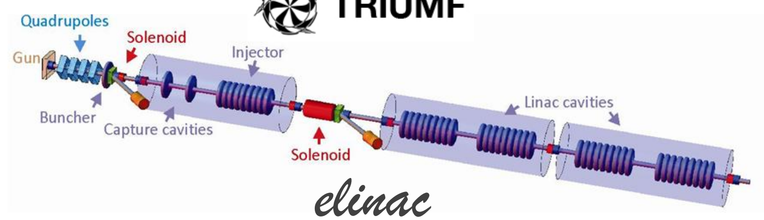
The International Linear Collider A Precision Probe for Physics at the TeV Scale

A. Bellerive

Carleton UNIVERSITY

TRIUMF



LC TPC

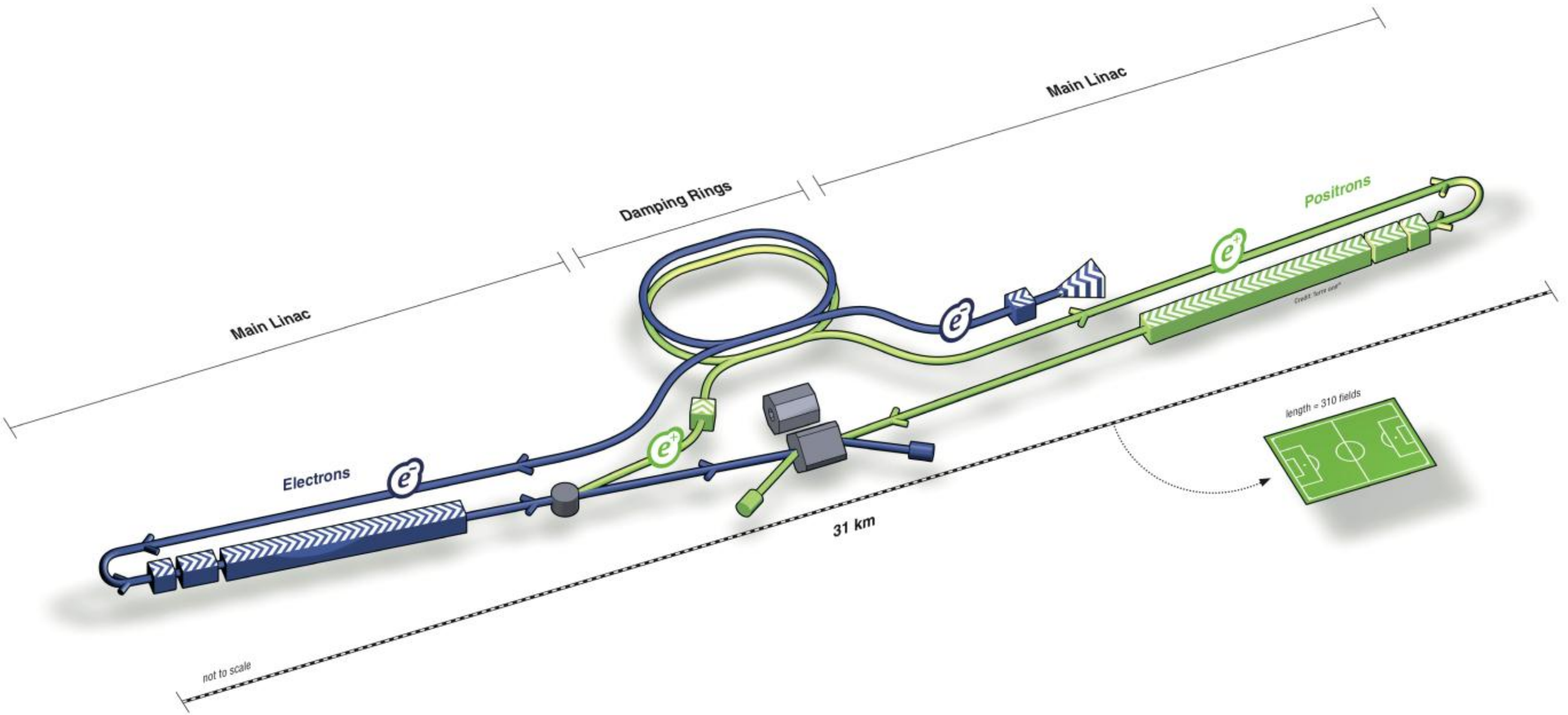
CALICE
Calorimeter for ILC

Outline

- Intro: **Physics Case at International Linear Collider (ILC)**
- ILC Technical Design Report
- E-linac at TRIUMF – The Canadian Connection
- International Linear Detector (ILD)
  - **Concept and Specifications**
- Calorimetry (CALICE) for the ILC
  - **Hadronic Calorimeter (HCAL)**
  - **Particle Flow Algorithms (PFAs)**
- Large Prototype TPC (LCTPC) for the ILC
  - **TPC Requirements**
  - **Micro Pattern Gas Detector (MPGD)**
- Summary

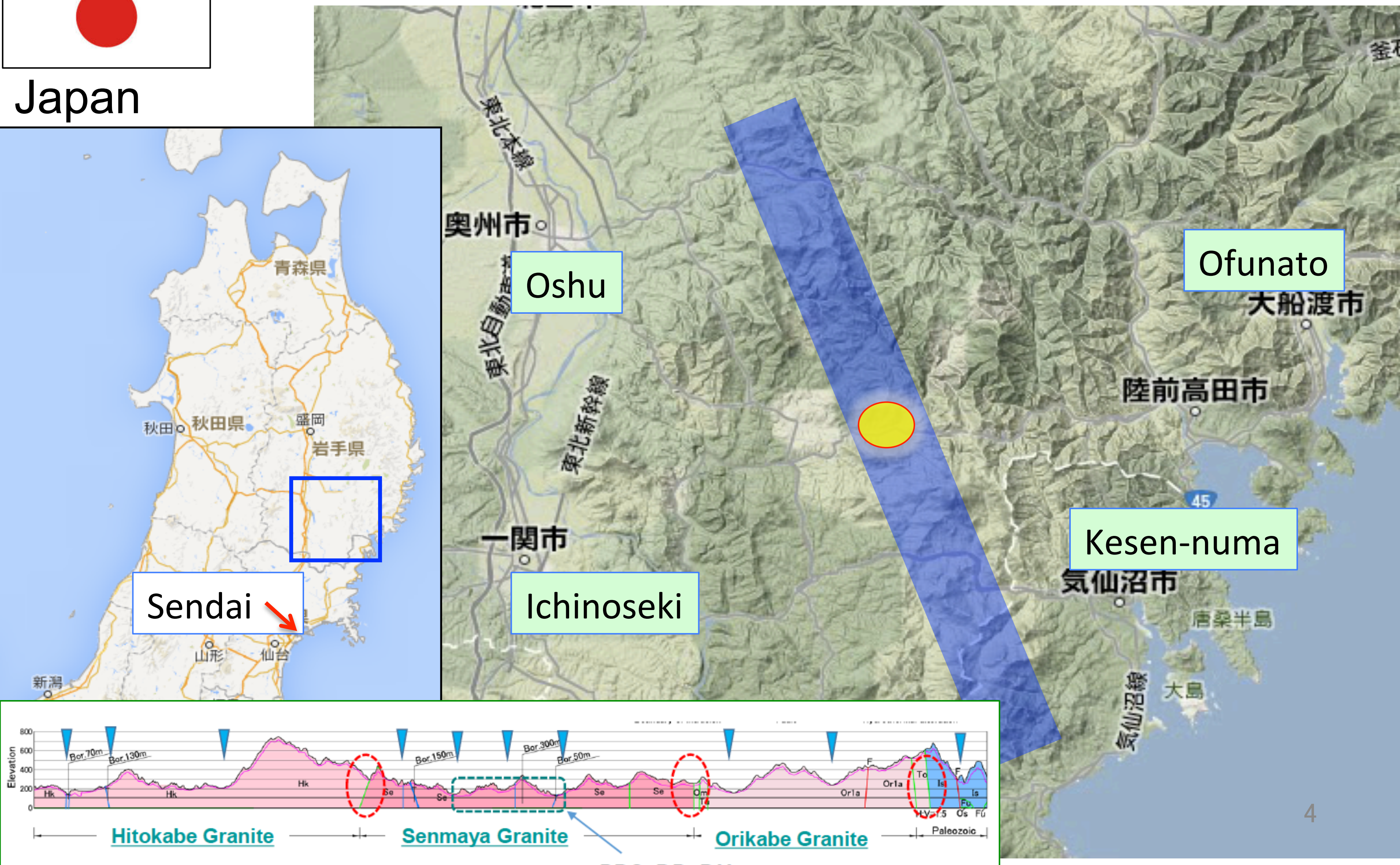
International Linear Collider

- Next collider: linear e^+e^- collider with length: ~ 31km
- Tunable center of mass energy of 200-500 GeV
- Upgradable to 1 TeV
- Two detectors with push-pull concept



ILC Candidate Location: Kitakami Area

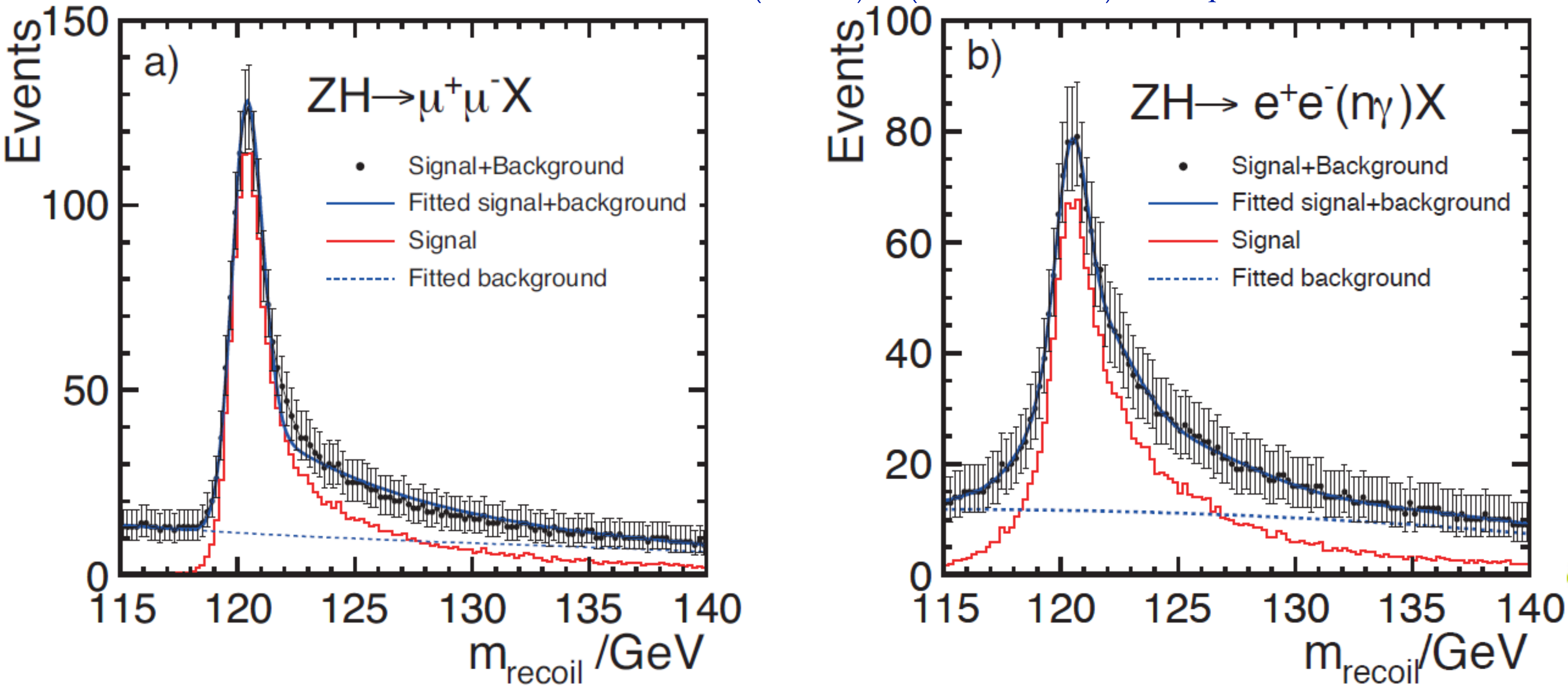
Japan



Physics Case

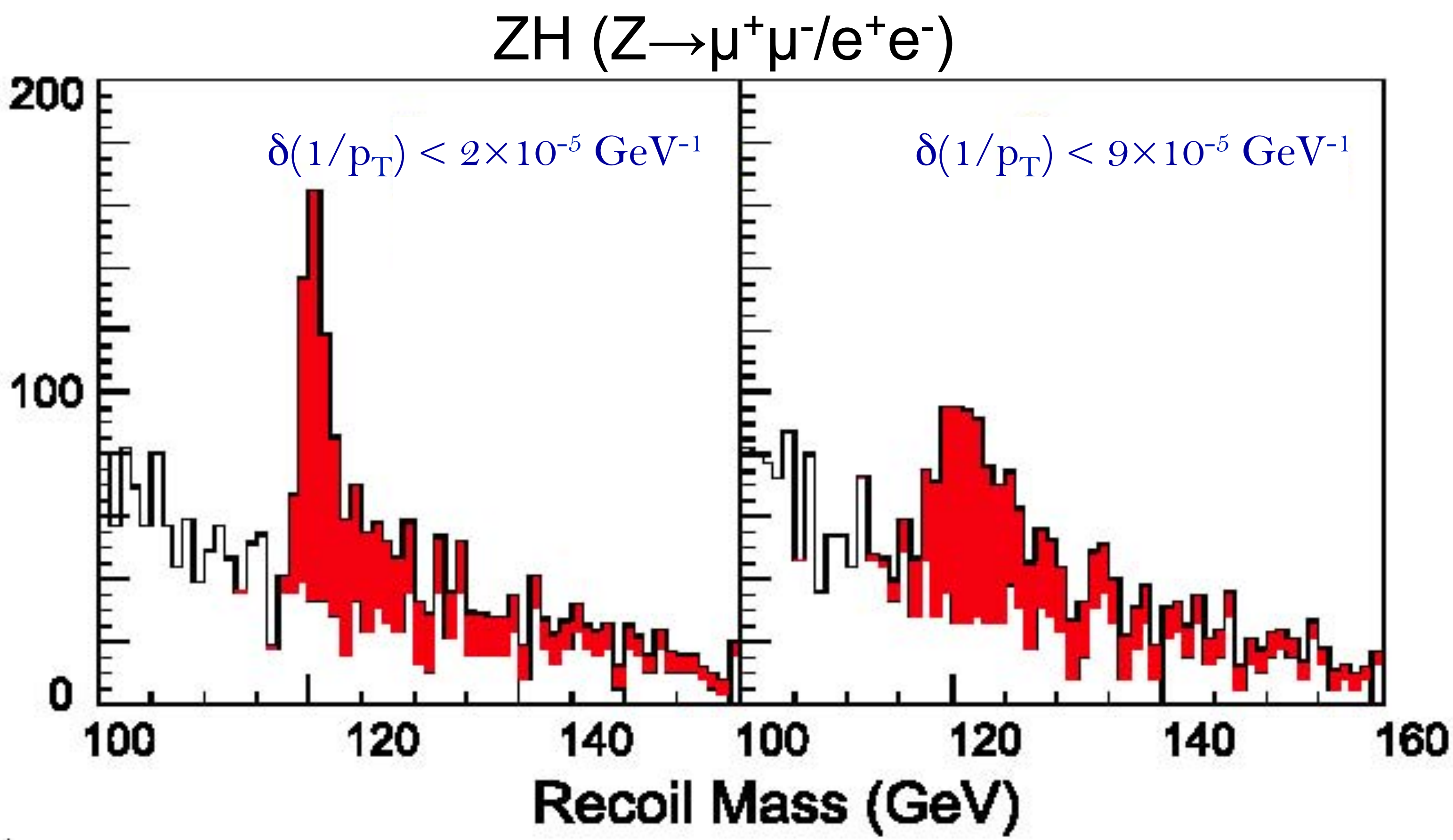
- Particle Flow Algorithm (PFA) aims to reconstruct every particle
- ILC Physics Menu
  - precision study of Higgs coupling
  - sensitivity model-independent
- Higgs recoil mass: $e^+e^- \rightarrow ZH\ (Z \rightarrow \mu^+\mu^-/e^+e^-) + X$

The results here are shown are for the P(e+, e−) = (+30%,−80 %) beam polarization



Measure Higgs with precision limited only by the knowledge of beam energy

Unprecedented demands on the tracker momentum resolution
Low background in e^+e^- machine

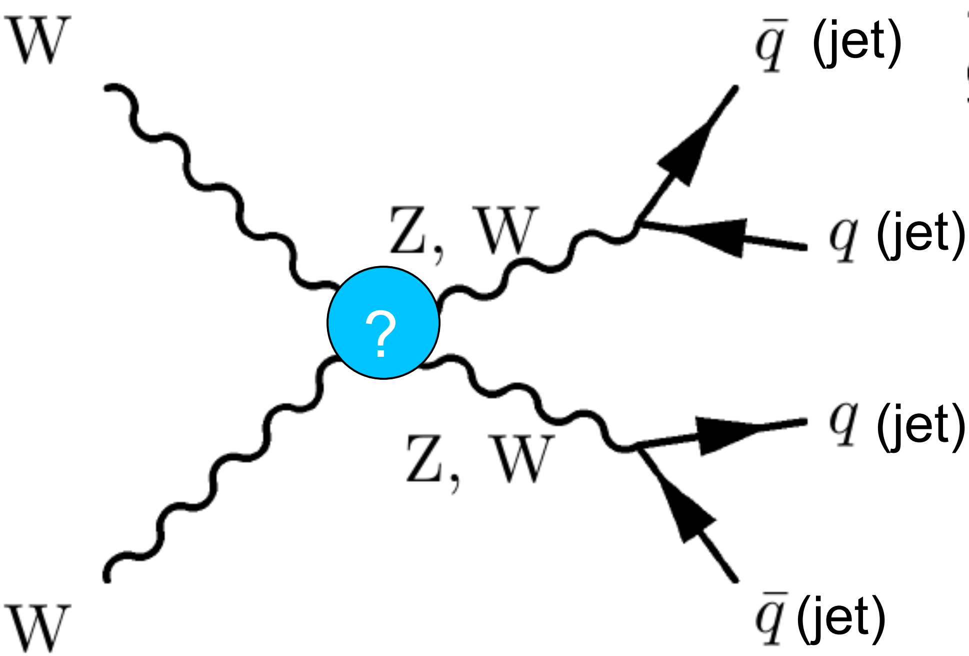


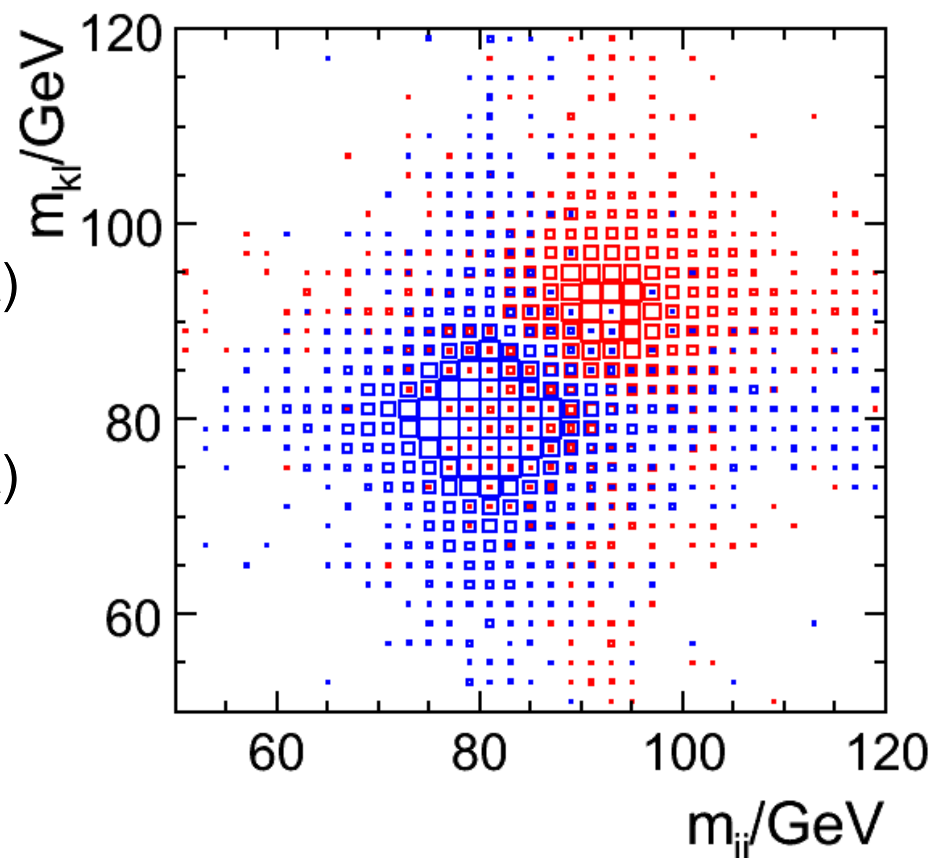
Cartoon demonstration of the $\mu^+ \mu^-$ recoil mass at $\sqrt{s}$ = 500 GeV.
M_H = 120 GeV, for two values of the ILD tracker resolution.

Hadronic decays of W and Z bosons

Need excellent jet energy and dijet mass resolution to separate W and Z bosons in their hadronic decays: need $3\%/E_{jet}$-$4\%/E_{jet}$

Basic mean: Highly granular calorimeters optimized for Particle Flow



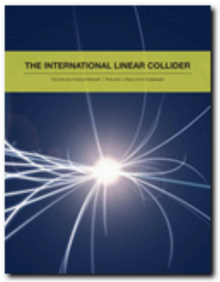


Technical Design Report (TDR)

Published on 12 June 2013

http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

Volume 1 - Executive Summary



Download the pdf (9.5 MB)

Volume 2 - Physics

Download the pdf (9.5 MB)

Volume 3 - Accelerator

Part I:
R&D in the Technical Design Phase

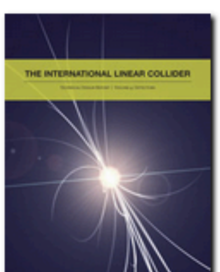
Download the pdf (91 MB)

Volume 3 - Accelerator

Part II:
Baseline Design

Download the pdf (72 MB)

Volume 4 - Detectors



Download the pdf (66 MB)

From Design to Reality

Download the pdf (5.5 MB)
Visit the web site

Long range plan

Plan for future of US particle physics (P5)

“Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.”

The meaning of “modest” will depend on the HEP budget (initial support will be by redirection of effort). The meaning of “appropriate” will depend on the areas where Japan would like the USA to help (current priority is for site-specific accelerator R&D and design efforts). USA awaits further discussions with the Japanese government.

European Strategy for Particle Physics

“Top priority is given to the continued operation of the LHC and its upgrade to higher energies and higher particle rates to ensure the exploitation of its full scientific potential. Other priorities for large-scale physics facilities are the development of a post-LHC accelerator project at CERN with global contribution, the European participation in the linear accelerator ILC and the development of a European neutrino research programme.”

ILC – Elinac Work at TRIUMF/UVIC

Dean Karlen

University of Victoria / TRIUMF

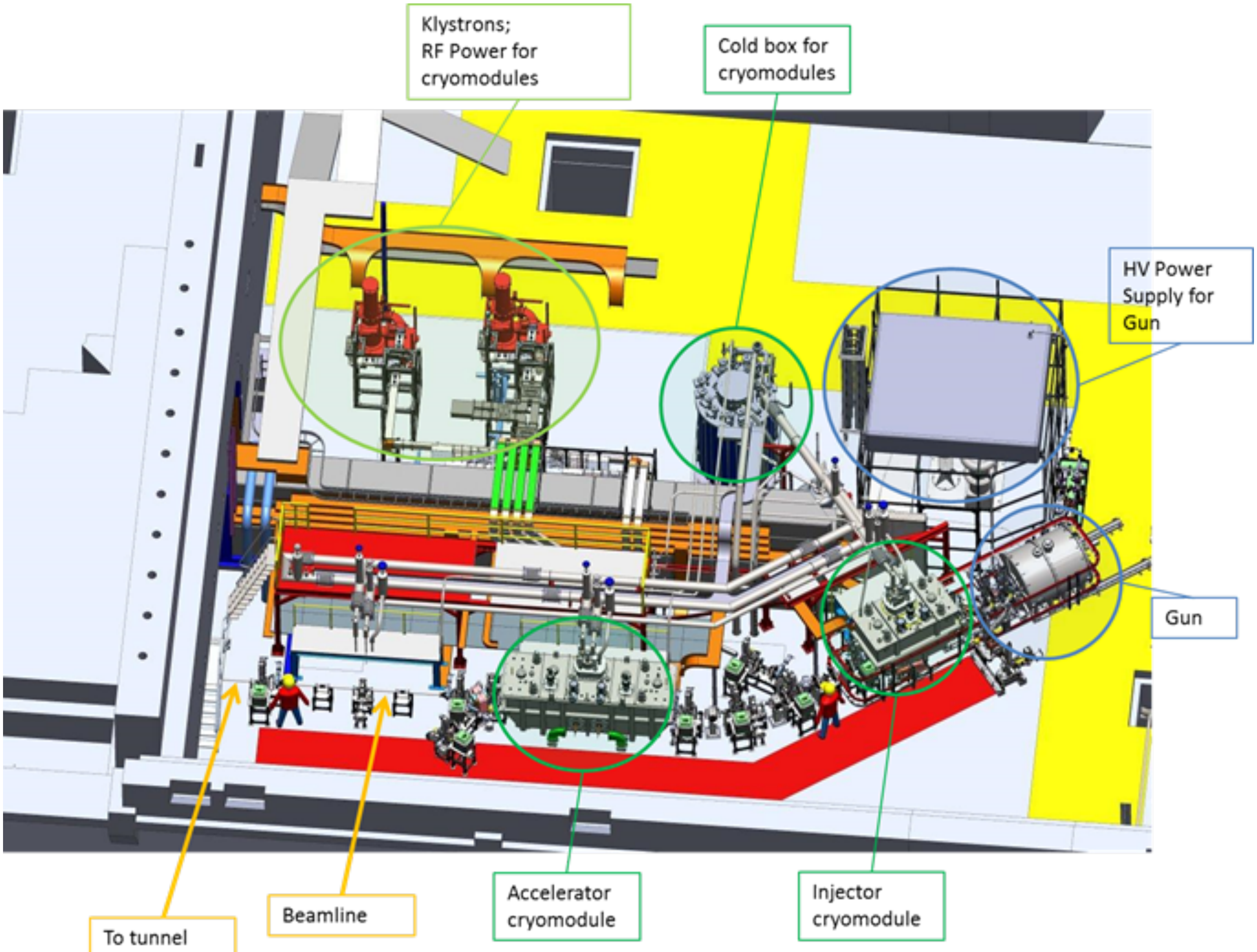
LCTPC/E-Linac – UVIC

(past 5 years)

E-Linac

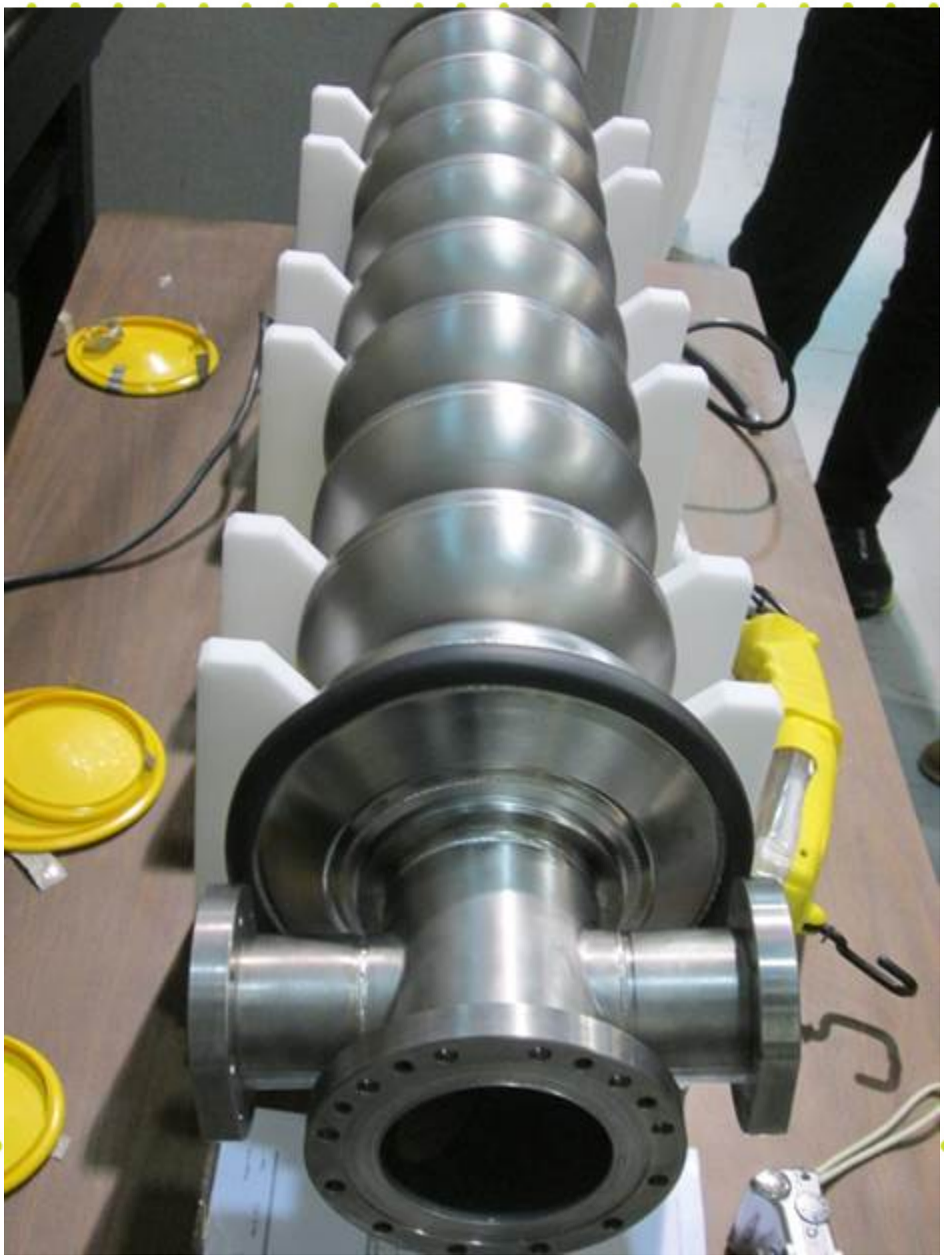
	Name	Institute	Position	Year	Months	Funding
1	Dean Karlen	UVIC	Faculty			
2	Doug Storey	UVIC	M.Sc	2009-11	(full-time)	
3	Jason Abernathy	UVIC	M.Sc	2010-	(full-time)	
4	Brett Hryciw	UVIC	B.Sc.	2012	4	

E-linac at TRIUMF

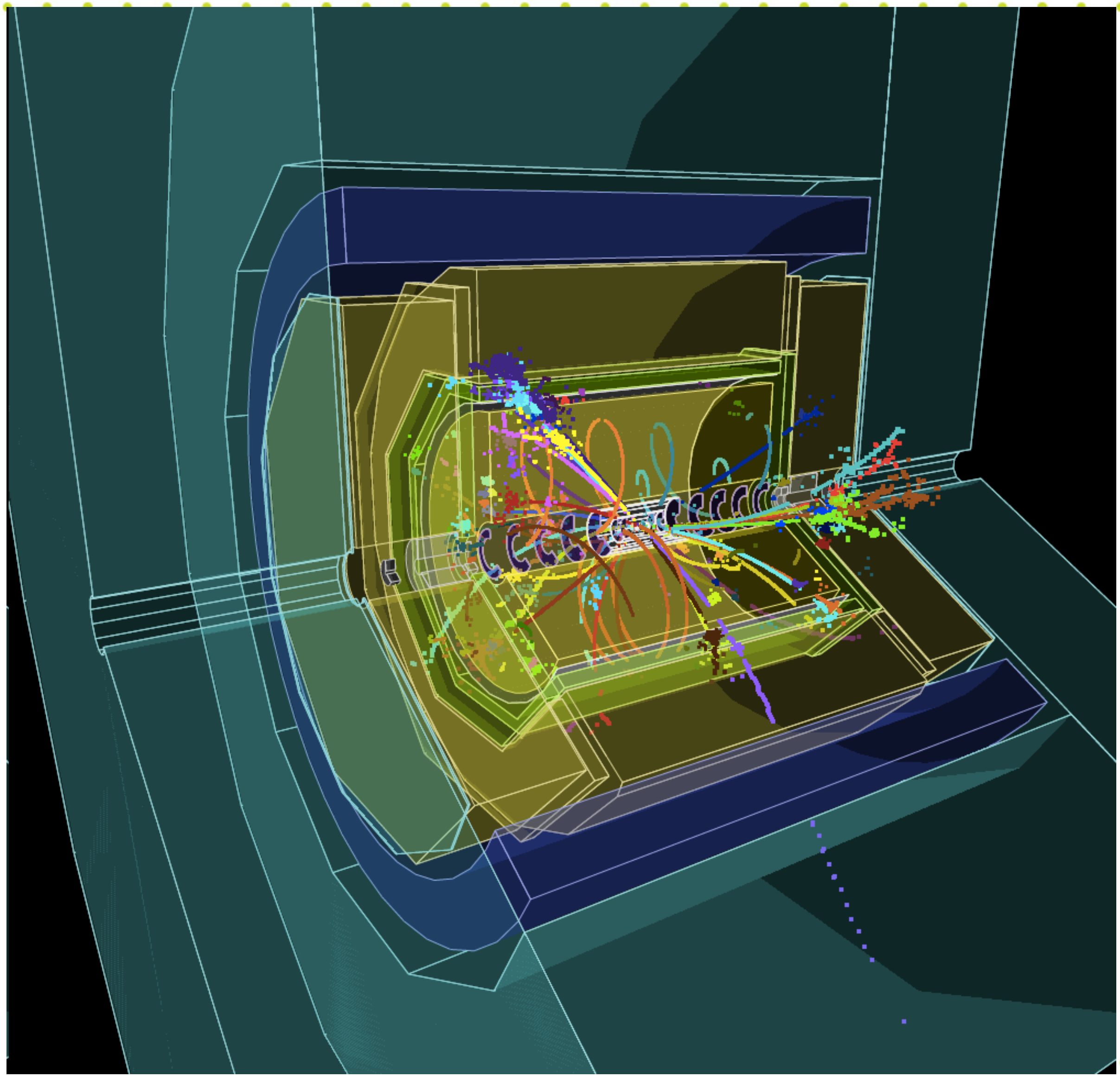


E-linac at TRIUMF

E-linac at TRIUMF

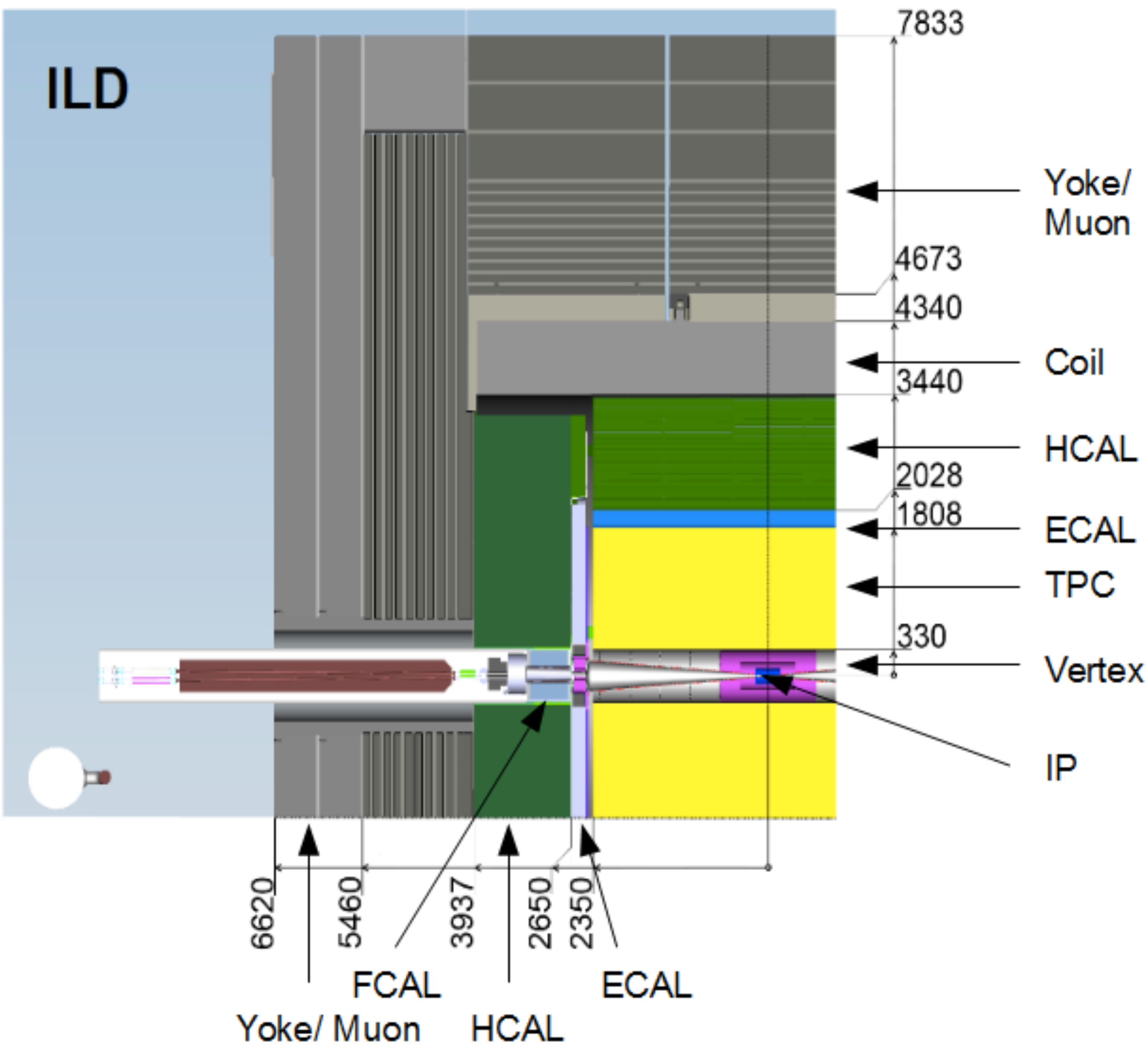


International Linear Detector



Dean Karlen:
International Detector Advisory Group (IDAG) and ILD Joint steering board

International Linear Detector



The large option

E_{cm} = 0.5 & 1 TeV

Components:

- Vertex
- Silicon tracking (SIT/SET/ETD/FTD)
- Gas TPC
- ECAL/HCAL/FCAL
- SC Coil (3.5 Tesla)
- Muon in Iron Yoke

ILD Requirements:

- **Momentum resolution:** $\delta(1/p_T) < 2\times10^{-5}\ \mathrm{GeV}^{-1}$
- **Impact parameters:** $\sigma(r\phi) < 5\ \mu\mathrm{m}$
- **Jet energy resolution:** $\sigma_E/E \sim 3\text{-}4\%$

International Linear Detector

ILD ECAL and HCAL

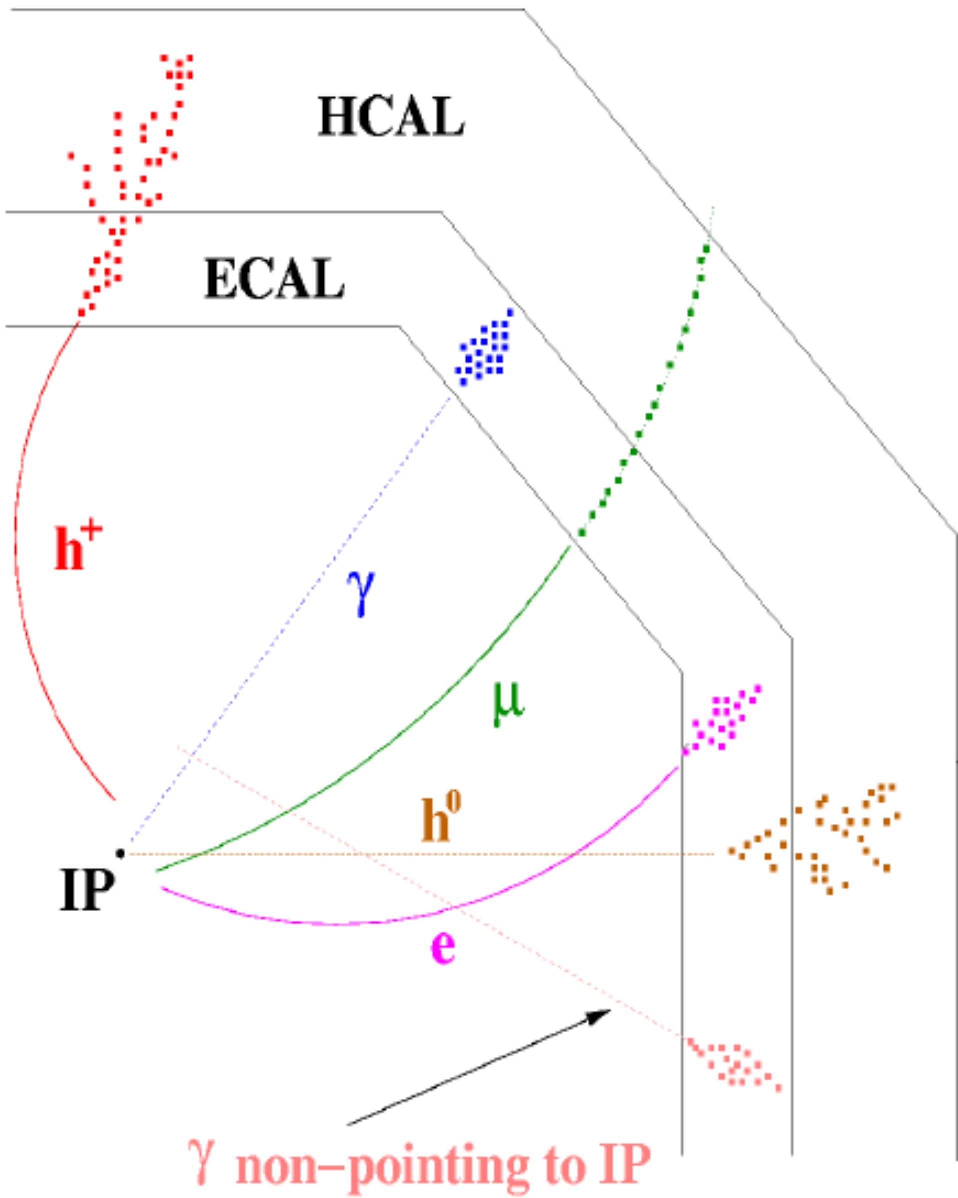
large radius and length
➔ to separate the particles
Hermitic, but compact (inside the coil of the solenoid)

large magnetic field
➔ to sweep out charged tracks

“no” material in front of calorimeters
➔ stay inside coil

small Molière radius of calorimeters
➔ to minimize shower overlap

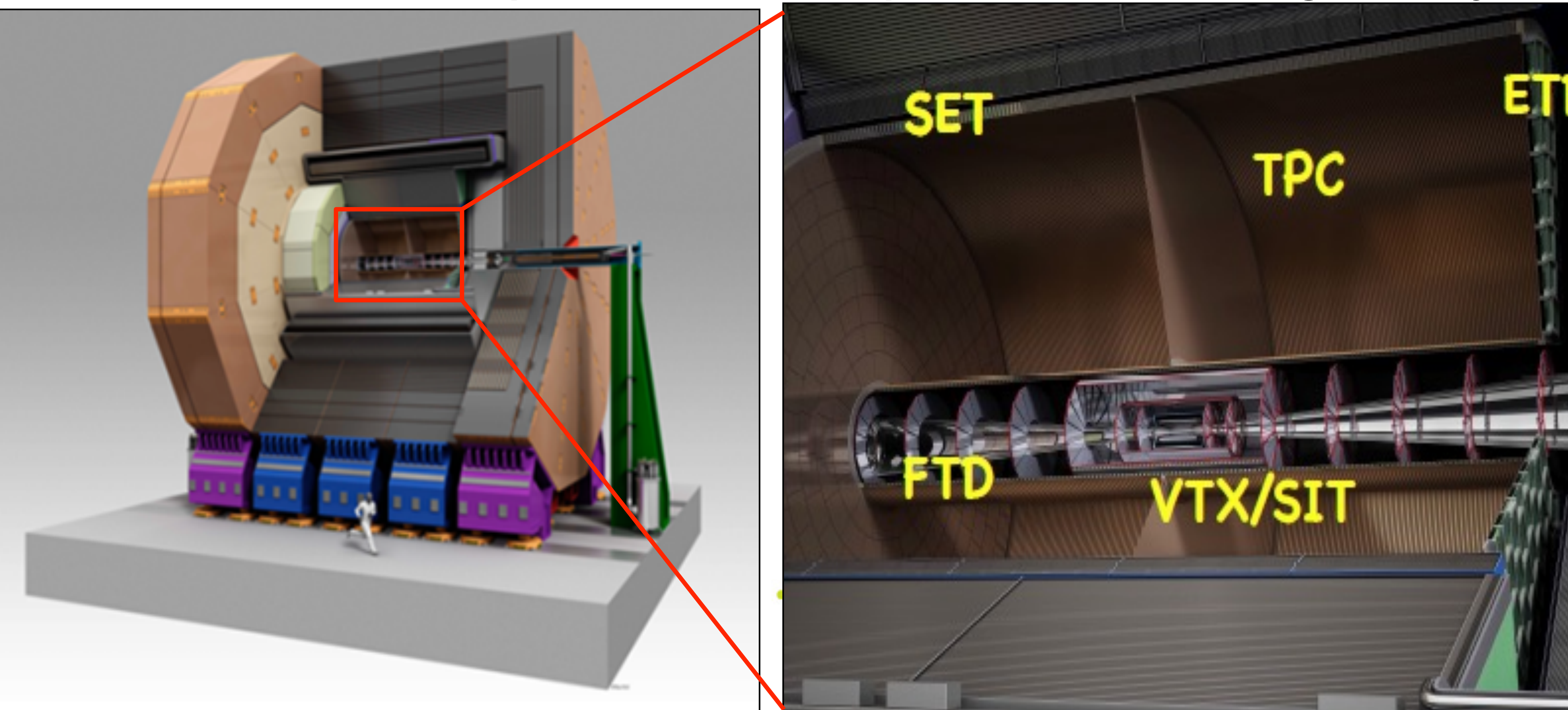
high granularity of calorimeters
➔ to separate overlapping showers



International Linear Detector

- Time Projection Chamber (TPC)
- Vertex (VTX) detector is realized with multi-layer of pixels
- Silicon strip (SIT) detectors are arranged to bridge the gap VTX and the TPC

TPC ≧200 continuous position measurements along each track in a gas with the point resolution of $\sigma_{r\varphi}$ < 100μm, and a lever arm of around 2m in the magnetic field of 3.5-4T . 2-track separation: 2 mm in Rφ and 6 mm in z in a high density



ILC – CALICE Work at McGill

François Corriveau

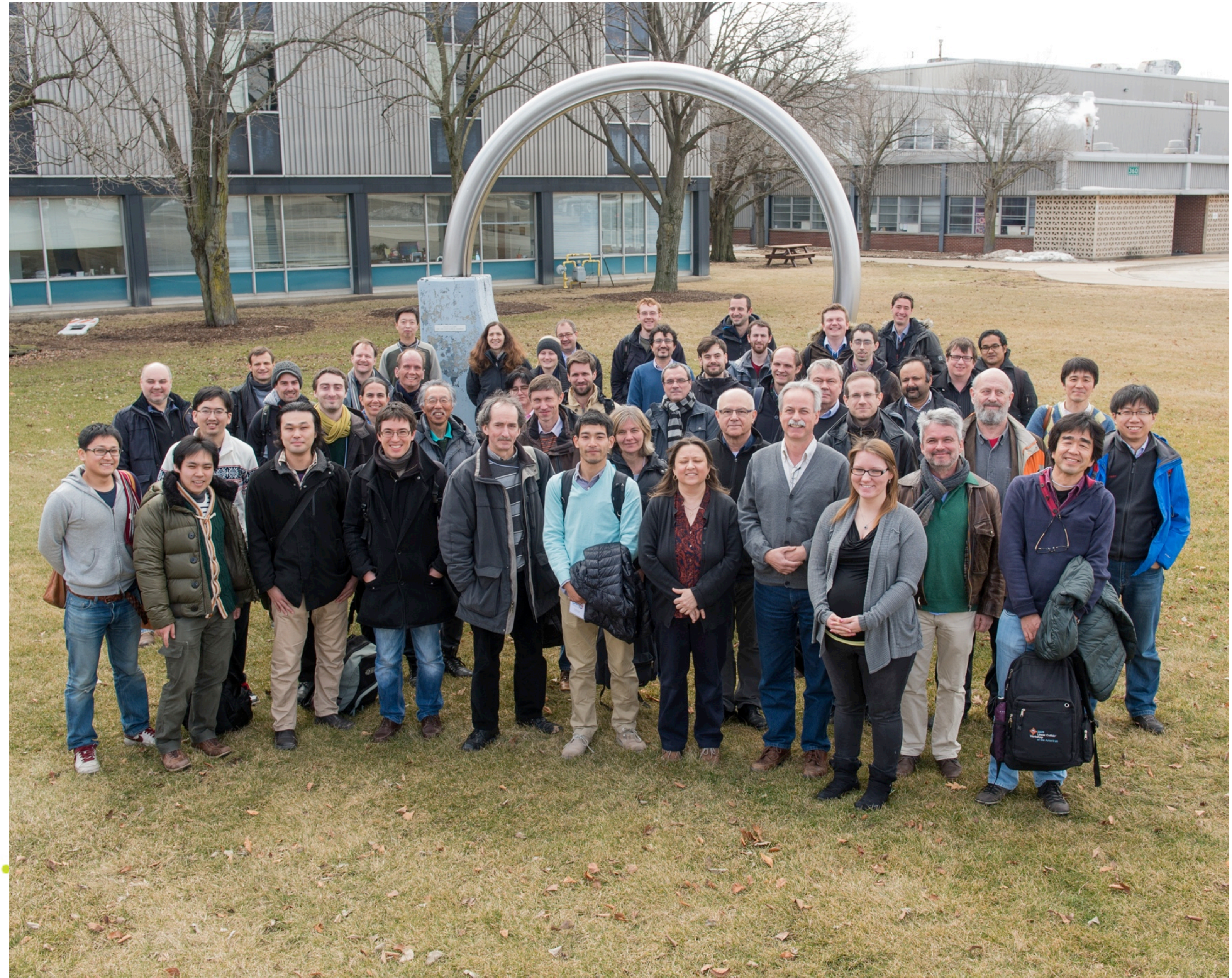
IPP / McGill University

CALICE – McGill

(past 5 years)

	Name	Institute	Position	Year	Months	Funding
1	François Corriveau	McGill	Faculty			
2	Zeyue Niu	Toronto	B.Sc.	2008	4	NSERC USRA
3	Alexandra Thomson	McGill	B.Sc.	2009	4+1	NSERC USRA
4	Dave Touchette	McGill	B.Sc.	2009	4 (½-time)	NSERC USRA
5	Michael Stoebe	Dresden	Diploma	2009	6	private (Germany)
6	Steffen Henkelmann	Göttingen	Diploma	2009	3	DAAD (Germany)
7	Daniel Trojand	McGill	M.Sc.	2009-11	(full-time)	Dept / NSERC Grant
8	Nicolas Tarantino	McGill	B.Sc.	2010	4+1	McGill SURA
9	Marc-Adrien Mandich	McGill	B.Sc.	2010	4 (½-time)	NSERC USRA
10	Juliane Reif	Regensburg	Diploma	2010	3	DAAD (Germany)
11	Madeleine Anthoniesen	McGill	B.Sc.	2010	4	NSERC Grant
12	Justus Zorn	Karlsruhe	B.Sc.	2012	3	DAAD (Germany)
13	Marilyne Thibault	McGill	B.Sc.	2013	4	NSERC USRA
14	Benjamin Freund	McGill	M.Sc.	2013-	(full-time)	NSERC Grant
15	Georg Manten	Heidelberg	B.Sc.	2014	3	DAAD (Germany)

CALICE Collaboration (2014 –ANL)



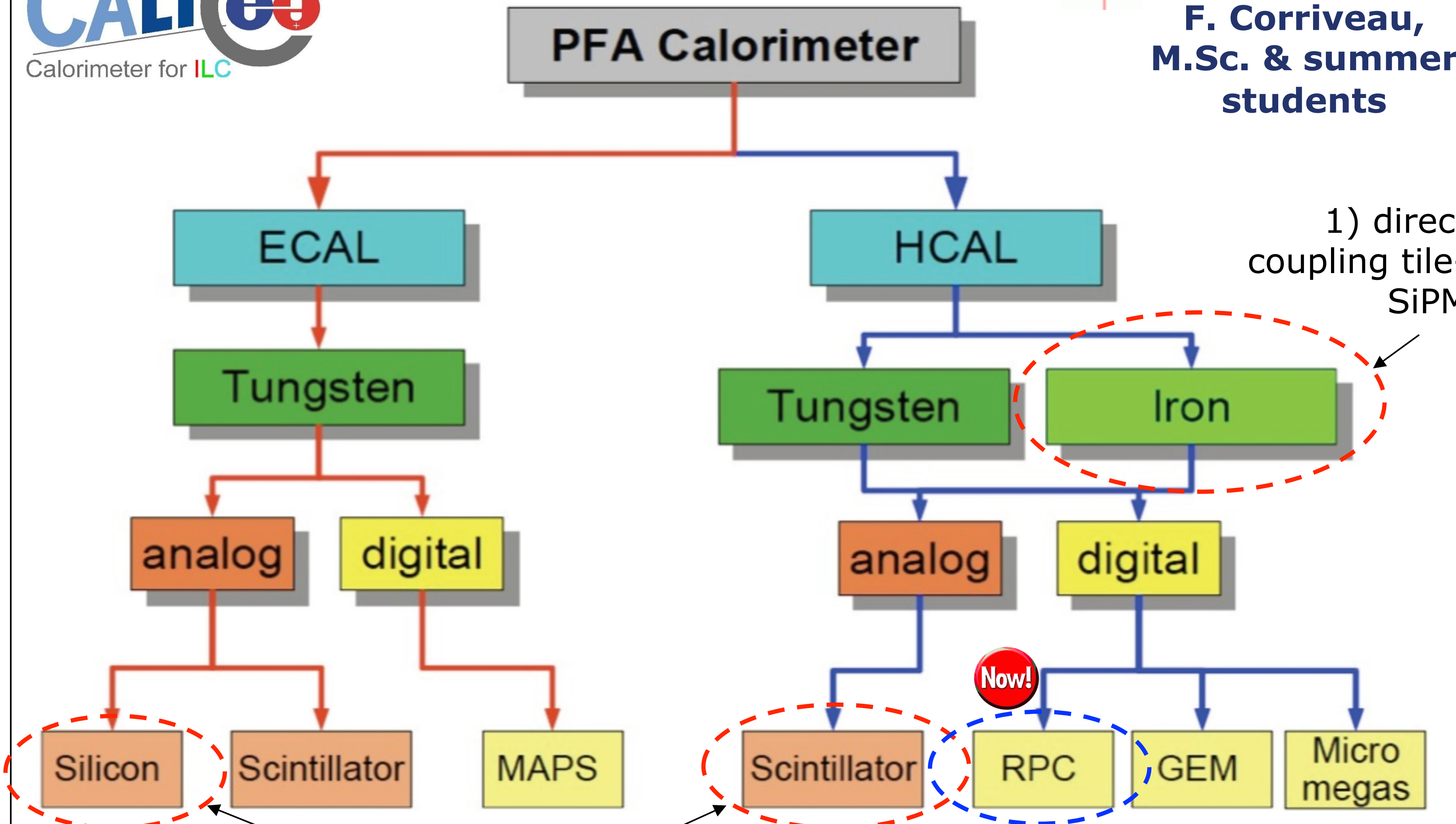
CALICE - Technologies

Calorimeter for ILC

studies based on Particle Flow Algorithms

Canada/McGill

F. Corriveau, M.Sc. & summer students



1) direct coupling tile-SiPM

2) test beam data analysis

3) prototype + test beams

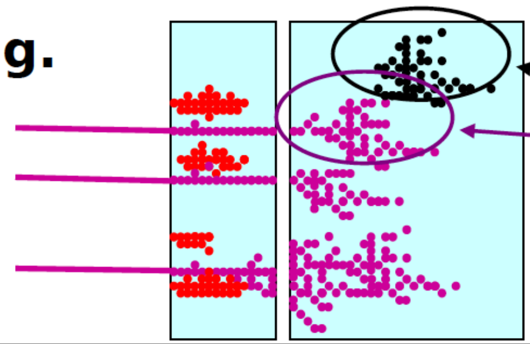
Particle Flow Algorithms (PFAs)

Source: CALICE Review by ECFA (Roman Pöschl)

Reconstruction of a Particle Flow Calorimeter:

- ★ **Avoid double counting of energy from same particle**
- ★ **Separate energy deposits from different particles**

e.g.

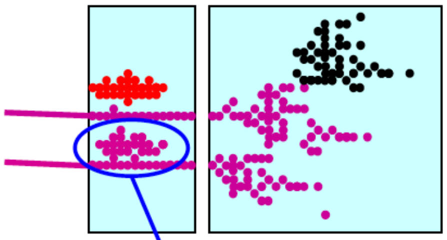


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution not the intrinsic calorimetric performance of ECAL/HCAL

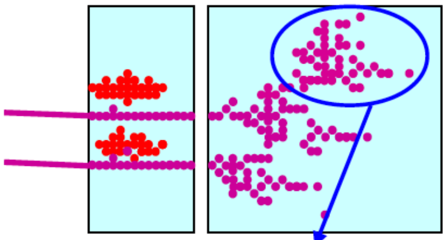
Three types of confusion:

i) Photons



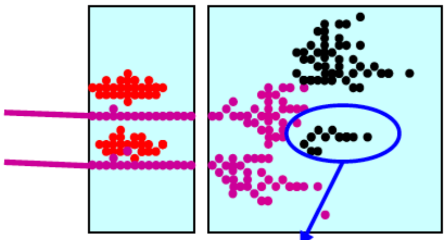
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



Reconstruct fragment as separate neutral hadron

Digital Hadronic Calorimeter

Description of the 1m^3 prototype

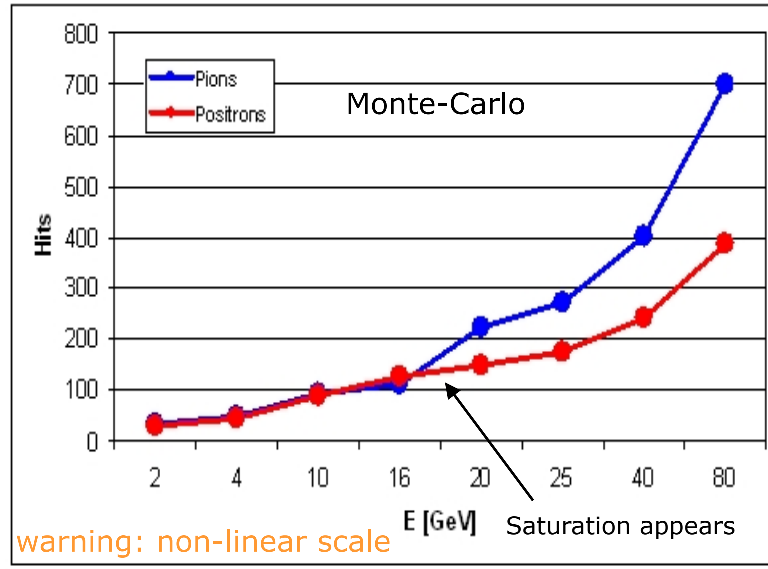
with J. Repond et al., ANL

Readout of 1 x 1 cm^2 pads with one threshold (1-bit) → **First Digital Calorimeter**
52 layers, each layer with 3 RPCs (1.1 mm gap), yielding ~480,000 readout channels

Assembly steps

Spraying of glass plates with resistive paint
Frame cutting and gluing to glass plates
Mounting of HV connections, etc.

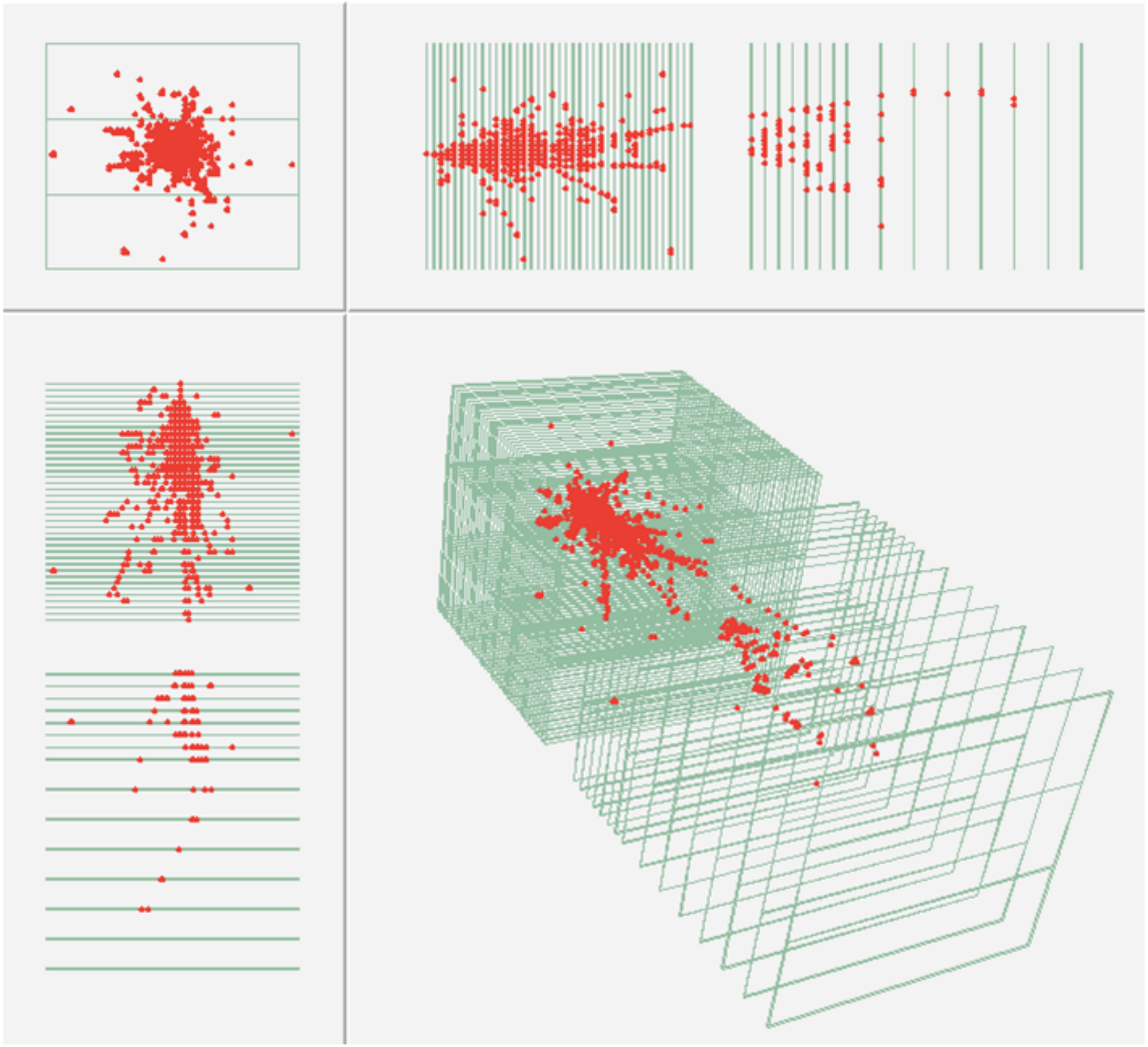
Test Beam Data Taking & Analysis



Linearity can be achieved, several models are available and being tested.

Ongoing analyses at McGill, especially on calibration, with more on energy, angular and position resolutions. Papers.

DHCAL 3D Event Display



Pions

high granularity

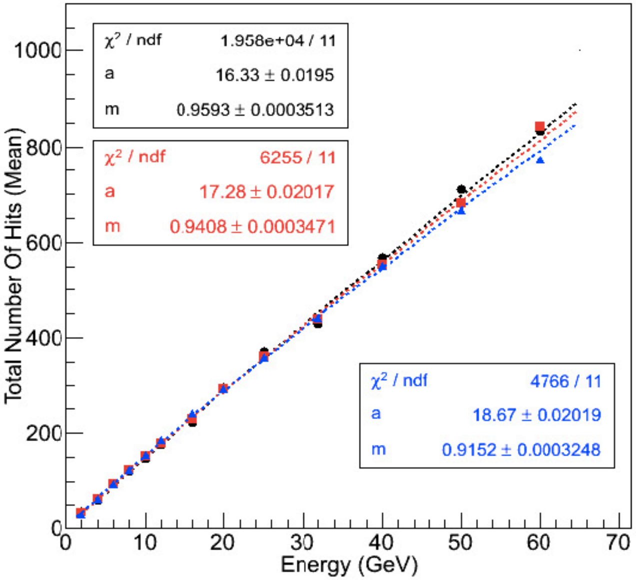
very low noise level

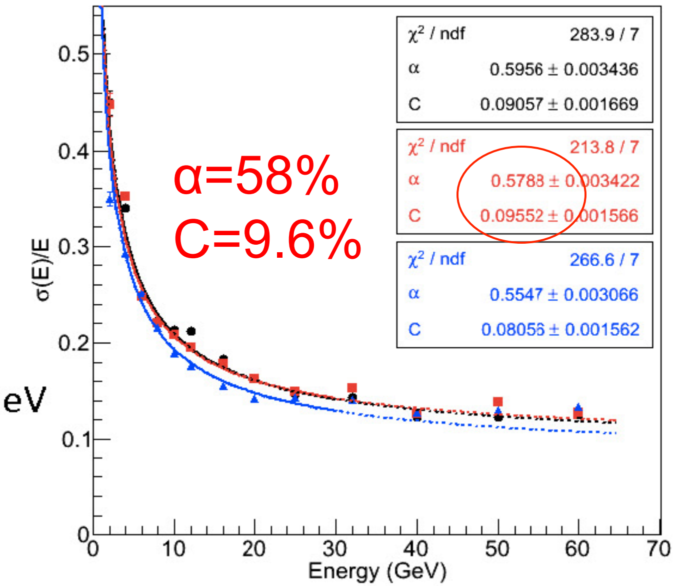
DHCAL Performance Results

Uncalibrated
Full calibration
Density Weighted calibration
MC

Pions

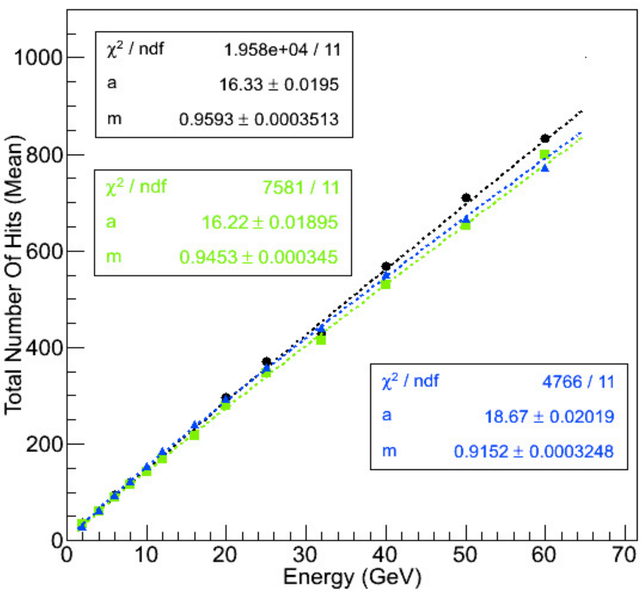
Res. Fit up to 25 GeV

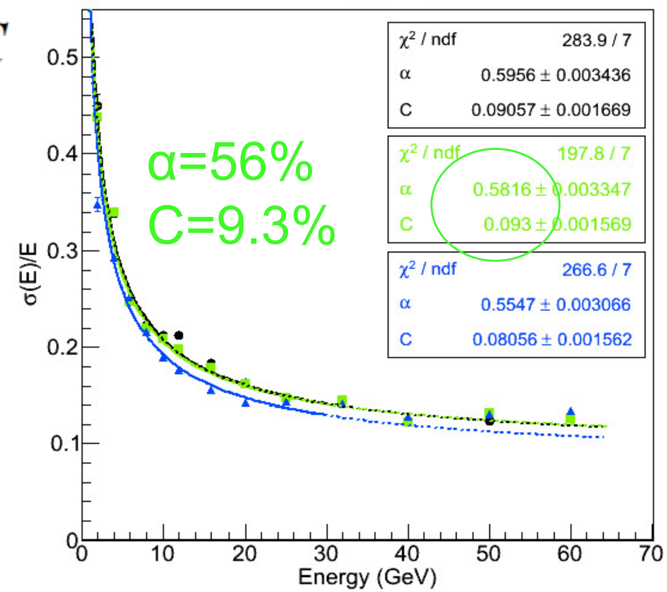




$$\frac{\sigma}{E} = \frac{\alpha}{\sqrt{E}} \oplus C$$

Measurements confirm prediction





ILC – LCTPC Work at Carleton/ UdeM/UVIC

Alain Bellerive

Carleton University

Madhu Dixit

TRIUMF / Carleton University

Jean-Pierre Martin

Université de Montréal

Dean Karlen

University of Victoria

LCTPC – UVIC

(past 5 years)

LCTPC

	Name	Institute	Position	Year	Months	Funding
1	Dean Karlen	UVIC	Faculty			
2	Jason Abernathy	UVIC	B.Sc.	2007, 2008, 2010	4	NSERC USRA
3	Patrick Conley	UVIC	B.Sc.	2009	4	NSERC USRA

LCTPC – Carleton

(past 5 years)

	Name	Institute	Position	Year	Months	Funding
1	Alain Bellerive	Carleton	Faculty			
2	Madhu Dixit	TRIUMF/ Carleton	Faculty			
3	Rashid Mehdiyev	Carleton	RA	2014-	(full time)	
4	Peter Hayman	Carleton	B.Sc.	2010-14	(part time)	ICUREUS and USRA
5	Nicholi Shiell	Carleton	Ph.D.	2012-13	9	
5	Nicholi Shiell	Carleton	M.Sc.	2010-12	(full time)	
6	Terry Buck	Carleton	B.Sc.	2011	4	IPP and NSERC USRA
7	Russel Wood	Carleton	M.Sc.	2008-10	(full time)	
8	Miroslav Vujicic	Carleton	B.Sc.	2009	4	NSERC USRA
9	Nicholi Shiell	Carleton	B.Sc.	2008	4	NSERC USRA
10	Stephen Turnbull	Carleton	B.Sc.	2008	4	NSERC USRA
11	Stephen Weber	Carleton	B.Sc.	2013	4	

Time Projection Chamber (TPC) for ILD

TPC is the central tracker ILD

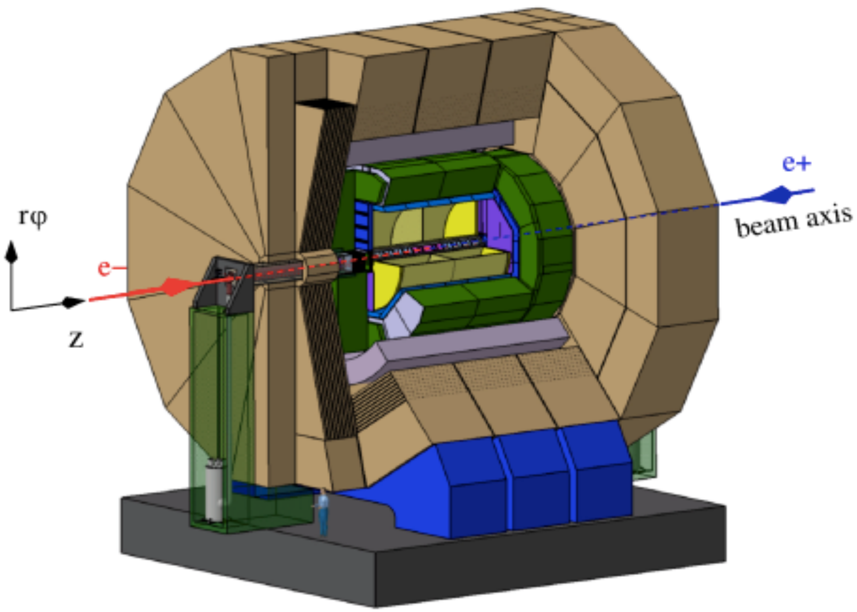
- Large number of 3D hits → continuous tracking
- More 200 positions measurements along each track
- Good track separation and pattern recognition
- Single hit $\sigma(r\phi)$ at z=0 < 60 μm

Low material budget inside the calorimeters (PFA)

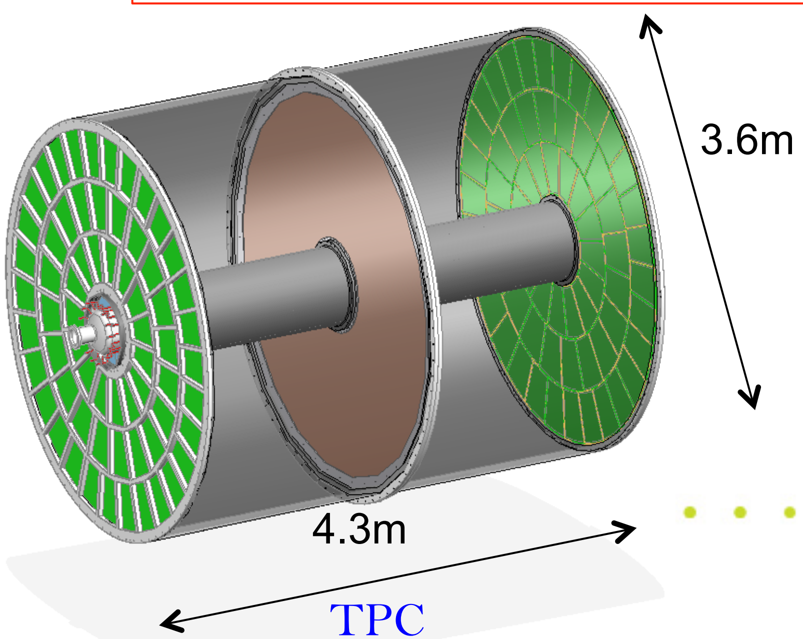
- Barrel: ~5% X_0
- Endplates: ~25% X_0

TPC Requirements:

- **Momentum resolution:**
  $\delta(1/p_T) < 9\times10^{-5}$ GeV^{-1}
- **Single hit resolution 3.5T:**
  $\sigma(r\phi) < 100$ μm
  $\sigma(z) < 500$ μm
- **Tracking eff.** for $p_T > 1$ GeV:
  > 97%
- **dE/dx resolution** ~5%

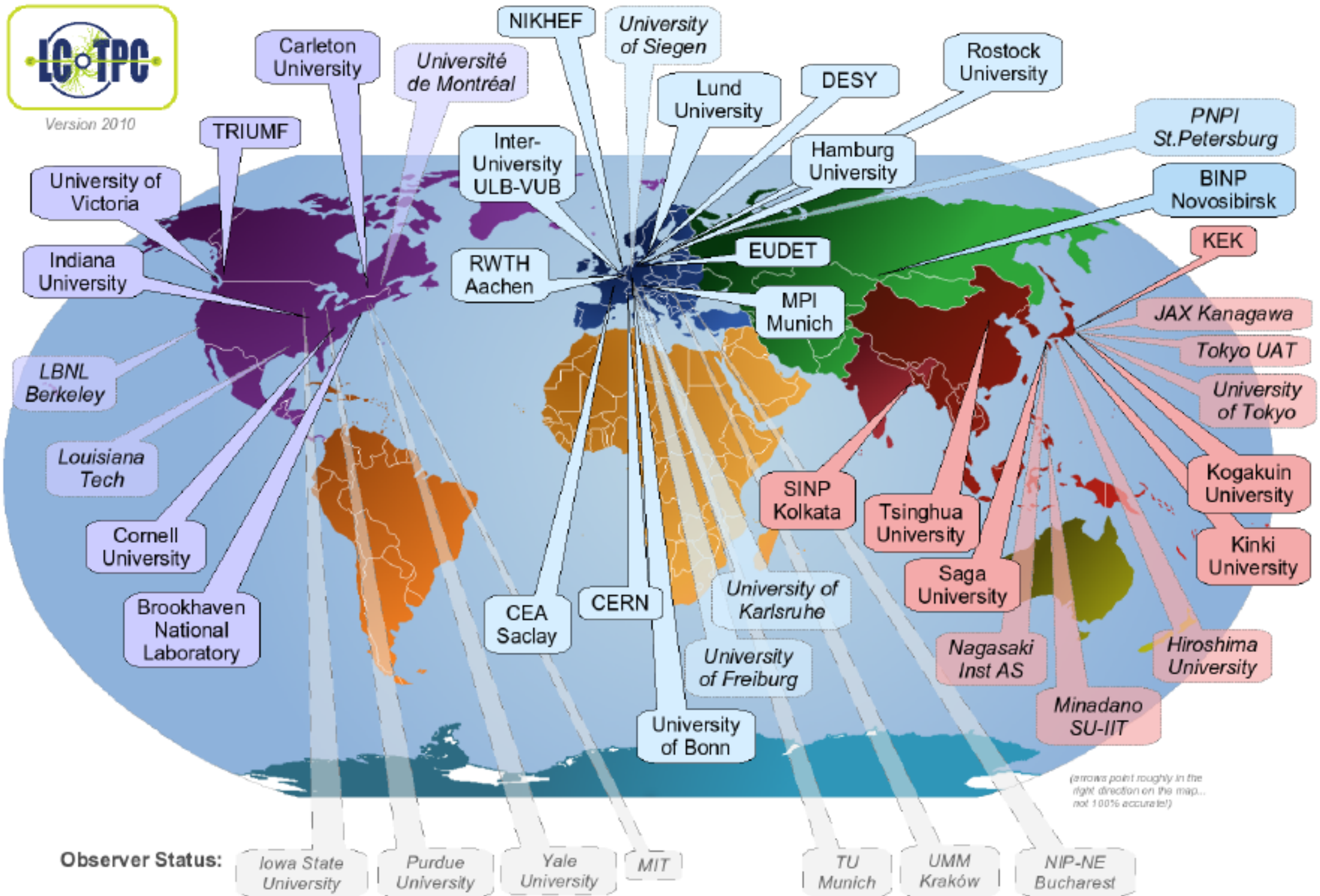


ILD



TPC

LCTPC Collaboration



Total of 12 countries from 38 institutions members + 7 observer institutes

Alain Bellerive: LCTPC North America Coordinator

Conceptual Design of a TPC

A 3D camera, which captures the passage of charged particles.

(1) Ionization: along path of charged particle

(2) Drift & Diffusion: spread as Gaussians in Transverse and Longitudinal planes (statistical)

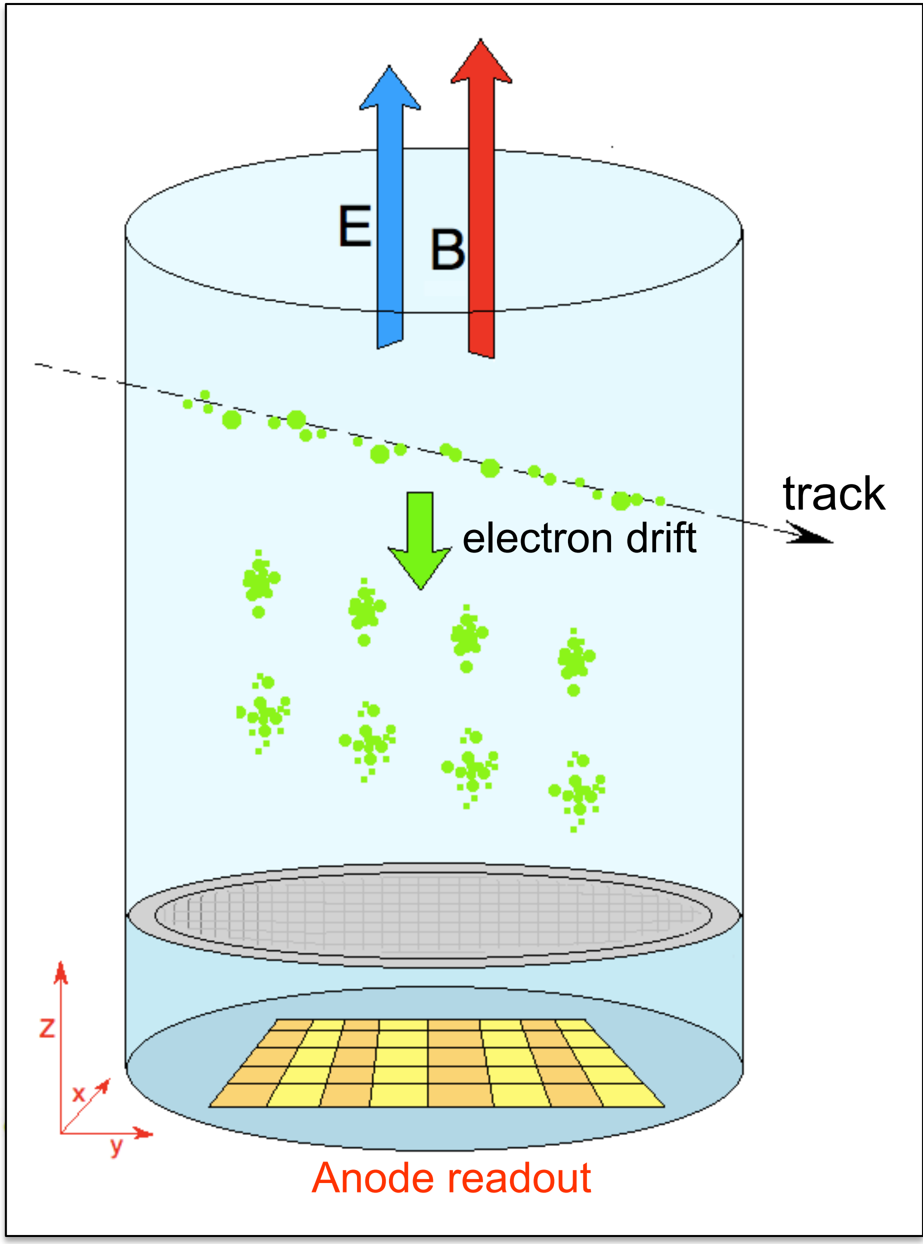
$$\sigma^2 = \sigma_0^2 + D^2 \cdot z$$

$$D = \text{diffusion}\left(\frac{\mu m}{\sqrt{cm}}\right)$$

Transverse diffusion is suppressed by the Magnetic field (Lorentz Force)

(3) Amplification: boost number of electrons

(4) Readout Pads: pads convert to digital record



Micro Pattern Gas Detector (MPGD)

Technology choice for TPC readout: Micro Pattern Gas Detector

- no preference in track direction
- no E×B effect
- fast signal & high gain
- low ion backdrift
- better ageing properties
- easier to manufacture

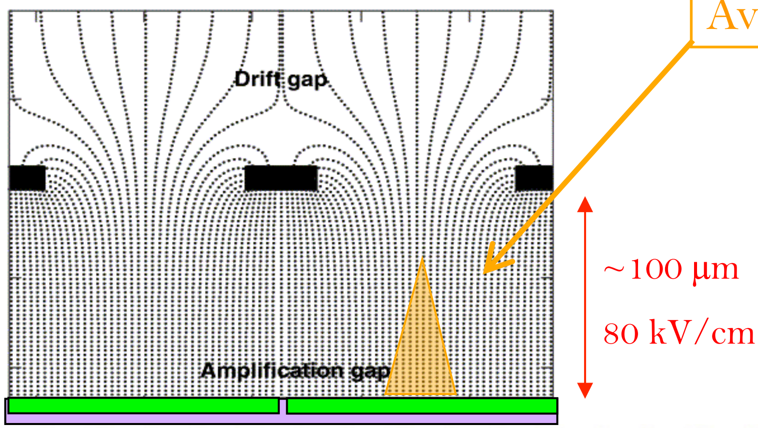
Micromegas (MM)

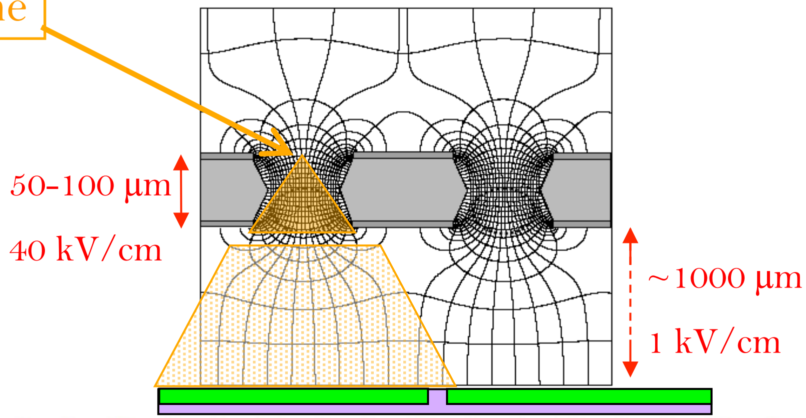
- MICROMEsh GAseous Structure
- metallic micromesh (typical pitch 50μm)
- supported by 50 μm pillars, multiplication between anode and mesh, high gain

GEM

- Gas Electron Multiplier
- 2 copper foils separated by kapton
- multiplication takes place in holes, with 2-3 layers needed

Avalanche

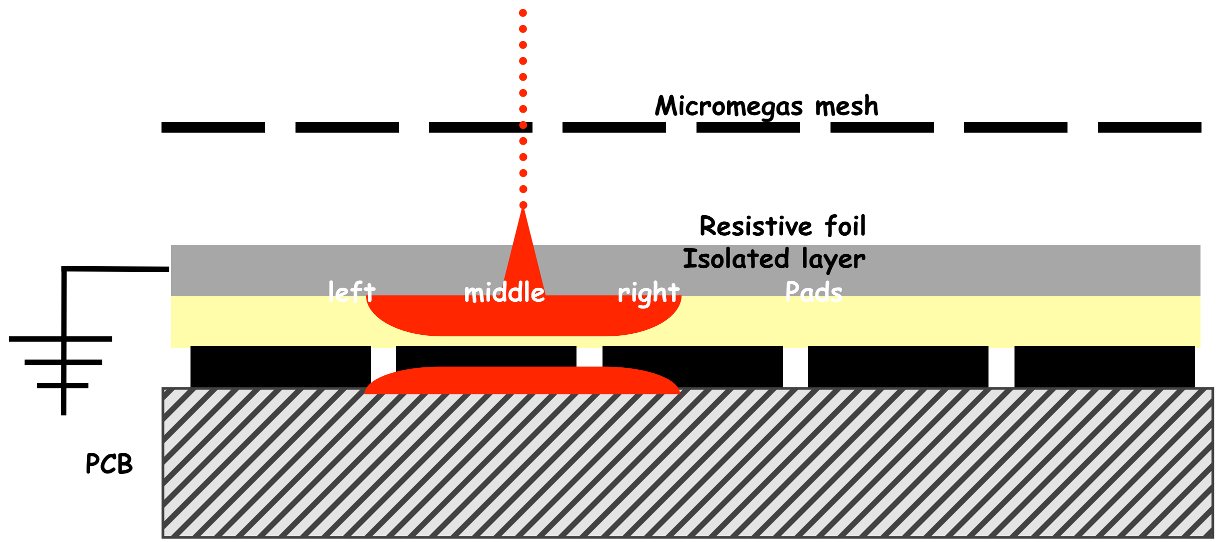




Discharge probability and consequences can be mastered (use of resistive coatings, several step amplification, segmentation) – MPGD more robust mechanically than wires

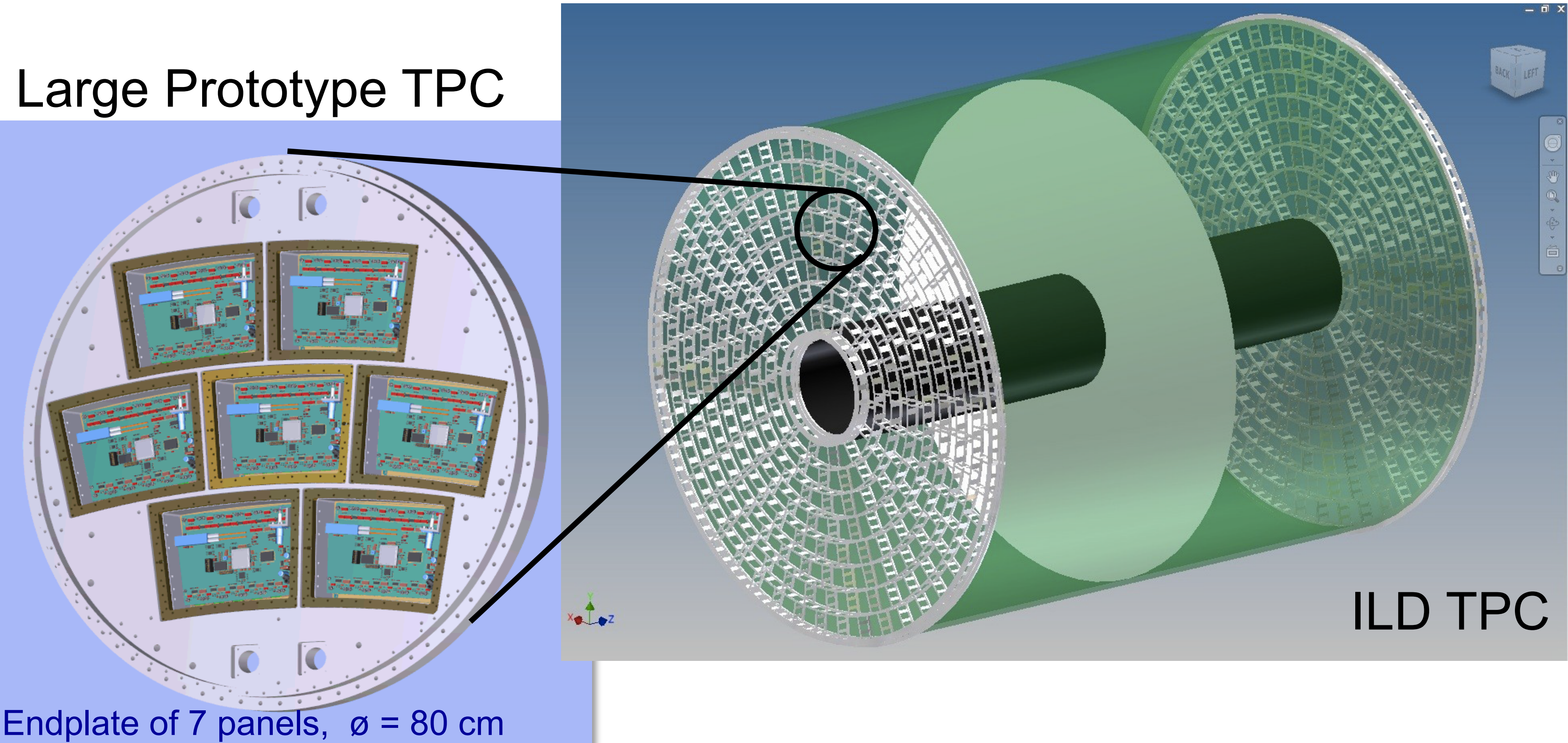
Micromegas (MM) Charge Dispersion

Resistive Anode



Large Prototype at DESY

- Two options for endplate readout with **pads**:
  - **GEM:** 1.2×5.8 mm² pads (smaller pad – more electronics)
  - **Resistive Micromegas:** 3×7 mm² pads (larger pads – less electronics)
- Alternative: **pixel** readout with pixel size ~55×55 μm²

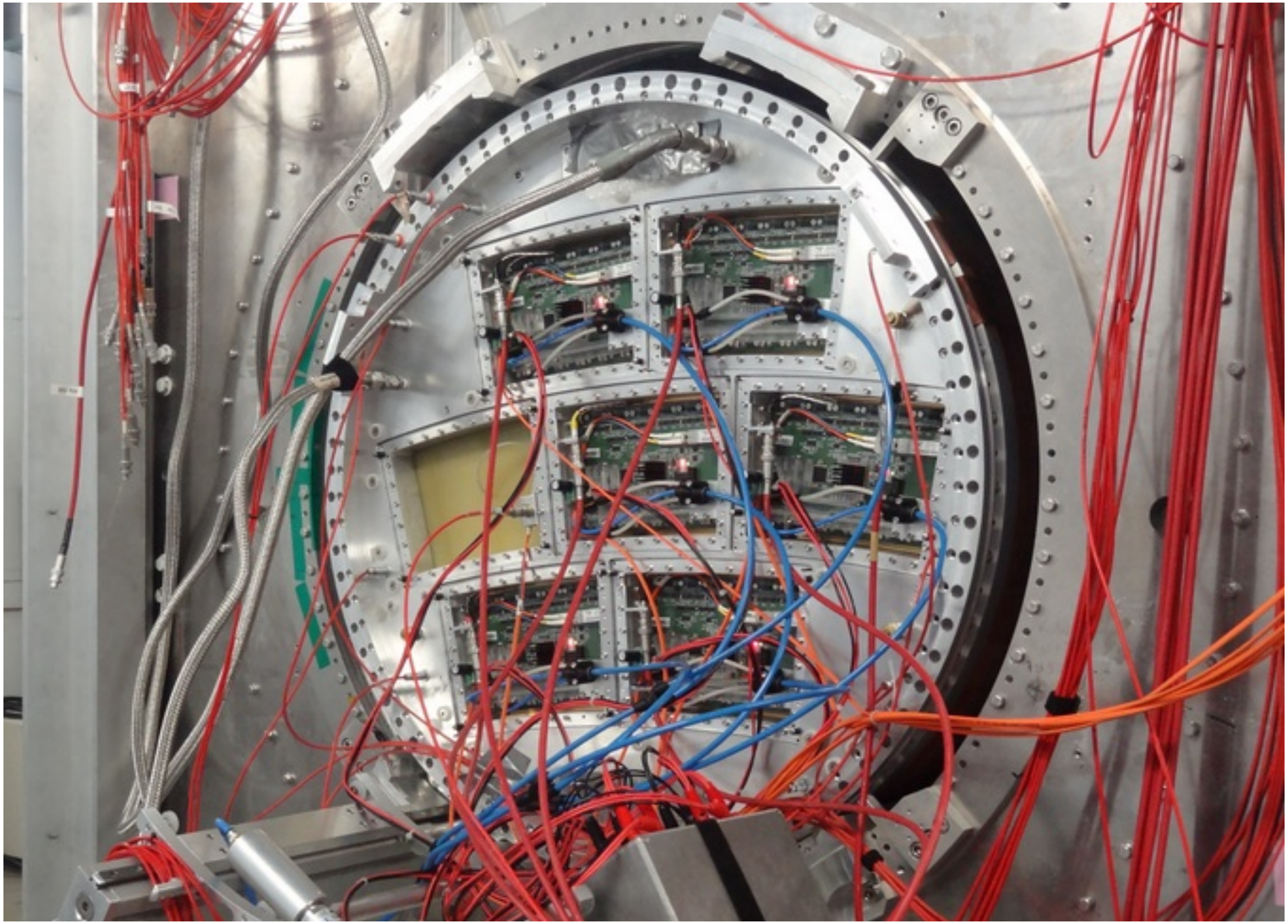


Multi-module LCTPC (MM)

Period
2012-2014

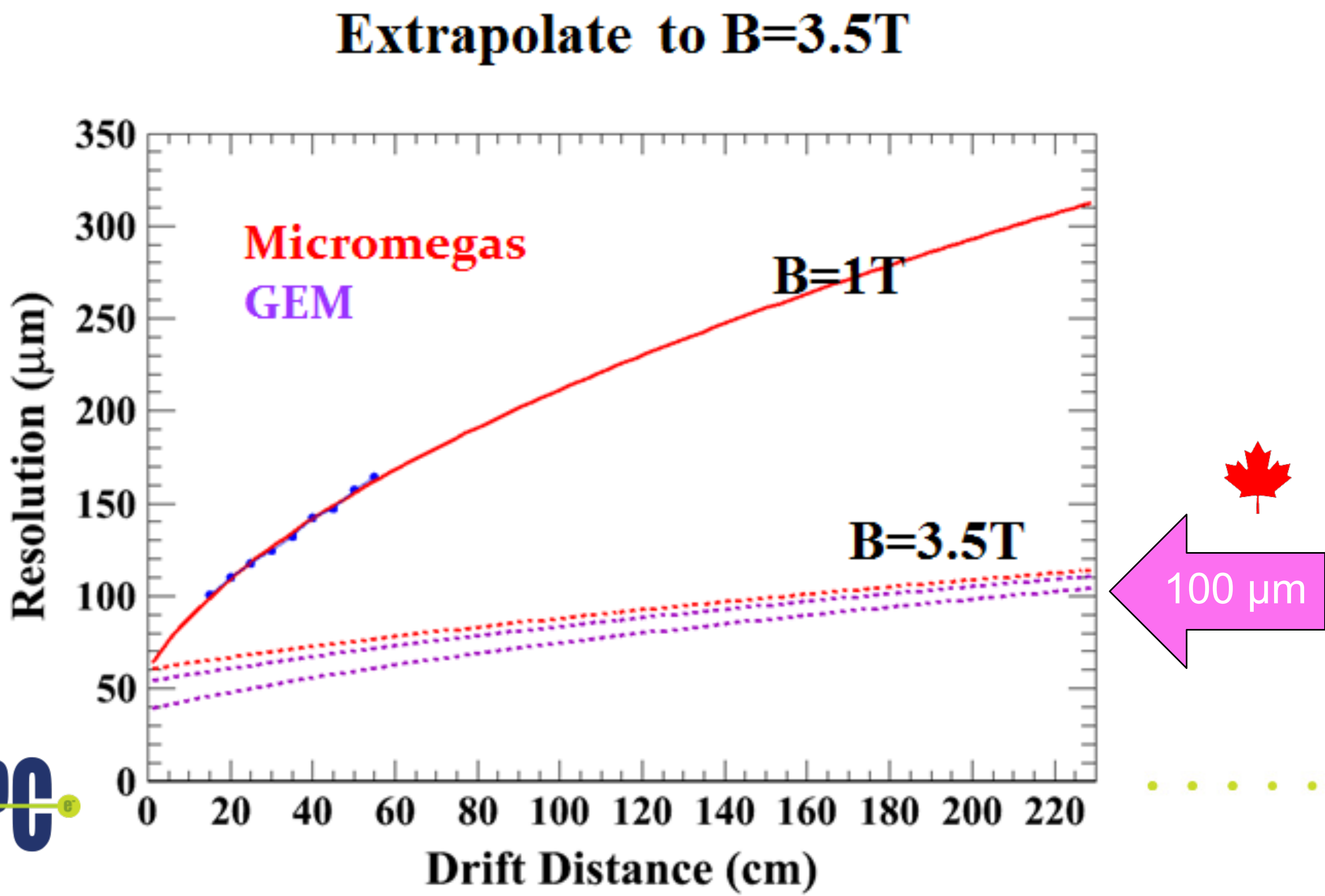
2013 data
6-module

2014 data
7-module
with cooling



Summary: Transverse Resolution

Micromegas (MM) and GEM



Summary

- There is renewed optimism for the ILC going forward - Canada is in a good position to participate on both the accelerator and detectors
- Great training ground for students… but Canada needs to get further engaged in global ILC hardware
- DHCAL concept has been proven by a large DHCAL physics. Test beam at Fermilab and CERN
- Results of CALICE indicate that it will meet resolution goal at ILC
- Further R&D in progress
- A lot of experience has been gained in building and operating MPGD TPC panels with LCTPC collaboration
- The characteristics of the MPGD, such as the uniformity, spatial resolution, stability studied in detail. Steady progress.
- Results of LCTPC indicate that it meet resolution goal at ILC
- On-going progress on time resolution, ion grid, multi-track pattern recognition as well as detailed simulation

More Physics Justification

There are two ways that we can make progress in understanding the origin of quark and lepton masses:

1. Discover new particles that extend the Standard Model.

We hoped these would appear in the first stage of the LHC. Now, apparently, we must wait for 2016 or later.

2. Study the new particle at 125 GeV that we have discovered.

This particle is likely to be the origin of mass. It could well be a gateway to new physics.

The Standard Model predicts that the Higgs boson couplings to each species are exactly proportional to the mass of that species. We need to test this prediction until it breaks.

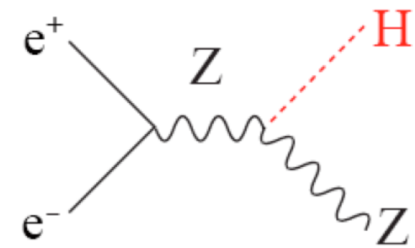
Source: ILC PAC Review (M.E. Peskin)

More Physics Justification

In particular, we need a comprehensive program that can test each individual coupling of the Higgs boson to the percent level.

The ILC is the only machine proposed today that can do this.

At 250 GeV, study $e^+e^- \to Zh$



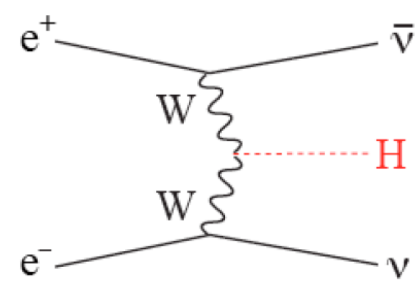
tagged Higgs production, branching ratios

At 500 GeV, add $e^+e^- \to \nu\bar{\nu}h$, $e^+e^- \to t\bar{t}h$, $e^+e^- \to Zhh$

absolute normalization of couplings, begin t and h couplings

At 1000 GeV, add $e^+e^- \to \nu\bar{\nu}hh$, $e^+e^- \to \nu\bar{\nu}\mu^+\mu^-$

high statistics, refined t, h, μ couplings



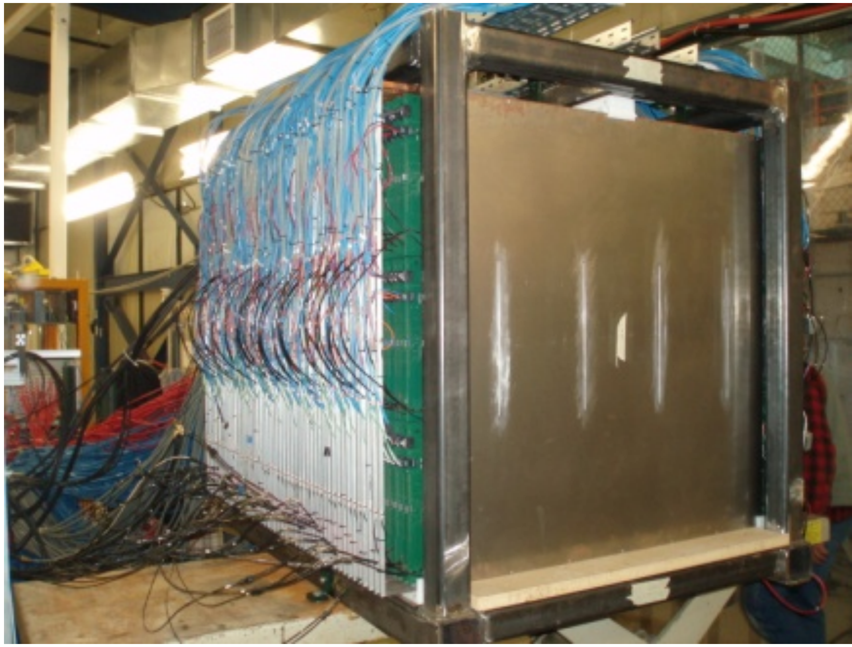
All of the steps are needed for a full program.

Source: ILC PAC Review (M.E. Peskin)

$1\ m^3$ – DHCAL Physics Prototype

Description

Readout of 1 x 1 cm^2 pads with one threshold (1-bit) → **Digital Calorimeter**
38 layers in DHCAL and 14 in Tail Catcher, each ~ 1 x 1 m^2
Absorber: 16mm Fe + (2mm Fe + 2mm Cu [cassette]) or 10mm W + (2mm Fe + 2mm Cu [cassette]), thicker Fe plates in Tail Catcher
Each layer with 3 RPCs, each 32 x 96 cm^2
~500,000 readout channels



Purpose

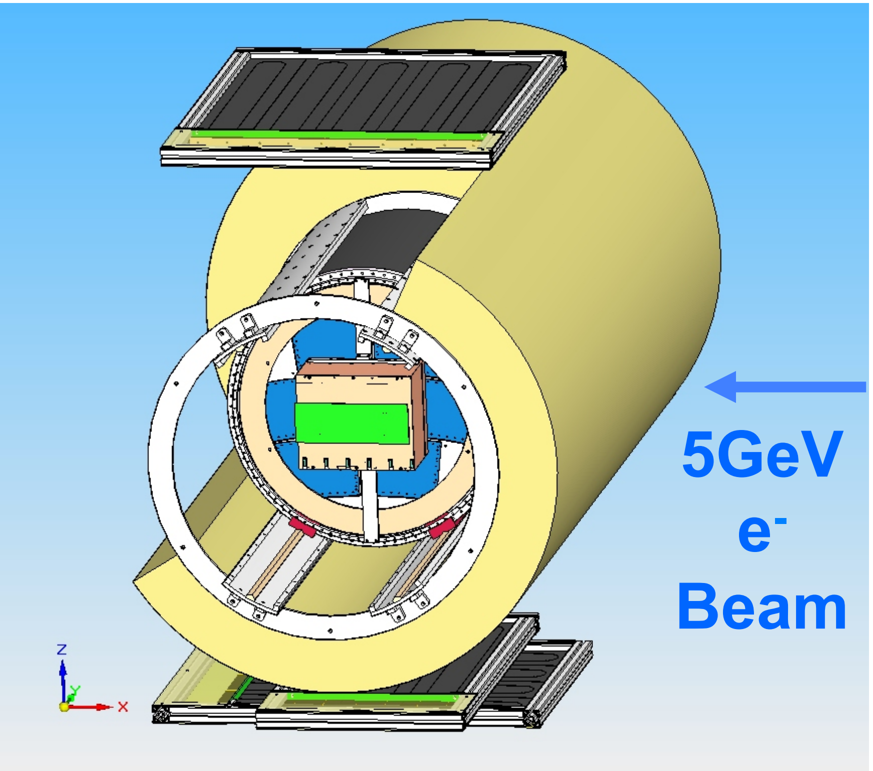
Validate DHCAL concept
Gain experience running large RPC systems
Measure hadronic showers in great detail
Validate hadronic shower models (Geant4)

Status

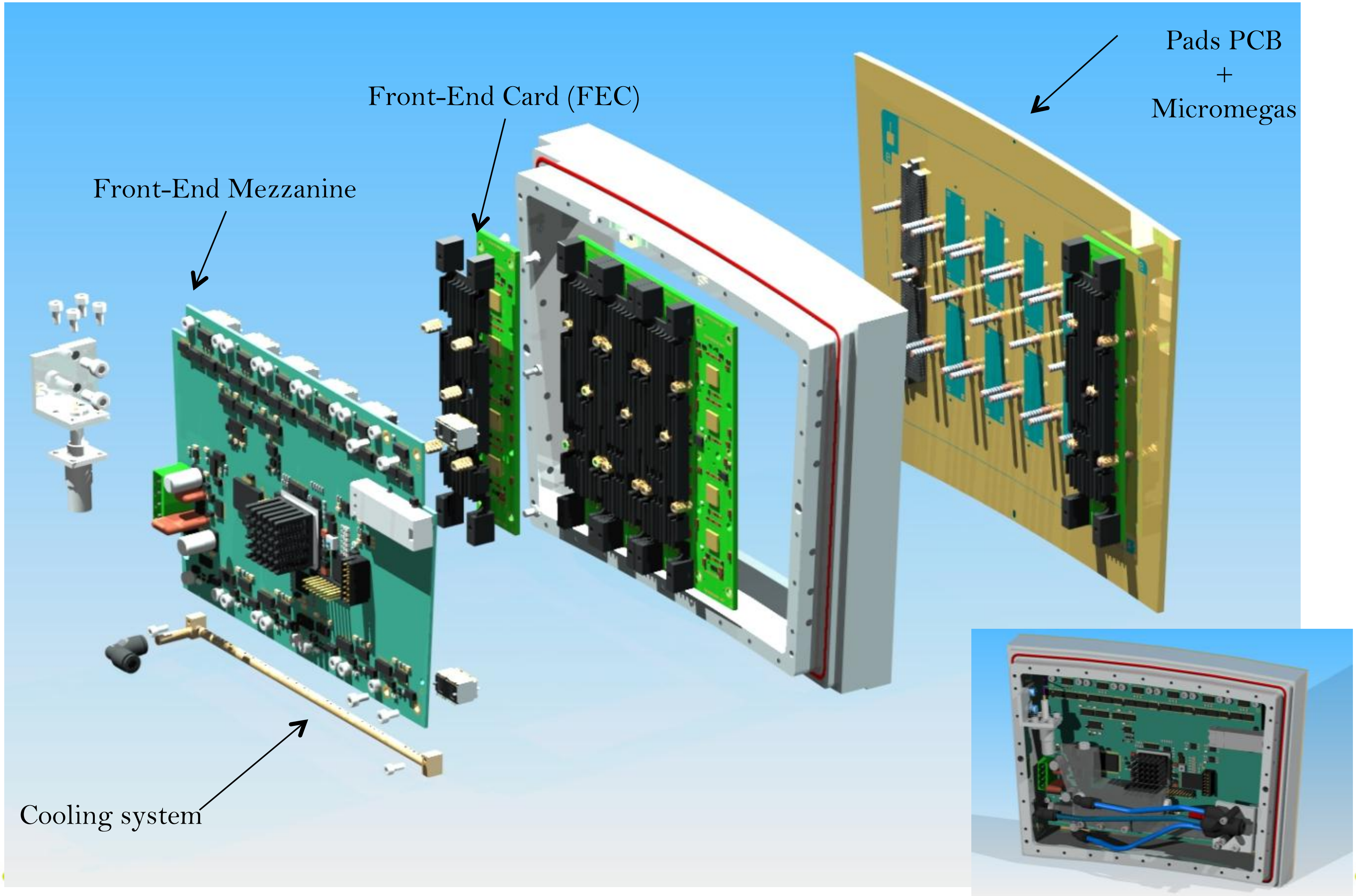
Started construction in 2008
Completed in January 2011
Test beam runs with Fe absorbers started in Oct. 2010 at Fermilab
Finished Fermilab test beam by the end of 2011
Test beam runs with W absorbers at CERN in 2012

Large Prototype at DESY

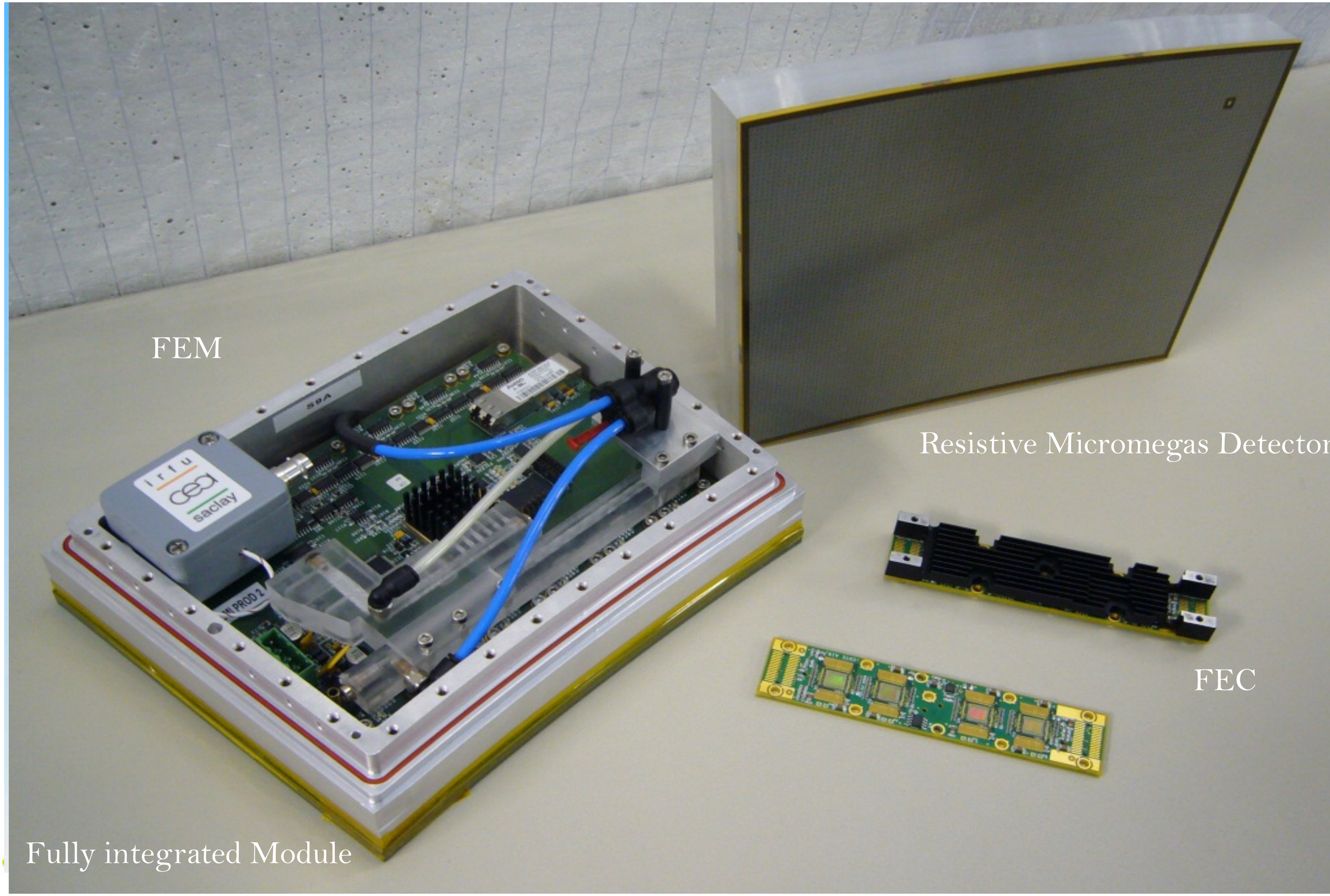
- Two options for endplate readout with **pads**:
  - **GEM:** 1.2×5.8 mm² pads (smaller pad – more electronics)
  - **Resistive Micromegas:** 3×7 mm² pads (larger pads – less electronics)
- Alternative: **pixel** readout with pixel size ~55×55 μm²



Resistive MM: Module Design

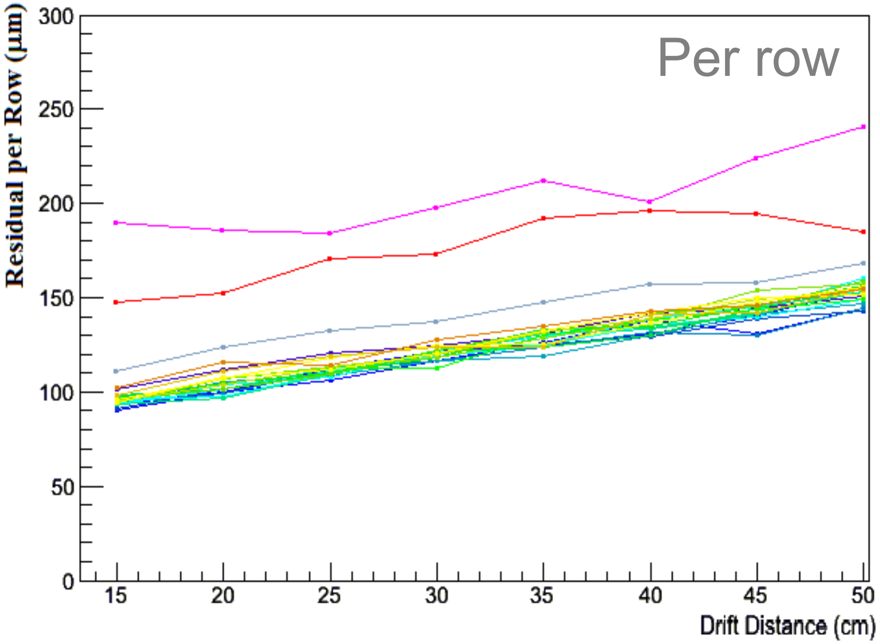


Resistive MM: Module Design

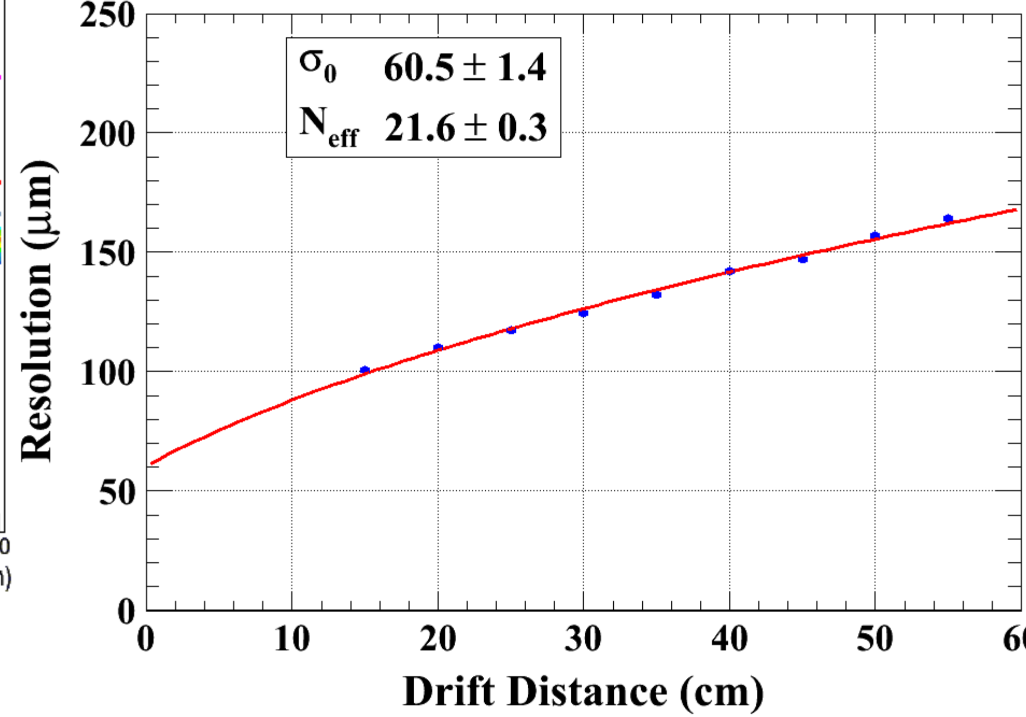


Transverse Resolution MM

2013 data6-modules
Middle module shown here



B=1 T C_d = 94.2 µm/√cm (Magboltz)



$$\sigma = \sqrt{\sigma_0{}^2 + \frac{C_d^2 \cdot z}{N_{eff}}}$$

σ_0 : the resolution at Z=0
N_{eff} : the effective number of electrons

Simple Z fit vs. Kalman Filter

Longitudinal (Z) Resolution vs Drift (Z)