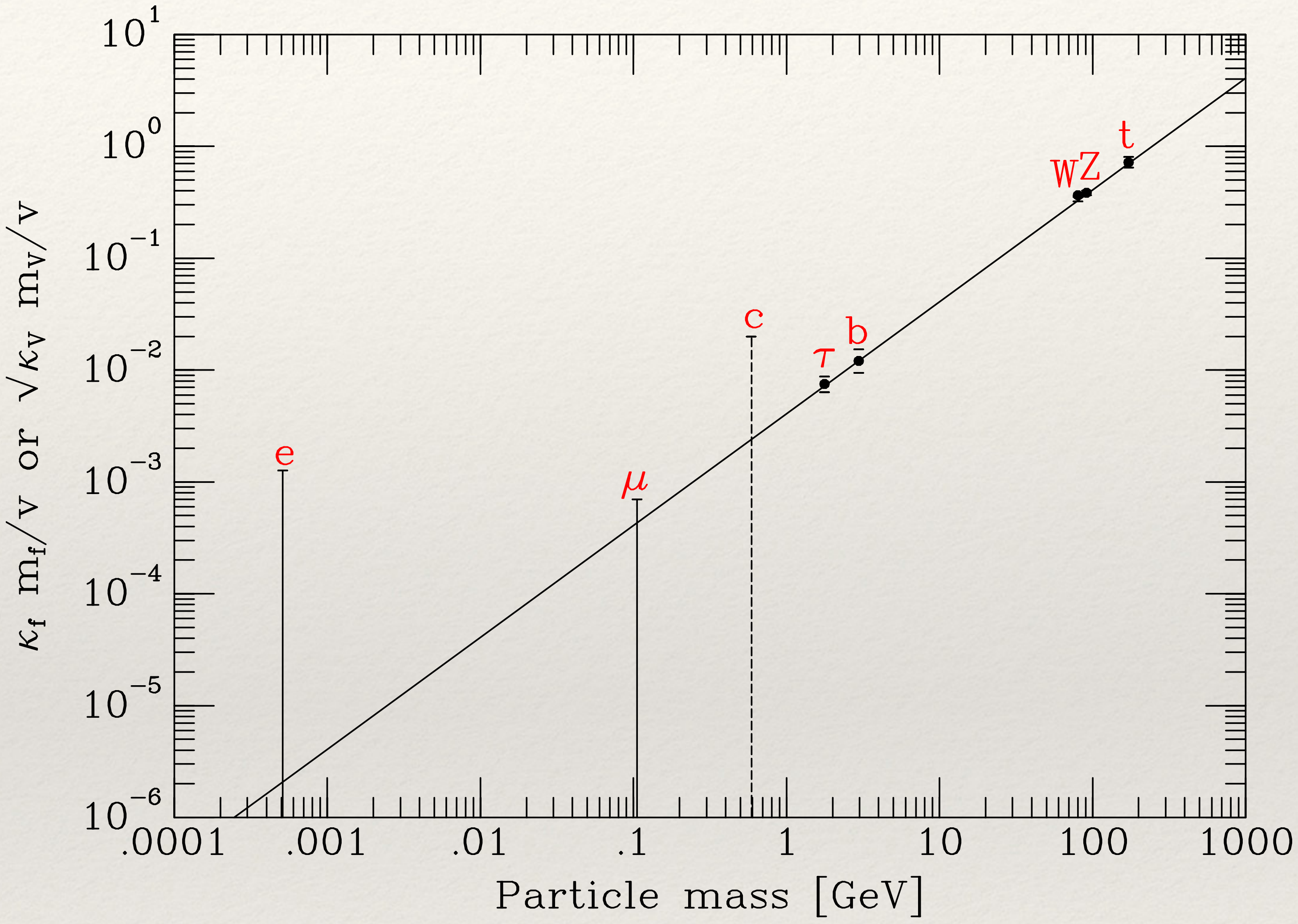
Overall viewpoint and theory

R. Keith Ellis
IPPP, Durham

- Strategy confirms the importance of approved HL-LHC and global neutrino program for the field.
- Gives a mandate to investigates the feasibility of FCC-ee and FCC-hh, whilst stressing the importance of investment in innovative accelerator technology.
- Establishes an electron-positron Higgs factory as the highest priority next collider.
- Enunciates the long-term goal to operate a proton-proton collider at the highest achievable energy.
- Reiterates the importance of our relationships with other fields of science, and our responsibilities in our own community and towards society at large.

Why Higgs?

- Higgs boson is the only fundamental scalar particle in standard model, unique fundamental particle with self-coupling.
- Coupling to heavy bosons confirms role in generation of W & Z mass
- Yukawa force introduces large number of parameters. About O(50%) of parameters of the SM associated with the Higgs.
- Higgs boson associated with many of the problems of the standard model (hierarchy problem, vacuum stability, theory of flavour, matter-antimatter asymmetry?, dark matter?)



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

Open questions

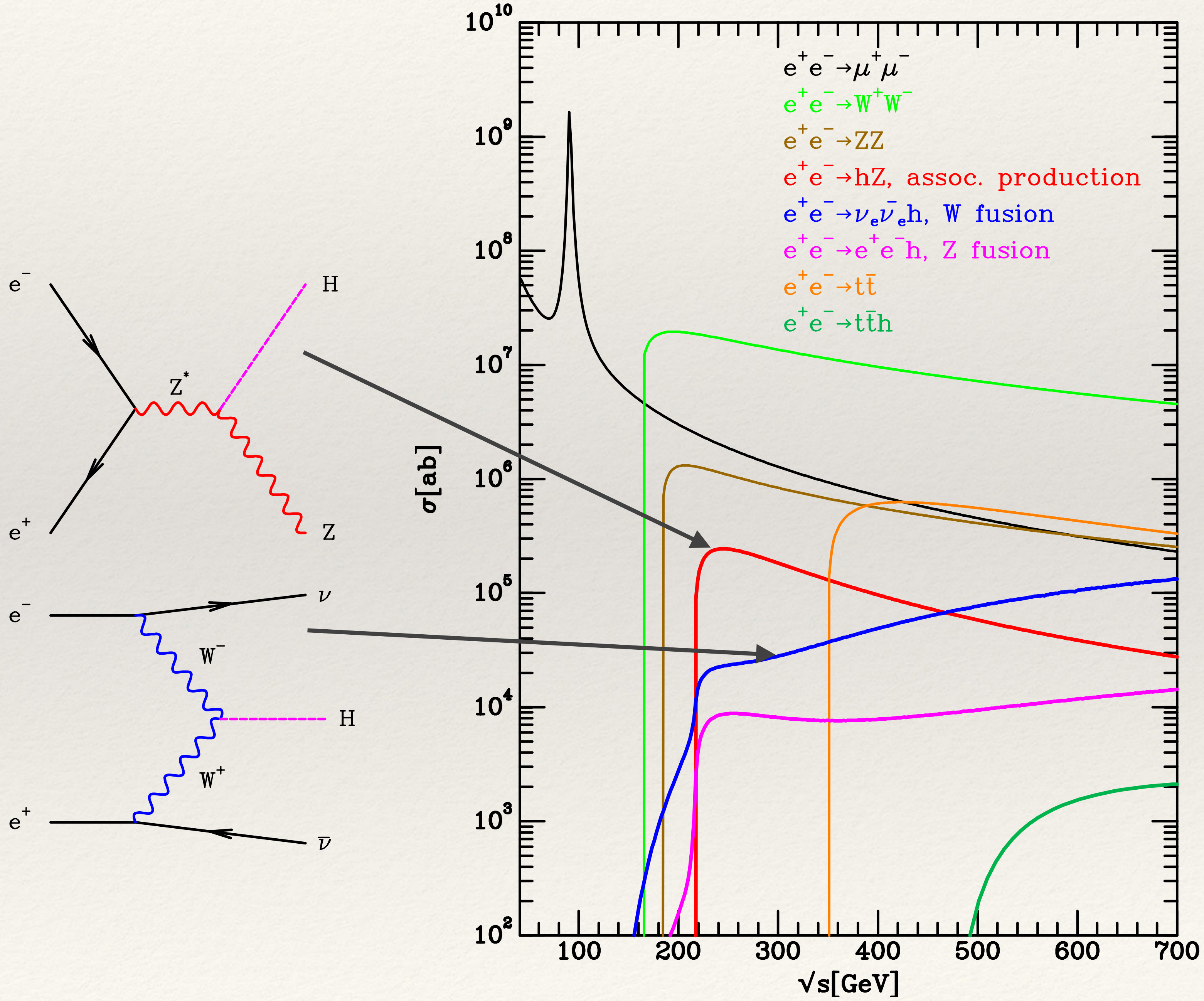
- Is H the only scalar degree of freedom?
- Is H elementary or composite?
- What keeps $M_H^2 \ll M_{Planck}^2$?
- Was the electroweak phase transition first order?
- Did CP violating Higgs interactions generate the baryon asymmetry?
- Are there light SM-singlet degrees of freedom, exploiting a Higgs portal (in particular, related to Dark Matter)?
- What is the solution of the flavour 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

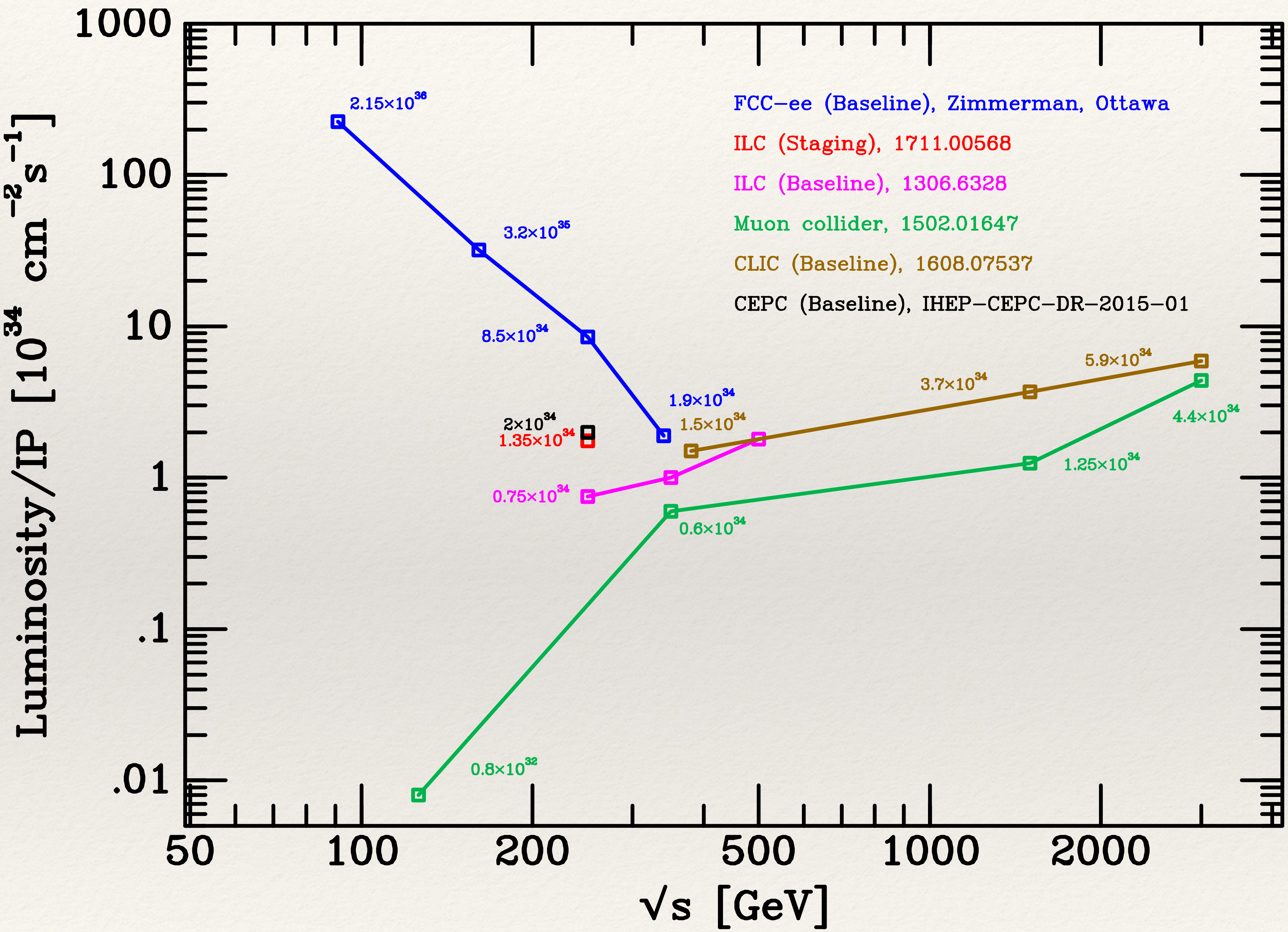
Heinemann and Nir 1905.00382

e+e- Higgs factories

- Two mechanisms, ZH associated production (dominant), and vector boson fusion.
- About a quarter of a million Higgs bosons produced, per inverse ab of data.
- Linear machines can have longitudinal polarization, 40% increase in cross-section+other benefits.
- Circular machines, have higher luminosity at $\sqrt{s} = 240$ GeV, (and $\sqrt{s} = M_Z$ and $2M_W$) falling rapidly with increasing energy, more than one detector operating simultaneously.

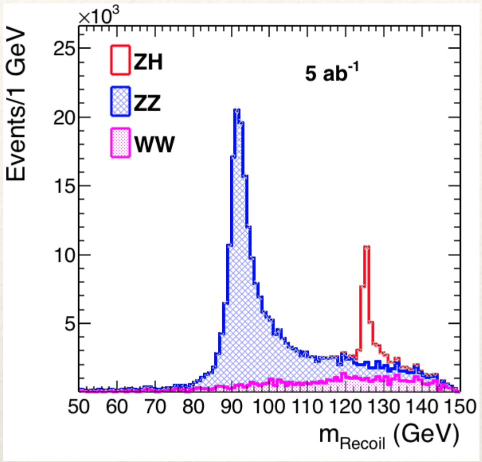


Luminosity at lepton colliders

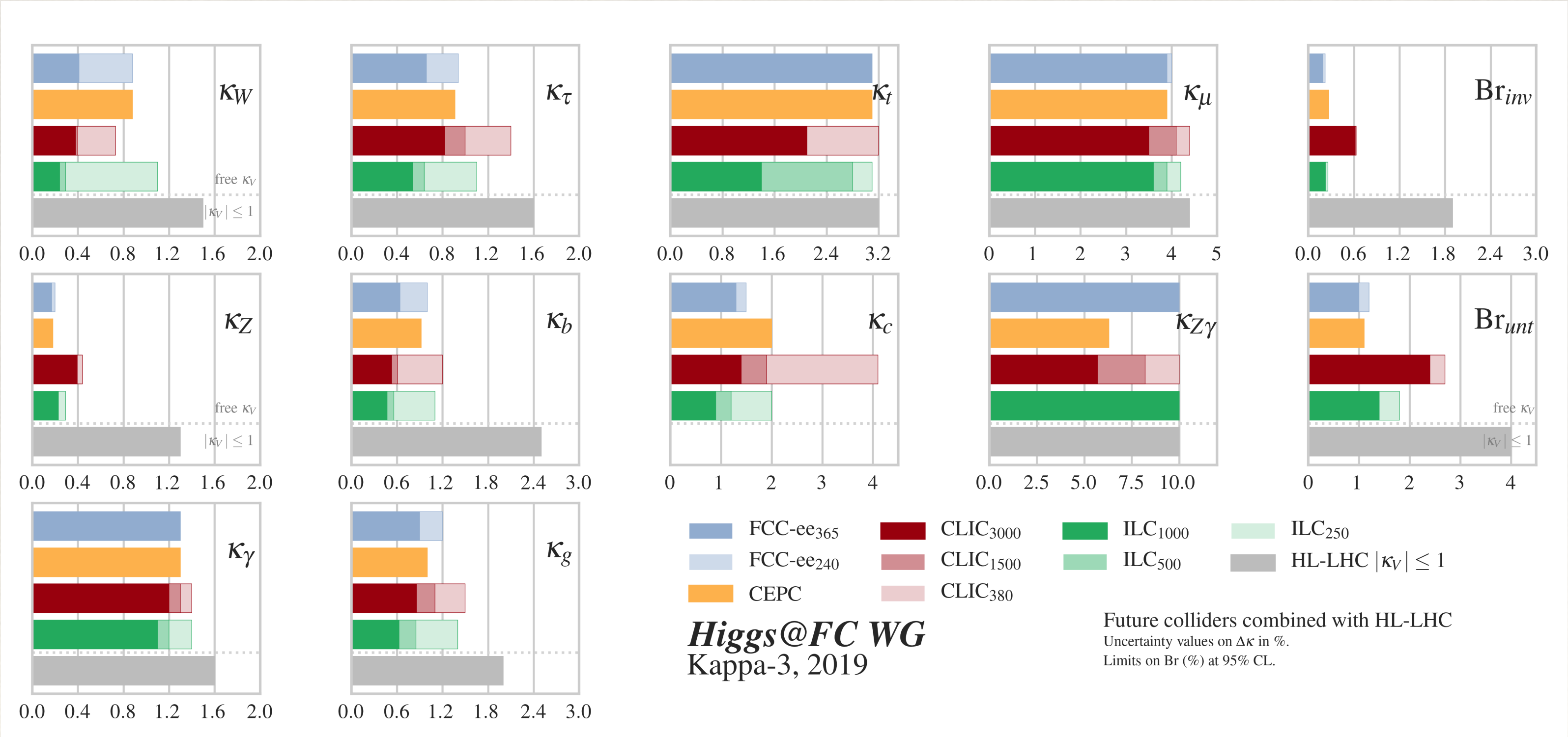


Key measurements at e+e-

- Measurement of total Higgs coupling, using recoil mass, interpreted as semi-direct measurement of total Higgs width.
- Improvements over HL-LHC (shown in grey), of many Higgs couplings couplings, especially Z,W,c,b and invisible and untagged branching ratios.
- Confirmed, (strengthened) by EFT analysis.
- First stage e+e- Higgs factories, do not directly probe ttH or Higgs self coupling.

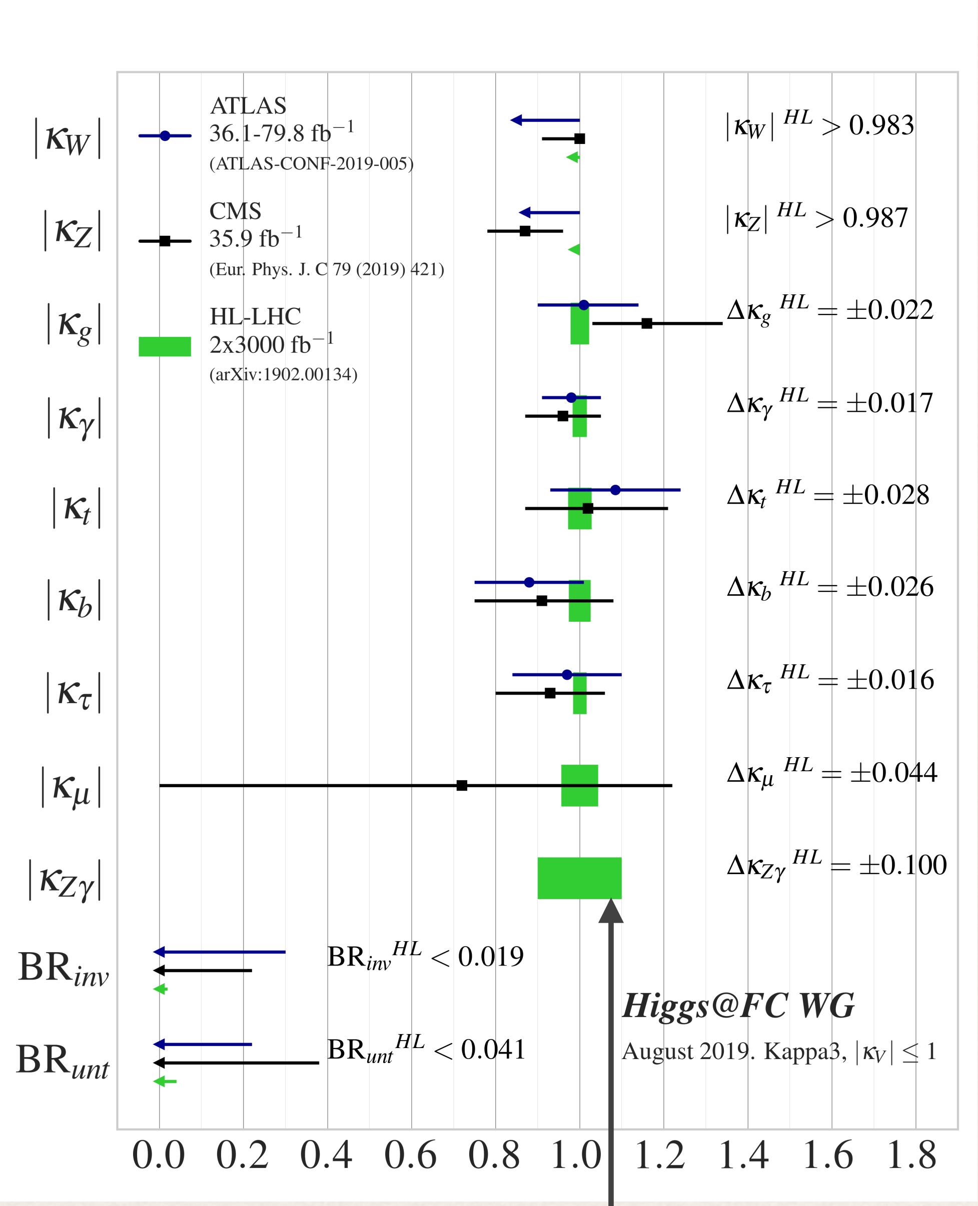


"Higgs width is probed to 1~2%"



Baseline for Higgs physics from HL-LHC

- Current Higgs coupling measurements 10-20%
- High luminosity LHC will provide great improvements in Higgs couplings.
- Improvements in theory necessary both for HL-LHC and Higgs factories, (an area of UK strength).

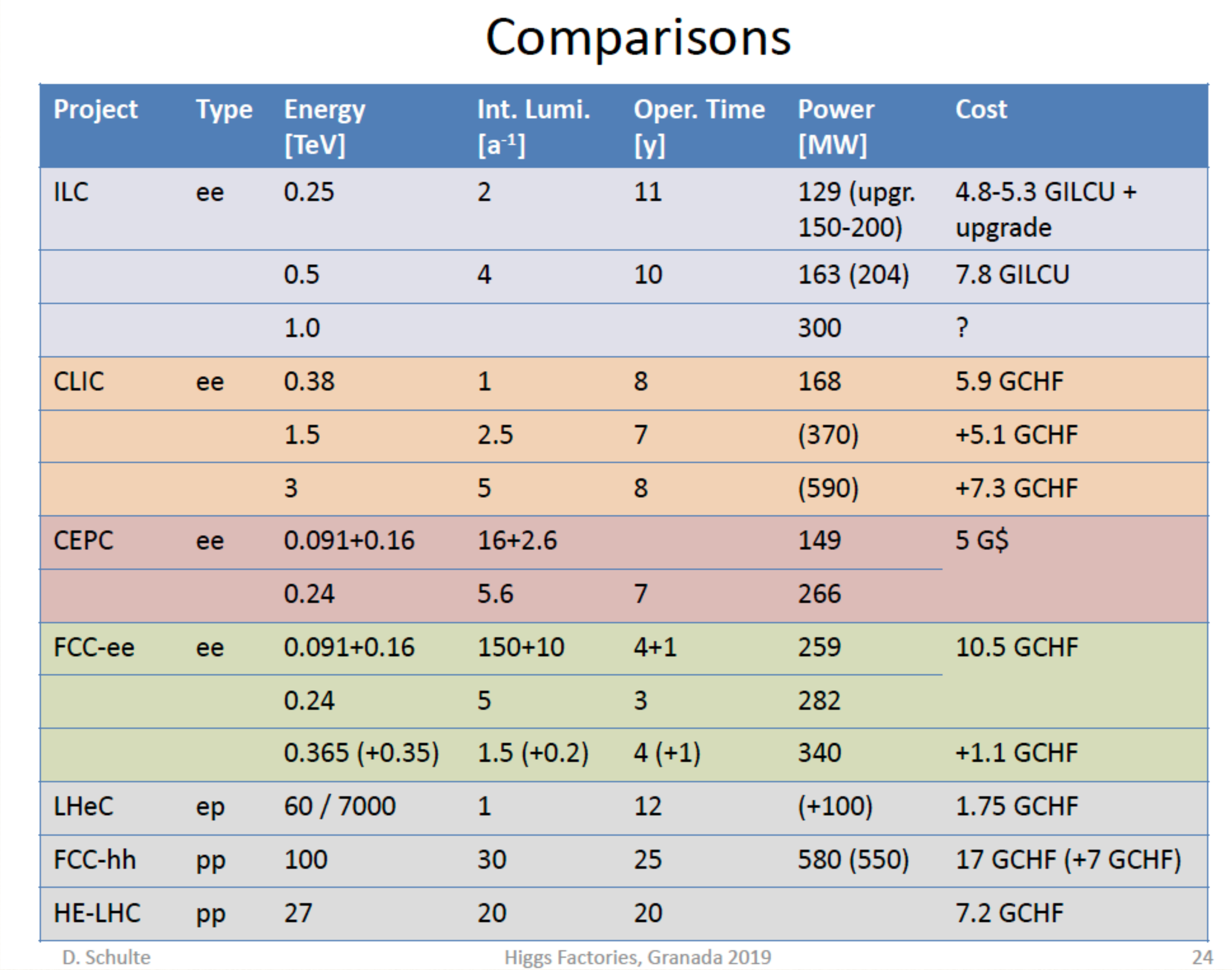


Limits on κ's achievable with HL-LHC shown in green.

Statement on theory

Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities. Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools

Backup



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	?
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

D. Schulte

Higgs Factories, Granada 2019

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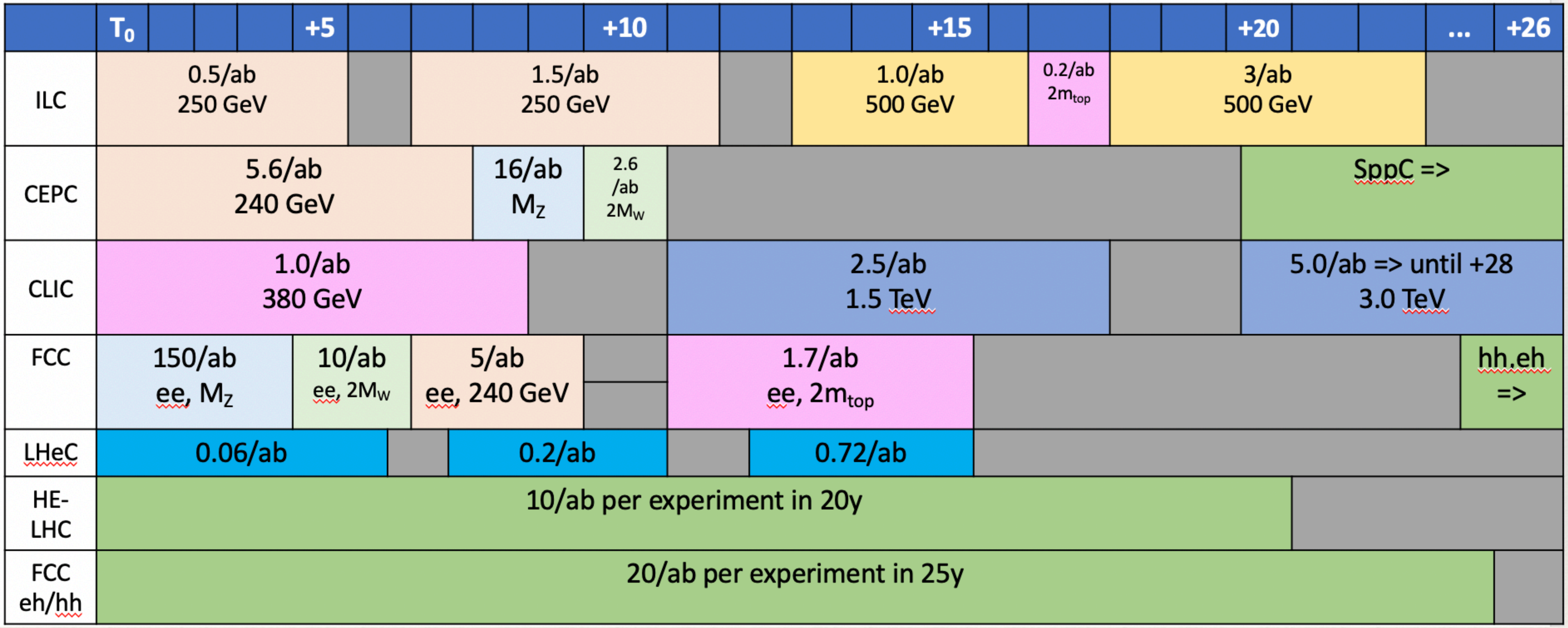
Timeline (from T_0)



<table>
<tr><th></th><th>T_0</th><th></th><th></th><th></th><th>+5</th><th></th><th></th><th></th><th></th><th>+10</th><th></th><th></th><th></th><th></th><th>+15</th><th></th><th></th><th></th><th></th><th>+20</th><th></th><th></th><th>...</th><th>+26</th></tr>
<tr><td>ILC</td><td colspan="5">0.5/ab
250 GeV</td><td></td><td colspan="5">1.5/ab
250 GeV</td><td></td><td colspan="4">1.0/ab
500 GeV</td><td>0.2/ab
$2m_{top}$</td><td colspan="5">3/ab
500 GeV</td><td colspan="2"></td></tr>
<tr><td>CEPC</td><td colspan="7">5.6/ab
240 GeV</td><td colspan="2">16/ab
M_Z</td><td>2.6
/ab
$2M_W$</td><td colspan="9"></td><td colspan="5">SppC =></td></tr>
<tr><td>CLIC</td><td colspan="8">1.0/ab
380 GeV</td><td colspan="2"></td><td colspan="7">2.5/ab
1.5 TeV</td><td colspan="2"></td><td colspan="5">5.0/ab => until +28
3.0 TeV</td></tr>
<tr><td>FCC</td><td colspan="4">150/ab
ee, M_Z</td><td colspan="2">10/ab
ee, $2M_W$</td><td colspan="3">5/ab
ee, 240 GeV</td><td></td><td colspan="5">1.7/ab
ee, $2m_{top}$</td><td colspan="7"></td><td colspan="2">hh,eh
=></td></tr>
<tr><td>LHeC</td><td colspan="6">0.06/ab</td><td></td><td colspan="3">0.2/ab</td><td colspan="2"></td><td colspan="3">0.72/ab</td><td colspan="9"></td></tr>
<tr><td>HE-LHC</td><td colspan="20">10/ab per experiment in 20y</td><td colspan="4"></td></tr>
<tr><td>FCC eh/hh</td><td colspan="23">20/ab per experiment in 25y</td><td></td></tr>
</table>

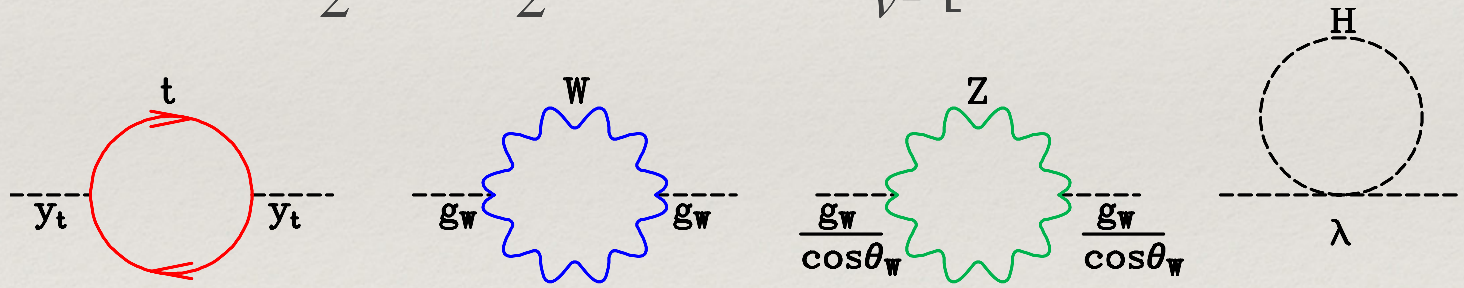
Naturalness

- Why is the Higgs mass 125 GeV rather than being of order of the Planck scale?
- Corrections to the Higgs mass contain quadratic divergences,

$$M_H^2(v) = M_H^{bare\,2} + \delta M_H^2 \qquad \delta M_H^2 = \frac{\Lambda^2}{16\pi^2}\sum_{n=1}^{\infty} C_n(\lambda_i)\ln^n(\Lambda/v)$$

- At one loop

$$C_1 = -12g_t^2 + \frac{3}{2}g_w'^2 + \frac{9}{2}g_w^2 + 12\lambda = \frac{6}{v^2}\left[-4m_t^2 + 2M_W^2 + M_Z^2 + M_H^2\right]$$



"Veltman condition"

- In principle the Standard model can be valid all the way to the Planck scale. Just live with an enormous cancellation between bare mass and the counterterm.

Naturalness and effective field theory

- The trouble really arises when we view the standard model as an effective theory, to be completed by a Beyond-the-Standard-model component. This gives two contributions to the renormalized Higgs mass coming from disparate scales.

$$\delta M_H^2 = \int_0^{\leq \Lambda_{SM}} dE \, \frac{dM_H^2}{dE} + \int_{\leq \Lambda_{SM}}^{\infty} dE \, \frac{dM_H^2}{dE} = \delta_{SM} M_H^2 + \delta_{BSM} M_H^2$$

$$\delta_{SM} m_H^2 \simeq \frac{3 y_t^2}{4\pi^2} \Lambda_{SM}^2$$

retaining only the top contributions

- The existence of the large cancellation, given what we know about the value of the Higgs mass, completely removes any hope the we can use the complete theory to calculate the Higgs mass.

Wulzer 1901.01017

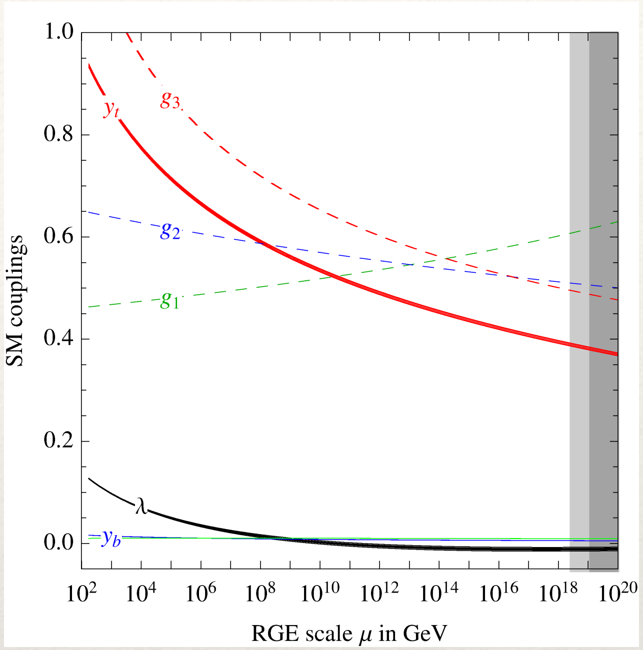
Naturalness and effective field theory

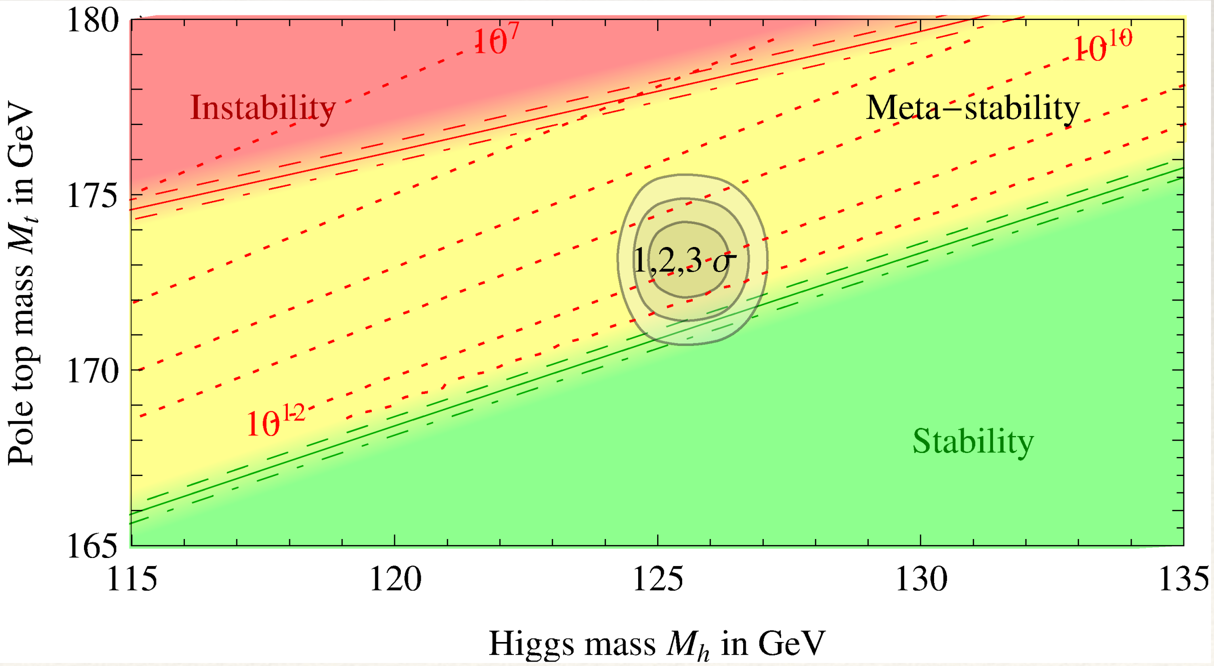
- The contribution $\delta_{BSM} M_H^2$ must also be large, to produce the observed Higgs mass.
- We can define a degree of fine tuning as $\varepsilon = \frac{M_H^2}{\delta M_H^2} < \frac{4\pi^2}{3y_t^2}\frac{M_H^2}{\Lambda_{SM}^2} = \left(\frac{450\ \text{GeV}}{\Lambda_{SM}}\right)^2$
- So if we take $\Lambda_{SM} = M_{GUT} \simeq 10^{16}$ GeV will require a fine tuning of order 10^{-24}. Thus to predict the Higgs boson mass would require an unattainable precision in the BSM sector.
- We can use this to attempt to define a figure of merit to relate measurements of Higgs couplings to direct searches.
- The details depend on the models, but clear that 1 per mille measurement of Higgs coupling can in some models be competitive with direct probes of the 10 TeV region with a hadron collider.

De Blas et al, 1905.03764

Dead or alive?

- The renormalization group controls the evolution of the couplings to high energy.
- Why does the renormalization group analysis, indicate a world teetering on the edge between stability and instability?
- Again a delicate dance between the top quark and the Higgs boson.



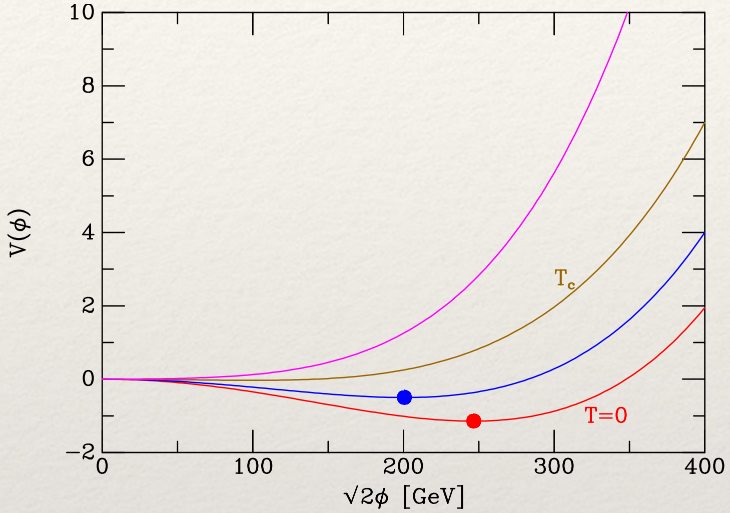


DeGrassi et al, 1205.6497

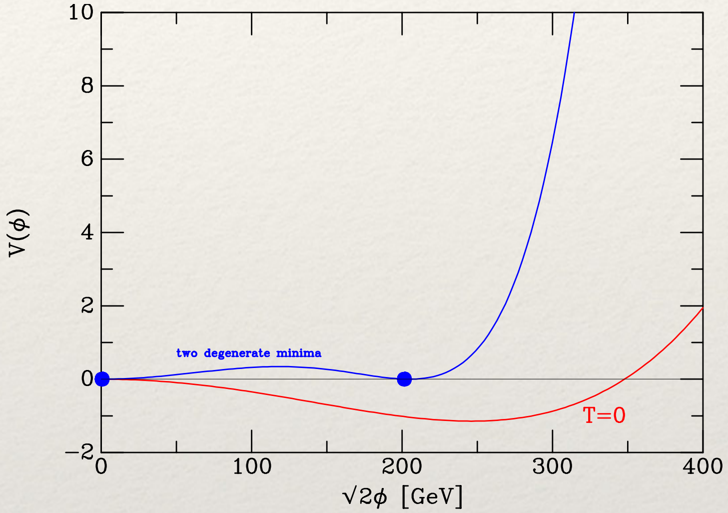
Higgs Potential

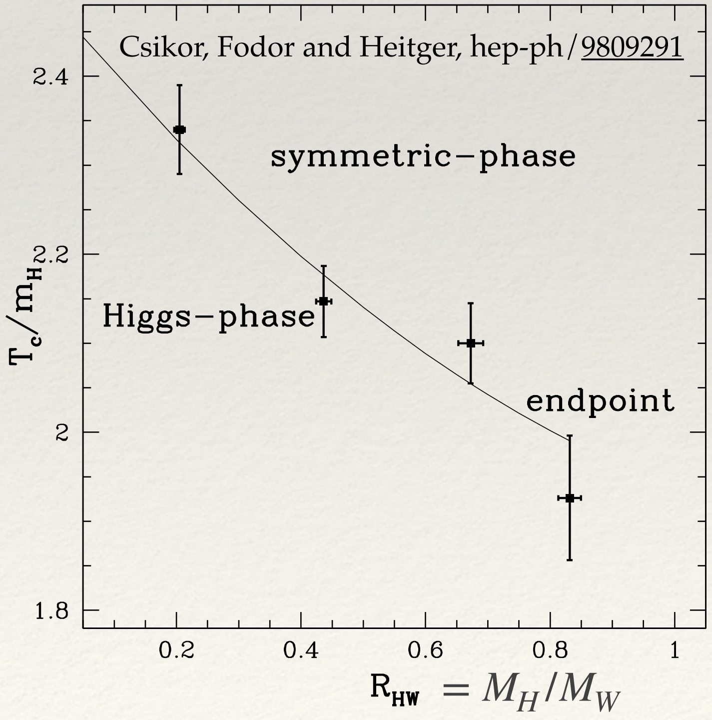
- Potentially important!
- The interest in the order of the EW phase transition is largely related to baryogenesis.
- Lattice simulations indicate a first-order phase transition at $M_H \leq 72$ GeV, and a cross-over otherwise.
- A strongly first order transition with sizeable sources of CP violation 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




Csikor, Fodor and Heitger, hep-ph/9809291

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

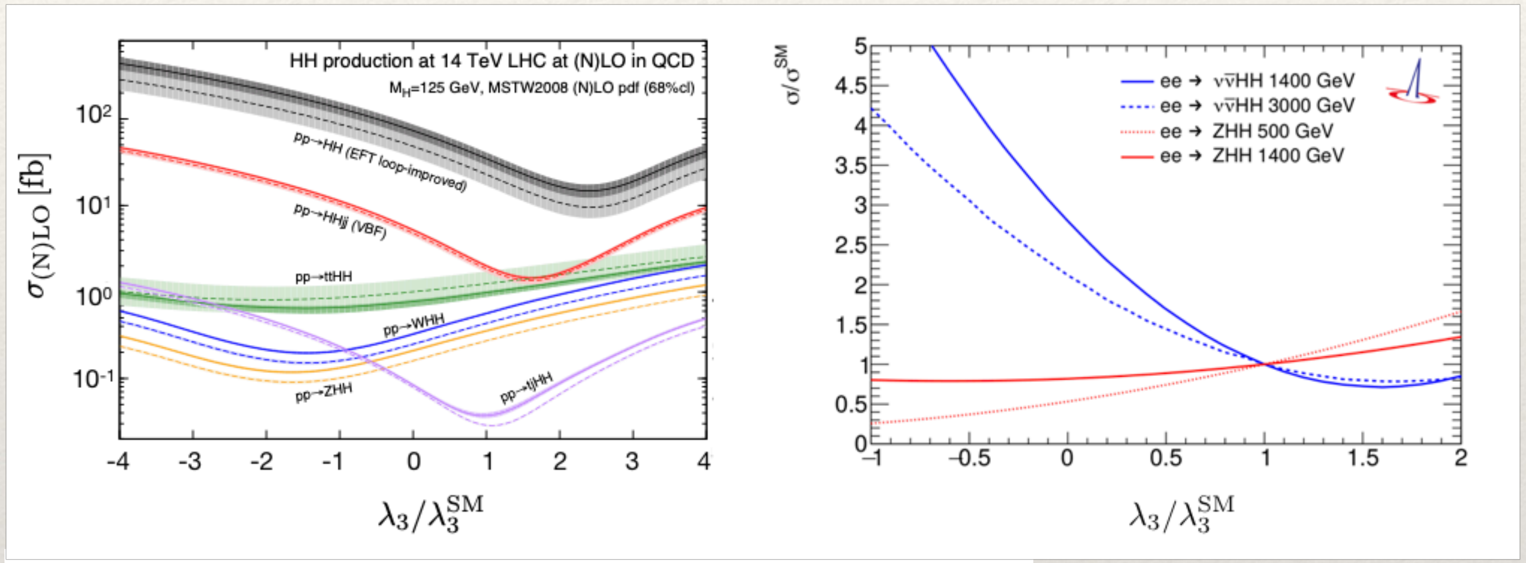
Measuring the Higgs potential

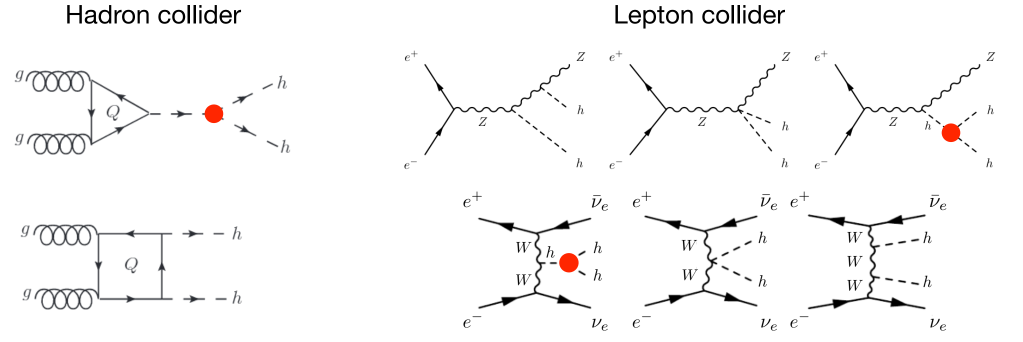
In SM potential fixed in terms of m_H and v

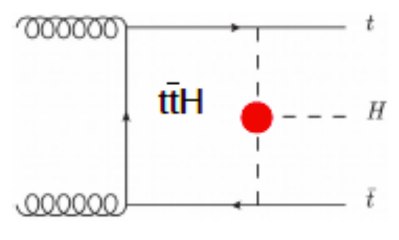
$$V(h) = \frac{1}{2}m_H^2h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

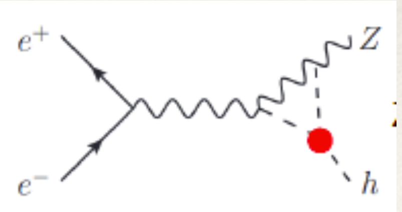
$$\text{with} \quad \lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \frac{m_H^2}{2v^2}$$

- 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

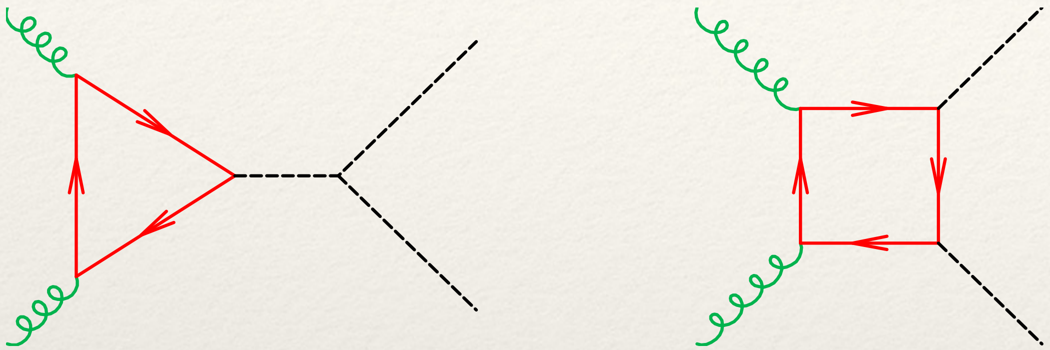


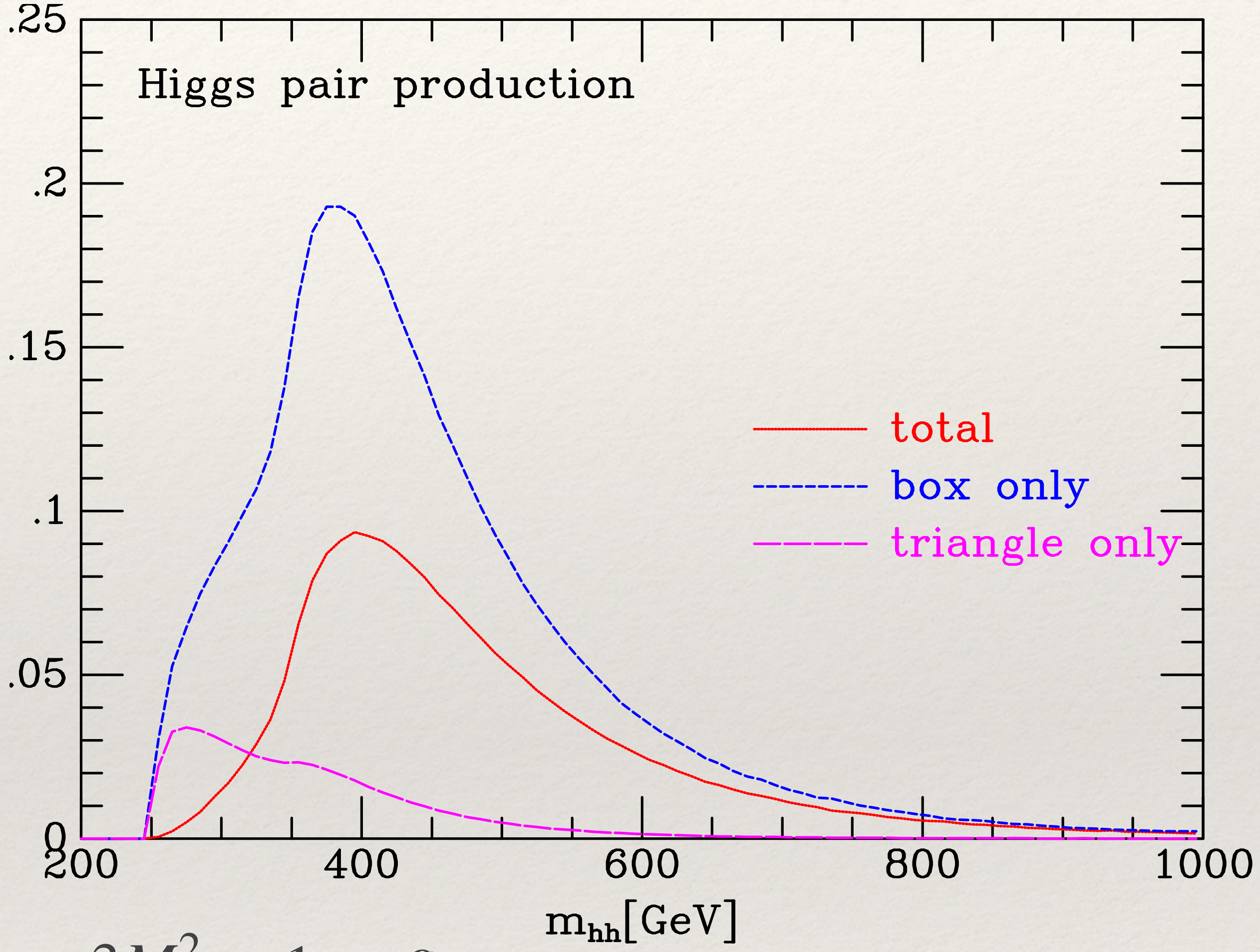






Higgs pair production





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

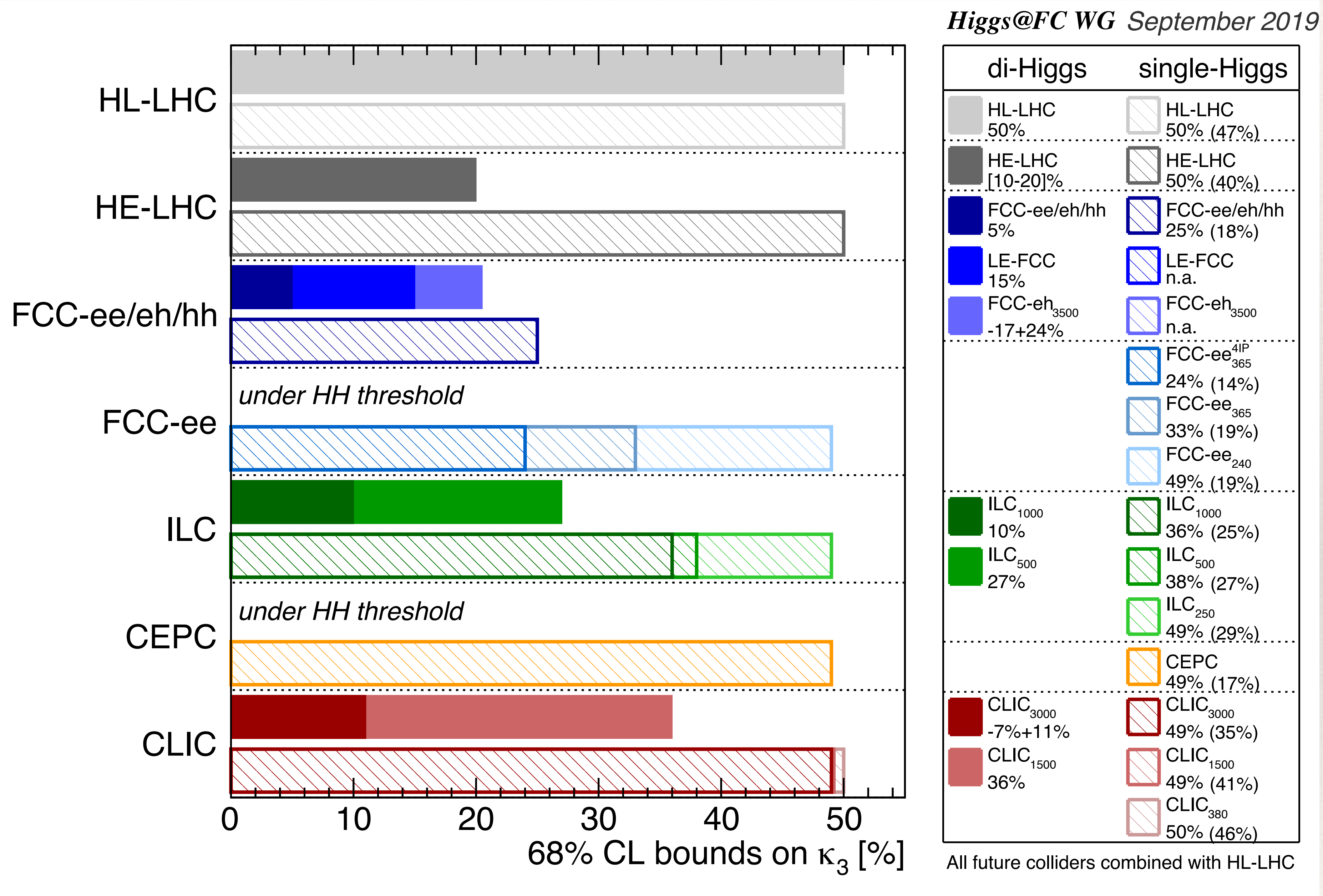
$$g_{ggHH} = - g_{ggH}$$

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

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

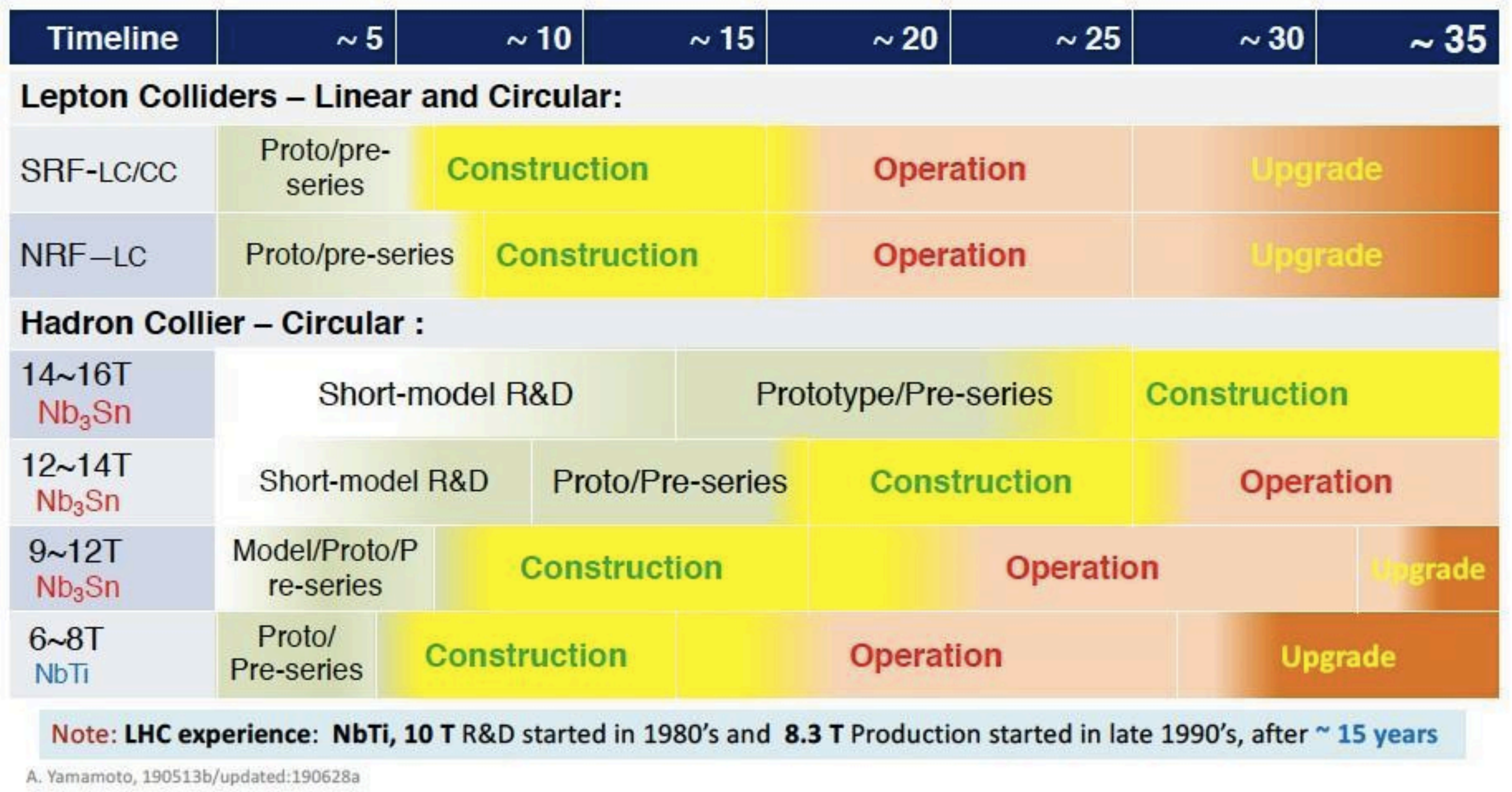
Sensitivity to λ via single-H and di-H production

- 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



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$_3$Sn	Short-model R&D		Prototype/Pre-series			Construction	
12~14T Nb$_3$Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
9~12T Nb$_3$Sn	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