

Future Colliders

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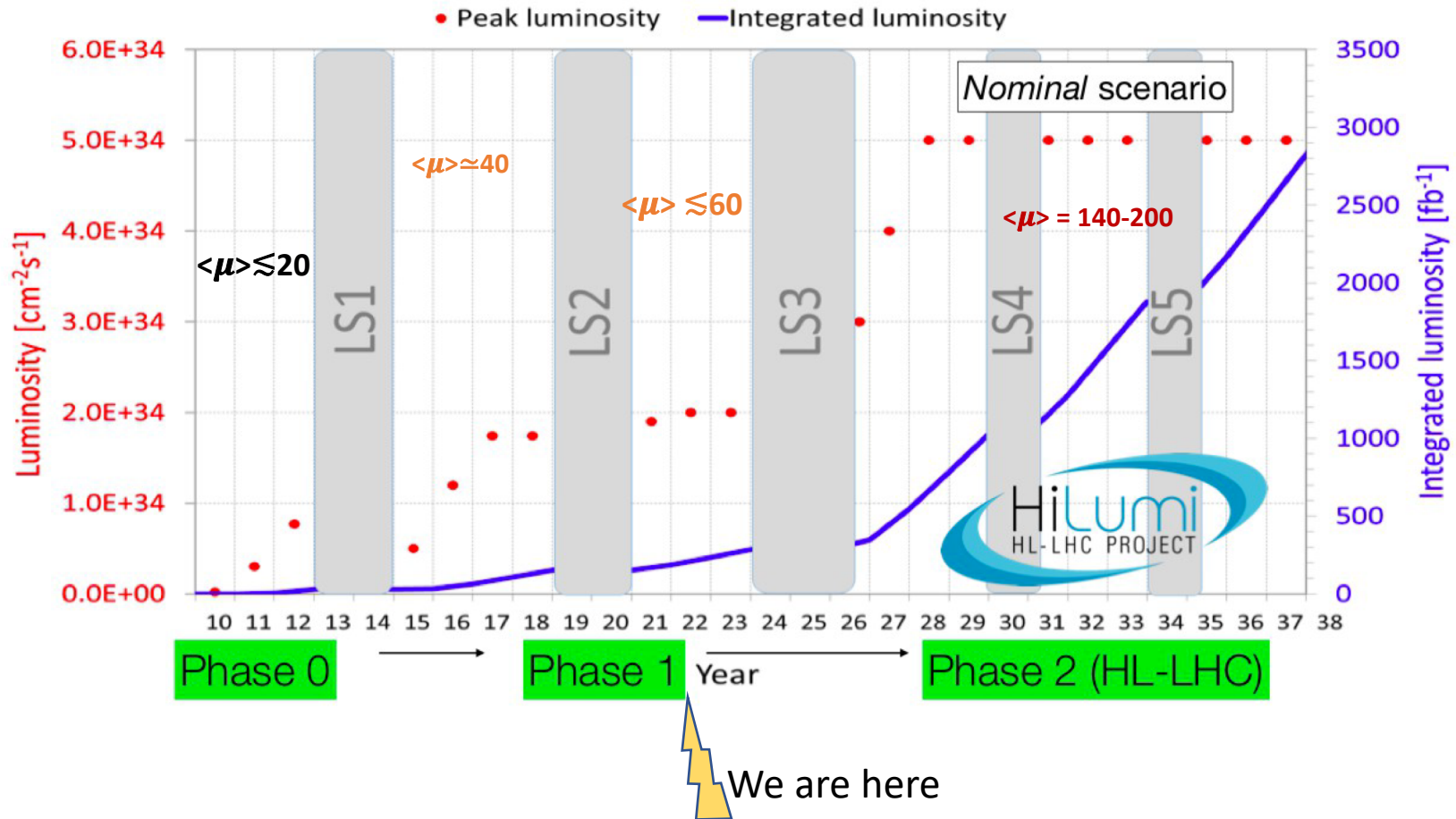
Talk at IUT, 14/09/2021



Outline

- **Standard Model At the LHC**
- **Higgs Boson**
- **Beyond SM**
- **Future Colliders**

LHC program



Since 2026-2027, the HL-LHCs instantaneous luminosity:

- ❖ will increase by a factor 5 to 7 compared to the LHC Run II
- ❖ will result in around 200 collisions per bunch crossing.

Cross Section of Various SM Processes

⇒ High Luminosity phase

$$10^{34}/\text{cm}^2/\text{s} = 10/\text{nb}/\text{s}$$

approximately

- 10^9 pp interactions
- 10^7 bb events
- 2000 W-bosons
- 500 Z-bosons
- 10 tt-pair

will be produced per second and

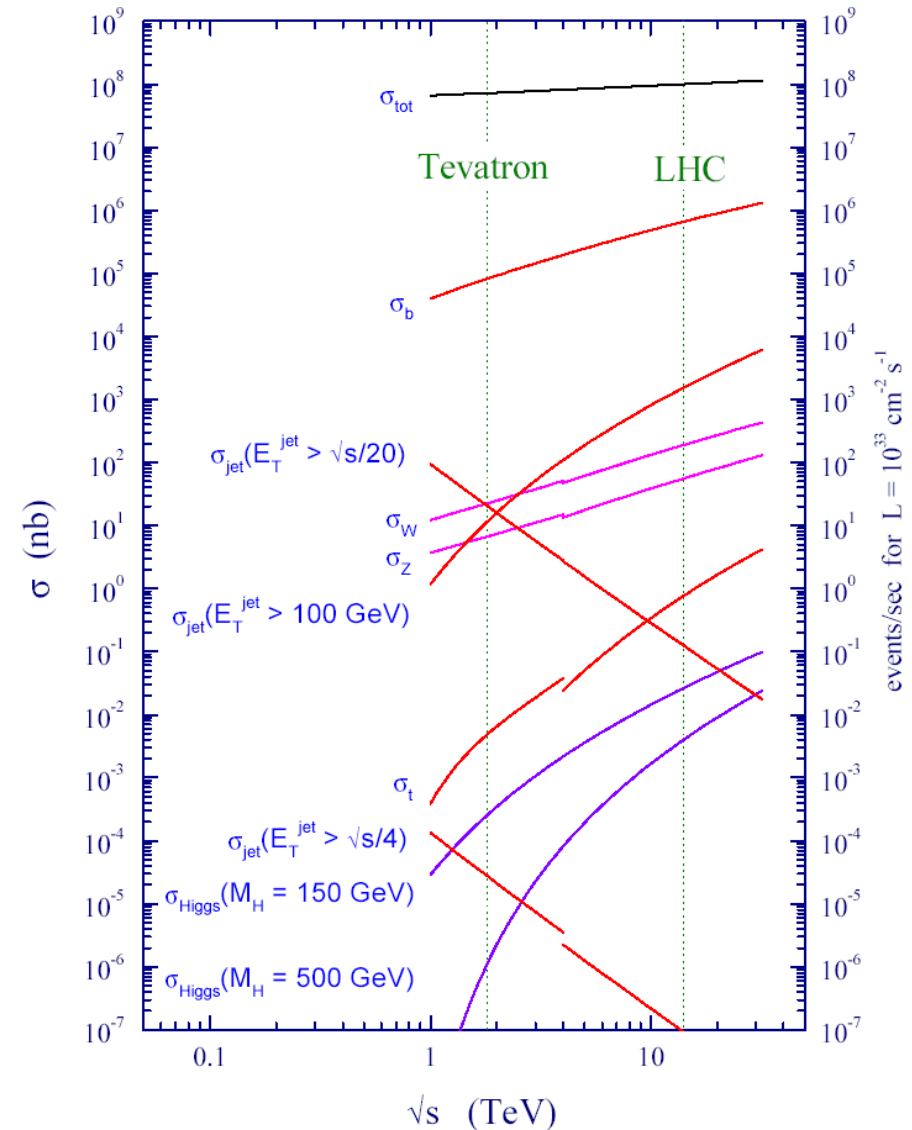
- 10 light Higgs

per minute!

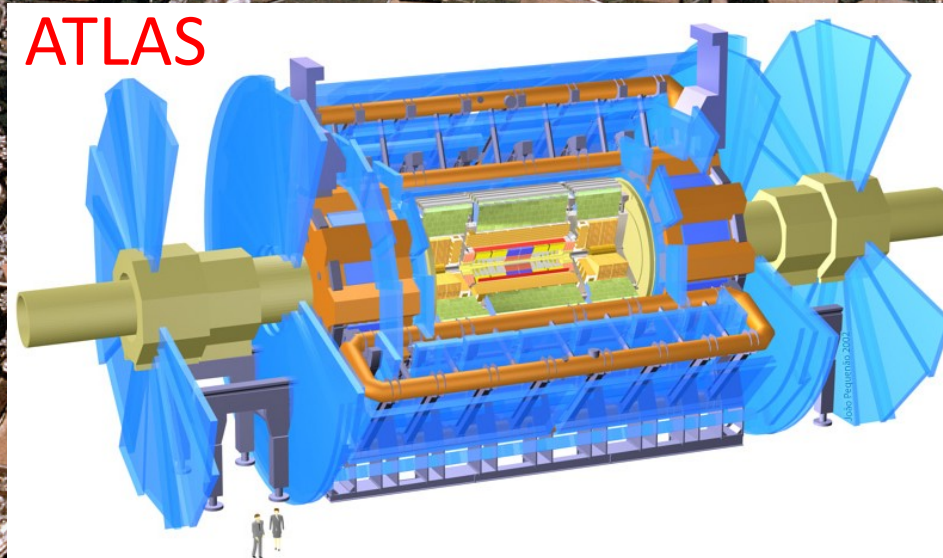
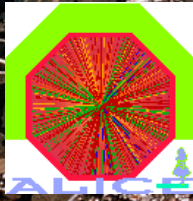
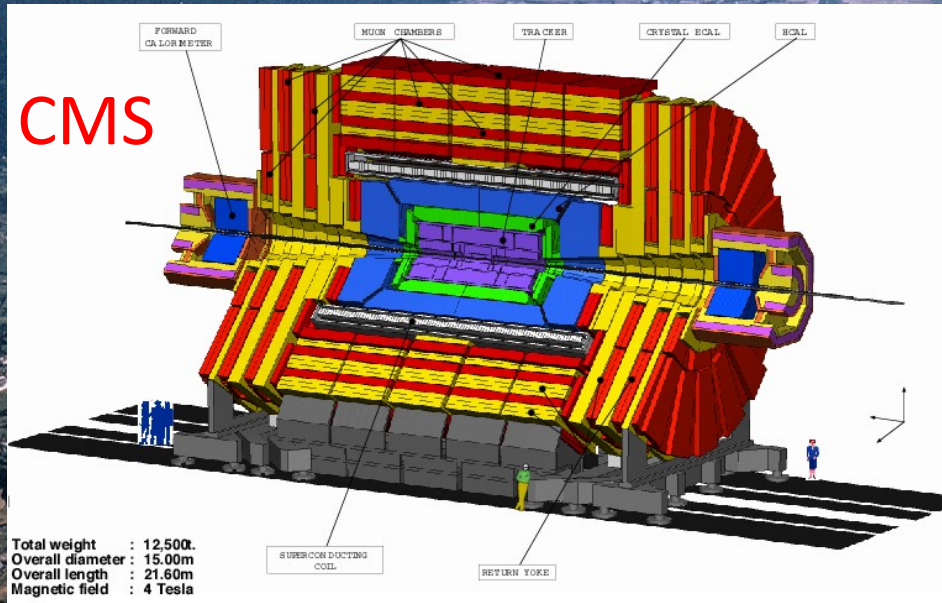
The LHC is a b, W, Z, top, Higgs, ... factory!

The problem is to detect the events!

proton - (anti)proton cross sections

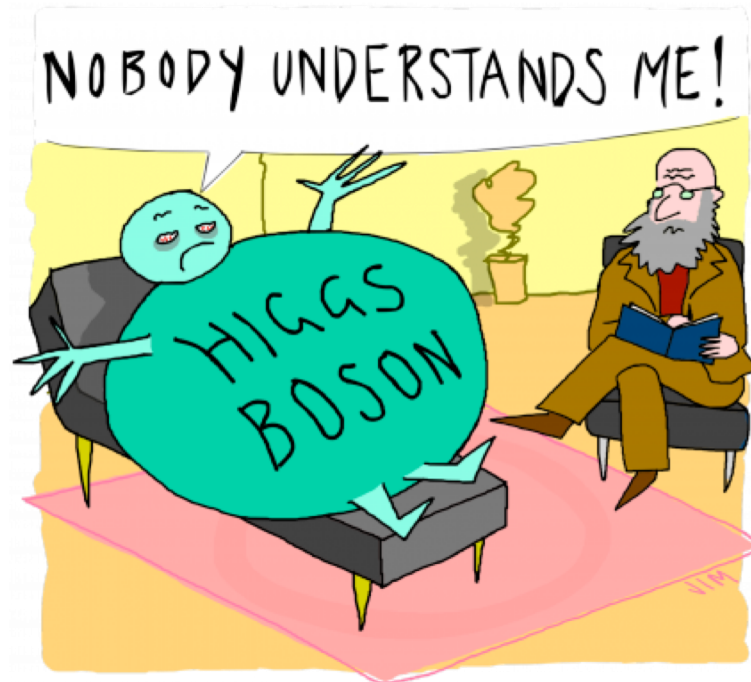


The Large Hadron Collider



Where we stand: Status of the Standard Model

Higgs Boson



- Precise Measurements of Properties and Couplings for Higgs
- Completing the unknown part of Higgs boson

Higgs couplings to SM fields: current status

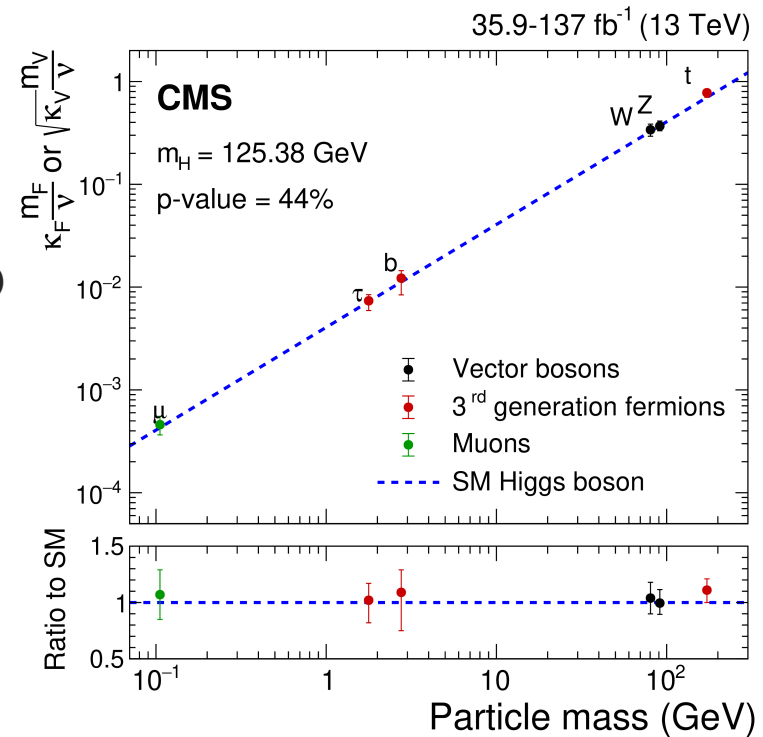
- Couplings to gauge bosons at **8-12%**
- Couplings to 3rd generation fermions at **15-20%**. For the muon: **~ 40%**

$$k_i = (\text{Higgs coupling to particle } i) / (\text{SM Higgs coupling to particle } i)$$

- **Gauge invariance of SM requires $k=1$**
- Simple rescaling; no momentum dependence
- We are just getting to the interesting regime:
Generically expect deviations:

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 6\% \left(\frac{1000 \text{ TeV}}{\Lambda} \right)^2$$

CMS-PAS-HIG-19-006



Higgs - τ
Summer 2017

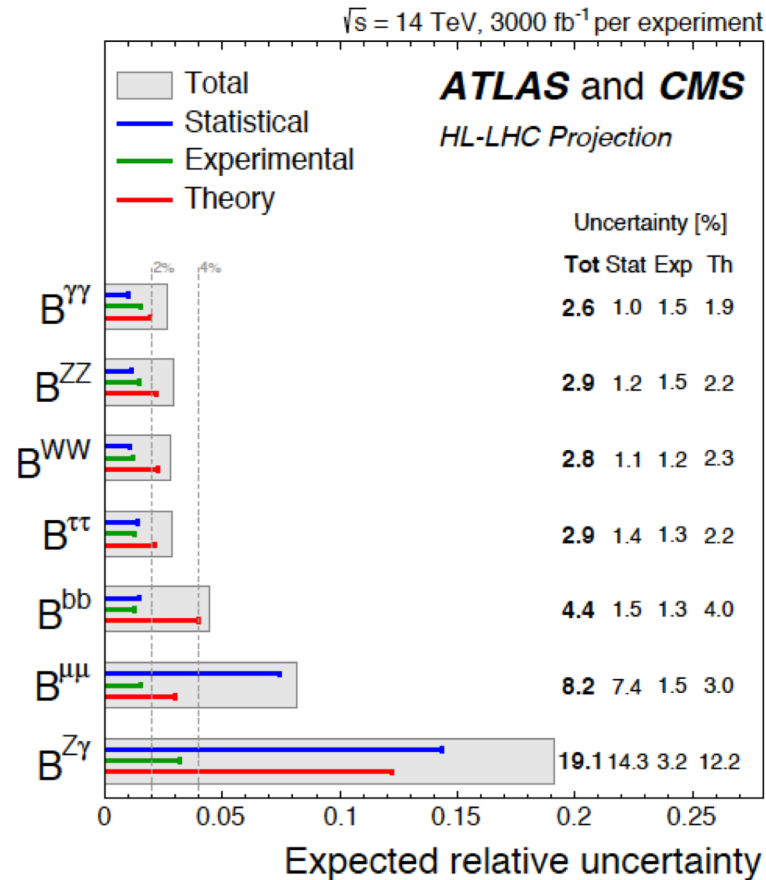
Higgs - b
Summer 2018

Higgs - top
Spring 2018

Higgs - μ
Summer 2020

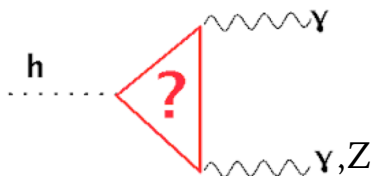
Err. 40%

Higgs production and decay at HL-LHC



Lots of theoretical work needed!

$BR H \rightarrow \mu\mu$ and $BR H \rightarrow Z\gamma$ statistically limited

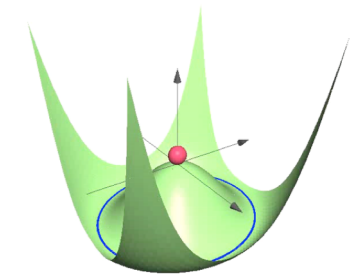


Other branching ratios and cross sections dominated by **theoretical** uncertainties

Need a future collider!

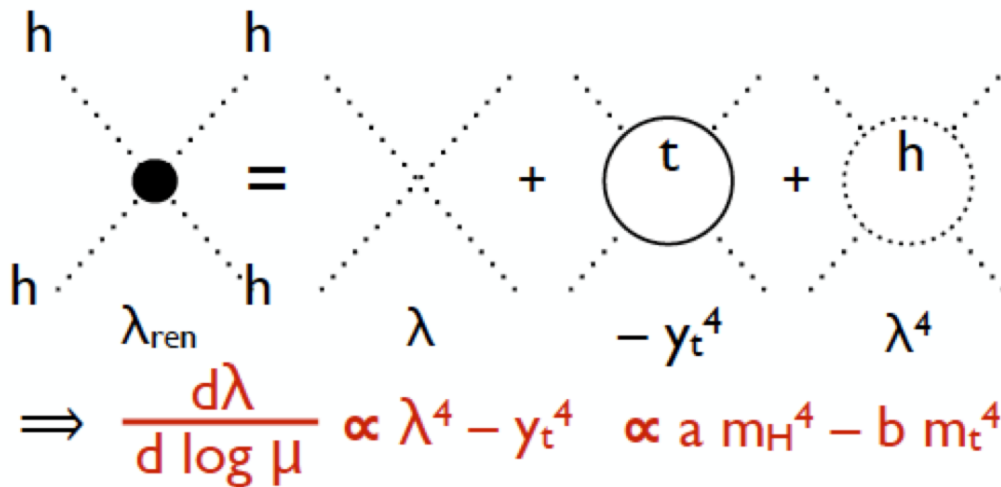
Higgs self coupling, Top Mass at HL-LHC

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4 \quad \lambda_{SM} = 0.13$$

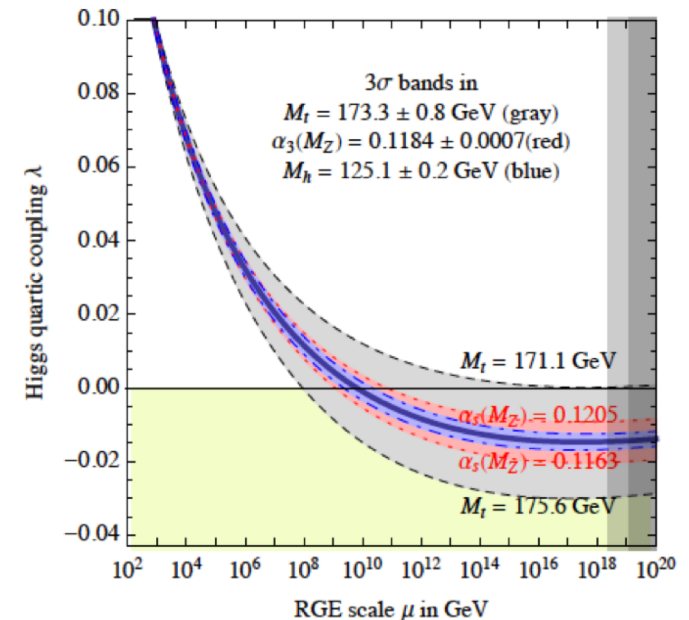


Giudice et al

Quantum fluctuations of Higgs, top, ...



If $\lambda < 0$, the potential is unbounded from below and has no state of minimum energy.



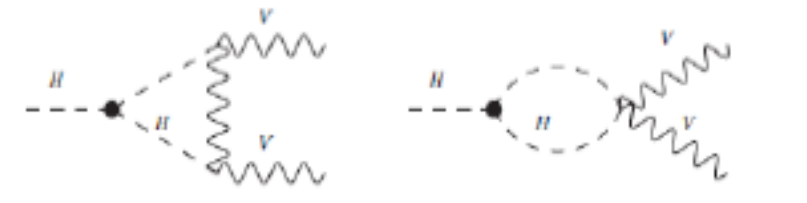
Indirect probes for Higgs self couplings

❖ **Unitarity**, $HH \rightarrow HH$, $\text{Re}(a_0) < 1/2$: $|k_\lambda| < 6.5$

$$k_\lambda = \lambda / \lambda_{\text{SM}}$$

❖ **Stability of Higgs potential**, Is Higgs potential bounded from below?
If we there is no NP, bounding the Higgs potential from below requires:
 $|k_\lambda| < 3$.

❖ Higgs Decay to ZZ and WW:



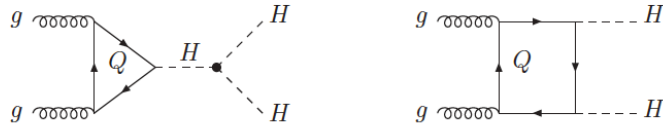
The image shows two Feynman diagrams for Higgs decay. The first diagram shows a Higgs boson (H) decaying into two Higgs bosons (H) via a loop of a vector boson (V). The second diagram shows a Higgs boson (H) decaying into two vector bosons (V) via a loop of a Higgs boson (H). To the right of the diagrams is the text "+ ...".

$$\lambda / \lambda_{\text{SM}} > -14.3$$

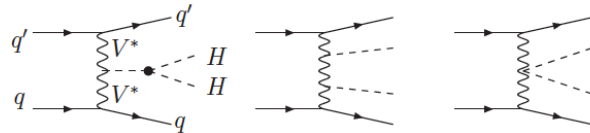
HH production at the LHC



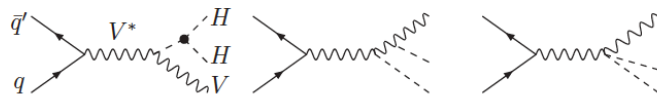
(a) gg double-Higgs fusion: $gg \rightarrow HH$



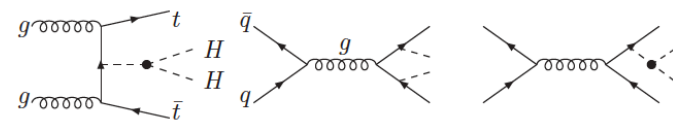
(b) WW/ZZ double-Higgs fusion: $qq' \rightarrow HHqq'$



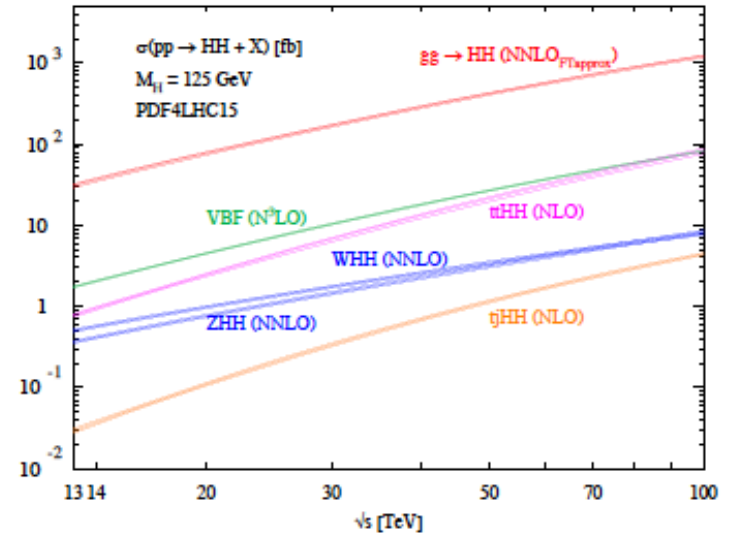
(c) Double Higgs-strahlung: $q\bar{q}' \rightarrow ZHH/WHH$



(d) Associated production with top-quarks: $q\bar{q}/gg \rightarrow t\bar{t}HH$



$$\sigma(gg \rightarrow HH) \approx 0.1\% \times \sigma(gg \rightarrow H)$$

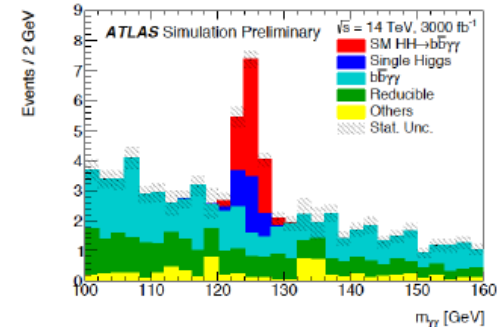


\sqrt{s} [TeV]	$\sigma_{gg \rightarrow HH}^{\text{NLO}}$ [fb]	$\sigma_{qq' \rightarrow HHqq'}^{\text{NLO}}$ [fb]	$\sigma_{q\bar{q}' \rightarrow WHH}^{\text{NNLO}}$ [fb]	$\sigma_{q\bar{q}' \rightarrow ZHH}^{\text{NNLO}}$ [fb]	$\sigma_{q\bar{q}/gg \rightarrow t\bar{t}HH}^{\text{LO}}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

HH search at the HL-LHC

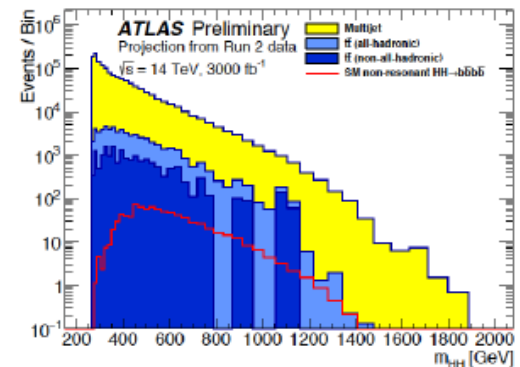
- **HH → bbyy:**

- Small BR: 291 events with $3ab^{-1}$
- Low bkg
- Photon resolution critical



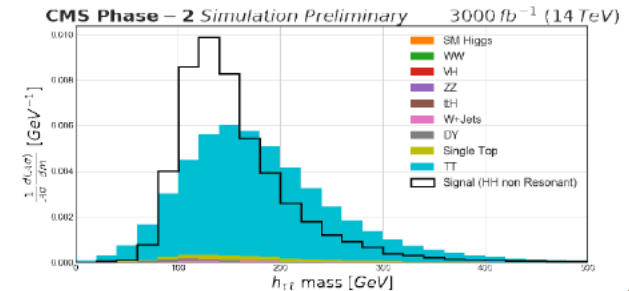
- **HH → bbττ:**

- Sizeable BR: ~8k events with $3ab^{-1}$
- Relatively low background
- Incomplete reconstruction of the event due to the presence of neutrinos
→ Challenging separation from tt and Drell-Yan bkg



- **HH → 4b:**

- Large BR: ~37k events with $3ab^{-1}$
- Large QCD bkg
- Large dependence on background modelling uncertainty



Results of HH study

Expected **significance** of HH production with(without) systematics at HL-LHC

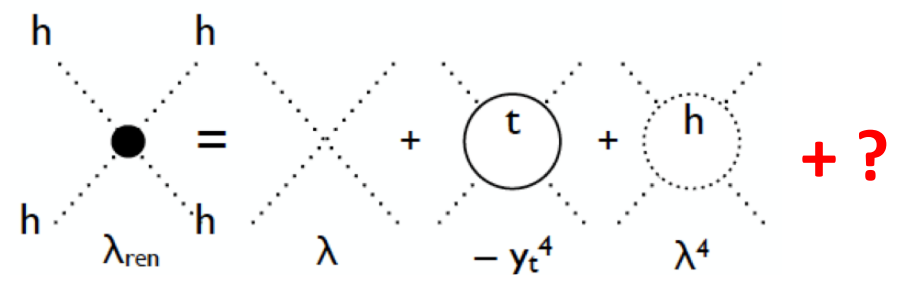
- **4σ (4.5σ) expected with ATLAS+CMS !**

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV (ll\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ (4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

Measurement of $k_\lambda = \lambda / \lambda_{SM}$

$0.52 < k_\lambda < 1.5$

Need a future collider!



Standard Model Complete...?

New Physics ?

Many unanswered questions based on experimental observations?

- Why 3 generations of fermions ?
- What is the origin of neutrino masses and oscillations ?
- What is the composition of dark matter ?
- What is the origin of the matter-antimatter asymmetry in the Universe?
- Why is gravity so weak ?
- Why is the Higgs boson so light ?
so-called “naturalness” or “hierarchy” problem
- What is the origin of the Universe’s accelerated expansion ?

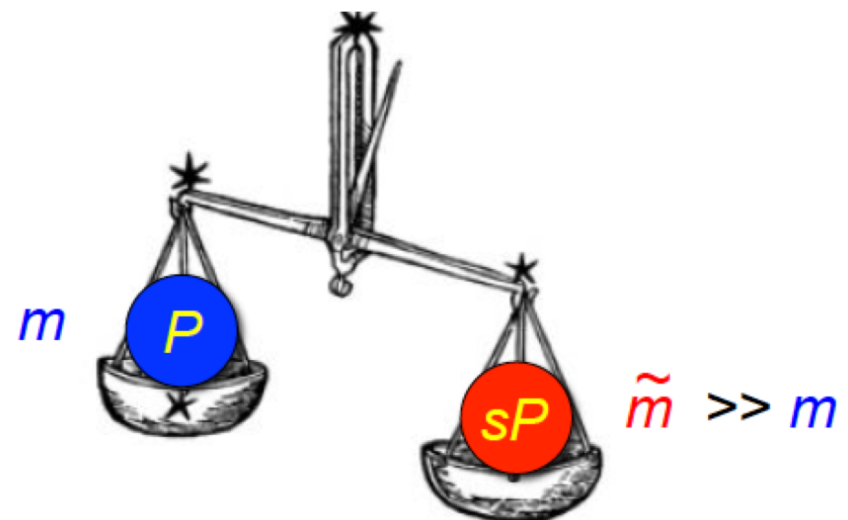
New Physics ? SUSY?

Symmetry between fermions and bosons

For each particle p with spin s , there exists a SUSY partner with spin $s-1/2$.

- helps stabilize Higgs potential
- gauge coupling unification
- dark matter candidate
- hierarchy (naturalness) problem
- fun for colliders
- baryogenesis?
- neutrino mass?
- mathematically interesting
- string theory needs it.

Supersymmetry cannot be an exact symmetry of our world (spin-0 electrons do not exist)



Search for SUSY

ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017

ATLAS Preliminary
 $\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_{T}^{miss}	$\int \mathcal{L} d\mathcal{L} [fb^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ / 1-2 τ	2-10 jets/3 b	Yes	20.3	\tilde{g}, \tilde{q}	1.85 TeV	$m(\tilde{g})=m(\tilde{q})$
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	0	2-6 jets	Yes	36.1	\tilde{g}	1.37 TeV	$m(\tilde{g}) < 200$ GeV, $m(\tilde{q}) = m(\tilde{q}^c)$
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{g}	608 GeV	$m(\tilde{g}) - m(\tilde{q}) < 5$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{g}) < 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{g}) < 200$ GeV, $m(\tilde{q}) = 0.5(m(\tilde{q}^c) + m(\tilde{g}))$
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.825 TeV	$m(\tilde{g}) < 400$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{g}) < 400$ GeV
	GMSB (\tilde{L} NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV	$c\tau(\text{NLSP}) < 0.1$ mm
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g}	1.65 TeV	$c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{g}) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	\tilde{g}	1.8 TeV	$m(\tilde{g}) < 880$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	$m(\text{NLSP}) > 430$ GeV
Gravitino LSP	0	mono-jet	Yes	20.3	$\tilde{g}^{1/2}$ <i>see table</i>	805 GeV	$m(\tilde{G}) > 1.3 \times 10^{-4}$ eV, $m(\tilde{g}) - m(\tilde{q}) > 1.5$ TeV	
1 st gen. $b, \text{med.}$	$\tilde{g}\tilde{g}, \tilde{g}\tilde{b}, \tilde{g}\tilde{b}^c$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{g}) < 800$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}, \tilde{g}\tilde{t}^c$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	1.97 TeV	$m(\tilde{g}) < 200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{b}, \tilde{g}\tilde{b}^c$	0-1 e, μ	3 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{g}) < 300$ GeV
3 rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c$	0	2 b	Yes	36.1	\tilde{t}_1	950 GeV	$m(\tilde{t}_1) < 420$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{t}_1	275-700 GeV	$m(\tilde{t}_1) < 200$ GeV, $m(\tilde{b}_1) = m(\tilde{b}_1^c) + 100$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{t}_1) = 2m(\tilde{t}_1^c), m(\tilde{b}_1) = 55$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/30.1	\tilde{t}_1	90-190 GeV	$m(\tilde{t}_1) = 1$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c$	0	mono-jet	Yes	3.2	\tilde{t}_1	90-323 GeV	$m(\tilde{t}_1) - m(\tilde{t}_1^c) = 5$ GeV
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{t}_1) < 150$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 + Z$	2 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_1	290-790 GeV	$m(\tilde{t}_1) = 0$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_1	320-880 GeV	$m(\tilde{t}_1) = 0$ GeV
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	2 e, μ	0	Yes	36.1	\tilde{t}_1	90-440 GeV	$m(\tilde{t}_1) = 0$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	2 e, μ	0	Yes	36.1	\tilde{t}_1	710 GeV	$m(\tilde{t}_1) = 0, m(\tilde{t}_1^c) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_1^c))$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	2 τ	0	Yes	36.1	\tilde{t}_1	760 GeV	$m(\tilde{t}_1) = 0, m(\tilde{t}_1^c) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_1^c))$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	3 e, μ	0	Yes	36.1	$\tilde{t}_1, \tilde{t}_1^c$	1.10 TeV	$m(\tilde{t}_1) = 0, m(\tilde{t}_1^c) = 0.5(m(\tilde{t}_1) + m(\tilde{t}_1^c))$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{t}_1, \tilde{t}_1^c$	580 GeV	$m(\tilde{t}_1) = m(\tilde{t}_1^c), m(\tilde{t}_1^c) = 0, \tilde{t}_1$ decoupled
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{t}_1, \tilde{t}_1^c$	270 GeV	$m(\tilde{t}_1) = m(\tilde{t}_1^c), m(\tilde{t}_1^c) = 0, \tilde{t}_1$ decoupled
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1^c, \tilde{t}_1\tilde{t}_1^c$	4 e, μ	0	Yes	20.3	$\tilde{t}_1, \tilde{t}_1^c$	635 GeV	$m(\tilde{t}_1) = m(\tilde{t}_1^c), m(\tilde{t}_1^c) = 0, \tilde{t}_1$ decoupled
	GGM (wino NLSP) weak prod., $\tilde{g}\tilde{g} \rightarrow \gamma\tilde{G}$	1 e, μ + γ	-	Yes	20.3	\tilde{W}	115-370 GeV	$m(\tilde{K}_2^0) = m(\tilde{K}_1^0), m(\tilde{K}_1^0) = 0, m(\tilde{K}_1^0) = 0.5(m(\tilde{K}_2^0) + m(\tilde{K}_1^0))$
	GGM (bino NLSP) weak prod., $\tilde{g}\tilde{g} \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	390 GeV	$c\tau < 1$ mm
								$c\tau < 1$ mm
Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived \tilde{t}_1	Disapp. trk	1 jet	Yes	36.1	\tilde{t}_1	430 GeV	$m(\tilde{t}_1) - m(\tilde{t}_1^c) = 180$ MeV, $\tau(\tilde{t}_1) = 0.2$ ns
	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived \tilde{t}_1	dE/dx trk	-	Yes	18.4	\tilde{t}_1	499 GeV	$m(\tilde{t}_1) - m(\tilde{t}_1^c) = 180$ MeV, $\tau(\tilde{t}_1) < 15$ ns
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}	890 GeV	$m(\tilde{g}) = 100$ GeV, $10^{-10} \text{ s} < c\tau(\tilde{g}) < 1000$ s
	Stable \tilde{g} R-hadron	trk	-	-	3.2	\tilde{g}	1.58 TeV	1806.05129
	Metastable \tilde{g} R-hadron	dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV	1804.04520
	GMSB, stable $\tau, \tilde{t}_1, \tilde{t}_1^c \rightarrow \tau(\tilde{t}_1, \tilde{t}_1^c) + \tau(e, \mu)$	1-2 μ	-	-	19.1	\tilde{t}_1	537 GeV	$10 < \text{tag} < 50$
	GMSB, $\tilde{t}_1 \rightarrow \gamma\tilde{G}$, long-lived \tilde{t}_1	2 γ	-	Yes	20.3	\tilde{t}_1	440 GeV	$1 < \tau(\tilde{t}_1) < 3$ ns, SP88 model
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1 \rightarrow e\nu\bar{\nu}/\mu\bar{\nu}\nu$	displ. $e\nu/\mu\bar{\nu}\nu$	-	-	20.3	\tilde{t}_1	1.0 TeV	$7 < \tau(\tilde{t}_1) < 740$ mm, $m(\tilde{g}) = 1.3$ TeV
GGM $\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	\tilde{t}_1	1.0 TeV	$6 < \tau(\tilde{t}_1) < 480$ mm, $m(\tilde{g}) = 1.1$ TeV	
RPV	LFV $\tilde{g}\tilde{g} \rightarrow \nu_i + X, \nu_i \rightarrow e\mu/\tau/\mu/\tau$	$e\mu, \tau\mu, \mu\tau$	-	-	3.2	\tilde{g}	1.9 TeV	$X_{111} = 0.11, X_{122}/X_{132} = 0.07$
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{q}	1.45 TeV	$m(\tilde{g}) = m(\tilde{q}), c\tau_{23} < 1$ mm
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1, \tilde{g}\tilde{t}_1^c \rightarrow e\nu\bar{\nu}, e\mu\bar{\nu}, \mu\mu\bar{\nu}$	4 e, μ	-	Yes	13.3	\tilde{g}	1.14 TeV	$m(\tilde{g}) > 400$ GeV, $A_{123} \neq 0$ ($k = 1, 2$)
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1, \tilde{g}\tilde{t}_1^c \rightarrow W\tilde{t}_1, \tilde{t}_1 \rightarrow \tau\nu, e\nu, \tau\nu$	3 e, μ + τ	-	Yes	20.3	\tilde{g}	450 GeV	$m(\tilde{g}) > 0.2m(\tilde{t}_1^c), A_{123} \neq 0$
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	0	4-5 large- R jets	-	14.8	\tilde{g}	1.08 TeV	$BR(\tilde{g} \rightarrow BR) = BR(\tilde{q} \rightarrow 0\%)$
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{g}\tilde{q}^c$	0	4-5 large- R jets	-	14.8	\tilde{g}	1.55 TeV	$m(\tilde{g}) = 800$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1, \tilde{g}\tilde{t}_1^c \rightarrow q\bar{q}q$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	2.1 TeV	$m(\tilde{g}) = 1$ TeV, $A_{123} \neq 0$
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1, \tilde{g}\tilde{t}_1^c \rightarrow q\bar{q}q$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{g}) = 1$ TeV, $A_{123} \neq 0$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow h\bar{h}$	0	2 jets + 2 b	-	15.4	\tilde{t}_1	410 GeV	$BR(\tilde{t}_1 \rightarrow h\bar{h}) > 20\%$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\tilde{t}_1 \rightarrow h\bar{h}$	2 e, μ	2 b	-	36.1	\tilde{t}_1	450-510 GeV	$BR(\tilde{t}_1 \rightarrow h\bar{h}) > 20\%$
Other	Scalar charm, $\tilde{t} \rightarrow c\tilde{t}_1^c$	0	2 c	Yes	20.3	\tilde{t}	510 GeV	$m(\tilde{t}_1^c) < 200$ GeV

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



“The 2 TeV line has been reached for some scenarios”

Search for New Physics

Many diverse theoretical ideas to extend the Standard Model (with new particles)

Is new physics at larger masses ? Or at smaller couplings ? Or both ?

Only way to find out: go look, following the historical approach:

Direct searches for new heavy particles

⇒ Need colliders with larger energies

Energy Frontier

Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles

⇒ Need colliders / measurements with unprecedented accuracy

Precision Frontier

Indirect evidence from Precision Measurements

Top quark

1990-1994: Mass predicted from quantum loops

$$m_{\text{top}}(\text{pred.}) = 178.0 \pm 10 \text{ GeV}$$

1995: Discovered at the Tevatron (DØ, CDF)

$$\text{Today: } m_{\text{top}}(\text{obs.}) = 173.23 \pm 0.7 \text{ GeV}$$

Higgs boson

1996-2011: Mass predicted from quantum loops

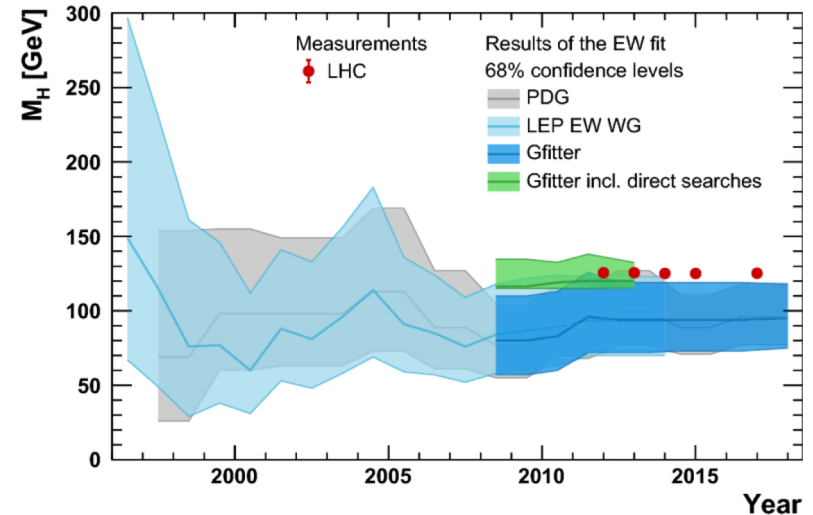
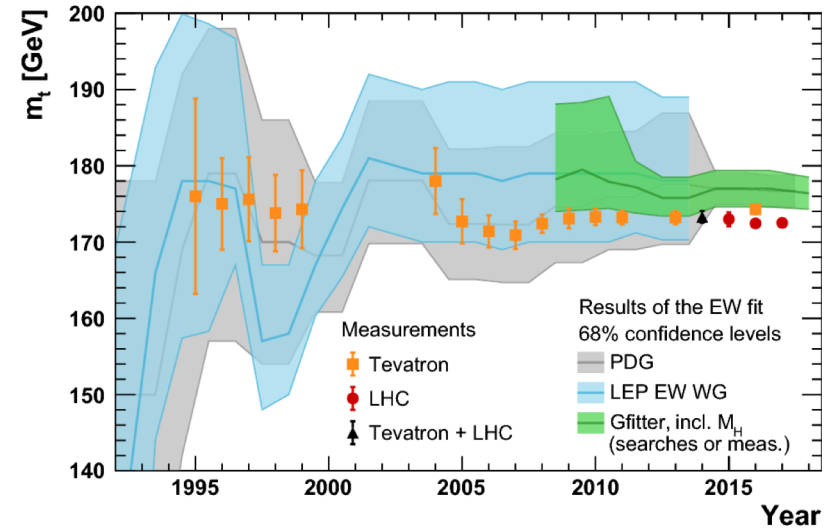
$$m_{\text{Higgs}}(\text{pred.}) = 98^{+25}_{-21} \text{ GeV}$$

2012: Discovery at the LHC (ATLAS, CMS)

$$\text{Today: } m_{\text{Higgs}}(\text{obs.}) = 125.09 \pm 0.24 \text{ GeV}$$

Lesson:

Precision measurements interpreted via quantum loop corrections can give very strong constraints on particles at higher masses than what can be directly probed!



Where we are heading

The LHC is still pretty much in its childhood

Factor 30 more luminosity to be collected



Important precision measurement

-Higgs couplings to 2-4%

-Top quark mass to 200 MeV

-W boson to 10 MeV ?

-Flavour physics measurements

-Until the end of HL-LHC (~2037 !)

-Exciting search programme for New Physics

-Stop: 1.5 TeV; squarks/gluinos: 3 TeV; Z': 7 TeV; etc.

The future machines

A very brief summary

e^+e^- Colliders

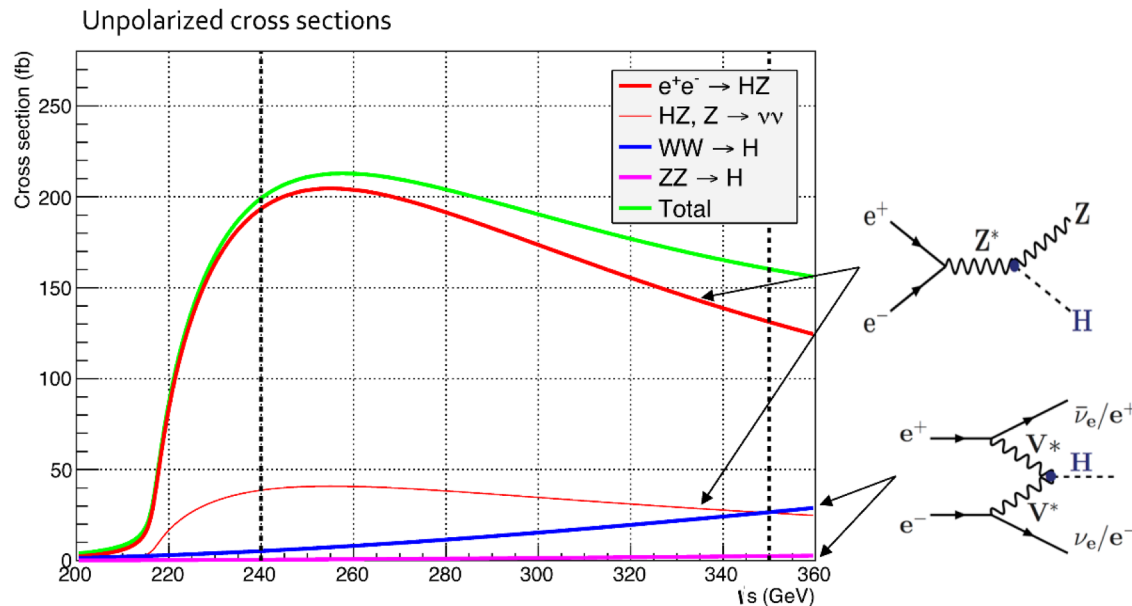
There seems to be no heavy new physics below 500 GeV

-The interest of $\sqrt{s} = 500$ GeV (and even 1 TeV) is no longer quite that obvious

One way out: study with unprecedented precision the Z, W, H bosons and the top quark

-Need to go up to the top-pair threshold (350+ GeV) anyway to study the top quark

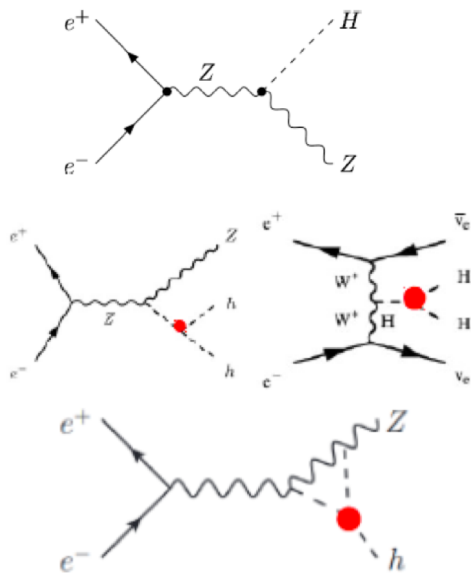
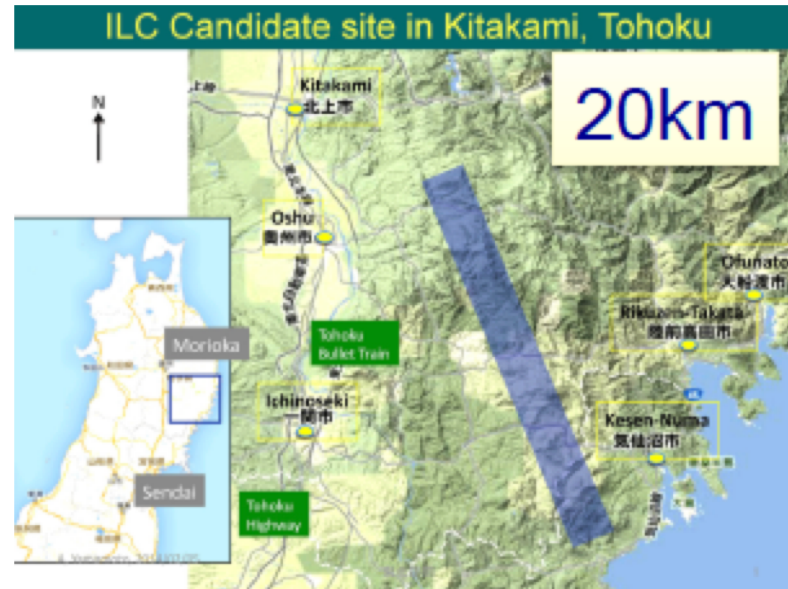
-Highest possible luminosities at 91, 160, 240 and 350+ GeV are needed



International Linear Collider (ILC)

ILC (Japan & Germany):

- ◆ Linear collider with high-gradient superconducting acceleration
- ◆ Ultimate: 0.5-1(?) TeV
- ◆ To secure funding: reduce cost by starting at 250 GeV (H factory)



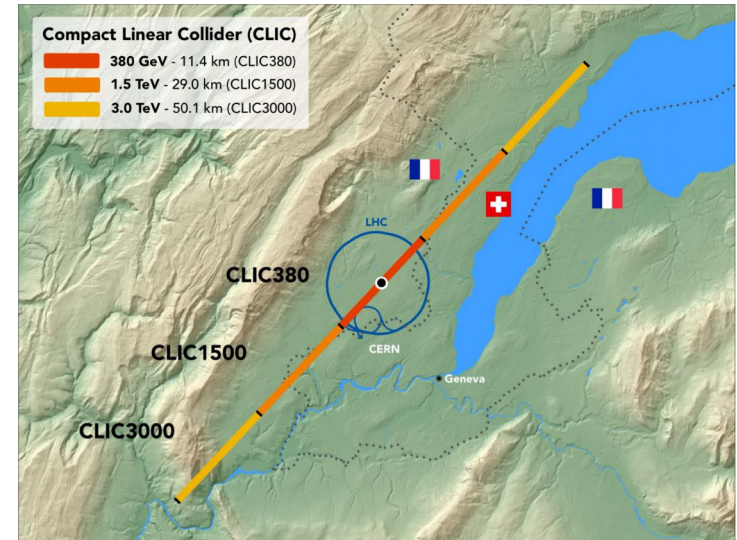
- Can deliver data to only one detector at a time
- In principle upgradeable to $\sqrt{s} = 1$ TeV
- No design to run at the Z pole

ILC: 5.0 (for 250 GeV); 7.8 (500 GeV)

Compact Linear Collider (CLIC)

CLIC (CERN):

- ◆ Linear collider with high gradient normal-conducting acceleration
- ◆ Ultimate: multi-TeV (3) e^+e^- collisions
- ◆ Use technology to overcome challenges
- ◆ Stages, for physics and funding



- Can deliver data to only one detector at a time
- No design to run at the Z pole

CLIC: 5.9 or 7.3 (for 380 GeV) + 5.1 (1500 GeV) + 7.1 (3000 GeV) (Tot: 19.5)

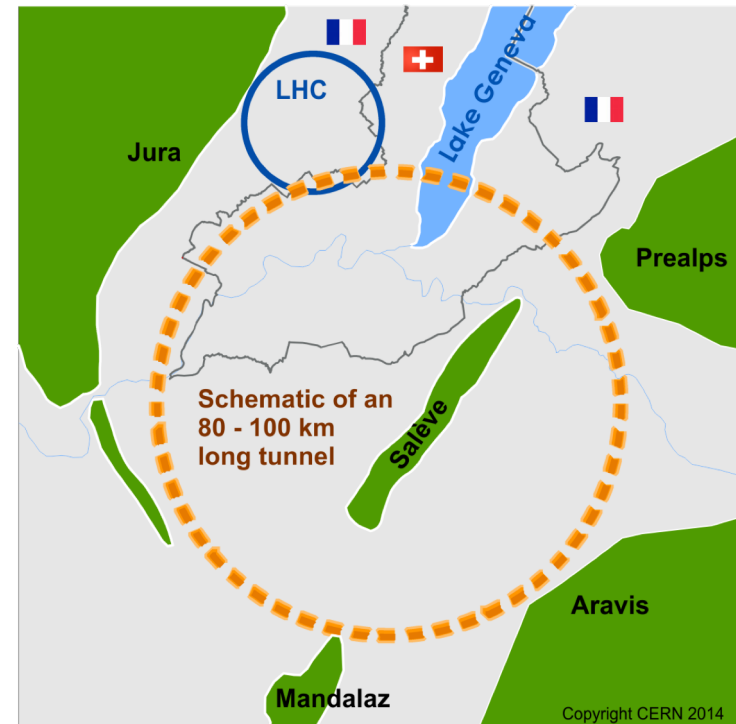
Future Circular Collider (FCC)

FCC-ee/FCC-hh (CERN):

- ◆ Protons to extend energy frontier
- ◆ 100 km ring with **16T** magnets
- ◆ Use FCC-hh tunnel for e+e- collider
- ◆ Technology for ee: “standard”

Two (possible four) experiments to serve

8~(11)T NbTi / (Nb ₃ Sn)
12~14T Nb ₃ Sn
14~16T Nb ₃ Sn



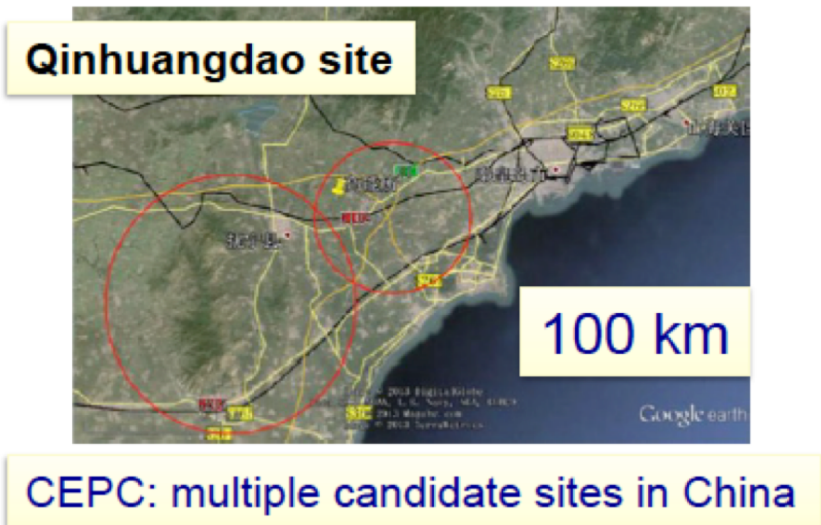
FCC-ee: 11.6; but 7.1 is the tunnel
 FCC-hh: tunnel + 17 (Tot: 24)

China Electron-Positron Collider (CEPC)

CEPC/SppC

Essentially an FCC-ee, then hh with

1. More conservative luminosity estimates
2. China



The cost would be about 7 BCHF if it is built in Switzerland. But the cost in China is lower, especially the civil construction. The goal is to reduce it by half to about 3.5 BCHF, or 20 billion Chinese Yuan.

LHeC

e^\pm beam: 60 GeV Energy Recovering Linac
operated synchronously - with HL-LHC:
p beam: 7 TeV, $\sqrt{s}=1.3$ TeV

operated synchronously
- with HL-LHC: p beam: 7 TeV, $\sqrt{s}=1.3$ TeV

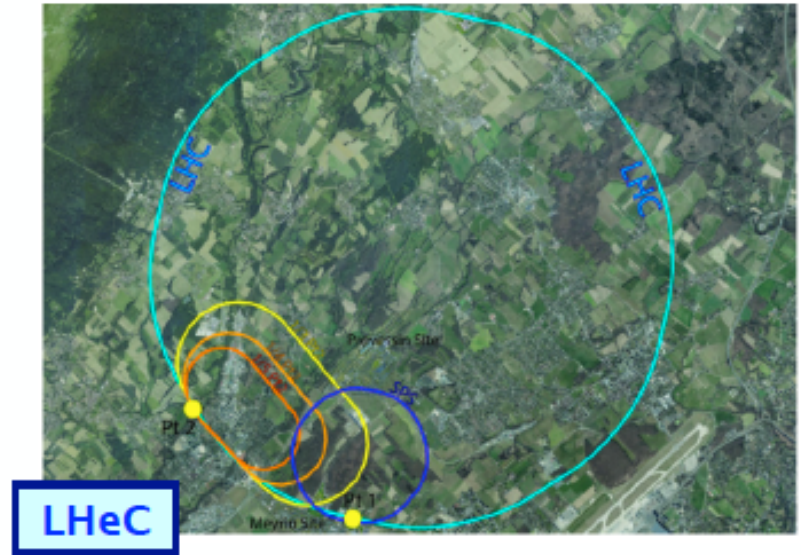
* Parton Density Functions

* Precision:

- Electroweak and top quark physics
- Higgs Couplings
- Strong interaction coupling

* Search for New Phenomena:

- SUSY
- Extension of SM Higgs sector
- Good probe of SMEFT
- ...



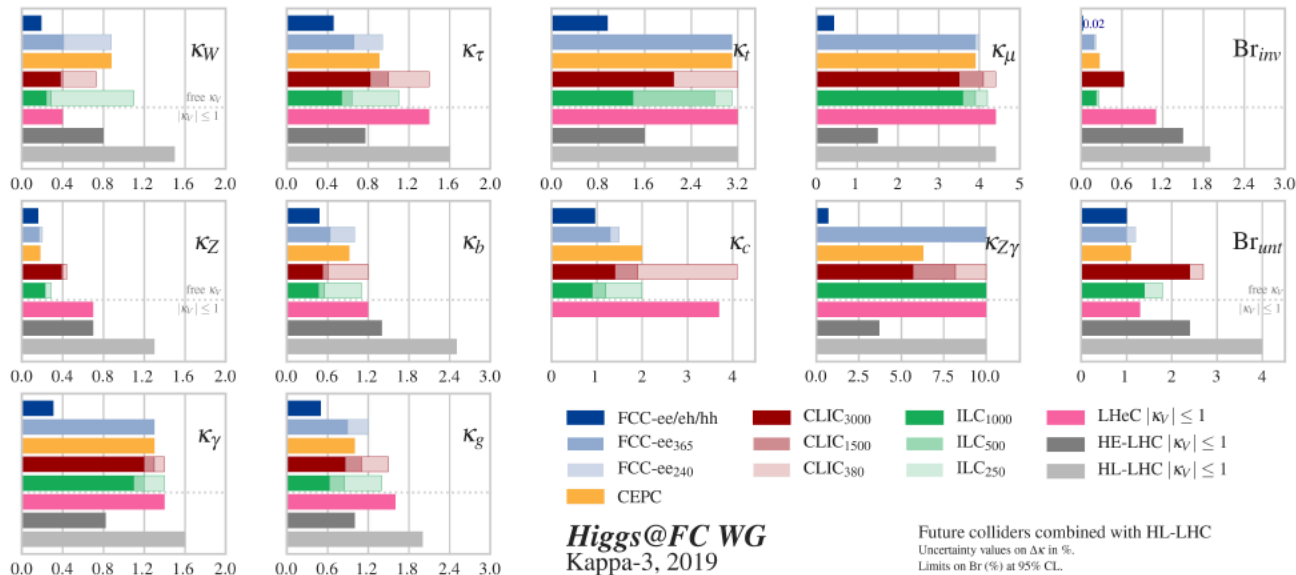
LHeC CDRs, arXiv:1206.2913, arXiv:2007.14491

$\text{Lint} = 1-2 \text{ ab}^{-1} (1-2\text{k} \times \text{HERA!})$

Higgs Measurements at HL-LHC and Future Colliders

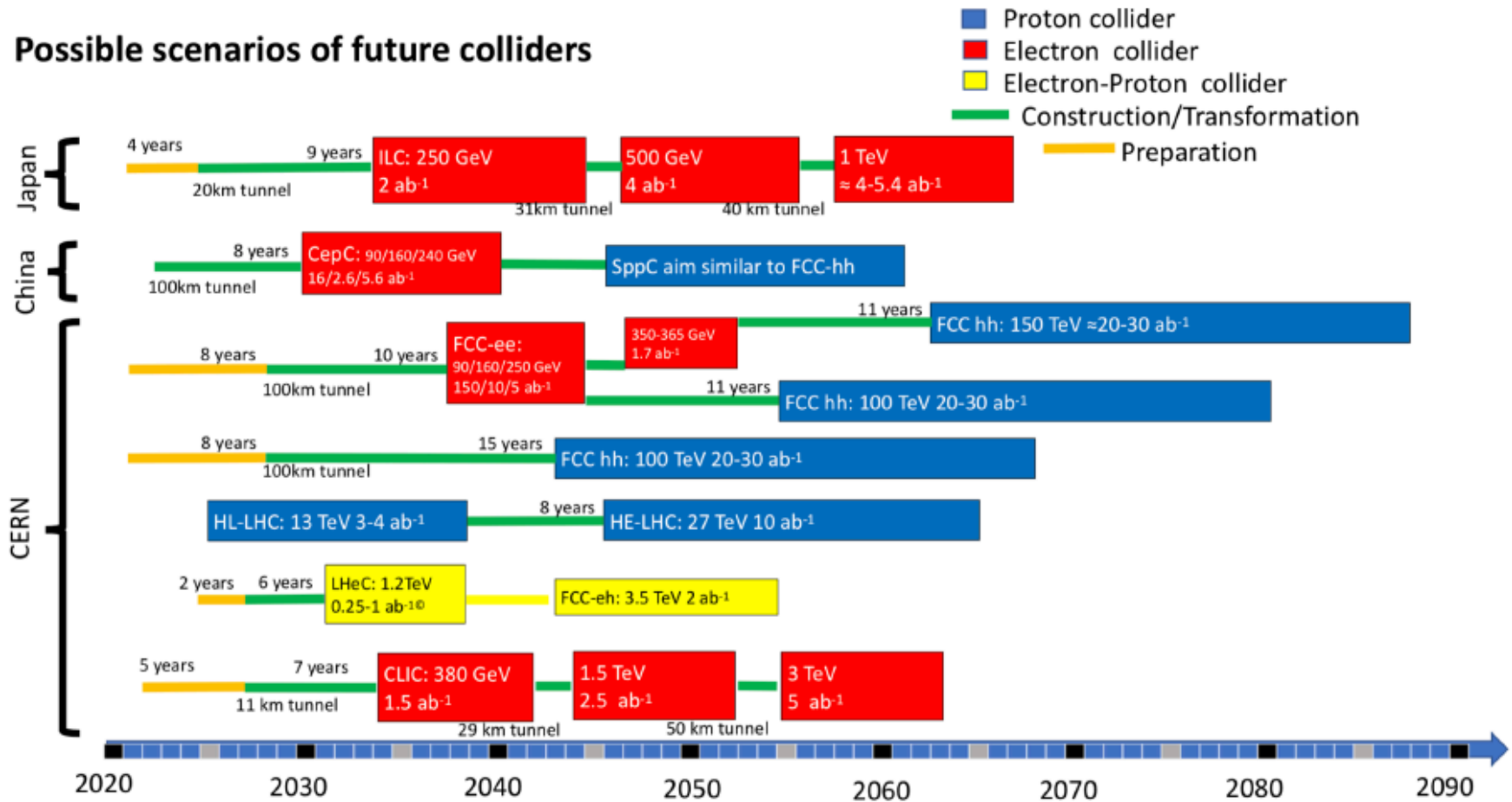
$$k_i = (\text{Higgs coupling to particle } i) / (\text{SM Higgs coupling to particle } i)$$

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2'	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98*	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	—	5.7	3.8	99*	86*	85*	120*	15	6.9	8.2	81*	75*	0.69
κ_c [%]	—	4.1	—	—	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	—	2.8	1.7	—	6.9	1.6	—	—	2.7	—	—	—	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	—	2.5	1.7	15	9.4	6.2	320*	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

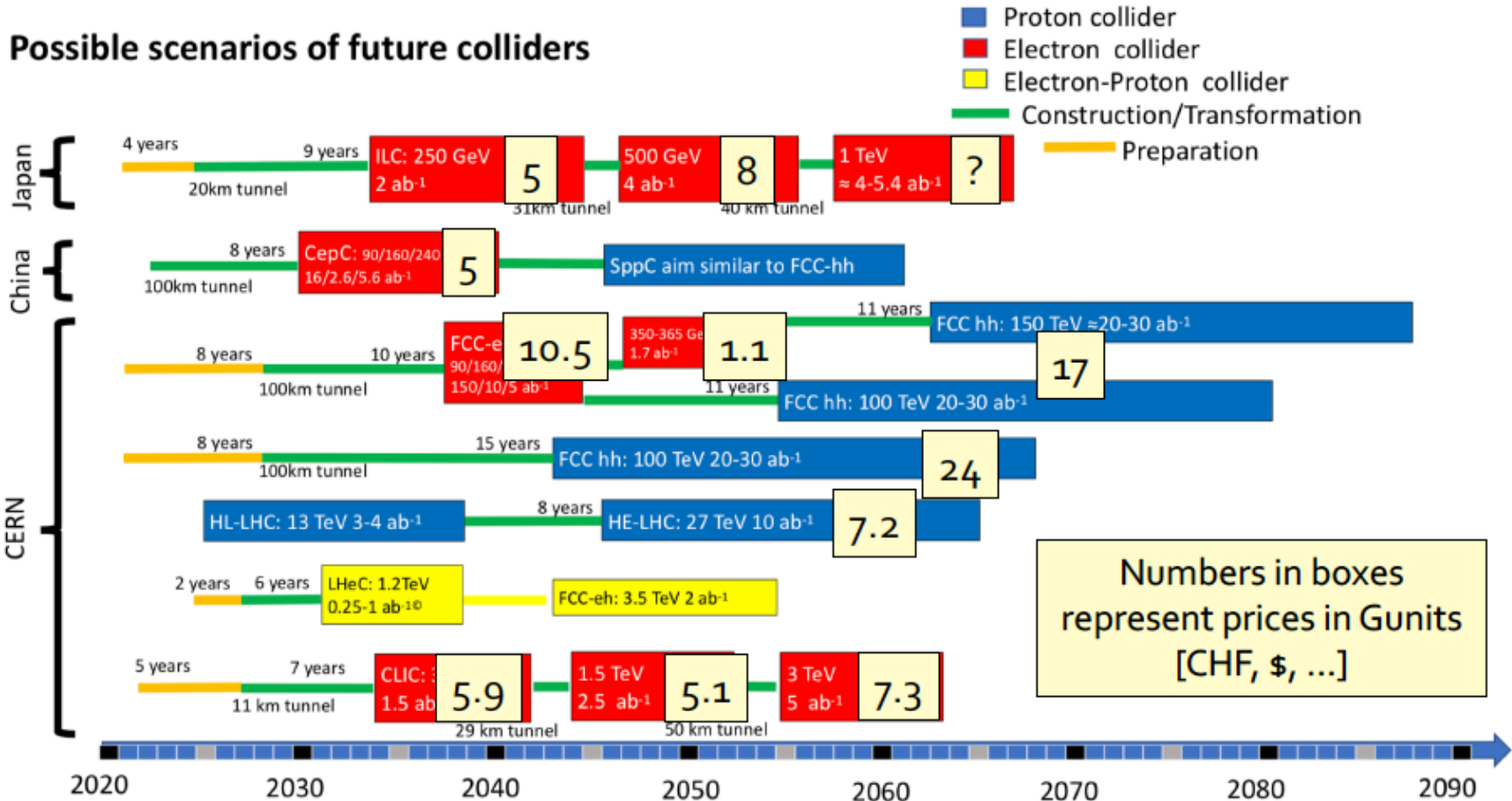


Summary of proposed future colliders

Possible scenarios of future colliders



Summary of proposed future colliders



Summary

*The Standard Model is a complete theory of particles and their interactions

- Theoretically complete since 40 years
- Experimentally complete since 2012 with the discovery of the Higgs boson
- Tested to be internally consistent at the quantum loop level via EW precision

measurements.

* The days of “guaranteed discoveries” are over, however, experimental observations suggest the existence of physics beyond the SM

- Dark matter, matter-antimatter asymmetry, neutrino masses, ...
- However, we do not know where this new physics is hiding

At high(er) masses \Leftrightarrow Energy Frontier / Precision Frontier

At small(er) couplings \Leftrightarrow Precision Frontier

There are several proposals for future, mostly at CERN: lepton colliders, pp, e-p

* e^+e^- colliders provide very clean experimental environments:

* Future e^+e^- colliders can be either linear or circular

Linear: necessary for energies > 500 GeV (synchrotron radiation)

Circular: superior luminosity performance for energies $\lesssim 375$ GeV

Thanks



*Artwork by Xavier Cortada (with the participation of physicist Pete Markowitz),
“In search of the Higgs boson”*