Particle Flow Algorithm and calorimeters design

Jean-Claude BRIENT
Laboratoire Leprince-Ringuet
CNRS-IN2P3 / Ecole polytechnique
**Start from physics @ILC,CLIC, Not from a technology ...**

**e+e- interaction 0.09 – 1.0 TeV**

The main interesting processes *(out of possible SUSY)*

<table>
<thead>
<tr>
<th>Multi bosons</th>
<th>Multifermions + Boson(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH</td>
<td>$e^+e^- H$, $e^+e^- Z$</td>
</tr>
<tr>
<td>WW</td>
<td>$\nu\nu H$, $\nu\nu Z$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$ttH$</td>
</tr>
<tr>
<td>ZHH</td>
<td>$e \nu W$</td>
</tr>
<tr>
<td>ZZZ</td>
<td>$\nu\nu WW$, $\nu\nu ZZ$</td>
</tr>
<tr>
<td>ZWW</td>
<td>$tt\text{bar in } b\bar{b} \text{bar } WW$</td>
</tr>
</tbody>
</table>

Etc … but also the taus decays reconstruction for SUSY, CP… etc
Start from physics @ ILC, CLIC, Not from a technology ...

e+e- interaction 0.09 – 1.0 TeV
The main interesting processes (out of possible SUSY)

Multi bosons
ZH
WW
ZZ
ZHH
ZZZ
ZWW

Multifermions + Boson(s)
e^+e^- H , e^+e^- Z
\nu\nu H , \nu\nu Z
ttH
e \nu W
\nu\nu WW, \nu\nu ZZ
ttbar in b\bar{b}ar WW

Etc … but also the taus decays reconstruction for SUSY, CP… etc

Need Boson Tagging

Best use of the luminosity … use the decays in jets

<table>
<thead>
<tr>
<th>Z to</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>\ell^+ \ell^-</td>
<td>10%</td>
</tr>
<tr>
<td>qq (jets)</td>
<td>70%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W to</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>\ell^\pm \nu</td>
<td>32%</td>
</tr>
<tr>
<td>qq' (jets)</td>
<td>68%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>H(120,SM) to</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>\ell^+ \ell^-</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>qq(jets), WW, ZZ</td>
<td>&gt;85%</td>
</tr>
</tbody>
</table>
Is it possible at ILC, CLIC?

Possible because S/B in jets final state is good enough on $e^+e^-$ machine.
Jet energy range of interest

Distribution of the jets energy
For some physics processes
\[\sqrt{s} = 1 \text{ TeV}\]
\[\nu \nu H (2\text{jets})\]
\[t \bar{t}\bar{t}\]
\[W^- W^+\]

\[\sqrt{s} = 0.5 \text{ TeV}\]
\[Z H(120)\]

But which physics needs a good Jet energy resolution for this process?

qqbar at 1 TeV

Needs to be good up to 250-300GeV
How Much Good?

Tagging improves as long as we have \( \sigma_{(dijet mass)} < \Gamma_{boson}^{tot} \)

⇒ jet energy resolution \( \Delta E \approx 30\% \sqrt{E} \)

Dijet masses in WW and ZZ events

Dilution factor vs cut:
integrated luminosity equivalent

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
In our detectors, the charged tracks are better measured than photon(s) which are themselves better measured than neutral hadron(s)

Resolution on the charged track(s) \( \Delta p/p \sim 10^{-5} \)
Resolution on the photon(s) \( \Delta E/E \sim 12\% \)
Resolution on the \( h^0 \) \( \Delta E/E \sim 45\% \)

\[
E_{\text{jet}} = E_{\text{charged tracks}} + E_\gamma + E_{h^0}
\]

Fraction:
- Charged tracks: 65\%
- Photon: 26\%
- Neutral hadrons: 9\%

\[
\sigma^2_{\text{jet}} = \sigma^2_{\text{ch.}} + \sigma^2_{\gamma} + \sigma^2_{h^0}
\]
gives about \((0.14)^2 E_{\text{jet}}\)

With a perfect detector, no confusion between species and individual reconstruction.
The « Particle Flow Algorithm » - PFA

In our detectors, the charged tracks are better measured than photon(s) which are themselves better measured than neutral hadron(s)

| Resolution on the charged track(s) | $\Delta p/p \sim q q \ 10^{-5}$ |
| Resolution on the photon(s)       | $\Delta E/E \sim 12\%$ |
| Resolution on the $h^0$            | $\Delta E/E \sim 45\%$ |

$$E_{jet} = E_{charged \ tracks} + E_\gamma + E_{h^0}$$

Resolution fraction:
- Charged tracks: 65%
- Photon(s): 26%
- $h^0$: 9%

With a perfect detector, no confusion between species and individual reconstruction

$$\sigma^2_{jet} = \sigma^2_{ch.} + \sigma^2_\gamma + \sigma^2_{h^0}$$
gives about $(0.14)^2 E_{jet}$

Energy threshold to be rec. (depends on species)

Loss of particles (not reconstructed)

Mixing between particles in the calorimeter

Real life and real detector

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
PFA is NOT Energy Flow!!

The goal: Reconstruct all particles in the event

PFA is well suited to have the best resolution on jets, and it is true as long as it is uncorrelated with particle species,........ Shower separation based ONLY on topology!!

This is NOT Energy flow, where balance of energy with tracker momentum is made to extract neutral from shower with charged hadrons.

Tracker info.

Energy Flow

Use balance of energy - momentum

PFA

Use geometrical separation

Pavia CALOR08 – J.-C.Brient (LLR CNRS/Ecole polytechnique)
Is it possible?

\[ e^+e^- \rightarrow W^+W^- \text{at } \sqrt{s} = 800 \text{ GeV} \]

Display from the true MC informations

With \( K^0 \)
Is it possible?

\[ e^+e^- \rightarrow W^+W^- \text{ at } \sqrt{s} = 800 \text{ GeV} \]

Display from the true MC informations

Display of the reconstructed event

Reconstruction

Charged pads

photons

Neutral hadron ECAL

With K^0
H1 reach cst=5%

ATLAS expected

cst=3% (Barrel only)

For the calorimetric approach
cst is the constant term

H1

Goal for e+e- physics below 1 TeV

$\Delta E = 30\% \sqrt{E} + 0.5$ GeV

PFA-GLD (ECAL+HCAL) 2x2cm

A. Miyamoto, S. Uozumi (KEK)
PANDORA-LDC 1x1 x30 ECAL + 40x3x3 HCAL

Mark Thomson (Cambridge)

ATLAS

ALEPH

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
on $e^+e^-$ interaction: $WW$, $ZZ$ production

FAST simulation (but taking into account pairing, Neutrinos, fiducial volume, effic. (E) per species, etc...)

Full simulation GEANT4 with PFA reconstruction
on e+e- interaction: \( \tau^\pm \) as a polarisation analyser

\[ e^+ e^- \rightarrow Z H \rightarrow Z \tau^+ \tau^- \]

CP violation, Higgs sector

\[ Z \rightarrow \mu \mu \]

\[ \text{qq et } H \rightarrow \tau^+ \tau^- \rightarrow \rho \nu \pi \nu \]

\[ \text{Dist.th. with Beamst.} \]

\[ \delta \varphi \sim \pi/(2\sqrt{N}) \]

A. Rougé

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
on e+e- interaction: $\tau^\pm$ as a polarisation analyser

$e^+ e^- \rightarrow ZH \rightarrow Z \tau^+ \tau^-$

CP violation, Higgs sector

$Z \rightarrow \mu \mu$, $qq \text{ et } H \rightarrow \tau^+ \tau^- \rightarrow \rho \nu \pi \nu$

Needs an ECAL which disentangles $\pi, \rho, a_1$ in the $\tau$ decays

$\delta \varphi \sim \pi/(2\sqrt{N})$

A.Rougé

Pavia CALOR08 – J.-C.Brient (LLR CNRS/Ecole polytechnique)
on e+e- interaction: $\tau^\pm$ as a polarisation analyser

$e^+ e^- \rightarrow ZH \rightarrow Z \tau^+ \tau^-$

CP violation, Higgs sector

$Z \rightarrow \mu\mu$, $q\bar{q}$ et $H \rightarrow \tau^+ \tau^- \rightarrow \rho \nu \pi \nu$

Needs an ECAL which disentangle $\pi, \rho, a_1$ in the $\tau$ decays

$\delta \phi \sim \pi/(2 \sqrt{N})$

A. Rougé

Full Simulation GEANT4 & Reconstruction with PFA

$\tau \rightarrow \pi \nu, \rho \nu$

<table>
<thead>
<tr>
<th></th>
<th>Jet mass $&lt; 0.2$</th>
<th>Jet mass in $0.2-2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \pi \nu$</td>
<td>82%</td>
<td>17%</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho \nu$</td>
<td>2%</td>
<td>90%</td>
</tr>
</tbody>
</table>

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
How the PFA performances depend on the hadronic shower model?

Related to shower size

**Prediction on shower size from the hadronic shower simulator**

- **HCAL** based on RPC
- **π⁻ 10 GeV**

G. Mavromanolakis (Cambridge Univ.)

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
M. Thomson (Cambridge Univ.)

| (PandoraPFAv02 +trackCheater) | $E_{\text{JET}}$ | $\sigma_{E}/E = \alpha/\sqrt{E_{jj}}$ $|\cos\theta|<0.7$ |
|-------------------------------|-----------------|------------------------------------------------|
| LDC00Sc QGSP_BERT             | 45 GeV          | 22.6 %                                           |
| LDC00Sc LHEP                  | 45 GeV          | 23.2 %                                           |
| LDC00Sc QGSP_BERT             | 100 GeV         | 29.3 %                                           |
| LDC00Sc LHEP                  | 100 GeV         | 30.2 %                                           |

It is not an answer but a first indication

.....

Built prototypes with the technology useable for PFA detector and goes to test beam to constraint the hadronic shower models

*(However, do not hope to have one single hadronic shower list working nicely for everything)*

.....

**CALICE** test beam with pion from very low energy 1GeV up to 100 GeV

*cf talk by E.Garutti*
Calorimeters optimised for PFA → CAlorimeters for the LInear Collider Experiment

The CALICE collaboration

281 physicists/engineers from 47 institutes and 12 countries coming from 3 regions (Americas, Asia and Europe)

The people and institutes (pdf)  (word)

The steering board  The technical board

Editorial/speakers bureau

Public documents

- Official documents PRC02-01 with DESY
- Official Memorandum Of Agreement - CALICE collaboration

Other official documents

Pavia CALOR08 – J.-C.Brient  (LLR CNRS/Ecole polytechnique)
Calorimeters optimised for PFA → Calorimeters for the Linear Collider Experiment

The CALICE collaboration

281 physicists/engineers from 47 institutes and 12 countries coming from the 3 regions (America, Asia and Europe)

The people and institutes (pdf) (word)

The steering board

The technical board

Editorial/speakers bureau

Public documents

- Official documents PRC02-01 with DESY
- Official Memorandum Of Agreement - CALICE collaboration

Other official documents

Partially funded by EU (EUDET)

May 2008
281 phys./eng.
47 institutes
12 countries

Design and test calorimeters (ECAL, HCAL) optimised for PFA

Test beam at DESY, CERN and Fermilab

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
Granularity (lateral) → Separate particles
Segmentation (in depth) → pattern of the shower (no shower confusion)
Large distance from IP → Open the jets
Large B field → The bending separate $h^\circ, \gamma$ from $h^\pm$

ECAL and HCAL inside the coil

a) Very high granularity device i.e. 120 Mchannels for an ECAL (cells 5x5mm$^2$)
b) Very compact calorimeter (to avoid large coil .... Cost) i.e. ECAL is 18 cm thick
c) Prototype in test beam is the only way to debug the concept and design
Granularity (lateral) → Separate particles
Segmentation (in depth) → pattern of the shower (no shower confusion)
Large distance from IP → Open the jets
Large B field → The bending separate $h^o$, $\gamma$ from $h^\pm$
ECAL and HCAL inside the coil

a) Very high granularity device i.e. 120 Mchannels for an ECAL (cells 5x5mm$^2$)
b) Very compact calorimeter (to avoid large coil .... Cost) i.e. ECAL is 18 cm thick
c) Prototype in test beam is the only way to debug the concept and design

a) → Embedded VFE, FE, ADC) ....
   Local zero supress, Low power dissipation
   → VERY good S/B at low S (mip)
   → STRICT control of the common mode !!
   → VERY STABLE response with time, temp., etc...
      (or way to control the calibration)
   → A DAQ system able to manage this very high number of channels

b) → very high density of channels (about 256 channels in 8 cm$^3$)

c) → Test beam at DESY, CERN and now Fermilab

---

Pavia CALOR08 – J.-C. Brient (LLR CNRS/Ecole polytechnique)
**The proposed solutions**

**ECAL**

**Solution 1:**
- **Tungsten (density) - silicon** (pixel size < Molièref radius)
  - Pixels size 5x5mm² and 30 readout layers
  - (86 Millions channels) or even MAPS

  *cf talk by R.Cornat*

**Solution 2:**
- **Tungsten - MPPC and scintillator strip**
  - Scint. Strip 1x4 cm X, Y and 30 readout layers
  - (about 5 Millions channels)

  *cf talk by D.Jeans*

---

**HCAL**

**Solution 1:**
- **Sampling calorimeter tungsten/Stainless steel** (density) – digital readout (pixel size)
  - Pixel size 1cm² and about 40 readout layers
  - (~50 Millions channels)

  *cf talks by J.Repond by I. Laktineh*

**Solution 2:**
- **Sampling calorimeter tungsten/Stainless steel** (density) – scintillator tile (small size)
  - Pixels size 9 cm² and about 40 readout layers
  - readout by silicon PM !!

  *cf talk by F.Sefkow*
MAPS 50 x 50 micron pixels

Ultimate granularity?

ZOOM

Silicon PIN diodes 16mm area cells

CALICE development in UK

Simulation GEANT4
2006 – 2007 CERN Test Beam with electrons, pions

Dense & Complex but

It is a fantastic tool

example here with the ECAL W-Si

TB for ECAL solution 1, Analysis of the electron test beam are close to the publication

MC/ real data at 2%

cf talk by D.Boumediene

- 30 readout layers in 20 cm
- 9720 channels in 18x18x20 cm³
- S/N at mip at about 8

NEXT (>2008) the hadrons response

Pavia CALOR08 – J.-C.Brient (LLR CNRS/Ecole polytechnique)
First study indicate that
1- software compensation would be feasible
2- Neutrons measurement could be done with time information vs E

Hardware compensation is not the only way to have compensation
**ECAL (solution 1)**

**Pion Test Beam MTBF-Fermilab**

**HCAL (solution 2)**

& a Tail Catcher Muon Tagger

Low energy pions beam

 .......... It will have strong impact

On GEANT4 hadronic shower

In near future
Detector optimised for PFA

- HCAL (120cm)
- ECAL (18cm)

DENSE & COMPLEX
i.e. 70-80 readout layers in 140 cm thick
Detector optimised for PFA

The calorimeter is the central part and the reconstruction software is essential.

The pattern recognition in the calorimeter is the core of the PFA performances.

The cost and complexity of the calorimeter is largely dominant.

Cost fraction
1/3 for the coil
1/3 for the calorimeter
1/3 for the rest

Ready for LOI expected at mid 2009.

It is however important to notice that these R&D for PFA calorimeter are strongly generic ....

From electronics to PFA, from CFI mechanics to DAQ new generation ....
Conclusion

- optimising for PFA give a new view on the calorimeters
  .. *the duty list is different*

- The optimisation goes through software .... Not so easy
  *one need to disentangle what is for proposed device and the part related to the software*

- The calorimeter is more than ever the central part of the detector

- The proposed solution are ultra high granularity device as well as for ECAL than for HCAL

- The CALICE collaboration propose to design, built and test prototypes & results begin to arrive

10 years after the proposal to use PFA for ILC
I am happy to see that LHC, TeVatron,... use or are expected to use it