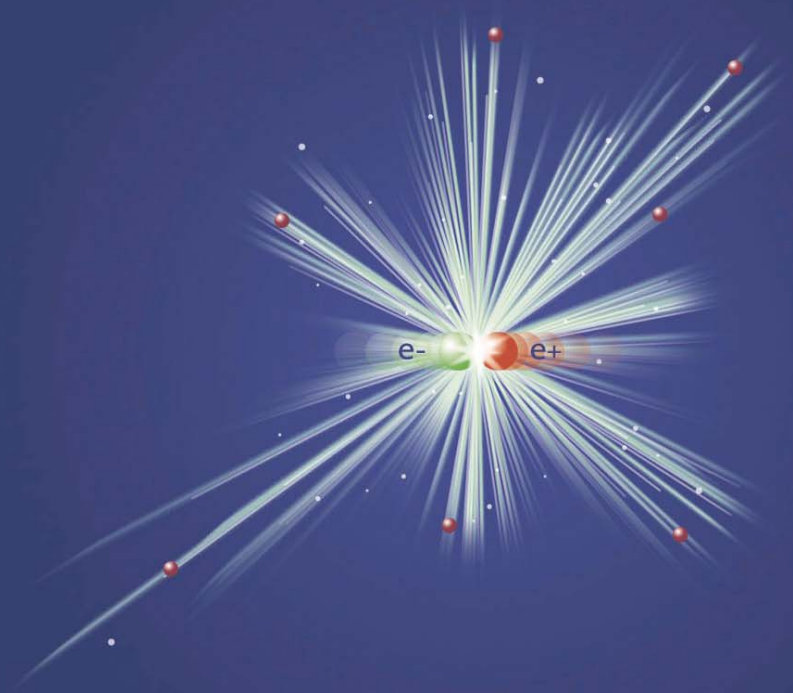
ILC Detector R&D and Design Studies



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APS 2006, April 22, 2006

Outline

The Physics Case for the Linear Collider (very short)

Introduction to International linear Collider (ILC)

Already in last two talks, but will do it again

Some physics examples to set the stage for detectors

Performance requirements for detectors

Efforts worldwide: generic R&D and Detector Design Studies

Comparison of efforts in US and rest of world

The Physics with the ILC

one page

The Large Hadron Collider (LHC), will open window to "remainder" of and physics "beyond" the Standard Model.

LHC

Starting in 2007

This is the energy/mass regime from ~0.5Tev to a few TeV

Completing the Standard Model and the symmetries underlying it plus their required breaking leads us to expect a plethora of new physics.

new particles and fields in this energy range

LHC will discover them or give clear indications that they exist.

We will need a precision tool to measure precisely and unambiguously their properties and couplings.

This is an e^+e^- machine with a centre of mass energy starting at 0.5 TeV up to several TeV

ILC

Starting next decade

The International Linear Collider

- **Baseline Machine:**

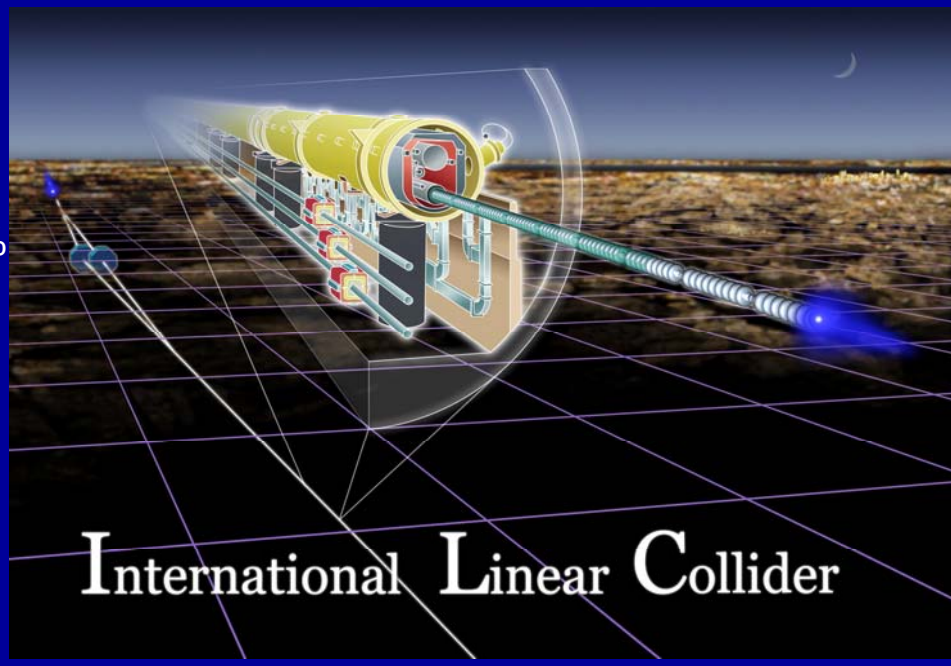
  E_{CM} of operation 200 – 500 GeV
  Luminosity and reliability for 500 fb^{-1} in 4 years
  Energy scan capability with <10% downtime
  Beam energy precision and stability below 0.1%
  Electron polarization of >80%
  Two interaction regions with detectors
  E_{CM} down to 90 GeV for calibration

- **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^-, $\gamma\gamma$, $e^-\gamma$ operation
  e^+ polarization ~ 50%
  Giga-Z with $\mathcal{L}$ = several 10^{33} $cm^{-2}s^{-1}$
  WW – threshold scan with $\mathcal{L}$ = 10^{33} $cm^{-2}s^{-1}$

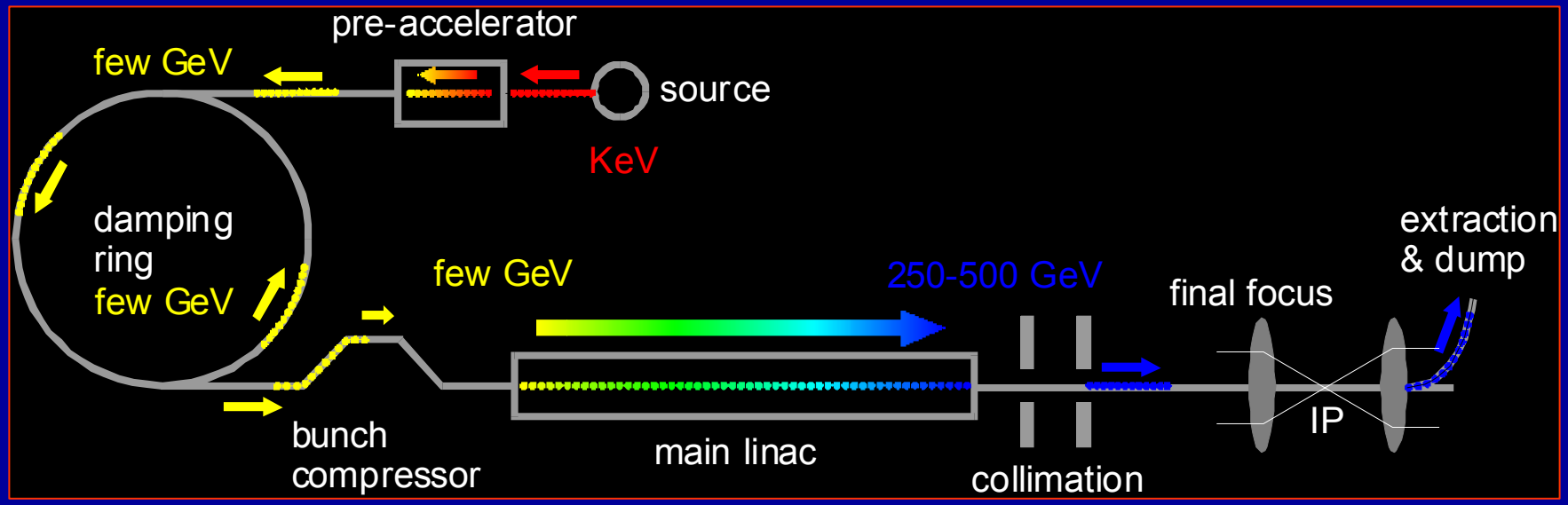


As defined in

International Scope Document

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

The Machine



- Enormously challenging with many different components, but …
  - Polarized electron and positron source & damping rings
  - Main accelerator structure
  - Beam Delivery system
  - …

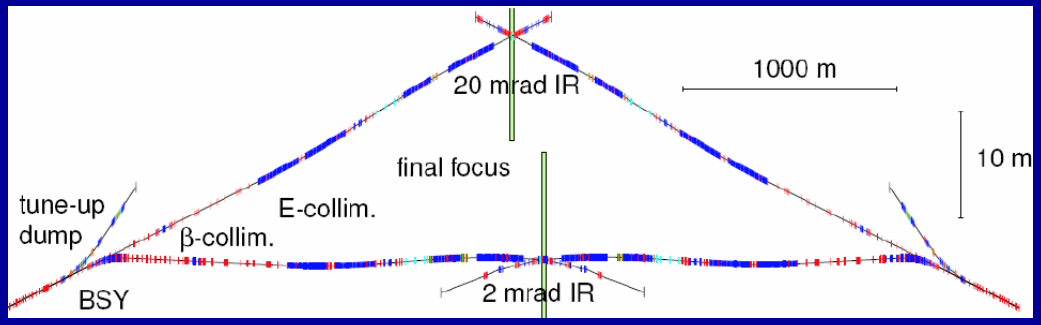
All described in previous 2 talks

- At end of accelerator need detector system to extract the physics from the collisions. Needs to be a precision tool able to live within IP environment.

This talk

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
Θcrossing [mrad]	0 - 20	0 - 20

Why ILC detector R&D ?

From a naïve perspective looks like simple problem

Extrapolating from LHC

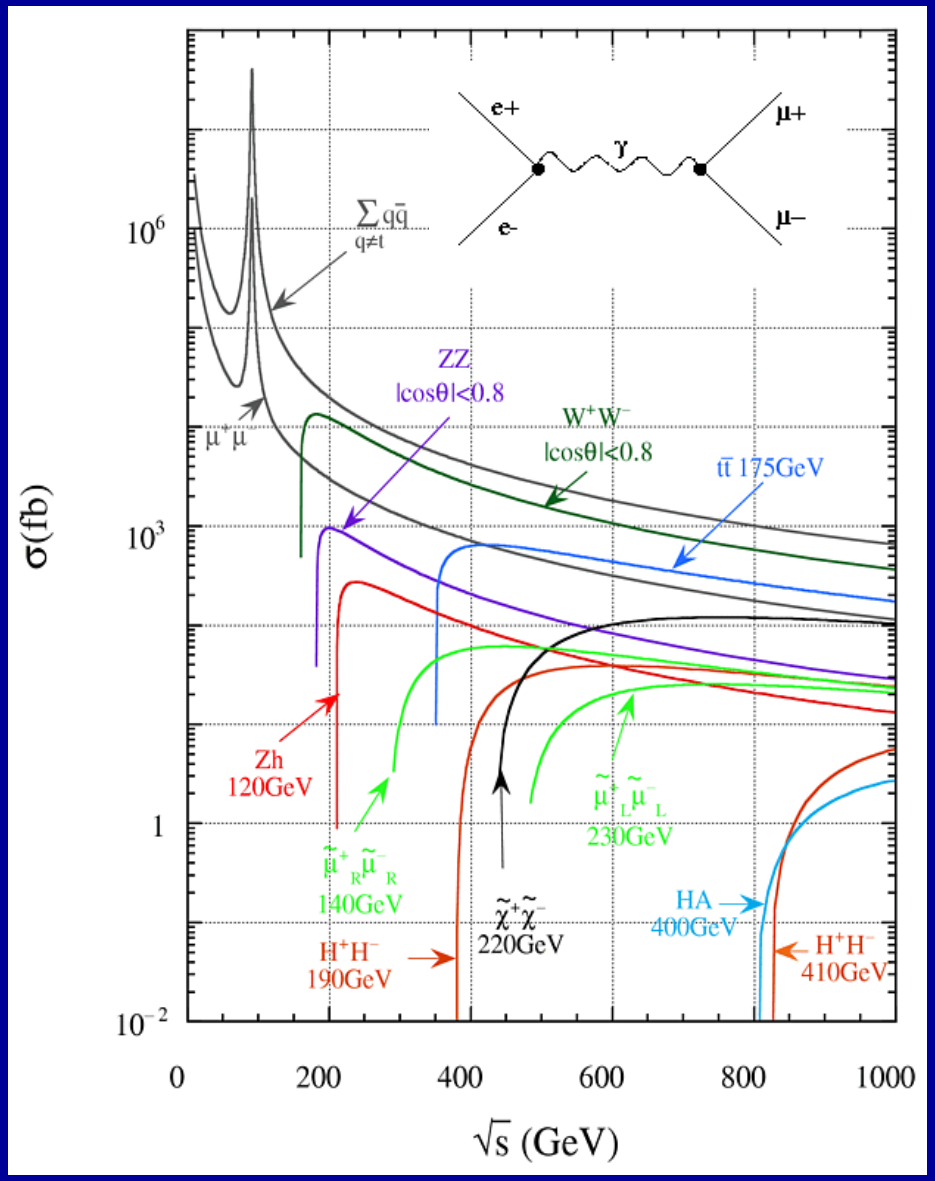
	LHC	ILC
Bunch Crossing	25 ns (40 MHz); DC	337 ns 0.5% duty cycle
Triggering: L1, L2, and L3	40 MHz → 1 kHz → 100 Hz	No hardware trigger ~ 100 Hz Software
Radiation	1-100 MRad/yr	≤ 10 kRad/yr
Physics Occupancy Per bunch	23 min. bias; 100 tracks	0.3 $\gamma\gamma$ → hadrons; 2 tracks

ILC

bunch spacing	337 nsec
#bunch/train	2820
length of train	950 μsec
#train/sec	5 Hz
train spacing	199 msec
crossing angle	0-20 mrad (25 for $\gamma\gamma$)

But there are other factors which require better performance.....

Detector Challenges: Physics Event Rates

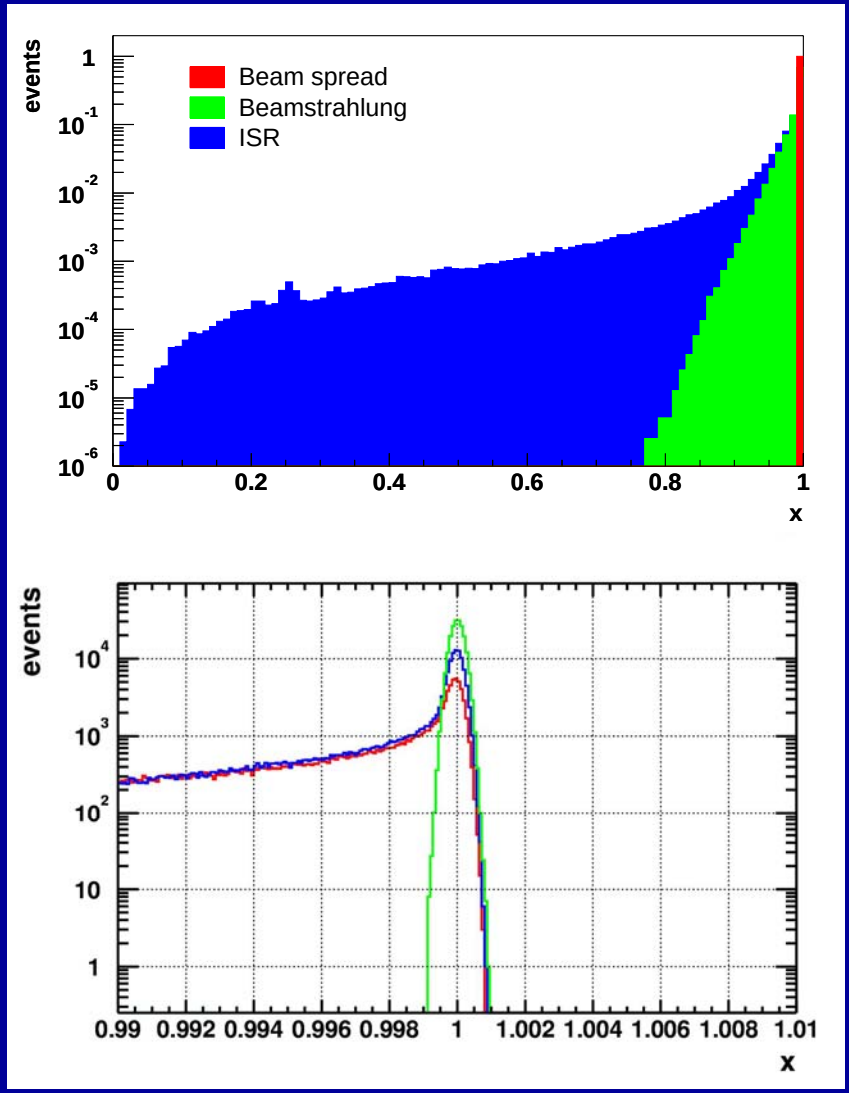


- s-channel processes through spin-1 exchange: $\sigma \sim 1/s$
- Cross sections relatively democratic:
  - $\sigma(e^+e^- \to ZH) \sim 0.5 * \sigma(e^+e^- \to ZZ)$
- Cross sections are small; for $L = 2 \times 10^{34}\ cm^{-2}s^{-1}$
  - $e^+e^- \to qq, WW, tt, Hx$ ~ 0.1 event /train
  - $e^+e^- \to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

Detector 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

Need: Reconstruct complete final state

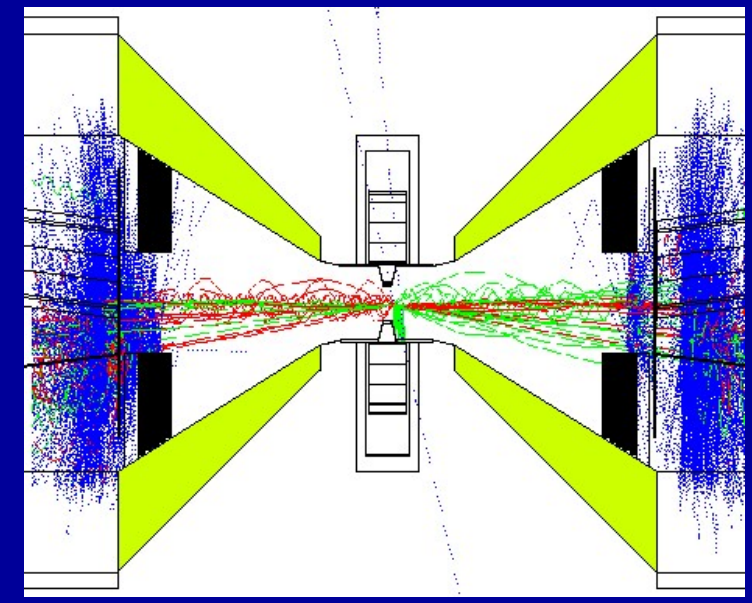


Backgrounds

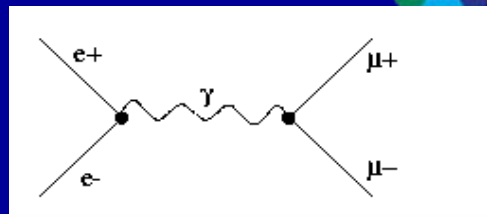
- "At the ILC the initial state is well defined, compared to LHC, but…."
- Backgrounds from the IP
  - Disrupted beams
    - Extraction line losses
  - Beamstrahlung photons
  - e^+e^- - pairs

√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



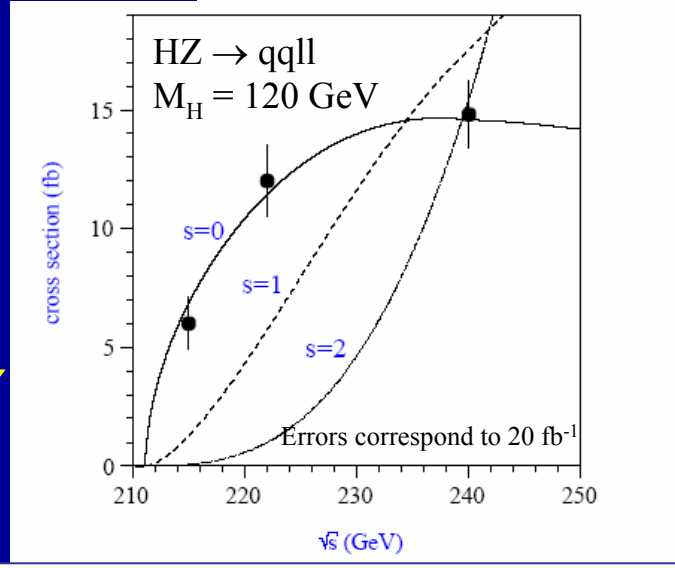
ILC Physics Characteristics



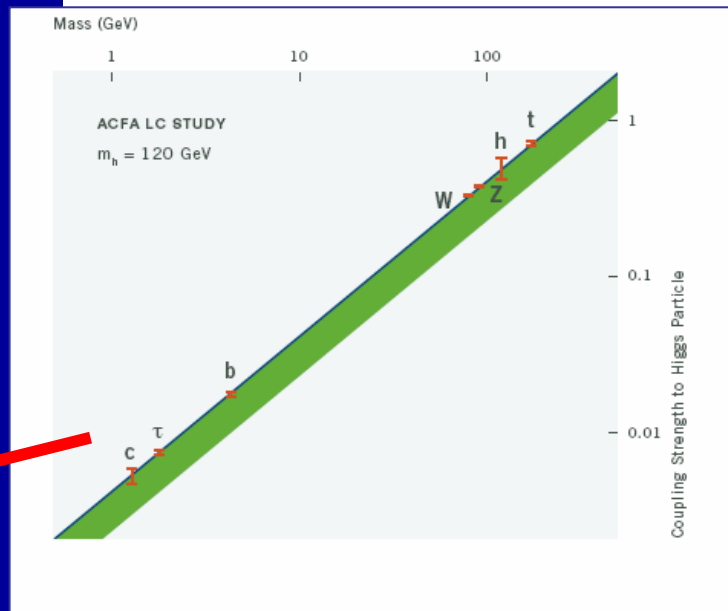
- Cross sections above Z-resonance are very small
- s-channel processes through spin-1 exchange
- Highly polarized e^- beam: ~ 80%

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

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



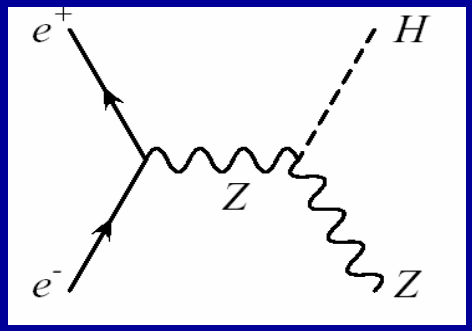
- Hermetic detectors with uniform strengths
  - Importance of forward regions
  - b/c tagging and quark identification
  - Measurements of spin, charge, mass, …
- Analyzing power of
  - Scan in center of mass energy
  - Various unique Asymmetries
    - Forward-backward asymmety
    - Left-Right Asymmetry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



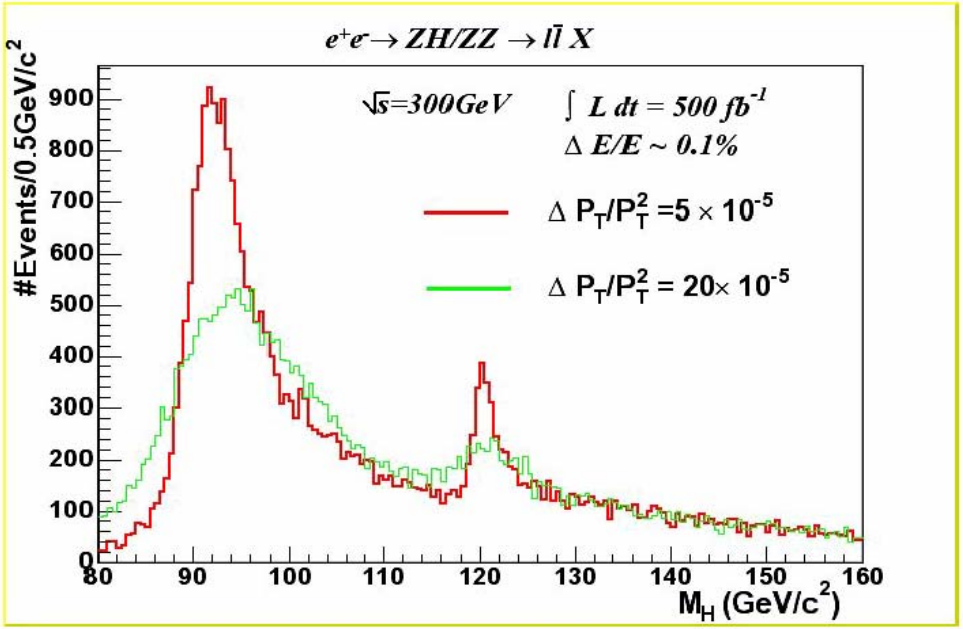
Identify all final state objects

Momentum resolution

- 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.



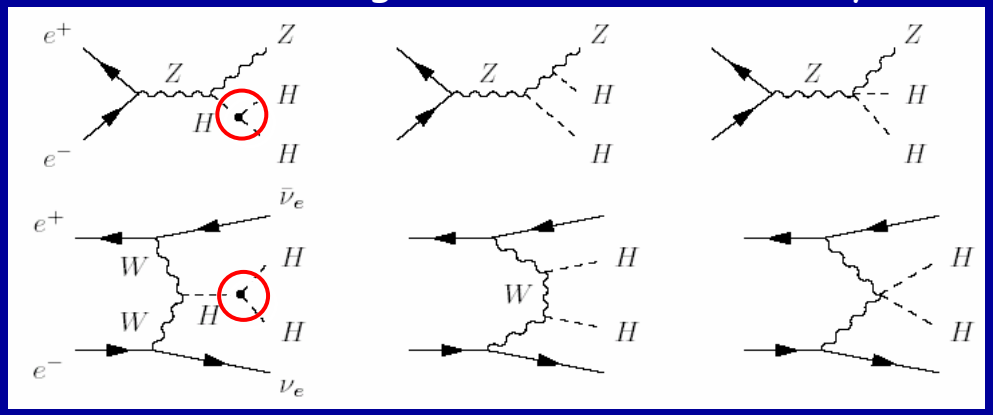
- Example:
  - $\sqrt{s}$ = 300 GeV
  - 500 fb^{-1}
  - beam energy spread of 0.1%
- Goal:
  - $\delta M_{ll} < 0.1 \times \Gamma_Z$
  - δM_H dominated by beamstrahlung

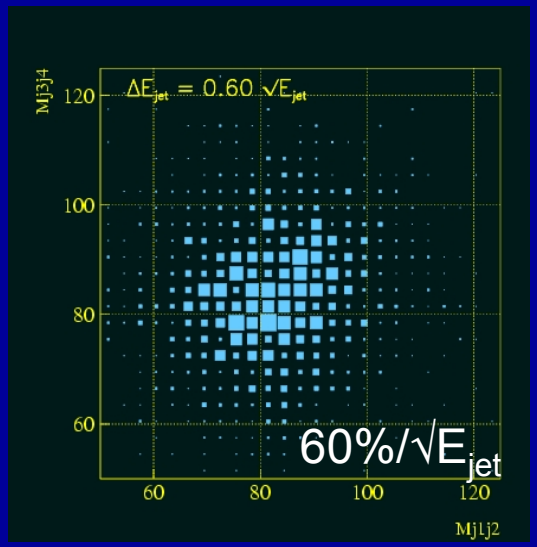


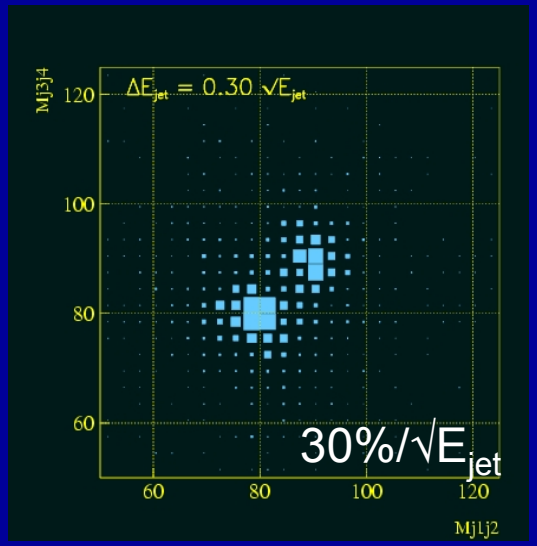
Illustrates need for superb momentum resolution in tracker

Jet energy resolution

- Many processes have W and Z bosons in the final state; events need to discriminate
- Need for precision calorimetry
  - $e^+e^- \rightarrow WW\nu\nu$, $WZe\nu$ 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







Equivalent to needing 40-200% more luminosity

Goal for now is: $30\%/\sqrt{E_{jet}}$

Design Driver for any ILC detector

To be able to achieve the jet resolution can NOT simply use calorimeters as sampling devices.

$$\frac{\sigma_E}{E} \cong 0.30 \frac{1}{\sqrt{E(GeV)}}$$

Have to use "energy/particle flow". Technique has been used to improve jet resolution of existing calorimeters.

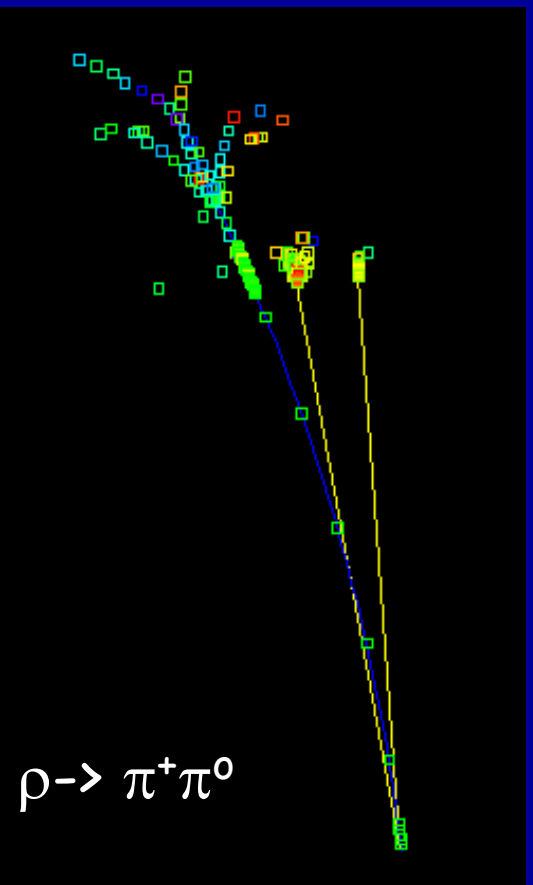
Algorithm:

- use EM calorimeter (EMCAL) to measure photons and electrons;
- track charged hadrons from tracker through EMCAL,
- identify energy deposition in hadron calorimeter (HCAL) with charged hadrons & replace deposition with measured momentum (very good)
- When completed only E of neutral hadrons (K's, Lambda's) is left in HCAL. Use HCAL as sampling cal for that.

Require: Imaging cal (use as tracker = like bubble chamber),
➔ very fine transverse & longitudinal segmentation
Large dynamic range: MIP…. to …..shower
Excellent EM resolution

Event display to illustrate granularity

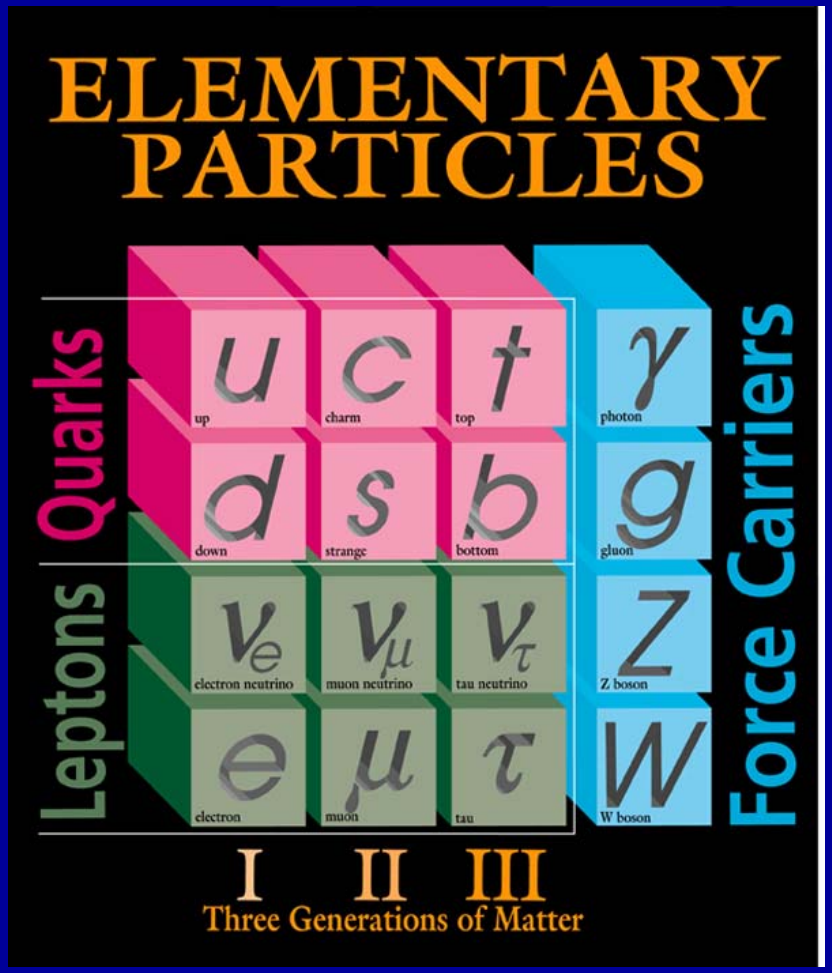
More detail



$\rho \rightarrow \pi^+\pi^0$

What should detector be able to do ?

Identify ALL of the constituents that we know & can be produced in ILC collisions & precisely measure their properties.



u,d,s jets; no ID
c, b jets with ID
t final states; jets + W's
ν's: missing energy; no ID
e, μ: yes
τ through decays
γ ID & measure
gluon jets, no ID
W,Z leptonic & hadronic

Use this to measure/identify the NEW physics

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 goal

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

- 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)

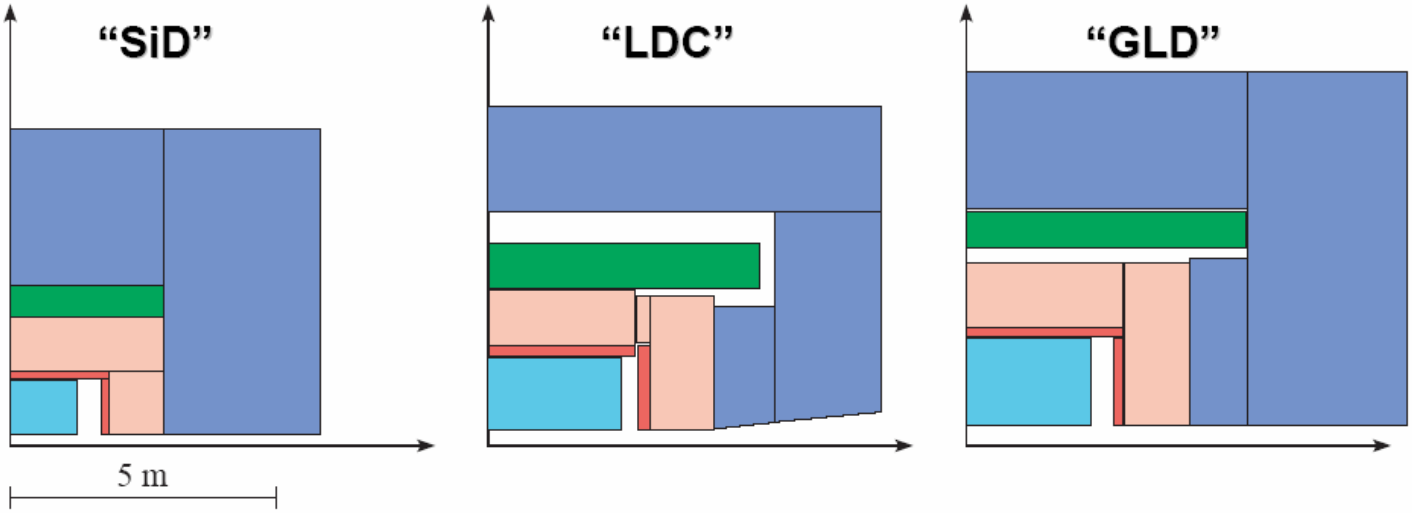
- Need factor 2 better than ZEUS

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

- 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

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

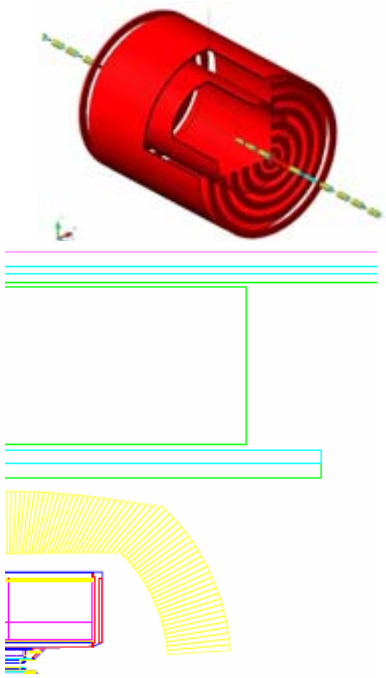
Detector Concepts



- Main Tracker
- EM Calorimeter
- Had Calorimeter
- Cryostat / Solenoid
- Iron Yoke / Muon System

- SiD: Silicon Detector — SiD: **B R²**
  - Small, 'all' silicon
- LDC: Large Detector Concept — LDC: **B R²**
  - TPC based
- GLD: Global Large Detector — GLD: **B R²**

"4th "



Different: no PFA; solenoid arrangement

These detector concepts studied worldwide, with regional concentrations

Recently submitted "Detector Outline Documents" (~150 pages each)

Physics goals and approach all similar. Approach of "4" different

Detector R&D efforts & Design Studies

	Vxd 4-5	SiLC	TPC	Jet	Calice EM	Calice HAD	LC cal	Cal Asia	EM OR/ SLAC	EM hybrid	muon
SiD	X	X			X	X		X	X	X	X
LDC	X	X	X	X	X	X	X	X	X	X	X
GLD	X	?	X	X		X	X	X			X

	Fwd trac	Fwd cal	Fwd Cher	DAQ	$\gamma\gamma$	BDIR
SiD	X	X		X		X
LDC	X	X	?	X		X
GLD	X	X	?	X		X

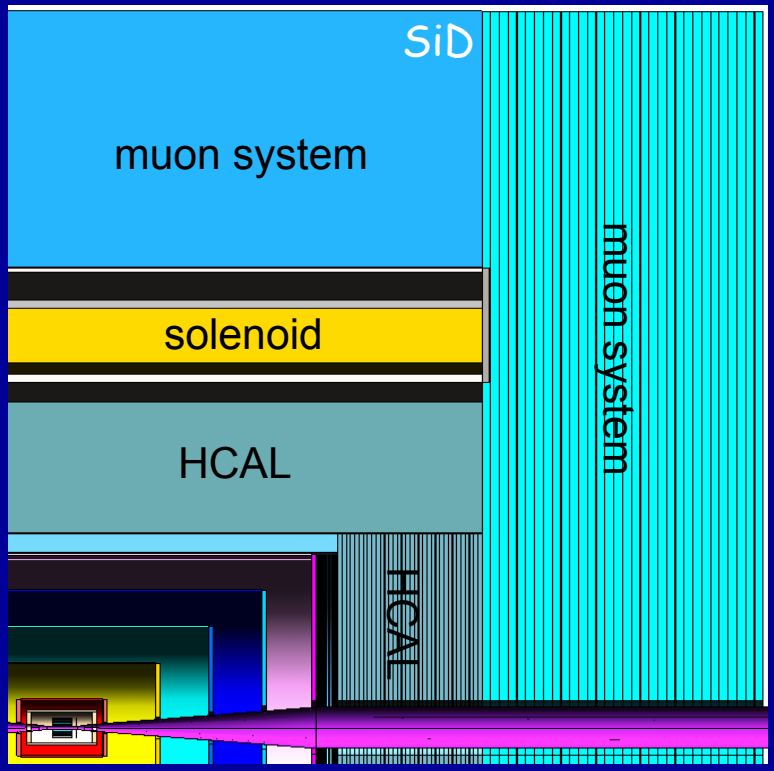
Nearly all detector R&D efforts are represented in the Design Studies (DS)

R&D efforts with concentration in Europe

SiD Design Concept

As example & because familiar with it

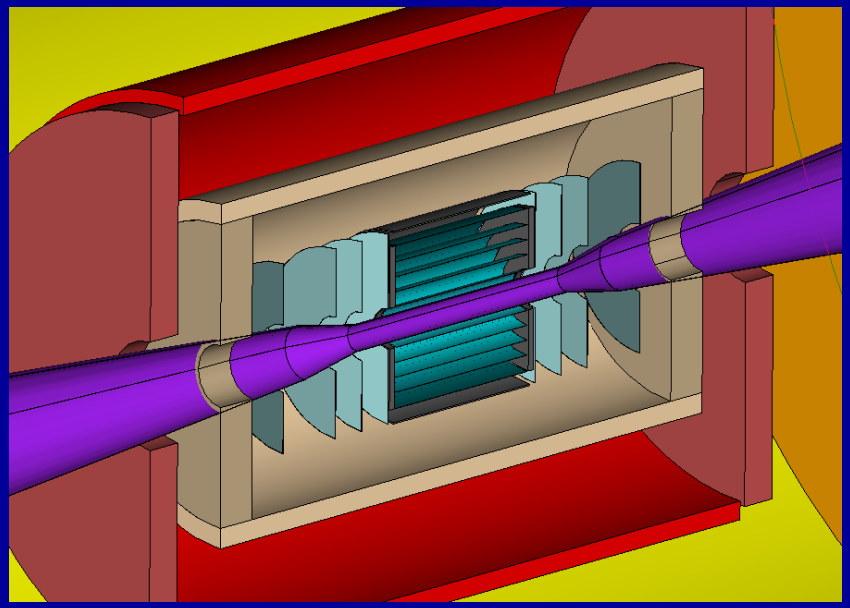
- Calorimetry is the starting point in the SiD design
- Premises at the basis of concept:
  - Particle flow calorimetry will deliver the best possible performance
  - Si/W is the best approach for the ECAL and digital calorimetry for HCAL
  - Limit calorimeter radius to constrain the costs
  - Boost 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



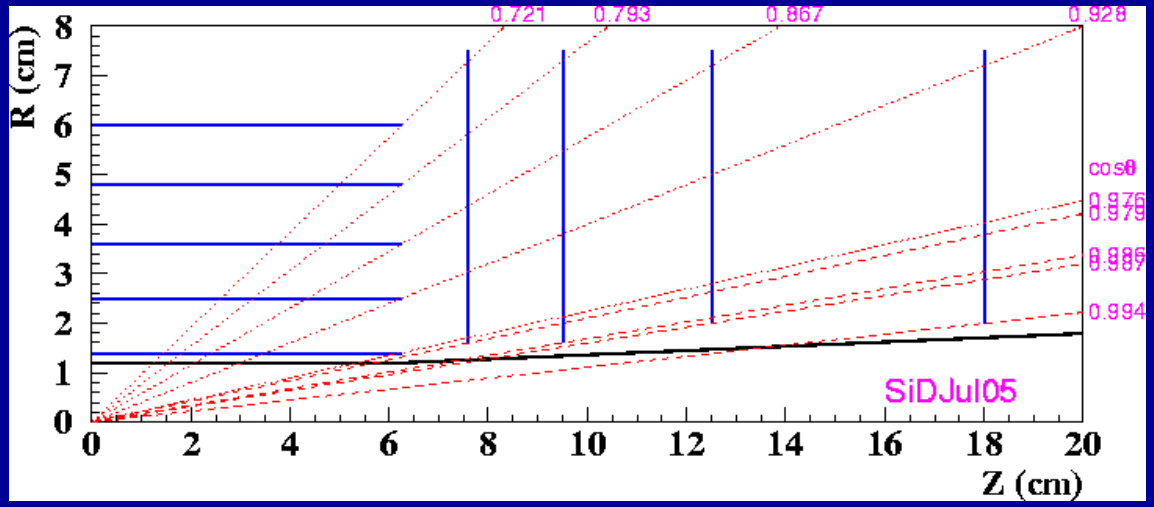
Vertexing and Tracking

- 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

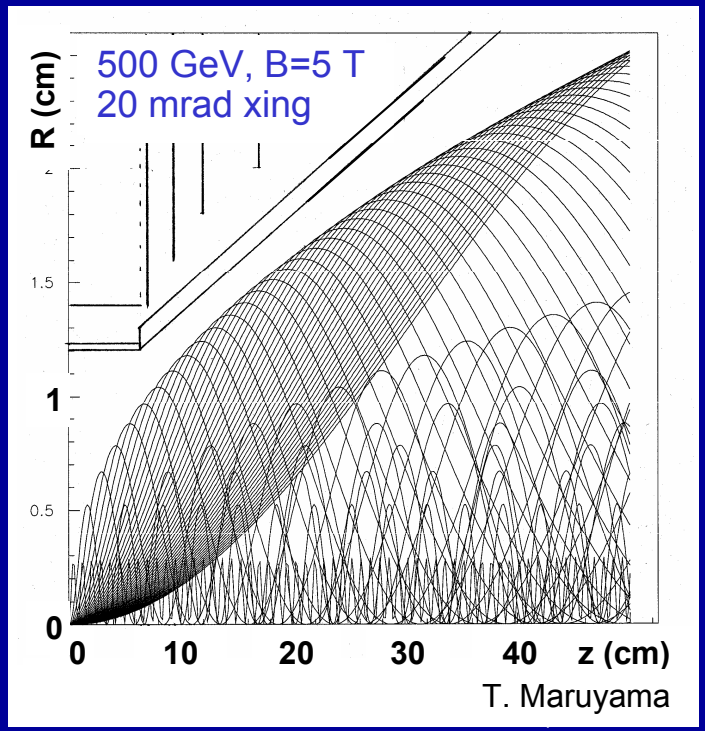


Vertex Detector



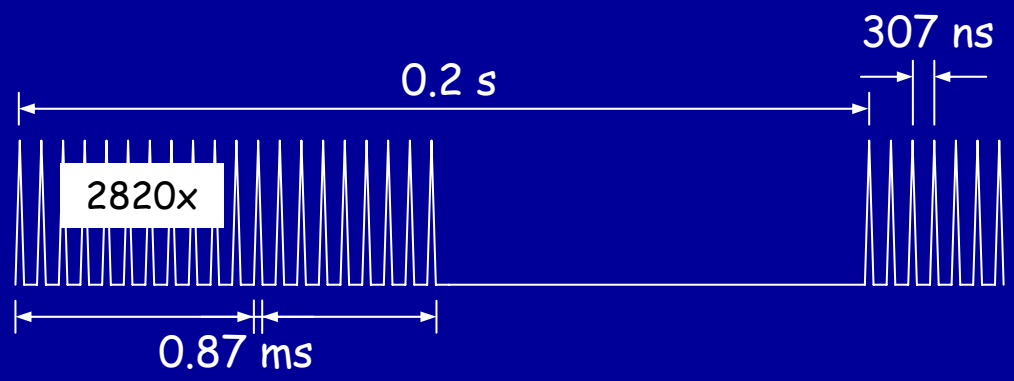
- Five Barrels
  - R_{in} = 14 mm to R_{out} = 60 mm
  - 24-fold phi segmentation
  - two sensors covering 6.25 cm each
  - All barrel layers same length
- Four Disks per end
  - Inner radius increases with z

- 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



Vertex Detector 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

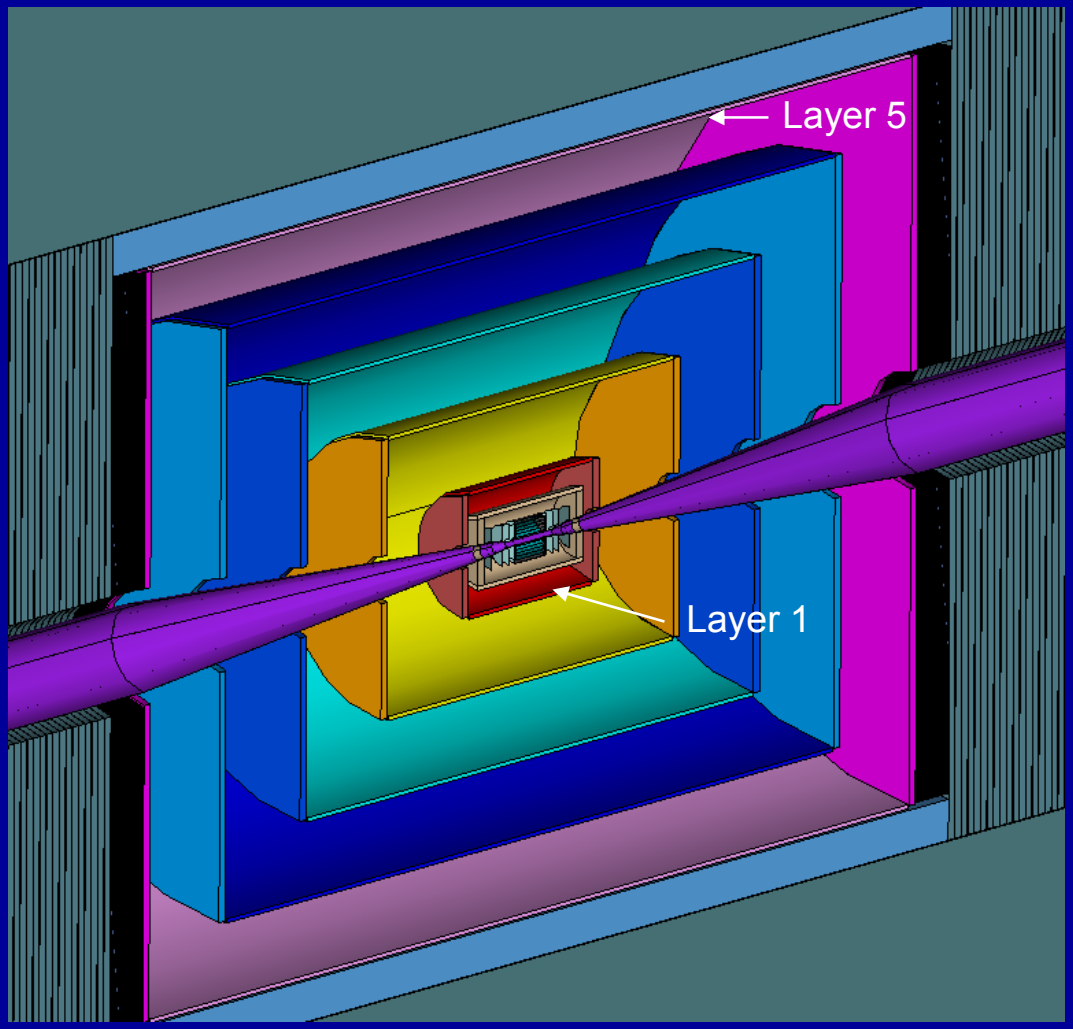
For SiD: cumulative number of bunches to reach hit density of 1/mm^2
- Layer 1: ~35
- Layer 2: ~250

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

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

Silicon Outer Tracker

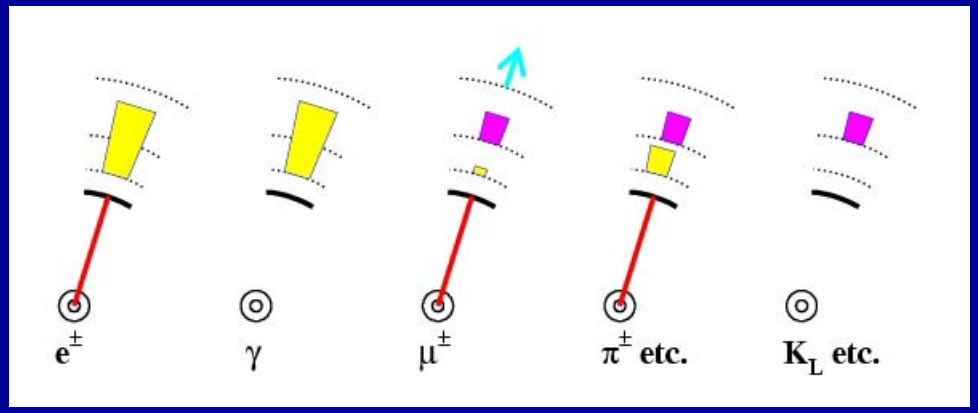
- 5-Layer silicon strip outer tracker, covering R_{in} = 20 cm to R_{out} = 125 cm, to accurately measure the momentum of charged particles



- 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

Calorimetry

- Goal is jet energy resolution of 30%/√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

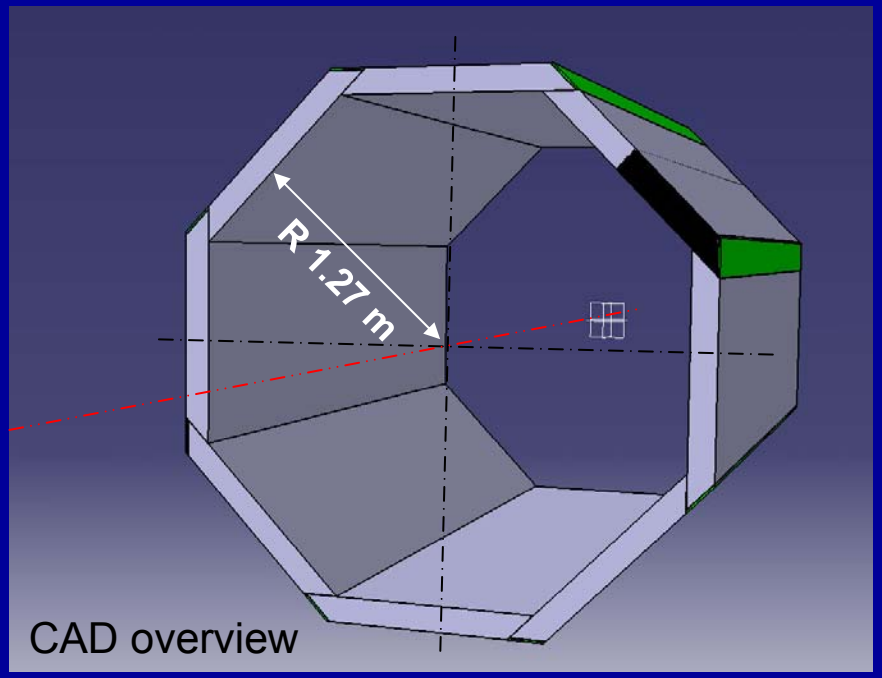
Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	~ 65 %	Tracker	Negligible
Photons	~ 25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	~ 10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$

~20%/√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



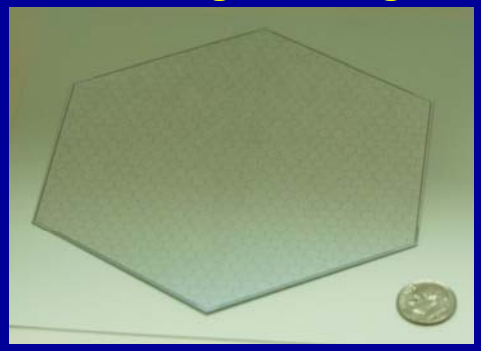
CAD overview

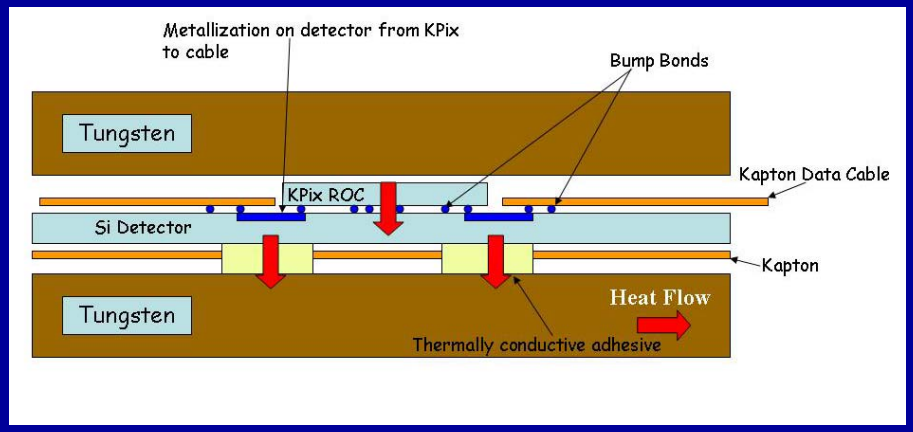
SLAC/Oregon/BNL Design
LAPP, Annecy, Mechanical Design

- 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





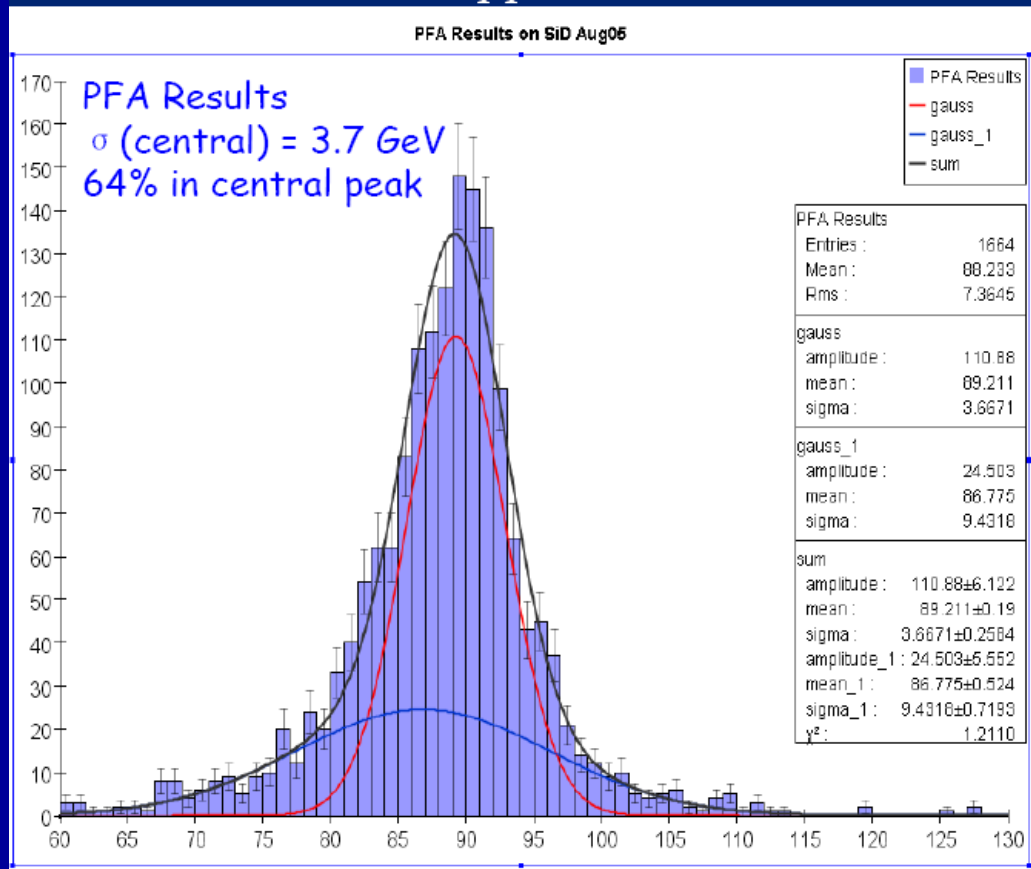
- Readout with kPix chip
  - 4-deep buffer (low occupancy)
  - Bunch crossing time stamp for each hit
- Testing
  - Prototype chip in hand with 2x32 channels
  - Prototype sensors in hand
  - Test beam foreseen in 2006

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
      - Gas Electron Multipliers
      - Scintillator
    - Passive
      - Tungsten
      - Steel
  - PFA Algorithms
    - Spatial separation
    - Hit density weighted
    - Gradient weighted

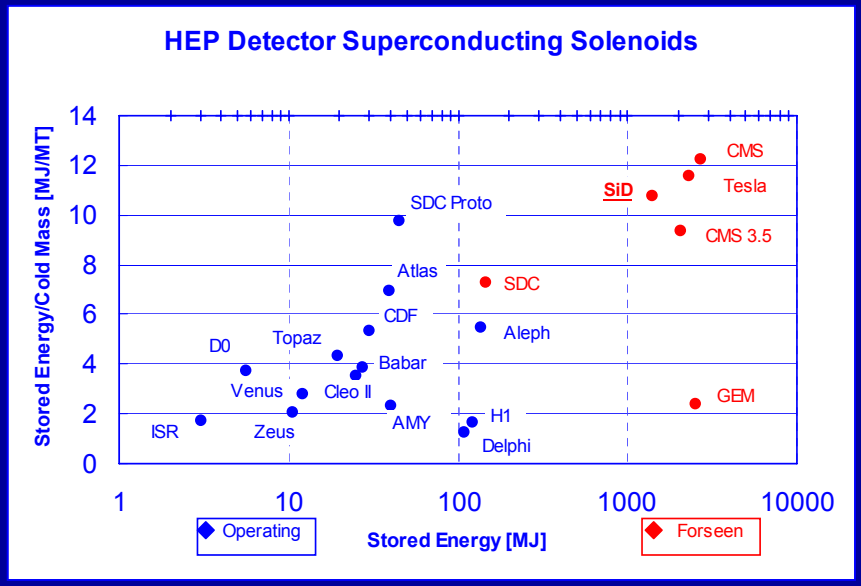
Current simulated performance of PFA

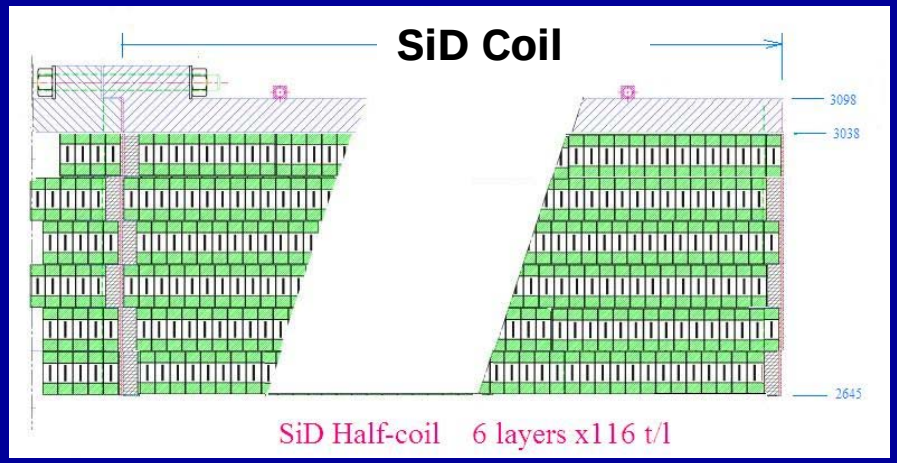
$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$ at 91 GeV



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



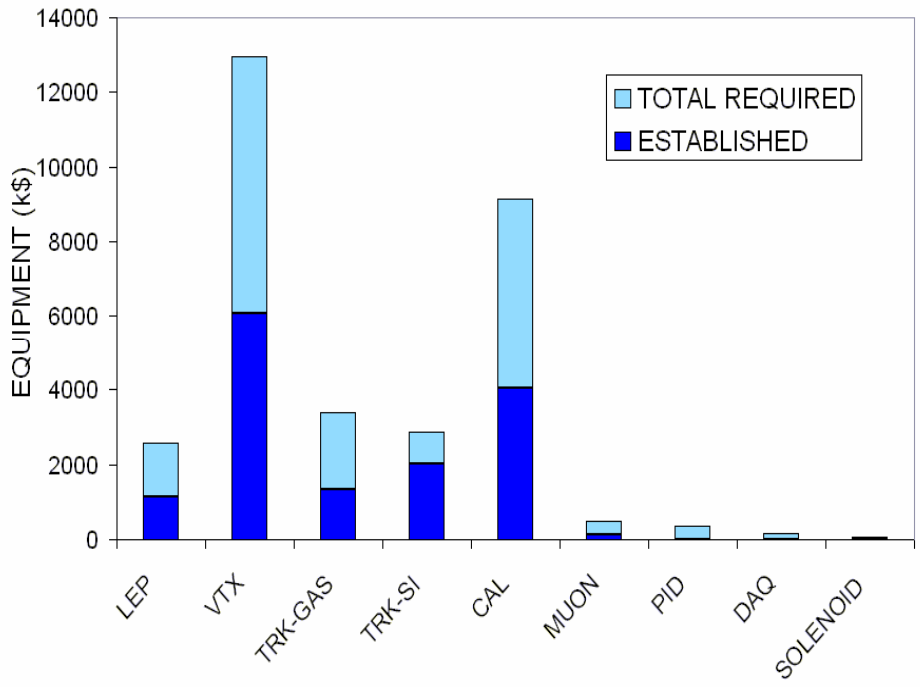


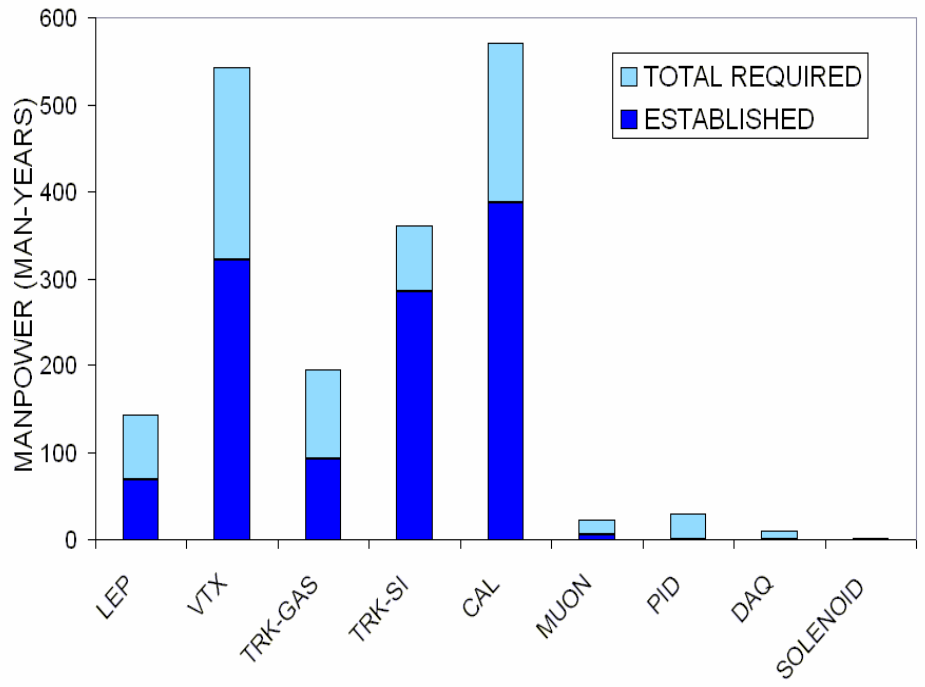
- Full feasibility study (with CERN, Saclay) of design based on CMS conductor
  - Start with CMS conductor design, but increase winding layers from 4 to 6
    - I(CMS)= 19500 A, I(SiD) = 18000 A; Peak Field (CMS) 4.6 T, (SiD) 5.8
    - Net performance increase needed from conductor is modest

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. Worldwide activities at:
  - https://wiki.lepp.cornell.edu/wws/bin/view/Projects/WebHome

ILC detector R&D needs: funded & needed

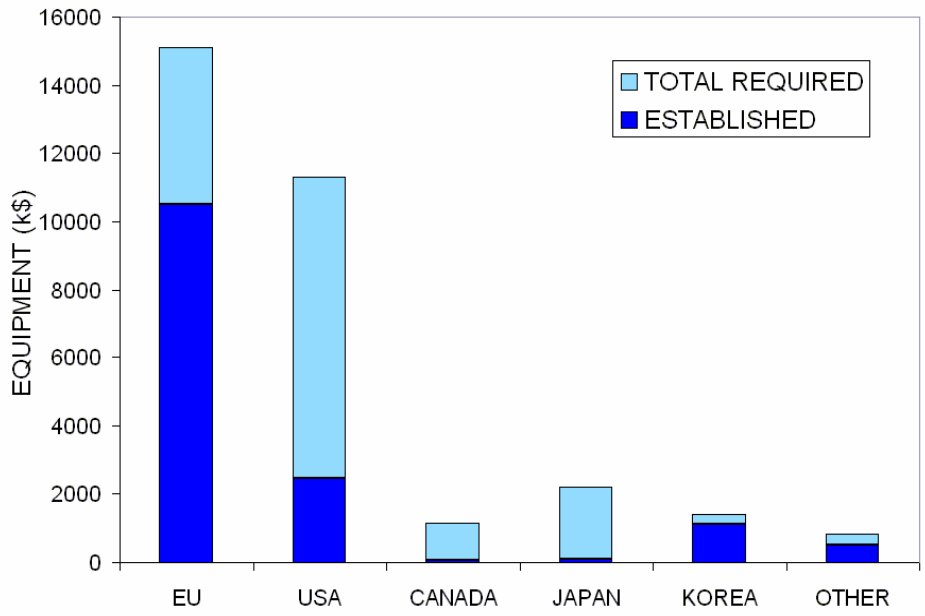


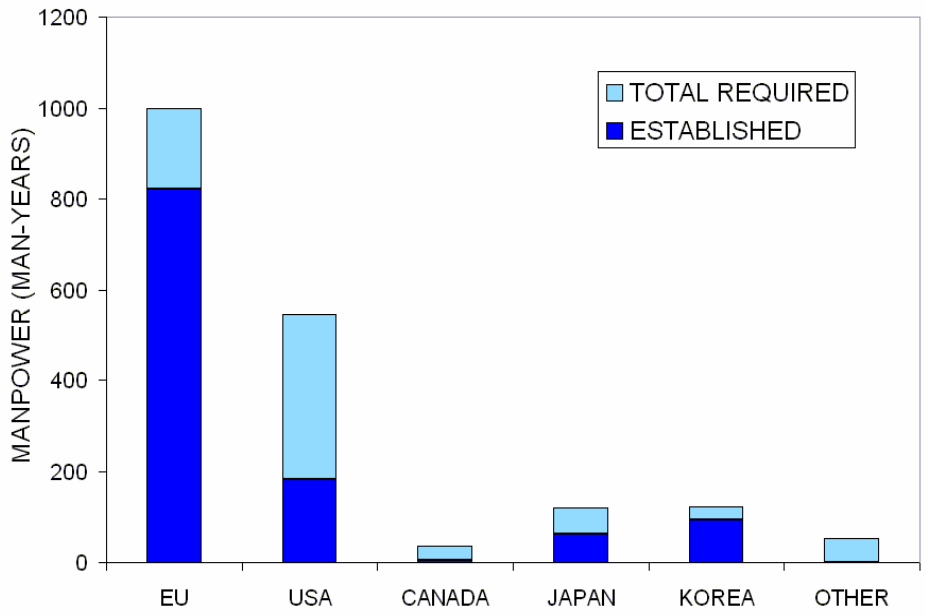


Urgent R&D support levels over the next 3-5 years, by subdetector type. 'Established' levels are what people think they will get under current conditions, and 'total required' are what they need to establish proof-of-principle for their project.

ILC detector funding worldwide

From WWS R&D panel report





Urgent R&D support levels over the next 3-5 years, by funding country or region. 'Established' levels are what people think they get under current conditions, and 'total required' are what they would need to establish proof-of-principle for their project.

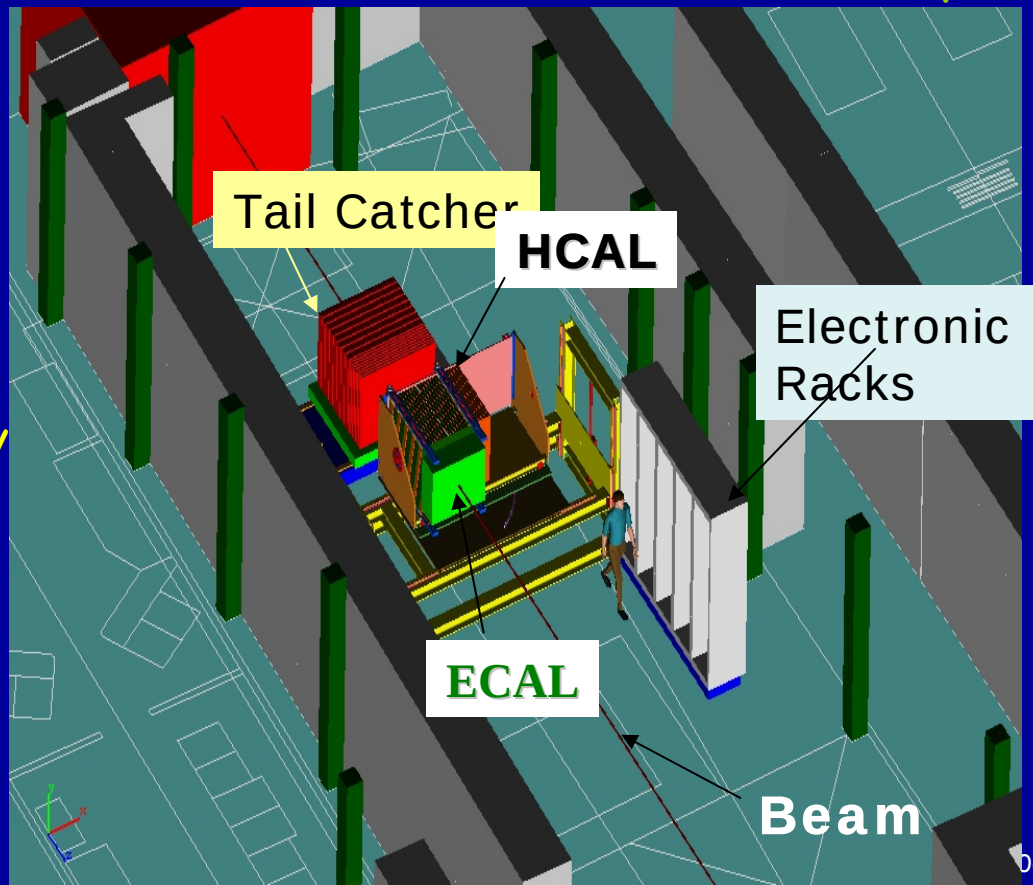
Example: US groups part of worldwide "Calorimeter" R&D (CALICE), but can not fulfill commitments, because of lack of funding: EM & HAD calorimeter efforts with testbeam (proof of principle)

Efforts underway to increase support in US for detector R&D as part of total US ILC R&D funding

Testbeam for ILC

- Proposal for multi-year testbeam program for study of high performance calorimeters for the ILC with the CALICE collaboration at Fermilab
  - Summer 2006: Muon system tests, RPC tests
  - Fall 2006: Muon Tailcatcher and RPC readout (slice tests)
  - tentative: summer 2007: CALICE full 1 m^3 EM and HCAL (scint + RPC)

Testbeam layout



Strong commitments, but limited funding for US partners:

NIU/ANL/UTA/Iowa/UoC: analog/digital hadron calorimetry
SLAC/Oregon/BNL: EMCAL
Tracking & Vertex tests

Conclusions

- The linear collider effort has a lot of momentum, worldwide & in US
  - The community has decided the ILC to be the next highest priority
  - US community endorses that point of view and would like to host the ILC
- The R&D for the accelerator is obviously needed
- BUT in order to do the physics, need high performance detectors
  - Physics program requires high performance
  - Need to establish different approaches (calorimetry)

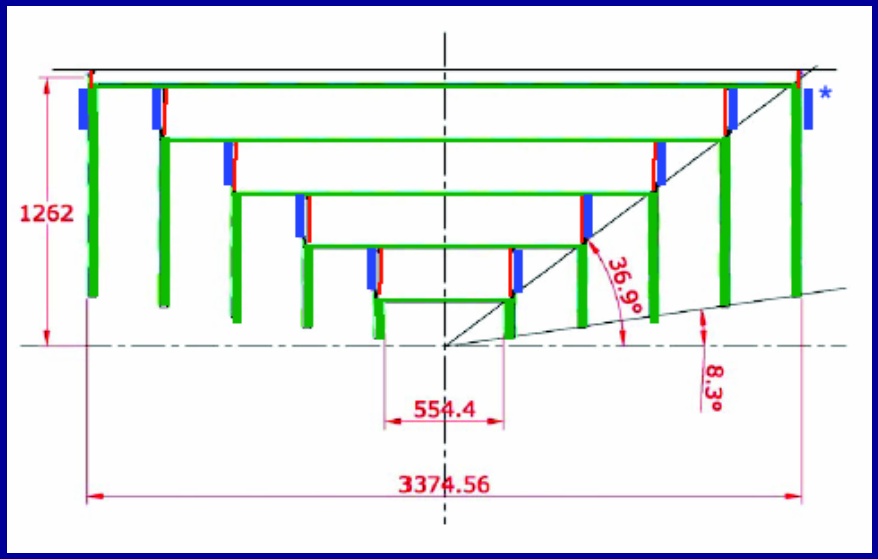
To be able to specify & cost ILC detectors in ~3-4 years, an active and funded R&D program has to be established in the US in the next year.

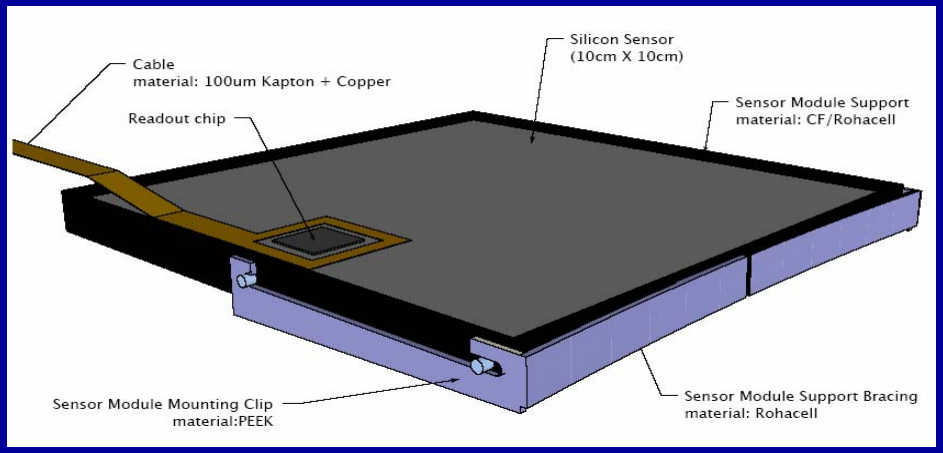
It should be an integral part of the US HEP program

Backup slides

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



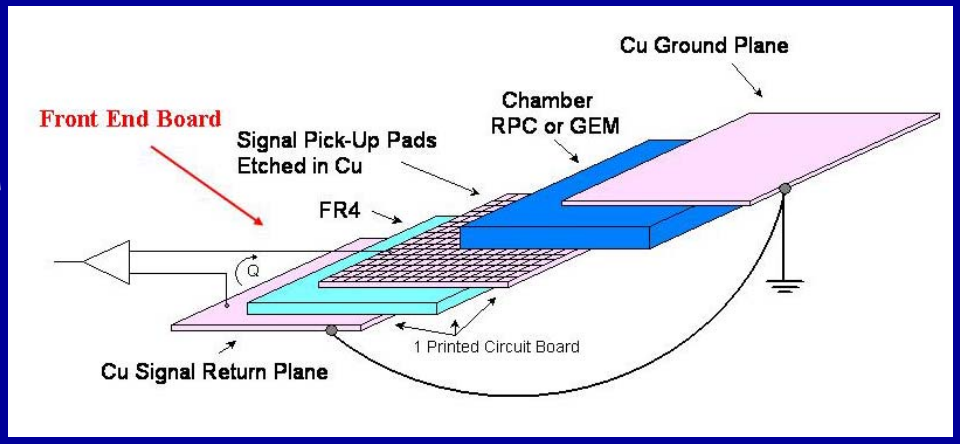


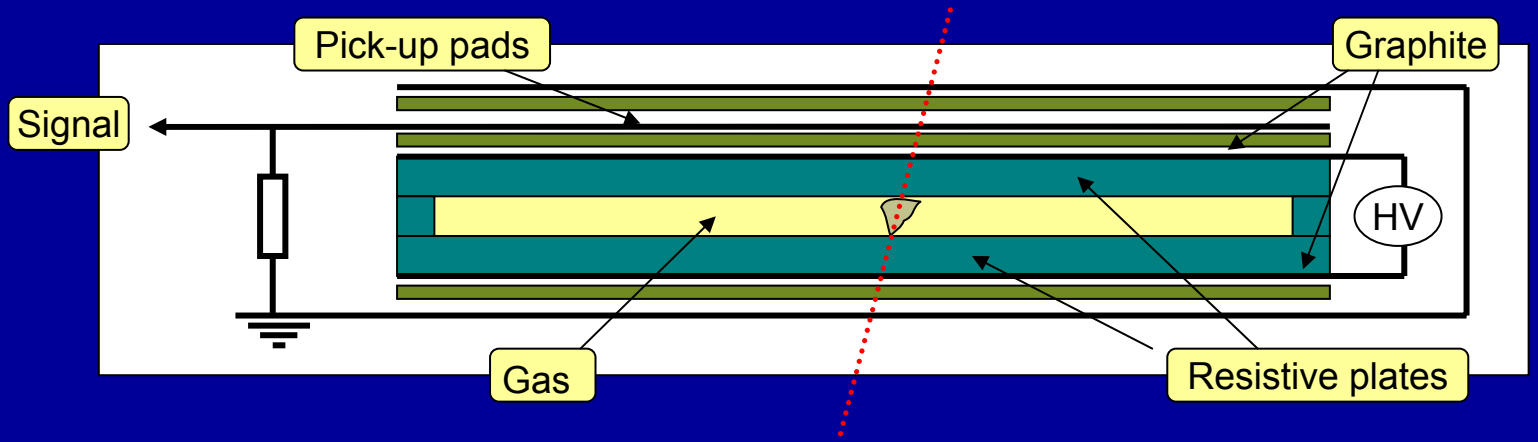
- Nested support
- Power/Readout mounted on support rings

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

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

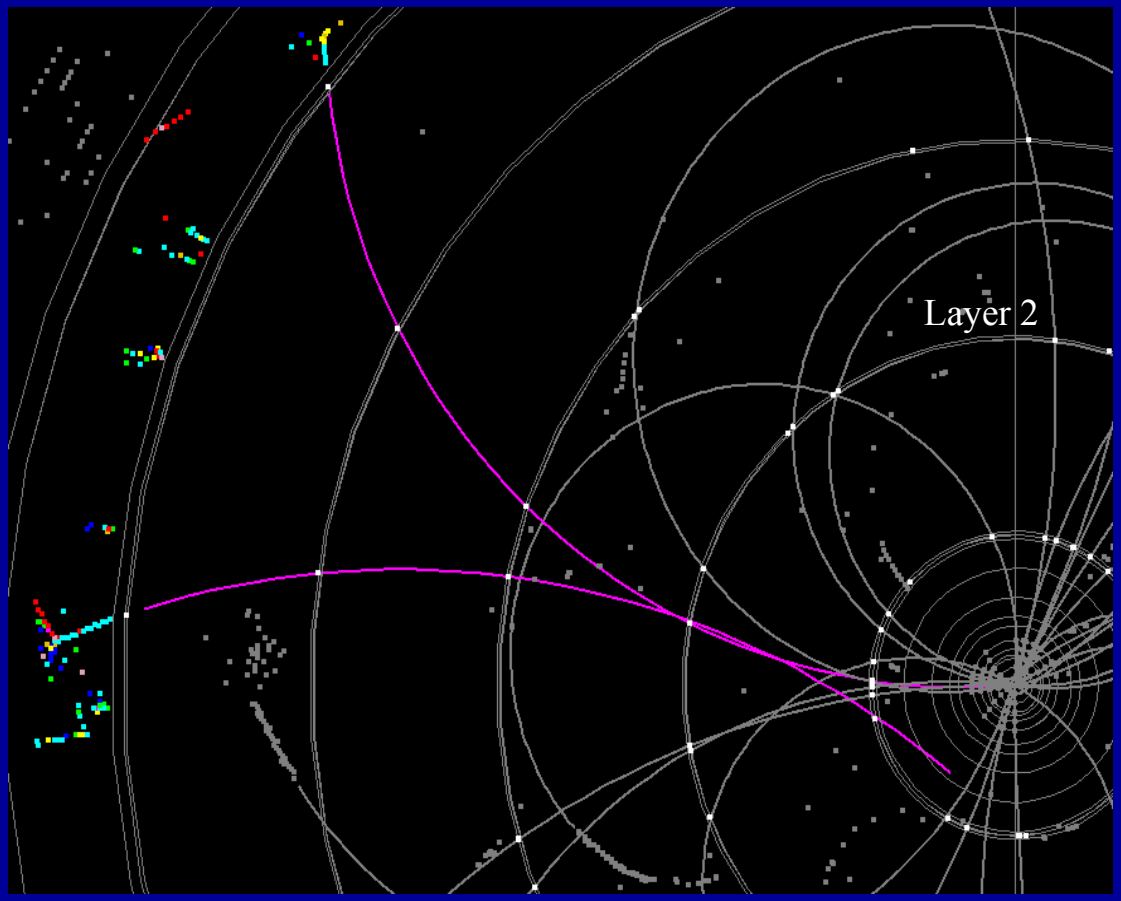
- Area of intensive work, not just within SiD, but in whole ILC community
- Many, many open issues
  - Algorithms
    - Cluster finding, …
  - Physics
    - Dependence on environment
    - Missing neutrinos, FSR, …
  - Detector
    - Linearity, e/p, E-resolution, granularity
    - Sampling fluctuations,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

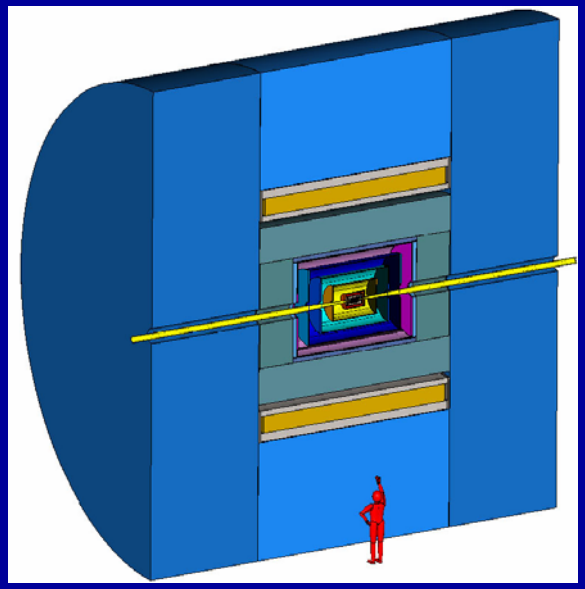
Fermilab Wine and Cheese, December 2 by Jose Repond

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

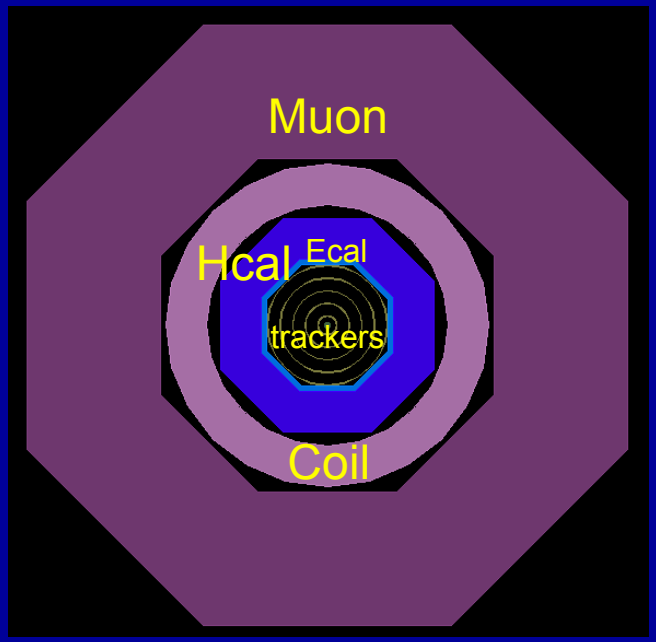


Muon System



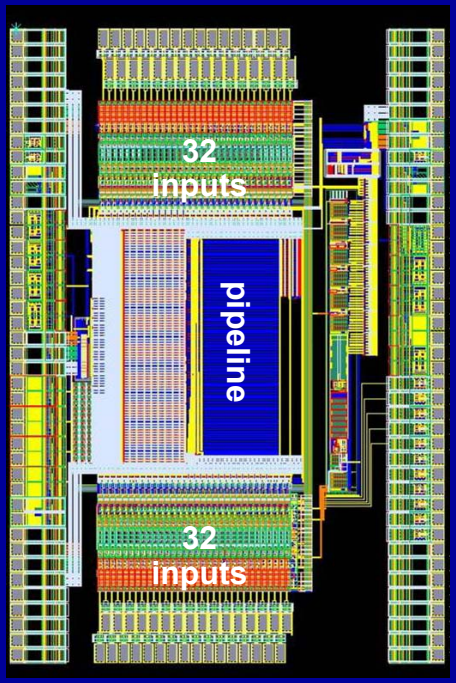
- Muon System Baseline Configuration
  - 48 layers, 5 cm thick steel absorber plates
  - RPC's as active medium
  - Muon ID studies done to date with 12 instrumented gaps with ~1cm spatial resolution
  - 6-8 planes of x, y or u, v upstream of Fe flux return for xyz and direction of charged particles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

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



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



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 …