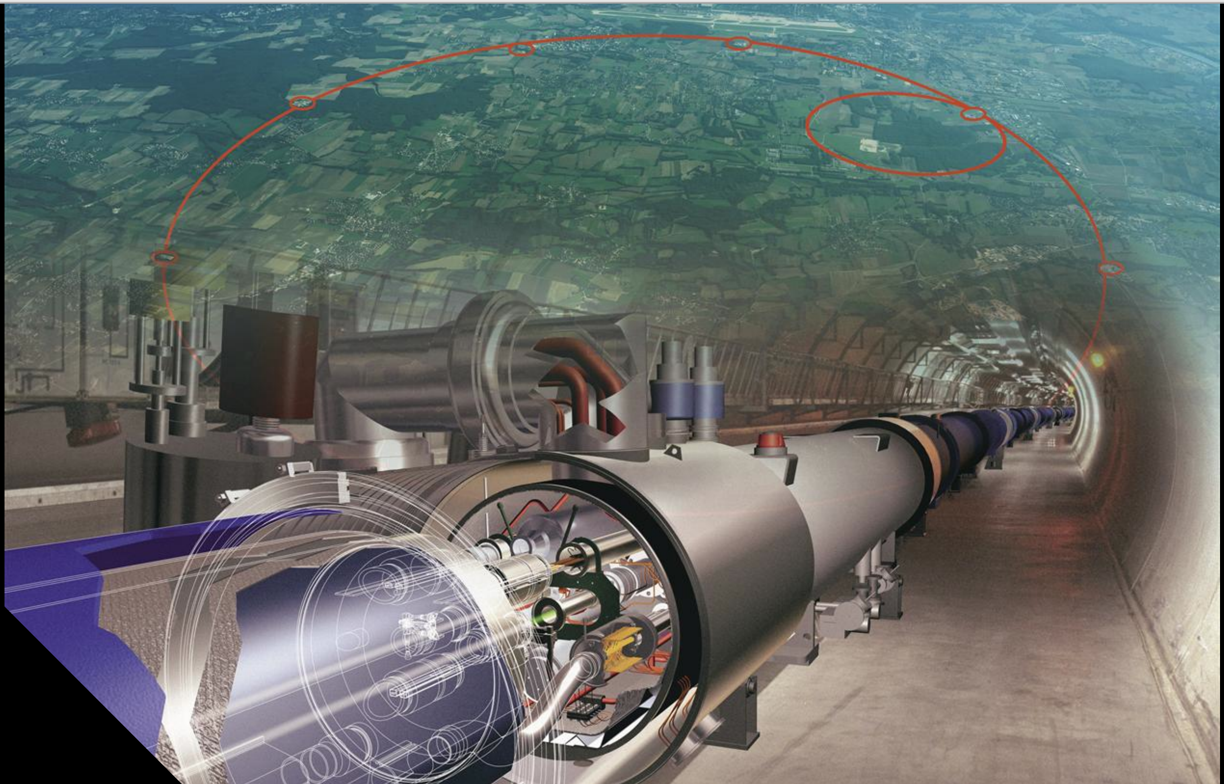
Road to an update of the European HEP Strategy

Jorgen D'Hondt
Vrije Universiteit Brussel
ECFA chairperson
(https://ecfa.web.cern.ch)

ICNFP meeting
August 24, 2019
Kolymbari, Crete



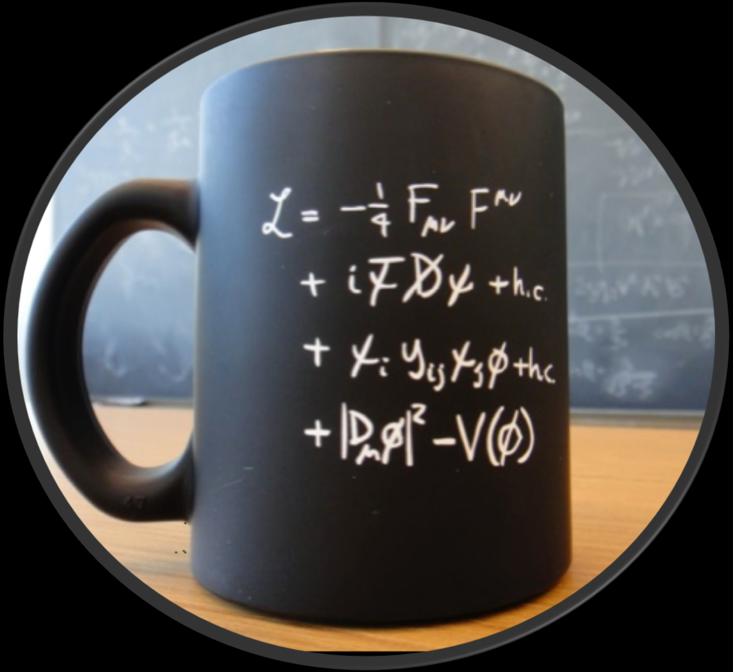
HEP@VUB
BRUSSELS

VUB

iihe
BRUXELLES BRUSSEL

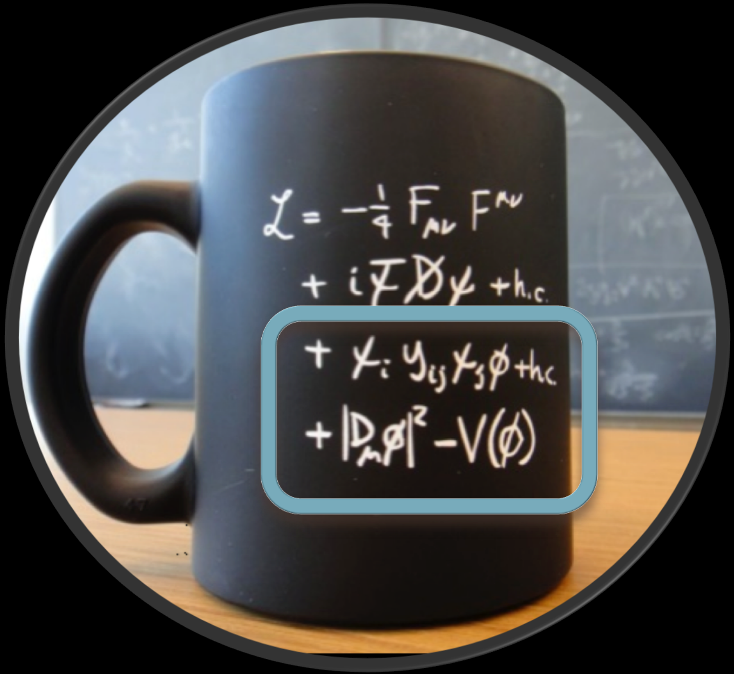
understand nature at the
largest and the smallest scales

Particle Physics today



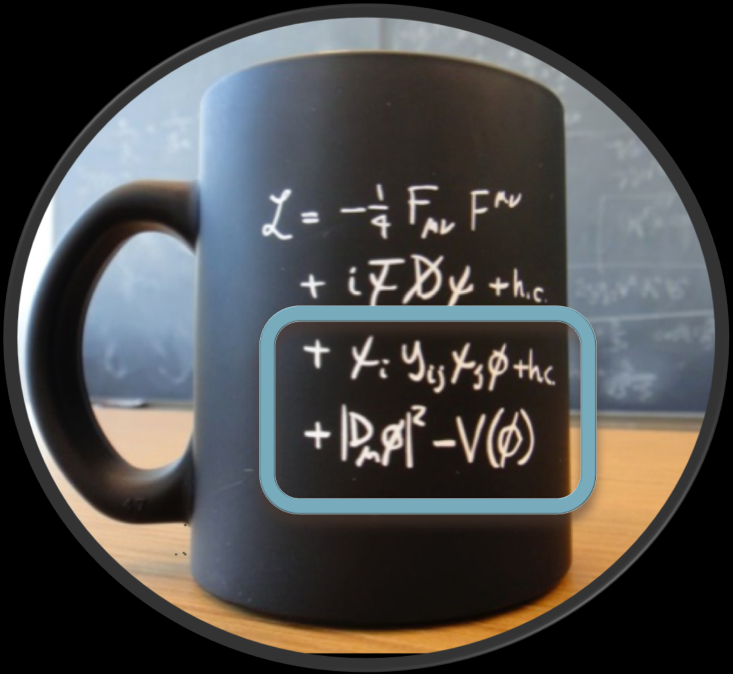
enormous success in describing matter at the smallest scales

Particle Physics today



enormous success in describing matter at the smallest scales

Particle Physics today



enormous success in describing matter at the smallest scales

describing $\neq$ understanding

Key open questions for particle physics?

Riccardo Rattazzi
@ Granada

Problems vs Mysteries

Problems

- Dark Matter
- Baryogenesis
- Strong CP
- Fermion mass spectrum & mixing

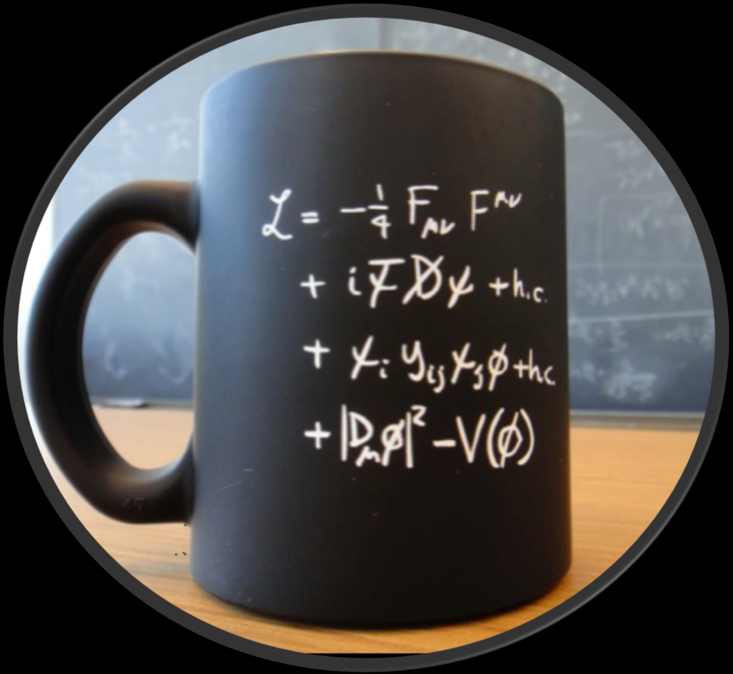
Plausible EFT solutions exist

Mysteries

- Cosmological Constant
- EW hierarchy
- Black Hole information paradox
- very Early Universe

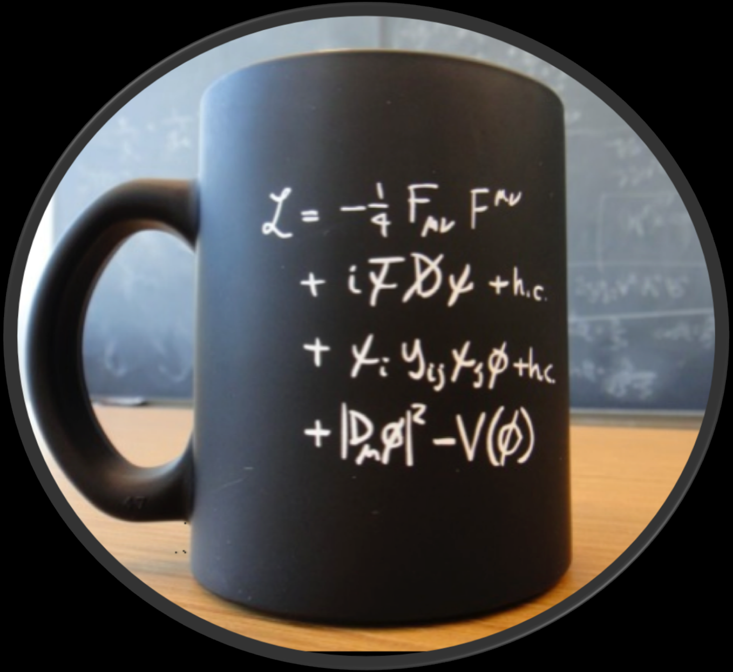
Challenge or outside EFT paradigm

Particle Physics today



new physics

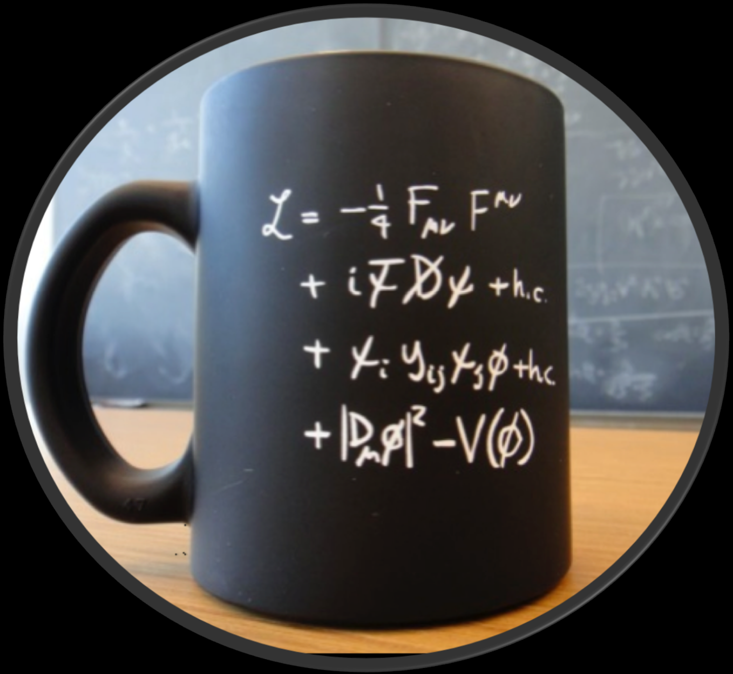
Particle Physics today



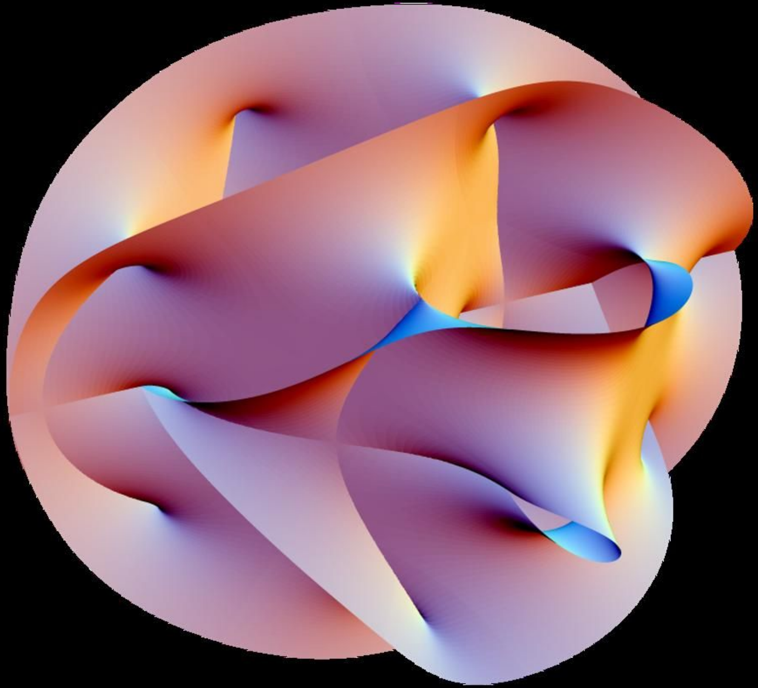
a simple design?

new physics

Particle Physics today



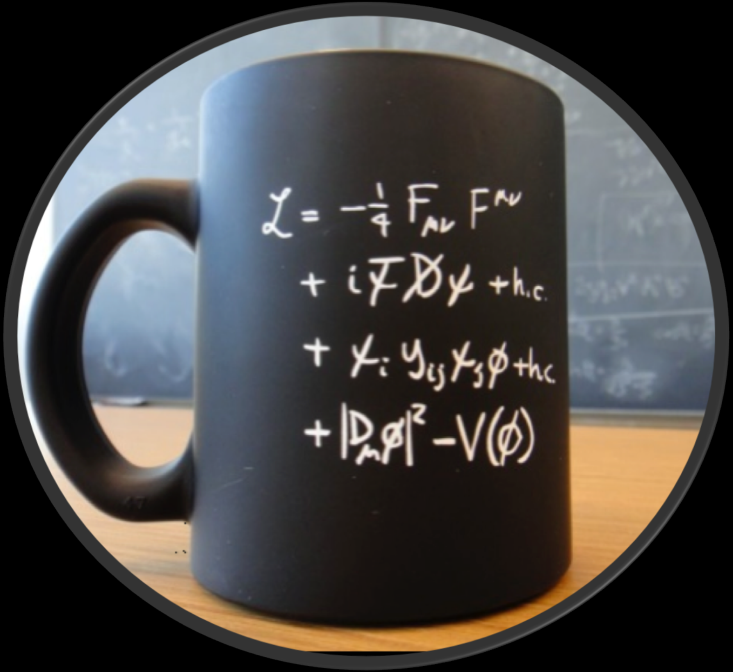
or more elegant ?



new physics

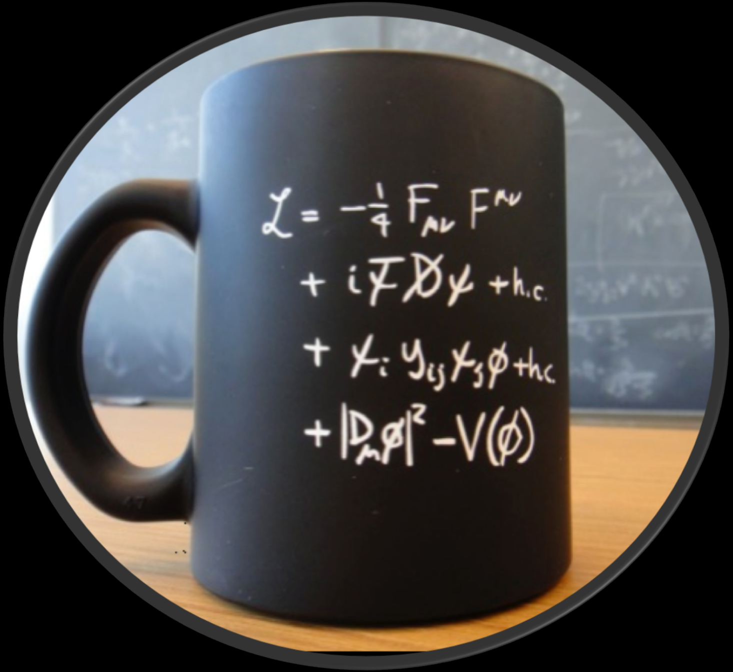
Particle Physics today

or more surreal?



new physics

Particle Physics today



connection

new physics

although there is no lack of novel theoretical ideas, there are no clear indications where new physics is hiding although there is no lack of novel theoretical ideas, there are no clear indications where new physics is hiding

an argument for a strong and diverse, yet coherent and concerted empirical exploration although there i…

th…

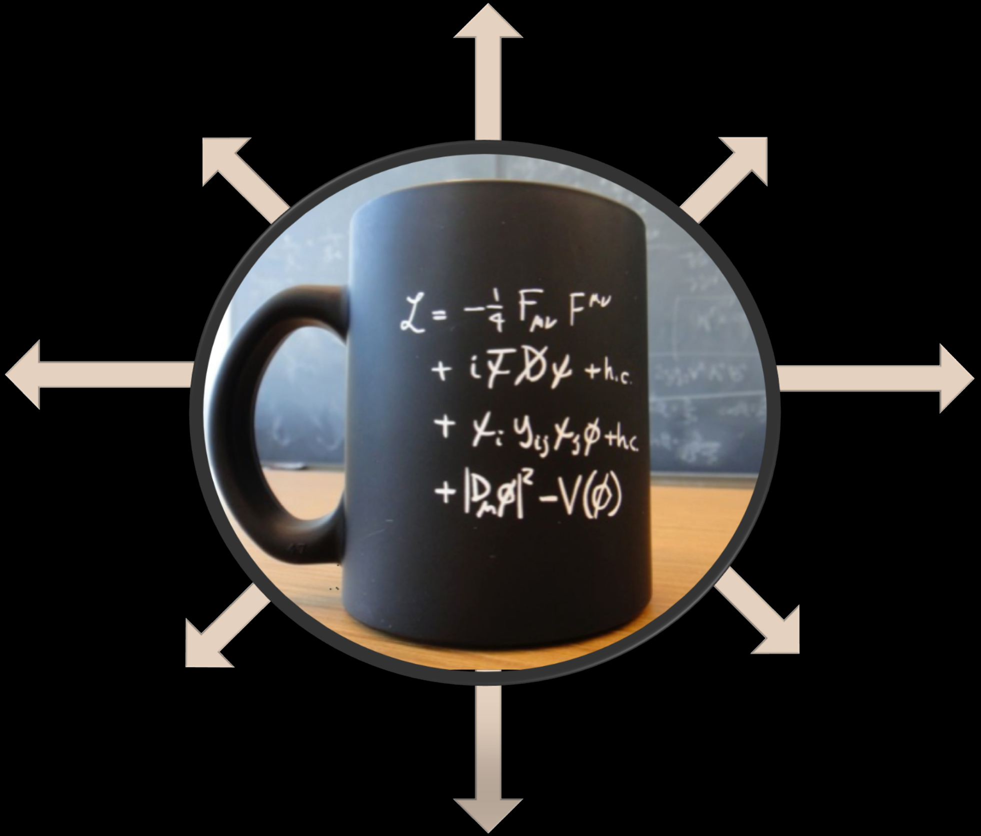
A strong research field needs a strong story

need for a strong and global scientific story how to make progress in unravelling the smallest and largest scales of Nature

…ent for a strong and diverse,
yet coherent and concerted empirical
exploration

higher energy interactions in the lab

earlier universe

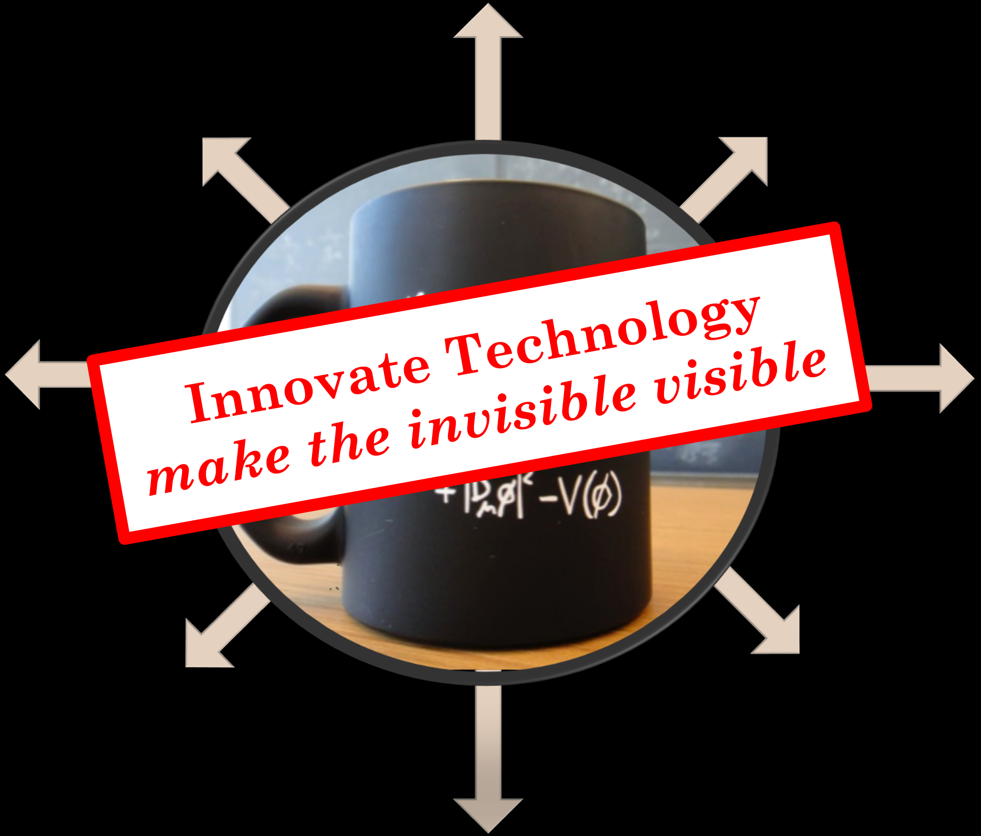


rarer processes

higher energetic phenomena in the universe

higher energy interactions in the lab

earlier universe



rarer processes

higher energetic phenomena in the universe

What is out there on our accelerator/collider technology front?

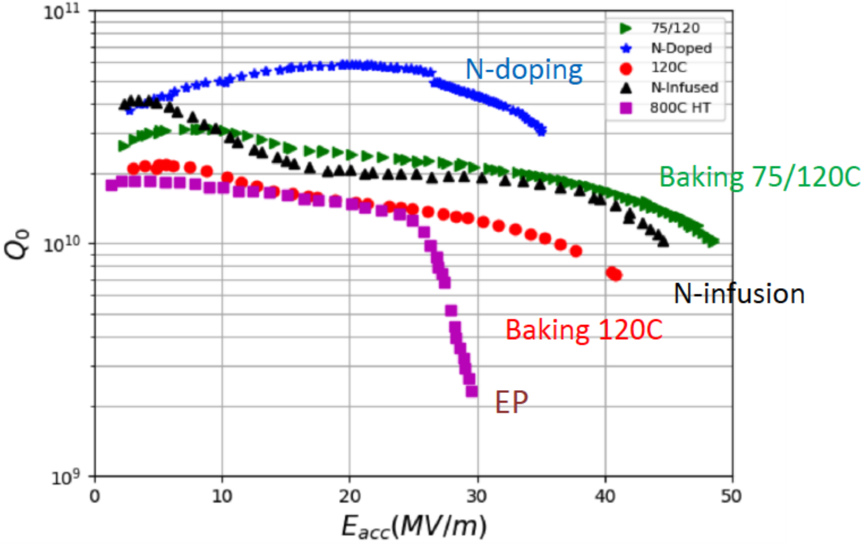
(only a very brief snapshot)

RF cavity R&D – *~50MV/m within reach while XFEL@DESY has ~30MV/m*

Akira Yamamoto
@ Granada

State of the Art in High-Q and High-G (1.3 GHz, 2K)

Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019



- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- **High-Q** by **N-Doping** well established, and
- **High-G** by N-infusion and **Low-T baking** still to be understood and reproduced, worldwide.

SC Magnet R&D – *16 T magnets would allow to reach much higher pp collision energies*

FRESCA2 @ CERN

EuCARD²

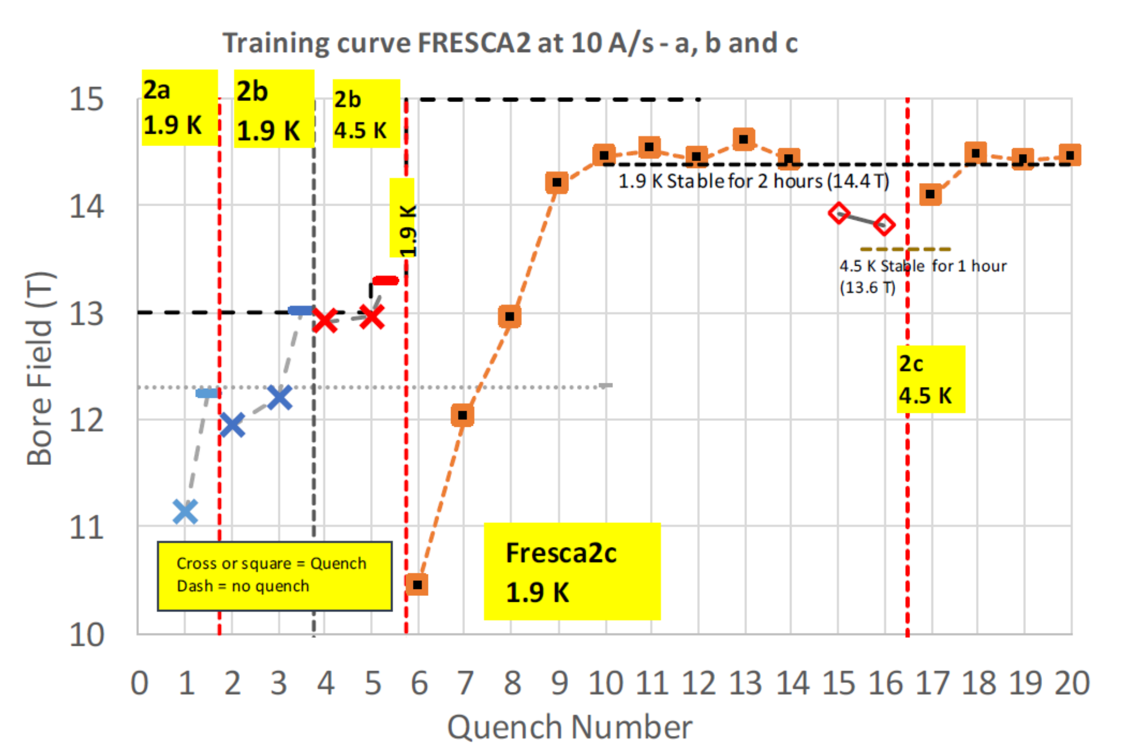
Test new superconductive cables (Nb_3Sn)

Dipole magnet
1.5 m long, 1 m diameter, 10 cm aperture

Nominal 13 T design, with an ultimate goal of 15 T, and reached 14.6 T (April 2018), a record for a magnet with a “free” aperture, and with only few quenches

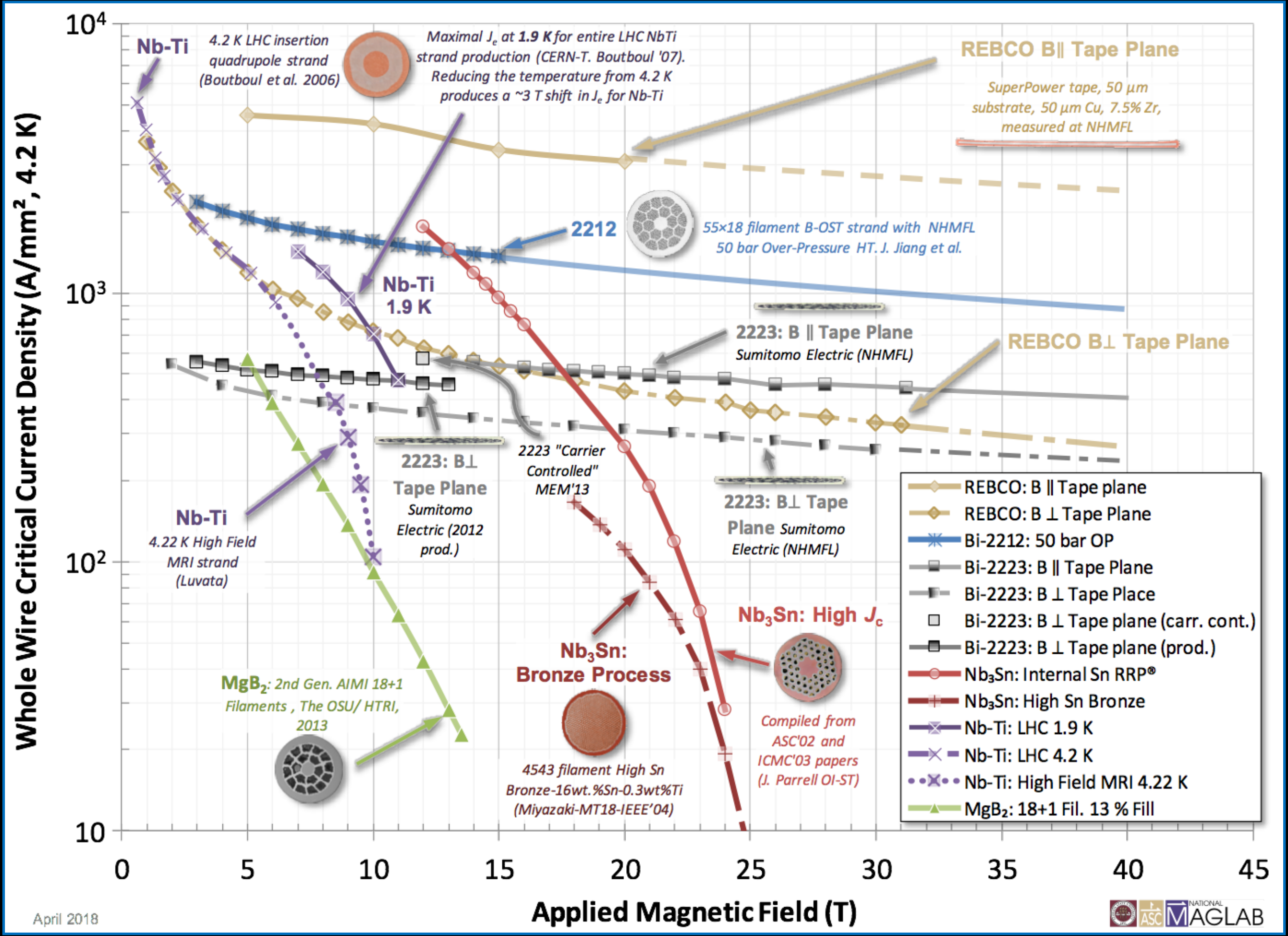
SC Magnet R&D – *16 T magnets would allow to reach much higher pp collision energies*

FRESCA2 @ CERN

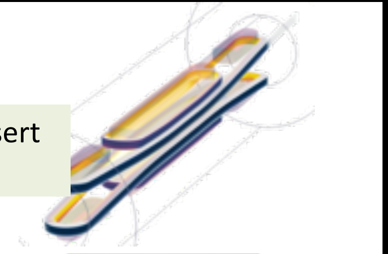


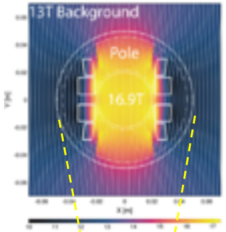
F. Toral @ Plenary ECFA meeting Nov 2018

SC Magnet R&D – *alternative materials for high-J_c at high magnetic field*

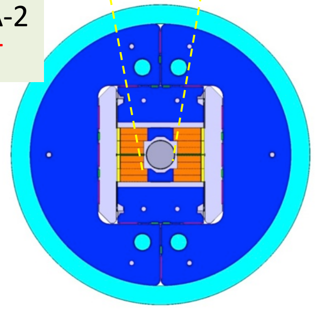


HTS-Insert
3~5 T





FRESCA-2
13-14 T



Eucard2: HTS-insert to be tested in 2019
(3-5) + (13-14)T : > 16 T

Technology readiness

Akira Yamamoto
@ Granada

Personal View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction			Operation		Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D			Prototype/Pre-series		Construction	

Technology readiness

Akira Yamamoto
@ Granada

Personal View on Relative Timelines

$\lesssim$8T NbTi magnets for a “low-energy” 100km *pp* collider immediately following HL-LHC ?

Timeline					~ 25	~ 30	~ 35
Lepton Collider							
SRF-LC/CC				tion		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction			Operation		Upgrade
12~14T Nb_3Sn	Short-model R&D		Proto/Pre-series		Construction	Operation	
14~16T Nb_3Sn	Short-model R&D			Prototype/Pre-series		Construction	

Technology readiness

Akira Yamamoto
@ Granada

Personal View on Relative Timelines

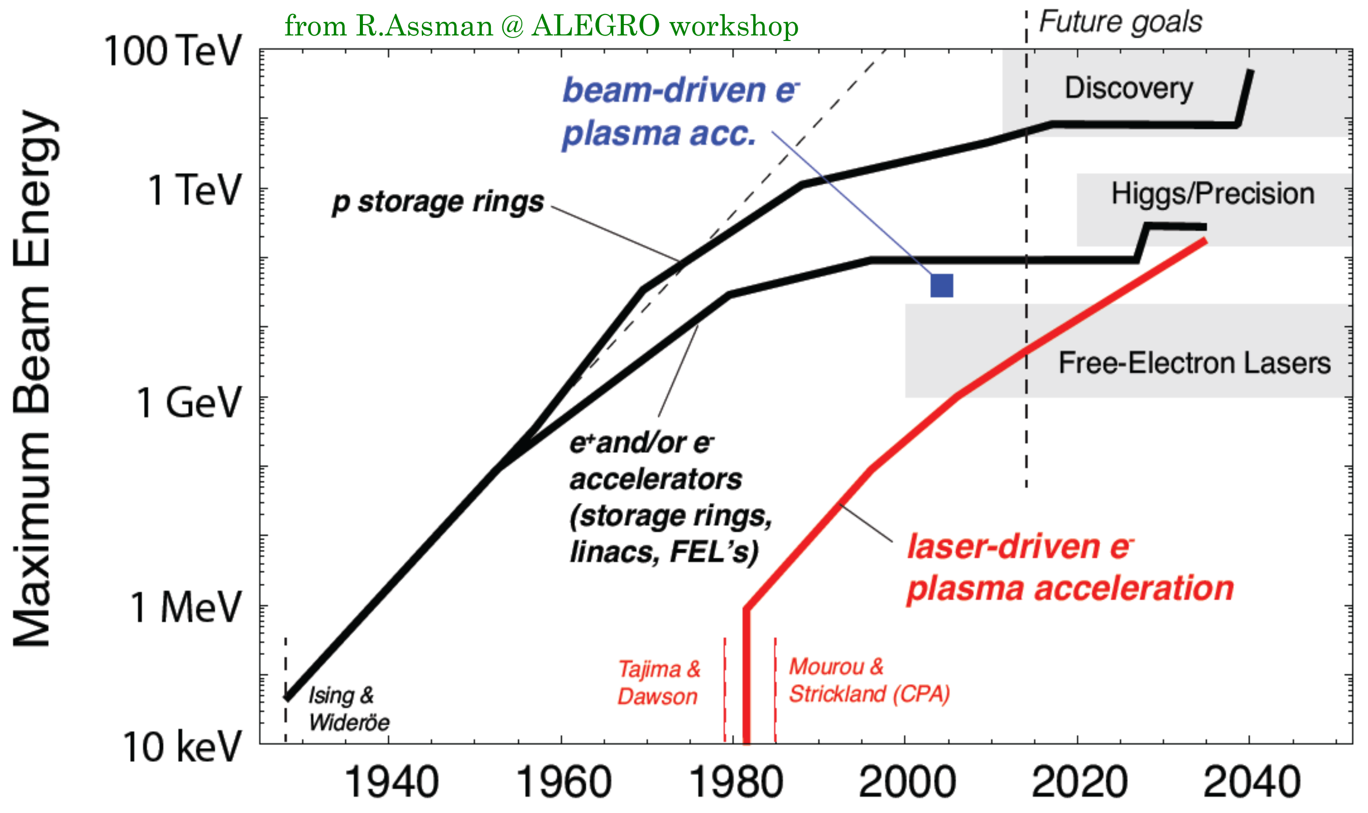
Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series					Upgrade	
NRF—LC	Proto/pre					Upgrade	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

<16T Nb_3Sn magnets ready for a "medium-energy" 100km *pp* collider immediately following HL-LHC ?

Accelerator R&D – Advanced Novel Accelerators (ICFA Panel)

ALEGRO (Advanced LinEar collider study GROup, for a multi-TeV Advanced Linear Collider)

ALEGRO delivered a document detailing the international roadmap and strategy of Advanced Novel Accelerators (ANAs).

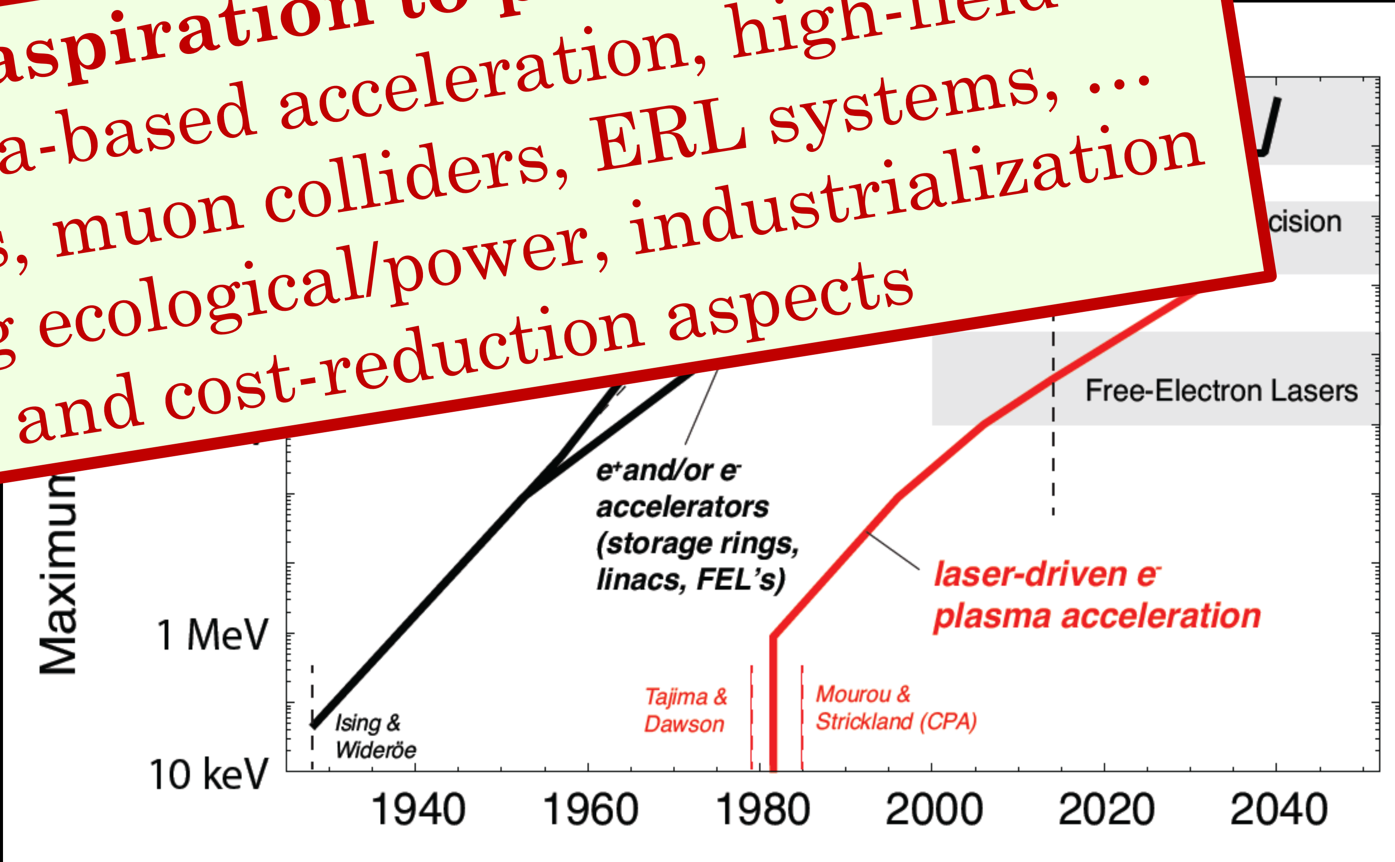


Accelerator R&D – Advanced Novel Accelerators (ICFA Pa

ALEGRO (Advanced LinEar collider study GROup, fo r)

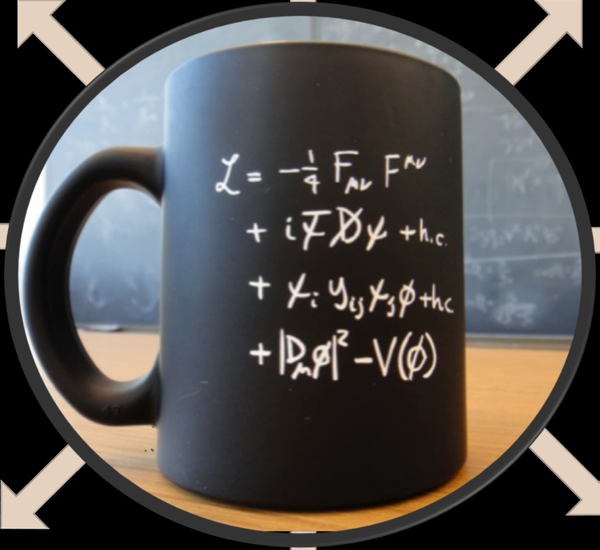
ALEG
docun
interna
and str
Novel A
(ANAs).

Strong aspiration to pursue R&D for:
plasma-based acceleration, high-field magnets, muon colliders, ERL systems, … including ecological/power, industrialization and cost-reduction aspects



higher energy interactions in the lab

earlier universe



rarer processes

higher energetic phenomena in the universe

higher energy interactions in the lab

earlier uni se

processes

Connection between particle physics
and astro(-particle) physics

e.g. jointly innovate technology
to make the invisible visible

higher energetic phenomena in the universe

we can only explore our aspirations
when we innovate technology

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when we innovate technology

we can only explore our aspirations
when we innovate technology

*our field of high-energy physics is
driven by our innovations in
technology*

from challenges to opportunities

foster the most talented researchers with aspirations in instrumentation, computing and software from challenges to opportunities

foster the most talented researchers with aspirations in instrumentation, computing and software

foster global R&D programs for technology and synergies with disciplines facing equivalent challenges

Long-term strategy for Particle Physics

European Strategy Update

Organization (2013 update):
http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/

UPDATE of the European Particle Physics Strategy (2013)

TODAY

Higgs discovery (2012)

Start data taking at the LHC (2010)

European Particle Physics Strategy (2006)

Organization (2006):
http://council-strategygroup.web.cern.ch/council-strategygroup/

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.

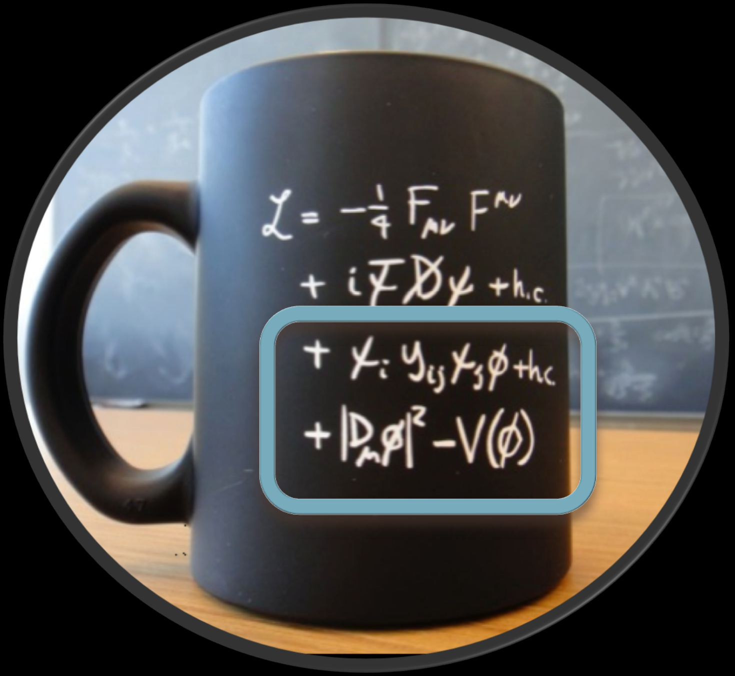
③ Europe looks forward to a [ILC] proposal from Japan to discuss a possible participation.

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.

1st priority

LHC and HL-LHC

Initial legacy impact of the LHC



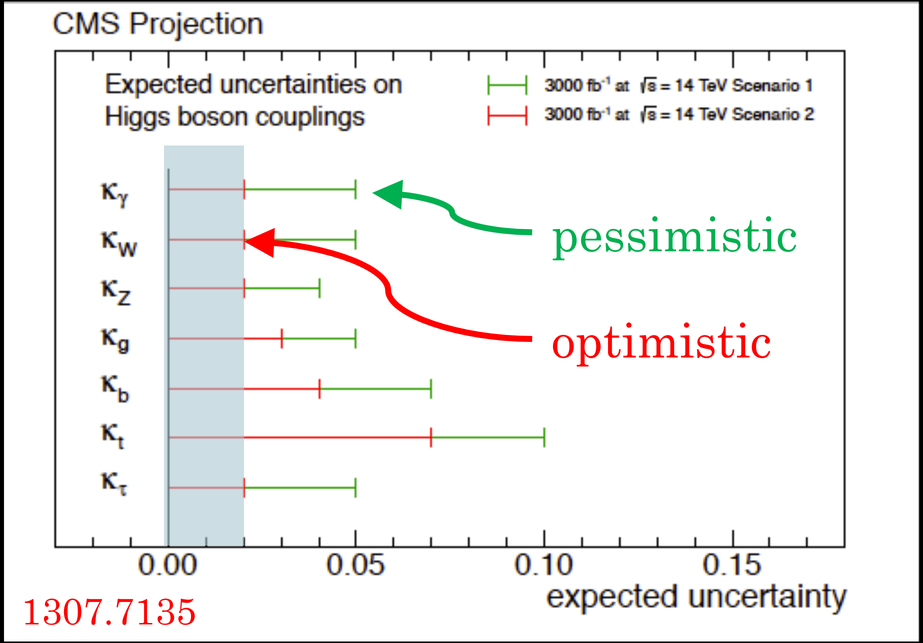
connection

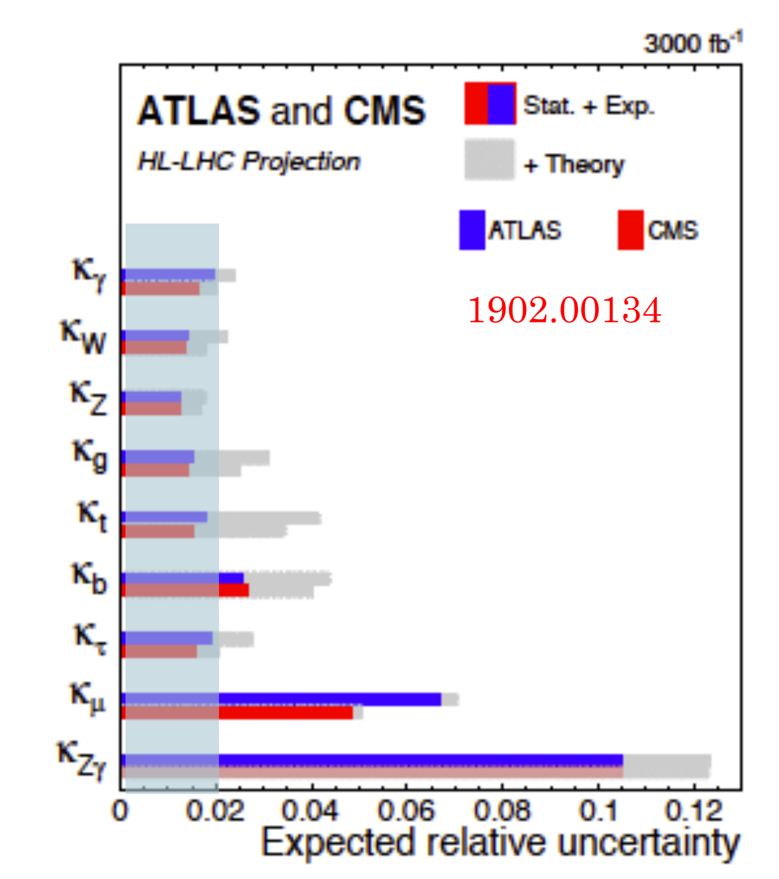
a MORE PRECISE and more COMPLETE description

new physics


High-Luminosity LHC: 300/fb (by 2023) → 3000/fb (by 2037)
HiLumi HL-LHC PROJECT
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)
CIVIL ENGINEERING
"CRAB" CAVITIES
FOCUSING MAGNETS
SUPERCONDUCTING LINKS
COLLIMATORS
BENDING MAGNETS
LHC TUNNEL
ALICE
ATLAS
LHCb
CMS
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
First scintillating fibre modules arriving at CERN
Calorimeter front-end board
Muon system readout ASIC
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)
64
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.

Potential HL-LHC performance in Higgs couplings
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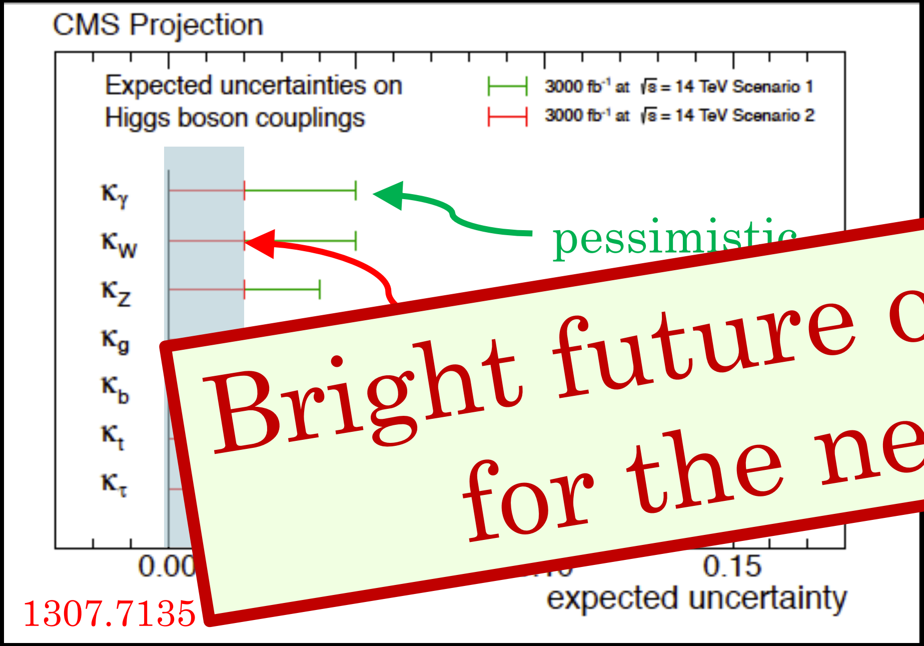
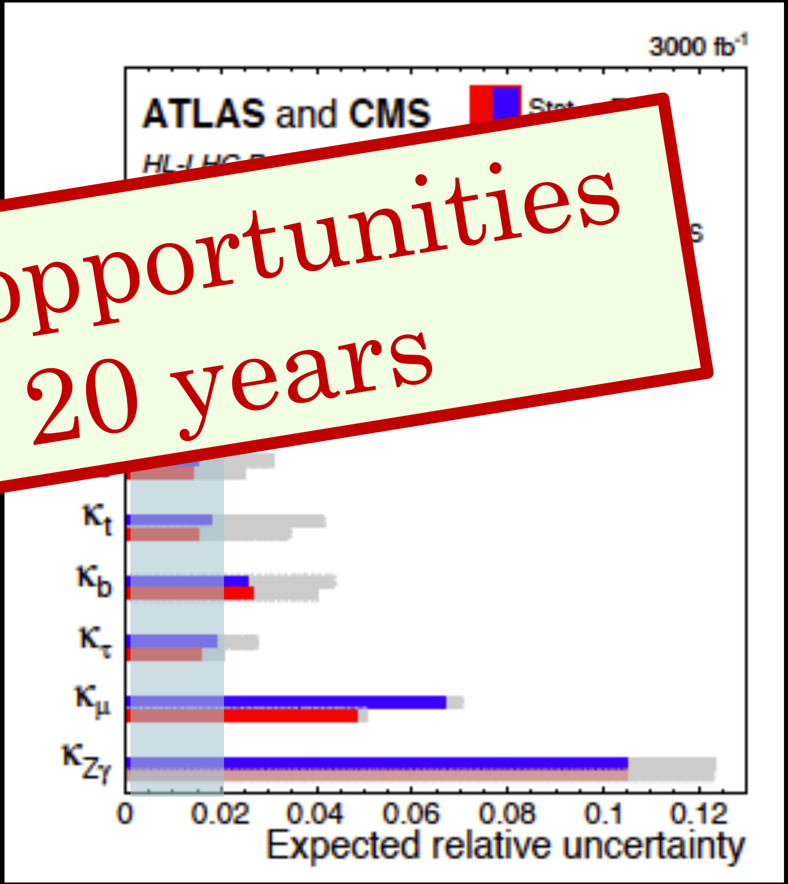




Bright future of opportunities for the next 20 years

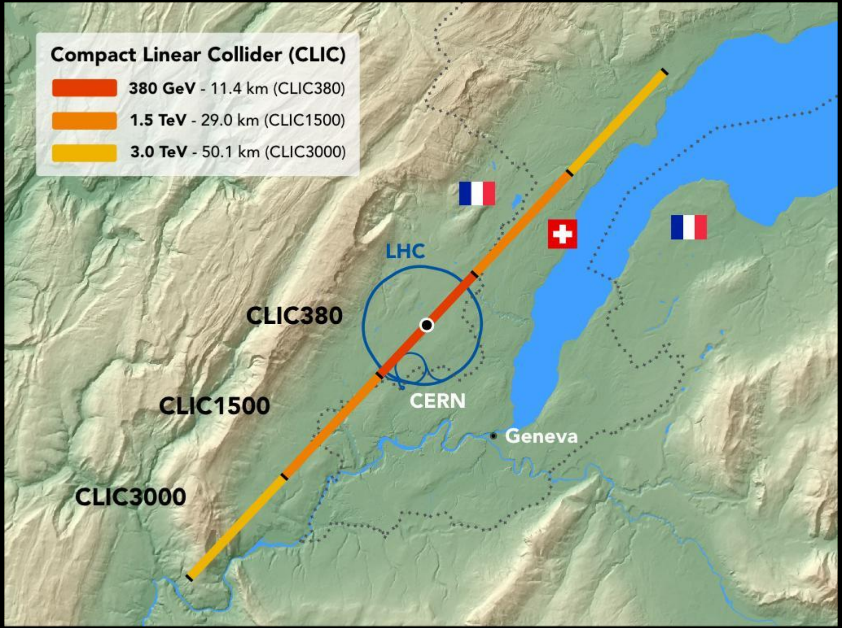
Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

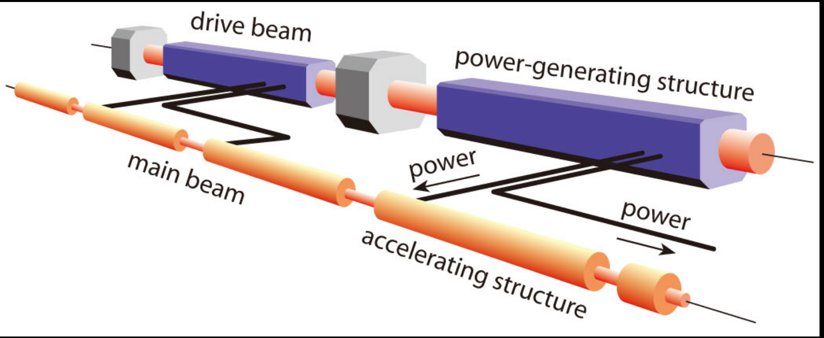
2nd priority

Future colliders at CERN

Concrete collider options studied at CERN

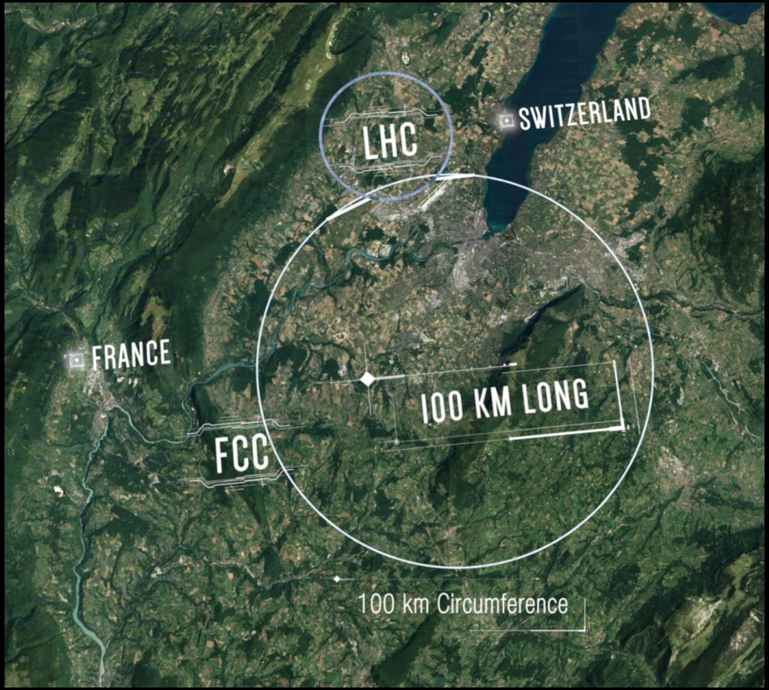
CLIC (ee), http://clic-study.web.cern.ch/



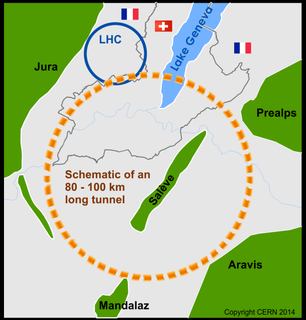


Concrete collider options studied at CERN

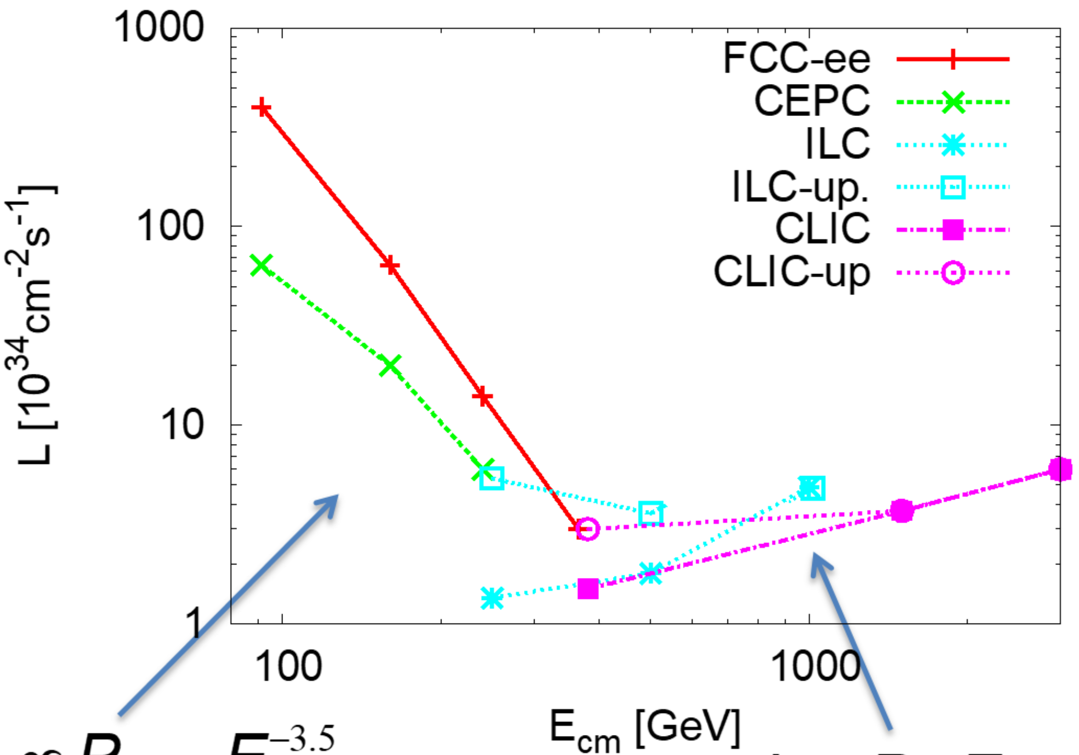
FCC (ee, ep, pp, pA, AA, eA), https://fcc-cdr.web.cern.ch/



- **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

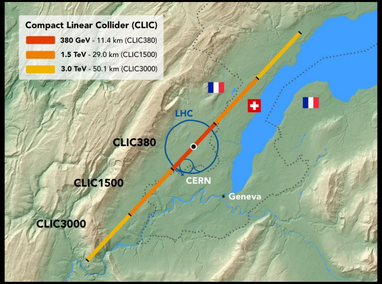


Luminosity per facility



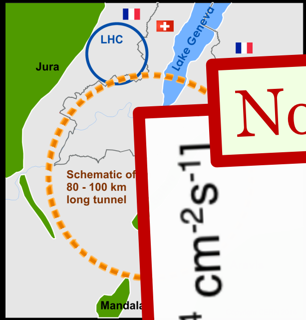
$$L \propto P_{synrad} E_{cm}^{-3.5}$$

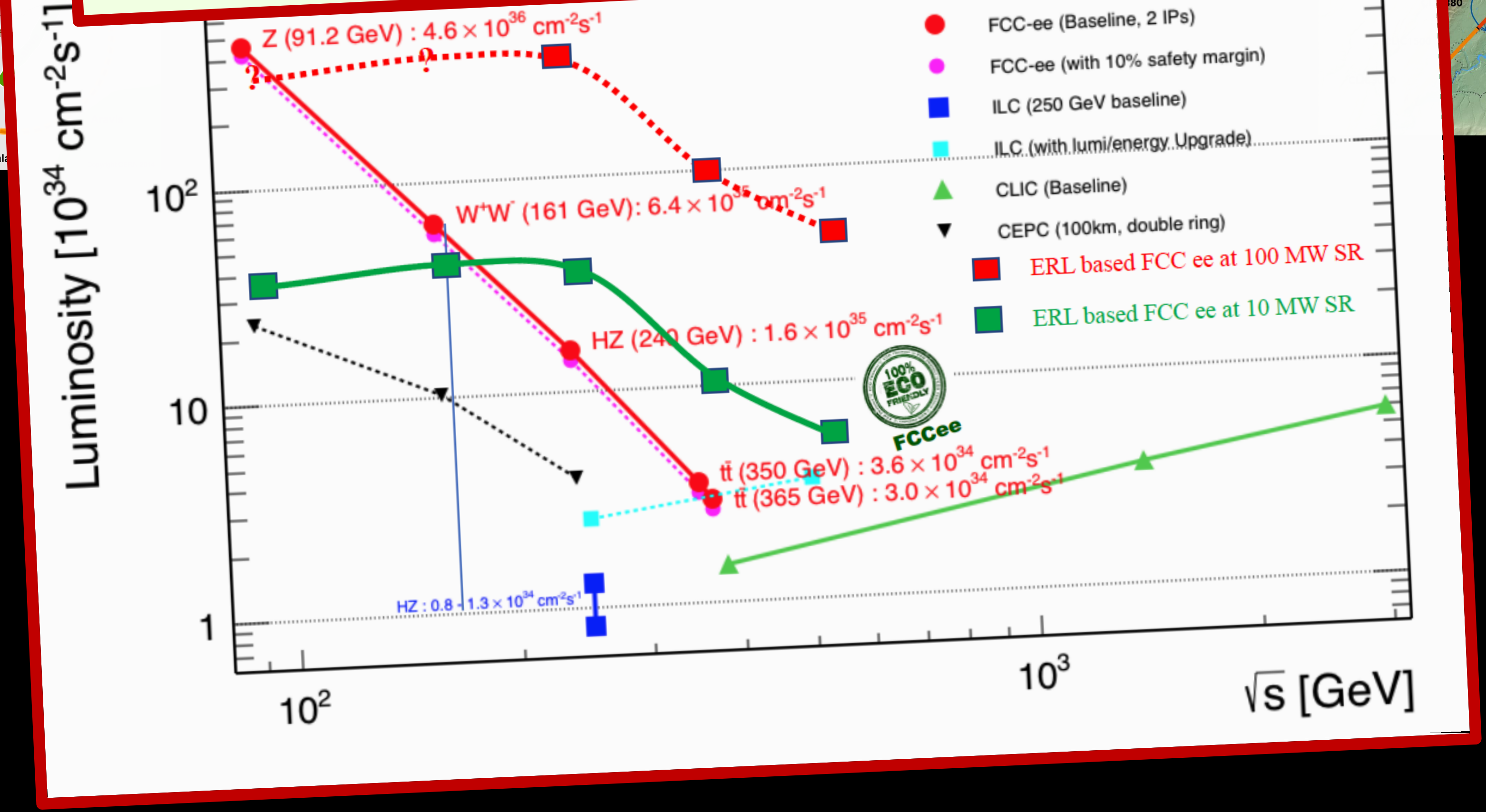
$$L \propto P_{RF} E_{cm}$$

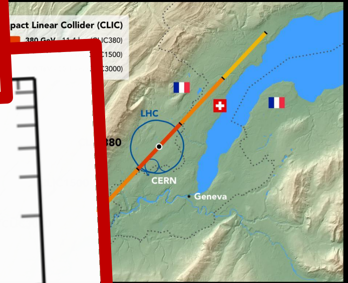


Daniel Schulte @ Granada

Novel thinking ongoing: ERL-based FCC-ee

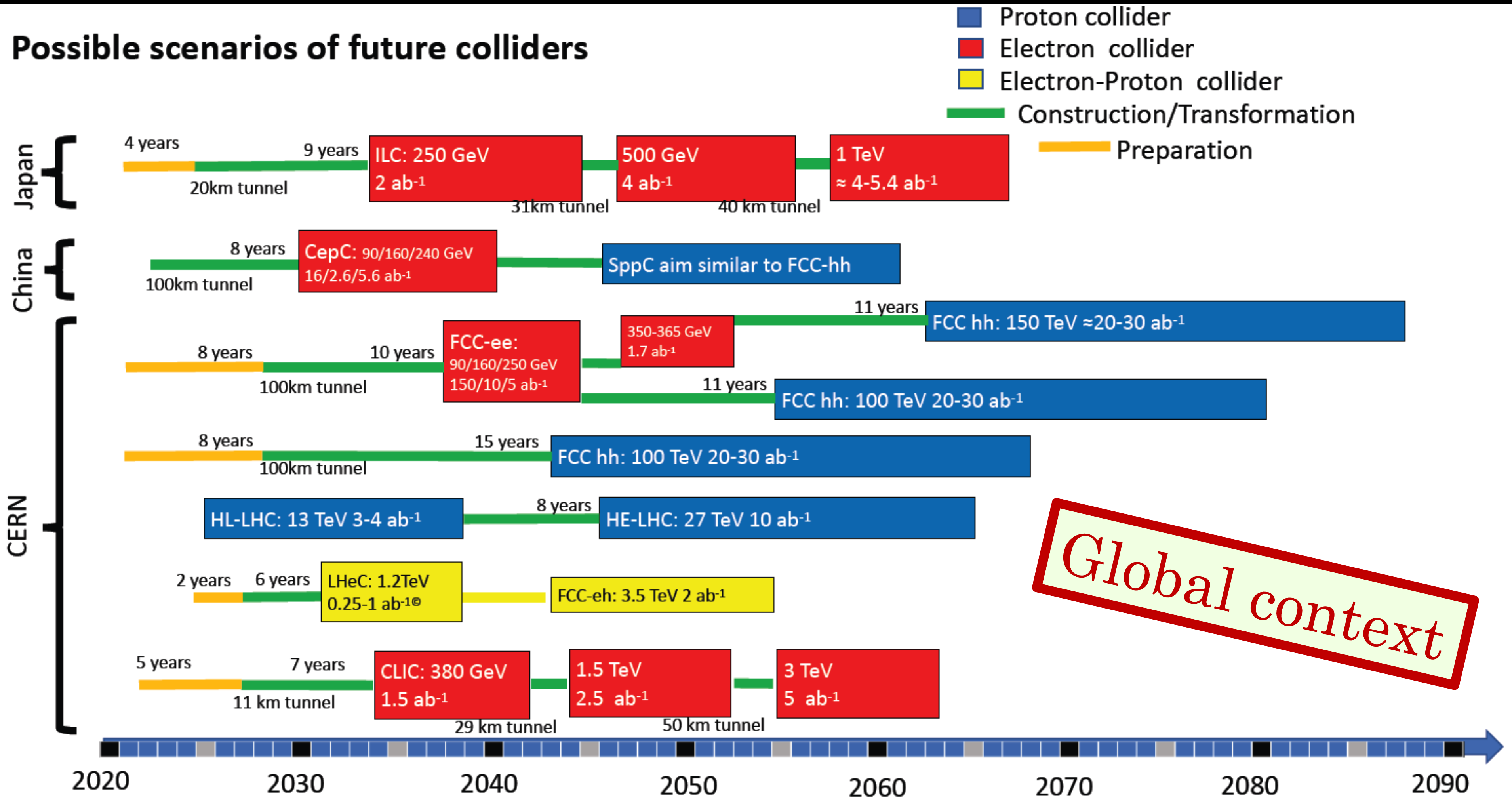






Maria Chamizo @ FCC week: https://indico.cern.ch/event/727555/contributions/3474689/

Possible scenarios of future colliders



Long-term strategy for Particle Physics

European Strategy Update

Organization (2013 update):
http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/

European Particle Physics Strategy (2006)

Start data taking at the LHC (2010)

Higgs discovery (2012)

UPDATE of the European Particle Physics Strategy (2013)

TODAY

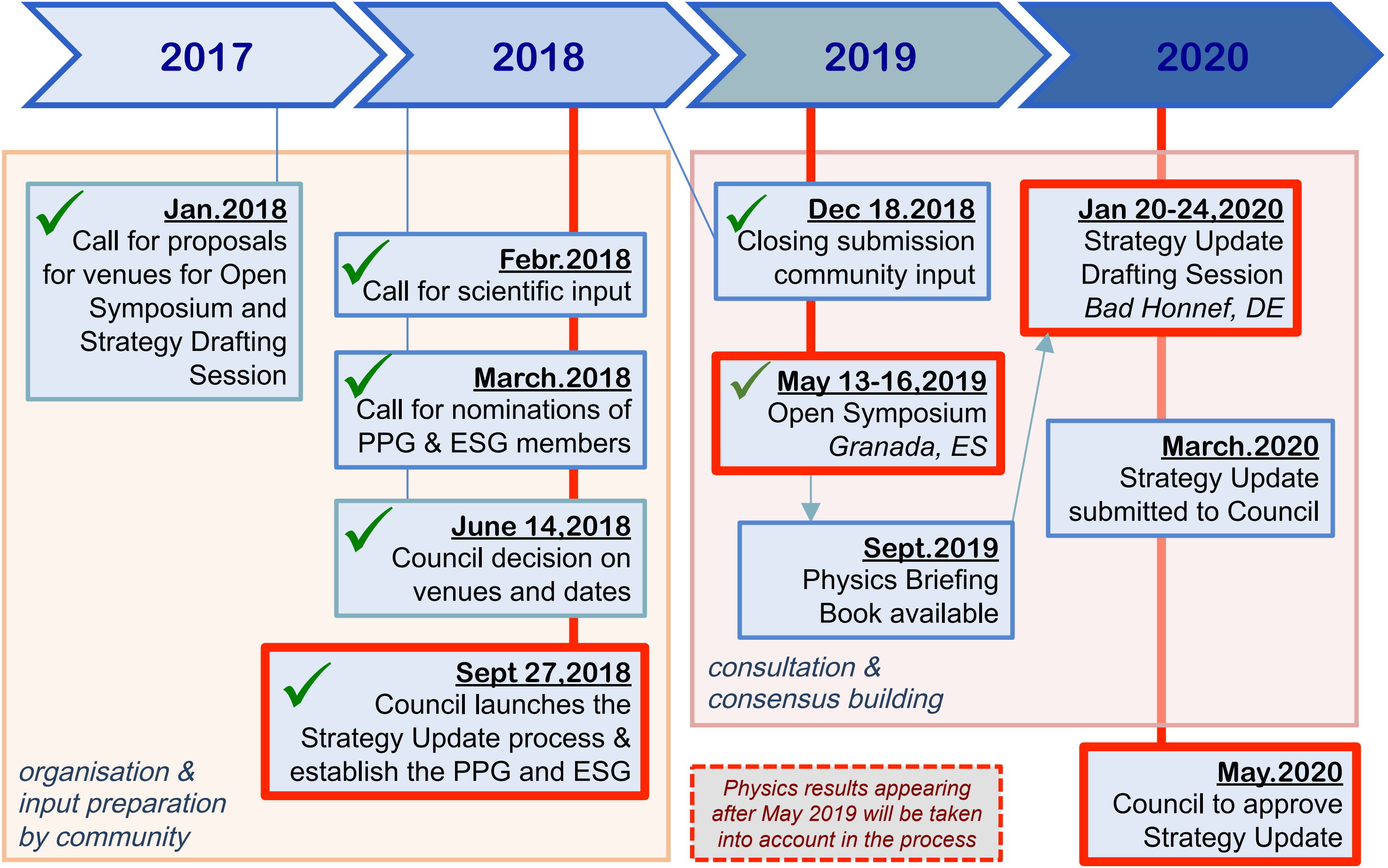
UPDATE of the European Particle Physics Strategy (2020)

https://europeanstrategy.cern

Start data taking HL-LHC (2026)

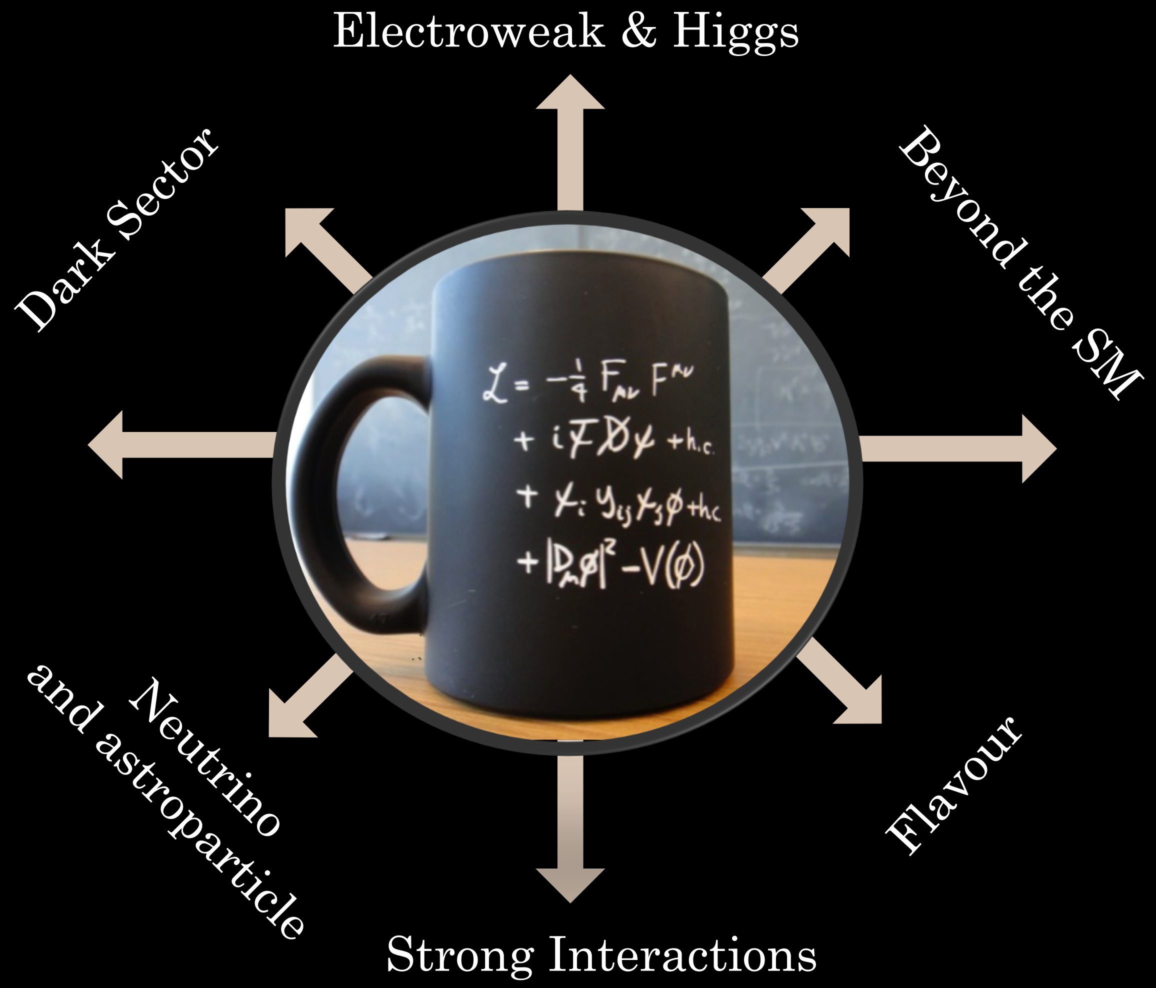
Major facility after HL-LHC

Organization (2006):
http://council-strategygroup.web.cern.ch/council-strategygroup/


2017
2018
2019
2020
Jan.2018
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
Council launches the Strategy Update process & establish the PPG and ESG
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
Physics results appearing after May 2019 will be taken into account in the process
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

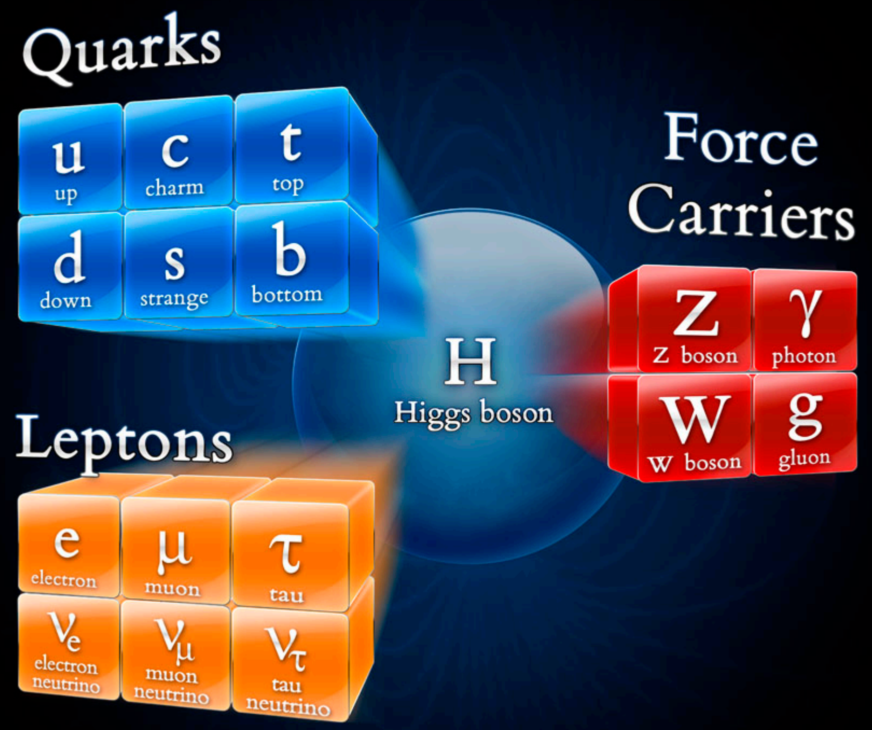
Open Symposium
Towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain
https://cafpe.ugr.es/eppsu2019/
~600 participants
Information captured in 8 thematic summary talks

The Granada physics themes



The Granada themes

Flavour & CP



The Granada themes

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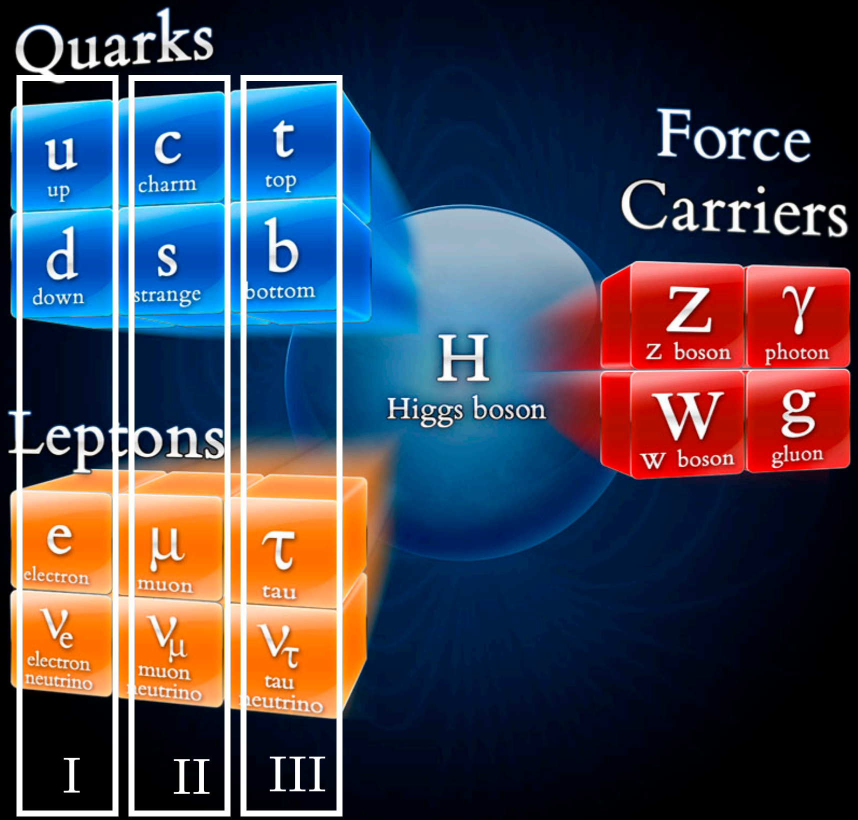
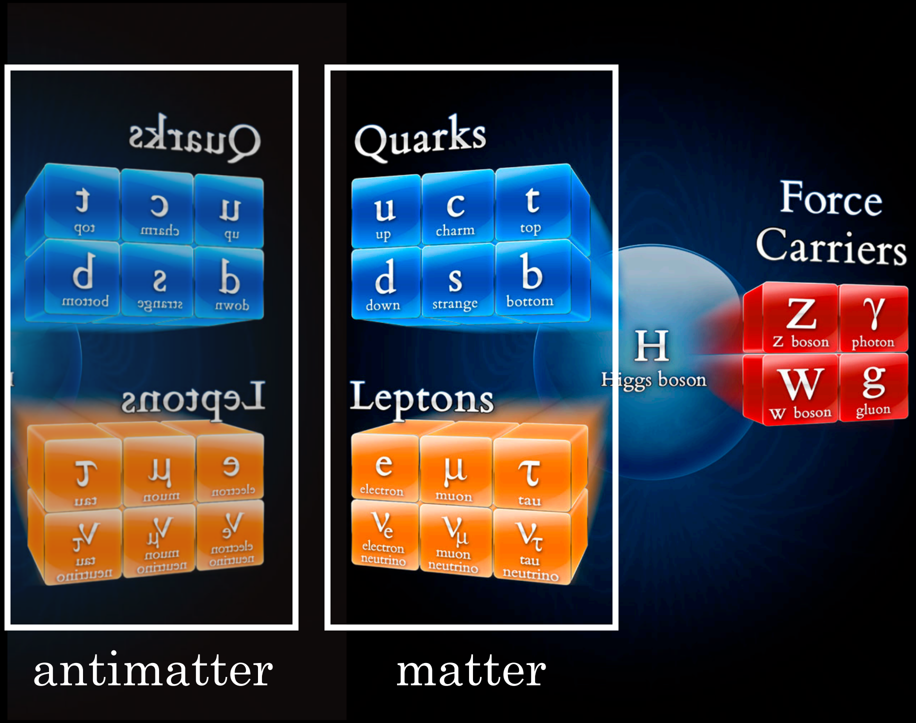


The Granada themes

Flavour & CP



The light sector (u,d,s + e,μ)

Three “clear” cases calling for diversity in the short/mid-term:

1. EDMs [d_e, d_n, d_N,.]	Strong CP EW CP	new: Storage rings
2. μ→e processes	1 → 2 Gen Lep. Mix.	Intense μ beams
3. Rare K decays	1 → 2 Gen. Quark Mix.	Intense K beams

Λ > 10^3 TeV for O(1) couplings
Storage ring JEDI/CPEDM start construction in 2027

Antonio Zoccoli @ Granada

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$\Lambda > 10^4$ TeV for O(1) couplings
Mu2e@FNAL, MEG@PSI, COMET@J-PARC, …
Sensitivity improvement x10000

Antonio Zoccoli @ Granada

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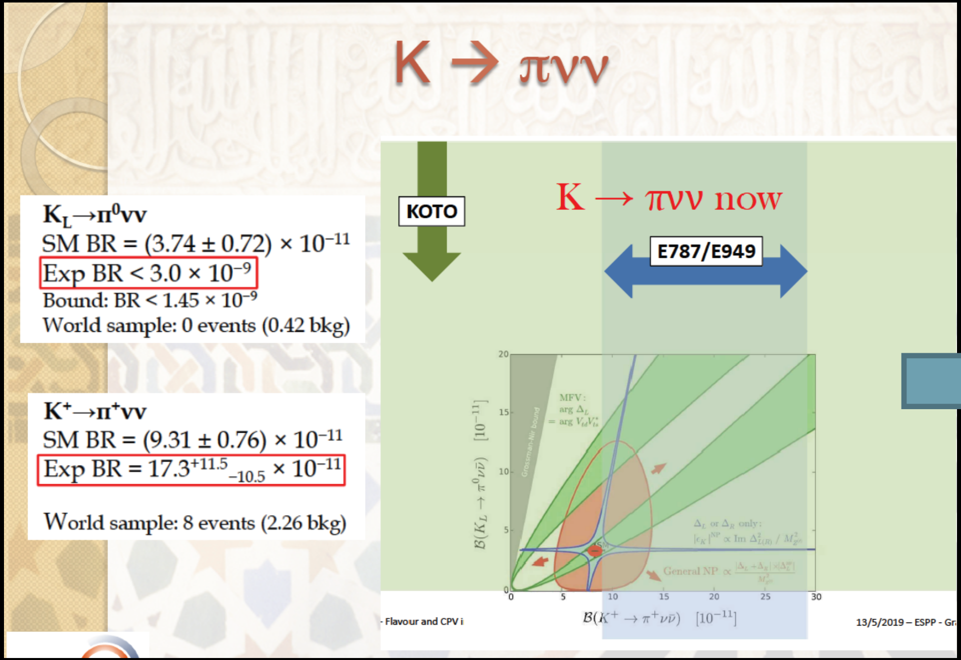
Sensitivity improvement x10000

Great potential
Difficult experiments

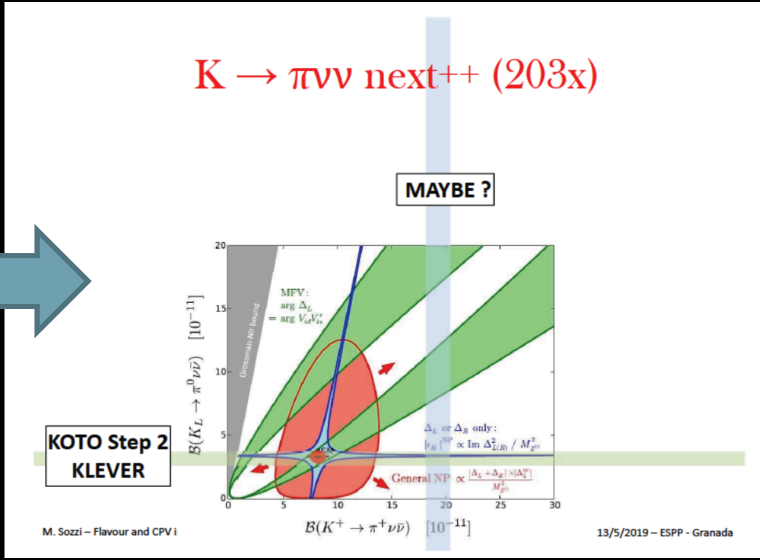
Antonio Zoccoli @ Granada

The light sector (u,d,s + e,μ): rare K decay evolution

NA62@SPS & KOTO@J-PARC



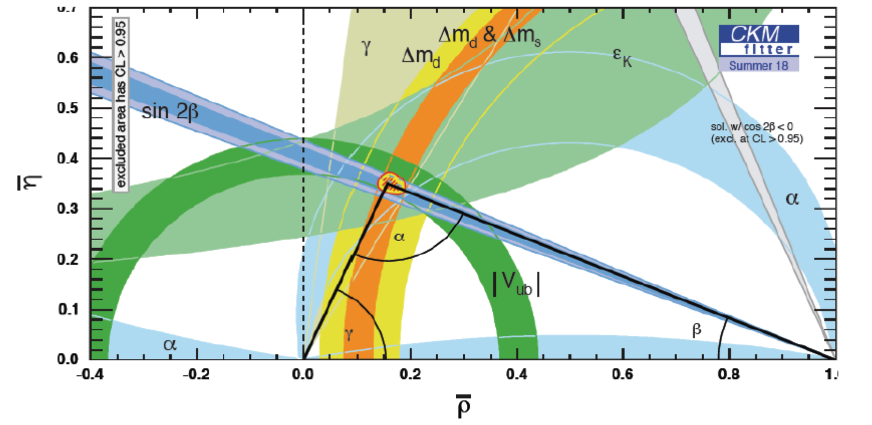
KOTO-Step2 & KLEVER@CERN



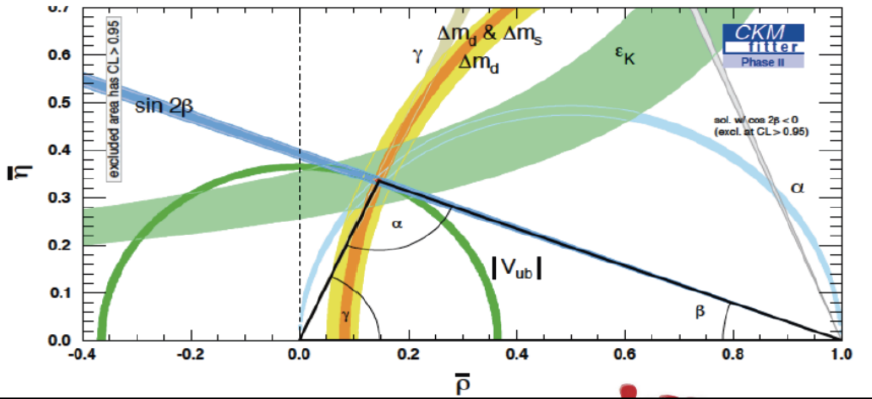
Antonio Zoccoli @ Granada

The heavy sector (b,c,t + τ + h)

Today



End of HL-LHC: Belle II + LHCb Upgrade II



Belle II+1= Belle III

Just started within Belle II

Goal: x5 increase in peak luminosity

- ❑ Doable from a machine perspective ?
- ❑ Detectors issues running at 4 10^{36} cm^{-2} s^{-1}
- ❑ Physics case

Under study, more before the end of 2019

Z^0 factories

Goal: $10^{11} - 10^{12}$ Z^0 (CEPC)
5. 10^{12} Z^0 (FCCee)
$BR(Z^0 \to b\bar{b}) = 15\%$

ILD-like detector + charged hadron PID.

FCC-pp a dedicated experiment (à la LHCb)

e^+e^- Super Charm-Tau Factories:
SCT (BINP, Novosibirsk) and STCF/HIEPA (China)
E: 2 to 6 GeV
Peak Luminosity (> 4 GeV) 10^{35} cm^{-2} s^{-1}

"Flavour is the usual graveyard for BSM electroweak theories"

Antonio Zoccoli

The Granada themes

Flavour & CP

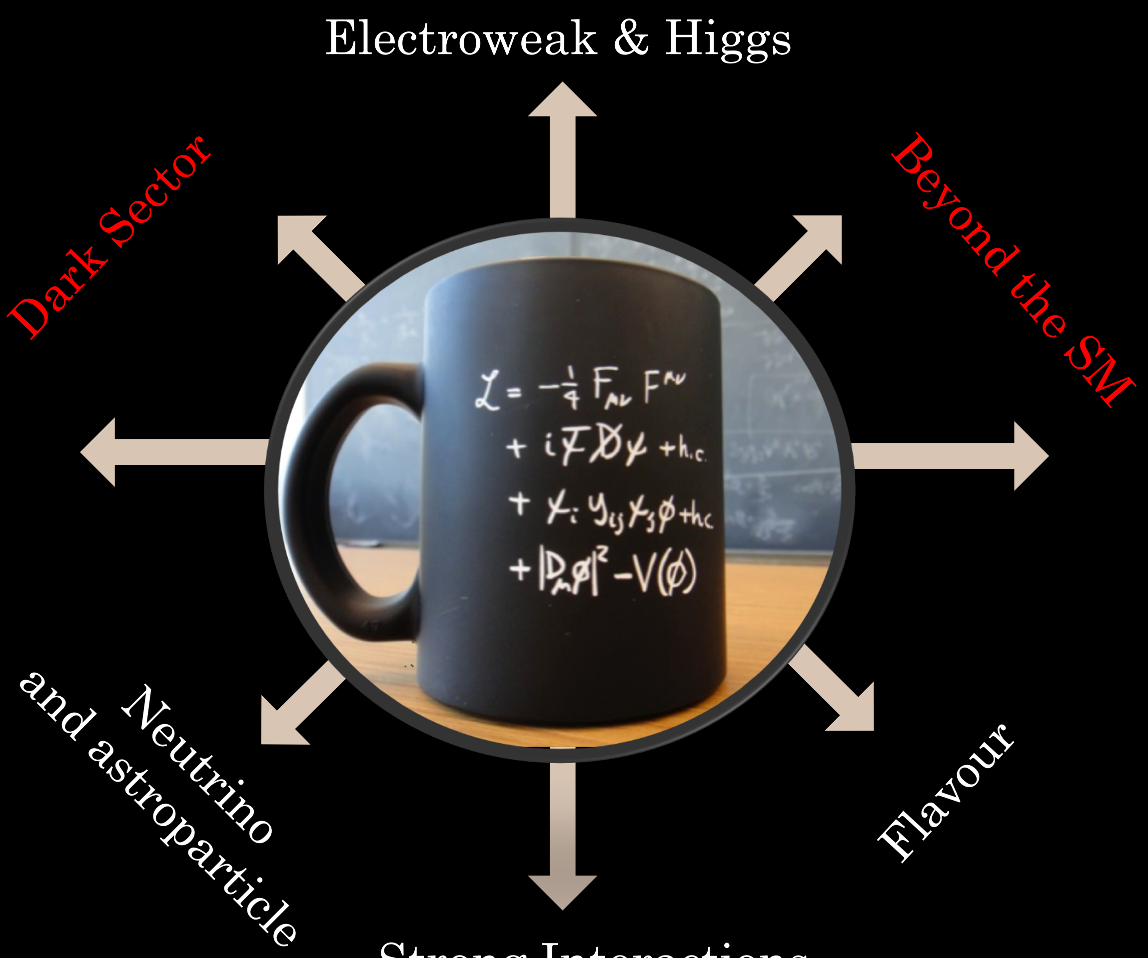
- Challenging experiments, but a must-have in our experimental portfolio
- Outstanding BSM scale reach: $\Lambda > 10^2$-10^5 TeV
- Particle-ID should be part of any future collider program at high energies
- Different environments (ee and pp) are complementary
- A Z^0-factory is a fantastic tool for flavour physics

The Granada themes

Beyond the SM

&

Dark Sector



The Granada themes

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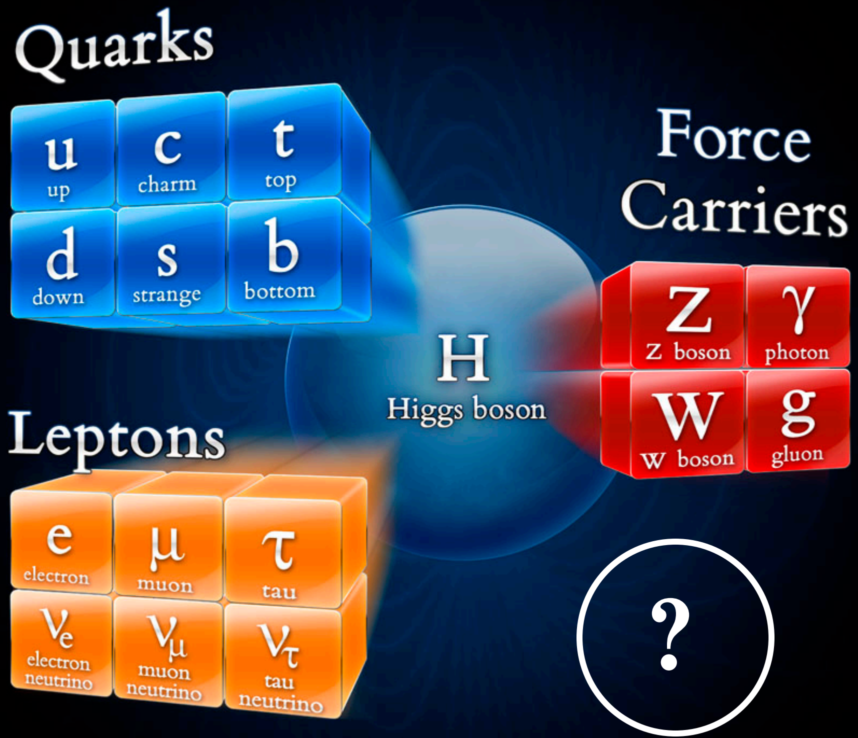
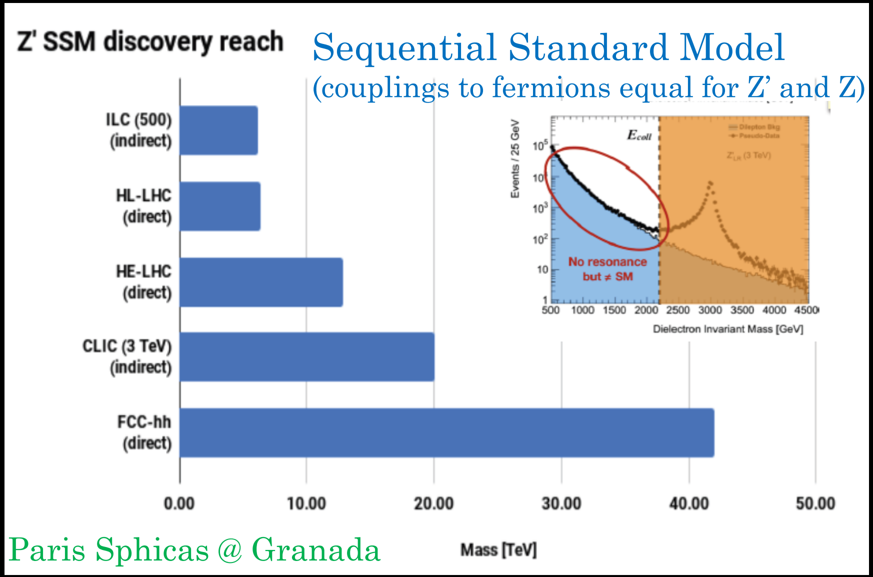
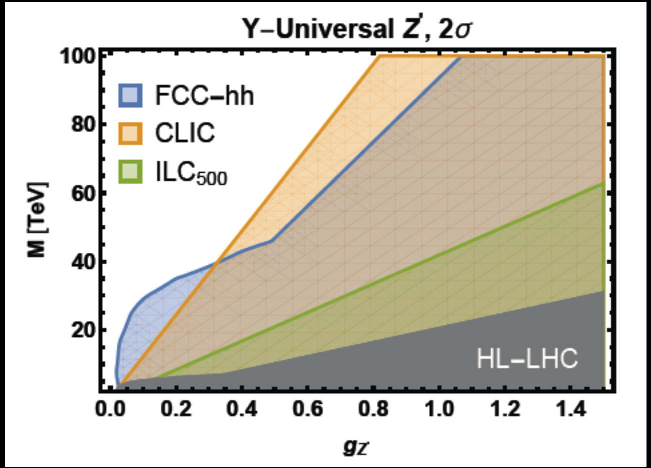


Are there new interactions or new particles around or above the electroweak scale?



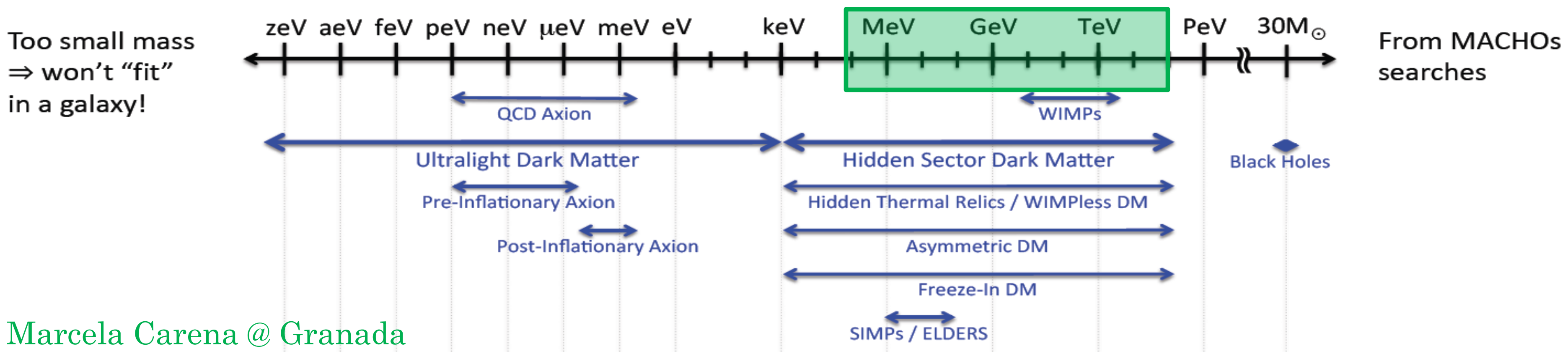
- In general, if the couplings become large the sensitivity at lepton colliders is enhanced
- For weak couplings the direct search at hadron colliders dominates the picture



Paris Sphicas @ Granada

Many more models are compared…

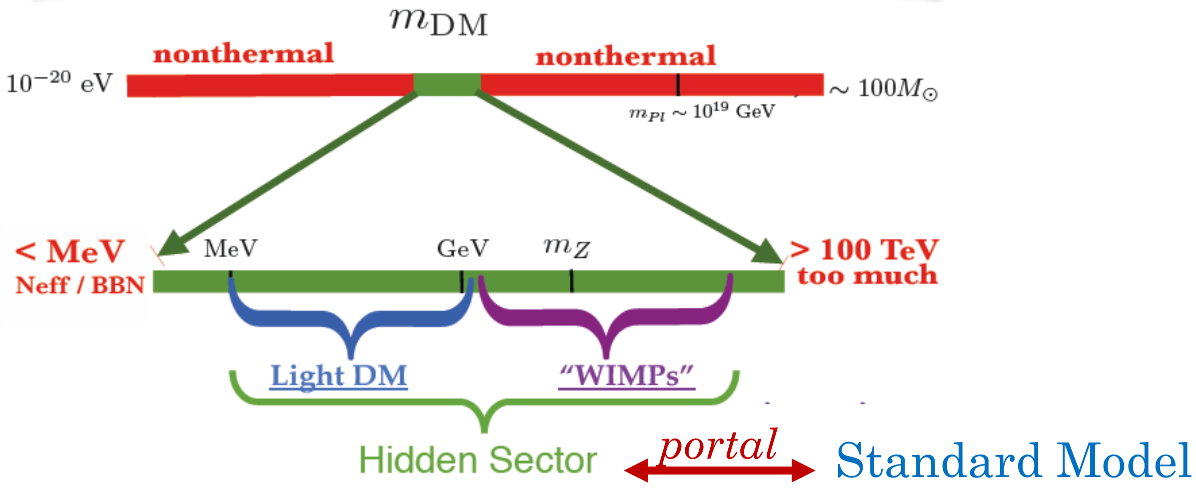
Dark Matter: Where to start looking? Very little clue on mass scale…



Marcela Carena @ Granada

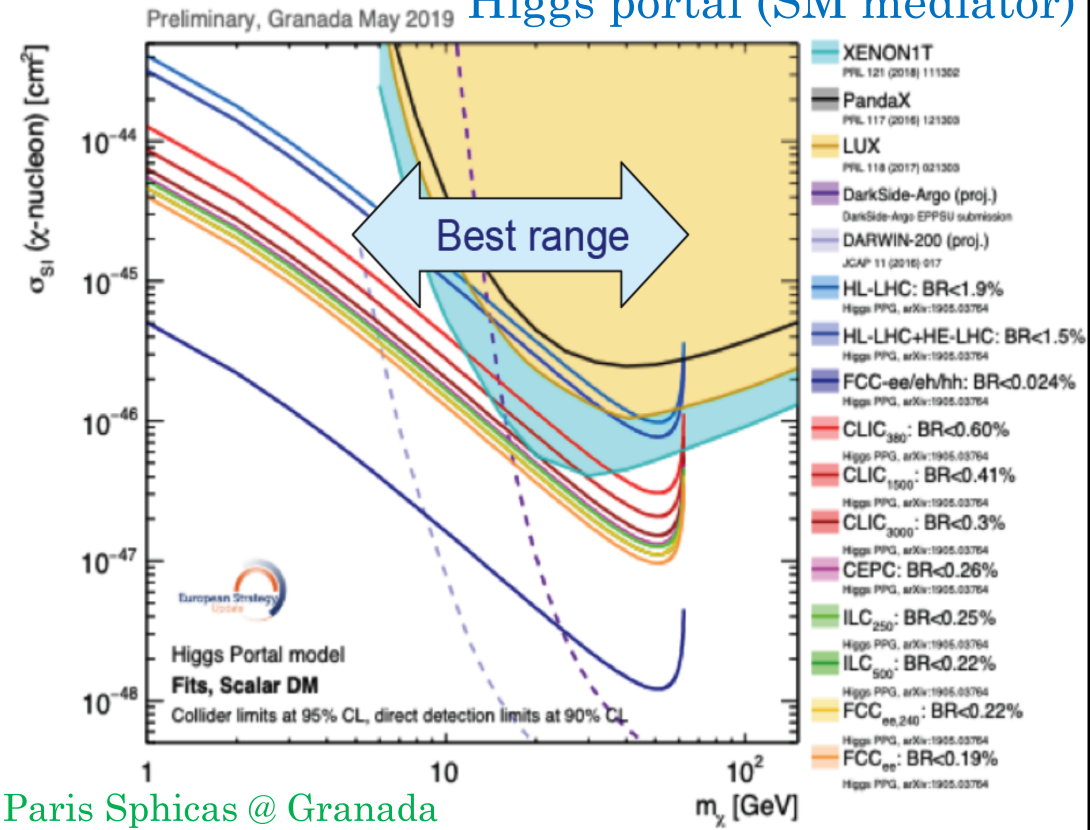
The assumption of Thermal Equilibrium in the early Universe narrows the viable mass range.

Interesting phenomena like long-lived particles and feebly interacting particles.



What cases of thermal relic WIMPs are still unprobed and can be fully covered by future collider searches?

Higgs portal (SM mediator)



Paris Sphicas @ Granada

A collider discovery will need confirmation from DD/ID for cosmological origin

A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction

A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID.

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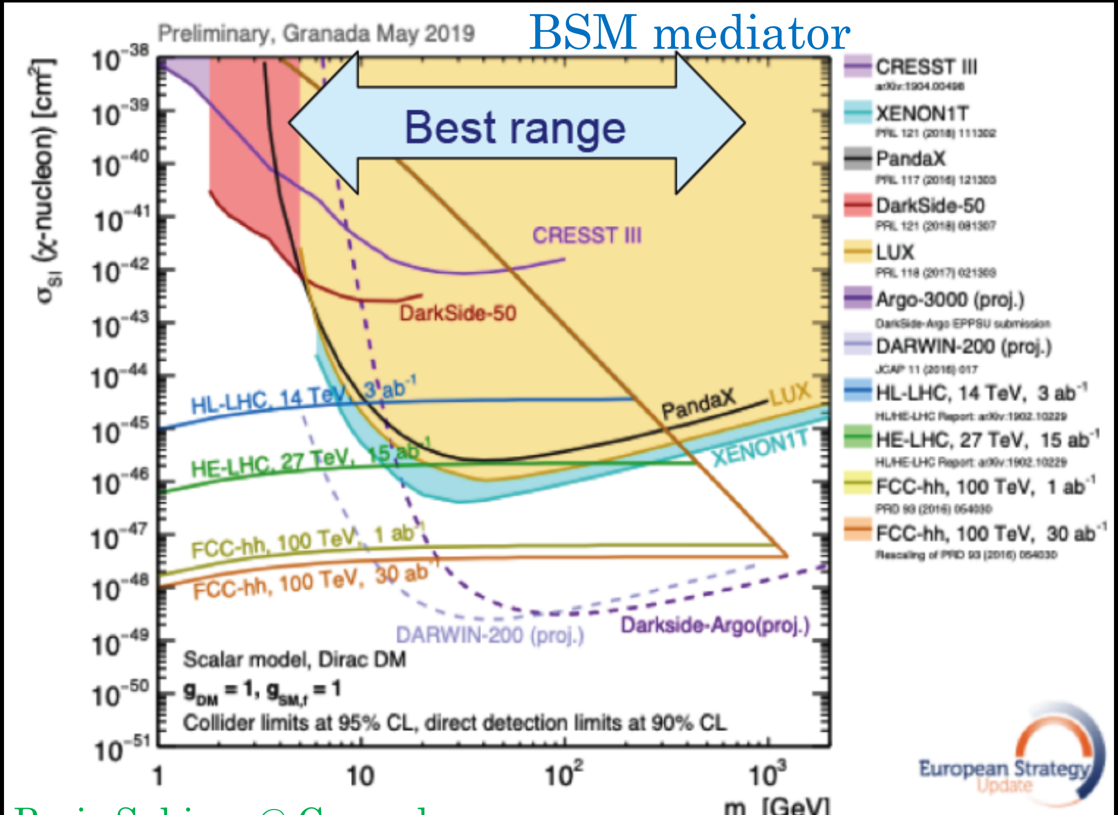

Paris Sphicas @ Granada

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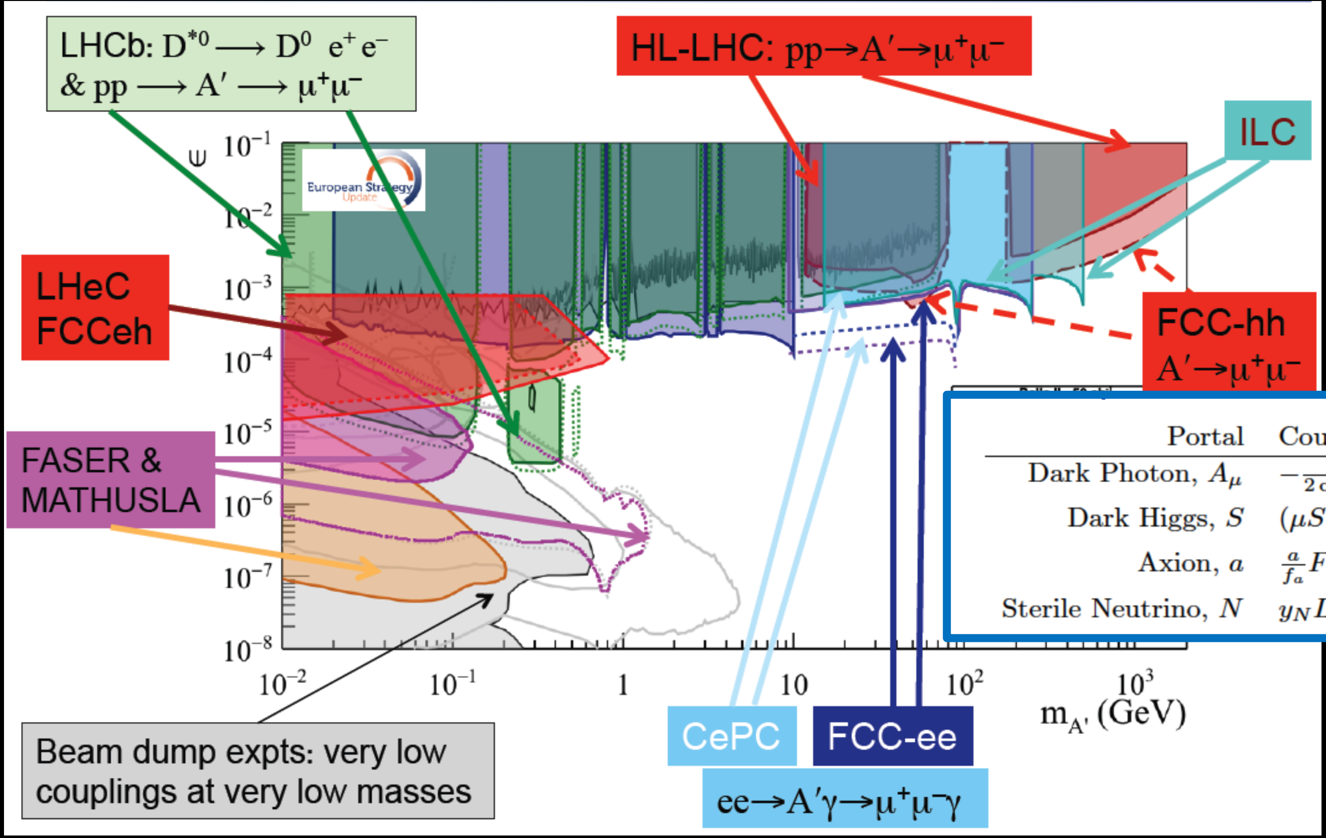
To what extent can current or future accelerators probe feebly interacting sectors?



Use four simplified models ("portals") from which benchmarks are identified to evaluate experimental sensitivity

PBC report, arXiv:1901.09966

Portal	Coupling	
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$	(Relaxion toy model, mixes \w Higgs)
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$	
Sterile Neutrino, N	$y_N L H N$	

Dark Photon case

The Granada themes

Beyond the SM

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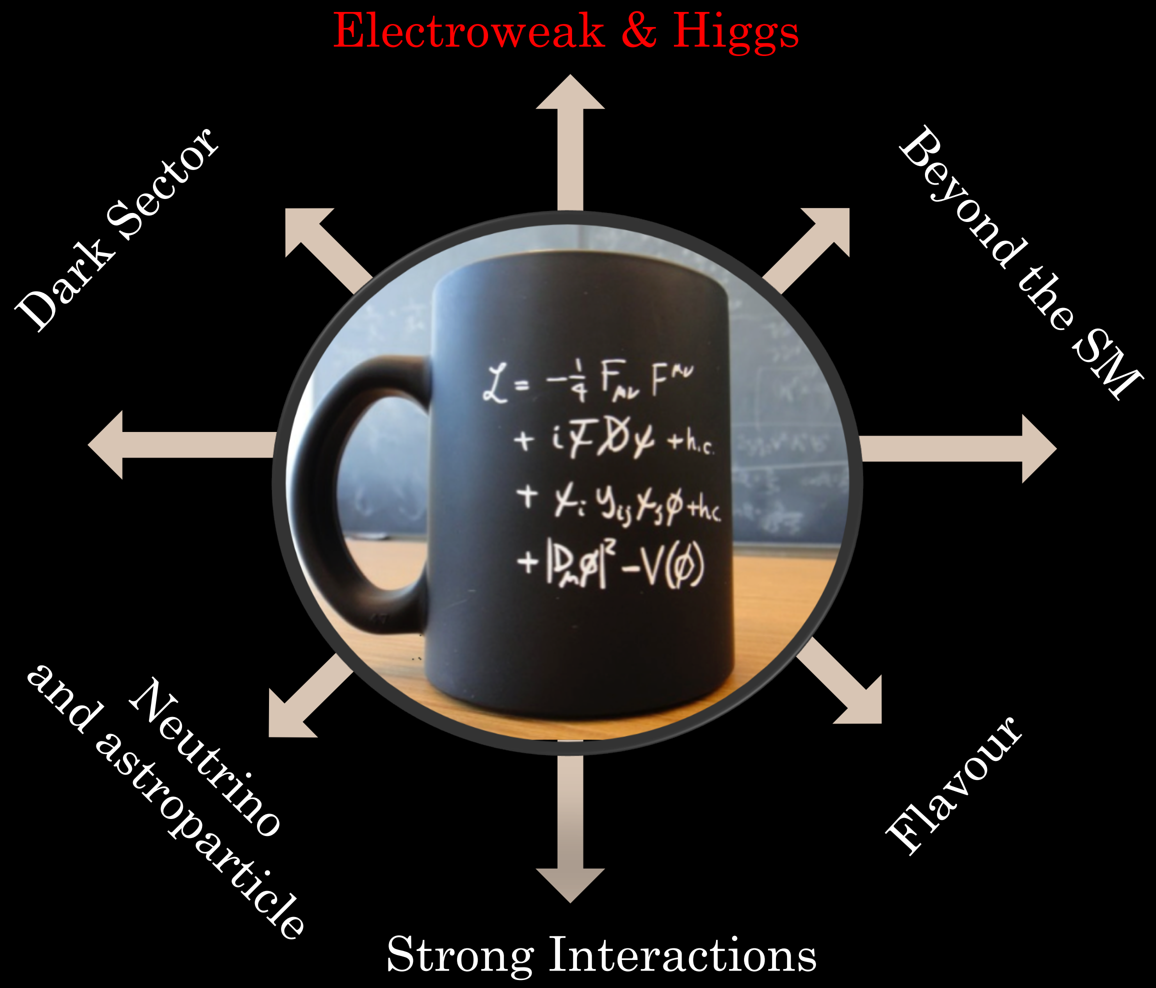
Dark Sector

- In the absence of concrete guidance, the parameter space for new physics is vast…
- Exploring synergies and coordination with adjacent fields is necessary, e.g. with the direct and indirect dark matter detection communities for common interpretation of results
- Complementarity between lepton and hadron colliders for dark matter searches with the combined FCC program providing the best sensitivity for the benchmarks
- Complementarity between beam dump and collider experiments for feebly interacting particles

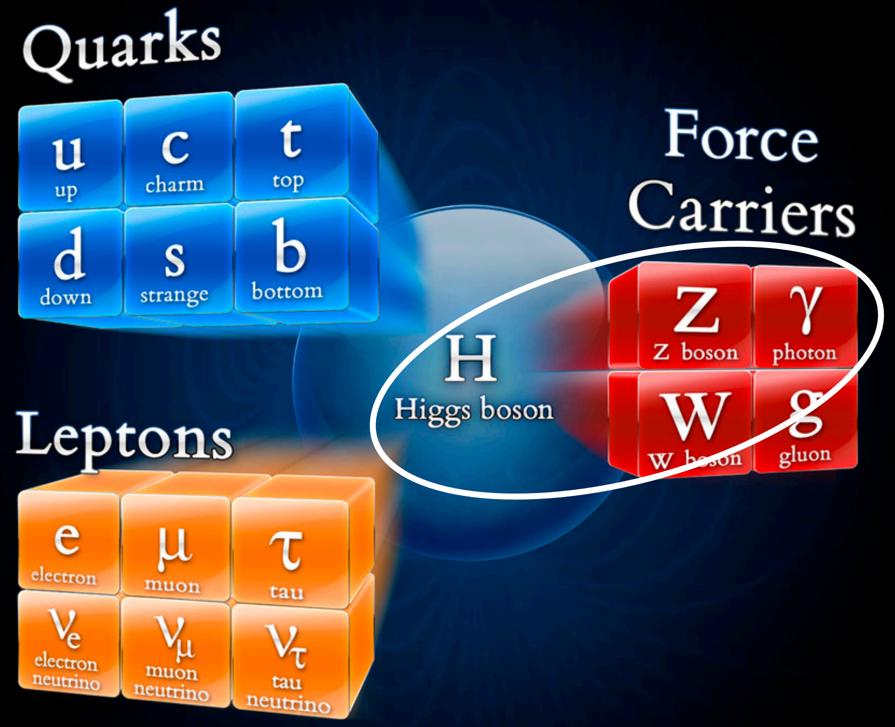
The Granada physics themes

EW & Higgs



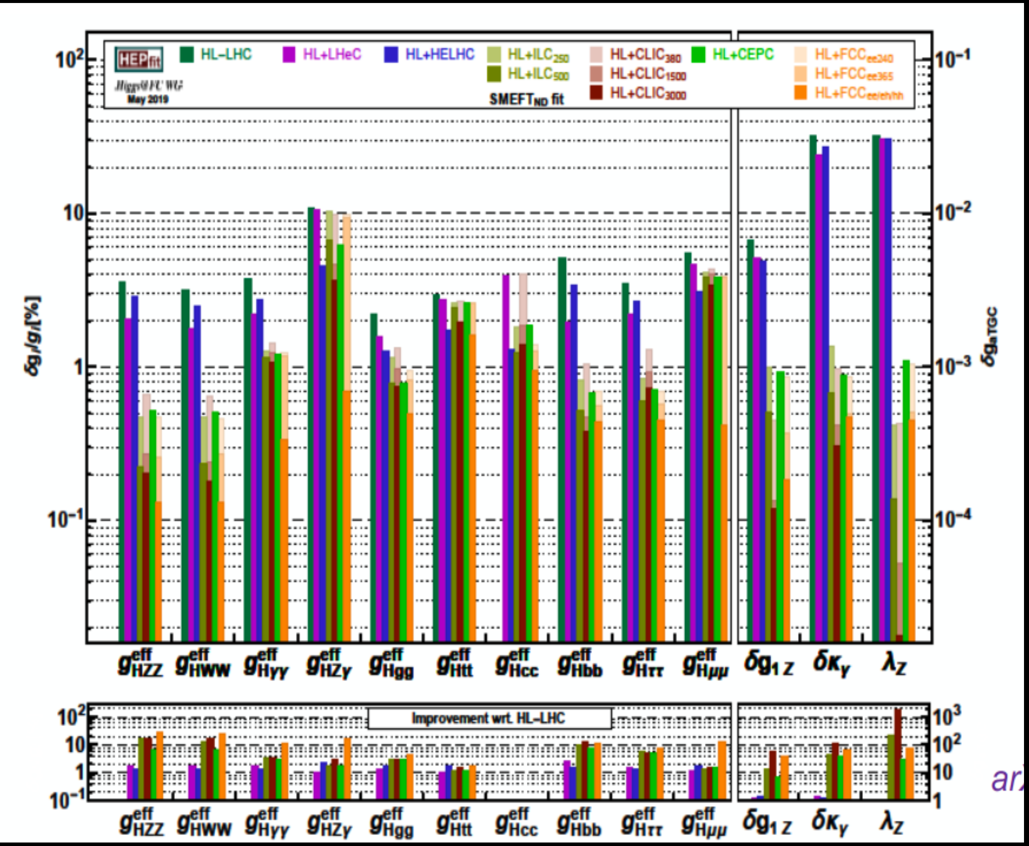
The Granada themes

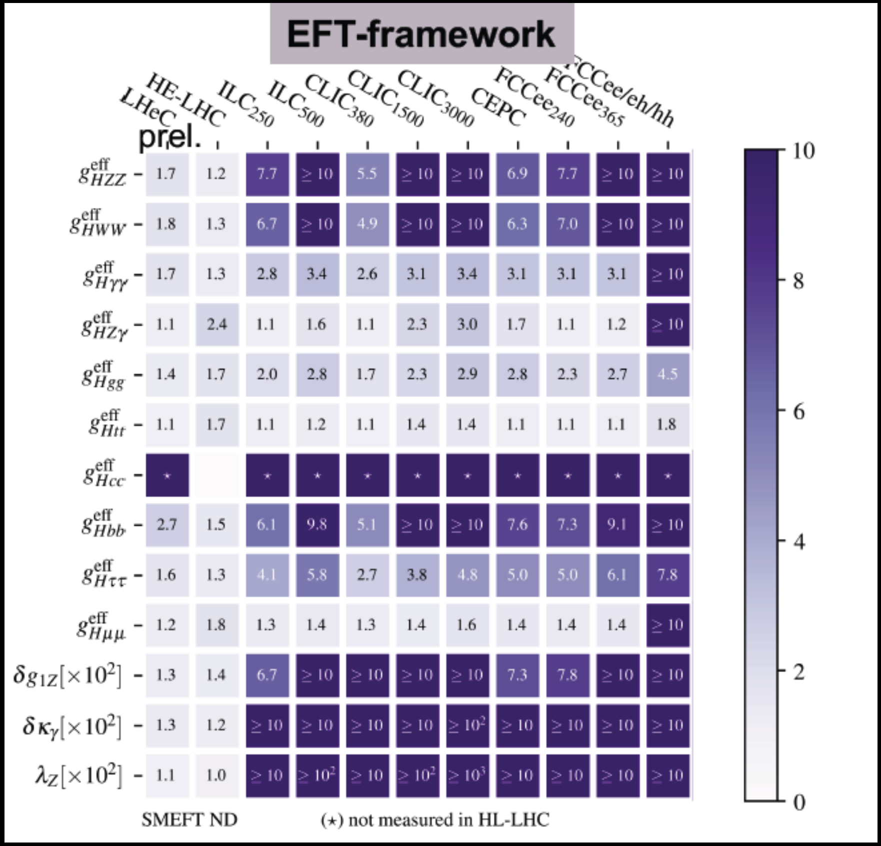
EW & Higgs



Potential to measure Higgs couplings

improvements wrt HL-LHC





Beate Heinemann @ Granada

arXiv:1905.03764 (ECFA/PPG working group: "*Higgs Boson Studies at Future Particle Colliders*")

of “largely” improved H couplings (EFT)

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
2nd/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

The Granada themes

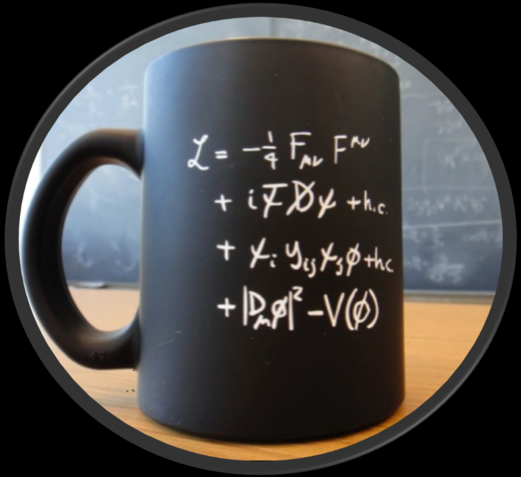
EW & Higgs

- Measuring Higgs couplings is perceived as one of the prime avenues in our search for new physics

1) With the HL-LHC one can probe many Higgs couplings to the few percent level
2) Additional to the HL-LHC sensitivity, all proposed first generation e^+e^- colliders can achieve major and comparable improvements
3) In a second stage, a higher energy e^+e^- collider or hadron collider are important to reach the ultimate sensitivity

There is new physics out there!

and it should be our main objective to discover it



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

some (personal) thoughts

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

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Several avenues towards the discovery of new physics

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

	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 ($\mu \rightarrow e$)	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

There is new physics to be discovered, but no guaranteed discovery path

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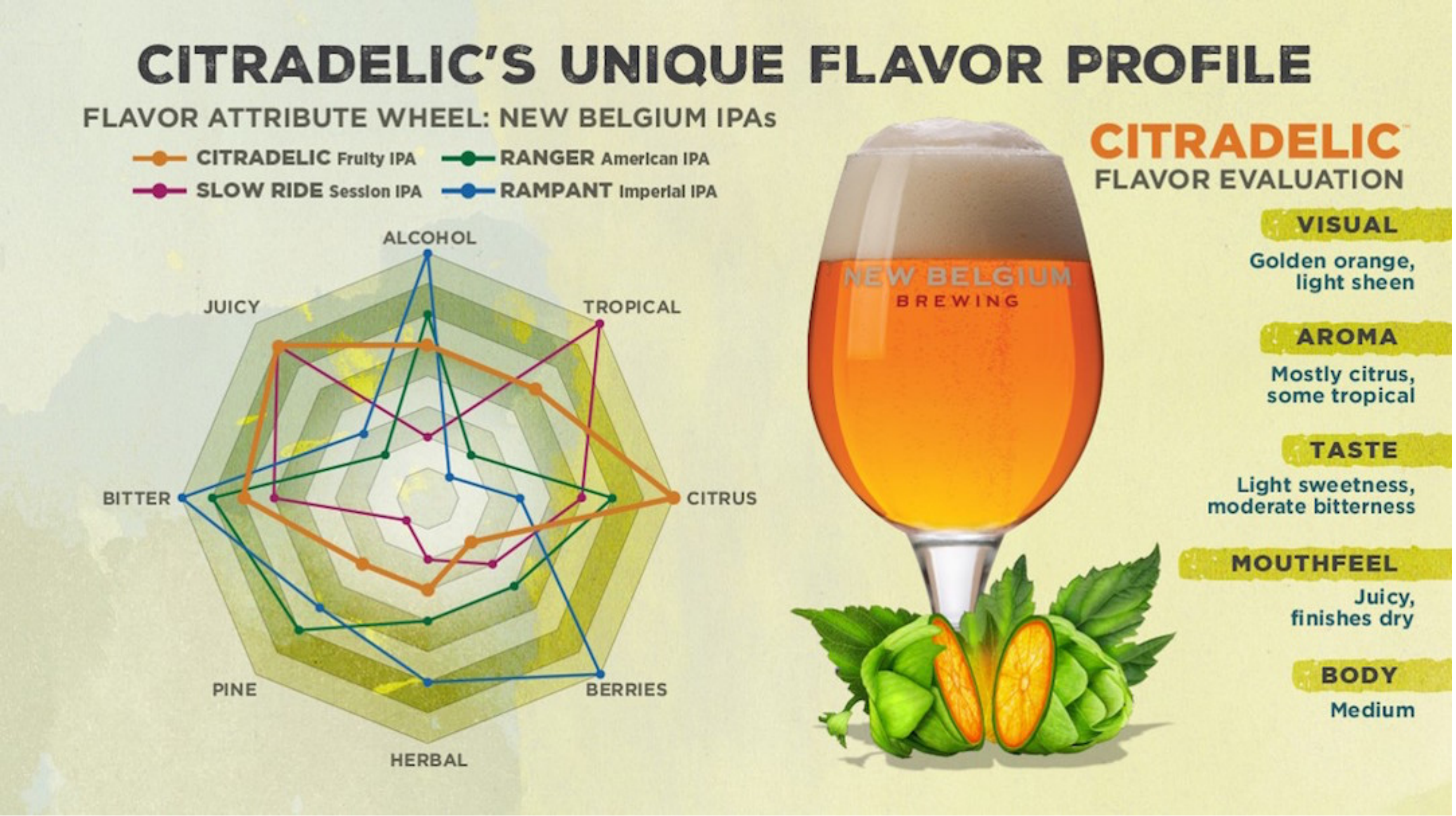
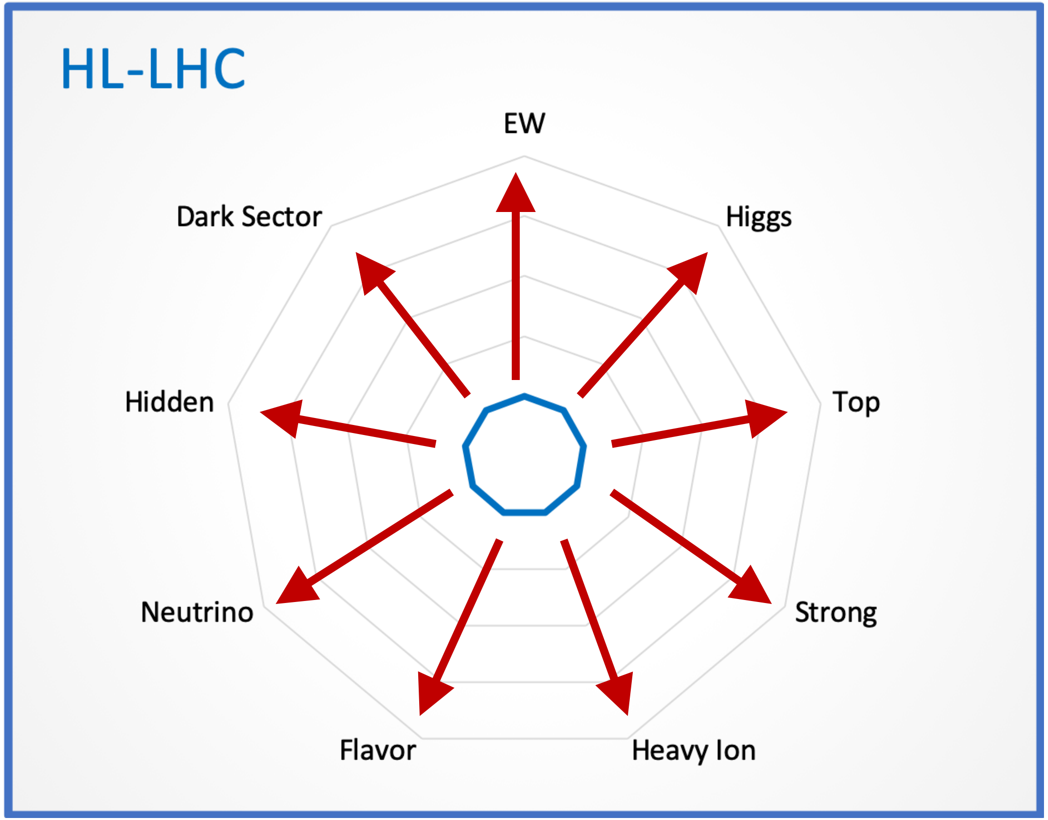
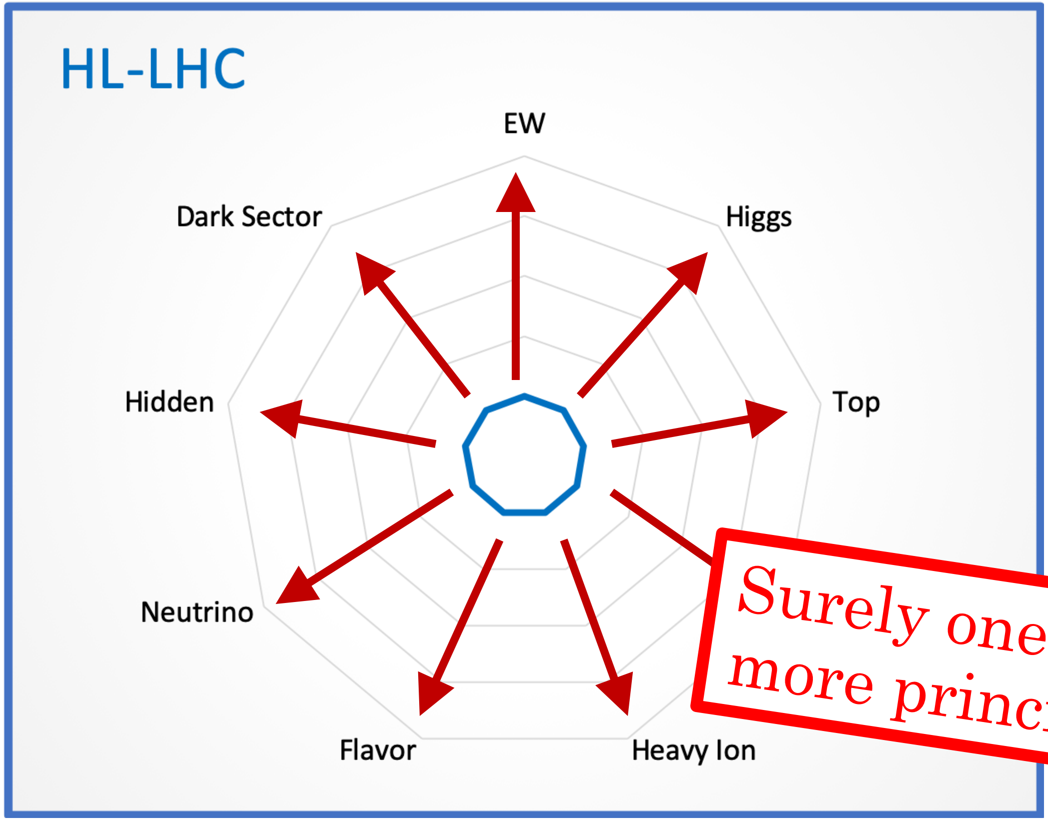


If you want to discover a great taste, you will have to sample several

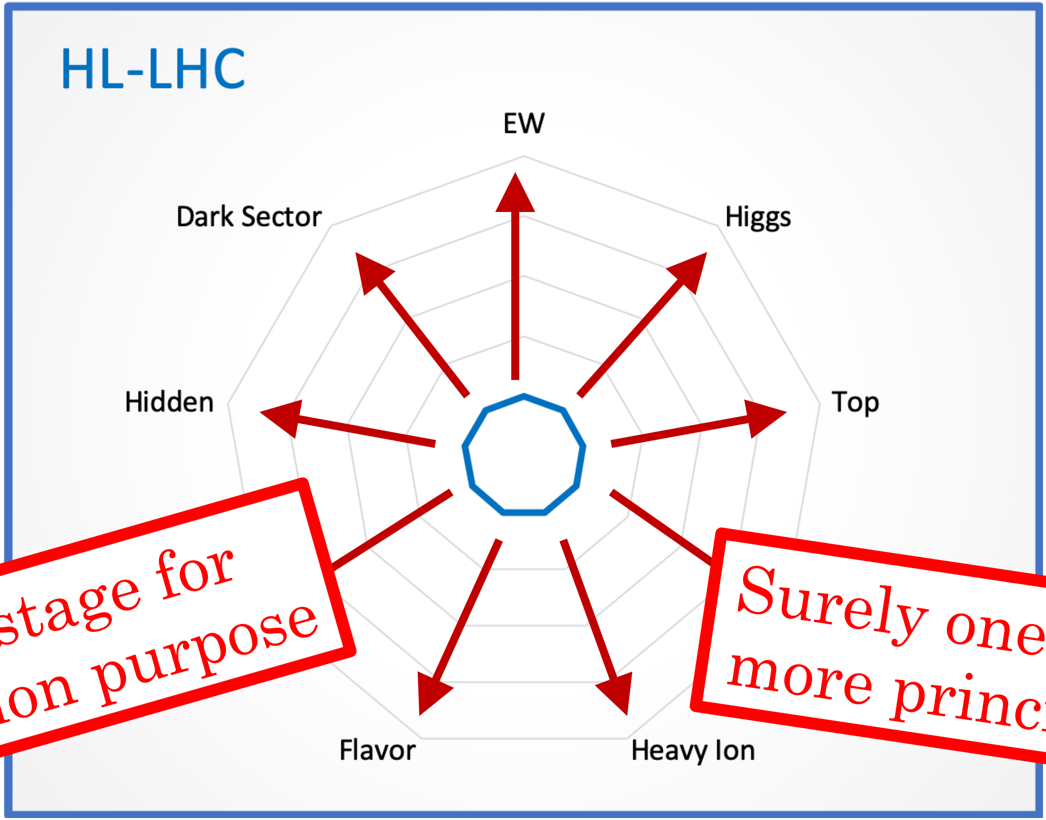


Progress relative to today's knowledge and including the expected performance of the HL-LHC



Progress relative to today's knowledge and including the expected performance of the HL-LHC

Surely one can think about more principle components



Progress relative to today's knowledge and including the expected performance of the HL-LHC

At this stage for illustration purpose

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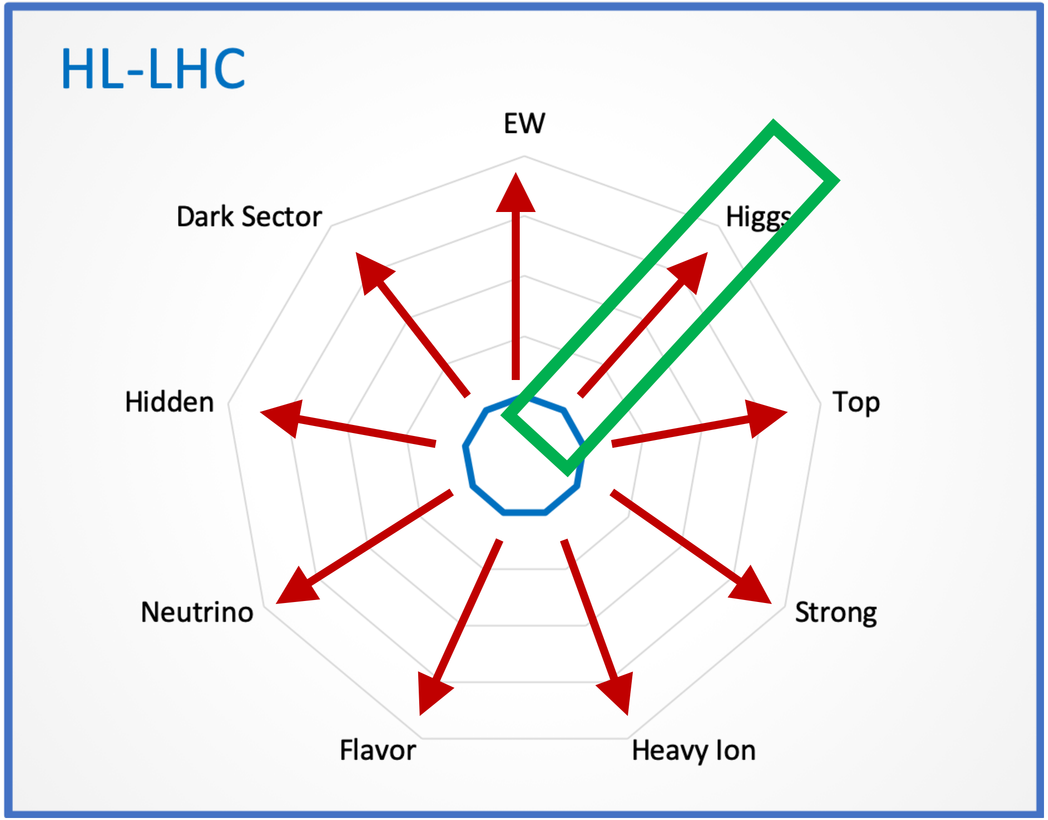


Progress relative to today's knowledge and including the expected performance of the HL-LHC

The Higgs-direction was explicitly quantified by the H@FC working group (arXiv:1905.03764)

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

2020-2040

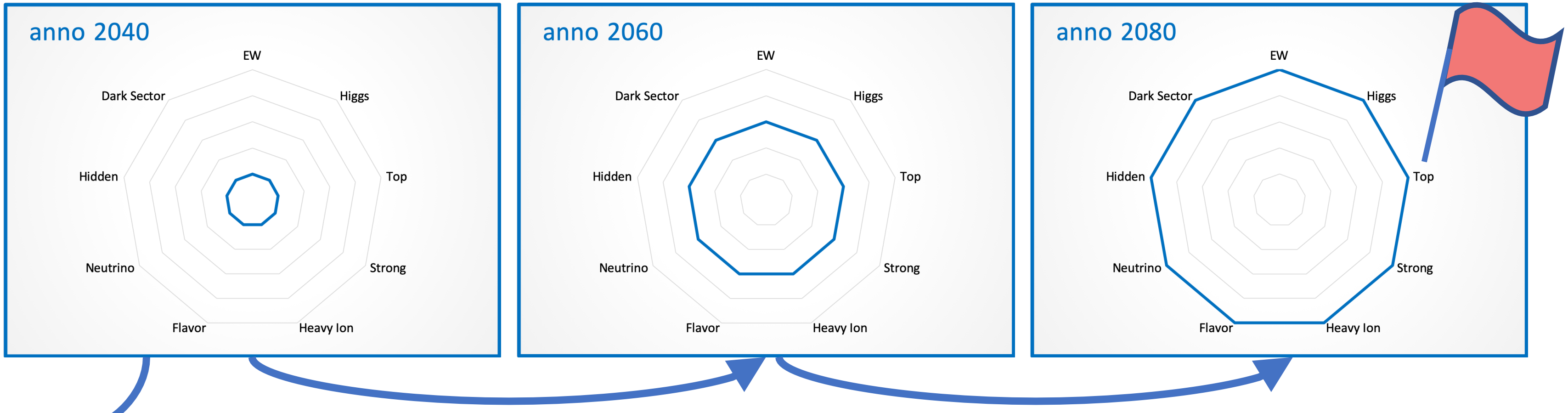
HL-LHC era

2040-2060

Z/W/H/top-factory era

2060-2080

energy frontier era

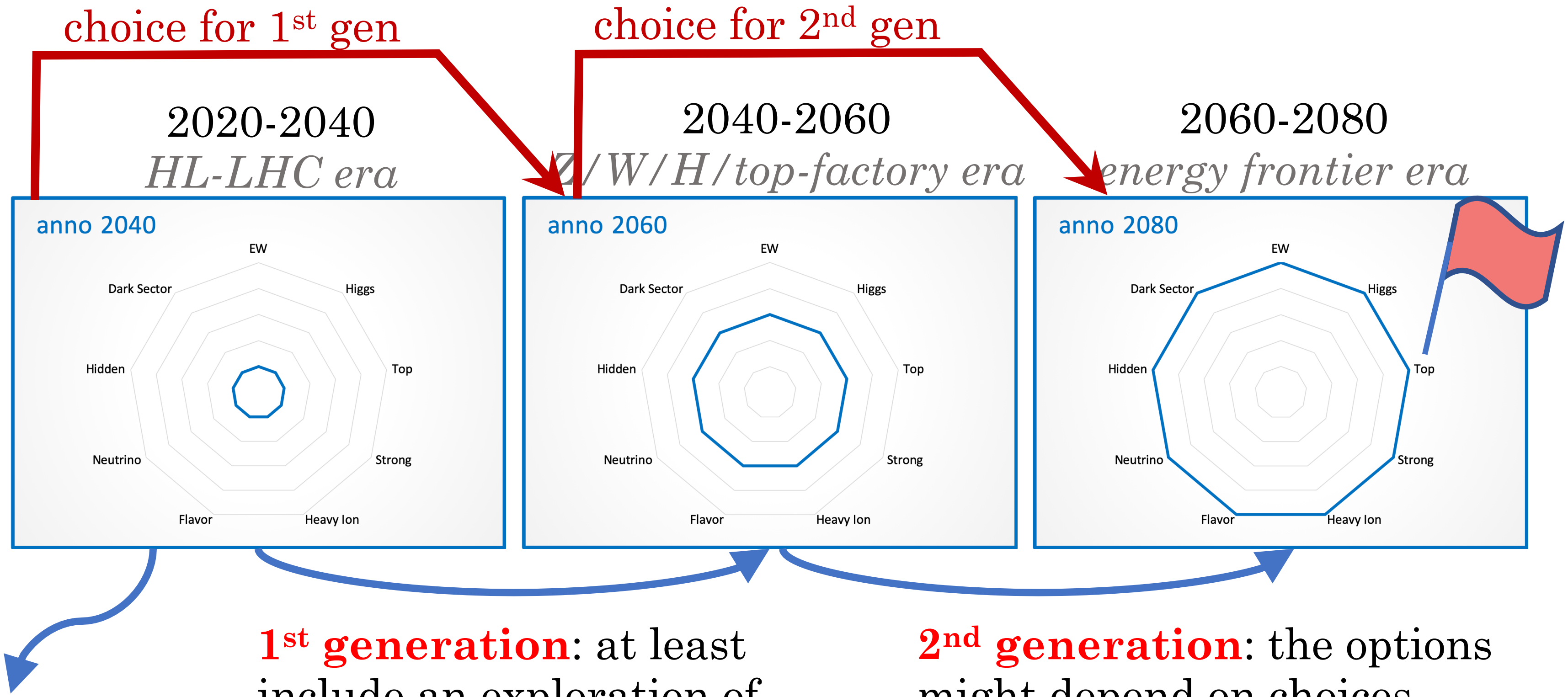


HL-LHC era

1st generation: at least include an exploration of the Higgs sector (very few major colliders)

2nd generation: the options might depend on choices made for the 1st generation (one major global collider)

Choices for 1^{st} gen collider(s) beyond the HL-LHC have to be made without knowing the HL-LHC results & choices for the 2^{nd} gen without knowing the results of the 1^{st} gen experiments



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choice for 1st gen

choice f...

...era

With the input from the Physics Briefing Book, the next step is to define some overall long-term scenarios (incl options and with an eye on evolutions in the global landscape) and discuss within the European Strategy Group their coverage, feasibility and community support

HL-LHC era

... at least include an exploration of the Higgs sector (very few major colliders)

2nd generation: the options might depend on choices made for the 1st generation (one major global collider)

Some (Personal) Key Thoughts

- CERN: CLIC vs FCC, i.e. strategy to prepare the strongest and most concrete project proposal (administrative, technical, organizational) for a final decision by the next strategy update such that a project can be launched timely, i.e. the late 2020'ies
- Europe & CERN: verify the status of ILC, CEPC, EIC, etc. to include the information in the final decision potentially at the next strategy update
- Make strategic choices for the most competitive and complementary non-collider programme in Europe
- Strong supporting statements for technology R&D (e.g. towards demonstrator facilities for novel accelerator technologies in the "*energy frontier era*")
- *Confrontation between aspirations of scientists and constraints of funding bodies: challenge to entangle both in a bottom-up strategy process*

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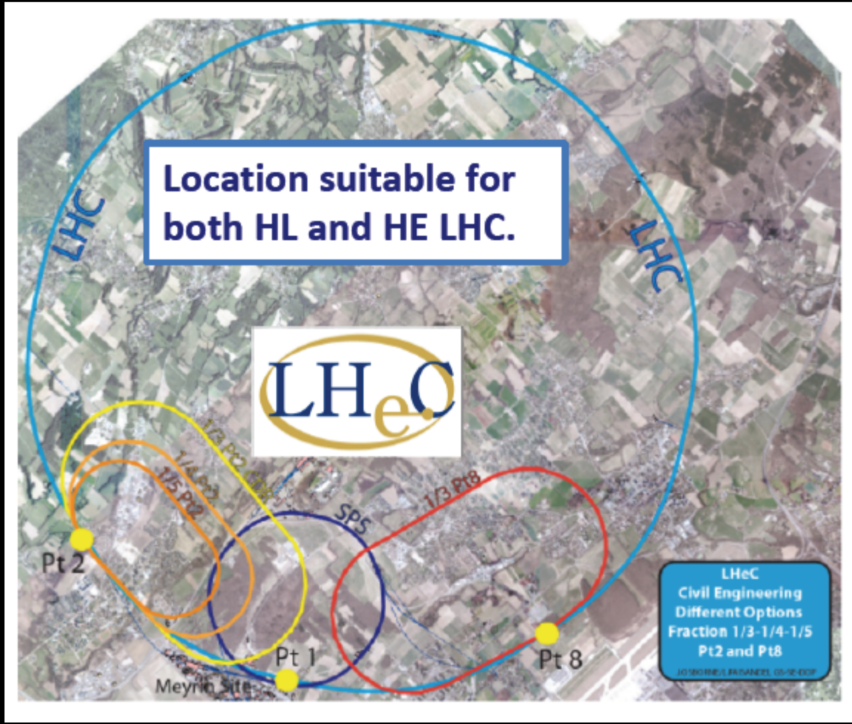
Thank you for your attention

Concrete collider options studied at CERN

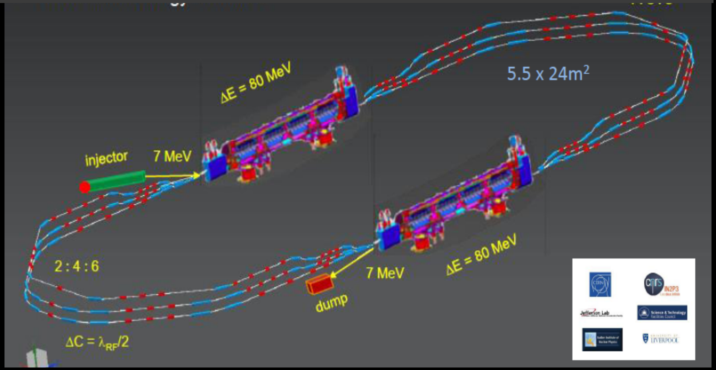
LHeC (ep), http://lhec.web.cern.ch

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



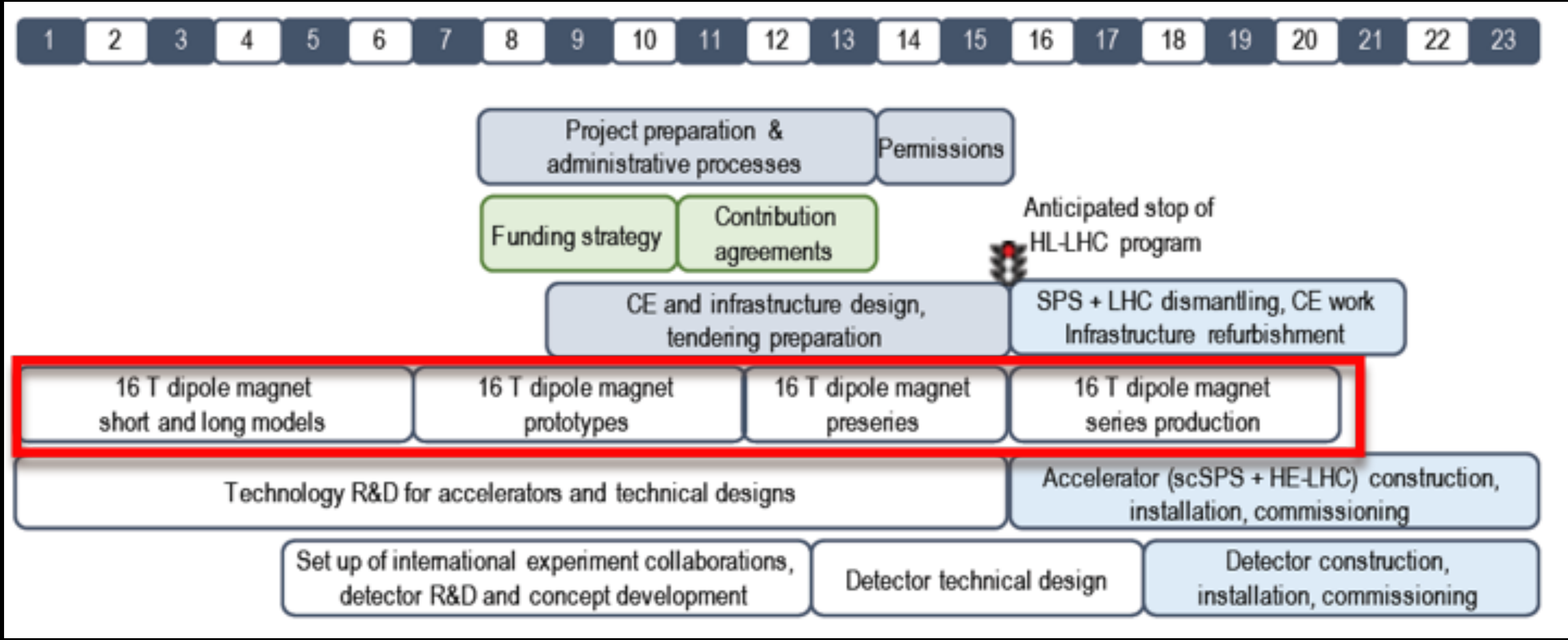
LHeC (60 GeV e- from ERL)
E_{cms} = 0.2 – 1.3 TeV
run with the HL-LHC ($\gtrsim$ Run5)

Energy Recovery Linac (ERL)
R&D demonstrator at Orsay, PERLE



Concrete collider options studied at CERN

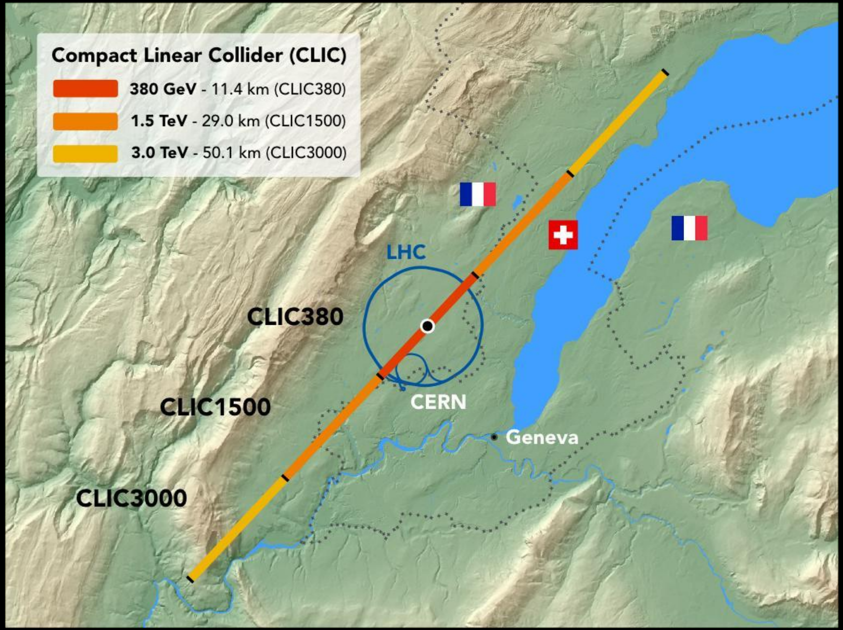
HE-LHC (pp, pA, AA, ep), https://fcc-cdr.web.cern.ch/

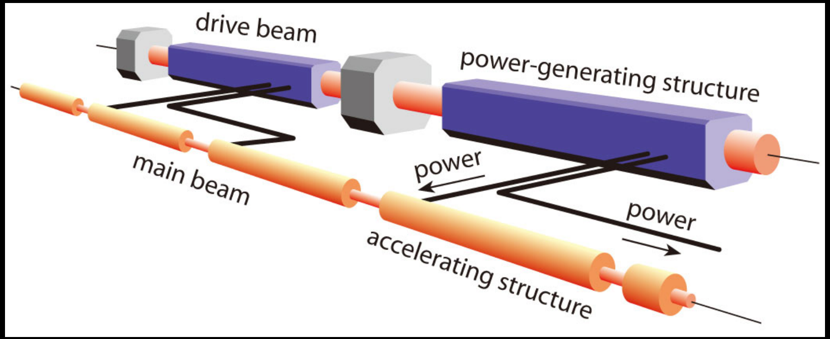


Technical schedule for HE-LHC with 16 T magnets

Concrete collider options studied at CERN

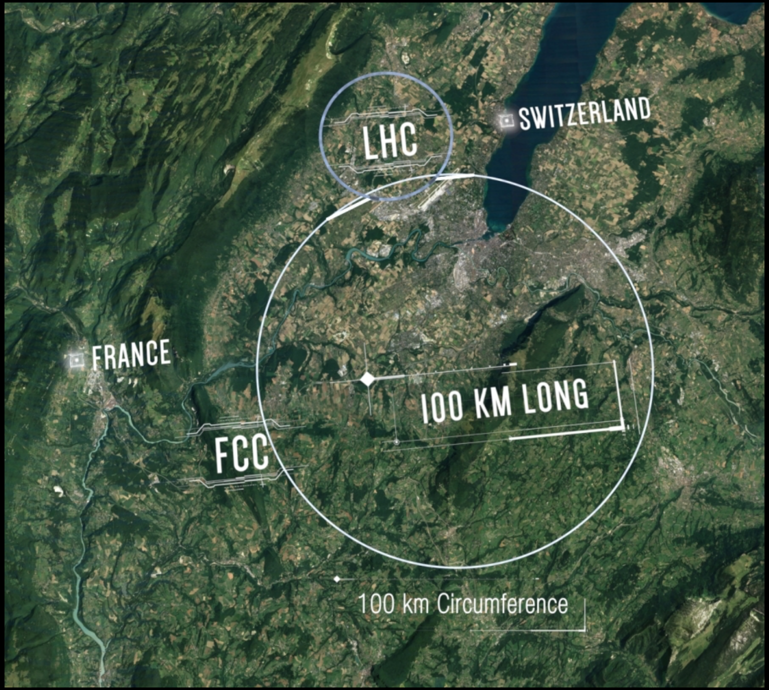
CLIC (ee), http://clic-study.web.cern.ch/





Concrete collider options studied at CERN

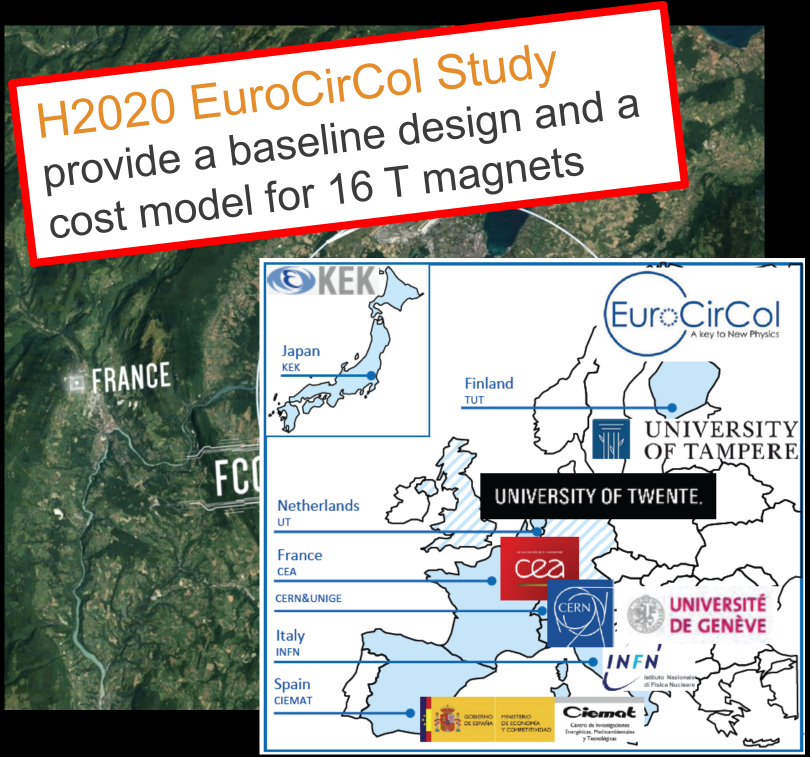
FCC (ee, ep, pp, pA, AA, eA), https://fcc-cdr.web.cern.ch/



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

Concrete collider options studied at CERN

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



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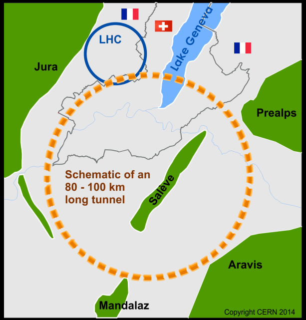
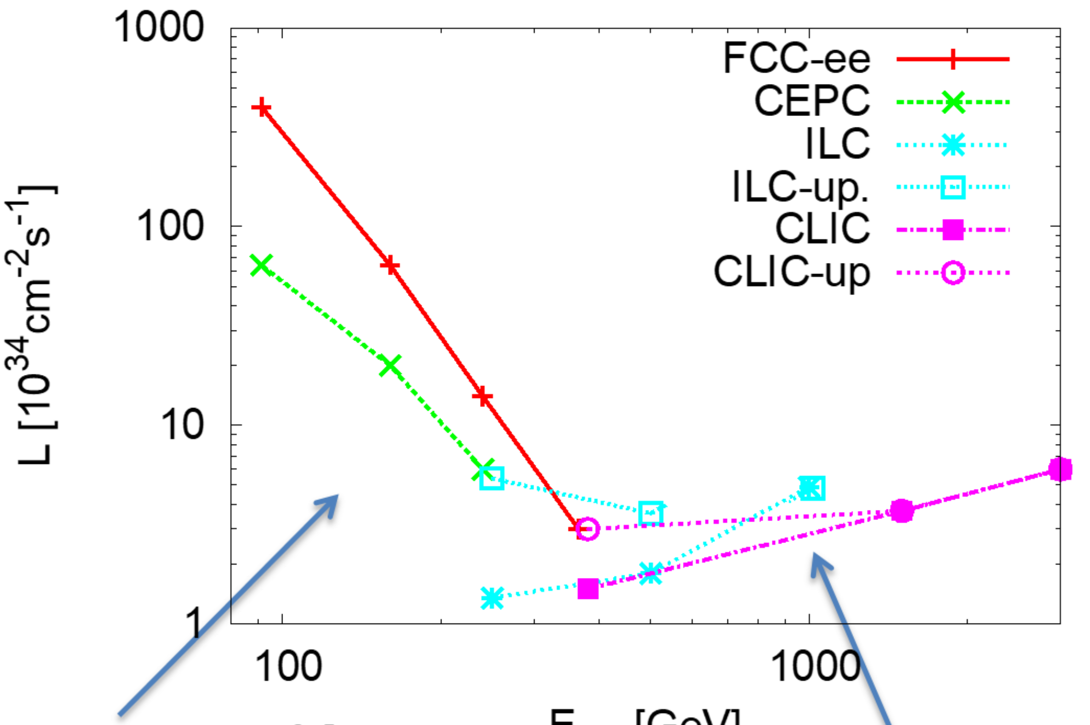
- ***pp*-collider (*FCC-hh*) @ 100 TeV**
- ***p-e* collider (*FCC-he*)**
- **HE-LHC** with *FCC-hh magnets*
- $\mu\mu$ **colider (*FCC-$\mu\mu$*)** option
- AA, Ap, Ae options

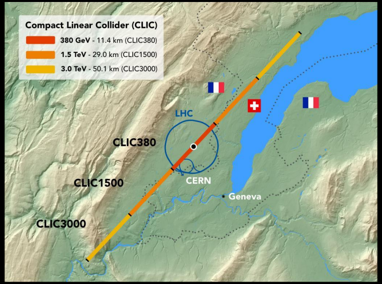


Luminosity per facility



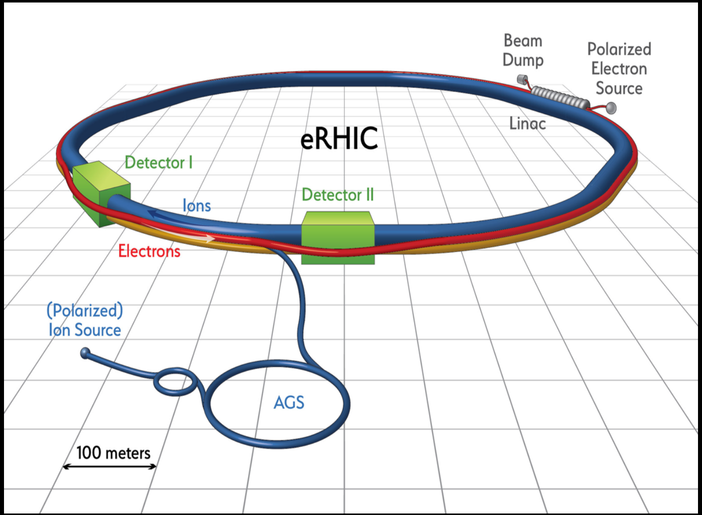
$L \propto P_{synrad} E_{cm}^{-3.5}$

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

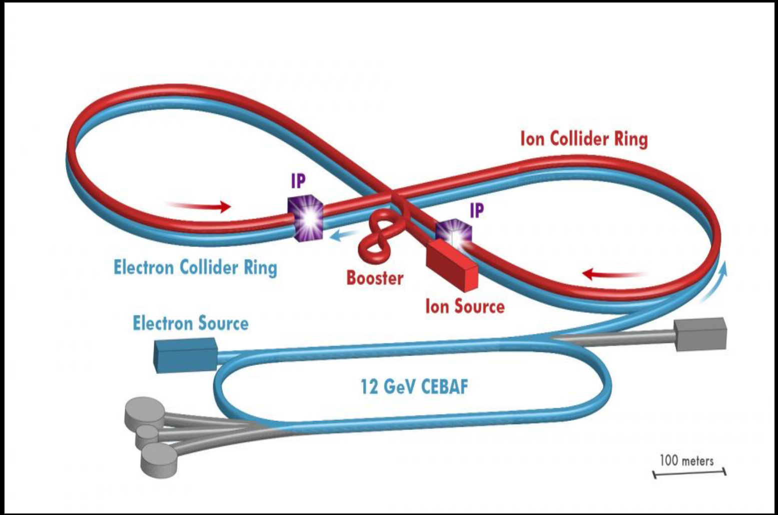


Other concrete collider options

EIC (eA, ep), http://www.eicug.org



Brookhaven NL

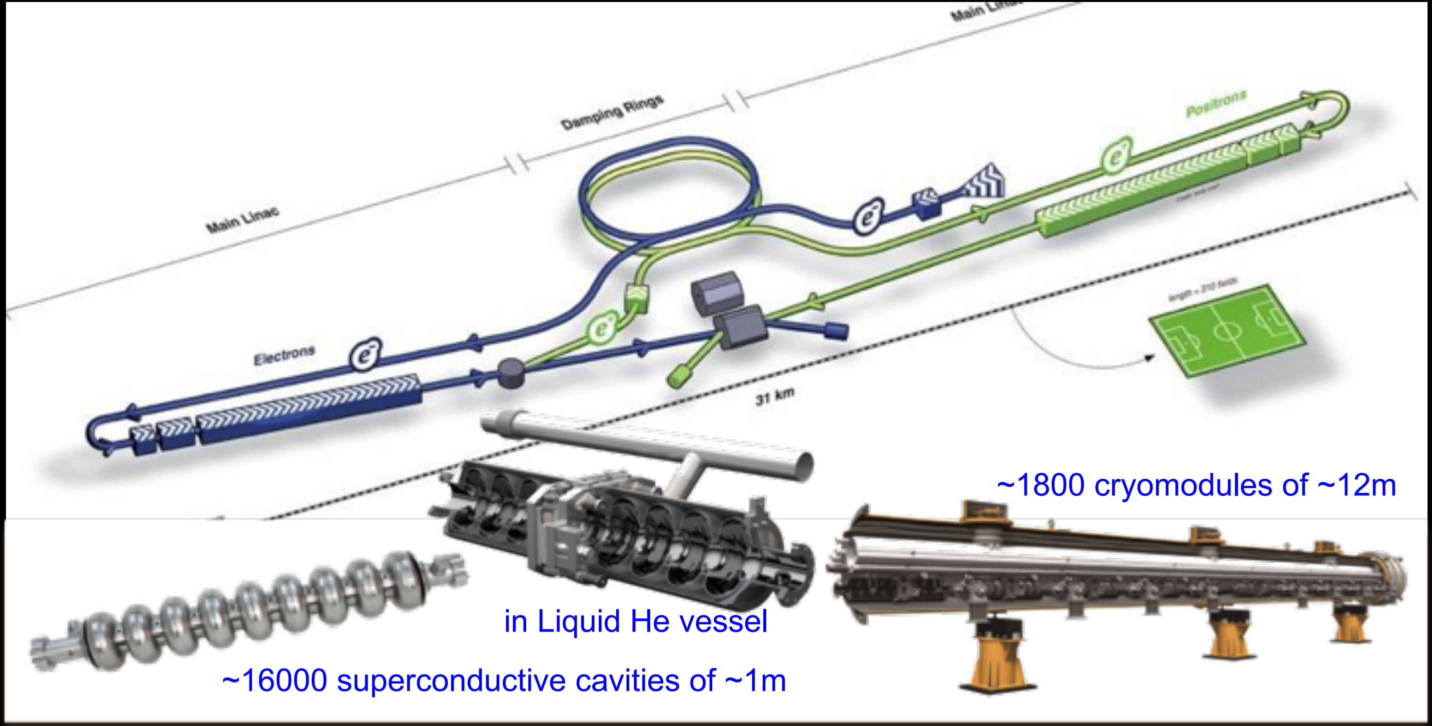


Jefferson Lab

EIC (3-20 GeV e-)
$E_{cms} = 0.02 - 0.13$ *TeV*

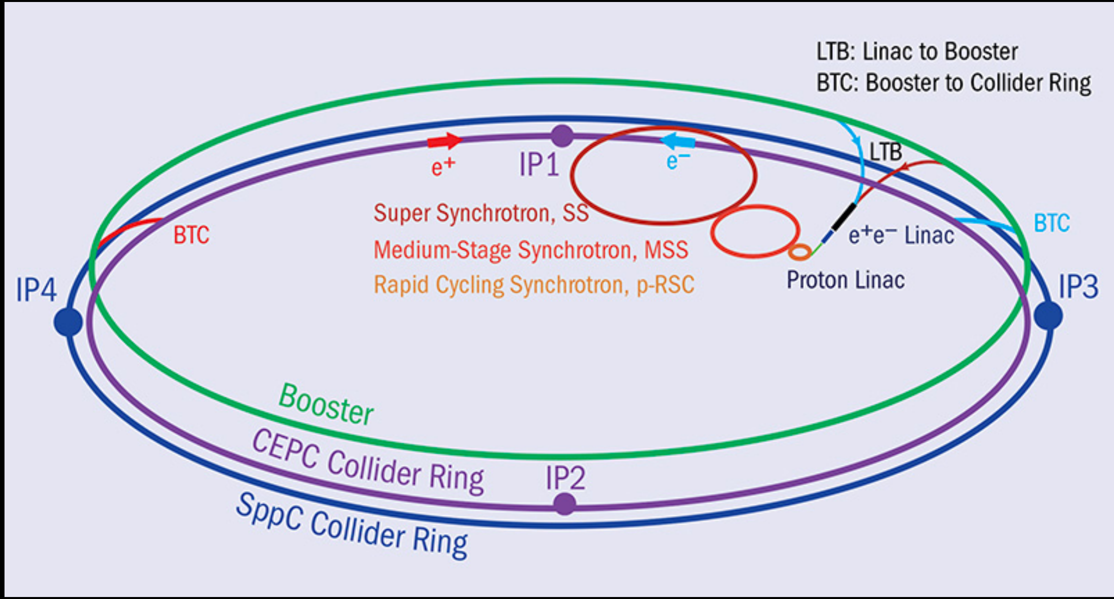
Other concrete collider options

ILC (ee), http://newsline.linearcollider.org



Other concrete collider options

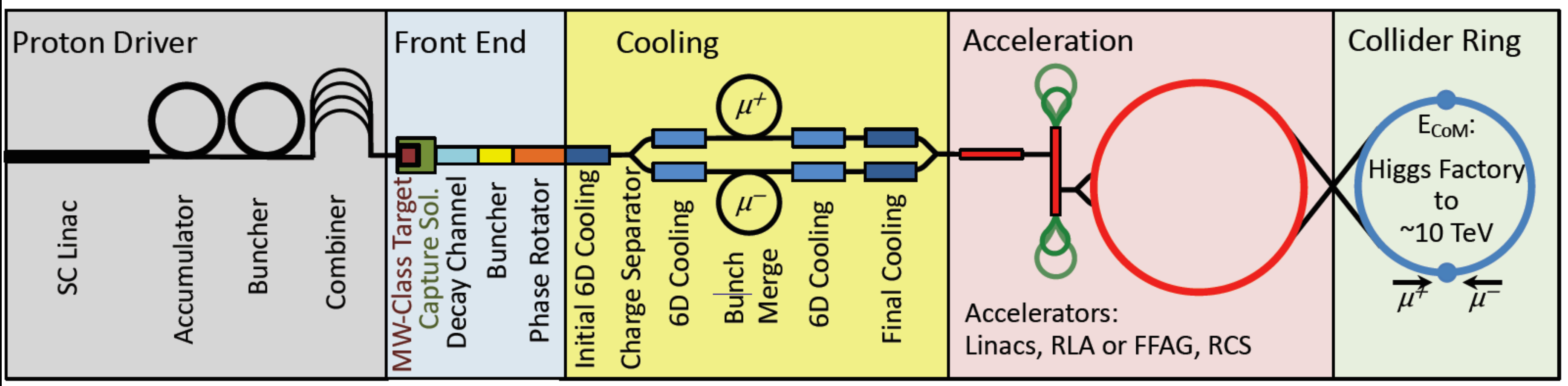
CEPC (ee), http://cepc.ihep.ac.cn



Other concrete collider options

Muon Collider, https://indico.cern.ch/event/801616/

need for a strong, concerted and global R&D effort



Short, intense proton bunches to produce hadronic showers

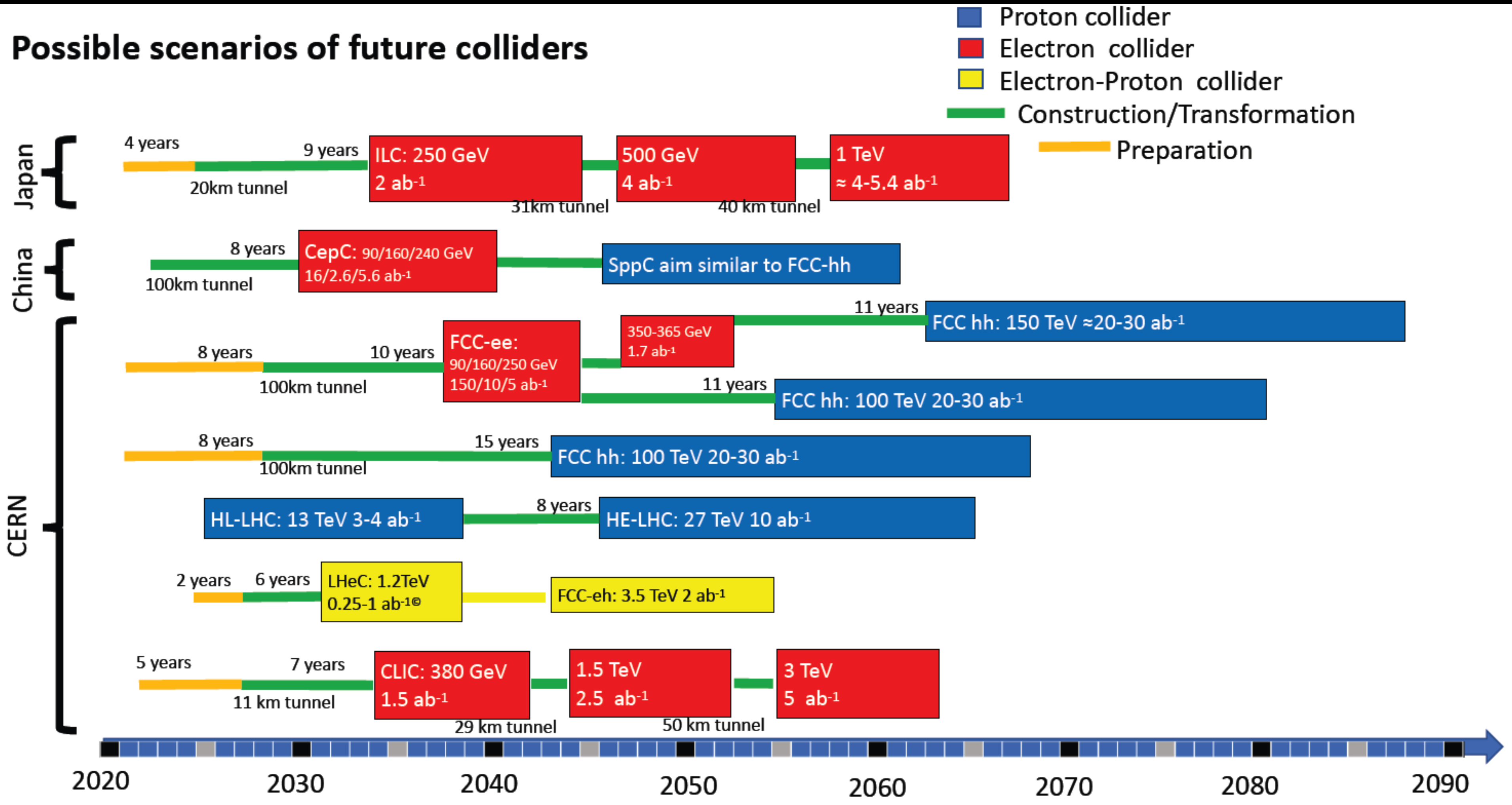
Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

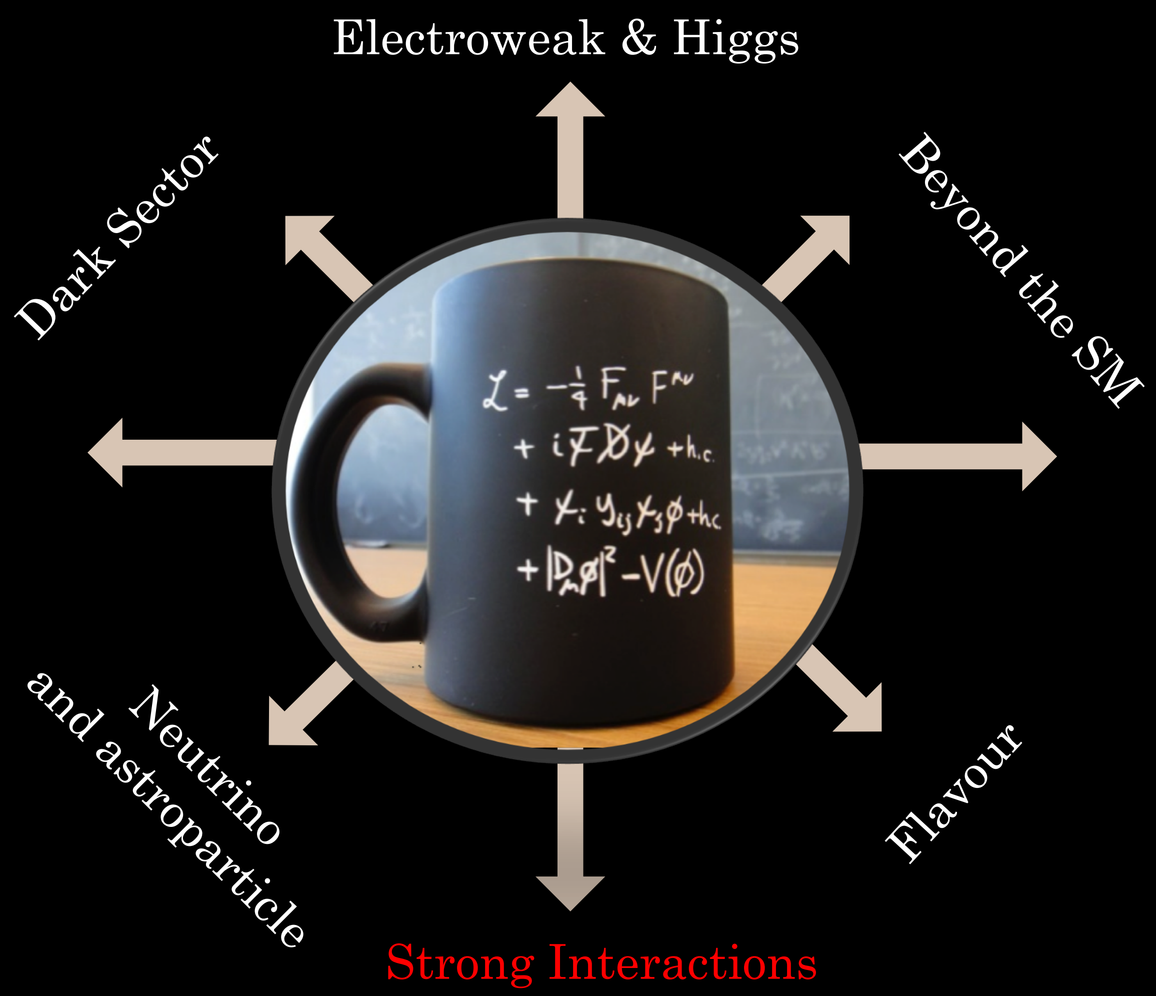
Collision

Possible scenarios of future colliders



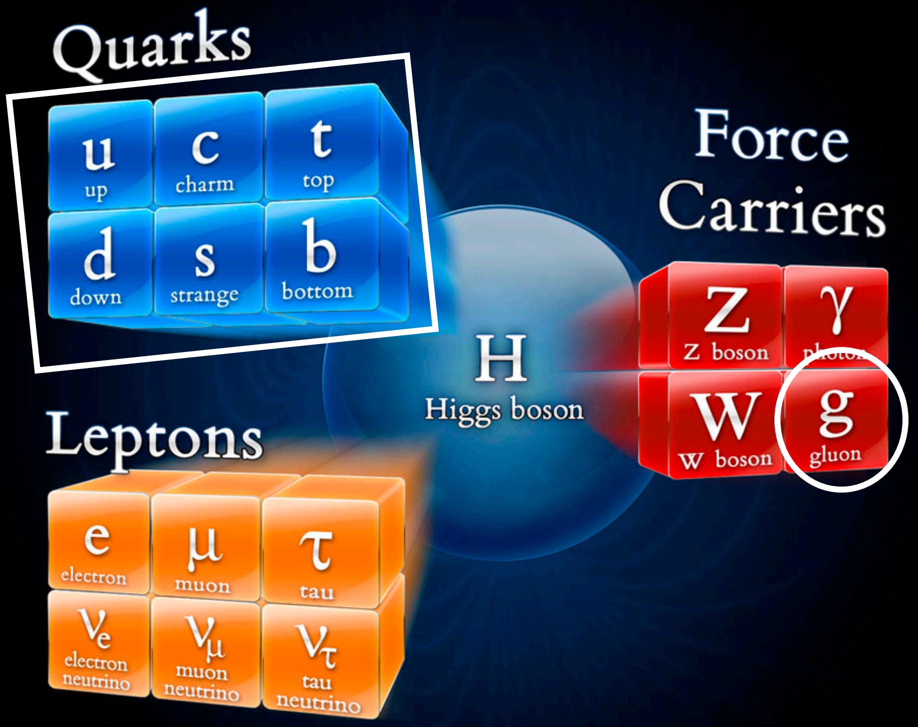
The Granada themes

Strong Interactions



The Granada themes

Strong Interactions



Strong interactions

QCD theory: $\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$

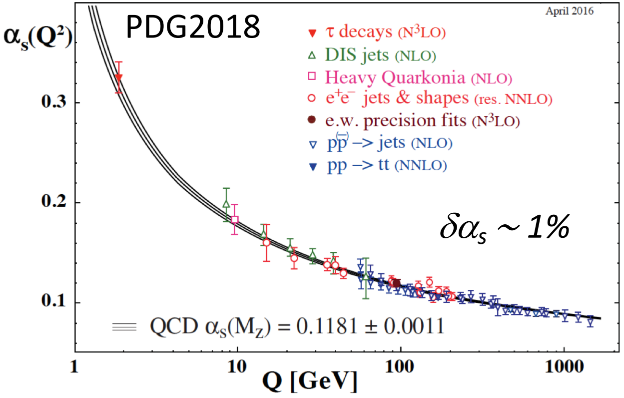
colour confinement

α_s (Q^2 low) ~ 1

key phenomena
(non-Abelian gauge group)

asymptotic freedom

α_s (Q^2 high) << 1



$\alpha_{EW} << \alpha_s$

"hot and dense QCD"

(low energy domain)

(lattice calculations)

"vacuum QCD"

(high energy domain)

(perturbative calculations)

European Strategy Update

Strong interactions

QCD theory: $\mathcal{L}_{\text{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$

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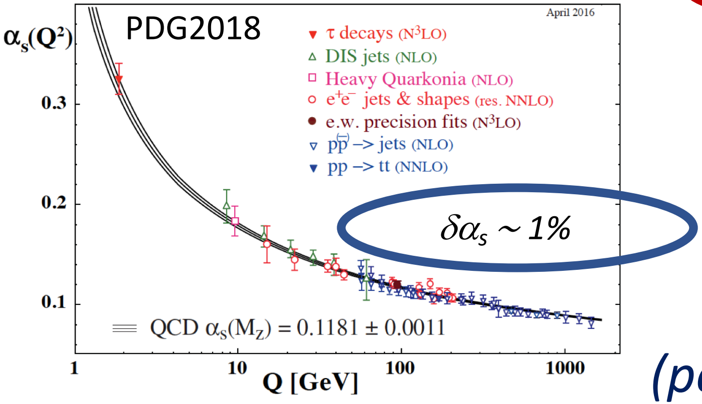

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(lattice calculations)

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European Strategy Update

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"hot and dense Q
(low energy doma
(lattice calculatio

"vacuum QCD"
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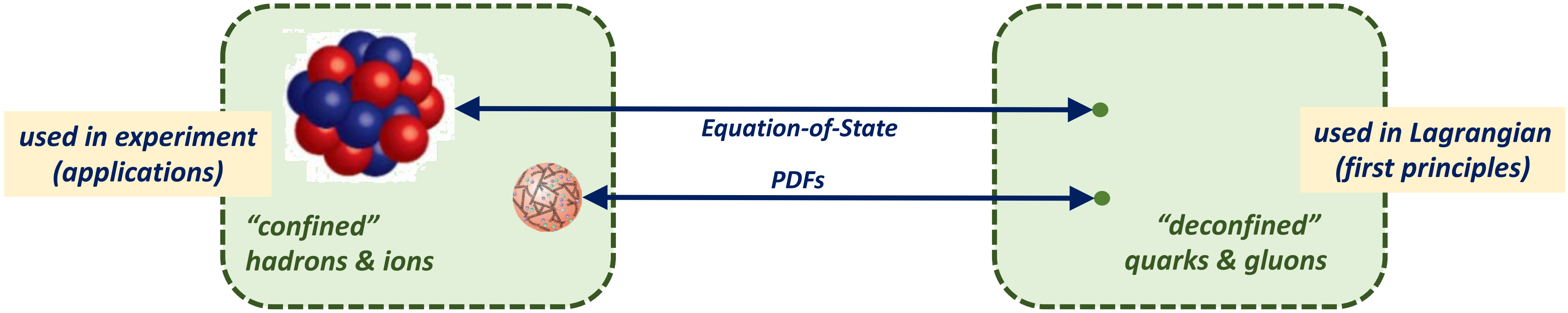
turbative calculations)

Today	$\delta\alpha_s$~1%
FCC-ee	$\delta\alpha_s$~0.1%
LHeC/FCC-eh	$\delta\alpha_s$~0.1%
FCC-hh	*up to 25 TeV*
Lattice-QCD	$\delta\alpha_s$~0.3%

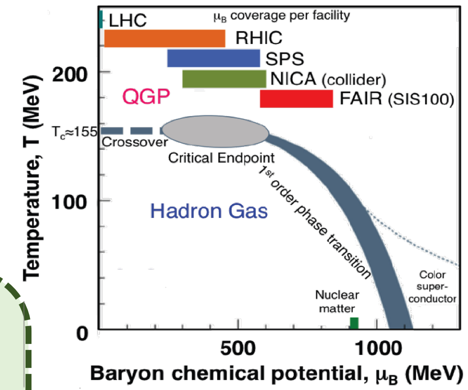
for EW&H physics need $\delta\alpha_s$~0.1%

“hot and dense QCD” ⟷ “vacuum QCD”



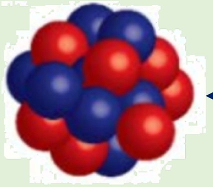
“hot and dense QCD” ⟷ *“vacuum QCD”*

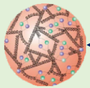
How do properties of the QGP emerge from the fundamental QCD interactions as a function of system size and under varying conditions of initial energy density and baryon chemical potential?



From LQCD: T_c (μ_B=0) = 156.5 ± 1.5 MeV

From experiment: determination of chemical freeze-out temperature





used in experiment (applications)

“confined” hadrons & ions

Equation-of-State

PDFs

used in Lagrangian (first principles)

“deconfined” quarks & gluons

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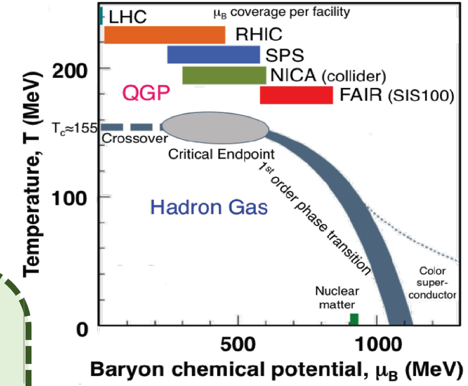

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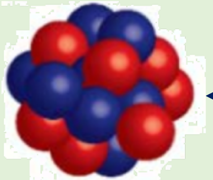

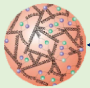

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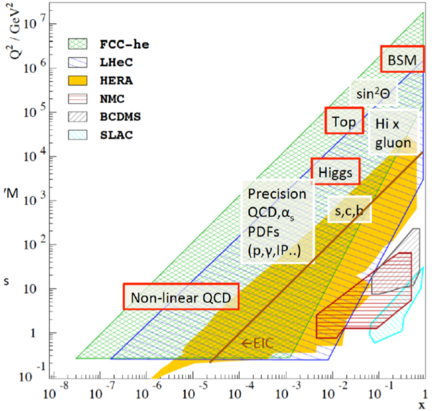


What are the experimental and theoretical pre-requisites to reach an adequate precision of perturbative and non-perturbative QCD predictions at the highest energies?

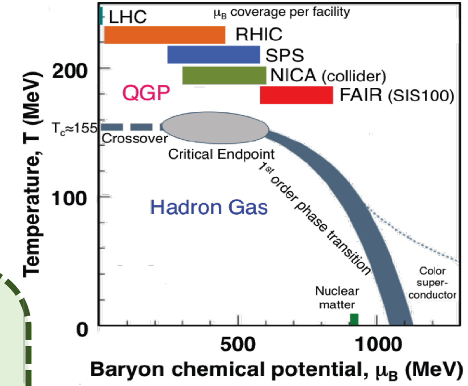
From QCD: evolution equations of PDFs

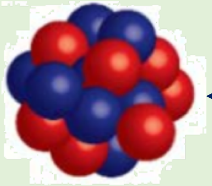
From experiment: PDF parameters values themselves

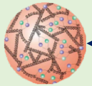
“hot and dense QCD” ⟷ “vacuum QCD”

How do properties of the QGP emerge from the fundamental QCD interactions as a function of system size and under varying conditions of initial energy density and baryon chemical potential?

Key facilities involve collisions with heavy ions







used in experiment (applications)

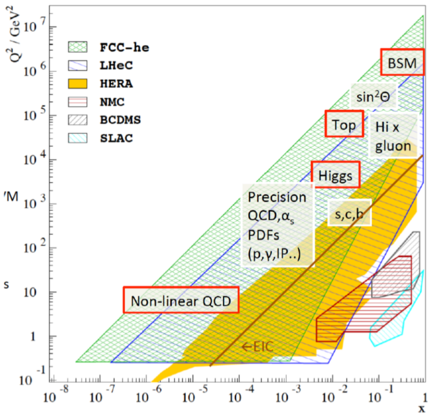
“confined” hadrons & ions

Equation-of-State

PDFs

used in Lagrangian (first principles)

“deconfined” quarks & gluons



What are the experimental and theoretical pre-requisites to reach an adequate precision of perturbative and non-perturbative QCD predictions at the highest energies?

Key facilities involve collisions with protons

"hot and dense QCD" ⟷ *"vacuum QCD"*

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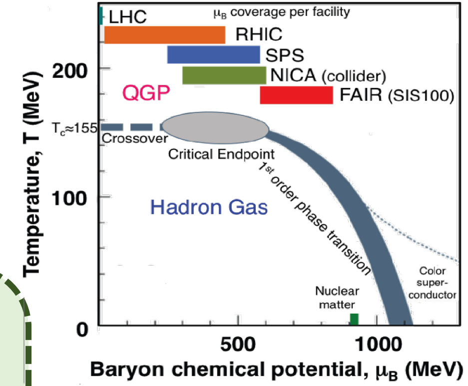
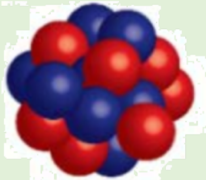


HL-LHC: increased luminosity, low-μ_B

HE-LHC/FCC: new probes

Fixed-target@SPS: high-μ_B

Fixed-target@(HL-)LHC: medium-μ_B



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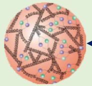
PDFs



"confined" hadrons & ions

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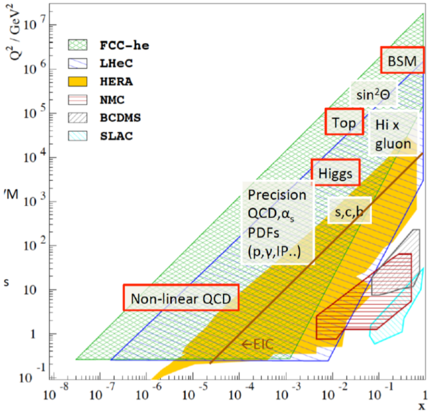


HL-LHC: mid-x (up to x2 improvement)

Fixed-target@(HL-)LHC: high-x

ep:
- EIC: first steps beyond collinear model
- LHeC: high-x & highest-Q^2 coverage
- FCC-ep: O(1%) on σ(W,Z,H) at FCC-pp

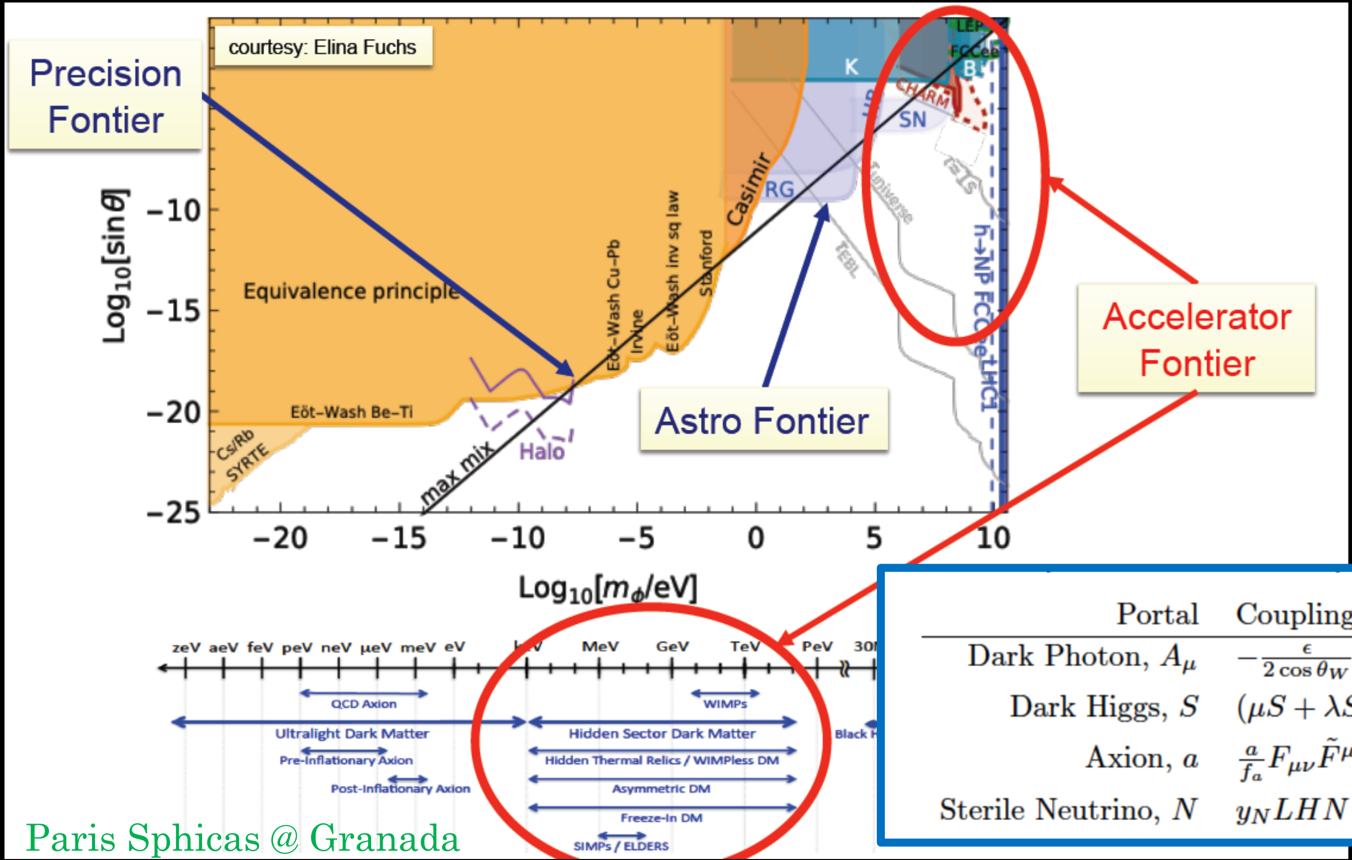
ERL system for electron beam at 60 GeV

The Granada themes

Strong Interactions

- A hadronic structure program with ep/pp/eA colliders provides vital ingredients for the high precision exploration
- A hot & dense QCD program at the SPS, is complementary to other emerging facilities worldwide, and brings unique contributions in the exploration of the QCD phase diagram
- A high-energy AA/pA/fixed-target program at the LHC, HL-LHC, HE-LHC and FCC is unique and provides essential science towards a profound understanding of nuclear and particle physics
- A high-luminosity e^+e^- collider at the EW scale provides a unique environment for high-precision QCD

To what extent can current or future accelerators probe feebly interacting sectors?



Use four simplified models ("portals") from which benchmarks are identified to evaluate experimental sensitivity

PBC report, arXiv:1901.09966

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$ (Relaxion toy model, mixes \w Higgs)
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$