Future Colliders

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Talk at IUT, 14/09/2021

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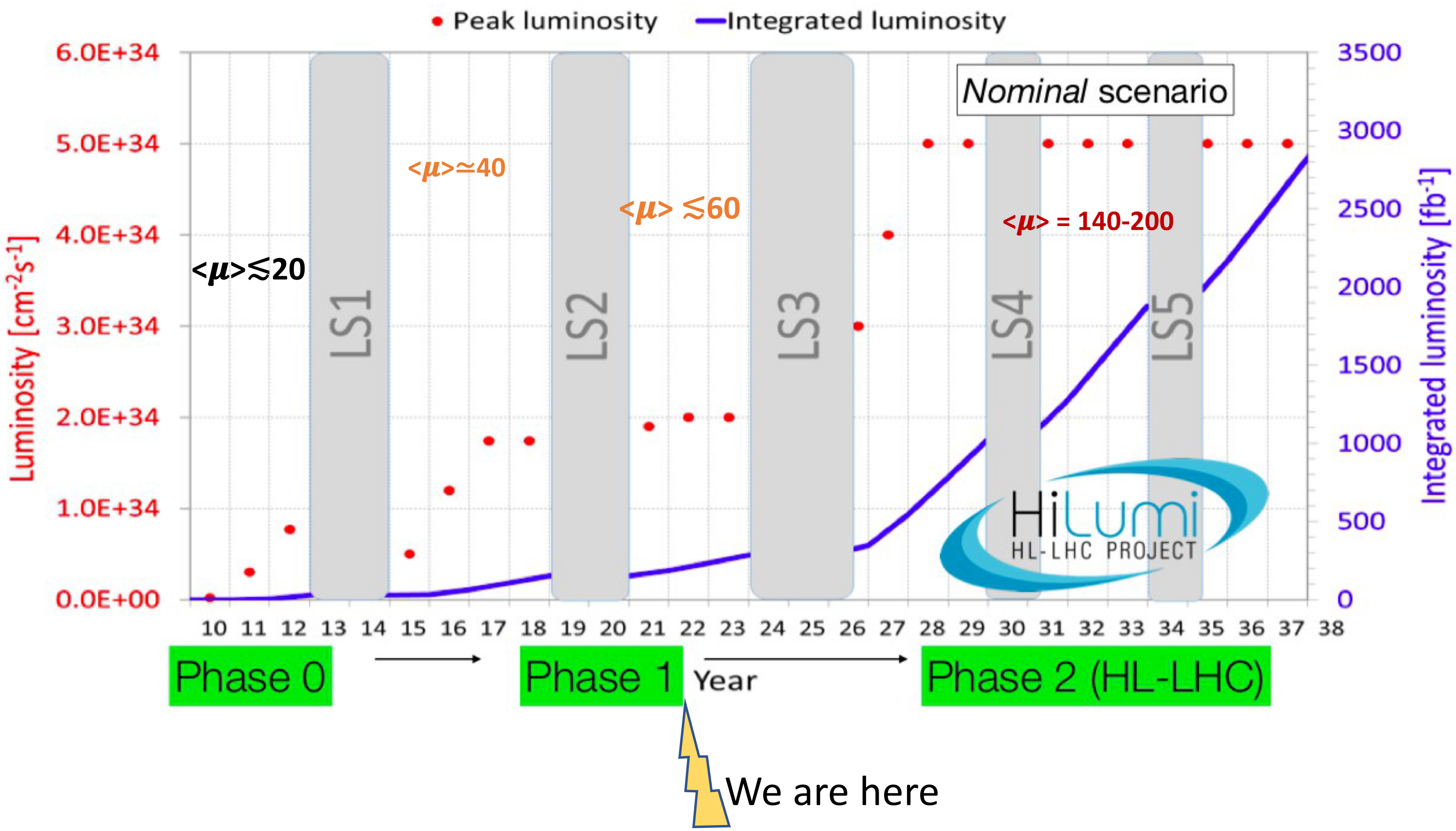
Outline

- **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

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⇒ High Luminosity phase

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

approximately

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

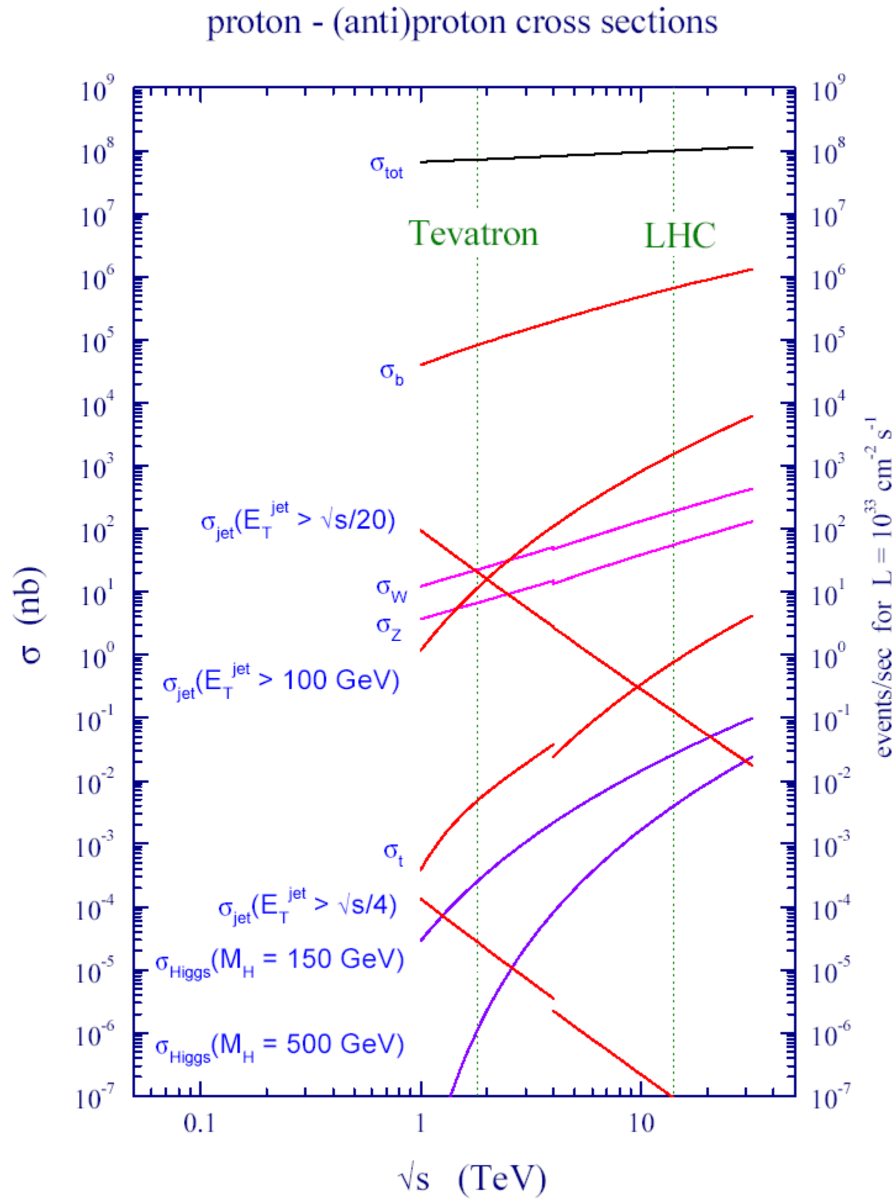
will be produced per second and

- 10 light Higgs

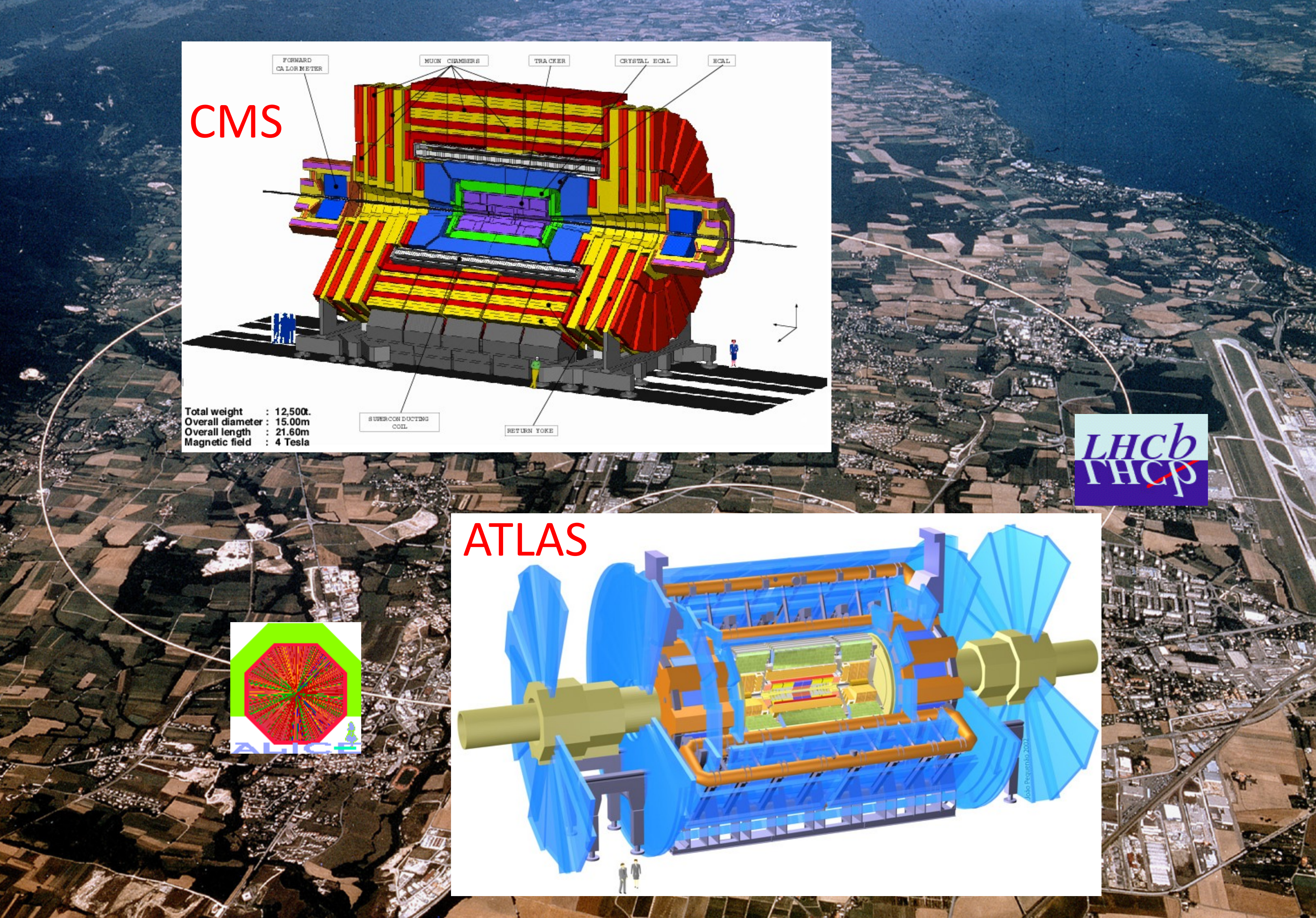
per minute!

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

The problem is to detect the events!

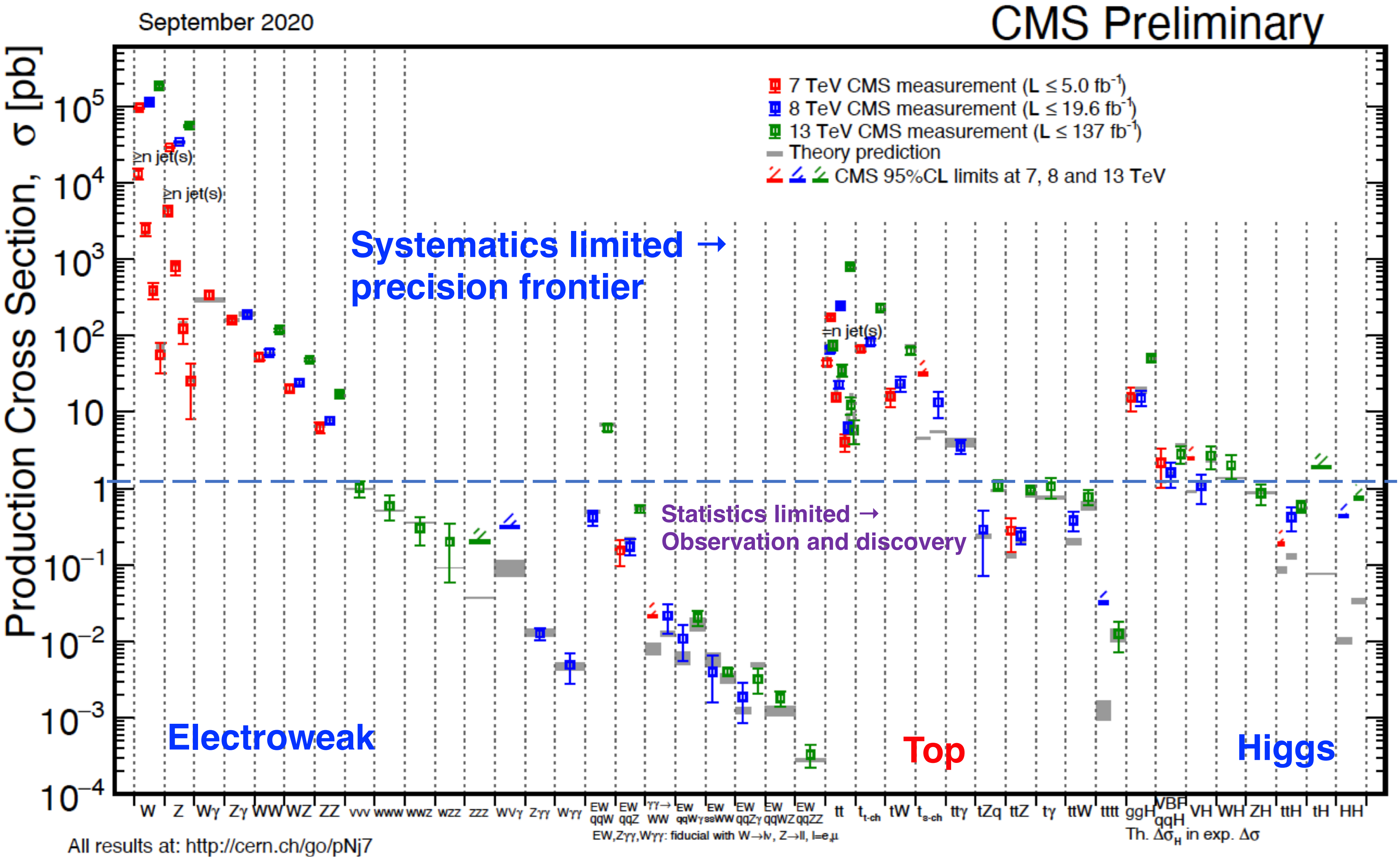


The Large Hadron Collider

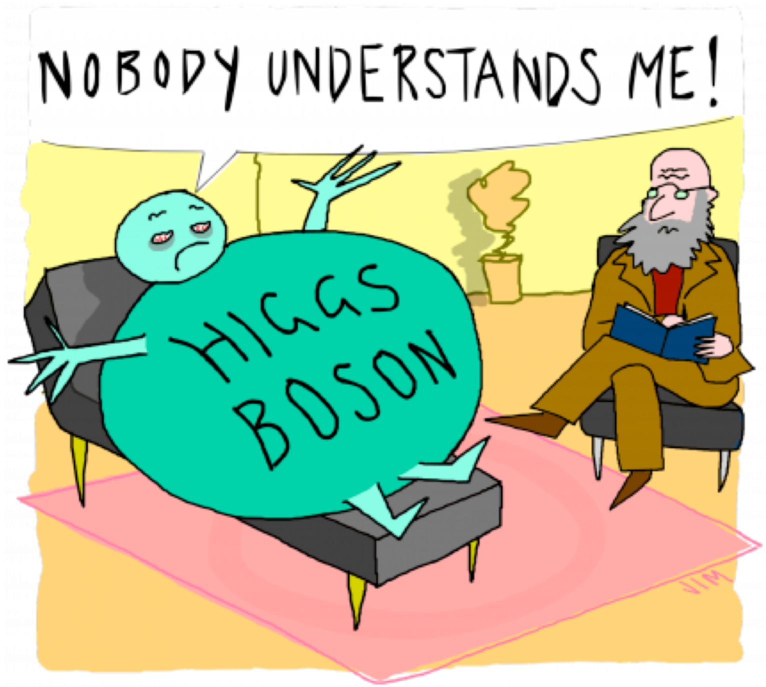


Where we stand:
Status of the Standard Model

CMS SM Results



Higgs Boson

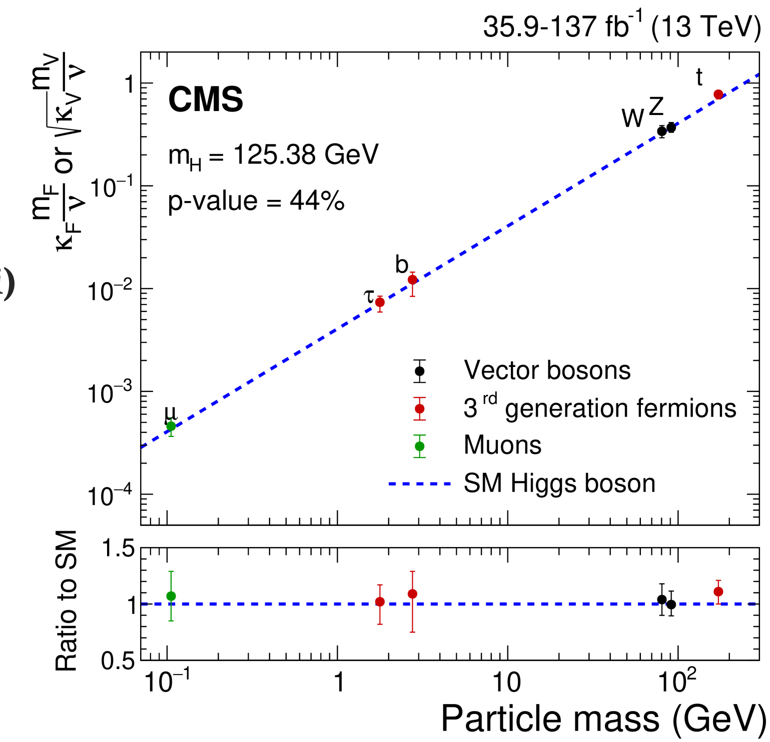


-Precise Measurements of Properties and Couplings for Higgs
-Completing the unknown part of Higgs boson

thewordofthemonth

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=(Higgs coupling to particle i)/(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:

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

Higgs - τ
Summer 2017

Higgs - b
Summer 2018

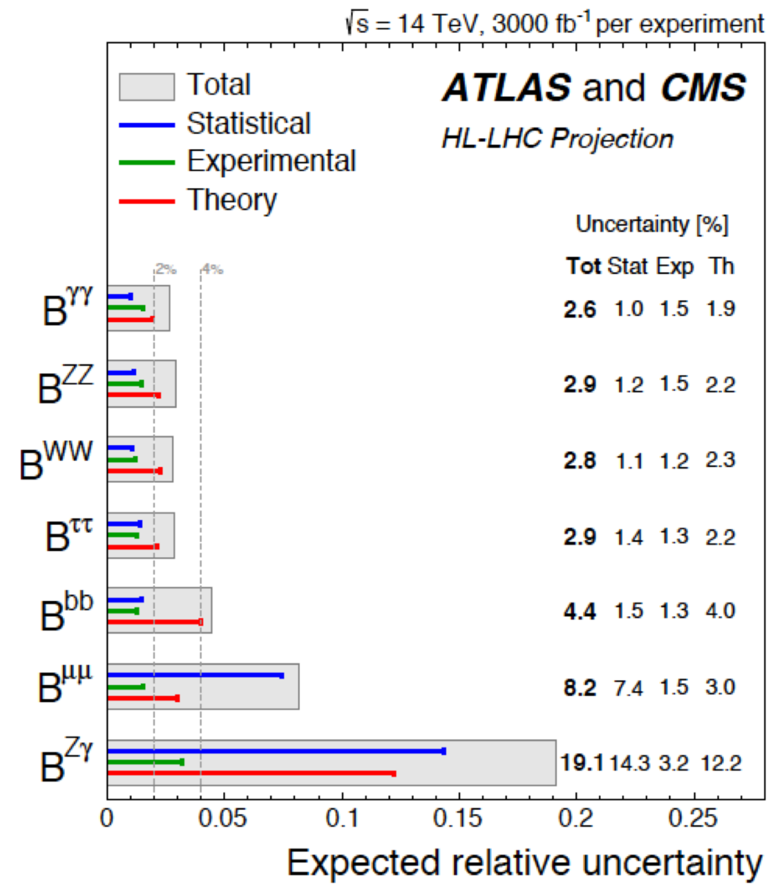
Higgs - top
Spring 2018

Higgs-μ
Summer 2020

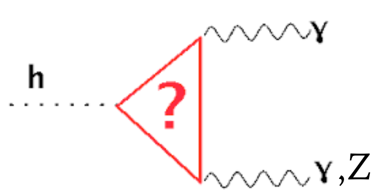
Err. 40%

CMS-PAS-HIG-19-006

Higgs production and decay at HL-LHC



Lots of theoretical work needed!



CERN-LPCC-2018-04

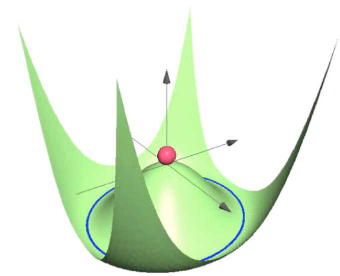
BR H→μμ and **BR H→Zγ** statistically limited

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

Need a future collider!

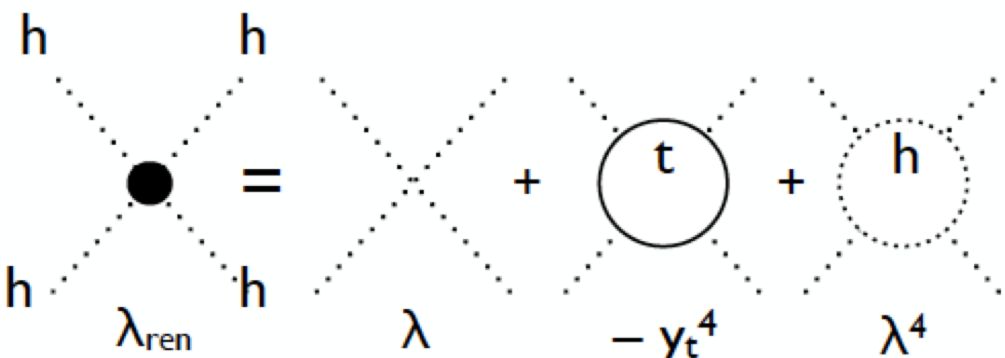
Higgs self coupling, Top Mass at HL-LHC

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

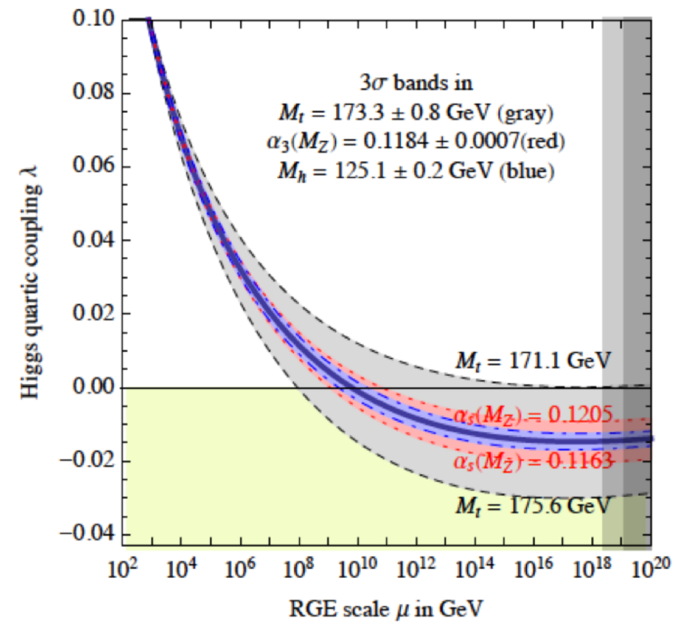


Giudice et al

Quantum fluctuations of Higgs, top, …



$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a\, m_H^4 - b\, m_t^4$$



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

CMS-PAS-FTR-16-006

HL-LHC: $\delta m_{top} \sim 200$ MeV

Need a future collider!

Indirect probes for Higgs self couplings

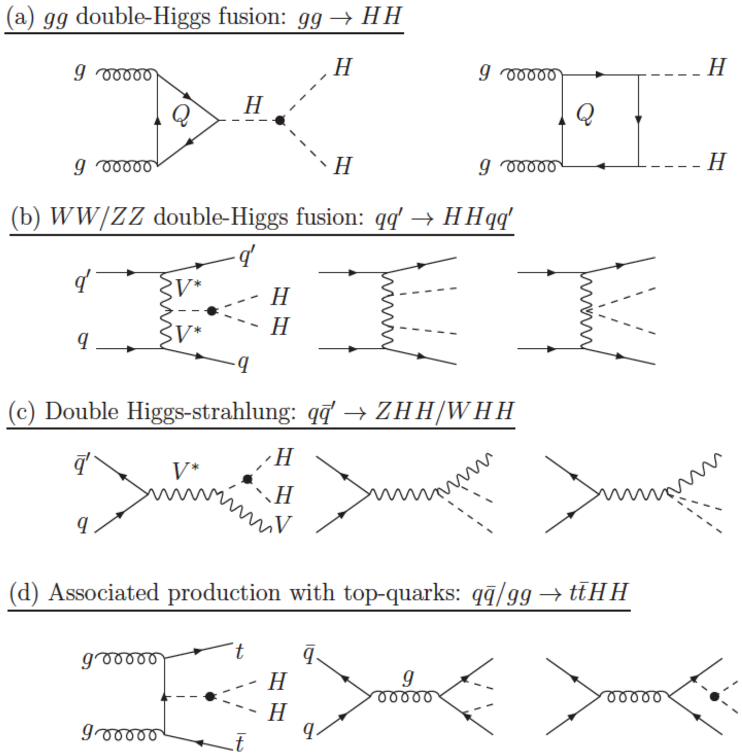
- Unitarity, HH→HH, Re $(a_0)<1/2$: $|k_\lambda| < 6.5$ $\quad k_\lambda = \lambda / \lambda_{SM}$

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

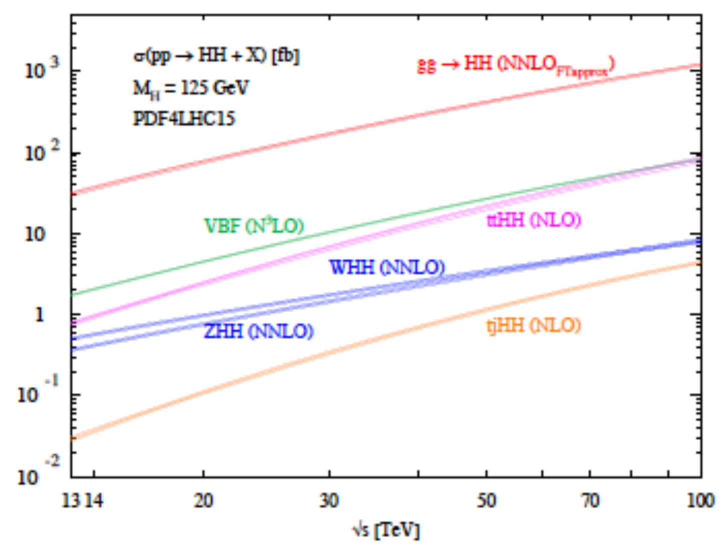
- Higgs Decay to ZZ and WW:

$+ \ldots \qquad \lambda/\lambda_{SM} > -14.3$

HH production at the LHC



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

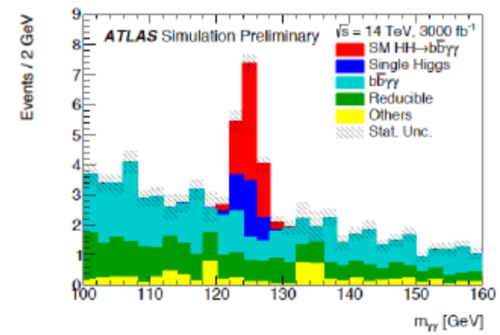


$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05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

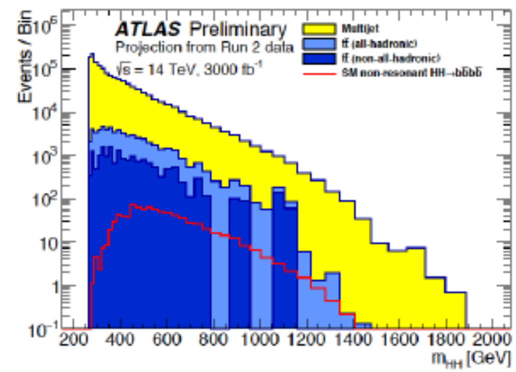
arXiv:1212.5581

HH search at the HL-LHC

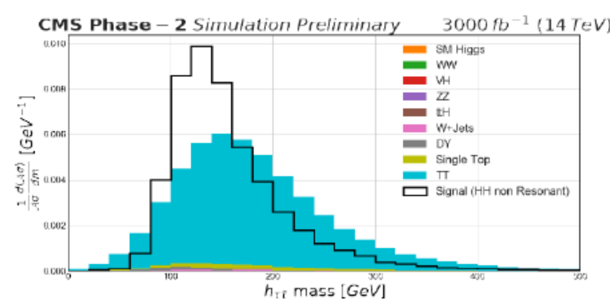
- **HH→bbγγ:**
  - Small BR: 291 events with 3ab $^{-1}$
  - Low bkg
  - Photon resolution critical



- **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



arXiv:1902.00134

Results of HH study

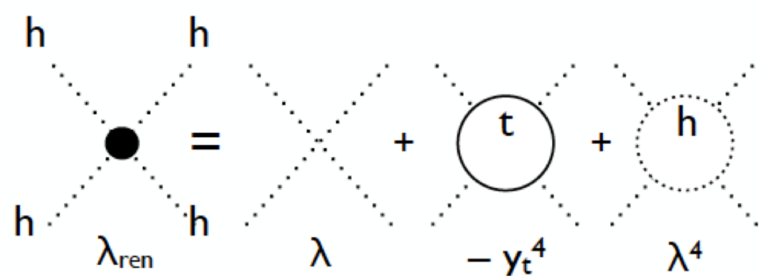
Expected **significance** of HH production with(without) systematics at HL-LHC

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

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	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?

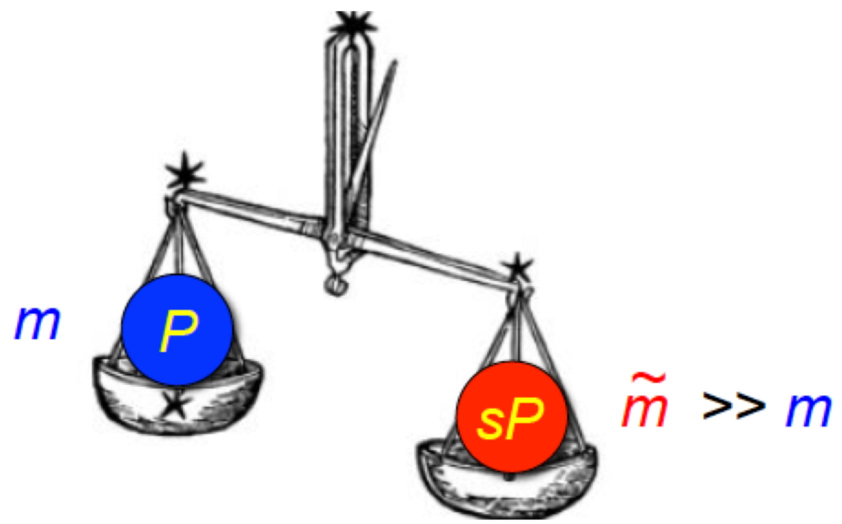
- Why 3 generations of fermions ?
- What is the origin of neutrino masses and oscillations ?
- What is the composition of dark matter ?
- What is the origin of the matter-antimatter asymmetry in the Universe?
- Why is gravity so weak ?
- Why is the Higgs boson so light ?
  so-called "naturalness" or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

New Physics ? SUSY?

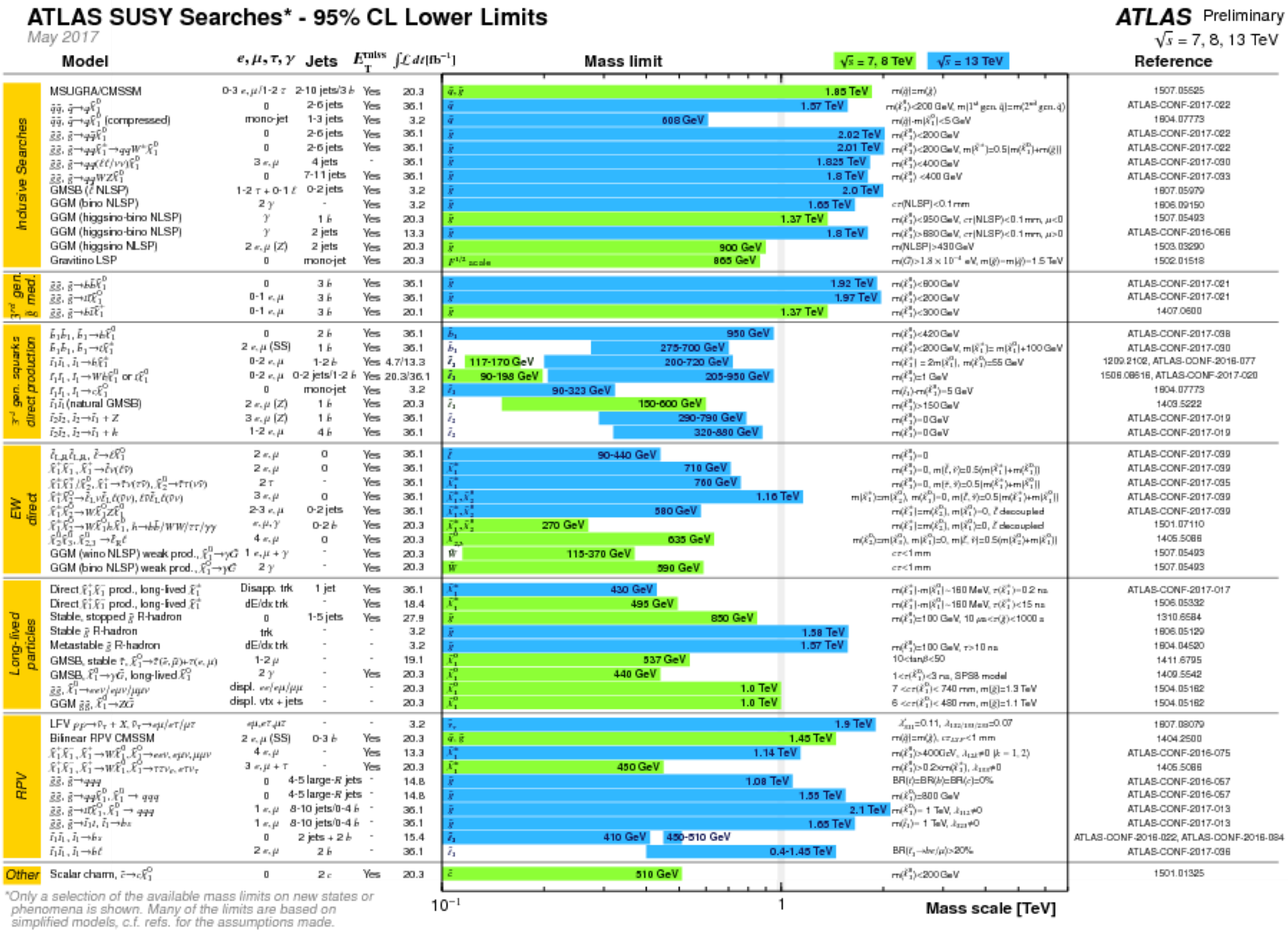
Symmetry between fermions and bosons
For each particle p with spin s, there exists a SUSY partner with spin s-1/2.

- 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



“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

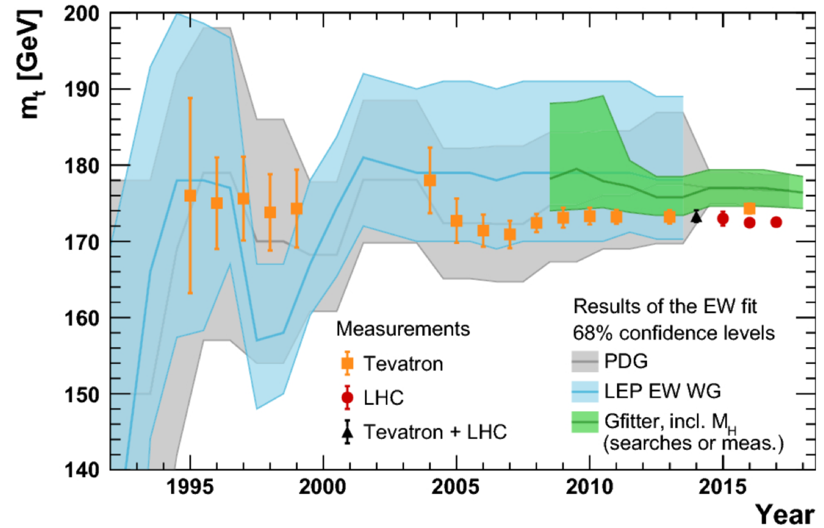
Top quark

1990-1994: Mass predicted from quantum loops

m_{top}(pred.) = 178.0 ± 10 GeV

1995: Discovered at the Tevatron (DØ, CDF)

Today: m_{top}(obs.) = 173.23 ± 0.7 GeV



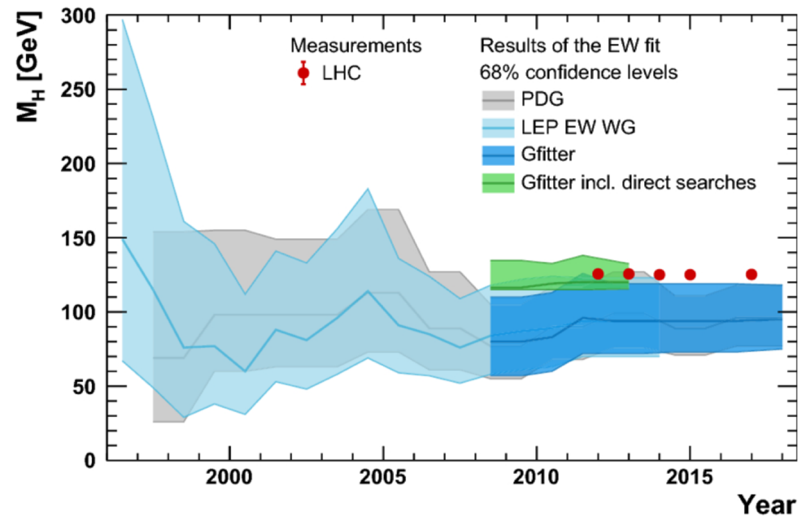
Higgs boson

1996-2011: Mass predicted from quantum loops

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

2012: Discovery at the LHC (ATLAS, CMS)

Today: m_{Higgs}(obs.) = 125.09 ± 0.24 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

-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.

Important precision measurement

-Higgs couplings to 2-4%

-Top quark mass to 200 MeV

-W boson to 10 MeV ?

-Flavour physics measurements

The future machines

A very brief summary

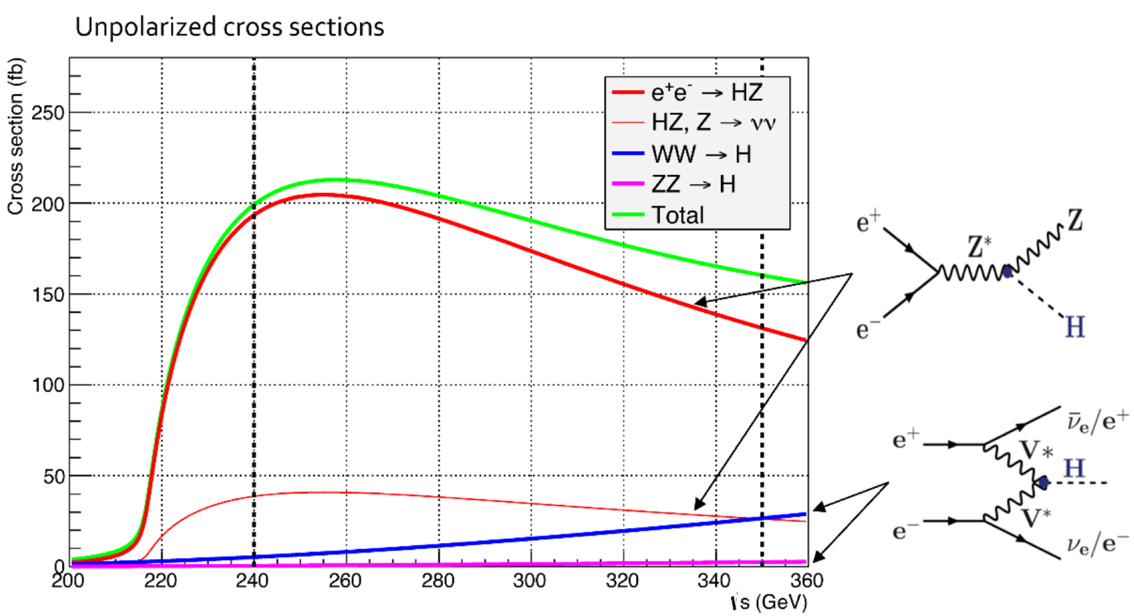
e^+e^- Colliders

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



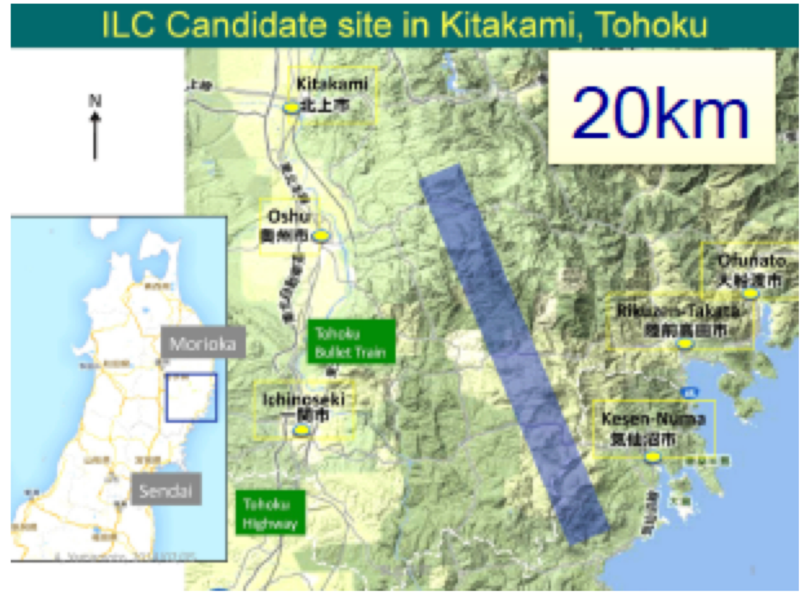
International Linear Collider (ILC)

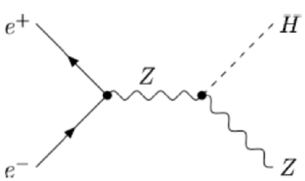
ILC (Japan & Germany):

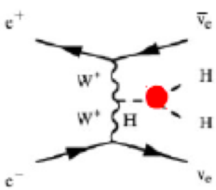
◆ Linear collider with high-gradient superconducting acceleration

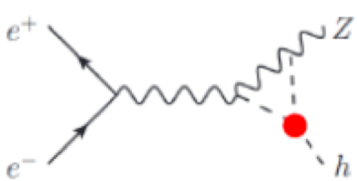
◆ Ultimate: 0.5-1(?) TeV

◆ 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

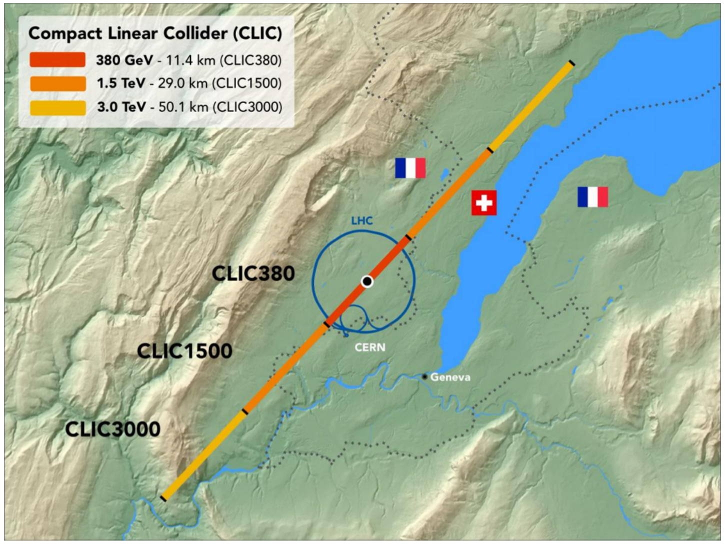
-No design to run at the Z pole

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



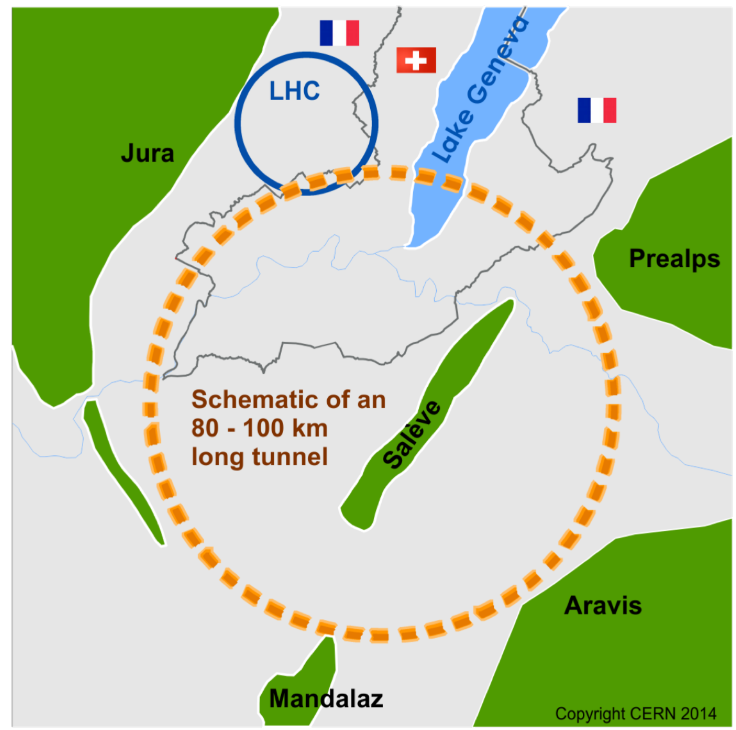
-Can deliver data to only one detector at a time
-No design to run at the Z pole

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 /(Nb3Sn)
12~14T	Nb_3Sn
14~16T	Nb_3Sn

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

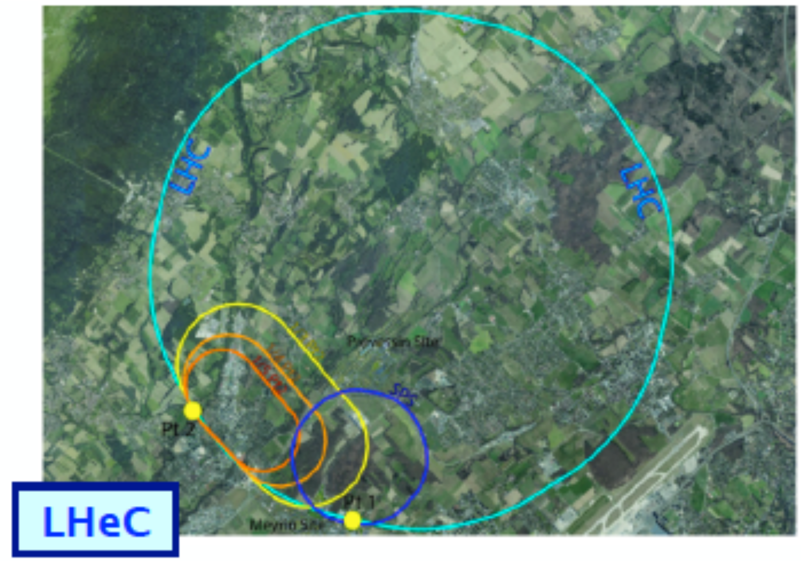
CEPC: multiple candidate sites in China

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± 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



LHeC CDRs, arXiv:1206.2913, arXiv:2007.14491

- **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**
  - **-…**

Lint = 1–2 ab^{-1} (1–2k × HERA!)

Higgs Measurements at HL-LHC andFuture Colliders

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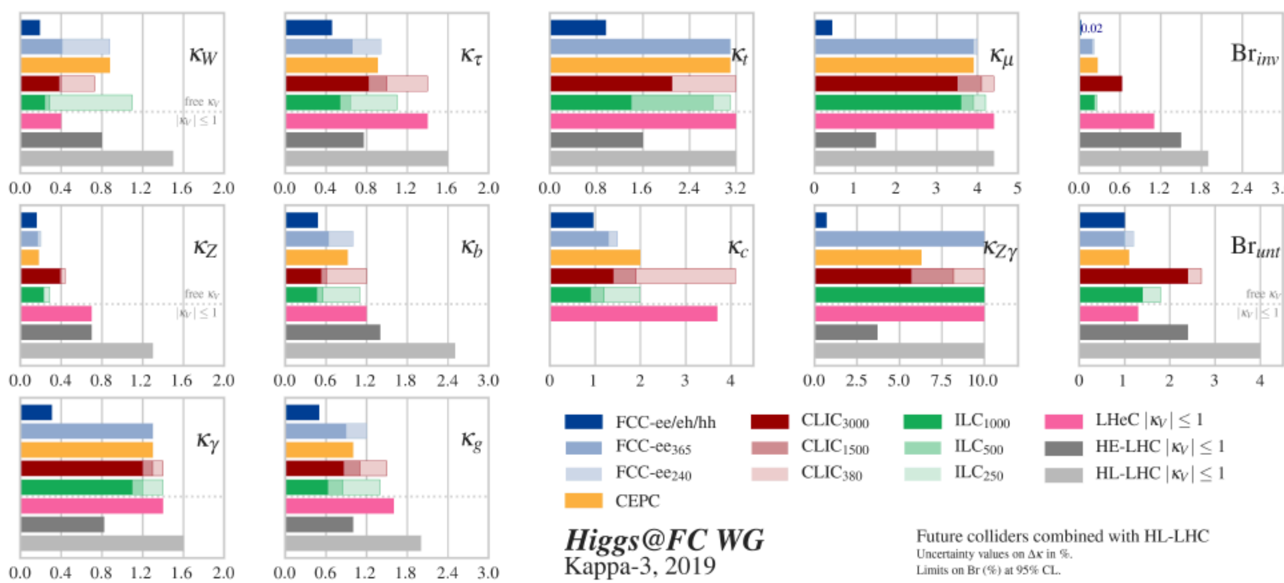
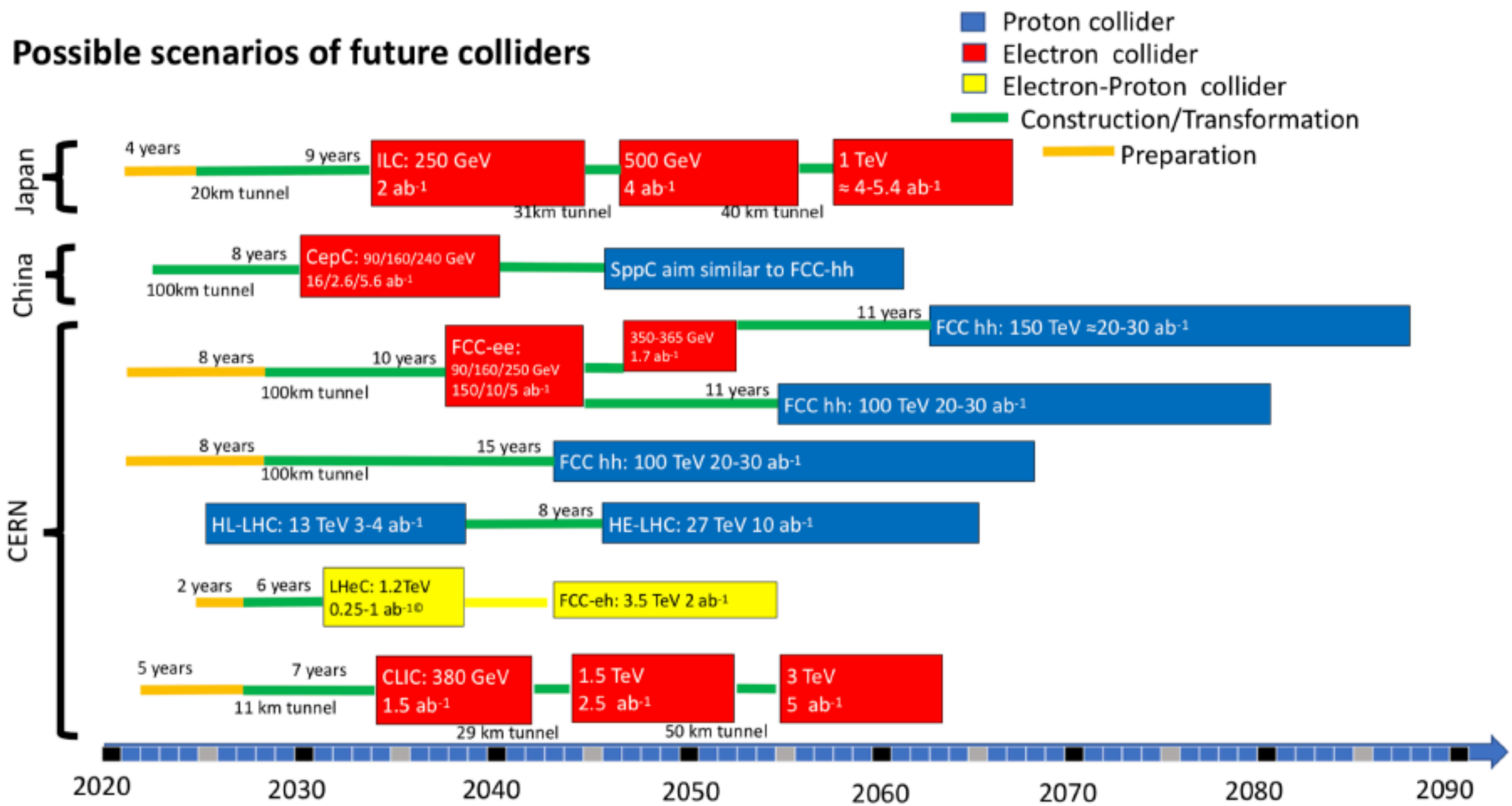
k_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)

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

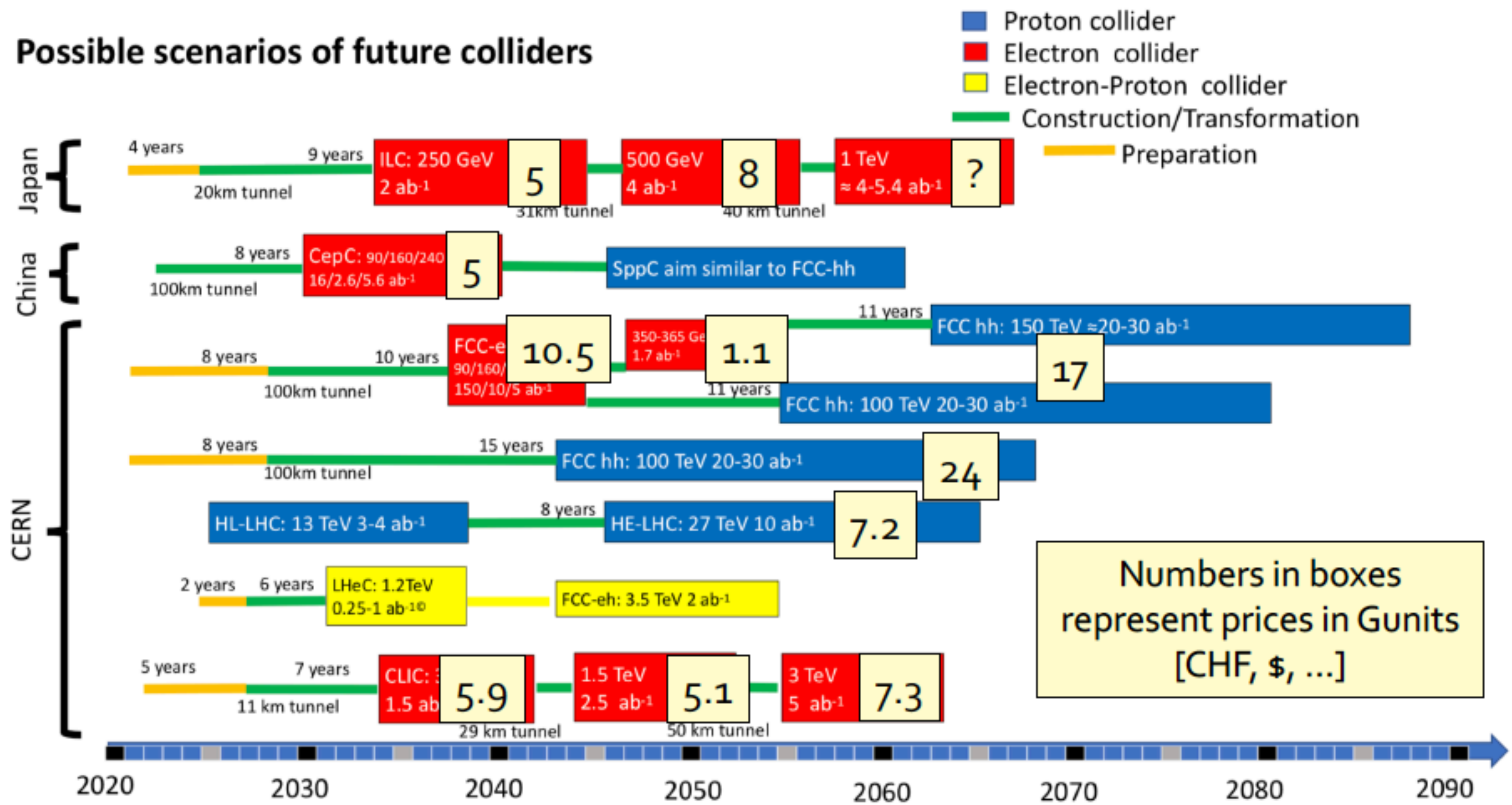


arXiv:1905.03764

Summary of proposed 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

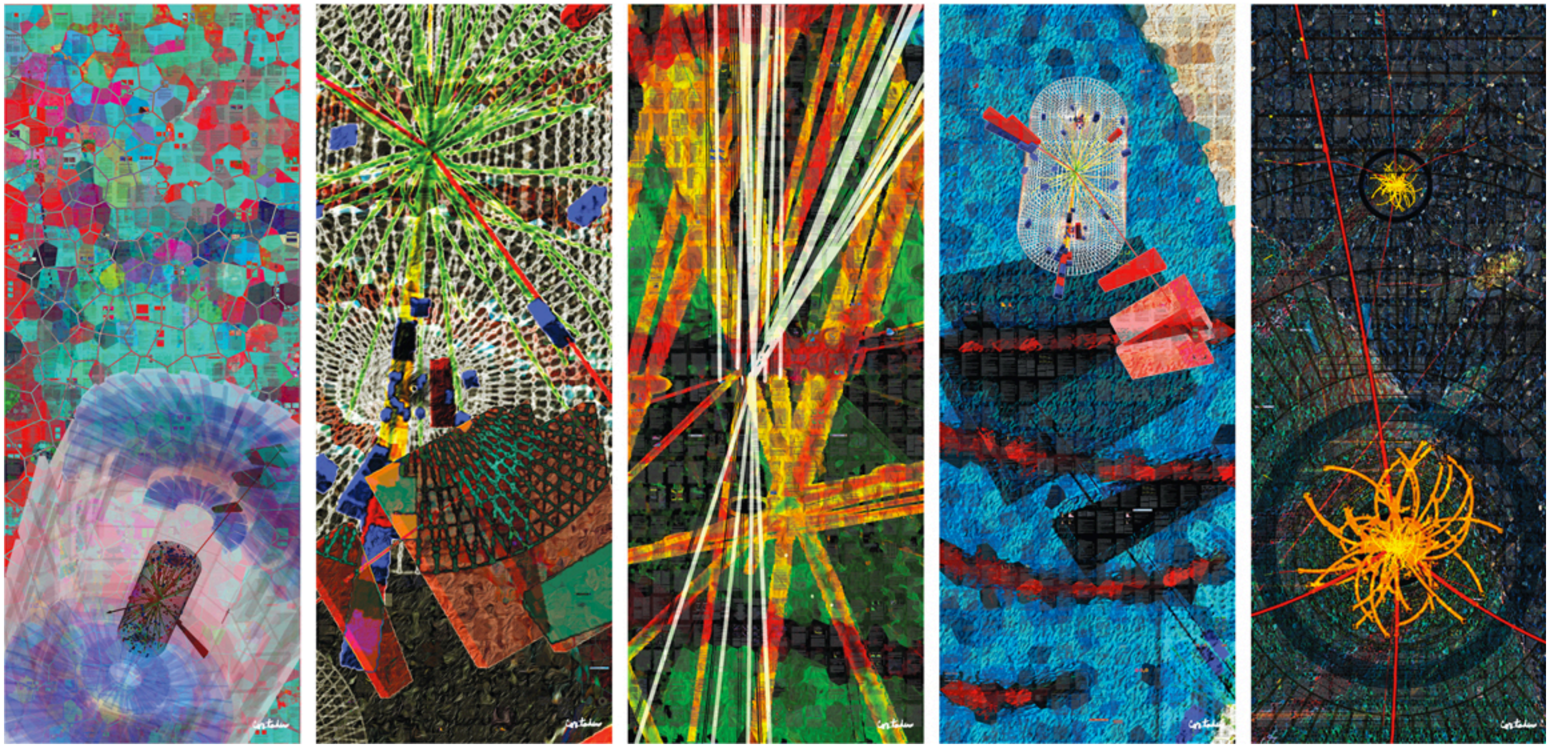
At high(er) masses ➪ Energy Frontier / Precision Frontier
At small(er) couplings ➪ Precision Frontier

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: superiour 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"