Progress with the European Strategy Update presented @ Higgs couplings 2019, Oxford

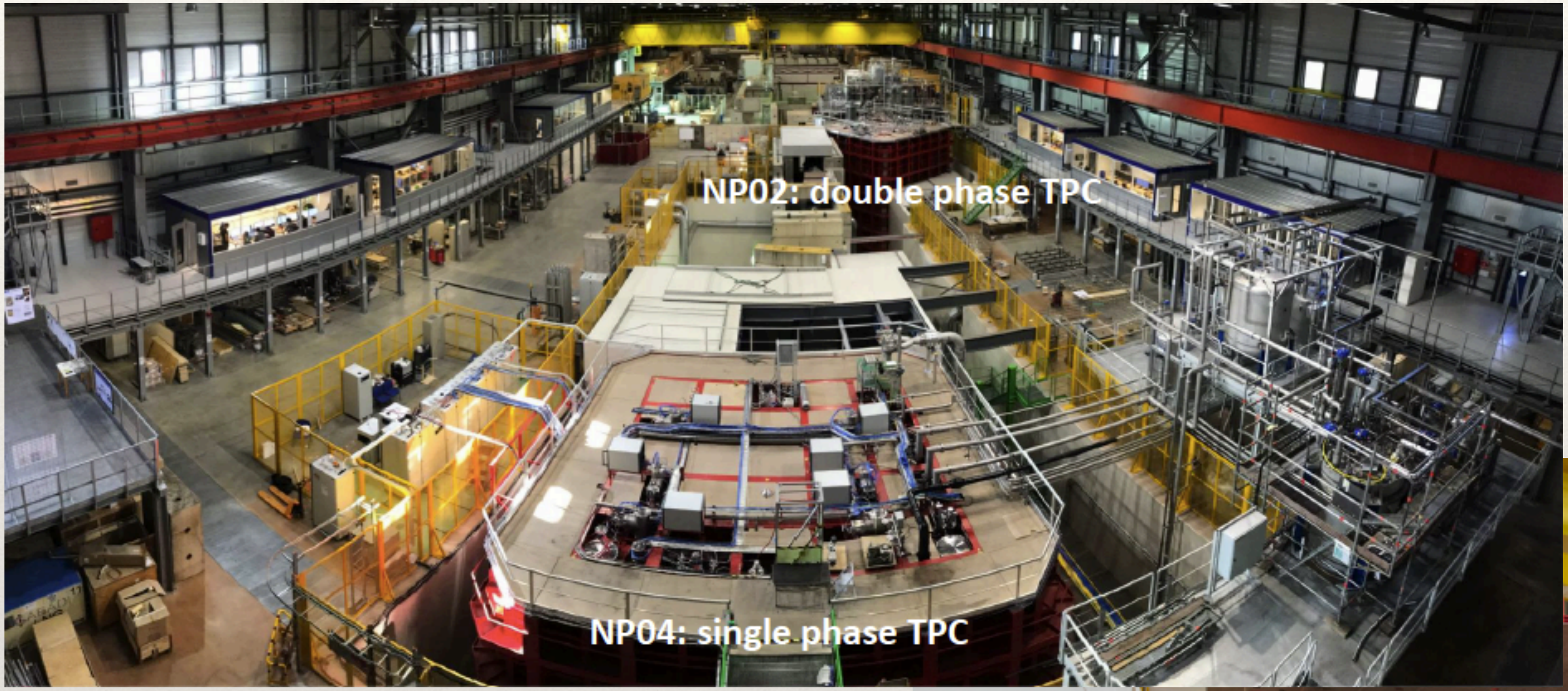
R. Keith Ellis
IPPP, Durham

- European Strategy for Particle Physics Update
- Proposed future colliders
- The importance of Higgs Physics
- Assessing the reach in Higgs Physics of future machines.

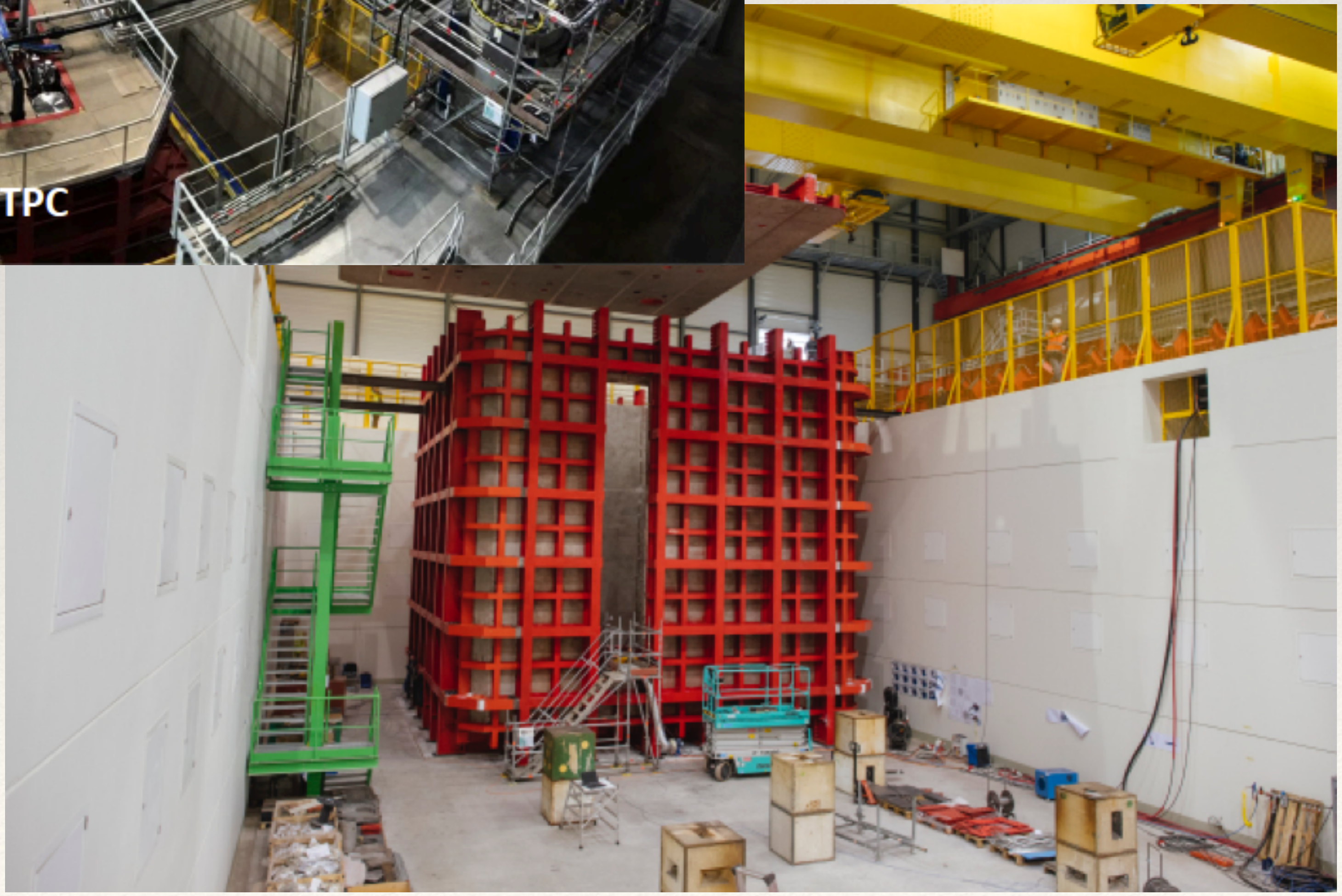
European Strategy 2013

- Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.
- CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.
- Europe looks forward to a [ILC] proposal from Japan to discuss a possible participation.
- CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

Last strategy process led to initiation of CERN/European activity in neutrino physics



Prototype cryostats for liquid Argon detectors at CERN



Status of ILC

- MEXT view of the ILC project: (From LCB and ICFA Meetings, Tokyo, 7 March 2019)
    - Following the opinion of the SCJ, MEXT has not yet reached declaration for hosting the ILC in Japan. The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain understanding and support from domestic academic community.
    - MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.
- September update on SCJ Master Plan:
    - ILC passed first selection, along with 60 other projects invited to a hearing (~ 30% of initial applicants).
    - SCJ will release Master Plan by the end of January 2020 (expect ~ 20 projects in final list).
- Hoping to get some useful indication for the ESPP update, a LCB meeting provisionally scheduled in Tokyo on 20 December 2019 to hear about progress from MEXT and Diet members promoting ILC.

European Strategy 2013 (Other scientific activities essential to the particle physics programme)

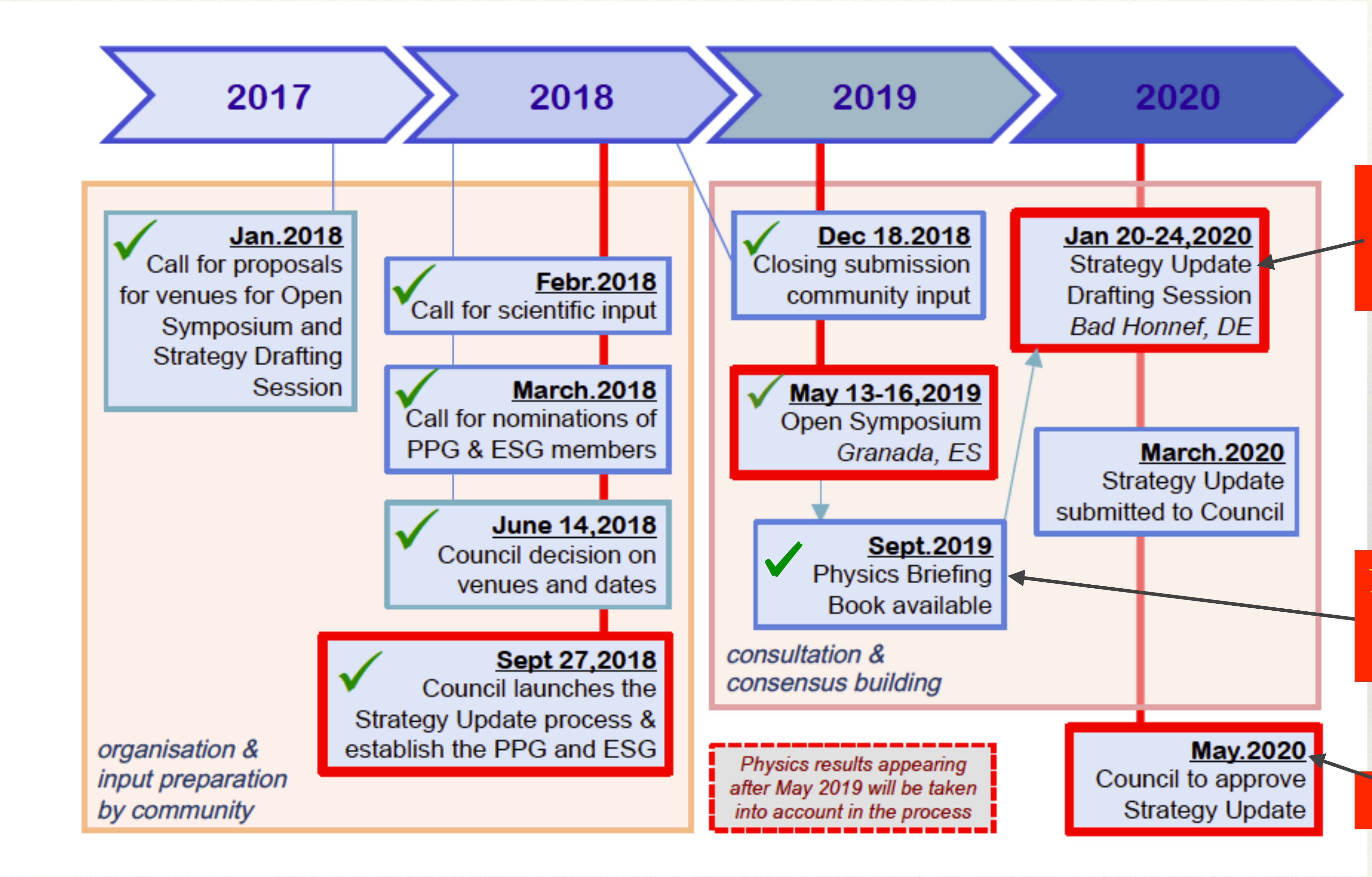
- Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.
- Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.
- Detector R&D programmes should be supported strongly at CERN, national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.
- In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.
- The CERN Laboratory should maintain its capability to perform unique experiments. CERN should continue to work with NuPECC on topics of mutual interest.

NuPECC = Nuclear Physics European Collaboration Committee
APPEC=Astroparticle Physics European Consortium

European Strategy 2013 (organisational issues)

- CERN should be the framework within which to organise a global particle physics accelerator project in Europe, and should also be the leading European partner in global particle physics accelerator projects elsewhere. Possible additional contributions to such projects from CERN's Member and Associate Member States in Europe should be coordinated with CERN.
- CERN and the particle physics community should strengthen their relations with the European Commission in order to participate further in the development of the European Research Area.

Strategy Timeline for 2020 update



ESG, about 80 people, UK representatives, Thomson & Butterworth

Briefing book, 1/10/2019 CDS (CERN-ESU-004)

Budapest

Briefing book

- Briefing book and strategy update concern a much broader spectrum of activities than just future colliders.

CERN-ESU-004
29 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Preparing CERN's future

I think it would be good for CERN if the 2020 Strategy update recommended:

- the direction for a future collider at CERN: linear or circular
  → so that its technical and financial feasibility can be assessed by next Strategy update in ~2026 → pre-requisite for project approval by the Council

- a compelling scientific diversity programme at the injectors, complementary to high-E colliders for physics reach and size/type of projects (→ attract a diverse community). Based on input from Physics Beyond Colliders (PBC) study group.

- a vigorous and transformational accelerator R&D programme at CERN and other European laboratories and institutions: high-field magnets (including High-Temperature Superconductors), high-efficiency klystrons, high-gradient accelerating structures, plasma wakefield, feasibility of muon colliders, etc.

F. Gianotti, Sept 2019

Proposed future colliders

Scenarios

	2020-2040	2040-2060 1st gen technology	2060-2080 2nd gen technology
CLIC	HL-LHC	CLIC380-1500	CLIC3000
CLIC-FCC-mixed	HL-LHC	CLIC380	FCC-h/e/A (Adv HF magnets)
FCC	HL-LHC	FCC-ee (90-365)	FCC-h/e/A (Adv HF magnets)
LE-to-HE-FCC-h/e/A	HL-LHC	LE-FCC-h/e/A (LF magnets)	FCC-h/e/A (Adv HF magnets)
LHeC+FCC-h/e/A	HL-LHC + LHeC	LHeC	FCC-h/e/A (Adv HF magnets)

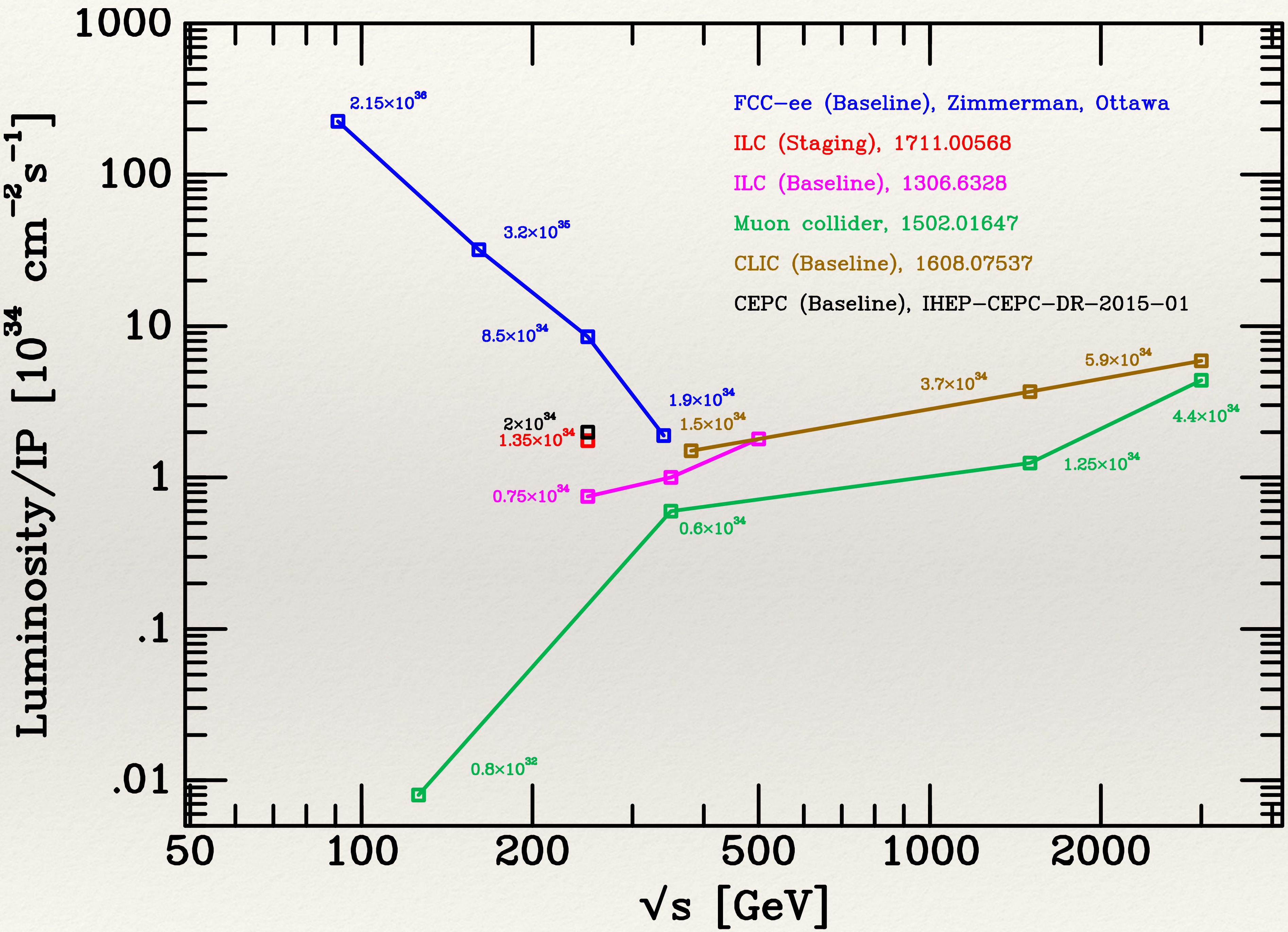
- To make the discussion more concrete we can imagine 5 scenarios, which can be pursued in Europe.
- We are working in a global context, but we should take the lead and decide what is best for Europe.
- Hope to make decisions which are robust, whatever happens elsewhere.
- Machine parameters and integrated luminosities defined for CERN machines, 1810.13022

Comparisons

Project	Type	Energy[TeV]	Int Lumi[ab^{-1}]	Oper time[y]	Power[MW]	Cost
ILC	ee	0.25	2	11	129	4.8-5.3 G ILCU
		0.5	4	10	163	7.98 G ILCU
		1.0			300	? 1 ILCU=1 US$(2012)
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3.0	5.0	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	16+2.6	4+1	259	5.1 GCHF(+5.4 GCHF)
		0.24	5	3	282	
		0.365+0.35	1.5(+0.2)	4(+1)	340	+1.1 GCHF
LHeC	ep	0.06/7	1	12	(+100)	1.75 GCHF
HE-LHC	pp	27	20	20		7.2 GCHF
FCC-hh-6T	pp	37.5	20	20		8.9 GCHF(+6 GCHF)
FCC-hh	pp	100	30	25	580(550)	17 GCHF(+7 GCHF)

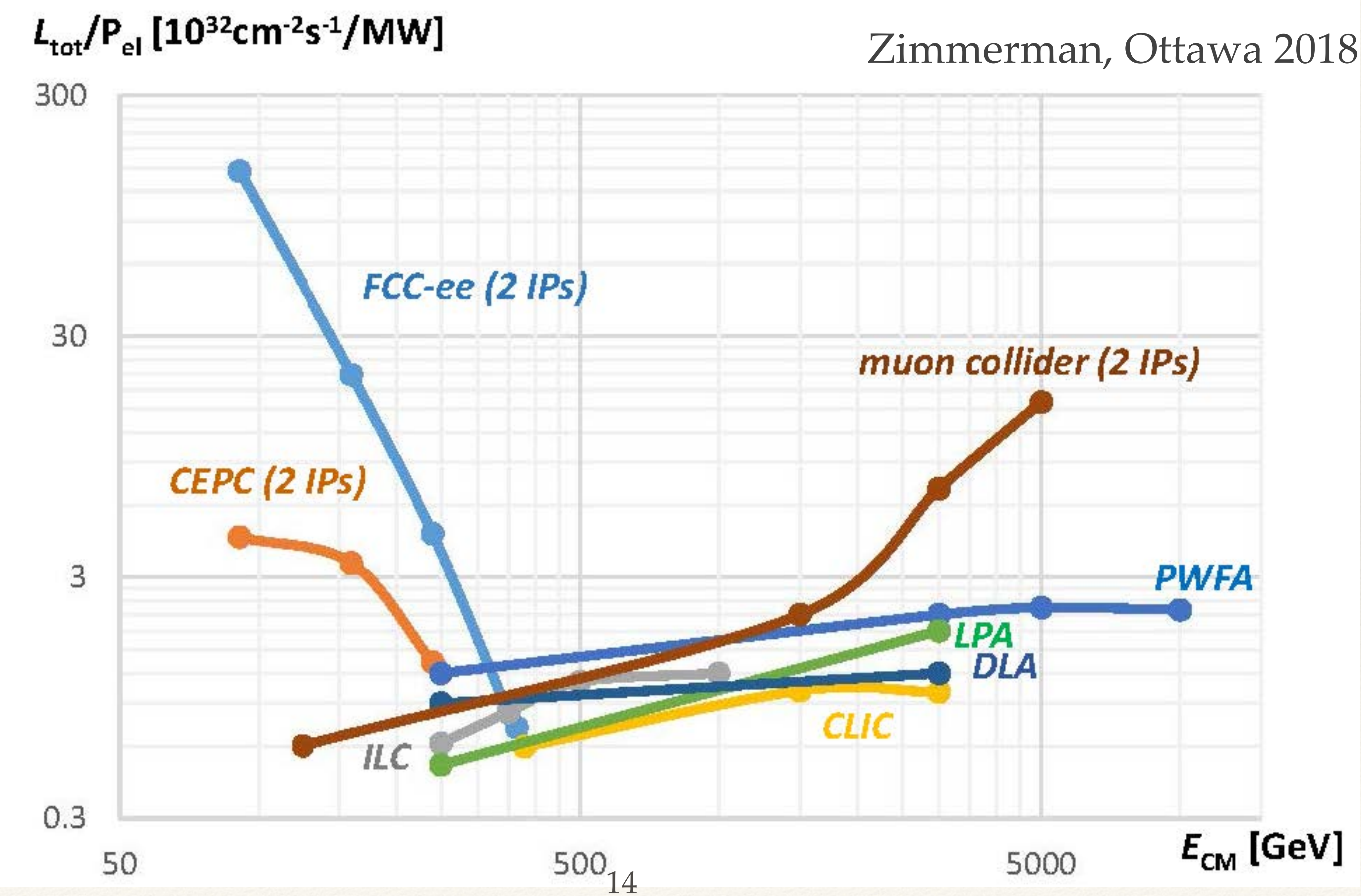
c.f. Schulte Granada

Luminosity at lepton colliders



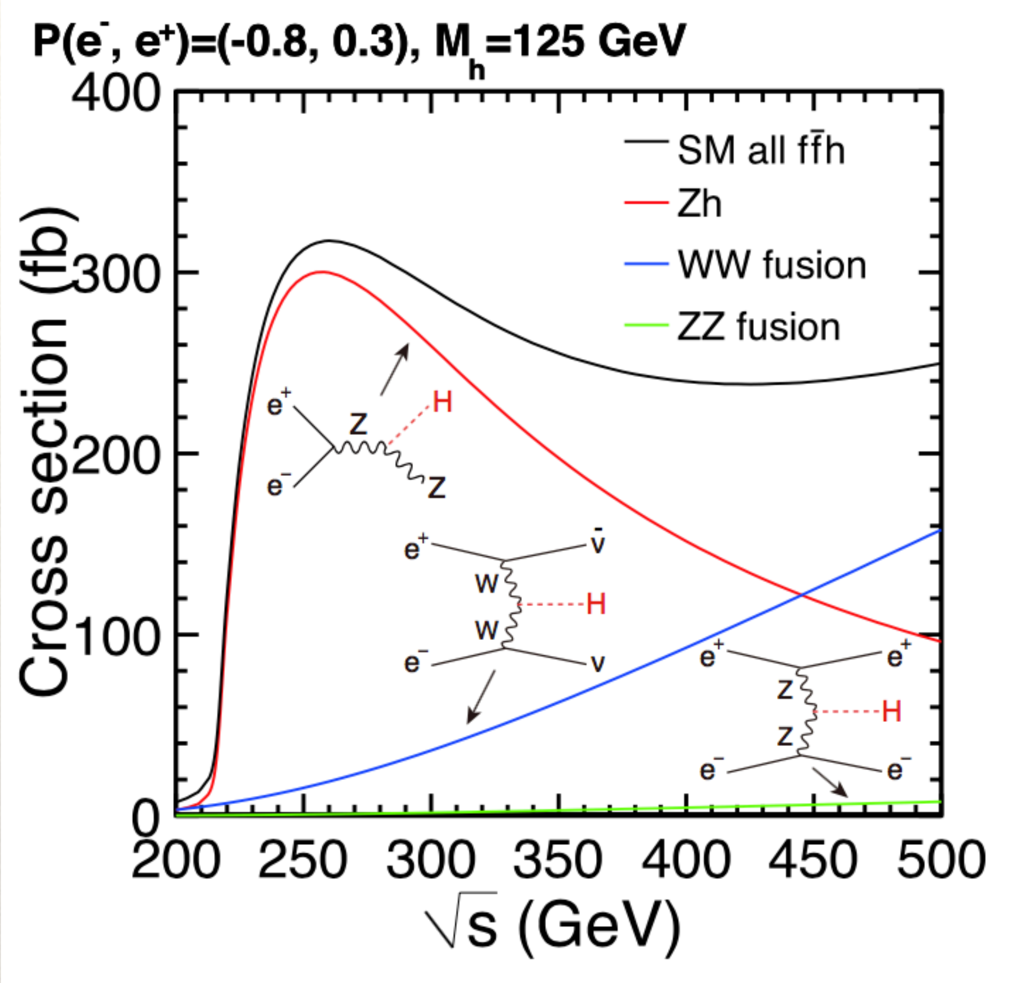
Lepton colliders

- Luminosity per Megawatt, wall plug power



Higgs at e$^+$e$^-$ collider: generalities

- WW fusion production ten times smaller at 250 than 500.
- ~40% increase in ZH cross section with polarization(-0.8,+0.3)
- In terms of precision Higgs parameters polarization is like a factor of ~2 in integrated luminosity.



Polarisation	Scaling factor		1608.07538
$P(e^-):P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17
−80% : −30%	0.83	1.26	1.07
+80% : 0%	0.88	0.20	0.88
+80% : +30%	0.69	0.26	0.92
+80% : −30%	1.08	0.14	0.84

Timescale for magnet development

- A limiting factor for setting the schedule for high energy hh machines is the time scale for magnet development.

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders – Linear and Circular:							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier – Circular :							
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
9~12T Nb_3Sn	Model/Proto/Pre-series	Construction			Operation		Upgrade
6~8T NbTi	Proto/ Pre-series	Construction		Operation		Upgrade	

Note: **LHC experience: NbTi, 10 T** R&D started in 1980's and **8.3 T** Production started in late 1990's, after ~ 15 years

A. Yamamoto, 190513b/updated:190628a

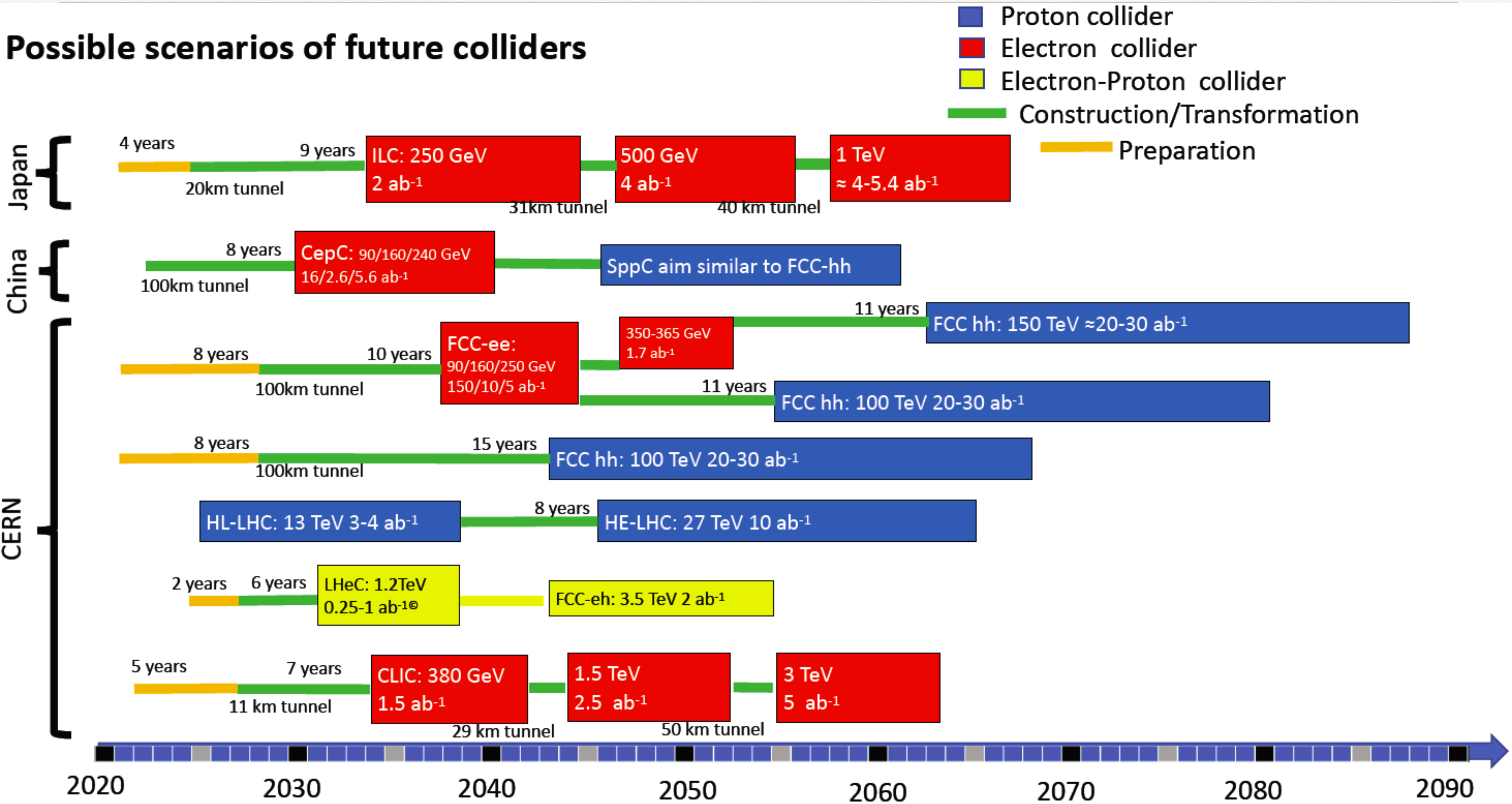
Yamamoto, Granada

Timeline (from T_0)

T_0 | +5 | +10 | +15 | +20 | ... | +26

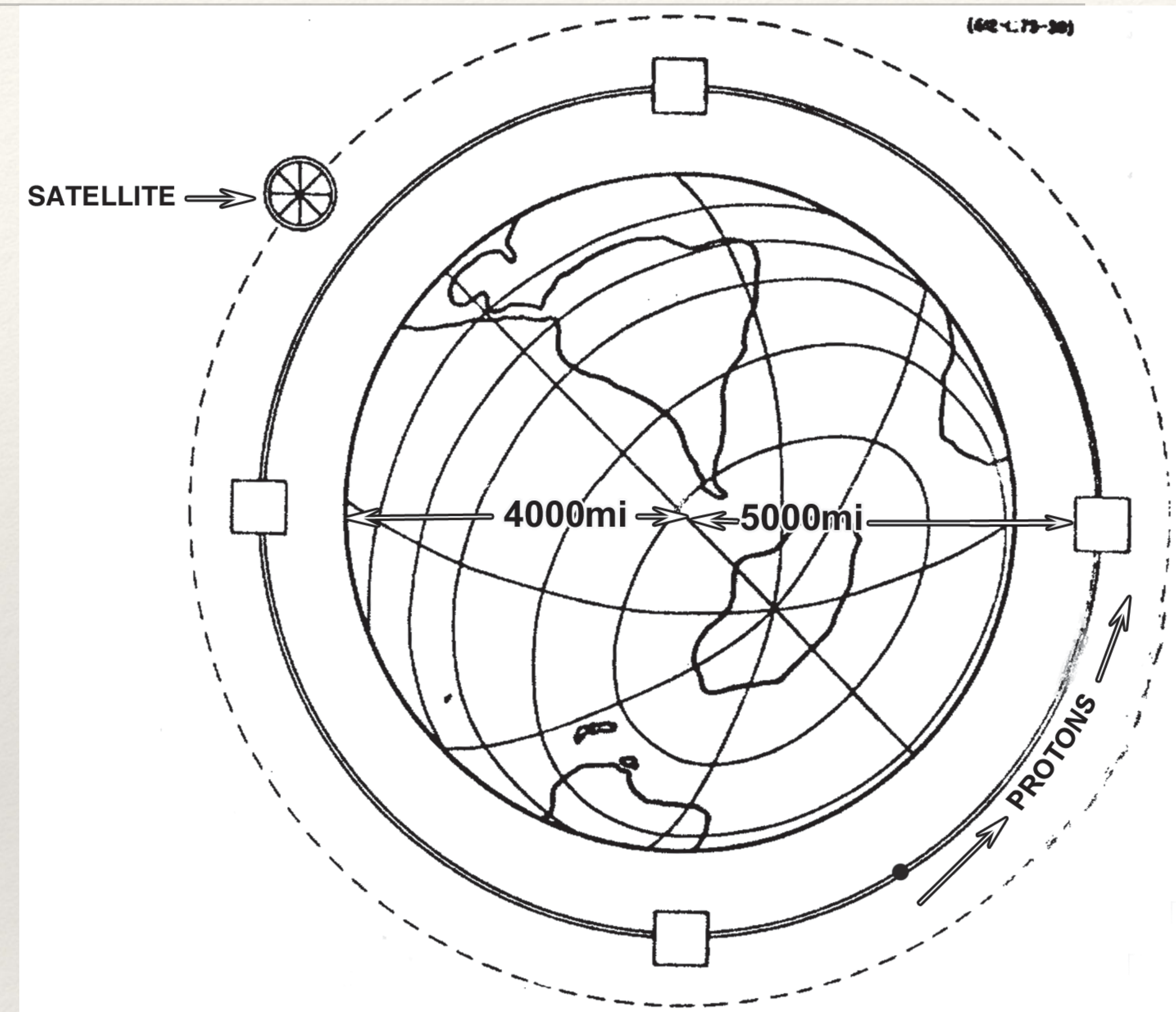
ILC	0.5/ab 250 GeV		1.5/ab 250 GeV		1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV
CEPC	5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$		SppC =>		
CLIC	1.0/ab 380 GeV		2.5/ab 1.5 TeV		5.0/ab => until +28 3.0 TeV		
FCC	150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV		1.7/ab ee, $2m_{top}$		hh,eh =>
LHeC	0.06/ab		0.2/ab		0.72/ab		
HE-LHC	10/ab per experiment in 20y						
FCC eh/hh	20/ab per experiment in 25y						

Possible timeline of future colliders



Global Strategy (mark1)

- In January 1954, Enrico Fermi made a presentation in New York, on the occasion of Fermi stepping down as president of the APS, and being replaced by Bethe. The title of the presentation was **What can we learn from High-Energy Accelerators?** The following are quotations from Fermi's notes.
- Fermi starts off by "Congratulate Society on Loosing(sic) mediocre President and getting eccellent(sic) one."
- "But to solve the mysteries, higher energy data are needed."
- "For these reasons clamoring for higher and higher energies.."
- "Preliminary design…8000 km, 20,000 gauss" (2 Tesla)
- "Energy of 5x10^{6}GeV, cost \$170 Billion" (√s=3TeV !)
- "What we can learn impossible to guess. . .main element surprise. . .some things look for, but see others"
- ". . .Look for multiple production. . .antinucleons.. .strange particles. . .puzzle of long lifetimes. . .large angular momentum?. . .double formation?" (now called associated production) .
- Human ingenuity allowed us to reach higher field and energies



JAN. 29, 1954

FRIDAY AFTERNOON AT 2:00

McMillin Theatre

(H. A. BETHE AND P. E. KLOPSTEG presiding)

Joint Ceremonial Session of the APS and the AAPT

Retiring Presidential Address of the American Physical Society

P1. What Can We Learn with High-Energy Accelerators? ENRICO FERMI, *University of Chicago.*

Presentation of the Oersted Medal of the AAPT

Response of the Oersted Medallist

P2. The Metaphysics of a Physics Teacher. C. N. WALL, *University of Minnesota.*

Higgs Physics=Guaranteed deliverable of future machine.

Known (in part) facets of Higgs Physics

- Fundamental? spin-0 particle;
- Coupling to heavy bosons confirms role in generation of W & Z mass;
- Coupling to charged third generation fermions t, b, τ confirms new Yukawa-type interaction;
- Many couplings known at the 10% level;

H^0 $J = 0$ PDG-2019

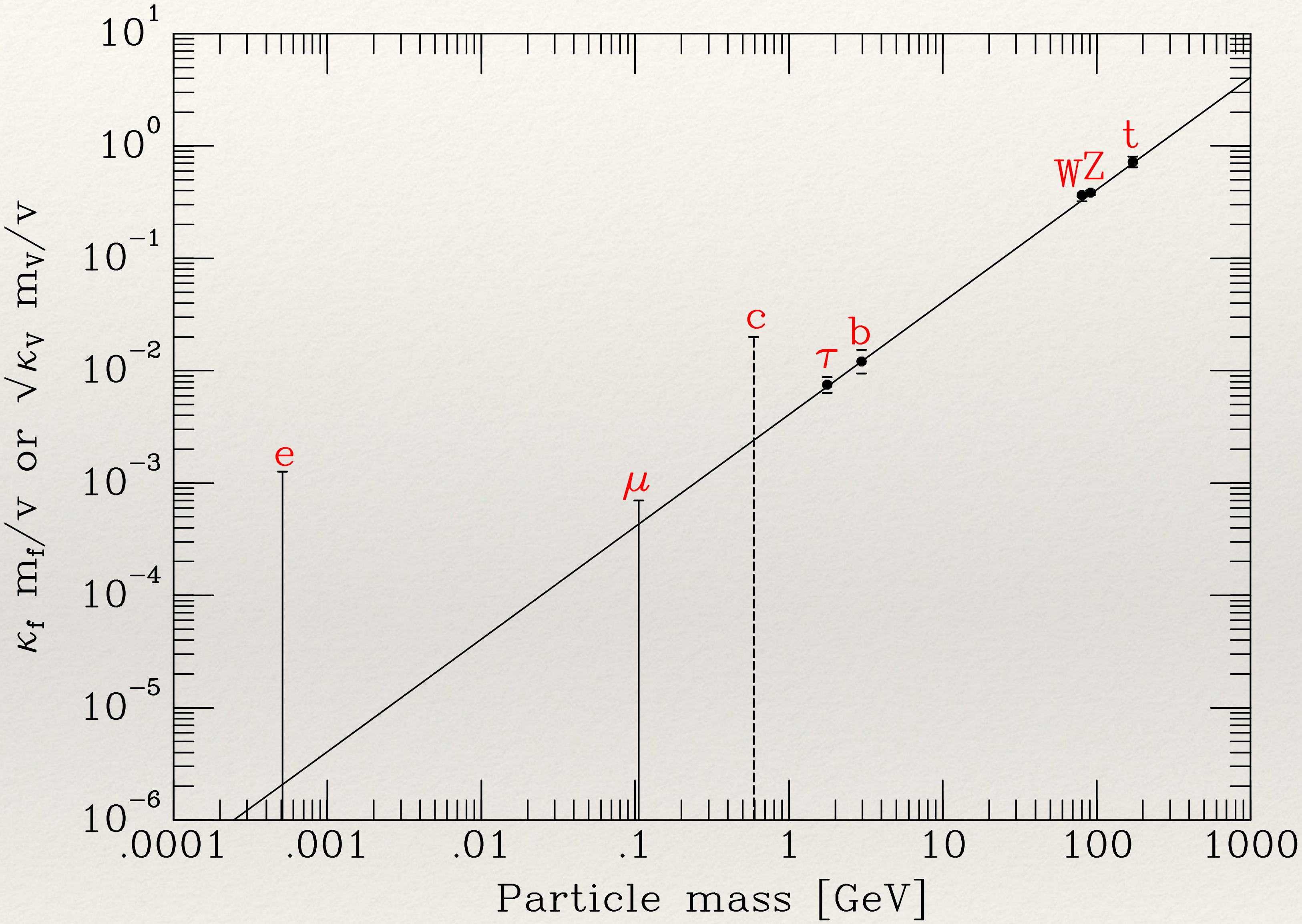
Mass $m = 125.10 \pm 0.14$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95% (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.10 \pm 0.11$
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.19^{+0.12}_{-0.11}$
$\gamma\gamma = 1.10^{+0.10}_{-0.09}$
$c\bar{c}$ Final State < 110, CL = 95%
$b\bar{b} = 1.02 \pm 0.15$
$\mu^+\mu^- = 0.6 \pm 0.8$
$\tau^+\tau^- = 1.11 \pm 0.17$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 1.28 \pm 0.20$
$H^0 H^0$ Production < 12.7
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV $= 57 \pm 7$ pb

Yukawa couplings of the Higgs boson

- Moving on from the results of the third generation of 2018.
- There is already information that coupling to μ and e is less than coupling to τ;
- Charm coupling less than the coupling to the top;
- Not yet demonstrated that coupling to charm less than coupling to bottom.



H decays 1909.02845, H→ ee, CMS, arXiv:1410.6679, H→cc, CMS-PAS-HIG-18-031 (as interpreted by me)

Open questions

- Is h the only scalar degree of freedom?
- Is h elementary?
- What keeps $m_h^2 << m_{planck}^2$
- Was the electroweak phase transition first order?
- Did CP violating h interactions generate the baryon asymmetry?
- Are there light SM-singlet degrees of freedom (in particular, related to Dark Matter)?
- What is the solution of the flavor puzzle(s)?

Heinemann and Nir 1905.00382

Higgs@Future Colliders

Higgs Boson studies at future particle colliders

J. de Blas[1,2], M. Cepeda[3], J. D'Hondt[4], R. K. Ellis[5], C. Grojean[6,7], B. Heinemann[6,8], F. Maltoni[9,10], A. Nisati[11,*], E. Petit[12], R. Rattazzi[13], and W. Verkerke[14]

Contents

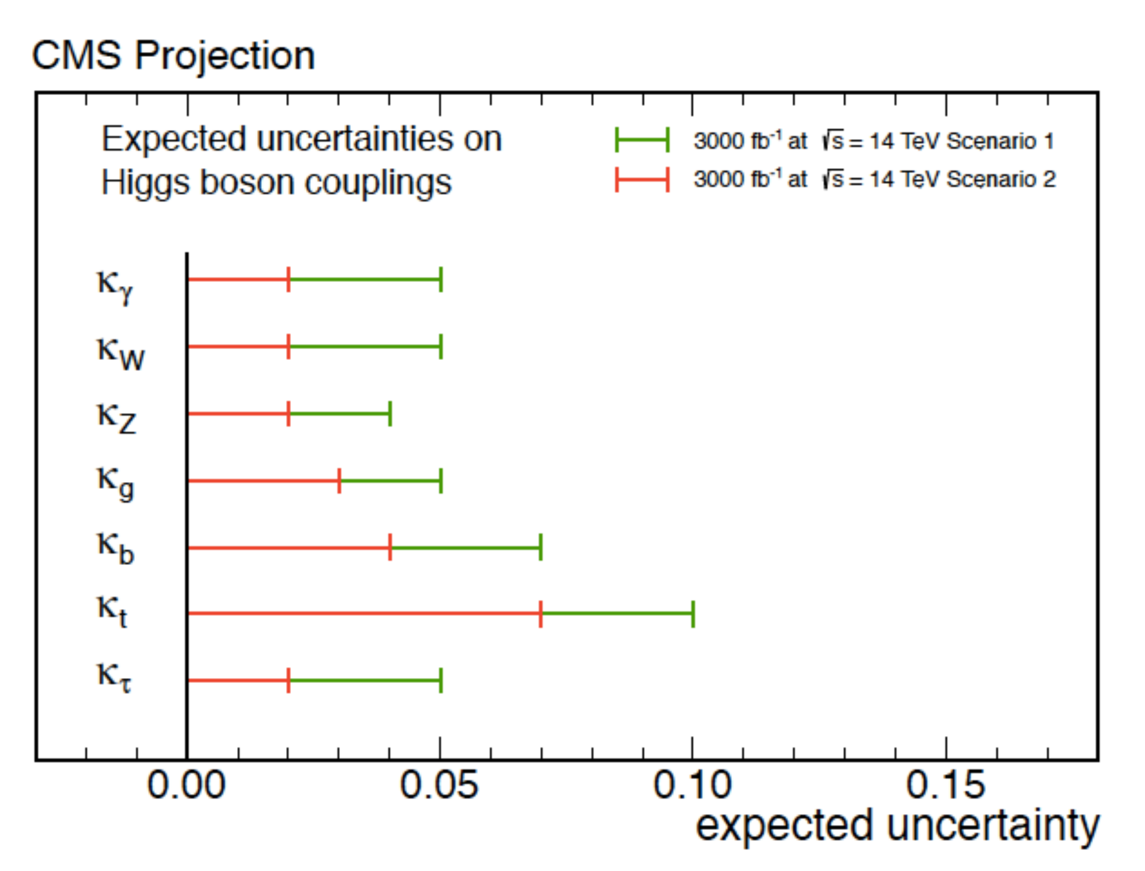
ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects of sufficient maturity using uniform methodologies. A first version of this report was prepared for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019). Comments and feedback received led to the consideration of additional run scenarios as well as a refined analysis of the impact of electroweak measurements on the Higgs coupling extraction.

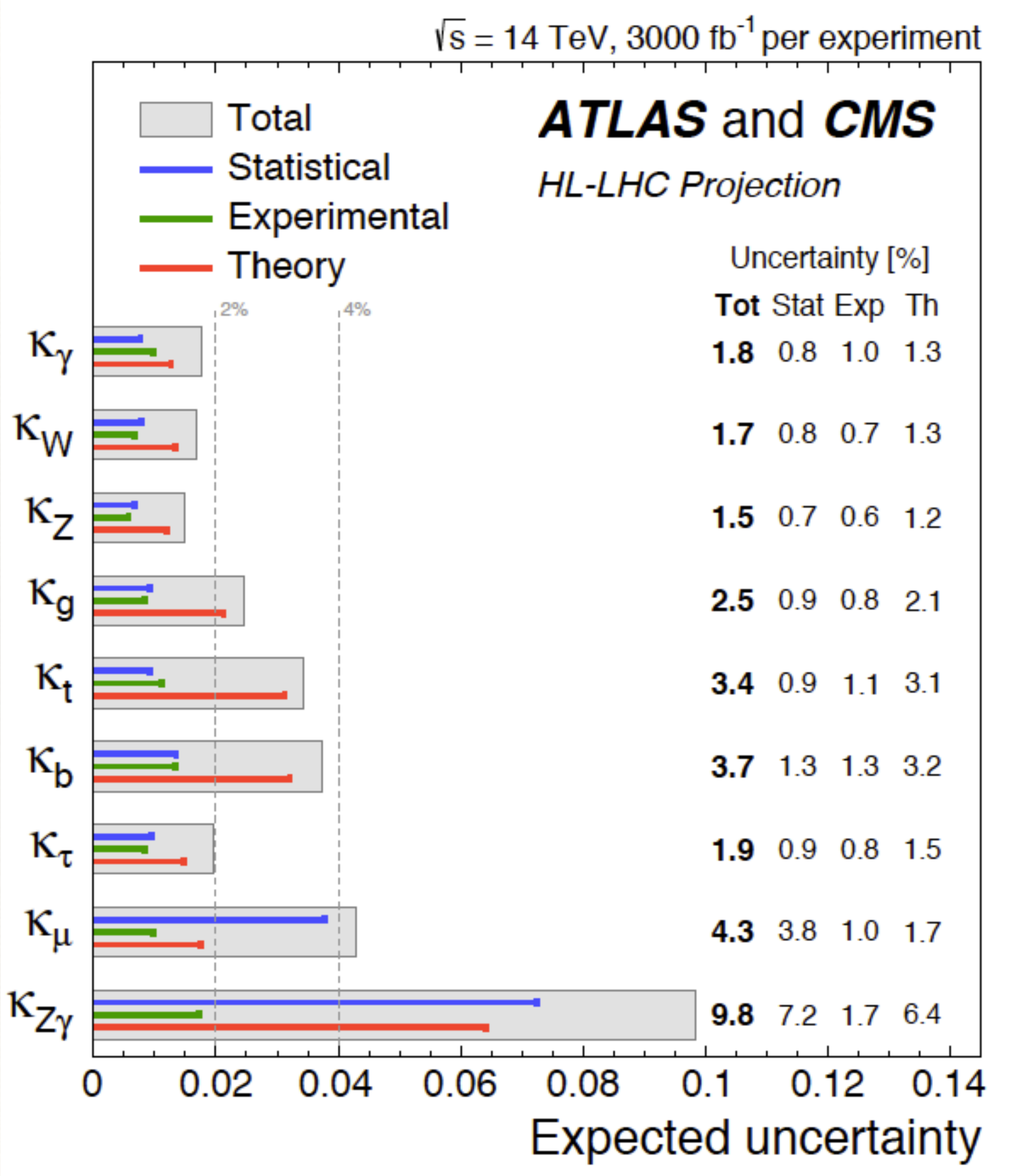
- Comparison using a single methodology (using the submitted inputs) of the potential of various future machines.

Start from the basis of HL-LHC

1307.7135

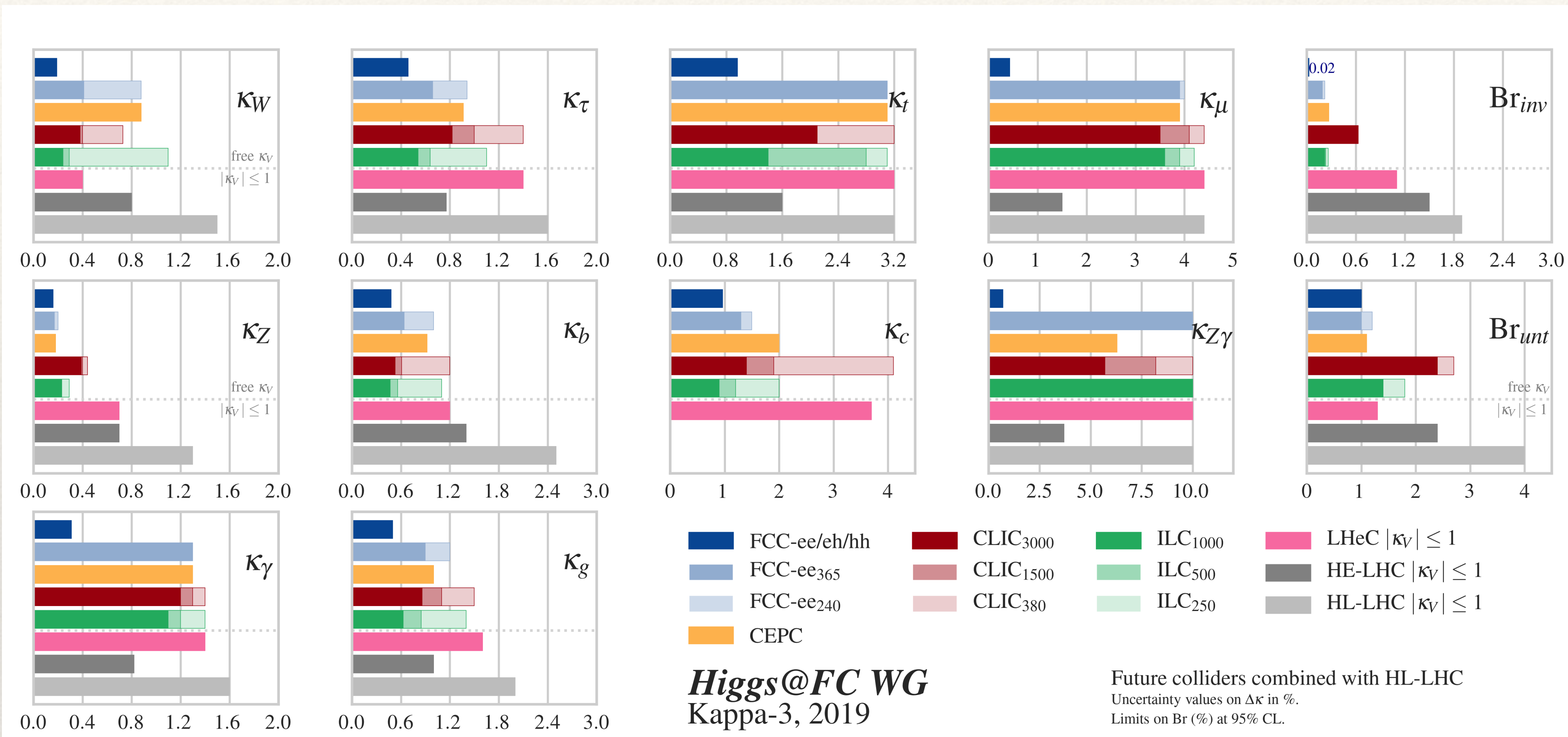


1902.00134



- Progress from 2013 to 2019
- 2% optimistic in 2013, achievable in 2019.
- Dominance of theoretical errors.

Kappa-scenario



- κ has the advantage that it is simple;
- the effects of polarization are undervalued in this approach;
- Would give indications of deviations from the SM, but not necessarily diagnostic information to interpret deviation;
- In this kappa framework HL-LHC projections are included and the untagged and invisible branching ratios are constrained by the measurements.

1905.03664v2

Improvement wrt HL-LHC

- First-stage e^+e^- machines all show large improvement in κ_Z, κ_c, Br_{inv}.
- The rare, statistically dominated decays, $Z\gamma$ and the top couplings are improved over HL-LHC only by FCC-hh.

	LHeC *	HE-LHC S2′ *	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	3.8	1.9	1.4	5.2	6.2	2.1	3.8	3.9	1.7	1.7	3.7	7.9
κ_Z *	1.9	1.9	4.5	5.9	5.7	3.0	3.2	3.3	7.2	6.5	7.6	8.1
κ_g	1.2	2.0	1.4	2.4	3.2	1.3	1.8	2.3	2.0	1.7	2.2	4.0
κ_γ	1.1	2.0	1.1	1.3	1.5	1.1	1.2	1.3	1.2	1.2	1.2	5.2
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	2.0	1.0	1.1	2.3	1.0	1.5	1.5	1.0	1.0	1.0	3.3
κ_b	2.1	1.8	2.3	4.5	5.3	2.1	4.1	4.7	2.7	2.5	3.9	5.2
κ_μ	1.0	2.9	1.0	1.1	1.2	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.1	2.1	1.5	2.5	3.0	1.1	1.6	2.0	1.8	1.7	2.4	3.5
Br_{inv}	1.7	1.3	7.3	8.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.1	1.7	2.2	2.9	2.9	1.5	1.7	1.7	3.6	3.3	4.0	4.0
Br_{unt} **		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

Colour scale: 0 – 5

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HLLHC

Improvement wrt HL-LHC in SMEFT

- First-stage e^+e^- machines all show improvement, especially (i.e. more than a factor of 10) for g_{HZZ}, g_{HWW}, g_{Hbb}, g_{Hcc}.

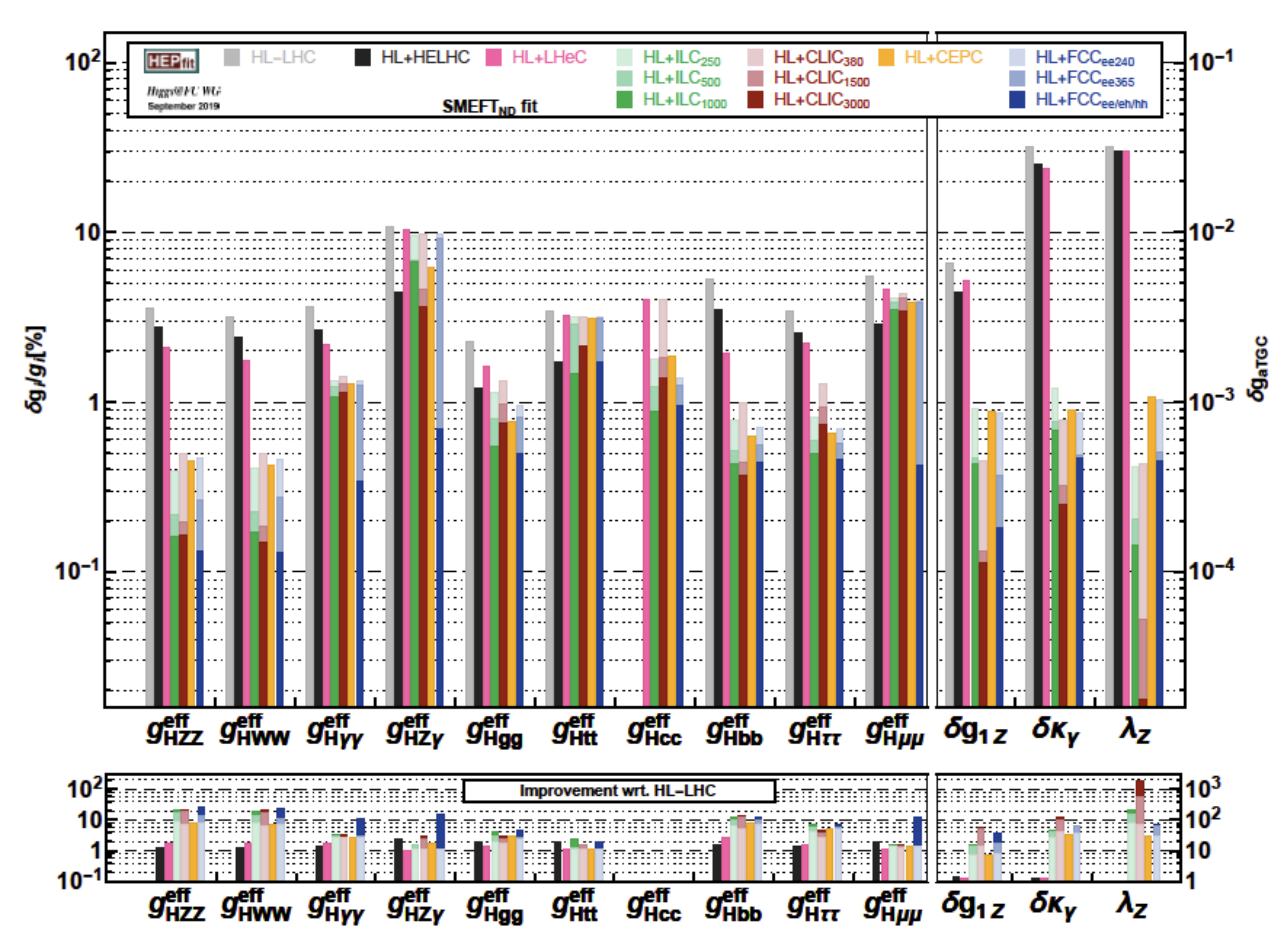
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{eff}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{eff}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

SMEFT analysis

- We consider SMEFT fit scenarios in the Higgs basis
- To assess the deviations from the SM in a basis-independent way we define effective couplings

$$g_{HX}^{eff\ 2} = \frac{\Gamma(H \to X)}{\Gamma^{SM}(H \to X)}$$



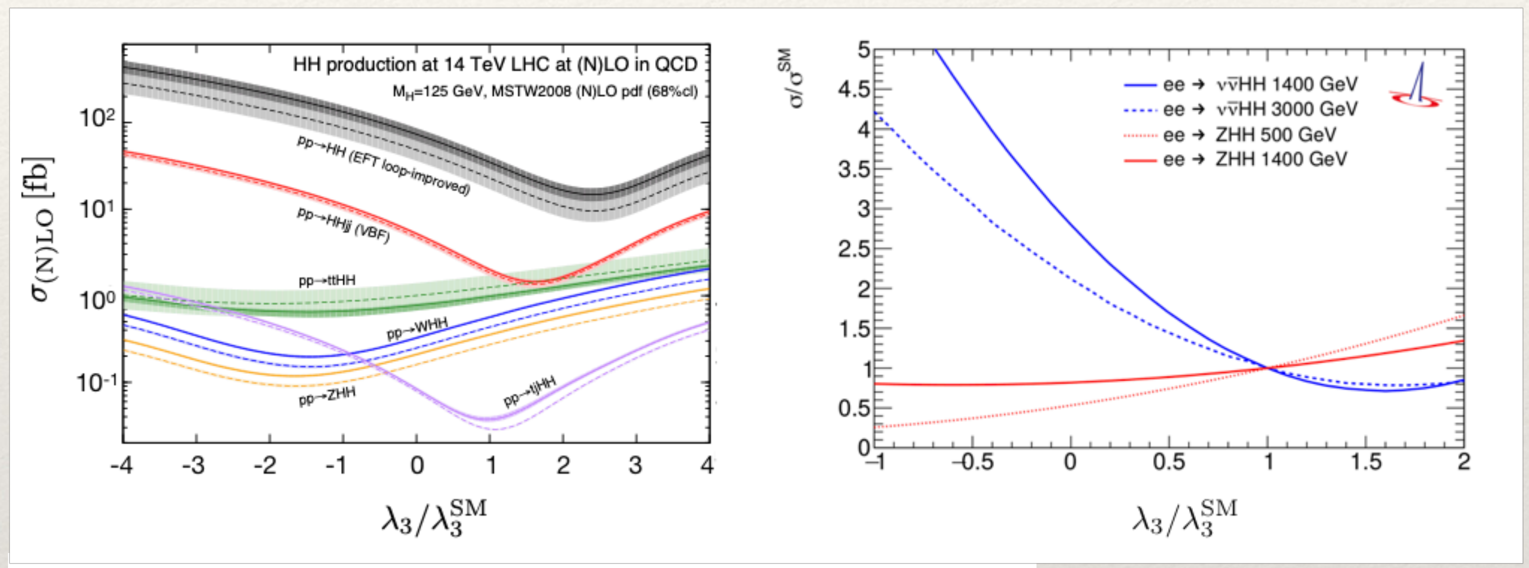
Measuring the Higgs potential

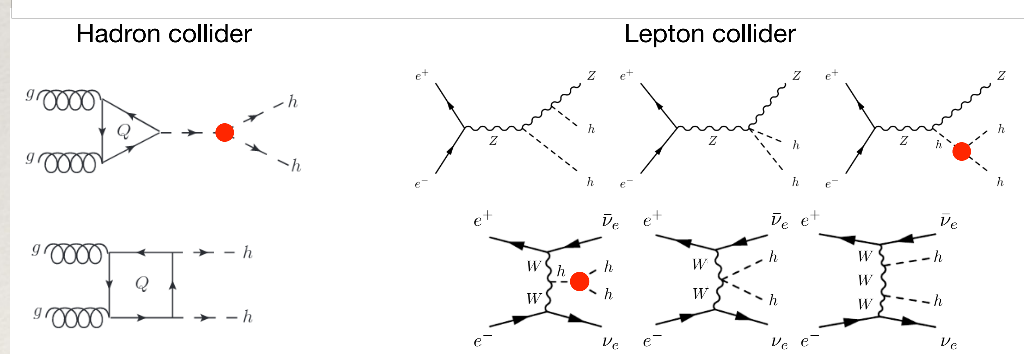
In SM potential fixed in terms of m_H and v

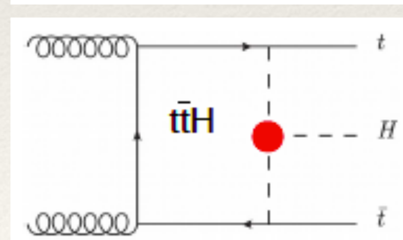
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

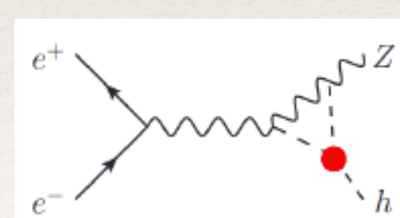
with $\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$

- First order phase transition at finite temperature can give a framework for baryogenesis
- Sensitivity to Higgs trilinear coupling in
  - double Higgs production
  - one-loop effects in single Higgs production



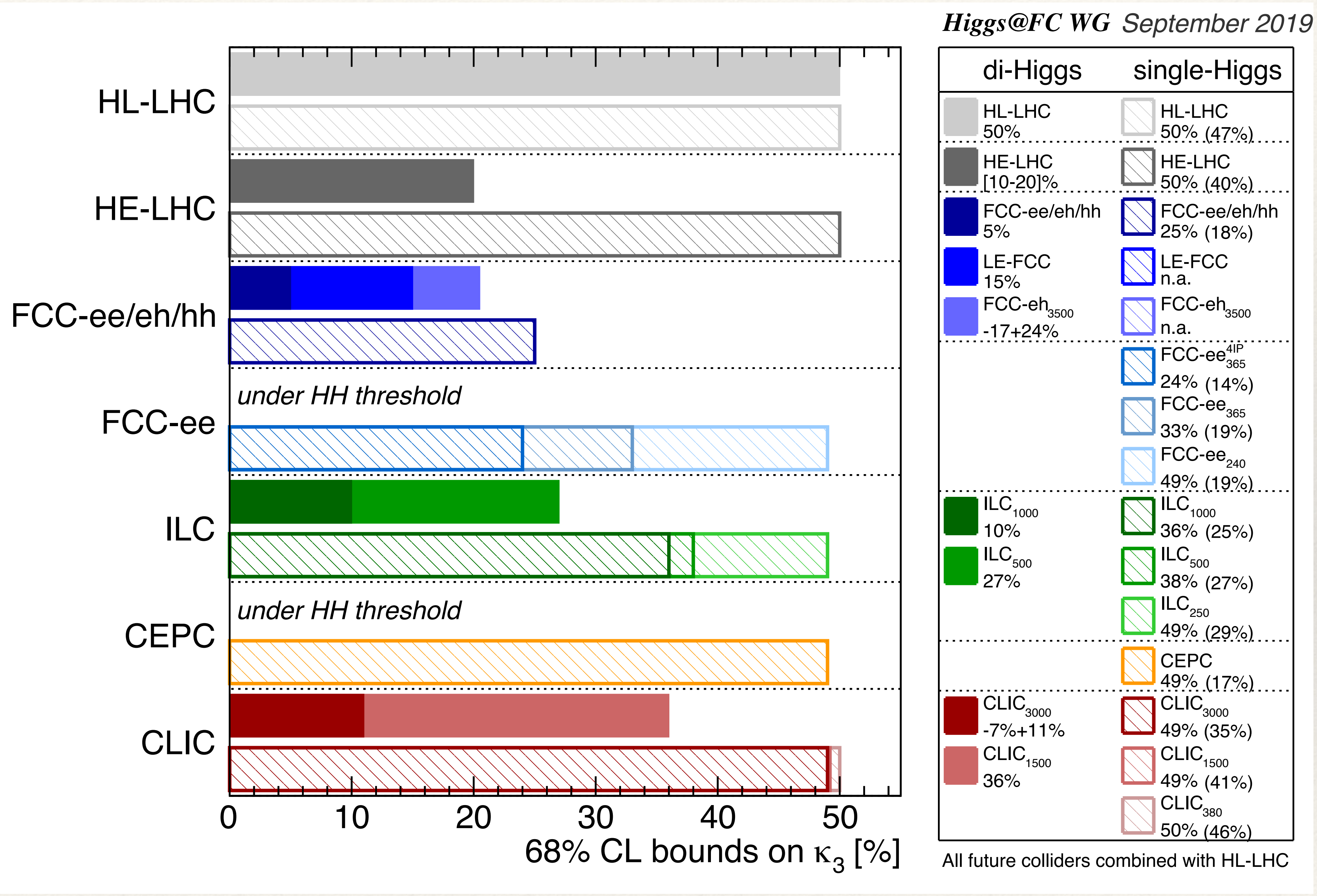






Sensitivity to λ via single-H and di-H production

- Di-Higgs
  - HL-LHC ~50%
  - Improved by HE-LHC(20%), LE-FCC(15%), ILC_{500}(25%)
  - Precisely by $CLIC_{3000}$(9%), FCC(hh)(5%)
  - Robust w.r.t. other operators
- Single Higgs
  - Global analysis FCCee_365 and ILC500 sensitive to ~35% when combined with LHC.
  - ~21% if FCC-ee has 4 detectors



Conclusions

- First stage e+e- Higgs factories have a similar reach, albeit with different time scales, and differing potential at other energies.
- Projected uncertainties at first stage e+e- Higgs factories are in many cases a significant improvement on HL-LHC, e+e- adds information about the $Br_{invisible}$, (semi-direct measurement of Higgs width);
- Higgs physics is the central concern of HL-LHC and beyond; this community (experiment and theory).