HIGGS BOSON: A PORTAL TO NEW PHYSICS

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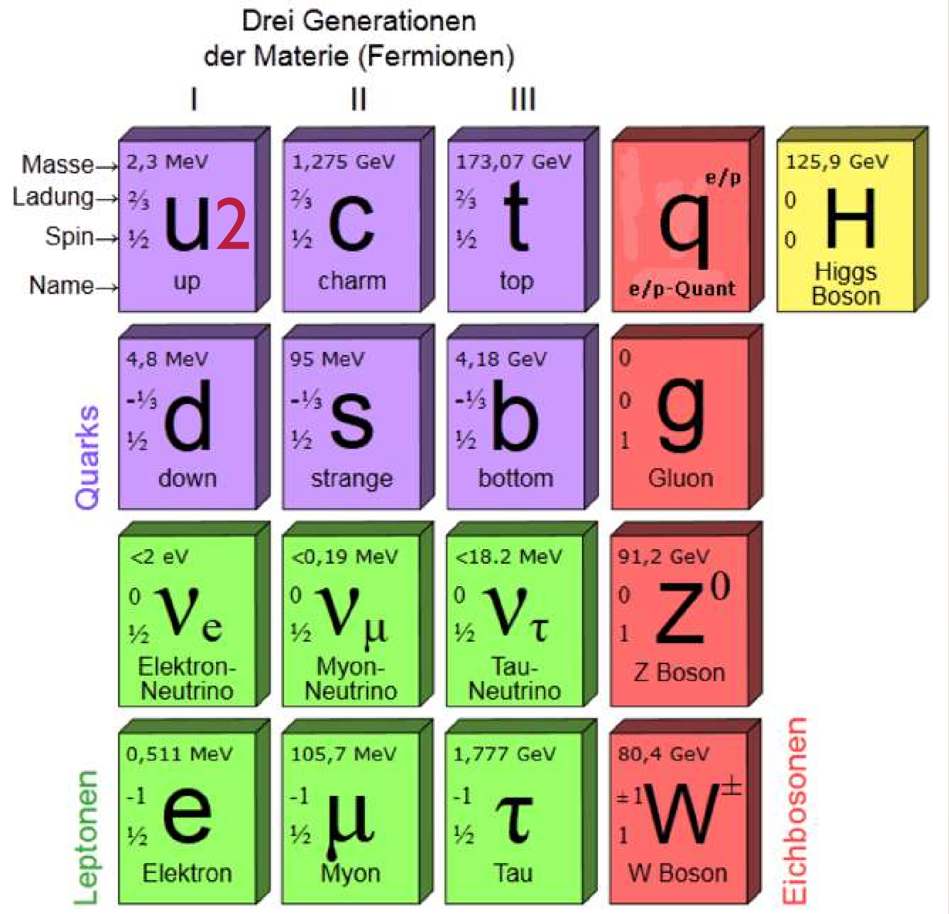


STANDARD MODEL OF PARTICLE PHYSICS

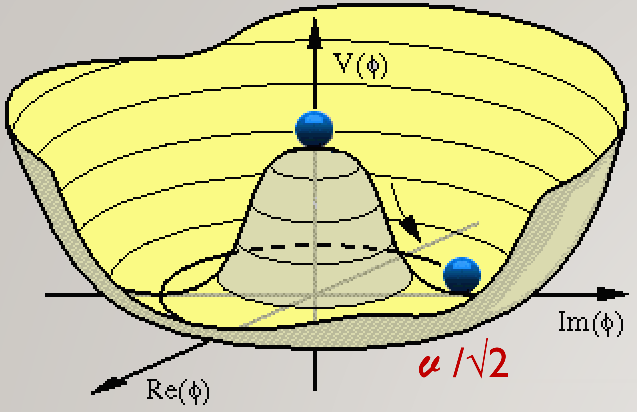
1. Describes elementary particles and their interactions
2. 'Equations of motion' in classical physics are substituted with the Lagrangian (particles are quantum and relativistic)
3. Interactions are consequence of symmetries (of the Lagrangian) to the local phase transformations giving rise to vector bosons (gauge symmetries)
4. Higgs mechanism: Assumption that there is a scalar field, with a ground state (vacuum v) that does not have the symmetries of the Lagrangian (spontaneous symmetry breaking)
5. Interaction with the scalar field (Higgs) introduces mass terms in the Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_{\gamma ff} = -eQ_f \bar{f}\gamma^\mu f A_\mu + \mathcal{L}_{Wff'} = -\frac{g}{\sqrt{2}}\left(\bar{f}\gamma^\mu(1-\gamma^5)f' W^+_\mu + h.c.\right) + \mathcal{L}_{Zff} = -\frac{g}{\cos\theta_W}\bar{f}\gamma^\mu(g_V^f - g_A^f\gamma^5)f\, Z_\mu + \mathcal{L}_{gqq} = -g_s\bar{q}\gamma^\mu T^a q\, G^a_\mu$$

$$+ \mathcal{L}_{\text{mass}} = M_W^2 W^+_\mu W^{-\mu} + \frac{1}{2}M_Z^2 Z_\mu Z^\mu + \mathcal{L}_{\text{Yukawa}} = -y_d\bar{Q}_L\phi d_R - y_u\bar{Q}_L\tilde{\phi}u_R - y_e\bar{L}_L\phi e_R + \text{h.c.}$$

$$M_W = \frac{gv}{2}, \qquad M_Z = \frac{gv}{2\cos\theta_W}.$$

$$m_f = \frac{y_f v}{\sqrt{2}}.$$



HIGGS VACUUM

$$V(\phi) = -\mu^2\,\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

and ϕ is a complex field doublet:

$$\phi = \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}$$

where we choose:

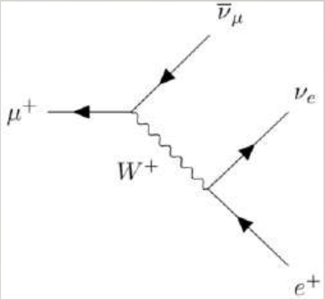
$\mu^2 < 0$ and $\lambda > 0$

and

$$v^2 = \frac{-\mu^2}{\lambda}, \qquad m_H^2 = 2\lambda v^2.$$

1. Higgs potential is determined with 2 free parameters μ and λ, where:
   1. $m_H^2 = -2\mu^2$ (if $\mu^2>0$ symmetries of $\mathcal{L}$ remains unbroken)
   2. λ is the coupling strength of Higgs self-interaction (self-coupling)
2. Absolute minimum of the potential (vev) v can be derived from μ and λ and it contributes to the energy density of the Universe
3. v can be determined from the Fermi constant G_F measured in muon decay $G_F = 1/(v^2\cdot\sqrt{2})$

   $$v = 246.22\ \text{GeV}.$$

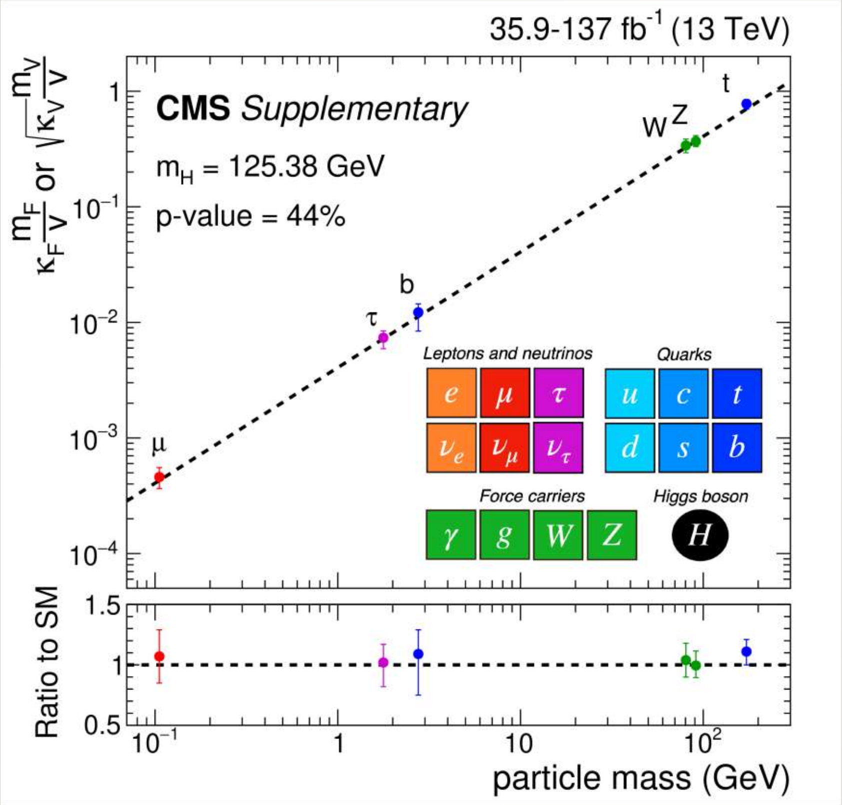


4. λ can be determined from the Higgs mass:

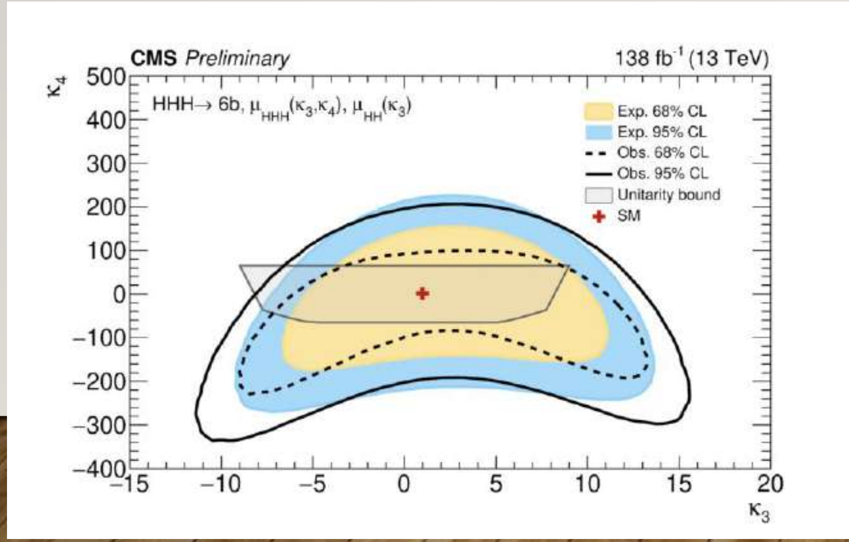
   $$m_H = 125.25 \pm 0.17\ \text{GeV}$$

   giving:

   $$\lambda = 0.1291 \pm 0.0004$$



https://ep-news.web.cern.ch/content/triple-higgs-frontiers-mapping-higgs-self-couplings-2025-hhh-workshop



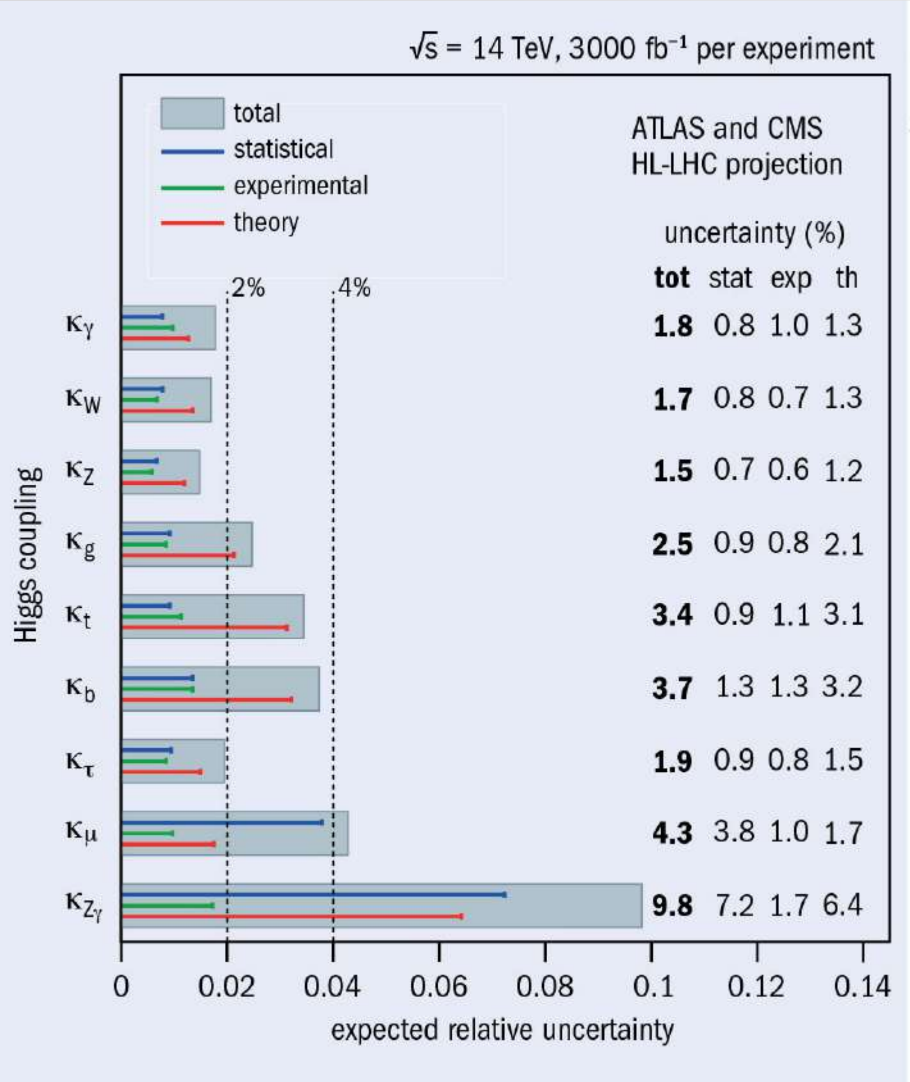
HIGGS COUPLINGS

1. Particles Yukawa couplings are linearly dependent on their masses:

$$m_f = \frac{y_f v}{\sqrt{2}}.$$

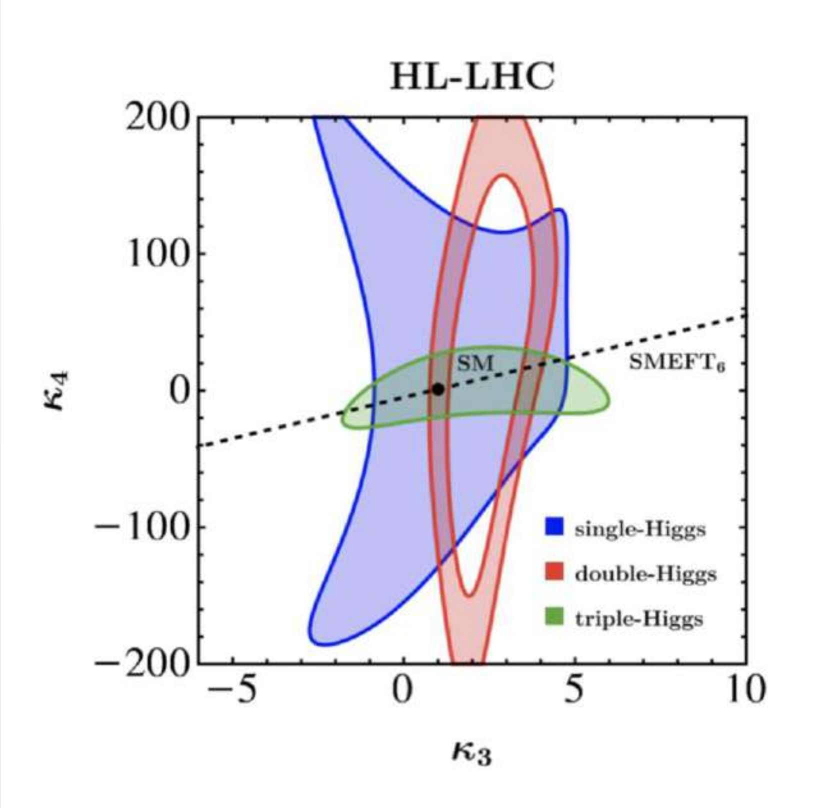
2. Any deviation of the linearity will be a sign of new physics
3. Higgs self-coupling has to be directly measured
4. More precise the measurements – better sensitivity to new physics
5. Current measurements gives relative uncertainties typically larger than (few times) 10%, while λ could deviate several times from the SM prediction.
6. HL-LHC full run should bring down relative uncertainty of λ to ~30%
7. Can Higgs couplings be measured better (more accurate) and how?

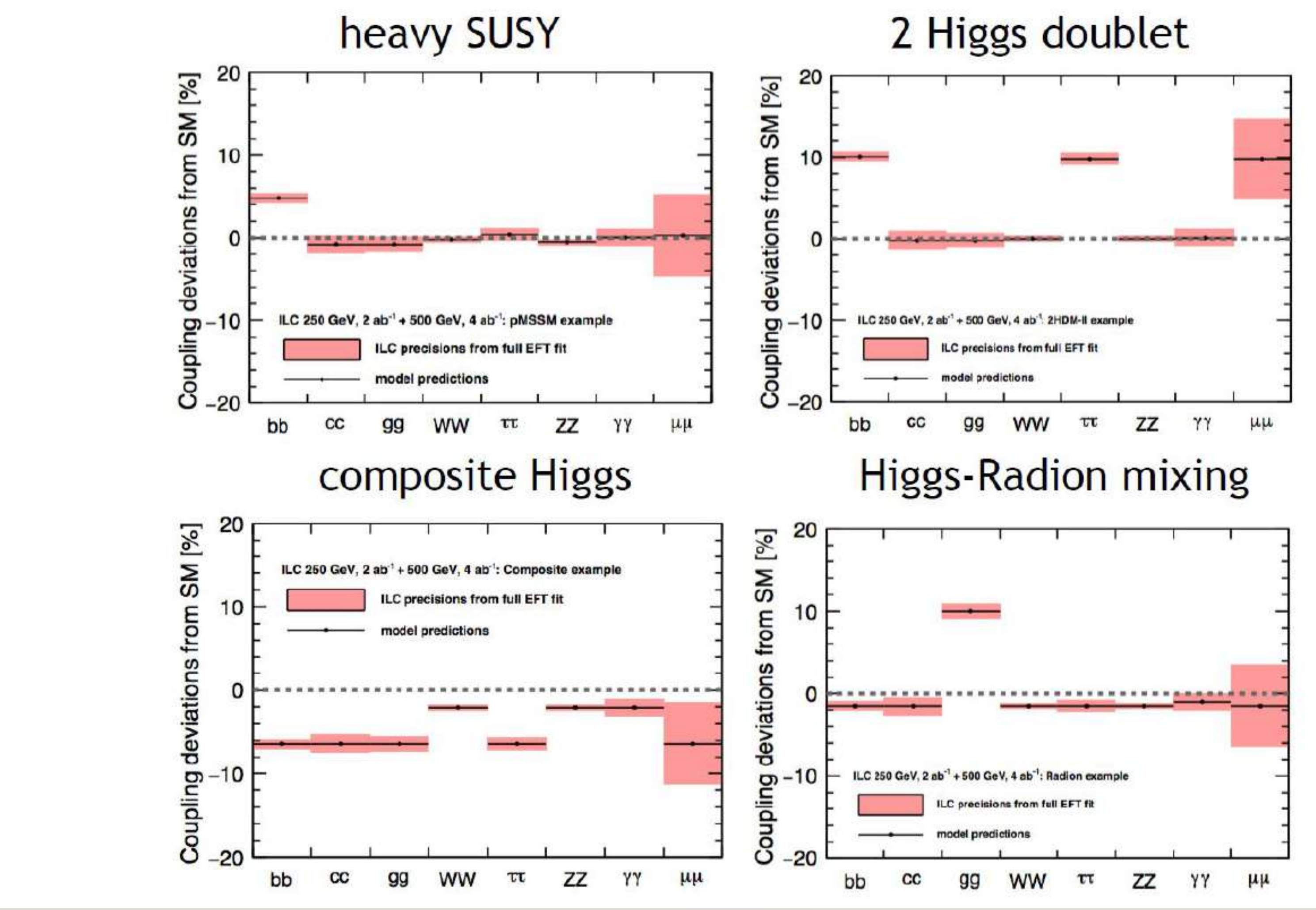
CAN HIGGS COUPLINGS BE BETTER MEASURED AND HOW?



HL-LHC, 13 TeV, 3 ab^{-1} (~10 years, 2041)

a few percent (relative statistical precision) for Higgs couplings

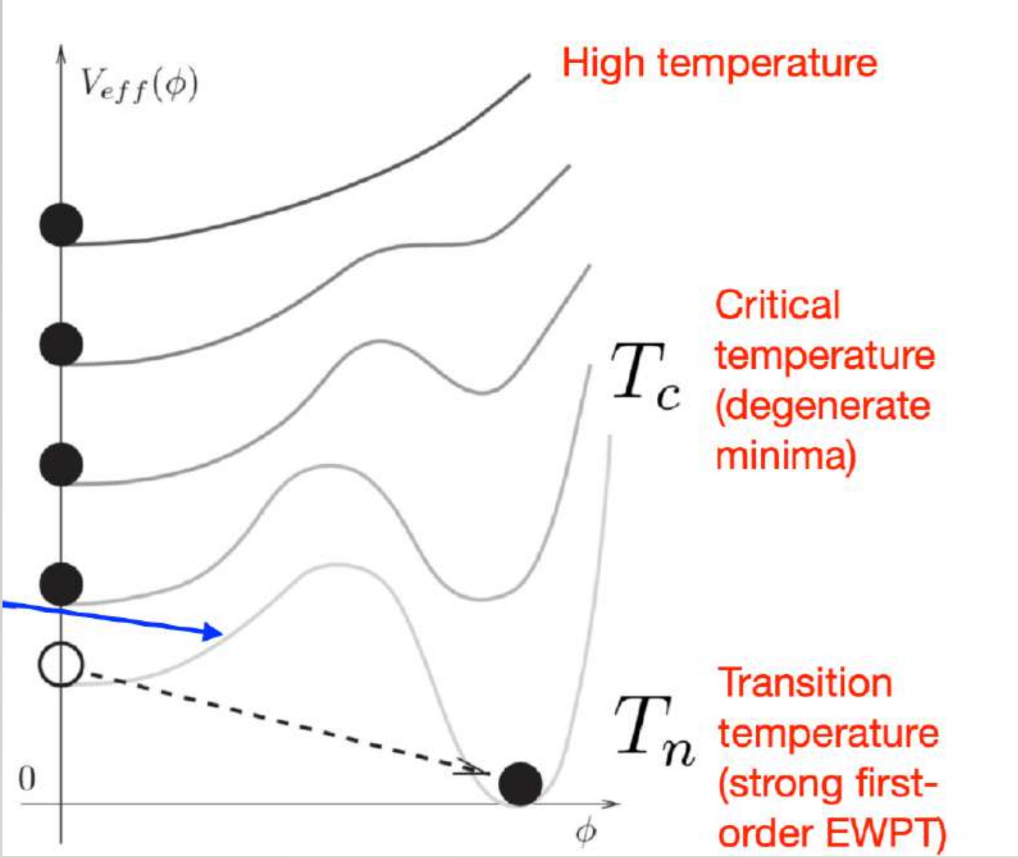


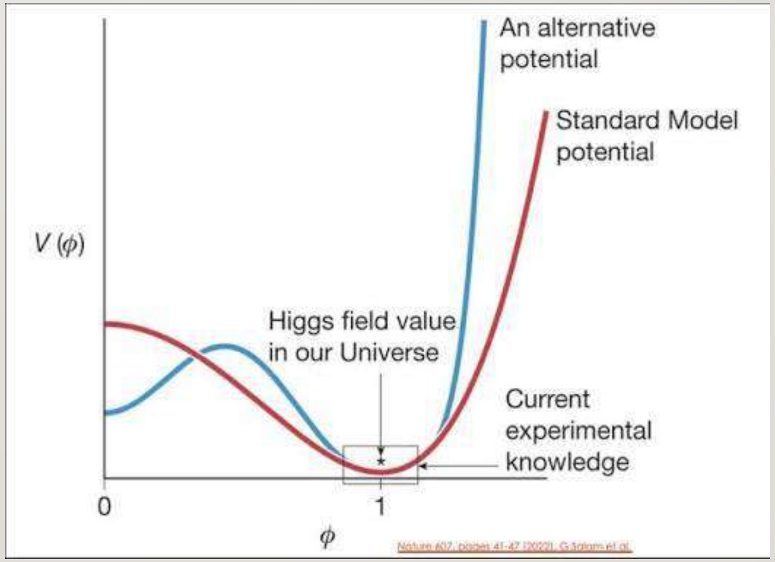


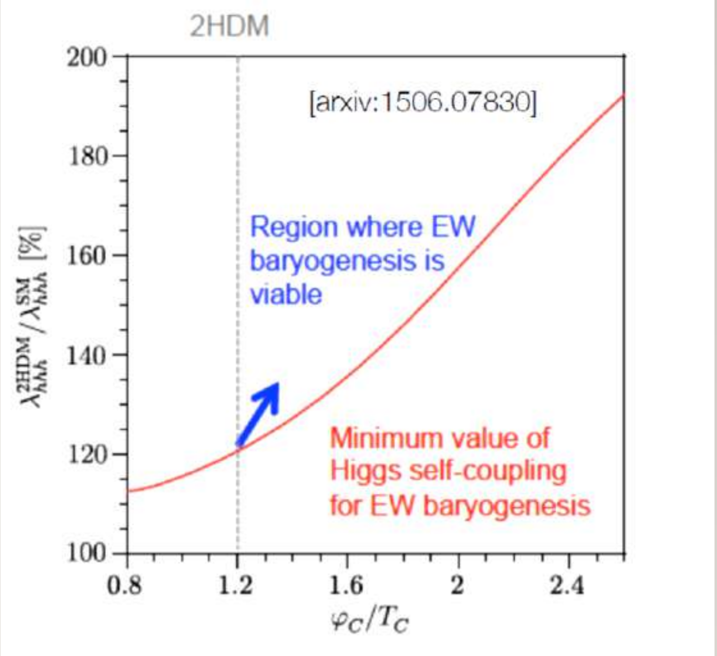
1. Depends on the model and coupling, but, in general, at a percent level or better

HIGGS SELF COUPLING

1. Which shape of the Higgs potential is realized in nature (is $\lambda=\lambda_{SM}$)?
2. Could Higgs be responsible for baryogenesis?
3. EW baryogenesis requires first-order phase transition (i.e. $\lambda > 1.2\ \lambda_{SM}$)

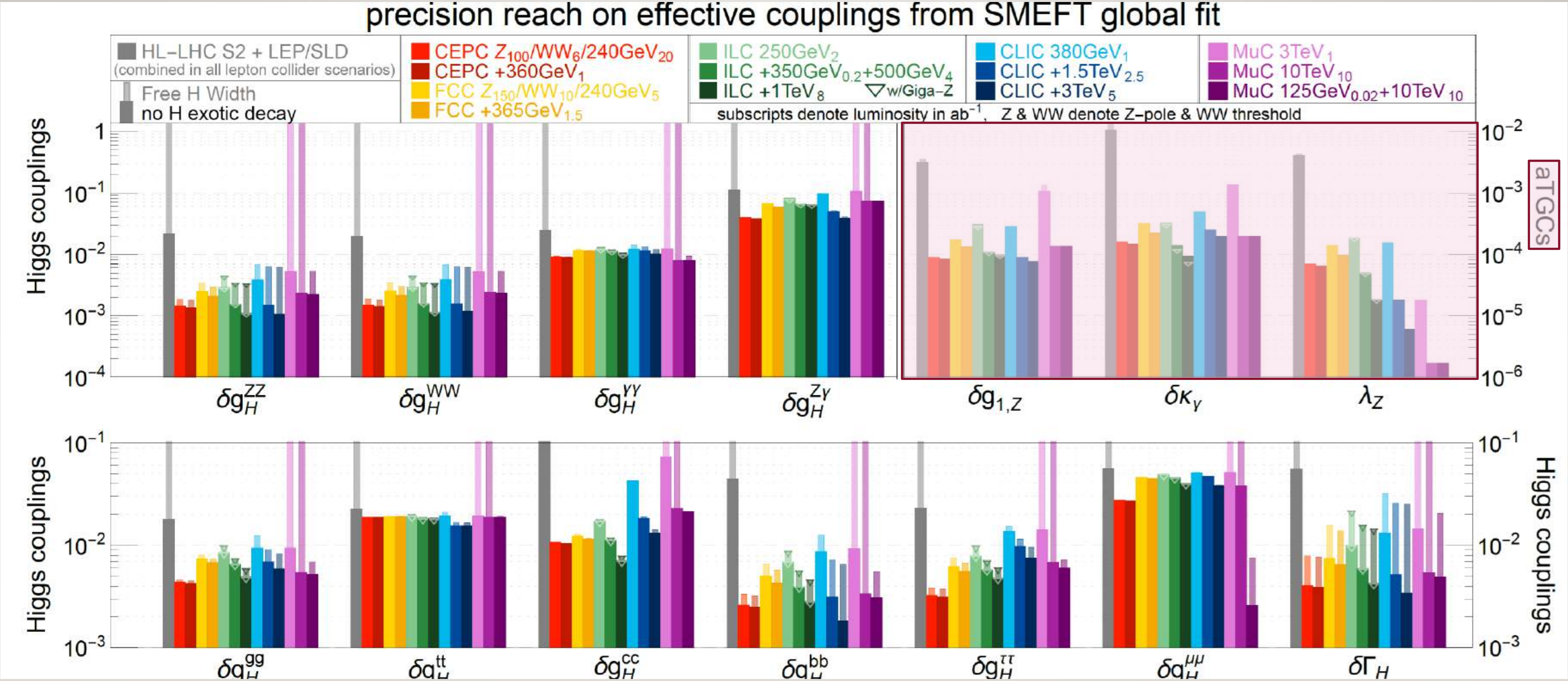






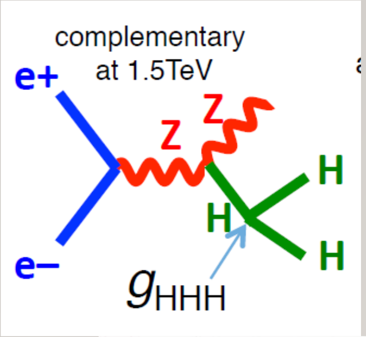
CAN WE MEASURE H.Cs BETTER (THAN AT HL-LHC)?

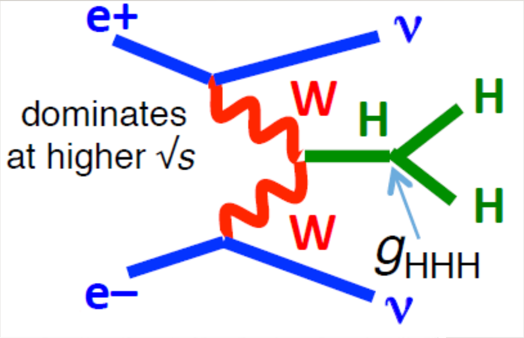
Yes, and for that e^+e^- (lepton) colliders are needed

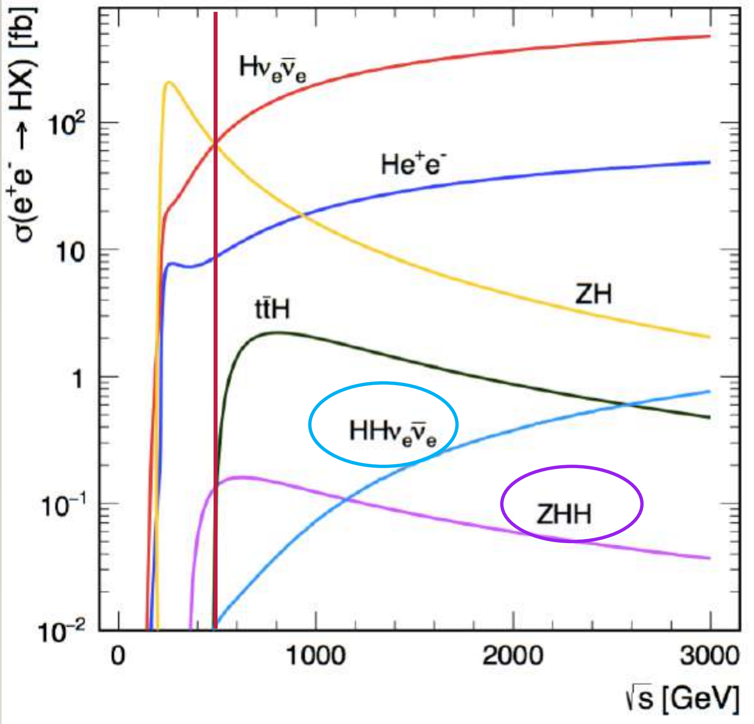


arXiv:2206.08326

CAN WE MEASURE λ BETTER (THAN AT HL-LHC)?

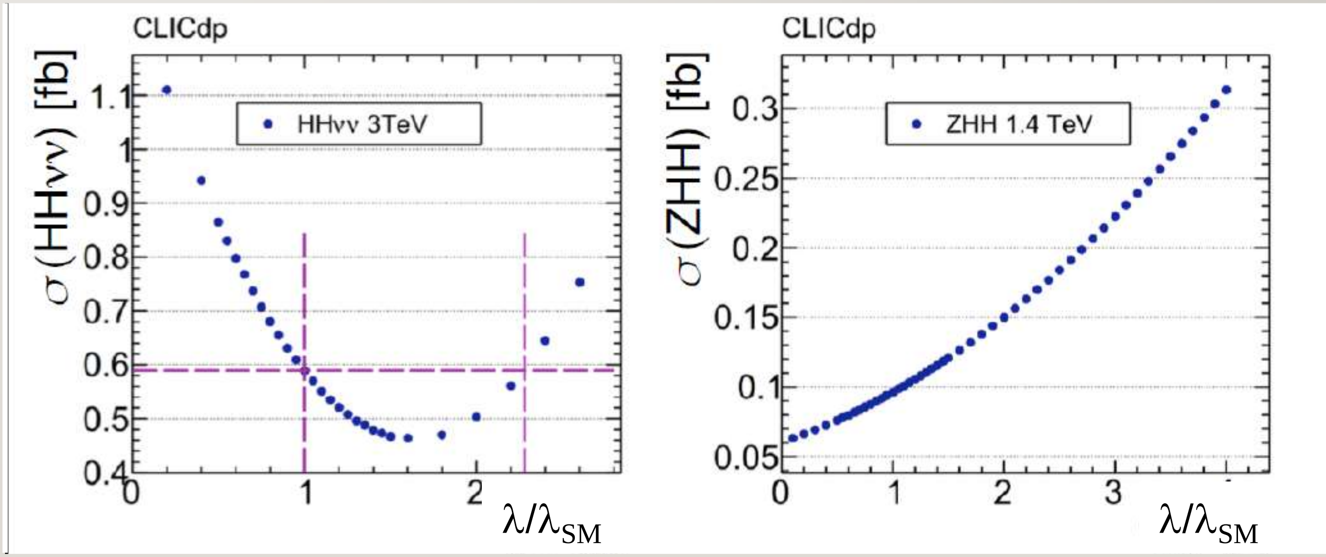




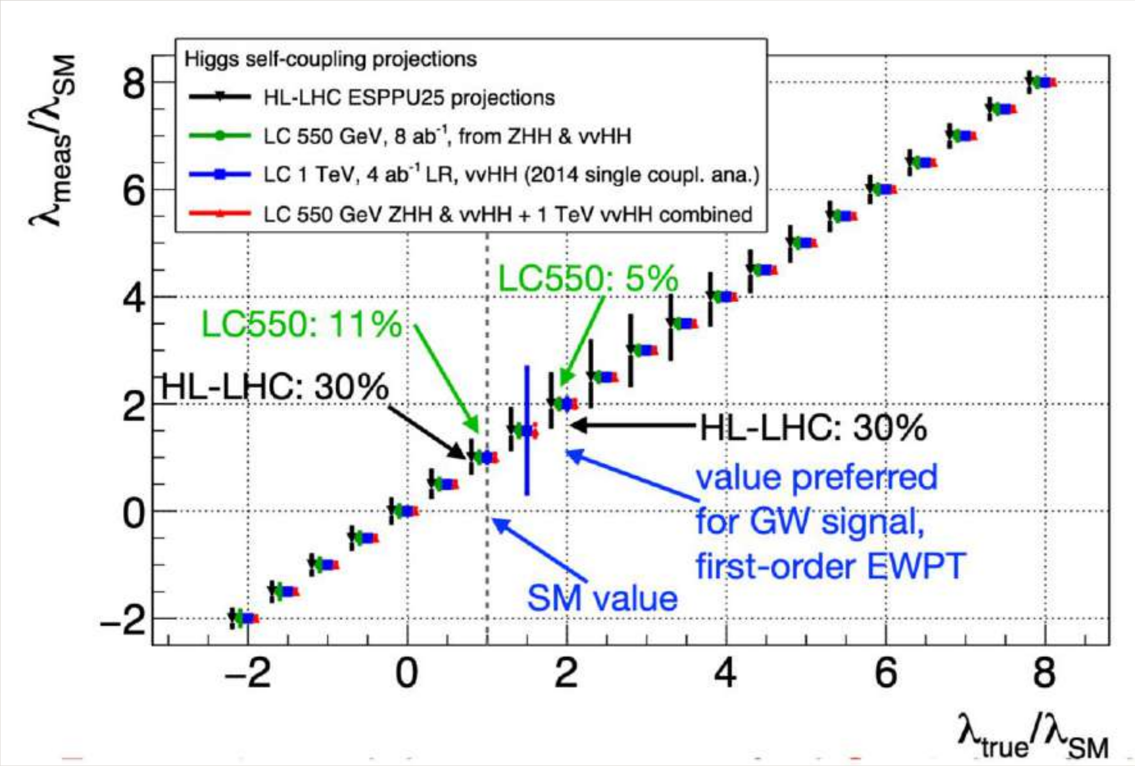


Yes, and for that e^+e^- (lepton) colliders are needed

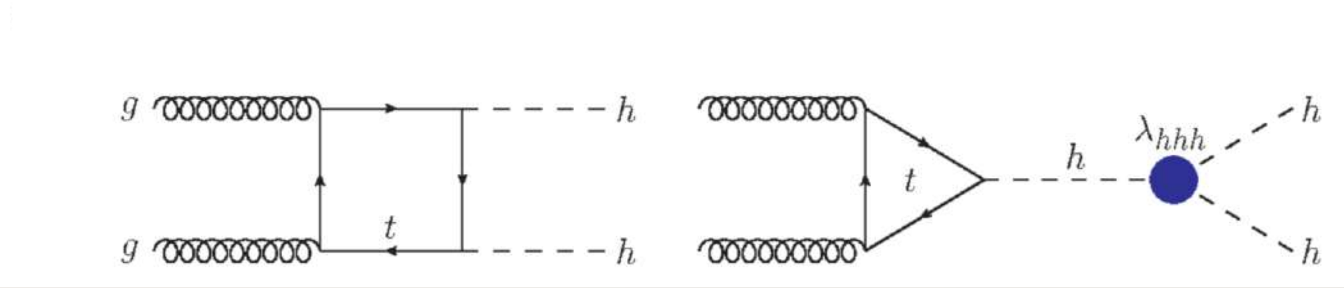
1. In particular those operating at and above 500 GeV
2. Because double Higgs production can be directly accessed (in WW-fusion)
3. In addition, one benefits from different HH$\nu\nu$ and ZHH cross-sections behavior w.r.t. λ

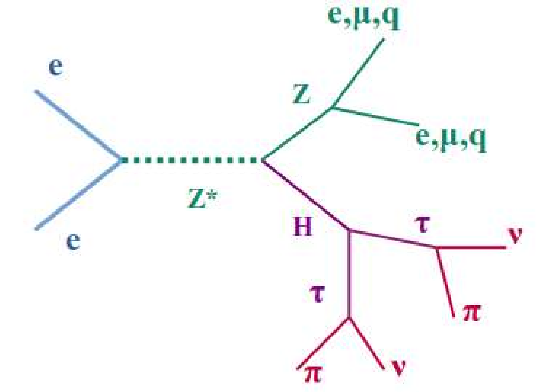


CAN WE MEASURE λ BETTER (THAN AT HL-LHC)?



1. Precision (relative) down to few percent, depending on λ
2. Significant gain w.r.t. HL-LHC
3. At hadron colliders destructive interference occurs between HH production channels
4. And that interference is larger for larger λ/λ_{SM}
5. To test EW baryogenesis one needs high-energy lepton collider(s)





Future colliders	Energy	Integrated luminosity	$\Delta\Psi_{CP}$ (68% CL)
ILC250	250 GeV	2 ab^{-1}	**75 mrad**
FCC-ee240	240 GeV	10.8 ab^{-1}	**44 mrad**
CEPC240	240 GeV	5.6 ab^{-1}	**16 mrad**

HIGGS HAVE OTHER PROPERTIES: SPIN

1. SM Higgs is a pure scalar $J^P = 0^+$
2. It has to be tested
3. Could 125 GeV mass eigenstate of a mixture of scalar and pseudoscalar?

$$h_{125} = H \cdot cos(\psi_{CP}) + A \cdot sin(\psi_{CP})$$

4. In that case CP symmetry is violated (maximally for $\Psi_{CP}=\pi/4$)
5. Higgs interactions (both production and decays) could provide CP violation - Saharov's condition (one of) for baryogenesis
6. Current ATLAS/CMS precision 279 mrad
7. HL-LHC (3 ab^{-1}) ~90 mrad

HIGGS INTERACTS WITH ANY MASSIVE PARTICLE

HADRON COLLIDERS

- No absolute measurement of the production cross-section (like ZH at e+e- colliders)
- Higgs couplings come in combination:

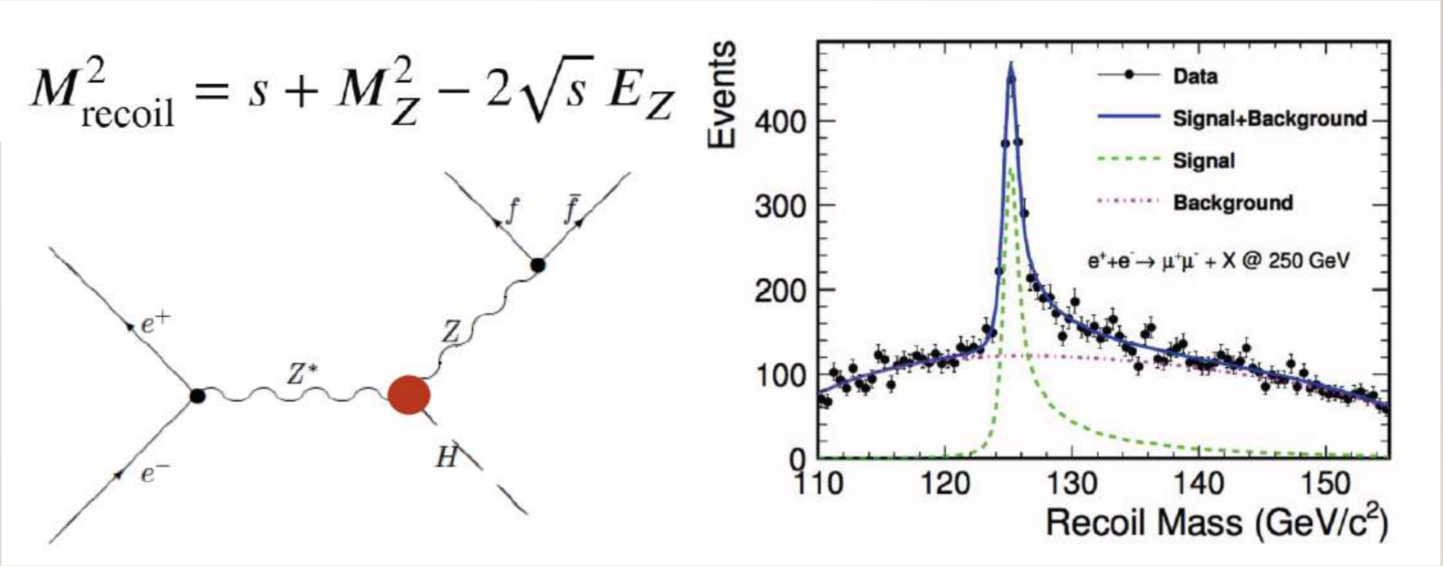
$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}}\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}}$$

- Only ratio of couplings can be directly determined (i.e. $g^2_{H\tau\tau}/g^2_{HWW}$)

LEPTON COLLIDERS

- Absolute measurement of the ZH cross-section
- Absolute measurement of the Higgs BRs
- Nearly model-independent determination of the Higgs total width and couplings

1. Higgs interactions (total width) includes yet undiscovered particles, invisible particles, Dark Matter particles (WIMP), etc.
2. These are additional reasons (to coupling mass linearity) why Higgs BR fractions have to be precisely measured (in particular Higgs to invisible)

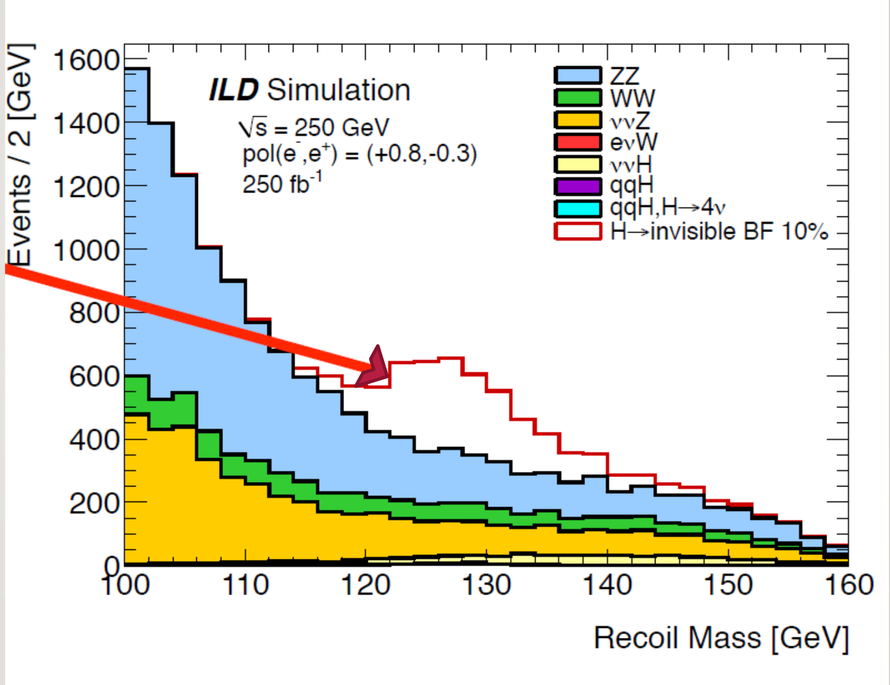


HIGGS INVISIBLE DECAYS AT LEPTON COLLIDERS

FCCee 240GeV

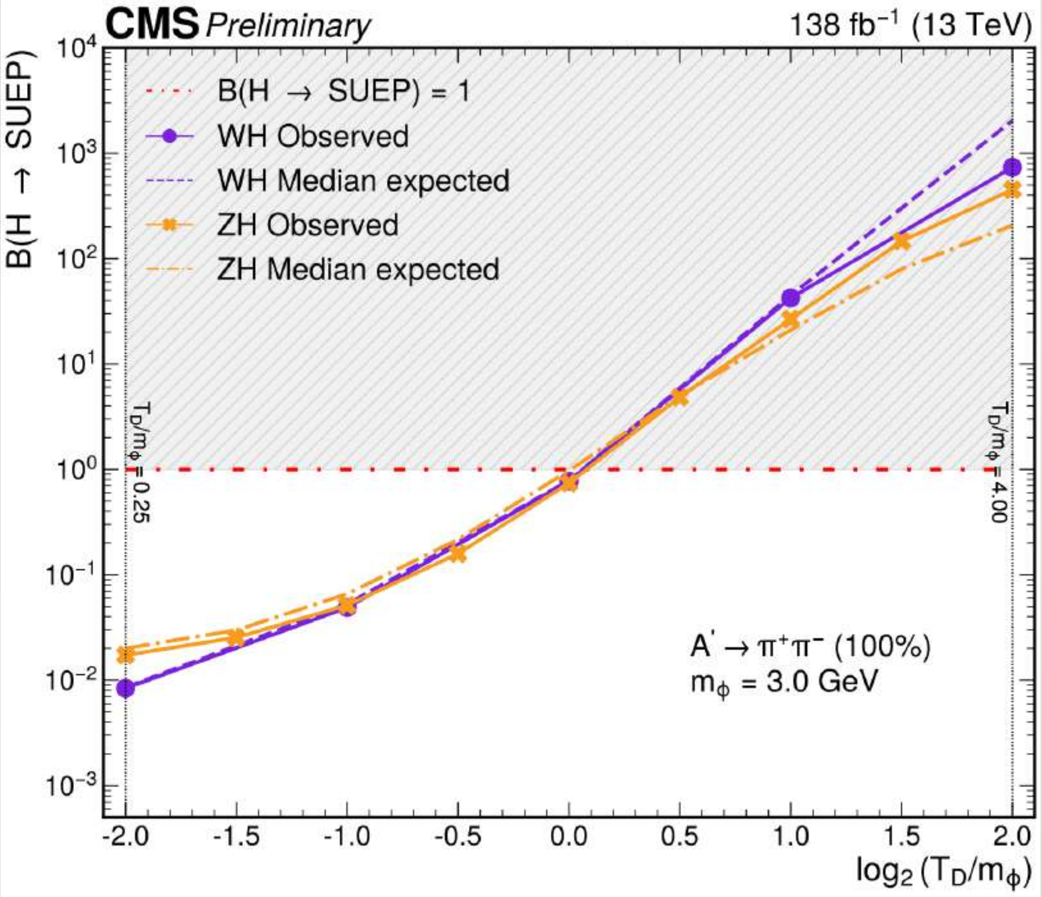
Expected 95% CL upper limits on the branching fraction for the *ee*, *μμ*, and *qq* channels.

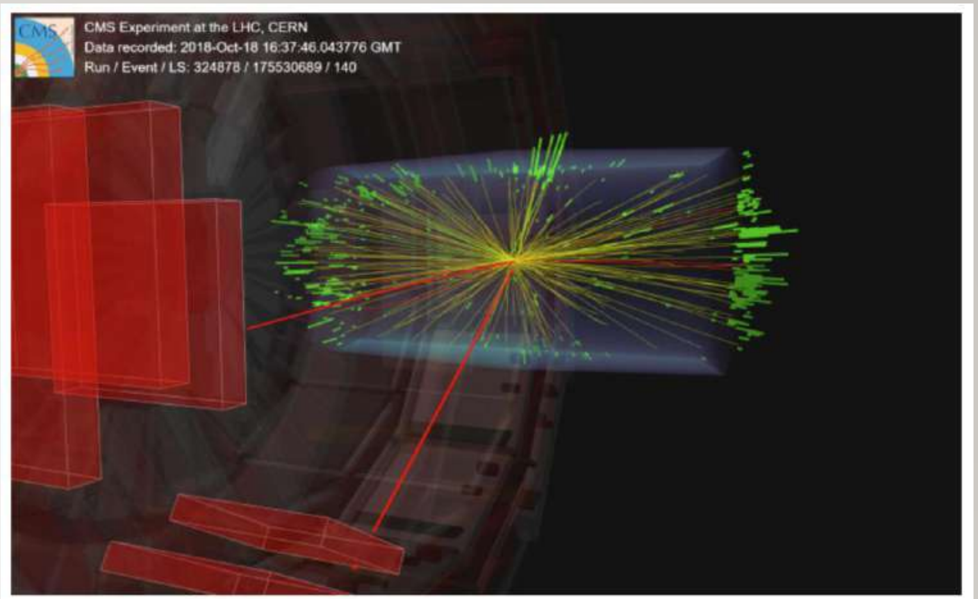
Physics	Upper Limit on $\mathcal{B}(H \to inv.)$
$Z(ee)H(\text{inv})$	0.43%
$Z(\mu\mu)H(\text{inv})$	0.35%
$Z(qq)H(\text{inv})$	0.15%
Combined	0.15%



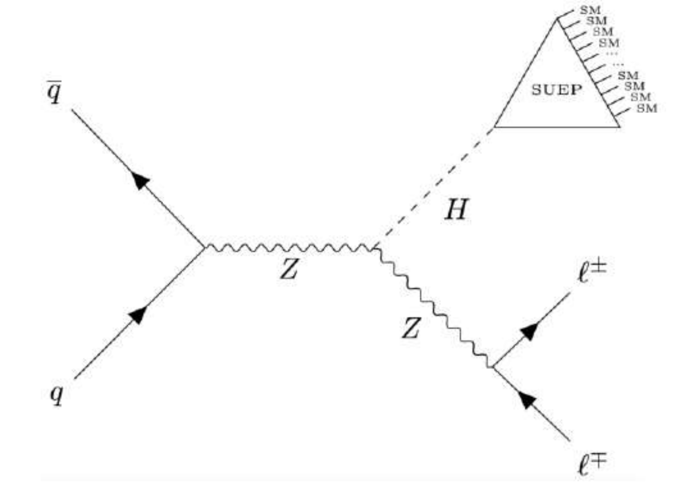
ILC 250GeV 95% CL (0.16-0.3)%

HIGGS INVISIBLE DECAYS AT LHC





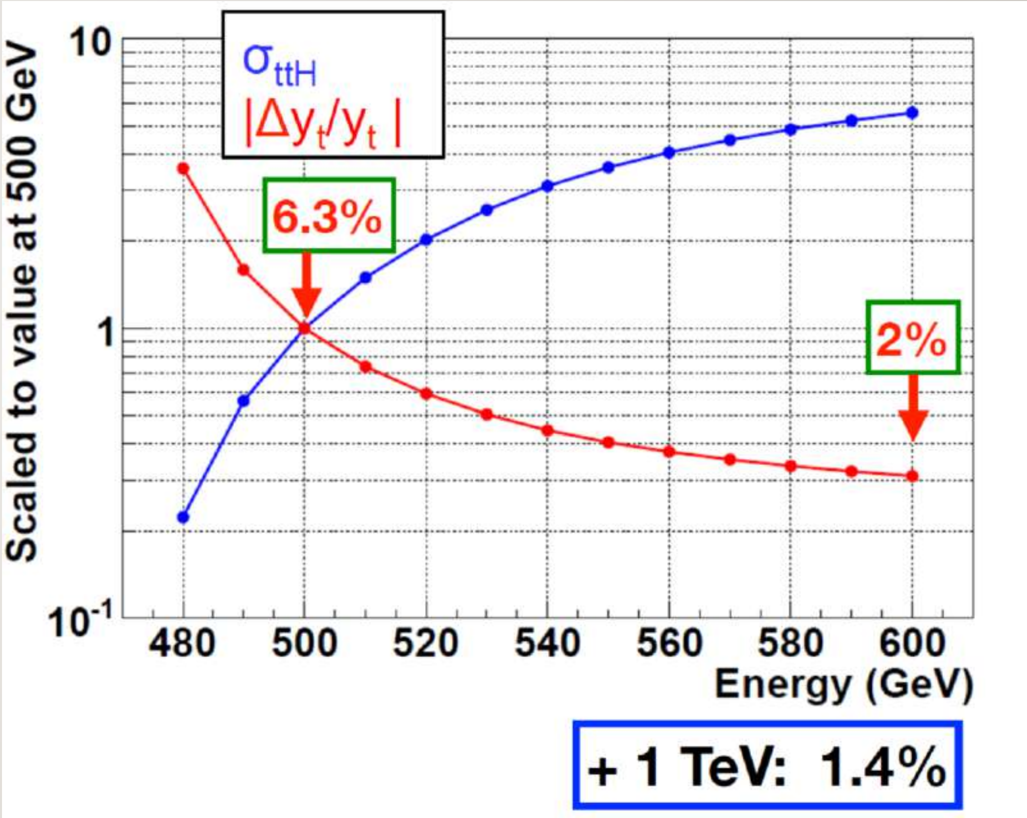
Soft Unclustered Energy Pattern (SUEP)



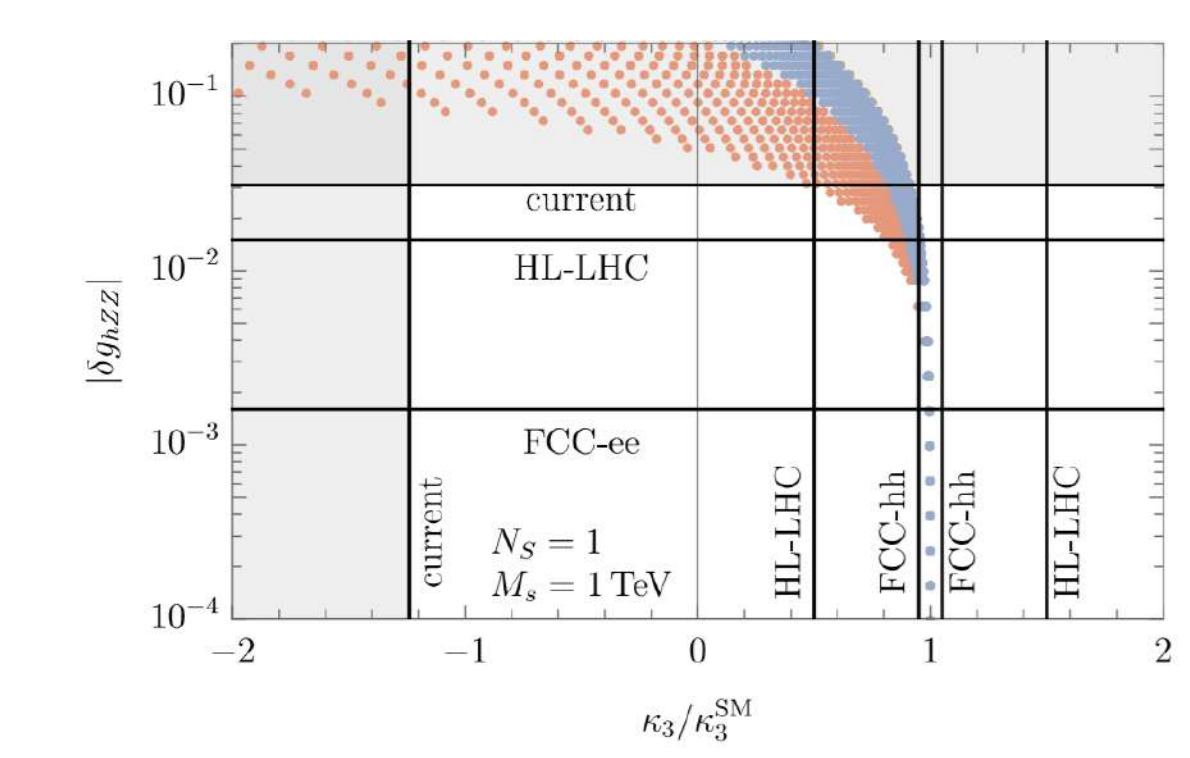
t-QUARK: HIGGS STRONGEST COUPLING

1. CP can be violated in ttH production (Higgs is to heavy to decay to top pair)
2. High energy lepton colliders are crucial for both CPV and top-Yukawa coupling y_t measurement
3. Reaching theoretical target (f_{CP}~10^{-2} for Higgs-fermion vertices) at 1 TeV
4. f_{CP}= fraction of the CP-odd contribution to the total interaction rate

$f_{CP} \cdot 10^{-2}$	500 TeV e^+e^- 0.5 ab^{-1}	1 TeV e^+e^- 1 ab^{-1}
	29	8



HIGGS AND VACUUM STABILITY



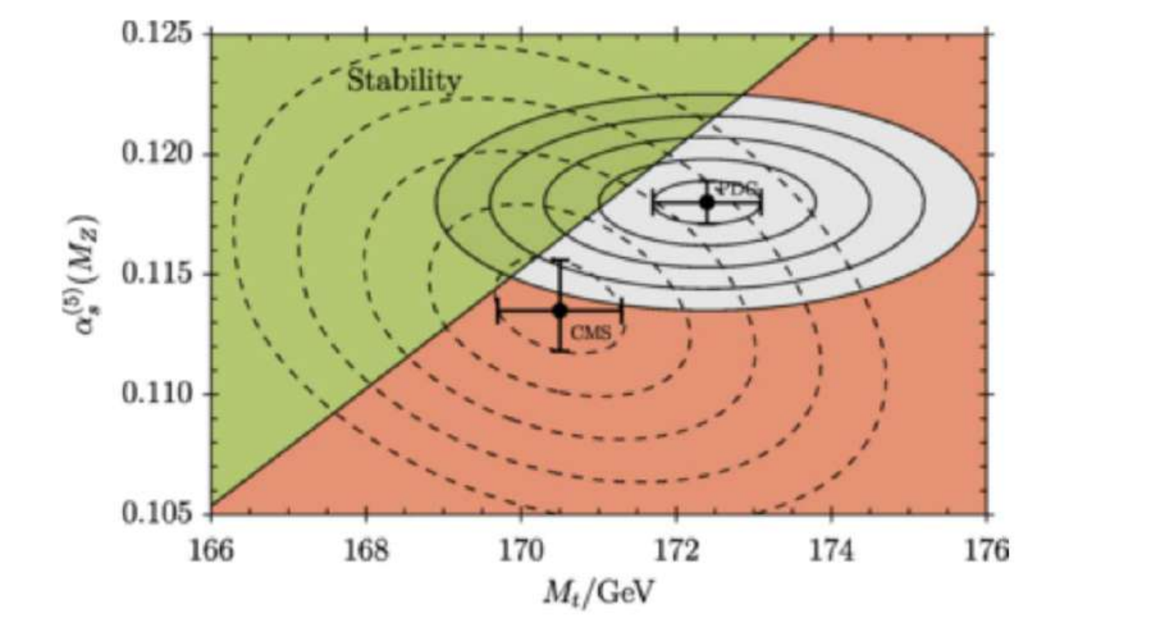
https://arxiv.org/pdf/2401.08811

1. We are still not (sufficiently) sure if Higgs is SM (dots correspond to various BSM realizations of Higgs)
2. We don't know Higgs coupling sufficiently precise
3. We don't know Higgs self coupling with sufficient precision
4. Sufficient = is relativistic vacuum stable (blue) or not (red)

1. New experiments are needed
2. Different ones suitable to different $\lambda(\kappa_3)$

   i.e. linear colliders for $\lambda > \lambda_{SM}$

HIGGS (top) AND VACUUM STABILITY



1. Understanding the vacuum stability also requires t-quark mass (Yukawa coupling) precision
2. Metastable vacuum (within 1 σ) – current
3. About 0.1–0.3% precision on the top Yukawa coupling would be needed to make a 5σ statement about whether the electroweak vacuum is truly metastable assuming the Standard Model is valid up to the Planck scale
4. Full FCC program (FCCee+FCChh) ~1% on y_t

HIGGS AND INFLATION

Think of a rubber sheet.

- The sheet = spacetime geometry.
- Curvature of the sheet = R.
- A heavy object deforming the sheet = energy density.

The usual Einstein theory says:

> Energy bends the sheet.

Higgs inflation adds:

> The amount by which the sheet bends depends also on the local Higgs field value.

The Higgs quartic coupling λ_4 is not directly measured at any collider. What colliders measure is mainly the **Higgs self-coupling** (trilinear coupling λ_3) through double-Higgs production. The quartic term in the potential is

$$V(H) = -m^2 H^\dagger H + \lambda_4 (H^\dagger H)^2,$$

and after electroweak symmetry breaking it gives

$$\lambda_3 = \lambda_4 v,$$

(up to conventional factors). Therefore, the experimental precision usually quoted is:

$$\frac{\Delta\lambda_3}{\lambda_3}$$

and this translates into a precision on λ_4 of essentially the same relative size.

1. Higgs field potential is at these energies ($10^{16\text{-}17}$ GeV) controlled by quartic coupling λ_4
2. And λ_4 running (with energy scale μ) goes like:

$$d\lambda_4 / d(\ln \mu) \sim -6\, y_t^4$$

1. Again, Higgs self-couplings are crucial to understand its connection to the Universe
2. As well as top Yukawa coupling

HOW FAR CAN WE GO IN PRECISION?

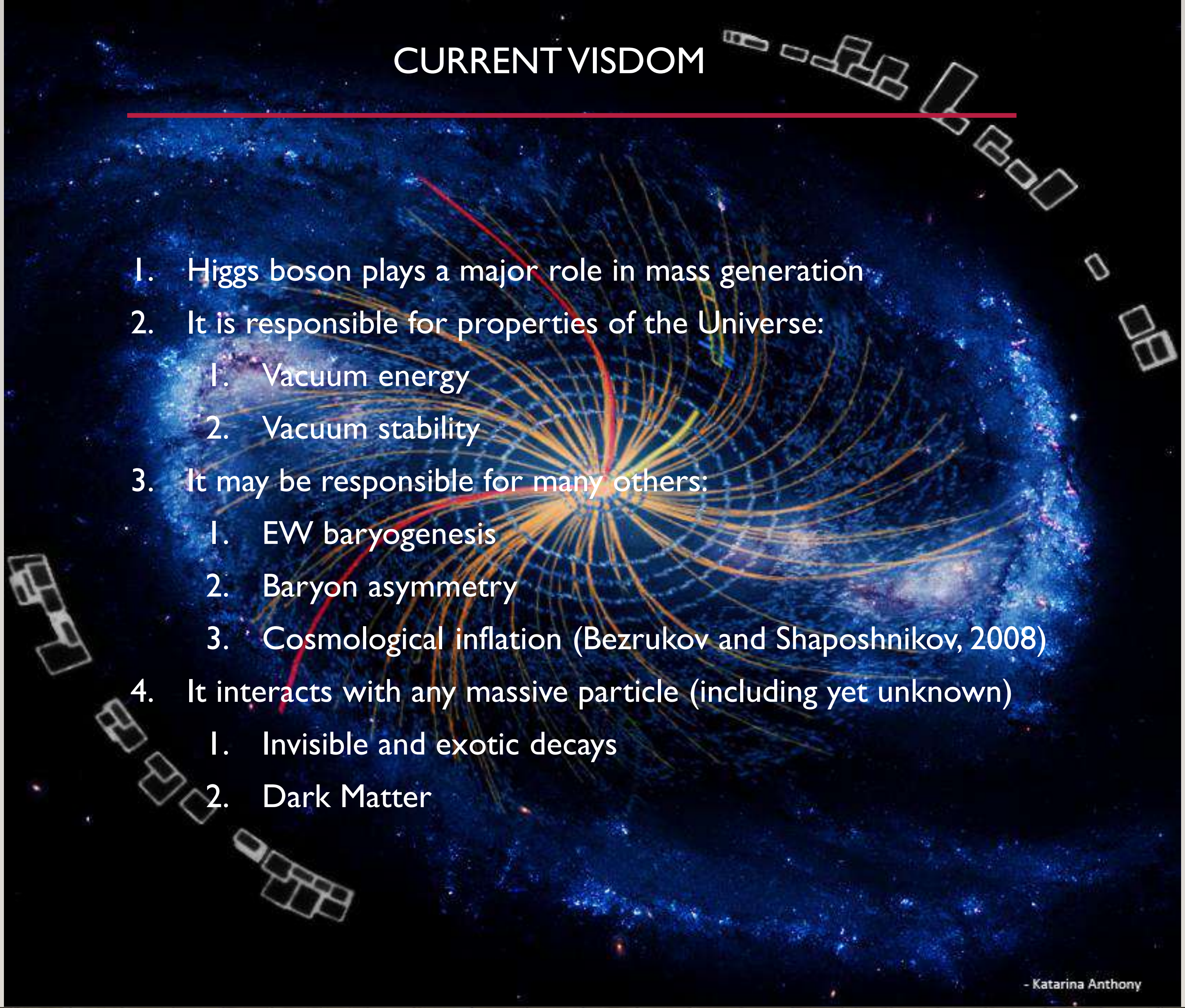
1. The goal is not comparison – it's the order of magnitude
2. 

Different assumptions and level of details
3. But, this is what we approximately can hope for
4. Two critical measurements require high energy (linear lepton or circular hadron) collider

Higgs observable	CIRCULAR LEPTON (FCC-ee)	LINEAR LEPTON (ILC)
Inclusive σ(ZH)	**0.17%**	**~0.30–0.35%**
Higgs mass	**≈5 MeV**	**≈14–20 MeV**
Total width ΓH	**≈1.1%**	**≈1.8–2.0%**
(g_{HZZ})	**0.16%**	**≈0.25–0.30%**
(g_{HWW})	**0.40%**	**≈0.5%**
(g_{Hbb})	**0.56%**	**≈0.7–0.8%**
(g_{Hcc})	**≈1.2%**	**≈1.5–1.8%**
(g_{Hgg})	**≈0.9%**	**≈1.0–1.2%**
(g_{H\tau\tau})	**≈0.6–0.7%**	**≈0.8–0.9%**
(g_{H\mu\mu})	**≈4%**	**≈5–6%**
(g_{H\gamma\gamma})	**≈1.3%**	**≈2%**
(g_{Htt})	**— (no direct measurement)**	**≈1.4%**
Higgs self-coupling (SM)	**— (no direct measurement) ≈40% (indirect)**	**<10%**
BR((H\to) invisible) 95% CL	**<0.2%**	**≈0.16-0.3%**
CP mixing angle ((H\to\tau\tau))	**44 mrad**	**75 mrad**

CURRENT VISDOM

1. Higgs boson plays a major role in mass generation
2. It is responsible for properties of the Universe:
    1. Vacuum energy
    2. Vacuum stability
3. It may be responsible for many others:
    1. EW baryogenesis
    2. Baryon asymmetry
    3. Cosmological inflation (Bezrukov and Shaposhnikov, 2008)
4. It interacts with any massive particle (including yet unknown)
    1. Invisible and exotic decays
    2. Dark Matter



CURRENT VISDOM

1. Higgs boson plays a major role in mass generation
2. It is responsible for properties of the Universe:
   1. Vacuum energy

The Higgs mass tells us where we start.

The top Yukawa tells us which direction the Higgs potential flows.

The Higgs self-coupling tells us whether the potential itself has the Standard Model shape.

Gravity asks what happens when the Higgs field is pushed to the largest possible values.

   3. Cosmological inflation (Bezrukov and Shaposhnikov, 2008)
4. It interacts with any massive particle (including yet unknown)
   1. Invisible and exotic decays
   2. Dark Matter

- Katarina Anthony

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Gravity asks what happens when the Higgs field is pushed to the largest possible values.

To probe Higgs relation to the Universe high energy colliders are needed: lepton (e^+e^-) linear @TeV or hadron circular @10^2 TeV

- Katarina Anthony

HIGGS BOSON: HOW TO MEASURE IT?

WHAT IS ON THE TABLE: e^+e^- COLLIDERS AND THEIR EXTENSIONS

WHAT IS ON THE TABLE?

	Collider	Size (km)	√s (GeV)	IPs	Beam polarization	Peak luminosity / IP (10^{34} cm^{-2} s^{-1})	Integrated luminosity (machine)	Integrated luminosity / detector	Higgs bosons / detector	Nominal run time
CIRCULAR	LEP3	27	240	2	No	~1	1.0 ab^{-1}	0.5 ab^{-1}	~100,000	~5 yr
	CEPC	100	240	2	No	**3.0**	11.2 ab^{-1}	5.6 ab^{-1}	~1.1 million	~7 yr
	FCC-ee	91	240	4	No	**8.5**	10.8 ab^{-1}	2.7 ab^{-1}	~500,000	~3 yr
	FCC-ee	91	365	4	No	**1.7**	2.7 ab^{-1}	0.675 ab^{-1}	~250,000	~4 yr
LINEAR	LCF	33	380	1	±80% e^-, ±30% e^+	**2.7**	1.0 ab^{-1}	1.0 ab^{-1}	~350,000	~8 yr
	ILC	21	250	1 *(2 with dual BDS)*	±80% e^-, ±30% e^+	~1.35	2.0 ab^{-1}	2.0 *(or 1.0 with 2 IPs)*	~500,000 *(250k/IP with 2 IPs)*	~11–12 yr
	ILC	31	550	1 *(2 with dual BDS)*	±80% e^-, ±30% e^+	~1.8	~4.0 ab^{-1} *(under discussion)*	4.0 *(or 2.0)*	~1 million	~8 yr
	ILC	48	1000	1 *(2 with dual BDS)*	±80% e^-, ±20–30% e^+	~4.9	8.0 ab^{-1}	8.0 *(or 4.0)*	~2.5 million	~10 yr

WHAT IS ON THE TABLE?

proposed by CERN | possibly considered by CERN | possibly proposed by China | possibly considered by CERN

CIRCULAR

Collider	Size (km)	√s (GeV)	IPs	Beam polarization	Peak luminosity / IP (10^{34} cm^{-2} s^{-1})	Integrated luminosity (machine)	Integrated luminosity / detector	Higgs bosons / detector	Nominal run time
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LINEAR

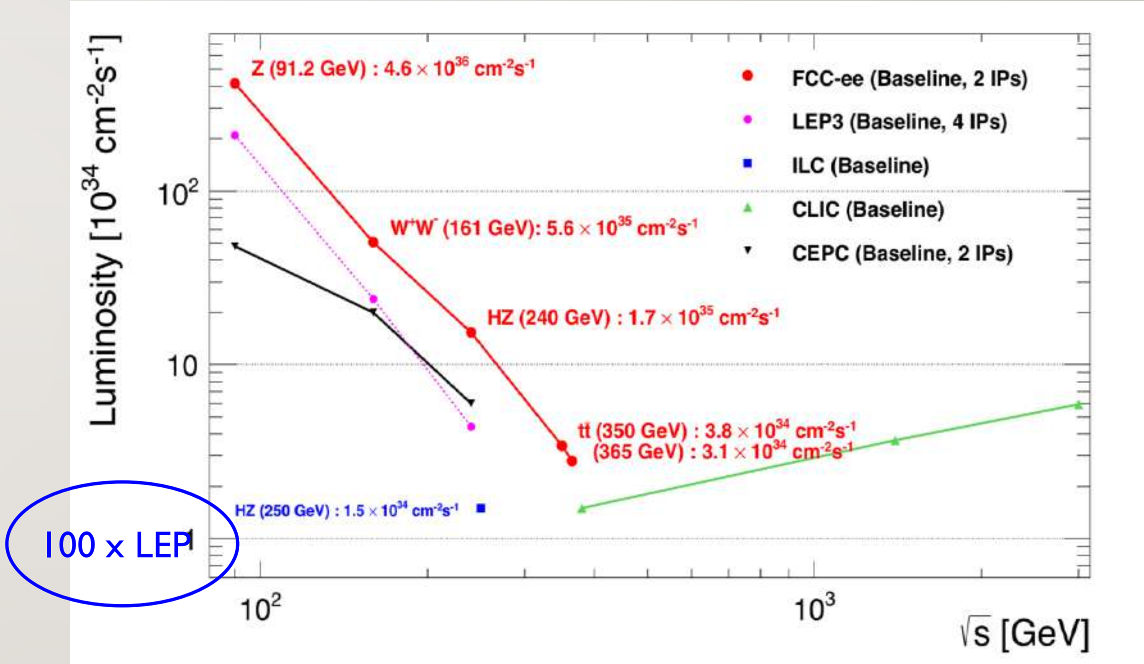
UNDERSTANDING THE TABLE

CIRCULAR

1. It seems that there is a preference towards circular machines
2. Beam is reusable, multiply integrated luminosity with number of IPs
3. Initially used leptons can be replaced by hadrons (pp): FCCee $\rightarrow$FCChh and CEPC $\rightarrow$ SPPC

LINEAR

1. Instantaneous luminosity can not compare (to circular)
2. But, beams can be polarized
3. Straightforward (literally) in length to higher energies where offer unique precision for λ and y_t



WHAT IS IN COMMON FOR FUTURE LEPTON COLLIDERS?

TECHNICAL DIFFERENCES ARE NUMEROUS, BUT

1. Based on SC RF technology (‘cold’ machines)
2. Know initial state $\rightarrow$ final state reconstructable from the first principles
3. Absolute normalization of the Higgs couplings (σ_{HZ} measurement based on recoil mass)
4. All require precise tracking, high granularity calorimeters and a hermetic detector
5. Particle flow paradigm in particle reconstruction

$\Downarrow$

Detector studies are common and transferable

PRINCIPAL DIFFERENCES ARE DETERMINED BY SHAPE

1. Large synchrotron radiation at circular colliders $\rightarrow$ heavier particles and/or larger radius

$$U_0 \propto \frac{E^4}{m^4 \rho}.$$

2. Very difficult to polarize circular beams - repeated bending in magnetic fields causes the particle spins to undergo billions of precessions, making them highly sensitive to depolarization (from synchrotron oscillations, beam-beam effects)
3. Circular have larger instantaneous luminosities due to high repetition rate *f* (i.e. 30 times more collisions per second at FCC240 than ILC250)

$$L = \frac{N_b N^2 f}{4\pi\sigma_x\sigma_y},$$

THE FUTURE MUST BE ~~BRIGHT~~ PRECISE

nonexistent technology

Higgs observable	FCC-hh (100 TeV)	SPPC (75–125 TeV)*	ILC (250+550+1000)	CLIC (380+1.5+3 TeV)	Muon Collider (10 TeV)
g_{HZZ}	~1%	~1%	**0.25–0.30%**	~0.3%	~0.4%
g_{HWW}	~1%	~1%	**0.5%**	~0.5%	~0.5%
g_{Hbb}	~1%	~1%	**0.7–0.8%**	~0.7%	~0.5–0.7%
g_{Hcc}	~2–3%	~2–3%	**1.5–1.8%**	~1.5%	~1–2%
g_{Hgg}	~1–2%	~1–2%	**1.0–1.2%**	~1%	~1%
$g_{H\tau\tau}$	~1%	~1%	**0.8–0.9%**	~0.8%	~0.6–0.8%
$g_{H\mu\mu}$	~2–3%	~2–3%	~5%	~4%	**≈1%**
Top Yukawa g_{Htt}	**1.5–2%**	~1–2%	**1.5–2%** (550 GeV + 1 TeV)	**≈2%**	≈1%
Higgs self-coupling λ_3	**3–5%**	≈3–5%	≈10%	≈5–7%	≈2–4%

AI estimates

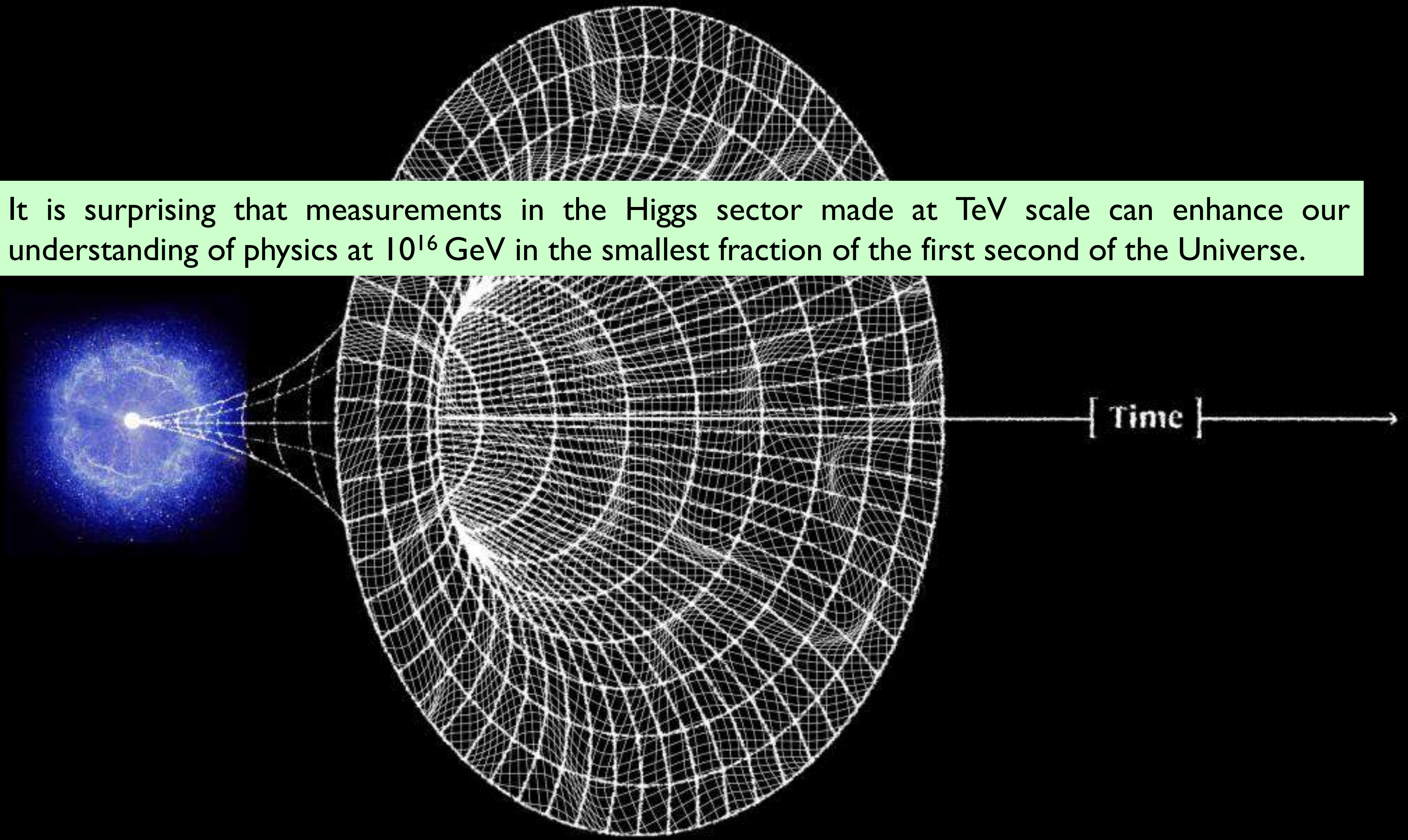
Collider project	Estimated construction cost	Comments
LEP3	≈7–10 BCHF Limited upgradability (inst. luminosity only)	Never fully costed; estimate based on reuse of LHC tunnel and new RF system.
CEPC (240 GeV)	≈5–6 BUSD	Includes 100 km tunnel and collider; significantly lower construction costs in China are assumed.
FCC-ee	≈10.8–11 BCHF Upgradable	Latest FCC Feasibility Study estimate (2024 CHF), including tunnel, infrastructure, accelerator and CERN contribution to experiments. Springer +1
FCC-hh (incremental after FCC-ee)	≈16 BCHF	Reuses the FCC tunnel and much of the infrastructure. Dominated by the 14 T magnet system. Springer
FCC integrated programme (FCC-ee + FCC-hh)	≈27 BCHF	Staged investment over several decades (construction costs only, excluding long-term operating costs and most personnel). Springer
ILC250	≈6.5–7 BUSD	Official estimate for the first stage.
ILC250→550→1000 GeV (Integrated program)	≈11–13 BUSD	Approximate total after staged upgrades; no single official number exists because the upgrades would be approved separately.
LCF (250–550 GeV)	Not yet published Should be significantly less than 10 BUSD Upgradable	No official cost estimate has been released; expected to depend strongly on the maturity and industrialization of the high-gradient SRF technology. IJCLab Events Di...

SUMMARY

1. Higgs boson plays a vital role in our understanding of the Universe (vacuum energy, vacuum stability, EW baryogenesis, baryon asymmetry, cosmological inflation)
2. Higgs properties (BRs, CP properties) provide key relations to BSM
3. Higgs self interaction (in particular λ) and top Yukawa coupling y_t are crucial to provide the understanding of the relativistic vacuum and cosmological evolution including baryogenesis
4. To gain the knowledge of the above, high energy interactions are needed and can be provided by a linear collider at a TeV scale or circular pp colliders at hundred of TeV

1. But, the problem is that they are not easily affordable…
2. So, one look for the staged options (extendible physics program)
3. Where the question if the world can afford even the first stage is still open

It is surprising that measurements in the Higgs sector made at TeV scale can enhance our understanding of physics at 10^{16} GeV in the smallest fraction of the first second of the Universe.



СПАСИБО!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