Muon Collider Detector Studies

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And the ILCroot simulation group:
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Main Detector Challenges

- If we can build a Muon Collider, it will be a precision machine!
- One of the most serious technical issues in the design of a Muon Collider experiment is the background
- The major source comes from muon decays:
  for 750 GeV muon beam with $2 \times 10^{12}$ muons/bunch $\sim 4.3 \times 10^5$ decays/m
- Large background is expected in the detector
- The backgrounds can spoil the physics program
- The Muon Collider physics program and the background will guide the choice of technology and parameters for the design of the detector.
Baseline Detector for Muon Collider Studies

Tracker+Vertex based on an evolution of SiD + SiLC trackers @ILC

See S. Striganov's talk
Vertex Detector (VXD)

10° Nozzle and Beam Pipe

VXD

- 100 \( \mu \)m thick Si layers
- 20 \( \mu \)m x 20 \( \mu \)m Si pixel
- Barrel: 5 layers subdivided in 12-30 ladders
- \( R_{\text{min}} \sim 3 \text{ cm} \) \( R_{\text{max}} \sim 13 \text{ cm} \) L~13 cm
- Endcap: 4 + 4 disks subdivided in 12 ladders
- Total length 42 cm

NOZZLE

- W - Tungsten
- BCH2 - Borated Polyethylene

PIPE

- Be – Beryllium 400 \( \mu \)m thick
- 12 cm between the nozzles
Silicon Tracker (SiT) and Forward Tracker Detector (FTD)

SiT

- 100 $\mu$m thick Si layers
- 50 $\mu$m x 50 $\mu$m Si pixel (or Si strips or double Si strips available)
- Barrel: 5 layers subdivided in staggered ladders
- Endcap: (4+2) + (4+2) disks subdivided in ladders
- $R_{\text{min}} \sim 20$ cm, $R_{\text{max}} \sim 120$ cm, L~330 cm

FTD

- 20 $\mu$m x 20 $\mu$m Si pixel
- Endcap: 3 + 3 disks
- Distance of last disk from IP = 190 cm

- Silicon pixel for precision tracking amid up to $10^5$ hits
- Tungsten nozzle to suppress the background
Dual-Readout Projective Calorimeter

- ~1.4° tower aperture angle
- 180 cm depth
- ~ 7.5 \( \lambda_{\text{int}} \) depth
- >100 \( X_0 \) depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nose)
- Barrel: 16384 towers
- Endcaps: 5544 towers

Energy resolution: < 30%/\( \sqrt{E} \)
MARS and ILCroot Frameworks

**MARS** – the framework for simulation of particle transport and interactions in accelerator, detector and shielding components.

- New release of MARS15 available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS)
- Among new features:
  - Refined MDI (Machine Detector Interface) with a 10° nozzle
  - Significant reduction of particle statistical weight variation
  - Background is provided at the surface of MDI (10° nozzle + walls)

**ILCroot** - Software architecture based on ROOT, VMC & Aliroot
- All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
- Extremely large community of ROOT users/developers

- It is a simulation framework and an offline system:
  - Single framework, from generation to reconstruction and analysis!!
  - Six MDC have proven robustness, reliability and portability
  - VMC allows to select G3, G4 or Fluka at run time (no change of user code)
- Widely adopted within HEP community (4th Concept, LHeC, T1015, SiLC)
- It is publicly available at FNAL on ILCSIM since 2006
Ingredients for these Studies

- MARS background provided at the surface of MDI (10° nozzle + walls)
- GEANT4 /fluka simulated particles in the detector (background + single muons from the I.P.)
- Reconstructed tracks from a parallel Kalman Filter in a 3.5 T B-field
- Reconstructed energy towers from a Dual Readout calorimeter
Tracking System Studies: Nozzle Effects on Tracking Performance

Hits densities in the vertex and the tracker detector

See N. Terentiev's talk

Reconstruction Efficiency & Resolutions

\[ \varepsilon_{tot} = \frac{\text{reconstructed tracks}}{\text{generated tracks}} = \varepsilon_{geom} \times \varepsilon_{track} \]

\[ \varepsilon_{geom} = \frac{\text{good tracks}}{\text{generated tracks}} \]

\[ \varepsilon_{track} = \frac{\text{reconstructed tracks}}{\text{good tracks}} \]

Defining “good tracks” (candidate for reconstruction)

DCA(true) < 3.5 cm

AND

at least 4 hits in the detector
Reconstruction Efficiency for Single Muons

- Geometrical Efficiency vs Theta
  - Nozzle effects start at $27^\circ$
  - Full efficiency at 200 MeV

- Kalman Filter Efficiency vs Theta

- Geometrical Efficiency vs Pt

- Kalman Filter Efficiency vs Pt
  - No background
Resolutions for single muons

1/Pt Resolution vs P

![Graph showing 1/Pt Resolution vs P]

 Theta Resolution vs P

![Graph showing Theta Resolution vs P]

Z₀ Resolution vs P

![Graph showing Z₀ Resolution vs P]

Asymptotic resolution: 4.5x10⁻⁵ GeV⁻¹

Well within requirements for precision physics

No background
Strategies to reduce clusters in the tracking system produced by the background

<table>
<thead>
<tr>
<th>Kalman Reconstruction</th>
<th>Clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics: 100 $\mu$ (0.2–200)GeV/c</td>
<td>92 (include geom. eff.)</td>
</tr>
<tr>
<td>Machine Background</td>
<td>-</td>
</tr>
</tbody>
</table>

Mostly soft $\gamma$'s absorbed in VXD

- physics from IP
- background

$\Delta E$ threshold 10 KeV (2400 e-)

Cluster timing cut: 7ns
Physics vs Background:
a strategy to disentangle reconstructed tracks from IP

Studies based on half background

$\chi^2/\text{ndf} < 2.1$

IP < 0.03 cm

Surviving tracks

<table>
<thead>
<tr>
<th></th>
<th>Surviving tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics: 100 $\mu$</td>
<td>89</td>
</tr>
<tr>
<td>Machine background</td>
<td>2110</td>
</tr>
</tbody>
</table>

3 lost
Effects of background Hits on the Reconstruction of Physics

**Effects on track parameter resolution are under study**

- **No fake cluster**
- **1 physics event = 100 muons**
- **< 5% of tracks have > 1 fake cluster**
Calorimetric Studies

Average background energy in a calorimeter tower produced in one bunch crossing

Integration time has little effect on visible energy
Background in the calorimeter for different particle species originating within 25 m from IP

Mostly neutrons and photons contribute to the energy into the calorimeter
Background in the calorimeter for different particle species originating beyond 25 m from IP

V. Di Benedetto

1 bin = 1 calorimeter cell

[5ns-105ns] time gate

Only muons contribute significantly to the energy into the calorimeter
Background Energy Fluctuation in the Calorimeter

Central barrel (45° < θ < 135°)
Fluctuations are ΔE/E~12%/cell
and ΔE ~ 3 GeV for a jet involving ~25 cells

Large angle endcap (20° < θ < 45°)
Fluctuations are ΔE/E~20%/cell
and ΔE ~ 6 GeV for a jet involving ~25 cells

Small angle endcap (8° < θ < 20°)
Fluctuations are ΔE/E~40%/cell
and ΔE ~ 20-25 GeV for a jet involving ~25 cells
Properties of Visible Energy in the Calorimeter

ILCroot simulation
Signal timing from calorimeter:
Bkg vs $\mu^+\mu^- \rightarrow \nu_\mu \bar{\nu_\mu} + Z_0 \rightarrow 2$-jets

~80% of the background hits is originated within foremost 20 cm of the calorimeter
Preliminary Physics Studies

- Production of a single $Z_0$ in a fusion process:
  $$\mu^+\mu^- \rightarrow \nu_\mu \bar{\nu}_\mu + Z_0 \rightarrow 2\text{-jets}$$

- How well can the invariant mass of the $Z_0$ be reconstructed from its decay into two jets?

- In particular, could the $Z_0$ be distinguished from a $W^{\pm}$ decaying into two jets in the process
  $$\mu^+\mu^- \rightarrow \mu^- \nu_\mu + W^+$$
  if the forward $\mu^-$ is not tagged?

- Madgraph and MARS15 as event generators
- ADRIANO calorimeter used in this study
- Recursive jet finder (from ILC studies)
- Full simulation, digitization and reconstruction
Some jet event display

Jets with energy of 435GeV and 68GeV in the endcap

Jets with energy of 234GeV and 117GeV in the barrel
Jets Reconstruction

Jet finder algorithm

- Divide jet in 2 non-overlapping regions:
  - **Core**: region of the calorimeter with nearby clusters
  - **Outliers**: isolated clusters
- Identify the **core** energy:
  - using calorimetric informations
- Identify the **jet axis**:
  - using infos from the tracking systems
- Reconstruct Outliers individually using:
  - trackers if calo and trackers have match clusters
  - Calo for neutral outliers
- Recursive algorithm

<table>
<thead>
<tr>
<th>Energy spectrum of reconstructed jets</th>
<th>htmp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>9226</td>
</tr>
<tr>
<td>Mean</td>
<td>156.1</td>
</tr>
<tr>
<td>RMS</td>
<td>106.5</td>
</tr>
</tbody>
</table>

Reconstructed Jet energy spectrum
No cuts applied
1 bin = 5 GeV
Zo Mass with Different Nozzles

Reconstructed $Z^0$ mass with three "nose" configurations

-6° nozzle
-10° nozzle

Minor difference observed

Fully reconstructed $Z^0$ mass (bin=1GeV)
No cuts applied
No leakage corrections
Merging Signal + Background

- Full calorimeter view
- Jet1
- Jet2

Background pick in endcaps

Zoom in energy axis to see the background fluctuations

~200 GeV jet
~100 GeV jet
Future Prospects

- The baseline detector configuration for Muon Collider studies performs well without background.
- Background is very nasty even with 10° tungsten nozzle, but fully understood.
- A second generation detector is being considered:
  - 3-D Si-tracker with precision timing
  - Two-section calorimeter with sophisticated time gate
  - 4-D Kalman filter

Timing is important at a Muon Collider!
Conclusions

- A full simulation and reconstruction of Si-tracking detectors and a dual-readout calorimeter is implemented in ILCroot framework

- MARS15 and ILCroot are stable and continuously improved for \( \mu \) Collider physics and detector studies (and much more!)
  - Synergies between MARS and ILCroot working groups are excellent
  - The machinery work smoothly for fast and full simulations

- Detector performance studies with and without background are well under way
  - Track reconstruction is expected to be only slightly affected by large background
  - ...but, up to \( 10^6 \) real tracks from the background could be fully reconstructed
  - Background in the calorimeter is under control for \( \theta > 20^\circ \)

- Preliminary physics studies are ongoing:
  - Physics is mostly unaffected for \( \theta > 20^\circ \)
  - For \( \theta < 20^\circ \) jet energy uncertainties need to be improved

Not a bad start for a baseline detector with no optimization yet
Backup slides
Biggest decision of the decade!

- ILC Enough
  - By far the easiest!
  - A Global program
- LHC Results
- ILC not enough
- CLIC
- Muon collider

P. Oddone
Fermilab Users Meeting, June 2011
Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

P. Oddone
Fermilab Users Meeting, June 2011
MUON COLLIDER MOTIVATION

If we can build a muon collider, it is an attractive multi-TeV lepton collider option because muons don’t radiate as readily as electrons \((m_\mu / m_e \sim 207)\):

- **COMPACT**
  - Fits on laboratory site
- **MULTI-PASS ACC**
  - Cost Effective operation & construction
- **MULTIPASS COLLISIONS IN A RING** (~1000 turns)
  - Relaxed emittance requirements & hence relaxed tolerances
- **NARROW ENERGY SPREAD**
  - Precision scans, kinematic constraints
- **TWO DETECTORS** (2 IPs)
- \(\Delta T_{\text{bunch}} \sim 10 \mu s \) ... (e.g. 4 TeV collider)
  - Lots of time for readout
  - Backgrounds don’t pile up
- \((m_\mu/m_e)^2 = \sim 40000\)
  - Enhanced s-channel rates for Higgs-like particles

S. Geer - Accelerator Seminar
SLAC 2011
Energy Spread

Beamstrahlung in any e+e collider
\[ \frac{\delta E}{E} \propto \gamma^2 \]
Challenges

• Muons are produced as tertiary particles. To make enough of them we must start with a MW scale proton source & target facility.

• Muons decay
   Everything must be done fast and we must deal with the decay electrons (& neutrinos for CM energies above \( \sim 3 \) TeV).

• Muons are born within a large 6D phase-space.
   For a MC we must cool them by \( O(10^6) \) before they decay

   New cooling technique (ionization cooling) must be demonstrated, and it requires components with demanding performance (NCRF in magnetic channel, high field solenoids.)

• After cooling, beams still have relatively large emittance.
10° Nozzle

Newer version
To further reduce MuX background

ILCroot event display
ILCroot: root Infrastructure for Large Colliders

- **Software architecture based on root, VMC & Aliroot**
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers

- **Re-alignment with latest Aliroot version every 1-2 years (v4.17 release)**

- **It is a simulation framework and an Offline Systems:**
  - Single framework, from generation to reconstruction through simulation. Don’t forget analysis!!!
  - It is immediately usable for test beams
  - Six MDC have proven robustness, reliability and portability

- **Main add-ons Aliroot:**
  - Interface to external files in various format (STDHEP, text, etc.)
  - Standalone VTX track fitter
  - Pattern recognition from VTX (for Si central trackers)
  - Parametric beam background (# integrated bunch crossing chosen at run time)

- **Growing number of experiments have adopted it:** Alice (LHC), Opera (LNGS), (Meg), CMB (GSI), Panda(GSI), 4th Concept, (SiLC ?) and **LHeC**

- **It is Publicly available at FNAL on ILCSIM since 2006**

- **Used for ILC, CLIC and Muon Collider studies**
Simulation steps in ILCroot: Tracking system

Signal:
- MC Generation ⇒ Energy Deposits in Detector
  - SDigitization ⇒ Detector response from single particle
  - Digitization ⇒ Detector response combined
  - Pattern Recognition ⇒ Recpoints
  - Track Finding ⇒ Tracks
  - Track Fitting ⇒ Track Parameters

Background:
- MC Generation ⇒ Energy Deposits in Detector
  - SDigitization ⇒ Detector response from single particle
  - Digitization ⇒ Detector response combined

Persistent Objects:
- hits
  - sdigits
  - digits
  - recpoints
  - tracks
  - DST tracks
Fast simulation and/or fast digitization also available in ILCroot for tracking system

- Fast Simulation = hit smearing
- Fast Digitization = full digitization with fast algorithms
- Do we need fast simulation in tracking studies? Yes!
  - Calorimetry related studies do not need full simulation/digitization for tracking
  - Faster computation for quick answer to response of several detector layouts/shielding

- Do we need full simulation in tracking studies? Yes!
  - Fancy detector and reconstruction needed to be able to separate hits from signal and background
Digitization and Clusterization of Si Detectors in Ilcroot: a description of the algorithms available for detailed tracking simulation and studies
Technologies Implemented

- 3 detector species:
  - Silicon pixels
  - Silicon Strips
  - Silicon Drift

- Pixel can have non constant size in different layers
- Strips can also be stereo and on both sides
- Dead regions are taken into account
- Algorithms are parametric: almost all available technologies are easily accomodated (MAPS, 3D, DEPFET, etc.)

Used for VXD SiT and FTD in present studies
SDigitization in Pixel Detector (production of summable digits)

- **Summable digit** = signal produced by each individual track in a pixel

- Loop over the hits produced in the layer and create a segment in Si in 3D:
  - Step (from MC) along the line >1 μm increments
  - Convert GeV to charge and get bias voltage:
    
    \[ q = \frac{dE \cdot dt}{3.6 \times 10^{-9}} \quad dV = \text{thick/bias voltage} \]

  - Compute charge spreading:
    
    \[ \sigma_{xy} = \sqrt{2k/e \cdot T^\circ \cdot dV \cdot L}, \quad \sigma_z = fda \cdot \sigma_{xy} \]

  - Spread charge across pixels using \( \text{Erfc}(xy,z,\sigma_{xy},\sigma_z) \)

- Charge pile-up is automatically taken into account
SDigitization in Pixels (2)

- Add coupling effect between nearby pixels row-wise and column-wise (constant probability)
- Remove dead pixels (use signal map)
Digitization in Pixels

Digit = sum of all sdigit corresponding to the same pixel

• Load SDigits from several files (signal or multiple background)
• Merge signals belonging to the same pixel
  – Non-linearity effects
  – Saturation
• Add electronic noise
• Save Digits over threshold
Clusterization in Pixel Detector

Cluster = a collection of nearby digit

Create a initial cluster from adjacent pixels (no for diagonal)

Subdivide the previous cluster in smaller NxN clusters

Reconstruct cluster and error matrix from coordinate average of the cluster

Kalman filter picks up the best cluster
Parameters used for the pixel tracking detectors in current MuX studies

Size Pixel X = 20 μm (VXD and FTD), 50 μm (SiT)
Size Pixel Z = 20 μm (VXD and FTD), 50 μm (SiT)
Eccentricity = 0.85 (fda)
Bias voltage = 18 V
cr = 0% (coupling probability for row)
cc = 4.7% (coupling probability for column)
threshold = 3000 electrons
electronics noise = 0 electrons
T° = 300 °K
Clusterization in Strip Detector

• Create a initial cluster from adjacent strips (no for diagonal)
• Separate into Overlapped Clusters
  – Look for through in the analog signal shape
  – Split signal of parent clusters among daugheter clusters
• Intersect stereo strips to get Recpoints from CoG of signals (and error matrix)
• Kalman filter picks up the best Clusters
SDigitization in Strips Detector

- Get the Segmentation Model for each detector (from IlcVXDSegmentationSSD class)
- Get Calibration parameters (from IlcVXDCalibrationSSD class)
- Load background hits from file (if any)
- Loop on the hits and create a segment in Si in 3D

  Step along the line in equal size increments
  - Compute Drift time to p-side and n-side:
    \[
    t_{\text{drift}}[0] = \frac{(y + (\text{seg} \to \text{Dy}() \times 1.0E-4)/2)}{\text{GetDriftVelocity}(0)};
    \]
    \[
    t_{\text{drift}}[1] = \frac{((\text{seg} \to \text{Dy}() \times 1.0E-4)/2 - y)}{\text{GetDriftVelocity}(1)};
    \]
  - Compute diffusion constant:
    \[
    \sigma[k] = \text{TMath::Sqrt}(2 \times \text{GetDiffConst}(k) \times t_{\text{drift}}[k]);
    \]
  - Integrate the diffusion gaussian from $-3\sigma$ to $3\sigma$
    - Charge pile-up is automatically taken into account
SDigitization in Strips (2)

• Add electronic noise per each side separately
  // noise is gaussian
  noise = (Double_t) gRandom->Gaus(0,res->GetNoiseP().At(ix));

  // need to calibrate noise
  noise *= (Double_t) res->GetGainP(ix);

  // noise comes in ADC channels from the calibration database
  // It needs to be converted back to electronVolts
  noise /= res->GetDEvToADC(1.);

• Add coupling effect between nearby strips
  - different contribution from left and right neighbours
  - Proportional to nearby signals

• Remove dead pixels (use signal map)

• Convert total charge into signal (ADC count)
  if(k==0) signal /= res->GetGainP(ix);
  else signal /= res->GetGainN(ix);
  // signal is converted in unit of ADC
  signal = res->GetDEvToADC(fMapA2->GetSignal(k,ix));
The Parameters for the Strips

- Strip size \((p, n)\)
- Stereo angle \((p \rightarrow 7.5 \text{ mrad}, n \rightarrow 25.5 \text{ mrad})\)
- Ionization Energy in Si = \(3.62\times10^{-9}\)
- Hole diffusion constant \((= 11 \text{ cm}^2/\text{sec})\)
- Electron diffusion constant \((= 30 \text{ cm}^2/\text{sec})\)
- \(v_p^{\text{drift}} (=0.86\times10^6 \text{ cm/sec}), v_n^{\text{drift}} (=2.28\times10^6 \text{ cm/sec})\)
- Calibration constants
  - Gain
  - ADC conversion \((1 \text{ ADC unit} = 2.16 \text{ KeV})\)
- Coupling probabilities between strips \((p \text{ and } n)\)
- \(\sigma\) of gaussian noise \((p \text{ AND } n)\)
- threshold
Track Fitting in ILCRoot

Track finding and fitting is a global task: individual detector collaborate.

It is performed after each detector has completed its local tasks (simulation, digitization, clusterization).

It occurs in three phases:

1. Seeding in SiT and fitting in VXD+SiT+MUD
2. Standalone seeding and fitting in VXD
3. Standalone seeding and fitting in MUD

Two different seedings:

A. Primary seeding with vertex constraint
B. Secondary seeding without vertex constraint

Not yet implemented
Kalman Filter (classic)

- Recursive least-squares estimation.
- Equivalent to global least-squares method including all correlations between measurements due to multiple scattering.
- Suitable for combined track finding and fitting
- Provides a natural way:
  - to take into account multiple scattering, magnetic field inhomogeneity
  - possibility to take into account mean energy losses
  - to extrapolate tracks from one sub-detector to another
Parallel Kalman Filter

• Seedings with constraint + seedings without constraint at different radii (necessary for kinks and V0) from outer to inner

• Tracking
  • Find for each track the prolongation to the next layer
  • Estimate the errors
  • Update track according current cluster parameters
  • (Possible refine clusters parameters with current track)

• Track several track-hypothesis in parallel
  • Allow cluster sharing between different track

• Remove-Overlap

• **Kinks and V0** fitted during the Kalman filtering
Tracking Strategy – Primary Tracks

- Iterative process
  - Seeding in SiT
  - Forward propagation towards to the vertex
    \[ \text{SiT} \rightarrow \text{VXD} \]
  - Back propagation towards to the MUD
    \[ \text{VXD} \rightarrow \text{SiT} \rightarrow \text{MUD} \]
  - Refit inward
    \[ \text{MUD} \rightarrow \text{SiT} \rightarrow \text{VXD} \]

- Continuous seeding –track segment finding in all detectors
VXD Standalone Tracking

- Uses Clusters leftover in the VXD by Parallel Kalman Filter
- **Requires at least 4 hits to build a track**
- Seeding in VXD in two steps
  - Step 1: look for 3 Clusters in a narrow row or 2 Clusters + IP constraint
  - Step 2: prolongate to next layers each helix constructed from a seed
- After finding Clusters, all different combination of clusters are refitted with the Kalman Filter and the tracks with lowest $\chi^2$ are selected
- Finally, the process is repeated attempting to find tracks on an enlarged row constructed looping on the first point on different layers and all the subsequent layers
- In 3.5 Tesla B-field $P_t > 20$ MeV tracks reconstructable
Event Display

ILCroot event display for 10 muons up to 200 GeV

green - hits
purple - reconstructed tracks
red - MC particle

10 generated muons
9 reconstructed tracks
Effects on Track Resolution

Background in the calorimeter for different particle species originating within 25 m from IP

Background in the calorimeter for different particle species originating in [25-200] m from IP

Future Prospects

Conclusions

Backup slides