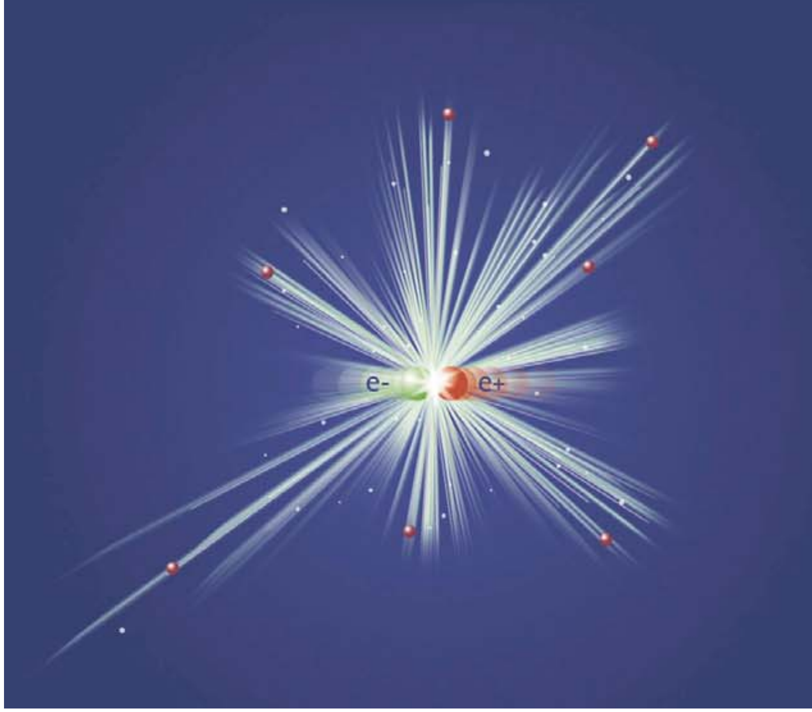
Detectors for the ILC



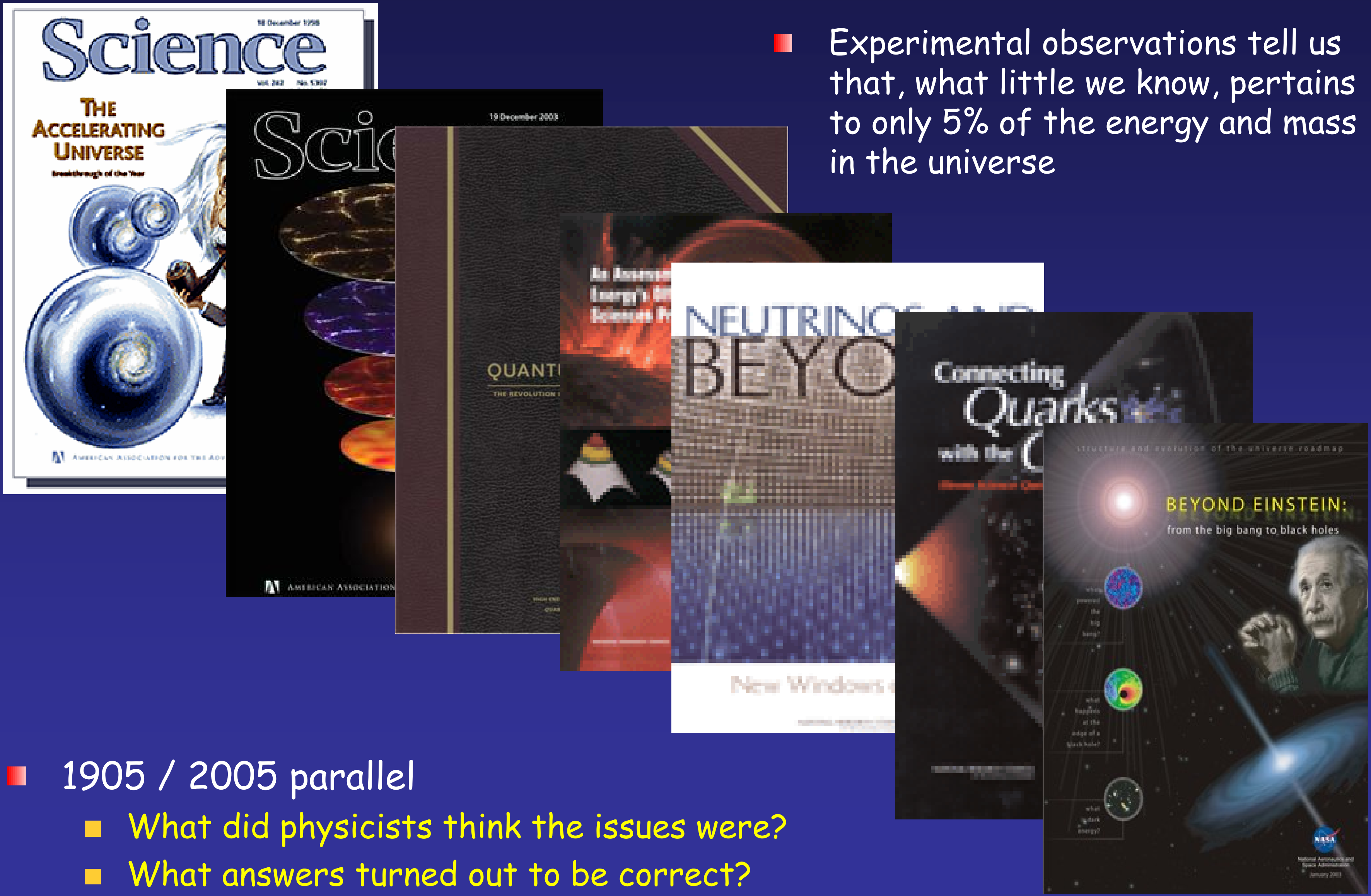
Marcel Demarteau
Fermilab

December 16, 2005

The Year 1905

- Some major issues at that time: kinetic theory of gases, black body radiation, 'the ether', Maxwell's equations, …
- Annus Mirabilis: 1905
  - That year Einstein published his thesis and 4 seminal papers
    - Photo-electric effect, March 1905
      - Ueber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, *Annalen der Physik* 17 (1905): 132-148
    - Brownian motion, May 1905
      - Ueber die von der molekularkinetischen Theorie der Waerme geforderte Bewegung von in ruhenden Fluessigkeiten suspendierten Teilchen, *Annalen der Physik* 17 (1905): 549-560
    - Special Relativity, June 1905
      - Zur Elektrodynamik bewegter Koerper *Annalen der Physik* 17 (1905): 891-921
    - $E = mc^2$, special relativity, September 1905
      - Ist die Traegheit eines Koerpers von seinem Energieinhalt abhaengig?, *Annalen der Physik* 18 (1905): 639-641
    - Molecular dimensions, Thesis 1905, published 1906
      - Eine neue Bestimmung der Molekueldimensionen *Annalen der Physik* 19 (1906): 289
- Answers came in the form of Quantum Mechanics and Relativity

The Year 2005

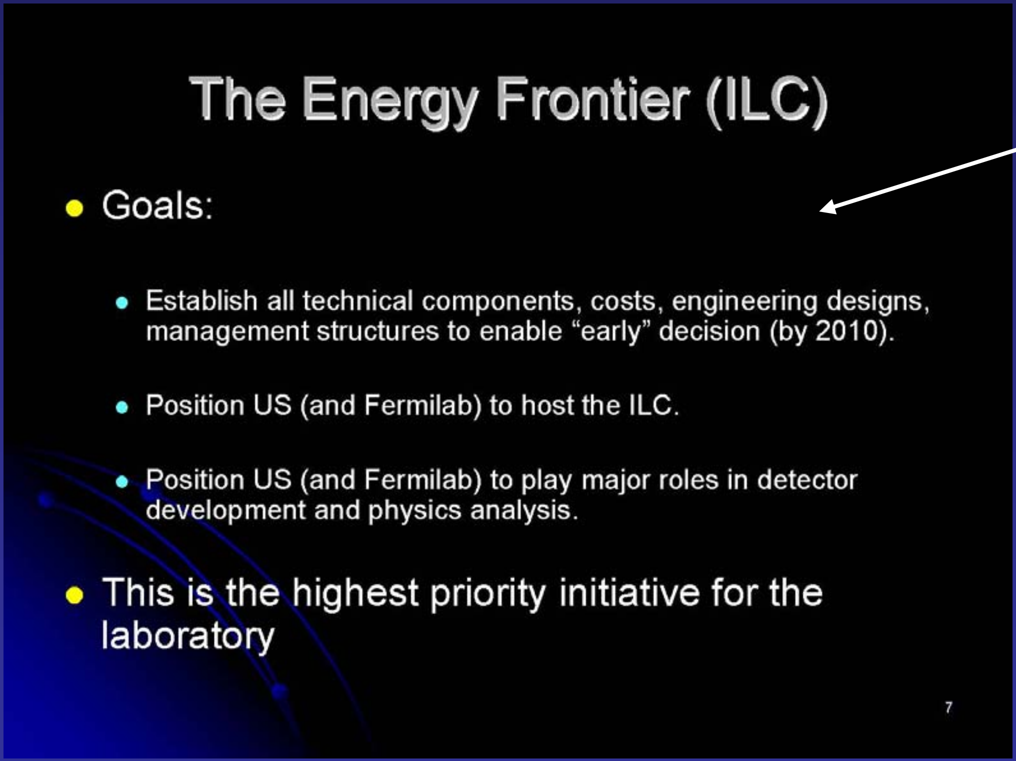


- Experimental observations tell us that, what little we know, pertains to only 5% of the energy and mass in the universe

- 1905 / 2005 parallel
  - What did physicists think the issues were?
  - What answers turned out to be correct?

The Year 2005 at Fermilab

- Experiments are the main vehicles which will provide the answers to these current outstanding issues
- Panels, committees, boards, groups, agencies, … worldwide
  - HEPAP, EPP2010, P5, NUSAG, ICFA, ECFA, SAGENAP, ACFA, PAC, DETF, ……
  - ILC is a main route to new horizons



The Energy Frontier (ILC)

- Goals:
  - Establish all technical components, costs, engineering designs, management structures to enable “early” decision (by 2010).
  - Position US (and Fermilab) to host the ILC.
  - Position US (and Fermilab) to play major roles in detector development and physics analysis.
- This is the highest priority initiative for the laboratory

From the Director

(EPP2010, P5)

- Fermilab has decided that the ILC is the highest priority initiative

The International Linear Collider

- Baseline Machine:

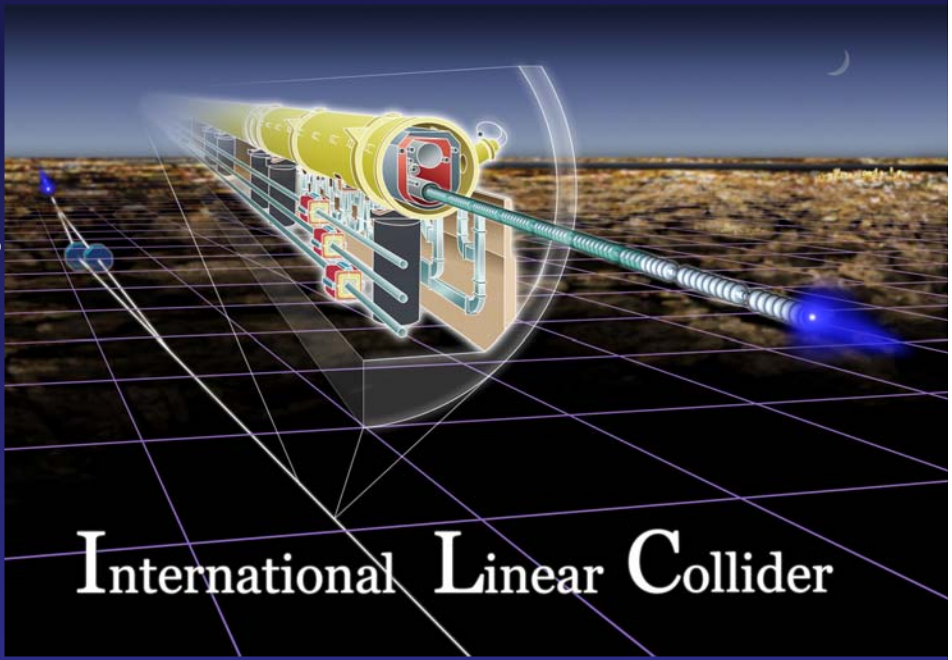
  E_{CM} of operation 200 – 500 GeV
  Luminosity and reliability for 500 fb^{-1} in 4 years
  Energy scan capability with <10% downtime
  Beam energy precision and stability below 0.1%
  Electron polarization of >80%
  Two interaction regions with detectors
  E_{CM} down to 90 GeV for calibration

- Upgrades:

  E_{CM} about 1 TeV
  Capability of running at any $E_{CM} < 1$ TeV
  $\mathcal{L}$ and reliability for 1 ab^{-1} in 3 – 4 years

- Options:

  Extend to 1 ab^{-1} at 500 GeV in ~2 years
  e^-e^-, γγ, e^-γ operation
  e^+ polarization ~ 50%
  Giga-Z with $\mathcal{L} =$ several 10^{33} $cm^{-2}s^{-1}$
  WW – threshold scan with $\mathcal{L} = 10^{33}$ $cm^{-2}s^{-1}$

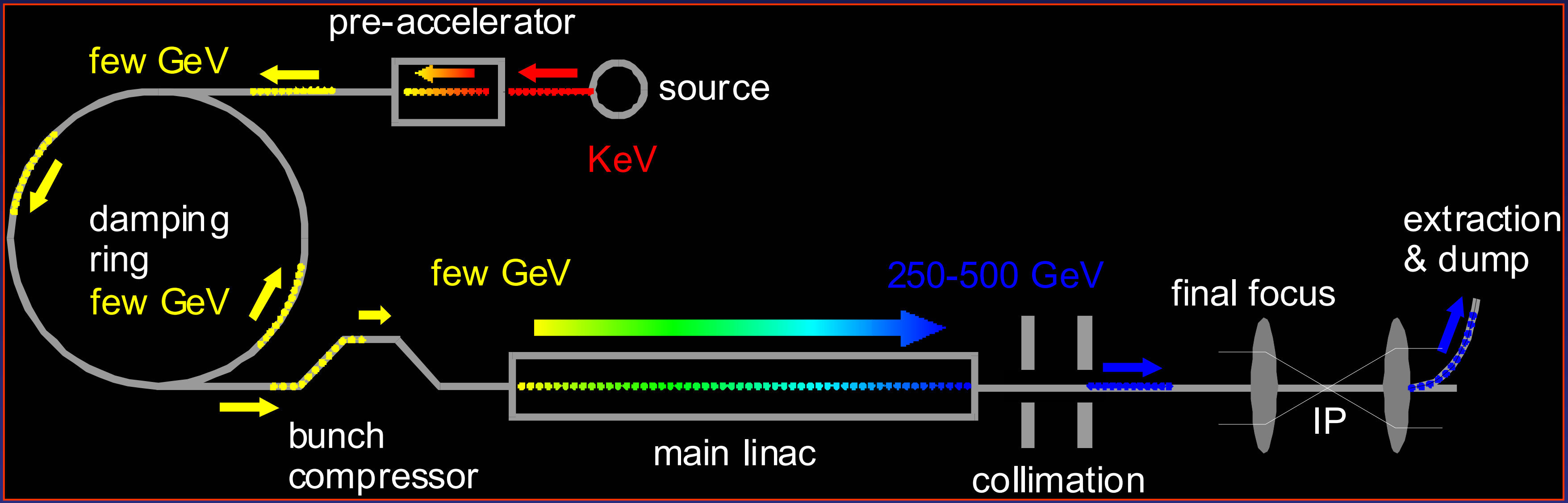


As defined in

International Scope Document

See www.fnal.gov/directorate/icfa/LC_parameters.pdf

The Machine



- Enormously challenging with many different components, but …
  - Positron source three options: undulator, laser compton and conventional source
  - Damping Rings three options with test facility (ATF) at KEK
  - Klystrons (modulators) three (two) viable, field tested solutions for each
  - String of test facilities: TTF-I and II (DESY), ILC SRF Facility (FNAL), STF at (KEK)
  - …
- Detector design to optimize for the physics and detector R&D are far behind; not even close to a prototyping stage for any of the components even though it is far from easy to extract the physics

Outline

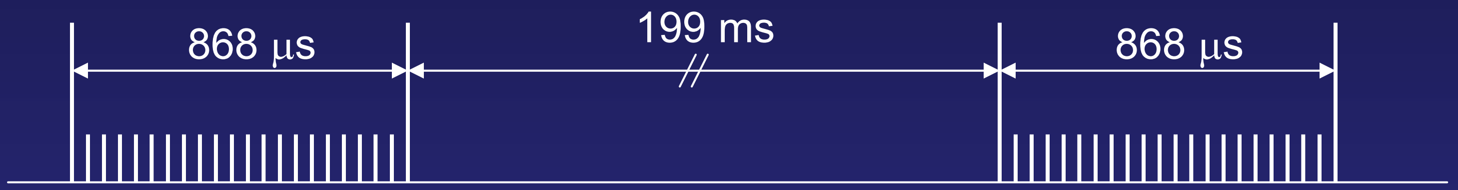
- Q: If we could start building the machine today, can we build the detectors?
- A: No

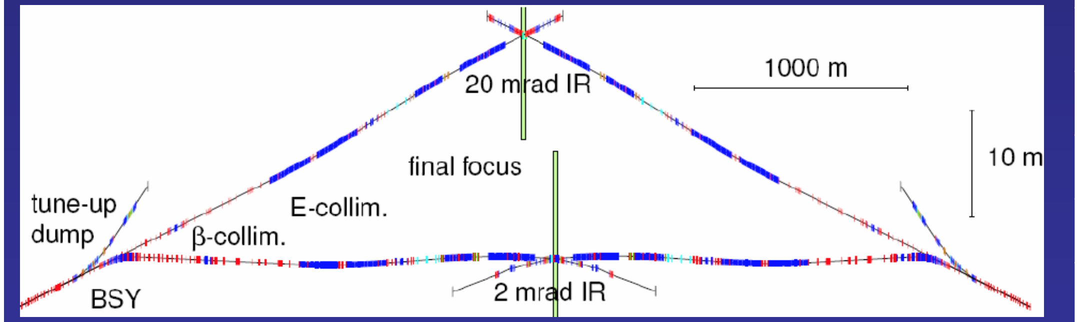
- Observation:
  - LHC: staggering increase in scale, but modest extrapolation of technology
  - ILC: modest increase in scale, but significant push in technology

- Outline:
  - ILC Challenges
    - Challenges coming from the machine
    - Challenges coming from the physics
  - The SiD Detector Concept
  - Detector R&D at Fermilab
    - What are we doing at the laboratory in which you can participate

Machine Parameters

- Time structure: five trains of 2820 bunches per second
  - bunch separation is 307.7 ns (LEP: 22 μs)



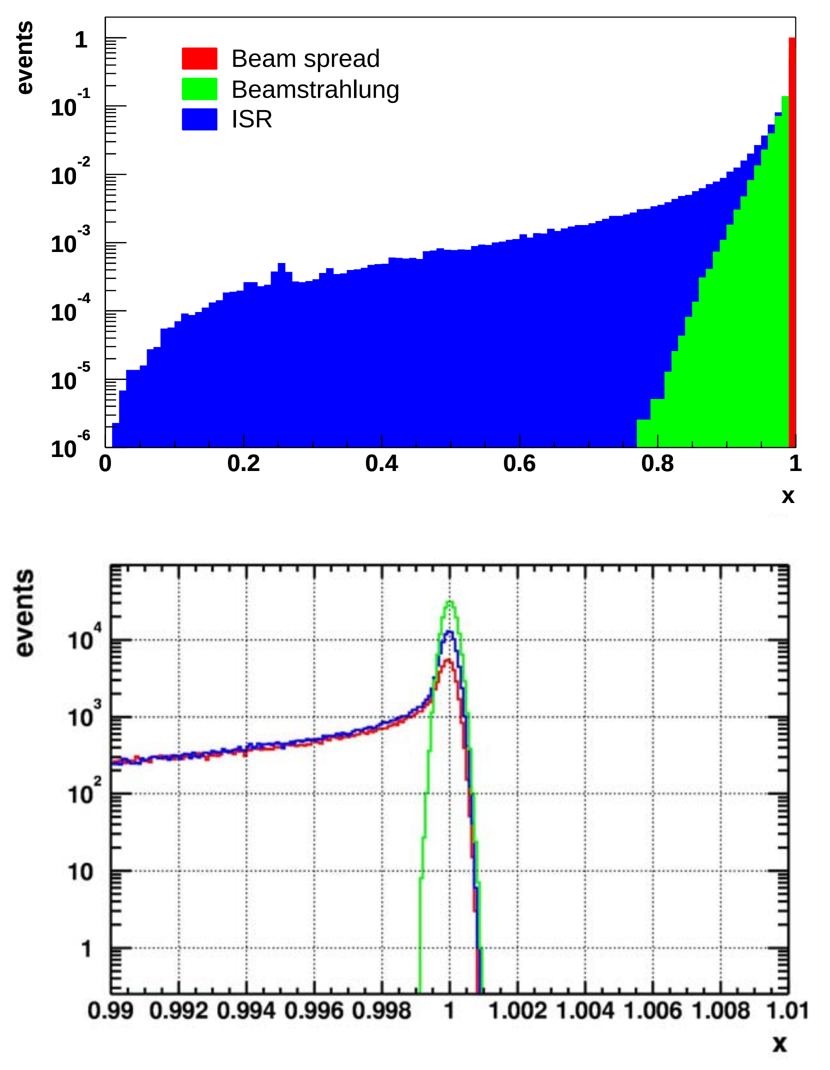


http://www-project.slac.stanford.edu/ilc/acceldev/beamparameters.html

E_{CMS} [GeV]	500	1000
L ($cm^{-2}s^{-1}$)	$2.0\ 10^{34}$	$3.0\ 10^{34}$
Bunches/Train	2820	2820
Bunch train length (μs)	868	868
Rep Rate [Hz]	5	5
T_{sep} (ns)	307.7	307.7
Gradient (MV/m)	30	30
N/bunch	$2.0\ 10^{10}$	$2.0\ 10^{10}$
σ_x, σ_y (nm)	655, 5.7	554, 3.5
σ_z (μm)	150	300
Θ crossing [mrad]	0 - 20	0 - 20

Challenges of the ILC

- Variation of the centre of mass energy, due to very high current, collimated beams: three main sources
    - Accelerator energy spread
        - Typically ~0.1%
    - Beamstrahlung
        - 0.7% at 350 GeV
        - 1.7% at 800 GeV
    - Initial state radiation (ISR)
        - Calculable to high precision in QED
        - Complicates measurement of Beamstrahlung and accelerator energy spread
        - Impossible to completely factorize ISR from FSR in Bhabha scattering
- But, there are many more challenges



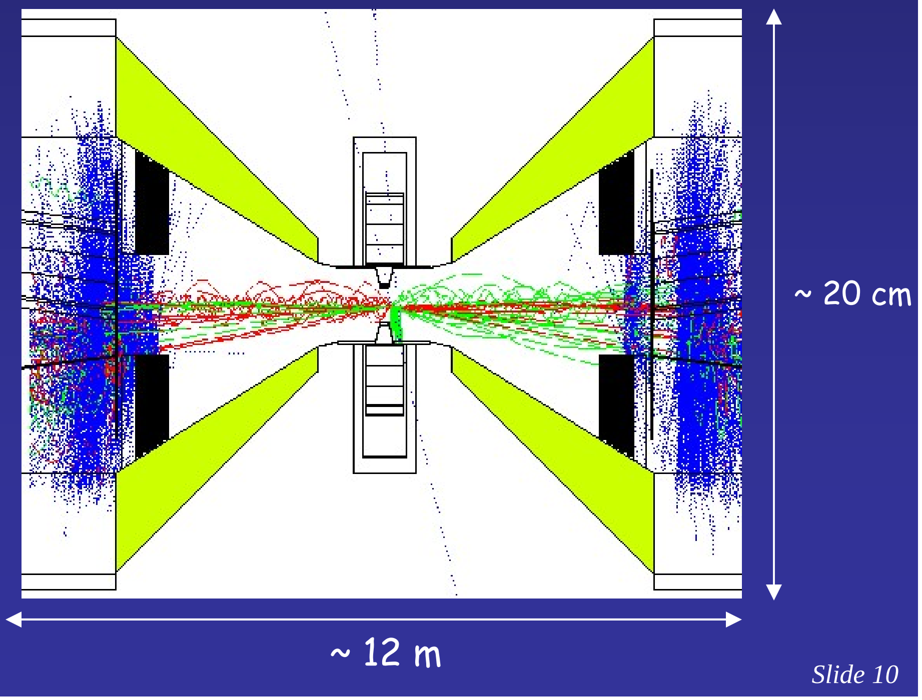
Backgrounds

- "At the ILC the initial state is well defined …"

- Backgrounds from the IP
  - Disrupted beams
    - Extraction line losses
  - Beamstrahlung photons
  - e^+e^- - pairs

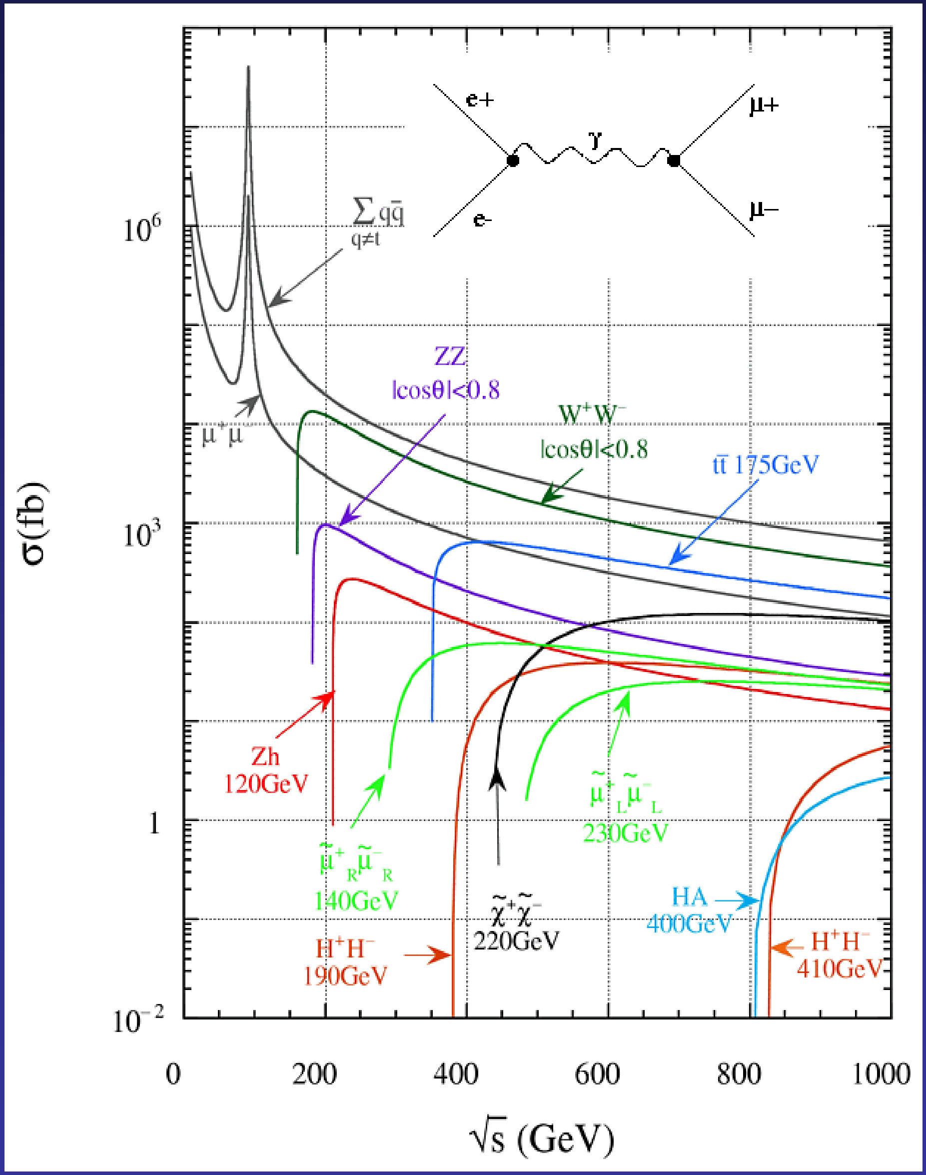
$\sqrt{s}$ (GeV)	Beam	# e^+e^- per BX	Total Energy (TeV)
500	Nominal	98 K	197
1000	Nominal	174 K	1042

- Backgrounds from the machine
  - Muon production at collimators
  - Synchrotron radiation
  - Neutrons from dumps, extraction lines

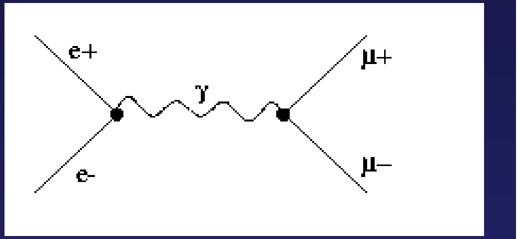


Physics Event Rates

- s-channel processes through spin-1 exchange: $\sigma \sim 1/s$
- Cross sections relatively democratic:
  - $\sigma\,(e^+e^- \to ZH) \sim 0.5 * \sigma(e^+e^- \to d\,d)$
- Cross sections are small; for $L = 2 \times 10^{34}\ cm^{-2}s^{-1}$
  - $e^+e^- \to qq$, WW, tt, Hx ~ 0.1 event /train
  - $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^- X$ ~ 200 /train
- Beyond the Z, no resonances
- W and Z bosons in all decay modes become the main objects to reconstruct
- Forward region critical
- Highly polarized e^- beam: ~ 80%



ILC Physics Characteristics

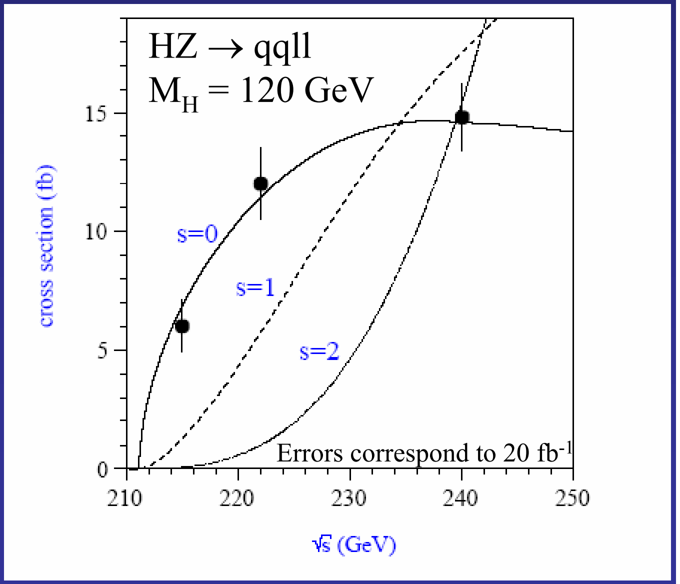


- Cross sections above Z-resonance are very small
- s-channel processes through spin-1 exchange
- Highly polarized e^- beam: ~ 80%

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

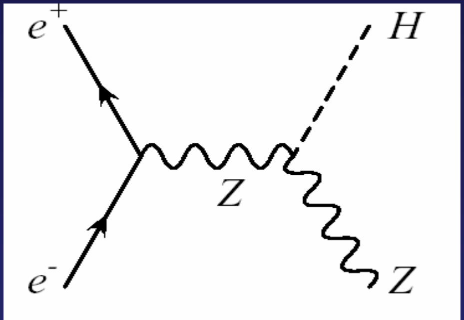
$$A_f = \frac{2g_{Vf}\,g_{Af}}{g^2_{Vf}+g^2_{Af}} \qquad A_b = 0.94 \quad A_c = 0.67 \quad A_l = 0.15$$

- Hermetic detectors with uniform strengths
  - Importance of forward regions
  - b/c tagging and quark identification in forward region
  - Measurements of spin, charge, mass, …
- Analyzing power of
  - Scan in center of mass energy
  - Various unique Asymmetries
    - Forward-backward asymmety
    - Left-Right Asymmetry
      - Largest effects for b-quarks

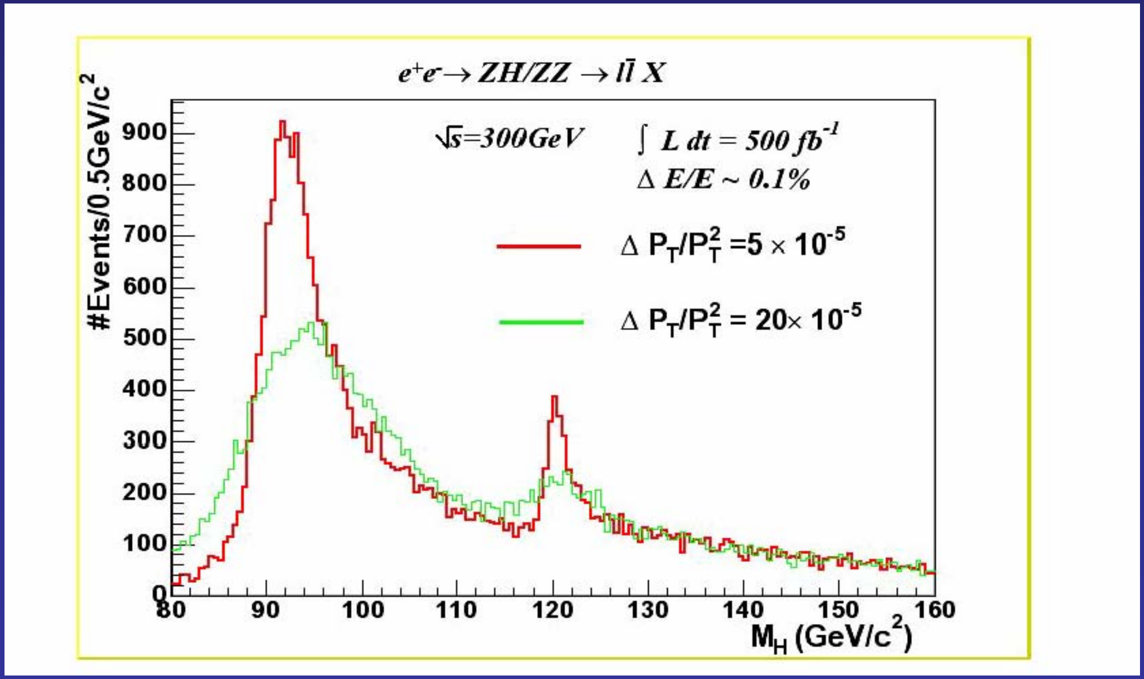


Higgs Recoil Mass

- Benchmark measurement is the measurement of the Higgs recoil mass in the channel $e^+e^- \to ZH$
  - Higgs recoil mass resolution improves until $\Delta p/p^2 \sim 5 \times 10^{-5}$
  - Sensitivity to invisible Higgs decays, and purity of recoil-tagged Higgs sample, improve accordingly.

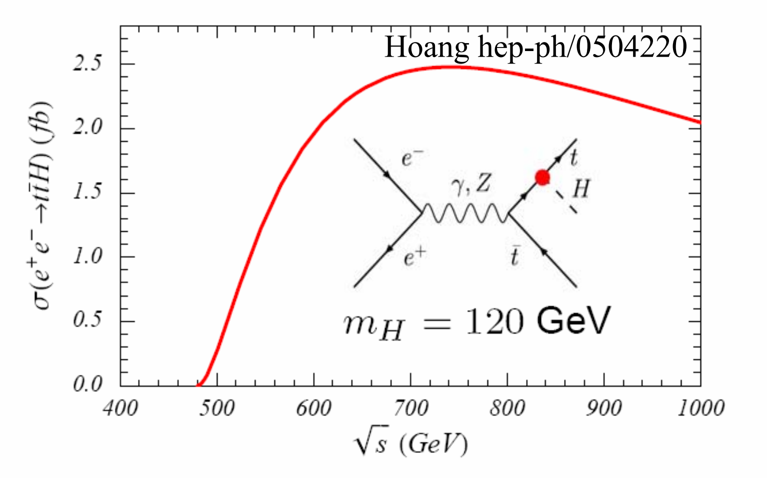


- Example:
  - $\sqrt{s}$ = 300 GeV
  - 500 fb^{-1}
  - beam energy spread of 0.1%
- Goal:
  - $\delta M_{\ell\ell} < 0.1 \times \Gamma_Z$
  - δM_H dominated by beamstrahlung



Top Yukawa Coupling

- $e^+e^- \to$ ttH   Largest coupling to any fermion; EWSB
- H → b-bbar
  - Spectacular signatures
    - qqqq + bbbb, qq l ν + bbbb
  - Stiff backgrounds
    - ttbar g, with g → b-bbar
- m_H around 120 GeV
  - ttbar Z background nearly irreducible
  - Need to have superior jet-mass resolution to discriminate from signal
- H → W^+W^-
  - Signatures:
    - 2 like sign leptons + 6 jets: l^+l^+ / l^-l^- $\nu\nu$ qqqq bb
    - 1 lepton + 8 jets: $l\nu$ qqqqqq bb
- $\delta\lambda_t/\lambda_t$ possible to about 5%
- Need good b-identification and calorimeter granularity



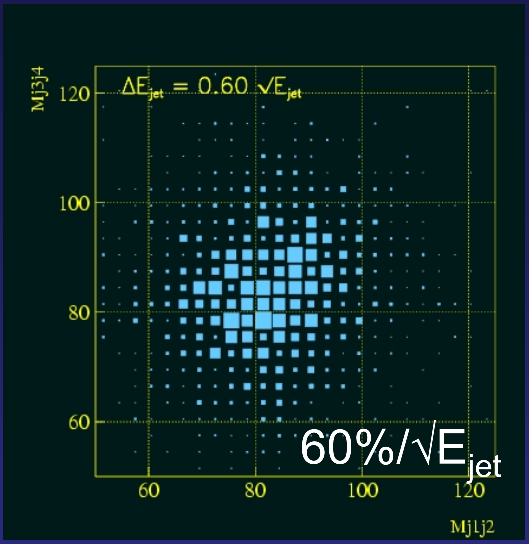
Final State	σ (fb)
t-tbar	~ 300
W^+W^-	~ 4300
ZZ	~ 240
t-tbarZ	~ 4.3

$\sqrt{s}$ = 500 GeV

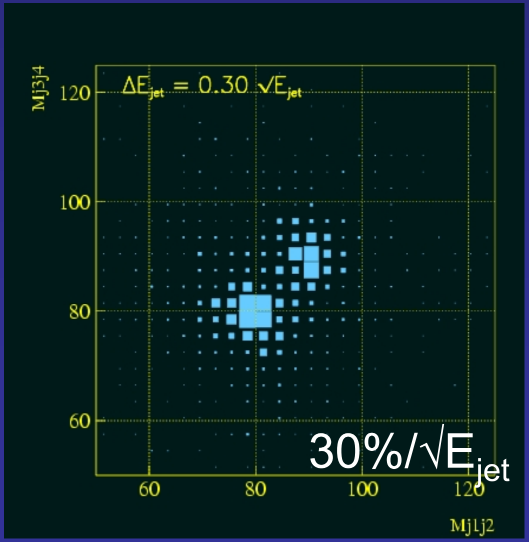
A. Juste et al.: hep-ph/9910301
A. Gay et al. LCWS04

Higgs Self-Coupling

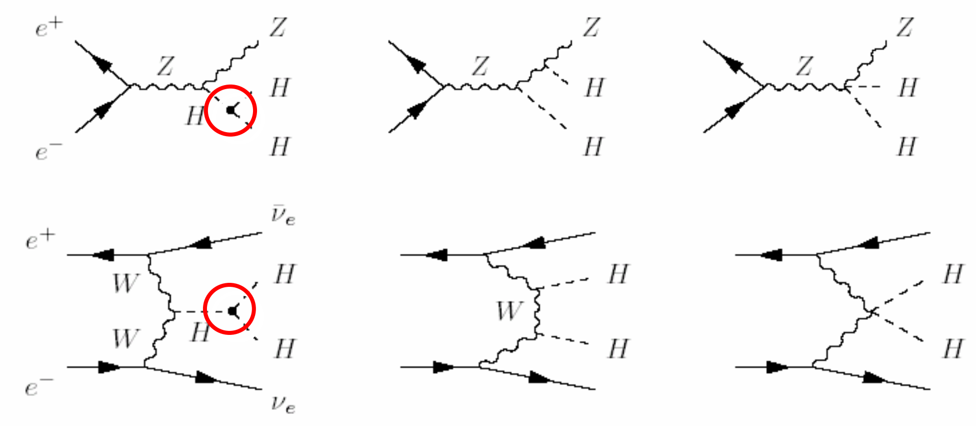
- Many processes have W and Z bosons in the final state; events need to discriminate
- Need for precision calorimetry
  - $e^+e^- \to WW\nu\nu$, $WZe\nu$ and $ZZ\nu\nu$ events
    - Can be indicative of strong EWSB
  - Measure Higgs Self-coupling λ_{HHH}
    - Two production processes
      - ➢ ZHH and W-fusion
    - Small cross section on large multijet background;
    - need high resolution calorimetry to identify



$60\%/\sqrt{E_{jet}}$



$30\%/\sqrt{E_{jet}}$



Dark Matter: M. Carena, C. Milstene Hep -ph 0508152

Some Detector Design Criteria

Requirement for ILC

- Impact parameter resolution

  $$\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)$$

- Momentum resolution

  $$\sigma\left(\frac{1}{p_T}\right) = 5\times10^{-5}\ (GeV^{-1})$$

- Jet energy resolution

  $$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$$

- Detector implications:
  - Calorimeter granularity
  - Pixel size
  - Material budget, central
  - Material budget, forward

Compared to best performance to date

- Need factor 3 better than SLD

  $$\sigma_{r\phi} = 7.7 \oplus 33/(p\sin^{3/2}\vartheta)$$

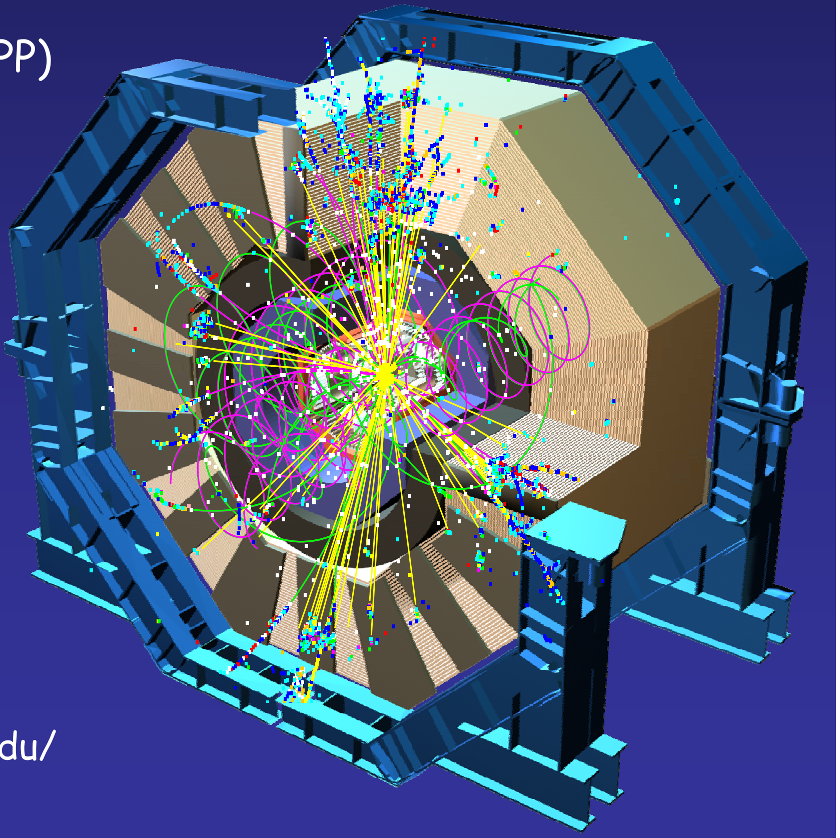
- Need factor 10 (3) better than LEP (CMS)
- Need factor 2 better than ZEUS

  $$\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$$

- Detector implications:
  - Need factor ~200 better than LHC
  - Need factor ~20 smaller than LHC
  - Need factor ~10 less than LHC
  - Need factor ~ >100 less than LHC

The SiD Detector

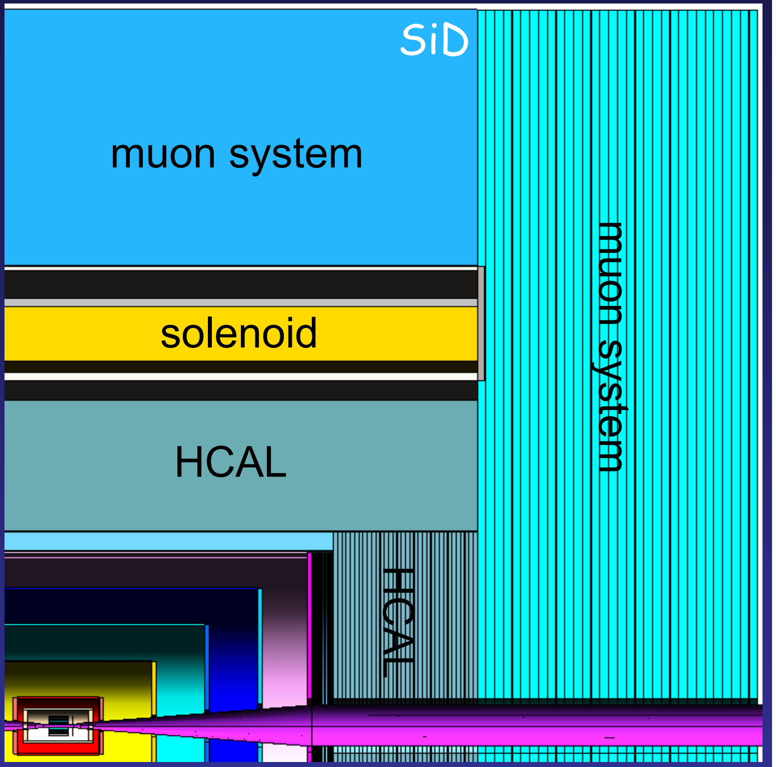
- The Silicon Detector (SiD) design study
  - Conceived at SLAC within the framework of the American LC Physics Group
  - Silicon based detector design study, 'consolidated' late 2004
    - Design Study coordinators:
      John Jaros (SLAC), Harry Weerts (ANL)
    - Asian and European Contacts:
      H. Aihara (Tokyo), Y. Karyotakis (LAPP)
    - SiD Executive Committee: above +
      A. White for R&D (U. Texas),
      M. Breidenbach (SLAC),
      J. Brau (Oregon)



- Web site for study: http://www-sid.slac.stanford.edu/

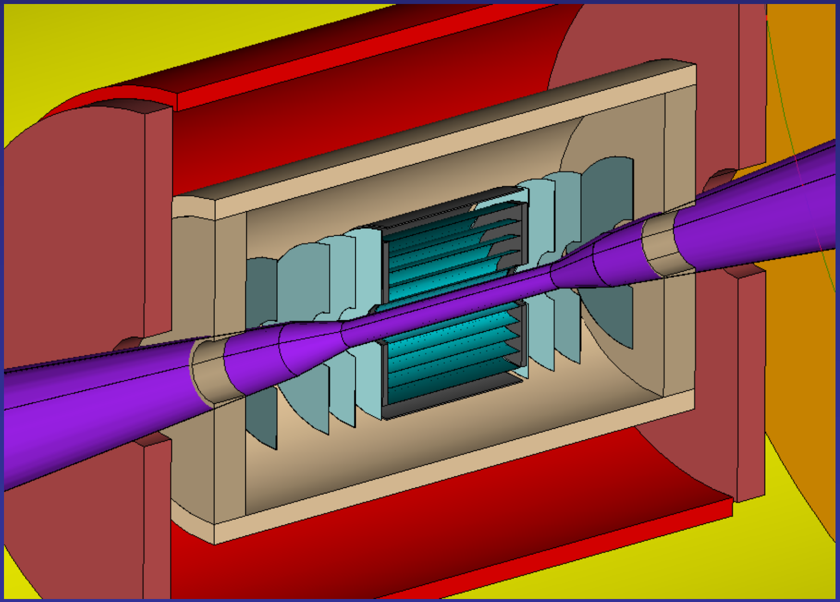
Design Concept

- Calorimetry is the starting point in the SiD design
- Premises at the basis of concept:
  - Particle flow calorimetry will deliver the best possible performance
  - Si/W is the best approach for the ECAL and digital calorimetry for HCAL
  - Limit calorimeter radius to constrain the costs
  - Boost B-field to maintain BR^2
  - Use Si tracking system for best momentum resolution and lowest mass
  - Use pixel Vertex detector for best pattern recognition
- Detector is viewed as single fully integrated system, not a collection of different subdetectors

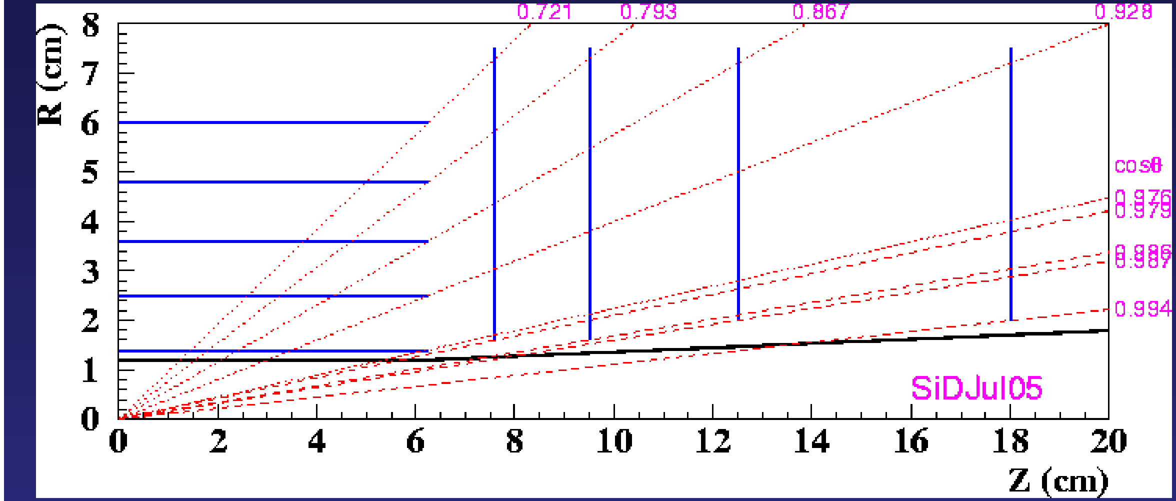


Vertexing and Tracking

- Tracking system is conceived as an integrated, optimized detector
  - Vertex detection
    - Inner central and forward pixel detector
  - Momentum measurement
    - Outer central and forward tracking
  - Integration with calorimeter
  - Integration with very far forward system
- Detector requirements
  - Spacepoint resolution: < 4 μm
  - Impact parameter resolution
    $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)\ \mu m$
  - Smallest possible inner radius
  - Momentum resolution 5 10^{-5} (GeV^{-1})
  - Transparency: ~0.1% X_0 per layer
  - Stand-alone tracking capability

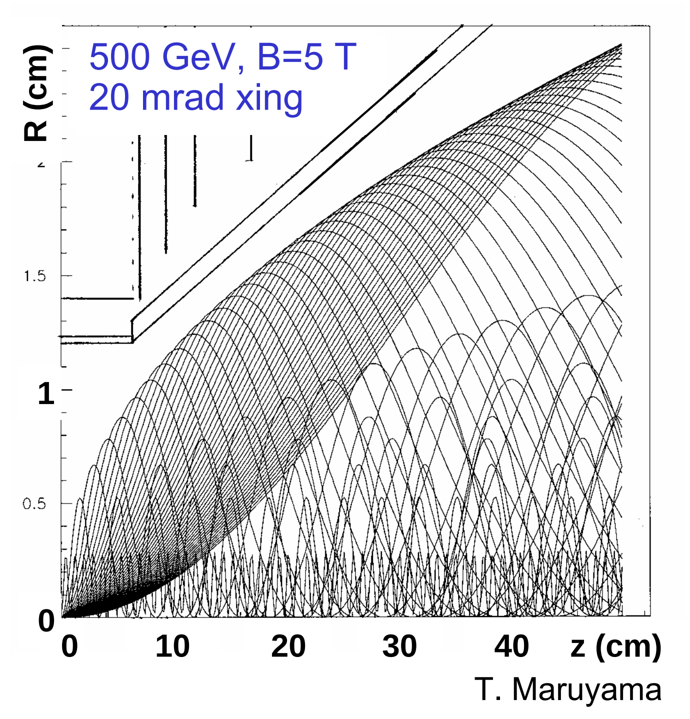


Vertex Detector



- Five Barrels
  - R_{in} = 14 mm to R_{out} = 60 mm
  - 24-fold phi segmentation
  - two sensors covering 6.25 cm each
  - All barrel layers same length
- Four Disks per end
  - Inner radius increases with z

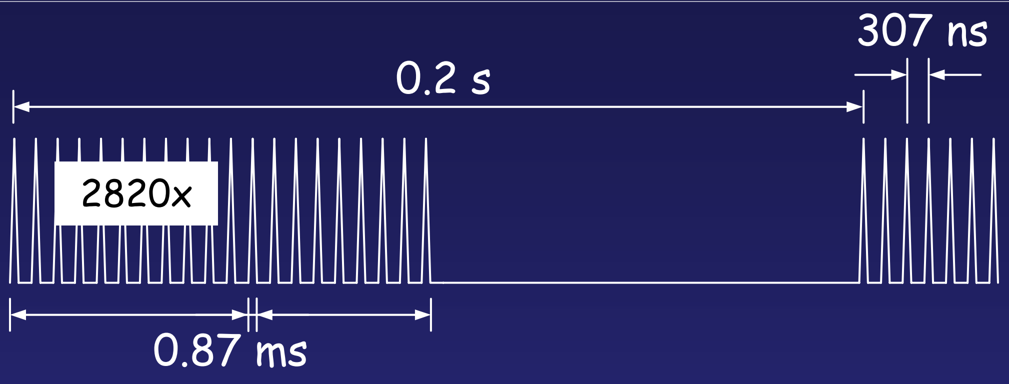
- Small radius possible with large B-field
- Goal is 0.1% X_0/layer (100 μm of Si):
  - Address electrical aspects:
    - Very thin, low mass sensors, including forward region
      - Integrate front-end electronics into the sensor
    - Reduce power dissipation so less mass is needed to extract the heat
  - Mechanical aspects:
    - Integrated design
    - Low mass materials



T. Maruyama

Sensors: The Challenge

- Beam structure



- What readout speed is needed ?
  - Inner layer 1.6 MPixel sensors; Background hits significantly in excess of 1/mm^2 will give patterns recognition problems
    - Once per bunch = 300ns per frame : *too fast*
    - Once per train ~100 hits/mm^2 : *too slow*
    - 5 hits/mm^2 => 50μs per frame: may be tolerable

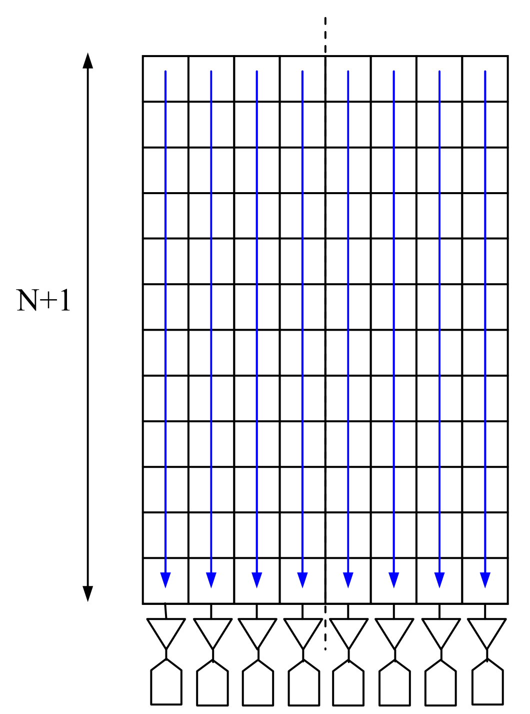
For SiD: cumulative number of bunches to reach hit density of 1/mm^2
- Layer 1: ~35
- Layer 2: ~250

- Fast CCDs
  - Development well underway
  - Need to be fast (50 MHz)
  - Read out in the gaps

- Many different developments
  - MAPS
  - FAPS
  - HAPS
  - SOI
  - 3D

Column Parallel CCD

- R&D carried out by LCFI Collaboration (Bristol, Glasgow, Lancaster, Liverpool, Oxford, RAL) in collaboration with e2v Technology



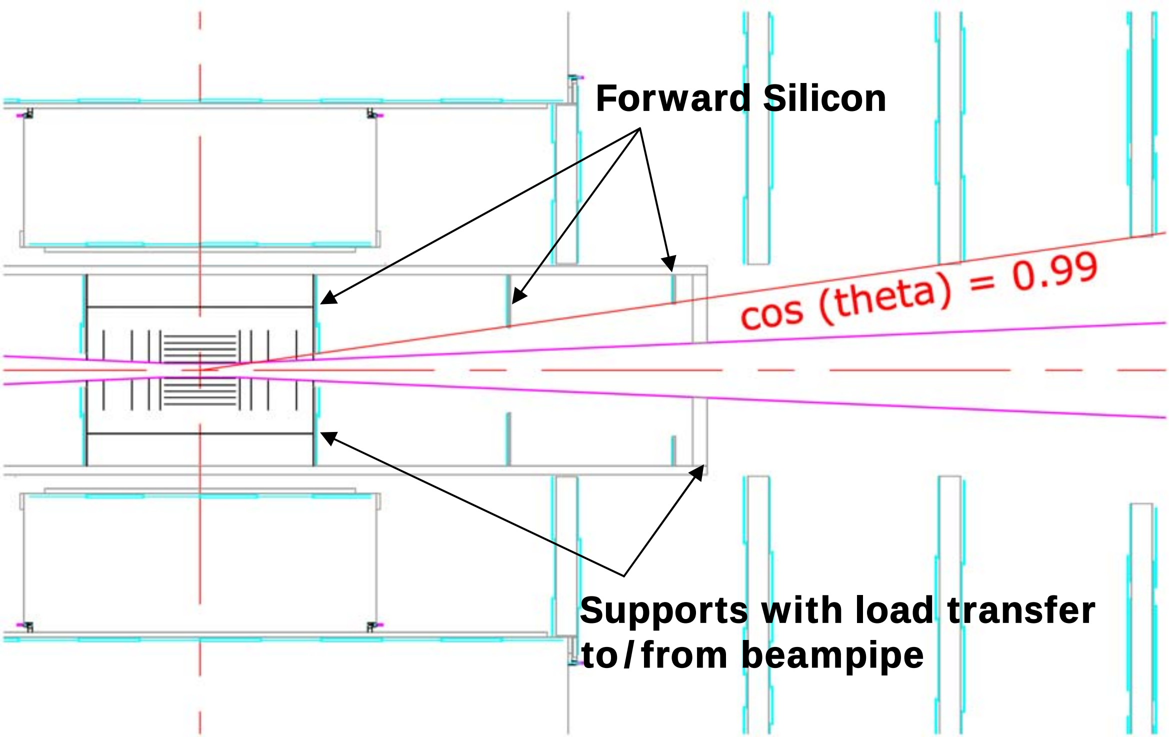
Column Parallel CCD

Readout time = $(N+1)/F_{out}$

- 20 μm x 20 μm pixel size
- Separate amplifier and readout for each column, compared to 'rolling shutter'
- Designed for 50 MHz clock speed
- Results:
  - Operates at clock > 25 MHz
  - Minimum clock of ~ 1.9 V
  - Noise is ~ 100 electrons
- Second generation of CP-CCD's
  - Symmetric clock
  - Goal is to clock at highest frequency at lowest voltage
- CCD design needs separate ro asic

Mechanics: The Challenge

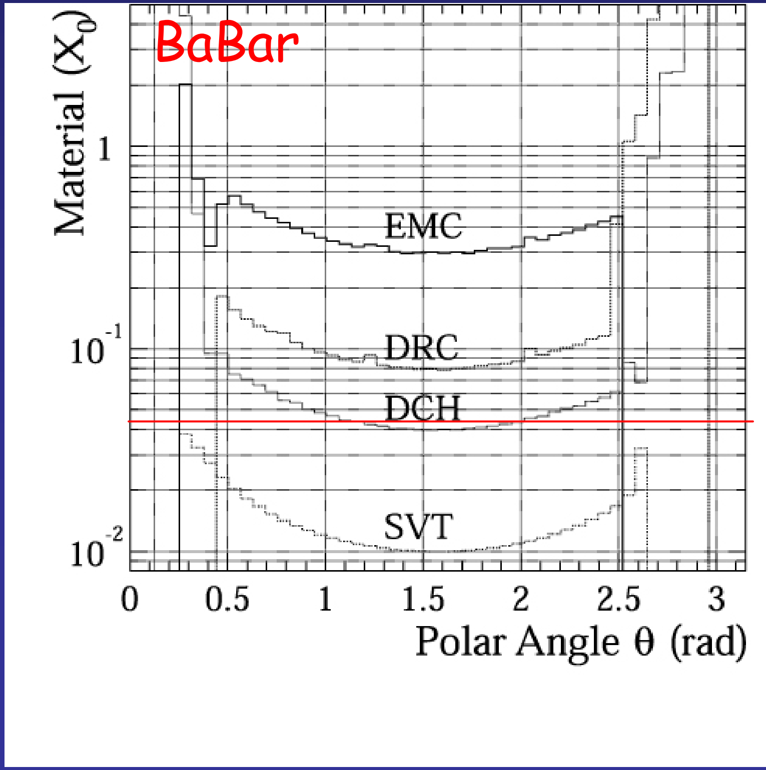
- Build and support a 5-layer/4-disk integrated, no-mass, giga-pixel detector that operates, with perfect alignment, at room temp. and -40 ^{0}C and is easily accessible

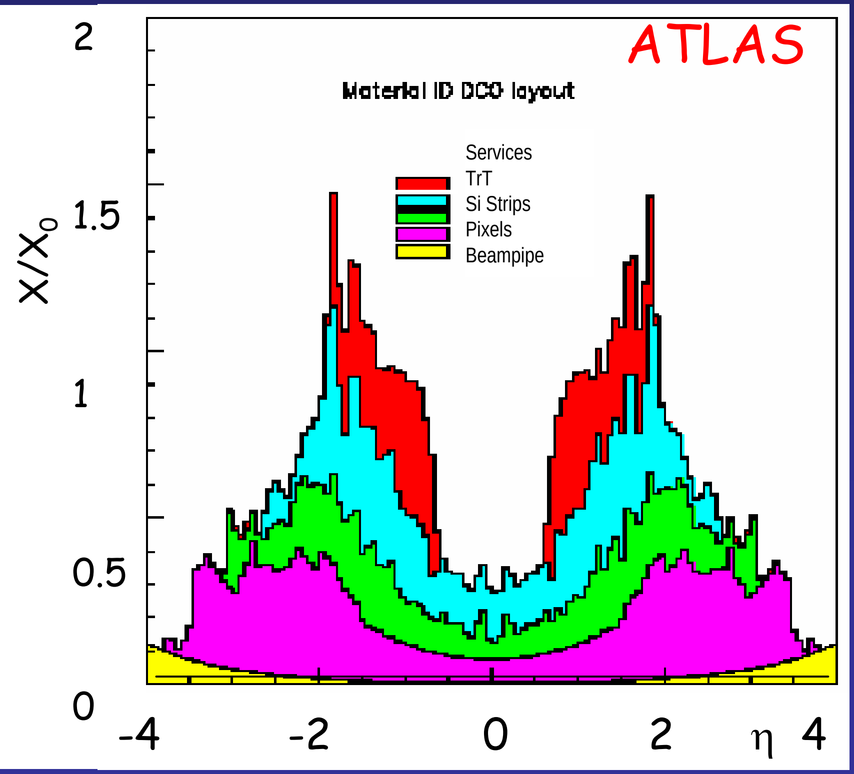


- Integrated design with forward tracker
  - Support structures are half-cylinders (thermally insulating)
  - Detector elements supported from half-cylinders
  - Support half-disks couple to the beam pipe at z ~ ± 0.2 m / ± 0.9 m

Material Budget Comparison

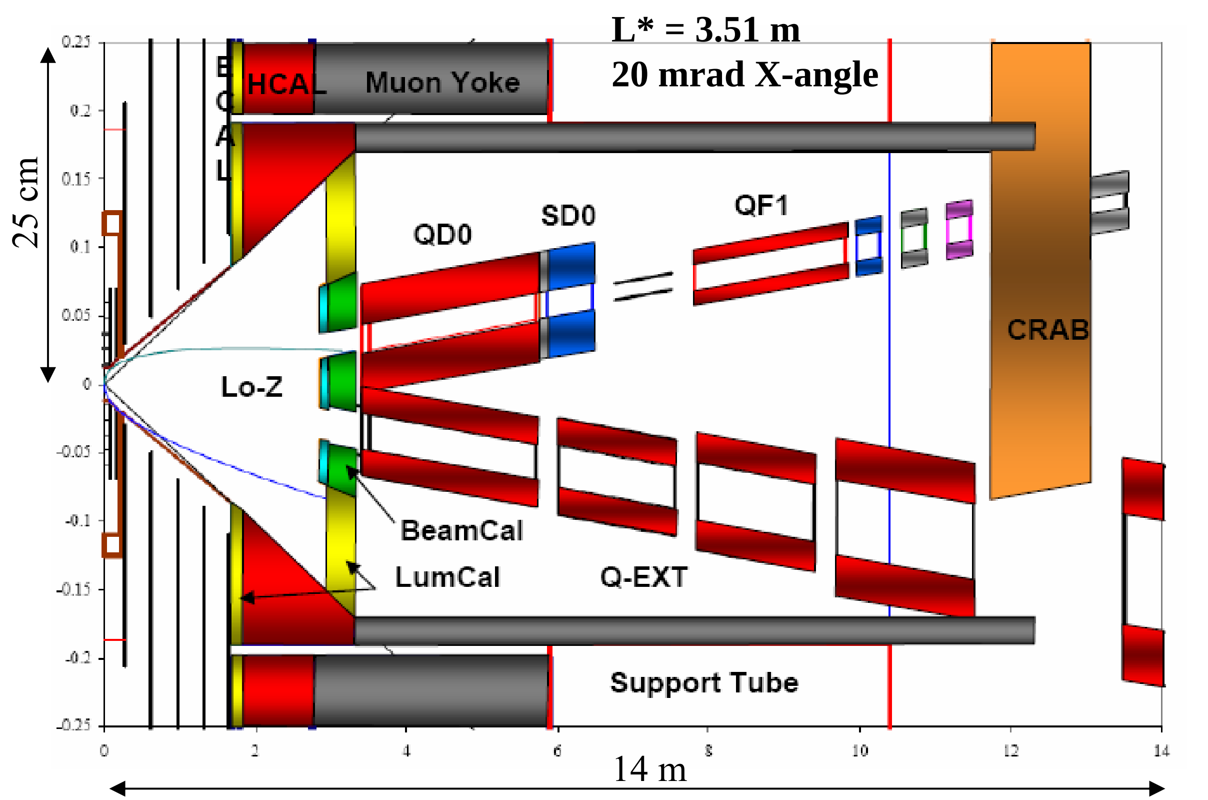
- Material budget, especially in the forward region, is a major issue
  - Babar: 5 layers of double-sided Si
  - Stays below 4% at normal incidence traversing SVT; average of 0.8% X_0 per layer
  - But, significant amount of material (far too much) in forward region
    - LHC type detectors would be inadequate





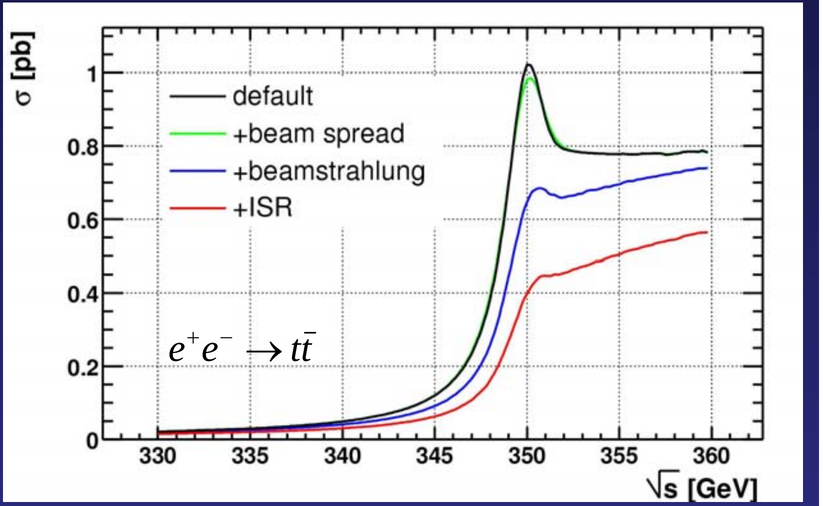
Very Forward Instrumentation

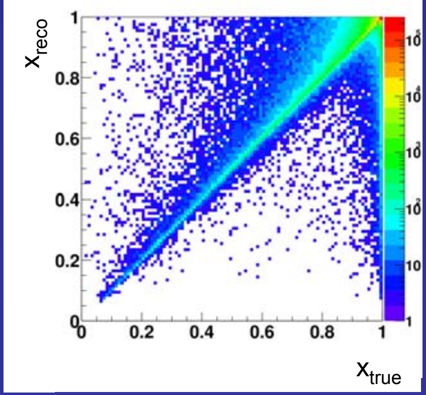
- Critical R&D area is interface between collider and detector
  - Precision luminosity measurement with LumCal from Bhabhas (83 to 27 mrad)
    - Aim for $\Delta L/L \sim 10^{-4}$ require $\Delta\theta = 1.4$ mrad
  - Fast beam diagnostics detecting e^+e^- pairs originated from the beamstrahlung photon conversion with BeamCal
  - Shield tracking volume and provide good hermiticity

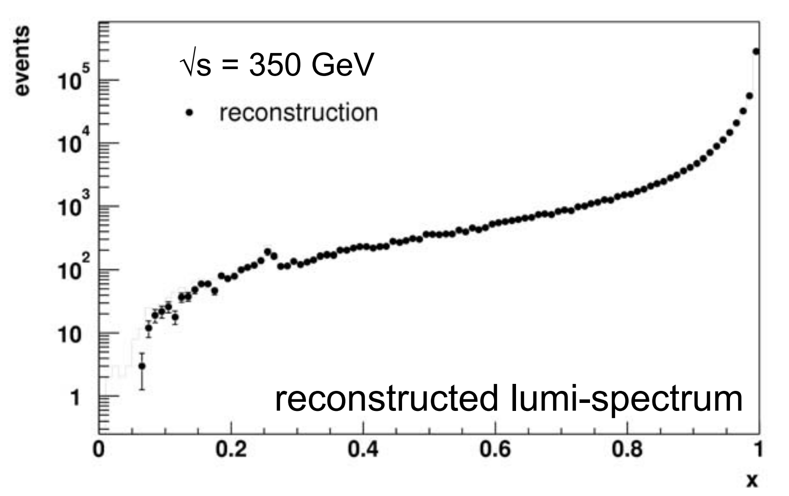


Measurement of d$\mathcal{L}$/dE

- Measurement of d$\mathcal{L}$/dE required to 0.1%
  - Precision set by Top threshold scan and Slepton masses
    - Δm_t ~ 100 MeV
    - need precise luminosity spectrum
  - Measured through Bhabha acolinearity
    - $\Delta\Theta/\Theta$~ 10^{-5} at very small angles: very demanding !
- Reconstructed luminosity-spectrum
  - Definition of true luminosity spectrum problematic due to overlap of ISR and FSR in Bhabha scattering
  - Main differences between measured and true x at x~1



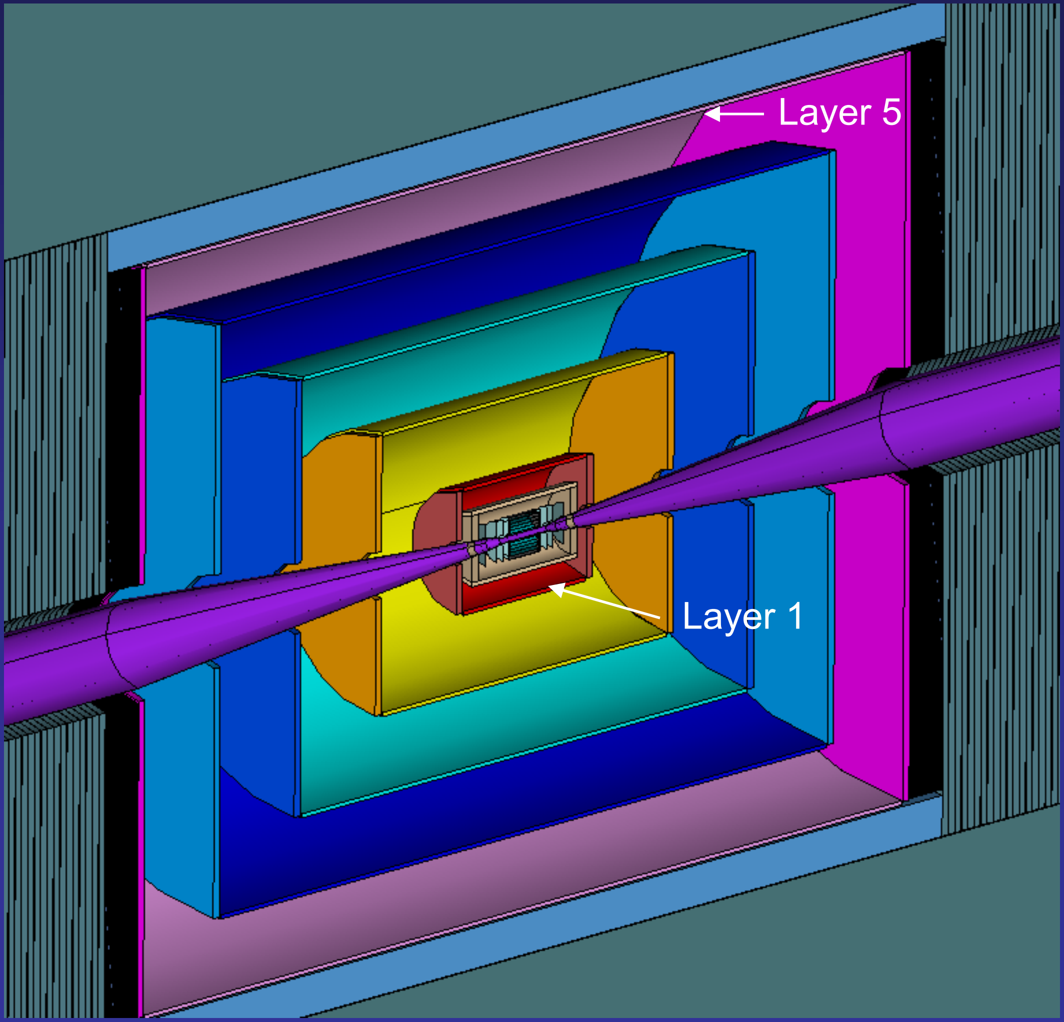




x = √s' / √s

Silicon Outer Tracker

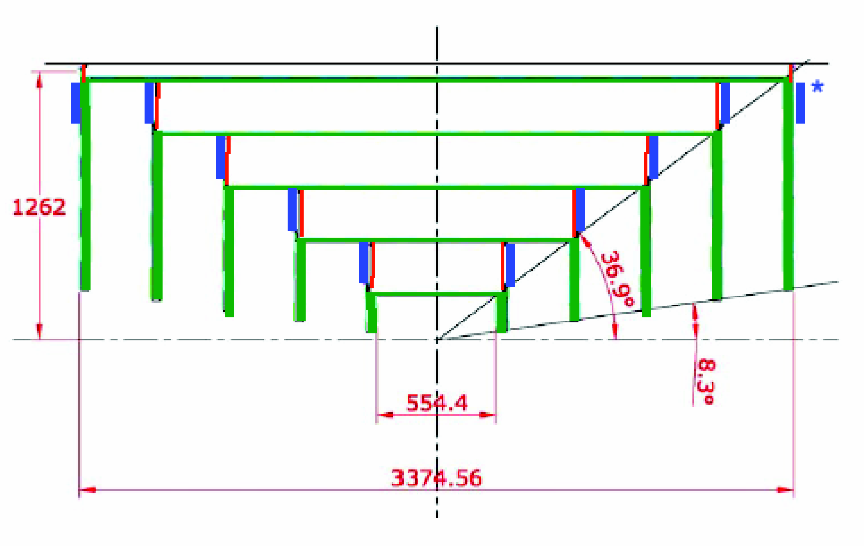
- 5-Layer silicon strip outer tracker, covering R_{in} = 20 cm to R_{out} = 125 cm, to accurately measure the momentum of charged particles

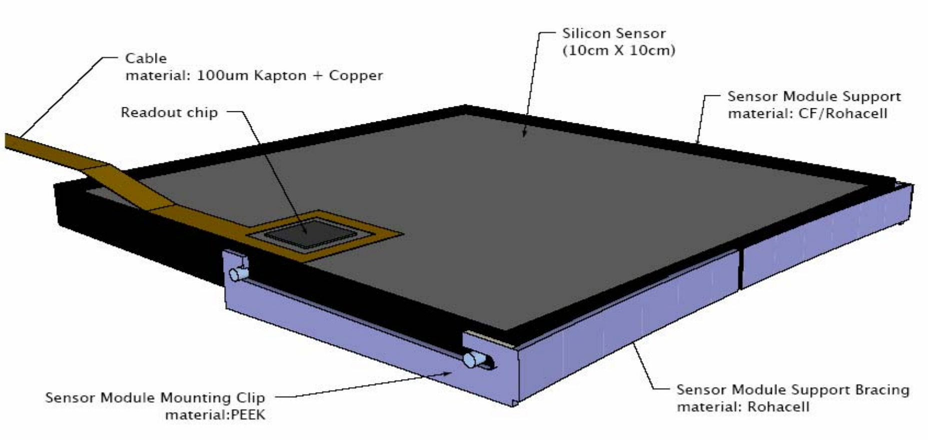


- Support
  - Double-walled CF cylinders
  - Allows full azimuthal and longitudinal coverage
- Barrels
  - Five barrels, measure Phi only
  - Eighty-fold phi segmentation
  - 10 cm z segmentation
  - Barrel lengths increase with radius
- Disks
  - Five double-disks per end
  - Measure R and Phi
  - varying R segmentation
  - Disk radii increase with Z

Tracker Design

- Baseline configuration
  - Cylinders are tiled with 10x10cm^2 modules with minimal support
  - Material budget 0.8% X_0/layer
  - z-segmentation of 10 cm
  - Active volume, R_i=0.218 m, R_o=1.233 m
  - Maximum active length = 3.3 m
  - Single sided in barrel; R, ϕ in disks
  - Overlap in phi and z



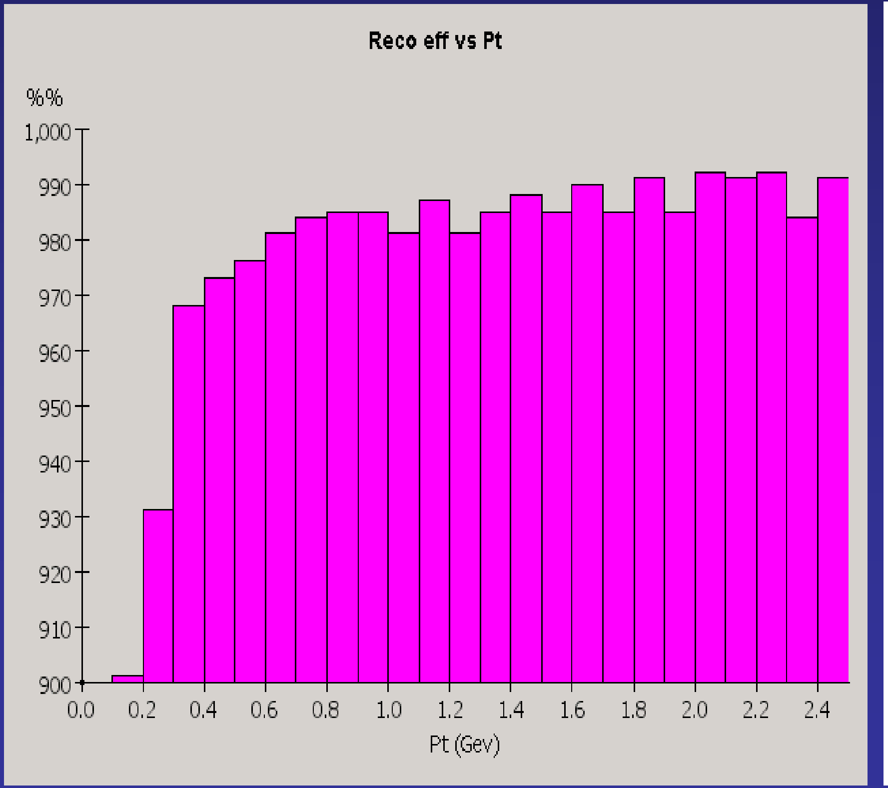


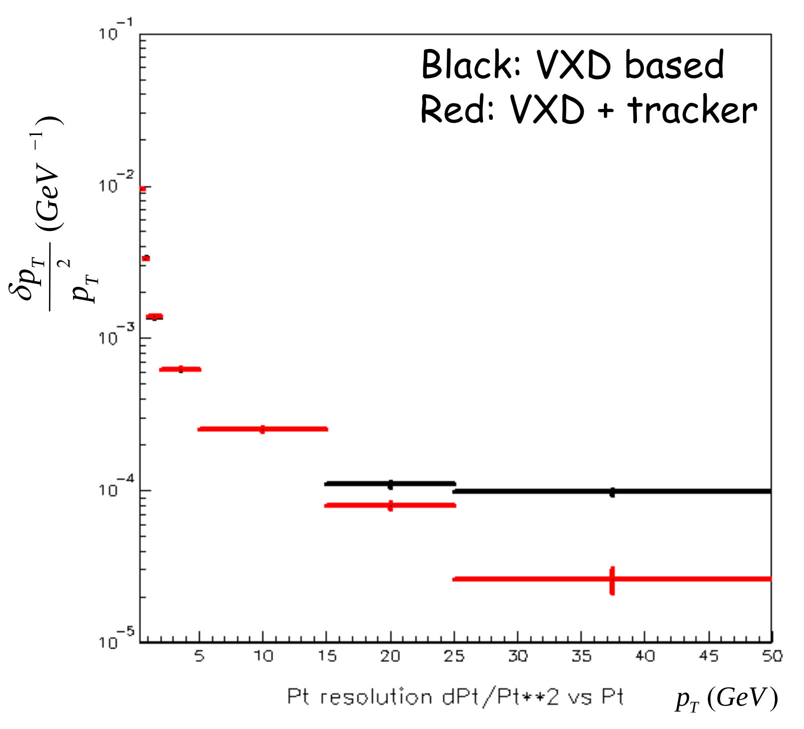
- Nested support
- Power/Readout mounted on support rings

- Disks tiled with wedge detectors
- Forward tracker configuration to be optimized

Tracker Performance

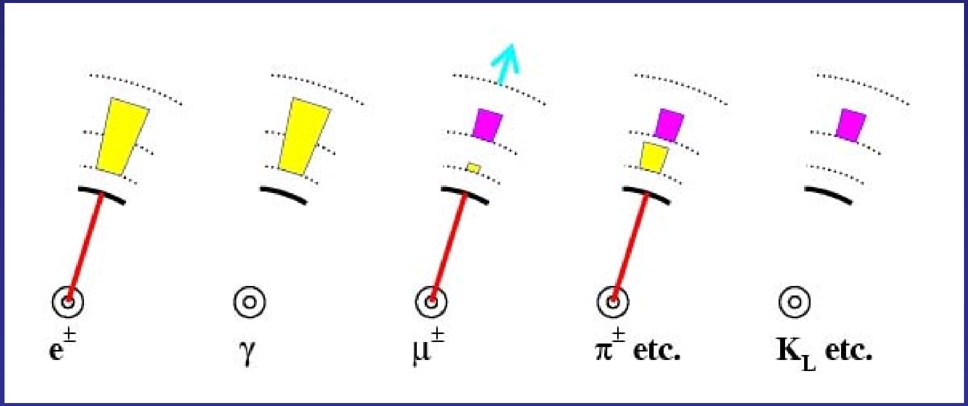
- Vertex detector seeded pattern recognition (3 hit combinations)
  - ttbar-events, full detector simulation and digitization, $\sqrt{s}$ = 500 GeV, background included
    - Efficiency for reconstructing track in vertex detector
      - Small fake rate (<1%); all forward and at low p_T
    - Momentum resolution for central region only





Calorimetry

- Goal is jet energy resolution of $30\%/\sqrt{E}$
- Current paradigm is that this can be achieved with Particle Energy Flow
- A particle flow algorithm is a recipe to improve the jet energy resolution by minimizing the contribution from the hadronic energy resolution by reducing the function of a hadron calorimeter to the measurement of neutrons and K^0's only



- Measure charged particles in the tracking system
- Measure photons in the ECAL
- Measure neutral hadrons in the HCAL (+ ECAL) by subtracting calorimeter energy associated with charged hadrons

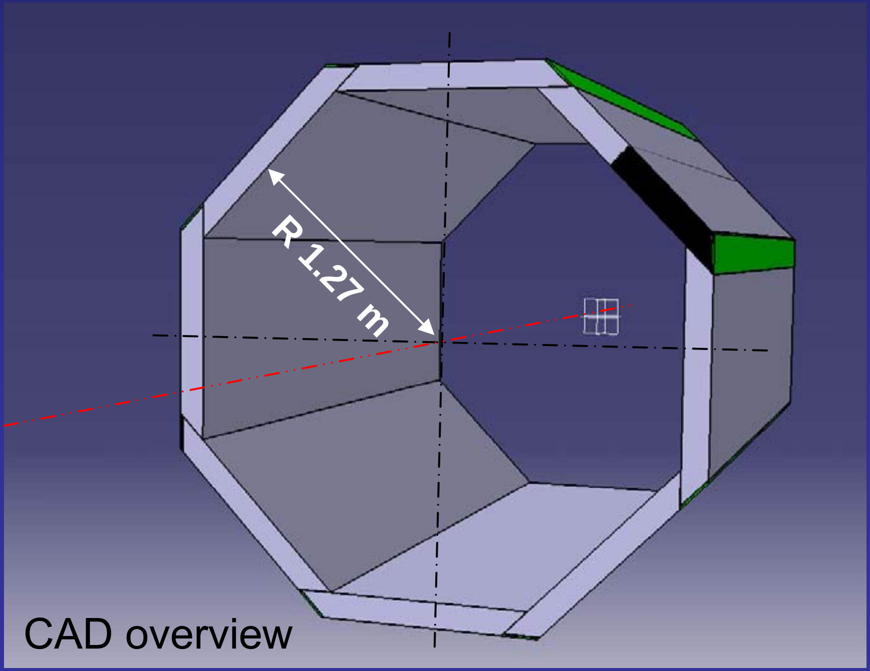
Particles in jets	**Fraction of energy**	**Measured with**	**Resolution** $[\sigma^2]$
Charged	~ 65 %	Tracker	Negligible
Photons	~ 25 %	ECAL with $15\%/\sqrt{E}$	$0.07^2 E_{jet}$
Neutral Hadrons	~ 10 %	ECAL + HCAL with $50\%/\sqrt{E}$	$0.16^2 E_{jet}$

$\Big\}$ $\sim 20\%/\sqrt{E}$

EM Calorimeter

- P-Flow requires high transverse and longitudinal segmentation and dense medium
- Choice: Si-W can provide 5 x 5 mm^2 segmentation and minimal effective Molière radius
  - Maintain Molière radius by minimizing the gap between the W plates
  - Requires aggressive integration of electronics with mechanical design

Absorber	X_0 [cm]	R_M [mm]
Iron	1.76	18.4
Copper	1.44	16.5
Tungsten	0.35	9.5
Lead	0.58	16.5



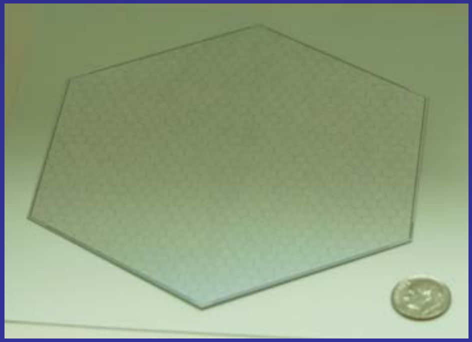
CAD overview

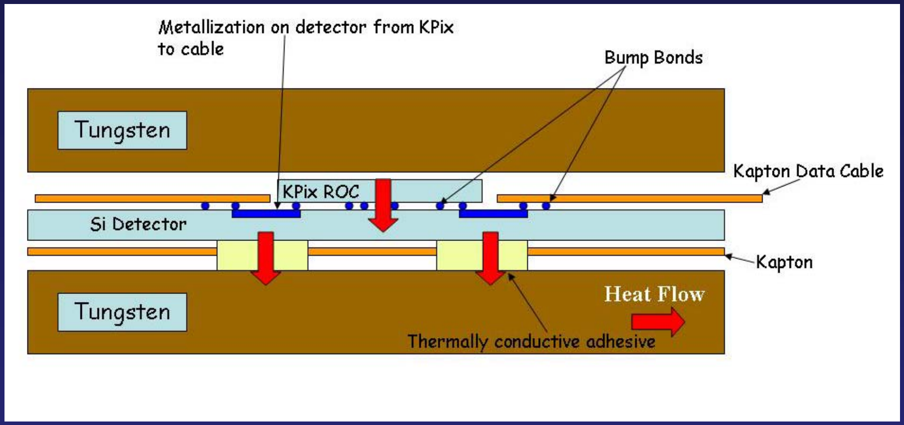
SLAC/Oregon/BNL Design
LAPP, Annecy, Mechanical Design

- 30 layers, 2.5 mm thick W
- ~ 1mm Si detector gaps
  - Preserve $R_M(W)_{eff}$= 12 mm
- Pixel size 5 x 5 mm^2
- Energy resolution 15%/√E + 1%

EM Calorimeter Layout

- Tile W with hexagonal 6" wafers
  - ~ 1300 m^2 of Si
  - 5x5 mm^2 pads
  - Readout by single chip
  - 1024 channels, bump-bonded
- Signals
  - Single MIP with S/N > 7
  - Dynamic range of 2500 MIPs
  - < 2000 e$^-$ noise
- Power
  - < 40 mW/wafer through power pulsing !
  - Passive edge cooling

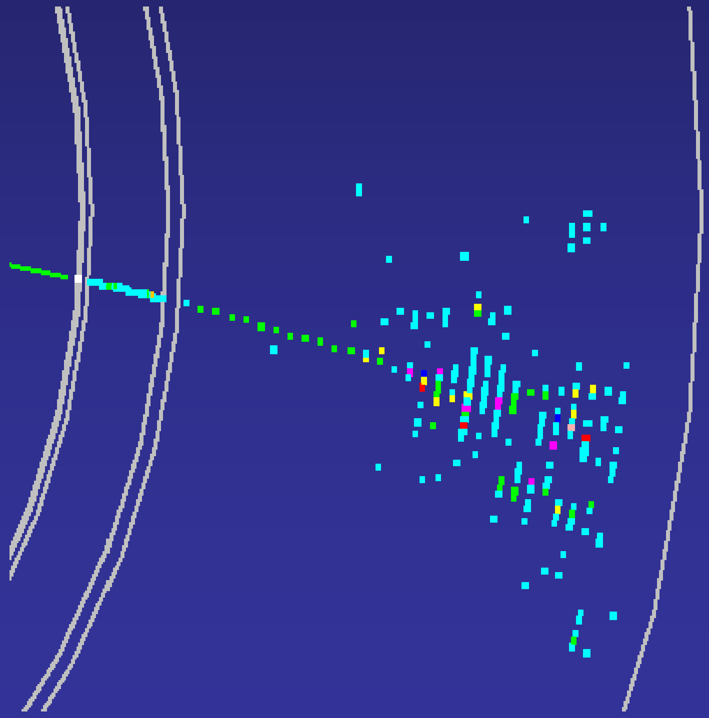




- Readout with kPix chip
  - 4-deep buffer (low occupancy)
  - Bunch crossing time stamp for each hit
- Testing
  - Prototype chip in hand with 2x32 channels
  - Prototype sensors in hand
  - Test beam foreseen in 2006

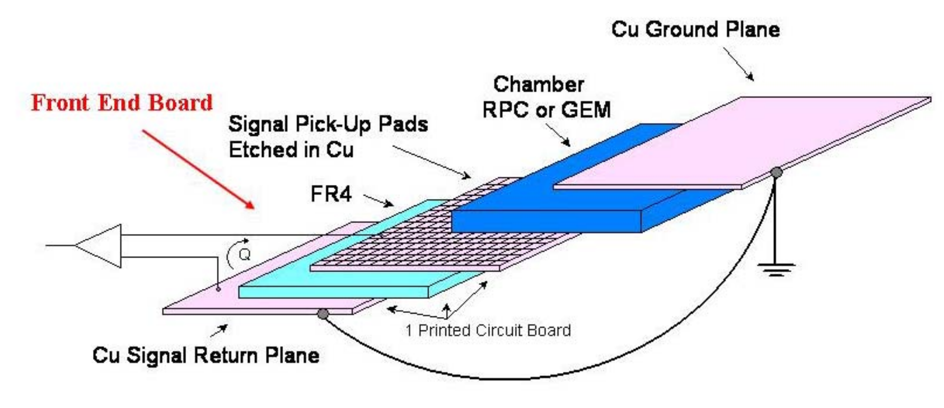
Hadron Calorimetry

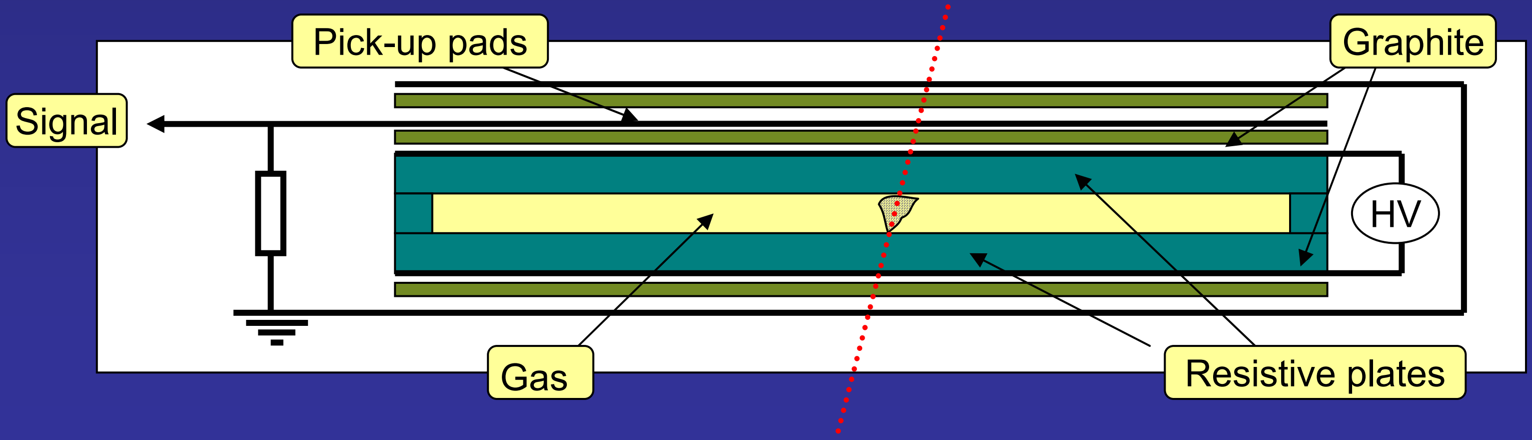
- Role of hadron calorimeter in context of PFA is to measure neutrals
  - HCAL must operate with tracking and EM calorimeter as integrated system
- Various Approaches
  - Readout
    - Analog readout -- O(10) bit resolution
    - Digital readout -- 1-bit resolution (binary)
  - Technolgoy
    - Active
      - Resistive Plate Chambers (RPC's)
      - Gas Electron Multipliers (GEM's)
      - Scintillator
    - Passive
      - Tungsten
      - Steel
  - Algorithms
    - Spatial separation
    - Hit density weighted
    - Gradient weighted



Hadron Calorimeter

- Current baseline configuration for SiD:
  - Digital calorimeter, inside the coil
    - R_i = 139 cm, R_o =237 cm
  - Thickness of 4λ
    - 38 layers of 2.0cm steel
    - One cm gap for active medium
  - Readout
    - RPC's as active medium (ANL)
    - 1 x 1 cm^2 pads
    - All options being explored





Particle Flow

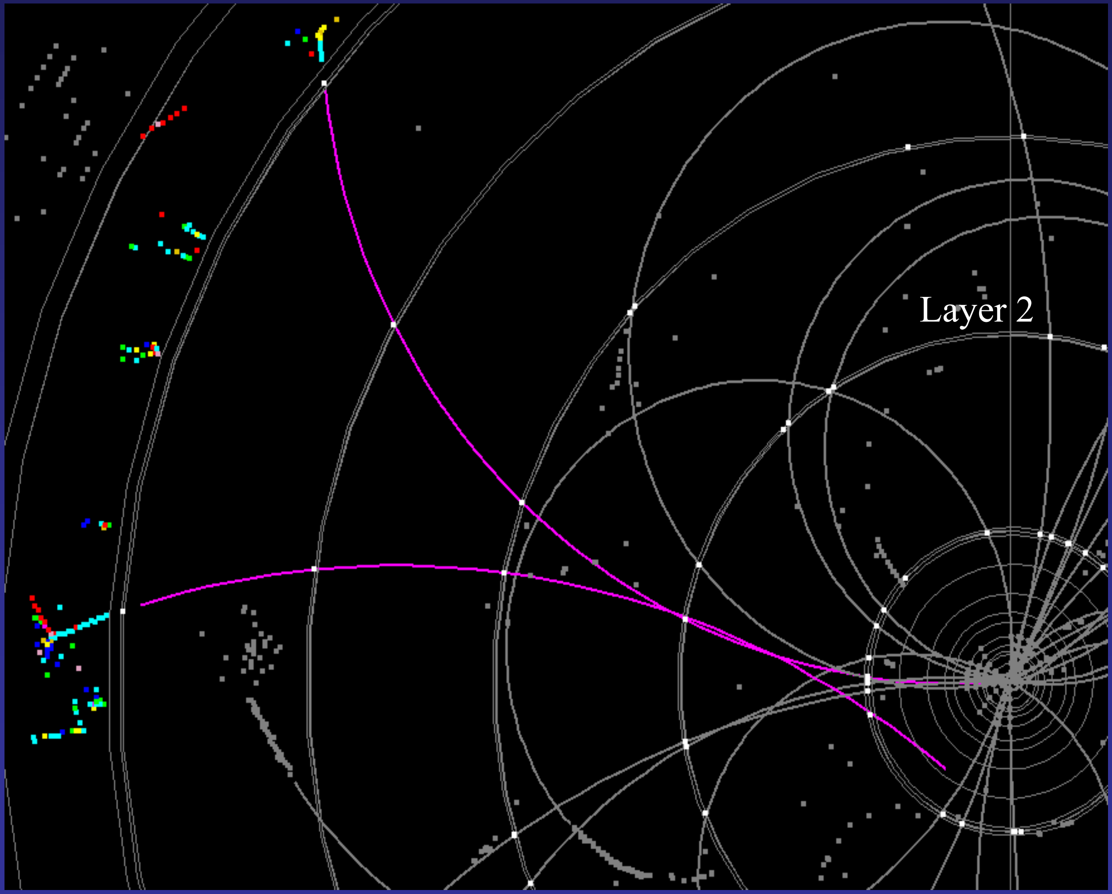
- Area of intensive work, not just within SiD, but in whole ILC community
- Many, many open issues
  - Algorithms
    - Cluster finding, …
  - Physics
    - Dependence on environment
    - Missing neutrinos, FSR, …
  - Detector
    - Linearity, e/p, E-resolution, granularity
    - Sampling fluctuations, leakage, …

	Algorithm	Institution
γ	Minimum Spanning Tree	Iowa
	H-matrix + nearest neighbor	ANL, KU, SLAC
Hadrons	Minimum Spanning Tree	Iowa
	Hit Density-weighted	ANL
	Spatial Density-weighted	NIU
	Directed Tree cluster	NIU
	NN based	ANL, SLAC
	Divisive	FNAL

Fermilab Wine and Cheese, December 2 by Jose Repond

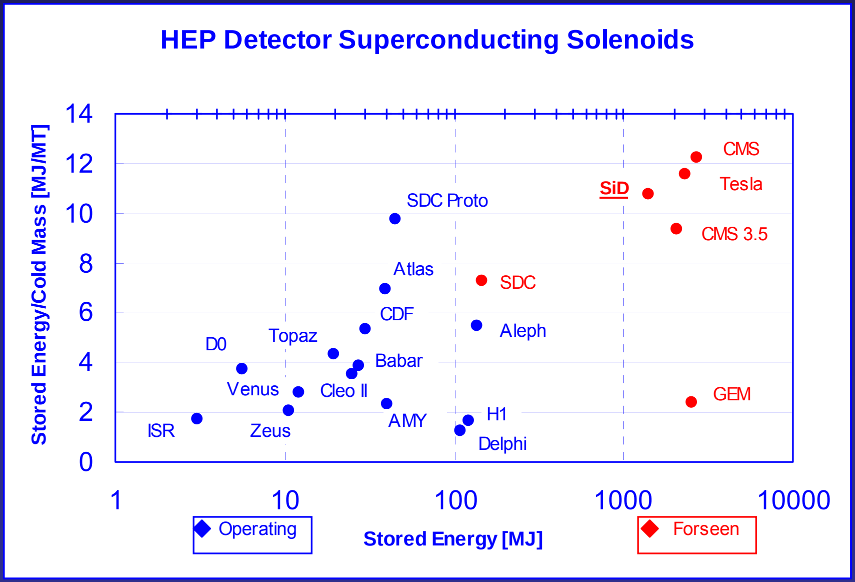
Calorimeter Tracking

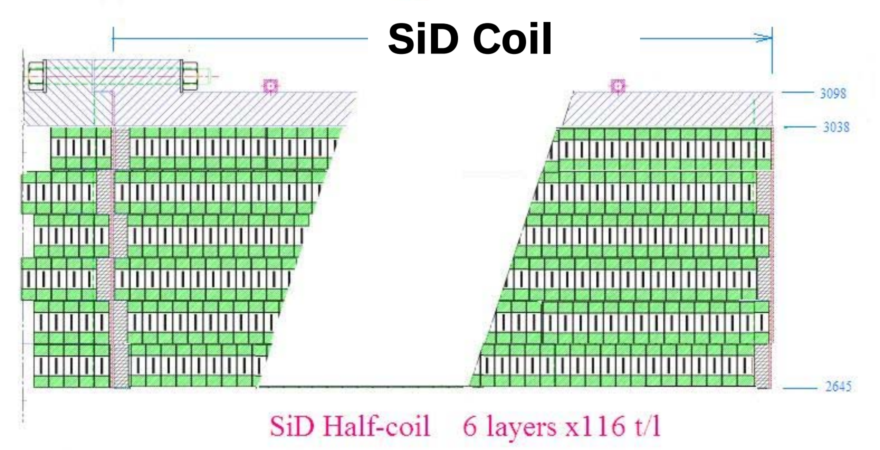
- With a fine grained calorimeter, can do tracking with the calorimeter
  - Track from outside in: K^0_s and Λ or long-lived SUSY particles, reconstruct V's
  - Capture events that tracker pattern recognition doesn't find



Solenoid

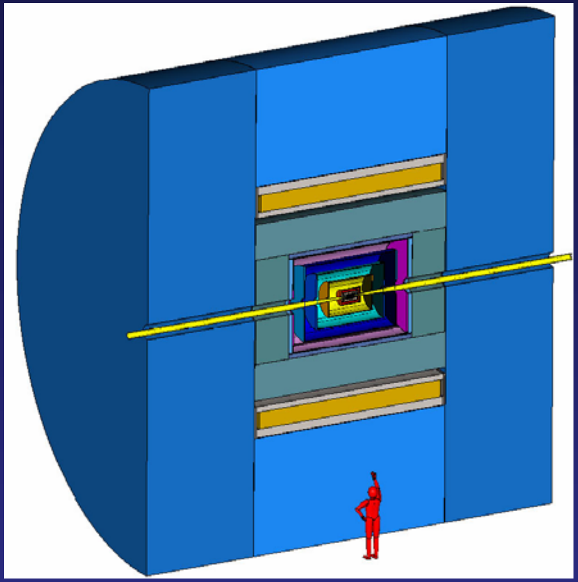
- Design calls for a solenoid with B(0,0) = 5T (not done previously)
  - Clear Bore Ø ~ 5 m; L = 5.4 m: Stored Energy ~ 1.2 GJ
    - For comparison, CMS: 4 T, Ø = 6m, L = 13m: 2.7 GJ





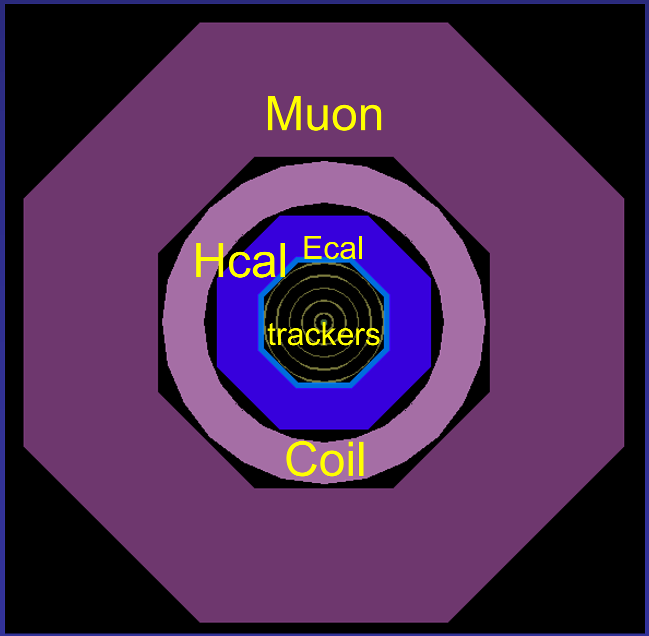
- Full feasibility study (with CERN, Saclay) of design based on CMS conductor
  - Start with CMS conductor design, but increase winding layers from 4 to 6
    - I(CMS)= 19500 A, I(SiD) = 18000 A; Peak Field (CMS) 4.6 T, (SiD) 5.8
    - Net performance increase needed from conductor is modest

Muon System



- Muon System Baseline Configuration
  - 48 layers, 5 cm thick steel absorber plates
  - RPC's as active medium
  - Muon ID studies done to date with 12 instrumented gaps with ~1cm spatial resolution
  - 6-8 planes of x, y or u, v upstream of Fe flux return for xyz and direction of charged particles that enter muon system.

- Technologies
  - RPC's of glass and bakelite
  - Scintllators with photo-detection
  - GEM's
  - Wirechambers



ILC Detector R&D at Fermilab

- Over the course of the last ~1.5 years involvement in detectors for the ILC has significantly gained momentum

- Goals:
  - Establish a coherent, focused ILC Detector R&D program at Fermilab
  - Focus on critical detector R&D areas
  - Tie in to strengths across the laboratory

- Approach:
  - Assume role as 'host' laboratory, i.e. inviting and open attitude
    - When possible, keep R&D general, not detector specific
    - When R&D detector specific, coupled to the SiD concept detector
  - Identify areas of synergy between existing Fermilab projects and ILC
  - Exploit regional common interests
  - Form collaborative efforts where possible

- Documentation:
  - http://ilc.fnal.gov/detector/rd/detrd.html

World Wide Study R&D Panel

- The World Wide Study Organizing Committee has established the Detector R&D Panel to promote and coordinate detector R&D for the ILC
  - https://wiki.lepp.cornell.edu/wws/bin/view/Projects/WebHome

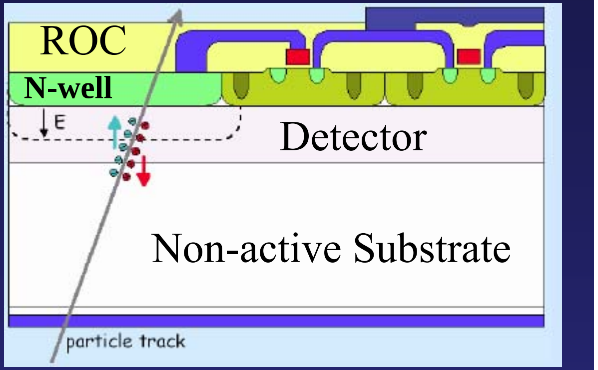
- Fermilab has nine submissions to this registry:
  - Vertex and Tracking detectors:
    - Mechanical design of vertex detector …… RD1
    - Active Pixels …… RD2
      - MAPS …… RD3a
      - SOI and 3D …… RD3b
    - Hybrid Pixels …… RD4
    - Beam pipe design …… RD5
  - Calorimetry:
    - PFA and Related Simulation Software …… RD6
    - Digital Hadron Calorimeter with RPC's …… RD7
  - 5T Solenoid design …… RD8
  - Scintillator-Based Muon System R&D …… RD9

Low Mass Vertex Detectors

- Baseline choice for a vertex detector for ILC detectors is ccd-based
- Multitude of R&D efforts ongoing in the area of low mass vertex detectors across the world
  - Thin, radiation hard, pixel detector desired by any experiment
    - Replacement detectors for LHC experiments; LHC upgrades
- Technologies being pursued, which all can be viable alternatives for a vertex detector at an ILC:
  - MAPS
  - SOI, 3D
  - Thin Si
- Many of the open issues for use of this technology as particle detectors are shared with industry

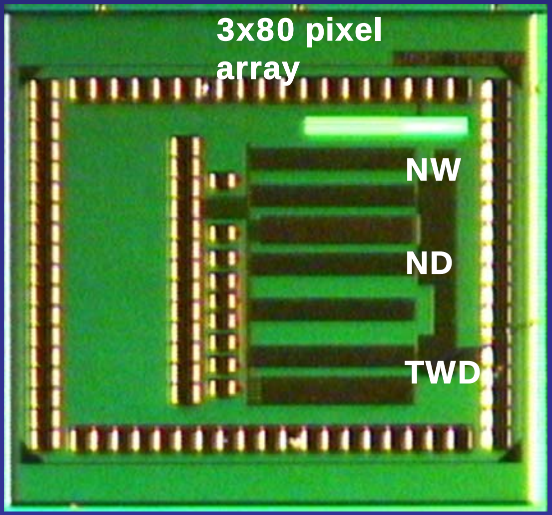
Monolithic Active Pixel Sensors

- A MAPS device is a silicon structure where the detector and the primary readout electronics are processed on the same substrate
- MAPS can be divided into two classifications:
  - Those using standard CMOS processes
  - Those using specialized processes



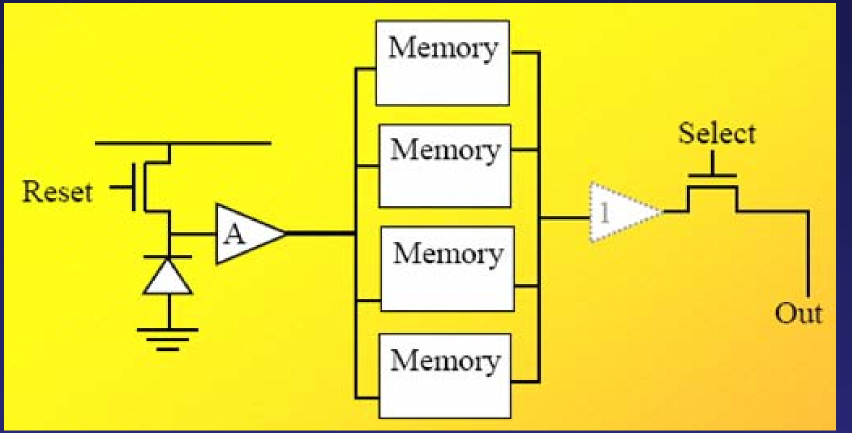
MAPS Principle

- As introduction into this area submitted a 130 nm chip in IBM CMOS process to study characteristics:
  - Feature devices on chip
    - Registers for SEU evaluation
    - LVDS drivers
    - Test devices
  - Pixel layout
    - 80 row x 3 column pixel readout array
      - Column with no diodes
      - Column with N-well
      - Column with triple N-well
    - Fine pitch features
  - In process of characterizing performance



Standard CMOS MAPS

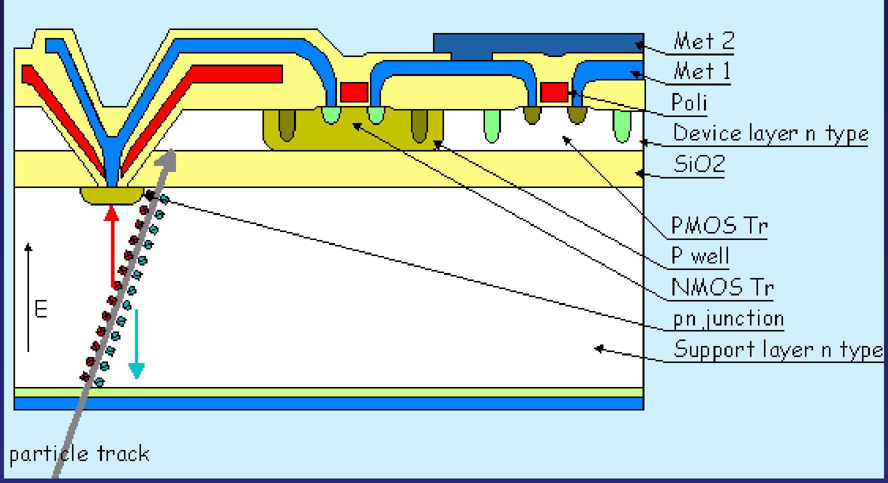
- MAPS with epi-layer
- Basic architecture is 3 transistor cell
  - signal created in epitaxial layer
  - thermal charge collection (no HV)
  - charge sensing through n-well/p-epi junction



- Development for Super-Belle; current version (Gary Varner, Hawaii):
  - pixel size: 20x20 μm^2; 36 transistors/pixel; 5 metal layers; TSMC 0.25 μm process
  - 128x928 pixels/sensor; double pipe-line 5 deep
  - Double correlated sampling with reset in abort gaps (500ns every 10μs)
  - Column select readout, 10μs frame readout
  - Signal~300e, Noise ~ 20-35e$^-$ → S/N ~ 10-15
- Started collaboration with Hawaii (Gary Varner), IReS (Marc Winter) and discussions with Bergamo (Valerio Re)
  - Strassbourgh exchange student will join project in spring '06

Silicon On Insulator

- Silicon on Insulator (SOI)
  - Non-standard process
  - Handle wafer, normally passive is the detector
  - Signal collected in fully depleted substrate, thus large signals
  - Electronics in the device layer
  - Should be rad. hard; can have NMOS and PMOS transistors

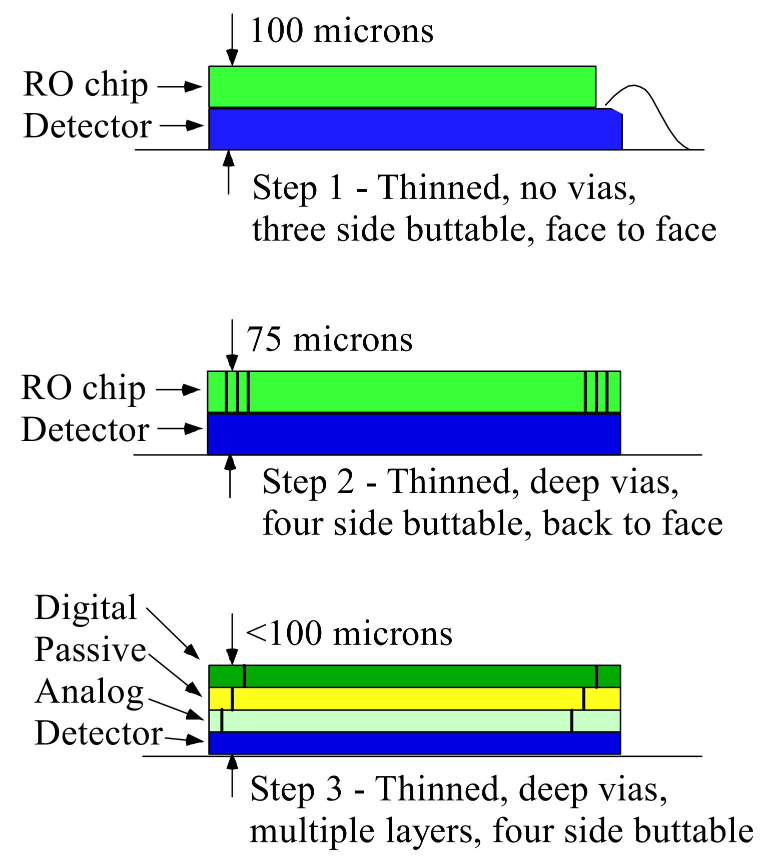


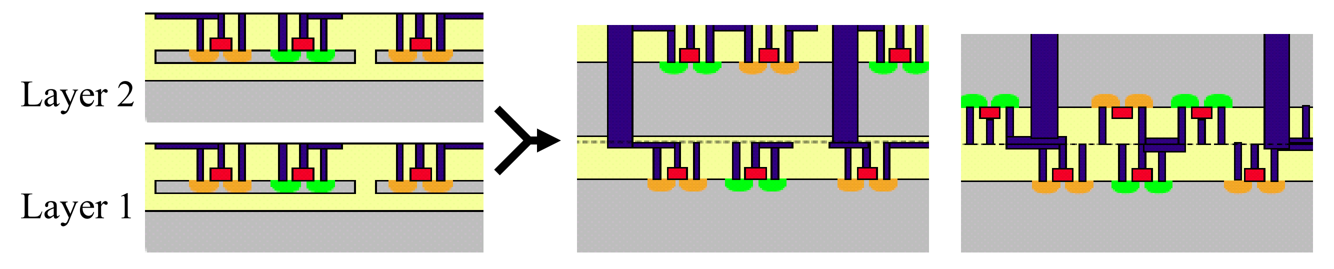
- Process Technology
  - Allows for production of pixel sensors which are thin (<50 microns)
  - Excellent and well controlled charge collection using fully depleted devices
  - Use full CMOS readout without parasitic charge collection
  - High-resistivity handle wafer as detector

- Collaboration with industry (American Semiconductor) through SBIR grants

3D Processes

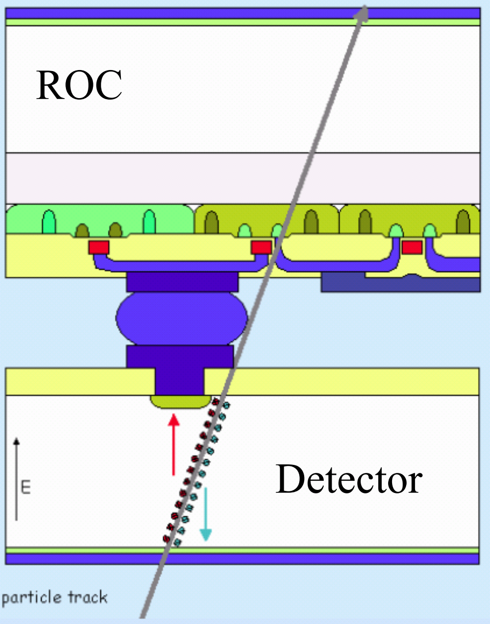
- A 3D device is a chip comprised of 2 or more layers of semiconductor devices which have been thinned, bonded, and interconnected to form a monolithic circuit
    - Layers can have devices made in different technologies
        - Process optimization for each layer
- Direction in industry
    - Early push for device scaling, circuit integration and packaging density
    - Interconnect and packaging issues are real barriers
    - Push towards planar approach: 3D
- Critical issue is thinning and bonding of the various layers

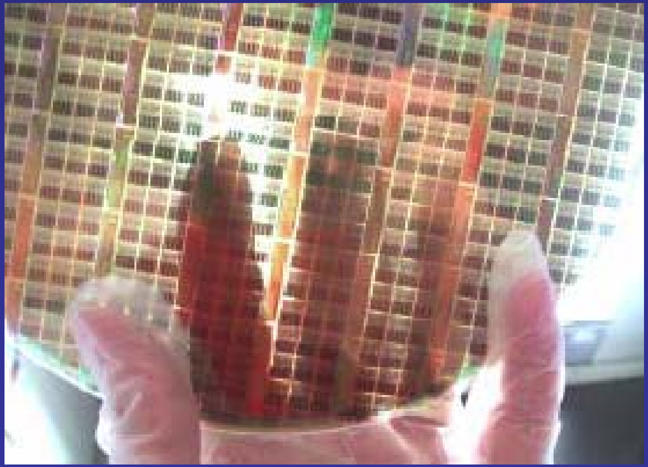




Hybrid Pixel Detectors

- Hybrid pixel detectors have separate detector and readout chip, connected by bump bond
    - sensor and read-out chip (roc) can be optimized separately
- Continuing issues with this technology:
    - cooling of detectors under high radiation
    - mass and cost
- Using the existing BTeV sensors and FPIX readout chip to study:
    - Thinning of roc down to 80 μm, bump bonded to BTeV sensors
        - ALICE thinned down to 150 μm
    - Thinned roc's bump bonded to new thin BTeV sensors
    - Power management and cooling requirements adequate for gas cooling of the hybrids with an ILC bunch structure
    - Efficiency, time resolution, readout speed, zero-suppressed readout.

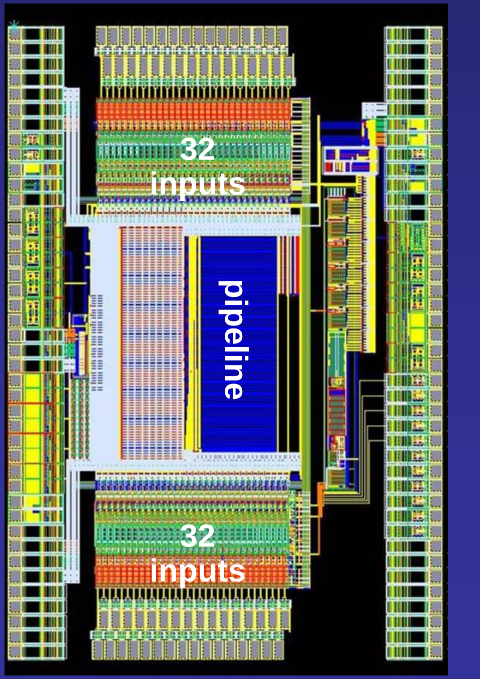




thinned wafer mounted on glass substrate

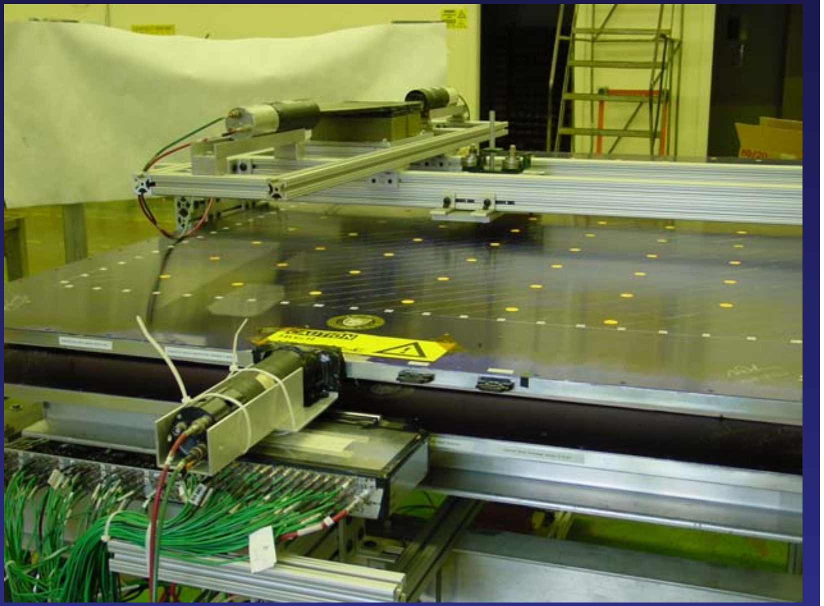
Calorimetry: PFA and Readout

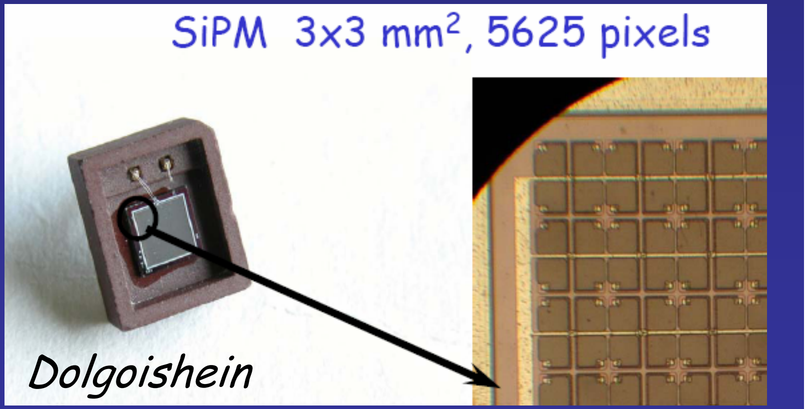
- Algorithm effort to look at particle flow and associated algorithms from a fresh perspective
  - Figure of merit for PFA's
    - decouple linearity, EM/HAD, response, calibrations
  - Fundamental limitations of energy resolution
  - Alternative approach to algorithm
    - grow clusters
    - split clusters
- Readout chip for Digital HCAL; Prototype chip in hand
  - For Fermilab testbeam in 2007 to prove DHCAL concept
  - 1 m^3, 400,000 channels, with RPC's and GEM's
    - 64 channels/chip; 1 cm x 1 cm pads
    - Detector capacitance: 10 to 100 pF
    - Smallest input signals: 100 fC (RPC), 5 fC (GEM)
    - Largest input signals: 10 pC (RPC), 100 fC (GEM)
    - Adjustable gain; Signal pulse width 3-5 ns
    - Trigger-less or triggered operation
    - 100 ns clock cycle
    - Serial output: hit pattern + timestamp



Muon System

- Scintillator based muon tracking system
  - Scintillator strip panels with Multi-Anode PMT (MAPMT)
    - MINOS style scintillator from Lab 6
    - Chamber 2.5 m x 1.25 m
    - Strips: 4.1 cm X 1 cm
    - HPK MAPMT 64 channels
- Explore different readout techniques
  - Silicon Photo Multipliers (SiPM)
    - Pixel Geiger Mode APDs
    - Gain 10^6, bias ~ 50 V, size 1 mm^2 with about 1000 pixels
    - QE x geometry ~ 15%
  - Exploit overlap and synergies with other detector systems
    - Also being considered for scintillator HCAL readout





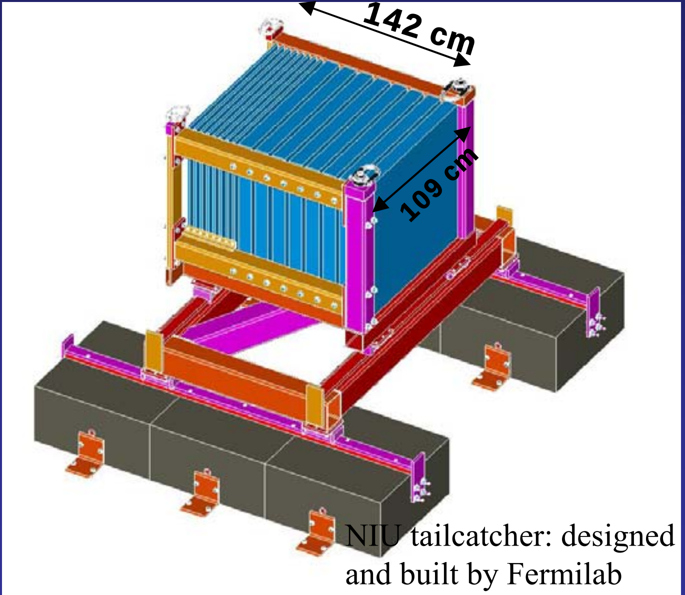
Testbeam

- Testbeam facility at MT6 set up, commissioned and supported
  - Beam parameters:
    - Momentum between 4 and 120 GeV
    - protons, pions, muons, electrons
  - Usage:
    - 14 MoU's, 8 completed
      - BTeV Hybrid Pixels (FNAL)
      - Belle MAPS (Hawaii)
      - CMS Pixels (NU, Purdue)
      - DHCAL (NIU, ANL)
  - Design study initiated to improve the beamline at MTest to better meet the requirements of the ILC community

- Particle flow calorimetry is a linchpin for ILC physics
- To date, PF not a proven concept based on Monte Carlo simulations
- Fermilab could nucleate around the testbeam to form an intellectual center and be a host for developing detector technologies for the ILC
- There are many natural synergies …

Testbeam for ILC

- Proposal for multi-year testbeam program for study of high performance calorimeters for the ILC with the CALICE collaboration
  - early 2006: Muon system tests, RPC tests
  - summer 2006: Muon Tailcatcher and RPC readout
  - tentative: summer 2007: CALICE full 1 m^3 EM and HCAL (scint + RPC)
- Strong regional commitments
  - NIU: analog/digital hadron calorimetry
  - ANL: digital hadron calorimetry
  - UofC, UTA, Iowa, …
- Overlapping physics fundamentals with other lab experiments: MIPP, Minerva, MINOS



NIU tailcatcher: designed and built by Fermilab

- Fermilab obvious place for full system test of slice of an ILC detector
- Opportunity for intellectual involvement in key issues of ILC

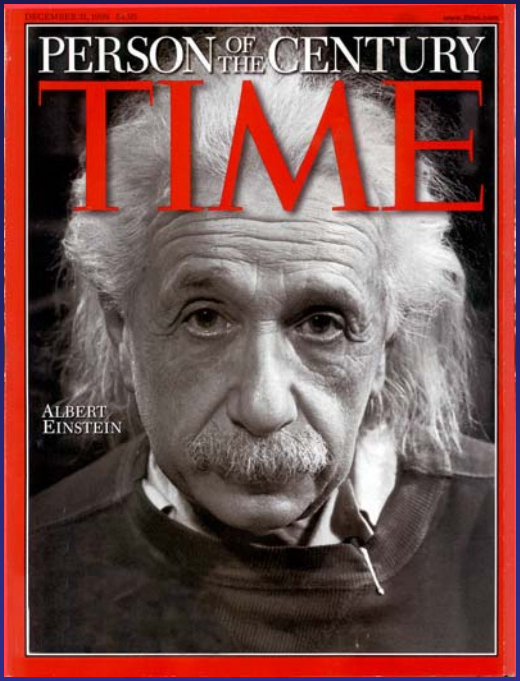
Software Support

- Software support
  - Activities are accompanied by simulation efforts to optimize the design
  - Fermilab Computing Division has installed the Simulation for the Linear Collider (SLIC) framework on Fermilab cluster
    - SLIC is core North-American simulation package
  - Farmlet available for simulations at ilcsim.fnal.gov

- Grid
  - All Grid infrastructure made available to the ILC community at Fermilab

- Simulations
  - Detectors for ILC are very advanced and in need of advanced simulation tools
  - Synergy to improve simulations for LHC experiments
  - Geant4 development for community as a whole
    - Improvement of hadronic shower developments
    - Analysis of test beam data, data from experiments with overlapping results (MIPP, Minverva, …)

The Year 2105



- We should be realistic enough to recognize that at this point in time we just cannot tell what answers lie ahead
- At the same time we should be bold and energetic enough to venture out to do the experiments which will tackle the outstanding questions

Conclusions

- The linear collider effort has a lot of momentum, worldwide
  - The community has decided the ILC to be the next highest priority
  - Fermilab endorses that point of view and would like to host the ILC
  - Fermilab has said that the ILC is the highest priority initiative
- Fermilab has an opportunity to play a unique role on the ILC scene
  - Lead and strengthen its position as potential host laboratory
  - Lead in the detector development and physics analyses
    - Detector R&D will benefit the community as a whole, possibly on a relatively short timescale

- Two opportunities mentioned:
  - The 'all-silicon' SiD detector design concept
  - Participation in detector R&D at the lab

- This is an invitation to participate in both