Detector Challenges
For $\mu^+ \mu^-$

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Fermilab

Snowmass on the Mississippi August 1, 2013
Muon Collider Motivations

➢ PRECISION PHYSICS
Lepton colliders provide elementary interactions at known initial state. i.e. $e^+e^- \rightarrow Z^0h^0 \ (Z^0\rightarrow l^+l^-) \Rightarrow M_{h^0}^2 = s + M^2Z^0 - 2E_{Z^0}\sqrt{s} \ (g^2 \propto \sigma = N/\mathcal{L}e)$, “Higgs recoil mass technique”.

➢ COMPACT
Synchrotron radiation ($1/\text{mass}^4$) does not limit muon circular acceleration, a circular machine with multi-TeV beams can be realized and it fits on laboratory site.

➢ NARROW ENERGY SPREAD
The beam energy resolution is not limited by beamstrahlung smearing, precision scans, kinematic constraints.

➢ TWO DETECTORS (2 IPs)
No need for “push-pull”.

➢ $\Delta T(\text{BUNCH}) \sim 10 \ \mu s \ \ldots \ (\text{e.g. 4 TeV collider})$
Lots of time for readout.
Backgrounds don’t pile up.

➢ ENHANCED S-CHANNEL HIGGS PRODUCTION
Higgs coupling is proportional to mass and $(m_{\mu}/m_e)^2 = \sim 40000$
Muon Collider 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).

➢ **MUONS ARE BORN WITHIN A LARGE 6D PHASE-SPACE**
   For a MuC we must cool them 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 LARGE EMITTANCE**

S. Geer- Accelerator Seminar SLAC 2011
Main Detector Challenges: Muons Decay!

➢ The Muon Collider will be a precision machine: the detector performance must be very demanding.

➢ One of the most serious technical issues in the design of a Muon Collider experiment is the background.

➢ The major source come from muon decays: for 750 GeV muon beam with $2 \times 10^{12}$ muons/bunch $\sim 4.3 \times 10^5$ decays/m/bunchX.

➢ Large background is expected into the detector from interactions of decay products with the beamline components and accelerator tunnel.

➢ The background affects the detector performance and 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.
Extensive and Detailed Simulation Studies: MARS and ILCroott Frameworks

- **MARS** – is the framework for simulation of particle transport and interactions in accelerator, detector and shielding components.
- New release of MARS15 is available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS).
- Background simulation in the studies shown in this presentation is provided at the surface of MDI (10° nozzle + walls).

- **ILCroott** – is a 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, ORKA, MuC)
  - Detailed detector simulation, full simulation and physics studies are presented in this presentation.
- It is available at Fermilab since 2006.
Part of the Solution: Shieldings

- Extensive studies (Mokhov et al., Fermilab) show a reduction of the background up to three order of magnitude using sophisticated shielding.
- Tungsten nozzle to stop gammas (generate neutrons), in Borated Polyetilene shell to absorb neutrons (and concrete walls outside the detector region).
- Detailed magnet geometry, materials, magnetic fields maps, tunnel, soil outside and a simplified experimental hall plugged with a concrete wall are simulated in MARS framework.

Number and species of particles per bunch crossing entering the detector, starting from $S_{\text{max}} = 75\text{m}$ for a 1.5 TeV collider.

<table>
<thead>
<tr>
<th>Particle</th>
<th>0.6-deg</th>
<th>10-deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>$1.5 \times 10^{11}$</td>
<td>$1.8 \times 10^{8}$</td>
</tr>
<tr>
<td>Electron</td>
<td>$1.4 \times 10^{9}$</td>
<td>$1.2 \times 10^{6}$</td>
</tr>
<tr>
<td>Muon</td>
<td>$1.0 \times 10^{4}$</td>
<td>$8.0 \times 10^{3}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$5.8 \times 10^{8}$</td>
<td>$4.3 \times 10^{7}$</td>
</tr>
<tr>
<td>Charged hadron</td>
<td>$1.1 \times 10^{6}$</td>
<td>$2.4 \times 10^{4}$</td>
</tr>
</tbody>
</table>

No time cut applied, can help substantially (see next)

All results below are presented for a 1.5 TeV collider and a 10° nozzle.
The Background Entering the Detector

Most of the background are low momenta photons and neutrons.

Timing cut can further reduce the background.

MARS Simulation

Still a lot of background!!!!!
Baseline Detector for Muon Collider Studies

➢ Detailed geometry (dead materials, pixels, fibers ..)
➢ Full simulation: hits-sdigits-digits. Includes noise effect, electronic threshold and saturation, pile up...
➢ Tracking Reconstruction with parallel Kalman Filter.
➢ Light propagation and collection.
➢ Jet reco

ILCroot Simulation
Vertex Detector (VXD)

10° Nozzle and Beam Pipe

**VXD**
- 75 µm thick Si layers in the barrel
- 100 µm thick Si layers in the endcap
- 20 µm x 20 µm Si pixel
- Barrel: 5 layers subdivided in 12-30 ladders
- \( R_{\text{min}} \sim 3 \text{ cm} \), \( R_{\text{max}} \sim 13 \text{ cm} \)
- Endcap: 4 + 4 disks subdivided in 12 ladders
- Total length 42 cm

**NOZZLE**
- W - Tungsten
- BCH2 – Borated Polyethylene
- Starting at ±6 cm from IP with \( R = 1 \text{ cm} \) at this z

**PIPE**
- Be – Beryllium 400 µm thick
- 12 cm between the nozzles
Silicon Tracker (SiT) and Forward Tracker Detector (FTD)

**SiT**
- 200 µm thick Si layers
- 50 µm x 50 µm Si pixel (or Si strips or double Si strips available)
- Barrel: 5 layers subdivided in staggered ladders
- Endcap: (4+3) + (4+3) disks subdivided in ladders
- $R_{\text{min}} \sim 20$ cm $R_{\text{max}} \sim 120$ cm $L \sim 330$ cm

**FTD**
- 200 µm thick Si layers
- 50 µm x 50 µm 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

- Lead glass + scintillating fibers
- ~1.4° tower aperture angle
- Split in two sections
- Front section 20 cm depth
- Rear section 160 cm depth
- ~ 7.5 \( \lambda_{\text{int}} \) depth
- >100 \( X_0 \) depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nozzle)
- Barrel: 16384 towers
- Endcaps: 7222 towers

➢ All simulation parameters corresponds to ADRIANO prototype #9 beam tested by Fermilab T1015 Collaboration in Aug 2012 (see also T1015 Gatto's talk at Calor2012)
➢ Several more prototypes tested with real beam.

ILCroot Simulation
Timing Is The Key

➢ Timing for MARS background particles
- MARS background (on a surface of the shielding cone) up to \(\sim 1000\) ns of TOF (time of flight w.r.t. BX)

➢ Timing of ILCRoot MARS background hits in VXD and Tracker
- TOF for neutron hits has long tale up to a few ms (due to “neutron gas”)

➢ Time gate width of 4 ns can provide a factor of 300-500 background rejection keeping efficiency of hits from IP particles higher than 99% at hit time resolution \(\sigma = 0.5\) ns.

N. Terentiev

With layer dependent time gate (TOF-T0) several times gain in MARS background rejection compared with global time gate (TOF)
Strategies To Reduce Clusters In The Tracking System Produced By The Machine 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>

Simulated in ILCroot 4 detectors with different timing capabilities:

- **Det. A** – No time information (integrates all hits).
- **Det. B** – Acquires data in a fixed 7 ns time gate (minimal timing capabilities).
- **Det. C** - Acquires data in a 3 ns time gate tuned to distance from IP (advanced timing capabilities).
- **Det. D** - Acquires data in a 1 ns time gate tuned to pixel distance from IP (extreme timing capabilities.)
Reconstructed Background Tracks
(from Kalman filter)

Full vs Fast simulation of the bkg

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Reconstructed Tracks (full simu)</th>
<th>Reconstructed Tracks (fast simu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Det. A (no timing)</td>
<td>Cannot calculate</td>
<td>Cannot calculate</td>
</tr>
<tr>
<td>Det. B (7 ns fixed gate)</td>
<td>75309</td>
<td>64319</td>
</tr>
<tr>
<td>Det. C (3 ns adjustable gate)</td>
<td>6544</td>
<td>4639</td>
</tr>
<tr>
<td>Det. D (1 ns adjustable gate)</td>
<td>1459</td>
<td>881</td>
</tr>
</tbody>
</table>

After $\chi^2$ and IP cuts

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

Impact Parameter (cm)

$\text{IP} < 0.03 \text{ cm}$

Full reconstruction is paramount when combinatorics is relevant

ILCroot Simulation
Timing Is Also The Key For Calorimetry

Sci signal is developed in sci fibers with 2.4 ns decay time
Cerenkov is read directly on LeadGlass
Time bin of 25 ps

Sci signal is developed in sci fibers
Cerenkov is read by WLS
Both with 2.4 ns decay time
Time bin of 25 ps
Background Rejection In The Calorimeter

<table>
<thead>
<tr>
<th>Time gate for each section</th>
<th>Front Section</th>
<th>Rear Section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scint</td>
<td>Cer</td>
</tr>
<tr>
<td>Front readout</td>
<td>6.3 ns</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>Back readout</td>
<td>5.7 ns</td>
<td>0.8 ns</td>
</tr>
<tr>
<td>Signal efficiency</td>
<td>83%</td>
<td></td>
</tr>
<tr>
<td>BG suppression</td>
<td>98.5%</td>
<td></td>
</tr>
</tbody>
</table>

Approach to reject machine background.

- Apply time cut.
- Individuate Region of Interest (RoI), i.e. regions where the energy is $2.5\sigma$ above the background level in that region.
- In the RoI apply soft energy subtraction, i.e. subtract the mean value of the background in that region.
- In the other regions apply hard energy cut, i.e. subtract $4\sigma$ of the background.
The Muon Collider as a H/A factory: Theory

- Heavy Neutral Higgses (H/A) and charged Higgses (H^±) are a simple possibility of New Physics beyond the Standard Model.
- H/A are likely to be difficult to find at the LHC, and at e+ e- colliders are produced in association with other particles, such as Z, since the electron Yukawa coupling is too small for s-channel production.
- The H and A can be produced as s-channel resonances at a Muon Collider. (Eichten and Martin arXiv:1306.2609).

H/A production in the Natural Supersymmetry model compared with Z^0h, Z^0H and heavy Higgs pair production.

Pseudo-data (in black) along with the fit result in the bb channel. The peak signal is more than an order of magnitude larger than the physics background.

\[ \sigma_B(\sqrt{s}) = c_1 \frac{(m_H m_A)}{s(\text{in } \text{TeV}^2)} \]
The Muon Collider as a H/A factory: “Reality”

- Fully simulated with track and calorimeter reconstruction in ILCroot framework. 4000 H/A events generated by Pythia at $\sqrt{s} = 1550$ GeV with a Gaussian beam energy smearing (R=0.001) (A. Martin).
- In these preliminary studies, considered the $b\bar{b}$ decay of the H/A which is the channel with the largest BR (64%).
- Applied a perfect b-tagging (using information from MonteCarlo truth).
- Reconstructed 2 jets applying PFA-like jet reconstruction developed for ILC benchmark studies.

ILCroot Event Display

**NO Time Gate NO Background**

\[ \sigma_M \frac{M}{M} = 3.0\% \]

Significant neutrino component

Dijet mass distribution including neutrino contribution

ILCroot Simulation

A. Mazzacane (Fermilab)
The Muon Collider as a H/A factory: “Reality” (cont’d)

- Applied 3 ns layer dependent time gate in the tracking system and the time gate shown in slide #16 in the calorimeter.

- Fully simulated signal and beam background. Applied 3 ns time gate and energy cut theta dependent to further reject the background.

\[
\frac{\sigma_M}{M} = 3.1\%
\]

\[
\frac{\sigma_M}{M} = 4.6\%
\]
Why MuC Detector R&D Is Important

➢ Background vs Physics rejection has unprecedented characteristics compared to previous HEP experiments.
  - The background is huge but out-of-time and enter in the detector with a quite uniform distribution.
  - The Machine Detector Interface (MDI) has an important role and has to be considered an integral part of the detector: i.e. the geometry changes as the shielding strategy evolves.
  - The MDI affects the physics program, especially Susy signals, by the presence of forward shielding and instrumentation.

➢ New detector technologies need to be exploited. Push for a new detector generation.

  **Tracking**
  - Simulations indicate the Si detectors are a good solution, but many issues have to be addressed.
  - The inner radius of the vertex is set by the beam background and the shielding nozzle. But the impact parameter resolution and the physics reach are affected.
  - High granularity is required to low occupancies. But charge sharing limits the pixel size.
  - Fast timing is crucial. But power requirements need to be understood.

  **Calorimetry**
  - PFA would not probably work at multi-TeV energies and in a MuC environment.
  - Fast Dual-Readout can be the best option, but the radiation hardness is crucial.
  - LAPPD for picosecond-level resolution and excellent photon-counting capabilities.
But Do Not Forget Software

➢ We understood many things since these studies began thanks to simulations. Therefore simulations are crucial:
- to guide through technologies and help identifying the figure of merit for each subdetector.
- to optimize parameters and to build prototypes to test.
➢ Established and already proved software architecture makes detector performance and physics studies possible in a realistic time scale and man power.
Conclusions

➢ Large background is expected in the detector for a Muon Collider experiment.
➢ Sophisticated shielding have been proposed to suppress the machine background.
➢ MARS15 simulation shows a reduction of the machine background ~ 3 orders of magnitude (depends on the nozzle angle).
➢ The baseline detector configuration for a Muon Collider has been developed in ILCroot framework and studies on the performance are well advanced.
➢ Full simulation and reconstruction of Si-tracking detectors and a dual-readout calorimeter are implemented in ILCroot framework (thanks to previous and detailed studies at ILC).
➢ Both tracking and calorimetry implemented ............
➢ The background is very nasty, even with a 10° nozzle, but it has been shown is not impossible to reach the physics goal at a Muon Collider experiment.
➢ Current studies show that timing cut is an effective tool to reducing the background to an acceptable level.
➢ However the needed timing for the Si detectors is at the limit of existing pixel devices (power consumption-cooling, material budget) and beyond the current calorimeter technology ⟹ Extensive R&D is needed.
➢ A second generation of detector and reconstruction algorithm under consideration:
  ➢ 3-D Si-pixel with precision timing
  ➢ 4-D Kalman filter
  ➢ Segmented calorimeters with enhanced timing.
The Muon Collider is the opportunity to bring back collider physics to US soil.

Nothing will ever happen in the future, if we don't start in the now.
Backup slides
Biggest decision of the decade!

LHC Results

- ILC Enough
  - By far the easiest!
  - A Global program

- 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
Introduction

Physics goals of a Muon Collider (MC) can only be reached with appropriate design of the ring, interaction region (IR), high-field superconducting magnets, machine-detector interface (MDI) and detector. All - under demanding requirements, arising from the short muon lifetime, relatively large values of the transverse emittance and momentum spread, unprecedented dynamic heat loads (0.5-1 kW/m) and background particle rates in collider detector.
Sources of Background and Dynamic Heat Load

1. **IP $\mu^+\mu^-$ collisions:** Production x-section 1.34 pb at $\sqrt{S} = 1.5$ TeV (negligible compared to #3).

2. **IP incoherent $e^\pm e^\pm$ pair production:** x-section 10 mb which gives rise to background of $3\times10^4$ electron pairs per bunch crossing (manageable with nozzle & detector B)

3. **Muon beam decays:** Unavoidable bilateral detector irradiation by particle fluxes from beamline components and accelerator tunnel – major source at MC: For 0.75-TeV muon beam of $2\times10^{12}$, $4.28\times10^5$ dec/m per bunch crossing, or $1.28\times10^{10}$ dec/m/s for 2 beams; 0.5 kW/m.

4. **Beam halo:** Beam loss at limiting apertures; severe, can be taken care of by an appropriate collimation system far upstream of IP.
SUMMARY (1)

1. Backgrounds originated at IP are negligible compared to other sources: hadrons from $\mu^+\mu^-$ collisions; incoherent pairs are captured by nozzles in the solenoid field.

2. Backgrounds induced by beam halo losses exceed the limits by orders of magnitude, but can be suppressed with an appropriate collimation system.

3. Muon beam decays are the major source of backgrounds in the MC detectors. They can drastically be reduced by sophisticated collimating nozzles at IP, and sweep dipoles and collimators in a 100-m region upstream IP.
Dipoles close to the IP and tungsten masks in each interconnect region help reduce background particle fluxes in the detector by a substantial factor. The tungsten nozzles, assisted by the detector solenoid field, trap most of the decay electrons created close to the IP as well as most of incoherent $e^+e^-$ pairs generated in the IP. With additional MDI shielding, total reduction of background loads by more than three orders of magnitude is obtained.
10° Nozzle

Newer version to further reduce MuC 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-allignement 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
      - Pattern Recognition ⇒ Recpoints
        - Track Finding ⇒ Tracks
          - Track Fitting ⇒ Track Parameters

Persistent Objects
- hits
  - sdigits
    - digits
      - recpoints
        - tracks
          - DST tracks

Fast Simulation
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 accommodated (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:
      \[ \sigma_{xy} = \sqrt{2k/e \cdot T \cdot dV \cdot L}, \quad \sigma_z = fda \cdot \sigma_{xy} \]
    - 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:
    tdrift[0] = (y+(seg->Dy()*1.0E-4)/2)/GetDriftVelocity(0);
    tdrift[1] = ((seg->Dy()*1.0E-4)/2-y)/GetDriftVelocity(1);
  • Compute diffusion constant:
    sigma[k] = TMath::Sqrt(2*GetDiffConst(k)*tdrift[k]);
  • Integrate the diffusion gaussian from -3σ to 3σ
    • 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-> 7.5 mrad, n->25.5 mrad)
- Ionization Energy in Si = 3.62E-09
- Hole diffusion constant (= 11 cm^2/sec)
- Electron diffusion constant (= 30 cm^2/sec)
- \( v^P_{\text{drift}} (=0.86E+06 \, \text{cm/sec}) \), \( v^N_{\text{drift}} (=2.28E+06 \, \text{cm/sec}) \)
- Calibration constants
  - Gain
  - ADC conversion (1 ADC unit = 2.16 KeV)
- Coupling probabilities between strips (p and n)
- \( \sigma \) of gaussian noise (p 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:

- Seeding in SiT and fitting in VXD+SiT+MUD
- Standalone seeding and fitting in VXD
- Standalone seeding and fitting in MUD

Two different seedings:

- Primary seeding with vertex constraint
- 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
Tracking System Studies: Nozzle Effects on Tracking Performance

Reconstruction Efficiency & Resolutions

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

\[ \epsilon_{geom} = \frac{\text{reconstructable tracks}}{\text{generated tracks}} \]

\[ \epsilon_{track} = \frac{\text{reconstructed tracks}}{\text{reconstructable tracks}} \]

Defining “reconstructable tracks” (candidate for reconstruction)

- tracks with DCA(\text{true}) < 3.5 cm
- \text{AND}
- at least 4 hits in the detector
Reconstruction Efficiency for Single Muons

Geometrical Efficiency vs Theta

Tracking Efficiency vs Theta

Geometrical Efficiency vs Pt

Tracking Efficiency vs Pt

Nozzle effects start at 27°

No background

Full efficiency at 200 MeV
Effect of the 10° nozzle

ILCroot event display for 10 muons up to 200 GeV

- green - hits
- purple - reconstructed tracks
- red - MC particle

10 generated muons
9 reconstructed tracks
Resolutions for single muons

1/Pt Resolution vs P

![Graph showing 1/Pt Resolution vs P with mean 40.05 and RMS 56.]

Theta Resolution vs P

![Graph showing Theta Resolution vs P with mean 48.47 and RMS 55.81.]

Z Resolution vs P

![Graph showing Z Resolution vs P with mean 77.13 and RMS 61.27.]

Asymptotic resolution: $4.5 \times 10^{-5}$ GeV$^{-1}$

Well within requirements for precision physics

No background
Physics vs Background in Det. B:
A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg

Momentum of surviving bkg tracks

Det. B = Acquires data in a fixed 7 ns time gate
Physics vs Background in Det. D:
A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg

Momentum of surviving bkg tracks

χ^2/ndf < 2.1
IP < 0.03 cm

Det. D = Acquires data in variable 1 ns time gate
Effects of background Hits on Physics

Fast sim of Det. B
100 muons

Fast sim of Det. B
100 muons + bkg

Effects on track parameter resolution are unaffected by background
Background in the calorimeter for different particle species originating within 25 m from IP

1 bin = 1 calorimeter cell

[5ns-105ns] time gate

Mostly neutrons and photons contribute to the energy into the calorimeter

V. Di Benedetto
Background in the calorimeter for different particle species originating beyond 25 m from IP

- Neutrons
- Muons
- Photons
- Electrons
- Others

Only muons contribute significantly to the energy into the calorimeter

1 bin = 1 calorimeter cell

[5ns-105ns] time gate

V. Di Benedetto
Longitudinal energy deposition produced in the calorimeter

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

Longitudinal segmentation of the calorimeter could be beneficial
Time Distribution of MuonCollider background and IP particles energy in Calorimeter

Background energy in the time range of Physics

Background energy in the time range of Physics

Time Distribution of MuonCollider background and IP particles energy in Calorimeter

Most of physics occurs between 5 and 10 ns

V. Di Benedetto
Angular distribution of background in Calorimeter for different integration time gates

### Integration time gate for each section

<table>
<thead>
<tr>
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<th>Front Section</th>
<th>Rear Section</th>
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<tbody>
<tr>
<td>Scint</td>
<td>100 ns</td>
<td>100 ns</td>
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<tr>
<td>Cer</td>
<td>100 ns</td>
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<table>
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<th>Integration time</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>100 ns</td>
</tr>
<tr>
<td>B</td>
<td>20 ns, 15 ns</td>
</tr>
<tr>
<td>C</td>
<td>15 ns, 6 ns</td>
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</tbody>
</table>

1 entry = $<1 \text{ cell}> |_{\varphi}$

V. Di Benedetto
Background energy distribution per tower
Calorimeter Front Section “conf C”

1 bin = 1 calorimeter cell

Most of the energy in the endcaps is originated by neutrons and in the barrel is originated by gammas

Calorimeter is now split in a front (20cm) and rear (160 cm) section
Background energy distribution per tower
Calorimeter Rear Section with “conf C”

1 bin = 1 calorimeter cell

Most of the energy in the endcaps is originated by neutrons

Calorimeter is now split in a front (20cm) and rear (160 cm) section
Time Distribution of MuonCollider background energy in Calorimeter

Light propagation in fibers and lead glass is implemented in ILCroot.

Calorimeter is now split in a front (20 cm) and rear (160 cm) section.

Sci signal is developed in fibers with 2.4 ns decay time.
Cerenkov readout directly on LeadGlass.

Front Section

Rear Section

Sci signal is developed in fibers.
Cerenkov readout by WLS.
Both with 2.4 ns decay time.
Preliminary Physics Studies

- Production of a single $Z^0$ in a fusion process:
  \[ \mu^+\mu^- \rightarrow \nu_{\mu} \nu_{\mu} + Z^0 \rightarrow \nu_{\mu} \nu_{\mu} q \overline{q} \]

- 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 (sig & bkg)

- ADRIANO calorimeter used in this study

- Recursive jet finder (from ILC studies)

- Full simulation, digitization and 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

---

**Energy spectrum of reconstructed jets**

<table>
<thead>
<tr>
<th>htmp</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
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<tr>
<td></td>
<td>9226</td>
<td>156.1</td>
<td>106.5</td>
</tr>
</tbody>
</table>

**Reconstructed Jet energy spectrum**

No cuts applied

1 bin = 5 GeV
$Z^0$ Mass with Different Nozzles

-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
- Background pick in endcaps
- Jet1
- Jet2
- Zoom in energy axis to see the background fluctuations
- ~200 GeV jet
- ~100 GeV jet

V. Di Benedetto
Baseline Detector for Muon Collider Studies

Timing Is The Key

Strategies To Reduce Clusters In The Tracking System

Reconstructed Background Tracks
(from Kalman Filter)

Dual-Readout Projective Calorimeter

Why MuC Detector R&D Is Important

But Do Not Forget Software

Conclusions

Introduction

Muon Collider Parameters

Sources of Background and Dynamic Heat Load

Background Supresses

10° Nozzle

ILCroot: root Infrastructure for Large Colliders

Simulation steps in ILCroot:

Tracking system

Fast simulation and/or fast digitization also available in ILCroot for tracking system

Digitization and Clusterization of Si Detectors in ILCroot:
a description of the algorithms available for detailed tracking simulation and studies.

Technologies Implemented

SDigitization in Pixel Detector (production of summable digits)

SDigitization in Pixels (2)

Digitization in Pixels

Clusterization in Pixel Detector

Parameters used for the pixel tracking detectors in current MuX studies

Clusterization in Strip Detector

SDigitization in Strips Detector

SDigitization in Strips (2)

The Parameters for the Strips

Track Fitting in ILCroot

Kalman Filter (classic)

Parallel Kalman Filter

VXD Standalone Tracking

Effect of the 10° nozzle

Physics vs Background in Det. B:
A strategy to disentangle reconstructed tracks from IP

Physics vs Background in Det. B:
A strategy to disentangle reconstructed tracks from IP

Reconstructed Background Tracks
(from Kalman Filter) after 2 and IP cuts

Effects of background Hits on Physics

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

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

Longitudinal energy deposition produced in the calorimeter