Confronting Detector Challenges of Lepton Collider Experiments

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Muon Collider 2011
Telluride
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Contributions from
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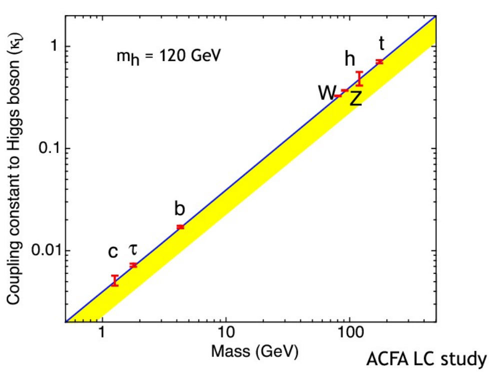
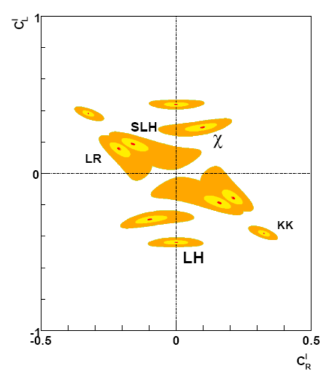
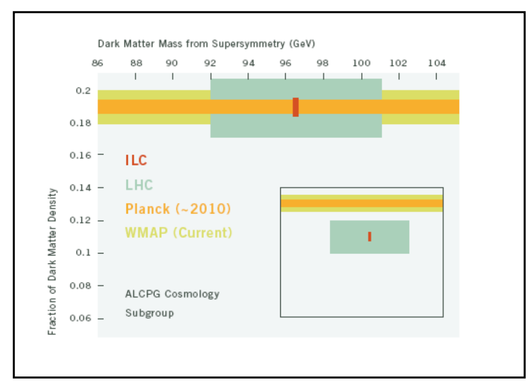
Lepton Collider Physics

- LHC should point the way <u>soon</u>…
  then Lepton Collider physics program can be sharpened –
  - Establish the mechanism for EWSB
    - - does Higgs boson have <u>Standard Model properties</u>? – or NOT?
  - Establish the nature of physics beyond the SM
    - such as SUSY, extra dimensions, …
  - Establish that accelerator-produced Dark Matter candidate does indeed resolve the cosmological Dark Matter problem
  - Open new windows for discovery at the precision frontier
  - Also – sensitivity to new physics which might be lost in hadron collider – eg. invisible decays or trigger losses

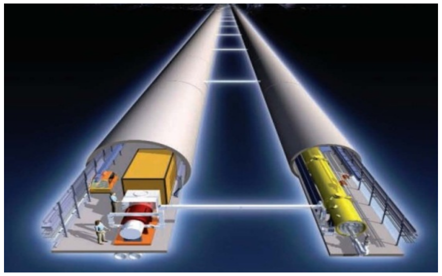




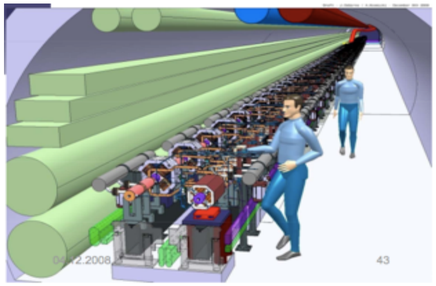


Lepton Collider Options

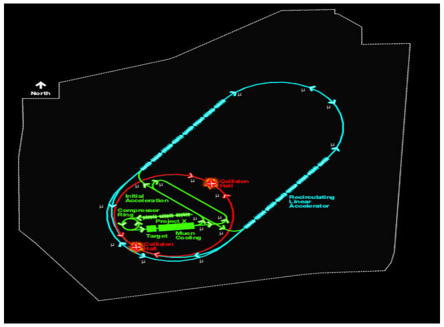
Once the LHC produces new physics, the trade-offs between the three Lepton Collider options aimed at precision physics will be front and center



- **ILC: 0.5-1.0 TeV e^+e^- linear collider**
  - Superconducting RF accelerating cavities
  - Technology demonstrated, ready to propose ~2012
  - Physics/Detectors well studied, R&D ready ~2012



- **CLIC: up to 3 TeV e^+e^- linear collider**
  - Two beam acceleration with warm RF
  - R&D underway, but technical demonstrations needed
  - Machine and Detector CDR in 2011, TDR in 2018-20?



- **Muon Collider: up to 4 TeV $\mu^+\mu^-$ storage ring**
  - Fermilab's Muon Accelerator Proposal will study technical feasibility and cost of the machine
  - Conceptual design ~2016-17

- Each presents a set of detector challenges

LHC Progress Means LC Requirements Could Be Known Soon

CHOICE DEPENDS ON AN INFORMED ANALYSIS

… physics issues defining required machine parameters...

- **What is the maximum energy required?**
  Is the new physics within the range of ILC, or needing CLIC or MC.
- **What range of energies/luminosities is needed?**
  Need to run at lower energies for Higgs, Top, Low Mass SUSY?
  Are threshold scans needed for precision measurements?
- **How does beam energy spread matter for the physics?**
  dL/dE differs among the machines. What is the impact?
- **Is beam polarization essential and can it be measured?**

…and detector capabilities enabling the machine

- **Can the detector do physics in the machine's environment?**
- **Is detector performance adequate for the physics goals?**
- **How critical is full solid angle coverage?**

Detector Requirements For Lepton Collider Physics Are Demanding

- Unambiguous identification of multi-jet decays of Z's, W's, top, H's, χ's,
  - ***Excellent jet energy resolution***
- Higgs recoil mass and χ decay endpoint measurements
  - ***Superb tracker momentum resolution***
- Full flavor identification and quark charge determination for heavy quarks
  - ***Precise impact parameter resolution***
- Identification and measurement of missing energy, eliminating SM backgrounds to SUSY
  - ***Full hermiticity***

Lepton Collider Detector R&D

- ILC
  - Several years of detector R&D have produced near maturity of detector technologies
- CLIC
  - Experimental design has defined the detector R&D needs, and program is beginning – building on ILC program
- MuC
  - Experimental design needed now to formulate R&D program

ILC Detectors
Physics Requirements Are Set

Physics Process	**Measured Quantity**	**Critical System**	**Critical Detector Characteristic**	**Required Performance**
$H \to b\bar{b}, c\bar{c}, gg$ $b\bar{b}$	Higgs branching fractions b quark charge asymmetry	Vertex Detector	Impact parameter ⇒ Flavor tag	$\delta_b \sim 5\mu m \oplus 10\mu m/(p\sin^{3/2}\theta)$
$ZH \to \ell^+\ell^- X$ $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu}$ $\to \mu^+\mu^- X$	Higgs Recoil Mass Lumin Weighted E_{cm} BR ($H \to \mu\mu$)	Tracker	Charge particle momentum resolution, $\sigma(p_t)/p_t^2$ ⇒ Recoil mass	$\sigma(p_t)/p_t^2 \sim few \times 10^{-5} GeV$
ZHH $ZH \to q\bar{q}b\bar{b}$ $ZH \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass BR ($H \to WW^*$) $\sigma(e+e- \to \nu\nu\ W+W-)$	Tracker & Calorimeter	Jet Energy Resolution, σ_E/E ⇒ Di-jet Mass Res.	~3% for E_{jet} > 100 GeV $30\%/\sqrt{E_{jet}}$ for E_{jet} < 100 GeV
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum resolution, Hermiticity ⇒ Event Reconstruction	Maximal solid angle coverage

Excellent performance needed to fulfill physics potential

New Physics Could Change Expectations

Physics surprises could reshape the standard detector. We may have to accommodate:

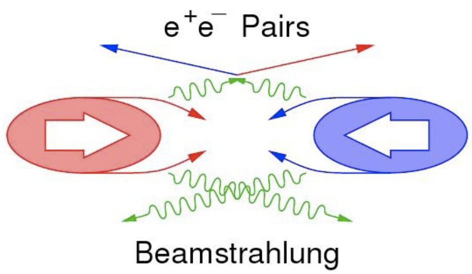
- Very long-lived massive particles which stop in the calorimeters or decay beyond the tracker?
- Extremely high decay multiplicities from mini-black holes or ???
- “Weakly” interacting (e.g., fractional or milli-charged) particles requiring enhanced detector sensitivity?

New technologies should expand detector capability. What can we do with:

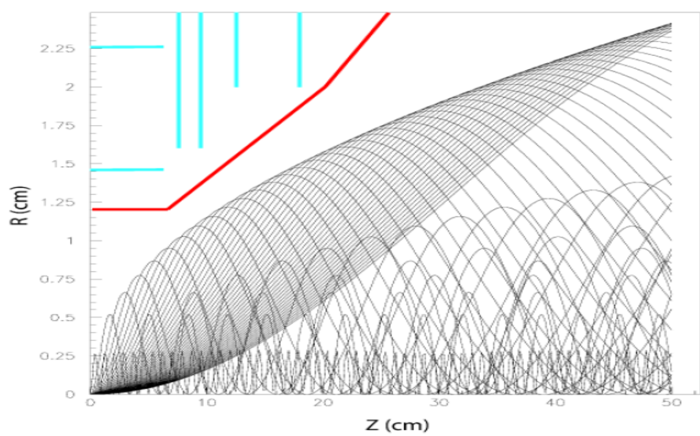
- Pico-second timing measurements?
- Vastly higher pixel counts?
  This could allow much more information per measurement and improved energy or spatial resolution. Particle flow calorimetry and cluster counting drift chambers are steps in this direction.
- Real time feedbacks?
  Astronomical observatories correct mirror sag, temp effects, and atmospheric distortions in real time. What can real time feedbacks do for particle physics observatories?

ILC Environment Poses Challenges

Tiny beam spots, intense collisions lead to e+e- pairs from beamstrahlung

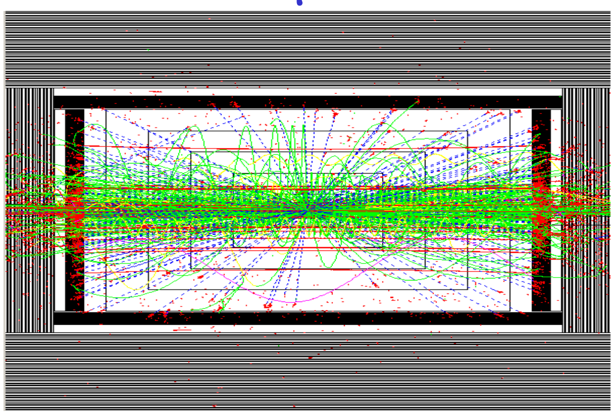


Most pairs at ILC are trapped by the solenoid, but vertex occupancies are still challenging

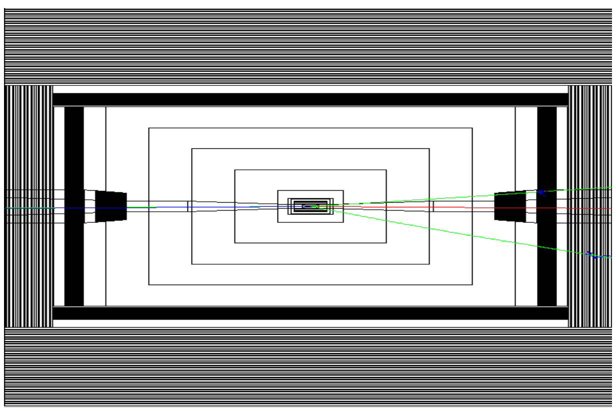


$\gamma\gamma \rightarrow$e+e-, μ+μ-, hadrons reactions put a premium on short detector livetimes

Livetime 40 μs ~ 130 BX



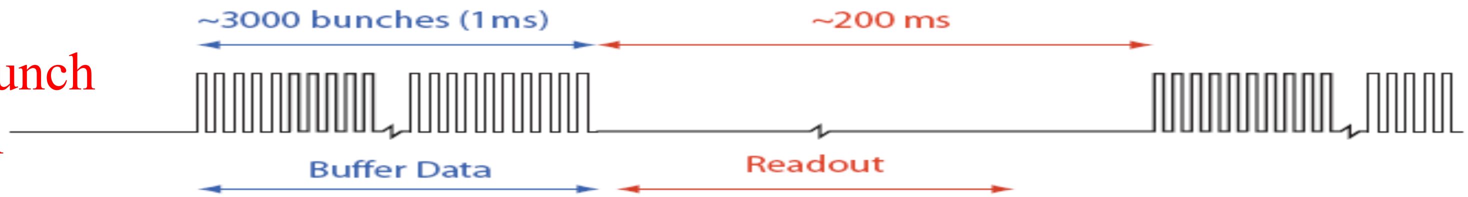
Livetime 100ns ~ 1 BX



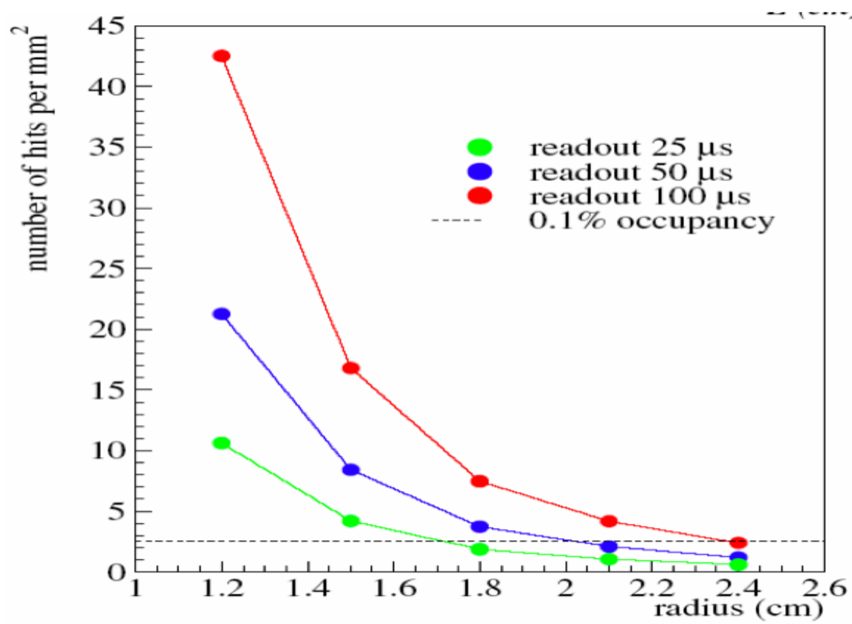
ILC Vertex Readout Challenge

- Bunch train structure can swamp the inner layers of the VXD with beamstrahlung induced pair backgrounds.

ILC bunch train



- To reduce occupancies to ≤ 5 mm^{-2}, must readout ≥50 times per bunch train. New sensor technologies are being developed to speed readout, reduce occupancy.

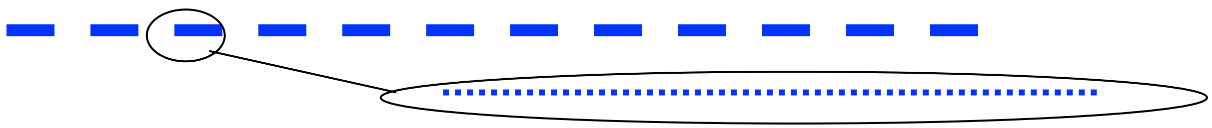


CLIC Environment More Challenging

Graphics from Lucie Linssen

Train repetition rate 50 Hz (vs 5 Hz at ILC)

CLIC

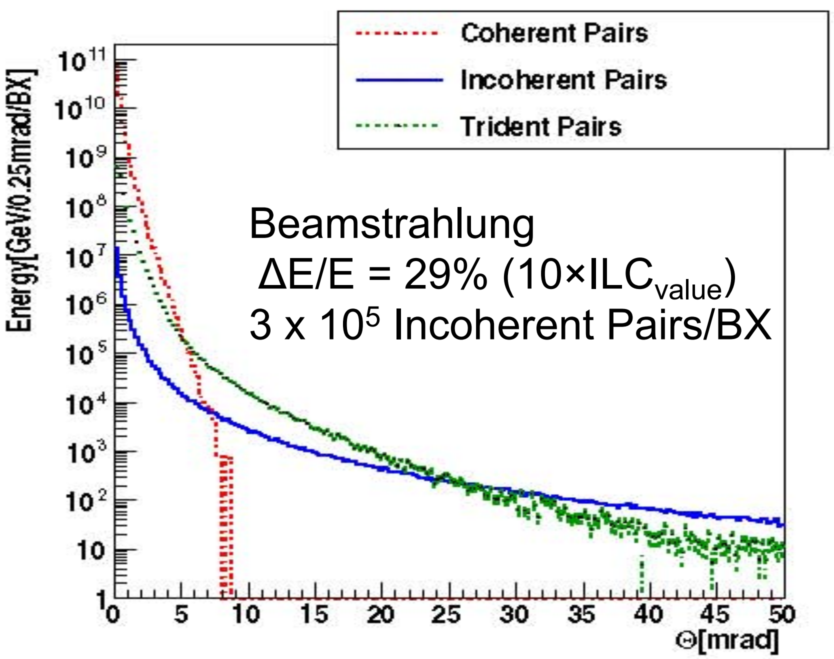


CLIC: 1 train = 312 bunches 0.5 ns apart 15k collisions/sec

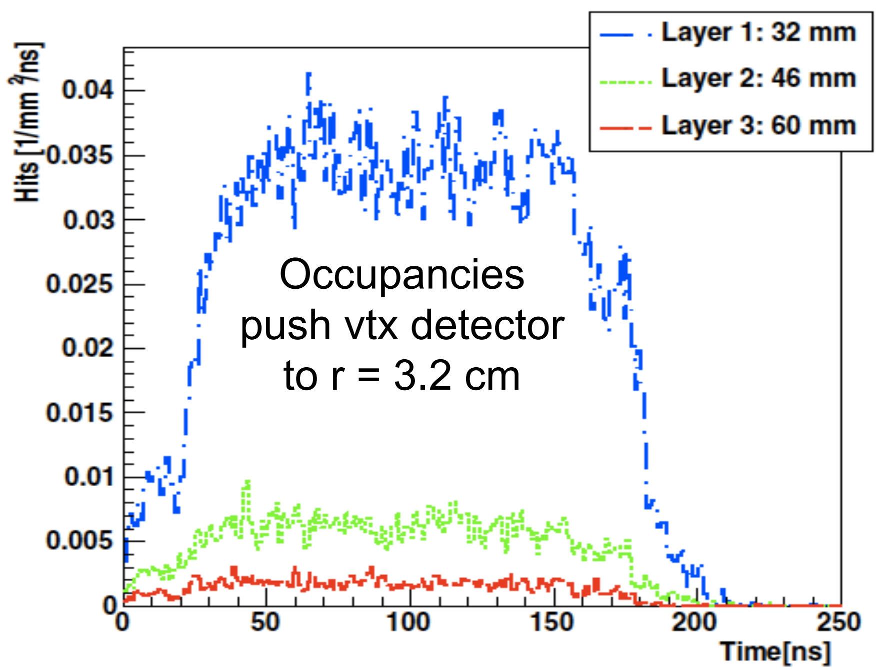
ILC: 1 train = 2820 bunches 308 ns apart 14k collisions/sec

CLIC smaller spots, higher energy, much more beamstrahlung

Beamstrahlung energy vs angle



Vertex detector occupancies vs time



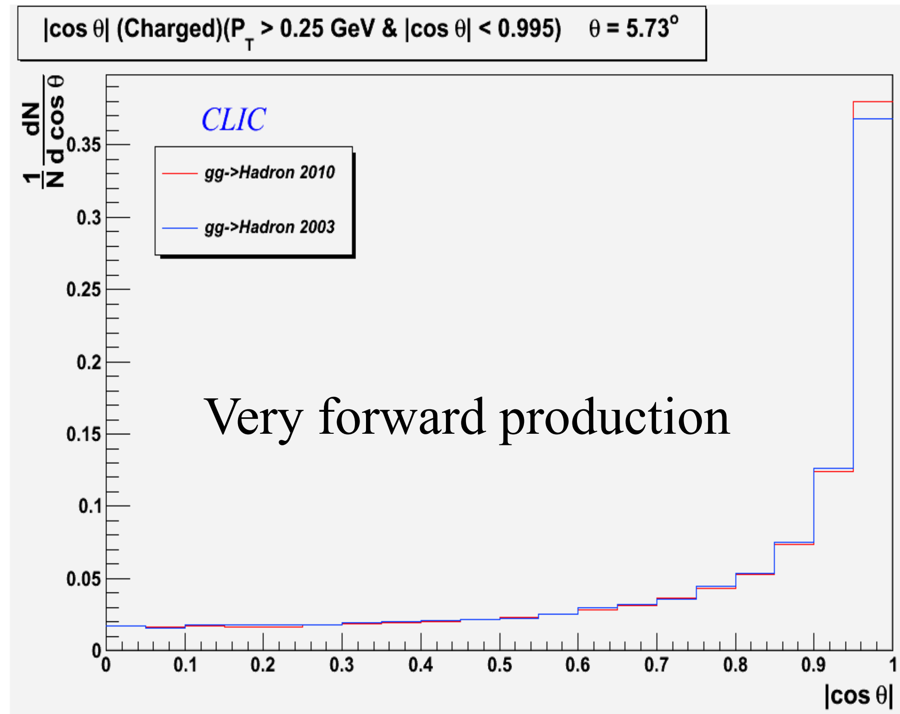
CLIC Environment: More $\gamma\gamma \to$hadrons

Per bunch crossing (every 0.5 ns)

3.3 $\gamma\gamma \to$hadrons events
28 particles into the detector
50 GeV deposited

Per bunch train (duration 156 ns)

9000 particles into the detector!
Most particles into forward detectors
15 TeV deposited!



5-10 NS TIME STAMPING REQUIRED

CLIC Environment Impacts Detector Design

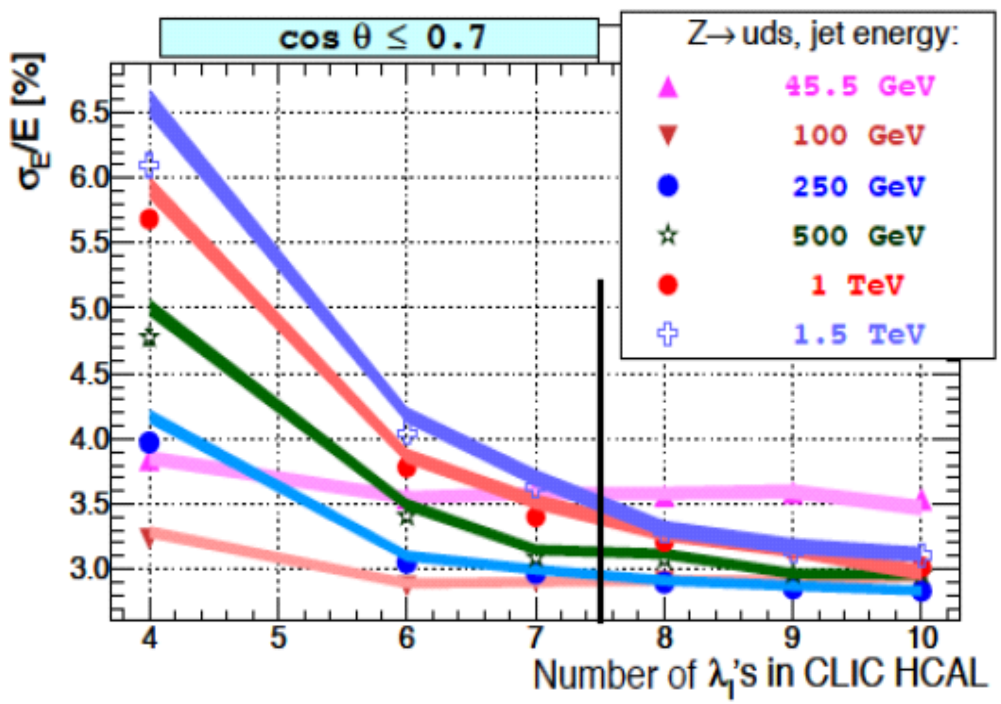
Vertex Detector Challenges (above and beyond ILC)

- Multi-hit capability with 10 ns time-stamping
- Read out full bunch train (300 bunches)
- DAQ between bunch trains (20 ms)

Calorimetry Challenges

- Good resolution at highest energies → 7.5 λ Hcal
- Excellent segmentation to separate particles in HE jets
- Time stamping ~5-10 ns

Pandora PFA used for Hcal Studies



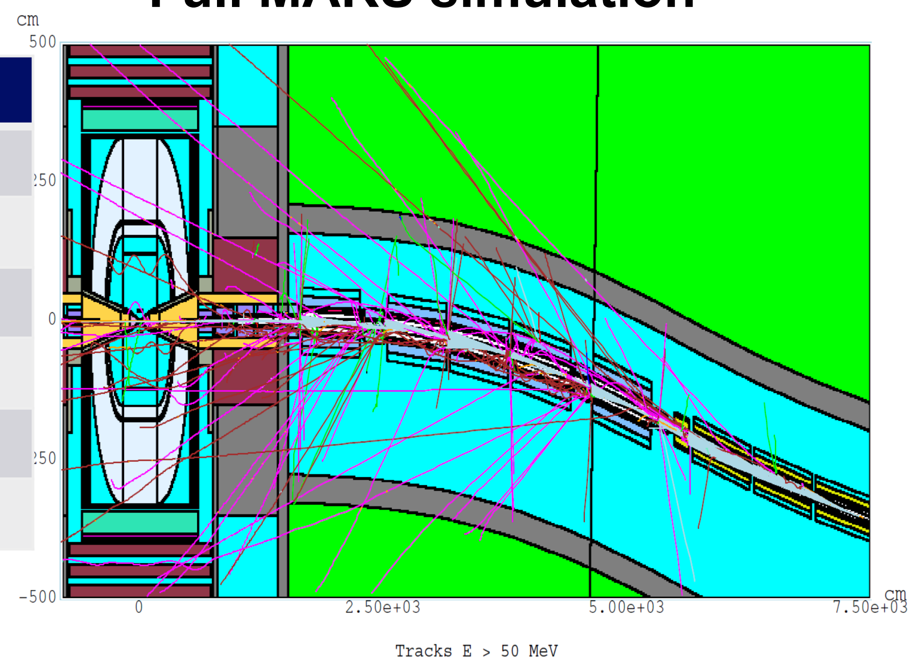
MuC Environment Extremely Challenging

1. IP incoherent e^+e^- pair production: 3×10^4 electron pairs/ bunch crossing
2. Beam halo: Severe beam loss at limiting apertures, but collimators help
3. Muon beam decays: **Intense Background!**
   – For 0.75-TeV muon beam of $2\text{x}10^{12}$, $4.3\text{x}10^5$ decays/m per bunch crossing, or $1.3\text{x}10^{10}$ decays/m/s for 2 beams

MuC parameters

E_{cms}	TeV	1.5	4
f_{rep}	Hz	12	6
n_b		1	1
Δt	μs	10	27
N	10^{12}	2	2
$\varepsilon_{x,y}$	μm	25	25
L	10^{34} /cm/s	1	4

Full MARS simulation



Graphics from Nikolai Mokhov and Sergei Striganov

MuC MDI Challenges

- Machine Detector Interface issues need thorough assessment
  - realistic machine lattice and full MARS simulations can assess the decay backgrounds.

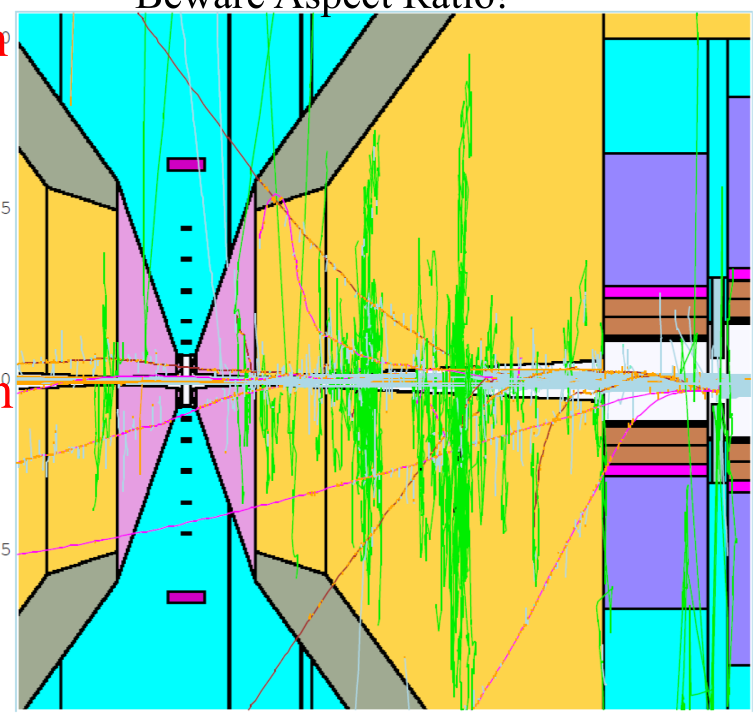
6m Conical Tungsten Mask

A tungsten cone at the IP intercepts the intense background of decay electrons.

$6 < z < 100$ cm $\theta = 10^0$
$100 < z < 600$ cm $\theta = 5^0$

Tungsten Cones on Beamline

Beware Aspect Ratio!

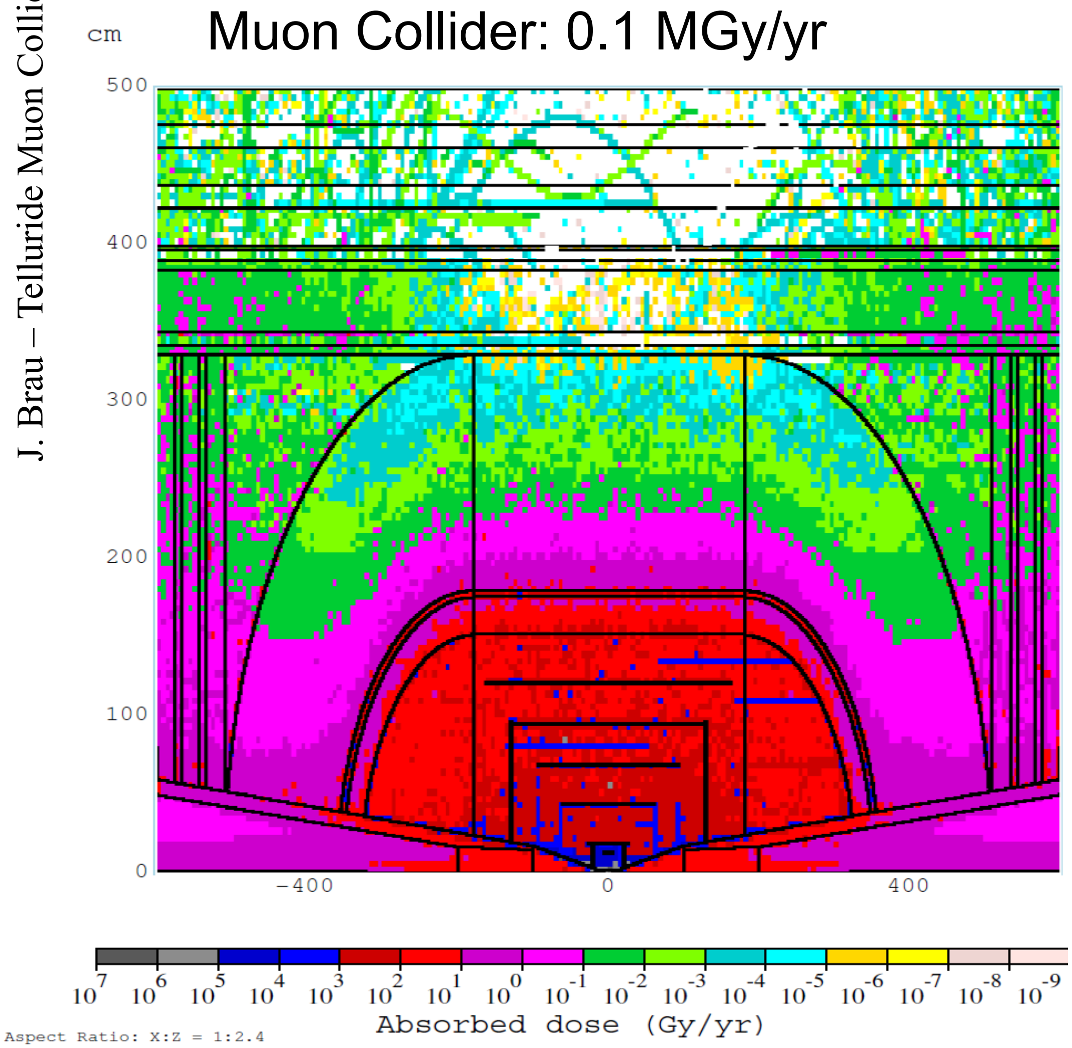


MuC Radiation Hardness Occupancy Challenges

Total Absorbed Dose ~ LHC

Total absorbed dose in Si at r = 4cm

Muon Collider: 0.1 MGy/yr

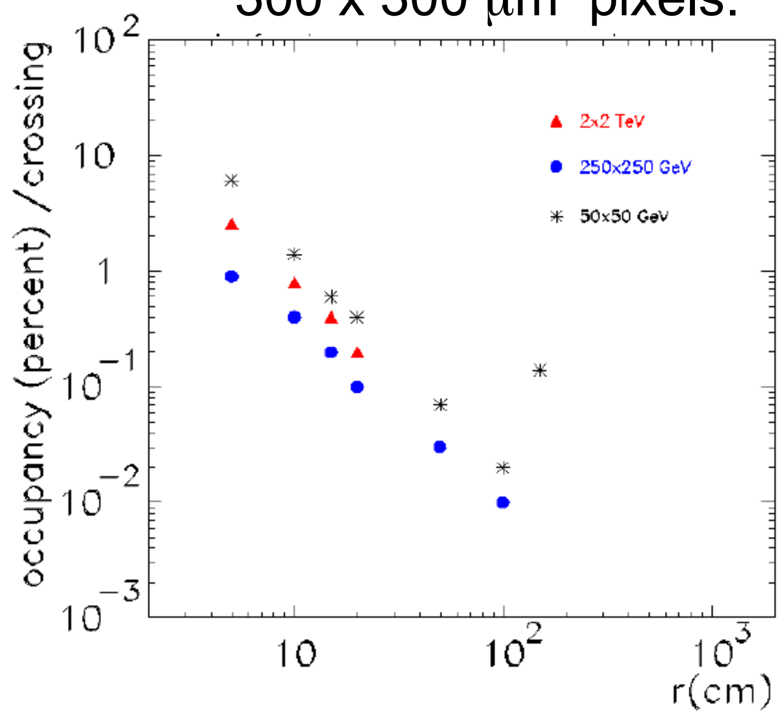


Vertex Radius

Backgrounds limit min radius to ≥ 5 cm

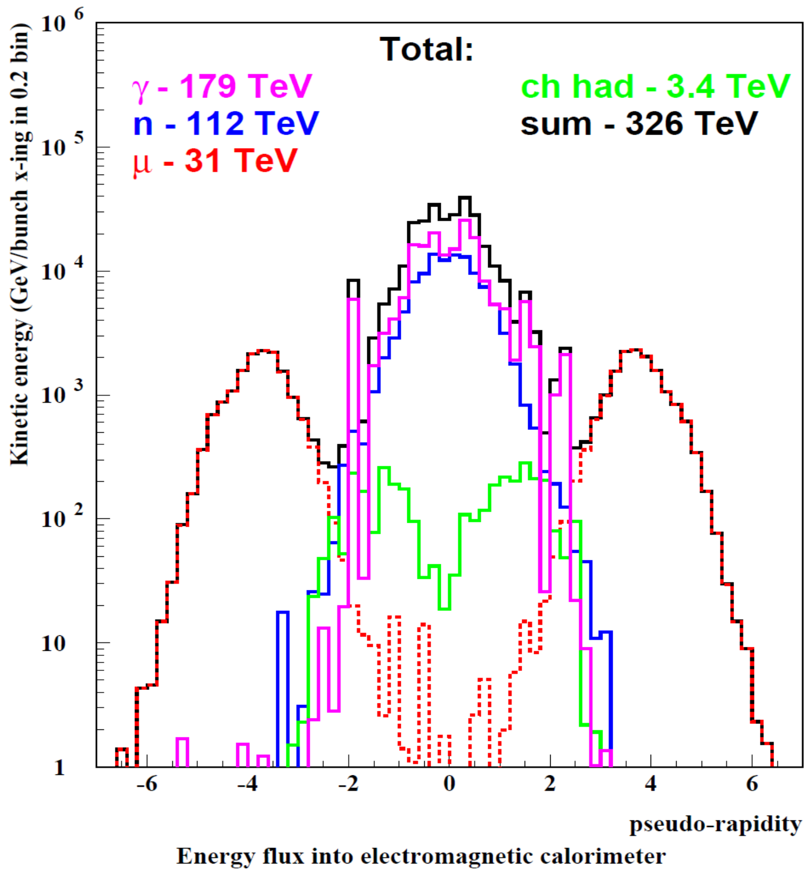
Vertex Occupancy

1.3% occupancy in inner layer with 300 x 300 μm^2 pixels.



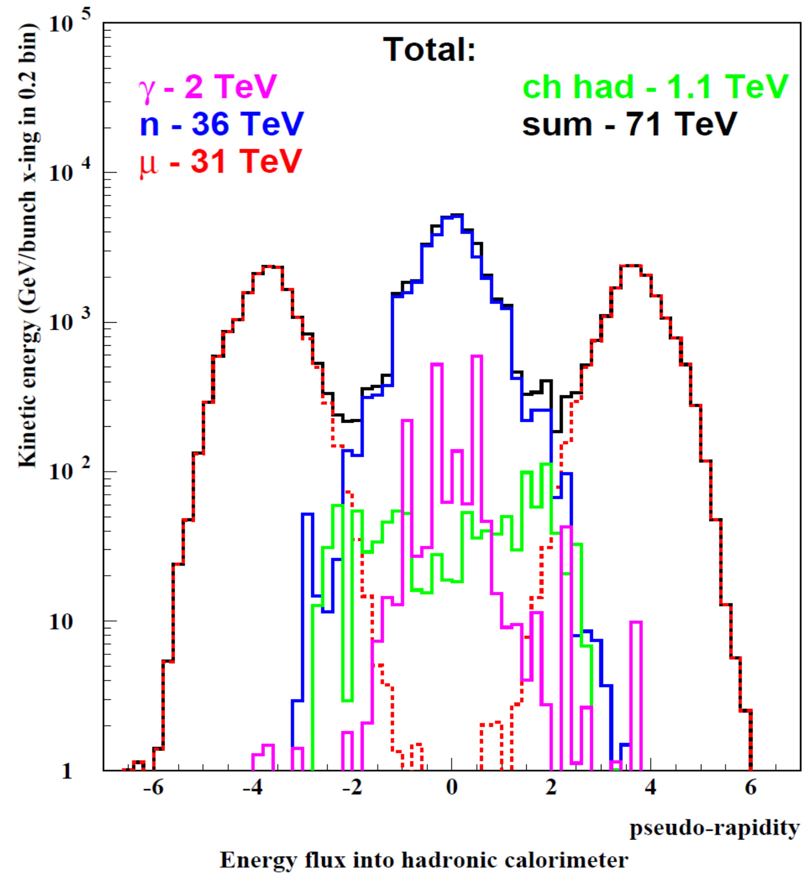
Large Calorimeter Depositions (~100 TeV)

Energy Flow into Ecal



Peak: ~1 GeV / 2x2 cm^2 cell with σ_E ~ 30 MeV

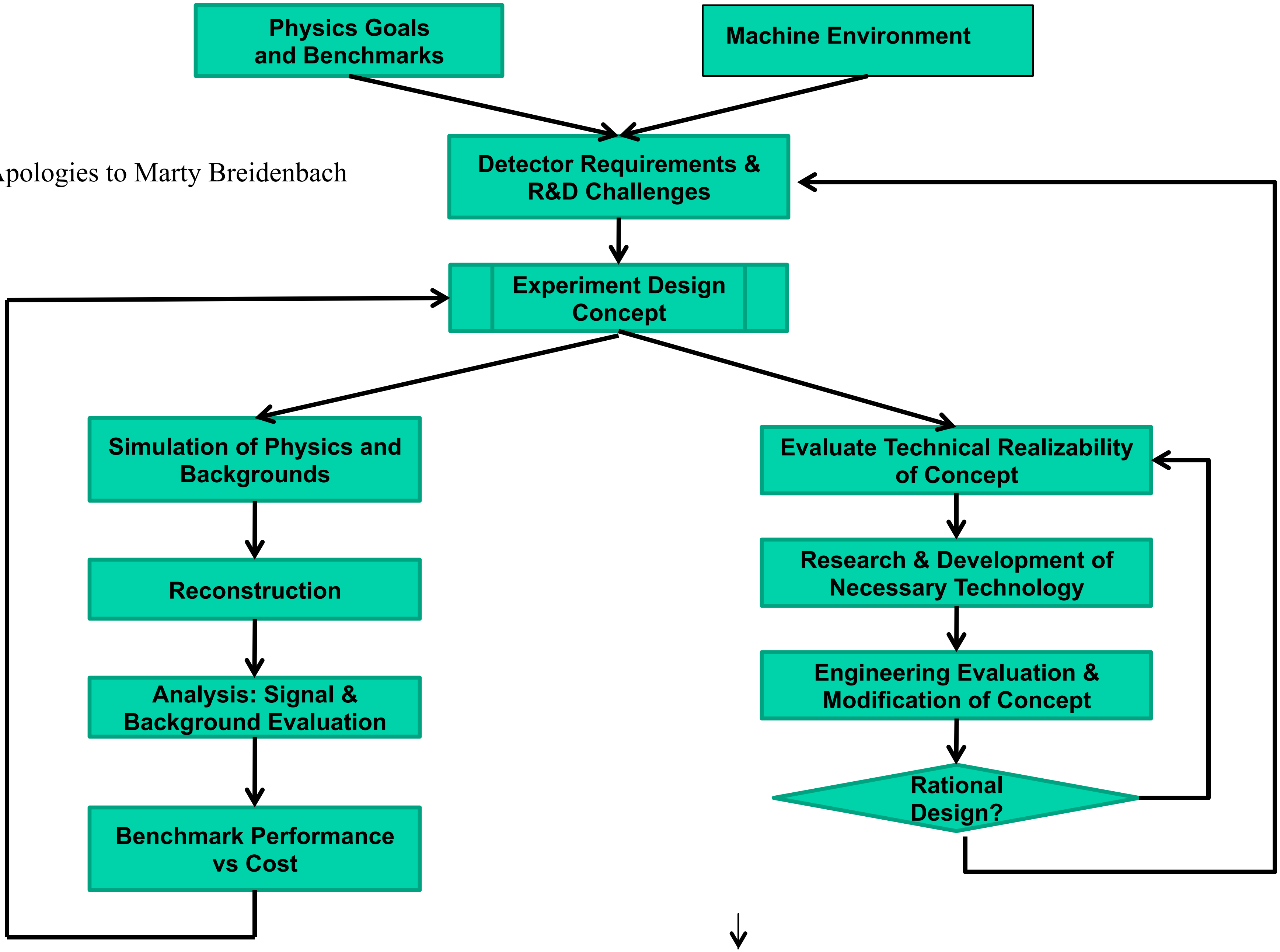
Energy Flow into Hcal



Peak: ~1.5 GeV / 5x5 cm^2 cell with σ_E ~ 80 MeV

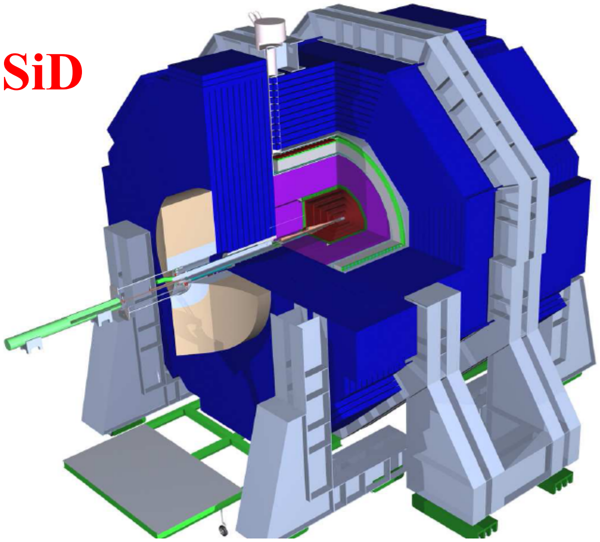
Steps in Detector Concept Development

Apologies to Marty Breidenbach

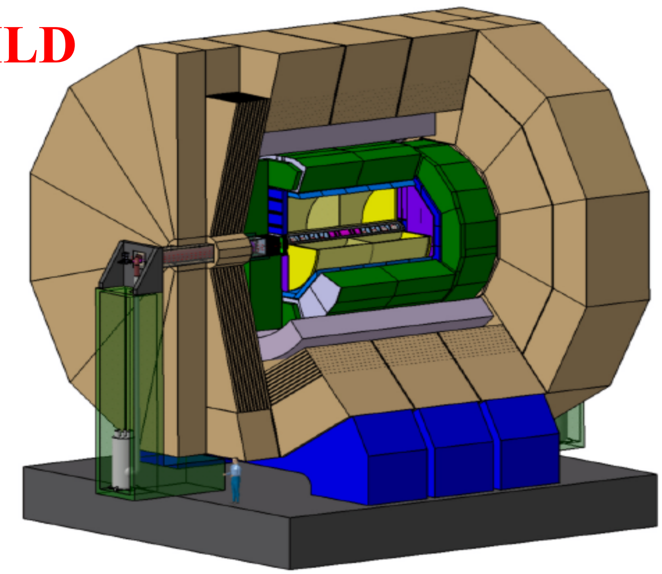


ILC Detectors Have Advanced Through This Process

SiD



ILD



- Evolution of ILC detector concepts is captured in a series of documents

Detector Outline Document	2006
Detector Concept Report	2007
Letters of Intent	2009
Detailed Baseline Design	2012

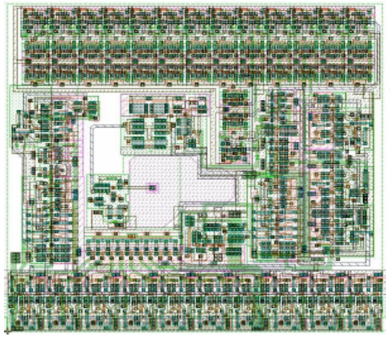
- Detector LoI

  Detailed detector description
  Status of critical R&D
  Full GEANT4 simulation
  Benchmark analyses
  Costs

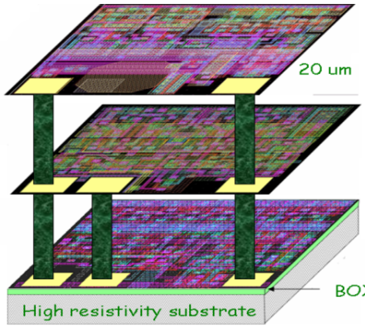
ILC Critical R&D

Vertex Detectors

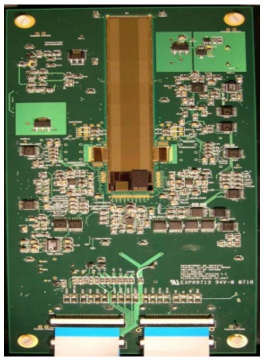
- Development of candidate VXD sensors have produced prototypes.
- Integration issues have been addressed (mechanics, power, heat,…)
- Tough requirements
  High resolution, fast readout, low mass, low heat
- Technical demonstration still needed.



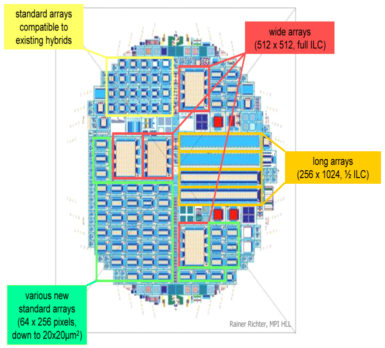
CMOS/Chronopix



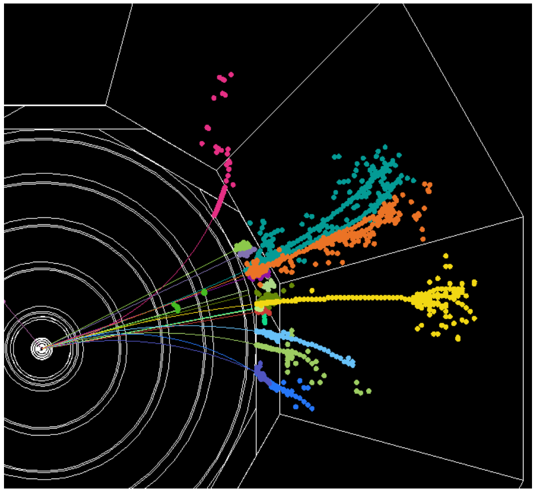
3D-SOI



CPCCD



DEPFET



Particle Flow Calorimetry

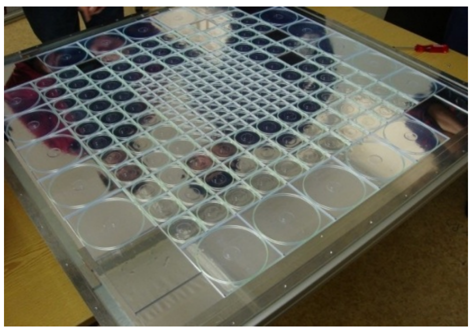
- Pandora PFA gives $\Delta E/E$ = 3-4% in full simulation
- Experimental confirmation coming from CALICE
- PFAs have become a design tool, useful for detector optimization.

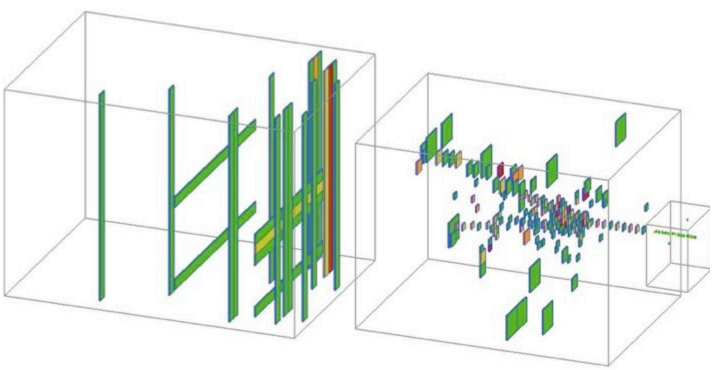
ILC Critical R&D

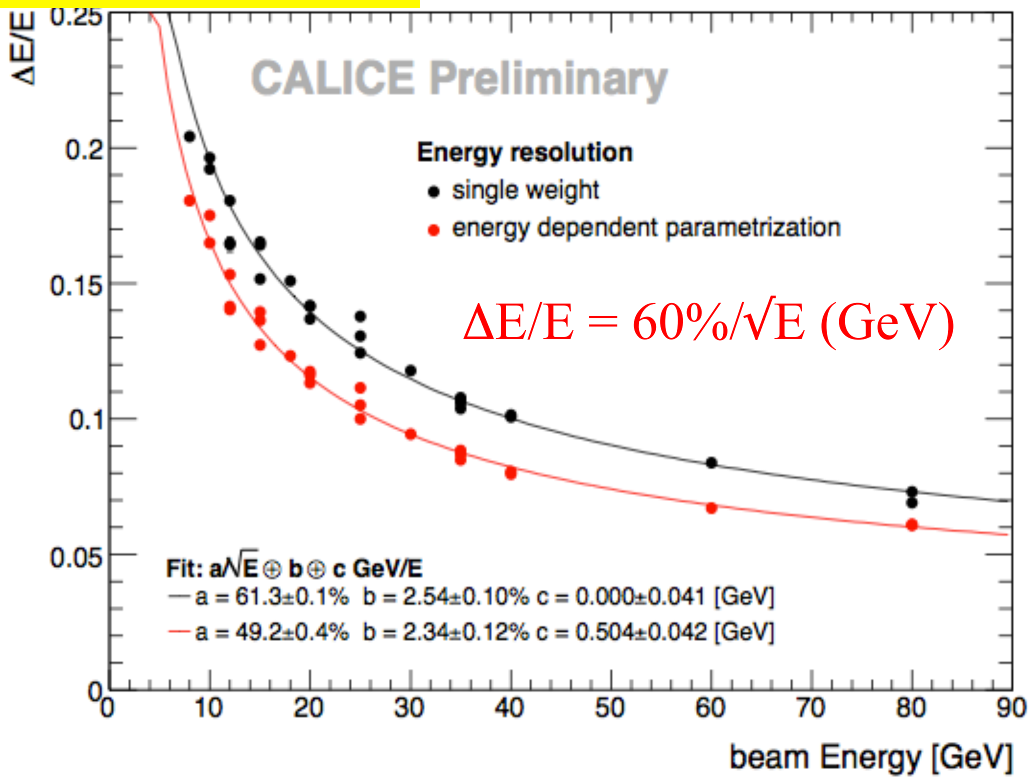
Hadronic Particle Flow Calorimetry

- 1 x 1 m^2 Scintillator Hcal (3 x 3 cm^2 pixels) has been beam tested
- 1 x 1 m^2 RPC digital Hcal (1 x 1 cm^2 pixels) also tested
- Hardware demonstrated, but “particle flow” is harder to prove!

CALICE Scintillator Hcal

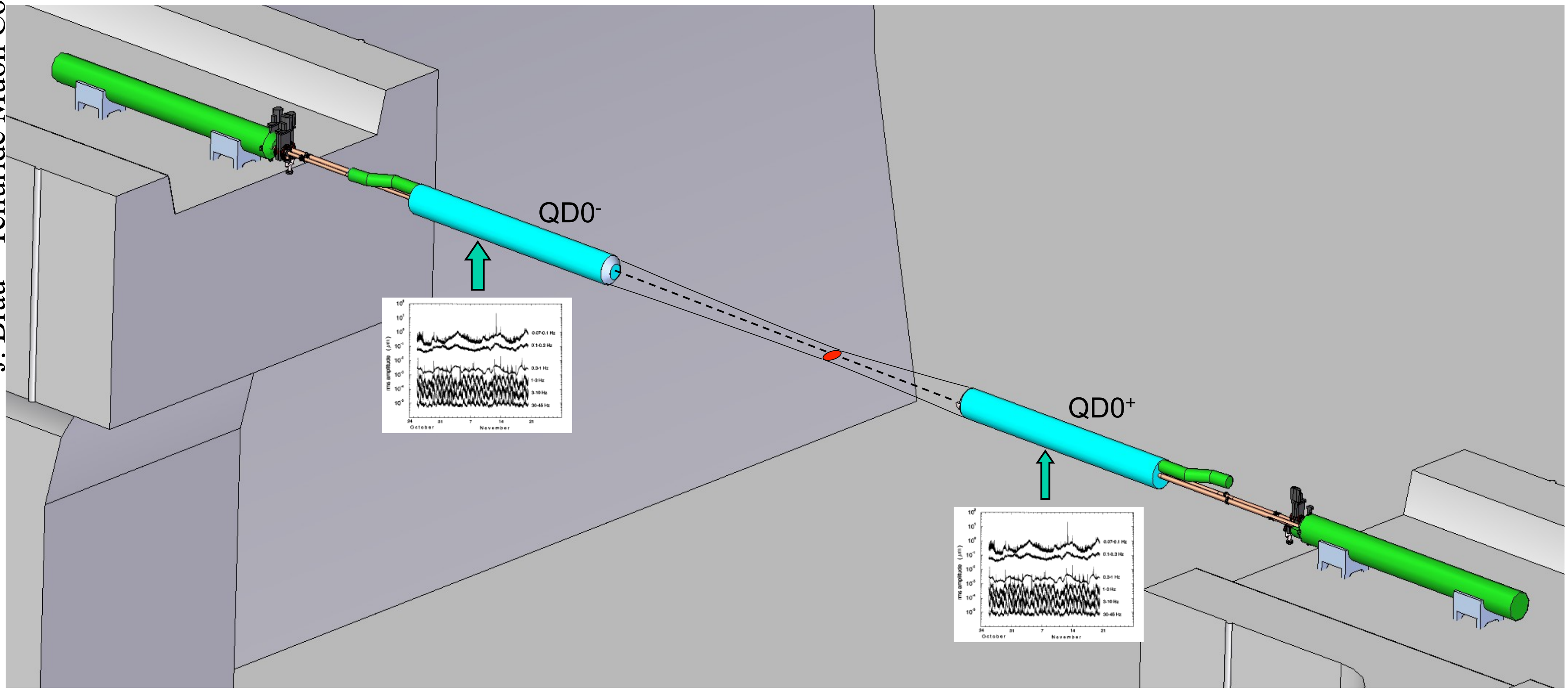






ILC Critical R&D: Vibrations and Support

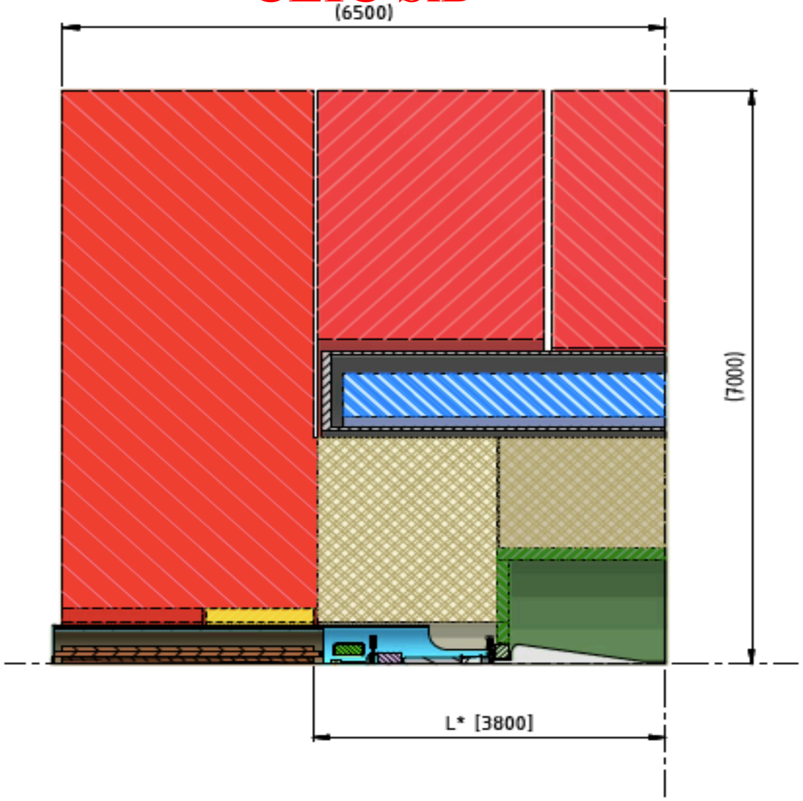
- Challenge: Stabilize final quads to 10's of nm against ground motion while allowing for detectors to move on and off beamline
- Engineering studies underway



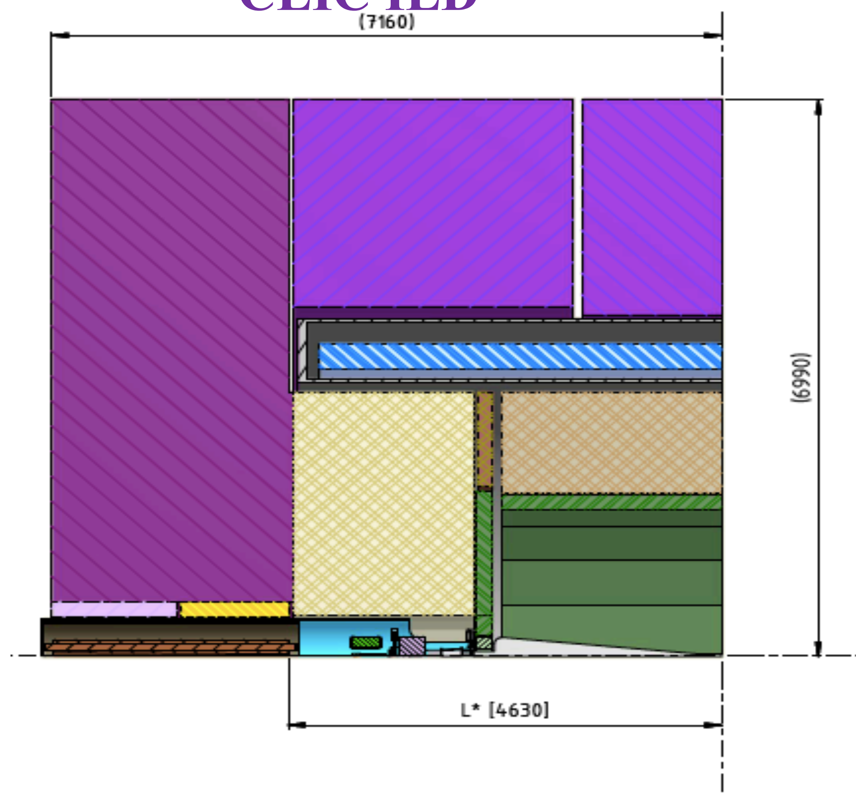
CLIC Developing Detector Concepts for CDR

- Machine backgrounds under study
- Detector requirements being evaluated
- ILD and SiD simulation/reconstruction frameworks used to jumpstart performance studies
- Embarking on critical R&D

CLIC SiD'



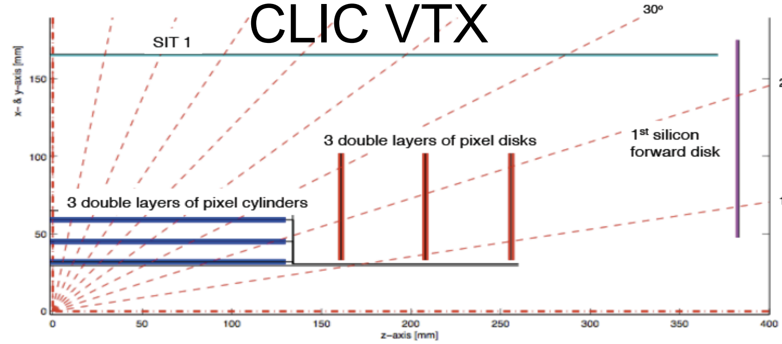
CLIC ILD'



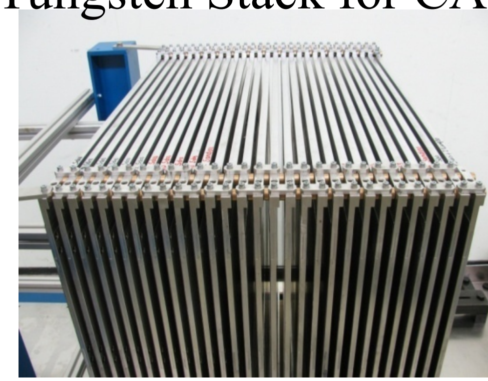
CLIC Detector R&D Underway

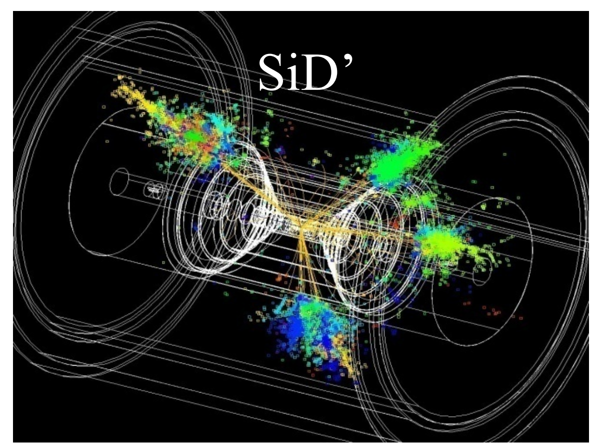
- CLIC Vertex Detector Concept
- Scintillator/Tungsten Hcal
  Density of W allows a compact Hcal
  Calice will test it
- Reinforced SC Magnet Conductor
- Support and Vibration Studies
  nm spots and short bunch trains (which defy feedbacks) require ~nm stability
- Defining and simulating concepts
- Benchmarking for CDR

CLIC VTX

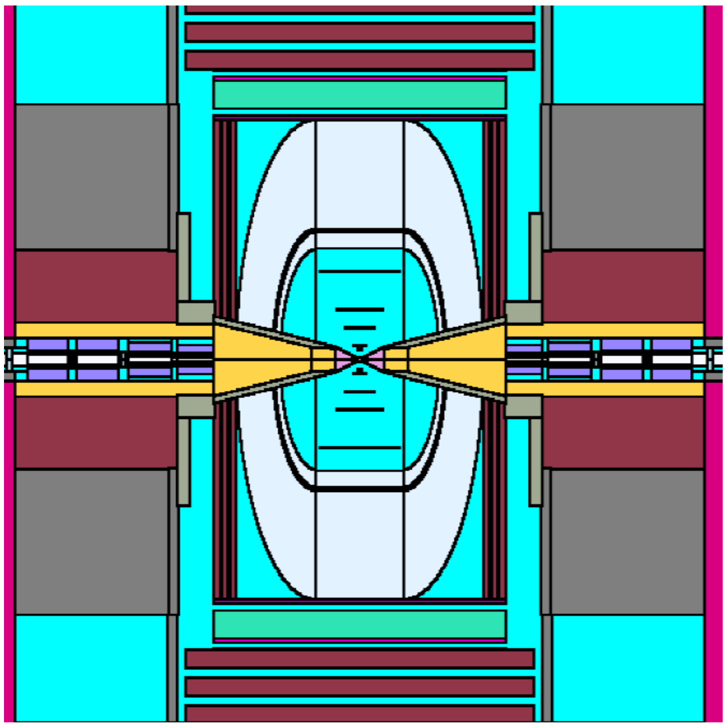


CLIC Tungsten Stack for CALICE





Developing MuC Detector Concepts



- Study of physics and detectors at the MuC is has recently increased
- Evaluation of backgrounds for realistic lattices is underway
- Development of MuC detector concepts lies ahead – LCSIM can be applied
- This is a challenging environment
  - Radiation hard detectors required
  - High Occupancies in tracking detectors
  - High Energy deposition in calorimeters
- Benchmarking of physics needed
  - Compare to CLIC – same physics

"White Paper" Proposal → LCFP

David MacFarlane described a "*Program of Detector Evaluation and R&D for Future Lepton Colliders*" in the August 2010 DPF newsletter

A proposal is being developed for a common program of detector performance evaluation and coordination of detector R&D should for lepton colliders, *the Lepton Collider Framework Proposal (LCFP).*

- Establish the physics capability of each lepton collider option
- Understand the machine capabilities, limitations, and timetables for each option
- Establish detector requirements at each collider, accounting for the very different machine environments
- Facilitate development of suitable detector concepts, exploiting the existing SLAC software framework for simulation and benchmarking
- <u>Coordinate</u> the necessary physics studies and <u>detector R&D</u> needed to establish concept viability
- Compare the physics potential of all the options on an equal footing

This coordinated Lepton Collider Program would apply the methodology and tools developed for ILC detector development to CLIC and MuC detectors

LCDRD Proposal

- DOE's *Collider Detector Research and Development* FOA announcement in January, 2011, moved R&D coordination to first step.

- The University Detector R&D Program for ILC detectors receives last funding at the end of FY11. LCDRD has been proposed as a continuation of this program, with an expanded scope.

- LCDRD adopted many of the ideas articulated for LCFP:
  * Support all Lepton Colliders: ILC, CLIC, MuC
  * Support detector concept development
  * Identify R&D critical for concepts and initiate it
  * Finish up ILC R&D, start CLIC R&D, identify needed MuC R&D
  * Support LCSIM simulation infrastructure for detector studies

LCDRD Consortium Proposal

- A broadly distributed solicitation (DPF, mailing lists) invited Detector R&D proposals aimed at <u>all three Lepton Collider options</u> to join the LCDRD Consortium Proposal and outlined LCDRD management plan
- 14 Proposals submitted to LCDRD
  others expressed possible future interest
- LCDRD Review Board reviewed and prioritized proposals
  J. Brau, J. Jaros, R. Lipton, A. Para, D. Peterson, H. Weerts
- LCDRD proposal was submitted 3/18/11 with SLAC administering
  - PIs - John Jaros, Jim Brau, Marcel Demarteau

LCDRD Proposals

Project No.	Topic	Institutions	PI	Project Description
1.1	Simulation	SLAC-Fermilab	Graf/Lipton	CD Simulation Framework
2.1	Vertex	Yale/Oregon	Baltay	Chronopix Development
2.2	Vertex	UC Santa Cruz	Battaglia	High Resistivity Pixel Sensors
3.1	Tracking	Michigan	Riles	Precision Alignment
3.2	Tracking	UC Santa Cruz	Schumm	Si Sensor and Readout
3.3	Tracking	New Mexico	Seidel	Si Sensors and Interconnects
4.1	Calorimetry	UT Arlington	White	GEM HCal
4.2	Calorimetry	Iowa	Onel	Digital HCal with RPCs
4.3	Calorimetry	Iowa	Onel	Dual Readout Calorimetry
4.4	Calorimetry	Oregon/Davis	Frey	Si/W ECal
4.5	Calorimetry	Iowa	Mallik	Particle Flow Algorithm
4.6	Calorimetry	Princeton	McDonald	RPC Aging Study
5.1	Beamline	Notre Dame	Hildreth	BPM Energy Spectrometer
5.2	Beamline	Oregon	Torrence	Extraction Line Spectrometer

Annual review and solicitation of new proposals; annual report to DOE

LCDRD Proposals

- Mostly continuations of SiD R&D
- Several proposals now explore applicability at CLIC or MuC
  - * Alignment
  - * Energy spectrometers
  - * PFA
  - * Dual readout calorimetry
- One proposal solidly directed at new lepton collider simulation studies, important for MuC and CLIC:
  - * Collider Detector Simulation Framework (LCSIM+)
- First attempt to include <u>CLIC and MuC</u> proposals met limited success – strive to <u>include more in the future</u>

LCDRD Proposal Status

- DOE announced on June 16 that funding decisions are delayed until FY12
- In the meantime, plan to evolve LCDRD/LCFP to cover outstanding LCFP goals
  * Physics simulation funds
  * Comparison of physics capability
  * Comparison of machines and detectors
- LCDRD PIs would like to hear from anyone interested in joining the consortium with a new proposal
  – Please contact Jaros, Brau, or Demarteau

Summary

- The physics goals motivating energy frontier lepton colliders set demanding requirements for detectors, some of which have been addressed with recent detector R&D for the ILC.
- The machine environments at ILC, CLIC, and MuC pose additional, and sometimes severe, challenges for detector design.
- A comprehensive process is required to develop new detector concepts to the point that they are realizable and their physics potential is understood. The LCSIM framework offers this.
- Comparing and contrasting the physics capabilities and technical readiness of experiments at ILC, CLIC, and MuC will allow a rational choice among the Lepton Collider options.
- A detector R&D proposal has been submitted to DOE to support the development of all Lepton Collider detectors in enough detail to guide that choice.