New perspective(s) in particle physics

R. Keith Ellis
IPPP, Durham

- I will report on plans for future accelerators from a European perspective;
- Much of the focus will be on the Higgs boson, which is associated with many of the problems of the standard model;
- Therefore a more precise study of its properties is major focus of future machines, both approved (HL-LHC) and projected(CLIC, CEPC,FCC,ILC);

Planning for the future of our field

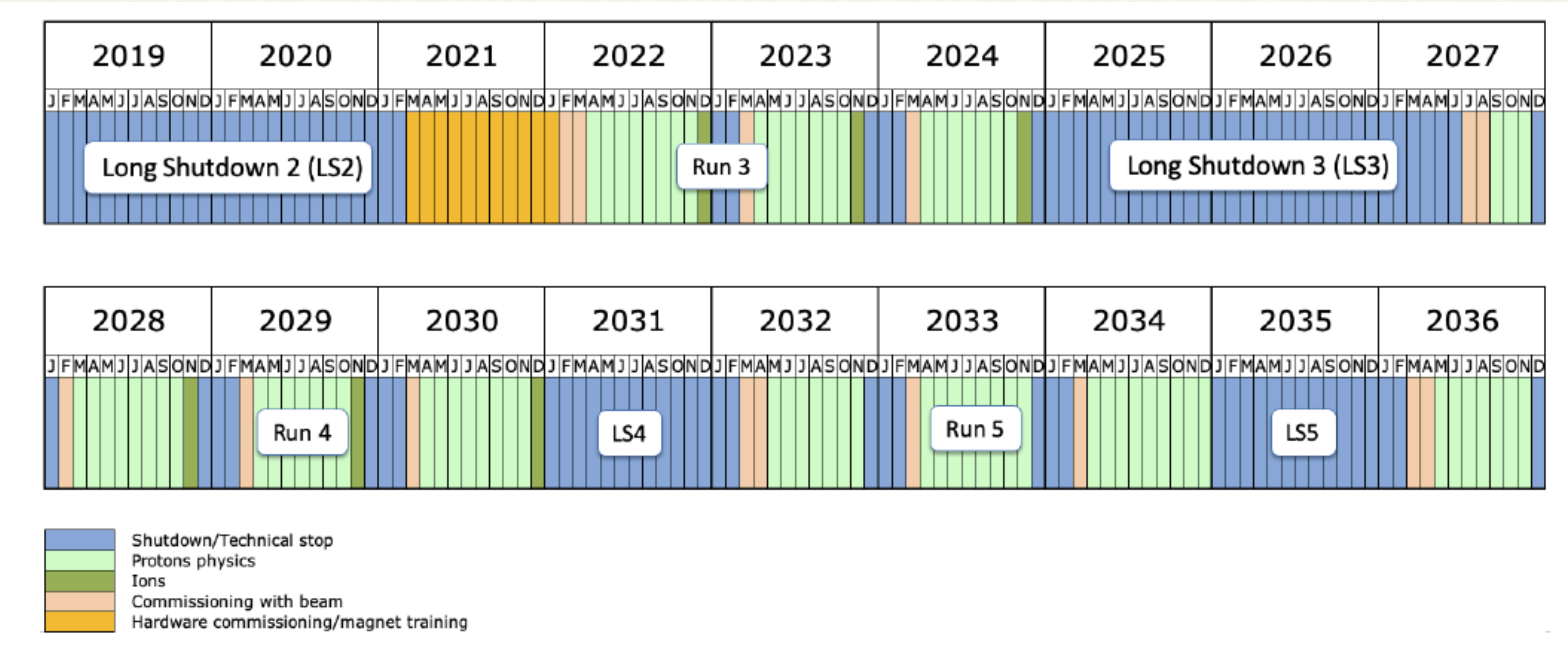
- European Strategy process (concluded June 2020);
  - Primarily a strategy for accelerator-based particle physics;
  - In Europe, Astroparticle Physics, Nuclear Physics have their own planning process.
- Snowmass process, (somewhat delayed by Covid);
  - Snowmass Community Summer Study (CSS): July, 2022 at UW-Seattle;
  - Snowmass Book and the on-line archive documents due: October 31, 2022.

HL-LHC

- European Strategy decision:-
    - "The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques."
    - "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited."

ie. ATLAS+CMS+LHCb+ALICE

LHC long-term schedule



- Accumulation of 3-4 ab^{-1} by the end of HL-LHC in ~2036

Current status

LHC summary

- LS2 in the LHC has finished
- 7oo8 sectors cold, magnet circuit powering tests ongoing
- Major dipole training programme has started
  - The target is 7 TeV but need to see how things evolve
- On schedule for beam test end September and closing machine for full beam commissioning in February 2022
  - Schedule to be revisited with experiments in June

M. Lamont, CERN director of accelerators, March 2021

Impact of LHC on Higgs physics

Known (in part) facets of Higgs Physics

- Great progress since 2012
- Fundamental? spin-0 particle;
- Coupling to heavy bosons confirms role in generation of W & Z mass;
- Signal strength defined as the ratio of the observed to the expected signal yield.
- Many couplings are hence known at the 10% level;

PDG-2019

H^0 $J = 0$

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

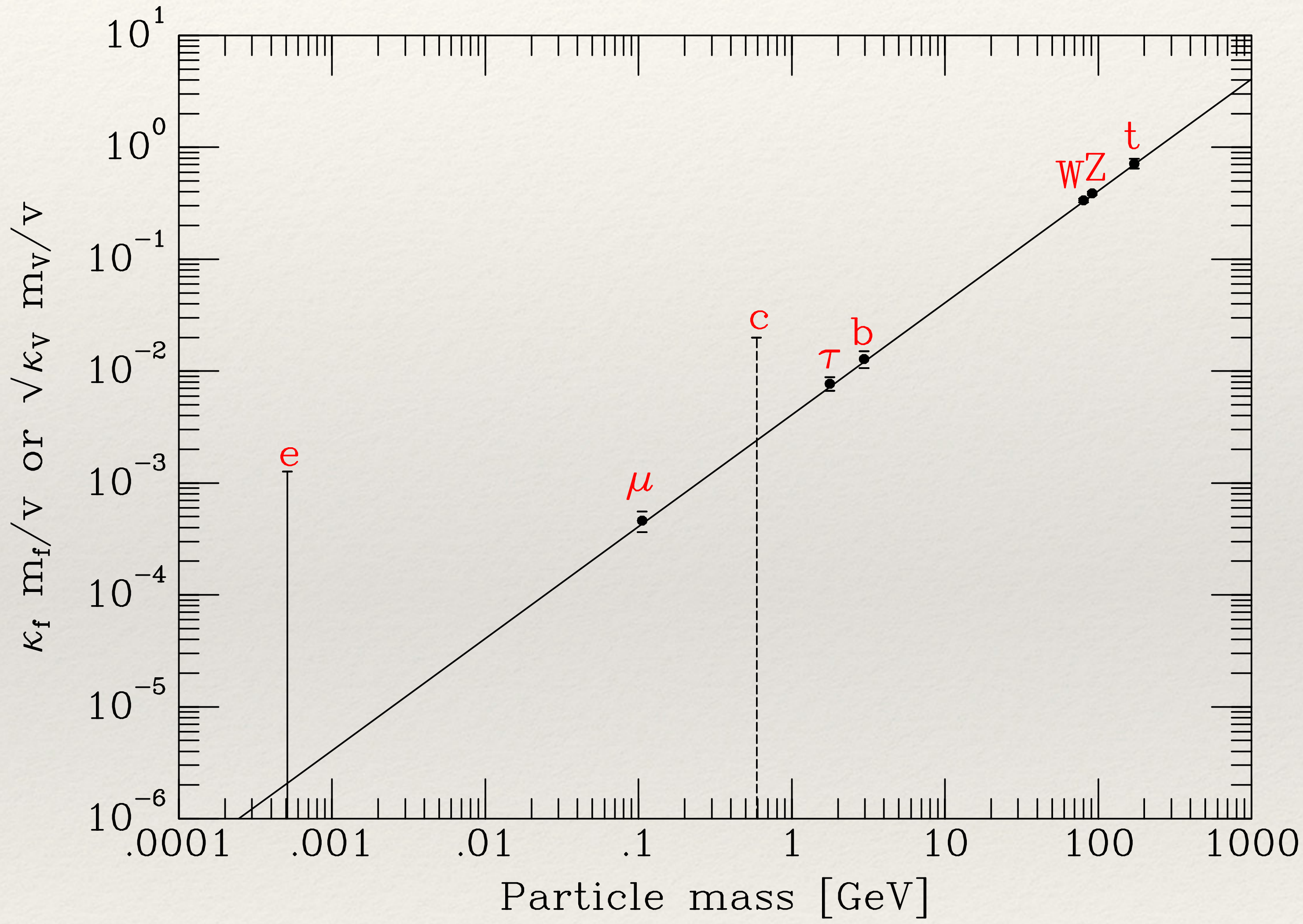
Combined Final States $= 1.10 \pm 0.11$
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.19^{+0.12}_{-0.11}$
$\gamma\gamma = 1.10^{+0.10}_{-0.09}$
$c\overline{c}$ Final State < 110, CL = 95%
$b\overline{b} = 1.02 \pm 0.15$
$\mu^+\mu^- = 0.6 \pm 0.8$
$\tau^+\tau^- = 1.11 \pm 0.17$
$Z\gamma < 6.6$, CL = 95%
$t\overline{t}H^0$ 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

Recent developments: Dalitz decay of the Higgs $h \to l^+l^-\gamma$,
Decay to muons, (ATLAS, CMS) $h \to \mu^+\mu^-$

Yukawa couplings of the Higgs boson

- Couplings to the charged fermions of the third generation established in 2018/2019;
- Coupling to μ observed at 3 sigma level by CMS;
- 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 arXiv:1909.02845 H→ ee, CMS, arXiv:1410.6679, H→cc, arXiv:1912.01662(as interpreted by me) H→$\mu\mu$ arXiv:2009.04363



Coupling to (charged) third generation fermions t, b, τ confirms a new Yukawa force, (i.e. beyond, strong, electroweak, gravity)

Higgs Physics provides guaranteed deliverables for future machines

- Mass of Higgs;
- Total Width of Higgs;
- Couplings of Higgs to all? particles;
- CP properties of Higgs couplings;
- Higgs invisible and untagged widths;
- Trilinear coupling of Higgs;
- Composite or elementary?

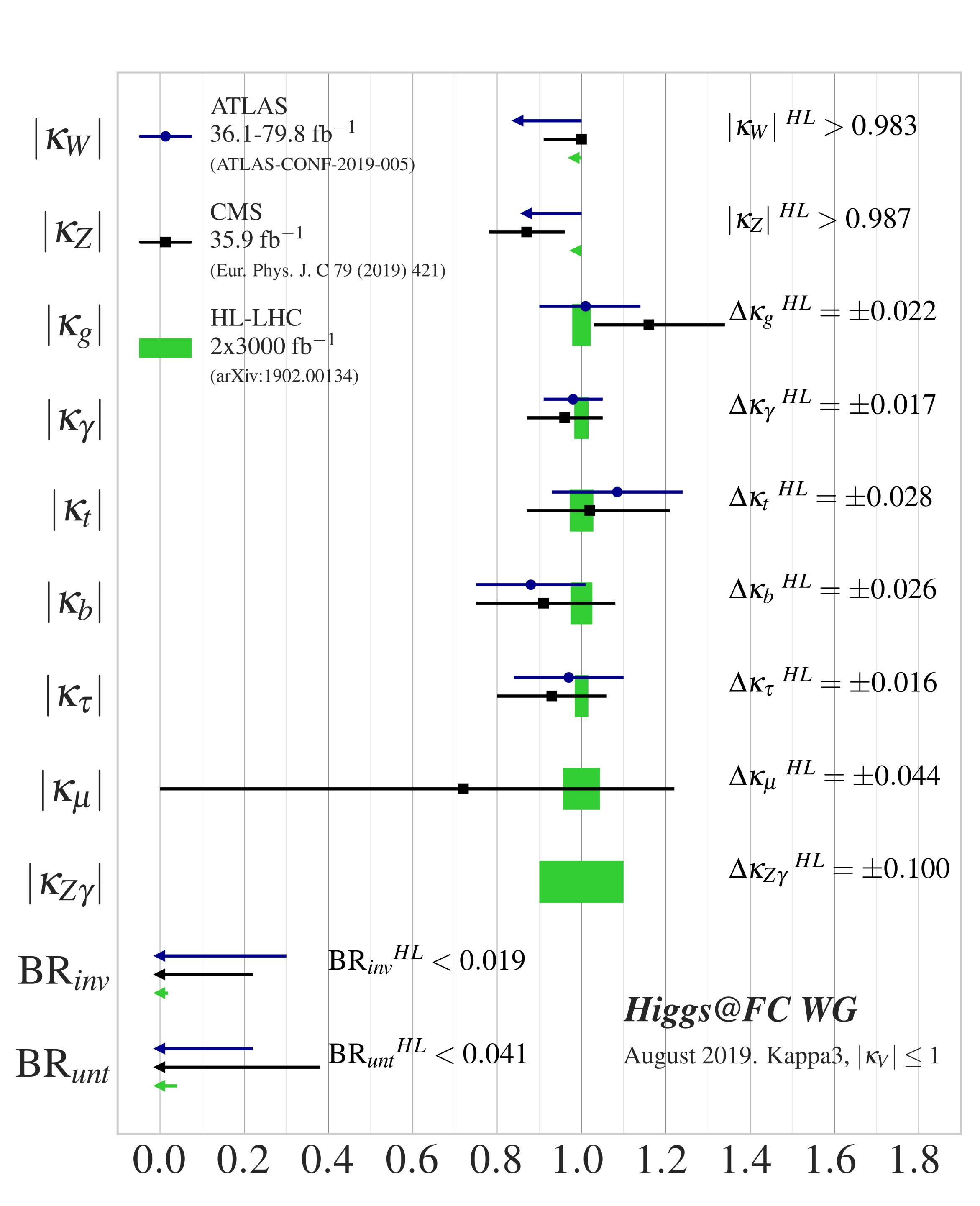
$$\mathcal{V}(\phi^\dagger\phi) = \lambda\,(\phi^\dagger\phi)^2 - \mu^2\phi^\dagger\phi\,.$$

$$\mathcal{L}_{\rm Higgs} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}M_h h^2 - \lambda_3\left(\frac{M_h^2}{2v}\right)h^3 - \lambda_4\left(\frac{M_h^2}{8v^2}\right)h^4$$

SM: $\lambda_3 = 1, \lambda_4 = 1$

Improvement in measurement of couplings expected from HL-LHC

- Important to remember that significant improvements are expected from HL-LHC;
- Only 5-6% of final LHC luminosity 3-4 fb^{-1} has been recorded;
- Kappa parameters: introduce the freedom to rescale all the couplings of the standard model.



Start from the basis of HL-LHC

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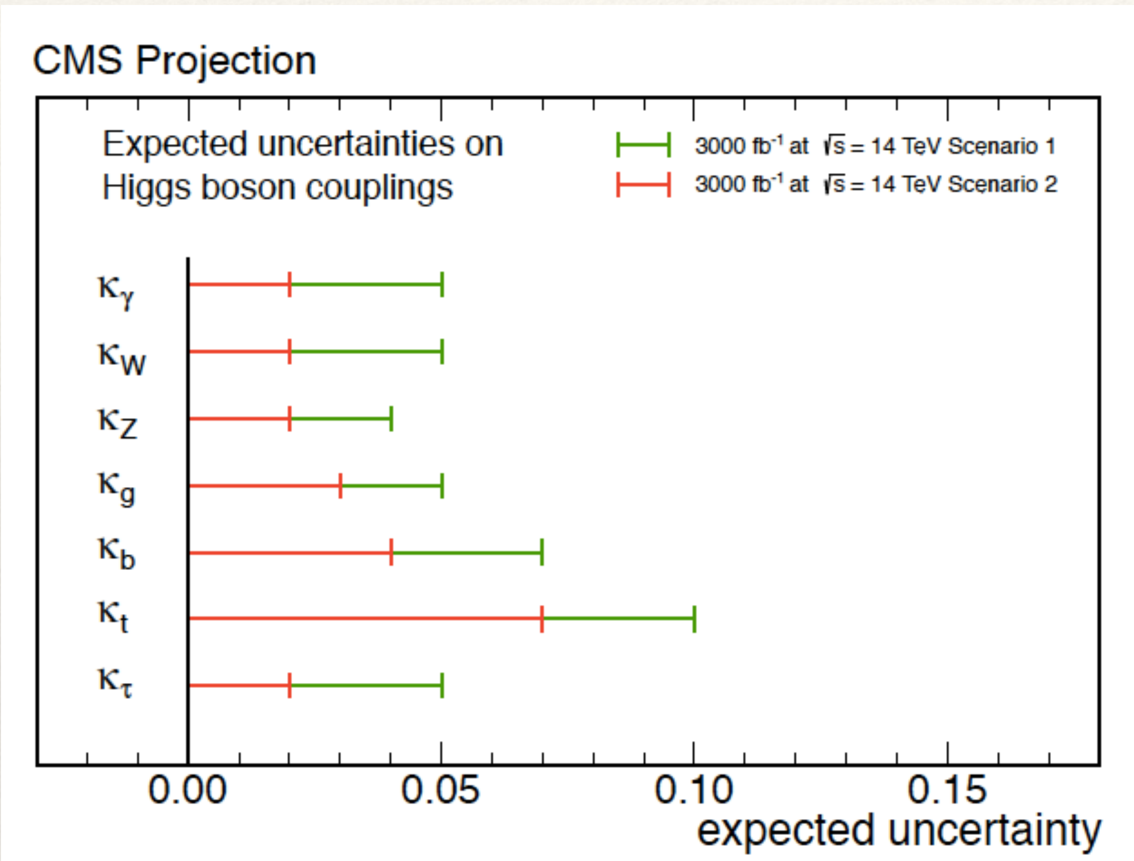

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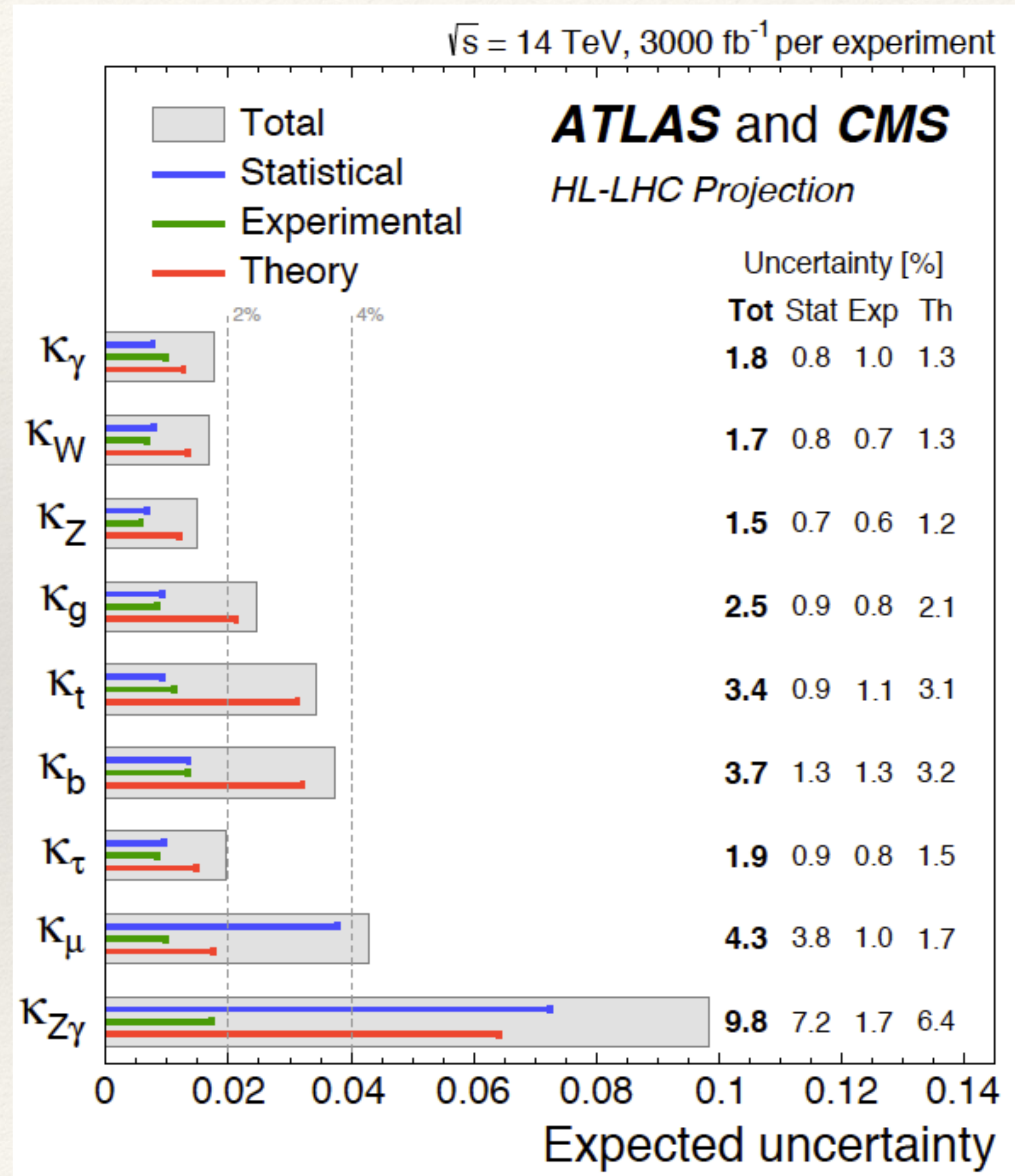


- Progress from 2013 to 2019
- With the availability of data, projections for the future have improved.
- Dominance of theoretical errors, for all modes except the two not yet seen at 5 σ level

European plan beyond HL-LHC

European Strategy: High priority projects

- "An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:"
- "the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;"

Dual medium terms goals: (e+e- Higgs factory + advanced accelerator R&D) Long term ambition: FCC-hh

- "Europe, together with its international partners, should investigate the 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. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."
- "The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate."

Support for ILC if decision is taken soon.

Proposed future colliders

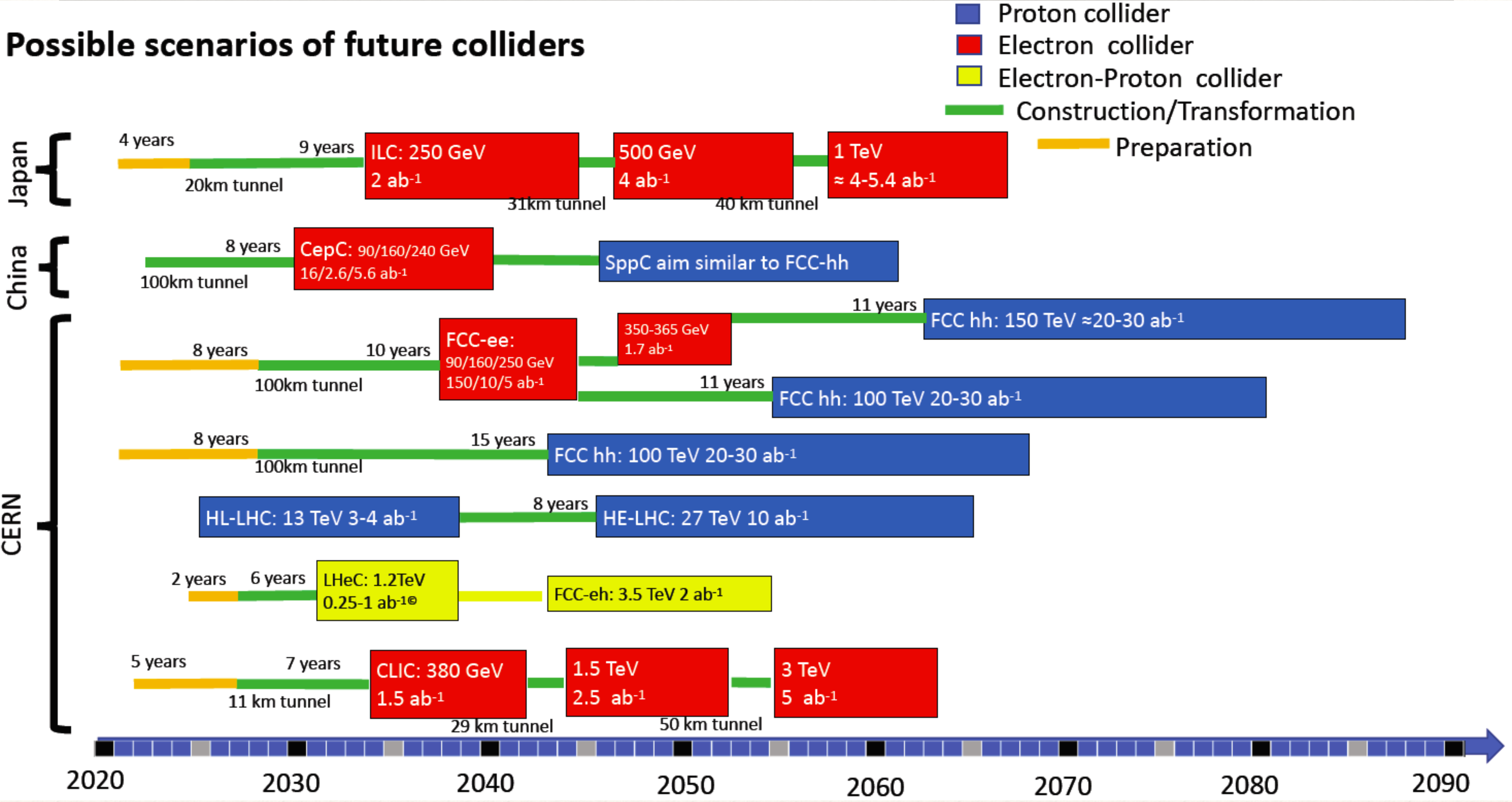
Comparisons

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	? ILCU=1US$ in 2012
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	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	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

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																							

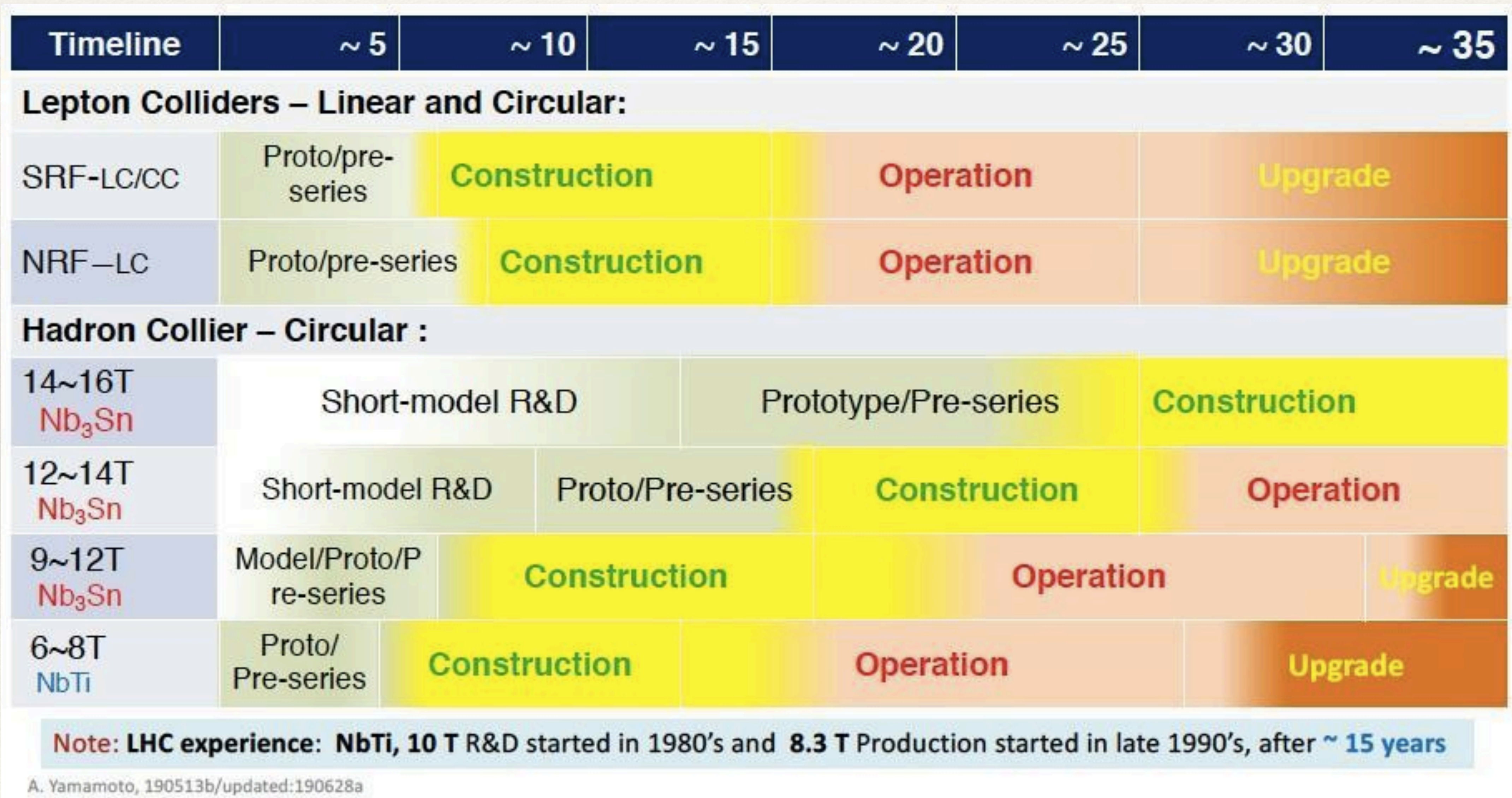
Possible timeline of future colliders



Ursula Bassler

Timescale for magnet development

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



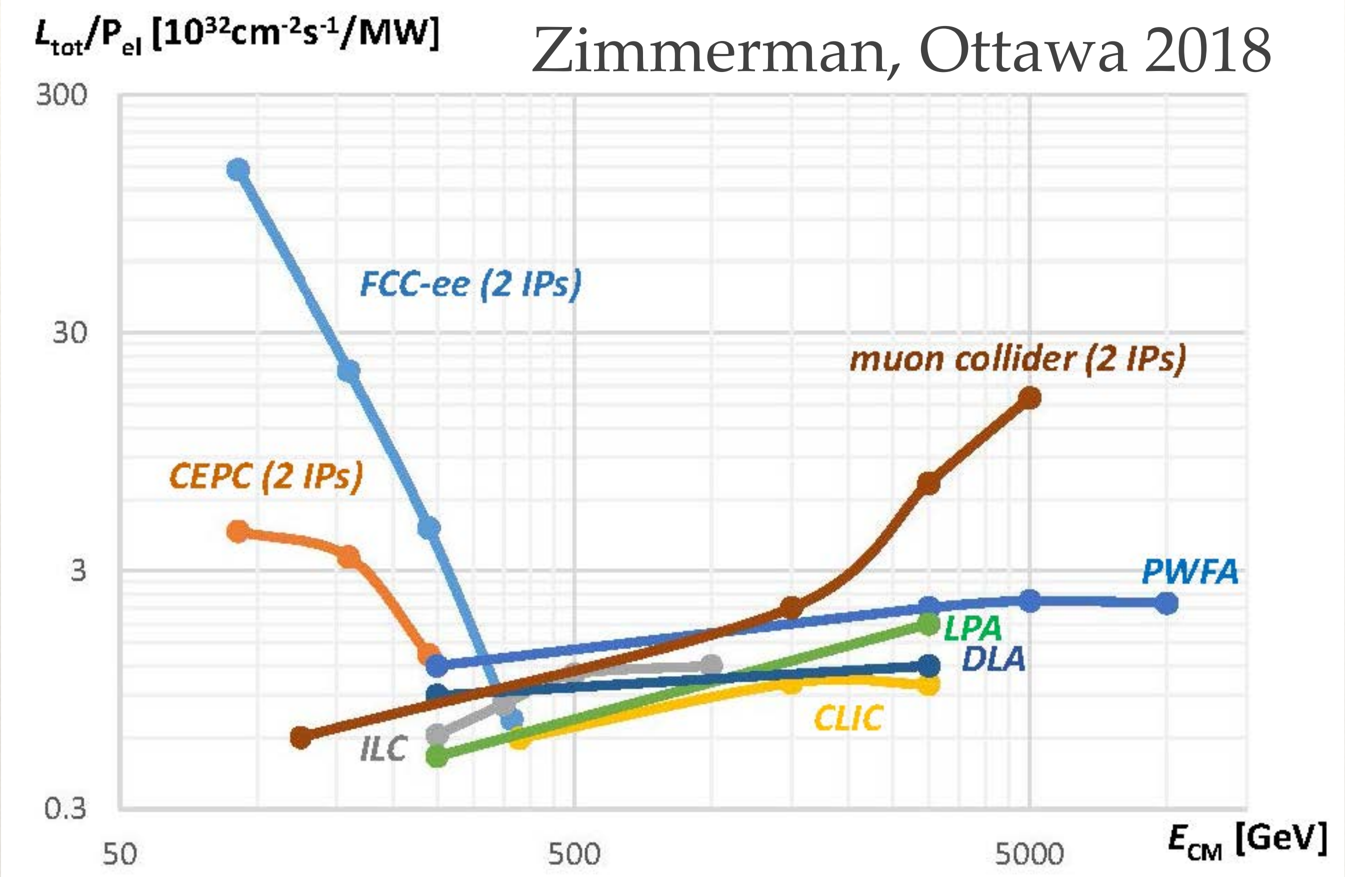
Yamamoto, Granada

FCC international partners

- Strategy of planning for FCC has been well received in the USA;
- Cooperation agreement between CERN and DOE signed in December 2020,
    - The FCC concept optimization;
    - Beam physics studies covering collider design;
    - Key technology development in view of a FCC-ee collider;
    - Longer-term activities that in view of a future FCC-hh collider: e.g. high-field magnet R&D for both Nb3Sn and HTS;
    - Broader topics of collaboration in view of preparation for project construction.

Muon collider advantages

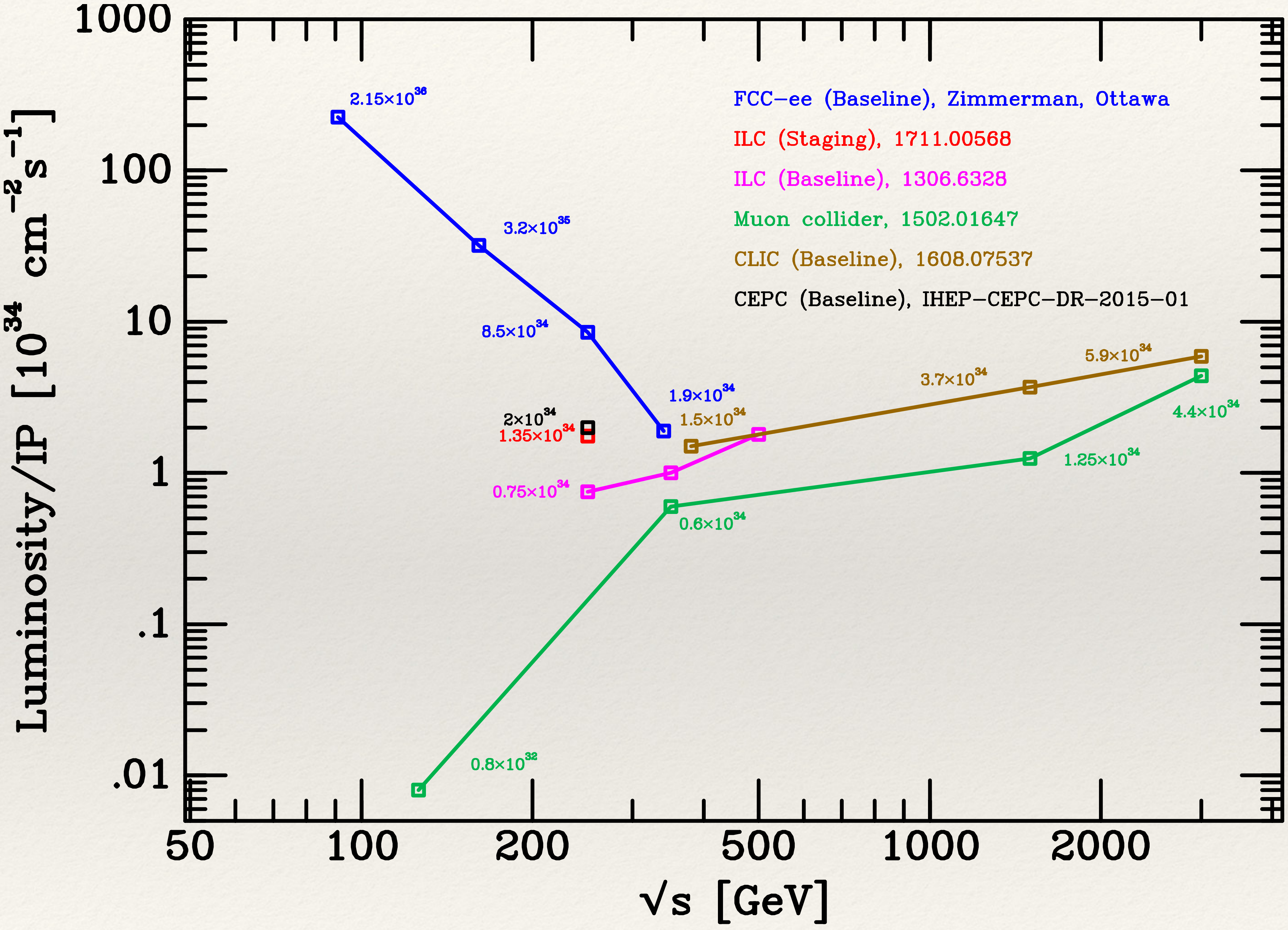
- R&D program, with physics at every step, Nustorm, Higgs factory, Neutrino Factory, High-energy lepton collider.
- Small size, leading to possibility of smaller civil construction, perhaps lower cost.
- Physics potential assessed in arXiv:2103.14043
- Challenge of creating cool muon beams, therefore a long way off.



- Luminosity per Megawatt, wall-plug power

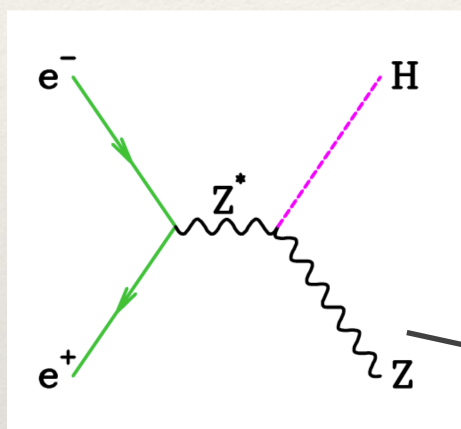
Higgs physics at proposed e^+e^- colliders

Luminosity at lepton colliders

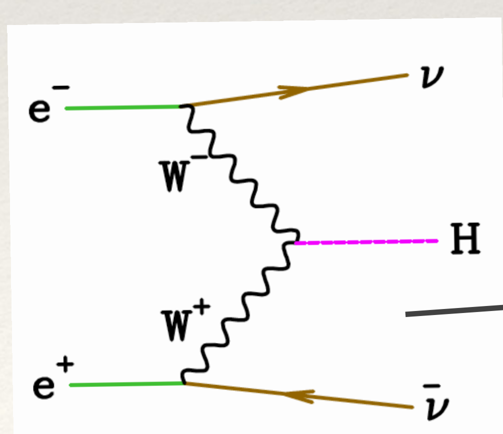


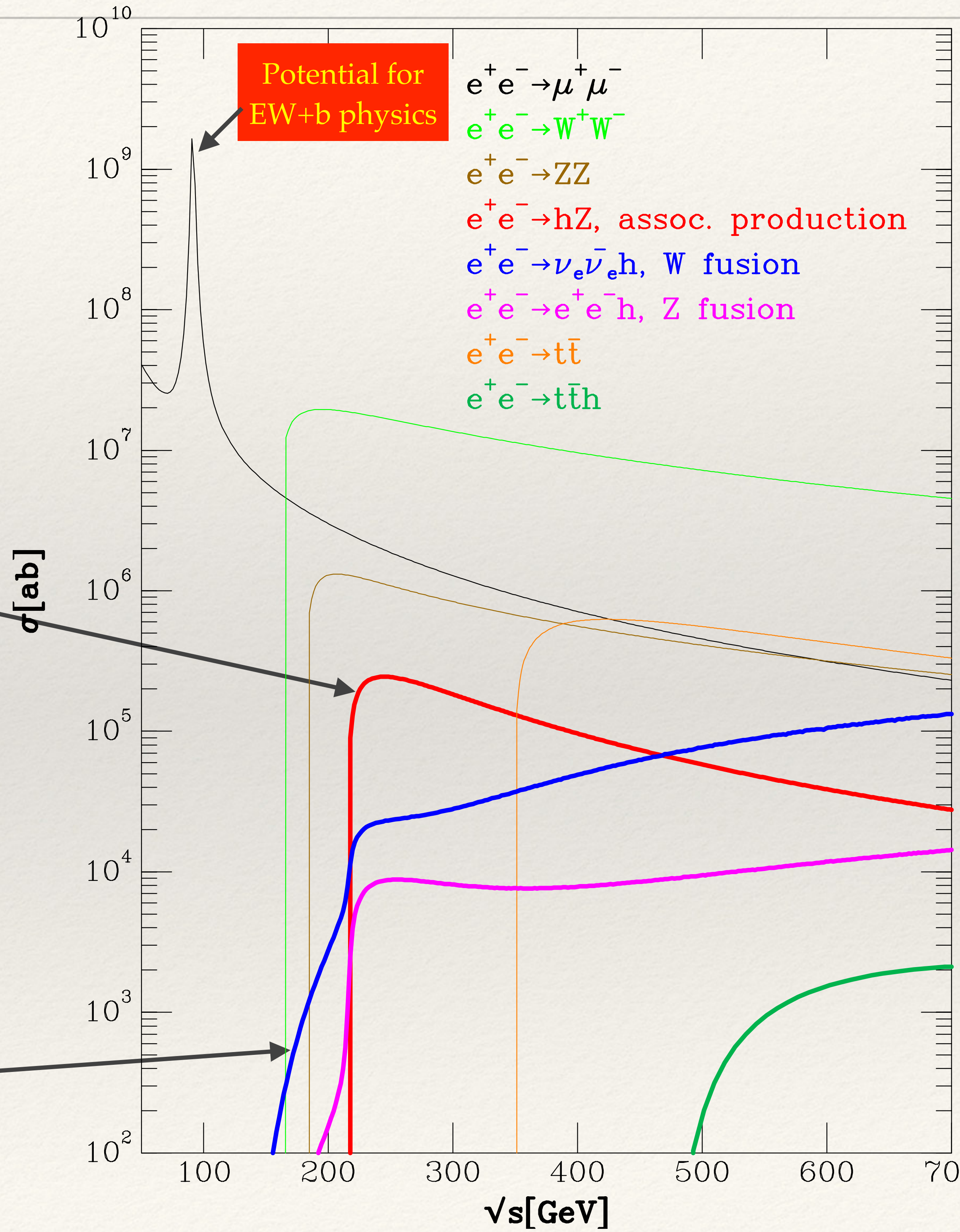
e^+e^- machines & Higgs bosons

- At √s~240 GeV we mainly produce the Higgs boson in association with a Z;



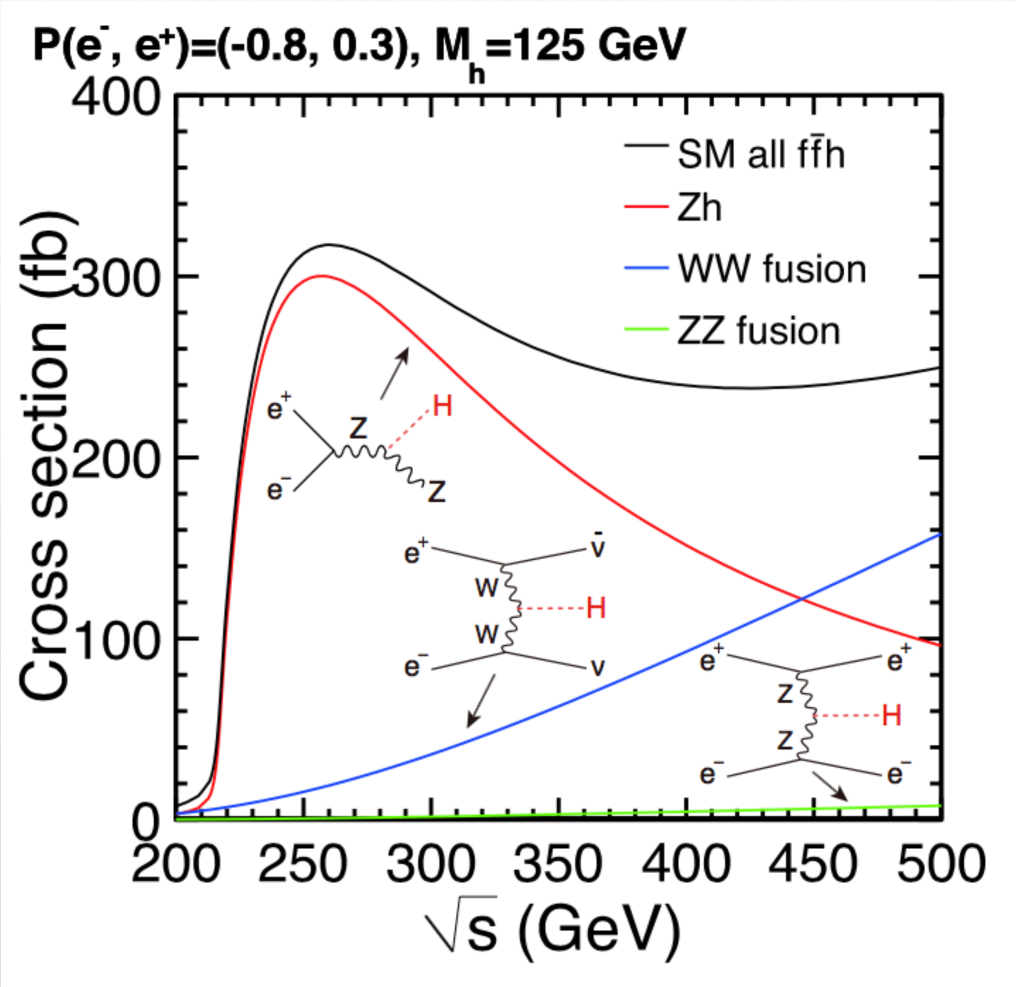
- At higher energy produce H by fusion of W-bosons (and Z).





Higgs at e⁺e⁻ collider: generalities

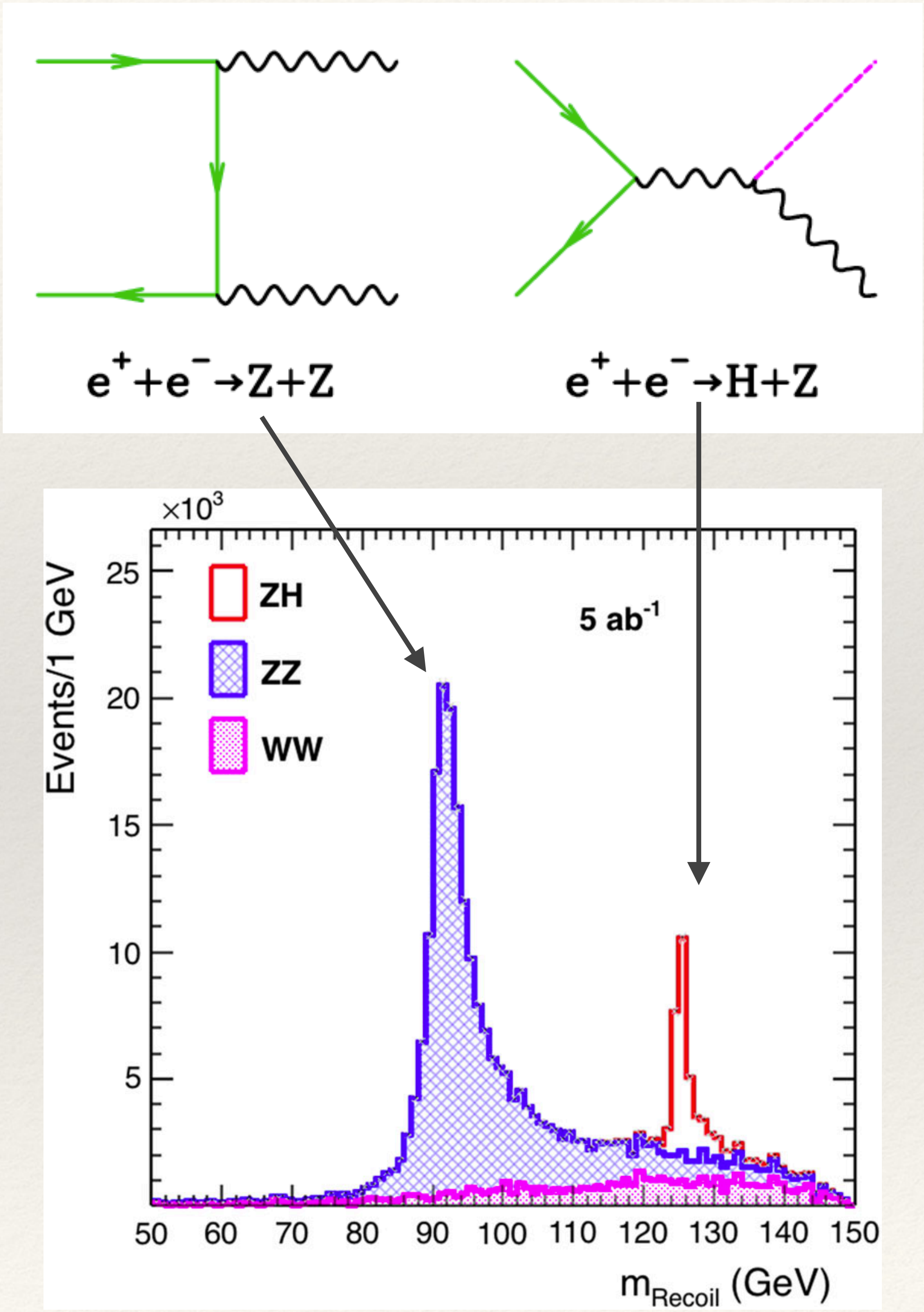
- WW fusion production ten times smaller at 250 GeV than at 500 GeV;
- ~40% increase in ZH cross section with polarization (-0.8,+0.3);
- In terms of precision Higgs parameters polarization is like a factor of ~2 in integrated luminosity;



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

Measurement of total ZH cross section

- Because the initial collision energy is known in e+e-, one can measure the mass of whatever is recoiling against the Z boson.
- We can thus detecting the Higgs boson without seeing the its decay.
- This gives a measurement of the ZH total cross section, independent of the Higgs boson decay width;
- Unique feature of lepton-lepton colliders;
- By subsequent analysis of identified Higgs events, one can measure BR to untagged and invisible;
- e.g. at FCC-ee$_{240}$, relative precision, $\delta\kappa_{\mathrm{inv}}=0.19\%$, $\delta\kappa_{\mathrm{untagged}}=1.2\%$;



Measurement of width

- Use total cross section and branching ratio.

$$\frac{\sigma(e^+e^- \to ZH)}{BR(H(\to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H(\to ZZ^*)/\Gamma_H} \approx \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H(\to ZZ^*)}\right]_{SM} \times \Gamma_H$$

- Often interpreted as a quasi-direct measurement of the Higgs width

Higgs width is probed to 1~2%

Collider	$\delta\Gamma_H$ [%] from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC_{250}	2.3	EFT fit [3,4]	2.2
ILC_{500}	1.6	EFT fit [3,4,14]	1.1
ILC_{1000}	1.4	EFT fit [4]	1.0
$CLIC_{380}$	4.7	κ-framework [98]	2.5
$CLIC_{1500}$	2.6	κ-framework [98]	1.7
$CLIC_{3000}$	2.5	κ-framework [98]	1.6
CEPC	2.8	κ-framework [103,104]	1.7
FCC-ee_{240}	2.7	κ-framework [1]	1.8
FCC-ee_{365}	1.3	κ-framework [1]	1.1

1905.03764

- All measurements of Higgs couplings at hadronic machines have to make assumptions about the total width.

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

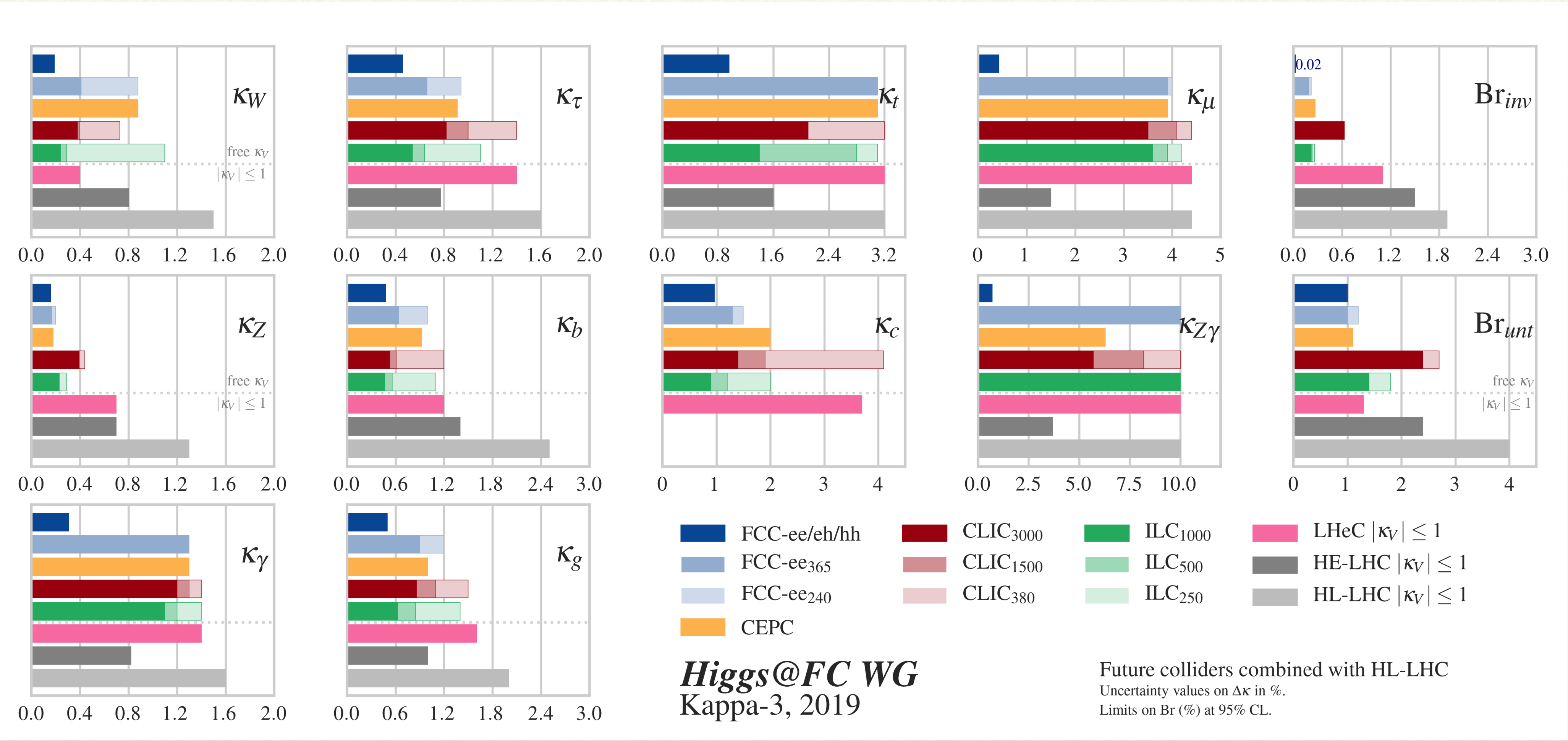
ABSTRACT

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 of the potential of various future machines
- using the inputs submitted to the update of the European Strategy for particle physics

arXiv:1905.03764

Kappa-scenario

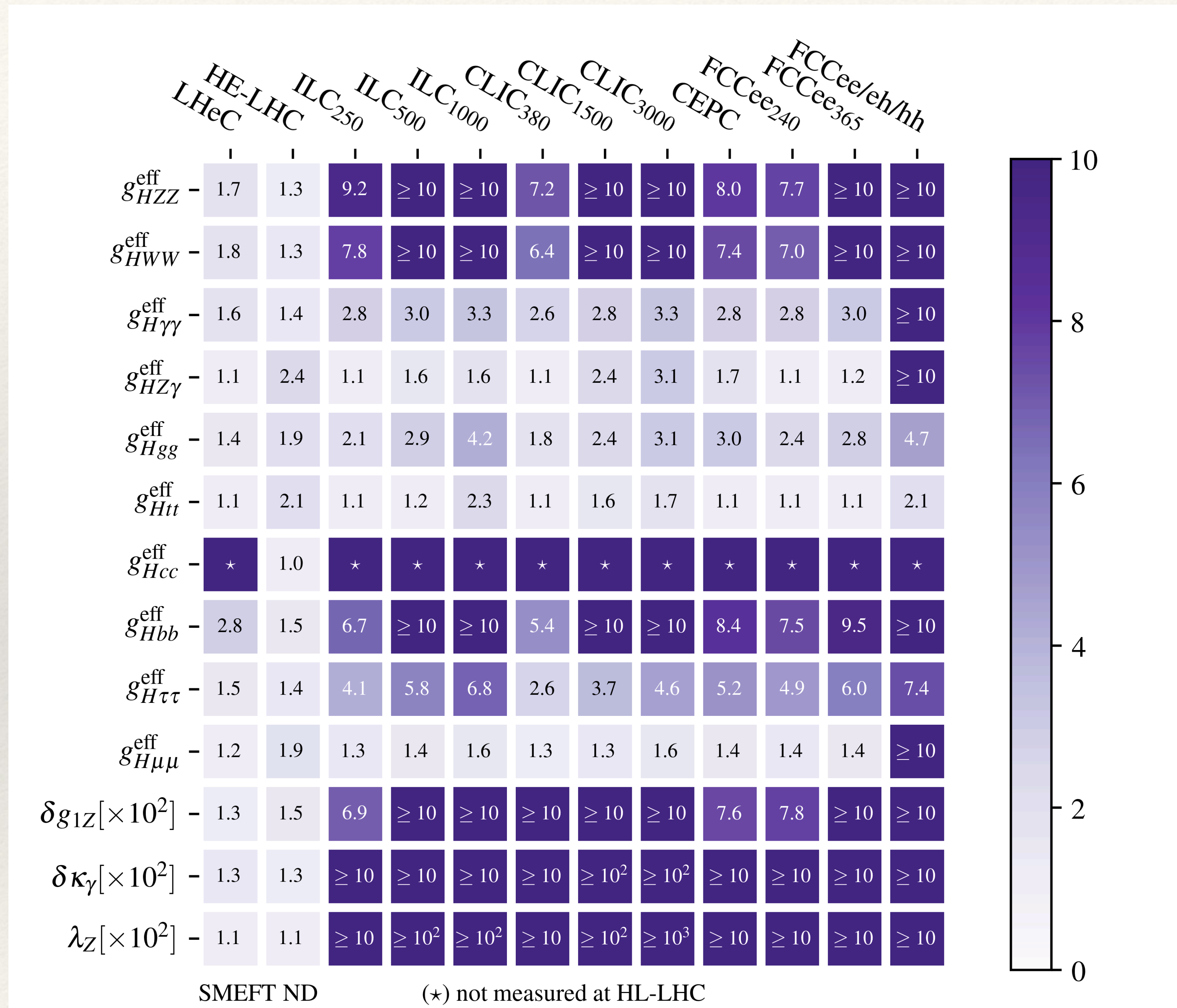


- κ has the advantage that it is simple;
- the effects of polarization are undervalued in this approach;
- would give indications of deviations from the SM, but not necessarily diagnostic information to interpret deviation;
- In this kappa framework HL-LHC projections are included, and the untagged and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

1905.03764v2

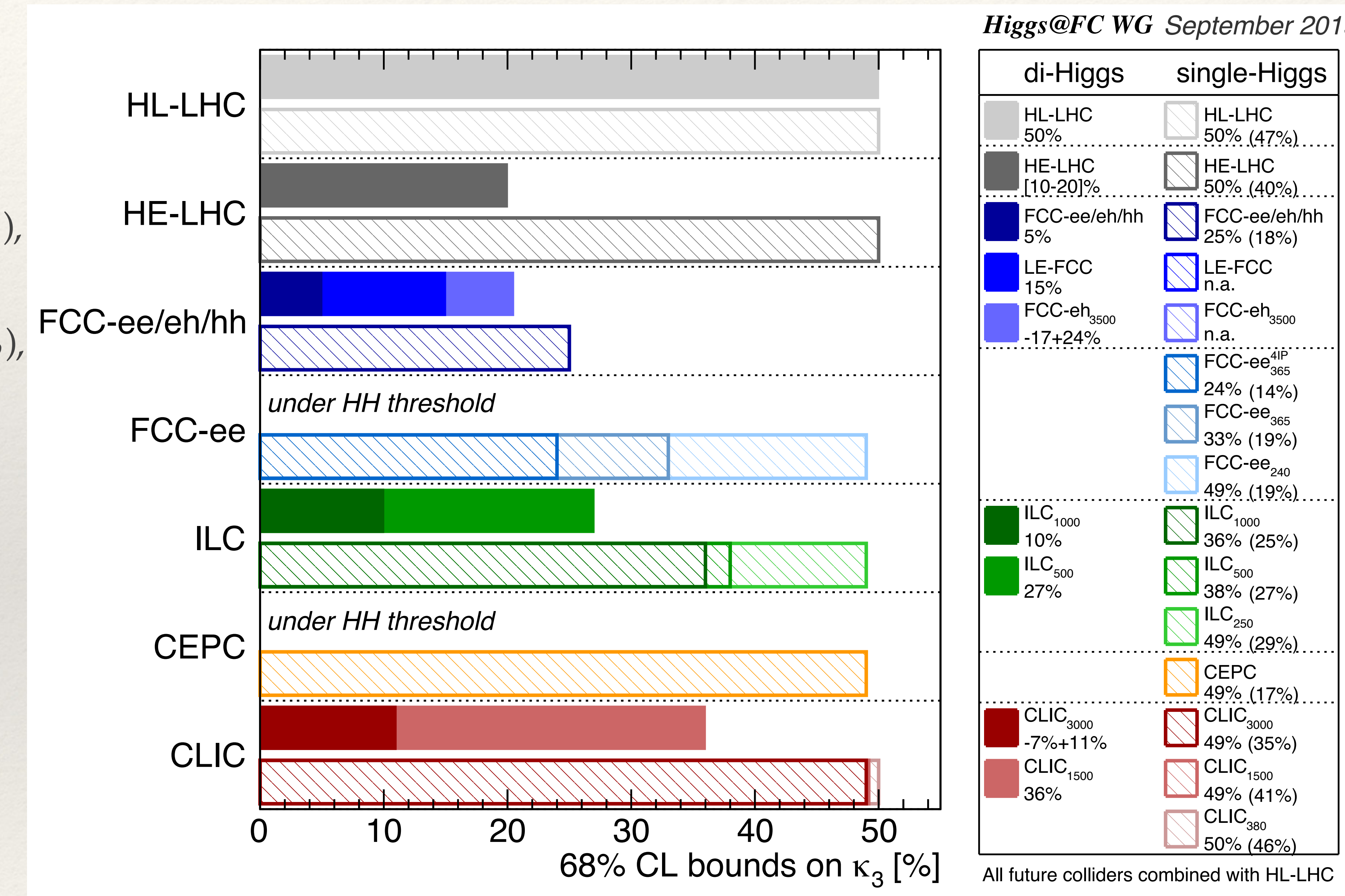
SMEFT analysis

- We consider (more sophisticated) SMEFT fit scenarios in the Higgs basis.
- To assess the deviations from the SM in a basis-independent way we define effective couplings
$$\left(g^{eff}_{HX}\right)^2 = \frac{\Gamma(H \to X)}{\Gamma^{SM}(H \to X)}$$
- Graphical representation of the improvement over HL-LHC in precision of couplings;
- Similar color for columns indicates similar reach for machines.
- Overall conclusion: first stage e+e- colliders all have similar reach, albeit with different time scales.



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

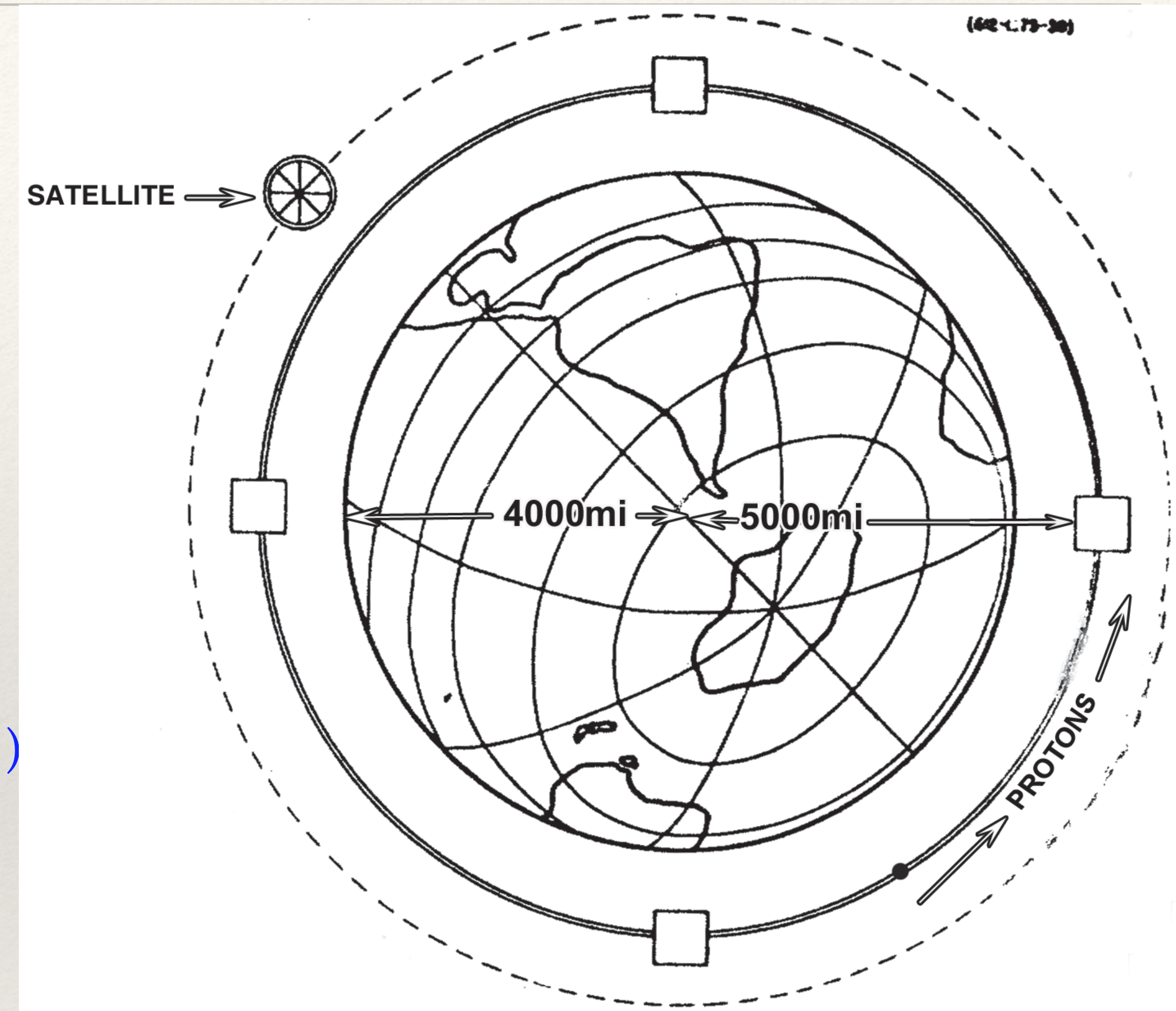
- Di-Higgs
  - HL-LHC ~50%
  - Improved by HE-LHC(20%), LE-FCC(15%), ILC500(25%)
  - Precisely by CLIC3000(9%), FCC(hh)(5%)
  - Robust w.r.t. other operators
- Single Higgs
  - Global analysis FCCee_365 and ILC500 sensitive to ~35% when combined with LHC.
  - ~21% if FCC-ee has 4 detectors



Precision measurement requires FCC-hh

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 Hans Bethe. The title of the presentation was **What can we learn from High-Energy Accelerators?**
- "Preliminary design…8000 km, 20,000 gauss" (2 Tesla)
- "Energy of 5×10^{6}GeV, cost \$170 Billion" ($\sqrt{s}$=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) .



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

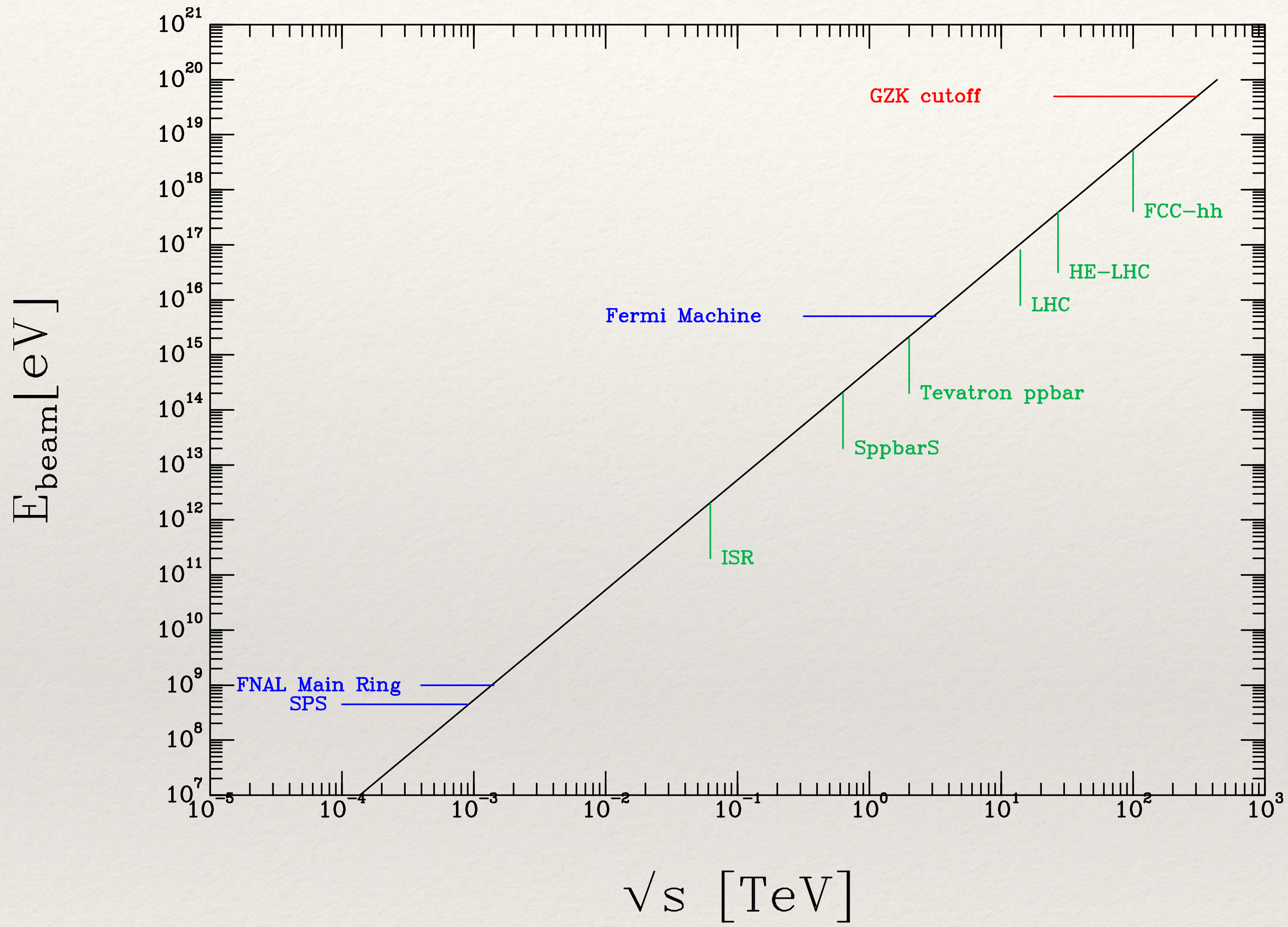
Retiring Presidential Address of the American Physical Society

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

Collider technique and superconducting magnets



	p[TeV/c]	B[T]	ρ
Fermi Machine	5000	2	8000[km]
LHC14	7.0	8.33	2,800[m]
LHC27	13.5	16	2,800[m]
μ-Higgs factory	0.0625	8.33	50[m]
μ-collider	0.625	8.33	500[m]
100TeVpp	50	16	10.4[km]

Table 1: Bending radius of various proposed machines

$$\frac{pc}{e}[TeV/c] = 0.299\, B[T]\, \rho\, [km]$$

- Current and future colliders have c.o.m energies fixed above that of the Fermi Machine, thanks to the colliding beam technique and the development of superconducting magnets.
- This is a message of hope: human ingenuity+technological progress will continue.

Epilogue

- Human ingenuity (colliders, superconducting magnets) have allowed the field to progress. There is no reason to think that the reservoir of human ingenuity has run dry.
- Vigorous R&D on alternative acceleration techniques and magnets is mandatory.
- 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 valuable information about the $Br_{invisible}$, (semi-direct measurement of Higgs width);
- Higgs physics is the central concern of HL-LHC. We hope it provides the key to understanding the shortcomings of the Standard model (hierarchy, EW potential, theory of flavour, Baryon asymmetry, dark matter, vacuum stability….)

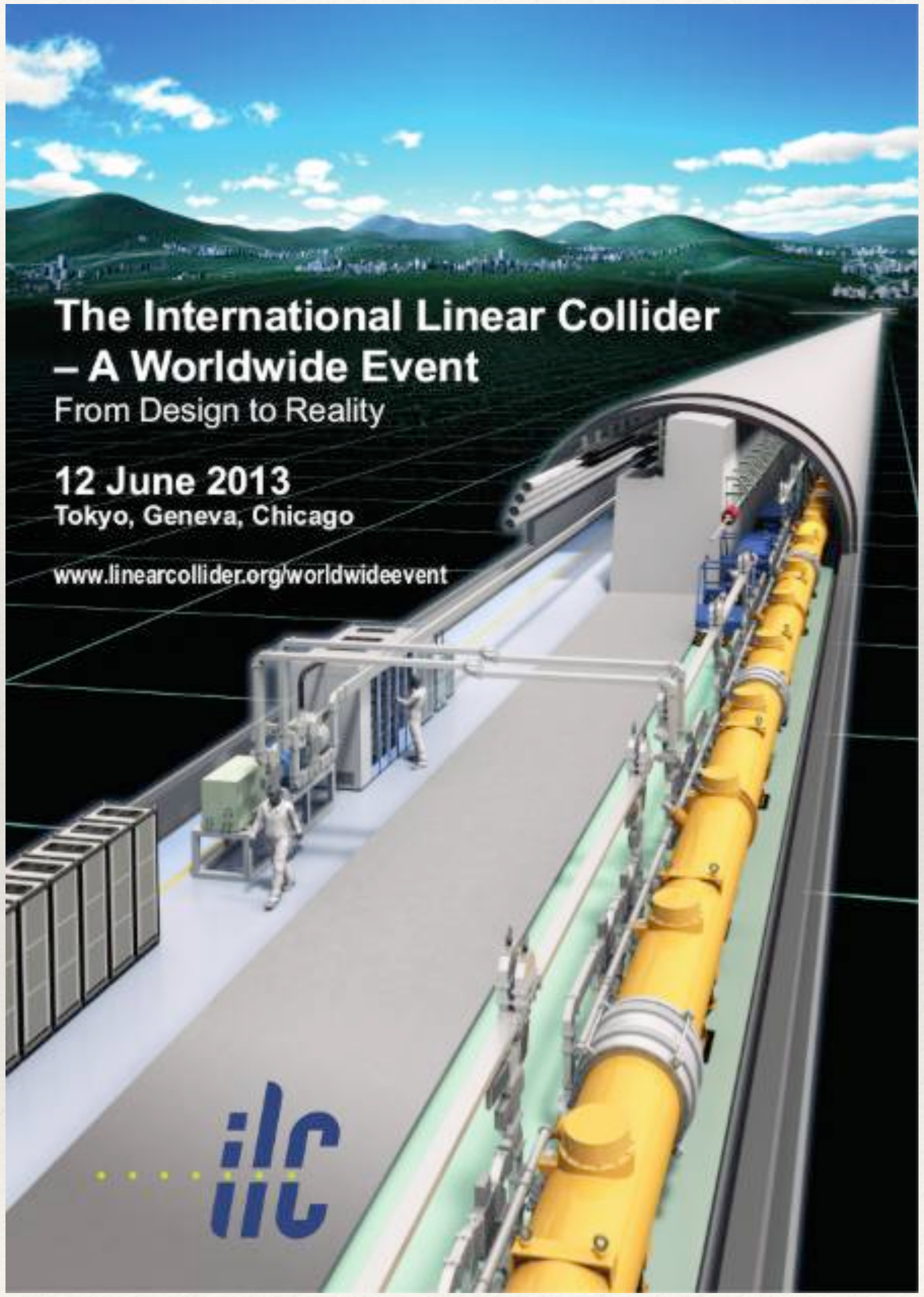
Thanks

- A big thank you to all of you who contributed to the success of Pheno-2021;
- Local organizing committee: (Brian Batell, Ben Carlson, Ayres Freitas, Joni George, Akshay Ghalsasi, Tao Han, Adam Leibovich, Cedric Weiland, Keping Xie);
- But of course there are many more….who unfortunately I can not identify from 5,800 km away.

Backup

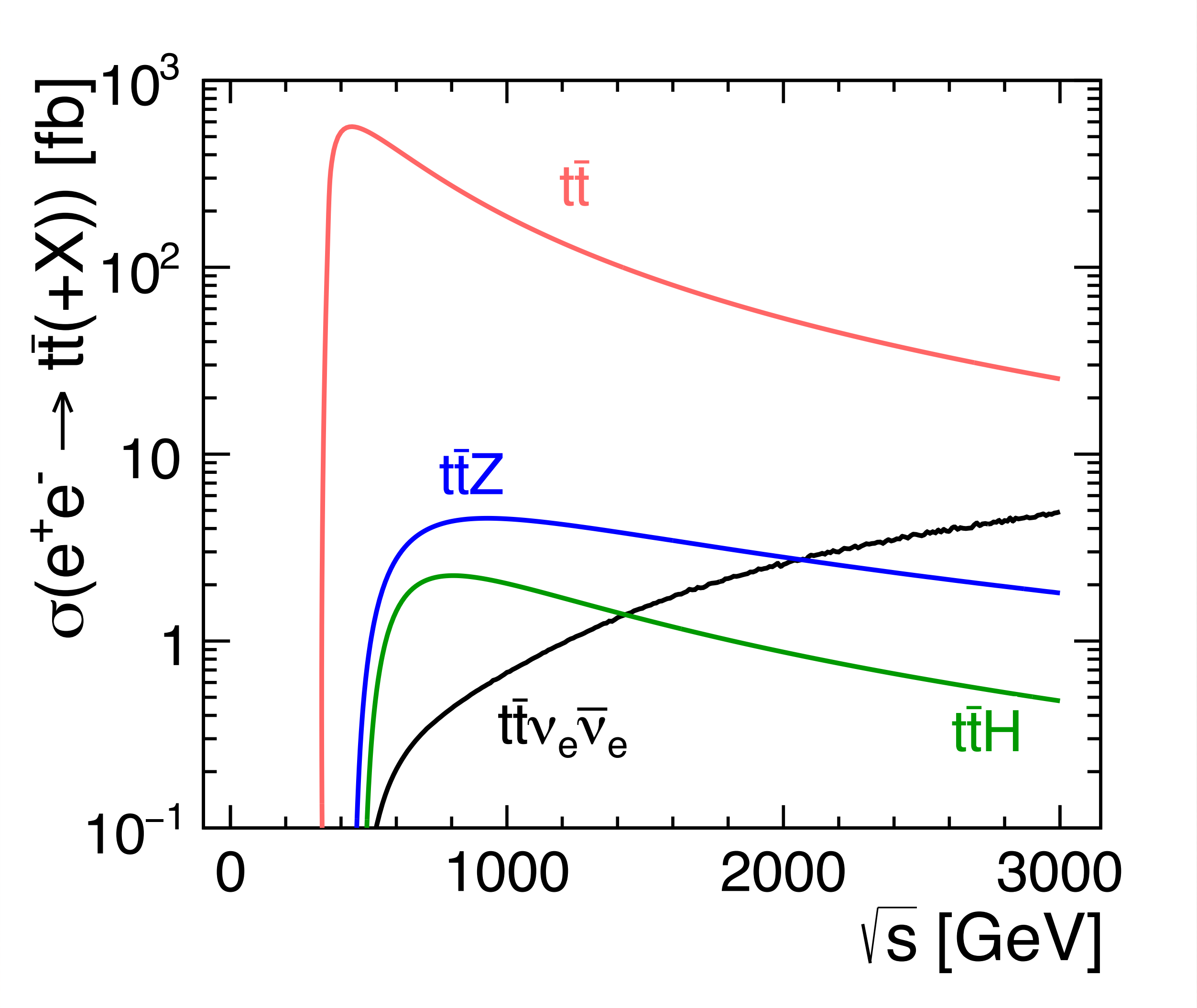
ILC advantages

- A very challenging machine, which now benefits from 20 years of R&D.
- Measurement of Higgs width, using missing mass technique (Common to all e+e- colliders).
- Polarization increases ZH cross section 40% and helps in analysis.
- Japan may pay a substantial fraction of the cost.



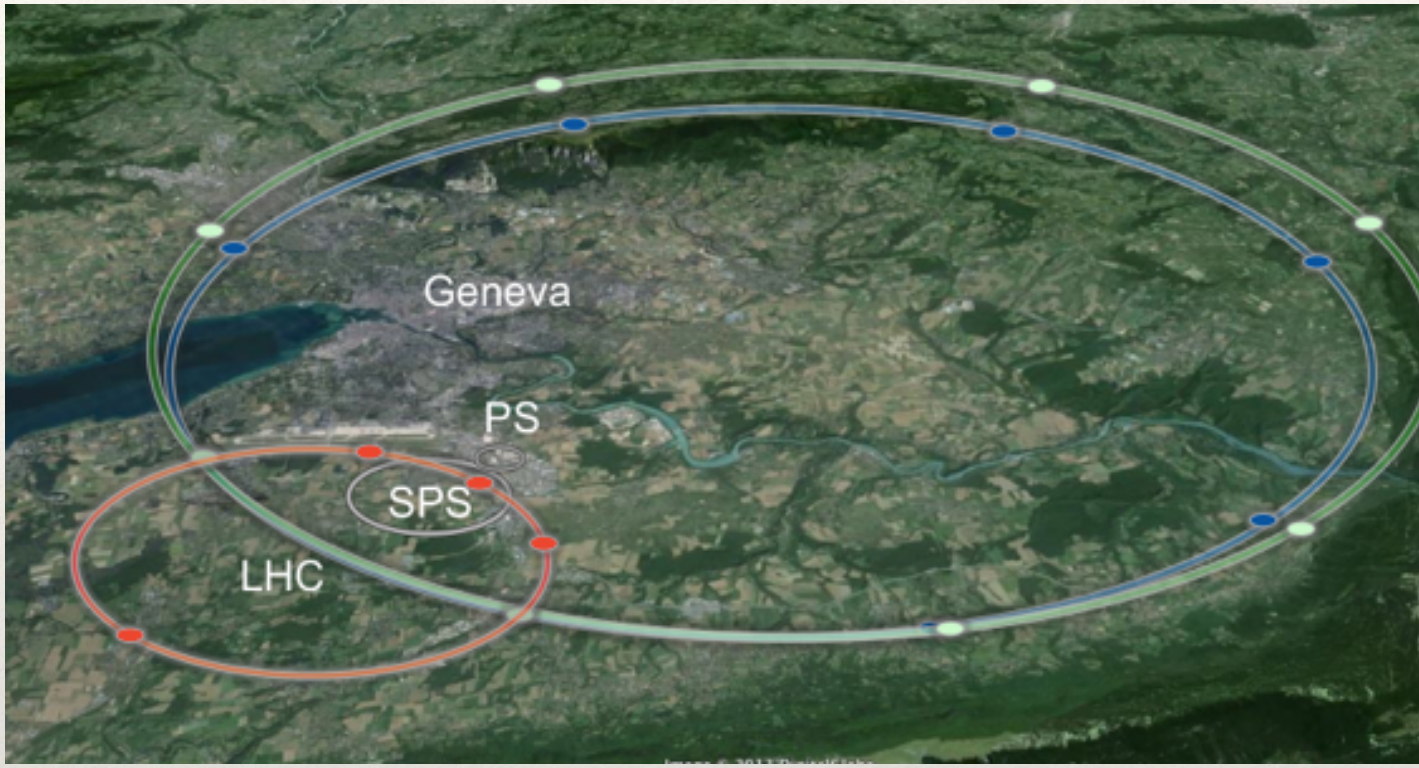
CLIC Advantages

- All the advantages of other e+e- machines, including polarization.
- Higher initial energy gives access to tt, (and subsequently ttZ, ttH)
- Possible path to high energy, projected energies, √s=380,1500,3000 GeV.

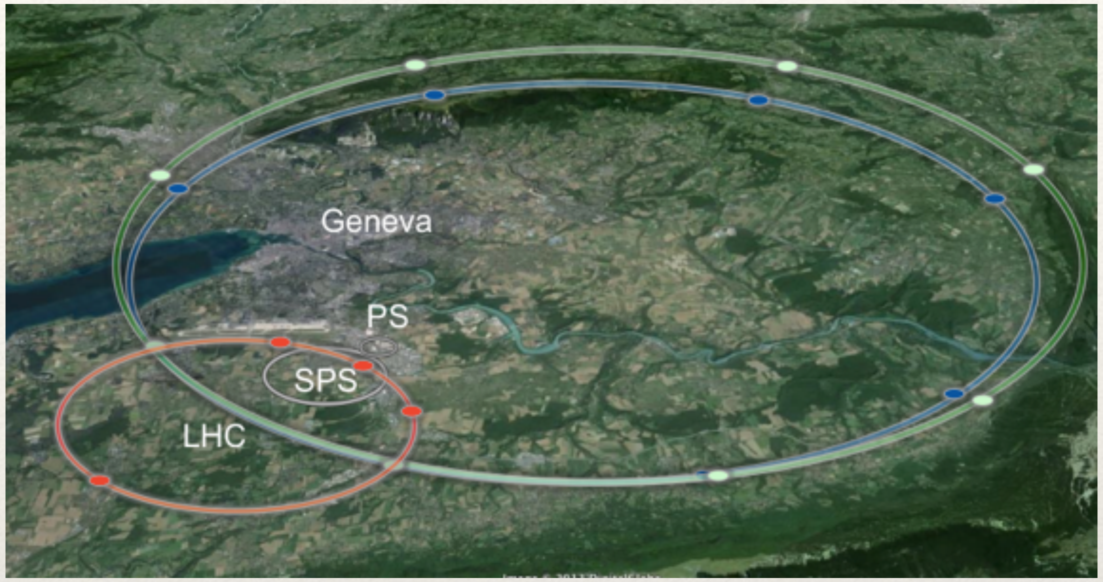


FCC(e+e-) Advantages

- Luminosity (superior to ILC).
- Access to physics at the $\sqrt{s}$=91,240,350 GeV
- Tunnel for further use
- TDR in 2018.
- c.f. CEPC, although limitation on energy consumption gives lower projected luminosity (but also lower cost).



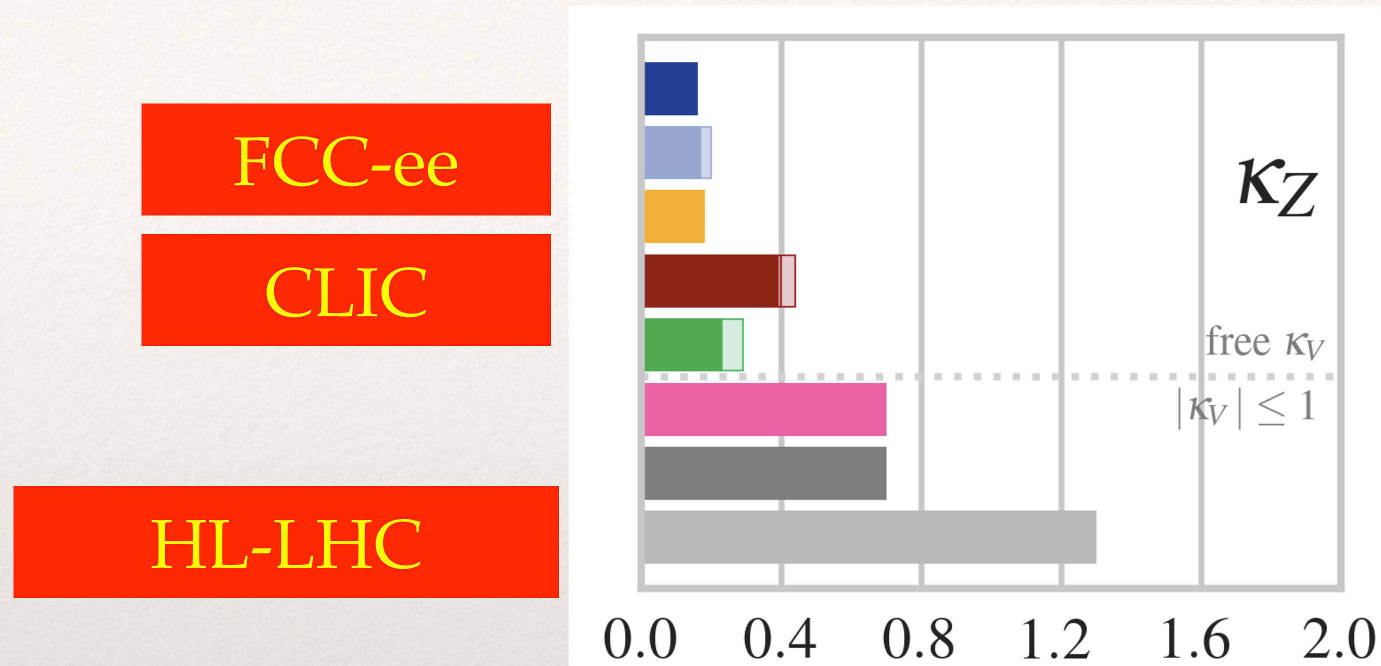
FCC(hh) advantages

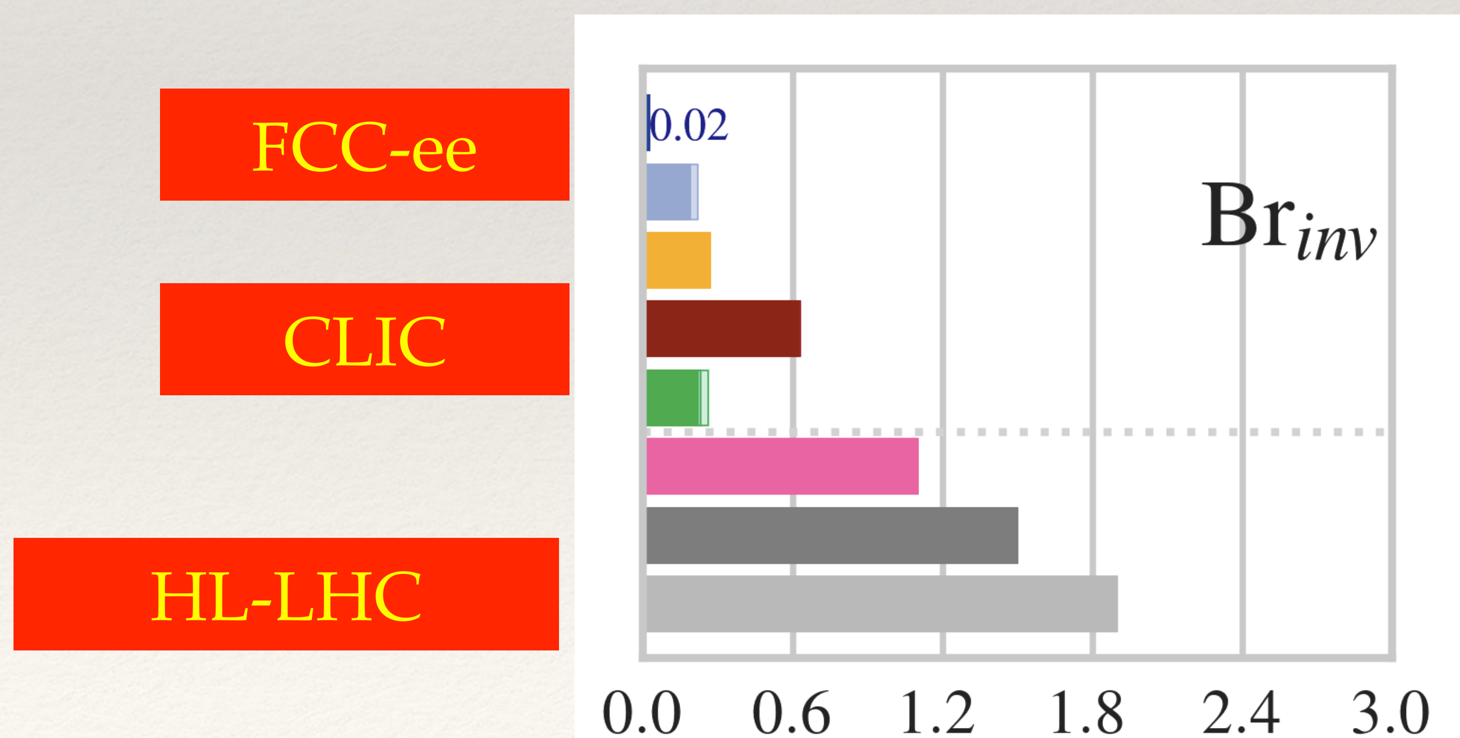


- Large jump in energy
- The highest energy hadron-hadron machines have always been considered discovery machines, and have not failed us, (SppS (W,Z), Tevatron (Top), LHC(Higgs).

Look at a couple in more detail

- Expected relative precision on kappa parameters in percent.





Open questions

- Is H the only scalar degree of freedom?
- Is H elementary or composite?
- What keeps $M_H^2 \ll M_{Planck}^2$?
- Was the electroweak phase transition first order?
- Did CP violating Higgs interactions generate the baryon asymmetry?
- Are there light SM-singlet degrees of freedom, exploiting a Higgs portal (in particular, related to Dark Matter)?
- What is the solution of the flavor puzzle(s)?
- Why extrapolating the theory to high energy are Higgs and top mass just so?

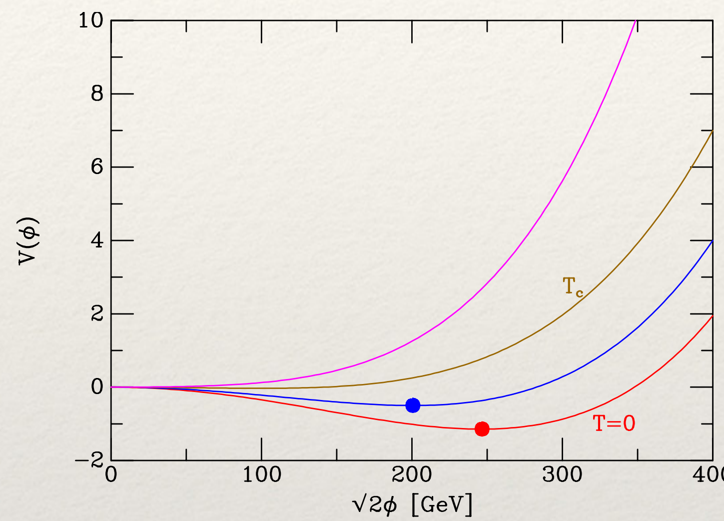
The Higgs boson raises as more questions than it answers

Heinemann and Nir 1905.00382

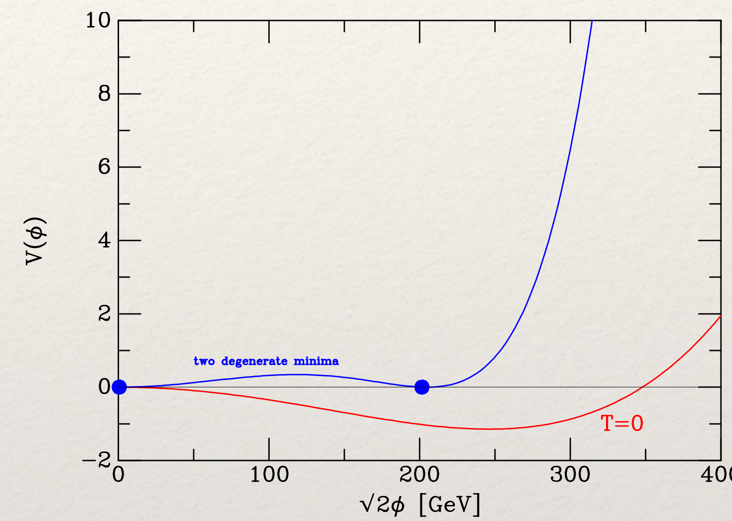
Higgs Potential

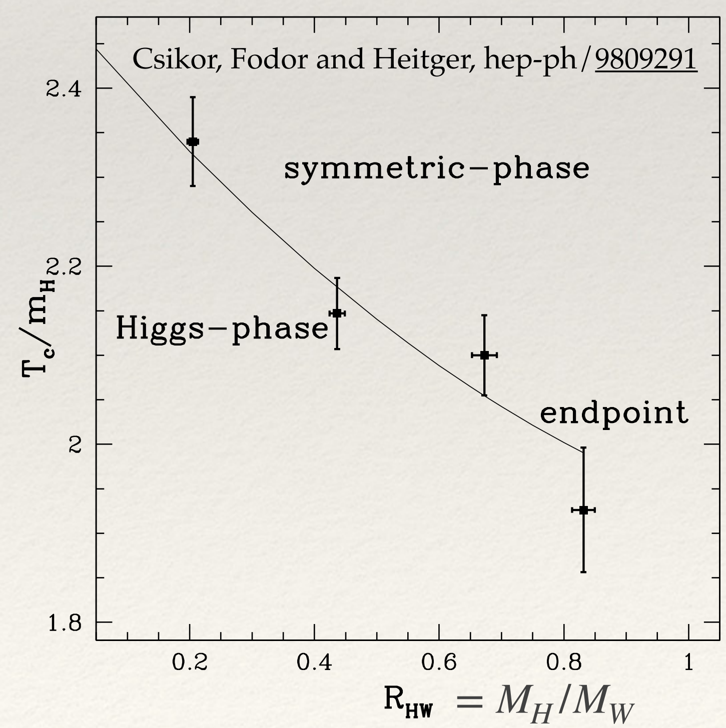
- Potentially important!
- The interest in the order of the EW phase transition is largely related to baryogenesis.
- Lattice simulations indicate a first-order phase transition at $M_H \leq 72$ GeV, and a cross-over otherwise.
- A strongly first order transition with sizeable sources of CP violation from BSM dynamics could generate the observed cosmological baryon asymmetry.
- The triple Higgs coupling gives information about the T=0 potential.

Crossover



1st order phase transition





- Sakharov conditions
- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium

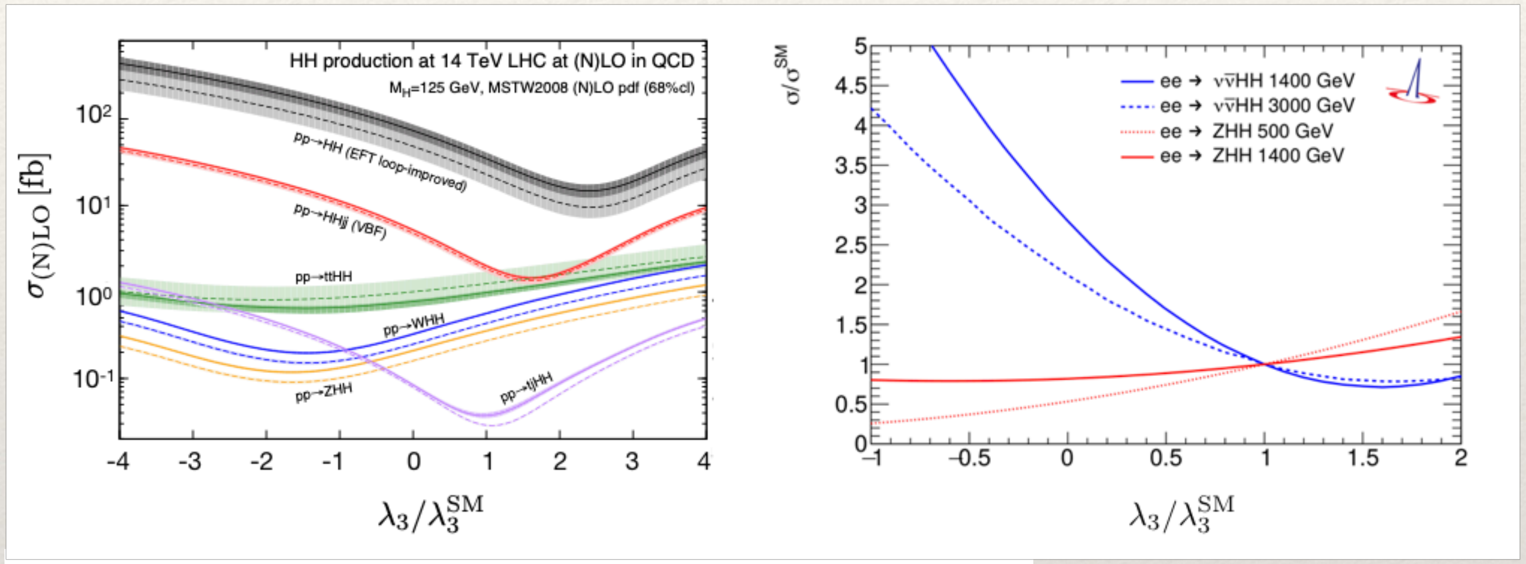
Measuring the Higgs potential

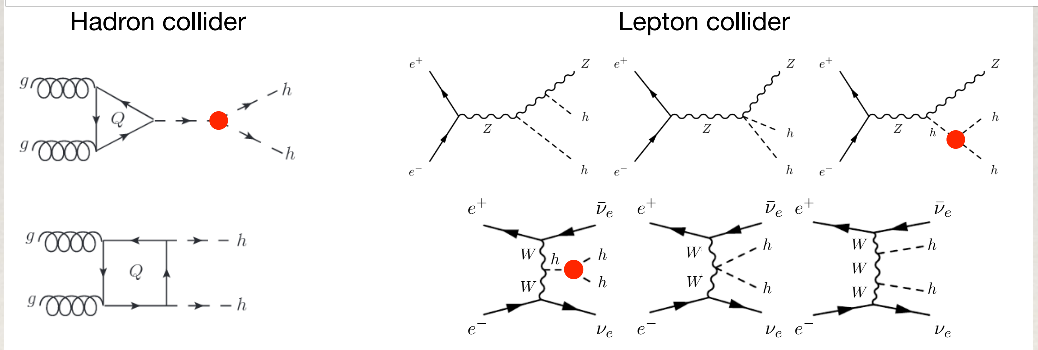
In SM potential fixed in terms of m_H and v

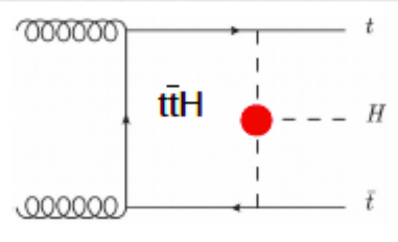
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

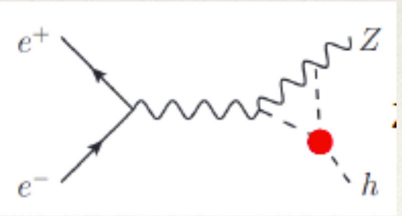
with $\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$

- 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

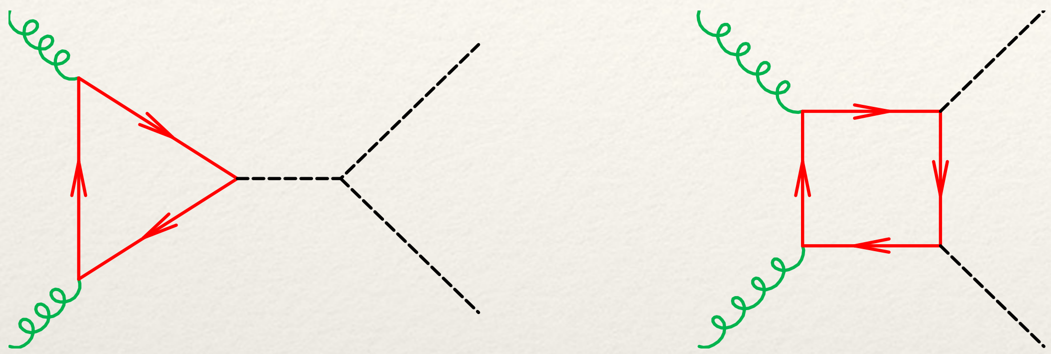


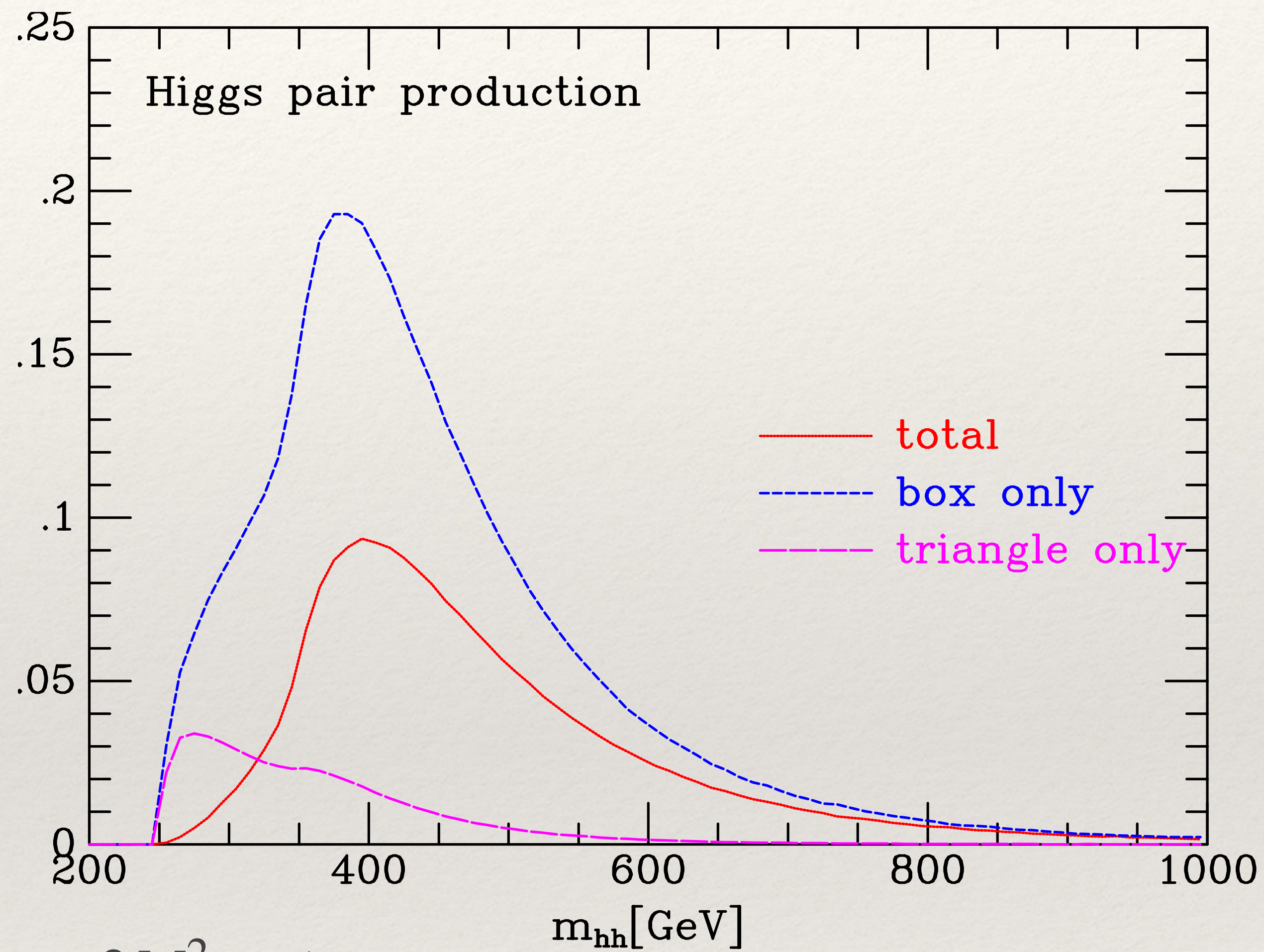






Higgs pair production





$$\mathscr{L} = \frac{1}{v} g_{ggH} H \left[\frac{1}{4} G^{\mu\nu} G_{\mu\nu}\right]$$

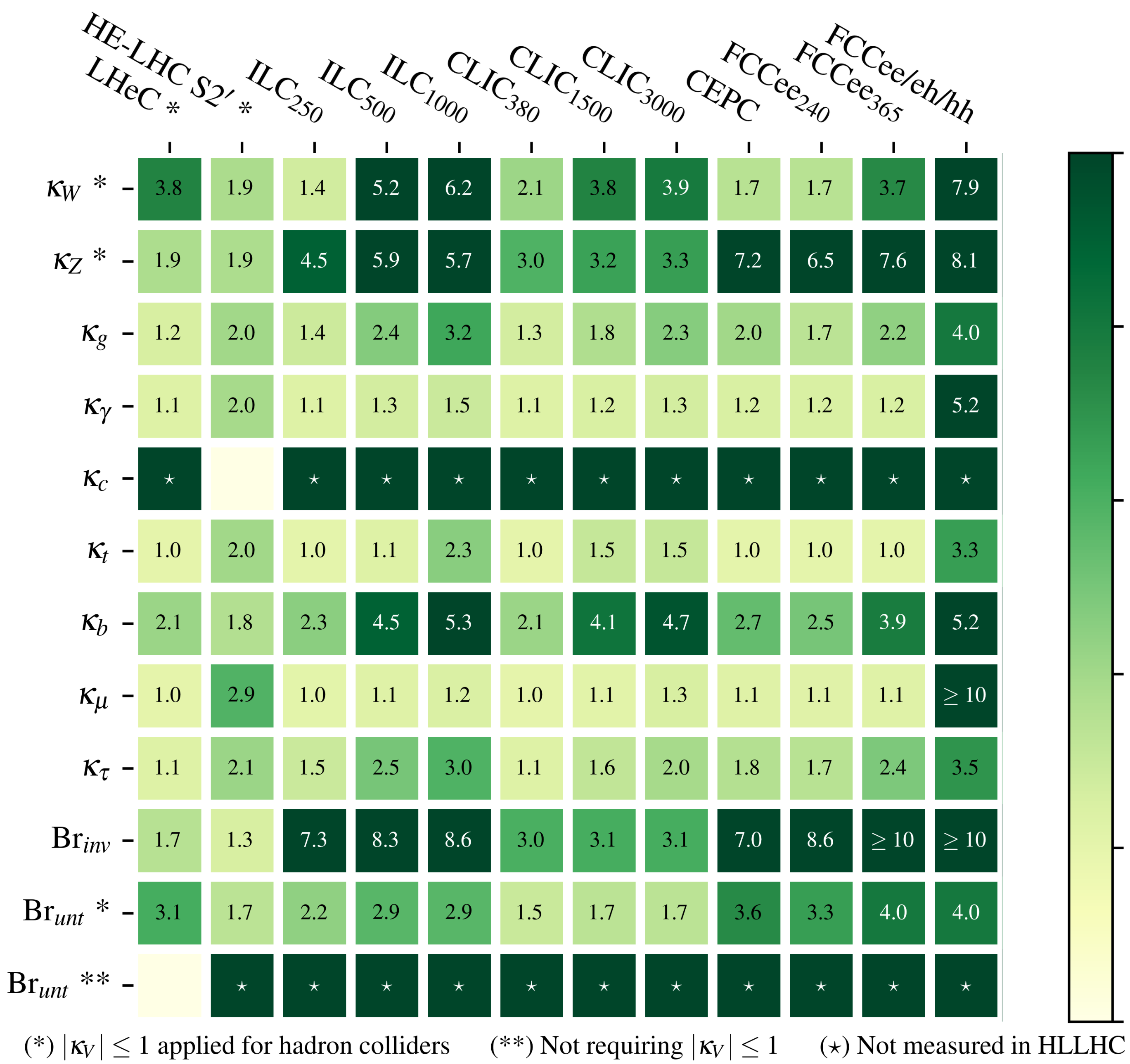
$$g_{ggHH} = -\, g_{ggH}$$

$$\mathscr{L} = \frac{1}{2v^2} g_{ggHH} HH \left[\frac{1}{4} G^{\mu\nu} G_{\mu\nu}\right]$$

$$\mathscr{M} = \left[\frac{g_{ggH}}{v} \frac{i}{[s - M_H^2]} (-i) 6\lambda v + \frac{g_{ggHH}}{v^2}\right] = \left[\frac{g_{ggH}}{v} \frac{3M_H^2}{[s - M_H^2]} \frac{1}{v} + \frac{g_{ggHH}}{v^2}\right] \to 0 \text{ for } s - M_H^2 = 3m_H^2$$

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.



Improvement of HL-LHC effective operator formalism

- Graphical representation of the improvement over HL-LHC in precision of couplings;
- Using an effective operator formalism — theoretically somewhat more respectable than kappa formalism;
- 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}.