Shaping the future of High-Energy Physics: 1:Theory

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- Tues: Nov 2, 2021, 4:00 PM → 6:00 PM Paris Sphicas: Experiment
- Wed: Nov 3, 2021, 4:00 PM → 6:00 PM Frank Zimmerman: Accelerators
- A broad scholarly overview of the scientific and technological considerations that led to the recommendations of the European Strategy for particle physics.

Planning for the future of our field

Drafting meeting in Bad Honnef (DE)

- 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); The P5, Particle Physics Project Prioritization Panel, will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.
    - Snowmass Community Summer Study (CSS): July, 2022 at UW-Seattle;
    - Snowmass Book and the on-line archive documents due: 31/10/2022.

European Strategy for particle physics 2020

- A modest document with 7 rubrics, (backed up by a briefing book of 254 pages, 1910.11775)
    1. Major developments from the 2013 Strategy, (HL-LHC, Neutrino experiments, especially DUNE@LBNF);
    2. General Considerations for the 2020 update;
    3. High Priority future initiatives (R&D on accelerator technology, technical and financial feasibility of FCC-hh and FCC-ee, ILC);
    4. Other essential activities for particle physics (dark matter, flavor physics and fundamental symmetries, theoretical physics, detector R&D);
    5. Synergies with neighboring fields (nuclear & particle physics);
    6. Organizational issues;
    7. Environmental and Social Impact;
- We shall be concerned with 1, 3 and 4.
- This is not to undervalue the topics under the other rubrics, (e.g. global collaboration, environmental impact, importance of diversity); theoretical physics has no special relevance for them.

Big issues of particle physics

- A forward-looking strategy has to address the big issues facing our field:-
  - The observed abundance of matter over antimatter;
  - The nature of dark matter;
  - The stabilization of the weak scale;
  - Masses, mixing and CP violation in the neutrino sector;
  - The theory of flavor and the number of fermion families;
  - Resolution of the strong CP problem;
  - (Other cosmological issues not addressed by accelerator experiments, such as size of the cosmological constant, quantum theory of gravity, number of space-time dimensions…);
  - A first order of business for accelerator-based particle physics is the complete characterization of the Higgs boson which is linked to many of these questions.

Standard Model Lagrangian

- The standard model is an $SU(3) \otimes SU(2)_L \otimes U(1)$ local gauge-invariant theory containing all possible terms of dimension 4, consistent with the symmetry.
- $\mathscr{L} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + i\bar{\psi}_j \gamma_\mu D^\mu \psi_j + \mathscr{L}_{Higgs}$
  $+\lambda^u \bar{q}_L H^c u_R + \lambda^d \bar{q}_L H V d_R + \lambda^e \bar{l}_L H e_R + h.c. \quad (H^c = i\sigma_2 H^*)$
- $\mathscr{L}_{Higgs} = |D_\mu H|^2 + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2$
- sum over $a = \{G, W, B\}$ corresponding to the field strengths of the gauge bosons of the three gauge groups.
- sum over j, $\psi_j = \{q_L, l_L, u_R, d_R, e_R\}$
- λ are all diagonal in generation space; V is the CKM matrix with 3 angles and one phase.

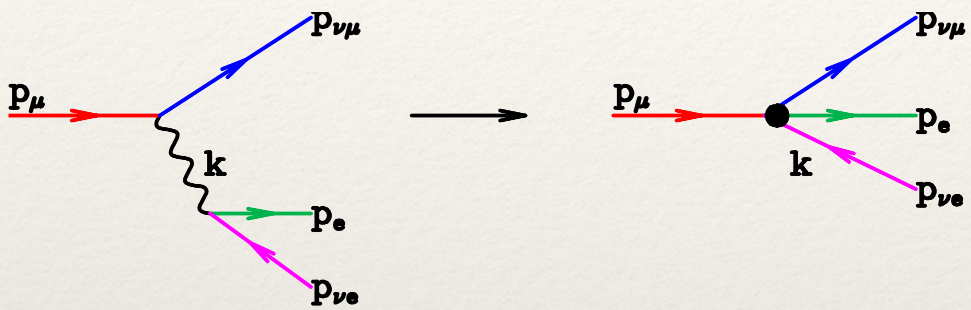
Field	SU(3)	$SU(2)_L$	$Y_{U(1)}$
q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
l_L	1	2	-1/2
e_R	1	1	-1
H	1	2	1/2

Accidental symmetries of the SM

- In the quark sector the Yukawa terms break the symmetry down to $U(1)_B$, corresponding to Baryon number conservation, $\Delta B = 0$;
- In the lepton sector, lepton number is conserved for every lepton flavor separately, $\Delta L_e = \Delta L_\mu = \Delta L_\tau = 0$;
- Unitary CKM matrix; no flavor-changing neutral currents; suppression of flavor changing currents at loop level, (GIM+Structure of CKM matrix);
- CP violation in the CKM matrix relies on there being three generations; if there are only two generations, or if the masses of any two quarks in up or down sector are degenerate, the CP phase can be rotated away;
- Custodial symmetry, e.g. in Electroweak Precision tests.

The Effective theory of weak interactions

- The paradigm for an effective field theory is the Fermi theory of weak interactions;



- In the standard model the muon decay amplitude is
$$\frac{-ig_W^2}{2}\bar{u}(\nu_\mu)\gamma^\alpha\gamma_L u(\mu)\bar{u}(e)\gamma^\beta\gamma_L v(\overline{\nu}_e)\left(-g_{\alpha\beta}+\frac{k_\alpha k_\beta}{M_W^2}\right)\frac{1}{k^2-M_W^2}\,.$$
- Perform a Taylor series in the momentum k^2 valid for $k^2 < M_W^2$, and retain only the first term. (The cut-off for the effective theory is thus of order M_W^2);
- We recover an effective theory governed by Fermi's Lagrangian involving a dimension six operator;
- $$L_{Fermi} = \frac{iG_F}{\sqrt{2}}\bar{\psi}_{\nu_\mu}\gamma^\alpha(1-\gamma_5)\psi_\mu\,\bar{\psi}_e\gamma_\alpha(1-\gamma_5)\psi_{\nu_e}\ \text{ with } \frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$

Rejected by Nature, "because it contained speculations too remote from reality to be of interest to the reader."

- We say that in the effective theory the W boson field has been integrated out.

Standard Model as an effective theory

- The rules for writing down an effective theory are the same as for the SM. Write down all terms consistent with the symmetries;
- The fields are exactly the same as the standard model, but now terms which are not renormalizable are permitted;
- $\mathscr{L}_{eff} = O(\Lambda^4) + O(\Lambda^2)\mathscr{L}_2 + O(1)\mathscr{L}_4 + O(\frac{1}{\Lambda})\mathscr{L}_5 + O(\frac{1}{\Lambda^2})\mathscr{L}_6 + \ldots$
- $\mathscr{L}_2 = -\frac{1}{2}h^2$ (the coefficient of $\mathscr{L}_2$ is the Higgs mass which is 125 GeV; so either the cutoff Λ is of order 100 GeV (new physics nearby), or the Higgs mass is fine-tuned, (more later).
- $\mathscr{L}_5 = c(\bar{l}_L H^c)(l_L H)$ is Weinberg operator, the unique operator of dimension 5 which can generate a mass for the neutrinos;
- $\mathscr{L}_6^{\Delta B \neq 0} = (\bar{d}^c_{\alpha\, a\, R}\, u_{\beta b R})\ \ (\bar{q}^C_{i\gamma c L} l_{j\, d\, L})\ \epsilon_{\alpha\beta\gamma}\epsilon_{ij}$+ 5 other operators. $\{\alpha\beta\gamma\}$ are SU(3) indices, i,j are SU(2) indices and $\{a, b, c, d\}$ are generation indices. These operators all violate baryon number, but conserve B-L. (In addition ~2500 baryon-number conserving dimension-6 operators).

SMEFT

- SMEFT is a effective field theory that describes SM interactions with new physics under certain assumptions;
    - the new physics lies above high energy cutoff scale denoted by Λ;
    - the new physics is Lorentz and gauge invariant;

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{i,n\geq 5} \frac{C_i \mathcal{O}_i^{(n)}}{\Lambda^{n-4}}$$

- each $\mathcal{O}_i^{(n)}$ is a local $SU(3) \otimes SU(2) \otimes U(1)$ operator of mass dimension n, built using fields from the light particle spectrum. The contribution of $\mathcal{O}_i^{(n)}$ leads to contributions that grow as $\left(\frac{E}{\Lambda}\right)^{n-4}$;
- Advantage: Universal with no dependence on particular UV-complete model; allows comparison of different processes;
- Disadvantage: Large number of Wilson coefficients, e.g. for dimension 6 there are 59 gauge invariant operators for unspecified flavor, 2499 total operators (non-baryon number violating).

Higgs basis

- For Higgs boson physics, we can justifiably focus on a small set of the 2499 dimension-6 operators that involve the Higgs field;
- In particular operators involving four fermion fields will be better constrained by other processes;
- These operators give rise to 5 different classes of processes;
    1. Higgs trilinear;
    2. Higgs couplings to vector bosons;
    3. Trilinear gauge couplings;
    4. Yukawa couplings;
    5. Vector couplings to fermions.

		Operator	Notation	Operator	Notation
Class 1	X^3	$\varepsilon_{abc}W_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{c\mu}$	$\mathcal{O}_W$		
	ϕ^6	$(\phi^\dagger\phi)^3$	$\mathcal{O}_\phi$		
	ϕ^4D^2	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$
	$X^2\phi^2$	$\phi^\dagger\phi B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi W^a_{\mu\nu}W^{a\mu\nu}$	$\mathcal{O}_{\phi W}$
		$\phi^\dagger\sigma_a\phi W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$\phi^\dagger\phi G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{\phi G}$
Class 2	$\psi^2\phi^2$	$(\phi^\dagger\phi)(\bar{l}^i_L\phi e^j_R)$	$(\mathcal{O}_{e\phi})_{ij}$		
		$(\phi^\dagger\phi)(\bar{q}^i_L\phi d^j_R)$	$(\mathcal{O}_{d\phi})_{ij}$	$(\phi^\dagger\phi)(\bar{q}^i_L\tilde{\phi}u^j_R)$	$(\mathcal{O}_{u\phi})_{ij}$
Class 3	$\psi^2\phi^2D$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}^i_L\gamma^\mu l^j_L)$	$\left(\mathcal{O}^{(1)}_{\phi l}\right)_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}^i_L\gamma^\mu\sigma_a l^j_L)$	$(\mathcal{O}^{(3)}_{\phi l})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}^i_R\gamma^\mu e^j_R)$	$(\mathcal{O}_{\phi e})_{ij}$		
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}^i_L\gamma^\mu q^j_L)$	$(\mathcal{O}^{(1)}_{\phi q})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}^i_L\gamma^\mu\sigma_a q^j_L)$	$(\mathcal{O}^{(3)}_{\phi q})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}^i_R\gamma^\mu u^j_R)$	$(\mathcal{O}_{\phi u})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}^i_R\gamma^\mu d^j_R)$	$(\mathcal{O}_{\phi d})_{ij}$
		$(\tilde{\phi}^\dagger iD_\mu\phi)(\bar{u}^i_R\gamma^\mu d^j_R)$	$(\mathcal{O}_{\phi ud})_{ij}$		

1905.03764

EFT in BSM-Higgs portal

- At dimension 4 and 5 we can add "Higgs portal" operators for spin-0 (S), spin-1,(V) and spin-$\frac{1}{2}$ (χ) dark matter electroweak singlet particles;
- $\Delta\mathscr{L}_4^S = -\frac{1}{2}M_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS} H^\dagger H S^2, \qquad \Delta\mathscr{L}_4^V = \frac{1}{2}M_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{HVV} H^\dagger H V_\mu V^\mu,$
$\Delta\mathscr{L}_5^\chi = -\frac{1}{2}M_\chi \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi.$
- The models described by these Lagrangians have a discrete $\mathbb{Z}_2$ symmetry or parity ensuring the stability of the DM particle;
- If the dark matter particles are light enough $M_X < M_H/2$ they can contribute to the invisible width of the Higgs boson;
- $$\Gamma_{\text{inv}}(H \to SS) = \frac{\lambda_{HSS}^2 v^2 \beta_S}{64\pi M_H}, \qquad \Gamma_{\text{inv}}(H \to VV) = \frac{\lambda_{HVV}^2 v^2 M_H^3 \beta_V}{256\pi M_V^4}\left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)$$
$$\Gamma_{\text{inv}}(H \to ff) = \frac{\lambda_{Hff}^2 v^2 M_H \beta_f^3}{32\pi\Lambda^2}.$$

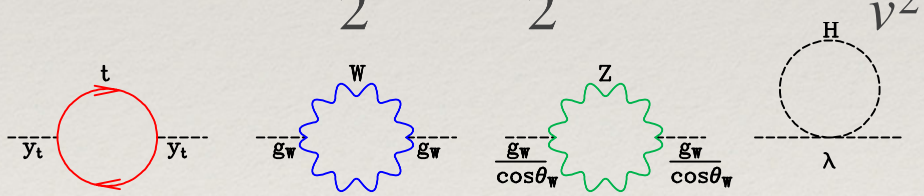
Stabilization of the Higgs Mass

- Why is the Higgs mass 125 GeV rather than being of order of the cutoff, e.g. 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 $C_1 = -12g_t^2 + \frac{3}{2}g_w^{\prime 2} + \frac{9}{2}g_w^2 + 12\lambda = \frac{6}{v^2}\left[-4m_t^2 + 2M_W^2 + M_Z^2 + M_H^2\right]$ "Veltman condition"



- In principle the Standard model can be valid all the way to the Planck scale, which is a depressing idea. 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;

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

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

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, because of the unattainable precision demanded of the BSM theory;
- Thus another way to express the naturalness problem, is that it sabotages any hope that we might have to predict the Higgs mass in a more complete theory.

Wulzer 1901.01017

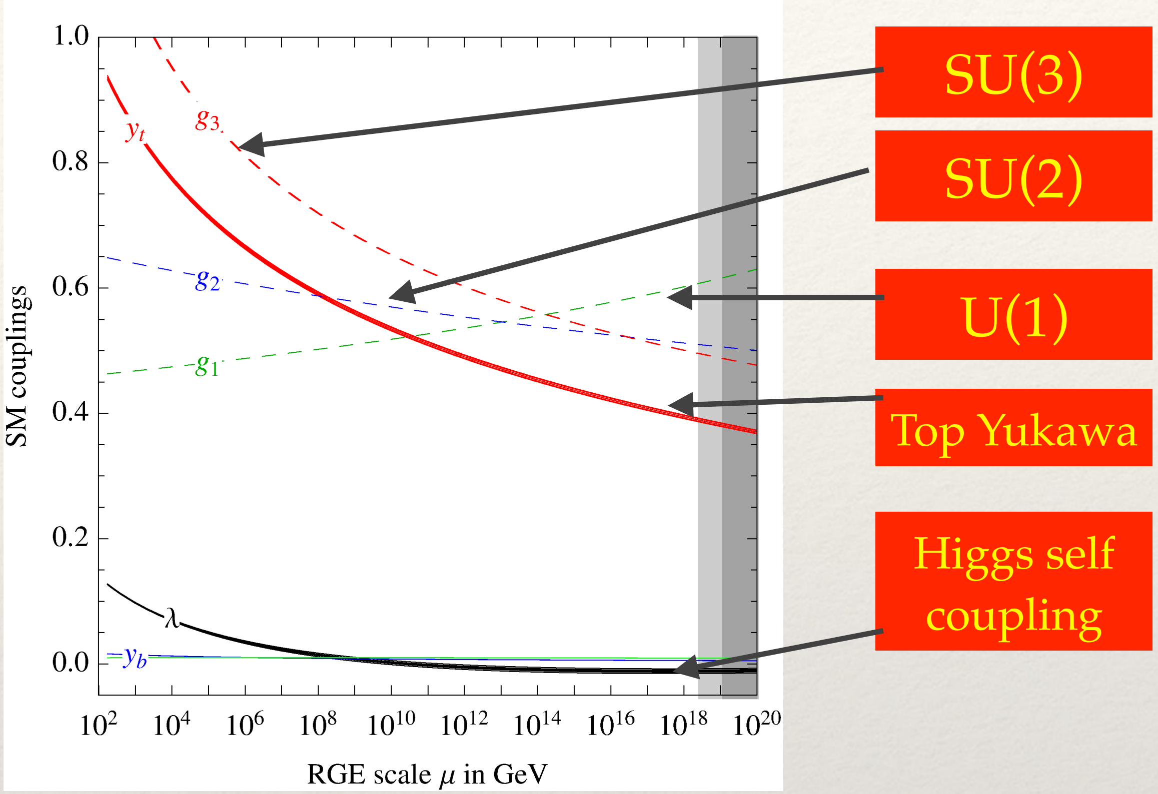
Naturalness and effective field theory

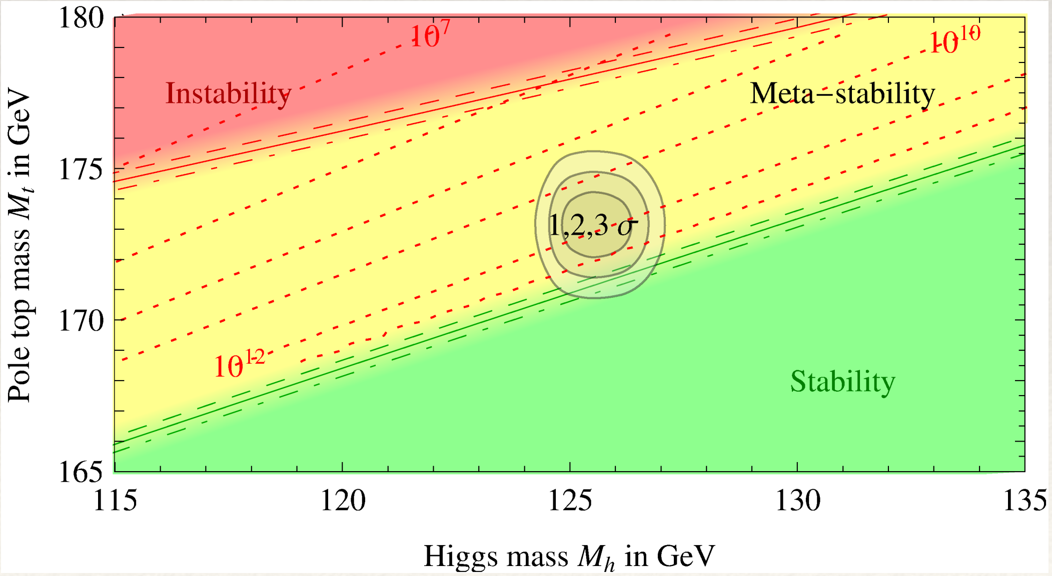
- The contribution $\delta_{BSM} M_H^2$ must also be large, to produce the observed Higgs mass.
- We can define a degree of fine tuning as $$\varepsilon = \frac{M_H^2}{\delta M_H^2} < \frac{4\pi^2}{3y_t^2}\frac{M_H^2}{\Lambda_{SM}^2} = \left(\frac{450\text{ GeV}}{\Lambda_{SM}}\right)^2$$
- So if we take $\Lambda_{SM} = M_{GUT} \simeq 10^{16}$ 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.
- The renormalization group analysis, indicates a world teetering on the edge between stability and instability. Why?
- A delicate dance between the mass of top quark ($\sim y_t$) and the mass($\sim \sqrt{\lambda}$) of the Higgs boson.





DeGrassi et al, 1205.6497

Baryon Asymmetry

Baryon asymmetry - a single number

- It is clearly important to establish why our Universe is predominantly made of matter, rather than anti-matter.
- Many theories can predict a single number, so we are really looking for a coherent picture of the evolution of the Universe, within the standard model or beyond.
- Searches of antimatter in cosmic rays, find no evidence of primordial antimatter.
- From CMB results the ratio of the number of Baryons to the number of photons is $\eta_B = \frac{n_B}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$. This value is further confirmed by the abundances of light elements in the interstellar medium.
- A better number to examine is the ratio of baryon number to entropy, n_b/s provides a measure of the baryon asymmetry whose value is unchanged as the Universe expands and cools.

For a recent review see, 2009.07294

Sakharov conditions for Baryon asymmetry

- Sakharov conditions, which are necessary to generate a Baryon Asymmetry were written down in 1967, shortly after the observation of CP violation in the $K_0 - \bar{K}_0$ system.
- Baryon number violation
    - if Baryon number were conserved a state with $B = 0$ could not evolve to a state with $B \neq 0$.
- C and CP violation.
    - C-symmetry violation is also needed so that the interactions which produce more baryons than anti-baryons will not be counterbalanced by interactions which produce more anti-baryons than baryons.
    - CP-symmetry violation is similarly required because otherwise equal numbers of left-handed baryons and right-handed anti-baryons would be produced, as well as equal numbers of left-handed anti-baryons and right-handed baryons.
- Interactions out of thermal equilibrium
    - Thermal equilibrium is a time-independent state in which the expectation values of all observables is constant.

Baryon asymmetry in the Standard model

SM

- B: Baryon number is violated by a non-perturbative effect ✓
  - $\partial_\mu J^\mu_B = \frac{n_f}{32\pi^2} g^2 F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}$ where $F^a_{\mu\nu}$ is the weak SU(2) field strength.
- CP: Because we have 3 generations, CP is violated in the standard model; ✗
  - Jarlskog invariant is formed from CKM matrix elements $Im\{V_{11}V_{22}V^*_{12}V^*_{21}\} = 3 \times 10^{-5}$. Measure of CP violation is $J \times \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{M_W^{12}} = 3 \times 10^{-19}$
    see also:hep-ph/9406288
- Non-equilibrium: ✗
  - In the standard model, if $m_H \leq 72$ GeV, there is a first order phase transition. For the physical Higgs mass $m_H = 125$ GeV there is a cross-over.
- CP violation via the CKM matrix is far too small to explain $\eta_B \sim 10^{-10}$;
- Since the SM does not work, for electroweak baryogenesis to be viable we require two new types of physics, hence the interest.

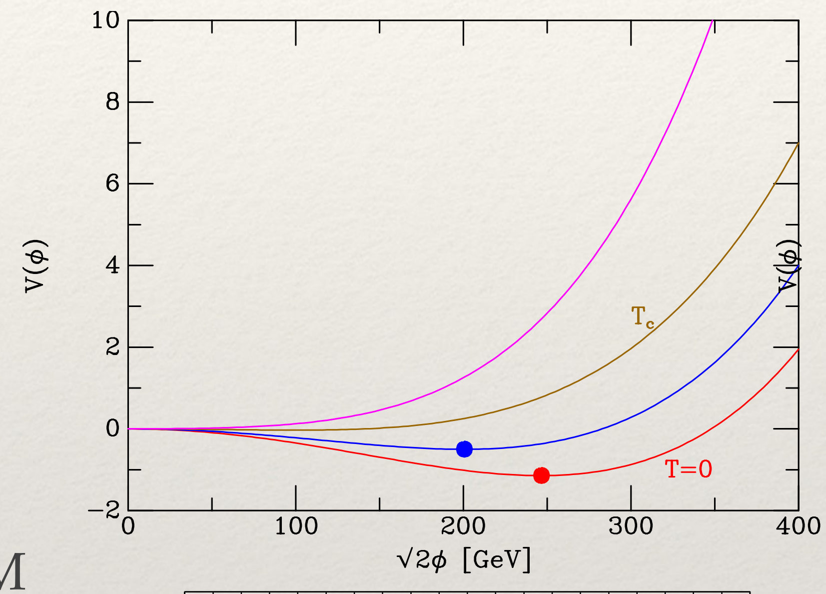
CP violation in the standard model

- In the CKM theory, the mass eigenstates differ from the weak eigenstates by a Unitary matrix V such that $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}$
- 3×3 unitary matrix depends on 9 real parameters;
- Since a real unitary matrix (i.e. orthogonal matrix) contains 3 independent parameters the remaining 6 parameters are phases;
- 5 of these can be removed by phase rotations of the q and q' fields;
- If any of the masses in the up or down sectors are degenerate we can remove the final phase and there is no CP violation;
- Jarlskog invariant is formed from CKM matrix elements $Im\{V_{11}V_{22}V_{12}^{*}V_{21}^{*}\} = 3 \times 10^{-5}$
- $J \times \dfrac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{M_w^{12}} = 3 \times 10^{-19}$

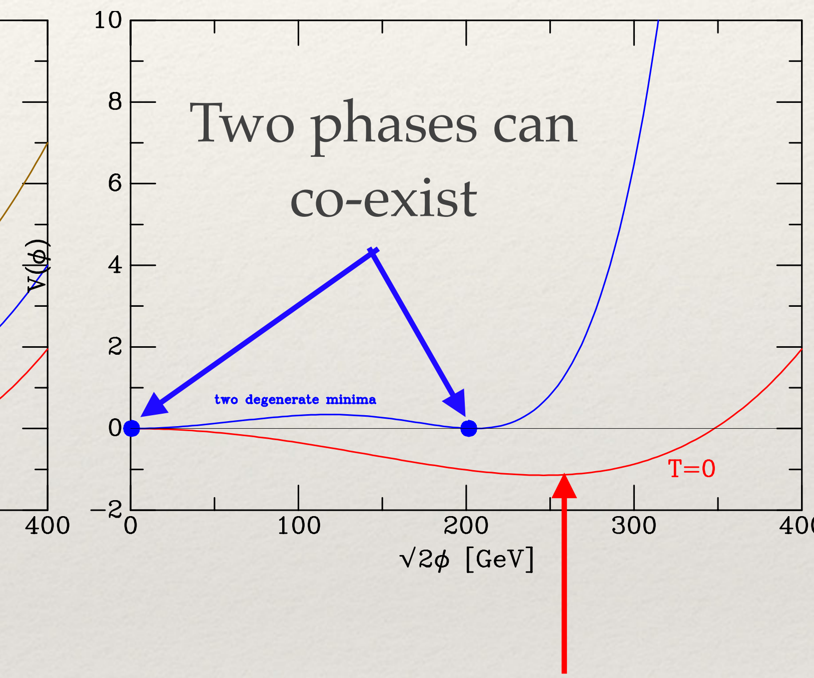
Higgs Potential

- 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.
- It is important to obtain more information about the Higgs potential.
- The triple Higgs coupling gives information about the T=0 potential.

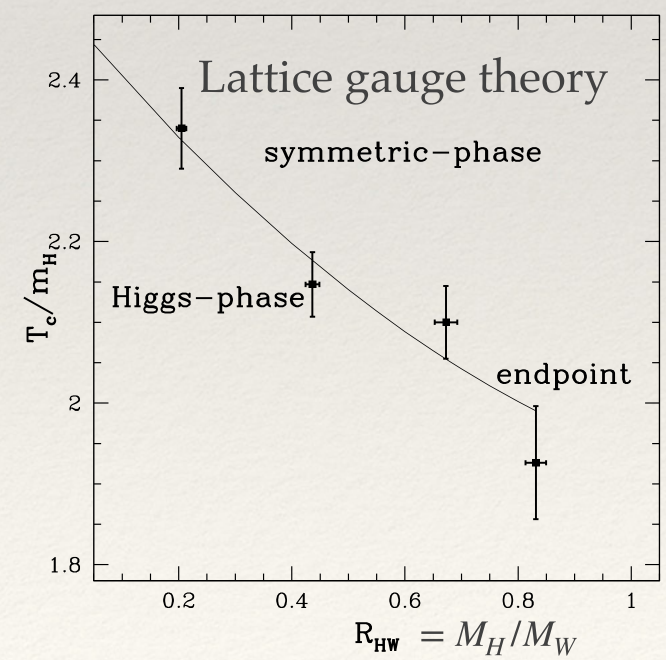
Crossover



1st order phase transition



At present we know the vacuum expectation value, v, and the curvature around the minimum, i. e. M_H



Csikor, Fodor and Heitger, hep-ph/9809291

Baryogenesis beyond the standard model

- The attractive part of Electroweak Baryogenesis is that it connects low-energy CP violation in BSM models with the Baryon Asymmetry of the Universe;
- The electron dipole moment, a CP violating quantity, has been measured by the ACME collaboration, $|d_e| < 1.1 \times 10^{-29}\ e \cdot cm$;
- This limit puts strong bounds on essentially all models of electroweak baryogenesis that can be treated perturbatively, (for examples, see 2009.07294)
- In strongly-coupled composite Higgs models, electroweak Baryogenesis is still possible;
- This underlines to importance of looking for new heavy resonances and non-standard model Higgs couplings.

Neutrino experiments

- New generations of neutrino experiments are DUNE, HyperK and Juno
- CERN has particular interest in DUNE, Neutrino platform, construction of cryostats for DUNE.
- Little discussion in 2020 document, because already established in 2013. (2020 document is an update.)

CERN Neutrino platform

Neutrino Oscillations

- Oscillations between the 3 species of neutrinos have been established;

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino flavor states, participate in weak interactions

Neutrino mixing matrix

Neutrino mass eigenstates

$$P = \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violating phase

P is a matrix of phases present for Majorana neutrinos; they are unobservable in oscillation experiments.

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot P$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - s_{13}s_{23}c_{12}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - s_{13}c_{12}c_{23}e^{i\delta} & -s_{23}c_{12} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \cdot P$$

Radically different flavor structure in neutrino physics

- Compare the hierarchical structure of the CKM matrix;

$$|V_{CKM}| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{pmatrix}$$

PDG

$$J_{CKM} = Im\{V_{11}V_{22}V_{12}^*V_{21}^*\} = 3 \times 10^{-5}$$

- and the democratic structure of the PMNS matrix.

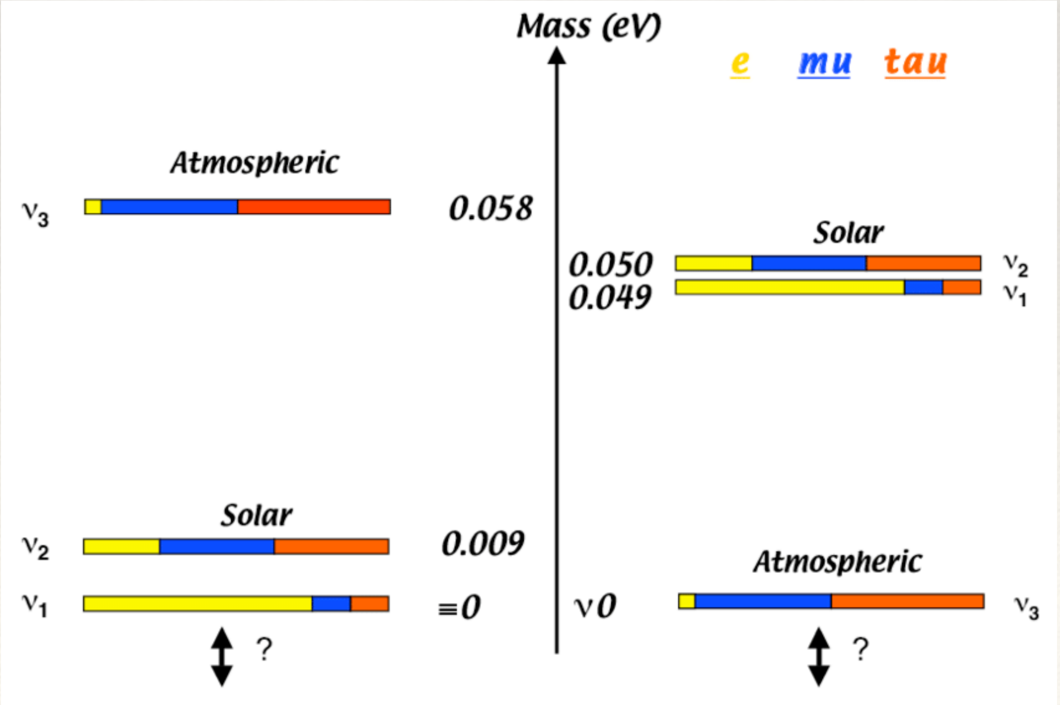
$$|U_{PMNS}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} = \begin{pmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.233 \ldots 0.507 & 0.461 \ldots 0.694 & 0.631 \ldots 0.778 \\ 0.261 \ldots 0.526 & 0.471 \ldots 0.701 & 0.611 \ldots 0.761 \end{pmatrix}$$

NuFit5.1

$$J_{PMNS} = s_{12}s_{13}s_{23}c_{12}c_{13}^2c_{23}\sin\delta = 3.3 \times 10^{-2}\sin\delta$$

CP violation is expected to be larger effect in the lepton sector

Graphical representation of the columns of U_{PMNS} in the normal and inverted mass hierarchy.



Normal Ordering Inverted Ordering

Physics goals in the Neutrino sector

- Search for neutrino-less double beta decay, to demonstrate that neutrinos are their own antiparticles (Majorana neutrinos);
- Establishing the hierarchy of masses;.
- Precision measurement of PMNS matrix;
- Search for CP violation in neutrino sector;
- Leptogenesis: CP violation in the neutrino sector could be responsible for matter-antimatter asymmetry. If $\Gamma(N \rightarrow l^{+} + X-) > \Gamma(N \rightarrow l^{-} + X+)$, anti-lepton excess can be converted to a baryon excess, by a non-perturbative B+L violating but B-L conserving process.
    - A definitive proof of leptogenesis requires production of heavy neutrinos (N) and measure their leptonic decays. Unachievable if the N is heavy;
    - Discovery of CP violation in the neutrino sector is not direct evidence for Leptogenesis, since a model is needed to connect the low-scale CPV observed here to high-scale CPV for heavy neutrinos that lead to Leptogenesis.

Neutrino masses and Mixings

- Is CP violated in the neutrino sector?
- Why are the neutrino masses so different from the other fermions?
- What is the absolute scale of neutrino mass?

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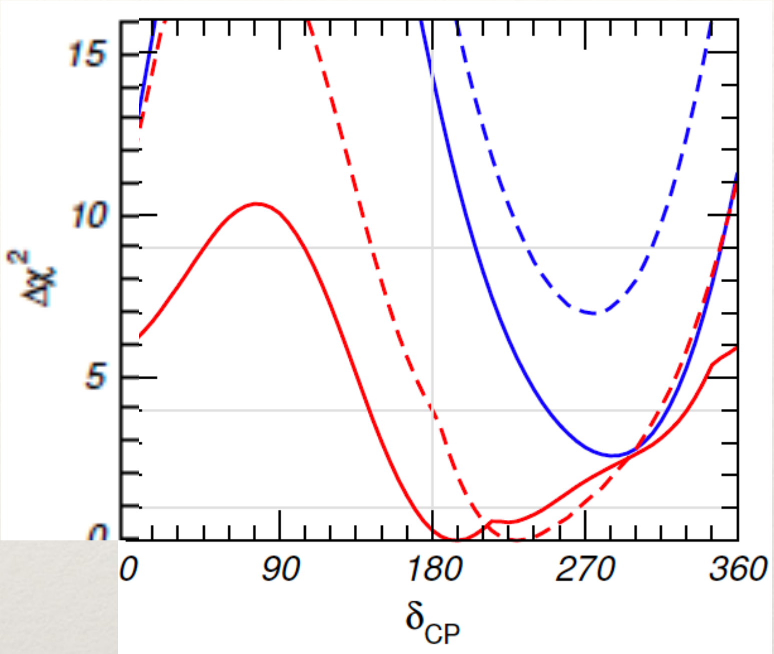
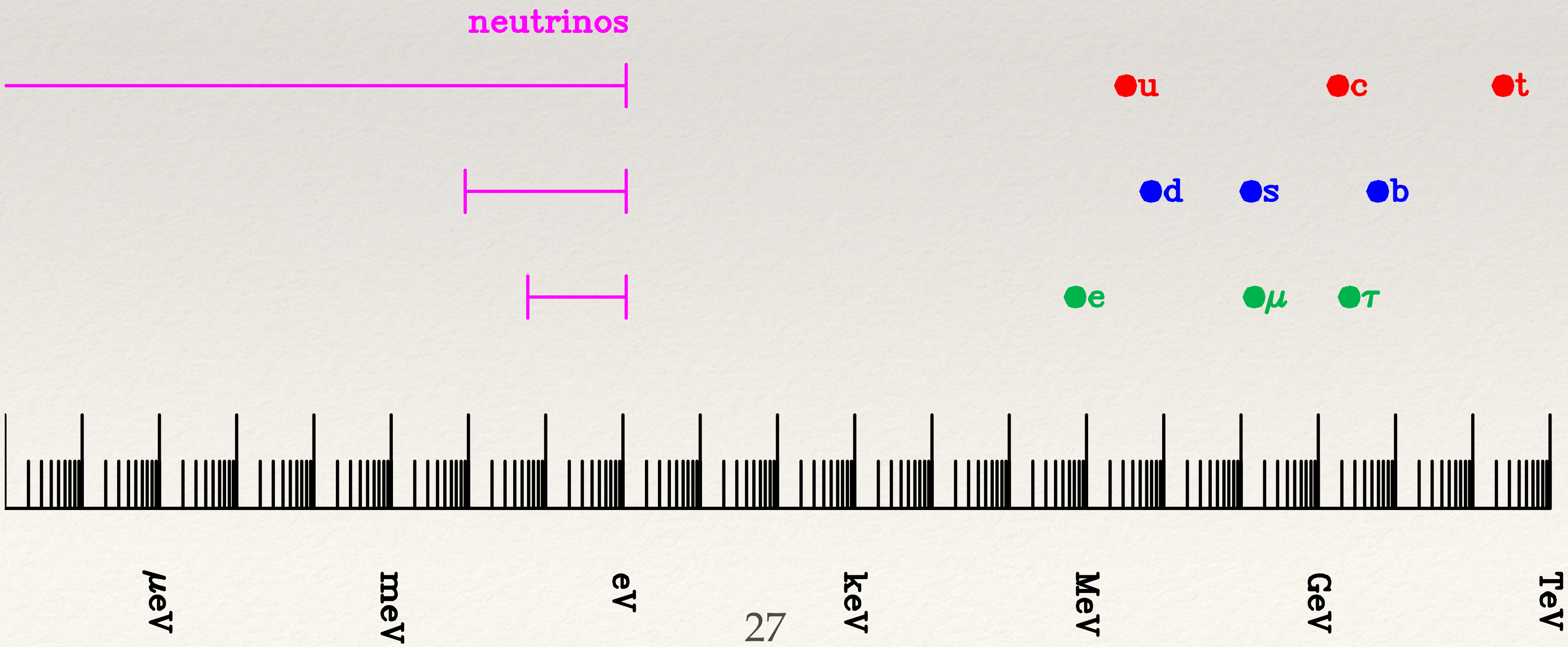


red=NO
blue=IO

Best fit is for NO, $\delta = 195^o$; for IO best fit is close to maximal CP violation



Oscillation Physics goals of DUNE

- Precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with the goal of measuring the charge-parity (CP) violating phase δ ;
- Determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), often referred to as the neutrino mass hierarchy;
- Precision tests of the three-flavor neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and $\bar{\nu}_\mu$ beams; (including the measurement of the mixing angle θ_{23}, and the determination of the octant in which this angle lies).

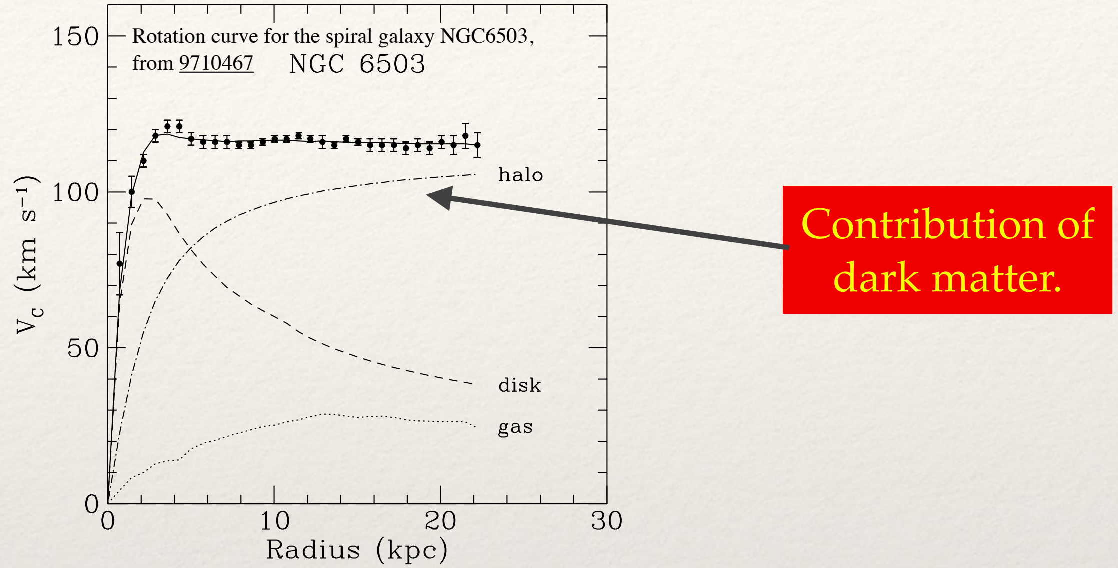
Recommendation

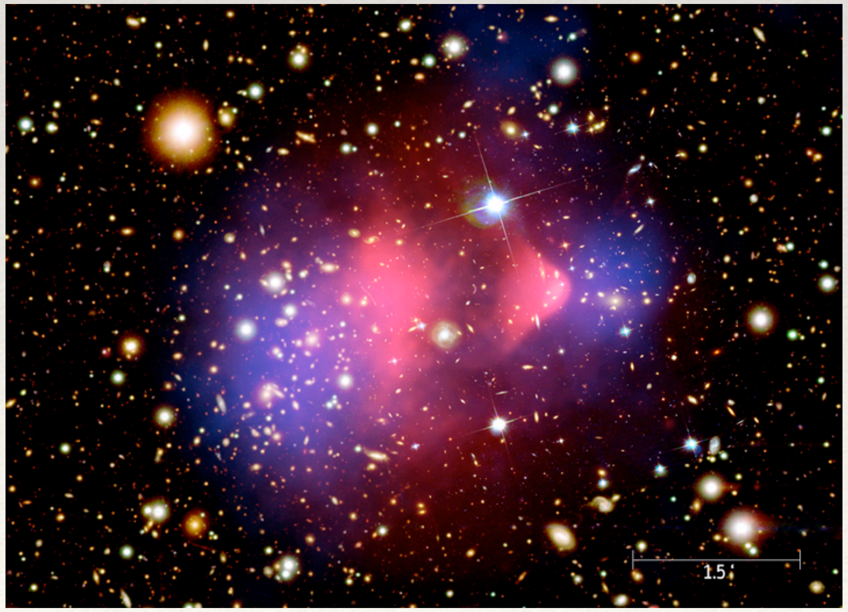
- "Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE)."

Dark Matter

Dark Matter

- Dark Matter problem has been with us for 100 years.
- The most robust observational evidence for Dark Matter comes from galactic rotation curves.
- Simulations of a universe full of cold dark matter (CDM) produce galaxy distributions that are roughly similar to what is observed.
- Planck results the cosmic ray background anisotropies, predict a universe with 6% matter, 26% dark matter and the rest dark energy,(1807.062090)

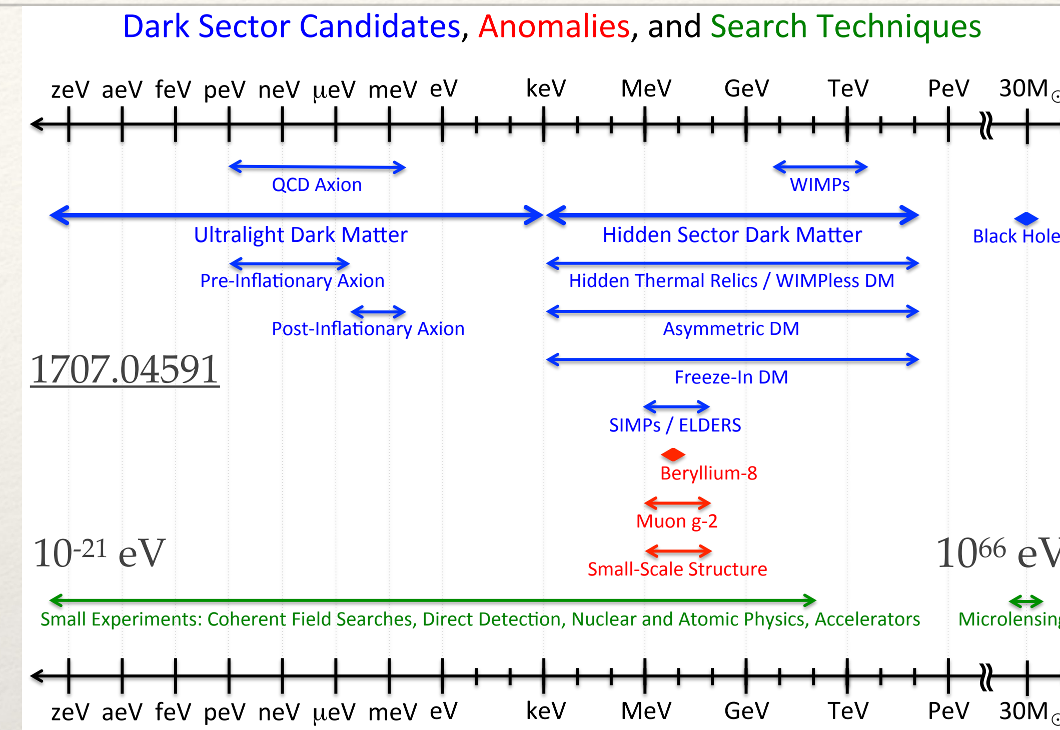


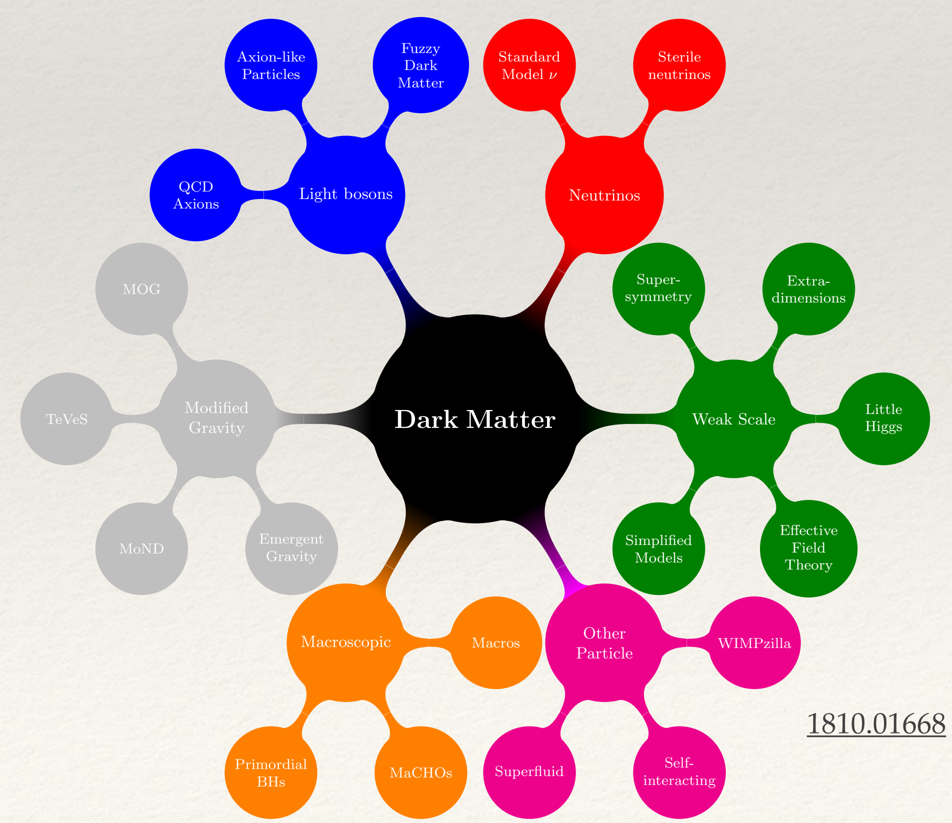


- The bullet cluster consists of two colliding cluster of galaxies;
- the pink clumps in the image and contains most of the baryonic, matter in the two clusters;
- Most of the matter in the clusters, determined by gravitational lensing,(blue) is separate from the baryonic matter (pink), giving direct evidence that nearly all of the matter in the clusters is dark.

How little we know about dark matter

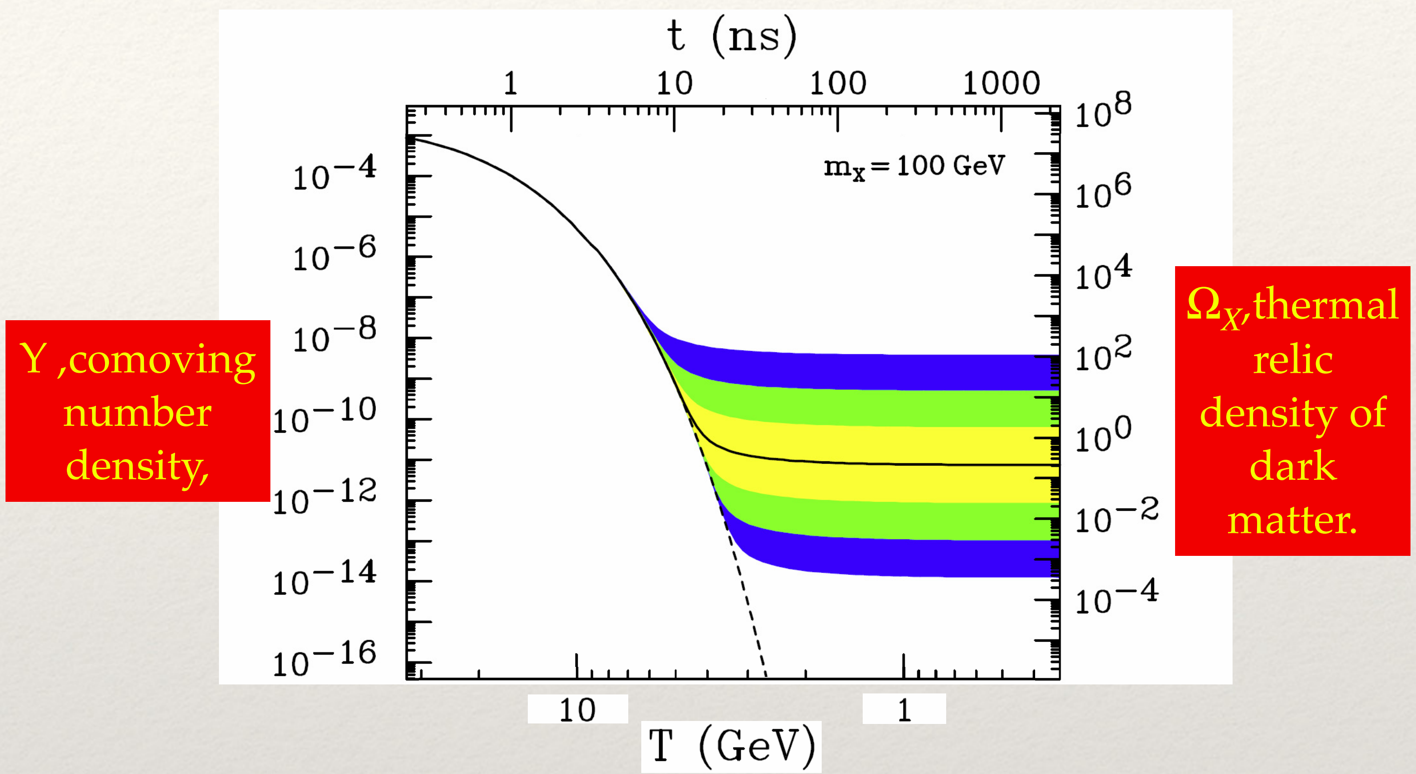
- The masses of viable candidates for Dark Matter run over 90 orders of magnitude.
- We are also ignorant about its couplings to ordinary matter;
- There are many different proposals for dark matter candidates;
- I shall consider Weakly Interacting Massive Particles (WIMPs) and Axions.

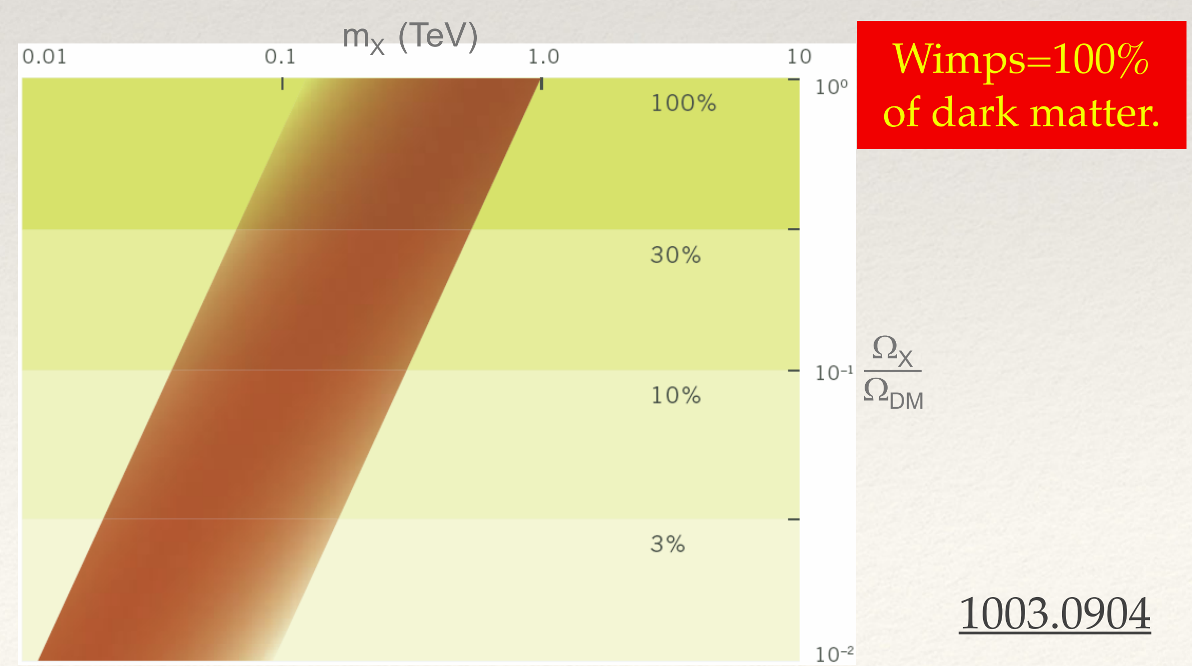




Wimp Miracle or Mirage?

- As the Universe expands the number of dark matter particles is Boltzmann suppressed. At freeze out the gas of dark matter particles is so dilute that they cannot find one another to annihilate.
- Wimps (miraculously?) appeared to be a perfect Dark Matter candidate, being produced with the right relic abundance, while having the correct mass to solve the hierarchy problem;
- In the minimal supersymmetric standard model, every standard model particle has a partner of a different spin, so the partners of the electroweak bosons would be natural dark matter candidates;
- Null searches at the LHC are constraining large regions of parameter space and arguments based on naturalness appear less compelling.
- So if they exist, WIMPS are further away in mass than they seemed — a mirage.





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Axions as Dark Matter

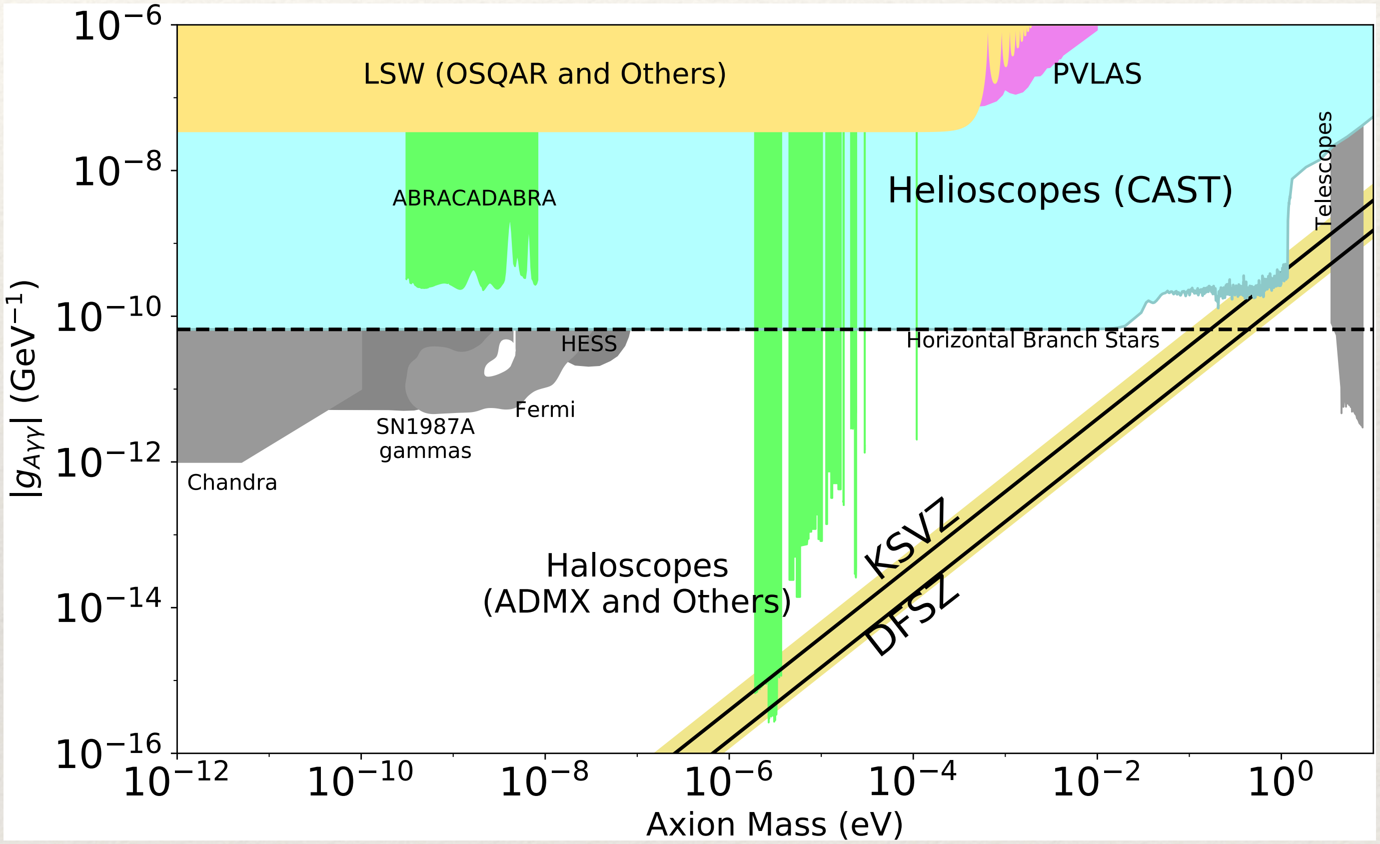
- Axions are a prime candidate for dark matter;
- Valuable role in the standard model solving the Strong CP problem;
- The discovery of the Higgs boson, (an apparently fundamental scalar particle, resulting from spontaneous symmetry breaking), has increased interest in other scalar/pseudoscalar particles;
- Coupling to the SM particles is suppressed by the energy that characterizes the symmetry breaking $g \sim \frac{1}{f_a}$.

Axions

- The QCD Lagrangian contains a CP violating term,
$\mathscr{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \sum_q \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{g_s^2}{32\pi^2}(\bar{\theta})G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$ with $-\pi < \bar{\theta} < \pi$ where $\bar{\theta}$ is the effective θ parameter after diagonalizing the quark masses;
- The electric dipole moment of the neutron is a CP violating effect, and yields $|d_n| = 3.6 \times 10^{-16}\theta\ e \cdot cm$, which requires an unnatural number, $\bar{\theta} < 5 \times 10^{-11}$, suggesting a symmetry principle at work;
- Introduce an axion field a,
$$\mathscr{L}_{QCD+a} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \sum_q \bar{q}(i\gamma^\mu D_\mu - m_q)q + \frac{g_s^2}{32\pi^2}\left(\frac{a}{f_a} - \bar{\theta}\right)G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$
- Non-perturbative fluctuations of the gluon fields, generate a potential with a minimum at $a = \bar{\theta}f_a$
- The axion is the pseudo-Nambu-Goldstone boson of the spontaneously broken $U(1)_{PQ}$.

Axion phenomenology

- Axion mass is generated by mixing with the neutral pion, $f_a m_a = f_\pi m_\pi$, so that
  $m_a = (5.7 \pm 0.007)\ \mu\text{eV} \left(\frac{10^{12}\ \text{GeV}}{f_a} \right)$
- Strength of axions couplings to SM particles $g \sim \frac{1}{f_a}$ hence $g \sim m_a$, so there is only one scale f_a in standard axion models
- Generalized axion models beyond K+SVZ and DFS+Z cover all the area above the yellow band.



Recommendation

- "The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world."***

High-priority projects

What machine(s) should we propose?

- At this point there is a wide spectrum of theoretical possibilities;
- We do not have the comfort of a no-lose theorem as we did for the LHC and the Higgs;
- We need a broad search on many fronts, using both colliders and physics beyond colliders;
- (And of course extensive R&D on accelerator science);
- Each higher energy collider has led to important discoveries ISR(jets), $Sp\bar{p}S$ (W,Z), Tevatron(t), LHC(h);
- The point of departure is defined by the results from HL-LHC, especially for the Higgs boson;

An important first step: the Higgs boson

- There is a strong case for further investigation of the Higgs boson;
- Many of the important questions are linked to the Higgs boson, (1905.00382)
    - Is h the only scalar degree of freedom?
    - Is h elementary?
    - What keeps $m_H \ll m_{Planck}$?
    - 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)?
- The results to be obtained from the HL-LHC constitute our point of departure.

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%-20% 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)

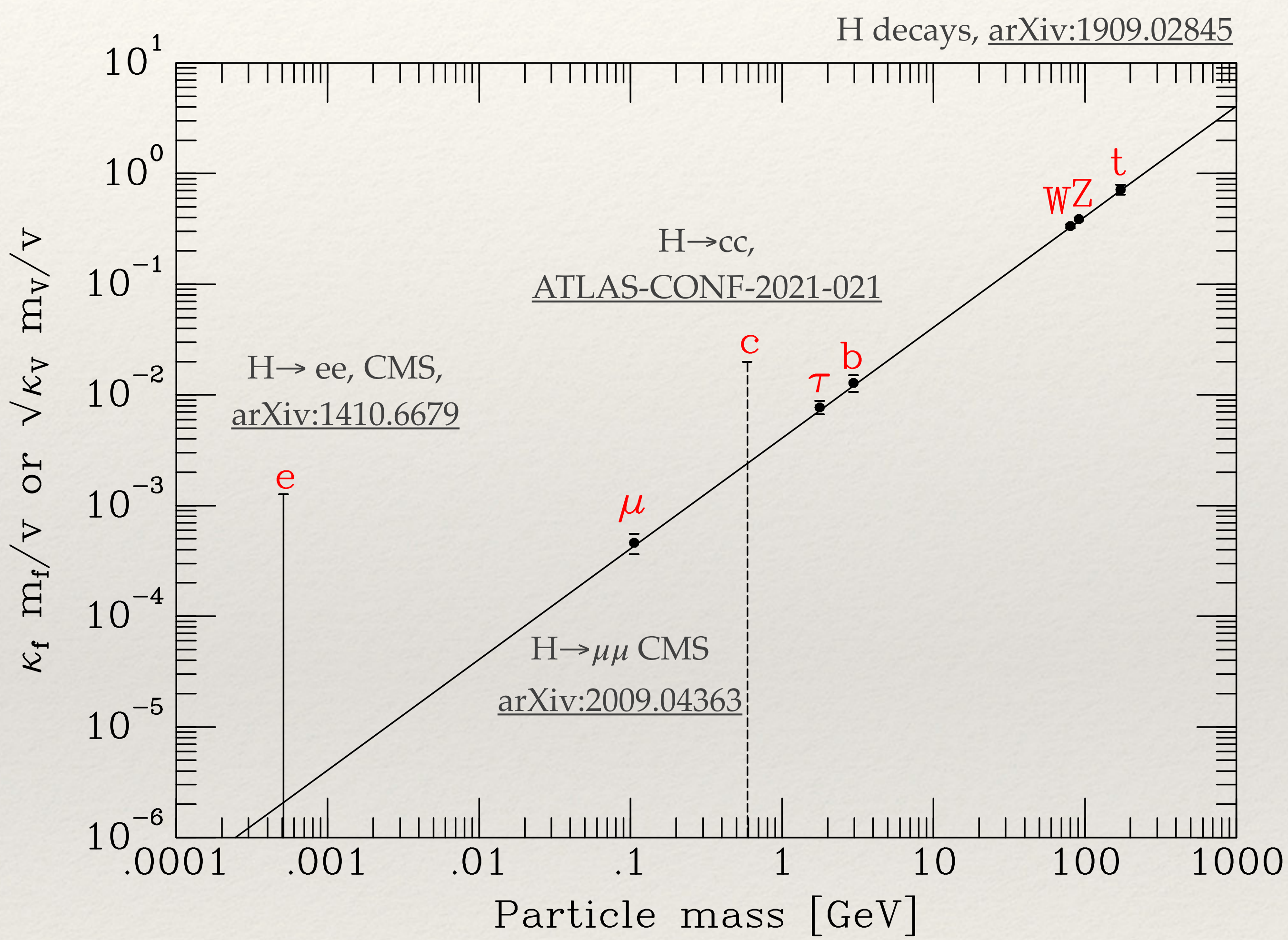
H^0 Signal Strengths in Different Channels

Combined Final States $= 1.10 \pm 0.11$
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.19^{+0.12}_{-0.11}$
$\gamma\gamma = 1.10^{+0.10}_{-0.09}$
$c\bar{c}$ 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^0H^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→ $l^+l^-\gamma$,
Decay to muons, (ATLAS, CMS) h→ $\mu^+\mu^-$

Yukawa couplings of the Higgs boson

- Couplings to the charged fermions of the third generation established by 2018/2019;
- Evidence of Coupling to μ observed by CMS(3σ) and ATLAS(2σ);
- 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.

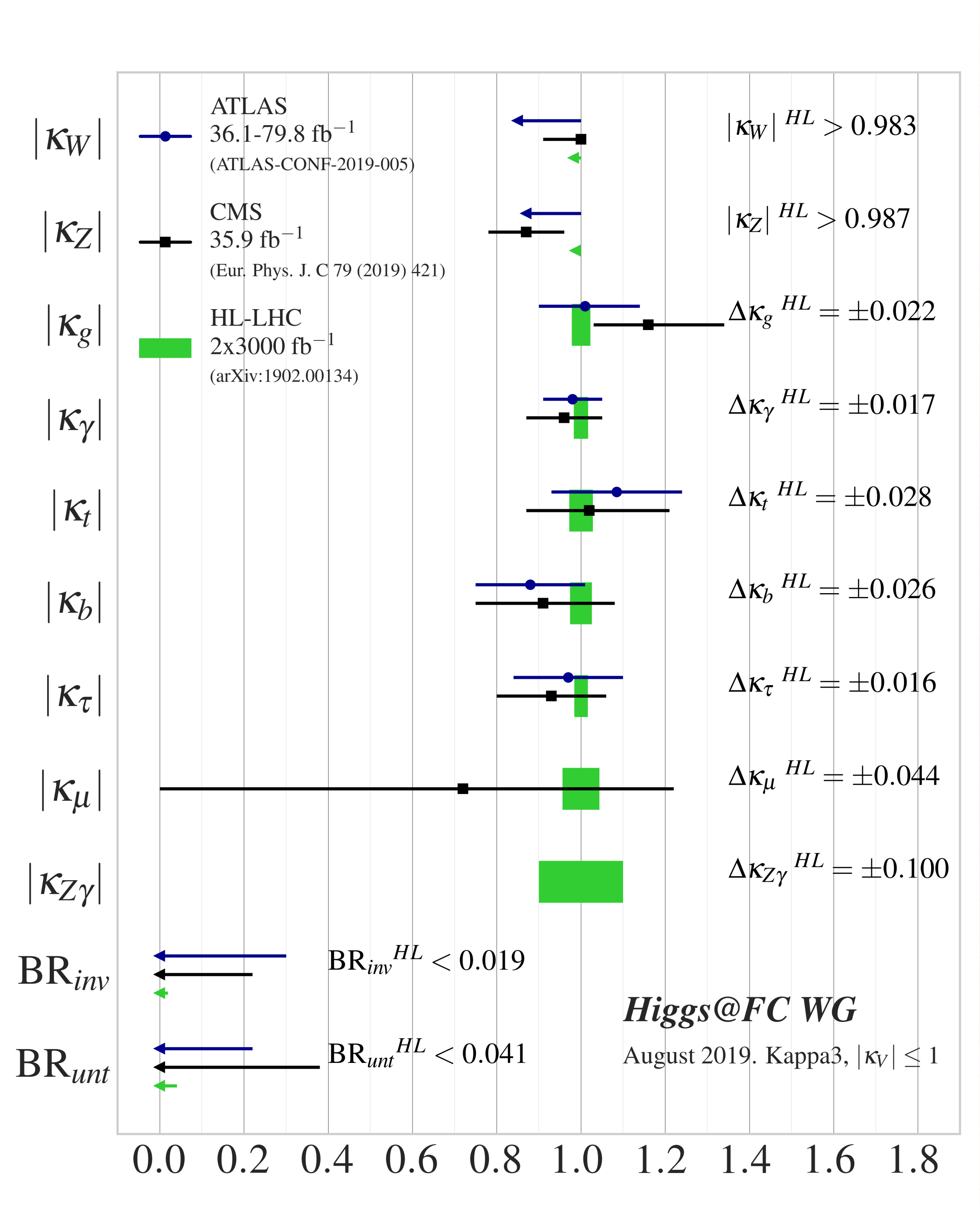


Coupling to (electrically charged) fermions t, b, τ, μ indicates a new Yukawa force, (i.e. beyond, strong, electroweak, gravity)

Potential to observe it indirectly in $t\bar{t}$ production

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;
- κ— simple to explain, but SMEFT introduces new kinematic structures.
- Green rectangles represent the precision expected at the conclusion of HL-LHC.



Start from the basis of HL-LHC

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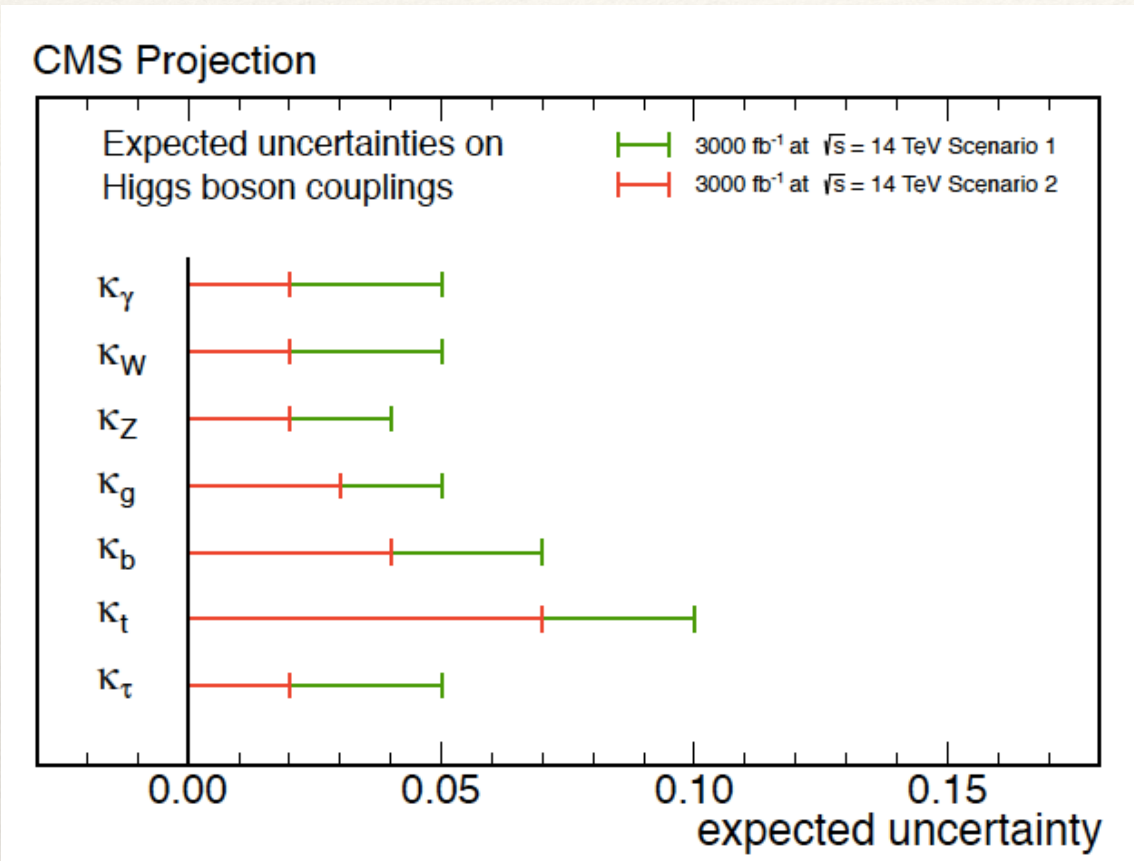

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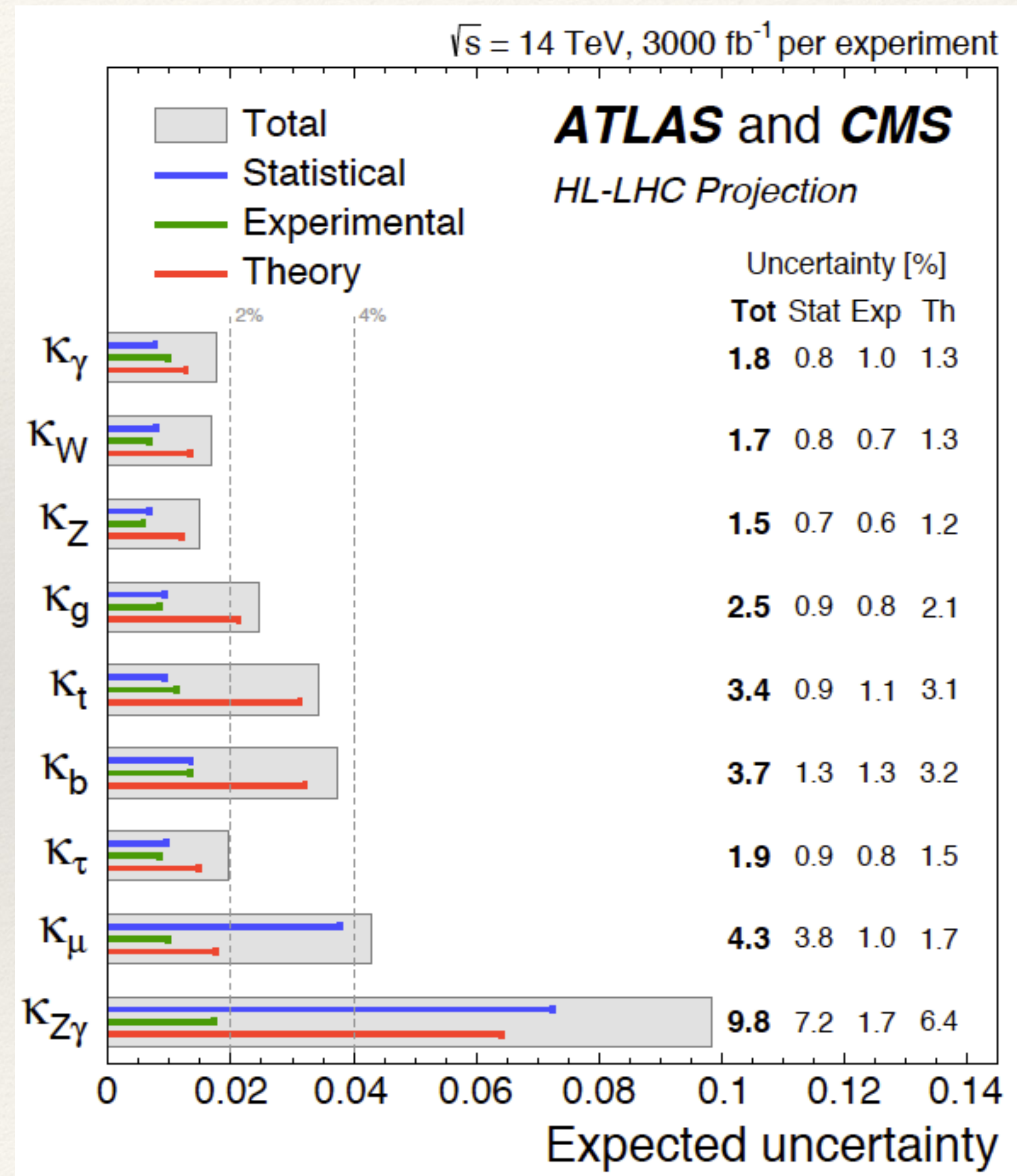


- Progress from in expectations from 2013 to 2019
- With the availability of data, projections for the future have improved.
- Dominance of theoretical errors, for all modes except the two not yet seen at 5 σ level

Recommendation

- "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."

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?

$$V(H^\dagger H) = \lambda (H^\dagger H)^2 - \mu^2 H^\dagger H$$

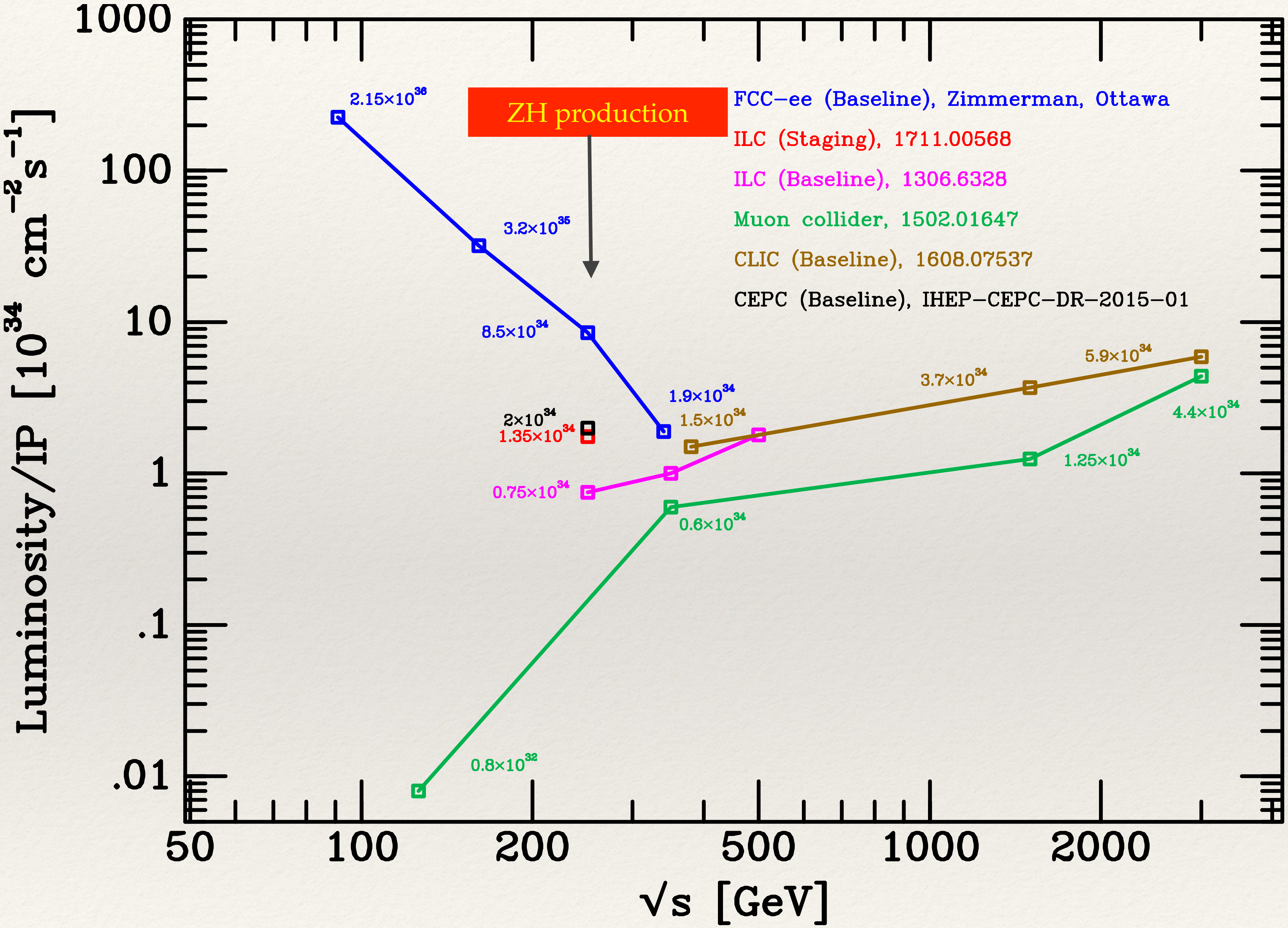
$$\mathcal{L}_{Higgs} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4 \qquad SM: \lambda_3 = 1, \lambda_4 = 1$$

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

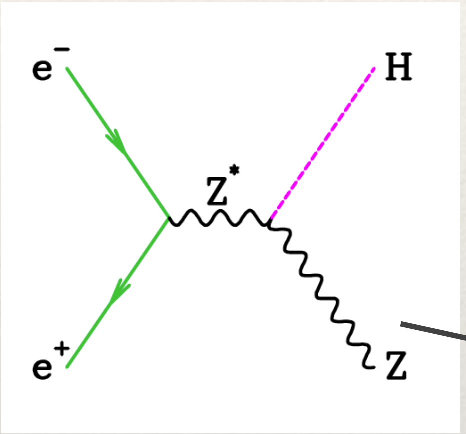
Luminosity at lepton colliders



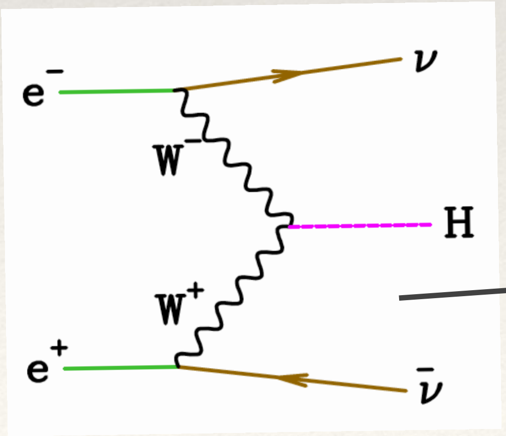
Higgs physics at proposed e^+e^- colliders

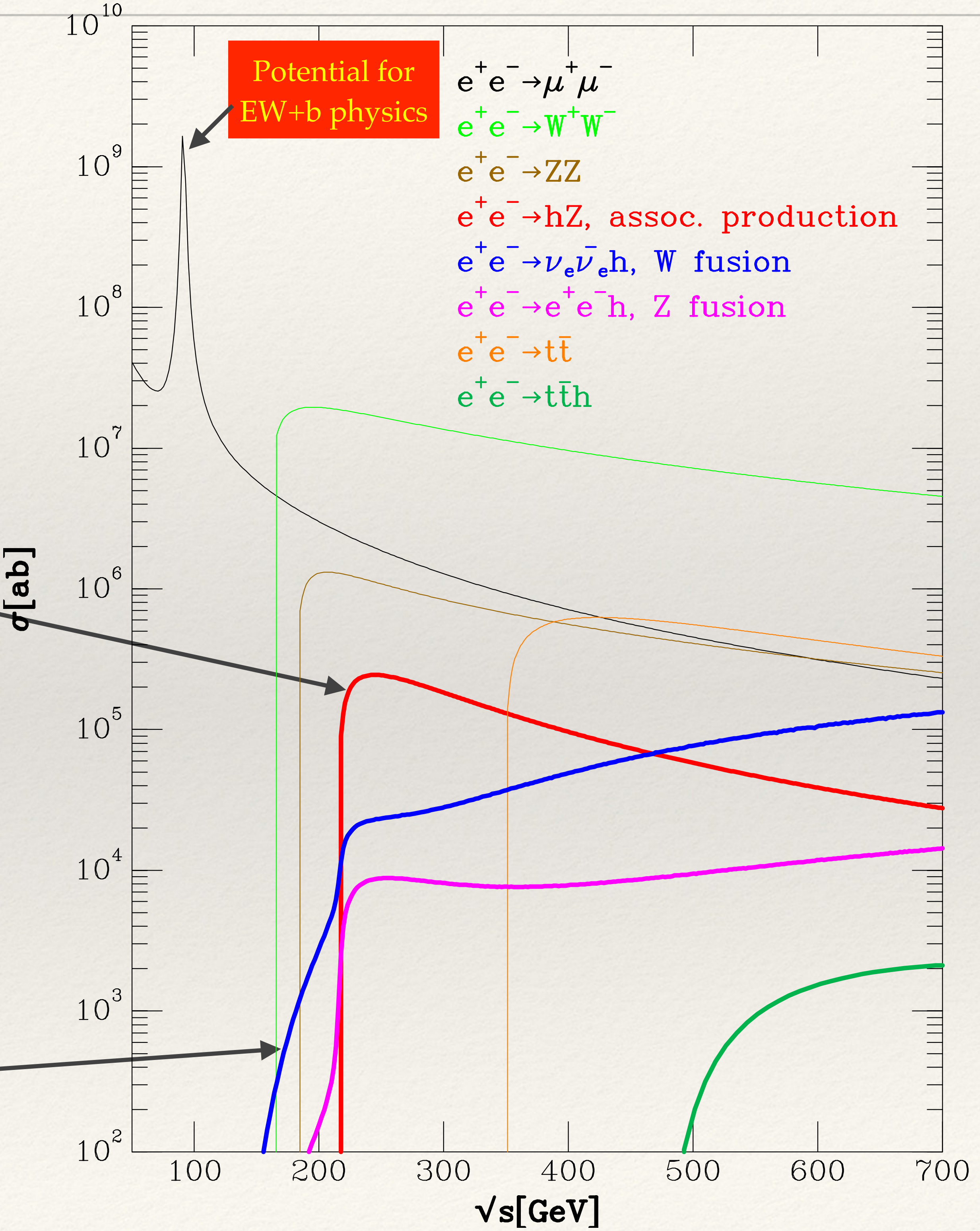
e⁺e⁻ machines & Higgs bosons

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



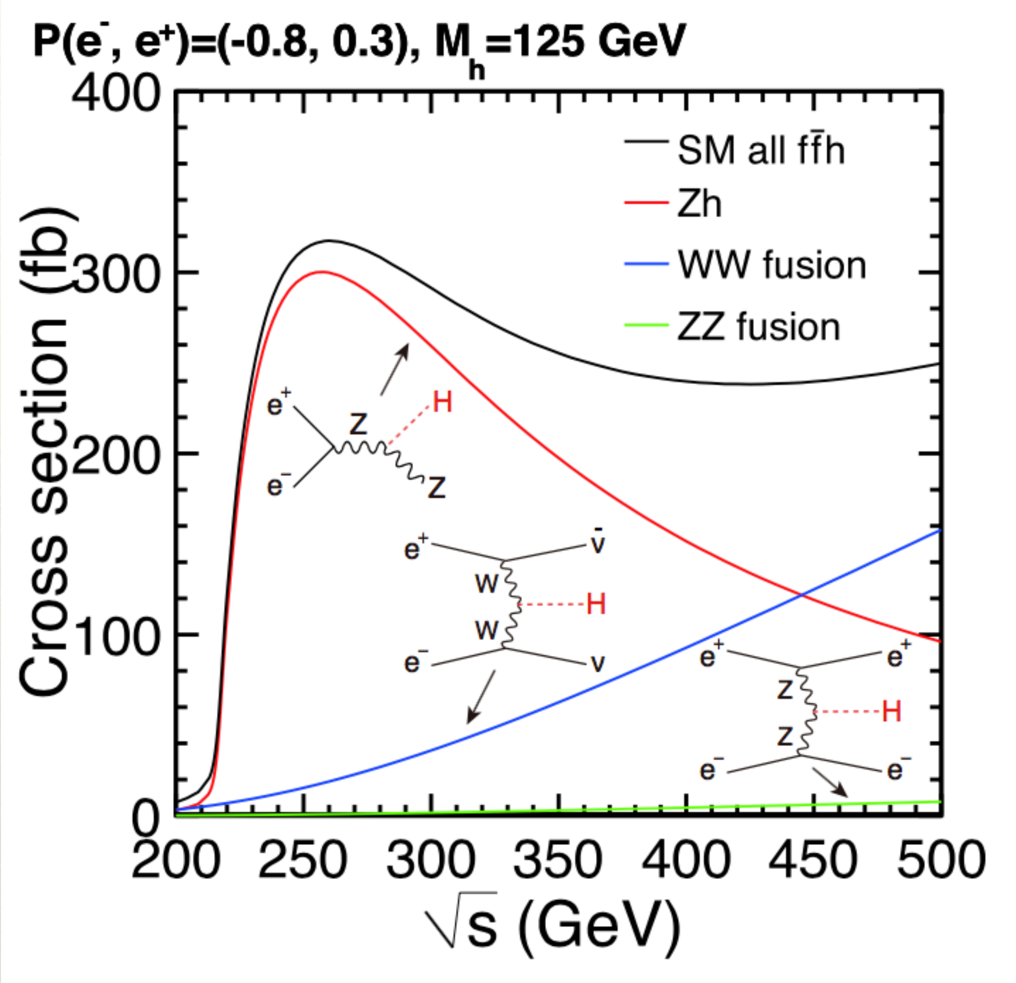
- At higher energy produce H by fusion of W-bosons (and Z).





Higgs at e^+e^- collider: generalities

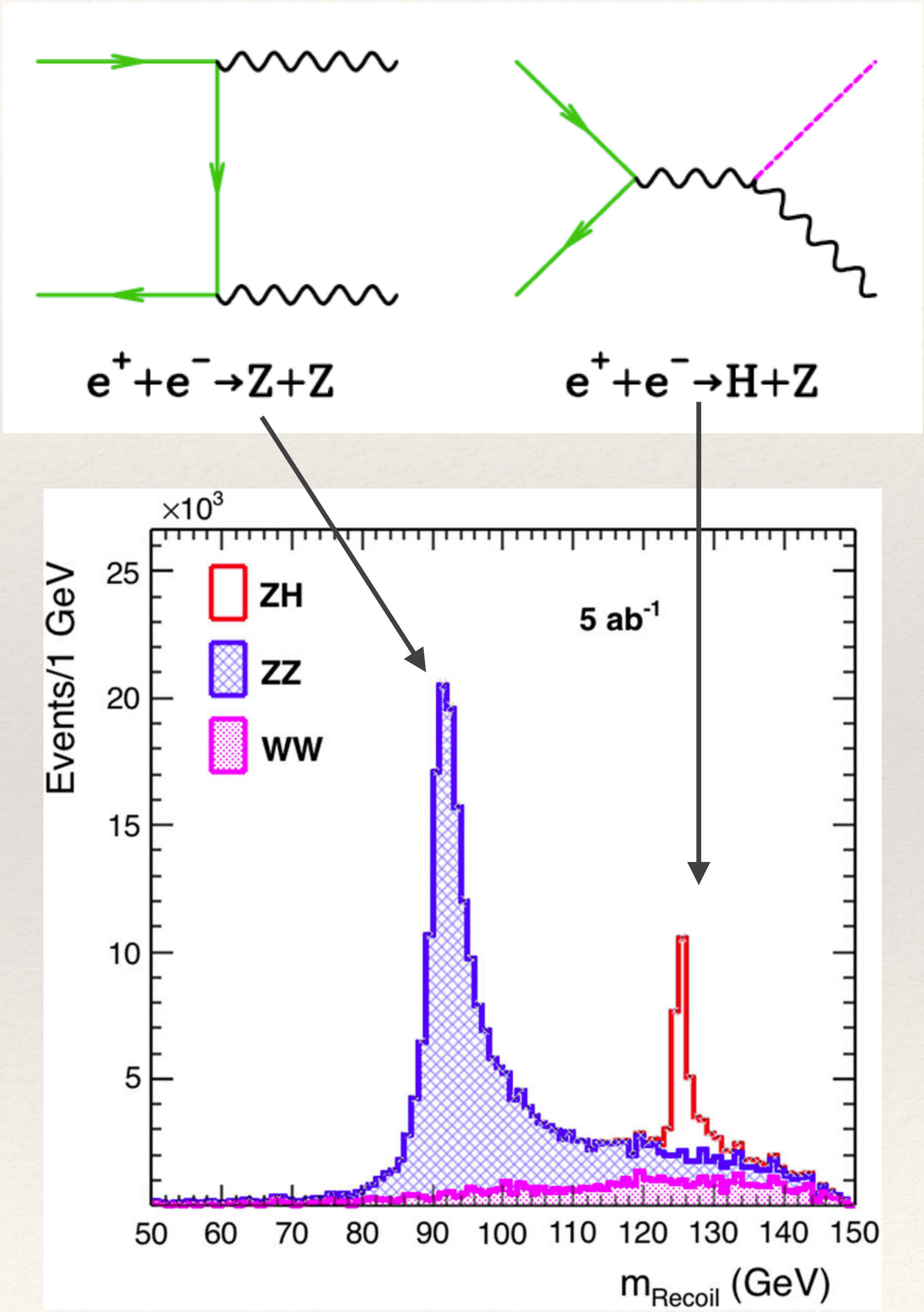
- WW fusion production ten times smaller at 250 GeV than at 500 GeV;
- ~40% increase in ZH cross section with polarization (-0.8,+0.3);
- In terms of precision Higgs parameters polarization is like a factor of ~2 in integrated luminosity;



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, $\delta\kappa_{\text{inv}}=0.19\%$, $\delta\kappa_{\text{untagged}}=1.2\%$;



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
$FCC\text{-}ee_{240}$	2.7	κ-framework [1]	1.8
$FCC\text{-}ee_{365}$	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

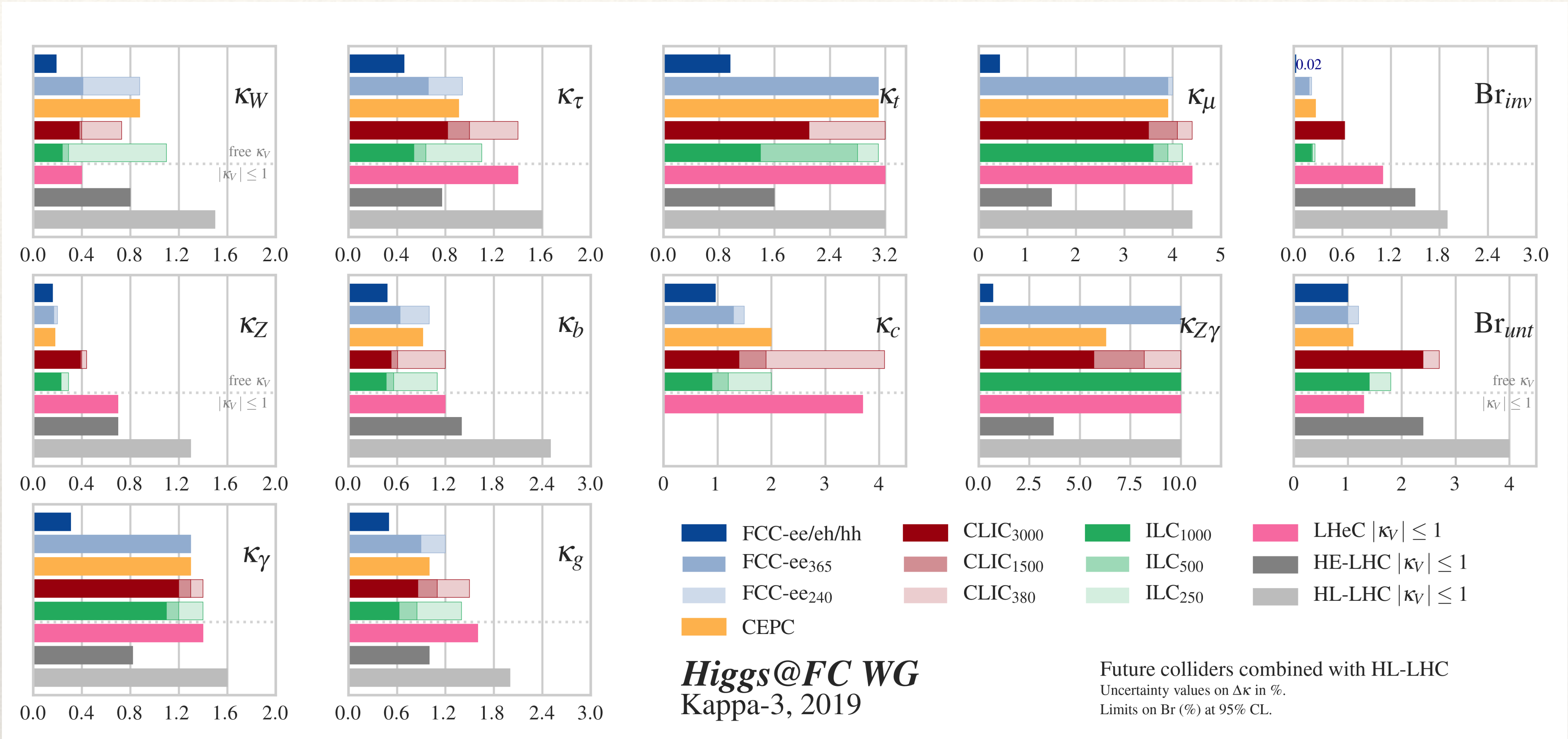
ABSTRACT

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.

arXiv:1905.03764

- 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

Kappa-scenario



- κ-parameters: introduce the freedom to rescale all the couplings of the standard model; κ has the advantage that it is simple;
- the effects of beam 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.

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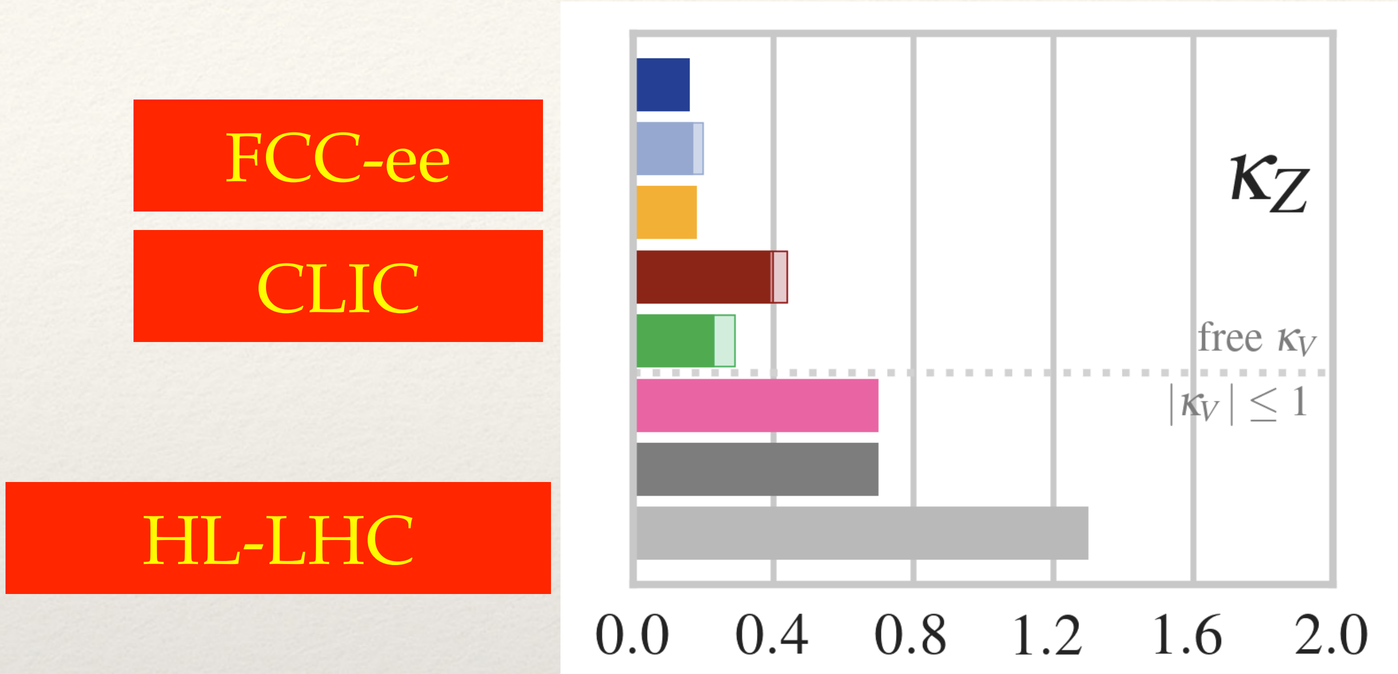
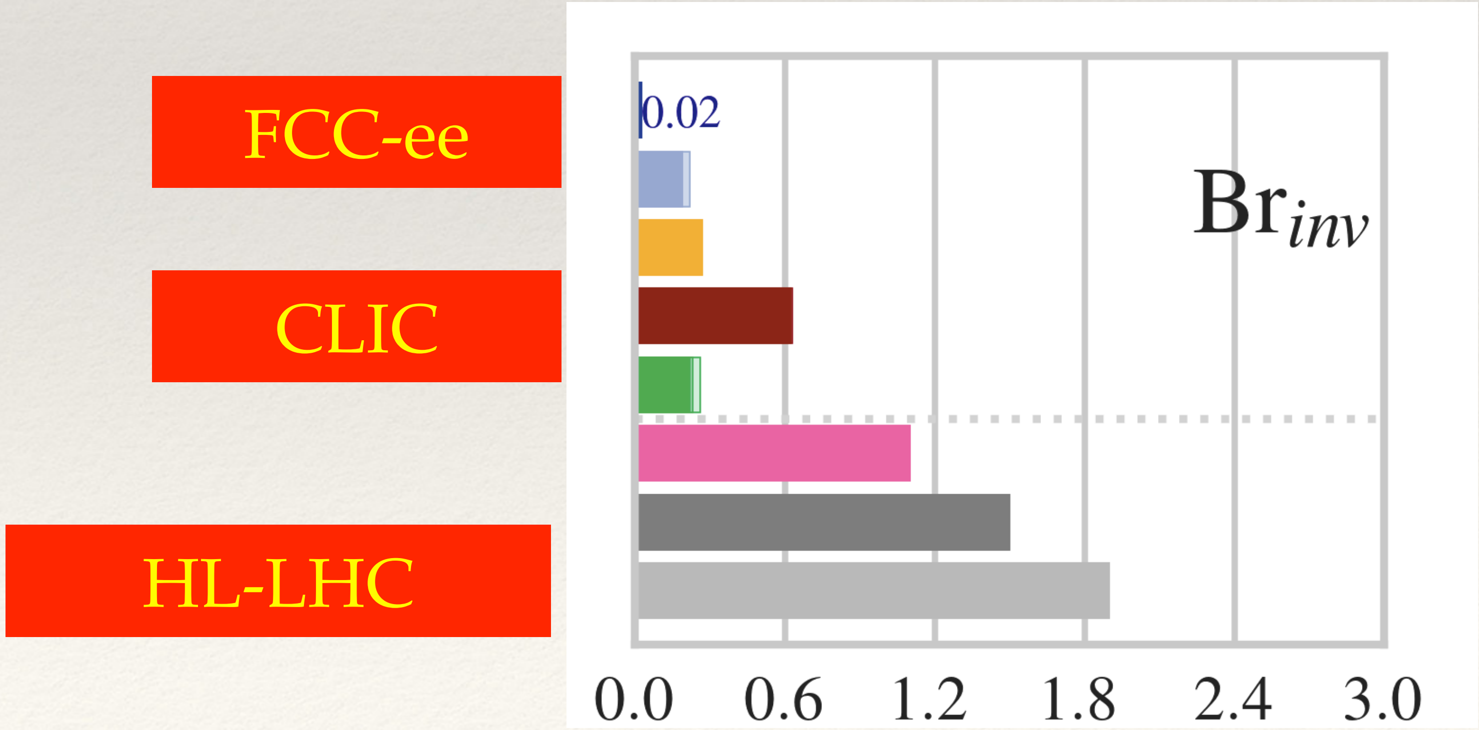
Look at a couple in more detail

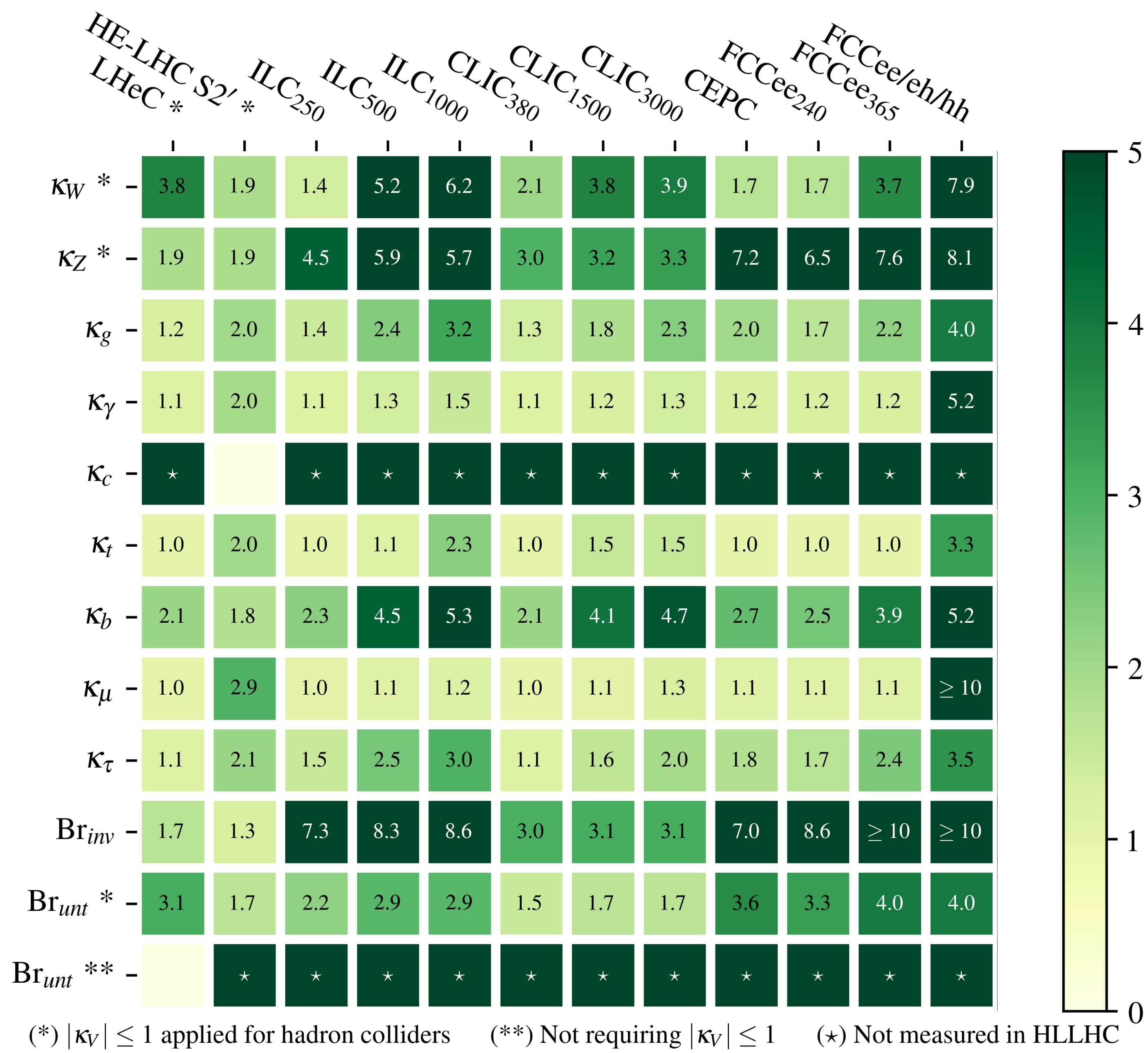
- Expected relative precision on kappa parameters in percent.





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.



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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
  $$\left(g_{HX}^{eff}\right)^2 = \frac{\Gamma(H \to X)}{\Gamma^{SM}(H \to X)}$$
- Graphical representation of the improvement over HL-LHC in precision of couplings;
- Similar color for columns indicates similar reach for machines;

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g_{HZZ}^{eff}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g_{HWW}^{eff}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g_{H\gamma\gamma}^{eff}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g_{HZ\gamma}^{eff}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g_{Hgg}^{eff}	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_{Htt}^{eff}	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_{Hcc}^{eff}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g_{Hbb}^{eff}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g_{H\tau\tau}^{eff}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g_{H\mu\mu}^{eff}$	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

1905.03764v2

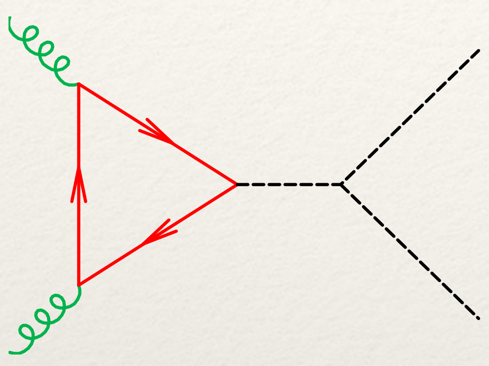
Overall conclusion: first stage e+e- colliders all have similar reach, albeit with different time scales.

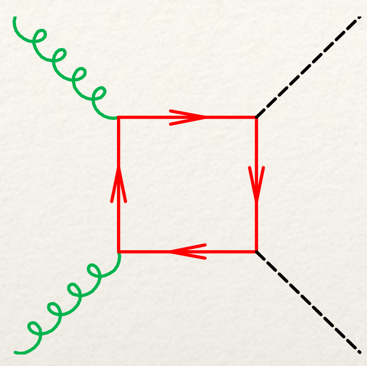
e+e- colliders beyond the Higgs factory

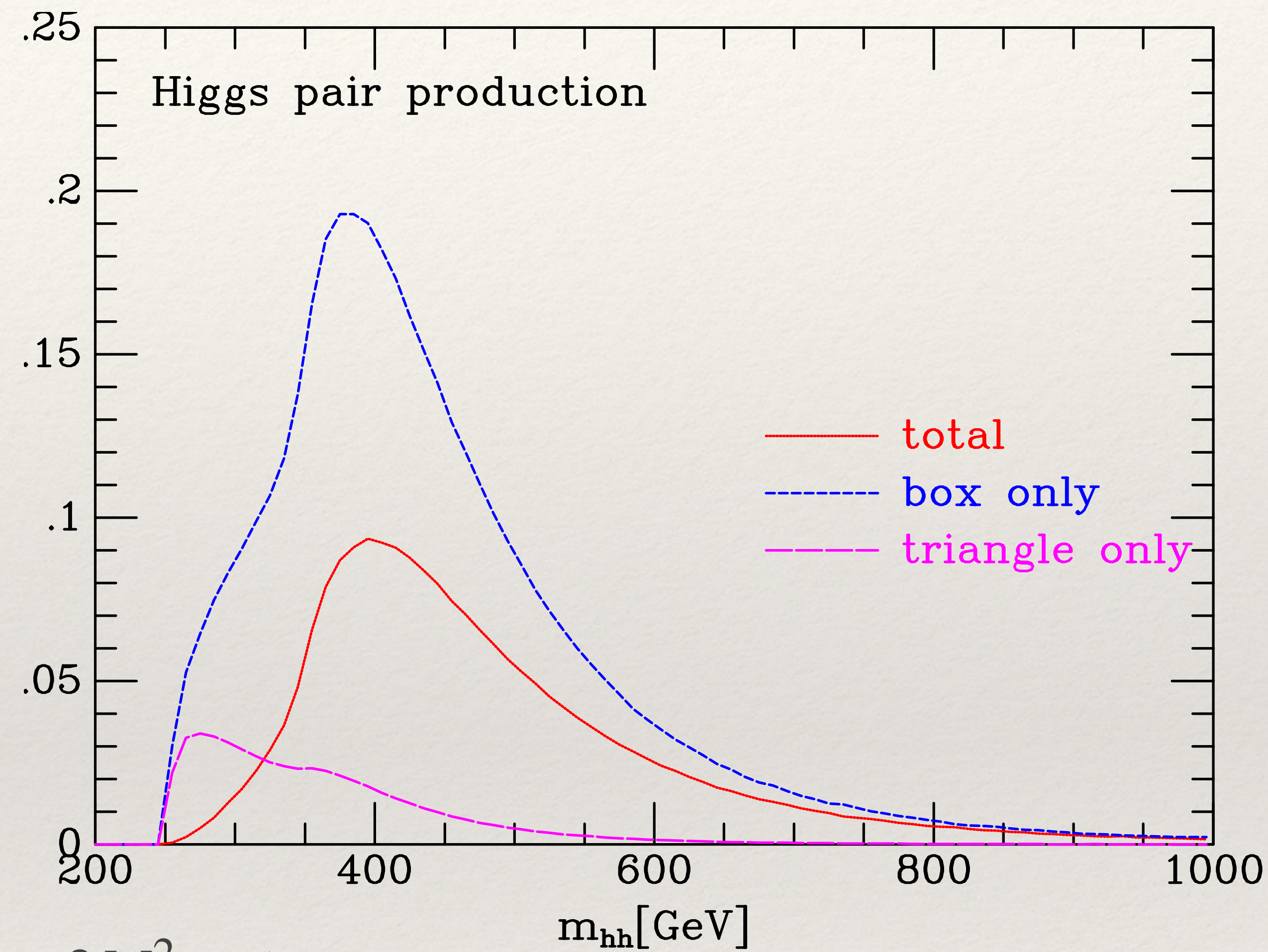
Collider	√s	$\mathcal{L}_{inst}$ [10^{34}] $cm^{-2}s^{-1}$	$\mathcal{L}$ [ab^{-1}]	Time [years]	
FCC-ee				15	Precise beam energy measurement using transverse polarization of the beams
	M_Z	100–200	150	4	5×10^{12}, decaying to b, c, τ etc: Precision electroweak and heavy flavor, scalar states
	$2M_W$	25	10	1–2	10^8 W bosons at threshold, $\Delta M_W = 0.5$ MeV, triple gauge couplings
$FCC\text{-}ee_{240}$	240 GeV	7	5	3	
$FCC\text{-}ee_{365}$	$2m_{top}$	0.8–1.4	1.5	5	Δm_t=10 MeV
CEPC				10	
	M_Z	17–32	16	2	
	$2M_W$	10	2.6	1	Similar to FCC-ee, but with a factor of ≥ 2 lower luminosity
	240 GeV	3	5.6	7	
ILC				>20	e^- and e^+ polarization boosts the statistical power of measurements by factor 2.5-10
(*)	M_Z	0.8	0.1	1–2	Determination of all 28 TGC parameters
ILC_{250}	250 GeV	1.35–2.7	2.0	11.5	Direct extraction of A_f-resolution of 3σ discrepancy in $\sin^2\theta_W$, Z-bosons rad return
ILC_{350}	350 GeV	1.6	0.2	1	
ILC_{500}	500 GeV	1.8–3.6	4.0	8.5	top electroweak couplings, Higgs self coupling at 27%, top Yukawa coupling at 6.3%
$ILC_{1000}^{(*)}$	1000 GeV	3.6–7.2	8.0	8.5	Higgs self coupling via double Higgs-strahlung and VBF measurements at 10-20%
CLIC				27	e^- polarization
(*)	M_Z	0.8	0.1	1–2	
$CLIC_{380}$	380 GeV	1.5	1.0	8	access to both single Higgs production processes;
$CLIC_{1500}$	1.5 TeV	3.7	2.5	7	$e^+e^- \to ZHH$, Higgs self-coupling -29% / +67%
$CLIC_{3000}$	3.0 TeV	6.0	5.0	8	Probing operators whose influence grows with energy

Source: arXiv:1905.03764

Higgs pair production in pp collisions







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

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

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

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

- Amplitude vanishes at threshold in the standard model;
- Sensitivity to λ is close to threshold.

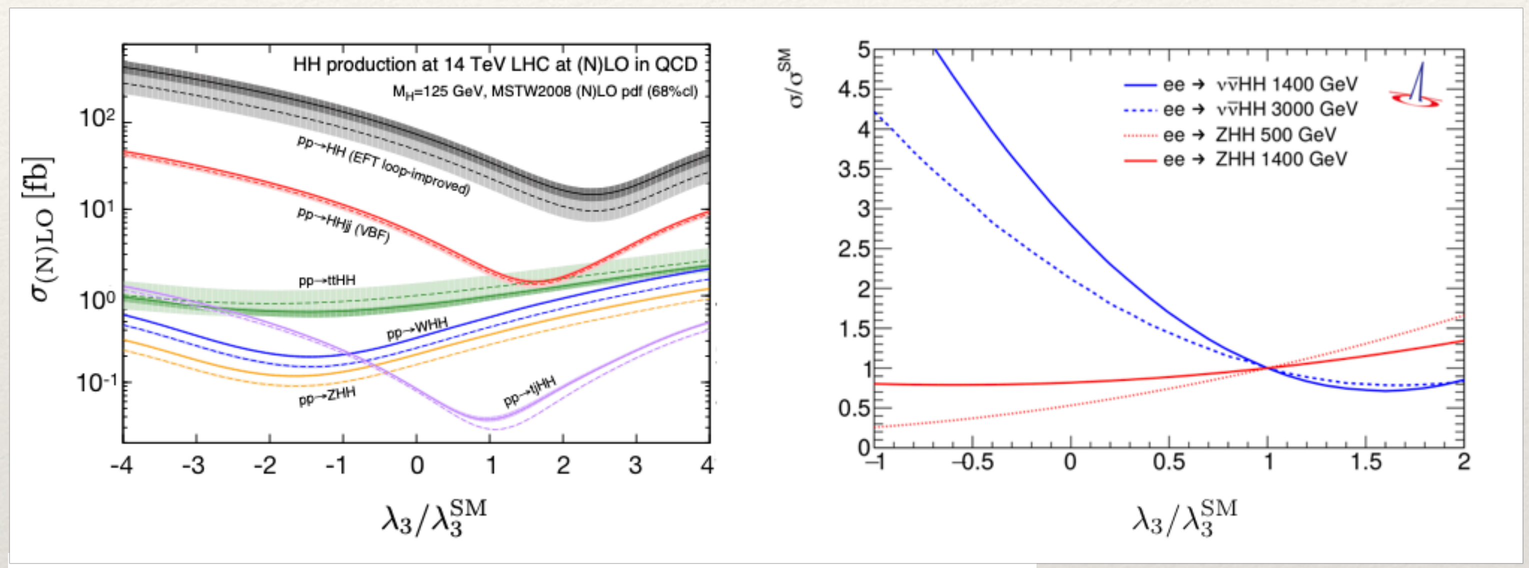
Measuring the Higgs potential

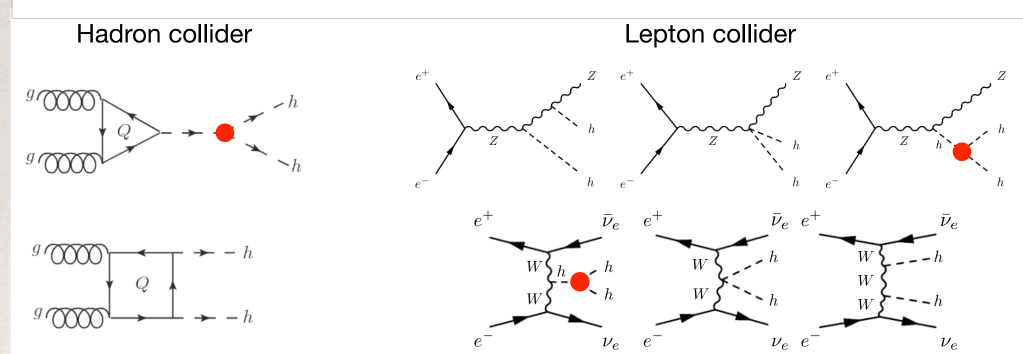
In SM potential fixed in terms of m_H and v

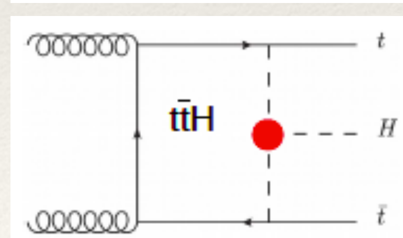
$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

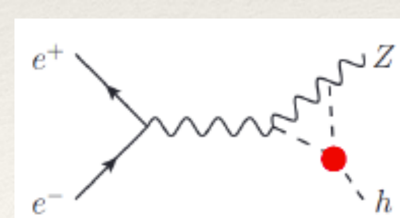
$$\text{with} \quad \lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

- 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



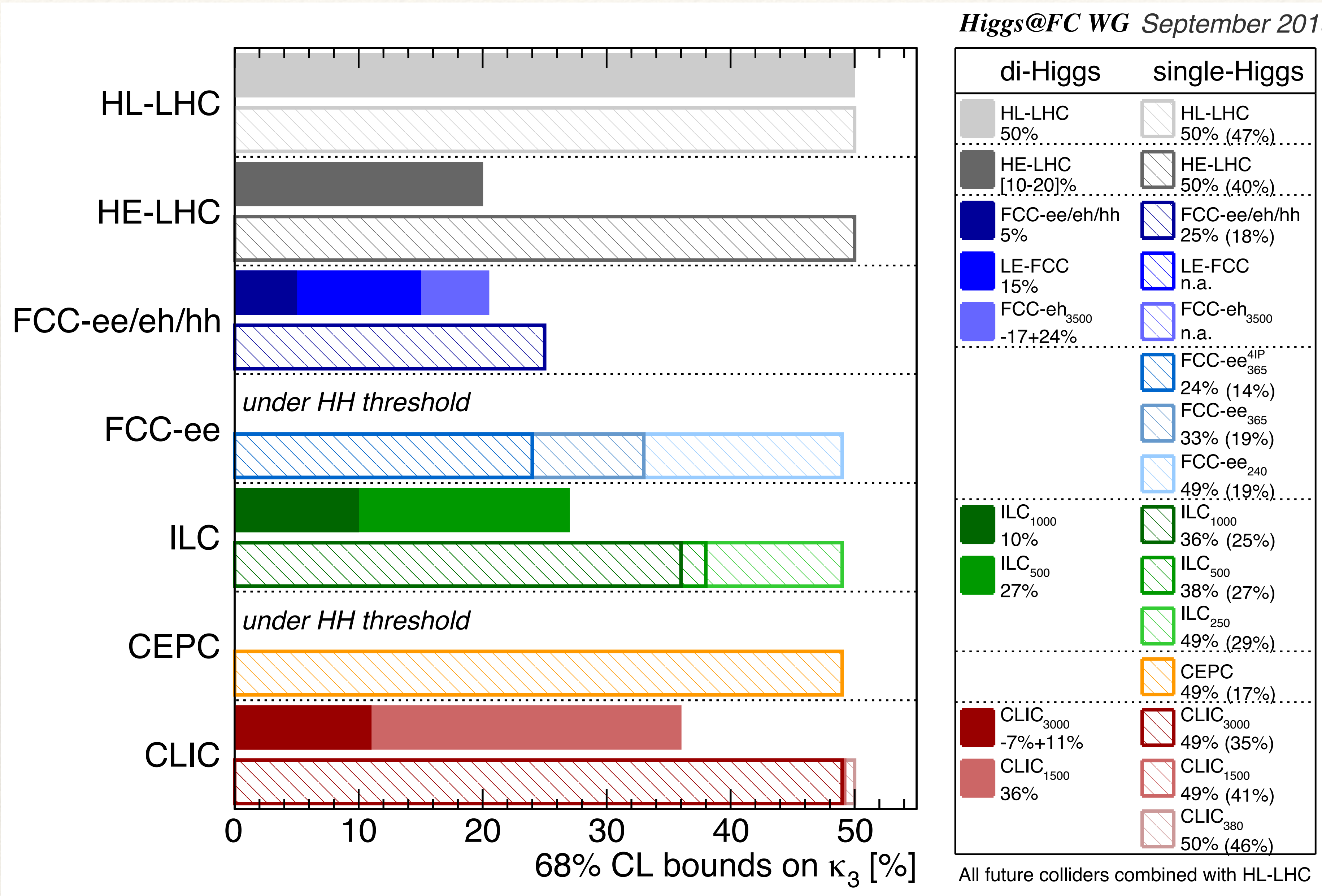






Sensitivity to λ via single-H and di-H production

- 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



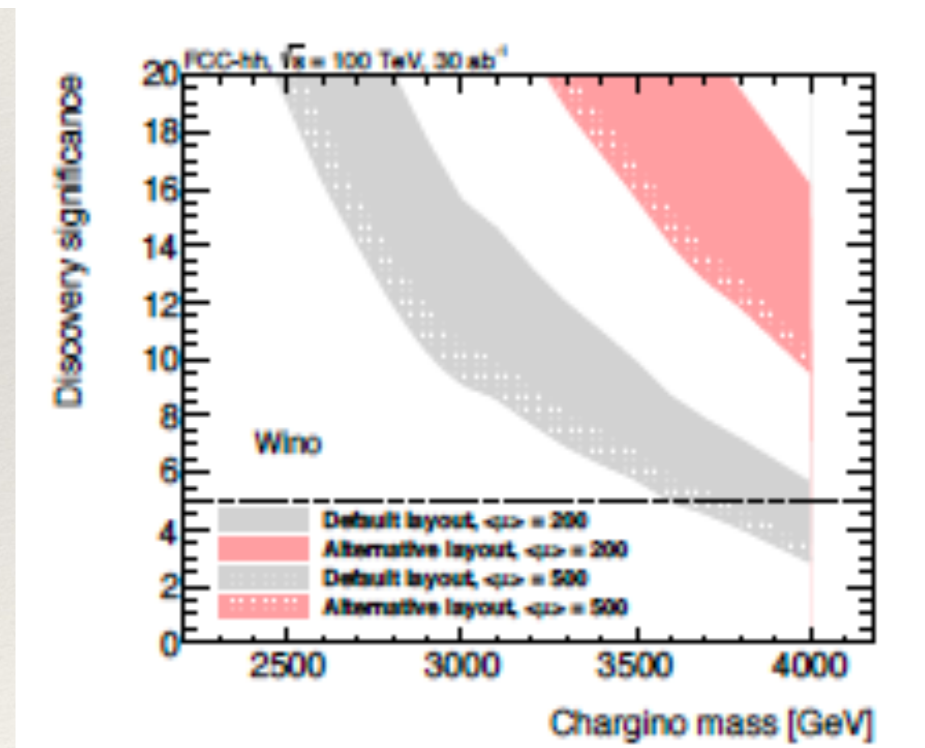
Precision measurement requires FCC-hh

FCC-hh

- FCC-hh defined as a pp collider at $\sqrt{s} = 100$ TeV and a luminosity of $20 - 30\ \mathrm{ab}^{-1}$, FCC-CDR-Vol1;
- Higgs physics: Higgs self-coupling, $t\bar{t}h$ coupling, rare decays $h \to Z\gamma, h \to \mu\mu$;
- Dark matter: first collider to have access to weakly interacting particles up to 3TeV;
- Finding the origin of new physics exposed by indirect evidence;
- Opportunities for ep and heavy ion physics.

$$N_{100} = \sigma_{100\ \mathrm{TeV}} \times 30\mathrm{ab}^{-1}, N_{14} = \sigma_{14\ \mathrm{TeV}} \times 3\mathrm{ab}^{-1}$$

	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390



More information on the physics of FCC-hh tomorrow from Paris Sphicas

Recommendation: 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.

Thank you