Particle physics – where to next ?

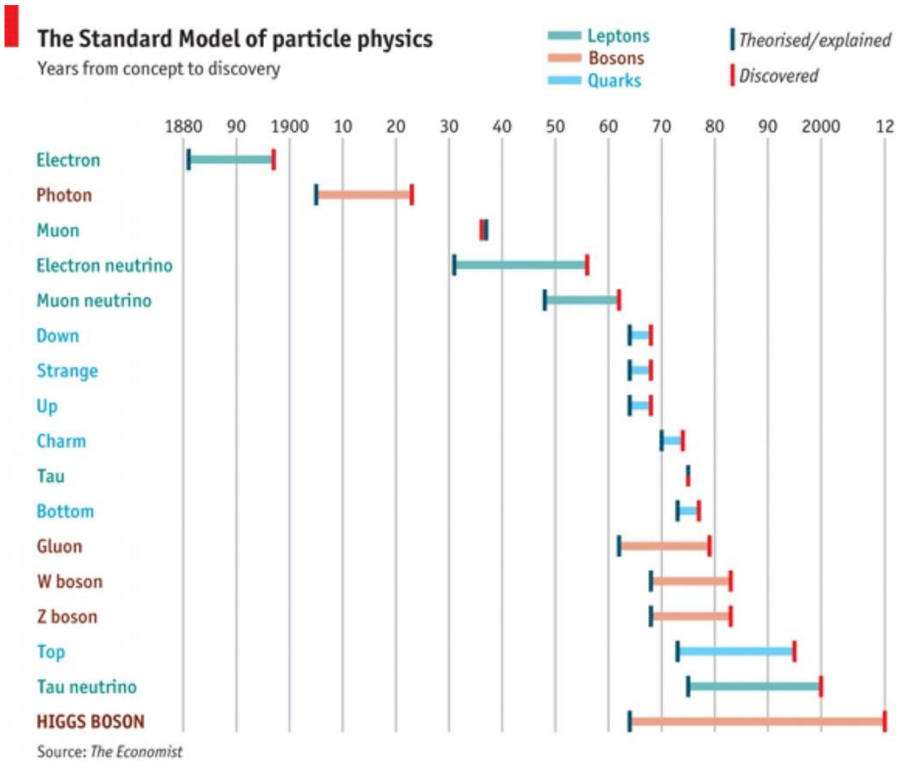
David Milstead

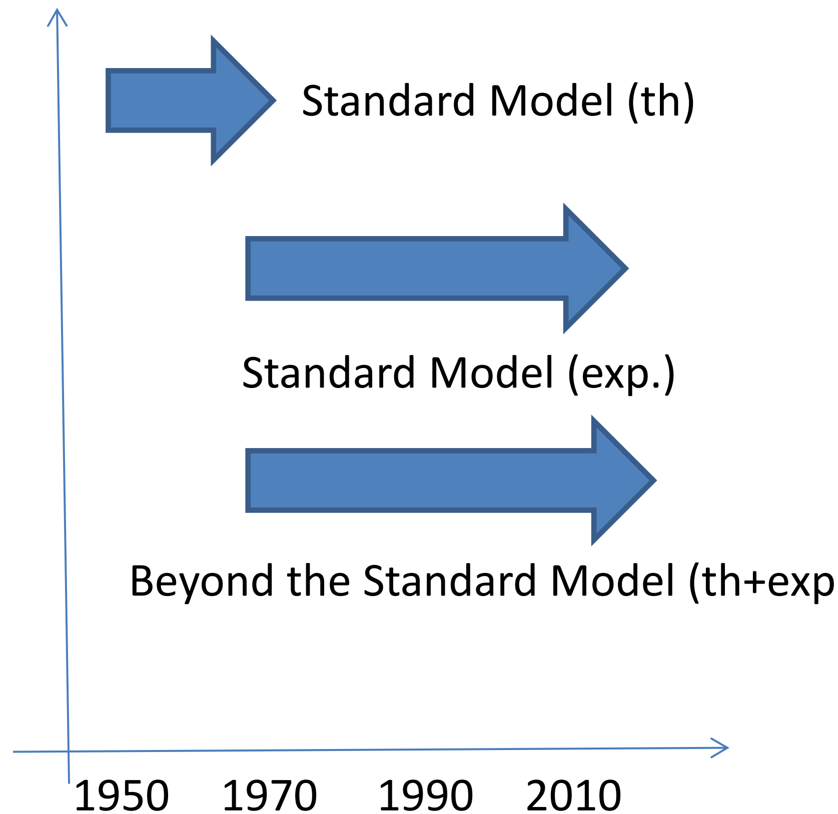
- Where are we ?
- What are we doing now ?
- What can/should we do in the future?
- The European PP Strategy Update

Disclaimer

- *PP is a very broad field.*
- *Focus on the issues surrounding EWSB and new physics*
- *Dark matter plays an important role in collider physics but is not discussed (much) here.*
- *Neutrinos are also largely ignored.*

A potted history of particle physics





Guiding paradigms

(1) SM development (~ 1950-1970)

Theory: gauge symmetries, renormalizability, EW symmetry breaking.

Experiment: Exploratory and guided by theory.

(2) SM validation (~ 1970->2035 ?)

Gradual process as increasing energy reveals more massive particles.

Experiment: Mostly guided by theory.

(3) Beyond-the-Standard Model searches (~ 1970->)

Theory: GUTs, naturalness, supersymmetry etc.

Experiment: Mostly ?? guided by theory (naturalness).

(2) is alive (EWSB+top poorly measured) but the end is coming.

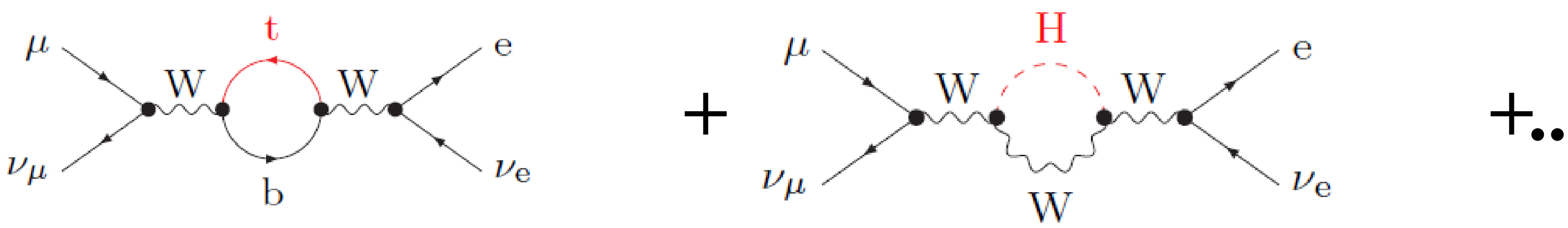
(3) is the present + future. What should our strategy be ?

Collider+non-collider + theory=beautiful SM physics

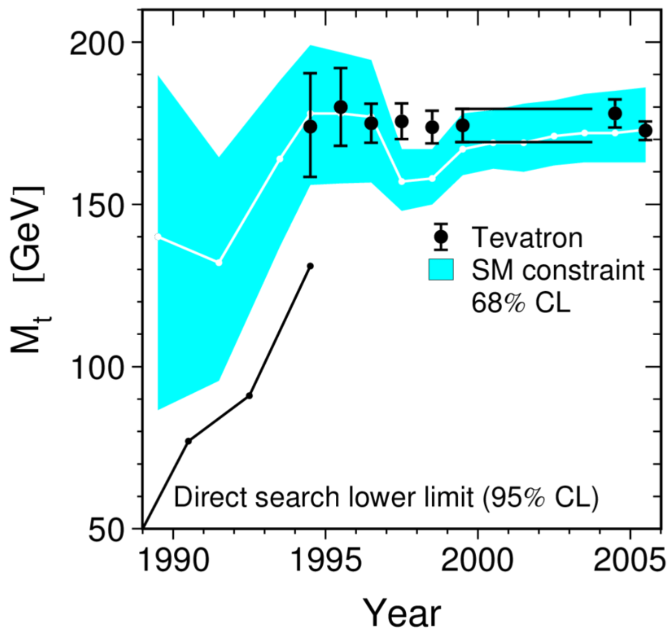
Precision muon lifetime : $\tau_\mu = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s

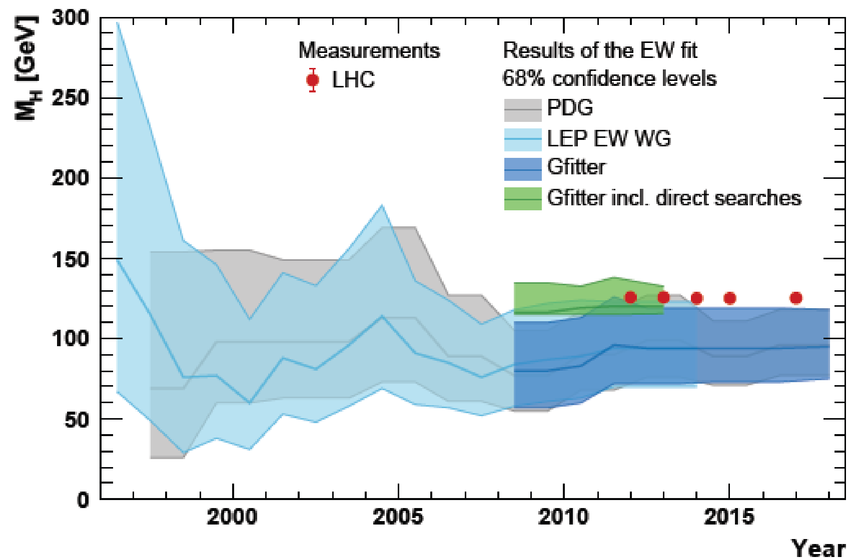
+ collider measurements (eg $M_W = 80.385 \pm 0.015$ GeV)

$\Rightarrow$ unobserved particle masses.



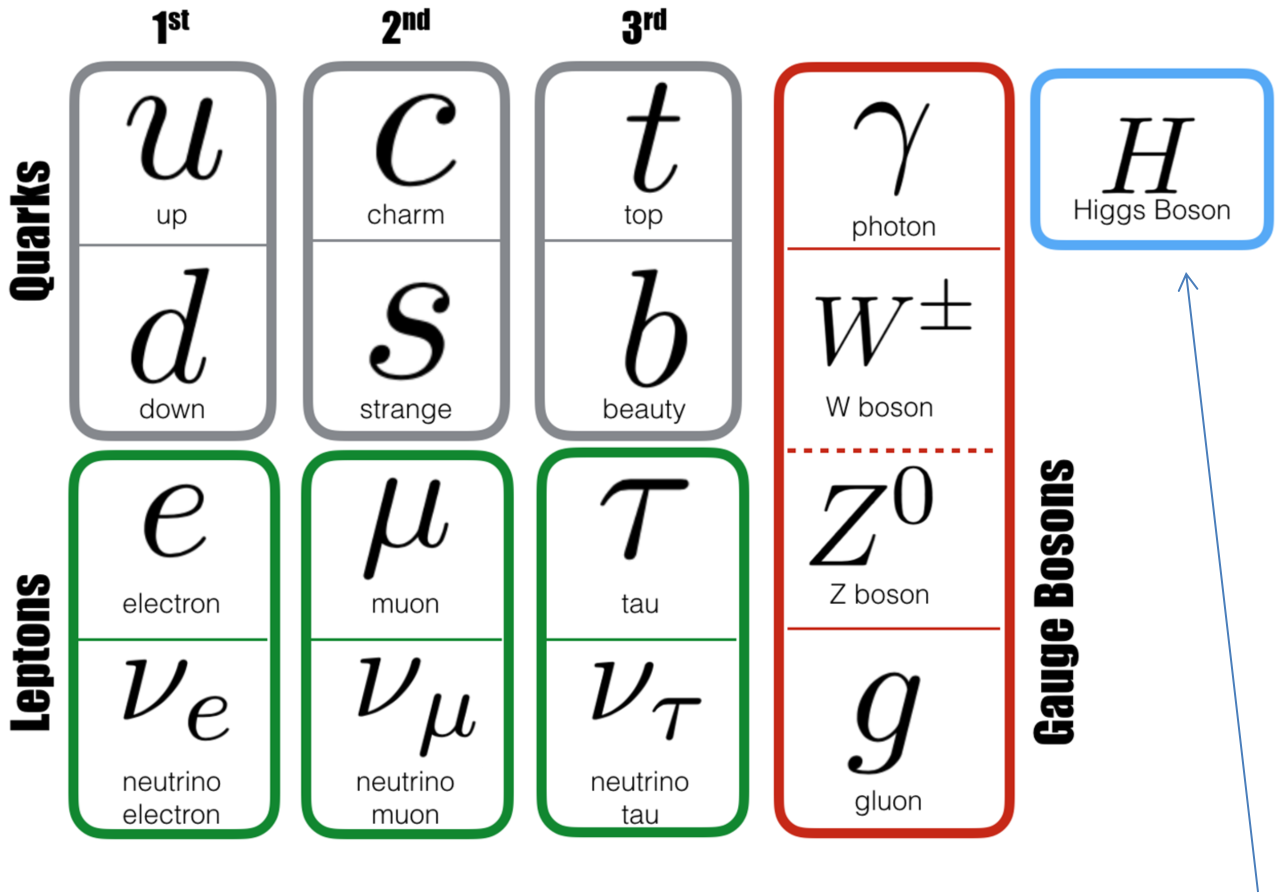
$\Rightarrow$ Predict top quark and Higgs boson masses ahead of discovery.





"No lose" experiments - SM particle discovery or new physics.

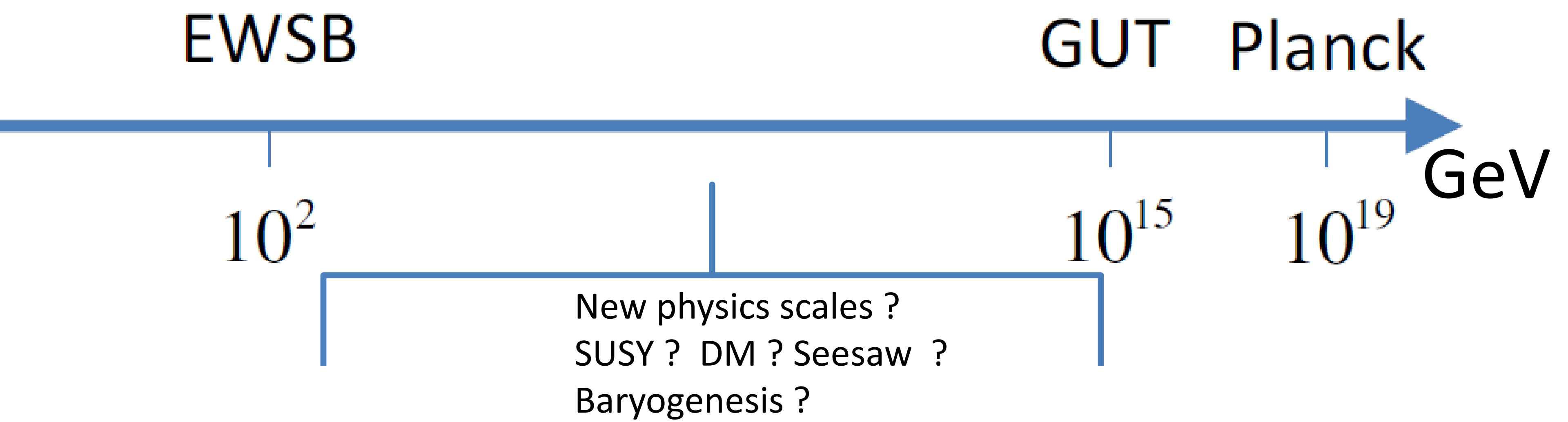
The Standard Model



Fundamental scalar !
We've never seen one of those before
And an entirely new field!

"Priority" issues for PP

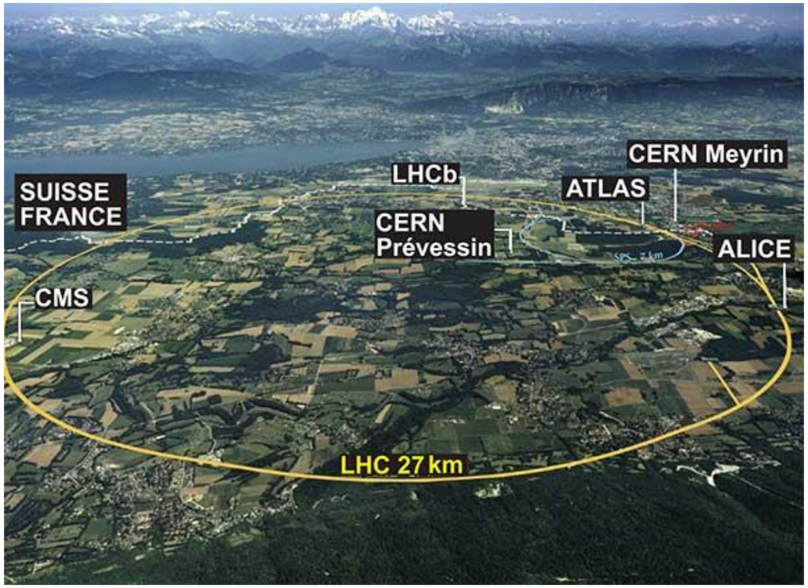
- SM
  - EWSB is poorly explored experimentally.
- Where is the new physics energy scale ?
  - Dark matter, naturalness, SUSY -> TeV scale ?

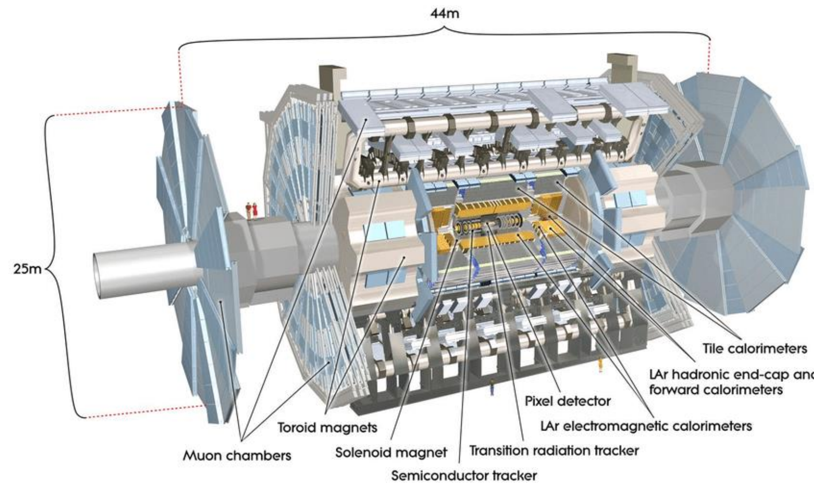


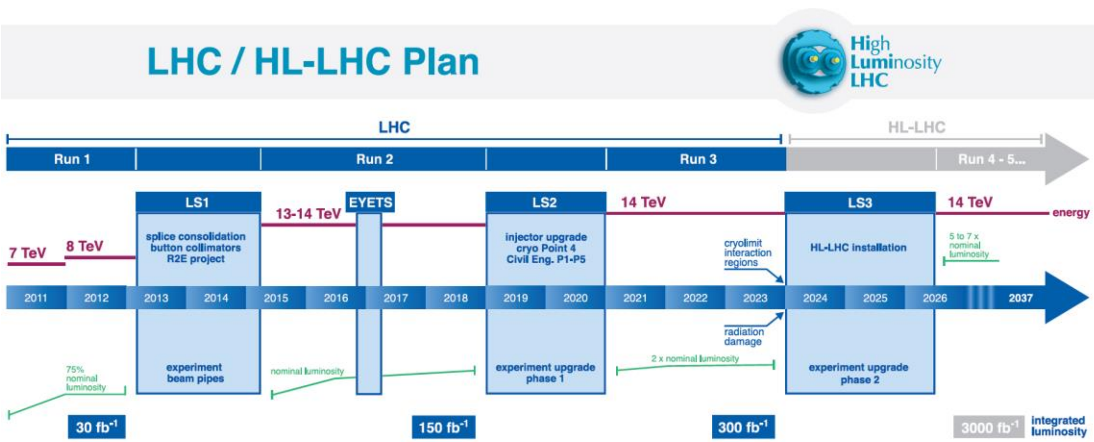
- Explore the energy and precision frontiers

The energy frontier

Main collider work horse – Large Hadron Collider







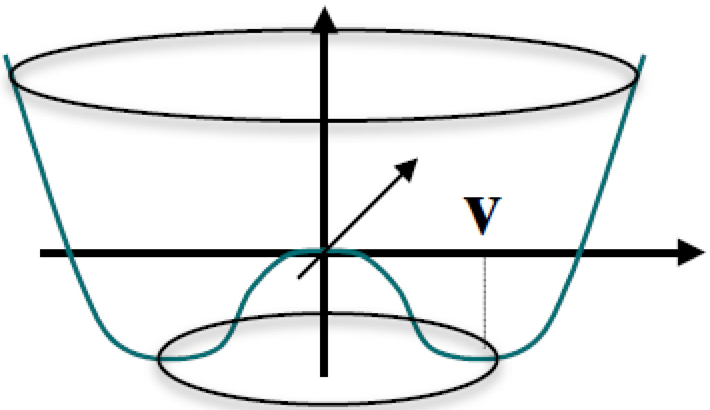
Luminosity and detector upgrades.

Taken ~% of total luminosity

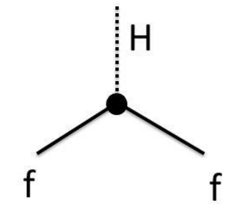
Built to find the Higgs

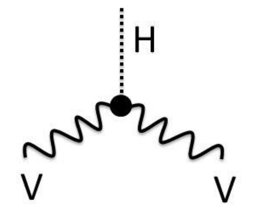
EWSB and the Higgs

V(H)



Couplings to massive particles



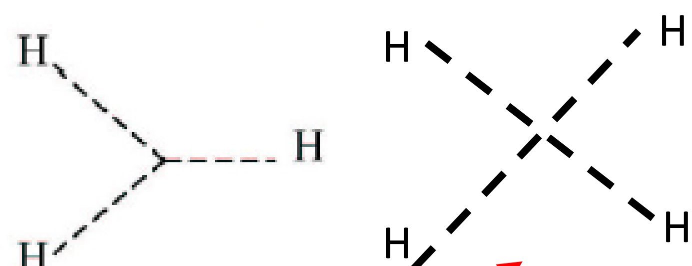


$$g_{Hf\bar{f}} = \frac{m_f}{v} \qquad g_{HVV} = \frac{2m_V^2}{v}$$

$$V(h) = \frac{M_H^2}{2} h^2 + 4\lambda v h^3 + \lambda h^4$$

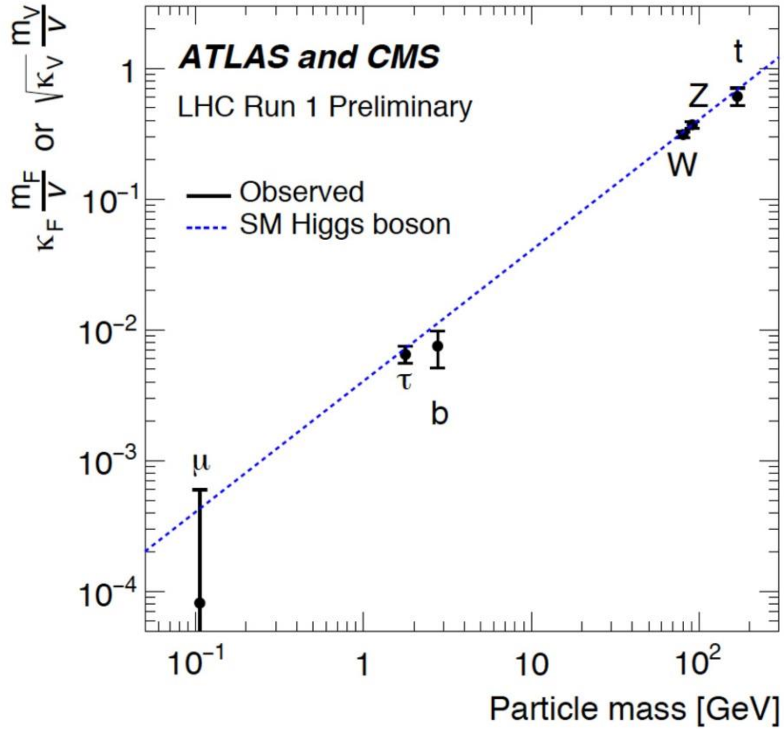
$$v^2 = -\frac{\mu^2}{2\lambda} = \left(\sqrt{2}G_F\right)^2 = (246\ \text{GeV})^2$$

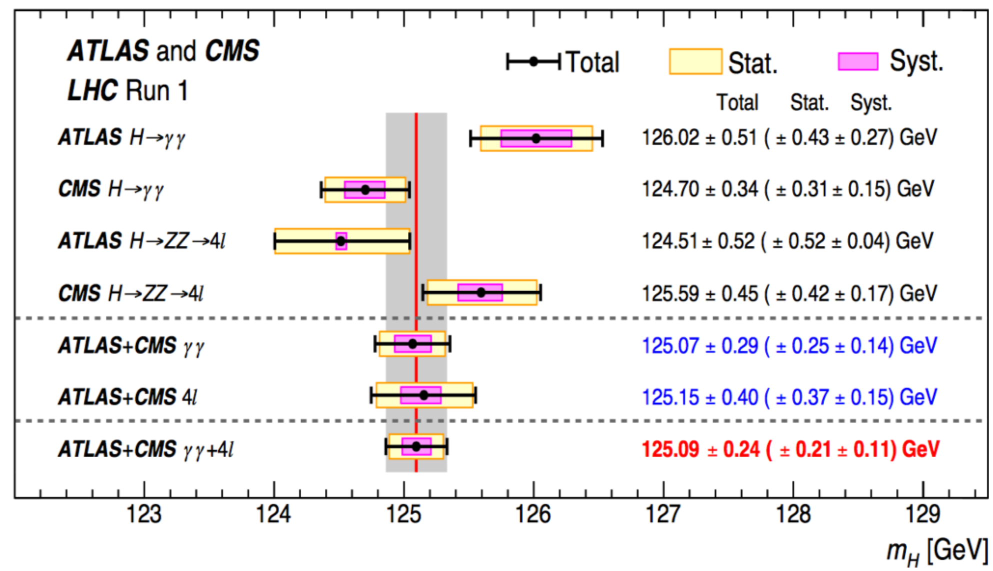
$$M_H = 126\ \text{GeV} \Rightarrow \lambda = 0.13$$



Self-couplings

The LHC Higgs





Looks and smells like a SM Higgs with ~125 GeV mass
Imprecise measurements.
Model-dependent (no absolute normalisation)
Missing couplings (eg self-interactions).

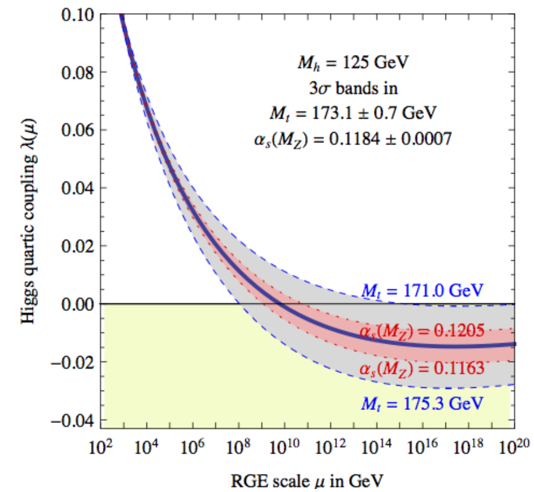
Vacuum (meta)-stability

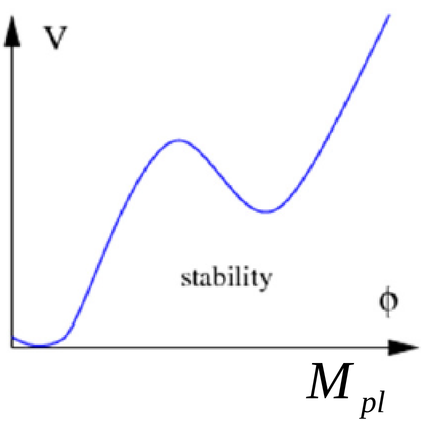
$$V(h) = \frac{M_H^2}{2} h^2 + 4\lambda v h^3 + \lambda h^4$$

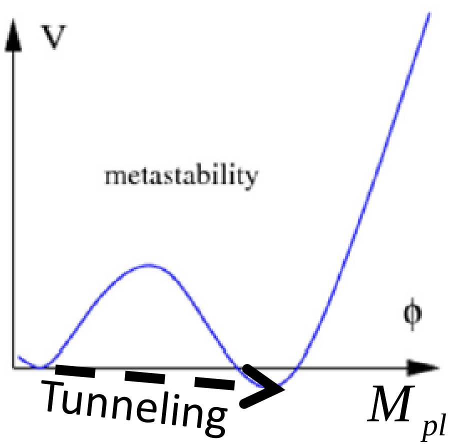
$\Rightarrow$ Large values of the Higgs field: $V(h) \sim \lambda(h) h^4$

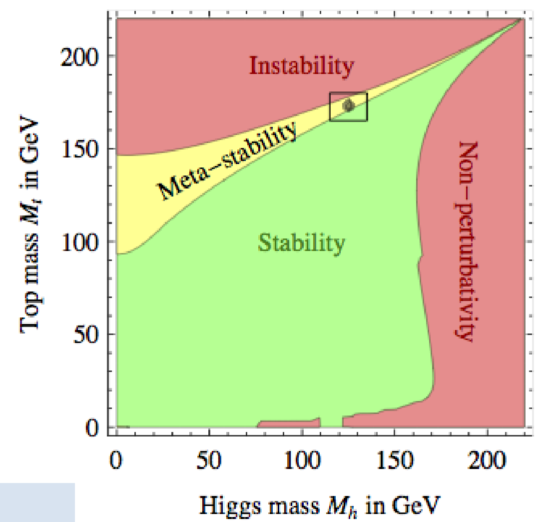
Renormalisation: $\lambda(h)$ runs due to top mass.

$\lambda(h)$ can turn negative









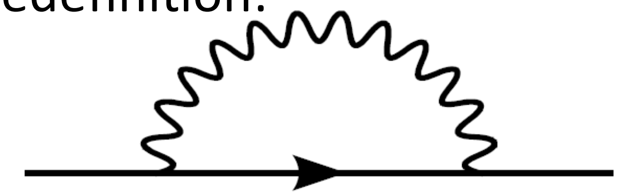
$P_{tunnel} \propto e^{-\frac{1}{\lambda}}$ $\Rightarrow$ no need to panic $\tau_{\text{vacuum}} > \tau_{\text{universe}}$

Interesting that the SM Higgs sits on edge of stability.

Naturalness and Higgs fine-tuning

Renormalize loop divergences away via mass redefinition:

$$m_{phys} = m_0 + \delta m_e \qquad \left[\delta m_e = \int_0^{\Lambda} f(k)dk \right]$$



$\equiv$ "new theory of short distance physics" + SM "long distance physics"

Λ= arbirary cut-off scale for SM integral.

Electron: $m_e \sim m_{e0} + \delta m_e, \quad \delta m_e \sim \frac{2\alpha}{\pi} \ln \frac{\Lambda_{pl}}{m_e} \sim 0.25 m_e$

Higgs: $m_H^2 \sim m_{0H}^2 + \delta m_H^2$

$$(100)^2 \sim m_0^2 + \mathcal{O}(1)\Lambda_{pl}^2 \sim \left(10^{19}\right)^2 - \left(10^{19}\right)^2$$

δm_H (long-distance) and m_{0H} (short-distance) should be decoupled !

Such fine tuning is implausible/unlikely !

The SM Higgs is unnatural!

$\Rightarrow$ New physics (SUSY,ED) at **Λ** ~ TeV to suppress fine-tuning.

The fine tuning problem

 $-$  $= 1\ \text{Å}^2$

Canada 9,984,670 km^2 $-$ United States 9,826,675 km^2 $=$ 157,995 km^2

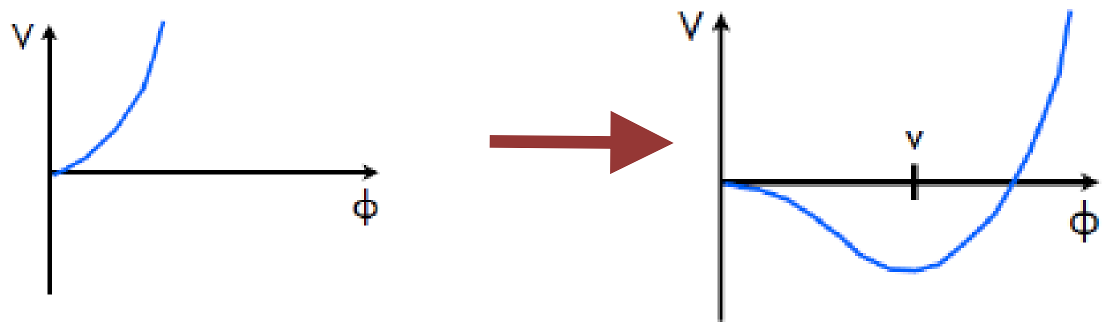
tuning of the Higgs mass would correspond to
the surface area of Canada and the United States
differing by approximately the size of an atom!

In order to protect the Higgs mass
from huge quantum corrections and to avoid finetuning,
we expect New Physics at or below the TeV scale
not far above the mass of the Higgs

From unbroken to broken symmetry

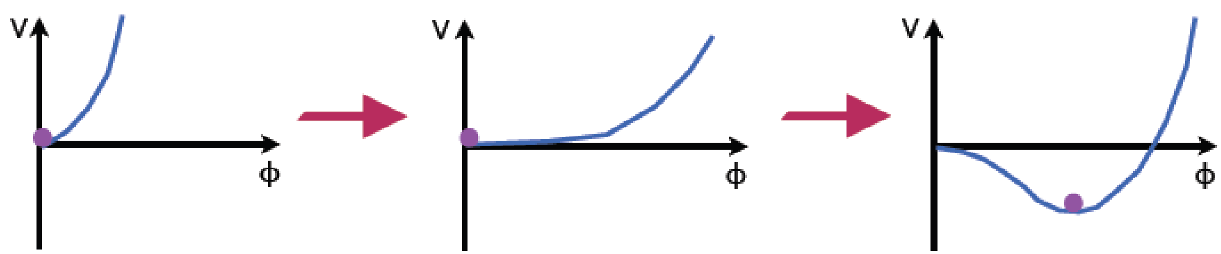
No broken symmetry in the early universe

$T \gg 100$ GeV $\qquad\qquad T = 0$

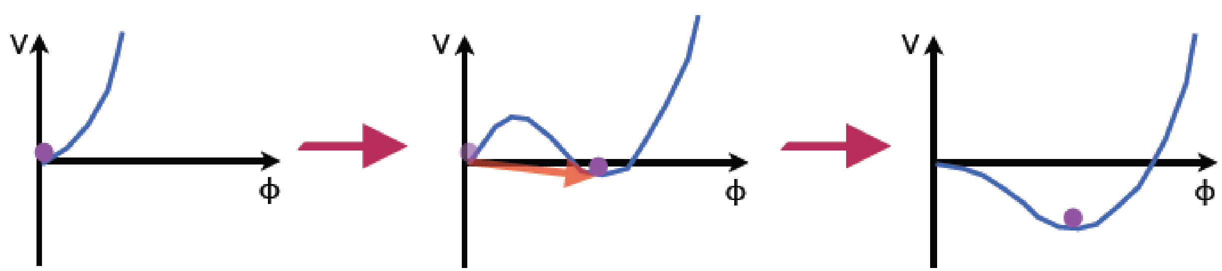


Phase transition

Second order



First order



Why is the phase transition important ?

SM has ingredients for baryogenesis :

baryon number and CP violation

Electroweak baryogenesis if first order phase transition.

$\Rightarrow$ Higgs mass < 70 GeV or new physics (eg SUSY).

$\Rightarrow$ Observable via anomalous cubic and quartic self-couplings.

$\Rightarrow$ Use the Higgs to explain baryogenesis !

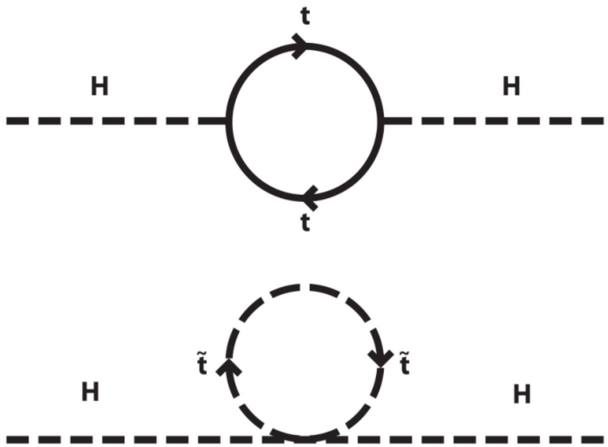
EWSB is the key issue for the energy frontier

- Experiment
  - The only (apparently) fundamental scalar ever observed.
  - Properties must be measured to high precision (mass, couplins to SM inc. self-couplings)

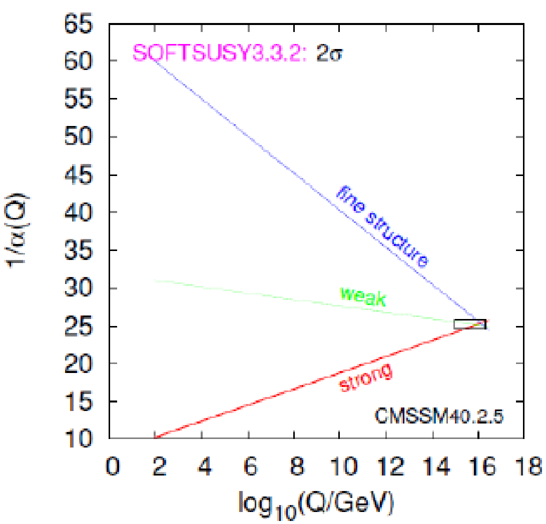
- Theory
  - Naturalness
  - Vacuum stability
  - Electroweak phase transition (baryogenesis)

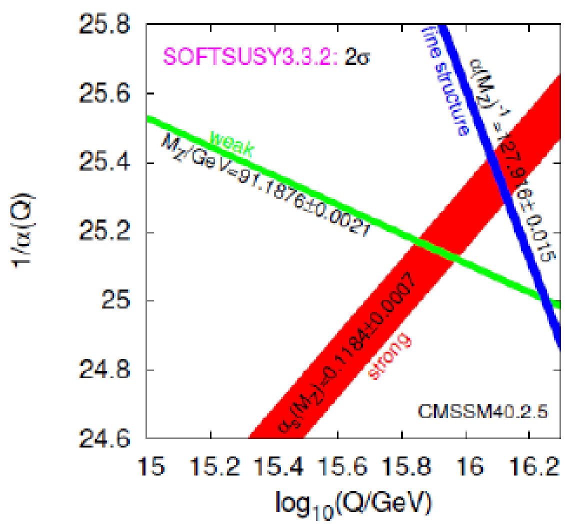
Major open questions about the Higgs can be posed.
Do we know the answers ?

Supersymmetry to the rescue ?



Stop and top cancel to suppress fine-tuning for SUSY ~TeV mass.

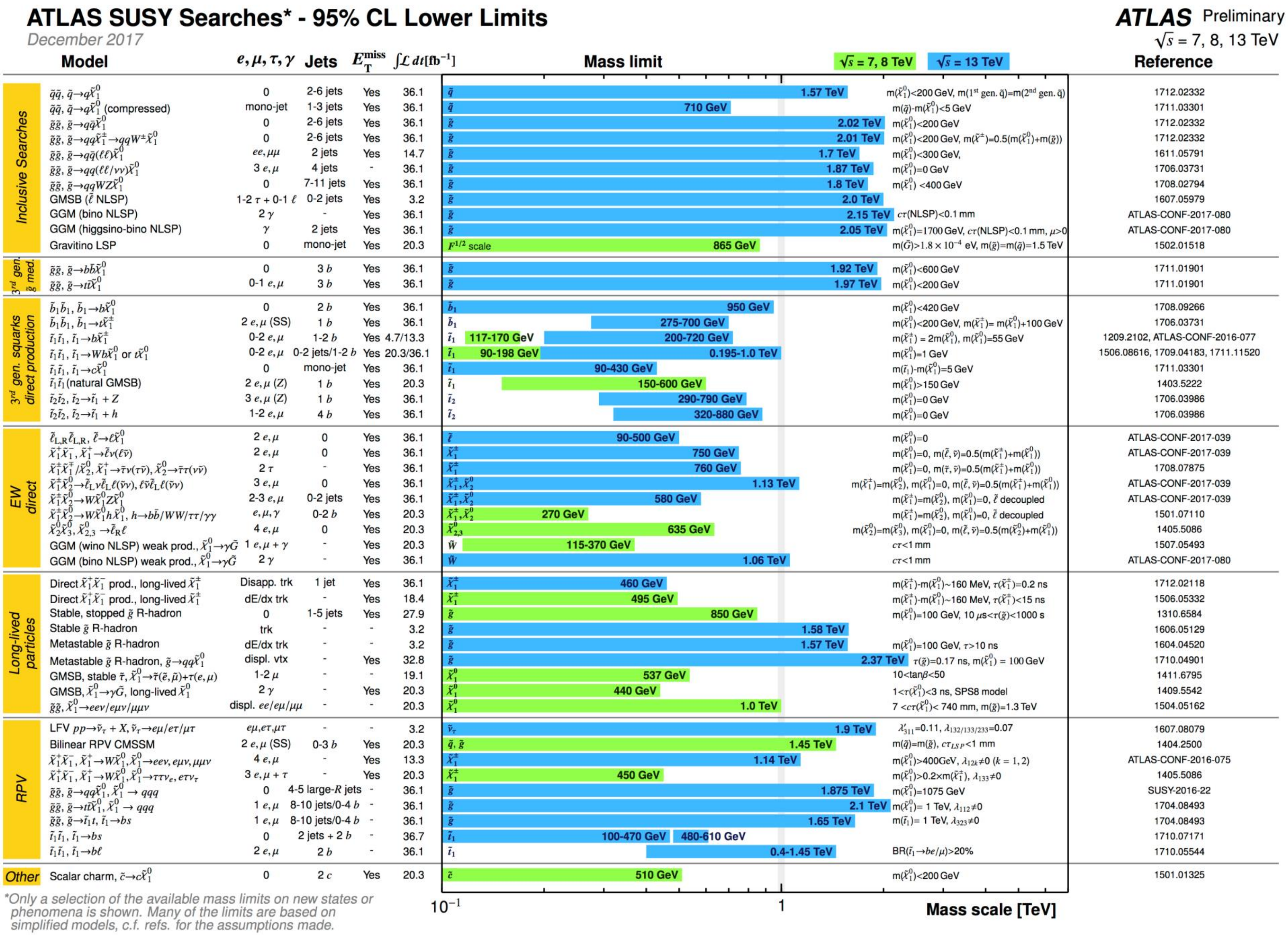




+ Approximate unification of gauge couplings

+ First order phase transition

+ WIMP dark matter candidate



No new physics (so far).

Exclusions up to ~2 TeV.

The naturalness score card

Observable	Theory	Successful prediction of new physics
Kaon mass difference	Effective	Yes – charm mass
Pion mass difference	Effective	Postdiction - ρ^0
Electron mass	Classical-quantum	Postdiction – e^+
Higgs mass	SM	No (SUSY, ED)
Strong CP	SM	No (Axions)
Cosmological constant	SM/GR	No

A mixed set of results for the main motivation for new TeV-scale physics

Is new physics ”around the corner” or hidden/invisible at the LHC ?
Is the basic reasoning correct ?
Quantum gravity may allow short/long distance mixing.

Baryogenesis

Electroweak baryogenesis is not the only model on the market….

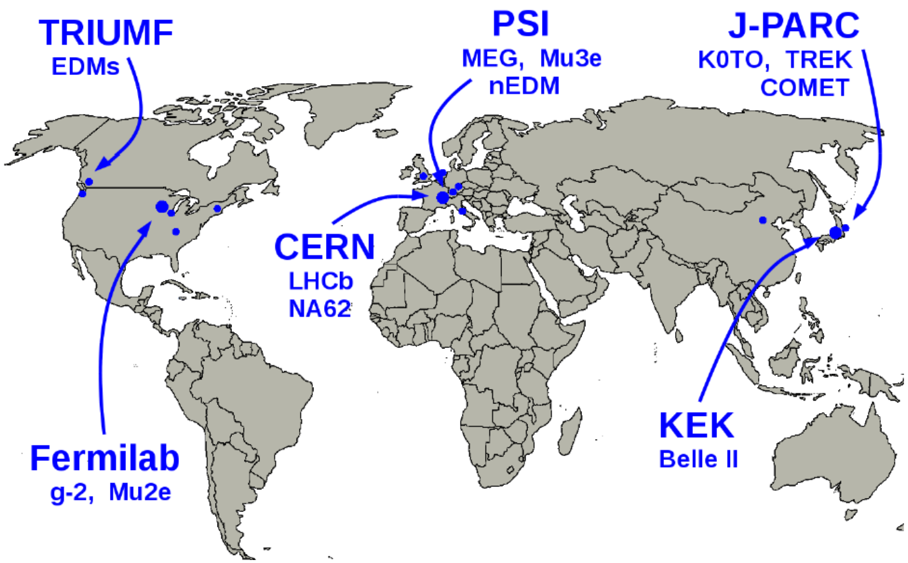
It is, however, broadly falsifiable.

Many models predict high mass states and can't be tested.

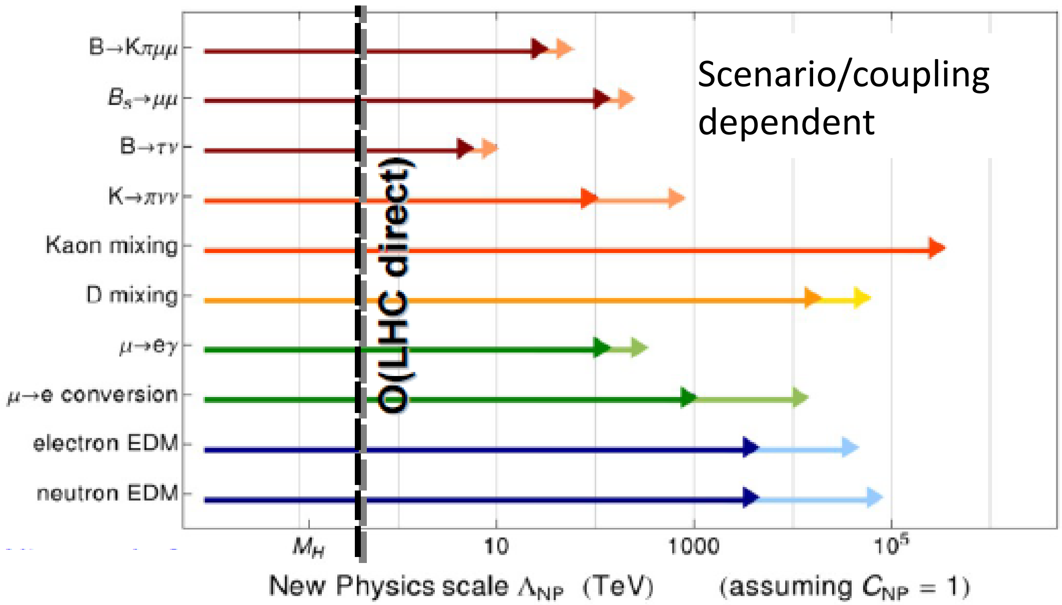
- Affleck-Dine baryogenesis
- GUT baryogenesis
- Leptogenesis
- Spontaneous baryogenesis
- Electroweak baryogenesis
- Dissipative baryogenesis
- Warm baryogenesis
- Cloistered baryogenesis
- Cold baroygenesis
- Planck baryogenesis
- WIMPy baryogenesis
- Dirac Leptogenesis
- Post-sphaleron baryogenesis
- Non-local electroweak baryogenesis
- Magnet assisted baryogenisis
- Singlet-assisted baryogenisis

The precision frontier

Precision frontier experiments



Broad and diverse program and international and national labs and institutions.



NP scale sensitivity beyond the LHC for range of couplings and new particles.

Electric dipole moment= new physics

Electric dipole moment along spin axis: $\bar{d} = d\hat{S}$

T-transformation:

$$d \to d \text{ (even)}, \ \hat{S} = \frac{\bar{S}}{|S|} \to -\hat{S} = \frac{\bar{S}}{|S|} \quad \left[S \equiv ML^2T^{-1} \text{ odd} \right]$$

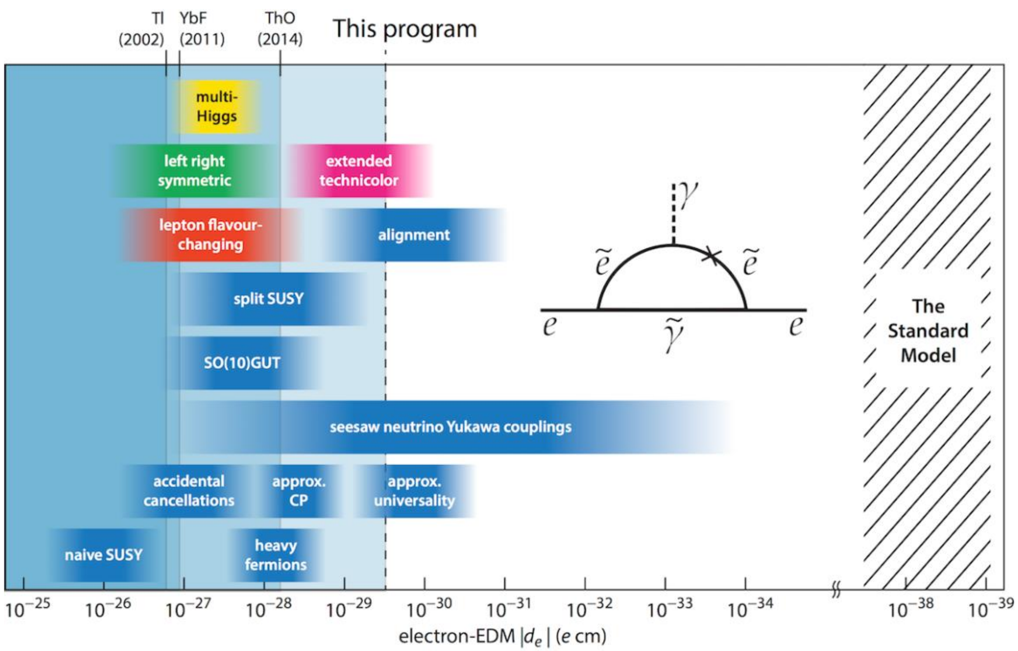
$\Rightarrow \bar{d} \to -\bar{d}$

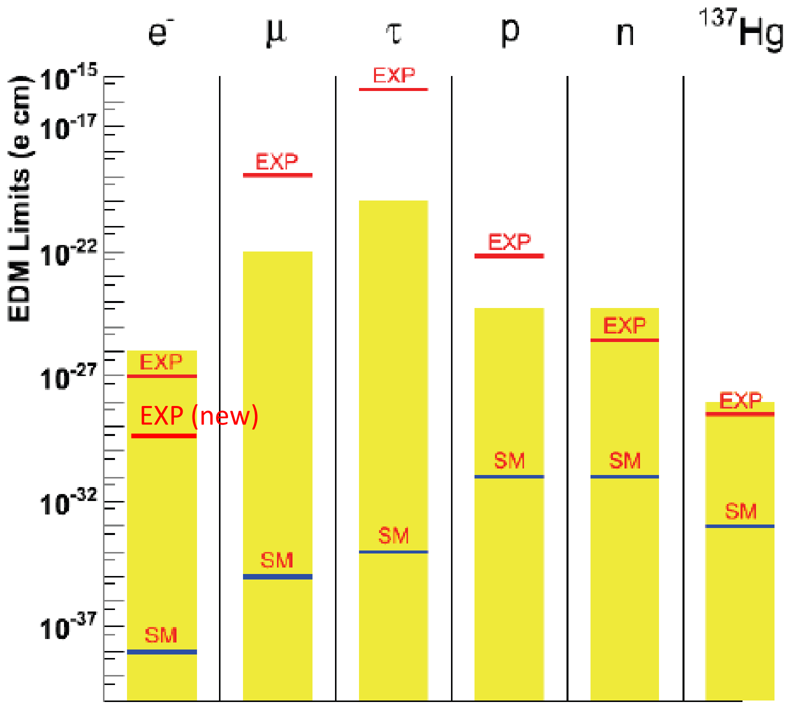
T-violation and CPT symmetry $\Rightarrow$ CP violation.

Measurement of a non-zero EDM $\Rightarrow$ measurement of CPV

SM EDMs tiny $\Rightarrow$ any observation = new physics.

Worldwide program of EDM searches





More constraining than LHC for certain scenarios.

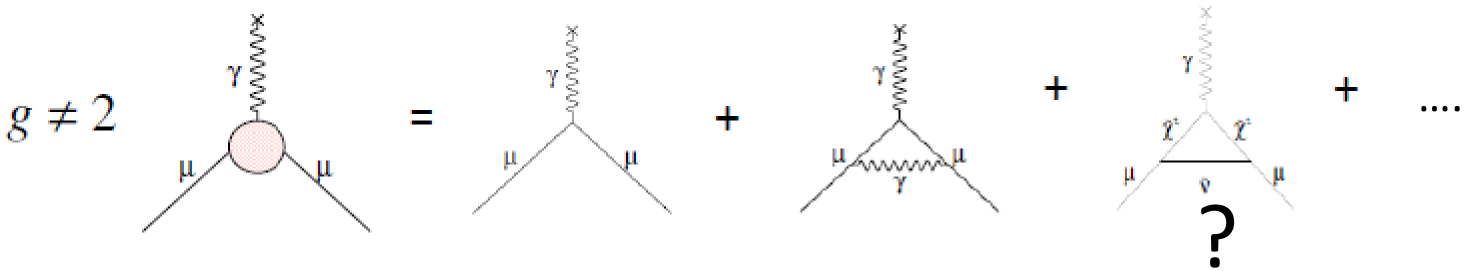
Eg e-EDM search (ACME)

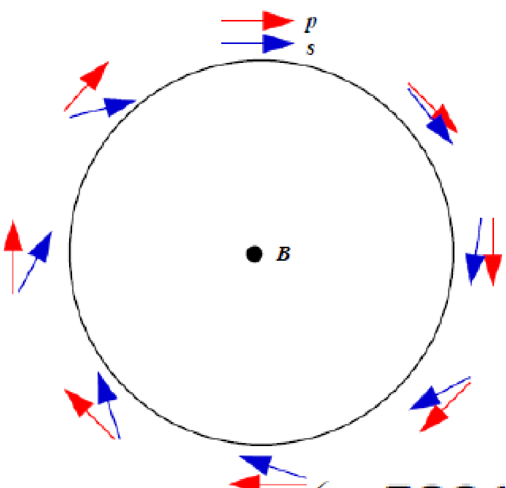
$$\frac{|d_e|}{e} \sim \kappa \hbar c \left(\frac{\alpha_{eff}}{4\pi} \right)^n \left(\frac{m_e c^2}{\Lambda^2} \right) \sin \phi_{CP}$$

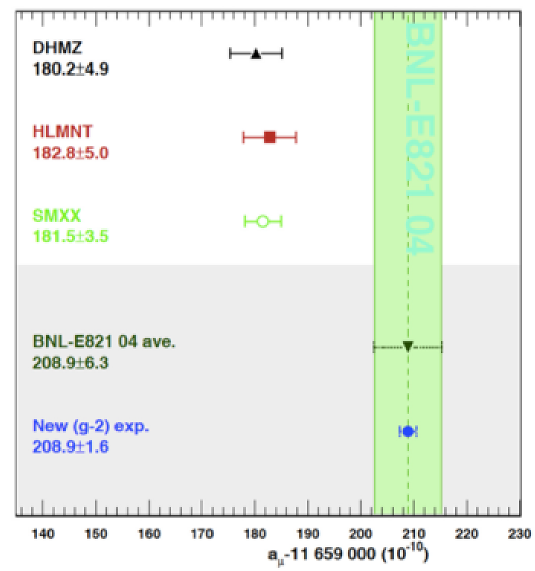
$\Rightarrow$ new physics scale > 3 TeV (1 loop)

g-2 muon – a crack in the SM ?

Magnetic moment for muon : $\mu = \frac{eg}{2m} S$





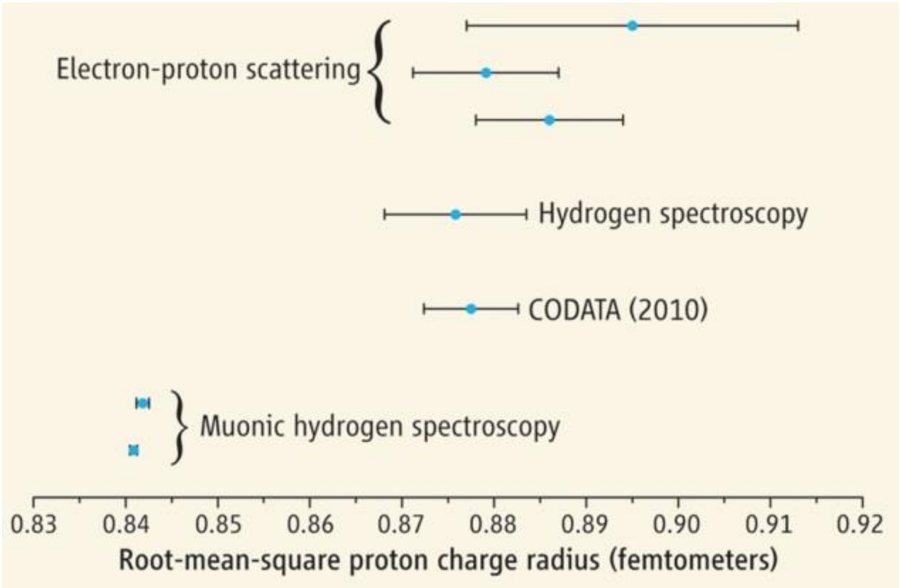


E821 Experiment

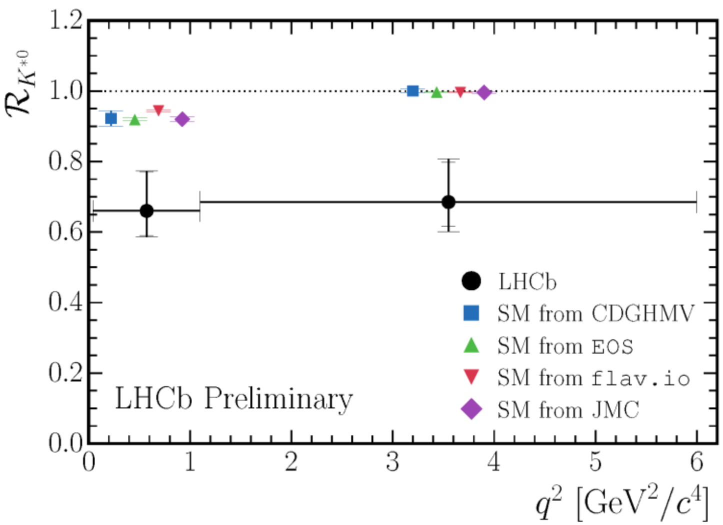
$$a_\mu = 11\ 659\ 208(6) \times 10^{-10} \ \ (0.5\text{ppm})$$

$\sim 3.5\sigma$ from theory!

Other cracks in the SM at the intensity frontier ?



Different proton radius measurements from muonic hydrogen and scattering+hydrogen spectroscopy.



Flavour anomalies

$$R(J/\psi) = \frac{\mathrm{Br}\left(B_c^+ \to J/\psi \tau^+ \nu_\tau\right)}{\mathrm{Br}\left(B_c^+ \to J/\psi \mu^+ \nu_\mu\right)} = 0.71 \pm 0.17 \pm 0.18$$

SM $R(J/\psi) = 0.25$

Deviations in $B \to K^* \mu^+ \mu^-, B \to K^* e^+ e^-$

Where are we ?

- A complete but poorly constrained SM in the top/EWSB sector.
  - We've discovered a very special particle and field
  - Precision needed.
- New physics processes excluded
  - masses up to 1-2 TeV from collider experiments.
  - >2 TeV from non-collider experiments (more scenario dependent)

- Some possible hints for new physics at 2-3 sigma level.
- The naturalness paradigm for new TeV-scale physics has (so far) not worked out.

Some interesting reactions

The Dawn of the Post-Naturalness Era

There are many indications that, following the recursive pattern of scientific revolutions, we are now witnessing the beginning of the phase of crisis. The lack of new physics in the initial stages of the LHC project is putting into question the logic of naturalness when applied to the Higgs; the absence of a positive detection in dark matter experiments is casting doubts about nature taking advantage of the WIMP miracle. We are not simply confronted with

Arxiv:1710.07663 (Giudice)

Saturday, August 06, 2016

The LHC "nightmare scenario" has come true.

Bizarre : the LHC has delivered ~% of its data.

Where are we going ?

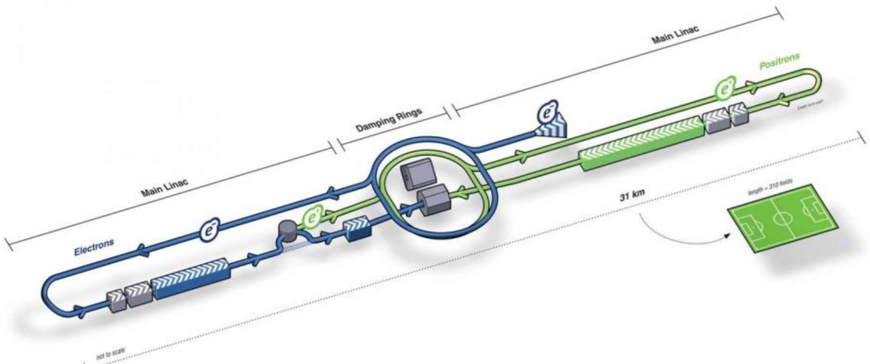
What will (almost certainly) happen ?

- The LHC will deliver $3000fb^{-1}$ by 2035
  - Sensitivity up to ~3 TeV in new physics
  - Greater precision on SM quantities

- New measurements of *g-2* muon
  - x 5 improvement in sensitivity

- New searches for electron, neutron EDMs + other non-collider experiments (SHIP, nnbar are possibilities).
  - ~order of magnitude improvement expected

What can happen ?



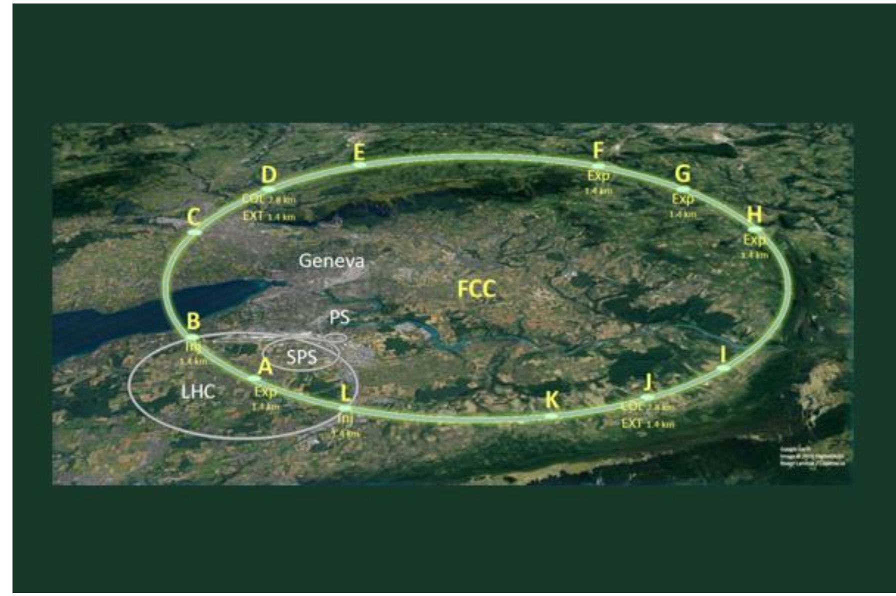
e^+e^- collider at

$\sqrt{s} = 200 - 3000$ GeV

for precision Higgs/EWSB.

Precision frontier - new physics

from deviations wrt SM.



hadron-hadron collider

at $\sqrt{s} \sim$ 100 TeV

Precision Higgs/EWSB +

new physics searches

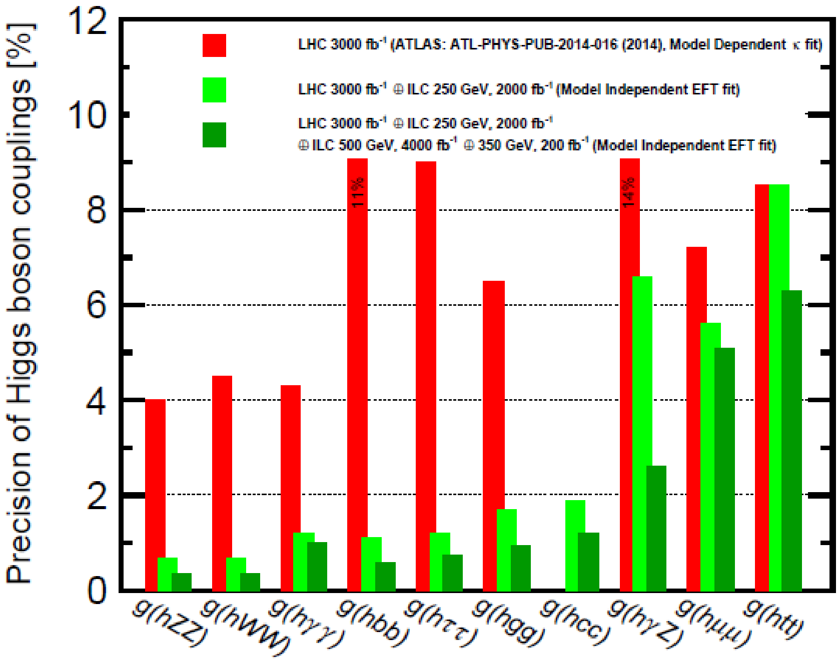
at energy frontier.

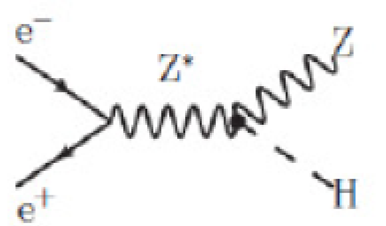
The collider market place

Collider	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (ab^{-1})	Location	Type	Date	Mature
ILC	0.25 0.5,1.0 ?	2	Japan	Linear e+e-	>2030	Shovel-ready TDR (2013)
CLIC	0.38 1.5,3	0.5 1.5,2	CERN	Linear e+e-	>2035	CDR (2012)
FCC-ee	0.25/0.36	10/2.6	CERN	Circular e+e-	>2035	No
LEP3	0.25	1	CERN	Circular e+e-	>2035	No
CEPC	0.25	5	China	Circular e+e-	>2035	CDR (2017)
HE-LHC	28	10	CERN	Circular hh	>2040	No
FCC-hh	100	10	CERN	Circular hh	>2045	No

$e^+ + e^- \Leftrightarrow$ high precision Higgs factory

$$\frac{\sigma(pp \to H + X)}{\sigma(pp \to X)} \sim 10^{-9} \qquad \frac{\sigma(e^+e^- \to H + X)}{\sigma(e^+e^- \to X)} \sim 0.01$$

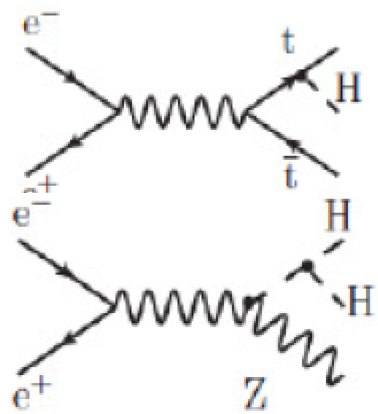




$\sqrt{s} = 250$ GeV

g_Z, BR's ,

(LHC)-invisible



+

$\sqrt{s} = 500$ GeV

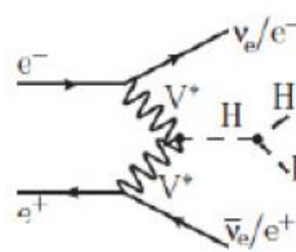
g_t, g_{HHH}

ILC~CLIC~LEP3 sensitivity, FCCee (x 2-5 better)

Tree-level sensitivity to new physics:

Δg <1% for Λ>1 TeV

Sensitivity to new physics in loops



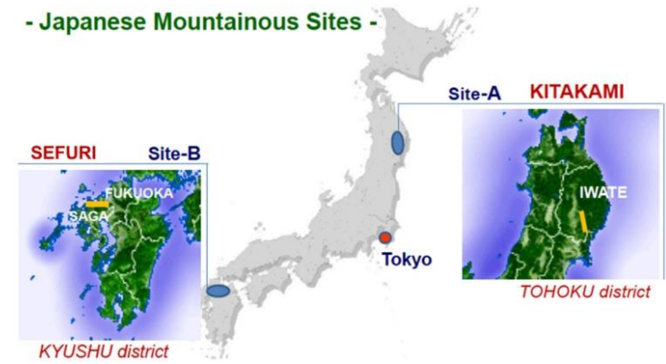
+

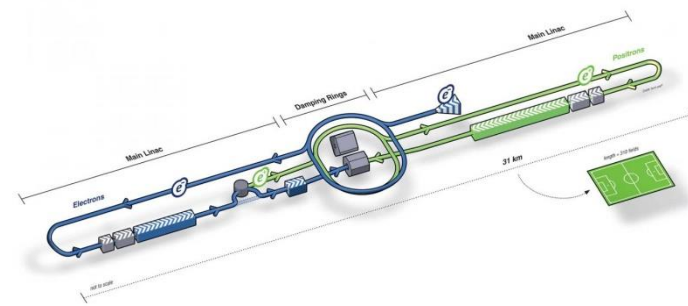
$\sqrt{s} = 1000$ GeV

g_{HHH}

International Linear collider

ILC Physics Goals	500 GeV	350 GeV	250 GeV
• precision Higgs couplings	✔	✔	✔
• gHWW and overall normalization of Higgs couplings	✔	✔	
• search for invisible and exotic Higgs decay modes	✔	✔	✔
• Higgs couplings to top	✔		
• Higgs self-coupling	✔		
• search for extended Higgs states	✔		
• precision electroweak couplings of the top quark	✔		
• precision W couplings	✔	✔	
• precision search for Z′	✔		
• search for supersymmetry	✔		
• search for Dark Matter	✔		
• top quark mass from threshold scan		✔	
• precision Higgs mass			✔





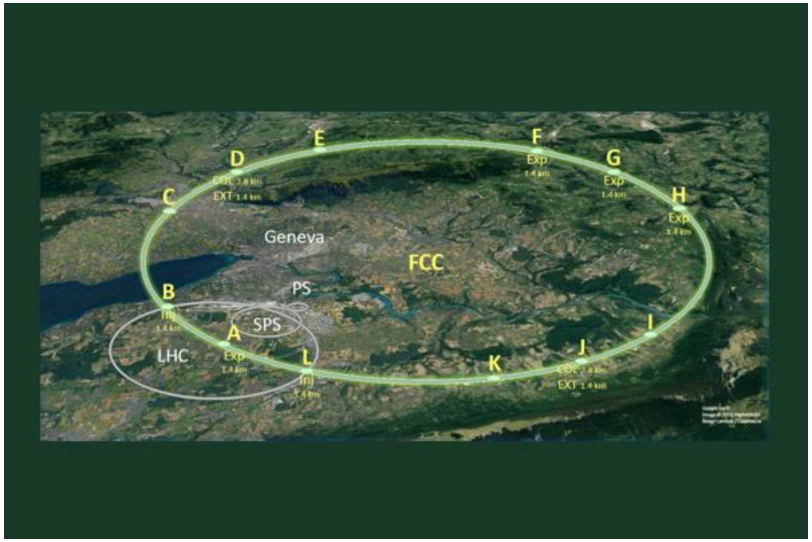
Original plan $\sqrt{s}$=500 GeV $\rightarrow$ 1 TeV .

Now $\sqrt{s}$=250 GeV , maybe 380 GeV, 500 GeV

Most (not all) core measurements are kept but a lot is lost.

Project started in the 1990's. Decision (hoped for) in 2018.

Hadron-hadron colliders



Future circular collider

pp collider at $\sqrt{s} = 100$ TeV

New tunnel (80-100 km).

16 T magnets

FCC-ee first ($\sqrt{s} = 380$ GeV) ?

High Energy LHC

pp collider at $\sqrt{s} = 28$ TeV

Existing tunnel

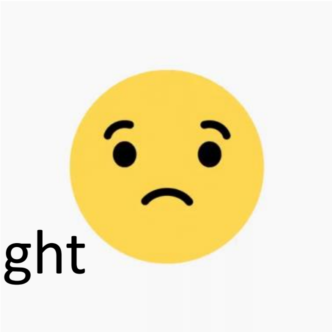
16 T magnets

LEP3 first ($\sqrt{s} = 240$ GeV) ?

hh physics at 100 TeV

- An order of magnitude lower in probed distance scale
- Factors ~5-10 in mass scale for new physics
- Complete exploration of the Higgs sector (quartic coupling)
  - Test electroweak baryogenesis
- High precision Higgs + SM measurements + DM searches

- No ”no lose” theorem unlike Tevatron and LHC.
- No consensus in community.
  - Magnet builders and theorists like it.
- For the first time in ~50 years its not clear that a new insight will come from pushing the high energy frontier.



The cards are on the table

How do we play them ?

(Some) questions for the PP strategy ?

- What benefits Swedish activities and interests ?
- Higgs/EWSB
  - Is a reduced ILC still attractive ?
  - Can we afford a complete Higgs sector exploration ?
  - Is a FCC affordable/justified if the null hypothesis persists ?
- Is it better for CERN/the community to invest in smaller scale experiments instead of a FCC if the null hypothesis persists ?
- How should CERN spend our money in the next 5-10 years ?
- What is the role of national labs ?
- How does CERN maintain a leading role ?
- ….

- Swedish contribution to European Strategy Update
- Document for end of 2018
- Meeting at UU, later at Lund
- UU bid for community symposium in May 2019
- Take part !

Swedish PP strategy meeting

Tuesday 13 Mar 2018, 12:30 → 17:05 Europe/Zurich

Room 80101, Ångströmlaboratoriet, Lägerhyddsvägen 1, 752 37 Uppsala (Other Institutes)

Videoconference Rooms: Swedish_PP_strategy_meeting

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  Doglioni_FutureHad... | strategy-e+e--summ... | strategy-e+e--summ...
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  HIBEAM-strategy.pdf | HIBEAM-strategy.pp...
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  Speaker: Ruth Pottgen (Lund University (SE))
  LDM_eBeam_PPstr...

Swedish process ongoing
Submission at the end of 2018

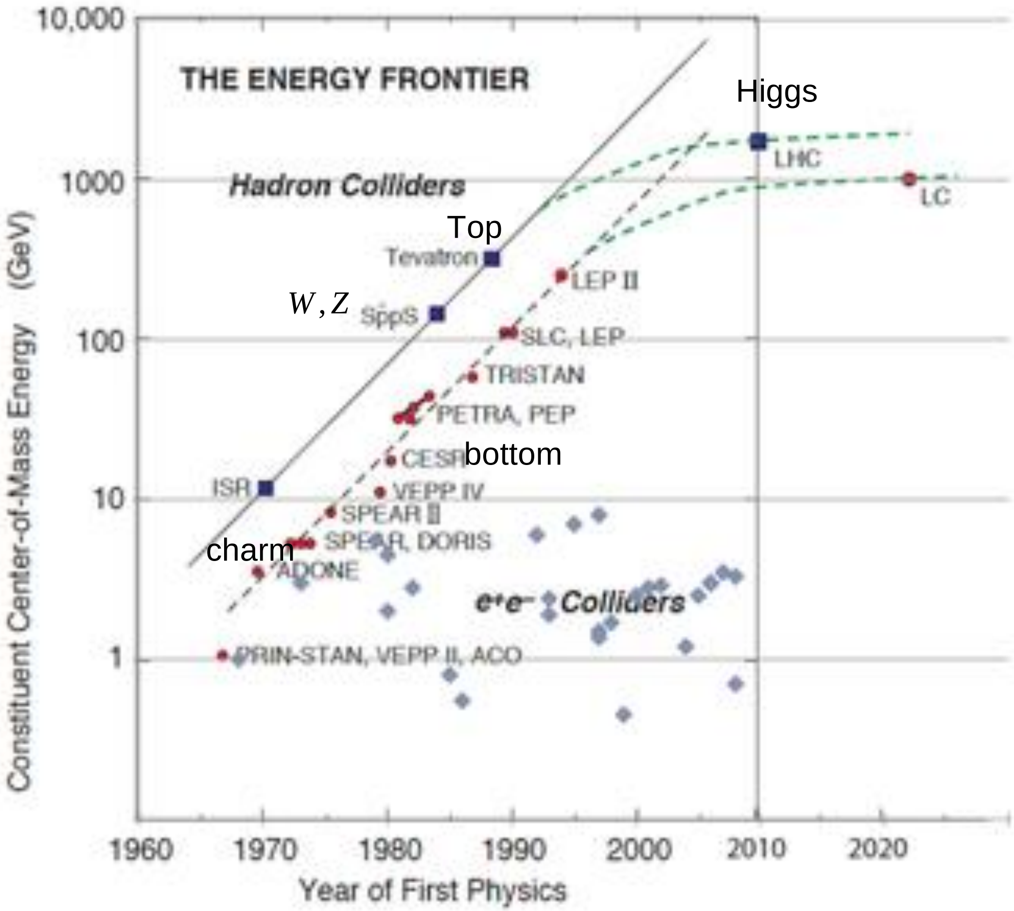
Summary

- The SM test paradigm is entering its final phase (EWSB)
- The BSM search paradigm has (so far) failed, as has its main motivator, naturalness.

- Lots of interesting projects and interesting unanswered questions.
- An e+e- collider is essential for progress.
- Its not obvious how we play the cards.
  - Tectonic plates will shift after Japan's ILC decision.
- Take part in the strategy update.

The European Particle Physics Strategy

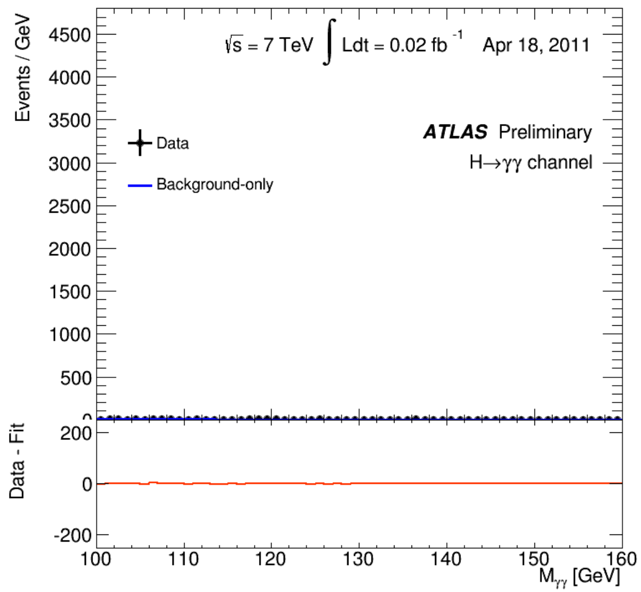
- 2006
  - First strategy
  - http://council.web.cern.ch/sites/council.web.cern.ch/files/European_Strategy/ESStatement.pdf
- 2013
  - Strategy update
  - https://cds.cern.ch/record/1567258/files/esc-e-106.pdf
- 2018
  - Strategy update process starts (submissions at end of 2018)
- 2019
  - Community Symposium (UU have bid to host)
- 2020
  - Strategy update



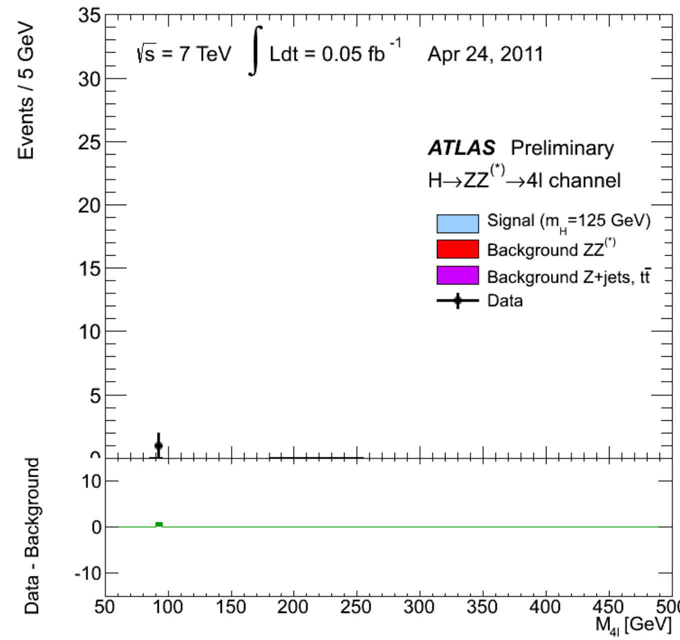
THE ENERGY FRONTIER
Hadron Colliders
e+e− Colliders
Higgs
Top
W, Z
bottom
charm
LHC
LC
Tevatron
SppS
LEP II
SLC, LEP
TRISTAN
PETRA, PEP
CESR
ISR
VEPP IV
SPEAR II
SPEAR, DORIS
ADONE
PRIN-STAN, VEPP II, ACO
10,000
1000
100
10
1
1960
1970
1980
1990
2000
2010
2020
Constituent Center-of-Mass Energy (GeV)
Year of First Physics

Observation of a Higgs → boson pairs

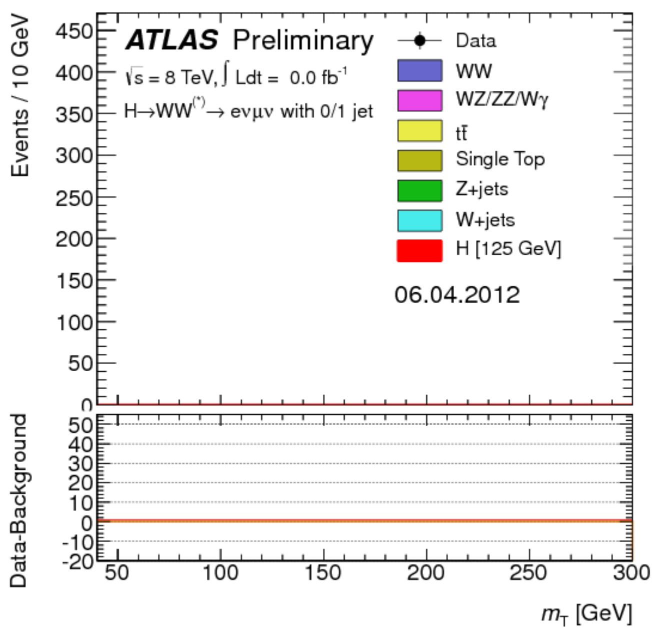
$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ \rightarrow 4\ell$



$H \rightarrow WW \rightarrow e\nu\mu\nu$



And (equally importantly) - no observation in any unexpected channel (yet).

Mixing scales

Collide protons at c.o.m. energy E and measure photons from collision.

Distance scale for collision $\sim \frac{1}{E}$ reduces with E.

$\Rightarrow$ Low E $\Leftrightarrow$ long distance and low photon energy $\left\langle E_\gamma \right\rangle$

E > Planck mass $\rightarrow$ Black hole !

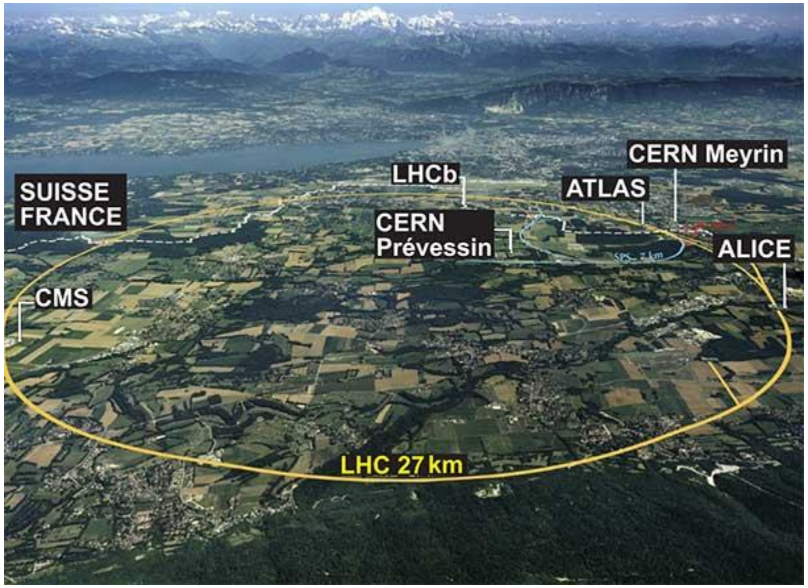
$\rightarrow$ Distance scale, Schwarzchild radius: $R_S = 2GE,$ increases with E.

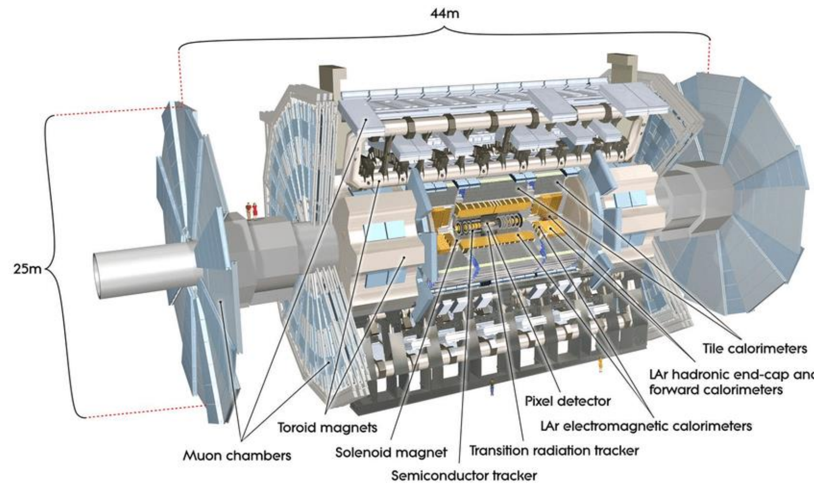
$\rightarrow$ Hawking radiation photons $\left\langle E_\gamma \right\rangle \sim \frac{k}{E}$ decreases with E.

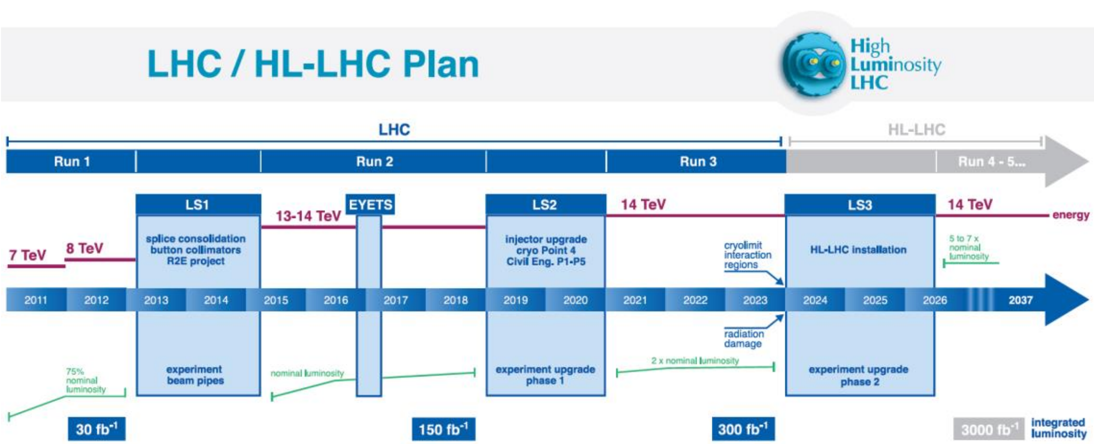
$\Rightarrow$ High E $\Leftrightarrow$ long distance and low photon energy $\left\langle E_\gamma \right\rangle$

$\Rightarrow$ Nature may not care about our prejudice for decoupled scales.

Large Hadron Collider



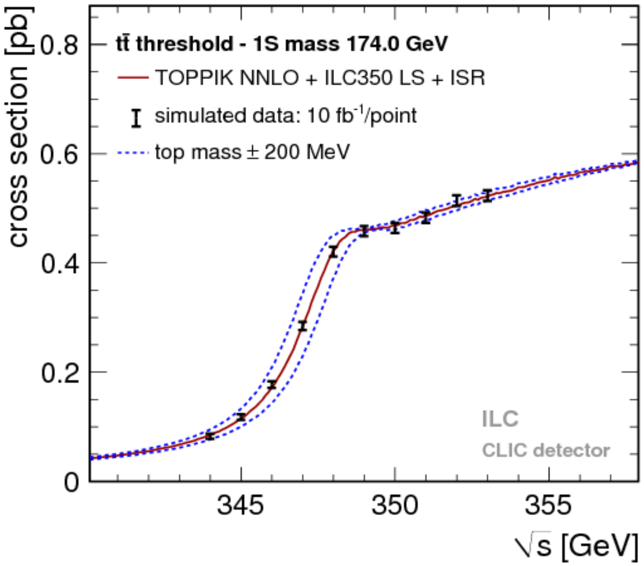




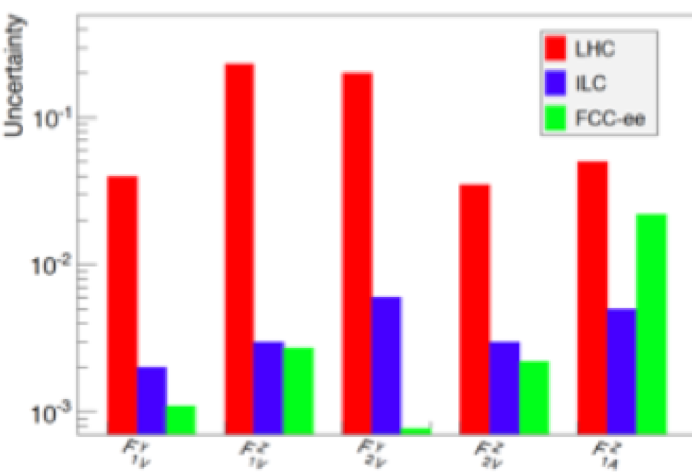
Luminosity and detector upgrades.

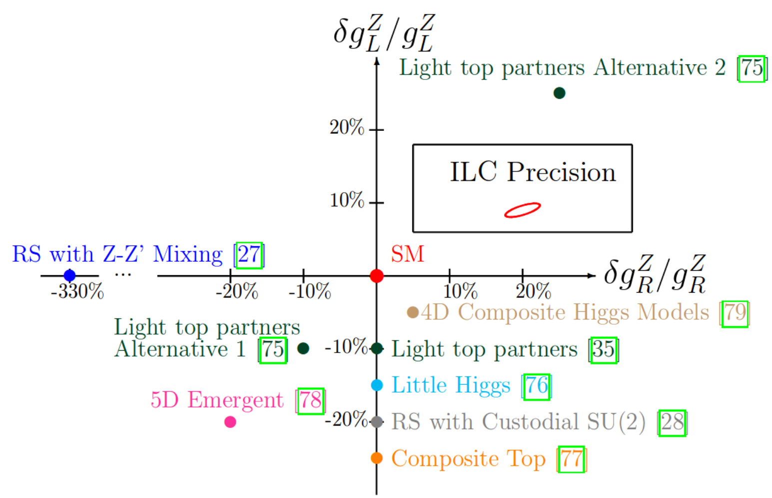
Taken ~% of total luminosity

Top Physics ($\sqrt{s} > 340$ GeV)



High precision threshold scan





Boson couplings

Organisational issues

Don’t even think of building a European collider outside of CERN!

l) Future major facilities in Europe and elsewhere require collaboration on a global scale. *CERN should be the framework within which to organise a global particle physics accelerator project in Europe, and should also be the leading European partner in global particle physics accelerator projects elsewhere. Possible additional contributions to such projects from CERN’s Member and Associate Member States should be coordinated with CERN.*

EU strategy

m) A Memorandum of Understanding has been signed by CERN and the European Commission, and various cooperative activities are under way. Communication with the European Strategy Forum on Research Infrastructures (ESFRI) has led to agreement on the participation of CERN in the relevant Working Group. The particle physics community has been actively involved in European Union Framework programmes. *CERN and the particle physics community should strengthen their relations with the European Commission in order to participate further in the development of the European Research Area.*

Wider impact of particle physics

Outreach

n) Sharing the excitement of scientific discoveries with the public is part of our duty as researchers. Many groups work enthusiastically in public engagement. They are assisted by a network of communication professionals (EPPCN) and an international outreach group (IPPOG). For example, they helped attract tremendous public attention and interest around the start of the LHC and the discovery of the Higgs boson. *Outreach and communication in particle physics should receive adequate funding and be recognised as a central component of the scientific activity. EPPCN and IPPOG should both report regularly to the Council.*

Spin-offs

o) Knowledge and technology developed for particle physics research have made a lasting impact on society. These technologies are also being advanced by others leading to mutual benefits. Knowledge and technology transfer is strongly promoted in most countries. The HEPTech network has been created to coordinate and promote this activity, and to provide benefit to the European industries. *HEPTech should pursue and amplify its efforts and continue reporting regularly to the Council.*

Training

p) Particle physics research requires a wide range of skills and knowledge. Many young physicists, engineers and teachers are trained at CERN, in national laboratories and universities. They subsequently transfer their expertise to society and industry. Education and training in key technologies are also crucial for the needs of the field. *CERN, together with national funding agencies, institutes, laboratories and universities, should continue supporting and further develop coordinated programmes for education and training.*

Concluding recommendations

q) This is the first update of the European Strategy for Particle Physics. It was prepared by the European Strategy Group based on the scientific input from the Preparatory Group with the participation of representatives of the Candidate for Accession to Membership, the Associate Member States, the Observer States and other organisations. Such periodic updates at intervals of about five years are essential. *Updates should continue to be undertaken according to the principles applied on the present occasion. The organisational framework for the Council Sessions dealing with European Strategy matters and the mechanism for implementation and follow-up of the Strategy should be revisited in the light of the experience gained since 2006.*

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Swedish process ongoing

Submission at the end of 2018

The European Strategy for Particle Physics
Update 2013

Preamble

Since the adoption of the European Strategy for Particle Physics in 2006, the field has made impressive progress in the pursuit of its core mission, elucidating the laws of nature at the most fundamental level. A giant leap, the discovery of the Higgs boson, has been accompanied by many experimental results confirming the Standard Model beyond the previously explored energy scales. These results raise further questions on the origin of elementary particle masses and on the role of the Higgs boson in the more fundamental theory underlying the Standard Model, which may involve additional particles to be discovered around the TeV scale. Significant progress is being made towards solving long-standing puzzles such as the matter-antimatter asymmetry of the Universe and the nature of the mysterious dark matter. The observation of a new type of neutrino oscillation has opened the way for future investigations of matter-antimatter asymmetry in the neutrino sector. Intriguing prospects are emerging for experiments at the overlap with astroparticle physics and cosmology. Against the backdrop of dramatic developments in our understanding of the science landscape, Europe is updating its Strategy for Particle Physics in order to define the community's direction for the coming years and to prepare for the long-term future of the field.

General issues

LHC and CERN

a) The success of the LHC is proof of the effectiveness of the European organisational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of [illegible] and universities closely collaborating with CERN. *Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.*

b) The scale of the facilities required by particle physics is resulting in the globalisation of the field. *The European Strategy takes into account the worldwide particle physics landscape and developments in related fields and should continue to do so.*

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

Full exploitation of the LHC up to ~2030

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to [illegible] *the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Design a new CERN-based collider

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when [illegible] *undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous*

accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

e+e- collider needed for the Higgs
International linear collider

e) [illegible] LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider [illegible] The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

Long-baseline neutrinos

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the [illegible] *programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

Other scientific activities essential to the particle physics programme

Theory

g) Theory is a strong driver of particle physics and provides essential input to experiments, witness the major role played by theory in the recent discovery of the Higgs boson, from the foundations of the Standard Model [illegible] calculations guiding the experimental searches. *Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.*

Precision frontier

h) Experiments studying quark flavour physics, investigating dipole moments, searching for charged-lepton [illegible] measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

Detector R&D

i) The success of particle physics experiments, such as those required for the high-luminosity LHC, relies on innovative instrumentation, state-of-the-art infrastructures and large-scale data-intensive computing. *Detector R&D [illegible] strongly at CERN, national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.*

Astro-particle symbiosis

j) A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the [illegible] fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.*

Nuclear-particle symbiosis

k) A variety of research lines at the boundary between particle and nuclear physics require dedicated experim[illegible] unique *experiments. CERN should continue to work with NuPECC on topics of mutual interest.*

Standard Model

Strong

Strong CP problem

Non-perturbative QCD: confinement

Yet to fail precision tests at 10^{-18} m in the perturbative sector

Electroweak

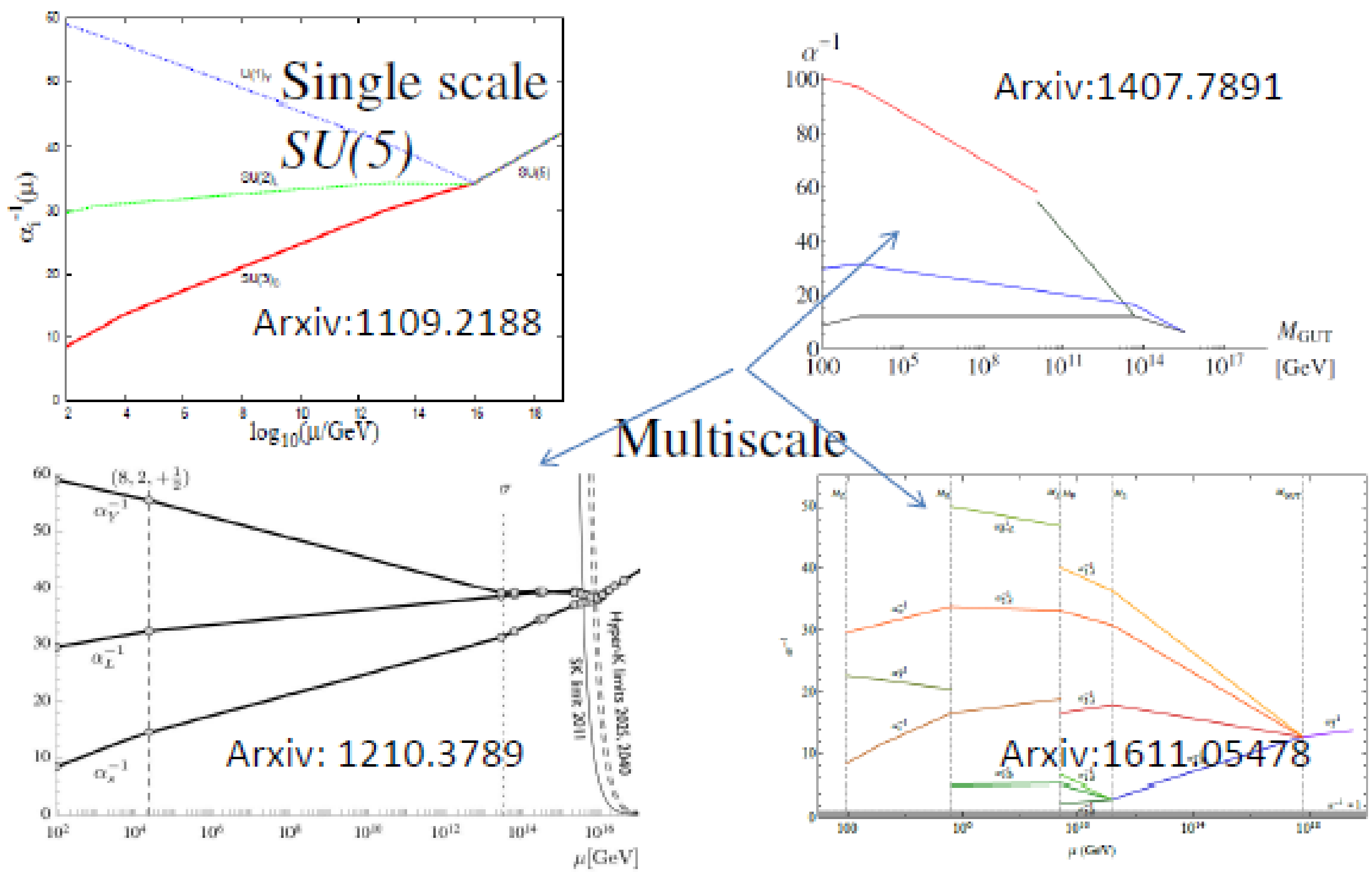
Symmetry breaking:
Higgs properties still to be precisely determined,
Naturalness
Top quark properties

Non-perturbative EW effects still to be observed.

+ neutrino mass, unification of strong+EW, no dark matter candidate, baryogenesis, electric charge quantisation …

Single and multi-scale Unification

Multiscale assume new physics at scale(s) between EW and GUT scale.



Another fine-tuning problem

CPV term in QCD Lagrangian:

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\text{CPV-strong}} \quad ; \quad \mathcal{L}_{\text{CPV-strong}} = \bar{\theta}\,\frac{\alpha_S}{8\pi} G_{a\mu\nu}\tilde{G}_a^{\mu\nu}$$

$$\bar{\theta} = \theta_{\text{QCD}} + \arg(\det M_q) \qquad 0 \le \bar{\theta} \le 2\pi$$

$\theta_{\text{QCD}} \equiv$ QCD vacuum term, $M_q =$ quark mass matrix (EW)

For $\bar{\theta} \sim \mathcal{O}(1)$ EDM neutron $d \sim 10^{-16}$ ecm.

Experimental limit on neutron EDM $d < 10^{-26}$ ecm

$\Rightarrow \bar{\theta} < \mathcal{O}\left(10^{-10}\right)$

$\Rightarrow$ Fine tuning between θ_{QCD} and $\arg(\det M_q)$ ($\equiv$ strong and EW) !

$\Rightarrow$ This is not "natural" $\Rightarrow$ Strong CP problem.