The International Linear Collider
A Precision Probe for Physics at the TeV Scale – Detector R&D

Carleton University · McGill · TRIUMF · University of Victoria

LC TPC · CALICE – Calorimeter for ILC

A. Bellerive – IPP June 14-15, 2015

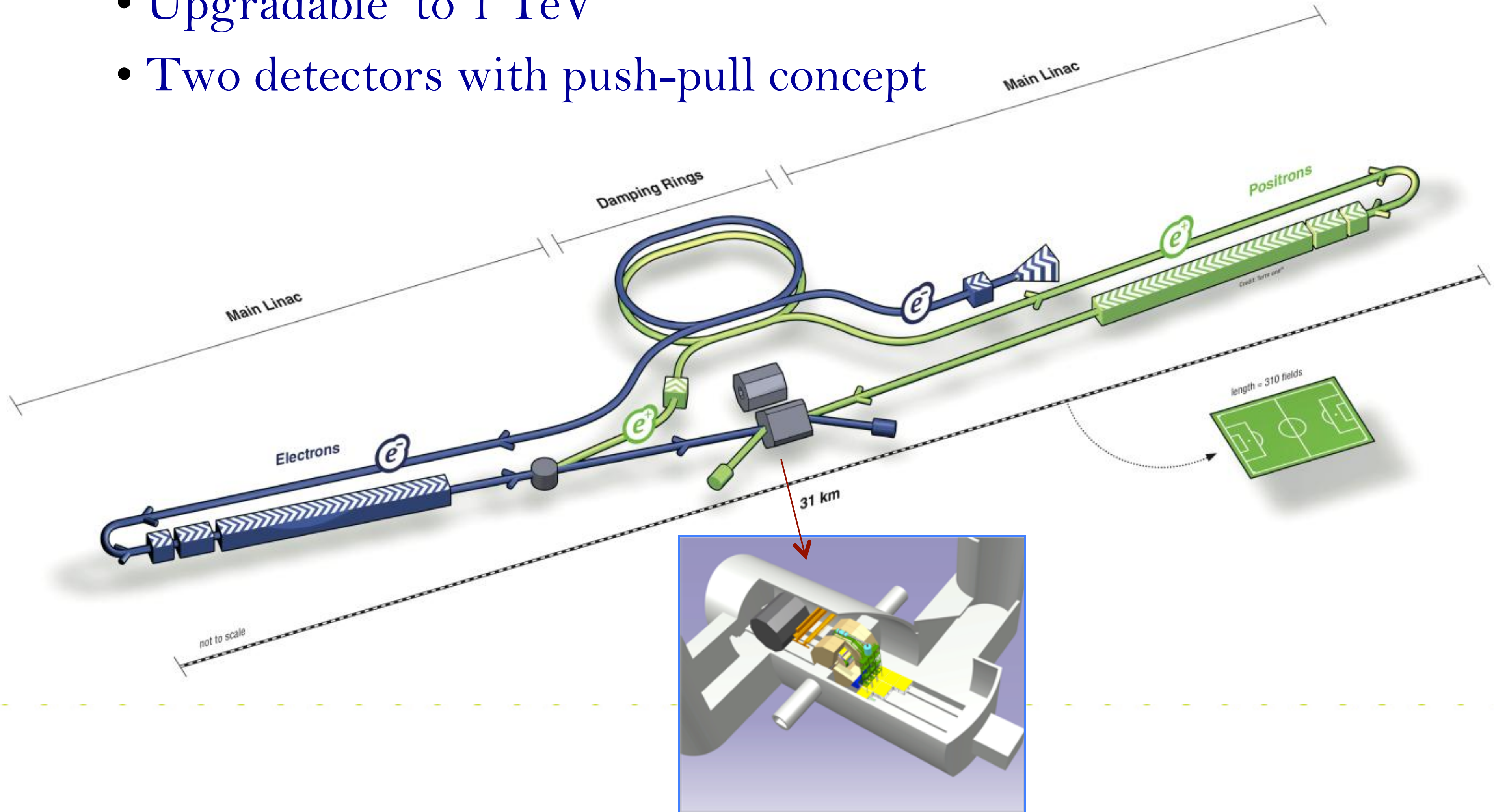
ALCW 2015 - Tokyo

Outline

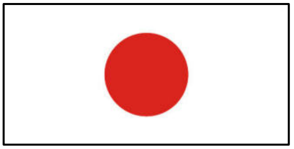
- Intro: **Physics Case at International Linear Collider (ILC)**
- ILC Technical Design Report
- International Linear Detector (ILD)
  - **Concept and Specifications**
- Calorimetry (CALICE) for the ILC
  - **Hadronic Calorimeter (HCAL)**
  - **Particle Flow Algorithms (PFAs)**
- Large Prototype TPC (LCTPC) for the ILC
  - **TPC Requirements**
  - **Micro Pattern Gas Detector (MPGD)**
- Summary: **LRP and R&D**

International Linear Collider

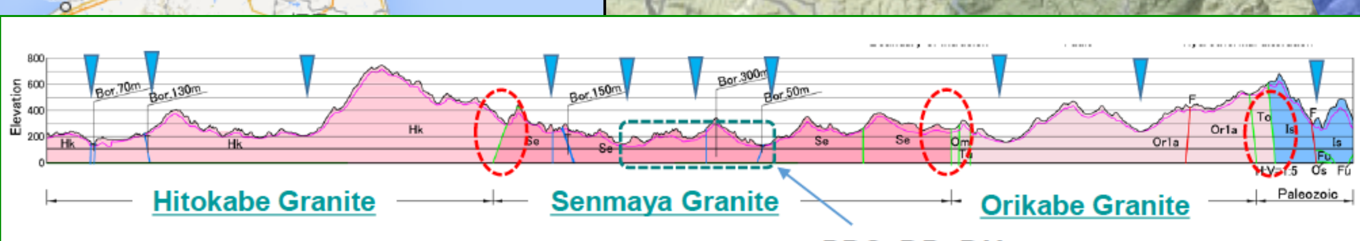
- Next collider: linear e^+e^- collider with length: ~ 31km
- Tunable center of mass energy of 200-500 GeV
- Upgradable to 1 TeV
- Two detectors with push-pull concept



ILC Candidate Location: Kitakami Area



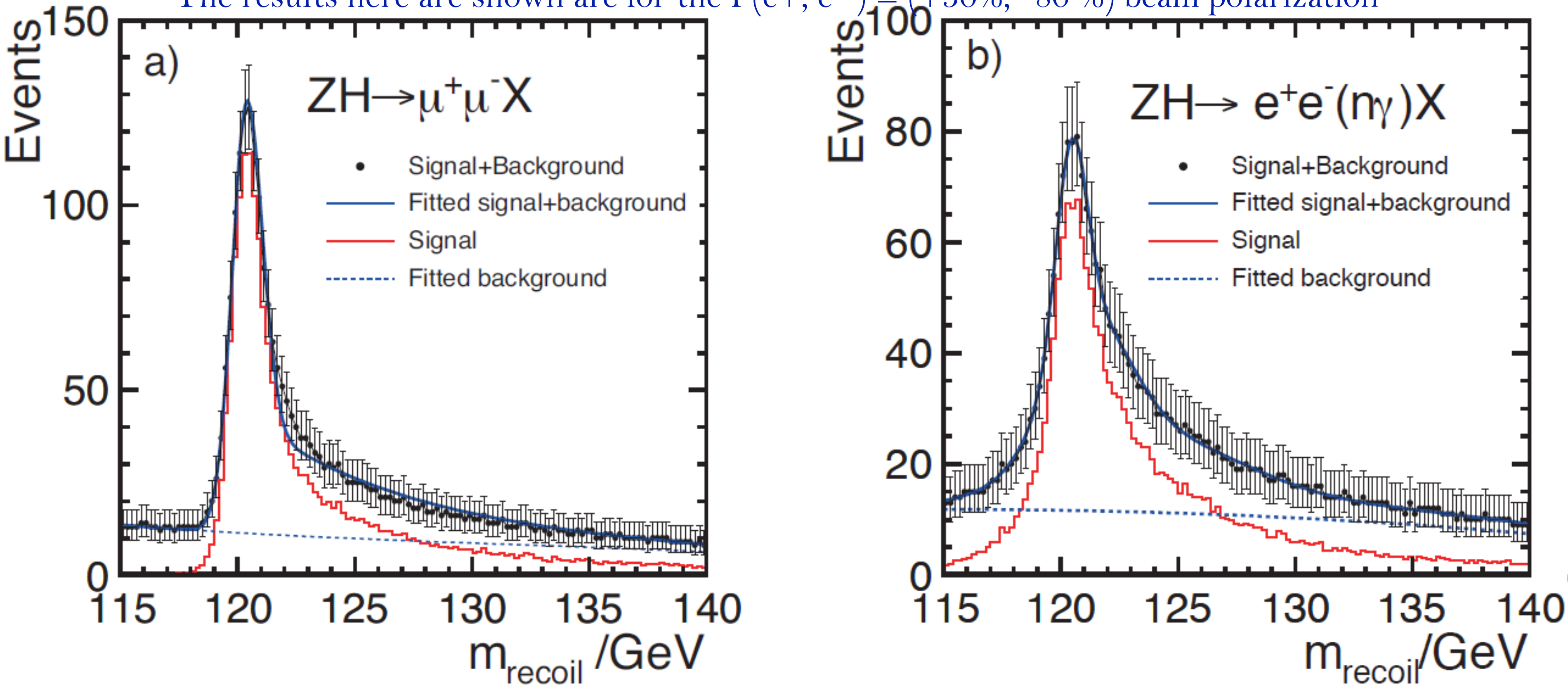
Japan



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: $e^+e^- \rightarrow ZH\ (Z\rightarrow \mu^+\mu^-/e^+e^-) + X$**

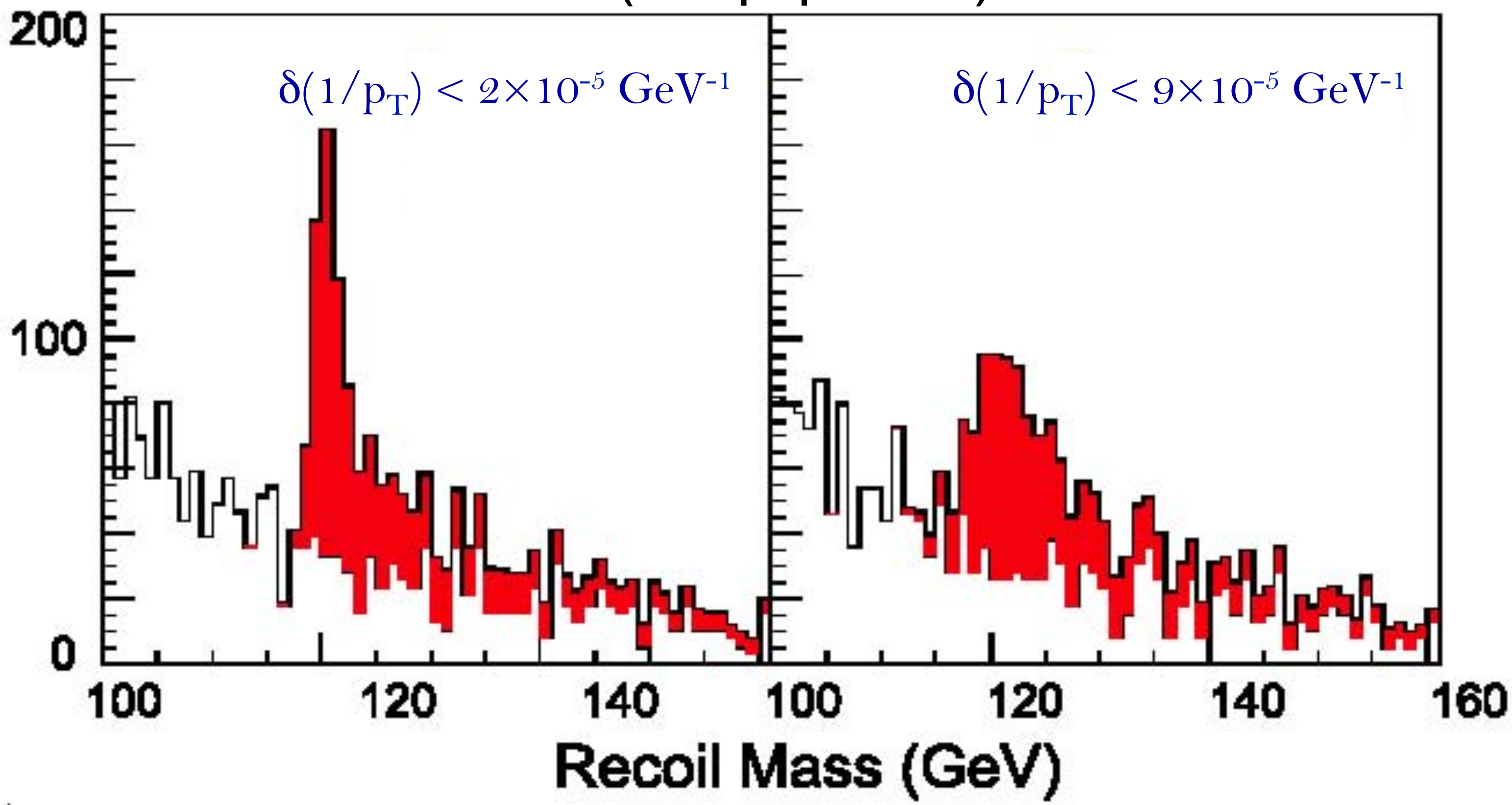
The results here are shown are for the P(e+, e−) = (+30%,−80 %) beam polarization



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

ZH ($Z \to \mu^+\mu^-/e^+e^-$)

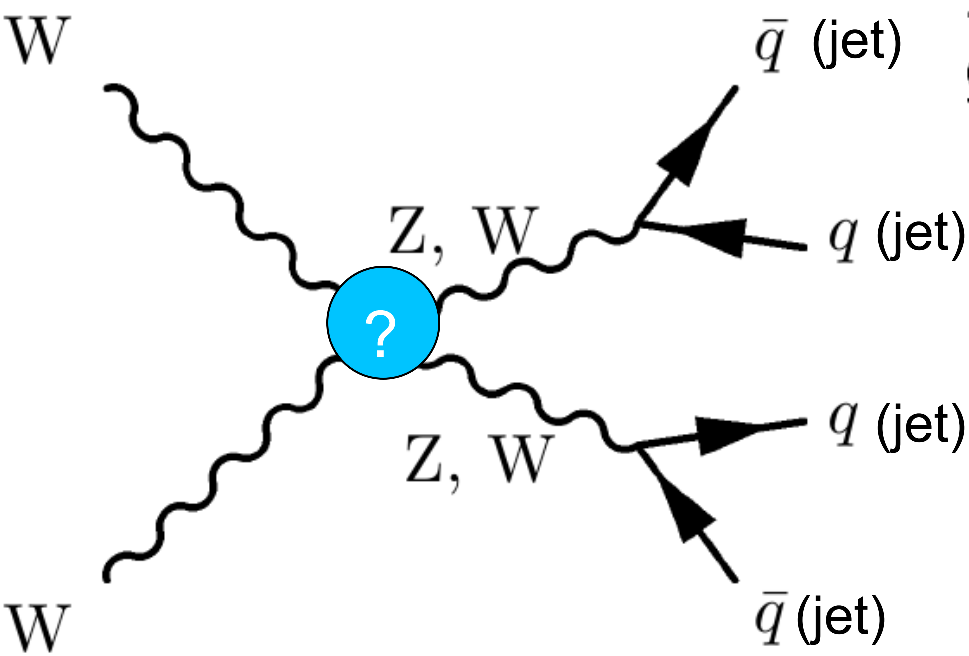


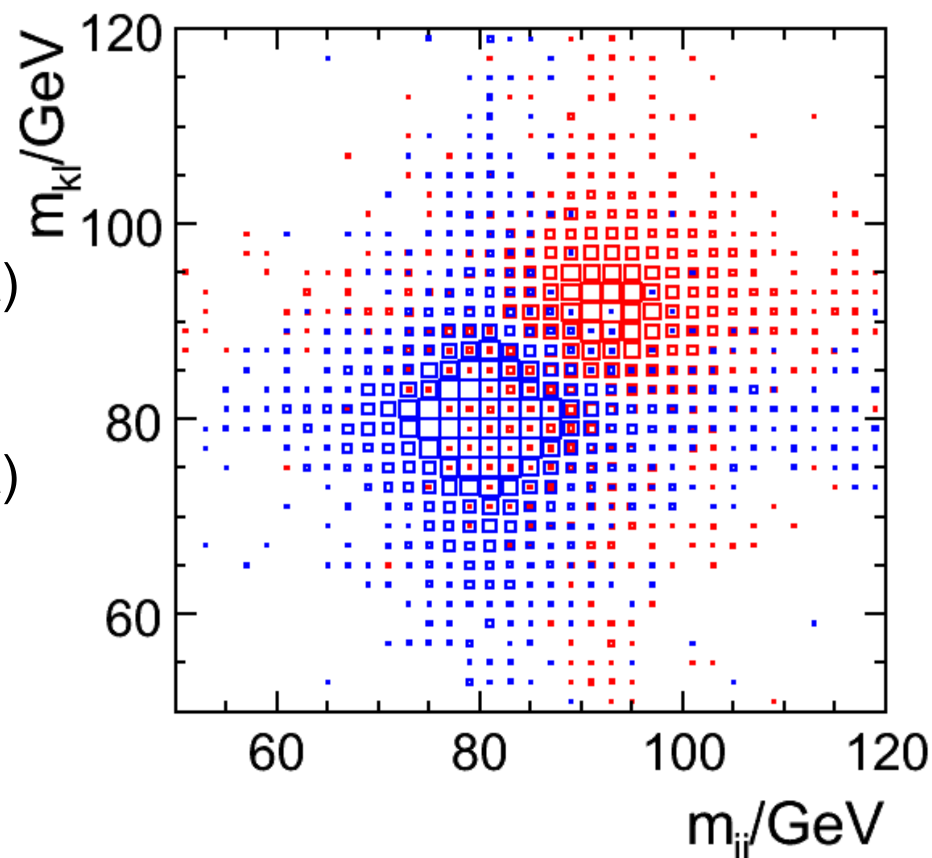
Cartoon demonstration of the $\mu^+ \mu^-$ recoil mass at $\sqrt{s}$ = 500 GeV.
M_H = 120 GeV, for two values of the ILD tracker resolution.

Hadronic decays of W and Z bosons

Need excellent relative jet energy 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



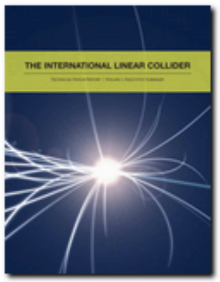


Technical Design Report (TDR)

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

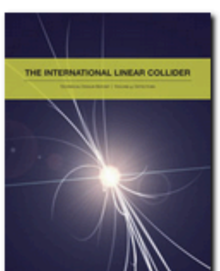
Download the pdf (91 MB)

Volume 3 - Accelerator

Part II:
Baseline Design

Download the pdf (72 MB)

Volume 4 - Detectors

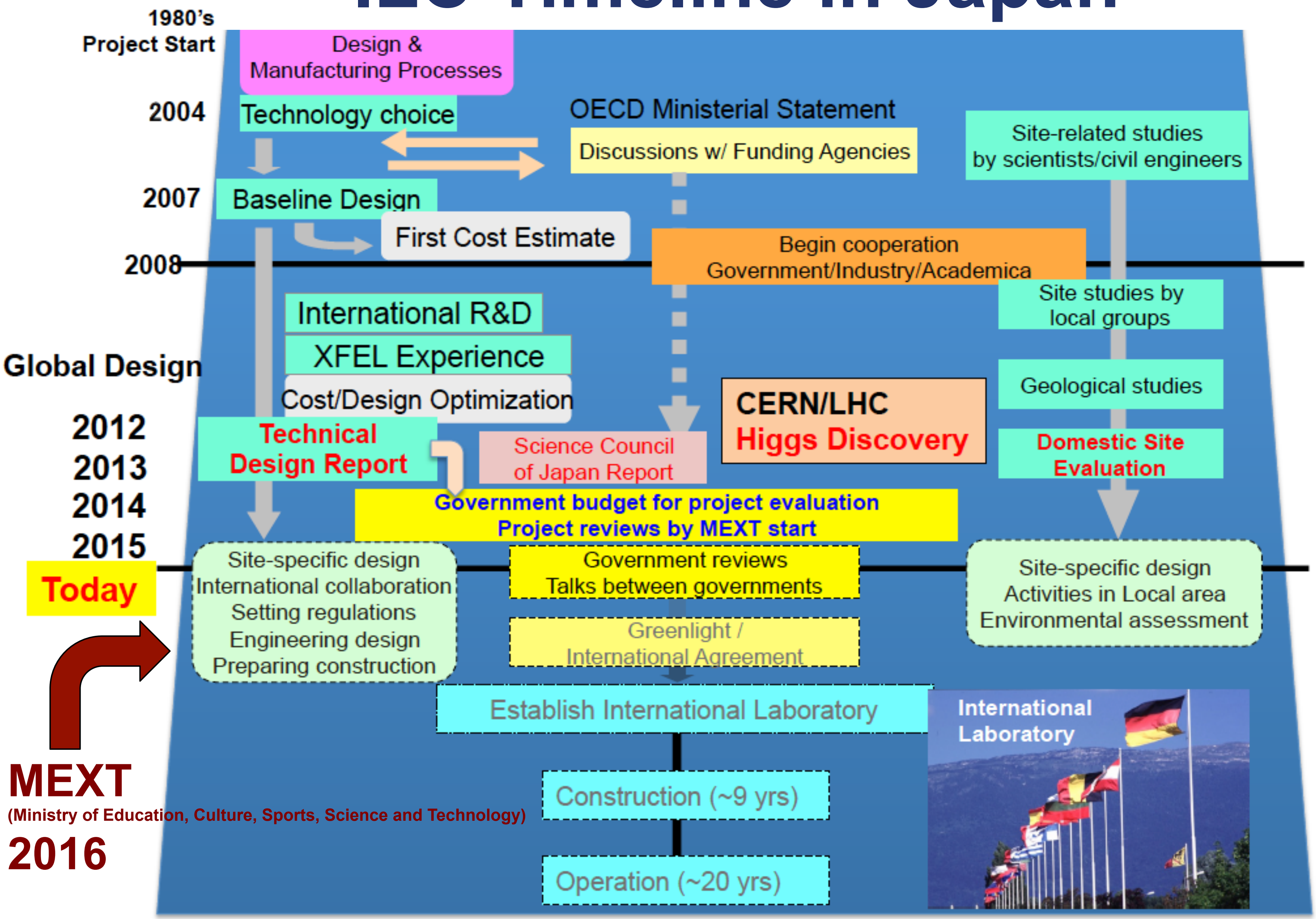


Download the pdf (66 MB)

From Design to Reality

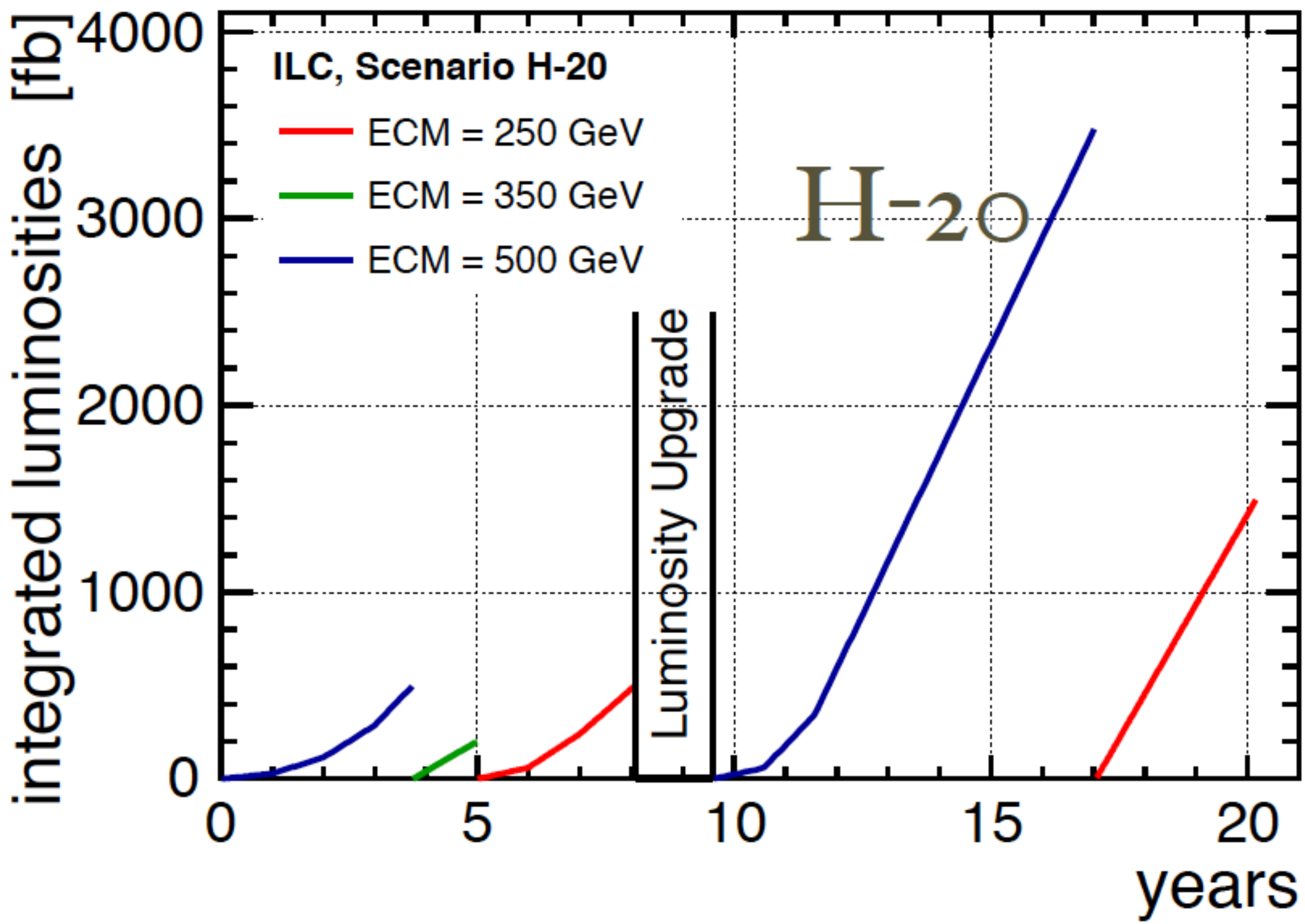
Download the pdf (5.5 MB)
Visit the web site

ILC Timeline in Japan

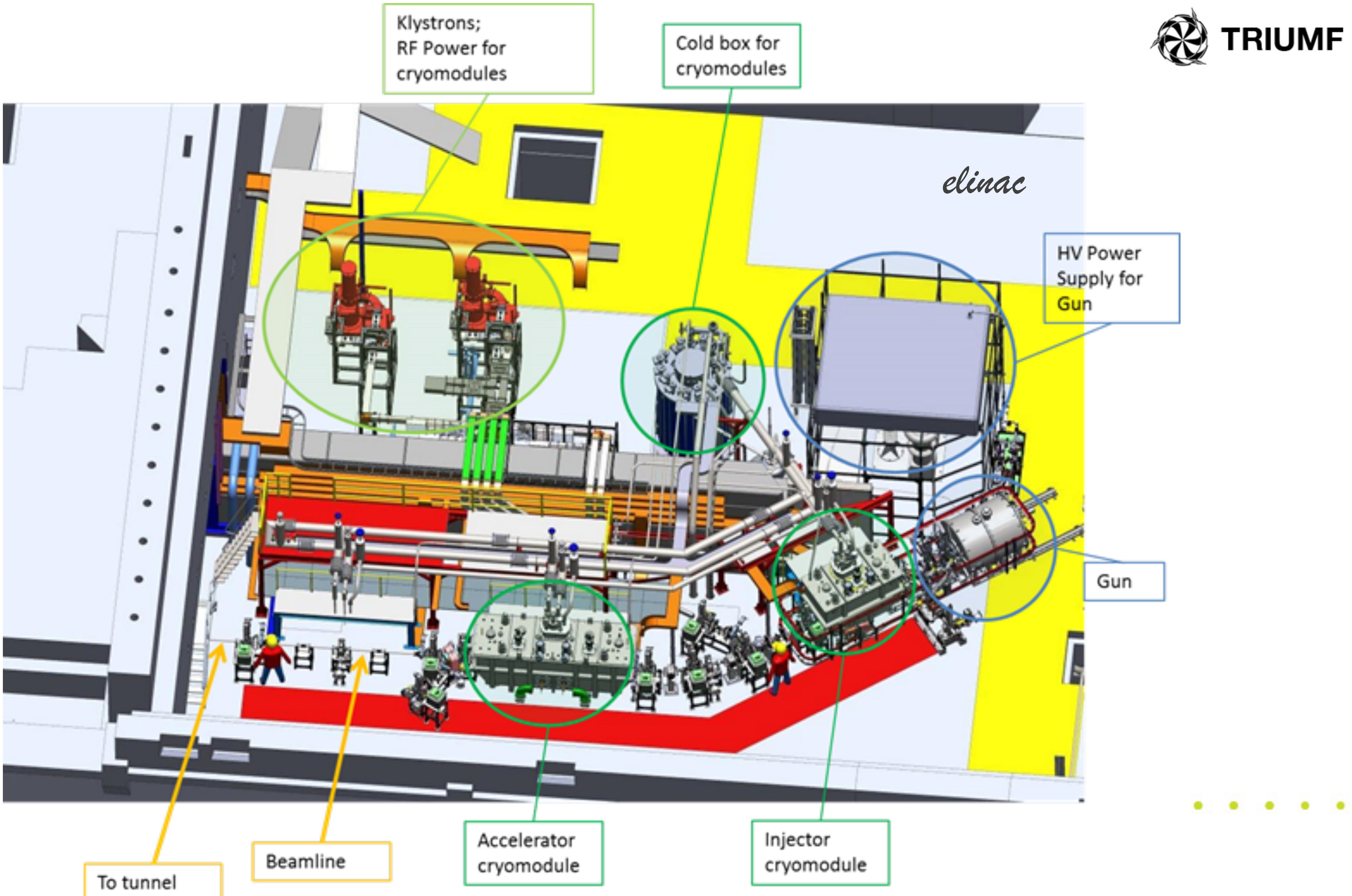


ILC scenario (approved ACW2015)

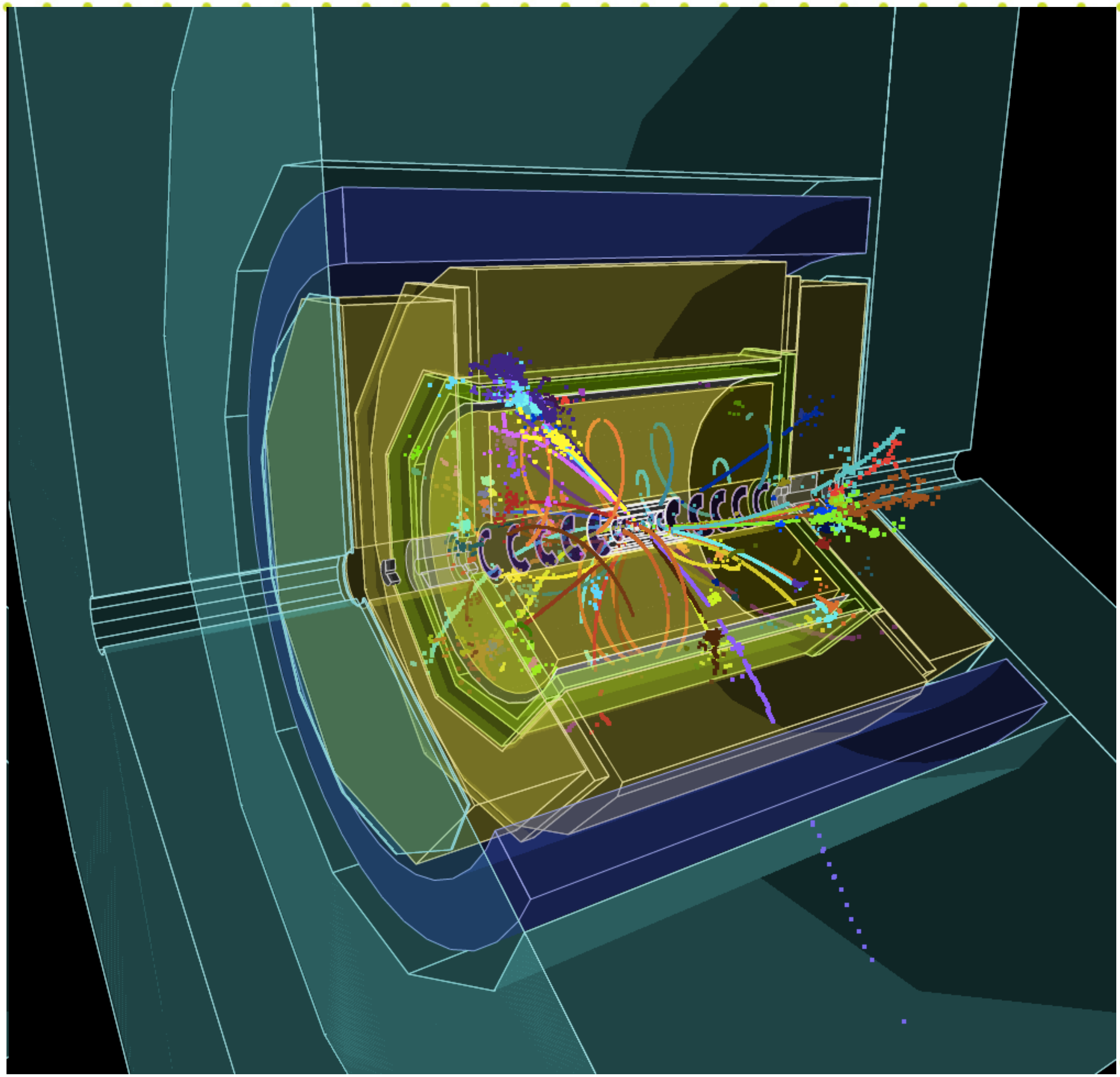
Integrated Luminosities [fb]



elinac: A Canadian Connection

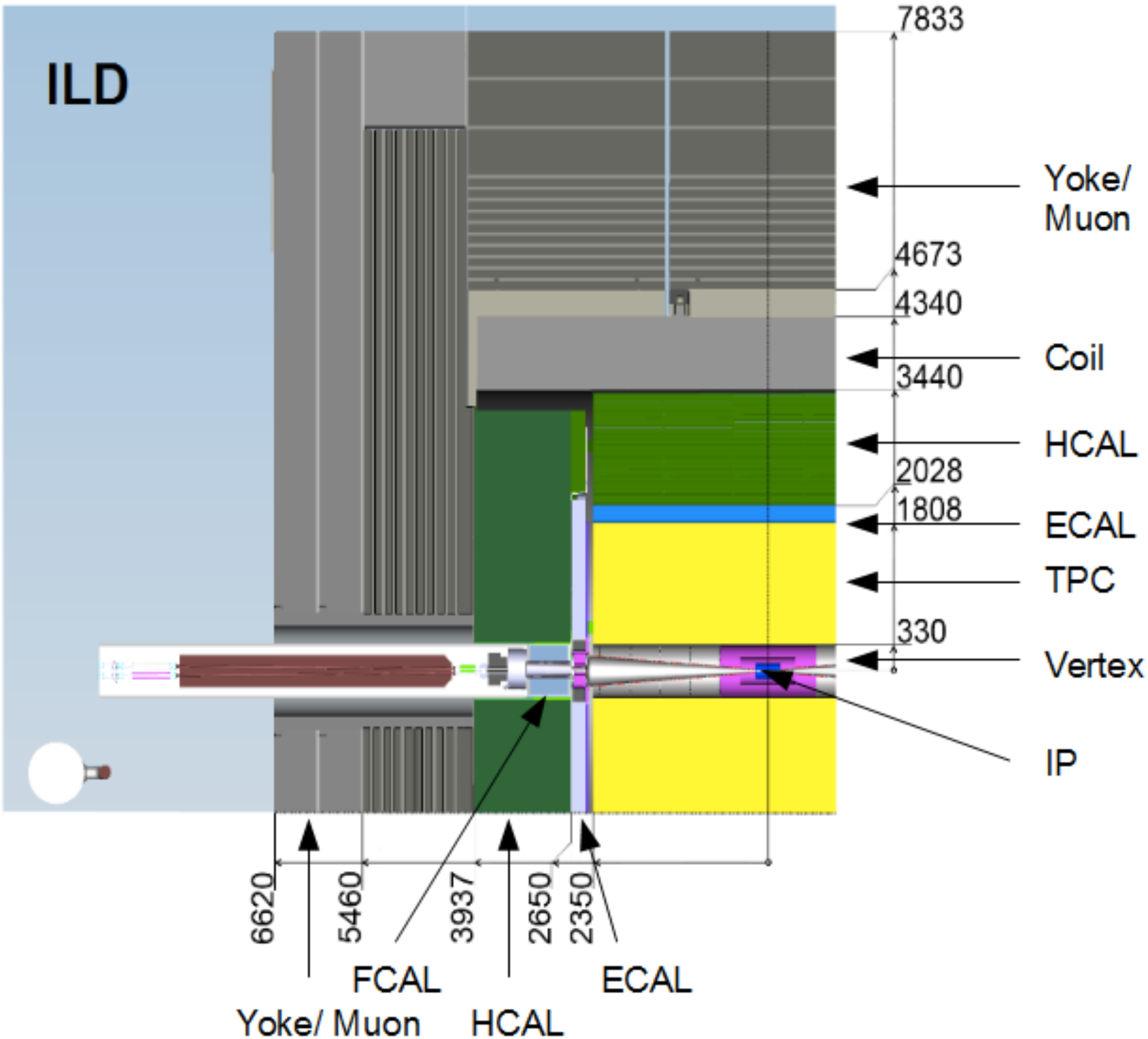


International Linear Detector



A. Bellerive: Secretary of the newly formed ILD Collaboration Institute 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:** $\delta(1/p_T) < 2\times10^{-5}$ GeV^{-1}
- **Impact parameters:** $\sigma(r\phi) < 5$ µm
- **Jet energy resolution:** $\sigma_E/E \sim 3\text{-}4\%$

The CALICE Collaboration

.. is one of the largest R&D collaboration in High Energy Physics
with ~360 physicists and engineers from 59 institutes out of 19 countries

Canada/McGill

Task: **F. Corriveau, M.Sc. & summer students**

Development, study and validation of finely segmented **imaging** calorimeters
with: large number of channels
one or just a few bits information per channel
such that jet particles are measured individually

Detectors:

Initially (2000) for ILC/CLIC detectors
Considering new detectors, e.g. the CMS endcaps, ALICE forward calorimeter
Now including developments of any imaging calorimeters

Large prototypes were already built and tested:

Silicon-W ECAL, Scintillator-W ECAL, Scintillator-Fe/W HCAL
RPC-Fe/W HCAL, RPC-Fe HCAL: e.g. Digital Hadronic Calorimeter (DHCAL)

Monte Carlo Simulations: G4

Electromagnetic shower simulations

Result reproduced at the < 1 % level
Multiple scattering still challenging
Validation tool to understand detectors!

Hadronic shower simulations

Precision better than 10% (shapes < 20%)
Improving fast thanks to detector feedback
Many physics lists available or in development

Adequate simulations are a prerequisite for understanding the physics of a given prototype

Geant4 and the CALICE Collaboration

March 2014: first common sessions at the CALICE collaboration meeting at Argonne

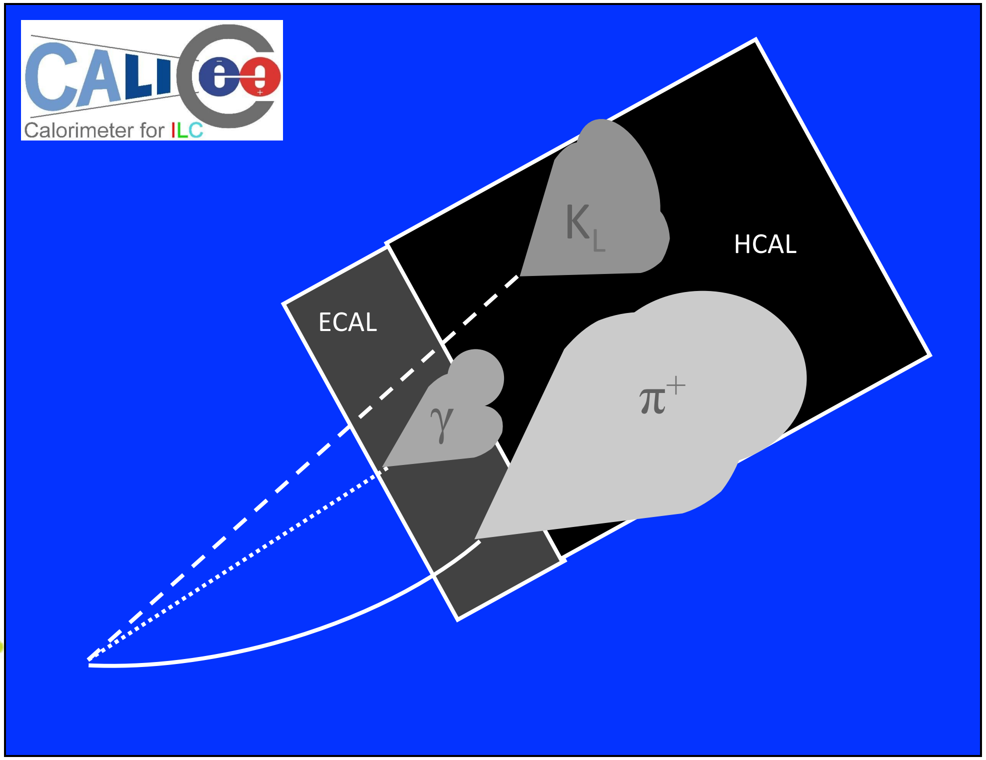
September 2014: common workshop in Madrid with discussions on:

Implementation of history of particle showers
Photon-production cross sections
Features in recent releases (GEANT10.x)

CALICE test beam data is getting used as cross-check and in tuning e.g. in physics lists

Particle Flow Algorithms

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL+HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion Term	If goal is to achieve a resolution of 30%/√E →		**$\leq 0.24^2\ E_{jet}$**



Reverse conceptual approach to build detectors: design them based on PFAs

PFAs need high granularity to obtain information from **each** particle in jet

→ factor ~2 better jet energy resolution than previously achieved

Digital Hadronic Calorimeter

Description of the 1m^3 prototype

with J. Repond et al., ANL

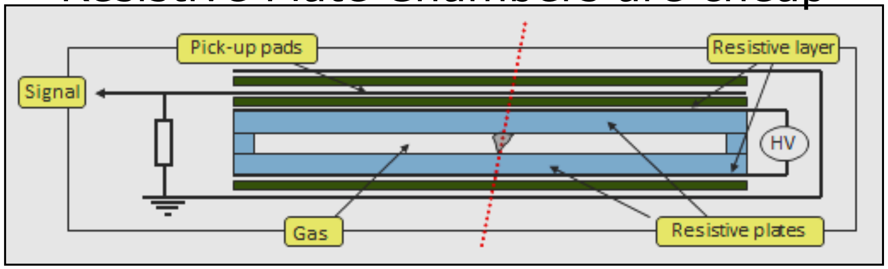
Readout of **1 x 1 cm^2** pads with one threshold (1-bit) → **First Digital Calorimeter**
54 layers, each layer with 3 RPCs (1.1 mm gap), yielding ~500,000 readout channels

NEW

Assembly steps

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

Resistive Plate Chambers are cheap

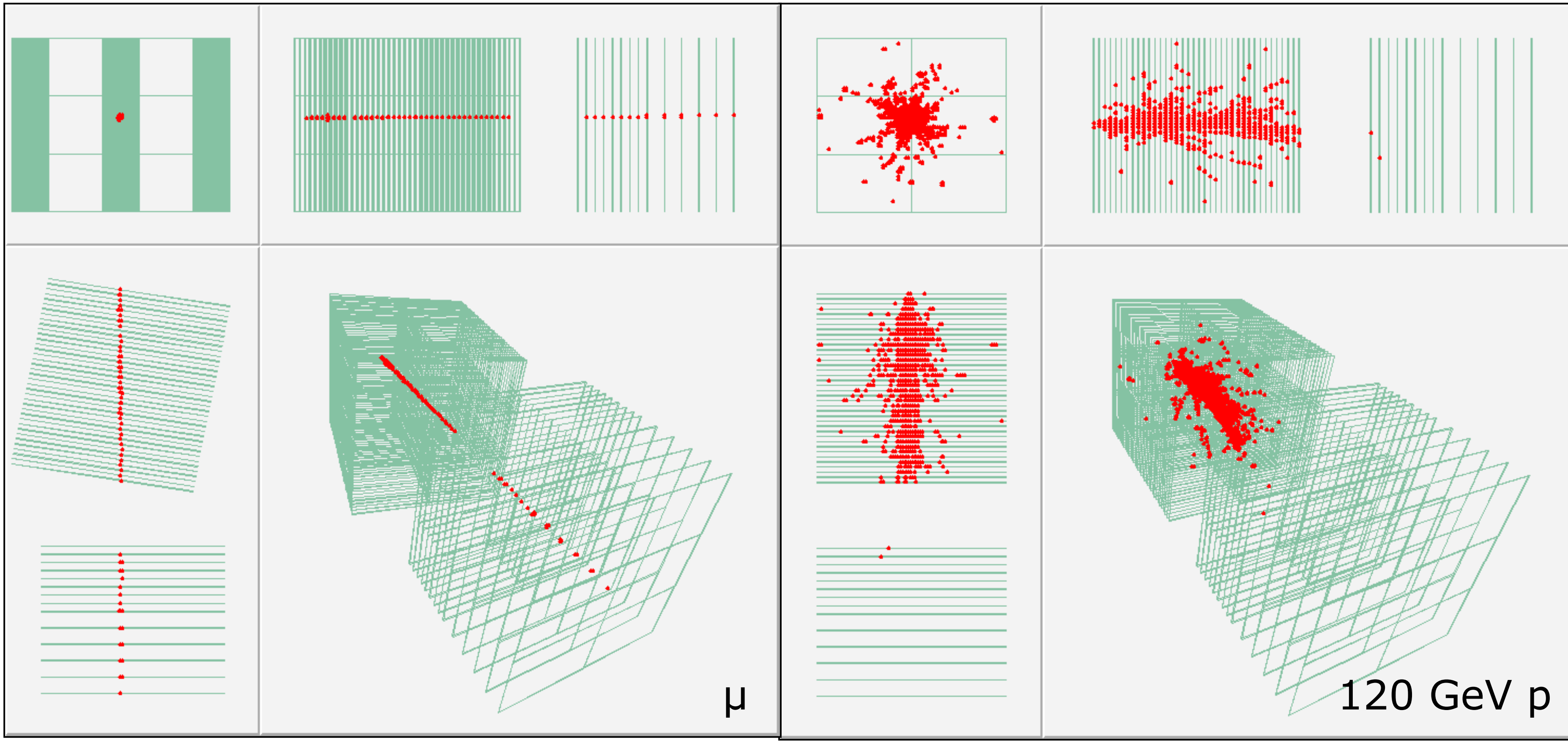


Test Beam Data Taking & Analysis

DHCAL Conference presentation:
"Production and commissioning of a large prototype Digital Hadron Calorimeter for future colliding beam experiments"

+ 1 DHCAL publication in JINST
+ 2 .. in the pipeline
+ 8 CALICE publications

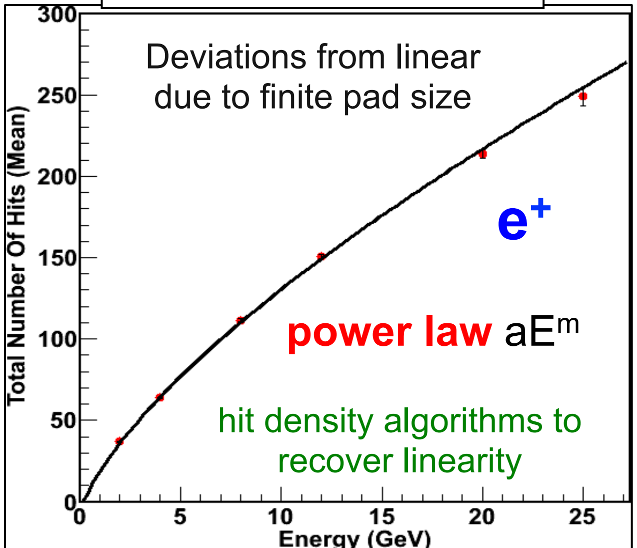
Events in DHCAL (Fe absorber)

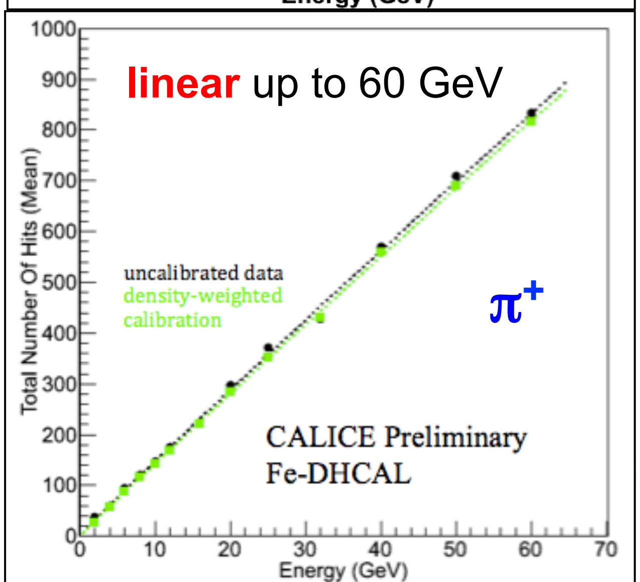


Characteristics: high granularity and very low noise level

DHCAL (Fe) Response

Linearity

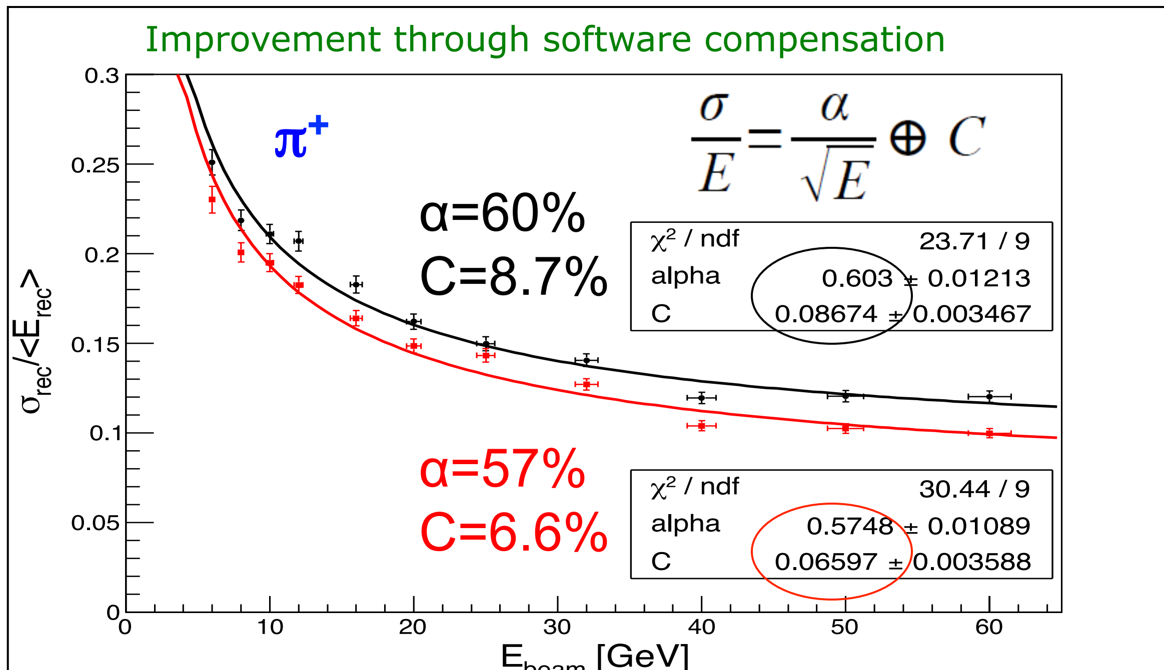




Energy Resolution

Steps:

- **calibration**: based on RPC efficiencies and on local hit multiplicity from muon data
- **positrons**: linearization of positron response based on hit densities
- **pions**: similar software compensation for showers, several % improvements



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

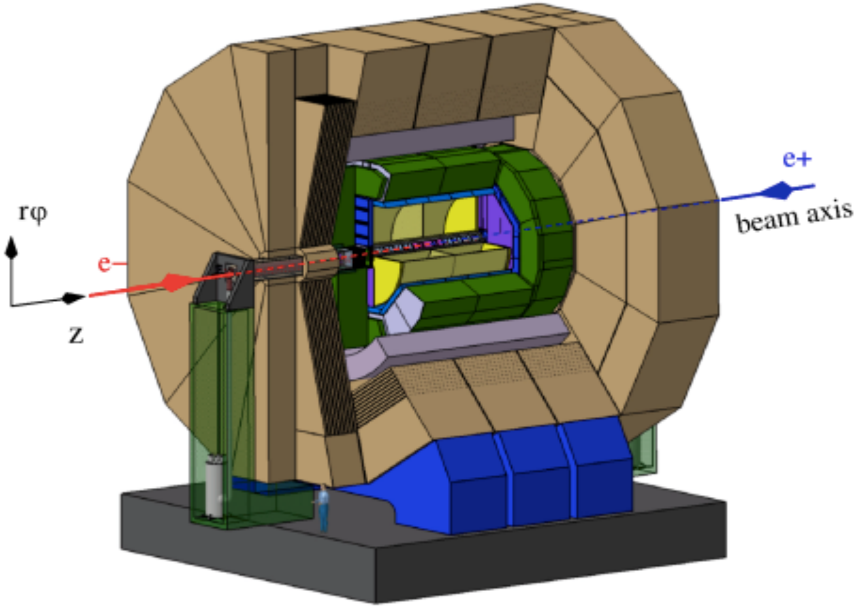
– Single hit $\sigma(r\phi)$ at z=0 < 60 μm

Low material budget inside the calorimeters (PFA)

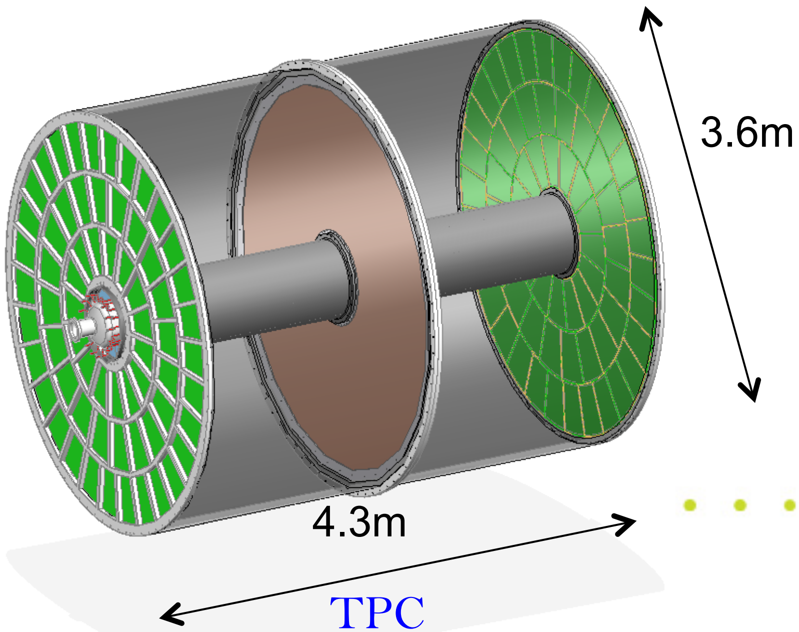
- Barrel: ~5% X_0
- Endplates: ~25% X_0

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



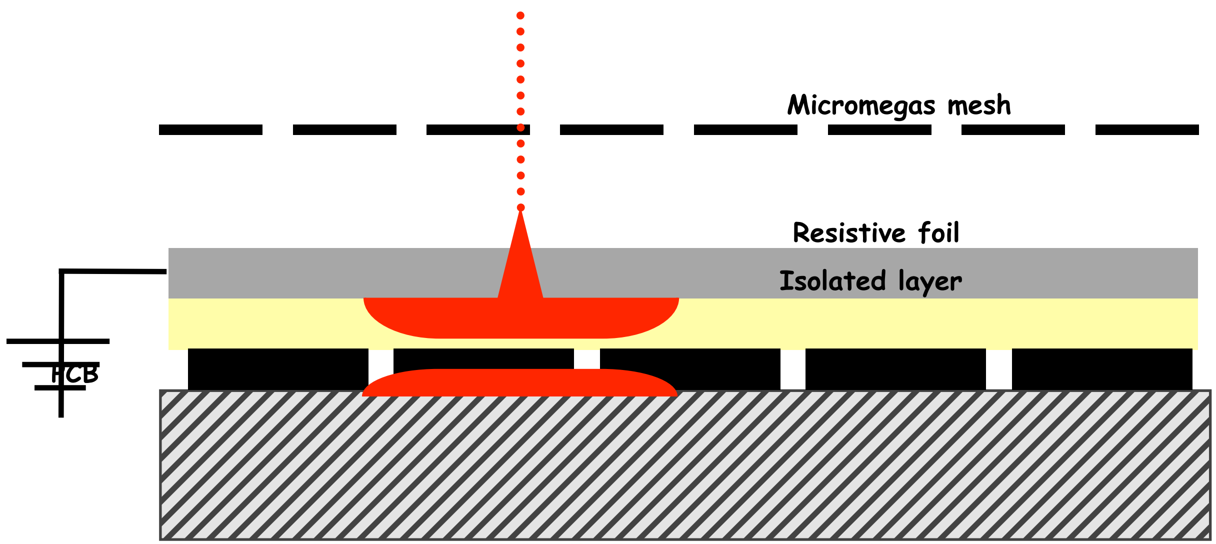
TPC

Micromegas (MM) Charge Dispersion

Resistive Anode

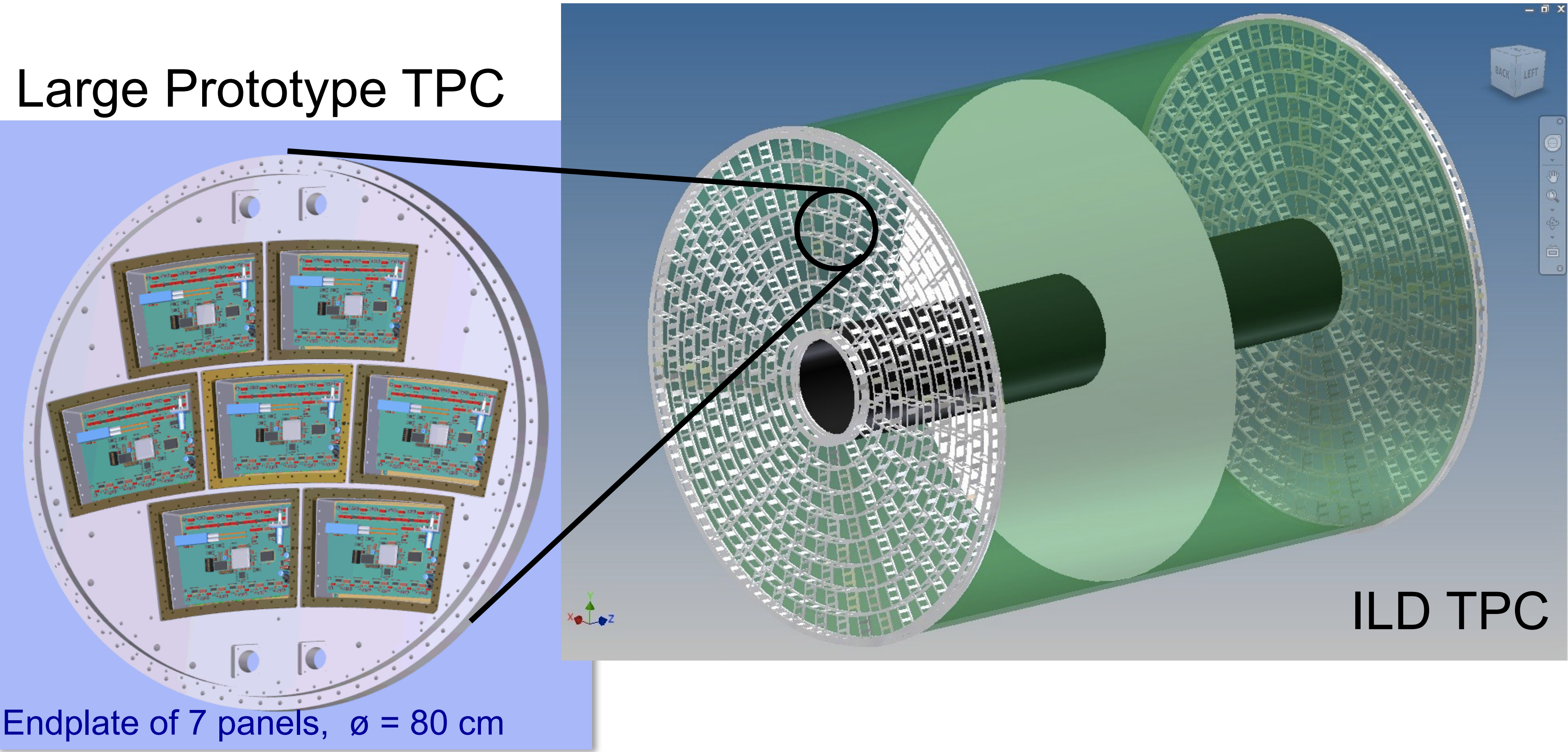
Canada/Carleton

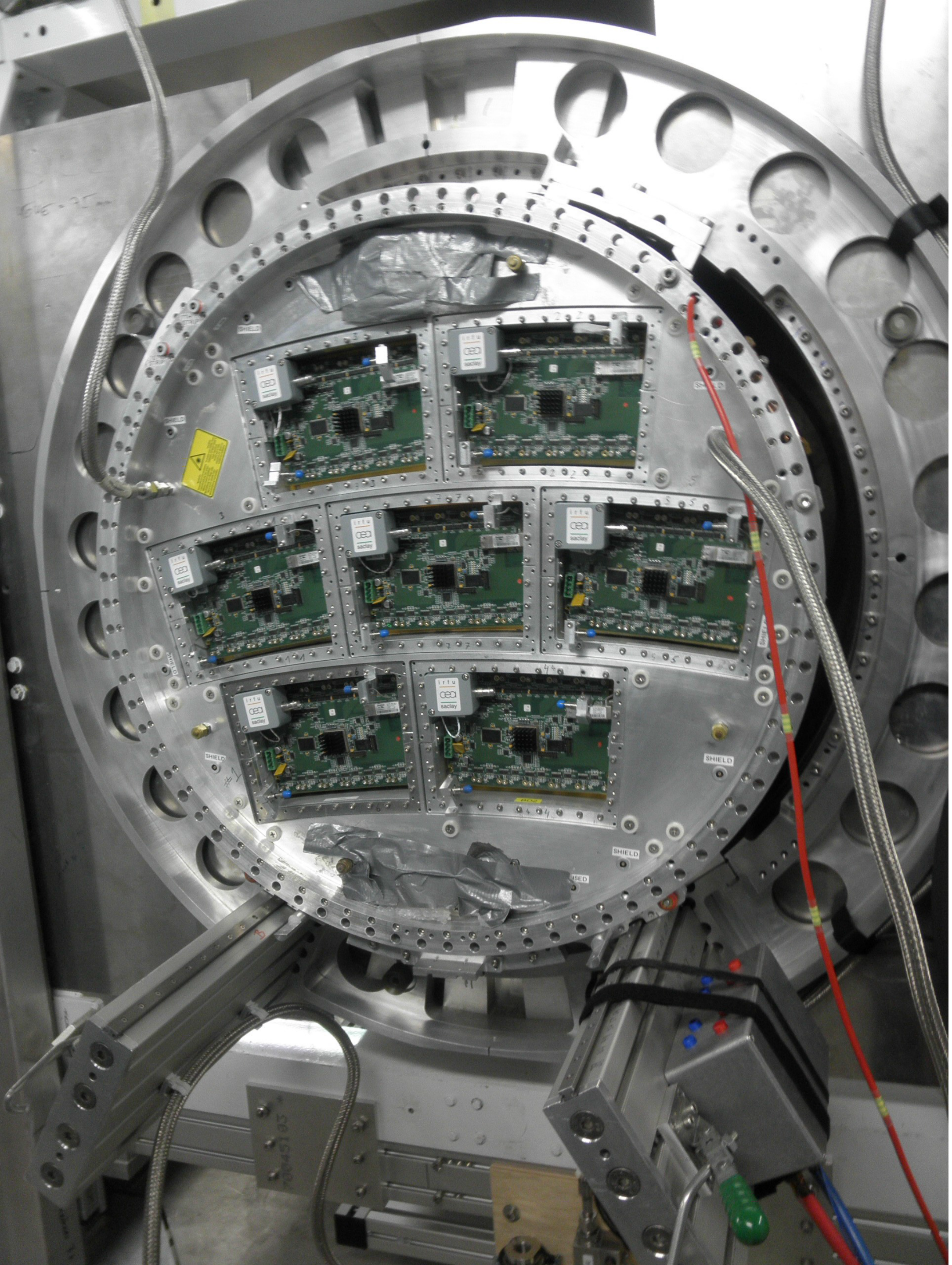
A. Bellerive, M. Dixit, M.Sc. & summer students



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

Period
2012-2015

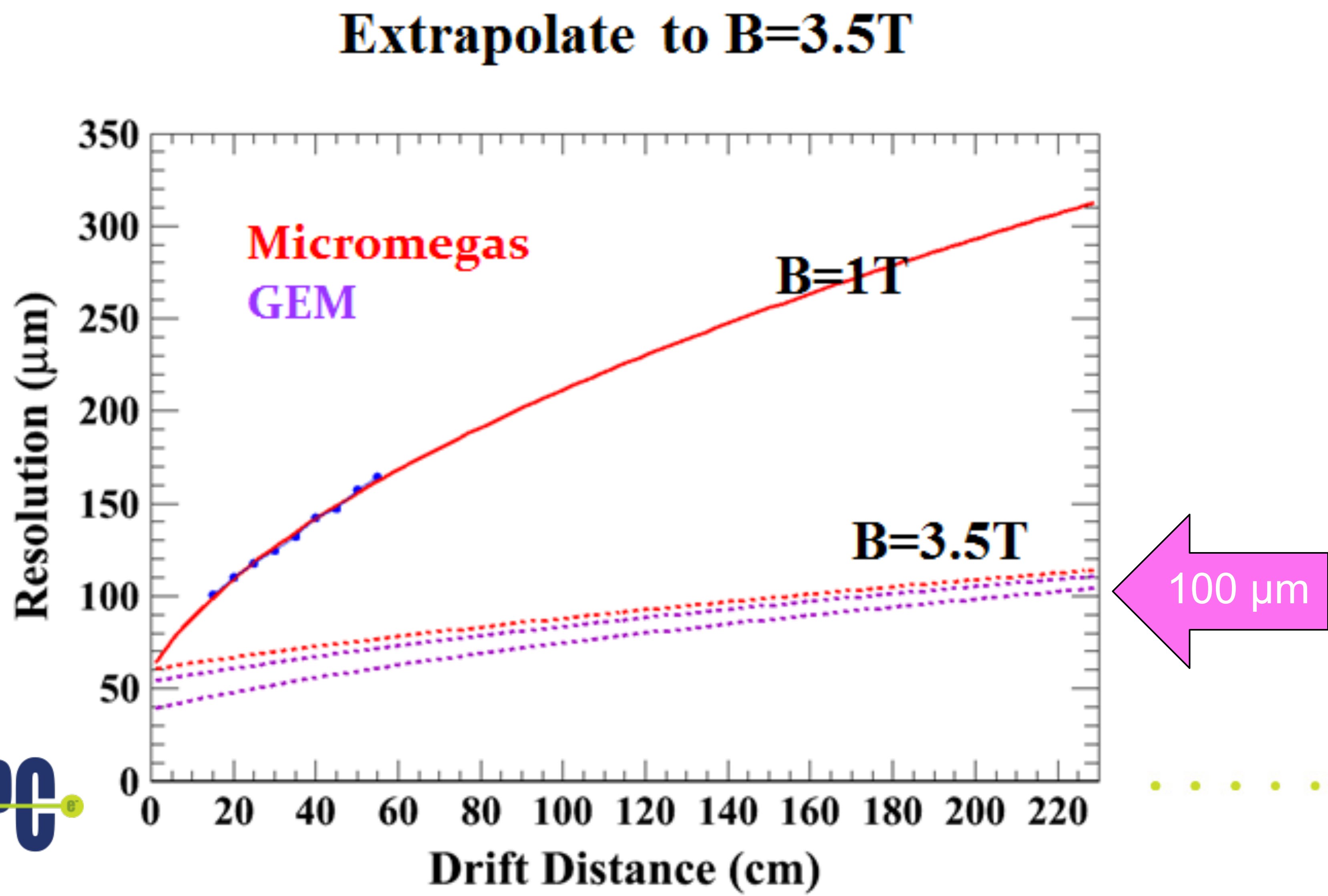
2013 data
6-module

2014 data
7-module with cooling

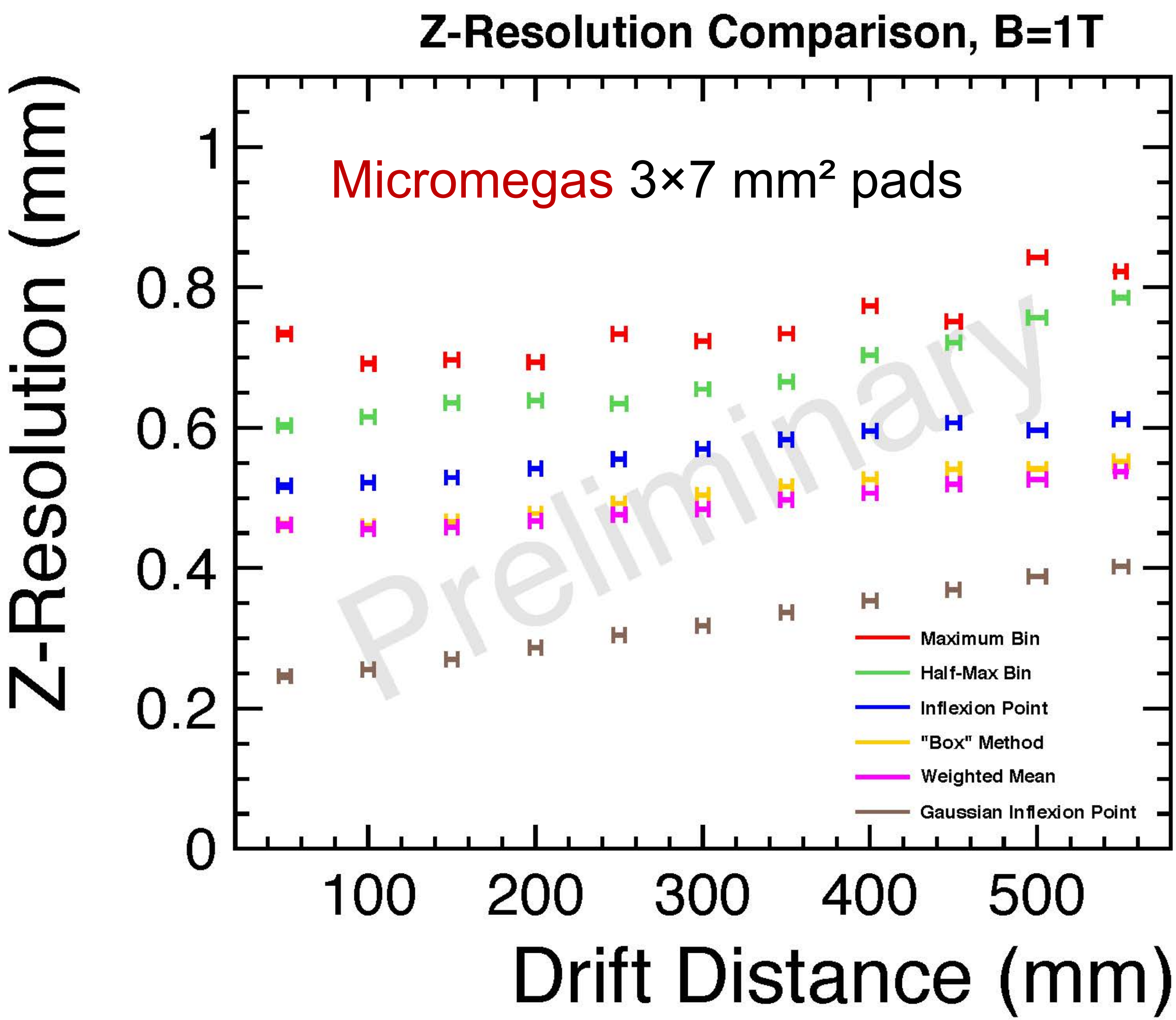
2015 data
7-module with cooling
2 new modules

Transverse (r-Φ) Resolution

Micromegas 3×7 mm² pads and GEM 1.2×5.8 mm² pads



Longitudinal (Z) Resolution



500 µm

Summary - LRP

1- Physics and research goals for the project: Described in TDR

2- Expected HQP training: LCTPC and CALICE extremely successful at training undergrad and graduate students

Numbers and role in the project: 3 faculties, 3 M.Sc., 2 USRA and honors projects with leading roles in ILD (LCTPC and CALICE)

3- Equipment needs, cost estimates and time profile:

- Detail in Technical Design Report (TDR)
- Timeline link to MEXT decision (2016)
- Expected international funding in place (2018)

4- Computing, CPU and storage: Typical international GRID LHC

5- Expected calls on technical support: Used MRS for testbeams. Need to full support (IPP, TRIUMF and MRS) for full scale ILD

6- Relationships with other projects being conducted in Canada

- T2K TPC and ATLAS MM & sTGC
- CALICE connected to calorimeter expertise (ATLAS)

7- Relationships with international partners: Described in TDR

Summary – R&D

- 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 (small NSERC project = no RTI/CFI)
- 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

http://lcws15.triumf.ca/

Extra slides

ALCW 2015 - Tokyo

Special Committee on ILC Project in Japan

Ministry of Education, Culture, Sports, Science and Technology

MEXT

Special Committee on ILC Project

Particle and Nuclear Physics Working Group

Established in June 2014
Several meetings in 2015

TDR Validation Working Group

Established in June 2014
Several meetings in 2015

Based on SCJ's recommendations, Special Committee investigates critical issues (TDR evaluation, cost, technology, personnel) required to judge hosting ILC or not by 2016.

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)

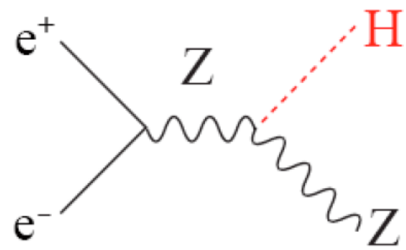
More Physics Justification

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

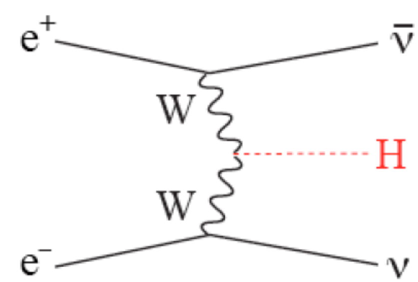


At 500 GeV, add $e^+e^- \to \nu\overline{\nu}h$, $e^+e^- \to t\overline{t}h$, $e^+e^- \to Zhh$

absolute normalization of couplings, begin t and h couplings

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

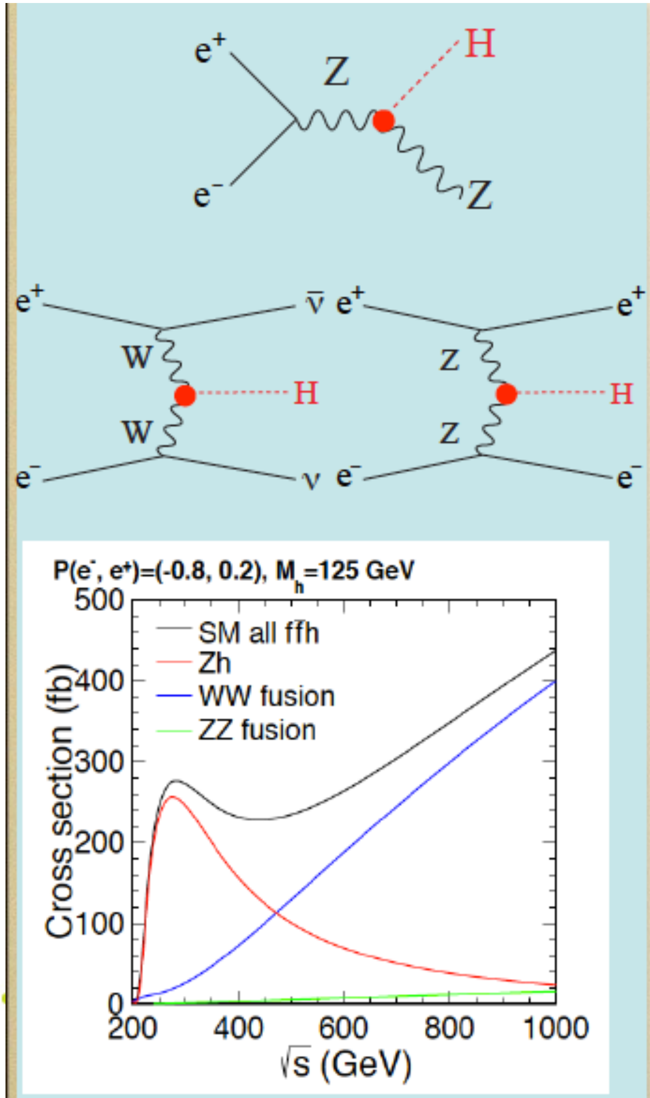
high statistics, refined t, h, μ couplings

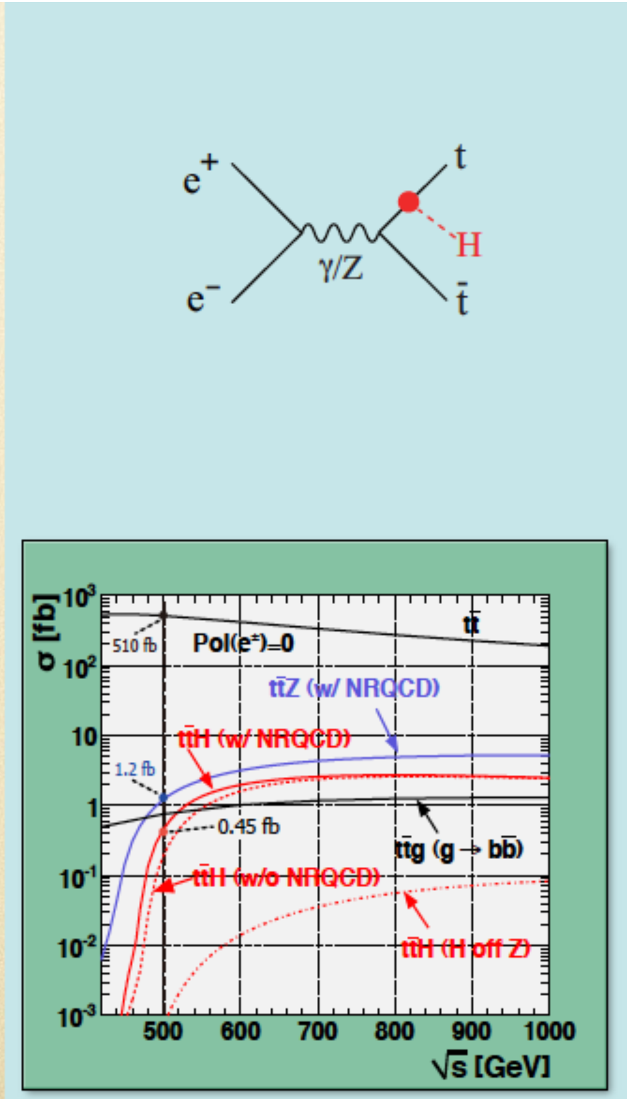


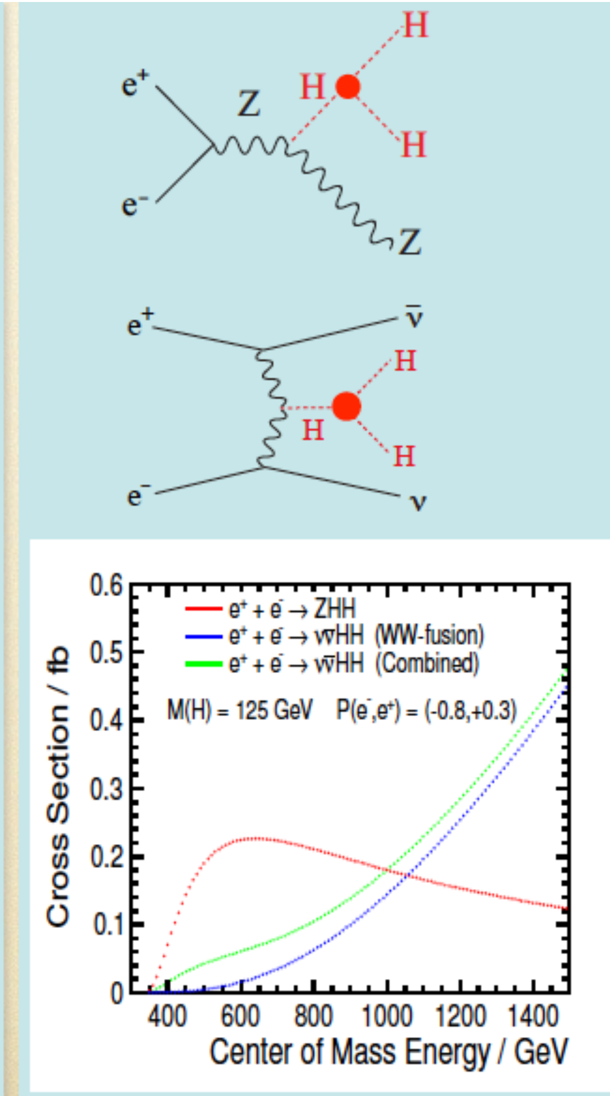
All of the steps are needed for a full program.

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

More Physics Justification







Long range plans

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."

Long range plans

Plan for future of Canada SAP 2011-2016

The Subatomic Universe: Canada in the Age of Discovery 2011–16
Natural Sciences and Engineering Research Council of Canada

Long range plans

Plan for future of Canada SAP 2011-2016

The ILC is a proposal for a new e+ e– linear collider with the stated aim of performing precision studies of the physics revealed by the LHC data. The project design will be completed by the end of 2012 and Canadians have played roles in both the accelerator and detector research and development, as well as theoretical efforts in ILC phenomenology and coordinating roles in the worldwide studies for the physics case.

By the end of 2012, the ILC community will complete a cost-to-performance optimization of the accelerator and detector designs. Given suitable physics motivation, this would put the international particle physics community in a strong position to move forward quickly to propose such a large internationally cooperative project.

Long range plans

Plan for future of Canada SAP 2011-2016

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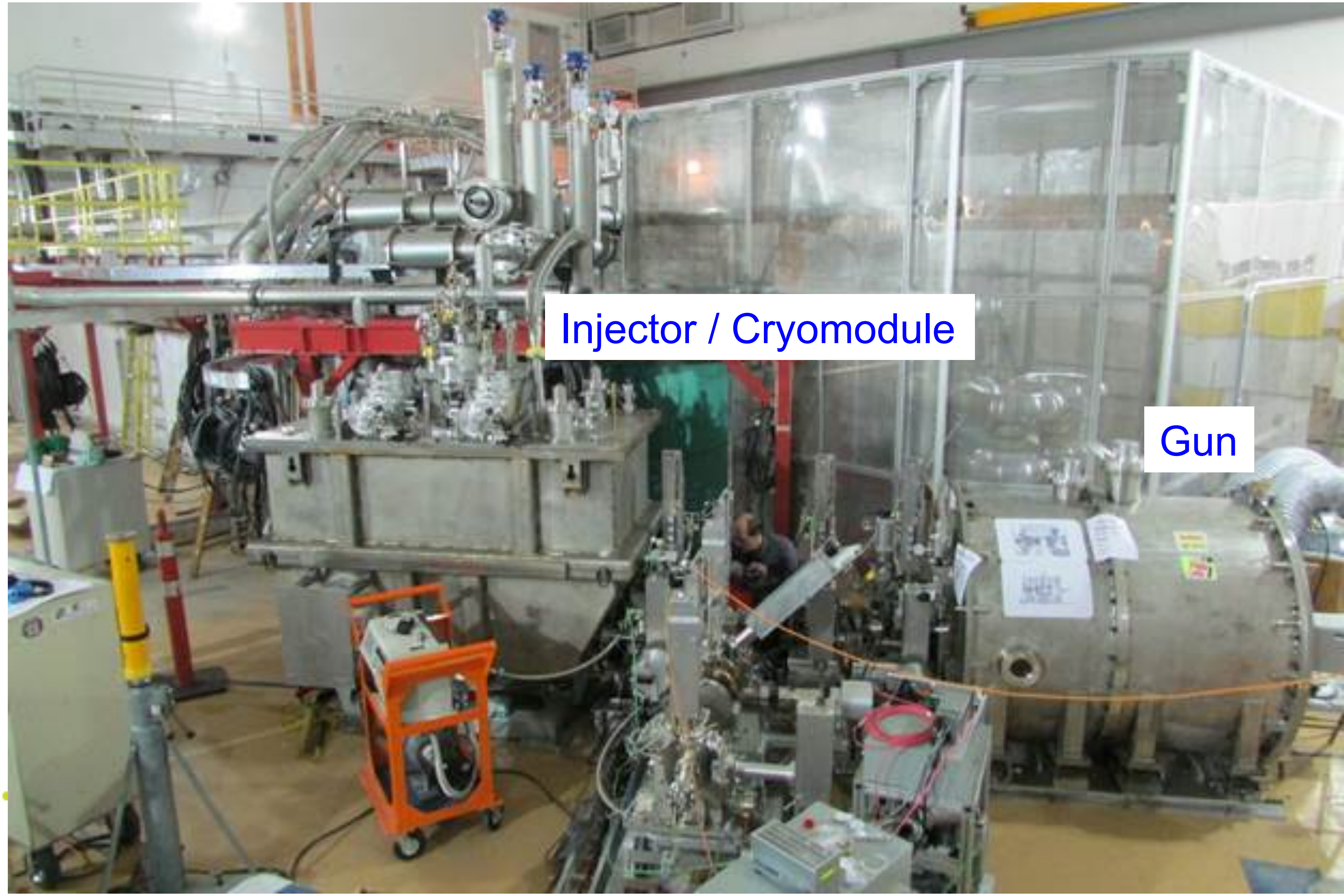
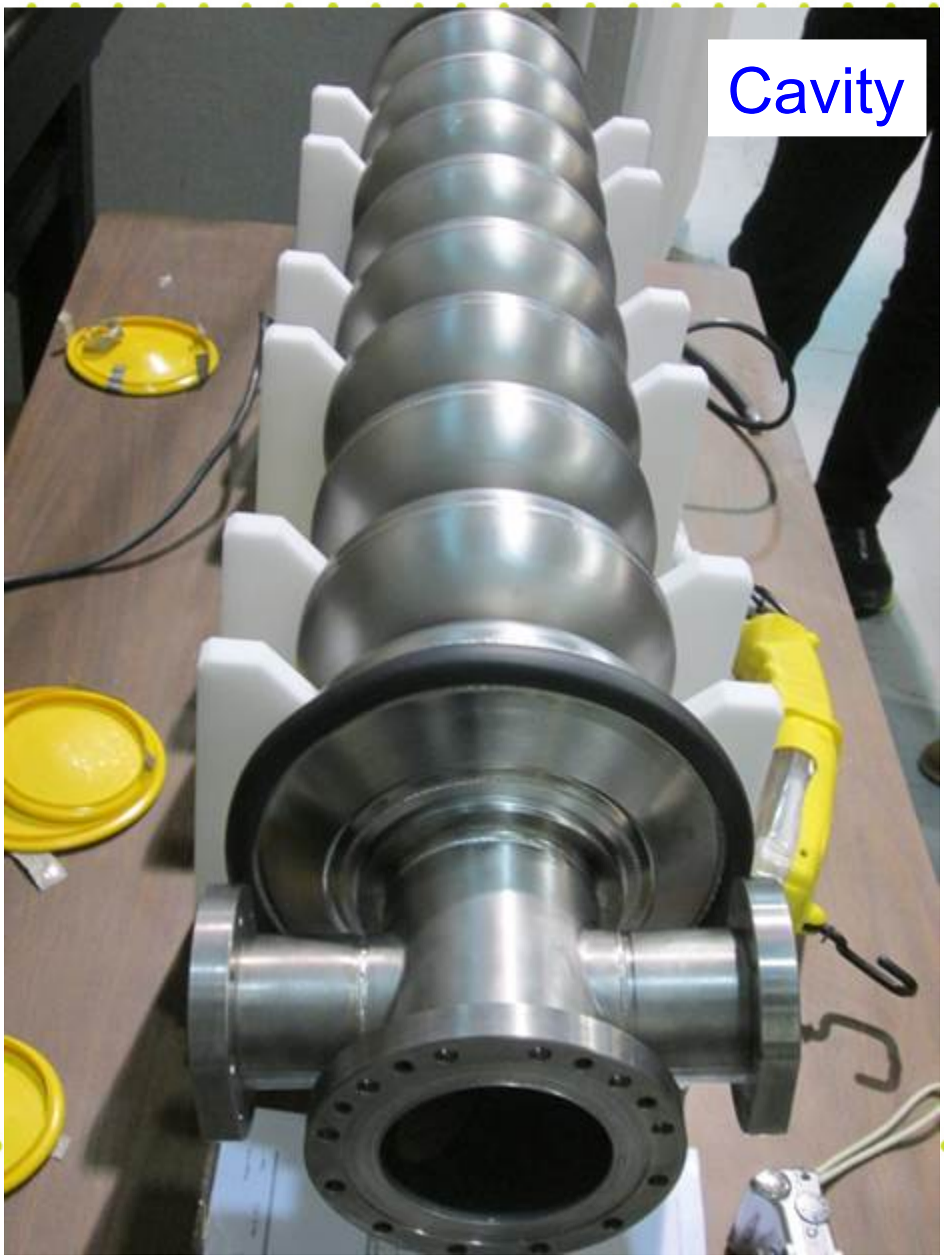
The Higgs boson !!!

By the end of 2012, the ILC community will complete a cost-to-performance optimization of the accelerator and detector designs. Given suitable physics motivation, this would put the international particle physics community in a strong position to move forward quickly to propose such a large internationally cooperative project.

E-linac at TRIUMF



E-linac at TRIUMF



International Linear Detector

ILD ECAL and HCAL

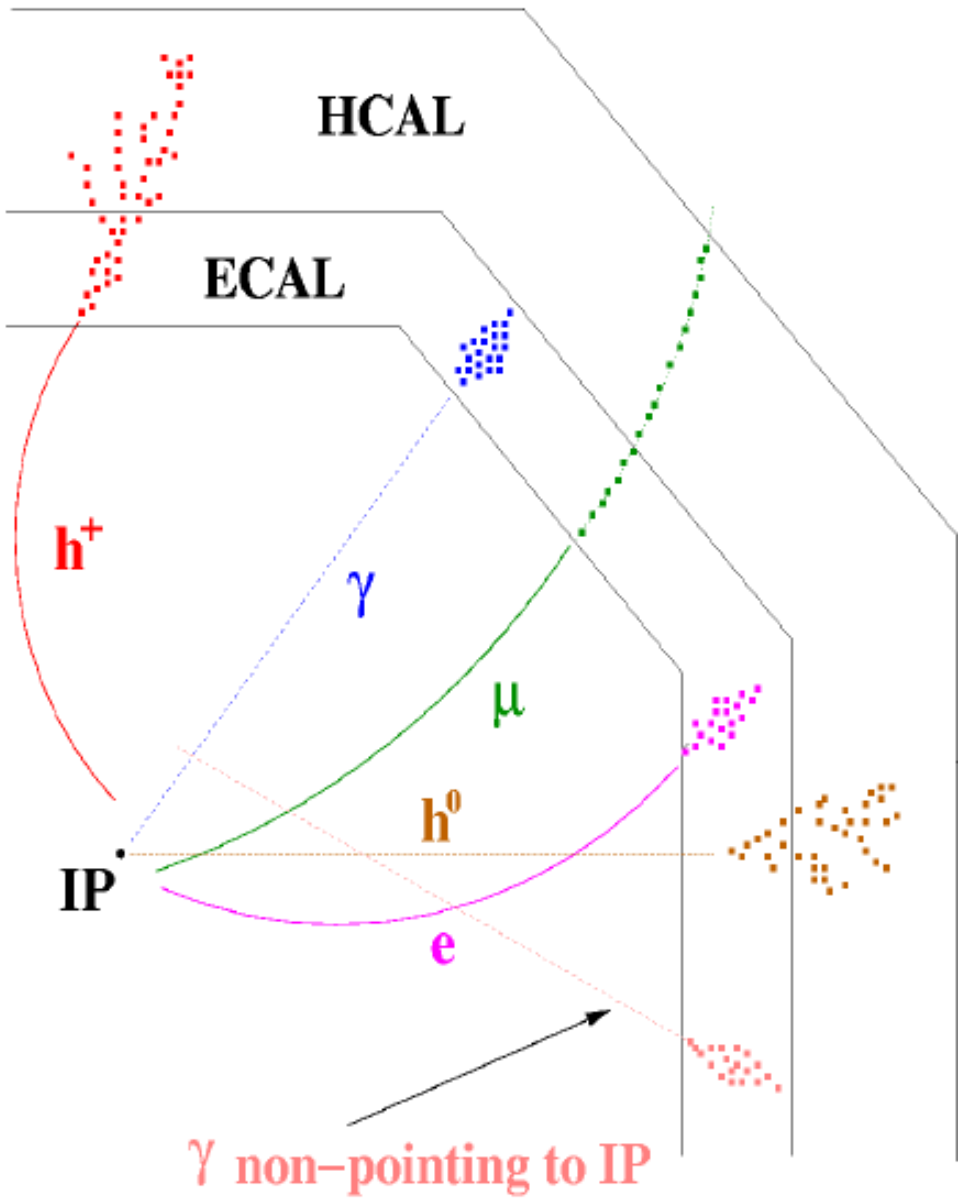
large radius and length
➔ to separate the particles
Hermitic, but compact (inside the coil of the solenoid)

large magnetic field
➔ to sweep out charged tracks

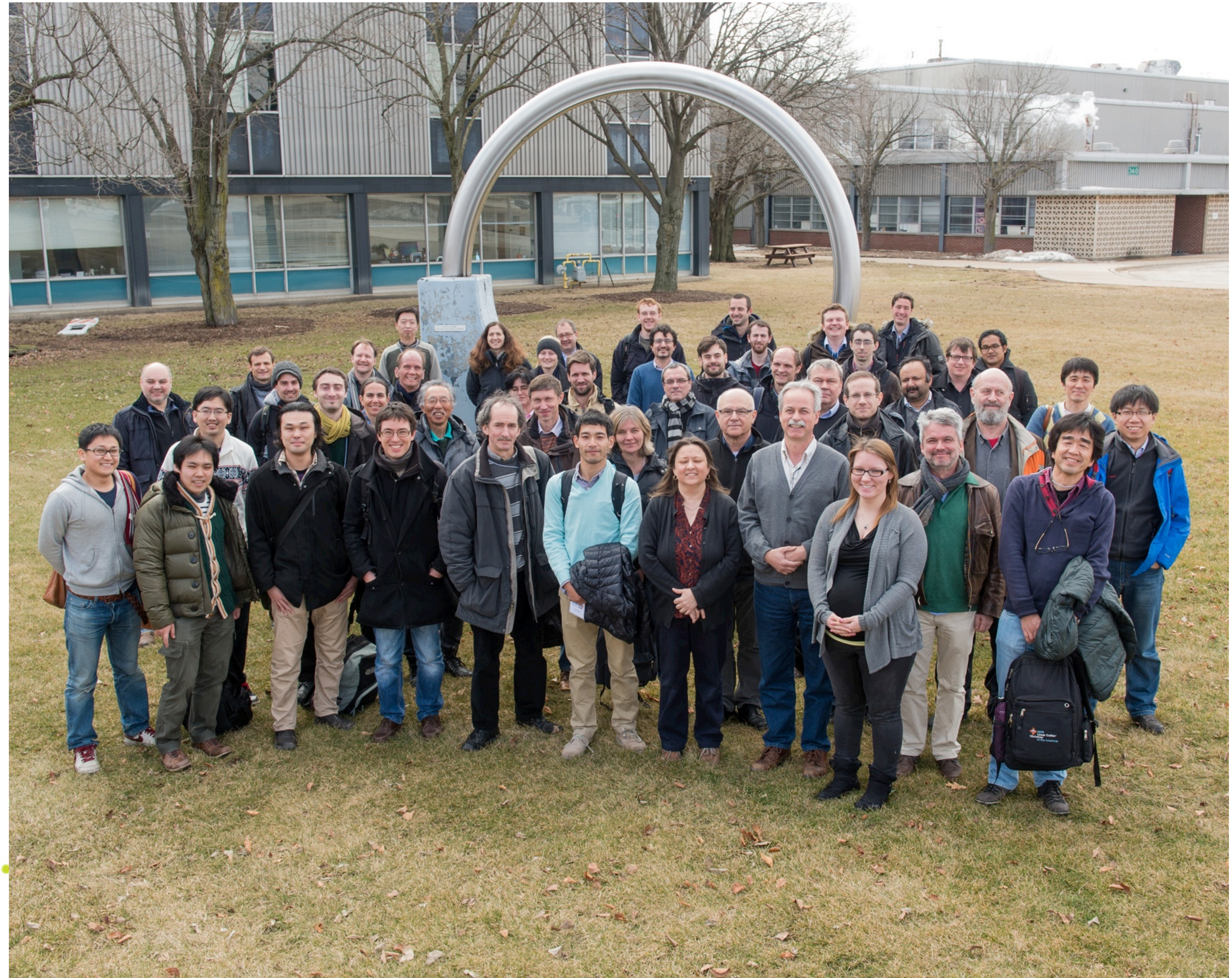
“no” material in front of calorimeters
➔ stay inside coil

small Molière radius of calorimeters
➔ to minimize shower overlap

high granularity of calorimeters
➔ to separate overlapping showers



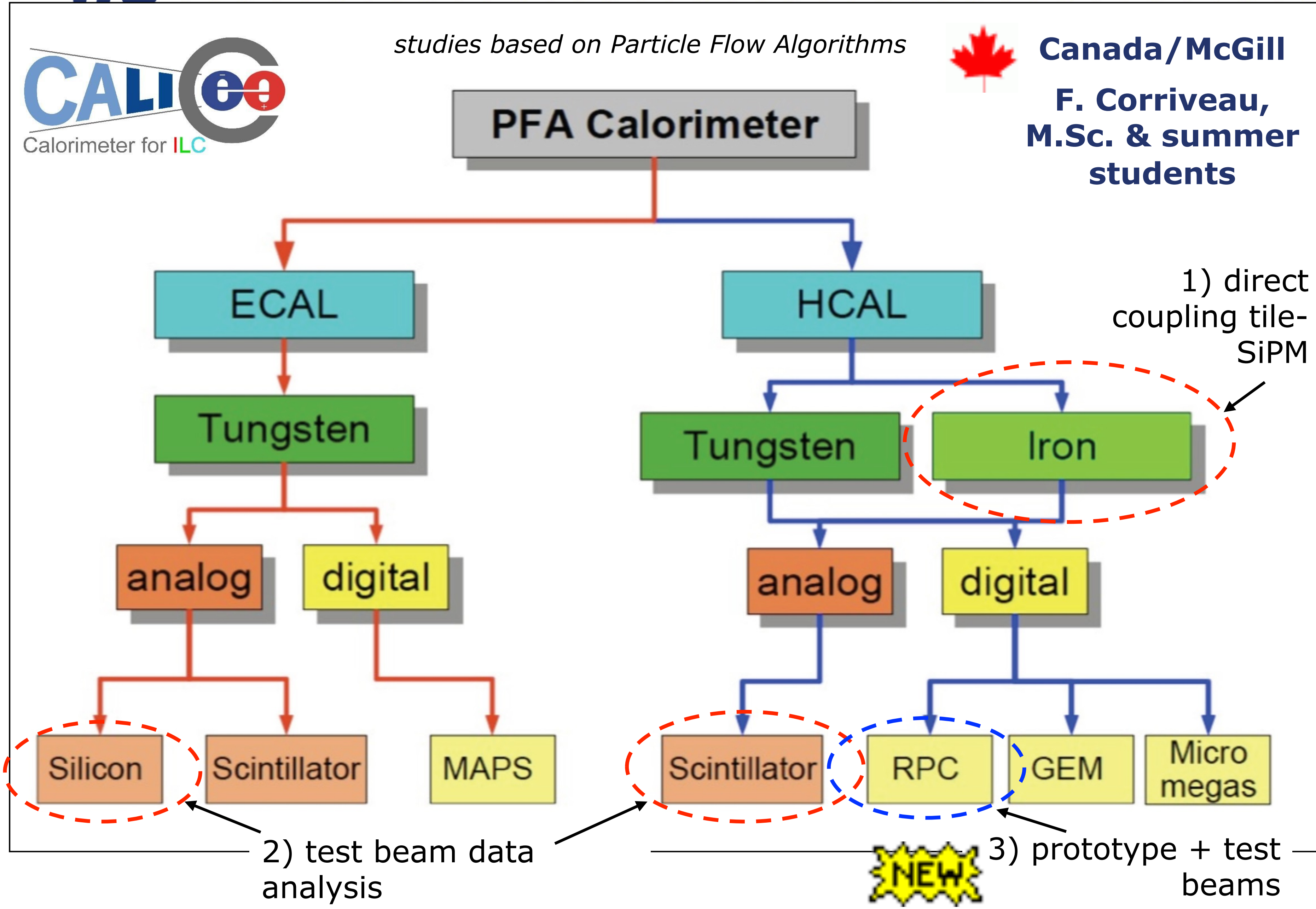
CALICE Collaboration (2014 –ANL)



CALICE – McGill

	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)	NSERC Grant / ANL
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 Anthonisen	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 / ANL
15	Georg Manten	Heidelberg	B.Sc.	2014	3	DAAD (Germany)
16	Kai Yasui	McGill	B.Sc.	2015	4	NSERC Grant
17	**Isabelle Viarouge**	McGill	**M.Sc.**	2015-	(full-time)	NSERC Grant
18	Katja Fahrion	Heidelberg	B.Sc.	2015	3	DAAD (Germany)

CALICE - Technologies



Particle Flow Algorithms (PFAs)

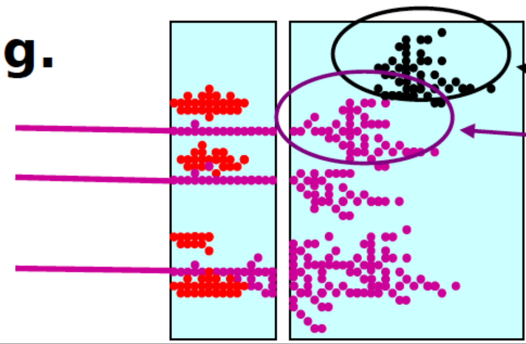
Source: CALICE Review by ECFA (Roman Pöschl)

Reconstruction of a Particle Flow Calorimeter:

★ **Avoid double counting of energy from same particle**

★ **Separate energy deposits from different particles**

e.g.

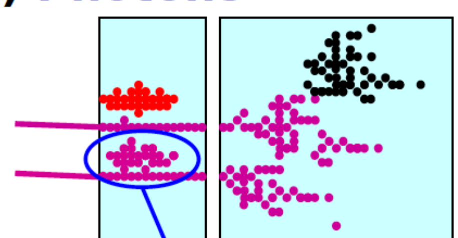


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

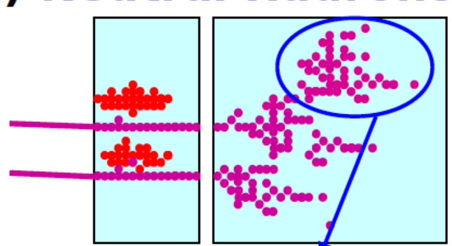
Three types of confusion:

i) Photons



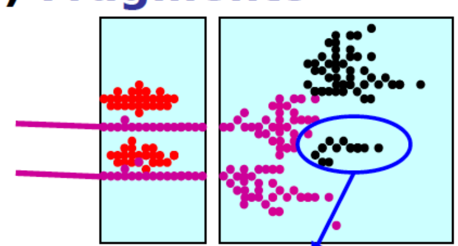
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments

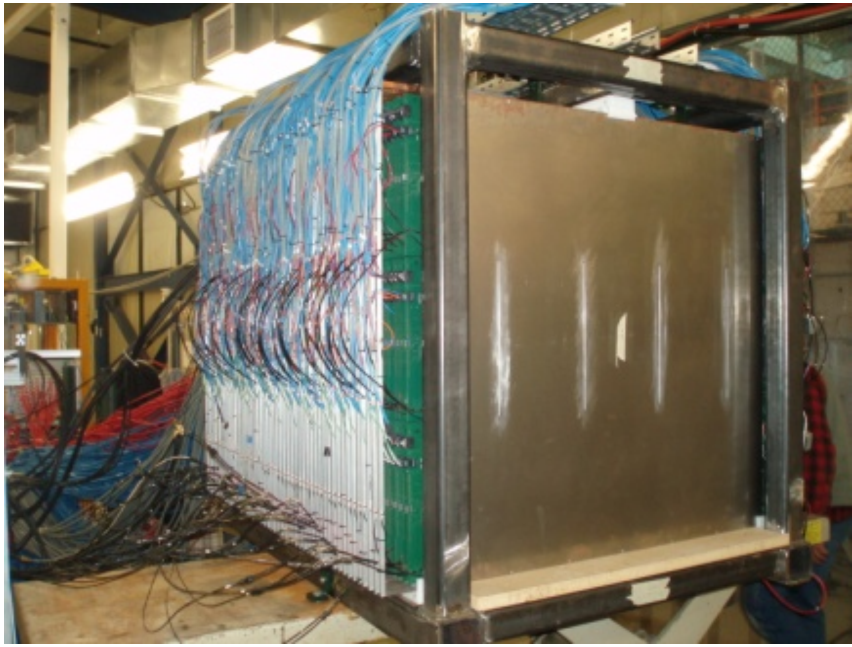


Reconstruct fragment as separate neutral hadron

1 m³ – DHCAL Physics Prototype

Description

Readout of 1 x 1 cm² pads with one threshold (1-bit) → **Digital Calorimeter**
38 layers in DHCAL and 14 in Tail Catcher, each ~ 1 x 1 m²
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 cm²
~500,000 readout channels



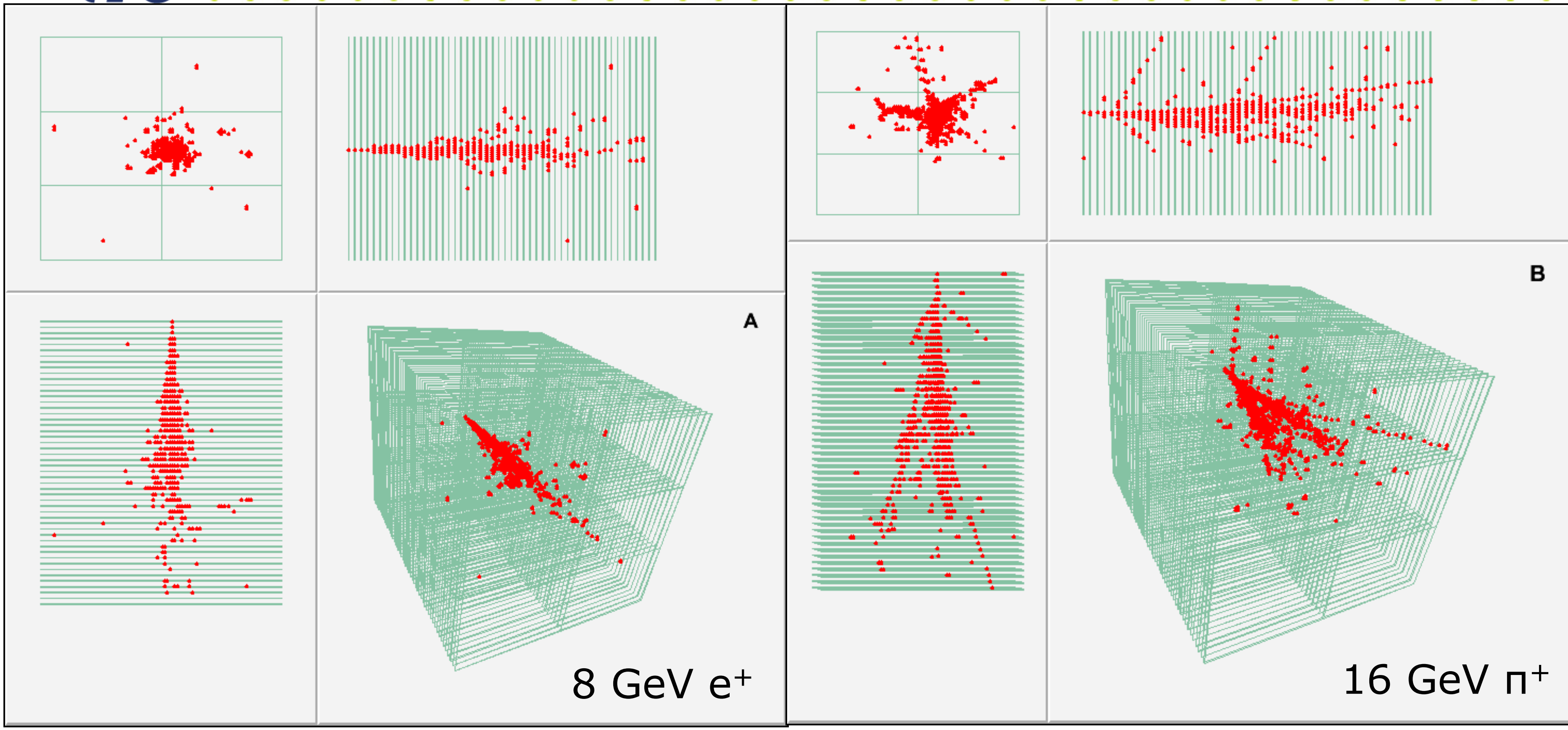
Purpose

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

Events in DHCAL (no absorber)

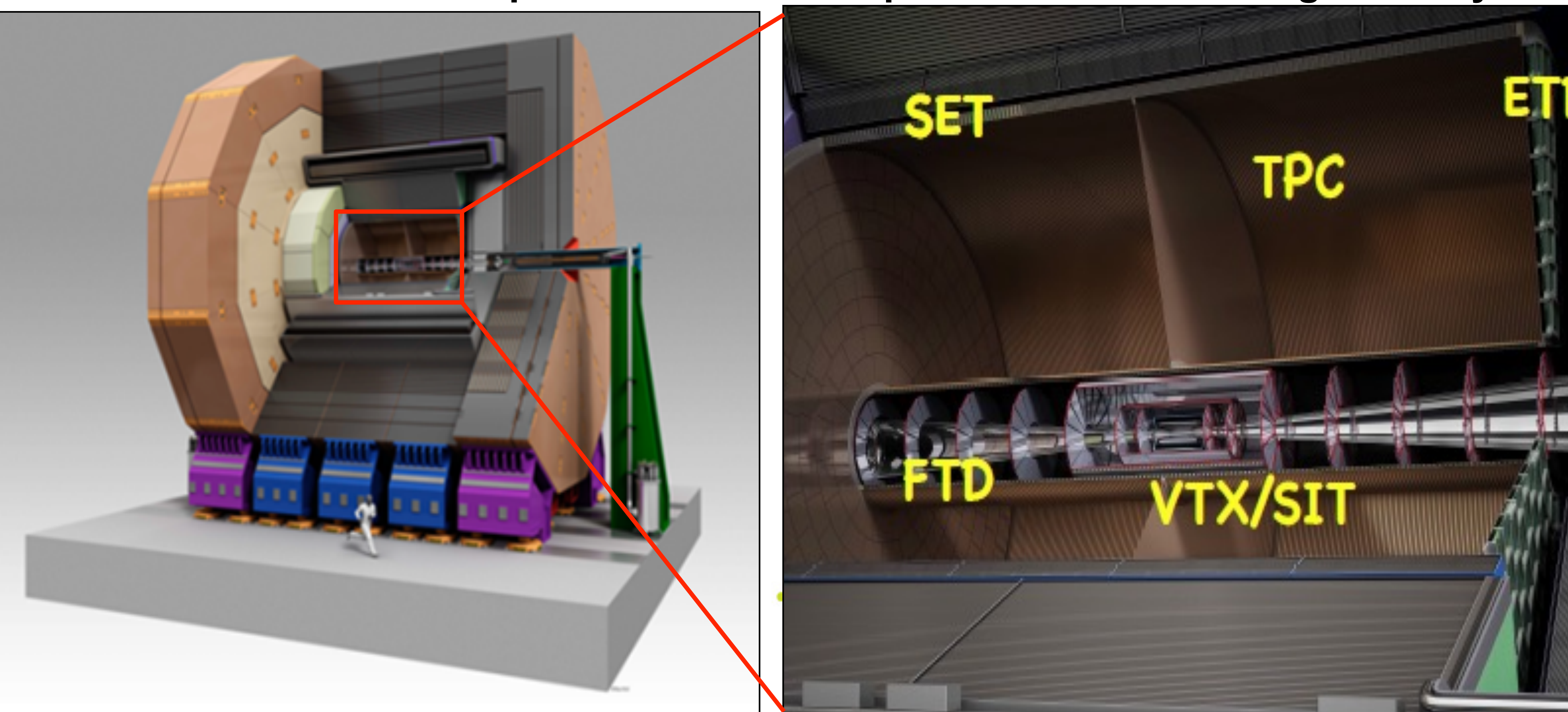


Only RPC & readout material: shower details at low energies to unprecedented level of details. Of special interest for the simulation of showers.

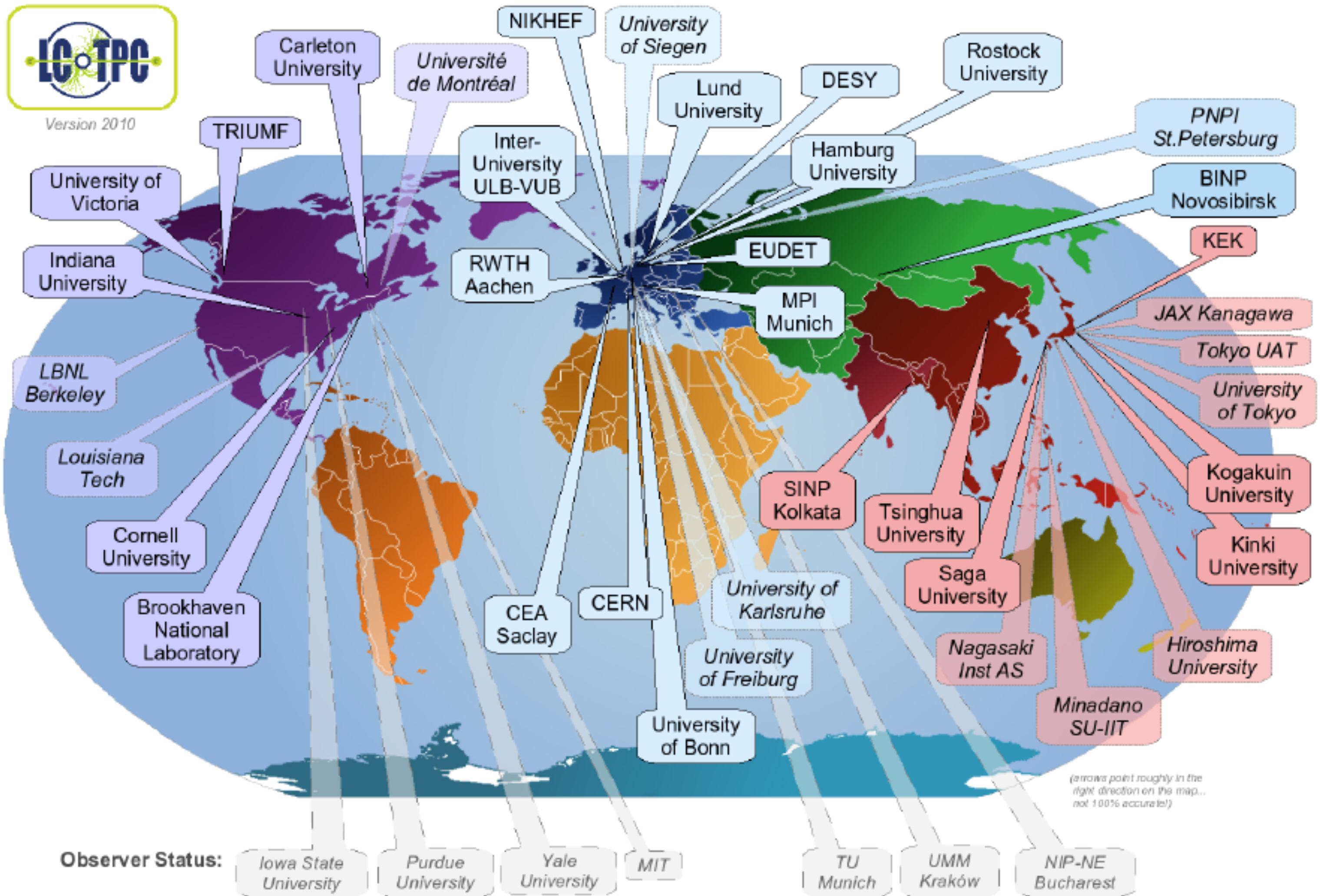
International Linear Detector

- **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



LCTPC Collaboration



Total of 12 countries from 38 institutions members + 7 observer institutes
Alain Bellerive: LCTPC North America Coordinator

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**	2014-15	(full time)	NSERC Grant
4	Peter Hayman	Carleton	B.Sc.	2010-14	(part time)	ICUREUS and USRA
5	**Nicholi Shiell**	Carleton	**Ph.D.**	2012-13	9	NSERC Grant
5	**Nicholi Shiell**	Carleton	**M.Sc.**	2010-12	(full time)	NSERC Grant
6	Terry Buck	Carleton	B.Sc.	2011	4	IPP and NSERC USRA
7	**Russel Wood**	Carleton	**M.Sc.**	2008-10	(full time)	NSERC Grant
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	NSERC USRA
12	**Roger Odel**	Carleton	**M.Sc.**	2014	(full time)	NSERC Grant
13						

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)

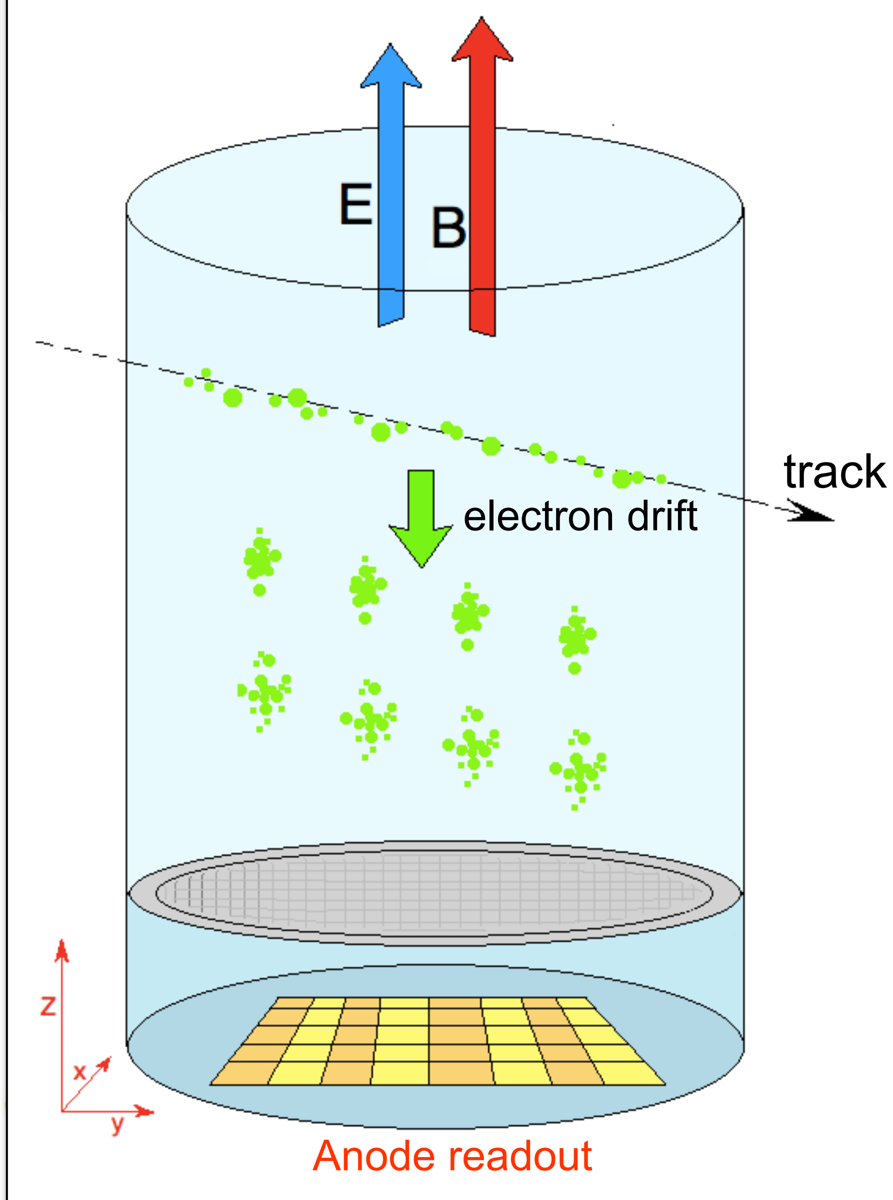
$$\sigma^2 = \sigma_0^2 + D^2 \cdot z$$

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

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

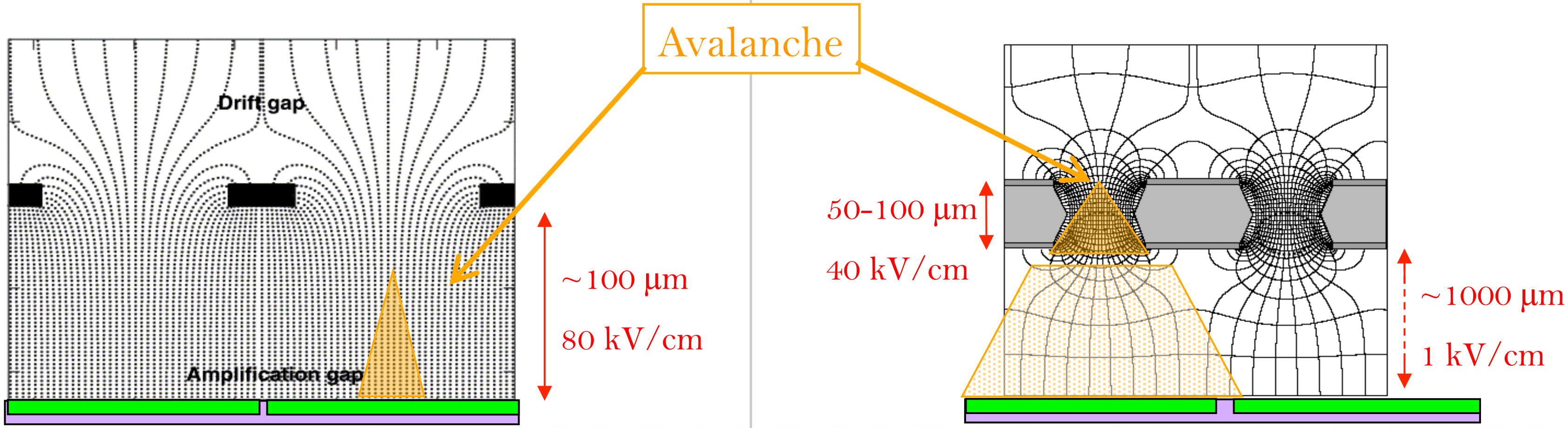
- no preference in track direction
- no E×B effect
- fast signal & high gain
- low ion backdrift
- better ageing properties
- easier to manufacture

Micromegas (MM)

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

GEM

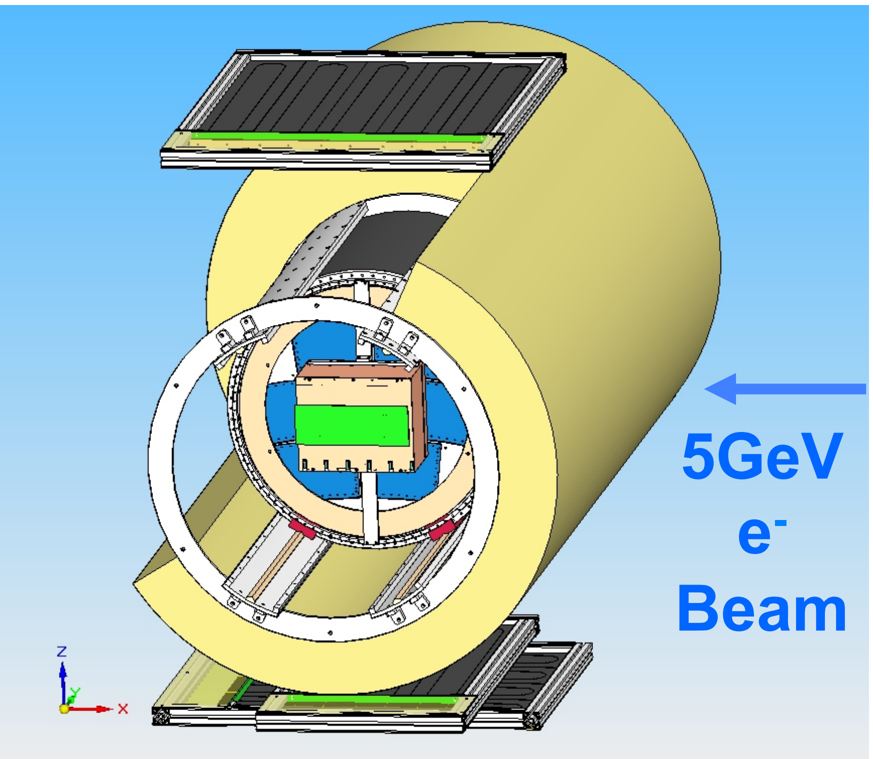
- Gas Electron Multiplier
- 2 copper foils separated by kapton
- multiplication takes place in holes, with 2-3 layers needed



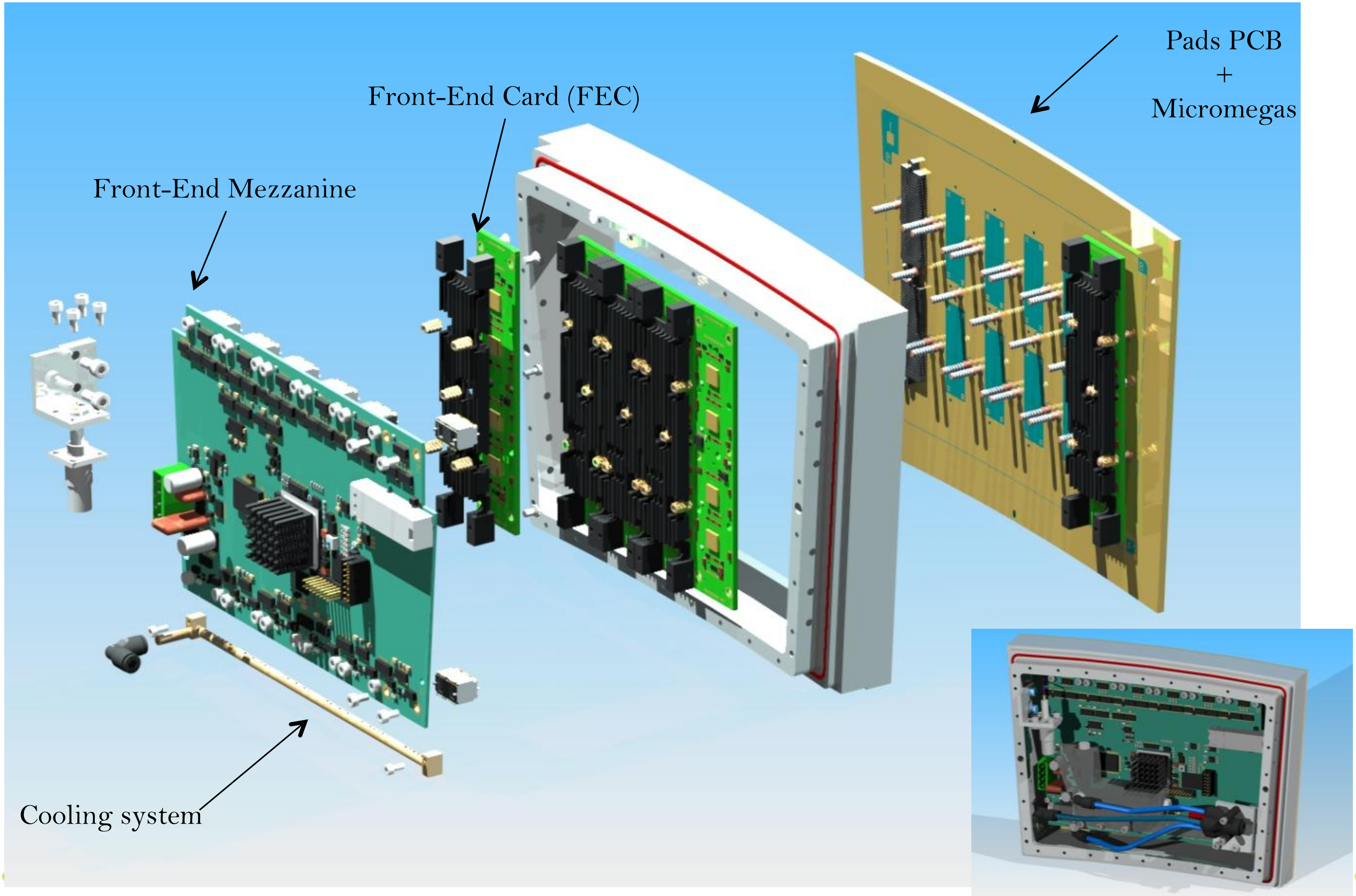
Discharge probability and consequences can be mastered (use of resistive coatings, several step amplification, segmentation) – MPGD more robust mechanically than wires

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