Instrumentation and Accelerator Technologies for ILC & other future Colliders

- ❑ Inform: What is at the horizon
- ❑ Priority: The Physics Questions
- ❑ HL-LHC: Consolidate
- ❑ ILC: Status and R&D
- ❑ Other options: CLIC, CEPC, C3, HE-LHC, LEP-3, FCC-ee, FCC-hh, EIC, LHeC, Muon Collider

CAP Congress

June 7, 2022

Alain Bellerive

Carleton UNIVERSITY

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This talk: list of opportunities for Canada

I am the messanger

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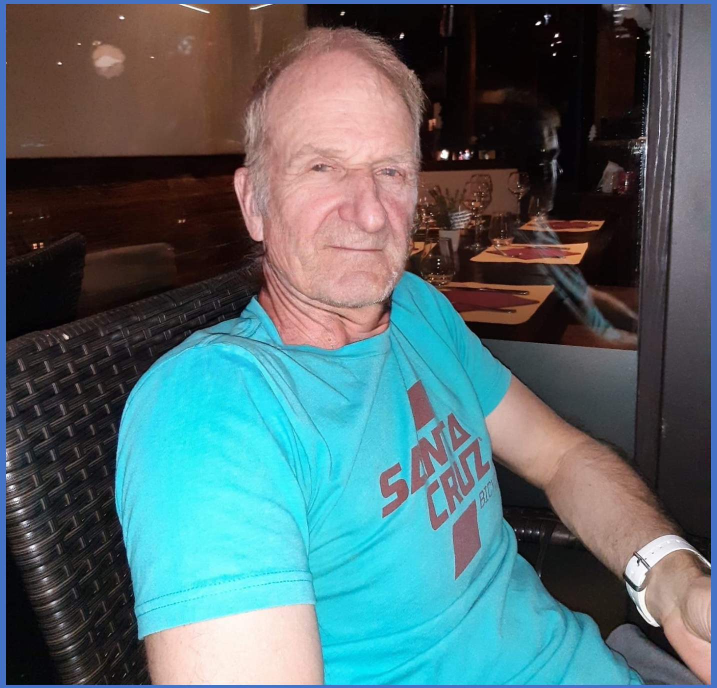
This talk: list of opportunities for Canada

I will retire before any future collider



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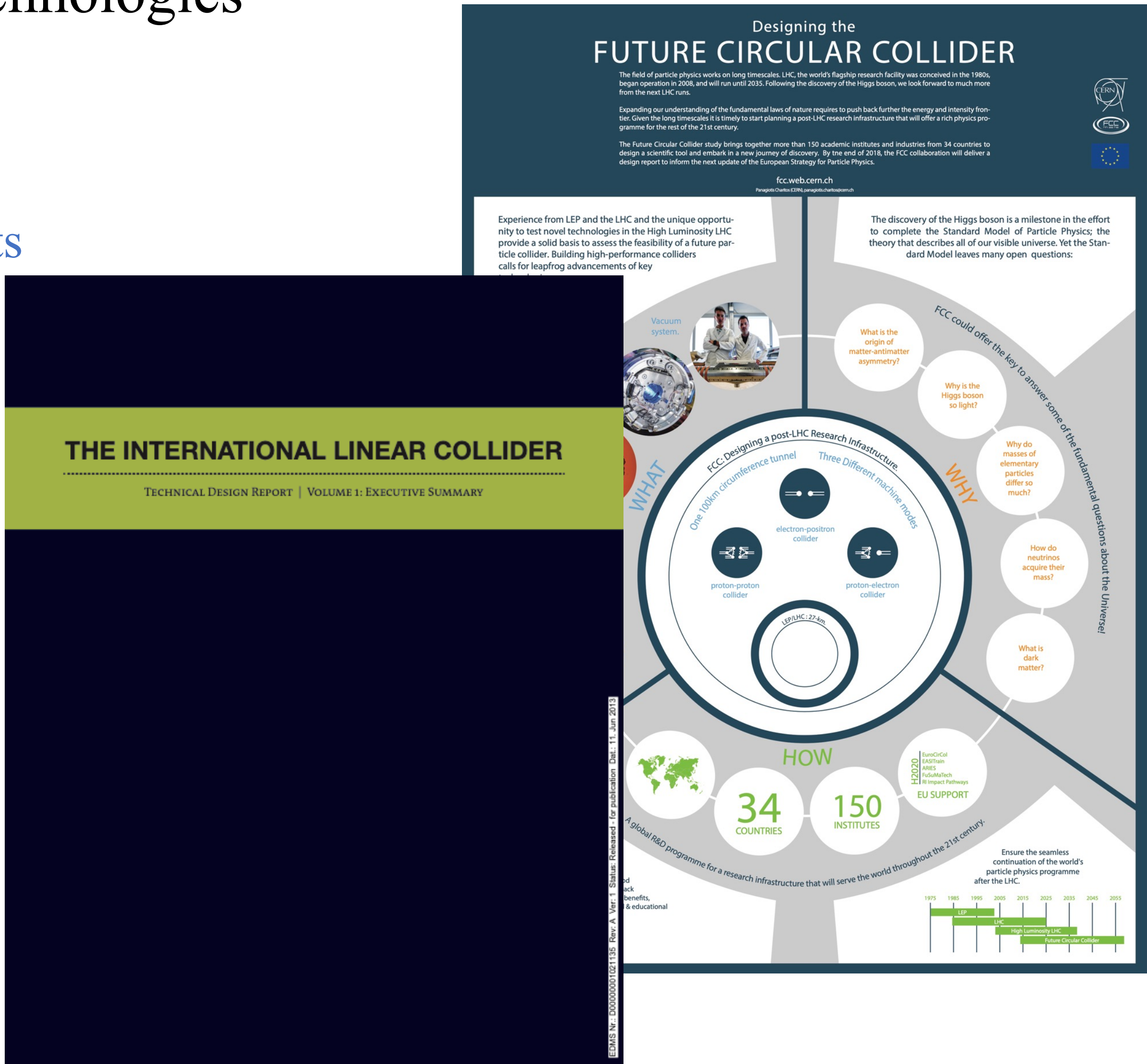
Beyond the HL-LHC: Technology Challenges

- Particle physics community gradually shifting focus towards the **post-LHC era**
- Physics program requires development of new technologies
  - Tracking and Calorimetry with high precision
  - Particle Flow Technique & Particle Identification
  - Cover large area and potentially high rate
  - Extremely high radiation levels close to collision points
  - Detector layouts, readout ASICs, data handling,…
  - Typical funding road: NSERC RTI → CFI
- Focus R&D to specific challenges:
  - Build on existing expertise / explore innovative ideas
  - Material quality (defects, doping, radiation effects,…)
  - New materials/detection techniques
  - Understand physics of radiation damage
  - **Identify synergy and partnership within Canada**
  - Usage of the MRS facilities and invest in youth

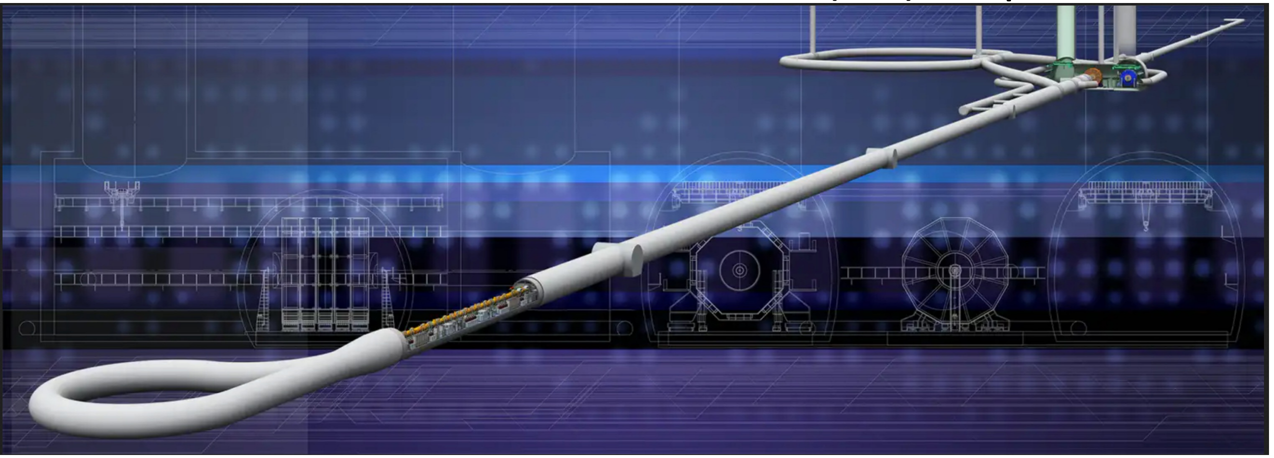


Need to get started on the next 20 year cycle of technology development

Future e^+e^- Colliders

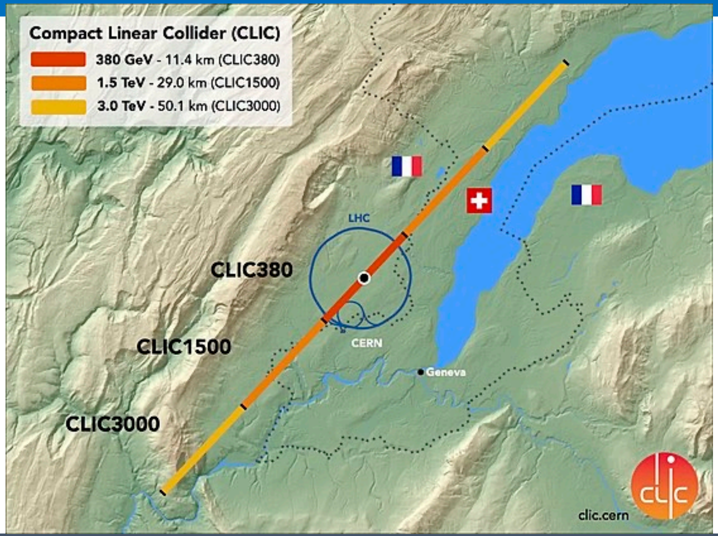
Two Linear Colliders (centre-of-mass-energy can be scaled up)

International Linear Collider (ILC) - Japan

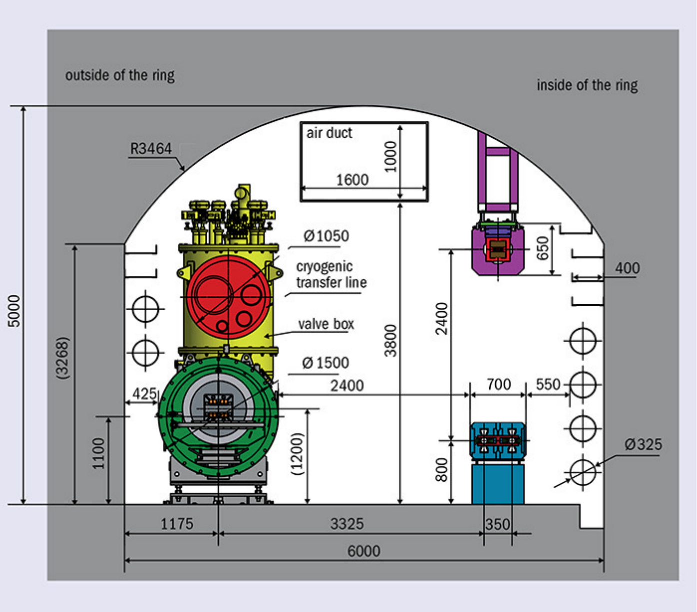


Compact
Linear
Collider (CLIC)

CERN



Two Circular Colliders (can be converted to hadron machines)

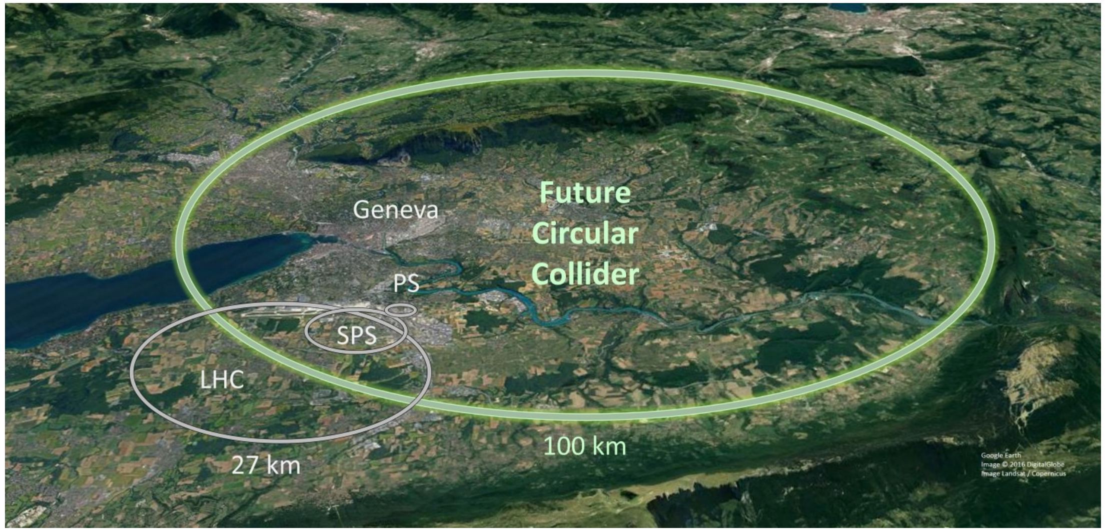


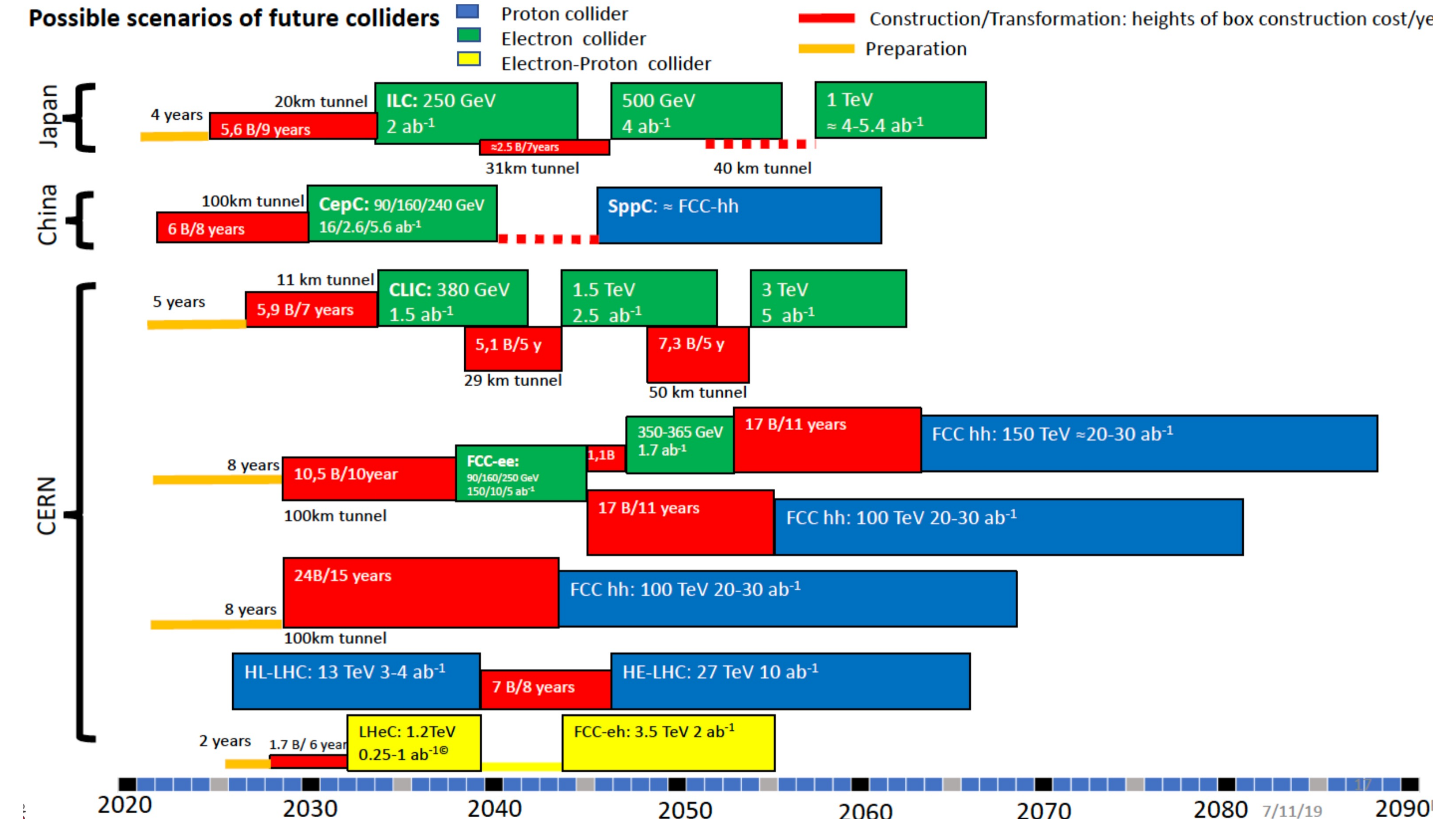
Circular
Electron
Positron
Collider (CEPC)

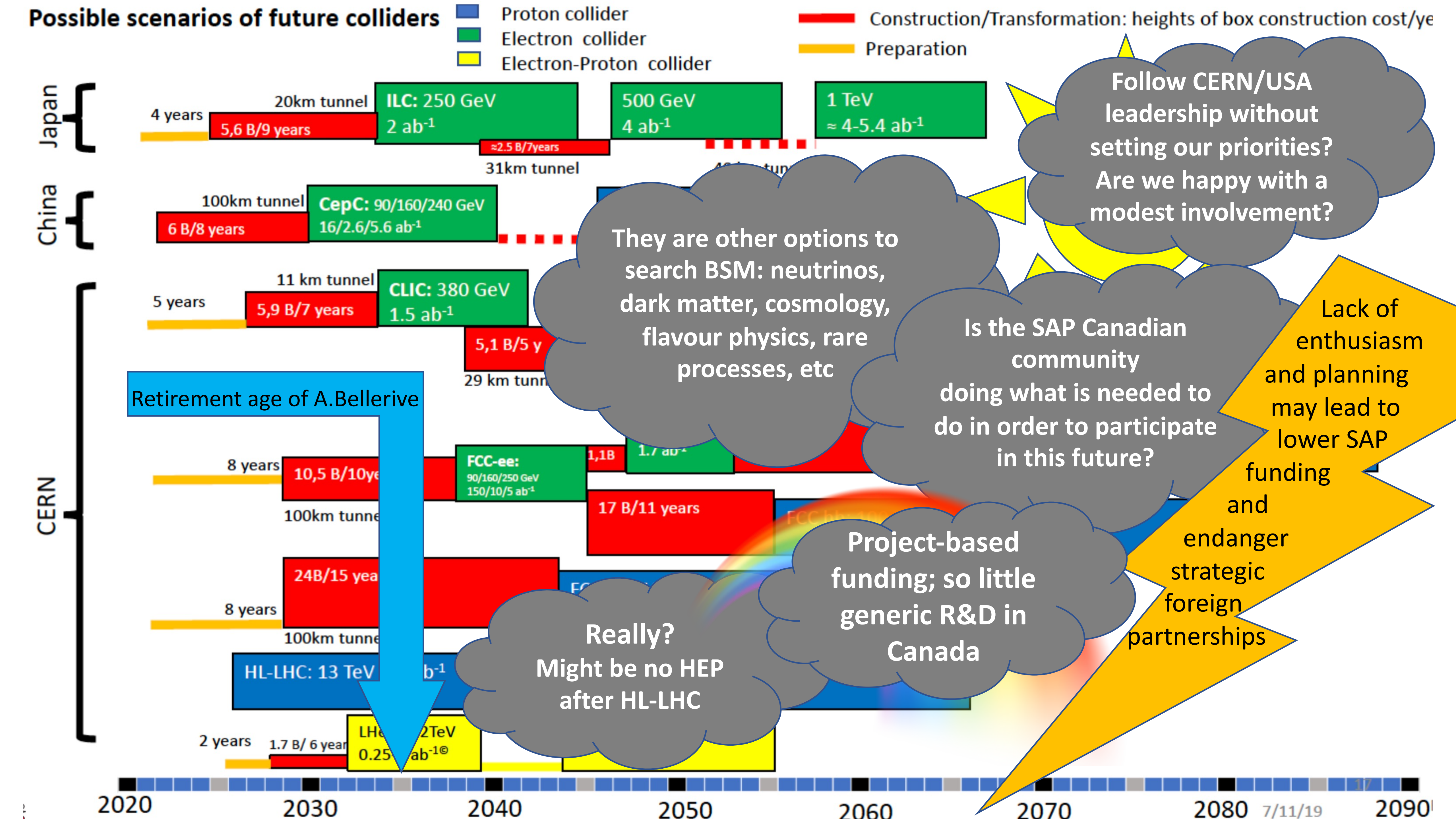
China

… could be politically challenging (no Canadian group yet engaged)

Future Circular Collider (FCC-ee) - CERN




Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/ye
Preparation
Japan
4 years
20km tunnel
5,6 B/9 years
ILC: 250 GeV
2 ab-1
≈2.5 B/7years
31km tunnel
500 GeV
4 ab-1
40 km tunnel
1 TeV
≈ 4-5.4 ab-1
China
100km tunnel
6 B/8 years
CepC: 90/160/240 GeV
16/2.6/5.6 ab-1
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
5,9 B/7 years
CLIC: 380 GeV
1.5 ab-1
5,1 B/5 y
29 km tunnel
1.5 TeV
2.5 ab-1
7,3 B/5 y
50 km tunnel
3 TeV
5 ab-1
8 years
10,5 B/10year
100km tunnel
FCC-ee:
90/160/250 GeV
150/10/5 ab-1
1,1B
350-365 GeV
1.7 ab-1
17 B/11 years
FCC hh: 150 TeV ≈20-30 ab-1
17 B/11 years
FCC hh: 100 TeV 20-30 ab-1
8 years
24B/15 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
7 B/8 years
HE-LHC: 27 TeV 10 ab-1
2 years
1.7 B/ 6 year
LHeC: 1.2TeV
0.25-1 ab-1©
FCC-eh: 3.5 TeV 2 ab-1
2020
2030
2040
2050
2060
2070
2080
7/11/19
2090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8 years
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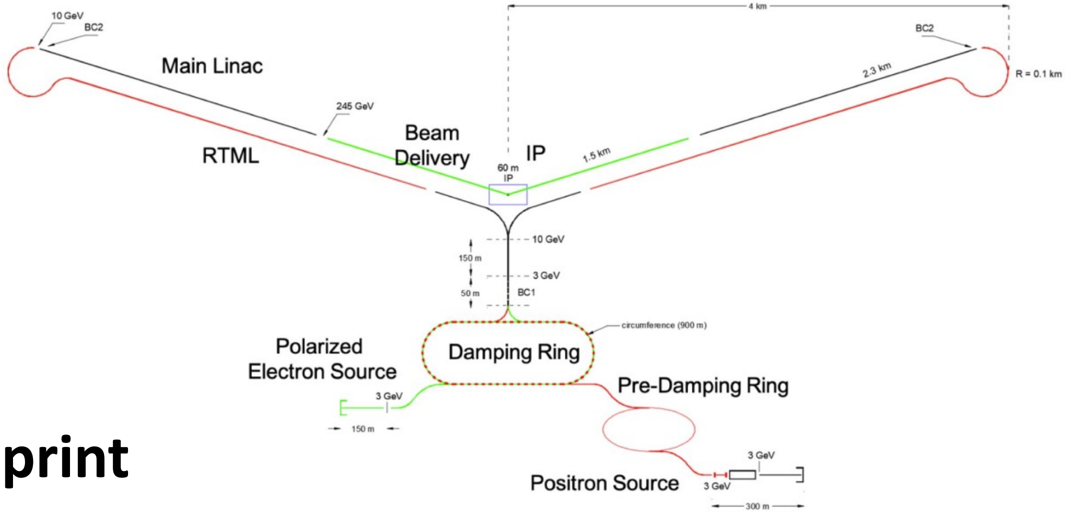
FCC-ee:
90/160/250 GeV
150/10/5 ab-1
1,1B
100km tunne
17 B/11 years
24B/15 yea
8 years
100km tunne
HL-LHC: 13 TeV
2 years
1.7 B/ 6 year
Retirement age of A.Bellerive
They are other options to search BSM: neutrinos, dark matter, cosmology, flavour physics, rare processes, etc
Follow CERN/USA leadership without setting our priorities? Are we happy with a modest involvement?
Is the SAP Canadian community doing what is needed to do in order to participate in this future?
Lack of enthusiasm and planning may lead to lower SAP funding and endanger strategic foreign partnerships
Project-based funding; so little generic R&D in Canada
Really? Might be no HEP after HL-LHC
2020
2030
2040
2050
2060
2070
2080
2090
7/11/19

Others Options

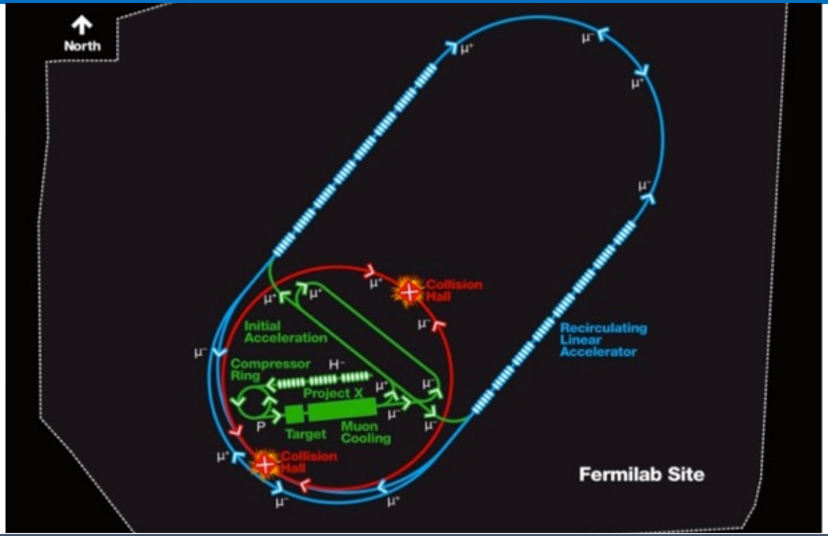
Lepton Colliders



C3 footprint

Muon Collider

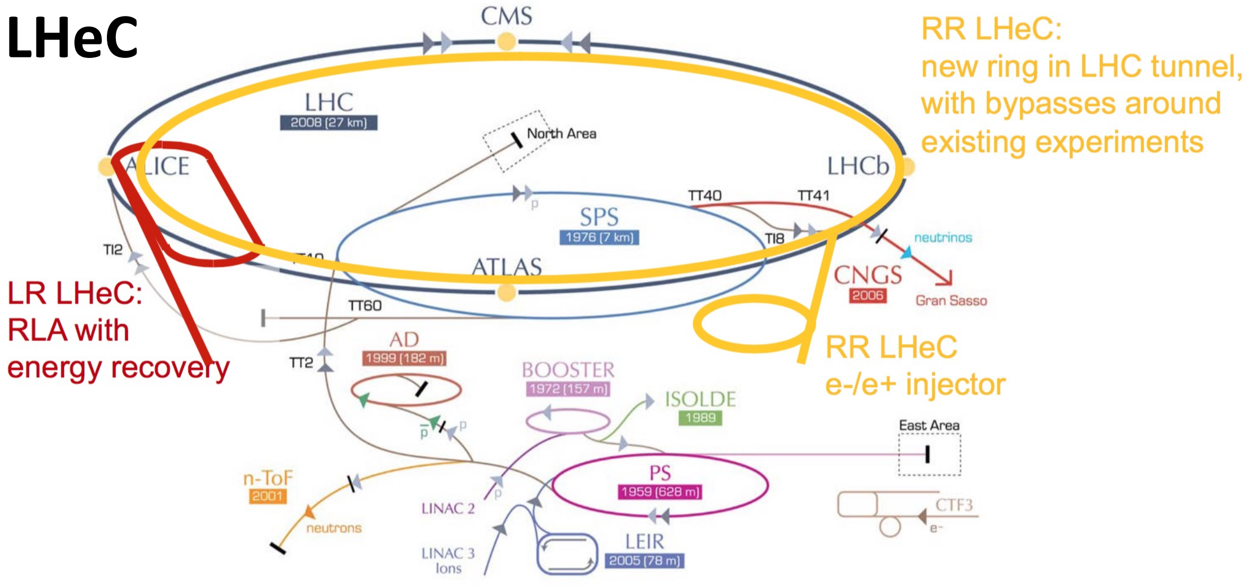
… here depicted on the FNAL site



Hadron-Electron Collider

Electron Ion Collider (EIC) – RICH + e-ring

LHeC



SNOMASS Energy Frontier Benchmark Scenarios

High Energy Machines

Snowmass 2021 EF Discovery Collider Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV	15
FCC-hh	pp	100 TeV	30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV	1 2
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 30 TeV	1 10 10

Higgs Boson Factories

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Source: Meenakshi Narain (FCC week May 2022)

SNOMASS Energy Frontier Benchmark Scenarios

High Energy Machines

Snowmass 2021 EF Discovery Collider Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{L}$
HE-LHC			
FCC-hh			
		…TeV	1
		3.5 TeV	2
…gy muon-collider	$\mu\mu$	3 TeV 10 TeV 30 TeV	1 10 10

Higgs Boson Factories

Snowmass 2021 Higgs Factory Study Scenarios

Collider	Type	$\sqrt{s}$	$\mathcal{P}$[%]	
HL-LHC	pp			
ILC and C…		…TeV	…/ ± 30 ±80/ ± 20	0.2 4 8
	ee	380 GeV 1.5 TeV 3.0 TeV	±80/0 ±80/0 ±80/0	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		150 10 5 1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

All options on the tables for the next P5 in the USA.

ALCC recommending that the next global accelerator should be an e^+e^- Higgs factory.

Critical to realize at least **one** such machine somewhere in the world.

Source: Meenakshi Narain (FCC week May 2022)

The Physics Questions?

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June 7, 2022

Alain Bellerive

Carleton University

Fundamental Questions at the Energy Frontier

- What is the origin of the electroweak scale?
  - The Higgs discovery is a unique handle on BSM physics and we need to make the most out of it.
  - Can we uncover the nature of UV physics from precision Higgs measurements (mass, width, couplings, Higgs self-interactions)?
  - How does this improve the constraining power of global EW fits?
  - Can we measure the shape of the Higgs potential? Can the Higgs boson give us insight into flavor physics and vice versa?
  - What are the implications for Naturalness?

- How to build a complete program of BSM searches via both model-specific and model independent explorations?

- Of course, the most important question is: **do *you* really want an electron-positron future?**

- Is the absolute probe a proton-proton machine so shall *you* wait 2044 for the 100 TeV FCC-hh?

- **Do *you* want the next e^+e^- machine to be 2034 (ILC, LEP3 or C3) or around 2040 (FCC)?**

Energy Frontier Colliders

- ❑ Discoveries at the Energy Frontier are intricately linked to new accelerators and detector instrumentation. Price tag & duration of deployment are major issues.

Proceed along two complementary axes for scientific justification:

1) Study known phenomena precisely at high energies [historically e^+e^- machines]
   - ➢ Factory of Higgs bosons, or other known particles
   - ➢ Electroweak (EW) physics
   - ➢ QCD and Strong Interactions

2) Search for direct evidence of BSM physics [usually hadron machines]
   - ➢ Next high energy frontier machine
   - ➢ Ultimate energy reach to potentially discover new physics

- ❑ **What are the most promising future colliders?**

High-Luminosity Large Hadron Collider
HL-LHC at CERN

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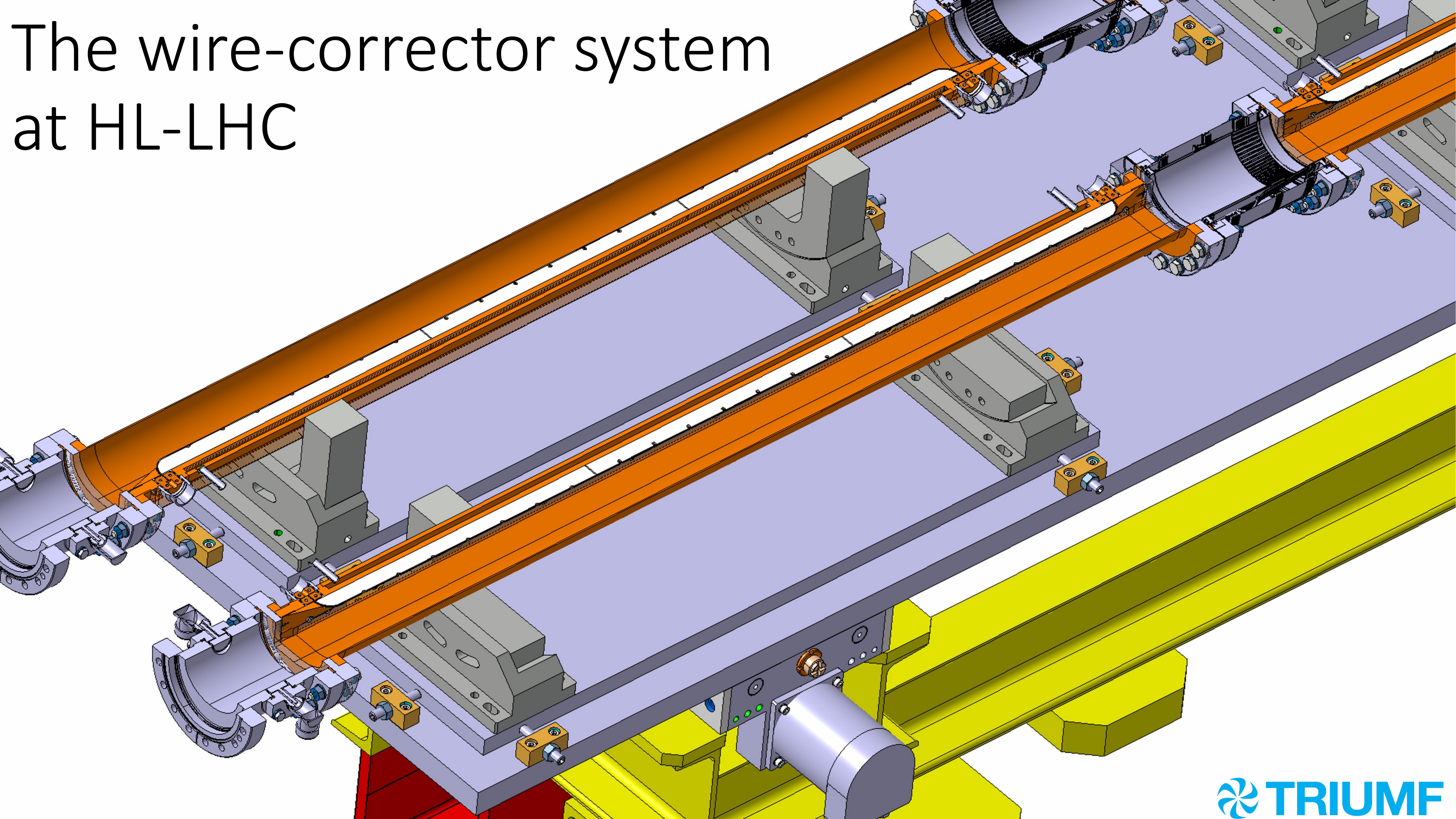
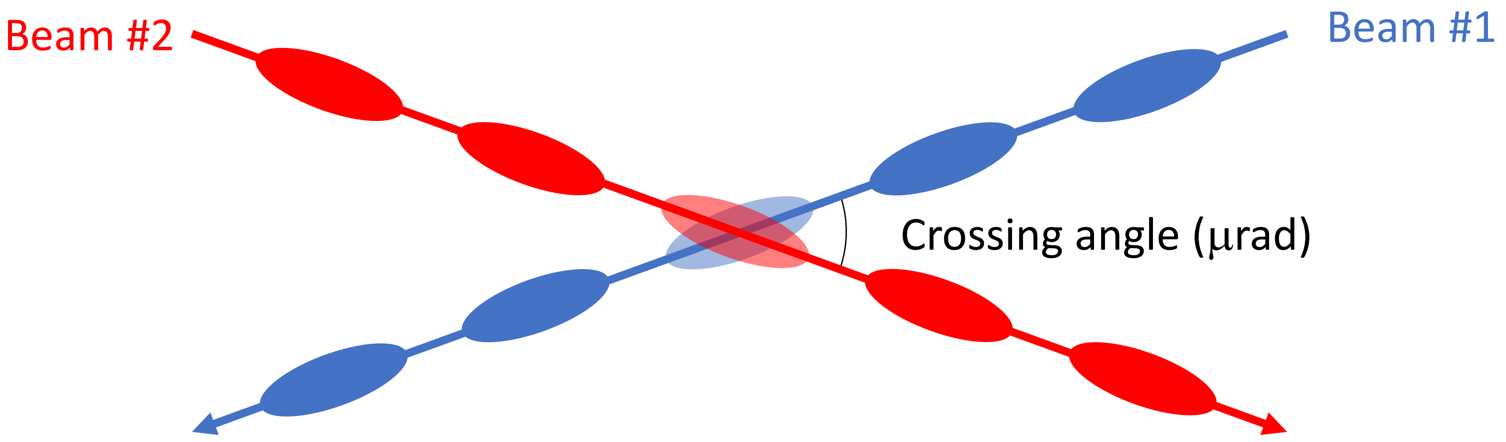
The wire-corrector system at HL-LHC



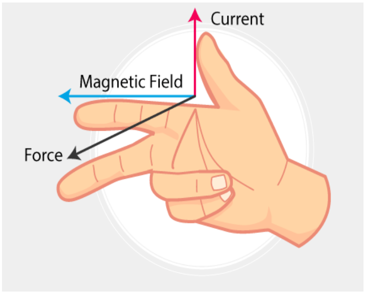
The concepts: expertise at TRIUMF

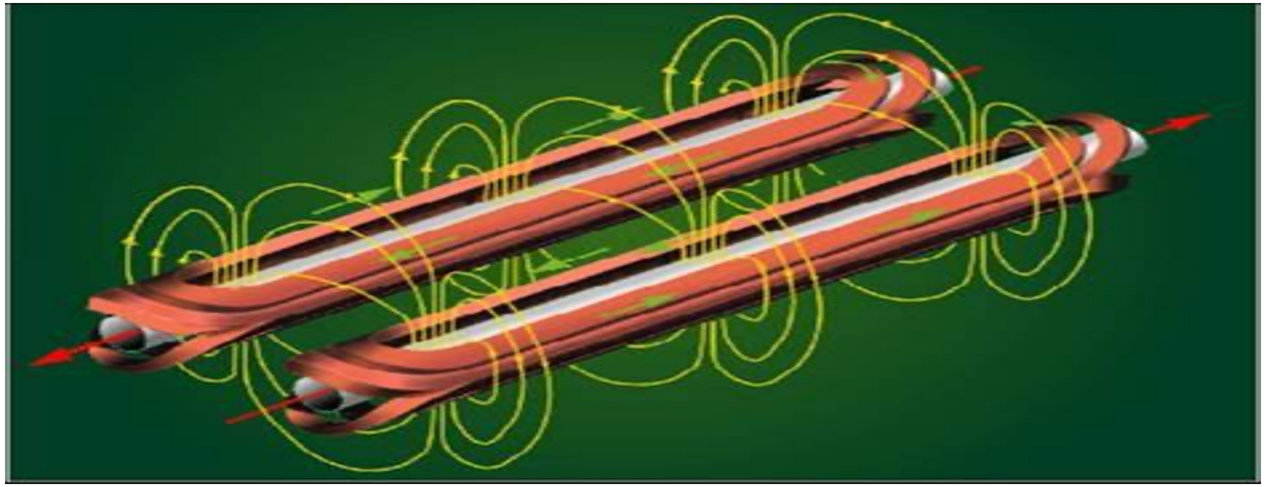


Beam separation (in unit of σ, beam size)

Need to minimize Long Range Beam-Beam interactions

Compensate by use of the **magnetic field** and Lorentz force ($\vec{F} = e\,\vec{v}\times\vec{B}$) from **two direct-current wires** positioned on each side of the Interaction Region (IP)



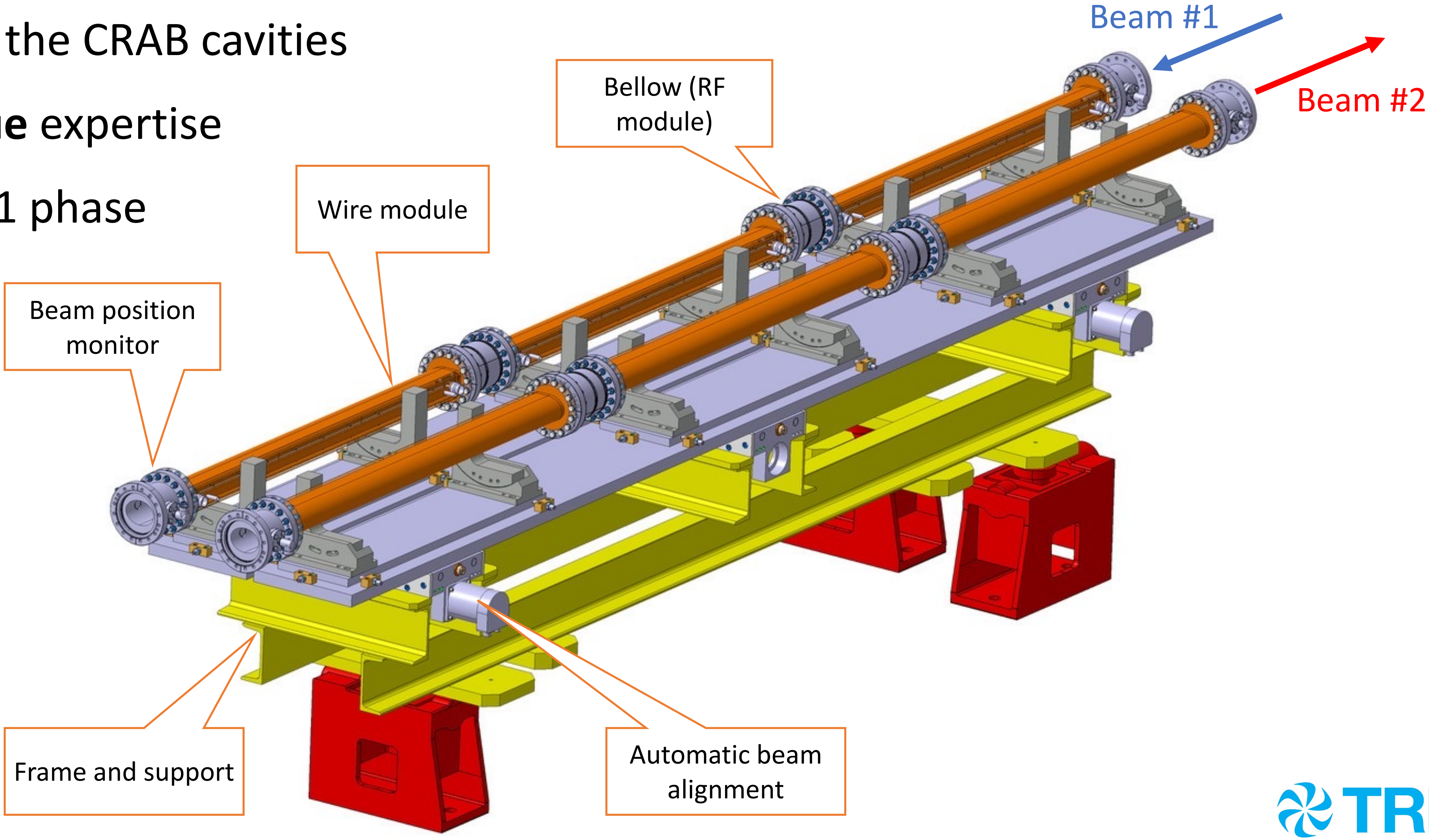


Original idea and validation by TRIUMF

Technical expertise in Canada and CERN

Main assembly

- Project to be coordinated with **ATLAS Canada** to optimize physics potential at HL-LHC
- Insure **stability** of the beams, maximize luminosity with minimum risk of collider operation
- Complements the CRAB cavities
- TRIUMF **unique** expertise
- Gate0 → Gate1 phase



TRIUMF

International Linear Collider
ILC in Japan

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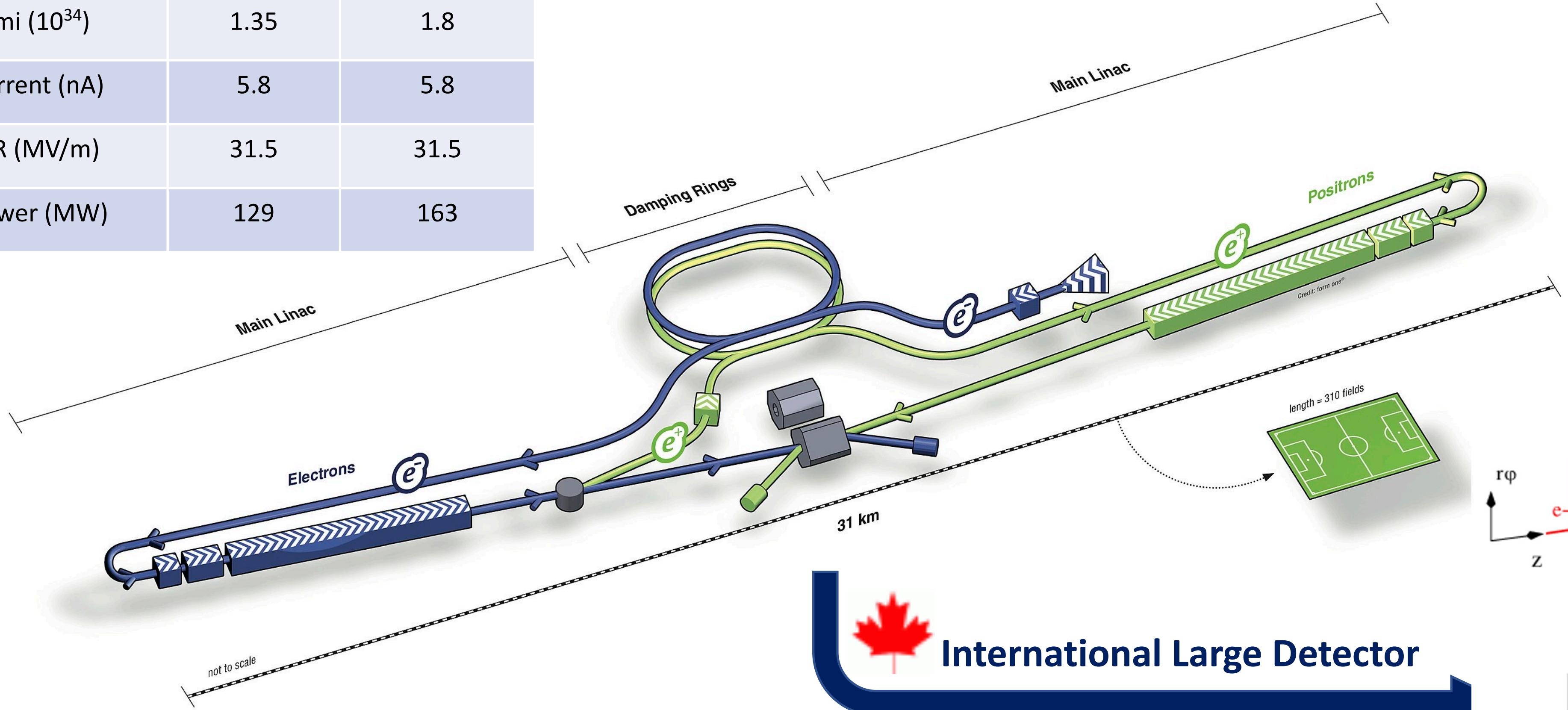
International Linear Collider (ILC) at $\sqrt{s}$ = 250 GeV

ILC is the most mature and timely-ready Higgs Factory to be deployed

The Linear Collaboration Board responded to the request from the International Committee for Future Accelerator to put in place an ILC Pre-Lab Development Team by 2022 for ILC in Japan … but it did not happen.

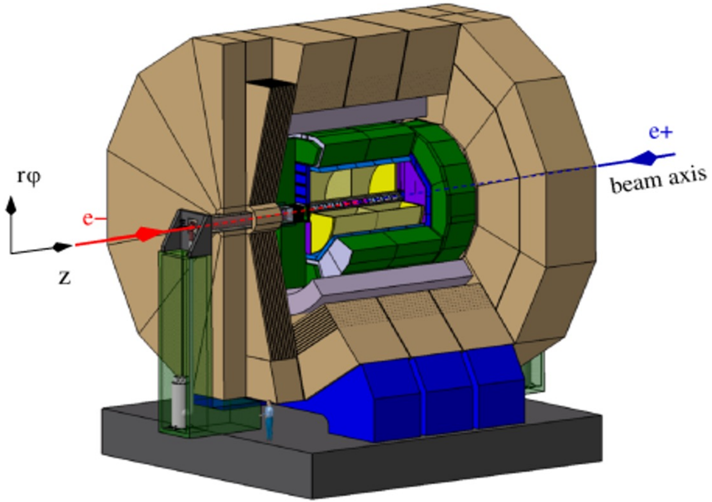
Parameters	250 GeV	500 GeV
Lenght (km)	20	31
Lumi (10^{34})	1.35	1.8
Current (nA)	5.8	5.8
SFR (MV/m)	31.5	31.5
Power (MW)	129	163



International Large Detector

ILD

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



Status Internaitonal Linear Collider - ILC

- ILC is a concrete achievable realistic practically shovel-ready with lots of potential coupled with synergy with light-sources in Europe & US and TRIUMF e-linac

- Context: build the ILC in Japan with construction 2026-2034. Physics 2034.

- International Development Team (IDT) had a mandate of 1-2 years to establish the ILC Pre-Lab

- **KEK informed the IDT that the Pre-lab budget request would not be made for the 2022 Japanese fiscal year. MEXT considered ILC to be premature with need for more international discussion on funding scenarios. Hence, no commitment from Japan to host the ILC.**

- KEK will identify ways to continue accelerator R&D funding set as priorities by the IDT

- **Detector Concepts (ILD & SiD) moving towards generic R&D for the next e^+e^- colliders**

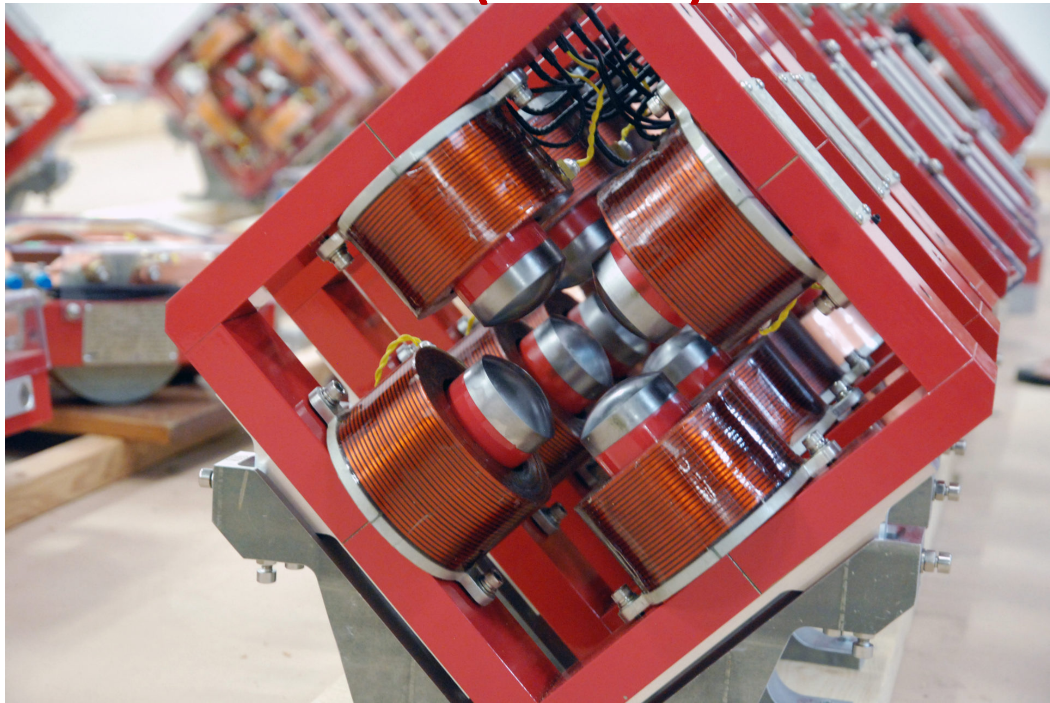
SCRF Industrialization Critical for future e^+e^- colliders

TRIUMF's e-linac - Electron Linear Accelerator

Many accelerator projects (light sources, medical isotope) world-wide are applying & advancing Superconducting Radiofrequency (SCRF) technology, SCRF cavity production and thus pushing SCRF performance (*e.g.* field gradient)

The second driver for TRIUMF's beam program is the **world's highest power e-linac for rare isotope production**, which came online in 2021

Technology used in e-linac is similar to what is intended to be used for ILC (and EIC)



TRIUMF

Micro Pattern Gas Detector (MPGD)

Technology choice for TPC readout: Micro Pattern Gas Detector

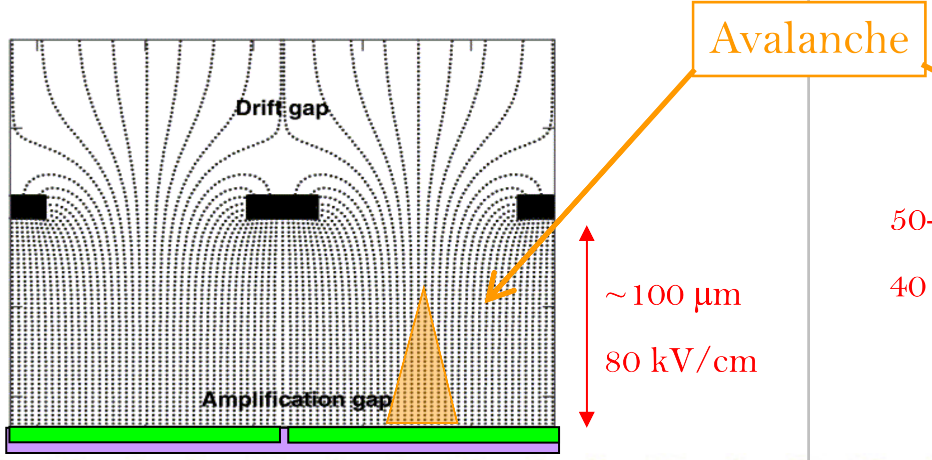
- no preference in track direction
- no E×B effect
- fast signal & high gain
- low ion backdrift
- better ageing properties
- easier to manufacture

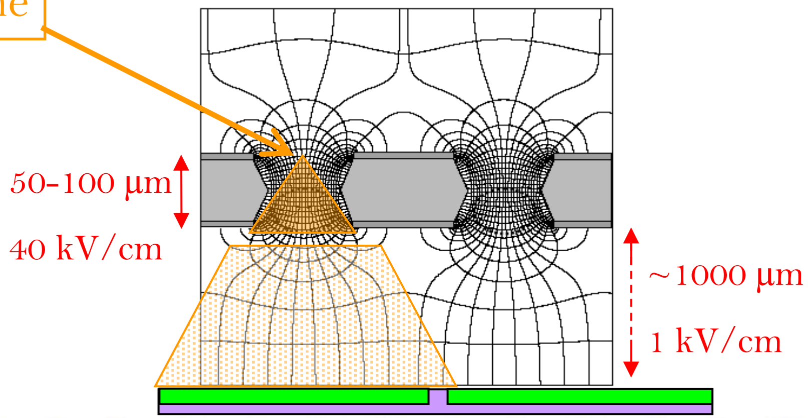
Micromegas (MM)

- 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





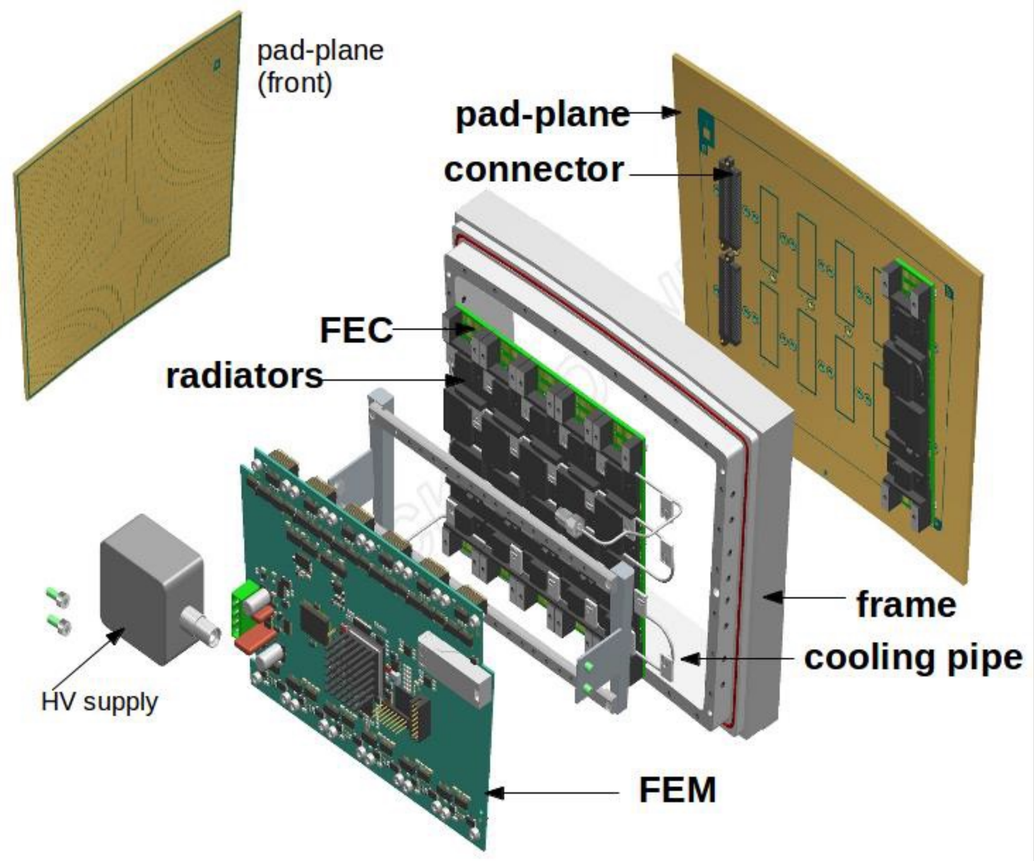
Discharge probability and consequences can be mastered (use of resistive coatings, several step amplification, segmentation) – MPGD more robust mechanically than wires

Time Projection Chamber (TPC) for ILD

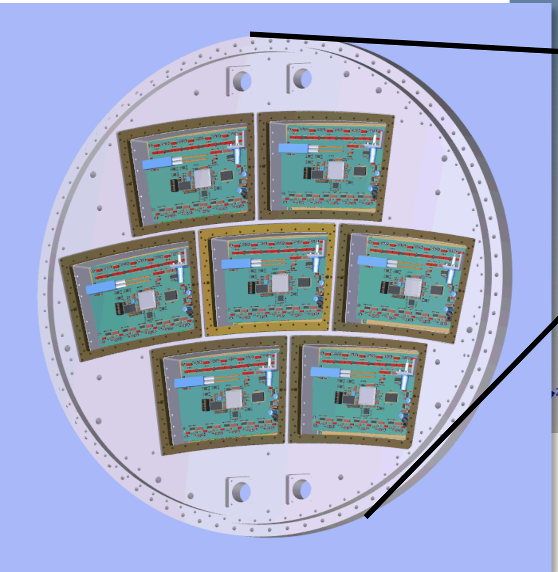
Main activities on micropattern gas detector (MPGD & RD51)
Funding since early-2000 – Carleton University

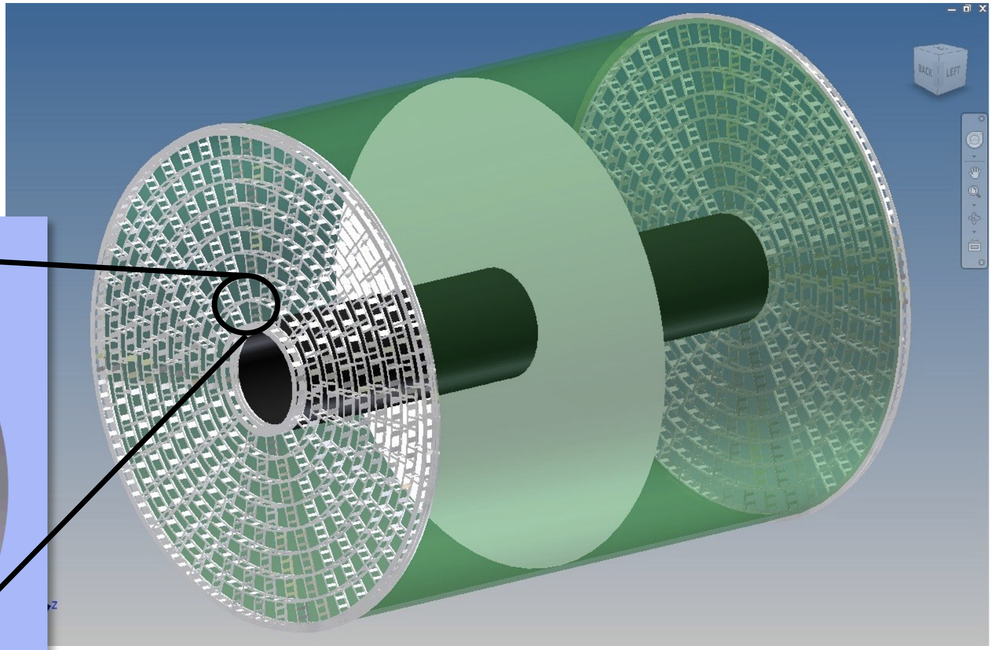
- Two options with similar resolution for endplate readout with **pads**:
  - **GEM:** 1.2×5.8 mm² pads (smaller pad – more electronics)
  - **Resistive Micromegas:** 3×7 mm² pads (larger pads – less electronics)
- Alternative: **pixel** readout with pixel size ~55×55 μm²

Micromegas module



Large Prototype TPC
Endplate of 7 panels, ø = 80 cm





ILD TPC

LCTPC Collaboration for ILD:

3 regions (America, Asia, Europe), 25 member institutions, 22 observer institutions
A. Bellerive co-spokeperson until August 2022

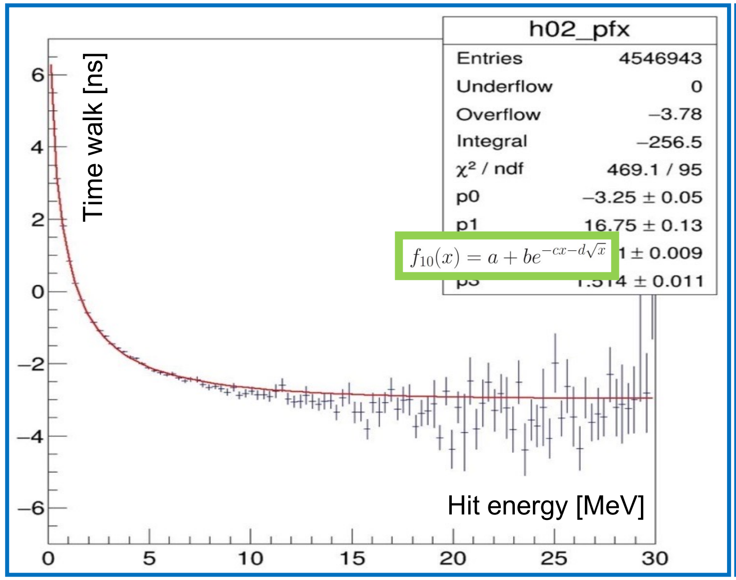
Calorimetry R&D at CALICE for ILD

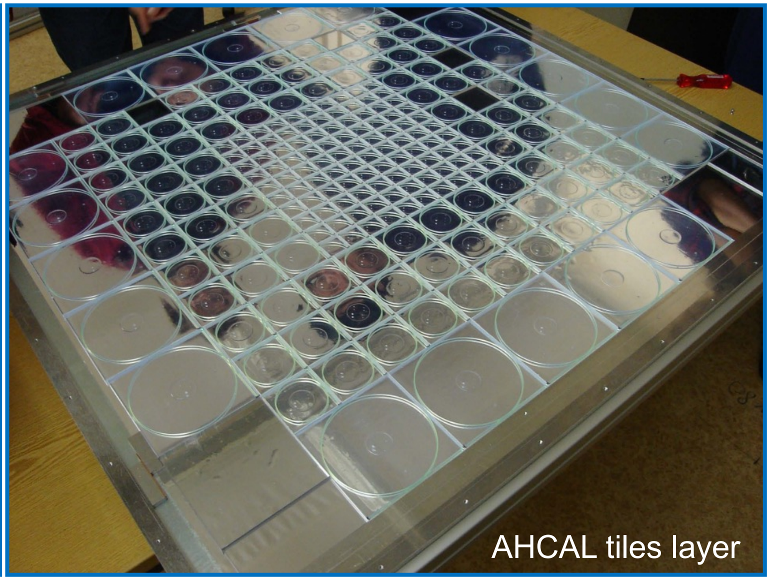
Main activities on very high granularity detectors (~ cm^2):

Started in 2006 working on the **Analog Hadronic Calorimeter (AHCAL)** with simulation, alignment and performance analyses, new algorithm.

With NSERC funding, McGill joined Argonne (ANL) to design, build and test the novel **Digital Hadronic Calorimeter (DHCAL)** prototype until completion. Several publications followed.

Now on the improved AHCAL with added accurate timing information for each hit to discriminate background and further particle ID. The new CMS forward detector is based on this technology.




AHCAL tiles layer

Test Beam Data Taking

CALICE Collaboration on calorimetry R&D:

18 countries, 60 institutes, 350 physicists/engineers
Originally for ILC experiments, now also generic R&D

Contact: François Corriveau

Build on expertise of ILC TPC and ATLAS sTGC GridPix

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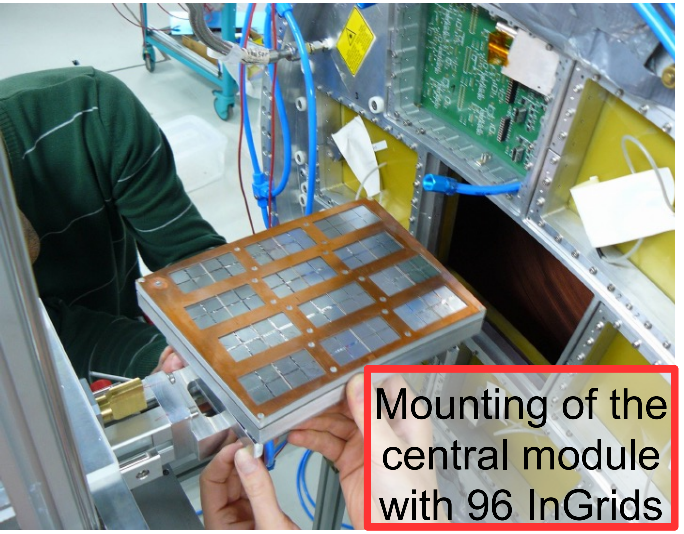
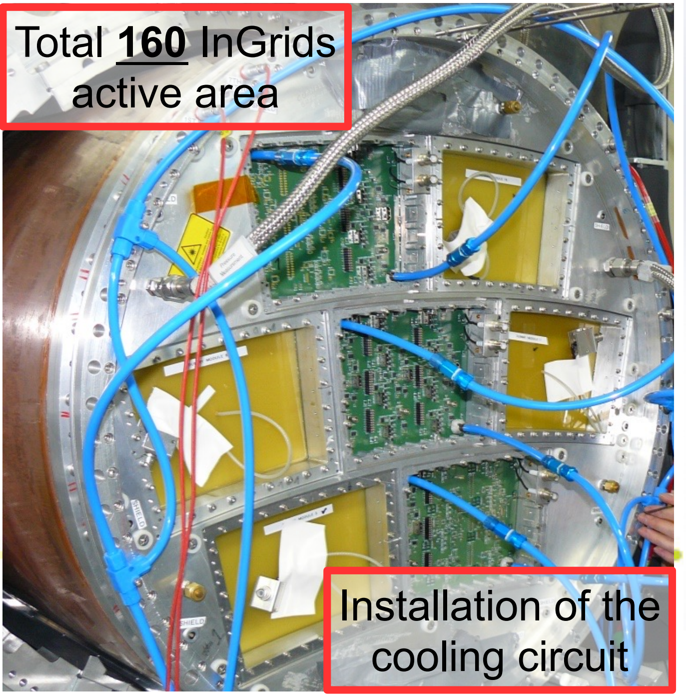
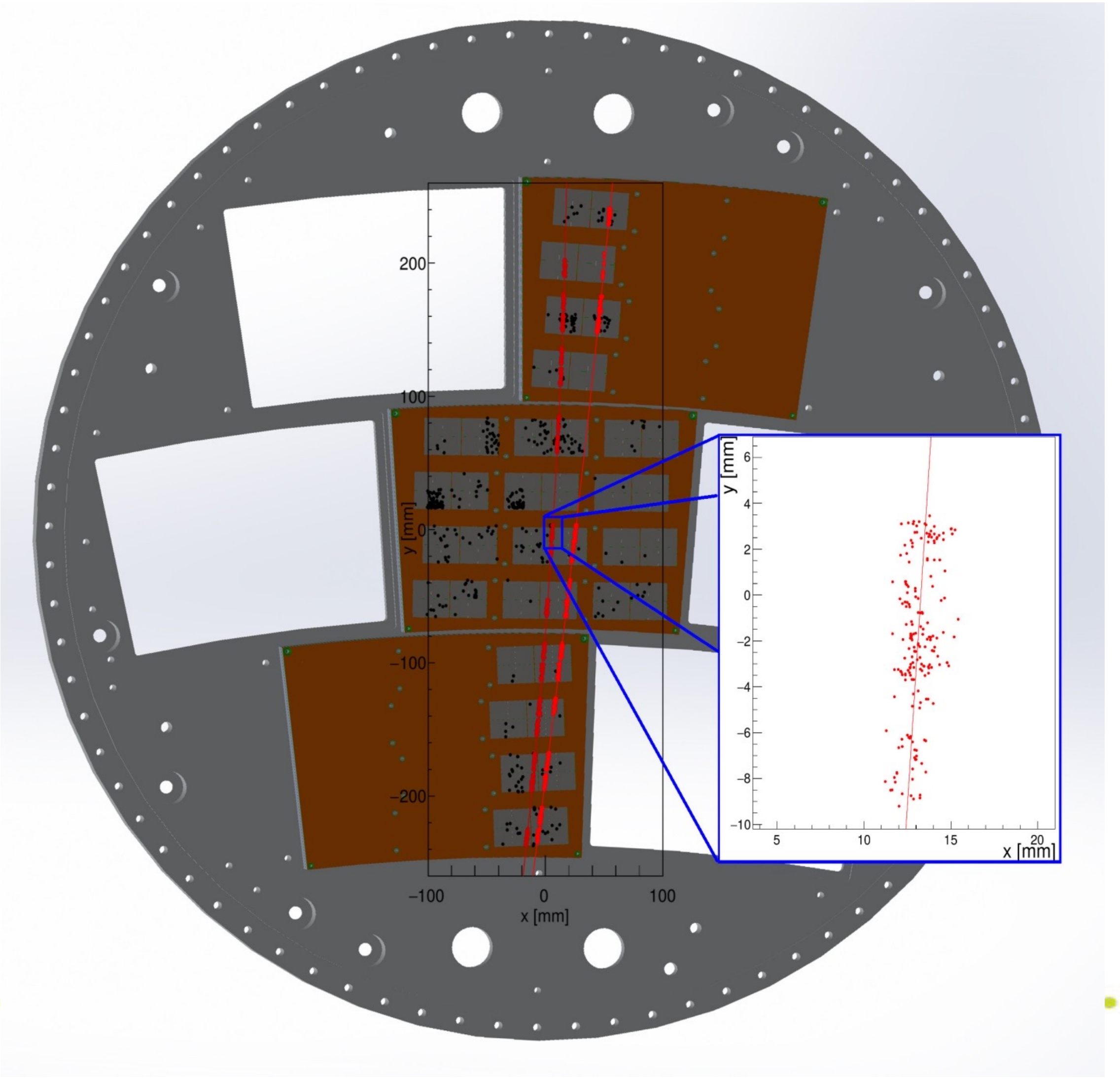
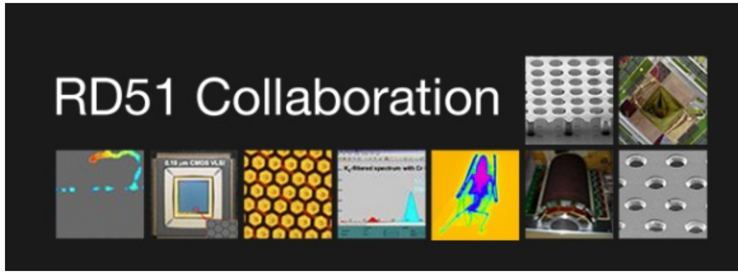
GridPix for Ultimate TPC (ILC, CEPC, Belle3, …)





Large scale application / Large active area



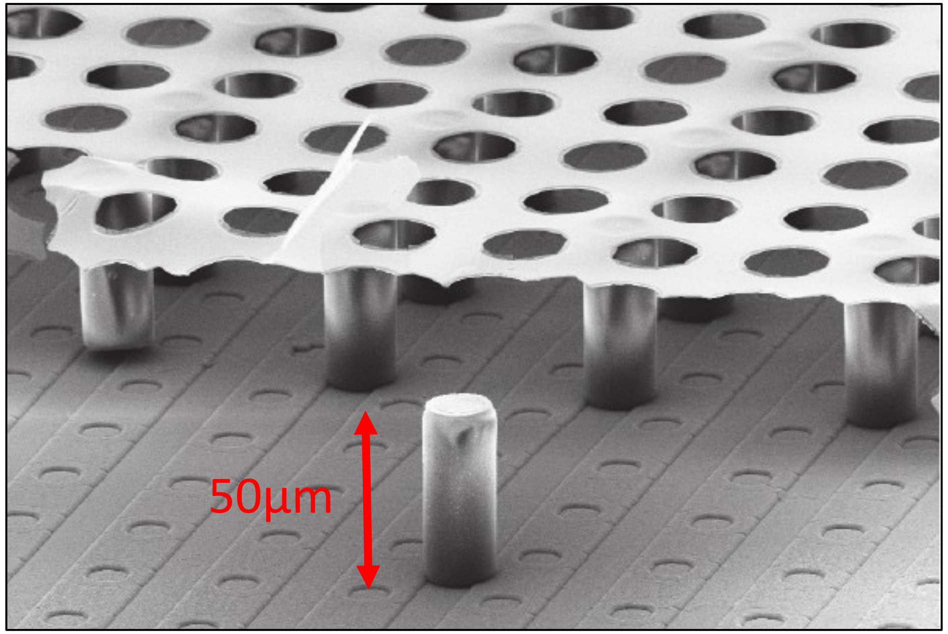


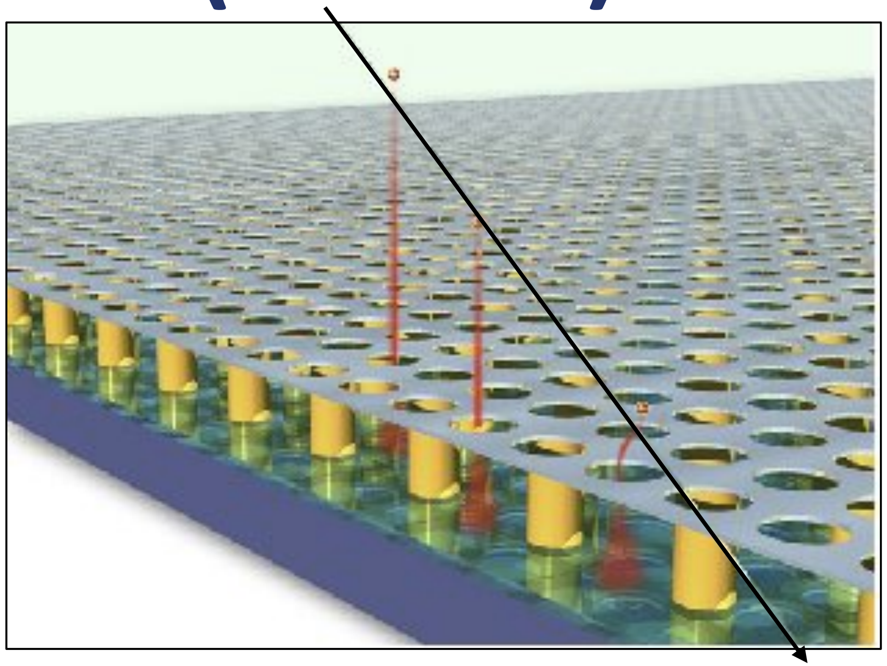
Part CERN R&D framework and EU Detector development

Whitepaper submitted to SNOWMASS

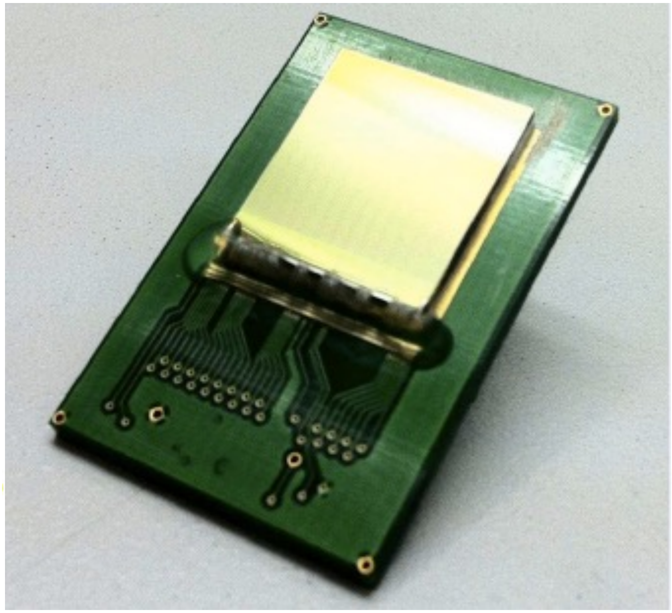
Contact: Alain Bellerive

Highly Pixelated Readout (GridPix)





- Micromegas on a pixelchip (**Timepix+Micromegas = GridPix**)
- Resistive protection layer (4-8 μm) on top of chip
- Insulating pillars between grid & pixelchip
- **One hole above each pixel / see each ionization electron**
- Amplification directly above the pixelchip
- Very high single point resolution, 2% dE/dx resolution
- Why not R&D in Canada?



Timepix: 256 x 256 pixels of size 55 x 55 μm^2

➢ Low threshold level ~500 e- (90 e- ENC)

Capitalized on ATLAS ITk investment
Radiation Hard Silicon Detectors
Future collider silicon-based tracker

CAP Congress

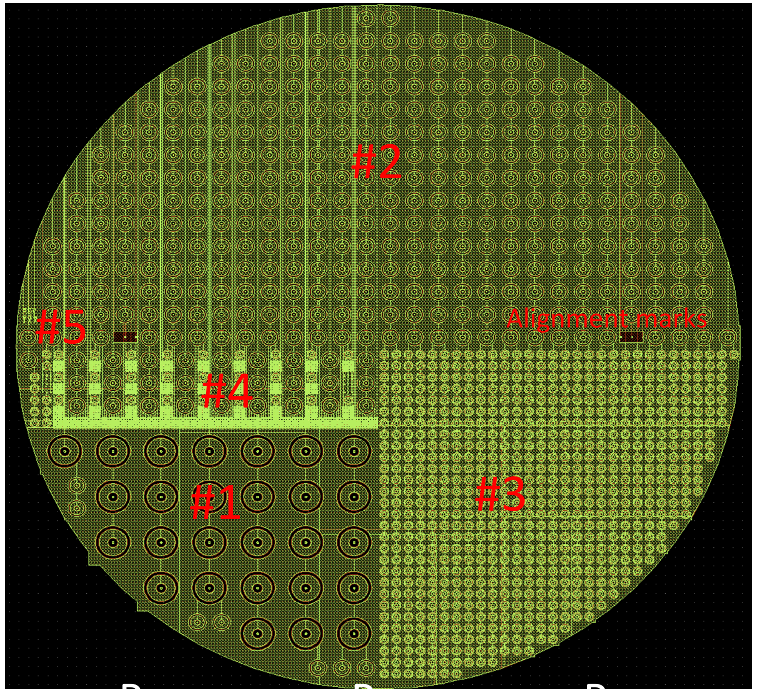
June 7, 2022

Alain Bellerive

Carleton University

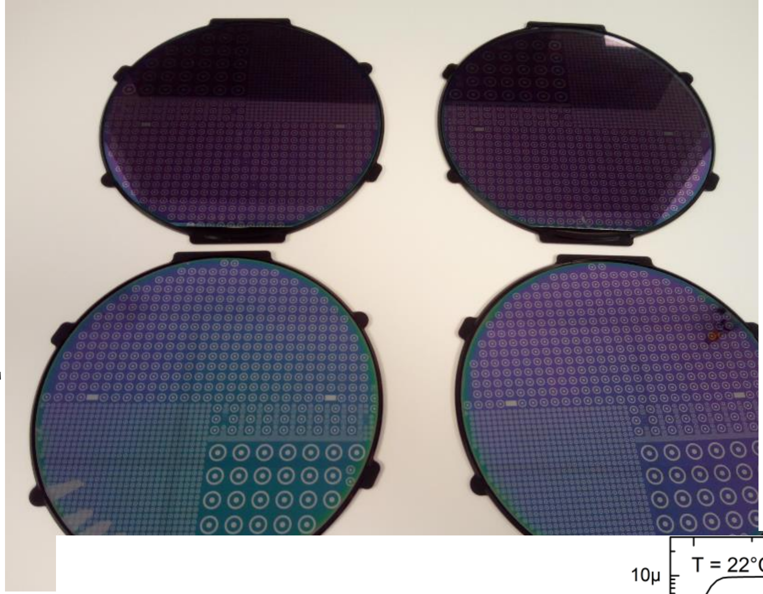
R&D Examples – Material Defects

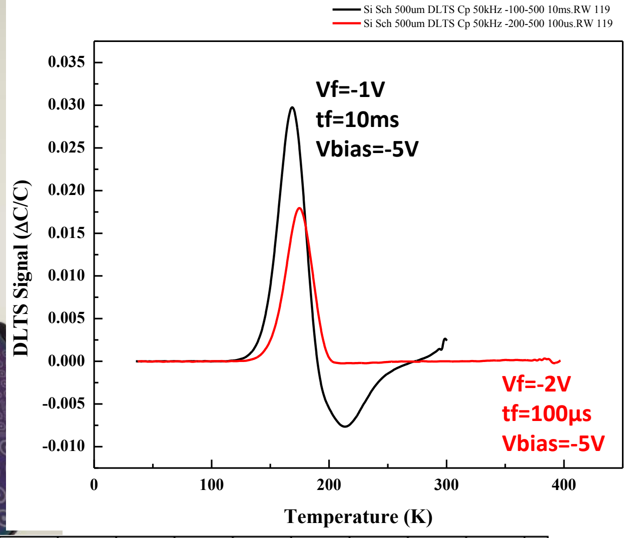
Radiation Damage of Epitaxial p-type Si – Schottky Diodes + pn Junctions

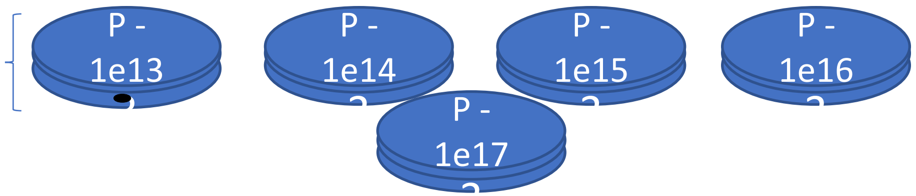


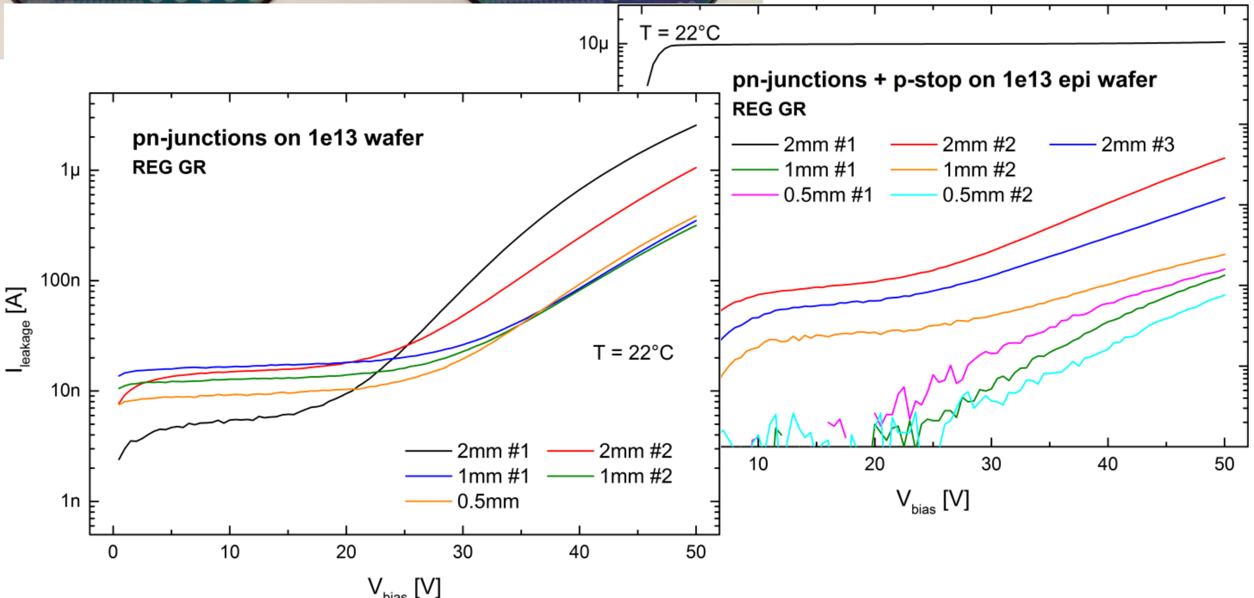
RAL/ITAC

Carleton/CUMFF









Si wafers (6 inches) of different epitaxial doping levels each

- P type doped with different **epitaxial** doping levels
- 10 Wafers /each doping type

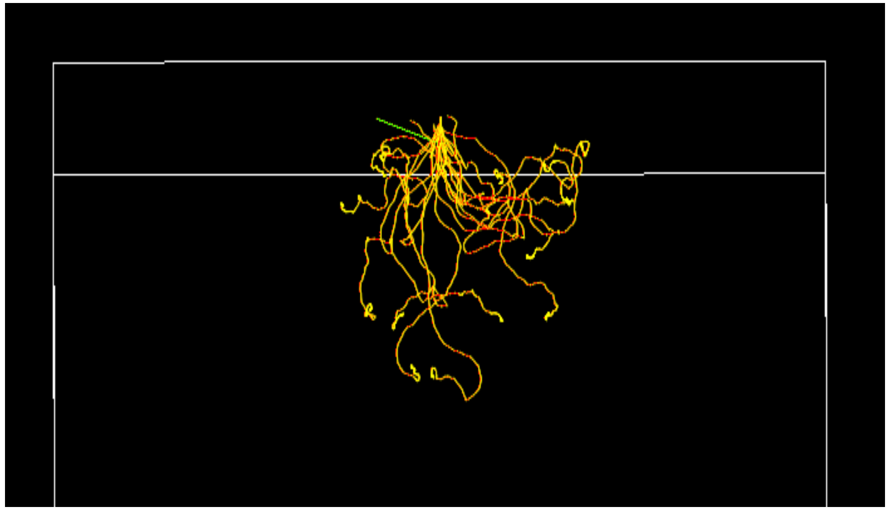
Contact: Thomas Koffas / Bernd Stelzer / Luise Poley

R&D Examples – New Materials

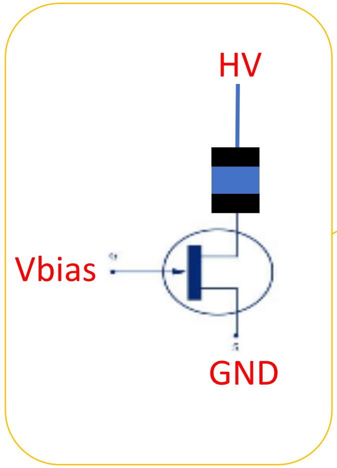
NRC GaN Fabrication Process Radiation Hardness

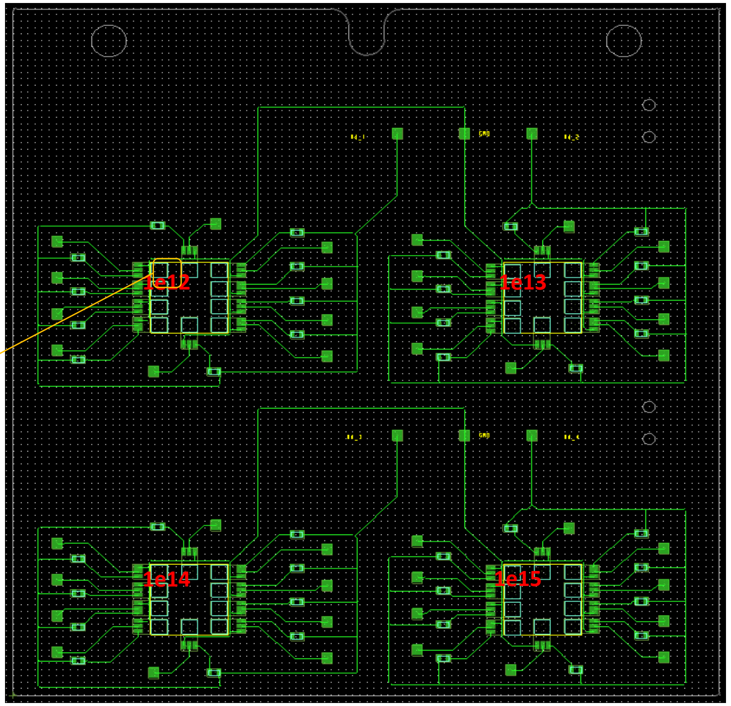
Modified GaN HEMT structure as rad-hard sensor for ionizing radiation

- GEANT4 simulations of 500 keV normally incident β-particles on a GaN slab demonstrate sufficient energy deposition for detection

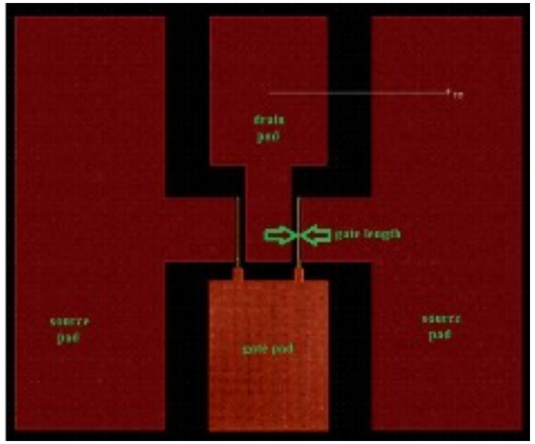


- TCAD simulations being performed on the modified GaN HEMT to investigate if gain can be achieved in a similar manner to that of LGADs
- Aim to irradiate some GaN HEMTs fabricated by NRC with 26MeV p up to **fluences of 10^{15} [cm^2]** (TID around 230Mrad [GaN]) to compare with previously irradiated Panasonic GanFETs used in Strips ITK





PCB holding up to 40 NRC 1x2 mm2 GaN devices, divided into 4 blocks. Each block of 10 devices receives a different p fluence, up to 1e15 [cm-2]



NRC 1x2 mm2 GaN HEMT layout
Each 1x2 mm2 chip contains 4 HEMTs, differing in gate length

Contact: Thomas Koffas / Bernd Stelzer / Luise Poley

R&D Framework – CERN Collaborations

The RD50 Collaboration

RD50

An international collaboration that aims to provide radiation-hard semiconductor devices for future colliders

New!

- ***63 institutes, 370 members***
  - 50 European institutes
  - 8 North American institutes
  - 2 Asian institutes
  - 1 Middle East institute

CERN
technology

Knowledge Transfer
Accelerating Innovation

CERN Technology Portfolio

TIMEPIX 3/4

Invest in knowledge in Calorimetery

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CALICE & Calorimetry

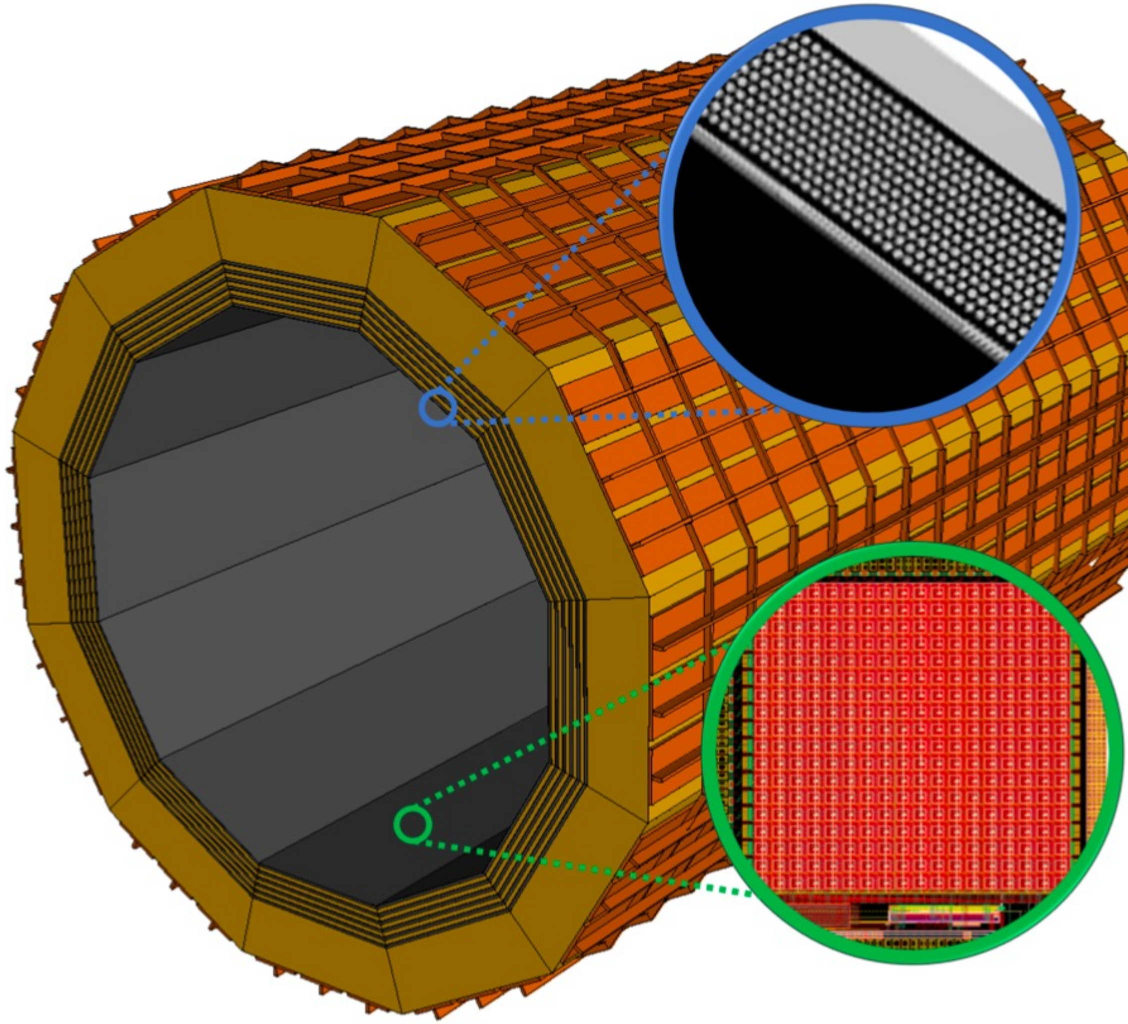
- Prototypes developed of the three main calorimetric subsystems (ECAL, HCAL, tail catcher/muon tracker) of a future detector.

- Evaluating the performance of alternative technological solutions within this combined system
  - SCECAL: scintillator / steel ECAL design
  - **SiW ECAL:** 30-layer silicon tungsten sampling calorimeter, active 9760 channels, 24 X_0 deep, approx. 20 x 20 x 30 cm^3
  - MAPS ECAL: studies into a novel digital ECAL concept, using 50-micron pixel pitch, the "Tera-pixel" calorimeter
  - **AHCAL** : analogue HCAL, scintillating tiles and **SiPMs**, 8184 channels, $1m^3$
  - **DHCAL**: the digital HCAL, **GEM** or RPC readout
  - TCMT: Tail Catcher and Muon Tracker

Contact: François Corriveau

Source: https://twiki.cern.ch/twiki/bin/view/CALICE/

EIC calorimeter concept



Portion of it would be Lead & Scintillating Fibres (Lead-SciFi) similar to the GlueX BCAL which was built by the Regina group. Could even contemplate a silicon-based ECal.

TRIUMF Initiative in SiPM

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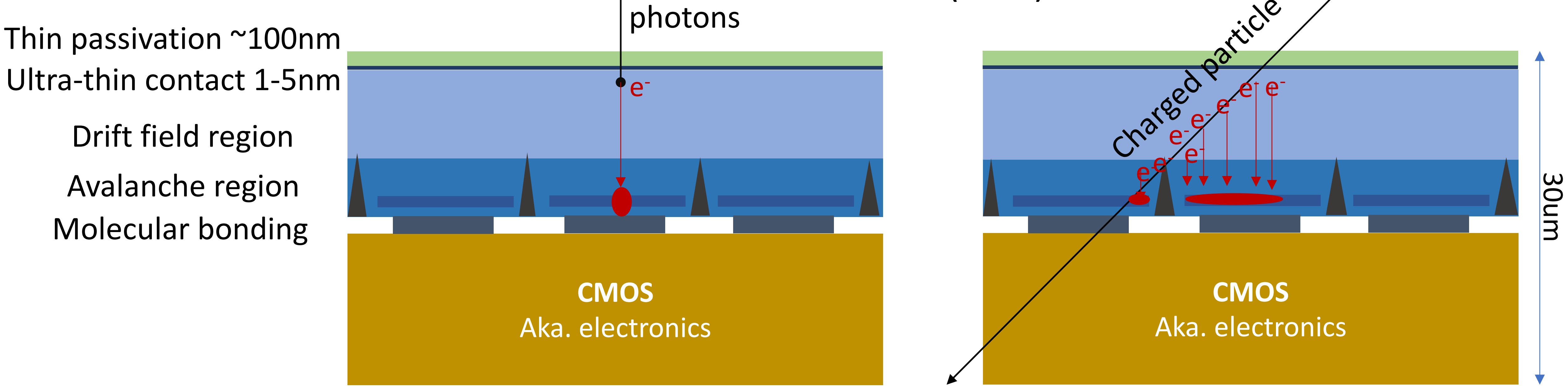
4Dimension Digital Detector, $4D^3$ concept

- **Single Photon Avalanche Diode**
  - 1 photon → $1e^-$ * 10^6 (Gain) → 10^6 e^-
- **Low Gain Avalanche Diode**
  - 1 MIP → $1{,}000e^-$ (15um ionization) * 100 (Gain) → 10^5 e^-



Signal close enough to be handled by similar electronics

Made in Canada technology: Sensor layer and 3D integration could be done at Teledyne-DALSA (Bromont, QC)

- **Aim is to achieve 10ps timing resolution for both and 10-100µm position resolution**
- Can be used for both calorimetry (HCAL) or tracking

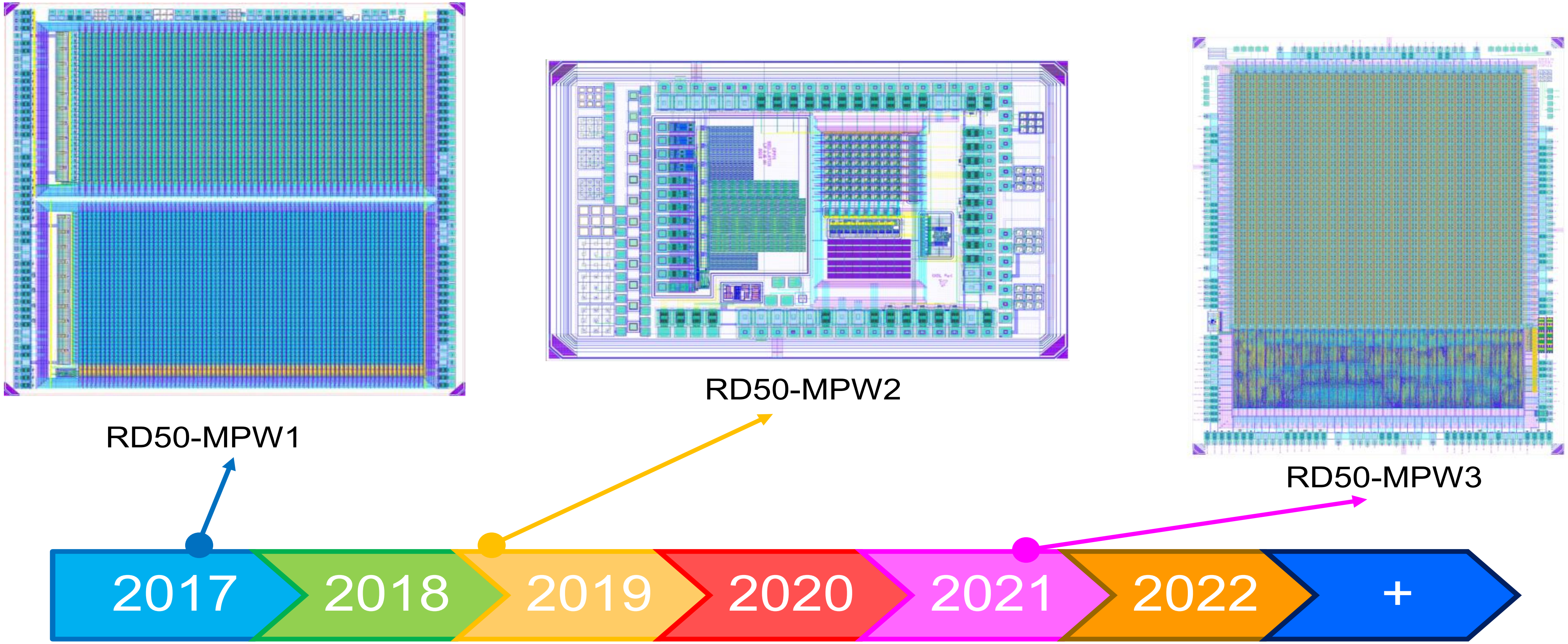
Contact: Fabrice Retiere (informal workshop Thursday https://indico.cern.ch/event/1072579/sessions/410154/#20220609)

Summary Get involved if *you* want an EF collider!

- ❑ Presented status of ILC and other energy frontier (EF) options. What is best for Canada?
- ❑ What collider/detector properties are necessary to probe the Higgs self-interactions?
- ❑ The *next* collider for precision physics or with ultimate energy reach for search BSM?
- ❑ **Identify technologies for discoveries; seek instrumentation innovation and synergy; build partnership; where do new approaches in searches or data analysis matter most?**
- ❑ What theory calculations do we need to capitalize on? Where does theoretical accuracy matter most? How to reduce theory systematics?
- ❑ **Dialogue among particle and nuclear physics committees, between theory and experiments!**
- ❑ Engaged Canada in international planning

extra

R&D Timescale Examples – New Structures/D-MAPs



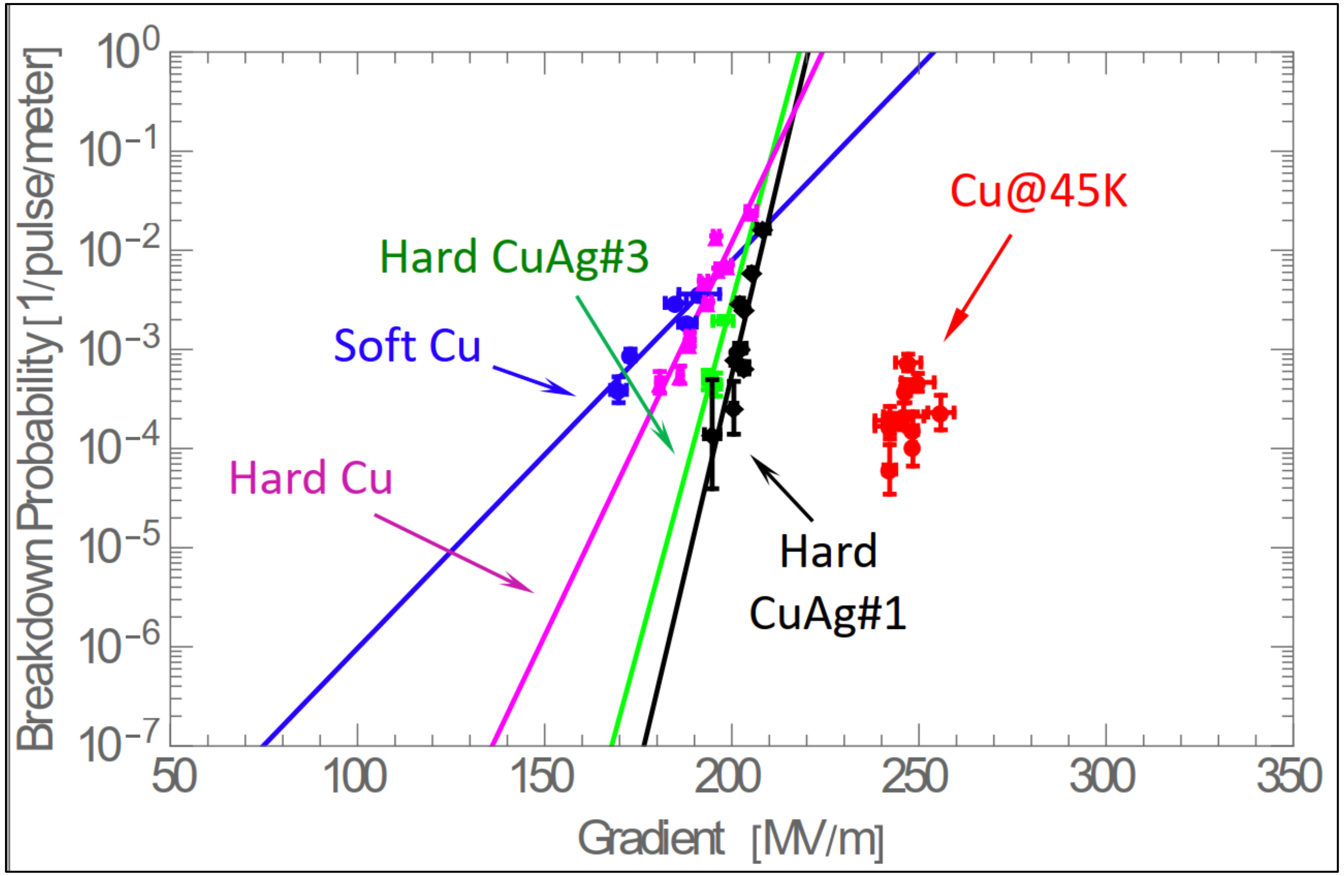
- 3 Depleted Monolithic Active Pixels Sensors (DMAPs) designed
  - Submission dates in timeline, chip delivery ~0.5 – 1 year later
- All in LFoundry 150nm process
- High resistivity substrates (up to ~2 kOhm/cm)

Contact: Thomas Koffas / Bernd Stelzer /Luise Poley

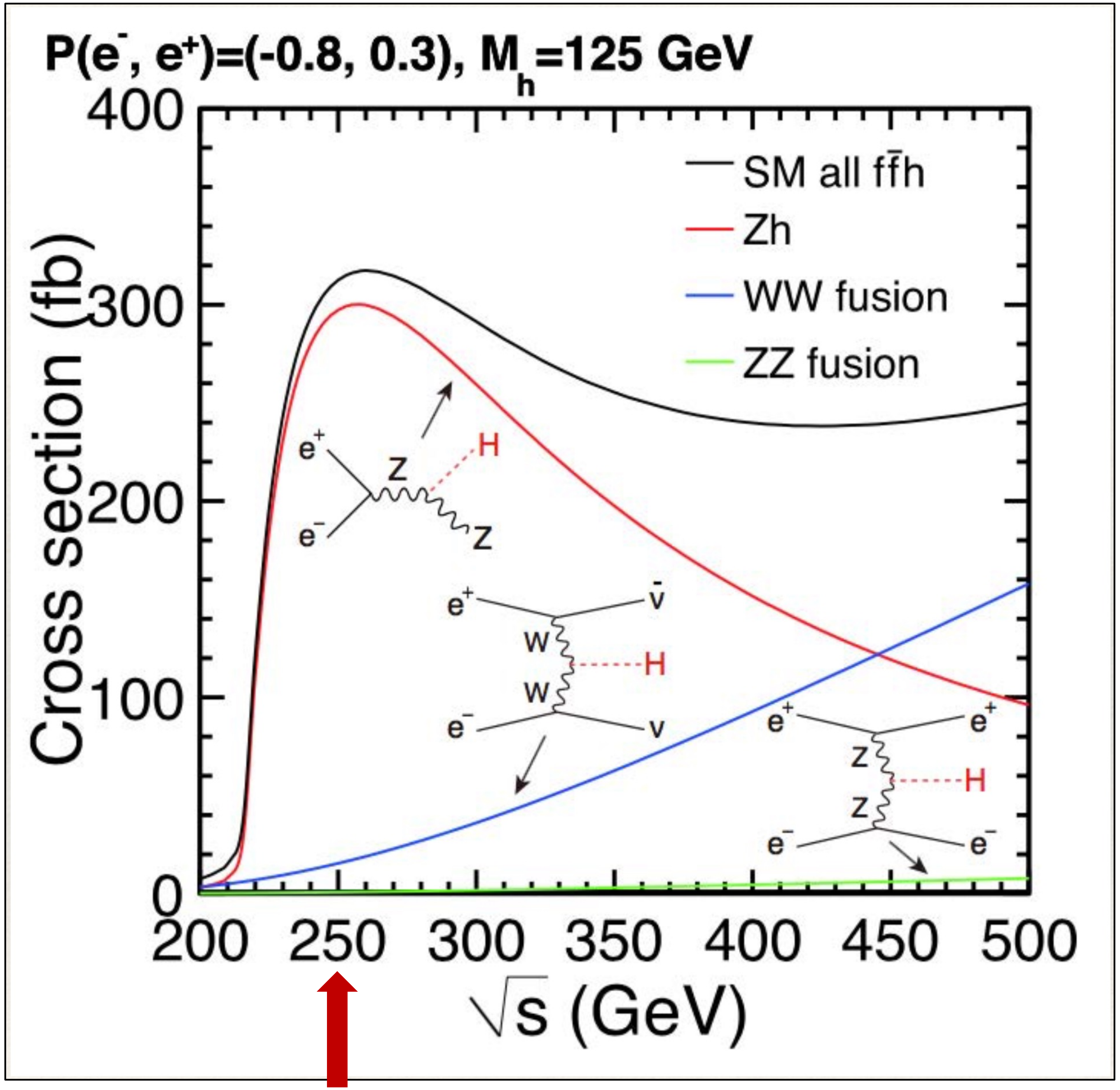
Cool Copper Collider (C3) versus ILC

- ILC:
  - beam acceleration by superconducting nine-cell **niobium** cavities operating at **2°K**
  - average gradient of 31.5 MV/m
  - total footprint of the ILC complex is ~ 20 km / 31 km long at $\sqrt{s} = 250/500$ GeV
  - Ready to build technology

- C3
  - SLAC-based development
  - beam acceleration by cryogenic **copper** cavities operating at **77°K** (liquid Nitrogen)
  - 8 km footprint for $\sqrt{s}$ of 250/550 GeV $\Longrightarrow$ gradient 70/120 MV/m
  - Require R&D program and proof of principle



The physics of electron-position collision at high-energy

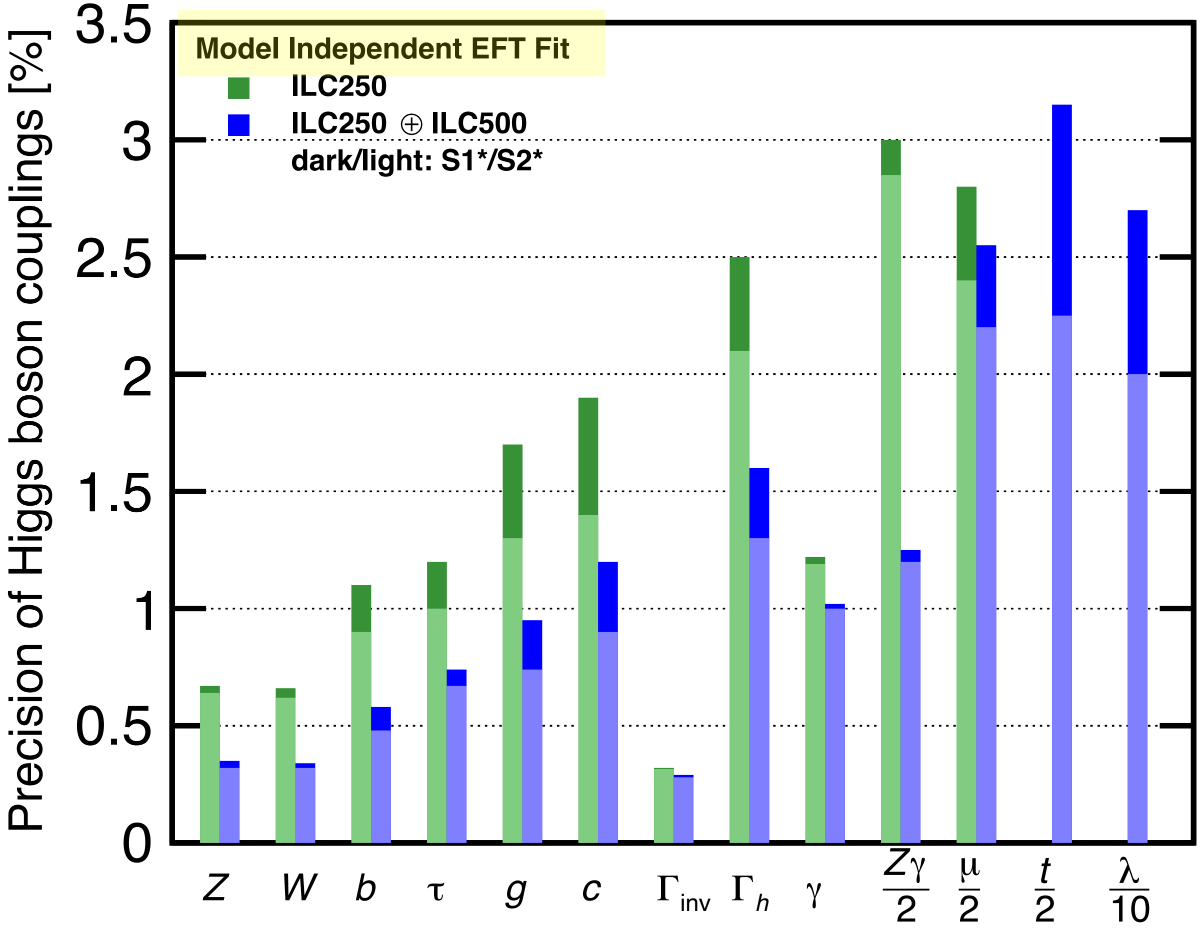


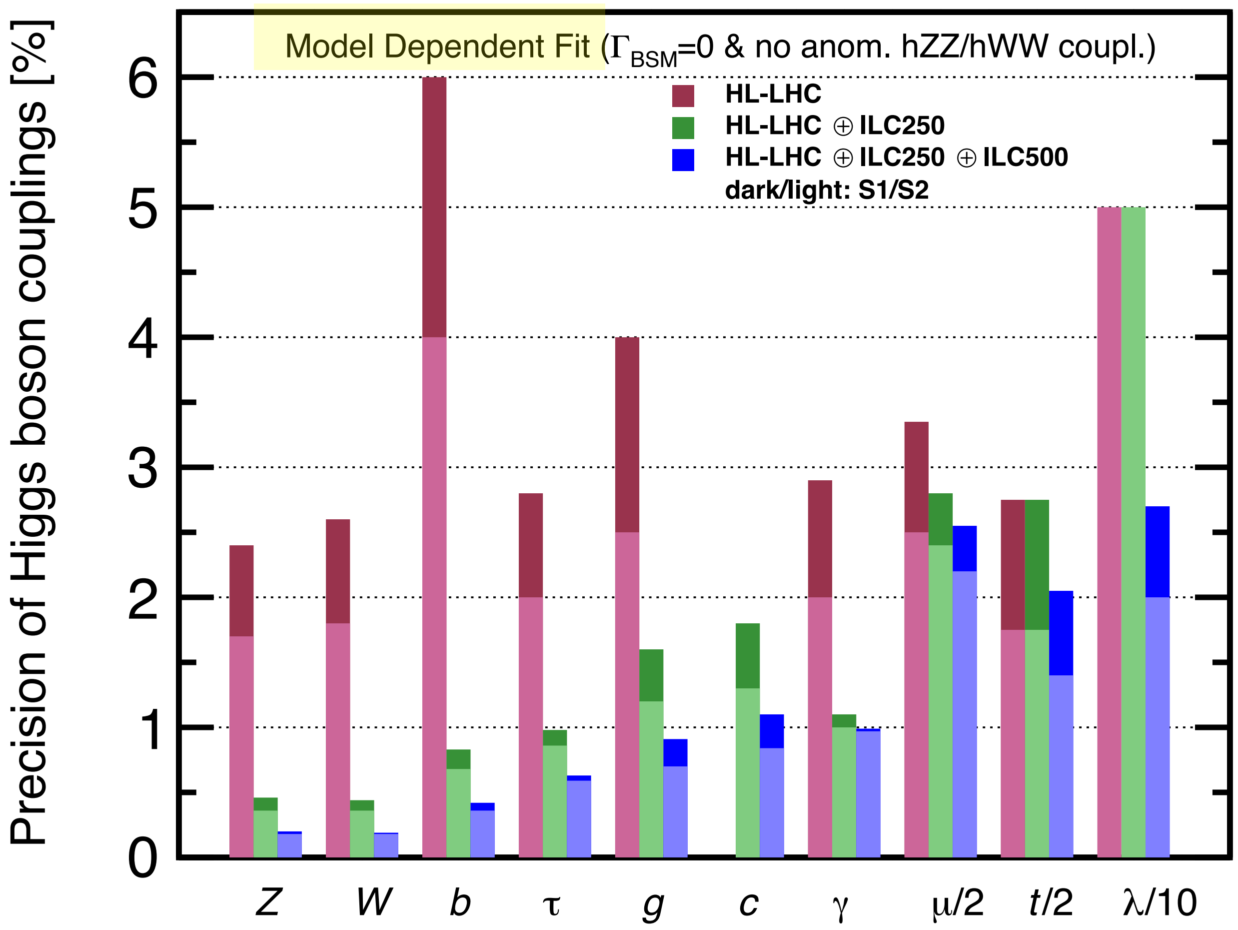
ILC@250 GeV = single Higgs production cross section maximum

The Higgs coupling (Effective Field Theory)

Precision studies of Z, W, *b*, tau and *c* at 250 GeV, while ILC also opens top Yukawa and Higsgs self-coupling (λ) below 500 GeV

Polarized ILC beams 2 ab^{-1} integrated luminosity is roughly equivalent to unpolarized 5 ab^{-1}





Absolute & model-independent Higgs coupling measurements possible with ILC 250 GeV data alone

ILC & HL-LHC complementory. ILC significantly improves LHC precisions so much higher sensitivity to BSM physics

arXiv:1901.09829

Why an ILC ?

The International Linear Collider (ILC) is only machine Higgs Factory that can
e^+e^- collision at 250 GeV addresses compelling physics questions: EW symmetry breaking and Higgs physics.
Electron-positron machines allow many probes of naturalness. Probes of "naturalness" can come from direct searches at the energy frontier, precision measurements of Higgs couplings, or precision *Z* studies!!!

250 GeV ILC is a new particle discovery machine!
Direct New Particle Searches
- **$>10^3$ higher luminosity than LEP2**
- **beam polarizations**
- **much better detectors (keep HEP at the cutting edge of knowledge & tehnology)**
- **natural evolution to higher electron-positron CM energy 350/380 GeV, 500 GeV, and beyond**

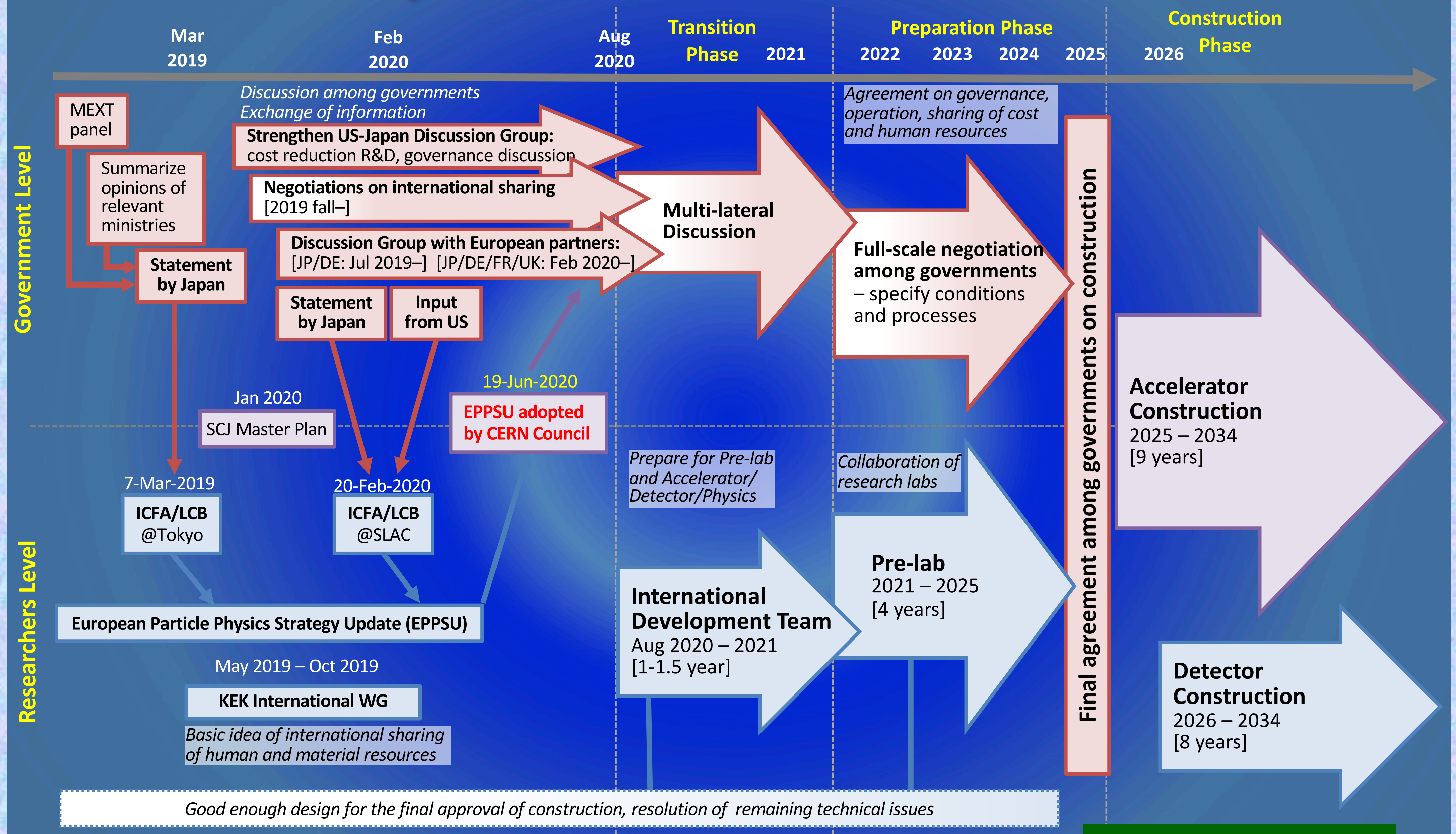
Enhance sensitivities to regions with small cross sections and compressed mass spectrum, which are challenging at LHC

Precision measurements
Past colliders whose energy regime has been explored before (LEP, HERA, Babar, CLEO, BELLE) still, though increased luminosity, enable a wealthy of physics to be studied and measured. Benefits from expertise of others (SNO, T2K, etc).

A dark sector particle could mix with the Higgs or *Z* bosons
- **Higgs decaying to missing energy and a few SM particle**
- **Benefits of improved performance of the detectors**

But isn't dark matter today's Higgs?
If it is lighter than half the Higgs mass and couples to it! This is done via the "missing mass" technique.

The 2020 Proposed Timelines Towards Realization of ILC



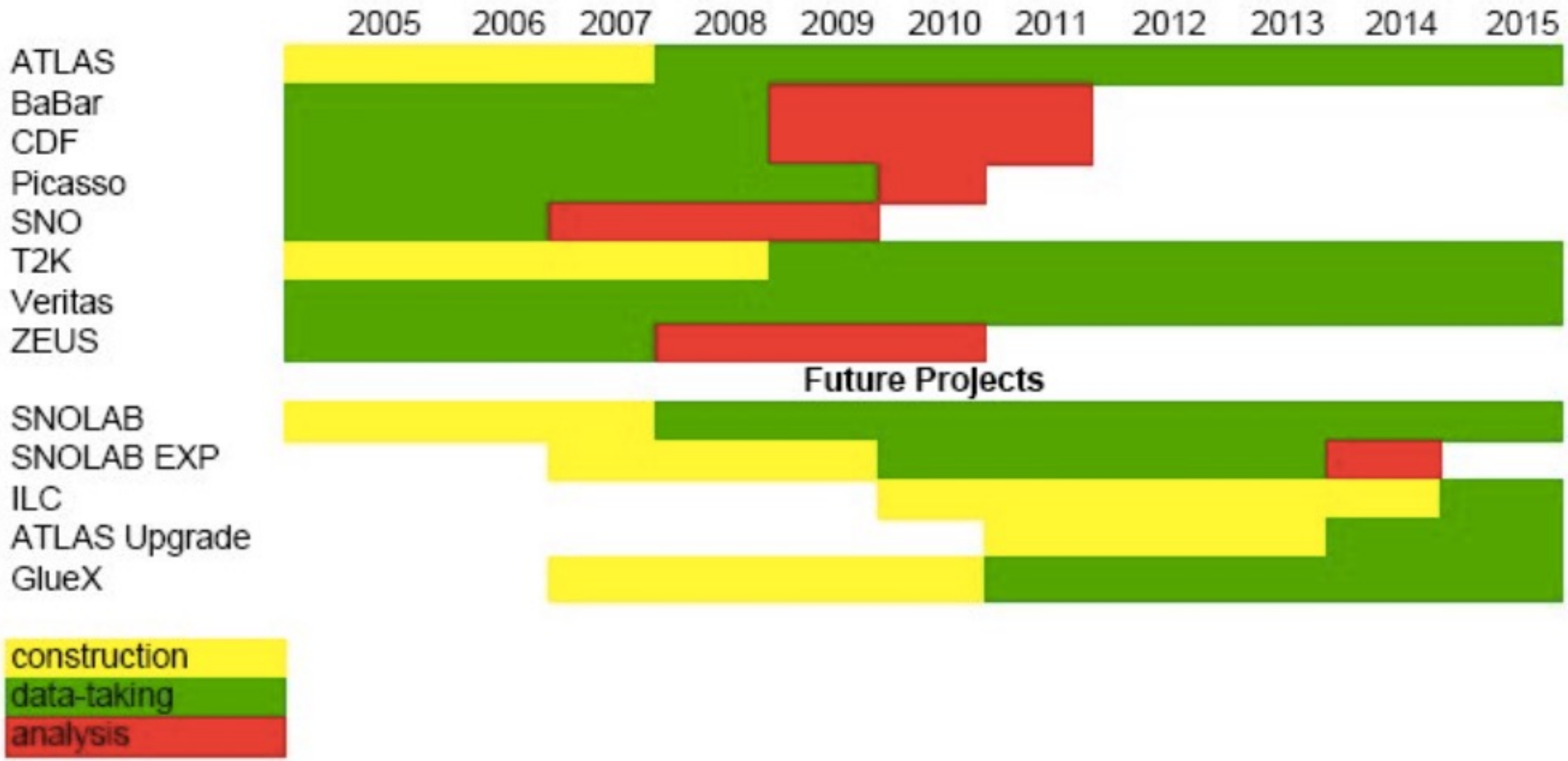
* ICFA: international organization of researchers consisting of directors of world's major accelerator labs and representatives of researchers
* ILC pre-lab: International research organization for the preparation of ILC based on agreements among world's major accelerator labs such as KEK, CERN, FNAL, DESY, etc.

IPP brief 2005 LRP

ILC has been in the planning for over 15 years!!!

In 2020, I see many more projects but a community of about same size (slightly larger)

IPP Project Timelines in the Next Decade



ILC

William Trischuk