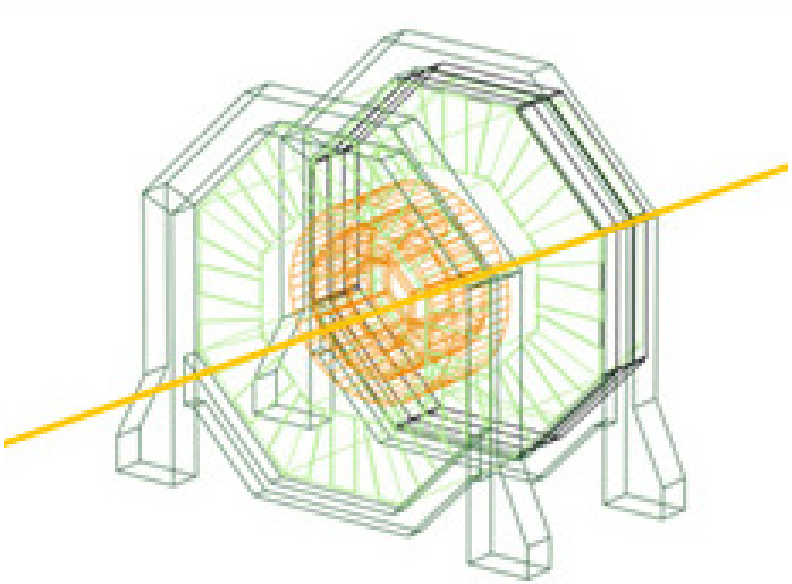
A Muon Collider Detector

‘A Perspective’



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Fermilab

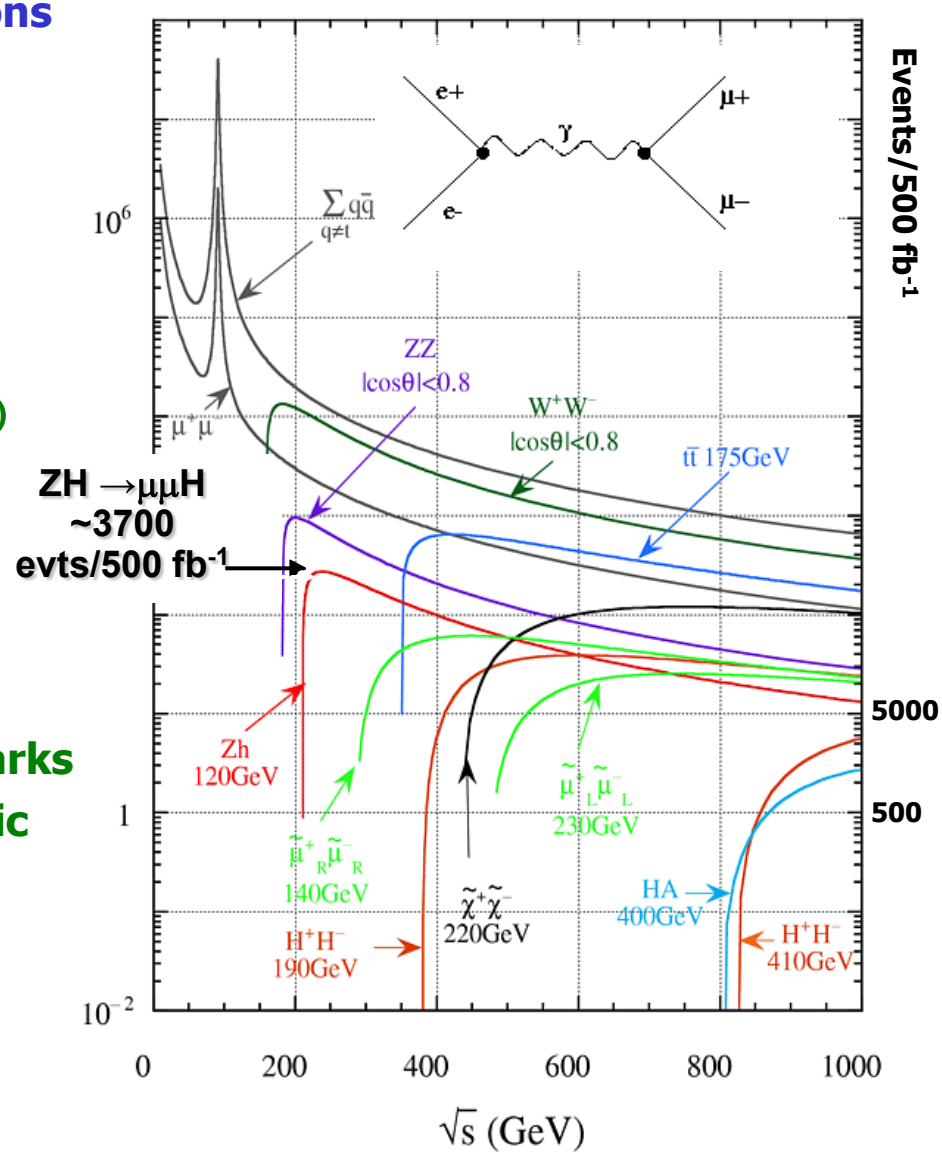
DoE Briefing
Germantown, June 24, 2009

Outline

- **Physics Goals**
  - **Underlying physics is fundamentally the same as for an e^+e^- collider**
  - **Premise is that μC comes online after the LHC has run its full course, including the upgrades of the LHC experiments**
  - **Need to improve on the measurements at the LHC; compare physics reach of various options available**
- **Detector Design**
- **Detector Performance Requirements**
- **Detector Environment**
- **Detector Technologies**
- **Observations**

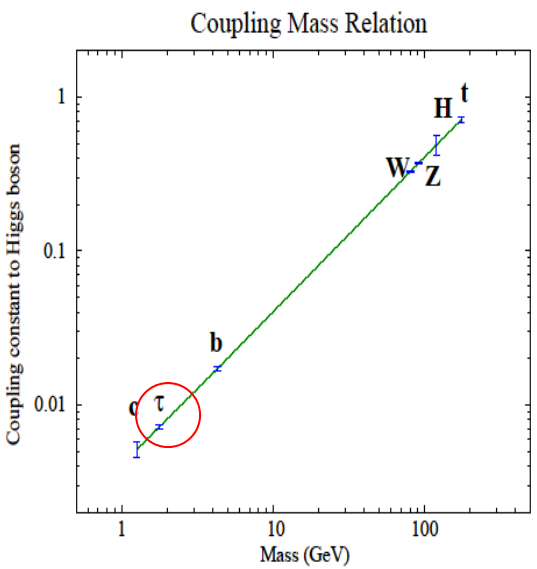
μC Physics

- 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%

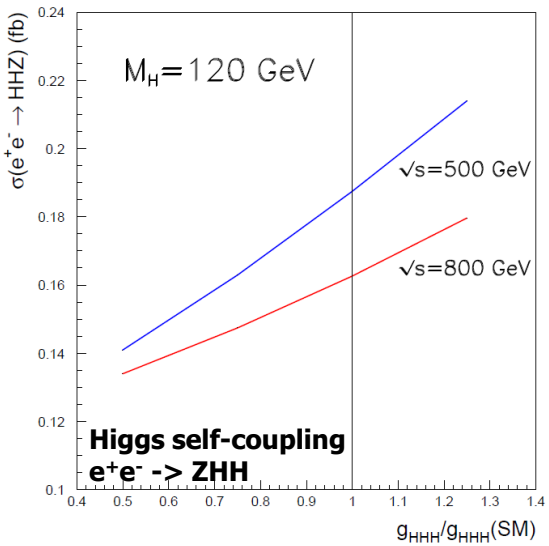


Detector Concept

- **Detector design is mainly driven by three criteria:**
  - **Physics goals**
    - Choice of detector technology driven by scientific "prejudice"
  - **Machine Detector Interface**
    - Beam backgrounds
    - Beam delivery system, L*
    - Machine parameters such as bunch crossing, duty cycle, …
  - **Cost**



- **Each criterion is (ideally) parametrized in a physics metric**
  - **Physics**
    - e.g.: Importance of palette of physics processes to be measured
  - **Machine Detector Interface**
    - e.g.: the importance of a luminosity/polarization measurement
  - **Cost**
    - e.g.: Resolution versus integrated luminosity (running time)



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%**

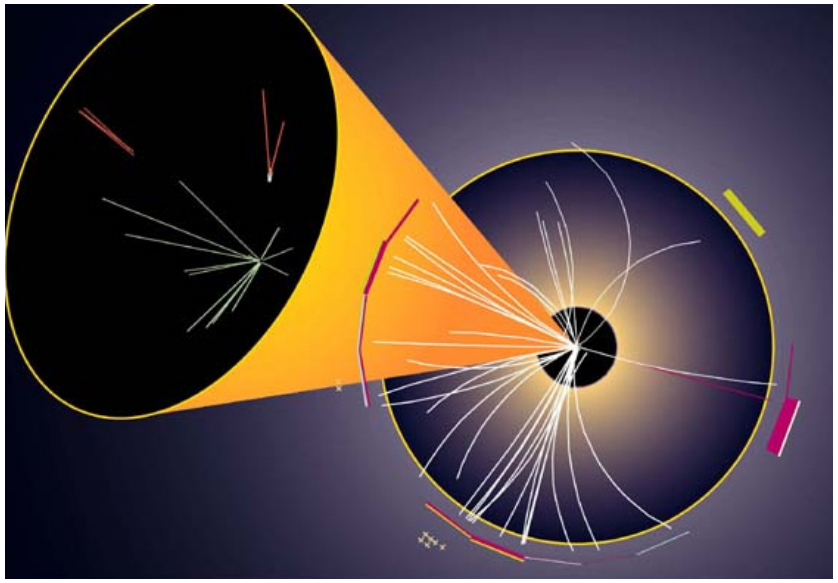
Detector	ILC	CLIC
Vertexing	$5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m}}{\mathrm{p}\,\sin^{3/2}\vartheta}$	$15\,\mu\mathrm{m} \oplus \frac{35\,\mu\mathrm{m}}{\mathrm{p}\,\sin^{3/2}\vartheta}$
Solenoidal Field	B = 3-5 T	B = 4 T
Tracking	$\frac{\delta \mathrm{p_T}}{\mathrm{p_T^2}} = 5 \cdot 10^{-5}$	$\frac{\delta \mathrm{p_T}}{\mathrm{p_T^2}} = 5 \cdot 10^{-5}$
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	$\frac{\sigma(\mathrm{E_{jet}})}{\mathrm{E_{jet}}} = 0.03$	$\frac{\sigma(\mathrm{E_{jet}})}{\mathrm{E_{jet}}} = 0.03$

Technology versus Environment

- **The overall performance of the detector is effectively governed by**
  a) **The intrinsic detector performance (choice of technology) and**
  b) **The environment in which it operates**

- **Environment**

- **Technology**
  - **Will give a few examples which will indicate that technology does not seem to be a bottleneck**



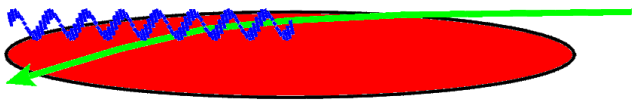
Machine Parameters

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

- **Observations:**
  - **Time stamping at CLIC at 0.5ns level; will have to integrate over full bunch train before readout; μC readout every bunch crossing, i.e. background can be factor 300 worse in μC to be comparable to CLIC**
  - **ILC / CLIC require power pulsing at 5 / 50HZ. Power requirements at a μC may be mitigated**

Beam Induced Background

- Source of background for CLIC and ILC are similar
- However, due to the higher beam energy and small bunch sizes they are significantly more severe at CLIC.



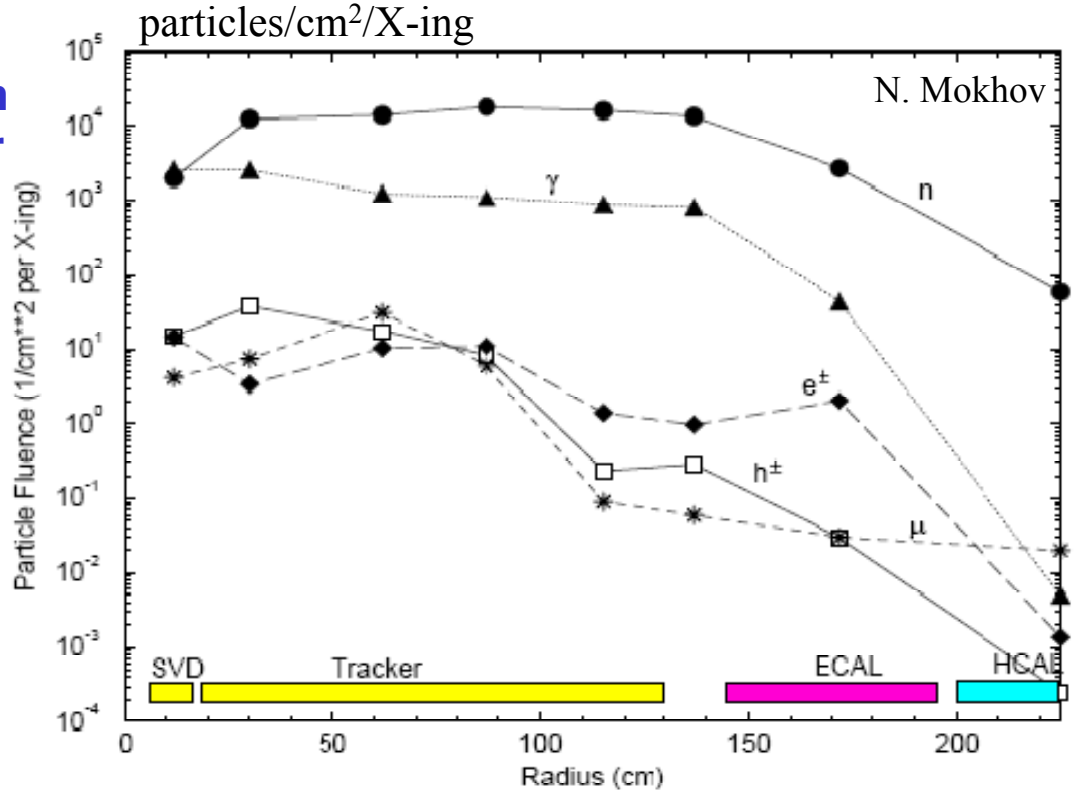
- Coherent pairs (3.8×10^8 per bunch crossing)
  - About a million times more than at 500 GeV
  - Disappear in beam pipe
- Incoherent pairs (3.0×10^5 per bunch crossing)
  - About 3x larger than at 500 GeV
  - Suppressed by strong B-field
- $\gamma\gamma$ interactions $\rightarrow$ hadrons: ~ 2.7/bx
  - 20×more than at 500 GeV
- Backscattered particles more energetic (neutrons)
  - Muon background from upstream linac difficult to stop due to high CLIC energy
- Synchrotron radiation
- Beam tails from the linac
- Backscattered particles from the spent beam (neutrons)
- Please note: at CLIC this occurs every 0.5 ns!

Decay 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}

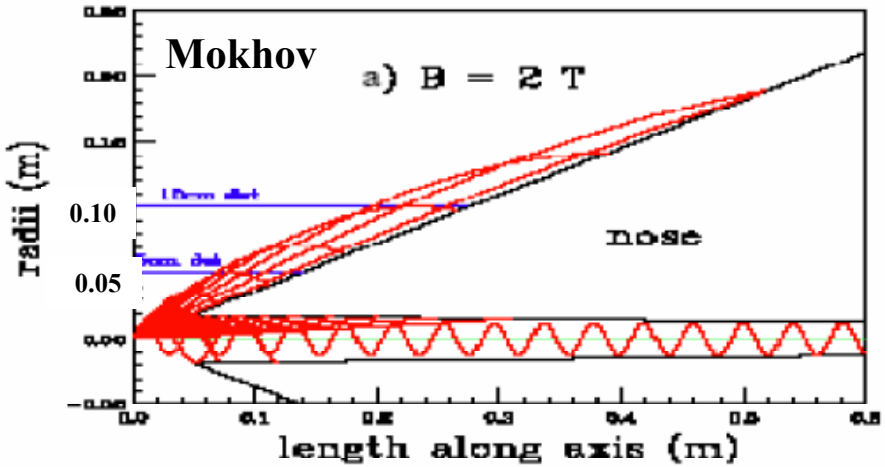
from: S. Kahn

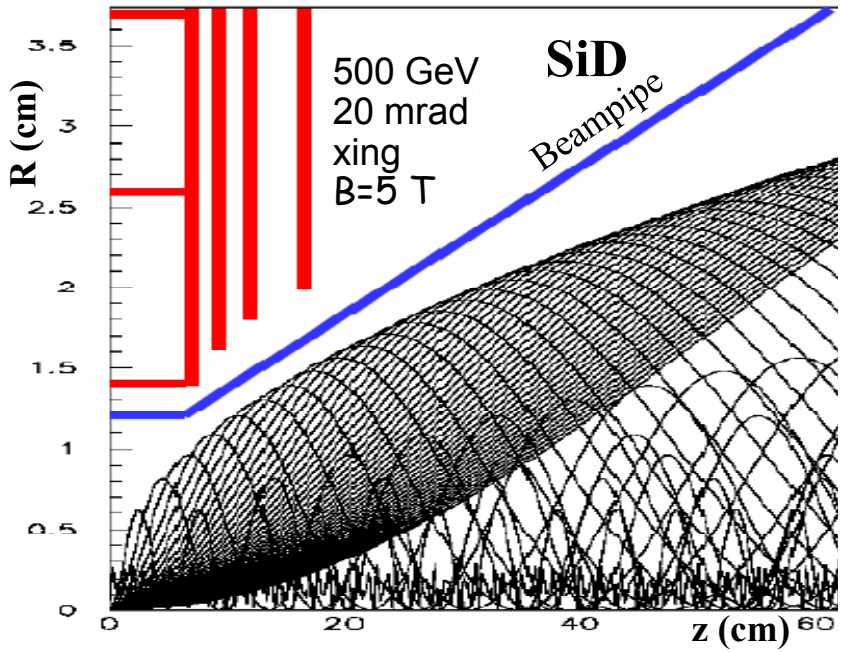
- **Background estimate from decay muons, inside ± 1.2m central region, 2x2 TeV, for best IR configuration considered to date, with collimating spoilers and SC sweeping magnets**
  - **Mean decay electron of 700 GeV**
- **Near uniform distribution across the detector**



Vertex Detector

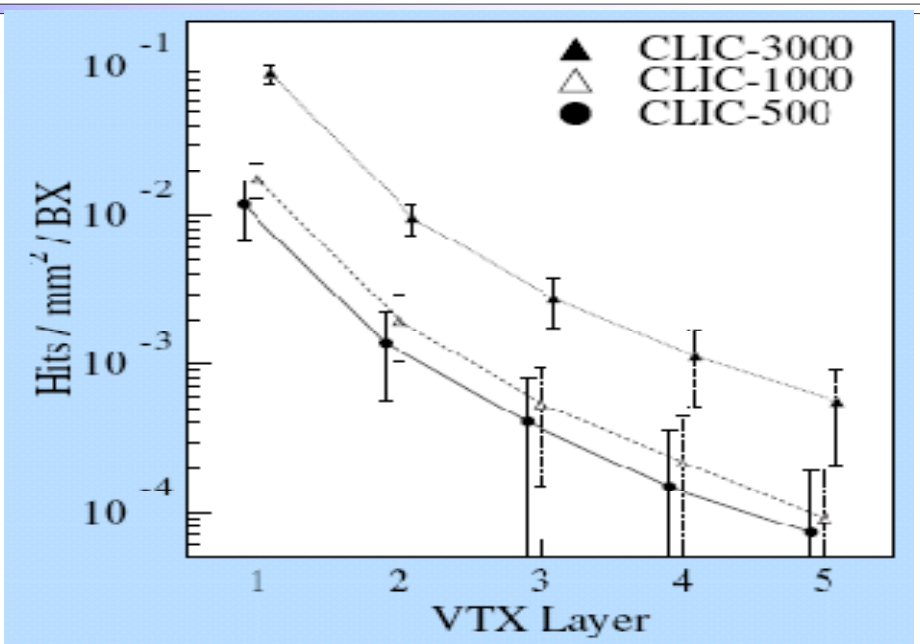
- **Inner radius set by avoiding beam background envelope**
- **Incoherent pair production from $\mu^+\mu^- \rightarrow \mu^+\mu^- e^+e^-$ significant for high energy muon colliders.**
  - **Estimated cross section of 10 mb giving 3×10^4 electron pairs per bunch crossing.**
  - **Nearly one order of magnitude less than CLIC**
- **There is a limitation to the field strength**





Vertex Detector

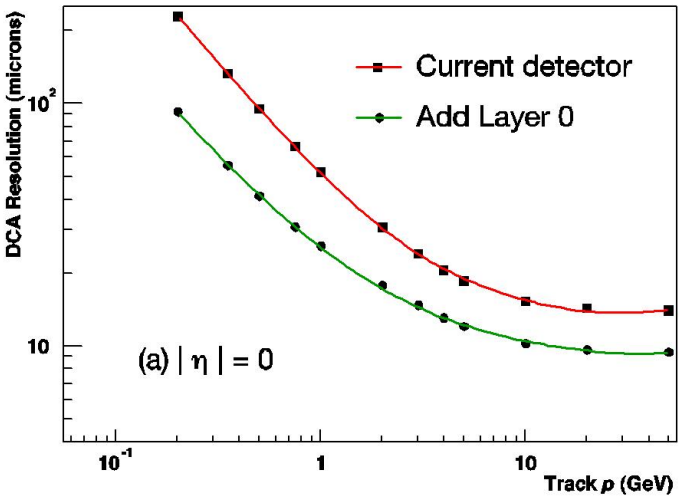
- Goal in terms of occupancies is 0.01-0.1 hit/mm^2 for the inner-most layers
- Limitation is the pattern recognition



- 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

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

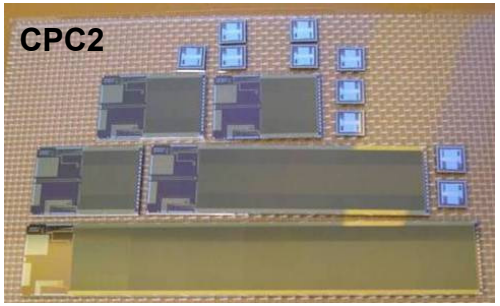
$$\sigma_{r\phi} \approx \sigma_{rz} \approx 15 \oplus 35/(p\sin^{3/2}\vartheta) \quad \text{CLIC}$$



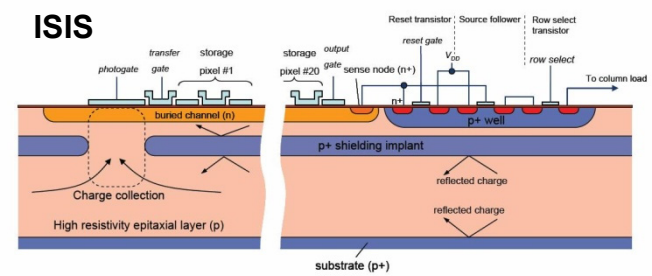
- Heavy flavor physics plays key role in physics menu; tagging b's is not sufficient.
- What is a realistic radius for the first layer vertex detector and how does it affect the physics reach?

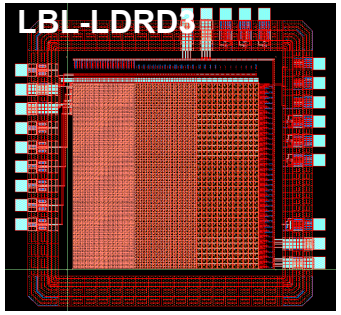
Vertex Detector Sensor Technology

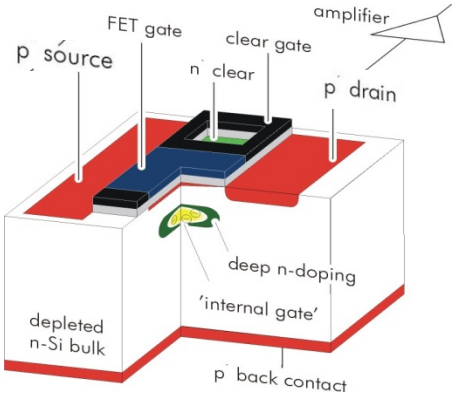
- Many technologies being explored for vertex detectors
- Even though no technology has been demonstrated to be a viable option for an e^+e^- environment, confident that a technology will be available:
  - Very leisure bunch crossing and repetition rate at μC



- Sensor Options
  - Column Parallel CCD
  - ISIS sensors
  - Monolithic Active Pixels
  - SOI devices
  - DepFet sensors
  - 3D sensors
  - ...







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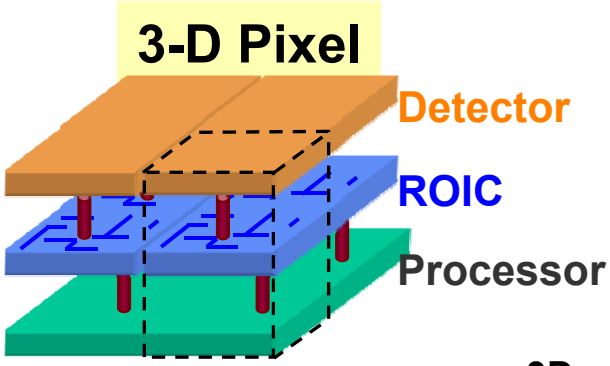


3D

- The technology (will) exist
- Issue is how close in the detector can go

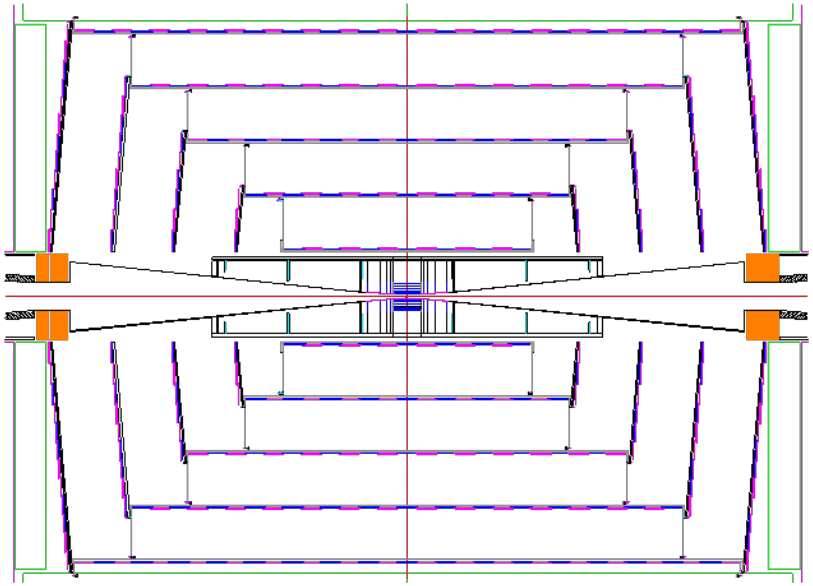
Tracker

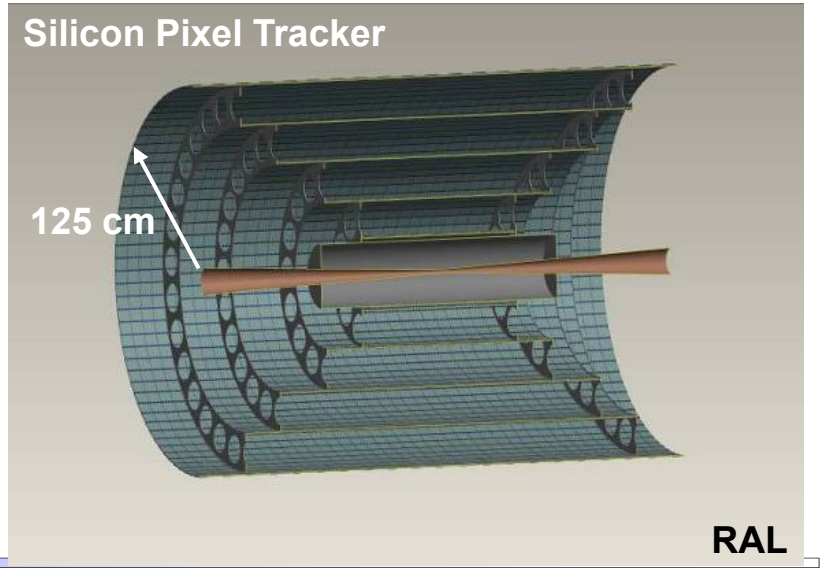
- **Goal for momentum resolution:**

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

- **Silicon Strip Tracker**
  - **Silicon strip tracker à la CMS/SiD**
  - **Single bunch time stamping already achieved at current generation experiments**
  - **Same requirements for low mass**
  - **Barrel / Disk geometry may be very robust in background rejection parallel to beamline**

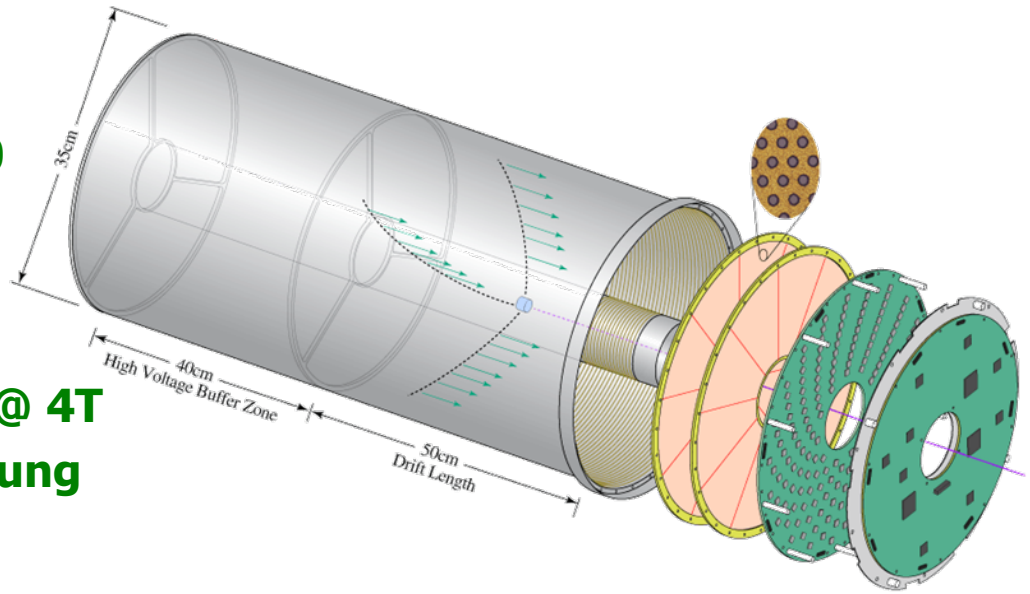
- **Silicon Pixel tracker at lower power**
  - **A pixel technology for an outer tracker may be well feasible for a lepton collider**
  - **Power requirements are stronly mitigated at μC**





TPC

- ILC TPC requirements
  - $\delta p/p \leq 0.1\%$, B=4T
  - Material <3% X_0 near $\eta = 0$ <30%X_0 endcap
  - pads per endcap > 10^6
  - pad size about 1x6 mm^2
  - hit resol. 100, 500 μm rϕ, z @ 4T
  - At the ILC ~10^3 beamstrahlung photons per bunch crossing



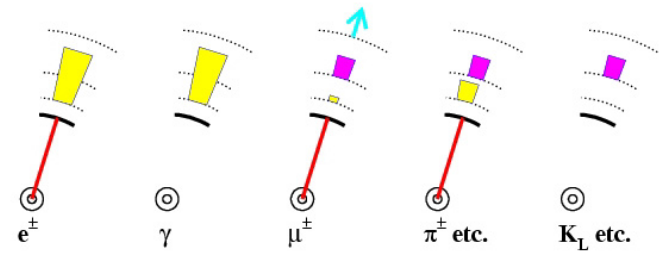
- The ILD TPC has a drift length of ~ 2.5m and will integrate over 100-150 bunch crossings; this problem does not exist for a μC
- At CLIC these problems are exacerbated (positive ion backflow)

- Coverage down to 10-15 degrees, similar to μC
  Resolution requirements are also similar to ILC/CLIC

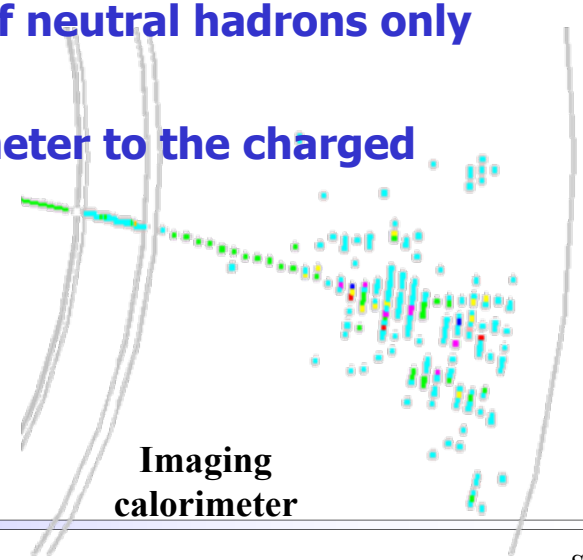
- Silicon tracker may be extremely robust in μC environment

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**

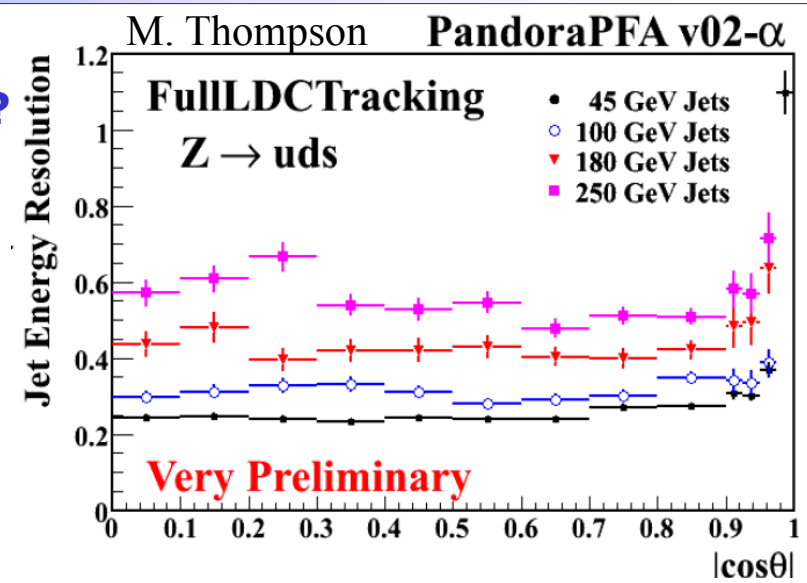


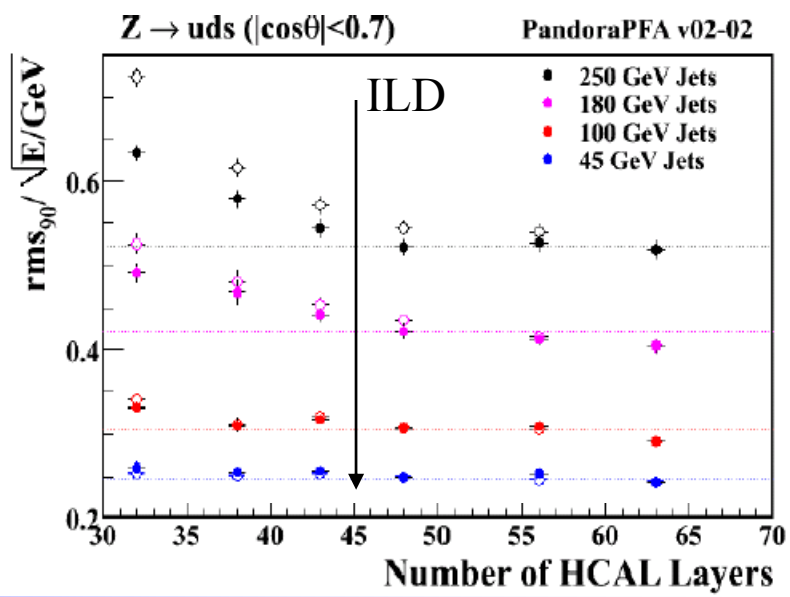
Particle Flow Viability

- **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

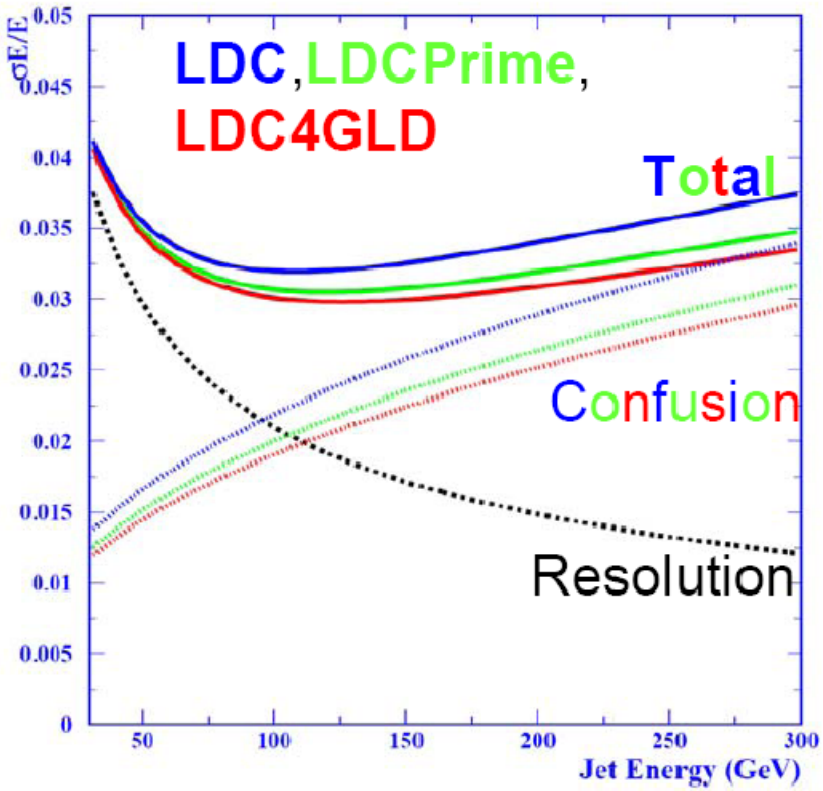
- **Note: at √s = 3 TeV average parton energy is 240 GeV (averaged over all SM processes)**





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 $E_{jet} \sim 110$ 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

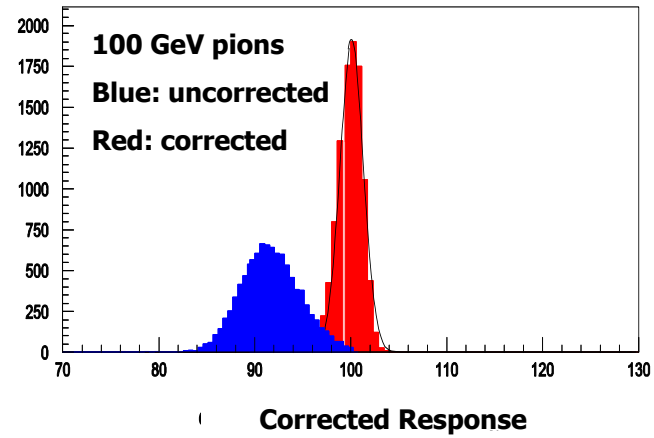
- In the background environment of a μC, the confusion may dominate. Gating of readout should be explored

- 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

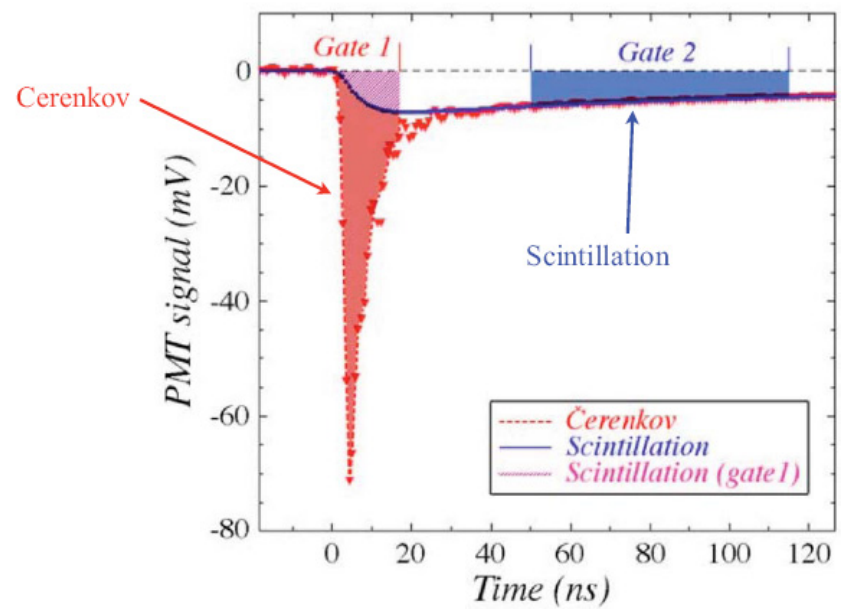
Dual Readout Calorimetry

- Correct on a shower-by-shower basis using the correlation of the total observed ionization (S) and Cherenkov (Č) light



- Two options currently under consideration:
  - Fiber readout
  - Total absorption crystal readout

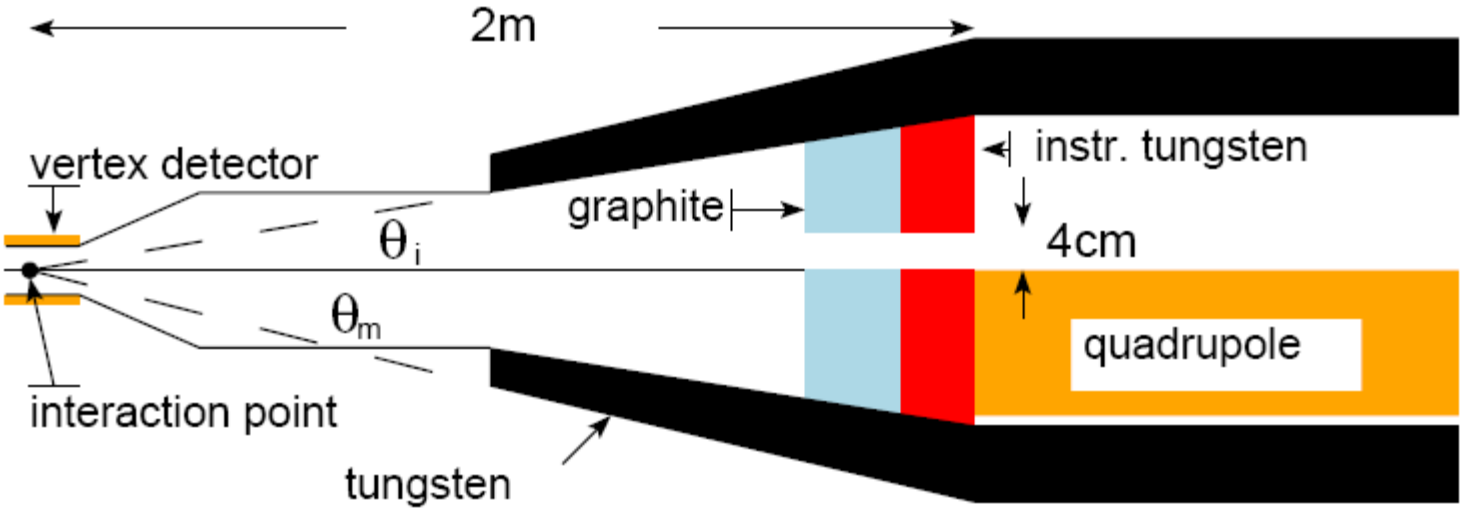
- Under consideration is the development of waveform digitizing electronics at multi-GHz to sample the full waveform
  - Provides timing information
  - Enables gating out-of-time background hits
  - Allows for full 'deconvolution' of signal



- Calorimetry for a μC is not a proven technology (neither is it for ILC/CLIC); R&D fully synergistic with ILC/CLIC and for that matter, any new project

The "Cone"

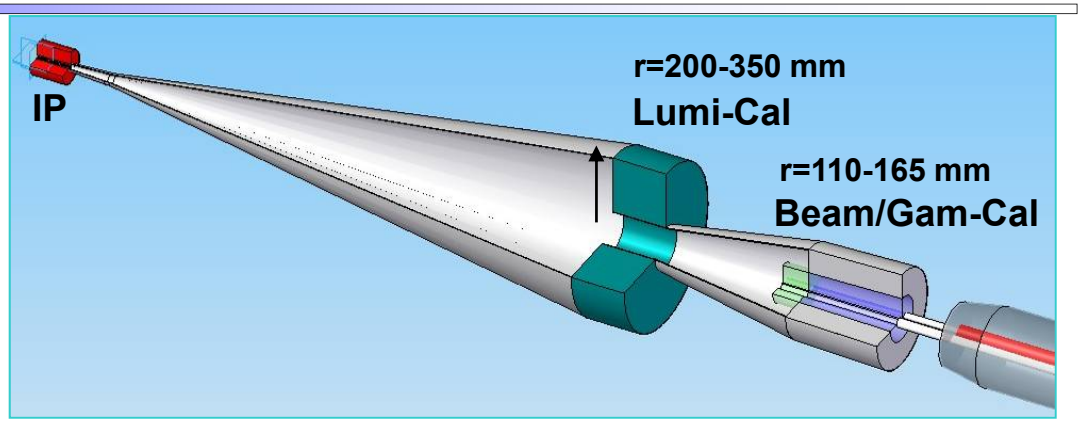
- **The forward region is an unresolved problem for all lepton colliders**



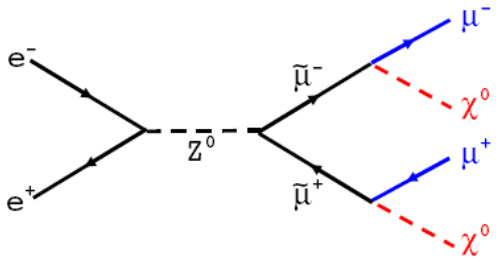
- **Initial studies at CLIC implement a Tungsten cone at about 130 mrad (7.5^0)**
- **This study was carried out for no crossing angle (crossing angle is 20 mrad)**
- **The impact on the forward region and the physics is unclear**

Machine Detector Interface

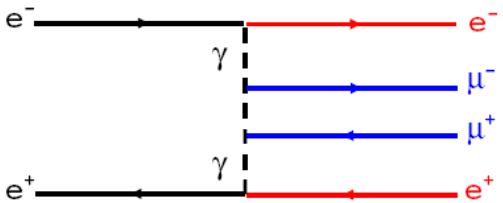
- **An integral detector part, which affects the physics program, is the MDI**
- **Especially the reach for SUSY signals are strongly affected by forward instrumentation**



- **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.

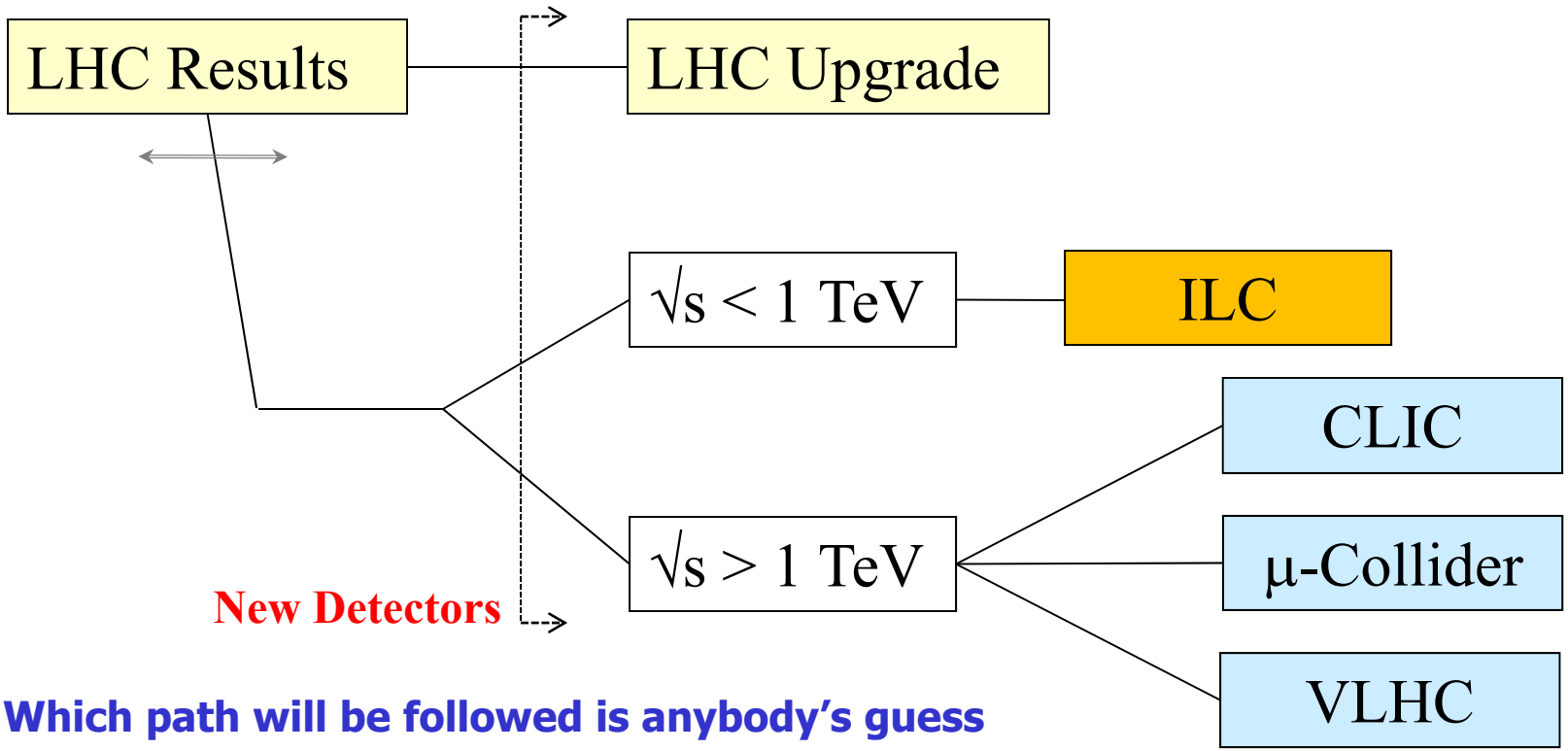
Detector Summary

- In many respects the challenges for the detector technologies for a μC detector are more modest than for an ILC/CLIC detector

- If a detector meets the technical requirements for the ILC/CLIC it will meet the requirements for the MC

- The issue is not the technical requirements of the detector; it is the beam environment that determines the physics reach!
  - Is there polarization? How well is it measured?
  - What is a realistic luminosity?
  - What is a realistic angular coverage?
  - What is a realistic inner vertex detector radius?
  - What is a realistic B-field?
  - ...

The Energy Frontier



- **Which path will be followed is anybody's guess**
- **Ultimately it is the physics reach which will determine if a project is viable or not**
- **The μC is an option for the US to return to the energy frontier**
- **It behooves us to carry out a fair comparison in physics reach between CLIC and the μC**
- **The synergies between the various projects are manifold**

5 Step Plan

1. Have a realistic beamline design and machine detector interface
   - Determine environmental background
   - Determine machine background

2. Specify minimum baseline parameter for the collider, such as beam polarization for both beams and beam energy spread

3. Determine physics program that can withstand the physics environment after ten years of running at the LHC and is competitive with an e^+e^- machine

4. Develop detector design concept for μC detector, with reasonable technology assumptions, folded with realistic detector geometry

5. Establish a software platform for the physics studies and study physics reach through full Monte Carlo simulations of benchmark processes and compare results with physics reach of sLHC and ILC/CLIC

Resources

	Year 1	Year 2	Year 3	Year 4	Year 5
Workshops & Travel					
M&S (K$)	0	15	15	15	15
Theory Studies					
M&S (K$)	0	10	10	15	15
Techs (FTE)	0	0.5	0.5	0.5	0.5
Post Docs (FTE)	0.2	1	1	1.5	1.5
Scientists (FTE)	0.2	0.8	0.9	1	1
Det & Bckgrd Simul.					
M&S (K$)	0	15	10	10	10
Post Docs (FTE)	0	1	1.5	2	2
Scientists (FTE)	0	1	1	1	1
Detector Development					
M&S (K$)	0	50	100	150	150
Engineers (FTE)	0	0.5	1	1	1
Post Docs (FTE)	0	0	0	0	0
Scientists (FTE)	0	0.5	0.5	0.5	0.5
M&S	**0**	**90**	**135**	**190**	**190**
FTE	0.4	5.3	6.4	7.5	7.5
SWF	**70**	**915**	**1080**	**1205**	**1205**
TOTAL	**70**	**1005**	**1215**	**1395**	**1395**

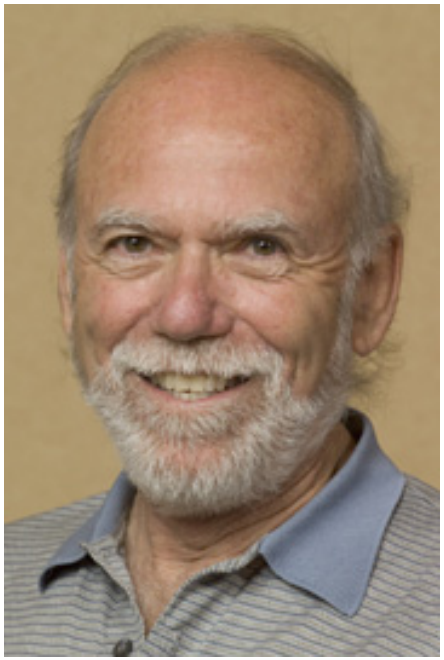
Concluding Observations

- **There is nearly full overlap in the development of new detector technologies with any new facility at the energy frontier**

- **One of the main differences between ILC – CLIC – μC is the Machine Detector Interface**
  - **The beam and decay backgrounds will determine critical detector parameters**
  - **Assuming similar detector technologies, the physics reach of a realistic detector geometry should be evaluated to enable a fair comparison between facilities**

- **The μC is the US option to return to the energy frontier. A leading role in the scientific foundation of the new energy frontier is well advised**

ILC Director's Corner, June 18



- "… the ILC programme needs to be viewed in the context of the broader efforts towards a next-generation lepton collider. The other major effort is CLIC … There are also R&D efforts towards developing a multi-TeV muon collider on yet a longer timescale.

  In one sense these efforts are in competition with each other, … but, in a more overriding sense, we are all working towards the same goal, to prepare for the next energy frontier machine for our field.

  Independent physics studies … have each given the highest priority for the future of the field to develop a lepton collider complementing the LHC while fully exploiting the Terascale. These parallel R&D programmes are all needed to determine the technical capabilities, readiness, risks and costs of these options, while the LHC discoveries will determine the desired technical requirements.

  http://www.linearcollider.org/cms/?pid=1000644