~ 1963

- What does the time frame of 1963 look like?

Me
L. B. Okun, Weak Interaction of Elementary Particles, Reading, Massachusetts; Pergamon Press, 1963

Based on lectures given in 1960 and 1961 (published first in Russian in 1963)
Chapter 19: What is to be measured, and why?

Enumerates 17 tests of general properties of the electroweak theory

- CP-invariance
- $\mu \rightarrow e \gamma$
- Two kinds of neutrinos
- ...
Many of the fundamental questions, and the specific processes to be studied, have been with us for a long time.

Fundamental breakthroughs have been accomplished through:
- New facilities
- New, transformational, experimental detection techniques
1963 – Today

- Many of the fundamental questions, and the specific processes to be studied, have been with us for a long time
- Fundamental breakthroughs have been accomplished through
  - New facilities
  - New, transformational, experimental detection techniques
- Already recognized in 1963. Premise of Lev Okun is that what is needed is improvements in experimental techniques

In the first square, we encounter at once a process which has not as yet been observed experimentally. This is the … your choice here … The theoretically predicted cross section for this process is so small that it cannot be detected without an essential improvement in experimental techniques.
Outline

- Two Thresholds
  - The Threshold of Promise
  - The Threshold of Challenge

- The value of direct precision measurements

- Future Experiments

- Illustration of new detector technologies

- Concluding remarks
The LHC has brought us to the threshold of discovery for new physics, and we expect to cross it, ...... momentarily ?

Will deliver .......... what it will deliver remains to be seen

We’re at the dawn of a new era where, no matter what, new frontiers will be explored !
Completing the Standard Model

- The present theory - the Standard Model - is a remarkable intellectual construction.

- Every particle physics experiment ever done - even though it pertains to only ~4% of visible matter - fits in this framework.

- But, the theoretical calculations are valid only with an ingredient that has not yet been observed — the notorious Higgs boson.

- The Higgs mechanism is the central issue in particle physics.
The Higgs Model

- The Higgs is different!
- Higgs is the only scalar particle in the SM
  - All the matter particles are $s = \frac{1}{2}$ fermions
  - All the force carriers are $s = 1$ bosons
- Postulated to give rise to mass through spontaneous electroweak symmetry breaking
  - Also to neutrino's if Dirac particles
- It would be the first fundamental scalar ever discovered
- Frankly, almost nothing is known about the Higgs
  - Nothing is known for the Yukawa-coupling
  - Nothing is known for the Higgs self-coupling
  - Single Higgs? Two Higgs field doublets? Additional singlet?
  - SUSY? MSSM? NMSSM? Extra-dimensions?
  - If the Higgs is discovered, mapping the potential is crucial

$$V(\phi) = \lambda \left( \phi^2 - \frac{1}{2} v^2 \right)^2$$
$$\phi = (v + H)/\sqrt{2}$$
$$m_H^2 = 2 \lambda v^2 = -2 \mu^2$$
The Threshold of Challenge: Beyond the LHC

- However promising the LHC, the field needs to plan beyond the LHC
- The next generation of detectors at all three frontiers - intensity, energy, cosmic - are extremely challenging

Challenges:
- Precision physics
- Cost
- Complexity
- Continuance

- Often, a scaling of existing technologies is difficult to justify
The Year 2000

  - An excess of $3\sigma$ beyond the background expectation was found, consistent with a Higgs boson with a mass near $114\text{GeV}/c^2$
    - LEP was running at $\sqrt{s} = 209 \text{GeV}$
  - Three candidate events for Aleph:
    - $M_{\text{rec}} = 110.0 \text{ GeV}$
      - three b-tags
    - $M_{\text{rec}} = 112.9 \text{ GeV}$
      - four b-tags
    - $M_{\text{rec}} = 114.3 \text{ GeV}$
      - two b-tags
  - LEP end result was an upper limit of $m_H > 114.4 \text{ GeV}$ at 95% CL

Each LEP experiment had a silicon strip vertex detector

<table>
<thead>
<tr>
<th>Layers</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
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<tbody>
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<td>6.6 / 9.2 / 10.6</td>
<td>6.4 / 7.9</td>
<td>6.1 / 7.4</td>
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<td>25</td>
<td>30</td>
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<tr>
<td>$\sigma_z$ (μm)</td>
<td>34</td>
<td>34</td>
<td>130</td>
<td>24</td>
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<tr>
<td>MS term (μm)</td>
<td>70</td>
<td>70</td>
<td>80</td>
<td>100</td>
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</tbody>
</table>

Precision detectors: $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \mp 10/(p \sin^{3/2} \theta) \mu m$

$\sigma_z = \sigma_{hit} \sqrt{1 + \frac{r_i}{r_o}}$

What would have happened if $R_{in}$ was much smaller?

Or with slightly better technology?
Indirect Constraints

- In SM sensitivity through loop corrects.
- Standard / Complete fit: all data except/including results from all direct Higgs searches
- Fit to all ewk measurements with five floating parameters:
  - $m_Z, m_H, m_t, \Delta \alpha_{\text{had}}(5)(m_Z), a_s(m_Z)$
- Standard fit:
  - $m_H = 84 + 30/-23$ GeV
  - 2σ interval: [42, 159] GeV
- Complete fit:
  - $m_H = 120.6 + 17.0/-5.2$ GeV
  - 2σ interval: [114, 155] GeV

http://Gfitter.desy.de/
Indirect Constraints

- Higgs mass constraints from the most sensitive observables
  - Tension between $m_W$, $A_t(SLD)$, and $A_{FB}^{0,b}$
- Exclude all sensitive parameters, except the one listed
  - $A_{FB}$ best reproduced with $m_H = 562$ GeV
  - The converse is also interesting: omit just $A_{FB}$; best fit $m_H = \sim 61 \pm 30/-26$ GeV
- All results compatible with each other at the 2.5$\sigma$ level (http://gfitter.desy.de)
Today

- Result from global fit to all electroweak data in $m_{\text{top}} - m_H$ plane
2017?

- Including ATLAS and CMS results
Precision

- The current indirect indications on the Higgs have an interesting spread

- If discovered: precision needed
  - Model independent measurement of absolute Higgs branching ratios
    - Not possible at LHC
    - Top quark Yukawa coupling: (ttH) signal seems out of reach at LHC
    - Higgs self-coupling (nearly) impossible at the LHC

- If not discovered: precision needed
  - Deep probes of the Standard Model required to find clues to the mechanism of electroweak symmetry breaking

- The LHC is certainly a discovery machine; the absolute precision will most likely come from a second view (with a lepton machine)
Future Collider Projects

- The community is exploring a lepton collider, which fully complements the LHC, as the next highest priority machine.
- In fact, there are four projects being discussed:
  - **sLHC**: upgrade of the LHC
    - Increase in luminosity by factor of 10
  - **ILC**: International Linear Collider
    - $e^+e^-$ collider based on SRF technology
    - $\sqrt{s} = 500$ GeV – 1 TeV
  - **CLIC**: $e^+e^-$ collider based on warm X-band technology
    - $\sqrt{s} = 3$ TeV
  - **Muon Collider**: $\sqrt{s} = 3$ TeV
Physics Environments

- Physics environments of LHC and ILC are radically different
  - Small, democratic cross sections
  - $W / Z$ separation in hadronic mode
- Emphasis on precision
  - Leptons are elementary particles
## Design Challenges

### Physics

- **Unambiguous identification of multi-jet decays of Z’s, W’s, top, H’s, χ’s,**
  
  \[
  ZHH
  \]

- **Higgs recoil mass and SUSY decay endpoint measurements**
  
  \[
  ZH \rightarrow \ell^+\ell^-X
  \]

- **Full flavor identification and quark charge determination for heavy quarks**
  
  \[
  ZH, H \rightarrow c\bar{c}, b\bar{b}, ...
  \]

- **Full hermiticity to identify and measure missing energy and eliminate SM backgrounds to SUSY**
  
  \[
  \tilde{u} \text{ decay}
  \]

- **The unexpected**
## Design Challenges

### Physics

- Unambiguous identification of multi-jet decays of Z’s, W’s, top, H’s, χ’s,

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\[
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\]

- Full hermiticity to identify and measure missing energy and eliminate SM backgrounds to SUSY

- The unexpected

### Detector

- Demands unprecedented jet energy resolution

\[
\frac{\sigma_{E_{jet}}}{E_{jet}} = 3\%
\]

- Pushes tracker momentum resolution

\[
\sigma(1/p_T) = 5 \times 10^{-5} \text{ (GeV}^{-1})
\]

- Demands superb impact parameter resolution

\[
\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2} \theta)
\]

- Instrumented forward region

\[
\Omega = 4\pi
\]

- Smarts
The next generation of (collider) detectors, which will have to improve significantly on the then current measurements coming mainly from the LHC, are required to be precision instruments:

- Physics requires it
- Configuration of future projects requires it
- The field itself requires it

The next generation detectors cannot be evolutionary, they have to be revolutionary!

Need to invest in transformational technologies.
The seeds for new transformational technologies have been planted in several areas:

- **Calorimetry**
  
  Requirement: 
  Factor of two better than best to date

- **Photo detection**

  Requirement: 
  Large PDE, large area, B-field insensitive, cost

- **Tracking**

  Requirement: 
  Factor of 10 (3) better than LEP (CMS)

- **3D Silicon**

  Requirement: 
  Factor of 3 better than SLD

...
Photo Detection
Photo Multiplier Tubes

- “Old” Technology
  - Used for decades
  - Robust, generally low noise
  - Simple biasing
- Time resolution ~2-3 nsec
- Spatial resolution limited by tube radius
- Total coverage offered is typically less than 40%
- Typical photocathode efficiency ~25%
- Few vendors

Can this technology address the challenges of the next generation of H$_2$O Čerenkov experiments?
Large-Area Pico-second Photo Detector (LAPPD)

- Newly funded by DOE and NSF (fall '09)
  - 4 National Labs
  - 5 Divisions at Argonne
  - 3 US small companies;
  - Electronics expertise at UofC and Hawaii
  - Photocathode expertise at Washington University, St. Louis and UIC

- Premise:
  - Apply advances in material science and nanotechnology to develop new, batch methods for producing cheap, large area photo-detectors
  - Continued improvement in at least one parameter by an order of magnitude
  - Develop path to a commercializable product on a three year time scale (Currently approaching the end of year 2)
LAPPD Goals

- Project with four primary goals:
  1. Large-Area Low-Cost Photo-detectors with good correlated time and space resolution (target 10 $/sq-in incremental area cost)
  2. Large-Area TOF particle/photon detectors with pico-second time resolution
      - < 1psec at 100 photo-electrons
  3. Understanding photo-cathodes so that we can reliably make high QE cathodes with tailored spectral response, and develop new materials and geometries
      - QE > 50%?, public formula
  4. Produce commercializable modules within 3 years
     - transfer technology to industry
LAPPD Approach

- **Base on Existing Technology: Micro Channel Plate (MCP) photo-multiplier**
  - Picosecond-level time resolution
  - Micron-level spatial resolution
  - Excellent photon-counting capabilities
  - Expensive

- **New Aspect: Fully Integrated Approach**
  - Exploit advances in material science and electronics to produce large-area MCP-PMTs:
    - Preserve time and space resolutions of conventional micro-channel plate detectors
    - At low enough cost per unit area
1. Photo-Cathode (PC)
   - Conversion of photons to electrons
   - Engineer III-V materials to develop robust high QE photo-cathodes

2. Micro-Channel Plates
   - Amplification of signal: two plates with tiny pores, held at high potential difference. Use Atomic Layer Deposition for emissive material on inert substrates to create avalanche

3. Transmission line, high speed readout
   - Anodes is a 50Ω scalable strip line silk-screen printing on glass ground plane (Borofloat 33)

4. Hermetic Packaging
   - Maintain vacuum and provide support. No internal connections; no penetrations

5. Electronics
   - Readout at both ends with fast custom CMOS SCA chip with 10GHz waveform digitization
LAPPD Deconstructed

1. Photo-Cathode (PC)
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Photo-Cathode Thrusts

- Space Science Laboratory, Berkeley: R&D focus on scaling up of traditional bi-alkali to larger area

- ANL/Wash U/UICU: R&D focus on theory inspired design
  - New novel photocathode technologies like nano-structured photocathodes
  - III-V have the potential for high QE, shifting toward the blue and robustness
  - Simulations, testing & characterization

- Argonne: R&D focus on design for industrial production of large-area photocathodes for a tile factory
  - In the process of setting up in-house photo-cathode production facility
MCP Development: Simplifying Construction

- Chemically produced and treated
- Pb-glass provides 3 functions:
  - Provides pores
  - Resistive layer supplies electric field in the pore
  - Pb-oxide layer provides secondary electron emission

Separate the three functions:
- Hard glass substrate provides pores
- Separate Resistive and Emissive layer functions
- Produce Tuned Resistive Layer (Atomic Layer Deposition, ALD) provides current for electric field
- Specific Emitting layer provides secondary electron emission
MCP Fabrication with ALD

- Start with glass capillary array (borosilicate), pulled to appropriate pore size

- Obtained MCP arrays with 33mm diameter, pore size 5 μm
- Goal is L/D = 40, D = 5 μm, 8”x8”
MCP Fabrication with ALD

- Apply resistive coating, 17nm, using Atomic Layer Deposition, in Beneq reactor
MCP Fabrication with ALD

- Apply emissive $\text{Al}_2\text{O}_3$ layer, using Trimethyl Aluminum $\text{Al(CH}_3\text{)}_3$ and ALD

- Wide parameter space studied
  - Relative composition of materials
  - Temperature for ALD
  - Different materials and thicknesses
MCP Fabrication with ALD

- Apply conductive coating for HV, using thermal evaporation or sputtering

- First time applying new technology, a factor >5 improvement obtained in gain of ALD treated MCPs compared to commercial MCPs; area will be substantially increased
MCP Testing

- Full laser test setup with fs laser at APS
  - Clean UV beam
  - Laser power monitoring
  - Position scan
  - Absolute laser arrival time on MCP (in progress)

- Results compared with simulation
Anode and Signal Readout

- Sealed tile construction: all glass
- Anode:
  - Silk-screened, no pins, penetrations, no internal connections
  - Transmission line readout both ends gets position and time
  - Signal is differential between ground (inside, top), and PC traces (outside)
  - Simulations indicate that these transmission lines could be scalable to large detectors without severe degradation of resolution.
- Cover large areas with much reduced channel count.
- Tile Factory being setup
Resolution depends on # photoelectrons, analog bandwidth, and signal-to-noise.

Simulations showed “pulse sampling” to give the best results.

ASIC (PSEC3) designed by UofC / Hawaii
- 130nm IBM Process
- 4 channels, 256 deep analog ring buffer
- Sampling tested at (almost) 18 GS/sec
- Each channel has its own ADC- 10 bits effective
- Fastest waveform sampling chip by a factor of ~3
Hermetic Packaging

- All glass hermetic package:
  - Use inexpensive borosilicate glass for containment vessel
  - Avoid use of pins penetrating glass for HV and signal
  - Cheap, reliable, reproducible containment vessel fabrication

- Constraints:
  - Support vessel against implosive atmospheric pressure
  - Top photocathode window seal at low temp. (<120 °C)
  - ~10 yr stability for seal with small leak rate
  - Minimum handling steps in fabrication
  - Avoid particulates in vacuum space
  - Materials chemically compatible with alkali metal photocathode
Construction of (Mock) Tile

2.97mm bottom Grid Spacer → add Mock MCP → add functionalized MCPs → add 1.1mm Grid spacer

Add mock MCPs, 33mm functionalized MCPs & top 1.1mm Grid spacer → full stack in mock tile → Mock tile after sealing and evacuation
Simulation and Testing

Microscopic/Materials-Level

Material Science Division, ANL
Constructing dedicated setup for low-energy SEE and PE measurements of ALD materials/photocathodes.
parts-per-trillion capability for characterizing material composition.

Berkeley SSL
Decades of experience.
Wide array of equipment for testing individual and pairs of channel plates.
Infrastructure to produce and characterize a variety of conventional photocathodes.

Macroscopic/Device-Level

HEP Laser Test Stand, ANL
Fast, low-power laser, with fast scope.
Built to characterize sealed tube detectors, and front-end electronics.
Highly Automated

Advanced Photon Source, ANL
Fast femto-second laser, variety of optical resources, and fast-electronics expertise.
Study MCP-photocathode-stripline systems close to device-level. Timing characteristics amplification etc.
**Applications**

- **Collider Detectors:**
  - At colliders 3-momenta of hadrons are measured.
  - Cannot follow the flavor-flow of quarks, the primary objects that are colliding.
  - Superb time resolution would allow measurement of true 4-momenta.

- **Large area H$_2$O Čerenkov detectors**
  - Pico-second timing resolution could allow for $\pi^0/e$ rejection.
    - 100 ps time resolution along the photon direction.
    - Corresponds to about 3 cm space resolution.
    - Vertex separation many cm.
3D Silicon
Vertical Integrated Circuits – 3D

- "Conventional MAPS"
  - Pixel electronics and detectors share area
  - Fill factor loss
  - Co-optimized fabrication
  - Control and support electronics placed outside of imaging area

- 3D Vertical Integrated System
  - Fully active sensor area
  - Independent control of substrate materials for each of the tiers
  - Fabrication optimized by layer function
  - Local data processing
  - Increased circuit density due to multiple tiers of electronics
  - 4-side abutable

- Technology driven by industry
  - Reduce R, L, C for higher speed
  - Reduce chip I/O pads
  - Provide increased functionality
  - Reduce interconnect power, crosstalk
3D R&D

- Example of R&D being carried out at MIT-LL

Six inch wafer thinned to 6 microns and mounted to 3 mil kapton.

4 Mb SRAM with 30 million transistors

Photos
MIT-LL
Fermilab and 3D

- Fermilab initiated a design effort in the 3D technology
  - Designed pixel array 64x64, 20x20 $\mu$m$^2$ pixels for a vertex detector in an ILC environment
  - 3-tier MIT-LL SOI process
    - Provides analog and binary readout information
    - 5-bit Time stamping of pixel hit (ILC environment)
    - Token passing, sparse readout

- Established 3D consortium with Multi-Project Wafer runs
Options

- Separation of different functions in separate layers

- FE electronics bonded to separate sensing element
The enabling technology for fine segmented dual readout calorimetry is pixelized photon detectors.

- Aka: SiPM (Silicon Photo-Multiplier), GM-APD (Geiger-Mode APD), SPAD (Single Photon Avalanche Diode), MPPC (Multi-Pixel Photon Counter).

Pixelized Photon Detector (PPD) is an avalanche photodiode operating in Geiger-mode.

- Array of pixels connected to a single output.
- Signal = Sum of all cells fired.
  - Very compact, High PDE (15~20% for 1600 pix).
  - Low bias voltage operation.
  - High thermal noise rate, x-talk and after-pulsing.
  - Insensitive to magnetic field.
- Portrayed as potential replacement of PMT.

It is an enabling technology for many applications.
True Digital SiPM

- True digital pixel devices can have appealing features
  - low power consumption, fast timing, response is a digital number proportional to number of hit pixels, masking untrusted pixels, triggering on number of hit pixels to mask dark rate, etc

Applications: X-ray counting, PET scanning, calorimetry, ...

Digital 3D SiPM concept

Front illumination

- top tier = SiPM wafer thinned to 6-10 \( \mu m \)
- bottom tier = ROIC wafer full thickness \( \sim 700 \mu m \)

Digital output

Logic:
- DT (digital threshold)
- TC (timing circuitry)
- DO (digital output)

AQ (active quenching)
- BC (bias control)
- DD (discharge detection)
- DP (digital pulse)

Digital lines detect digital pulses in time window
Track Trigger for LHC

- Form a track-trigger at the first trigger level
  - Momentum filter using a pair of Si sensors separated by ~1mm
  - Interconnected vertically
  - Local hit processing

- Data flow is vertical!
  - Hit data from one sensor processed in local ASIC
  - Hit data from other sensor transmitted through interposer
  - Data correlated in ASIC, trigger decision formed
Triumphs of Instrumentation

Digital Cameras the Size of Cathedrals

Sept. 15, 2008
Cathedrals

- Our current experiments are cathedrals of science!
- Our future experiments are (bigger?) cathedrals of science!

- Have we become cathedral builders?
  - Time scale of experiments
  - Size of experiments
  - Cost of experiments
  - Complexity of experiments
  - Erosion of knowledge

- Is there a limit?

- Renewed investment in fundamental, scalable technologies needed

Cologne start 1248; completed 1880
# Discoveries in Physics

<table>
<thead>
<tr>
<th>Facility</th>
<th>Original purpose, Expert Opinion</th>
<th>Discovery with Precision Instrument</th>
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</thead>
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<td>P.S. CERN (1960)</td>
<td>$\pi$ N interactions</td>
<td>Neutral Currents -&gt; Z, W</td>
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<tr>
<td>AGS Brookhaven (1960)</td>
<td>$\pi$ N interactions</td>
<td>2 kinds of neutrinos, Time reversal non-symmetry, New form of matter (4$^{th}$ Quark)</td>
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<td>FNAL Batavia (1970)</td>
<td>Neutrino physics</td>
<td>5$^{th}$ Quark, 6$^{th}$ Quark</td>
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<td>SLAC Spear (1970)</td>
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<td>Partons, 4$^{th}$ Quark, 3$^{rd}$ electron</td>
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<td>ISR CERN (1980)</td>
<td>PP</td>
<td>Increasing PP Cross section Gluon</td>
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<td>PETRA Hamburg (1980)</td>
<td>6$^{th}$ Quark</td>
<td></td>
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<tr>
<td>Super Kamiokande (2000)</td>
<td>Proton decay</td>
<td>Neutrinos have mass</td>
</tr>
</tbody>
</table>

- **Hubble Space Telescope**
  - Galactic survey
  - Curvature of the universe, dark energy

*Exploring a new territory with a precision instrument is the key to discovery.*

Samuel Ting, La Thuile 2006
Concluding Remarks

- The field is at the dawn of an era with fundamental consequences for the field

- A renewed emphasis on instrumentation is needed entering this new era of physics for the viability of the field

- It is the instruments that are the enablers of science, pure and applied

- Transformational new technologies are emerging. The physics, the challenges of the new projects and, our field itself requires investing in and developing these scalable, transformational technologies for (particle) physics
Backup Slides
Calorimetry
Calorimetry

- **Goal:** $\sigma(E)/E \sim 3-4%$
  - Ability to separate $Z \rightarrow qq$ from $W \rightarrow qq'$

- **Paradigms:**
  - Total Absorption Calorimetry
  - Particle Flow Algorithm (PFA)

- **Enabling Technologies:**
  - New generation of Photon Detectors
  - Highly integrated microelectronics

---

Brookhaven -- M. Demarteau, May 11, 2011
Total Absorption Hadron Calorimetry

- Total absorption calorimetry proven to be highly successful for EM calorimeters
  - Crystal Ball: “Castles in the sky”

- Extend to hadron calorimeters using dual readout and the enabling technology of Pixelated Photo Detectors

- Current crystal technology can be used to demonstrate concept
- Better suited crystals or glasses can be developed later
Dual Readout Calorimetry

- Dual-Readout: measure every shower twice
  - Scintillation light: measure of total energy released in the calorimeter
    - Prop. to total path length of all charged particles
  - Čerenkov light: measure of the EM component of shower
    - Prop. to total path length of the relativistic particles in the shower, $\beta > 1/n$ particles

- Calibrate $C=S$ for electron showers

- Correct on a shower-by-shower basis using the correlation of the total observed ionization ($S$) and Čerenkov ($\hat{C}$) light
Dual Readout Simulation

- Model total absorption calorimeter
  - In addition, BGO with twice the density: 15 g/cm³
  - Calibrate with electrons
    - Define scintillator signal to be electron energy
    - Small correction for clustering
    - Normalize Čerenkov signal: Č = S

<table>
<thead>
<tr>
<th>Name</th>
<th>Layers</th>
<th>Thickness/Layer (cm)</th>
<th>Segmentation (cm x cm)</th>
<th>BGO</th>
<th>PbWO₄</th>
</tr>
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<tbody>
<tr>
<td>ECAL Barrel</td>
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<td>3</td>
<td>3 x 3</td>
<td>21.4</td>
<td>1.1</td>
</tr>
<tr>
<td>HCAL Barrel</td>
<td>17</td>
<td>6</td>
<td>5 x 5</td>
<td>4.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Total Barrel</td>
<td>25</td>
<td></td>
<td></td>
<td>5.8</td>
<td>7</td>
</tr>
<tr>
<td>ECAL Endcap</td>
<td>8</td>
<td>3</td>
<td>3 x 3</td>
<td>21.4</td>
<td>1.1</td>
</tr>
<tr>
<td>HCAL Endcap</td>
<td>17</td>
<td>6</td>
<td>5 x 5</td>
<td>4.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Total Endcap</td>
<td>25</td>
<td></td>
<td></td>
<td>5.8</td>
<td>7</td>
</tr>
</tbody>
</table>

10 GeV electrons
σ/E = 0.017 Scintillator
σ/E = 0.052 Čerenkov

A. Para
H. Wenzel
Dual Readout Simulation

- Derive correlation between C/S and S/E using single pions

- Various parametrizations fitted (for different energies)
Dual Readout Simulation

- Corrected single pion response

BGO dense (15 g/cm³)

Events

Single pion response:
15% stochastic term

Different curves
different physics models

W and Z separation in jets

Brookhaven -- M. Demarteau, May 11, 2011
The enabling technology for fine segmented dual readout calorimetry is pixelized photon detectors

- Aka: SiPM (Silicon Photo-Multiplier), GM-APD (Geiger-Mode APD), SPAD (Single Photon Avalanche Diode), MPPC (Multi-Pixel Photon Counter)

Pixelized Photon Detector (PPD) is avalanche photodiode operating in Geiger-mode

- Array of pixels connected to a single output
- Signal = Sum of all cells fired
  - Very compact, High PDE (15~20% for 1600 pix)
  - Low bias voltage operation
  - High thermal noise rate, x-talk and after-pulsing
  -Insensitive to magnetic field
- Portrayed as potential replacement of PMT

It is an enabling technology for many applications
Some ILC Parameters

- **Time structure**
  - five trains of 2625 bunches per second (5 Hz repetition rate)
  - bunch separation is 369.2 ns (LEP: 22 μs)

- **Readout options driven by physics**
  - Once per train; time stamping sets time resolution
  - Once per bunch

- **Duty cycle** (1 ms of data - 199 ms idle) allows for “power pulsing”
  - Switch power to quiescent mode during idle time

- **Single IR with 14 mrad crossing angle**

- **Beam size:** $\sigma_x = 640 \text{ nm}$, $\sigma_y = 6 \text{ nm}$
Some CLIC Parameters

- **Time structure**
  - fifty trains of 312 bunches per second (50 Hz repetition rate)
  - bunch separation is 0.5 ns (ILC: ~370 ns)

- **Beam size**
  - $\sigma_x = 40$ nm, $\sigma_y = 1$ nm

- **Duty cycle**: 156 ns of data - 20 ms idle
  - Power pulsing at 50 Hz

- **10 CLIC trains for one ILC train**
- With current technology, cannot read out single bunch crossings
- Integrate readout over full bunch train with time stamping
Some CLIC Parameters

- **Time structure**
  - fifty trains of 312 bunches per second (50 Hz repetition rate)
  - bunch separation is 0.5 ns (ILC: ~370 ns)

![Diagram showing time structure]

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### Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>ILC</th>
<th>CLIC</th>
<th>$\mu^+\mu^-$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (TeV)</td>
<td>14</td>
<td>0.5</td>
<td>3</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>L ($10^{34}$cm$^{-2}$s$^{-1}$)</td>
<td>2</td>
<td>2</td>
<td>5.9</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Bunch X (ns)</td>
<td>25</td>
<td>369</td>
<td>0.5</td>
<td>3800</td>
<td>6400</td>
</tr>
<tr>
<td>Nb</td>
<td>2808</td>
<td>2625</td>
<td>311</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Train duration</td>
<td>70 ms</td>
<td>1 ms</td>
<td>156 ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>40M</td>
<td>5</td>
<td>50</td>
<td>65</td>
<td>32</td>
</tr>
</tbody>
</table>

- The ILC and CLIC are single-pass machines
- The LHC is a CW machine and a Muon Collider has about 1000 turns before the muons decayed away
A major issue, that could determine the viability of the physics program at a future project, are the backgrounds.

Background sources:
- Beam-beam backgrounds at IP
  - Beamstrahlung
  - Pair and hadron production
  - secondary neutrons
- Machine produced background before IP
  - Beam tails from linac
  - Synchrotron radiation
  - Muons, beam-gas scattering
- Spent beam background
- Decays of colliding particles

Affects detector performance and design
- Detector component radiation aging and damage.
- Reconstruction of background objects
- Deterioration of detector resolution (e.g., jets energy resolution due to extra energy from background hits).
Muon Collider Backgrounds

- Background at a muon collider is ferocious due to muon decay
  - Decay length for 0.75 TeV muons is $4.7 \times 10^6$ m.
  - With $2.1 \times 10^{12}$ muons/bunch: $4.28 \times 10^5$ decays/m in a single pass
  - Creates a background at the level of 0.5 kW/m in the tunnel!

- Previously addressed by solid tungsten cone of 20° in the detector volume
  - Seriously impact on the physics

- Recent study with updated geometry
  - 6° tungsten cone
    - http://indico.fnal.gov/conferenceDisplay.py?confId=2855
Muon Collider Backgrounds

- Single 750 GeV bunch of $2 \times 10^{12}$ muons approaching from the right in the figures
- Detector model: $B_z = 3.5$ T, $6^0$ tungsten nozzle in a BCH$_2$ shell starting at $\pm 6$ cm from IP with $R=1$ cm at this $z$. 

![Neutron fluence: density/cm$^2$/bunch](image1)

![Photon fluence: density/cm$^2$/bunch](image2)
Muon Collider Backgrounds

- Compare machine background versus occupancy from physics event $\mu^+\mu^- \rightarrow Z \rightarrow q\bar{q}bar$

- With cone angle increased to 10°, 5σ inner radius up to 1m from IP, masks between FF quads, $e^-$ and $\gamma$ flux reduced by ~300

N. Mokhov
S. Striganov
Pair Production

- Beamstrahlung photons, beam particles or virtual photons all interact and create $e^+e^-$ pairs
  - Breit-Wheeler process ($\gamma\gamma \rightarrow e^+e^-$)
  - Bethe-Heitler process ($e^\pm\gamma \rightarrow e^\pm e^+e^-$)
  - Landau-Lifshitz process ($e^+e^- \rightarrow e^+e^-e^+e^-$)

- Geometry of vertex detector and vacuum chamber chosen in such a way that most of pairs do not hit the apertures
Muon Collider Schematic

- Muon Collider and Neutrino Factory

In present MC baseline design, Front End is same as for NF
X-Ray Imaging

- Integrating Pixel Imaging application
  - Application for X-ray photon correlation spectroscopy (XPCS) in collaboration with BNL to calculate autocorrelation function per pixel

- Functionality
  - 64x64 array of 80x80 μm² pixels
  - γ flux: 1000 γ/pixel/s
  - Dead timeless, triggerless operation
  - Sparsified binary readout (no energy information)
  - High speed frame readout time
  - 16 serial high speed LVDS output lines

- Pads for backside bump bonding allows for 4-side buttable arrays
Sensor Design

- Sensors need to be developed to be mated to the 3D circuits
  - Will allow for complete testing of technology
    - 3D circuits and bonded devices
    - Integrated devices with interposer
    - Test beam characterization
- Four sensors designs fabricated at BNL
  - CMS short strips
  - CMS long strips (not DBI bonded)
  - VIP
  - Imaging sensor
- Exploring sensor fabrication at XFAB
An Example: Higgs at an $e^+e^-$ Collider

- Model independent measurement of absolute Higgs branching ratios: key of EW-symmetry breaking; not possible at LHC
  - Establish $\Gamma(H \rightarrow ff) \sim m_f$
  - Key process is $ZH$ strahlung, with $Z \rightarrow \ell\ell$
  
  \[
  BR(H \rightarrow X) = \frac{[\sigma(HZ) \cdot BR(H \rightarrow X)]_{\text{meas}}}{\sigma(HZ)_{\text{meas}}} 
  \]

- Completely model independent
- Requires identification of all final state objects !!

- Higgs self-coupling determines the shape of the Higgs potential
  \[
  V = \frac{1}{2} m_H^2 H^2 + \frac{1}{2} \frac{m_H^2}{\nu} H^3 + \frac{1}{8} \frac{m_H^2}{\nu^2} H^4
  \]
  - tri-linear self-coupling (nearly) impossible at the LHC
  - quartic self-coupling impossible at the (S)LHC

- Top quark Yukawa coupling
  - LHC: $ttH$ signal seems out of reach