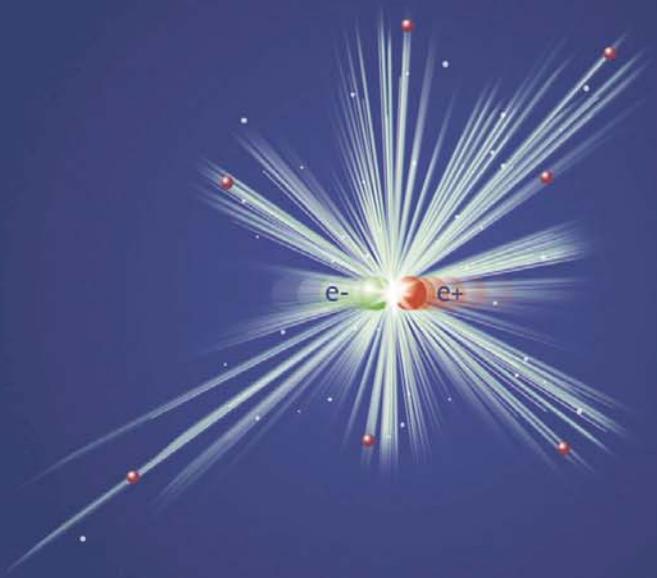


Detectors for the ILC

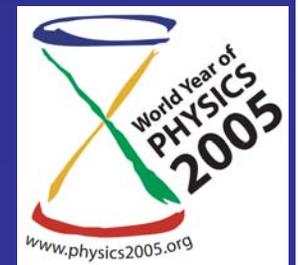


Marcel Demarteau
Fermilab

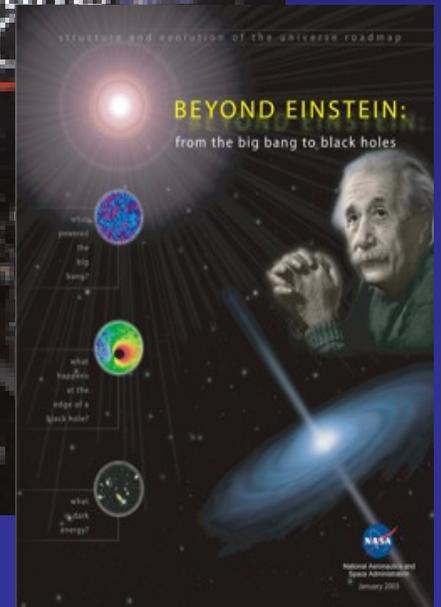
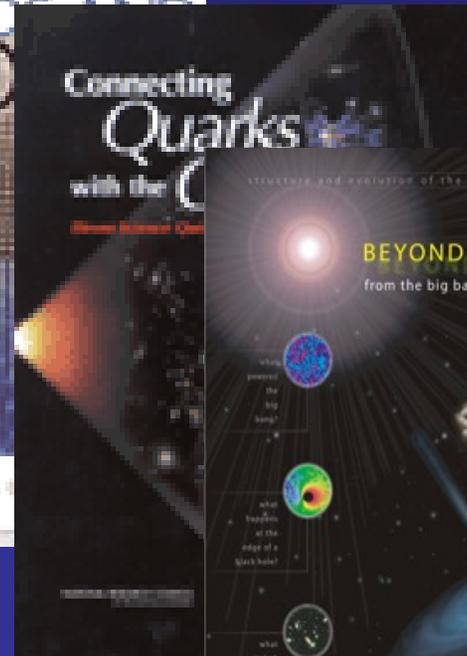
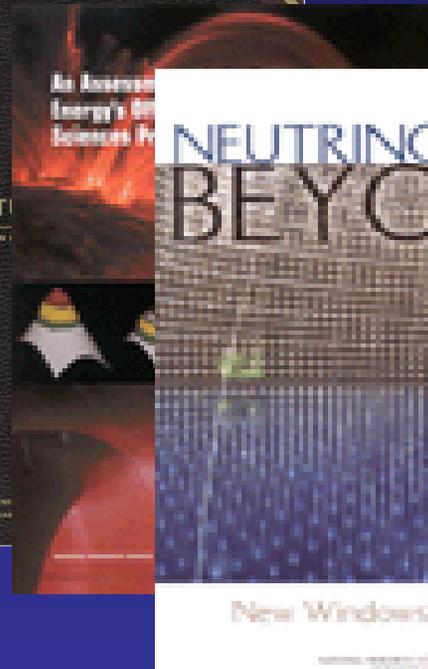
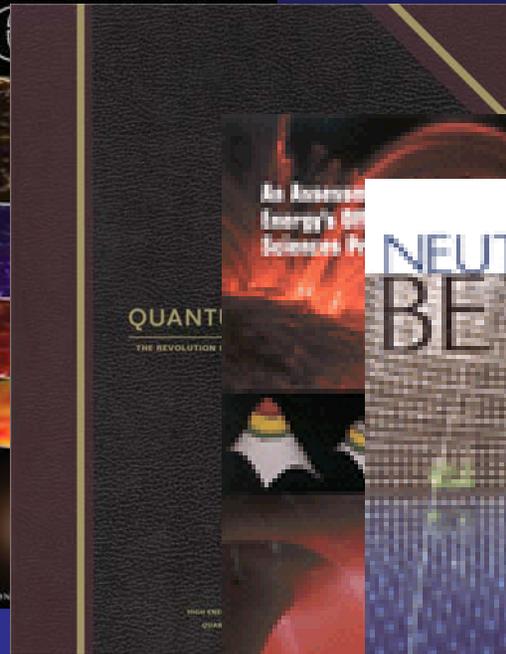
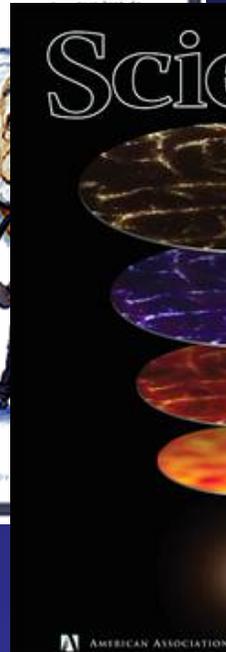
December 16, 2005

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

7

From the
Director
(EPP2010, P5)

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

The International Linear Collider

■ Baseline Machine:

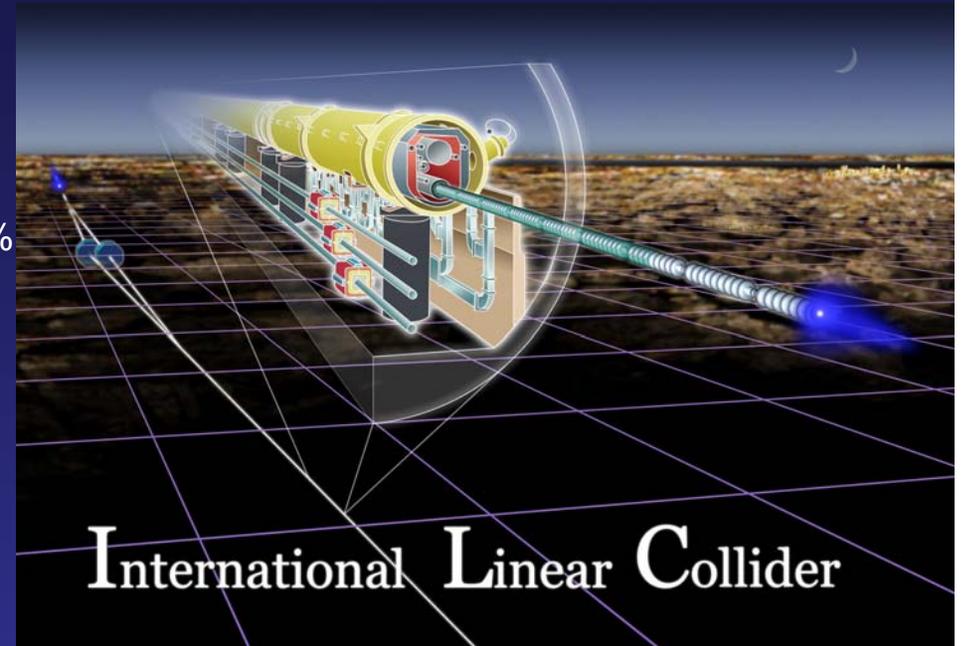
E_{CM} of operation 200 – 500 GeV
Luminosity and reliability for 500 fb^{-1} in 4 years
Energy scan capability with $<10\%$ downtime
Beam energy precision and stability below 0.1%
Electron polarization of $>80\%$
Two interaction regions with detectors
 E_{CM} down to 90 GeV for calibration

■ Upgrades:

E_{CM} about 1 TeV
Capability of running at any $E_{\text{CM}} < 1 \text{ TeV}$
 \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^- , $\gamma\gamma$, $e^-\gamma$ operation
 e^+ polarization $\sim 50\%$
Giga-Z with $\mathcal{L} = \text{several } 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
WW – threshold scan with $\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

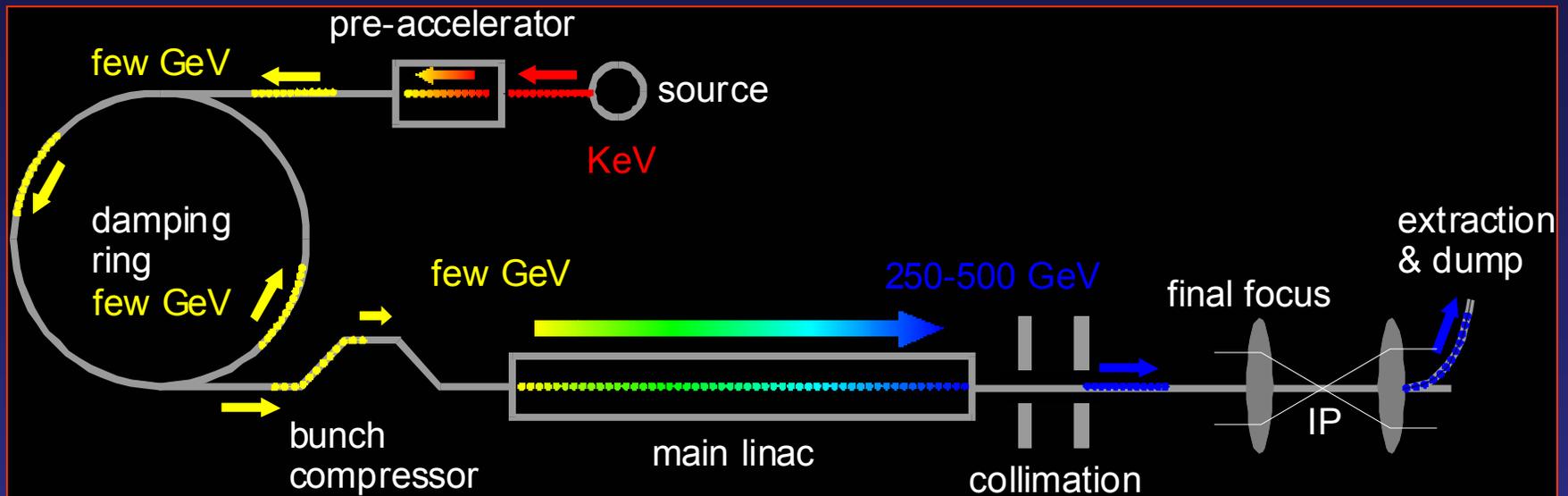


As defined in

International Scope Document

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

The Machine



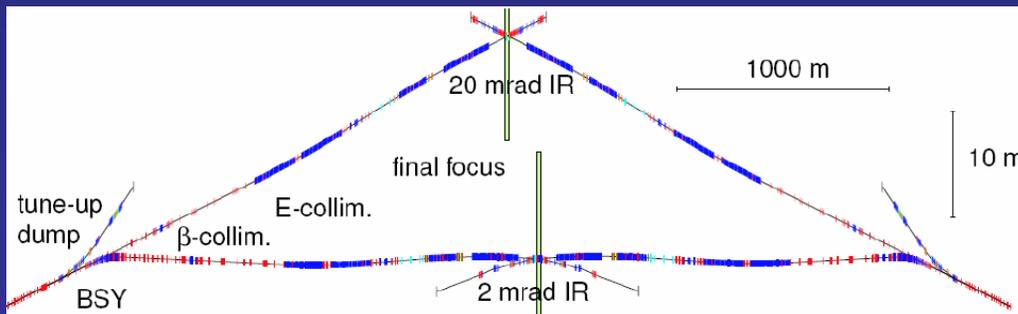
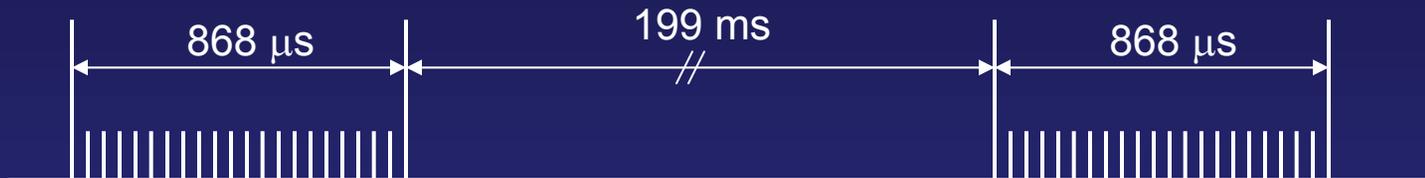
- Enormously challenging with many different components, but ...
 - Positron source three options: undulator, laser compton and conventional source
 - Damping Rings three options with test facility (ATF) at KEK
 - Klystrons (modulators) three (two) viable, field tested solutions for each
 - String of 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 μ s)

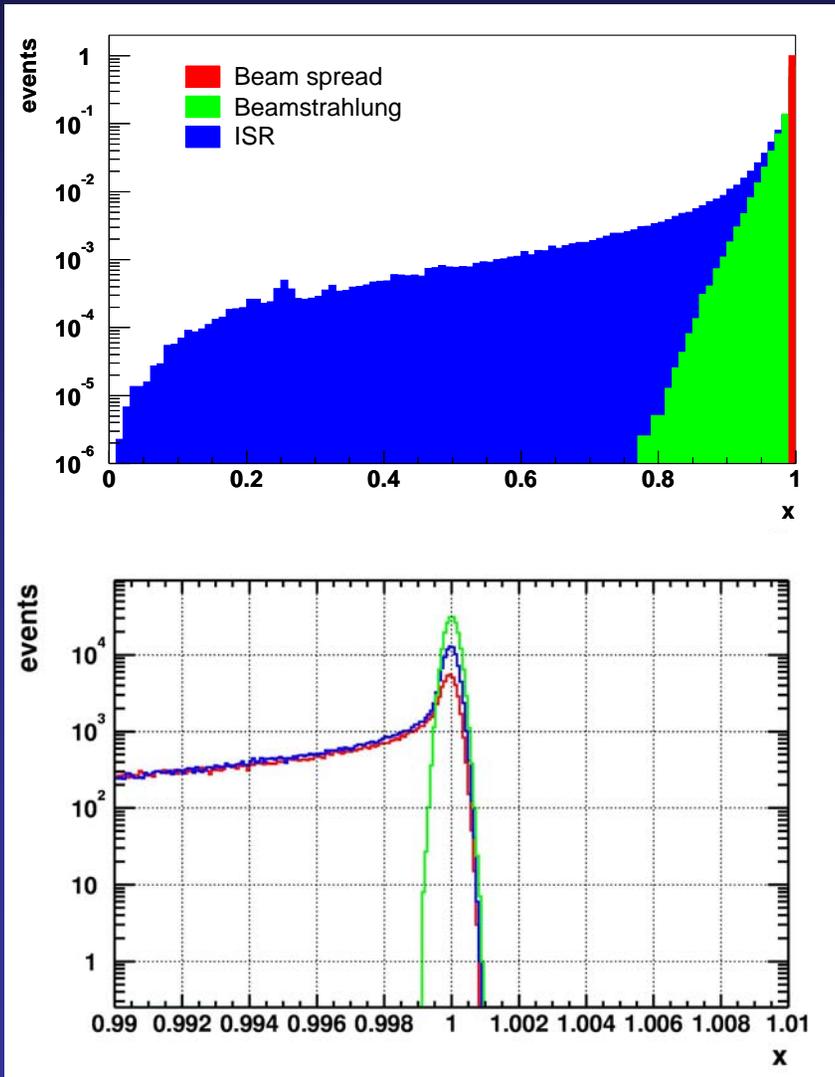


E_{CMS} [GeV]	500	1000
L ($\text{cm}^{-2}\text{s}^{-1}$)	$2.0 \cdot 10^{34}$	$3.0 \cdot 10^{34}$
Bunches/Train	2820	2820
Bunch train length (μ s)	868	868
Rep Rate [Hz]	5	5
T_{sep} (ns)	307.7	307.7
Gradient (MV/m)	30	30
N/bunch	$2.0 \cdot 10^{10}$	$2.0 \cdot 10^{10}$
σ_x, σ_y (nm)	655, 5.7	554, 3.5
σ_z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

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

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 $\sim 0.1\%$
 - 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 ..."

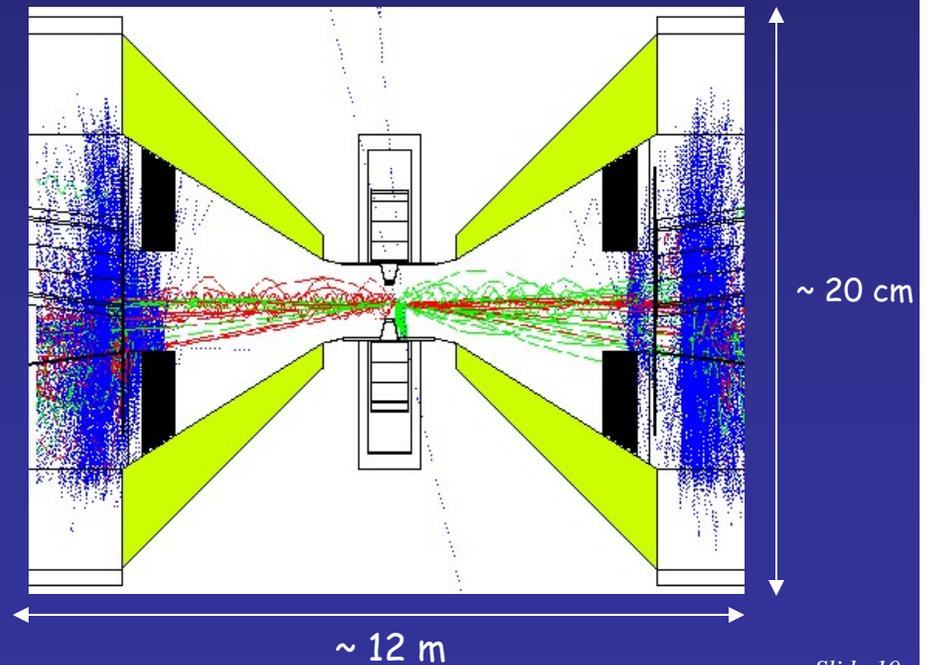
■ Backgrounds from the IP

- 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

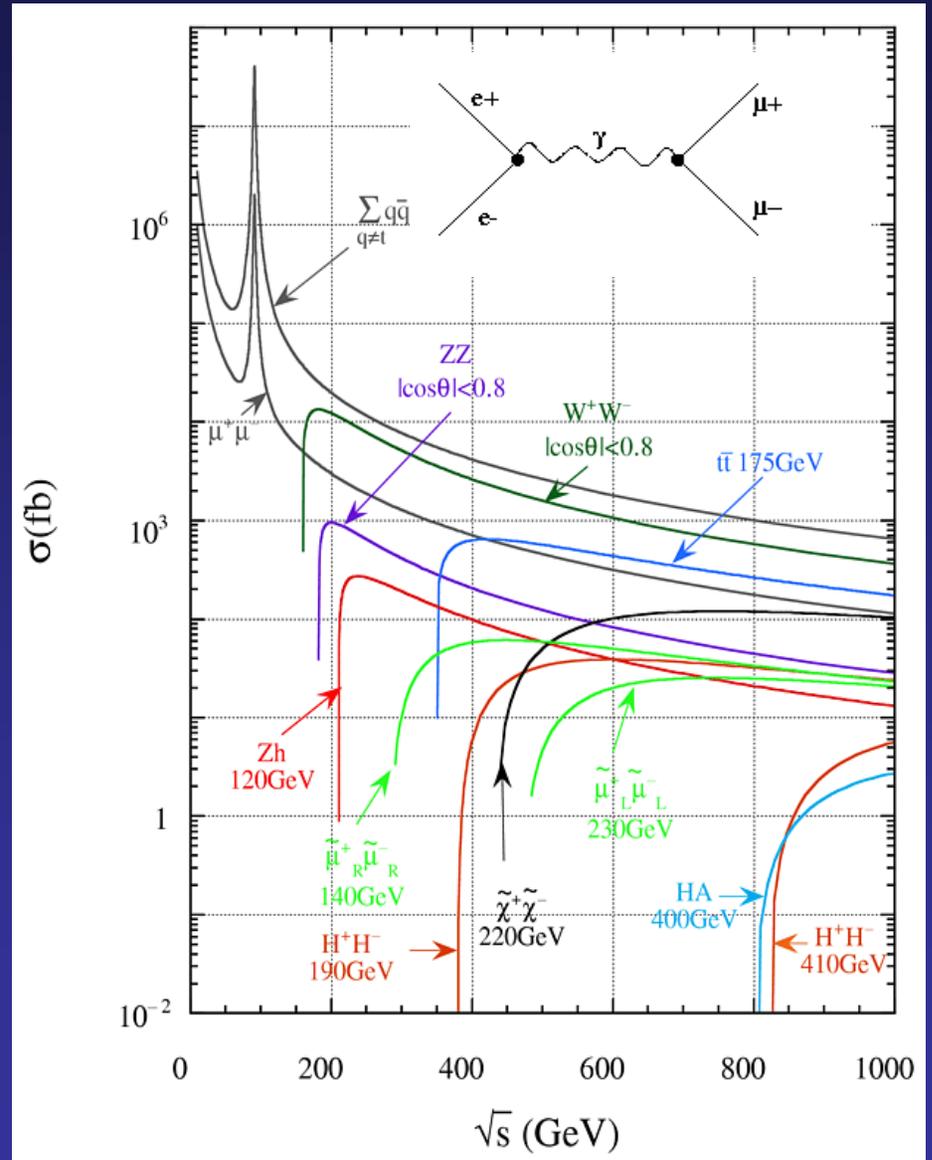
■ Backgrounds from the machine

- 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:
 - $\sigma(e^+e^- \rightarrow ZH) \sim 0.5 * \sigma(e^+e^- \rightarrow d d)$
- Cross sections are small; for $L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - $e^+e^- \rightarrow qq, WW, \tau\tau, Hx \sim 0.1 \text{ event /train}$
 - $e^+e^- \rightarrow e^+e^- \gamma\gamma \rightarrow e^+e^- X \sim 200 \text{ /train}$
- 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: $\sim 80\%$



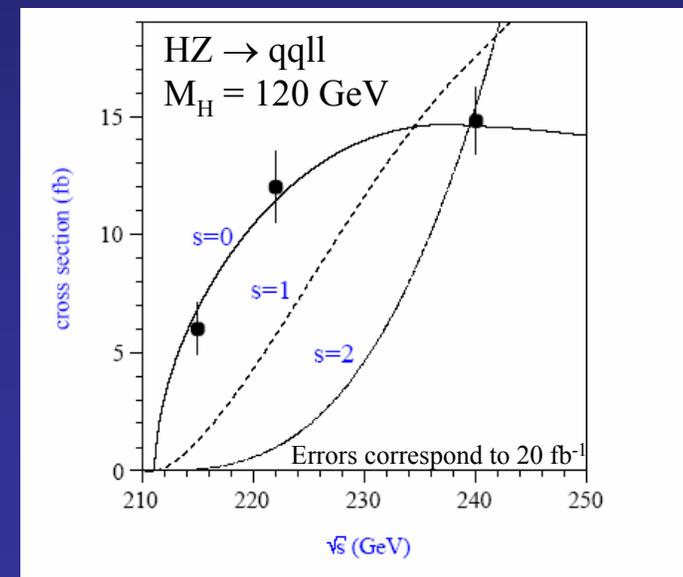
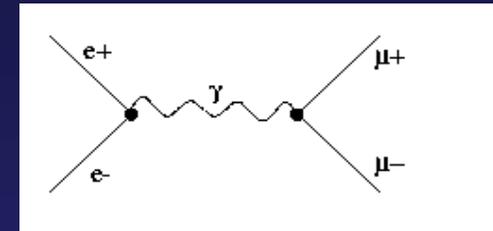
ILC Physics Characteristics

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

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

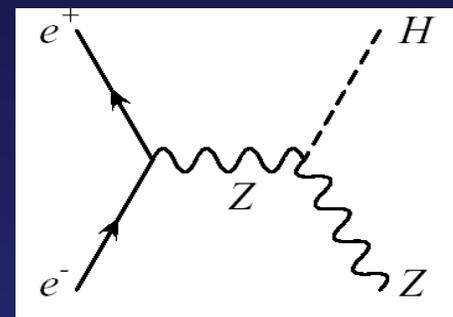
$$A_f = \frac{2g_{vf}g_{Af}}{g_{vf}^2 + g_{Af}^2} \quad A_b = 0.94 \quad A_c = 0.67 \quad A_l = 0.15$$

- 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 asymmetry
 - Left-Right Asymmetry
 - Largest effects for b-quarks

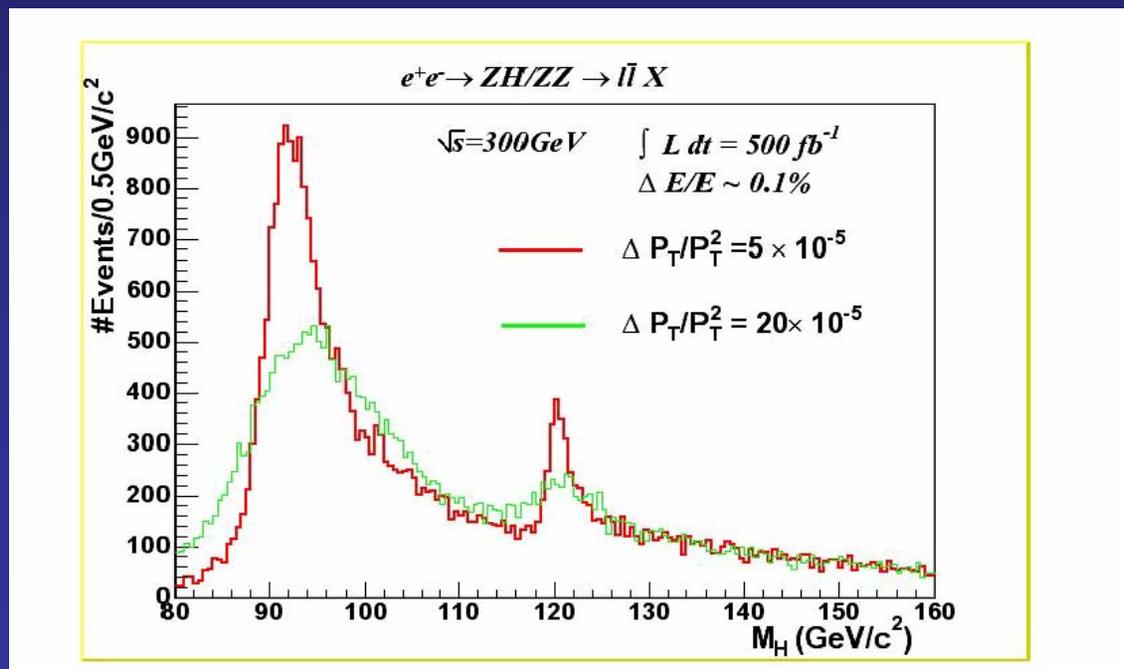


Higgs Recoil Mass

- Benchmark measurement is the measurement of the Higgs recoil mass in the channel $e^+e^- \rightarrow ZH$
 - 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.

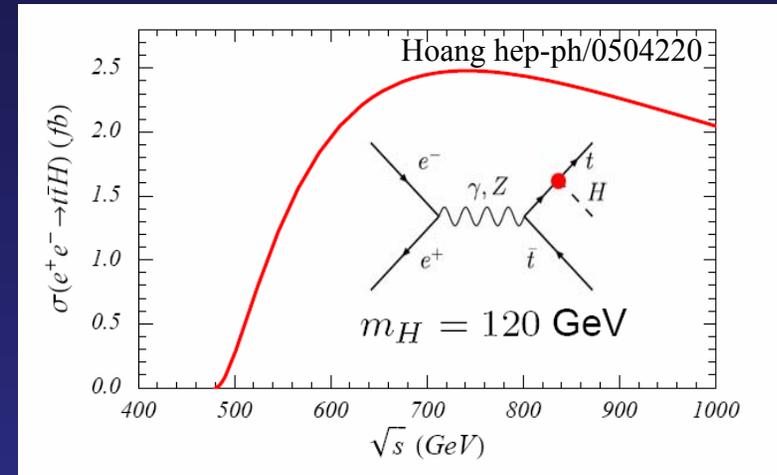


- Example:
 - $\sqrt{s} = 300 \text{ GeV}$
 - 500 fb^{-1}
 - beam energy spread of 0.1%
- Goal:
 - $\delta M_{\ell\ell} < 0.1 \times \Gamma_Z$
 - δM_H dominated by beamstrahlung



Top Yukawa Coupling

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



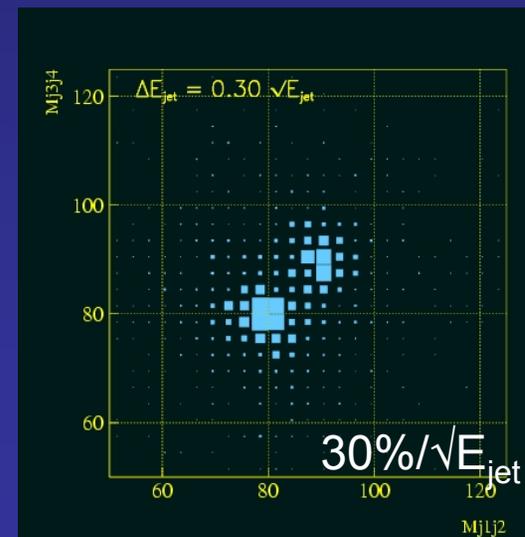
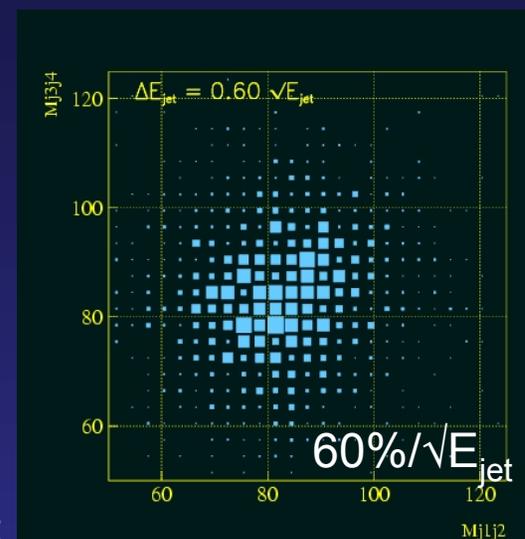
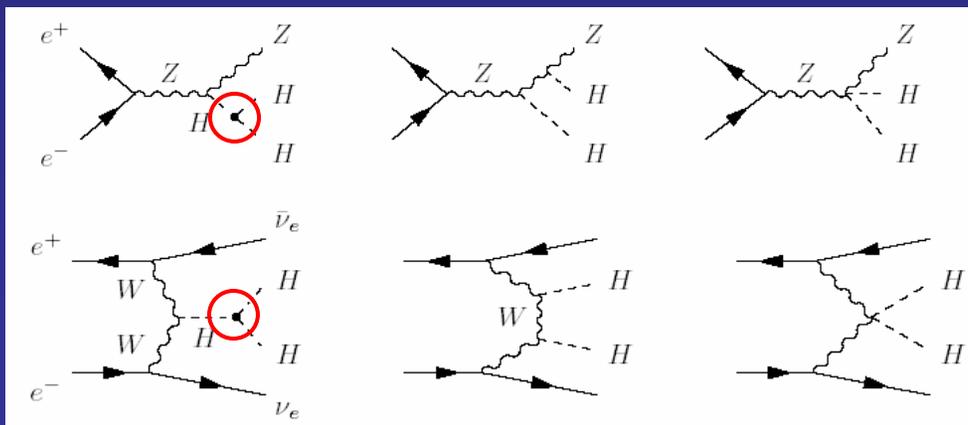
Final State	σ (fb)
t-tbar	~ 300
W^+W^-	~ 4300
ZZ	~ 240
t-tbarZ	~ 4.3

$\sqrt{s} = 500$ 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
 - $e^+e^- \rightarrow WW\nu\nu, WZ\nu\nu$ 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



Some Detector Design Criteria

Requirement for ILC

- Impact parameter resolution

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

- Momentum resolution

$$\sigma \left(\frac{1}{p_T} \right) = 5 \times 10^{-5} \text{ (GeV}^{-1}\text{)}$$

- 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

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

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

- Need factor 2 better than ZEUS

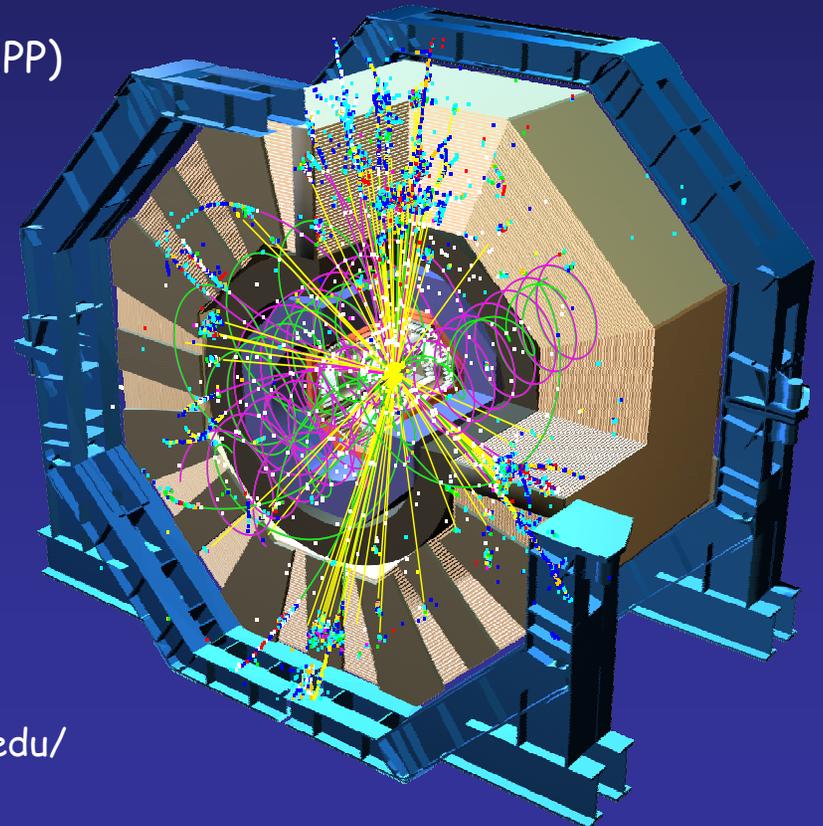
$$\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$$

- 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

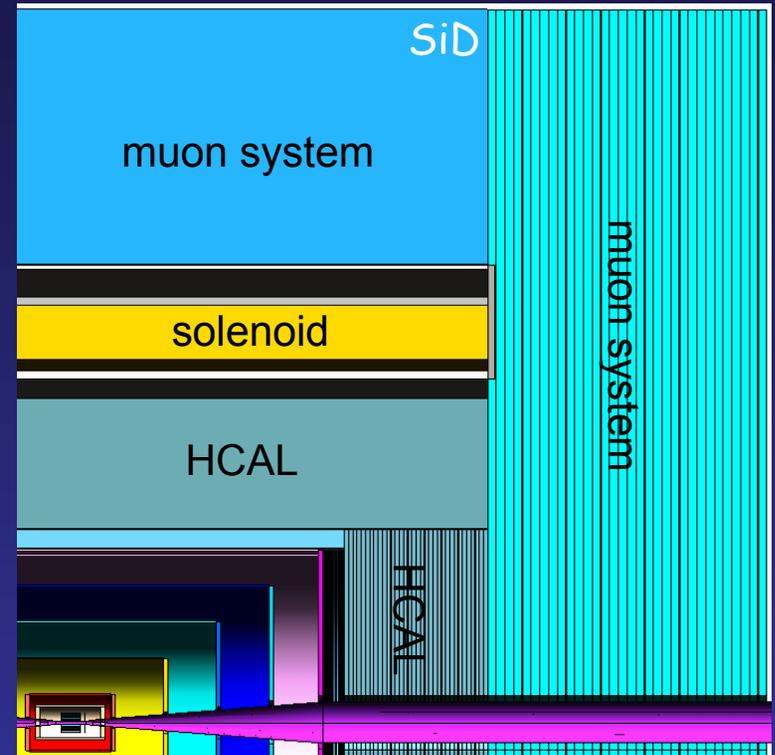
- The Silicon Detector (SiD) design study
 - Conceived at SLAC within the framework of the American LC Physics Group
 - Silicon based detector design study, 'consolidated' late 2004
 - Design Study coordinators:
John Jaros (SLAC), Harry Weerts (ANL)
 - Asian and European Contacts:
H. Aihara (Tokyo), 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/>

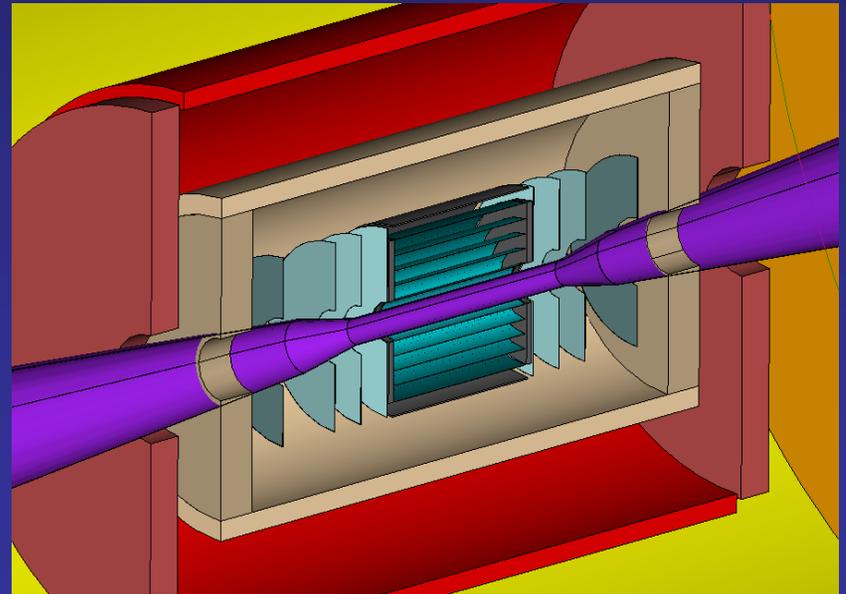
Design Concept

- 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

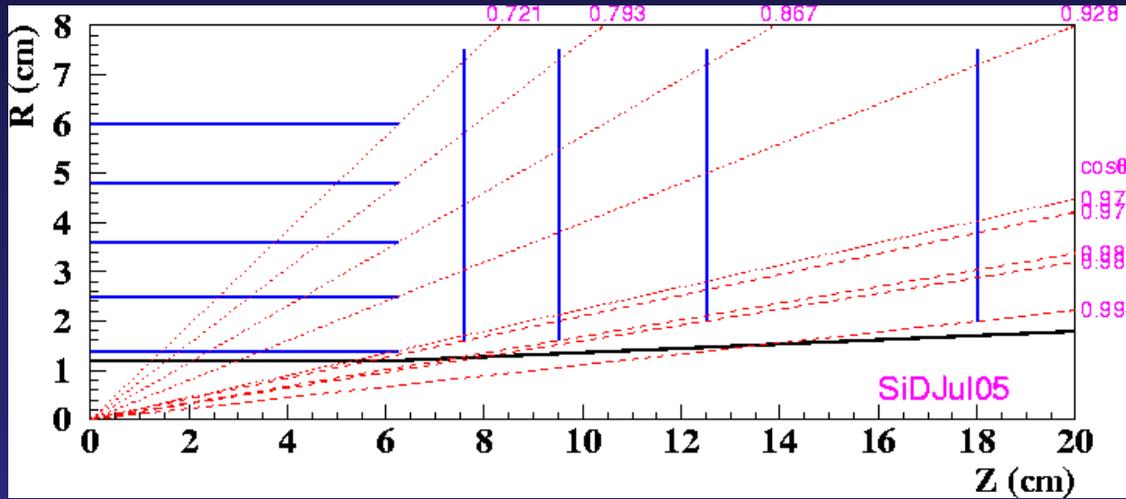


Vertexing and Tracking

- 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: $< 4 \mu\text{m}$
 - Impact parameter resolution
 - $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10 / (p \sin^{3/2} \theta) \mu\text{m}$
 - Smallest possible inner radius
 - Momentum resolution $5 \cdot 10^{-5} (\text{GeV}^{-1})$
 - Transparency: $\sim 0.1\% X_0$ per layer
 - Stand-alone tracking capability



Vertex Detector



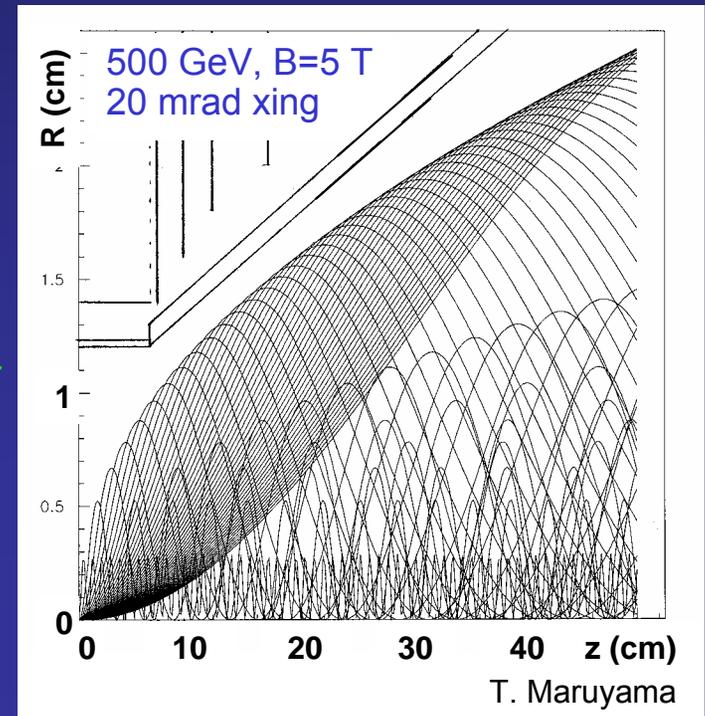
- Small radius possible with large B-field
- Goal is 0.1% X_0 /layer (100 μm of Si):
 - Address electrical aspects:
 - Very thin, low mass sensors, including forward region
 - Integrate front-end electronics into the sensor
 - Reduce power dissipation so less mass is needed to extract the heat
 - Mechanical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

■ Five Barrels

- $R_{in} = 14 \text{ mm}$ to $R_{out} = 60 \text{ mm}$
- 24-fold phi segmentation
- two sensors covering 6.25 cm each
- All barrel layers same length

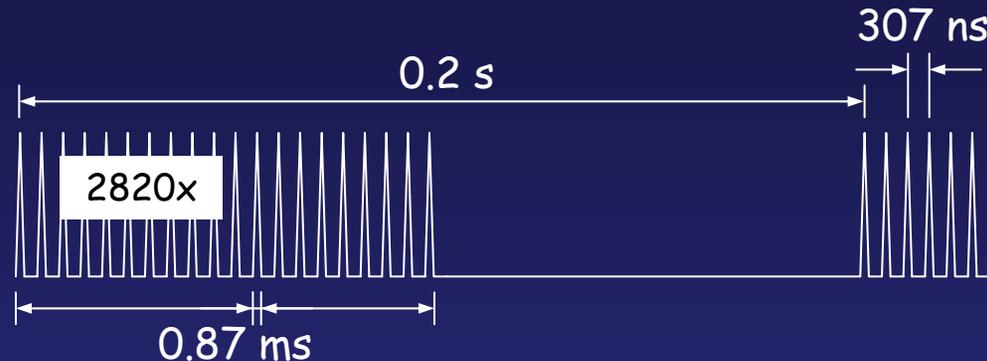
■ Four Disks per end

- Inner radius increases with z



Sensors: The Challenge

■ Beam structure



■ What readout speed is needed ?

- Inner layer 1.6 MPixel sensors; Background hits significantly in excess of $1/\text{mm}^2$ will give patterns recognition problems

- Once per bunch = 300ns per frame : *too fast*
- Once per train ~ 100 hits/ mm^2 : *too slow*
- 5 hits/ $\text{mm}^2 \Rightarrow 50\mu\text{s}$ per frame: may be tolerable

For SiD: cumulative number of bunches to reach hit density of $1/\text{mm}^2$

- Layer 1: ~ 35
- Layer 2: ~ 250

■ Fast CCDs

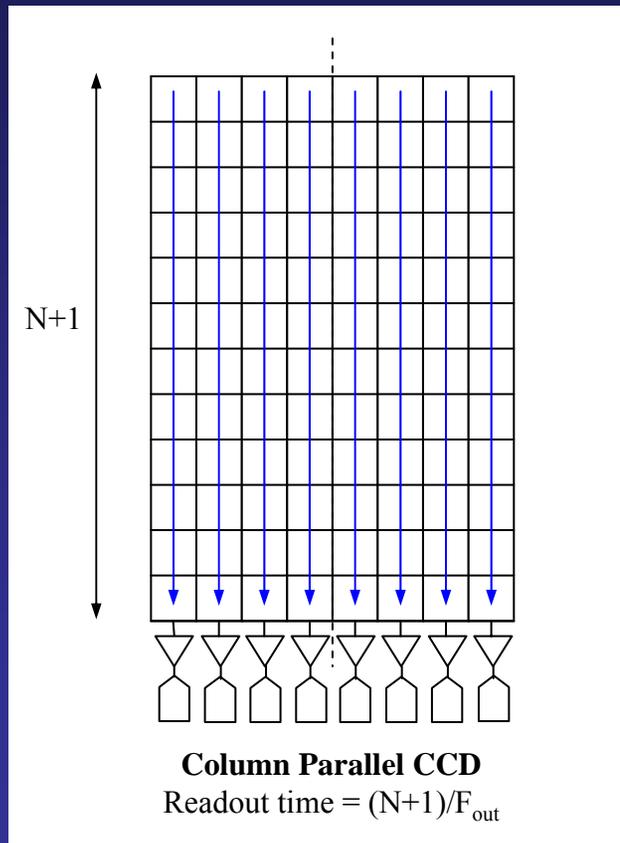
- Development well underway
- Need to be fast (50 MHz)
- Read out in the gaps

■ Many different developments

- MAPS
- FAPS
- HAPS
- SOI
- 3D

Column Parallel CCD

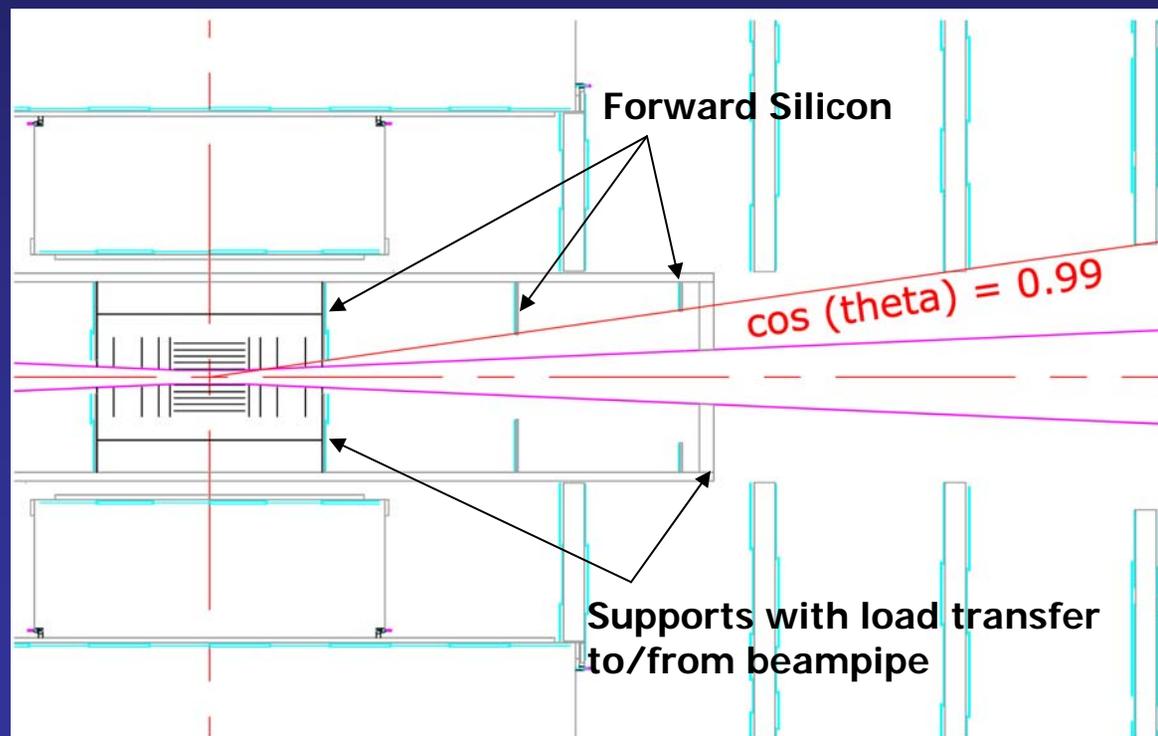
- R&D carried out by LCFI Collaboration (Bristol, Glasgow, Lancaster, Liverpool, Oxford, RAL) in collaboration with e2v Technology



- 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

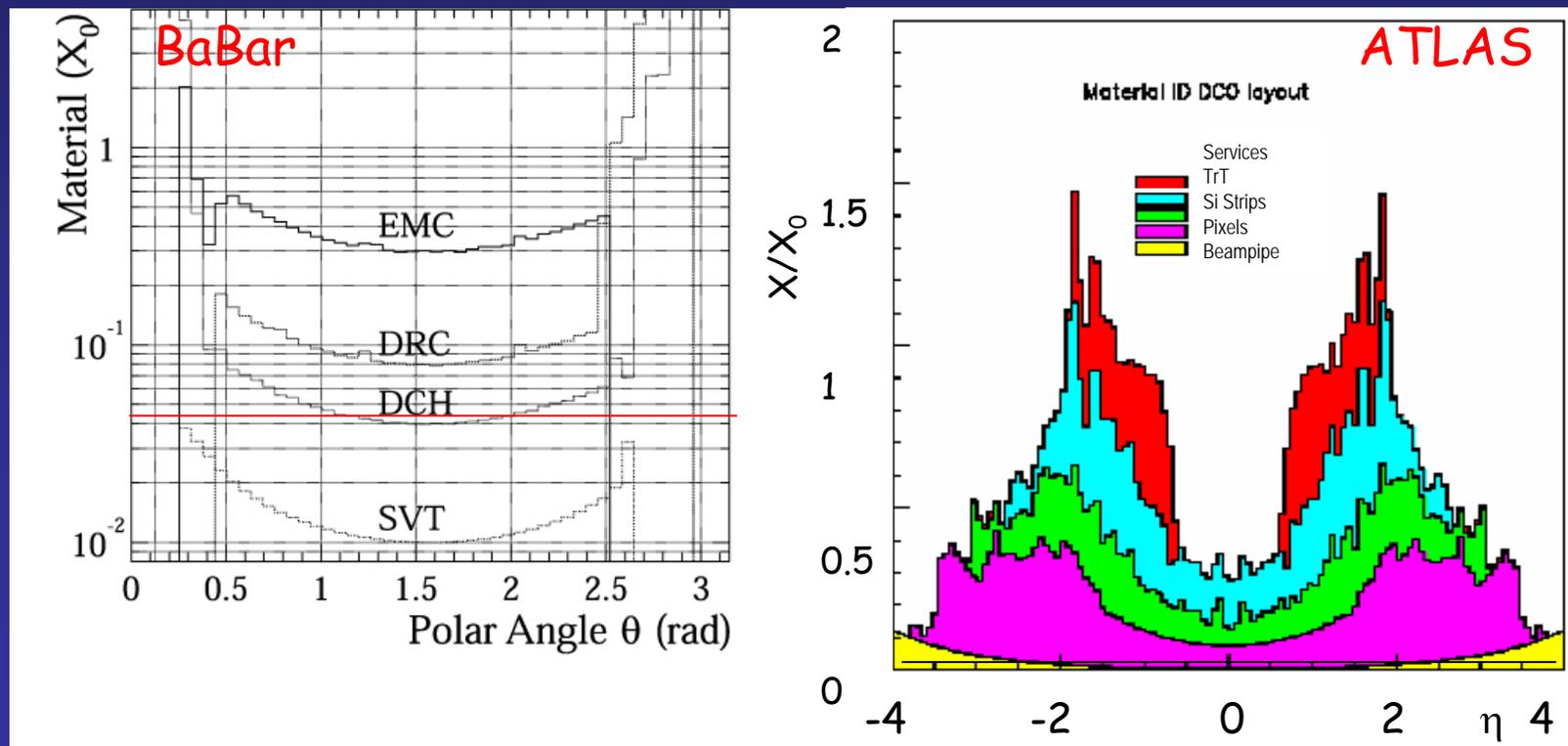
- Build and support a 5-layer/4-disk integrated, no-mass, giga-pixel detector that operates, with perfect alignment, at room temp. and $-40\text{ }^{\circ}\text{C}$ and is easily accessible



- 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 $z \sim \pm 0.2\text{ m} / \pm 0.9\text{ m}$

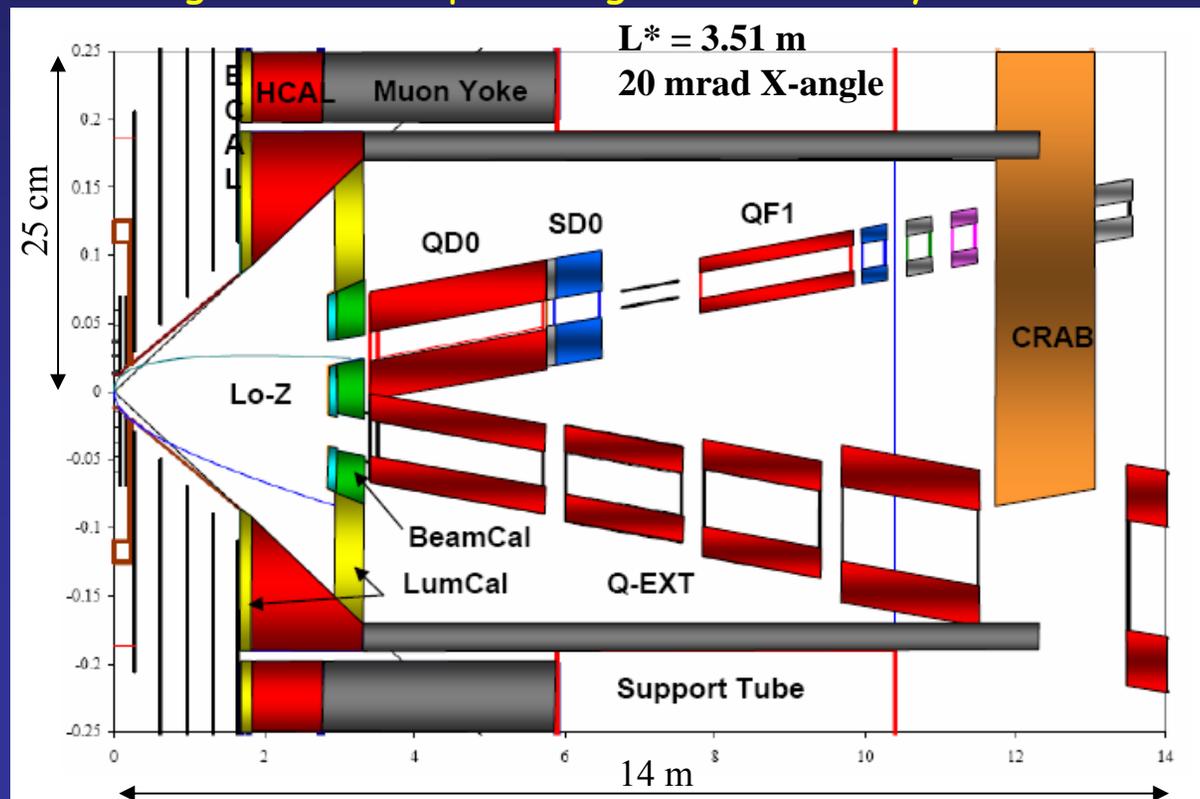
Material Budget Comparison

- 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

- $\Delta m_{\pm} \sim 100 \text{ MeV}$

- need precise luminosity spectrum

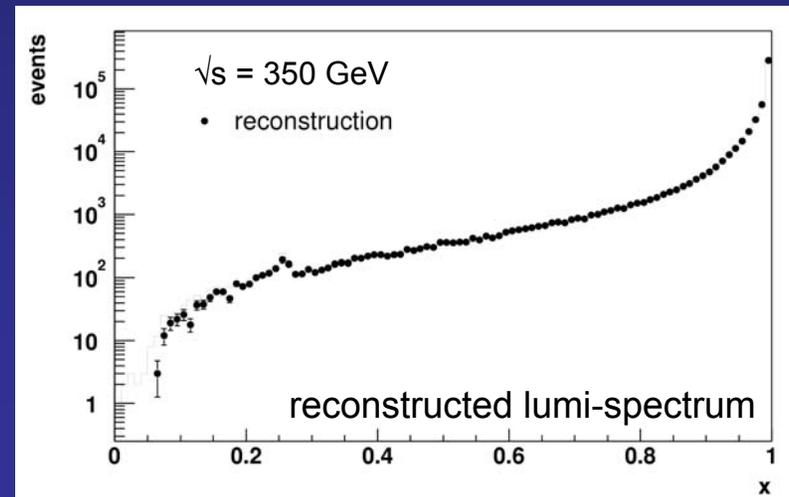
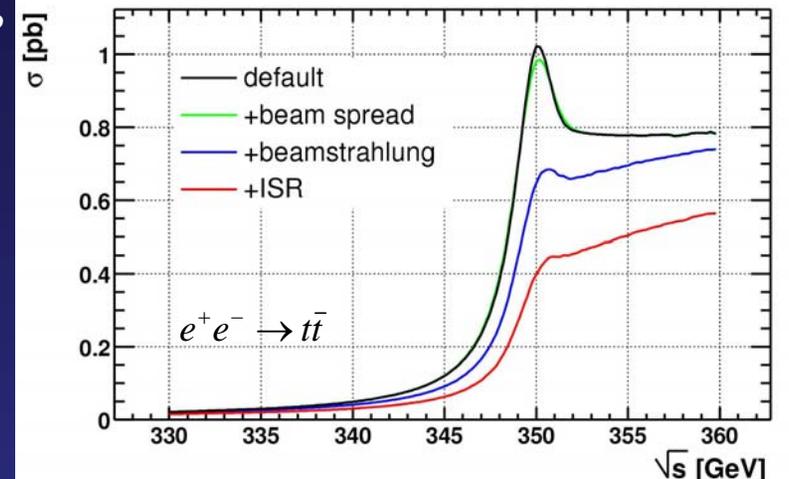
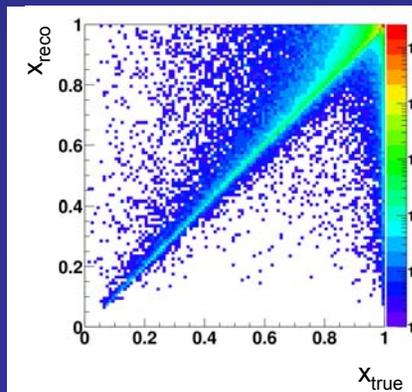
- Measured through Bhabha acolinearity

- $\Delta\theta/\theta \sim 10^{-5}$ 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

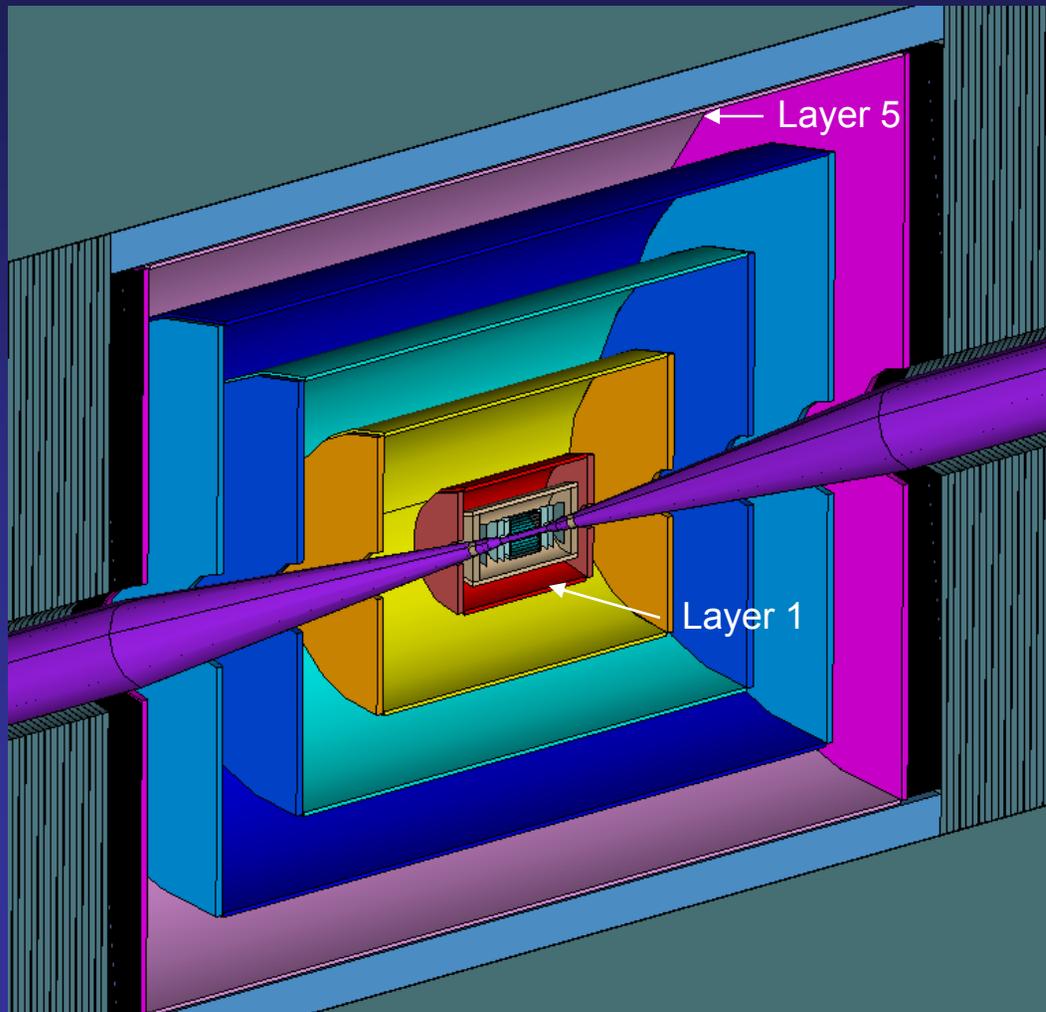
- Main differences between measured and true x at $x \sim 1$



$$x = \sqrt{s'} / \sqrt{s}$$

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

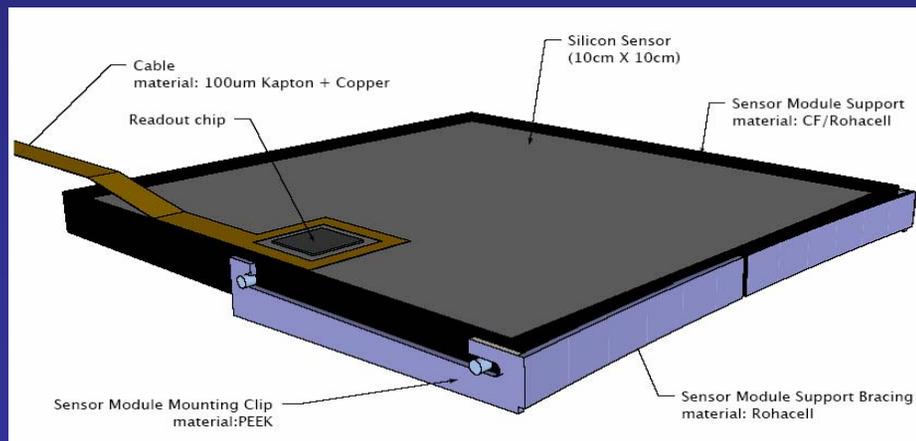


- Support
 - Double-walled CF cylinders
 - Allows full azimuthal and longitudinal coverage
- Barrels
 - Five barrels, measure Phi only
 - Eighty-fold phi segmentation
 - 10 cm z segmentation
 - Barrel lengths increase with radius
- Disks
 - Five double-disks per end
 - Measure R and Phi
 - varying R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

Tracker Design

■ Baseline configuration

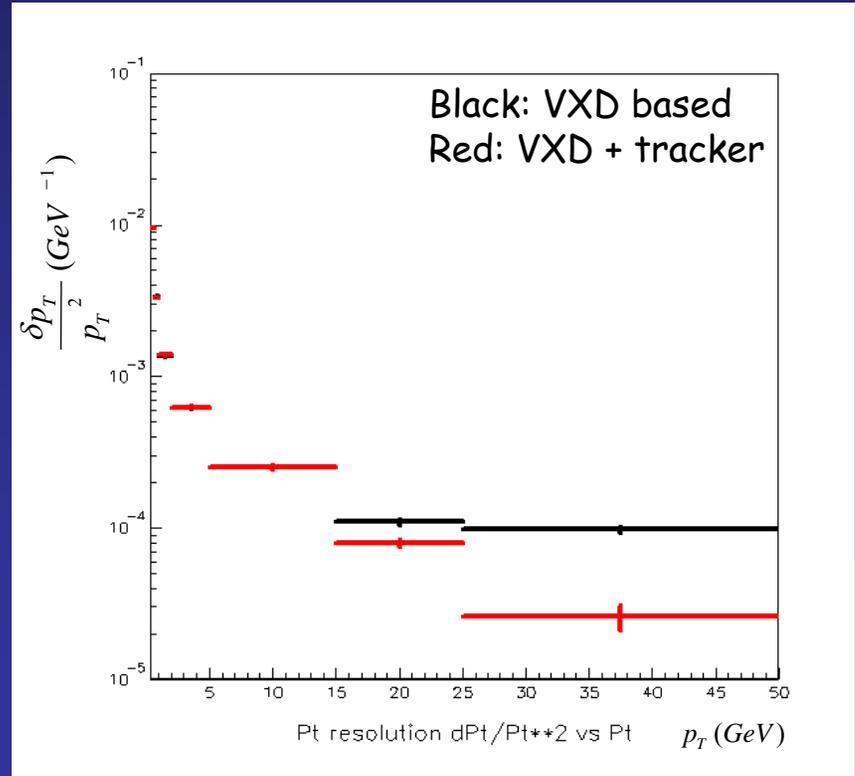
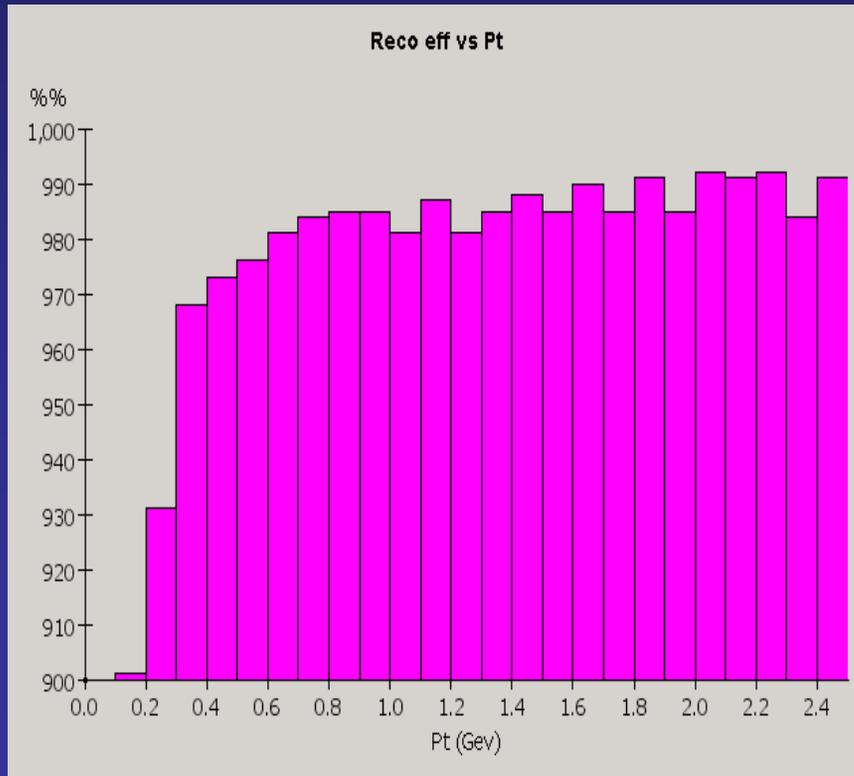
- Cylinders are tiled with $10 \times 10 \text{ cm}^2$ modules with minimal support
- Material budget $0.8\% X_0/\text{layer}$
- z-segmentation of 10 cm
- Active volume, $R_i=0.218 \text{ m}$, $R_o=1.233 \text{ m}$
- Maximum active length = 3.3 m
- Single sided in barrel; R, ϕ in disks
- Overlap in phi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



- Nested support
- Power/Readout mounted on support rings
- Disks tiled with wedge detectors
- Forward tracker configuration to be optimized

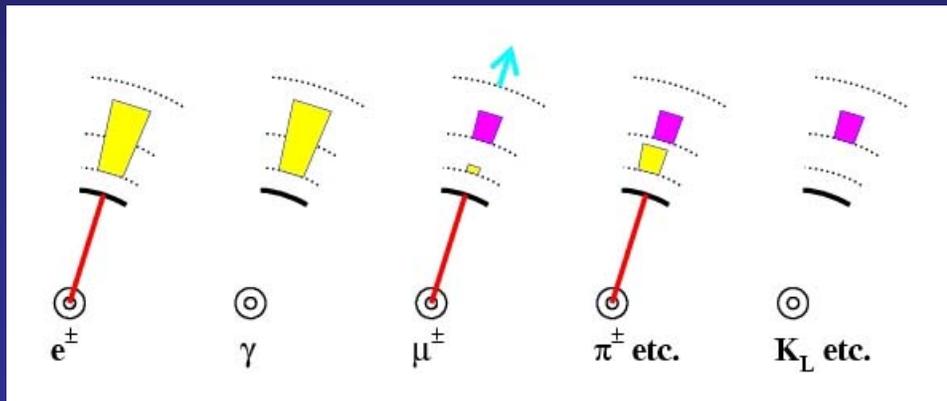
Tracker Performance

- Vertex detector seeded pattern recognition (3 hit combinations)
 - $t\bar{t}$ -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

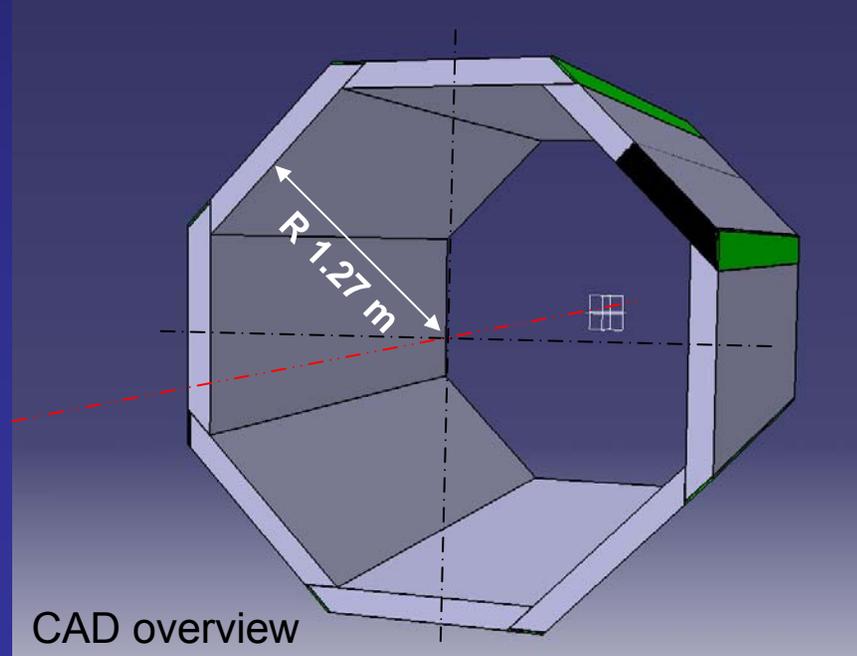
Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	~ 65 %	Tracker	Negligible
Photons	~ 25 %	ECAL with $15\%/\sqrt{E}$	$0.07^2 E_{\text{jet}}$
Neutral Hadrons	~ 10 %	ECAL + HCAL with $50\%/\sqrt{E}$	$0.16^2 E_{\text{jet}}$

} ~20%/√E

EM Calorimeter

- P-Flow requires high transverse and longitudinal segmentation and dense medium
- Choice: Si-W can provide $5 \times 5 \text{ mm}^2$ 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



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

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

EM Calorimeter Layout

■ Tile W with hexagonal 6" wafers

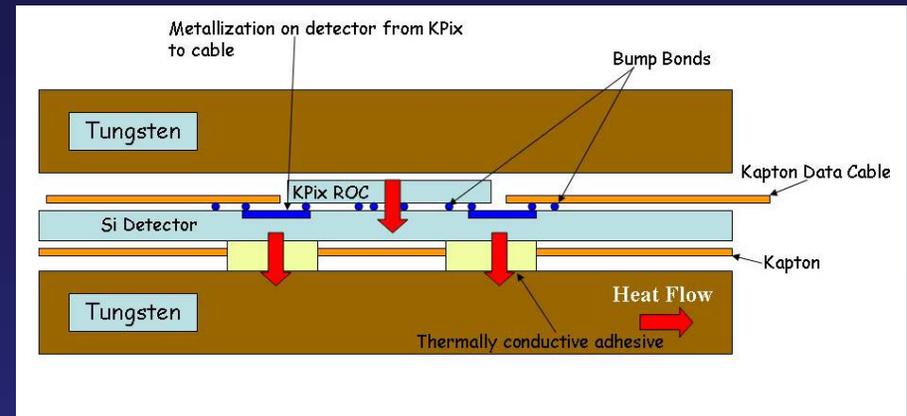
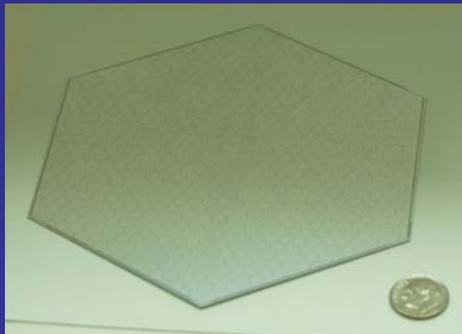
- ~ 1300 m² of Si
- 5x5 mm² pads
- Readout by single chip
- 1024 channels, bump-bonded

■ 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

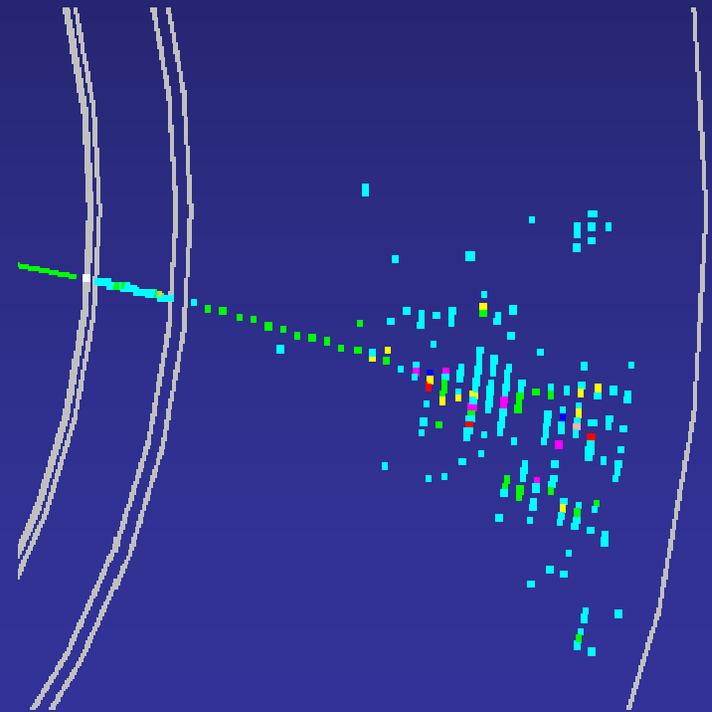
- 4-deep buffer (low occupancy)
- Bunch crossing time stamp for each hit

■ Testing

- Prototype chip in hand with 2x32 channels
- Prototype sensors in hand
- Test beam foreseen in 2006

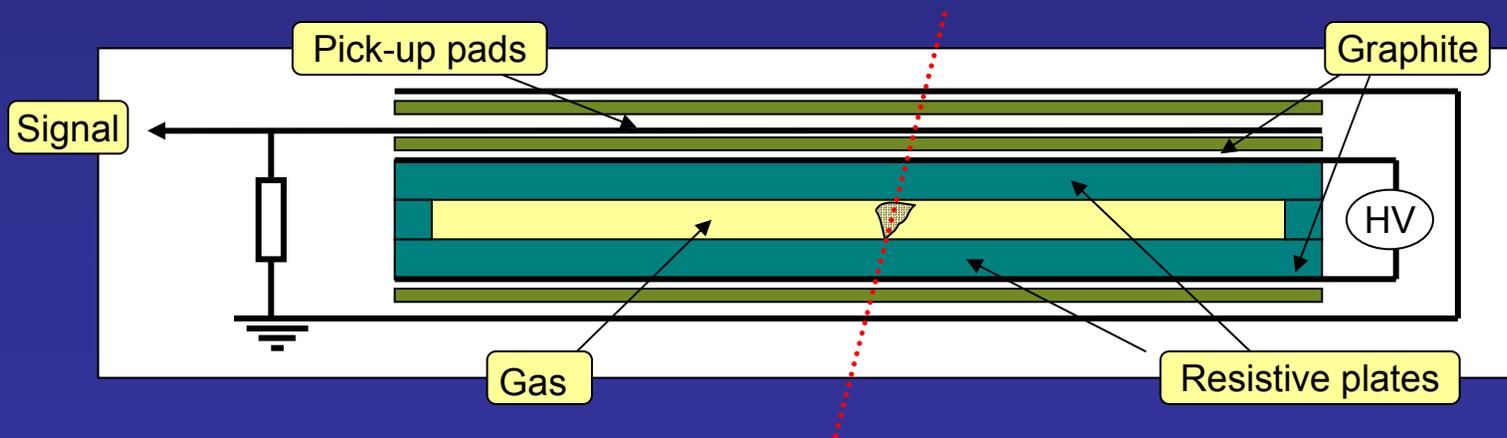
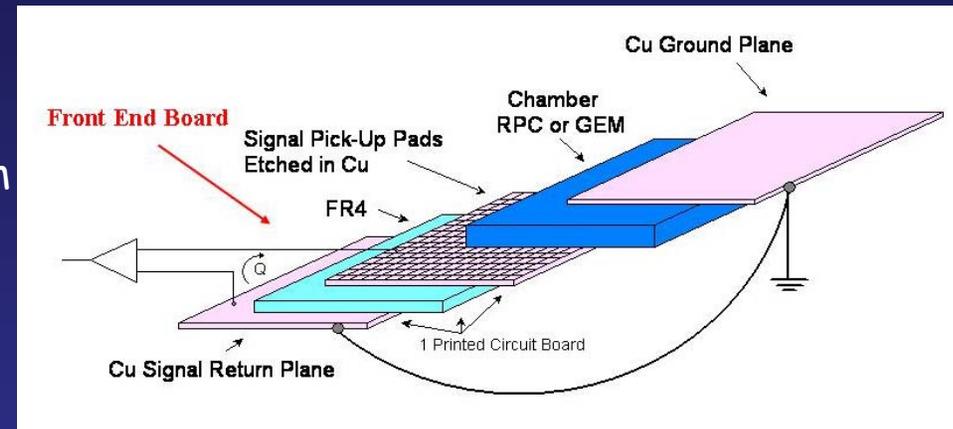
Hadron Calorimetry

- 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)
 - Technology
 - 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)
 - 1×1 cm² pads
 - All options being explored



Particle Flow

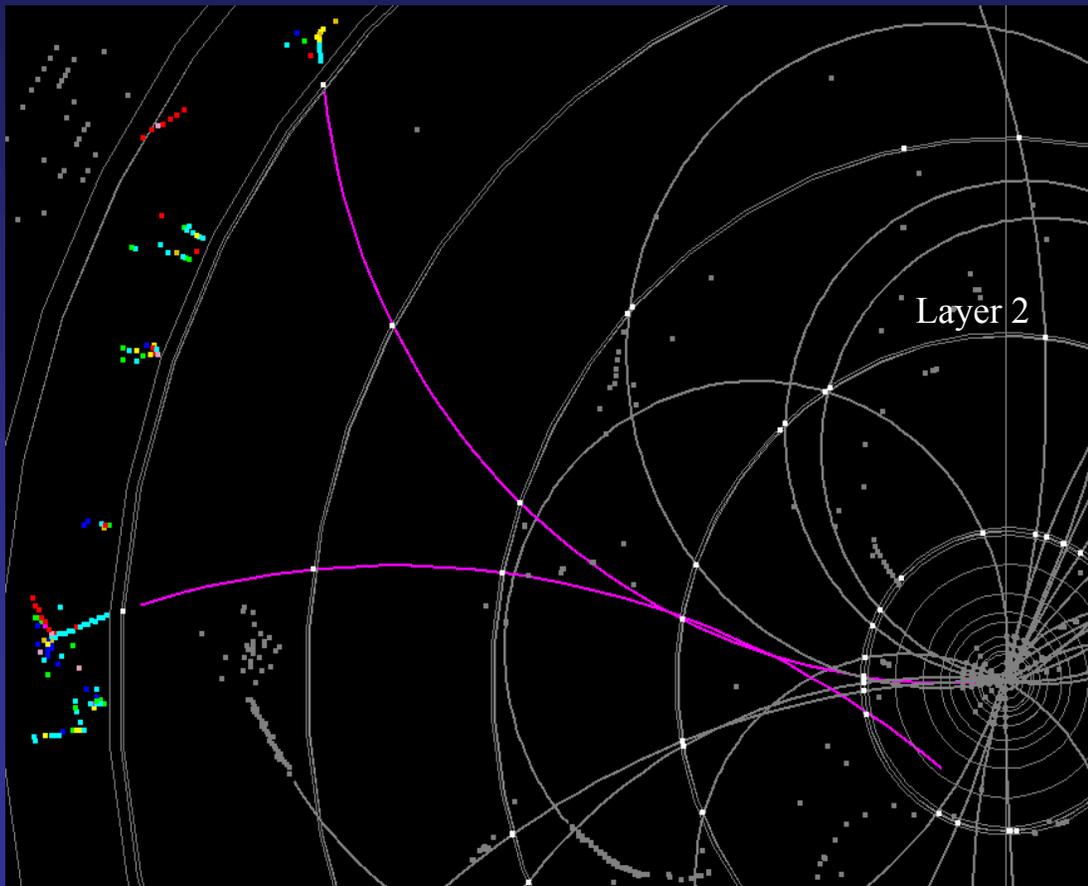
- Area of intensive work, not just within SiD, but in whole ILC community
- Many, many open issues
 - **Algorithms**
 - Cluster finding, ...
 - **Physics**
 - Dependence on environment
 - Missing neutrinos, FSR, ...
 - **Detector**
 - Linearity, e/p, E-resolution, granularity
 - Sampling fluctuations,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

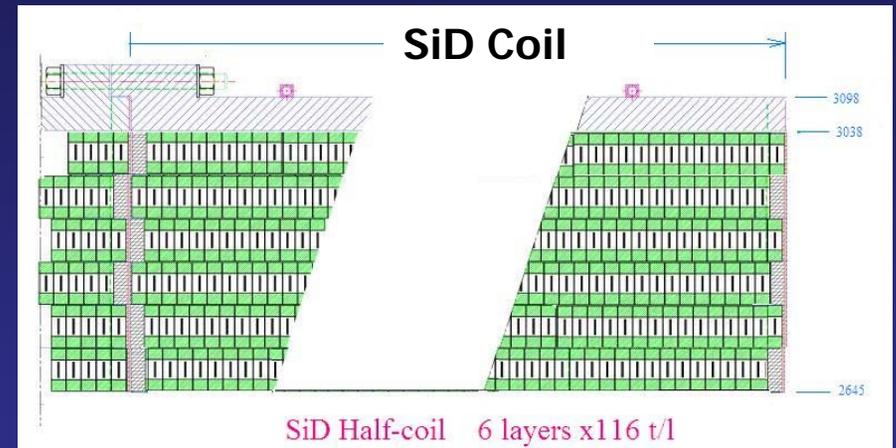
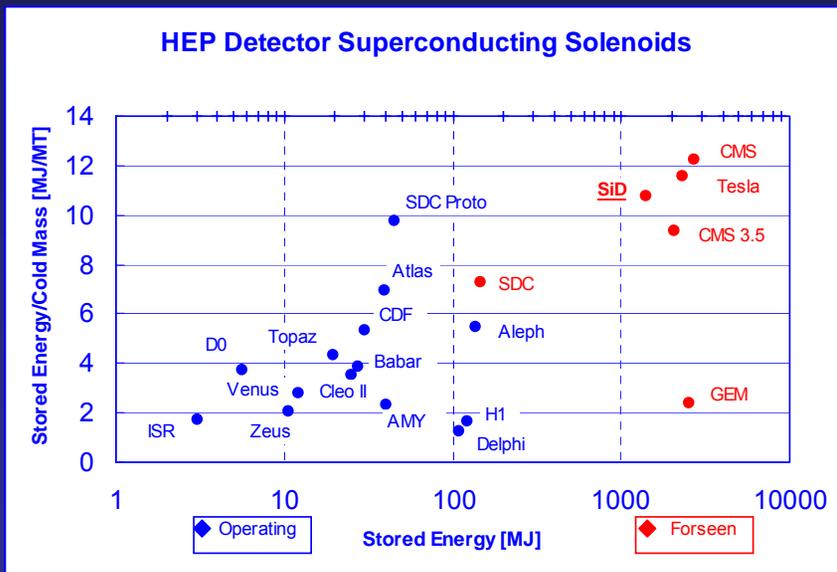
Calorimeter Tracking

- 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



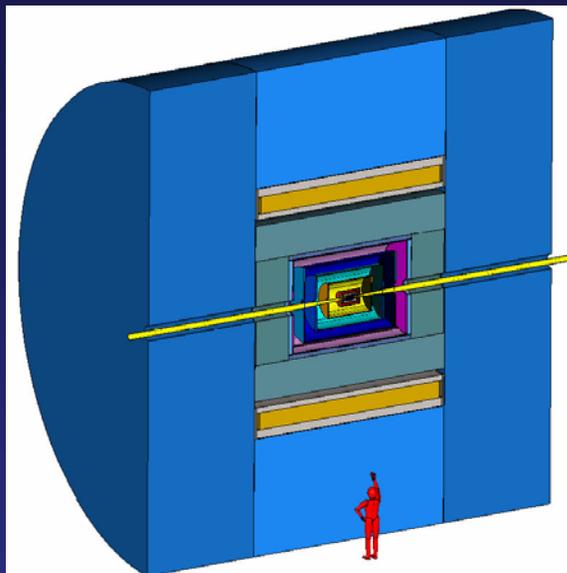
Solenoid

- Design calls for a solenoid with $B(0,0) = 5\text{T}$ (not done previously)
 - Clear Bore $\varnothing \sim 5\text{ m}$; $L = 5.4\text{ m}$; Stored Energy $\sim 1.2\text{ GJ}$
 - For comparison, CMS: 4 T, $\varnothing = 6\text{ m}$, $L = 13\text{ m}$: 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
 - $I(\text{CMS}) = 19500\text{ A}$, $I(\text{SiD}) = 18000\text{ A}$; 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 $\sim 1\text{cm}$ 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
- Scintillators 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>

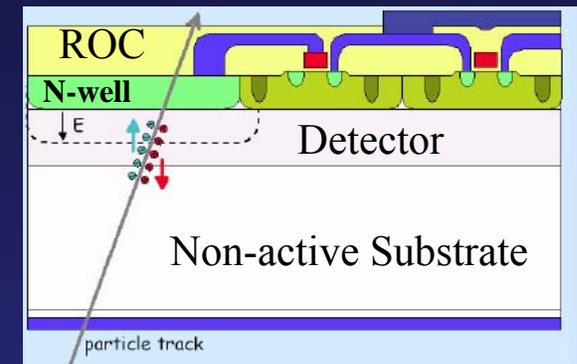
- Fermilab has nine submissions to this registry:
 - **Vertex and Tracking detectors:**
 - Mechanical design of vertex detector RD1
 - Active Pixels RD2
 - MAPS RD3a
 - SOI and 3D RD3b
 - Hybrid Pixels RD4
 - Beam pipe design RD5
 - **Calorimetry:**
 - PFA and Related Simulation Software RD6
 - Digital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

Low Mass Vertex Detectors

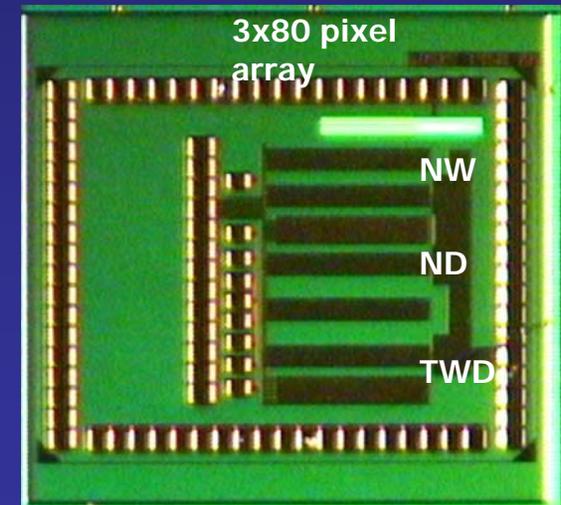
- Baseline choice for a vertex detector for ILC detectors is ccd-based
- Multitude of R&D efforts ongoing in the area of low mass vertex detectors across the world
 - Thin, radiation hard, pixel detector desired by any experiment
 - Replacement detectors for LHC experiments; LHC upgrades
- Technologies 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
- 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

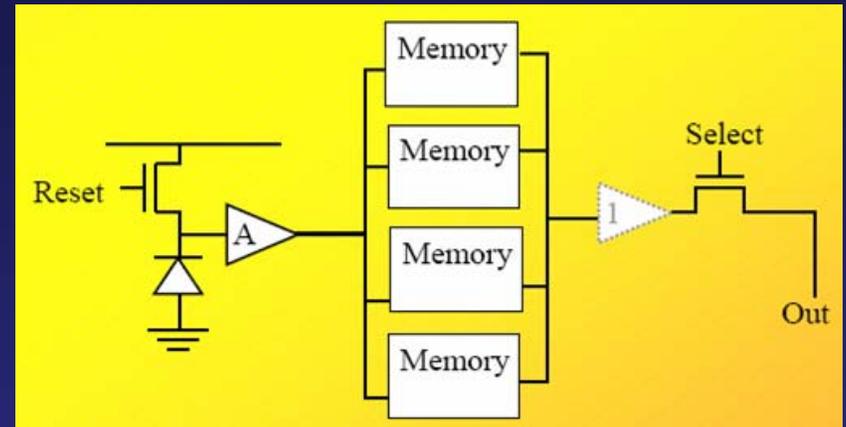


MAPS Principle



Standard CMOS MAPS

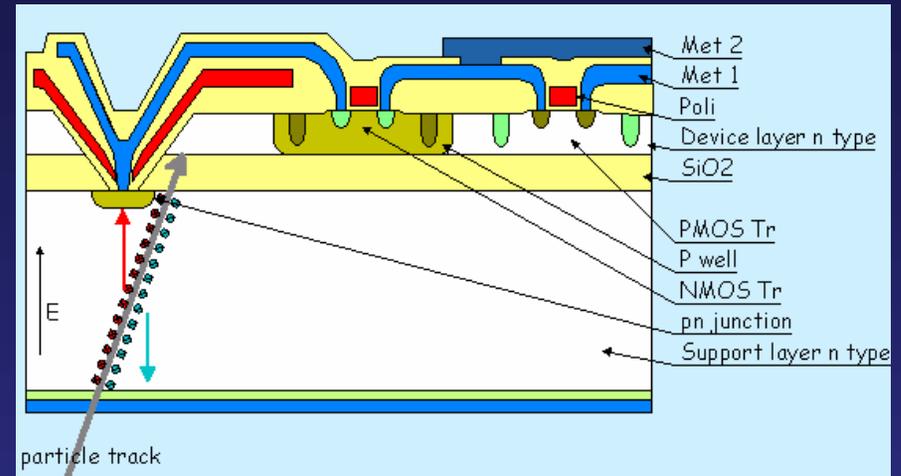
- MAPS with epi-layer
- Basic architecture is 3 transistor cell
 - signal created in epitaxial layer
 - thermal charge collection (no HV)
 - charge sensing through n-well/p-epi junction



- Development for Super-Belle; current version (Gary Varner, Hawaii):
 - pixel size: $20 \times 20 \mu\text{m}^2$; 36 transistors/pixel; 5 metal layers; TSMC $0.25 \mu\text{m}$ process
 - 128×928 pixels/sensor; double pipe-line 5 deep
 - Double correlated sampling with reset in abort gaps (500ns every $10 \mu\text{s}$)
 - Column select readout, $10 \mu\text{s}$ frame readout
 - Signal $\sim 300e^-$, Noise $\sim 20-35e^- \rightarrow S/N \sim 10-15$
- 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

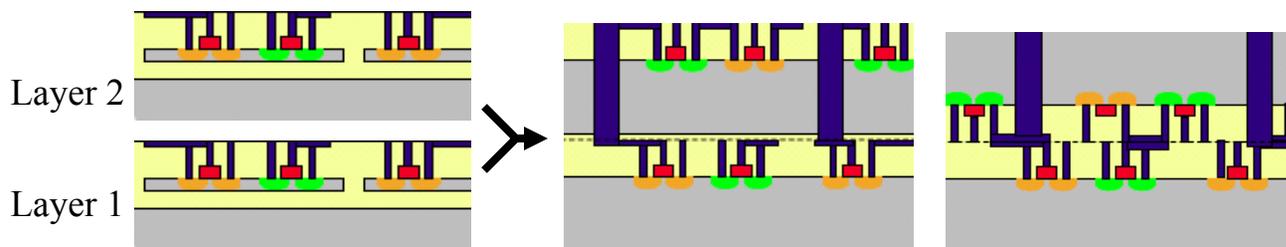
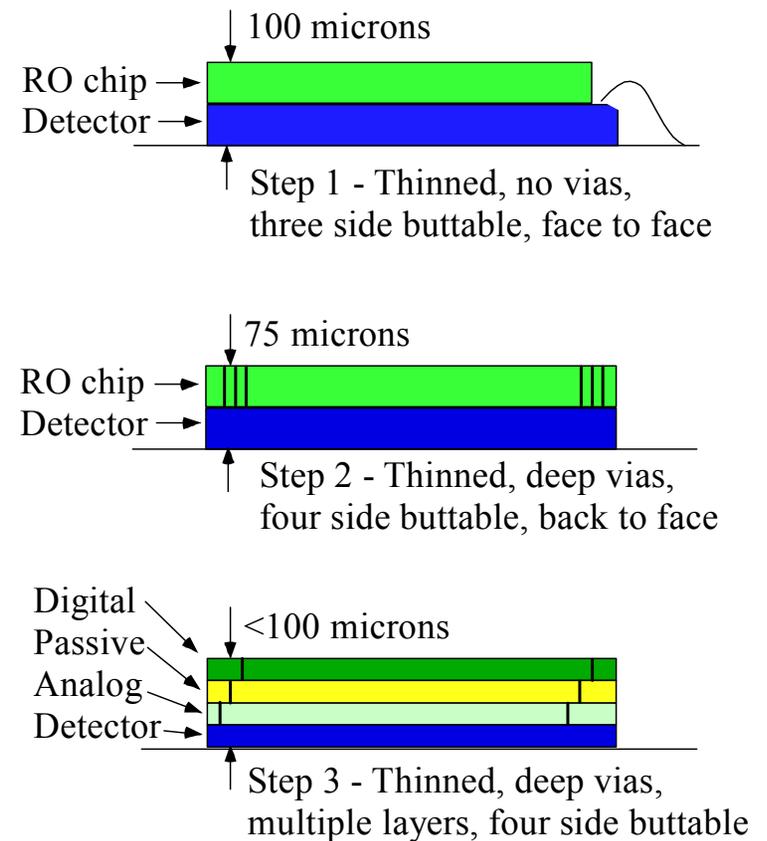
- Silicon on Insulator (SOI)
 - Non-standard process
 - Handle wafer, normally passive is the detector
 - Signal collected in fully depleted substrate, thus large signals
 - Electronics in the device layer
 - Should be rad. hard; can have NMOS and PMOS transistors



- 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

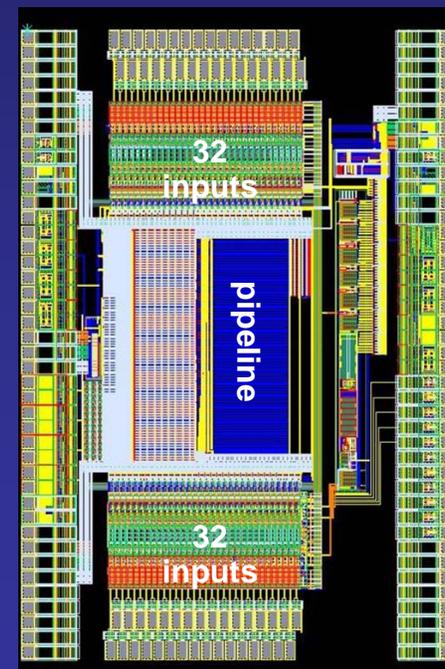
3D Processes

- 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



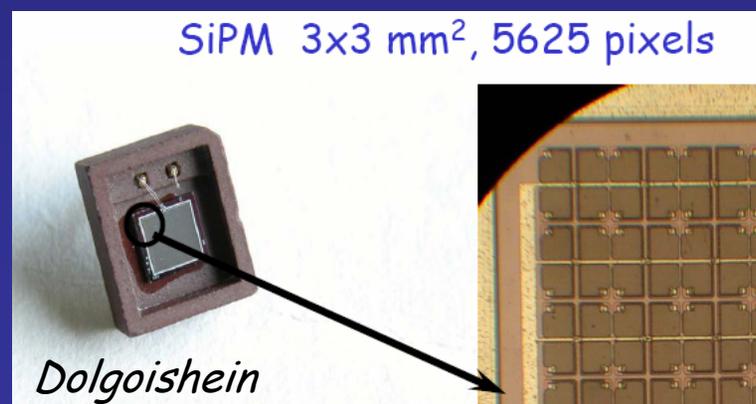
Calorimetry: PFA and Readout

- 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 m³, 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 $\sim 15\%$
 - 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 ...

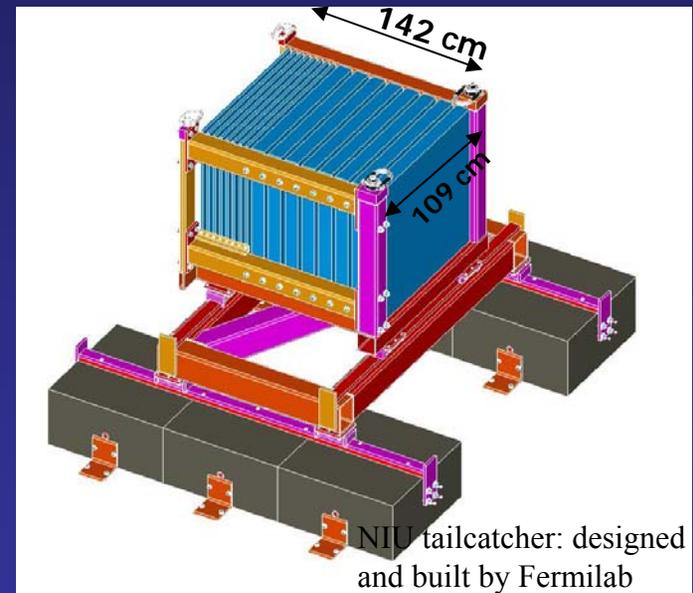


Testbeam for ILC

- 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 m³ 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



- 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

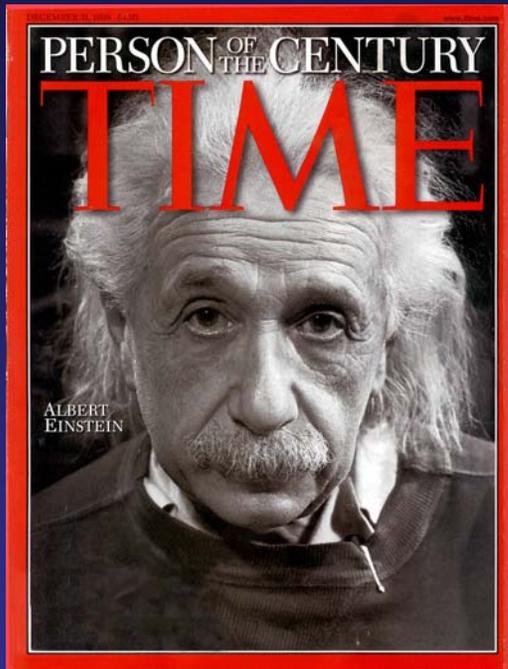
- All Grid infrastructure made available to the ILC community at Fermilab

■ 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, Minerva, ...)



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