CALORIMETRY AT HADRON COLLIDERS
Luc Poggioi, University Paris 6&7

Introduction
Framework
Requirements
Constraints
Calorimeters parameters

Calorimeters
Past: UA1, UA2
Present: CDF, D0
Future: ATLAS, CMS

Conclusions
Introduction

High energy physics signatures involve $\gamma$, $\gamma$, (\mu), jets, $P_T$

- Well covered by calorimeters

What makes calorimeters popular at colliders (large s)?

- Resolution improves as $1/E^{1/2}$
- Jets are better defined objects (track information less usable apart for b-tagging)
- Cultural aspect: track versus shower

What makes calorimeter so specific at hadron colliders?

- Discovery potential: W, Z, top
- Importance of hadron calorimeters
- Wealth of physics and difficulty of environment (background)

- Essential to extract the physics
Requirements

**e-γ measurement**
- Inclusive, top, single γ
- Resonances: $H \rightarrow γγ$, $4e$, $Z'/W' \rightarrow ee$

**hadrons, jets measurement**
- Inclusive di jet QCD
- Resonances $W \rightarrow jj$, $H \rightarrow bb$, $Z'/W' \rightarrow jj$, $t \rightarrow jj$
  
  For resonances, energy & angular resolution are crucial

**e-γ identification** ↔ **e-γ/jet-hadron separation**
- Essential against QCD backgrounds

**$p_T$ measurement**
- SUSY, $H \rightarrow ZZ \rightarrow llvv$, $H \rightarrow WW \rightarrow lv jj$, $A \rightarrow ττ$

**Trigger**
- Clean topologies allow easy trigger
- High selectivity needed (background)
Constraints

- High energy & discovery potential
- Small signals
- Wide range of E

- Good multi-objects mass resolution
- Large dynamic range for electronics
- Control of response on large E range

Large QCD backgrounds

- e-γ identification
- Good multi objects mass resolution
- Trigger selectivity
- Control of $F_T^{miss}$
Calorimetry at Hadron Colliders

Hadron collider processes are flat in $\eta$

- Inelastic $pp$ ($\sigma \sim 60$ mb) produces large multiplicities (7 charge/$\eta$ unit) up to 5

For signals, calorimeters must perform down to large $\eta$ (3) and cover up to $\eta \sim 5$

High luminosity $\Rightarrow$ pile-up

- Fast calorimeters, challenging electronics
- Radiation resistance
- Granularity

Large calorimeters needed

- Cost
- Quality control
- Calibration, monitoring

Integration constraints

- Operation in magnetic field
- Depth available
- Upstream material (tracker)
Calorimeter parameters

Overall performance

Energy resolution

\[ \sigma = a \cdot \sqrt{E} + b + c \]

- \(a\) sampling term
- \(b\) constant term
- \(c\) noise term (pile up + electronics)

Linearity

Due to large range of \(E\), the 3 terms are crucial, as well as linearity

\(e/\pi\)

Essential for linearity of hadron/jet response and jet energy resolution

Segmentation

Lateral \(\Delta \eta \times \Delta \phi\)

Longitudinal - Projectivity (trigger)

Preshower/presampler

Allows \(e/\gamma\) identification wrt hadrons-jets and particle direction measurement
Calorimetry at Hadron Colliders

**Hermiticity**
- $\eta$ coverage
- Cracks at transition regions (barrel-endcap-forward)
  - Allows measurement of genuine $E_T^{\text{miss}}$ and limitation of fake $E_T^{\text{miss}}$

**Speed**
- Allows to limit the pile up (and electronics for ionization devices) contribution to the noise term

**Radiation resistance**
- Crucial for high luminosity colliders (charged, $\eta$)

**Calibration**
- Stability in space & time
- Possibility to calibrate & monitor the response

**Read-out**
- Able to stand rates & maintain performance
The past: UA1 & UA2

Sppc

\[ p\bar{p} \rightarrow s^{1/2} \ 546 \ & 630 \ \text{GeV} \ - \text{Luminosity up to} \ 3\times10^{30} \text{cm}^{-2}\text{s}^{-1} \ - \text{bunch-crossing} \sim 4 \mu\text{s} \]

\[ \rightarrow \text{no pile-up/radiation/read-out problems} \]

\[ \rightarrow \text{Physics include} \ W, \ Z \ \text{observation \& measurement (cross-sections, RR), searches for new particles (top, SUSY), and QCD studies} \]

Lego Plot \[ W \rightarrow e \nu \]

\[ W, Z \rightarrow q\bar{q} \quad W \ & Z \ \text{are not resolved} \]

Technologies

Use well known techniques: sampling calorimeter, with scintillators read out by WLS \ & photo-tubes \rightarrow \text{fast, cheap, easy to build}
UA1

Full coverage (em & had) down to 0.2° ($\eta \sim 6.3$)

Use absorber Pb for em & Fe for HAD

**em barrel:** gondolas (non-projective)

- 1.2mm Pb/1.5 mm scint
- 4 depths compartments
- each read-out by up & down PMT

$\sigma/E \sim 15%/E^{1/2}$ $\sigma_x \sim 6$ cm/$F^{1/2}$

(in endcap, gas position detector after $11X_0$ $\rightarrow \sigma_{x,y} \sim 2$mm

Scintillator aging $\rightarrow \sigma/E$ moved from 15% to 21% in 2 years

**had barrel:** C

- 50mm Fe/10mm scint
- 2 depths compartments

$\sigma/E \sim 80%/F^{1/2}$

**em response monitored by $^{60}$Co source, laser, testbeam, minimum-bias**

**em scale uncertainty $\sim 3\%$ (cell cell non uniformities)**
Calorimetry at Hadron Colliders

UA2

Central calorimeter (projective orange slices)

Forward (up to $\eta \leq 3$)

Parameters
- 3 segments (1em, 2 had)
- 4 5 $\lambda$ deep
- segment $10^0 \times 15^0$

- Scintillator r/o by WLS plates (less dead space)
- Careful correction of $\lambda_{\text{att}}$ in WLS $\rightarrow$ uniformity $\sim 1\%$
- $\sigma/E \sim 14\%/F^{1/2} e$
- $\sigma/E \sim E^{1/4}$ jet (depth)

- Electron ID uses preshower (no B field)

- Careful calibration (test beam, source, laser) and understanding of low $E\pi$ response
The present: CDF & D0

Tevatron

$pp \ s^{1/2} \ 1.8 \ TeV$ Luminosity up to $10^{31}\ cm^2 s^{-1}$ bunch crossing 3.5 $\mu s$ (Run I)

Upgrade (main injector) in 1999 up to $10^{32}\ cm^2 s^{-1}$ bunch crossing 396 to 132 ns (Run II)

$\sim 1$ minimum-bias/crossing

Physics include top discovery and study, electroweak ($W$ mass, $WZ/Z\gamma$ couplings), QCD (high $E_T$ jets), Higgs (in $bb$) and SUSY searches

CDF

$tt \rightarrow WbWb$
$\rightarrow ev jjjj$
jets (2,3) $W$
jets (1,4) b-tagged in SVX

LEDGO view
Technologies

2 directions to build big calorimeters which measure well e, jets and $E_T^{\text{miss}}$

- Choose well proven technique, rather cheap and uniform for em and had

- Sampling calorimeter with scintillator CDF

- Give emphasis to had reponse, uniformity and homogeneity

- Choose ionization calorimetry (LAr) with Uranium to achieve compensation D0

CDF
Calorimetry at Hadron Colliders

**Basics**
- Full coverage up to 4.2
- 3 stations central, end plug & forward
- Organized in em + had section projective towers \((0 \ 1 \times 15^0/5^0)\)
- Central uses scintillator + shower max in em
- Forward & plug uses proportional tubes (gas)

**Performance**
- Scint response monitored by moving \(^{137}\)Cs source
- \(\sigma/E\) - 2% @ 50 GeV central
  - 4% in plug for e
- \(\sigma/F\) - 11% @ 50 GeV central
  - 20% in plug for \(\pi\)

**Limitations**
- Poor resolution in plug + forward (+ Texas towers)
- Slow response of gas
- Hot spots coming from Č light produced in light guides
CDF upgrade

Replace old gas plug + forward by a new scintillator plug $(1.1 < \eta < 3.5)$

Principle

Scintillator tiles r/o by WLS fibers spliced to clear fibers -> better hermiticity
- good segmentation ($0.1 \times 7.5^0$ in $\eta \times \phi$)
- $e$ + had section
- Position detector with scint. strips in $e$ + had section
- Projective towers

Now uniform performance (e and jets) on the full $\eta$ range
Energy resolution

Plug Upgrade Test Beam Preliminary

- $\sigma(E)/E = 16\% \sqrt{E}$ for electrons in ECA
- $\sigma(E)/E = 15.5\% \sqrt{F}$ for Plug Pre-shower added to ECA

END Plug Upgrade

Relative Energy Resolution

- $\sigma(E)/E = 17\% \sqrt{F}$ for electrons in ECA
- $\sigma(E)/E = 8\% \sqrt{F}$ for hadrons in ECA

Poor had resolution & non linearity reflects non compensation

Uniformity

- EM Calorimeter Uniformity Scan (50 GeV)
- HAD Calorimeter Uniformity Scan (50 GeV)

em transverse Unif. ~1.6%

had Unif. ~2.3%
Position resolution

\[ \sigma_{x,y} \sim 2 \text{mm} > 50 \text{ GeV} \]

SMD

6mm strips

Tower to tower response

good QA & QC allows
good uniformity (1.8%
wrt Cs source)

Absolute energy scale

\( \text{em scale given by } Z \rightarrow ee, \quad F/p \)

matching

had scale given by \( Z+\text{jet} \) & \( \gamma+\text{jet} \) events \( p_T \) balance
Full liquid Argon calorimeter in 3 cryostats

3 regions

- em \((U)\)
- Fine had \((U)\)
- Coarse had \((Fe/Cu)\)

Depth

- \(7.9 \lambda\)

~ 5000 semi projective towers \(0.1 \times 0.1 \, \text{ln} \, \Delta \eta \times \Delta \phi\)
in em shower max \(0.05 \times 0.05\)

\(\eta\) coverage

- 4.1 em
- 5.2 had

depth

- 4 em
- 1 to 4 had

geometry

- gap 2.3 mm
- 2, 6 mm U
Noise and dynamic range

- MIP signal clearly seen above noise

- Full dynamic range 15 bit (400 GFV)

- 10 (70) MeV for em (had) section (electronics + U)

Energy resolution

\[ \frac{\sigma}{E} = \frac{16\%}{\sqrt{E}} \oplus 0.3\% \]

\[ \frac{\sigma}{E} = \frac{41\%}{\sqrt{E}} \oplus 3\% \]

Position resolution (using shower max)

\( \sim 1\text{mm} > 50\text{ GeV e} \)

\[ \frac{e}{\pi} \text{ ratio} \]

- 1.1 @ 10 GeV
- 1.04 @ 150 GeV
**Correction for transition regions**

Dedicated procedure allows to correct for energy lost in modules walls & cryostats

**Barrel/endcap transition**

- Typical of liquid calorimeters
- Bad region $0.8 < |\eta| < 1.4$
- Use dedicated **massless gaps** + ICD
- ICD is made of scintillator tiles $0.1 \times 0.1 \text{ in } \Delta \eta \times \Delta \phi$
- R/O by WLS fibers + phototubes

![Graph showing event distribution with MG and ICD](image)

- CC+EC+ICD+MG
- CC+EC only

100 GeV.e

$\eta = 1.25$

Full recovery of response
Calorimeter read out upgrade

For Run II, old signal peaking time of 2.2 µs too long
- new shaping time @ 400 ns
- SCA (analog pipeline r/c) to reduce dead time (0% @ 10kHz)
- New preamplifiers + low noise drivers to reduce electronics noise
- Expect same noise levels as for Run I

Calibration

- For e, energy scale given by J/ψ, π⁰, Z
- The jet energy scale is essential for top mass & high E_T jets

For jets, dedicated procedure to correct for lateral leakage, 0-suppression of asymmetric pedestals, and underlying event
The future: ATLAS & CMS

LHC

\[ pp^{1/2} \ 14 \text{ TeV} \]

Luminosity from low regime \(10^{33}\text{cm}^2\text{s}^{-1}\) (2005) up to high regime \(10^{34}\text{cm}^{-2}\text{s}^{-1}\) (2008) - bunch crossing 25 ns

On average 23 minimum bias/crossing

Constraints on the calorimeters

\[ \text{Dose (Gy/yr)} \]

Doses

20Gy/yr

\(10^{12}\text{n/cm}^2\)

In worst regions for front-end

- Radiation resistance (detector & electronics)
- Time response of the calorimeter
- Challenging front-end & read-out
Constraints from the physics

- Powerful electron/photon ID \( \sigma_{\text{jet}} = 10^{-5} \) (10 \(^3\) @ SppC)
- Extremely precise electromagnetic calorimetry (H \( \rightarrow \gamma\gamma\), \( m_H \approx 100 \text{ GeV} \))
  both for sampling & constant term (also \( Z' \rightarrow ee\), \( m_{Z'} \approx 1 \text{ TeV} \))
- Very precise hadronic calorimetry for finding jets down to \( \eta \sim 5 \)
  (Heavy Higgs production via WW/ZZ fusion), and measuring them (top, \( Z'\), high \( E_T \) QCD)
- Precise and unbiased \( E_T^{\text{miss}} \) measurement (SUSY, Higgs

Technologies

End 80's-early 90's a lot of R&D went on to match LHC calorimeters requirements

Ionization liquids

- Make them faster (dopants, accordion), more hermetic plates // incoming particles (accordion), no cryogenics
  (warm liquids), compensating (warm liquids)

Crystals

- Make them radiation hard & fast (PbWO\(_4\))

Scintillators

- Make them more rad hard, more hermetic \( \rightarrow \) use fibers as active medium // incoming particles (SPACAI), fibers as WLS
  (shashlik)
WALIC

Following developments for UA1 upgrade, warm liquids U(Fe)/TMP, should provide

- hermiticity (no cryostats)
- better had energy resolution thanks to compensation by acting on Birk's constant

Problems

- TMP is a solvent → use clean & specific materials
- TMP needs high level of purity
- TMP not enough rad-hard
- Flammable

In addition the need for compensating calorimeters for LHC appeared less critical (possibility to compensate offline à la H1 with highly segmented calorimeters

Electrostatic transformer (EST) allows to minimize capacitance (hence noise) of large had cells
SPACAL
Aiming at fast compensating calorimeters using Pb/scintillator implies low sampling ratio (4:1)
To improve em resolution & hermiticity →
Use scintillating fibers with WLS integrated // in coming particles.

Energy resolution
σ/E = 13%/E^{1/2} + 1%(local) with 1mm fibers

Energy resolution
Down to 9.5%/E^{1/2} with 0.5mm fibers

For π, σ/E = 30%/E^{1/2} + 1%
(after λ_{att} correction in fibers)

e/π separation
good due to projective structure (short & long fibers)
Problems

- Lateral uniformity not good enough
- Constant term in em resolution ~ 2%
- Since no WLS, light collected on big surfaces
- Need to use big surface light detectors
- Again, compensation has appeared less crucial

But technique used in H1, and KLOE&CHORUS (fibers + incoming particles)

Shashlik

- Use traditional Pb/scintillator plates (2mm/4mm) read-out by WLS fibers running // incoming particles
- Hermiticity, and small light detector surface, but loss in light yield

Results

\[ \alpha/E = 8.7\% + E^{1/2} + 0.5\% \]

Uniformity under control

Radiation effects induce constant term of 1.5\%
Emphasis on
- ultimate e/γ measurement
- accurate μ measurement

3 elements
- em
- had
- forward

em & had are in 4T field

L. Poggioli  CALOR97, Tucson, 10/11/97
Electromagnetic calorimeter ECAL

Basics

- Use PbWO_4 projective crystals
- \( \eta \) coverage up to 2 \( \phi \)
- Granularity \((0.0145)^2\)
- No depth segmentation

Choice of PbWO_4

- Allows to get the ultimate em energy resolution (homogeneous calorimeter)
- Fast scintillation (85% of light after 25ns)
  - Dense \((X_0=0.9\text{cm} \rho_M=2\text{cm})\)

Potential issues

- Radiation hardness
- Growing of about 100k crystals
- Read out in 4T field
- Monitoring light yield (e.g., \( T^0 \) coeff \( \sim 4\%/^{0}\text{C} \))
Read-out

definite need for APD

Energy resolution

Latest test beam results on 15 crystals
- sampling term $4.3\% \pm 0.35\%$
- constant term $0.40\% + 0.08\%$

The sampling term is limited by photon statistics
Light yield

- \(70 \, \gamma/\text{MeV}\)
- \(Q\)-efficiency \(\sim 70\%\)
- APD/Xtal surface ratio \(\sim 1/25\)

\(~1500\, \text{pe}/\text{GeV}\)

R/O Xtals with
2 APDs will bring sampling term \(\sim 3\%/E^{1/2}\)

Radiation hardness

Big progress in stoichiometry & doping (Nb, La..)
and in annealing

radiation hardness is under control

Uniformity in depth

Shower developing deep can compensate for rear leakage due to attenuation in crystals

Uniform way to make longitudinal response uniform by grinding 1 crystal face

Grinding seems to be crystal independent
Calorimetry at Hadron Colliders

**Calibration**

Uses 2 lasers
- 523nm near peak emission
- 670nm

Correlation between beam & laser is constant for all crystals
T monitored to ± 0.1°C

→ Allows to correct for changes in response due to radiation

**Mechanics**

Use alveolae 2x6

**Preshower**

- Used for γ direction (η) in EC
- Also used in barrel @ high luminosity

Pb
Si
Calorimetry at Hadron Colliders

Read-out

- Light to light system
  - Use high-speed optical link (800 Mbits/s)
  - Noise ~ 25 MeV/Xtal

Physics performance

- H → γγ signal in 5x5 crystals
  - Only non-converted γ

Using tracker & gold calorimeter granularity

- 87% converted γ may be recovered w/o performance loss
Hadron calorimeter HCAL

Basics
- coverage up to $\eta = 3$
- Use scintillating tiles
- Fine granularity 0.09$^2$
- Sits in 4T field with limited depth
  - use Cu/Fe absorber
- Scintillator outside coil
  - as tail catcher
Structure of active medium

Scintillating tiles with embedded WLS fibers (cf. SDC & CDF plug upgrade)
Read-out with Hybrid PhotoDiodes (HPD) // B field
Radiation & B-field effect on scintillator under control

Performance

- ECAL + HCAL gives $\frac{\sigma}{E} = \frac{65\%}{\sqrt{E}} \pm 5\%$

- Not too critical for $H \rightarrow WW \rightarrow 4\nu$, since jets have high $P_T$ for Heavy Higgs
- Not too critical for $H \rightarrow tb$, since ISR & FSR and hadronization spoils resolution
- May be critical for high $E_T$ jets & deviation to QCD
Forward calorimeter VFCAL

**Overall structure**
- Complete coverage up to $\eta \approx 5$
- Absorber Cu or Fe
- Active medium: quartz fiber/beam
- R/O with light air guides & PMT

**Hermetic structure, fine granularity**

**Principle**
Light comes from $\pi^0$ (46° angle)
- Only sensitive to electromagnetic (em) part of shower
- Insensitive to n, slow hadrons
- Narrower, faster showers

**Results**
- $\sigma/E = 12\%$ @ 1TeV (logarithmic dependence)
- Probably good enough for jet tags & $E_T$
Calorimetry at Hadron Colliders

ATLAS

Inputs
- calorimeter out side central coil
- μ toroid system
- no constrain on calorimeter

Choices
- Full coverage up to η=5
- Liquid argon for em & end cap+forward homogeneity, uniformity, performance
- Central had made of scintillating tiles, well known technique & low cost
**Em calorimeter**

**Accordion**
- Use Pb/LAr sampling structure with plates // incoming particles
- Hermiticity & signals path length minimal
- Use 3 depths compartments with 1st one highly segmented in \( \eta \) (0.003)
- \( \gamma \)/isolated \( \pi^0 \) rejection ~ 3 (for \( H \rightarrow \gamma \gamma \))

**Achieving speed**
- Signals (\( t_D \sim 600 \) ns for gap ~ 7.5mm) are bi-polar shaped and signal peak = energy
- The equivalent time response is ~ 2 BC
Optimizing the response wrt dead material

- Integrated coil into cryostat
- Presampler in front of calorimeter
- In transition region, use scintillator (cf. D0)

![Diagram of calorimeter system]

- Response recovery with scintillator @ $\eta = 1.5$
- Benefit of presampler for $\eta = 1.3$
Prototype performance

em endcap with electrodes (kaptons)
Fully projective structure

Uniformity of response on big area overall constant term ~ 0.7%

\[ \sigma_\eta \sim 40\text{mrad}/E^{1/2} \] does not spoil H $\rightarrow \gamma\gamma$ mass resolution

\[ \frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} + \frac{0.3}{E} + 0.3\% \]
Electronics
Dedicated charge injection calibration
calibration to $\rightarrow 0.25\%$

Noise in em cluster is trade off between electronics & pile-up noise $\rightarrow$ optimizing peaking time

Warm preamps + shapers + analog pipelines (SCA) located at feedthrough exit

Overall dynamic range 16 bits
5 samples/event
had scintillating tile calorimeter $|\eta| < 1.7$

**Principle**

- Fe/Sc tiles oriented $//\,$ particles
- tiles read-out by WLS fibers at both ends

hermetic, cheap, easy to build

Non uniformities across tiles recovered by masking
Liquid argon had end-cap

Recessing the endcaps to access the central detector flexible cryolines

Principle

Cu/Fe absorber gap 1.8 mm basic electrode is EST smaller voltage applied

- coverage down to $h - 3$
- granularity 0 1x0 1 2 depth samplings
- readout is made by cold GaAs preamplifiers
Calorimetry at Hadron Colliders

Calibration

- using Cs source (Cf. CDF) allows tile response equalization to ~2%
- In addition laser system to monitor PMTs response (designed for standing stray fields)

Test beam results (em+had)

Weighting à la H1 gives $38%/E^{1/2} + 1.6%$
Calorimetry at Hadron Colliders

Results

Prototype during construction (notches for signal cables)

Electron energy resolution
1.7 GeV noise

Simulated jet response for cone of 0.4,
\( \sigma/E \sim 80%/E^{1/2} + 2.5\%

Resolutions of HEC (pad cluster)

Jets at \( \eta = 2.45 \)

\[
\begin{array}{lll}
R &=& 0.4 \\
P1 & & 81.82 \pm 5.68 \\
P2 & & 2.49 \pm 0.24 \\
\hline
R &=& 0.7 \\
P1 & & 57.29 \pm 5.07 \\
P2 & & 2.06 \pm 0.24 \\
\hline
R &=& 0.8 \\
P1 & & 54.93 \pm 3.34 \\
P2 & & 2.064 \pm 0.1494
\end{array}
\]
Forward calorimeter FCAL

Integrated in end-cap cryostat → radiation hardness more critical, but better $\eta$ coverage, up to 4.9

**Principle**

- To limit ion-build up, use small LAr gaps (~250$\mu$m)
- 3 depths compartments with Cu&W as absorber → compact showers
- granularity 0.2x0.2
- warm electronics

Forward jet tag

Maquette

Good tagging efficiency up to $\eta \sim 4.7$
Conclusions

Calorimeters at hadron colliders play an essential role for electron & photon identification and measurement, jets and $E_T^{\text{miss}}$ measurement, and trigger.

The advent of new machines (higher energy and higher luminosity) has made calorimeters even more essential for extracting the physics.

The last decade has seen a huge progress in calorimetry technique - owing to Tevatron upgrade, SSC and LHC -, with brand new approach or by adapting existing techniques.

The new machines have also demonstrated the importance to design the calorimeters as a part of the whole experiment, and the growing importance of hadron calorimetry.