Status of Linear Collider projects: physics, accelerator, detector, and project implementation

Taikan Suehara
(ICEPP, U. Tokyo)

Contents

- History of LC
- Linear collider concepts & LC Vision activities
- Comparison of circular and linear Higgs factories
  - on physics and project implementation
- LC-based detector developments
- Consideration of governance of future colliders

Brief History of Linear Colliders (after SLC)

- 1984-90: 3 different projects formed
  JLC (NC) in Japan, NLC (NC) in US, Tesla (SC) in Europe
- 2004: ITRP report: superconducting collider as ILC
  Global Design Effort (GDE) started
- 2012: CLIC Conceptual Design Report
- 2013: ILC Technical Design Report (as 500 GeV collider)
- 2017: Re-baseline of ILC to 250 GeV (with Higgs at 125 GeV)
- 2019: First proposal of Cool Copper Collider
- 2020: ILC International Development Team (IDT) formed
- 2022: ILC pre-lab proposal (not approved immediately)
- 2023: ILC Technology Network started with MEXT funding

ILC at EPPSU and snowmass/P5

- EPPSU 2013
  The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*
- EPPSU 2020

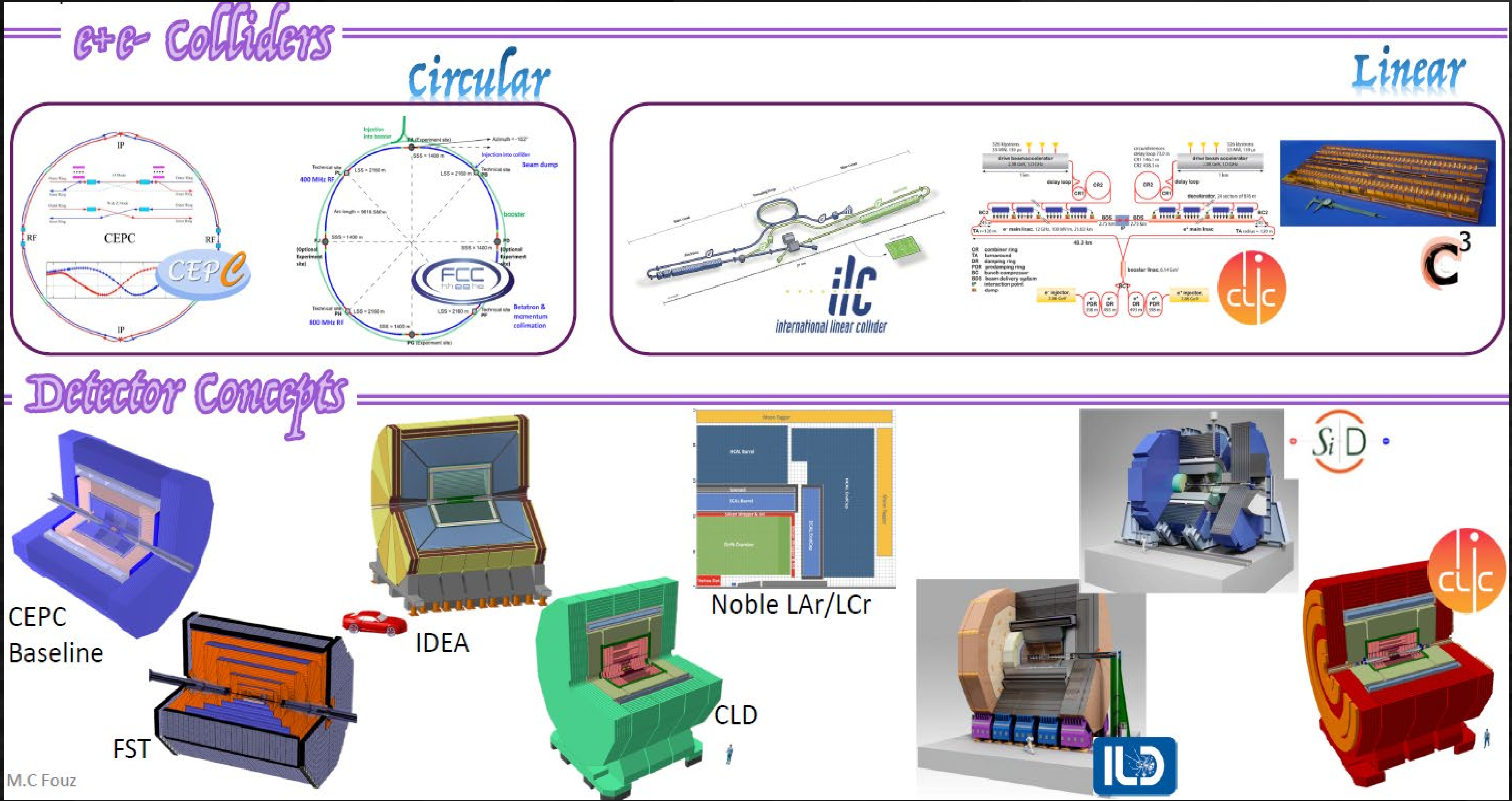
> ***The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.***

- P5 2023
  A Higgs factory is the next step toward fully revealing the secrets of the Higgs boson within the quantum realm. We advocate substantial US participation in the design and construction of accelerators and detectors for an off-shore facility, and we advocate investment of effort to support development of the Future Circular Collider-electron (e–) positron (e+) (FCC-ee) and the International linear Collider (ILC), along with a parallel and increasingly intensive program of R&D pursuing revolutionary accelerator and detector technologies.

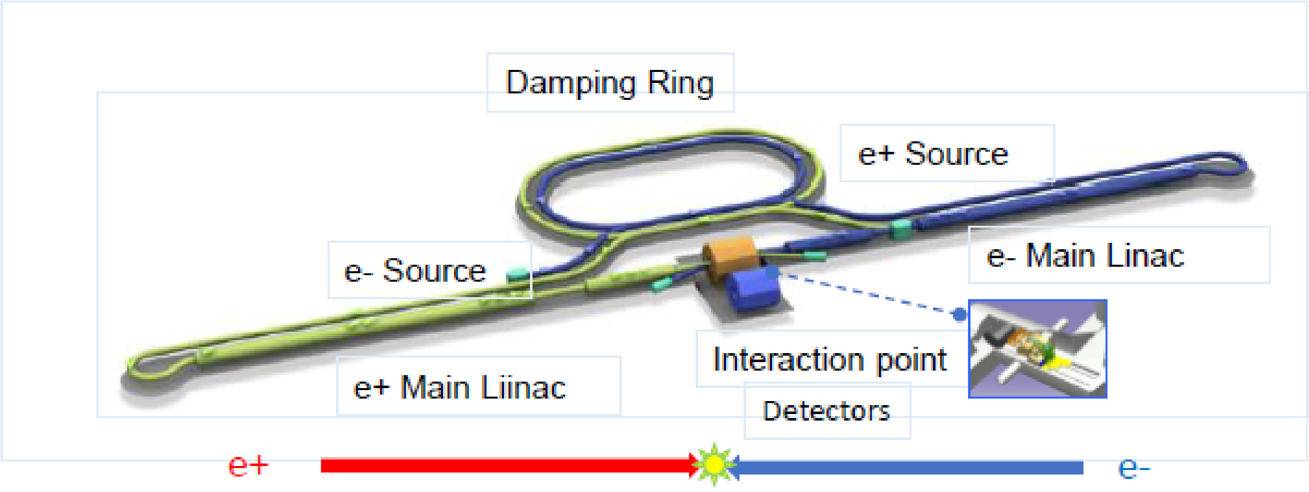
LC concepts overview

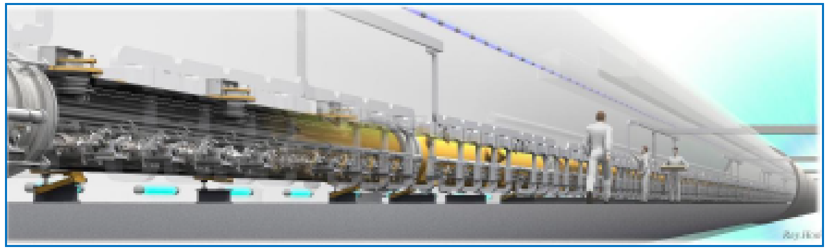
Slides partially taken from ECFA HTE workshop 2024 (Oct. 9-11) by Steinar Stapnes (CERN)

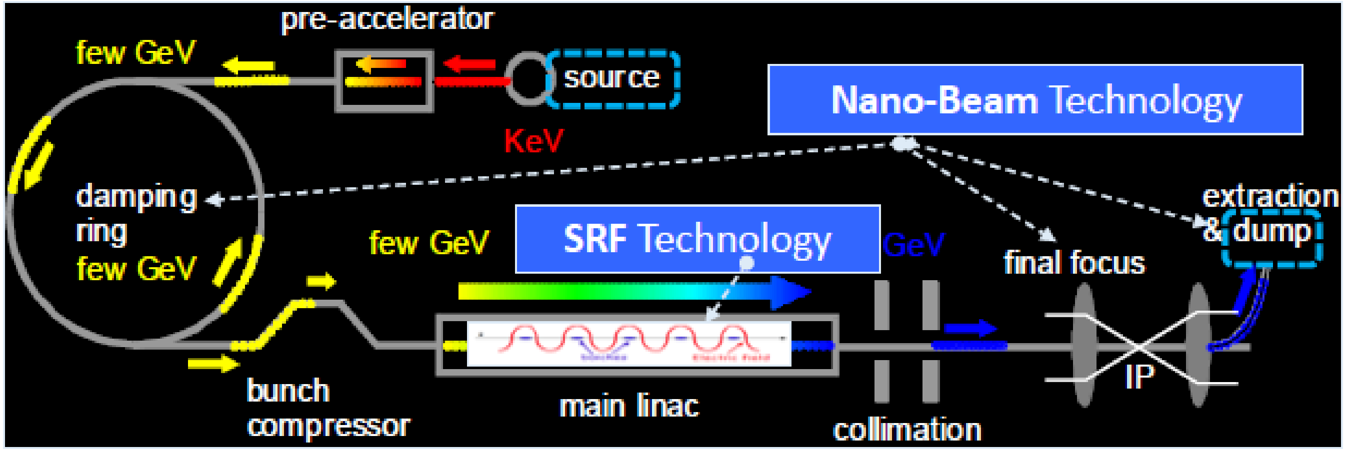
Higgs factories and detectors



ILC: accelerator overview







Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	**7.7** nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) $Q_0 = 1x10^{10}$
#SRF 9-cell cavities (CM)	~ 8,000 (~ 900)
AC-plug Power	111 / 138 MW

S. Michizono, LCWS2023

ITN and technical targets

ILC Technology Network (ITN)

-- global collaboration program---

- Acc. R&Ds focusing on
  - SRF
  - e- & e+ Sources
  - Nano-beam

} Synergy with other colliders

ILC-related technical work mainly by MEXT budget (~3M$/year) with global partners
Topics selected from pre-lab work packages

Europe: CERN works as a hub
Labs in France/Germany/UK express interests, real program starting
US: P5 to recommend R&D for HF
DOE implementing plan

Work Package Primes for ITN

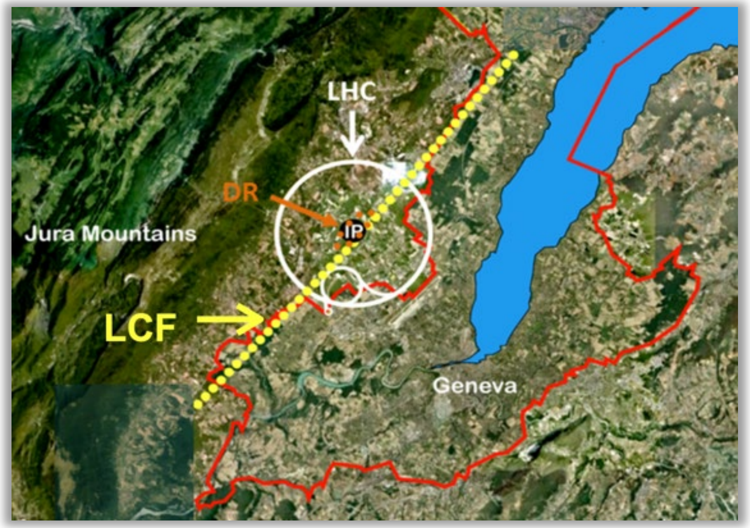
SRF	WPP	1	Cavity production
SRF	WPP	2	CM design
SRF	WPP	3	Crab cavity
e-, e+ Sources	WPP	4	E- source
e-, e+ Sources	WPP	6	Undulator target
e-, e+ Sources	WPP	7	Undulator focusing
e-, e+ Sources	WPP	8	E-driven target
e-, e+ Sources	WPP	9	E-driven focusing
e-, e+ Sources	WPP	10	E-driven capture
e-, e+ Sources	WPP	11	Target replacement
Nano-Beam	WPP	12	DR System design
Nano-Beam	WPP	14	DR Injection/extraction
Nano-Beam	WPP	15	Final focus
Nano-Beam	WPP	16	Final doublet
Nano-Beam	WPP	17	Main dump

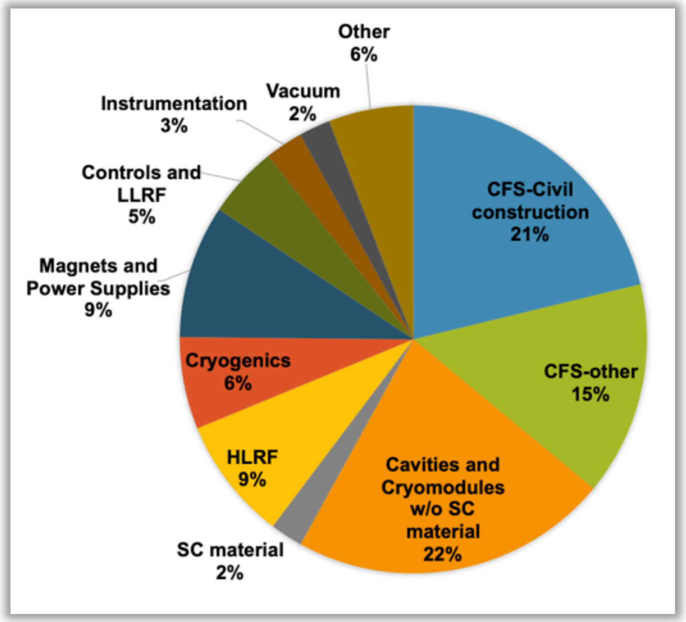
Some recent ILC developments

Right: ILC Technology Network (ITN), interest/capability matrix from 28 labs/universities

SRF	WPP	1	Cavity production	√		√	√	√			√	√	√				√	√	√		√	√		√	√	
	WPP	2	CM design	√				√				√			√	√	√	√	√			√		√	√	
	WPP	3	Crab cavity			√	√							√					√			√	√		√	√
Sources	WPP	4	E-source			√						√							√		√			√		
	WPP	6	Undulator target				√												√	√			√			
	WPP	7	Undulator focusing				√												√	√			√			
	WPP	8	E-driven target	√		√												√	√							
	WPP	9	E-driven focusing	√														√	√							
	WPP	10	E-driven capture	√															√					√		
	WPP	11	Target replacement	√																						
Nano-beams	WPP	12	DR System design	√	√				√	√		√							√				√	√		
	WPP	14	DR Injection/extraction	√					√										√				√	√		
	WPP	15	Final focus	√			√		√		√							√			√			√		
	WPP	16	Final doublet	√	√													√								
	WPP	17	Main dump	√			√					√														

Below cost matrix, updating SCRF and CFS (~75%), escalation and currency updates for the rest (~25%)





European ITN studies are distributed over five main activity areas:

ML related tasks
- SRF and ML elements: Cavities and Cryo Module, Crab-cavities, ML quads and cold BPMs (INFN, CEA, DESY, CERN, IJCLAB, UK, CIEMAT, IFIC)

Sources
- Pulsed magnet and wheel/target (Uni.H, DESY, CERN)

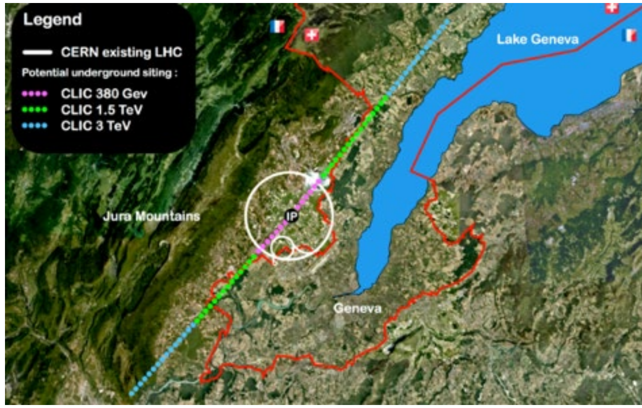
Damping Ring including kickers
- Low Emittance Rings (UK)

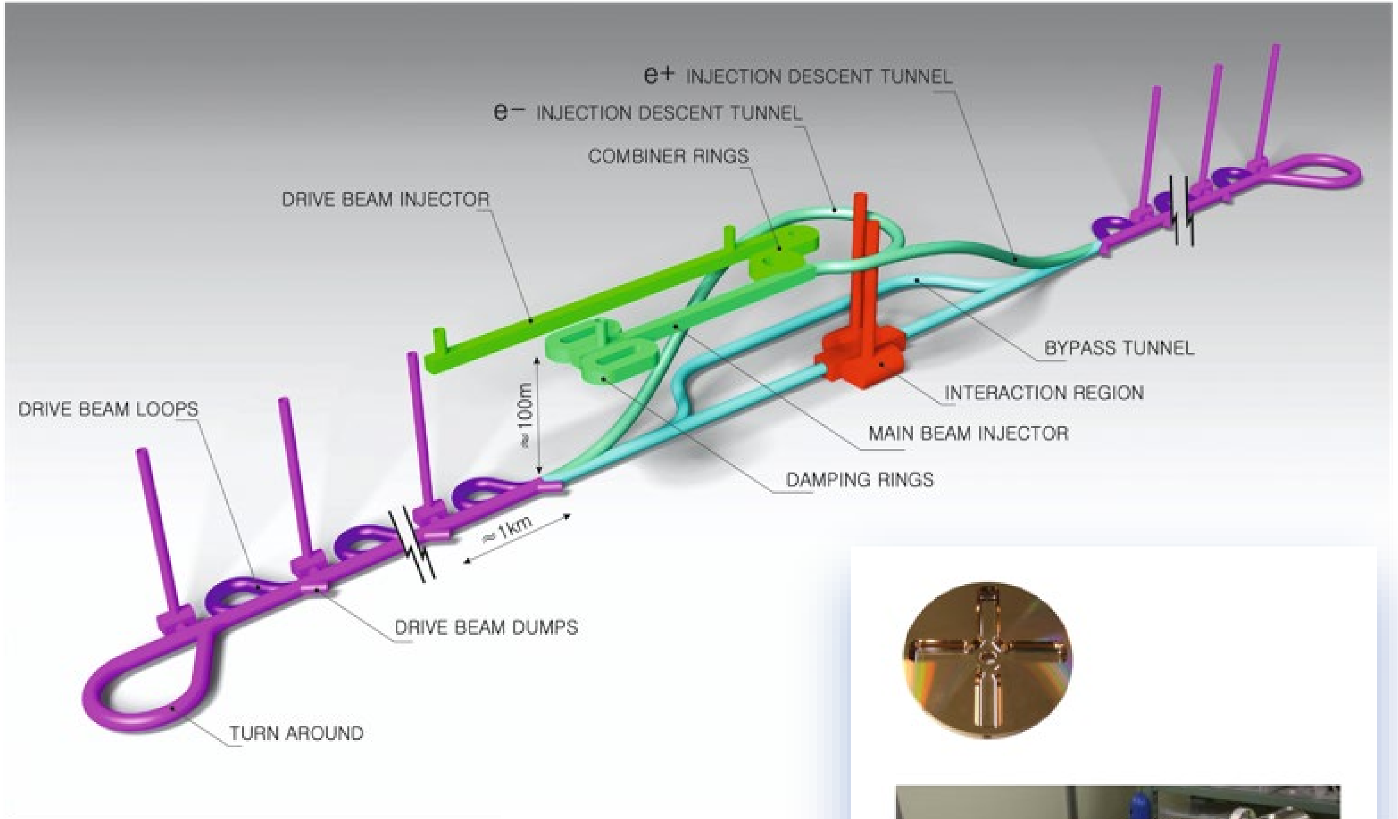
ATF activities, final focus and nanobeams
- ATS and MDI (UK, DESY, IJCLAB, CERN, IFIC)

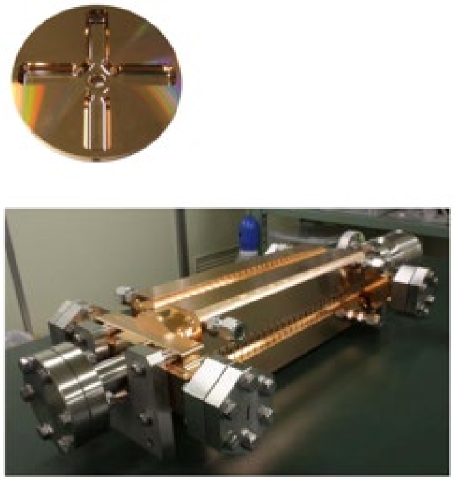
Implementation
- Dump, CE, Cryo – follow up efforts at CERN
- Sustainability, Life Cycle Assessment (CERN, DESY, CEA, UK groups)
- EAJADE started (EU funding) (DESY, UK, CEA, CNRS, IFIC, INFN, UHH, CERN)

For the ESPP (see also later):
Updated: ILC in Japan with updated technology results, updated CFS (CE and conv. Systems), environmental studies and costing
New: An LC starting with ILC technology at 250 GeV with upgrade options (site independent), and an implementation of such a facility at CERN (footprint picture)

The Compact Linear Collider (CLIC)







Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

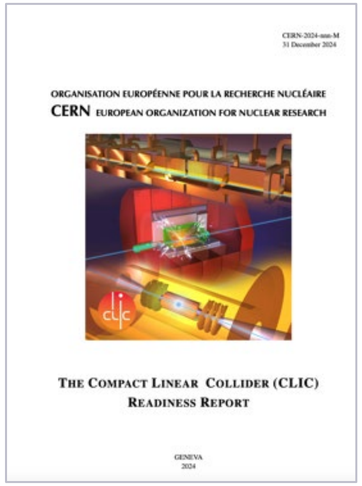
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier) presented in previous ESPP updates
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

The CLIC ESPP update

Guidelines:

Preparing “Project Readiness Report” as a step toward a TDR

Assuming ESPP in ~ 2025-6, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

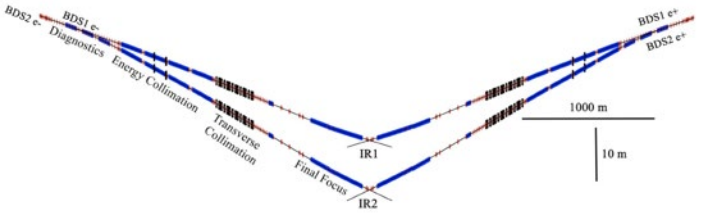


However, several important changes:

- Energy scales: 380 GeV and 1.5 TeV with one drivebeam
- Consider also 100 Hz running at 250 GeV (i.e. two parallel experiments, two BDSs)
- Several updates on parameters (injectors, damping rings, drive-beam) based on new designs, results and prototyping (e.g. klystrons, magnets) - however no fundamental changes beyond staying at one drivebeam
- Technology results updates, including more on use of them in other projects (e.g. alignment, instrumentation, X-band RF is small linacs)
- Update costing and power – interplay between inflation and CHF
- Life Cycle Assessments
- More detailed prep phase planning (next 5-7 years)

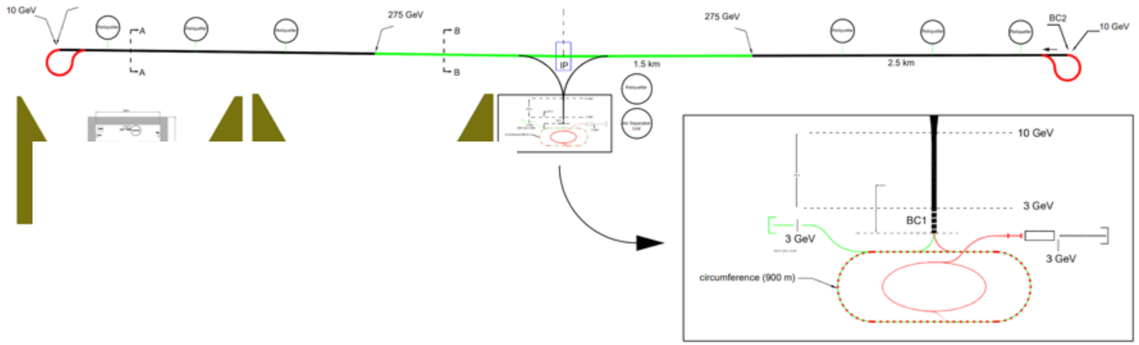
Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	1×10^{34} cm^{-2} s^{-1}	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	1×10^{34} cm^{-2} s^{-1}	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20



Project summary for Snowmass already include some of these changes, i.e. luminosity improvements, 100 Hz study, power update for 380 GeV: LINK

C^3 Accelerator Complex

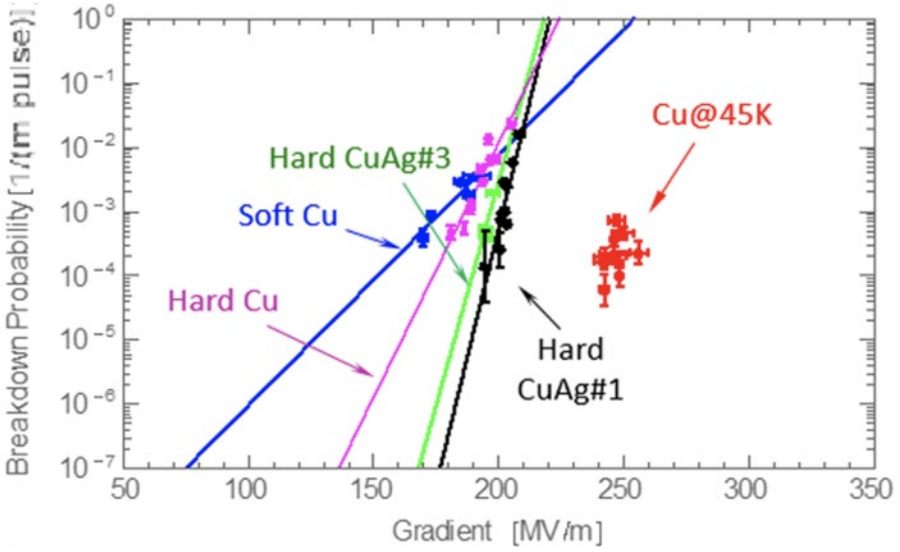


8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

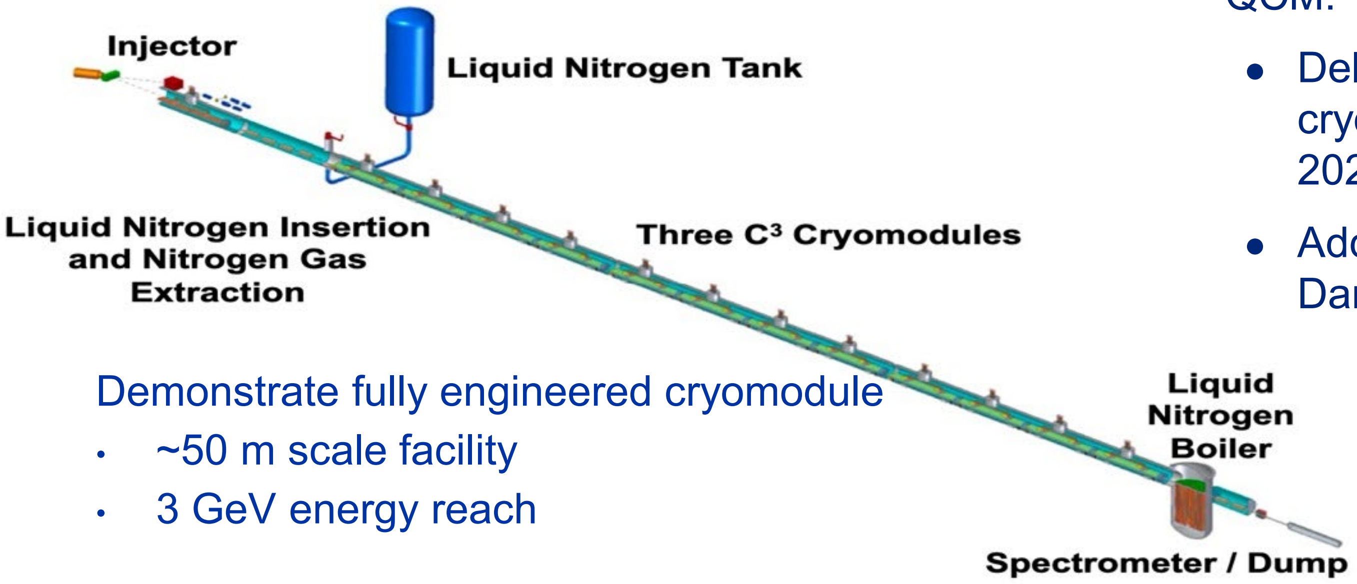
Snowmass paper:
https://arxiv.org/pdf/2203.07646.pdf



Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [$\times10^{34}$]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

C^3 recent developments and immediate plans

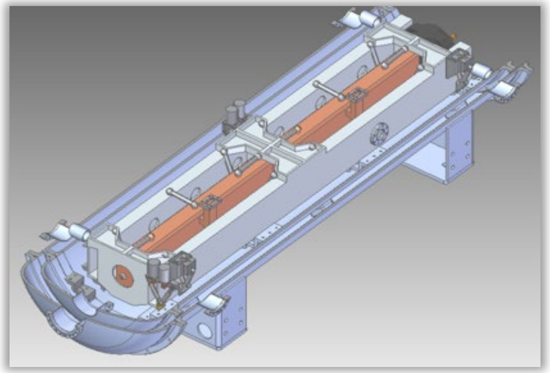


Demonstrate fully engineered cryomodule

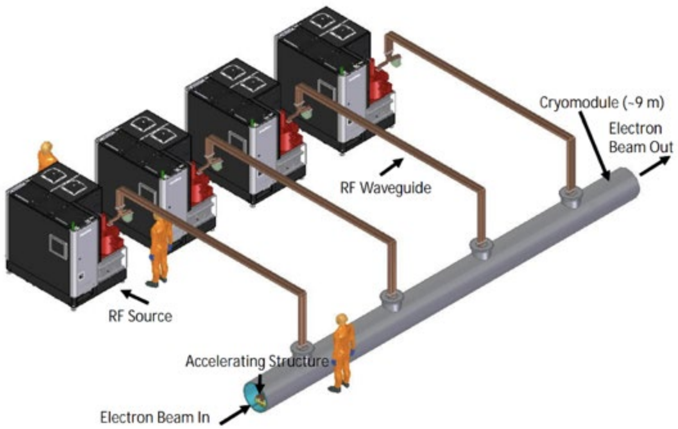
- ~50 m scale facility
- 3 GeV energy reach

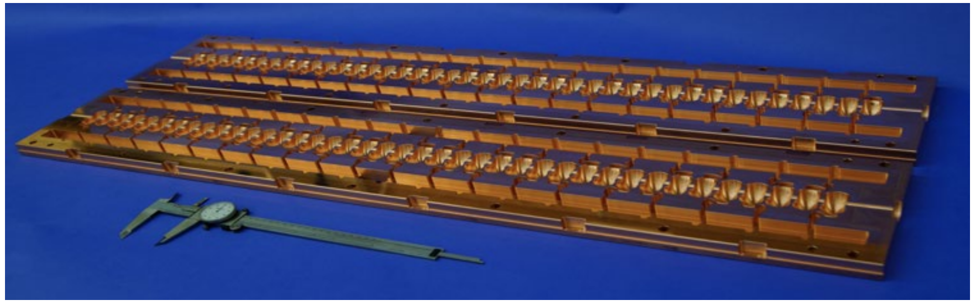
QCM:

- Delivery of prototype quarter cryomodule (QCM) expected Fall 2024
- Address Gradient, Vibrations, Damping, Alignment, Cryo, etc

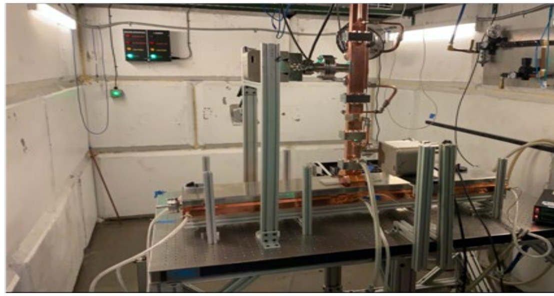


C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



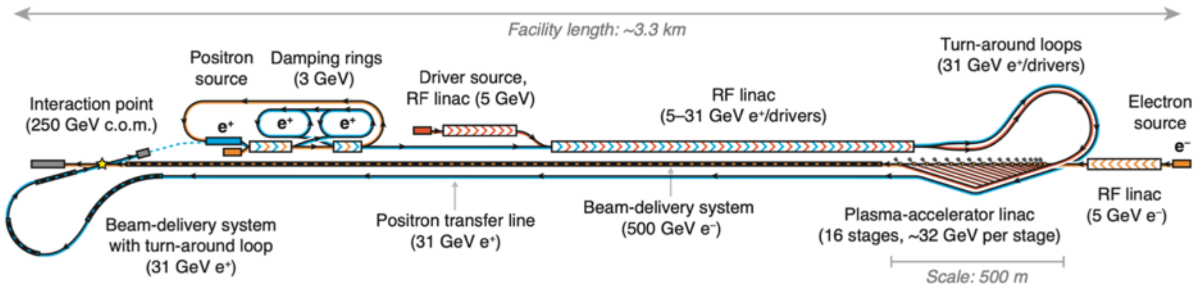


C^3 Prototype One Meter Structure



High power Test at Radiabeam

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

>Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

>Length dominated by e⁻ beam-delivery system

New concept, aiming for pre-CDR (LINK)

- 500 GeV for electrons with plasma acceleration
- 31 GeV positrons with RF based linac, used also to provide electron drivebeam for the plasma acceleration
- Reach 250 GeV collision energy, luminosity 10^{34}

Asymmetric technologies, energies and bunch charges

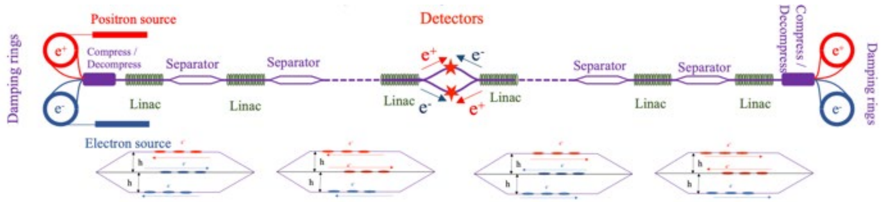
Small footprint, lower cost

Several key plasma acc. challenges:
Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling and more

Conventional beam(s) challenges:
Positron production, damping rings, RF linac, beam delivery system

Experimental challenges with asymmetric beams

Energy recovery options, potentially very large luminosities but early stage of development



Twin LC with energy recovery

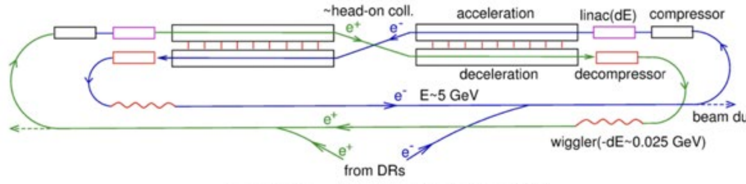


Figure 3-10. Conceptual layout of the ERLC.

LC: normal vs superconducting RF

Normal conducting tech.

- Higher gradient demonstrated
- Smaller beam size with dense bunch structure
  - Less safety margin to keep luminosity
- Concern on power consumption

Superconducting tech.

- Higher gradient more difficult
  - Because of quenching at large magnetic field
- Larger bunch spacing easier to get luminosity
- Less power consumption in nature

Comparison in terms of luminosity

$$L = f n_b \frac{N^2}{4\pi\sigma_x^*\sigma_y^*}$$

	ILC (SCRF)	CLIC (X-band,NCRF)	C3 (C-band, Cold NCRF)
L [/cm^2/s]	1.35E+34	1.5E+34	1.3E+34
Duty factor	8.3E-03	1.2E-05	1.9E-04
Bunch interval [ns]	554	0.5	5.26
Bunch crossing [kHz]	6.5	18	16
Bunch charge[nC]	3.2	0.83	1
Emittance [nm rad]	5000/35	900/20	900/20
β at IP	almost same size		

- In case NCRF, it is necessary to keep the bunch charge low and pursue designs that focus on emittance (but it seems challenging design)
- In case SCRF, high bunch charge (3.2nC) is possible with reasonable design parameters (e.g. power consumption etc)
- SCRF looks feasible when aiming for the early realization of a machine with sufficient luminosity

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Also, SC tech has more application on FEL etc.

LC Vision activities

LC Vision Team: T. Barklow, T. Behnke, M. Demarteau, A. Faus-Golfe, B. Foster, M. Hogan, M. Ishino, D. Jeans, B.List, J.List, V. Litvinenko, S. Michizono, T. Nakada, E. Nanni, M. Nojiri, M. Peskin, R. Patterson, R. Pöschl, A. Robson, D. Schulte, S. Stapnes, T.Suehera, C. Vernieri, M. Wenskat, J. Zhang

- Target of LC Vision team:
  - Make and publish a concurrent view of general Linear Collider facility starting from SCRF at ~250 GeV and having multiple upgrade paths (SCRF with higher gradient, NCRF, plasma, …)
  - Establish a concrete plan on LC@CERN for a candidate of next CERN collider
- Several documents will be published from LC Vision team for European strategy

LC Vision structure

Chairs: J. List, S. Stapnes

Coordination Group

Halina Abrahmovic, Erik Adli, Ties Behnke, Ivanka Bosovic, Phil Burrows, Marcel Demarteau, Yuanning Gao, Carsten Hensel, Mark Hogan, Masaya Ishino, Daniel Jeans, Imad Laktineh, Andy Lankford, Benno List, Kajari Mazumar, Shin Michizono, Emmanuela Musumeci, Tatsuya Nakada, Mihoko Nojiri, Dimitris Ntounis, Jens Osterhoff, Ritchie Patterson, Aidan Robson, Daniel Schulte, Taikan Suehara, Geoffrey Taylor, Caterina Vernieri, Marcel Vos, Georg Weiglein, Filip Zarnecki, Jinlong Zhang, Laura Monaco, Patrick Koppenburg, Hitoshi Murayama, NN Canada

Expert Team 1
"Physics-driven run plan and EPPSU documents"
Roman Poeschl, Michael Peskin

Expert Team 3
"SCRF upgrades"
Sergey Belomestnykh, Hiroshi Sakai, Marc Wenskat

Expert Team 5
"ERL upgrades"
Walid Kaabi, Vladimir Litvinenko, Kaoru Yokoya

Expert Team 7
"Beyond Collider"
Yasuhito Sakaki, Ivo Schulthess

Expert Team 2
"LCF@CERN"
Steinar Stapnes, Thomas Schörner

Expert Team 4
"C3/CLIC upgrades"
Angeles Faus-Golfe, Enrico Nanni

Expert Team 6
"Plasma upgrades"
Brian Foster, Spencer Gessner

Expert Team 8
"Alternative Collider Modes"
Tim Barklow, Gudi Moortgat-Pick

Scenarios for Expert Teams

to get started

- let's assume we start with a Linear Facility, with 2 Beam Delivery Systems (2 IRs), length
  - a) **~20 km** (e.g. 250 GeV SCRF)
  - b) **~30 km** (e.g. 550 GeV SCRF — CEPC complementarity from day-one)
- **what could "your" technology offer as**
  - i. **decision-ready in < 5 years (e.g. 2-3 year targeted engineering effort after EPPSU adoption in early 2026)?**
    - **ILC-like SCRF**
    - alternative collider modes, beyond-collider facilities?
    - anything else?
  - ii. **as upgrade, decision-ready after the first years of data-taking of initial facility (e.g. 2045-2050)?**

Circular or Linear? A consideration

Target Energies of e+e- colliders

91~250 GeV — Oblique parameters, W/Z mass, b/τ rare decays

250 GeV — Higgs couplings (~1%), Higgs rare decay (light BSM)
(TeV BSM indirect search)

350 GeV — Top mass → vacuum stability

500–550 GeV — Higgs self coupling (20–30%), ttH coupling

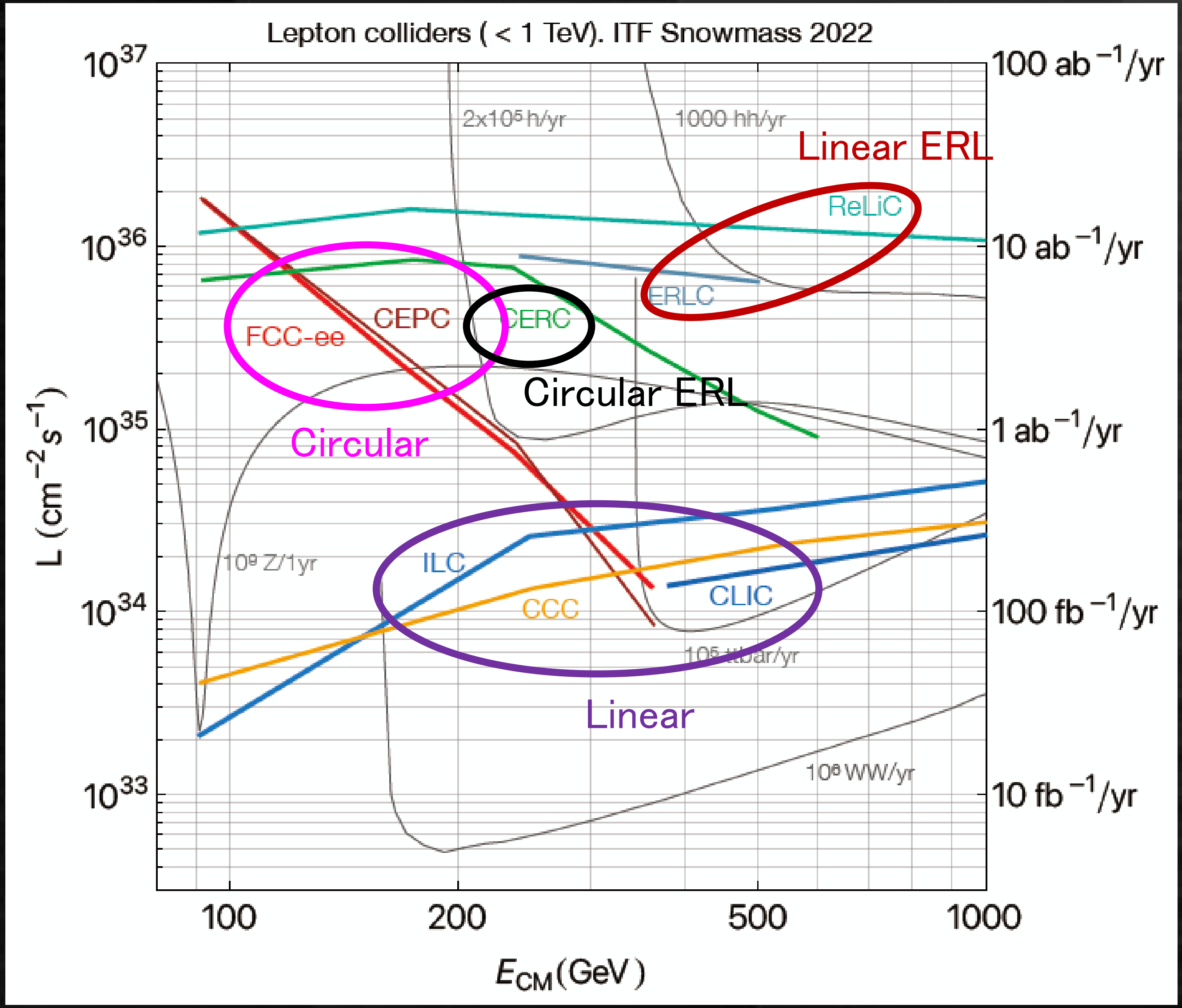
1 TeV — Higgs self coupling (10%) → baryogenesis

250 GeV – a few TeV — TeV BSM direct search

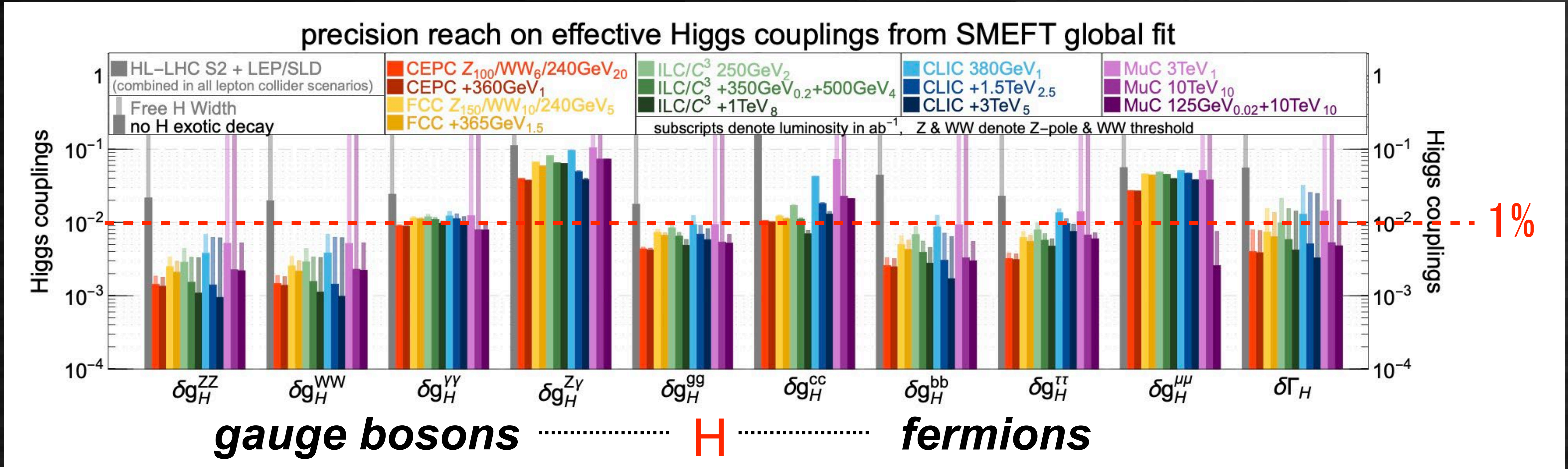
Natural SUSY (250 GeV – 1 TeV) 1 TeV Higgsino 3 TeV Wino

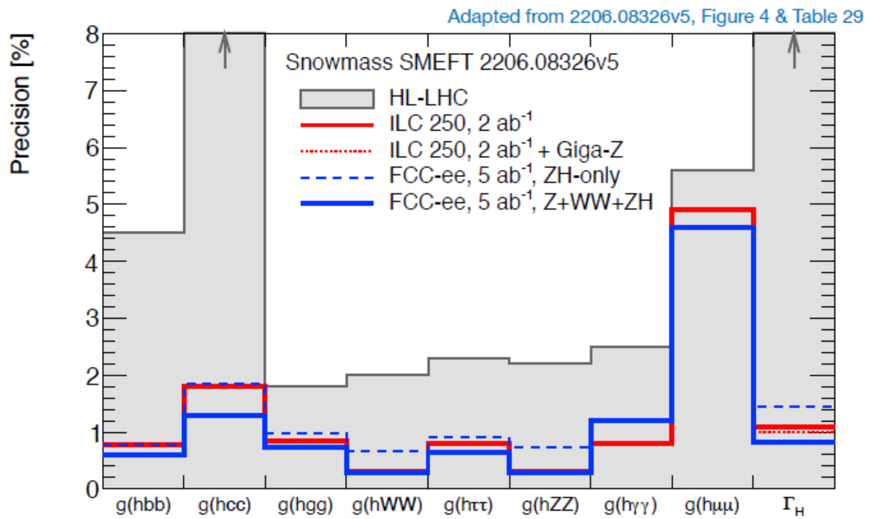
Circular and Linear collider?

- Luminosity @ 240/250 GeV
  - A few times higher at circular colliders
- Luminosity @ 350 GeV
  - Less efficient with circular
- Polarization
  - Obvious in LC
  - Not excluded but not guaranteed in circular
- Self coupling, ttH
  - Indirect only in circular



Higgs couplings: comparison





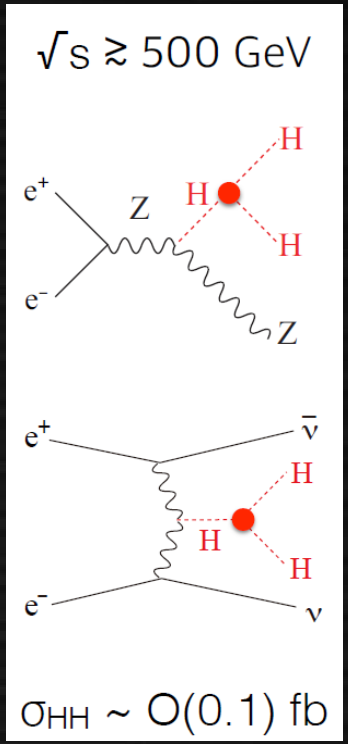
Circular collider utilizes Z/WW measurement for better Higgs coupling measurements

Performance comparable in SMEFT global fits

- Linear: polarization helps
- Circular: more luminosity

Higgs self coupling: direct vs indirect

Double-Higgs at 500-1000 GeV LC

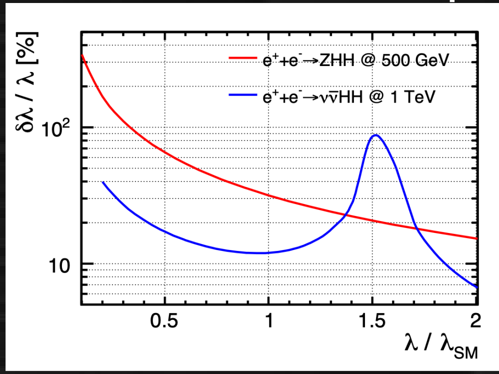


Difficult analysis

- Small cross section
- Complicated final states
- Interference diagrams

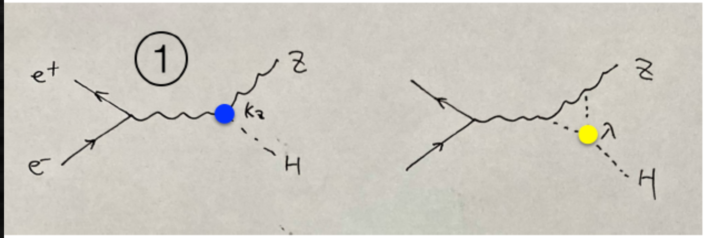
channel	√s [GeV]	L [ab^{-1}]	δλ
s-channel	500	4	27%
t-channel	1000	4	10%

Improvement by MLreco under study



Better resolution to higher λ in s-channel: opposite to HL-LHC

Single Higgs with circular colliders

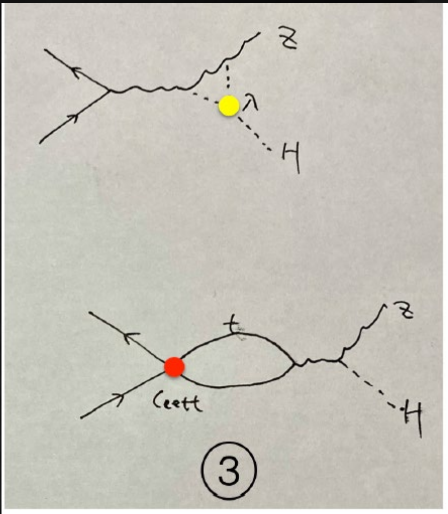


[McCullough, '13]

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- **$\delta\sigma_{ZH} < 1\%$** is a necessity; but not sufficient
- δσ could receive contributions from many other sources
  —> **δh ~ O(500)%** at 250GeV only; [Gu, et al, arXiv:1711.03978]

Difficult to separate at single energy



Combined with ZH @ 365 GeV can partially disentangle the contributions
→ < 100% λ determination possible

See J.Tian's slides at ECFA2024

Comparisons of physics in general

- Higgs physics @ 240/250 GeV – comparable performance
  - Golden channel for Higgs factory – sensitivity to many TeV models
- Self coupling – the final key topic on Higgs
  - Precise measurement only possible with LC (and 100 TeV collider)
  - 500/1000 GeV have unique features
  - Indirect measurement at 250+365 possible – but not too precise
- BSM search towards 1 TeV Higgsino
  - Search up to $\sqrt{s}/2$ (thus ~2 TeV necessary for 1 TeV Higgsino)
  - More comprehensive search than hadron colliders (no loopholes)
  - Great gain in high energy e+e- collider
- Flavor physics
  - CC clearly have higher potential but some can be done in LC

Comparison in project aspects

- Tunnel length
  - Much longer in circular colliders (100 vs 20 km)
    - Higher cost (FCCee > 2xILC, CEPC less clear) and environmental impact
    - Need to be careful of cost uncertainty! (remember SSC)
- Electricity: 2-3x higher (/day) in circular colliders
  - CC has higher luminosity but no pol. and need Z+H program
- Upgradability
  - CC: up to 365 GeV, then replace to hadron collider
  - LC: up to a few TeV, by extension and/or higher gradient
    - (more if fully plasma-based acceleration)

ECFA Higgs factory studies

ECFA
European Committee for Future Accelerators

ECFA workshops on e+e- Higgs/EW/Top factory

16 focused topics to explore

Combine physics/detector efforts for Higgs factories and avoid duplication, making common software etc.
Parallel (and close relation) to FCC FS, ILC IDT etc.

WG 1: Physics Potential
Conveners: Patrick Koppenburg (NIKHEF), Jenny List (DESY), Fabio Maltoni (UC Louvain / Bologna) and Jorge de Blas (Univ. Granada)
More information on WG 1 activities

WG 2: Physics Analysis Methods
Conveners: Patrizia Azzi (INFN-Padova / CERN), Fulvio Piccinini (INFN Pavia) and Dirk Zerwas (IJCLab/DMLab)
More information on WG2 activities

WG 3: Detector R&D
Conveners: Mary Cruz Fouz (CIEMAT Madrid), Giovanni Marchiori (APC Paris), Felix Sefkow (DESY)
More information on WG3 activities

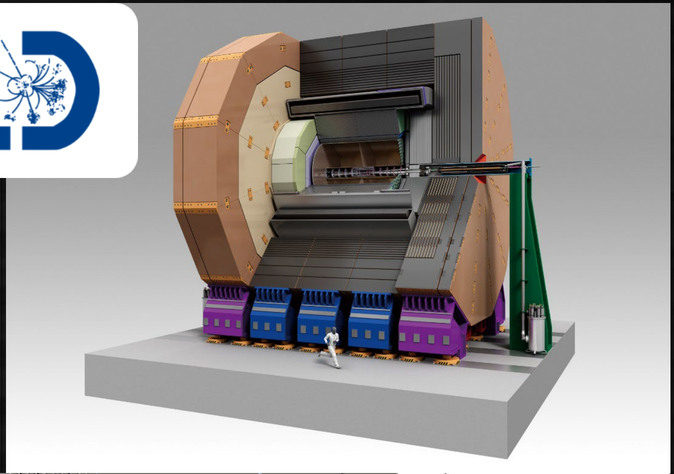
topic	lead group
1 HtoSS	HTE
2 ZHang	HTE (GLOB)
3 Hself	GLOB
4 Wmass	PREC
5 WWdiff	GLOB
6 TTdet	HTE
7 TTscan	GLOB (HTE)
8 LUMI	PREC
9 EXscalar	SRCH
10 LLPs	SRCH
11 EXtt	SRCH
12 CKMWW	FLAV
13 BKtautau	FLAV
14 TwoF	HTE
15 BCfrag	FLAV (PREC)
16 Gsplit	PREC (FLAV)

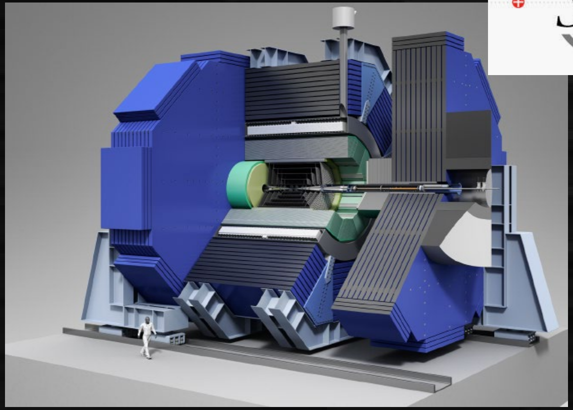
Yearly workshops
https://indico.desy.de/event/33640/ (October 2022, DESY, Germany)
https://agenda.infn.it/event/34841/ (October 2023, Paestum, Italy)
https://indico.in2p3.fr/event/32629/ (October 2024, LPNHE, France)

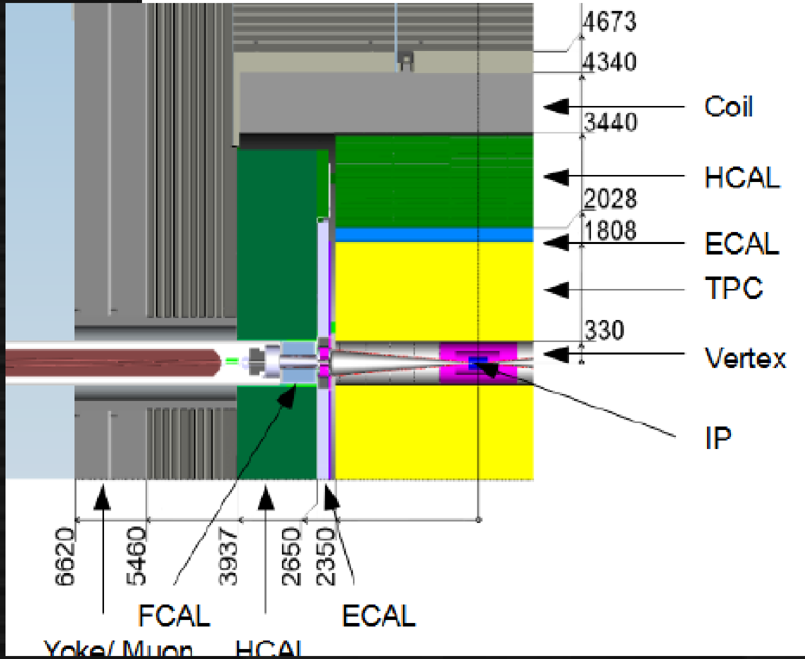
Common detector for Higgs factories?

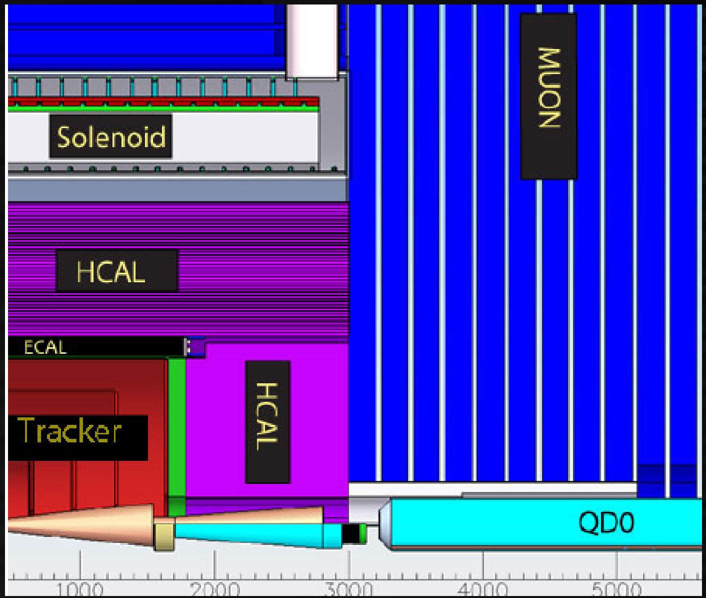
eg. ILD for FCCee

Detectors for ILC: ILD and SiD









Two (similar) concept based on Particle Flow reconstruction

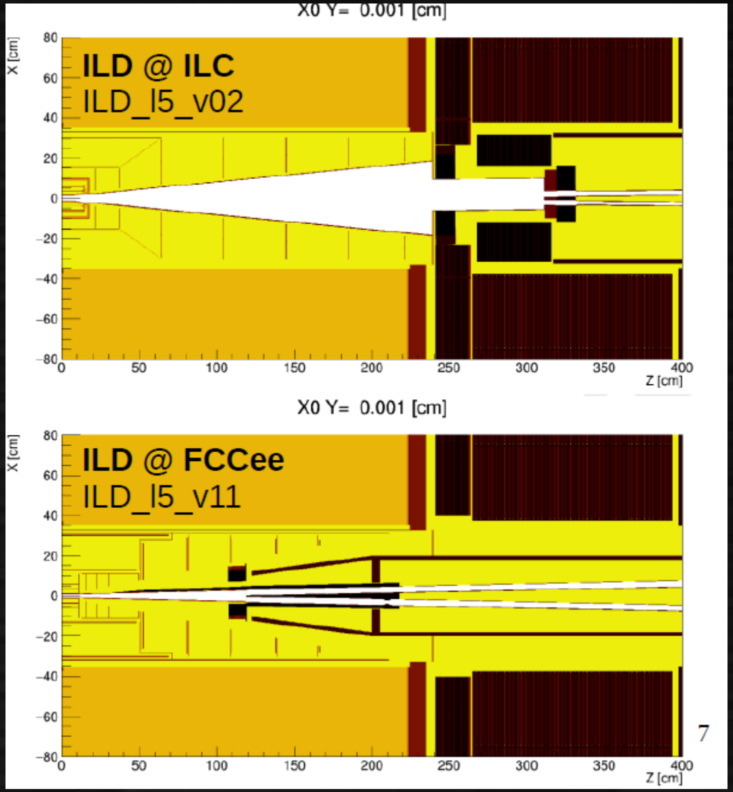
Already mature baseline design

- Monolithic silicon vertex
- Silicon tracker (inner/outer for ILD)
- Time projection chamber (only for ILD)
- Highly-granular ECAL/HCAL with several options
  - Silicon pads
  - Scintillator strips/tiles
  - Resistive plate chamber
  - Silicon pixels (MAPS)
- 3.5/5T solenoid outside HCAL

Difference on detector requirements

- Common features:
  - Precise vertexing, low material tracker, good momentum and jet energy resolution, (quasi) triggerless readout, 4pi coverage
- Magnetic field: limited to 2 Tesla in Z-pole operation
  - Degraded performance of Particle Flow expected
- High rate (at Z-pole): Problem on ion backflow in TPC
- PID more important at Z-pole operation
  - Flavor physics
- Continuous readout: power-pulsing cannot be used
  - Cooling more severe

TPC beamstrahlung study at ILD (D.Jeans)



			FCCee-91	FCCee-240	ILC-250
model	B-field [T]	MDI	thousand ions / bunch crossing mean $\pm$ RMS		
ILD_l5_v02	3.5 (uniform)	ILC	6.5 ± 19.9	14 ± 14	960 ± 150
ILD_l5_v02_2T	2.0 (uniform)	ILC	6.9 ± 11.1	15 ± 11	4700 ± 300
ILD_l5_v03	3.5 (map)	ILC	5.7 ± 7.9	14 ± 11	1100 ± 200
ILD_l5_v05	3.5 (map, anti-DID)	ILC	0.6 ± 1.5	3.7 ± 9.7	450 ± 110
ILD_l5_v11β	2.0 (uniform)	FCCee	390 ± 120	1000 ± 170	110000 ± 2400
ILD_l5_v11γ	2.0 (map)	FCCee	270 ± 100	800 ± 140	100000 ± 1900

FCCee MDI system induces ~50x increase in TPC activity compared to ILC

Collider Detector model	FCCee-91 ILD_l5_v11γ	FCCee-240 ILD_l5_v11γ	ILC-250 ILD_l5_v05
average BX frequency	30 MHz	800 kHz	6.6 kHz
primary ions / BX	270 k	800 k	450 k
primary ions in TPC at any time	1.8×10^{12}	1.4×10^{11}	6.5×10^{8}
average primary ion charge density nC/m^3	6.8	0.54	0.0025

primary ion density in TPC: 2500 times higher at FCCee-91 than ILC-250
200 times higher at FCCee-240 than ILC-250

Combination of MDI and high rate gives big charge, causing track distortion

Recent focus: timing measurement

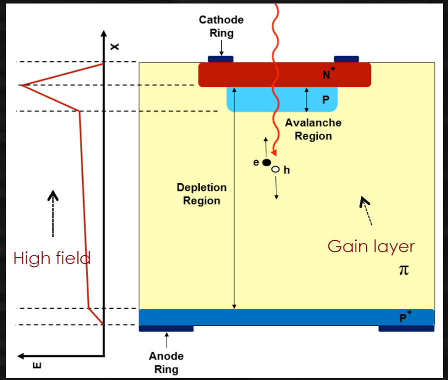
Several technologies recently targets < 30 psec timing measurements

- LGAD (silicon) / SPAD
- Scintillator / Cherenkov based
- RPC / gas based

Possible application at HF detectors

- Pileup rejection? (for circular HF)
- Hadron PID with time-of-flight ~30 ps
- Improving particle flow performance (5D imaging calorimeter) ~10 ps
- Photons from b/c hadrons ~3 ps

Needs innovative sensors & software



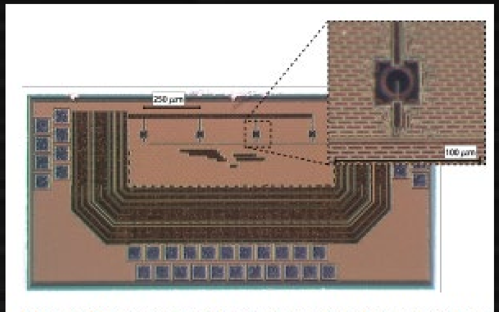
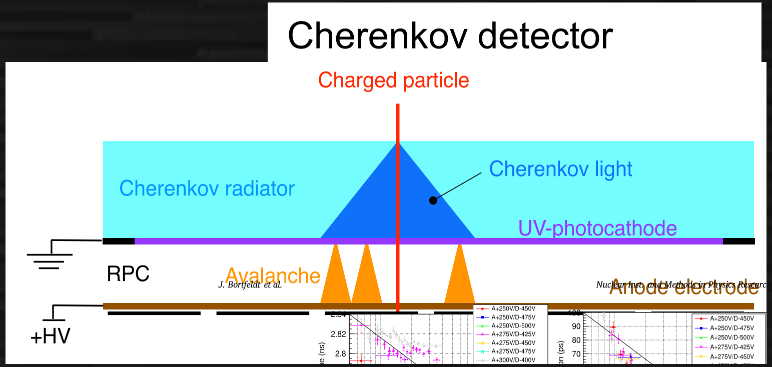
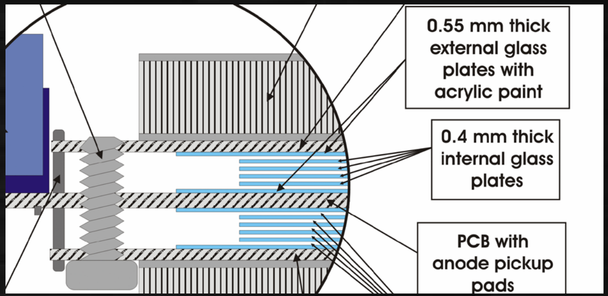
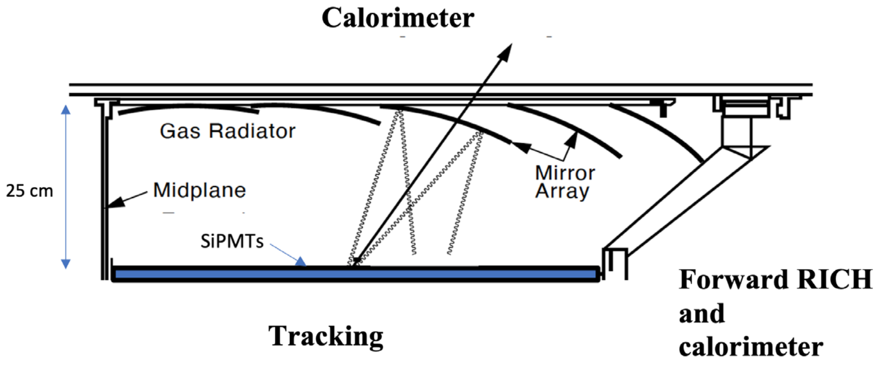


FIG. 1: Micrograph of the implemented chip embedding 25 μm diameter SPADs with integrated pixel circuit [20].

Still significant effort required towards realistic design at HF





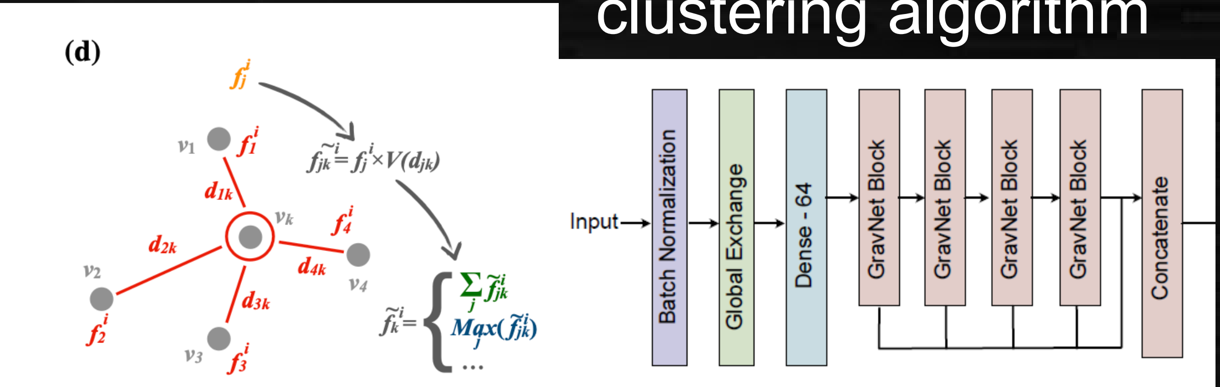


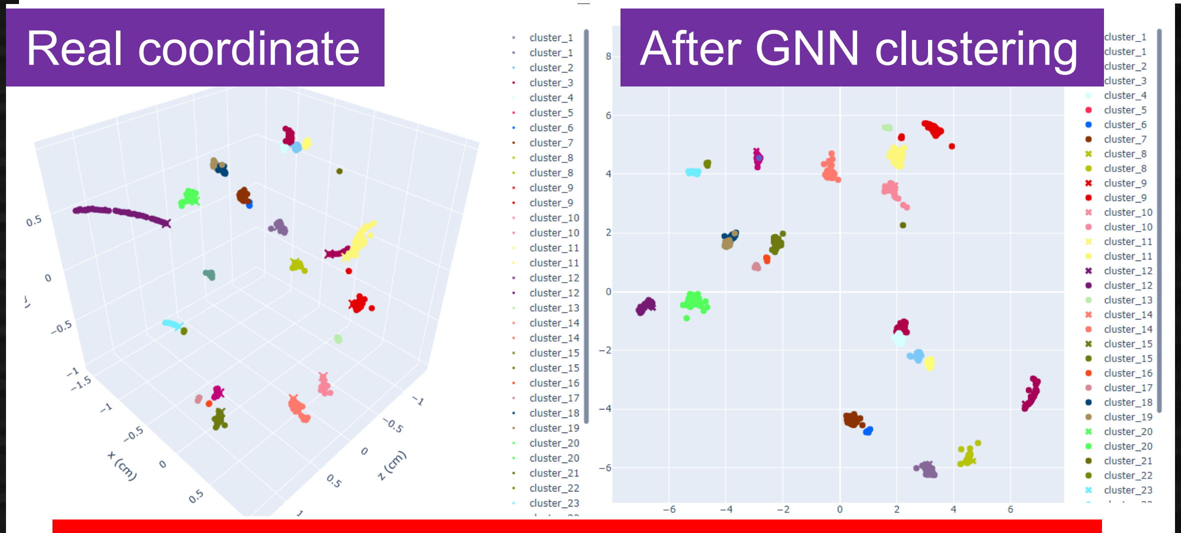
Alternative idea to use RICH for PID

Resent focus: applying deep learning

Particle flow with Graph Neural Network

Adding track-cluster matching to HGCAL clustering algorithm

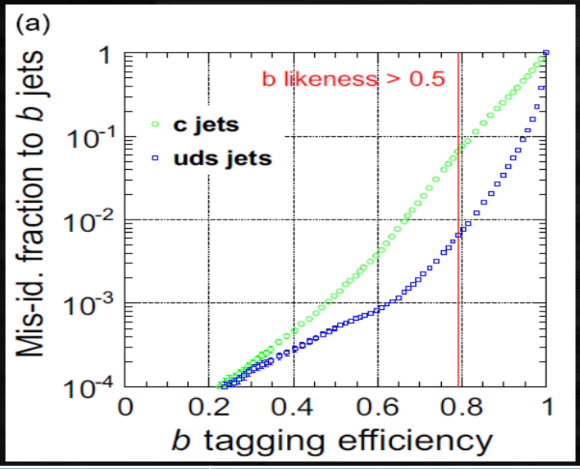


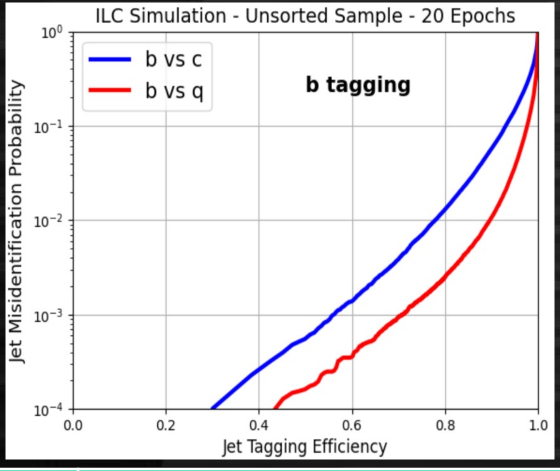


Good synergy with hadron colliders

Flavor tagging with GNN/Transformer

Applying algorithm developed at CMS flavor tagging: 5-10 better rejection than old (BDT) method





	b-tag 80% eff.		c-tag 50% eff.	
Method	c-bkg acceptance	uds-bkg acceptance	c-bkg acceptance	uds-bkg acceptance
LCFIPlus	10%	1%	10%	2%
ParT	1.29%	0.25%	1.02%	0.43%

ILD for circular collider

- ILD will be submitted to the European strategy as "general Higgs factory detector"
  - Will consider to participate EoI call of FCCee
- Modification (electronics, cooling, magnetic field) necessary for circular colliders
  - No detailed study possible before the European strategy but should have rough ideas of possible modification
- ILD @ (I)LC remains mainstream for ILD

Global project?

ILC is proposed as a global project (at least for IDT)

2) Issue on global versus international

T. Nakada

Global Project: Starts and evolves as a collaborative project of partner countries. There could be some leading members, but **decisions** on the project, such as the scheme for cost and responsibility sharing, project organisation, and host and site location, **are made collectively**. ITER (an example of top down approach) and SKA (an example of bottom up approach) are examples of large global projects. HEP experiments have a similar decision making principle.

International Project: Initiated as a project of a laboratory to which other countries join with small contribution, a total of *O*(10~20%) of the accelerator, like HERA (started as a DESY project) and LHC (started as a CERN project). It remains as the project of a single laboratory with **limited participation in decision making for the partners**.

→ Need ILC to be recognized as a global project

NB: Implementation of ITER is not necessarily judged as a success, but they succeeded to start as a global project.

Consideration for global project

	Global project	International project
First call for discussion	Not obvious	Host state
Approval of project	International agreement	Host state followed by agreements with participating states
Cost covered by host	~50%?	80-90%
Decision body	Council by member states	Mostly on host country
Operation responsibility	Shared by member states?	Host state

Key issues for global project:

- Initial call of discussion/negotiation is not obvious
  easily stacked on “chicken/egg problem”
- Decision can take time and vulnerable to international situations

But EF colliders have to be “global” some day if too big to cover by part of the world

Summary

- LC is still a very competitive option for Higgs factory
  - Luminosity@250 GeV compensated by polarization
  - Big advantage on energy upgrade (self coupling and BSM search)
  - Compact and affordable → sustainable collider
- Cooperation between circular and linear collider is more important than before
  - Many synergies esp. in physics and detectors
  - LC Higgs factory has longer history with sophisticated design/software/analysis
- Despite many difficulties, we are willing global discussion on Higgs factories for optimal solutions and worldwide cooperation.

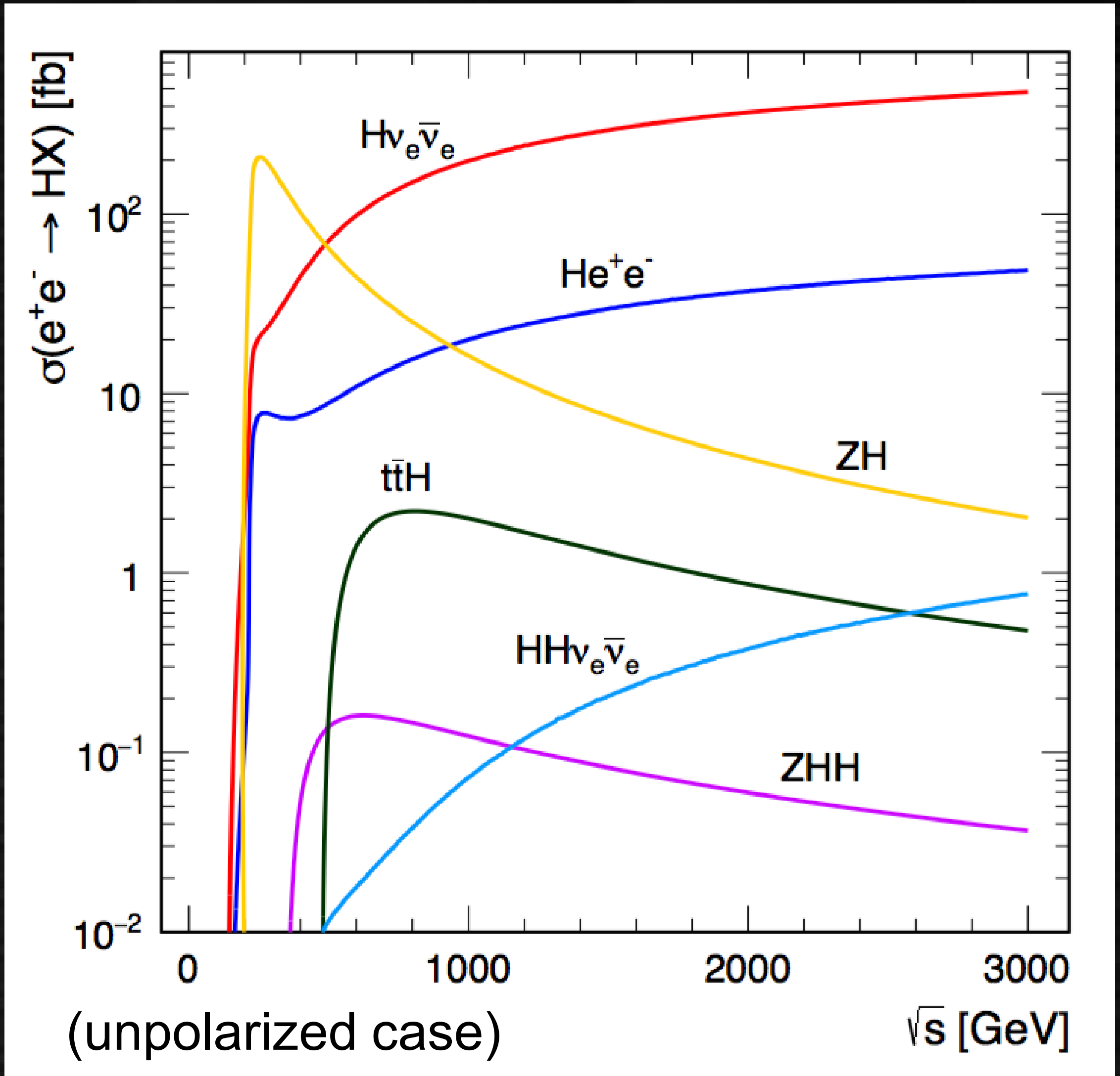
Physics of Linear Colliders

Focus on higher energies

Higgs physics

- Probing additional Higgs sectors with Branching Ratio
  - SUSY, Composite Higgs, … most of "standard" TeV BSMs
  - ~1% branching ratio: around 1 TeV as heavy Higgs scale
- Probe to light BSMs – Higgs portal (DM etc.)
  - Invisible decay, exotic decay
- Higgs self coupling
  - Determine Higgs potential
  - Sensitive to electroweak baryogenesis
- Vacuum stability
  - Higgs (and top) mass

Higgs production and CM energies



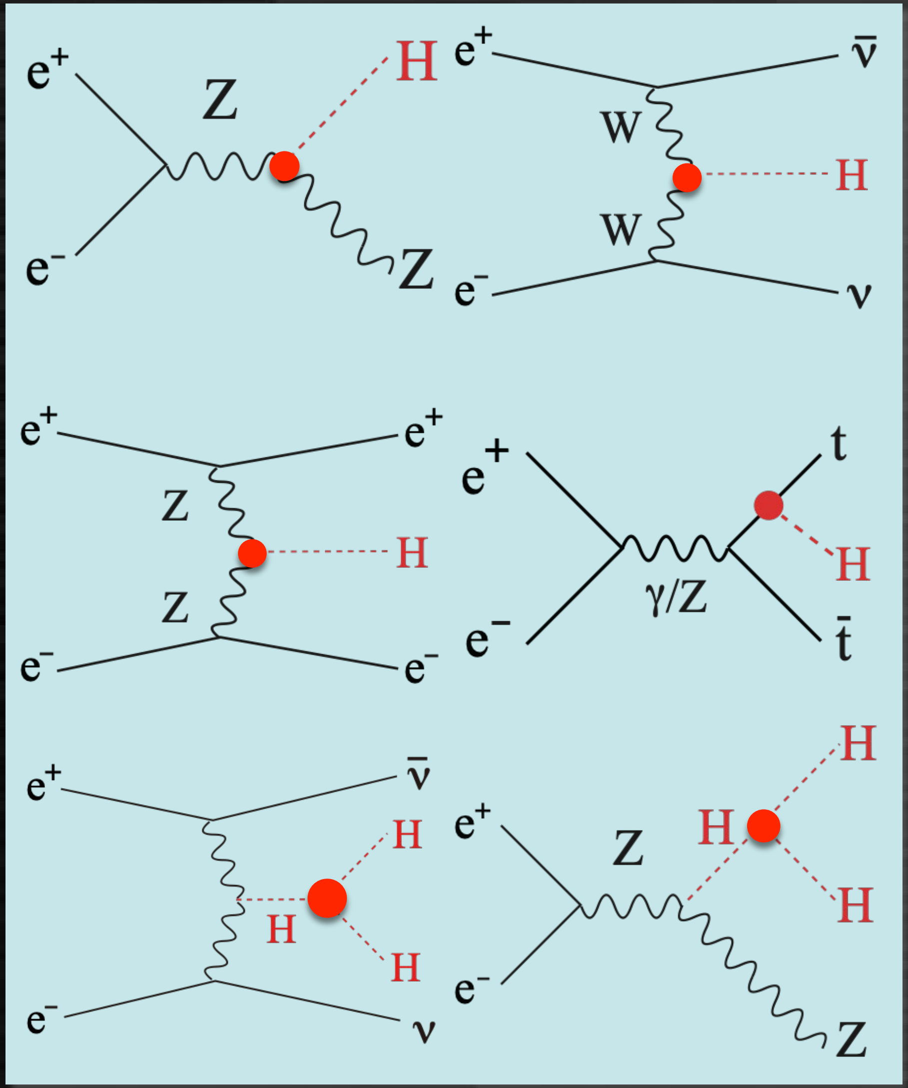
240-250 GeV:
ZH @ ~100 fb

350 GeV
ννH @ ~50 fb

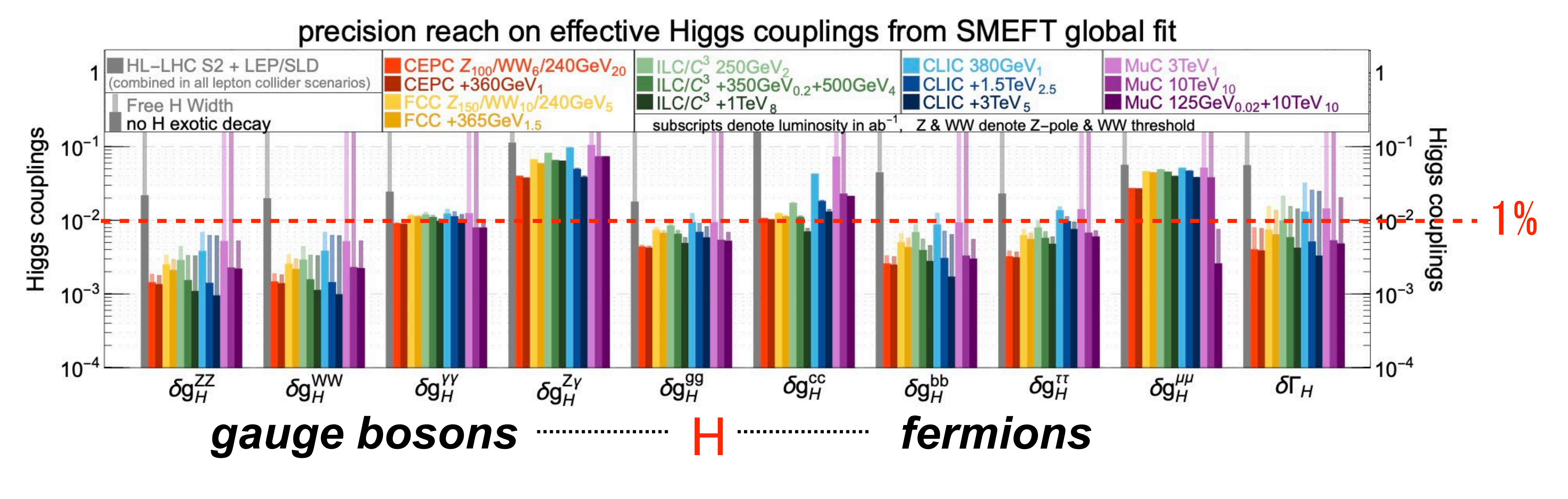
500-600 GeV:
ννH @ ~100 fb
ttH @ ~1 fb
ZHH @ ~0.1 fb

1000 GeV:
ννHH @ ~0.1 fb

2000-3000 GeV:
ννHH @ ~0.5 fb



Higgs BR measurements



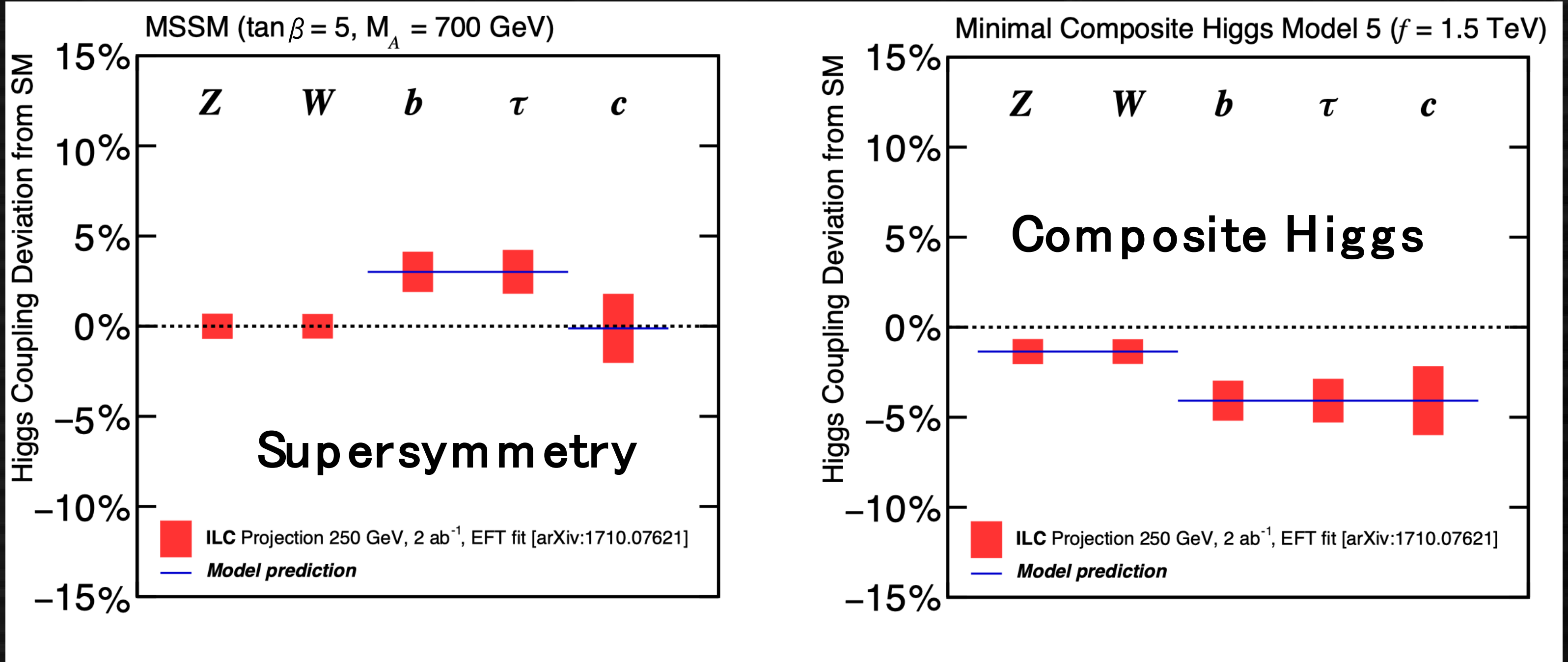
Any HFs: ~1% (or less depending decay channels) BR of dominant decays

- Factor 5-10 improvements from HL-LHC (except μμ and γγ)
  → fingerprinting BSM models

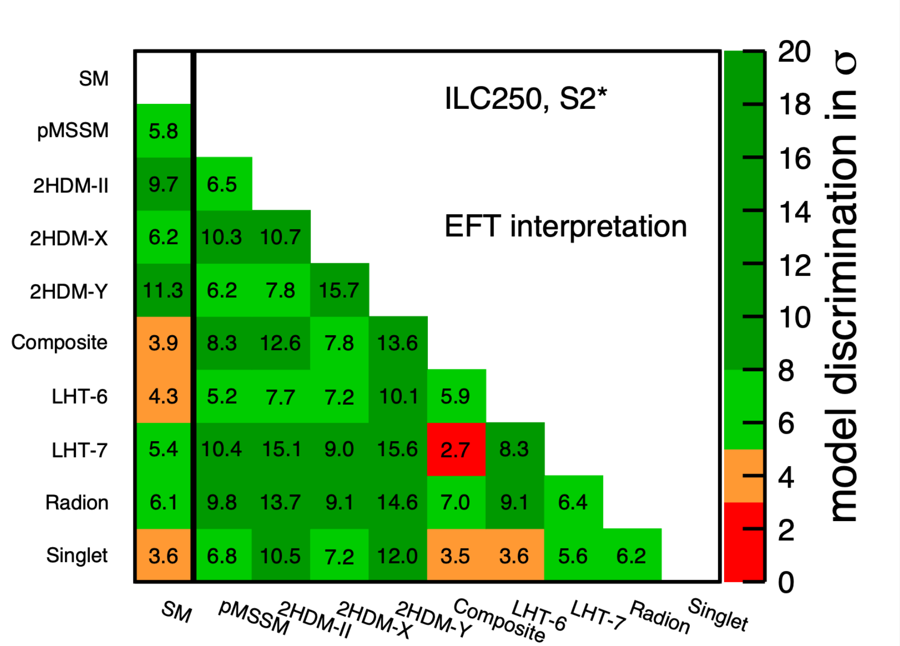
Much more model independent: total cross section, total width,
30-param SMEFT with various electroweak precision measurements

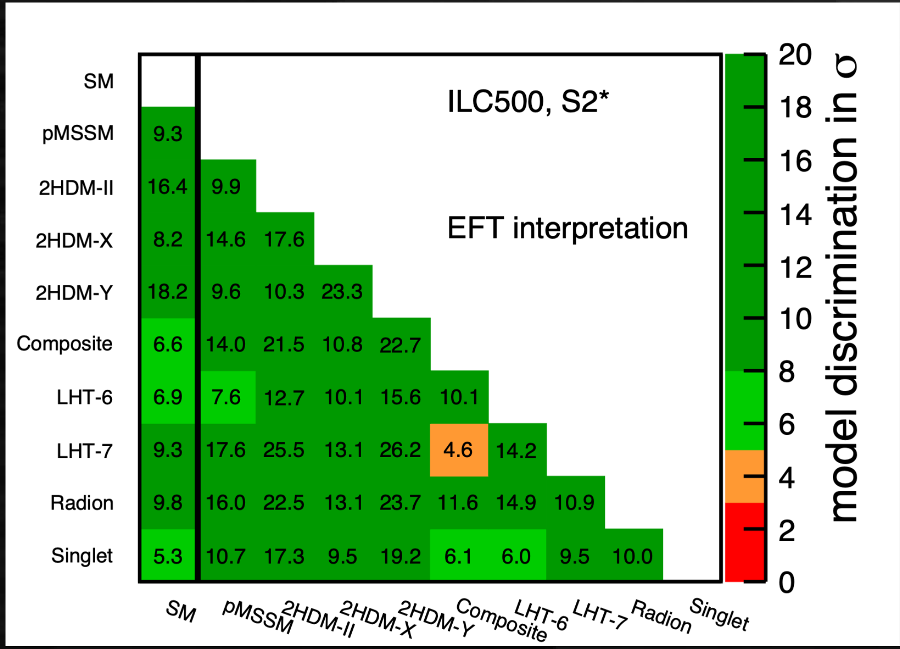
BSM fingerprinting

Deviation of branching ratio to SM varies by BSM models
→ fingerprinting of BSM models by BR measurements



[ILC TDR, arXiv: 1306.6352]

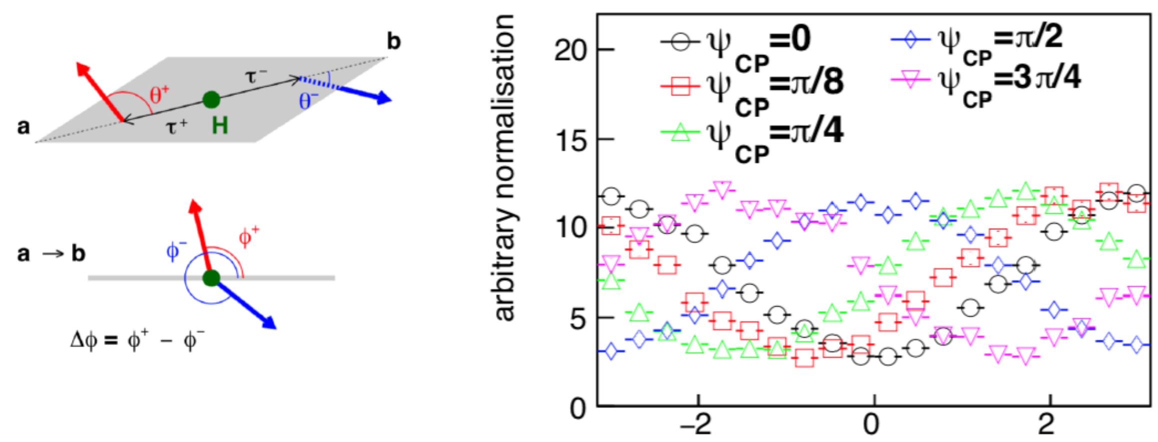




Higgs CP properties

H → ττ

$$L_{Hff} = -\frac{m_f}{v} H\bar{f}(\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP})f$$



$\Delta\Phi_{CP} \sim 4.3°$ (theoretically ~1 degree reachable)

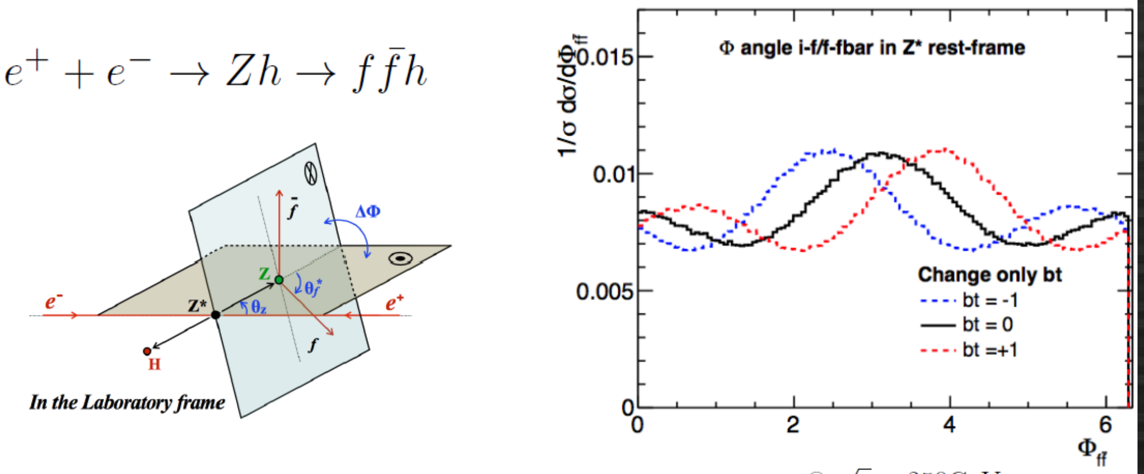
Jeans et al, arXiv:1804.01241

H → ZZ

$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

(CP-even) (CP-odd)

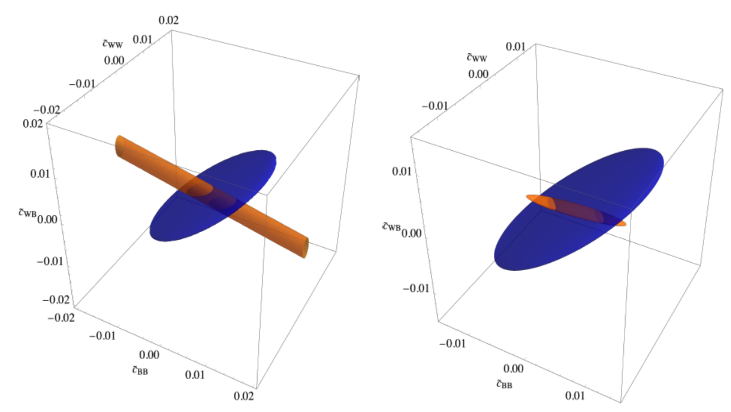
$e^+ + e^- \rightarrow Zh \rightarrow f\bar{f}h$



@ $\sqrt{s} = 250\text{GeV}$

$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

Ogawa et al, arXiv:1712.09772



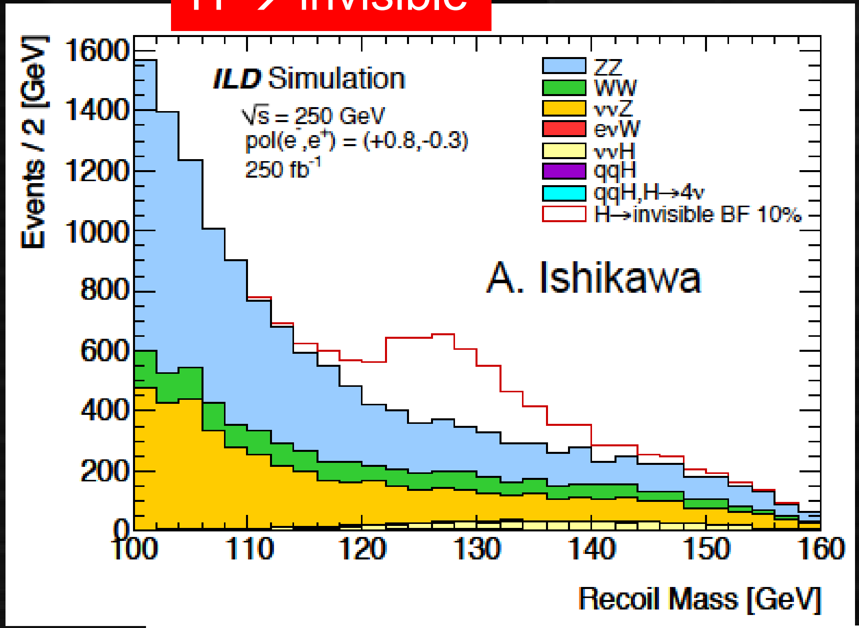
Sensitivity to CPV operators complimentary to HL-LHC
Blue: HL-LHC, Orange: ILC250

Exotic Higgs decay for probing light BSM

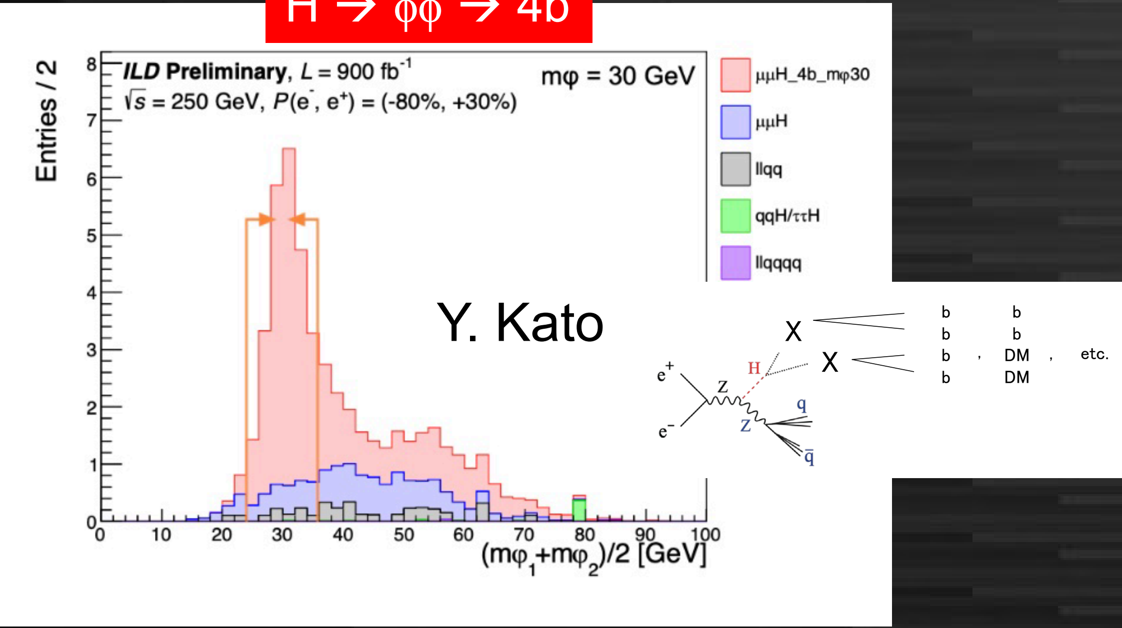
Full simulation studies

Not fully covered → more studies needed!

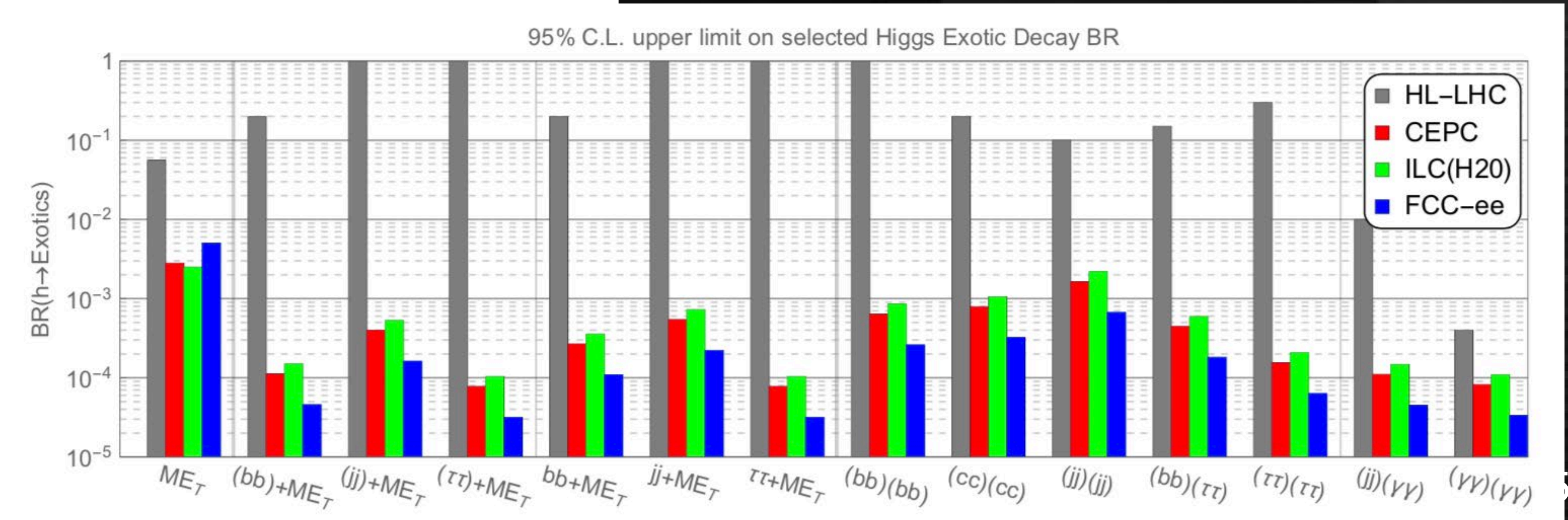
H → invisible



H → ϕϕ → 4b



Rough assumption for various exotic decays:
Probe most channels with 0.1 – 0.01% branching ratio
arXiv:1612.09284



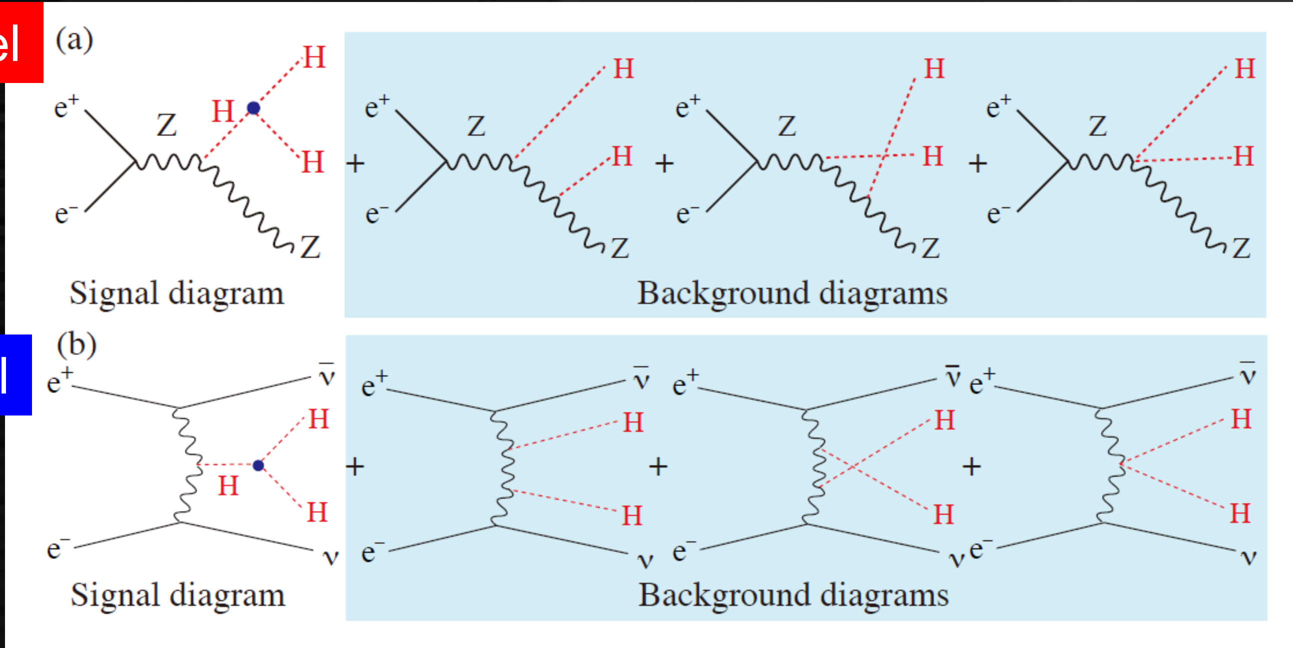
Higgs self coupling

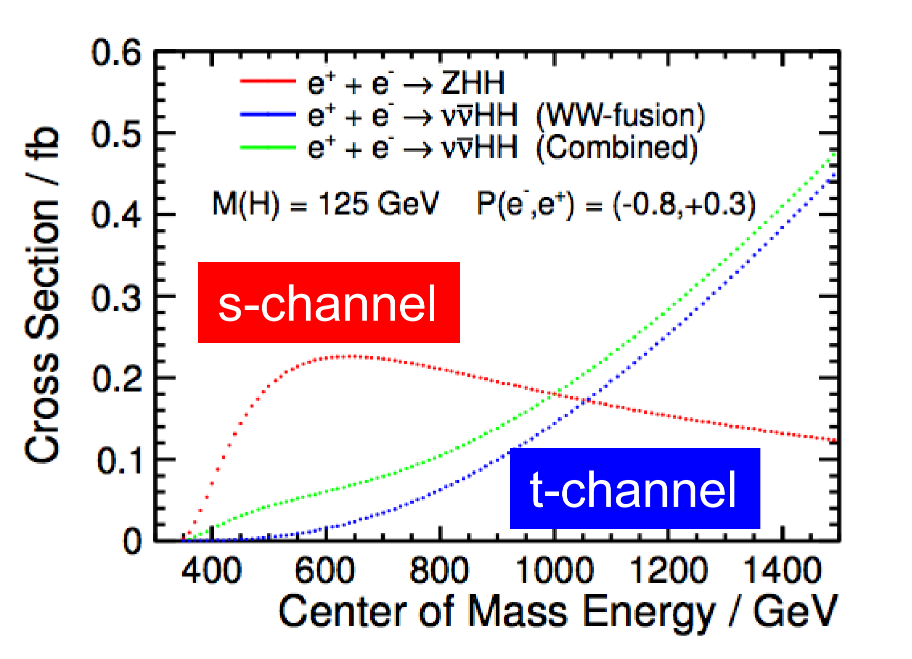
$$V(\eta_H) = \frac{1}{2}m_H^2\eta_H^2 + \lambda v\eta_H^3 + \frac{1}{4}\lambda\eta_H^4$$

Direct probe of Higgs potential
Essential for electroweak baryogenesis
(1st order phase transition requires >10% more l)

s-channel

t-channel





Extremely small cross section:
O(100) events / ab^{-1}

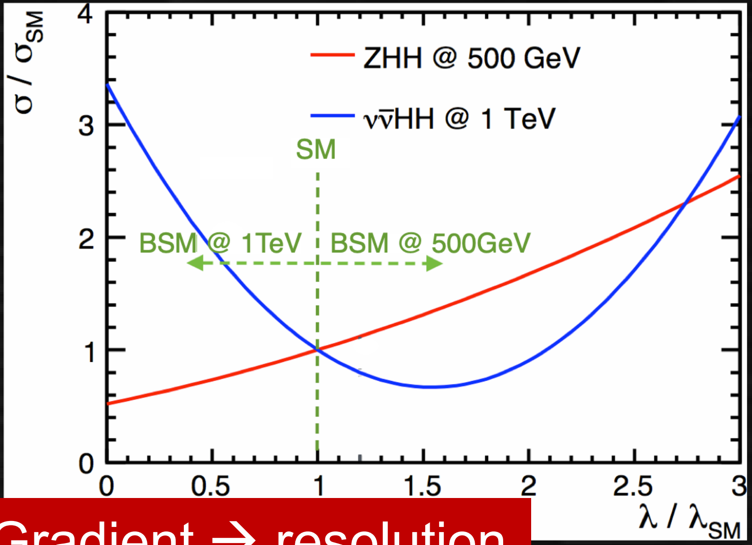
Effect of insensitive diagram → next page

channel	√s[GeV]	L [ab^{-1}]	λ precision
s-channel	500	4	27%
t-channel	1000	4	10%

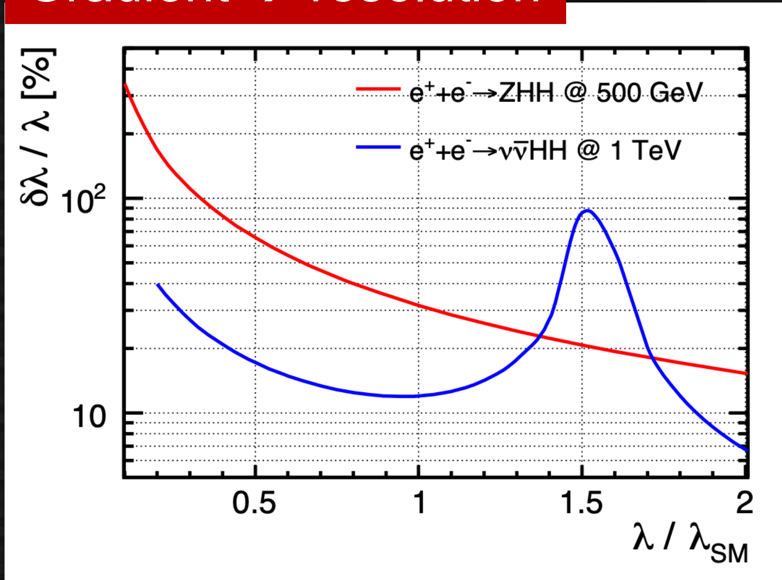
Ultimate precision at linear collider: ~5% at 2-3 TeV

Higgs self coupling (cont.)

Effect of interference

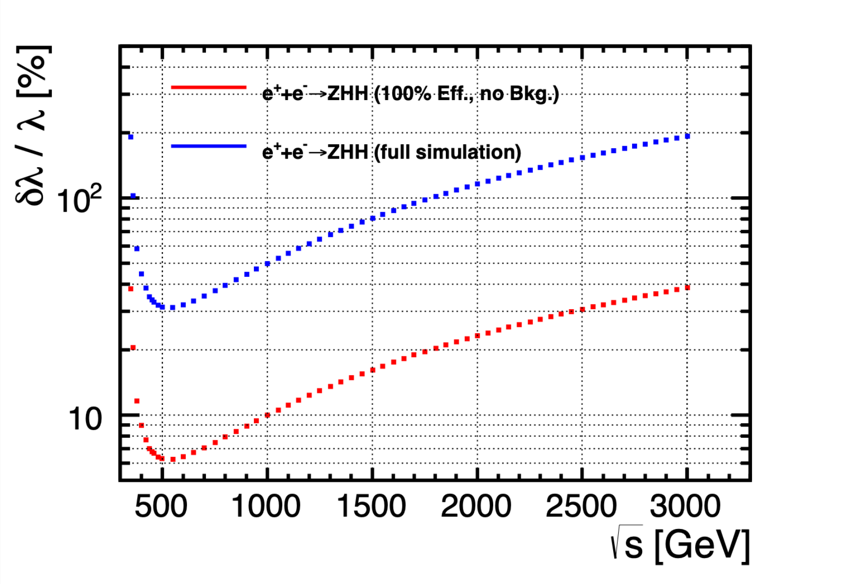


Gradient → resolution



500 GeV: better at higher λ (20% @ λ ~ 1.5)
1 TeV: best at 0.8 < λ < 1.2, insensitive at λ ~ 1.5

Possibility for improvements



Reconstruction of multi-jet environments
(Jet energy resolution, flavor tagging)
→ Deep learning based reconstruction
Improvements possible but not easy

Self coupling from
NLO ZH cross section

$$\sigma_{i,\mathrm{NLO}} = Z_{\mathrm{H}} \sigma_{i,\mathrm{LO}} \left(1 + \kappa_\lambda C_{1,i}\right)$$

Considered in FCC context
(since > 500 GeV impossible)

- Loop contribution
- Assuming no BSM loop (qualitatively different from double-Higgs search)

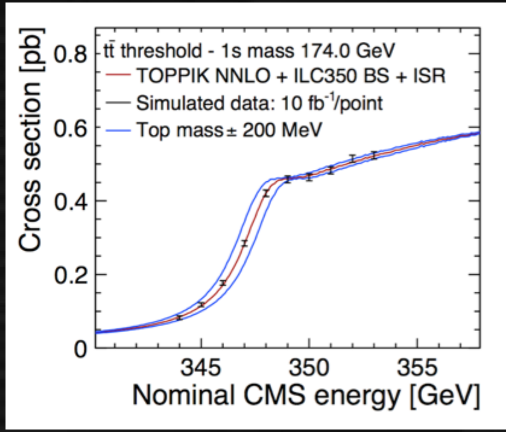
→ ~30% resolution feasible at 250 GeV (FCCee study)
(to be investigated for LC)

Linear vs circular in Higgs studies

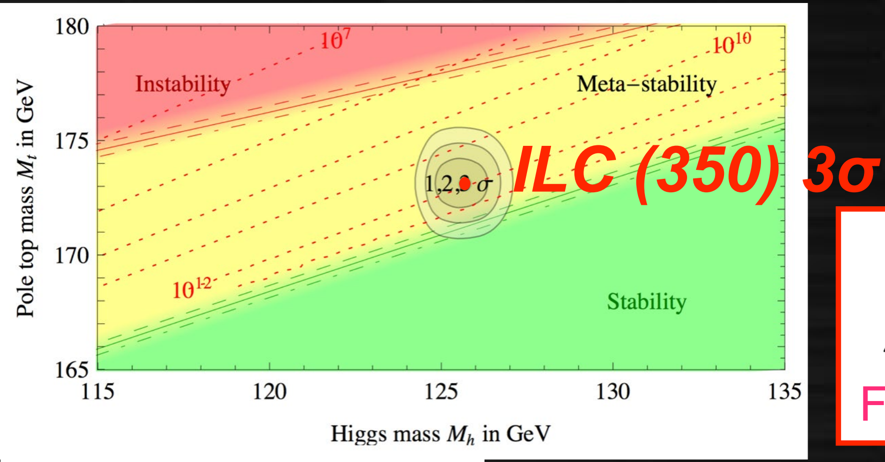
- 240/250 GeV for Higgs coupling
  - FCCee has a few times more sensitivity / 2+ detectors
  - ILC has electron/positron polarization
    → Complemental sensitivity, claimed to "similar value" in EPPSU
- Higher energy
  - Higgs self coupling is the biggest topic on Higgs at >500 GeV
    - Indirect measurement at FCCee
      - But difficulty to disentangle with deviation of other couplings (ZZH etc.)
    - Ultimate sensitivity (if multi-TeV) comparable with FCChh

ttbar threshold and ttH

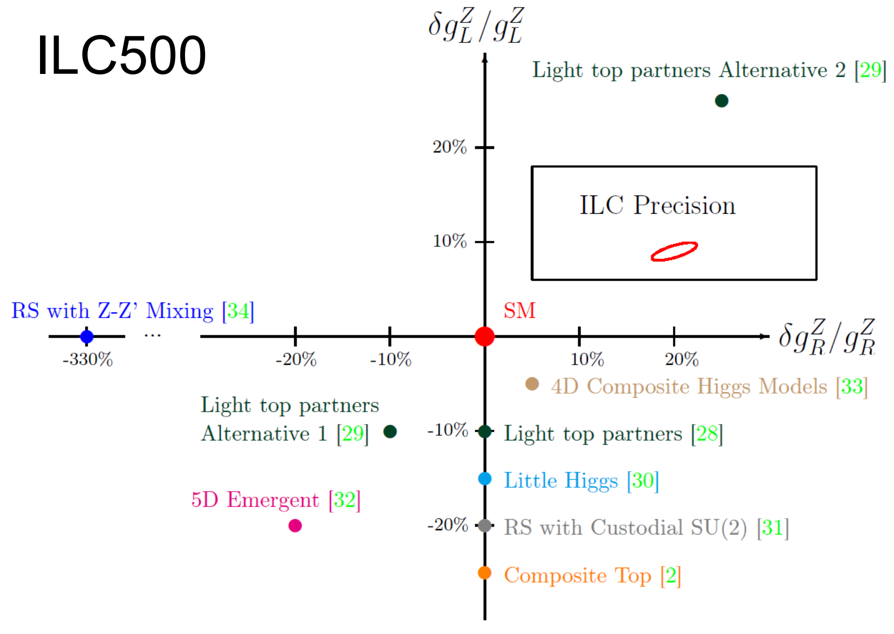
Threshold scan @ 350 GeV



"Potential-subtracted mass" which is theoretically compatible to Msbar mass can be directly observed



arXiv:1205.6497, Degrassi et al.



Form factor measurement at open-top region

$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$
$$\Delta m_h \simeq 14\ \mathrm{MeV}$$

Final answer on stable/metastable vacuum

Direct top-Yukawa measurement needs > 550 GeV CM energy

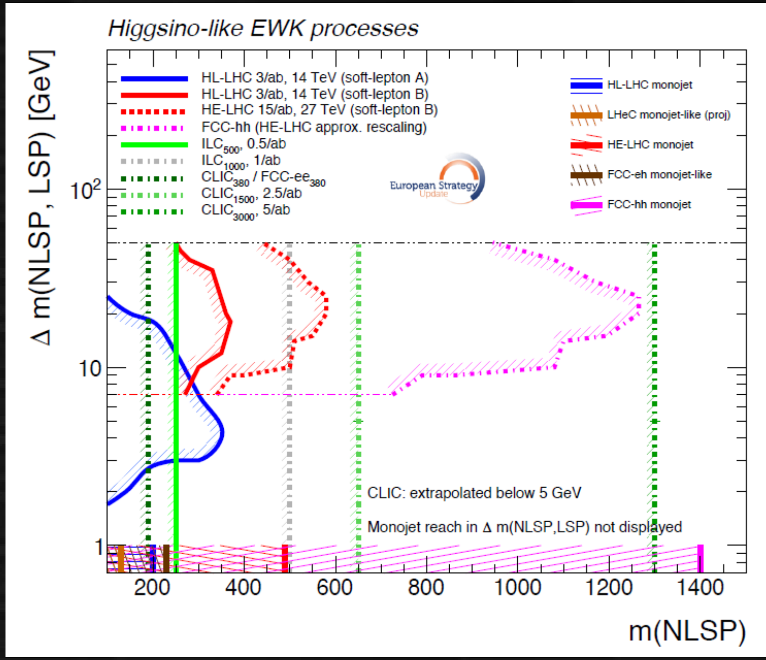
~2.8% possible

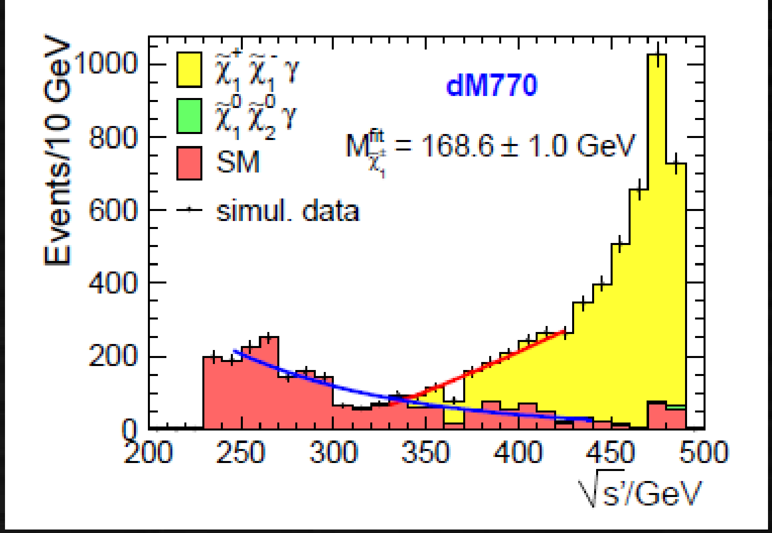
550 GeV can prove HH self coupling as well

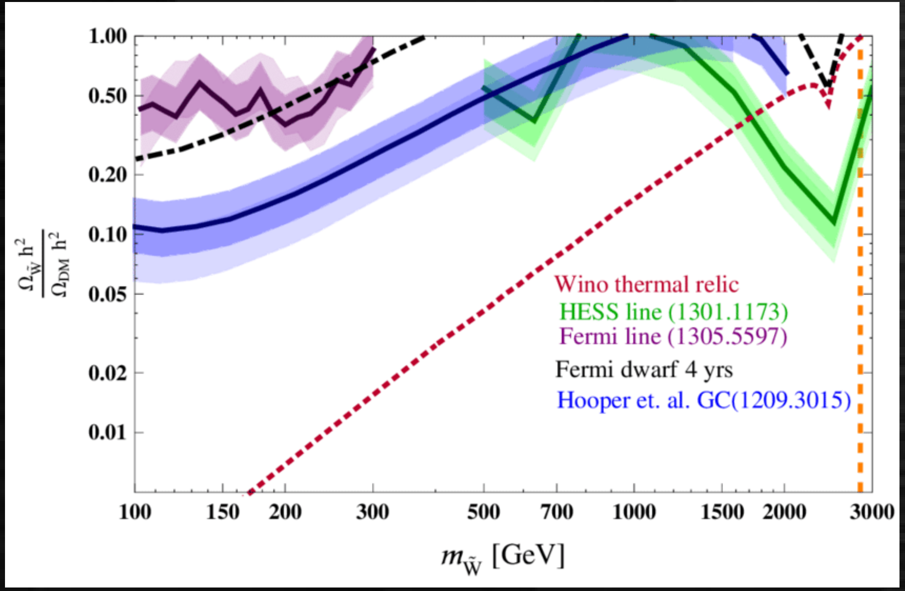
Other EW precision variables like 2f cross section (sensitive to Z'/WIMP) triple gauge coupling etc.

Ultimate target: direct search of TeV WIMP

- Big motivation of SUSY consistent with thermal DM
  - < 3 TeV Wino → 6 TeV collider needed (probably needs novel acceleration)
  - 1 TeV Higgsino → 2 TeV collider (~final target of SC or NC RF accelerator)
- Degenerated SUSY: easy to fill the gap by e+e- collider





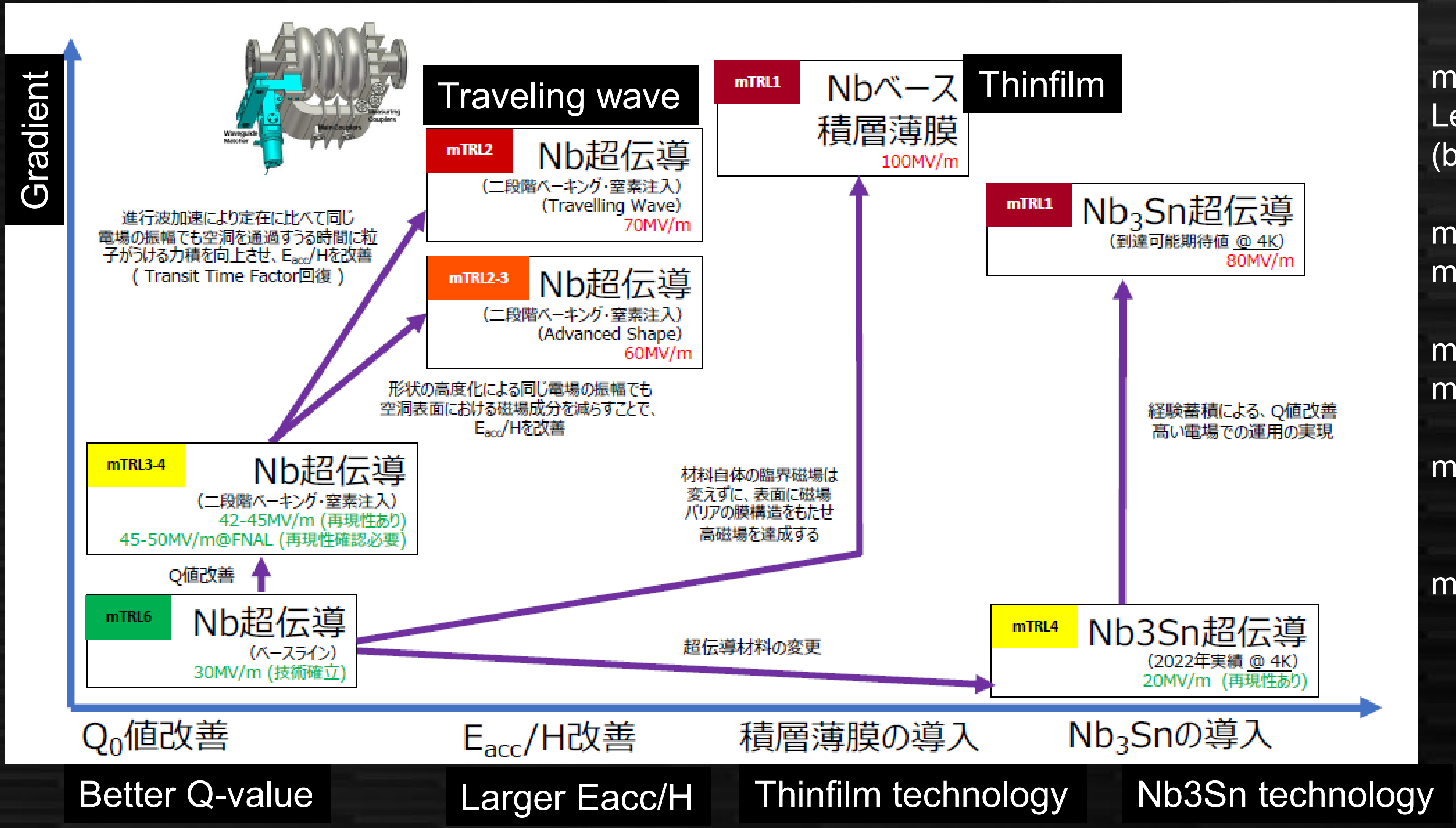


Technology of LC

Accelerator (focus on energy upgrades)

Detector/Analyses

Upgrade path for superconducting RF



modified Technology Readiness Level for accelerator technology (based on TRL on space industry)

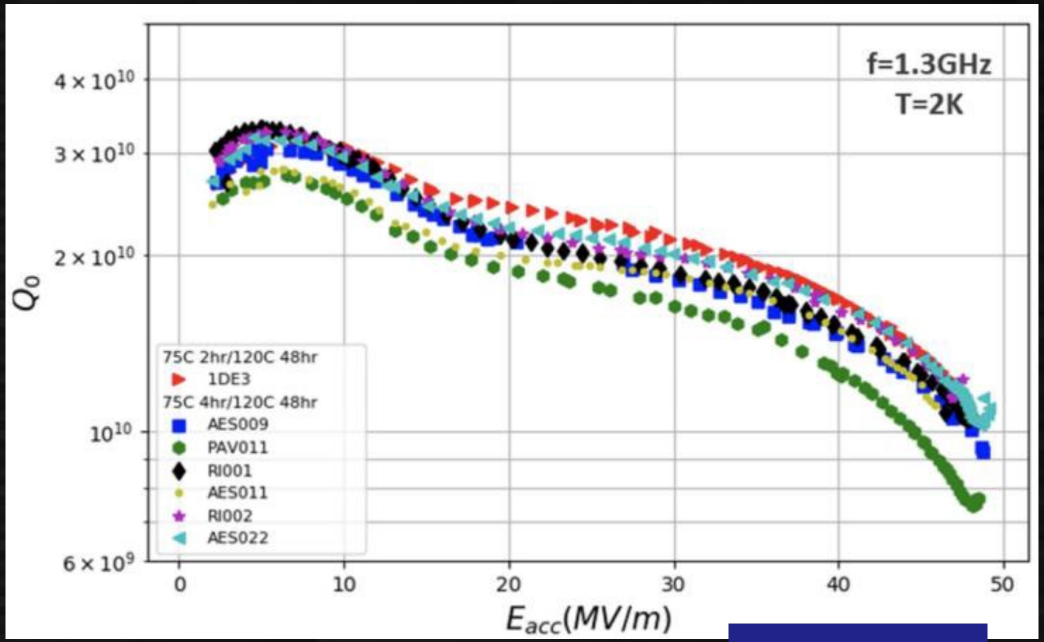
- mTRL1: ideas not proven
- mTRL2: ideas not proven
  but path exists for demo
- mTRL3: ideas proven at lab level
- mTRL4: ideas proven as
  system with reproducibility
- mTRL5: the proven system
  meets requirements as
  collider realization
- mTRL6: mass production ready

Optimization on surface structure

Surface treatment (near future)

> 45 MV/m demonstrated recently with 75C/120C baking method (creating some oxidization at surface)

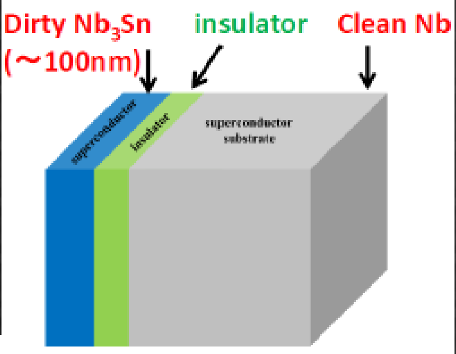
More understanding needed for reproducibility

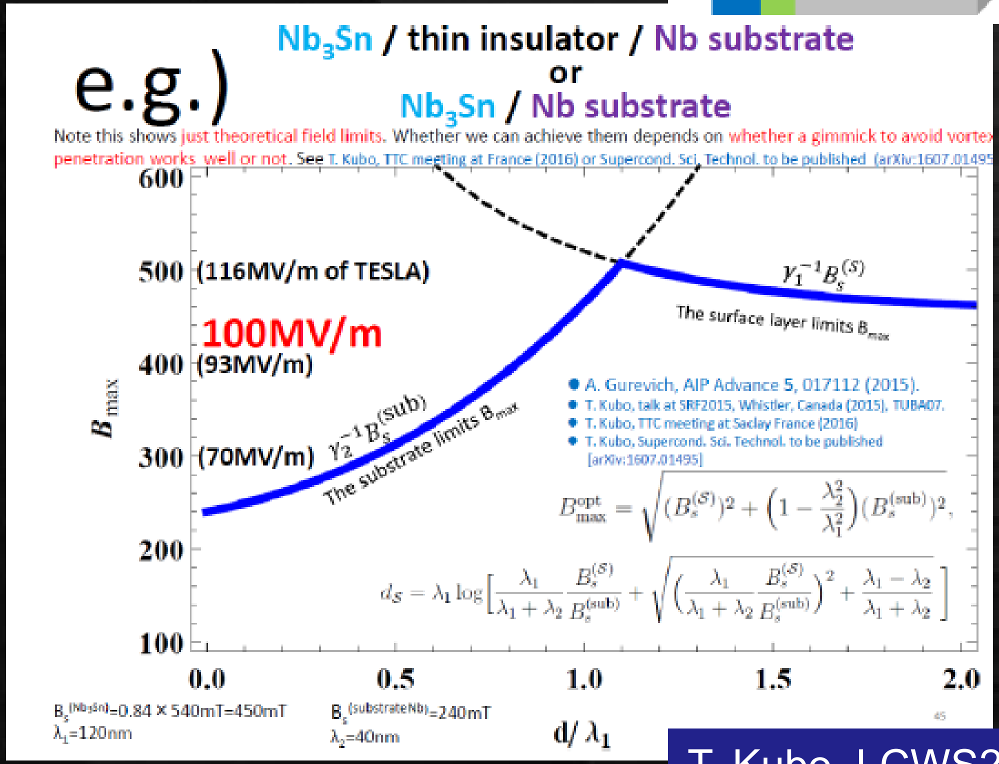


LCWS2023

Thinfilm structure (far future)

theoretical calculation indicates > 100 MV/m is possible (but no demonstration yet)

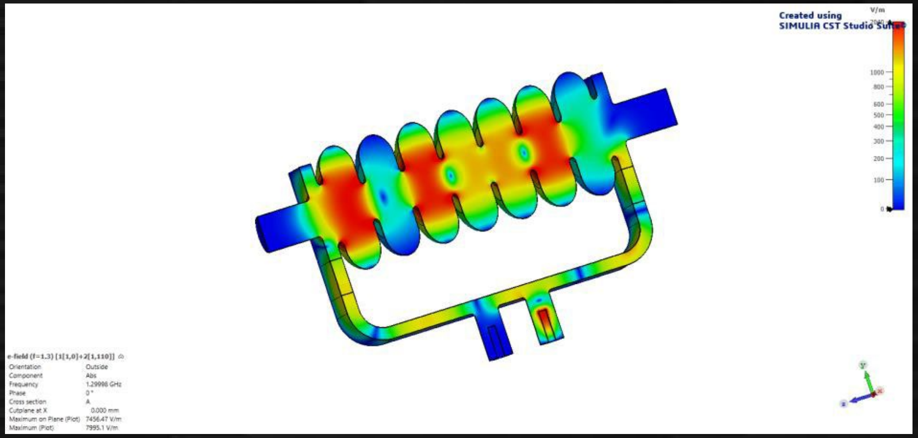




T. Kubo, LCWS2016

Traveling-wave cavity

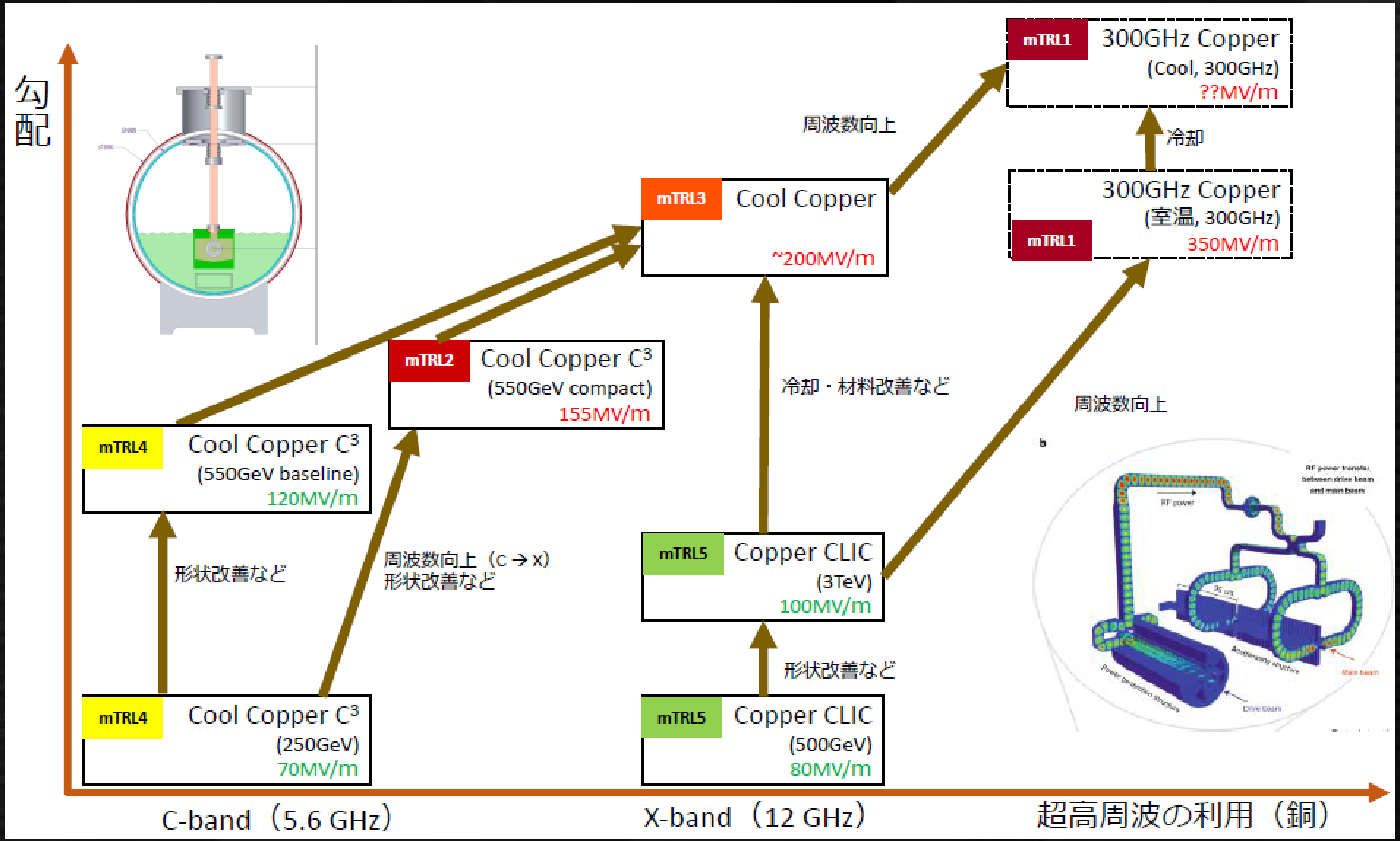
- Pro
  TW structure allows lower peak field at same gradient → higher gradient with acceptable field emission
- Con
  Exact phase matching by loop structure: especially difficult with Q@10^{10}



Advantages of TW Structures

- ❑ Travelling wave improves transit time factor and therefore allows lower BOTH B_{pk}/E_{acc} and E_{pk}/E_{acc}
  - RF power returns not through the accelerating structure (to form a standing wav with harmful peaks), but through a separate feedback Nb waveguide
- ❑ Travelling wave cavities operate at maximal group velocity in contrast to SW operating at zero group velocity, and therefore allow
  - Longer cavities → smaller gaps between cavities → higher average gradient;
  - Smaller aperture → additional increase in gradient because smaller B_{pk}/E_{acc} an E_{pk}/E_{acc}
  - Field profile tuning easier,
- ❑ Travelling wave $\pi/2$ structures offer higher G*R/Q → lowers Cryo power.
- ❑ By choosing the Low-Loss cell shape + reduced aperture it is possible to lower B_{pk}/E_{acc} by 48% over the TESLA structure!
- ❑ **Opening the door to E_{acc} > 70 MV/m !!**

High gradient with NC/novel acceleration



Novel acceleration (plasma etc.)

modified Technology Readiness Level for accelerator technology (based on TRL on space industry)

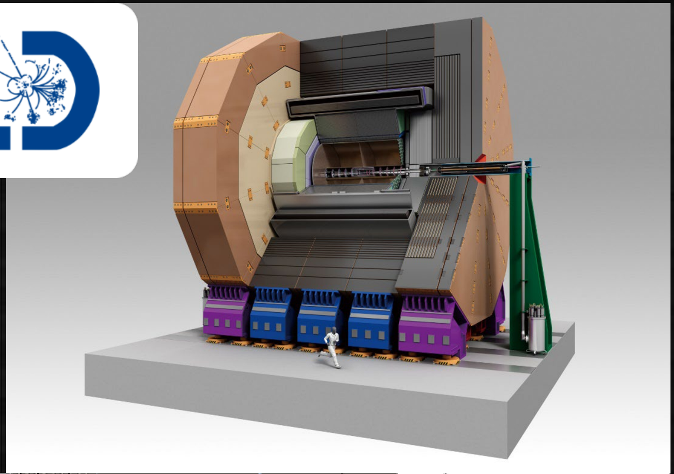
mTRL1: ideas not proven
mTRL2: ideas not proven
but path exists for demo
mTRL3: ideas proven at lab level
mTRL4: ideas proven as
system with reproducibility
mTRL5: the proven system
meets requirements as
collider realization
mTRL6: mass production ready

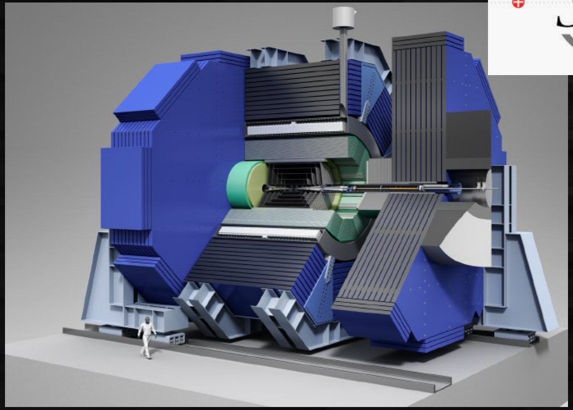
SC collider (e.g. ILC) may be possible to transform to NC/novel acceleration

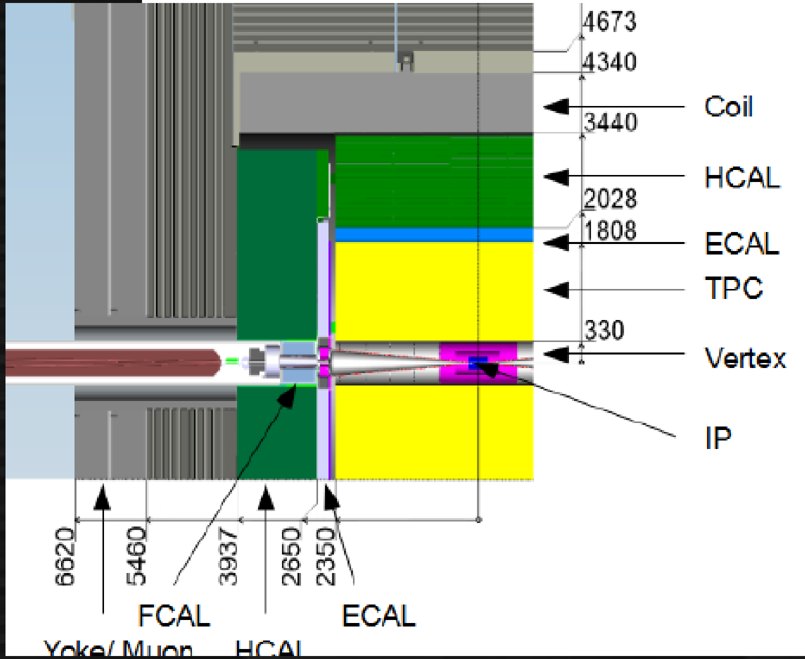
Summary on accelerator technology

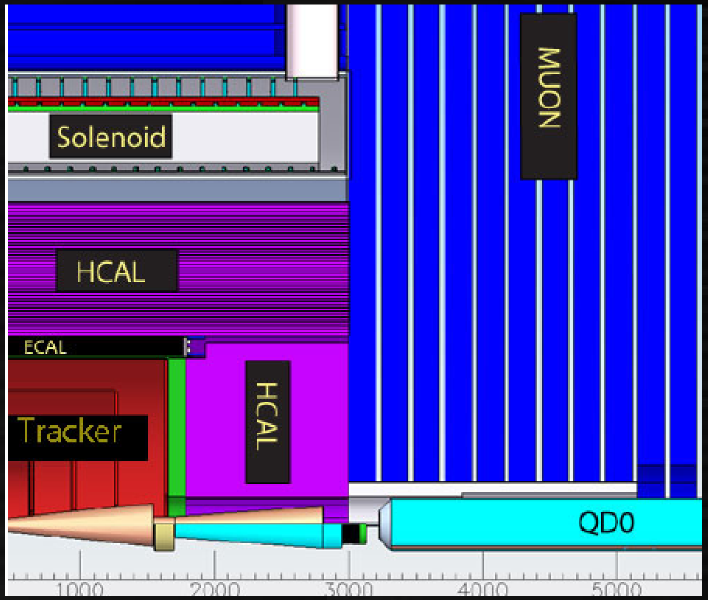
- For ILC 250 GeV for Higgs factory, no critical issues exist, technical maturity is being improved by ITN for Superconducting RF, e+/e- source and nanobeam
- Path towards > 100 MV/m with superconducting technology exist but needs significant step-by-step R&D
- Possibly replace to normal-conducting RF or novel acceleration (but more difficult on luminosity)
- 30-50 year plan towards multi-TeV collider
  Good complementarity to 10 TeV pCM hadron/muon collider

Detectors for ILC/Higgs factories









Two (similar) concept based on Particle Flow reconstruction

Already mature baseline design

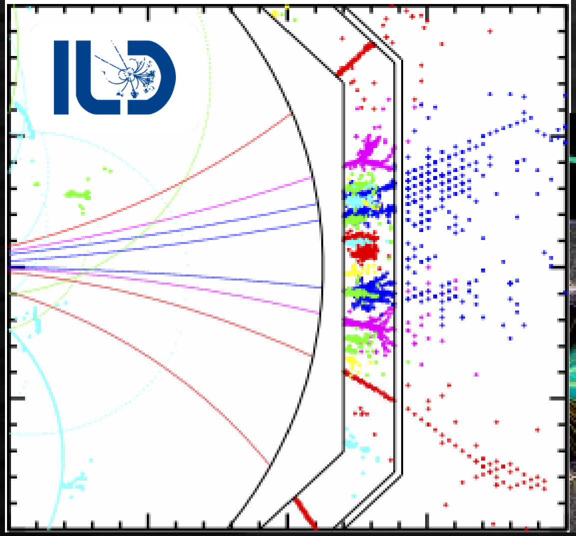
- Monolithic silicon vertex
- Silicon tracker (inner/outer for ILD)
- Time projection chamber (only for ILD)
- Highly-granular ECAL/HCAL with several options
  - Silicon pads
  - Scintillator strips/tiles
  - Resistive plate chamber
  - Silicon pixels (MAPS)
- 3.5/5T solenoid outside HCAL

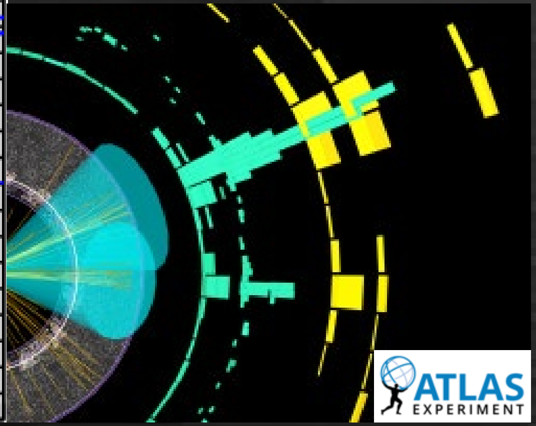
Particle flow concept

Separating particles inside jets to do track-cluster matching

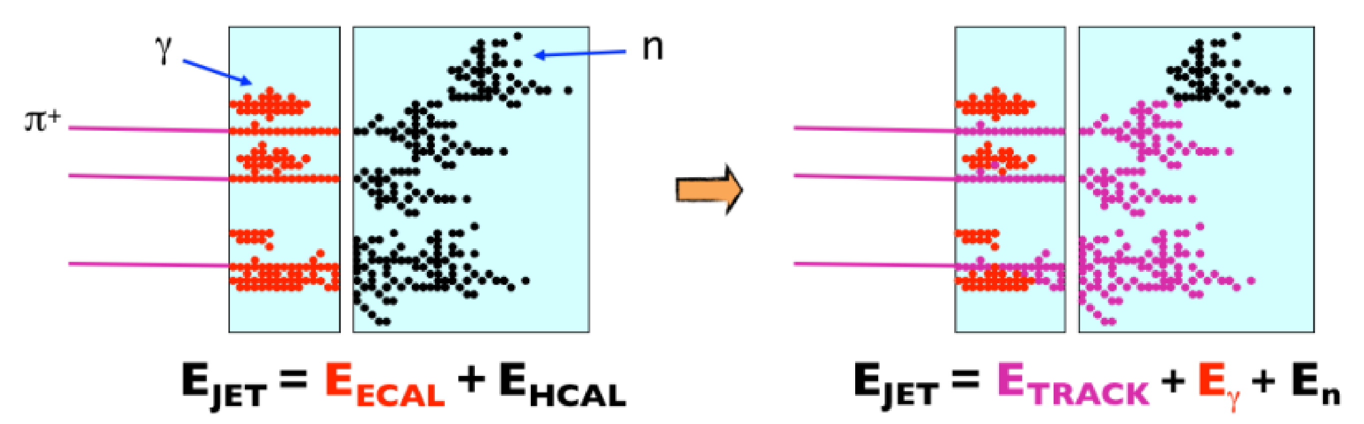
Requiring
- Highly-granular calorimeters
- Intelligent pattern recognition

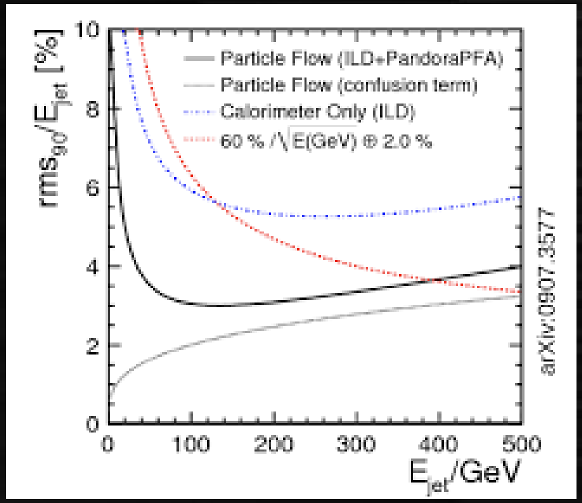
Different granularity on ILD - ATLAS





Developed in ILC, first full application in CMS HGCAL at HL-LHC (partial use already in ATLAS/CMS)





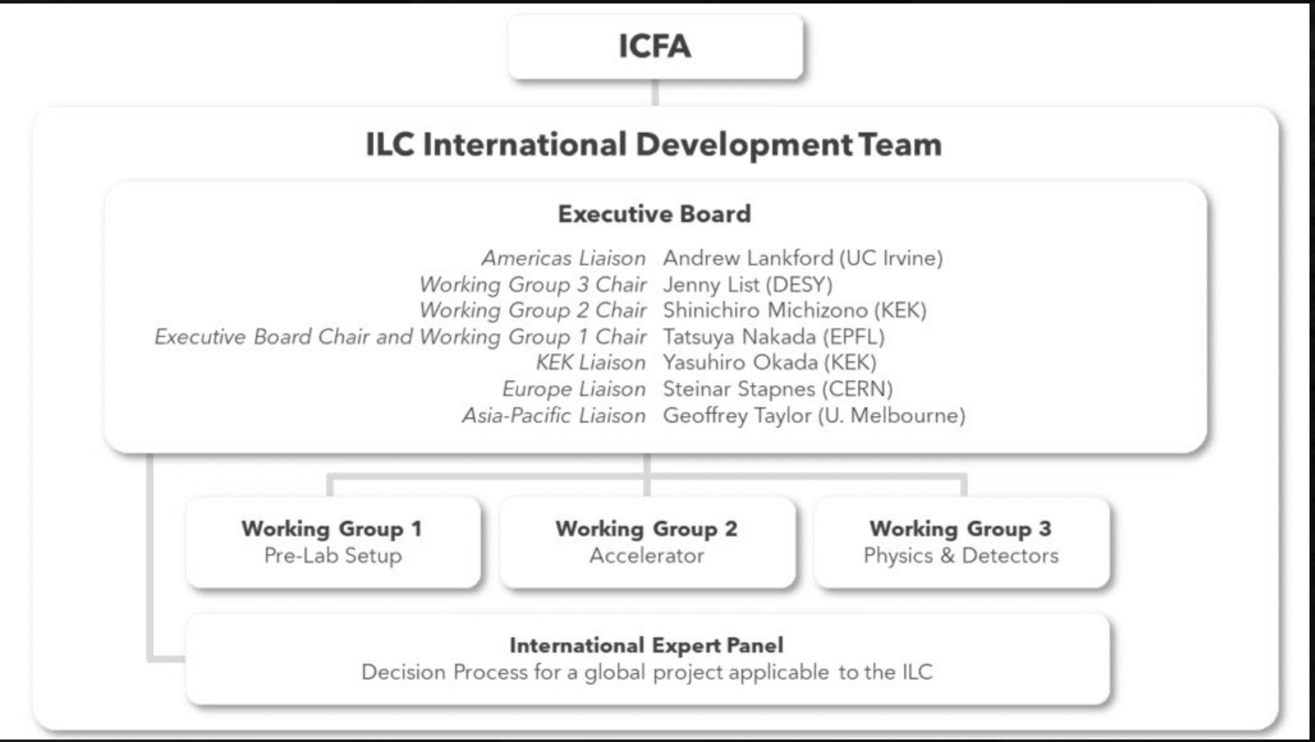
Possible to obtain jet energy resolution of

$$\frac{\delta E_{\text{jet}}}{E_{\text{jet}}} \cong \frac{30\%}{\sqrt{E_{\text{jet}}[\text{GeV}]}}$$

~2 times better than calo-only

Strategies for Realization

ILC: International Development Team



See LCWS2023: https://indico.slac.stanford.edu/event/7467/

WG3 physics group hosts series of physics meetings
https://agenda.linearcollider.org/category/266/
(Next: July 13th)
Mailing list subscription:
https://agenda.linearcollider.org/event/9154/

Established in 2020: aiming for ILC pre-lab
Pre-lab proposal in 2021
https://arxiv.org/abs/2106.00602
→ MEXT expert panel (2021)

- Not mature enough for proceeding to pre-lab
  - Mainly in international situation
- Accelerator technology should be developed in preparation for next step

→ Two steps towards pre-lab

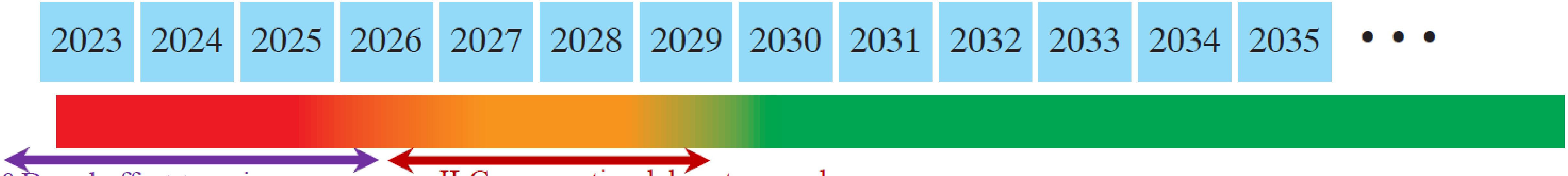
- International Technology Network (ITN)
  - Collaboration framework with US/Europe
  - Doing time-critical works of pre-lab
  - Japanese part is funded by MEXT
- International Expert Panel
  - Among researchers connected to FA
  - Discussing how to proceed “global” projects

5) Overall ILC timeline

T. Nakada

-success oriented and asuming no major incident-

Technology Network Phase | **Preparatory Phase** | **Construction Phase**
~10 years for the construction and commissioning



R&D and effort to gain a common view and understanding.

ILC preparation laboratory and intergovernmental discussion/negotiation

- Technology Network Phase responds to the recommendations by the MEXT Expert Panel.
- ITN work packages are two to four years.
- MEXT funding programme for ILC-accelerator R&D is planned for five years.
- For entering the Preparatory Phase, interested government authorities, not only Japanese but also European and US, must become ready to discuss ILC specific matters.
- Given ITN, the Preparatory Phase could be less than the four years in the Pre-lab proposal for the accelerator and site-related work.
- P5 discussion in the U.S. and FCC Feasibility Study at CERN will impact the timeline.

ILC Cost and cost sharing

ILC cost
(2013(TDR), modified for 250 GeV in 2017)

- Accelerator (incl. civil and facility):
  515-583 BY (3.0-3.6 BCHF)
- Total (incl. 2 detectors & labor):
  736-803 BY (4.4-4.8 BCHF)

cf. FCCee (2023)
12.8 BCHF (2 IP, 240 GeV)

Cost sharing model
(proposed by KEK international WG 2019)
https://www.kek.jp/ja/newsroom/attic/20191001_%20ILC%20Project.pdf

- Civil (20-24%) by host
- Facility (14-16%)
  primary by host,
  support by non-host members possible
- Technical (57-68%)
  (equally?) shared among members

Can assume FCCee in Europe ~ ILC in Japan for economic scale…

Global project: CERN council-like structure assumed
Decision by each stakeholder (not primary by host)

Possible path forward (1)

- FCC FS (or proceeding discussion at CERN council) concludes that FCCee needs to be a global project
- International discussion for Higgs factory starts
  - ILC in Japan will be proposed
    (this is still not obvious but there is no clear showstopper)
  - FCC in CERN will also be proposed
  - (LC in Europe as another option?)
- Comparison/Negotiation among international partners

- Can conclude either way to go! (hopefully before 2030)

Possible path forward (2, others)

Scenario 2

- FCC FS (or proceeding discussion at CERN council) concludes that CERN can host FCCee as an international project
- Japan (&US) needs to decide whether to join FCCee or not
  - Probably we join at some fraction at least
- LC realization is pushed to future (> 2050)
  - As > 500 GeV machine with higher gradient (>70 MV/m)
  - Or a muon collider?

Other possibilities

- Japan (and US) will decide to proceed before FCCee conclusion
- ILC in Japan is given up for some reason
  - Neither likely to happen very soon

Final comment

- ILC has a long-standing history, with mature technologies (almost) ready to be built
- LC has a future path towards multi-TeV collider which enables full exploration of TeV BSM
  - Also have sensitivity to light BSM
- World desires e+e- Higgs factory as a successor to HL-LHC, and ILC is a cost-effective and realistic way to go
- All e+e- HF project have big synergies, collaboration started at ECFA HF framework or so, to be investigated further

Backup

US: Snowmass and P5

Energy Frontier - Vision

Snowmass Community Summer Study (CSS)
Seattle, July 17-26, 2022

Meenakshi Narain (Brown U.), Laura Reina (FSU), Alessandro Tricoli (BNL)

The immediate future is the HL-LHC
The intermediate future is an e^+e^- Higgs factory

The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C^3, CLIC) or circular collider (FCC-ee, CepC).

- **The various proposed facilities have a strong core of common physics goals**: it is important to **realize at least one somewhere in the world.**
- **A fast start towards construction is important**. There is **strong US support** for initiatives that could be realized on a time scale relevant for early career physicists.
- **For the next decade and beyond**
  - **2025-2030**: Establish a targeted e^+e^- Higgs Factory detector R&D for US participation in a global collider
  - **2030-2035**: Support and advance construction of an e^+e^- Higgs Factory
  - **After 2035**: Begin and support the physics program of an e^+e^- Higgs Factory

The long-term future is a multi-TeV collider

P5 (Particle Physics Project Prioritization Panel)

Panel Members

- *Shoji Asai (University of Tokyo)*
- *Tulika Bose (Wisconsin)*
- *Francis-Yan Cyr-Racine (New Mexico)*
- *Cameron Geddes (LBNL)*
- *Karsten Heeger (Yale) - Deputy Chair*
- *JoAnne Hewett (SLAC) - HEPAP chair, ex officio*
- *Kendall Mahn (Michigan State)*
- *Jelena Maricic (Hawaii)*
- *Christopher Monahan (William & Mary)*
- *Peter Onyisi (Texas Austin)*
- *Tor Raubenheimer (SLAC)*
- *Richard Schnee (South Dakota School of Mines and Technology)*
- *Jesse Thaler (MIT)*
- *Abigail Vieregg (Chicago)*
- *Lindley Winslow (MIT)*
- *Bob Zwaska (Fermilab)*
- *Amalia Ballarino (CERN)*
- *Kyle Cranmer (Wisconsin)*
- *Sarah Demers (Yale)*
- *Yuri Gershtein (Rutgers)*
- *Beate Heinemann (DESY)*
- *Patrick Huber (Virginia Tech)*
- *Rachel Mandelbaum (Carnegie Mellon)*
- *Petra Merkel (Fermilab)*
- *Hitoshi Murayama (Berkeley) - Chair*
- *Mark Palmer (Brookhaven)*
- *Mayly Sanchez (Florida State)*
- *Seon-Hee (Sunny) Seo (IBS Center for Underground Physics)*
- *Christos Touramanis (Liverpool)*
- *Amanda Weinstein (Iowa State)*
- *Tien-Tien Yu (Oregon)*

P5 makes project priority based on inputs including snowmass.
Report will be on later this year?
EF townhall: https://indico.bnl.gov/event/18372/

1) Development up to now

T. Nakada

After MEXT concluded that "approval of the Pre-lab could only be made once the prospect for foreign contributions to the ILC would be clarified", the IDT made in depth analysis for the cause of the long lasting "chicken and egg" problem, i.e. a better understanding of a global project

The IDT also took a particular note on some of the recommendations by the MEXT ILC Advisory Panel

- to put the hosting issue aside for the moment and continue with the accelerator R&D work
- to have an environment for intergovernmental discussions among the potential partners.

and developed the next step, i.e.

- ILC Technology Network (ITN) and IDT International Expert Panel (IEP),

Which was agreed by ICFA

4) Moving forward toward Preparatory Phase

T. Nakada

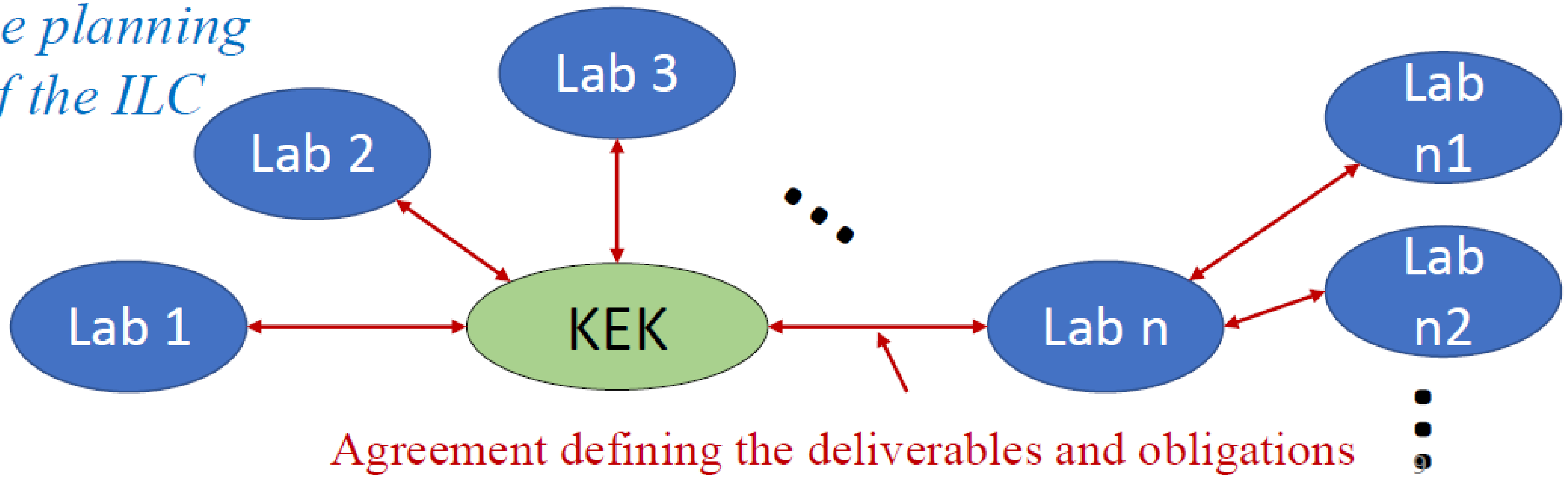
Move forward with engineering study, benefiting from the fact that:

- Pre-lab proposal identified the necessary technical preparations for ILC construction
- Many of the identified topics are in line with broader interests in accelerator R&D
- Increased Japanese budget for the ILC related technology R&D provides a seed for required resources

9.7 oku-yen this FY, 5-year package

ILC Technology Network (ITN), based on bilateral agreements between KEK and partner laboratories worldwide, has been launched to execute important work packages, based on its own organisation.

NB: IDT-WG2 will continue planning and overall coordination of the ILC accelerator development,



4) Moving forward toward Preparatory Phase

T. Nakada

IDT International Expert Team has been working for

- establishing difference between "International" and "Global" projects (as explained before)
- analysing ILC as Global Project and identify the root cause for the current " chicken and egg" problem (as explained before)
- finding a way to move ILC forward

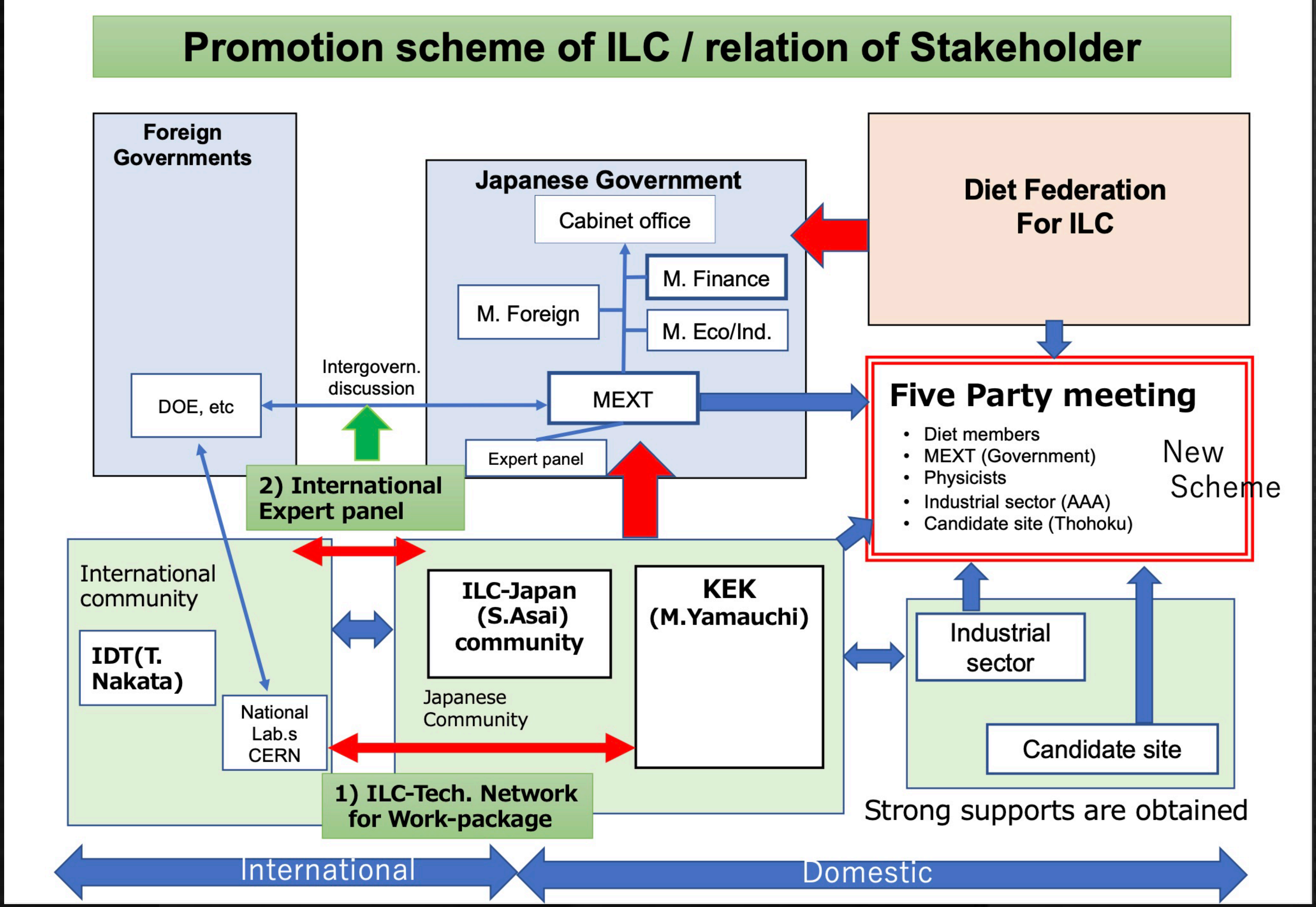
Int. Expert Panel members (Chaired by the IDT EB Chair)

Ursula Bassler	(FR)	Philip Burrows	(GB)
Beate Heinemann	(DE)	Stuart Henderson	(US, ICFA Chair)
Karl Jakobs	(DE, EFCA Chair)	Andrew Lankford	(US, IDT-EB Americas)
Nadia Pastrone	(IT)	Antonio Pich	(ES)
Steinar Stapnes	(CERN, IDT-EB Europe)	Nigel Smith	(CA)
Geoffrey Taylor	(AU, IDT-EB Asia-Pacific)	Katsuo Tokushuku	(JP)

ILC-Japan and WG/TFs

ILC-Japan (est. 2021)
EB: Asai (chair), Yamauchi, Okada, Ishino, Saito, Koseki, Michizono, Kuriki, Ushiroda, Mori

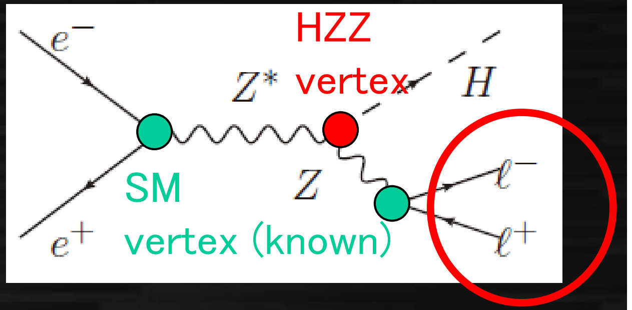
- Physics WG
  Core group members:
  M. Ishino (chair)
  T. Suehara, D. Jeans,
  J. Tian, K. Fujii,
  K. Tsumura, T. Kitahara,
  T. Nobe, K. Nakamura
- Collaboration TF (Kuriki)
- PR TF (Okada)
- Intl. Negotiation TF (Asai)
- Accelerator R&D TF (Michizono)



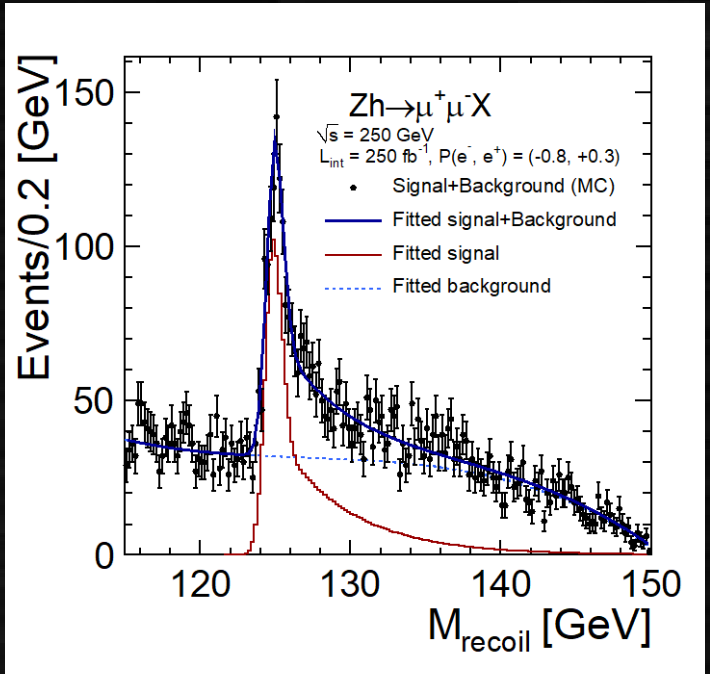
ILC-Japan indico directory: https://agenda.linearcollider.org/category/280/
ILC-J physics WG (general meetings): https://agenda.linearcollider.org/category/283/

HF signature modes: recoil mass & total width

Higgs recoil mass



$$m_h = \sqrt{E_h^2 - p_h^2}$$



4-momentum of Z – initial 4-momentum
= 4-momentum (incl. mass) of H

- Highest mass accuracy (~14 MeV)
- Fully model-independent total ZH cross section (→ HZ coupling)

$$\sigma_{ZH} = F_1 \cdot g_{HZZ}^2$$

Total decay width

Recoil mass

Y_n = observable F_n = coefficient

$$Y_1 = \sigma_{ZH} = F_1 \cdot g_{HZZ}^2$$

ZH→Zbb

$$Y_2 = \sigma_{ZH} \times \mathrm{Br}(H \to b\bar{b}) = F_2 \cdot \frac{g_{HZZ}^2 g_{Hb\bar{b}}^2}{\Gamma_T}$$

ννH→ννbb

$$Y_3 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b}) = F_3 \cdot \frac{g_{HWW}^2 g_{Hb\bar{b}}^2}{\Gamma_T}$$

ννH→ννWW*

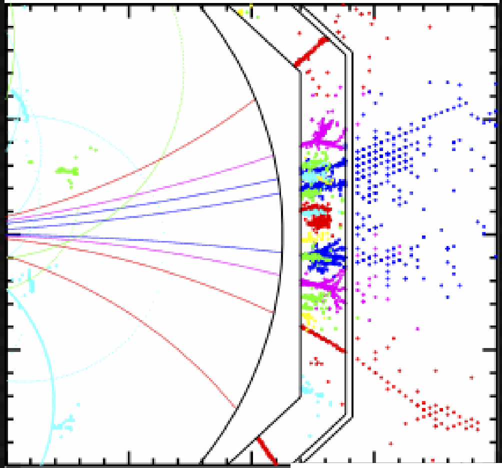
$$Y_4 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to WW^*) = F_4 \cdot \frac{g_{HWW}^4}{\Gamma_T}$$

1. g_{HZZ} obtained from Y1
2. g_{HWW} obtained from Y1 x Y3 / Y2 & g_{HZZ}
3. Γ_T (full width) obtained from Y4 & g_{HWW}
4. g_{Hbb} obtained from Y2/Y3, g_{HZZ}/g_{HWW}, Γ_T

A few % at 250 GeV, ~1% at 500 GeV

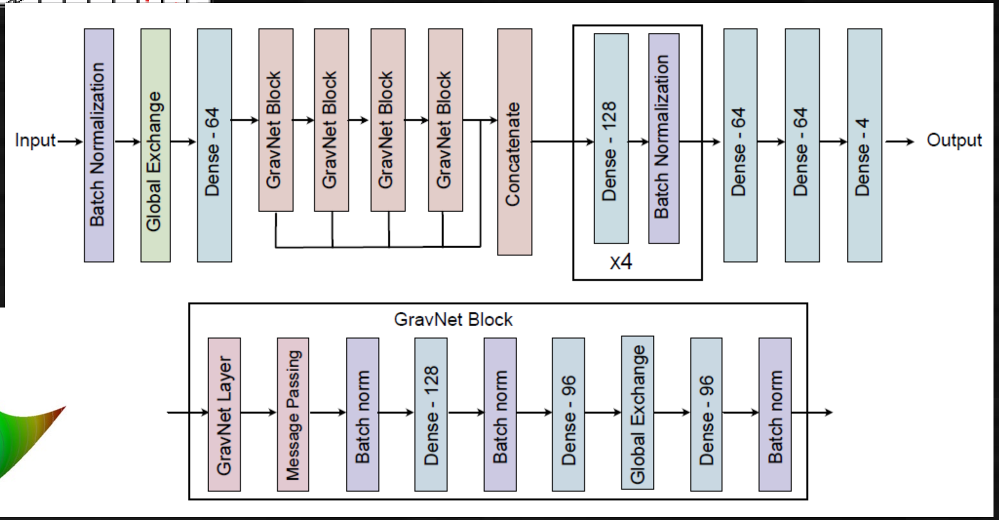
Reconstruction: possible improvements by DNN

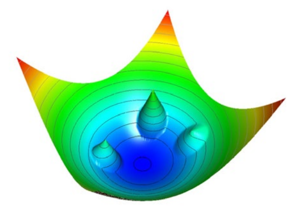
Particle flow (for jet reconstruction)



Reconstruct particles in jets and subtract contribution from charged particles

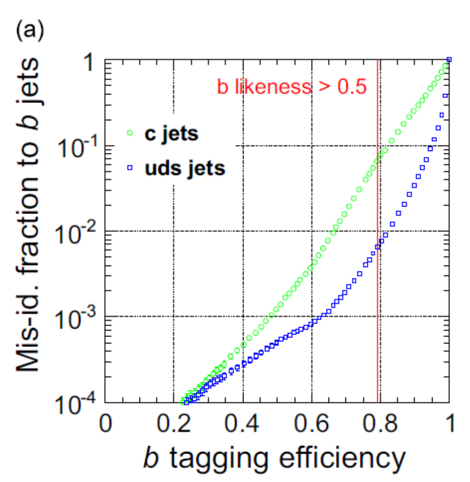
PandoraPFA: human-tuned algorithm developed in ~2008
Still used in most of analyses



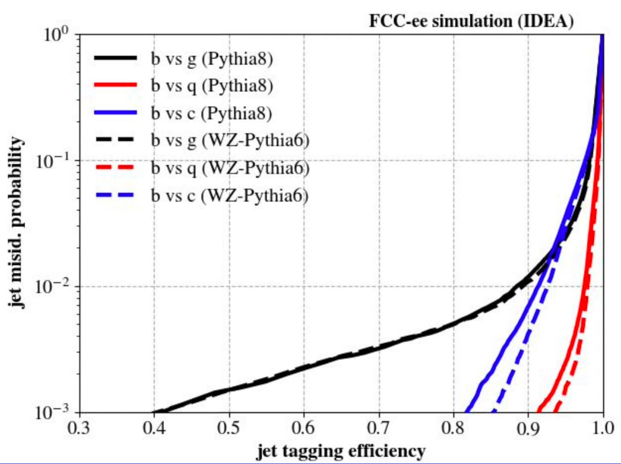


GNN algorithm developed for CMS HGCal being tried

Flavor tagging (b/c/s/g tagging)



LCFIPlus:
b/c tagging software developed in 2012
BDT used with ~40 input params



FCCee ParticleNet:
>10 times better!
Maybe due to fast simulation (no scattering)
but still worth to try with full simulation

Using PID (kaon-tag) can help → both hardware (dE/dx, timing, Cherenkov) and algorithm studies

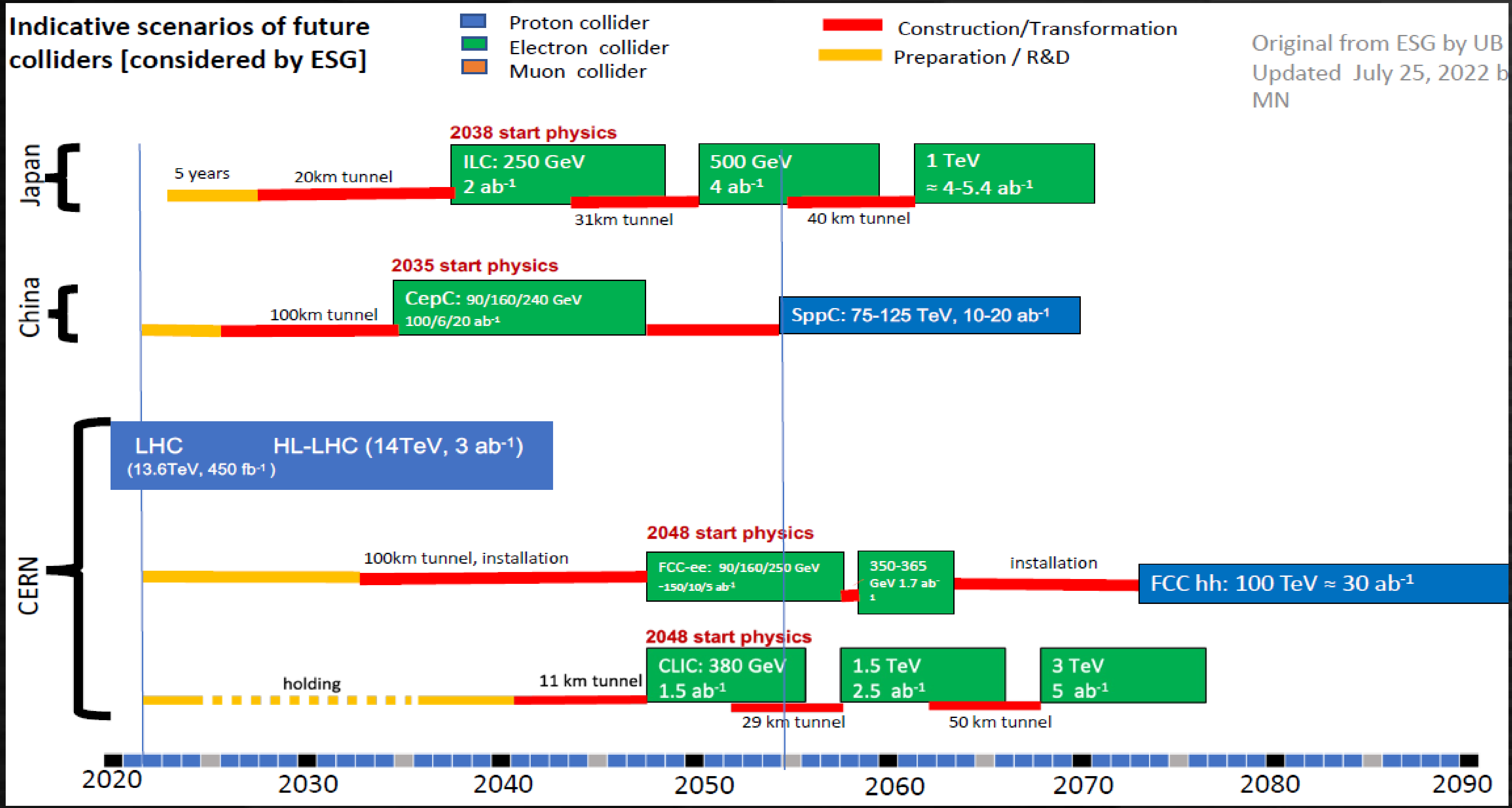
Critical technologies for Higgs factories

- Superconducting linac (ILC)
  - 31.5 MV/m almost proven, experiences in Euro-XFEL (10% scale)
  - Upgrade paths: 45 MV/m, 70 MV/m, ~100 MV/m
    by surface treatment, traveling wave, thin-film
- Normal-temperature (CLIC)
  - Acc. gradient proven (and higher), but no big production experience
  - Concern on luminosity and power
- Cryogenic normal-conducting (C^3)
  - New idea, still basic demonstration stage
- Circular (FCCee / CEPC)
  - High cost (2x ILC) for Higgs factory, detailed design still ongoing
  - Big issue on magnet (>20 yr needed?) for proceeding hadron collider

Higgs factories: possible timeline

Caution: always later in reality…

- ILC: 2038- (TDR)
  - 2+4y preparation
  - 10y construction
- CEPC: 2035- (TDR)
- FCC: 2048- (CDR)
  - FS: -2025
  - HL-LHC: -2042
    (Parallel construction)
- CLIC: 2048- (CDR)
- C^3: 2040's (Pre-CDR)

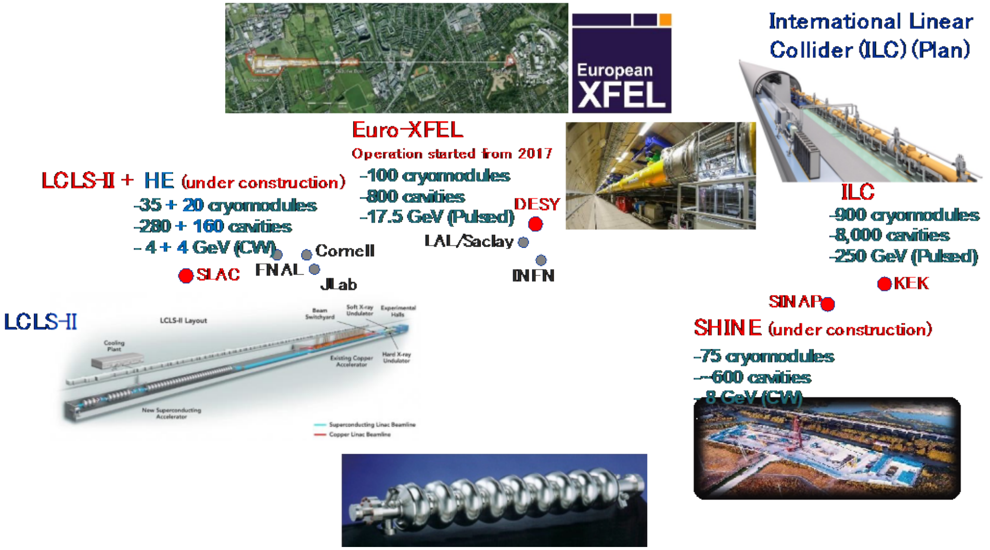


e^+e^- collider projects

- Linear colliders
  - ILC (Japan) 250 GeV (initial) → multi-TeV
    Superconducting LC to be started in end of 2030s. The most mature project.
  - CLIC (CERN) 380 GeV → 3 TeV
    Normal conducting (X-band) LC. The alternative option to FCC in EPPSU. Affordable for CERN.
  - CCC (US) 250 GeV → 550 GeV?
    Cooled normal conducting (C-band) LC. Currently at Pre-CDR. Realization in > 2040.
  - HELEN (US)
    Superconducting LC. High gradient realized by traveling wave cavities. Still rough design stage.
- Circular colliders
  - FCCee (CERN) 91 GeV → 240 GeV → 365 GeV
    Coupled with 100 TeV hadron collider. Need non-CERN contribution. Operation start at 2048 (at Z-pole?)
  - CEPC (China)
    Slightly conservative than FCCee. TDR just published. To be upgraded to SppC (hadron collider)

The ILC250 accelerator facility

Undulator based polarized positron source



Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade
Centre of mass energy	$\sqrt{s}$	GeV	250	250
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.7
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)
Repetition frequency	f_{rep}	Hz	5	5
Bunches per pulse	n_{bunch}	1	1312	2625
Bunch population	N_{e}	10^{10}	2	2
Linac bunch interval	Δt_{b}	ns	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8
Beam pulse duration	t_{pulse}	µs	727	961
Average beam power	P_{ave}	MW	5.3	10.5
RMS bunch length	σ^*_{z}	mm	0.3	0.3
Norm. hor. emitt. at IP	$\gamma\epsilon_{\text{x}}$	µm	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\text{y}}$	nm	35	35
RMS hor. beam size at IP	σ^*_{x}	nm	516	516
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %
Site AC power	P_{site}	MW	111	128
Site length	L_{site}	km	20.5	20.5

Parameters and plans for luminosity and energy upgrades are available, including information about relevant SCRF R&D for such upgrades at (Snowmass input)