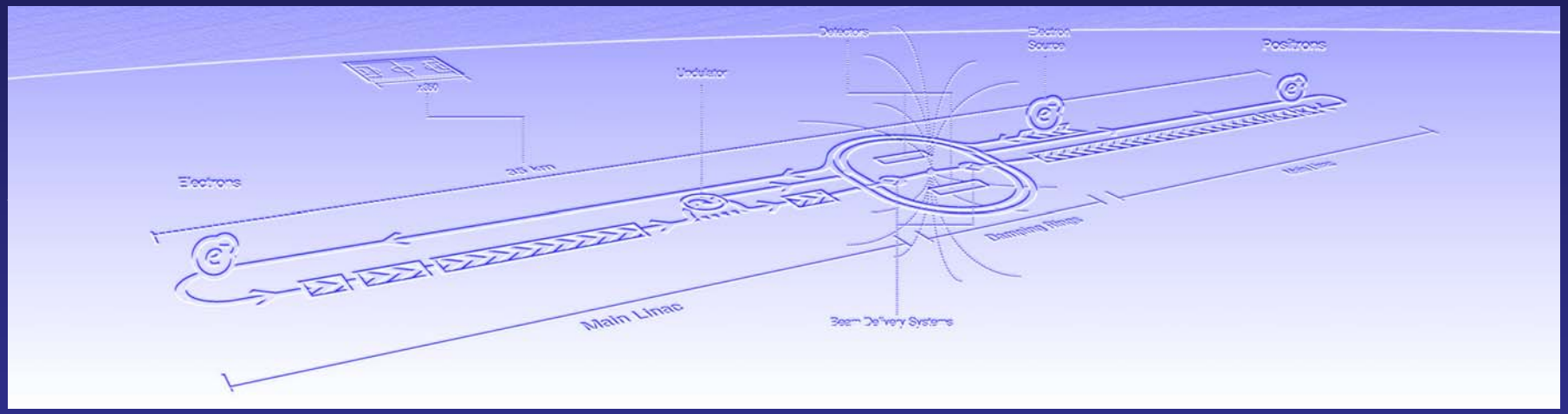
A Wal★mart ILC Detector ?



Tevatron University

Marcel Demarteau
Fermilab

April 26, 2007

Walmart …

- Walmart evokes very different reactions in different people
- The place to go for everything …
  and always at "the lowest prices, always"
- Company's business practices:
  - Anti-union stance
  - Workers' issues
  - Cut-throat competition
- The place to go for

- "An often heard common misconception is that detectors for the proposed International Linear Collider could easily be built with today's technology. That is to say that one could almost procure or build such a detector "off the shelf" …… at a retail store"
- **I'll make an attempt to remove that misconception**

Walmart …

- Forbes Special Report March 08, 2007:

  The World's Richest People

RANK	NAME	CITIZENSHIP	AGE	NET WORTH ($BIL)	RESIDENCE
26	Sergey Brin	United States	33	16.6	United States
26	Larry Page	United States	34	16.6	United States
26	Alice Walton	United States	57	16.6	United States
29	Helen Walton	United States	87	16.4	United States
30	Michael Dell	United States	42	15.8	United States
31	Steven Ballmer	United States	51	15.0	United States
31	Kirk Kerkorian	United States	89	15.0	United States
31	Raymond, Thomas & Walter Kwok	Hong Kong	NA	15.0	Hong Kong
34	Francois Pinault	France	70	14.5	France
35	Suleiman Kerimov	Russia	41	14.4	Russia
36	Vladimir Lisin	Russia	50	14.3	Russia
37	Jack Taylor & family	United States	84	13.9	United States
38	Vladimir Potanin	Russia	46	13.5	Russia
38	Mikhail Prokhorov	Russia	41	13.5	Russia
40	Oleg Deripaska	Russia	39	13.3	Russia
40	Michael Otto & family	Germany	63	13.3	Germany
42	[illegible]	United States	71	13.0	United States
42	Abigail Johnson	United States	45	13.0	United States
44	[illegible]	Germany	72	12.8	Germany
45	Barbara Cox Anthony	United States	83	12.6	United States
45	[illegible]	United States	87	12.6	United States
45	Mikhail Fridman	Russia	42	12.6	Russia
48	Vagit Alekperov	Russia	56	12.4	Russia
49	Charles Koch	United States	71	12.0	United States
49	David Koch	United States	66	12.0	United States

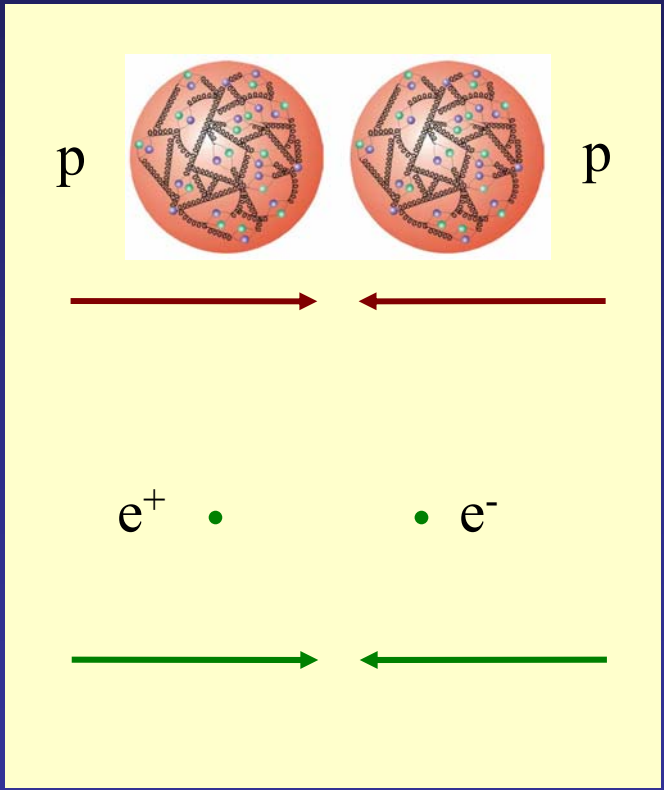
So, if you want a [illegible]
– or an ILC for [illegible]
don't ask Bill Ga[illegible]

Exploring the Terascale

- The LHC:
  - Will lead the way and has a large reach
  - Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - Broadband initial state
- The ILC:
  - A (second) view with high precision
  - Electron-positron collisions with fixed energies, adjustable between 0.1 and 1.0 TeV
  - Well defined initial state
- Together, these are our tools for the terascale

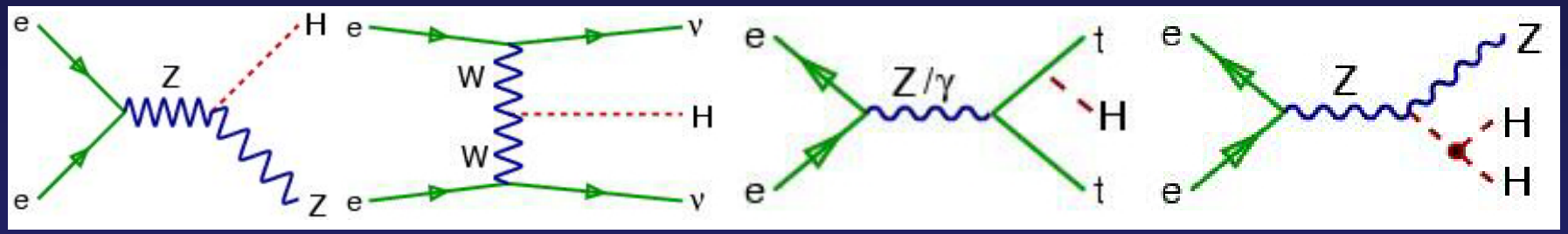
Why an e^+e^- Collider ?

- Electrons and positrons are elementary particles
- Particles have well-defined energy, angular momentum
- Process uses full center of mass energy
- Energy can be scanned precisely
- Particles are produced more or less democratically
- Final states can generally be fully reconstructed
- The high precision of e^+e^- means that it is sensitive to phenomena far above its CM energy because of quantum corrections – as LEP proved



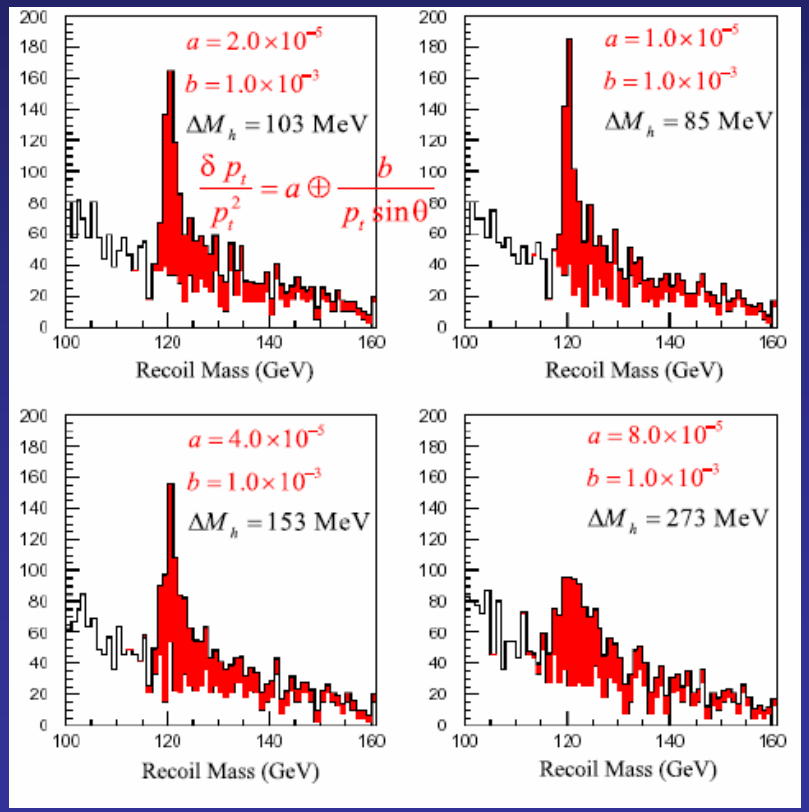
- The ILC is first and foremost a precision machine
  - Fully complementary with pp-collider
- Example: Higgs boson

Precision Higgs Physics



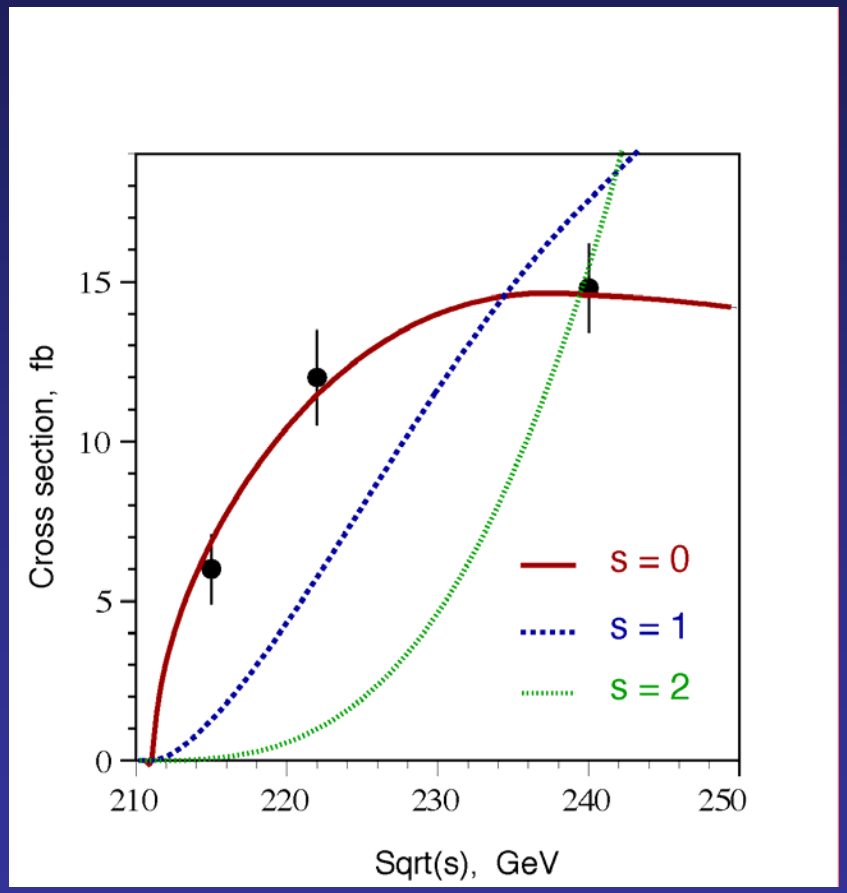
- Many model-independent Studies
  - Mass
  - Spin
  - Absolute Branching Ratios
  - Total width
  - Top Yukawa coupling
  - Self coupling

- Benchmark measurement is the measurement of the Higgs recoil mass in the channel $e^+e^- \rightarrow ZH$
  - Completely model independent
  - Goal of ΔM_H=60 MeV; m_H=120 GeV
  - Sensitive to invisible Higgs decays
  - Higgs recoil mass resolution improves until $\Delta p/p^2 \sim 2 \times 10^{-5}$



Precision Higgs Physics

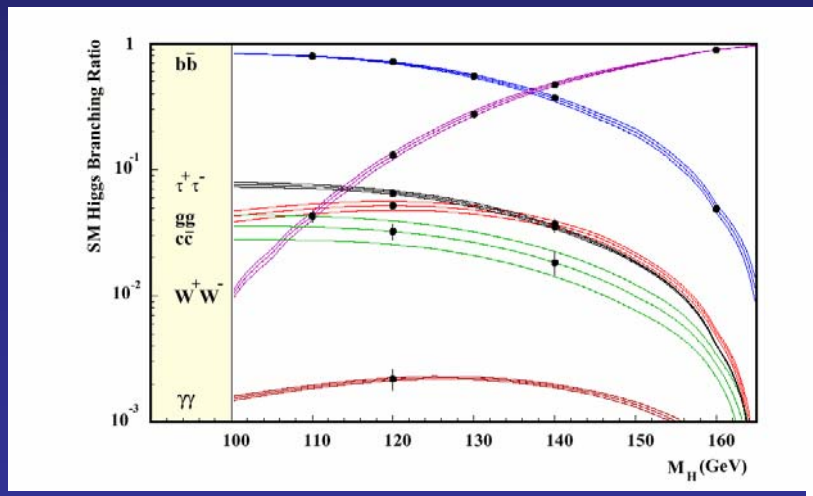
- Measurement of the Higgs' quantum numbers
  - Higgs is the only scalar particle in the Standard Model

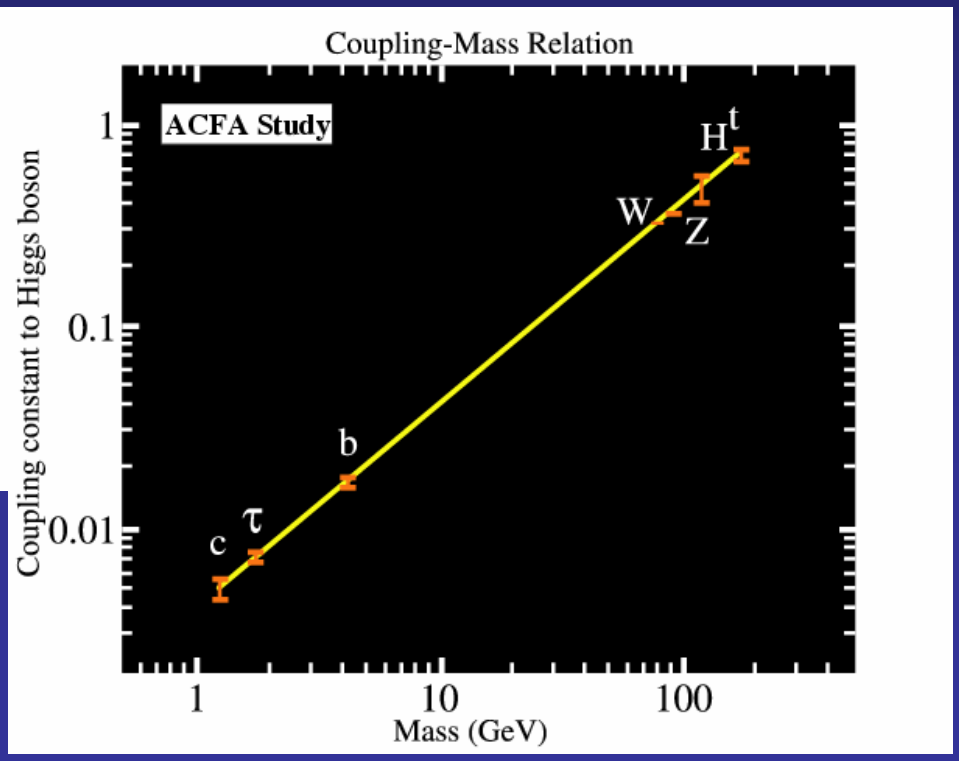


- m_H = 120 GeV; 20 fb^{-1} per energy point
- Note that an ILC will measure the spin of any Higgs it can produce by measuring the energy dependence from threshold

Precision Higgs Physics

- Measurement of the absolute branching ratios of the Higgs with high precision
  - Tests SM symmetry breaking; needed to distinguish SM Higgs from other Higgs particles
  - Very good discrimination needed between b- and c- and s-jets with charge identification
    - It does not suffice to only tag b-quarks !



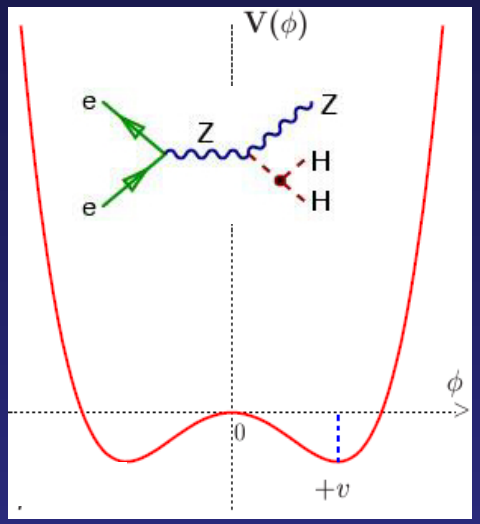


Precision Higgs Physics

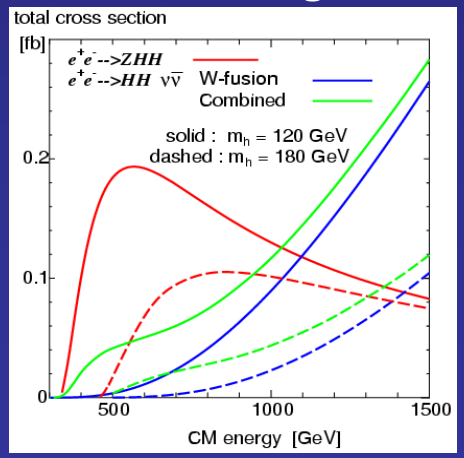
- Measurement of the Higgs potential through Higgs self coupling
  - $e^+e^- \rightarrow ZHH \rightarrow qqbbbb$

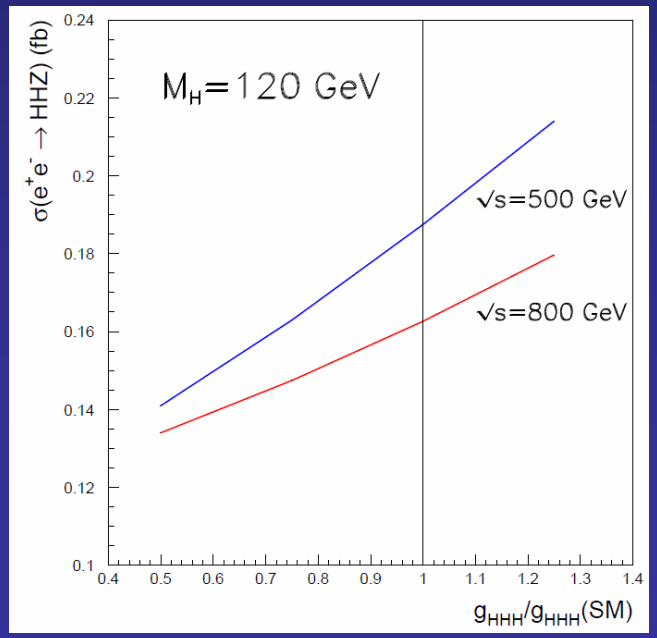
$$V(\varphi) = \frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\,\varphi^4 \qquad g_{HHH} = -6\mu^2 / \mathrm{v}$$

$$m_H^2 = 2\lambda\,\mathrm{v}^2 = -2\mu^2$$



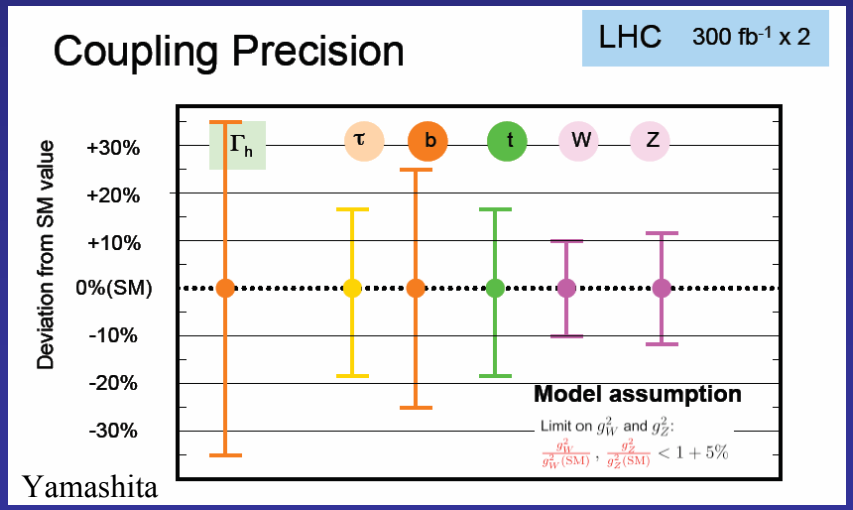
- Precision $\Delta g_{HHH}/g_{HHH}$ ~ 35% with 2 ab^{-1}
- Measurement only possible at the ILC
- Places very stringent requirements on jet energy resolution to reduce the backgrounds

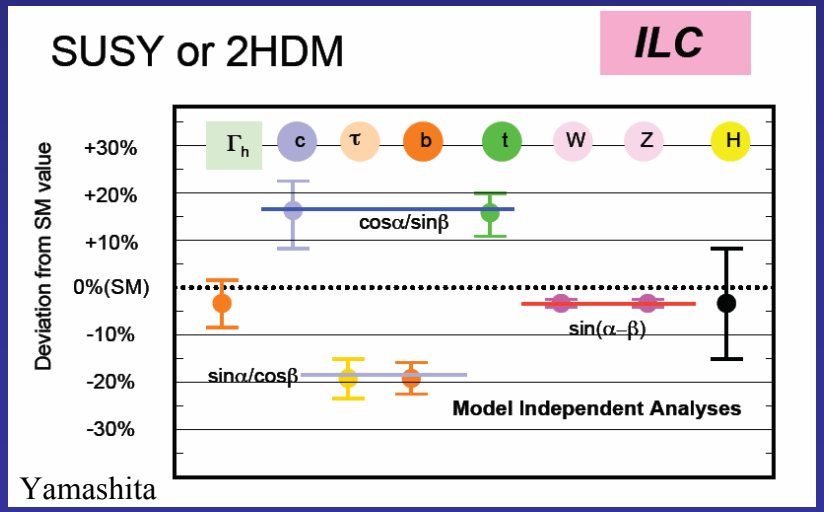




Precision Higgs Physics

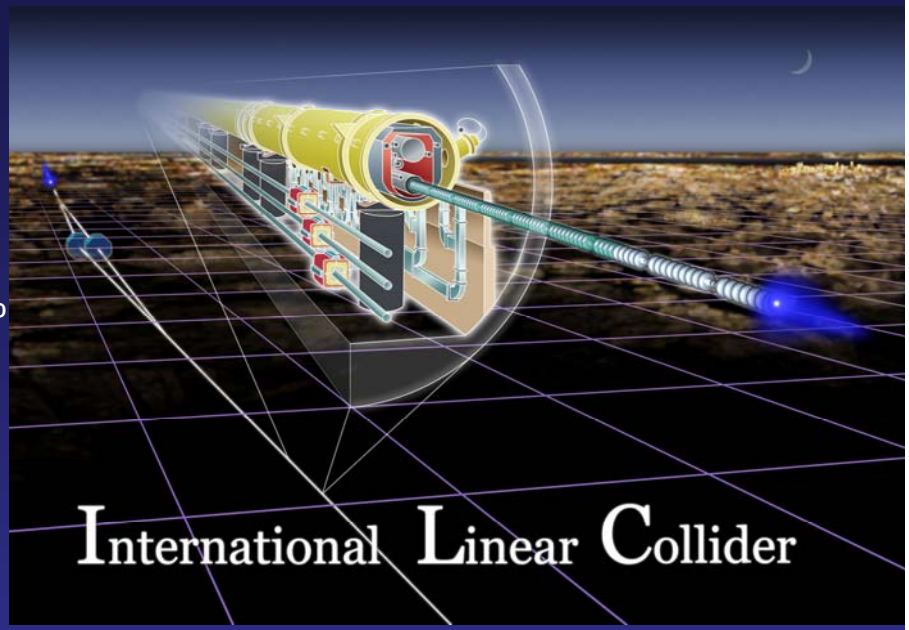
- Frankly, almost nothing is known about the Higgs; believing in the SM, electroweak fits tell us that there is at least one with mass below ~200 GeV. But,
  - Nothing is known for Yukawa-coupling
  - Nothing is known for self-coupling
  - Single Higgs? Two Higgs field doublets? Additional singlet?
  - SUSY? MSSM? NMSSM? Extra-dimensions?
- Precision of measurement of the deviation of the coupling constants from the SM prediction





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 between 200-500 GeV with <10% downtime
  - Beam energy precision and stability below 0.1%
  - Electron polarization of > 80%
  - Two detectors
  - E_{CM} down to 90 GeV for calibration
- Upgrades:
  - E_{CM} to 1 TeV
  - Capability of running at any E_{CM} < 1 TeV
  - $\mathcal{L}$ and reliability for 1 ab^{-1} in 3 – 4 years
- Options:
  - e^-e^-, $\gamma\gamma$, e-γ operation
  - e^+ polarization ~ 50%
  - Giga-Z with L = several 10^{33} $cm^{-2}s^{-1}$
  - WW – threshold scan with L = 10^{33} $cm^{-2}s^{-1}$



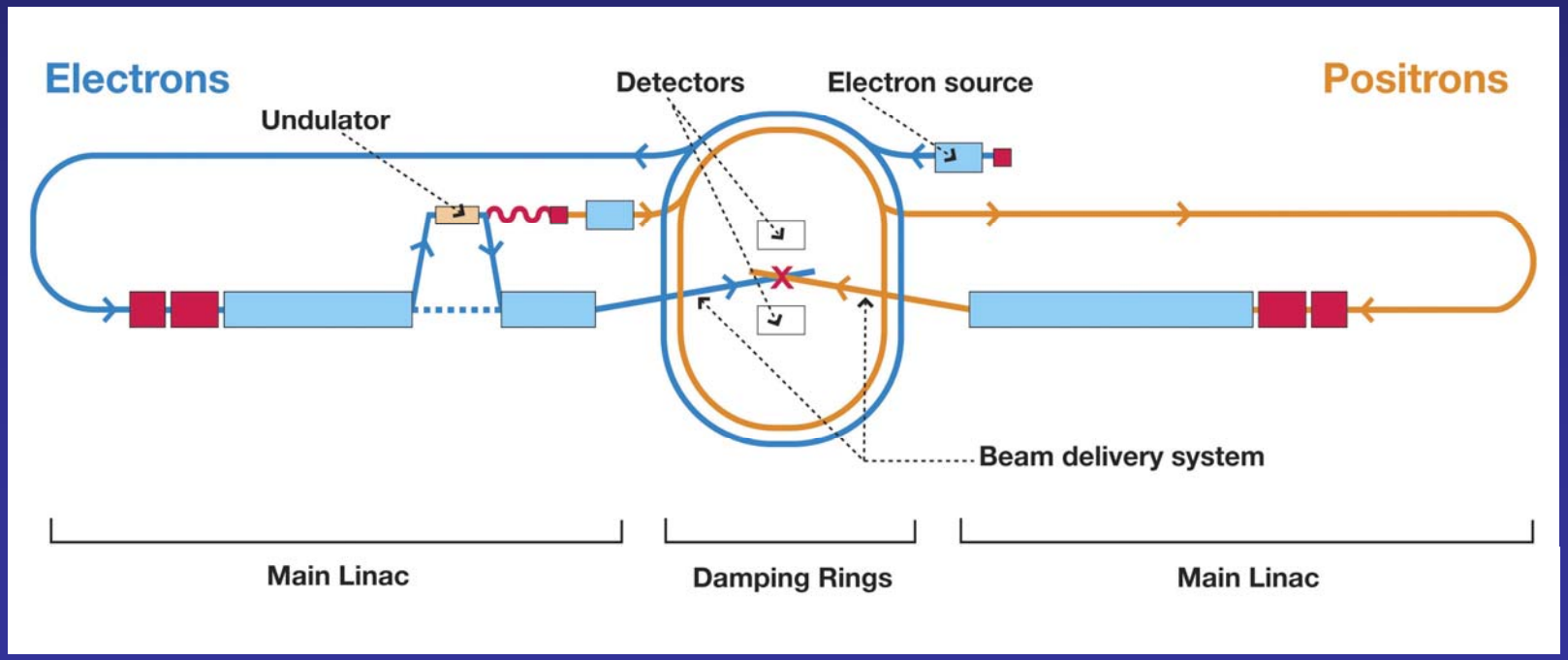
As defined in

ILCSC Parameters Document

See www.fnal.gov/directorate/icfa/LC_parameters.pdf with update at:
www.linearcollider.org/newsline/pdfs/20061207_LC_Parameters_Novfinal.pdf

ILC Schematic

- Two 11 km Superconducting (SC) linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - Circular damping rings for electrons and positrons
  - Helical undulator-based positron source, conventional electron source
- Single IR with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability



Beam Parameters

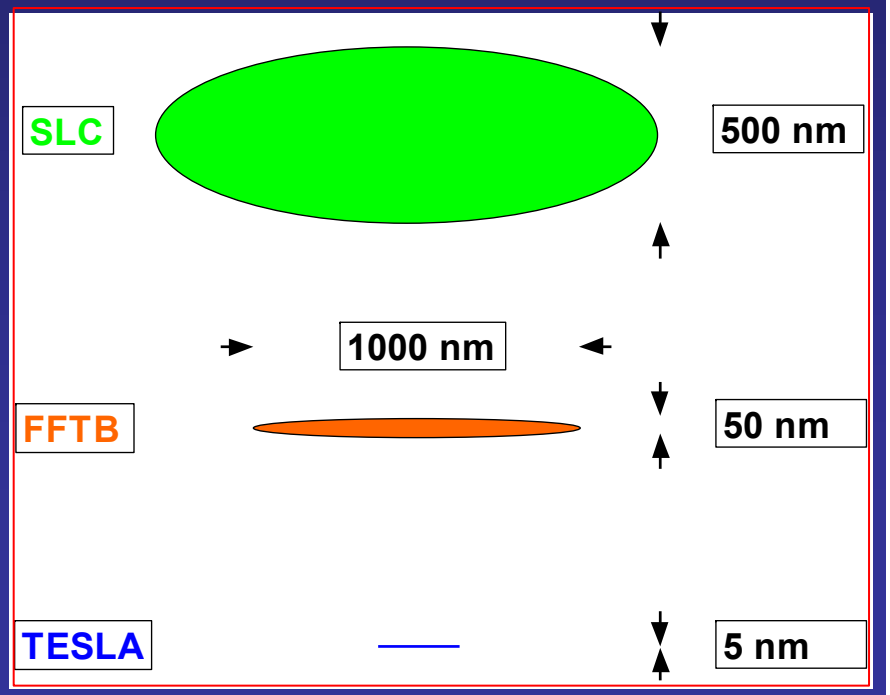
	Nominal	Low N	Large Y	Low P
Repetition rate frep (Hz)	5	5	5	5
Number of particles per bunch N (10^{10})	2	1	2	2
Number of bunches per pulse nb	2625	5120	2625	1320
Bunch interval in the main linac tb (ns)	369.2	189.2	369.2	480
in units of RF buckets	480	246	480	624
Average current in the main linac Iave (mA)	9	9	9	6.8
$\gamma\varepsilon x$ at IP (mm·rad)	10	10	12	10
$\gamma\varepsilon y$ at IP (mm·rad)	0.04	0.03	0.08	0.035
Beta function at IP βx (mm)	20	11	11	11
Beta function at IP βy (mm)	0.4	0.2	0.6	0.2
R.m.s. beam size at IP σx (nm)	639	474	474	474
R.m.s. beam size at IP σy (nm)	5.7	3.5	9.9	3.8
R.m.s. bunch length σz (μm)	300	200	500	200
Disruption parameter Dx	0.17	0.11	0.52	0.21
Disruption parameter Dy	19.4	14.6	24.9	26.1
Beamstrahlung parameter Yave	0.048	0.05	0.038	0.097
Energy loss by beamstrahlung δ_B	0.024	0.017	0.027	0.055
Number of beamstrahlung photons n_γ	1.32	0.91	1.77	1.72
Luminosity enhancement factor H_D	1.71	1.48	2.18	1.64
Geometric luminosity Lgeo 10^{34} cm^{-2} s^{-1}	1.2	1.35	0.94	1.21
Luminosity L 10^{34} cm^{-2} s^{-1}	2	2	2	2

Linear Collider Challenge

- The ILC is a linear collider – thus there is no synchrotron radiation produced in bending the e^+/e^- in a circular orbit.

- The challenges stem from:
  - In storage machines, the beams pass through each other many times/ second, giving many chances for interaction
  - In the ILC, they pass through each other once and then are dumped

- The only way to restore the luminosity is
  - Low emittance machine optics
  - Contain emittance growth through acceleration phase
  - Squeeze the beams as much as possible
  - Increase bunch charge

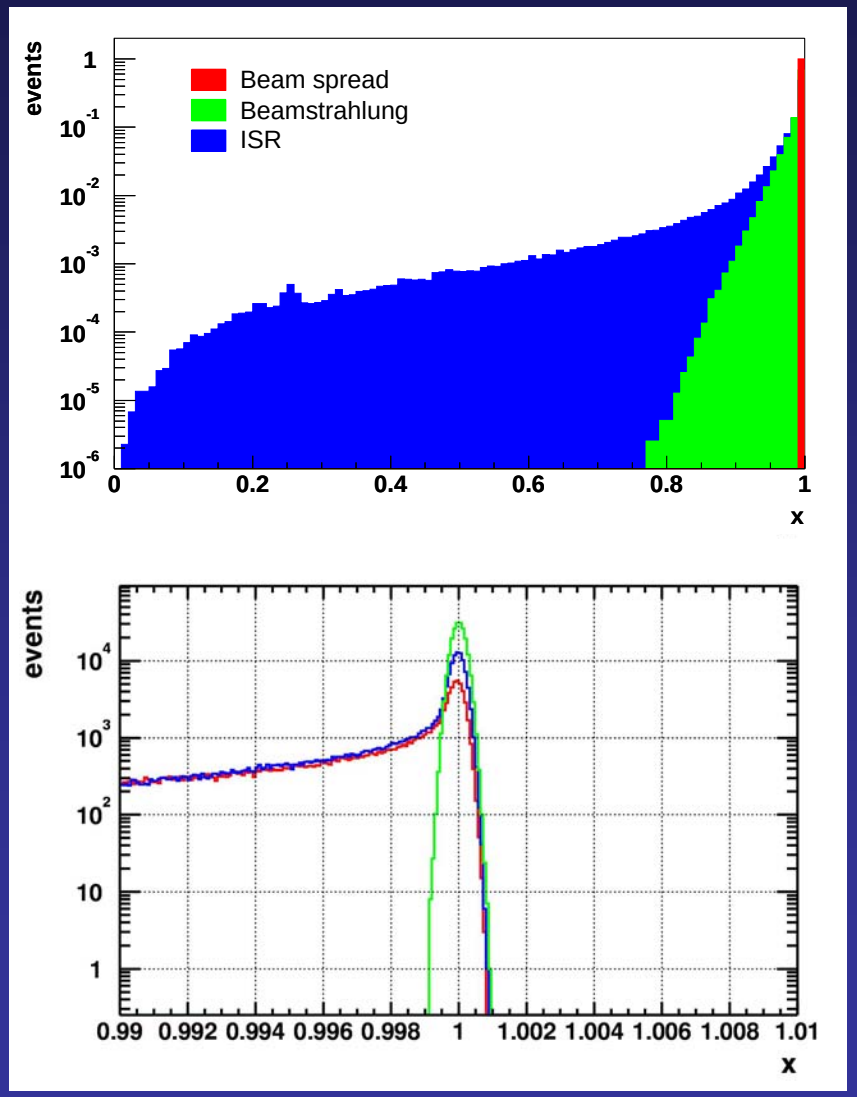


Outline

- The ILC detectors have to be designed and built such that they realize and maximize the physics output of the ILC
- What are the ILC challenges for the detector design?
- Outline:
  - ILC machine environment
  - ILC Physics environment
  - ILC Detector requirements based on physics requirements

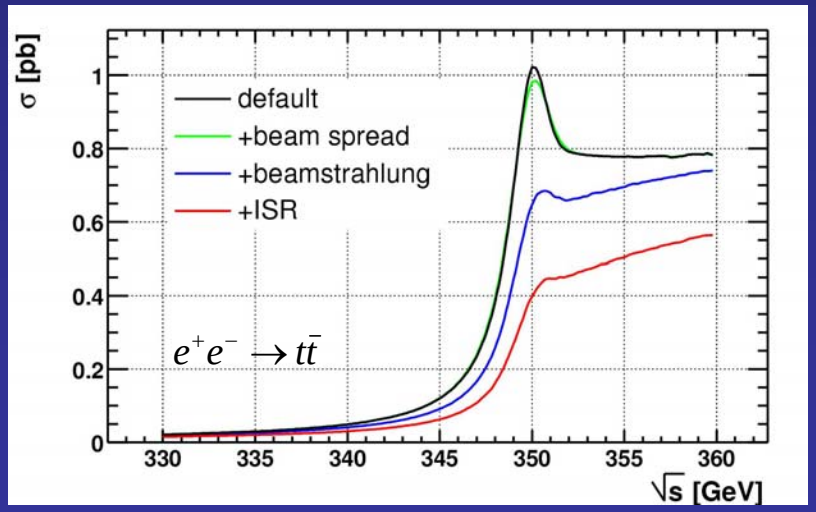
Challenges of the ILC

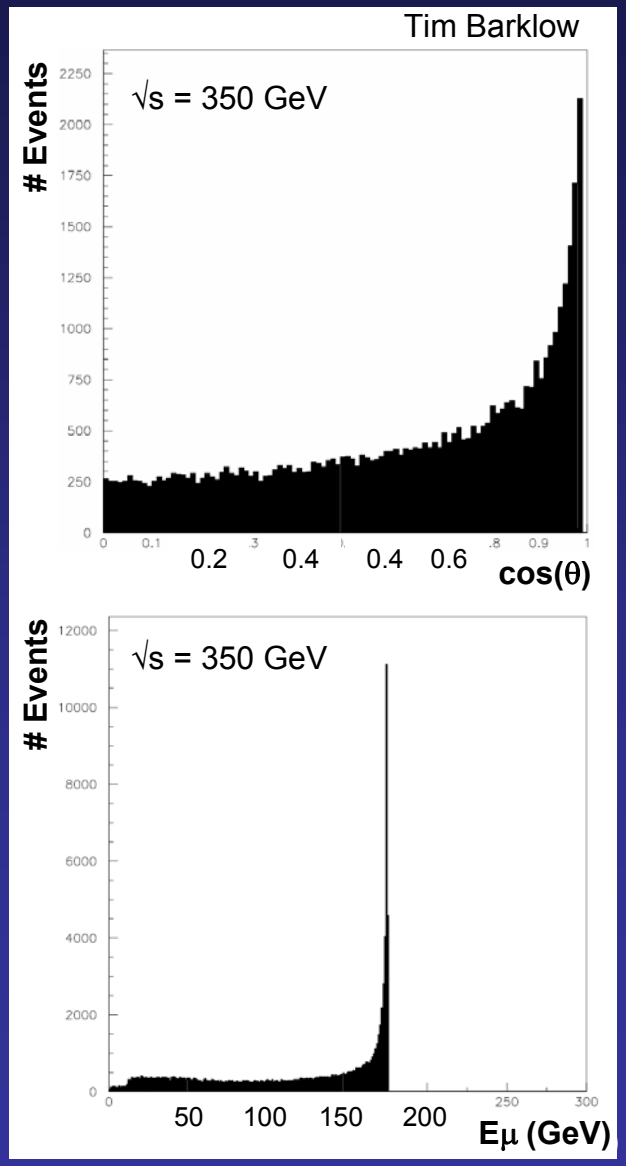
- Variation of the centre of mass energy, due to very high current, collimated beams: three main sources
  - Accelerator energy spread
    - Typically ~0.1%
  - Beamstrahlung
    - 0.7% at 350 GeV
    - 1.7% at 800 GeV
  - Initial state radiation (ISR)
    - Calculable to high precision in QED
    -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



E_{CM} Determination

- Center of mass energy requirements
  - Top mass: 200 ppm (Δm_t=35 Mev)
  - Higgs mass: 200 ppm (Δm_H=60 MeV; m_H=120 GeV)
  - Giga-Z program: 50 ppm
- Determine E_{CM} from $e^+e^- \rightarrow \mu^+\mu^-\gamma$
  - $e^+e^- \rightarrow \mu^+\mu^-\gamma \qquad at\ \sqrt{s} = 350\ GeV, \mathcal{L} = 100\ fb^{-1}$
  - Events predominantly forward
- Determination of the Luminosity spectrum
  - top-quark pair production threshold scan





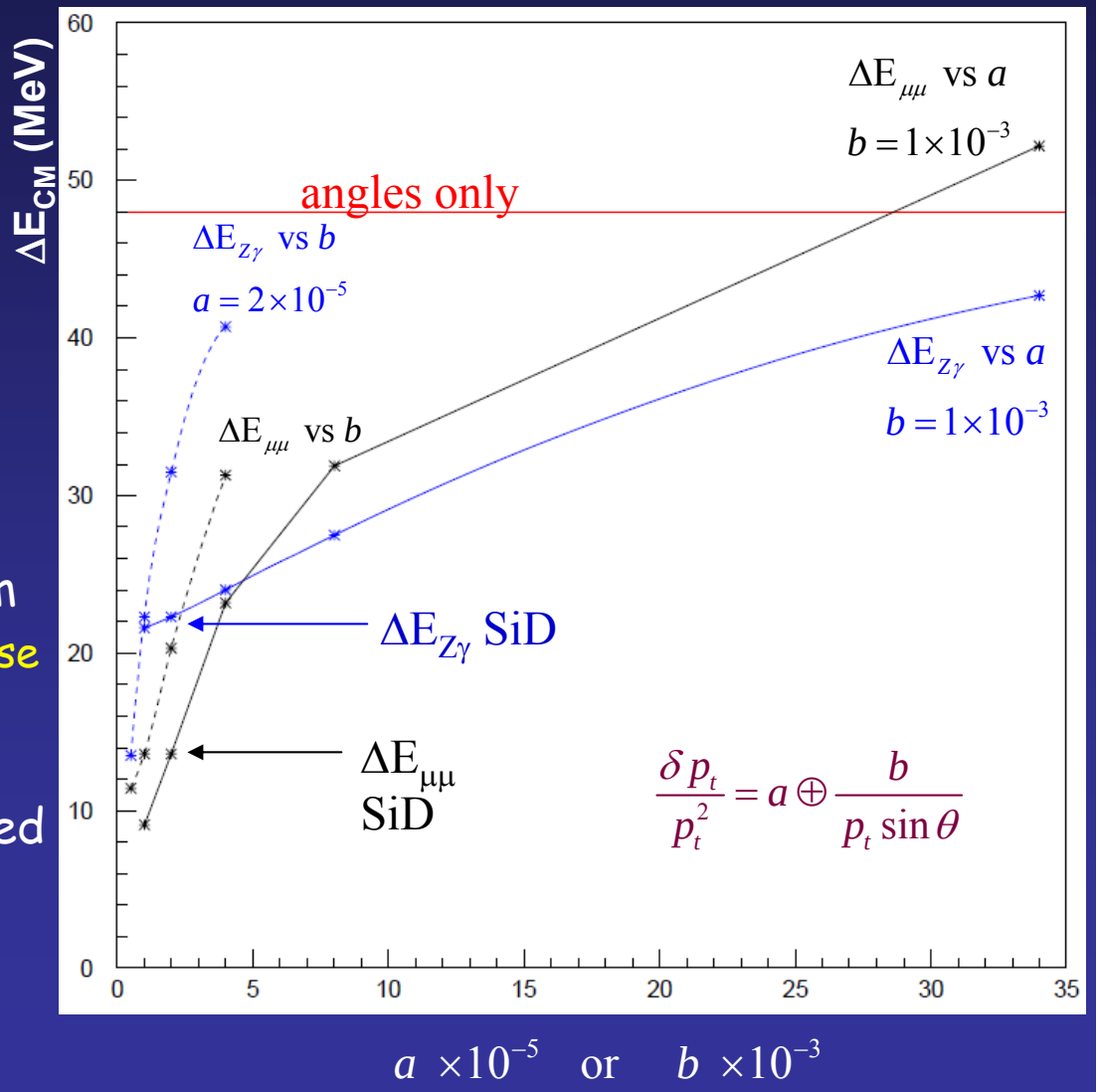
E_{CM} Determination

- Momentum resolution parametrization

$$\frac{\delta p_T}{p_T^{\,2}} = a \oplus \frac{b}{p_T \sin\vartheta}$$

- Three options considered
  - Angles from $\mu^+\mu^-$ only
  - $\Delta E_{Z\gamma}$: $Z\gamma \rightarrow \mu^+\mu^-\gamma$
  - $\Delta E_{\mu\mu}$: $e^+e^- \rightarrow \mu^+\mu^-$ with μ^+/μ^- each the full beam energy
- Large sensitivity to MS term
  - 40% increase for x2 increase in b.
- Good momentum resolution and low mass tracker required over full angular region

Tim Barklow



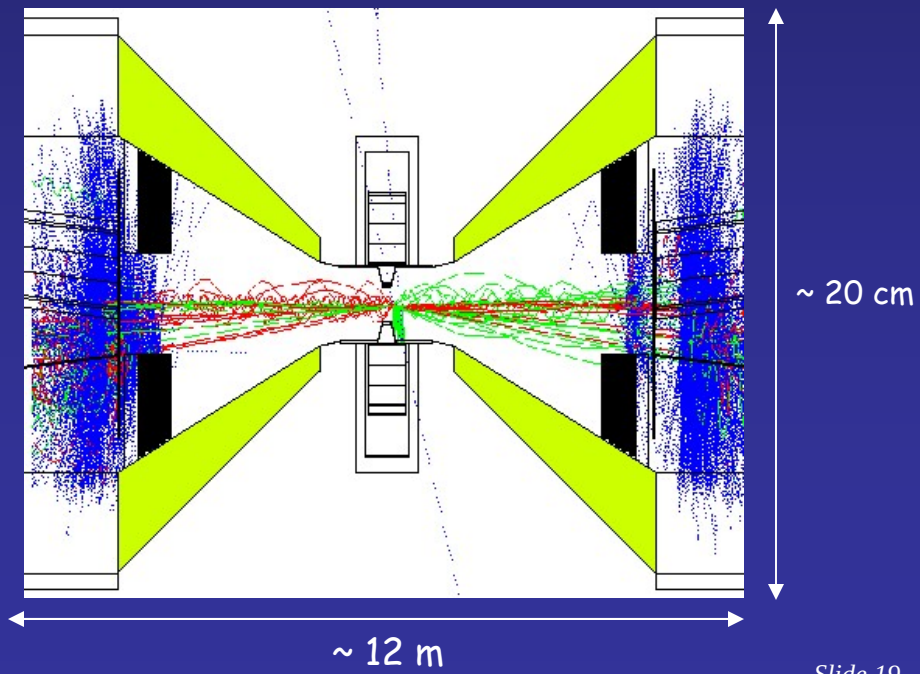
Backgrounds

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

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

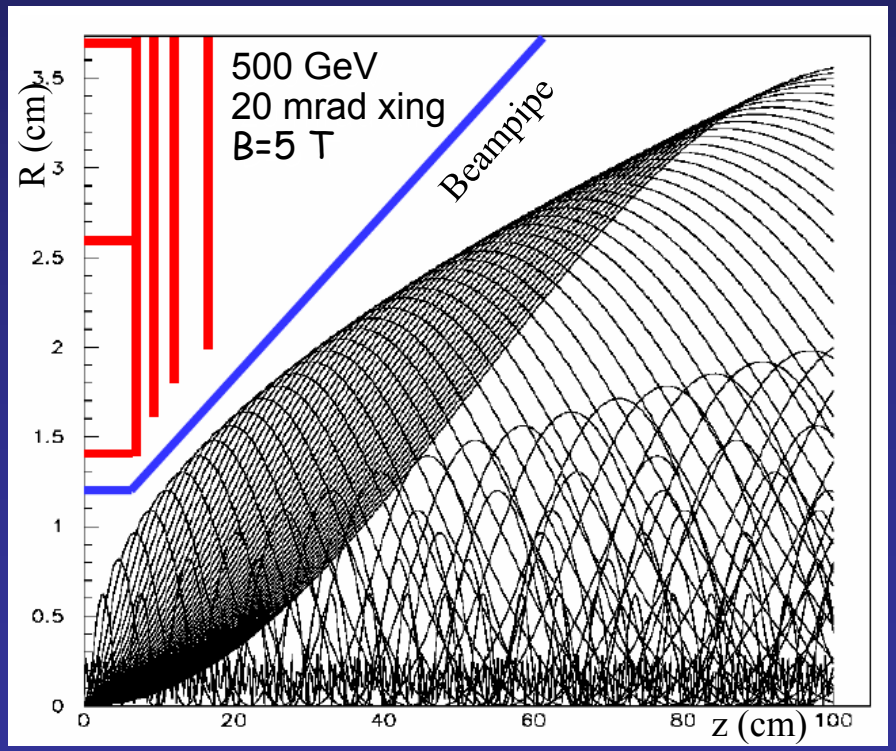
√s (GeV)	Beam	# e^+e^- per BX	Total Energy (TeV)
500	Nominal	98 K	197
1000	Nominal	174 K	1042

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



Beampipe Radius

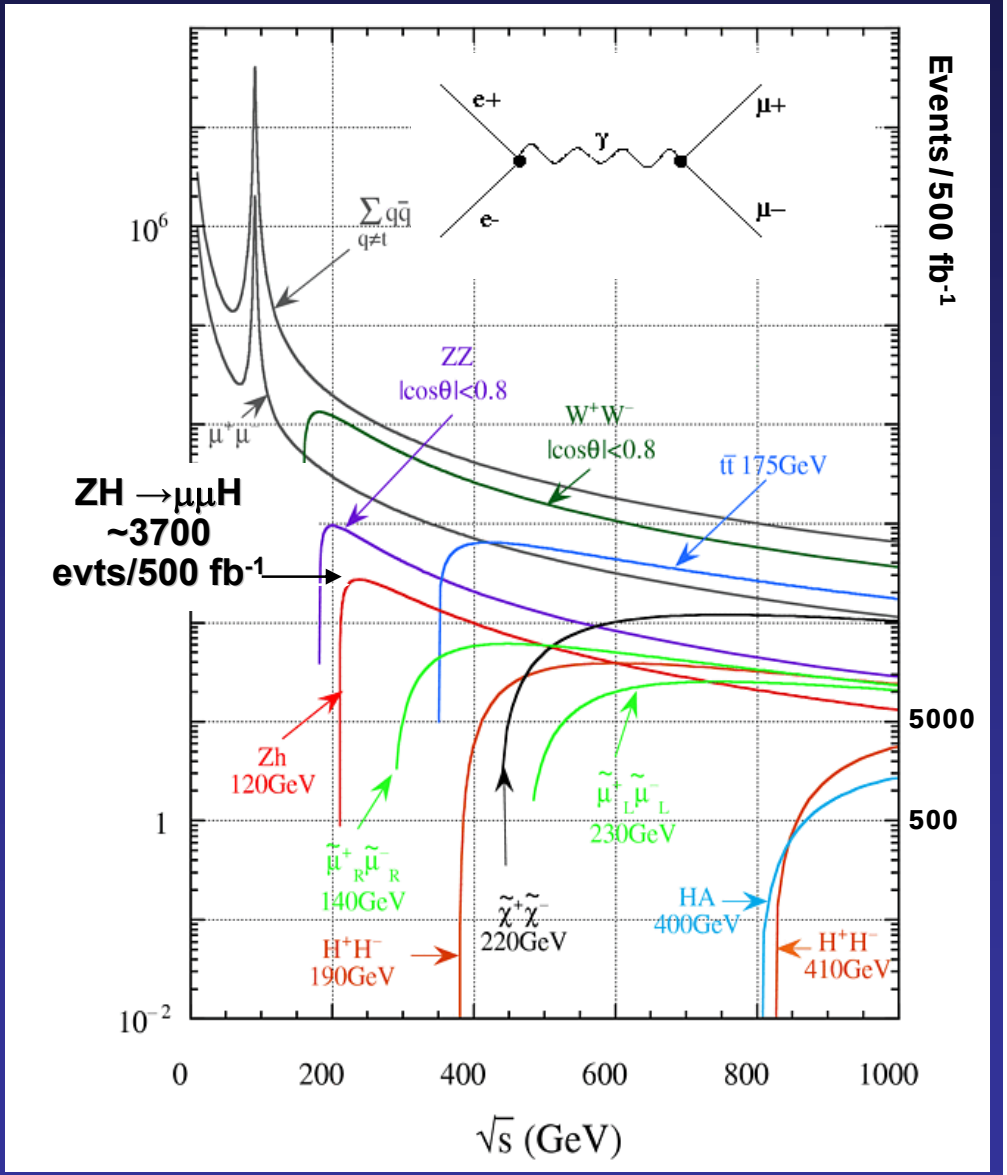
- Beampipe radius a critical parameter, which is determined by the background from e^+e^- -pairs
- Study of machine- tracker interface
  - Pairproduction envelope as function of z position along the beam axis



- Stay-clear for the soft e^+e^- pair background
  - $R \sim 1/\sqrt{B}$
- The closer the first detector layer is to the IP the better the vertexing
- Radius absolutely critical to do the physics one wants to do.

ILC Physics Characteristics

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

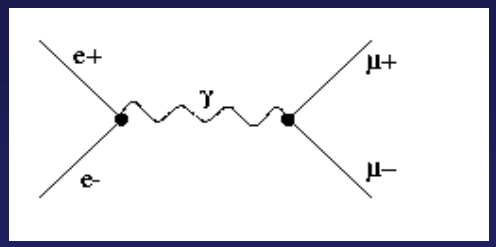


Polarization at the ILC

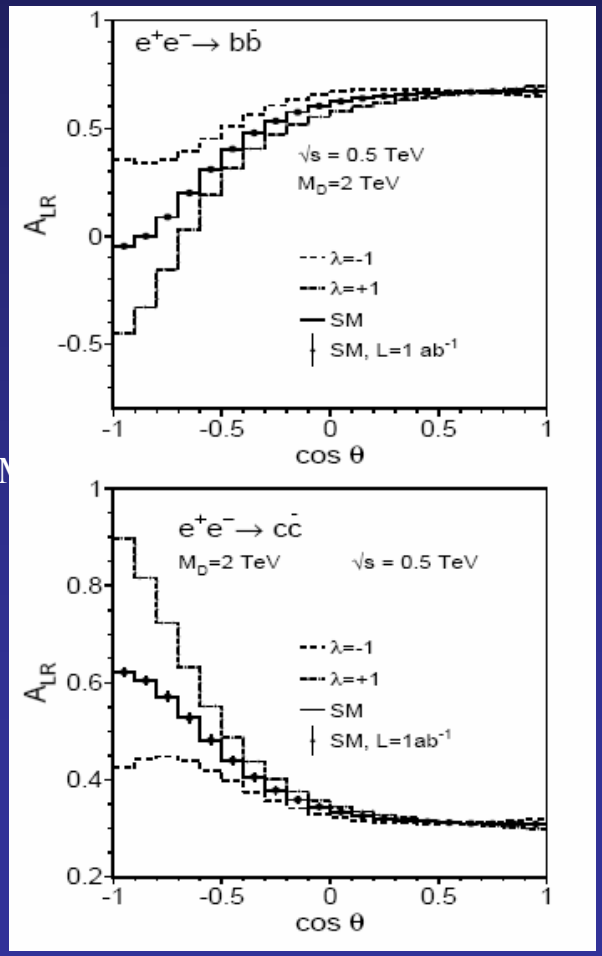
- Highly polarized e^- beam: ~ 80%

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

$$\mathcal{A}_f = \frac{2g_{Vf}g_{Af}}{g^2_{Vf}+g^2_{Af}} \qquad \mathcal{A}_b = 0.94 \quad \mathcal{A}_c = 0.67 \quad \mathcal{A}_l = 0.15$$

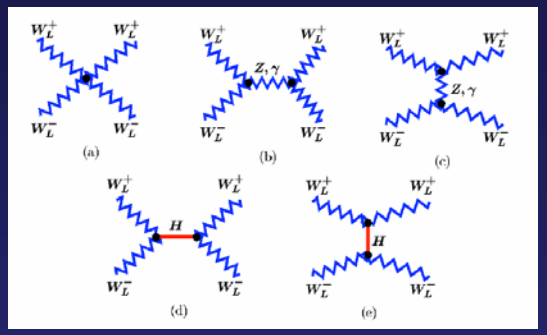


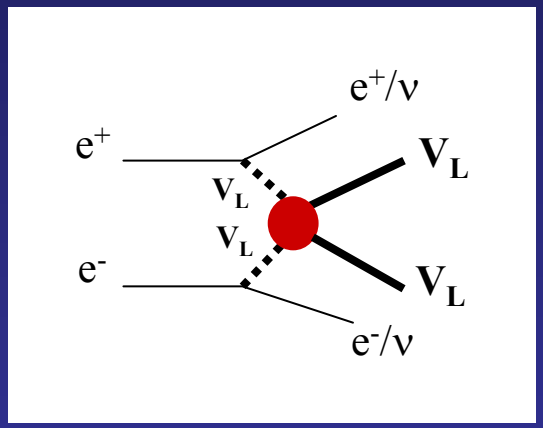
- Analyzing power of
  - Scan in center of mass energy
  - Various unique Asymmetries
    - Forward-backward asymmetry
    - Left-Right Asymmetry
  - Example: Model with extra dimensions
    - Coupling of graviton in 4-dimensions proportional to λ/M
    - Largest effects for b-quarks
      - $\sqrt{s}$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



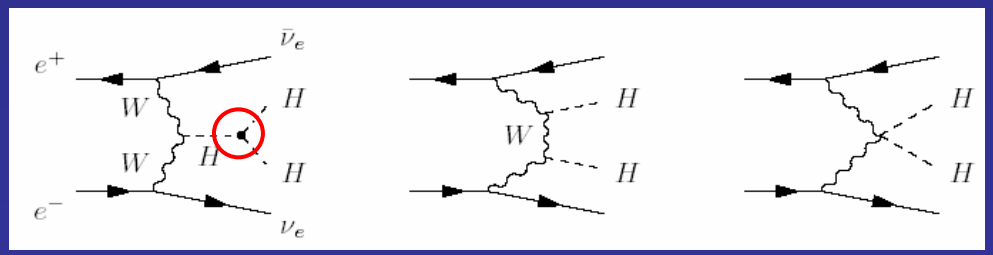
Precision EW Physics

- In the SM unitarity is conserved in the scattering of W_L through the Higgs mechanism
- Precise measurements of vector boson scattering can be indicative of strong EWSB
  - $e^+e^- \rightarrow WW\nu\nu$, $WZe\nu$ and $ZZ\nu\nu$ events
- Need to discriminate W- and Z-bosons, also in the hadronic decay mode
  - Separation of W and Z at 3σ level !
  - Requires jet energy resolution of 3% ($\delta m/m \approx \delta E/E$)





- Note the similar signatures for the measurement of the Higgs self-coupling
- Both areas of physics unique to the ILC



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

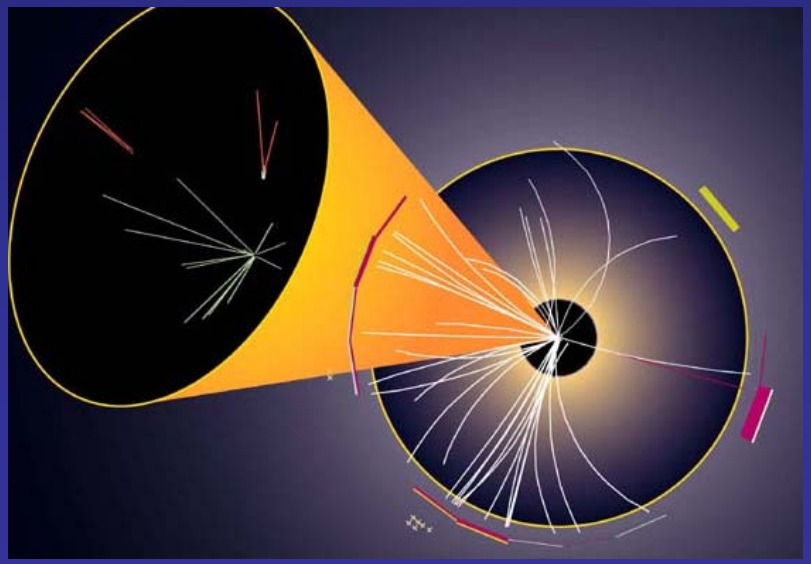
$$\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$$

- 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

Summary ILC Detector Requirements

- In brief, the ILC detectors are precision detectors
  - Identify each and every particle
  - With high efficiency and high purity
  - Over the full angular range

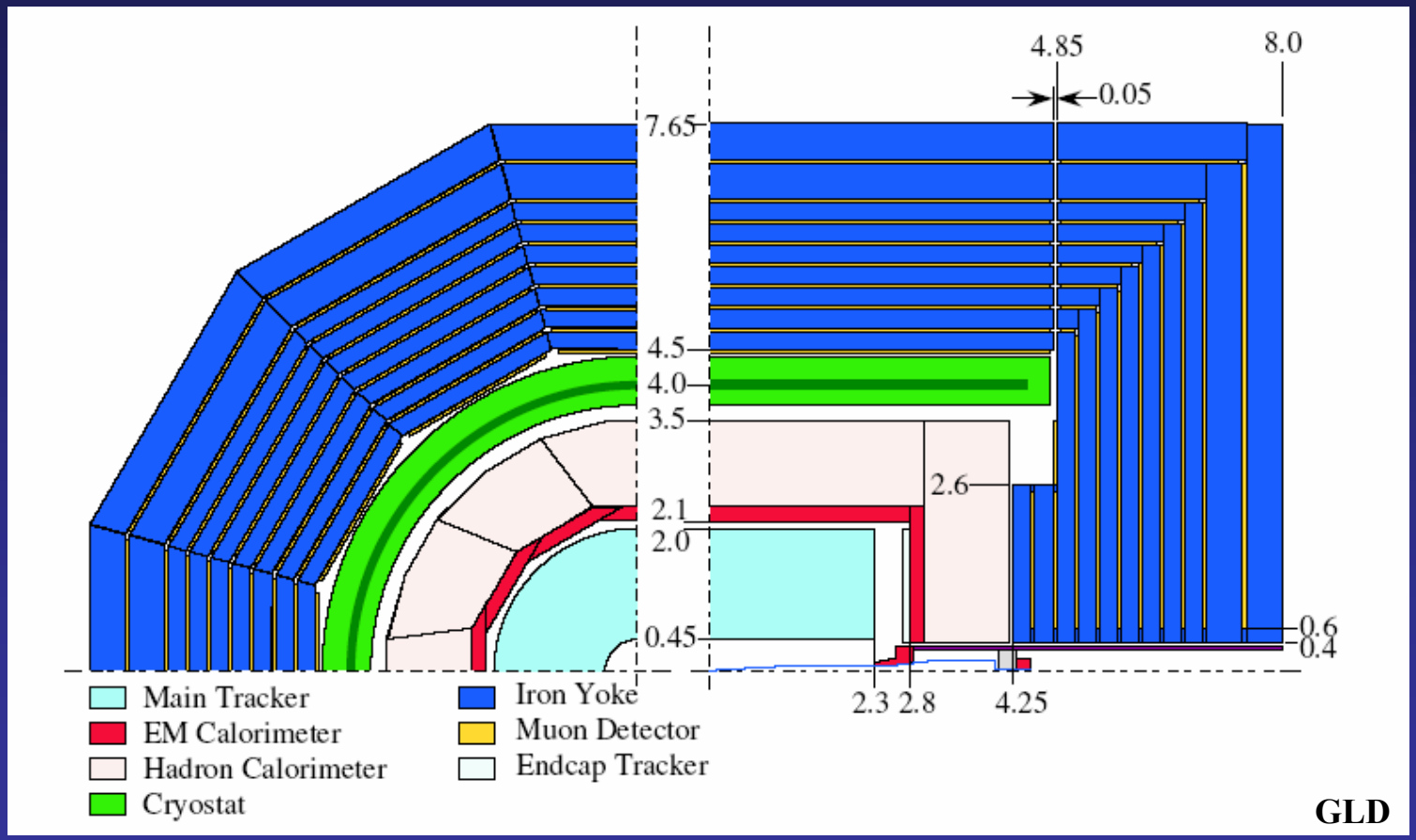
  - Examples:
    - Differentiate between Z's and W's in their hadronic decay
    - Differentiate between b- and c-quarks
    - Differentiate between b quark and anti-b quark



ILC Detectors

ILC Detector Overview

- Overall layout of the detectors in principle not very different from collider detectors at the Tevatron



- Solenoid is outside ECAL + HCAL in all cases ➔ needed for jet energy resolution
- Hermetic detectors with very far forward coverage

Four ILC Detector Concepts

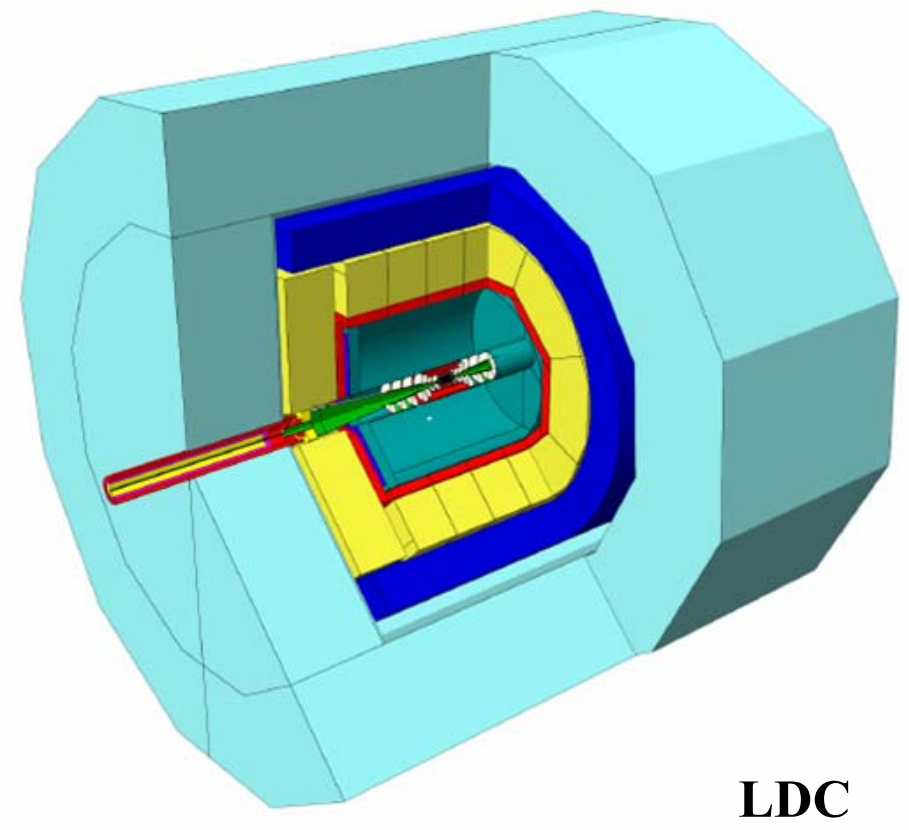
- LDC - Large Detector Concept
  - Evolved from the TESLA project
  - http://www.ilcldc.org/
- GLD – Gaseous Large Detector
  - Accompanied the JLC design
  - http://ilcphys.kek.jp/gld/
- SiD - Silicon Detector
  - Accompanied the NLC machine concept
  - http://www-sid.slac.stanford.edu/
- 4th concept
  - Didn't like the other three concepts in certain areas and proposed their own
  - http://www.4thconcept.org/

- Each detector is viewed as single fully integrated system, not a collection of different subdetectors

- For more details, see the Detector Outline Documents (DOD), submitted by each of the four detector concept groups.

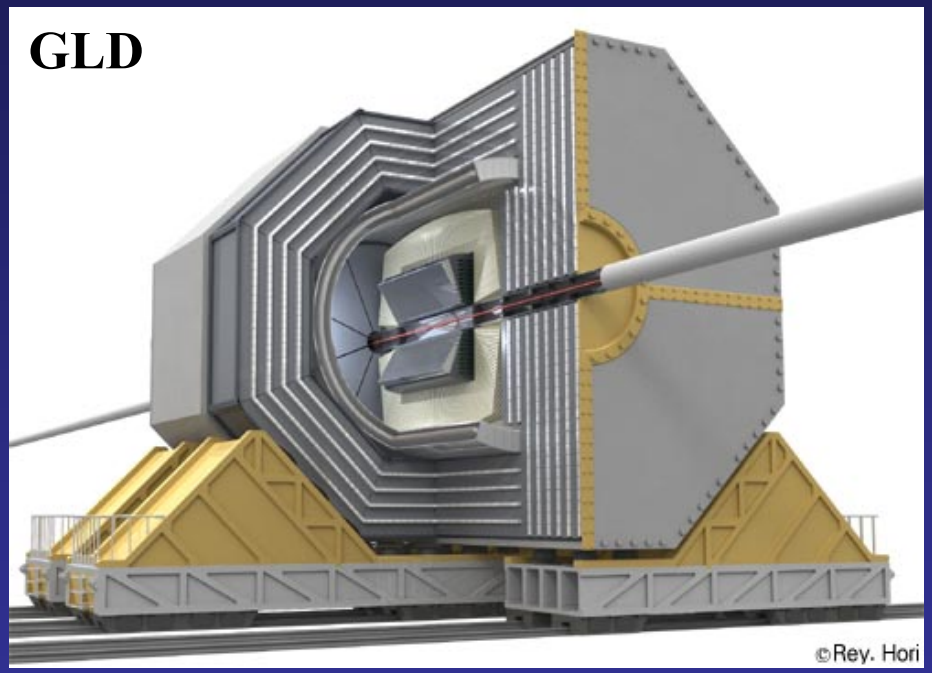
LDC Concept

- Design philosophy
  - Based on the premise of Particle Flow Calorimetry
  - Fine resolution calorimeter for particle flow
    - Si-W for ECAL
    - Analogue scintillator based HCAL
  - Gaseous tracking for high tracking efficiency and redundancy
  - Large radius of TPC (30 – 150 cm) and high B-field (4T) for required momentum resolution and Particle Flow



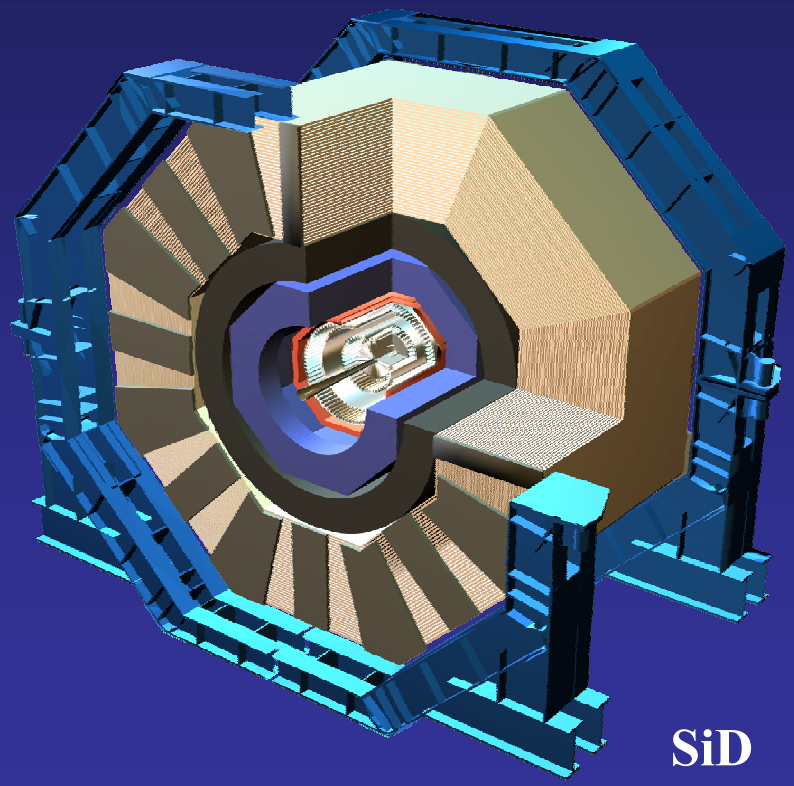
GLD Concept

- Design philosophy
  - Based on the premise of Particle Flow Calorimetry
  - Fine grained scintillator-W calorimeter
  - Gaseous tracking for high tracking efficiency and redundancy
  - Largest radius for TPC (45 – 200 cm) and moderate B-field (3T) for required momentum resolution and Particle Flow



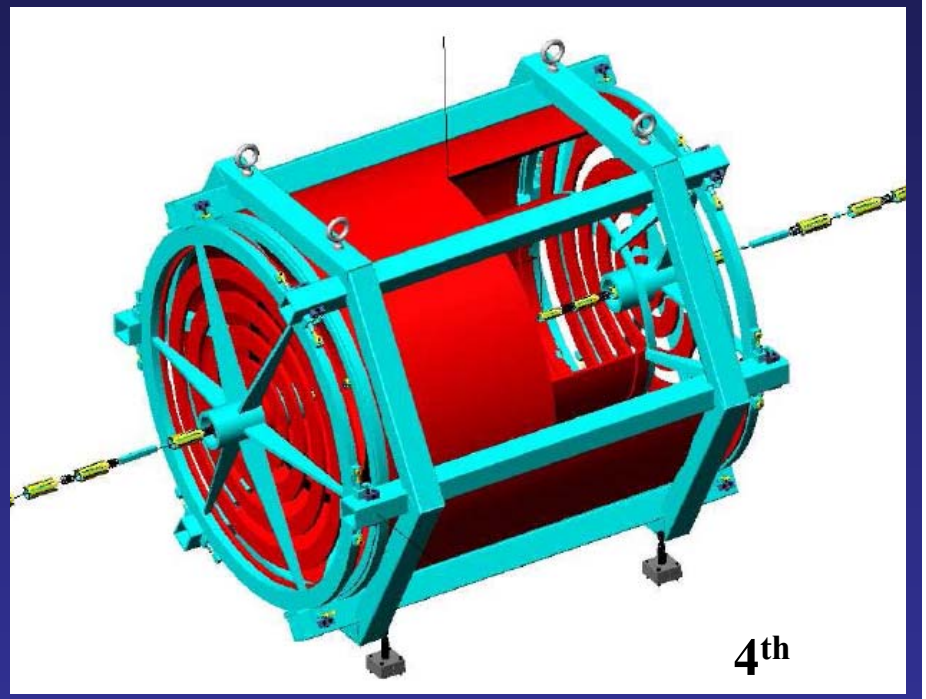
SiD Concept

- Design philosophy
  - Based on the premise of Particle Flow Calorimetry
  - Fine resolution calorimeter for particle flow
    - Si-W for ECAL
    - Digital calorimetry for HCAL
  - Limit calorimeter radius to constrain the costs; Boost B-field to maintain BR^2 allow for smallest possible beampipe radius
  - Si tracking system for best momentum resolution and lowest mass
  - Highest B-field (5T) for required momentum resolution and Particle Flow



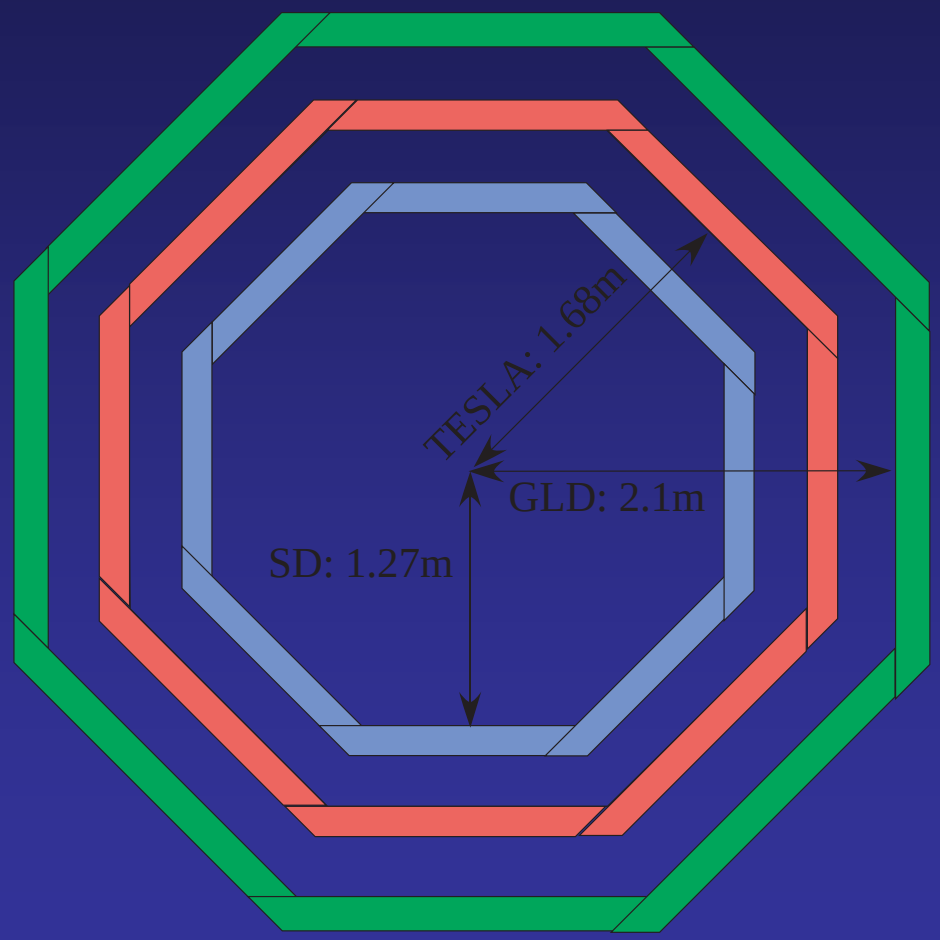
4th Concept

- Design philosophy
  - Not based on the premise of Particle Flow Calorimetry
  - Dual-readout or triple-readout calorimeter
  - Gaseous tracking for high tracking efficiency and redundancy
  - Modest radius and modest B-field for required momentum resolution
  - Open dual solenoid geometry without iron flux return



Relative Detector Size

- Radius of front plate of EM calorimeter for three of the detector concepts



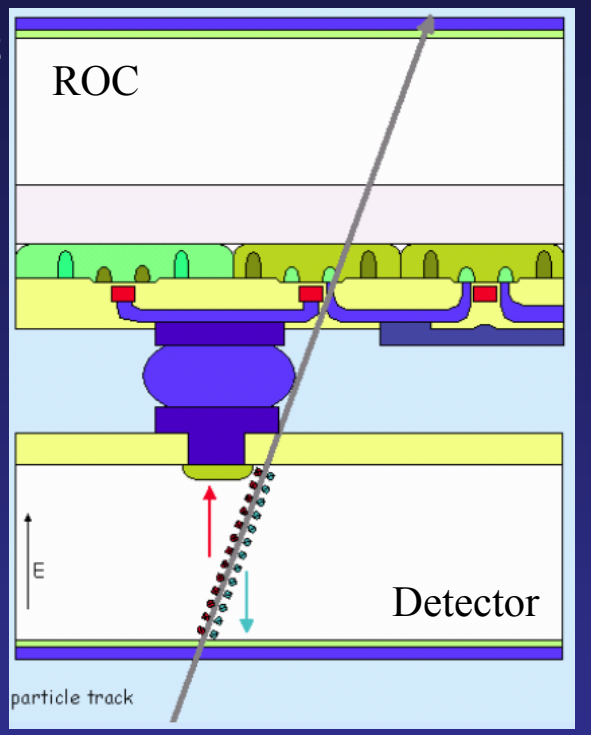
Detector Concepts Overview

Detector	Premise	Vertex Detector	Tracking	EM calorimeter	Hadron calorimeter	Solenoid	Muons
LDC	PFA	5-layer silicon pixel	TPC gaseous	Silicon-Tungsten	Analog-scintillator	4 Tesla	Instrumented flux return
GLD	PFA	6-layer fine pixel ccd	TPC Gaseous	Scintillator -Tungsten	Digital/Analog Lead scintillator	3 Tesla	Instrumented flux return
SiD	PFA	5-layer silicon pixel	Silicon strips	Silicon-Tungsten	Digital Steel - RPC	5 Tesla	Instrumented flux return
4th	Dual Readout	5-layer silicon pixel	TPC gaseous	Dual/triple -readout Crystal	Dual/triple-readout Tungsten-fiber	3.5 Tesla	Iron free dual solenoid with drift tubes

Vertex Pixel Detectors

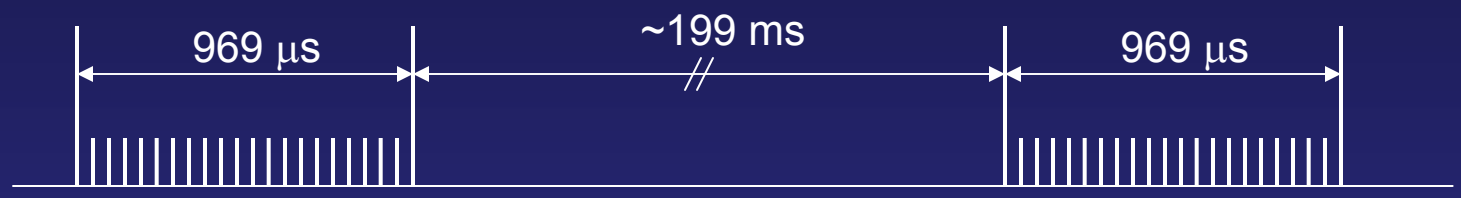
Why LHC Pixel Sensors Fall Short ?

- All LHC pixel detectors are hybrid pixel detectors: Separate detector and readout chip, connected by bump bonds
  - sensor and read-out chip (roc) can be optimized separately
- Issues with this technology:
  - At least twice the mass of the detector since the readout chip is as thick as the silicon sensor
  - Power consumption in the chip is high
  - Need active cooling of detectors
  - Bump bonding is very expensive
  - Pixel size is too large
    - CMS pixel size is 100x150μm^2 = 15,000 μm^2
    - Atlas pixel size is 50x400μm^2 = 20,000 μm^2
    - ILC need ~ 20x20μm^2 = 400 μm^2
    - Area LHC/ILC = 50



Pixel Sensors: The Challenge

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



- What readout speed is needed ?
  - Inner layer ~2M Pixel sensors; Background hits significantly in excess of 1/mm^2 will give pattern recognition problems
    - Once per bunch = 369ns per frame : *too fast*
    - Once per train ~100 hits/mm^2 : *too slow*
    - 5 hits/mm^2 => 50μs per frame: may be tolerable
  - Note: fastest commercial imaging ~ 1ms / MPixel

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

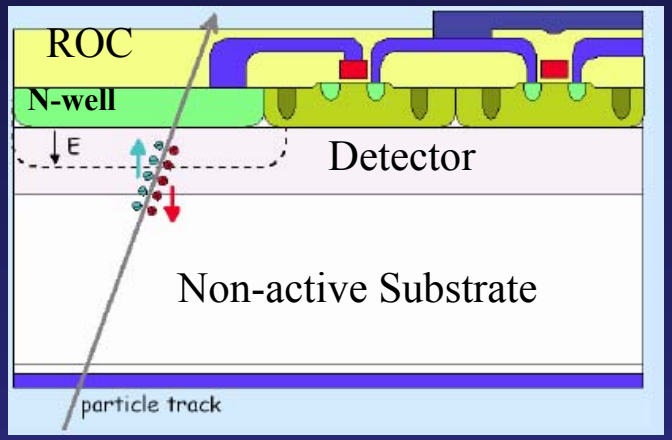
- Overall pixel detector has about 1 Giga pixels !

Pixel Sensors

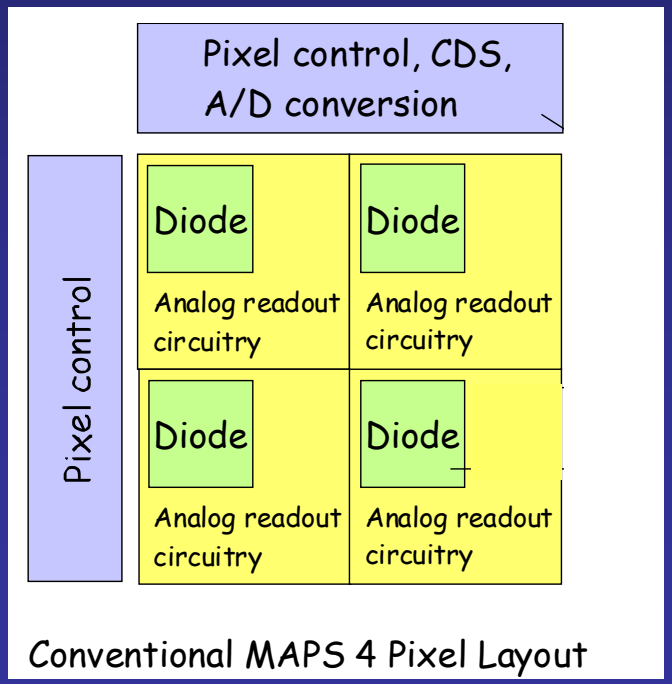
- Pixel detectors (for the ILC) are very difficult
  - Good angular coverage with many layers close to vertex
  - Excellent point resolution (< 4 μm)
  - Superb impact parameter resolution ($5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$)
  - Transparency (~0.1% X_0 per layer)
  - Robust pattern recognition (track finding in vertex detector alone)
  - Integration over small number of bunch crossings (<150 = ~50 μs)
  - EMI immunity; Power Constraint (< ~100 Watts)
- Issues being addressed through low mass approaches
  - Reduce mass using alternate materials
  - Reduce power so less mass is needed to extract heat
- Significant progress has been made to address these issues by integrating sensors and front end electronics within the pixel cell: Monolithic Active Pixel Sensors (MAPS)
  - Readout during bunch trains
    - CCD's: FPCCD, SCCCD, CPCCD
    - MAPS, DEPFET, SOI …
  - Readout between trains
    - FAPS, ISIS, 3D

MAPS

- MAPS is a generic name for a silicon structure where the detector and the primary readout electronics are all processed on the same substrate: Monolithic Active Pixel Sensor
  - Signals generated in the epitaxial layer
    - Few microns thick, small signals
  - Charge collection through diffusion
    - Device not depleted, relatively long collection time
- Many different monolithic designs being pursued at different locations



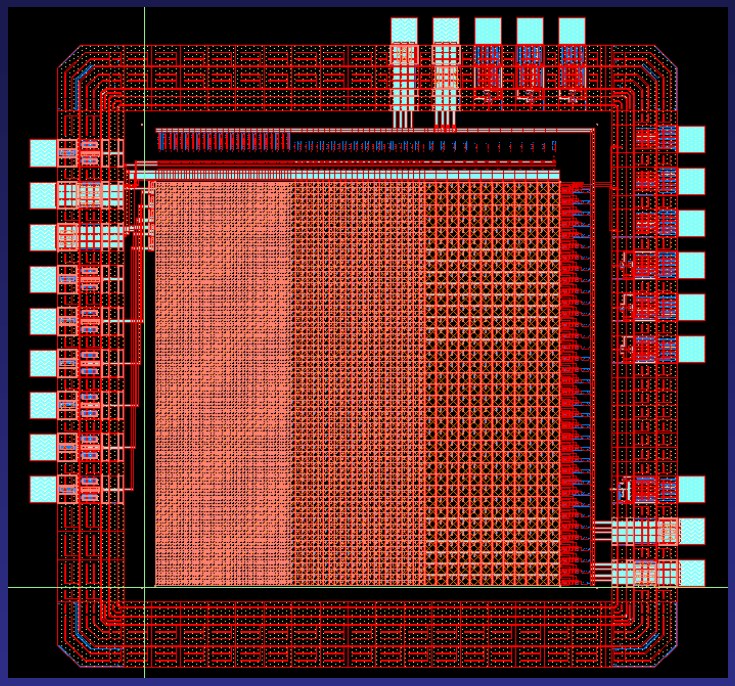
MAPS Principle



Conventional MAPS 4 Pixel Layout

MAPS

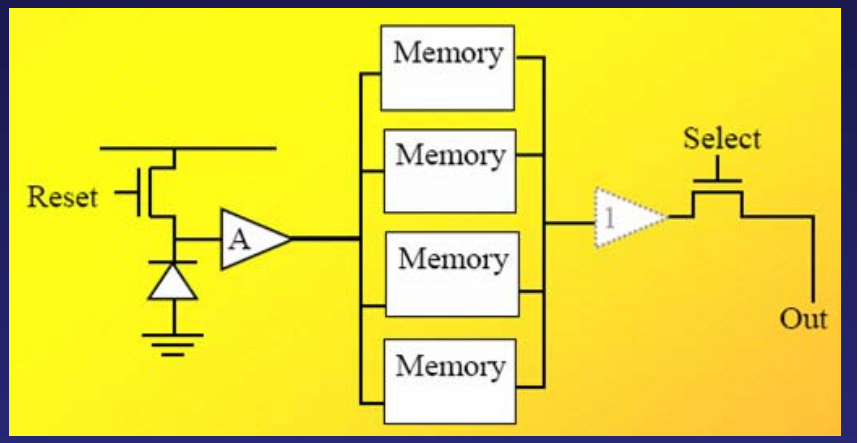
- LBNL effort: CMOS pixel test structure
  - 0.35 μm OPTO AMS prototype, 3-T pixels
  - serial analog readout
  - Three pixel geometries
    - 40x40 μm pixels
    - 20x20 μm pixels
    - 10x10 μm pixels
  - Extensive bench testing
    - Hit resolution, radiation hardness
    - Charge collection uniformity
    - S/N characterization



- Follow up submissions
  - In-pixel Correlated Double Sampling (CDS)
  - Various diode sizes and option of rolling shutter for read out at high rate
  - Include 4-bit fast ADCs on the chip periphery

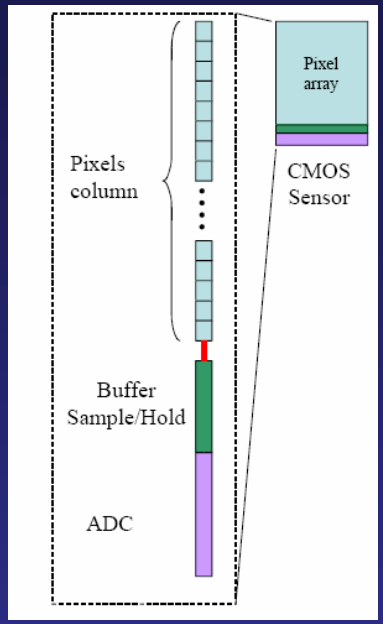
FAPS

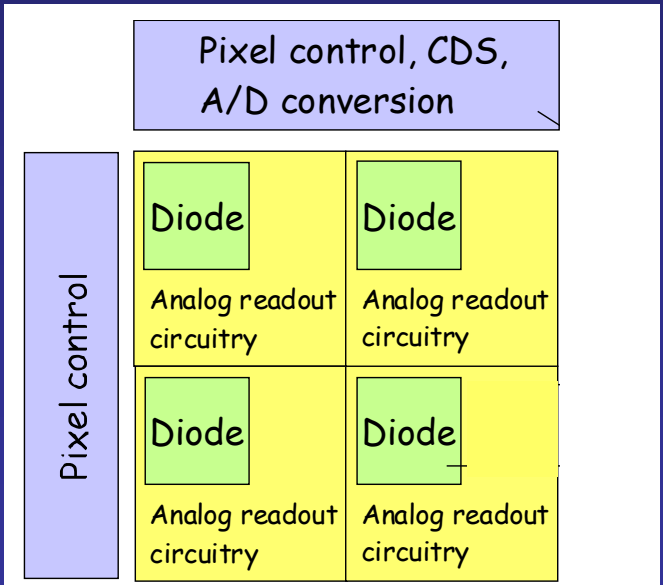
- Flexible Active Pixel Sensors
- Basic pixel architecture is a 3 transistor cell
  - Signal created in epitaxial layer
  - Signal stored in memory cells
  - pixel size: 20x20 μm^2
  - 36 transistors/pixel
  - TSMC 0.25 μm process
  - Correlated Double Sampling (CDS)



MAPS Devices

- Principle strategy is to implement as much intelligence in the pixel as possible
  - But, space for logic is shared with space for the detector
- Transfer data to the periphery as fast as possible
- Add first level data processing on the periphery



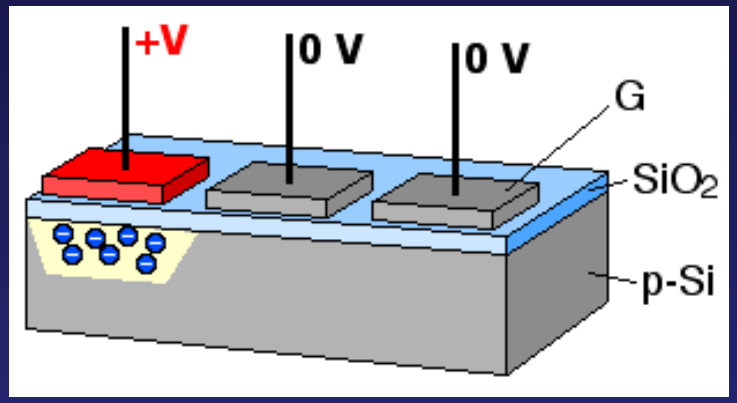


Conventional MAPS 4 Pixel Layout

- Fundamental Limitations of MAPS devices
  - Small signal dependent on epi thickness
  - Most designs are limited to NMOS transistors
  - Slow rise time set by diffusion
  - Uniformity of signal response
  - Periphery adds dead areas and mass
  - Not 100% fill factor

Charge-Coupled Devices – CCD's

- A CCD is an integrated circuit containing an array of linked - coupled - capacitors.
- Thin epitaxial layer of silicon is normally active area of the sensor
- Each capacitor can transfer its electric charge to its neighbors through a "buried channel"
- Under the control of an external circuit, applied voltage is used to create potential wells which move the charge to the end of an array to the read out at the perimeter

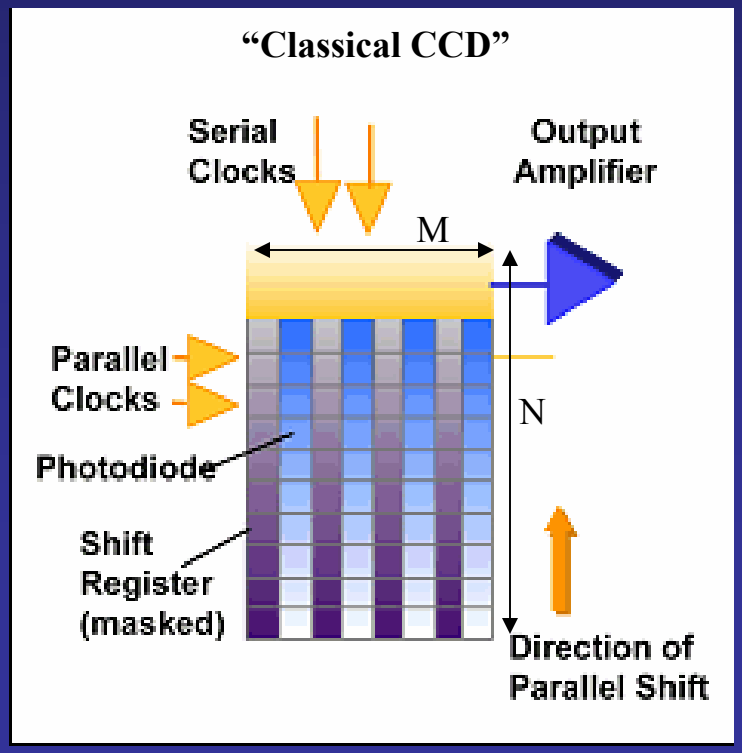


- Classical CCD readout: "rolling shutter"
  - Readout time is: $N \times M / f_{ext}$

    N = number of rows

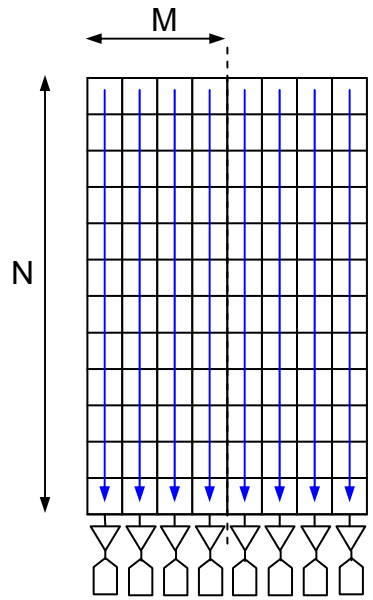
    M = number of colums

    f_{ext} = external readout frequency



Column Parallel CCD

- Idea for CP-CCD is simple: read out a vector instead of a matrix
  - Readout time shortened by orders of magnitude
- But: every column needs its own amplifier and ADC
  - Requires readout chip
  - Need to operate at 50 MHz to meet ILC readout rate spec.
  - 20 Amp clock current; driving of CPCCD is a major challenge

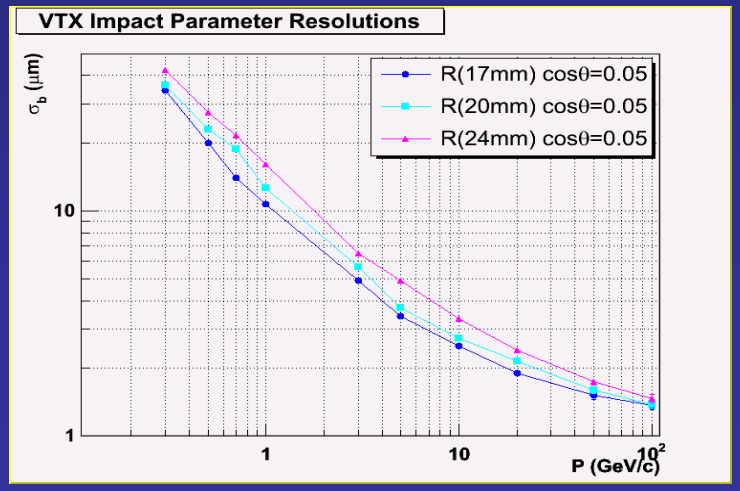


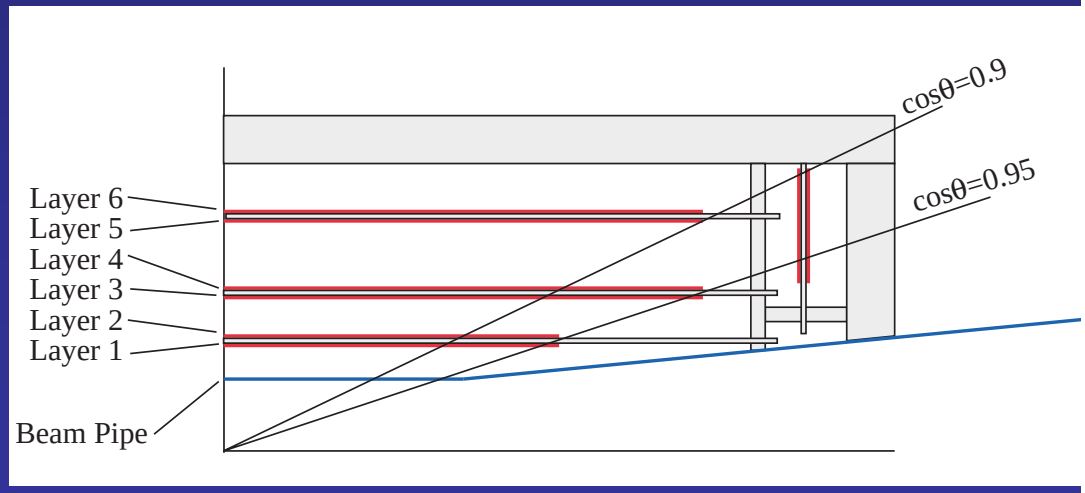
Column Parallel CCD
Readout time = N/f_{out}

- Prototype being developed
  - 20 μm x 20 μm pixel size
  - Separate amplifier and readout for each column, compared to 'rolling shutter'
  - Designed for 50 MHz clock speed
    - Second generation will have symmetric clock
- Note: readout clock of 50MHz still moves charge 2500 times in 50 μs
  - 2500 x 20 μm = 5mm

Fine Pixel CCD

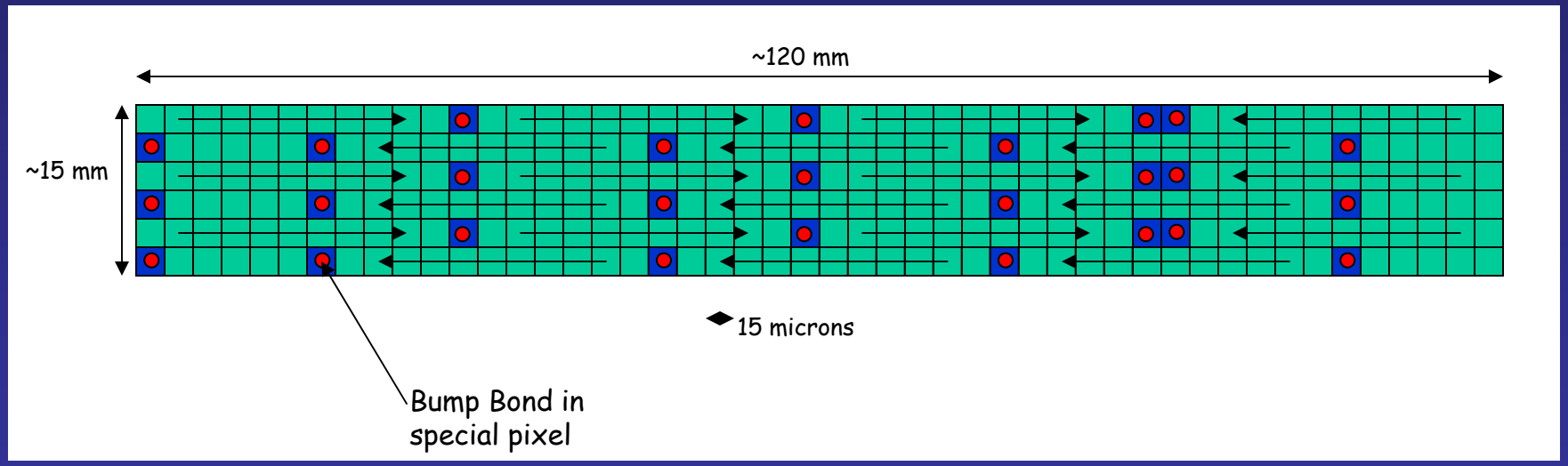
- Baseline for GLD detector concept
- Idea: make ultra fine pixels: 5μmx5μm
- Accumulate 1 train and readout between trains
  - Background rejection by cluster shape and hit pattern (~1/20)
- Three doublets = 6 layers in the barrel region plus one doublet in the forward region
- Three options for the inner radius: R = 17, 20 and 24 mm



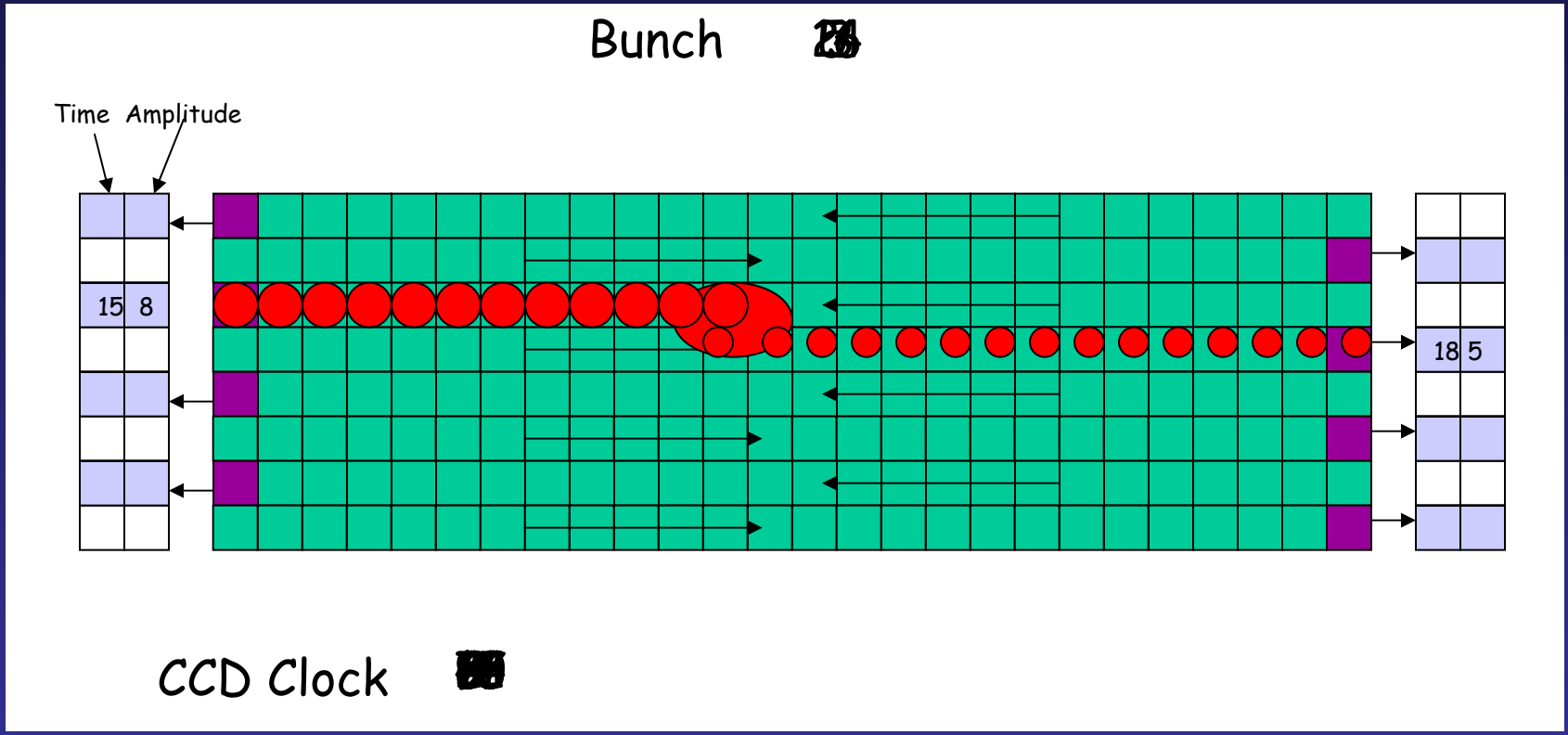


Short Column CCD

- Idea is to make CCD's with short columns ~512 pixels and no rows
- CCD design:
  - Charge sharing across columns
  - Adjacent columns move in opposite directions
  - 15 micron pixels, 3 clocks/bunch (~10 MHz)
  - ~500 pixels in a column to have satisfactory background rejection.



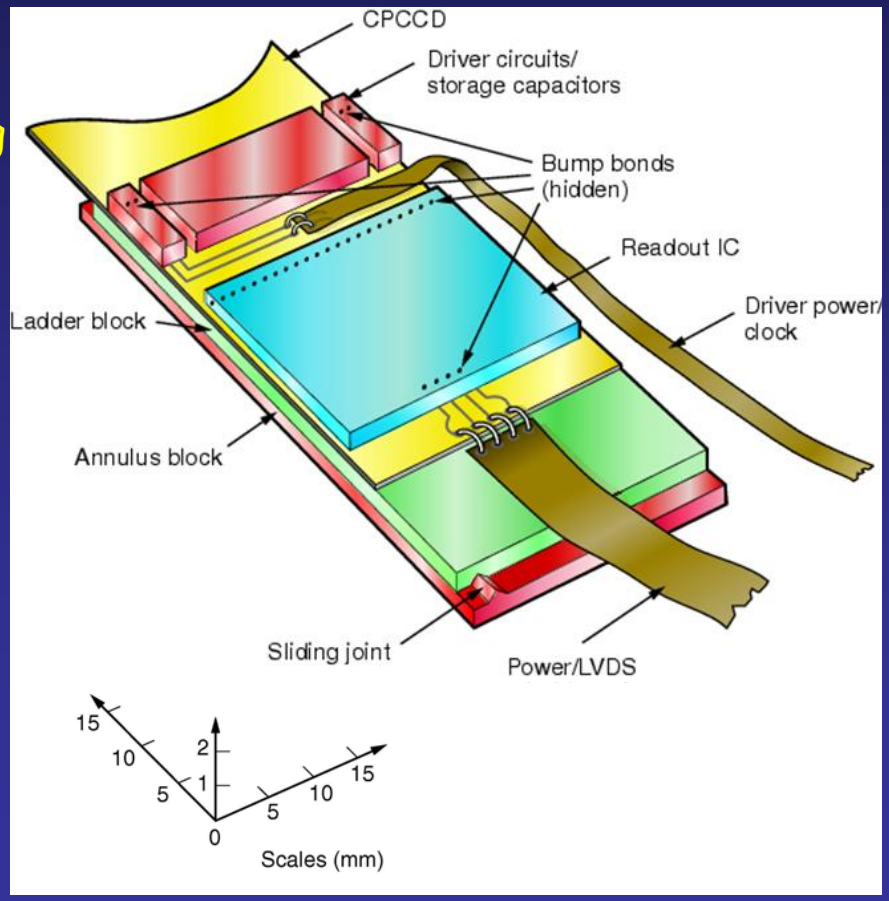
Short Column CCD



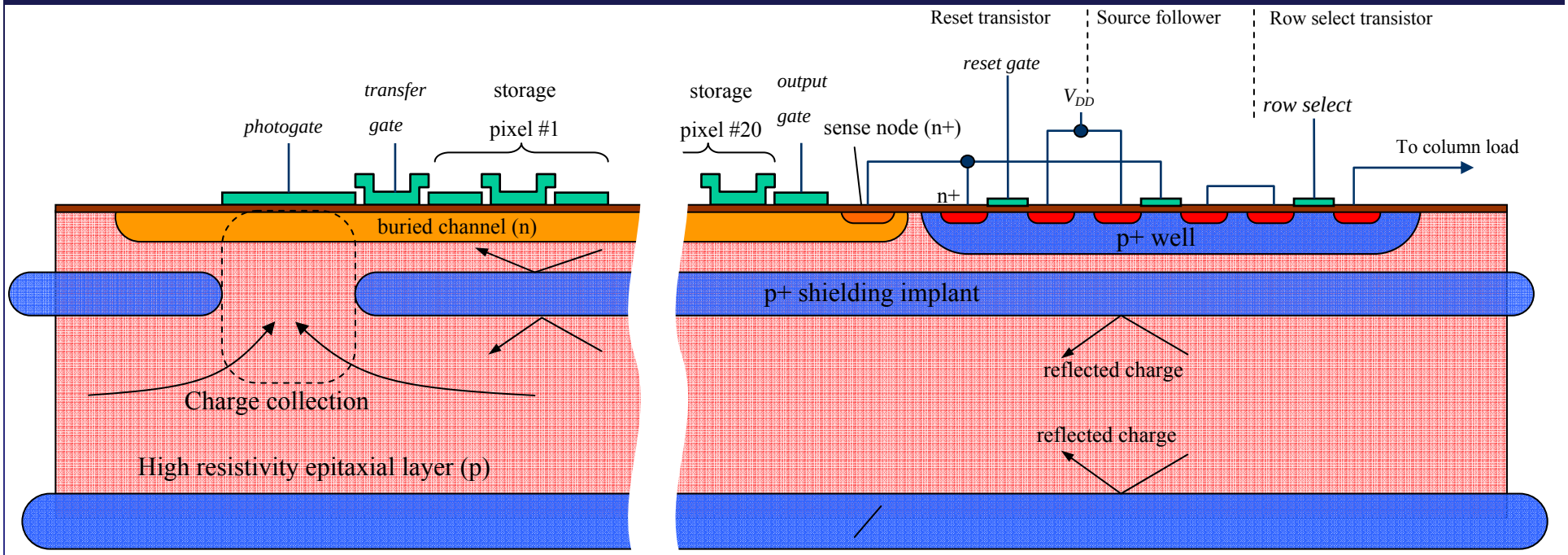
- Utilizes CCD correlation of position with bunch twice to "solve" for position and bunch time; requires charge sharing
- Reduced number of readout cells by CCD column length, ~100
- Clock CCD at ~10 MHz, cf 50 MHz for CPCCD

CCD Devices

- Simple CCD solution – integrating through train and reading out in the intertrain period – does not work: too much confusion to untangle.
  - Japanese FPCCD might be exception
- Any alternative CCD option needs
  - Large drive power for readout during the train
  - Additional electronics to process data coming off the chip
- A lot of material in active tracking volume, especially with readout electronics at the periphery



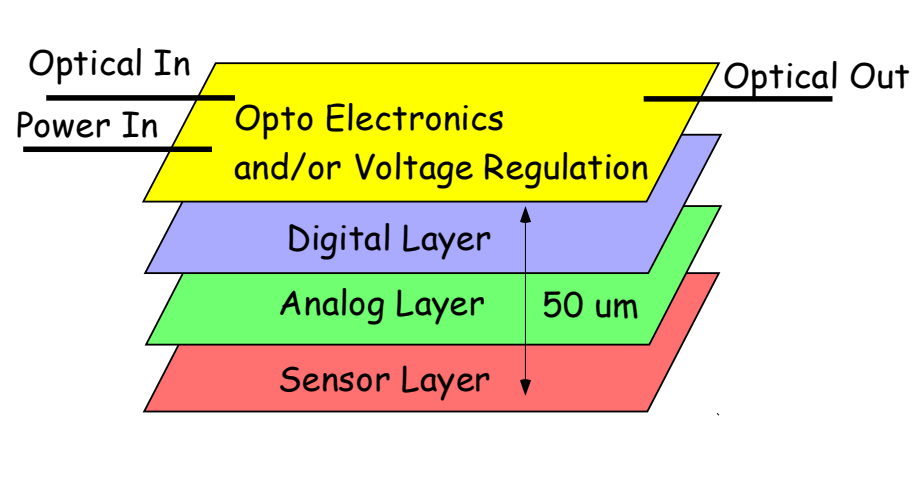
In-Situ Storage Image Sensors



- For ISIS sensors, charge is collected onto a photogate from epi-taxial Si layer as in a conventional CCD
- Each pixel has its own 20-cell CCD register : store raw charge during collisions with inter-train readout
- Increased resistance to Electromagnetic Interference (EMI)
- Column-parallel readout during quiet time at ~1 MHz: much reduced clocking requirements

Vertical Scale Integrated Circuits (3D)

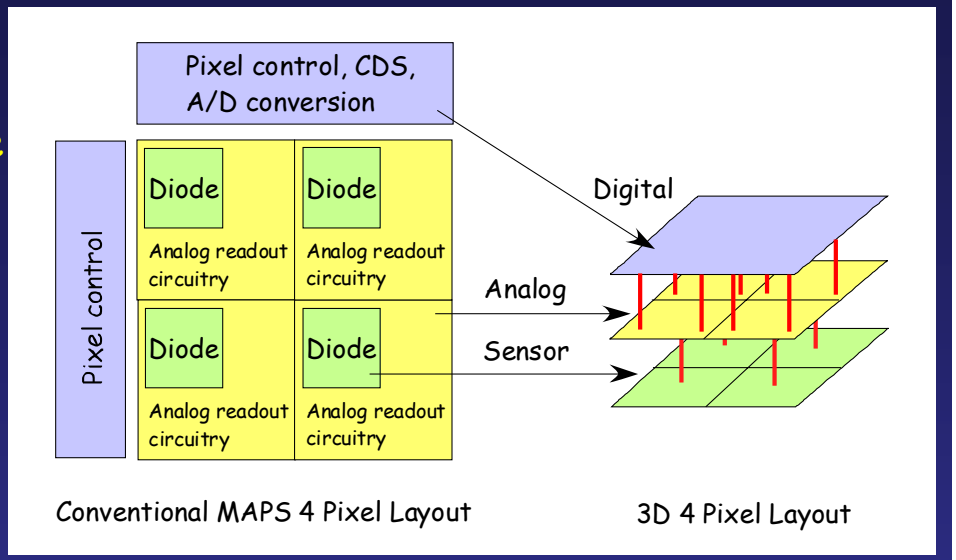
- Fermilab is pursuing a completely alternative approach – 3D –, which we believe holds most promise. Currently the only institution world-wide following this technology
- A 3D device is a chip comprised of 2 or more layers of semiconductor devices which have been thinned, bonded, and interconnected to form a monolithic circuit
  - Layers can have devices made in different technologies
    - Process optimization for each layer

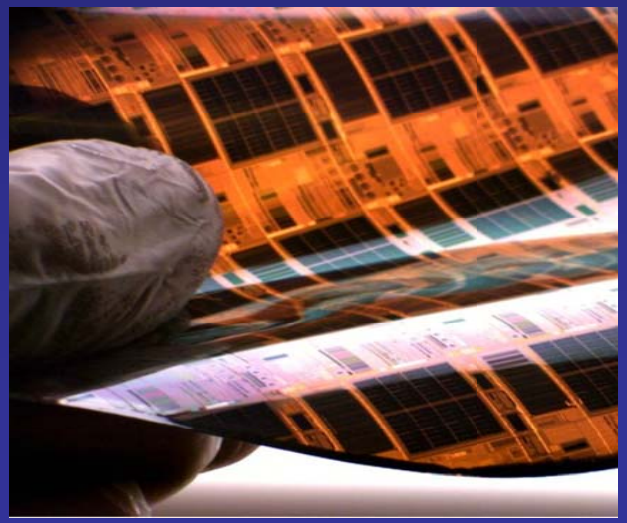


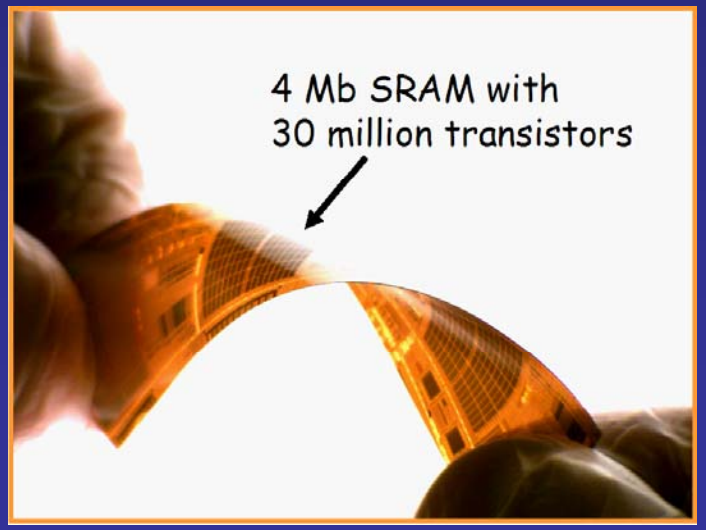
- Technology driven by industry
  - Reduce R, L, C for higher speed
  - Reduce chip I/O pads
  - Provide increased functionality
  - Reduce interconnect power, crosstalk
- Critical issue are:
  - Layer thinning to < 10 μm
  - Precision alignment (< 1 μm)
  - Bonding of the layers
  - Through-wafer via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

3D versus Monolithic Active Pixels

- Advantages of 3D devices:
  - Significantly higher functionality in a pixel cell using current feature sizes
  - NMOS and PMOS transistors
  - Processing of each layer can be optimized
  - 100% active, minimal perimeter area requirements





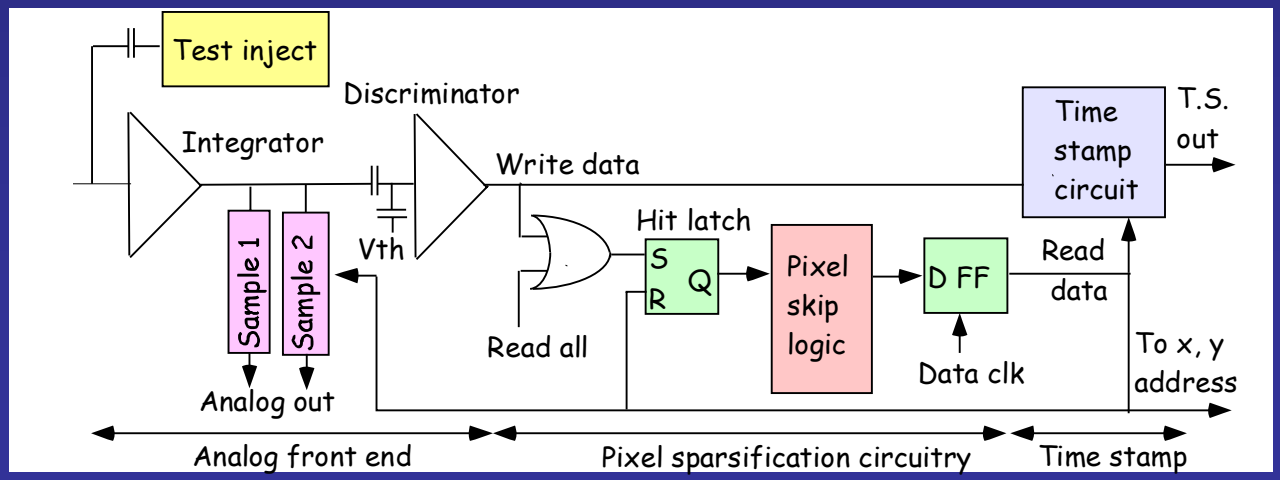


Photos MIT-LL

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

Architecture of Demonstrator Chip

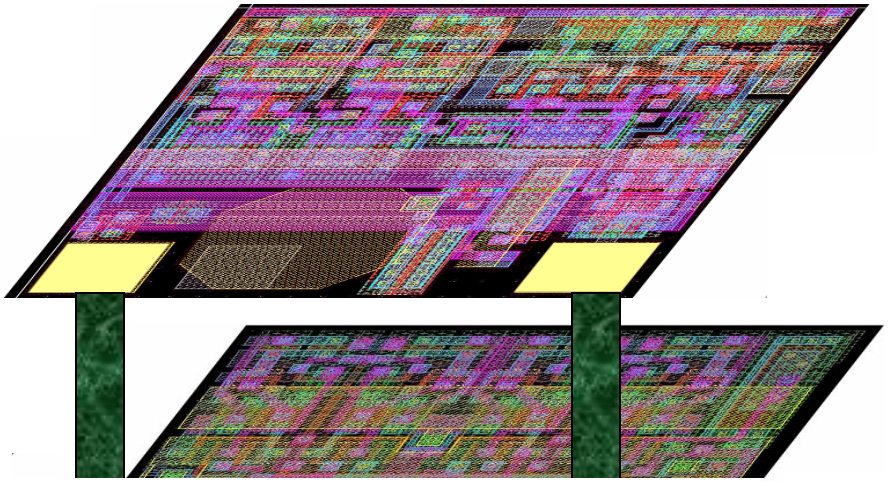
- Design:
  - Provide analog and binary readout information
  - Time stamping of pixel hit for ILC environment
    - Divide bunch train into 32 time slices; each hit pixel can store one time stamp equivalent to 5 bits of time information
  - Sparsification to reduce data rate
    - Use token passing scheme with look-ahead to reduce data output
      - During acquisition, a hit sets a latch
      - Sparse readout performed row by row with x- and y-address stored at end of row and column
  - Chip divided into 3 tiers
    - Pixels as small as possible but with significant functionality.
    - Design for 1000 x 1000 array but layout only for 64 x 64 array.



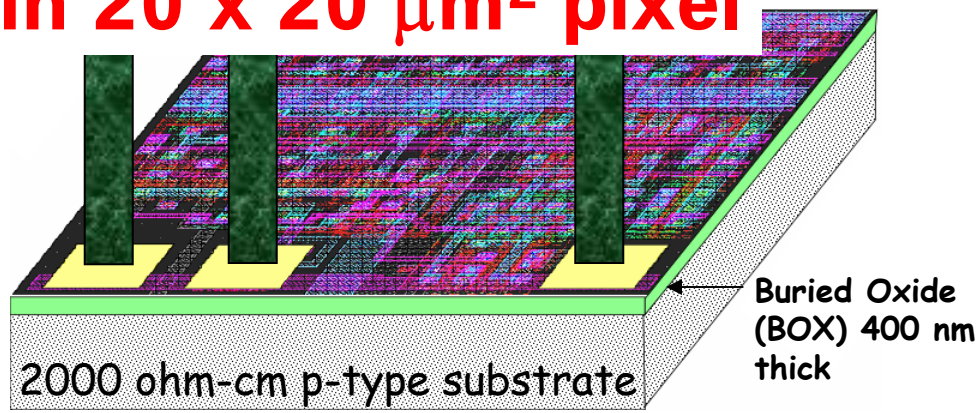
Schematic pixel cell block diagram

3D Stack

- Form 2 vias, 1.5 x 7.3 µm, through tier 3 to tier 2
- Tier 3
  - Integrator, DCS plus readout
  - Discriminator
  - 2 vias
  - 38 transistors
- Bond Tier 3 to Tier 2
- Form 3 vias, 1.5 x 7.3 µm, through Tier 2 to Tier 1
- Tier 2
  - 5 bit digital time stamp
  - Analog time stamp (ts)
    - Either analog or digital ts
  - 3 vias
  - 72 transistors
- Bond Tier 2 to Tier 1
- Tier 1
  - OR for READ ALL cells
  - Pixel skip logic for token passing
  - 3 vias
  - 65 transistors



175 Transistors in 20 x 20 μm^2 pixel



Summary Vertex Pixel Detectors

- Many different technologies are being pursued
- Each one has its pros and cons

- An established technology that meets the ILC requirements does not exist as of yet

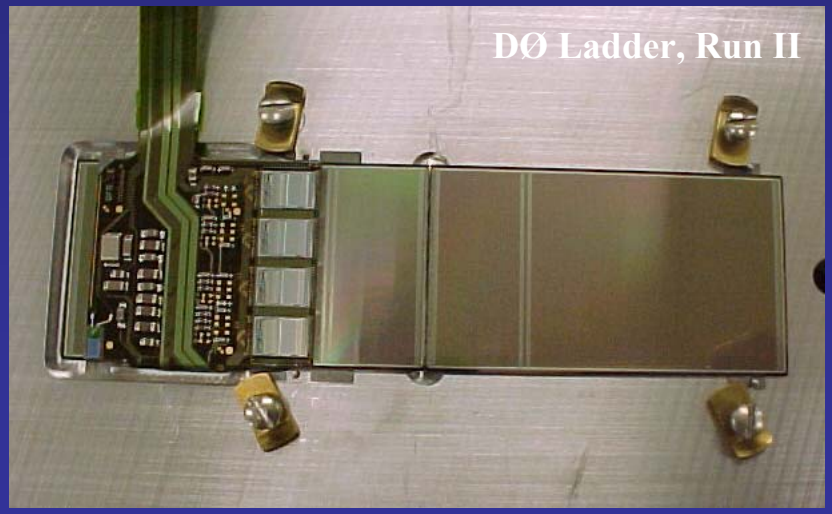
- The problems associates with a 1 Giga-pixel detector – that fits within a cylinder of length 35 cm and diameter of 20 cm – are not easy

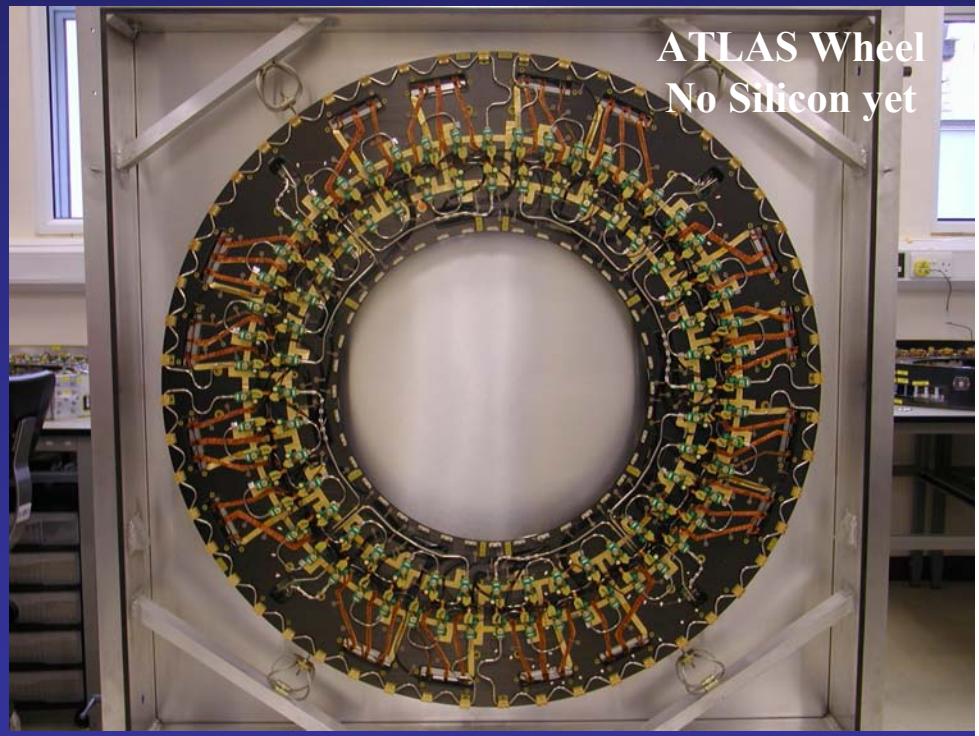
Tracking Detectors

- Silicon Strip Detectors

Why Are Current Trackers Inadequate?

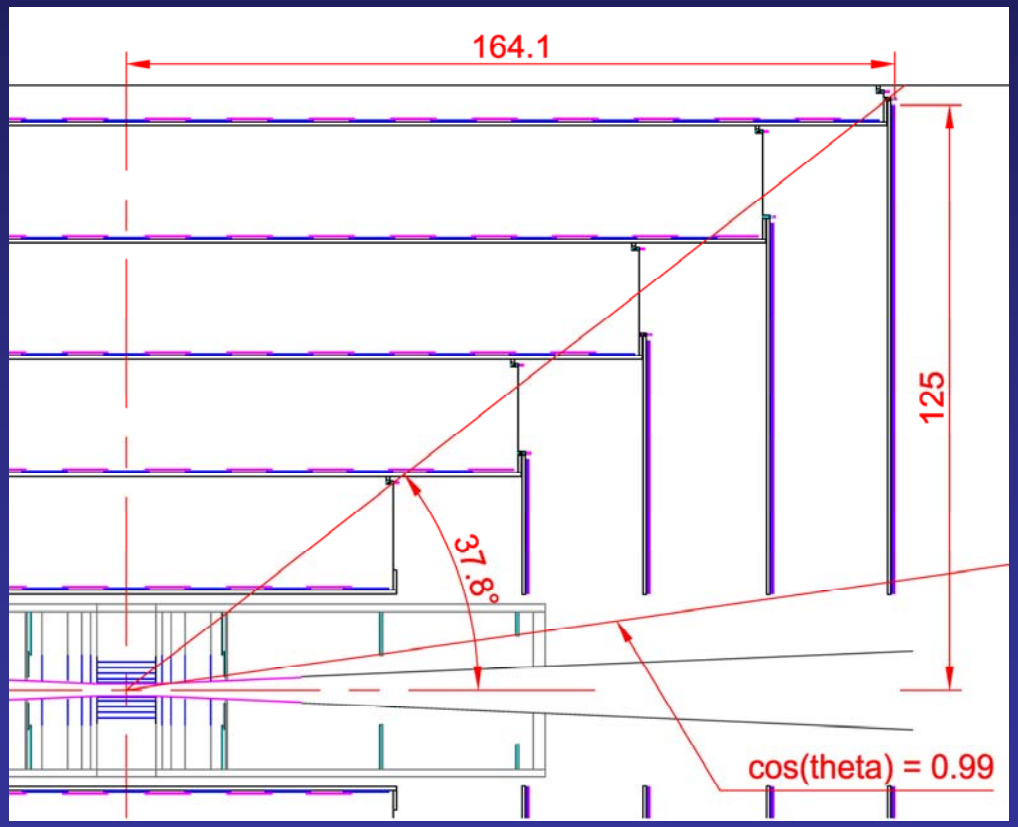
- Momentum resolution required is at least a factor 3 better than the current estimate for the CMS all silicon tracker
- More importantly, resolution needs to be maintained for full angular region!
- Main issue is mass
  - No active cooling
  - Low mass support structures
  - Low power readout





SiD Tracker

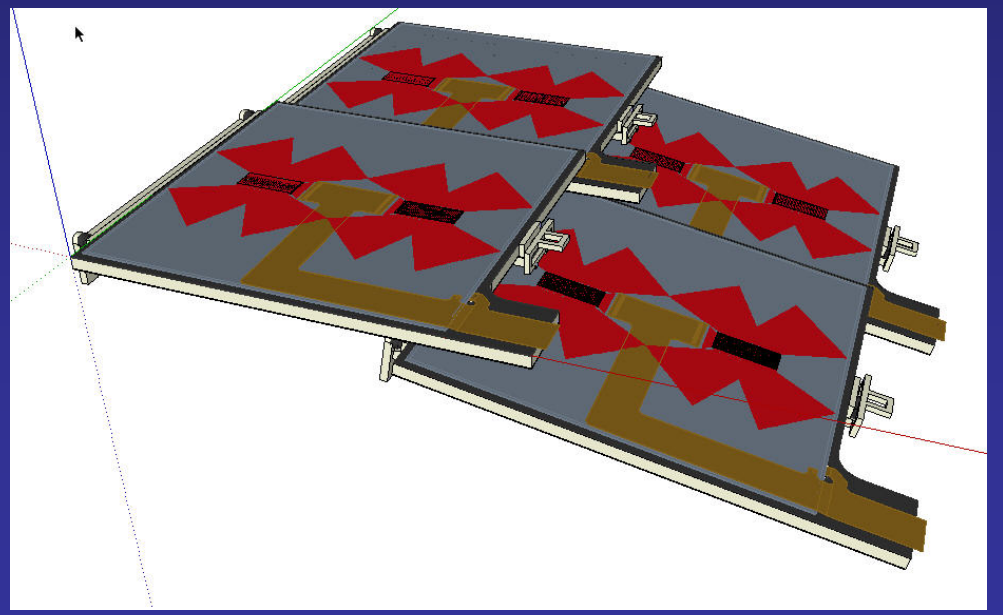
- 5-Layer silicon strip outer tracker, covering R_{in} = 20 cm to R_{out} = 125 cm
- Barrel – Disk structure: goal is 0.8% X_0 per layer



- 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
  - Four double-disks per end
  - Measure R and Phi
  - varying R segmentation
  - Disk radii increase with Z

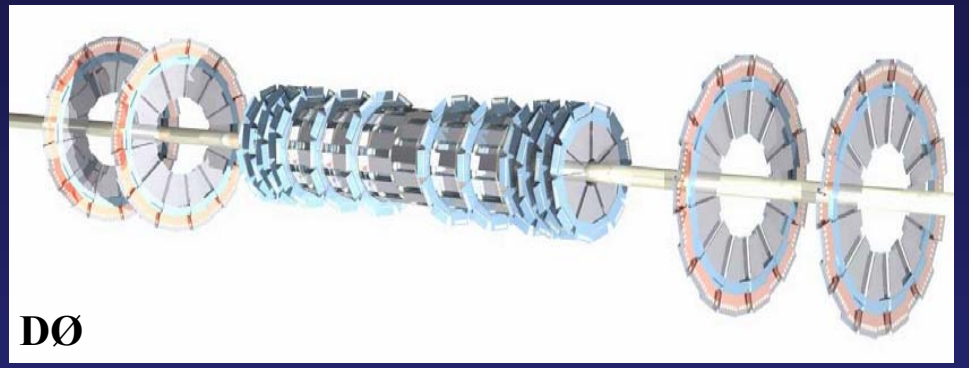
SiD Silicon Modules

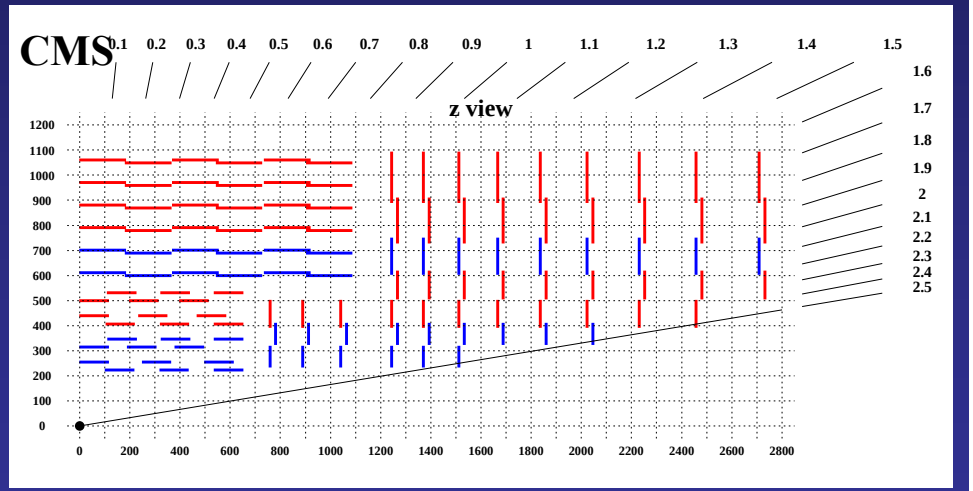
- Recall: one train for 1ms, 199ms quiet time at the ILC
- Employ power pulsing, that is, "switch off" the front-end readout electronics between trains
  - Factor of >80 in power reduction; tracker can be air-cooled
  - But have to deal with enormous Lorentz forces
- Idea is to have a hybrid-less design
- Readout chip directly bump-bonded on the silicon sensor
  - Sensor size 93.5mm x 93.5mm
  - Strip/Readout pitch 25 / 50 μm
  - Number of RO (IM) strips 1840 (3679)
    - Need two readout chips
  - Double metal layer optimized for strip geometry
    - Minimize capacitance and balance with trace resistance for S/N goal of 25

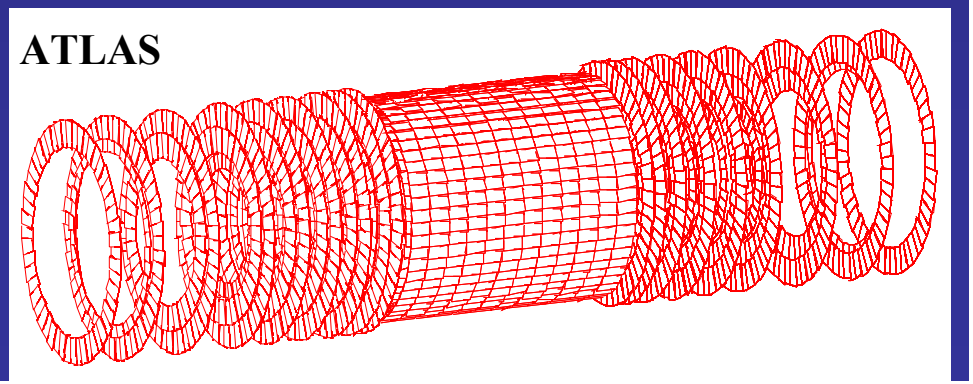


Forward Tracking

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





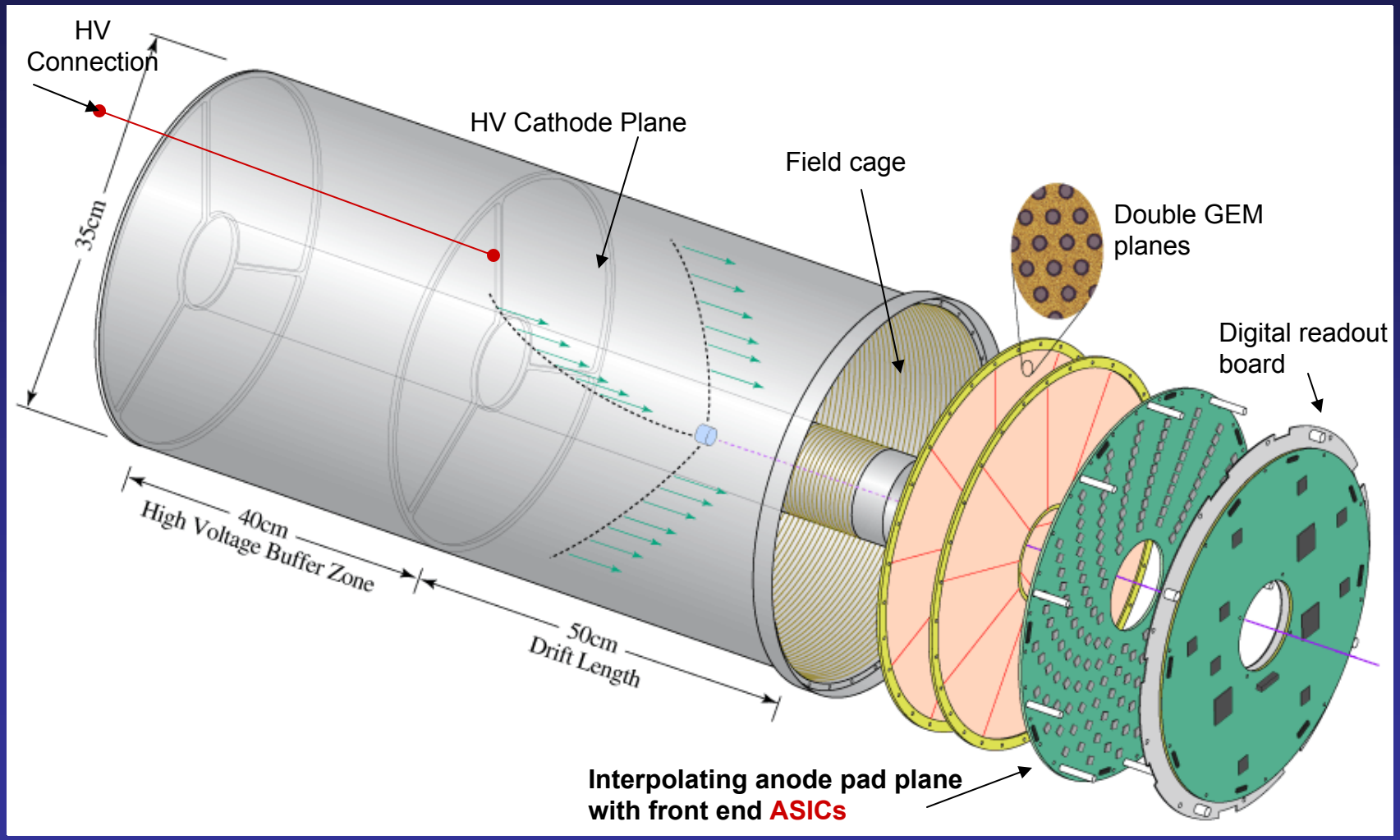


Tracking Detectors

- Time Projection Chambers

Time Projection Chamber

- Three concept detectors employ a TPC as central tracker



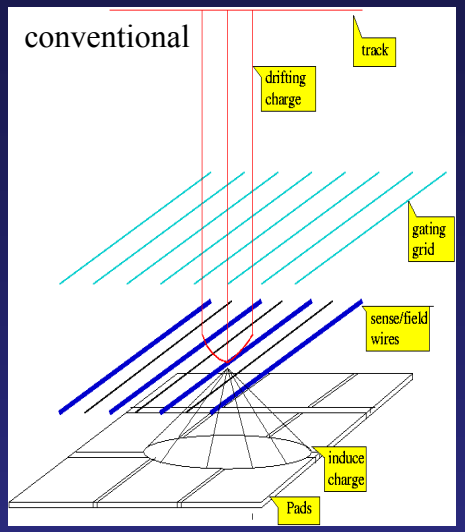
Why R&D on TPC's ?

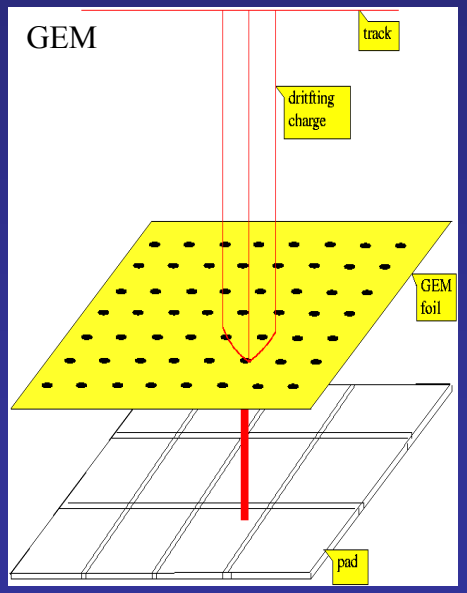
- Largest TPC ever built: ALICE TPC
  - $|\eta| < 0.9$ (full length tracks)
  - $845 < r < 2466$ mm, 95 m^3 drift volume
  - drift 2 x 2.5 m, 100 kV, 92 μs
  - Gas mixture: Ne/CO2/N2 (90/10/5)
    - gas gain 20000
  - Material budget 3.5% X_0 near $\eta = 0$
  - Momentum resolution $dp/p \leq 1\%$, B=0.4T
- Readout Chambers
  - 18 sectors each side, 2 chambers/sector
  - MWPC's, 557568 cathode pads, pad sizes 4x7.5, 6x10, 6x15 mm2
  - position resolution 800 … 1250 μm ($r\phi$, z)

- ILC
  - Much better momentum resolution: $\delta(1/p) \sim 10^{-4}$; Higher magnetic fields
  - Material budget < $0.03X_0$ to outer fieldcage in r; < 0 $30X_0$ for readout endcap in z
  - Number of readout pads $>10^6$ per endcap
  - Pad size about 1x6 mm^2
  - Single point resolution in r-φ 100μm, in r-z < ~ 500μm (rz) @ 4T

TPC End Plate Detectors

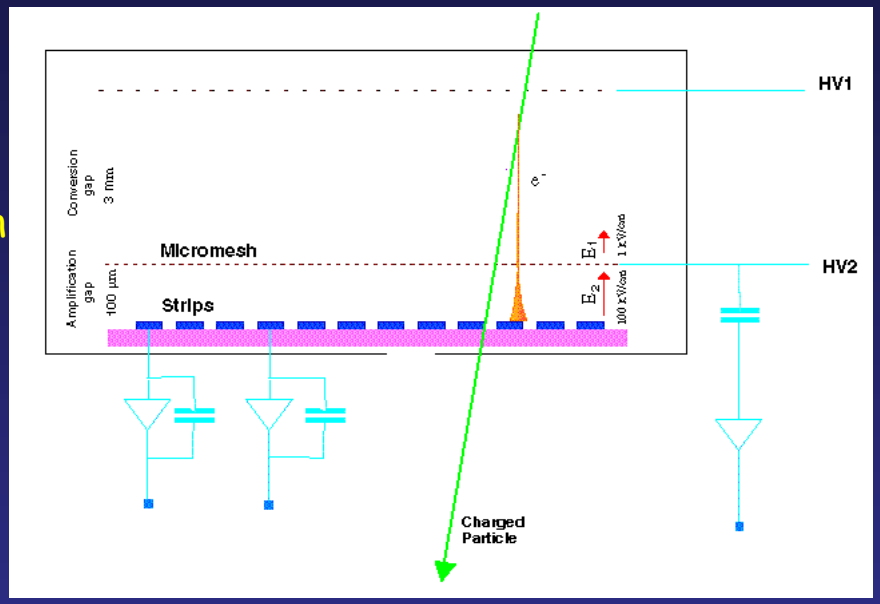
- The conventional solution – adopted by ALICE – uses wires
  - Gas amplification at wires only
  - Signal is induced on pads by +ions
    - Slow collection
    - Wide signals and limited resolution
  - Strong frame needed which adds a lot of material
  - Wires can break
- The alternative is to use Micro-Pattern Gas Detectors (MPGD)
  - Amplification of the signal where drift electrons hit the end plate
  - Directly detect amplified electrons on pads - fast
- There are currently two options being pursued
  - Gas Electron Multiplier (GEM) detectors
  - Micro MEsh GAseous Structure (Micromegas) detectors
- with two kinds of readouts
  - pad readout
  - CMOS readout



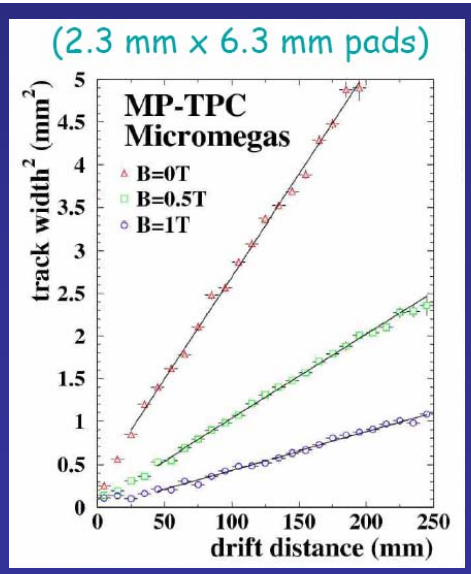


MicroMegas

- A micromesh, with pitch ~50μm, separates the gaseous volume into two regions
  - A conversion gap where the ionization takes place and where the electrons drift in a moderate field
  - A narrow amplification gap for the creation of the avalanche

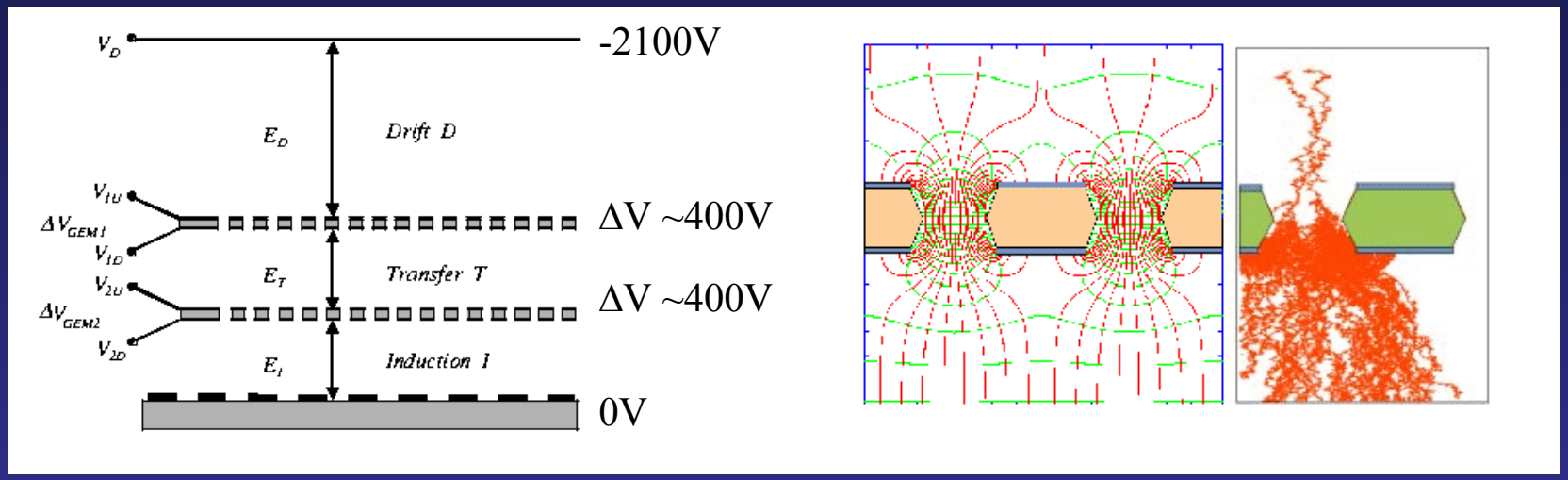


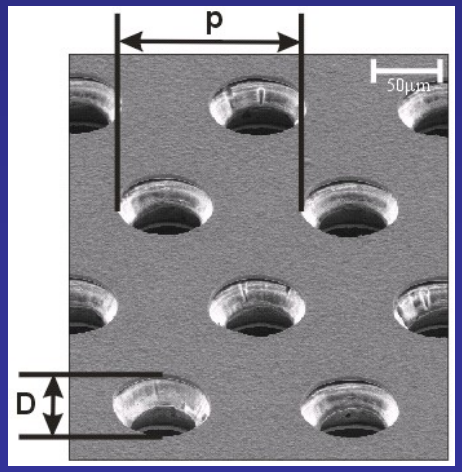
- Series of studies on
  - Ion-backflow
  - Performance characterization
  - Gas characterization
  - Better resolution through charge sharing between readout pads



GEMs

- Gas Electron Multiplier: copper foils separated by kapton, multiplication takes place in holes, uses 2 or 3 stages

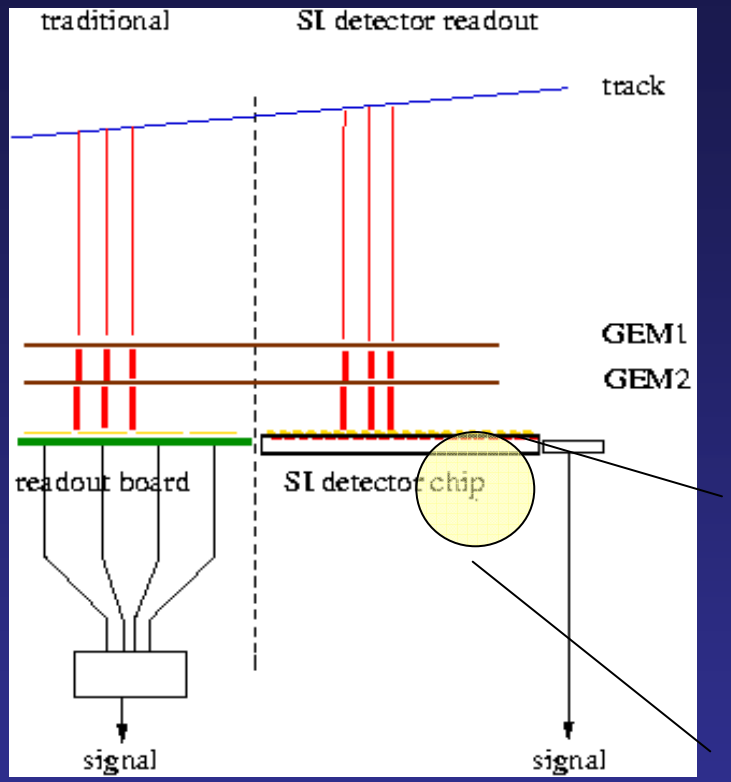




P~140 µm
D~60 µm

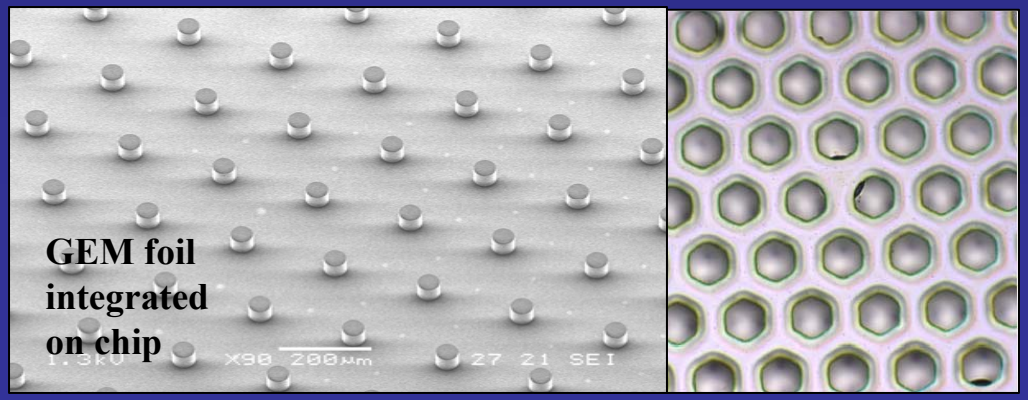
- Readout again with pads
- TPC's proposed for the ILC have 2-10 million readout channels

TPC CMOS Readout

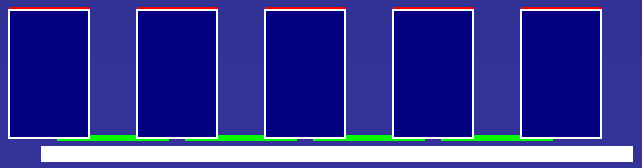


- Use CMOS technology to directly collect signals from GEMs or Micromegas: MediPix chip
  - Charge collection with granularity matching primary ionization cluster spread
- On-chip processing of signals
- 3rd coordinate (time) being added: Medipix2

- Integrate grid with pixel chip through wafer processing



'GEM'

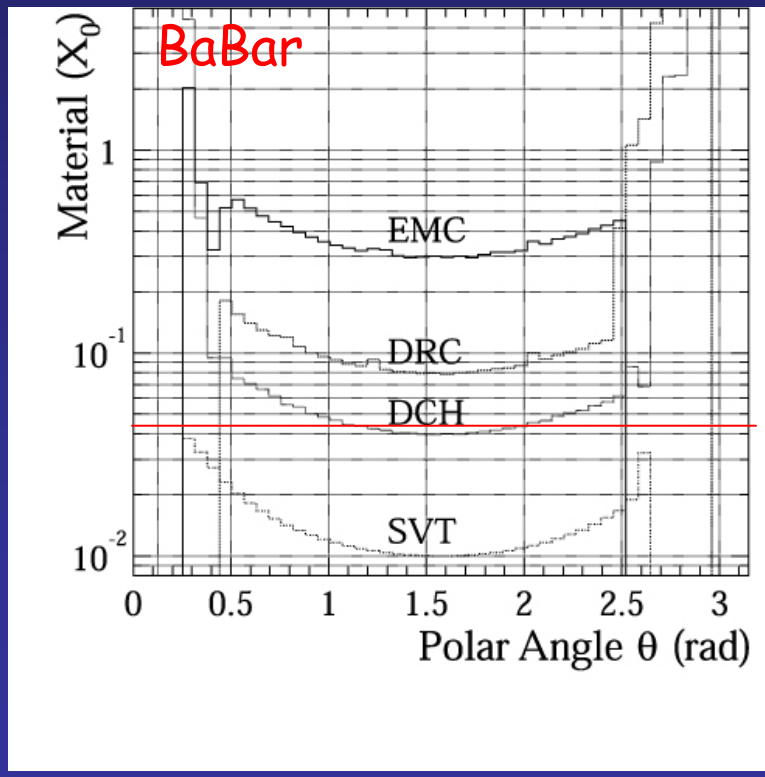


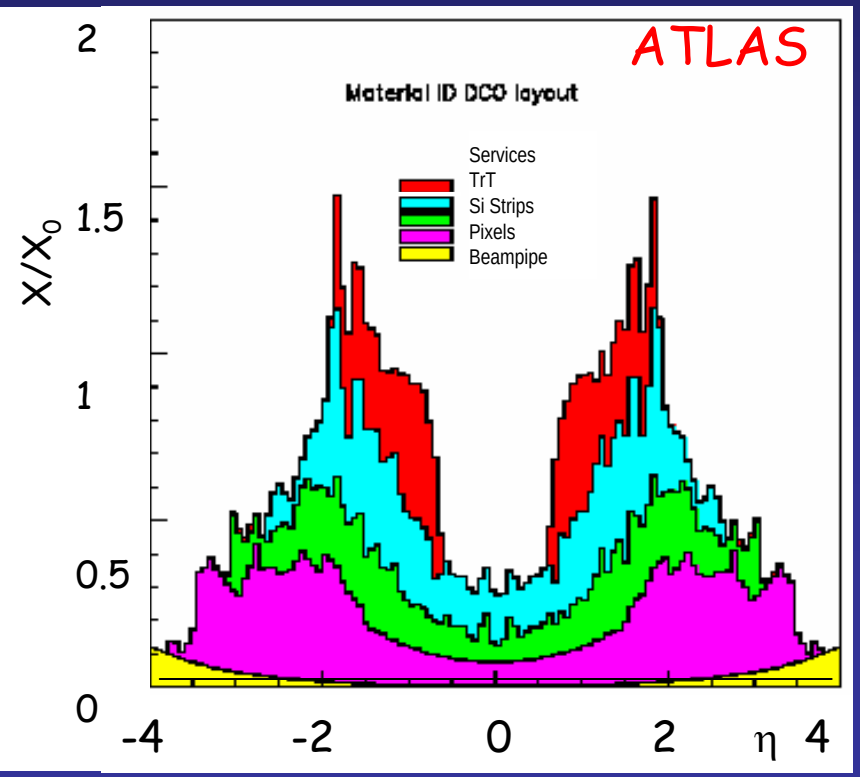
TPC Endplate

- ALICE TPC Endplate

Material Budget

- 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

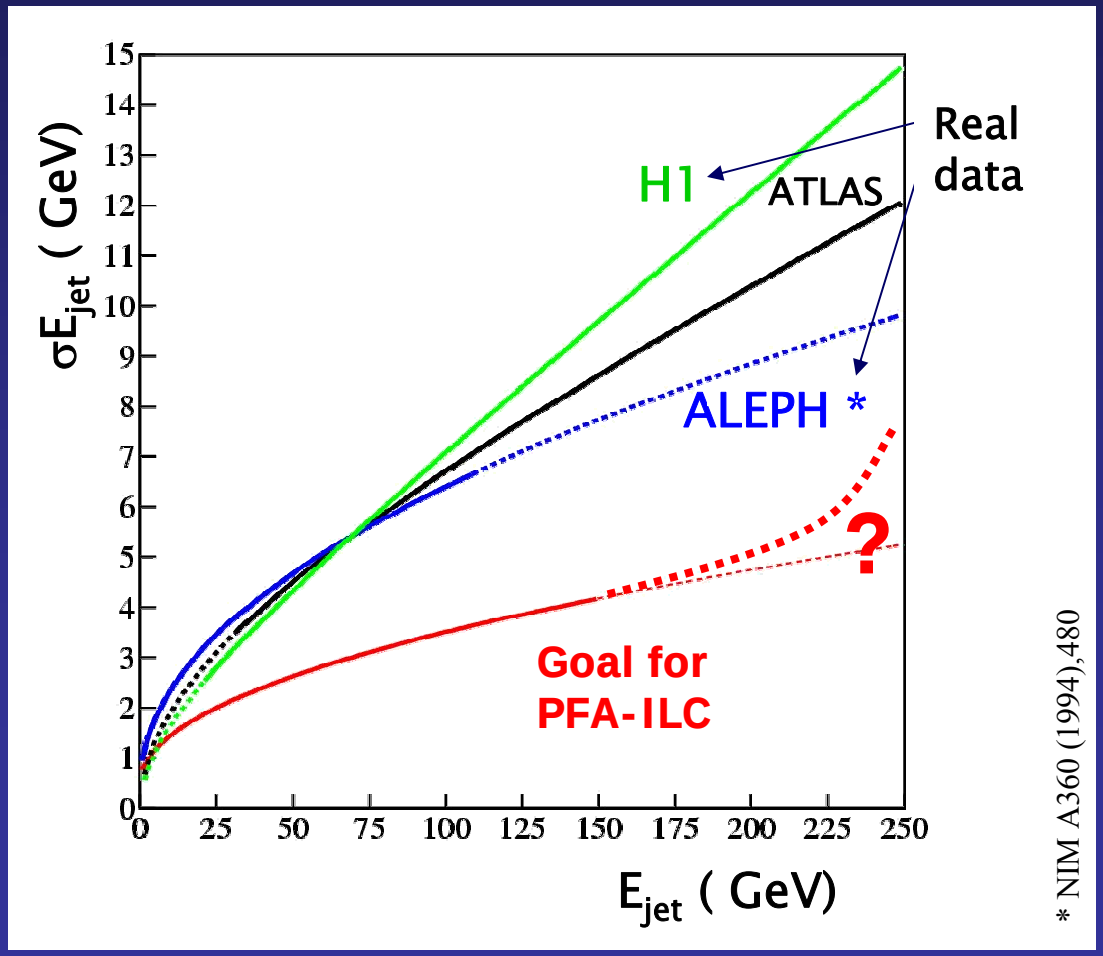




Calorimetry

Why R&D on Calorimetry ?

- Goal is jet energy resolution of $\delta E/E$ of ~ 3%, or $\sigma(E)/E \sim 30\%/\sqrt{E}$
  - Need to be able to separate $Z \rightarrow qq$ from $W \rightarrow qq'$
- No experiment has been able to obtain such jet energy resolutions

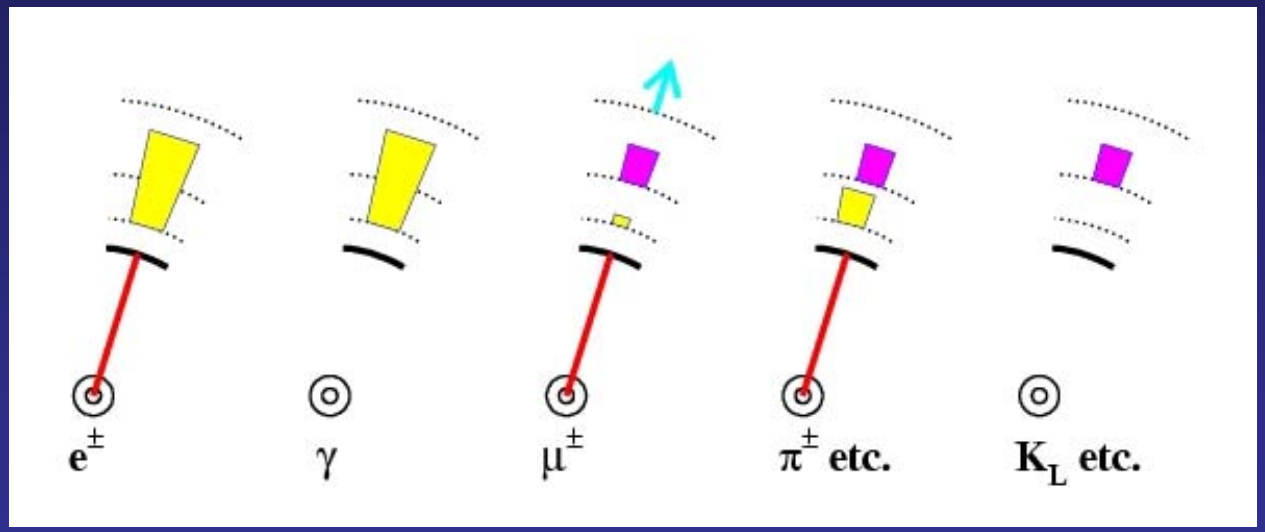


- Currently the main paradigm is that this can be achieved with a so-called Particle energy Flow Algorithm (PFA)
  - LDC, GLD and SiD all follow the PFA approach
  - 4th detector concept believes in "dual readout"

Particle Flow Calorimetry

Particle Flow Calorimetry

- 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



- Reconstruct momenta of individual particles in jet avoiding double counting
  - Measure photons in the ECAL
  - Measure charged particles in the tracking system
  - Measure neutral hadrons in the HCAL (+ ECAL) by subtracting calorimeter energy associated with charged hadrons

Jet Energy Resolution in Particle Flow

- Jet energy resolution factorizes as:

$$\sigma^2(E_{jet}) = \sigma^2{}_{chd} + \sigma^2{}_{\gamma} + \sigma^2{}_{h^0} + \sigma^2{}_{confusion}$$

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

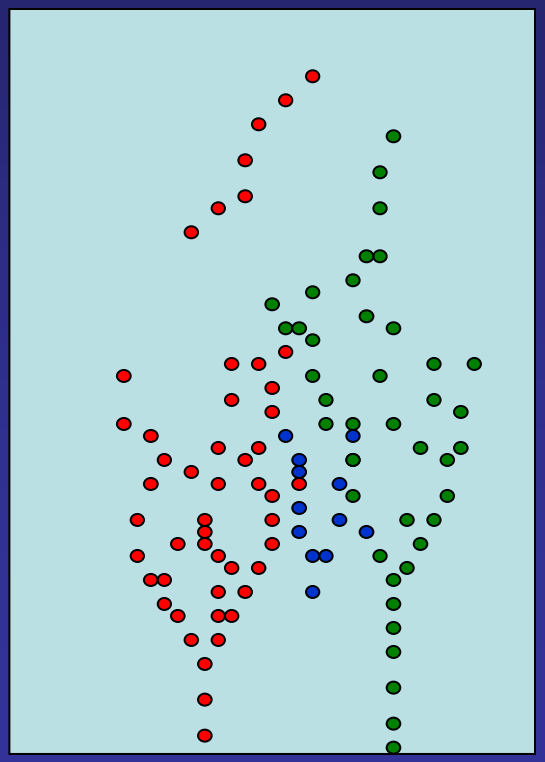
  - Excellent tracker: $\sigma^2{}_{chd} << \sigma^2{}_{\gamma} + \sigma^2{}_{h^0} + \sigma^2{}_{confusion}$
  - Perfect PFA: $\sigma^2{}_{confusion} = 0$

- Calorimetric performance is not the limiting factor; single particle resolution not the dominant contribution to the jet energy resolution

- The confusion term accounts for, for example, assigning energy deposits to wrongly reconstructed particles (double-counting etc.)

Particle Flow Challenges

- Tracking efficiency:
  - Not really. If some tracks are not reconstructed the corresponding energy will be measured with the resolution of the hadron calorimeter. Not a serious obstacle to reach the '30%' challenge if the tracking efficiency ≥ 90%
- Subtraction 'quality':
  - Some of the energy deposited by neutral hadrons can be mistakenly removed => reduces the jet energy
  - Some of the energy deposits of charged particles may not be properly subtracted and identified as neutral particles: double counting => increase the jet energy
- Fluctuations of the above effects will likely dominate the energy resolution
- PFA:
  - Identify and discard all red/green points
  - Difficulties:
    - Identify 'blue' cluster in the midst of the red/green one
    - Properly identify the disconnected red cluster (a.k.a. 'fragment')



From: Adam Para

The $64M Question

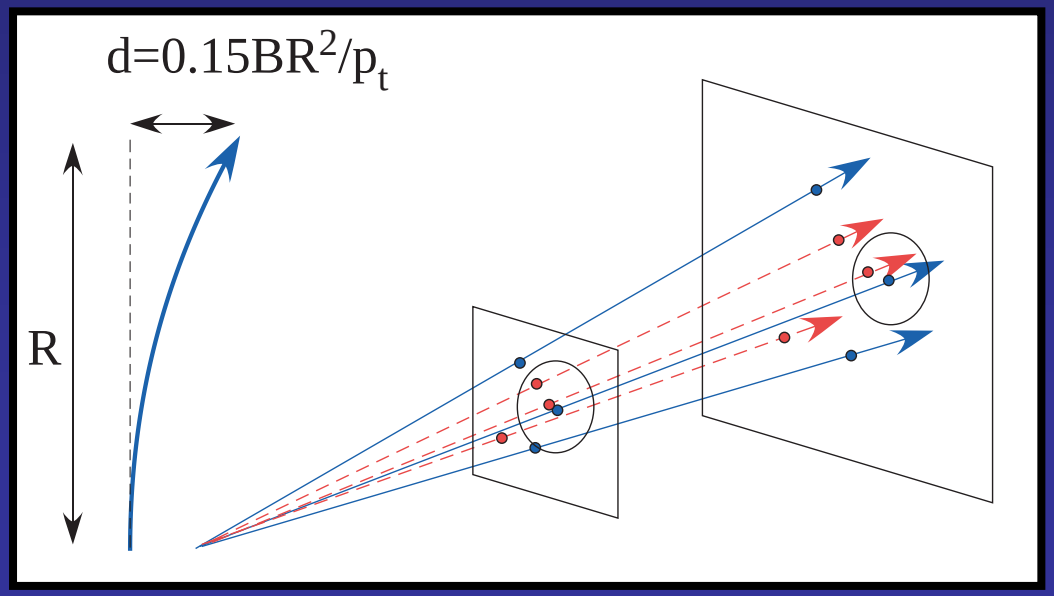
- PFA: a brilliant idea used as a baseline in three main detector concepts
- Novelty is in reducing the role of the hadron calorimeter to the measurement of neutral long-lived hadron only.

- What are the implications for the calorimeter ?
  - Electromagnetic calorimeter/granularity
  - Sampling of the hadron calorimeter
  - Active medium: gas/scintillator
  - Transverse segmentation
  - Digital or analog readout

- Does it work at all ?

PFA "Figure of Merit"

- For good jet energy resolution need to separate energy deposits from different particles
- Requirements:
  - Large detector–spatially separate particles
  - High B-field–separate charged/neutrals
  - High granularity ECAL/HCAL–resolve particles
- Physics argues for increase, cost argues for decrease in R, B, granularity
- EM and HAD calorimeter inside magnetic field



Often quoted "Figure of Merit"

$$\frac{BR^2}{\sqrt{\sigma^2 + R_M{}^2}}$$

B : Magnetic field
R : CAL inner radius
σ : CAL granularity
R_M : Effective Moliere length

PFA Status

- For full status report, see Mark Thomson's ALCPG talk at
  http://ilcagenda.linearcollider.org/conferenceDisplay.py?confId=1279
  - At the Z-pole obtained 30% jet resolution
    - Determined using rms_{90}: rms of region that contains 90% of events
  - Resolution degrades rapidly with increasing energy

E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\lvert\cos\theta\rvert<0.8$
45 GeV	0.30
100 GeV	0.37
180 GeV	0.57
250 GeV	0.75

  - At the Z-pole, there's only a weak dependence on the B-field
    - Confusion is not dominating the resolution for these low energy jets

B-Field	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$	
	All angles	$\lvert\cos\theta\rvert<0.7$
2 Tesla	34.1±0.3%	30.8±0.4 %
4 Tesla	33.4±0.3 %	29.2±0.4 %
6 Tesla	34.4±0.3 %	29.7±0.4 %

  - At the Z-pole, there seems to be a weak dependence on the segmentation
    - 10x10cm is clearly too coarse

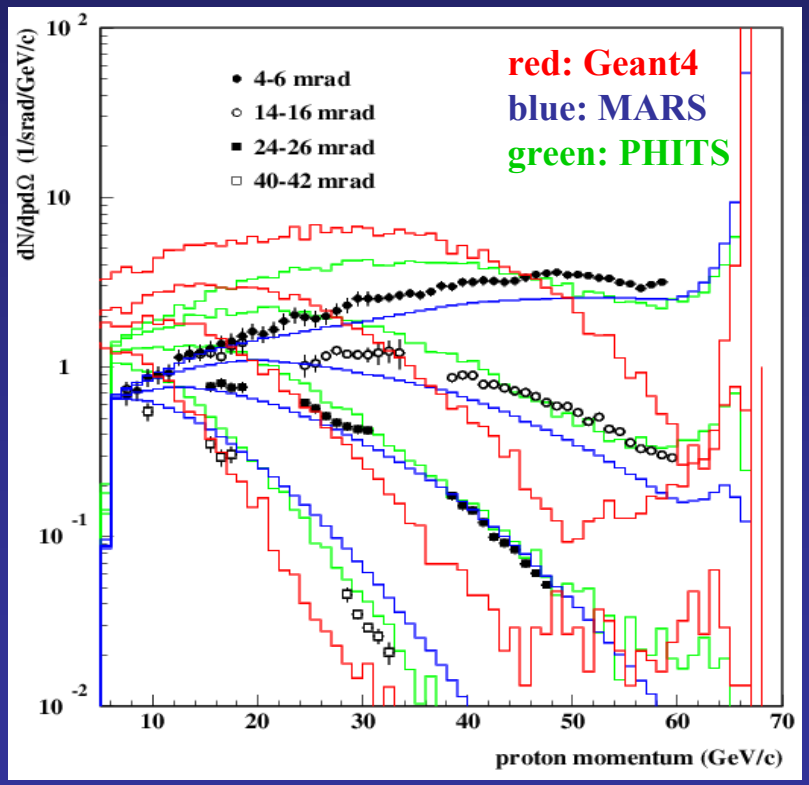
Detector Model	$\sigma_{Evis}/E = \alpha\sqrt{(E/GeV)}$	
	Z @91 GeV	tt@500 GeV
LDC00Sc 1cm x 1cm	31.4 ± 0.3 %	42 ± 1 %
LDC00Sc 3cm x 3cm	30.6 ± 0.3 %	45 ± 1 %
LDC00Sc 5cm x 5cm	31.3 ± 0.3 %	48 ± 1 %
LDC00Sc 10cm x 10cm	33.7 ± 0.3 %	56 ± 1 %

- Quote from Mark: "These studies are interesting but not clear how seriously they should be taken: how much is due to the detector, how much due to imperfect algorithm"

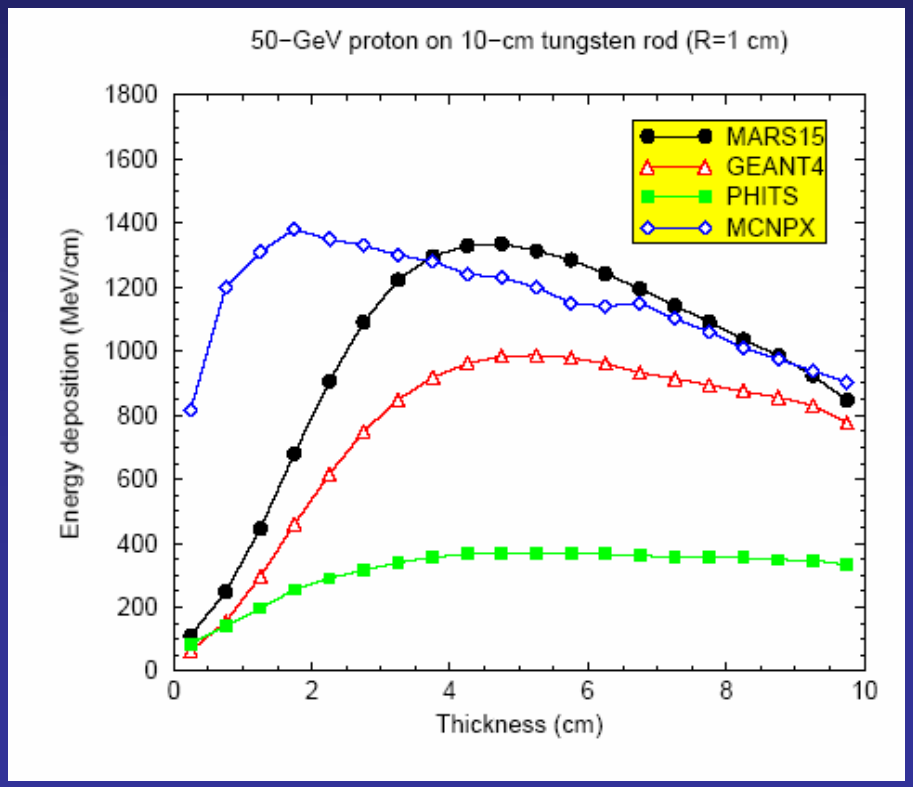
How Reliable are Simulations ?

- All results based on simulations.
- Common claim that simulators model longitudinal shower development well, but is less accurate in transverse shower development
- Two examples

p + Al @ 67 GeV/c -> p X



p + W (R=1cm) @ 50 GeV/c

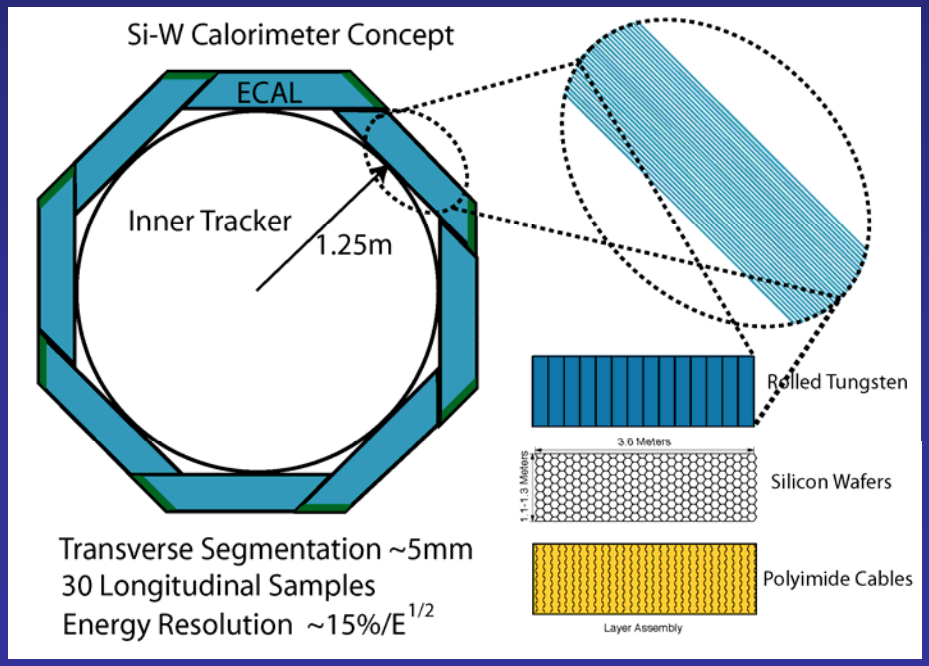


Calorimeters

EM Calorimeter

- P-Flow requires high transverse and longitudinal segmentation and dense medium
- LDC and SiD Choice: Si-W can provide 5x5 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

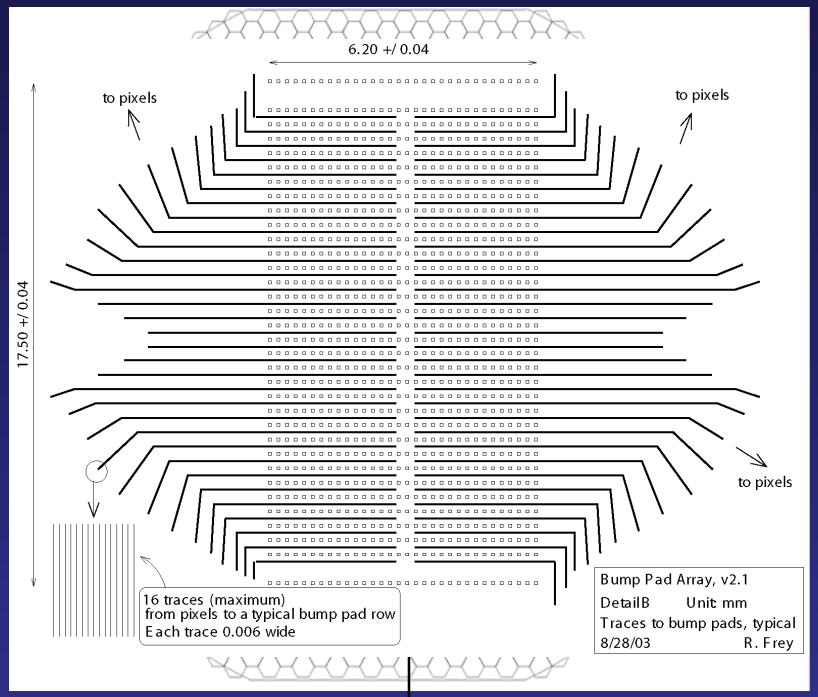


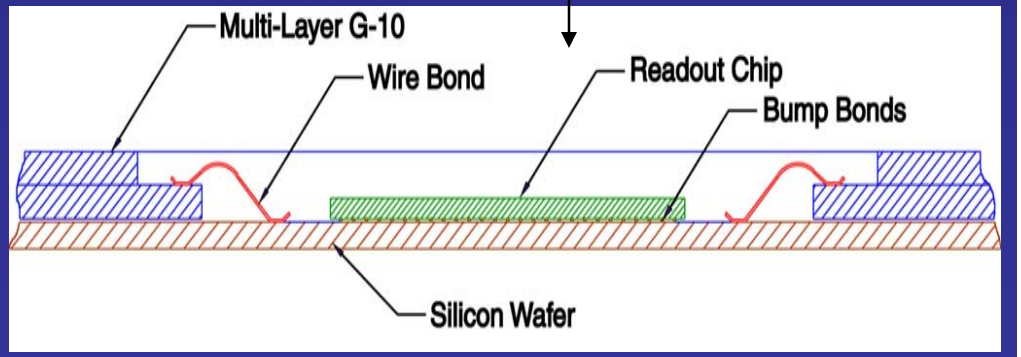
SiD EM Calorimeter

- 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%

SiD EM Calorimeter Layout

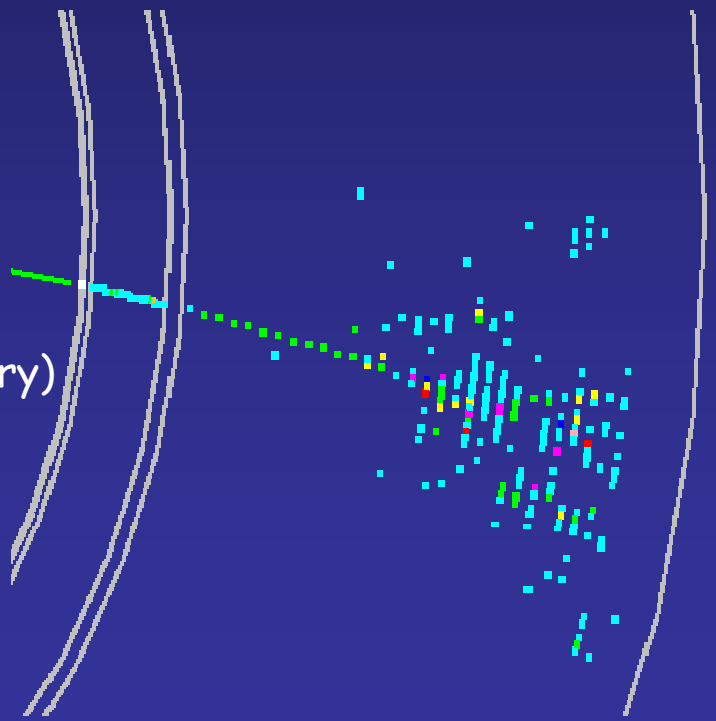
- Tile W with hexagonal 6" wafers
  - 5x5 mm^2 pads
  - Each wafer read-out by single chip
  - 1024 channel chip, bump-bonded
- Design Constraints
  - Compact: gap needs to be as small as possible
    - Keep Molière radius small
    - Control the cost
  - Low power: single power-pulsed chip
  - Heat removal
  - Large dynamic range
- Scale
  - ~ 1300 m^2 of Si
  - ~ 100 million readout channels





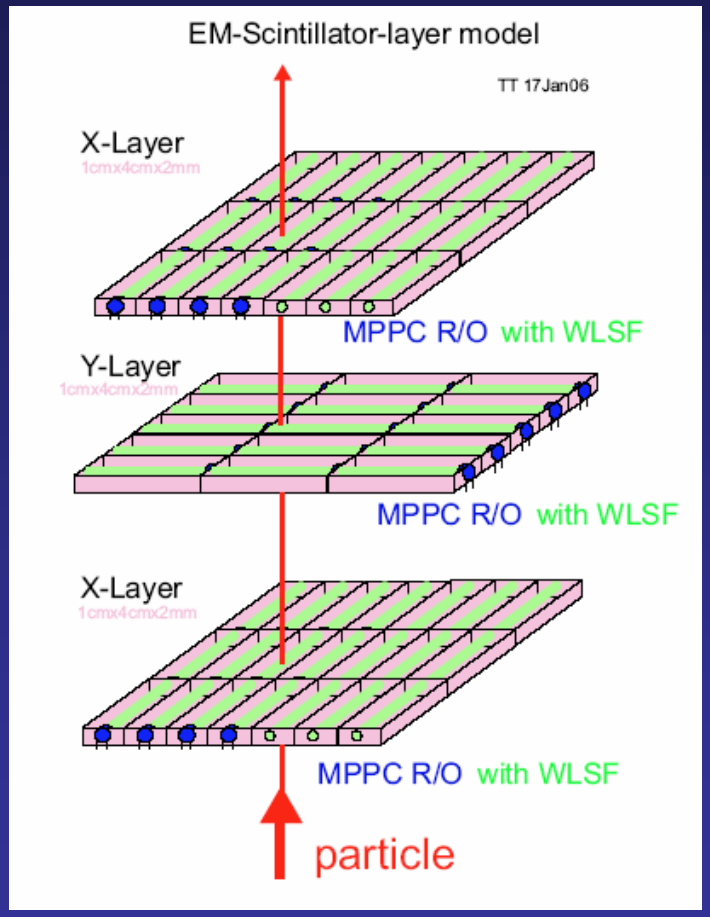
Hadron Calorimetry

- Diversity of Approaches
  - Technolgoy
    - Active
      - Resistive Plate Chambers (RPC's)
      - Gas Electron Multipliers (GEM's)
      - MicroMegas
      - Scintillator (analogue)
    - Passive
      - Tungsten
      - Steel
  - Readout
    - Analog readout -- O(10) bit resolution
    - Digital readout -- 1-bit resolution (binary)
      - Open question if this will work

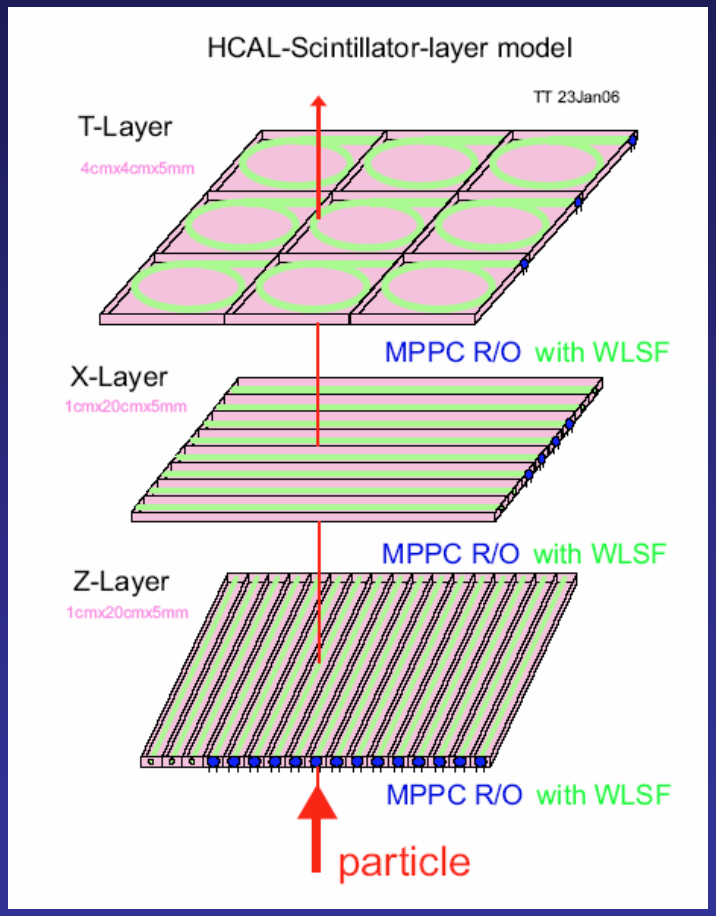


GLD Calorimetry

- Scintillator based for both EM and HAD (LDC choice for HAD)



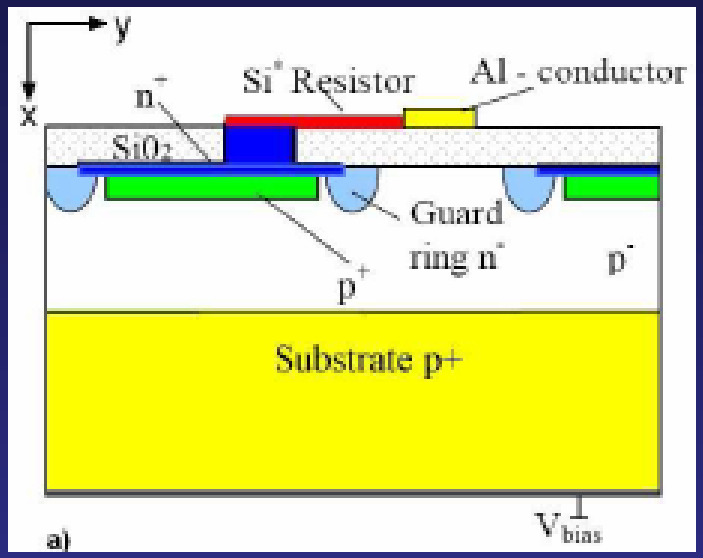
ECAL
W/Scint./Gap
3/2/1 (mm) x 33 layers

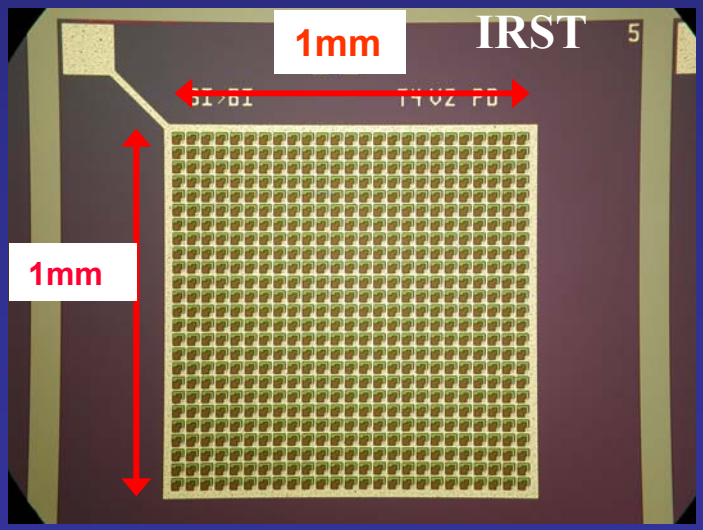


HCAL
Fe/Scint./Gap
20/5/1 (mm) x 46 layers

Enabling Technology

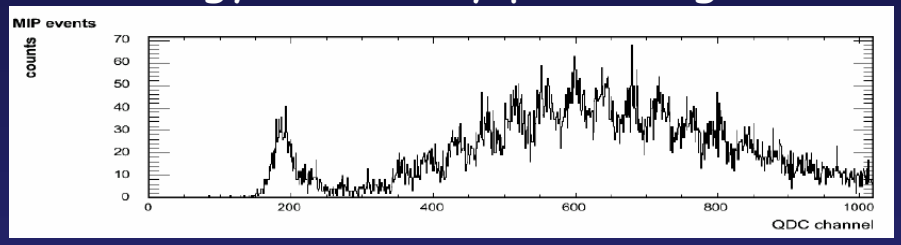
- The technology that enables the high granularity (~25M channels) is Geiger Mode Avalanche Photo Diodes – called Multi-Pixel Photon Counter (MPPC) or Silicon photo-multiplier (SiPM)
  - Array of pixels connected to a single output
  - Signal = Sum of all cells fired
  - If probability to hit a single cell < 1 => Signal proportional to # photons
- Characteristics:
  - Pros
    - Very compact
    - High PDE (15~20% for 1600 pix)
    - Insensitive to magnetic field
    - High gain (10^5~10^6)
    - Operational at V_{bias}=70~80 V
    - Good timing resolution
  - Cons
    - Thermal noise rate (100kHz~300kHz @ 0.5 pe)
    - Response is non-linear due to limited number of pixels (saturation effect)
    - Sensitive to temperature change
    - Cross-talk between pixels



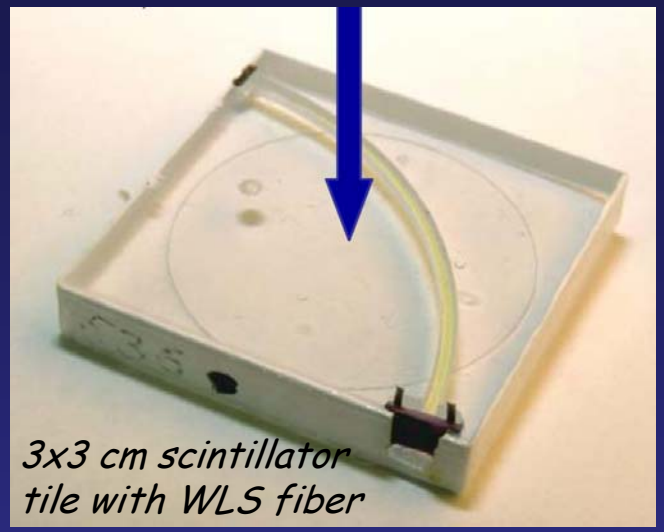


Viability of Technology

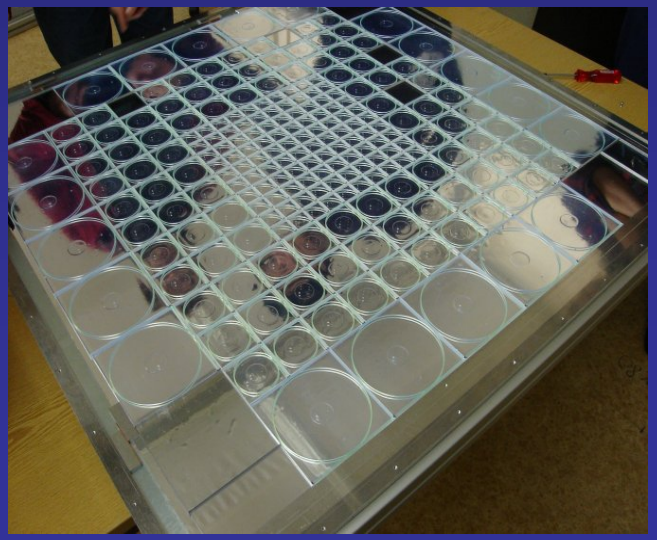
- Technology looks very promising



- MPPC devices not yet commercially available on large scale; technology brand new
  - MPPC
    - Optimization of detector design
    - Cross talk and after-pulsing
    - Detector characterization
  - Calorimeter modules
    - WLS or direct coupling of MPPC on scintillator and photon yield
    - Mechanical and electrical integration a major issue
- Physics
  - Granularity: 1x1, 3x3, 5x5mm^2 tiles
  - Uniformity of response
  - Dynamic range

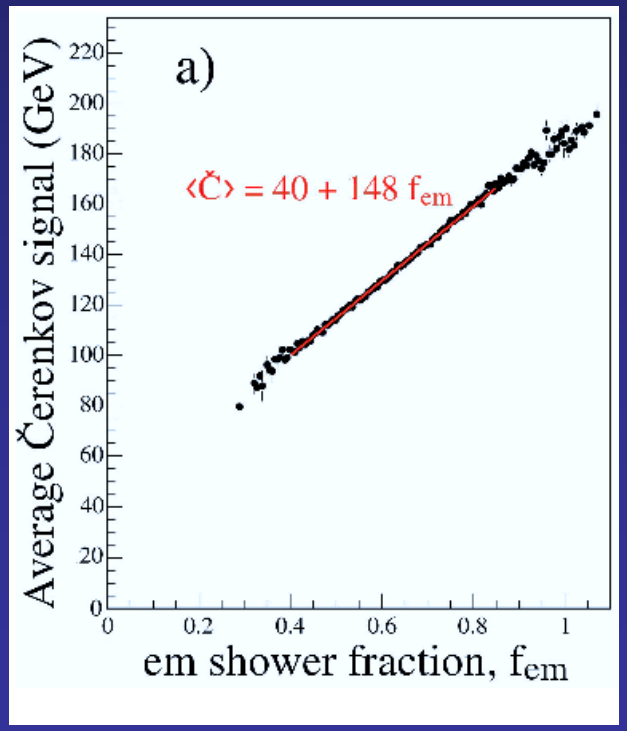


3x3 cm scintillator tile with WLS fiber



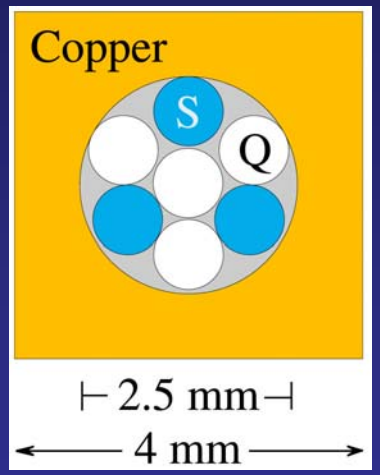
Dual Readout Calorimetry

- The 4th concept does not rely on PFA, but tries to improve the energy resolution employing "traditional" calorimetry
- Based on the premise that
  - Spatial fluctuations are huge ~λ_{int} with high density EM deposits
    - fine spatial sampling
  - EM fraction fluctuations are huge, 5%→95% of total shower energy
    - Measure the EM component of showers
- Dual-Readout: measure every shower twice
  - Scintillation light
  - Cerenkov light
    - EM shower: relativistic electrons, relatively large amount of Cherenkov light
- Linear relation between the measured Cerenkov light and the EM fraction of a shower
  - Allows for determination of the EM and HAD component of a shower separately
    => better resolution

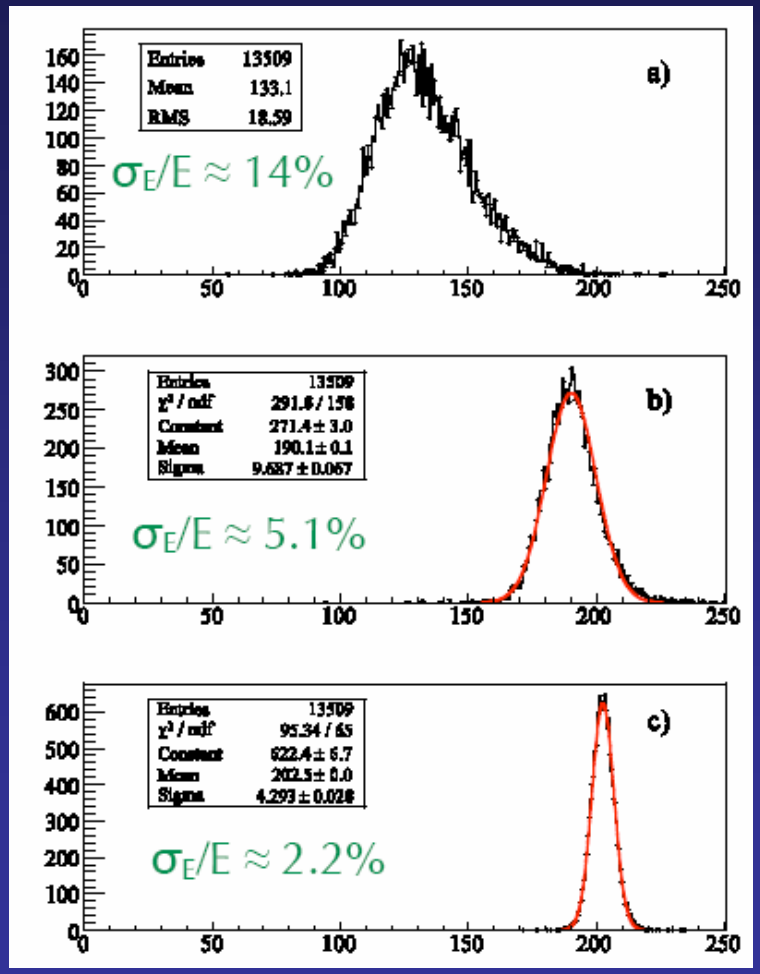


Dual Readout Calorimetry

- Dual REAdout Module (DREAM) approach
  - Three scintillating fibers
  - Four quartz fibers
  - Embedded in copper

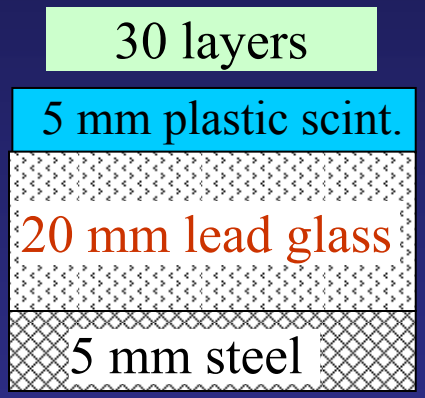


- Response to 200 GeV π+ beam
  - Scintillator response only
  - Scintillator + Cerenkov light
    - $f_{EM}\,(C/E_{shower} - 1/n_C)$
  - Correct for leakage fluctuations

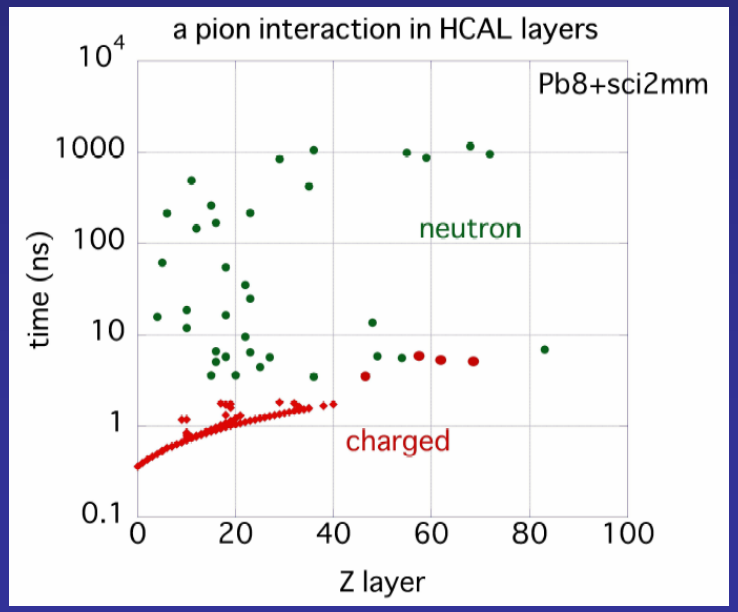


Dual Readout Calorimetry

- The DREAM approach doesn't have longitudinal segmentation
- Alternate approach is dual readout sampling calorimeter



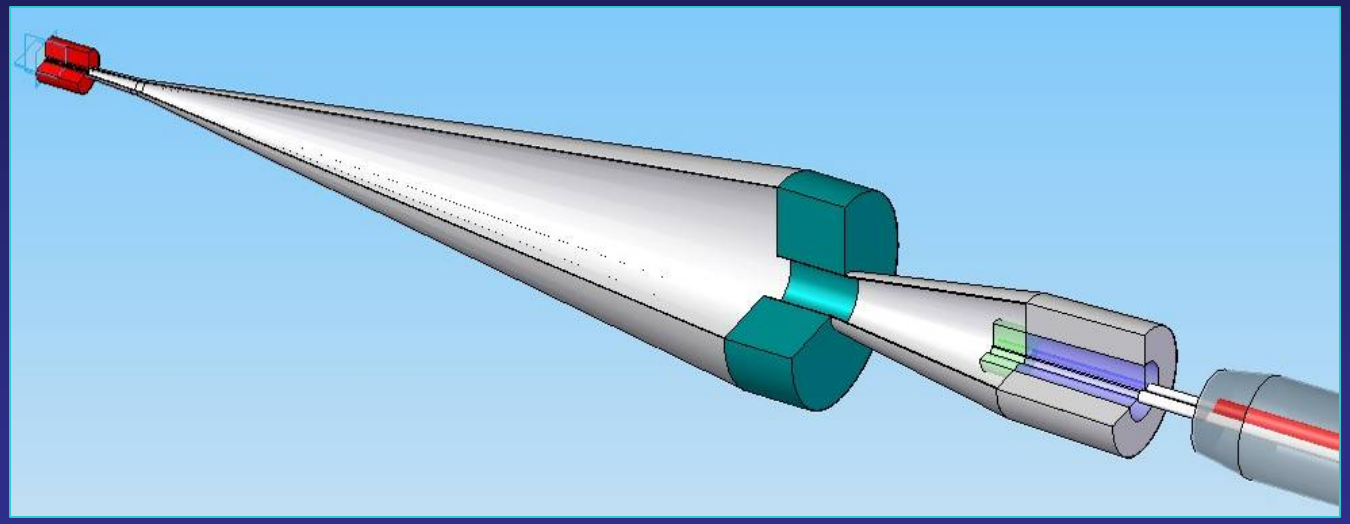
- Readout can again be achieved with MPPC's
- Uniform calorimeter, the same structure for EM/Hadron section
- Easy transverse and longitudinal segmentation
- High yield/detection efficiency of the Cherenkov photons



- Possible extension: triple readout
  - Add a neutron sensitive medium to measure neutron response and timing of neutrons
  - MPPC technology with fast timing could enable this

And, … there's more …

- Muon systems
- Magnets
- Far Forward region
  - Beam Cal
  - Lumi Cal



- Beam Measurements
  - Beam Energy
  - Beam polarization

A Wal★Mart ILC Detector ?

A LEP/LHC Detector for the ILC ?

- I don't think so !!
- At the ILC, the vertex detector and calorimeter, for example, employ technologies that are probably the biggest departures from the present day detector technologies.
- For the calorimeter it involves several detector subsystems in a common measurement. It probably requires an unusually segmented hadron calorimeter, which is likely not to perform very well on its own if used in single mode readout
- For the vertex pixel detectors it requires unprecedented advances in scale, material and power budget
- These technologies are as of yet unproven
- Ergo, we would not be able to carry out the physics program we want to do and the R&D is very much needed

What is an ILC Detector ?

Closing Remark

- The ILC is the only candidate accelerator proposed for the US
- The machine follows an aggressive schedule to be ready for a decision on the ILC around 2010, when the first LHC results will become available
- There is a lot of R&D that needs to be done to bring the detector concepts to the same level of readiness
- If we are not ready, we have only ourselves to blame for a missed opportunity

- If any of this interests you, we would be very happy for you to join the effort for a year or so

- Detectors are an integral part of physics and there is the added benefit that there is a nice overlap with the upgrades planned for the LHC experiments.