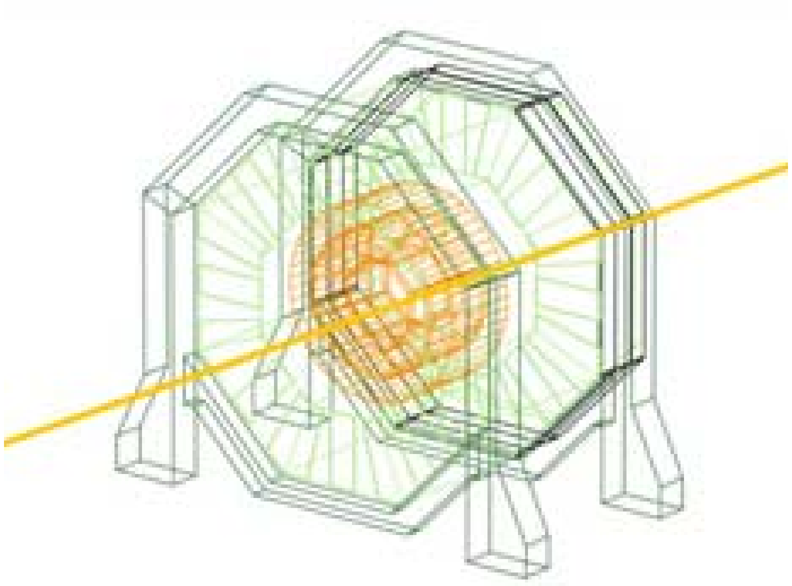
A Muon Collider Detector

‘in Perspective’



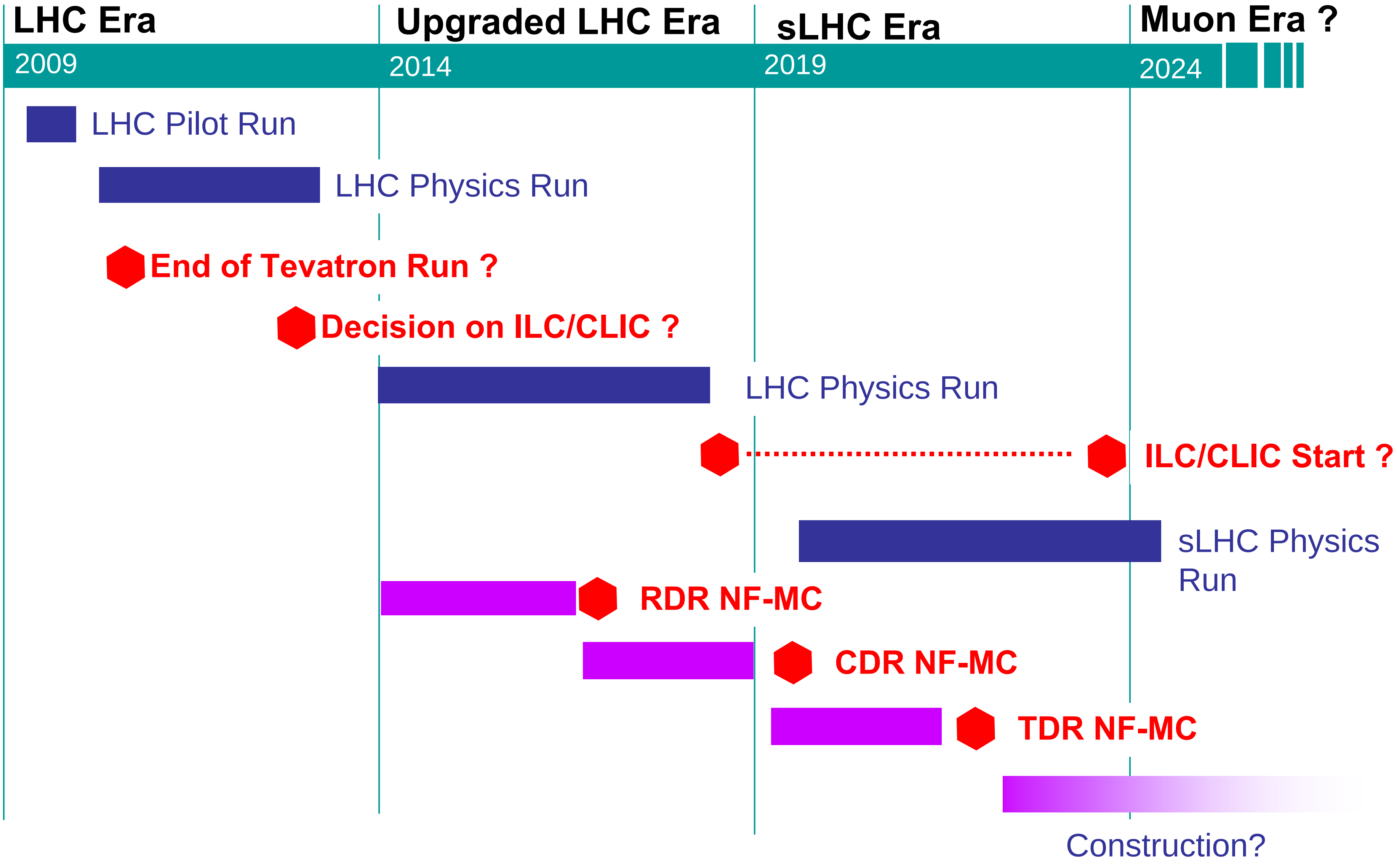
Marcel Demarteau

Fermilab

Neutrino Factory and Muon Collider
Collaboration Meeting

Berkeley, January 25-28, 2009

Evolution of Frontiers



LHC Era 2009

Upgraded LHC Era 2014

sLHC Era 2019

Muon Era ? 2024

LHC Pilot Run

LHC Physics Run

End of Tevatron Run ?

Decision on ILC/CLIC ?

LHC Physics Run

ILC/CLIC Start ?

sLHC Physics Run

RDR NF-MC

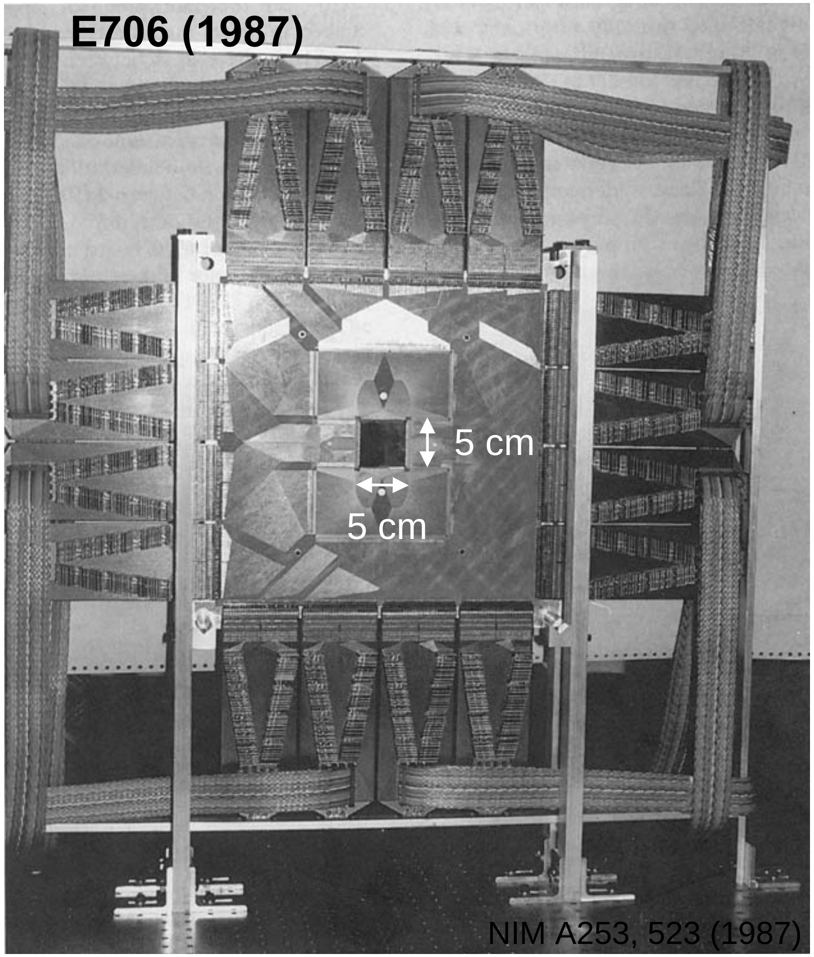
CDR NF-MC

TDR NF-MC

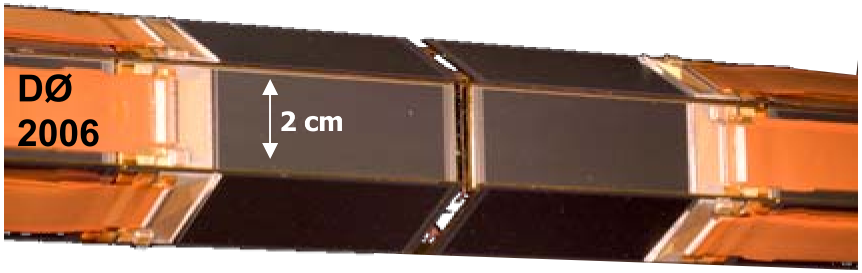
Construction?

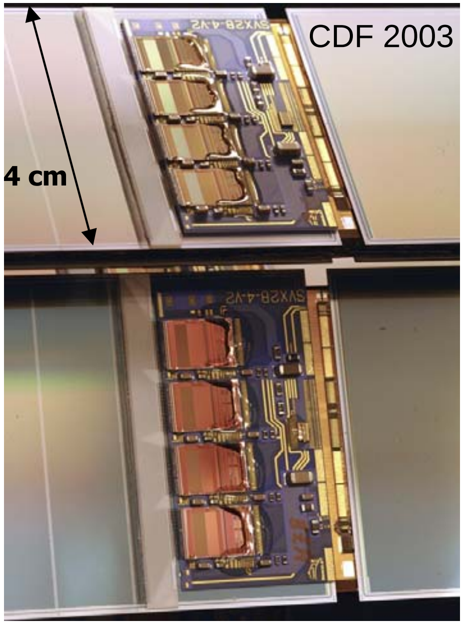
Evolution of Detectors

- **An example**



NIM A253, 523 (1987)





Please note: the LHC was proposed in 1987!

Much more functionality integrated in much smaller volume

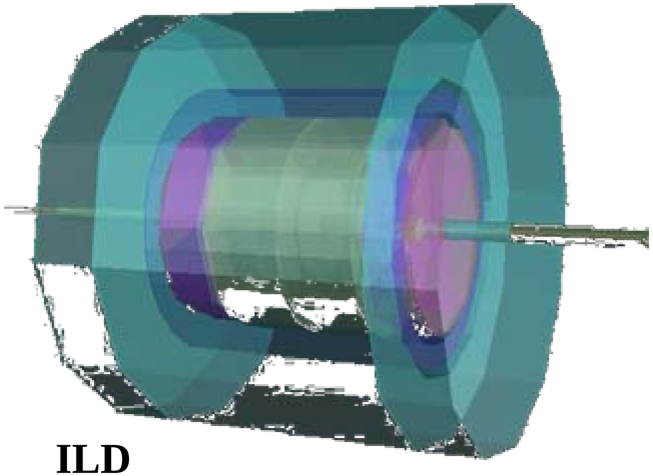
Evolution …

- **Feels a bit like …**

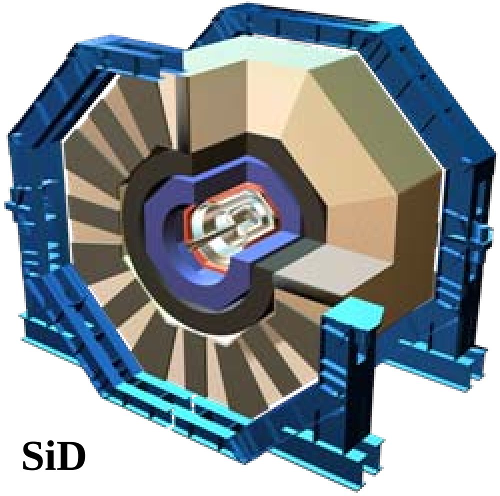
Folds into a briefcase !

Benchmark

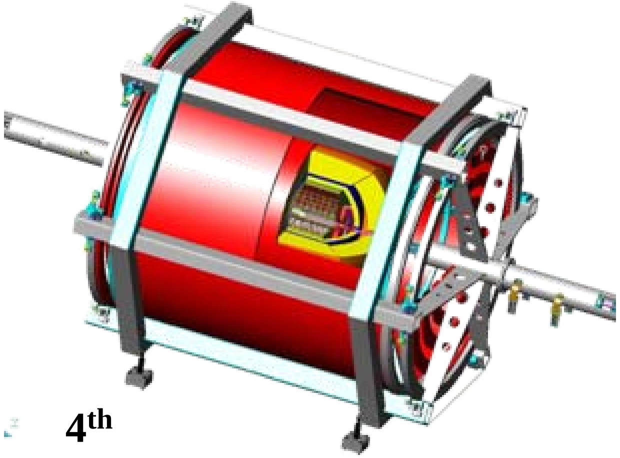
- Although technologies will certainly make substantial progress one can use current state of the art technology being developed for an e^+e^- collider as a reference



ILD



SiD



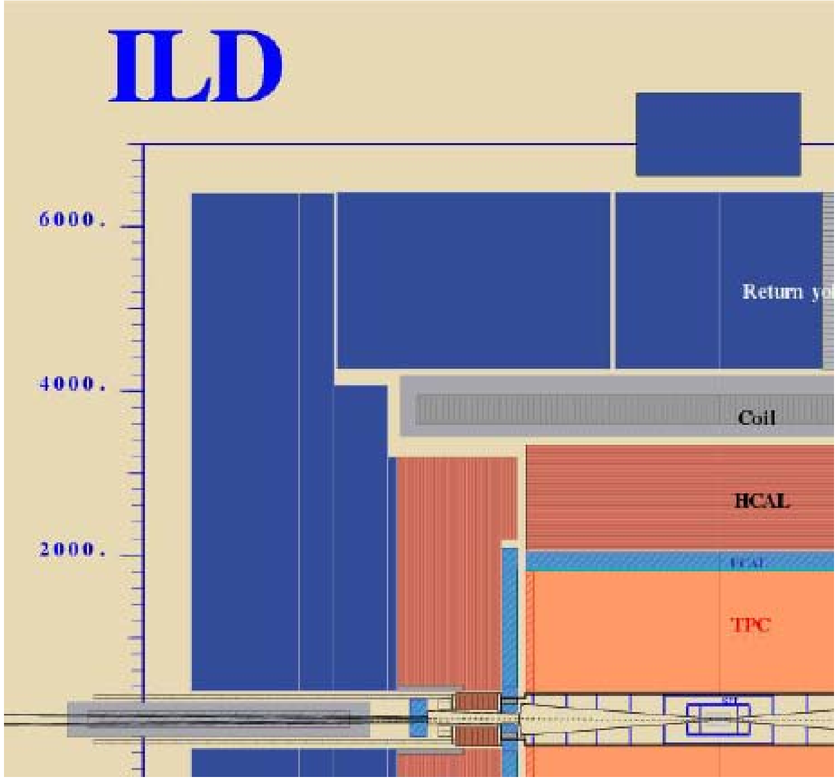
4th

- Premise is that μC comes online after the LHC has run its full course
  - Need to improve on the measurements at the LHC
- Scenario I: Assume competition between μC and ILC/CLIC
- Scenario II: Assume only μC and no ILC/CLIC
- Bottom line is to compare performance of detectors (and subsequently what the physics reach is)

Detector Parameters

- **Reference parameters for ILC detectors**

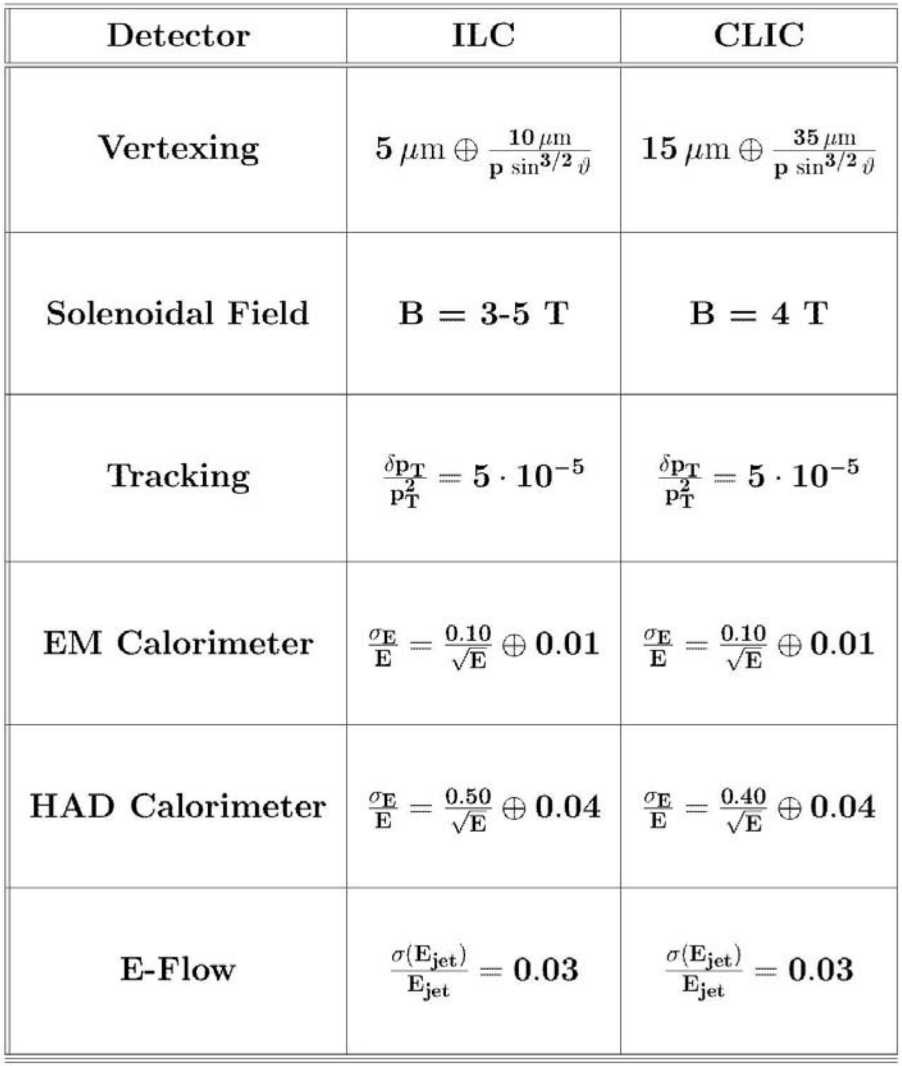
	SiD	**ILD**
Detector	**Radius (cm) Min – Max**	**Radius (cm) Min - Max**
Vertex Detector	**1.5 – 6.0**	**2.0 – 10.0**
Central Tracking	**20 – 125**	**25 – 180**
Barrel Ecal	**127 – 141**	**182 – 203**
Barrel Hcal	**142 – 250**	**205 – 338**
Coil	**260 – 340**	**342 – 420**
Barrel Iron	**344 – 610**	**425 – 640**



- **Project how these parameters translate to a μC detector (or, how realistic are the old assumptions) ?**

Performance Parameters

- **Vertexing driven by heavy flavor identification**
  - **Physics reach greatly enhanced by ability to identify c from b, and q from qbar**
- **Solenoid driven by technology and cost**
- **Tracking driven by measurement of Higgs recoil mass**
- **Calorimetry driven by differentiation between W and Z in the hadronic decay mode**
  - **Need a 3σ resolving power for background rejection: jet energy resolution of ~3%**



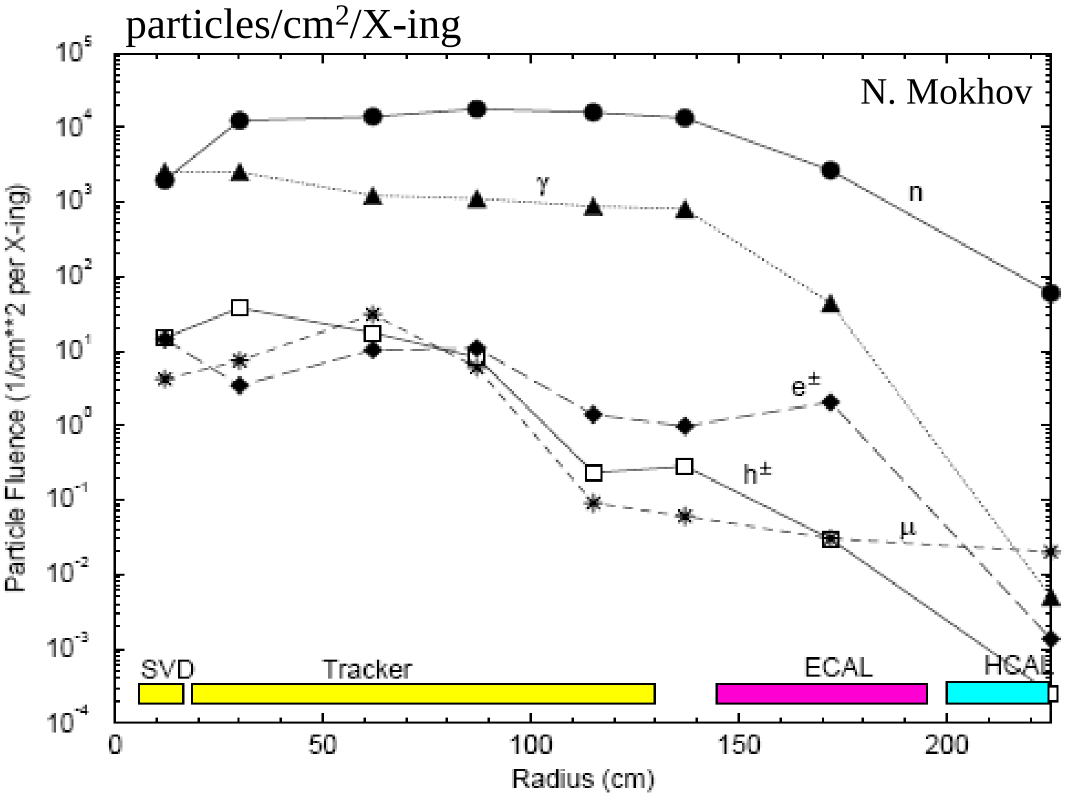
Detector	ILC	CLIC
Vertexing	$5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m}}{\mathrm{p}\,\sin^{3/2}\vartheta}$	$15\,\mu\mathrm{m} \oplus \frac{35\,\mu\mathrm{m}}{\mathrm{p}\,\sin^{3/2}\vartheta}$
Solenoidal Field	$\mathrm{B} = 3\text{-}5\ \mathrm{T}$	$\mathrm{B} = 4\ \mathrm{T}$
Tracking	$\frac{\delta \mathrm{p_T}}{\mathrm{p_T^2}} = 5 \cdot 10^{-5}$	$\frac{\delta \mathrm{p_T}}{\mathrm{p_T^2}} = 5 \cdot 10^{-5}$
EM Calorimeter	$\frac{\sigma_\mathrm{E}}{\mathrm{E}} = \frac{0.10}{\sqrt{\mathrm{E}}} \oplus 0.01$	$\frac{\sigma_\mathrm{E}}{\mathrm{E}} = \frac{0.10}{\sqrt{\mathrm{E}}} \oplus 0.01$
HAD Calorimeter	$\frac{\sigma_\mathrm{E}}{\mathrm{E}} = \frac{0.50}{\sqrt{\mathrm{E}}} \oplus 0.04$	$\frac{\sigma_\mathrm{E}}{\mathrm{E}} = \frac{0.40}{\sqrt{\mathrm{E}}} \oplus 0.04$
E-Flow	$\frac{\sigma(\mathrm{E_{jet}})}{\mathrm{E_{jet}}} = 0.03$	$\frac{\sigma(\mathrm{E_{jet}})}{\mathrm{E_{jet}}} = 0.03$

Background

Collider	*μ per bunch*	*Decays/meter*
50 × 50 GeV	4×10^{12}	2.6×10^{7}
250 × 250 GeV	2×10^{12}	2.6×10^{6}
2 × 2 TeV	2×10^{12}	3.2×10^{5}
2.5 × 2.5 TeV LEMC	1.6×10^{11}	2.0×10^{4}

from: S. Kahn

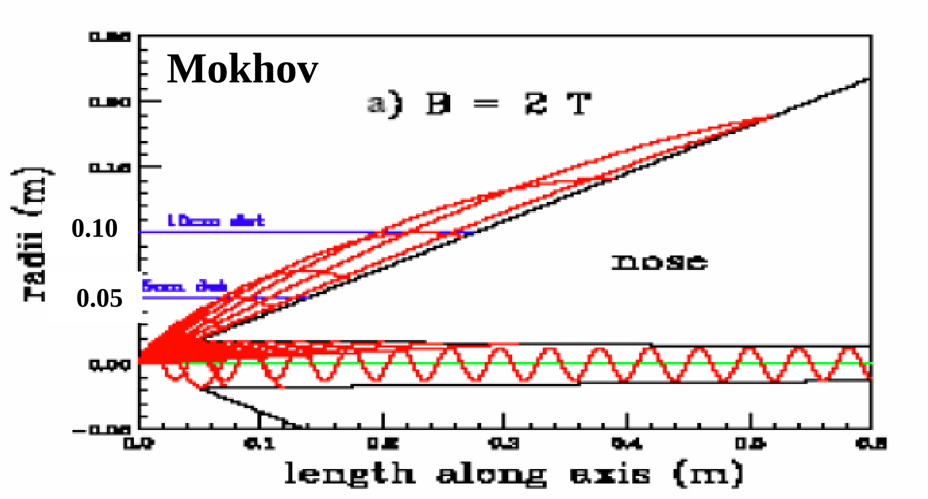
- **Background estimate from decay muons, inside ± 1.2m central region, 2x2 TeV, for best IR configuration considered to date, with collimating spoilers and SC sweeping magnets**
  - **Mean decay electron of 700 GeV**
- **Near uniform distribution across the detector**

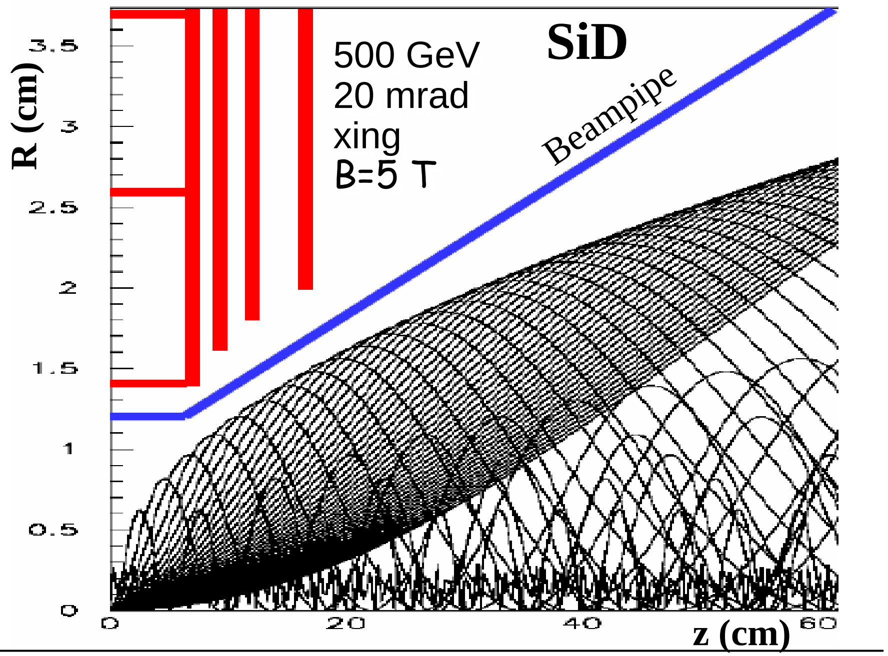

particles/cm^2/X-ing

N. Mokhov

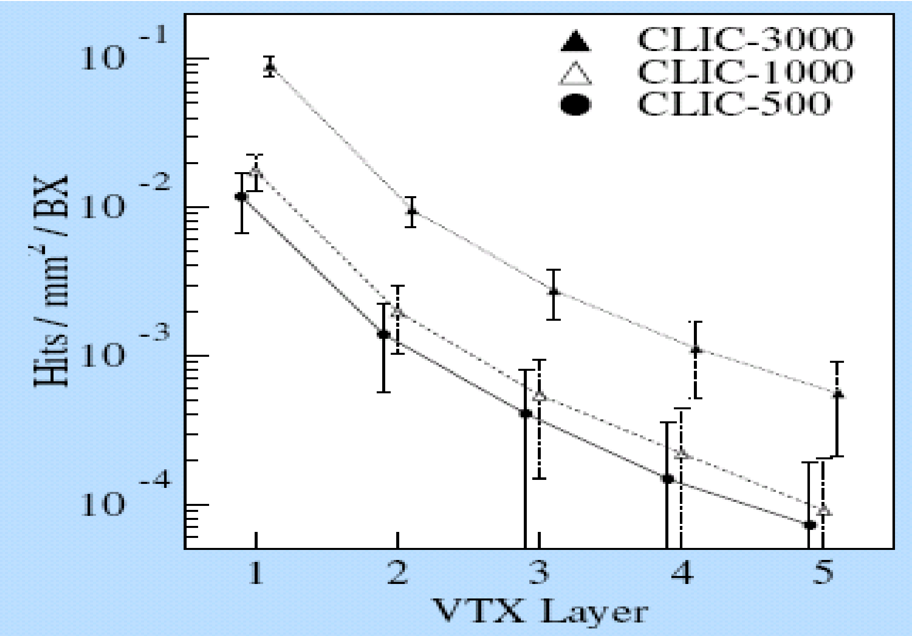
Vertex Detector

- **Inner radius set by avoiding beam background 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.**
  - **If, in 2 Tesla field, 10% of electrons make it into 10 cm fiducial volume, large background**
- **There is a limitation to the field strength**
- **Please note that vertex detectors at an e^+e^- machine end well before a radius of 10cm. Even the Dzero silicon detector has a radial extent of only ~11cm.**





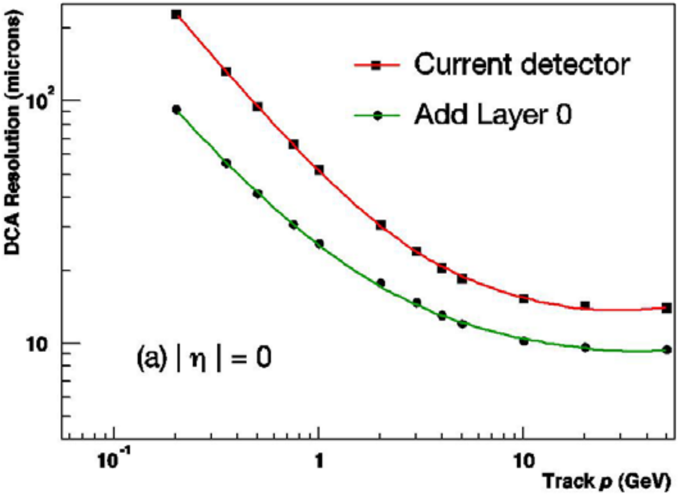
Vertex Detector



- **Goal in terms of occupancies is 0.01-0.1 hit/mm^2 for the inner-most layers**
- **Limitation is the pattern recognition**
- **Even if the occupancies can be kept in check, impact parameter resolution degrades nearly linearly with radius of first layer; pixel size has limitations due to charge sharing**

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

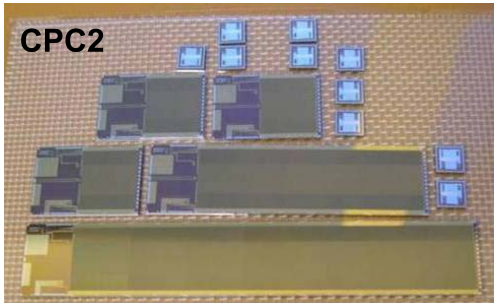
$$\sigma_{r\phi} \approx \sigma_{rz} \approx 15 \oplus 35/(p\sin^{3/2}\vartheta)$$ **CLIC**



- **Heavy flavor physics plays key role in physics menu; tagging b's is not sufficient.**
- **What is a realistic radius for the first layer vertex detector and how does it affect the physics reach?**

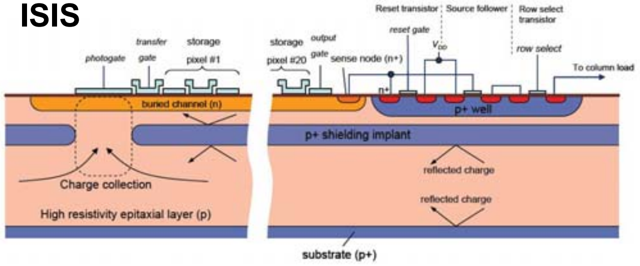
Vertex Detector Sensor Technology

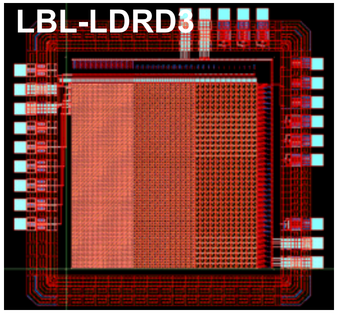
- **Many technologies being explored for vertex detectors**
- **Even though no technology has been demonstrated to be a viable option for an e^+e^- environment, confident that a technology will be available:**
  - **Very leisure bunch crossing and repetition rate**

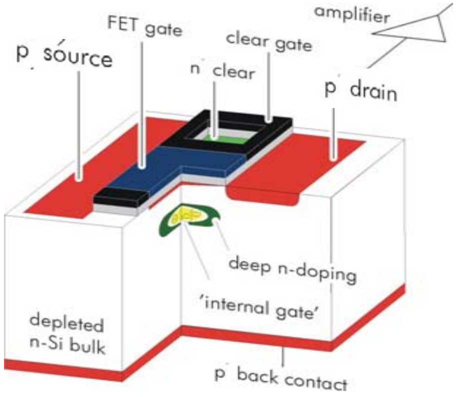


- **Sensor Options**
  - **Column Parallel CCD**
  - **ISIS sensors**
  - **Monolithic Active Pixels**
  - **SOI devices**
  - **DepFet sensors**
  - **3D sensors**
  - **…**
- **Possibility for very low mass devices …**

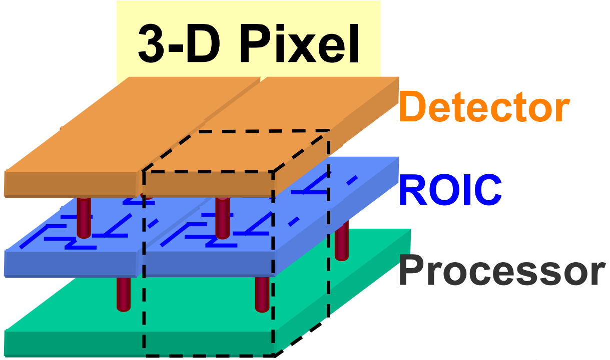
ISIS







DEPFET



3D

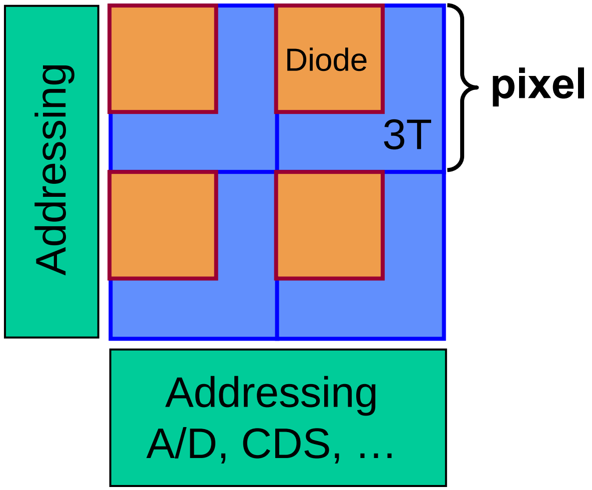
Vertical Integrated Circuits – 3D

- "Conventional MAPS"
  - Pixel electronics and detectors share area
  - Fill factor loss
  - Co-optimized fabrication
  - Control and support electronics placed outside of imaging area

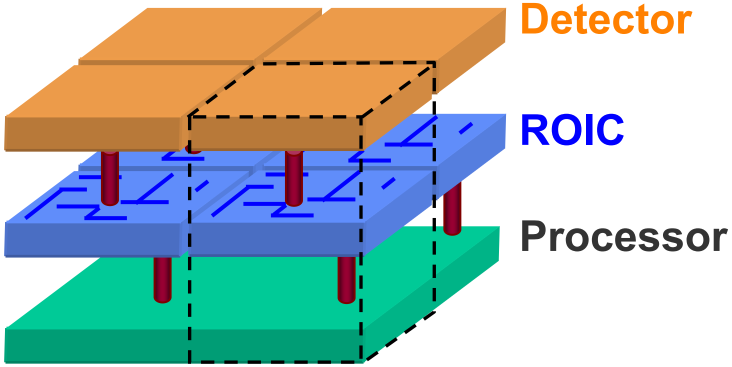
- 3D Vertical Integrated System
  - Fully active sensor area
  - Independent control of substrate materials for each of the tiers
  - Fabrication optimized by layer function
  - Local data processing
  - Increased circuit density due to multiple tiers of electronics
  - 4-side abuttable

- Technology driven by industry
  - Reduce R, L, C for higher speed
  - Reduce chip I/O pads
  - Provide increased functionality
  - Reduce interconnect power, crosstalk

Conventional MAPS

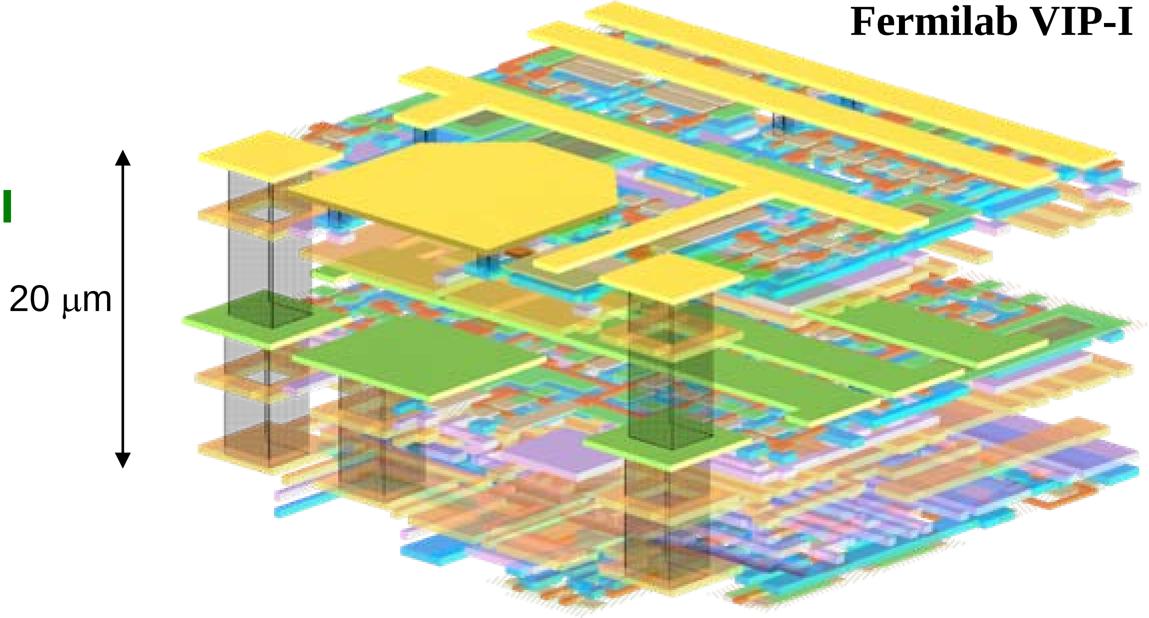


3-D Pixel



3D Demonstrator Chip

- Fermilab started to actively pursue the 3D technology in early 2006
- MIT Lincoln Laboratories had developed the technology that enables 3D integration, with infrastructure to allow for 3D Multi-Project Runs
- Three-tier pixel array designed by Fermilab: Vertical Integrated Pixel (VIP) chip
  - Pixel array 64x64, 20x20 μm^2 pixels; design for 1000 x 1000 array
  - Provides analog and binary readout information
  - 5-bit Time stamping of pixel hit (ILC environment)
  - Token passing scheme readout
  - Sparse readout
- Chip divided into 3 tiers
  - ~ 7 μm / tier
  - 175 transistors / pixel

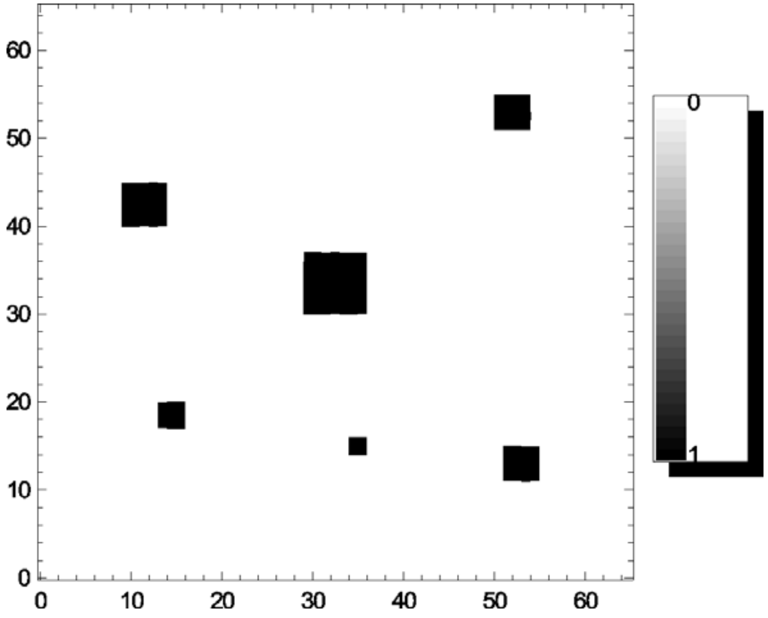


Fermilab VIP-I

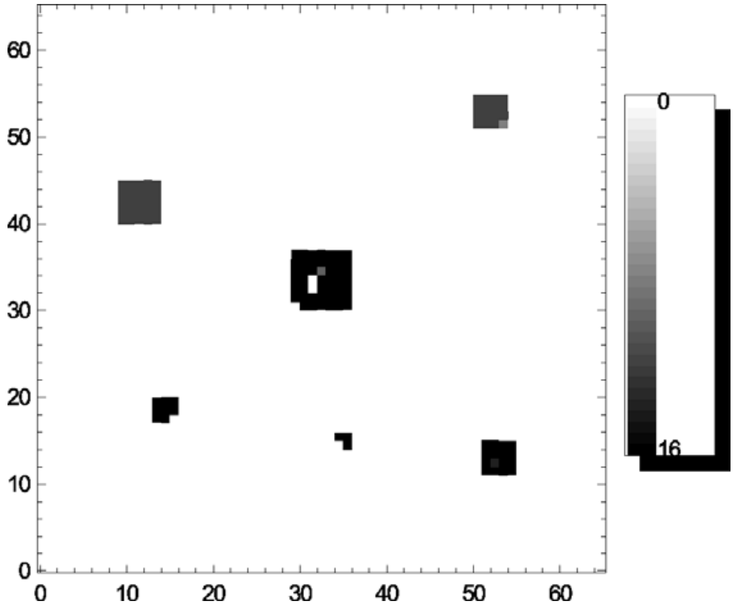
VIP-1 Chip Test Results

- **VIP-1 chips received and tested: Chip works !**
- **Major breakthrough in the development of advanced ASICs and integrated detector systems for particle physics**
- **Opens the way for really advanced, low-mass devices**

- **Example result: data readout out with sparsification on full array**



Preselected injection pattern of pixels to the front-end amplifiers



Readout pattern of pixels from the preselected injection pattern reported as hit

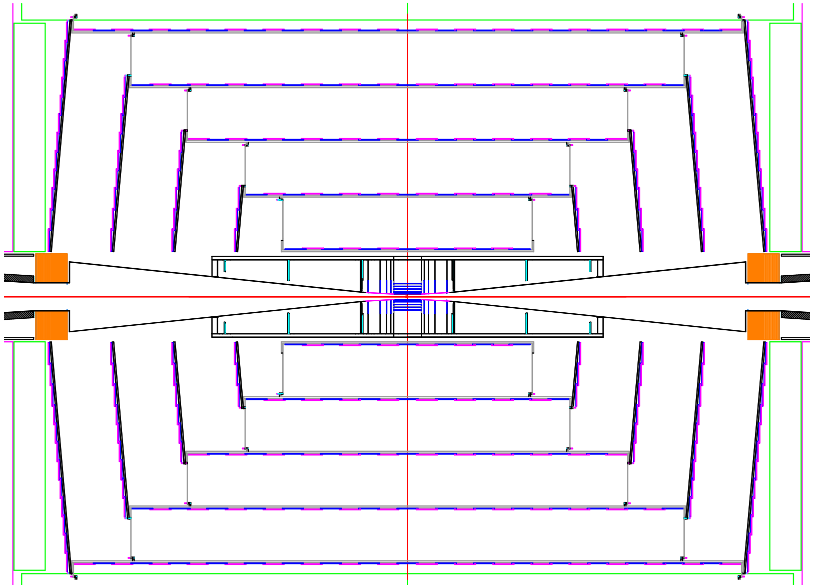
Tracker

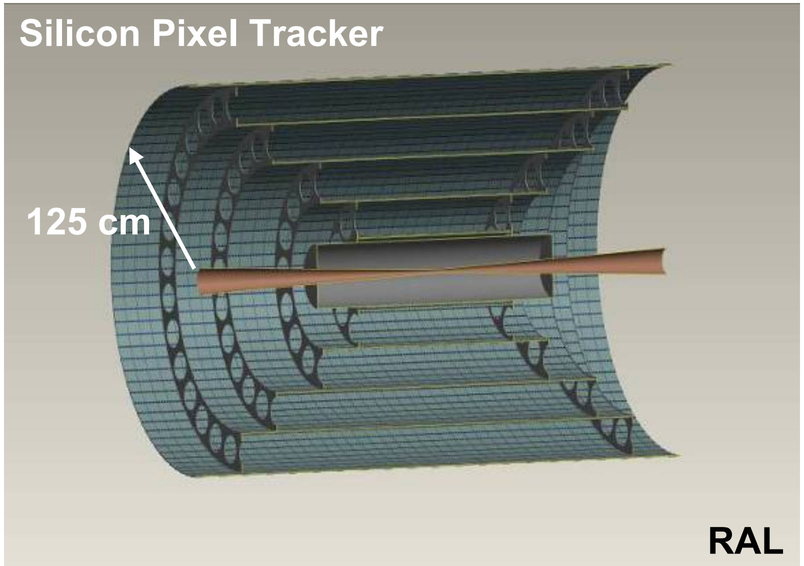
- **Goal for momentum resolution:**

$$\frac{\delta p_T}{p_T^{\,2}} = 2-5\cdot 10^{-5}$$

- **Many possibilities for a large volume tracker**
  - **Silicon strip tracker à la CMS/SiD**
  - **A highly redundant TPC-based tracking design**
    - Emphasizes pattern recognition capabilities, which may be desirable in high background environment
  - **Low mass drift chamber**
  - **Silicon Pixel tracker at lower power**

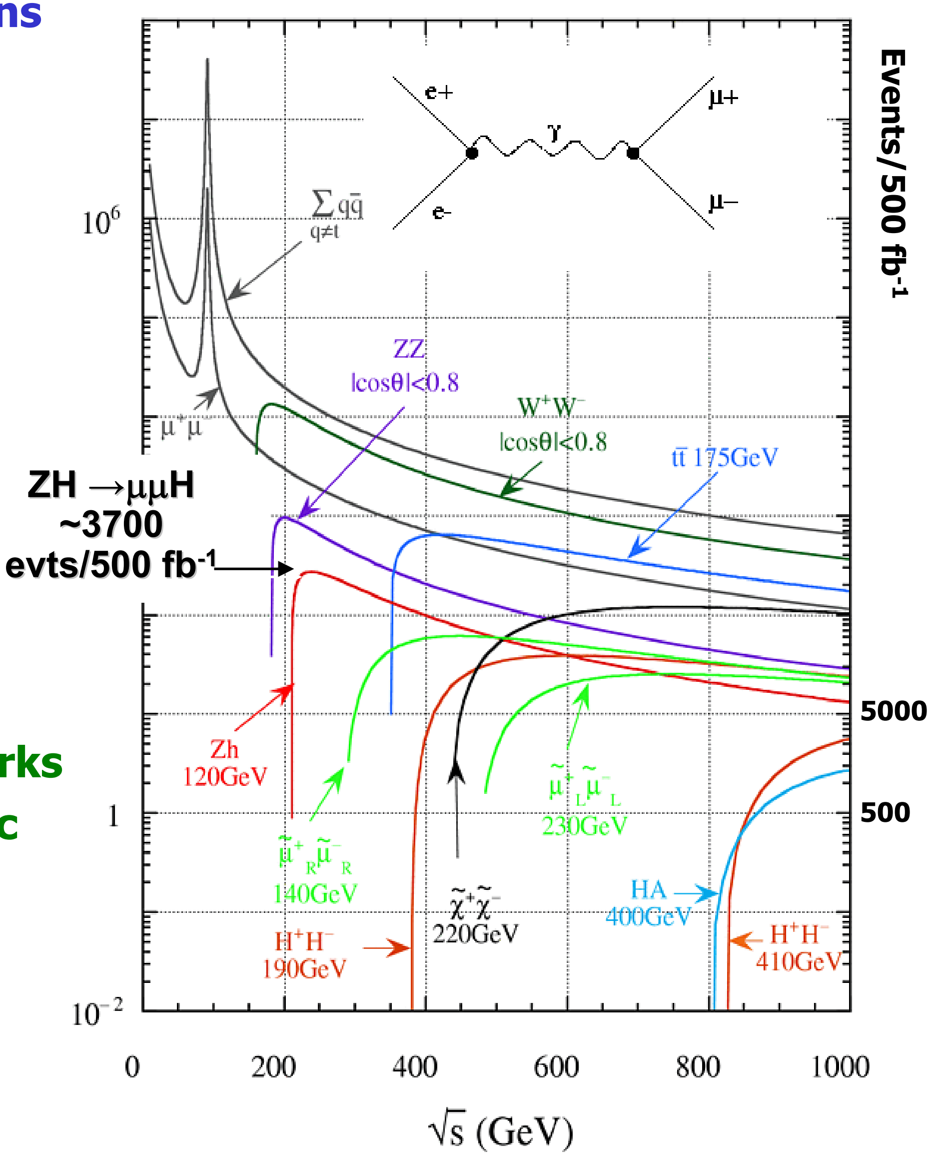
- **Establish physics needs for:**
  - **Particle identification**
  - **dE/dx**
  - **V0-reconstruction**
  - **γ-conversions**





μC Physics

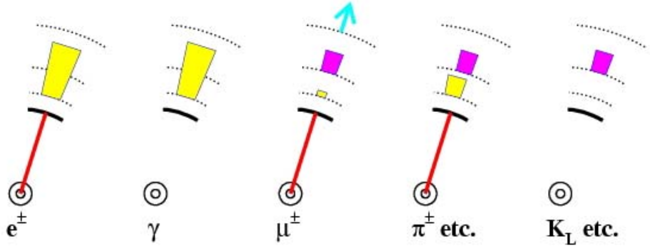
- For many processes the cross sections are essentially the same as for CLIC
- Processes through s-channel spin-1 exchange: $\sigma \sim 1/s$
  - Cross sections relatively democratic
  - Cross sections are small
  - Angular distribution: $(1 + \cos^2\theta)$
    - Premium on forward region, which is troublesome at μC
    - Hermetic detectors
- Near perfect particle identification required
  - Distinguish quarks from antiquarks
  - Discriminate W and Z in hadronic decay mode
- W/Z discrimination leads to requirement on jet energy resolution of 3%



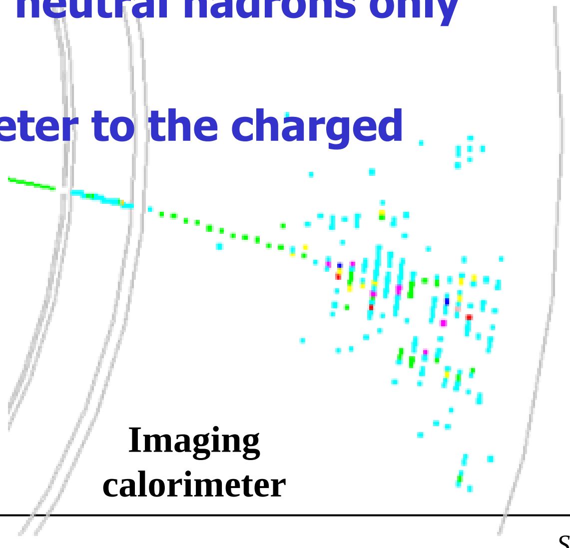
ZH →μμH
~3700
evts/500 fb^{-1}

Particle Flow

- **Major paradigm at ILC/CLIC is obtaining better energy resolution through Particle Flow Algorithms (PFA)**
  - **PFA: Reconstruct momenta of individual particles in jet; avoid double counting**
    - Measure photons in the ECAL
    - Measure charged particles in the tracking system
    - Subtract calorimeter energy associated with charged hadrons
    - Measure neutral hadrons in the HCAL (+ ECAL)



- **PFA: a brilliant idea !**
- **Novelty is in reducing the role of the hadron calorimeter – and thus the hadron energy resolution – to the measurement of neutral hadrons only**
- **Key is the proper association of hits in the calorimeter to the charged particle tracks**
- **Implications for the calorimetry**
  - **Granularity, longitudinal and transverse !**
  - **Sampling of the hadron calorimeter**



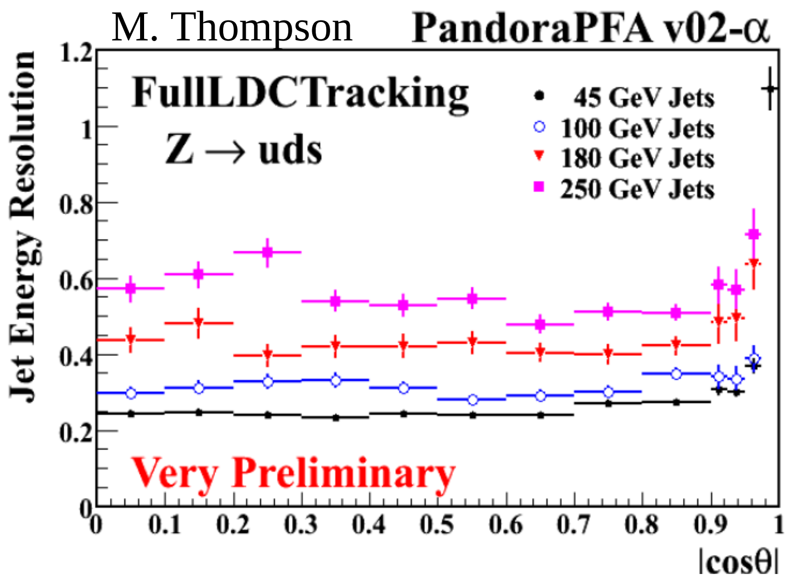
Imaging calorimeter

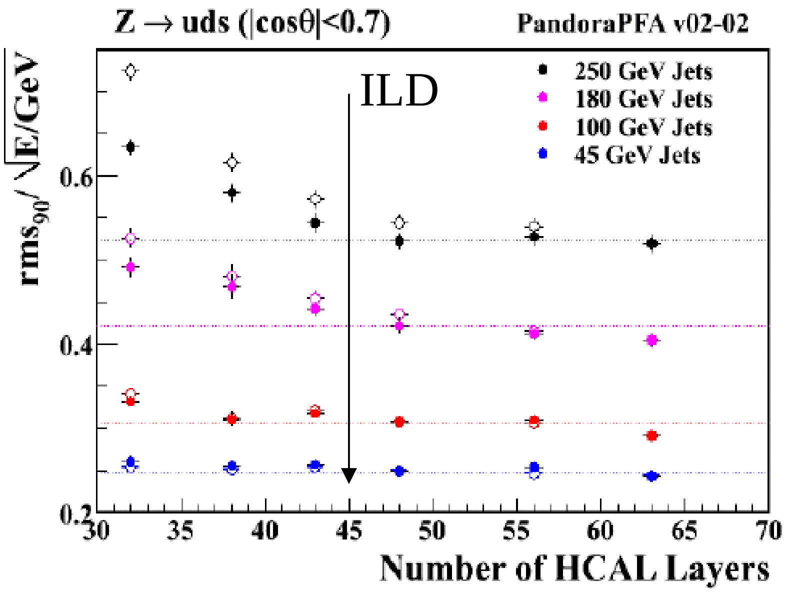
Particle Flow Viability

- **Is PFA viable for multi-TeV collisions ?**
- **Is PFA viable in the environment of a μC ?**

- **Pandora PFA Performance**
  - **At low energies 25%/√E obtained**
  - **At higher energies resolution degrades**
    - Performance of "conventional" good calorimeter
  - **Resolution improves with increasing thickness of calorimeter at higher energies**
    - Deep calorimeter needed 8λ -> 10λ

- **Note: at √s = 3 TeV average parton energy is 240 GeV (averaged over all SM processes)**



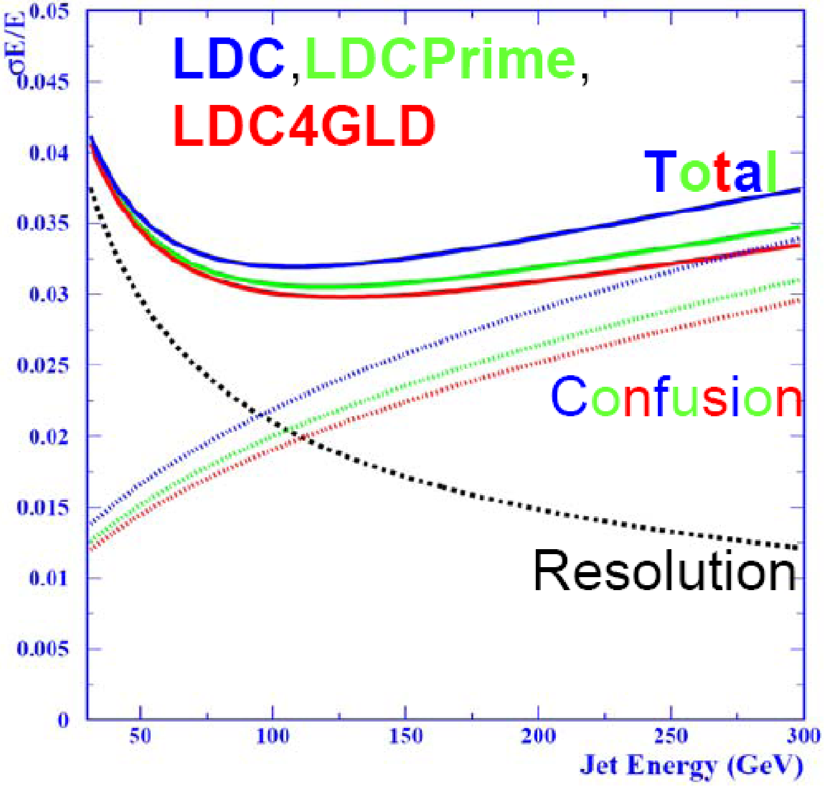


Particle Flow Viability

- Study within the ILD concept based on Pandora PFA: Confusion term increases nearly linearly with jet energy
  - Cross-over intrinsic resolution and confusion at E_{jet} ~ 110 GeV

- Particle Flow calorimetry not à priori obvious for multi-TeV events but it may be possible to get adequate performance tuning HCAL depth, tracker outer radius, B field and by optimizing PFA

- However, IMHO, in the background environment of a μC, the confusion will dominate the resolution in a PFA context and will be near irreducible

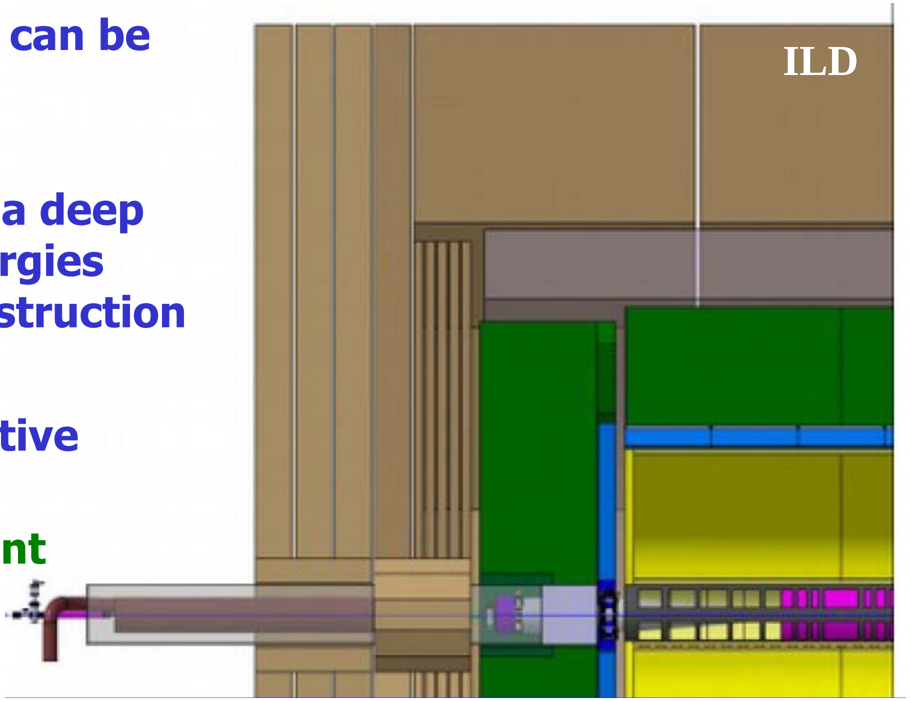


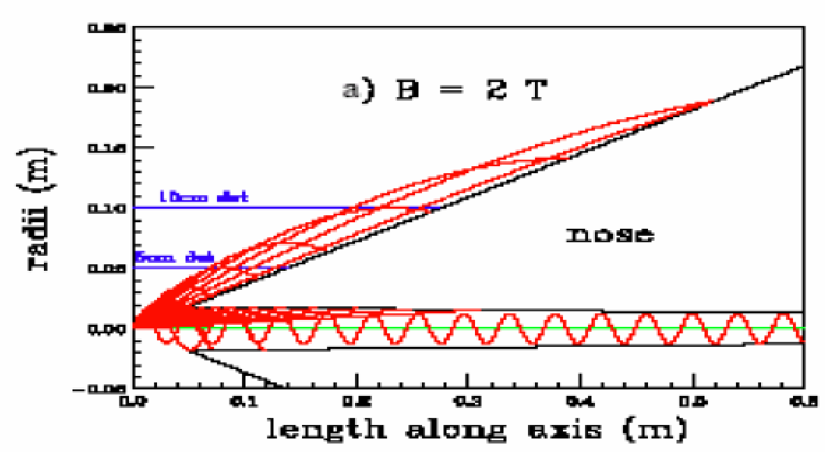
- Furthermore, event reconstruction, jet clustering and gluon radiation affect the physics reconstruction performances beyond particle flow response

- If the premise of required jet energy resolution holds for a μC detector, a lot of R&D needs to be done

B-Field

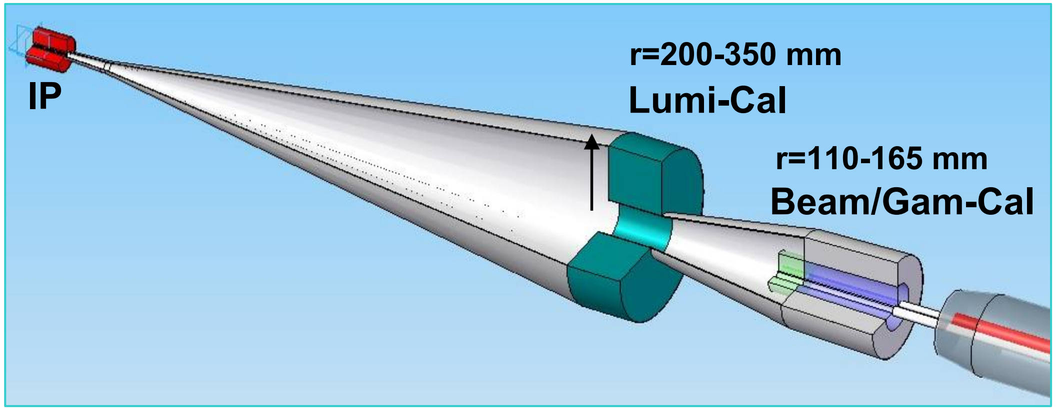
- **At an e^+e^- machine beam backgrounds can be contained through the solenoidal field**
- **Calorimetry studies show the need for a deep calorimeter at high center of mass energies independent of algorithm for jet reconstruction**
- **Cost of solenoid may simply be prohibitive for going to large field strengths**
  - **3 Tesla may be the limit with current technology (and resources)**
- **Backgrounds have large momentum spread**
- **Is there an intrinsic limit to the ability to contain the background ?**



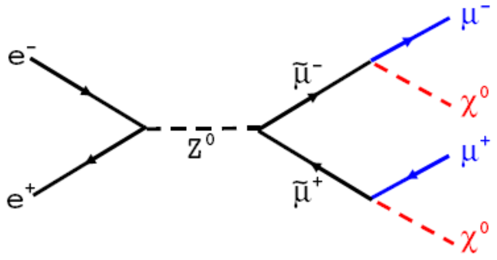


Machine Detector Interface

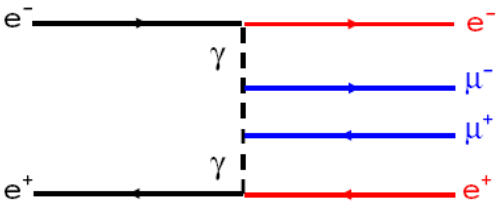
- **An integral detector part, which affects the physics program, is the MDI**
- **Especially the reach for SUSY signals are strongly affected by forward instrumentation**



- **At ILC/CLIC**
  - **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.

Concluding Remarks

- **A full updated background study should get high priority, with full simulation of the beam line delivery system and the machine detector interface elements**

- **The results of this study could dictate the design of the detector**

- **Without this information, the evaluation of the physics reach may be seriously misjudged**

- **Study of physics reach should include peripheral measurements such as luminosity spectrum, energy and polarization**