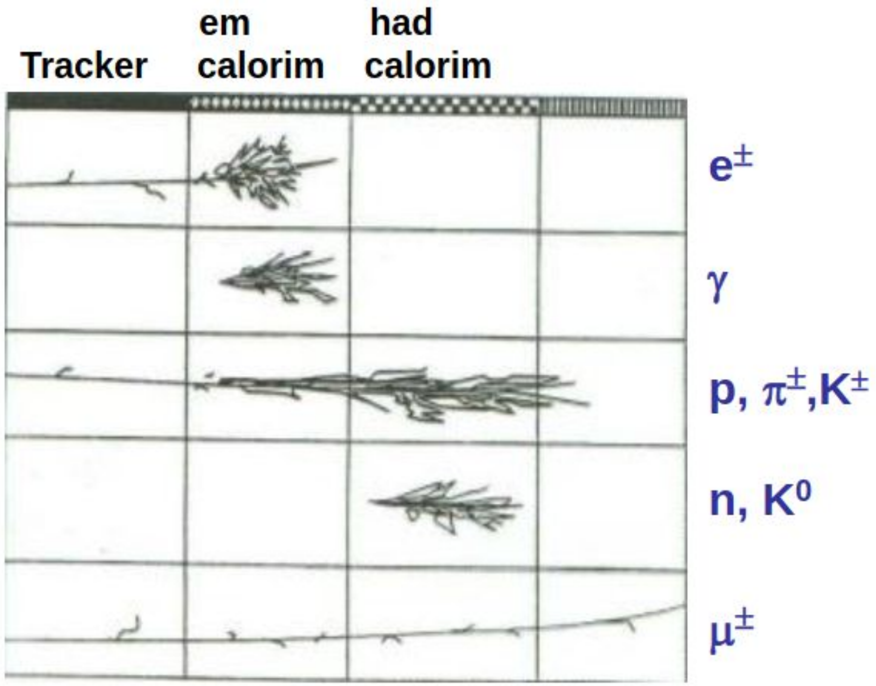
- Many charged particles in the shower

The charged particles ionize or excite the calorimeter medium

Photo-detectors or anodes/dynodes then detect these “quanta”

Calorimetry





Homogeneous calorimeters

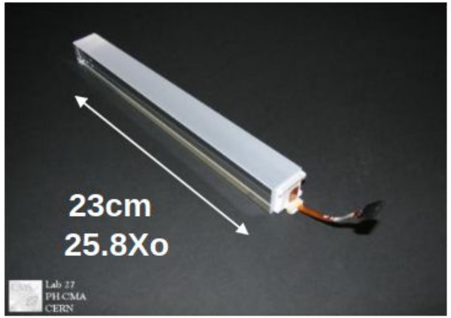
Single medium, both absorber and detector

- **Liquified Ar/Xe/Kr**
- **Organic liquid scintillators, large volumes**
- **Dense crystal scintillators: PbWO4, CsI(Tl)**
- **Lead loaded glass**

Almost entirely for electromagnetic calorimetry

Babar ECAL CsI(Tl)
ALICE ECAL ($PbWO_4$)

Si photodiode
or PMT



CMS ECAL ($PbWO_4$)

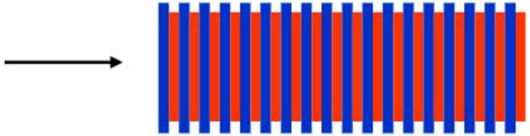
Sampling calorimeters

Layers of passive absorber (ie Pb or Cu) alternating with active detector layers such as plastic scintillator, liquid argon or silicon;

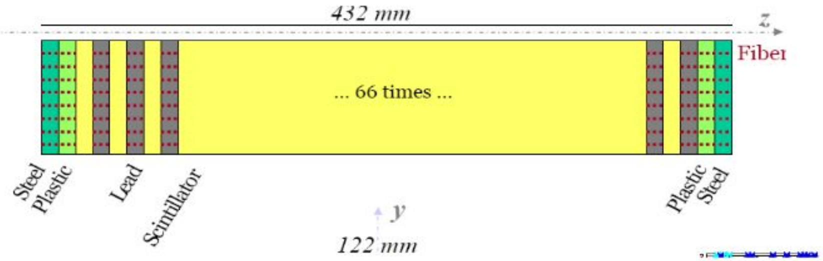
- Only part of the energy is sampled

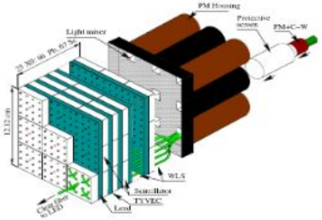
- Used for both electromagnetic and hadron calorimetry

- Cost effective

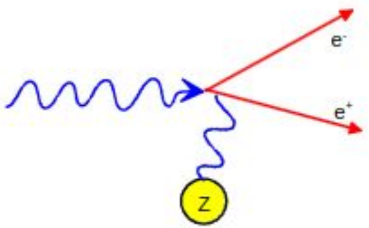


ATLAS	ECAL & HCAL
ALICE	EMCAL
CMS	HCAL
LHCb	ECAL





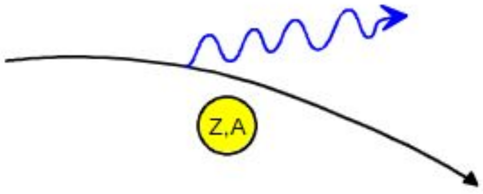
Electromagnetic calorimeter



Electromagnetic cascades

- $e^{+/-}$ bremsstrahlung and photon pair production

By far the most important processes for energy loss by electrons/positrons/photons with energies above 1 GeV Leads to an e.m. cascade or shower of particles



- Bremsstrahlung

Characterised by a 'radiation length', X_o, in the absorbing medium over which an electron loses, on average, 63.2% of its energy by bremsstrahlung.

$1/m_e^2$ dependence

$$-\frac{dE}{dx} \propto \frac{Z^2 E}{m_e^2}$$

Electromagnetic calorimeter

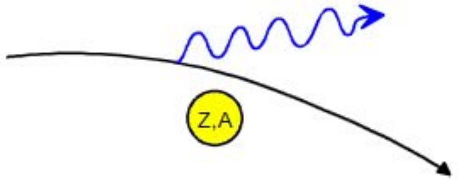
Pair production

- Characteristic mean free path before pair production, $\lambda_{pair} = 9/7\ X_o$

Bremsstrahlung and pair production dominate the processes that degrade the incoming particle energy

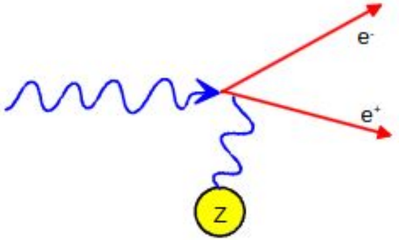
50 GeV electron

Loses 32 GeV over 1 X_0 by bremsstrahlung



50 GeV photon

Pair production to $e^+ e^-$, 25 GeV to each particle
Energy regime degraded by 25 GeV



Electromagnetic calorimeter

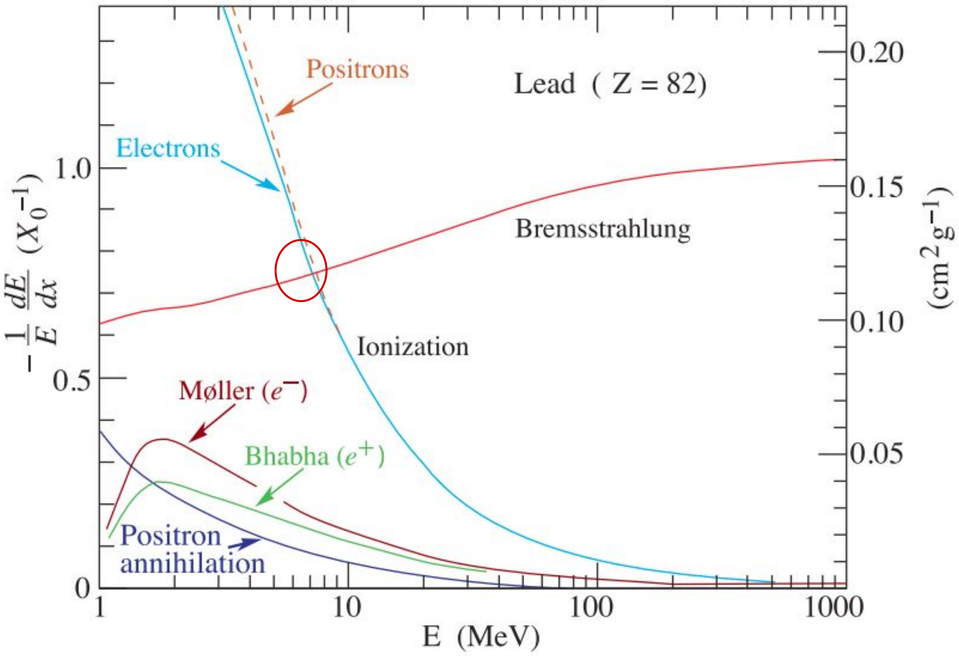
Below a certain critical energy E_c;

$e^{\pm}$ energy losses are greater through ionisation than bremsstrahlung

- **Slow decrease in number of particles in the shower**
- **Electrons/positrons are stopped**

Photons progressively lose energy by compton scattering, converting to electrons via the photoelectric effect, and absorption

$$E_c \approx \frac{610 MeV}{Z + 1.24} \Longrightarrow \textbf{Pb } (Z=82), \quad \mathbf{E_c = 7.3\ MeV}$$

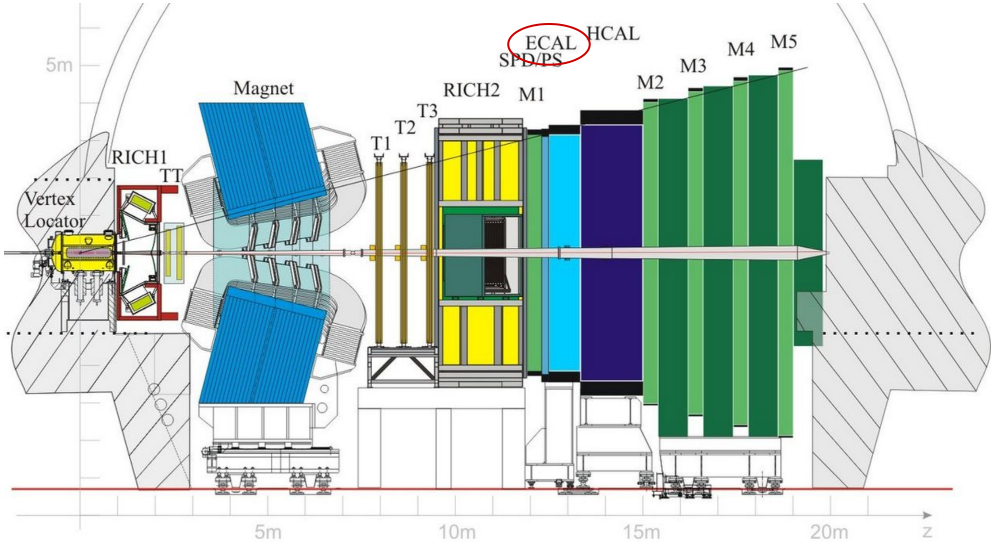


Shashlik calorimeter

Shashlik calorimeter - name for a layout for a sampling calorimeter

Stacking of alternating slices of absorber (ie lead, brass) and scintillator materials (crystal, plastic), which is penetrated by a wavelength shifting fiber (WLS) running perpendicular to the absorber and scintillator tubes

An example of detector that uses a shashlik ECAL is LHCb detector



Shashlik calorimeter

What are necessary requirements for a good ECAL?

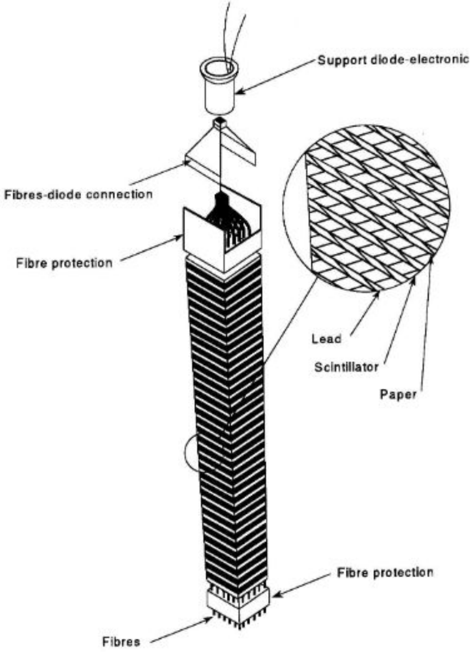
- **Good energy resolution [$\sigma/E=0.10/E^{1/2}$]**
- **Operation in presence of high magnetic field**
- **High radiation resistance**
- **High speed**
- **As good hermeticity as possible**

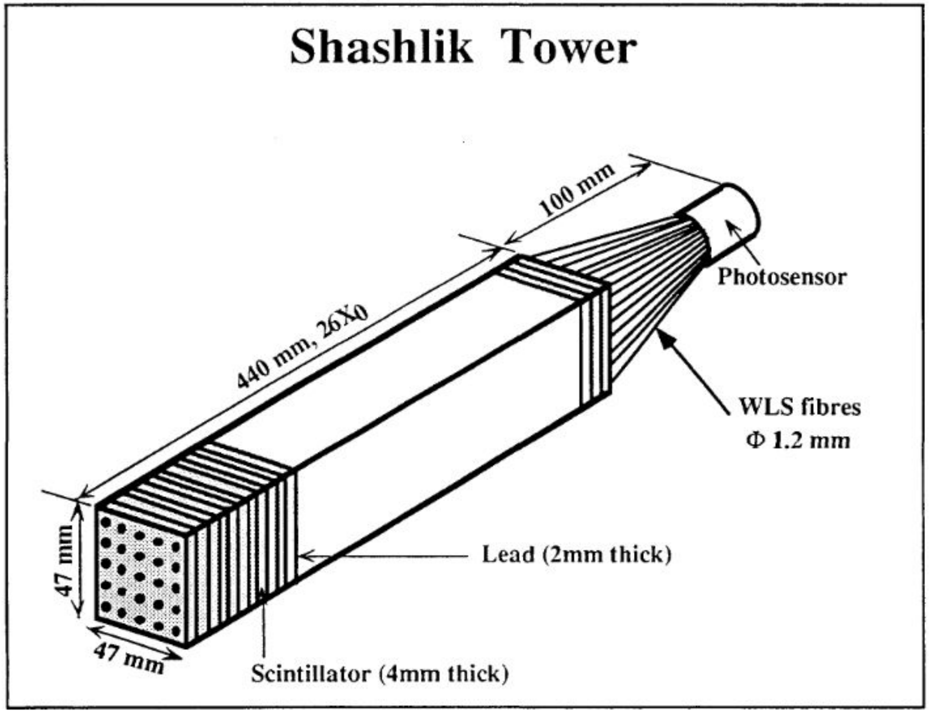
Shashlik detector can be designed to meet all the requirements

Focus on shashlik type of calorimeter design for CMS detector

Shashlik calorimeter - description

There are 75 layers altogether, giving total radiation length of about 27.5 X_o





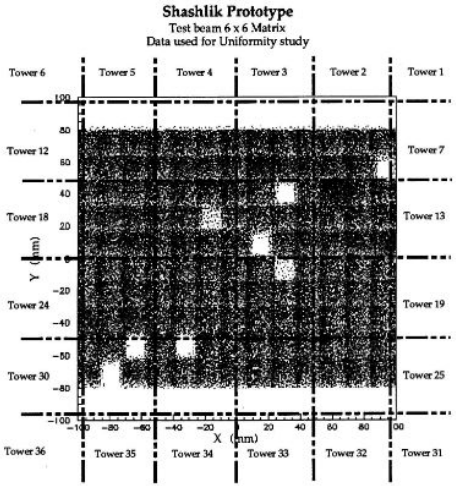
Mechanical design of a CMS Shashlik calorimeter prototype tower equipped with 25 aluminized WLS fibers
WLS - Wave-Length Shifting

Shashlik calorimeter - response uniformity

Uniformity of response, both in lateral and longitudinal directions, is the crucial issue for the calibration of a calorimeter

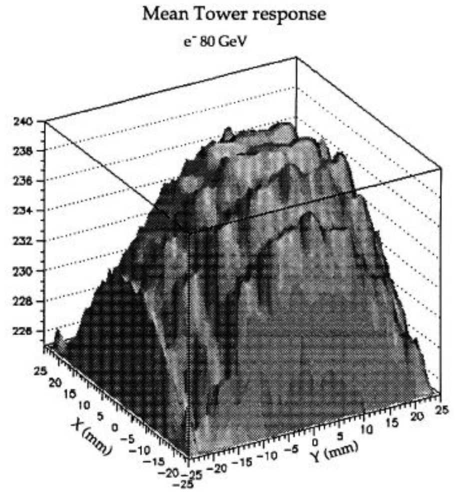
The aim of this study is to find the law governing the response non-uniformity and by its parametrization to perform uniformity corrections

This is done by studying the reconstructed shower energy, summing the energy deposited in the central tower



Sketch of the 6 × 6 test beam shashlik matrix and the 80 GeV electron data impact points ($5 \cdot 10^6$ triggers) taken for the uniformity study. The empty squares correspond to unusable data files

Mean response (sum of 9 towers) for the 16 central towers of the 6 x 6 matrix exposed to 80 GeV electrons



Shashlik calorimeter - energy resolution

The energy resolution of a calorimeter is generally parametrized as:

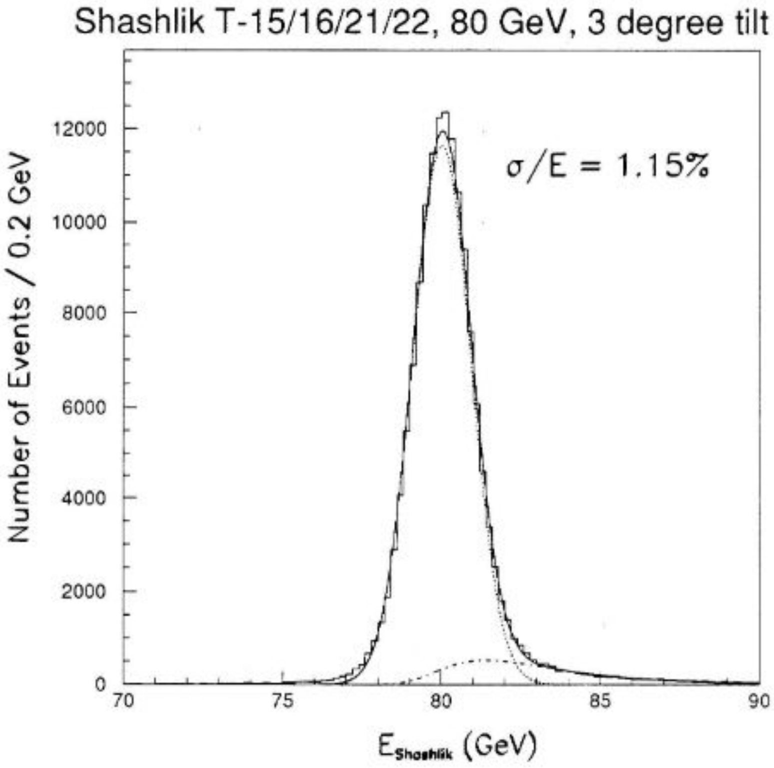
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

where a denotes stochastic term, b is the noise term and c the constant

The reconstructed energy in shashlik towers for 80 GeV electrons

Energy resolution was acquired from beam testing at CERN in 1994

Only 4 towers were used in this test



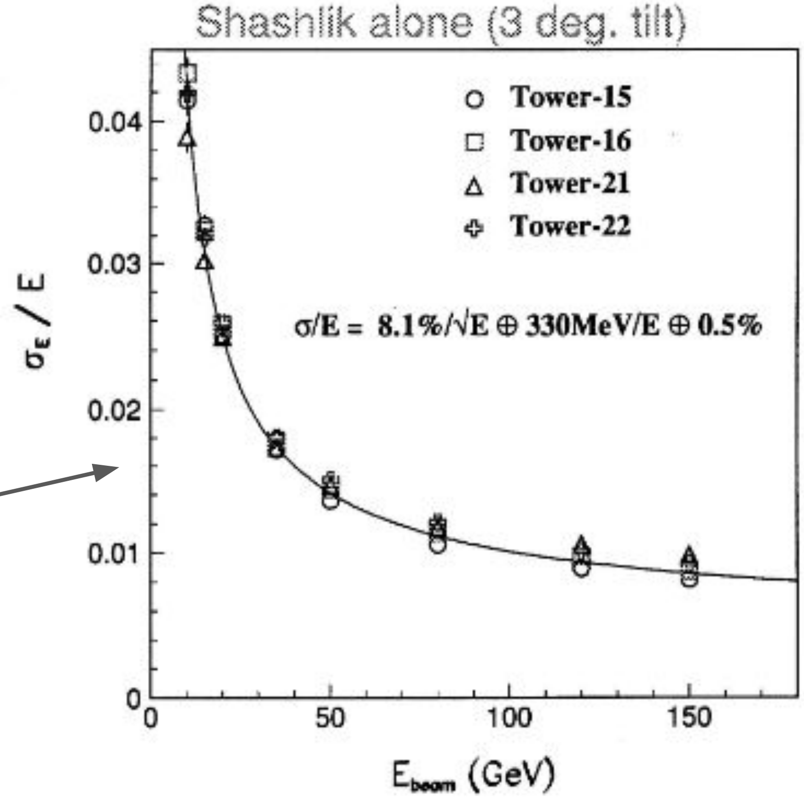
Shashlik calorimeter - energy resolution

Average resolution of 4 towers:

$$\frac{\sigma_E}{E} = \frac{8.1\%}{\sqrt{E(GeV)}} \oplus \frac{0.33}{E(GeV)} \oplus 0.5\%$$

Influence of magnetic field in the field strength of 3T was also tested - no significant effect on energy resolution

Energy resolution of the new shashlik prototype (shashlik alone)

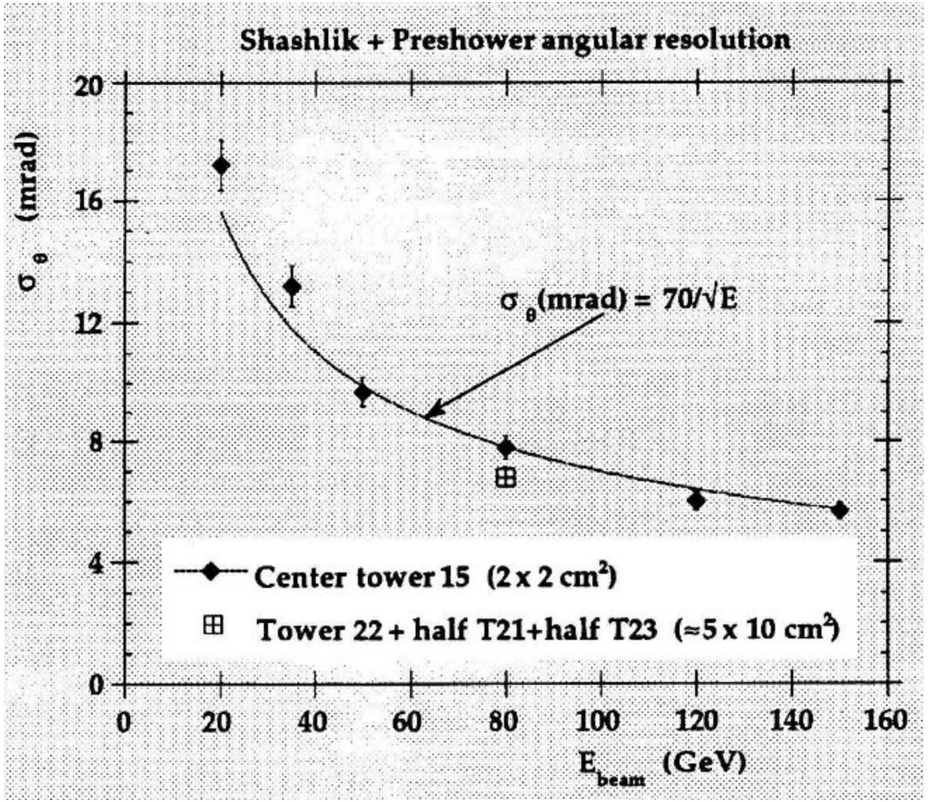


Shashlik calorimeter - angular resolution

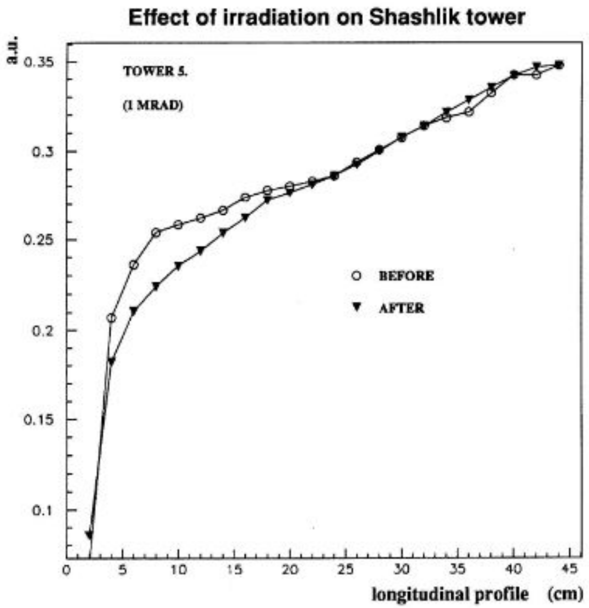
Figure shows dependence of the angular resolution as a function of the electron energy at the tower center

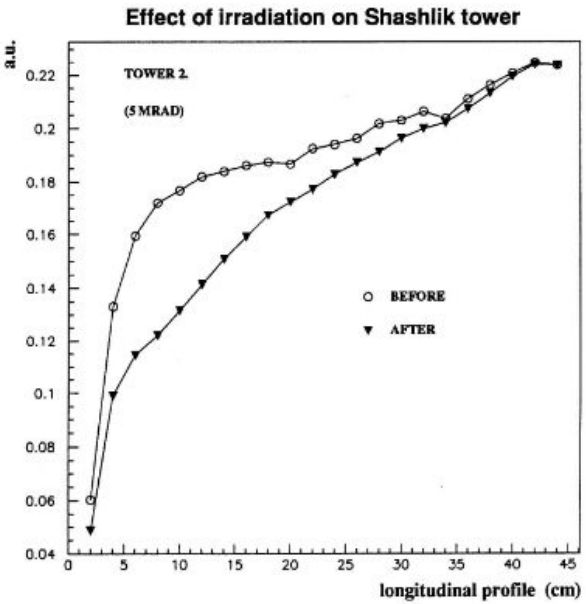
Angular resolution obtained from the fit:

$$\sigma_\theta = \frac{70 \text{ mrad}}{\sqrt{E(\text{GeV})}}$$



Shashlik calorimeter - radiation damage tests





Figures show the effects of 1 Mrad and 5 Mrad doses on the longitudinal response of a tower to ^{60}Co photons

Damage is maximum at the shower maximum

A study of the effects of radiation damage on light yield collection showed that in addition to the overall decrease in light collected, the non-uniformity of response across a calorimeter tower increases.

That leads to an increase of the contribution of the constant term to the energy resolution.

Conclusion

Calorimetry - one of the most important and powerful detector techniques in experimental physics

Design of shashlik calorimeter for CMS detector includes novel technique to read-out the light from a lead/scintillator sampling calorimeter using WLS optical fibers

Shashlik calorimeter - relatively low cost to build

Very good energy resolution can be achieved

Estimated that an irradiation of 1 Mrad (corresponding to 10 years of LHC operation at nominal luminosity in the CMS barrel) produces a loss of light of about 10%

The resultant loss in energy resolution is small

References

[1] Beam test results of the Shashlik electromagnetic calorimeter, CMS Technical Note TN/95-104

[2] Godinović, N., Puljak, I. i Sorić, I. (1995). Performance of the "SHASHLIK" electromagnetic calorimeter. *Fizika B, 4* (3), 217-228

[3] Shashlik calorimetry a combined Shashlik + preshower detector for LHC: R&D proposal, J. Badier (Ecole Polytechnique), G. Bonneaud (Ecole Polytechnique), A. Busata (Ecole Polytechnique), P. Busson (Ecole Polytechnique), C. Charlot (Ecole Polytechnique) et al.

[4] A Shashlik + Preshower Detector as Electromagnetic Calorimeter For LHC, CERN/DRDC 94-47 RD36 - Status Report January 9th 1995