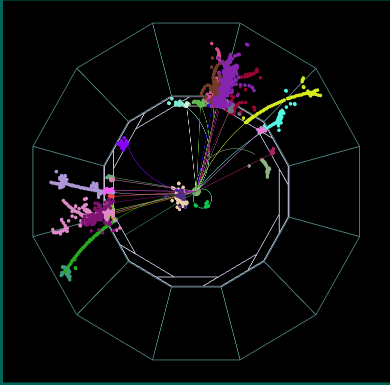


Lepton Collider Detectors

Confronting the Challenges of Lepton Collider Experiments

Jim Brau

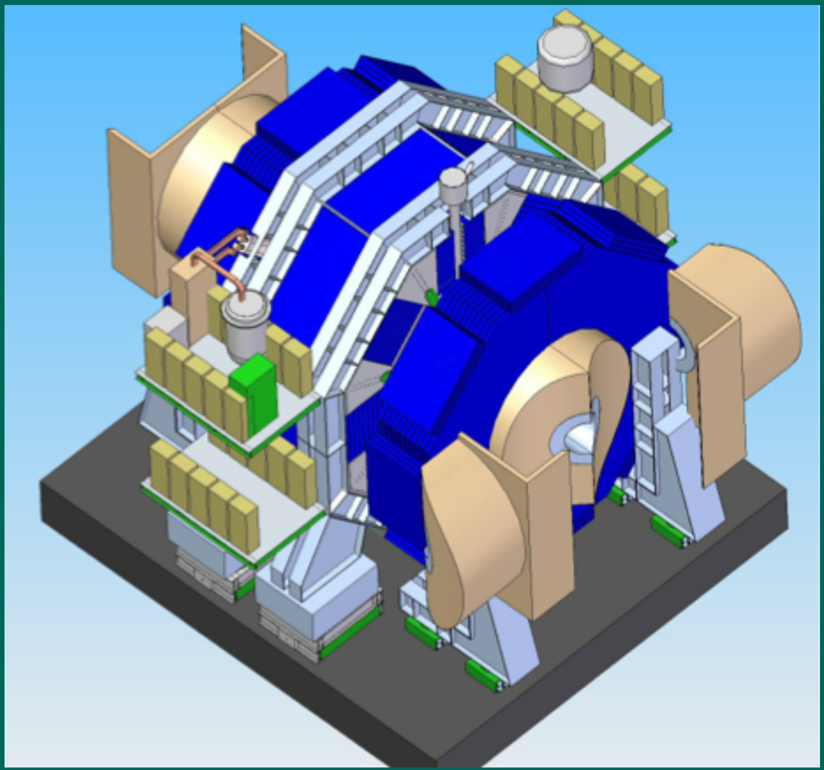
EDIT 2012

Fermilab

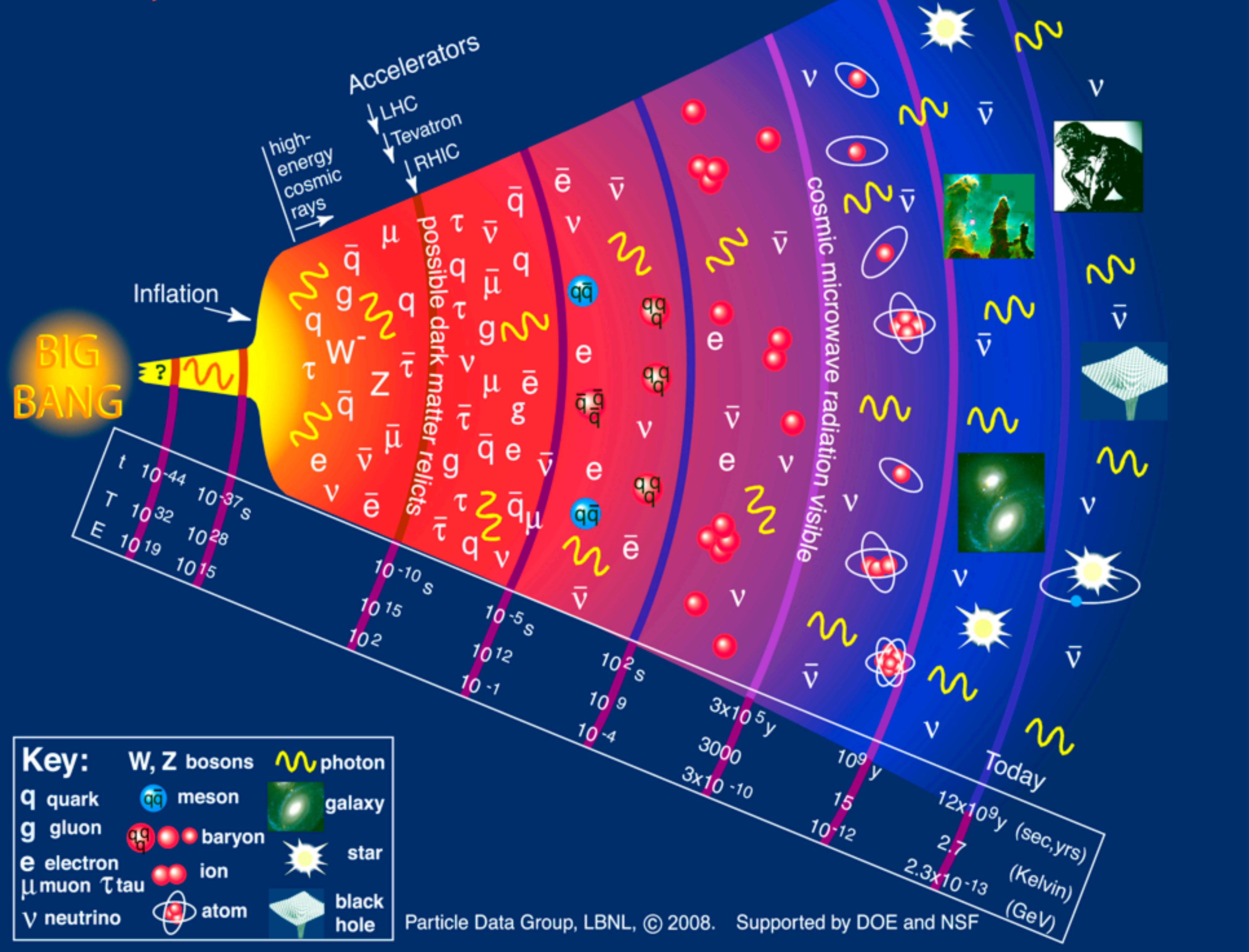
February 24, 2012

Lepton Collider Detectors

- Physics Goals and Requirements
- Collider Environment and Impact
- Detector Technologies

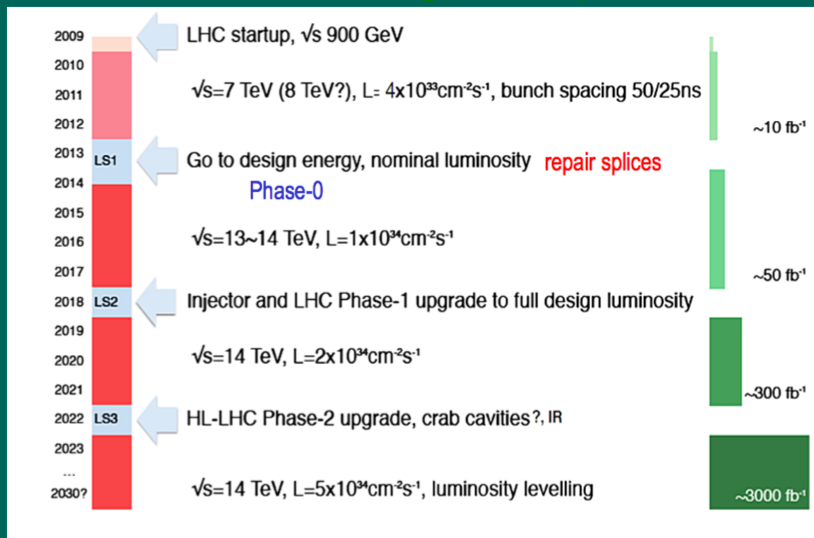


History of the Universe



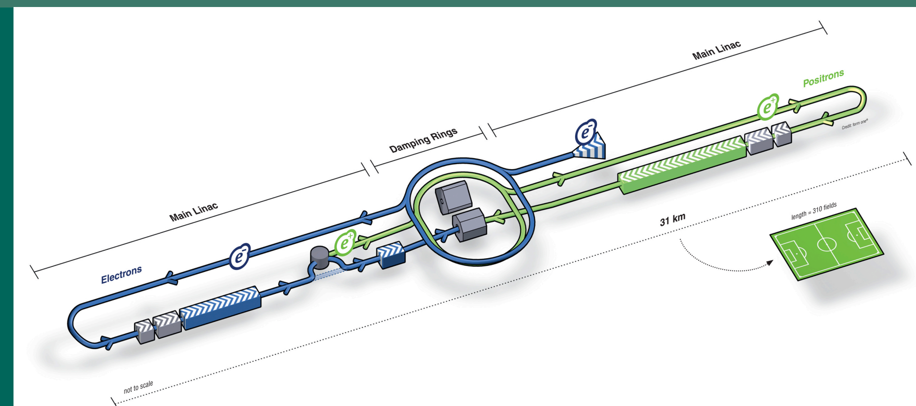
Exploring the Energy Frontier

- ✱ Terascale Physics Era is underway
  - – LHC has accumulated 5 fb^{-1} @ 7 TeV, and have a long-term plan for achieving 3000 fb^{-1} @ 14 TeV



- ✱ A Lepton Collider is the essential complement to the LHC
- ✱ Lepton Collider options cover range of new physics energies
  - – ILC will be ready to go when LHC sets the energy scale with new physics – if higher energy is required, CLIC and MuC are possible
- ✱ Experiments are challenging, demanding aggressive, focused detector R&D

Standard Model Developed from Hadron and Lepton Collisions



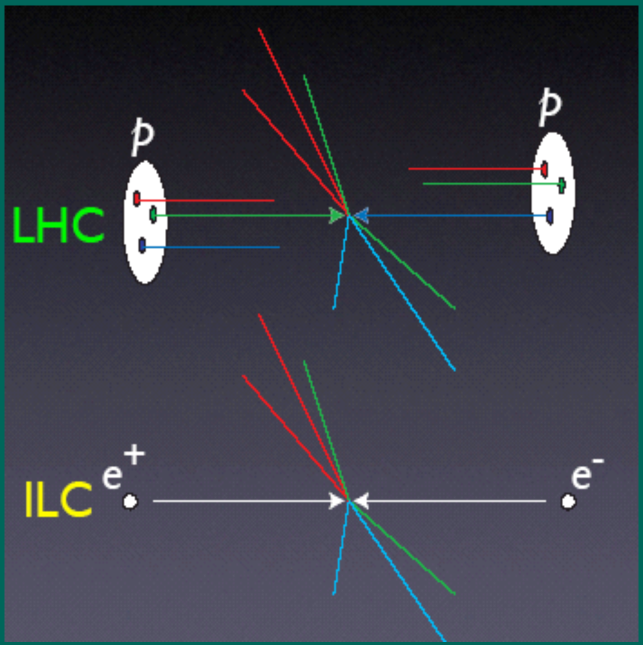
SM particle	discovery	detailed study
	SLAC	HERA
	PETRA	Fermilab/ SLC/LEP
c	BNL SPEAR	SPEAR
τ	SPEAR	SPEAR
b	Fermilab	Cornell/DESY/SLAC/KEK
Z	SPPS/CERN	LEP and SLC
t	Fermilab	LHC +? (LC meas. Yukawa cp.)

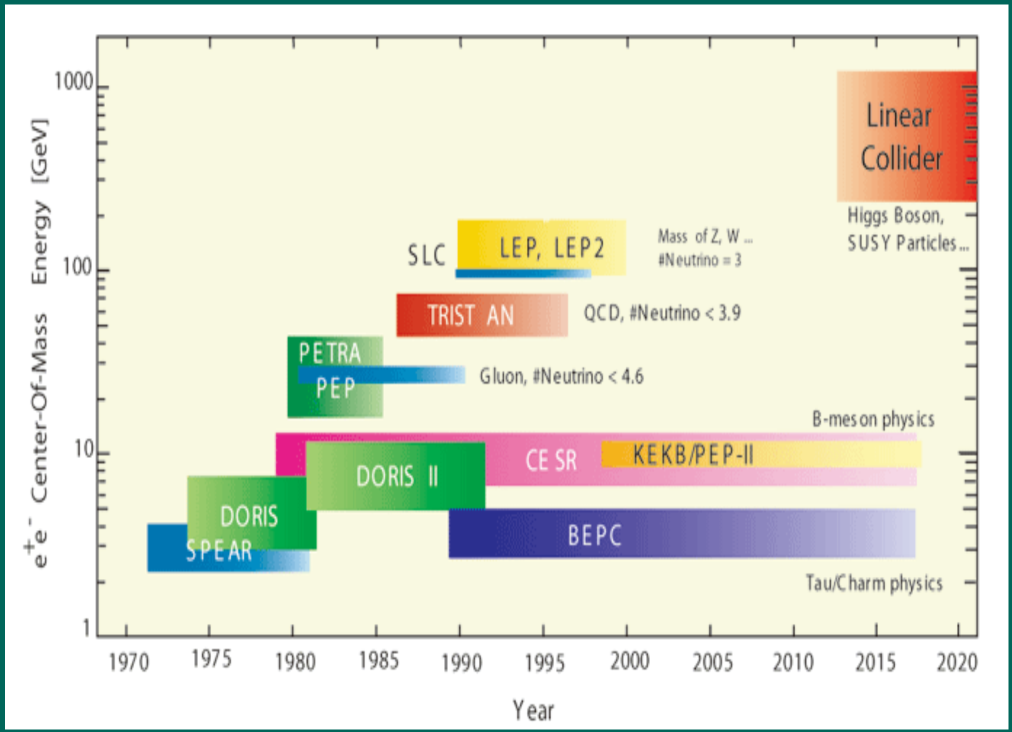
Electron experiments frequently gave most precision as well as discovery

LESSON FOR THE FUTURE

Complementarity of Lepton & Hadron Colliders

Astronomers examine the universe with different wavelengths
(visible, radio, X-ray, IR, etc.)
Particle Physics uses different initial states
for <u>independent</u> searches and tests
Such complementarity is a powerful tool across all sciences



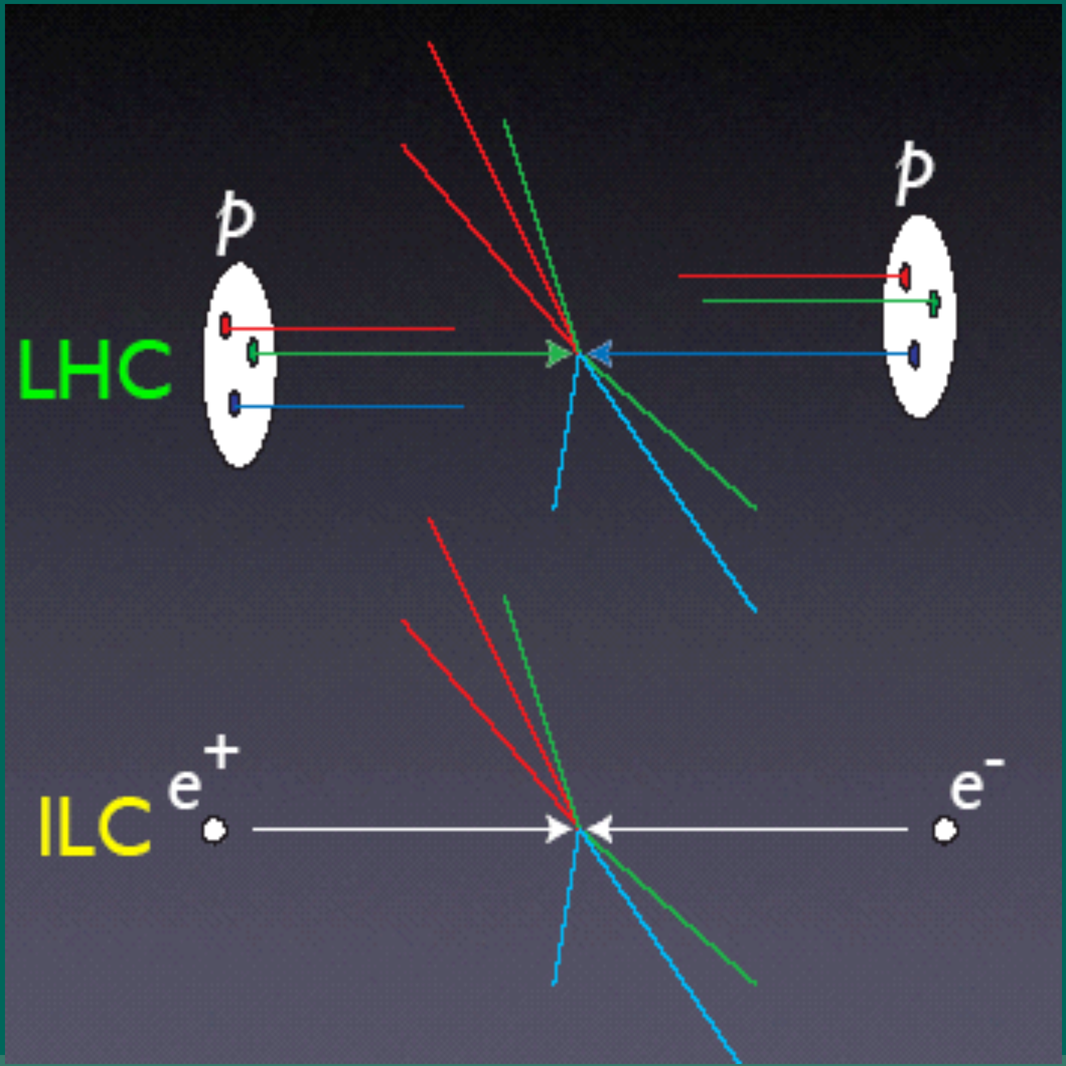


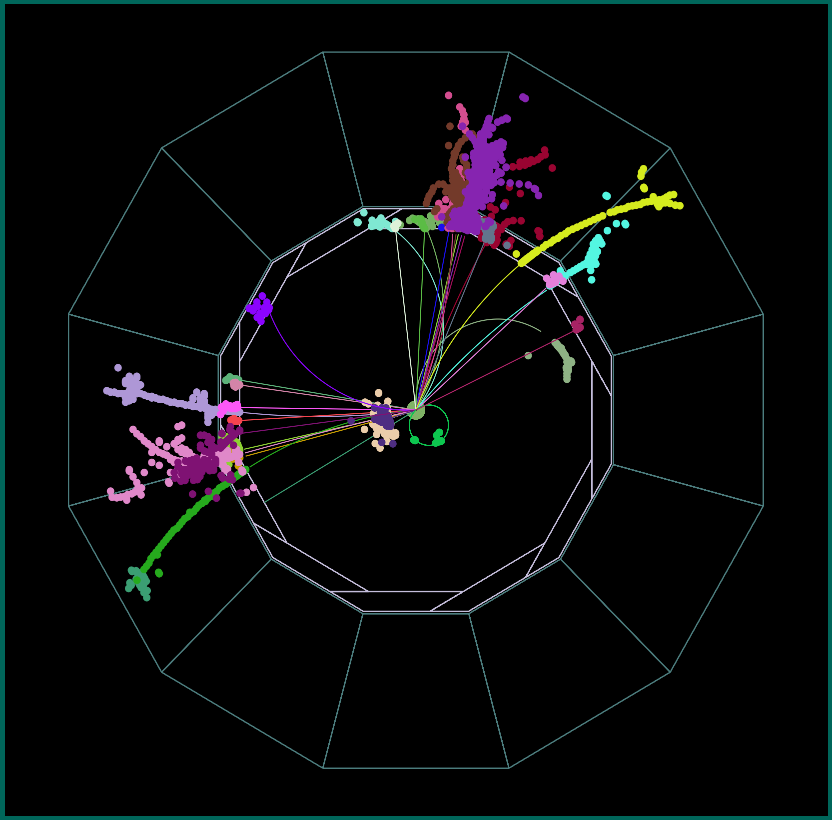
Virtues of Lepton Colliders

Elementary interactions at known E_{cm}*

eg. $e^+e^- \rightarrow$ Z H

* beamstrahlung manageable

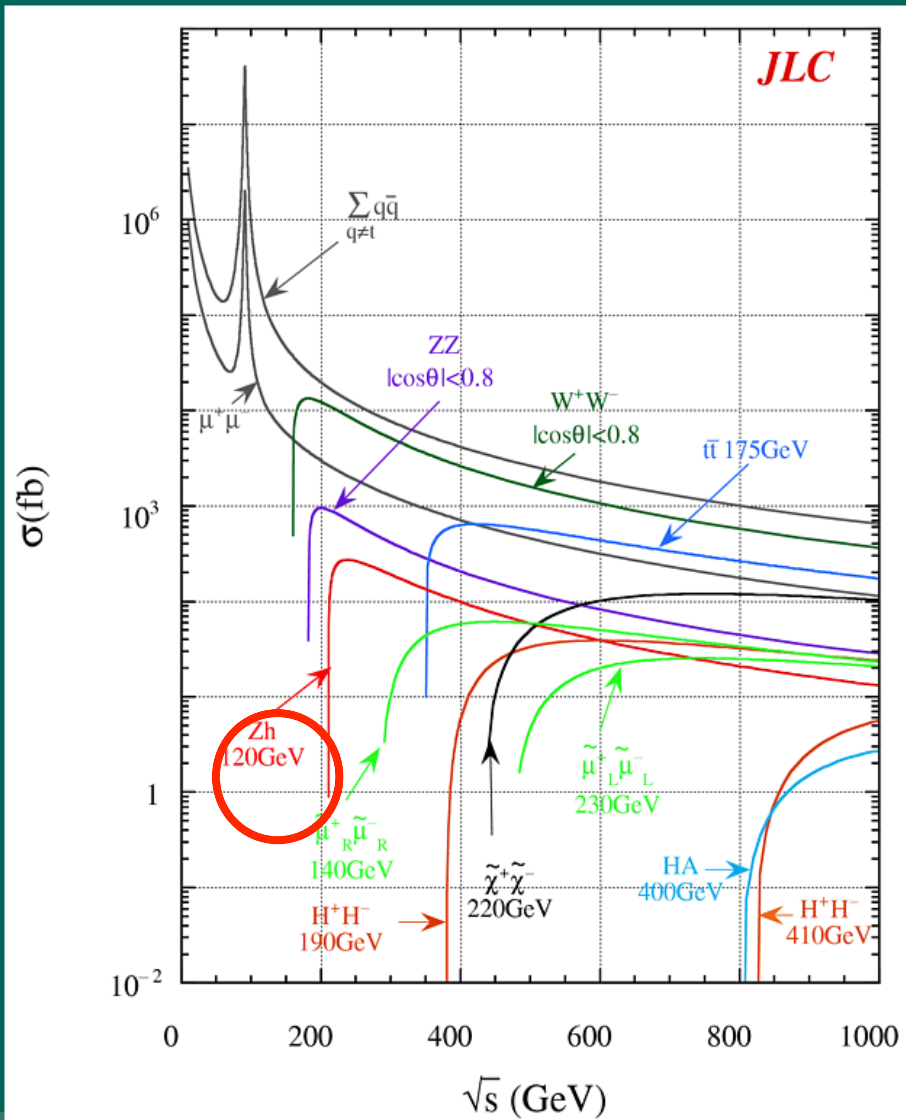


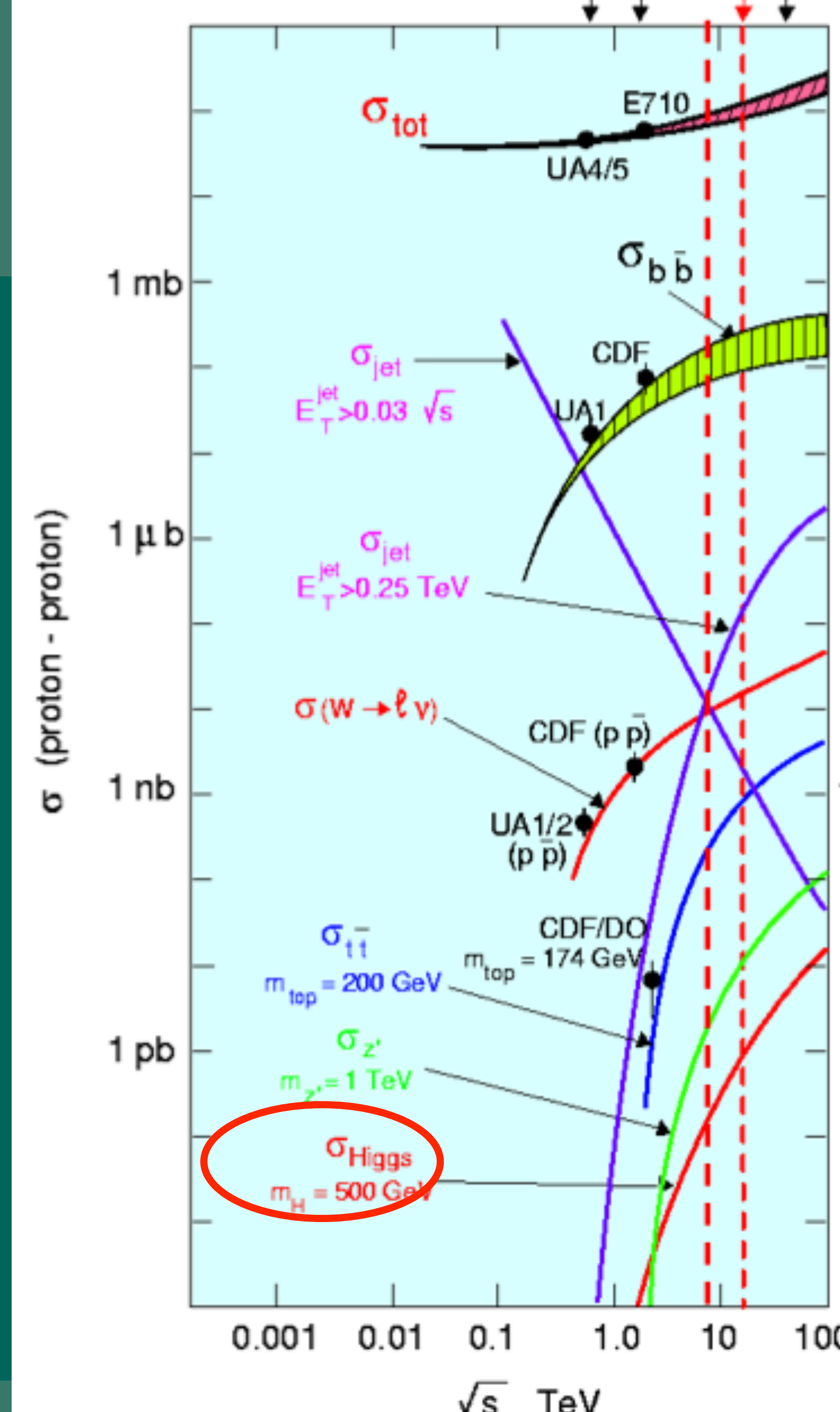


Virtues of Lepton Colliders

Democratic Cross sections

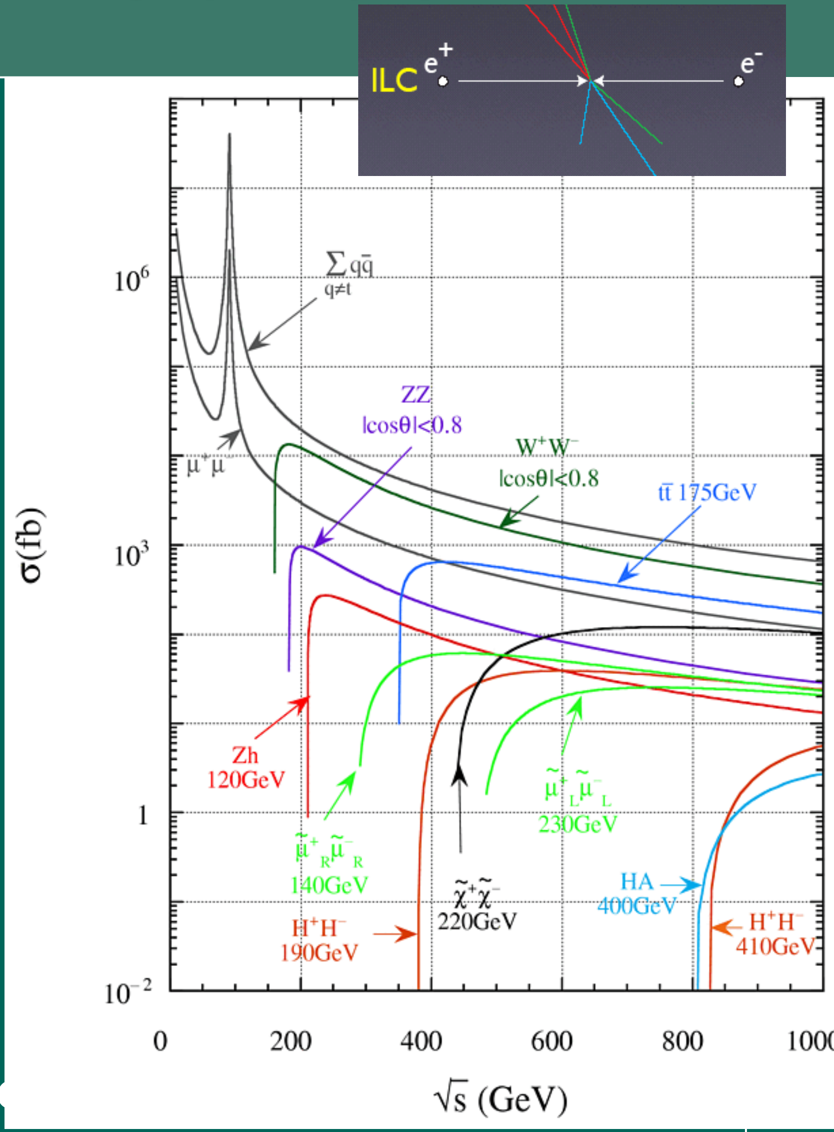
eg. σ (e⁺e⁻ → ZH) ~ 1/2 σ(e⁺e⁻ → d $\bar{d}$)





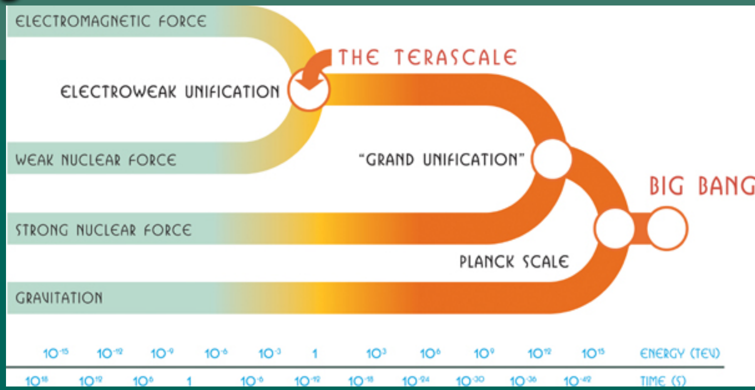
Virtues of Lepton Colliders

- Elementary interactions at known E_{cm}*
  eg. $e^+e^- \rightarrow$ Z H   * beamstrahlung manageable
- Democratic Cross sections
  eg. σ ($e^+e^- \rightarrow$ ZH) ~ 1/2 σ($e^+e^- \rightarrow d\bar{d}$)
- Inclusive Trigger-free data
  total cross-section
- Highly Polarized Electron Beam
  ~ 80%   (also positron pol. – R&D)
- Calorimetry with Particle Flow Precision
  σ_E/E_{jet} ~ 3% for E_{jet} > 100 GeV
- Exquisite vertex detection
  eg. $R_{beampipe}$ ~ 1 cm and σ_{hit} ~ 3 μm
- Advantage over hadron collider on precisi
  eg. H $\rightarrow c\bar{c}$



MODEL INDEPENDENT MEASUREMENTS

Terascale Physics

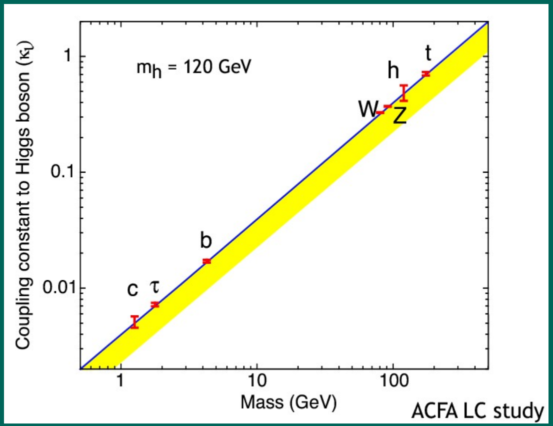


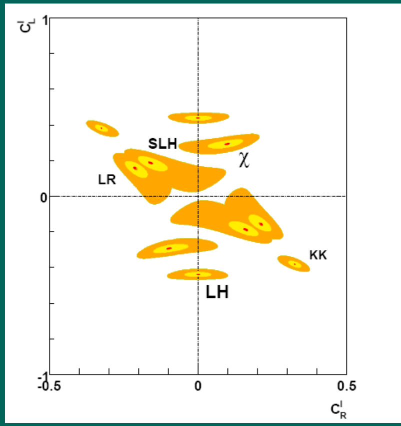
- Electroweak Symmetry Breaking
- Many theories aim to explain
  Hierarchy Problem
  - SUSY, XDimensions, New Strong Dynamics, Unparticles, Little Higgs, Z′, …

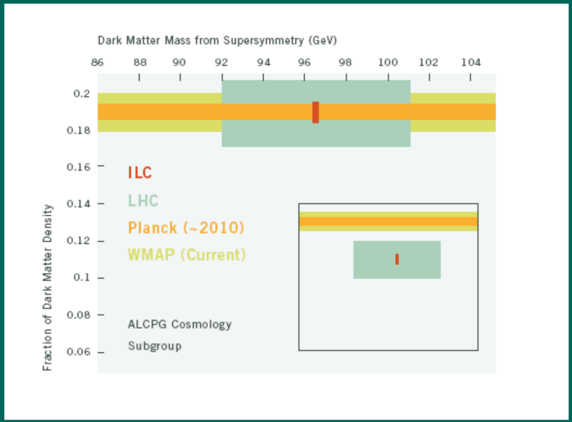
- Lepton Collders explores all of these
  - Precision mass couplings (including the Higgs)
  - Direct production of new states
  - High energy behavior of cross sections
    (including asymmetries, CP violation, etc.)

Lepton Collider Physics

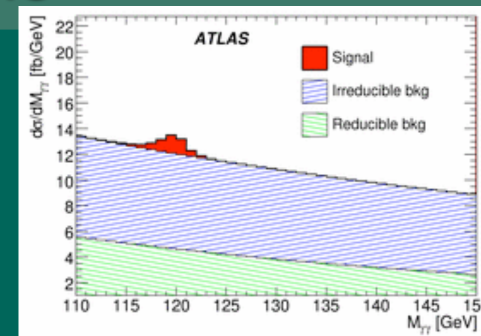
* LHC should point the way <u>soon</u>…
  then Lepton Collider physics program can be sharpened –
  – Establish the mechanism for EWSB
    • - does Higgs boson have <u>Standard Model properties</u>? – or NOT?
  – Establish the nature of physics beyond the SM
    • such as SUSY, extra dimensions, …
  – 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







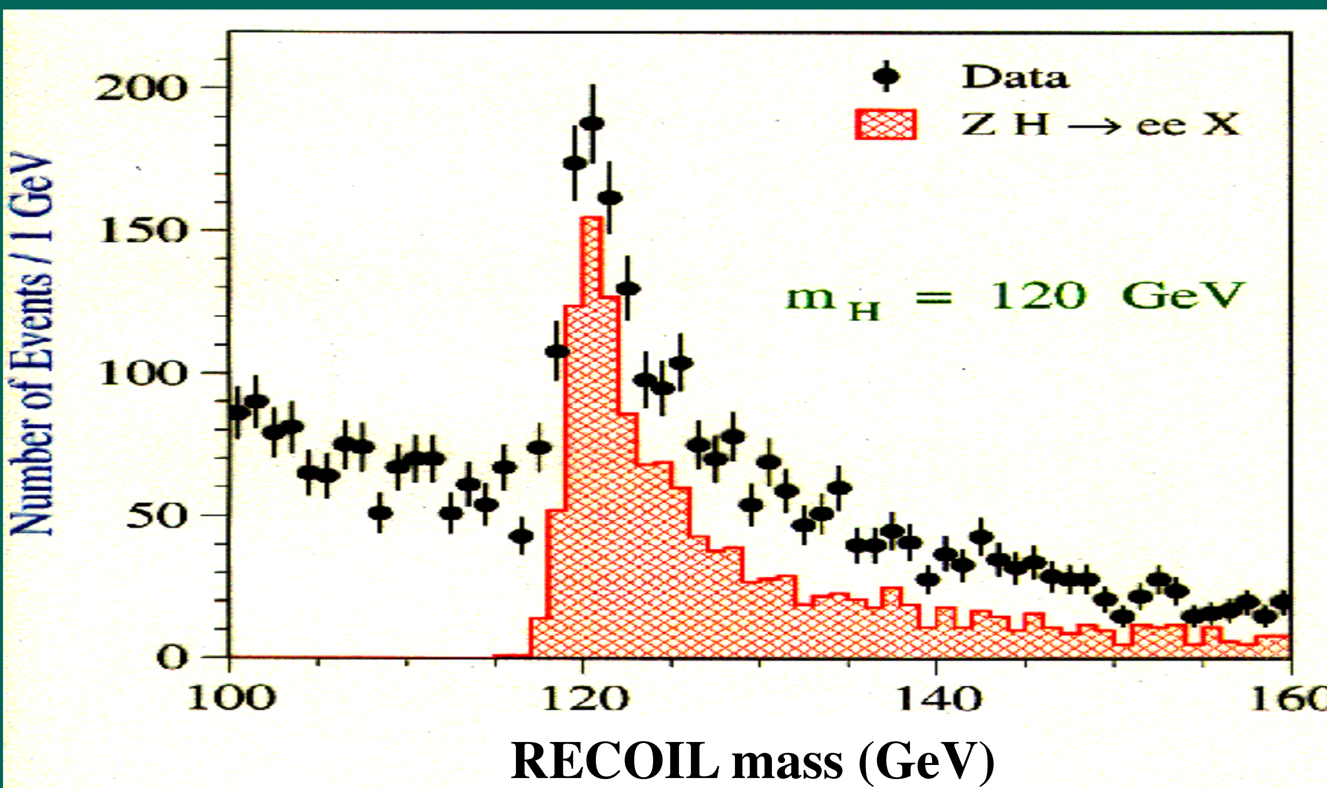
ILC Higgs Studies
- the Power of Simple Interactions



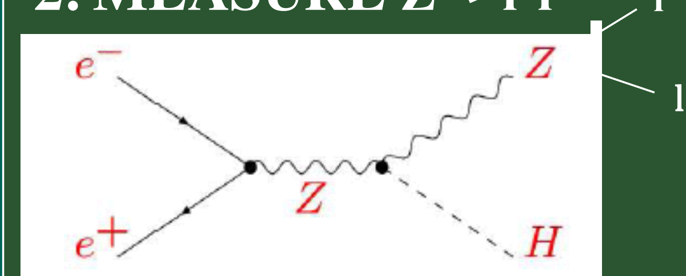
ILC observes Higgs recoiling from a Z, with known CM energy⇓

- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

(⇓ - some beamstrahlung)



1. KNOWN INTIAL STATE
2. MEASURE $Z \to l^+l^-$



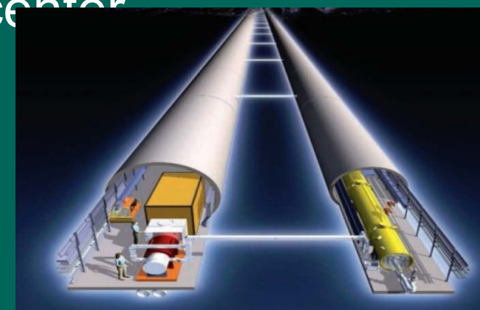
3. CALCULATE RECOIL

Invisible decays are included

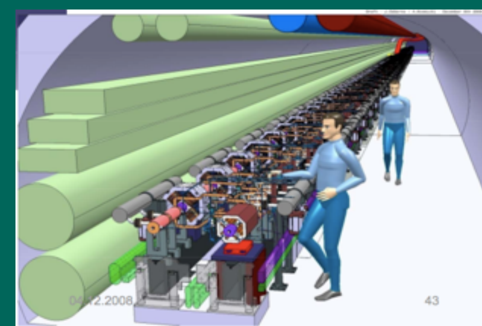
500 fb^{-1} @ 500 GeV, TESLA TDR, Fig 2.1.4

Lepton Collider Options

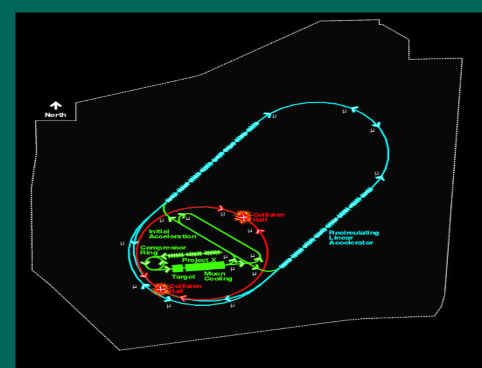
Once the LHC produces new physics, the trade-offs between the three Lepton Collider options aimed at precision physics will be front and center.



- **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 range of ILC, or needing CLIC or MuC.
- **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

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.

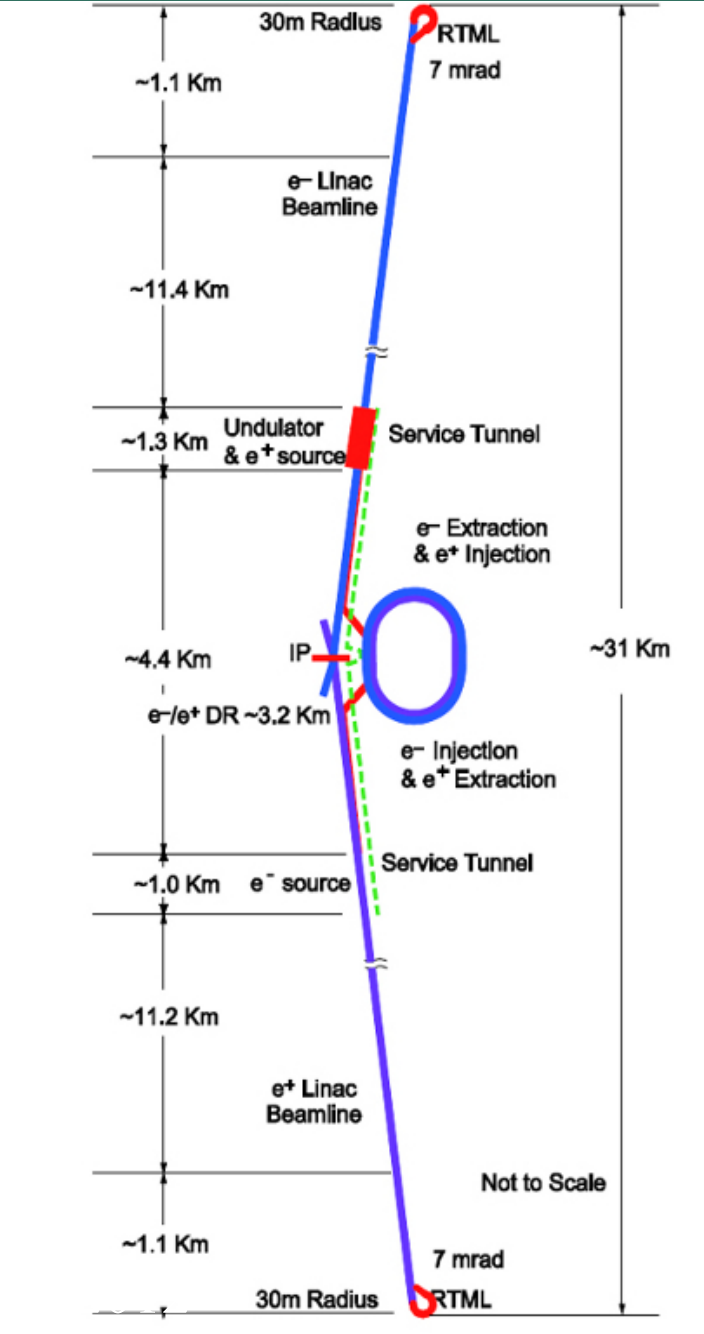
- Pico-second timing measurements?
- Vastly higher pixel counts?

  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?

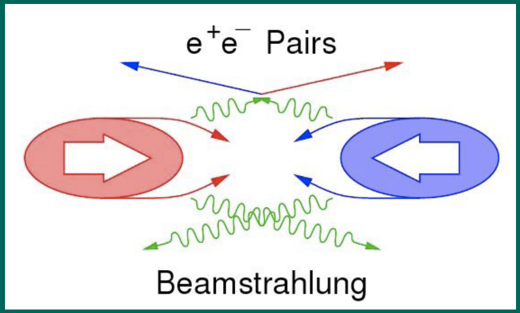
The International Linear Collider

- 500 GeV E_{cm}
  - Two 11 km SuperRF linacs at 31.5 MV/m
  - Centralized injector (polarized electrons)
  - Circular damping rings
  - Undulator based positron source (polarized)
  - Single IR for two detectors (push-pull) w/ 14 mr crossing angle
- Upgradable to 1 TeV
- Options
  - Hi luminosity at M_z / W pair threshold
  - $\gamma\gamma$, $e\gamma$, e^-e^-

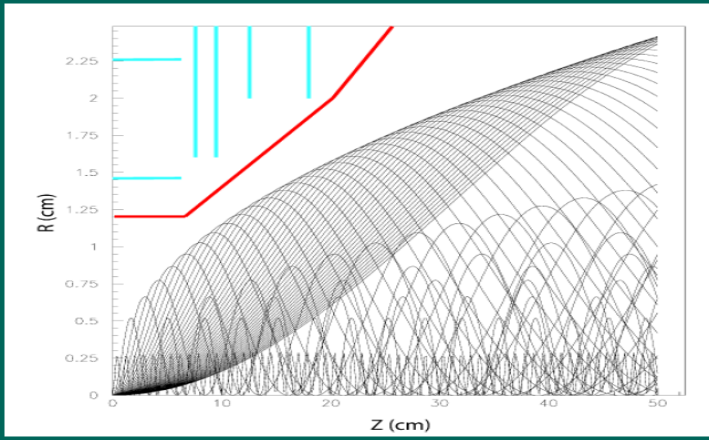


ILC Environment Poses Challenges

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

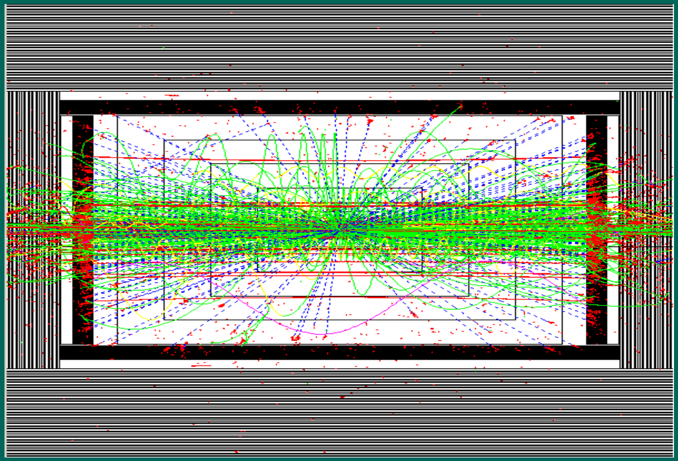


Most pairs at ILC are trapped by the solenoid, but vertex occupancies are still challenging

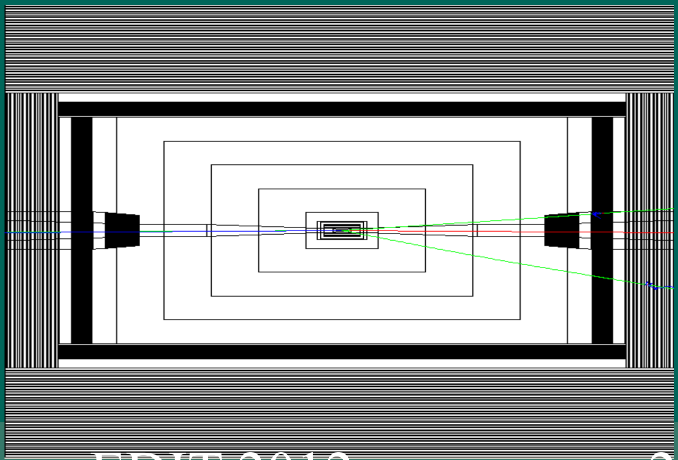


γγ→e+e-, μ+μ-, hadrons reactions put a premium on short detector livetimes

Livetime 40 μs ~ 130 BX



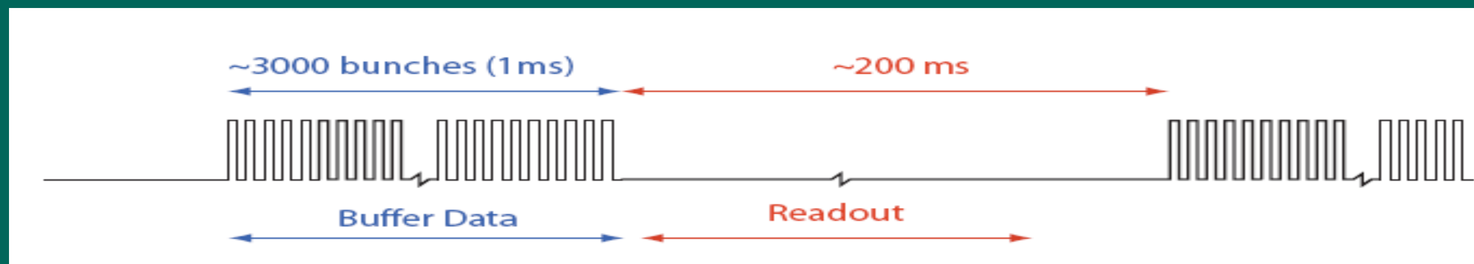
Livetime 100ns ~ 1 BX



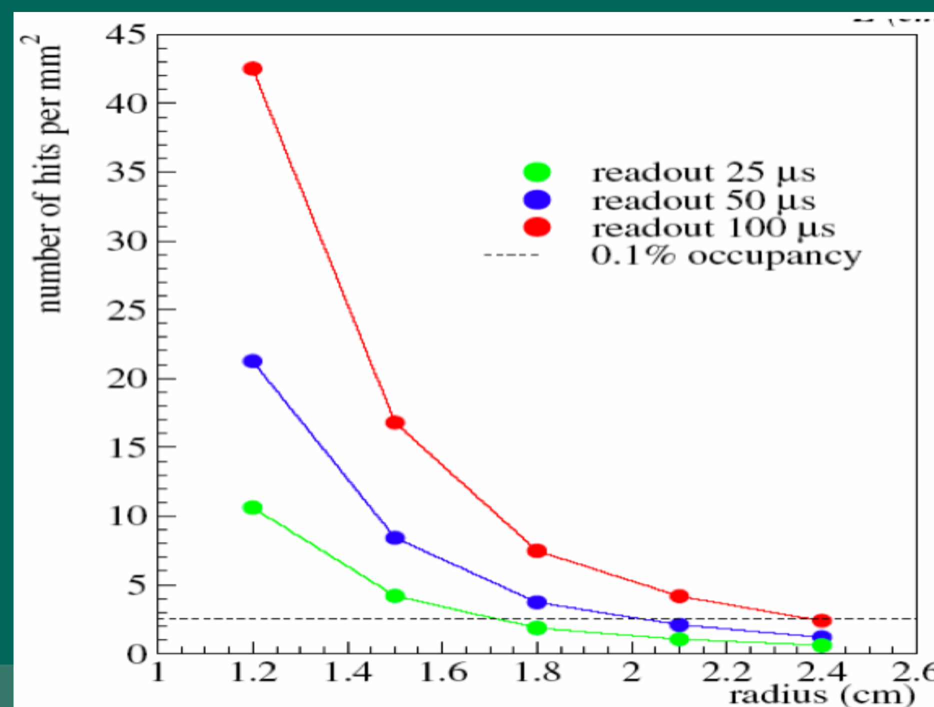
ILC Vertex Readout Challenge

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

ILC bunch train



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



CLIC Environment More Challenging

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

CLIC

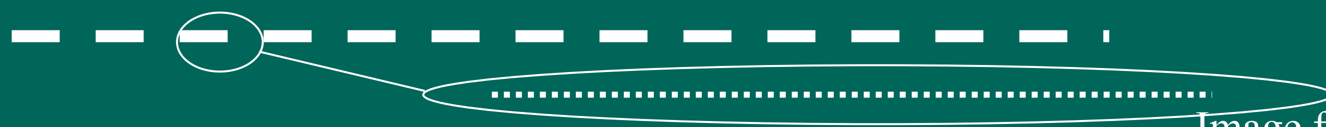
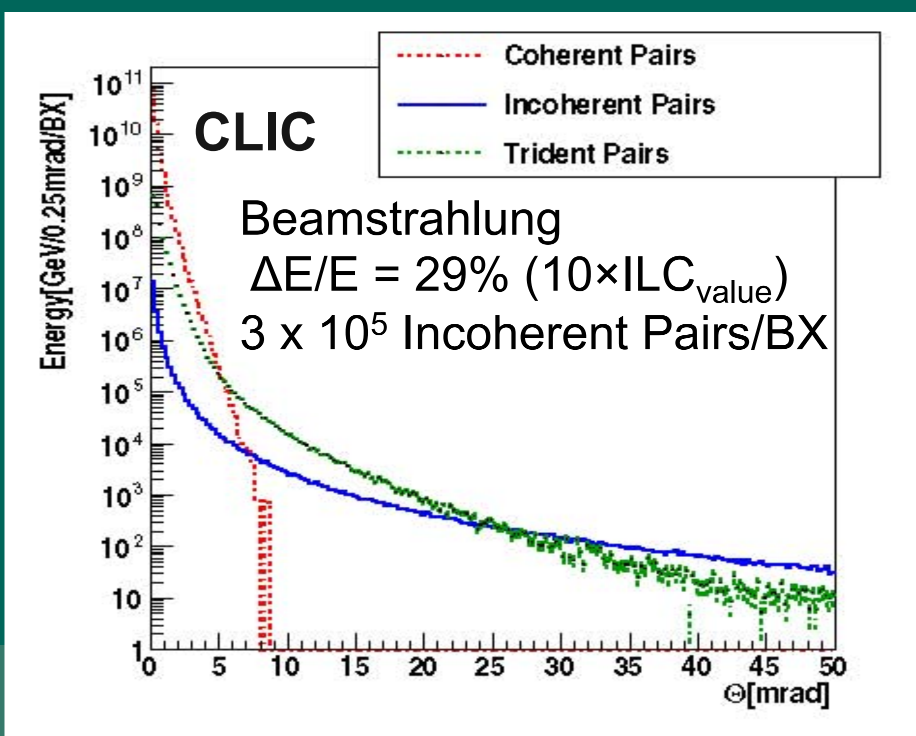


Image from L. Linssen

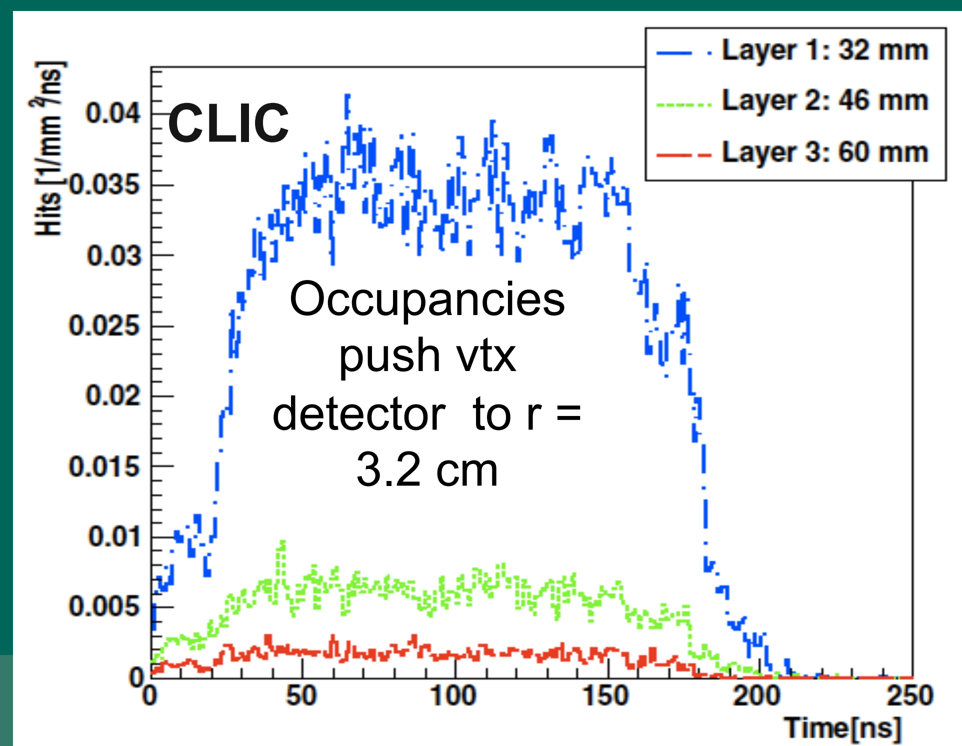
CLIC:	1 train = 312 bunches	0.5 ns apart	15k collisions/sec
ILC:	**1 train = 2820 bunches**	**308 ns apart**	**14k collisions/sec**

CLIC smaller spots, higher energy, much more beamstrahlung

Beamstrahlung energy vs angle



Vertex detector occupancies vs time



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

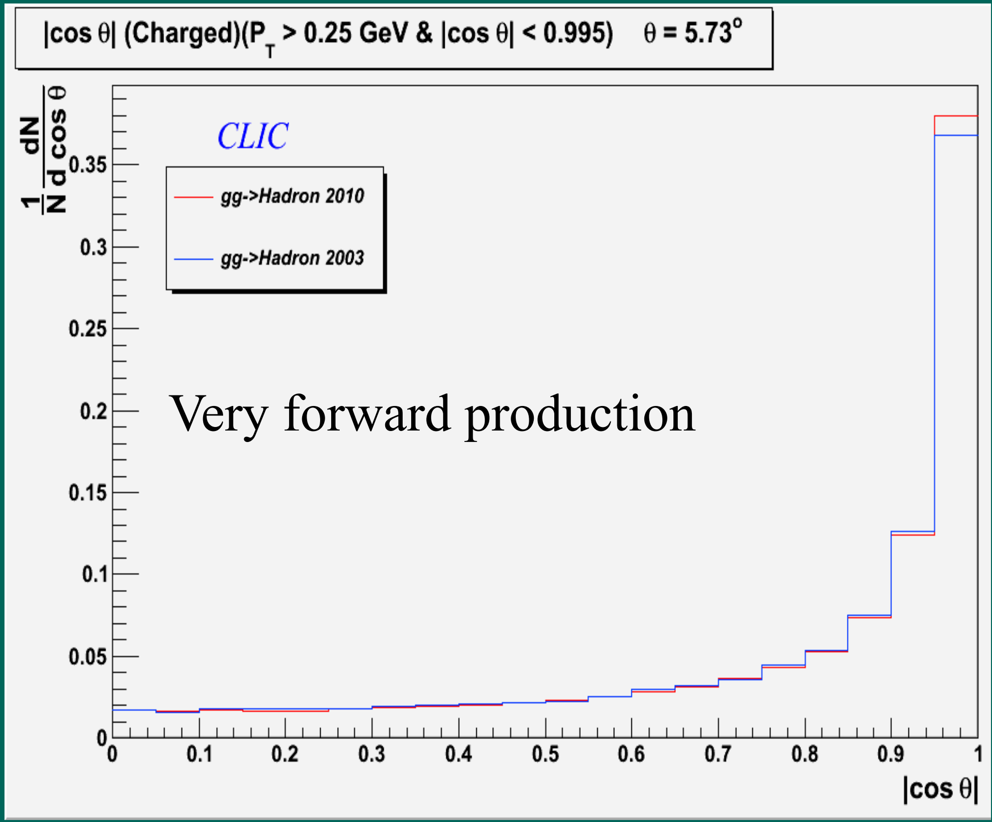
Per bunch crossing (every 0.5 ns)

3.3 $\gamma\gamma \rightarrow$ 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

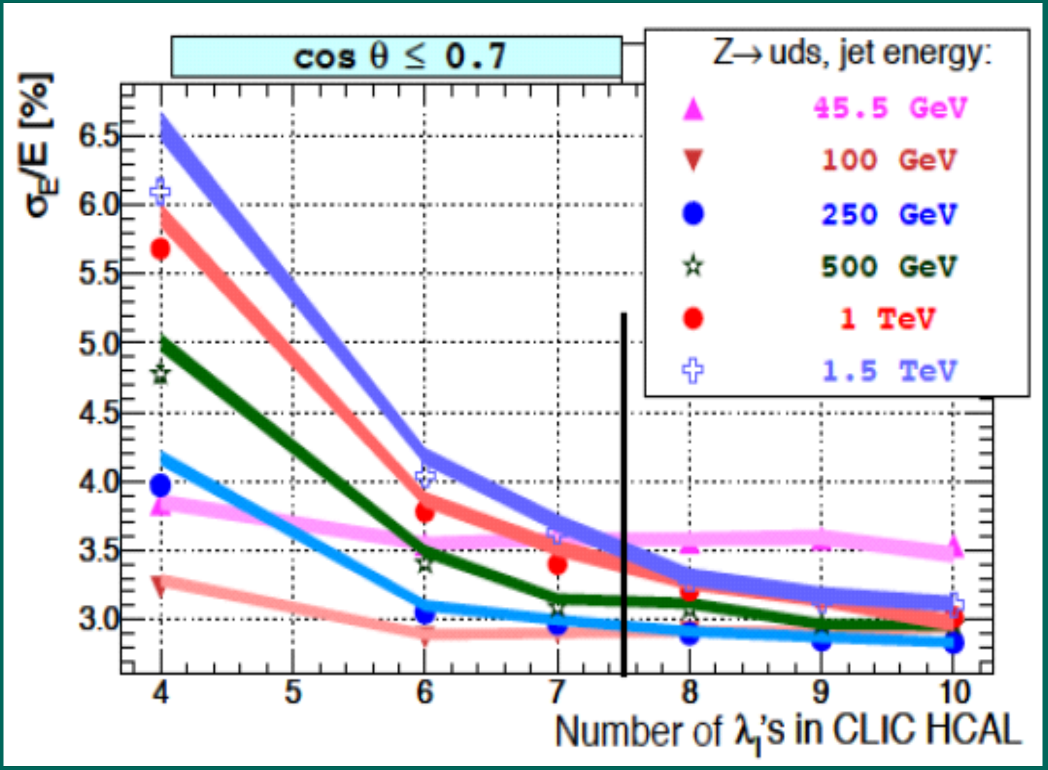
Vertex Detector Challenges (above and beyond ILC)

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

Pandora PFA used for Hcal Studies

Calorimetry Challenges

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

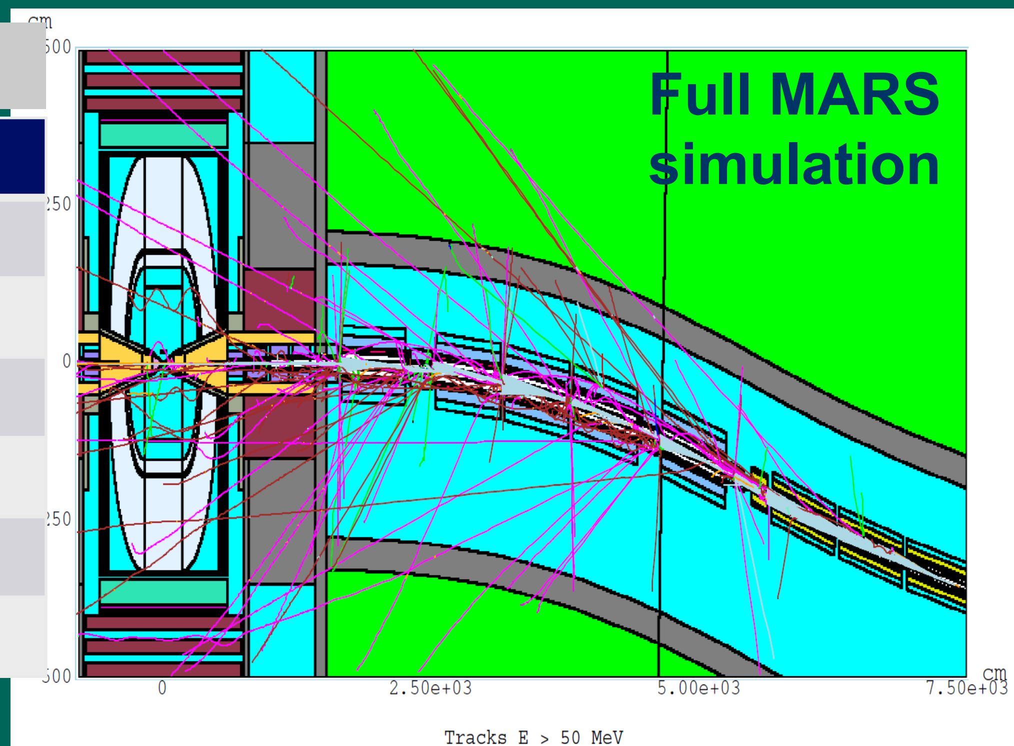


MuC Environment Extremely Challenging

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 2×10^{12}, 4.3×10^5 decays/m per bunch crossing, or 1.3×10^{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



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.

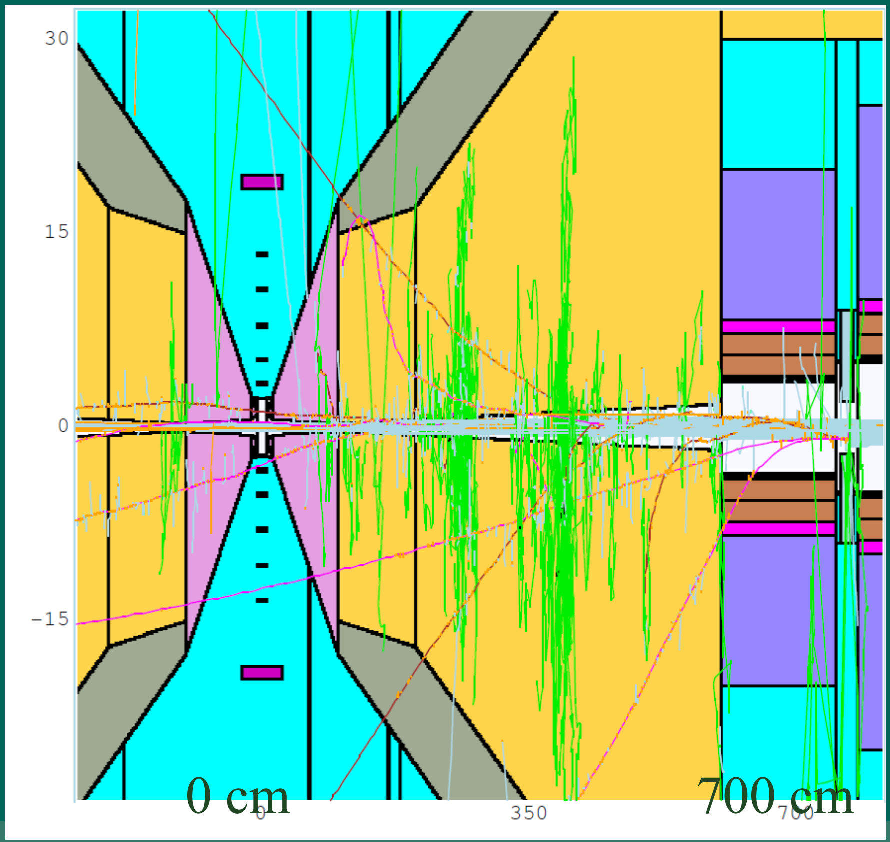
$6 < z < 100$ cm $\theta = 10^0$
$100 < z < 600$ cm $\theta = 5^0$

Tungsten Cones on Beamline

Beware Aspect Ratio!

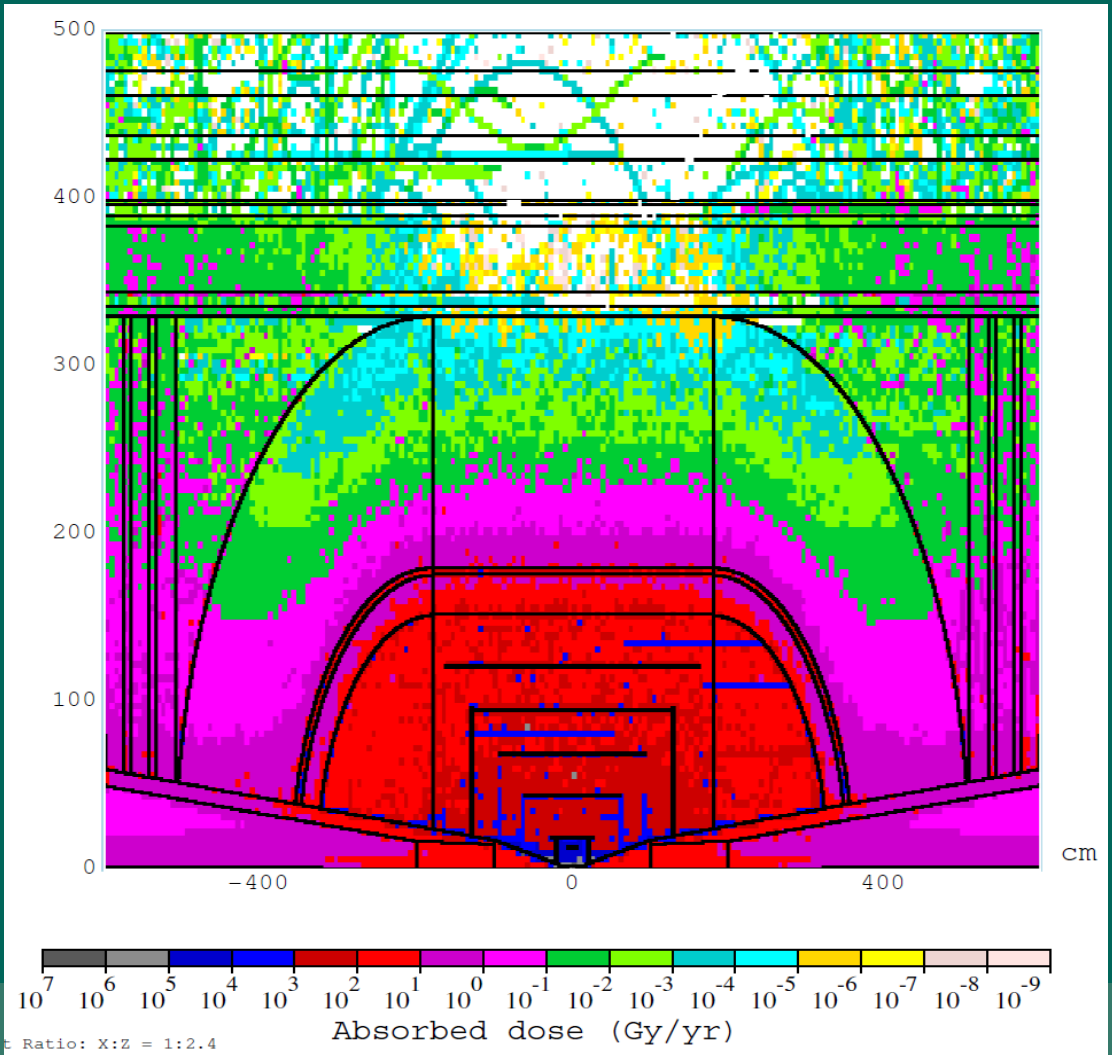
30 cm -

0 cm -



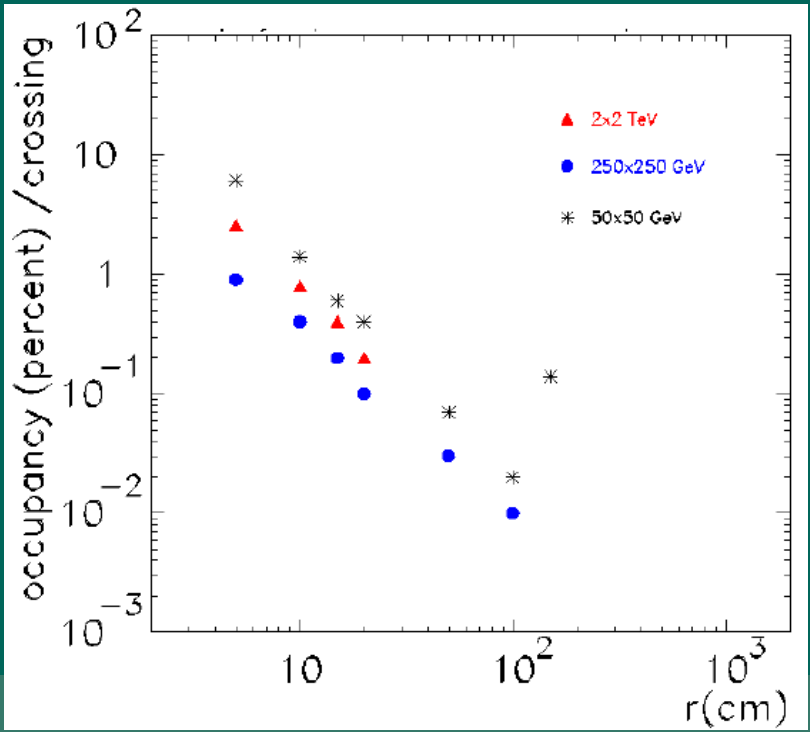
MuC Radiation Hardness
Occupancy Challenges

Total Absorbed Dose ~ LHC
Total absorbed dose in Si at r = 4cm
Muon Collider: 0.1 MGy/yr



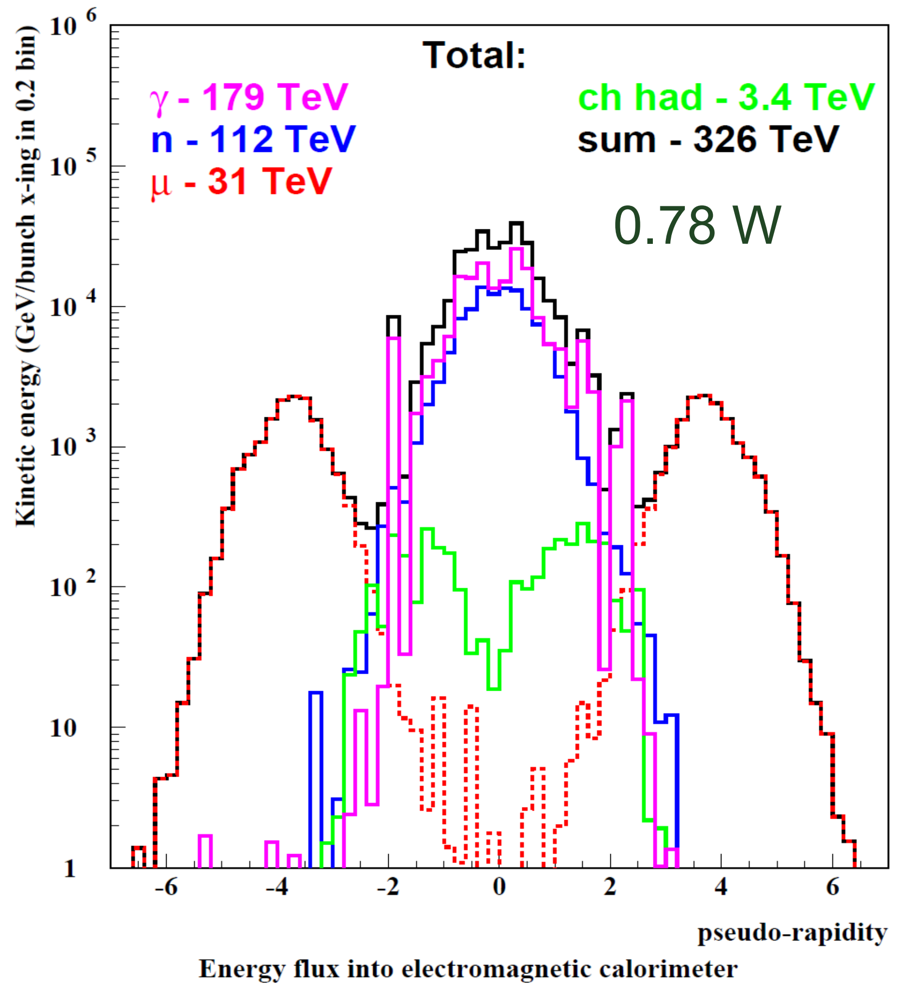
Vertex Radius
Backgrounds limit min radius to ≥ 5 cm

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

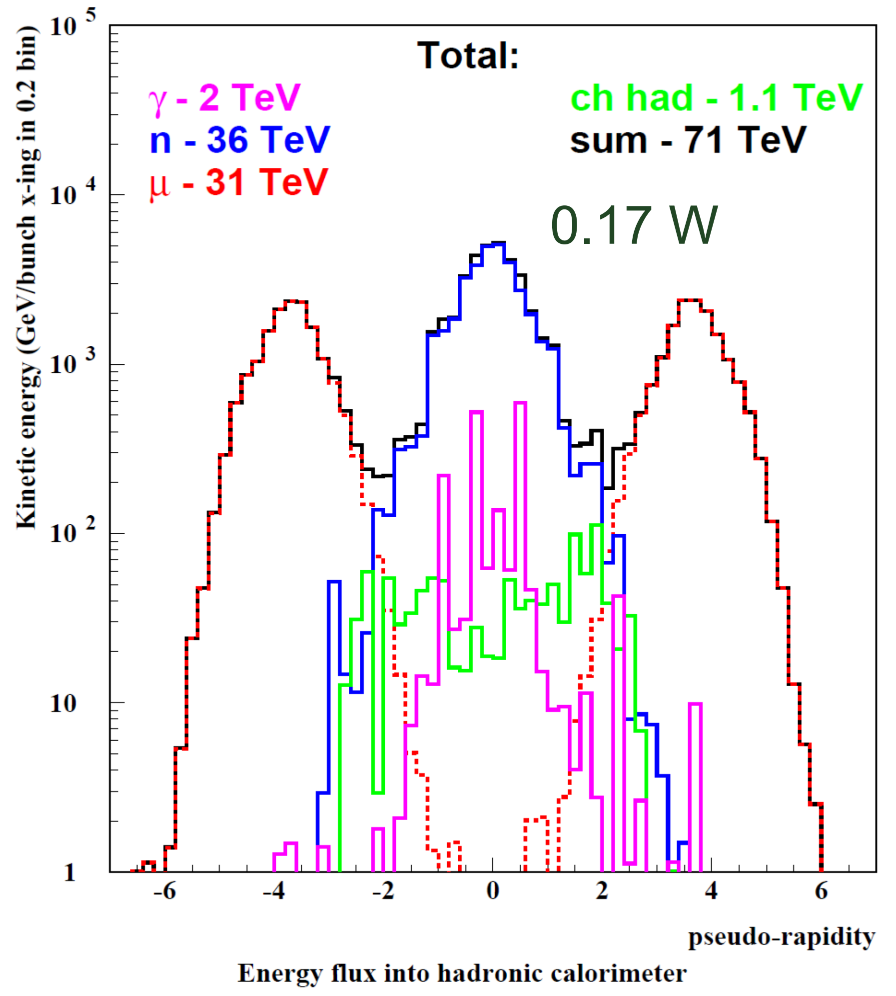


MuC Calorimeter Depositions (>100 TeV)

Energy Flow into Ecal



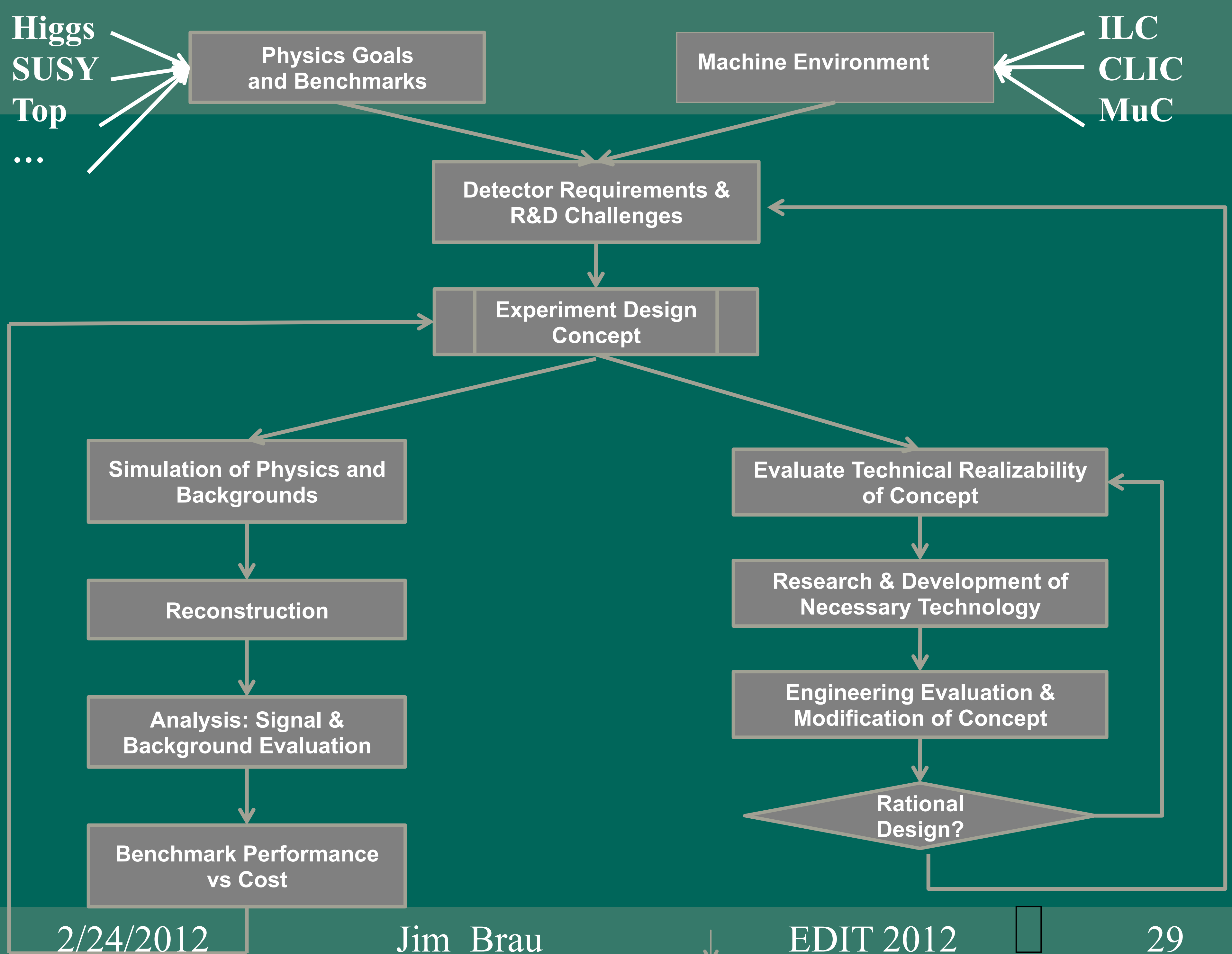
Energy Flow into Hcal



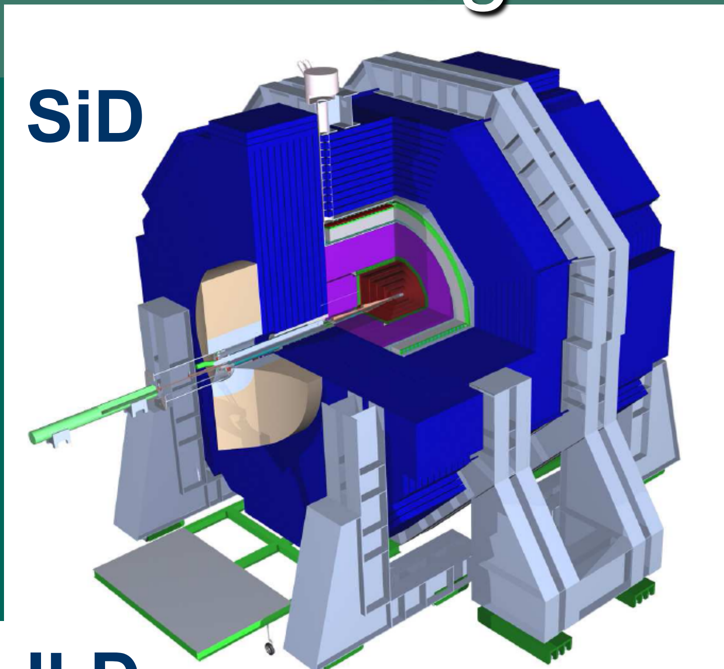
Peak: ~1 GeV / 2x2 cm^2 cell with σ_E ~ 30 MeV

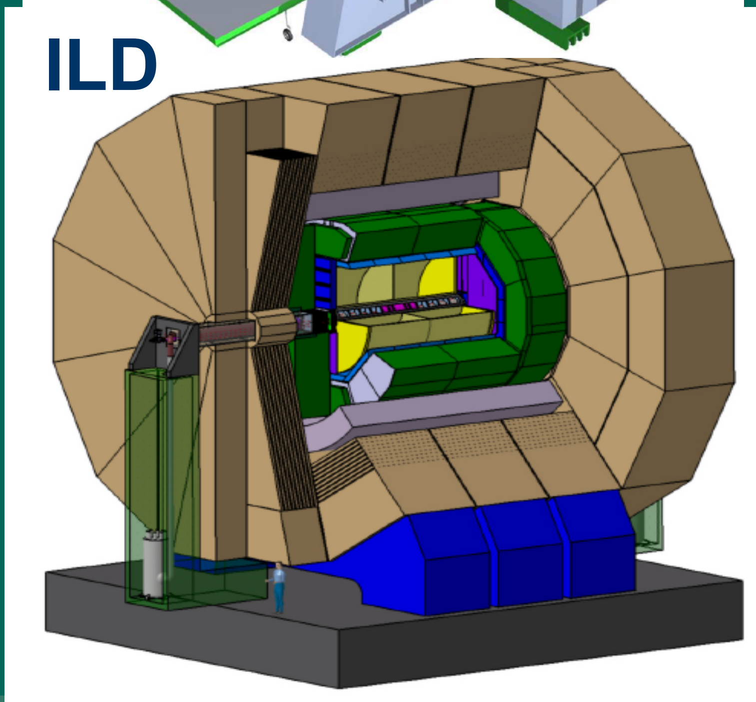
Peak: ~1.5 GeV / 5x5 cm^2 cell with σ_E ~ 80 MeV

Steps in Detector Concept Development



ILC Detectors Have Advanced Through This Development Process





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

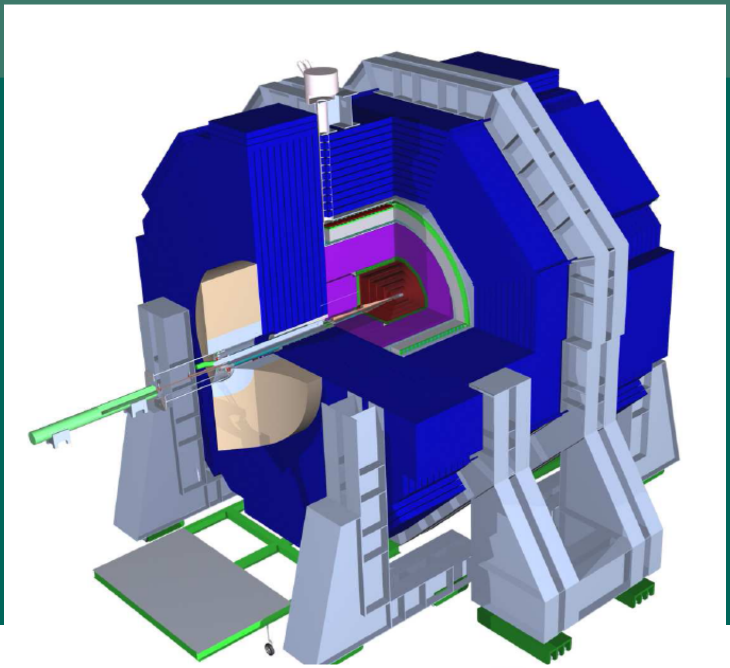
Detector Outline Document	2006
Detector Concept Report	2007
Letters of Intent (LoI)	2009
Detailed Baseline Design	2012

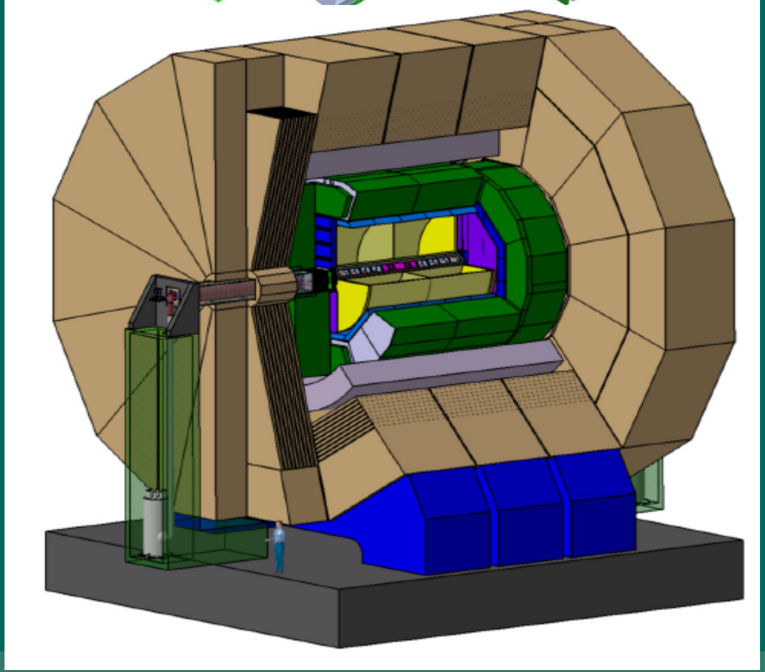
- Detector LoI (2009)

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

- This year – Detailed Baseline Design

Optimized & Validated ILC Detectors





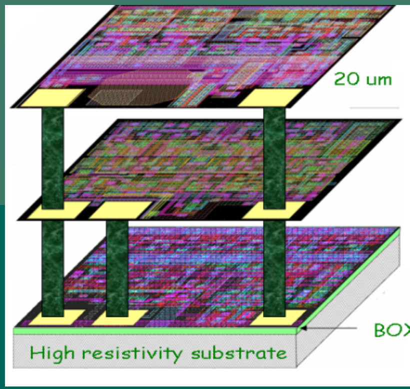
SiD

- Compact volume using high precision silicon tracking with 5 Tesla B-field
- Silicon timing capability provides robustness to backgrounds
- Calorimetry based on Particle Flow and Si-W Ecal
- Cost constrained design to meet all ILC physics goals

ILD

- Relatively large detector -3.5 Tesla B-field
- Designed for Particle Flow with a highly granular calorimeter
- State-of-the-art gaseous tracker (TPC)
- Solid state vertex detector & assists TPC tracking

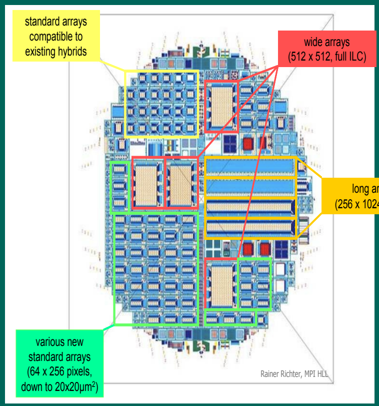
ILC Vertex Detectors



3D-SOI

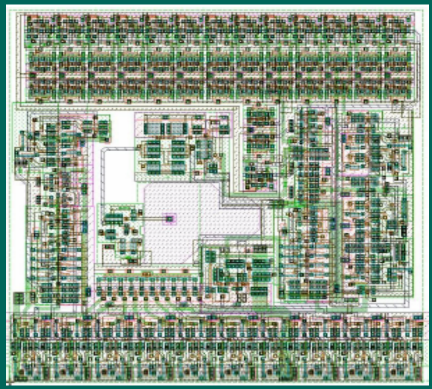
Requirements

- Superb impact parameter resolution (5µm ⊕10µm/(p $\sin^{3/2}\theta$))
- Excellent spacepoint precision (< 4 microns)
- Transparency (~0.1% X_0 per layer)
- Track reconstruction (find tracks in VXD alone)
  - Requires good angular coverage with several layers close to IP
- Sensitive to acceptable number of bunch crossings
  (<150 BX = 45 msec)
- Electromagnetic interference (EMI) immunity
- Power Constraint (< 100 Watts) - to achieve optimal transparency

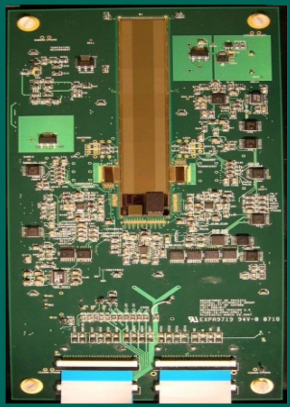


DEPFET

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



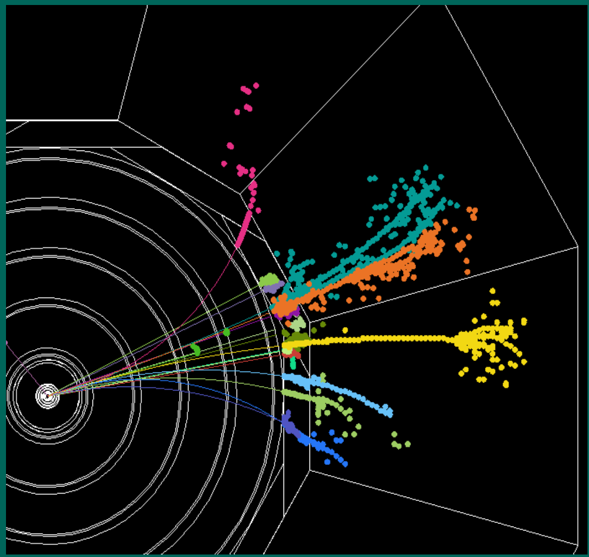
CMOS/Chronopix



CPCCD

ILC Particle Flow Calorimetry

•Conventional calorimetry relies on energy measurement in calorimeter, alone.



Particle Flow Calorimetry

•Charged particles are measured in tracker before calorimeter with much higher precision that calorimeter offers.

•So

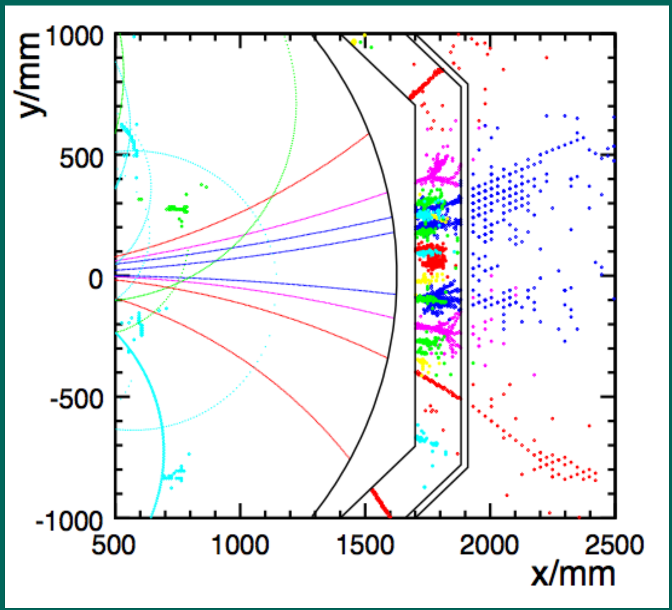
- Identify energy deposited in calorimeter by each charged track.
- Use tracker for charged particle measurements and calorimeter for neutral particles

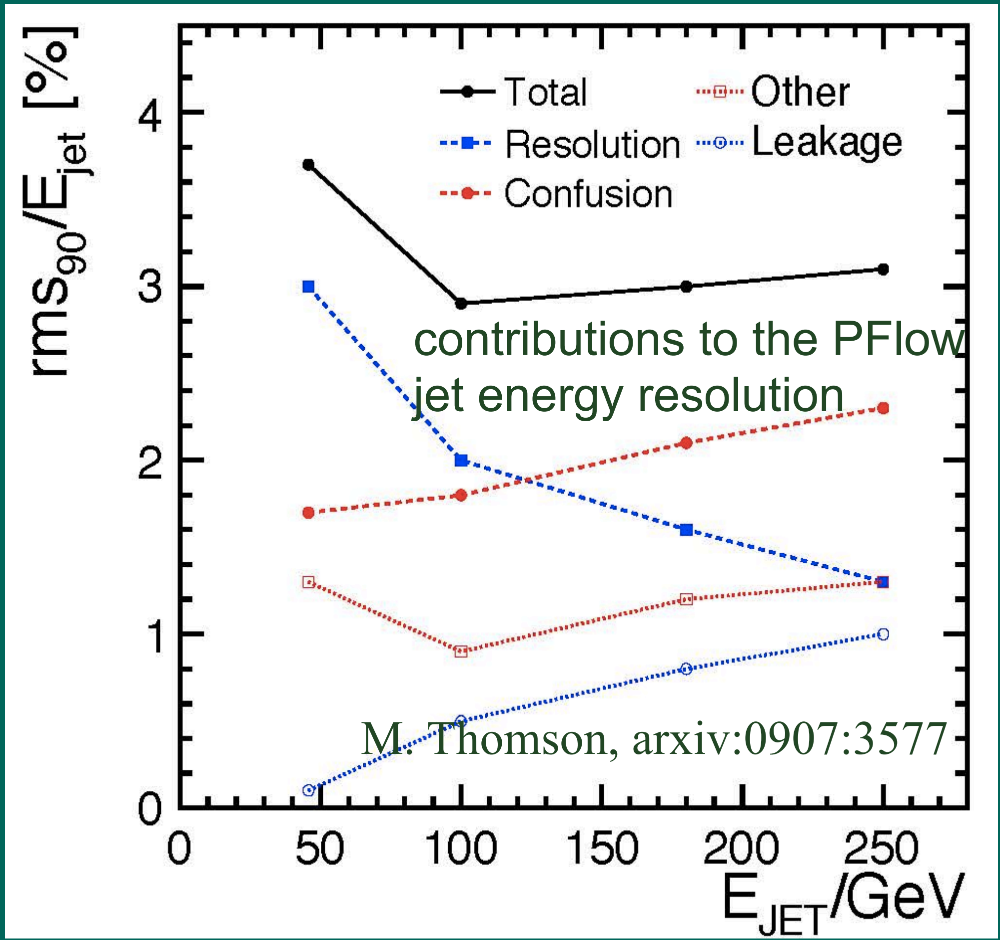
•This separation of each individual track (charged and neutral), requires a finely segmented calorimeter.

Jet Component	Resolution
Hadrons (60%)	Near perfect (TRK)
Photons (30%)	20% / √E (ECAL)
Neut Had (10%)	60% / √E (CAL

ILC Particle Flow Calorimetry

- Simulation (PandoraPFA) gives ΔE/E = 3-4% in full simulation
- Experimental confirmation coming from CALICE
- PFAs have become a design tool, useful for detector optimization.



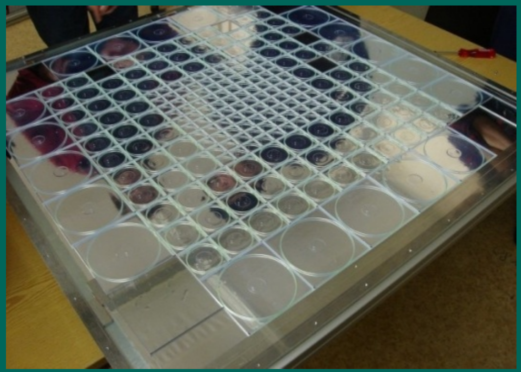


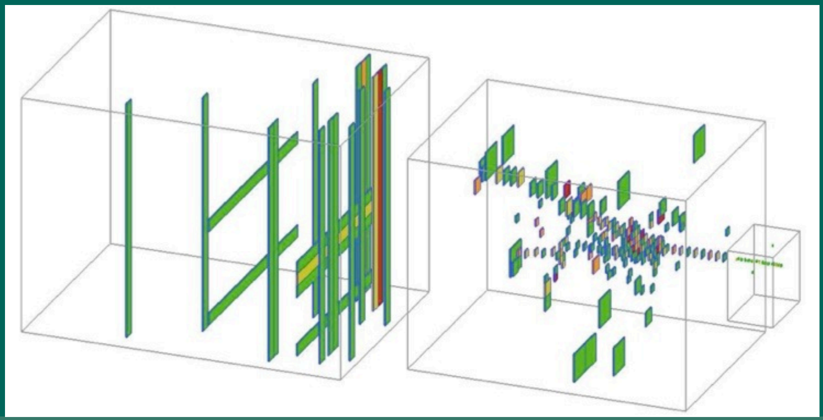
ILC Hadronic Calorimetry

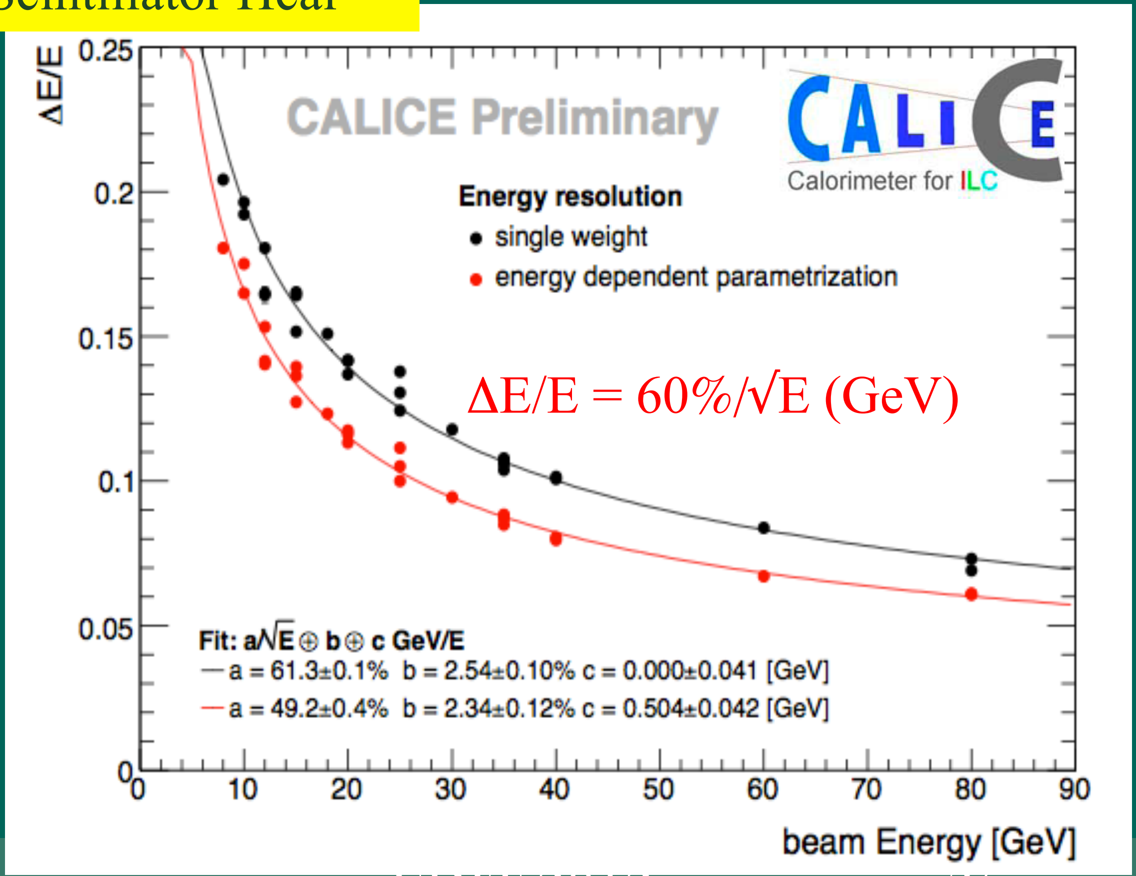
Hadronic Particle Flow Calorimetry

- 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



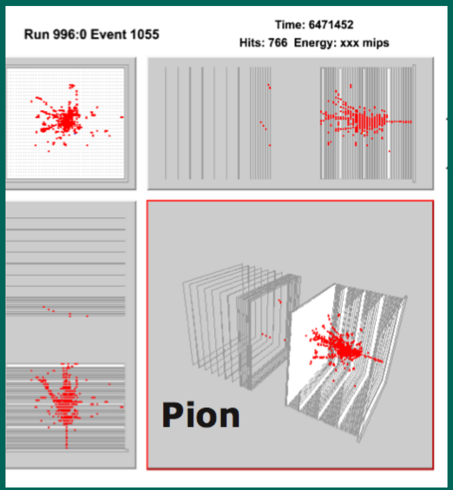


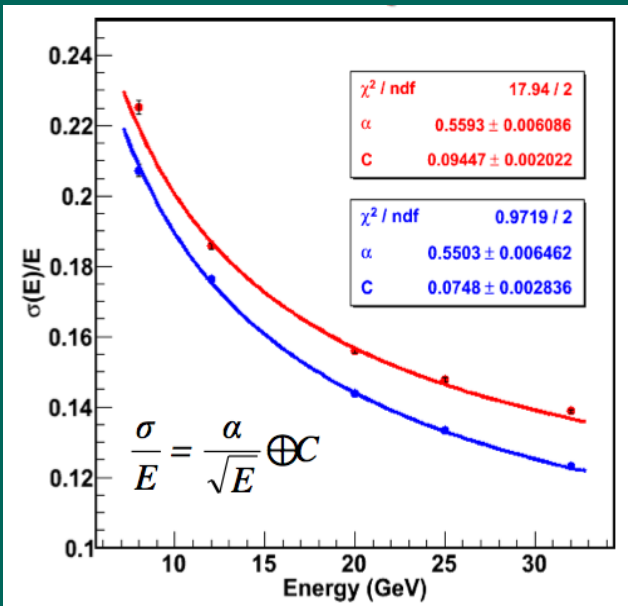


ILC Digital Hadronic Calorimetry

Resistive Plate Chamber (RPC) 1 m^3 prototype

- 1 x 1 cm^2 pads with one threshold (1-bit) → Digital Calorimeter
  38 layers in DHCAL and 14 in tail catcher (TCMT)
  ~480,000 readout channels
- Validate DHCAL concept with large RPC systems
  Measure hadronic showers in great detail
  Inform hadronic shower models (Geant4)





Standard pion selection
+ No hits in last two layers
(longitudinal containment)

ILC EM Calorimetry (Si/W)

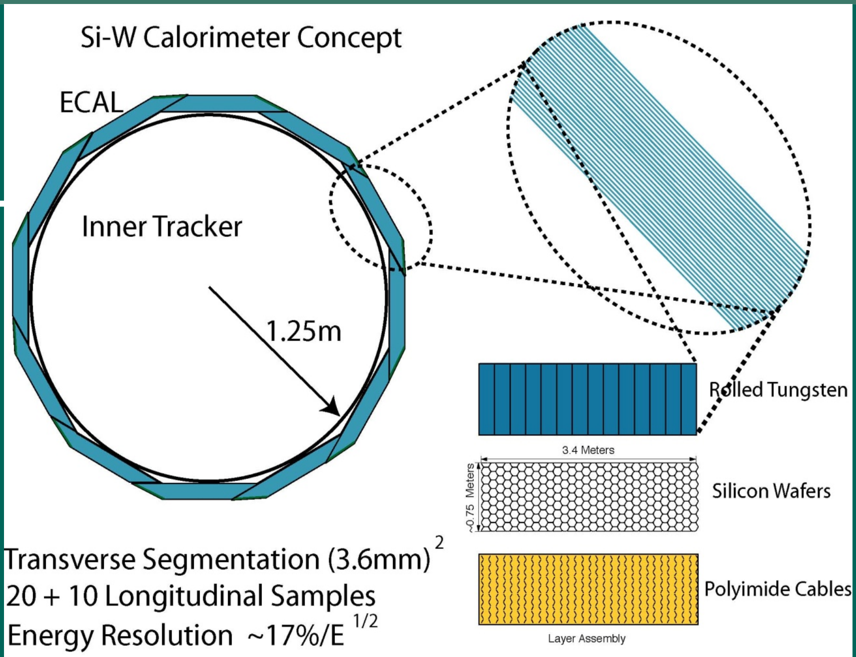
- Silicon-tungsten calorimeter offers very high density, with fine segmentation
  - critical component of PFA

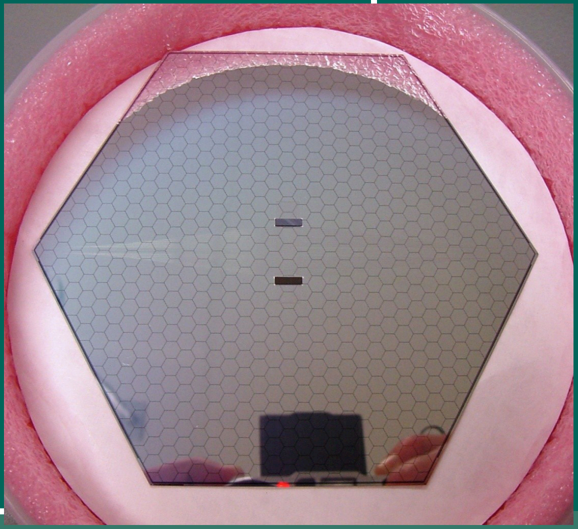
SiD Si/W ECAL Development

Silicon sensors:
- Hamamatsu 6-inch
- low leakage current; DC coupled

Integrated readout chip (KPiX):
- 1k channels
- low noise (10% of MIP)
- large dynamic range: ~10^4
- full digitization and muliplexed output
- passive cooling (power pulsing)

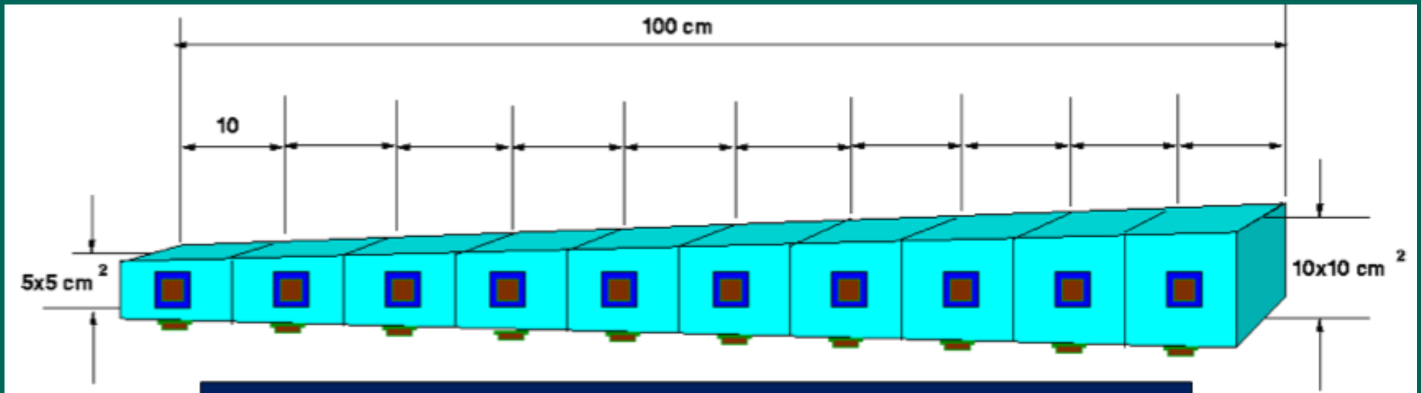
Interconnects:
- Flex cable
- R&D on KPIX – sensor interconnects





Dual Readout Calorimetry

- Fluctuations in hadronic shower driven by
  - Nuclear binding energy losses & π^0 energy variations
- Measure separately the EM shower component
  - DREAM Collaboration measured in HE calorimeter with separate scintillating and quartz fibers
  - Correct for EM fraction event by event (Q/S method)
- Fermilab team (A. Para et al.) proposes a total absorption homogeneous HCAL
  - measure both Cherenkov and Scintillation light with a longitudinally segmented crystal HCAL with photodiodes



R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

ILC Tracking

Tracking options (two general approaches for ILC)

TPC (choice of ILD)

- **Builds on successful experience of PEP-4, ALEPH, ALICE, DELPHI, STAR, …..**
- Large number of space points, making reconstruction straight-forward
- dE/dx $\Rightarrow$ particle ID, bonus
- Tracking up to large radii
- Minimal material (endplate), important for calorimetry

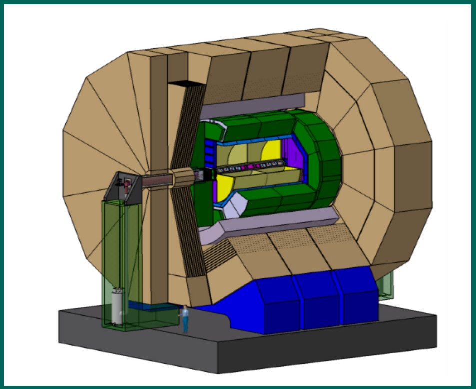
Silicon (choice of SiD)

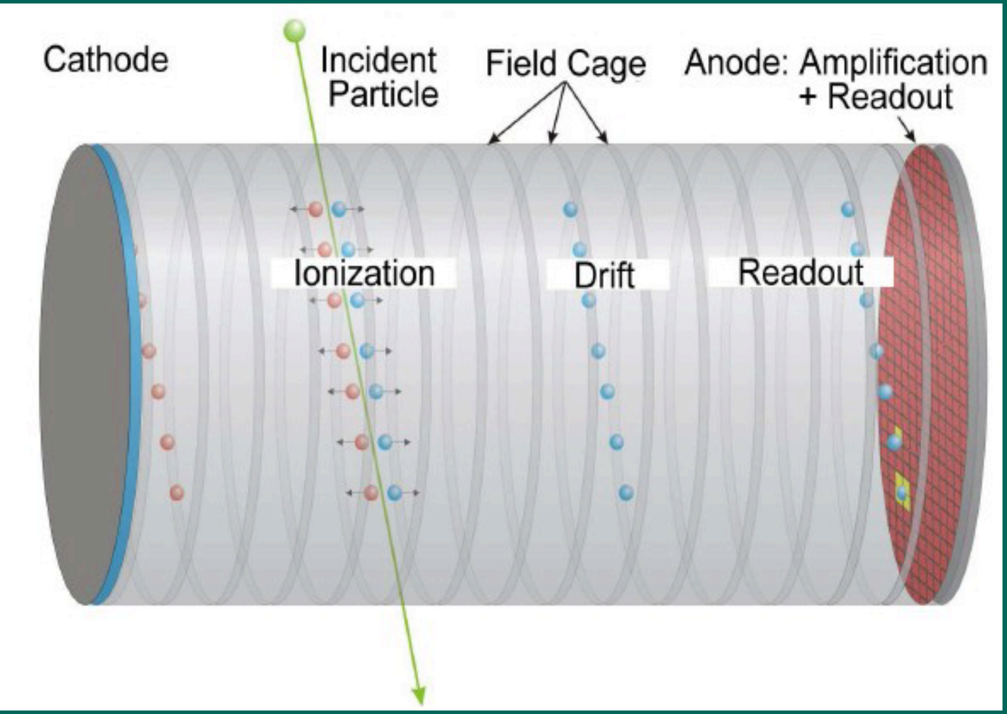
- Superb spacepoint precision allows tracking measurement goals to be achieved in a compact tracking volume
- Robust to spurious, intermittent backgrounds
  - **ILC is not a storage ring**

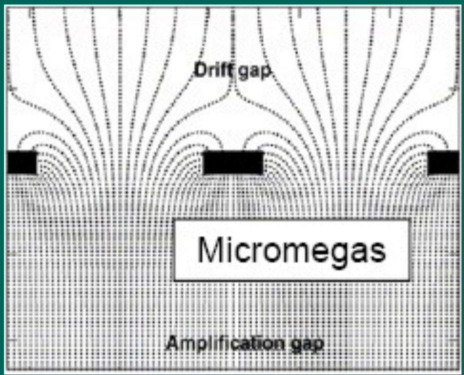
ILC Time Projection Chamber

ILD

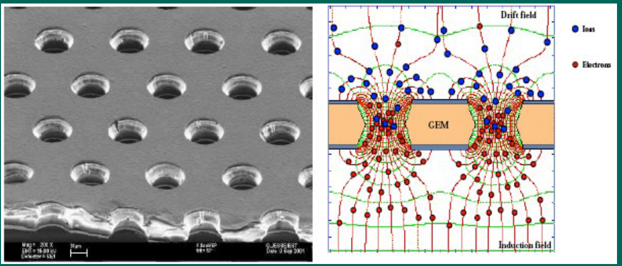
- Three read-out schemes:
  - GEM, MicroMegas, Pixels







- Readout time ~ 40 μsec

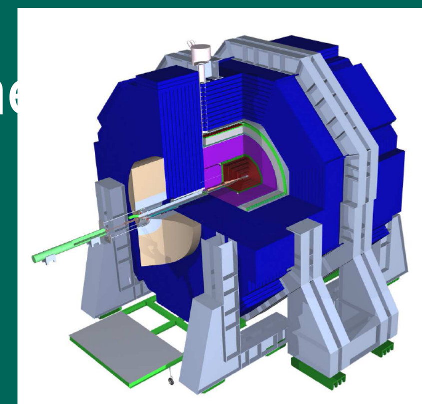


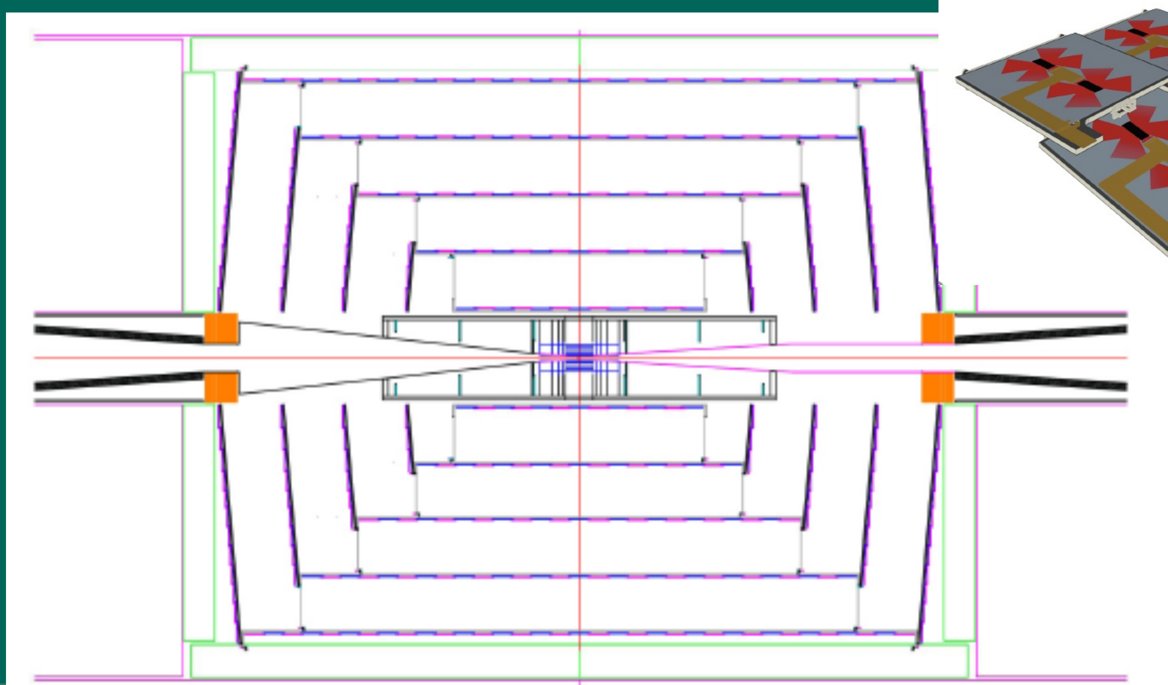
Gas Electron Multiplier GEM

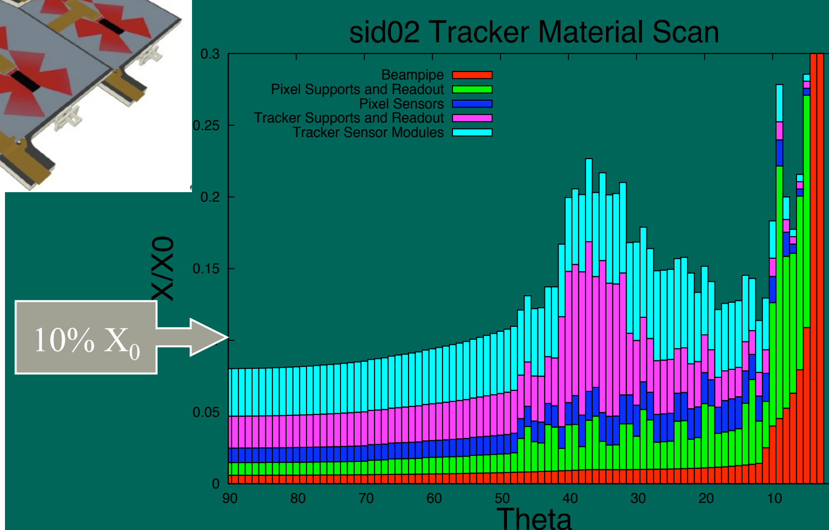
ILC Silicon Tracking

SiD

- Superb resolution allows small tracking volume
  - $<1\%\ \sigma_p/p$ at 100 GeV
- Fast - robust to backgrounds
- Very low mass support (passive cooling)
  - Modular low mass sensors tile CF cylinders - $0.6\%X_0$/layer

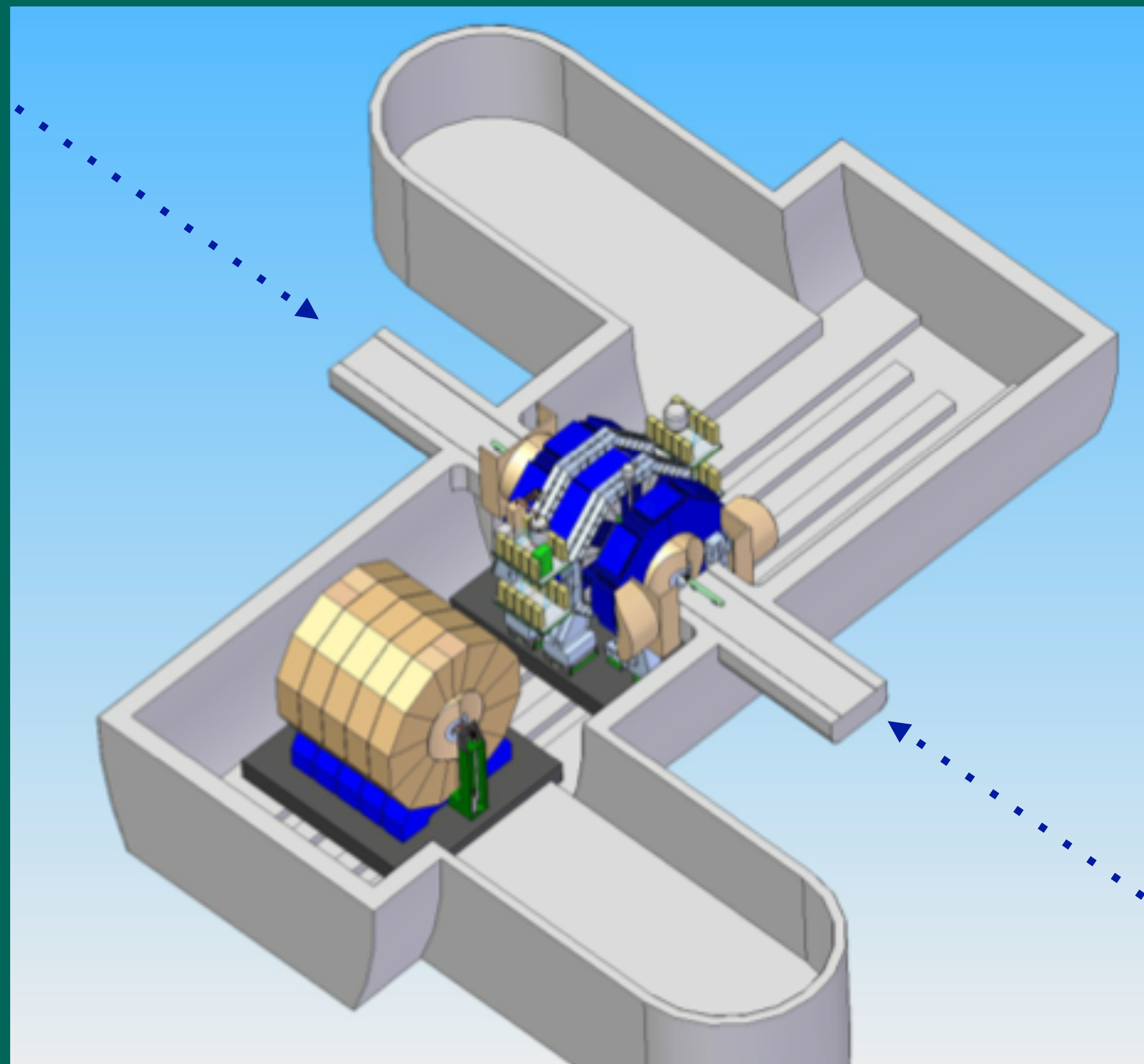






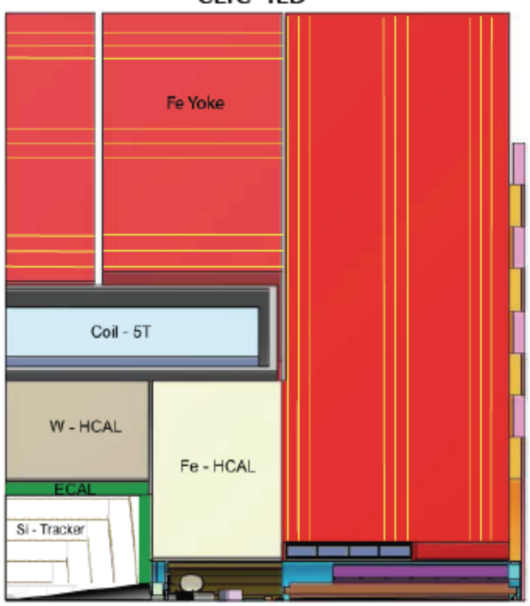
Push Pull

- Interaction Region designed for ILD and SiD to share the beamline, in a push-pull configuration



CLIC Detector Concepts

CLIC ILD



CLIC_SiD

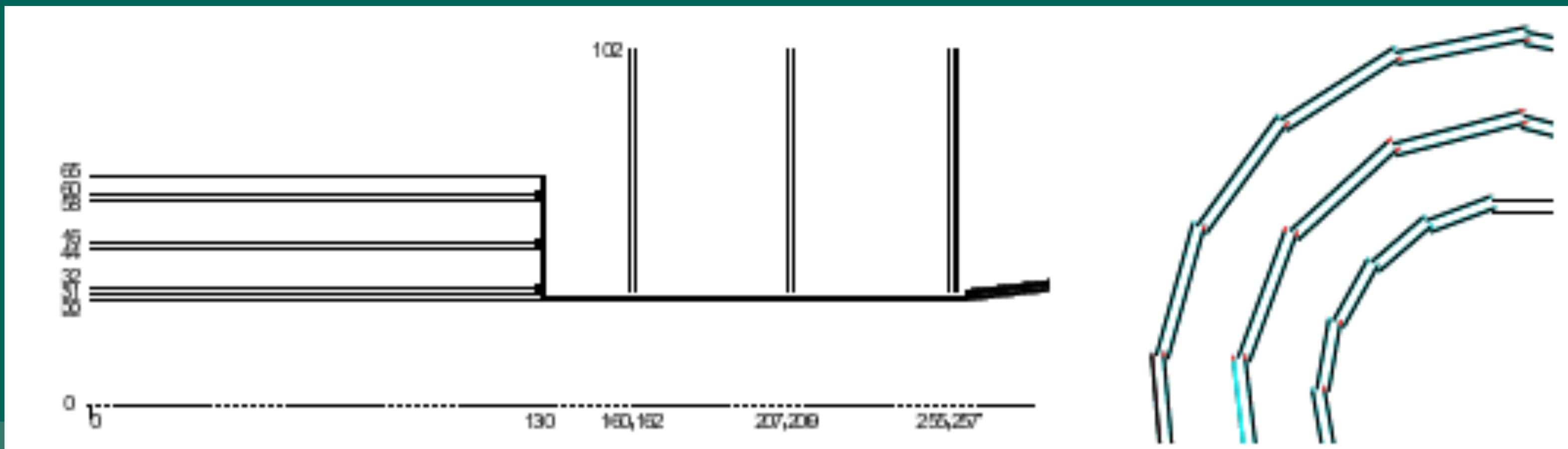
Concept	ILD	CLIC_ILD	SiD	CLIC_SiD
Tracker	TPC/Silicon	TPC/Silicon	Silicon	Silicon
Solenoid Field (T)	3.5	4	5	5
Solenoid Free Bore (m)	3.3	3.4	2.6	2.7
Solenoid Length (m)	8.0	8.3	6.0	6.5
VTX Inner Radius (mm)	16	31	14	27
ECAL r_{min} (m)	1.8	1.8	1.3	1.3
ECAL Δr (mm)	172	172	135	135
HCAL Absorber B / E	Fe	W / Fe	Fe	W / Fe
HCAL λ_I	5.5	7.5	4.8	7.5
Overall Height (m)	14.0	14.0	12.0	14.0
Overall Length (m)	13.2	12.8	11.2	12.8

- Design for up to 3 TeV CM (eg. HCAL thicker)
- Machine backgrounds challenging
- Detector requirements being pursued
- ILD and SiD simulation/reconstruction frameworks used to jumpstart performance studies and guide detector R&D

CLIC Detector R&D

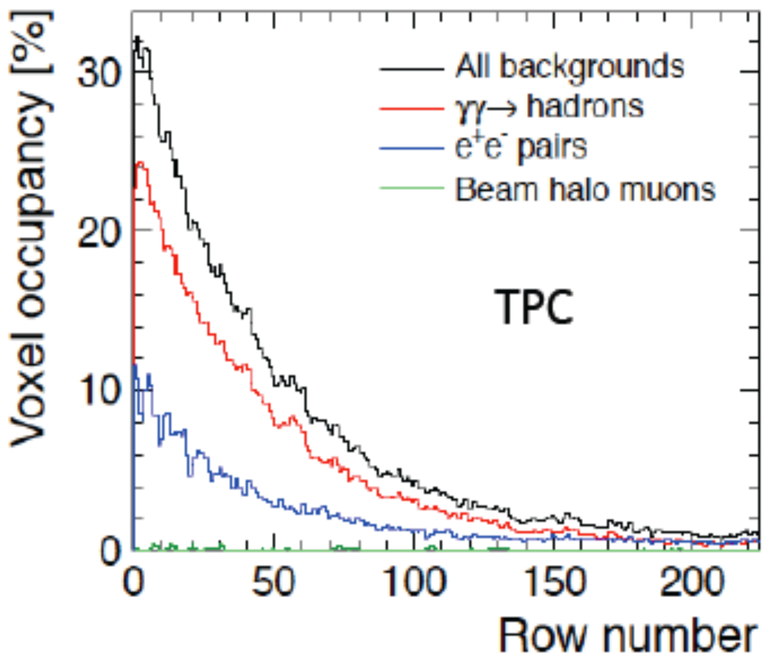
Vertex Detector

- Most challenging requirement from beam structure – O(5 nsec) hit time resolution
- Pixel technology with small pixel sizes of O(20 μm)
- O(0.2% X_0) material per layer;
  - High-density interconnect, thinning of wafers, ASICs or tiers;
  - low-mass construction and services
  - Advanced power reduction, power delivery, power pulsing and cooling developments



CLIC Detector R&D

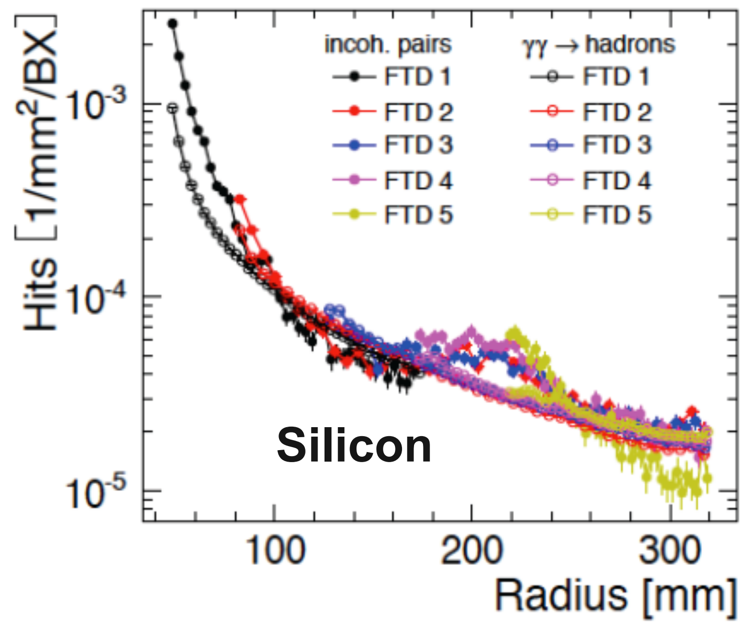
Tracking



High occupancies in the TPC, mostly due to yy=>hadrons. One may consider pixelised readout for the TPC in this region or suppress the inner pad rows.

requires technology/layout changes

High occupancies per bunch train in inner strip tracking layers



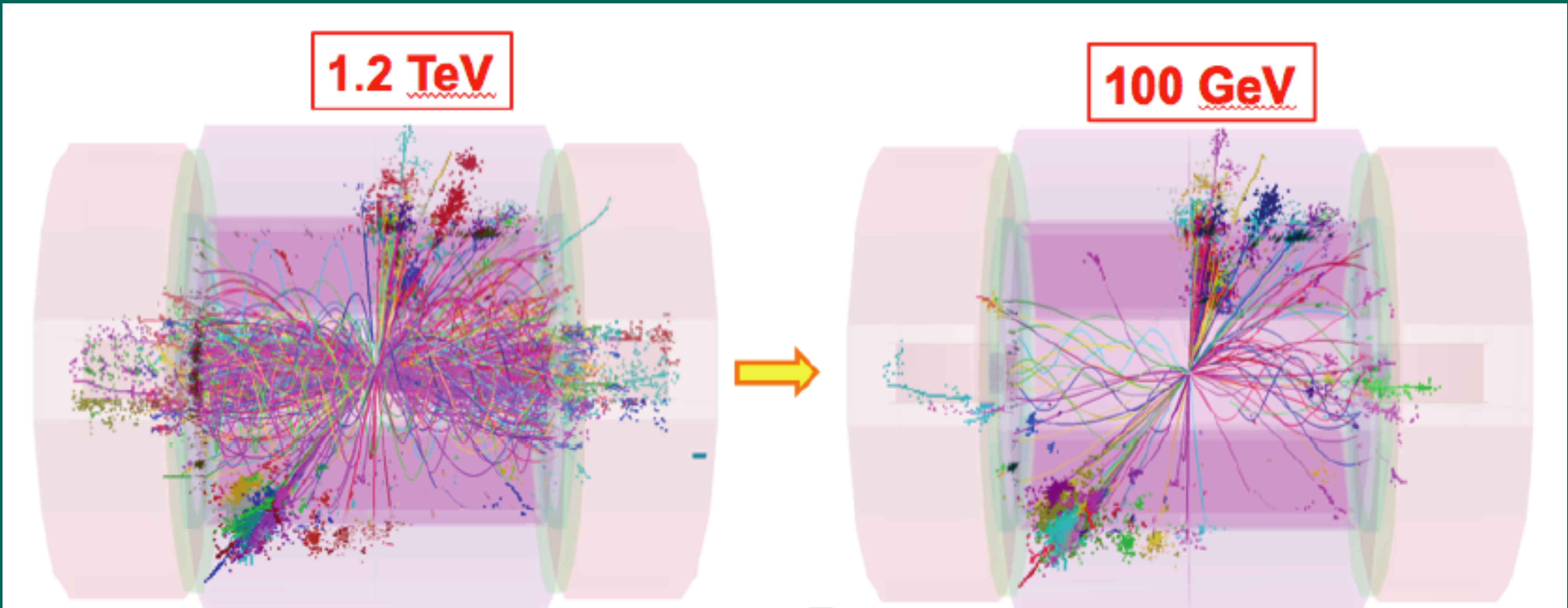
~2.9 hits/strip per 156 ns bunch train in FTD2, including safety factor

=> Requires technology choices and hardware R&D

CLIC Challenges Overcome

Background suppression successfully shown by

- ✱ Precise selective timing cuts on reconstructed particles (PFO's)
- ✱ Well-adapted jet reconstruction (taken from hadron colliders)



$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8 \text{ jets}$$

CLIC Detector R&D

- Scintillator/Tungsten Hcal
  Density of W allows a compact Hcal test W Stack
  Calice will test it

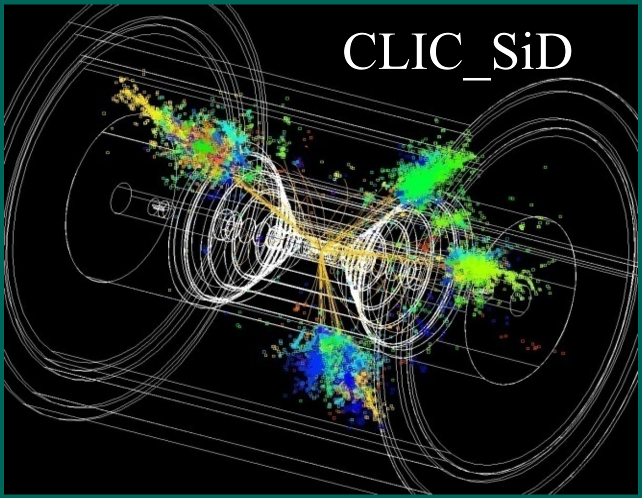
CLIC Tungsten Stack for CALICE

- Reinforced SC Magnet Conductor

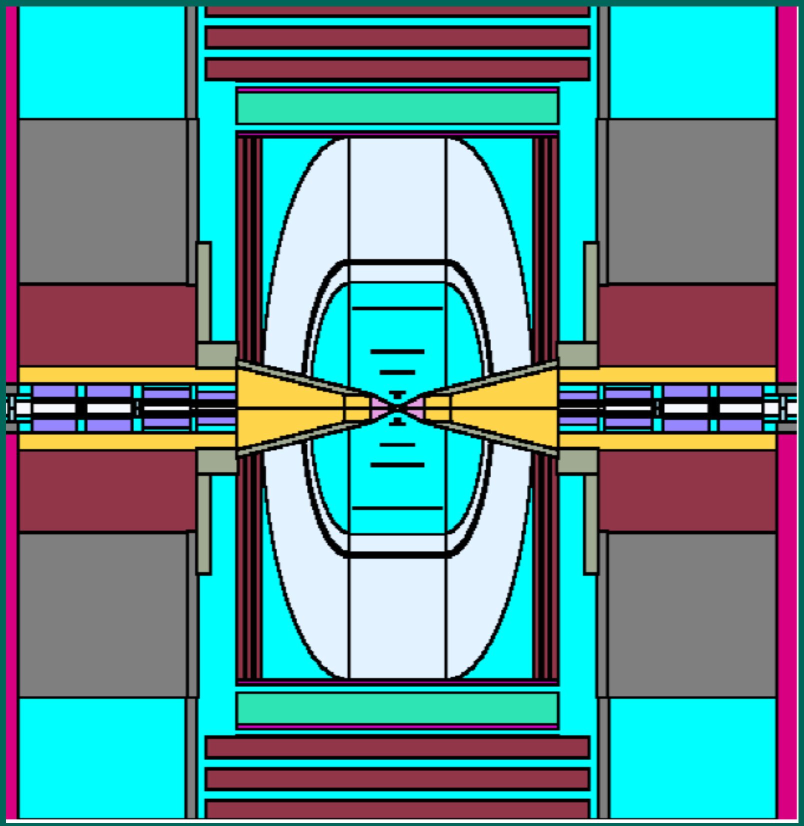
- Support and Vibration Studies
  nm spots and short bunch trains
  (which defy feedbacks) require
  ~nm stability

- Defining and simulating concepts

- Benchmarking physics channels

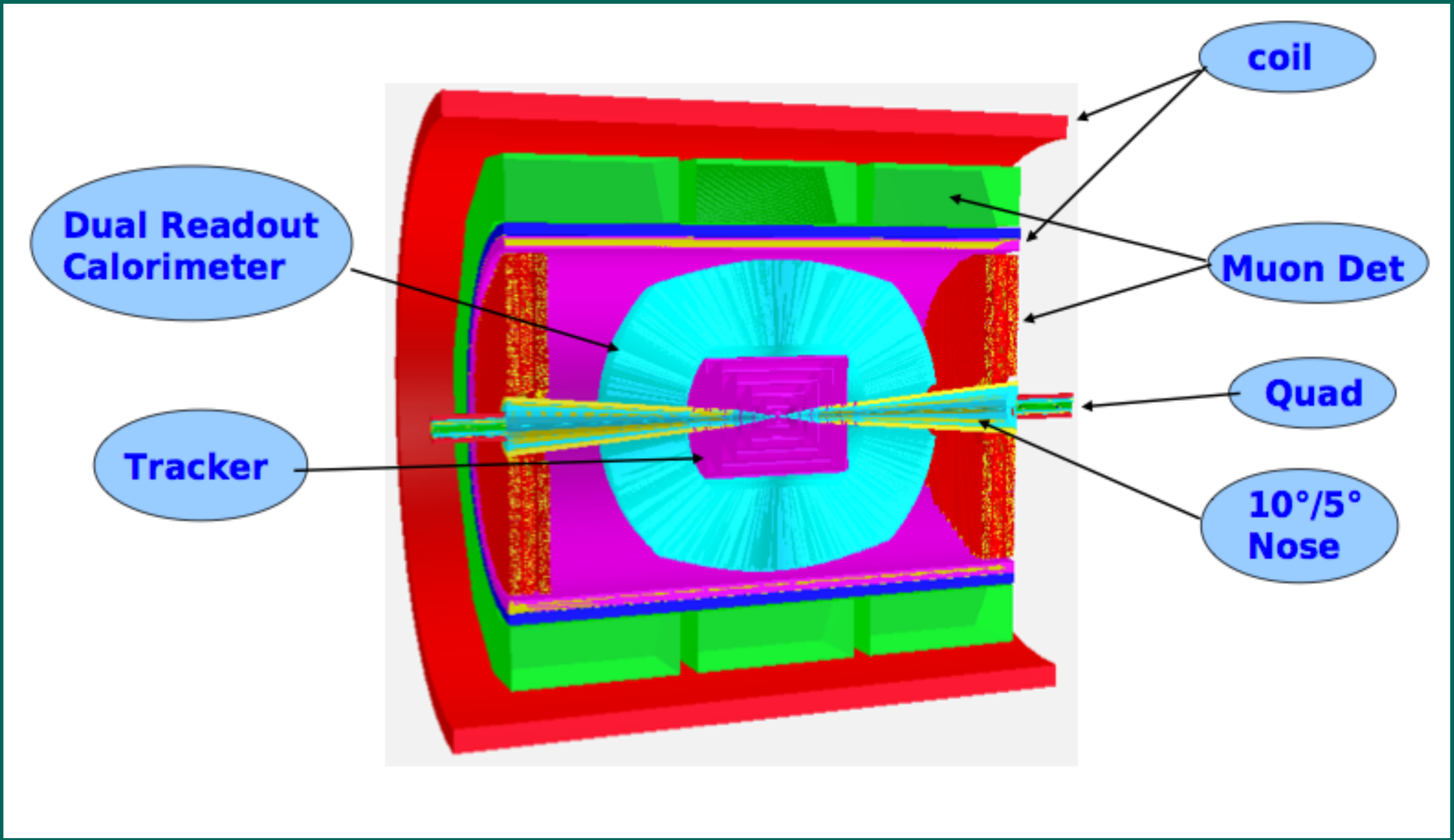


Developing MuC Detector Concepts

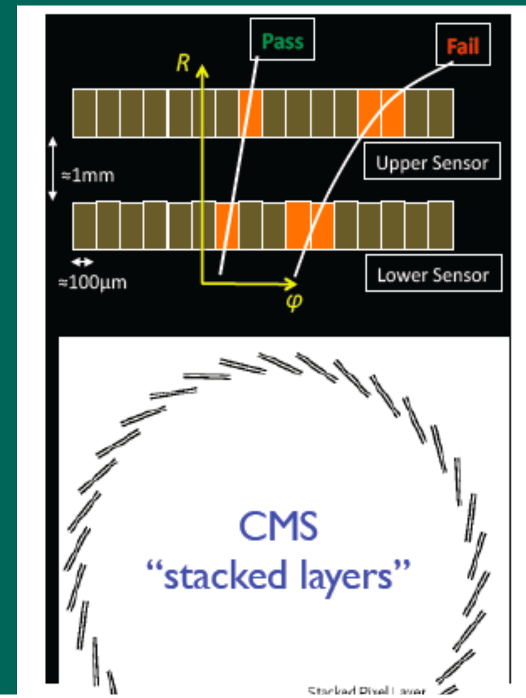


- The Muon Collider is an extremely challenging environment for physics
  - Radiation hard detectors required
  - High Occupancies in tracking detectors
  - High Energy deposition in calorimeters
- Ideally, achieve similar physics performance as other two Lepton Collider options:
  - Is this possible given the environment?
  - Open question

Model MuC Detectors



Muon Collider Detectors



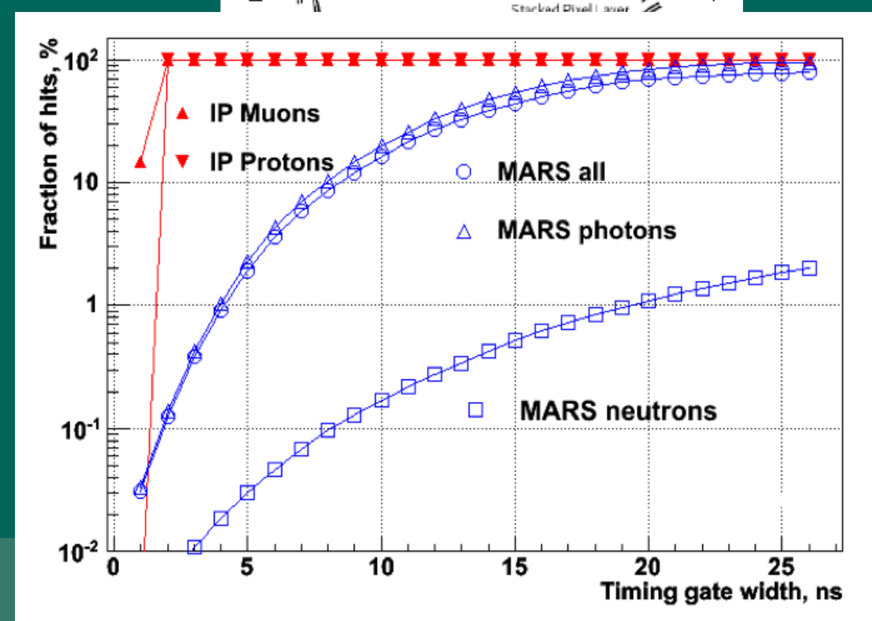
<u>Tracking</u>

- ✱ Horrendous background
  - – Absorbed dose ~ LHC (concentrated)
  - – Compare to ILC ~ LHC/10,000
- ✱ Paired layers with timing info?
  - – rad-hard technologies and actively cooled sensors

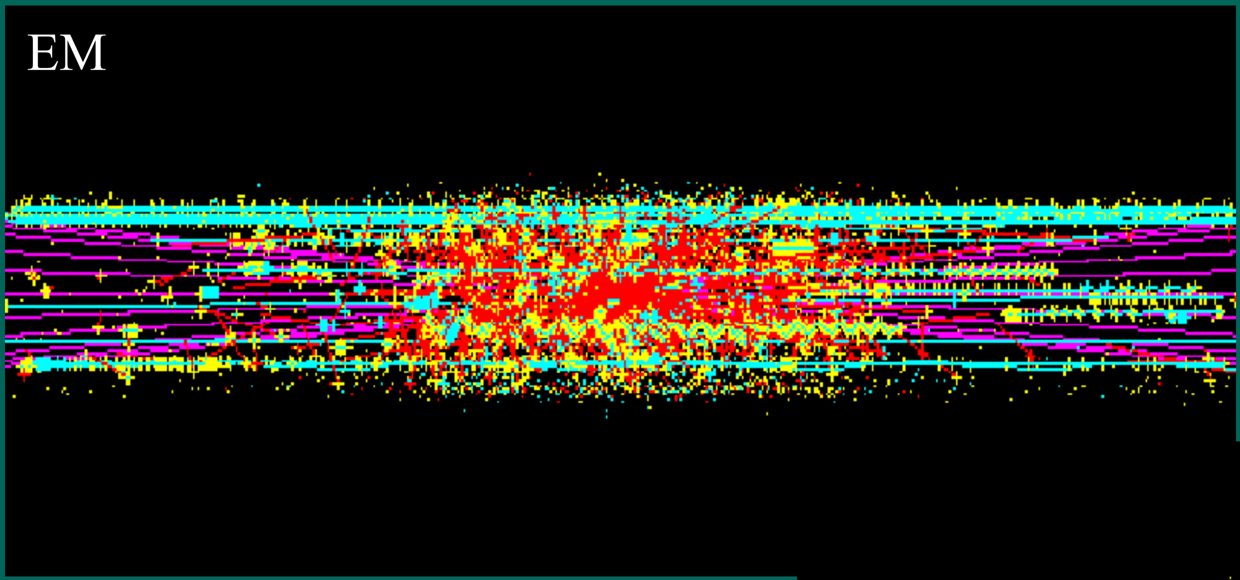
<u>Calorimetry</u>

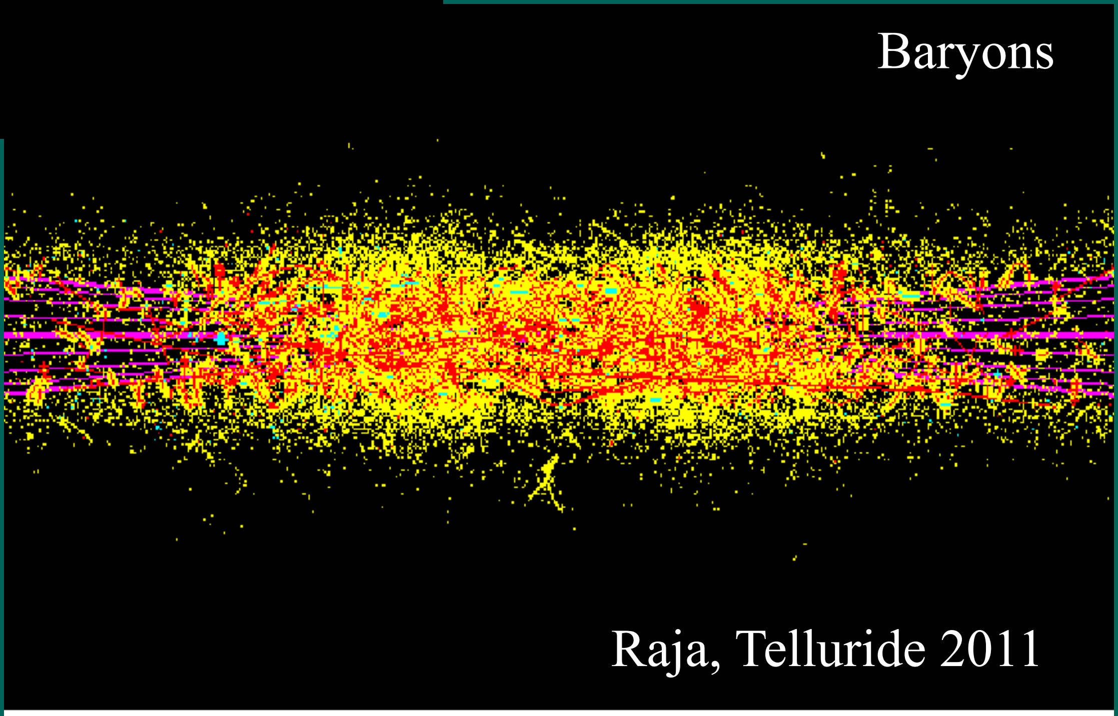
Traveling trigger? (pixel calorimeter)

- ✱ Each crossing, a trigger is generated.
- ✱ Each cal pixel triggered by 2 ns gate.
- ✱ Gate start coincides with the time taken for light to travel from IP to the pixel.
- ✱ End of trigger = t light + 2 ns.



Particles in the MuC Detector

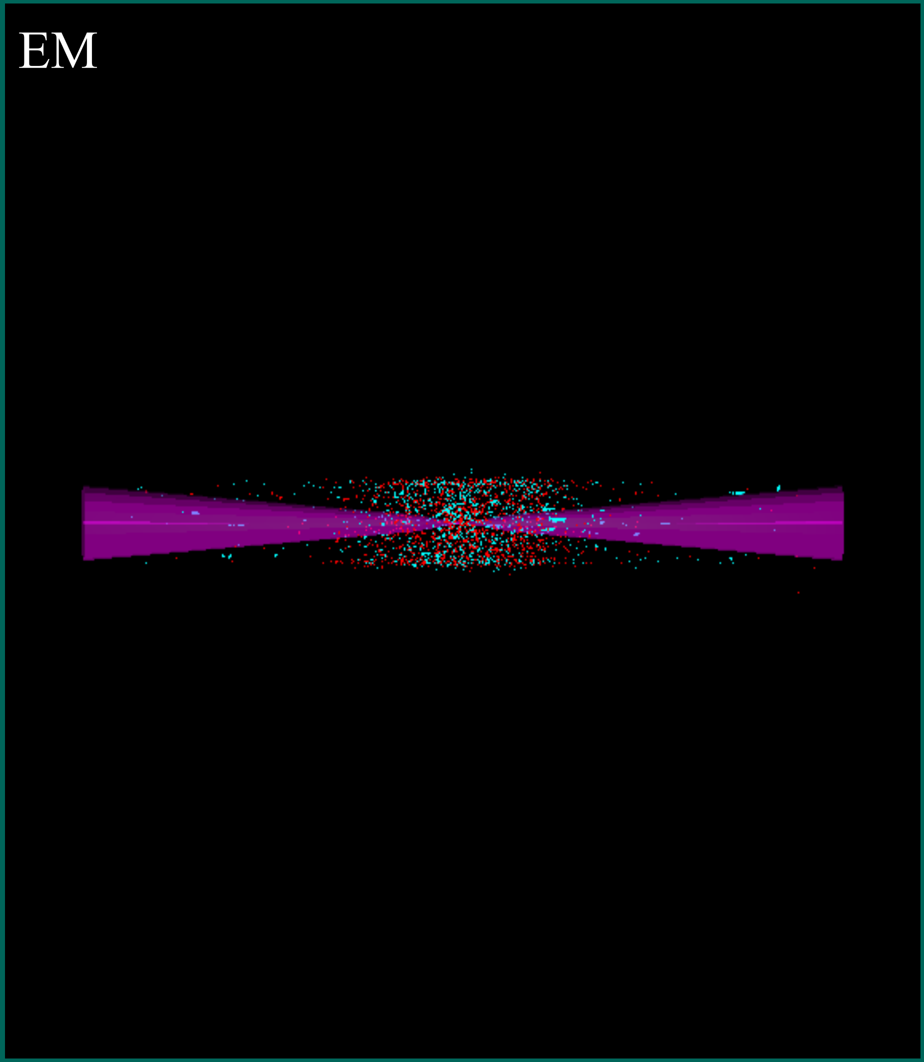




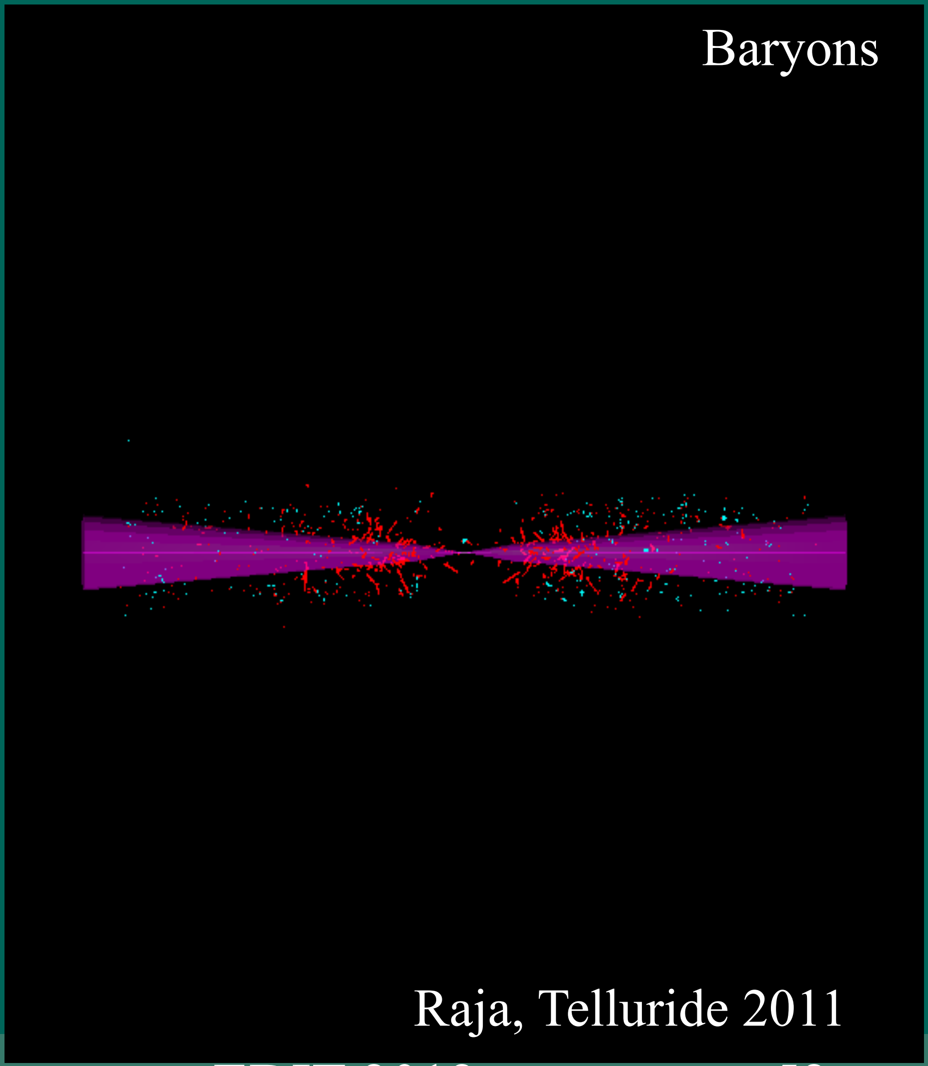
- 2×10^8 EM
  - ~100 TeV energy
- 4.6×10^7 baryons
  - ~1000 TeV energy

Note – yellow hits > 2 nsec out of time

Employing the Traveling Trigger



2 ns traveling trigger



Summary

- The Lepton Collider is the next energy frontier facility needed to complement the LHC.
- Three collider options with differing capabilities and technical readiness offer technologies for this LHC companion

  ILC, CLIC, MuC

- The physics goals motivating these energy frontier lepton colliders set demanding requirements for detectors, some of which have been addressed with recent detector R&D for the linear collider.
- The machine environments at ILC, CLIC, and MuC pose additional, and sometimes severe, challenges for detector design.
- **If the physics of the LHC justifies it, the ILC is now ready for a construction start.**
- **If multi-TeV Lepton Collider needed, CLIC or MuC may be answer after additional successful R&D.**