Possible Future Collider Experiments in Particle Physics

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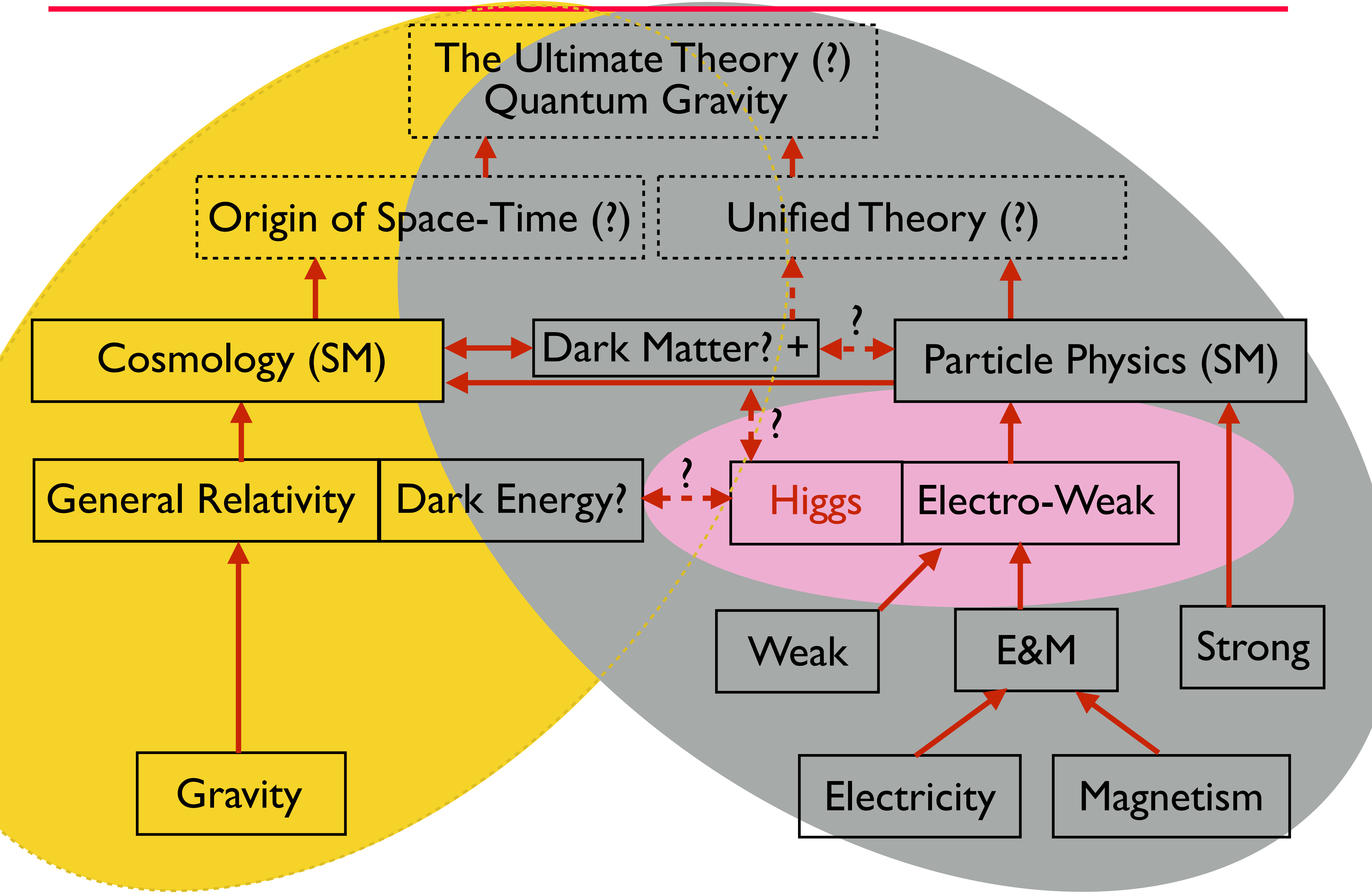
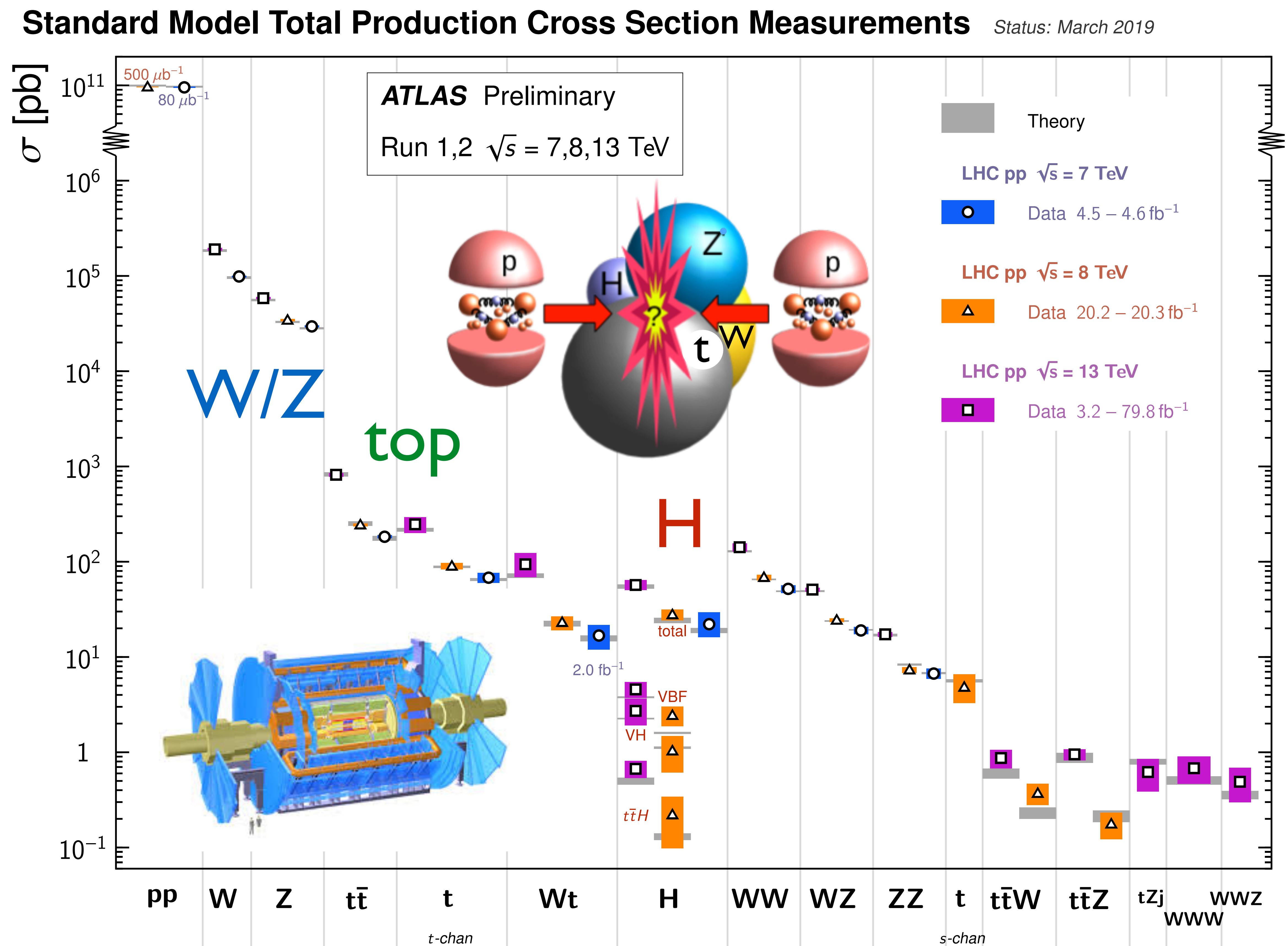
Johns Hopkins University QuarkNet Physics Workshop

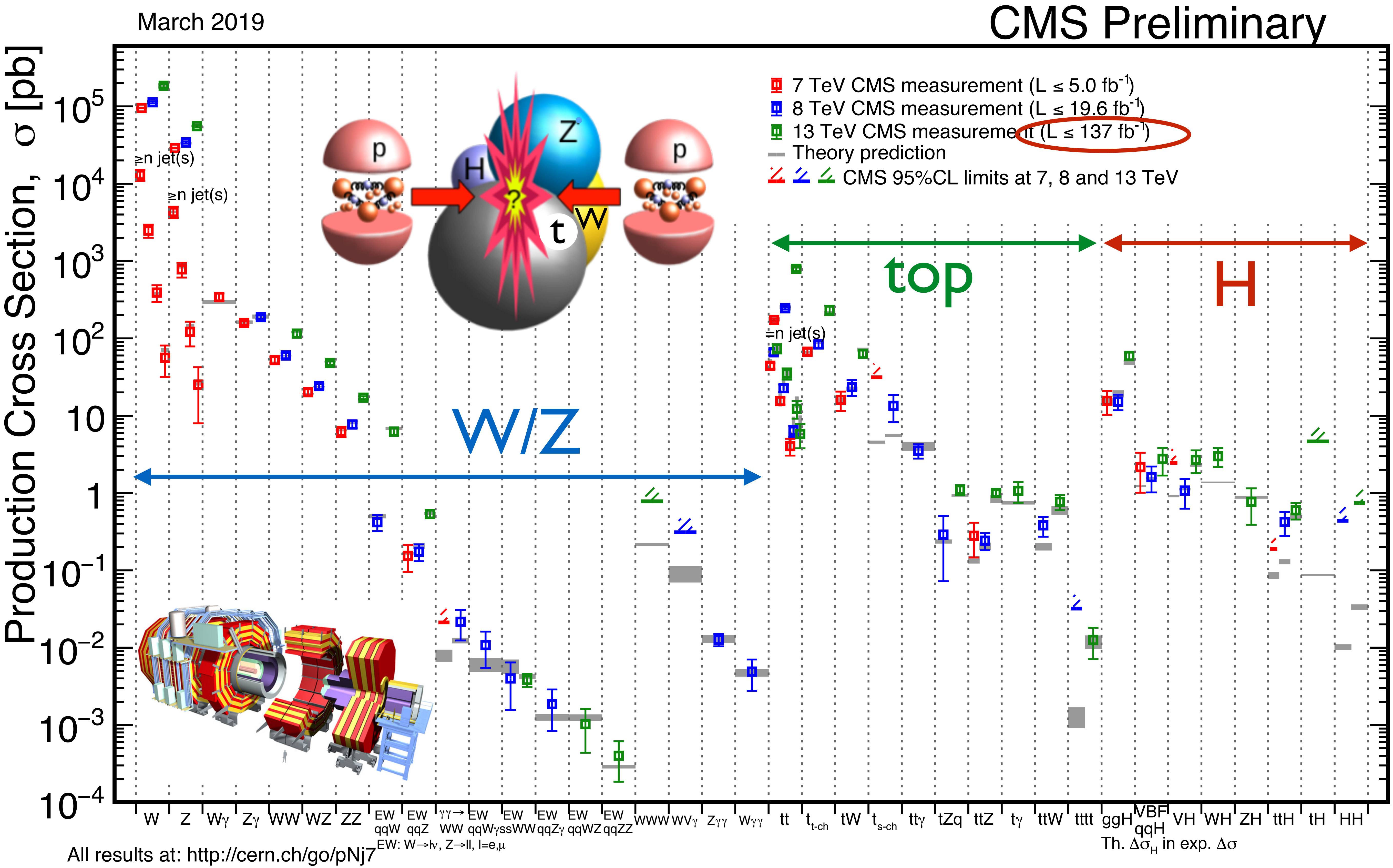
Vision of the World by an Exp. Particle Physicist



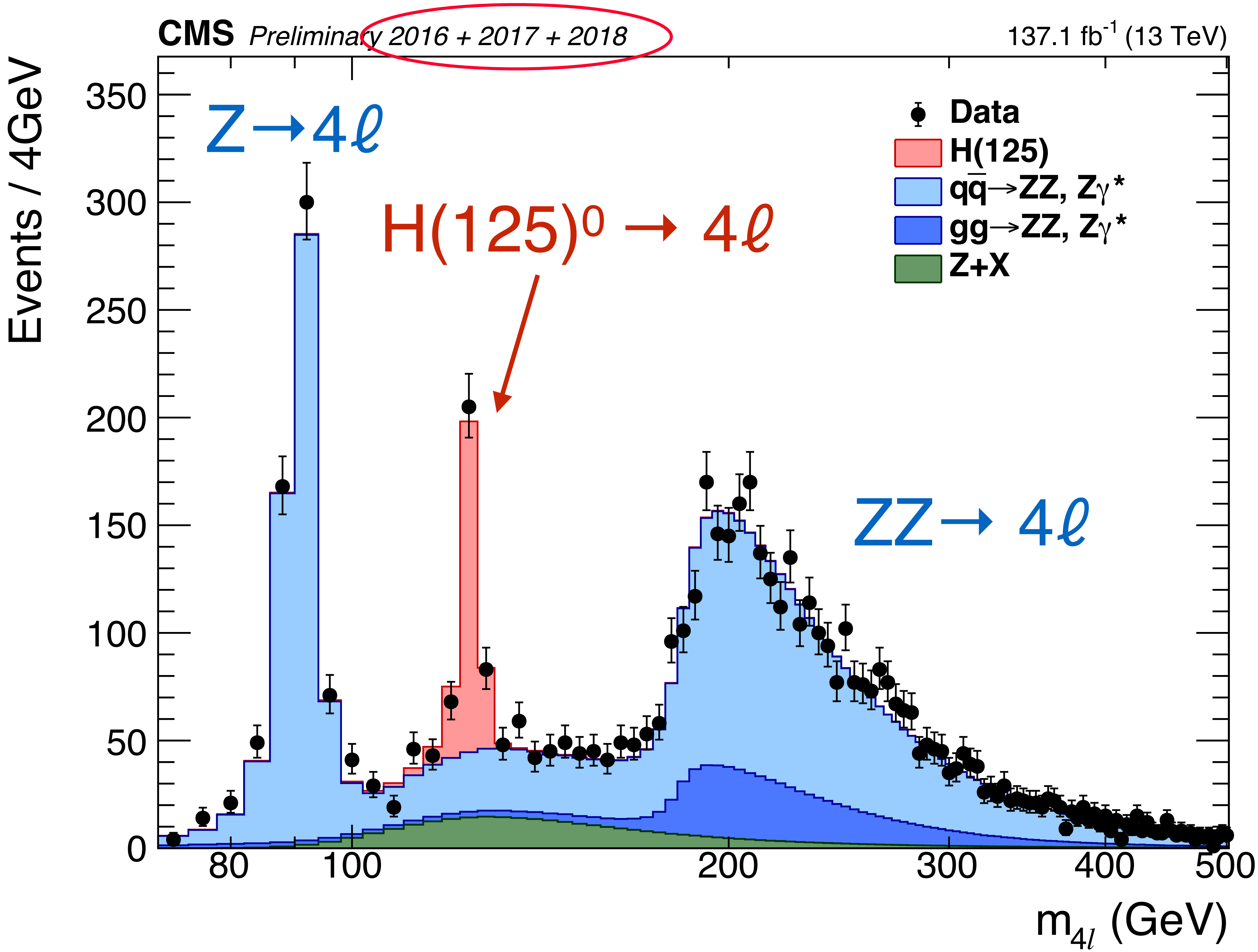
A bird's-eye view on Electro-Weak Physics at ATLAS



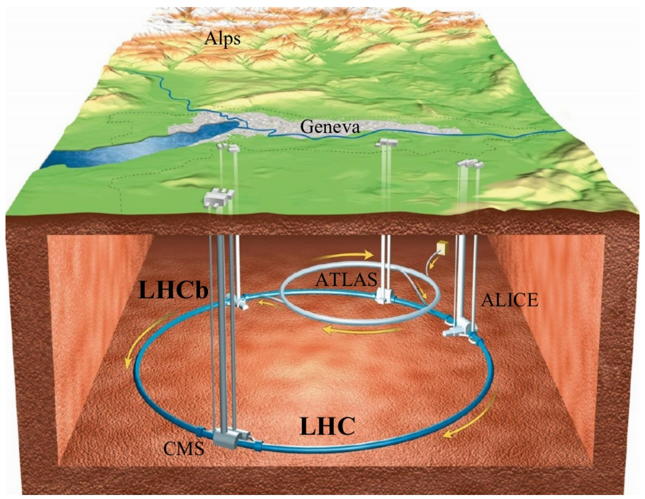
A bird's-eye view on Electro-Weak Physics at CMS

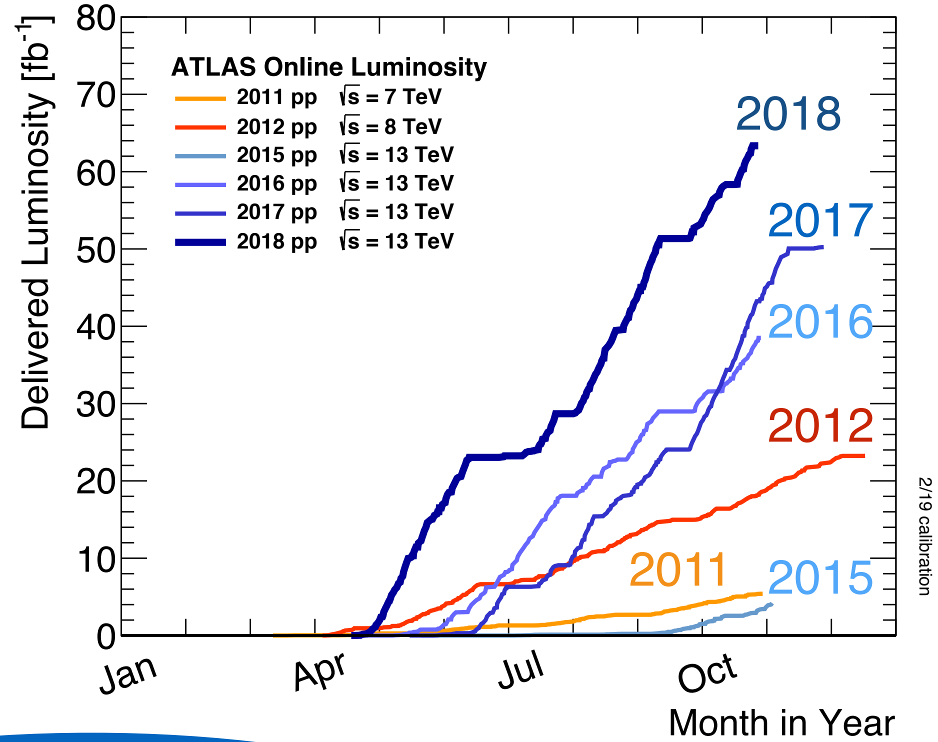


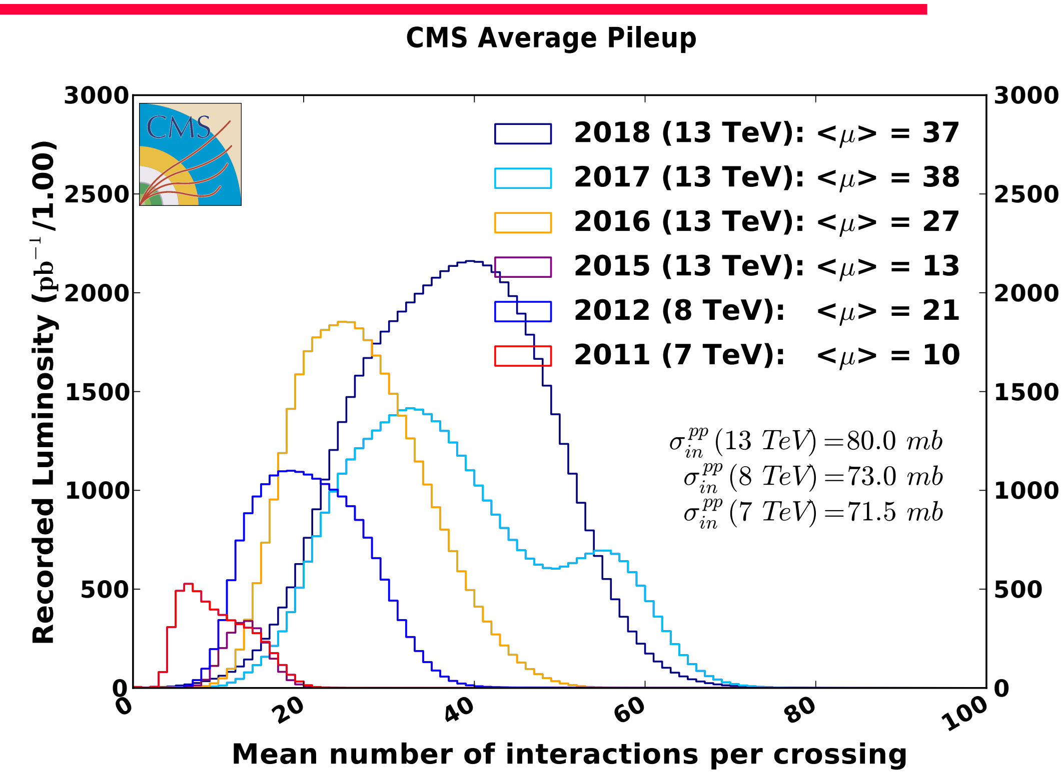
Higgs→4ℓ boson yield



LHC and High-Lumi-LHC (next 20 years)

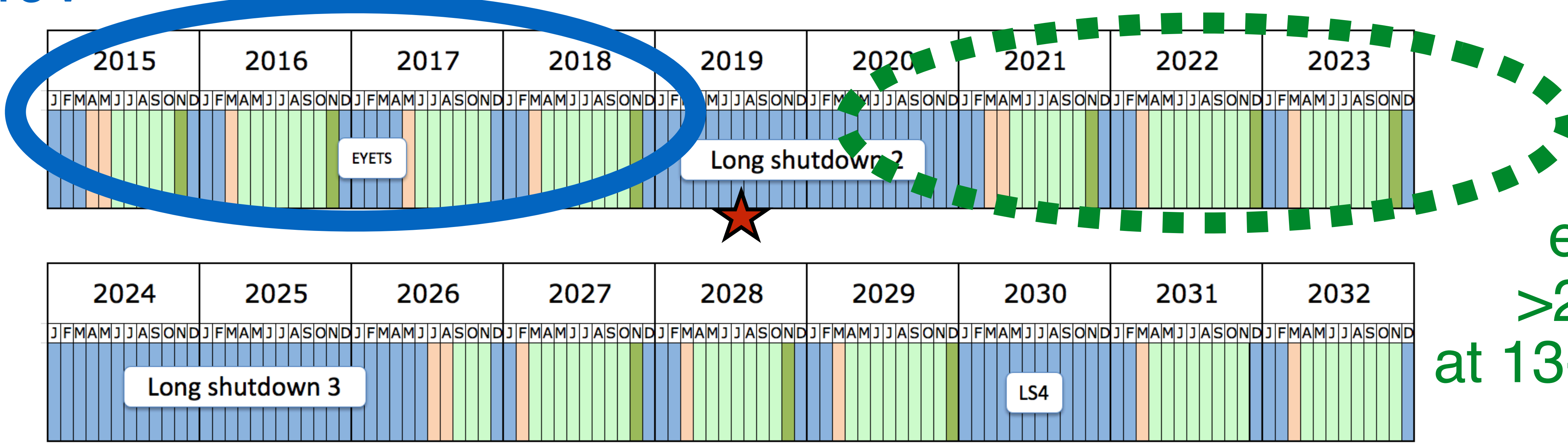






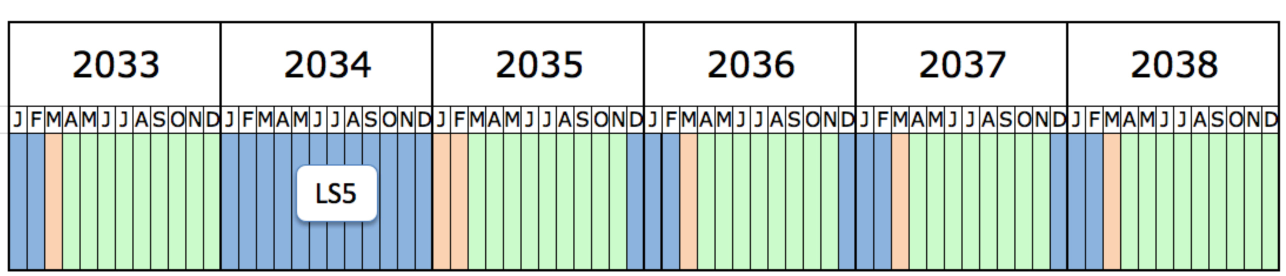
~140 fb^{-1}
at 13 TeV

Run-2



Run-3

expect
>200 fb^{-1}
at 13-14 TeV



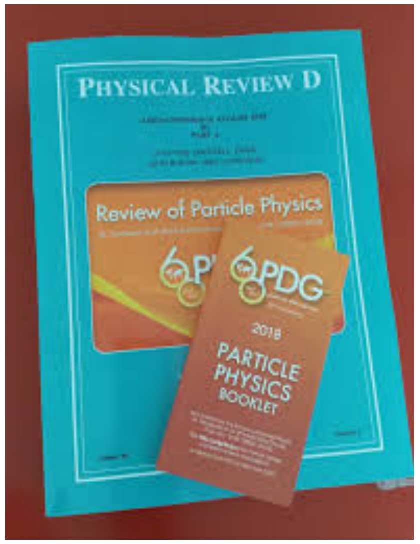
HL-LHC
(Runs-4,5,6)

expect
>3000 fb^{-1}

Heaviest known particles H^0, W/Z, top in the PDG

PDG particle data group pdg.lbl.gov (2018)
Reviews, Tables, and Plots

— mass
— width / lifetime
— quantum numbers
— coupling strength



H^0

$J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}$ e Top = +1

Mass (direct measurements) $m = 173.0 \pm 0.4$ GeV [a,b] (S = 1.3)
Mass (from cross-section measurements) $m = 160^{+5}_{-4}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 173.1 \pm 0.9$ GeV
$m_t - m_{\bar{t}} = -0.16 \pm 0.19$ GeV
Full width $\Gamma = 1.41^{+0.19}_{-0.15}$ GeV (S = 1.4)
$\Gamma(W b)/\Gamma(W q(q = b, s, d)) = 0.957 \pm 0.034$ (S = 1.5)

W

$J = 1$

Charge = ± 1 e
Mass $m = 80.379 \pm 0.012$ GeV
W/Z mass ratio = 0.88153 ± 0.00017
$m_Z - m_W = 10.803 \pm 0.015$ GeV
$m_{W^+} - m_{W^-} = -0.029 \pm 0.028$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV

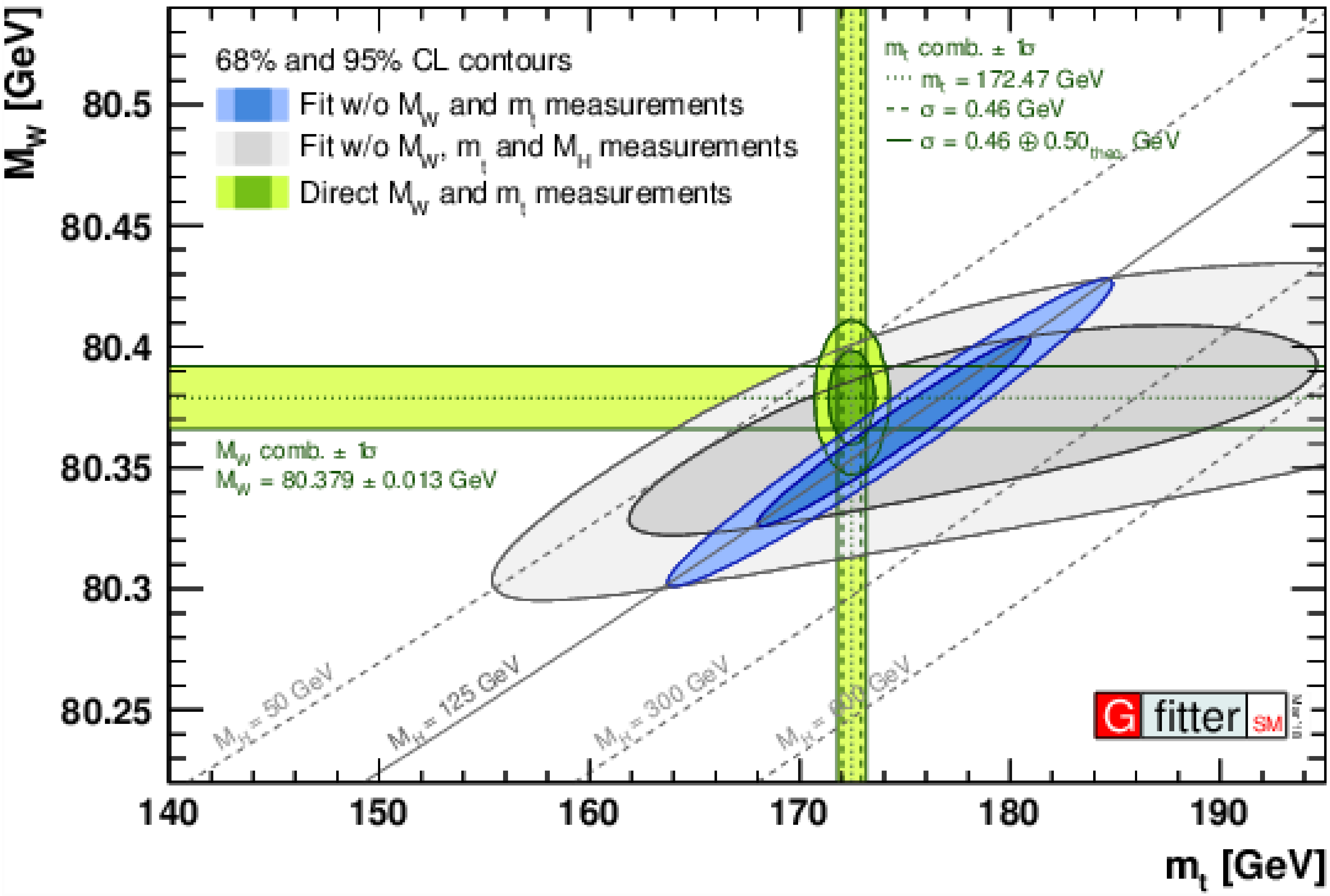
Z

$J = 1$

Charge = 0
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
$\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]
$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV

H,W/Z, top: the mass

- the heaviest fundamental SM particles: m_H, m_W, m_t
  — fundamental parameters
  — over-constrain SM



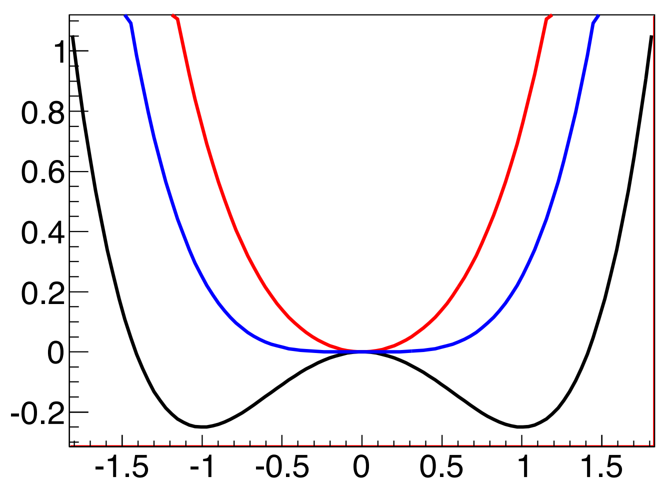
Fundamental Questions in Higgs (EW) Physics

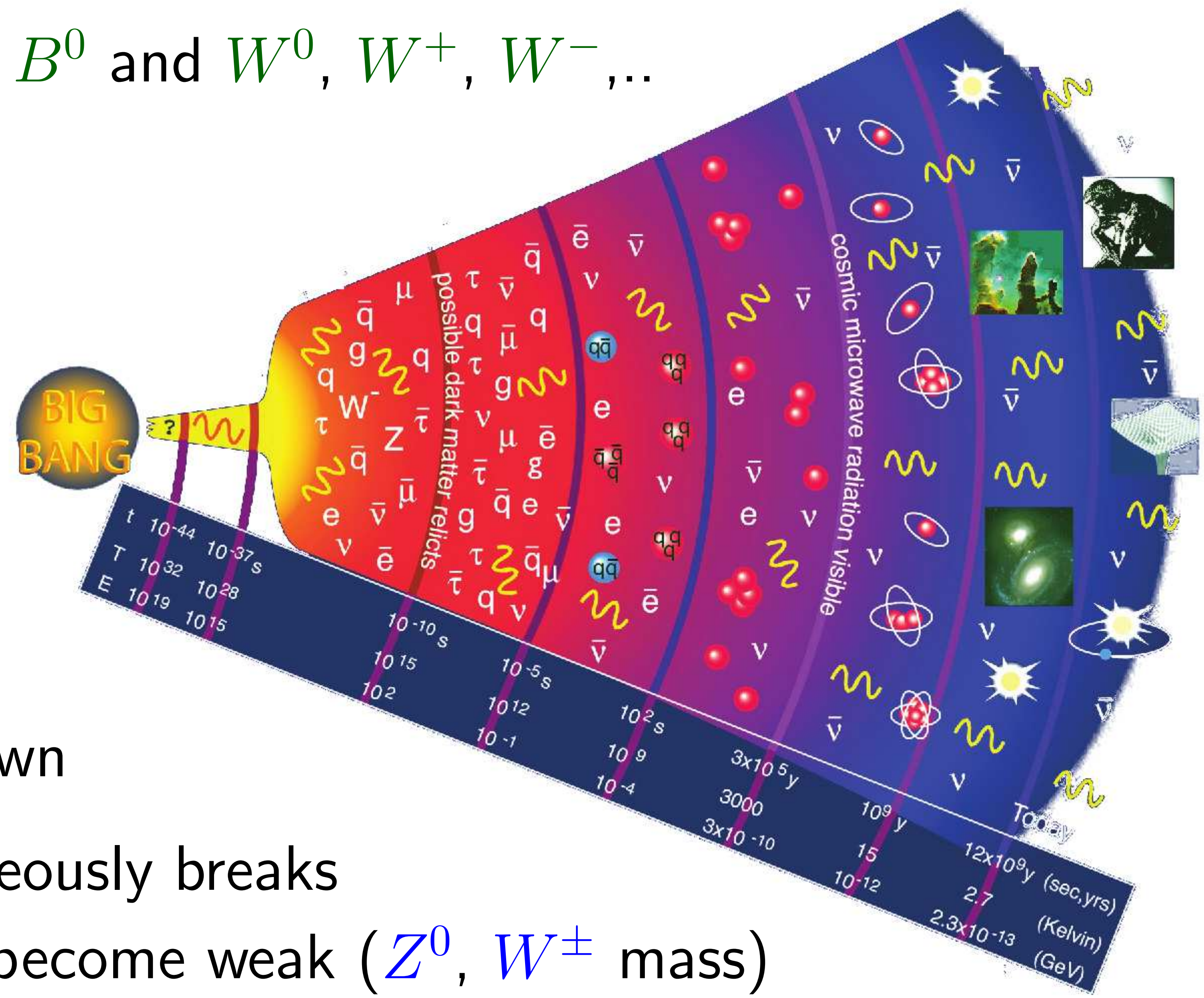
- Is Higgs the SM boson?
  - does it connect to Dark Matter?
  - does it generate CP violation? (matter dominance)
  - is it elementary?
  - is it the only Scalar (spin-0^{++}) particle ?
  - how does it couple to fermions, bosons, itself ?
  - what is the Higgs potential ?
  - what is the EW phase transition ?
  - why is its mass << Planck scale ?

CMS: arXiv:1809.05937

Fundamental Questions in Higgs (EW) Physics

- Early moments of the Universe
  - massless particles: B^0 and W^0, W^+, W^-,..
  - all forces unify

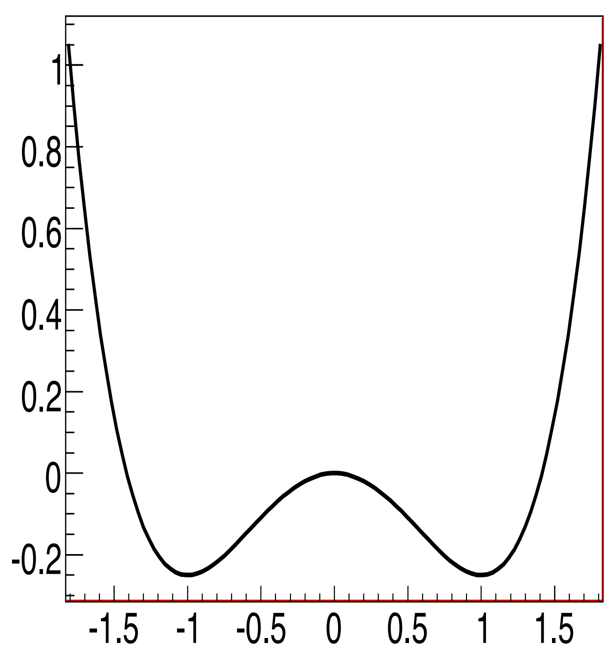


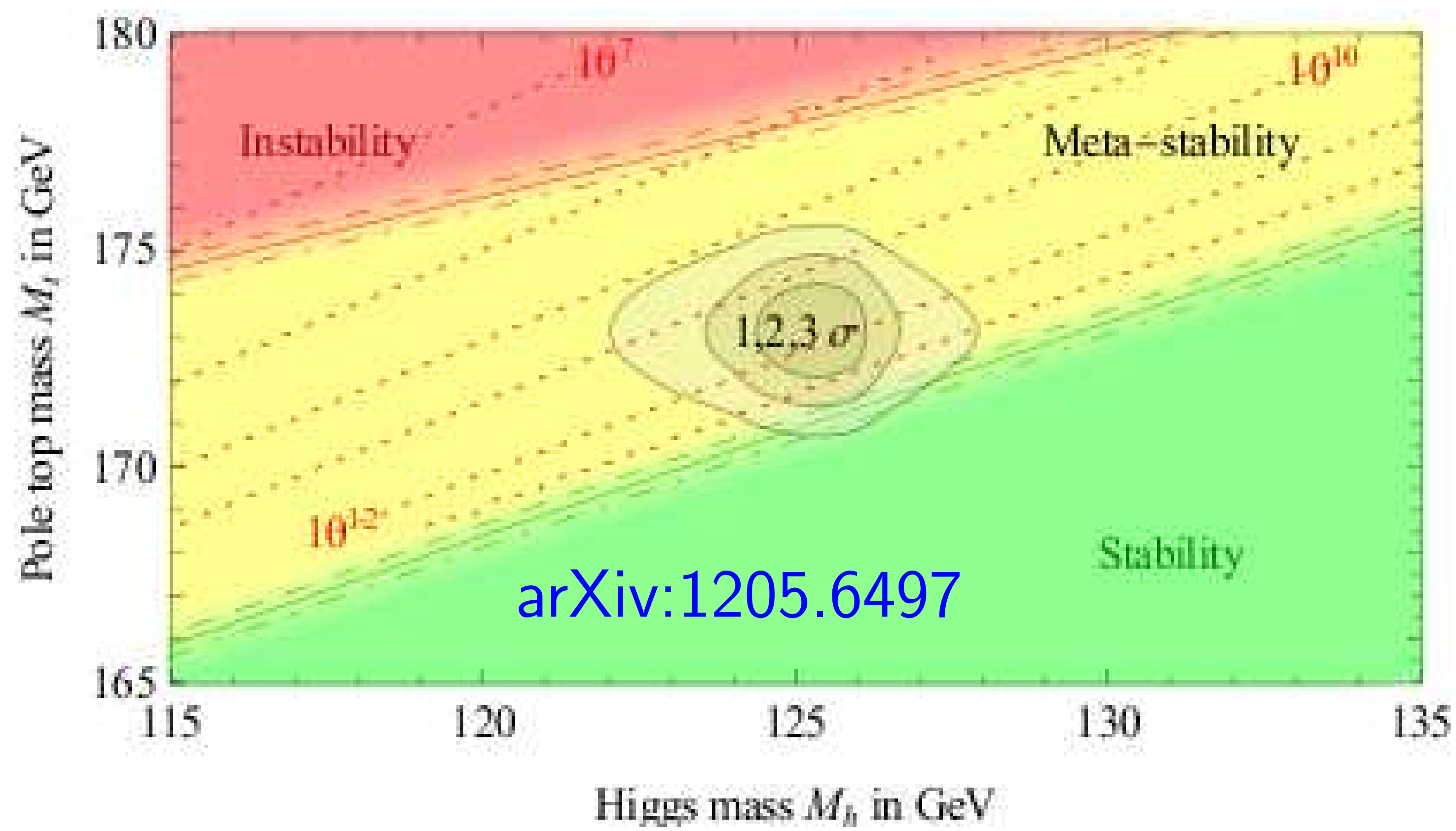


- As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak (Z^0, $W^{\pm}$ mass)
  - Higgs field – possible mechanism

Stability of the Vacuum

- Higgs self-coupling $\lambda < 0$ at higher scale
  - may tunnel thru "potential barrier" $\Rightarrow$ unstable Universe
  - tunneling time $>$ Universe lifetime $\Rightarrow$ metastable Universe
  - for $m_H \sim$ 126 GeV$/c^2$ and SM Higgs field $\Rightarrow$ metastable





Proposed Future Experimental Higgs Program

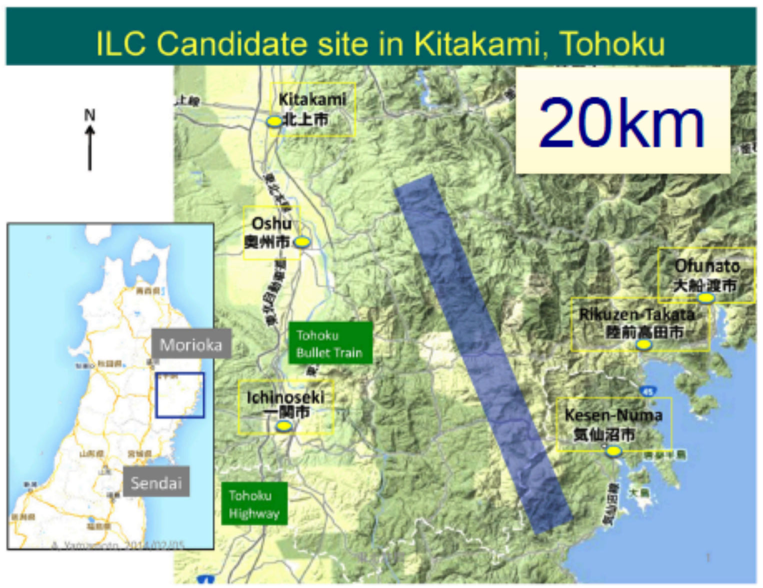
Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

arXiv.org:1905.03764

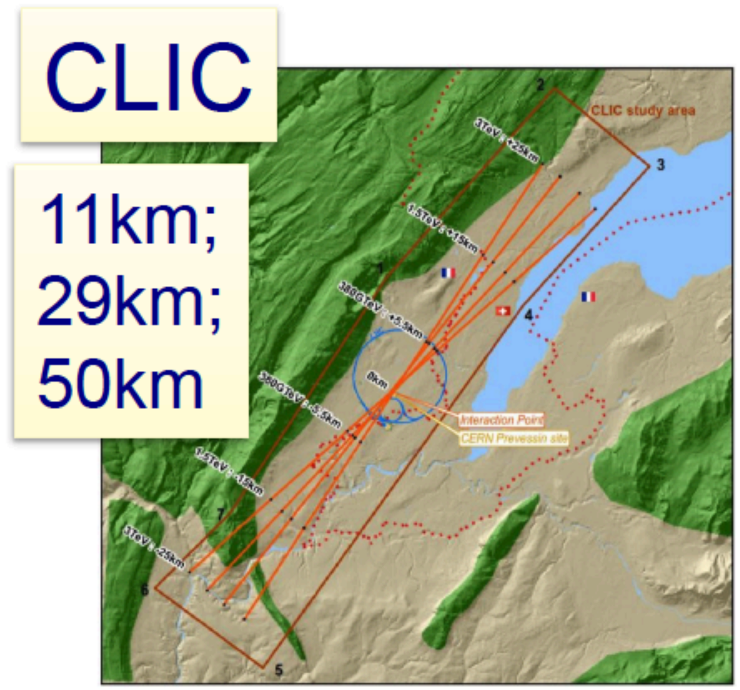
Proposed Future Experiment: Main Players

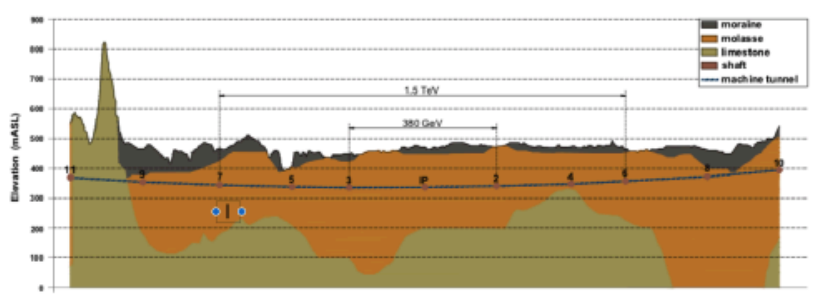
First: electron-positron colliders:

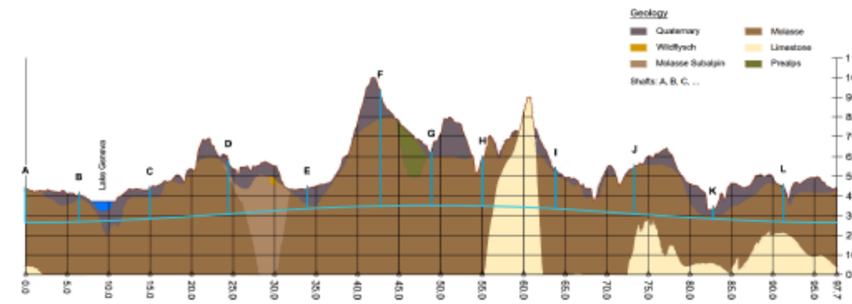
circular ones to be staged to proton-proton

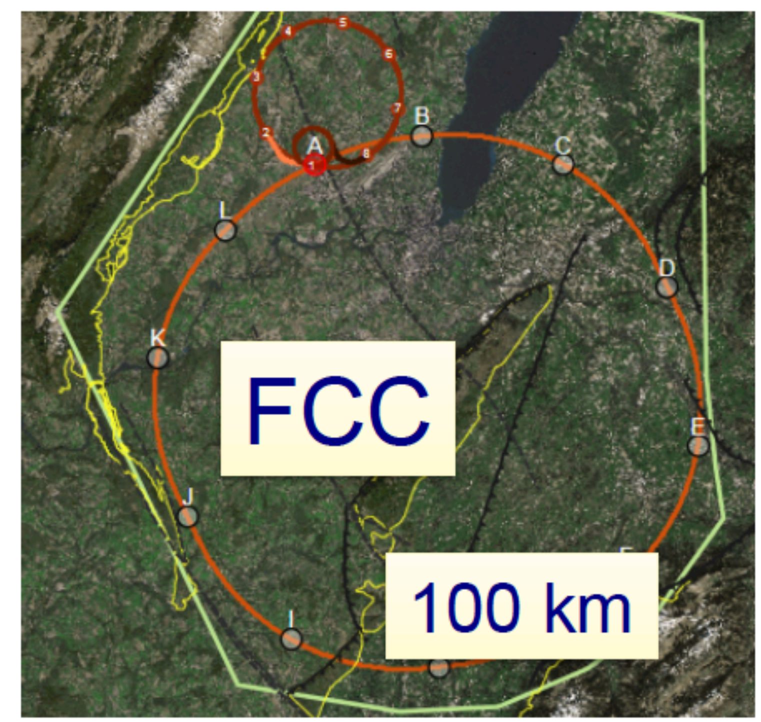


CEPC: multiple candidate sites in China









Proposed Future Experiment: Main Players

ILC (Japan):

Linear collider with high-gradient superconducting acceleration

Ultimate: 0.5-1(?) TeV

To secure funding: reduce cost by starting at 250 GeV (H factory)

CLIC (CERN):

Linear collider with high gradient normal-conducting acceleration

Ultimate: multi-TeV (3) e+e– collisions

Use technology to overcome challenges

Stages, for physics and funding

FCC-ee/FCC-hh (CERN):

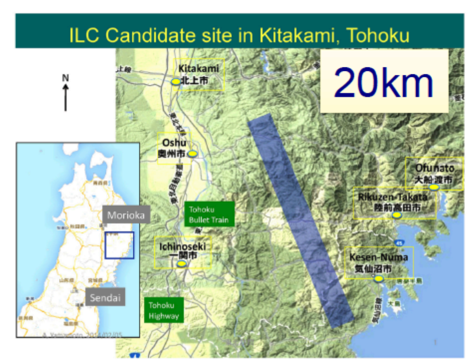
CEPC/SppC (China):

Start as e+e- H factory

Protons to extend energy frontier

100 km ring with 16T magnets

Technology for ee: "standard"



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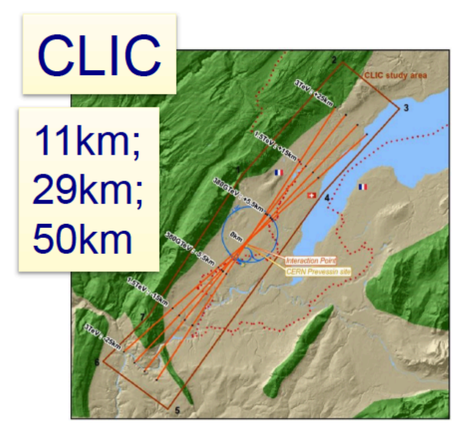
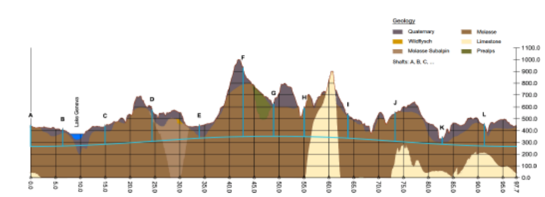
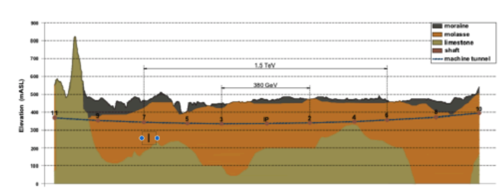
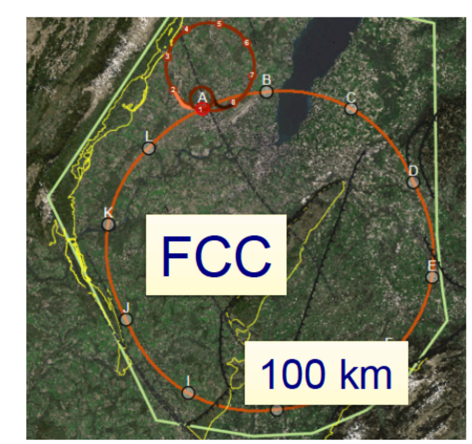








Other:

LHeC/FCC-eh; extend LHC with minimal cost

Proposed Future Experiment: Main Players

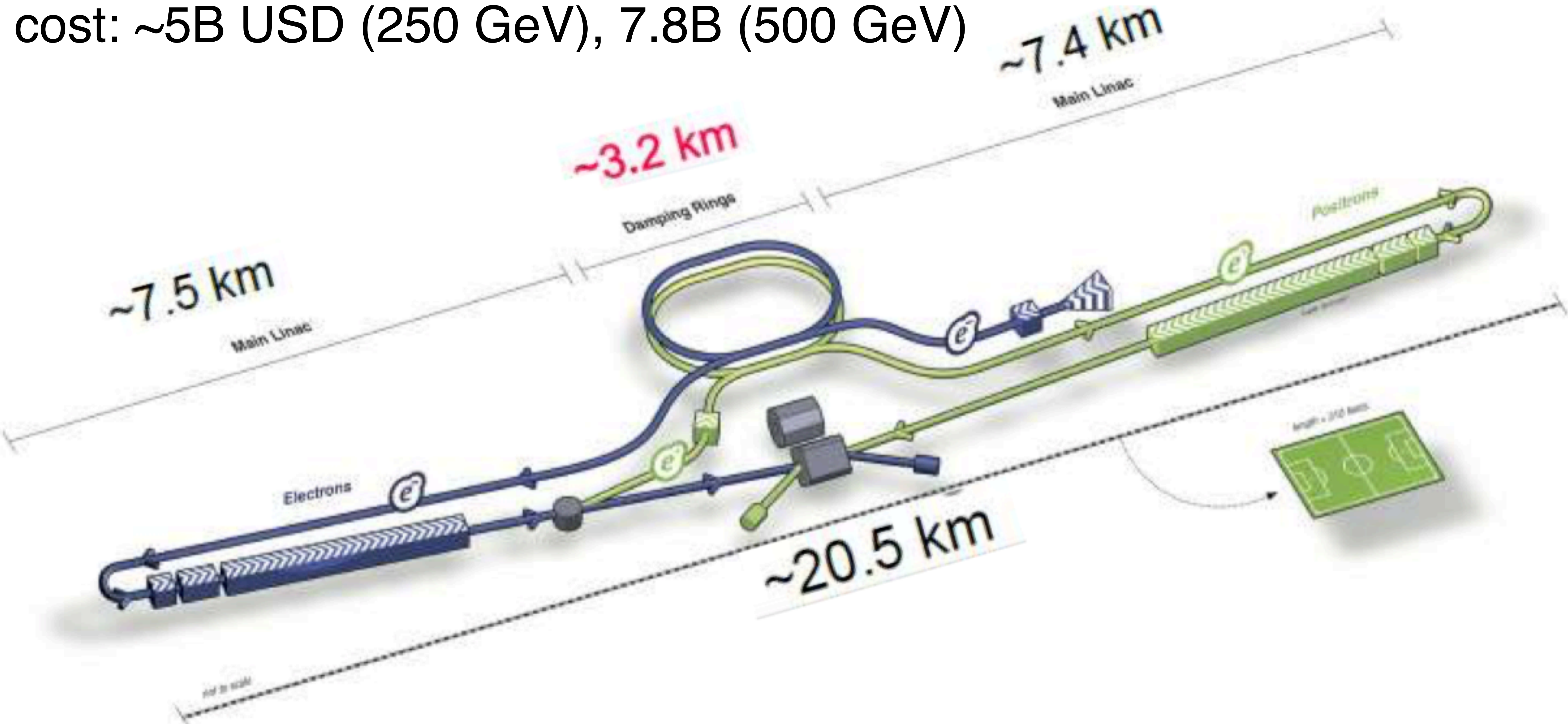
ILC (Japan):

Linear collider with high-gradient superconducting acceleration

Ultimate: 0.5-1 (?) TeV

To secure funding: reduce cost by starting at 250 GeV (H factory)

cost: ~5B USD (250 GeV), 7.8B (500 GeV)

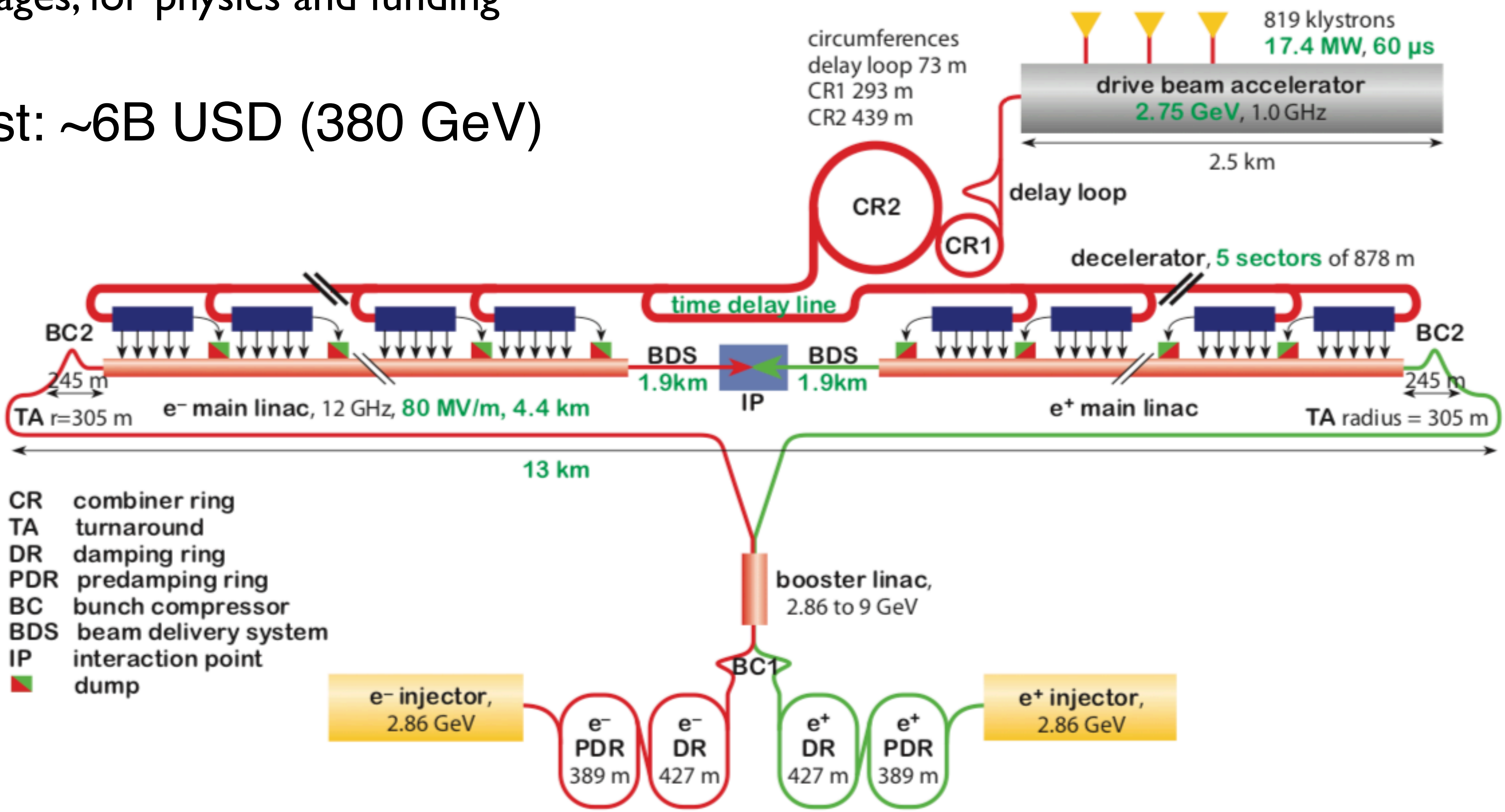


Proposed Future Experiment: Main Players

CLIC (CERN):

- Linear collider with high gradient normal-conducting acceleration
- Ultimate: multi-TeV (3) e+e– collisions
- Use technology to overcome challenges
- Stages, for physics and funding

cost: ~6B USD (380 GeV)

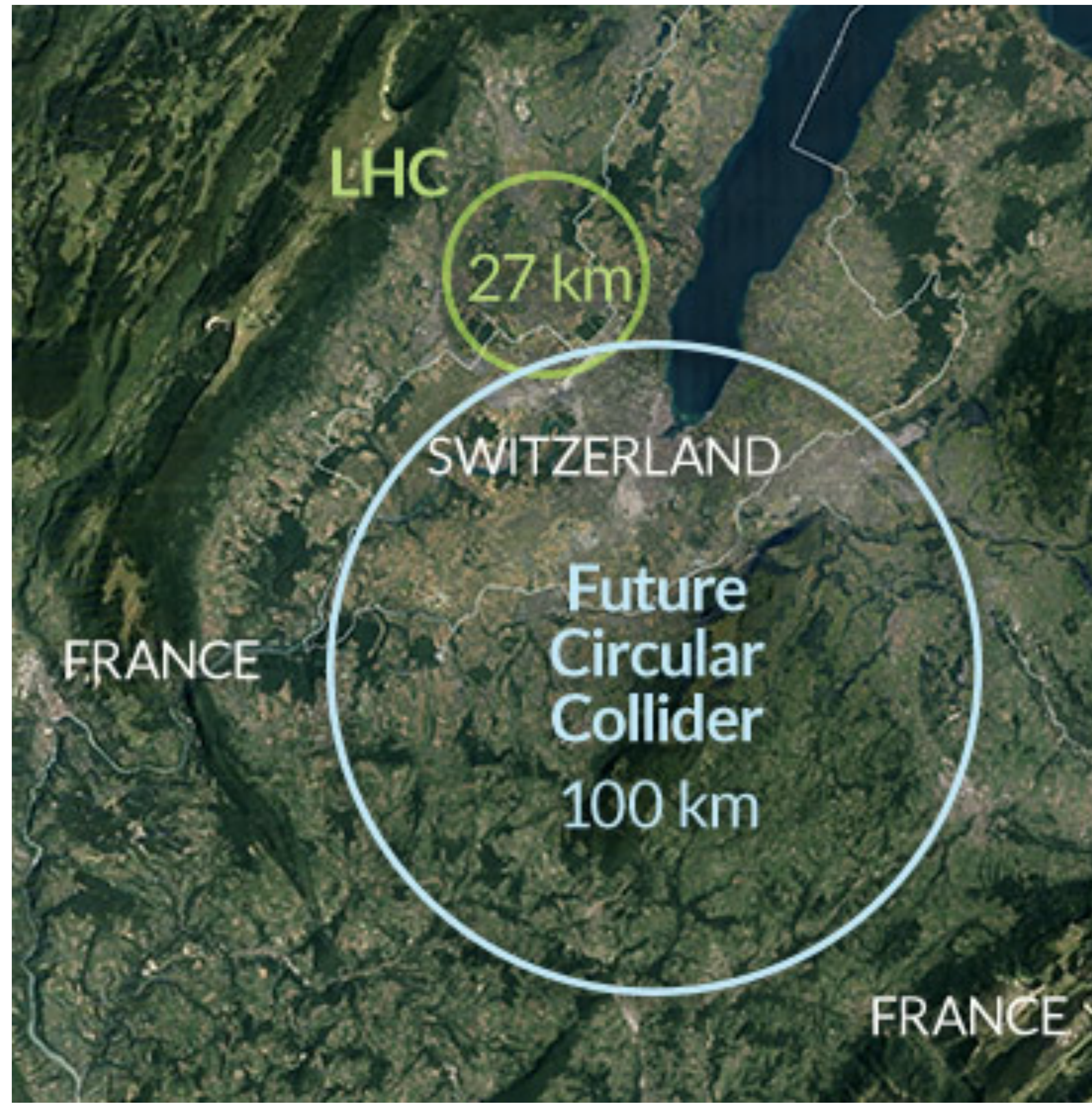


Proposed Future Experiment: Main Players

FCC-ee/FCC-hh (CERN):
CEPC/SppC (China):
Start as e+e- H factory
Protons to extend energy frontier
100 km ring with 16T magnets
Technology for ee: "standard"

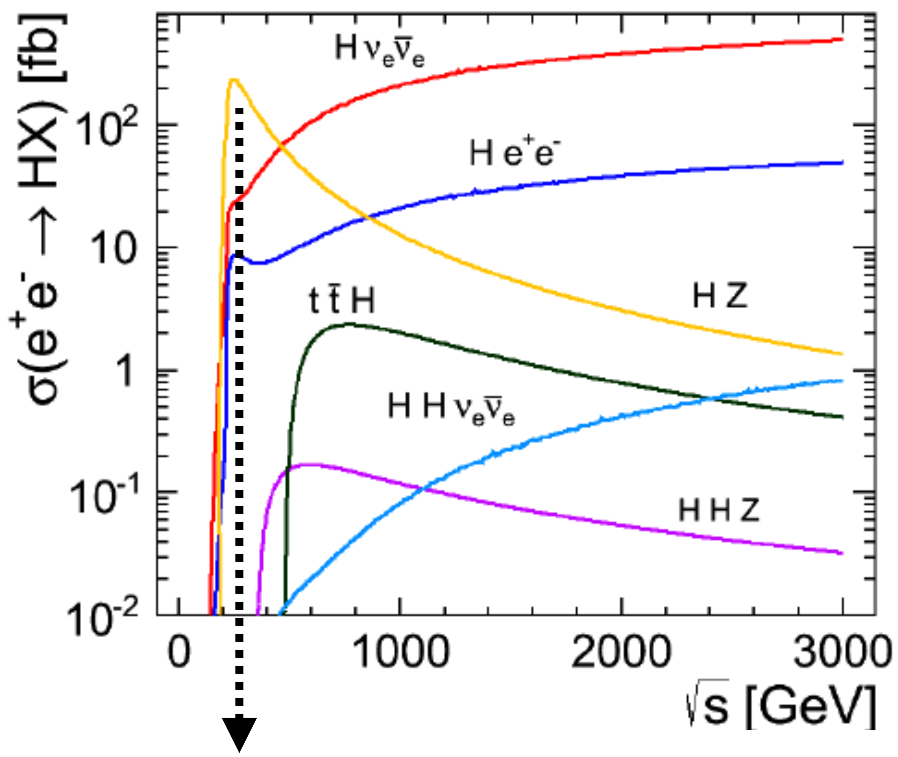
FCC-ee cost: ~11.6B USD
(7.1 is the tunnel)

FCC-hh cost: tunnel (above)
+ 17B

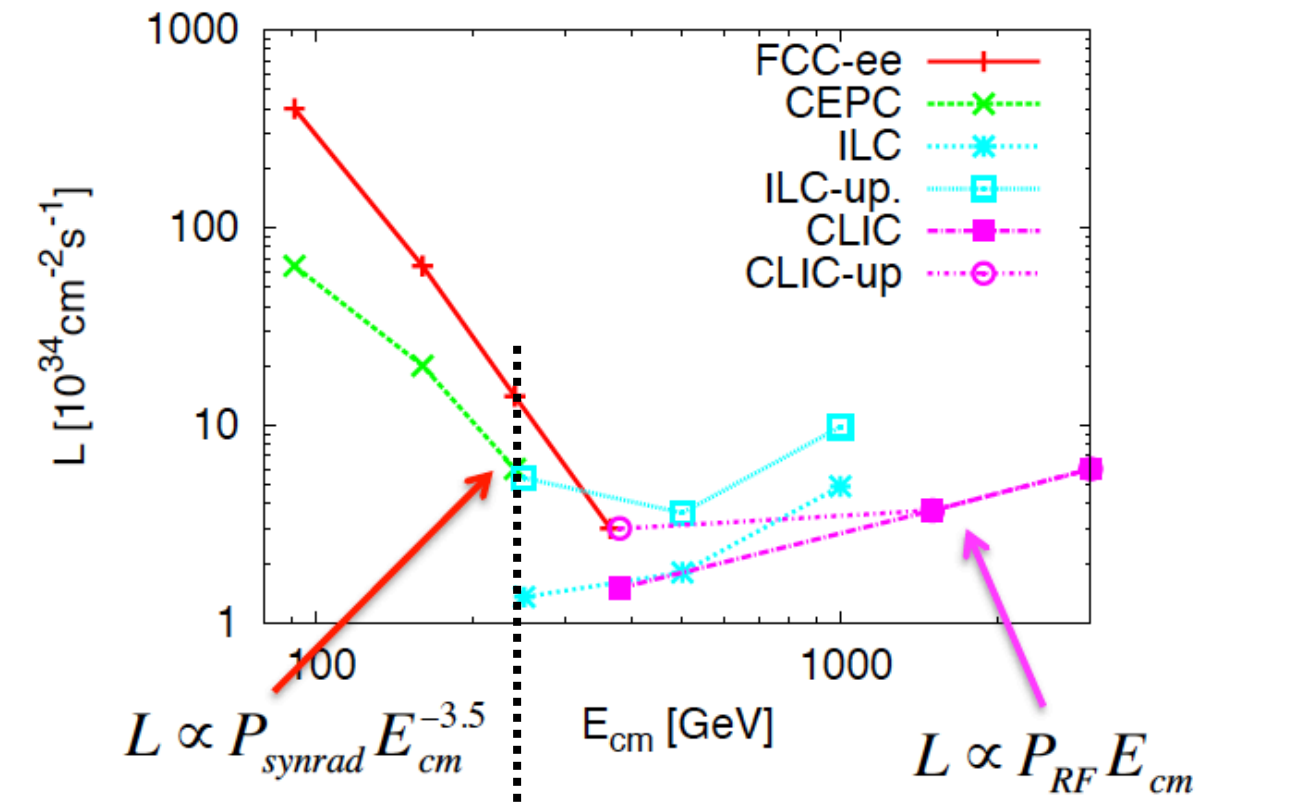


Stage-1: Higgs Factories

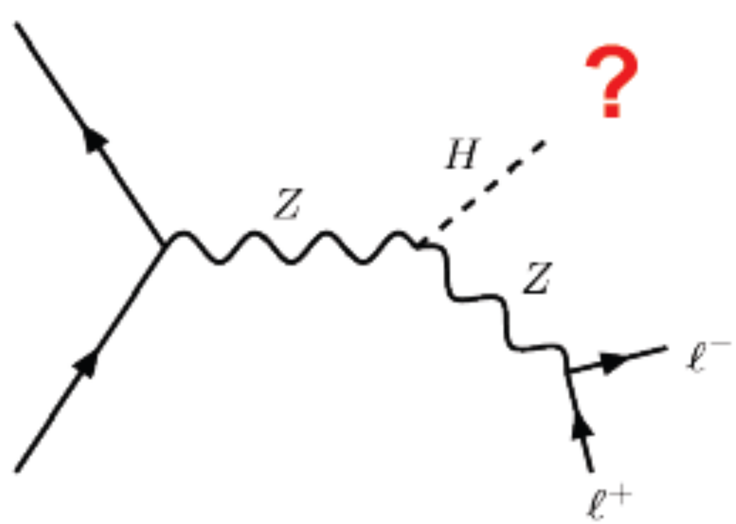
Higgs cross section vs energy



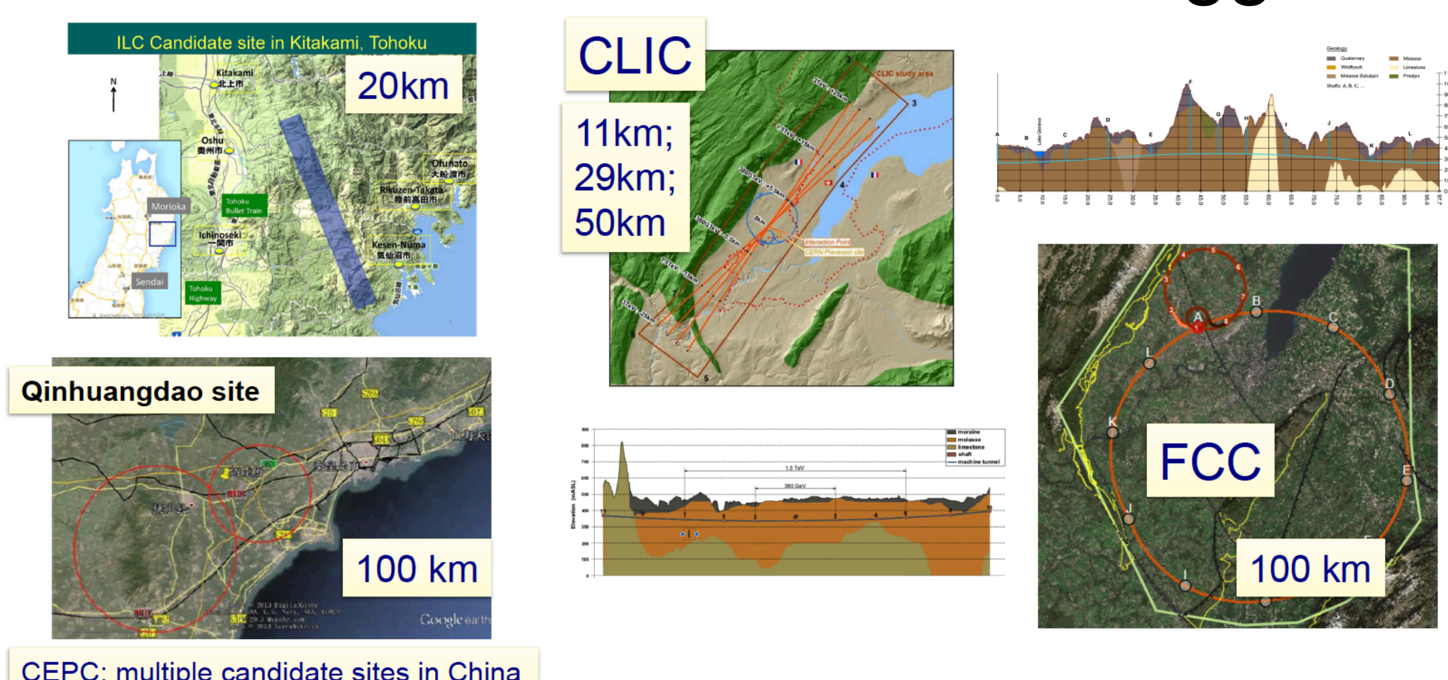
Accelerator luminosity vs energy



Higgs Factory

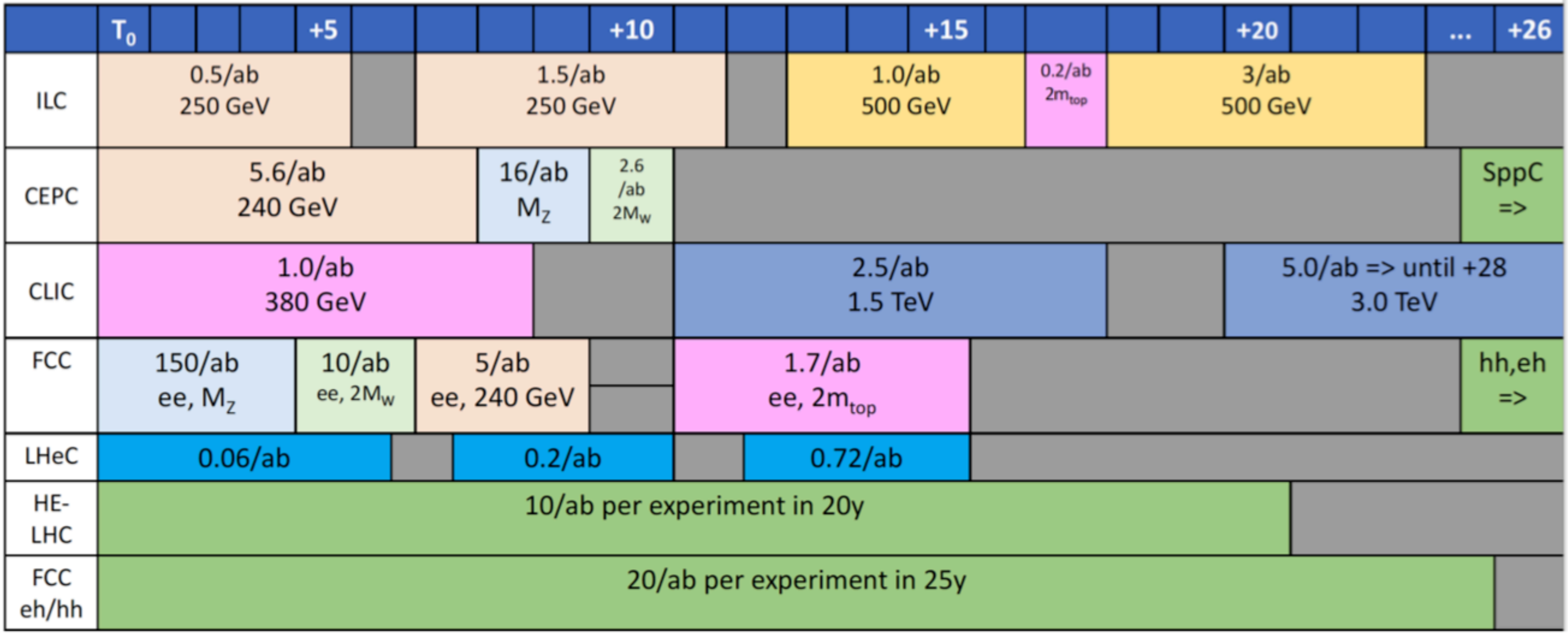


Higgs Factory



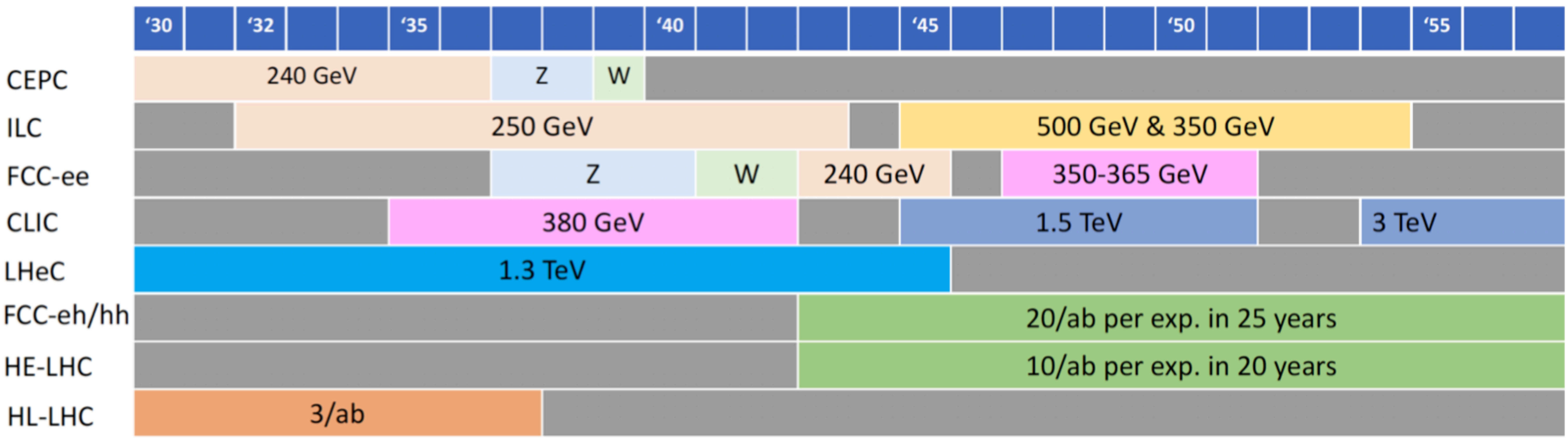
Timeline

Starting at T_0

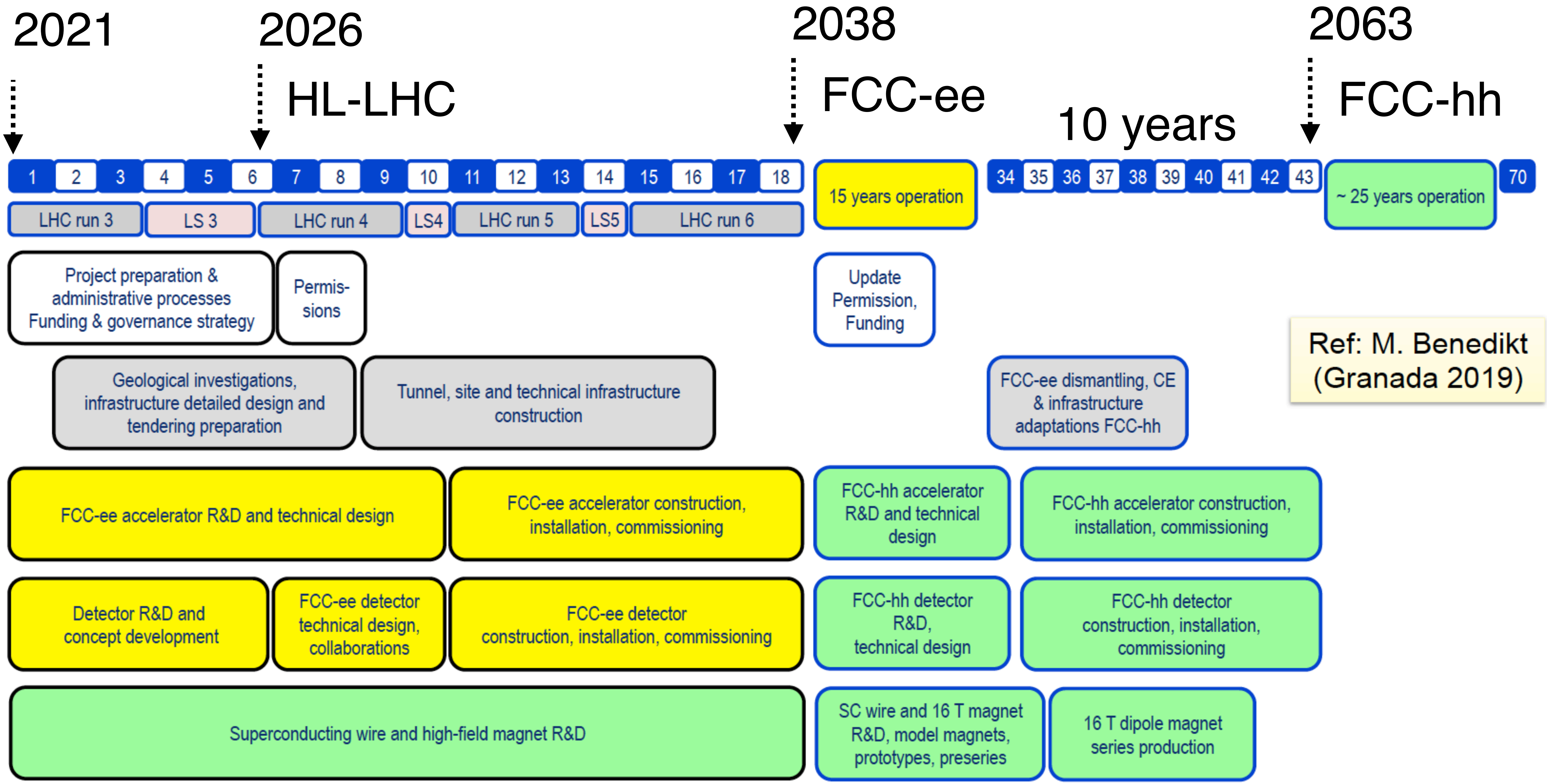


Timeline

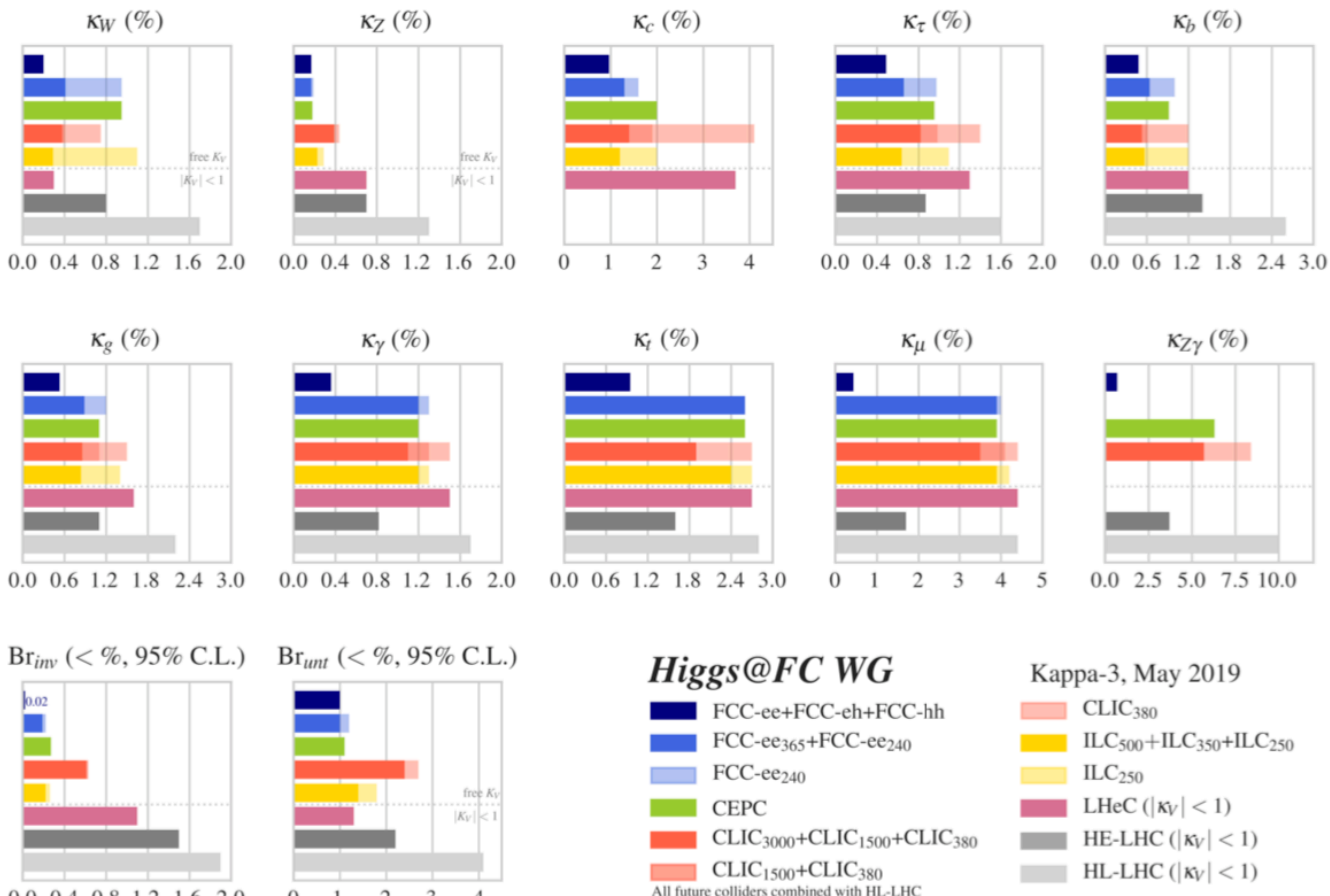
Starting at the earliest time (FCC-hh independent of FCC-ee):



FCC(CERN) vision of the next 70 years

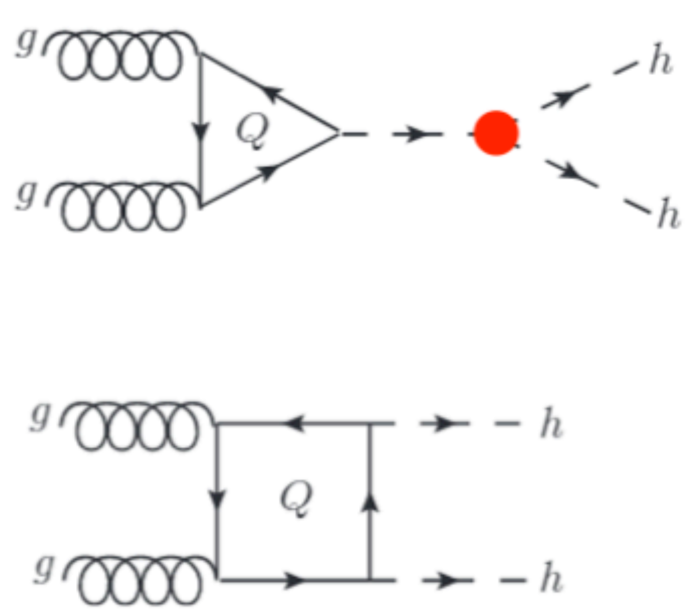


Precision of Higgs Couplings at Future Colliders

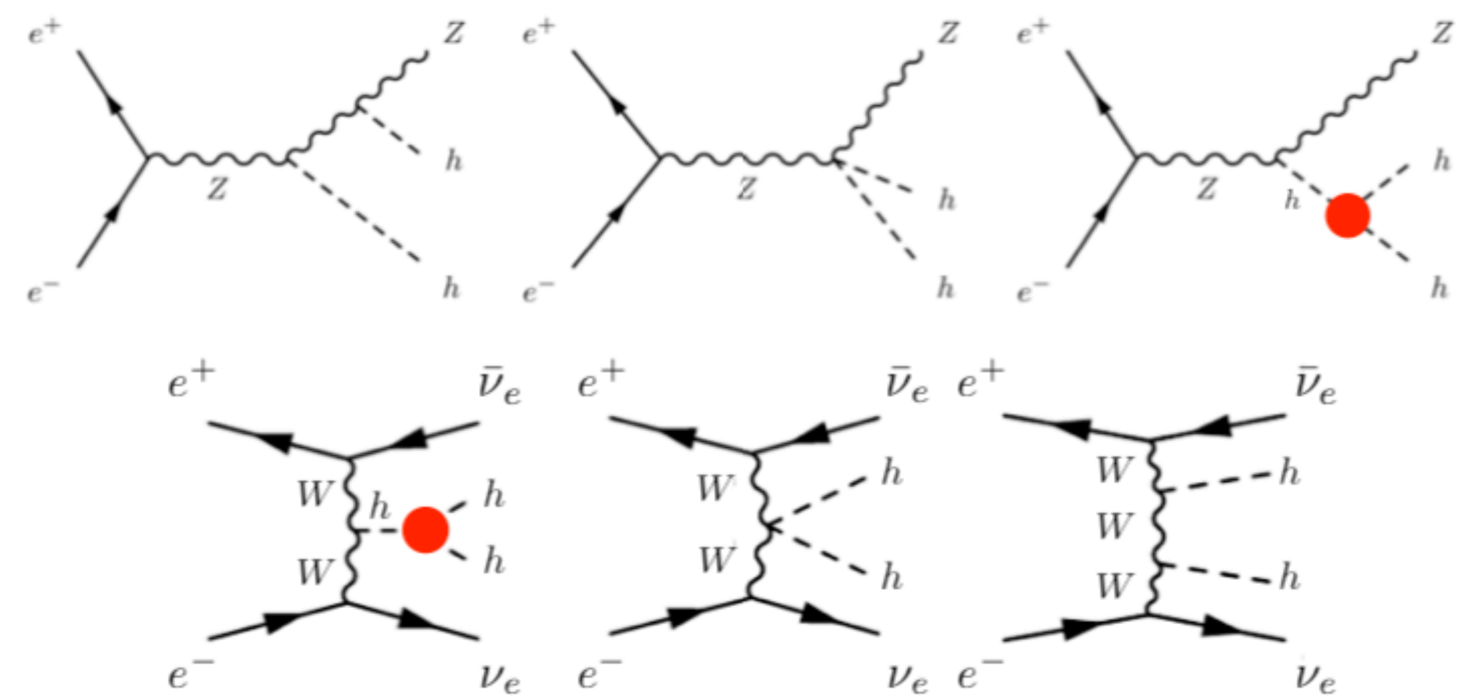


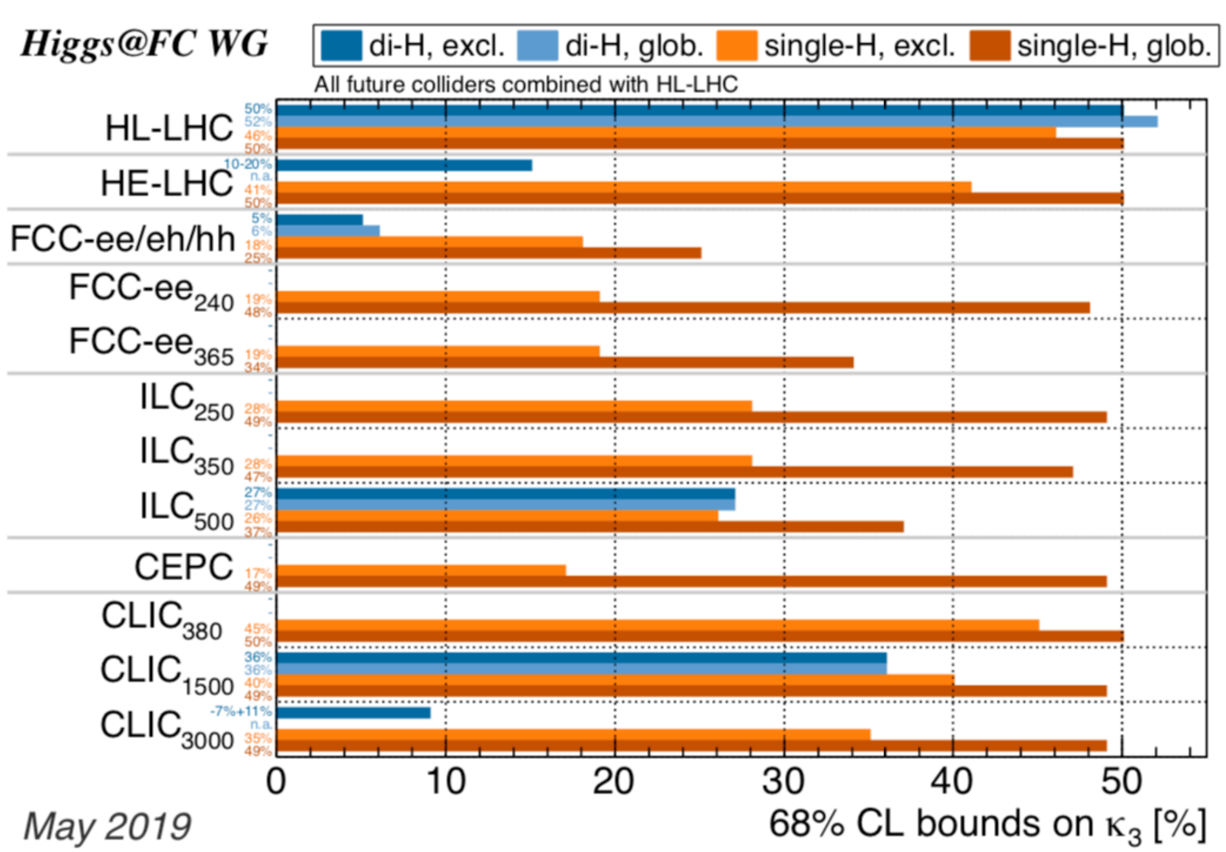
Higgs self-coupling and potential

Hadron collider



Lepton collider





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

Future of Higgs Physics

- Higgs is fundamentally new state mass-energy

  — a lot to be understood

  — rich program with LHC (till ~2024) and HL-LHC (till ~2038)

  — a lot of thinking about the next steps

  — two major directions of thinking (both Europe and Asia)

  (A) linear e+e- collider as a Higgs factory
  staged to longer baseline = higher energy

  (B) circular e+e- collider as a Higgs factory
  staged to pp collisions = much higher energy reach

  it all comes down to cost / benefit analysis…

  — where does US stand?

The Future of Particle Physics: "Snowmass" process

1982: Concentrate on the next collider: The concept of the SSC was born.

1984, 1986 Snowmass Studies on SSC reference design and physics

1988: ***High Energy Physics in the 1990s***

Broader goal – more people (>500)

1990: ***Research Directions for the Decade***

Physics opportunities at the SSC + Complementary opportunities

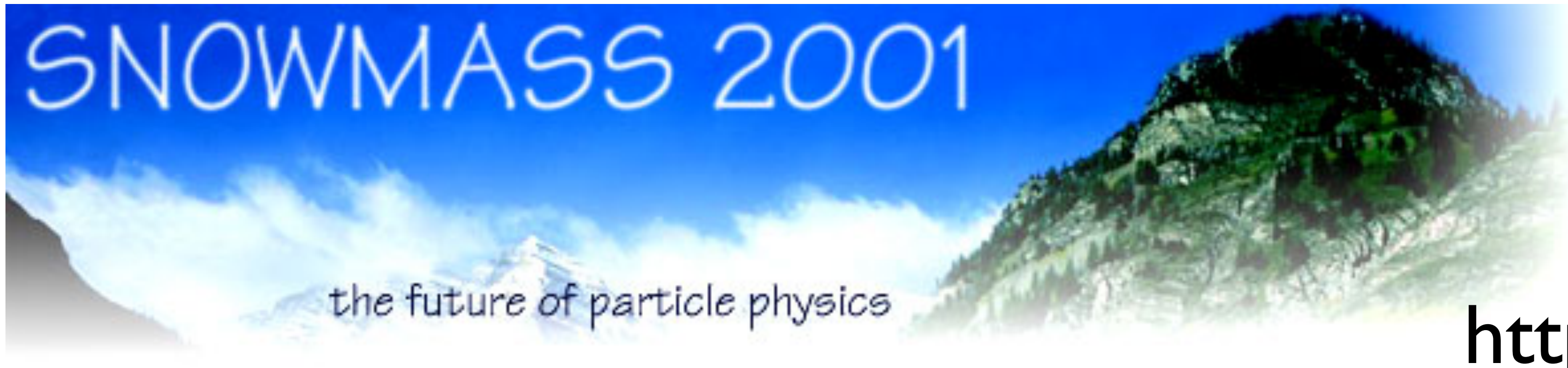
2001: ***A summer study on the future of particle physics***

2013: Similar in its scope to 2001, but spread out through the year

It has become a decadal community planning process

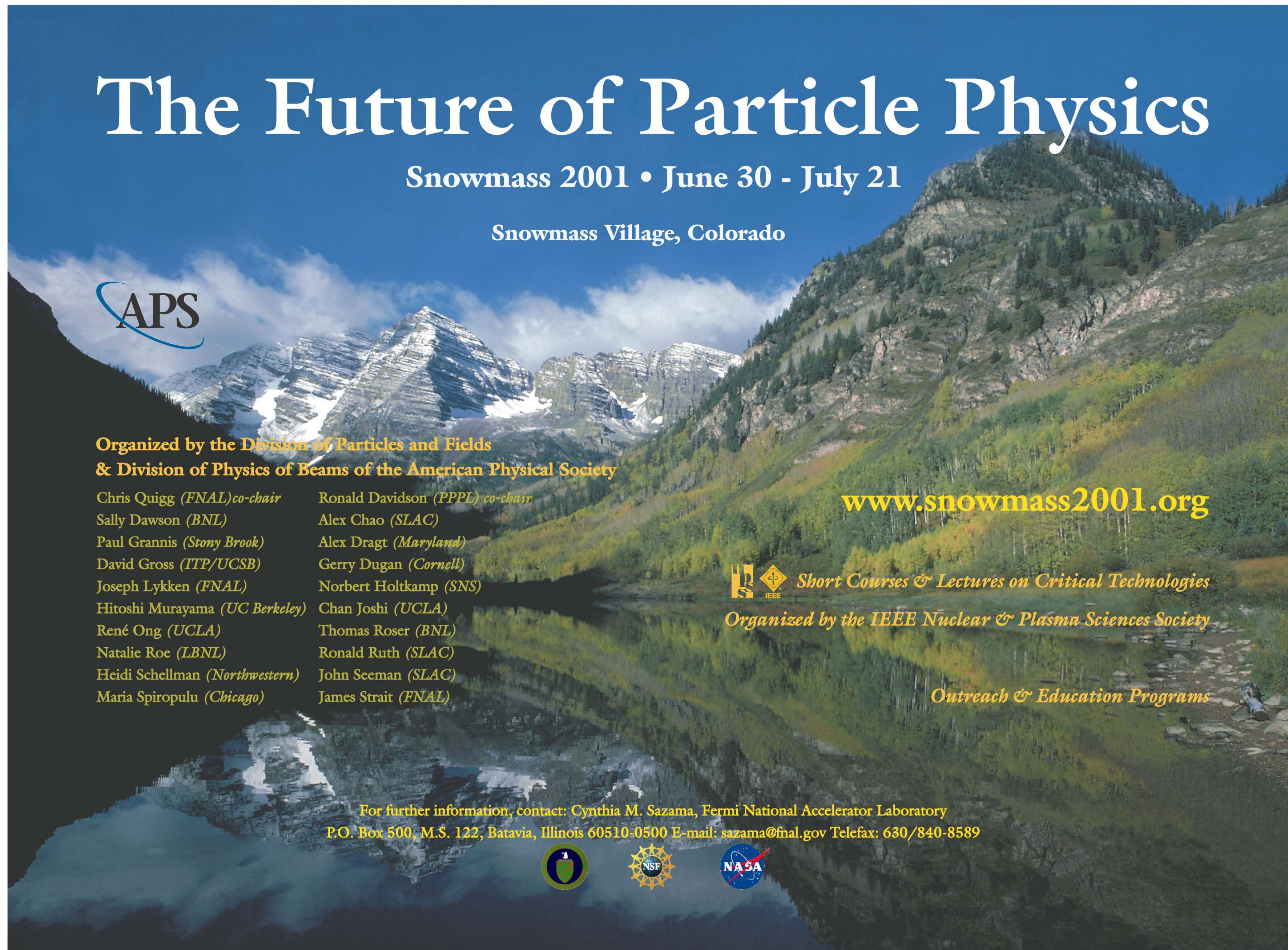
CMS: arXiv:1809.05937

The Future of Particle Physics: Snowmass 2001



http://www.snowmass2001.org

Organized by the **Division of Particles and Fields**
and the **Division of Physics of Beams**
of the **American Physical Society**



The Future of Particle Physics: Snowmass 2013

http://www.snowmass2013.org/

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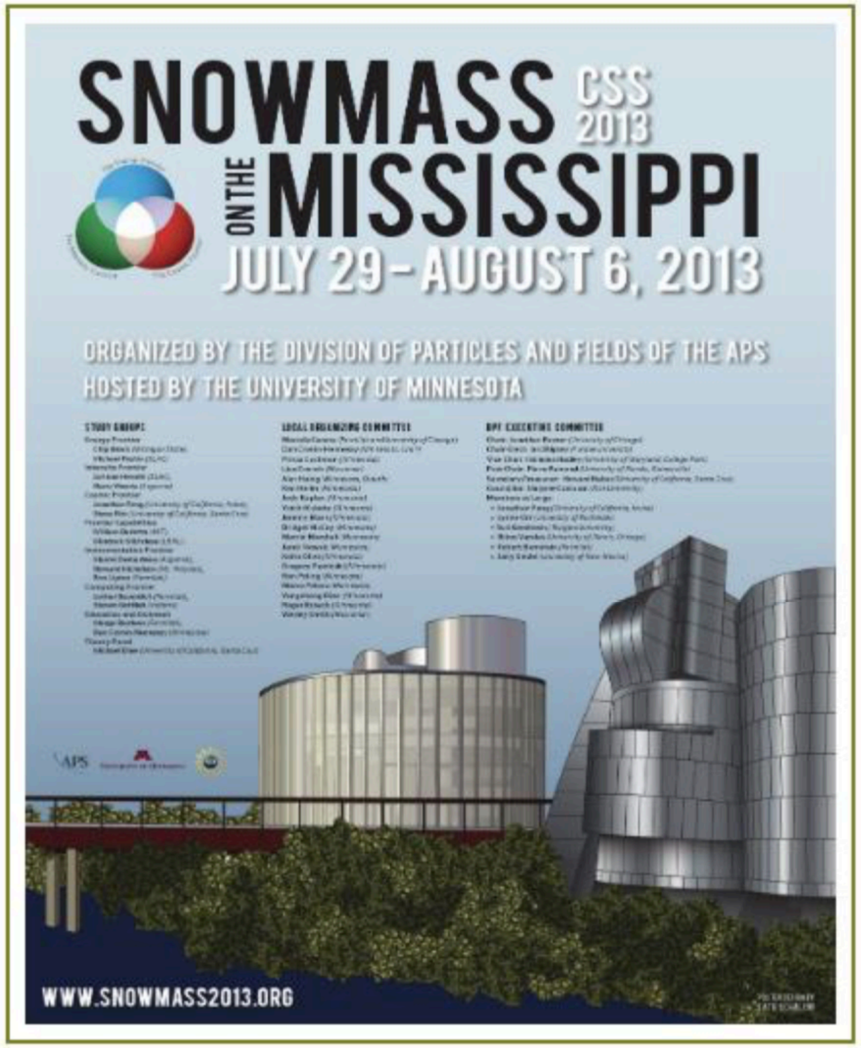
The owner of **snowmass2013.org** is offering it for sale for an asking price of 499 USD!

The Future of Particle Physics: Snowmass 2013



The planning process included more than a year of workshops. It presented a status of the field and exciting opportunities going forward. It did NOT prioritize

Charge: *The American Physical Society's Division of Particles and Fields is initiating a long-term planning exercise for the high-energy physics community. Its goal is to develop the community's long-term physics aspirations. Its narrative will communicate the opportunities for discovery in high-energy physics to the broader scientific community and to the government.*

The DPF is independent of funding agencies; free to define our science goals as a global community

Future of Particle Physics

2014 US strategic planning (P5), advise NSF and DOE through HEPAP
(P5 = Particle Physics Project Prioritization Panel)

- Use the Higgs boson as a new tool for discovery
- Explore the unknown: new particles, interactions, and physical principles
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation

- What is the nature of physics at the electroweak scale and beyond?
- What structures underlie the forces and matter in the universe?
- What is the nature of neutrino masses?
- What is the nature of dark matter in the universe?

Snowmass 2021

This is what we expect to happen:

Fall 2019: Finalize topics and cross-cutting categories,
Select conveners, call for site selection for summer 2021

Spring 2020: Secure funding for workshops and overall plan
Choose 2021 site, date, and duration

Fall 2020 – Spring 2021: Conduct workshops, prepare initial white papers

Summer 2021: Snowmass Summer Study.

Report due by December 2021

Parallel efforts in Europe and Asia…