ILC Detector R&D

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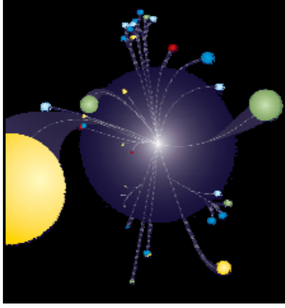


Marcel Demarteau

Fermilab

TWEPP07 – Prague, September 7, 2007

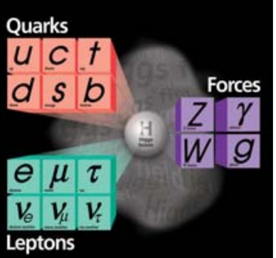
ILC Related Talks at this Meeting

- Significant fraction of presentations related to the ILC
- Talks:
  - Giulio Villani: A MAPS based readout for Tera-Pixel EM calorimeter at the ILC
  - Yasuo Arai: Electronics and Sensor Study with the OKI SOI process
  - Robert Wieland: 3D System Integration for high density interconnects
  - Christian Kreidl: Steering and Readout chips for DEPFET sensor matrices
  - Peter Murray: Development of an ASIC for readout of CCD's at the vertex detector of the ILC
  - Pierre Barrillon: MAROC, Multi-Anode Readout Chip
  - Christophe de la Taille: HARDROC, Hadronic RPC detector readout chip
  - Jean-François Genat: A 130nm CMOS evaluation digitizer chip for Si strip readout at the ILC
  - Peter Göttlicher: System aspects of the ILC electronics and power pulsing
  - Marc Weber: Power distribution for sLHC trackers: challenges and solutions
  - Giulio Villani: Serial powering of silicon sensors
- Posters:
  - David Cussans: A simple test beam trigger and event tagging unit for ILC test beams
  - Fréderic Dulocq: Digital part of SiPM integrated readout chip asic for ILC hadronic calorimeter
  - Enrico Pozzati: MAPS in 130nm and 90nm triple well CMOS technologies for HEP applications
  - Ludovic Raux: SPIROC, dedicated very front-end electronics for an ILC prototype hadronic calorimeter with SiPM readout
  - Julien Fleury: SKIROC, a front-end chip to readout the imaging Si-W calorimeter for the ILC

Slide 2

Status Quo

- The present theory – the Standard Model – is a remarkable intellectual construction
- Every particle physics experiment ever done – even though it pertains to only 5% 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
- One of the central issue is the Higgs mechanism



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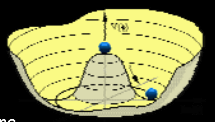
The Higgs Model

- The Higgs is different !
- Higgs is the only scalar particle in the SM
  - All the matter particles are s=½ 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



$$V(\varphi) = \lambda\left(\varphi^2 - \tfrac{1}{2}v^2\right)^2$$
$$\varphi = (v + H)/\sqrt{2}$$
$$m_H^2 = 2\lambda v^2 = -2\mu^2$$

- 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

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The LHC

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

- No matter what, new frontiers will be explored !

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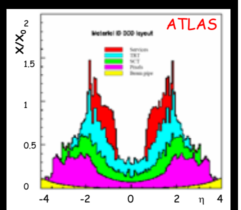
But …

- The LHC does have its (irreducible) limitations:
  - Physics limitations, e.g. in Higgs sector
    - Model independent measurement of absolute Higgs branching ratios
    - Top quark Yukawa coupling: (ttH) signal seems out of reach
    - tri-linear self-coupling (nearly) impossible; quartic self-coupling impossible
  - Detector limitations
    - Material distribution
    - Power issues
      - Atlas pixel system 10 kW of power
        - 3/3 barrel/disk layers, 1.8 m^2 of Si 80M channels
  - Collider limitations
    - Broad parton momentum distribution
    - Multiple interactions
    - No "dials", like polarization



- The LHC is certainly a discovery machine; the absolute precision will come from a (second) view with an e^+e^- machine

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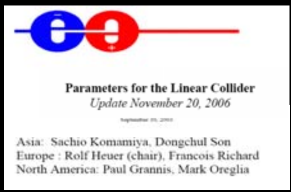
The ILC

- The community endorses an ILC, which fully complements the LHC, as the next highest priority machine
- Physics drives the ILC


Parameters for the Linear Collider
Update November 20, 2006
Asia: Sachio Komamiya, Dongchul Son
Europe: Rolf Heuer (chair), Francois Richard
North America: Paul Grannis, Mark Oreglia

http://www.linearcollider.org/newsline/pdfs/20061207_LC_Parameters_Novfinal.pdf

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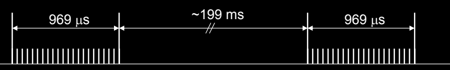
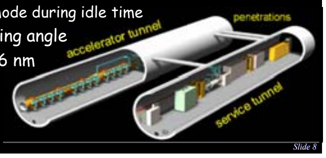
Some ILC Parameters

- Time structure
  - five trains of 2625 bunches per second
  - 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: σ_x = 640 nm, σ_y = 6 nm



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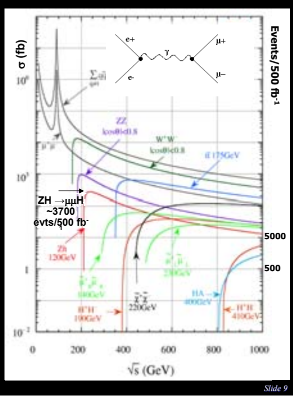
ILC Physics Characteristics

- Machine design luminosity $\mathcal{L} = 2 \times 10^{34}\ cm^{-2}s^{-1}$ ($\sqrt{s}$ = 500 GeV)
- Processes through s-channel spin-1 exchange: $\sigma \sim 1/s$
  - Cross sections relatively democratic
  - Cross sections are small
  - Angular distribution: $(1 + \cos^2\theta)$
    - Premium on forward region
    - Hermetic detectors
  - Relatively large backgrounds
    - 100k e^+e^- - pairs per bunchX
- Near perfect particle identification
  - Discriminate W and Z in hadronic decay mode
  - Distinguish quarks from antiquarks
- Highly polarized e^- beam: ~ 80%
  - To employ discriminating power requires running at both polarities



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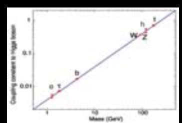
An Example: Higgs at the ILC

- Model independent measurement of absolute Higgs branching ratios: key of EW-symmetry breaking; not possible at LHC
  - Establish $\Gamma(H \to f\bar{f}) \sim m_f$
  - Key process is ZH strahlung, with Z→ ℓℓ

$$BR(H \to X) = \frac{[\sigma(HZ) \cdot BR(H \to X)]_{meas}}{\sigma(HZ)_{meas}}$$

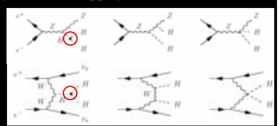
  - Completely model independent
  - Requires identification of all final state objects !!



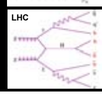
- Higgs self-coupling determines the shape of the Higgs potential

$$V = \frac{1}{2} m_H^2 H^2 + \frac{1}{2}\frac{m_H^2}{v} H^3 + \frac{1}{8}\frac{m_H^2}{v^2} H^4$$

  - 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



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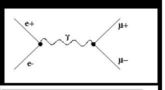
An Example: Polarization at the ILC

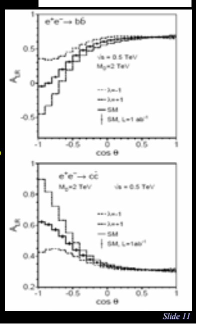
- Highly polarized e^- beam: ~ 80%

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma_{f\bar{f}}^{tot}\left[(1-\mathcal{P}_e A_e)(1+\cos^2\vartheta)+2(A_e-\mathcal{P}_e)A_f\cos\vartheta\right]$$

$$A_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2} \qquad A_b = 0.94 \quad A_c = 0.67 \quad A_l = 0.15$$



- Analyzing power of
  - Scan in center of mass energy
  - Various unique Asymmetries
    - Forward-backward asymmetry
    - Left-Right Asymmetry
  - Example: Model with extra dimensions
    - Coupling of graviton in 4-dimensions proportional to λ/M_D^4
    - Largest effects for b-quarks
      - $\sqrt{s}$ = 500 GeV, M_D = 2 TeV
      - $\mathcal{P}_e$ = 0.8, L = 1 ab^{-1}
    - Sensitivity is in the far backward region
    - No sensitivity for leptonic final states (A_e = 0.15)
- Hermetic detectors with uniform strengths
  - Importance of forward regions
  - b/c identification in forward region



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Specification for an ILC Detector

- ILC detectors are precision detectors: fully reconstruct the final state over the full angular region
  - Identify each and every particle, with high efficiency and high purity, over the full angular range
    - Differentiate between Z's and W's in their hadronic decay
    - Differentiate between b- and c-quarks
    - Differentiate between b- and anti-b quark
- Although these requirements are common drivers for all experiments, they are non-negotiable requirements for the ILC !

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The ILC Concept Detectors

Detector	Premise	Vertex Detector	Tracking	EM calorimeter	Hadron calorimeter	Sole-noid	Muon System
LDC	PFA	5-layer pixels	TPC Gaseous	Silicon-Tungsten	Analog-scintillator	4 Tesla	Instrumented flux return
GLD	PFA	6-layer fine pixel ccd	TPC Gaseous	Scintillator-Tungsten	Digital/Analog Pb-scintillator	3 Tesla	Instrumented flux return
SiD	PFA	5-layer silicon pixel	Silicon strips	Silicon-Tungsten	Digital Steel - RPC	5 Tesla	Instrumented flux return
4^{th}	Dual Readout	5-layer silicon pixel	TPC Gaseous	2/3-readouts Crystal	2/3-readouts Tungsten-fiber	3.5 Tesla	Iron free dual solenoid

- Requirements:
  - Impact parameter resolution: $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p \sin^{3/2} \vartheta)$
  - Momentum resolution: $\sigma(1/p_T) = 5 \times 10^{-5}\ (GeV^{-1})$
  - Jet energy resolution: $\sigma_E / E = (3-4)\%$

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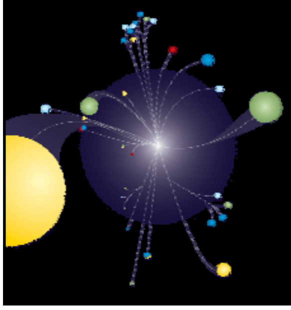
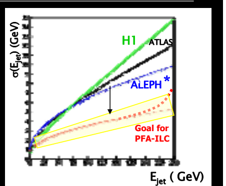


Calorimetry

Calorimetry

- Goal: $\sigma(E)/E$ ~ 3-4%
  - Ability to separate Z → qq from W → qq'
- Paradigms:
  - Dual or Triple Readout
  - Particle Flow Algorithm (PFA)
- Enabling Technologies:
  - New generation of Photon Detectors
  - Highly integrated microelectronics
- Strategies:
  - Digital versus Analogue readout



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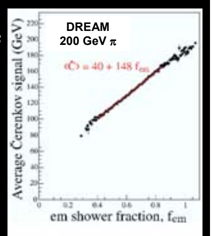
Multiple Readout Calorimetry

- Dual-Readout: measure every shower twice
  - Scintillation light: from all charged particles
  - Čerenkov light: β=1 particles, mainly EM
- By measuring separately both components can determine e/h fraction and correct the response (set e/h=1)
- Approaches:
  - Scintillating and quartz fibers embedded in Cu (DREAM);
    - no longitudinal segmentation
  - Leadglass-Scintillator sampling
  - Doped crystals



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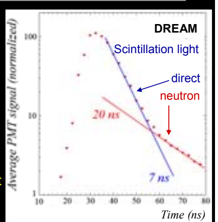
Multiple Readout Calorimetry

- Add measurement of third component:
  - "Traditional" compensating calorimetry
    - Suppress EM component (high Z absorbers)
    - Partially recover invisible hadronic energy
      - Capture slow neutrons in ^{238}U, emit low energy γ's
      - Collisions processes with hydrogen in scintillator
  - Use timing information of pulse formation
    - Neutron interactions have long time component
- Also exploit
  - PID though difference Scint. and Č – light
- R&D pursued by:
  - DREAM collaboration
  - Fermilab / Italian groups
  - University of Washington



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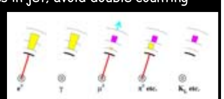
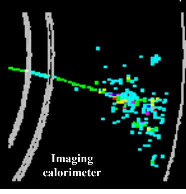
Particle Flow Algorithm

- The other paradigm to obtain better energy resolution: PFA
  - PFA: Reconstruct momenta of individual particles in jet; avoid double counting
    - Measure photons in the ECAL
    - Measure charged particles in the tracking system
    - Subtract calorimeter energy associated with charged hadrons
    - Measure neutral hadrons in the HCAL (+ ECAL)



- PFA: a brilliant idea !
- Novelty is in reducing the role of the hadron calorimeter – and thus the hadron energy resolution – to the measurement of neutral hadrons only
- Implications for the calorimetry
  - Granularity, longitudinal and transverse !
  - Sampling of the hadron calorimeter
  - Digital or analog readout



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Calorimeter Architectures

- One of the main drivers for imaging calorimeters is granularity
  - Need to separate energy deposits from different particles

	Electromagnetic		Hadronic	
Active element	Analogue	Digital	Analogue	Digital
Silicon	kPIX SKIRoc Cells ~0.5x0.5 cm^2	MAPS Cells ~50x50 μm^{22}	Too expensive	Too expensive
Scintillator	PPD readout	-	PPD readout Cells ~3x3cm^2	-
Gas	-	-	-	RPC GEM MicroMegas Cells ~1x1 cm^2

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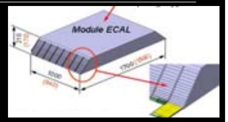
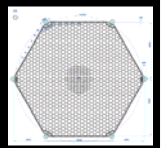
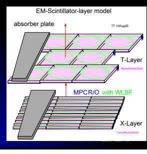
Analogue Electromagnetic Calorimeter

- Silicon-Tungsten sampling calorimeter
  - Total Si area (incl. endcaps) ~2000 m^2
  - Total number of channels up to 80×10^6
  - Average dissipated power 1-4 $\mu W/mm^2$
  - LDC approach:
    - Sensitive silicon layers are on PCBs
      - 1x1cm^2 pads, ~1.5m long × 30cm wide
    - Pad readout digitized to ~16 bits by VFE ASIC
  - SiD approach:
    - 6" hexagonal wafers with 1024 13 mm^2 pixels
    - Readout with one ASIC, connected to readout cable







- Scintillator-Tungsten sampling calorimeter
  - GLD approach:
    - Tile and strip configuration
    - WLS fiber readout with Photo-detector

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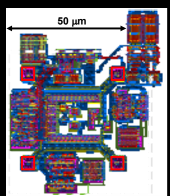
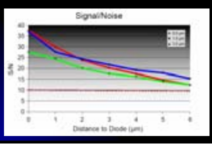
Digital Electromagnetic Calorimeter

- EM calorimeter based on Monolithic Active Pixel Sensors
  - Intrinsic high granularity through wafer processing
  - CMOS process cheaper than high resistivity pure silicon
- ECAL MAPS design
  - Binary readout, threshold adjustment for each pixel
  - Pixels 50μm×50μm, 4 diodes for Charge Collection
    - With ~100 particles/mm^2 in the shower core and 1% prob. of double hit the pixel size should be ~40 μm×40 μm
  - Prototype device with two types of readout
  - Time Stamping with 13 bits (8192 bunches)
  - Hit buffering for entire train, readout between trains
  - Capability to mask individual pixels
  - Total number of ECAL pixels around 8×10^{11}: Terapixels





- Device being simulated
  - Signal to Noise > 15 for 1.8 μm Diode Size
  - Critical issue for Terapixel system

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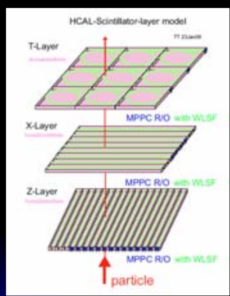
Analogue Hadron Calorimeter

- Planes of scintillator and absorber: GLD: z/x/T; LDC: tiles only



- Very high granularity
  - 4x4cm^2x5mm; 1x20cm^2x5mm (GLD)
  - 3x3 / 6x6 / 12x12 cm^2 tiles (Calice)
  - Each element read out separately
- Massive number of readout channels ~50M channels
- Photon detection of scintillator light
  - Collection through WLS fiber
  - Direct coupling of detector on scintillator
- Enabling technology: Geiger-mode Avalanche Photo Diodes

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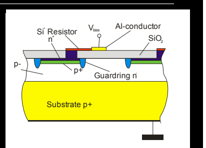
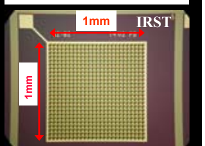
Geiger-mode Avalanche Photo Diode

- The technology that enables this high granularity is Geiger-mode Avalanche Photo Diodes (MRS, MPPC, SiPM, PPD)
  - Array of pixels connected to a single output
  - Signal = Sum of all cells fired; binary device !
  - If probability to hit a single cell < 1 → Signal proportional to # photons
- Characteristics:
  - Pros
    - Very compact
    - High PDE (15~20% for 1600 pix)
    - Insensitive to magnetic field
    - High gain (10^5~10^6)
    - Operational at V_{bias}=70~80 V
    - Good timing resolution
  - Cons
    - Thermal noise rate (100kHz~300kHz @ 0.5 pe)
    - Response is non-linear due to limited number of pixels (saturation effect)
    - Sensitive to temperature change
    - Cross-talk and after-pulsing
- Vendors
  - Hamamatsu, SensL, IRST, Mephi, Pulsar, CPTA/Photonique, Dubna/Mikron, Kotura, aPeak, …





3x3x0.5 cm^3 UNIPLAST 1 mm WLS Kuraray fiber Y11(300)

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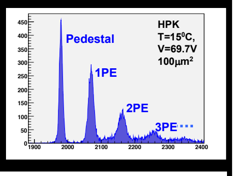
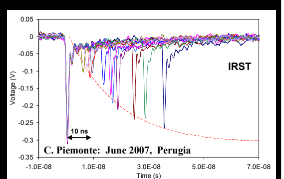
PPD Characterization

- Technology recently on production level scale, many aspects still to be understood
  - Static measurements
    - I-V curves, uniformity and stability
  - Dynamic tests (as function of V,T)
    - Dark count, Gain
    - Optical crosstalk, after-pulsing
    - Photo Detection Efficiency (PDE), QE
      - How to increase PDE
    - Signal rise time and fall time
    - Recovery time



- Example: single pixel test device
  - Events with after-pulses measured on a single micro-pixel
    - The amplitude of the after-pulse increases as the cell recovers to its operational condition



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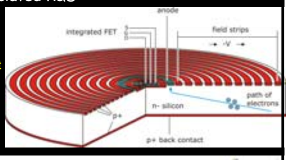
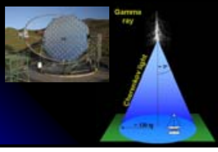
PPD R&D

- Broad range of applications with associated R&D
  - Back Illuminated Drift SiPM (Max Planck, Munich)
    - Each pixel of the array is a drift diode with a Geiger APD as amplifying element in the center
    - Increase PDE since light enters through homogeneous back side, not covered by any structure
  - T2K, L=295km, E~0.6GeV (KEK, Kobe, Kyoto, Shinshu, Tokyo)
    - ECal, pizero detector, Fine Grain detector
    - Total number of devices: ~60,000, number of pixel: ~500





- Imaging Air Čerenkov Telescope
  - MAGIC
- PET imaging

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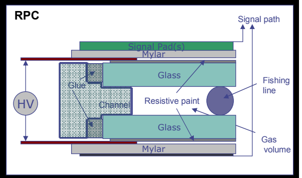
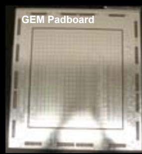
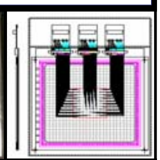
Digital Hadron Calorimetry

- Three technologies:
  - Resistive Plate Chamber (RPC)
    - Single gap
    - Coated glass as resistive plates
    - Avalanche mode
    - Readout pads ~1x1 cm²
  - Gas Electron Multiplier (GEM)
    - Separate drift and amplif. gap
    - Aiming at ~1x1cm² readout
  - Micro MEsh GAseous Structure
    - Fine mesh separates 3mm drift and 0.1mm amplification gaps
- R&D
  - Performance metrics
    - MIP detection efficiency uniformity
    - Readout multiplicity
    - Noise rate, rate capability
  - Gain experience in large scale and long-term operation and production
  - Identify critical operational issues



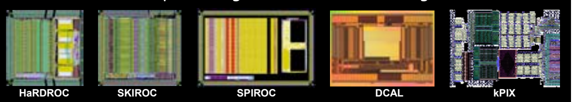




Slide 26

Calorimeter Readout

- An illustrious array of (2nd generation) ASIC's designed

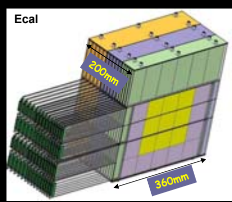


- HaRDROC (LAL)
  - Hadronic calorimeter RPC ROC
  - 64 channels, preamp + shaper+ 2 discrim. power pulsing
  - Serial output at 1 or 5 MHz
- SKIROC (LAL)
  - Silicon Kalorimeter Integrated ROC
  - 36 channels, 16 bit Preamp + bi-gain shaper + autotrigger + analog memory + Wilkinson ADC
- SPIROC (LAL)
  - SiPM ROC, 36 channels, self triggrd
  - Dynamic range: 1 pe → 2000 pe
  - 12 bit ADC and TDC: step ~ 100 ps – accuracy ~1ns
- DCAL (FNAL)
  - RPC and GEM digital HCAL
  - 64 channels, time stamp (100ns)
  - Smallest (largest) input signals: 100 (10pC) fC (RPC), 5 (100) fC (GEM)
  - Trigger-less or triggered operation
  - Serial output
- KPIX (SLAC)
  - Si EM calorimeter
  - 1024 channels, 4 buffers, single BX time stamping
  - Dynamic range: 3.8 fC - 8.0 pC
  - TSMC 0.25μm CMOS

Slide 27

The $64M Question

- ILC calorimetry: Will it work?
- CALICE collaboration in the process of mounting 1m³ prototype tests at CERN and Fermilab



- Ecal: silicon – tungsten
  - Active area of 18*18 cm²
  - 6x6 1x1cm² Si pads
  - Conductively glued to PCB
  - 30 layers, 24 X_0, 6.5k channels

- Hcal: scintillator – steel
  - Active area of 1x1x1 m³
  - 3x3/6x6/12x12 cm² Scint. tiles
  - 38 layers, 2cm steel plates
  - ~ 8000 tiles, SiPM readout

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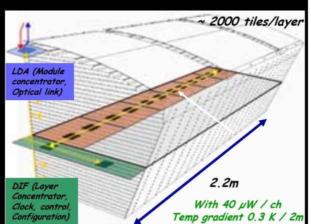
CALICE and Future Plans

- The 1 m³ tests carried out by Calice and others are critical
  - Need to establish the technology
    - Huge channel counts, fine granularity; digital versus analogue readout
    - GEMs and micromegas are novel for calorimetry
  - Need to establish the assembly techniques
    - Extremely tight mechanical and electrical integration
  - Need to establish the viability of the concept of PFA
    - Understand differences seen in simulation in scintillator and gas
    - Requires close coupling to Monte Carlo simulations
  - Need to establish scalability



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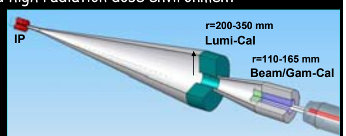
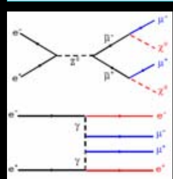
Forward Calorimetry

- Challenges for forward calorimetry are high precision and fast readout in high occupancy and high radiation dose environment
- Lumi-Cal (40-140 mrad)
  - Precise measurement of the integrated luminosity ($\Delta L/L \sim 10^{-3}$) using Bhabha's
  - Veto for 2-γ processes
- Beam-Cal (5-40 mrad)
  - Beam diagnostics using beamstrahlung pairs
  - Provide 2-γ process veto
- Gam-Cal (< 5mrad)
  - Beam diagnostics using beamstrahlung photons





Physics signal: e.g. SUSY smuon production

Background signal: 2-photon event, may fake the above signal if the electron is not detected.

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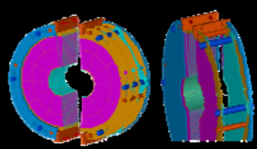
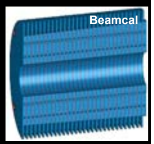
Forward Calorimeters

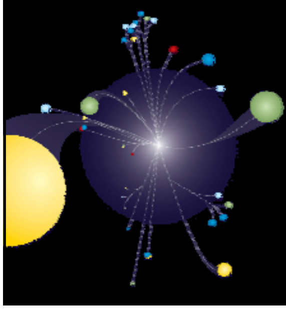
- Lumi-Cal
  - Si/W calorimeter, 30-40 layers
  - laser position monitoring system

ΔL/L	1.0 10^{-4}
inner radius	4.2 μm
radial offset	640 μm
distance	300 μm



- Beam-Cal
  - Sensor/W calorimeter, 30 layers
  - Radiation dose: ≈ 500 MRad/annum
    - Energy deposit of ~200 TeV per beam crossing
  - Sensors:
    - Polycrystalline Chemical Vapor Deposit Diamond sensors
      - Element Six_{TM}
      - Fraunhofer Institute for Applied Solid-State Physics – IAF
    - GaAs sensors
    - SiC
    - radiation hard silicon





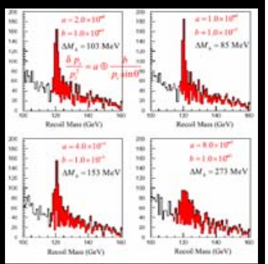
Tracking

Tracking

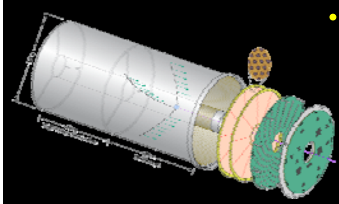
- Goal:
  - Superb momentum resolution

$$\frac{\delta p_T}{p_T^2} = 2-5\cdot10^{-5} \oplus \frac{1\cdot10^{-3}}{p_T \sin\vartheta}$$

  - Robust pattern recognition and good two track separation
  - Tolerant to high machine background
- Paradigms:
  - Silicon Tracking
    - •superb position resolution
    - •compact tracker
  - Time Projection Chamber (TPC)
    - many space points (~200)
    - Two track resolution <2/5-10mm (r,ϕ)/(r,z)
- Enabling Technologies:
  - Advances in Si processing
  - Precision TPC readout



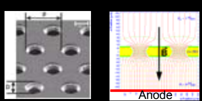
TPC Tracking



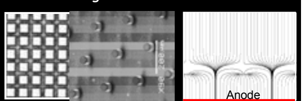
- ILC TPC
  - δp/p ≤ 0.1%, B=4T
  - Material <3% X_0 near η = 0 <30%X_0 endcap
  - pads per endcap > 10^6, pad size about 1x6 mm^2
  - hit resol. 100, 500 μm rϕ, z @ 4T
- ALICE TPC
  - δp/p ≤ 1%, B=0.4T
  - Material 3.5% X_0 near η = 0
  - MWPC readout, ~500k cathode pads, pad sizes 4x7.5, 6x10, 6x15 mm^2
  - hit resol. 800 … 1250 μm rϕ, z
- Readout
  - GEM
  - MicroMegas
  - CMOS Pixels

TPC Readout

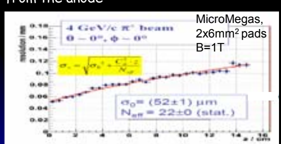
- GEM



- MicroMegas

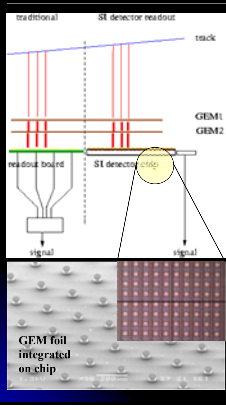


- two copper foils separated by polyimide
  - uses 2 or more stages for safer operation
  - high electric field inside the holes, in which multiplication takes place
- 50 μm amplification region is displaced from the anode



- micromesh sustained by pillars
  - amplification between mesh and pads/strip plane
  - single stage
- 50 μm amplification region includes the anode
- Now "Bulk Micromegas" can be obtained by lamination of a woven grid on an anode with a photo-imageable film
- The ILC-TPC resolution goal, ~100 μm for all tracks, appears feasible.

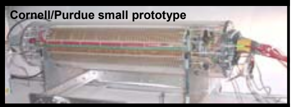
TPC CMOS Readout



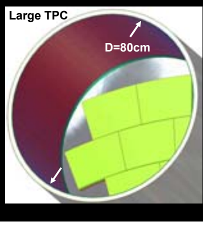
- Use bare CMOS chip as anode to directly collect signals from GEMs or Micromegas: MediPix chip
  - Charge collection with granularity matching primary ionization cluster spread
  - On-chip processing of signals
- Currently:
  - 3rd coordinate (time) being added: TimePix chip
  - Integration of GEM/Micromegas grid and CMOS sensor through wafer processing (InGrid)
- Prospects:
  - Ionization cluster counting is possible to improve part. id. performance
  - Potential for large improvements in pattern recognition and dE/dx
  - "Digital Bubble Chamber"

TPC R&D

- Many prototype TPC's built
  - Interchangeable gas-amplification
  - Wide range of studies:
    - Gas and resolution studies
    - Candidate gas amplification devices
      - Direct comparison of triple-GEM and Bulk Micromegas
    - Ion/electron transmission studies
    - Ion feedback measurements



- Plan for large prototype TPC
  - 60 cm drift length, 80 cm diameter
  - Interchangeable gas-amplification modules designed to directly compare gas-amplification technologies
  - Need for large bore high magnetic field!
- R&D synergistic with T2K
  - T2K will have 3 TPCs
    - 72 Micromegas modules
    - Total area ~ 9 m²
    - 124416 readout channels



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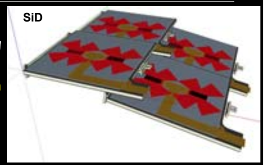
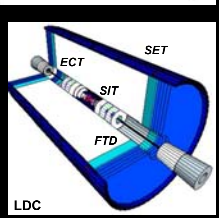
Silicon Tracker

- All silicon tracking, SiD
  - "Power-pulsing" allows for gas cooling
  - Hybrid-less design
    - 100x100mm² sensor from 6" wafer with 1840 (3679) readout (interm.) strips
    - Integration of pitch adapter through 2nd metal layer in sensor for signal routing
    - Sensor (1840 channels) read out with two asics (kPix)
    - Power and clock routed over the sensor !



- Silicon as " intermediate layers"
  - Double-sided layers to act as tracker
    - d-s silicon R&D actively being pursued in Korea
  - Single-sided layers to "link" subdetectors
    - Long-ladders with associated FE Asic



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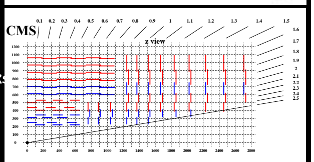
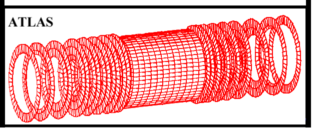
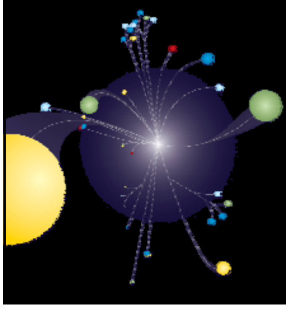
Forward Tracking

- Forward region is critically important to the ILC
  - Angular distribution: $(1+\cos^2\theta)$
- What is the best strategy for forward tracking? Is there a unique solution ?
  - How many measurements ?
  - Barrels interspersed with disks
  - Detector tiling: large or small angle stereo ?
  - Short strips, pixels ?
  - Ghosting, track finding efficiency
  - How to minimize mass ?



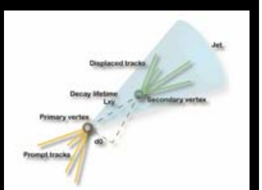




Vertexing

Vertexing

- Goal:
  - Superb impact parameter resolution
    $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)$
  - Minimal material budget: < $0.1\%X_0$ / layer
    - Equivalent to 100 μm of Silicon
  - Minimal power consumption (<50W)
  - Ability to determine quark charge
  - Tolerant to high machine background



- Paradigms:
  - Readout during the train
  - Readout in-between trains

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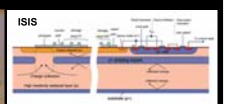
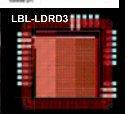
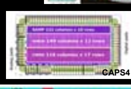
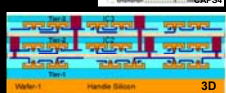
ILC Candidate Technologies

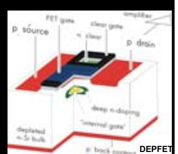
- CCD's
  - Column Parallel (UK)
  - Fine Pixel (Japan)
  - ISIS (UK)
  - Split Column (SLAC)
- CMOS Active Pixels
  - Mimosa series (Ires)
  - INFN
  - LDRD 1-3 (LBNL)
  - CAP 1-4 (Hawaii)
  - Chronopixel (Oregon/Yale)
- SOI
  - American Semiconductor/FNAL
  - LDRD-SOI (LBNL)
  - CAP5 (Hawaii)
  - OKI/KEK
- 3D
  - VIP (FNAL)
- DEPFET (Munich)











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Sensor Architectures

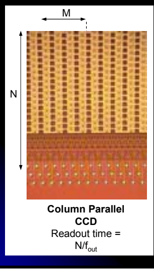
- An incomplete attempt at listing some of the current architectures design for ILC pixel detectors

	CMOS MAPS	CCD	DEPFET	SOI	3D
Rolling Shutter	Mimosa 1-N LDRD 1,2	Normal CCD		LDRD-SOI	
Column Parallel	Mimosa 8 LDRD3	CP-CCD SC-CCD	DEPFET/ CURO		
Pipelined Storage	Mimosa-12 CAP	ISIS		CAP-5	
Time Stamp	Chronopixel			ASI SBIR	VIP-1

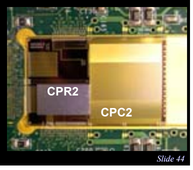
- With apologies to all other technologies, I will only mention three: CP-CCD, Mimosa, 3D

Column Parallel CCD

- CP-CCD: read out a vector instead of a matrix
  - Readout time shortened by orders of magnitude
  - But every column needs its own amplifier and ADC: readout chip
  - Need to operate at 50 MHz to meet ILC readout rate spec.
  - Driving of CP-CCD is a major challenge

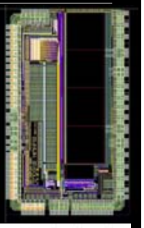


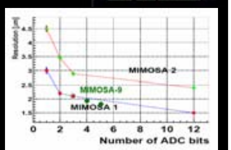
- 2nd generation large area sensors : CPC2
  - Devices with 2-level metal clock distribution
  - 25 µm and 50 µm epi layers
  - Reaches 45 MHz operation (designed for 50 MHz)
- Dedicated readout chip
  - CPR2, bump bonded at VTT to CPC2
- Dedicated clock drive chip
  - CPD1, requirement of 2 V_{pk-pk} at 50 MHz over 40 nF



Mimosa

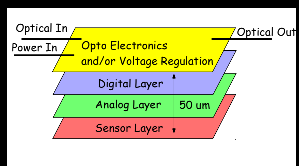
- Mimosa-16 being developed as beamline telescope for DESY (and Fermilab) testbeam:
  - Column parallel readout
  - 32 // columns of 128 pixels (pitch: 25 µm)
  - ~11–16 µm epitaxy
  - on-pixel CDS
- Final geometry:
  - 1024 columns of 512 pixels, 20 µm pitch
  - Expected hit resolution < 2.5 µm
  - Sensitive area = 20.48 x 10.24 mm2
  - pixels with integrated CDS
  - sensor with integrated 4/5-bit ADC
  - possibly zero-suppression
- Read-out speed
  - default $t_{r.o.}$ = 512 lines / 5 MHz ~ 100 µs
- Possible variant
  - 1280 columns of 640 pixels, 16 µm pitch with binary readout





Vertical Integration – 3D

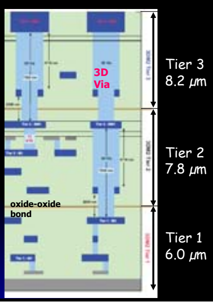
- A 3D device is a chip comprised of 2 or more layers of semiconductor devices which have been thinned, bonded, and interconnected to form a monolithic circuit
- Advantages of 3D
  - Increased circuit density due to multiple tiers of electronics
  - Fully active sensor area
  - Independent control of substrate materials for each of the tiers
    - Process optimization for each layer
  - Ability to mate various technologies in a monolithic assembly

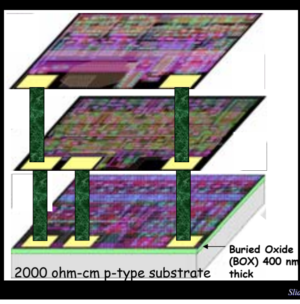


- Technology driven by industry
  - Reduce R, L, C for higher speed
  - Reduce chip I/O pads
  - Provide increased functionality
  - Reduce interconnect power, crosstalk
- Critical issue are:
  - Layer thinning to < 10 mm
  - Precision alignment (< 1 mm)
  - Bonding of the layers
  - Through-wafer via formation

VIP Chip

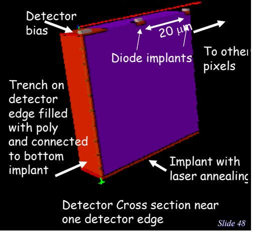
- 3D chip Vertical Integrated Pixel (VIP) chip submitted by Fermilab to DARPA funded MIT-LL 0.18 µm 3D process
  - Chips due to arrive in a couple of weeks; key features:
    - Analog pulse height, sparse readout, high resolution time stamp, front-end power ~ 1875 µW/mm² (before cycling), 175 transistors in 20x20 µm² pixel.





Sensor Technology

- Device thinning is becoming very common
  - CCD's are regularly thinned to 20 µm
  - LBL has thinned over 15 Mimosa CMOS MAPS chips down to 40 µm
    - Yield of functional chips ~90%
    - Studies of charge collection and S/N before/after back-thinning
      - Some evidence of small signal loss after thinning
    - Sensors will be used in Fermilab beam telescope
  - Fermilab has thinned BTeV Fpix chips/wafers to 15/20 µm with ~75% yield
- Thinned Edgeless Sensors
  - Sensors sensitive to the edge can be fabricated by a combination of trench etching, thinning, and laser annealing
  - Fermilab producing a set of detectors thinned to 50-100 µm at MIT-LL for beam and probe tests



Detector Cross section near one detector edge

What is in a 3-letter Acronym ?

- ILC – HLC: acronym is different by one letter – adjacent in the alphabet – (and a permutation)
- Is R&D really that specific? Sure, but …
- If R&D is of high enough caliber, it is to a large extent 'generic', i.e. it will find its way into any new experiment
- There's a premium on Communication and Collaboration
  - LHC solutions will find wide application and conversely ILC solutions will be applicable to the LHC
  - Funding agencies (at least in the USA) are also looking towards more overall coordination

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Concluding Remarks and Observations

- My apologies to all projects not mentioned
- LHC will break new territory, but it will take time
  - $Data_{publ} = \varepsilon * \delta * \gamma * \beta * \alpha * Data_{deliver}$; $t_{publ} = \gamma_5 * \gamma_4 * \gamma_3 * \gamma_2 * \gamma_1 * \gamma_0 * t_0$
    publ. – calibrated – qualified – anal. – rec.
  - It will find a SM-like Higgs if it's there
- We can engineer detectors in ways we never could before; this is mostly driven by advances in the semiconductor industry, making it economically possible
- The ILC detector systems have a lot of synergies with other projects
- Coordination and communications will allow more rapid progress with the limited resources that are available

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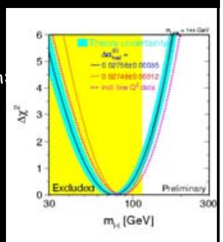
Backup Slides

Slide 51

m_W, m_t, m_H, A_{FB}, $\sin^2\theta_W^{eff}$, A_{LR} and all that

- But, there are other "features" of the standard model
- Global SM electroweak fit has diminished quality:
  - A_{FB}^b vs. A_{LR} persistent problem: 3.2σ, $CL = 0.0016$
    - Suppose A_{FB} systematics: without A_{FB}, m_H from SM fit far below 114 GeV
  - With new m_W from CDF, m_H also moving further into the directly excluded region
    - $m_H > 114$ GeV @ 95 C.L. LEP direct exclusion
    - $m_H = 80^{+36}_{-26}$ GeV
    - $m_H < 153$ GeV @ 95 C.L.
- Triangulating the Standard Model through:
  - Direct top quark mass measurements
  - Direct W-mass measurements
  - Direct Higgs boson limits
  - Precision measurements in general
- Constraints currently mainly from
  - Tevatron
  - Belle and BaBar



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Calorimeter Readout

- Lots of work on associated downstream readout and software
- Emphasis on building common infrastructure
  - VME readout electronics, adaptable to different channel counts
  - On-detector readout board used for all SiPM detectors
  - Common online DAQ software system
  - Common event reconstruction and analysis output format (LCIO)

EM calorimeter
Si pad readout
14-layer board

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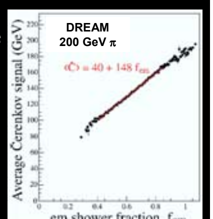
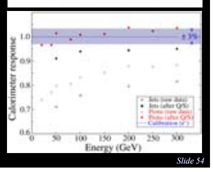
Multiple Readout Calorimetry

- Dual-Readout: measure every shower twice
  - Scintillation light: from all charged particles
  - Čerenkov light: β=1 particles, mainly EM
- By measuring separately both components can determine e/h fraction and correct the response (set e/h=1)
- Approaches:
  - Scintillating and quartz fibers embedded in Cu (DREAM);
    - no longitudinal segmentation
  - Leadglass-Scintillator sampling
  - Doped crystals





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