Lecture 2: HL-LHC and Beyond

Sinead Farrington
STFC PPD / U. of Edinburgh

Beyond HL-LHC?

- **Experiment-led: notwithstanding huge theoretical developments both in precision and in model-building**
- **Future Colliders (FCC/ILC/CLiC/CepC/Muon/eh)**
  - Last European strategy update 2020 (paraphrase):

  1) next collider should be e+e-
  2) And we should work on magnet technologies to enable an energy frontier collider

  - Snowmass (US): supports activity to prepare for future energy frontier colliders; also supports “Higgs factory” from 2035.

LHeC

LHeC

Colli Outline

Log(ep→HX)

The *eh* programmes of LHC and FCC are designed to operate **synchronously** with *hh*

Interesting physics programme on its own and synergic:

- PDFs, strong coupling constant, low-x measurements
- **W mass, top mass, on other precision measurements in EWK and Top sectors**
- **Higgs measurements with additional sensitivity → precision higgs facility together with LHC**
- **Searches for new physics, including prompt and long-lived new scalars from Higgs, SUSY particles, neavy neutrinos, dark photons and axions**
- High-energy and high-density measurements of heavy ion collisions

→ the LHeC(FCC-eh) will contribute to the main objectives of the HL-LHC(FCC-hh), empowering its programme and bringing in more variety

Some key examples in the following

much more in CDR https://arxiv.org/abs/2007.14491, https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf, Eur. Phys. J. C (2022) 82:40, FCC CDR: EPJC 79, no. 6, 474 (2019) , Phys Eur. Phys. J. ST 228, no. 4, 755 (2019)

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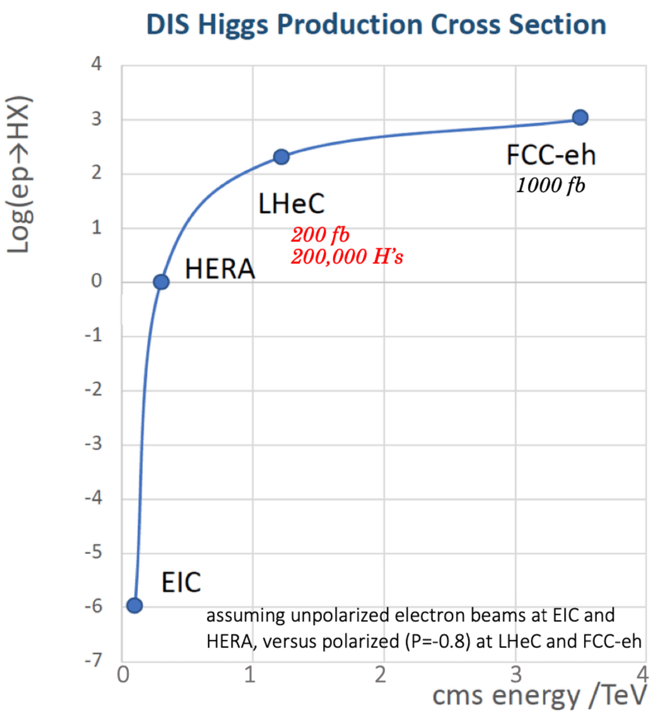
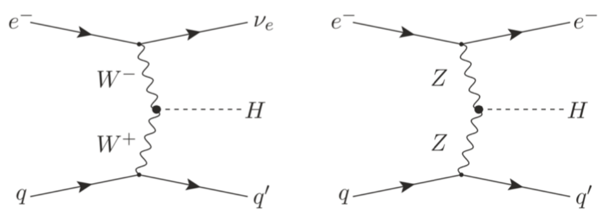
LHeC

Collision energy above the threshold for EW/Higgs/Top



= the real game change between HERA and the LHeC/FCC-eh



compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

at these energies and luminosities, interactions with all SM particles can be measured precisely

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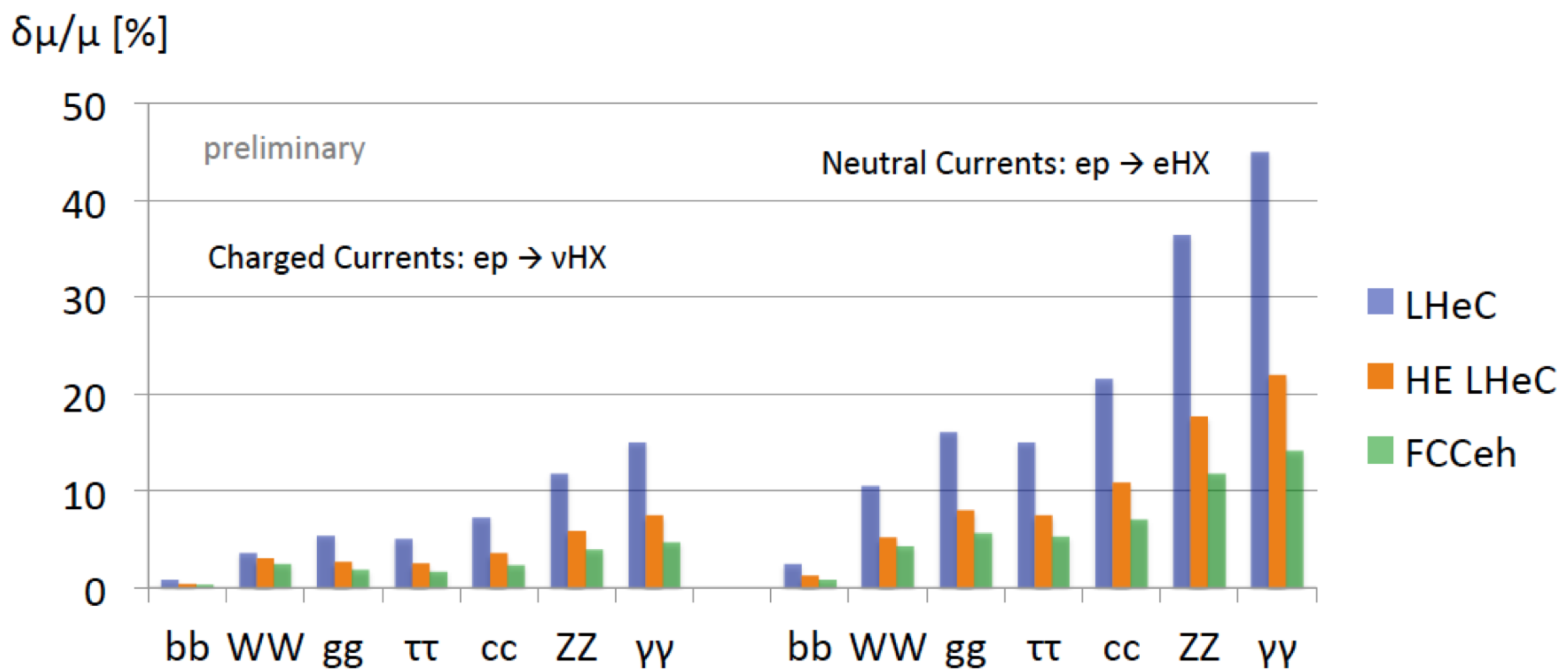
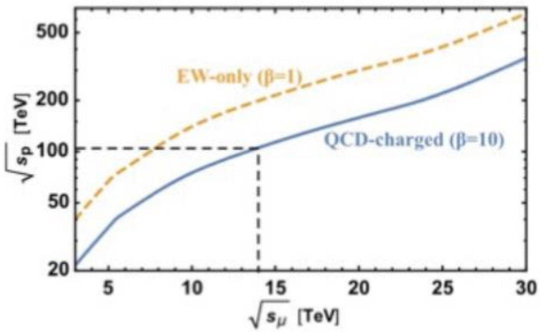
LHeC


δμ/μ [%]
50
40
30
20
10
0
preliminary
Neutral Currents: ep → eHX
Charged Currents: ep → νHX
bb WW gg ττ cc ZZ γγ
bb WW gg ττ cc ZZ γγ
LHeC
HE LHeC
FCCeh

Colliders

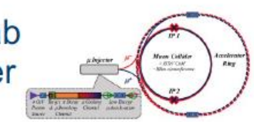
Hadron (pp)

Composite $\sqrt{\hat{s}} \ll \sqrt{s}$
"Messy" collisions



100 TeV pp ≈ 10-15 TeV μμ

Muon collider (Fermilab siting) ~ 10 TeV (bigger version to come)



Lepton

Fundamental $\sqrt{\hat{s}} \sim \sqrt{s}$ => Clean(er) collisions

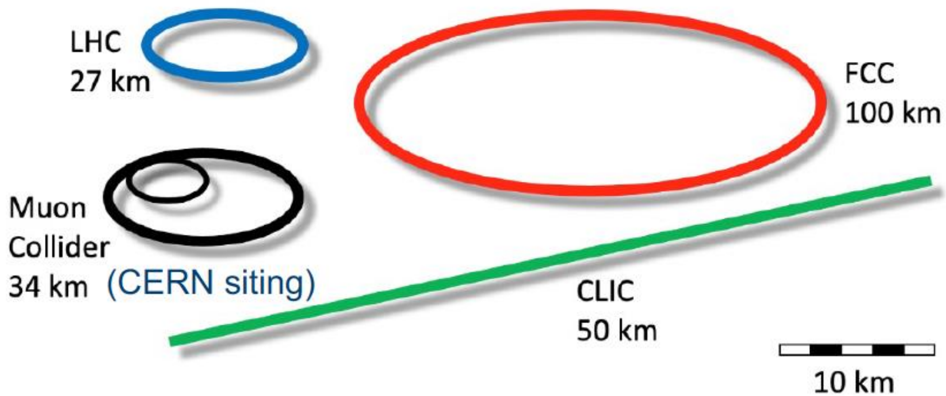
$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

e^+e^-

~100 km ring for ~240 GeV

$\mu^+\mu^-$

~10 km ring for ~10 TeV



Adapted from S. Williams

e^+e^-

The e+e- Physics Program

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
“boosted” B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau\nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau\tau$
$B \to K^* \nu\nu$
$B_s \to \varphi \nu\nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

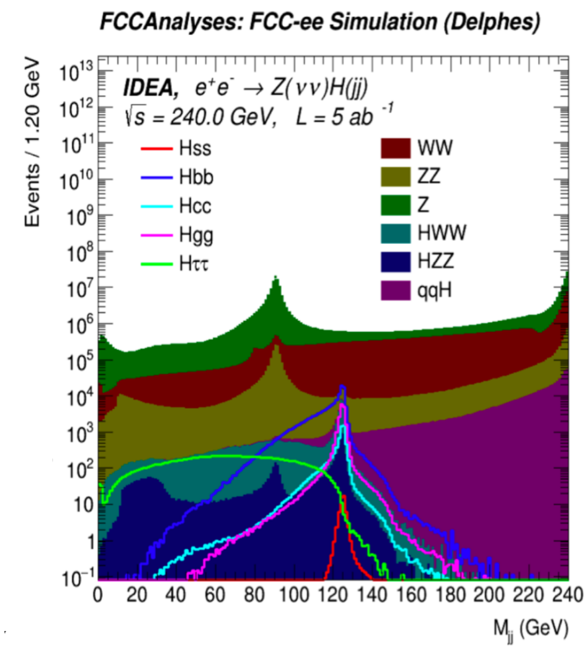
Axion Like Particles (ALPs)

Exotic Higgs decays

M. Selvaggi

e+e- Collider

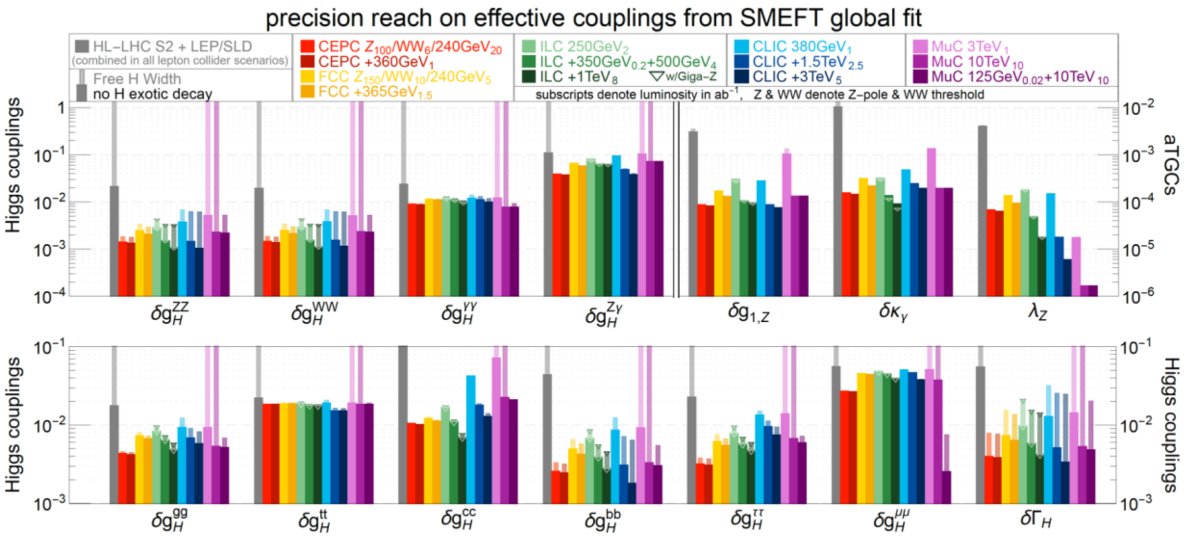
- **ILC/CLIC/FCCee/CepC/HALHF**
- **Rich program of Higgs/W/Z/Top physics**
- **Choice of CoM energy**
- **Higgs width, Higgs coupling to second generation**
  - (What about first generation?)
  - GigaZ program



- **Linear collider: polarized beams, lower instantaneous luminosity, upgradeable with length extension**
- **Circular collider: unpolarized beams but higher instantaneous luminosity, not so easily upgraded (though can step through energies well). Reuse the tunnel for a high energy proton-proton collider**

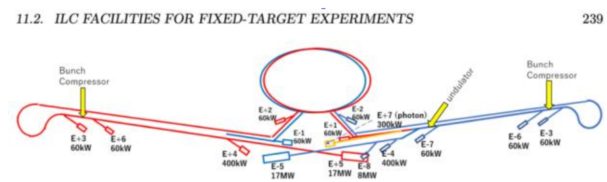
e$^+$e$^-$ Science

arXiv:2206.08326



A wide programme:

- ILCX – e.g. beam-dump experiments, dark sector physics, light dark matter,



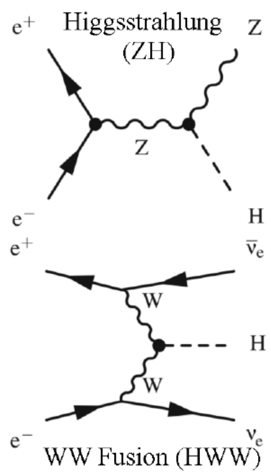
e+e- colliders show very comparable performance for single-Higgs program, despite quite different assumed integrated luminosities => longitudinal beam polarization an important factor for LCs

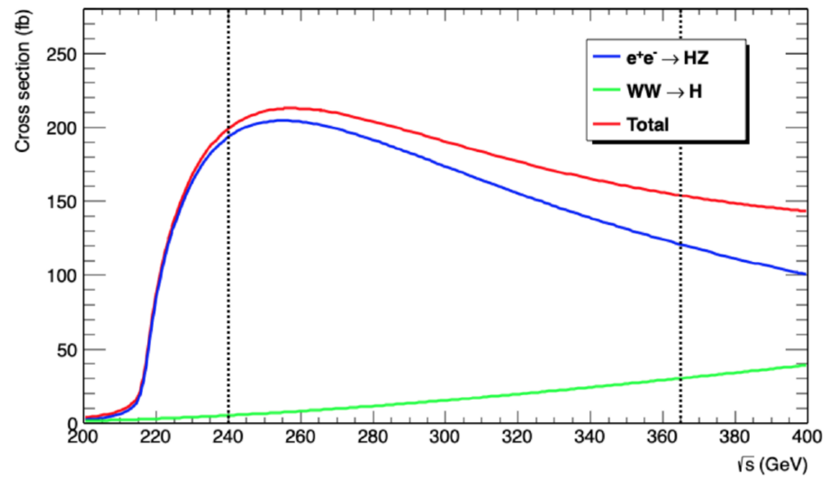
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

- **Higher energies:** Improved Higgs, extended models, top well above threshold with polarization, new physics searches and measurements
- Z running also possible

S. Stapnes

Higgs Physics in e+e-



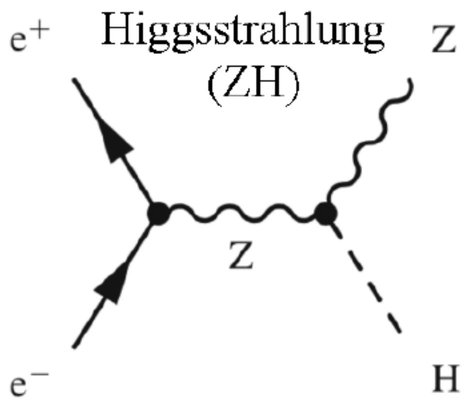


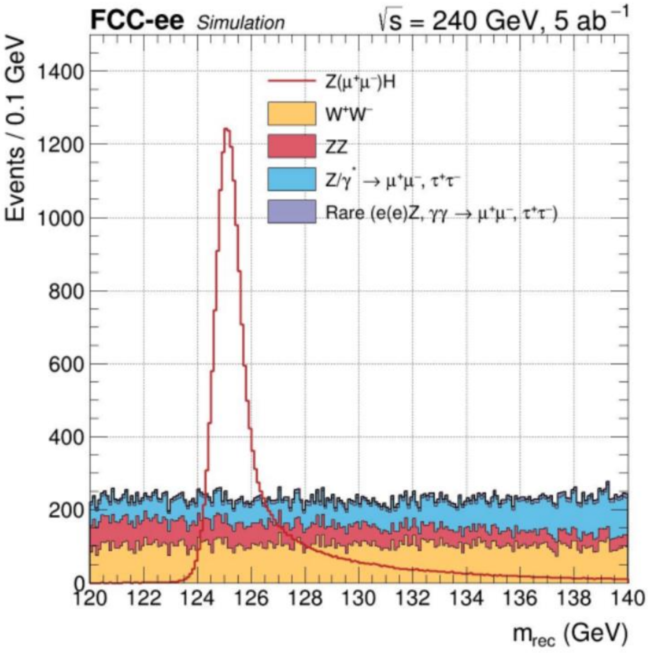
- >1 million ZH events
- ~100000 WW fusion

- Large rates, no pile-up or underlying event
- No QCD background

- Some model-dependence can be removed as a result and because of the possibility to measure absolute rates

Higgs Physics in e+e-





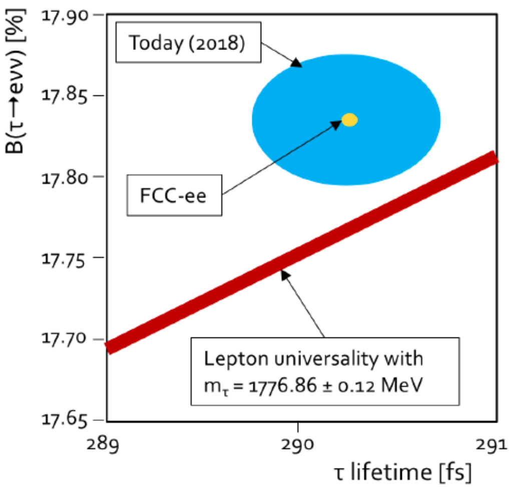
- Z observed through leptonic decay
- Recoil mass off the Higgs can be reconstructed
- Precise ZH production cross-section
- Therefore quasi model-independent extraction of the Higgs total width

Higgs Physics in e+e-

- 5×10^{12} Z bosons at Z pole
  - EW precision program
  - Sensitivity for BSM effects
  - Flavour physics

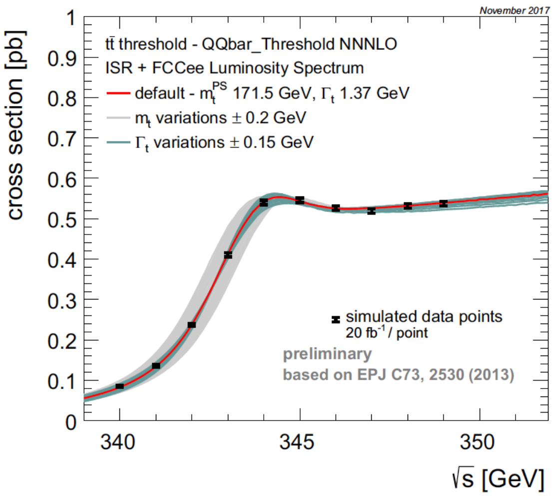
Quantity	current	ILC250	ILC-GigaZ	FCC-ee
$\Delta\alpha(m_Z)^{-1}$ ($\times10^3$)	17.8*	17.8*		3.8 (1.2)
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)
Δm_H (MeV)	170*	14		2.5 (2)
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)
ΔA_e ($\times10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)
ΔA_μ ($\times10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)
ΔA_τ ($\times10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)
ΔA_b ($\times10^5$)	2000*	53 (35)	9 (50)	2.4 (21)
ΔA_c ($\times10^5$)	2700*	140 (25)	20 (37)	20 (15)

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150



Top Physics in e+e-

- $t\bar{t}$ threshold scan will enable most precise measurements of top-quark mass and width.
- Precise measurements of top quark EW couplings provide essential input to precise extraction of top yukawa at FCC-hh.

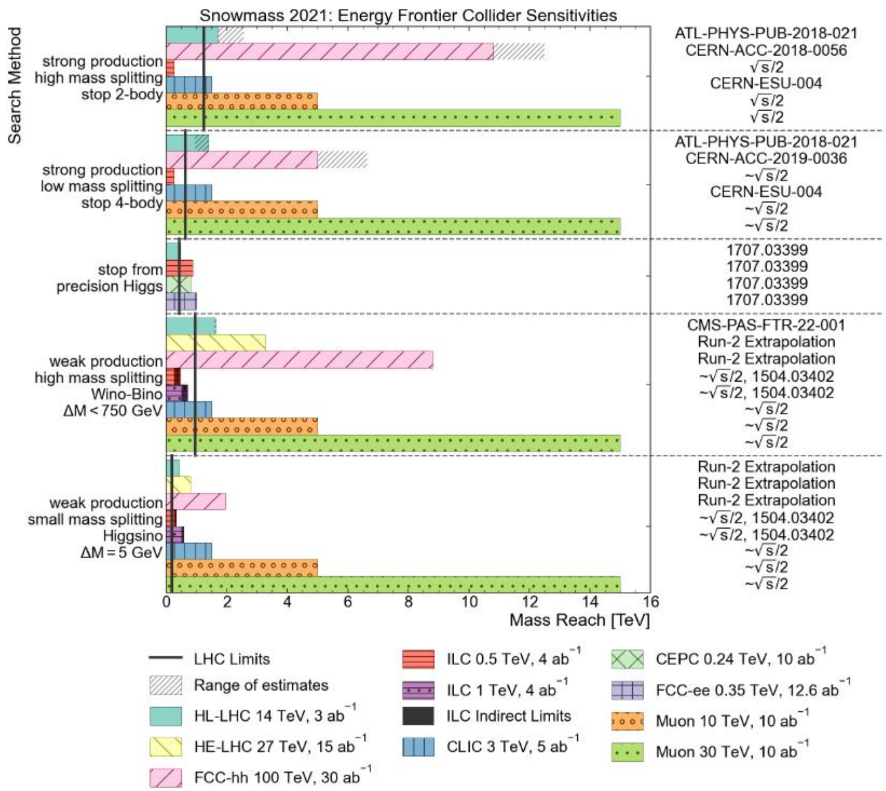


Electroweak Precision in e^+e^-

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e $(\times 10^5)$	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ $(\times 10^5)$	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ $(\times 10^5)$	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b $(\times 10^5)$	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c $(\times 10^5)$	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\mathrm{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e $(\times 10^3)$	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ $(\times 10^3)$	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ $(\times 10^3)$	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b $(\times 10^3)$	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
$\delta R_c(\times 10^3)$	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

BSM sensitivity

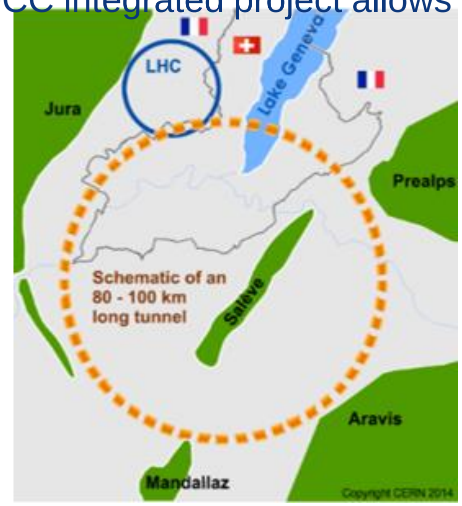
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		2 M_{top}		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

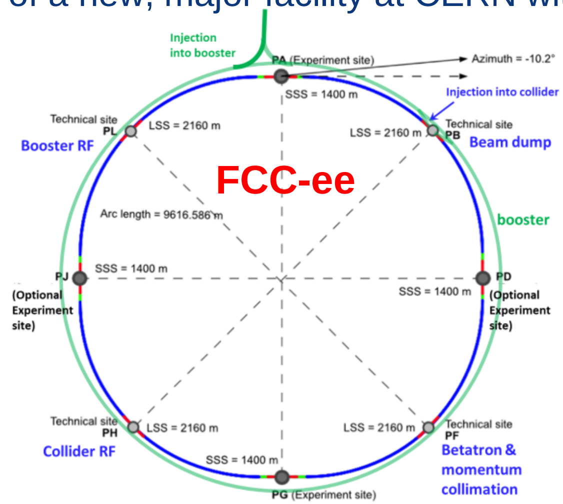


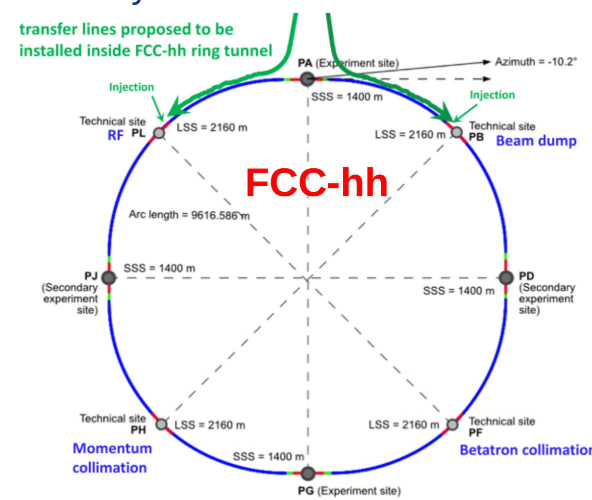
FCC Integrated Programme

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC





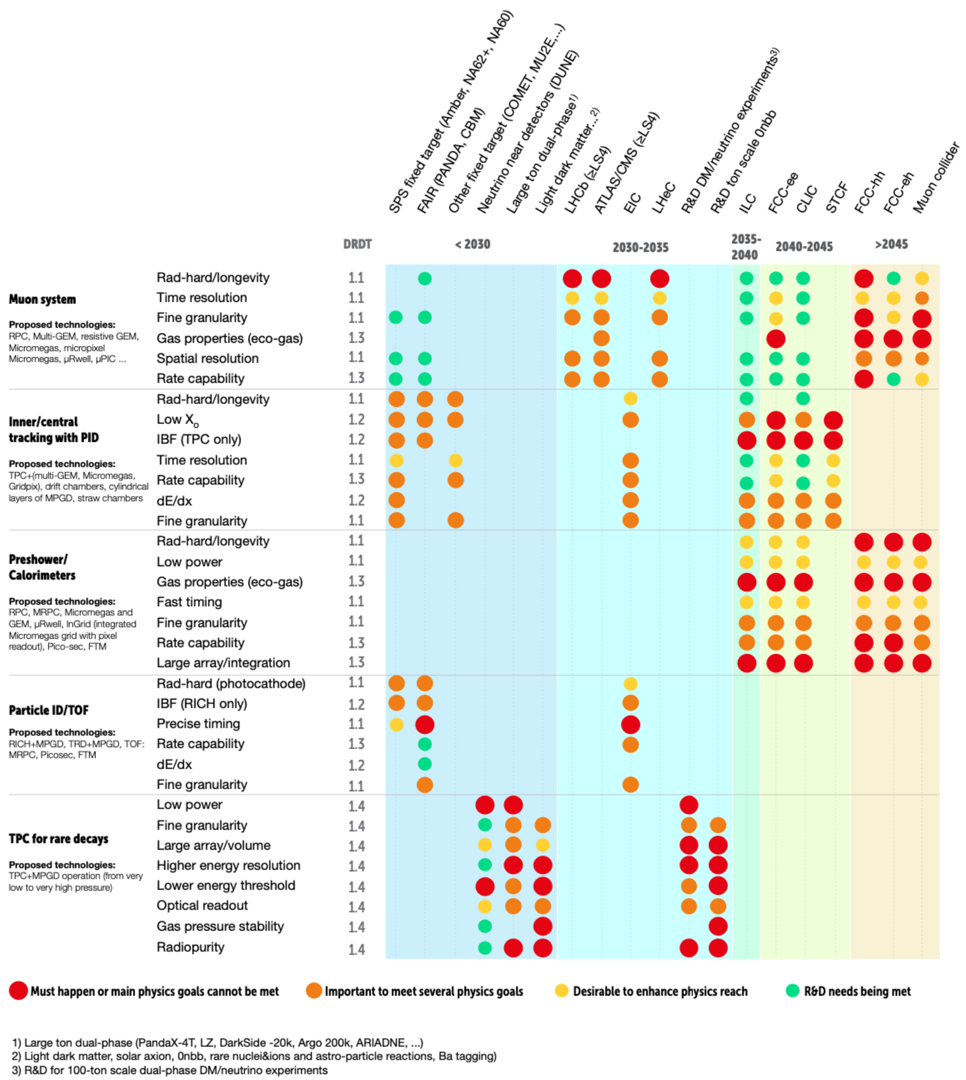


2020 - 2046 | 2048 - 2063 | 2074 -

Higgs self-coupling determined to 5% — F. Zimmerman

What about Detector Technology

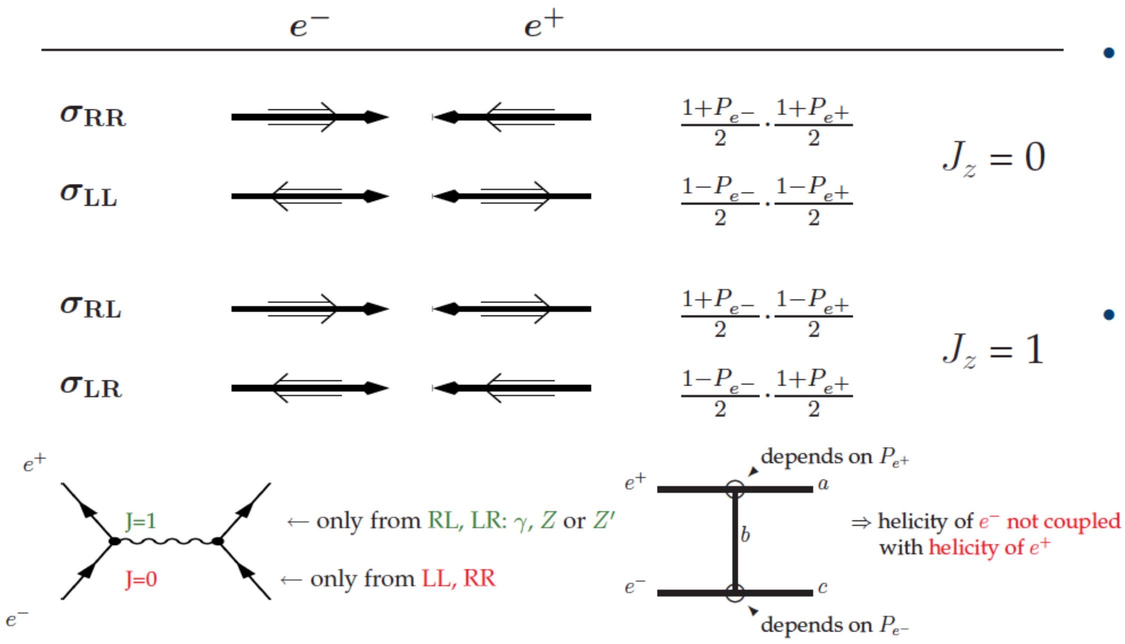
CERN-ESU-017



Linear Colliders

(Polarised Beams)

One advantage of linear e^+e^- colliders is the opportunity to exploit beam polarization which can benefit precision SM measurements and BSM searches. Baseline design of ILC assumes 80% longitudinal polarization of electron beam and 30% polarization of positron beam.



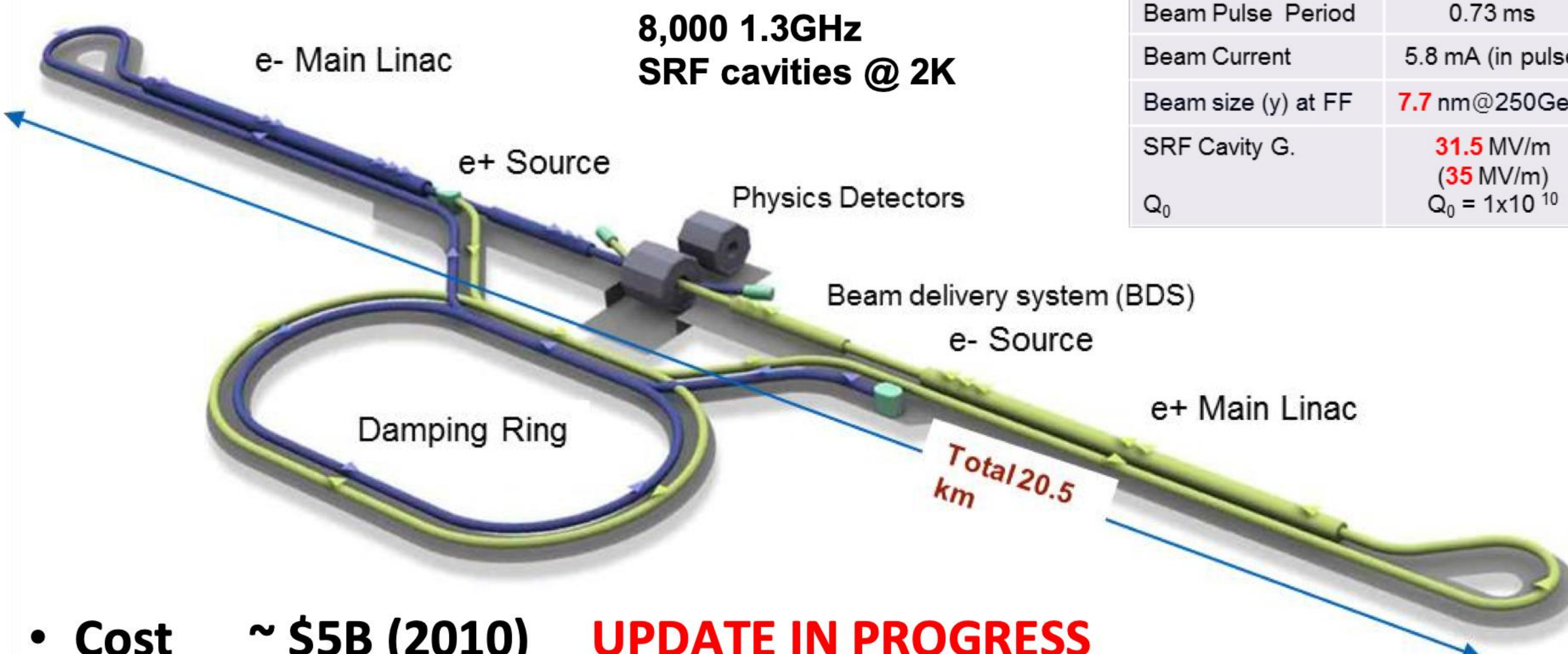
- Enhance cross-section for SM vector-boson production OR suppress backgrounds in search for scalars.
- For t/u-channel exchanges, helicities of incoming beams directly coupled to helicities of outgoing particles.

S. Williams

ILC

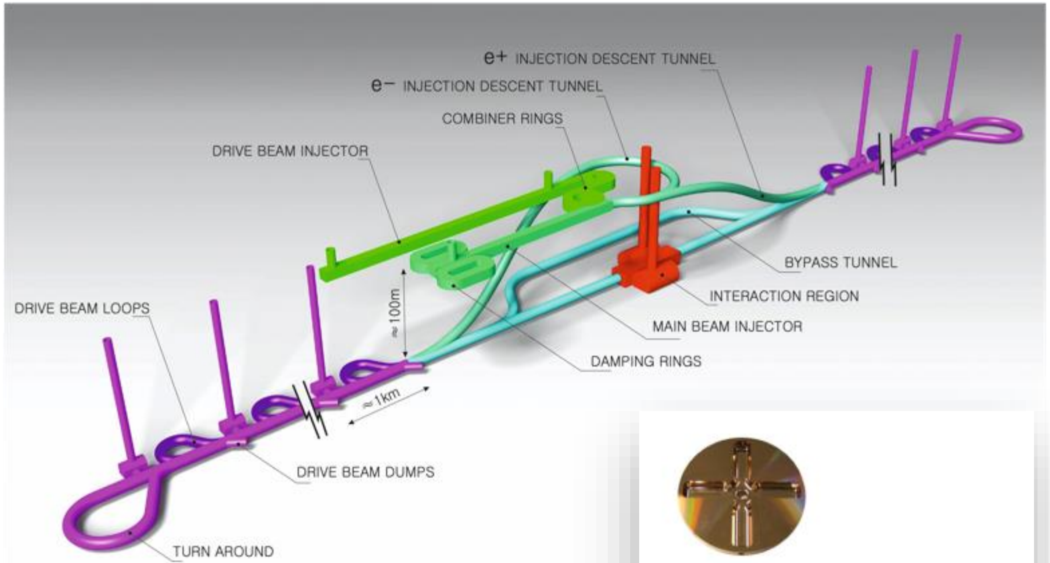
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	$1.35 \times 10^{34}\ cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$

8,000 1.3GHz SRF cavities @ 2K

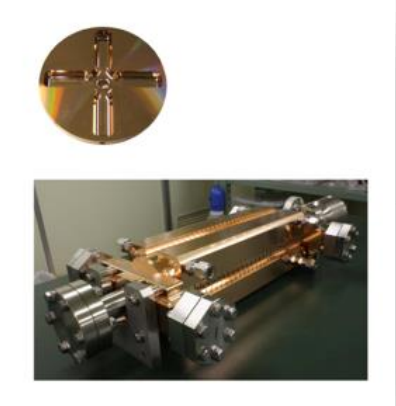


- **Cost ~ $5B (2010)** **UPDATE IN PROGRESS**
- **Power ~ 111 MW** **FOR EPPSU MARCH 25**

The Compact Linear Collider (CLIC)



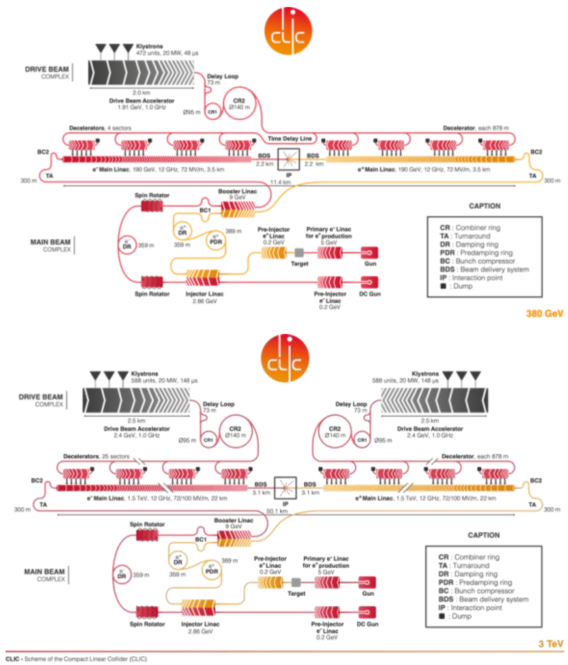
Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

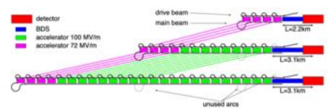


- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- 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.

S. Stapnes

CLIC to 3 TeV





Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV

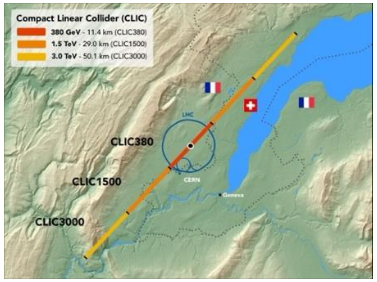


Table 1.1: Key parameters of the CLIC energy stages.

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

The CLIC accelerator studies are mature:

- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

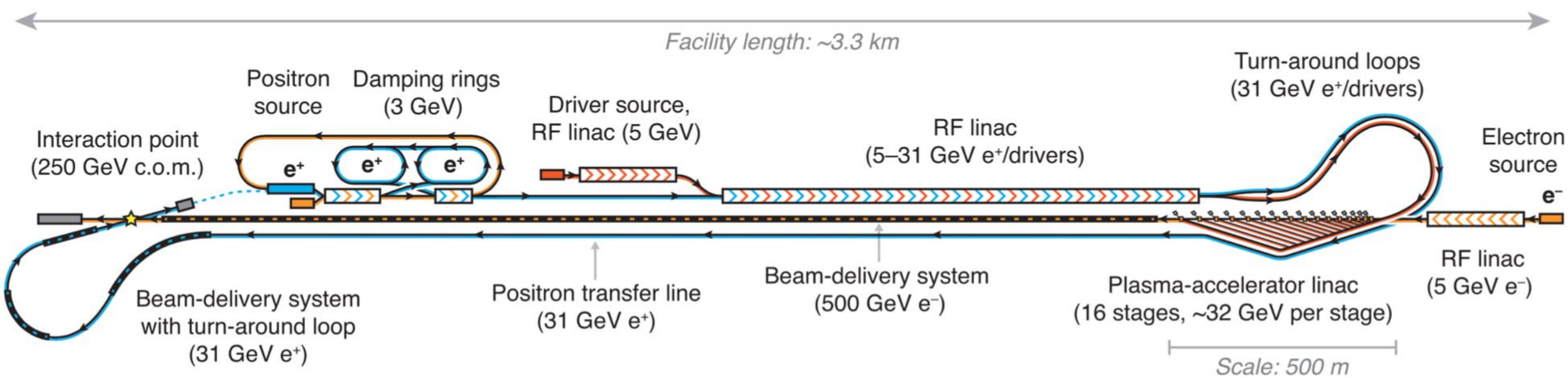
S. Stapnes

New J. Phys. 25 093037 (2023)

HALHF

Hybrid, Asymmetric, Linear Higgs Factory

- based on plasma-wakefield (electrons) and radio-frequency acceleration (positrons)
- Plasma-wakefield aim: orders of magnitude higher accelerating gradients



- Smaller, cheaper than other linear colliders
- Has technological challenges to overcome, and demonstrate
- Novel technology – scalable
- Will yield asymmetric collisions
  - Aim for same program as ILC/CLIC
  - Could be seen as an upgrade to ILC/CLIC

Future Circular Collider

FUTURE CIRCULAR COLLIDER

European Strategy for Particle Physics

2013 Update of European Strategy for Particle Physics:

"***CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines***."

→ FCC Conceptual Design Reports (2018/19)

Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

2020 Update of European Strategy for Particle Physics:

"***Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage***."

F. Zimmerman

FCC Feasibility Study (2021-2025): high-level objectives

- demonstration of the **geological, technical, environmental and administrative feasibility of the tunnel and surface areas** and optimisation of **placement and layout of the ring** and related infrastructure;
- pursuit, **together with the Host States, of the preparatory administrative processes required for a potential project approval** to identify and remove any showstopper;
- **optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies**;
- elaboration of a **sustainable operational model for the colliders and experiments in terms of human and financial resource needs**, as well as **environmental aspects and energy efficiency**;
- development of a **consolidated cost estimate**, as well as the **funding and organisational models** needed to enable the project's technical design completion, implementation and operation;
- **identification of substantial resources from outside CERN's budget** for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- **consolidation of the physics case and detector concepts** for both colliders.

Results will be summarised in a Feasibility Study Report to be released at end 2025

F. Gianotti

F. Zimmerman

Why we need Cern's €16bn atom smasher

The Future Circular Collider could unlock some of the secrets of the universe

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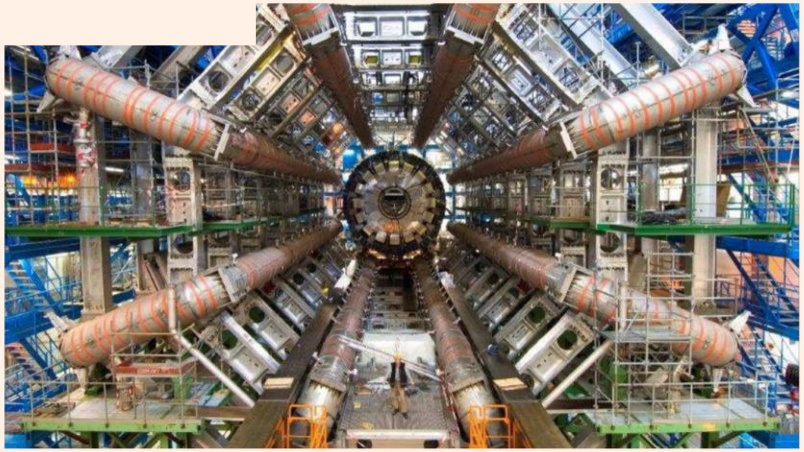
But the promise of technological spin-offs is very much a secondary justification. The reason to invest in the FCC is to gain fundamental knowledge about the way the universe works. This will be rewarding in a cultural or philosophical sense. It may also pay off practically in the far future through applications we cannot foresee today — just as 21st-century technology in fields from computing to satellite navigation depends on an understanding of quantum theory and relativity, whose foundations were laid by pioneering physicists almost a century ago.



ATLAS is one of two general-purpose detectors at the Large Hadron Collider © CERN

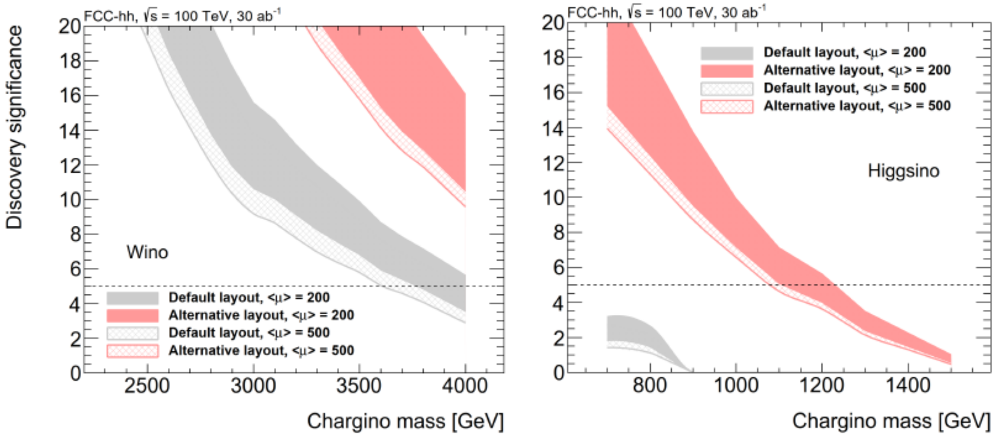
The editorial board FEBRUARY 9 2024 121

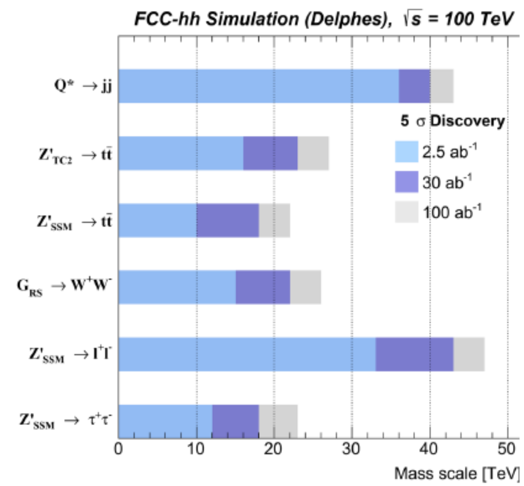
Multi-TeV Collisions
1) FCChh
2) Muon Collider

Hadron Collider

- Rich program of Higgs/W/Z/Top physics
- Search capability
- Probe up to ~40 TeV directly
- Higgs self-coupling (only a ~1-3 TeV scale ee collider can compete)
- Technologically challenging: accelerator magnets, detector occupancy and readout – see HL-LHC detectors, pileup of ~1000 vs 200 (HL-LHC) vs 60 (LHC)

FCChh New physics





Cover full mass range for discovery of WIMP dark matter candidates

Substantial discovery reach for heavy resonances

Formidable challenges:

- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

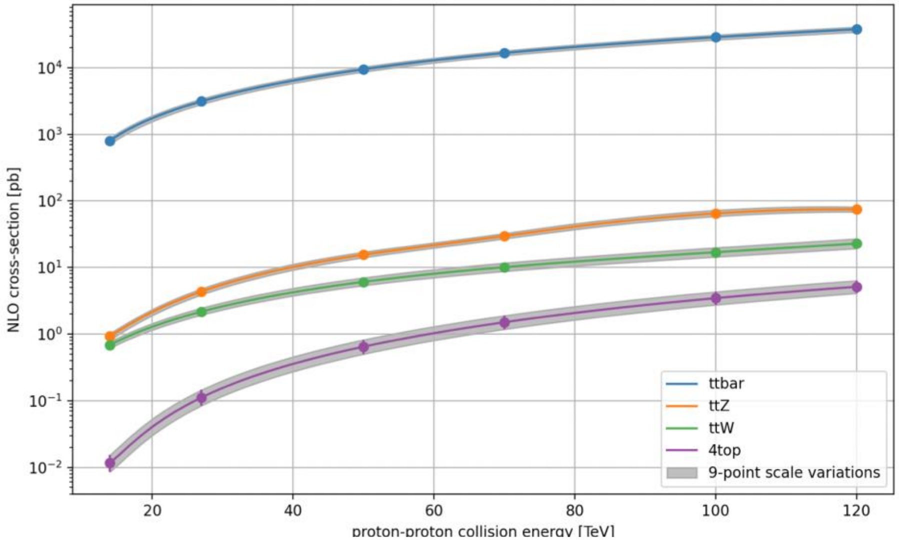
Higgs Self-Coupling

- **Obtainable from hadron collider or from highly upgraded linear colliders**

collider	Indirect-h	hh	combined
HL-LHC [40]	100-200%	50%	50%
ILC_{250}/C^3-250 [31, 33]	49%	–	49%
ILC_{500}/C^3-550 [31, 33]	38%	20%	20%
ILC_{1000}/C^3-1000 [31, 33]	36%	10%	10%
$CLIC_{380}$ [35]	50%	–	50%
$CLIC_{1500}$ [35]	49%	36%	29%
$CLIC_{3000}$ [35]	49%	9%	9%
FCC-ee [36]	33%	–	33%
FCC-ee (4 IPs) [36]	24%	–	24%
(100 TeV) FCC-hh [41]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [39]	-	15-30%	15-30%
μ(10 TeV) [39]	-	4%	4%

Study of FCChh energies

J. Howarth



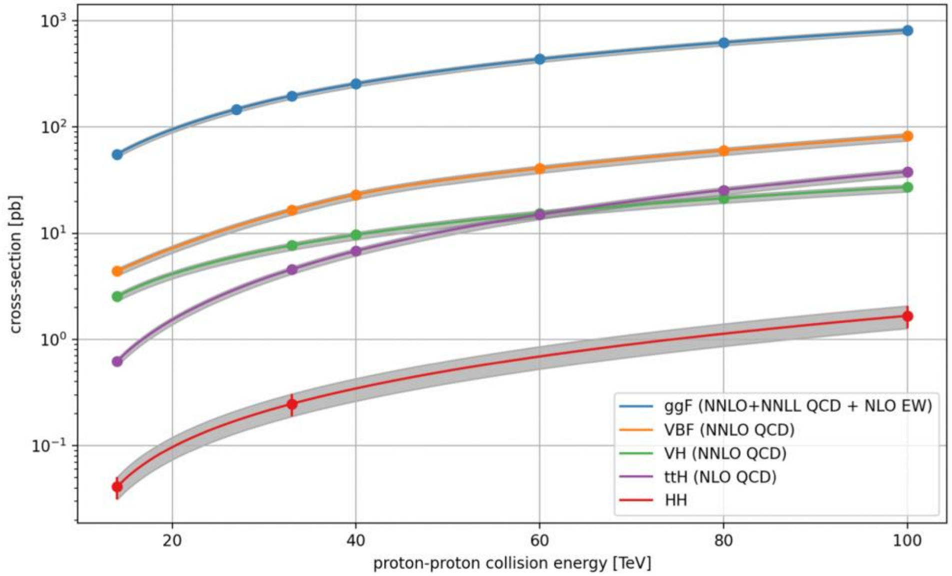
Energy for order of magnitude increase in xsec, relative to LHC:

$t\bar{t}$: 50 TeV (FCC$_{hh}$)

$t\bar{t}Z$: 50 TeV (FCC$_{hh}$)

$t\bar{t}W$: 70 TeV (FCC$_{hh}$)

$t\bar{t}t\bar{t}$: 27 TeV (HE-LHC)
2x 70 TeV (FCC$_{hh}$)



Energy for order of magnitude increase in xsec, relative to LHC:

ggF: 70 TeV (FCC$_{hh}$)

VBF: 65 TeV (FCC$_{hh}$)

VH: 80 TeV (FCC$_{hh}$)

$t\bar{t}H$: 35 TeV (HE-LHC)

HH: 45 TeV (FCC$_{hh}$)

FCChh CDR Higgs Couplings

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\rightarrow \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)\mathrm{B}(\mathrm{H}\rightarrow\mathrm{b\bar{b}})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu)/\mathrm{B}(\mathrm{H}\rightarrow 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mathrm{e}2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\rightarrow\gamma\gamma)/\mathrm{B}(\mathrm{H}\rightarrow 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H}\rightarrow\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\rightarrow\mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(\mathrm{t\bar{t}H}) \times \mathrm{B}(\mathrm{H}\rightarrow \mathrm{b\bar{b}})/\sigma(\mathrm{t\bar{t}Z}) \times \mathrm{B}(\mathrm{Z}\rightarrow \mathrm{b\bar{b}})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\rightarrow \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

CDR=Conceptual Design Report

Experiment/Theory exchange

- Whatever is built next requires joined up approach to understanding where limiting systematics will be
- Calculating extreme precision is less useful where experimental uncertainties are going to be large

Magnets

S. Gibson

- Limits: Critical current, Critical B field, Critical temperature
  - remember: typically coil-dominated magnets
- Materials: NbTi (LHC current), Nb_3Sn (HL-LHC, FCC-hh)
  - Nb_3Sn supports ~2x maximum B, but more costly

FUTURE CIRCULAR COLLIDER

R&D on HTS high-field magnets

- **High Temperature Superconductors**: an **enabling technology** for high field (≥ 15 T) magnets - a **sustainable opportunity** for future accelerator technology
- **Focus** of the LDG Accelerator R&D Roadmap is presently on **REBCO**, but alternative options are also considered (**IBS** as in China)
- To exploit the potential, a rigorous **R&D program** is required
- **R&D on conductor** is essential for subsequent successful implementation in HTS magnets. This requires:
  - reaching **controlled**, **homogeneous** and **reproducible properties** on industrially available conductor;
  - achieving **long** (~ 1 km) **lengths** of industrially available conductor;
  - **innovation** via development of **high-current cables**;
  - validation of the technology via **a parallel programme** of small **demonstrator coils**; this is needed to provide feedback to conductor R&D and to support/launch magnet design and development

Michael Benedikt and Frank Zimmermann, CERN

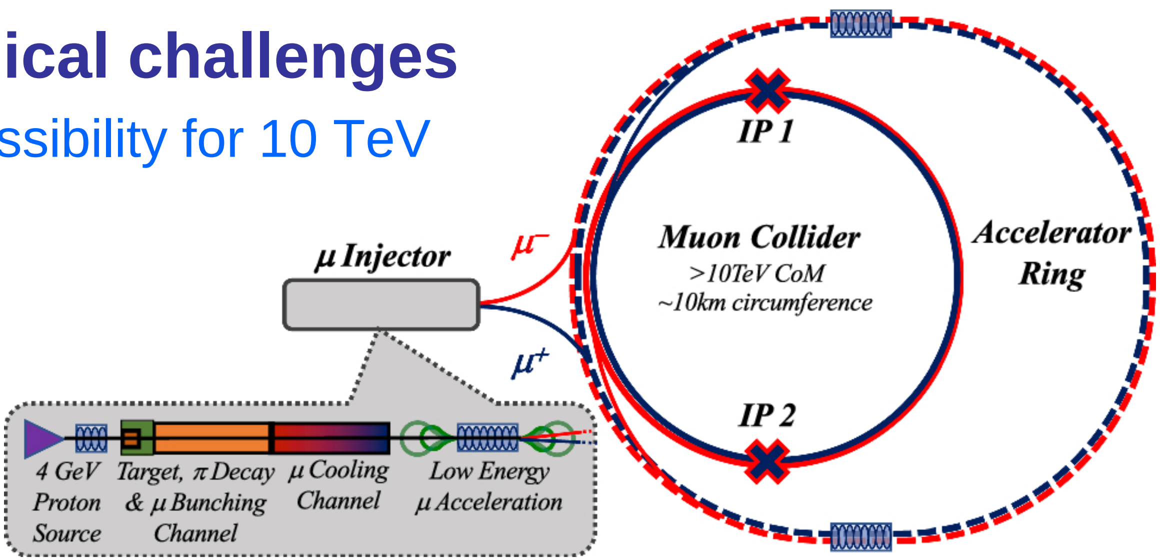
Muon Collider

Muon Collider Technology

- **Synchroton radiation 2Bn times less than electron**

$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

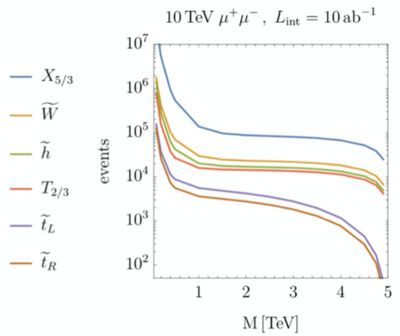
- **However muon lifetime is only 2.2μs**
- **Smaller energy consumption than ee, smaller footprint**
- **Looking towards demonstrator facility**
- **Significant technical challenges**
  - But an exciting possibility for 10 TeV

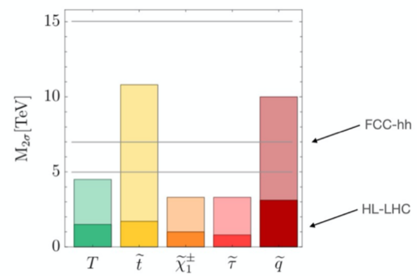


A unique facility

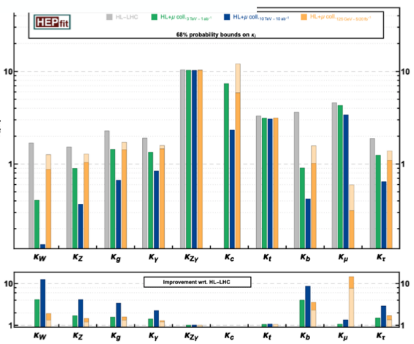
To give insight on fundamental questions:

* Higgs potential
* Precision H couplings



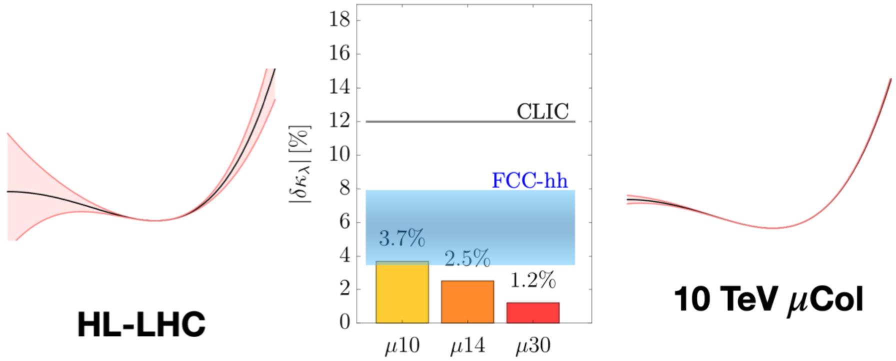


* Very high energy-scale BSM
* And many many more!



Jorge De Blas et al.

High energy lets us finally improve on Higgs Potential



Note that we can get to threshold for EW phase transition at EW scale with FCC-hh and μCol

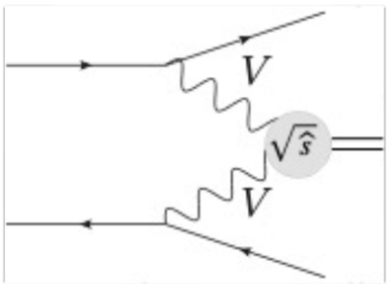
Patrick Meade P5 BNL Town Hall Meeting

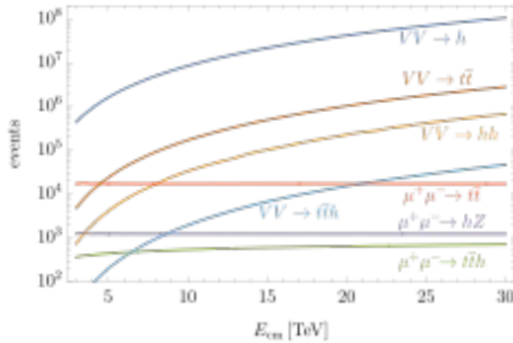
κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	1.4
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

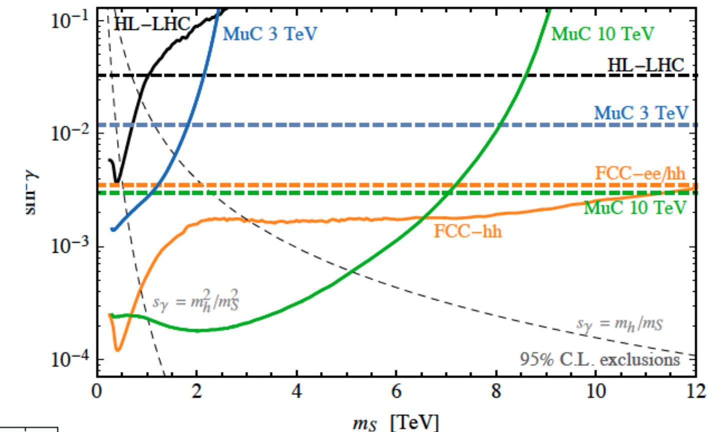
Matthew Forslund and Patrick Meade

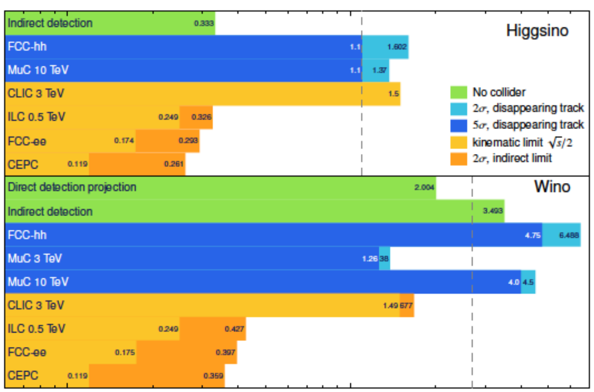
Muon Collider

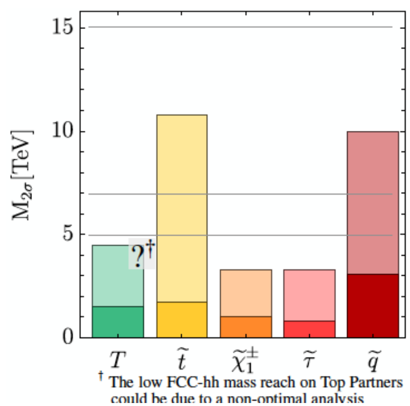
A high-energy muon collider would also be a vector-boson collider=> direct BSM and providing "Higgs factory" (see next slide)





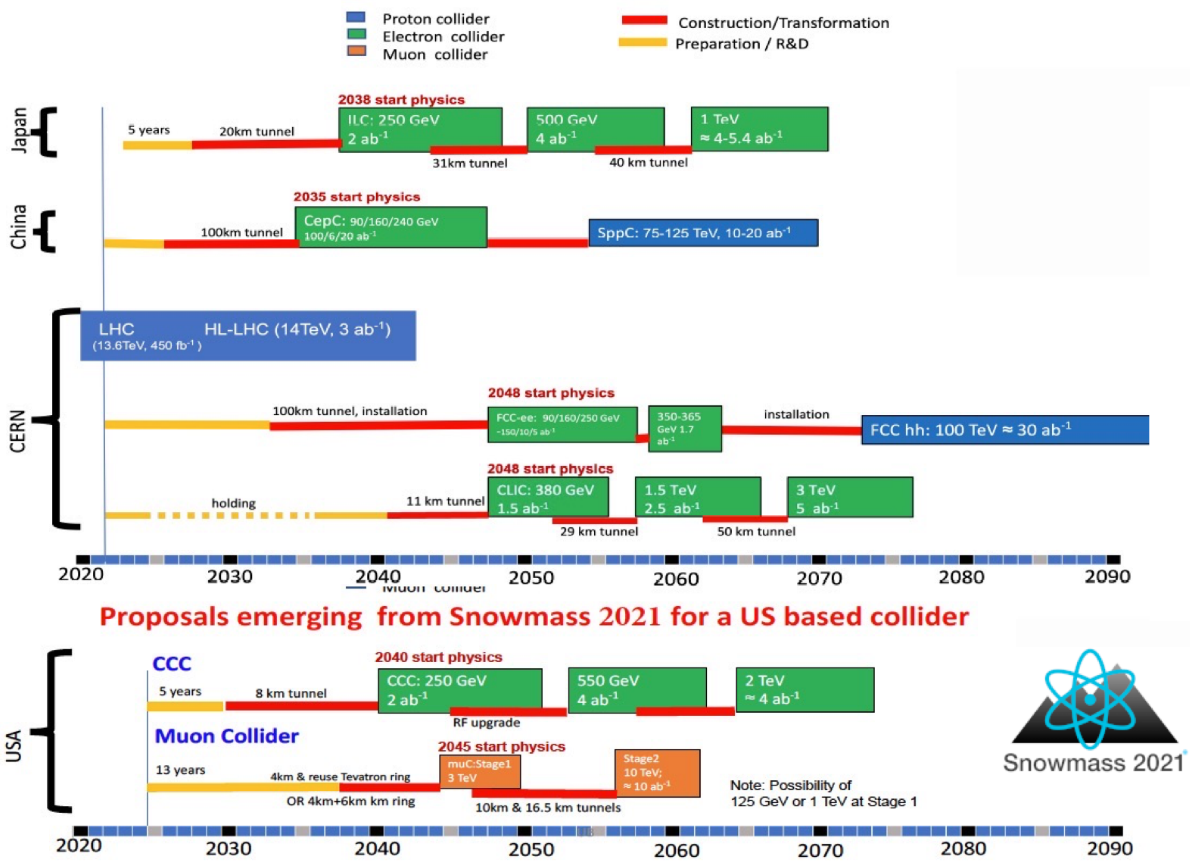


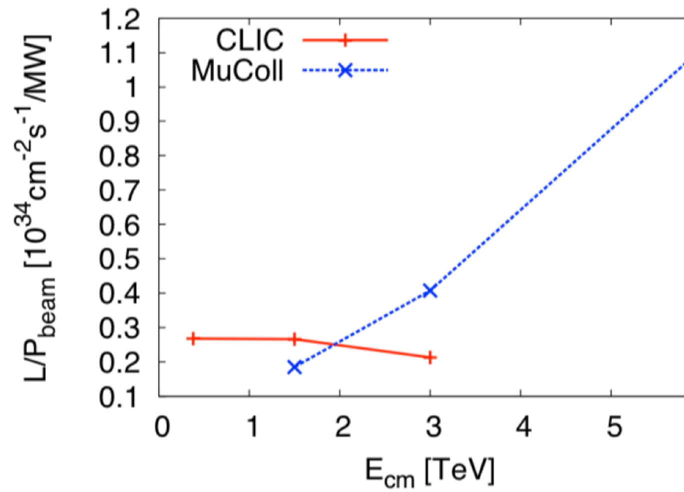




Above: exclusion for scalar singlet mixing with Higgs
Left: comparison of HL-LHC (solid), FCC (shaded) and tentative muon collider reach at 10, 14, 30 TeV (lines)

Future Collider Timelines?





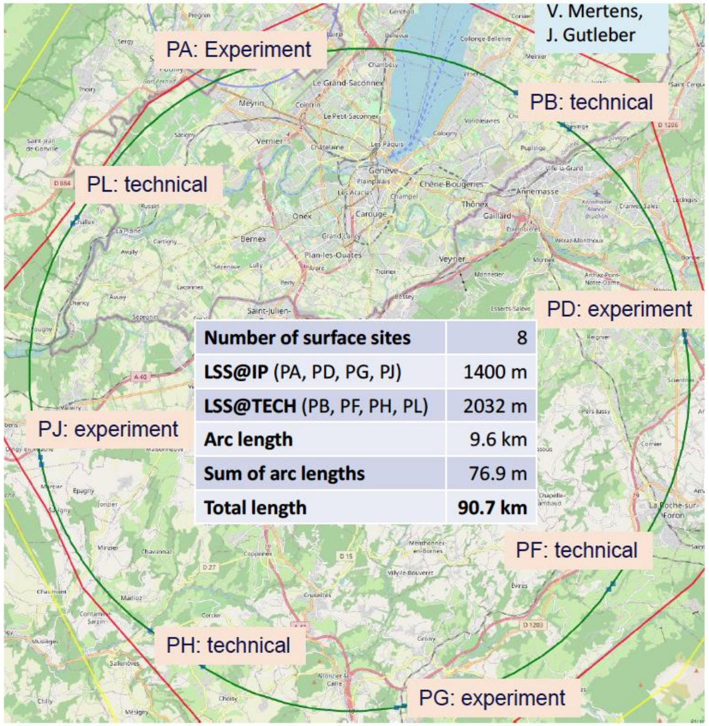
FCC Feasibility Study

- **Advanced**

Status of FCC feasibility study: mid-term review

For more details see slides by S. Williams at CEPC workshop.

- Mid-term review just completed (approval by council soon).
- Key updates:
  - Choice of ring placement and 4 IPs (higher statistics).
  - Adaptation of accelerator RF/ optics for new placement (details in backup).
- Significant R+D ongoing to improve energy efficiency (including HTS).



Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

Beyond…

- **Beyond Colliders**
  - SHIP will happen – sensitivity to many BSM signatures
  - Dark matter experiments will happen
  - Quantum technology is there
    - And ripe for a strategic internationalized set of experiments
  - DUNE/HyperK are underconstruction
  - Muon experiments…
  - …
- **The field has a multi-pronged approach to understanding the nature of fundamental interactions**
  - We are well-equipped to delve deeper into how these work, and a complementary set of approaches best builds-on (and preserves) the knowledge we have achieved to date

What we don't know

- Nature of neutrinos
- Mass hierarchy of neutrinos
- CP violation (how did the universe come to be matter-dominated?)
- Is there only one Higgs boson?
- Is supersymmetry realised in nature?
- Why three generations?
- Nature of dark matter
- …which questions to ask?

Discussion questions

- Which parameter do you most want to measure and why?
- Which three?