EM Calorimeter R&D for Future Experiments

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Brookhaven National Lab
Workshop on Detector R&D
FNAL, Oct 8, 2010

Outline

- Overview of recent EM calorimeters
  - State of the art of the field
  - Available technologies
- R&D efforts for future experiments
  - Performance Requirements
  - SuperB, LHC upgrade, Linear Collider detectors

EM Calorimetry

- EM Calorimeters measure EM showers and early hadron showers
  - Energy, position, time
- Typical EM calorimeter resolution
  - $\sigma_E/E = a/\sqrt{(E)} + b/E + c$
  - sampling, noise and constant terms
- Technology choices depends on
  - Energy range, energy resolution requirements
  - Position resolution requirements, particle identification
  - Radiation environment, readout speed
- Requirements on measurements of hadronic final states affect EM calorimeter choices.
  - Overall optimization vs EM optimization

    e.g., compensation → low sampling fraction (ZEUS Calorimeter)

Some Recent EM Calorimeters

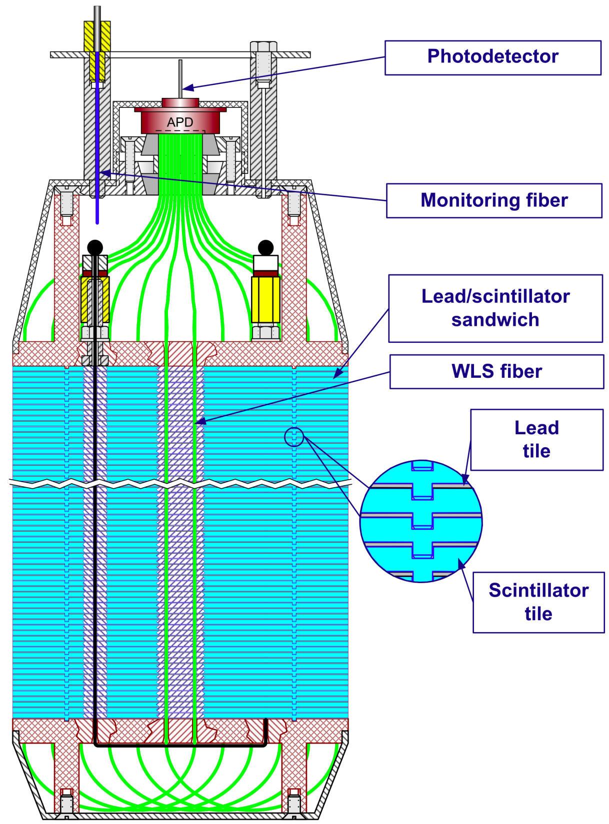
- Crystal EM calorimeters
  - BGO: L3
  - CsI(Tl): CLEO-II, Belle, BaBar, BES III
  - CsI: KTeV, E787/E949
  - PWO: CMS, ALICE, PANDA
- Scintillator sampling EM calorimeters
  - Shashlyk: E865, HeraB, PHENIX, LHCb, ALICE
- Silicon sampling EM calorimeters
  - SLD, ALEPH, OPAL, DELPHI
- Noble liquid EM calorimeters
  - LAr: D0, SLD, H1, ATLAS
  - LKr: KEDR, NA48
  - LXe: MEG

Shashlik EM Calorimeter

- Stacks of alternating scintillators and Pb absorbers
- Readout with WLS fibers threaded through stacks
- Relatively inexpensive
- Readout with PMT or APD
- Monitoring with LED through clear fibers
- Resolution can be improved with increasing sampling fraction
  - The KOPIO prototype reached remarkable performance :

$$\sigma_E/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)\%/\sqrt{E\,(\mathrm{GeV})}$$

LHCb Module



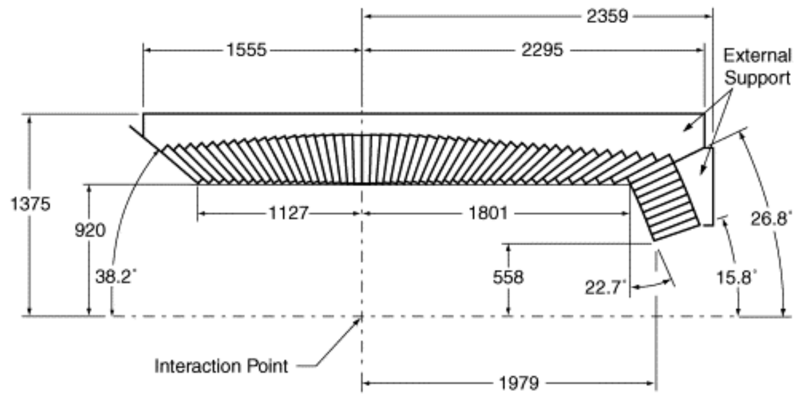
Prototype for KOPIO

Crystal EM Calorimeters

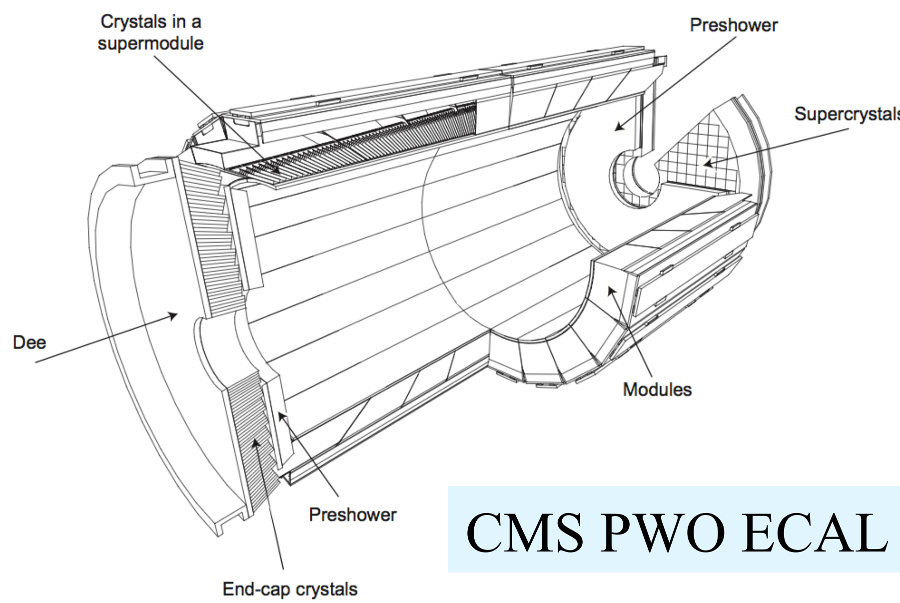
- CsI(Tl) used for EM calorimetry for B and charm factories
  - Slow (~1000ns), dense (X_0=1.86cm),
  - not very radiation hard (10% / krad)
  - good energy resolution at low energy
    - π^0 reconstruction
  - BaBar: $\frac{\sigma_E}{E} = \frac{(2.32 \pm 0.30)\%}{\sqrt[4]{E(\mathrm{GeV})}} \oplus (1.85 \pm 0.12)\%.$
- PWO used in LHC
  - Dense, fast and radiation hard
  - Relatively low light yield
  - APD and VPT readout
    - 4.5p.e./MeV
  - CMS energy resolution:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$$

  - Candidate EMCal for mu2e experiment



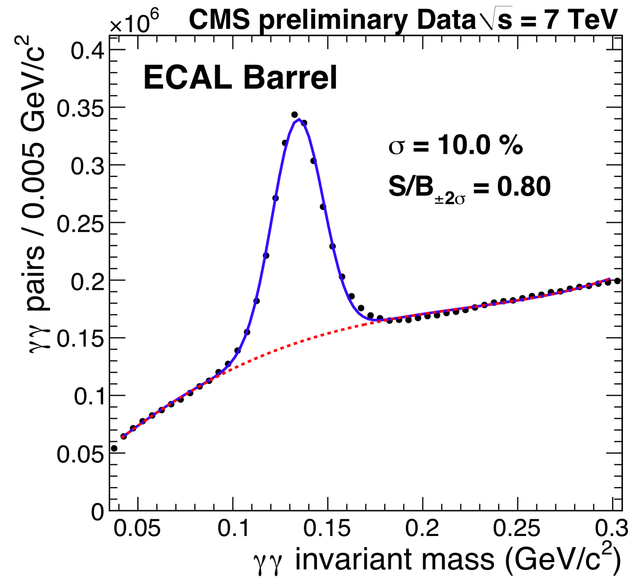
BaBar EMC (6580 CsI(Tl) crystals)

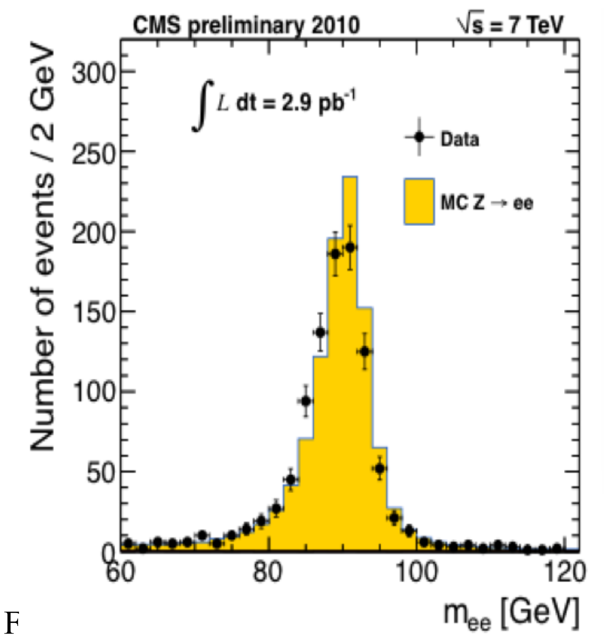


CMS PWO ECAL

CMS EM Calorimeter Performance

- A total of 76,000 crystals
- Calibrated in testbeam
- In situ calibration with
  - φ-symmetry intercalibration
  - π^0, η, J/ψ resonance
  - W/Z
- channel-to-channel calibration precision
  - 0.6% in the central barrel
- global energy response scale
  - ~ 1% in the barrel
  - ~ 3% in the endcaps.





Crystals for HEP Calorimeters

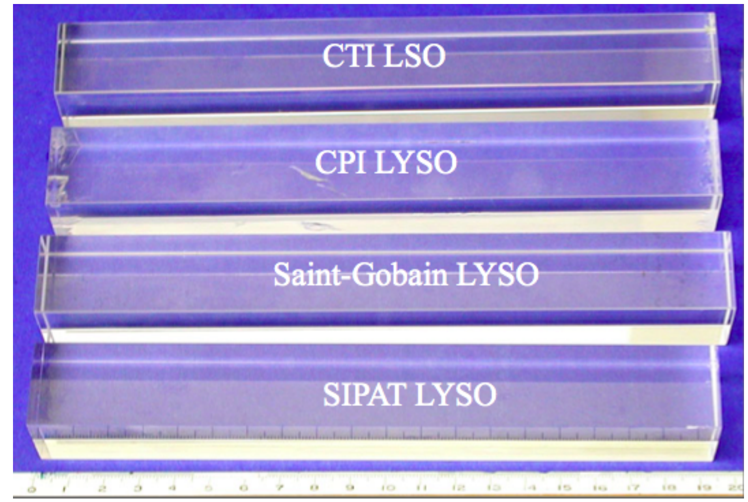
L.Zhang, Calor 2010

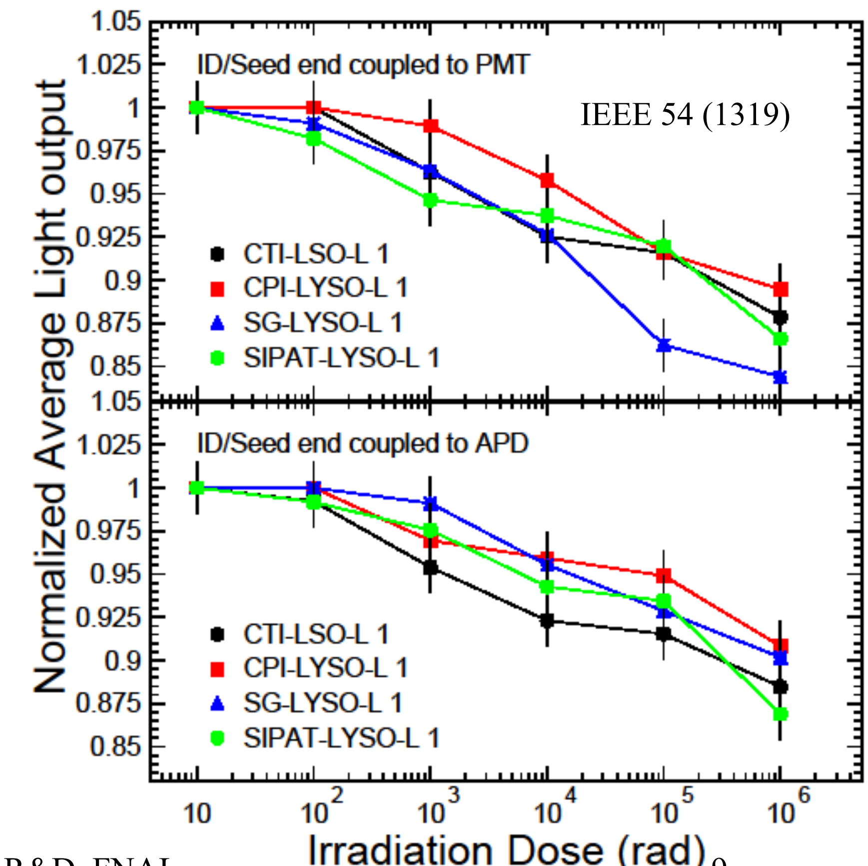
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm³)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	(L*) (GEM) TAPS	L3 BELLE	KLOE-2 SuperB SLHC?	CMS ALICE PANDA	HHCAL?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

LSO/LYSO(Ce) crystal

- Widely used in Medical imaging
- High light yield (85% NaI)
- Dense: X_0=1.14cm, R_M=2.07cm
- production capability of large size
- d(LY)/dT ~ -0.2%/K
- Radiation damage
  - 10-15% after 1MRad γ
  - Caused by loss in transmission
  - Recover after annealing
- Critical issues
  - Ce-doping uniformity
  - Production cost
- Potential applications
  - Super-B Endcap EM calorimeter

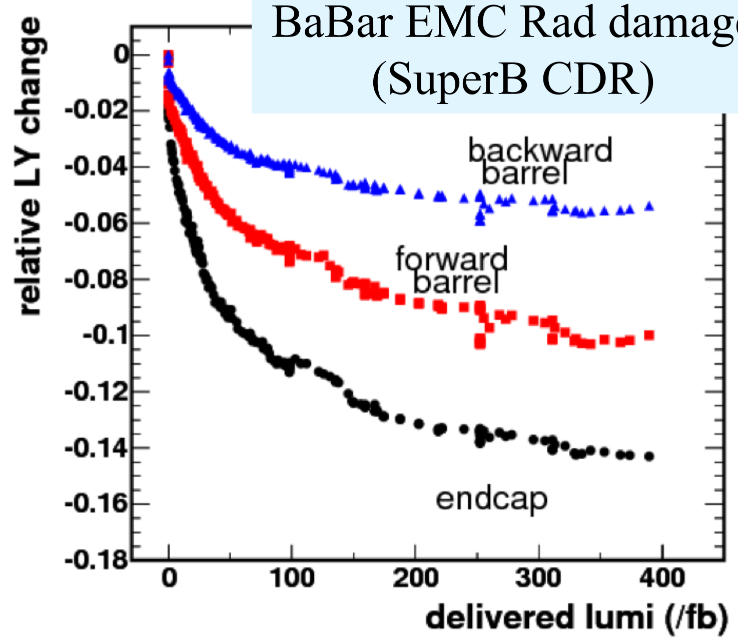


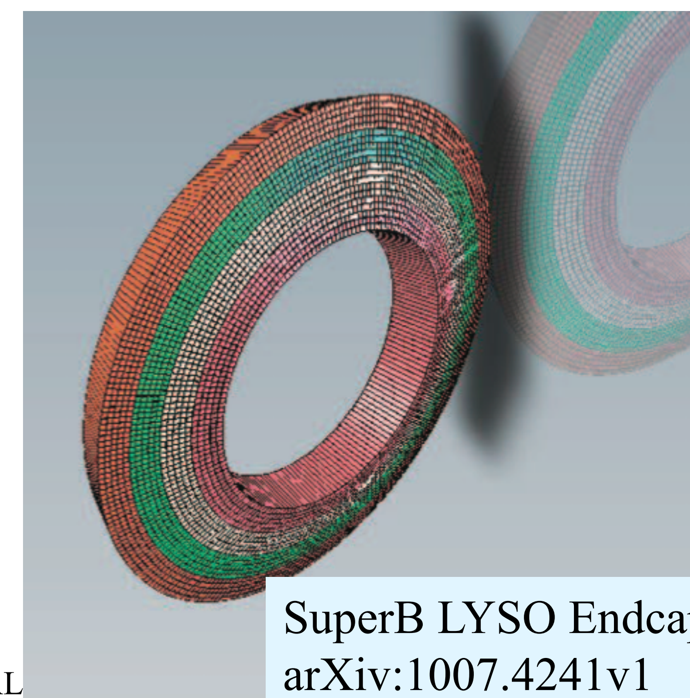


EM Calorimeter in SuperB

- SuperB:
  - e+e- B factory at L = $10^{36}/cm^2/s$
  - Upgraded BaBar detector
- Radiation damage to BaBar EMC
  - Endcap: 1.5krad → >15% loss
- SuperB EMC baseline:
  - Re-use BaBar CsI(Tl) barrel calorimeter
    - background rates ~ 1krad/year
  - Replace the endcap with rad hard crystals
    - LYSO is the leading candidate
- Two beam tests with LYSO crystals are planned in the near future.

BaBar EMC Rad damage (SuperB CDR)





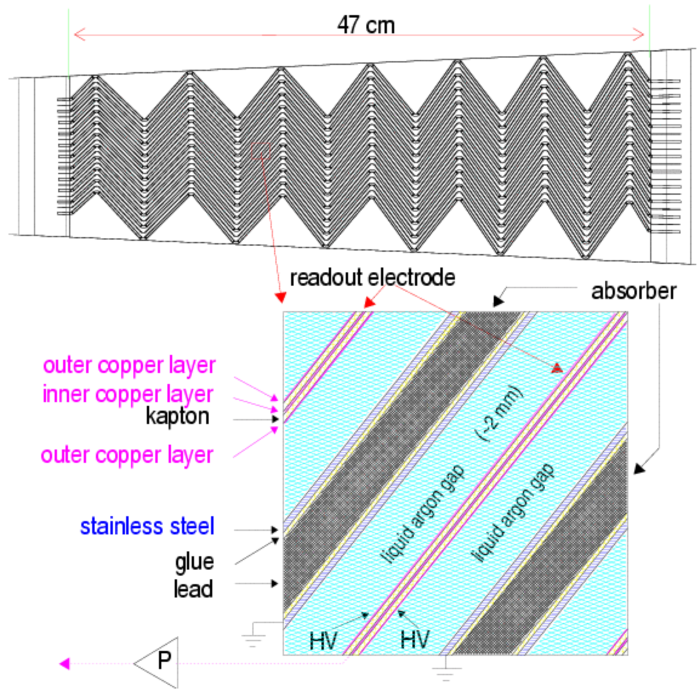
SuperB LYSO Endcap
arXiv:1007.4241v1

Noble Liquid Ionization Calorimeters

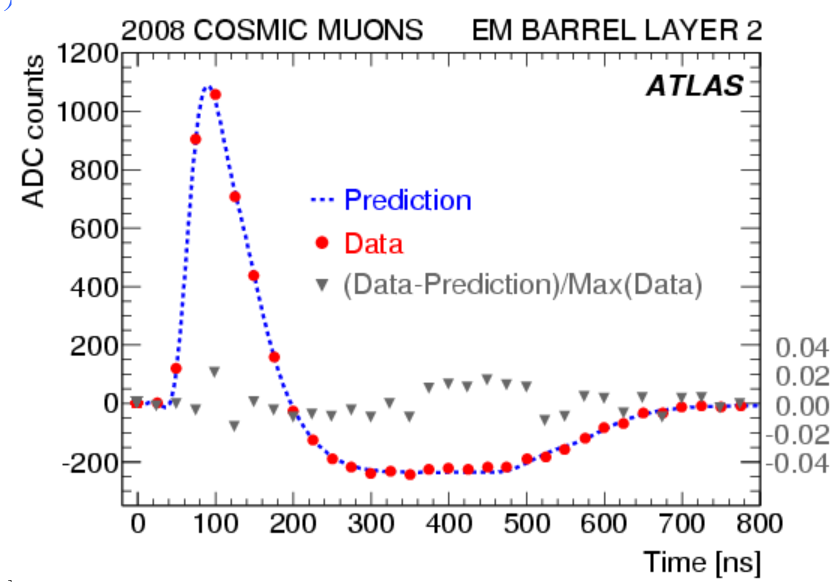
- Well-established technique for large EM Calo
  - High density medium, → ion chamber mode, gain==1.
    - LAr: 1.4g/cm^3, LKr: 2.4g/cm^3
  - Cell-to-cell uniformity ensured by mechanical precision and electronics calibration
    - Small constant term
  - Ease for segmentation, radiation hard
- Challenges
  - Operation of cryogenics, liquid purity
  - Inactive material, long drift time (typically 400-500 ns)
- Accordion LAr calorimeter
  - Hermetic coverage in phi
  - Avoid interconnects → fast charge transfer time
  - Fast shaping → reducing pileup effects
  - ATLAS LAr EM Barrel Energy Resolution (testbeam)

$$\sigma_E/E = 10.1\ \%/\sqrt{E} \oplus 0.17\ \%$$

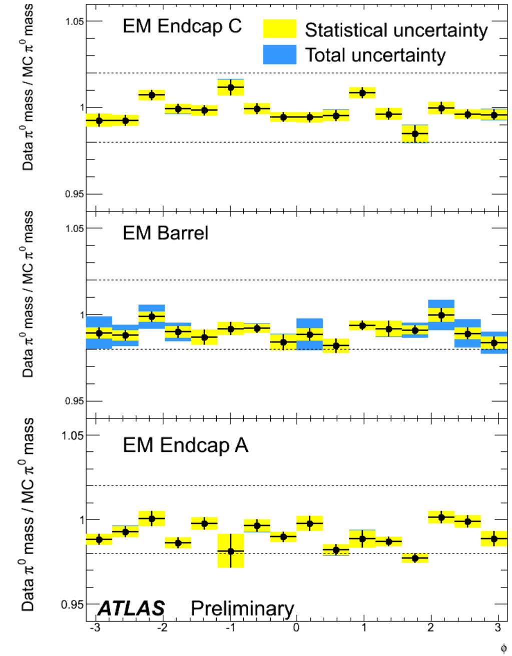
  - Excellent timing resolution: 83ps at 245 GeV
- Total absorption LAr TPC for neutrinos



ATLAS Accordion EM Calorimeter

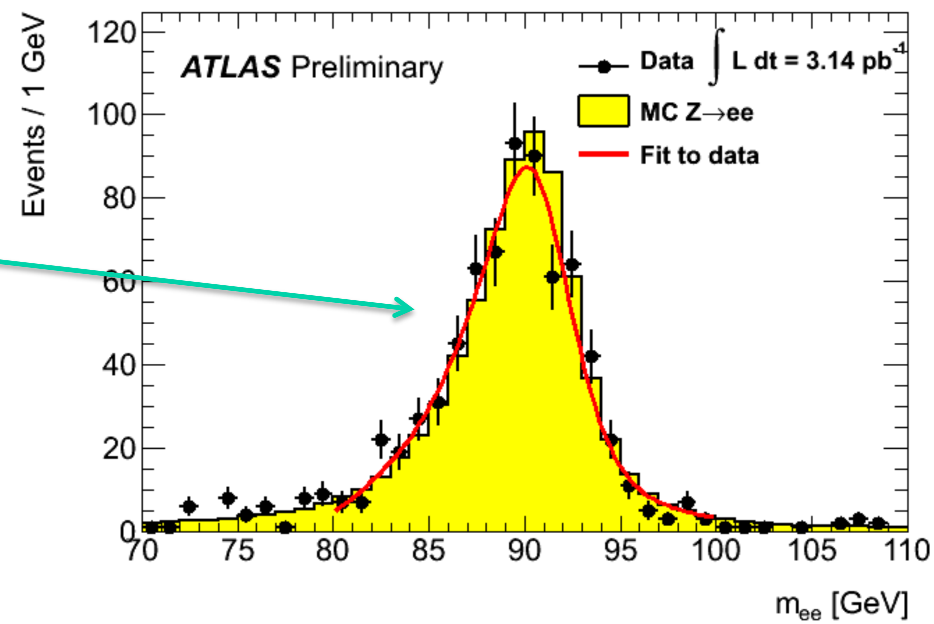


ATLAS EM Calorimeter Performance

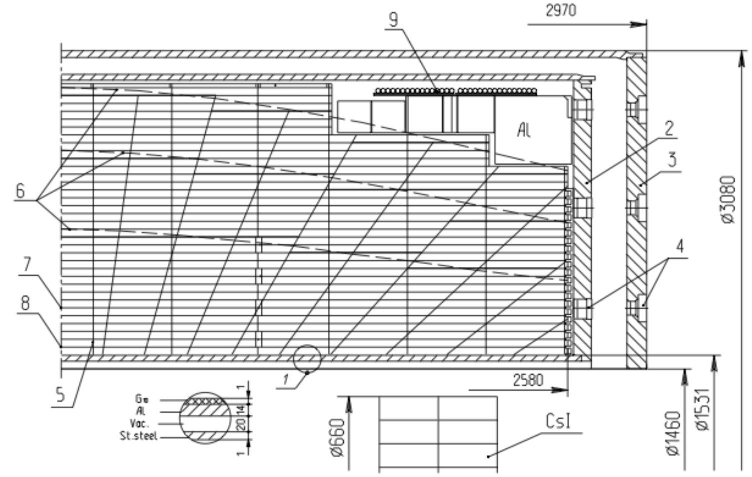


- 180,000 channels
  - ~ 2% dead channels (optical links to be repaired)
  - 0.02% permanently dead.
- Precision electronics calibration

- Energy scale measured in testbeam with test modules
- In situ uniformity measurements with π^0 (<2%)
- Absolute energy scale with Z
  - Consistent within 1-2%
  - More refined calibration with larger Z statistics



Liquid Krypton Calorimeter



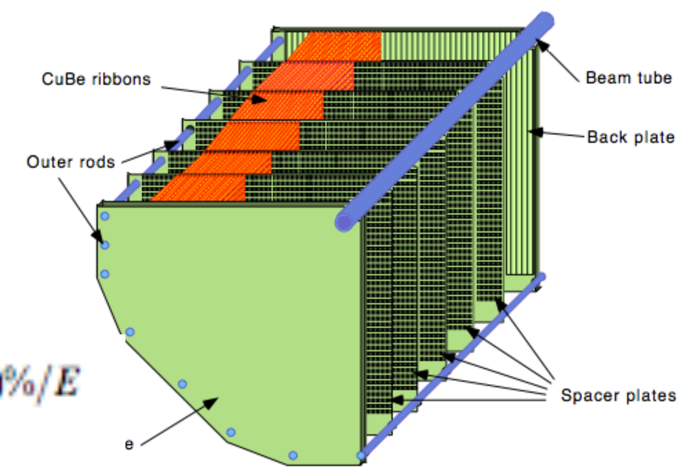
KEDR LKr EM Cal

KEDR

- Highly segmented total absorption LKr EM calorimeter at VEPP-4M (e+e- τ/charm physics)
- Readout with 10×10cm^2 pads and 5mm strips
- Energy resolution: 3% at 1.8GeV
- Spatial resolution: 0.8mm at 1GeV

NA48

- 10 m^3 of liquid krypton
- 13212 readout towers of 2cm×2cm
- 1cm drift
- Energy resolution $$\sigma(E)/E = (3.2 \pm 0.2)\%/\sqrt{E} \oplus (9 \pm 1)\%/E \oplus (0.42 \pm 0.05)\%$$
- Position resolution ~1mm, E>25GeV



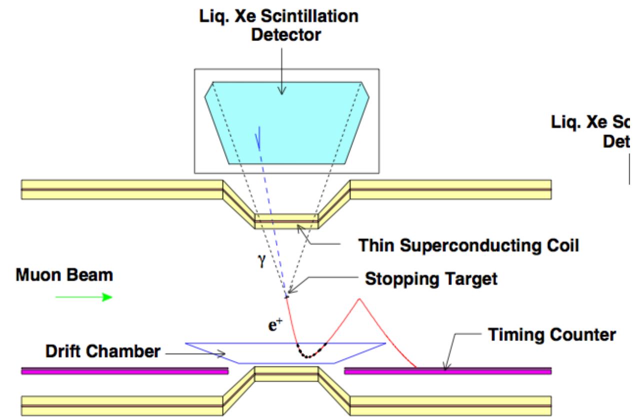
NA48 LKr Cal Electrodes

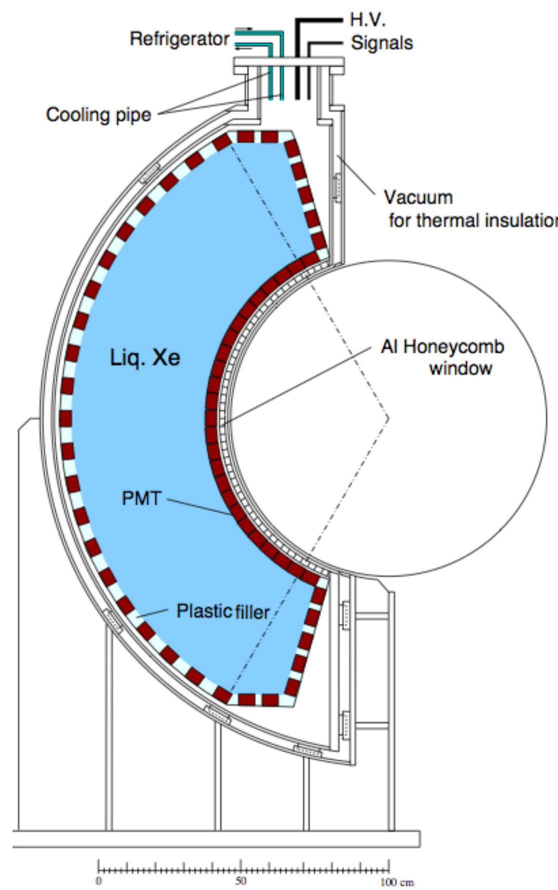
MEG Liquid Xenon Calorimeter

- Measure γ from $\mu \rightarrow e\gamma$
  - 58MeV photons
- Scintillation light from Xe:
  - λ_{peak}=174 nm(PM quartz windows)
  - τ : 4 ns, 20 ns and 45 ns
  - 40000 pe/MeV (~ 0.8 NaI)
  - absorption by impurities
  - 800 litres at 165K, 17X_0 deep
- Performance

Measurement	Resolution (FWHM)
γ Energy (on 55 MeV)	4.8
γ Position (mm)	15.0
γ Time (nanosecond)	0.15

Calor 2008)





Requirements for EM Calorimeters
LHC vs ILC

- Excellent EM resolution
  - H→γγ, H→>4leptons
- High rate/radiation environment
  - Radiation damage
  - Pileup noise
- Particle identification
  - ~ 10^4 rejections
- Large dynamic range
  - 10 MeV to a few TeV
- Precision EM measurement supersedes hadronic measurements

- Excellent reconstruction of hadronic final state
  - Resolving W/Z mass in hadronic decays
  - Identification of tau leptons
- Measure EM, charged and neutral hadrons in calorimeter separately
- Moderate requirements on EM energy resolution and particle identification
  - Relatively low background env

Challenges for future experiments

- High Luminosity at LHC

  L_{peak} ~ a few 10^{34}/s/cm^2, L_{int} ~3000fb^{-1} by 2030
- Radiation damage to detector and electronics

  Performance degradation for PWO in CMS ECAL Endcap

  Radiation damage to ATLAS frontend electronics
- Trigger is high rate environment

- ILC physics requires unprecedented jet energy resolution

  Approaching 20-30%$\sqrt{E}$
- New techniques are needed

  Particle Flow Calorimetry

  Dual Readout
- Significant impact on EM Calorimetry

ATLAS Calorimeter Readout Upgrade

- LAr EM calorimeter should operate well in high luminosity
- Radiation levels and physics performance requires replacement of frontend electronics
  - Designed 15 years ago for surviving 10 years of operation (L_{int} ~$1000 fb^{-1}$)
- Opportunity to apply modern technology and revise architecture:
  - trigger-less data transfer to off-detector electronics, fully digital trigger
- Several major R&D challenges

Collaboration of Arizona, SMU, Columbia, BNL plus a few other ATLAS institutes

Digitize all channels at 40MHz

Rad hard fast ADC

Fast data transfer off detector

100 Gbps for each 128 channels

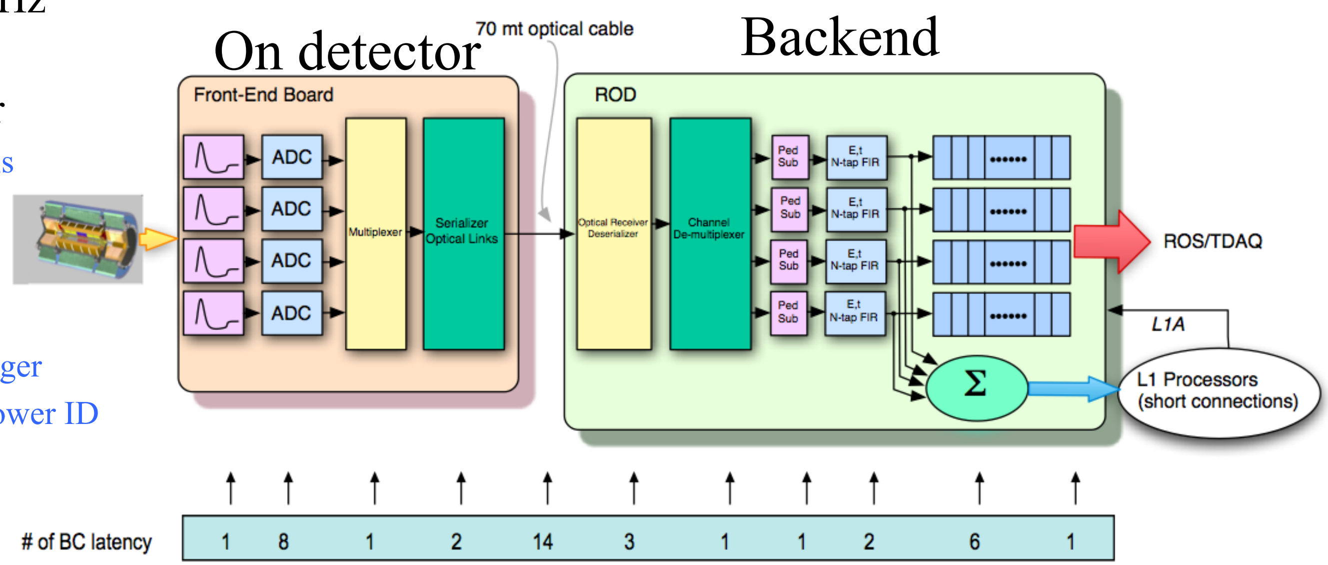
Fast rad hard optical links

Digital signal processing

E, t reconstruction

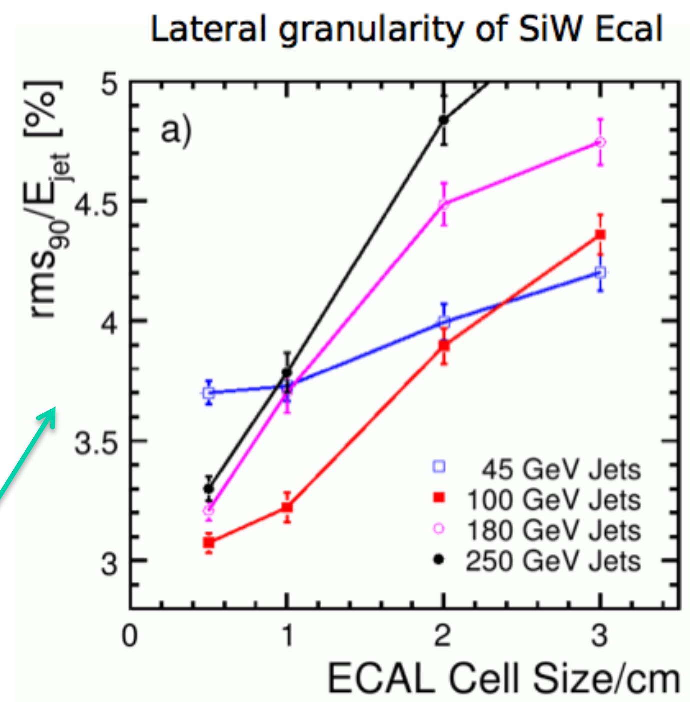
Digital trigger sums for L1 trigger

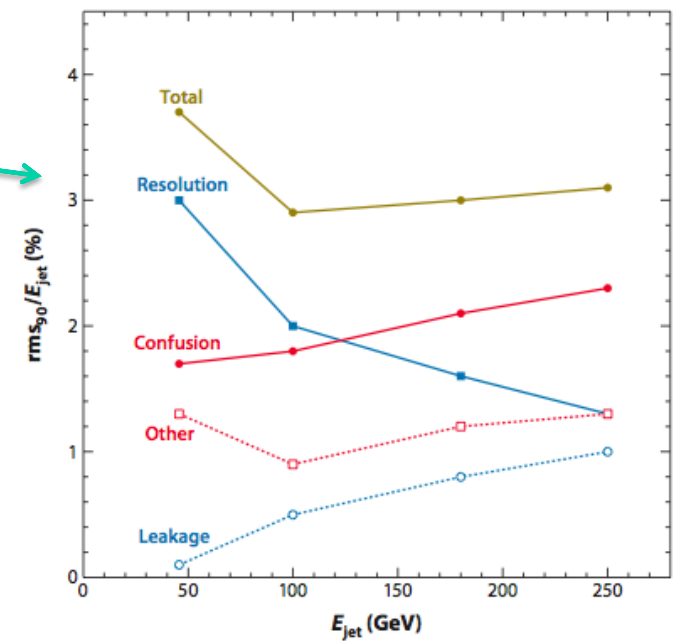
Complex algorithm for EM shower ID



Particle Flow Calorimetry for Linear Collider

- Originated from energy-flow calorimetry developed at LEP
- Measure energy of all the particles in a jet
  - Tracker for the charged particles,
  - EM calorimeter for prompt photons
  - EM and hadronic calorimeters to capture neutral hadrons
- Requires highly segmented calorimeter
  - Resolution dependence on the readout granularity
- Energy resolution ~ 3-4% demonstrated by PFAs on MC events for E=45-200GeV
- SiW is the leading choice for a compact, highly granular EM Calorimeter
  - Readout integrated on the silicon wafer ensure small Moliere radius
  - e.g., SiD: 2.5mm Pb + 1.25 mm Si readout gap

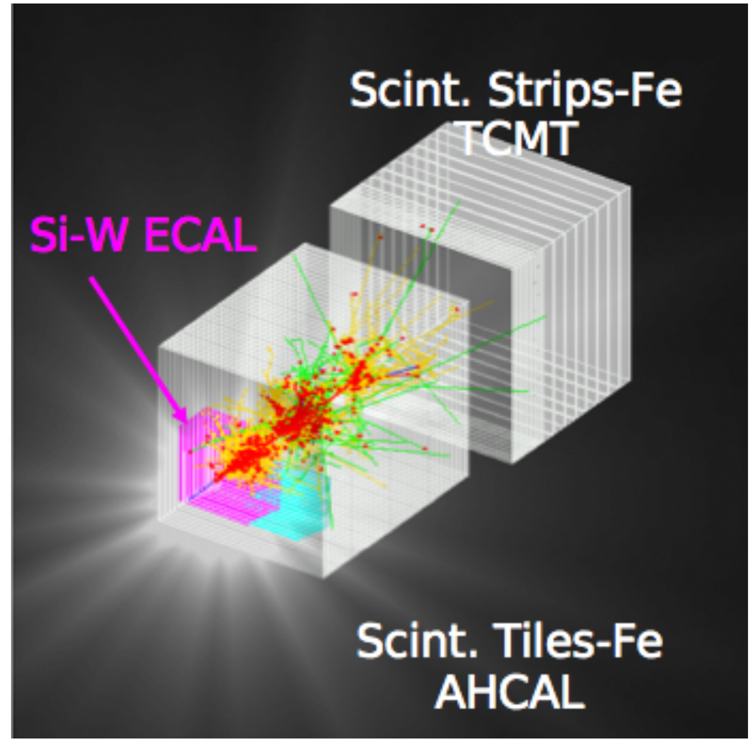


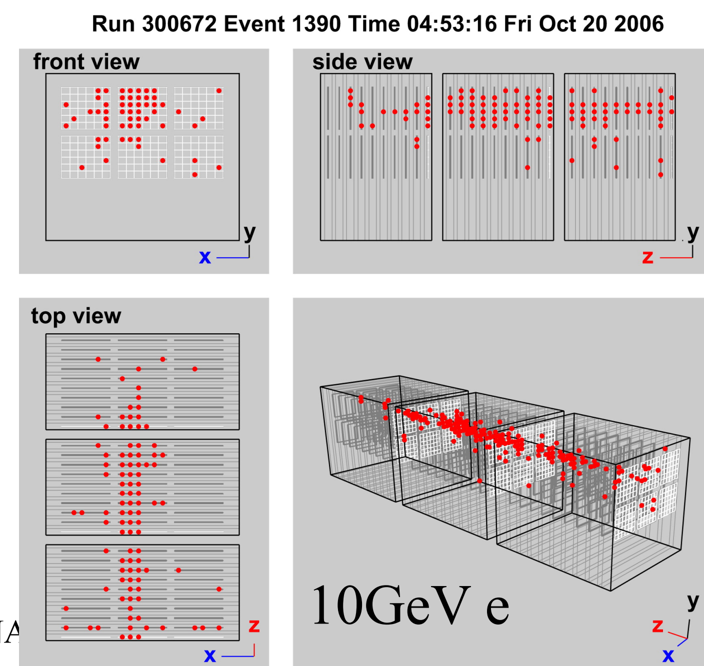


CALICE

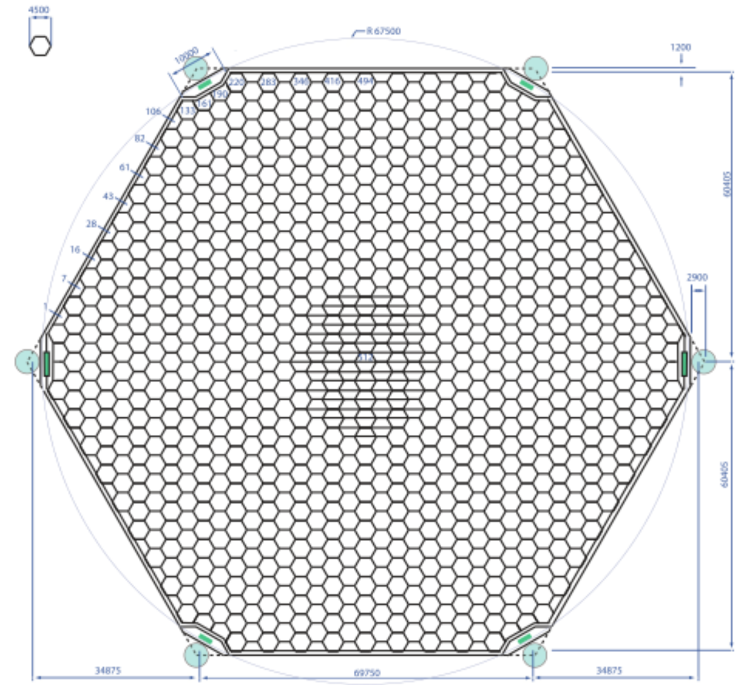
- Prototype calorimeters to establish the technology
- Collect hadronic showers data with unprecedented granularity to
  - tune clustering algorithms
  - validate existing MC models
- Leading to a highly granular calorimeter optimized for ILC
- SiW EM Calorimeter
  - 10 x 1.4 mm (0.4 X0)
  - 10 x 2.8 mm (0.8 X0)
  - 10 x 4.2 mm (1.2 X0)
  - 24 X_0 total, 1 λ_I
- Signal to Noise Ratio ~8/1
- Resolution

  $(16.6 \pm 0.1)/\mathrm{sqrt}(E) \oplus 1.1 \pm 0.1\%$





Integrated Si Readout



SiD Design Group

Oregon, SLAC, Davis, BNL

- Development of Si sensors with readout
  - Satisfying SiW EM Calorimeter requirements
- Sensor:

  6 inch wafer, 13 mm^2 pixel
- KPiX:

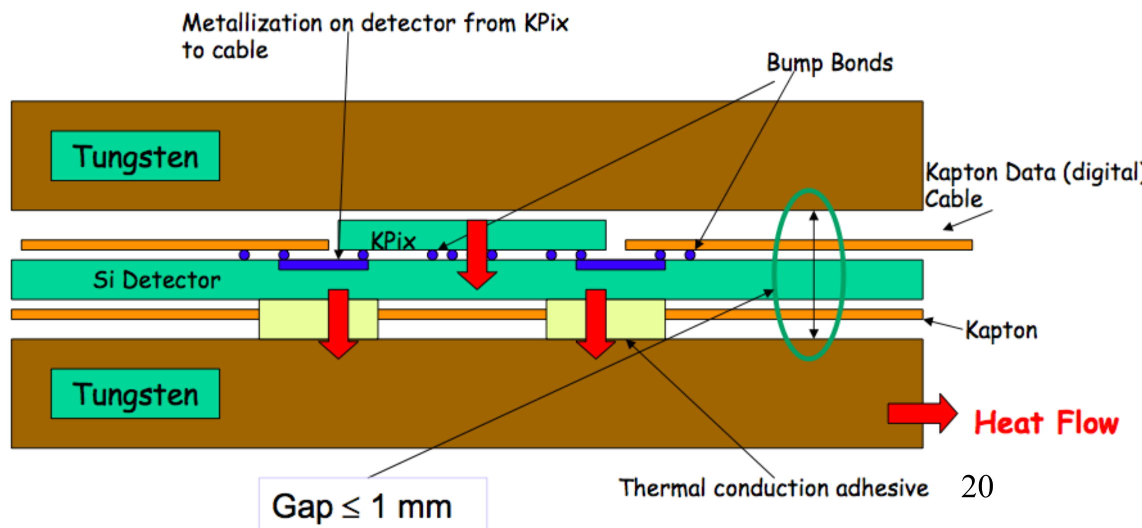
  Self-trigger charge sensitive ASIC for time and amplitude measurements
  - Buffer up to 4 events

  Readout gap: 1mm, R_M=1.3cm

  Pulsed power: 20μW/channel
  - ILC bunch trains, 200ms gap

  64 channel chip tested,

  1024 channel chip in development

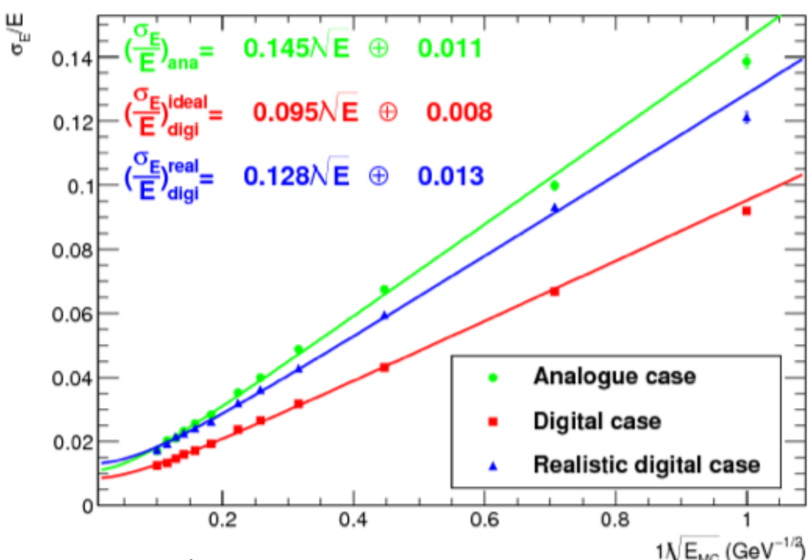


Digital EM Calorimeter with MAPS

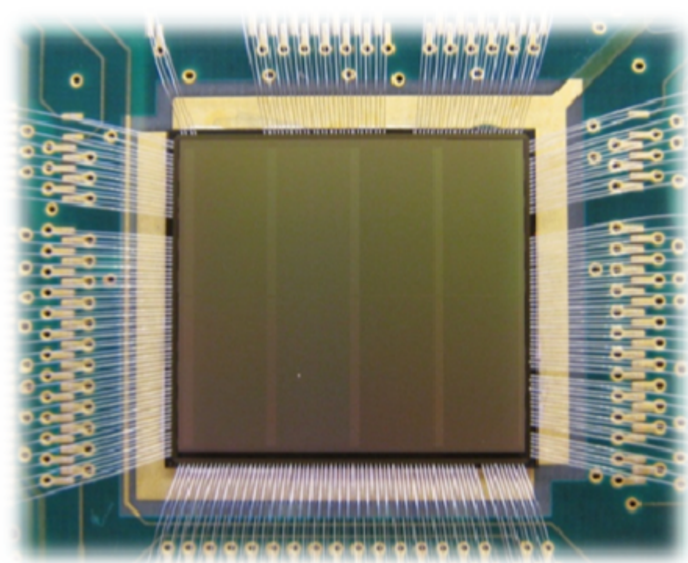
- Digital approach: Counting particles in shower
  - Ideal digital EM calo achieves better resolution (MC simulation)
- Monolithic Active Pixel Sensors

  50X50μm^2 digital readout in a single CMOS chip

  Designed to fit into Si-W ECAL in SiD. ~ 1M pixels/sensor
- Prototypes are being developed



arXiv:0901.4457v1



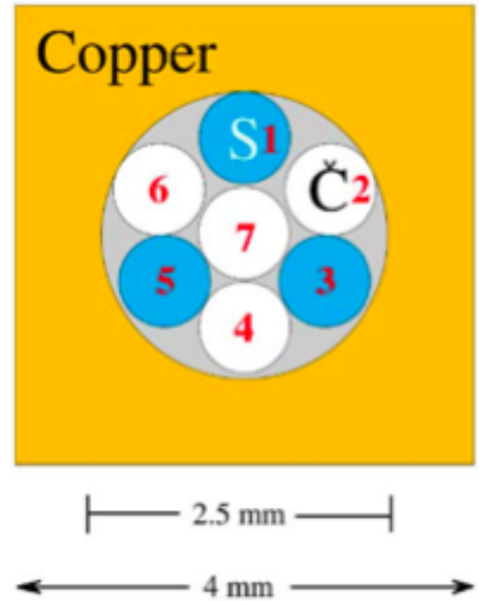
Dual Readout Calorimetry

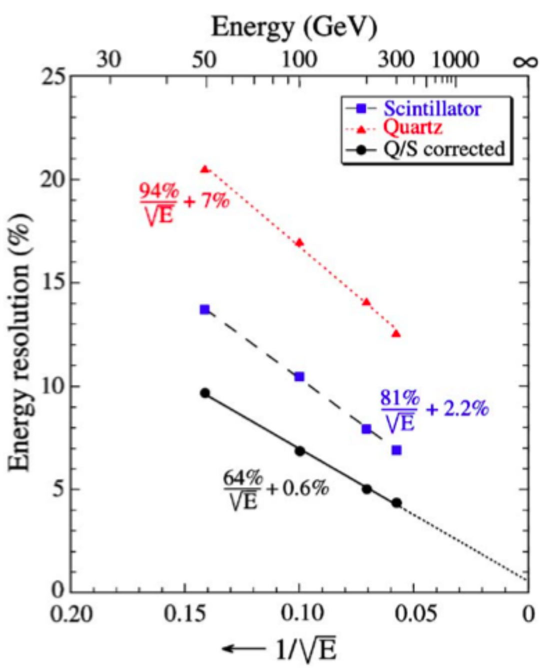
- Compensating calorimeter rely on equalizing EM and hadron responses
- Dual Readout Calorimeters measure these two dominant components of showers separately
  - Scintillation light from all charged particles
  - Cherenkov light from fast particles (EM)
  - Shower-by-shower corrections based on Scint/Cherenkov
- From Monte Carlo studies:
  - Energy resolution (0.2-0.25)/$\sqrt{E}$ (Gaussian)
  - No (small) constant term

DREAM

Texas Tech, UCSD
Iowa State, Trieste

- A fullsize test of dual readout calorimeter of Cu embedded with quartz and scintillating fibers
  - R&D started in 2002
  - Improved hadron energy resolution (2005)
- More recent tests of crystals: BGO, PWO
- BGO+fiber calorimeter proposed for "4th" ILC LOI
  - Expect jet resolution $\sigma/E \approx 29\%/\sqrt{E} \oplus 1.2\%$,





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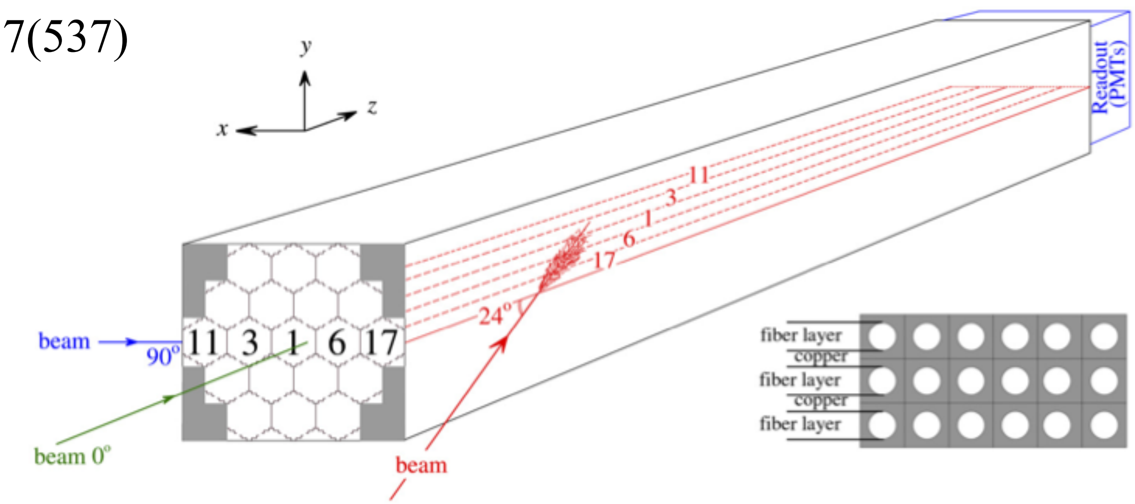
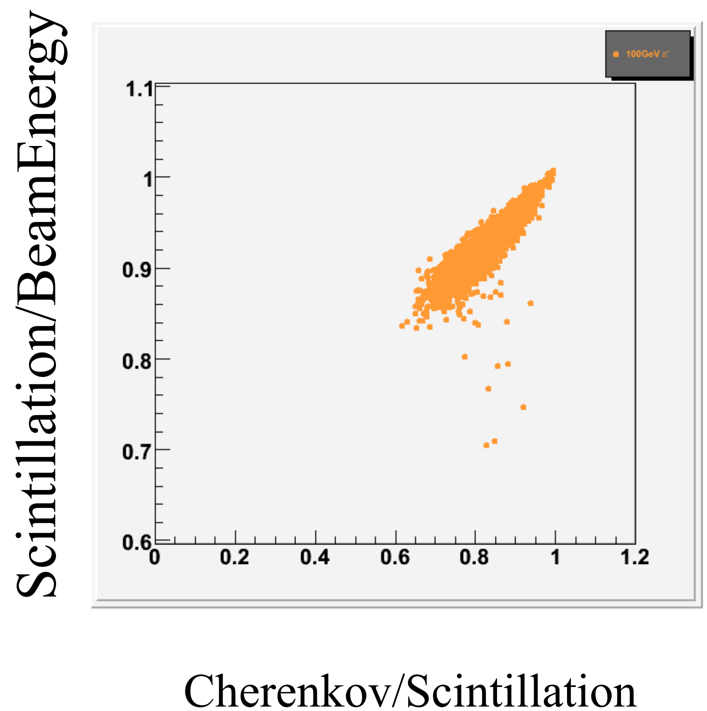


Dual Readout with Crystals (HHCAL)

- Homogeneous total absorption EM and hadron calorimeter using crystals
  - Readout both Cerenkov and scintillation light
- Aim for best resolutions for both EM and hadrons
  - ~2%/√E for electrons
  - ~15%/√E for hadrons
  - ~23%/√E for jets
- Early conceptual design stage
  - EM: 5×5×5cm^3 , Had: 10×10×10cm^3
  - Search for ideal crystals
  - Dense (λ~20cm), inexpensive (~100m^3)
  - Readout techniques: APD, SiPM…
- Workshops in CALOR 2010 and IEEE 2010



Simulation
(A.Para, Beijing 2010)

EM calorimeter for Muon Colliders?

- First thoughts on background and detector for muon collider documented in "*$\mu^+\mu^-$ COLLIDER, A FEASIBILITY STUDY*" in 1996
  - Particle flux near the interaction points were estimated
  - EM calorimeter similar to ATLAS/GEM design
  - New detector concepts are being considered now

- Concept for linear collider detector has been developed aggressively recently

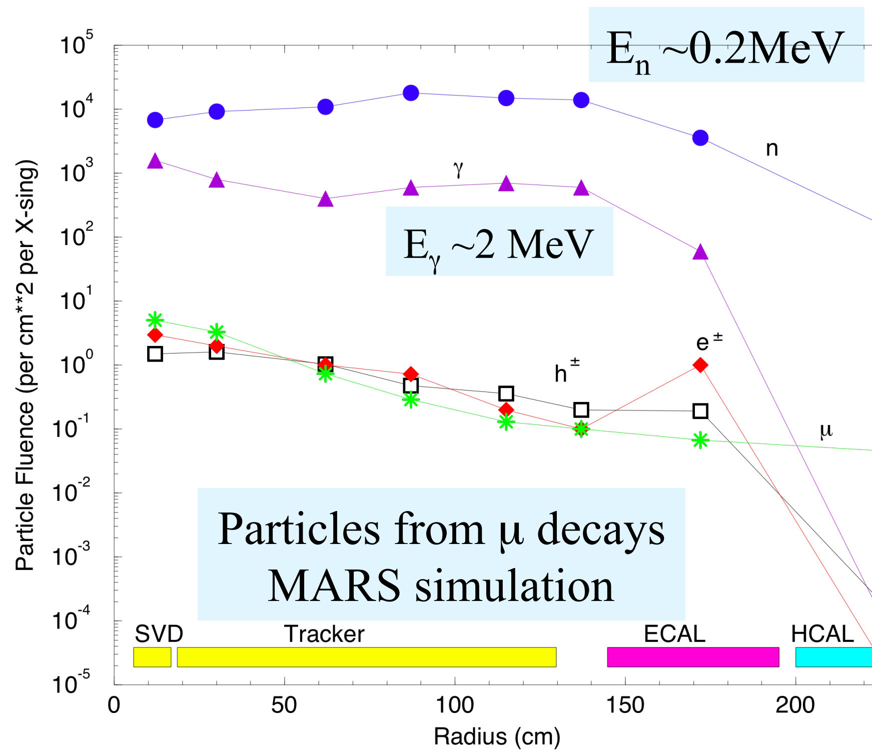
  Similar physics, but very different environment

  Additional background from muon halo and muon decays near intersection region.

  ~ 10^4 GeV soft photons/crossing

  ~ 10^5 GeV thermal neutrons/crossing

  Whether the techniques developed for ILC can be applied to Muon collider detector should be studied.



2×2TeV Muons,10^{12}/bunch

Summary

- EM Calorimeters are essential part of HEP experiments
  - A variety of technologies are available
  - Optimization for different applications
- R&D efforts are directed towards new requirements from future experiments
  - High rate/high radiation environment
  - Search for better calorimetry for ILC
    - Particle Flow Calorimetry
    - Dual Readout Calorimetry