HIGGS FACTORIES

FREYA BLEKMAN

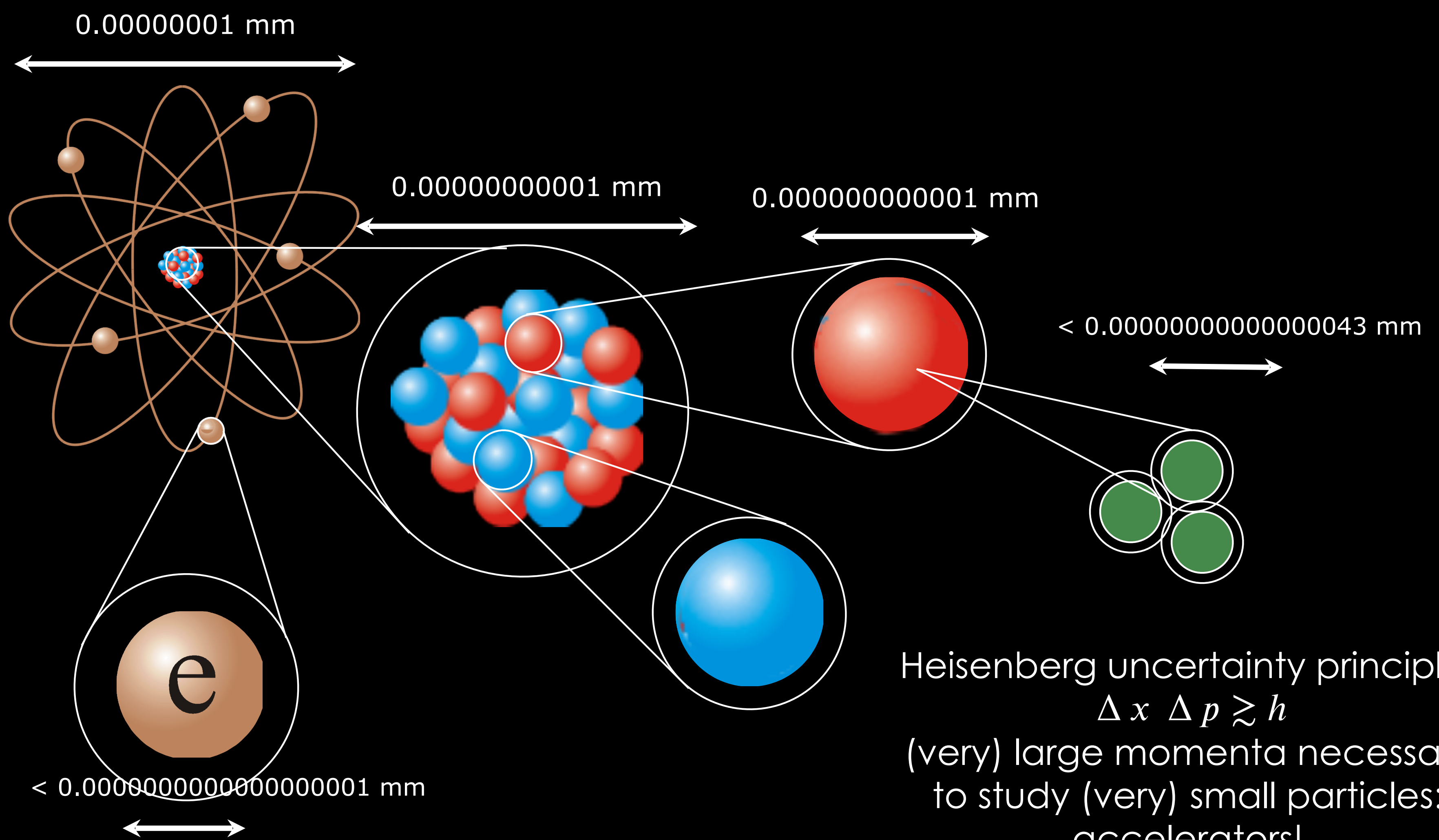
Helmholtz Matter and the Universe Days
Friday 21 October 2022, Darmstadt

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.

UHH
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

freyablekman

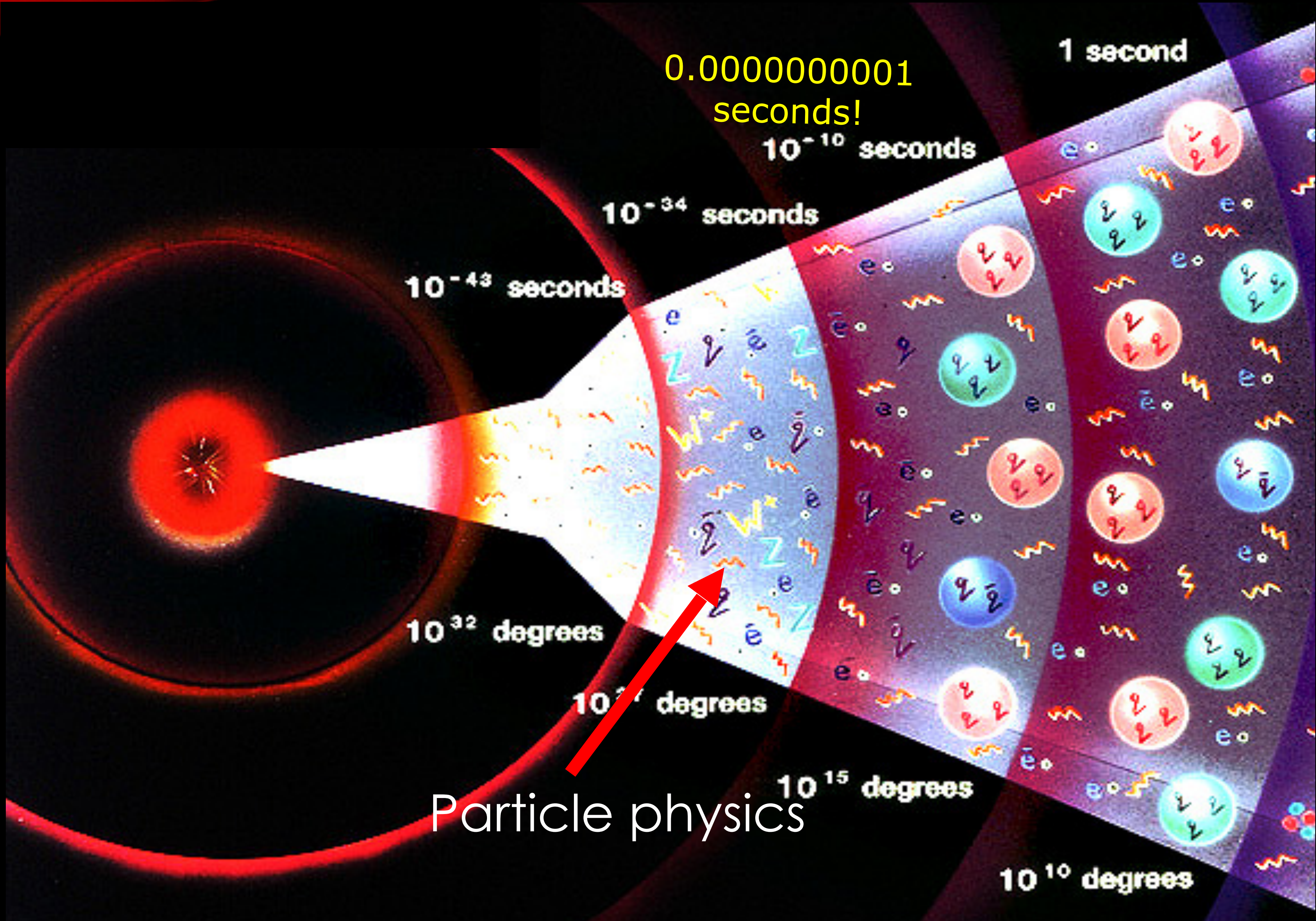


Heisenberg uncertainty principle:

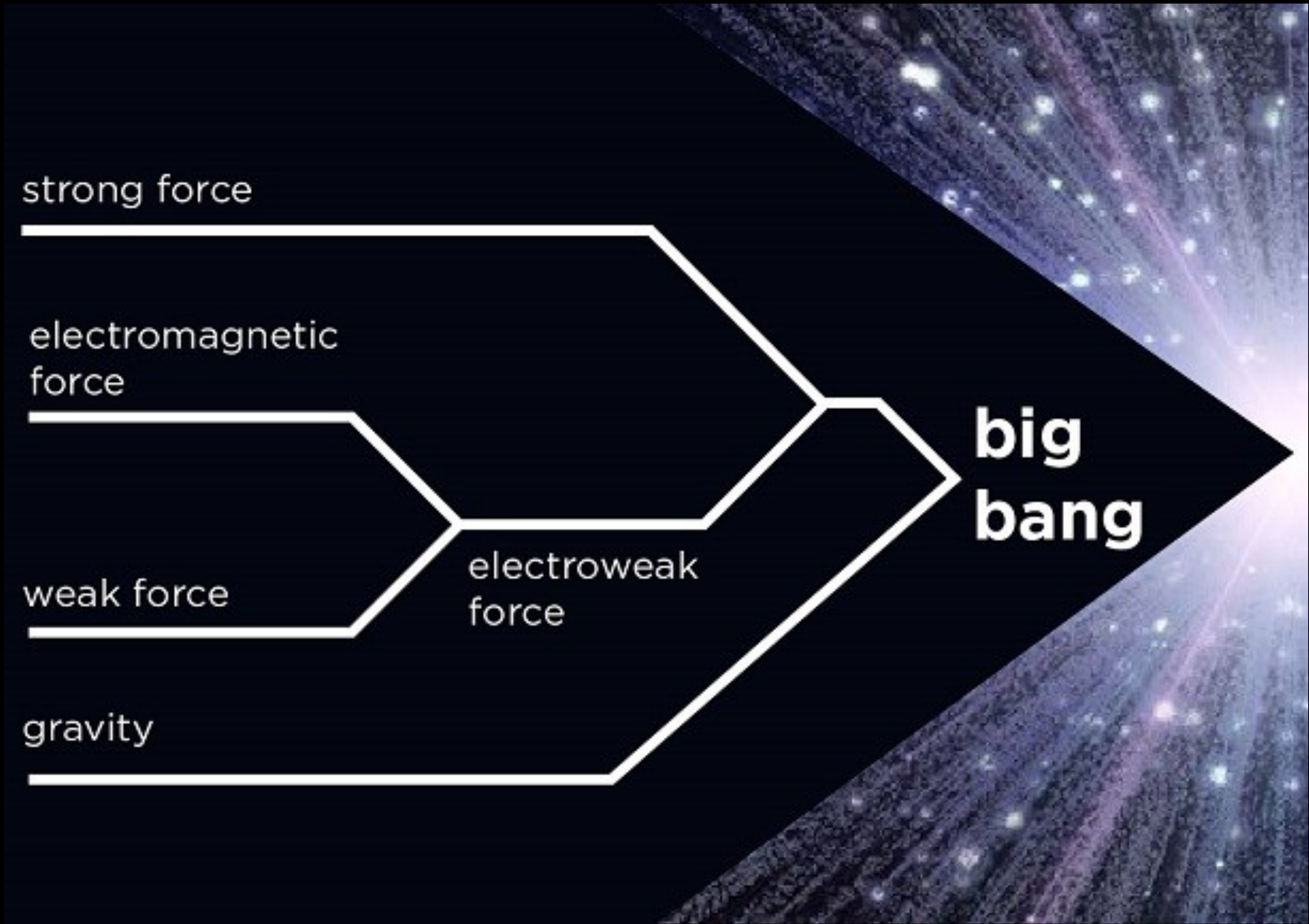
$$\Delta x \ \Delta p \gtrsim h$$

(very) large momenta necessary to study (very) small particles: accelerators!

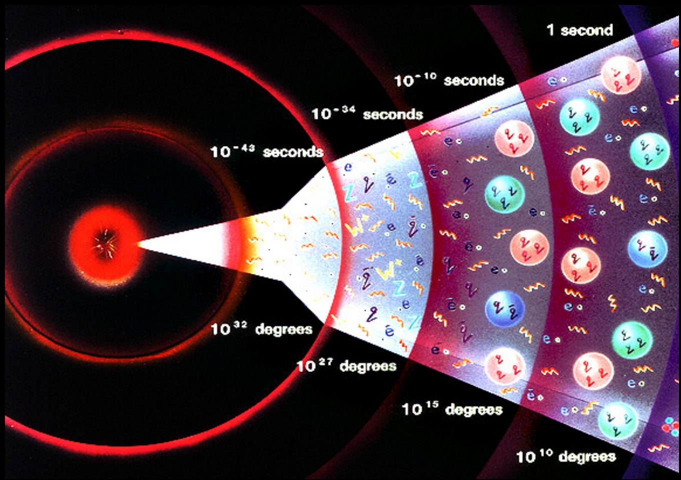
THE BIG BANG...

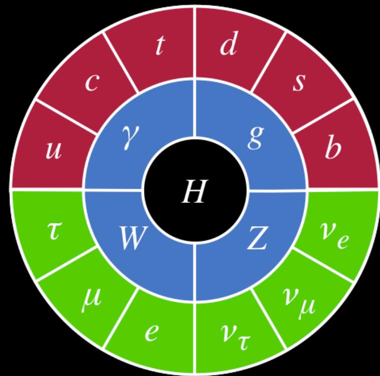

0.0000000001
seconds!
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
Particle physics

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$


strong force
electromagnetic force
weak force
gravity
electroweak force
big bang

WHAT HAPPENED (JUST) AFTER THE BIG BANG?

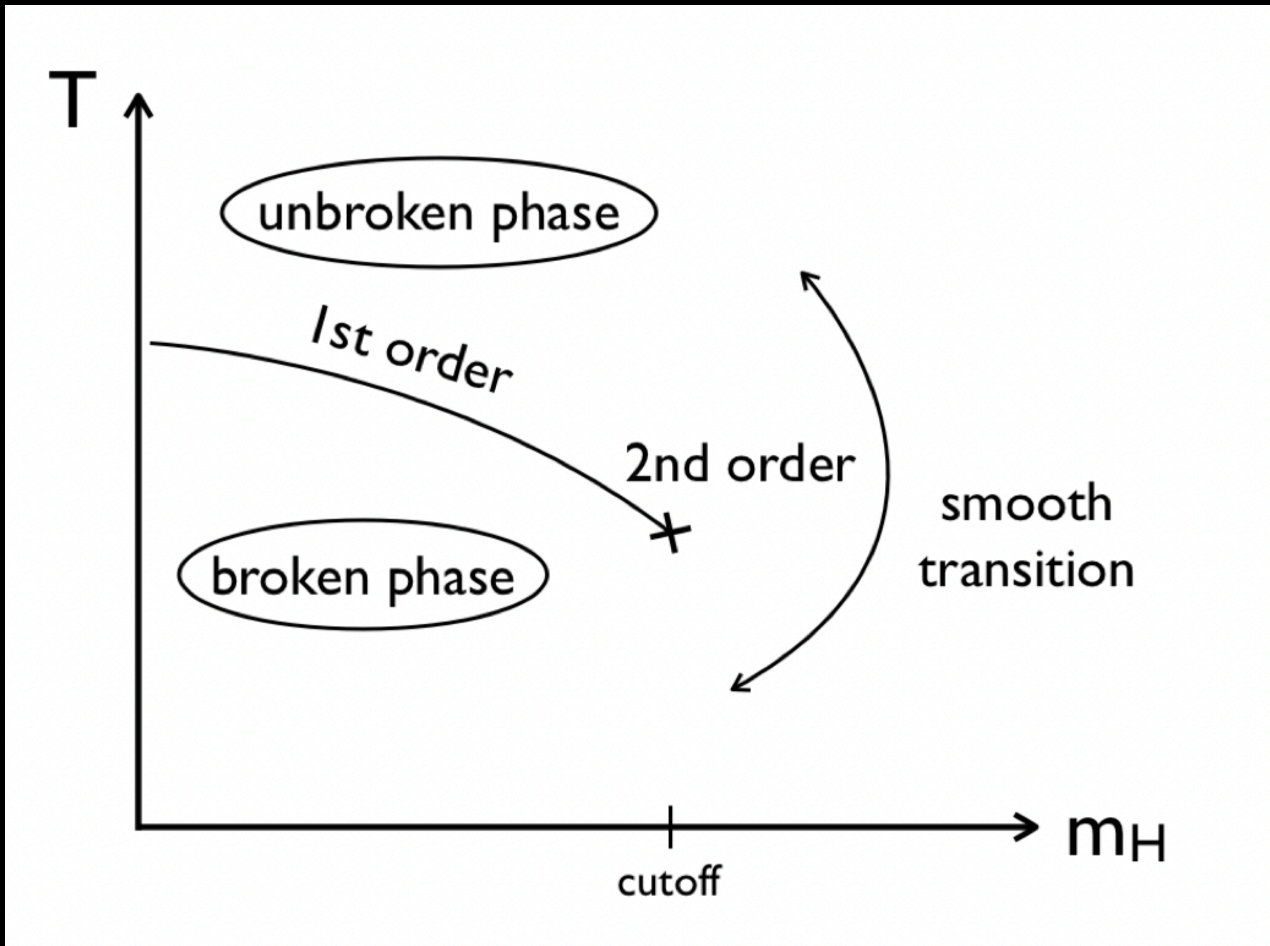




T ≅160 GeV

This is known as the
Electroweak phase transition

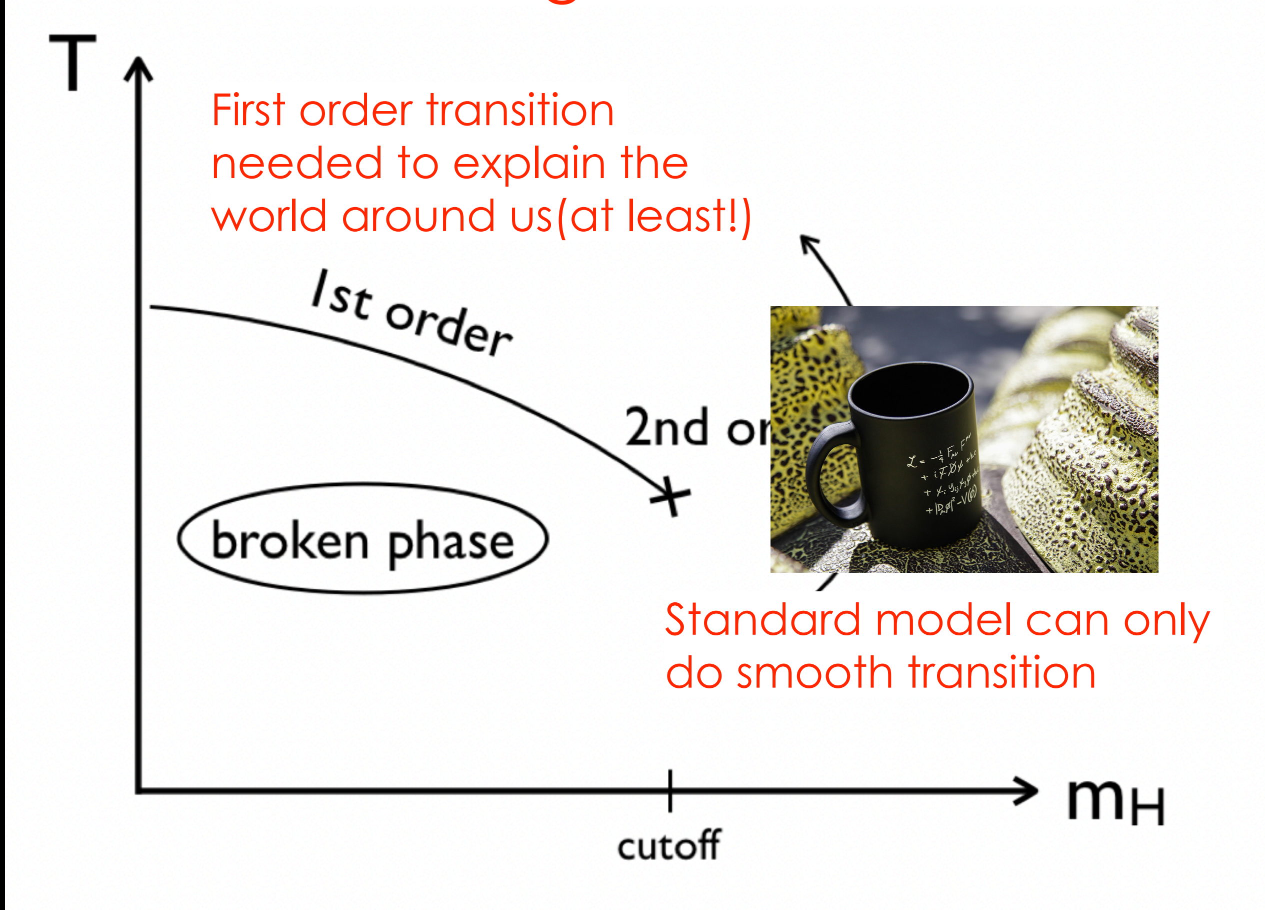
ELECTROWEAK PHASE TRANSITION



Papaefstathiou, A., White, G. The electro-weak phase transition at colliders: confronting theoretical uncertainties and complementary channels. *J. High Energ. Phys.* **2021**, 99 (2021), arXiv:2010.00597

ELECTROWEAK PHASE TRANSITION

The SM + Higgs mechanism alone is inconsistent with our knowledge of the universe!



Papaefstathiou, A., White, G. The electro-weak phase transition at colliders: confronting theoretical uncertainties and complementary channels. *J. High Energ. Phys.* **2021**, 99 (2021), arXiv:2010.00597

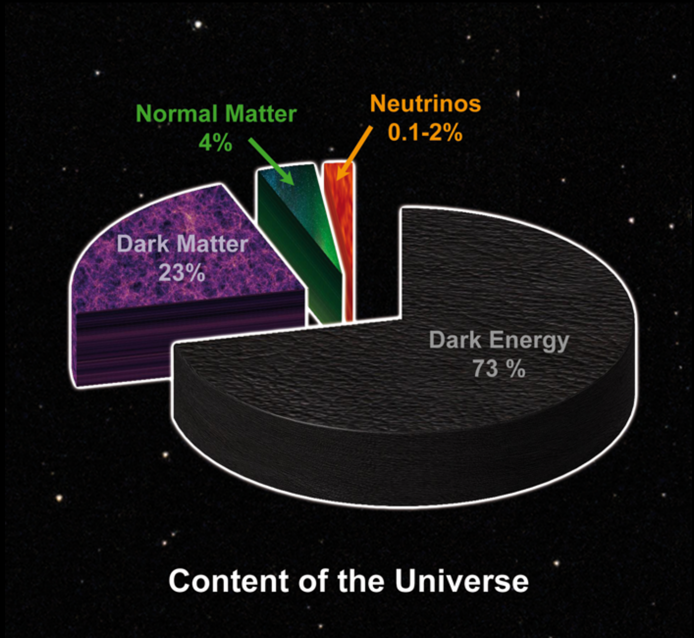
freyablekman

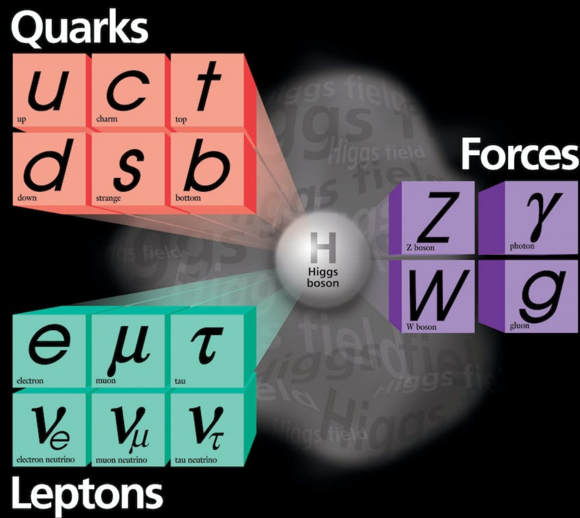
HIGGS - BIG QUESTIONS UNSOLVED

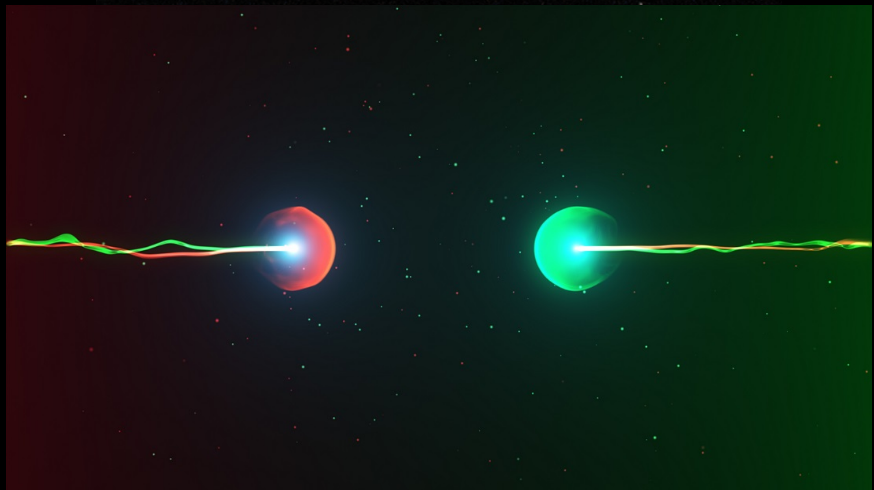
Particle whose mass is set by the interaction with the Higgs field	Role of the particle masses	Impact on everyday life	Has the Higgs-particle interaction been experimentally confirmed?
Up quark ($m_{up} \approx 2.2$ MeV c^{-2}) Down quark ($m_{down} \approx 4.7$ MeV c^{-2})	Affects the mass of the proton and neutron	Differences in quark masses ($m_{up} < m_{down}$) contribute to protons (made of two up and one down quarks) being lighter than neutrons (made of one up and two down quarks). As a result, protons are stable, as required for the existence of hydrogen.	No
Electron	Atomic radius $\propto 1/m_e$	A different value of the electron mass would modify the energy levels and chemical reactions of all known elements.	No
W boson	Radioactive beta decay rate $\propto 1/m_W{}^4$	Many radioactive decays, and the fusion reactions that power the Sun, involve the *W* boson. The *W* mass affects the rate of all of these reactions.	Yes

Salam, G.P., Wang, LT. & Zanderighi, G., The Higgs boson turns ten. *Nature* **607**, 41–47 (2022), arXiv:2207.00478

GREAT! BUT…?!?

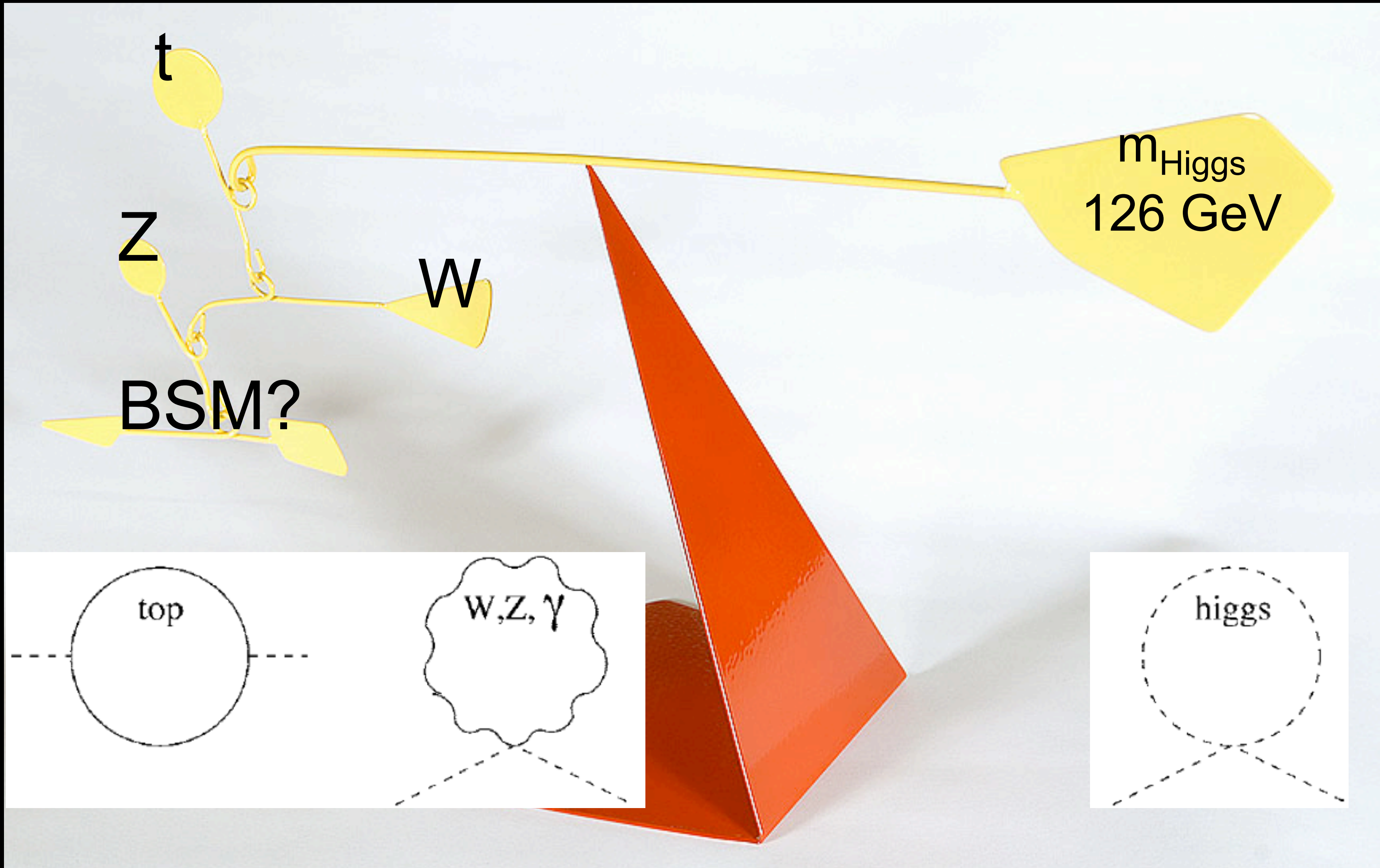

Normal Matter
4%
Neutrinos
0.1-2%
Dark Matter
23%
Dark Energy
73 %
Content of the Universe

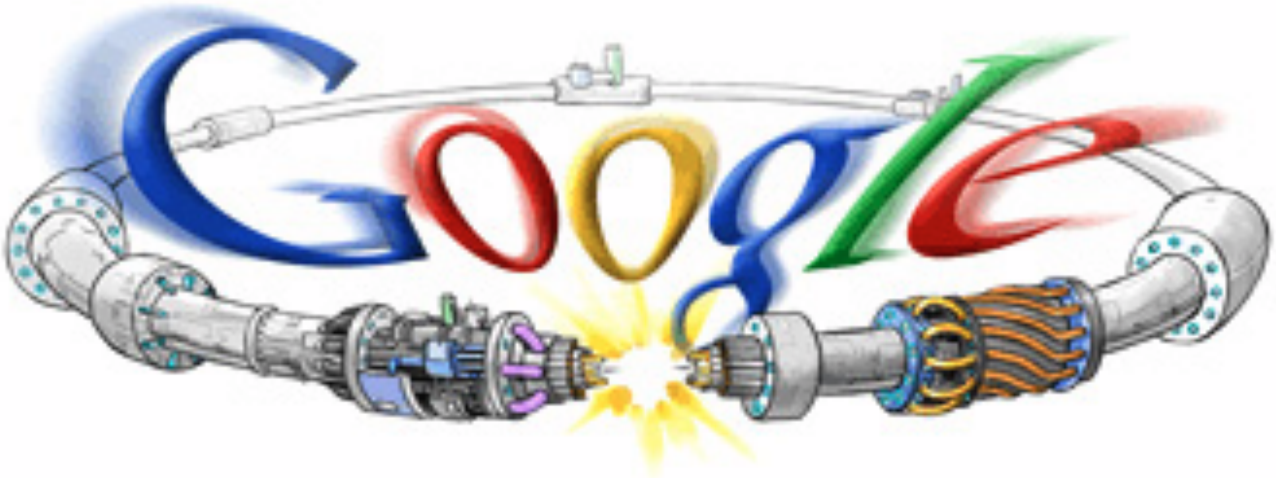

Quarks
u
c
t
d
s
b
Forces
Z
γ
W
g
H
Higgs boson
e
μ
τ
ν_e
ν_μ
ν_τ
Leptons




τ
ν μ
e

THE NEED FOR LOOPS





“Physics at smaller $\Delta x \gtrsim h / \Delta p$”

Google Search | I'm Feeling Lucky

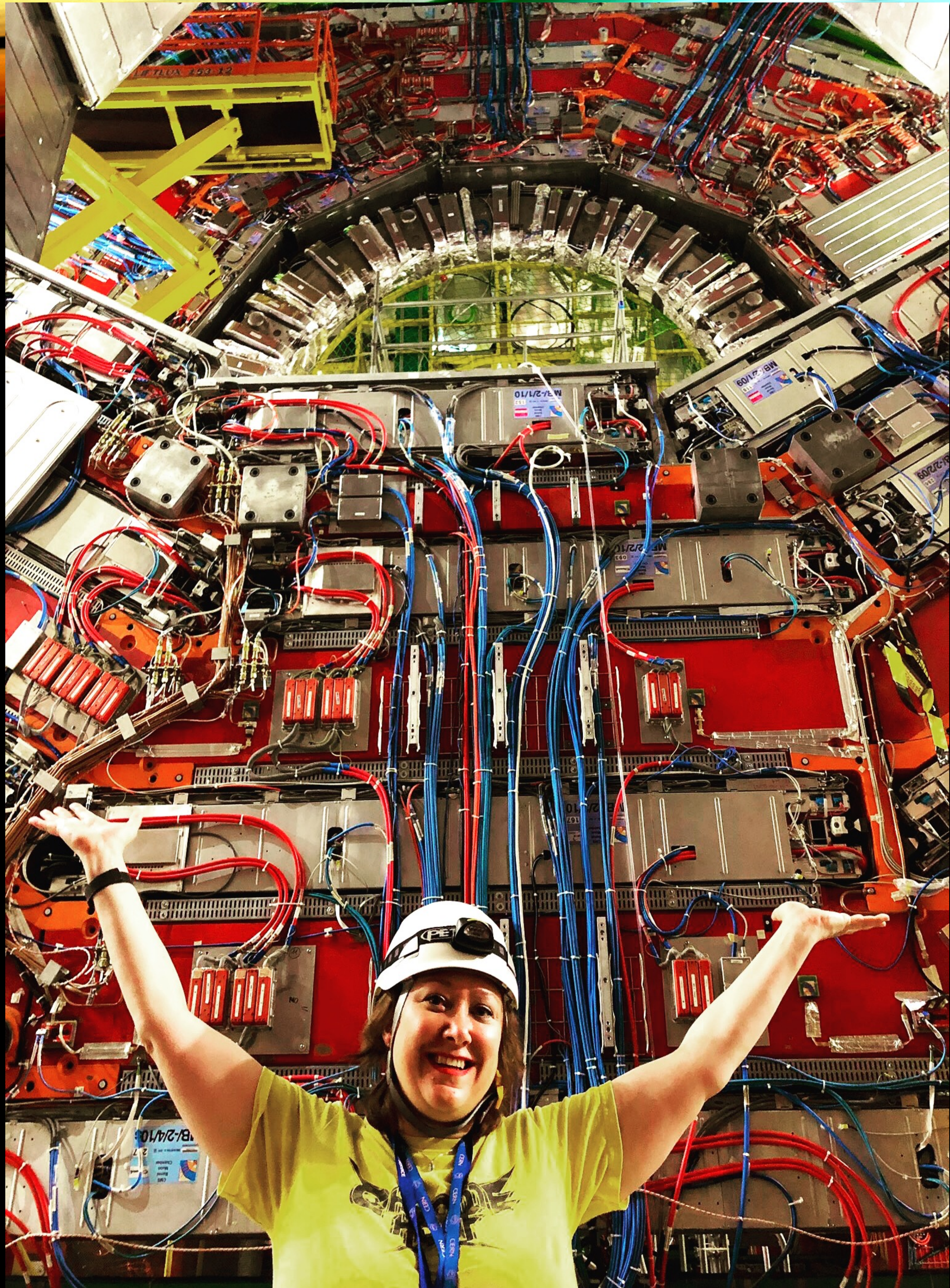
Advanced Search
Preferences
Language Tools

Make your homepage beautiful with art by leading designers

Advertising Programs - Business Solutions - About Google

THE LARGE HADRON COLLIDER

Can only get us so far!




Alles Gute zum
30
GEBURTSTAG!

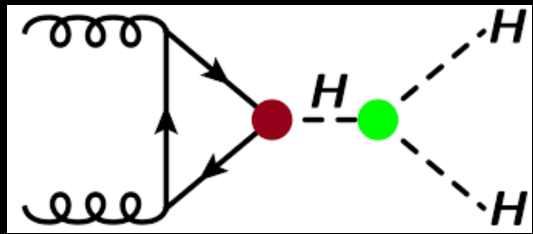
ELECTROWEAK PHASE TRANSITION IS EVERYTHING

The Higgs boson is the key!

Measuring its couplings and properties better than a few percent accuracies is essential

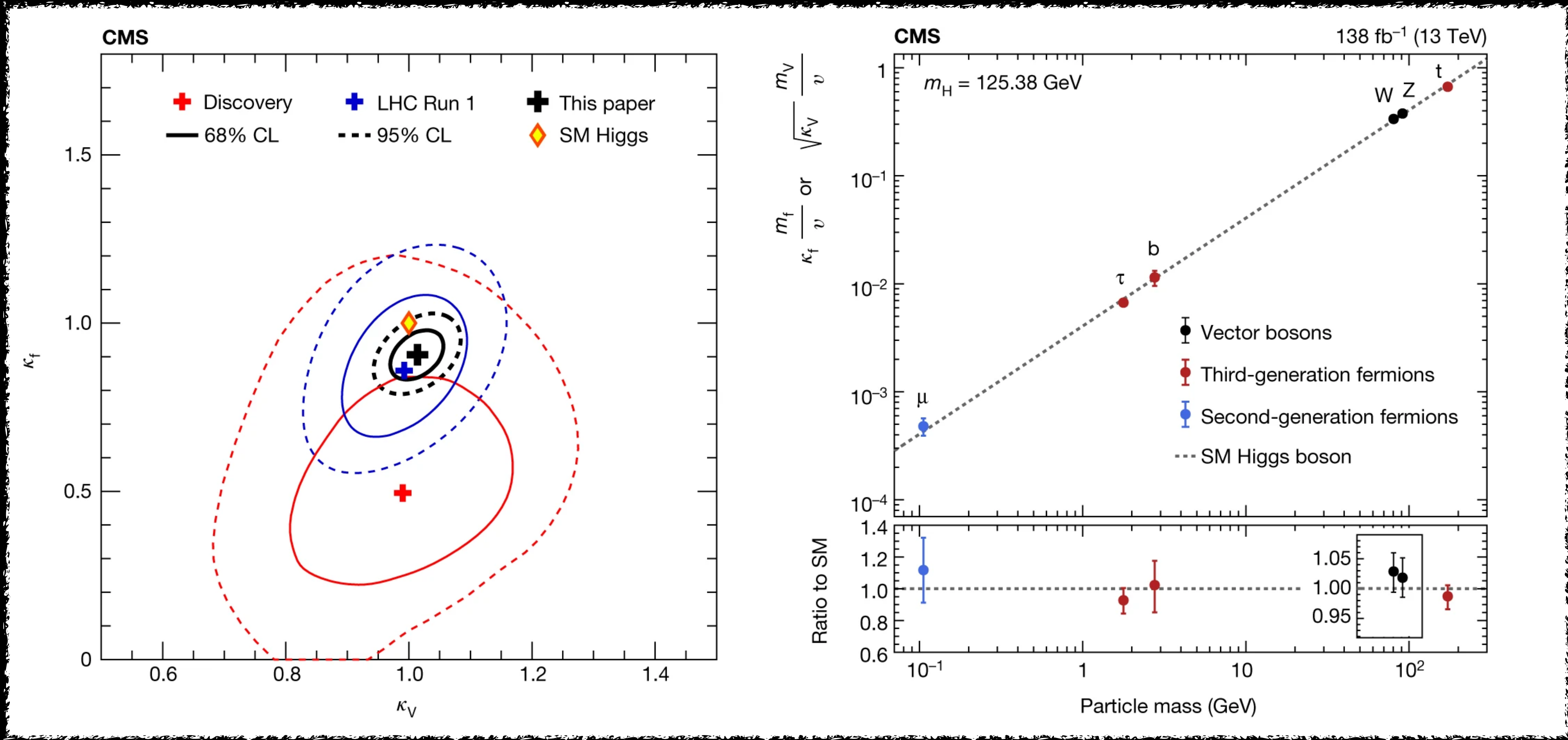
There is consensus that a Higgs factory is the highest priority

the question is how exactly?



Bass, S.D., De Roeck, A. & Kado, M. The Higgs boson implications and prospects for future discoveries. *Nat Rev Phys* **3**, 608–624 (2021).

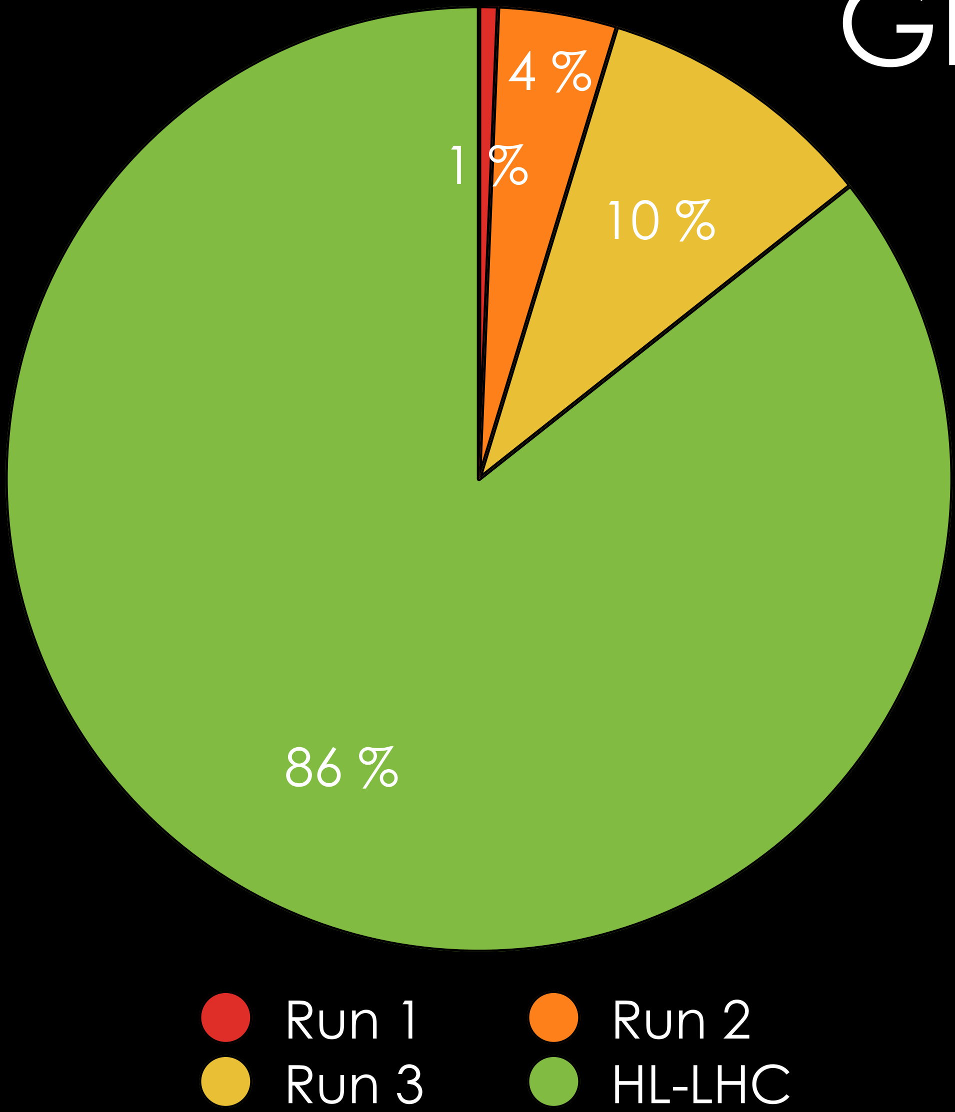
HIGGS AT THE LHC



The CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. *Nature* **607**, 60–68 (2022). arXiv:2207.00043

freyablekman

WE ARE JUST GETTING STARTED



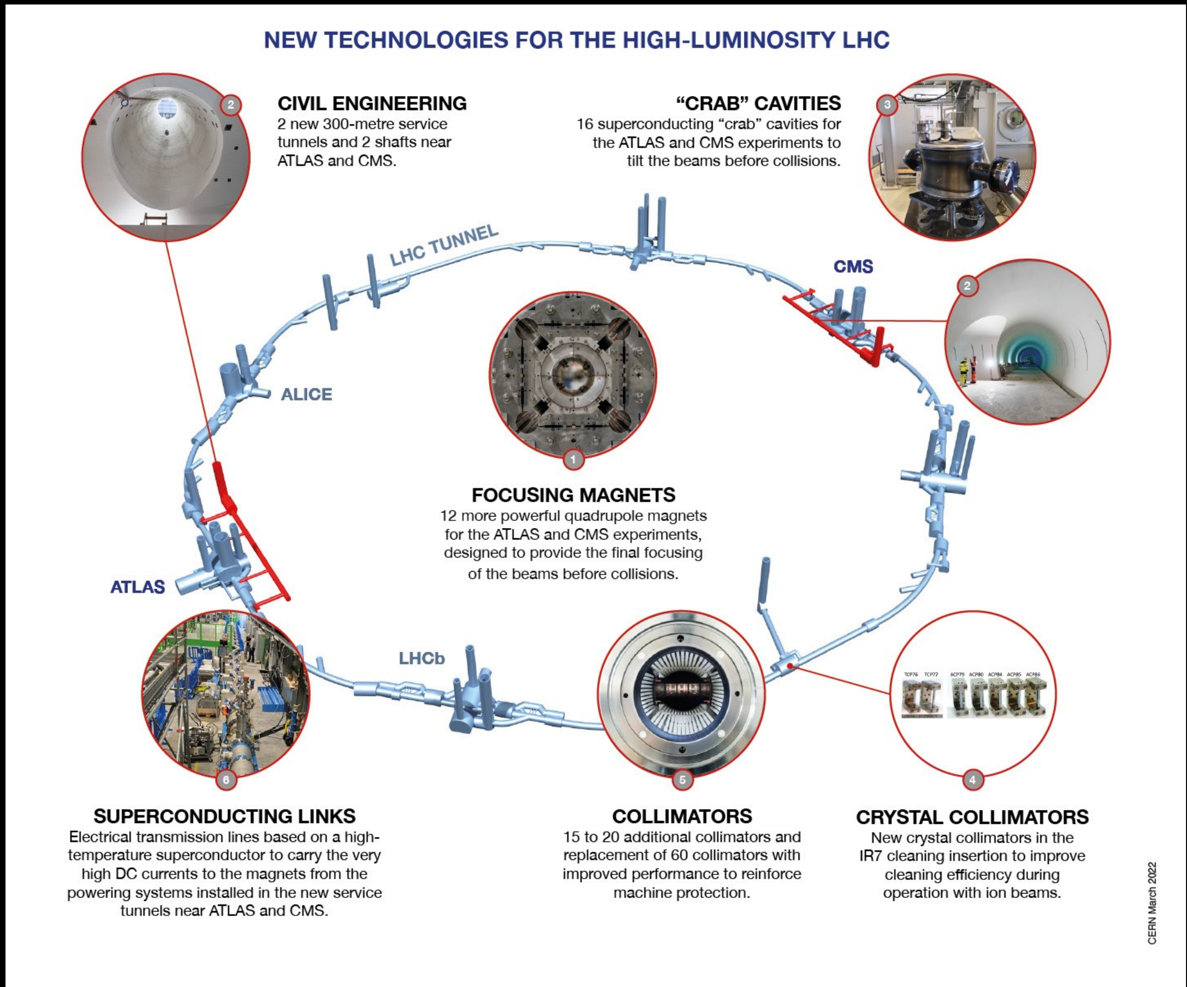
Regularly forgotten:

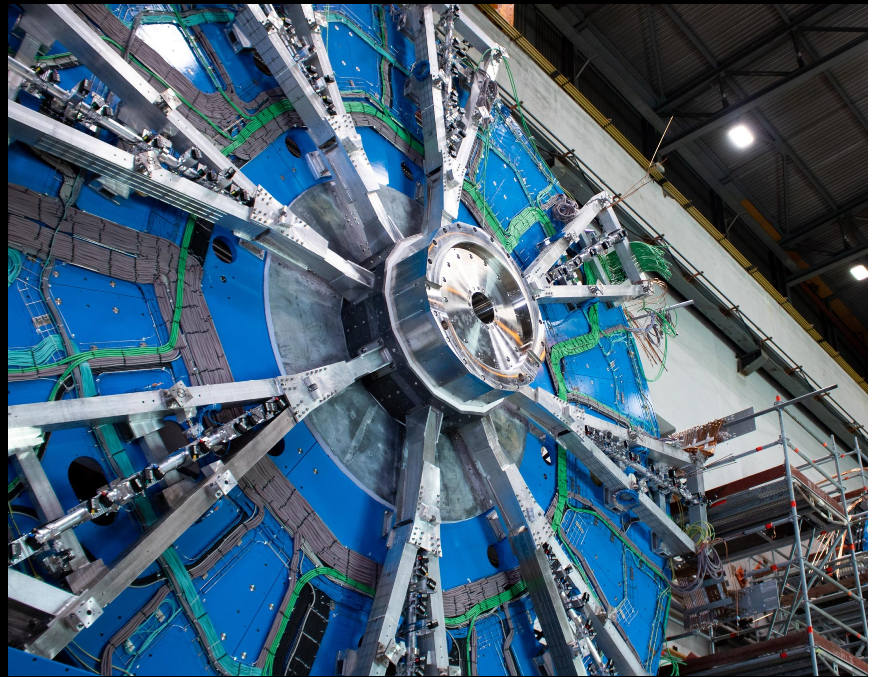
We have examined not even 5% of the LHC data

There can still be surprises

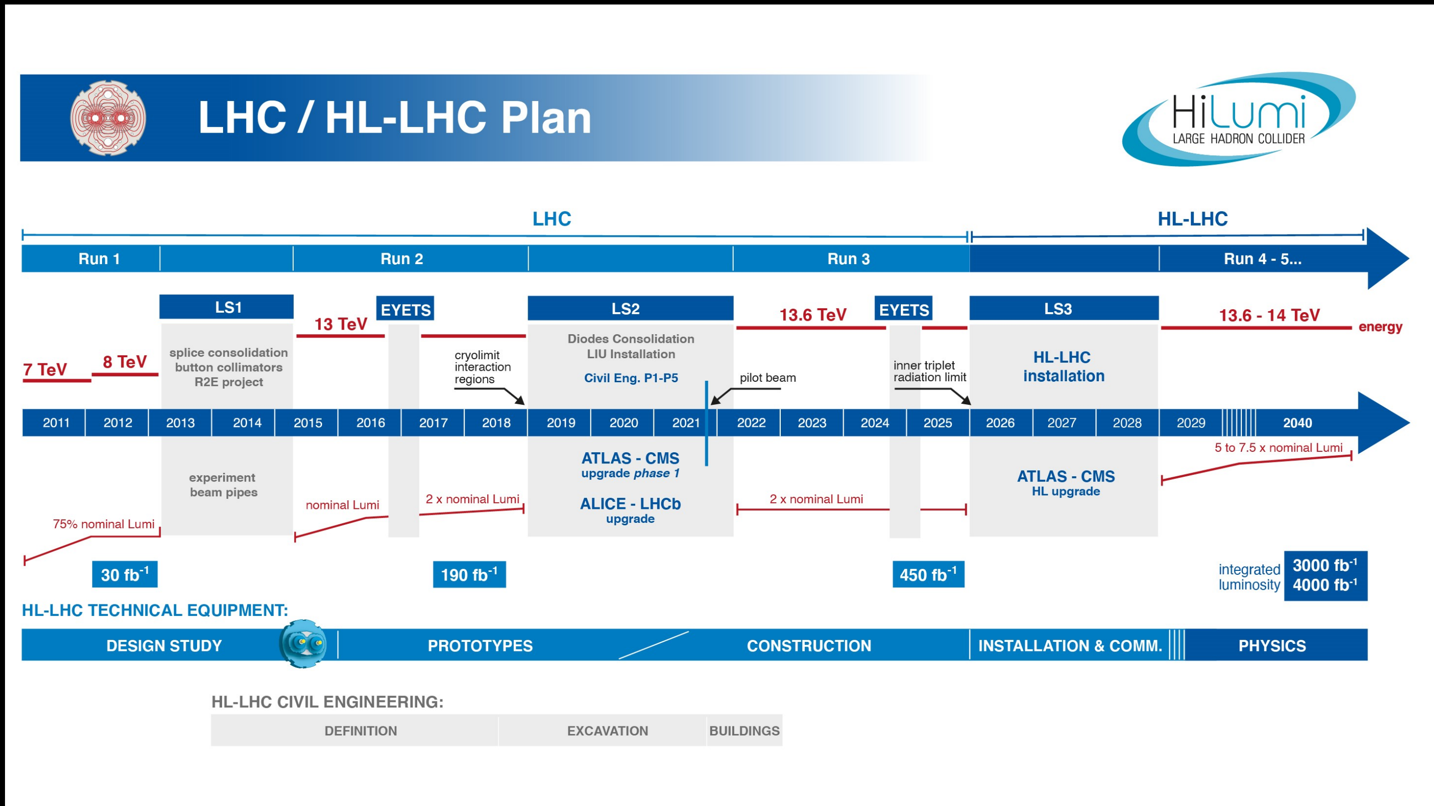
And any future collider should be able to study surprises too

HIGH LUMINOSITY LHC
ESSENTIALLY ALREADY A FUTURE COLLIDER





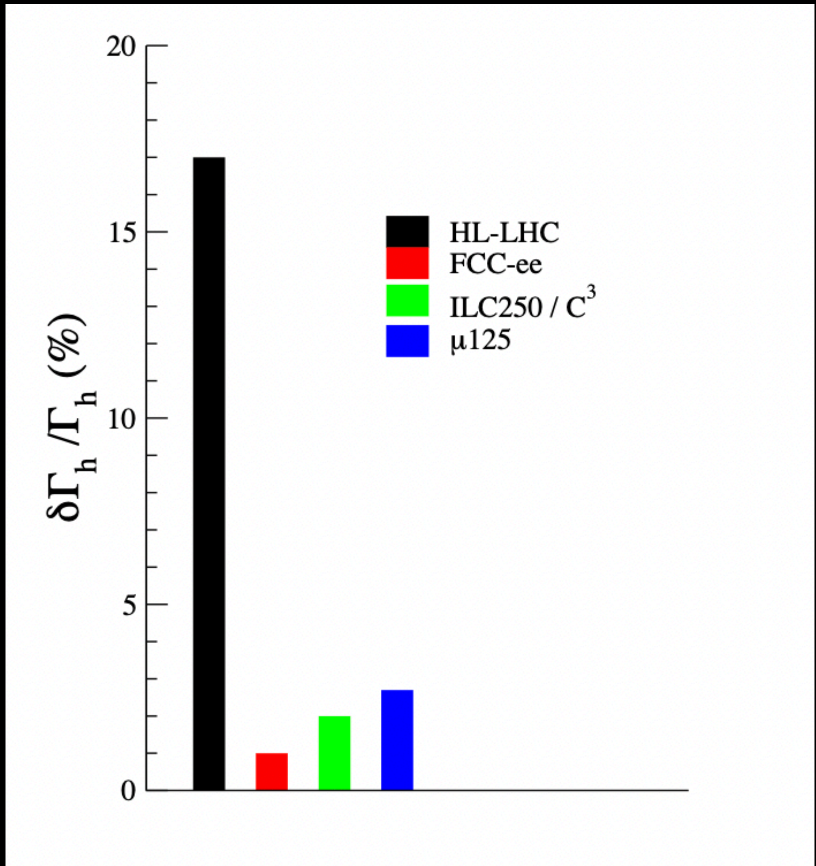
HIGH LUMINOSITY LHC
ESSENTIALLY ALREADY A FUTURE COLLIDER



Quote from HL-LHC teams:

> ''we are a research lab, we must have a plan but we can change it ''

HIGGS AND THE STANDARD MODEL AFTER HL-LHC



HL-LHC gives 10-few% precision on SM properties of the Higgs boson

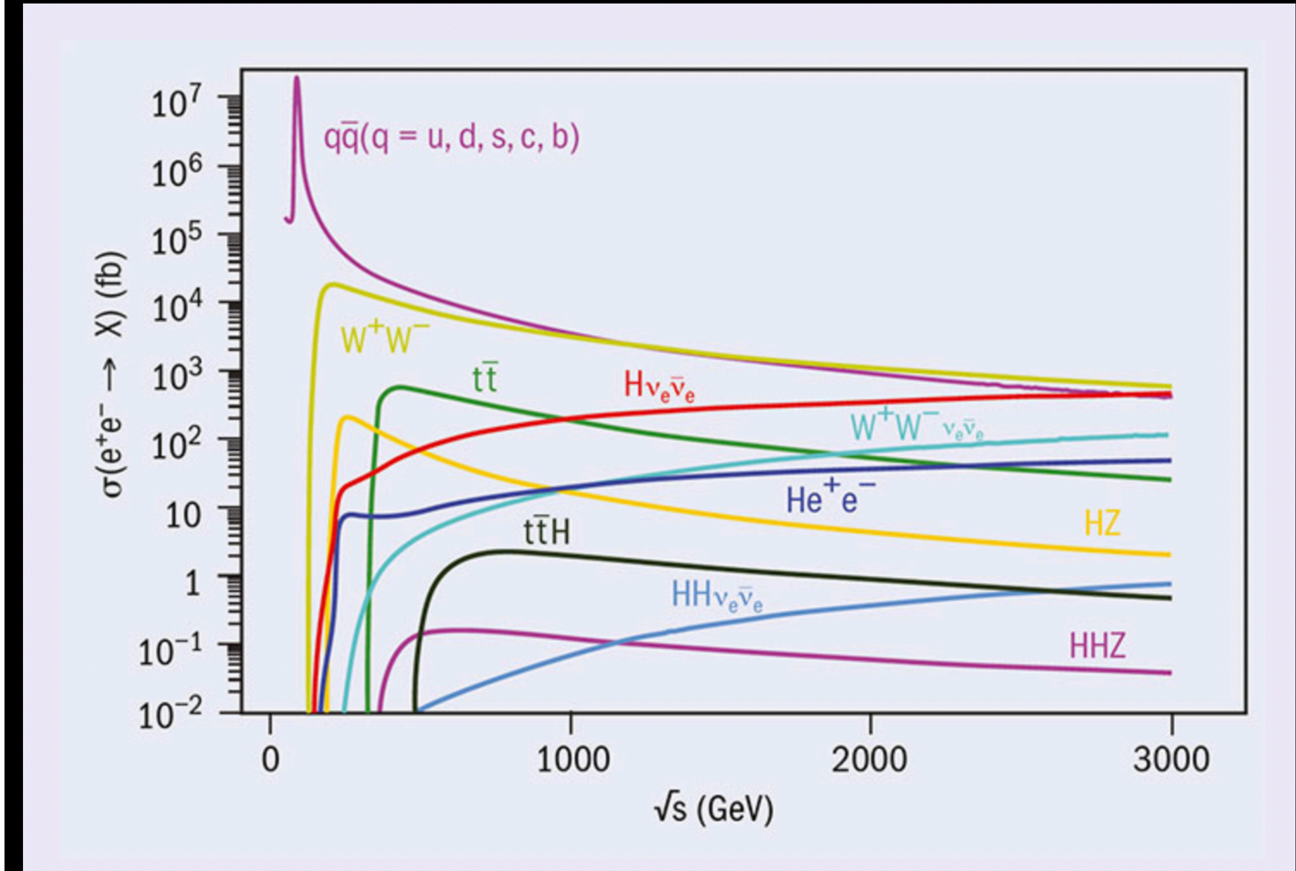
Example: Higgs full decay width (and decay to invisible particles, both essential for investigating link to DM)

BTW: same is true for many other SM parameters via SMEFT

S. Dawson et al, Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics, arXiv:2209.07510

freyablekman

COLLISION ENERGY DETERMINES WHAT WE CAN STUDY



Higgs factory =

Very high statistics e+e- machine with Z+H at maximum (240-250 GeV)

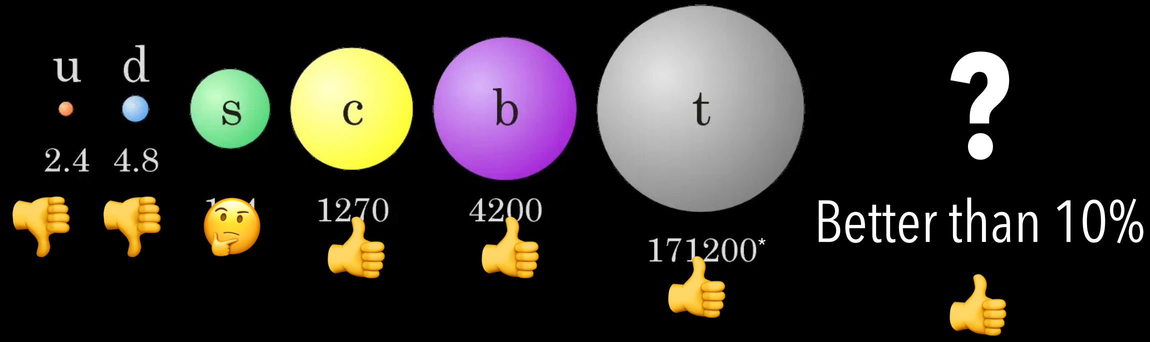
Run at lower energies like Z pole and WW threshold possible with circular accelerators

Runs at higher energies (ttbar, higher) most challenging for the accelerator aspect

CERN courier, https://cerncourier.com/a/clic-steps-up-to-the-tev-challenge/

freyablekman

WISHLIST OF TOPICS
TO DETERMINE FEASIBILITY AND NEEDS



Measuring Higgs boson couplings to quarks and gauge bosons at least one order of magnitude more precisely (needs also theory improvement btw!)

More details: J. List, Open study questions, 1st ECFA workshop on e+e- Higgs/EW/Top factories, https://indico.desy.de/event/33640/

*) Masses not to scale. But they do increase

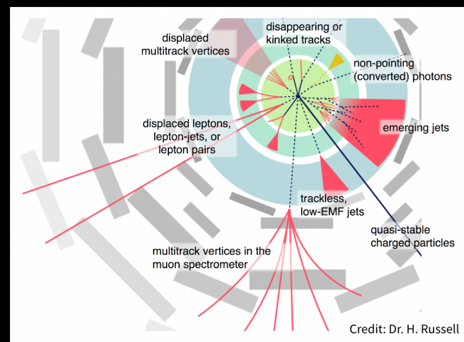
WISHLIST OF TOPICS
TO DETERMINE FEASIBILITY AND NEEDS

Measure decay of Z boson to b, c s, tau are all relatively poorly measured and give access to higher order (loop) effects up to very high scales. And strong coupling constant!
(needs also theory improvement btw!)

W boson mass and other properties much more precisely(and not just because of CDF recent result) important for internal consistency SM tests

Top quark mass should be precisely measured (20-50 MeV)

Bonus: search for undiscovered particles. Benchmark: long-lived particles as great for detector design aspirations



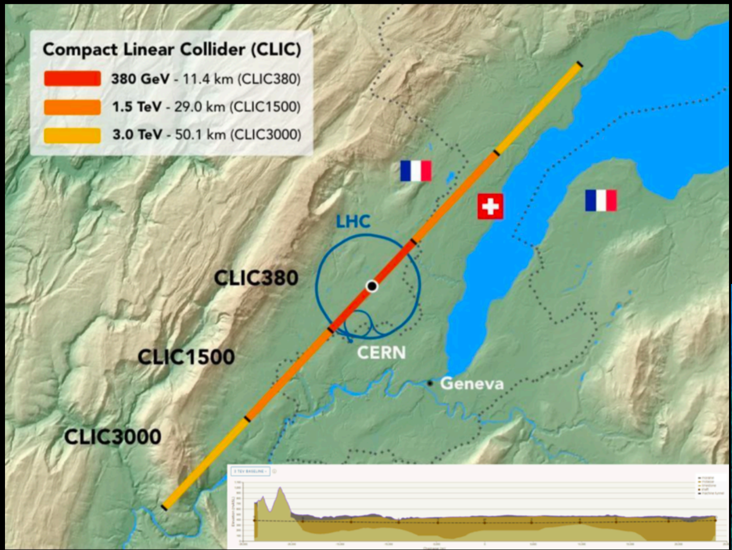
More details: J. List, Open study questions, 1st ECFA workshop on e+e- Higgs/EW/Top factories, https://indico.desy.de/event/33640/

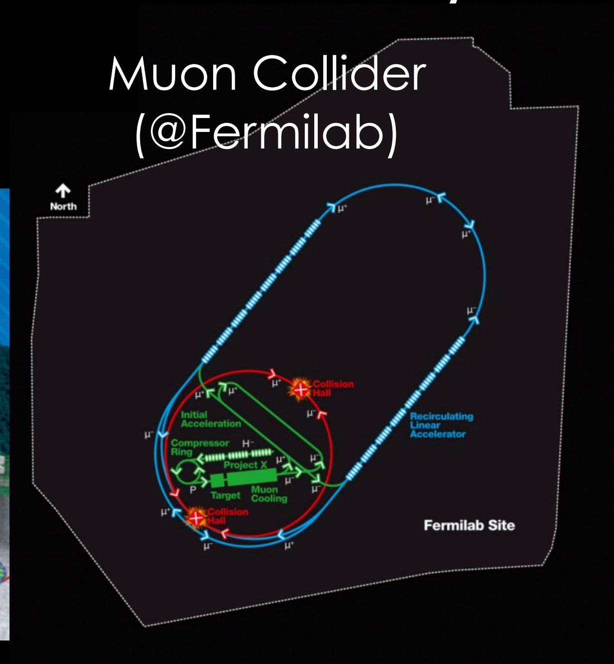
freyablekman

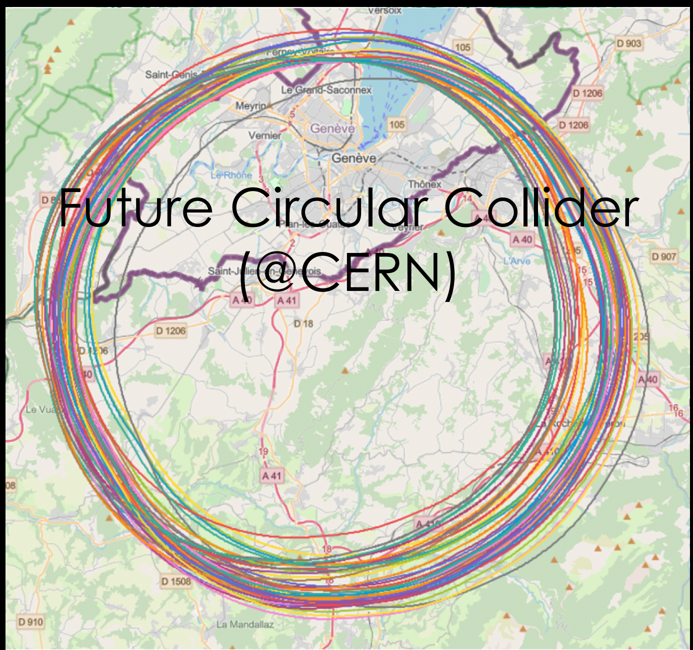
EXAMPLES

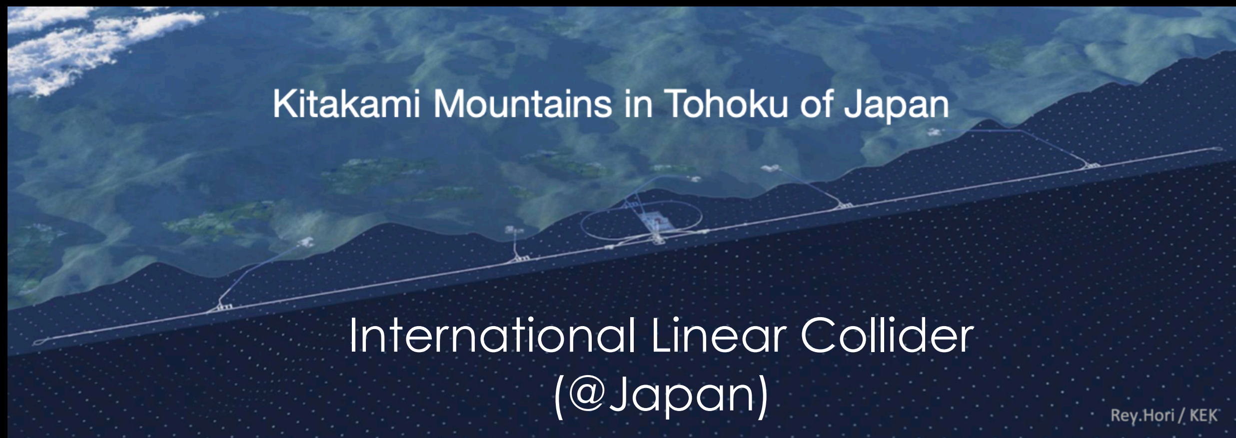
NOT TO SCALE (OF INTEREST)

Compact Linear Collider
(@CERN)





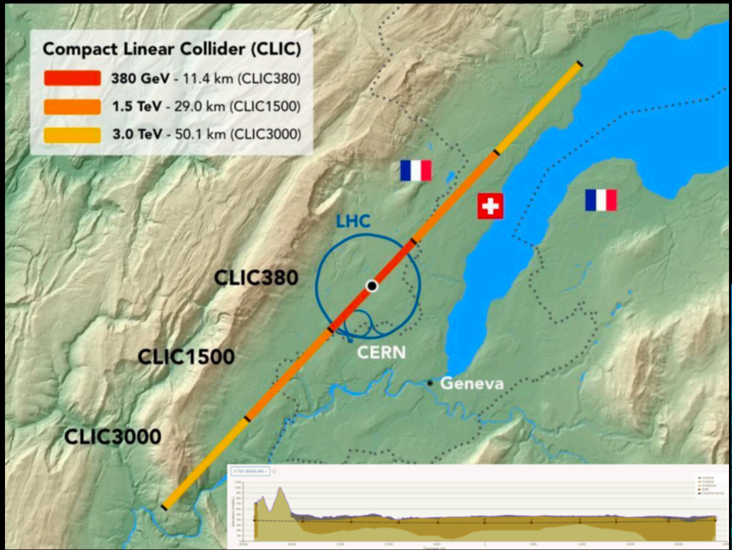


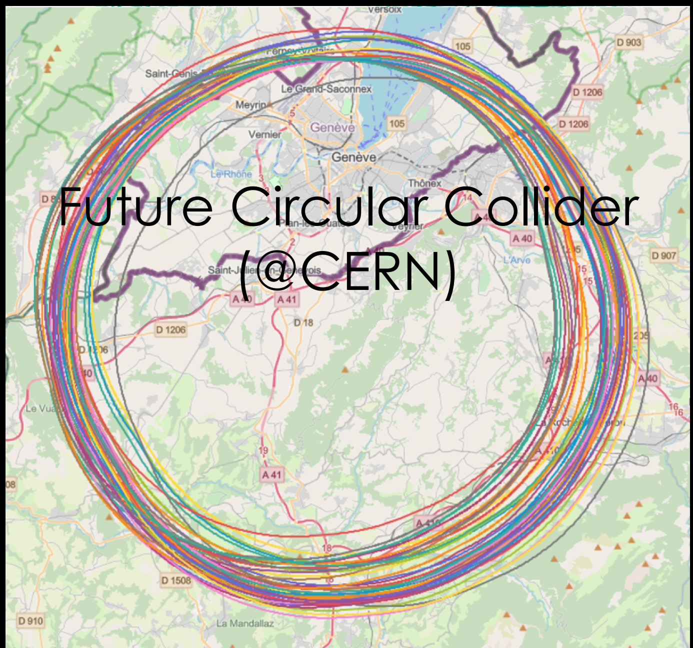


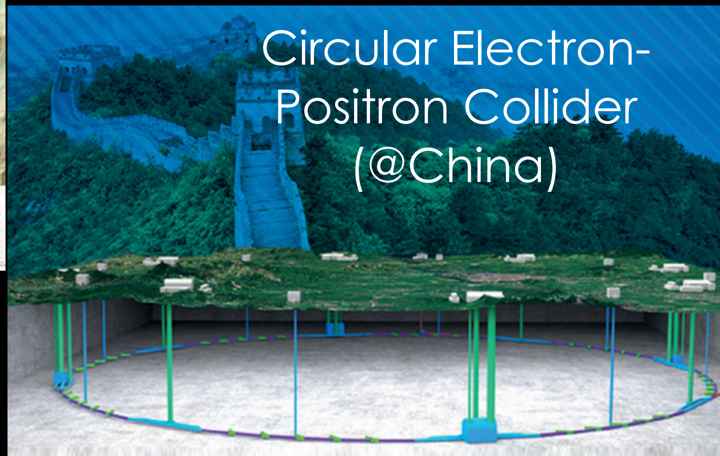
freyablekman

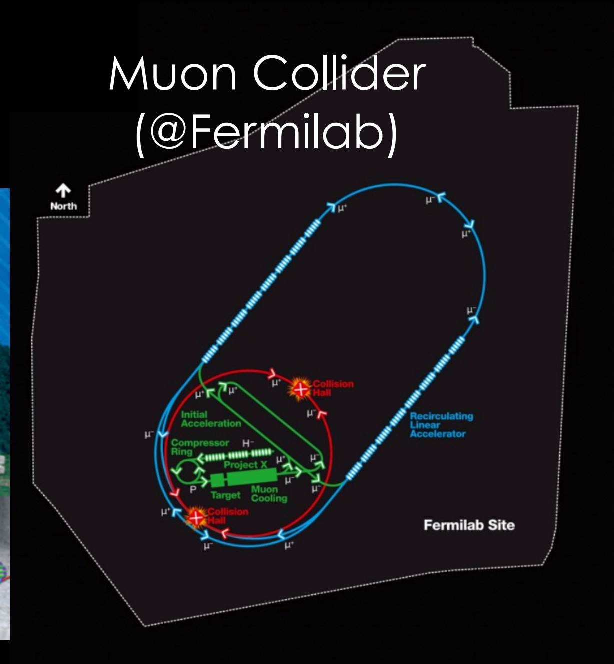
CAN I USE IT AGAIN?

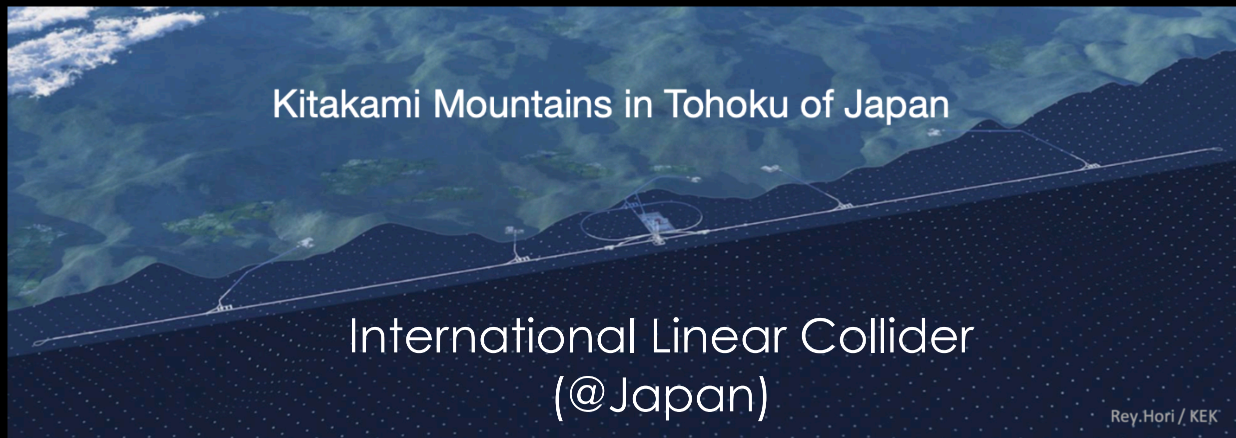
Compact Linear Collider (@CERN)



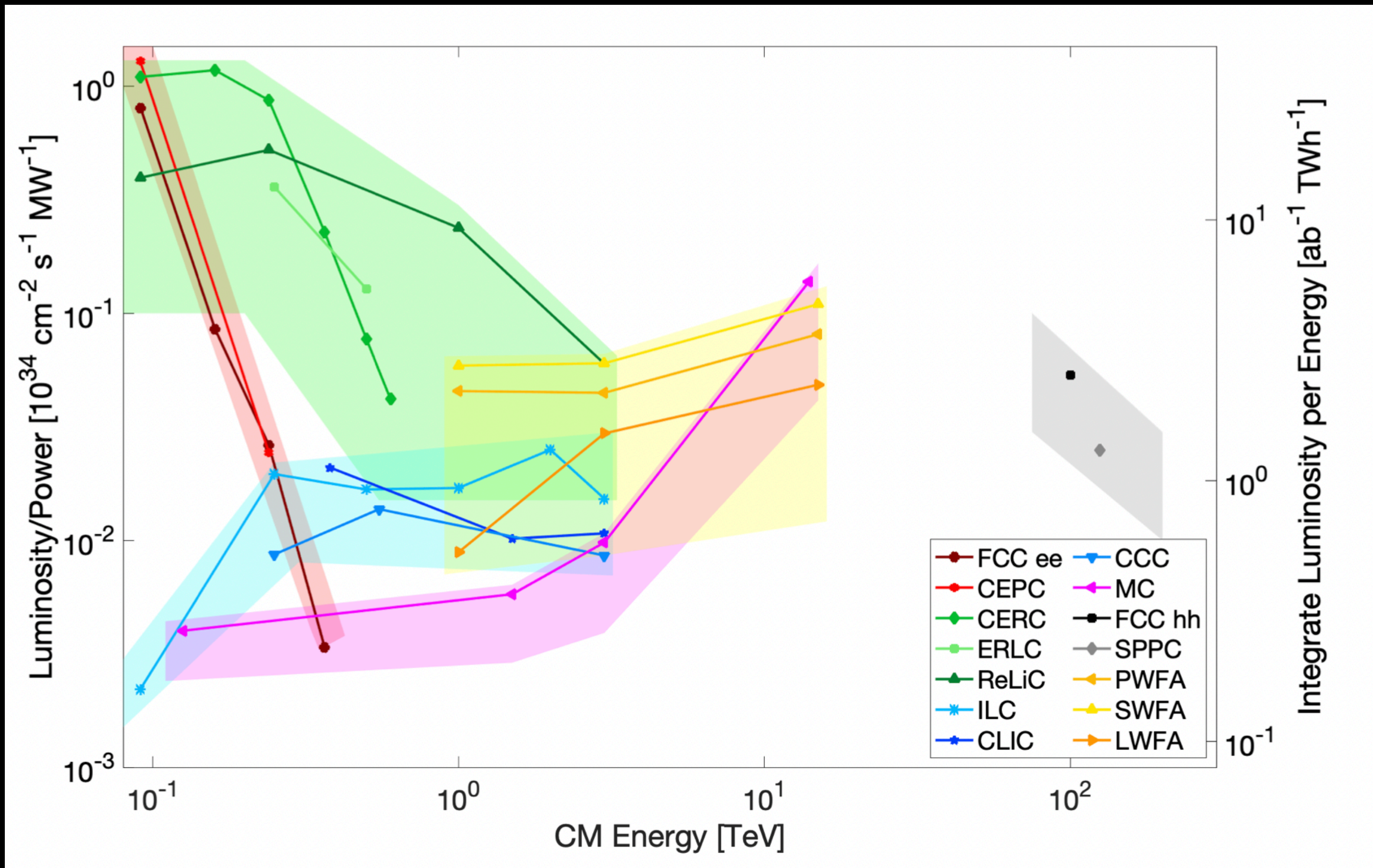








POWER USE AND ENVIRONMENTAL IMPACT ARE PART OF THE DECISION MAKING



Circular, e+e-

Energy recovering colliders e+e-

Muon Collider

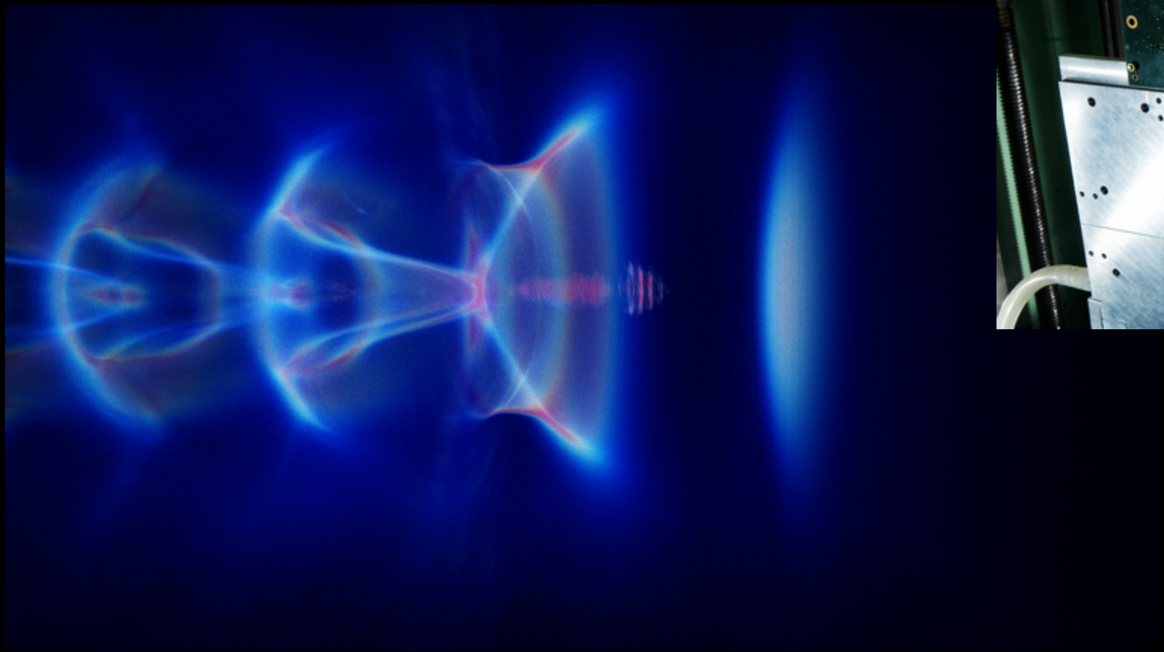
Linear Colliders

Wakefield accelerators

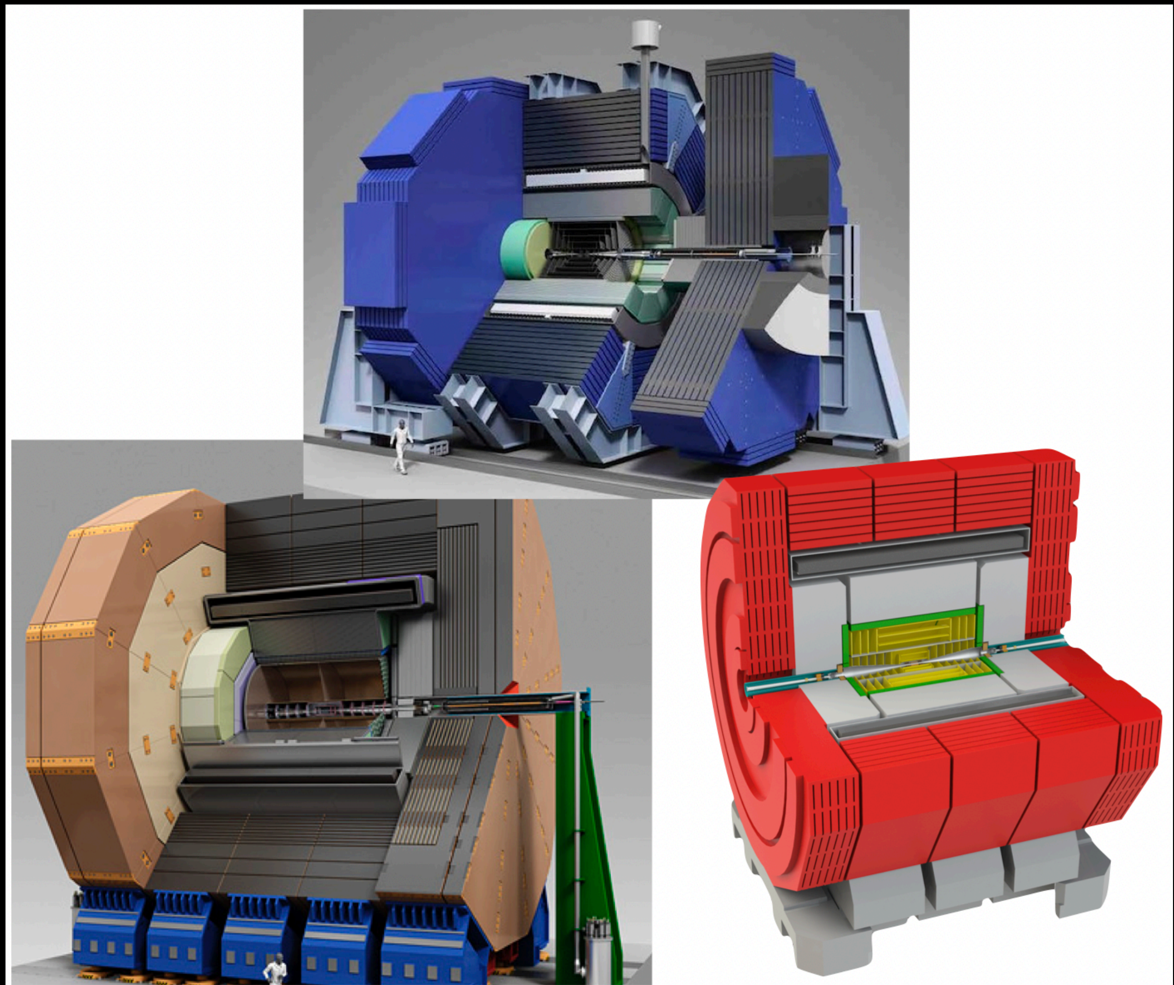
T. Roser et al, Report of the Snowmass 2021 Collider Implementation Task Force, arXiv:2208.06030

freyablekman

INNOVATION ON ACCELERATOR SIDE

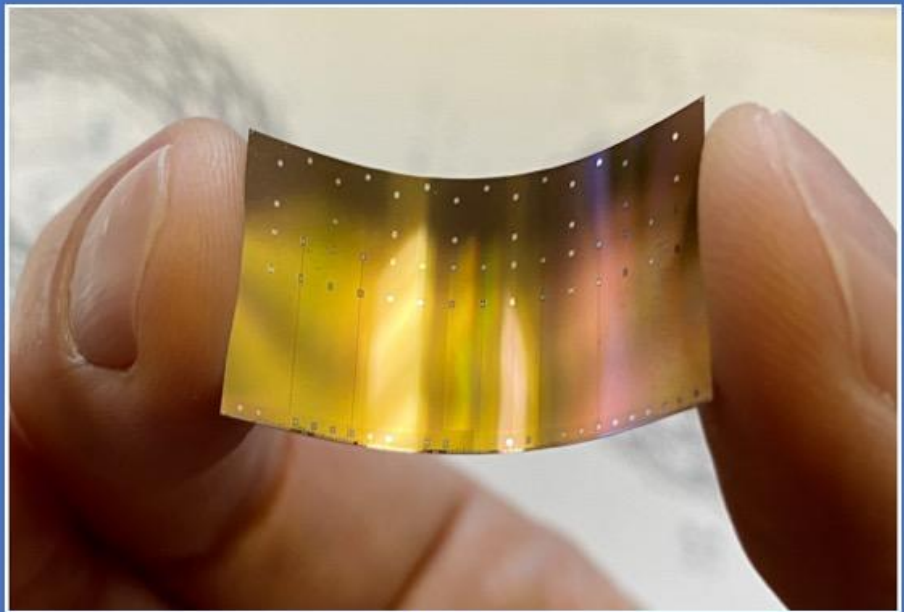


CAN WE STUDY SUCH COLLISIONS IN ENOUGH DETAIL?

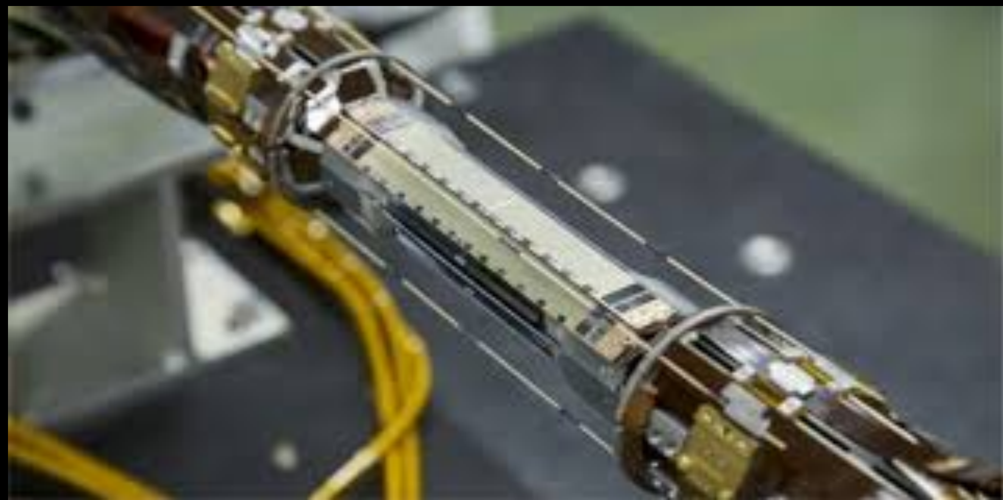


Different complimentary detectors to study collisions at same collider is well-established strategy in collider physics

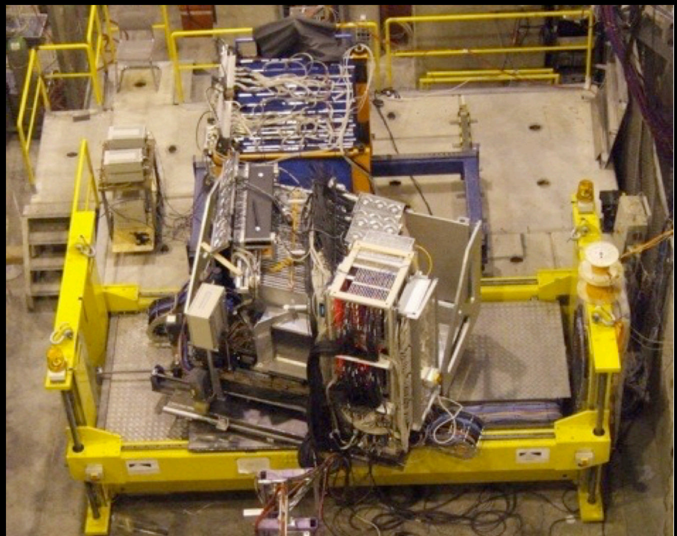
TRACKING DETECTORS
MORE LIKE BELLE II OR ALICE THAN ATLAS/CMS

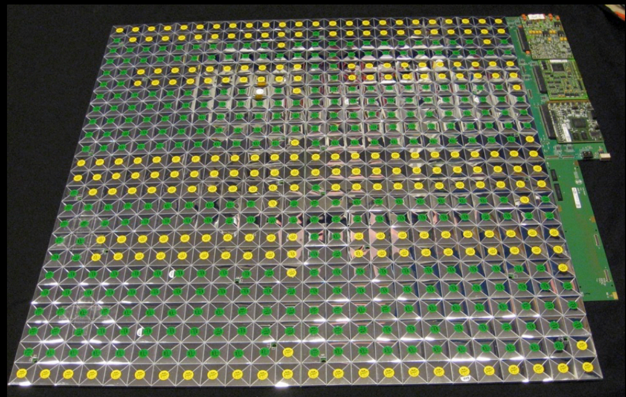


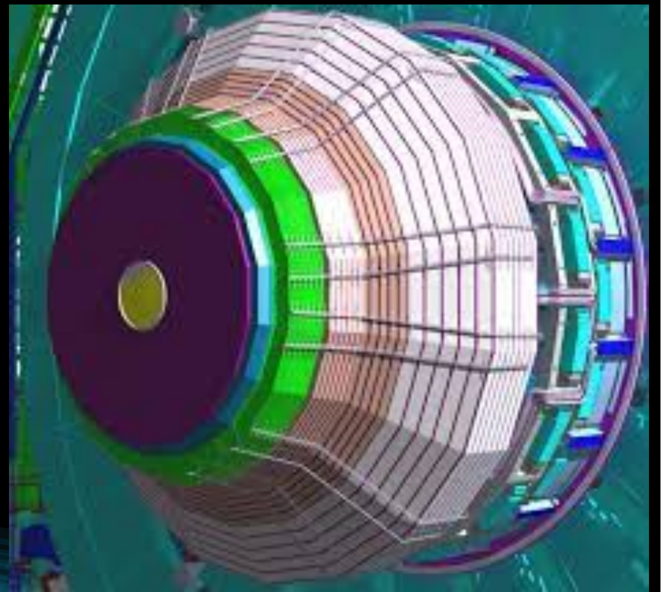
ITS3

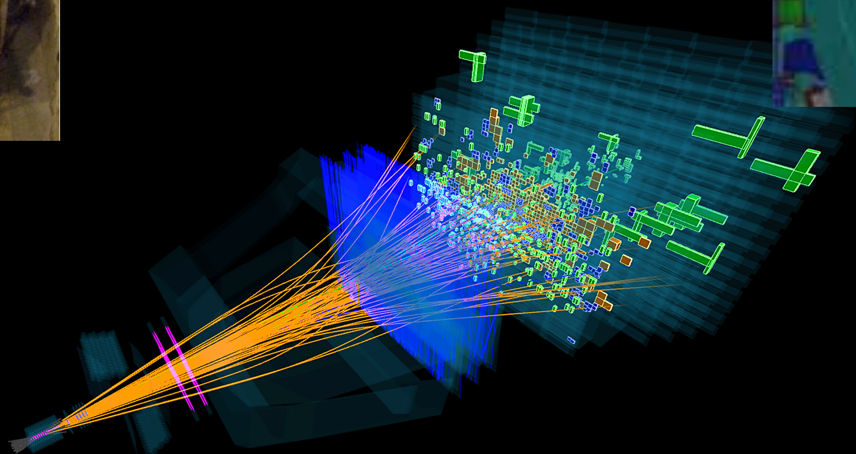


OTHER DETECTORS - CALORIMETRY INNOVATION









DECISIONS

Highly multidimensional choices

Community has indicated clear need for a Higgs factory

But what factory - and part of a bigger plan

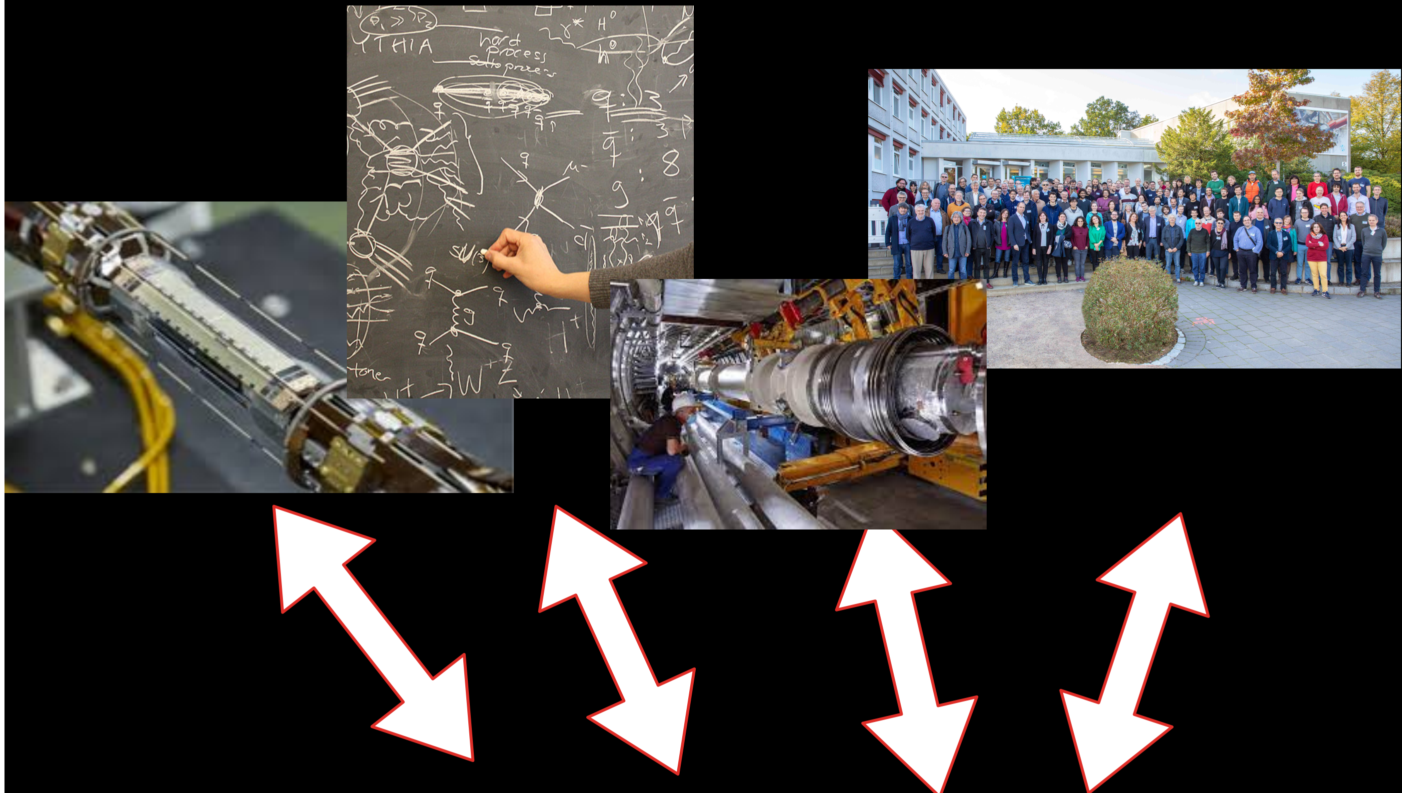
Timelines are long. Potential costs are high.

SO HOW FURTHER?

EUROPE: ECFA, part of a structured roadmap process to study what is possible in Europe and create consensus

USA equivalent: Snowmass + P5

HOW DOES THAT WORK?



HOW DOES THAT WORK?

JENAA

Joint ECFA-NuPECC-APPEC Activities

THE HIGGS BOSON IS THE KEY

Measuring the Higgs boson couplings and properties better than a few percent accuracies is essential to understand why our universe is the way it is

There is consensus that a Higgs factory is the highest priority

The question is *how exactly*?

And if we build to upgrade or just a Higgs factory

freyablekman

HISTORY

Royal visit to CERN

The Duke of Edinburgh paid an informal visit to CERN on April 28th.

Flying his own "Heron" from Malta to Britain, he had landed at Geneva airport the evening before.

The Royal party arrived at CERN at 10 o'clock in the morning of April 28th. With the Duke were Rear-Admiral C. D. Bonham-Carter, H. E. Sir William Montagu-Pollock, British Ambassador to Switzerland, Mr. D. Balfour, H. M. Consul-General in Geneva and Mr. H. L. Verry, United Kingdom delegate to the CERN Council.

After being greeted at the entrance to the Administration Building by Mr. F. de Rose, President of the Council of CERN, Mr. Adams and Mr. Dakin, Sir John Cockcroft and Sir Harry Melville, U. K. delegates to the Council of CERN and Prof. P. Scherrer, representing the Swiss Confederation, the Duke went to the CERN Council Chamber.

Mr. de Rose gave there a short introductory talk: "The reason for creating CERN was that in our various countries it was realized after the war that the tools for the people who try to understand matter, were

The Duke of Edinburgh

The Duke of Edinburgh was born on June 10th, 1921.

He served in the Royal Navy throughout the war, in the Home Fleet, in the Mediterranean and the Far East.

The Duke of Edinburgh has shown particular interest in scientific and industrial developments. In 1951, he was appointed President of the British Association for the Advancement of Science. Since that time he has paid numerous visits to scientific and industrial establishments of all kinds, both in the United Kingdom and the Commonwealth.

In 1959 he represented the British Association for the Advancement of Science at scientific meetings in India and Pakistan.

June 1960

Prince Philip turned to his host, president of Council François de Rose, and asked:
"What have you got in mind for the future? Having built this machine, what next?"

De Rose replied:
"Well, that's a big problem. We have a group who are investigating new principles of acceleration to see whether it is possible to go into higher energies than 25 GeV. But before we present a new project we will have to be absolutely sure that if is feasible and that it is justified. For the moment we are going to work with the present 25 GeV machine to see what results we can get, because no one has ever explored what happens when you bombard matter at such an energy. We do not really know whether we are going to discover anything new by going beyond 25 GeV."

Different era Another early issue likened the 120 million Swiss Franc cost of the PS to "10 cigarettes for each of the 220 million inhabitants of CERN's 12 Member States".

BACKUP

- Matter vs antimatter asymmetry
  - Standard Model cannot provide enough CP violation to explain dominance of matter
- The Standard model does not describe why different particles have different masses
  - Or nowadays rephrased: the Standard Model does not provide a description of the Higgs boson Yukawa couplings
- Dark Matter
  - if it exists, it is very likely not described by the Standard Model
  - Neither is dark energy!
- Standard Model neutrinos are massless
  - The 2015 Nobel Prize (Kajita and McDonald) was for neutrino oscillations, directly proving that neutrinos have mass
- Gravity is not included

Outstanding Questions in Particle Physics *circa* 2011

Quarks and leptons:
- why 3 families ?
- masses and mixing
- *CP* violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

EWSB
- Does the Higgs boson exist?

Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

Neutrinos:
- ν masses and and their origin
- what is the role of H(125) ?
- Majorana or Dirac ?
- *CP* violation
- additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

Outstanding Questions in Particle Physics *circa* 2022

... there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

These questions are compelling, difficult and intertwined → require multiple approaches high-E colliders, neutrino experiments (solar, short/long baseline, reactors $0\nu\beta\beta$ decays), cosmic surveys (CMB, optical/IR spectroscopic and photometric), dark matter direct, indirect and astrophysical detection, precision measurements of rare decays and phenomena, dedicated searches (WIMPS, axions, dark-sector particles), …

Main questions and main approaches to address them

	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos			x	x	x
Dark Matter	x			x	x
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

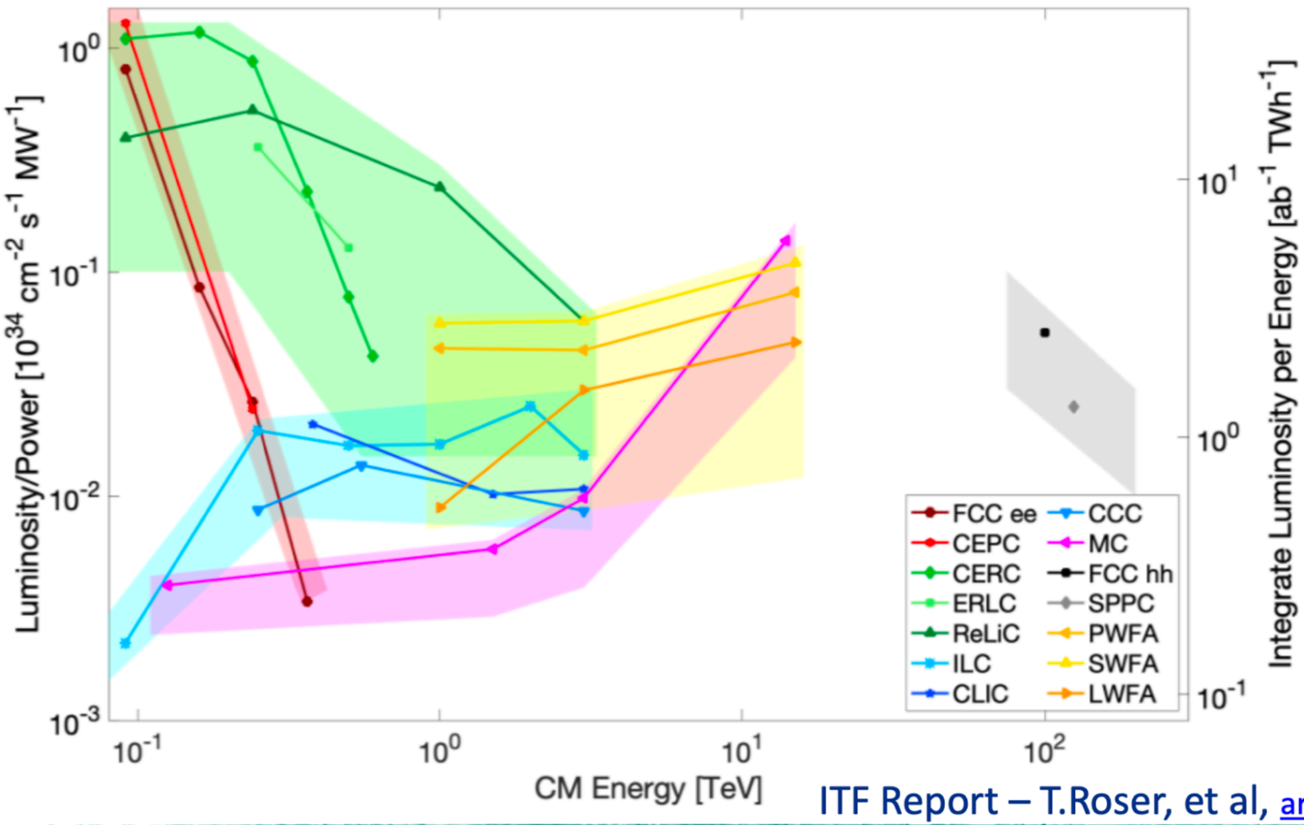
These complementary approaches are ALL needed: their combination is crucial to explore the largest range of E scales, properly interpret signs of new physics, and build a coherent picture of the underlying theory.

Setting the Stage

Energy, Luminosity & Power - the Snowmass View

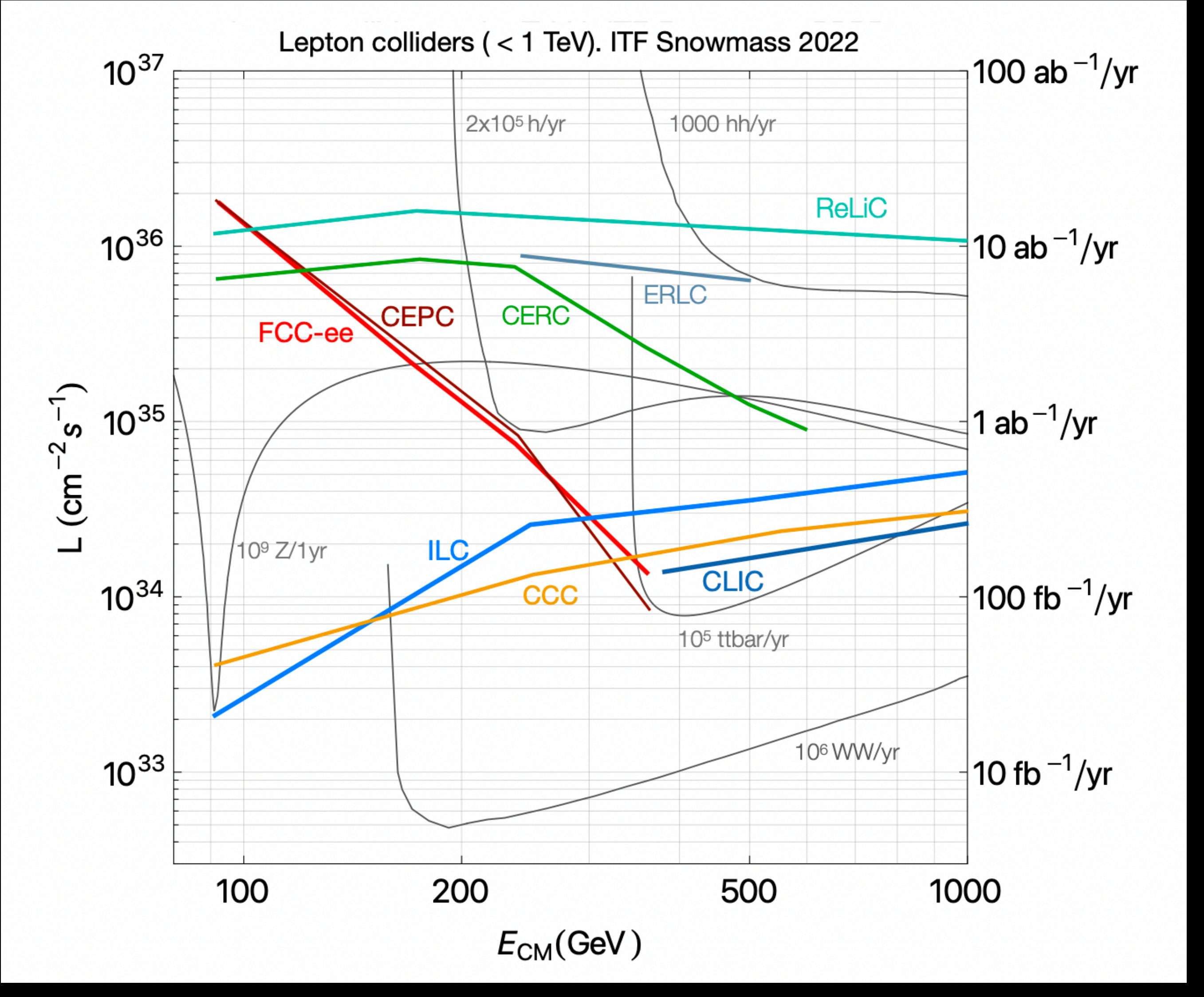
Circular *ee*	ERL based *ee*	Linear *ee*	Muon coll	Wakefield	Hadron *pp*

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Integrated luminosity assumes 10^7 seconds per year.
- The luminosity is per IP.
- Data points are provided to the ITF by proponents of the respective machines.
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



taken from V. Shiltsev @ eeFACT'22

ITF Report – T.Roser, et al, arXiv:2208.06030

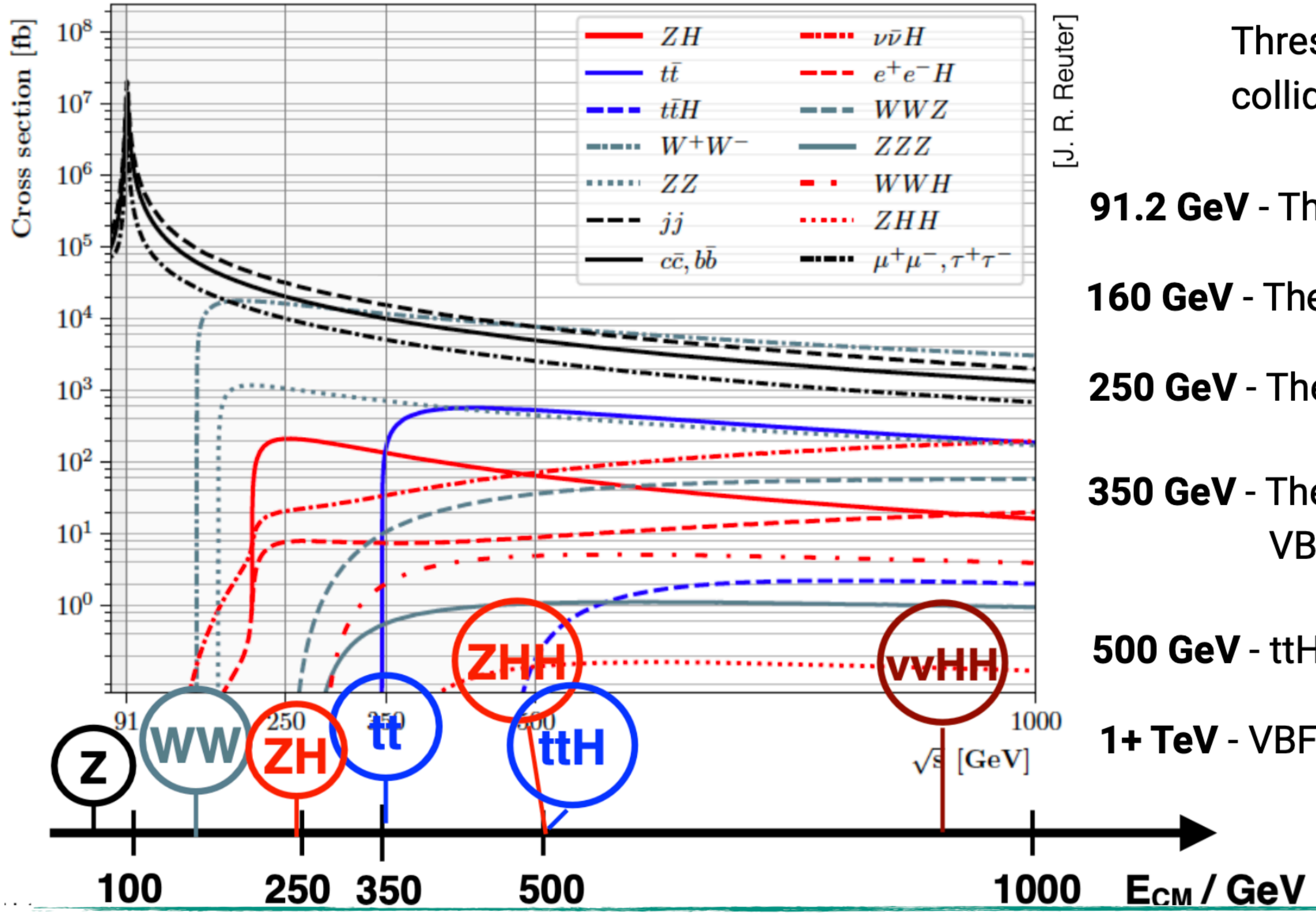


Lepton colliders (< 1 TeV). ITF Snowmass 2022
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
$L\ (cm^{-2}s^{-1})$
100 ab $^{-1}$/yr
10 ab $^{-1}$/yr
1 ab $^{-1}$/yr
100 fb $^{-1}$/yr
10 fb $^{-1}$/yr
2x10⁵ h/yr
1000 hh/yr
ReLiC
ERLC
CEPC
CERC
FCC-ee
10⁹ Z/1yr
ILC
CLIC
CCC
10⁵ ttbar/yr
10⁶ WW/yr
100
200
500
1000
E_{CM}(GeV)

Setting the Stage

Perspectives of Energy

Karlsruher Institut für Technologie



Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole

160 GeV - The WW threshold

250 GeV - The ZH maximum

350 GeV - The top threshold, VBF Higgs production

500 GeV - ttH, ZHH

1+ TeV - VBF double Higgs

Precision electroweak, Flavour, QCD, ...

Higgs properties & couplings

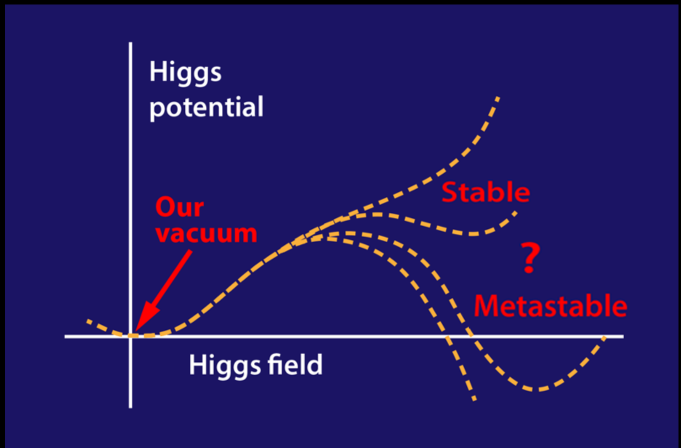
Top properties, Top as probe

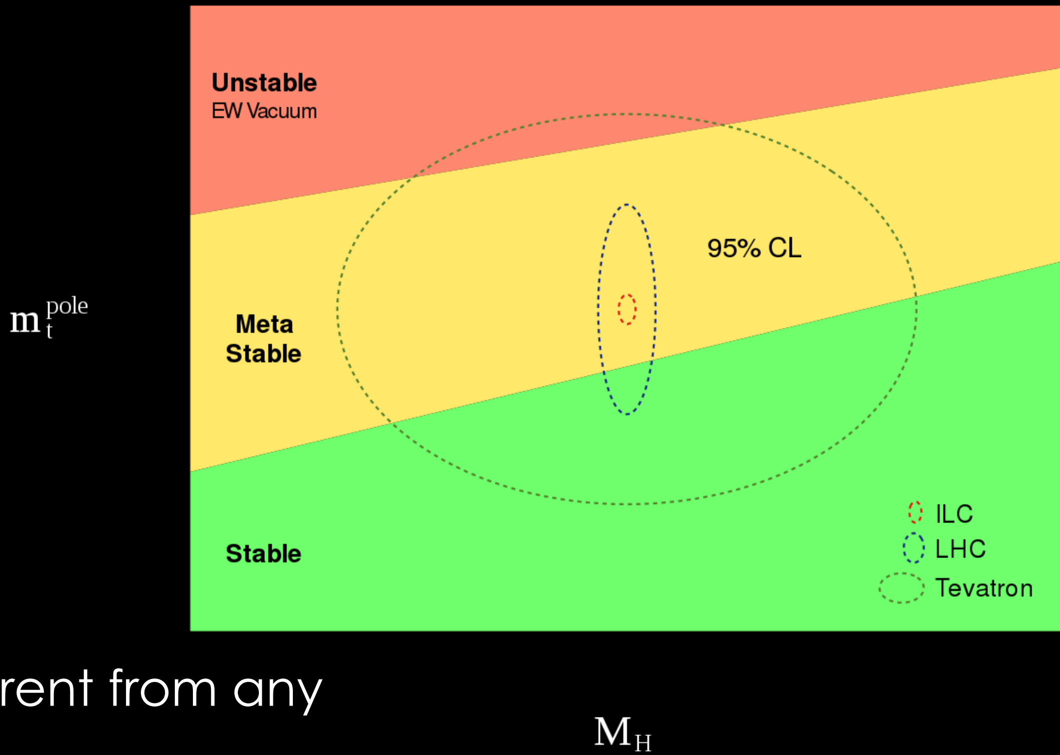
Direct top Yukawa Higgs selfcoupling

Search at the energy frontier

freyablekman

HIGGS AND THE STANDARD MODEL



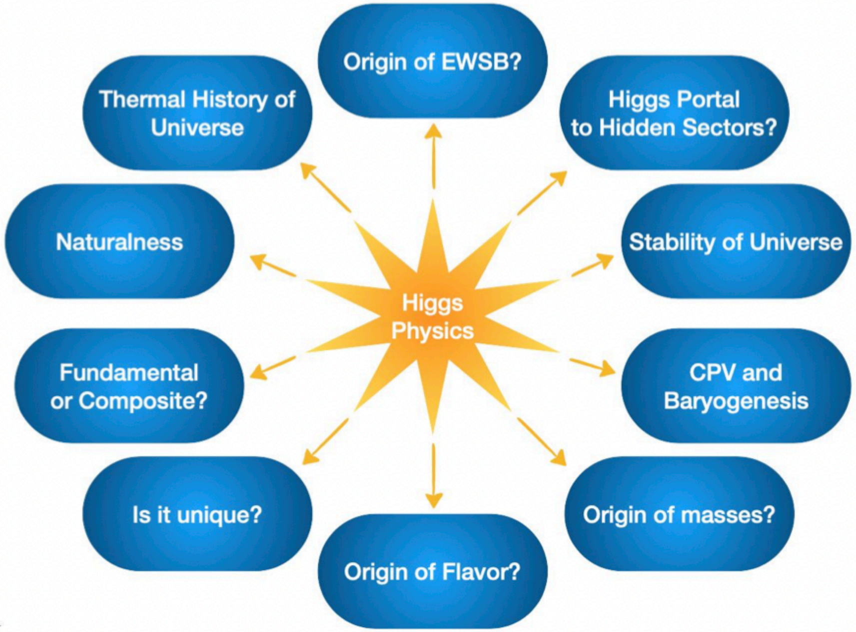


Completely new particle - very different from any particle that was studied in past
that is after 10 years, known to some accuracy

Linked to puzzling questions in fundamental physics

Pushing the Higgs-boson precision program is crucial

The Higgs discovery has given us a unique handle on BSM physics and any future plan needs to make the most out of it.



Energy Frontier Higgs Factory First Stages

EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings: Tree	Gauge Couplings: Loop induced	Higgs Width	λ_3	λ_4
LHC/HL-LHC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC: ILC/C^3 250	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$*	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC: CLIC 380	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC: FCC-ee 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$
Higgs Factory + HL-LHC: CEPC 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$	$> \mathcal{O}(1)$

Order of Magnitude for Fractional Uncertainty: ★ $\lesssim \mathcal{O}(10^{-3})$ ◆ $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ ◆ $\mathcal{O}(1)$ □ $> \mathcal{O}(1)$? No study Beyond HL-LHC

Higgs Factories

- **Higgs couplings at sub-percent level**
- **Search for exotic Higgs decays**
- **Explore Higgs portal to hidden sector**
- **Stress-test consistency of the SM**
- **Direct access to low-mass/weak-coupling BSM**

From Snowmass 21 EF Higgs Topical Group Report (arXiv:2209.07510)

9

L. Reina, https://indico.desy.de/event/33640/contributions/122884/attachments/77558/100365/ECFA22-2.pdf

2020 update of European Strategy for Particle Physics

"An electron-positron Higgs factory is the highest priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

⬇

FCC Feasibility Study (FS) launched in 2021:

- ❑ To be carried out in 2021-2025 → input to the next Strategy update
- ❑ Mid-term review in Autumn 2023
- ❑ Will cover the integrated programme (FCC-ee followed by FCC-hh)

F. Gianotti (slides from introduction FCC week 2022)

Detector Parameters

MAX-PLANCK-INSTITUT FÜR PHYSIK

	ILD (IDR_L/IDR_S)	SiD	CLICdet	CLD	IDEA	CEPC baseline
Vertex technology	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Vertex inner radius	1.6 cm	1.4 cm	3.1 cm	1.75 cm	1.7 cm	1.6 cm
Tracker technololy	TPC + Silicon	Silicon	Silicon	Silicon	Drift chamber + Si	TPC + Silicon
Tracker outer radius	1.77 m / 1.43 m	1.22 m	1.5 m	2.1 m	2.0 m	1.8 m
Calorimeter	PFA	PFA	PFA	PFA	Dual readout	PFA
(ECAL) inner radius	1.8 m / 1.46 m	1.27 m	1.5 m	2.15 m	2.5 m	1.8 m
ECAL technology	Silicon	Silicon	Silicon	Silicon	-	Silicon
ECAL absorber	W	W	W	W	-	W
ECAL thickness	24 X_0 (30 layers)	26 X_0 (30 layers)	22 X_0 (40 layers)	22 X_0 (40 layers)	-	24 X_0 (30 layers)
HCAL technology	Scintillator	Scintillator	Scintillator	Scintillator	-	RPC
HCAL absorber	Fe	Fe	Fe	Fe	-	Fe
HCAL thickness	5.9 λ_I (48 layers)	4.5 λ_I	7.5 λ_I (60 layers)	5.5 λ_I (44 layers)	8 λ_I (2 m)	4.9 λ_I (40 layers)
(HCAL) outer radius	3.34 m / 3.0 m	2.5 m	3.25 m	3.57 m	≤4.5 m	3.3 m
Solenoid field	3.5 T / 4 T	5 T	4 T	2 T	2 T	3 T
Solenoid length	7.9 m	6.1 m	8.3 m	7.4 m	6.0 m	8.0 m
Sol. inner radius	3.42 m / 3.08 m	2.6 m	3.5 m	3.7 m	2.1 m	3.4 m

HIGGS SELF COUPLING

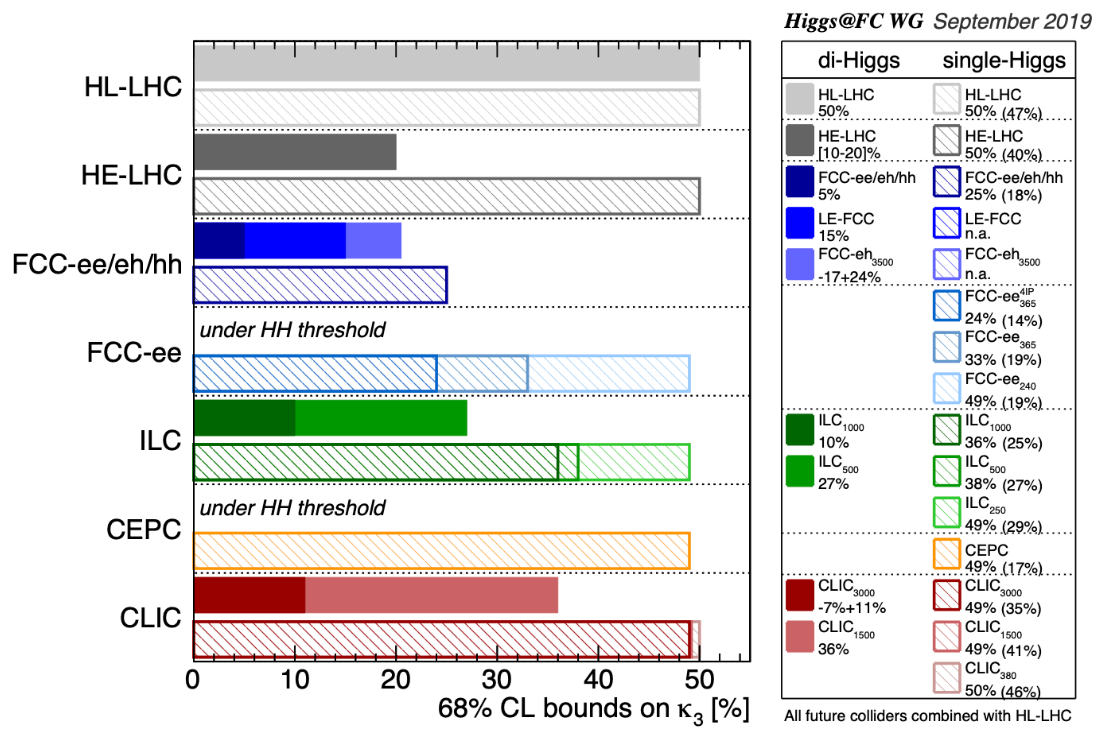


Figure 11. Sensitivity at 68% probability on the Higgs cubic self-coupling at the various FCs. All values reported correspond to a simplified combination of the considered collider with HL-LHC. Only numbers for Method (1), i.e. "di-H excl.", corresponding to the results given by the future collider collaborations, and for Method (4), i.e. "single-H glob." are shown (the results for Method (3) are reported in parenthesis). For Method (4) we report the results computed by the Higgs@FC working group. For the leptonic colliders, the runs are considered in sequence. For the colliders with $\sqrt{s} \lesssim 400$ GeV, Method (1) cannot be used, hence the dash signs. Due to the lack of results available for the *ep* cross section in SMEFT, we do not present any result for LHeC nor HE-LHeC, and only results with Method (1) for FCC-eh.

J. De Blas et al, Higgs Boson Studies at Future Particle Colliders, arXiv:1905.03764

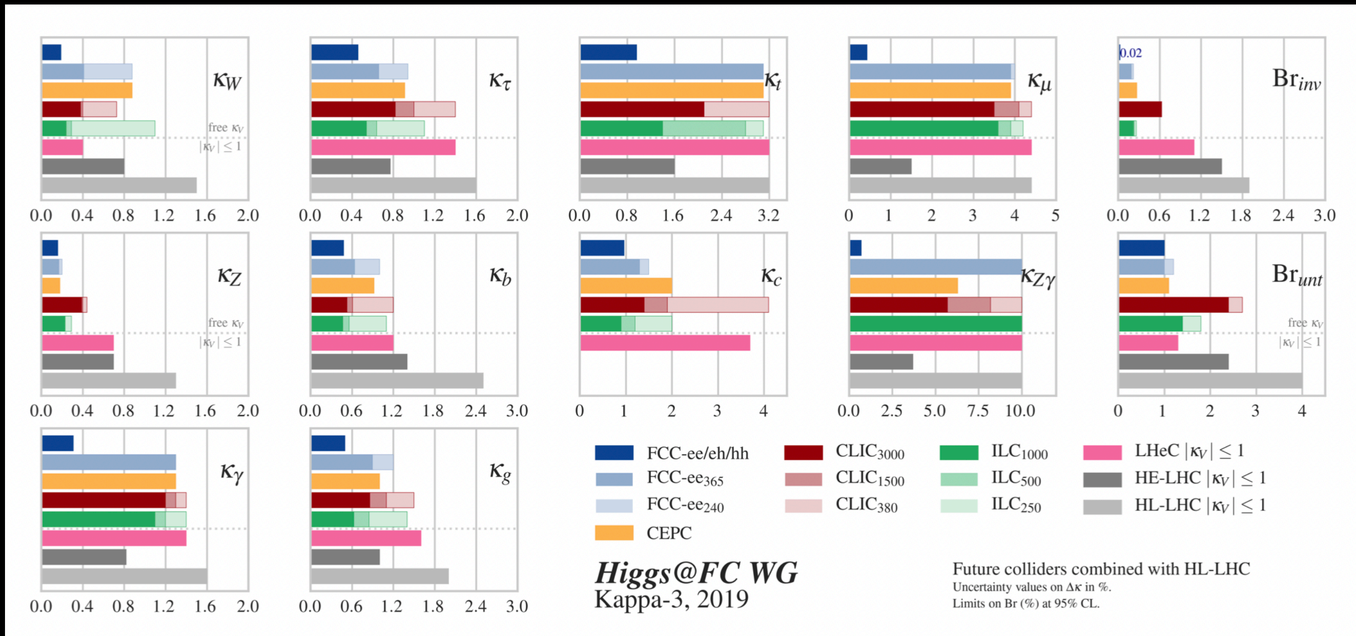
HOW MUCH will it cost?

A cost study has been performed as part of the FCC study covering FCC-ee and FCC-hh as standalone options as well as for an integrated project. The FCC study takes into account the cost optimization in a number of key areas for building a future circular collider.

- The cost for an ultra-high intensity lepton collider is in the order of 4 billion euro
- The cost for a 100 TeV energy frontier hadron collider is about 15 billion euro
- The cost for a 100 km tunnel infrastructure is about 5 billion euro that can serve a two-stage project: first a lepton collider operating followed by a hadron collider. This integrated scenario can offer a research programme of seven decades.

All the FCC numbers are here: https://fcc.web.cern.ch/fcc-qa-guide

HIGGS AND THE STANDARD MODEL AFTER HL-LHC



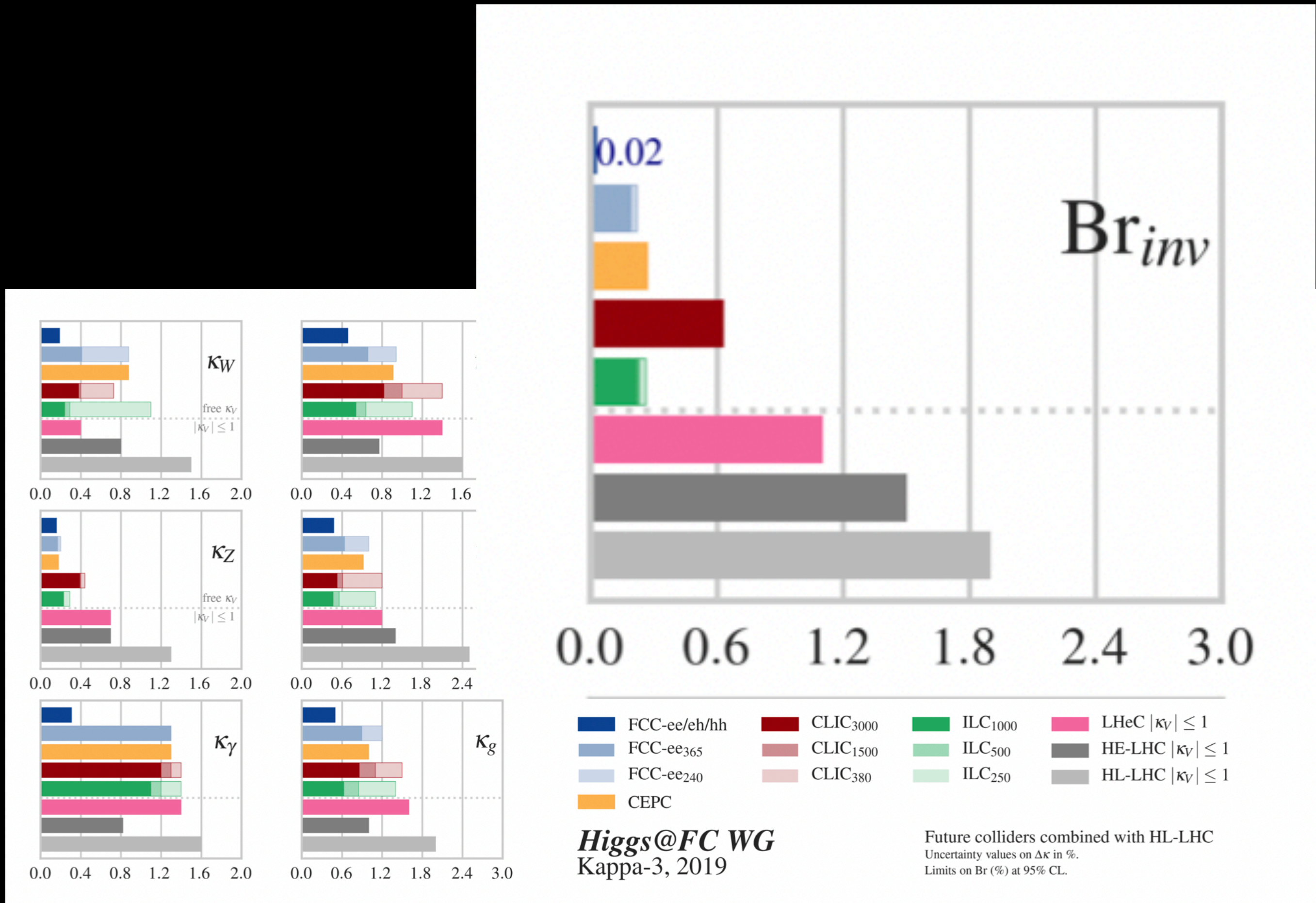
HL-LHC gives 10-few% precision on SM properties of the Higgs boson

Future Higgs factories should improve by order of magnitude

BTW: same is true for many other SM parameters via SMEFT

J. De Blas et al, Higgs Boson Studies at Future Particle Colliders, arXiv:1905.03764

HIGGS AND THE STANDARD MODEL AFTER HL-LHC



HL-LHC gives 10-few% precision on SM properties of the Higgs boson

Future Higgs factories should improve by order of magnitude

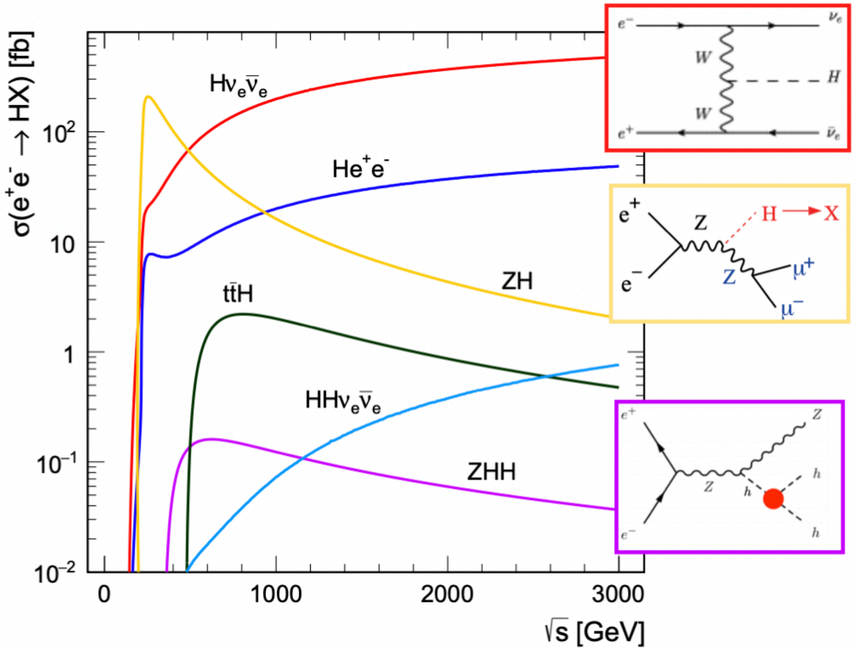
BTW: same is true for many other SM parameters via SMEFT

J. De Blas et al, Higgs Boson Studies at Future Particle Colliders, arXiv:1905.03764

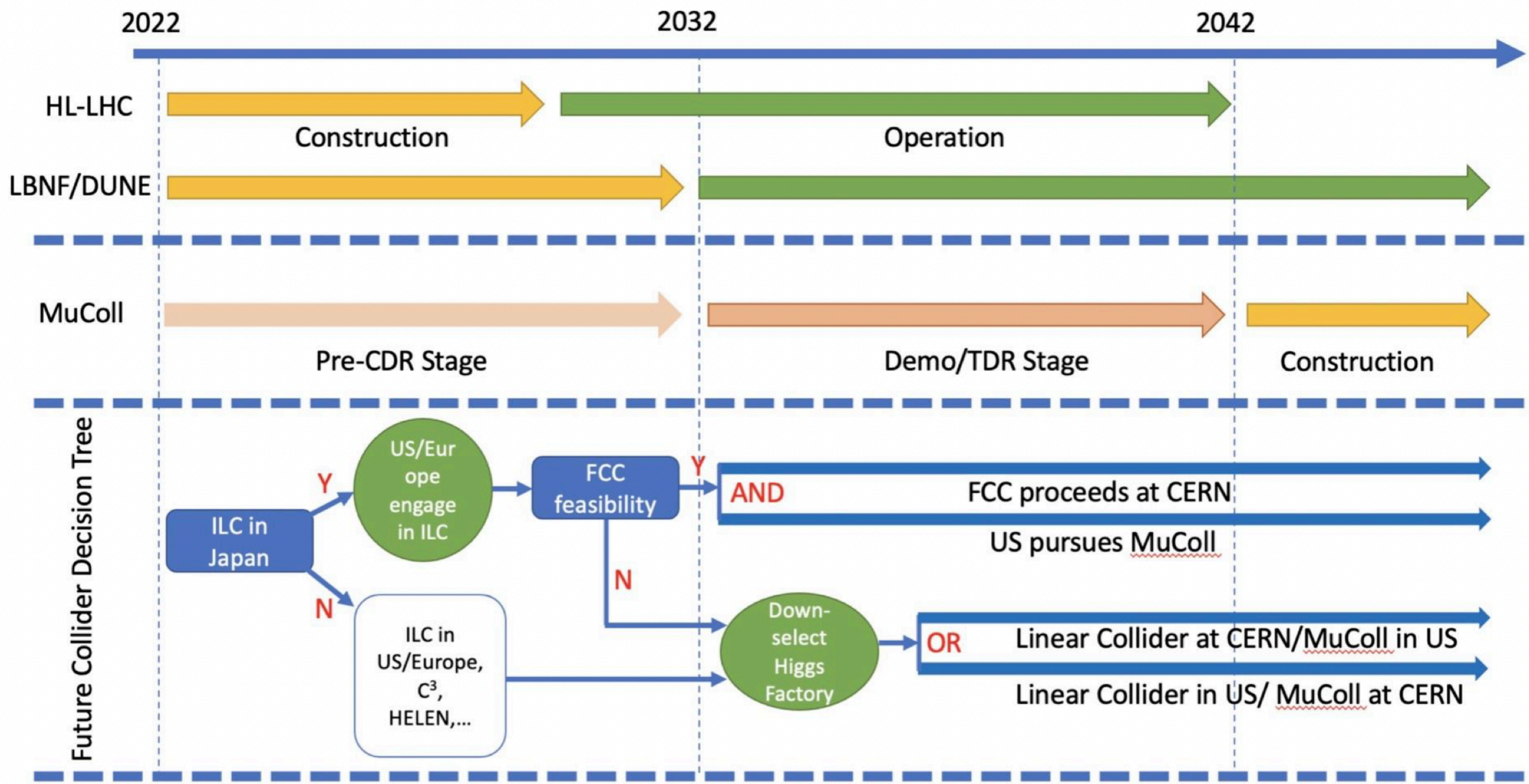
freyablekman

Higgs self-coupling

The next big thing in Higgs physics



collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC$_{250}$/C^3-250	49%	—	49%
ILC$_{500}$/C^3-550	38%	20%	20%
CLIC$_{380}$	50%	—	50%
CLIC$_{1500}$	49%	36%	29%
CLIC$_{3000}$	49%	9%	9%
FCC-ee	33%	—	33%
FCC-ee (4 IPs)	24%	—	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%



From Muon Collider Forum's Report (arXiv:2209.01318)