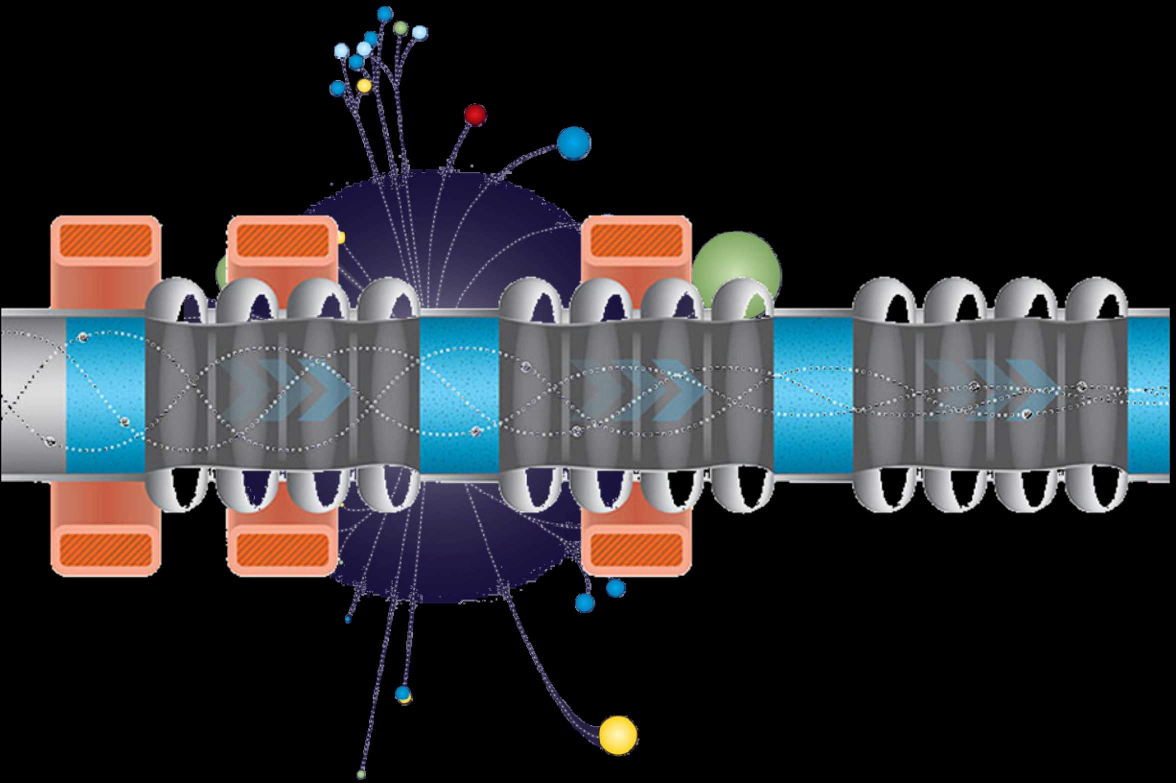
Muon Collider Detector

Old Design and New Developments



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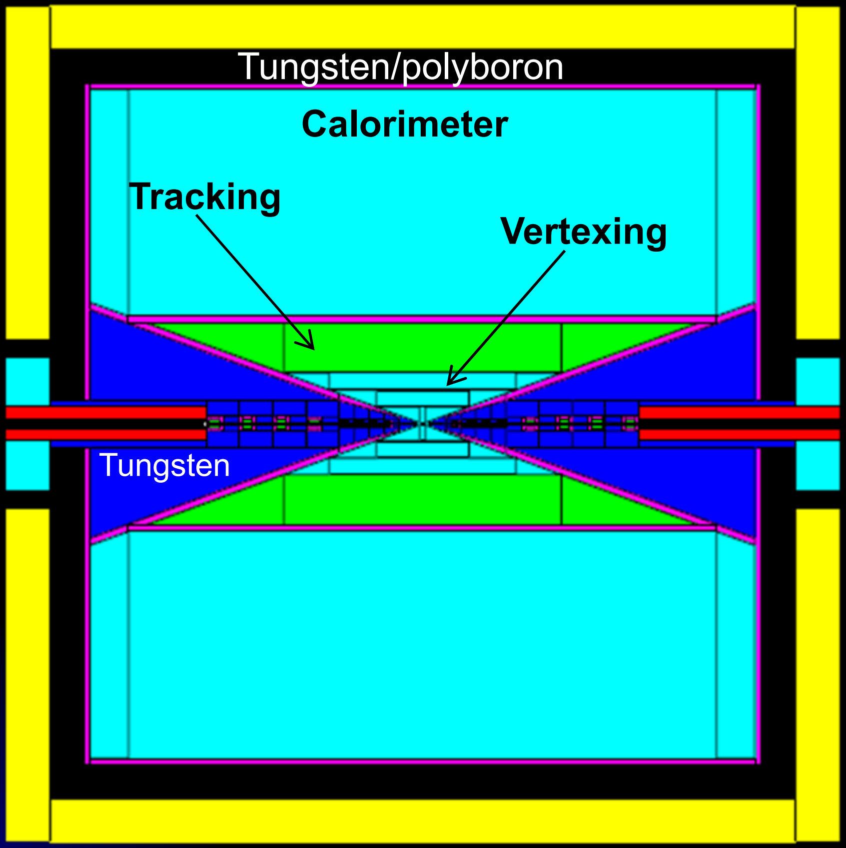
Fermilab

Muon Collider Workshop

Fermilab November 10-12, 2009

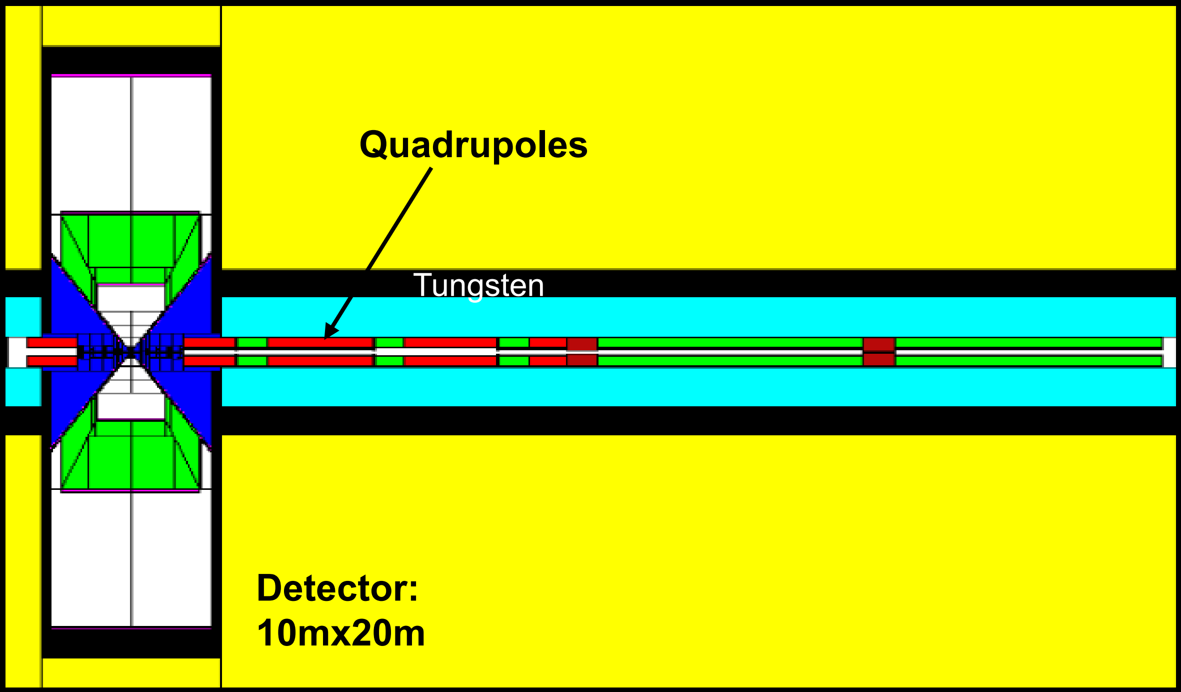
Design Study

- In 1996, at the 'DPF/DPB Summer Study on New Directions in High-energy Physics' in Snowmass, a design study was carried out for a Muon Collider Detector
  - Contributions at: http://www.slac.stanford.edu/pubs/snowmass96/



- Design study focused on central region
- Study not really updated since 1996
- Shown +/- 10 meters of interaction region, as modeled in GEANT

Final Focus



- Last 130 m of beam delivery system (BDS):
  - four quadrupoles: final focus for the intersection region
  - One 8T dipole used as scraper
  - 2T detector solenoid
  - 2 bunches with 2.10^{12} muons/bunch, bunch length (width) 3mm (3μm)
  - $L=10^{35} cm^{-2} s^{-1}$, 2x2 TeV

Backgrounds

- Fluences for two bunches of 10^{12} μ's each (Snowmass study)
  http://www.slac.stanford.edu/pubs/snowmass96/PDF/DET081.PDF
- Longitudinal Fluence

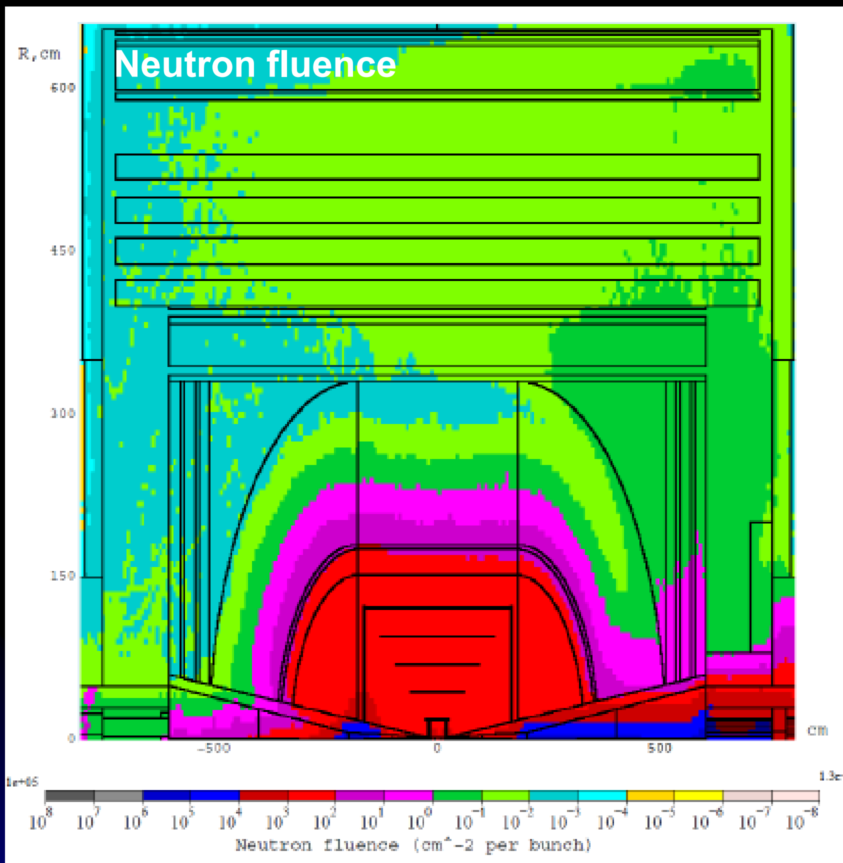
Detector	Radius(cm)	γ's	neutrons	$e^{\pm}$	$\pi^{\pm}$	protons	$\mu^{\pm}$
Vertex	5-10	7900	1100	69	14.4	0.8	1.5
	10-15	3100	1200		3.7	0.05	0.5
	15-20	1600	1000		4.6	4.0	2.3
Tracker	20-50	450	870		0.8	3.9	0.3
	50-100	120	520		0.1	2.2	0.06
	100-150	130	330		0.003	0.4	0.01
Calorimeter	160-310						0.002
Muon	310-10000						0.0002

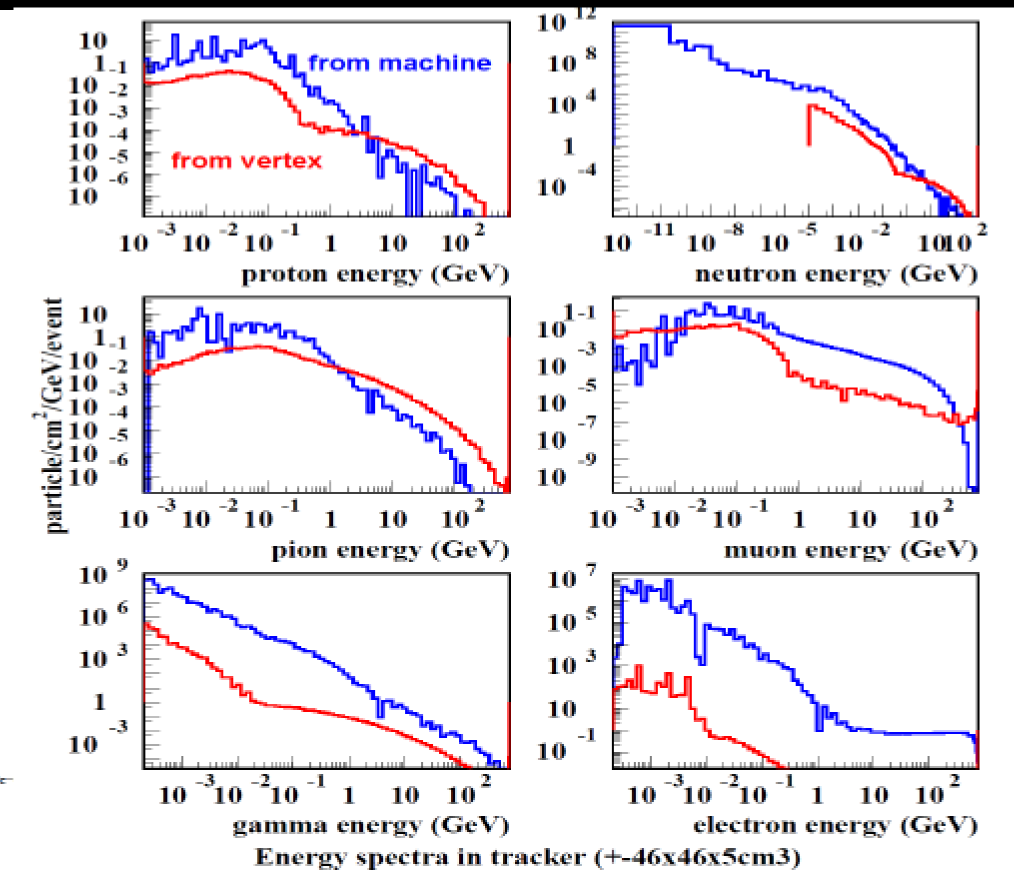
- Radial Fluence

Detector	Radius(cm)	γ's	neutrons	$e^{\pm}$	$\pi^{\pm}$	protons	$\mu^{\pm}$
Vertex	5	16900	1600	84.0	9.5	1.7	.35
	10	4800	1400	9.4	4.5	1.4	0.43
	15	2200	1400	2.1	2.1	1.1	0.33
	20	1250	1400		1.3	1.9	0.20
Tracker	50	440	1500		0.22	4.2	0.032
	100	160	360		0.04	0.8	0.008

Updated Backgrounds

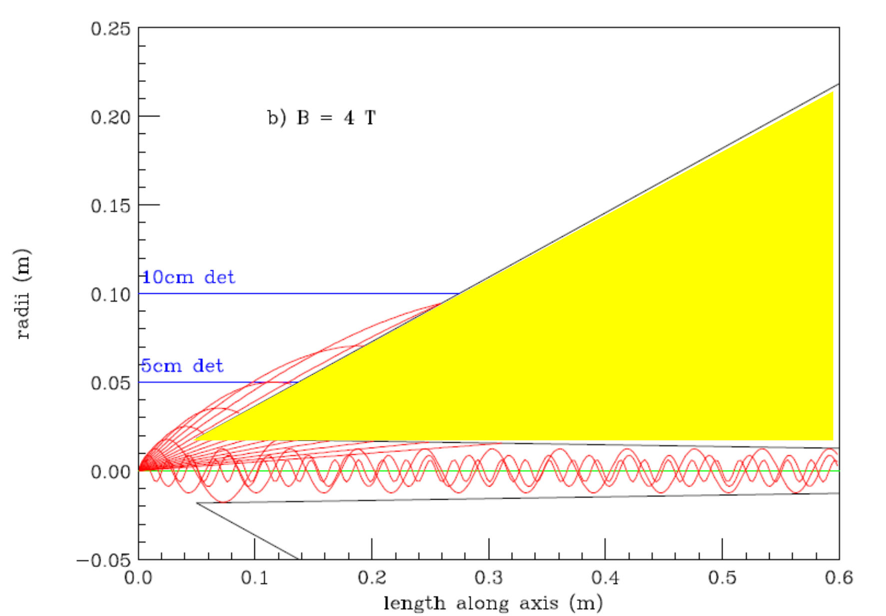
- From Nikolai Mokhov's talk yesterday





Beam Envelope

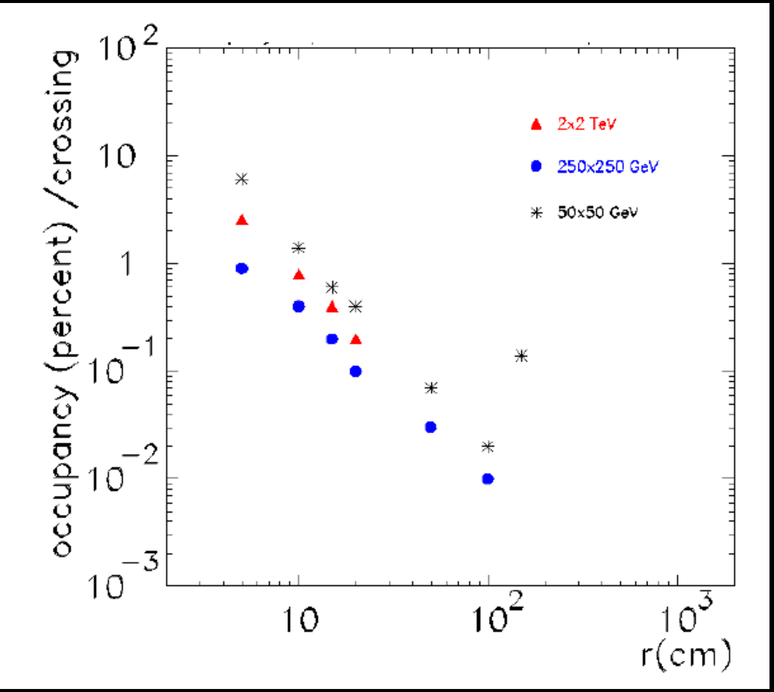
- Incoherent pair production from $\mu^+\mu^- \rightarrow \mu^+\mu^- e^+e^-$ significant for high energy muon colliders.
  - Estimated cross section of 10 mb giving 3×10^4 electron pairs per bunch crossing.
  - In 2 Tesla field, 10% of electrons make it into 10 cm fiducial volume
  - In 4 Tesla field, fluence factor 2 less at 5cm than at 2T



- Beam envelope will dictate the radius of the inner layer of the vertex detector, which is critical for heavy flavor physics program.
- Please note that studies to date have mitigating effect of 20 degree W cone.

Old Design: Vertex Detector

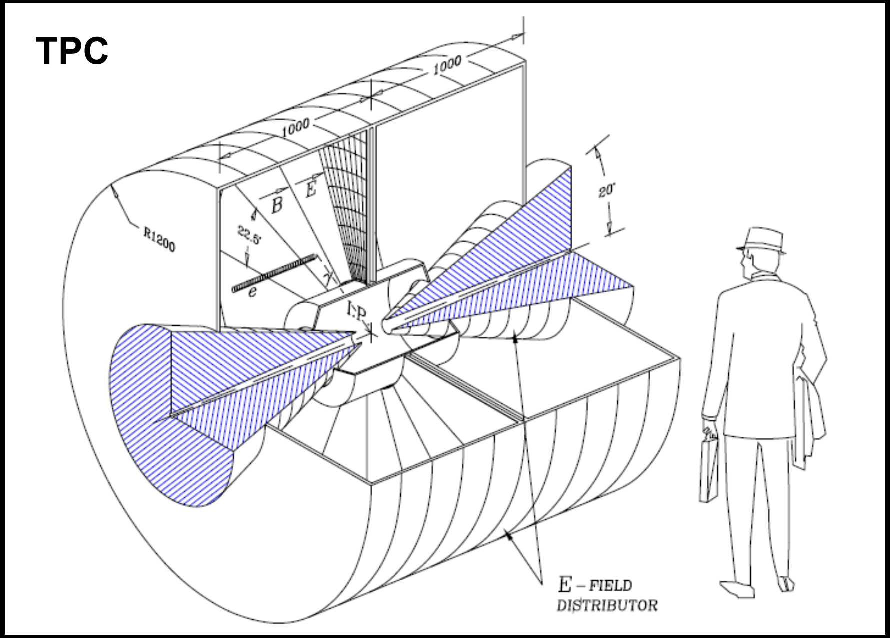
- Old design proposed Si pad detector
  - Pads: 300 μm × 300 μm
  - Assuming interaction probabilities of 0.003 and 0.0003 for low energy photons and neutrons, respectively
- Occupancy at 2x2 TeV at R=5 cm is about 3% for barrel region



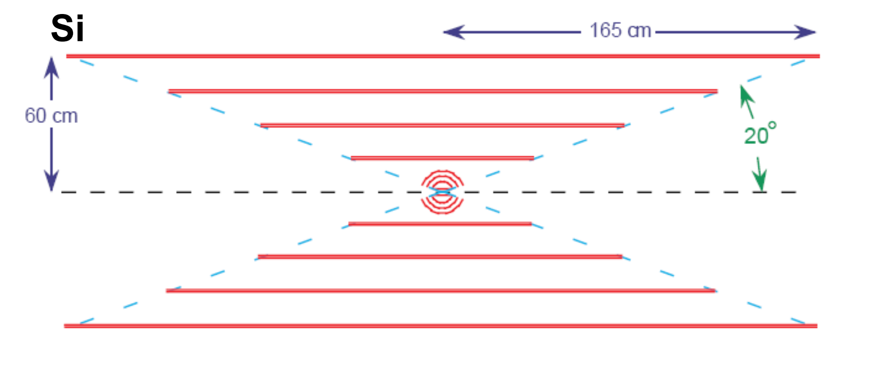
- With today's pixel technologies occupancies should be quite manageable in the barrel region. Forward region unexplored territory
- The issue will be: how close in to the IP can the first layer of the vertex detector be
  - Dzero and CDF have first layer starting at ~17 mm !
  - ILC detectors start at ~12 mm

Old Design: Tracking

- Options considered:
  - Conical shaped TPC
    - Pitch 0.3×0.4 cm^2
  - Conical 4-layer Si strip tracker
- The long bunch crossing time an advantage for both options



- Large neutron flux:
  - Gas mixture for TPC
  - Radiation hardness Si

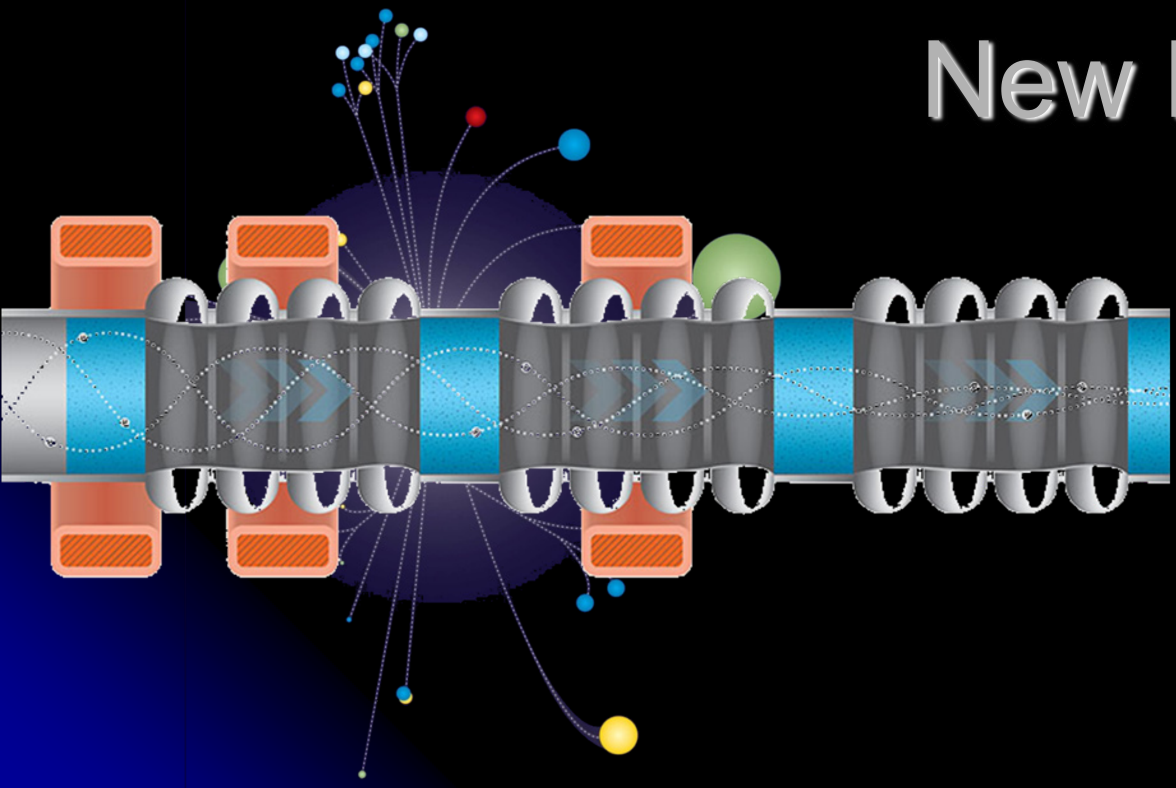


- Effects of large backgrounds:
  - Pattern recognition
  - Mass budget for Si tracker with stereo readout
  - Positive ion build up in TPC

Old Design: Calorimetry

- Calorimeter of 4 m length considered, with R_{in} = 120 cm
- EM Calorimeter: 2x2cm^2 cells, 25 X_0
  - Photon flux gives: $\langle E_{Tower} \rangle$ ~ 400 MeV, σ_E ~ = 30 MeV
- Hadron Calorimeter:
  - Fluence of ~100 n/cm^2 at R = 150 cm with $\langle E_n \rangle$ = 30 MeV gives total energy flow into hadron calorimeter of ~ 140 TeV
    - Large uncertainty on this quantity
  - LAr/Cu sampling calorimeter was proposed in 1996
  - Assumed small fraction of the neutrons to knock off protons and only about 10% of the proton ionization to be visible in the liquid
  - With 10^4 towers, $\langle E_{Tower} \rangle$ ~ 100 MeV

New Developments



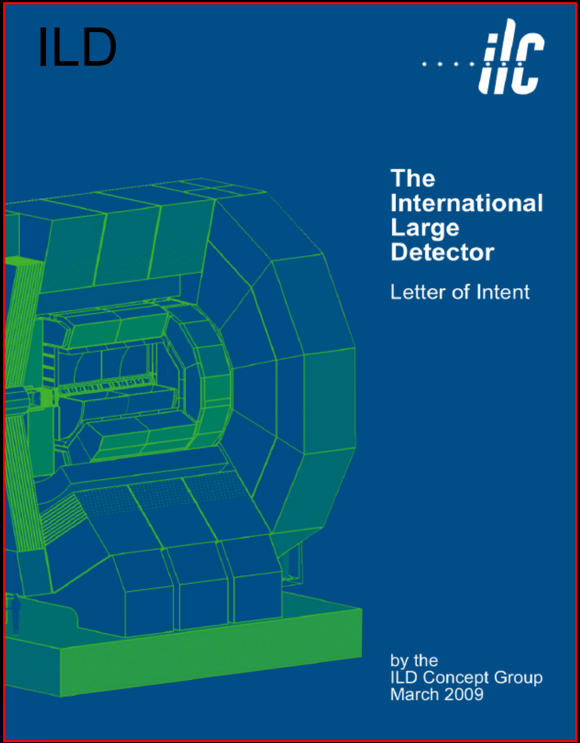
New Developments

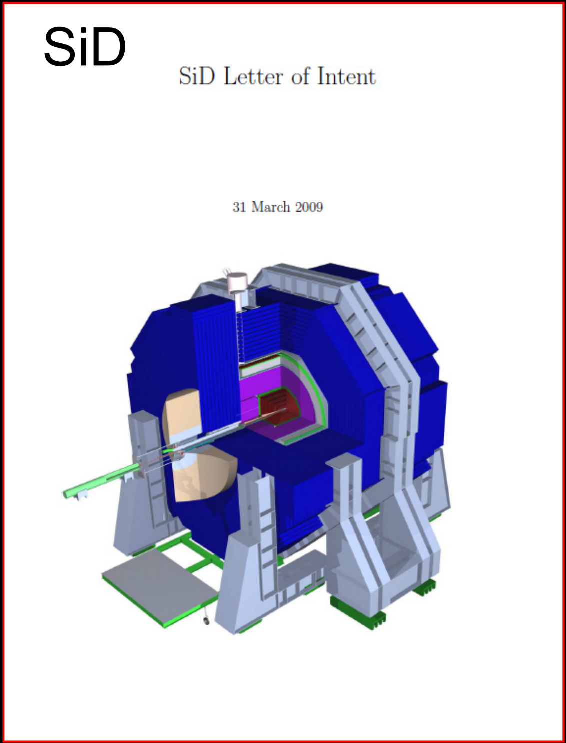
- Specifications for e^+e^- colliders have been clearly formulated over the course of the last years for:
  - Collider parameters
    - Energy, Luminosity, Polarization, Final Focus, Beam Delivery, Train Structure, Repetition Rate, Bunch Structure, …
  - Measurement of collider parameters
    - Energy, Luminosity, Luminosity Profile, Polarization
  - Collider detectors
    - See table
- More than a decade of detector R&D has occurred, in large part driven by the ILC project, to meet these specifications
- A benchmark for physics processes now exists

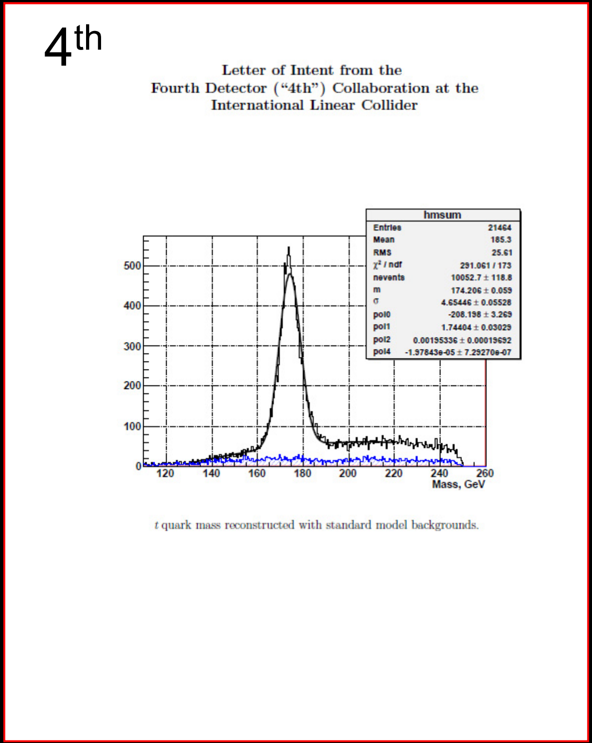
Detector	ILC
Vertexing	$5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m}}{\mathrm{p}\,\sin^{3/2}\vartheta}$
Solenoidal Field	$\mathrm{B} = 3\text{-}5\ \mathrm{T}$
Tracking	$\frac{\delta \mathrm{p_T}}{\mathrm{p_T^2}} = 5 \cdot 10^{-5}$
EM Calorimeter	$\frac{\sigma_\mathrm{E}}{\mathrm{E}} = \frac{0.10}{\sqrt{\mathrm{E}}} \oplus 0.01$
HAD Calorimeter	$\frac{\sigma_\mathrm{E}}{\mathrm{E}} = \frac{0.50}{\sqrt{\mathrm{E}}} \oplus 0.04$
E-Flow	$\frac{\sigma(\mathrm{E_{jet}})}{\mathrm{E_{jet}}} = 0.03$

ILC Benchmark Reference

- The three ILC detector concepts submitted LOIs on March 31, 2009



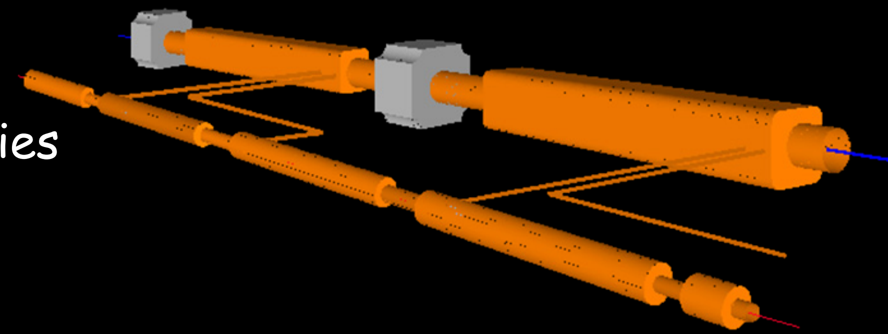




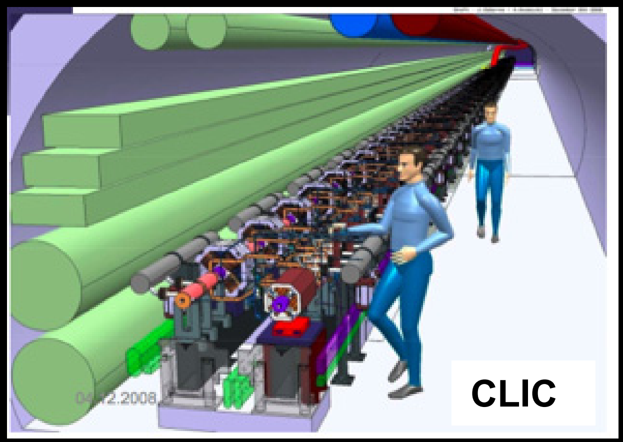
- These documents form a solid reference and benchmark for the detector and physics performance at a lepton collider in the energy range of 500 GeV – 1 TeV

CLIC Benchmark Reference

- The CERN Linear Collider Physics and Detector project has called for a 4-volume Conceptual Design Report (CDR) by the end of 2010.
  - Executive summary document
  - CLIC accelerator and site facilities
  - Physics and Detectors
  - Costing



- The CDR will mostly be based on simulation studies for the CLIC case and existing ILC hardware experience
  - CLIC-specific hardware R&D will commence after 2010
  - The CDR will not demonstrate feasibility for all issues



- Reports provide useful reference for μC physics reach and create synergies

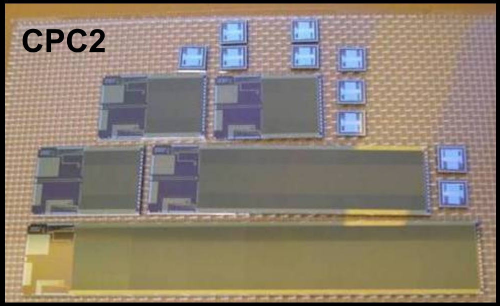
New Detector Developments

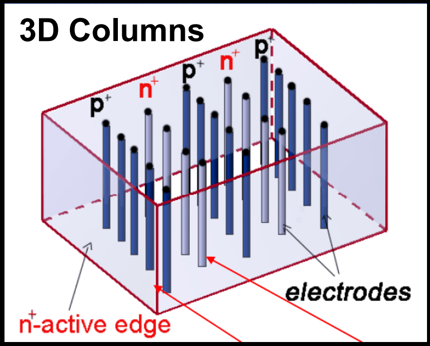
- The detectors proposed for lepton colliders are real precision detectors
  - Identify each and every particle, with high efficiency and high purity, over the full angular range
    - Differentiate between Z's and W's in their hadronic decay
    - Differentiate between b- and c-quarks
    - Differentiate between b- and anti-b quark
- The technologies being pursued are often transformational technologies
- Highlight some technologies with long time horizon

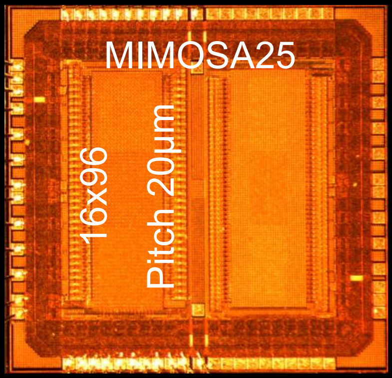
Parameter	LHC	ILC	CLIC	$\mu^+\mu^-$	$\mu^+\mu^-$
E (TeV)	14	0.5	3	1.5	3
L ($10^{34}cm^{-2}s^{-1}$)	2	2	5.9	1	4
Bunch X (ns)	25	369	0.5	3800	6400
Nb	2808	2625	311	1	1
Train duration	70 ms	1 ms	156 ns		
Rep. Rate	40M	5	50	65	32

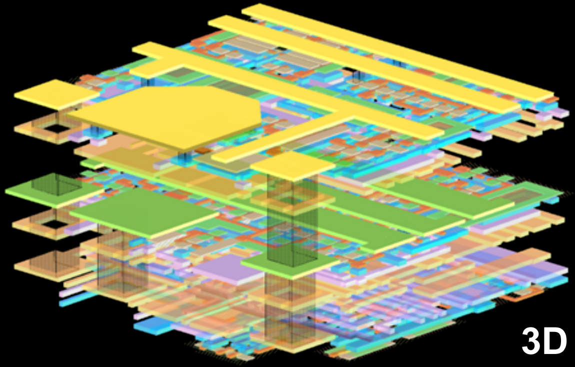
Vertex Detector Technologies

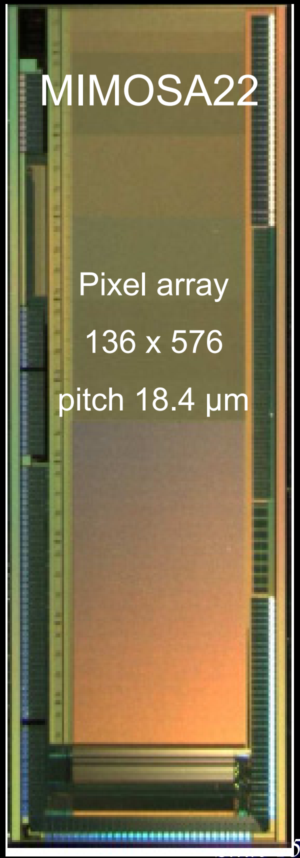
- CCD's
  - Column Parallel (UK)
  - Fine Pixel (Japan)
  - ISIS (UK)
- CMOS Active Pixels
  - Mimosa (Strasbourg)
  - INFN
  - LDRD 1-3 (LBNL)
  - CAP 1-4 (Hawaii)
  - Chronopixel (Oregon/Yale)
- SOI
  - American Semiconductor/FNAL
  - SOI (LBNL), CAP5 (Hawaii)
  - OKI/KEK
- 3D Vertical Integration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





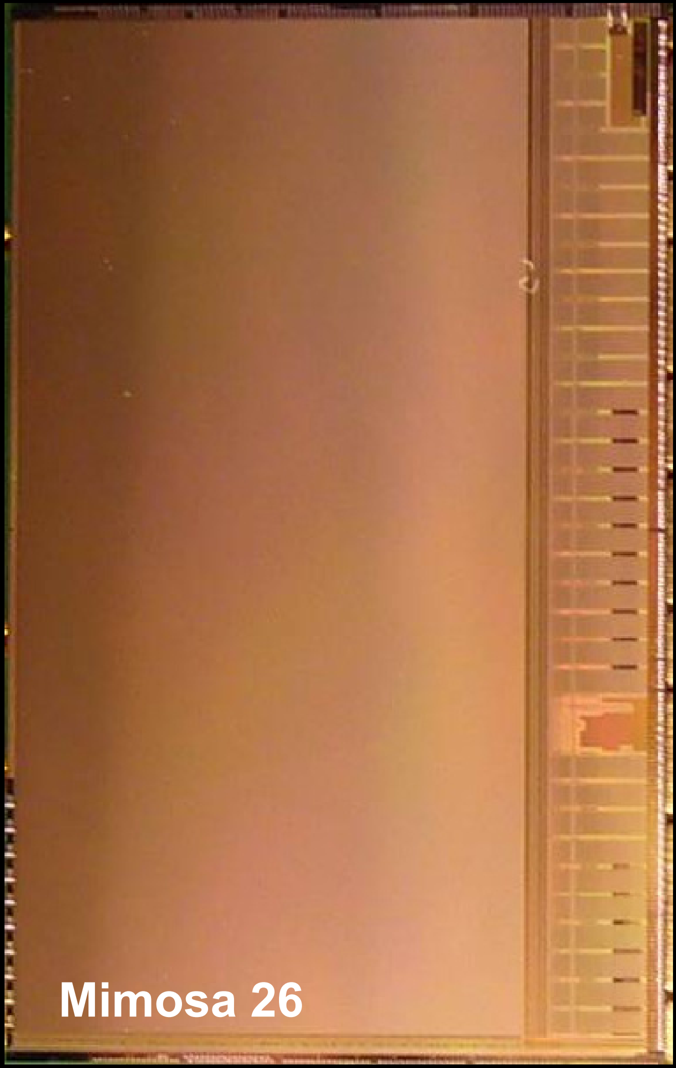






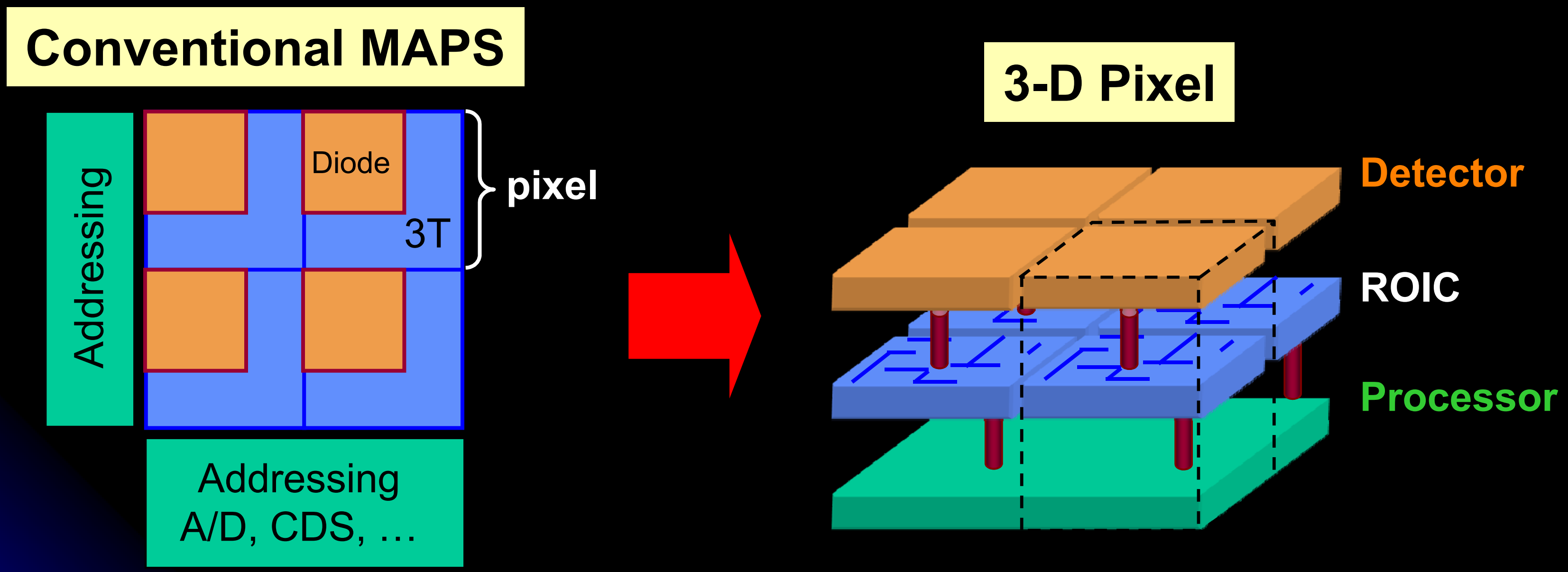
Mimosa-26

- Mimosa-26 has been deployed as beam test telescope at DESY and CERN
  - Column parallel readout
  - Pixel size 18.4 x 18.4 μm^2
  - Chip size: 13.7 x 21.5 mm^2
  - 1152 // columns of 576 pixels
  - ~11–16 μm epi-taxy
- Architecture
  - Amplifier, CDS and zero suppression, with integrated 4/5-bit ADC per pixel
- Specifications:
  - Each pixel Integration time: ~ 100 μs: R.O. speed: 10 k frames/s
  - Acceptable hit density: ~ 10^6 particles/cm²/s
- Possible variant
  - 16 μm pitch with binary readout



Vertical Integration – 3D

- Vertical integration of thinned and bonded silicon tiers with vertical interconnects between the IC layers
  - Technology driven by industry
- If the technology can be brought to fruition, potential nearly unlimited: transformational new detectors
  - Fermilab currently studying possible application for CMS Track Trigger



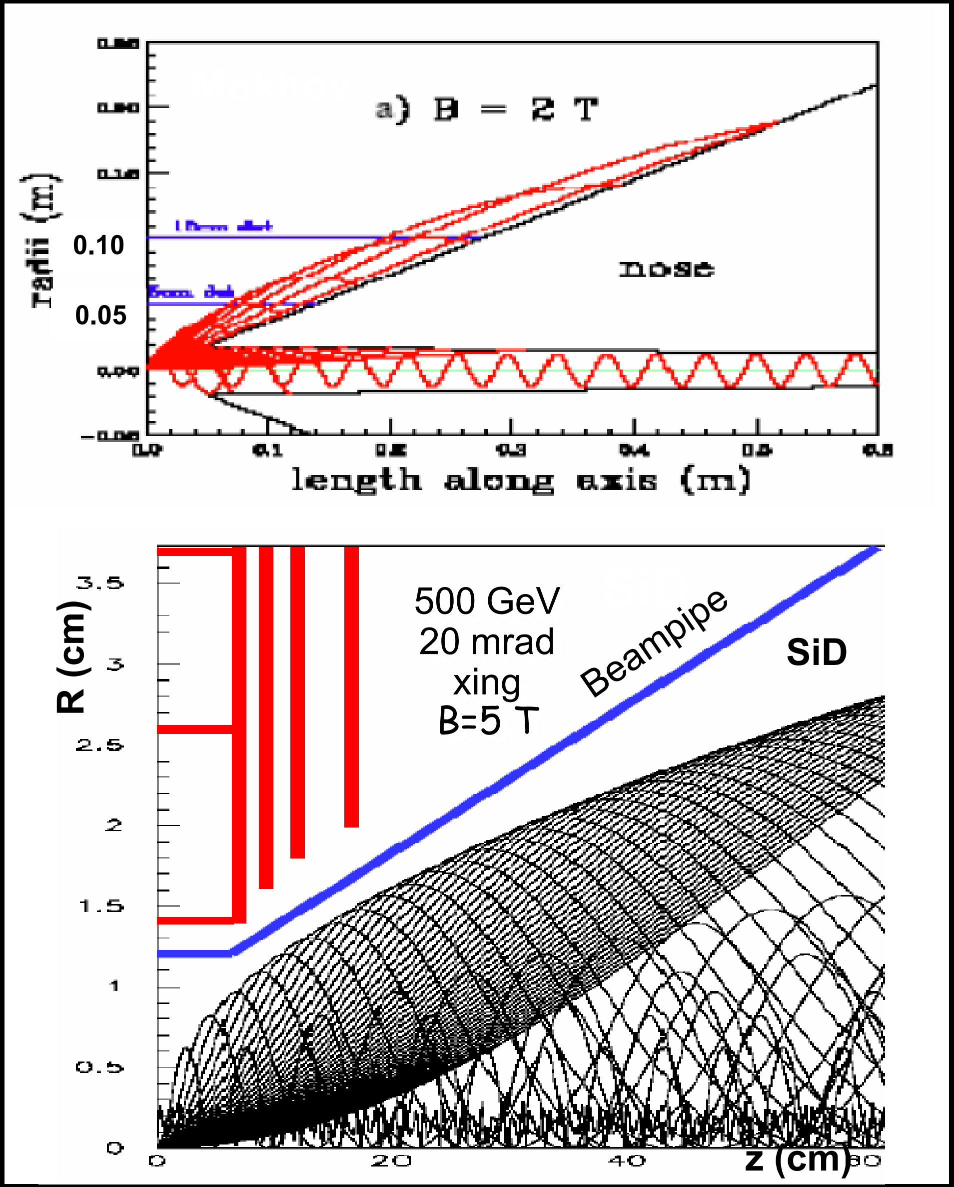
Vertexing

- The issue for a vertex detector – on the timescale of >2025 – is most likely not going to be the detector technology, but most likely the radius of the first layer and its angular coverage
  - Impact parameter resolution

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

    increases ~linearly with R_{in}
  - Quantify physics balance

    $$\left.\frac{\partial Ph}{\partial R_{in}}\right|_{L=const} \qquad \left.\frac{\partial Ph}{\partial L_{in}}\right|_{L=const}$$

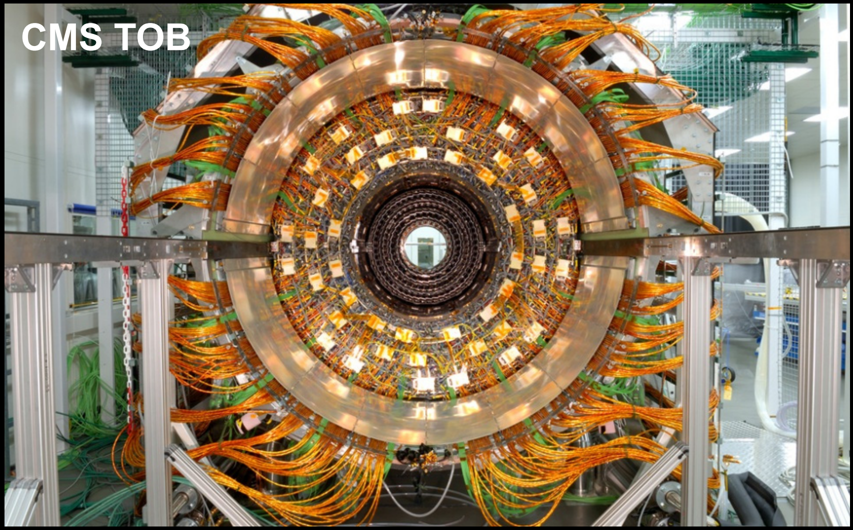


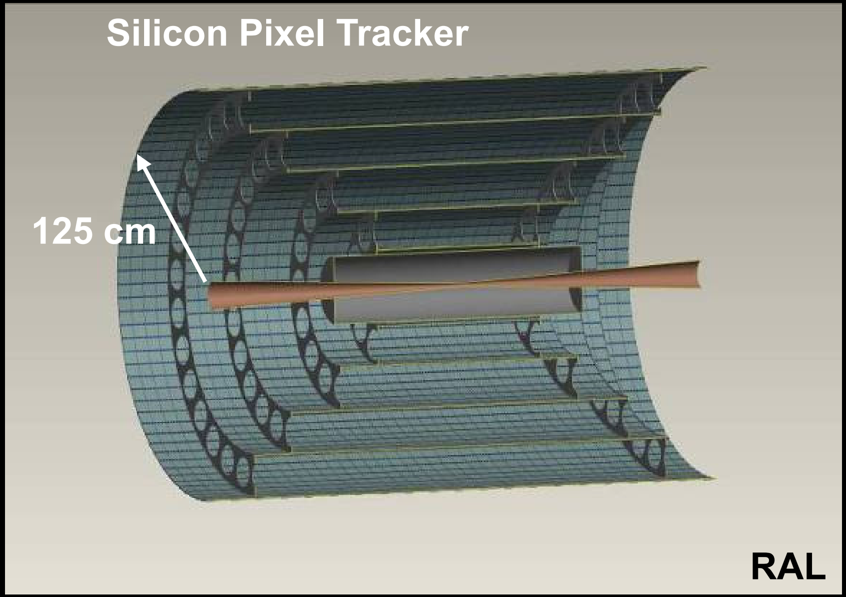
Silicon Tracking

- Robust Si trackers have been built already: CMS
- Robust Si tracker designed for ILC by SiD concept:
  - Robust pattern recognition and good two track separation
  - Superb momentum resolution

$$\frac{\delta p_T}{p_T^2} = 2 - 5 \cdot 10^{-5} \oplus \frac{1 \cdot 10^{-3}}{p_T \sin \vartheta}$$

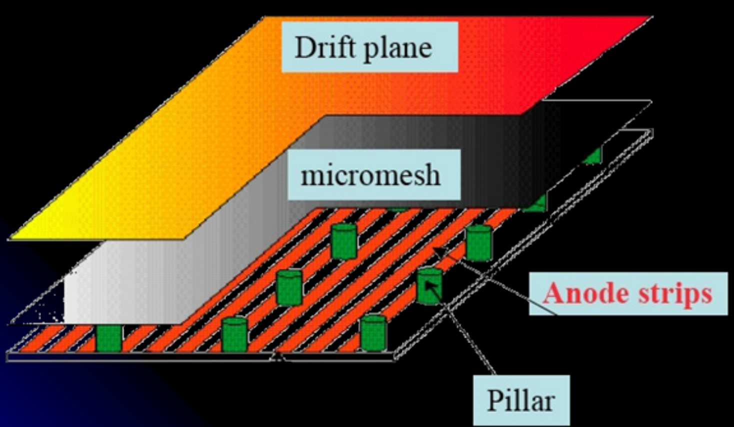
- Effects of large neutron flux need to be understood
- Currently even Si pixel trackers being considered
  - Extremely high granularity
  - Low power consumption
  - Large bunch crossing time benefit



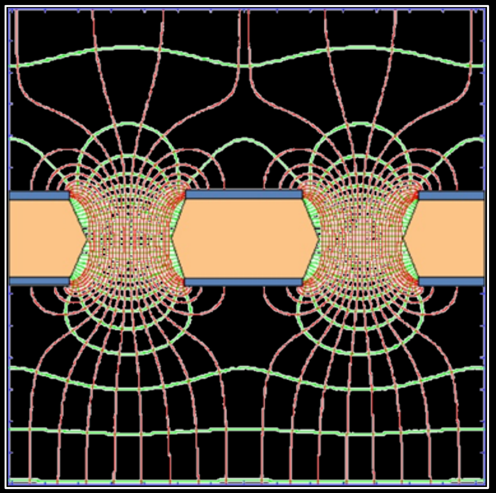


TPC Tracking

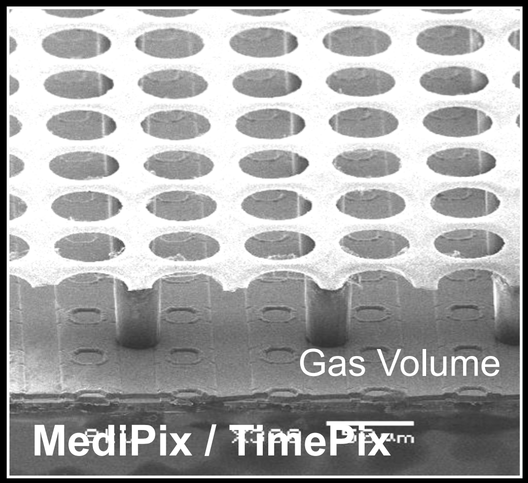
- R&D ongoing on three TPC technologies
  - MicroMegas: gap with thin cathode mesh
  - GEM: thin metal-coated polymer foils
  - Gas amplification + CMOS
    - Use bare CMOS chip as anode to collect signals gas amplification
    - Charge collection with granularity matching primary ionization cluster spread
    - If CMOS chip includes 3rd coordinate (time), image the ionization process



Y. Giomataris et al, NIM A376 (1996) 239

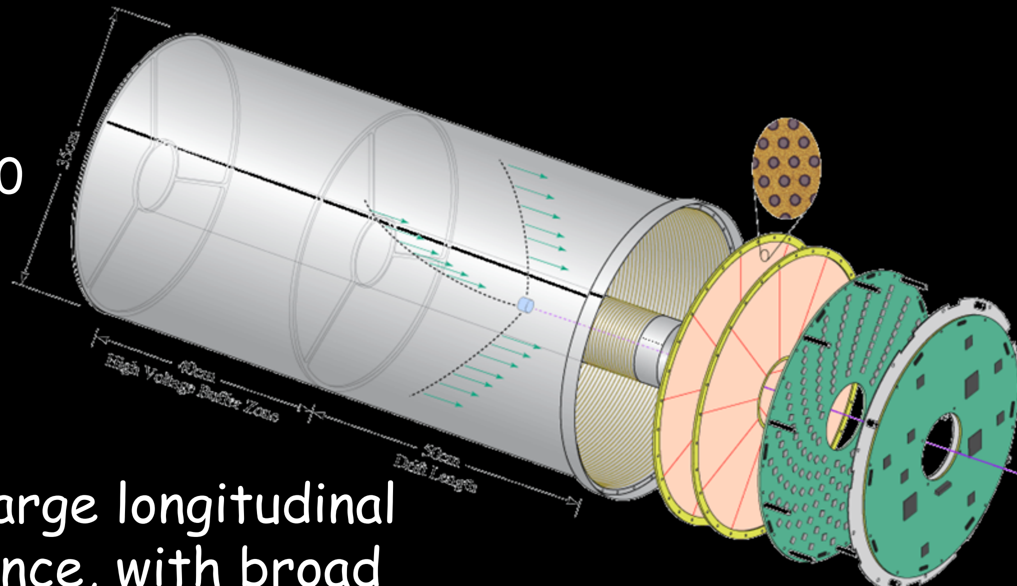


F. Sauli, NIM A386 (1997) 531

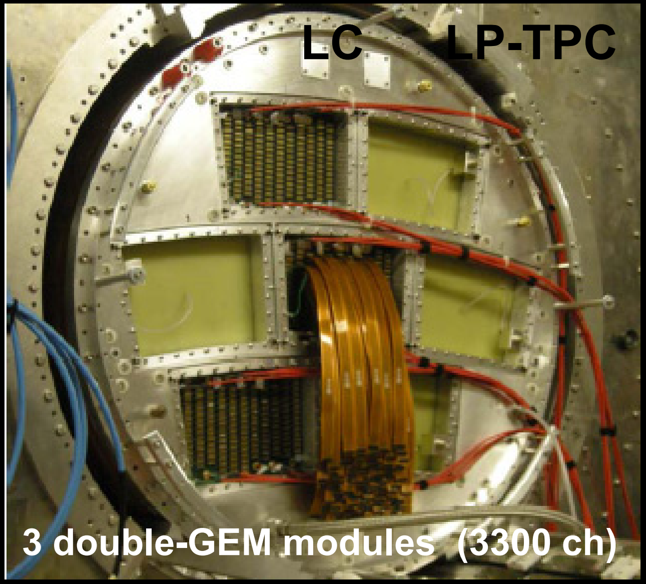


TPC Tracking

- TPC R&D goals:
  - $\delta p/p \leq 0.1\%$, B=4T
  - Material <3% X_0 near $\eta = 0$ <15%X_0 endcap
  - pads per endcap > 10^6
  - Average hit resolution of 100/500 μm $r\phi/z$ @ 4T
- Positive ion build-up with large longitudinal and radial background fluence, with broad time distribution, may significantly affect performance



- Tracking in forward region not addressed by TPC
- To understand issues, need full simulation, including all backgrounds, to quantify performance



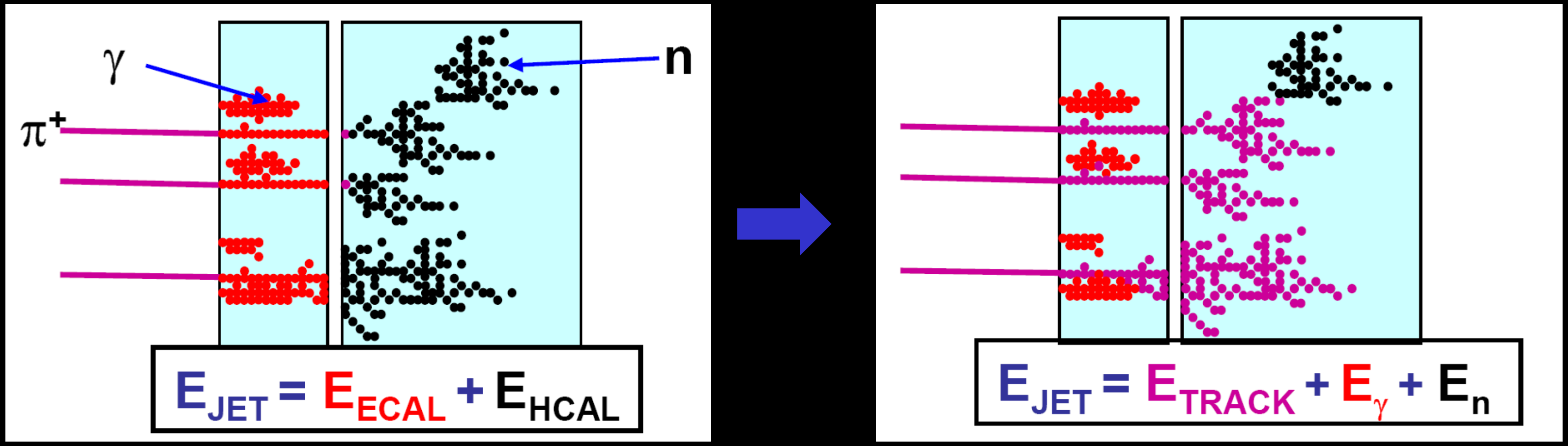
Calorimetry

- Superb calorimetry lies at the heart of lepton collider detectors, partly because of the very small cross sections
- It has been accepted that a jet energy resolution of 3-4% is required for a lepton collider
  - Ability to separate $Z \rightarrow qq$ from $W \rightarrow qq'$
- An extremely active R&D program is being carried out

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

PFA

- Goal: obtain a jet energy resolution of 3-4% for 40 Gev < E_{jet} < 500 GeV, through a combined use of the tracking and ECAL system and using the HCAL to only measure neutrals

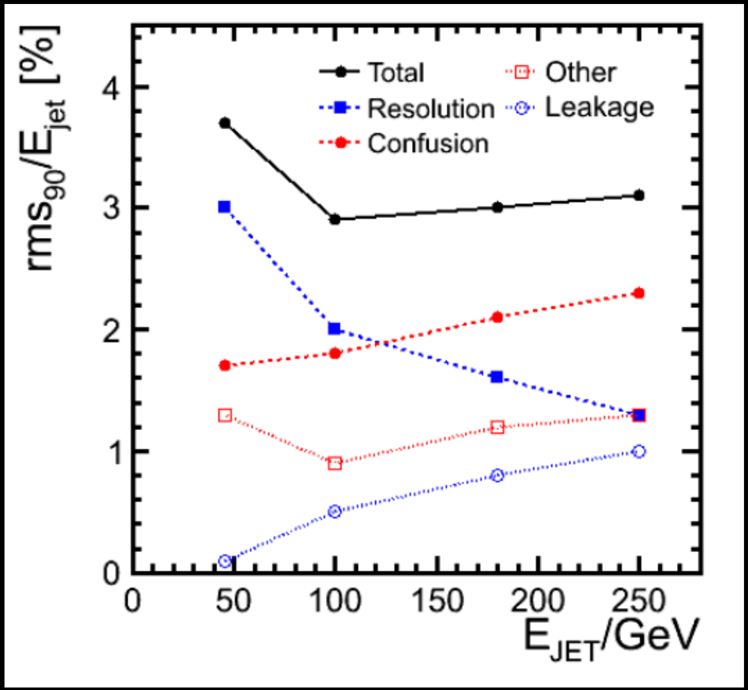


- Robust PFA algorithms have been developed within the ILC community
  - Goal of 3% energy resolution achieved based on MC studies

E_{JET}	σ_E/E (rms_{90})	
	ILD	SiD
45 GeV	3.7 %	5.5 %
100 GeV	2.9 %	4.1 %
180 GeV	3.0 %	4.1 %
250 GeV	3.1 %	4.8 %

PFA Performance

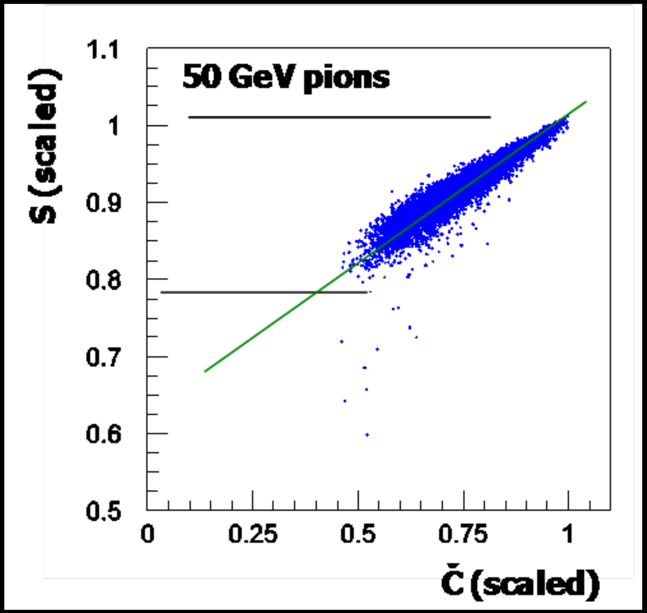
- Quantitative understanding of PFA performance being developed (M. Thomson, ALCPG09)
- Breakdown of the various contributions to the energy resolution
- At high energy the confusion term dominates
  - Confusion = incorrect assignment of hits to tracks / EM clusters
  - Cross-over at E_{jet} = ~100 GeV
- How viable is PFA at a μC ?
  - Large longitudinal background
  - Timing of hits?
  - Background of neutrons?

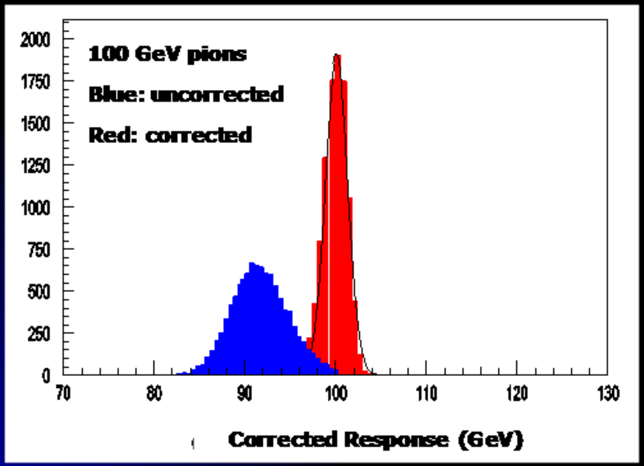


Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

250 GeV Jets

Dual Readout Calorimetry

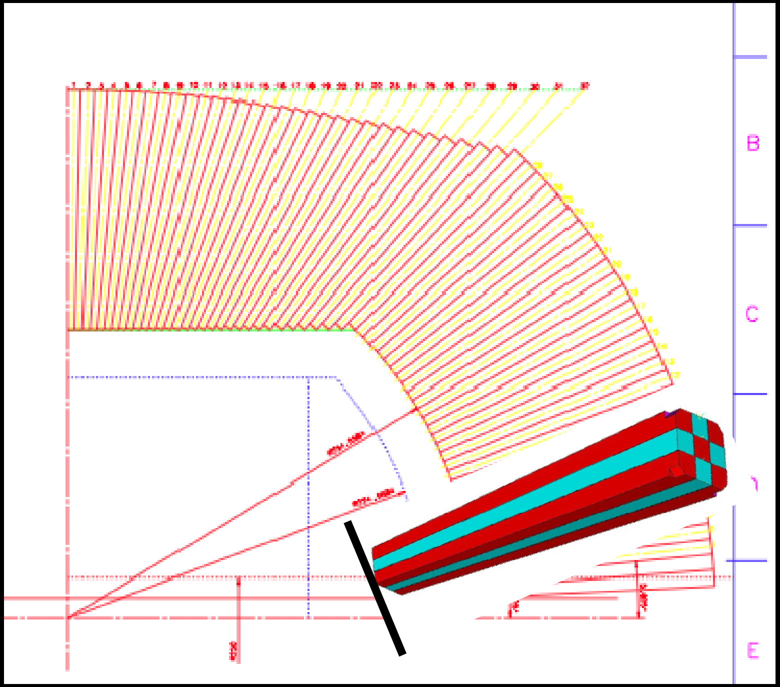




- Dual-Readout: measure every shower twice
  - Scintillation light: from all charged particles
  - Čerenkov light: β=1 particles, mainly EM
- Correct on a shower-by-shower basis using the correlation of the total observed ionization (S) and Čerenkov (Č) light
- From Monte Carlo studies:
  - Energy resolution $(0.2\text{-}0.25)/\sqrt{E}$ (Gaussian)
  - No (small) constant term
- Technologies:
  - Embedded scintillating and quartz fibers
  - Crystals

Fiber Calorimetry

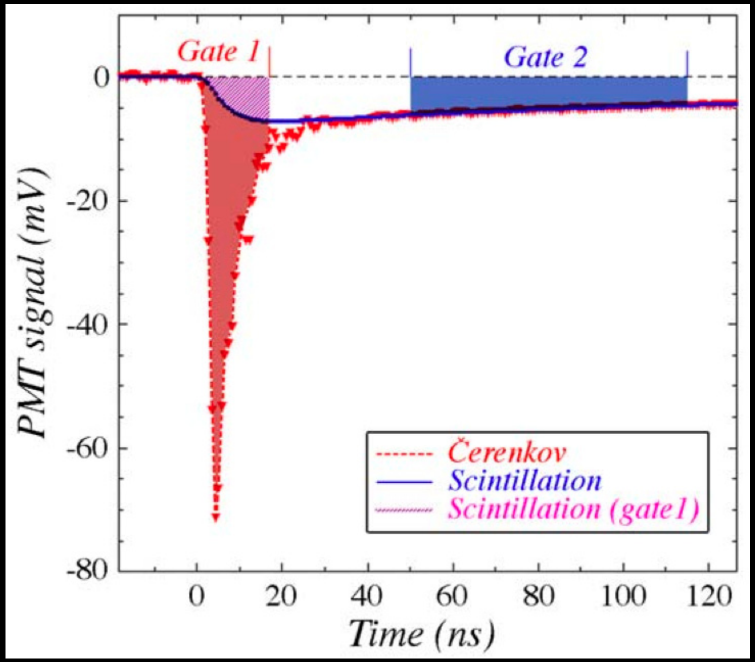
- ILC 4th concept proposed fiber calorimeter employing copper matrix loaded with 1 mm diameter alternating scintillating and clear fibers every 2 mm.
  - Based on well-established dual readout calorimetry with DREAM

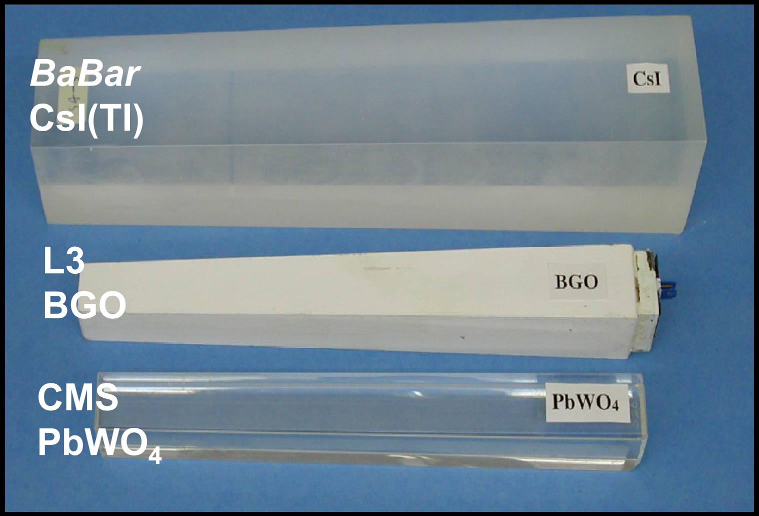


- Could measure the neutron content of a shower by the time-history of the scintillation signal
  - Neutron velocity ~ 0.05c
- Such a calorimeter has no longitudinal segmentation
- Do GHz waveform digitizers provide background rejection?

Crystal Calorimetry

- Total absorption hadron calorimetry has been proposed with dual readout
  - Differentiate Čerenkov and scintillation light
    - Optical filters
    - Timing
  - Timing allows differentiation using one readout
  - Modest longitudinal segmentation possible



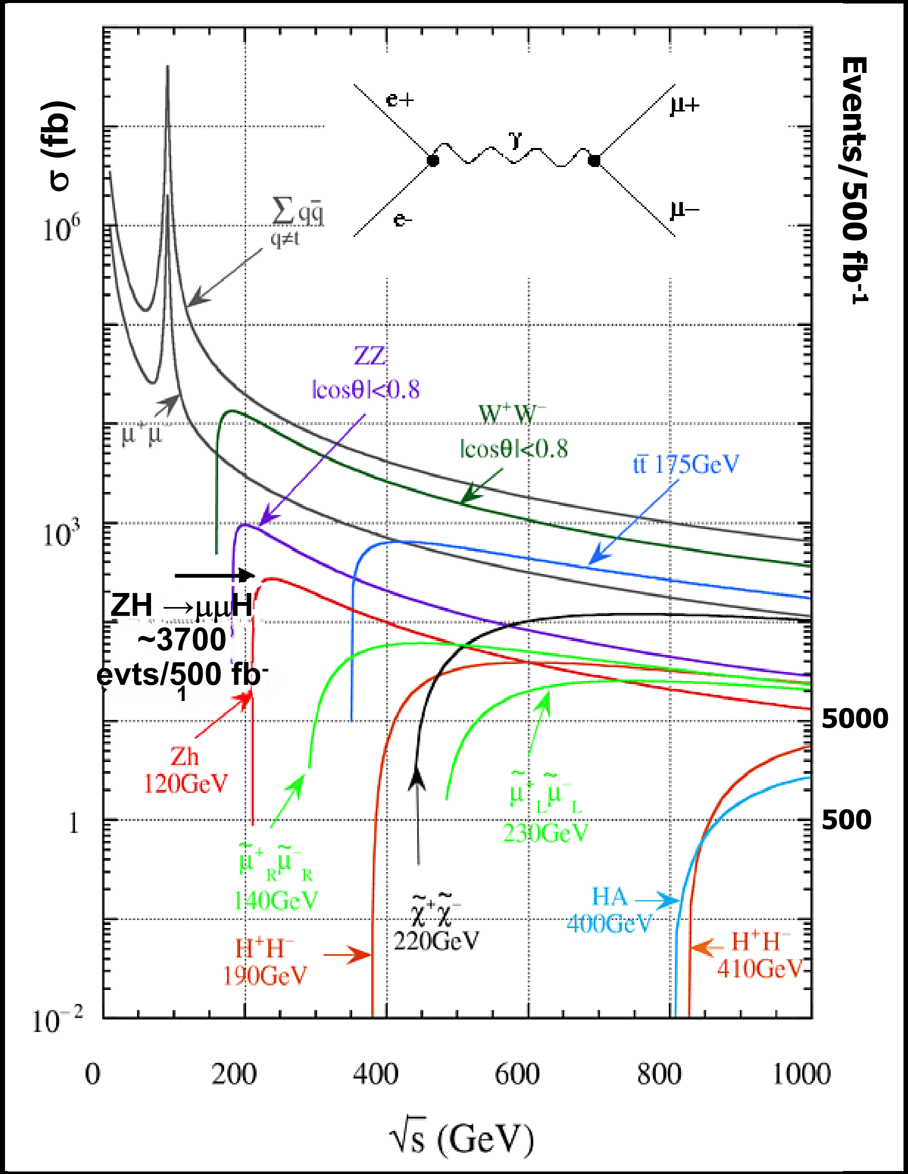


- What is the effect of the neutron cloud in the calorimeter?

- Will gating and/or GHz waveform sampling help in background rejection?

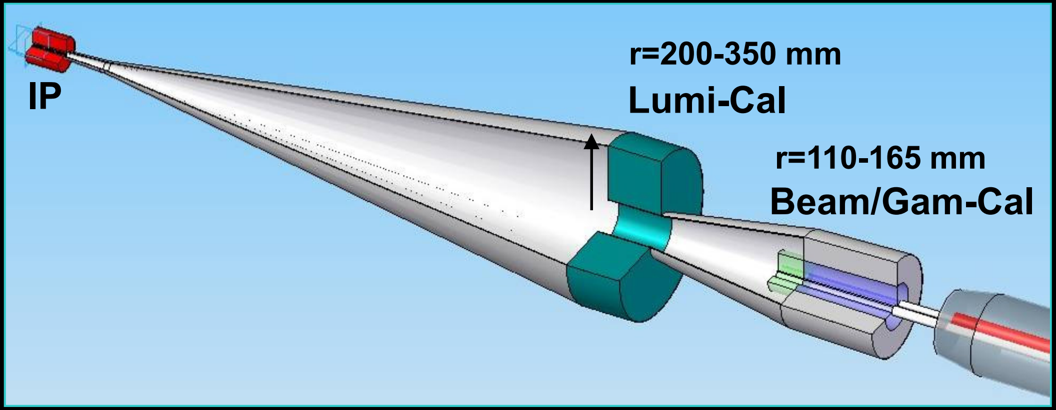
LC Physics Characteristics

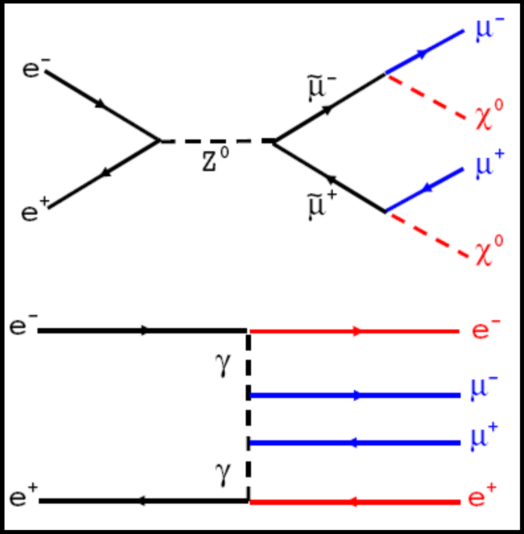
- Processes through s-channel spin-1 exchange: $\sigma \sim 1/s$
- Cross sections are small, but ~half the cross section is in the forward region
  - Angular distribution: $(1 + \cos^2\theta)$
- That region, which contains critical physics, has not been explored in μC studies to date



Instrumented Cone

- At e^+e^- machines the forward region is fully instrumented with calorimetry
  - High precision, fast readout
  - High radiation environment
- Lumi-Cal (40-140 mrad)
  - Precise measurement of the integrated luminosity ($\Delta L/L \sim 10^{-3}$) using Bhabha's
  - Veto for 2-γ processes
- Beam-Cal (5-40 mrad)
  - Beam diagnostics using beamstrahlung pairs
  - Provide 2-γ process veto
- Gam-Cal (< 5mrad)
  - Beam diagnostics using beamstrahlung photons





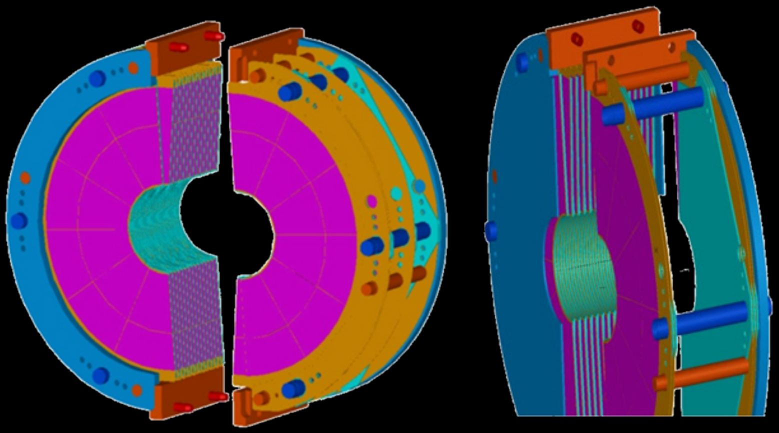
Physics signal: e.g. SUSY smuon production

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

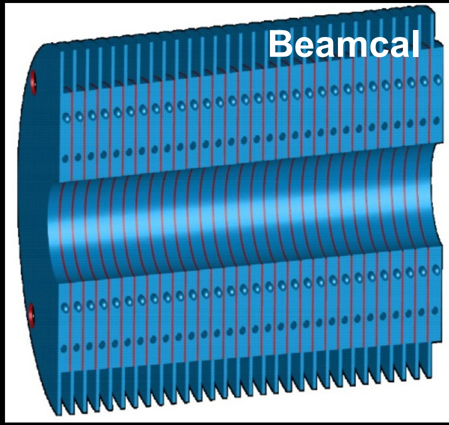
Forward Calorimeters

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

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



- Beam-Cal
  - Sensor/W calorimeter, 30 layers
  - Radiation dose: ≈ 500 MRad/annum
    - Energy deposit of ~200 TeV per beam crossing
  - Sensors:
    - Polycrystalline Chemical Vapor Deposit Diamond sensors
    - GaAs sensors
    - SiC
    - radiation hard silicon



Observation

- Backgrounds, backgrounds, backgrounds !!!
- To first order, the backgrounds will drive critical parameters of the μC detector design, not the physics
- Of course it is a bi-directional process but ultimately it is a trade-off in machine design versus detector performance and physics reach
- New detectors with unprecedented granularity are being pursued, which will aid in dealing with backgrounds
- Large degree of sophistication comes with a price; we have to remain realistic
  - World's supply of W is ~60,000 tons at $25/kg = $1.5 billion

Concluding Remarks

- There has been enormous progress in detector development since 1996 that a μC detector can exploit
- The backgrounds, however, pose significant challenges, which could be addressed with a targeted R&D program. Much study and development is needed
- The physics reach will be determined by a critical interplay between the beam delivery system and the detector performance
- Detectors at lepton colliders are precision instruments. Both the e^+e^- and $\mu^+\mu^-$ communities have a lot in common and a lot to share, with mutual benefit. Synergies should be capitalized on
- Much more in WG-2

5 Step Program

1. Specify reasonable baseline parameter set for the collider
2. Have a realistic beamline design and machine detector interface with full simulation of all backgrounds available for detector simulation
3. Develop detector design concept for μC detector, with optimistic but reasonable technology assumptions
4. Carry out simulation with full backgrounds included
5. Determine derivatives, sensitivities to detector and MDI parameters