European Particle Physics Strategy Update and Future Prospects

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

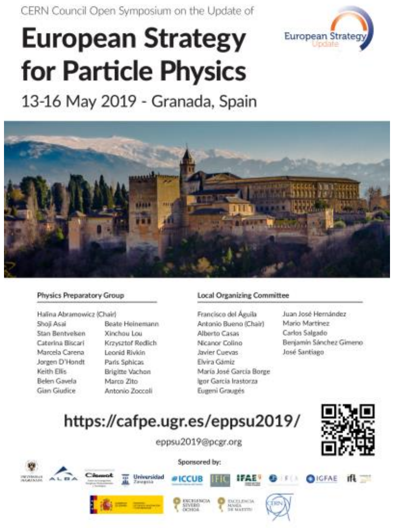
2021 CERN-Fermilab HCP summer school, Sept 4th 2021

What is the European Strategy of Particle Physics?

- Last Update: May 2013 => **New Update: June 19th 2020**
- Important bodies (see backup for lists of members)
  - Physics Preparatory group (PPG):
    - Organizes Symposium (May 2019) and prepares *briefing book* (Sept. 2019)
    - Provides scientific input to strategy based on input of community
  - European Strategy Group (ESG):
    - Drafts the strategy update (Jan. 2020)
  - Strategy secretariat:
    - H. Abramowicz (chair), J. D'Hondt, K. Ellis, L. Rivkin
    - Coordinates the process
  - CERN Council:
    - Approved strategy in June 2020
- CERN management is responsible for implementing strategy
- Strategy also serves as important guideline for national funding agencies

Input to Strategy

- 160 papers submitted
  - Including national inputs
- Symposium (Granada): 600 participants
- PPG prepared “Physics Briefing Book” *[arXiv:1910.11775]*
- Six working groups:
  - WG1: Social and career aspects for the next generation
  - WG2:Issues related to Global Projects hosted by CERN or funded through CERN outside Europe
  - WG3: Relations with other groups and organisations
  - WG4: Knowledge and Technology Transfer
  - WG5: Public engagement, Education and Communication
  - WG6: Sustainability and Environmental impact



CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
Jorge de Blas[4,5], Maria Cepeda[6], Christophe Grojean[2,7], Fabio Maltoni[8,9], Aleandro Nisati[10], Elisabeth Petit[11], Riccardo Rattazzi[12], Wouter Verkerke[13] *(Contributors)*

Strong Interactions: Jorgen D'Hondt[14], Krzysztof Redlich[15] *(Conveners)*
Anton Andronic[16], Ferenc Siklér[17] *(Scientific Secretaries)*
Nestor Armesto[18], Daniël Boer[19], David d'Enterria[20], Tetyana Galatyuk[21], Thomas Gehrmann [22], Klaus Kirch[23], Uta Klein[24], Jean-Philippe Lansberg[25], Gavin P. Salam[26], Gunar Schnell[27], Johanna Stachel[28], Tanguy Pierog[29], Hartmut Wittig[30], Urs Wiedemann[20] *(Contributors)*

Flavour Physics: Belen Gavela[31], Antonio Zoccoli[32] *(Conveners)*
Sandra Malvezzi[33], Ana Teixeira[34], Jure Zupan[35] *(Scientific Secretaries)*
Daniel Aloni[36], Augusto Ceccucci[20], Avital Dery[36], Michael Dine[37], Svetlana Fajfer[38], Stefania Gori[37], Gudrun Hiller[39], Gino Isidori[22], Yoshikata Kuno[40], Alberto Lusiani[41], Yosef Nir[36], Marie-Helene Schune[42], Marco Sozzi[43], Stephan Paul[44], Carlos Pena[31] *(Contributors)*

Neutrino Physics & Cosmic Messengers: Stan Bentvelsen[45], Marco Zito[46,47] *(Conveners)*
Albert De Roeck [20], Thomas Schwetz[29] *(Scientific Secretaries)*
Bonnie Fleming[48], Francis Halzen[49], Andreas Haungs[29], Marek Kowalski[2], Susanne Mertens[44], Mauro Mezzetto[5], Silvia Pascoli[50], Bangalore Sathyaprakash[51], Nicola Serra[22] *(Contributors)*

Beyond the Standard Model: Gian F. Giudice[20], Paris Sphicas[20,52] *(Conveners)*
Juan Alcaraz Maestre[6], Caterina Doglioni[53], Gaia Lanfranchi[20,54], Monica D'Onofrio[24], Matthew McCullough[20], Gilad Perez[36], Philipp Roloff[20], Veronica Sanz[55], Andreas Weiler[44], Andrea Wulzer[4,12,20] *(Contributors)*

Dark Matter and Dark Sector: Shoji Asai[56], Marcela Carena[57] *(Conveners)*
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Accelerator Science and Technology: Caterina Biscari[61], Leonid Rivkin[62] *(Conveners)*
Philip Burrows[26], Frank Zimmermann[20] *(Scientific Secretaries)*
Michael Benedikt[20], Pierluigi Campana[54], Edda Gschwendtner[20], Erk Jensen[20], Mike Lamont[20], Wim Leemans[2], Lucio Rossi[20], Daniel Schulte[20], Mike Seidel[62], Vladimir Shiltsev[63], Steinar Stapnes[20], Akira Yamamoto[20,64] *(Contributors)*

Instrumentation and Computing: Xinchou Lou[65], Brigitte Vachon[66] *(Conveners)*
Roger Jones[67], Emilia Leogrande[20] *(Scientific Secretaries)*
Ian Bird[20], Simone Campana[20], Ariella Cattai[20], Didier Contardo[68], Cinzia Da Via[69], Francesco Forti[70], Maria Girone[20], Matthias Kasemann[2], Lucie Linssen[20], Felix Sefkow[2], Graeme Stewart[20] *(Contributors)*

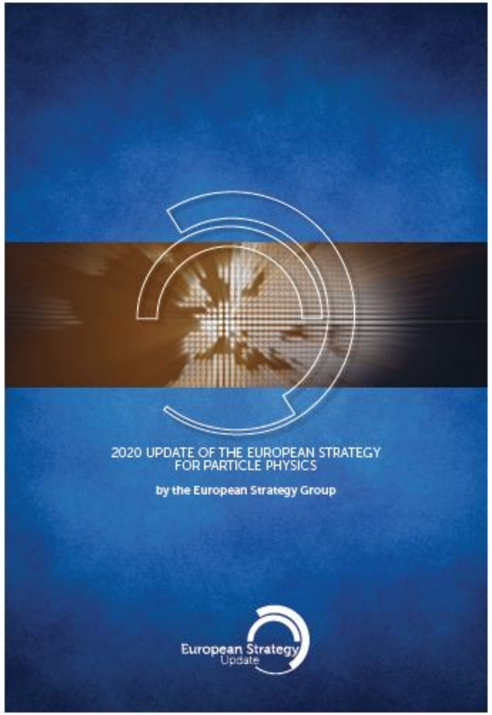
Editors: Halina Abramowicz[71], Roger Forty[20], and the Conveners

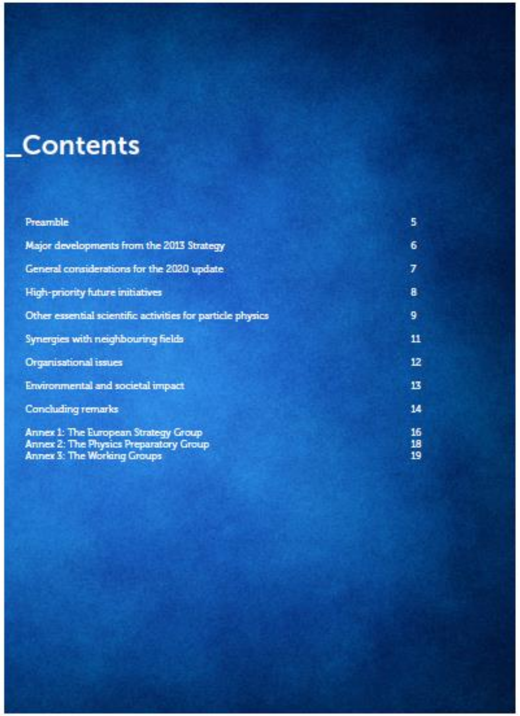
European Strategy Group (ESG)

- Members of ESG:
  - Strategy Secreteriat
  - Representatives of each CERN member state & from each relevant national laboratory
  - CERN DG
  - Charis of ECFA and SPC
- Invited also to Bad Honnef:
  - President of CERN council
  - Representatives from observer and associate member states, EU and JINR
  - chairs of ApPEC FALC, ESFRI, NUPPEC
  - PPG members

Documents submitted: June 19th 2020

Main document




_Contents

Deliberation document

https://europeanstrategyupdate.web.cern.ch/

Summary of statements & recommendations

- 2 statements on **Major developments from 2013 strategy**
- 3 statements on **General considerations for the 2020 update**
- 2 statements on **High-priority future initiatives**
- 4 statements on **Other essential scientific activities**
- 2 statements on **Synergies with neighbouring fields**
- 3 statements on **Organisational issues**
- 4 statements on **Environmental and societal impact**

Letters for itemizing the statements are introduced for identification, they do not imply prioritization

https://europeanstrategyupdate.web.cern.ch/

Summary of statements & recommendations

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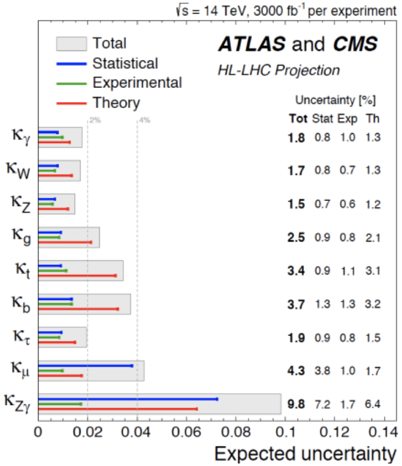
my focus today!

Major Developments since 2013 Strategy

2 statements: HL-LHC and Long Baseline Neutrinos



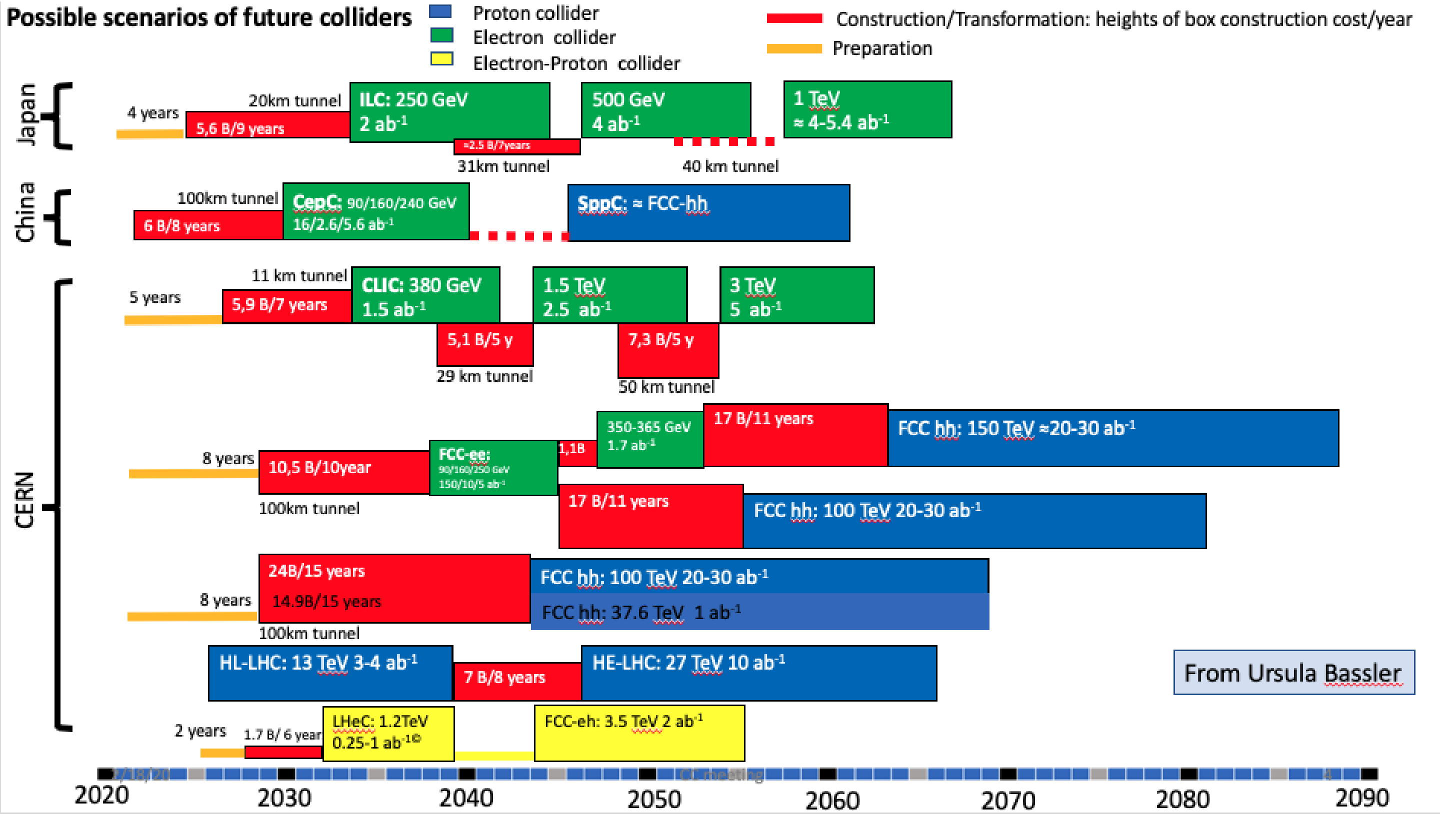
General considerations for the 2020 update

3 recommendations:

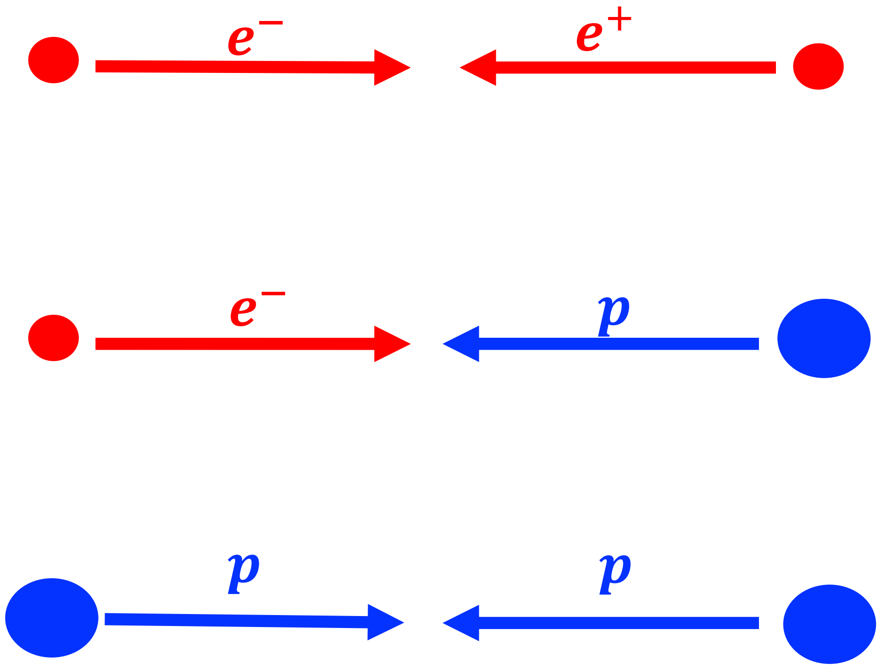
a) Preserve leading role of CERN for the European particle physics community
b) Strengthen the European particle physics ecosystem of research centres
c) Acknowledge the global nature of particle physics research

High-priority future initiatives

2 recommendations: new collider and accelerator R&D



Collider Types

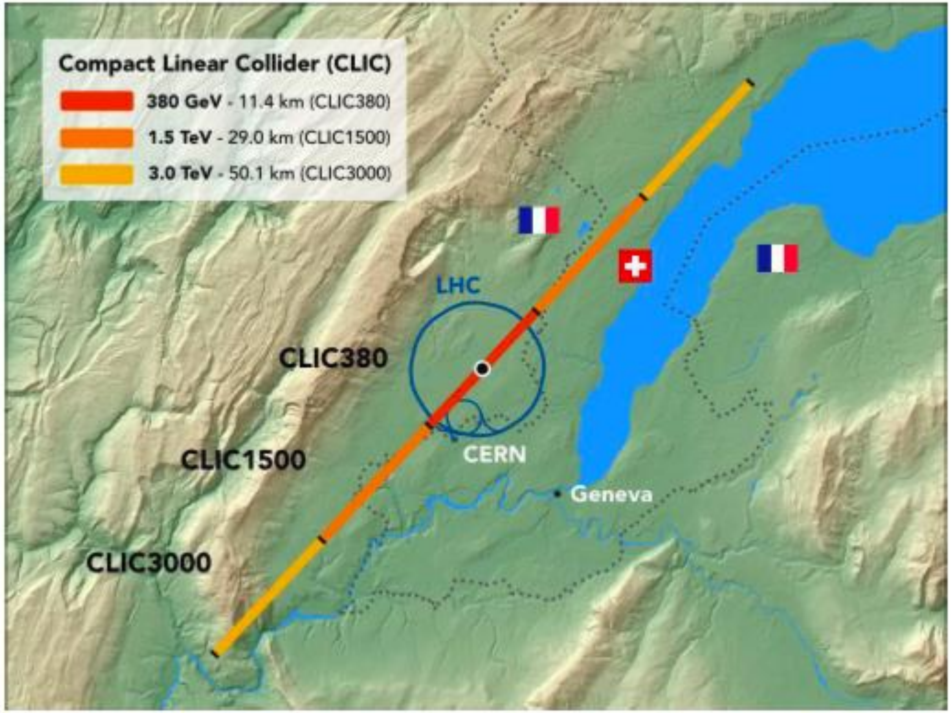


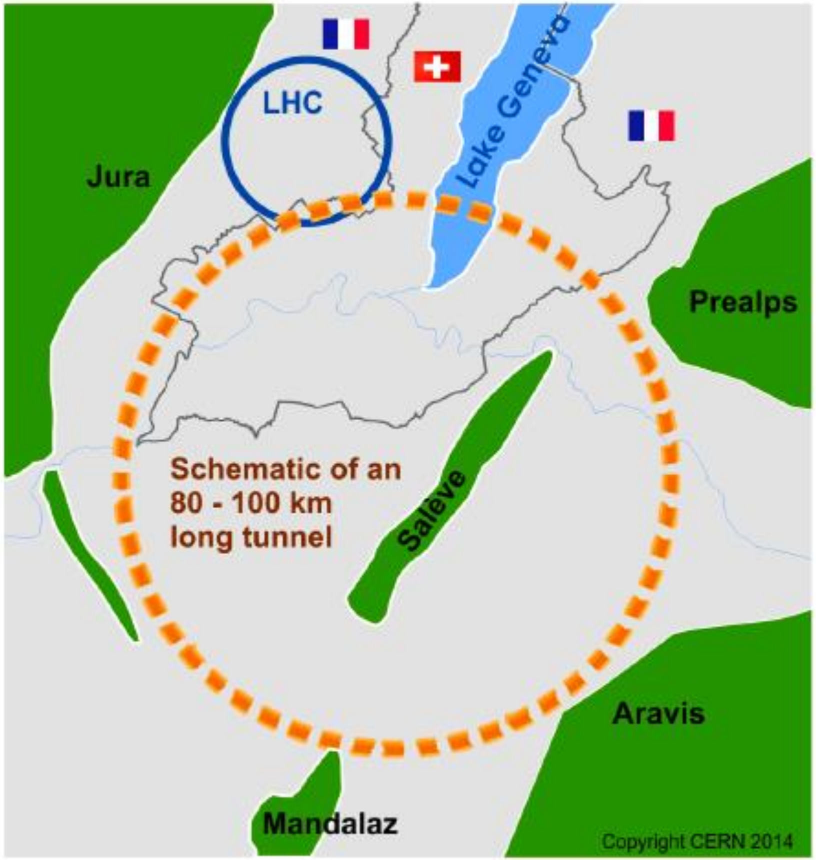
Linear: ILC, CLIC
Circular: FCC-ee, CEPC
(aka „Higgs factories“)

LHeC, FCC-eh
(additional LINAC for e to collide with p parasitically)

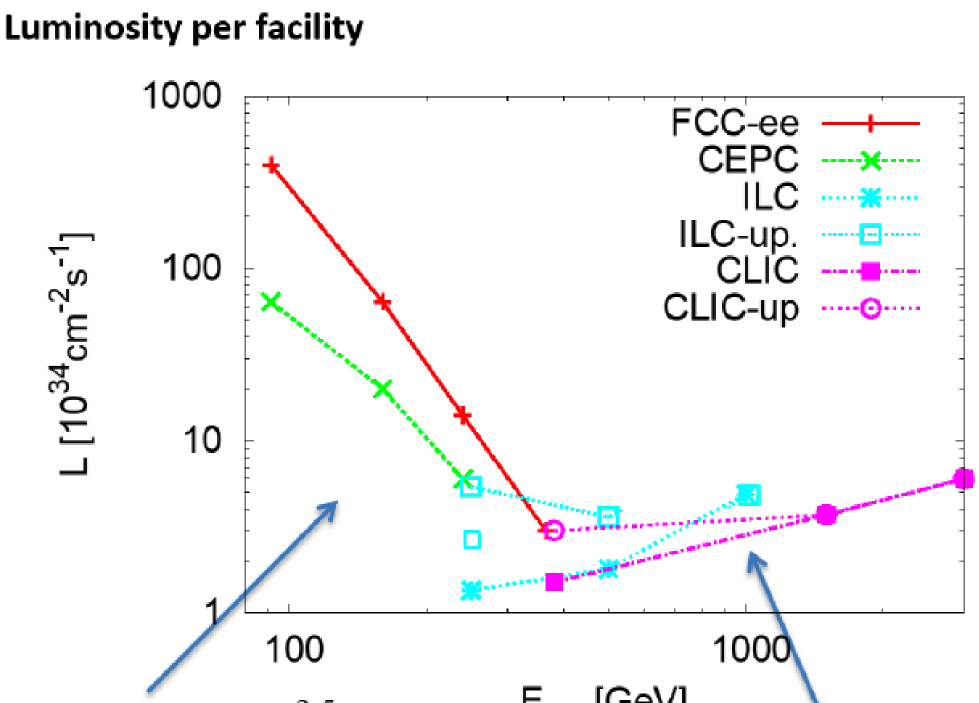
LHC tunnel: HL-LHC, HE-LHC
New tunnel: FCC-hh, SppC

Collider Designs at CERN





e^+e^- Colliders: circular vs linear

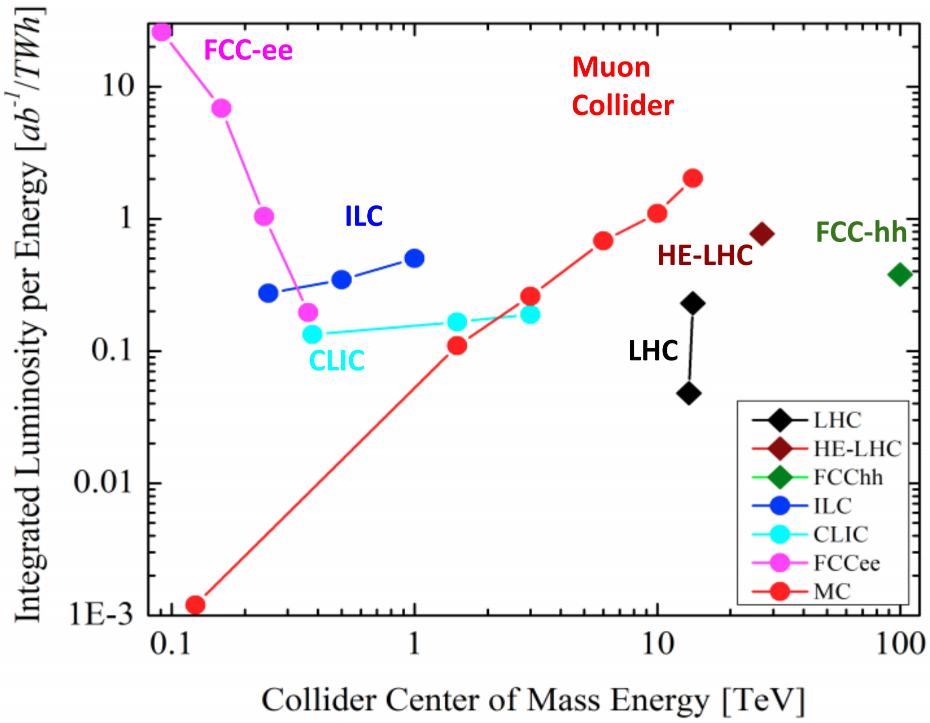


$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$

- Circular colliders
  - Provide more luminosity at low energy
  - Serve also as EWK and B factory
- Linear colliders
  - Provide less luminosity at low energies
  - Extendable to higher energies (>500 GeV)
- Considered to be mature
  - Could start construction in 5-10 years

Integrated luminosity per unit energy



arXiv: 2007.15684
arXiv: 2003.09084

Another (very) important metric to consider (cost & climate)

New collider: discussion

It is essential for particle physics in Europe and for CERN to be able to propose a facility after the LHC

- There are two ways to address the remaining mysteries: Higgs factory and the energy frontier
- Europe is in the privileged position to be able to propose both: CLIC or FCCee as Higgs factory, CLIC (3 TeV) or FCChh (100 TeV) for the energy frontier
- The dramatic increase in energy possible with FCChh leads to this technology being considered as the most promising for a future facility at the energy frontier.
- It is important therefore to launch a feasibility study for such a collider to be completed in time for the next Strategy update, so that a decision as to whether this project can be implemented can be taken on that timescale.

New collider: statement and recommendation

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

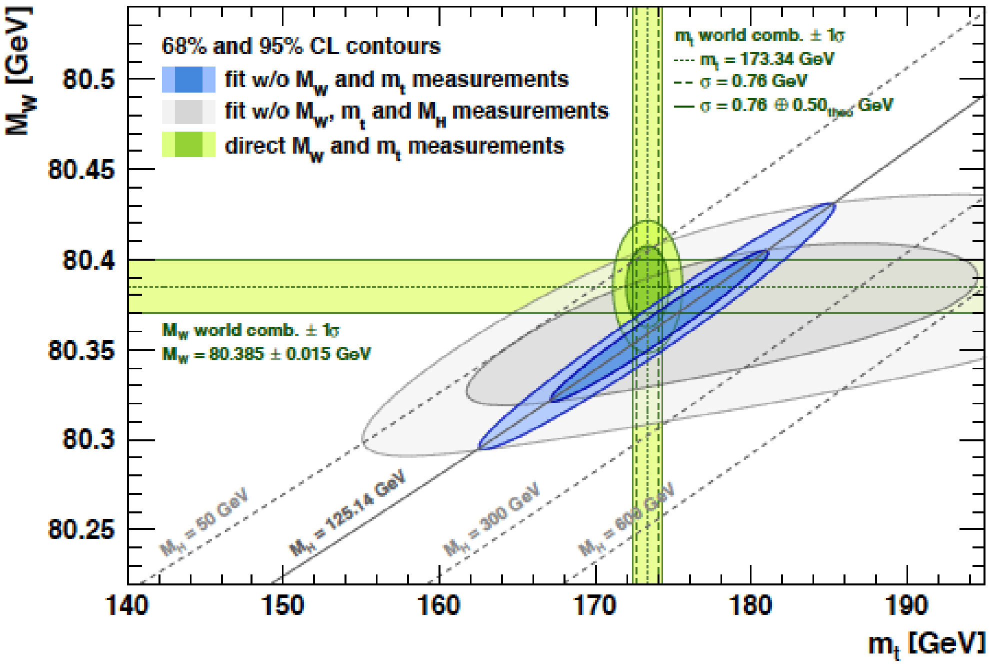
- *the particle physics community **should ramp up its R&D effort focused on advanced accelerator technologies**, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, **should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage**. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

*The **timely realisation of the electron-positron International Linear Collider (ILC) in Japan** would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate*.

(Some) Physics Opportunities at Future Colliders

Electroweak Interactions

- Discovered mechanism to break electroweak symmetry
  - Higgs mechanism
- Provides technical solution but very unsatisfactory
- Higgs sector contains 15 ad-hoc parameters
  - Only 3 in gauge sector!



G. Giudice: *"Essentially all problems or unsatisfactory aspects of the Standard Model are ultimately related to the structure of Higgs interactions"*

Simplicity vs Naturalness

The two Chief Systems

Simplicity ↑

I. The SM is valid up to $\Lambda_{UV} \gg TeV$

- B, L and Flavor: beautifully in accord with observation
- Higgs mass & C.C. hierarchy point beyond naturalness
  - multiverse
  - cosmological relaxation, Nnaturalness, ...
  - failure of EFT ideology (UV/IR connection)

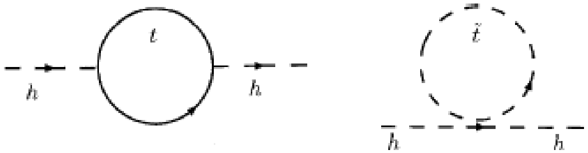
II. Naturalizing New Physics appears at $\Lambda_{UV} \sim 1\,\mathrm{TeV}$

- Constraints on B, L, Flavor & CP met by clever model building

↓ Naturalness

R. Rattazzi

Measuring Naturalness



Hierarchy Paradox → ***unavoidable*** and ***global*** perspective on energy frontier exploration

In any model with calculable m_h: $$m_h^2 = \sum_i \Delta m_i^2$$

fine tuning $$\epsilon \equiv \frac{m_h^2|_{exp}}{\Delta m_h^2|_{max}}$$

offers a measure of where Nature stands in the negotiation between Simplicity and Naturalness

Measures of fine tuning

- Direct searches: depends on top partner constraints in model (e.g. SUSY varieties, composite H, twin H)
  - **LHC now:** $\epsilon \lesssim 10^{-2} - 1$
  - **FCC-hh:** $\epsilon \lesssim 10^{-4} - 10^{-2}$ (if nothing)
- **Higgs observables:** $\epsilon \sim \delta g/g$
- **Electroweak precision:** $\epsilon \sim 10^2 \times \delta\hat{S}/\hat{S}$

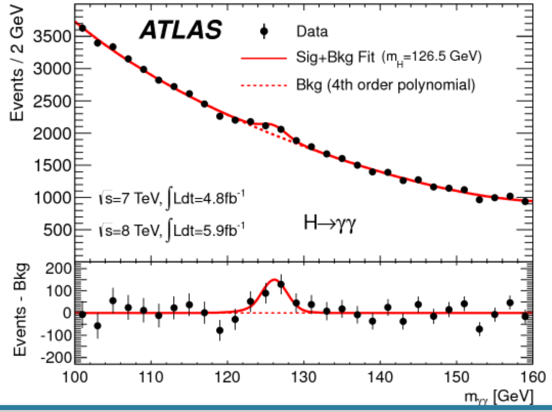
↓

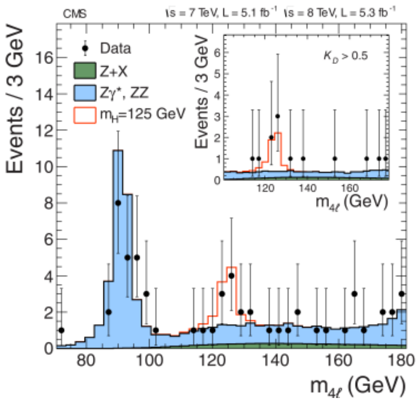
Higgs and EWK precision observables can test naturalness beyond direct searches

R. Rattazzi

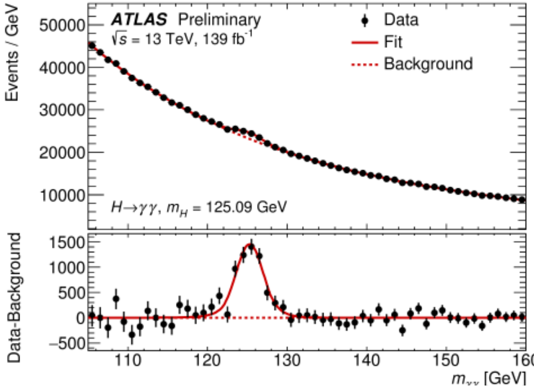
Higgs: 2012 vs now

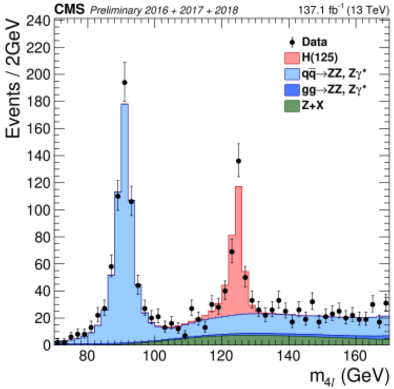
July 2012:
~10 fb^{-1}
@7-8 TeV



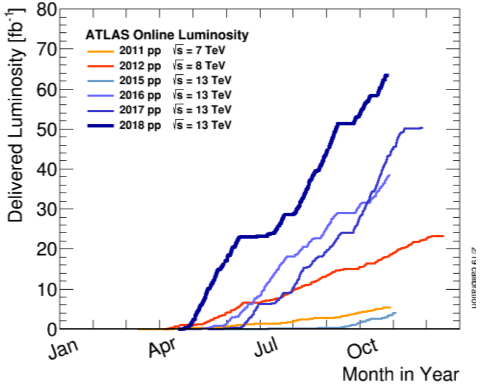


Today:
~140 fb^{-1}
@13 TeV



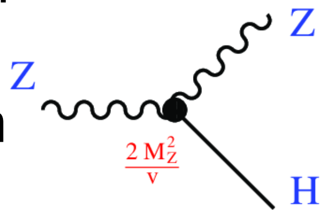


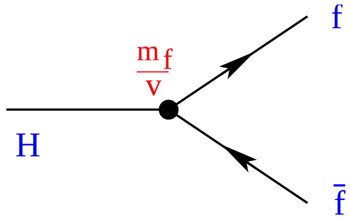
LHC luminosity



Higgs Coupling Determination

- LHC Higgs measurements depend on production and decay
  - E.g. $pp \rightarrow ZH \rightarrow l^+l^- f\bar{f}$
- In SM coupling values precisely known
  - Except for uncertainties on mass values
- Kappa framework adds ad-hoc scalar modifiers
  - $\kappa_i = 1$ in SM for particles i (i=Z,W, tau, b…)





$$(\sigma \cdot \mathrm{BR})(i \rightarrow \mathrm{H} \rightarrow f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \rightarrow \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

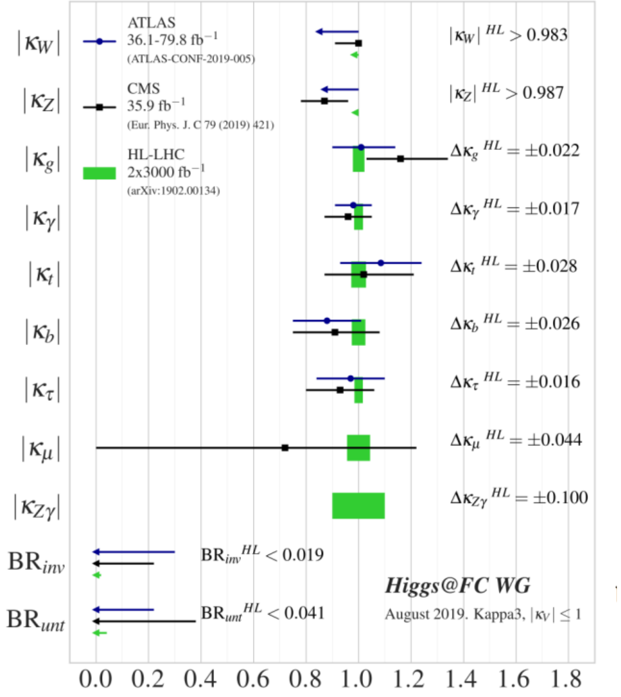
(Note: assumes only SM-like interactions, EFT often used for more complete description)

Include BSM in kappa via :

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$

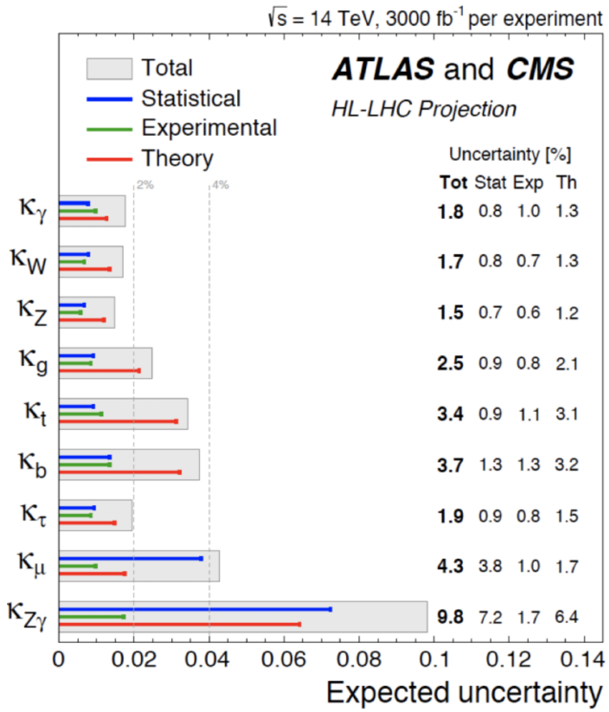
Higgs Coupling Constraints: LHC and HL-LHC

LHC now vs HL-LHC



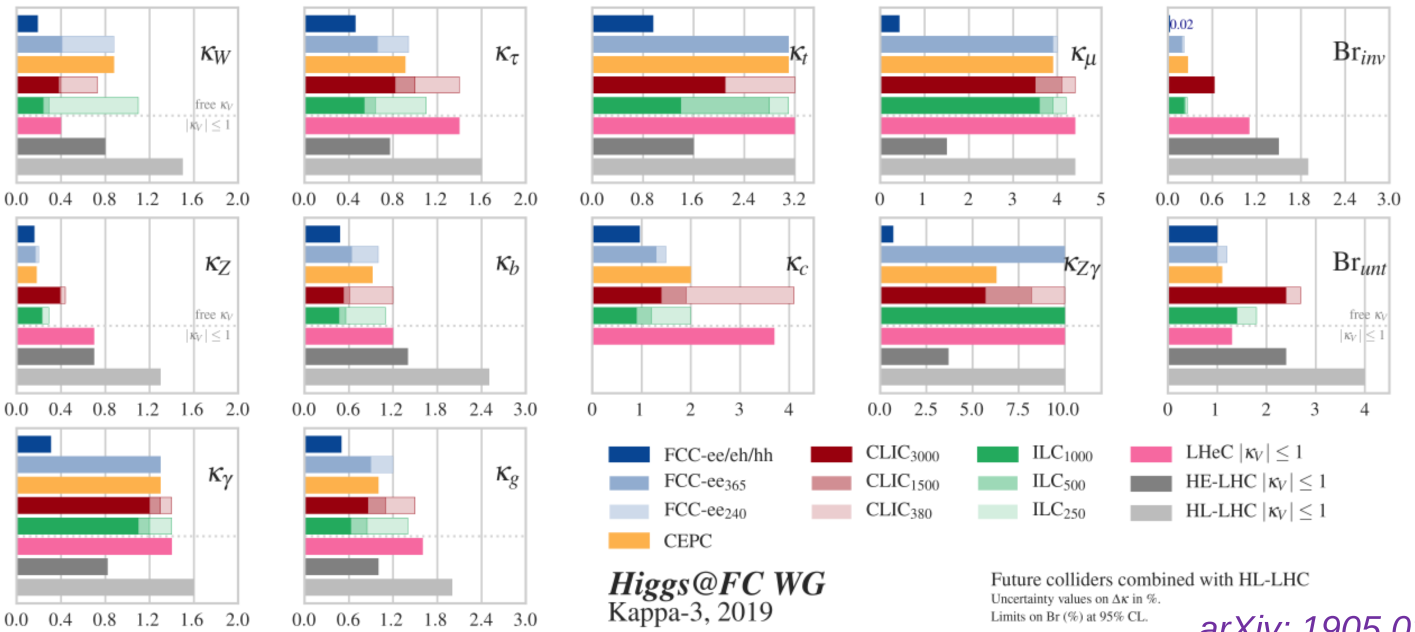
10%

High Luminosity LHC (HL-LHC)



10%

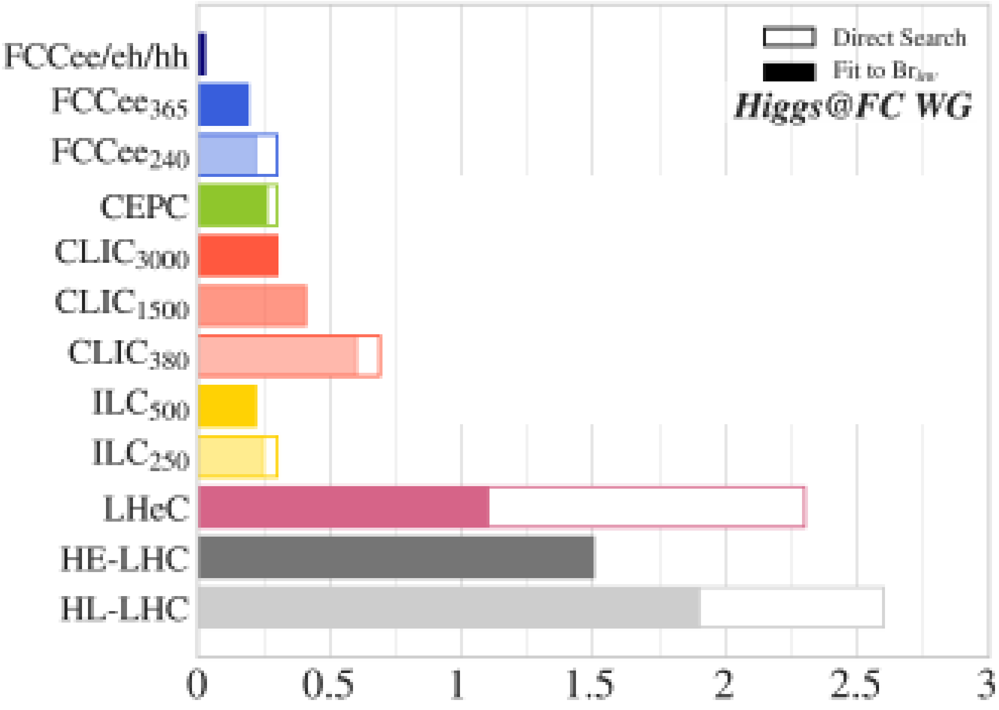
Higgs: Coupling Constraints: Future Colliders

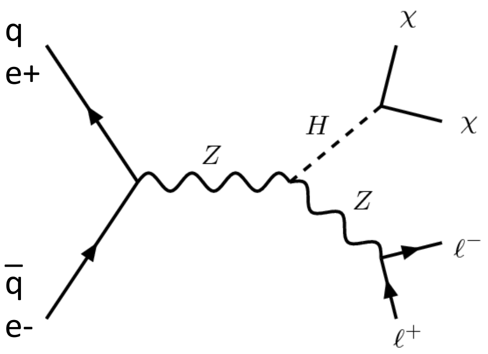


arXiv: 1905.03764

- HL-LHC achieves 1-3% precision in most cases
- Higgs factories achieve factor 2-10 improvement + add κ_c + less assumptions (for $\mathrm{Br}_{\mathrm{unt}}$)
  - HZ coupling measured with 0.2% precision!
- FCC-hh dramatically improves top and rare decays ($\kappa_t, \kappa_{Z\gamma}, \kappa_\gamma, \kappa_\mu$) and $\mathrm{Br}_{\mathrm{inv}}$

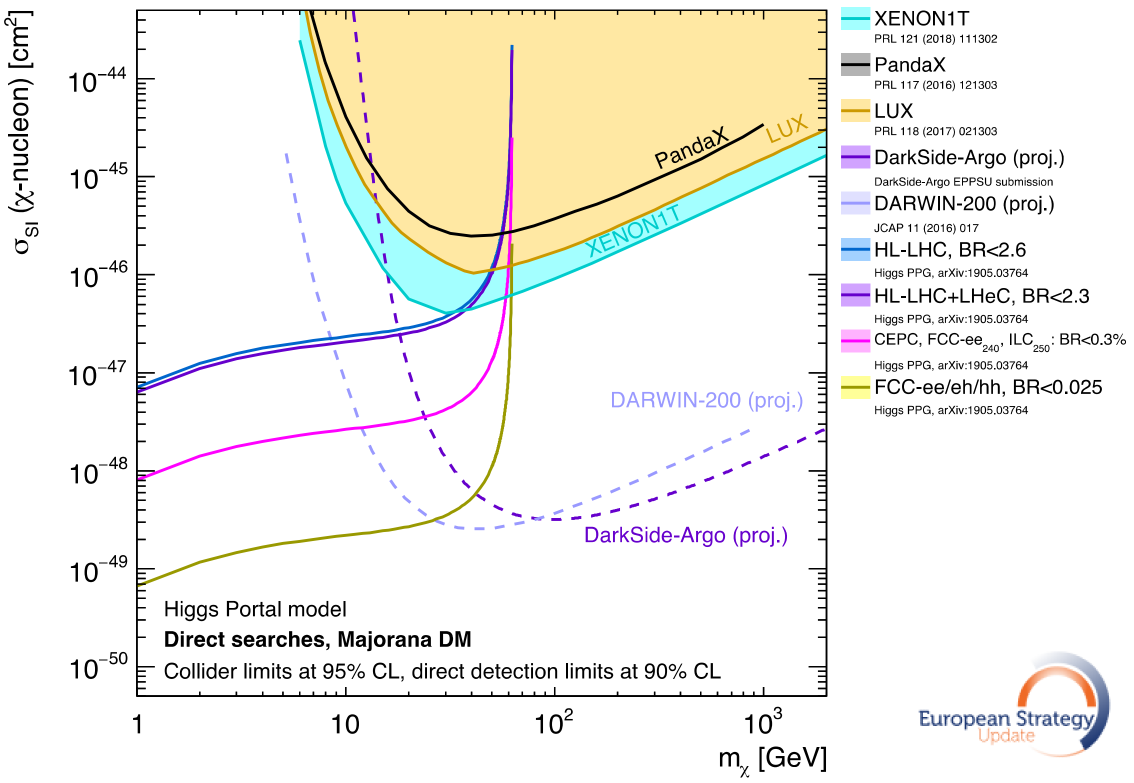
Future prospects on invisible H decays





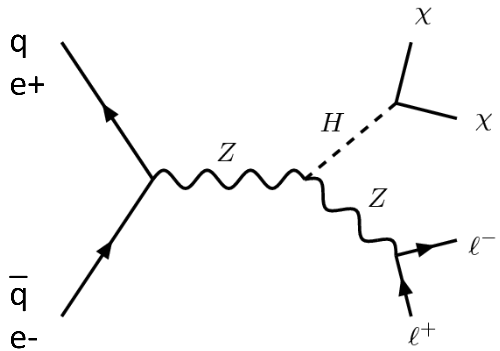
- Major improvements compared to current sensitivity of ~10%
  - HL-LHC : <2.6%
  - e+e- colliders: ~0.3%
  - FCC-hh: ~0.025% (below SM value)

Future prospects on invisible H decays



(Current LHC sensitivity: ~10^{46} cm^2)

European Strategy Update

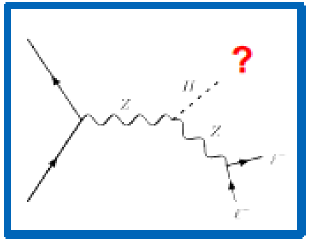


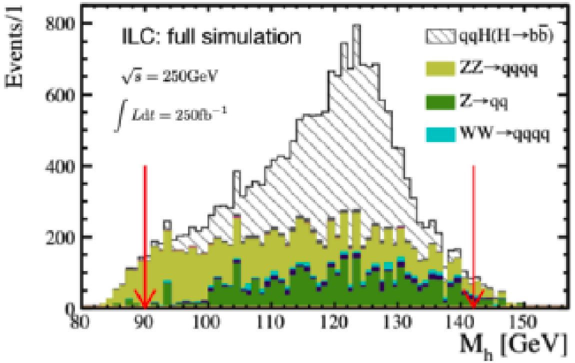
- LHC and direct detection experiments are complementary
  - Higgs more sensitive at low mass but looses all sensitivity for $m_H < 2m_\chi$
- Comparison of sensitivities is model-dependent
  - Ideal case: WIMP is in overlap region => excellent to learn the underlying physics

Higgs width and/or untagged decays

Unique feature of lepton-lepton colliders:

- **Detecting the Higgs boson without seeing decay: "recoil method"**
- **Measure ZH cross section with high precision without assumptions on decay**
- **Often interpreted as quasi-direct measurement of width**





$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

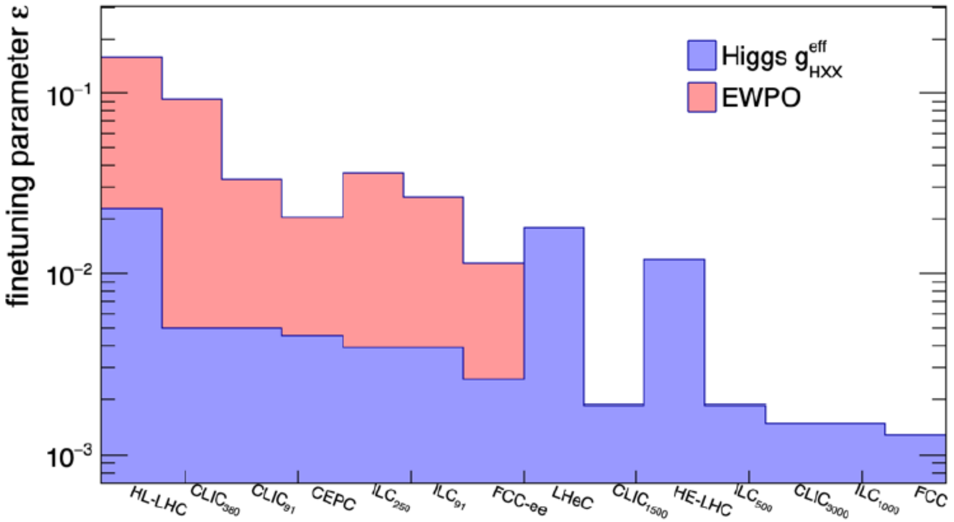
In kappa-framework: $\Gamma_H = \dfrac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$

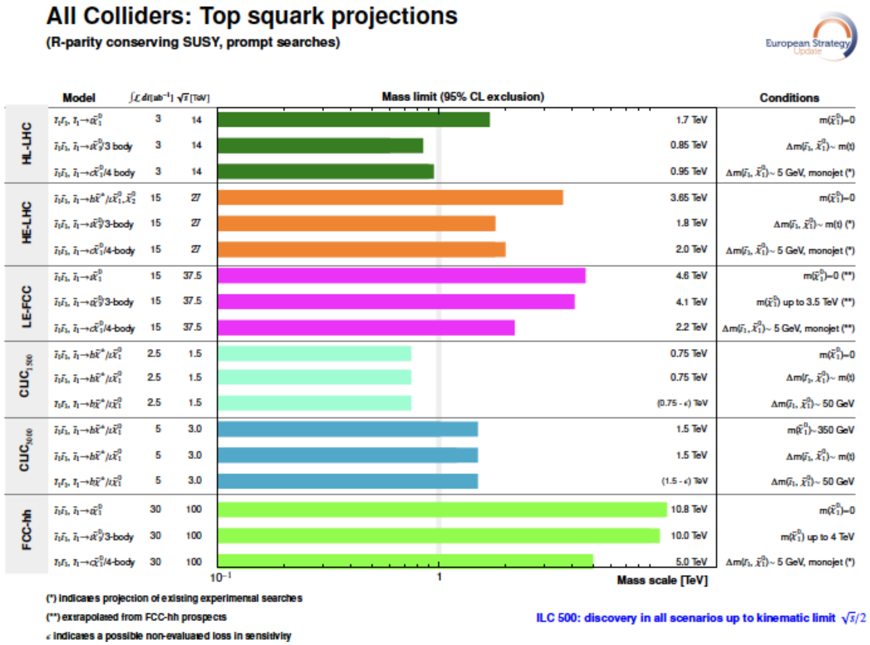
Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764

=> Will probe width with 1-2% precision

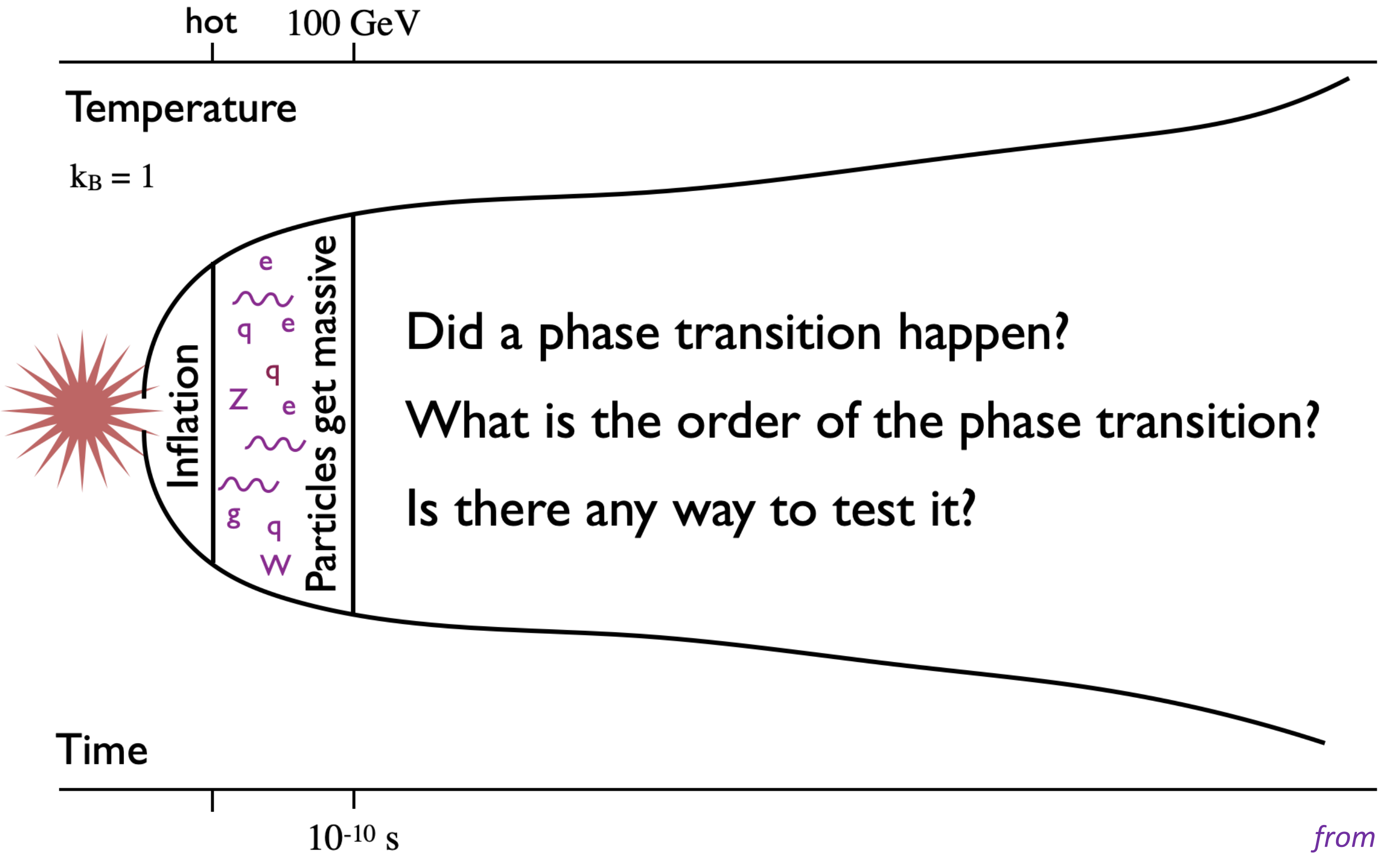
Is our world natural?





- Will probe naturalness to levels of 10^{-3} with Higgs couplings
  - Down to 10^{-2}-10^{-4} with direct searches (depending on how strongly NP is coupled)

The electroweak phase transition

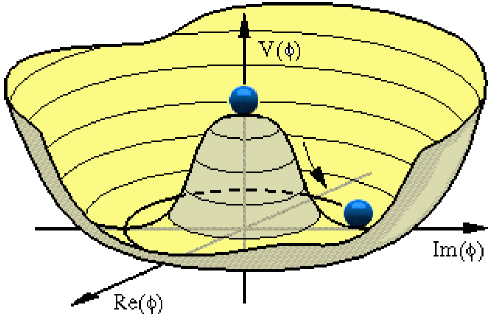


Did a phase transition happen?

What is the order of the phase transition?

Is there any way to test it?

Standard Model

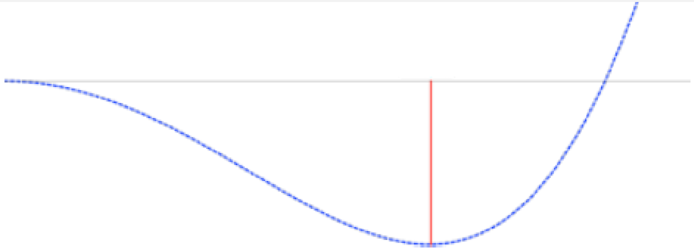


from Selya Ipek

The Higgs Potential

Higgs potential:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



$$\frac{\mu}{\sqrt{\lambda}} \equiv v \quad 246 \text{ GeV}$$

In SM: shape of potential determined by $\lambda_{hhh} = \frac{m_h^2}{2v^2} = \lambda_{4h} \approx 0.13$

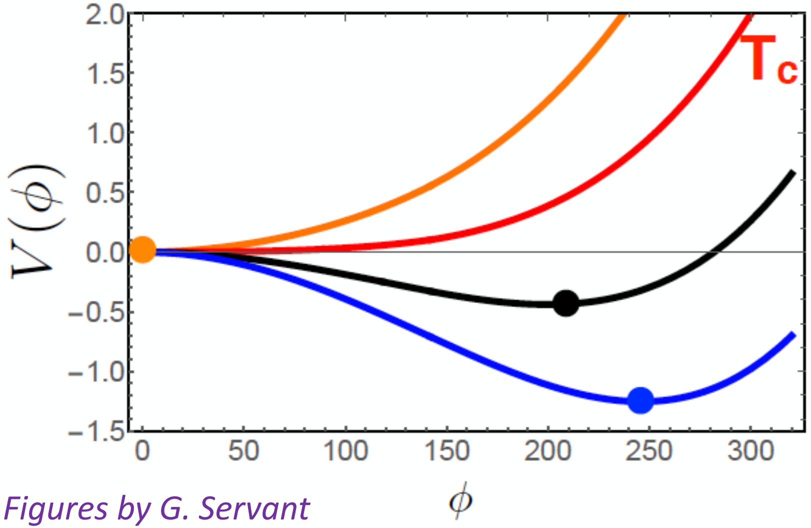
Electroweak potential

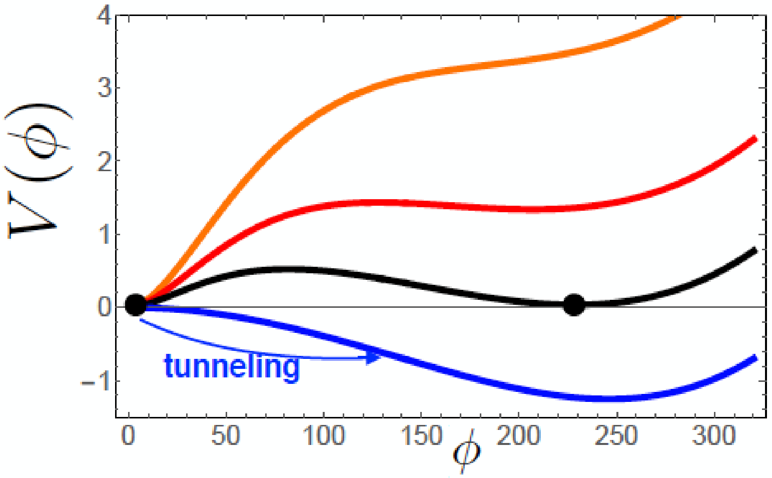
Standard Model

- Electroweak phase transition (EWPT) is a “smooth crossover”
- Electroweak symmetry restored for $T \geq T_C = 130$ GeV

Alternative idea

- Electroweak phase transition via tunneling: 1st order transition
  - Two phases co-exist
- Electroweak baryogenesis possible if strong 1st order transition





Figures by G. Servant

Electroweak potential

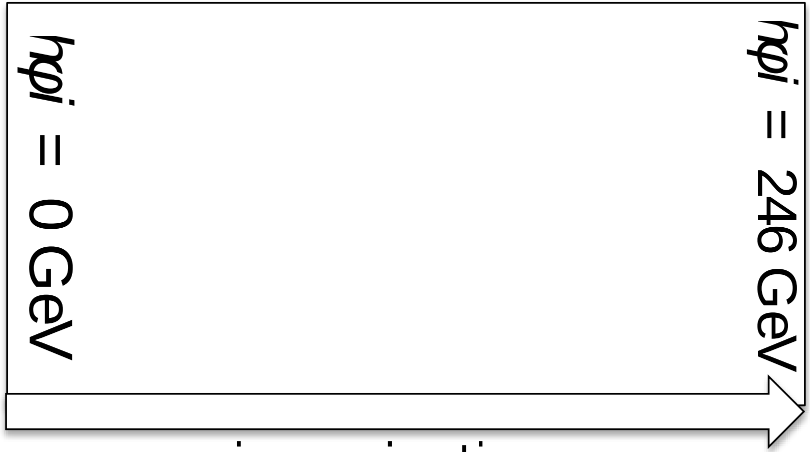
Standard Model

- Electroweak phase transition (EWPT) is a “smooth crossover”
- Electroweak symmetry restored for $T \geq T_C = 130$ GeV

Alternative idea

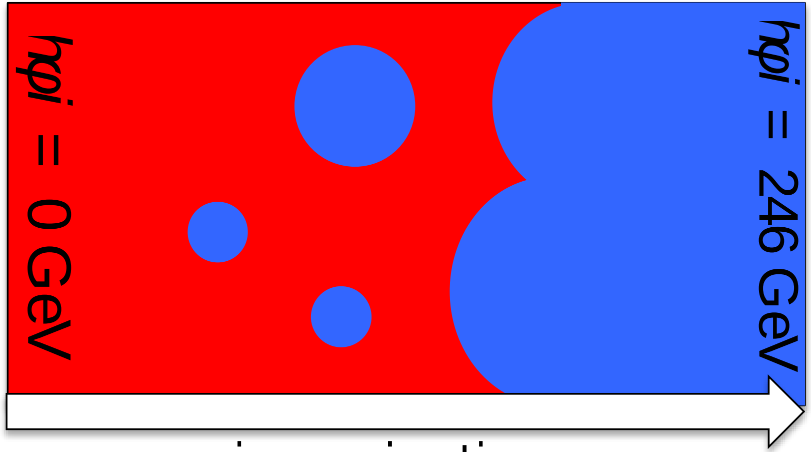
- Electroweak phase transition via tunneling: 1st order transition
  - Two phases co-exist
- Electroweak baryogenesis possible if strong 1st order transition
  - Relevant for matter-antimatter asymmetry

Continuous Crossover



increasing time

First Order Phase Transition



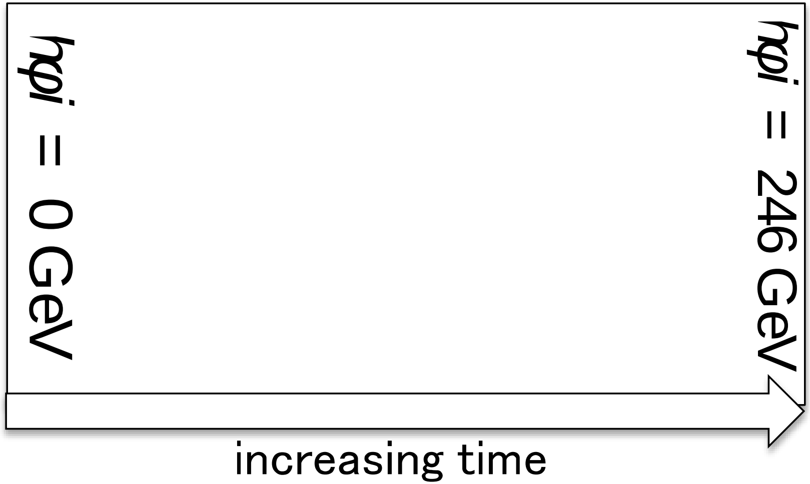
increasing time

Electroweak potential

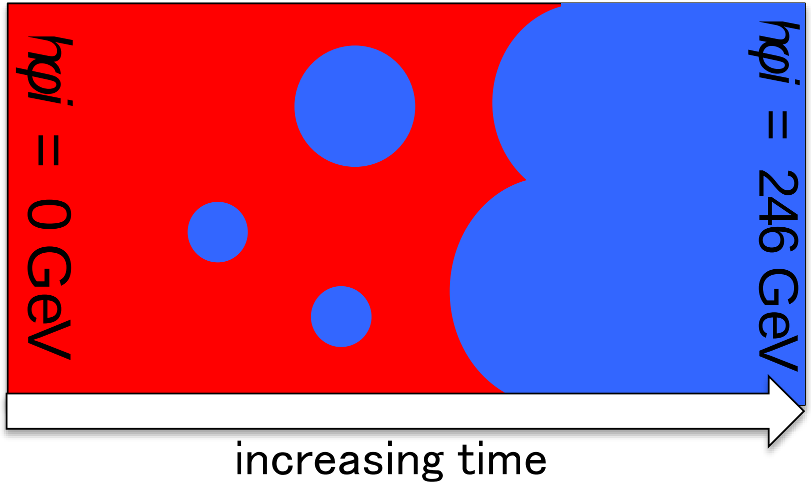
Three Sakharov conditions necessary for matter-antimatter asymmetry:

1. Baryon number violation
2. C and CP symmetries violated
3. Interactions out of thermal equilibrium

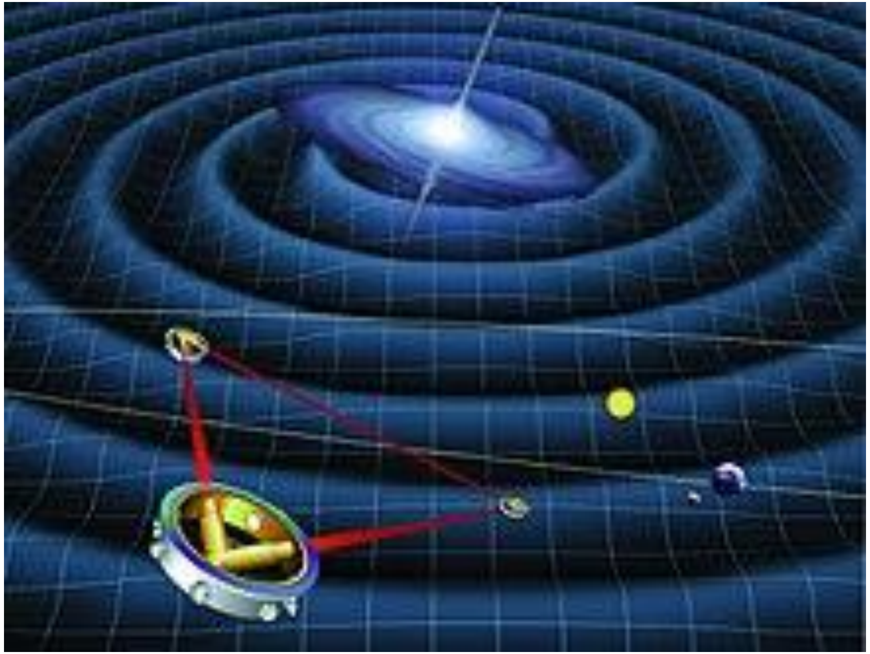
Continuous Crossover



First Order Phase Transition

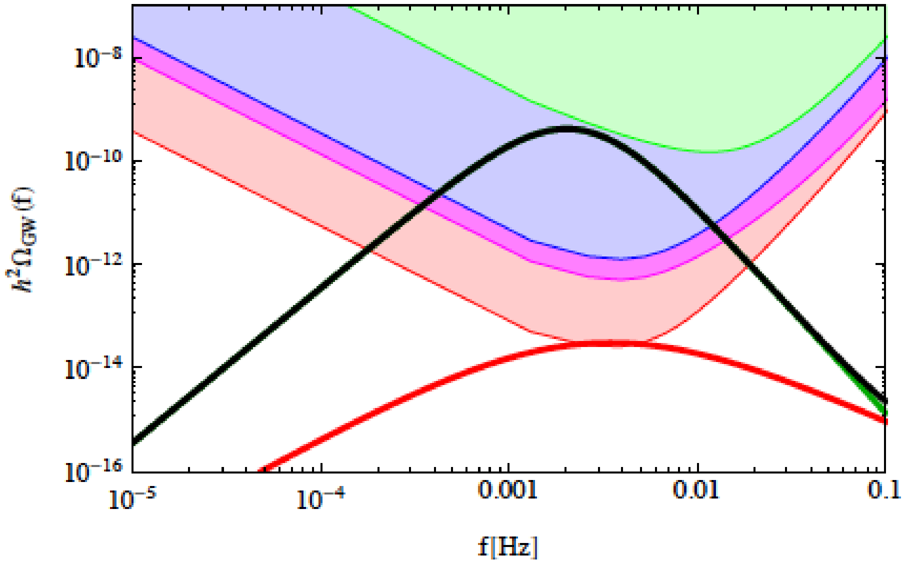


Consequences: 1st order phase transition



- **Gravitational waves if PT strong**
- **Could be detectable by LISA interferometer**

arXiv: 1512.06239

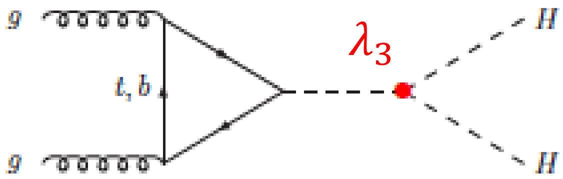


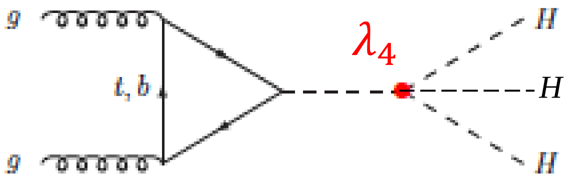
Electroweak potential: generically

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + O(H^5)$$

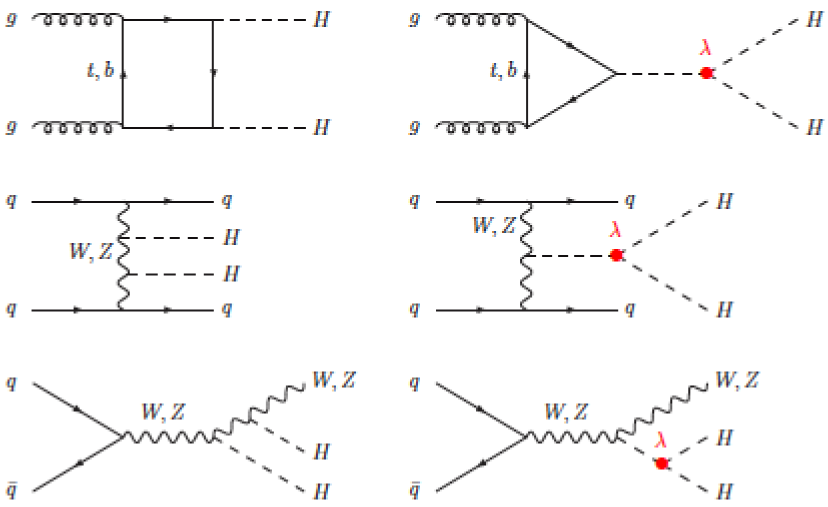
⇒ Goal: determine λ_3 and λ_4 experimentally

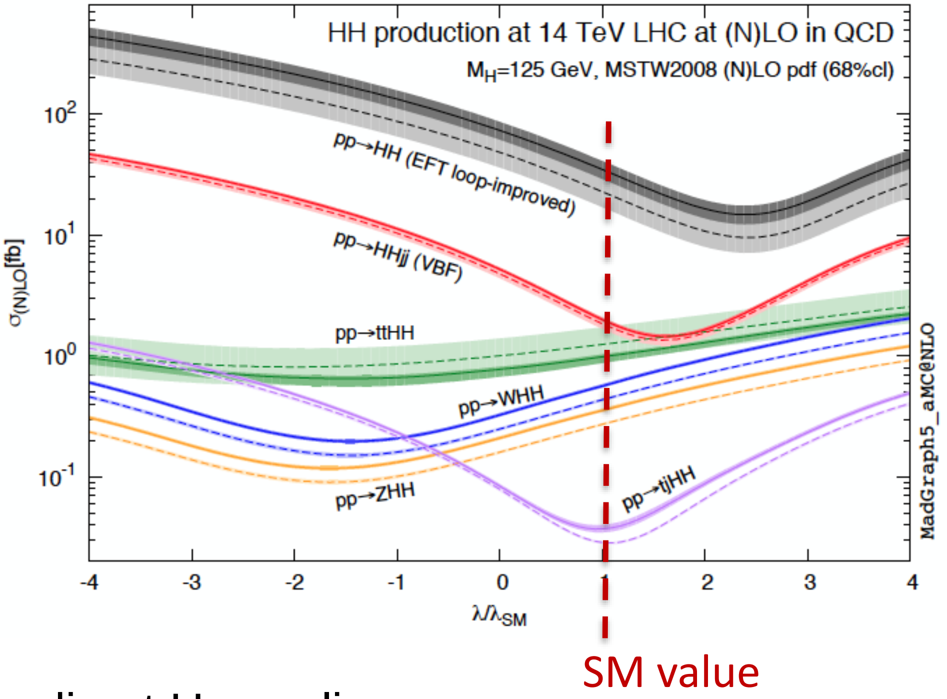
⇒ measure Higgs triple and quartic self-couplings





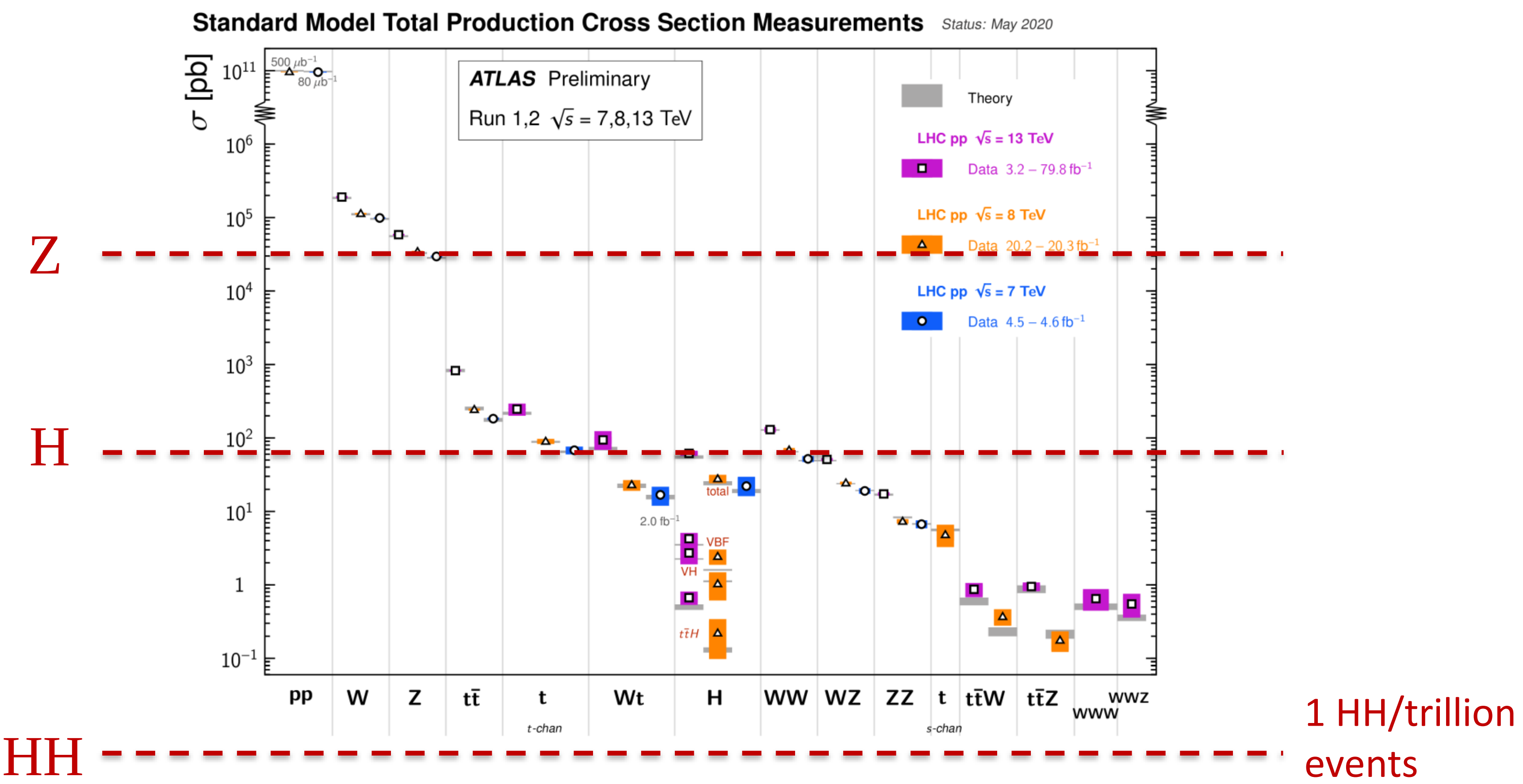
Di-Higgs Production at the LHC





- Di-Higgs production also occurs w/o direct H coupling
  - Destructive interference of the processes
- Cross section very low: 40 fb

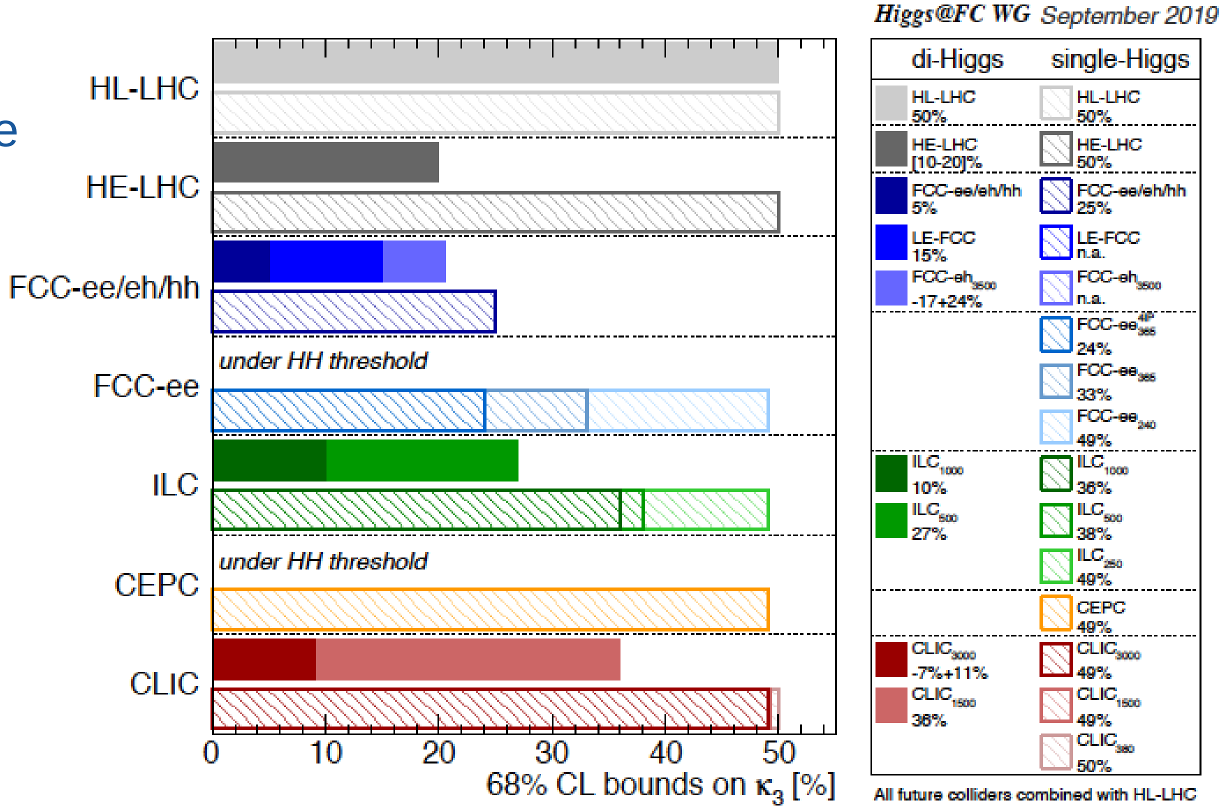
Standard Model Cross Sections at the LHC



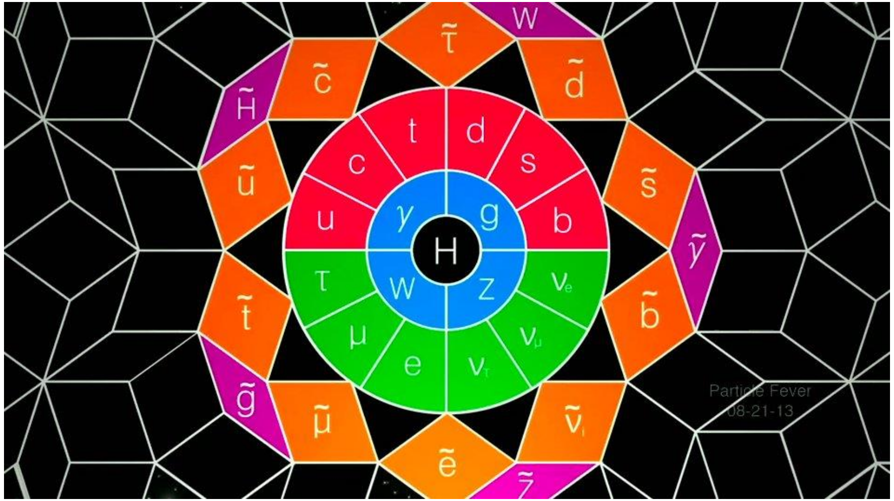
Sensitivity to λ_3: future colliders

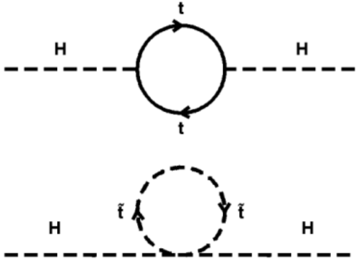
- HL-LHC: ~50%
  - Already relevant for phase transition!
- Future high-energy colliders: 5-10%
  - FCC-hh : 5%
  - CLIC & ILC1 TeV: ~10%

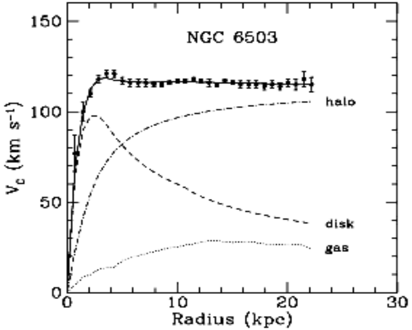
- At FCC-hh: access to λ_4



Supersymmetry

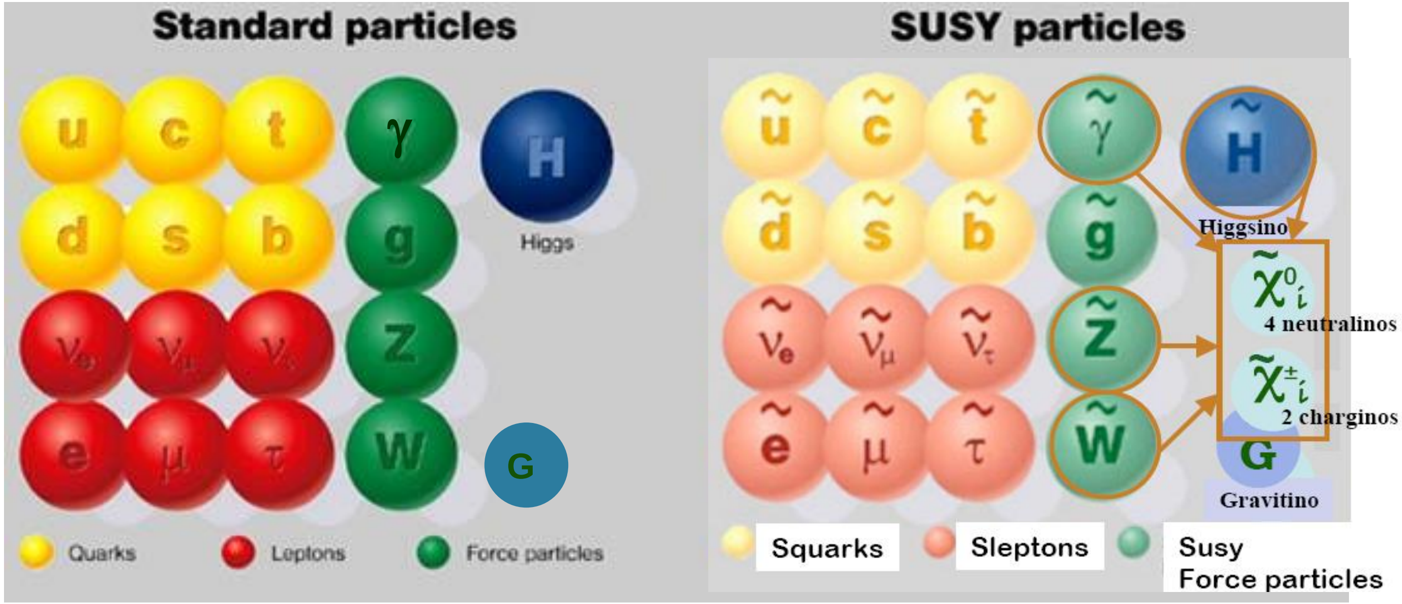


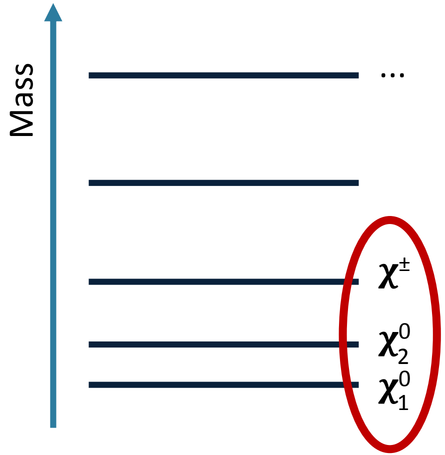




- Supersymmetry well motivated
  - Can solve/reduce finetuning problem
  - Has natural candidate for dark matter => focus here on gaugino sector
  - Enables unification of gauge forces at GUT scale
  - Can provide explanation for g-2 anomaly

Supersymmetric particles

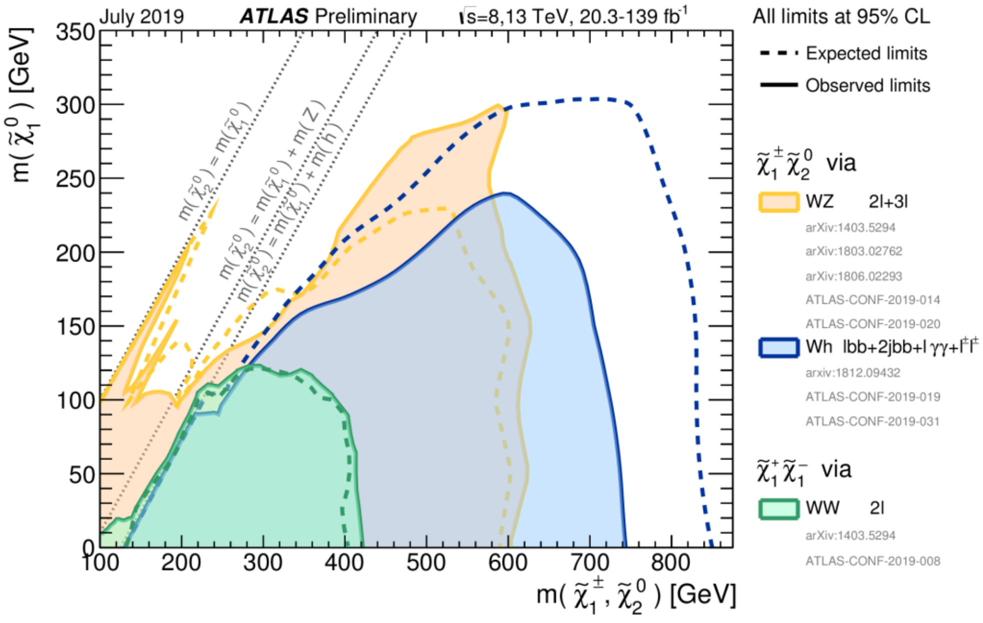




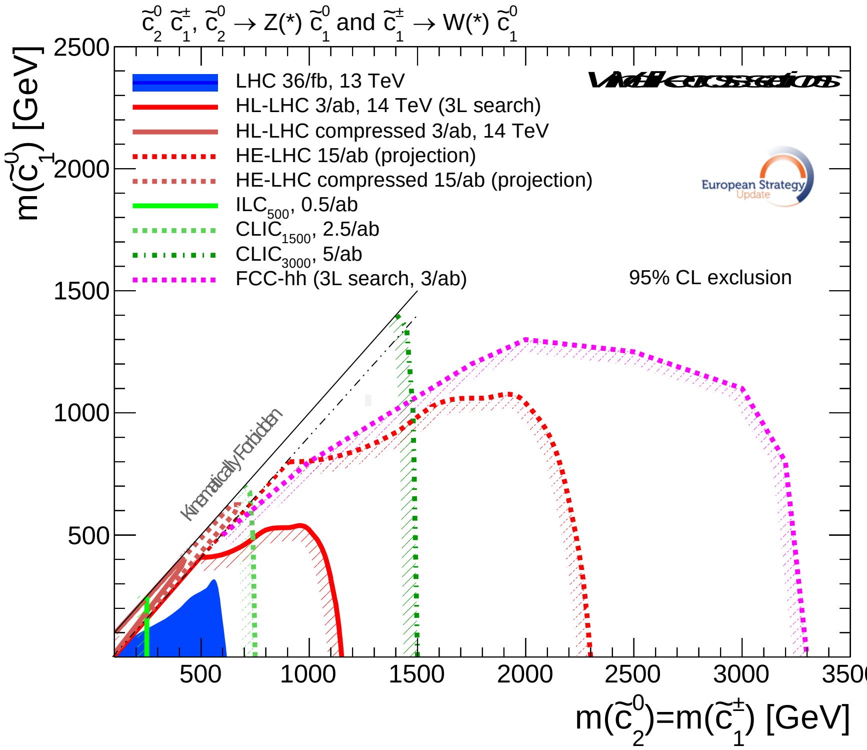
- Superpartners of W, Z, photon and H mix
  - Mass eigenstates are charginos $\chi_i^{\pm}$ and neutralinos χ_i^0
  - Lightest neutralino (χ_1^0) is DM candidate
- Phenomenology of χ_1^0 lightest depends on mixing scenario “Wino, Higgsino, Bino“
  - Explain DM density in Universe by single particle: m (χ_1^0) = 2.7 TeV (Wino) or 1.1 TeV (Higgsino)

Charginos and Neutralinos

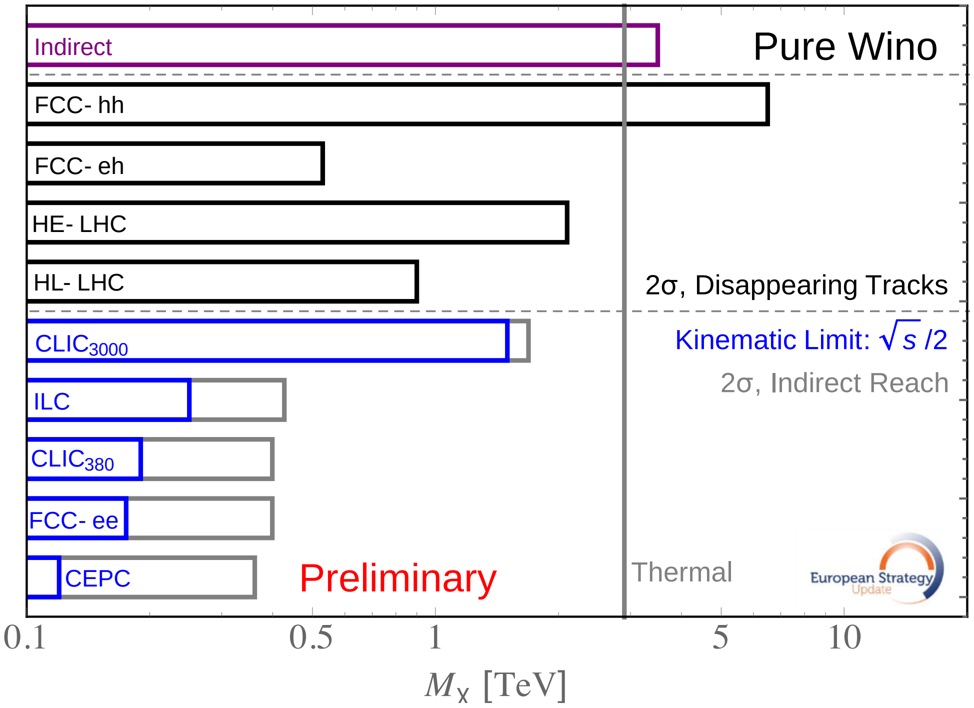
Present constraints



Future constraints

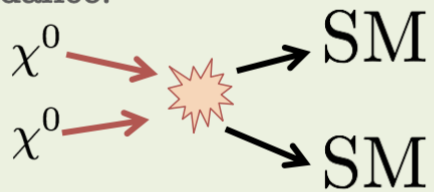


Sensitivity to dark matter: Wino case



Thermal Abundance

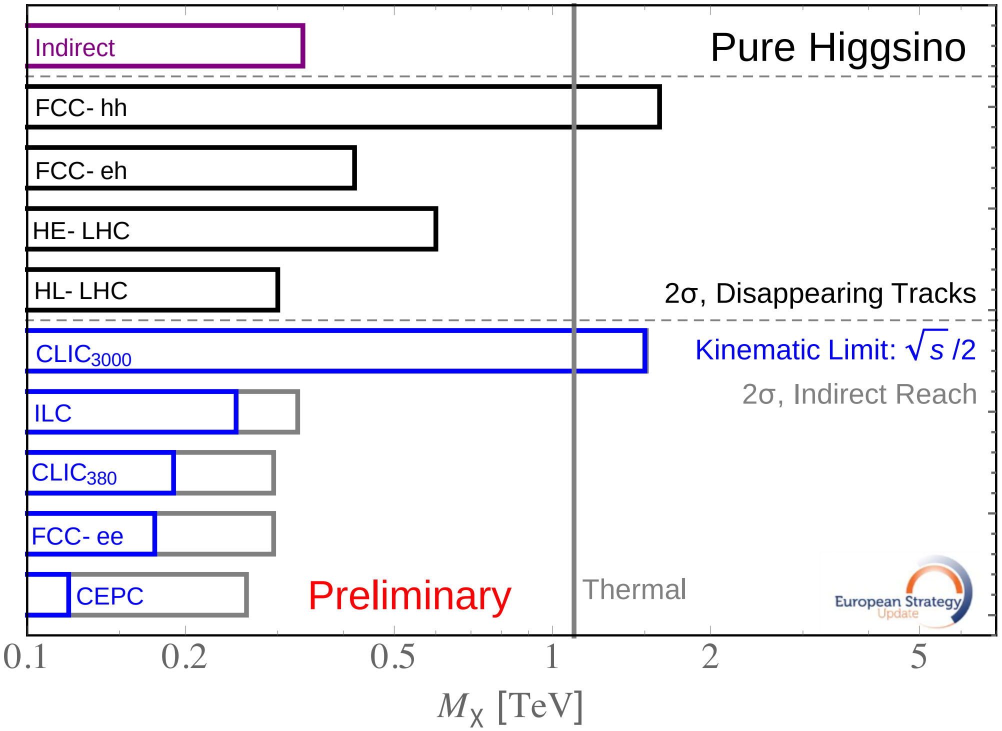
Annihilations in the early Universe determine, under some assumptions, the relic abundance:



For Winos, obtaining the abundance this way requires a mass in the ballpark of 2.9 TeV.

M. McCollough

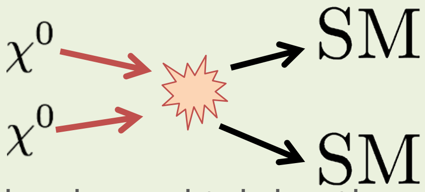
Sensitivity to dark matter: Higgsino case



M. McCollough

Thermal Abundance

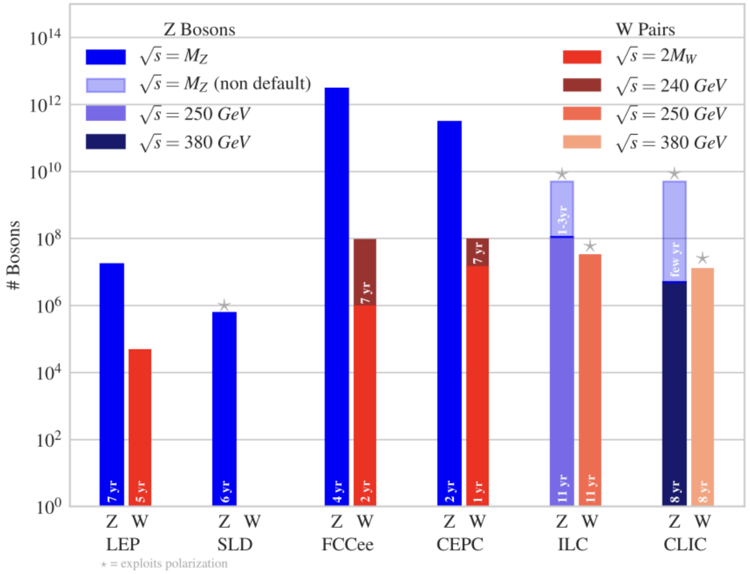
Annihilations in the early Universe determine, under some assumptions, the relic abundance:



For Higgsinos, obtaining the abundance this way requires a mass in the ballpark of 1.1 TeV.

Summary of new collider motivations

- Higgs precision
  - Probe finetuning to ~0.1%
  - Anomalies in fermion couplings?
  - Anomalous H decays (to new particles)?
- Higgs-self coupling
  - What is the order of the EW phase transition?
- Improve reach for new particle searches
  - High mass (hh, μμ and linear ee) and low couplings (ee colliders)
  - E.g. probe thermal WIMP scenario at FCC-hh and muon collider
- ee colliders are Z factories
  - Electroweak precision
  - Flavor factories => see later
- ...



Fun fact:
# of Z's in 15' of FCC-ee equal to 7 years at LEP

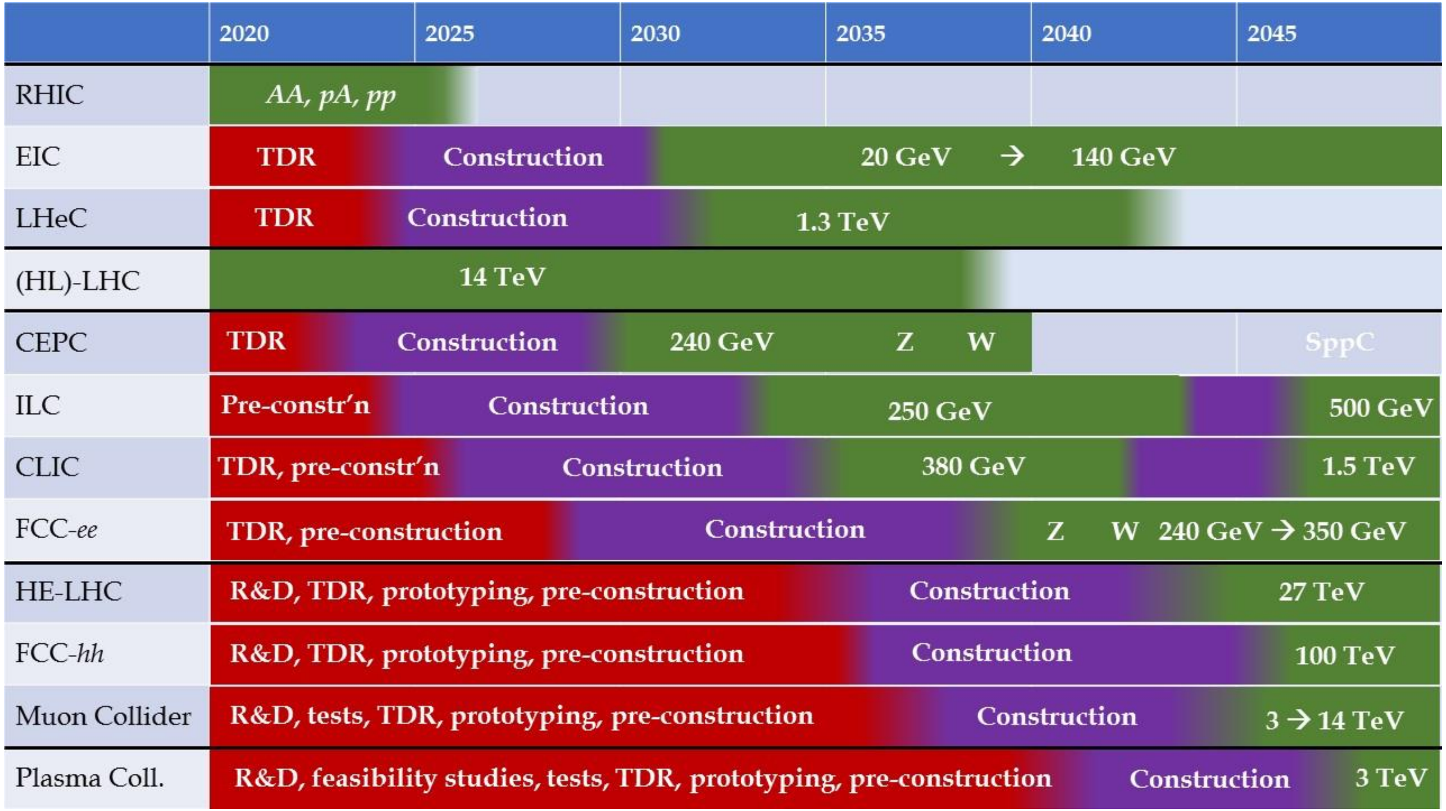
Accelerator R&D: statement & recommendation

b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

Roadmap being defined by lab directors group by end of 2021,
⇒ see talk by D. Newbold at EPS conference

Future Colliders: Schedule

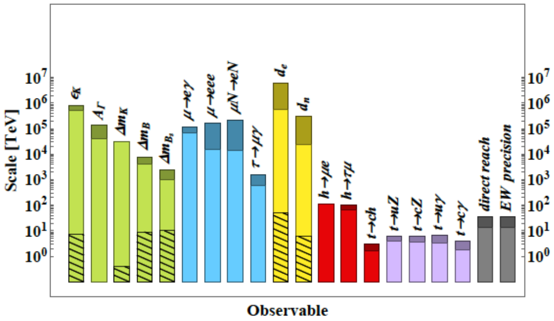
arXiv: 2003.09084: V. Shiltsev, F. Zimmermann

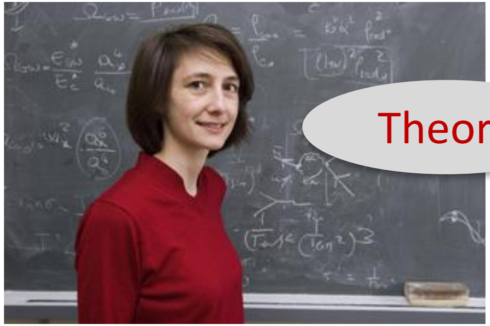


(purely technical driven, w/o funding considerations)

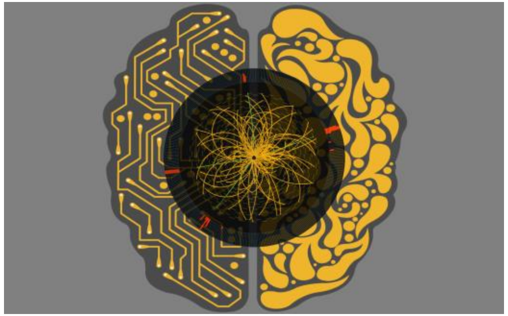
Other essential scientific activities

4 recommendations





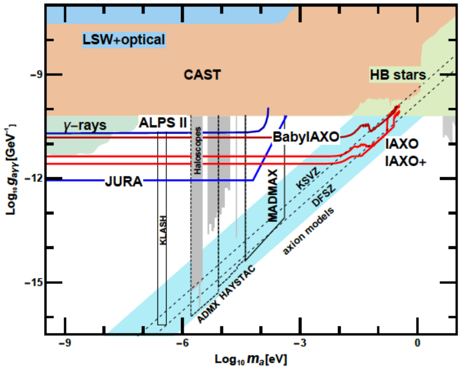
Theory



Diverse Science

Instrumentation

Computing



Diverse science programme: strategy discussion

***Diverse science at low energy*: exploration of dark matter and flavour puzzle**

- **Dark matter**: may have masses between 10^{-22} eV and $10 \mathrm{x} M_{\odot}$ (primordial black holes)
- **Observed pattern of masses and mixings of fermions** remains a huge puzzle
- **Proton structure** understanding needed to fully exploit the potential of present and future hadron colliders
  - added value from fixed target experiments and from ***Electron Ion Collider*** (CD0) in BNL

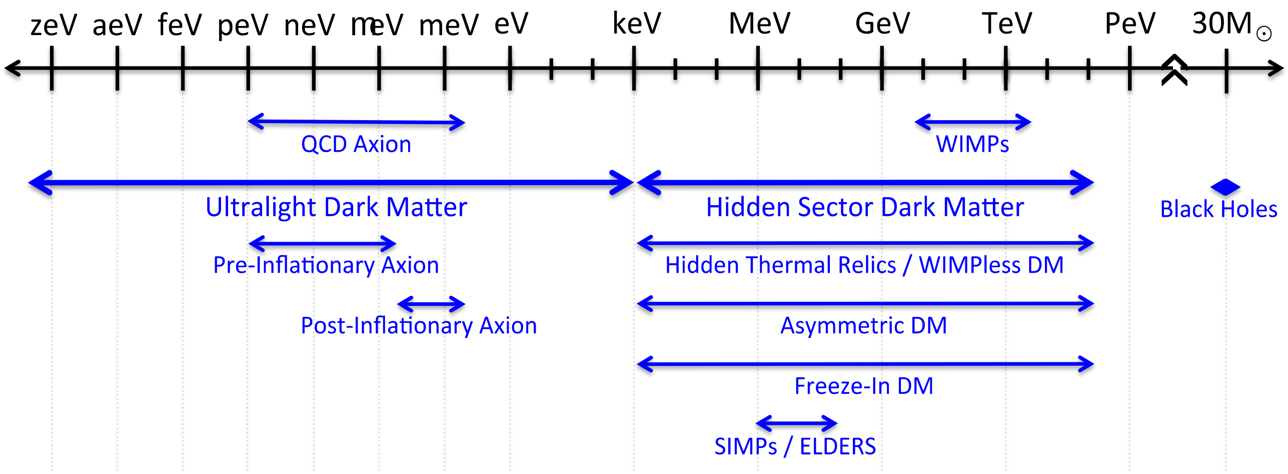
Practical issues:

- ***Beam Dump Facility and LHeC option at CERN, are difficult to resource*** within the CERN budget, considering the other recommendations of this Strategy
- ***Role of the National Laboratories in advancing the exploration of the lower energy regime cannot be over-emphasised***
  - e.g. axions at DESY, rare muon decays in PSI, dark photon in Frascati, COSY as demonstrator for proton EDM in Jülich)

S. Asai, M. Carena

Dark Matter Candidates: Very little clue on mass scales

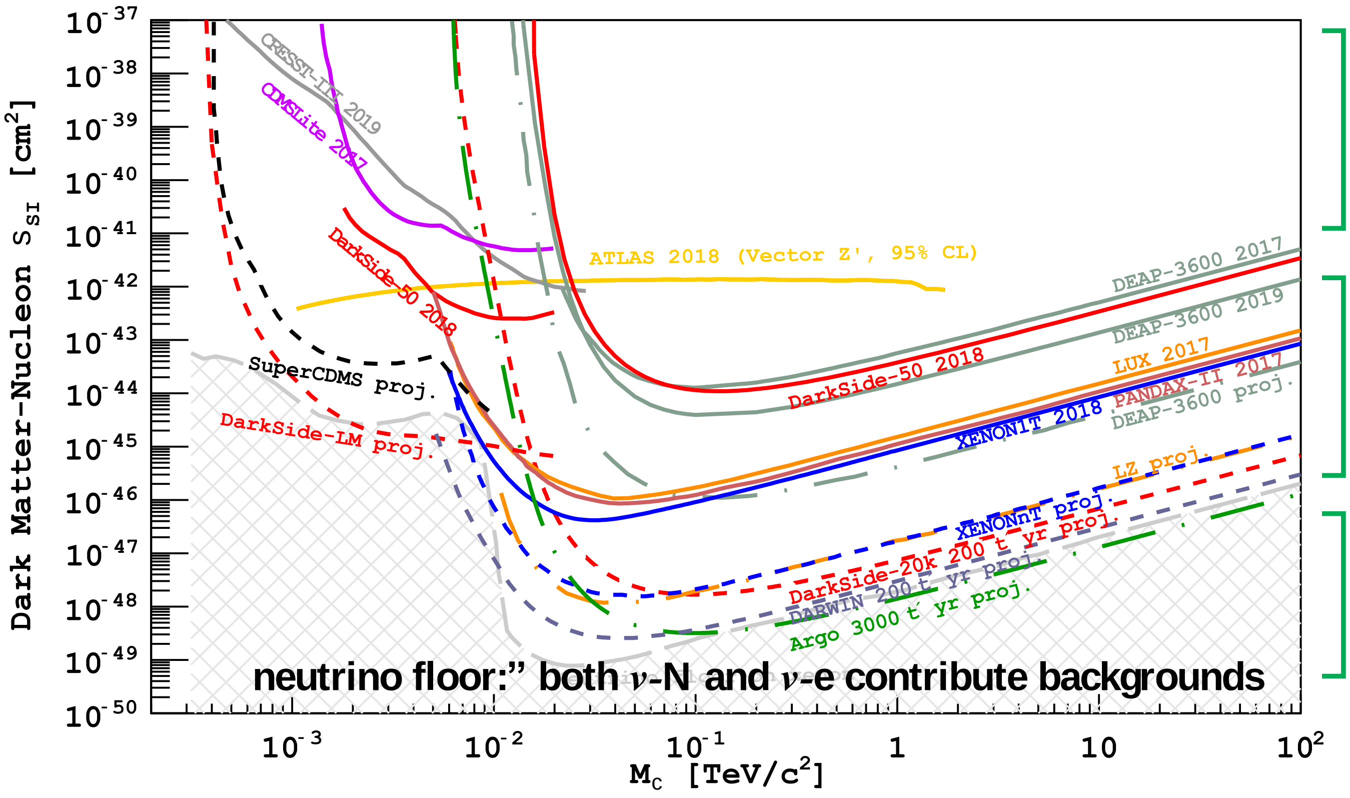
Too small mass
⇒ won’t “fit”
in a galaxy!

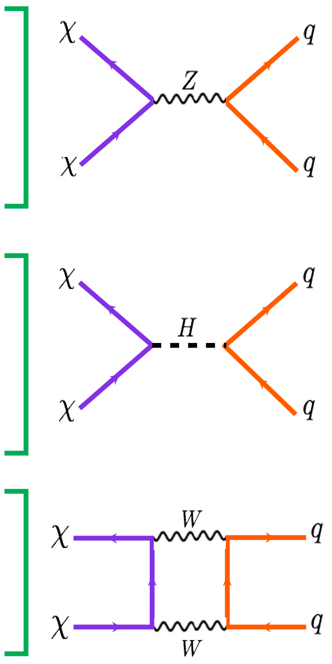


From MACHOs
searches

WIMP Direct Detection Searches

Primary Weak Interactions

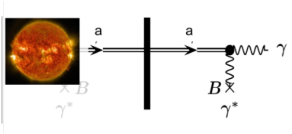




Marching down to the Neutrino Floor

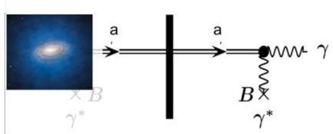
J. Monroe's talk

Axion/ALP searches:
Mature Key Techniques



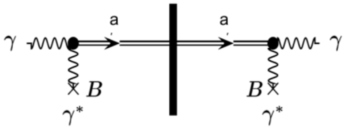
Helioscopes

- Build on success of CAST hosted by CERN
- Proposed BabyIAXO, leads to IAXO, with large discovery potential



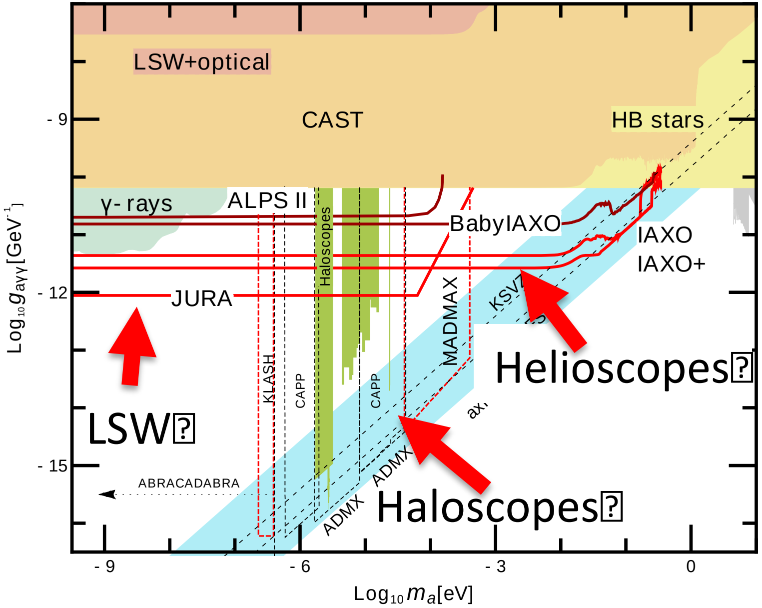
Haloscopes

- ADMX (US) is leading the field
- In Europe, MadMax is new key player
- Smaller efforts developing new techniques



Light-shining-through-walls

- ALPS II is well underway
- STAX is a new idea RF based
- JURA is long term plan

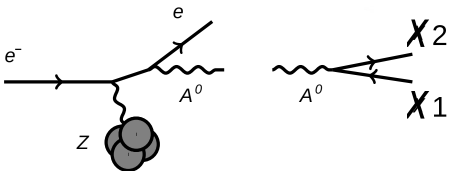


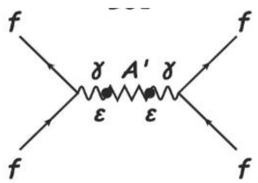
Searches relevant for both QCD Axions and more general Axion-like particles (ALPs)

Lindner and Irastorza's talks

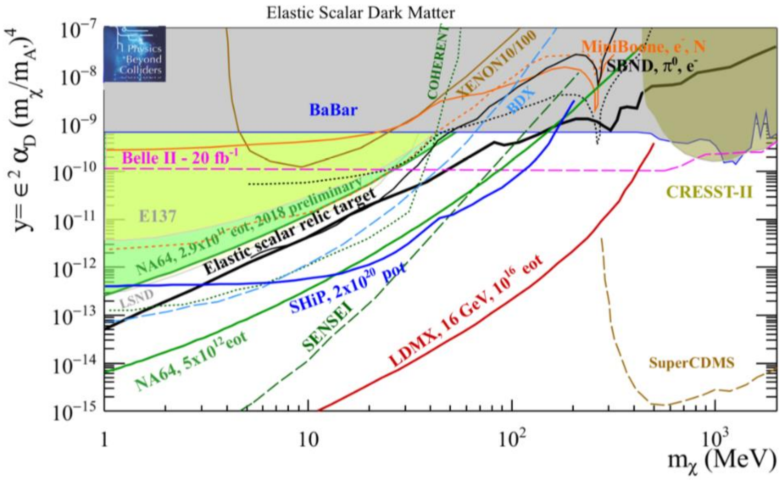
Other Dark Matter Ideas

- Strong motivation for WIMP and QCD axion DM remains
- But many alternative ideas, e.g. dark photon decaying visibly or invisibly

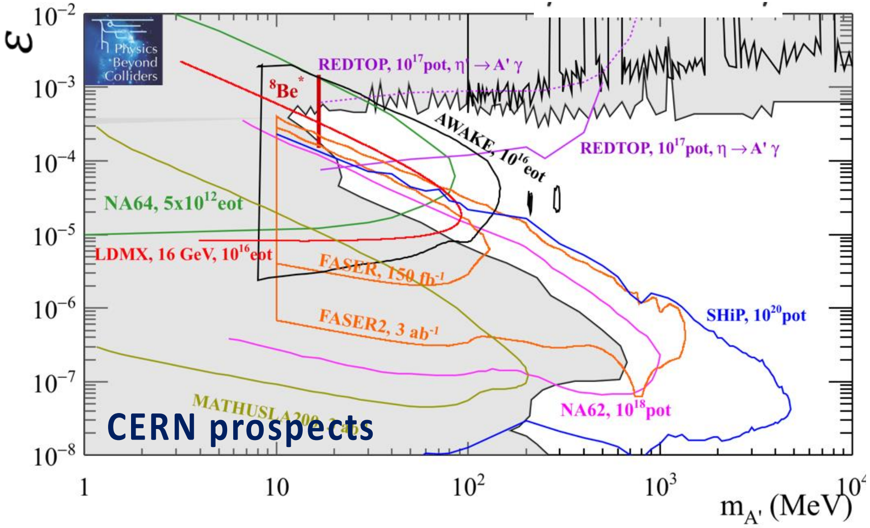




Physics Beyond Colliders at CERN- Beyond the Standard Model Working Group Report (2019) arxiv: 1901.09966



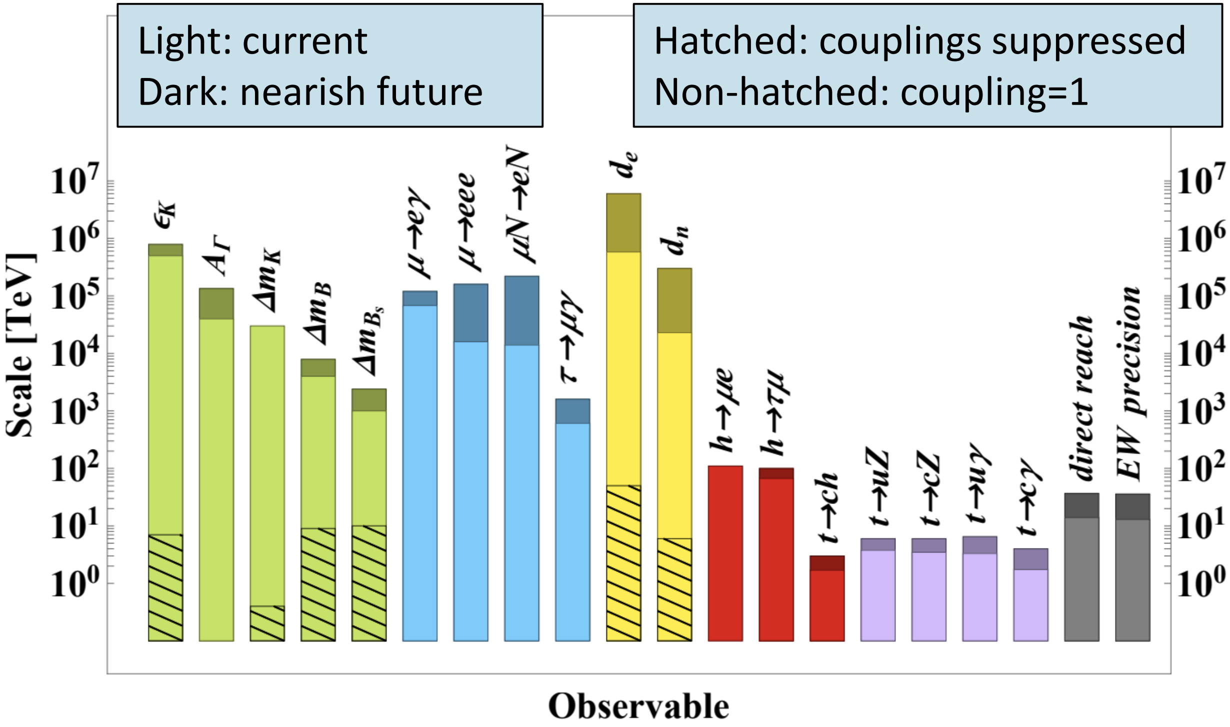
$m_{A^0} = 3m_\chi$ $\alpha_D = 0.1$



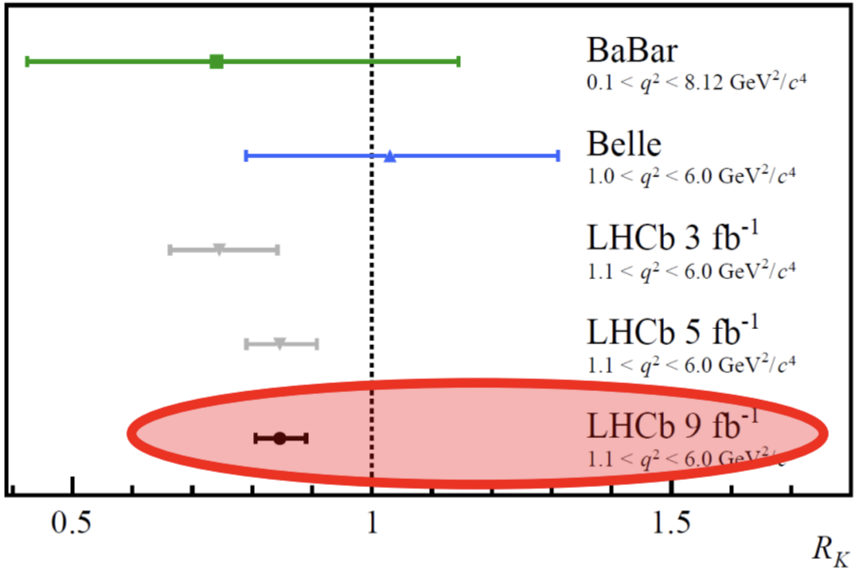
Flavor

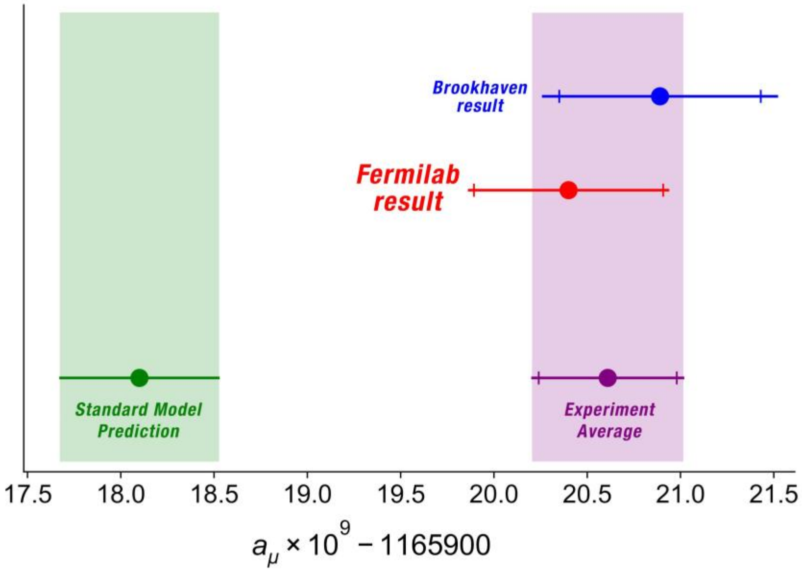
- Flavor is still among the most puzzling features of the SM!
- Flavor probes energy scales way beyond the reach of direct searches
  - Depending on assumption on couplings
- Many very interesting experiments ongoing

Nearish future:
HL-LHC, Belle-II, MEG-II, Mu2e, Mu3e, COMET, ACME, PIC, SNS



Flavor II





- Several anomalies related to muons require follow-up
  - $\mathrm{B} \to H\mu^+\mu^- / B \to He^+e^-$
  - muon g-2
- Circular ee colliders are excellent B-factories too (Tera-Z mode)

Diverse science programme: statement and recommendation

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

Theory: statement and recommendation

b) Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities. *Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.*

Instrumentation: statement and recommendation

c) The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. *Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.*

Roadmap to be followed up by ECFA (ECFA=European Committee for Accelerators)
=> See talk by P. Allport at EPS

Computing & Software: statement and recommendation

d) Large-scale data-intensive software and computing infrastructures are an essential ingredient to particle physics research programmes. The community faces major challenges in this area, notably with a view to the HL-LHC. As a result, the software and computing models used in particle physics research must evolve to meet the future needs of the field. *The community must vigorously pursue common, coordinated R&D efforts in collaboration with other fields of science and industry to develop software and computing infrastructures that exploit recent advances in information technology and data science. Further development of internal policies on open data and data preservation should be encouraged, and an adequate level of resources invested in their implementation.*

Synergies with neighbouring fields

2 recommendations:

- Nuclear Physics
- Astroparticle Physics

NuPECC

APPEC

Organisational issues

3 recommendations:

a) Global Science, Europe and CERN
b) Relation with European Commission
c) Open Science

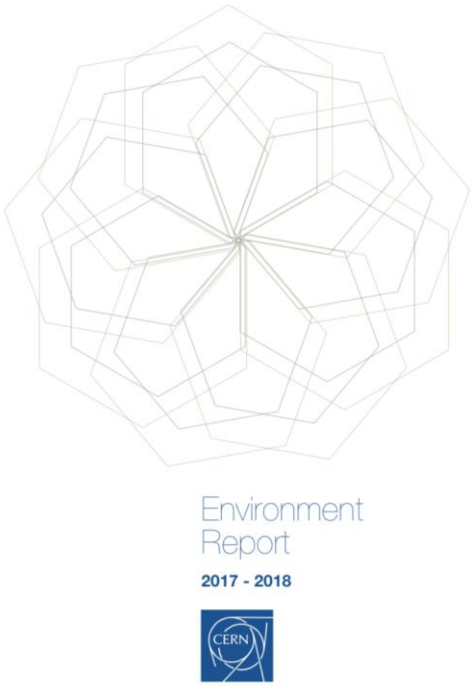
Environmental and societal impact

4 recommendations:

a) Mitigate environmental impact of particle physics
b) Investment in next generation of researchers
c) Knowledge and technology transfer
d) public engagement, education and communication

Environmental impact/climate change: statement and recommendation

a) The energy efficiency of present and future accelerators, and of computing facilities, is and should remain an area requiring constant attention. Travel also represents an environmental challenge, due to the international nature of the field. *The environmental impact of particle physics activities should continue to be carefully studied and minimised. A detailed plan for the minimisation of environmental impact and for the saving and re-use of energy should be part of the approval process for any major project. Alternatives to travel should be explored and encouraged.*



Training the next generation: discussion

Next generations of particle physicists

- The exploratory nature of particle physics and its fundamental questions about the Universe fascinates many inside and outside the field and **draws in talented students**
- National laboratories, research institutes and universities worldwide provide the training ground of future young scientists. Education and training in key technologies are crucial for the needs of the field and society at large
- It is essential to **make the research environment in particle physics as attractive as possible** and in particular to consider the worries expressed by the early career researchers (document under the auspices of ECFA)
- The principles **of equality, diversity and inclusion** should be clearly and recognisably present in all of the field’s activities
    - Training appropriate to this end should be available at CERN and other institutes, and best practices shared among them.

Training the next generation:
statement and recommendation

b) Particle physics, with its fundamental questions and technological innovations, attracts bright young minds. Their education and training are crucial for the needs of the field and of society at large. *For early-career researchers to thrive, the particle physics community should place strong emphasis on their supervision and training. Additional measures should be taken in large collaborations to increase the recognition of individuals developing and maintaining experiments, computing and software. The particle physics community commits to placing the principles of equality, diversity and inclusion at the heart of all its activities.*

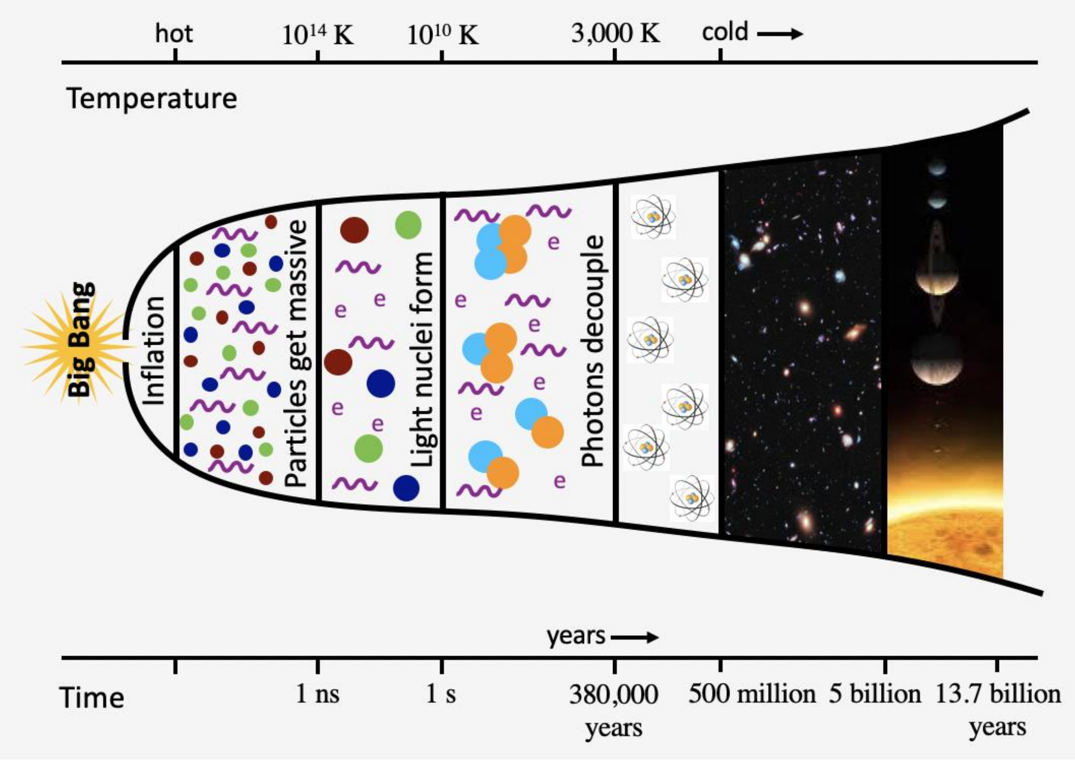
Early-career researchers panel created under the auspices of ECFA,
in which these subjects can be discussed and monitored

Knowledge Transfer & Outreach and Education: statements and recommendations

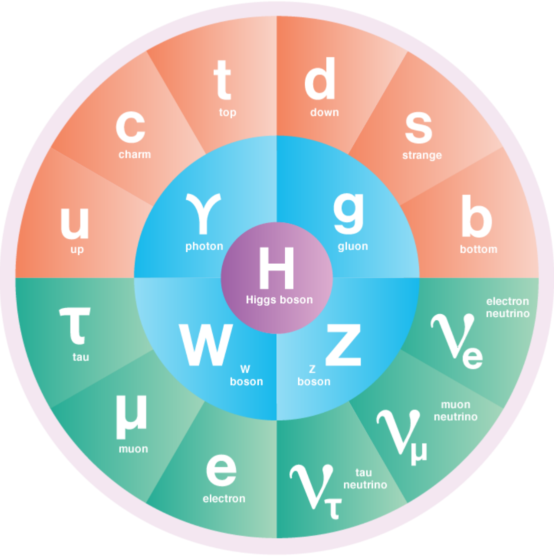
c) Particle physics has contributed to advances in many fields that have brought great benefits to society. Awareness of knowledge and technology transfer and the associated societal impact is important at all phases of particle physics projects. *Particle physics research centres should promote knowledge and technology transfer and support their researchers in enabling it. The particle physics community should engage with industry to facilitate knowledge transfer and technological development.*

d) Exploring the fundamental properties of nature inspires and excites. It is part of the duty of researchers to share the excitement of scientific achievements with all stakeholders and the public. The concepts of the Standard Model, a well-established theory for elementary particles, are an integral part of culture. *Public engagement, education and communication in particle physics should continue to be recognised as important components of the scientific activity and receive adequate support. Particle physicists should work with the broad community of scientists to intensify engagement between scientific disciplines. The particle physics community should work with educators and relevant authorities to explore the adoption of basic knowledge of elementary particles and their interactions in the regular school curriculum*

Concluding Remarks I



from Selya Ipek



⇒ **Exploring the early phase of Universe is likely key to many puzzles in our Universe, e.g. flavor, matter-antimatter asymmetry, dark matter, ...**

Concluding Remarks II

- The questions we have in particle physics today are the most exciting since the beginning of the last century when the structure of the atom was explored

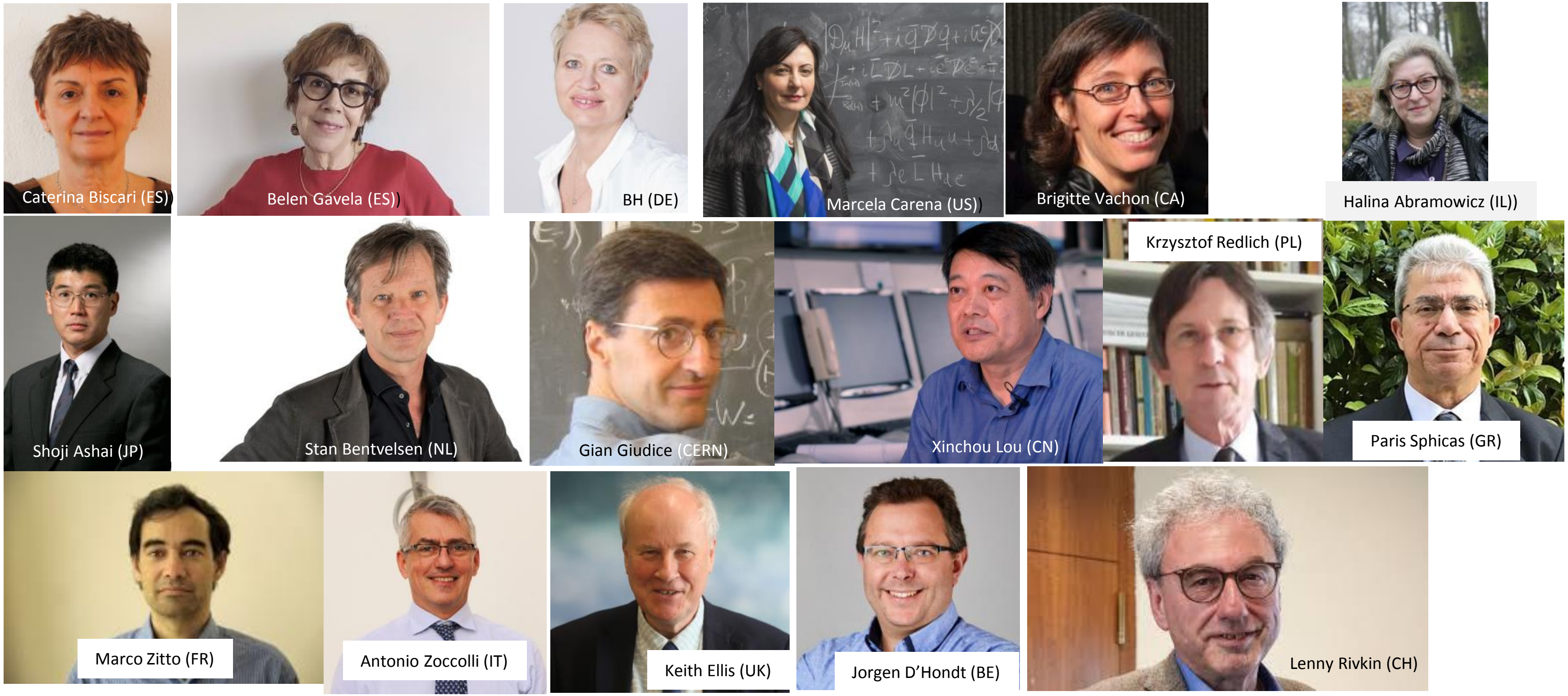
- This 2020 update of the European Strategy for Particle Physics has focussed on both near and long-term priorities for the field.
  - Given the scale of our long-term ambition, the European plan needs to be coordinated with other regions of the world.

- Implementation of strategy has started at CERN, in European Labs and in relevant committees (e.g. ECFA and LDR)

- A further update of the Strategy foreseen in the second half of this decade

Backup

Physics Preparatory Group (PPG)



HL-LHC: statement and recommendation

a) Since the recommendation in the 2013 Strategy to proceed with the programme of upgrading the luminosity of the LHC, the **HL-LHC** project was approved by the CERN Council in June 2016 and is proceeding according to plan. In parallel, the LHC has reached a centre-of-mass energy of 13 TeV, exceeded the design luminosity, and produced a wealth of remarkable physics results. Based on this performance, coupled with the innovative experimental techniques developed at the LHC experiments and their planned detector upgrades, a significantly **enhanced physics potential** is expected with the HL-LHC. The required high-field superconducting Nb_3Sn magnets have been developed. *The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.*

Neutrino Physics: statement and recommendation

b) The existence of non-zero neutrino masses is a compelling sign of new physics. The **worldwide neutrino physics programme** explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. *Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).*

Global Projects, Europe and CERN: discussion

Global projects, Europe and CERN

- **Large future projects, because of their size, complexity, duration and cost, will need to be planned on a global scale**
- Need to consider governance and funding around either CERN hosting a next-generation collider as a **globally funded project** or a European contribution to a next-generation collider constructed outside Europe, and specifically the role that CERN would play
- For the case of a **new global facility hosted at CERN, long-term commitments are needed from non-European states** and must take account of both construction and operating costs and must be compatible with the provisions of the CERN Convention
- For the case of a **European contribution to a new global facility outside Europe, CERN should**, if so decided by the CERN Council**, provide strategic coordination and technical support for European contributions**
- The modalities of European participation in a global facility outside Europe remain to be decided, as and when the need occurs

Theory: discussion

Essential role of theory for advancement in particle physics

- European theoretical research spans a wide range of subjects, from **abstract ideas of string theory to the detailed simulation of collider physics processes**
- Results from neighbouring fields, such as cosmology, nuclear physics and astrophysics, condensed matter and atomic physics, computation and quantum information enrich the scientific dialogue
- **Theory plays an essential role in assessing the strategic importance** for future investments in accelerators and experimental infrastructure
- Calculation-intensive areas such as precision phenomenology at colliders, lattice field theory or the development of Monte-Carlo event generators and other software tools require long time scales to yield results
- Outreach activities benefit from the special perspective that theoretical physicists bring

Neutrino oscillations: discussion

Neutrino oscillations are a compelling sign of new physics, making neutrinos massive particles

- Essential to pursue the exploration of the neutrino sector with accelerator, reactor, solar, atmospheric and cosmic neutrino experiments
- Two complementary approved programmes are in preparation with the DUNE (US) and Hyper-Kamiokande (Japan) experiments
  - strong participation of European physicists with CERN support through the Neutrino Platform
- The community is very keen for the Neutrino Platform to continue operation at CERN
- Balanced European support for this worldwide effort important to secure the determination of neutrino properties

Environmental and Societal Impact: discussion

Climate change and particle physics

- In a world with increasing demand on limited resources and undergoing climate change it is crucial to keep energy consumption, sustainability and efficiency in mind when discussing the future of particle physics
- In the discussion of the optimal choice for a new facility, **the energy efficiency of the accelerator should** be considered alongside factors such as cost, timescale and physics reach
- Research into environmentally-friendly alternatives for materials with high global warming potential for use in particle physics detectors should be strongly stimulated and supported
- The community should invest in both hardware and software efforts to improve the energy efficiency of its computing infrastructures
- The community is expected to be in the vanguard of alternatives to physical travel such as virtual meeting rooms. and should support low-carbon forms of travel and carbon offsetting, whenever travel is unavoidable

Synergies with other fields: statements and recommendations

Particle, Nuclear and Atomic Physics

- **CERN has a strong nuclear physics programme**: ISOLDE and n_TOF facilities & the HI programme at LHC
- Future European facilities (**FAIR, NICA , ESS**) and **EIC** in the US envisage research programmes of interest to HEP
- There are also **synergies with atomic physics**, e.g. antihydrogen experimental programme at CERN's AD antiproton decelerator and its upgrade, ELENA.
- Particle and laser physicists aspire to explore the **strong field of QED by joining forces at the EU-XFEL facility** in Hamburg.
- The nuclear physics roadmap in Europe is coordinated by the Nuclear Physics European Collaboration Committee (NuPECC) and there are well established communication lines between the two communities

a) A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments and facilities. Europe has a vibrant nuclear physics programme at CERN, including the heavy-ion programme, and at other European facilities. In the global context, a new electron-ion collider, EIC, is foreseen in the United States to study the partonic structure of the proton and nuclei, in which there is interest among European researchers. *Europe should maintain its capability to perform innovative experiments at the boundary between particle and nuclear physics, and CERN should continue to coordinate with NuPECC on topics of mutual interest.*

Synergies with other fields: statements and recommendations

Particle and Astroparticle Physics

- **Synergies exist at the level of infrastructure, detectors, computing, interaction models and physics goals** (ex.: neutrinos, dark matter, cosmic rays and gravitational waves)
- The need to foster these synergies has been clearly identified in the national inputs
- The astro-particle physics roadmap in Europe is coordinated by APPEC; APPEC seeks strong cooperation with CERN
- The APPEC theory centre for AP physics, EuCAPT, was established recently: CERN chosen as first host
- It would be appropriate to establish a new procedure (like "Recognised Experiments") for **collaborations seeking CERN's technical support**, which should be limited to providing technical expertise and infrastructure services in a **cost-neutral way** for CERN

a) Astroparticle physics, coordinated by APPEC in Europe, also addresses questions about the fundamental physics of particles and their interactions. The ground-breaking discovery of gravitational waves has occurred since the last Strategy update, and this has contributed to burgeoning multi-messenger observations of the universe. *Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.*

B. Gavela, A. Zoccoli

Flavor

- Large variety of flavor physics probes ongoing and/or being considered
  - EDM: n, p
  - Kaon: $K \to \pi\nu\nu$
  - Lepton: $\mu \to e\gamma, \mu \to eee$
  - Charm and B: LHCb, Belle-II
  - Top: $t \to cH, t \to cZ, \ldots$
  - Higgs: $H \to \tau\mu, \tau e, \mu e, \ldots$
- Realisation that Tera-Z is excellent B-factory too

Conclusions

Flavor physics crucial for BSM search:

- Outstanding BSM scale reach → $\Lambda > 10^2 – 10^5$ TeV
- Complementarity of low-energy, HE frontier and feebly interacting searches

Flavour is a major legacy of LHC:

- Main results from LHCb. ATLAS and CMS also contributing and enlarging their flavor physics scope

→ Charged hadron PID is mandatory for a full physics program.

→ Essential that HE future experiments follow this same path

- Important to have experiments in very different environments (pp and e+e-), and with PID

In the longer term:

- Z_0-factory is a fantastic tool for Flavor Physics

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Strategy Secretariat

- H. Abramowicz (Chairperson)
- J. D'Hondt (ECFA Chairperson, *ECFA: European Committee for Future Accelerators*)
- K. Ellis (SPC Chairperson, *SPC: Science Policy Committee @ CERN*)
- L. Rivkin (European LDG Chairperson, *LDG: Lab Directors Group*)

- Contact: EPPSU-Strategy-Secretariat@cern.ch

Responsible for the organization of the process.

Composition of the PPG

Physics Preparatory Group (PPG), Council appointment, September 2018:

- H. Abramowicz, J. D'Hondt, K. Ellis, L. Rivkin (*Strategy Secretary*)
- C. Biscari (ES), Belen Gavela (ES), Beate Heinemann (DE), Krzysztof Redlich (PL)
- Stan Bentvelsen (NL), Paris Sphicas (GR), Marco Zito (FR), Antonio Zoccoli (IT)
- Gian Giudice (*CERN*)
- Shoji Asai and Xinchou Lou (*delegates from Asia*)
- Marcela Carena and Brigitte Vachon (*delegates from the Americas*)

Responsible to organize the Open Symposium and to deliver to the European Strategy Group (ESG) a Briefing Book.

European Strategy Update

Names at
http://europeanstrategyupdate.web.cern.ch/composition-esg

Composition of the ESG

European Strategy Group (ESG) composition, adopted by Council, December 2013:

- the Strategy Secretary (acting as Chairperson),
- one representative appointed by each CERN Member State,
- one representative for each of the Laboratories participating in the major European Laboratory Directors' meeting, including its Chairperson,
- the CERN Director-General,
- the SPC Chairperson,
- the ECFA Chairperson.

Responsible to deliver a draft Strategy Update to Council.

Invited:

- the President of the CERN Council,
- one representative from each of the Associate Member States,
- one representative from each Observer State,
- one representative from the European Commission and JINR,
- the Chairpersons of ApPEC, FALC, ESFRI, and NuPECC,
- the members of the Physics Preparatory Group.

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- the ECFA Chairperson.

For Germany: Siggi Bethke

For DESY: Joachim Mnich

Responsible to deliver a draft Strategy Update to Council.

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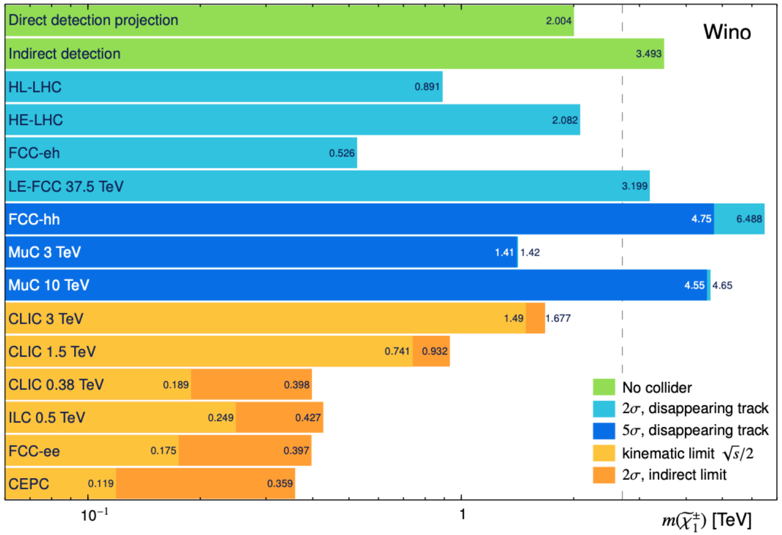
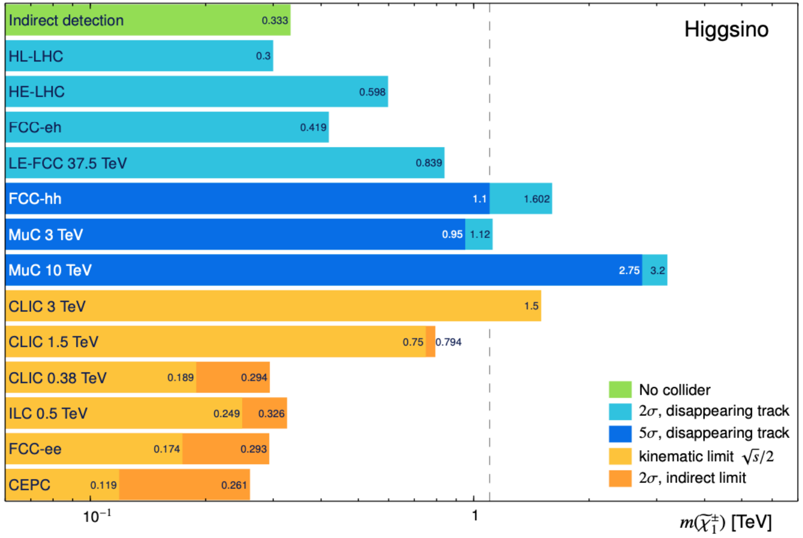
- the members of the Physics Preparatory Group.

Incl. BH

SUSY DM reach at Muon Colliders

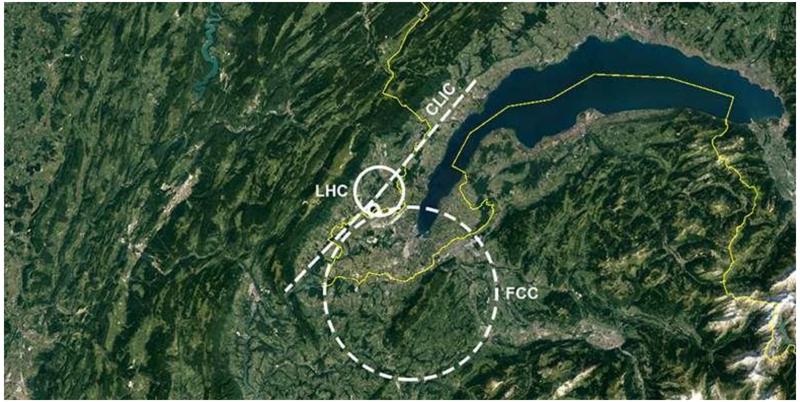
arXiv:2102.11292
(Capdevilla, Meloni, Simonello, Zurita)





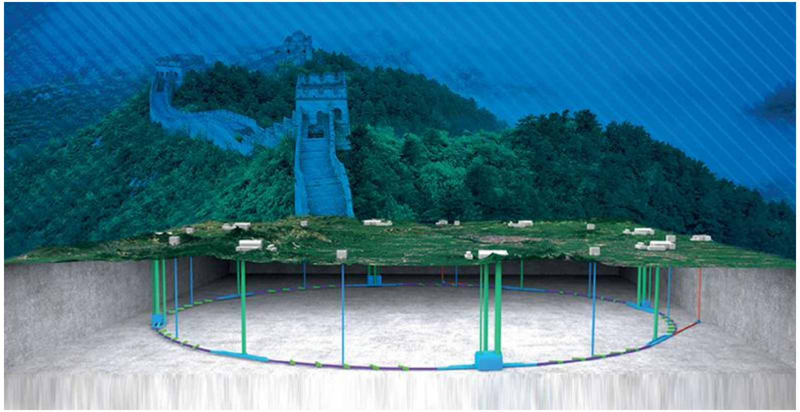
- Muon collider has very competitive physics reach compared to FCC

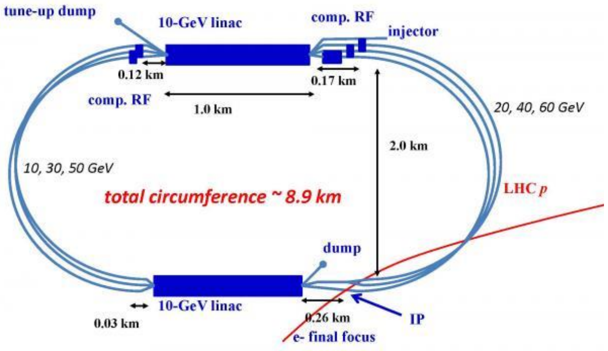
Future Colliders



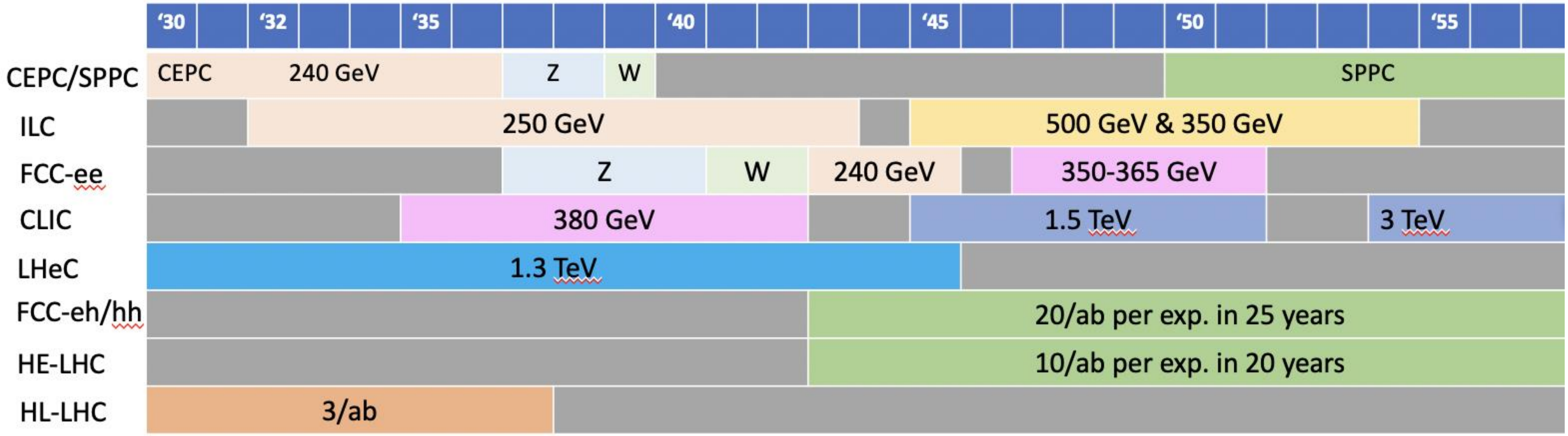
Proposed colliders:

- Linear e+e-: ILC, CLIC
- Circular e+e-: FCC-ee, CePC
- pp: HE-LHC, FCC-hh, SppC
- ep: LHeC, FCC-eh





Future Colliders: √s and tentative timescales



Global Projects, Europe and CERN: statement and recommendation

a) An ambitious next-generation collider project will require global collaboration and a long-term commitment to construction and operations by all parties. *CERN should initiate discussions with potential major partners as part of the feasibility study for such a project being hosted at CERN. In the case of a global facility outside Europe in which CERN participates, CERN should act as the European regional hub, providing strategic coordination and technical support. Individual Member States could provide resources to the new global facility either through additional contributions made via CERN or directly through bilateral and multilateral arrangements with the host organisation.*

European Commission & Open Science: statements and recommendations

b) The particle physics community and the European Commission have a strong record of collaboration. *The relationship between the particle physics community and the European Commission should be further strengthened, exploring funding-mechanism opportunities for the realisation of infrastructure projects and R&D programmes in cooperation with other fields of science and industry.*

c) European science policy is quickly moving towards Open Science, which promotes and accelerates the sharing of scientific knowledge with the community at large. Particle physics has been a pioneer in several aspects of Open Science. *The particle physics community should work with the relevant authorities to help shape the emerging consensus on Open Science to be adopted for publicly-funded research, and should then implement a policy of Open Science for the field.*

CERN’s Leadership Role

Considerations (from deliberation document):

- With the construction and efficient operation of the LHC, CERN has established itself as the world's premier particle physics laboratory
- Cooperation between the Member, Associate Member and non-Member States and the concentration of the European particle-physics effort at CERN have created a unique resource in terms of scientific accomplishments, human capital, international collaboration, technical expertise, and research infrastructure
- CERN and other accelerator-based laboratories worldwide use cutting-edge technologies (RF cavities, superconducting magnets, cryogenics and high vacuum, management of large data volumes, etc.). shared throughout Europe for the benefit of the Member and Ass. Member States

a) Europe, through **CERN**, has world leadership in accelerator-based particle physics and related technologies. The future of the field in Europe and beyond depends on the continuing ability of CERN and its community to realise compelling scientific projects. *This Strategy update should be implemented to ensure Europe’s continued scientific and technological leadership.*

European Ecosystem

European Ecosystem:

- European National Laboratories collaborate, together with research institutes and universities, in large programmes at CERN and in activities performed locally and at other large laboratories
- European research centres provide a variety of large technical platforms dedicated to development, testing and production of accelerator and detector components
- European research centres afford fruitful synergies with other communities that go well beyond the boundaries of particle physics
- High visibility of European research centres in supranational large projects

b) The European organisational model centred on close collaboration between CERN and the national institutes, laboratories and universities in its Member and Associate Member States is essential to the enduring success of the field. This has proven highly effective in harnessing the collective resources and expertise of the particle, astroparticle and nuclear physics communities, and of many interdisciplinary research fields. Another manifestation of the success of this model is the collaboration with non-Member States and their substantial contribution. *The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.*

Global nature of particle physics research

Global nature of particle physics research

- The increase in scale of the leading particle physics facilities and the resulting decrease in their number worldwide has led to the globalisation of the field
- The timely realisation of complementary, large-scale projects in different regions of the world remains essential for the progress of the field, as well as for the development of the key technologies
- Europe has chosen to participate in the long-baseline programmes in Japan and the US rather than building its own facility. Instead, it has secured reciprocal support for the realisation of the HL-LHC project.
- Europe's long-term vision is to maintain its leadership in pushing the exploration of the energy frontier, and this vision is supported by the other regions

c) The broad range of fundamental questions in particle physics and the complexity of the diverse facilities required to address them, together with the need for an efficient use of resources, have resulted in the establishment of a global particle physics community with common interests and goals. This Strategy takes into account the rich and complementary physics programmes being undertaken by Europe's partners across the globe and of scientific and technological developments in neighbouring fields. *The implementation of the Strategy should proceed in strong collaboration with global partners and neighbouring fields.*