The Linear Collider Facility and the International Large Detector concept

Uli Einhaus
with material from many people

Experimental Physics and Astro-Particle Physics Seminar Uni Zürich
01.12.2025

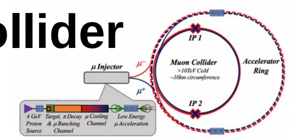
The Landscape of Proposed Next-Gen Colliders

at CERN

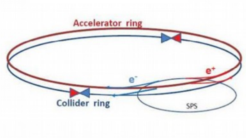
elsewhere

+ CERC
+ ReLiC
+ ERLC
+ ...

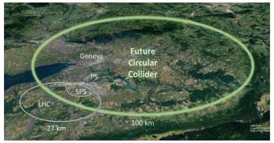
Muon Collider



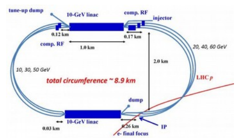
LEP3



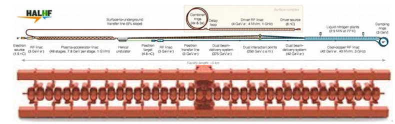
FCC-hh



LHeC

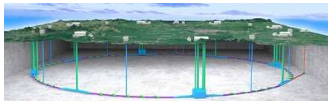


HALHF



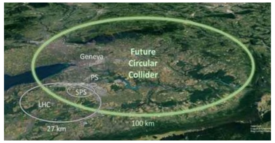
C³

SppC



HTE factory

FCC-ee



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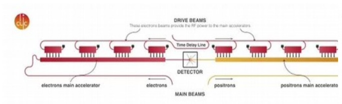

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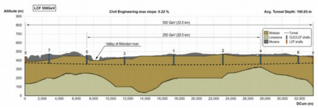
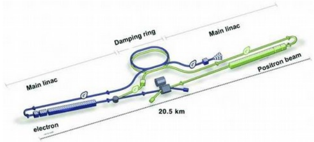
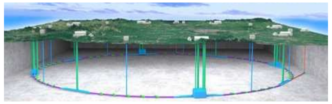


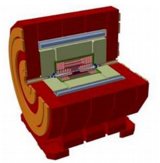
ILC



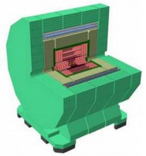
CEPC



CLICdp



CLD



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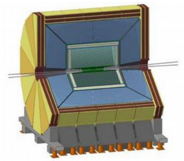
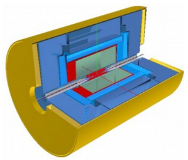


ALLEGRO



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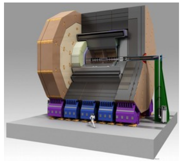
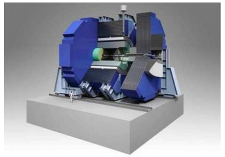
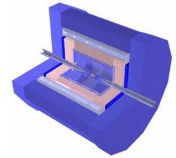


SiD



CEPC Baseline



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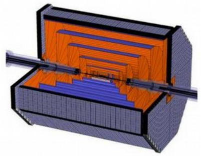
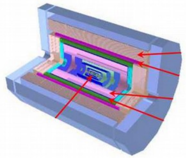


CEPC 4th concept



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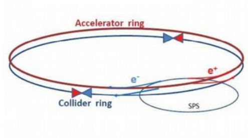
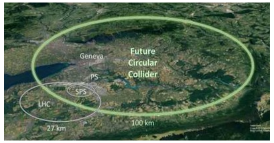
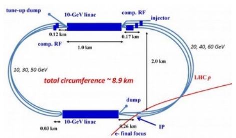
LEP3



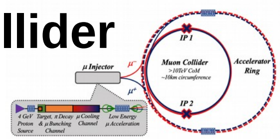
FCC-hh



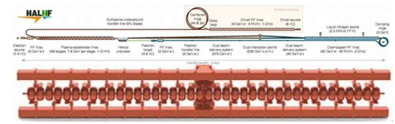
LHeC



Muon Collider

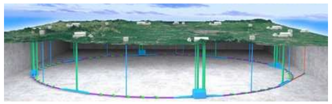


HALHF



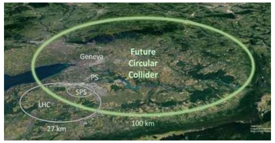
C³

SppC

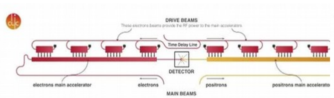


HTE factory

FCC-ee



CLIC



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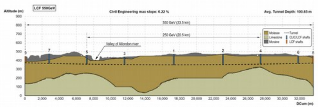

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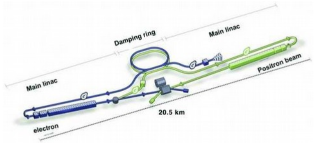
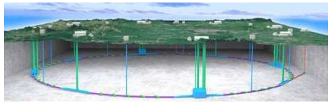
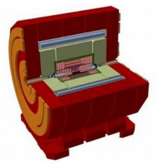


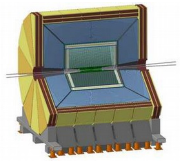
CEPC



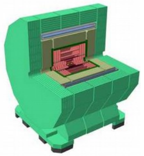
CLICdp



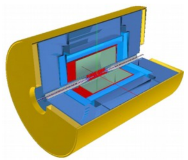
IDEA



CLD



ALLEGRO



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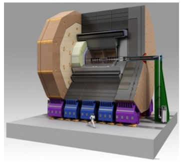

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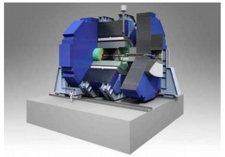
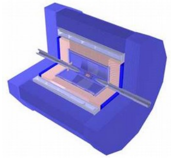


CEPC Baseline



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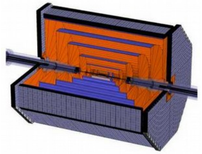
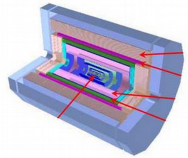


CEPC 4th concept



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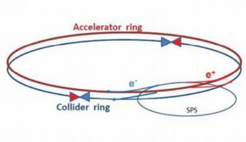
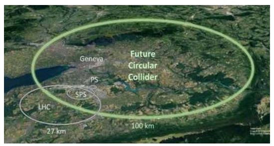
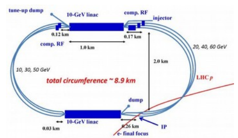


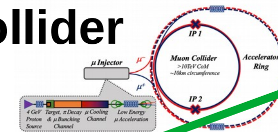
FCC-hh



LHeC

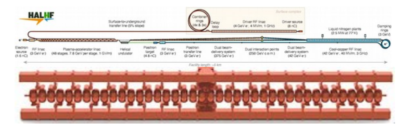


Muon Collider



Linear Collider Vision

HALHF



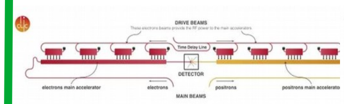
C³

SppC

HTE factory

FCC-ee

CLIC



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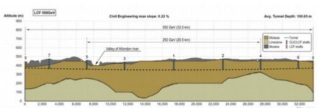

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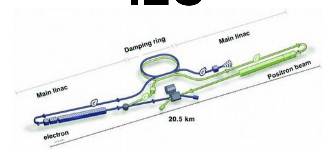
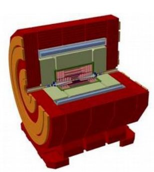
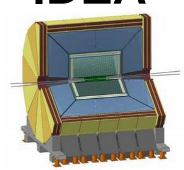


CEPC

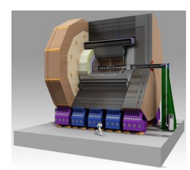
CLICdp



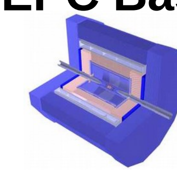
IDEA



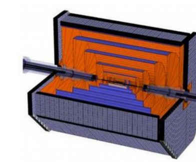
ILD



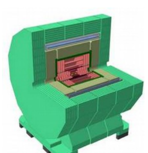
CEPC Baseline



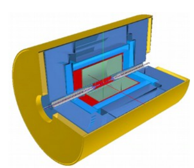
FST



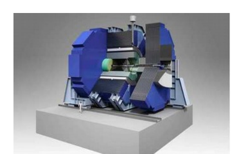
CLD



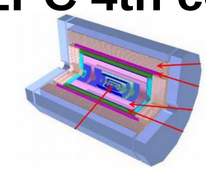
ALLEGRO



SiD



CEPC 4th concept



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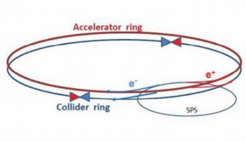
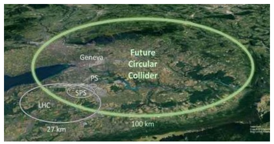
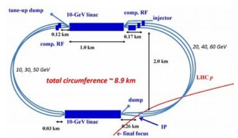
LEP3



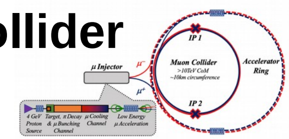
FCC-hh



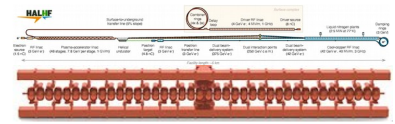
LHeC



Muon Collider

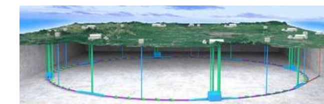


HALHF



C³

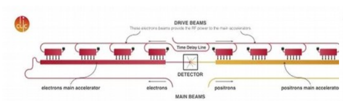
SppC



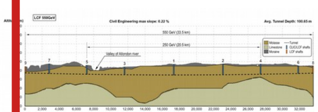
HTE factory

FCC-ee

CLIC

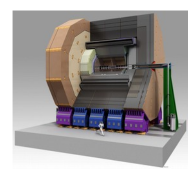


LCF

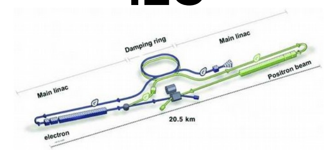


this talk

ILD



ILC



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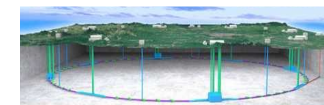
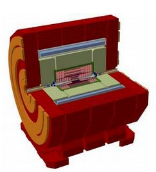
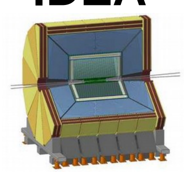


CLICdp



IDEA



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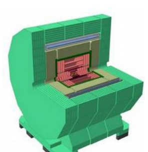
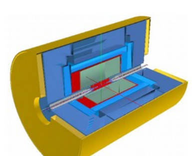
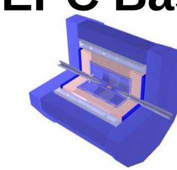


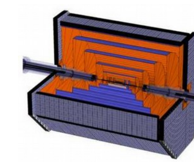
ALLEGRO



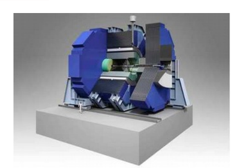
CEPC Baseline



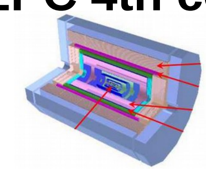
FST



SiD



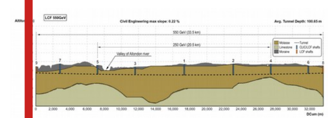
CEPC 4th concept



Disclaimer

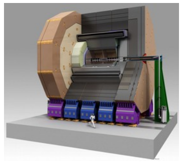
- LCF and ILD are generally uncorrelated:
  - LCF does not have proposed detector concepts
  - ILD was designed for ILC, as was SiD
    ILD has been proposed for FCC-ee, as have CLD, IDEA and ALLEGRO
- LCF and ILD have considerable personnel overlap, though
  - E.g. many physics studies for LC done with ILD

LCF

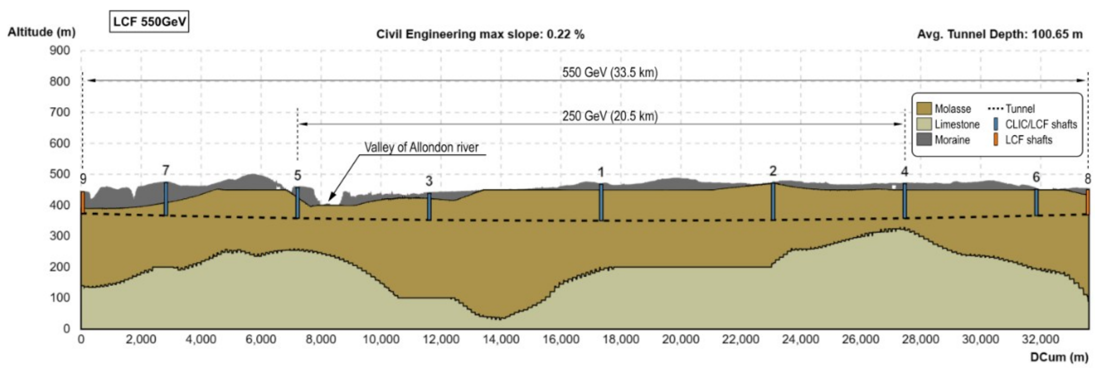


this talk

ILD



The Linear Collider Facility



A bit of History

- 90s-2000s: LEP I performed the Mega-Z, LEP II reached up 209 GeV, SLC ran at Z-pole with polarisation
- At the time it was clear that the future for e+e- would be linear - circular machines suffer from too much synchrotron radiation and cannot be effective enough beyond LEP II
- 4 proposals for linear machines (USA, Germany, Japan, CERN) were formulated
  - The first three were later unified in the Global Design Effort (GDE) into one: the International Linear Collider (ILC), proposed for Japan using the superconducting radio frequency (SCRF) accelerators designed for TESLA in Hamburg
  - In parallel, CLIC was proposed at CERN
- CLIC CDR 2012
- ILC TDR 2013, political advances since then but no definitive decision
- Intention: run in parallel to HL-LHC

A bit of History

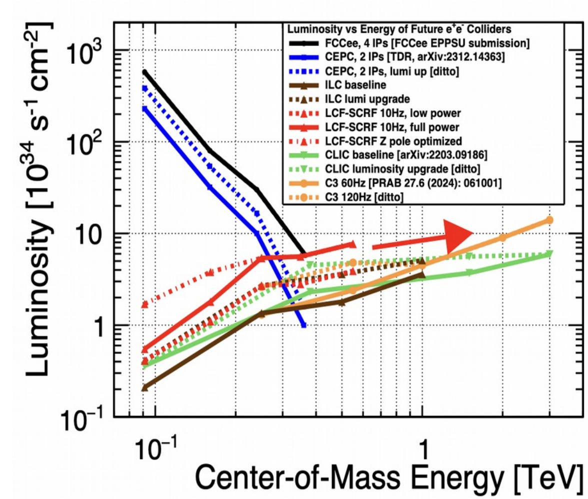
- In the meantime: new studies showed that a circular machine might actually be feasible - the FCC-ee
- CERN started looking into its next flagship and successor to the HL-LHC
- CLIC and FCC-ee strong contenders for Higgs factory, strategy update 2020 decided to make a feasibility study for one of them: FCC (including a conceptual study for the later FCC-hh)
- Without a decision in Japan, belief in a success of ILC waned, though through the ITN a moderate budget continued to exist for accelerator R&D
- A new LC concept was proposed in the USA: C^3, fitting the Fermilab site; P5 report determined that the USA would not build the next Higgs factory
- For the 2025 strategy update the FCC feasibility report was done, still significant interest in LC remained in Europe and the official target of the EPPSU was to determine the next flagship at CERN
- Prime contender: FCC; LC supporters came together and propose the LCF

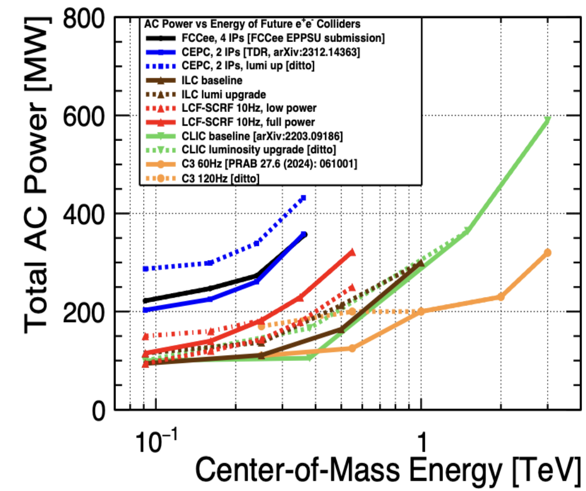
Goals of Linear Colliders

- Physics opportunities from Z-pole to TeV

- Lower cost to get to Higgs and top than a circular machine
- Power similar to LHC, or lower, for initial configuration
- Footprint (33.5 km) similar to LHC

- Start timely with mature technology: SCRF of ILC/TESLA
- Flexible (E, L, cost, power) to adapt to development in physics and technology
- Does not determine footprint of future energy frontier machines (hadrons or muons), and it has its own upgrade opportunities
- Encourage accelerator and detector R&D for all these options

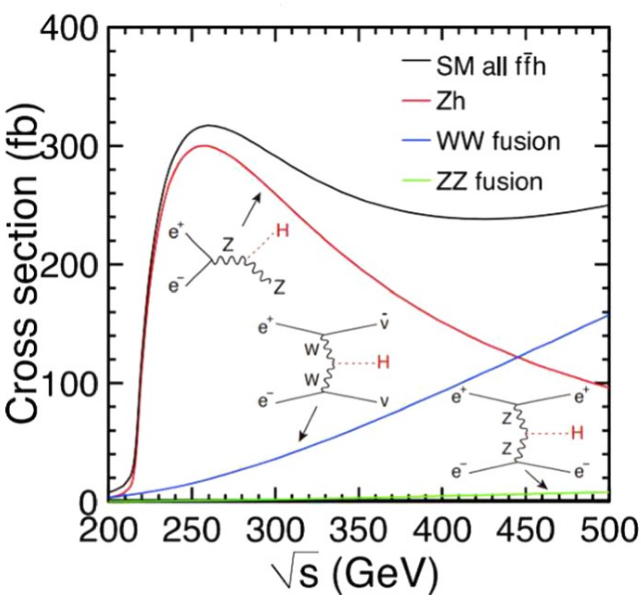


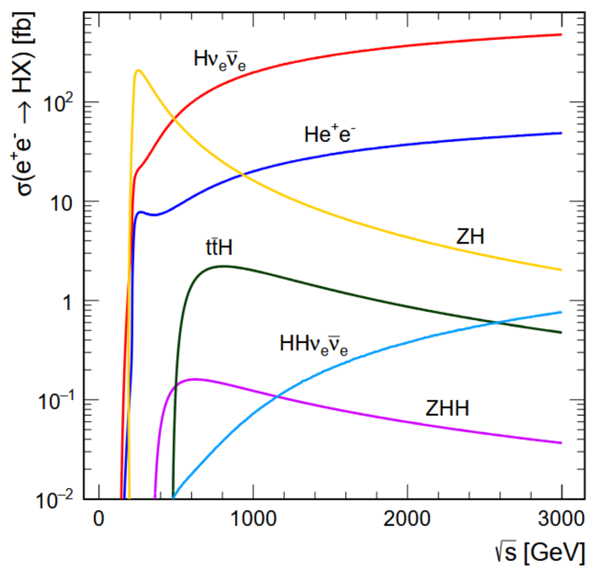


Slide adapted from S. Stapnes at Venice Symposium

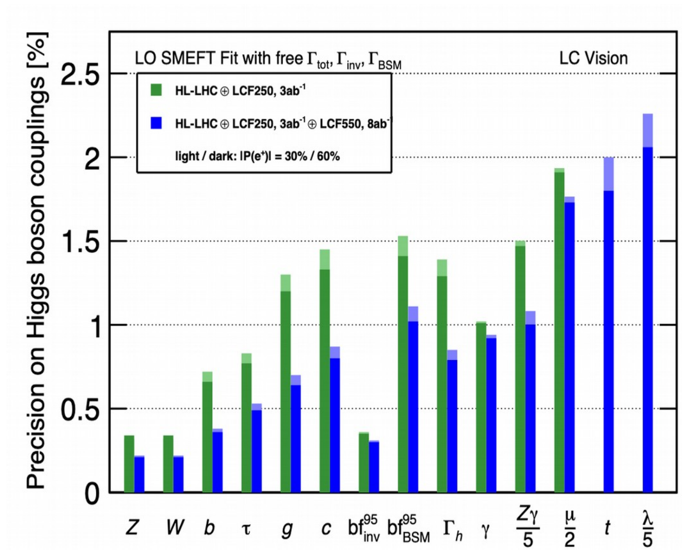
Physics Highlights: Higgs

- Higgs is the primary target of any future flagship → Higgs factory!
- At 250 GeV dominated by ZH, at higher energies benefits from combination with W fusion → better control os systematics, fully model independent coupling analysis
- Both channels with polarisation allows to constrain all Higgs coupling from global SMEFT fit





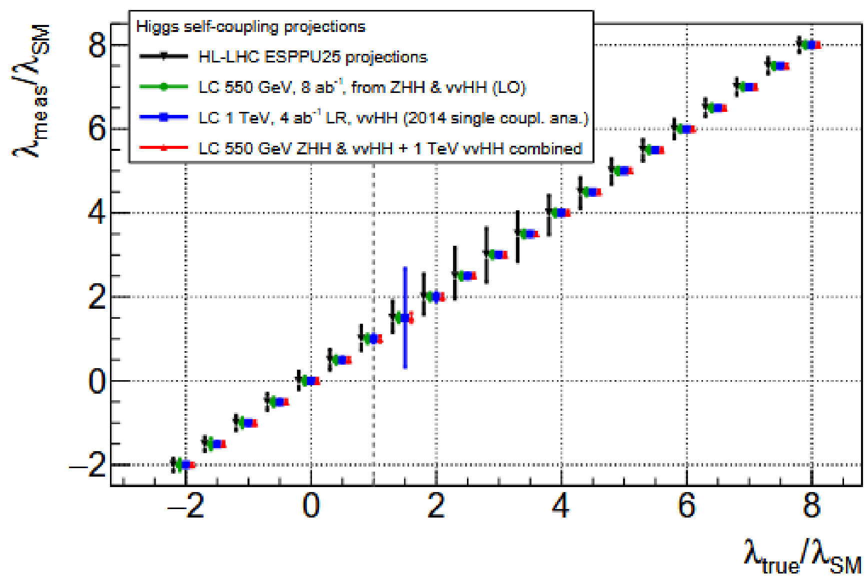
3ab^{-1} @250 GeV, 8ab^{-1} @550 GeV

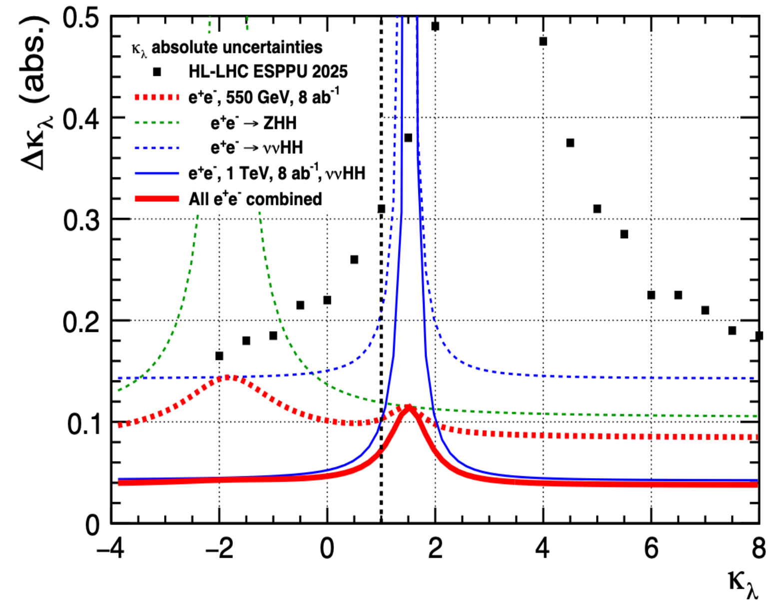


https://arxiv.org/abs/2503.19983

Physics Highlights: Higgs

- ‘Holy grail’: Higgs self coupling
- Current techniques: direct, model-independent measurement of $\Delta\lambda/\lambda_{SM}$ = 11%
- Multiple energies allow precise determinination self coupling independent of the value



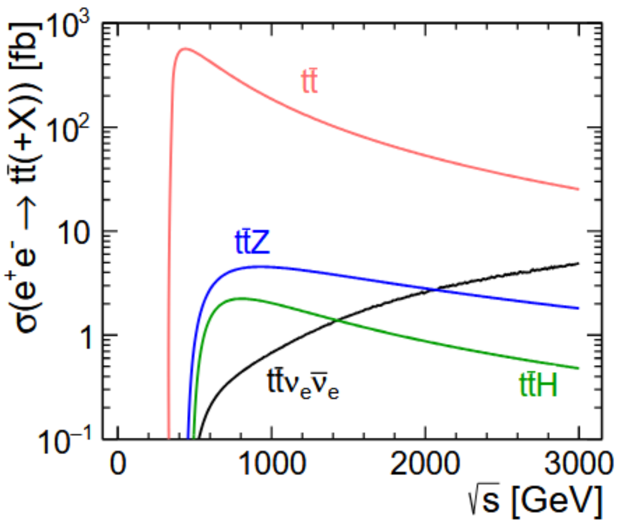


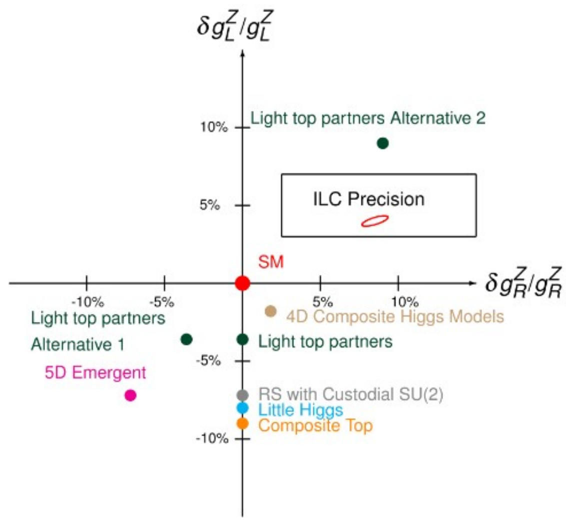
https://arxiv.org/abs/2503.19983

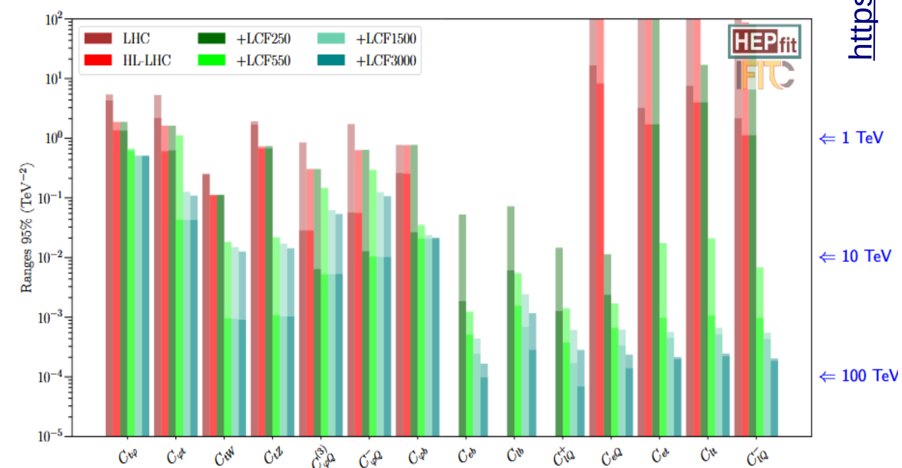
Physics Highlight: Top

- Top threshold scan with 10 points and a few 100 fb^{-1} for mass and width
- Higher energies: top Yukawa to 1%, BSM contraints, CP properties → direct access to left and right couplings through beam polarisation allows to discriminate between many BSM models
- SMEFT BSM operators of t and b quarks can excluded to > 10 TeV scale

https://arxiv.org/abs/2503.19983



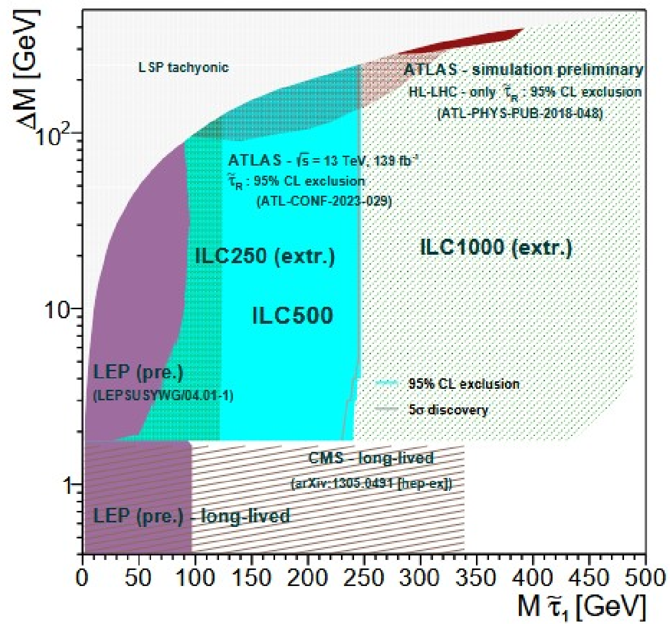


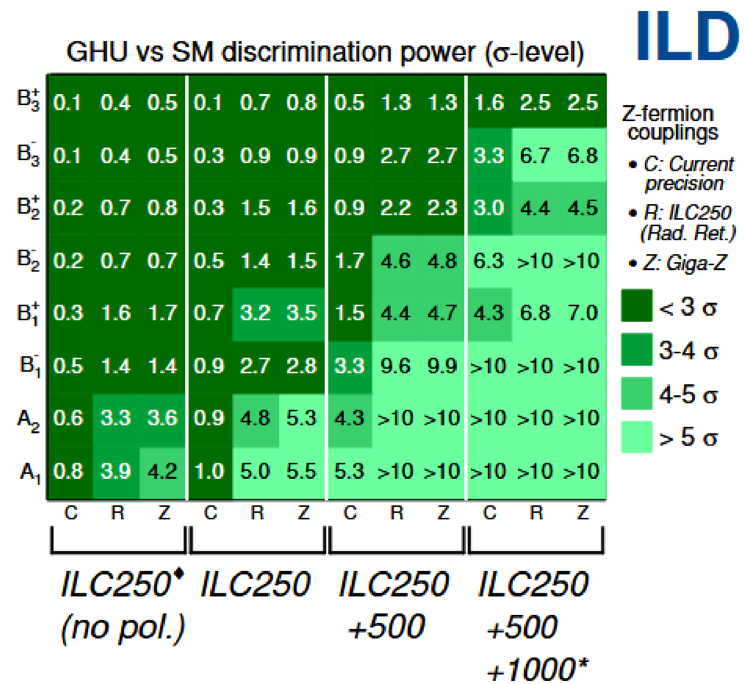


Physics Highlight: BSM

- Specific models can be tested and excluded
  - Example: SUSY stau up to the kinematic limit
- Also large power to differentiate between BSM models
  - Example: $e^+e^- \to q\bar{q}$ forward backward asymmetry A_{FB} with sensitivity to various BSM models

https://arxiv.org/abs/2410.14622





	ILC250♦ (no pol.) C	R	Z	ILC250 C	R	Z	ILC250 +500 C	R	Z	ILC250 +500 +1000* C	R	Z
B_3^+	0.1	0.4	0.5	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
B_3^-	0.1	0.4	0.5	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
B_2^+	0.2	0.7	0.8	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
B_2^-	0.2	0.7	0.7	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
B_1^+	0.3	1.6	1.7	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
B_1^-	0.5	1.4	1.4	0.9	2.7	2.8	3.3	9.6	9.9	>10	>10	>10
A_2	0.6	3.3	3.6	0.9	4.8	5.3	4.3	>10	>10	>10	>10	>10
A_1	0.8	3.9	4.2	1.0	5.0	5.5	5.3	>10	>10	>10	>10	>10

https://arxiv.org/abs/2403.09144

What does the LCF entail?

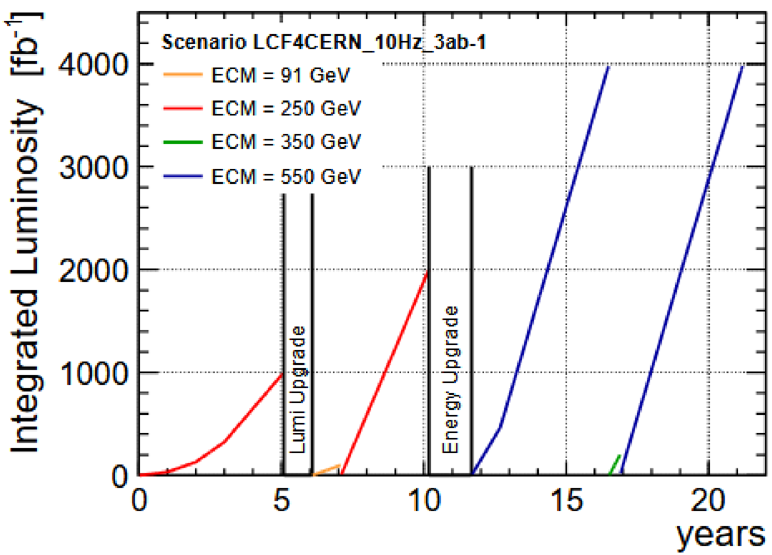
- 33.5 km, 2 IPs with shared lumi
- Start with SCRF: mature technology in use for > 10 years at DESY, with still some open potential
- Polarised beams $P(e^-)=80\%$, $P(e^+)=30\%$ (with potential to go to 90%/60%)
- 250 GeV at $2.7\text{x}10^{34}$ cm^{-1} s^{-1} for 8.3 GCHF
- Lumi x2 for 0.8 GCHF; 550 GeV for 5.5 GCHF
- future upgrades via better technology (CLIC, C^3, plasma), not longer tunnel

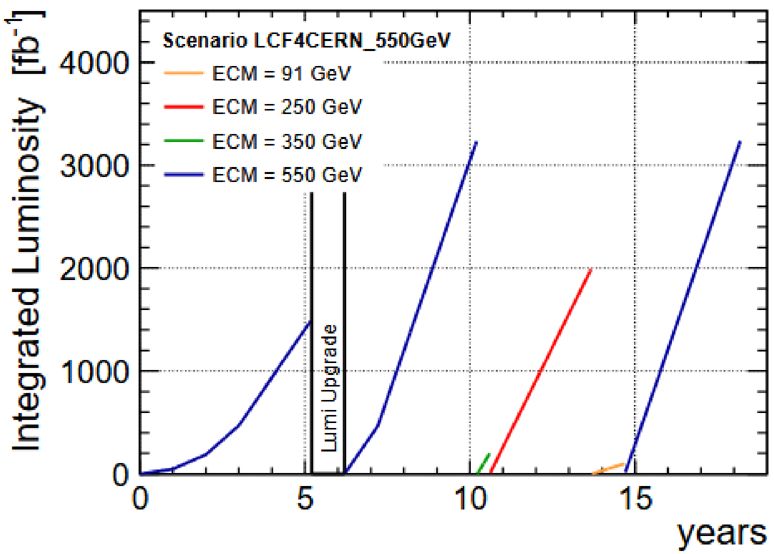
	91 GeV	250 GeV	350 GeV	550 GeV	1-3 TeV
$\int \mathscr{L}$ (ab^{-1})	0.1	3	0.4	8	8
beam polarisation (e^-,e^+; %)	80/30	80/30	80/30	80/60	80/20
($--$, $-+$, $+-$, $++$) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)

LC Vision Summary Document

Running scenario

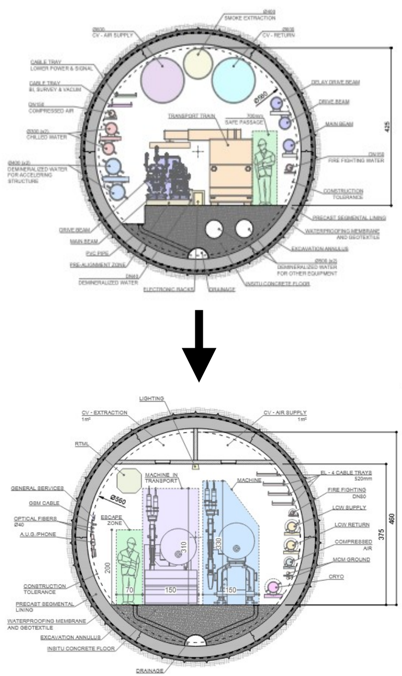
- Start with 250 GeV allows continuous enhancement following financial availabilities
- Start with 550 GeV more aggressive, still cheaper than FCC-ee ;)

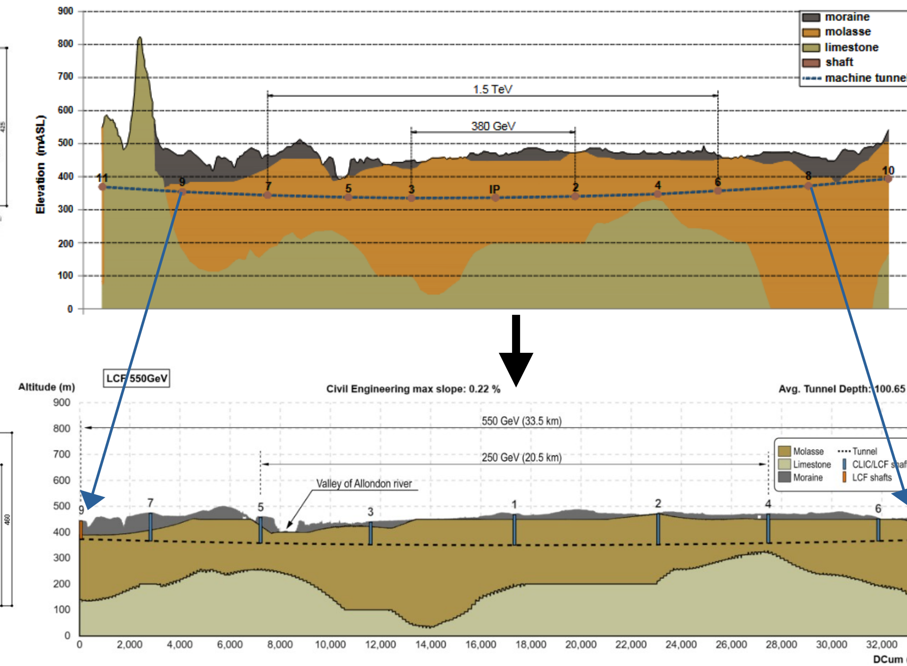




LCF Civil Engineering

- Applying 15 years of site studies and civil engineering for CLIC to initial SCRF accelerator
- SCRF: 33.5 km
  CLIC NCRF 1.5 TeV: 29 km
- Injectors and experimental areas on Prevessin site (“CERN attributed land”)





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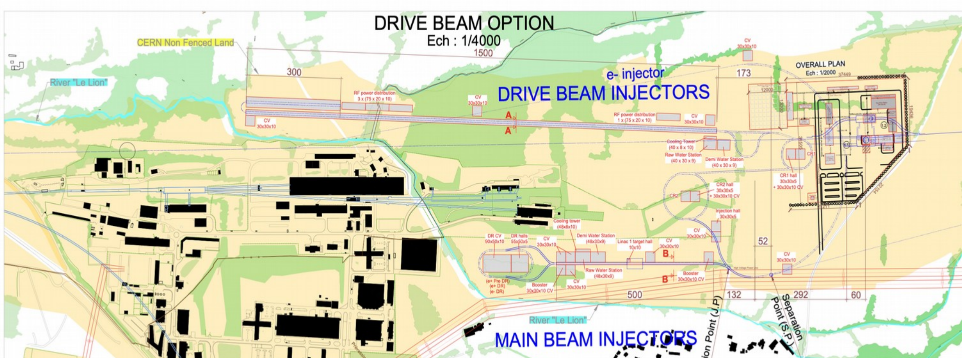


LCF Strategy Input Backup Document
CLIC 2018 Summary Report

LCF Costing

ILC/LCF Cost exercises – and international reviews:
- ILC TDR 2013, 500 GeV primarily
- ILC in Japan 2018, 250 GeV, reviewed by LCC
- Updates and review recently done for ILC Japan 12/2024

For “ILC like” implementation at CERN:
- Redid CE costing based on ILC layout with CLIC footprint
- Redid civil facilities costing
- Use 2024 costing for all components in their respective currencies, and change to CHF with exchange rate

From “comparative report”
- Low Power (1312 bunches per train),
- Full Power (2625 bunches per train)
- CLIC 550 GeV is 30% higher than CLIC 380
- In the report two experiments (not in table) are estimated to 795 MCHF

CLIC cost exercises – and international reviews:
- CLIC CDR 2012, 3 TeV primarily and 500 GeV
- CLIC PiP 2018, 380 GeV primarily
- Updated 2024-25

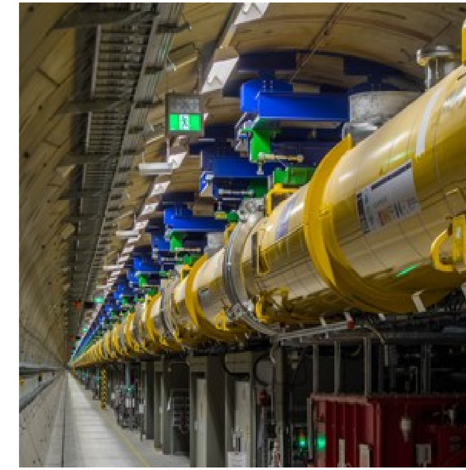
Unit: MCHF	LCF 250 (LP)	Δ LCF 550 (FP)	CLIC 380	Δ CLIC 1500	Cost Class
Collider	3864	4204	2471	4684	3/3-4
Main Beam inj./transfer	1181	86	1046	23	3/3-4
Drivebeam inj./transfer	-	-	1060	302	3/3-4
Civil Engineering	2338	0	1403	703	4
Technical Infrastructure	1109	1174	1361	1404	4
	8492	**5464**	**7341**	**7116**	

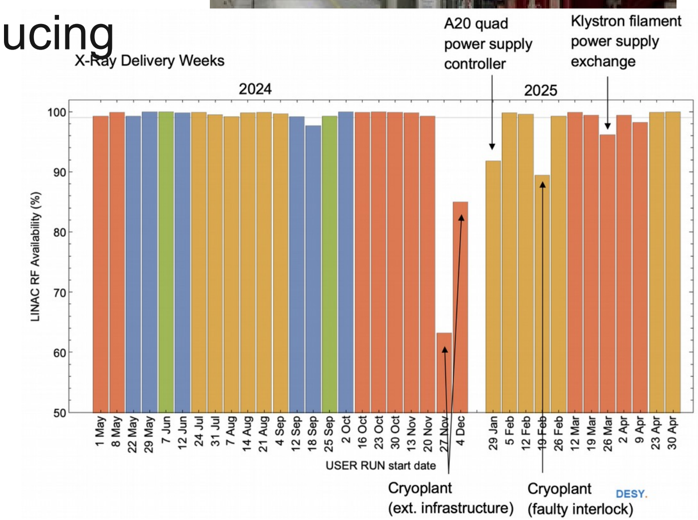
Likely consistent with running CERN budget!

Slide adapted from S. Stapnes at Venice Symposium

Why SCRF?

- Very detailed and mature technical design and industrialisation, several FEL linacs build and being operated
- Can be upgraded in energy and luminosity
- Worldwide interest in technology, in particular in Europe and leading industries in Europe
- SCRF R&D, e.g. at KEK and SLAC, could open a path to in-kind contributions from intercontinental partners, potentially reducing work and financial load on CERN during the HL period
- Can this be turned into a financing advantage and/or schedule advancement?





EU-XFEL linac availability 2024-25

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Schedule towards the LCF

Prep phase I:

Placement scenario

Design optimisation and finalisation

Main technologies R&D conclusions

Technical Design Report

→ Necessary investment to make sure a plan B is ready (~25-35 MCHF,150-180 FTE)

Construction:

Civil engineering

Construction of components

Installation and hardware commissioning

2026-28 | T_0-T_0+5 | T_1-T_1+10 | T_1+11

CERN Council plan determination(?)

Prep phase II:

Site preparation

Environmental evaluation

Engagement with host states

Project authorisation processes

Industrialisation of key components

Engineering design completion

Beam commissioning

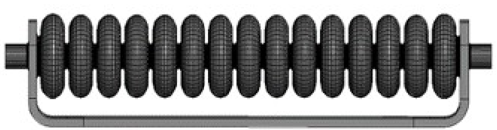
followed by physics

Slide adapted from S. Stapnes at Venice Symposium

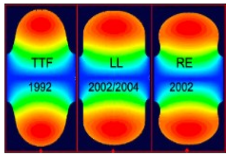
SCRF Upgrades

- Current SCRF plans with 31.5 MV/m, need ~60 MV/m to reach 1 TeV in LCF tunnel
- SCRF is one of the key directions of Accelerator R&D Roadmap
  - significant synergies with ERL needs
  - needs to be accompanied by R&D on high-efficiency klystrons, couplers, He refrigerators, etc.
- **5-year horizon:** standing-wave, bulk niobium cavities: **50-60 MV/m**
  - new baking recipe, new shapes

ILC (TESLA) 9-cell standing wave cavity



Traveling wave 15-cell SRF cavity

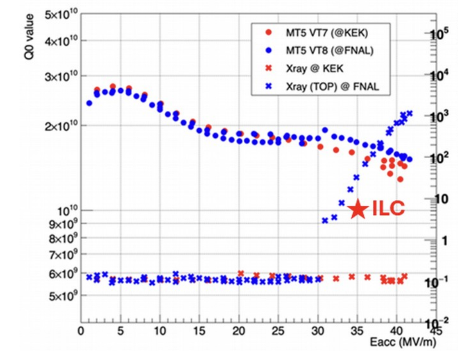


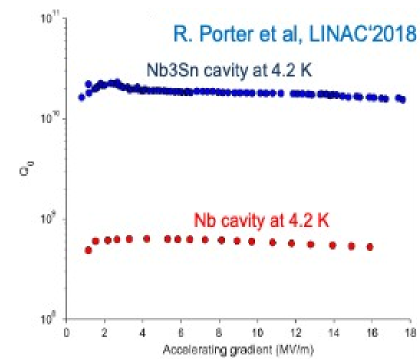
Examples of optimized cavity geometries

- **10-year horizon:** traveling-wave cavities **60-70 MV/m**, HELEN concept
  - substantially lower k_M => higher gradients for same magnetic quench limit
  - 2x higher R/Q => lower losses
  - higher stability of field distribution -> longer structures
- **>10-year or break-through:** Nb_3Sn or multilayer cavities **100 MV/m**
  - to-date only reached gradients up to 24MV/m with Nb_3Sn
- Progress is funding-limited!

Results from FG 9-cell cavity using 2-step baking **KEK and FNAL**

Possible to achieve > 40 MV/m with high Q_0

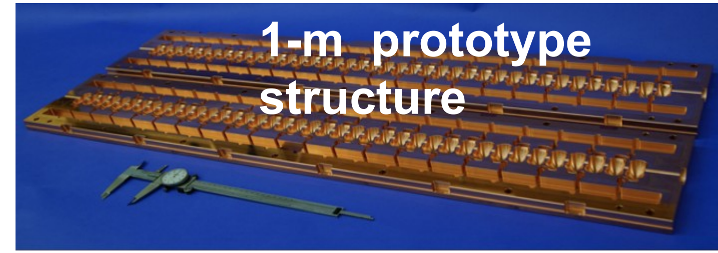


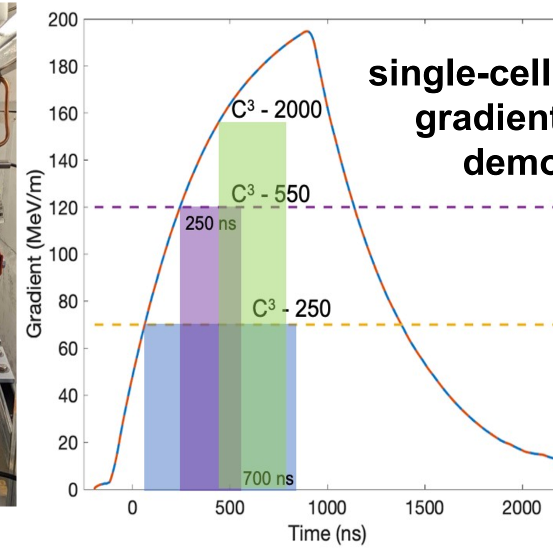


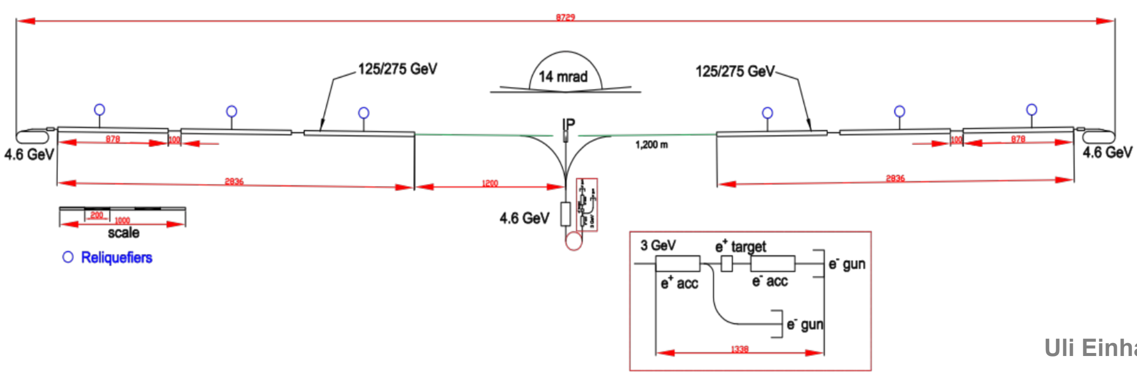
Slide adapted from J. List at Venice Symposium

Cool Copper Technology

- C^3 technology**:**
  - normal-conducting C-band copper cavities
  - operated at **~80K** with liquid N_2
  - gradients demonstrated up to **155 MV/m**
- R&D:
  - plan towards demonstrator established during Snowmass
  - since then significant progress on system design, accelerator structure design, cryo-module design, high gradient testing, vibration measurements, damping materials, alignment system, low-level RF & klystrons, etc.
- stand-alone facility 8km: 250/550 GeV (**70/120 MV/m**)







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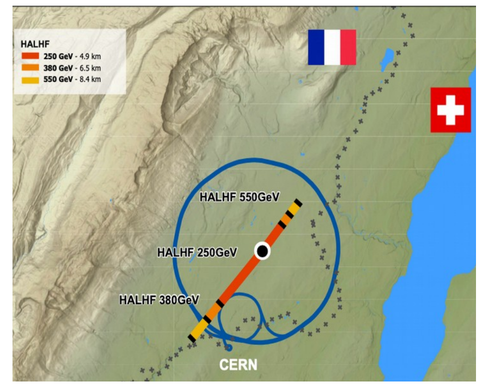
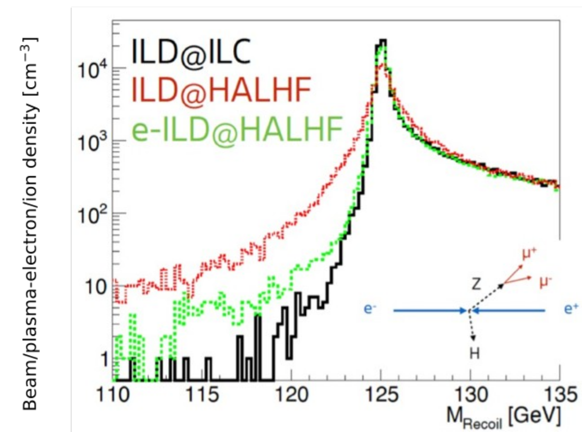
HALHF - Hybrid Asymmetric Linear Higgs Factory

- e^+e^- LC using e-beam-driven plasma wakefield acceleration for e^- and SCRF for e^+
- Asymmetric collisions with γ=1.67 (HERA: γ=3), luminosity ~ILC baseline
- Higgs factory proposal - small & cheap:
  - 250 GeV: 4.9 km, 3.8 BCHF
  - 550 GeV: 8.4 km, 6.3 BCHF
- R&D estimate: 213 MCHF & 341 FTEyrs over ~15 years





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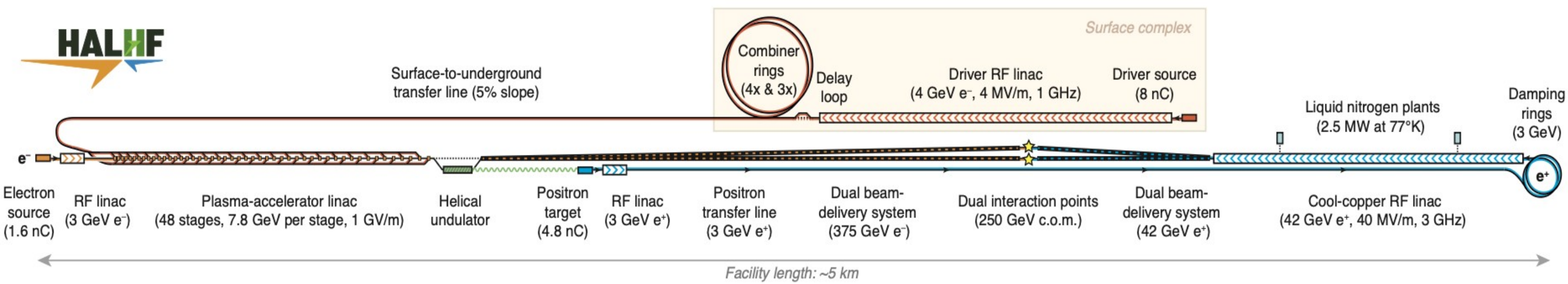
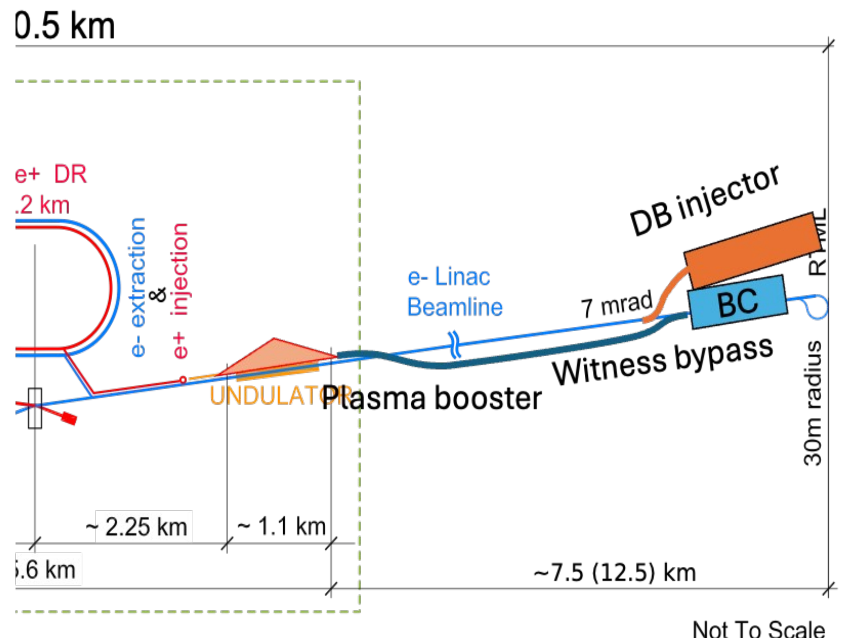


A Plasma Upgrade for the LCF

- Example: 250 GeV (125 GeV on 125 GeV) → 550 GeV (550 GeV on 137.5 GeV, γ=1.2)
  - e^+ : only small increase in E needed - either operate at 35 MV/m or add few cryomodules
  - e^- : re-purpose main linac to produce drive-beams for plasma stages
    → low gradient - high current operation
  - needs lateral space for plasma stages next to undulator source
  - needs ~10x shorter bunches than LCF standard
- conceptually possible, in detail many open questions

→ room for exciting R&D and creative system design!

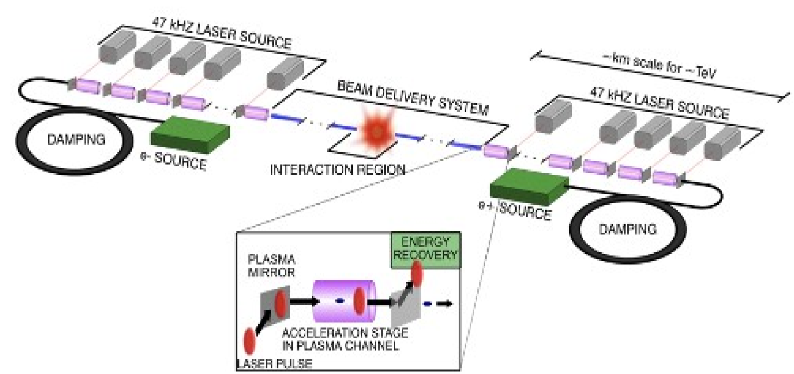


Slide adapted from J. List at Venice Symposium

The 10 TeV pCM Collider

- 3 paths to 10 TeV parton-center-of-mass: pp at ~100TeV or leptons at 10 TeV, either via muon collider or wakefield-driven e^+e^- collider 10 TeV
- Wakefield Collider Study
  - HEP-wide community effort, involving theorists, experimentalists and LC experts (~100 participants at last collaboration meeting)
  - by 2028 produce a unified, self-consistent concept, including cost scales for a 10-TeV pCM wakefield collider → via laser-, beam- or structure-based wakefields
  - study the physics case for 10 TeV e^+e^-, e^-e^-, and $\gamma\gamma$ collisions
  - identify the required R&D test facilities
- R&D programme: AWAKE (CERN), FACET II (SLAC), FLASH-Forward (DESY), AWA (ANL), BELLA (LBNL), SPARC-LAB (INFN), etc.

- R&D challenges
  - optimisation of power efficiency
  - demonstration of collider plasma modules with 10 GeV energy gain, > 100 pC of charge and normalized emittance < 100 nm
  - staging of collider modules
  - positron acceleration in plasma (not a problem with structure-based wakefields)
  - BDS and beam-beam effects at 10 TeV pCM
  - significant synergies with LCF-related R&D



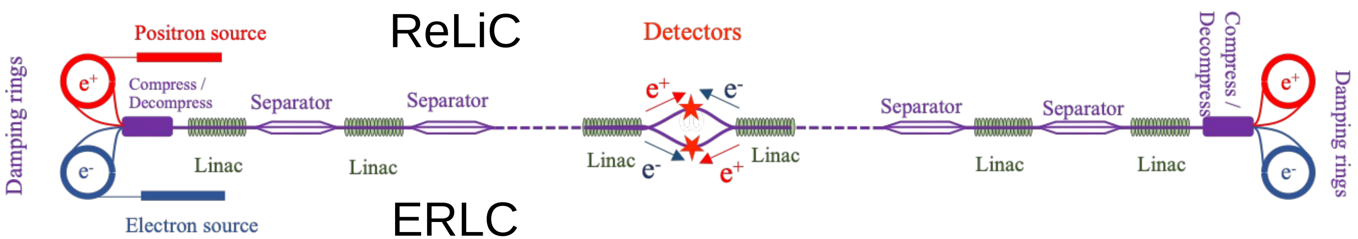
Slide adapted from J. List at Venice Symposium

Further Options: ERLs

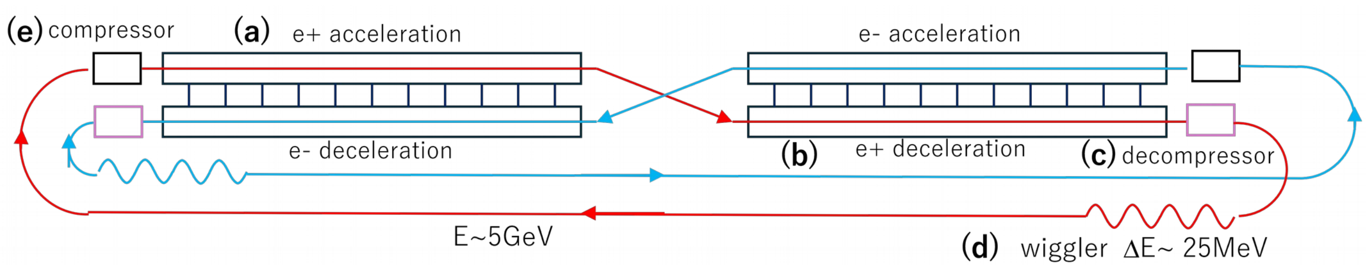
- Energy Recovery Linacs (ERLs)
  - boost luminosity up to 10^{36} / cm^2 / s and high e+ polarisation
  - by re-using particles and energy, requires to limit beam-strahlung, far from disruption limit
- Key R&D challenges: efficient liq. He refrigerators & cavities

	LCF	ReLiC[1]	ReLiC[2]	ReLiC[3]	ReLiC[3]
Centre-of-mass energy [GeV]	250	250	250	250	550
Accel. Grad. [MeV/m]	31.5	12.55	12.55	12.55	27.6
Cavity Q_0 [10^{10}]	2	4	4	4	4
Liquid He temperature [K]	2	2	2	4.5	4.5
Bunch population [10^{10}]	2	2.5	2.5	2.5	2.5
Collision frequency [MHz]	2.62	1.5	1.5	1.5	1.5
Duty cycle	0.0012	cw	cw	cw	cw
Beam current, all beams [mA]	0.042	12	12	12	12
Normalised emittance hor.[μm] / vert.[nm]	5/25	4/1	4/1	4/1	4/1
β_x / β_y [m] / [mm]	0.013/0.41	2.2/0.19	2.2/0.19	2.2/0.19	4/0.36
σ_x / σ_y at IP [μm] / [nm]	0.52/7.7	6/0.9	6/0.9	6/0.9	6/0.9
D_x / D_y	0.5/34.5	0.01/87	0.01/87	0.01/87	0.01/88
Υ_{max}	0.068	0.0028	0.0028	0.0028	0.0031
Luminosity [10^{34} cm^{-2}s^{-1}]	2.7	140	140	140	153
AC Site Power [MW]	111	~135	~105	~95	~ 250

Slide adapted from J. List at Venice Symposium

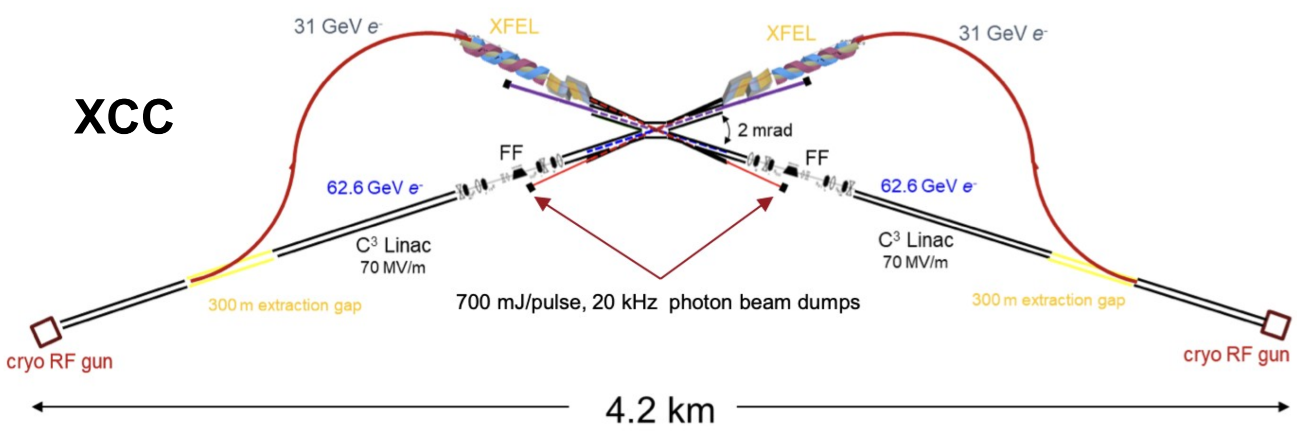


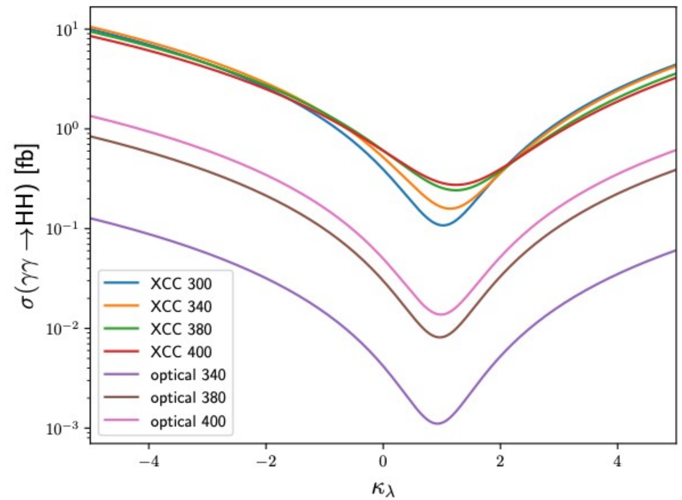
ERLC



Further Options: γγ-Collider

- γγ / eγ collider offers complementary physics opportunities to e^+e^-
  e.g. self-coupling in $\gamma\gamma \rightarrow HH$ with different BSM behaviour than e^+e^- / pp
- high-intensity lasers convert e beam(s) into γ beam(s) directly at the IP



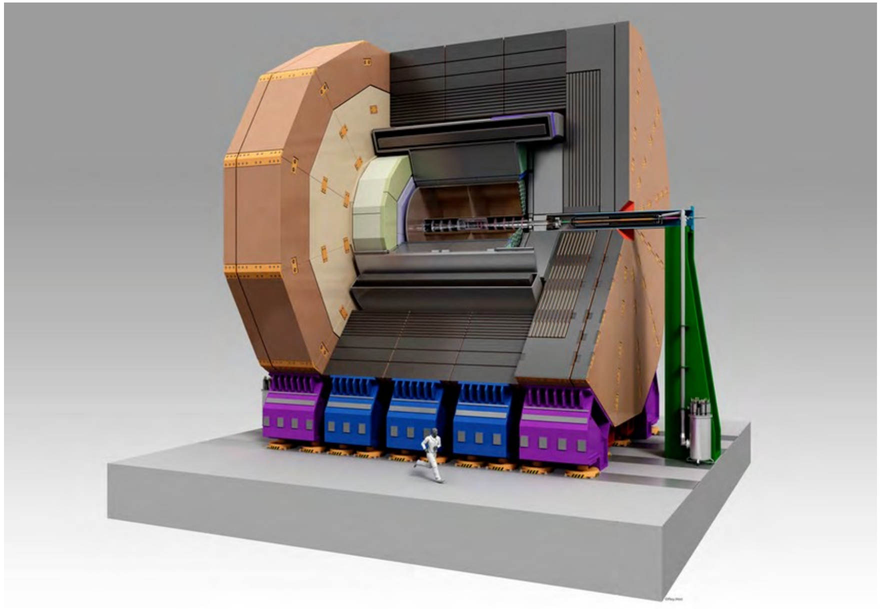


Conclusion LCF

- A Linear Colider Facility as CERN next flagship provides:
  - mature, timely & cost-effective
  - excellent physics reach through high energies and polarisation
  - great flexibility in the future to react to developments in physics, technology and politics

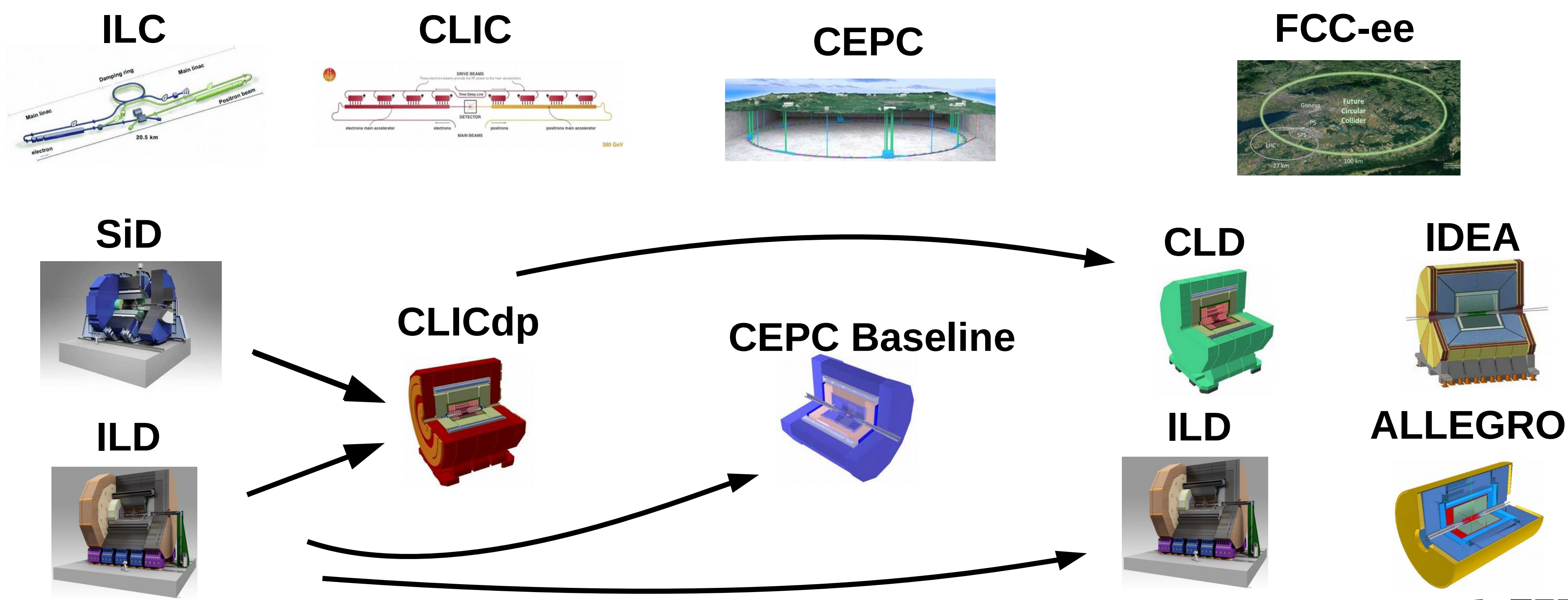
- The LCF needs:
  - a clear commitment to the necessary investment as a realistic plan B
  - accelerator R&D for future upgrades

The International Large Detector



A bit of History

- ILC TDR 2013 accompanied by 2 detector reference designs, ILD and SiD
- Over the years these had an impact on detector concepts at all proposed HTE factories



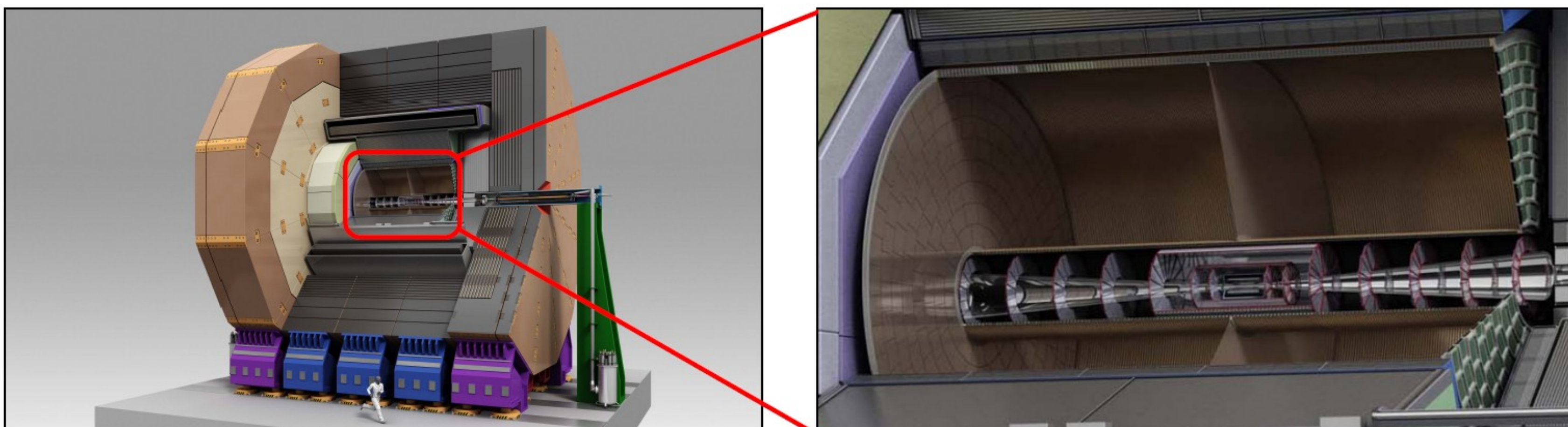
ILD Layout and Performance

- Multi-purpose detector designed for 250 GeV to 1 TeV optimised for particle flow
- Time projection chamber (TPC) as main tracker allows for continuous tracking and dE/dx PID
- High granularity calorimeter with minimal material in front of it inside 3.5 T solenoid
- Nearly 4π hermeticity with elaborate forward region
- Resolutions:

vertexing:	$\sigma_b < (5 \oplus 10/p\sin^{3/2}\theta)\,\mu m$		~ CMS/4
momentum:	$\sigma_{1/p_T} = 2\cdot 10^{-5} GeV^{-1} \oplus 10^{-3} \sin^{1/2}\theta/p$		~ CMS/40
jet energy:	$\sigma_{E_{Jet}}/E_{Jet} < 3.5\%$	above 100 GeV	~ ATLAS/2
dE/dx:	$\sigma_{dE/dx}/\mu_{dE/dx} < 5\%$		~ ALICE

[Interim Design Report 2020]

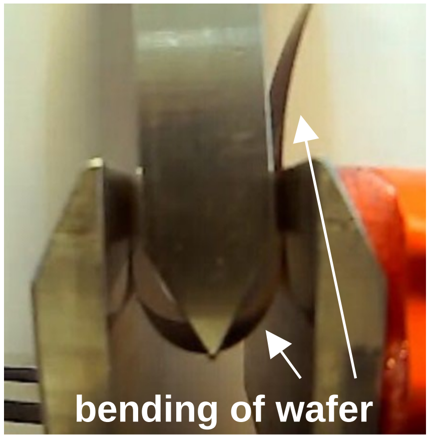
[https://arxiv.org/abs/1306.6329]



Silicon Tracking

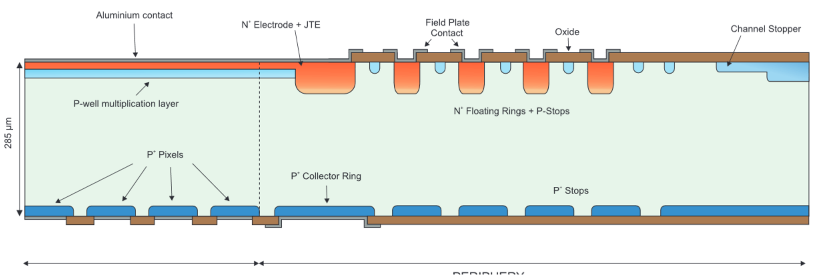
- ILD foresees Silicon vertex tracker and TPC envelope and is considering a number of options (CMOS, DEPFET, MAPS, (i)LGADs) and is monitoring the ongoing developments, e.g.

- ALICE ITS3 for the vertex detector
  - Bendable MAPS, minimal material budget of 0.05% per layer
  - Point resolution < 5 µm



https://indico.slac.stanford.edu/event/7467/contributions/5958/

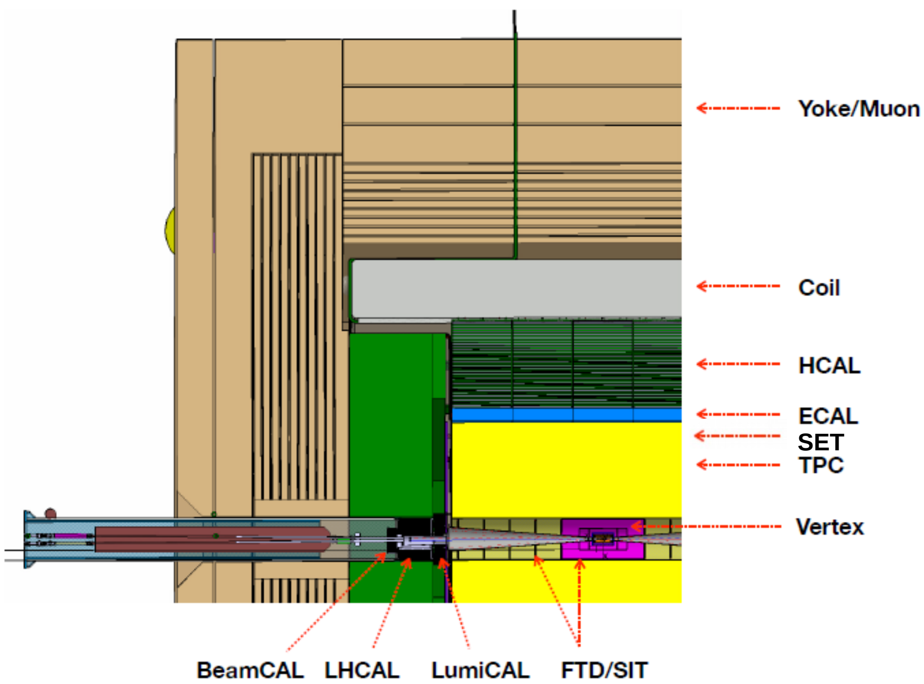
- (i)LGADs for the Si envelope
  - Timing resolution O(10 ps)
  - ‘Inverting’ more complex but optimises fill factor

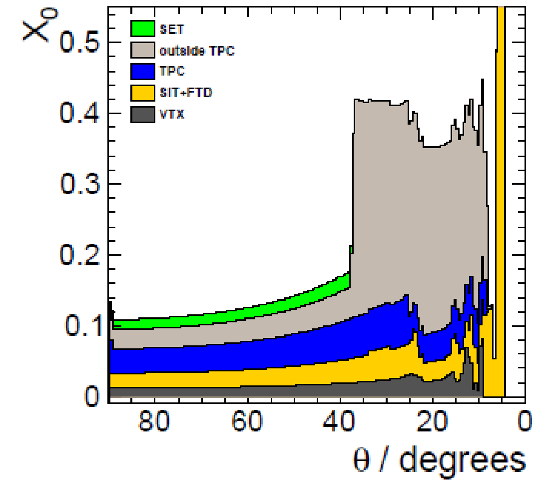


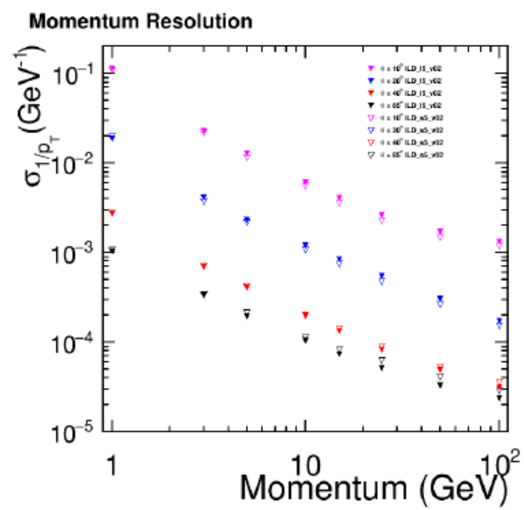
https://doi.org/10.3390/s23073450

Tracker Material Budget

- How can we optimise the vertex and tracker further to minimise material budget, currently dominating the momentum resolution over a large range?
- Is gas-flow cooling of vertex detector possible at CC?

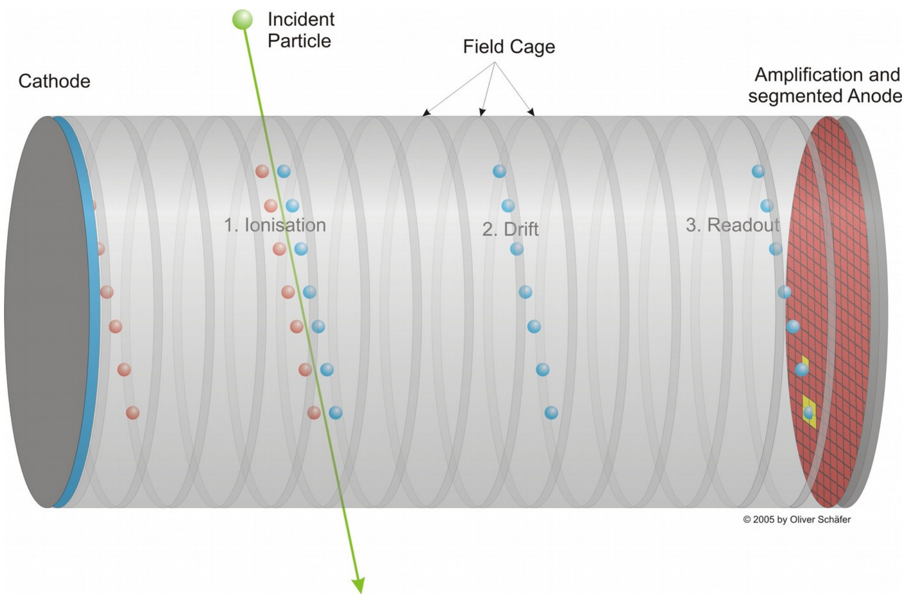


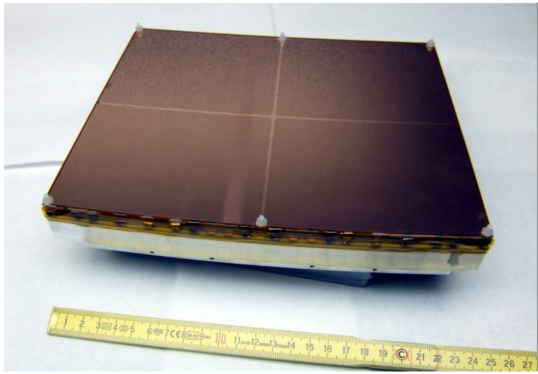




Time Projection Chamber

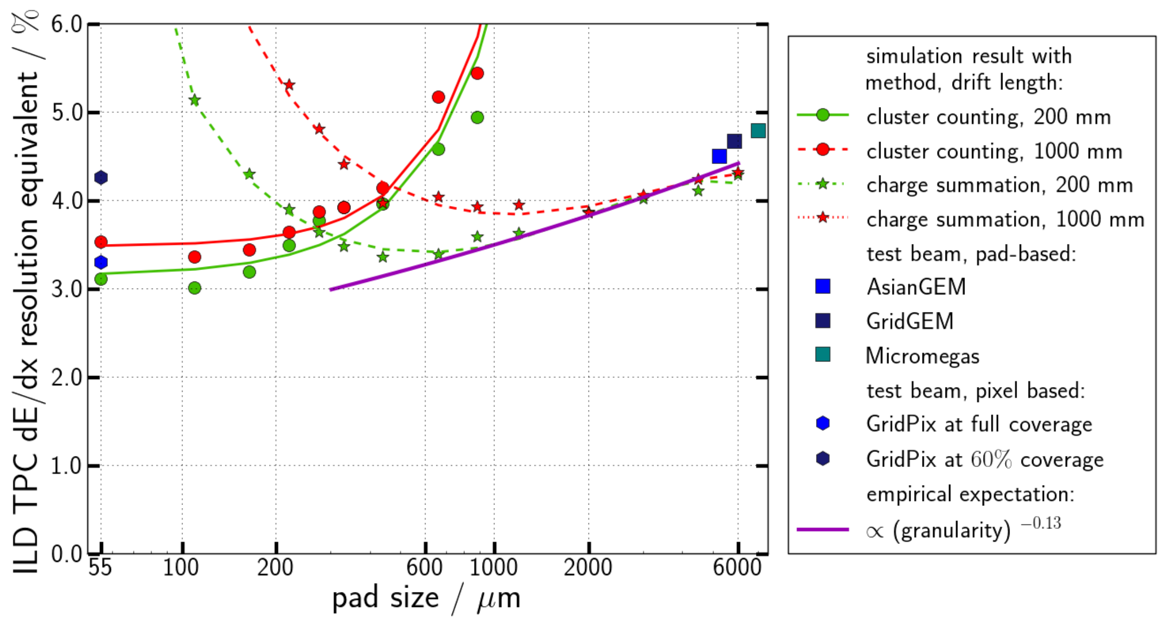
- Large gaseous tracker allowing for continuous tracking and large lever arm for ParticleFlow as well as built-in PID via ionisation (dE/dx / dN/dx)
- Hardware development driven by the LCTPC collaboration, now in DRD1
- TPC: pad-based readout (GEMs, Micromegas) well established, ongoing development of PixelTPC readout





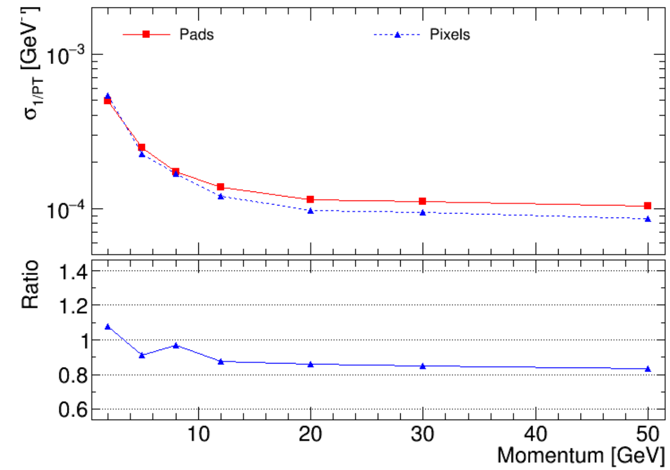
Time Projection Chamber

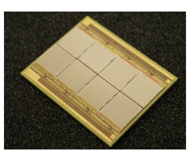
- Conventional dE/dx with pad-based readout measured in test beam to have a relative resolution of 4.5%, giving pion-kaon separation > 3σ up to 20 GeV
- With pixels one can utilise high granularity to do cluster counting to avoid Landau tail of hit energy distribution
- Detailed TPC simulation study of dE/dx resolution vs. granularity
  - ILD aim: 5%
  - Achieved with pads: 4.6%
  - Achievable with granularity of 200 µm: 3.5%

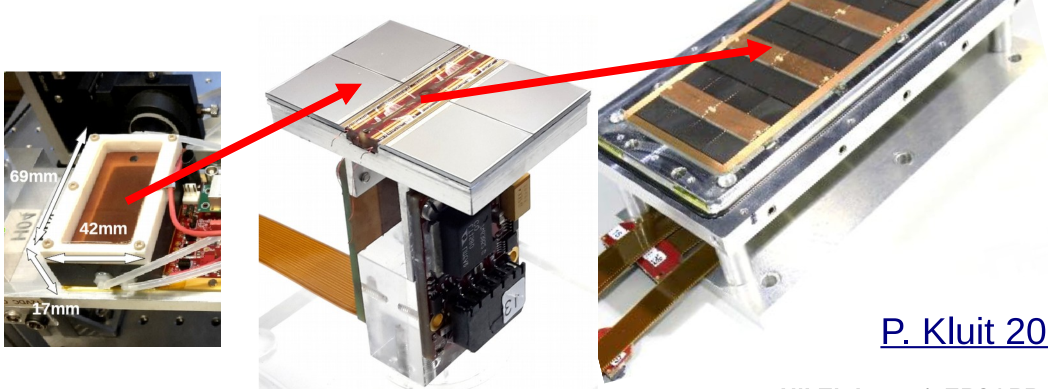


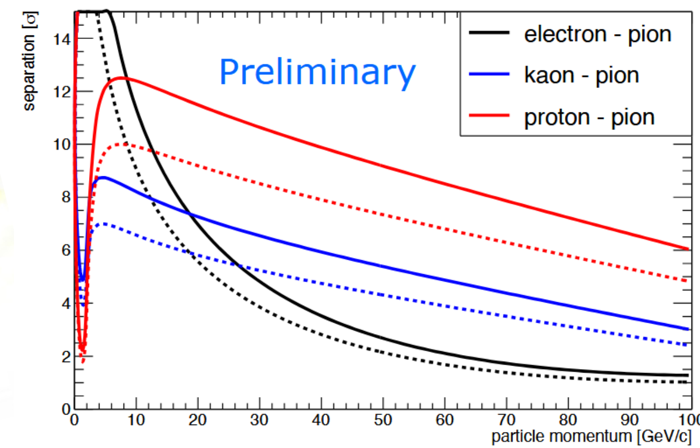
Time Projection Chamber

- Conventional dE/dx with pad-based readout measured in test beam to have a relative resolution of 4.5%, giving pion-kaon separation > 3σ up to 20 GeV
- With pixels one can utilise high granularity to do cluster counting to avoid Landau tail of hit energy distribution
- Test beam studies with GridPix of 55μm granularity: 15% improved momentum resolution and a dE/dx resolution equivalent of 2.5-3% with pion-kaon separation up to 100 GeV







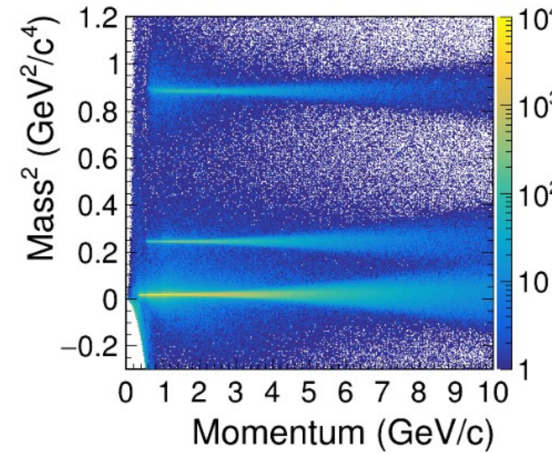


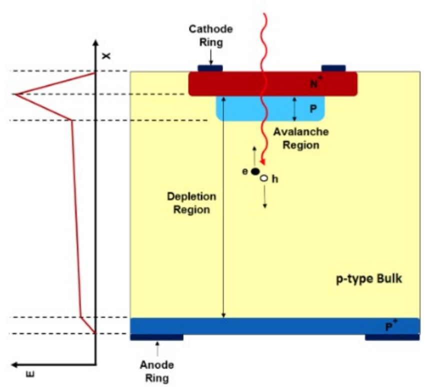
[P. Kluit 2025]

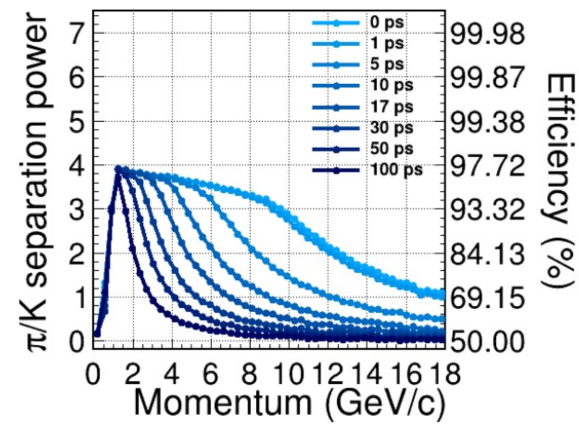
Time of Flight

- Measure TOF between IP and end of tracker to determine particle mass
- Several possibilities to implement, to reach 30 ps:
  - dedicated timing layer with 30 ps
  - 2-layer Silicon outer tracker with 45 ps
  - 10 ECal layers with 100 ps each
- Possible technology: LGADs with 30 ps
- Crucial: precision of relative track length as important as of relative timing!

$$L = \sum_{i=1}^{N_{\text{hits}}-1} L_i = \sum_{i=1}^{N_{\text{hits}}-1} \left| \frac{z_{i+1} - z_i}{\tan \lambda_i} \right| \sqrt{1 + \tan^2 \lambda_i}$$



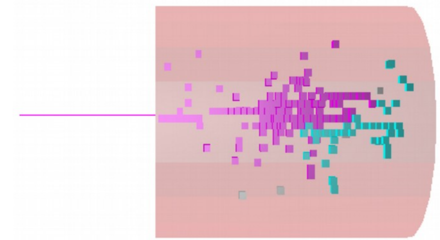




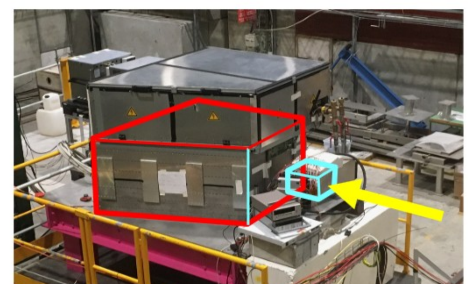
PhD Thesis B. Dudar

Hardware: Main Calorimetry Status

- A number of options being developed, previously by CALICE, now integrated in DRD Calo (DRD6)
  - SiW ECAL, Scintillator ECAL
  - AHCAL (Sci), (T-)SDHCAL (RPCs)
- All using high granularity (~ 5 mm ECAL, ~ 1-3 cm HCAL; 10^8 channels) for particle flow as well as power pulsing for ILC beam structure with passive cooling
- SiW ECAL and AHCAL inspired CMS HGCAL (to be installed in 2026/27); common develop-ments and beamtests with AHCAL
- SDHCAL: 1 cm gran., 3 thresholds
- Sci ECAL: 45x5 mm² strips reduce channels by 10

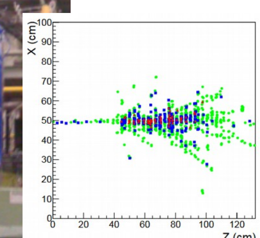


Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits



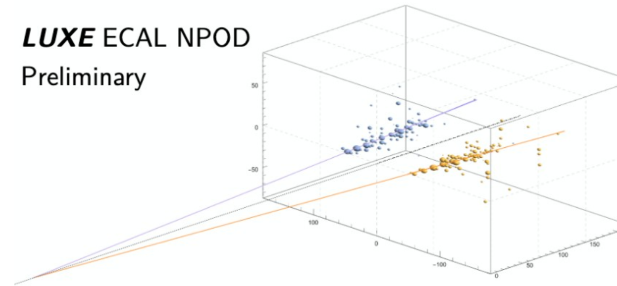
SiW-ECAL
- 15 layers 18×18 cm²
- 0.5×0.5 cm² Si cells
- 2.8+5.6 mm W (24 X0)

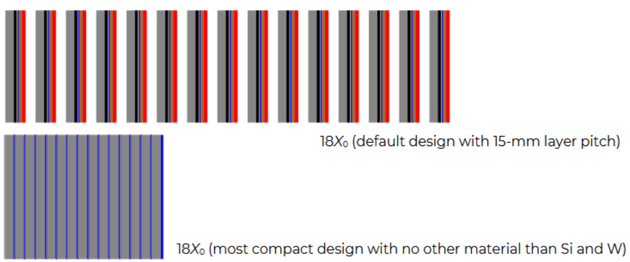
AHCAL :
- 38 layers 72×72 cm²
- 3×3 cells scintillator + SiPM
- 1.7 cm Stainless Steel (~4λ)

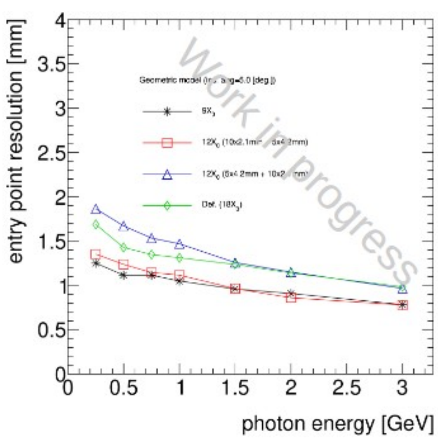


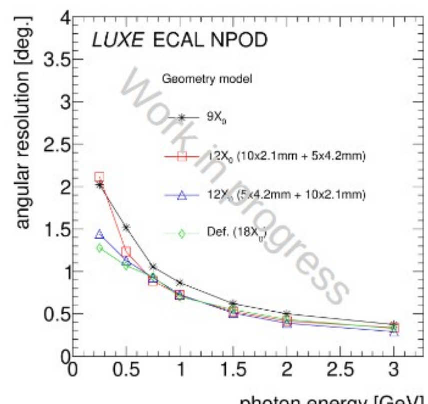
Hardware: From Higgs Factory to Dark Matter

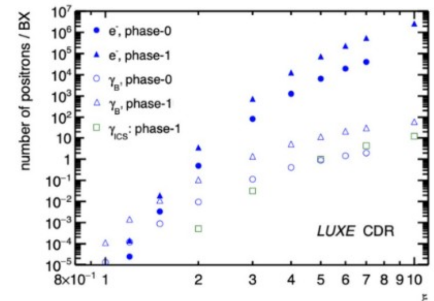
- High granularity SiW ECal being applied to the LUXE experiment
- Particular interest: beam-dump experiment NPOD, study to optimise the ECal geometry to get best resolutions
- Inverse effects of more tungsten on entry point and angular resolution and → work in progress!



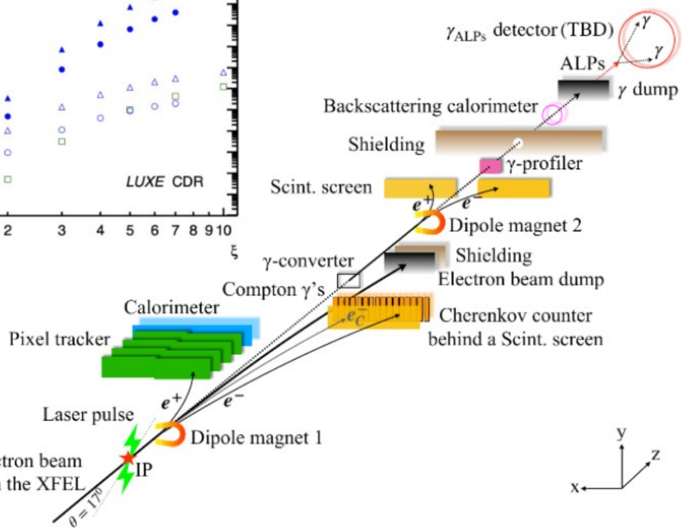






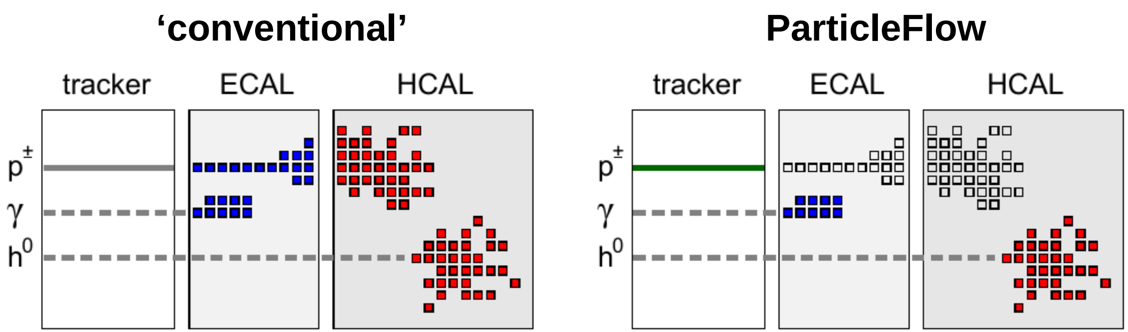


S. Huang 2025



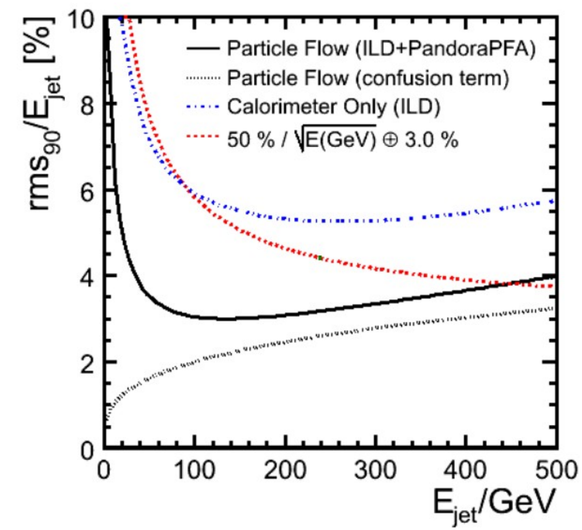
ParticleFlow Overview

- Idea: utilise the best subdetector for each particle / jet constituent
  - work horse: highly granular calorimeter
  - future collider detectors (e.g. ILD) developed with PFlow in mind, also applied to existing detectors (e.g. CMS HGCAL for HL-LHC)



$$\sigma_{jet} = f_{charged} \cdot \sigma_{Tracker} \oplus f_{\gamma} \cdot \sigma_{ECal} \oplus f_{neutral} \cdot \sigma_{HCal} \oplus \sigma_{confusion} \oplus \sigma_{leakage}$$

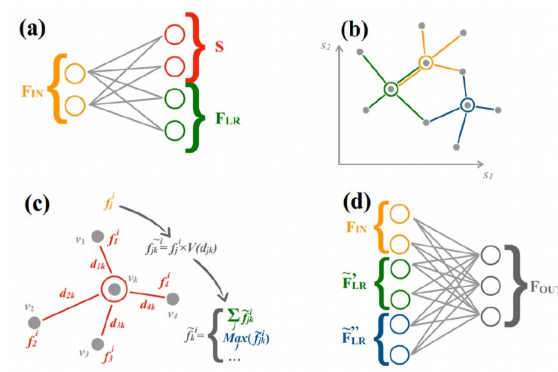
M. Thompson

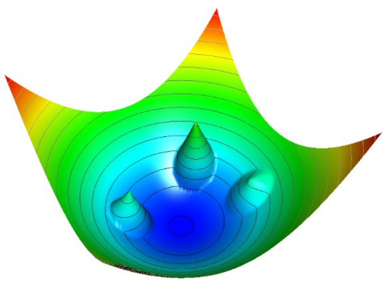


- Use neural networks and timing to reduce confusion term

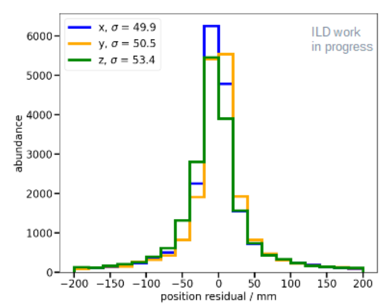
CALO5D

- Task: utilise ps-timing in calorimeter to improve its performance
- Mostly using ML approaches, easy to add timing, all work-in-progress
- Example: ParticleFlow with a GravNet and Object Condensation
- Take all calo hits of ILD and let the NN predict the particles and their properties, e.g. position and energy
- So far some impact seen, but very limited

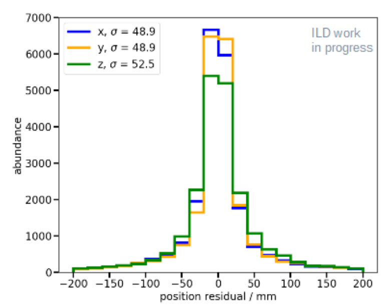




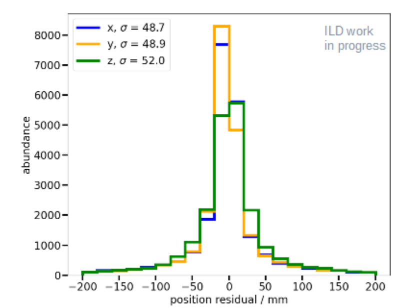
no timing



smearing with 100 ps

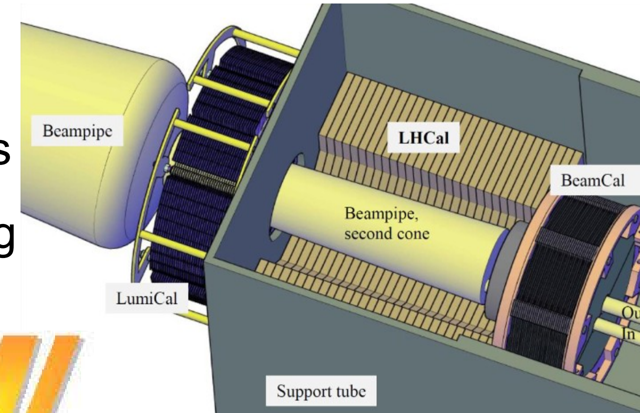


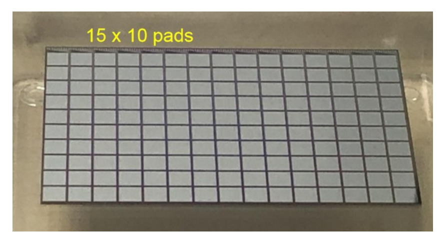
perfect timing

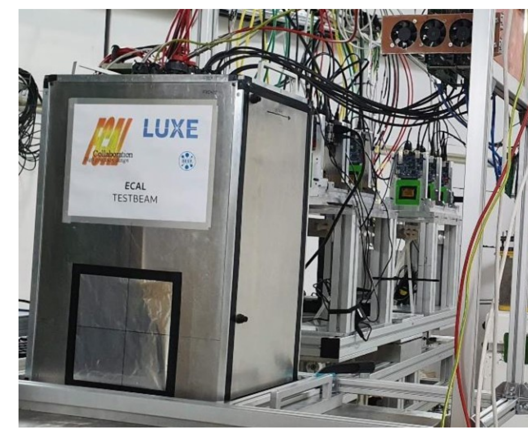


Hardware: Forward Calorimeter System

- Development by the FCAL collaboration: high granularity calorimeter for the forward region
- LumiCal: precise luminosity measurement counting Bhabhas
- BeamCal: fast luminosity measurement using beamstrahlung
- Both: large polar angle coverage, i.e. hermiticity down to θ = 6 mrad (η = 5.8)
  → particle flow, new particle searches (invisibles)
- Design done, detailed simulations, prototype for LumiCal with Si, possible application at LUXE
- Spin-offs went into CMS luminometer and beam condition monitor
- New: GaAs sensors with integrated routing
- Plan: continue developing prototypes; lots of beam test data to analyse!





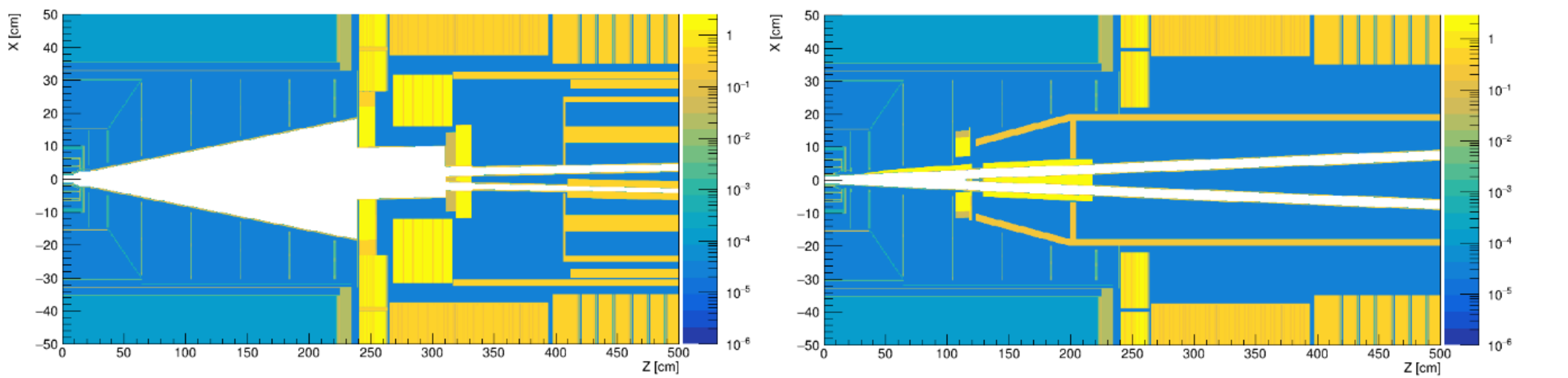


https://agenda.linearcollider.org/event/9625/#1-status-and-plans-of-the-fcal

ILD at a Circular Collider?

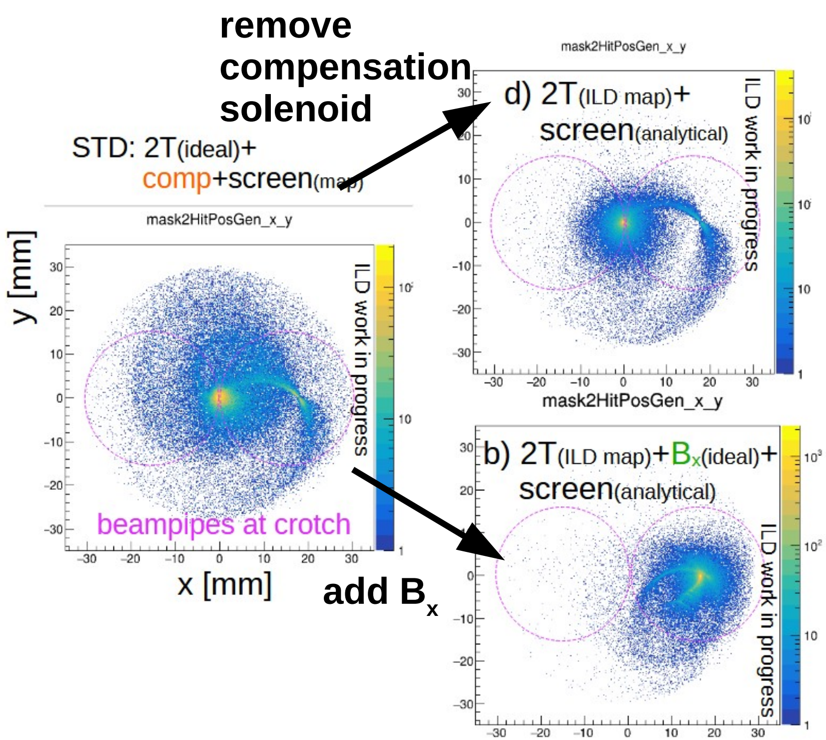
- ILD was developed to work at a linear collider
- At a circular collider (FCC, CEPC) conditions are different:
  - continuous beams instead of trains → no power pulsing, no TPC gating
  - different beam delivery system and beam stability requirements→ redesign of forward region
  - B = 2 T, while ILD @ILC has B = 3.5 T → mom. res. (lever arm, TPC drift diffusion)
- ILD detector model for the FCC-ee developed and under study

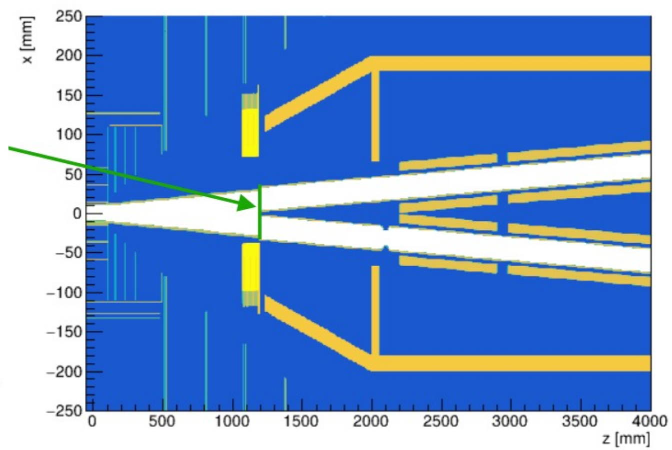
ILC D. Jeans 2022 FCC

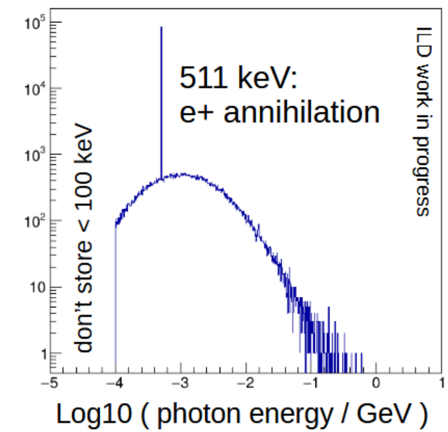


Beam Background in the TPC

- Distortions in TPC due to ions from physics (hadronic Z decays) are O(100 μm), but stable at O(1 μm); however, 2 orders more ions come from beam background
- Around 2k sub-100 MeV photons enter the main tracker in each bunch crossing, mostly coming from the 'crotch', i.e. the split of the beam pipes
- Work is ongoing to study how the MDI can be adapted to mitigate this



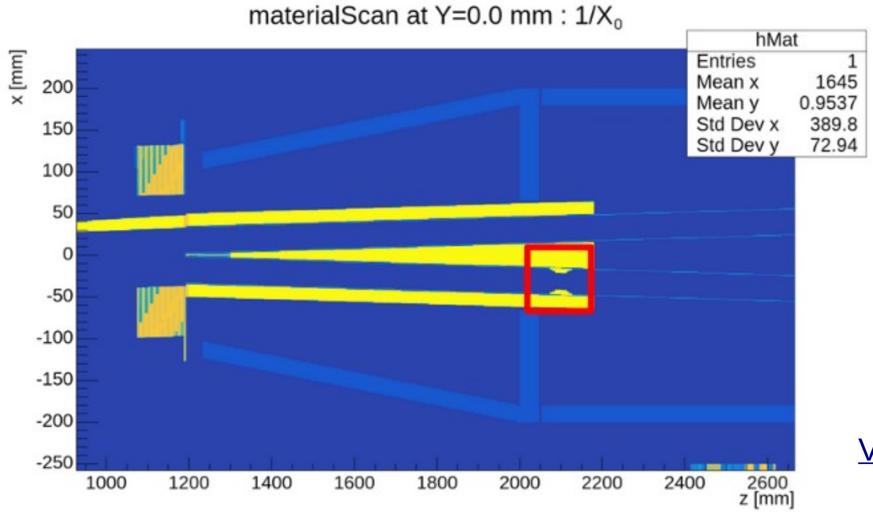




D. Jeans 2025

Impact of Synchrotron Radiation

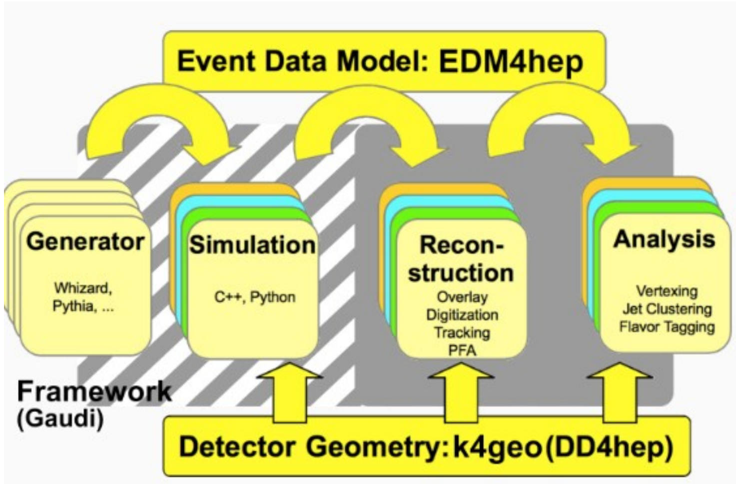
- Another source of background at a circular collider is synchrotron radiation
- Was determined to be < 1% occupancy for CLD
- In an ongoing study with ILD the backgrounds were found to lead to O(100%) occupancy – though probably due to a misplaced mask in the common FCC-ee MDI
- → Lots of work still to do for all detectors to optimise the MDI!

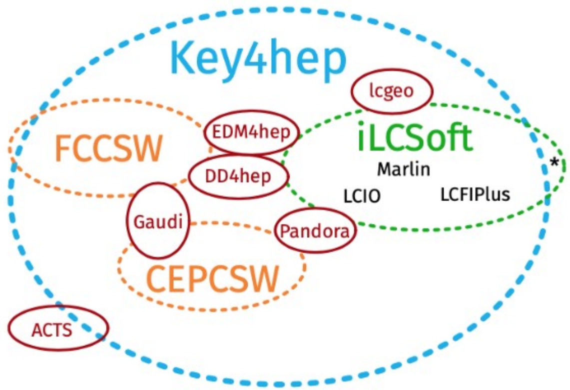


V. Schwan 2025

Software Environment

- Extensive software framework iLCSoft, including detector model, driving full geant4 simulation, reconstruction, detector optimisation and physics studies
- Several large MC productions, most recent one in 2020 for 250 GeV E_{CM}, now going for high-level reco add-on with newest algorithms
- Detector model being updated for usage at a circular collider
- Future collider community has agreed on common framework: Key4hep, ILD is actively contributing
- iLCSoft is part of the common environment, central reconstruction tools are usable via a wrapper and the plan is to move to native Key4hep in the future

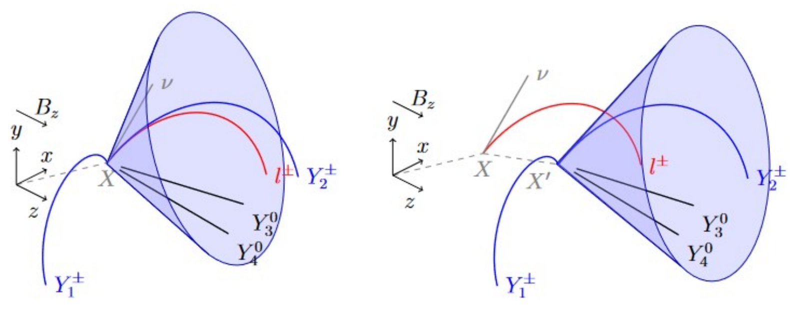




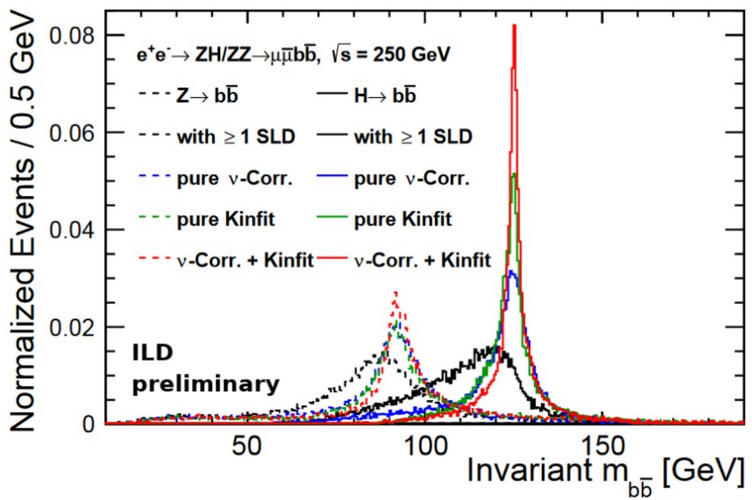
https://indico.cern.ch/event/1283129/#8-overview-of-key4hep

Higgs Self-Coupling: Neutrino Correction & ErrorFlow

- Primary Higgs decay channel is $b\bar{b}$, often with 1 or 2 semi-leptonic decays (SLDs) of the b- or consecutive c-hadrons
- Less prevalent but still an issue in $c\bar{c}$, WW or ZZ channels
- Neutrinos of SLDs carry invisible energy, broaden invariant-mass peak of the reconstructed Higgs
- New: dedicated reconstruction of the missing energy/momentum using knowledge of initial state in e+e- collisions
- → Needs hermiticity and efficient vertexing



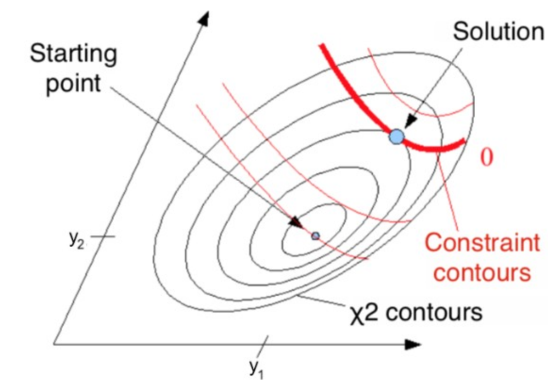
Y. Radkhorrami 2023

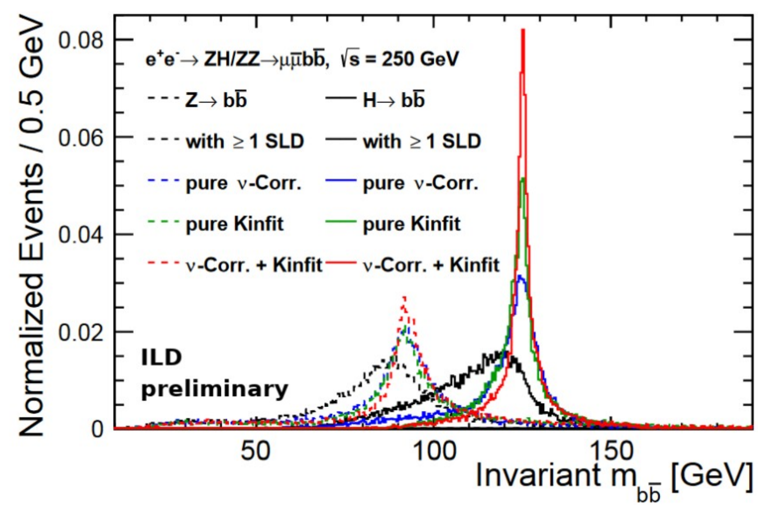


https://arxiv.org/abs/2212.07264

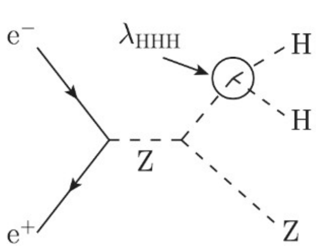
Higgs Self-Coupling: Neutrino Correction & ErrorFlow

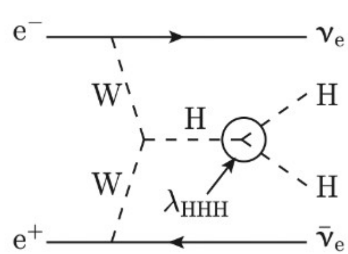
- Use kinematic fit to constrain event reconstruction (incl. inv. mass)
- New: with high-efficiency particle flow assess uncer-tainty on reconstructed parameters of each fit object (e.g. b-jets) individually and with full covariance matrix to optimise fit performance → ErrorFlow
- → Needs particle flow with individual assessment of each particle
- Delivers an excellent separation of Higgs peak from underlying Z bkg. in $b\bar{b}$ inv. mass, improves di-jet mass resolution by ~ factor 2
- Use for Higgs self-coupling in ZHH to suppress ZZH





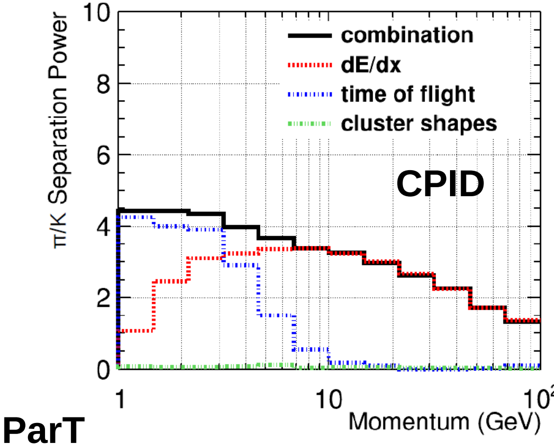
https://arxiv.org/abs/2212.07264





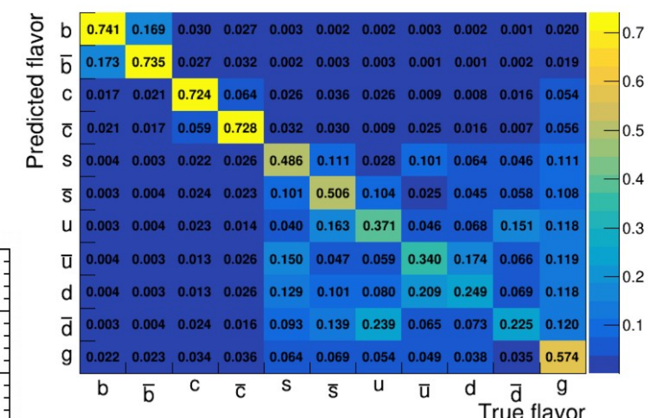
Higgs Self-Coupling: PID and Flavour Tagging

- New: Comprehensive PID (CPID) to combine different PID information in ILD – still with conservative dE/dx… fed into falvour tagger:



- New: neural-network-based flavour taggers, here: [Particle Transformer (ParT)](#)
  → 15% higher efficiency at same background rejection, enters in 3rd power in HH→bbbb

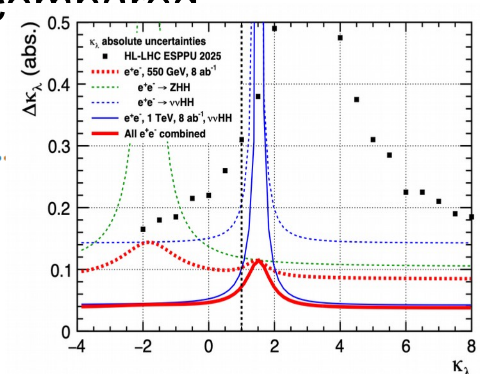
ParT



T. Suehara 2025

- Result: significantly improved prospects for Higgs self coupling measurements compared to previous study

B. Bliewert 2025



From $[\Delta\lambda/\lambda]_{SM} = 27\%$ **at ILC500 in the 2014 analysis to..**

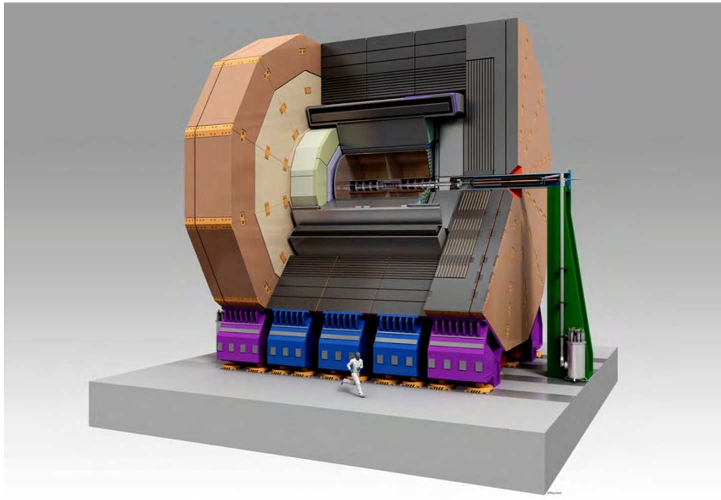
ILC550 @ $L_{int} = 4ab^{-1}$**:** $[\Delta\lambda/\lambda]_{SM} \rightarrow$ **15%**

LCF550 @ $L_{int} = 8ab^{-1}$**:** $[\Delta\lambda/\lambda]_{SM} \rightarrow$ **11%**

Conclusions - ILD

- ILD is a well established detector concept
- Work horse for many HTE factory analyses with full simulation
- Adaption to FCC-ee under active study
- A detector update seems to be due but work is person-power limited

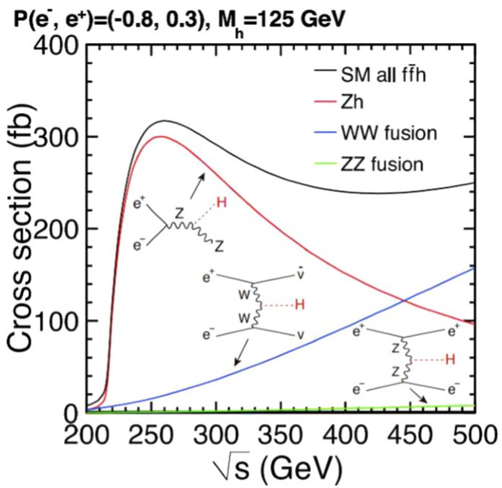
  → Many opportunities to bring in fresh ideas, new hardware proposals, reconstruction algorithms and physics analysis!

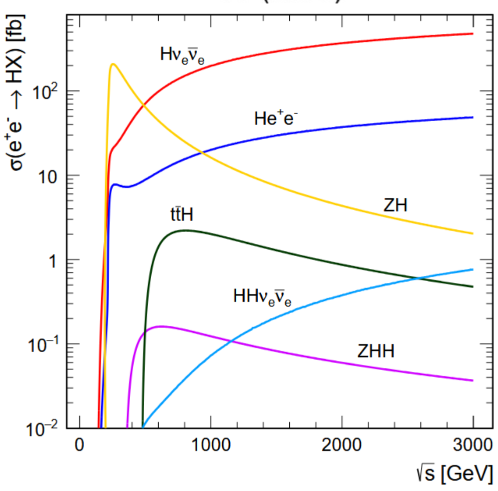


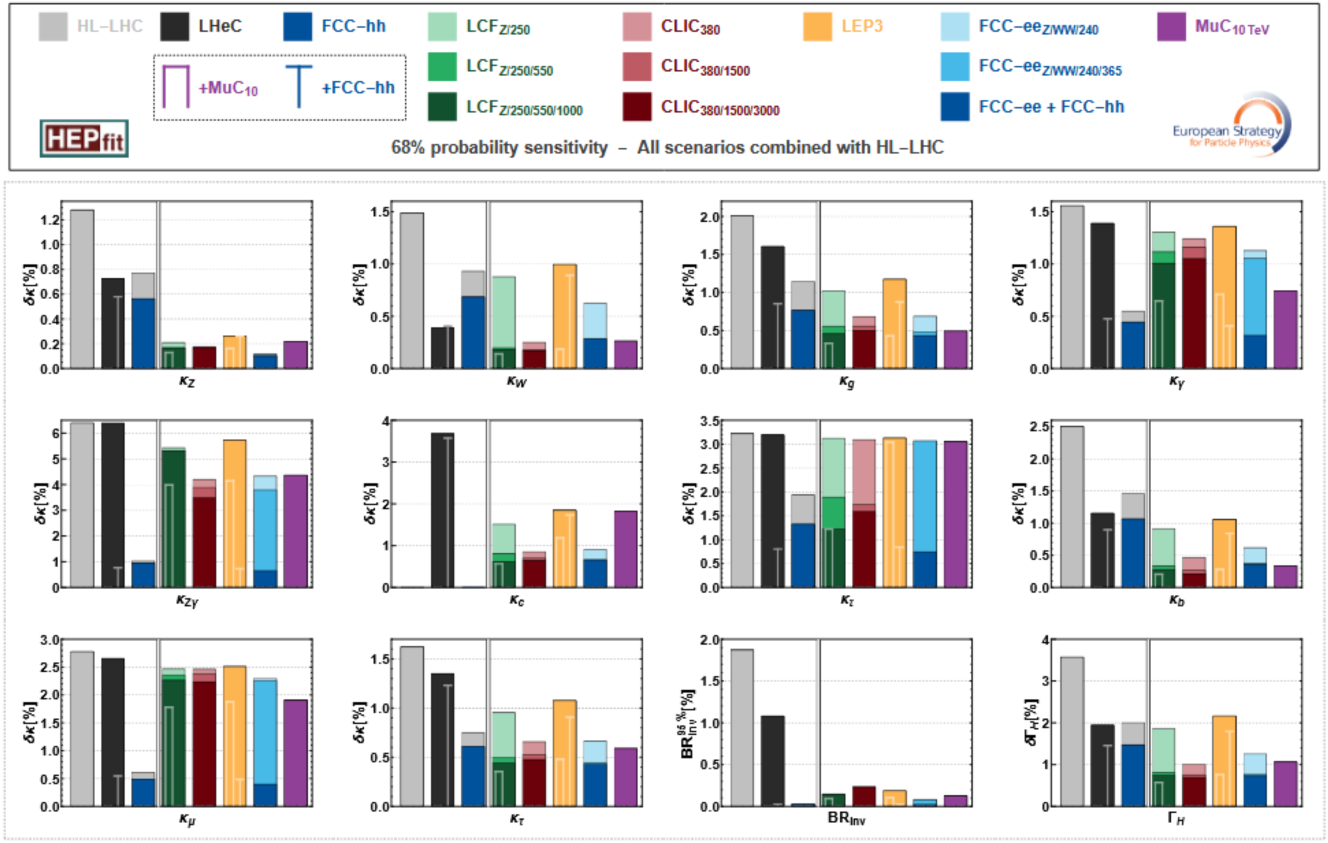
Backup

Physics Highlights: Higgs

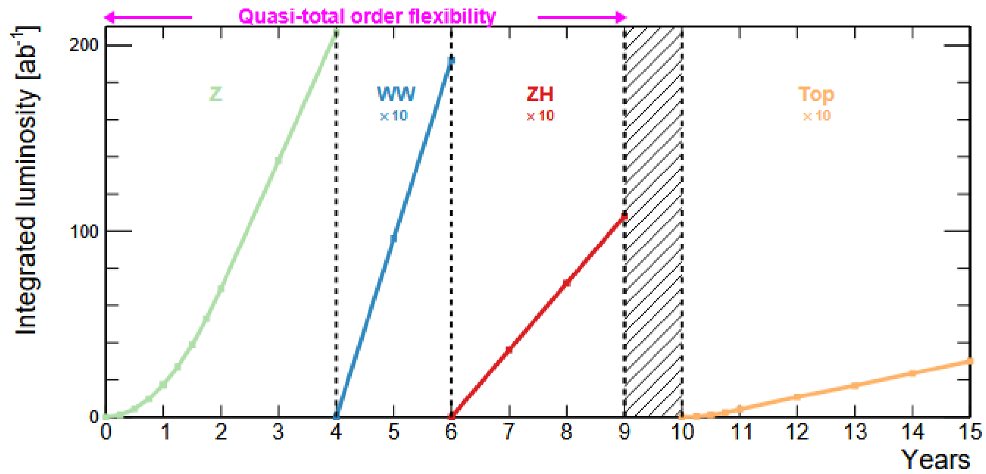
- Higgs is the primary target of any future flagship → Higgs factory!







- FCC-ee reference



Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	144	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated Lumi (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	$6\,10^{12}$ Z	$2.4\,10^{8}$ WW	$2.2\,10^{6}$ HZ + 65k WW $\rightarrow$ H	$2\,10^{6}\,t\bar{t}$ + 370k HZ + 92k WW $\rightarrow$ H	