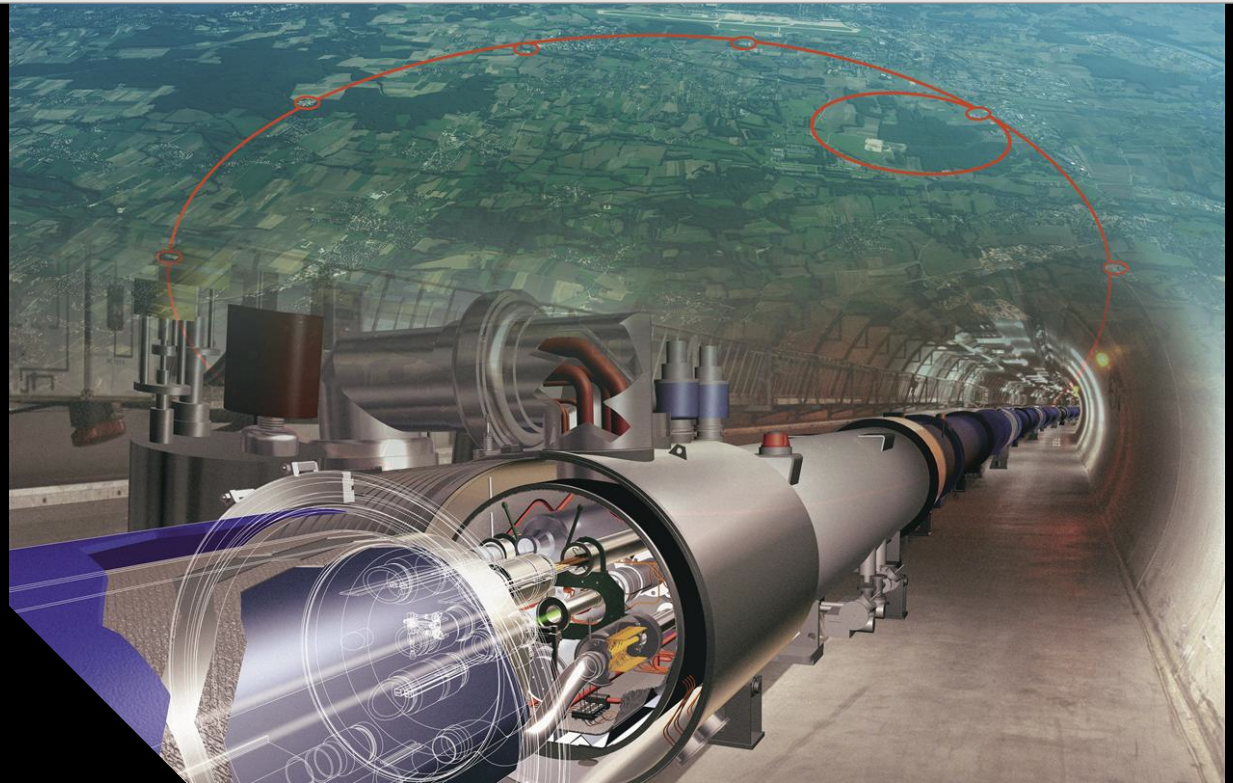
Towards an update of the European Strategy for Particle Physics

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

LFC19 workshop
Sept 9-13, 2019
Trento, Italy



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HEP@VUB BRUSSELS
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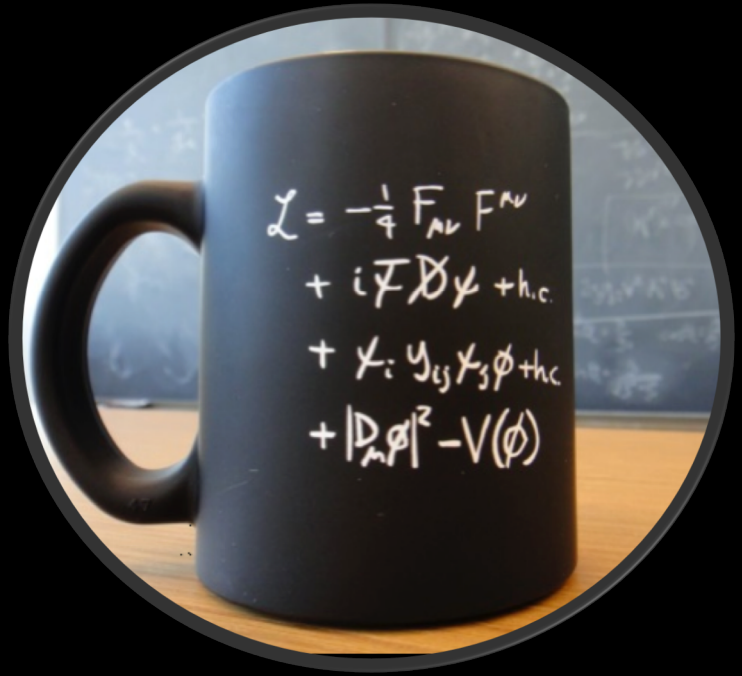
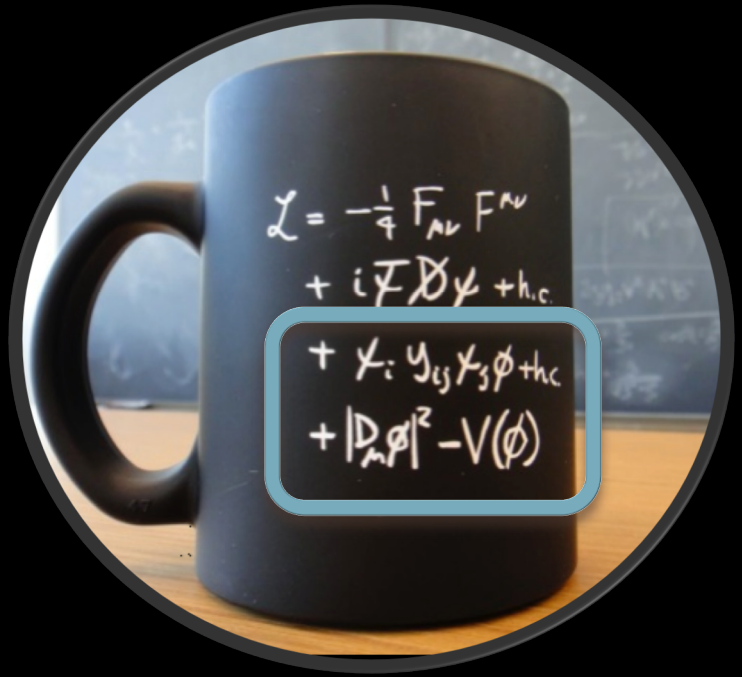
understand nature at the
largest and the smallest scales

Particle Physics today



enormous success in describing matter at the smallest scales

Particle Physics today



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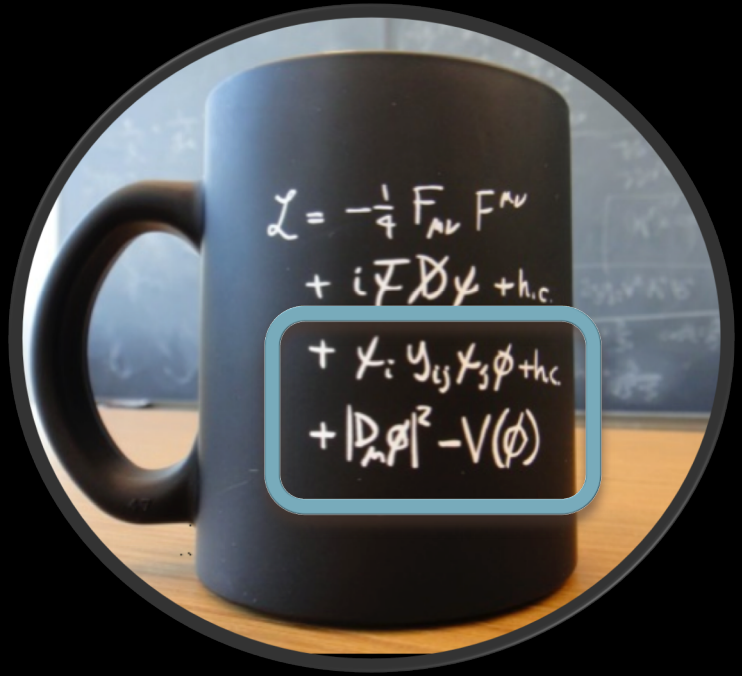

enormous success in describing matter at the smallest scales

describing ≠ understanding

Key open questions for particle physics?

Riccardo Rattazzi
@ Granada

Problems vs Mysteries

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

Plausible EFT solutions exist

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

Challenge or outside EFT paradigm

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

...lt for a strong and diverse, yet coherent and concerted empirical exploration

we can only explore our aspirations
when we innovate technology

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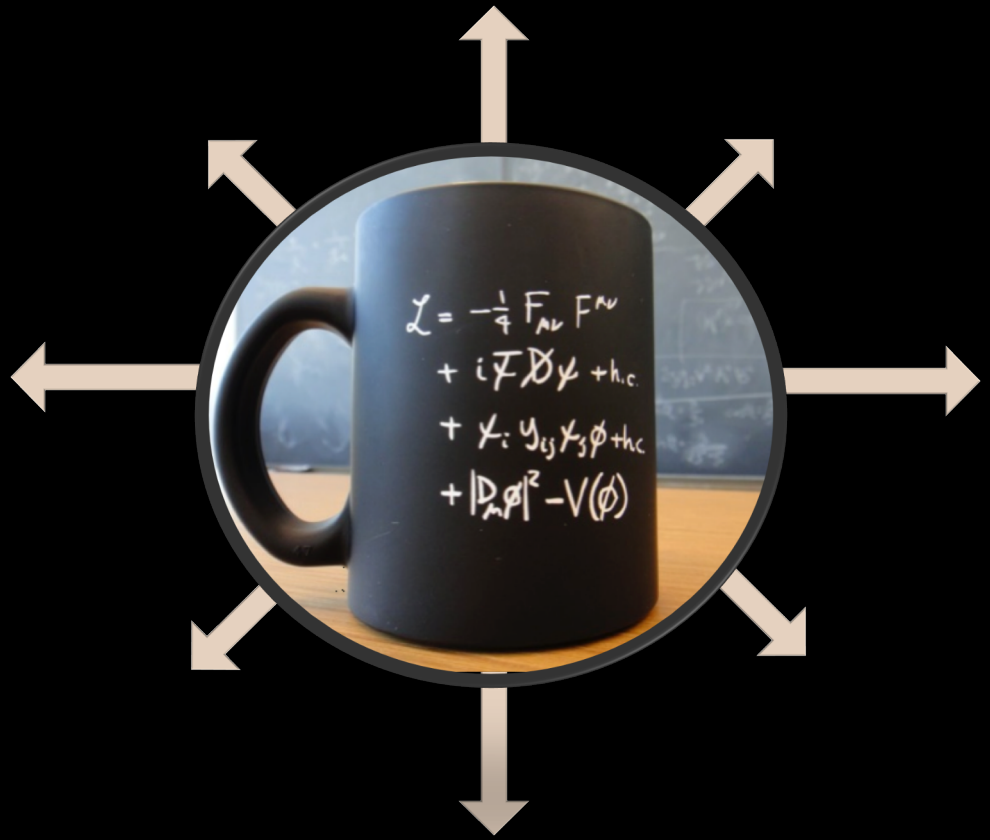
our field of high-energy physics is
driven by our innovations in
technology

higher energy interactions in the lab

earlier universe



rarer processes

higher energetic phenomena in the universe

higher energy interactions in the lab

earlier universe

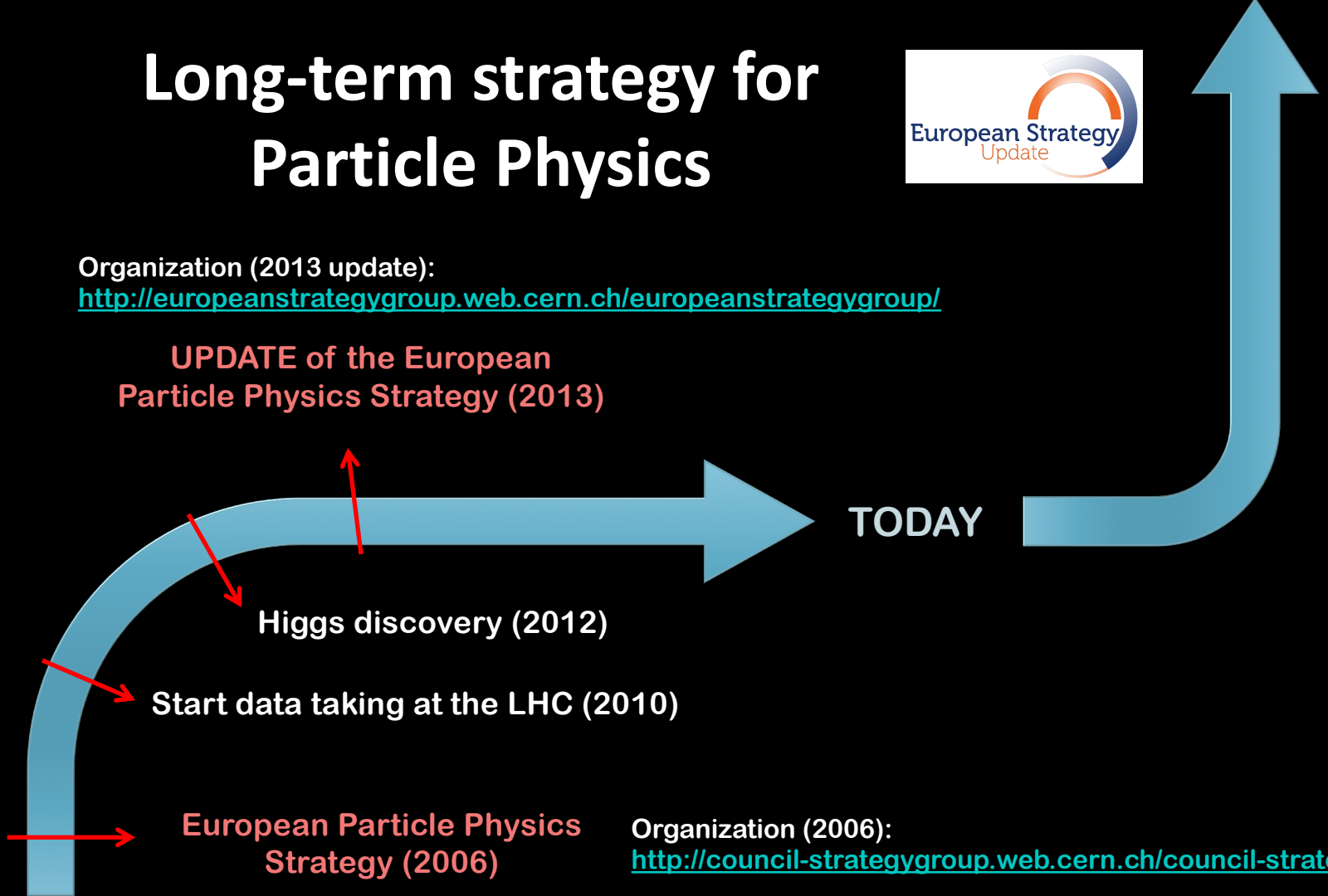
Innovate Technology
make the invisible visible

rarer processes

higher energetic phenomena in the universe

Long-term strategy for Particle Physics

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



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.

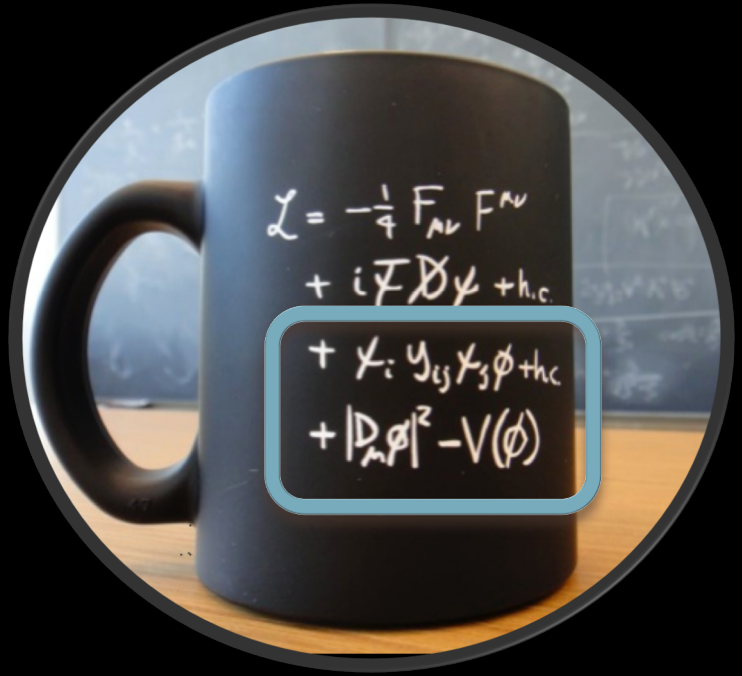
③ Europe looks forward to a [ILC] proposal from Japan to discuss a possible participation.

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

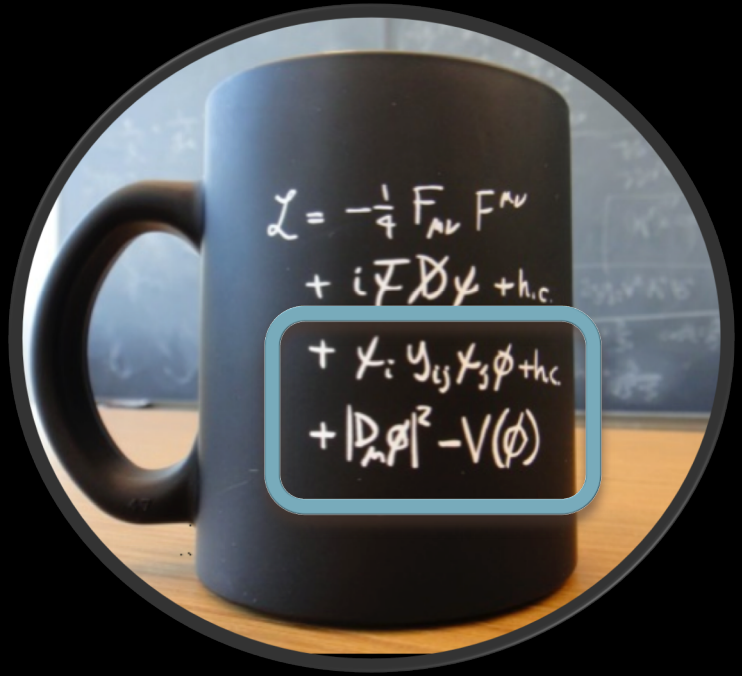
LHC and HL-LHC

Initial legacy impact of the LHC



a MORE PRECISE and more COMPLETE description

Initial legacy impact of the LHC



a MORE PRECISE and more COMPLETE description

connection

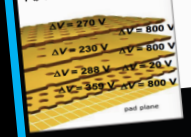
new physics

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

LHCb – Upgrade LS2

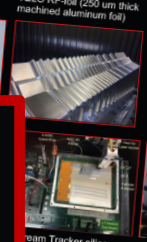
Construction well advanced

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

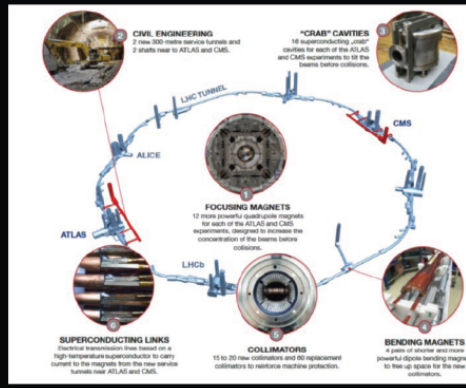
eam Tracker silicon or module under test

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

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

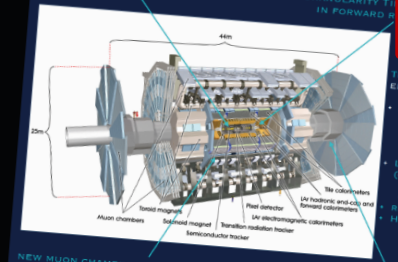
Formal approval by CERN Council (June 2016)
Cost to Completion : 950 MCHF (material)

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:

- LO HARDWARE TRIGGER:
  - LO CALORIMETER
  - LO TOPOLOGICAL
  - LO MUON
  - LO 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)

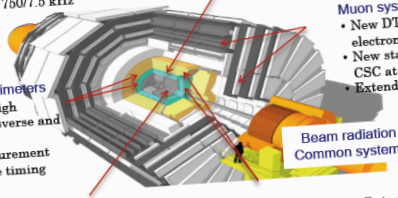
64

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 $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



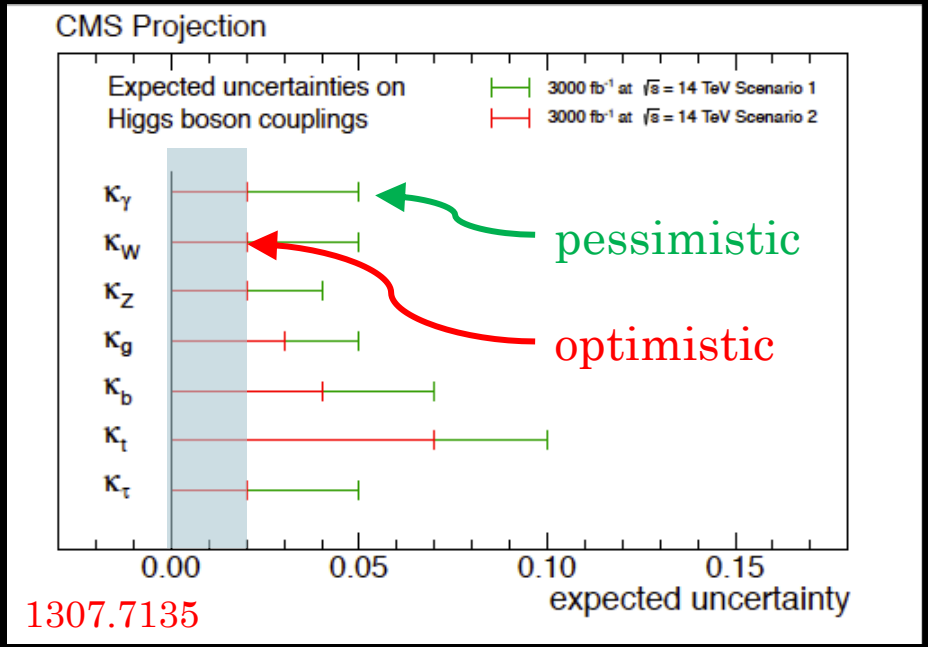
New Endcap Calorimeters
- Rad. tolerant - High granularity transverse and longitudinal
- 4D shower measurement including precise timing capability

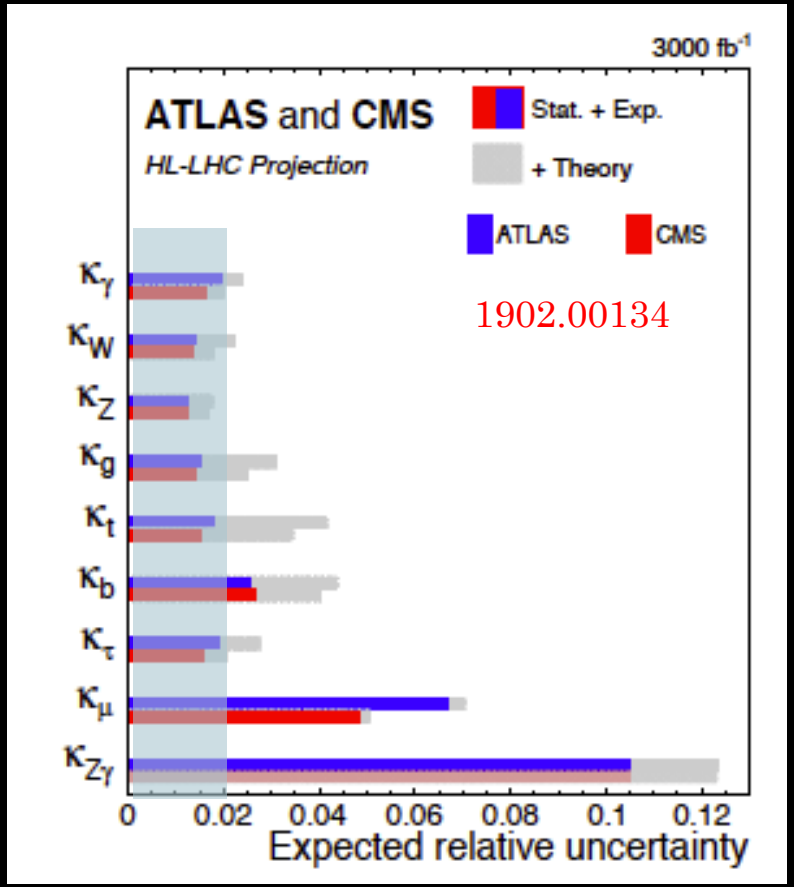
Beam radiation and luminosity
Common systems and infrastructure

New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout (strips) for Trigger
- Extended coverage to $\eta \simeq 3.8$

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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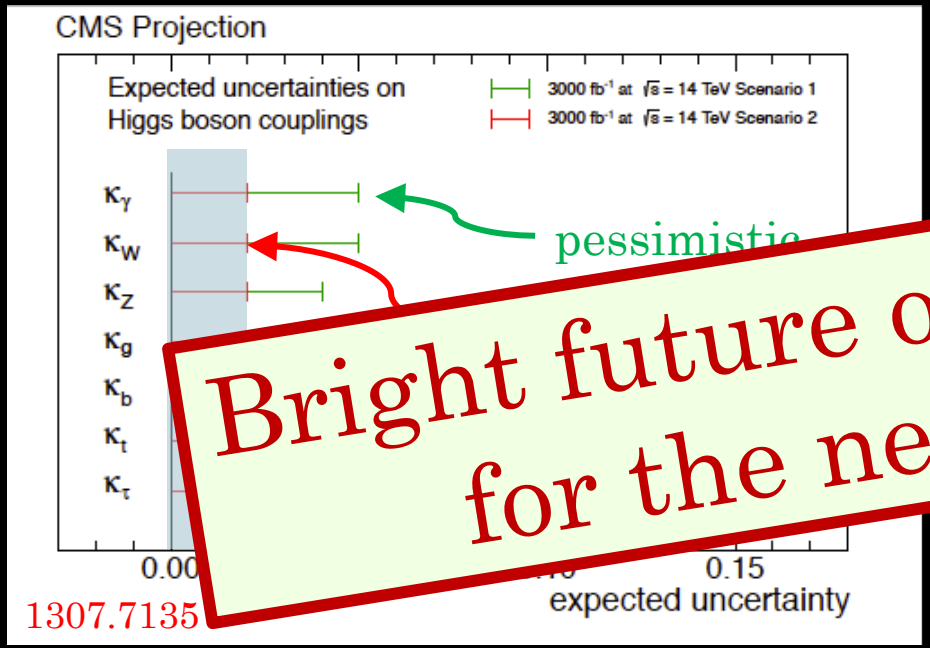


Bright future of opportunities for the next 20 years

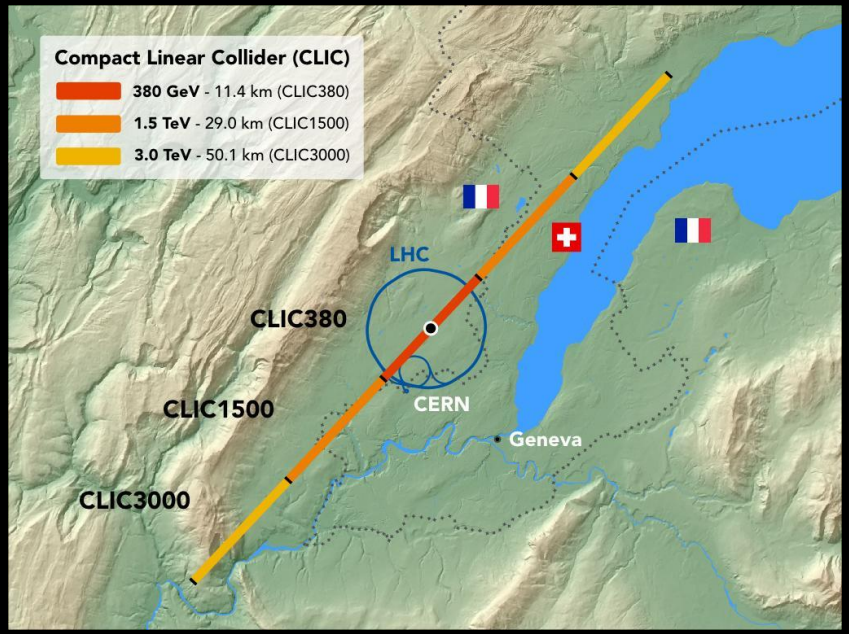
Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

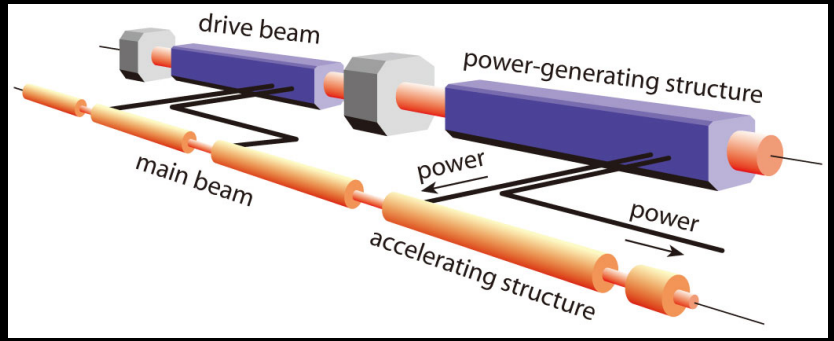
2nd priority

Future colliders at CERN

Concrete collider options studied at CERN

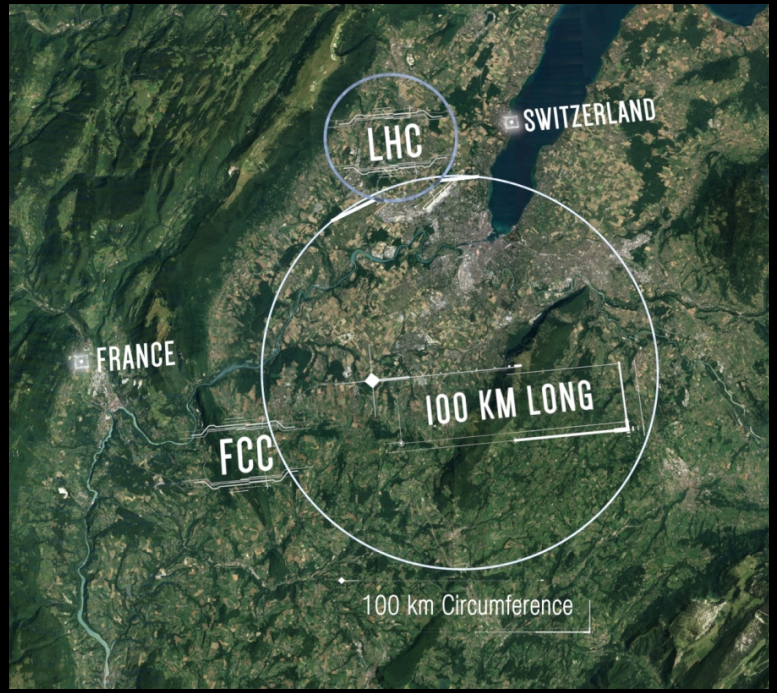
CLIC (ee), http://clic-study.web.cern.ch/





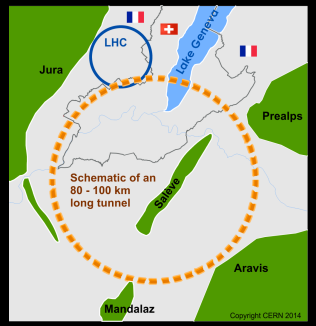
Concrete collider options studied at CERN

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

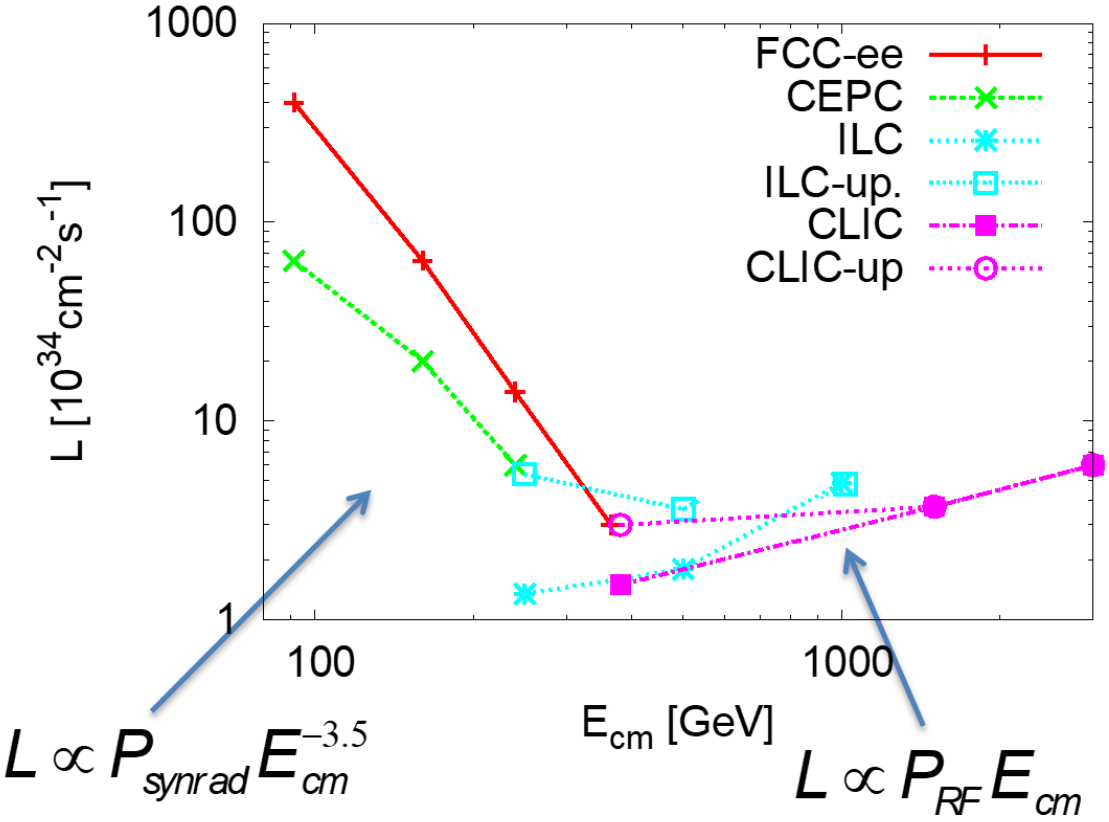


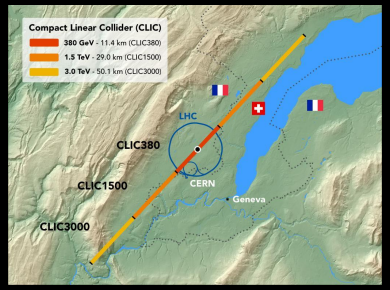
- **e^+e^- collider (*FCC-ee*) @ 90-365 GeV** as potential first step

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

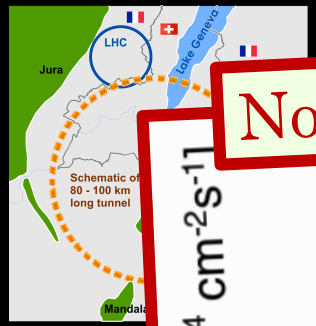


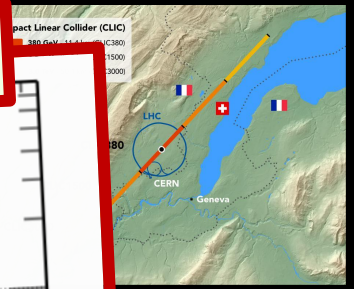
Luminosity per facility

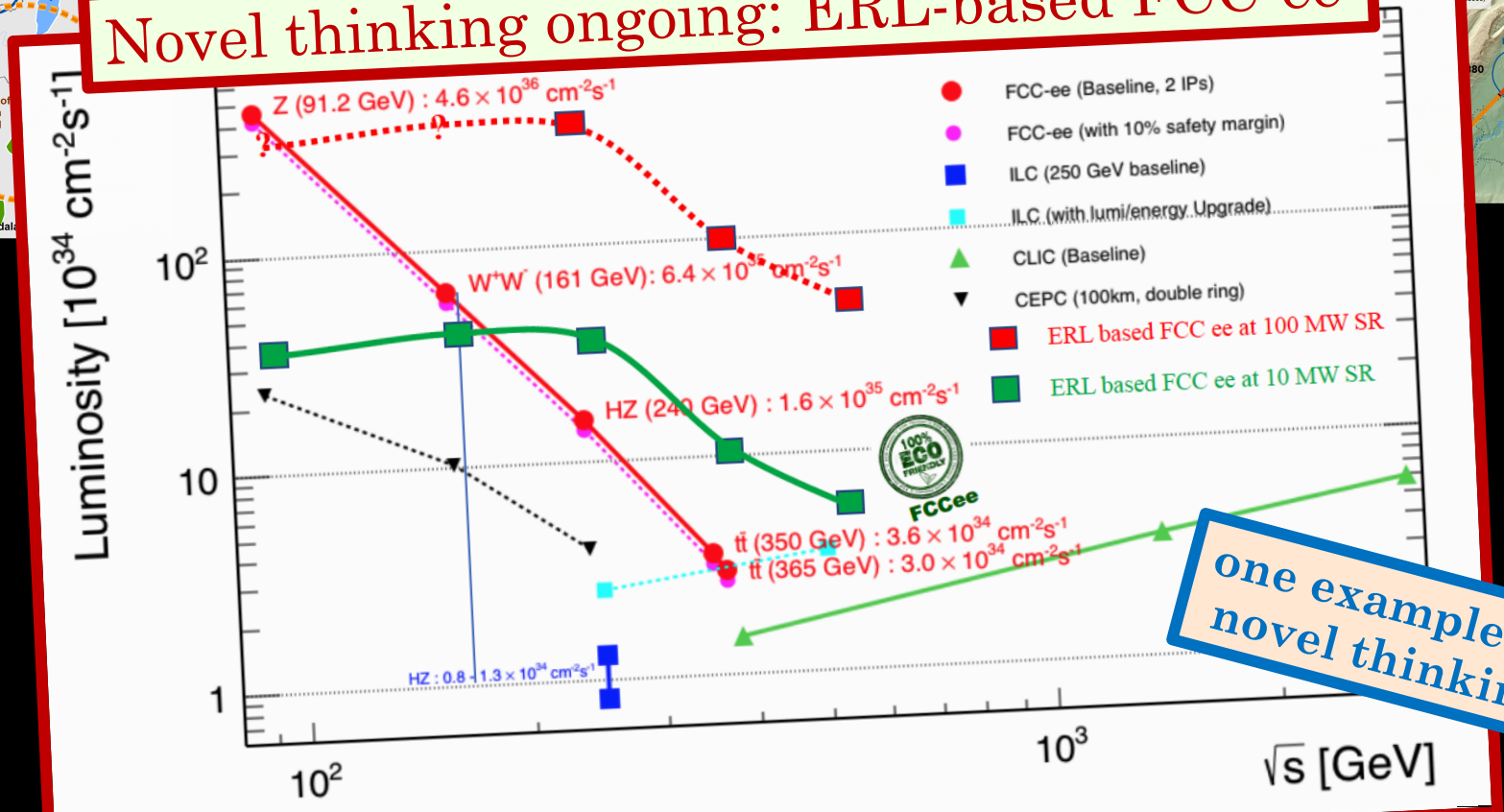




Novel thinking ongoing: ERL-based FCC-ee



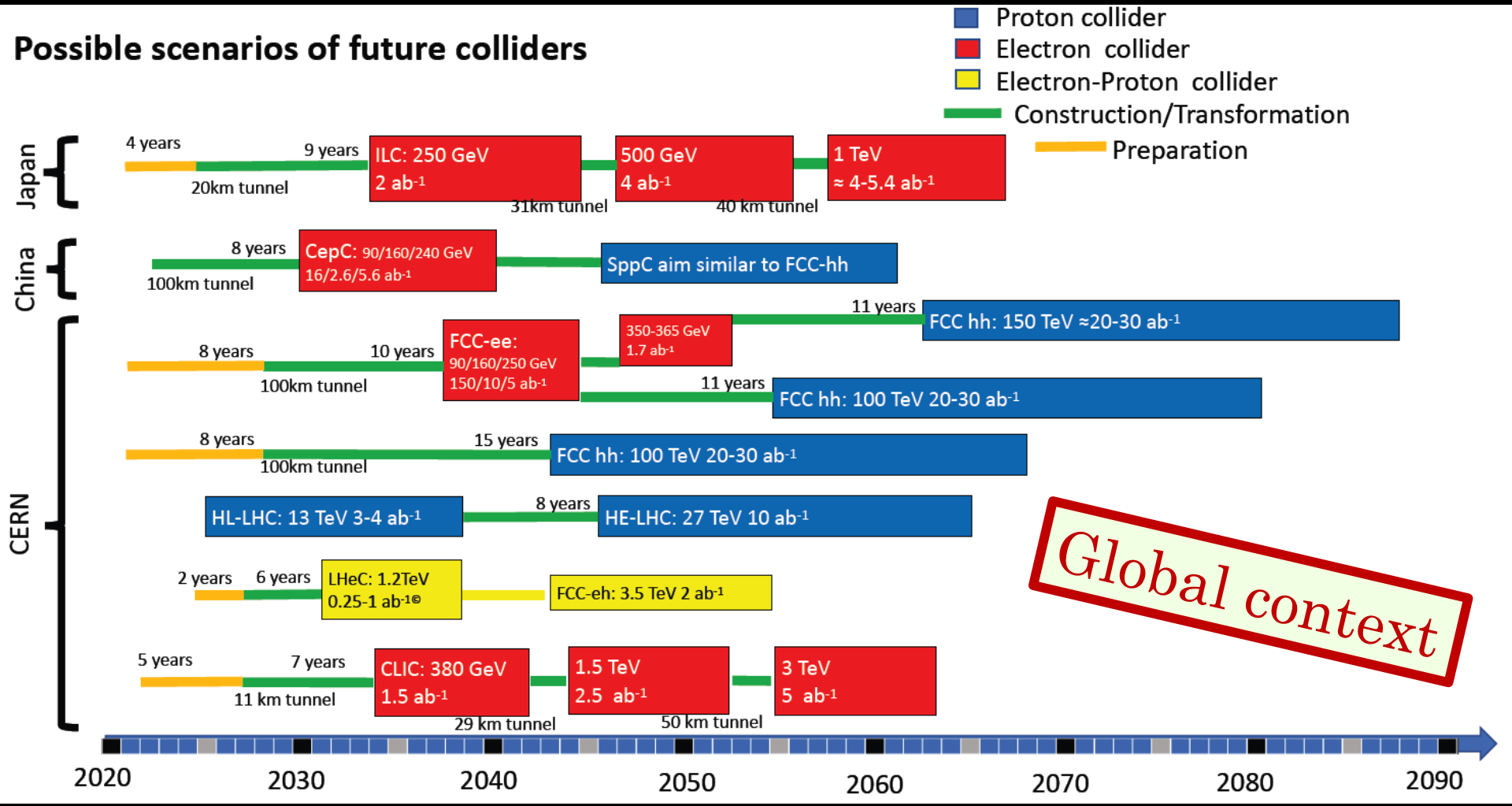




one example of novel thinking

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

Possible scenarios of future colliders



Global context

Long-term strategy for Particle Physics

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

UPDATE of the European Particle Physics Strategy (2013)

Major facility after HL-LHC

Start data taking HL-LHC (2026)

TODAY

Higgs discovery (2012)

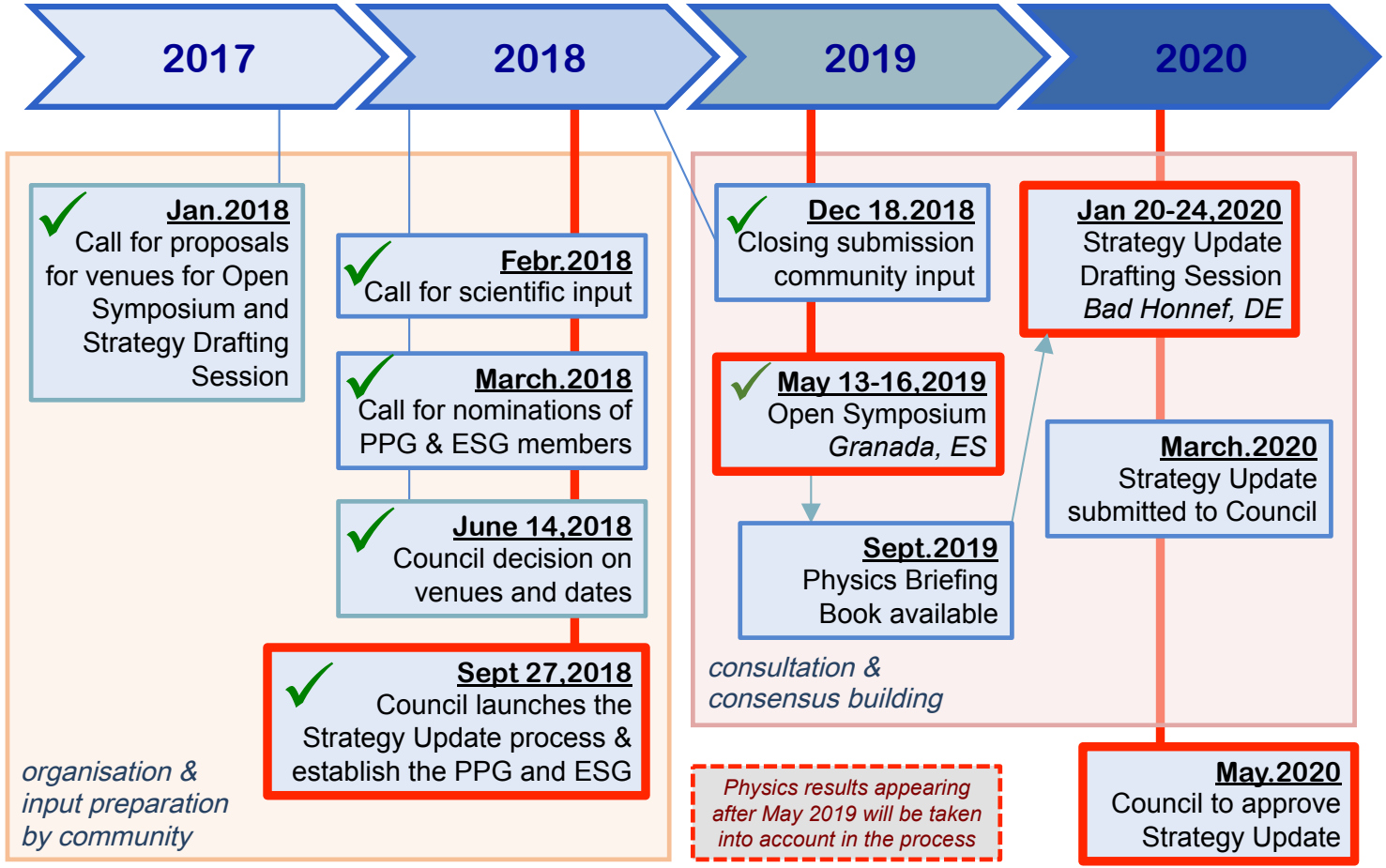
Start data taking at the LHC (2010)

UPDATE of the European Particle Physics Strategy (2020)

https://europeanstrategy.cern

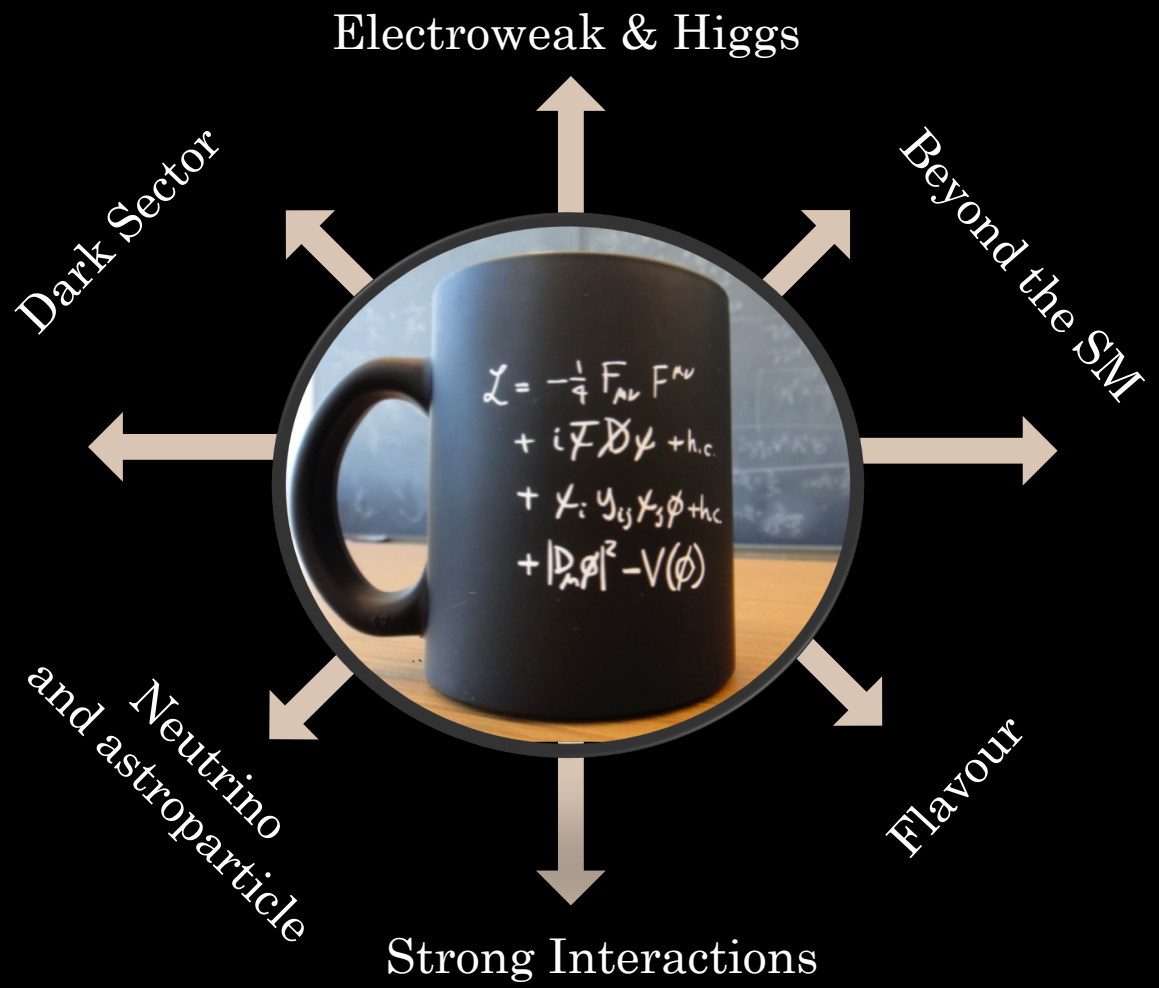
European Particle Physics Strategy (2006)

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

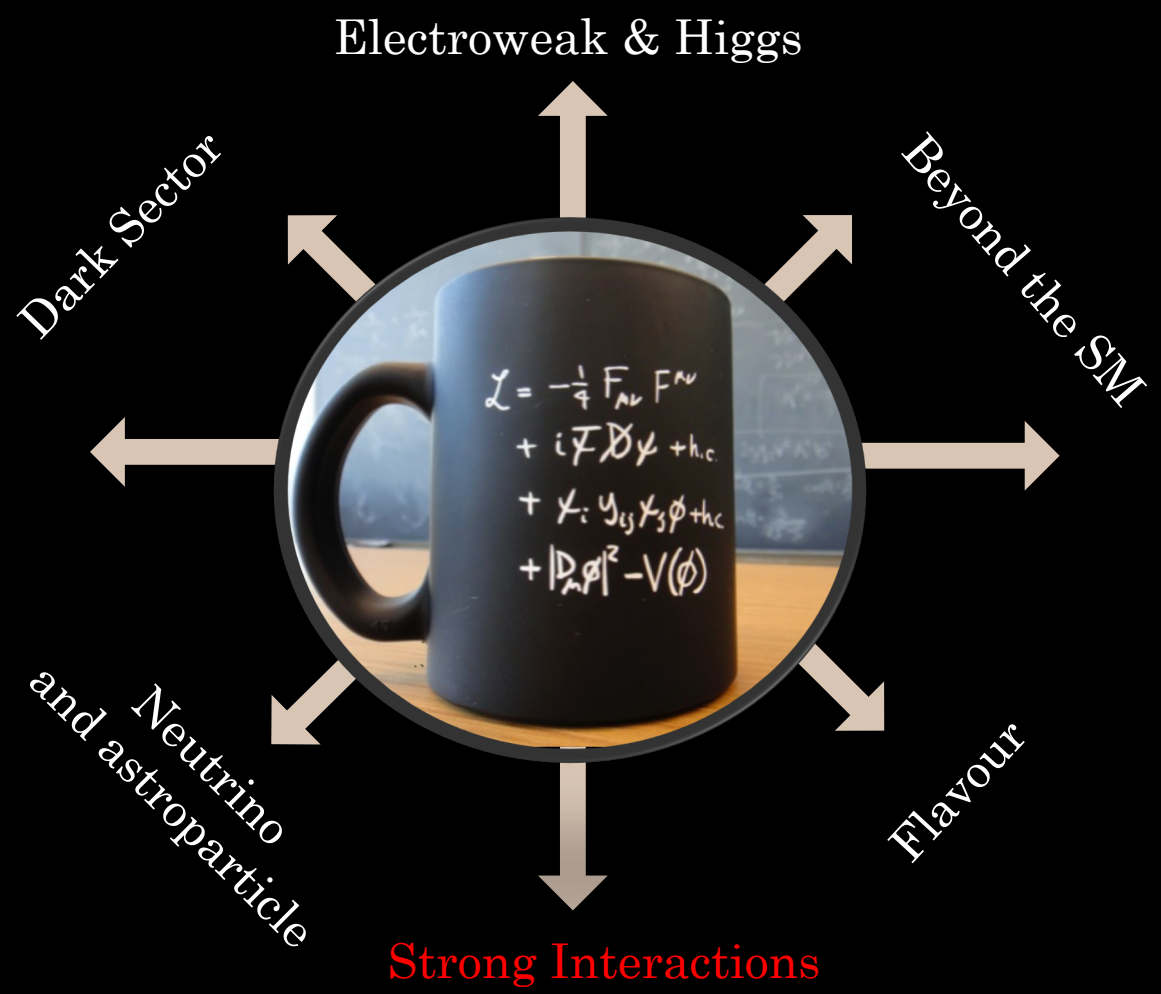
Open Symposium
Towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain
https://cafpe.ugr.es/eppsu2019/
~600 participants
Information captured in 8 thematic summary talks

The Granada physics themes



The Granada themes

Strong Interactions



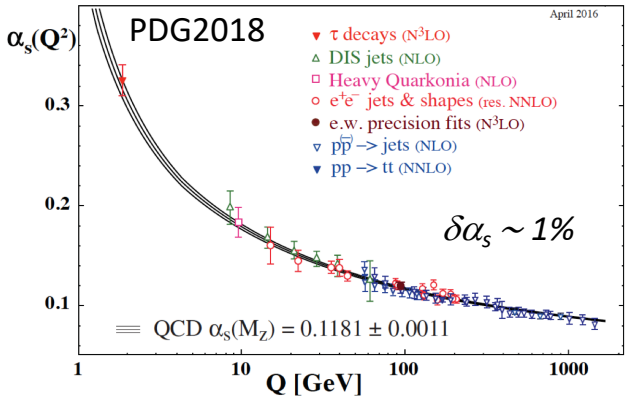
Strong interactions

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

colour confinement

α_s (Q^2 low) ~ 1

key phenomena (non-Abelian gauge group)



asymptotic freedom

α_s (Q^2 high) << 1

"hot and dense QCD"

(low energy domain)

(lattice calculations)

"vacuum QCD"

(high energy domain)

(perturbative calculations)

$\alpha_{EW} << \alpha_s$

European Strategy Update

Strong interactions

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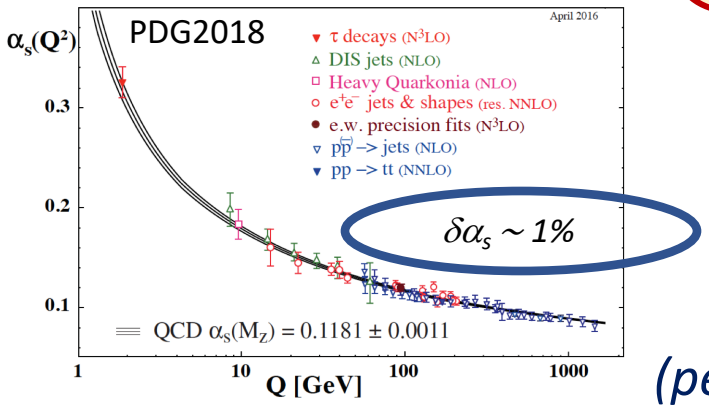

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European Strategy Update

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α_s (Q^2 low) ~ 1

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asymptotic freedom
α_s (Q^2 high) << 1

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 Q
(low energy dom
(lattice calculatio

"vacuum QCD"
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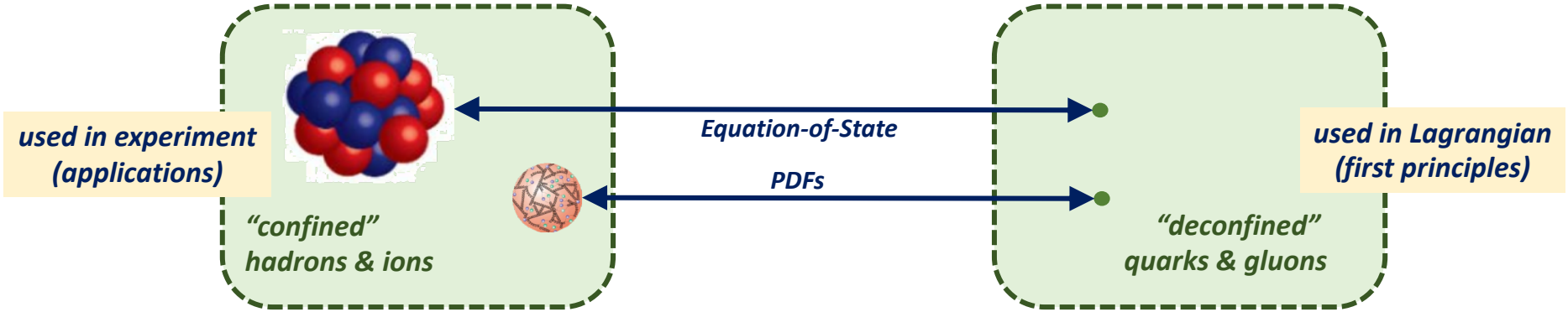
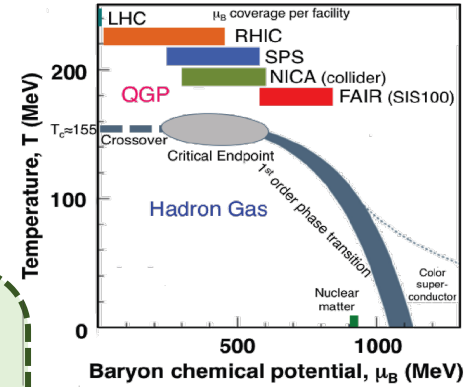
turbative calculations)

“hot and dense QCD” ⟷ *“vacuum QCD”*



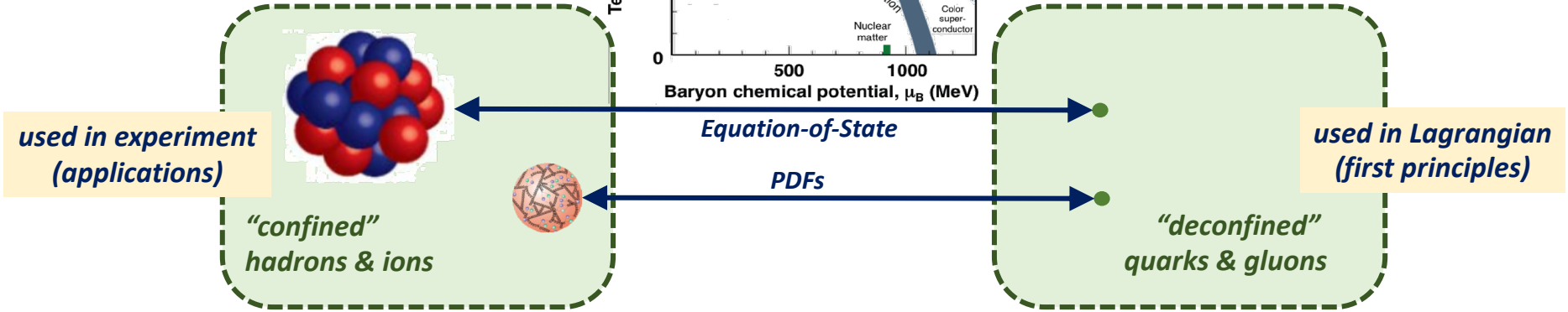
“hot and dense QCD” ⟷ *“vacuum QCD”*

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



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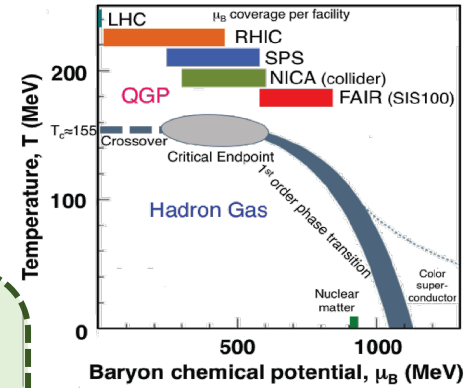


From LQCD: T_c (μ_B=0) = 156.5 ± 1.5 MeV

From experiment: determination of chemical freeze-out temperature

used in experiment (applications)

used in Lagrangian (first principles)

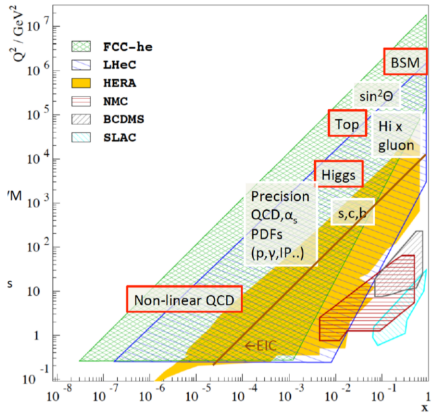
Equation-of-State

PDFs

“confined” hadrons & ions

“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?

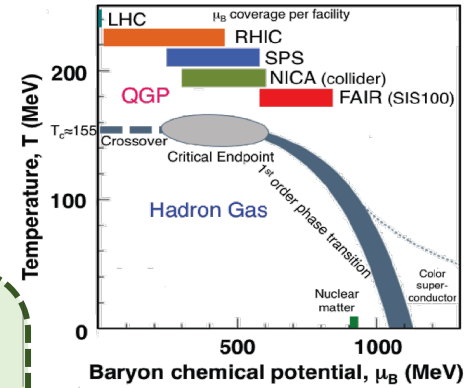


From QCD: evolution equations of PDFs

From experiment: PDF parameters values themselves

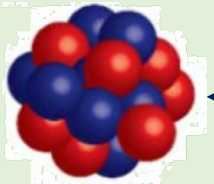
“hot and dense QCD” ⟷ *“vacuum QCD”*

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

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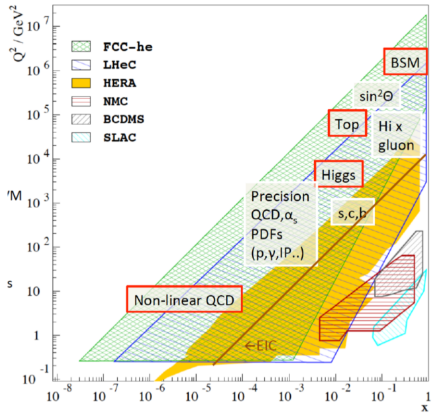

Key facilities involve collisions with protons

"hot and dense QCD" ⟷ *"vacuum QCD"*

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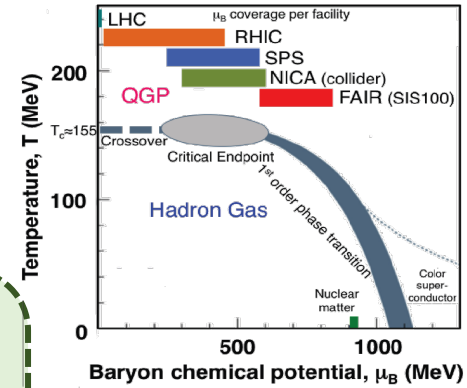

HL-LHC: increased luminosity, low-μ_B
HE-LHC/FCC: new probes
Fixed-target@SPS: high-μ_B
Fixed-target@(HL-)LHC: medium-μ_B

used in experiment (applications)

used in Lagrangian (first principles)

Equation-of-State

PDFs

"confined" hadrons & ions

"deconfined" quarks & gluons

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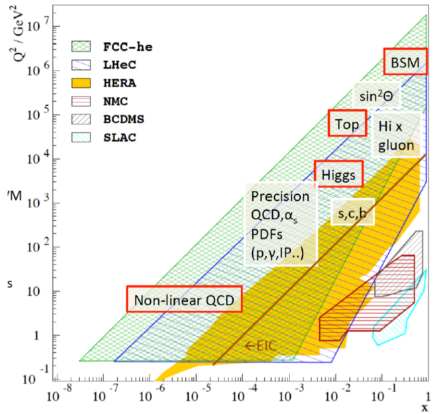


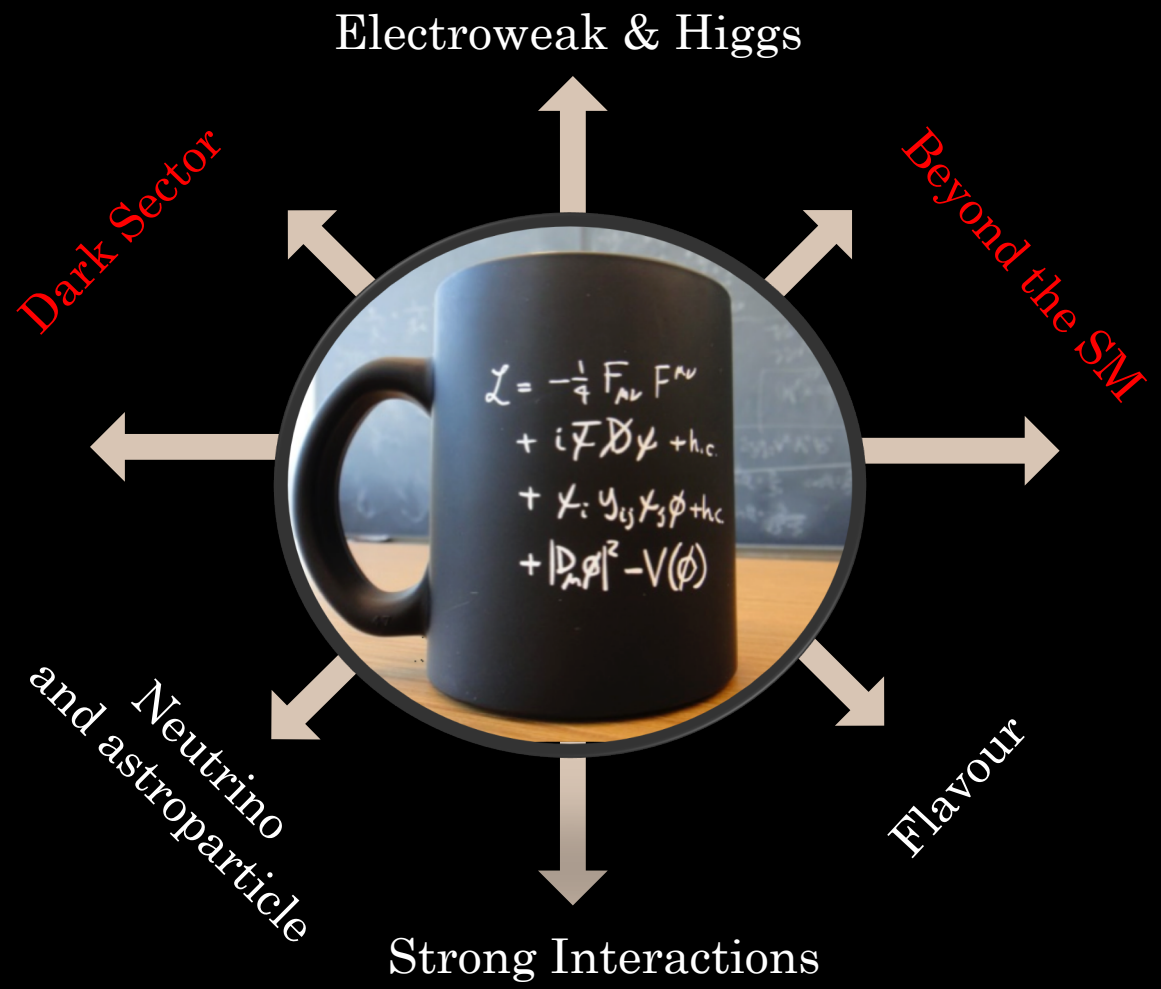
HL-LHC: mid-x (up to x2 improvement)
Fixed-target@(HL-)LHC: high-x

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

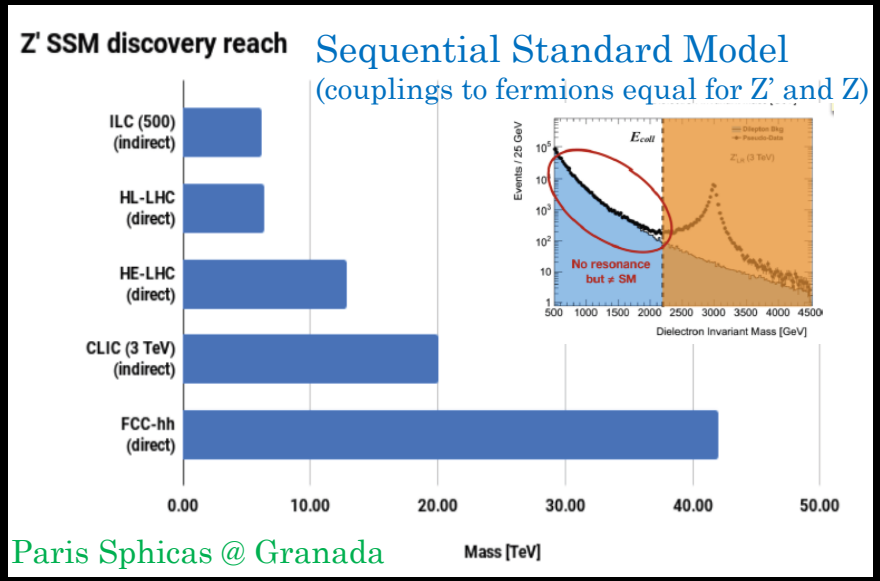
ERL system for electron beam at 60 GeV

The Granada themes

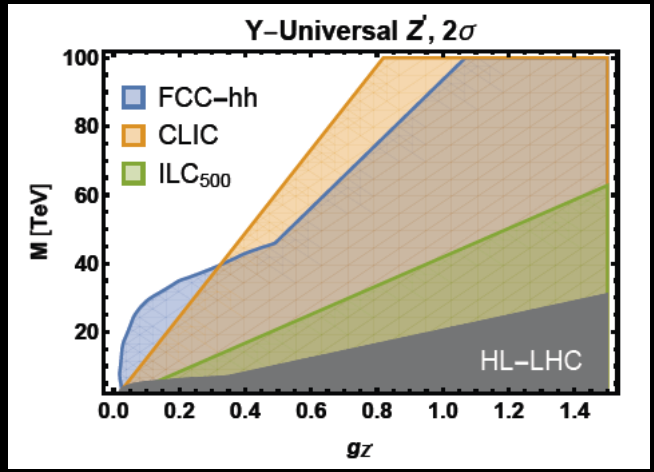
Beyond the SM
&
Dark Sector



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



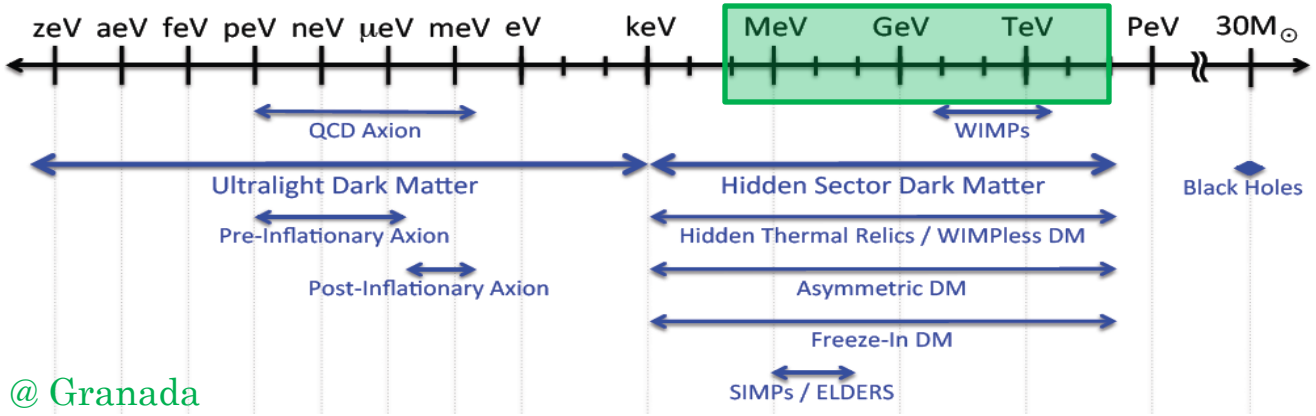
- In general, if the couplings become large the sensitivity at lepton colliders is enhanced
- For weak couplings the direct search at hadron colliders dominates the picture



Many more models are compared…

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

Too small mass
⇒ won't "fit"
in a galaxy!

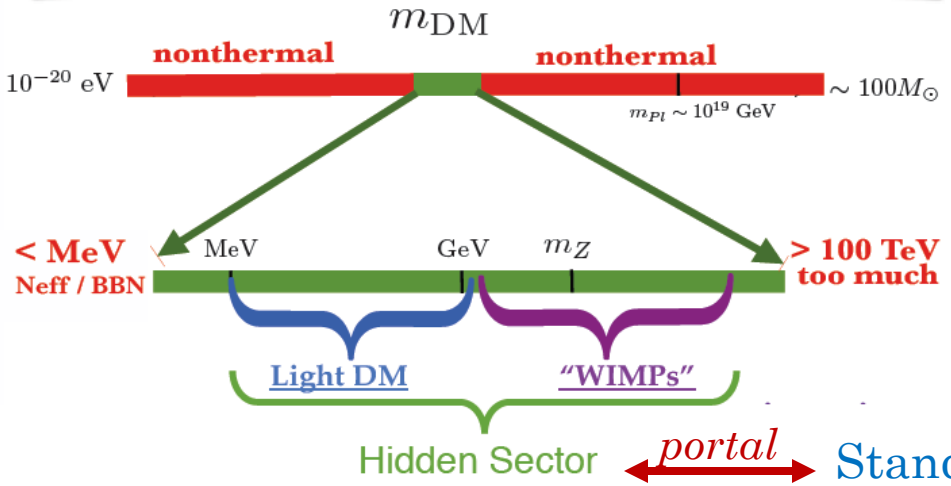


From MACHOs searches

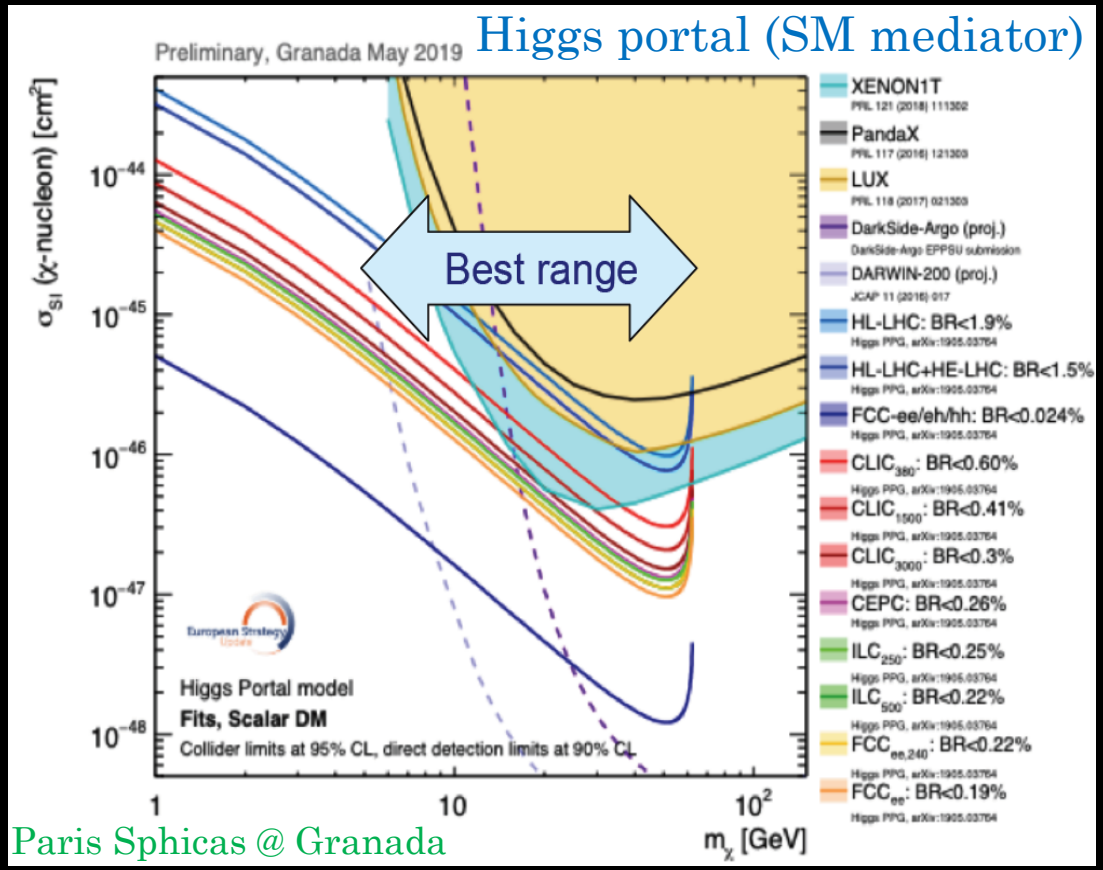
Marcela Carena @ Granada

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?



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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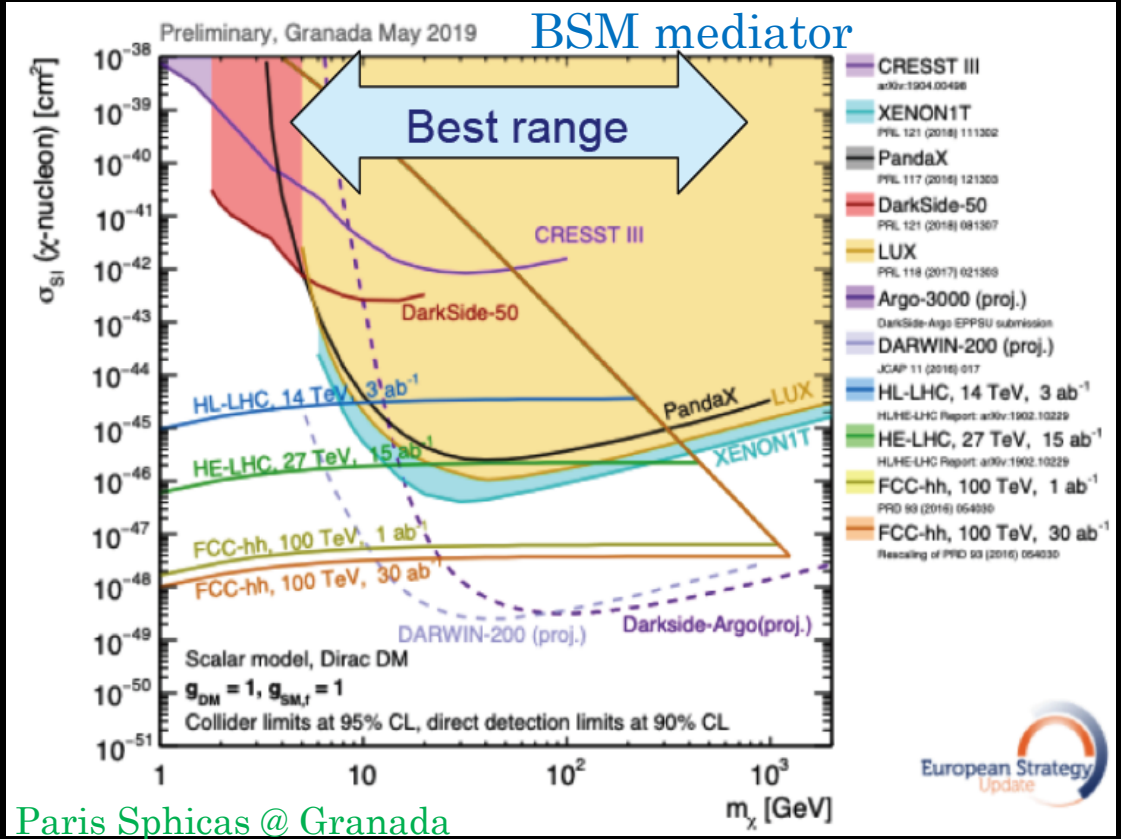

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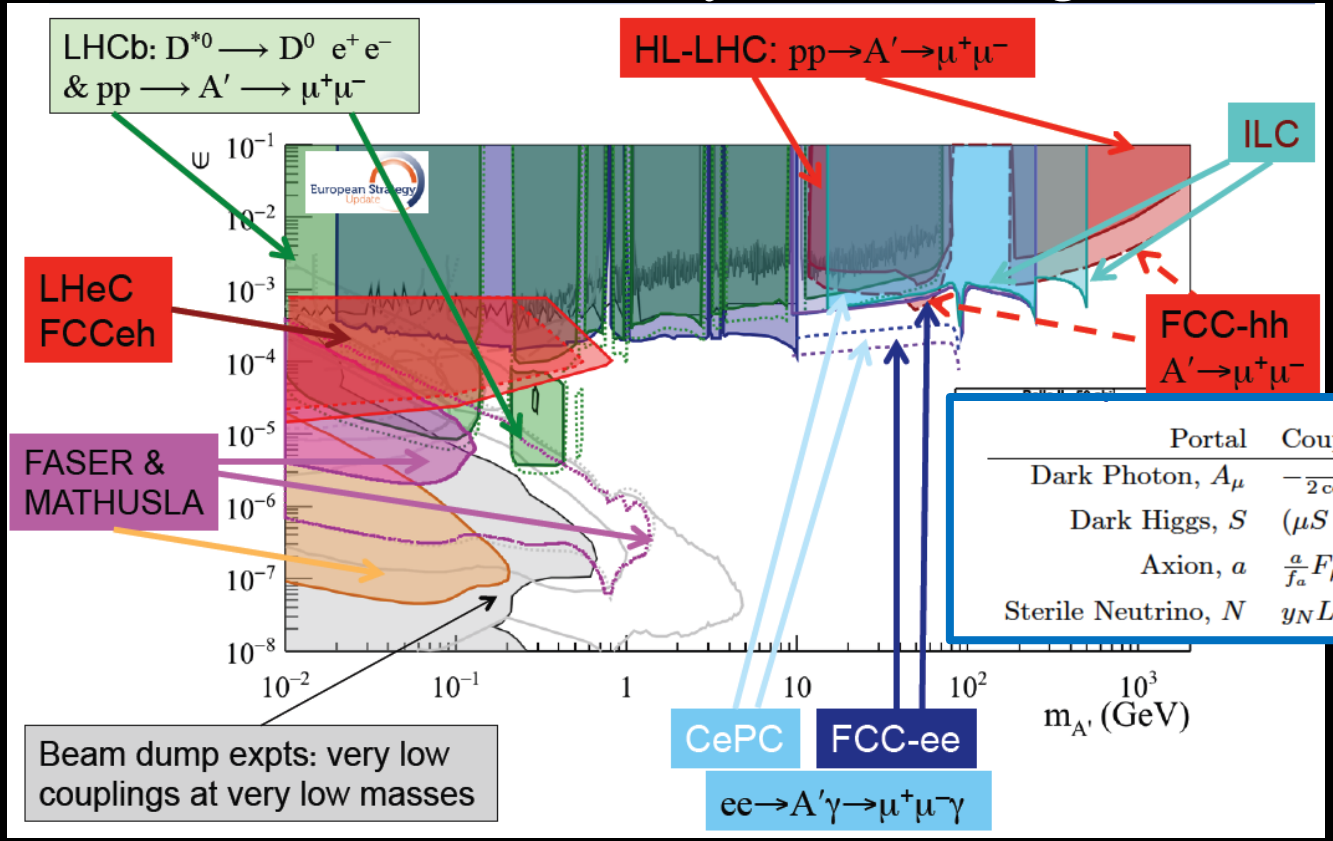
To what extent can current or future accelerators probe feebly interacting sectors?



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

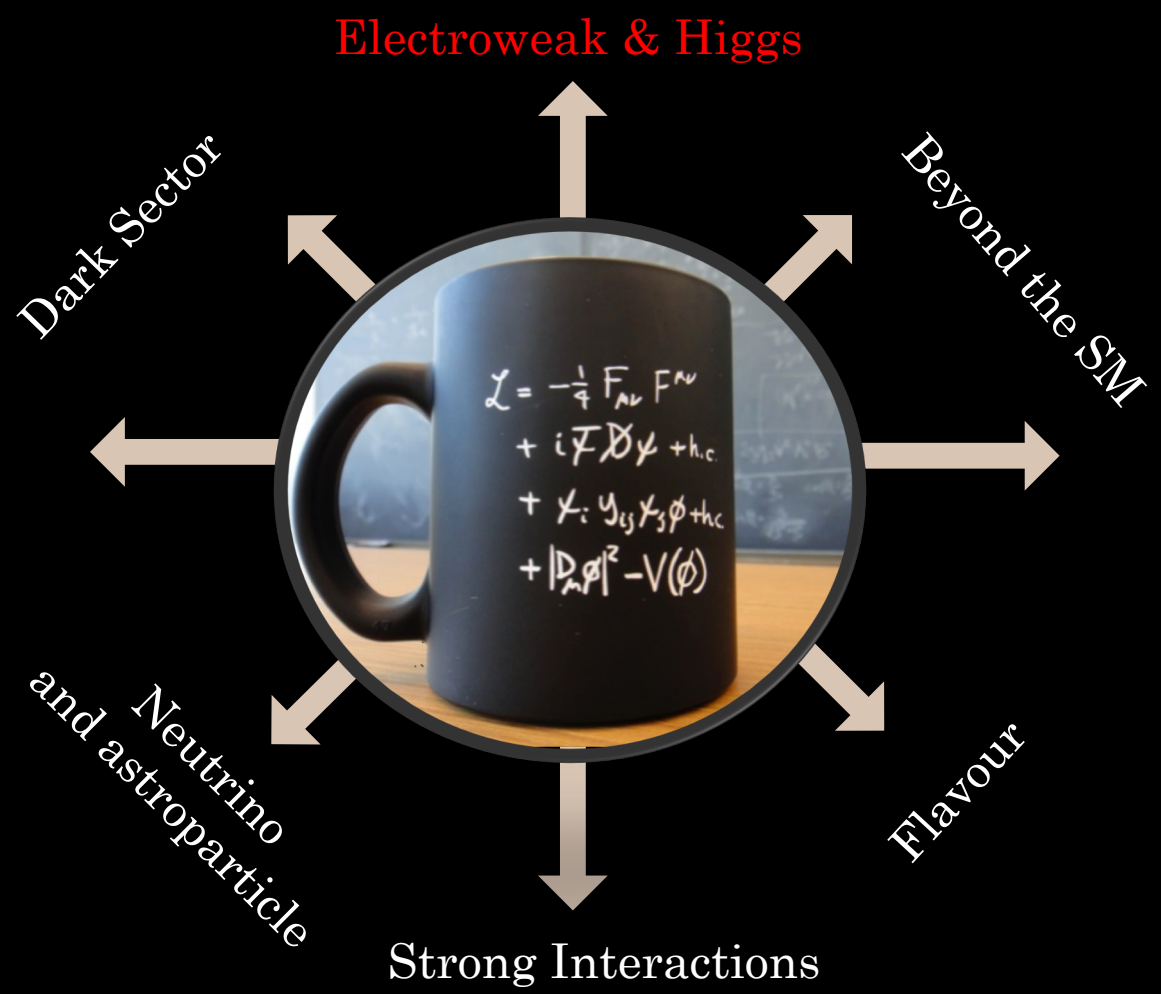
PBC report, arXiv:1901.09966

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	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$	
Sterile Neutrino, N	$y_N L H N$	

Dark Photon case

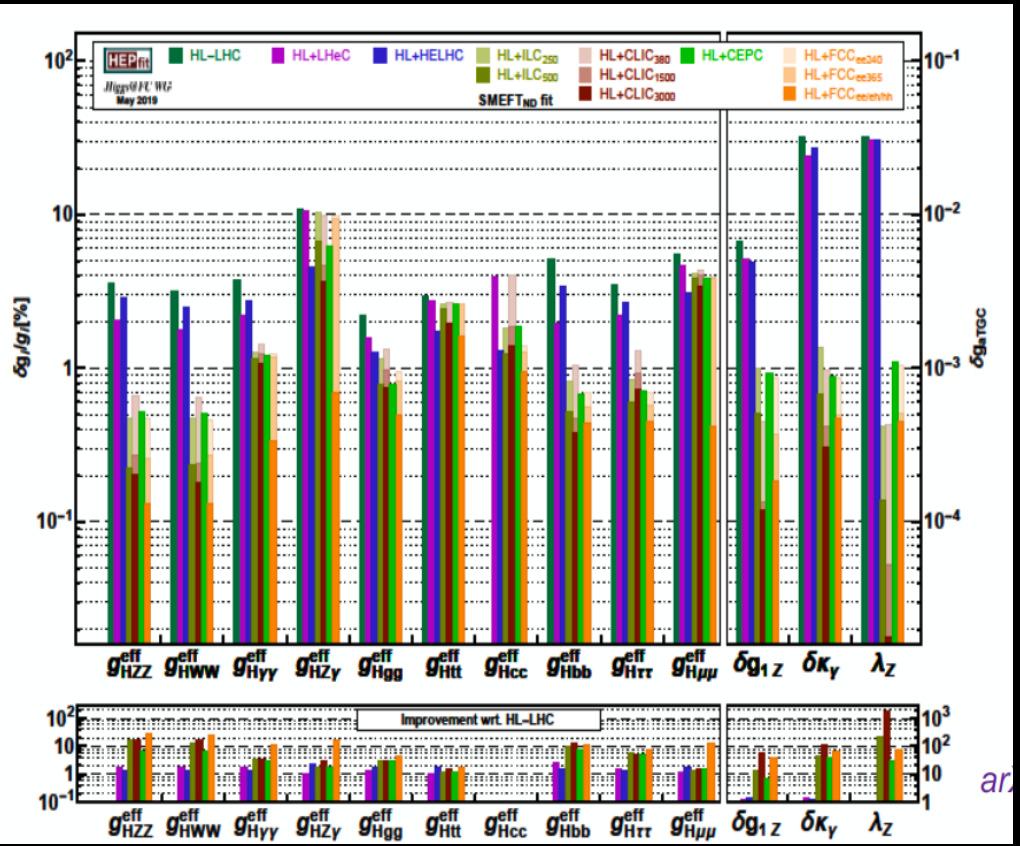
The Granada physics themes

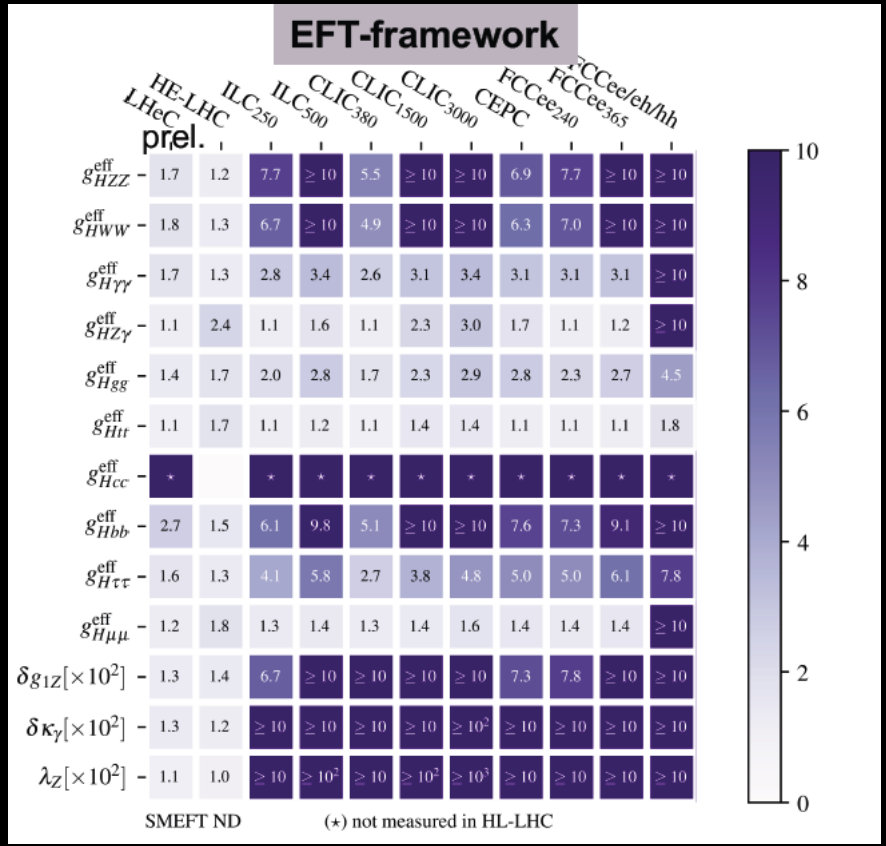
EW & Higgs



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)

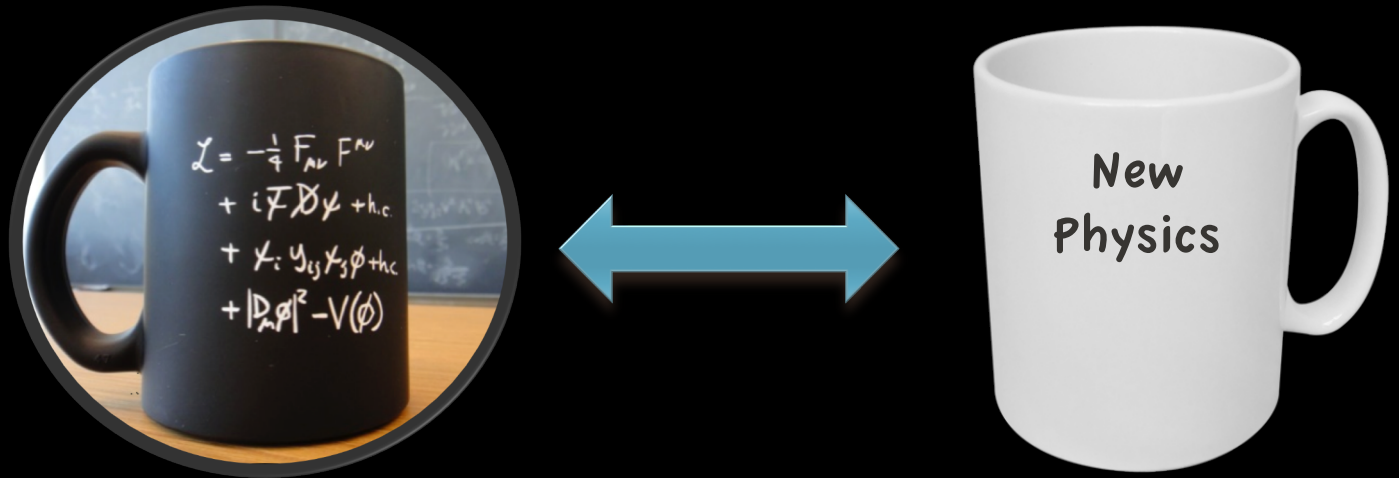
		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
hh	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

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

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 (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

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

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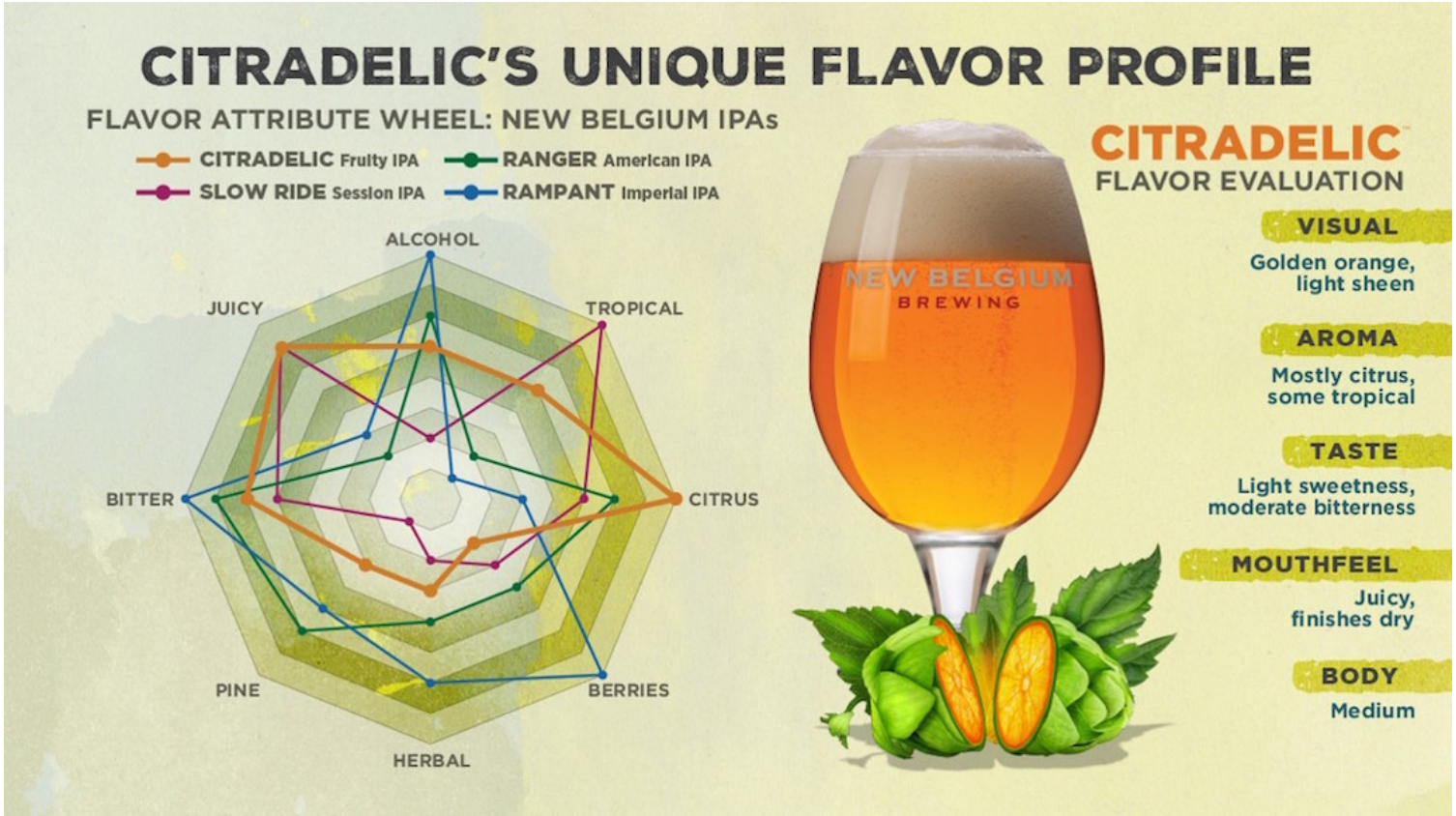
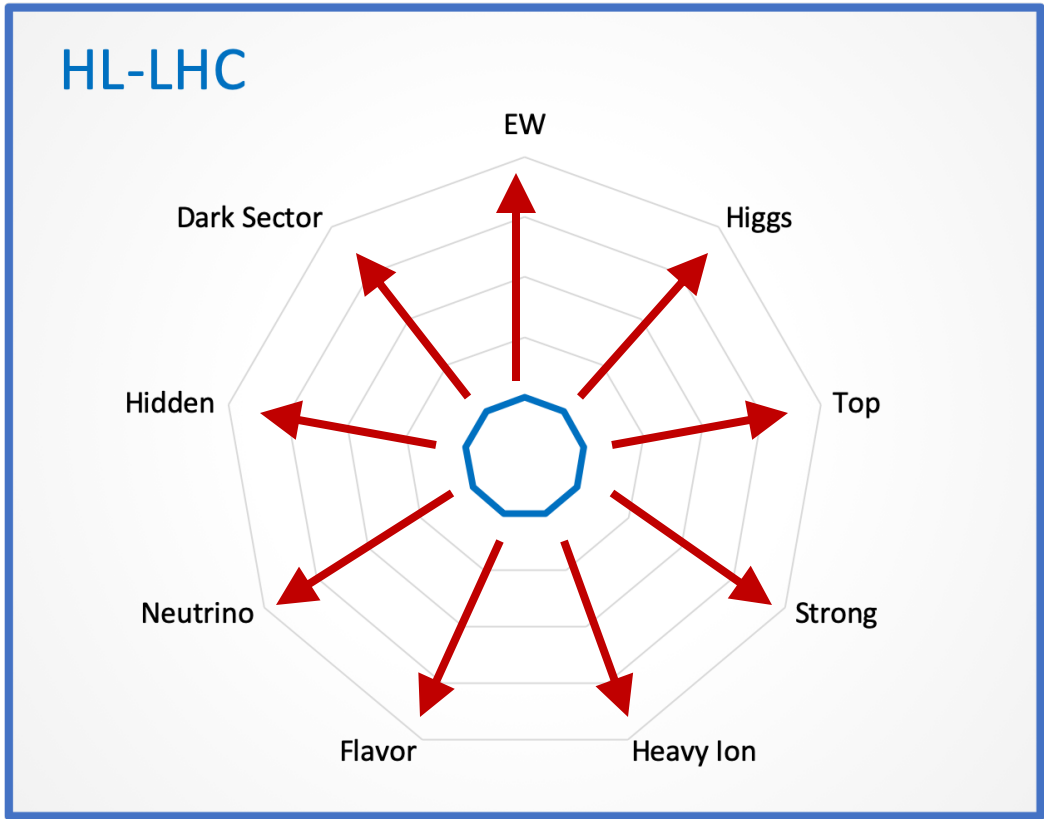
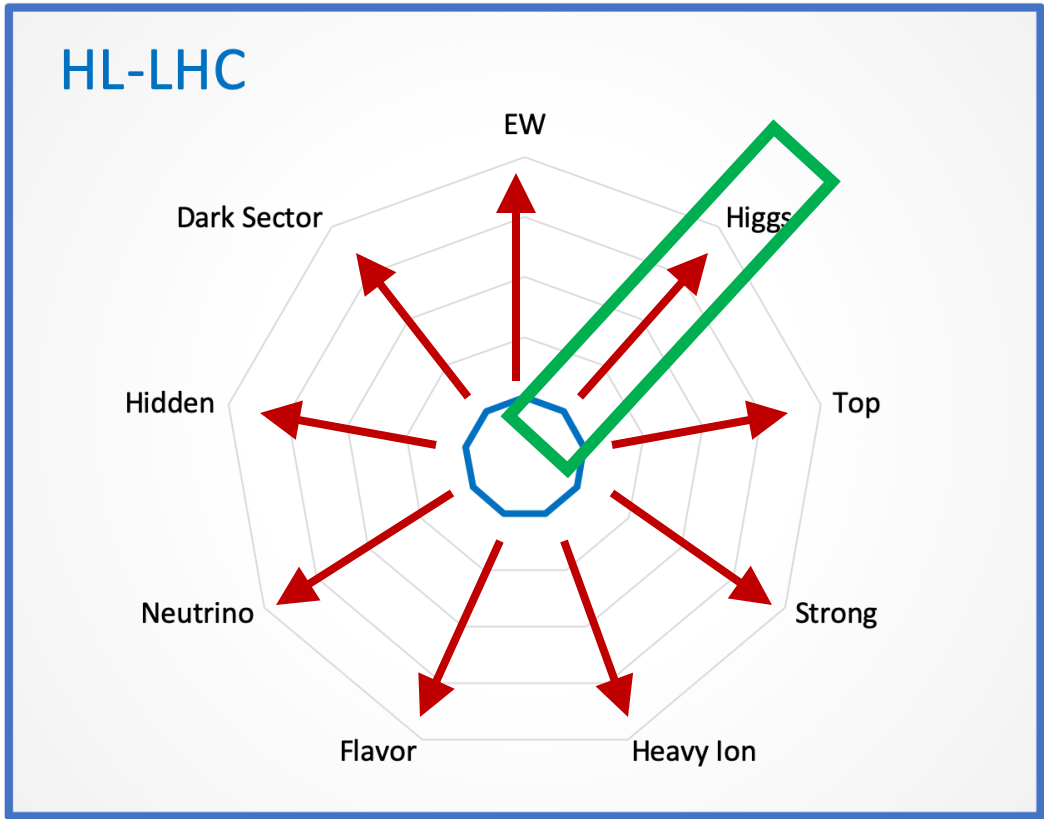


If you want to discover a great taste, you will have to sample several

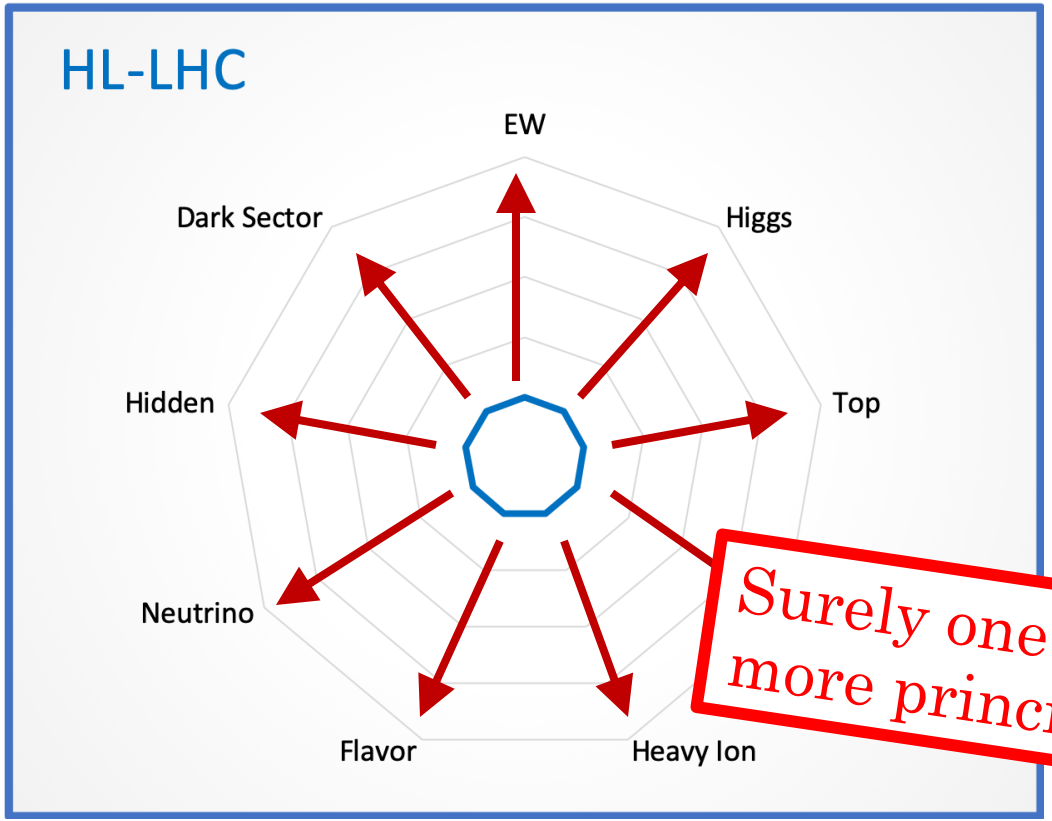


Progress relative to today's knowledge and including the expected performance of the HL-LHC



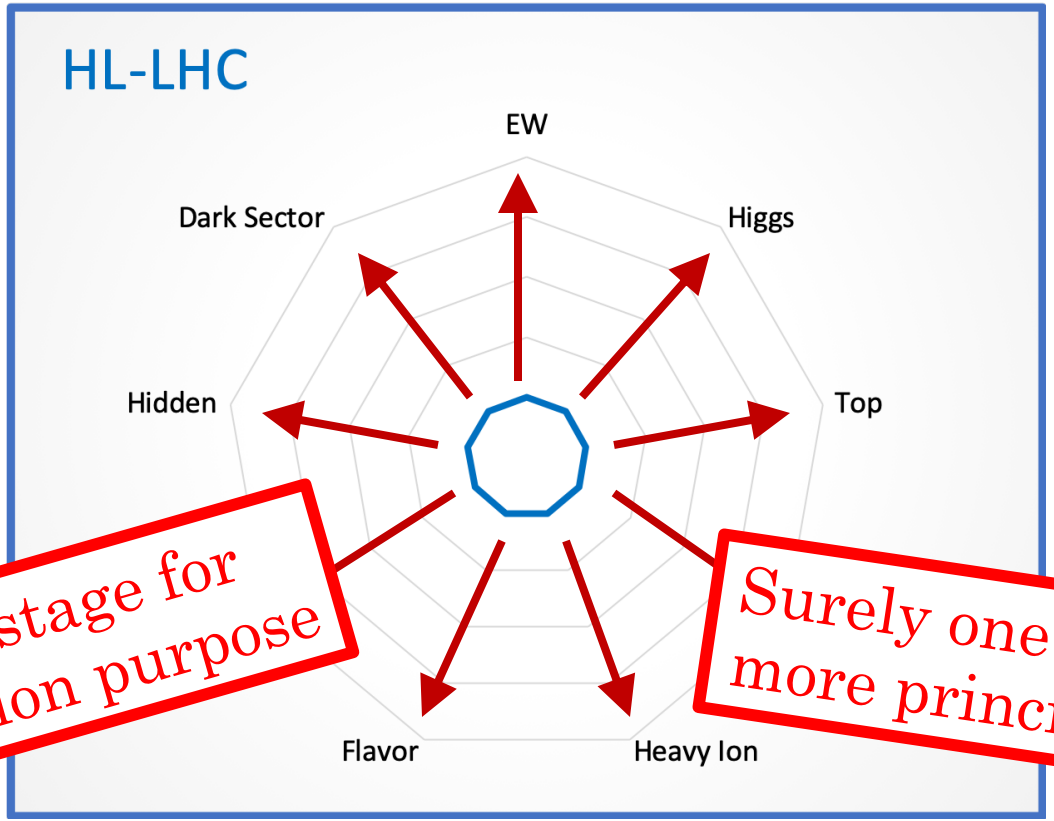
Progress relative to today's knowledge and including the expected performance of the HL-LHC

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



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

Surely one can think about more principle components

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

choice for 1st gen

choice for 2nd gen

2020-2040
HL-LHC era

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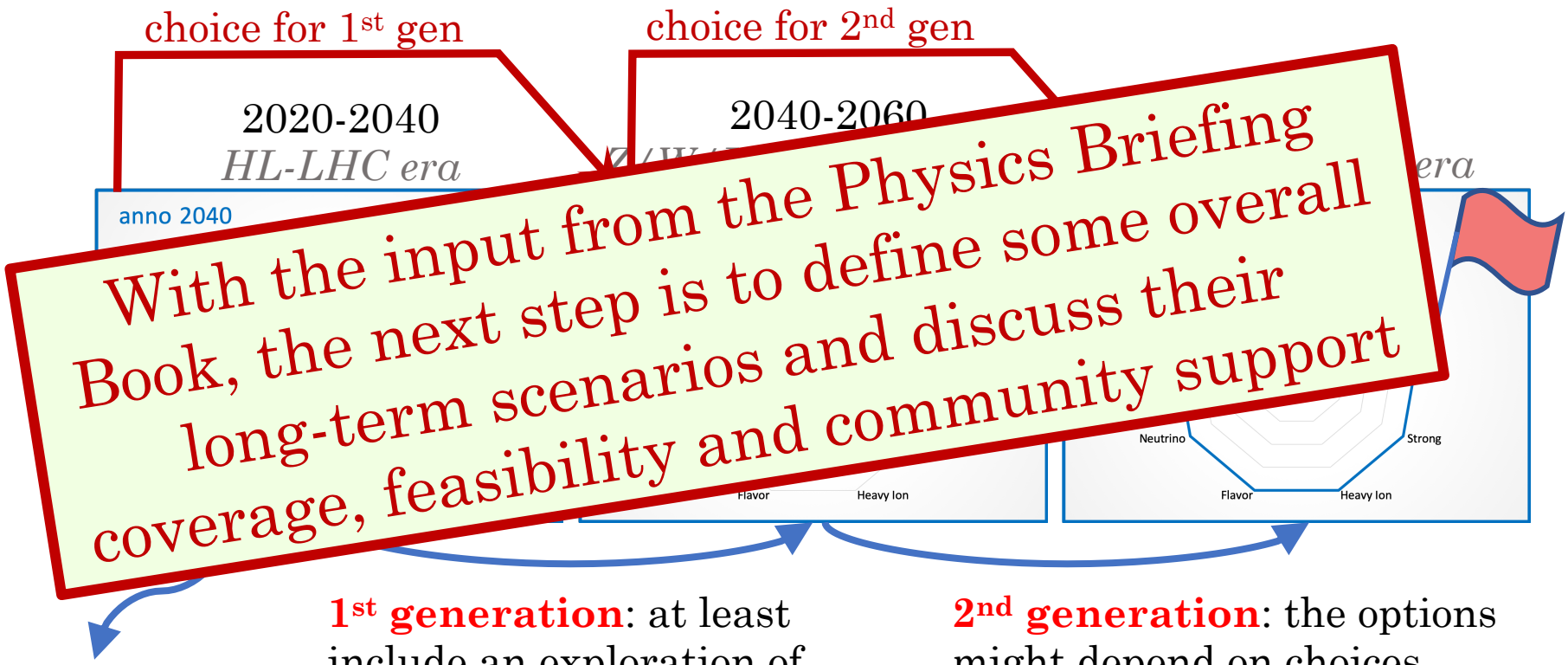

With the input from the Physics Briefing Book, the next step is to define some overall long-term scenarios and discuss their coverage, feasibility and community support

HL-LHC era

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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*

Some
(Personal)
Key Thoughts

Thank you for your attention

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