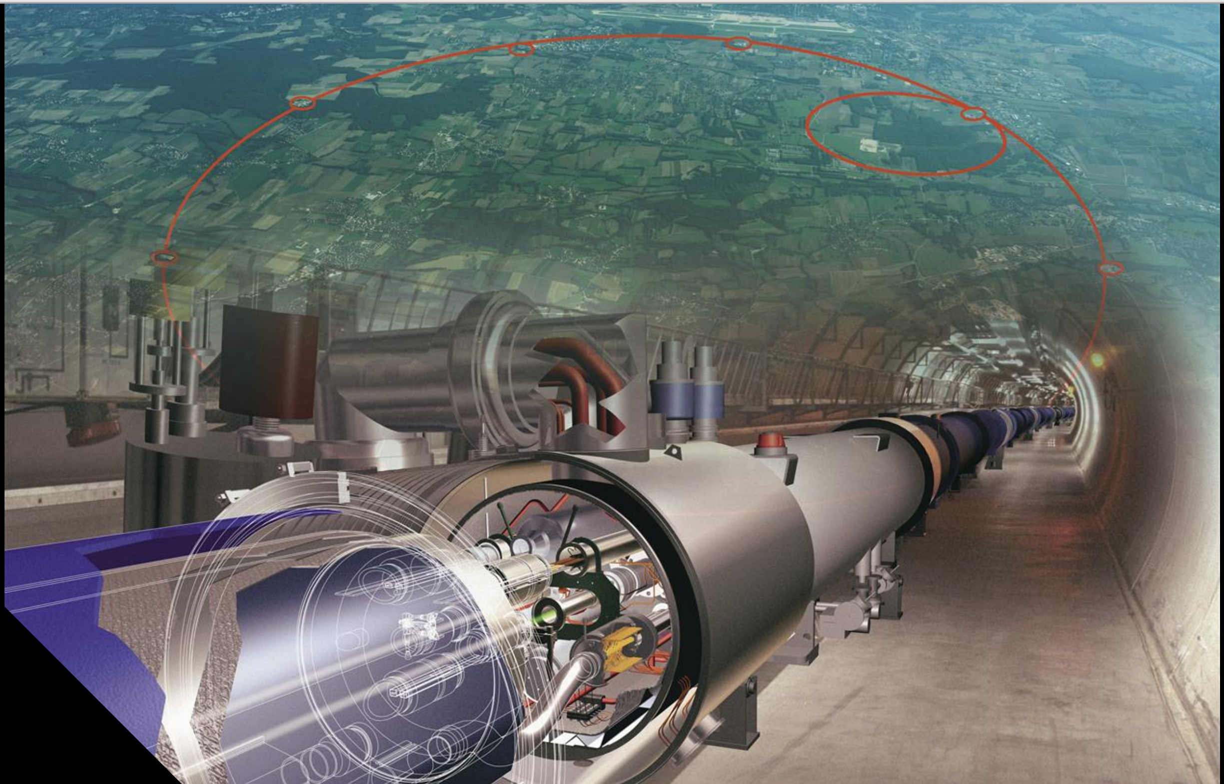
Towards an update of the European Strategy for Particle Physics

Jorgen D'Hondt
Vrije Universiteit Brussel
ECFA chair

LCWS2019 – Sendai
28 Oct – 1 Nov



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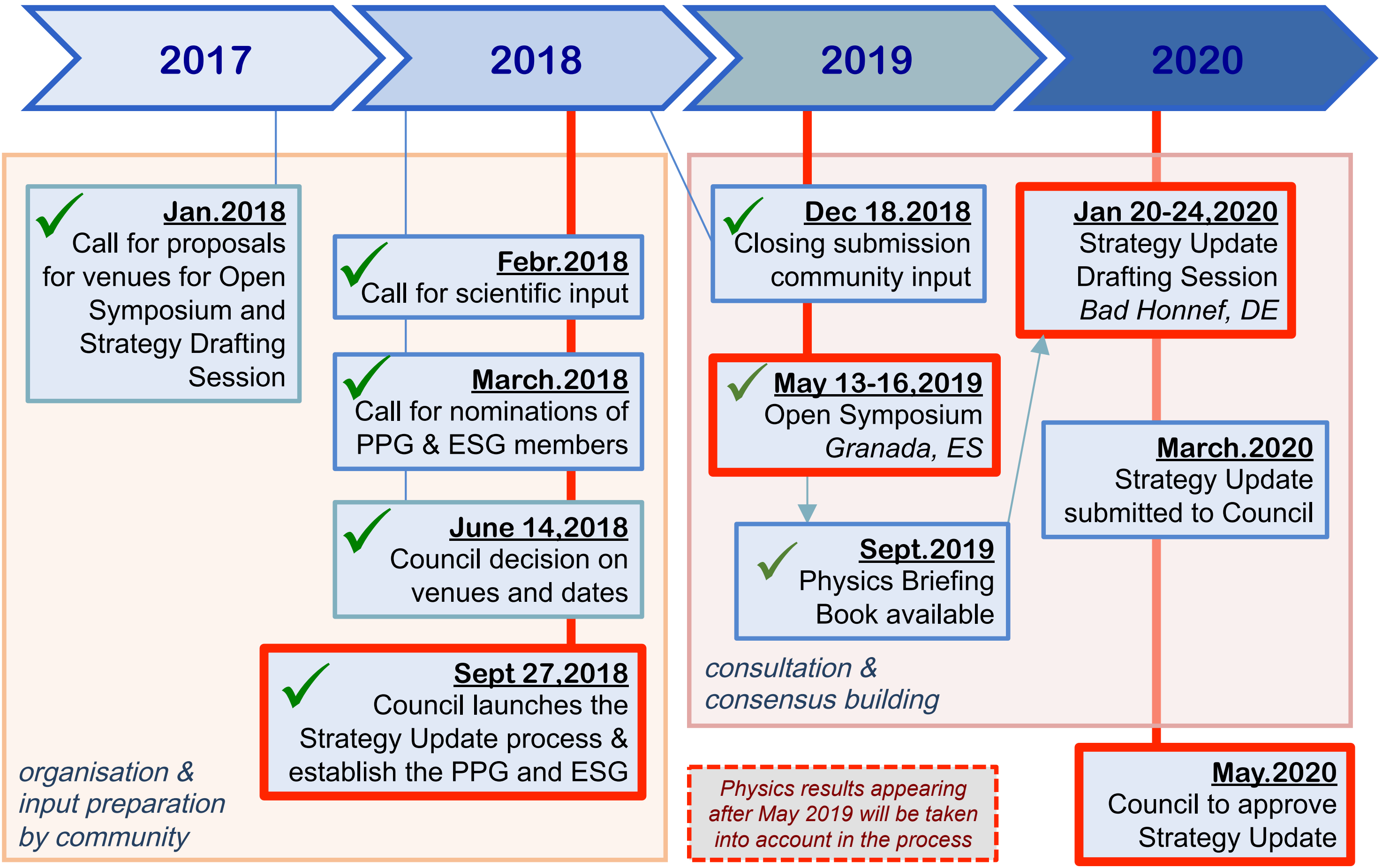

2017
2018
2019
2020
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Call for proposals for venues for Open Symposium and Strategy Drafting Session
Febr.2018
Call for scientific input
March.2018
Call for nominations of PPG & ESG members
June 14,2018
Council decision on venues and dates
Sept 27,2018
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organisation & input preparation by community
Dec 18.2018
Closing submission community input
May 13-16,2019
Open Symposium
Granada, ES
Sept.2019
Physics Briefing Book available
consultation & consensus building
Jan 20-24,2020
Strategy Update Drafting Session
Bad Honnef, DE
March.2020
Strategy Update submitted to Council
May.2020
Council to approve Strategy Update
Physics results appearing after May 2019 will be taken into account in the process

Open Symposium
Towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain
https://cafpe.ugr.es/eppsu2019/
~600 participants
Information captured in 8 thematic summary talks

Joint session ECFA and EPS-HEPP

"Towards an update of the European Particle Physics Strategy"
Agenda, 13 July 2019 – https://indico.cern.ch/event/845382/

1) Overview of the ESPP Open Symposium – *Halina Abramowicz*
2) Technology path towards future colliders – *Caterina Biscari*
3) Community challenges and opportunities for detector R&D – *Ariella Cattai*
4) Higgs at Future Colliders – *Christophe Grojean*
   (new version H@FC WG report at https://arxiv.org/abs/1905.03764)
1) Physics Beyond Colliders – *Claude Vallee*
2) Synergies between astroparticle, particle and nuclear physics – *Caterina Doglioni*
3) Computing and Software challenges – *Graeme Stewart*

ECFA Newsletter #3: https://cds.cern.ch/record/2688156/files/ECFA-Newsletter-3-Summer2019-final.pdf

Physics Briefing Book
Physics Preparatory Group

- Overviewing the submitted input and the discussions in Granada
- Excluding references etc. about 200 pages
- The work of many!
- http://cds.cern.ch/record/2691414

Physics Briefing Book

European Strategy Update

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)*
Babette Döbrich[20], Caterina Doglioni[53], Joerg Jaeckel[28], Gordan Krnjaic[57], Jocelyn Monroe[58],
Konstantinos Petridis[59], Christoph Weniger[60] *(Scientific Secretaries)*

Accelerator Science and Technology: Caterina Biscari[61], Leonid Rivkin[62] *(Conveners)*
Philip Burrows[26], Frank Zimmermann[20] *(Scientific Secretaries)*
Michael Benedikt[20], 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], Amber Boehnlein[68], Simone Campana[20], Ariella Cattai[20], Didier Contardo[69],
Cinzia Da Via[70], Francesco Forti[71], Maria Girone[20], Matthias Kasemann[2], Weidon Li[65],
Lucie Linssen[20], Felix Sefkow[2], Graeme Stewart[20] *(Contributors)*

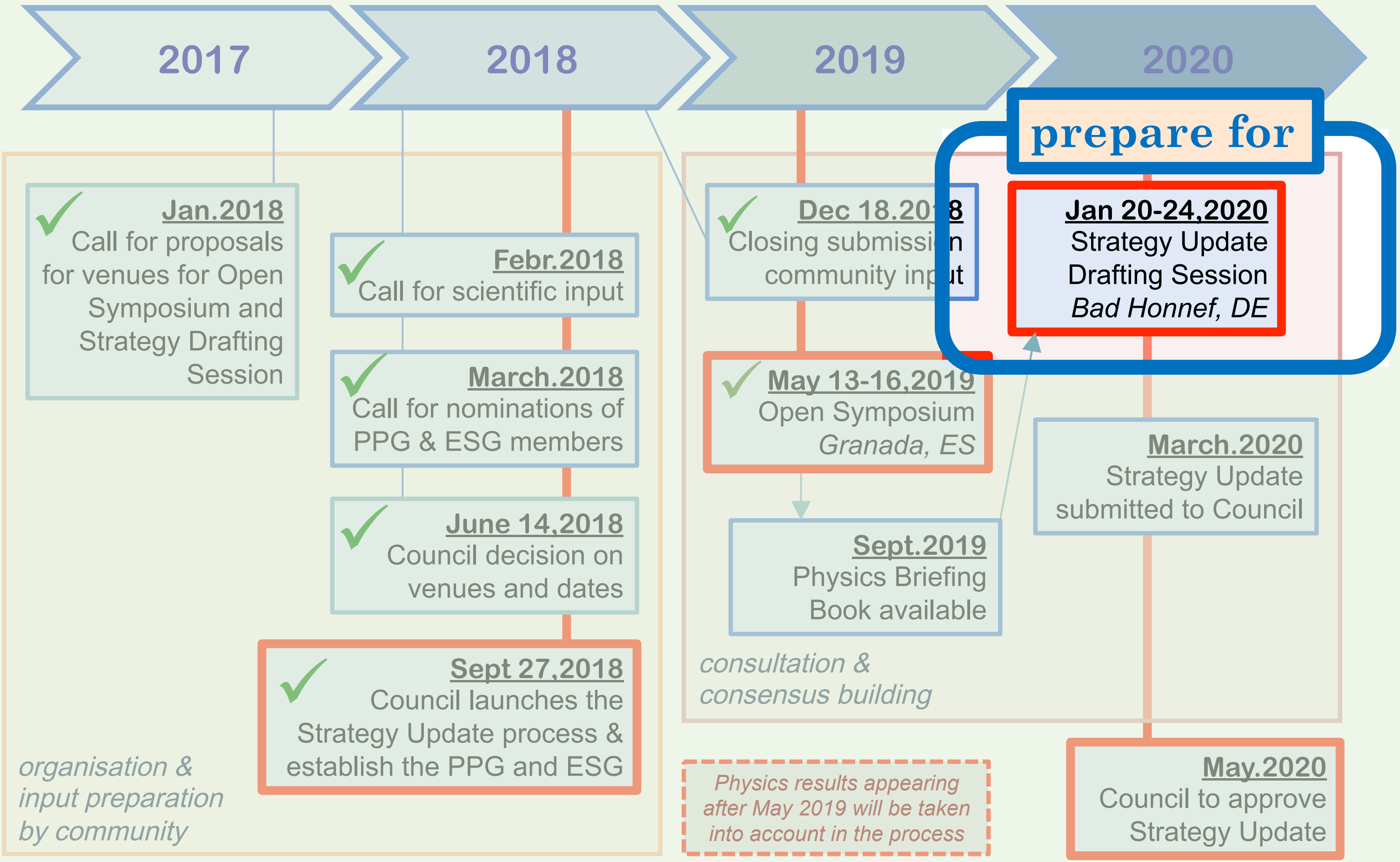
Editors: Halina Abramowicz[72], Roger Forty[20], and the Conveners

Open Plenary ECFA session

"Advanced Accelerator Technologies"
at CERN, Council Chamber, 14 November 2019
https://indico.cern.ch/event/847002/overview

1) Towards colliders using plasma wakefields (2 hours)
2) Towards a muon collider (2 hours)
3) Towards using accelerator HTS magnets in HEP colliders (2 hours)

Will be webcasted and will appear in the ECFA Newsletter #4
(more on ECFA Newsletters at https://ecfa.web.cern.ch/content/ecfa-newsletters)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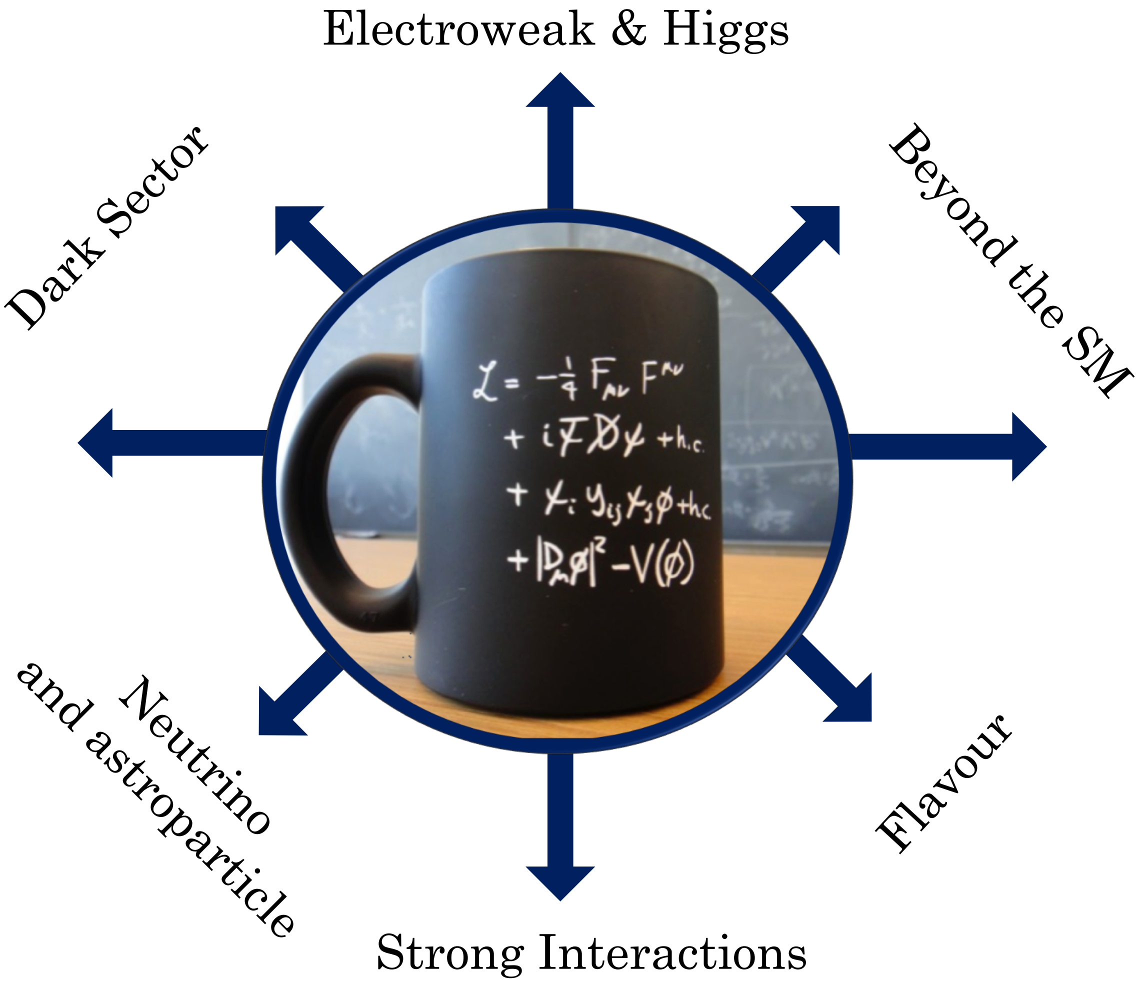
Accelerator technology at Granada

Not written in stone, but on the collider front we might identify three eras

- the *immediate future* (2020-2040)
  e.g. the HL-LHC era
- the *mid-term future* (2040-2060)
  e.g. the Z/W/H/top-factory era
- the *long-term future* (2060-2080)
  e.g. the energy frontier era

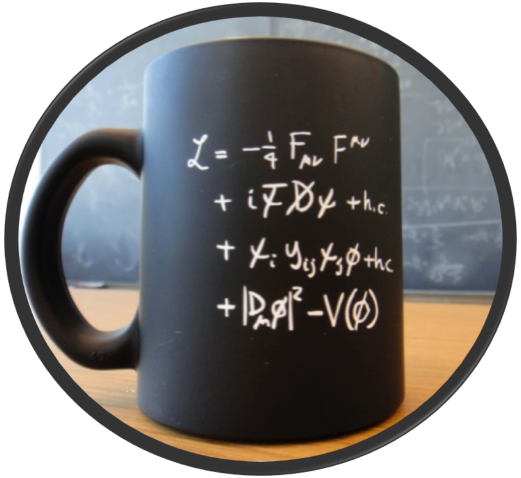
	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
our technology	SCRF ~ 30 MV/m B ~ 11 T	SCRF ~ 50 MV/m B ~ 14 T plasma demo muon demo	SCRF ~ 70 MV/m B > 16 T (HTS?) plasma collider muon collider
other technology	AI for new physics quasi-online analysis digital imaging new transistors	quantum computing self-learning simulation	...
societal threats	eco friendly gases careers at mega-research facilities	energy consumption long-term engagement global vs sustained collaboration	human vs machine

The Granada physics themes



There is “new physics” out there!

and it should be our main objective to discover it
in an effort to understand fundamental interactions



**The exploration of the scalar sector with colliders
is only one avenue to search for new physics**

Not written in stone, but several avenues towards the discovery of new physics

- *indirect exploration at the precision frontier*
- *breaking the Standard Model*
- *direct searches of hidden & visible sectors*
- …

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Some examples on the next slide

	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
precision frontier	H couplings to few % ν mass/mixing/nature QGP phase-transition b/c-physics	H couplings to % EW & QCD & top QGP vs Lattice QCD b/c/τ-physics	H couplings to ‰ H self-coupling to % proton structure di-boson processes
breaking the SM	next-gen K-beams proton precision e & n EDM lepton flavor (μ→e)	p EDM storage rings	rare top decays small-x physics
direct searches	Beam Dump Facility eSPS (light DM) Long-Lived Signals / ALPs DM vs neutrino floor	heavy neutral lepton	new high-mass part. next-gen hidden exp. low-mass DM

One can debate, but with a granularity of 20 years and in the absence of clear indications for new physics, the following general principle is probably wise:

in each era you would want to take important steps forward for the largest variety of directions where new physics can be found

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With the input from the Physics Briefing Book, and with a view of updating the current strategy, the next step is to define some overall long-term scenarios and discuss their coverage, feasibility and community support

Scenarios with a view to update the Strategy

Scenarios with a view to update the Strategy

start from the current Strategy

The European Particle Physics Strategy 2013

https://cds.cern.ch/record/1567258/files/esc-e-106.pdf - with the highest priority

① Europe’s top priority should be the exploitation of the full potential of 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.

② CERN should 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.

③ Europe looks forward to a [ILC] proposal from Japan to discuss a possible participation.

④ CERN should develop a neutrino 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.

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The European Particle Physics Strategy 2013

Other scientific activities essential to the particle physics programme

① 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.

② Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world. Examples: quark flavour physics, dipole moments, charged-lepton flavour violation, etc.

③ Detector R&D programmes should be supported 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.

④ 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.

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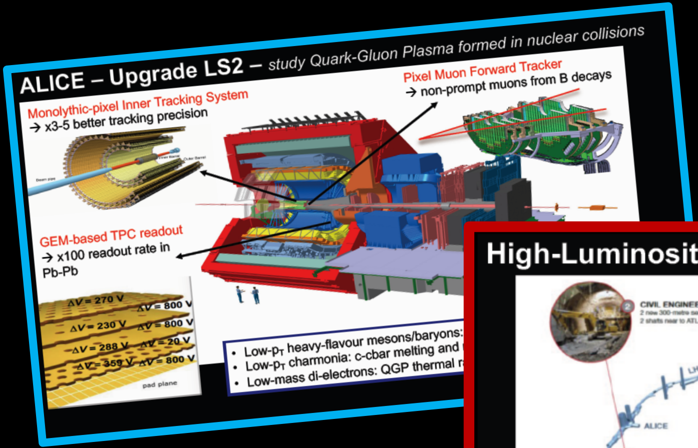
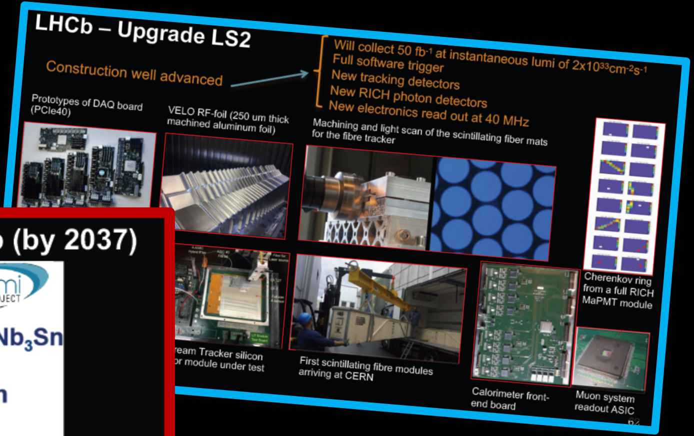
1st priority

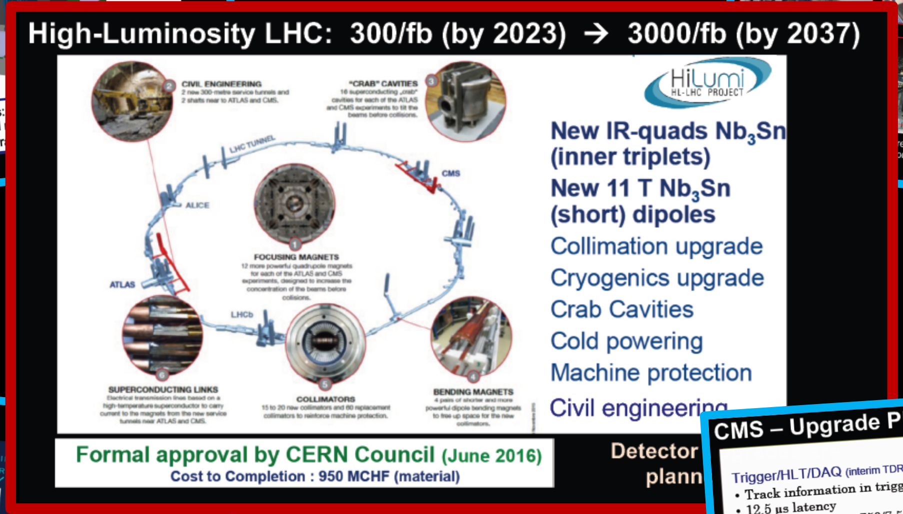
LHC and HL-LHC

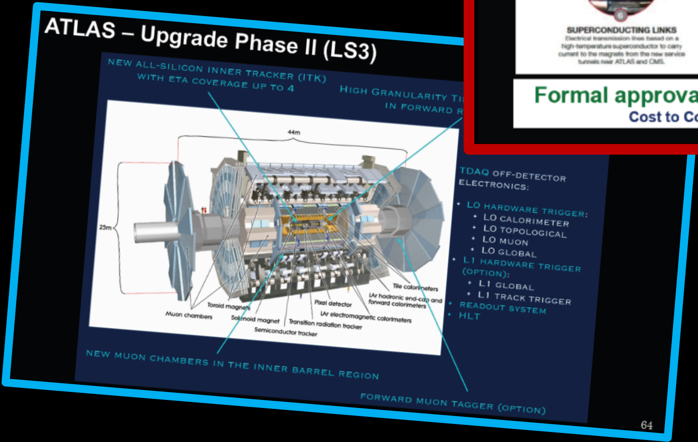
FRONT PAGE

Upgrades


ALICE – Upgrade LS2 – study Quark-Gluon Plasma formed in nuclear collisions
Monolythic-pixel Inner Tracking System
→ x3-5 better tracking precision
Pixel Muon Forward Tracker
→ non-prompt muons from B decays
GEM-based TPC readout
→ x100 readout rate in Pb-Pb
• Low-p_T heavy-flavour mesons/baryons:
• Low-p_T charmonia: c-cbar melting and
• Low-mass di-electrons: QGP thermal r


LHCb – Upgrade LS2
Construction well advanced
Will collect 50 fb^{-1} at instantaneous lumi of $2x10^{33}cm^{-2}s^{-1}$
Full software trigger
New tracking detectors
New RICH photon detectors
New electronics read out at 40 MHz
Prototypes of DAQ board (PCIe40)
VELO RF-foil (250 um thick machined aluminum foil)
Machining and light scan of the scintillating fiber mats for the fibre tracker
Cherenkov ring from a full RICH MaPMT module
ream Tracker silicon or module under test
First scintillating fibre modules arriving at CERN
Calorimeter front-end board
Muon system readout ASIC


High-Luminosity LHC: 300/fb (by 2023) → 3000/fb (by 2037)
HiLumi HL-LHC PROJECT
CIVIL ENGINEERING
"CRAB" CAVITIES
LHC TUNNEL
CMS
ALICE
ATLAS
LHCb
FOCUSING MAGNETS
SUPERCONDUCTING LINKS
COLLIMATORS
BENDING MAGNETS
New IR-quads Nb_3Sn (inner triplets)
New 11 T Nb_3Sn (short) dipoles
Collimation upgrade
Cryogenics upgrade
Crab Cavities
Cold powering
Machine protection
Civil engineering
Formal approval by CERN Council (June 2016)
Cost to Completion : 950 MCHF (material)
Detector
plann


ATLAS – Upgrade Phase II (LS3)
New all-silicon inner tracker (ITk) with eta coverage up to 4
High granularity ti in forward r
TDAQ off-detector electronics:
• L0 hardware trigger:
• L0 calorimeter
• L0 topological
• L0 muon
• L0 global
• L1 hardware trigger (option):
• L1 global
• L1 track trigger
• Readout system
• HLT
New muon chambers in the inner barrel region
Forward muon tagger (option)
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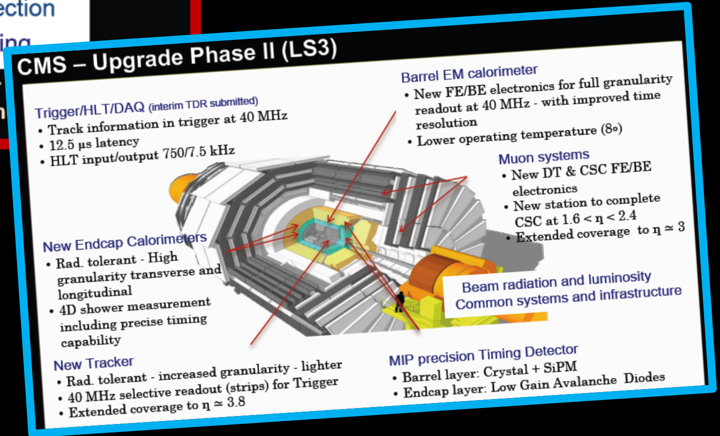
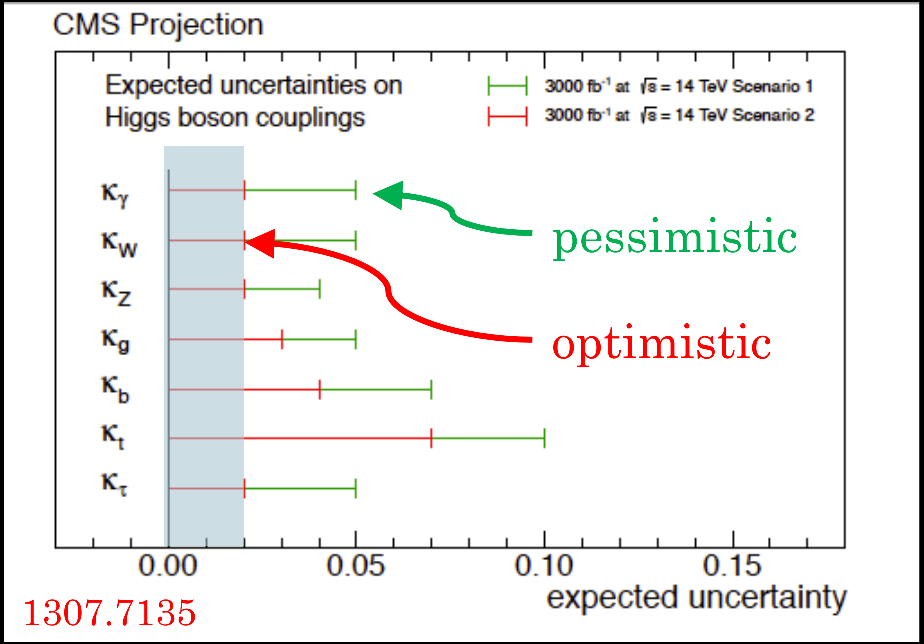
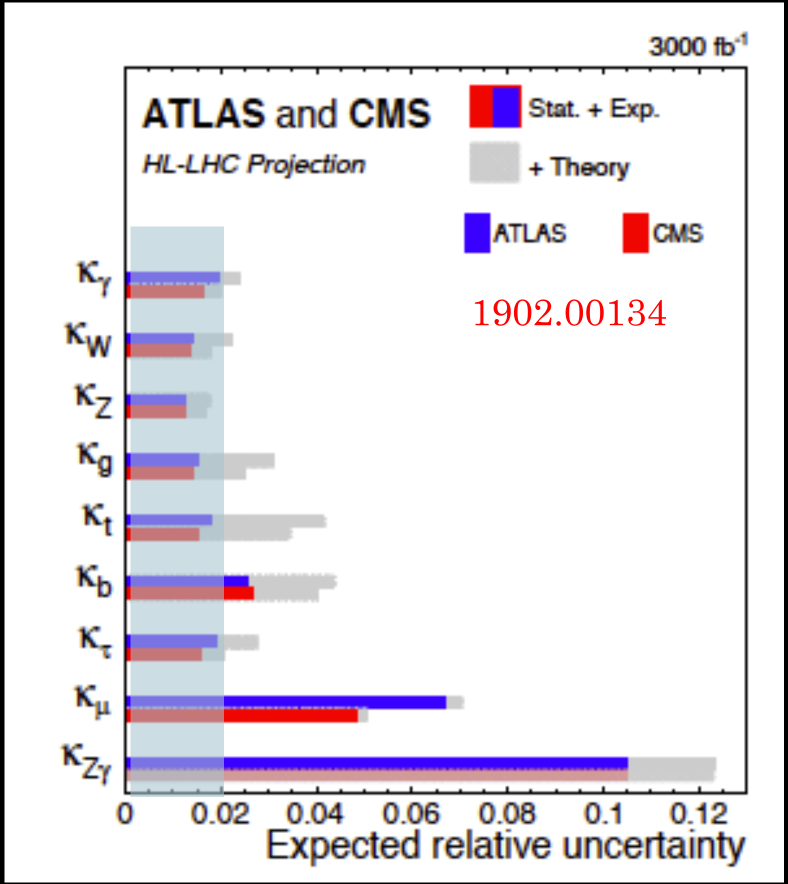

CMS – Upgrade Phase II (LS3)
Trigger/HLT/DAQ (interim TDR submitted)
• Track information in trigger at 40 MHz
• 12.5 μs latency
• HLT input/output 750/7.5 kHz
Barrel EM calorimeter
• New FE/BE electronics for full granularity readout at 40 MHz - with improved time resolution
• Lower operating temperature (8°)
Muon systems
• New DT & CSC FE/BE electronics
• New station to complete CSC at 1.6 < η < 2.4
• Extended coverage to η ≃ 3
New Endcap Calorimeters
• Rad. tolerant - High granularity transverse and longitudinal
• 4D shower measurement including precise timing capability
Beam radiation and luminosity
Common systems and infrastructure
New Tracker
• Rad. tolerant - increased granularity - lighter
• 40 MHz selective readout (strips) for Trigger
• Extended coverage to η ≃ 3.8
MIP precision Timing Detector
• Barrel layer: Crystal + SiPM
• Endcap layer: Low Gain Avalanche Diodes

Potential HL-LHC performance in Higgs couplings
anno 2013 versus anno 2019





Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

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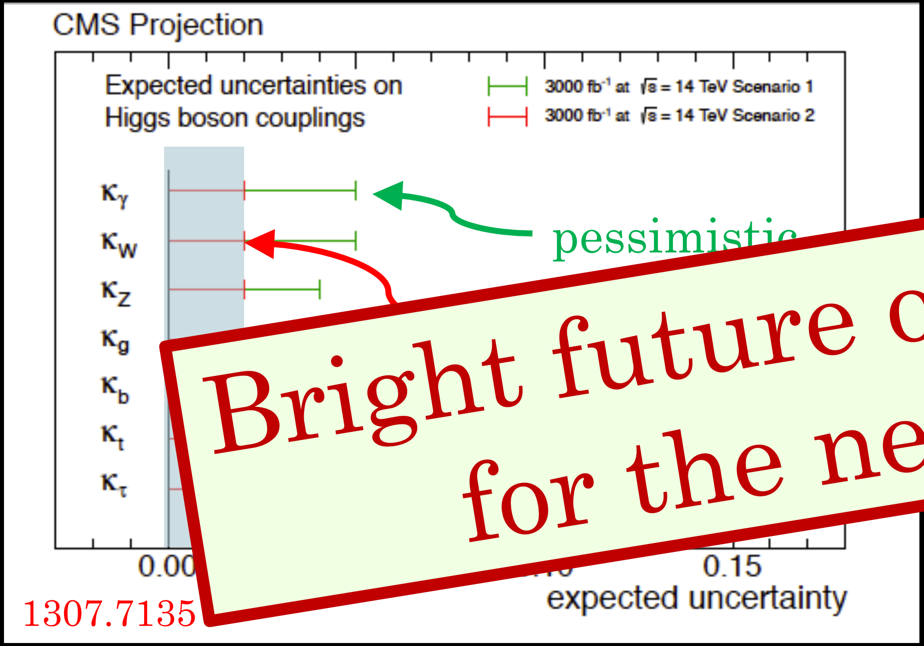

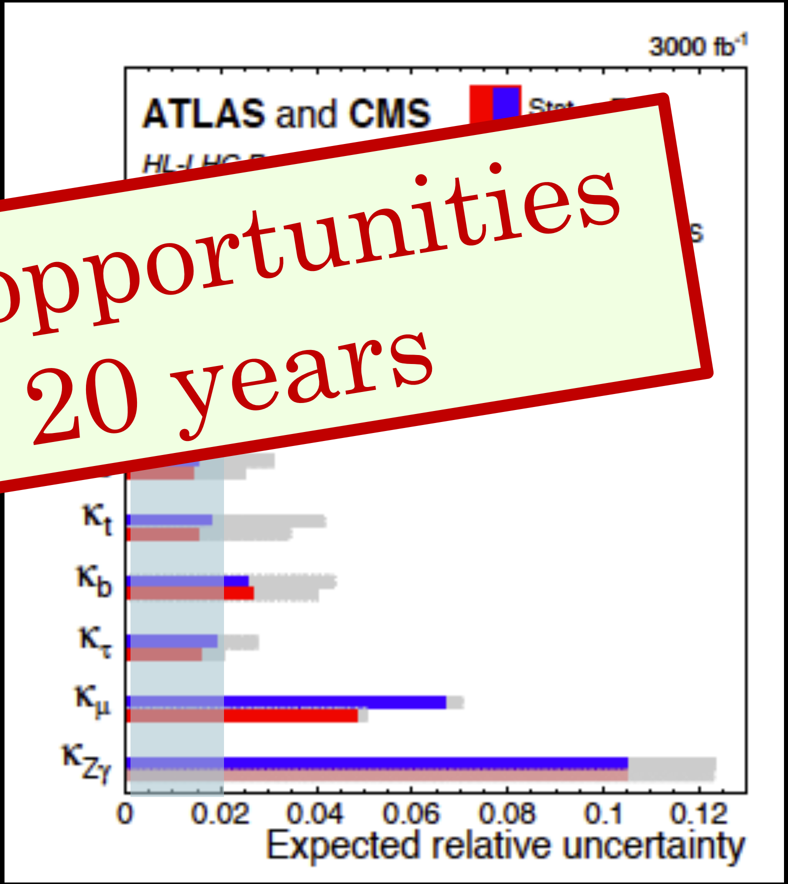

Bright future of opportunities for the next 20 years

Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

Competition for the Interaction Region at Point-2@LHC: next generation Heavy Ion experiment beyond LS4 and the LHeC ?

This is a very important choice with potentially a major impact.
Two very strong communities in Europe.

Both options are at the proposal stage.

Strategy input document
(Id110) "*A next-generation LHC heavy-ion experiment*"

Emerging from the current ALICE collaboration

Strategy input document
(Id159) "*Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC*" (i.e. LHeC and PERLE)
after peer review now in print J.Phys.G

Following a call from the CERN-DG
CDRs: arXiv:1206.2913 and arXiv:1705.08783

Workshop on LHeC/PERLE/FCCeh 24-25 Oct
https://indico.cern.ch/event/835947/

3rd priority

ILC at Japan

FRONT PAGE

Towards an update of the strategy

Europe looks forward to a [ILC] proposal from Japan to discuss a possible participation.

ICFA meeting, Tokyo, 6-8 March 2019

- We were informed about the position of MEXT on the ILC project. We heard as well as a speech from Hon. Kawamura from the Federation of Diet Members for the ILC. https://www.kek.jp/en/newsroom/2019/03/13/2100/
- In response, the ICFA statement: https://icfa.fnal.gov/wp-content/uploads/ICFA_Tokyo_Statement_March2019.pdf
- The letter from the Linear Collider Board (LCB): https://icfa.fnal.gov/wp-content/uploads/LCB_letter_to_MEXT-signed.pdf

"MEXT has not yet reached declaration for hosting the ILC in Japan at this moment"

"MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update"

"MEXT will continue to discuss the ILC project with other governments while having an interest in the ILC project"

4th priority

Neutrino Platform

FRONT PAGE

Towards an update of the strategy

CERN should develop a neutrino 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.

Since 2014 the CERN Neutrino Platform fosters the collaboration of ~90 European institutions in detector R&D and construction.
e.g. DUNE@LBNF (US) and ND280@T2K (Japan)

Upgrades are considered in due time for these long-baseline neutrino projects.
e.g. doubling the beam power at DUNE (from 1.2MW to 2.4 MW)

The European Particle Physics Strategy 2013

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Would it be adequate to move the diversity program to the front page?

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Scientific Diversity Program
(both at CERN and elsewhere in Europe)

Listed below those facilities/experiments in Europe in the realm of particle physics

- Beam Dump Facility (SHiP, TauFV)
- eSPS (LDMX)
- COMPASS/AMBER as QCD facility, MUonE, KLEVER, nuSTORM, MATHUSLA, FASER, CODEX-b, milliQan, LHCSpin, REDTOP, DIRAC, …
- CPEDM@Julich, ESSvSB@ESS, PERLE@Saclay, LFV@PSI, …

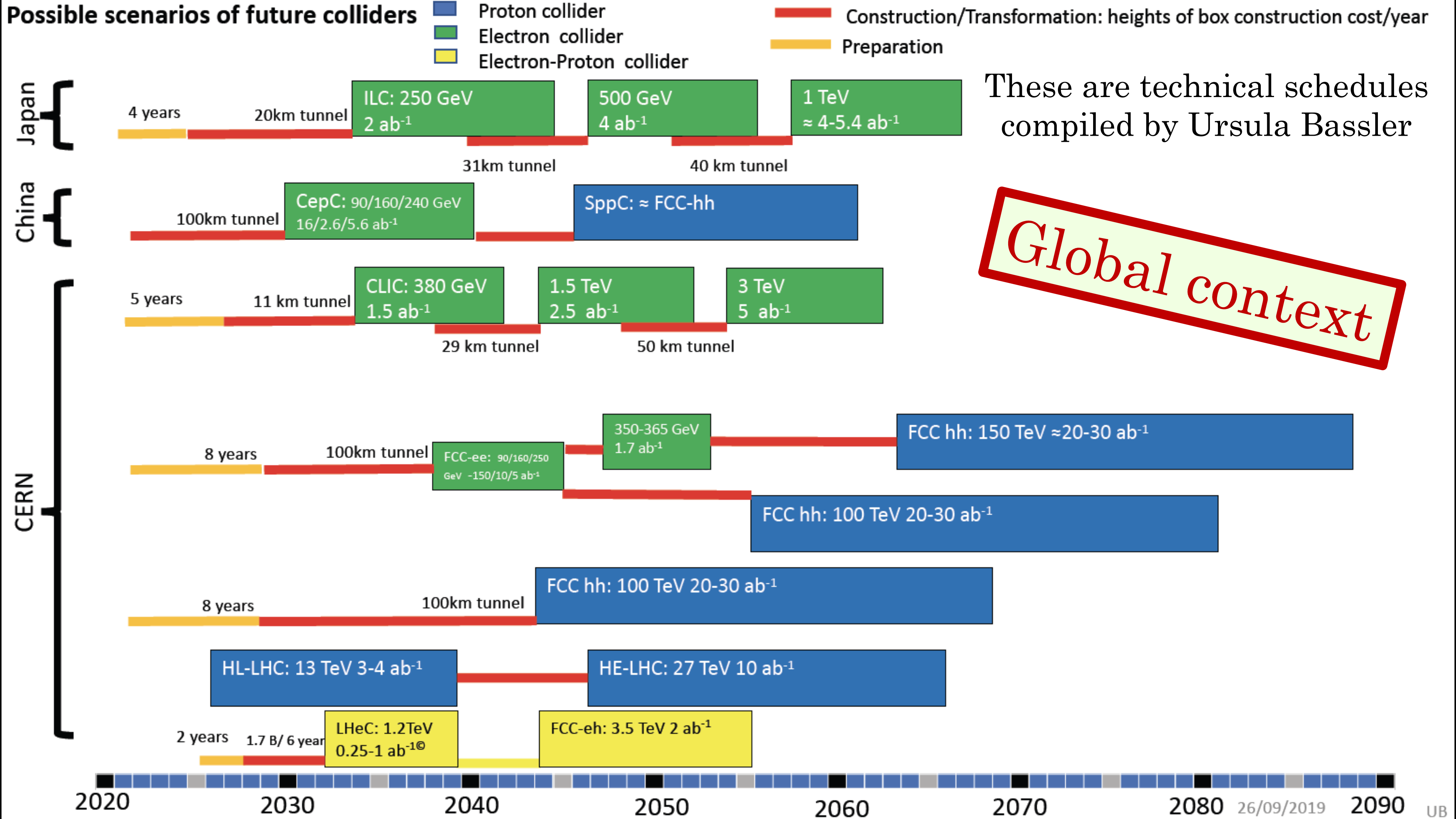
2nd priority

Future colliders at CERN
Accelerator R&D

FRONT PAGE

Towards an update of the strategy

CERN should 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.


Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/year
Preparation
These are technical schedules compiled by Ursula Bassler
Global context
Japan
4 years
20km tunnel
ILC: 250 GeV 2 ab-1
31km tunnel
500 GeV 4 ab-1
40 km tunnel
1 TeV ≈ 4-5.4 ab-1
China
100km tunnel
CepC: 90/160/240 GeV 16/2.6/5.6 ab-1
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
CLIC: 380 GeV 1.5 ab-1
29 km tunnel
1.5 TeV 2.5 ab-1
50 km tunnel
3 TeV 5 ab-1
8 years
100km tunnel
FCC-ee: 90/160/250 GeV -150/10/5 ab-1
350-365 GeV 1.7 ab-1
FCC hh: 150 TeV ≈20-30 ab-1
FCC hh: 100 TeV 20-30 ab-1
8 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
HE-LHC: 27 TeV 10 ab-1
2 years
1.7 B/ 6 year
LHeC: 1.2TeV 0.25-1 ab-1©
FCC-eh: 3.5 TeV 2 ab-1
2020
2030
2040
2050
2060
2070
2080
26/09/2019
2090
UB

Towards an update of the strategy

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CLIC

FCC

LHeC
(1.7GCHF)

Physics opportunities and major technology challenges in the PBB.

Some key elements one can consider in an overall ambition

- to deliver to the research community a compelling scientific program which includes the global aspiration for a Higgs factory but in general exploring new territories in the search for new physics at the precision, the intensity and the high-energy frontiers
- because a new collider is essential to make progress, to have a new major collider facility operational at CERN as soon as possible after the HL-LHC program
- allow for options for the long-term future
- to support major **accelerator R&D** to prepare for the 1st and 2nd generation colliders, i.e. the 2040-2060 and 2060-2080 eras
- to support a **scientific diversity program** to complement the physics reach achievable with colliders

Embrace these thoughts into “scenarios” with future colliders in Europe.

With a strawman view to update the current strategy and to prepare the discussion within the European Strategy Group (ESG), “scenarios” can be defined revolving around future colliders at CERN.

- Each scenario has a 1st generation collider in the 2040-2060 era and options for the 2nd generation collider in the 2060-2080 era.
- Some scenarios might depend on decisions made outside of Europe, i.e. to be verified on the occasion of the next European Strategy update, typically within 7 years (around the start of the HL-LHC).
- For the 2nd generation colliders, advanced accelerator technologies might come in (e.g. plasma, muon, HTS magnets), depending on the performance of the advanced technologies in for example demonstrator facilities.
- Accordingly each scenario has a moment in time to verify the readiness of the advanced accelerator technologies, i.e. at the moment when concrete decisions are to be made about the 2nd generation collider.

A landscape for colliders in Europe

	2020-2040		2040-2060	2060-2080
			1st gen technology	2nd gen technology
CLIC-all	HL-LHC		**CLIC380-1500**	CLIC3000 / other tech
CLIC-FCC	HL-LHC		**CLIC380**	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC		**FCC-ee (90-365)**	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC		**LE-FCC-h/e/A (low-field magnets)**	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC	**+ LHeC**	**LHeC**	FCC-h/e/A (Adv HF magnets) / other tech

- All elements related to the CLIC, FCC and LHeC proposals are discussed in their CDRs.
- The LE-to-HE-FCC-hh(e/A) scenario with the hadron collider version of the FCC moves from initially lower-field magnets to higher-field magnets, potentially HTS magnets.
- The LHeC+FCC-h/e/A scenario includes the LHeC (could be included in all scenarios) and foresees FCC-h/e/A at a later stage directly with high-field magnets.

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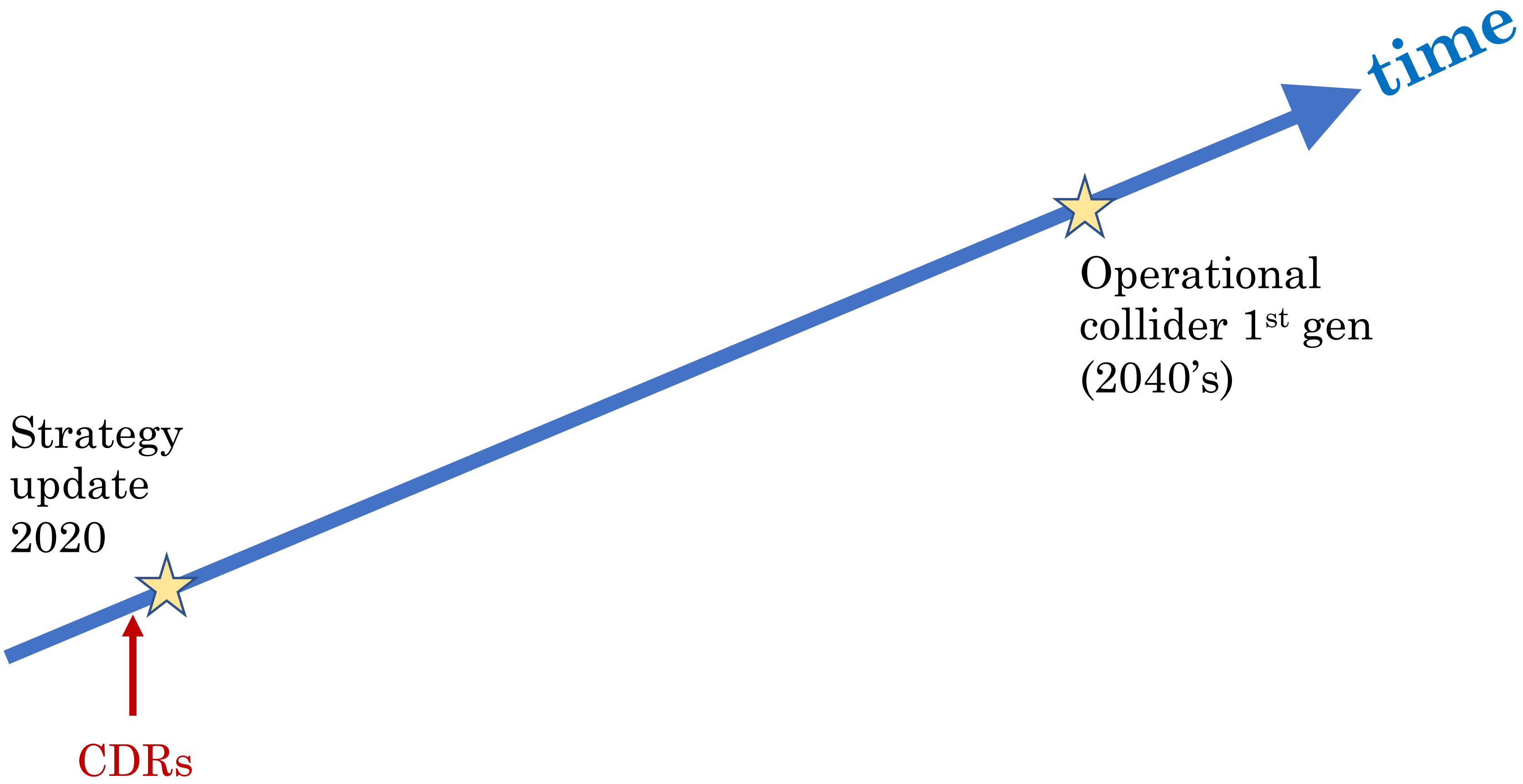
- Need to provide guidance in this strategy update for the technology for the 1st generation collider at CERN, leaving open options to deploy other technologies for the 2nd generation.
- Accordingly, around 2045 the community will have to consider which technologies are available for high-energy and high-luminosity colliders in the 2060-2080 era.
- While planning for success, the chosen scenario will have to be verified at the time of the next strategy update, taking into account the global context (e.g. ILC, CEPC, EIC, etc).

Typical path: select a scenario and plan for success



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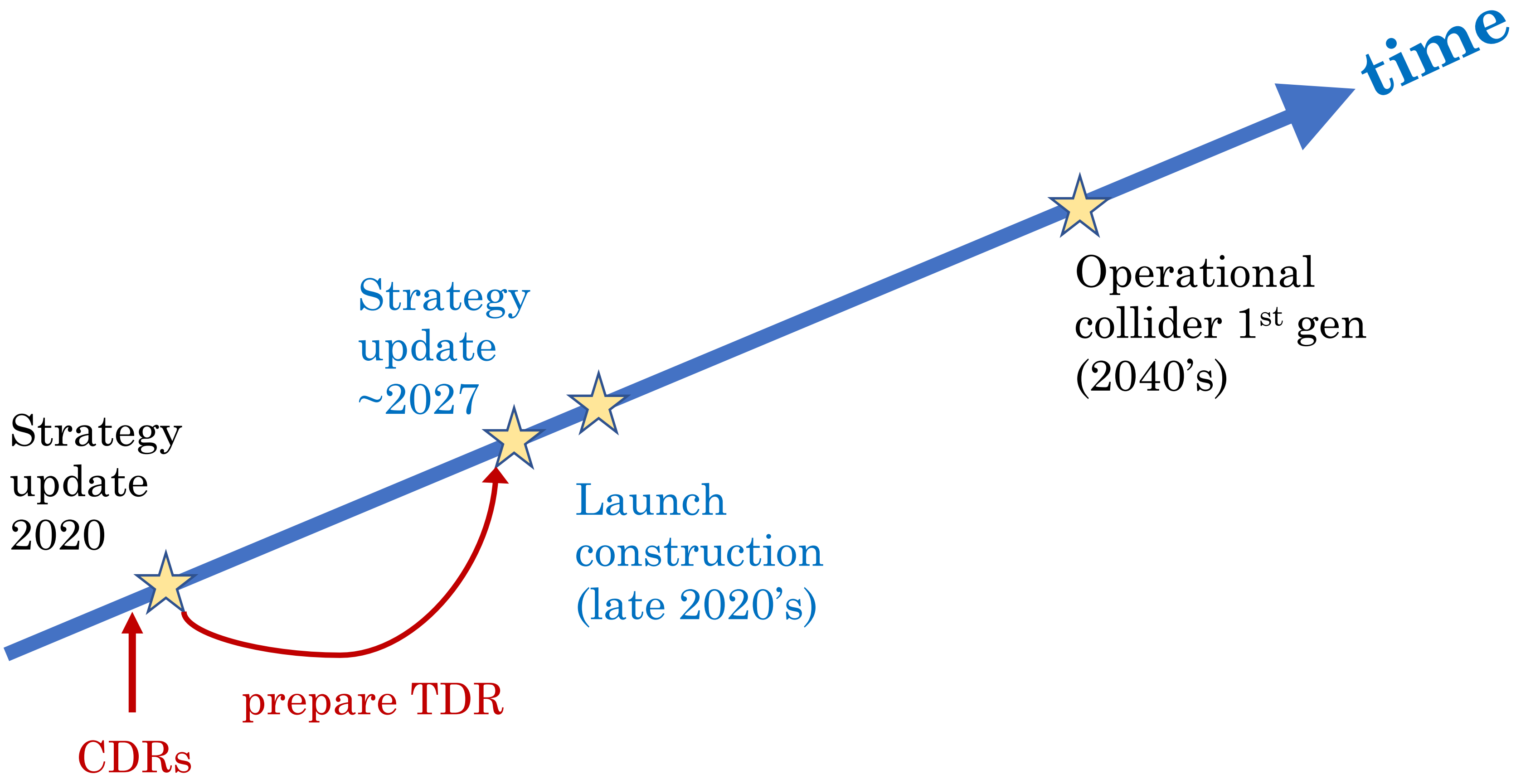

Nothing is written in stone at this stage

for new colliders in Europe, the European Strategy Group will discuss at least these strawman scenarios with a focus on the 1st generation collider

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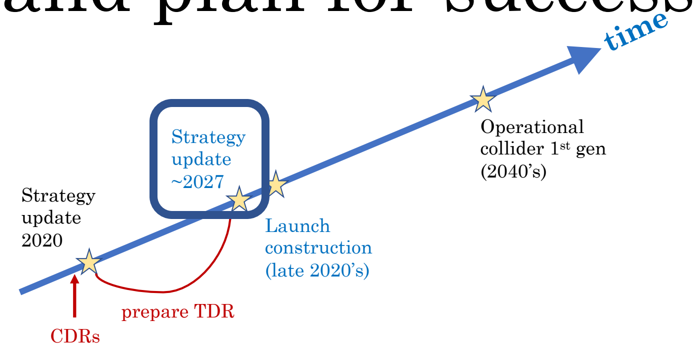
Thank you for your attention!

Typical path: select a scenario and plan for success



To realize a particular scenario, the following objectives could be considered in the overall strategy update.

Main expectations of the next Strategy update (in about 7 years)

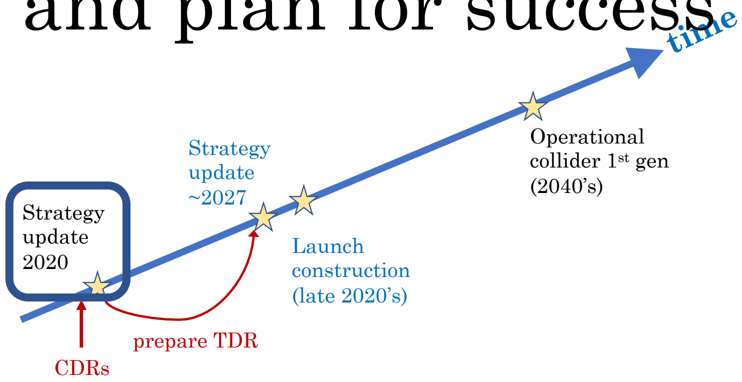
- Receive the TDR for 1st generation of the scenario for final approval
- Decide to concretely engage in the 1st generation of the scenario, or to adapt according to the global context
- Decide on the strategy for further development of high-field magnets
- Decide on the basis of CDRs to construct a muon and/or plasma-based collider demonstration facility

Typical path: select a scenario and plan for success

Goals to reach by the time of the next Strategy update (within ~7 years)

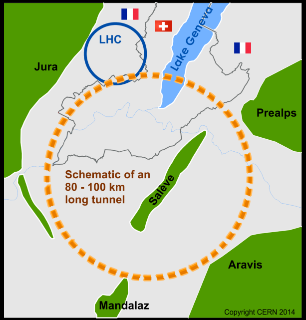
- Concrete technical and administrative plans for the civil engineering for the 1st generation scenario, including cost optimization studies
- Concrete financial organization plan for civil engineering, accelerator and experiments for 1st generation scenario, including cost optimization studies
- In the context of the particular scenario, set up proto-collaborations for experiments to propose initial detector designs
- Verify the technical feasibility and cost optimization for alternative scenarios
- CDRs for demonstration collider facilities for a muon collider and a plasma-based collider

Typical path: select a scenario and plan for success

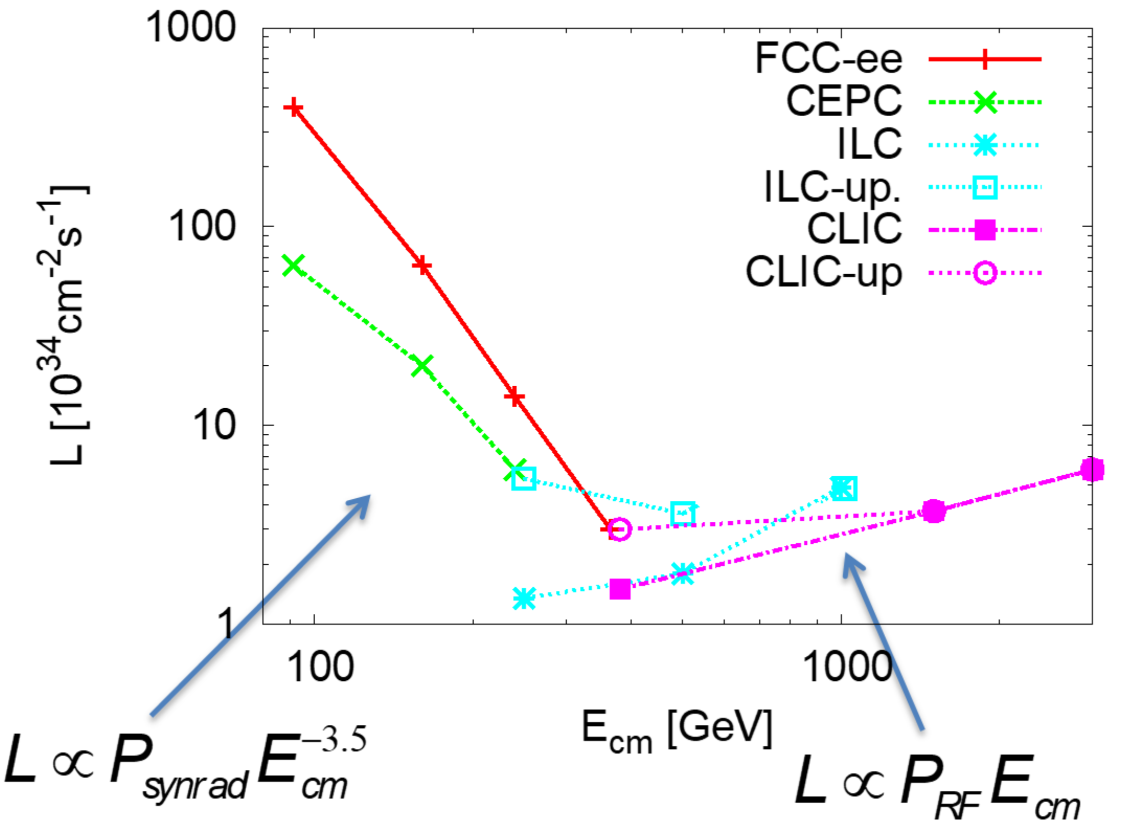


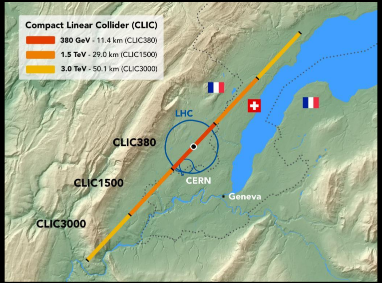
Would require from the 2020 Strategy update

- Strong statement to investigate the full program of the scenario, including technical and administrative plans, and commission a TDR for the 1st generation of the scenario
- Commission CDRs for demonstration facilities for a muon collider and a plasma-based collider, and support statements for the development of high-field magnets
- Openness towards opportunities for a major collider outside Europe



Luminosity per facility

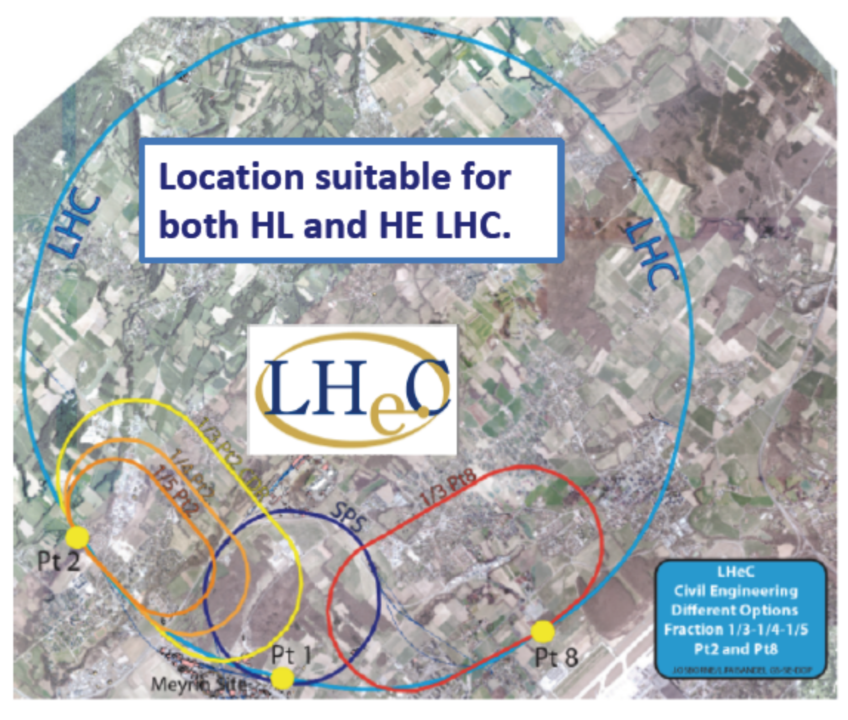




Concrete collider options studied at CERN

LHeC (ep), http://lhec.web.cern.ch

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913]



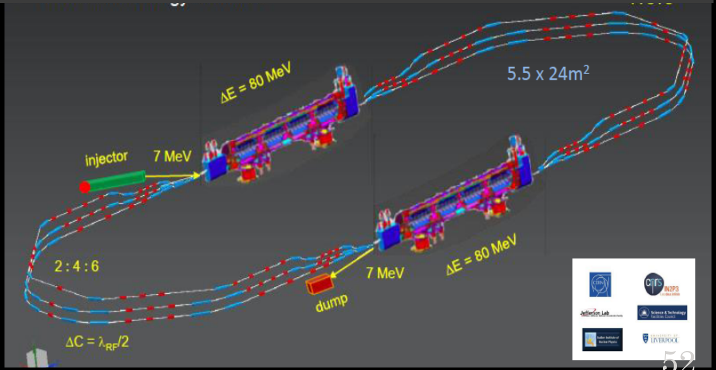
LHeC (60 GeV e- from ERL)

E_{cms} = 0.2 – 1.3 TeV

run with the HL-LHC (≳ Run5)

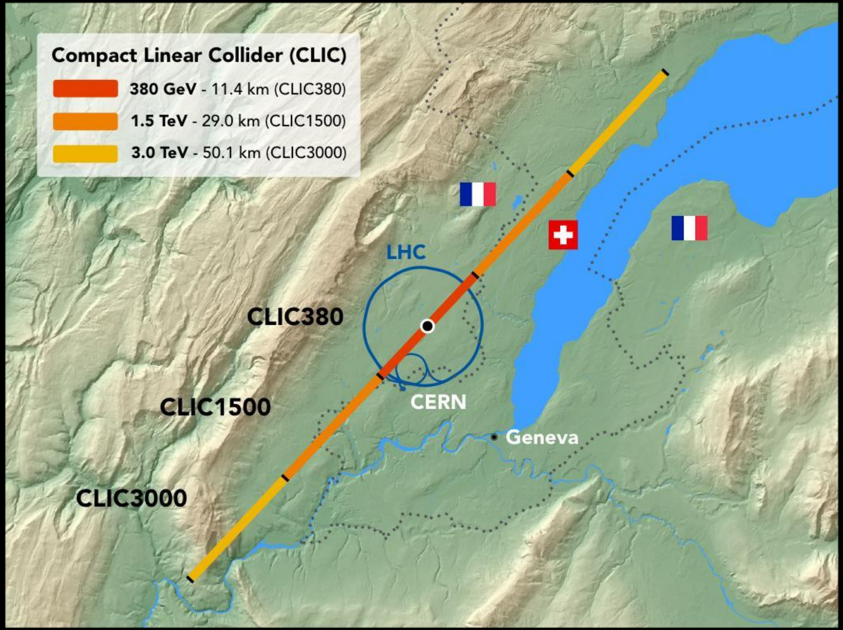
Energy Recovery Linac (ERL)

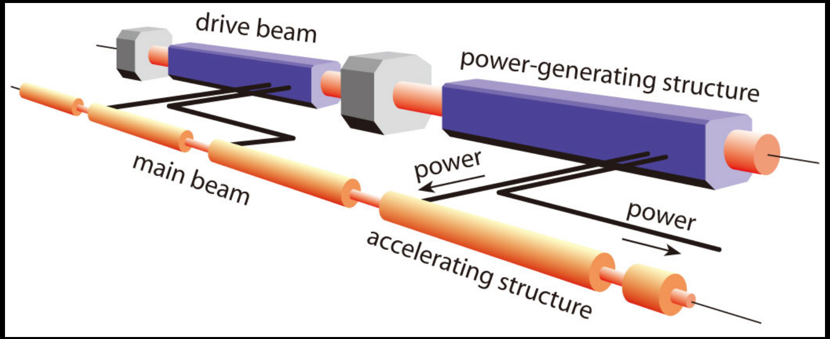
R&D demonstrator at Orsay, PERLE



Concrete collider options studied at CERN

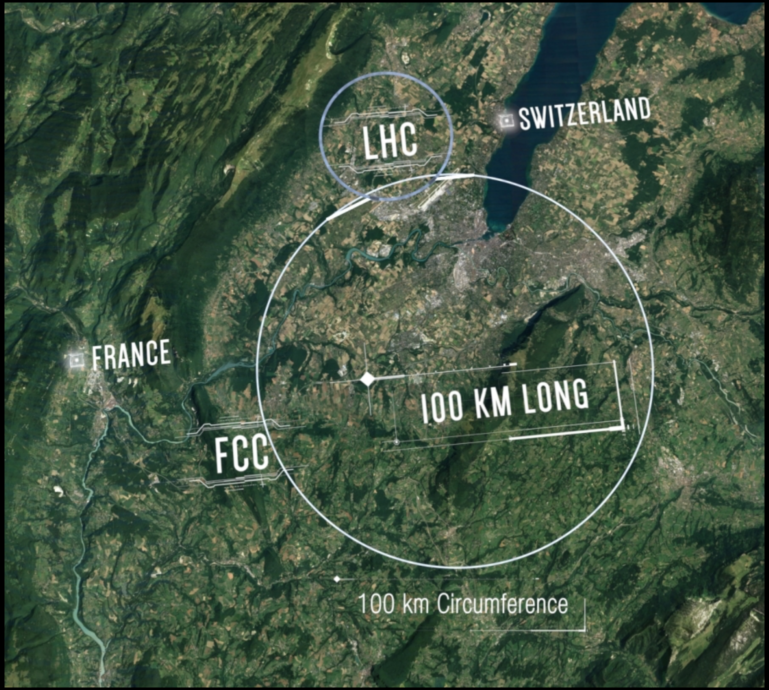
CLIC (ee), http://clic-study.web.cern.ch/





Concrete collider options studied at CERN

FCC (ee, ep, pp, pA, AA, eA), https://fcc-cdr.web.cern.ch/



- **e^+e^- collider (*FCC-ee*)** **@ 90-365 GeV** as potential first step

  (ERL-technology, CLIC injector, …)
- ***pp*-collider (*FCC-hh*)** **@ 100 TeV**
- ***p-e* collider (*FCC-he*)**
- **HE-LHC** with *FCC-hh magnets*
- **$\mu\mu$ colider (*FCC-$\mu\mu$*)** option
- AA, Ap, Ae options