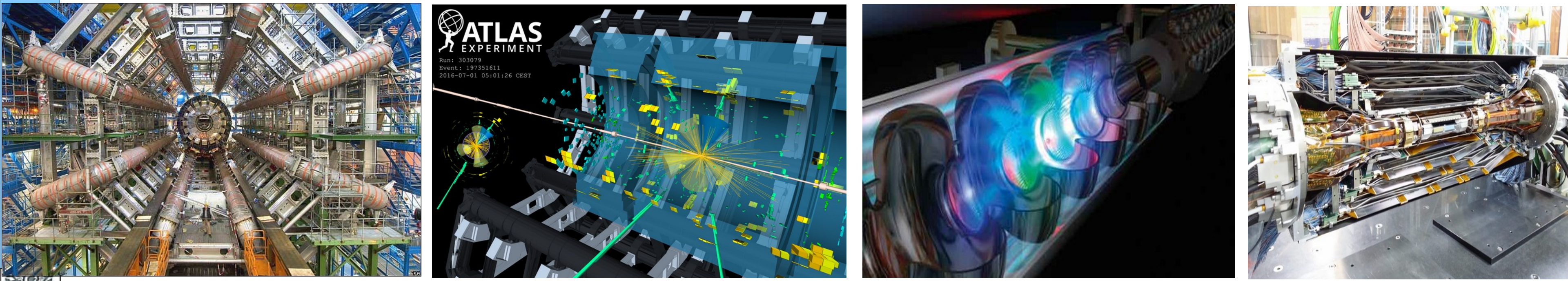
The next collider at the energy frontier: from accelerator and detector technology to the scientific programme

Lecture 2



Marcel Vos, IFIC (UV/CSIC) Valencia

Colliders

Timelines for colliders

Particle physics 1984-today

LEP/SLC (91-200 GeV e^+e^-, 1989-2005)

Tevatron (2 TeV $p\bar{p}$, 1983-2011)

SSC (40 TeV, cancelled 1992/3)

1984: first LHC workshop

1990: start of R&D programme

1994: LHC approved by the CERN council

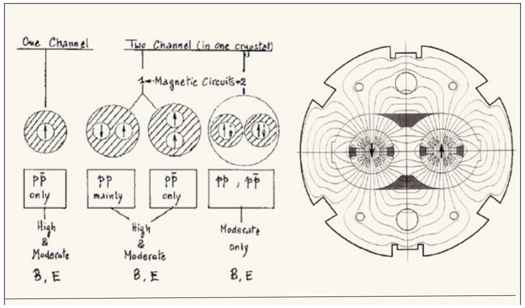
1998: start of civil engineering

2005: start of installation

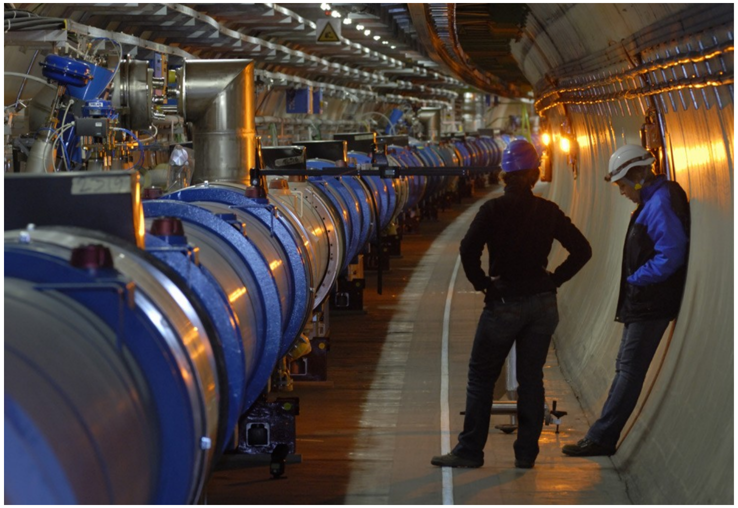
2008: a false start

2010: start of operation

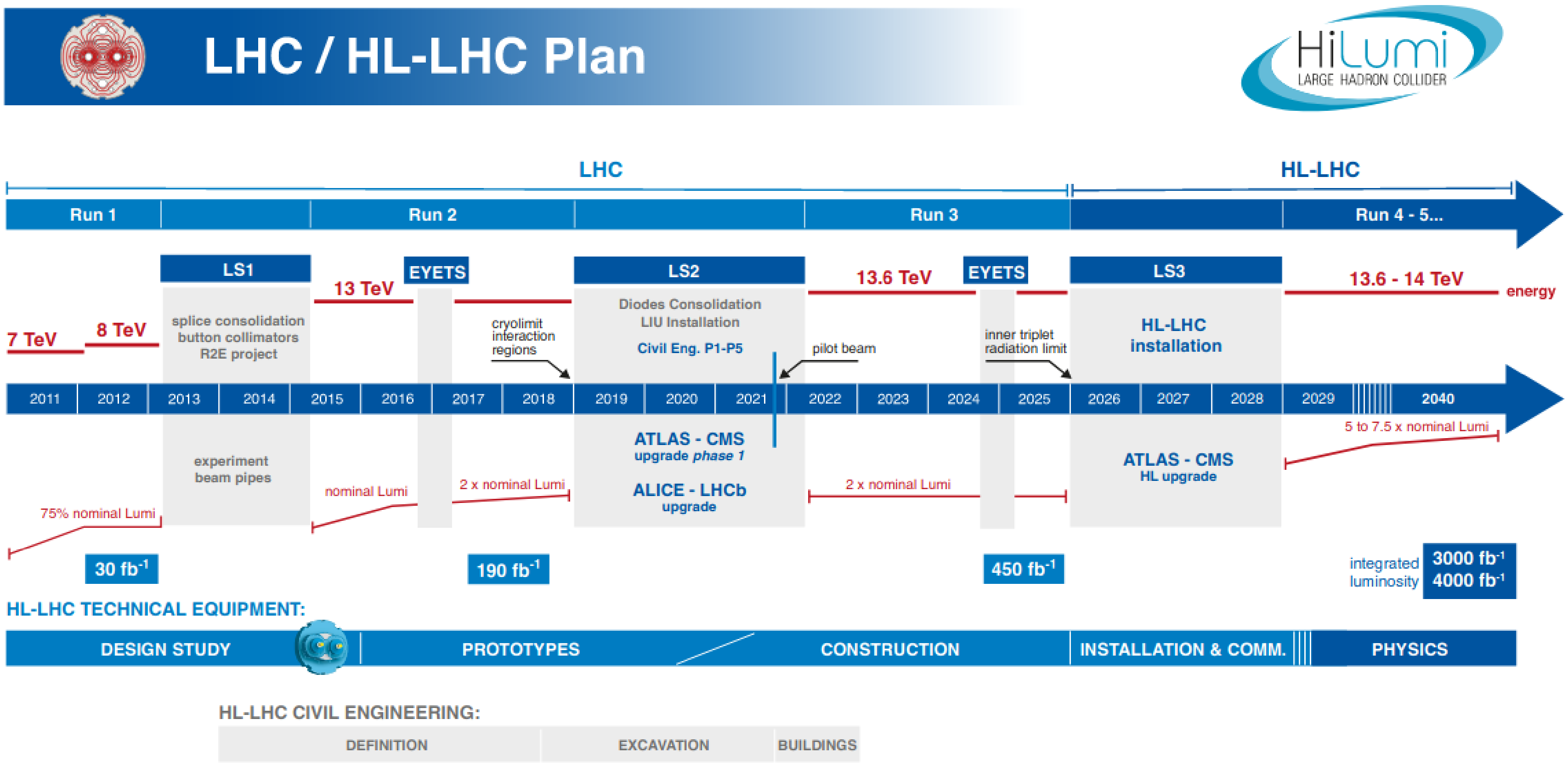
The Large Hadron Collider is the result of a tremendous collective effort over several decades



26 years

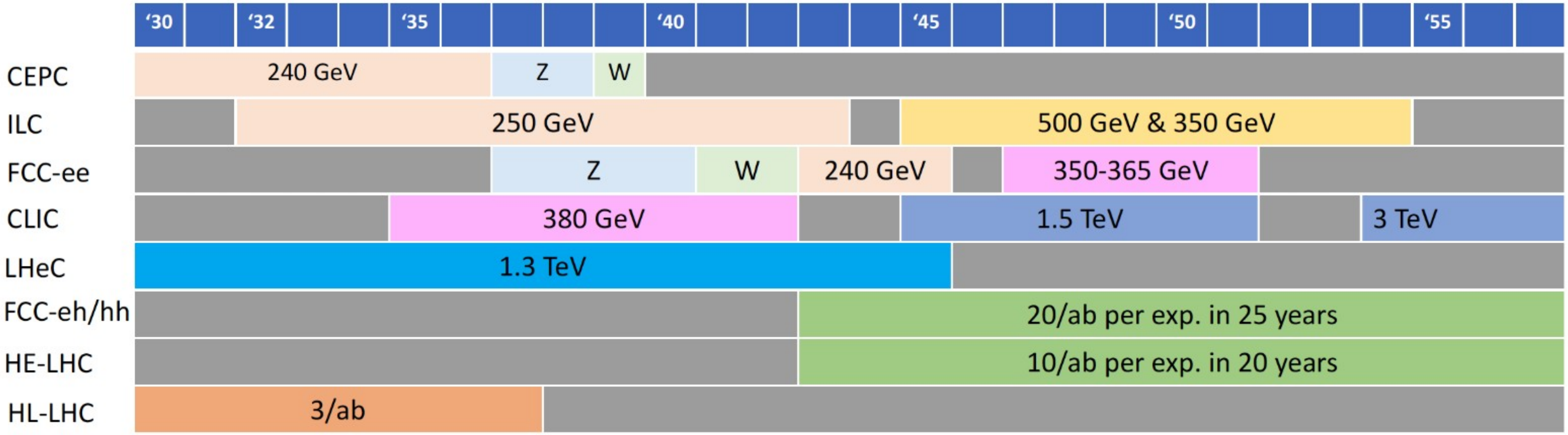


Particle physics today-2040



The Large Hadron Collider and its approved “high-luminosity” stage will remain the main game in town for another couple of decades

Future collider planning...



	'30		'32			'35					'40					'45					'50					'55		
CEPC	240 GeV							Z		W																		
ILC			250 GeV														500 GeV & 350 GeV											
FCC-ee								Z				W		240 GeV				350-365 GeV										
CLIC						380 GeV										1.5 TeV									3 TeV			
LHeC	1.3 TeV																											
FCC-eh/hh														20/ab per exp. in 25 years														
HE-LHC														10/ab per exp. in 20 years														
HL-LHC	3/ab																											

Future collider projects (even if limited to currently accessible technologies) may span most of the remainder of the century (i.e. FCCee+FCChh would reach 2085 in the most optimistic scenario)

Careful planning includes possible scenarios (concrete projects are discussed later) that allow us to adapt to new insights in the next decades

Expect the unexpected...

Despite the long lead times and the careful planning exercise, one paper can change the whole picture:

Confirmation of flavour anomalies...

See lectures by Diego, Marie-Helene, Andreas

Discovery of dark matter particle...

See lectures by Miguel, Gianpiero, Alberto

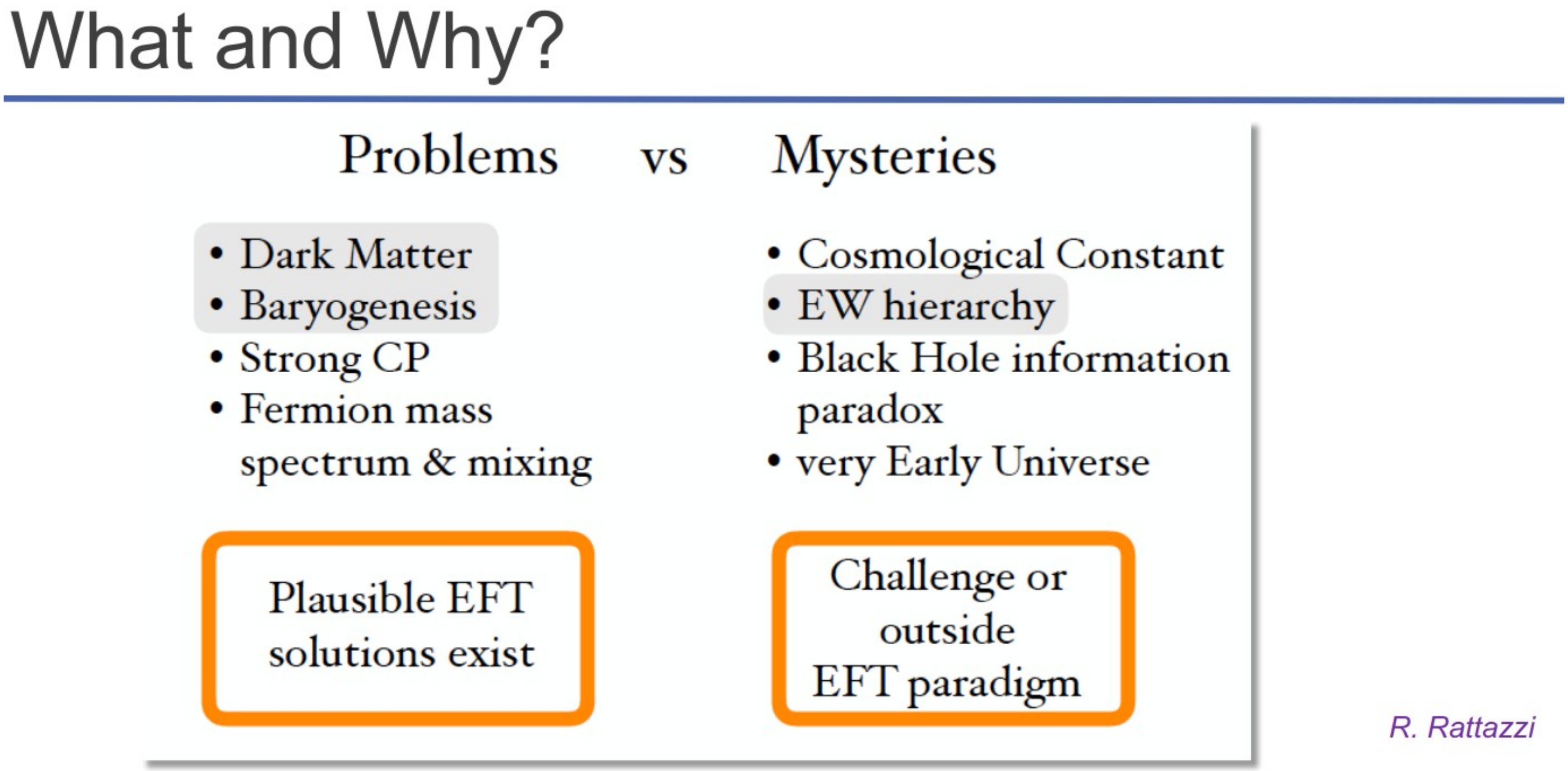
A “who ordered this” discovery…

But also: breakthrough in accelerator technology

Colliders

Particle physics, what’s next?

Big questions



What and Why?

Problems vs Mysteries

Problems	Mysteries
• Dark Matter • Baryogenesis • Strong CP • Fermion mass spectrum & mixing	• Cosmological Constant • EW hierarchy • Black Hole information paradox • very Early Universe
Plausible EFT solutions exist	Challenge or outside EFT paradigm

R. Rattazzi

From B. Heinemann, Granada meeting towards European strategy update

Possible experimental answers

An epoch of experiment-driven exploration….

The LHC had its “no-loose” theorem (either it discovers the Higgs boson, or rules out the existence of the SM Higgs boson and probes unitarity in vector-boson scattering)

The case for the LHC was boosted by (with hindsight unrealistic) expectations in some sectors about the discovery of SUSY partners, but this was not needed to convince the field of fundamental physics of its science case

The LHC made a significant leap in center-of-mass and integrated luminosity and thus improved our **BSM sensitivity** beyond that at previous facilities:

- Higgs boson (still experimentally BSM)
- New resonances
- New long-lived particles

- New SM processes
- New SM phenomena
- New SM precision measurements

Each of these novel studies in an unexplored energy/intensity regime could dig up a surprise

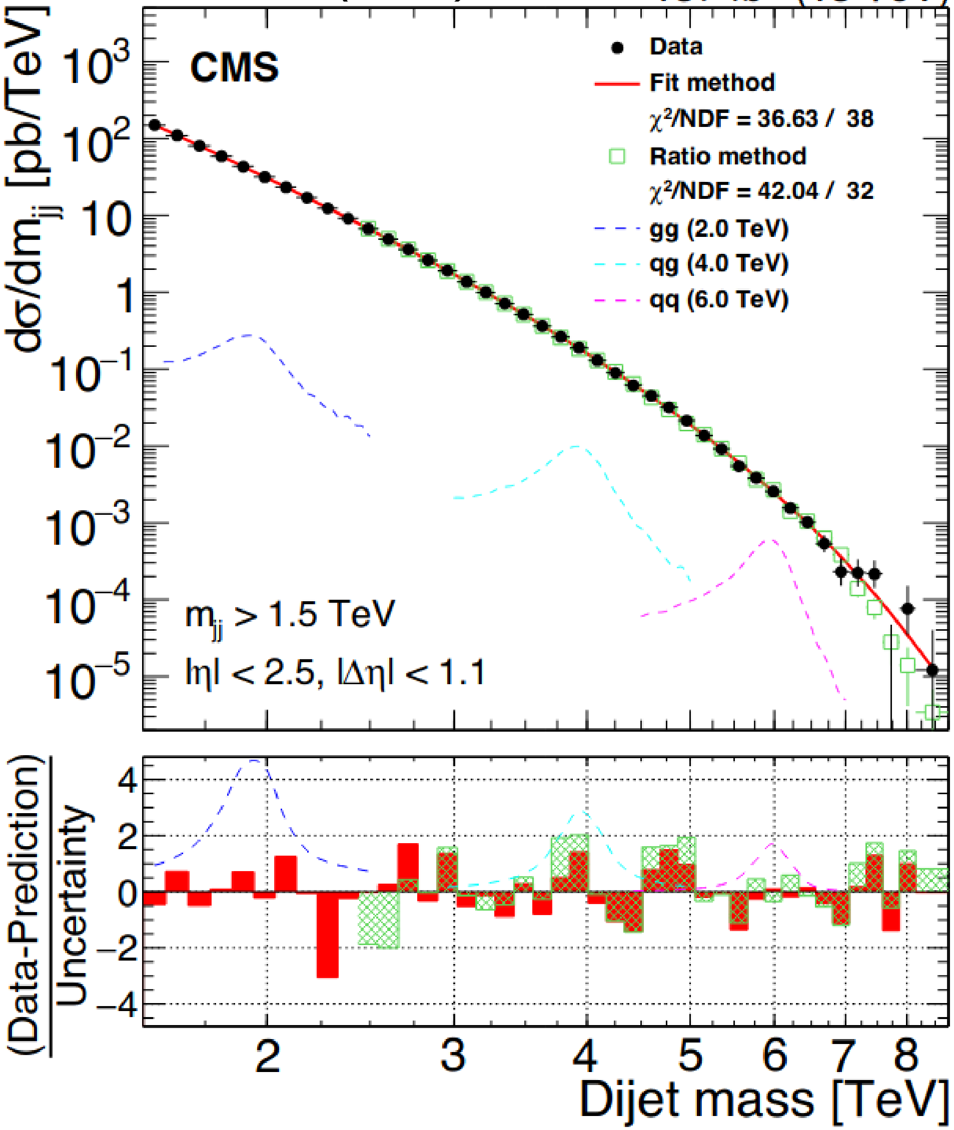
Look for a spectacular resonance

Di-jet resonance search, looking for massive new states that decay to jets

Reach all the way up to 8 TeV

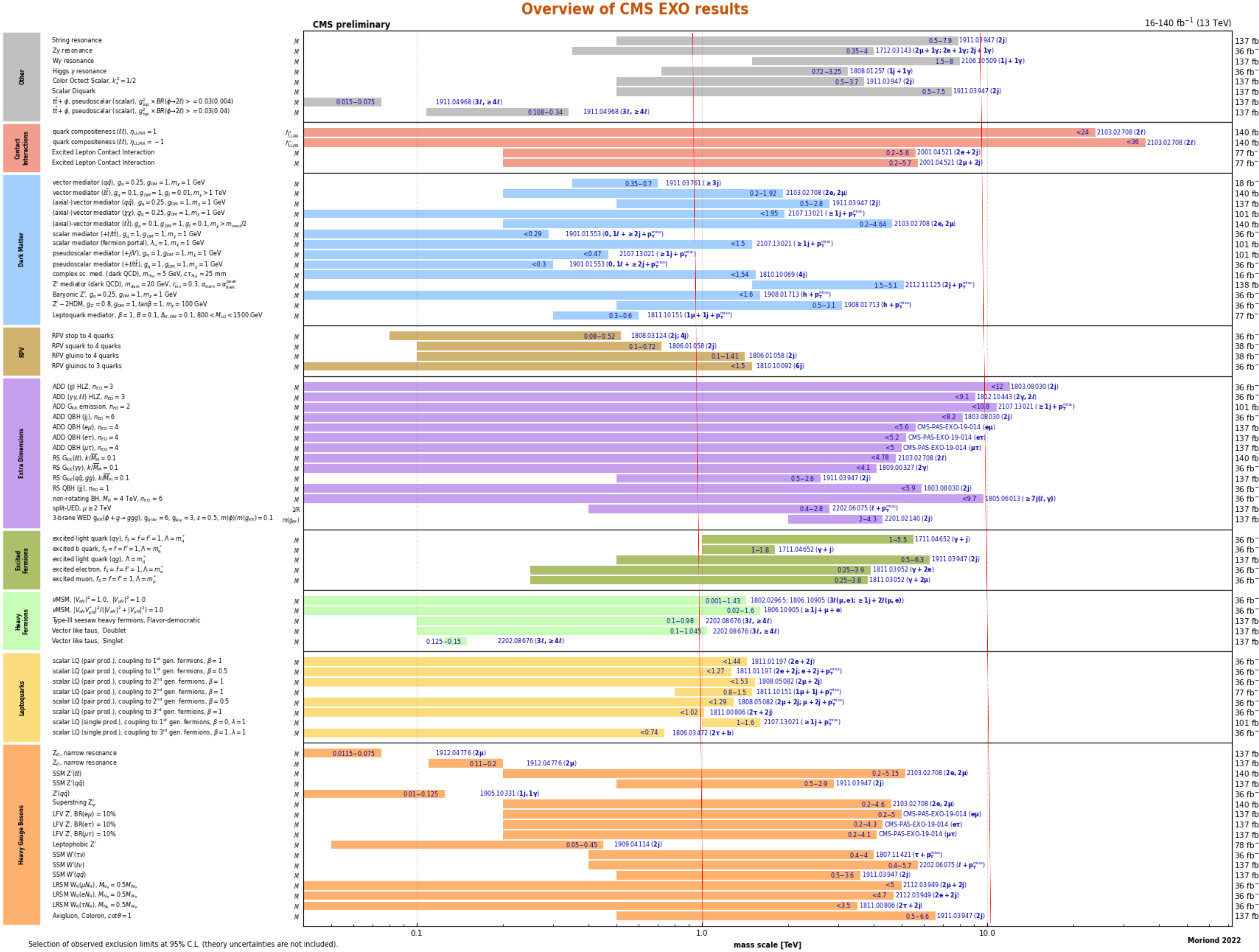
Yields tight limits on a variety of proposed extensions of the SM (including hypothetical particles that couple dark matter to SM)

JHEP05 (2020) 033



Leave no stone unturned

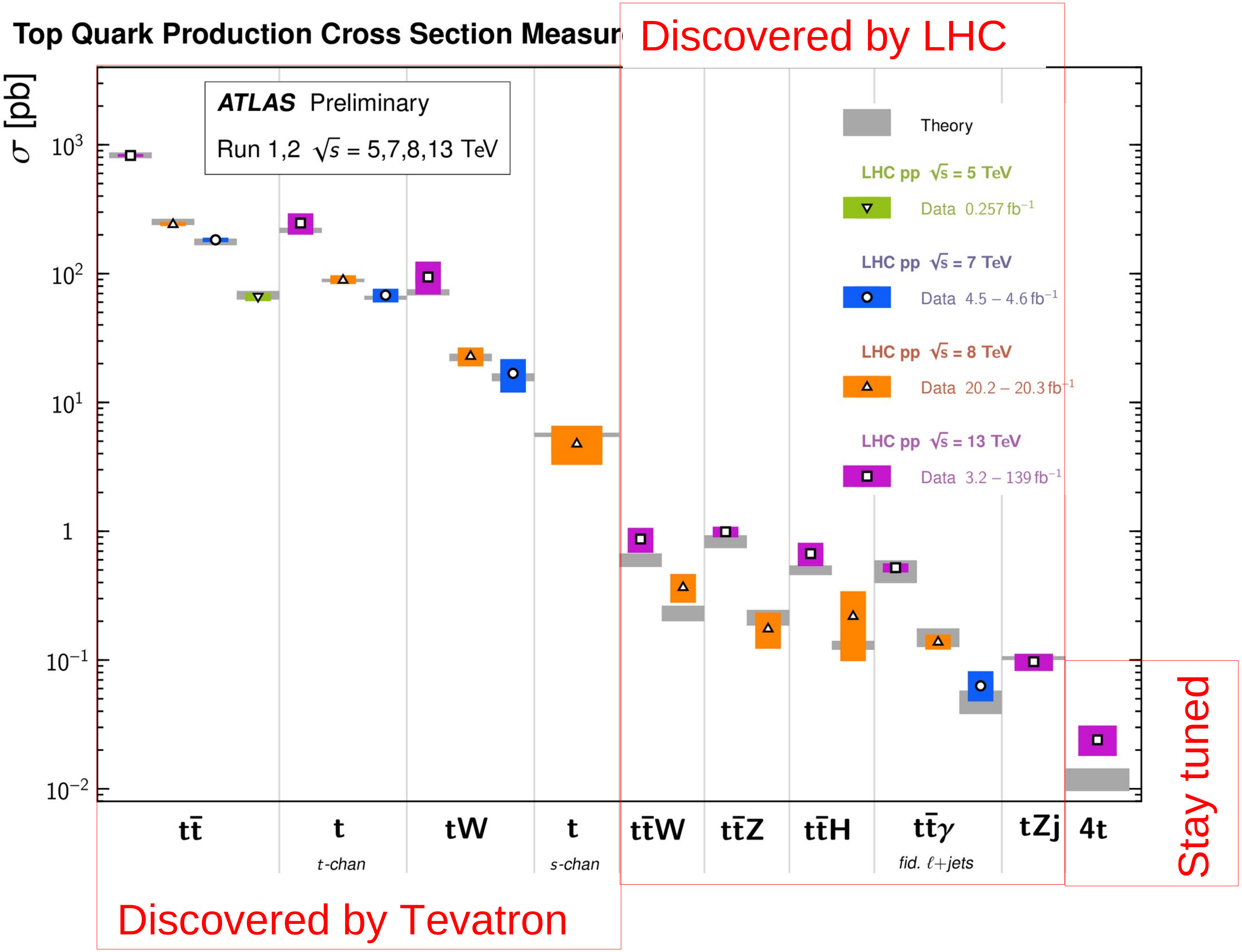
BSM scenarios, from Z' to LQ to dark matter



1.0 TeV **10 TeV**

More Standard **THEORY*** processes

* Paris Sphicas, ICHEP2020



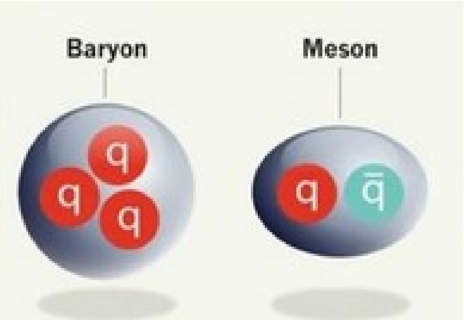
Discovered by LHC

Discovered by Tevatron

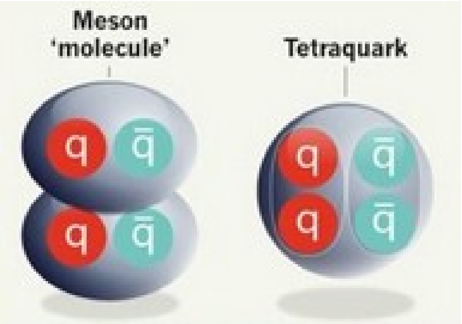
Stay tuned

ATLAS: observed: 4.7σ (expected 2.4σ)
CMS: observed: 2.6σ (expected: 2.7σ)

Exotic QCD: tetra-quarks!

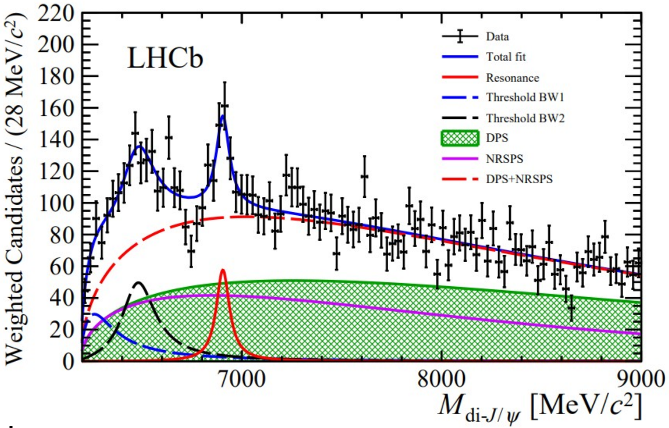


Textbooks: quarks are confined in colour-neutral bound states, as a triplet of quarks (baryon, i.e. p = uud) or as a quark-antiquark pair (meson, i.e. $K^- = u\bar{s}$)



B-factories: and tetra-quark and penta-quark states!!

2003: Belle finds the X(3872), PRL 91 (2003) 262001
… Confirmed by many experiments
… Many more states found: Y's, Z's
… Measurement of many properties
… Debate: proper tetraquark or meson molecule?
2020: LHCb announces the charming T_{cccc}
2022: LHCb finds pentaquark + pair of tetraquarks



New family of (composite SM) particles!!

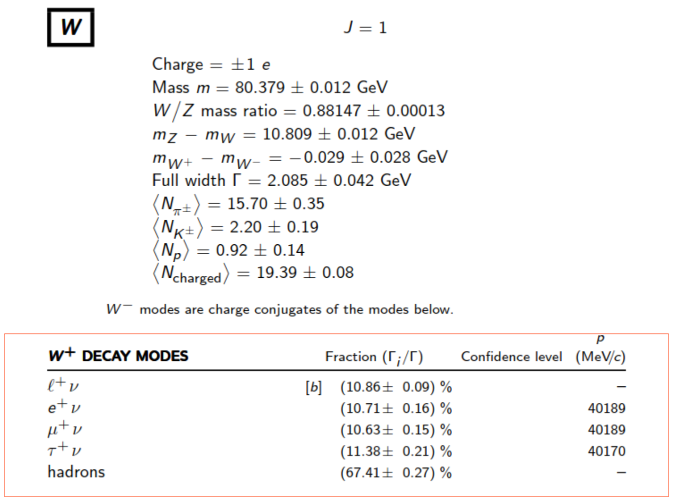
Niels Tuning: "Particle Zoo 2.0"
https://home.cern/news/news/physics/lhcb-discovers-three-new-exotic-particles

Known processes – put to a new use

Known processes in incredible numbers:

pp → $t\bar{t}$ (discovered Tevatron 1995)

Particle Data Group Summary 2019



W $J = 1$

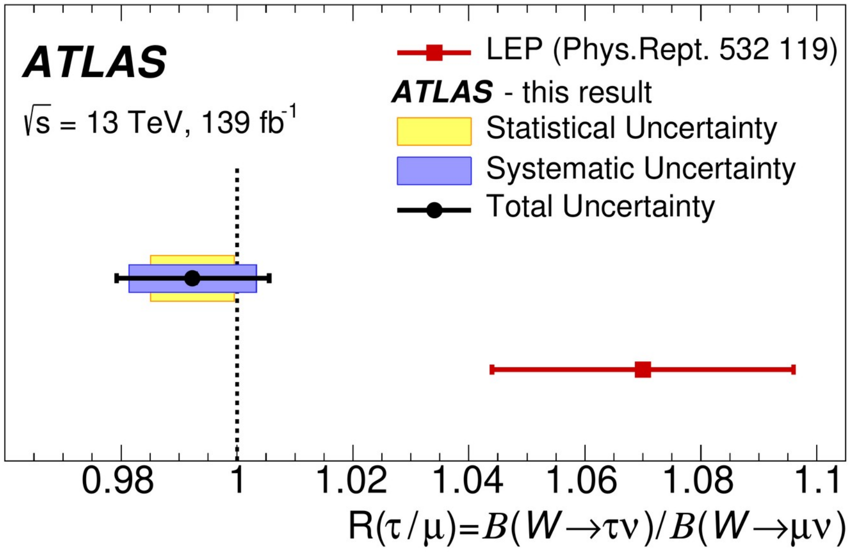
Charge $= \pm 1\ e$
Mass $m = 80.379 \pm 0.012$ GeV
W/Z mass ratio $= 0.88147 \pm 0.00013$
$m_Z - m_W = 10.809 \pm 0.012$ GeV
$m_{W^+} - m_{W^-} = -0.029 \pm 0.028$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_p \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

W^- modes are charge conjugates of the modes below.

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+ \nu$	[b]	(10.86 ± 0.09) %		–
$e^+ \nu$		(10.71 ± 0.16) %		40189
$\mu^+ \nu$		(10.63 ± 0.15) %		40189
$\tau^+ \nu$		(11.38 ± 0.21) %		40170
hadrons		(67.41 ± 0.27) %		–

LEP legacy: 2.7σ deviation

The ATLAS experiment, 2020



The incredible number of $t\bar{t}$ events, and a very good understanding of the detector, now allow the LHC to discard a persistent tension in the LEP legacy

SM EFT

The large number of precise measurements provides a powerful test of the SM

The SMEFT provides a convenient framework to order the data and search for patterns of deviations that could point to new phenomena

The SMEFT “expands around the SM”

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

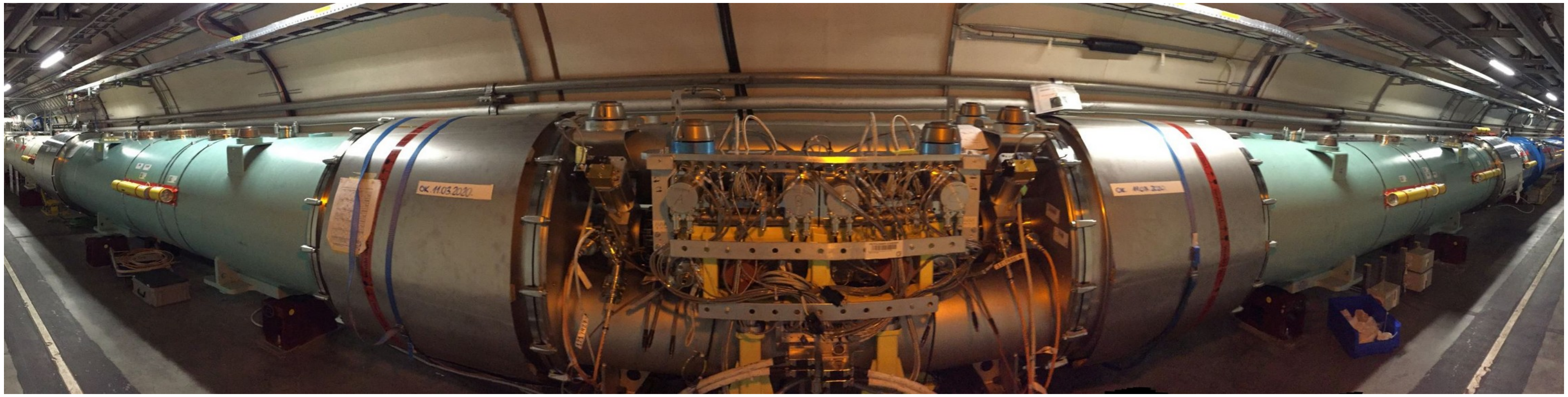
Scoring collider projects: bounds on Wilson coefficients C_i provide a good figure of merit for the “model-agnostic” BSM sensitivity of precision measurements at future colliders. Global fits to prospects measure the “breadth” of the programme, as well as the sensitivity of single measurements (see arXiv:2206.08326).

Analogy: Fermi’s theory of radioactive decay is a good example of an effective theory. He “integrates out” the W and Z bosons that would only become apparent at higher energy. The SM replaces this effective picture with a more complete theory and expands the energy domain it can be applied to. The SMEFT expands the SM yet one level higher.

HL-LHC prospects

https://arxiv.org/pdf/1910.11775.pdf

Long live the LHC



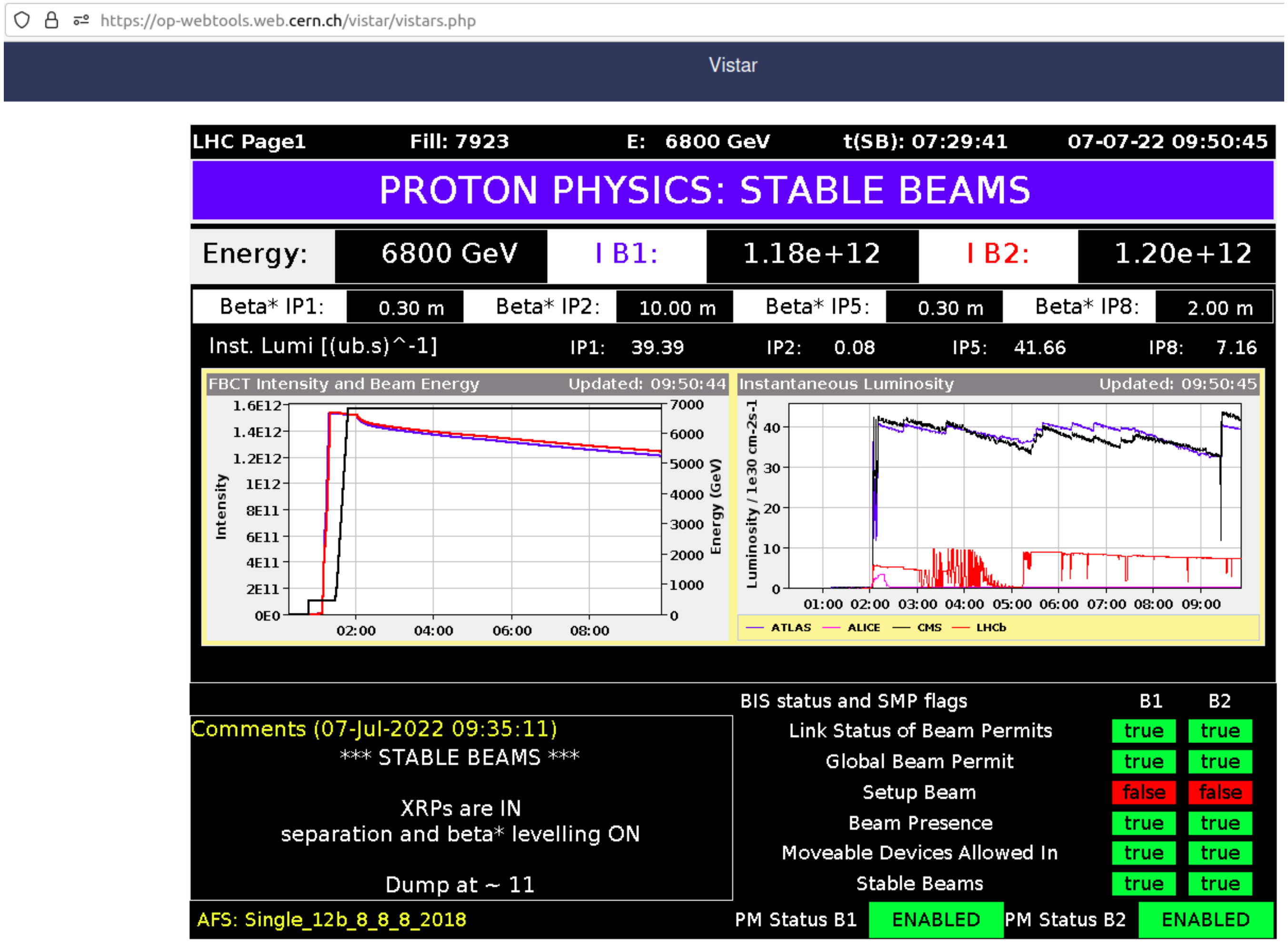
LHC run 2 ended in 2018 with 140 fb^{-1} at 13 TeV

LHC had a “long shutdown 2” to consolidate magnet connections

LHC run 3

See also https://www.youtube.com/watch?v=06kFq1QF5-s

Run 3 has started: LHC operation at 13.6 TeV
Collect O(10/fb) this year and 300/fb until 2025



LHC Page1 Fill: 7923 E: 6800 GeV t(SB): 07:29:41 07-07-22 09:50:45

PROTON PHYSICS: STABLE BEAMS

Energy:	6800 GeV	I B1:	1.18e+12	I B2:	1.20e+12

Beta* IP1:	0.30 m	Beta* IP2:	10.00 m	Beta* IP5:	0.30 m	Beta* IP8:	2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 39.39 IP2: 0.08 IP5: 41.66 IP8: 7.16

Comments (07-Jul-2022 09:35:11)
*** STABLE BEAMS ***

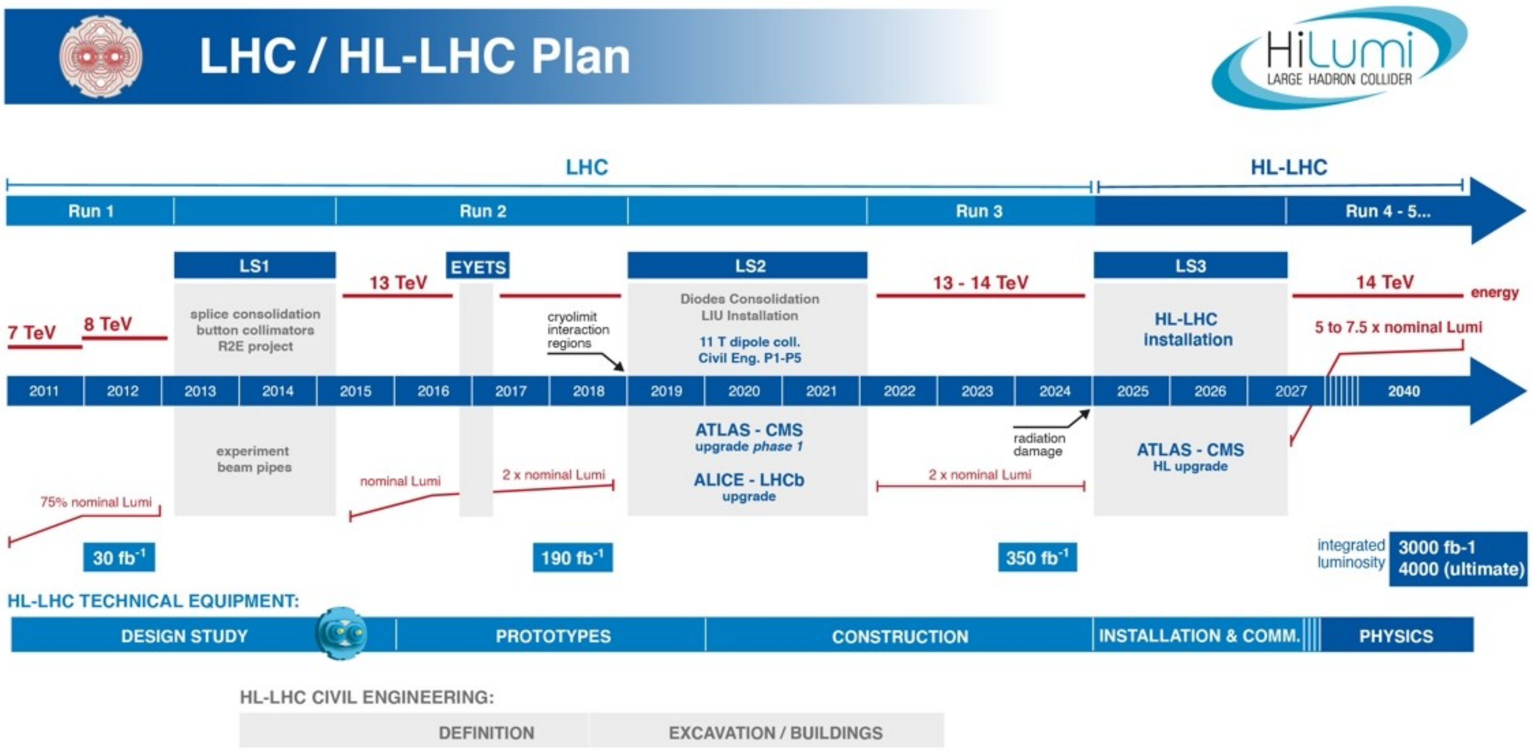
XRPs are IN
separation and beta* levelling ON

Dump at ~ 11

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_12b_8_8_8_2018 PM Status B1 ENABLED PM Status B2 ENABLED

High-Luminosity LHC



Preparation and excavation for the luminosity upgrade of the LHC ongoing

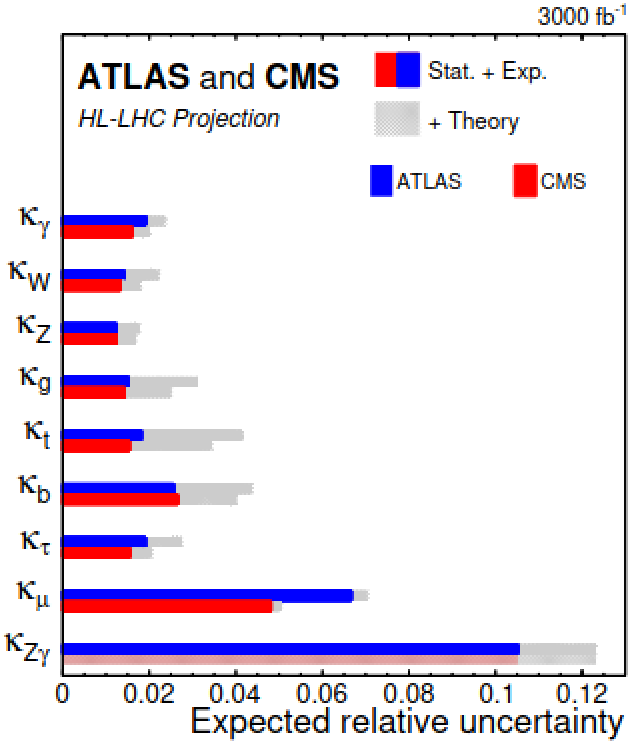
High-lumi operation 2027...2040 (20 more years!)

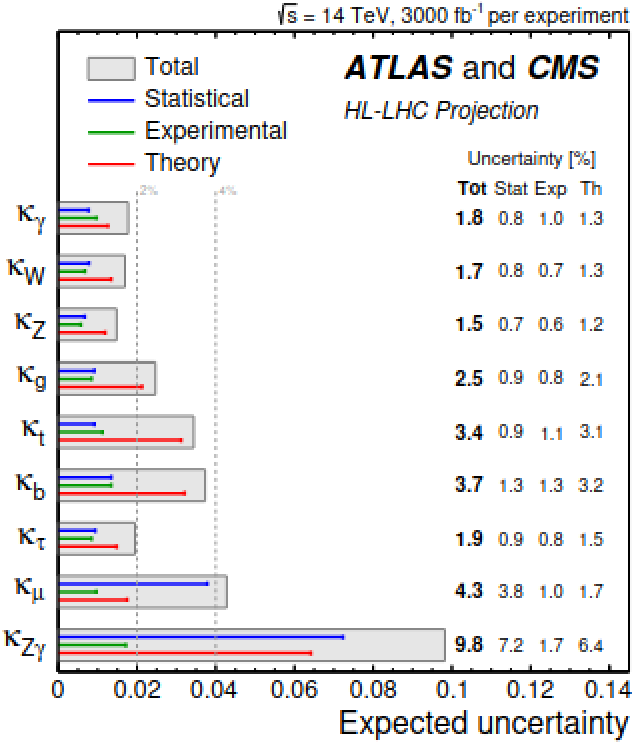
HL-LHC will deliver 3-4 ab^{-1} at 14 TeV (over 20 times the current data set)

Higgs boson summary

Projections for Higgs coupling measurements, derived in the “S2 scenario” and reported in the “kappa framework”

S2 assumes 3000/fb and progress on all fronts, halving theory uncertainties and scaling experimental uncertainties with 1/sqrt(L)





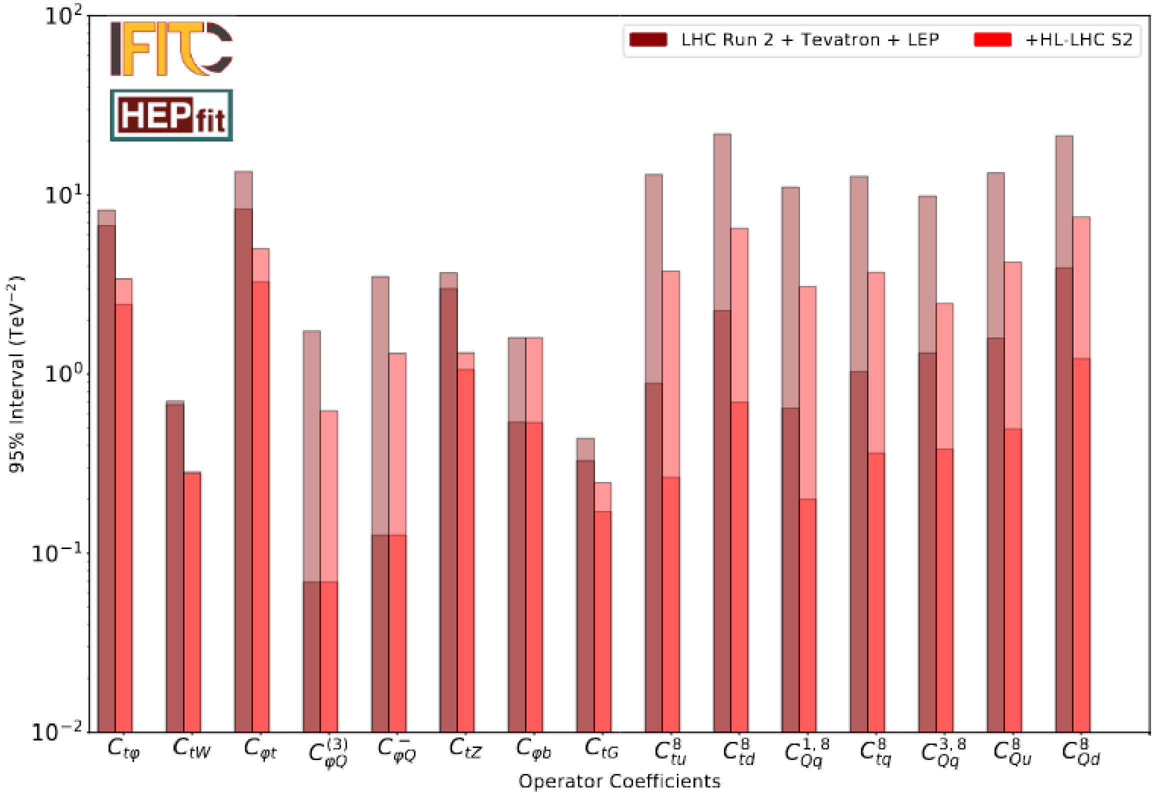
Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

CERN Yellow Rep.Monogr. 7 (2019) 221-584, arXiv:1902.00134

Top quark physics

The top quark is important for its own sake, and its connections to the Higgs sector



From:
arXiv:2206.08326

Based on
JHEP12(2019)098

🟥 Individual bounds
▨ Global bounds

HL-LHC can gain a factor 2-5 in all operator coefficients
EW couplings first measured at LHC, progress limited by theory
4-fermion operators qqtt driven by boosted regime (but poor global bounds)

How can new colliders help?

The 2020 update of the European Strategy for Particle Physics approved by the CERN council in May 2020 (and similar roadmaps from China, Japan and the US) provides a concise and clear answer:

“An electron-positron Higgs factory is the highest-priority next collider”

2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

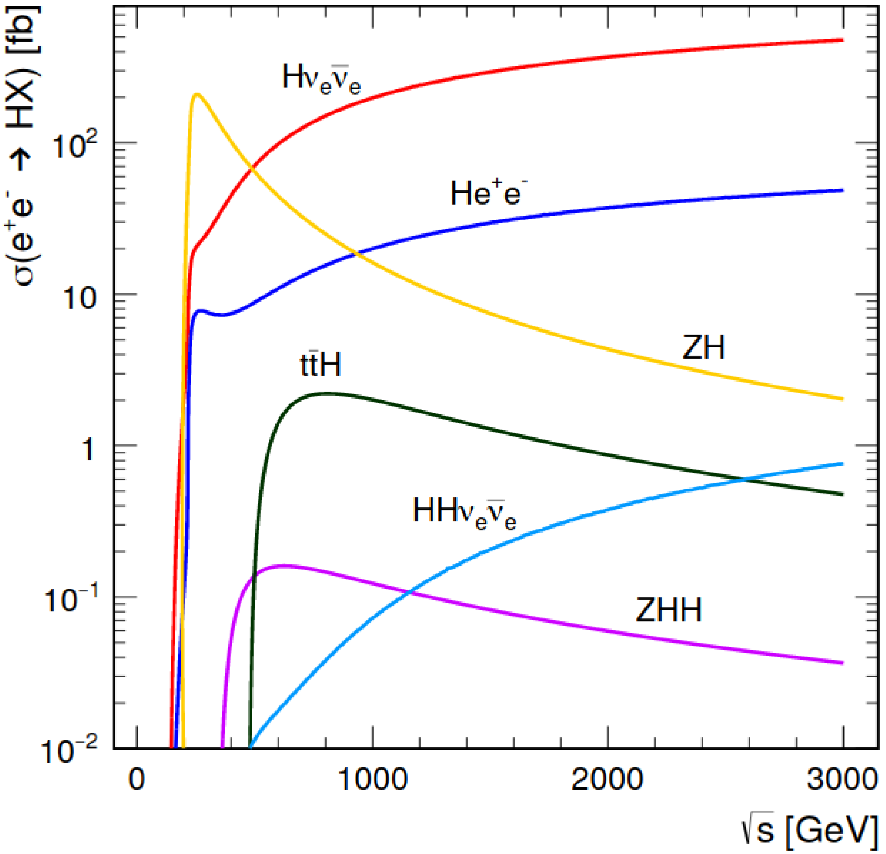
by the European Strategy Group

European Strategy
Update

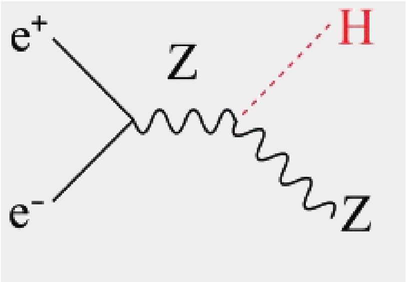
Never trust a one-sentence summary:

https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

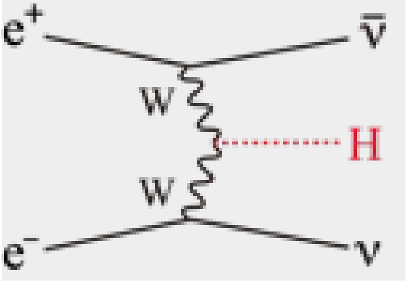
The electron-positron program



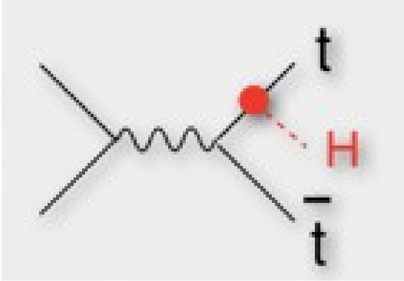
Higgs-strahlung



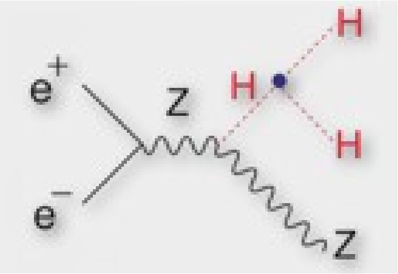
Vector-boson-fusion (VBF)



Associated production with a top quark pair



Di-Higgs production



Electron-positron collider projects

Four main contenders:

Project	**Type**	**Energy (GeV)**	**Design report**	**Host**
ILC	linear	(91)-250-500-1000	TDR 2012	Japan
CLIC	linear	380-1500-3000	CDR 2013	CERN
CEPC	circular	91-240-360	CDR 2018	China
FCCee	circular	91-240-365	CDR 2019	CERN

Four “Higgs/EW/top factory” projects.

Note: The CLIC Higgs factory stage operates at 380 GeV. FCCee stretches to reach the top threshold at 365 GeV, ILC/CLIC have a “GigaZ” option.

Luminosity vs. sqrt(s)

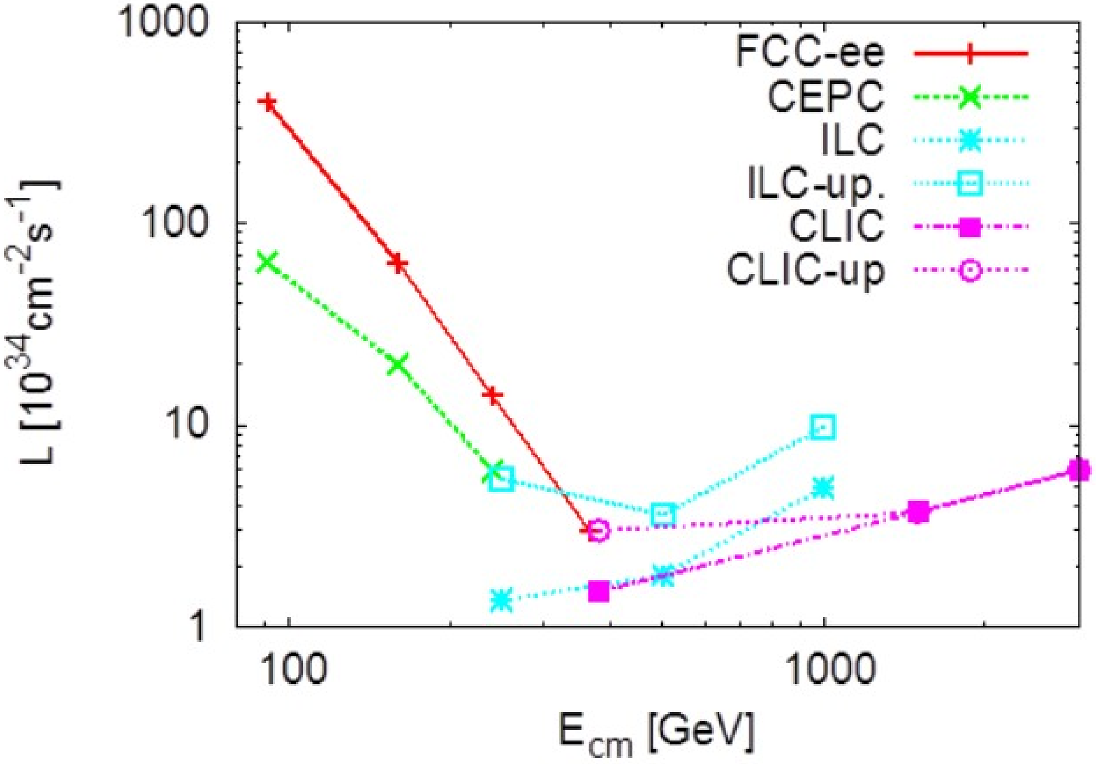
FCCee/CEPC clearly excell at low energy (10^{12} Z-bosons in a few years!)

Synchrotron radiation causes fast decrease of luminosity with sqrt(s) of circular colliders
For 100 km circumference, operation above ~360 GeV becomes very challenging

At linear colliders the luminosity increases
(~ linearly) with sqrt(s)

ILC/CLIC can access energies in range from 250 GeV to several TeV, but struggle at lower energy

https://arxiv.org/pdf/1910.11775.pdf



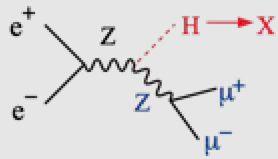
Note: there is a trade-off between luminosity and power consumption
Note: instantaneous luminosity must be folded with operation schedule

The next energy-frontier installation

One scientific goal – precision Higgs/top/EW physics. Projects for circular (FCCee, CEPC) and linear colliders (ILC, CLIC) cover the following

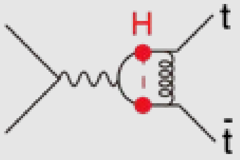
91 GeV *Giga or TeraZ (best in circular machines)*

- ➔ Ultra-precision electro-weak physics



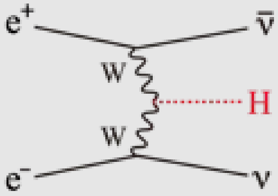
250 GeV *“Higgs factory”*

- ➔ Higgs boson couplings << 1%



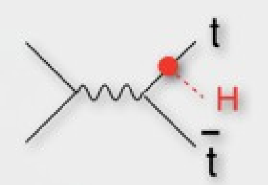
350 GeV *$t\bar{t}$ threshold*

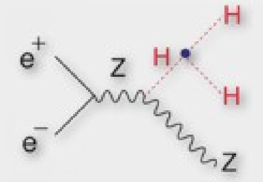
- ➔ Top precision (mass, α_s, top Yukawa)



500 GeV *(linear colliders)*

- ➔ Top Yukawa coupling $e^+e^- \rightarrow ttH$
- ➔ Higgs self-coupling $e^+e^- \rightarrow ZHH$



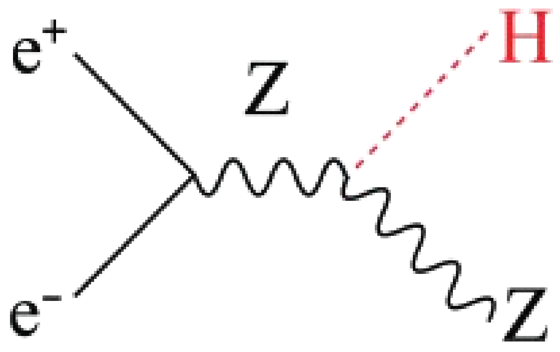


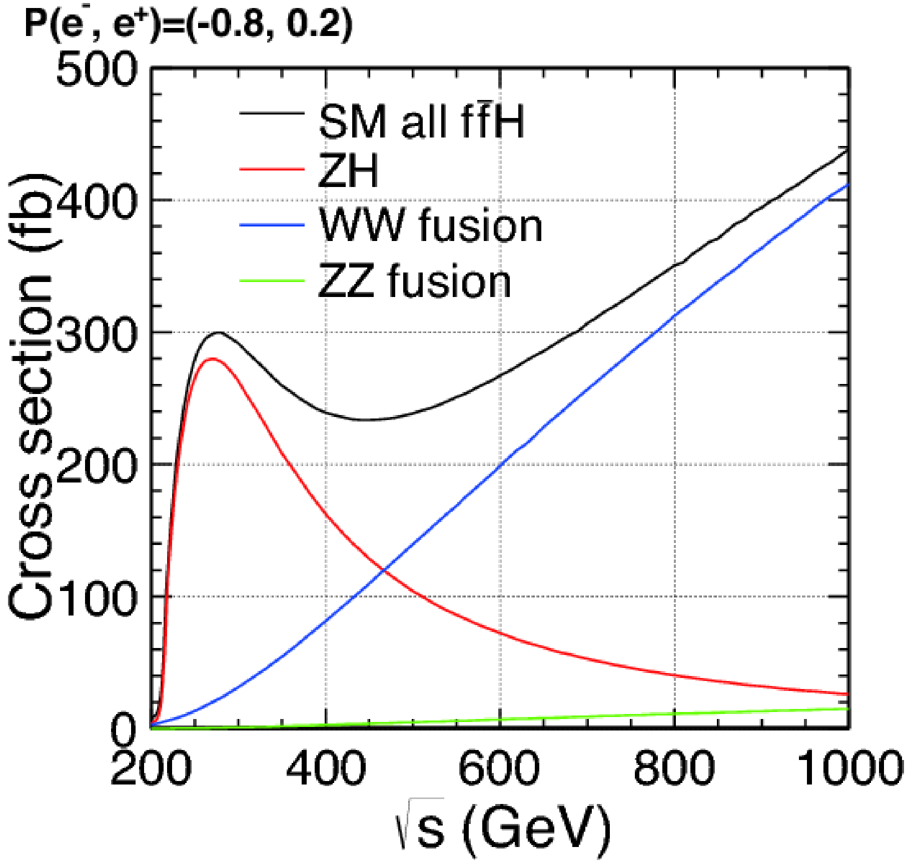
1 TeV – 3 TeV *(ILC upgrade + CLIC)*

- ➔ New physics

The next collider: the Higgs factory run

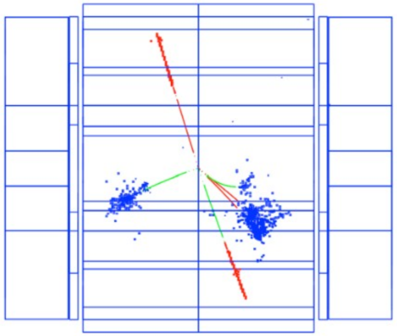
A Higgs factory is an e^+e^- collider operated at ~250 GeV, where the rate of the Higgs-strahlung process is maximum





Produce approx. 1 million Higgses
in perfectly controlled conditions

Higgs factory advantages

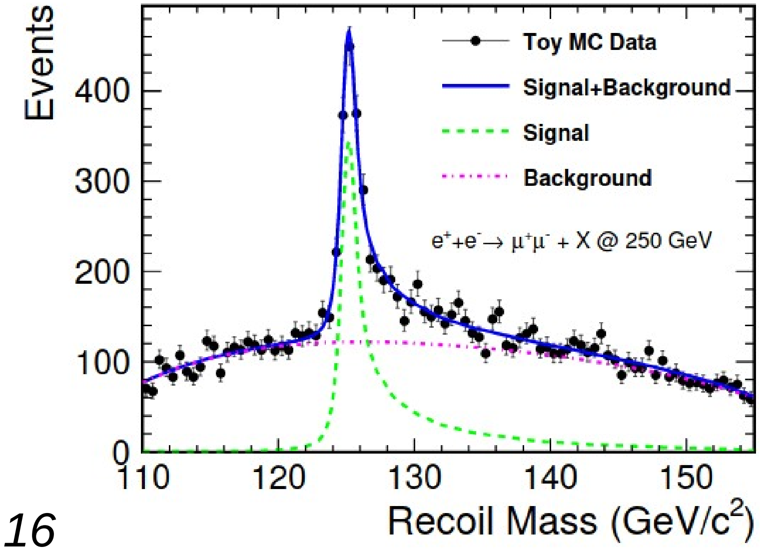


$e^+e^- \rightarrow ZH \rightarrow \mu\mu\tau\tau$

Well-known initial state
(e^+e^- annihilate and transfer all their energy)
Excellent detector performance
(rates and radiation levels limit LHC detectors)
Machine induced backgrounds nearly negligible
(Pile-up and Underlying Event limit LHC analyses)
SM backgrounds of same order as signal
(LHC analyses muddle through orders of magnitude)
SM rates can be precisely predicted
(QCD and PDF uncertainties limit LHC precision)

Recoil-mass analysis yields sharp Higgs peak without ever touching the Higgs decay products → ideal laboratory to count Higgs decays

Absolute normalization of Higgs couplings as total width is accessible



ILD interim design report, arXiv:2003.01116

Higgs couplings

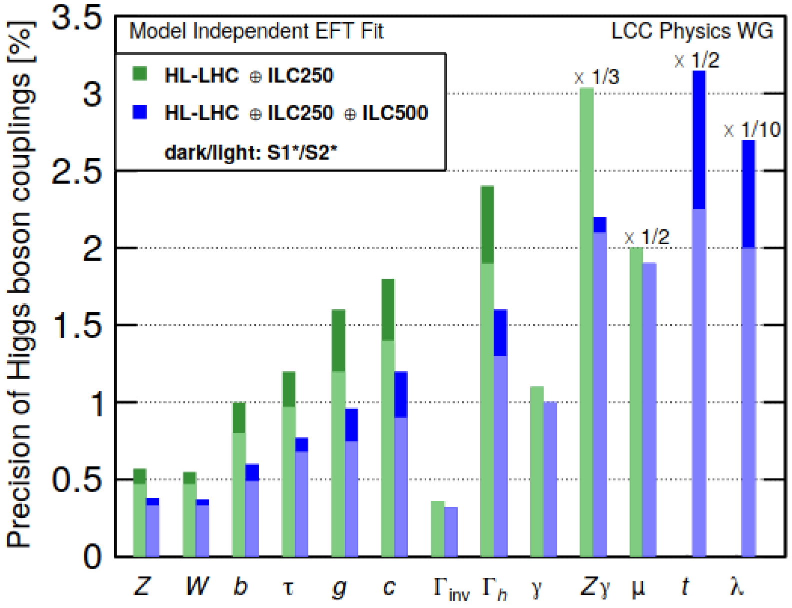
Improve Higgs couplings to Z, W and b to sub-% precision

Precision measurements also for gluon and charm (hard at LHC)

ILC500 is important for all couplings

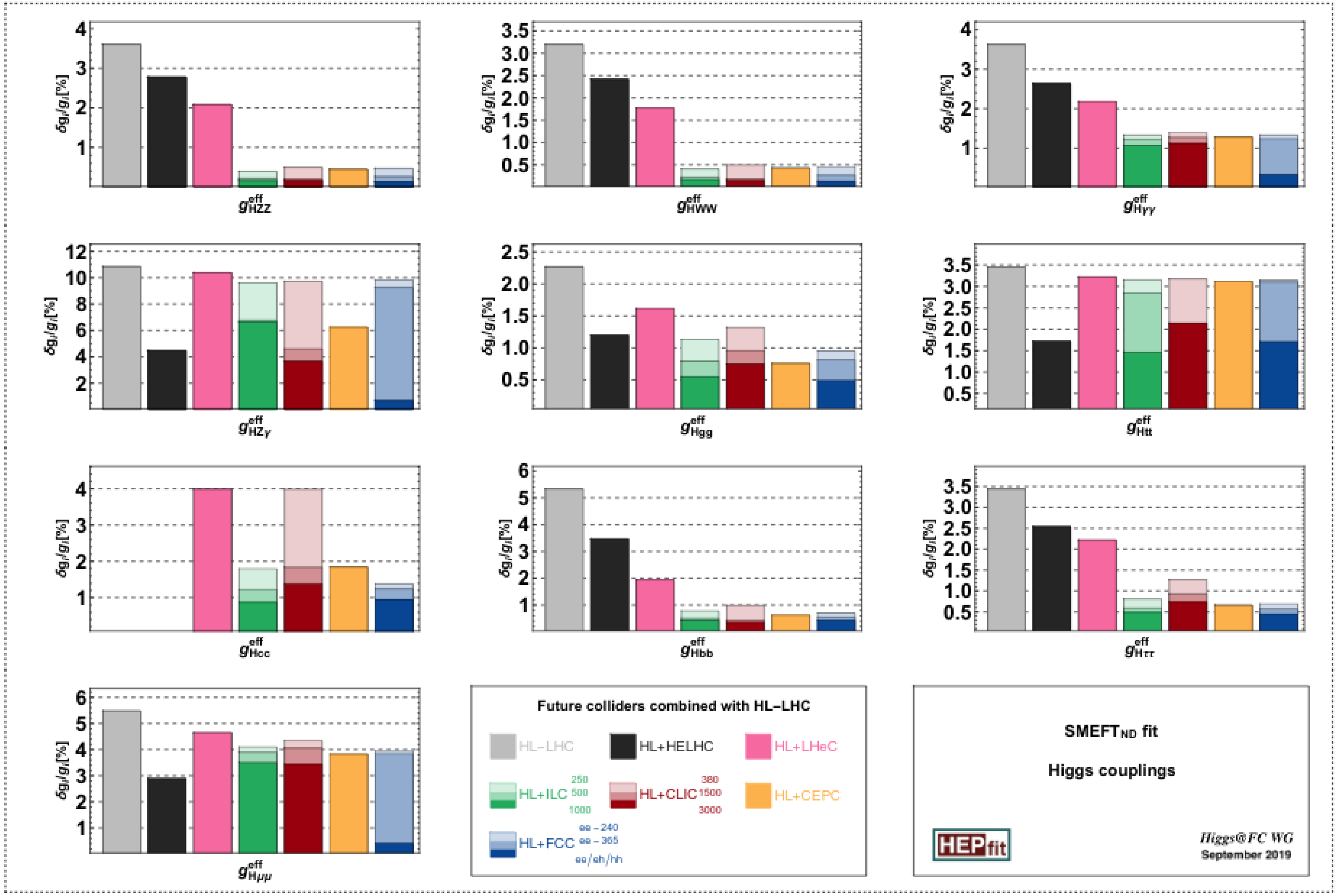
LHC data remain crucial for muons and photons

arXiv:1903.01629



Higgs couplings

https://arxiv.org/pdf/1910.11775.pdf

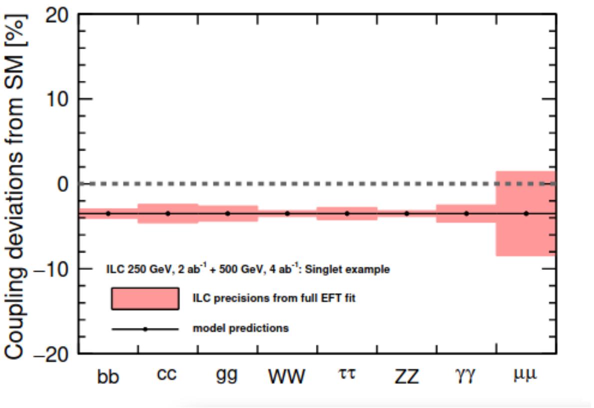


All projects bring great improvement over expected LHC legacy

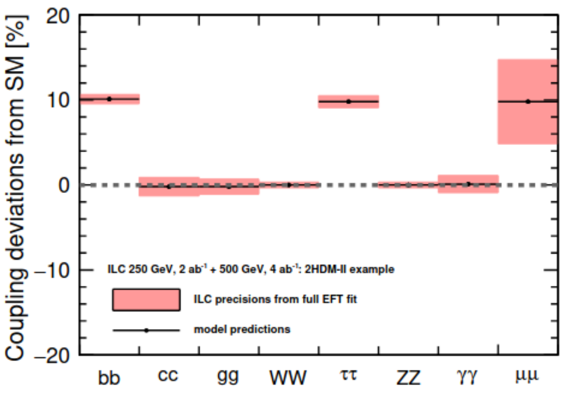
Note: inputs have large and varying degrees of uncertainty,
especially lepton and hadron colliders are hard to compare

Higgs couplings

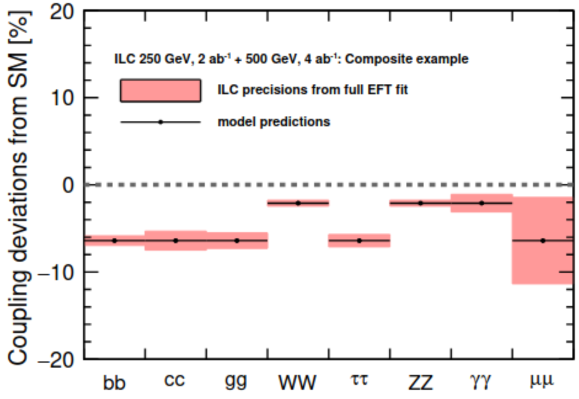
ILC input to Snowmass, arXiv:2203.07622



singlet (all)



2HDM-II (b, τ)



composite (b,c,g τ)

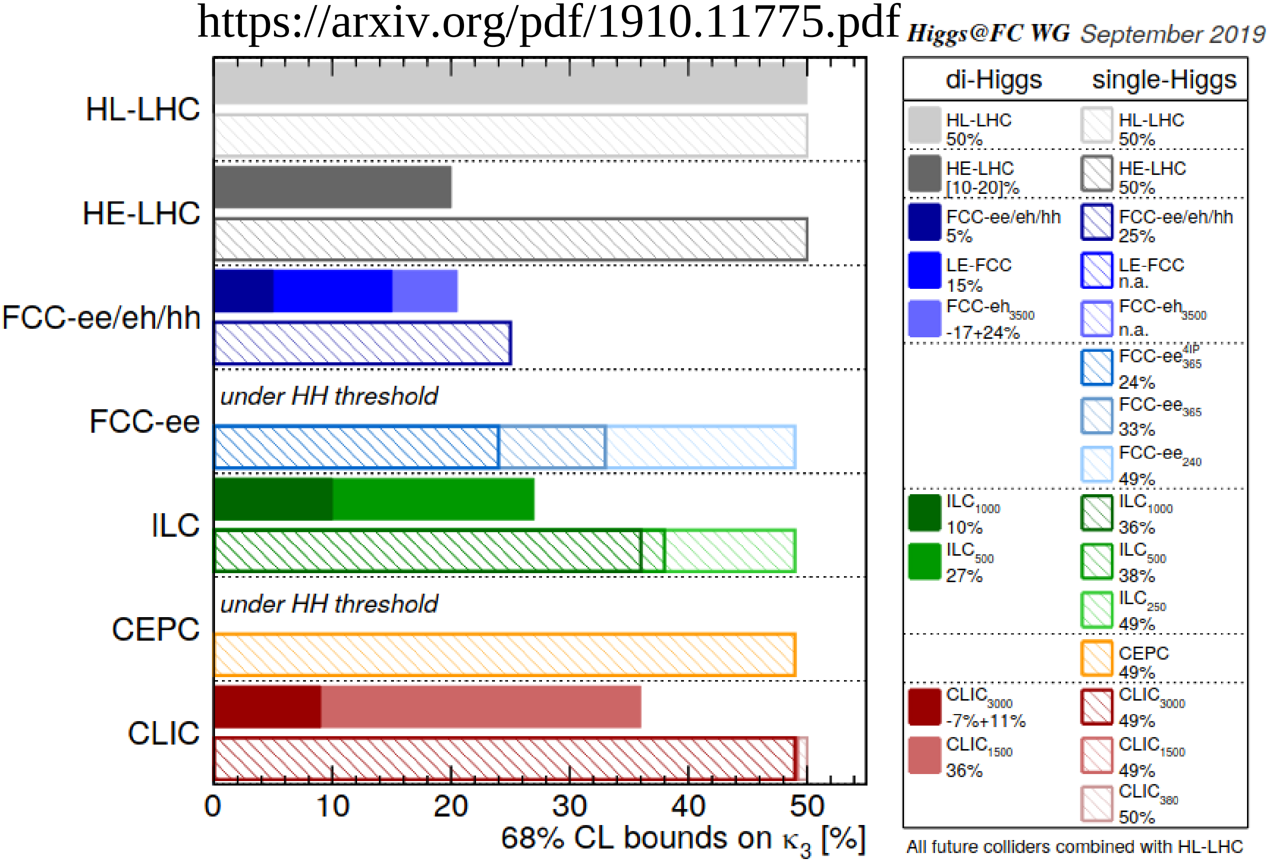
Qualitative (charm) and quantitative (few % → few per mille) improvements over HL-LHC precision, important complementarity

Viable BSM scenarios provide different patterns of experimentally accessible deviations in coupling measurements

Higgs self-coupling

The Higgs boson self-interaction is a key prediction of the Higgs mechanism

https://arxiv.org/pdf/1910.11775.pdf

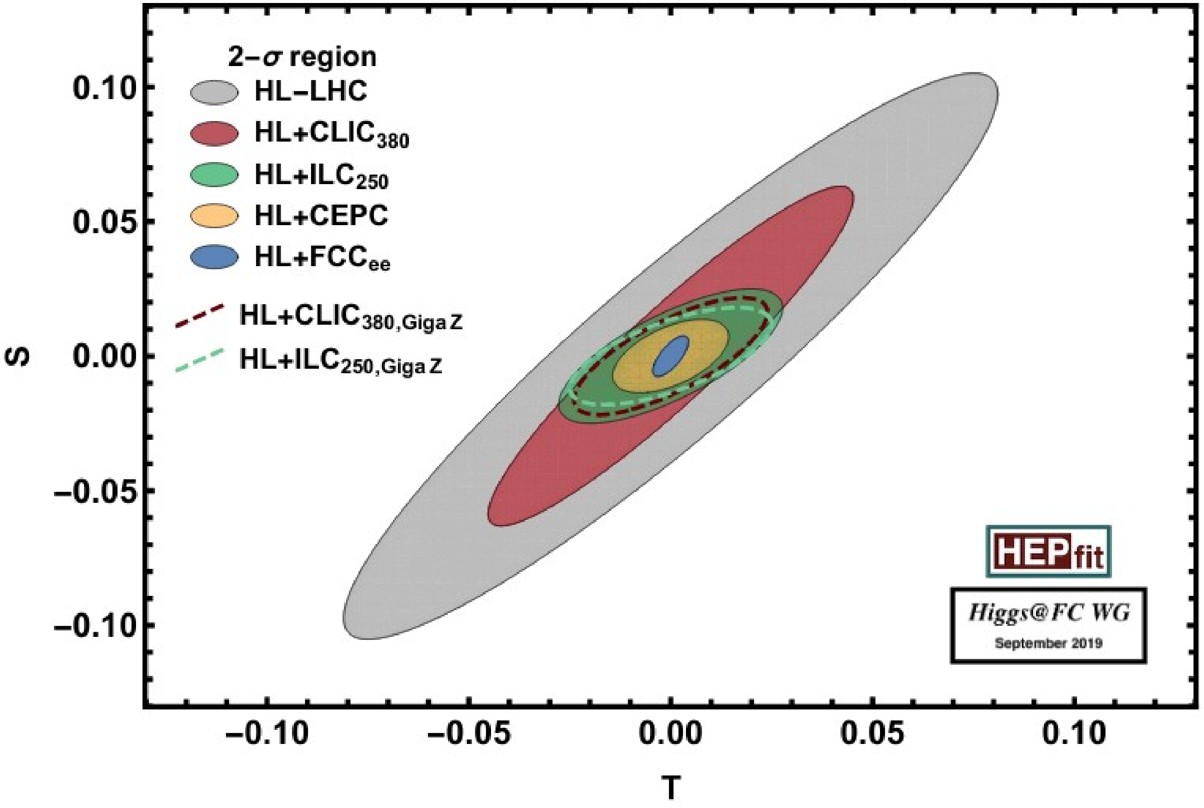


Complementary sensitivity from loop effect in single-Higgs boson production [////] and direct production
[■]

High-energy operation needed for a direct measurement of Higgs self-coupling

Electro-weak precision

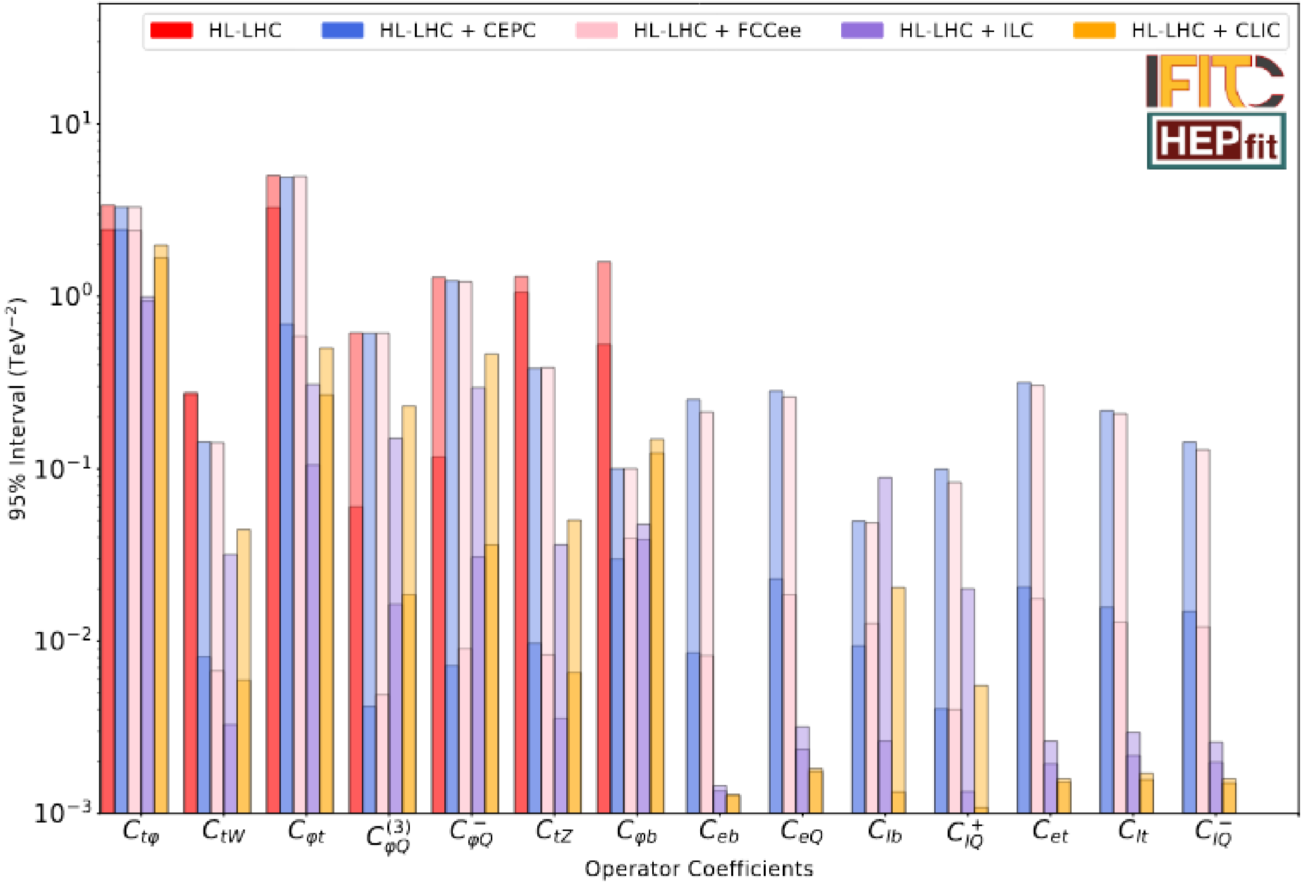
Revisit Z-pole electro-weak precision physics already expored by LEP and SLC, with greater luminosity, better detectors and better theory



The sheer luminosity of the circular machine “TeraZ” run is unbeatable

Top physics at e+e-

From: arXiv:2206.08326

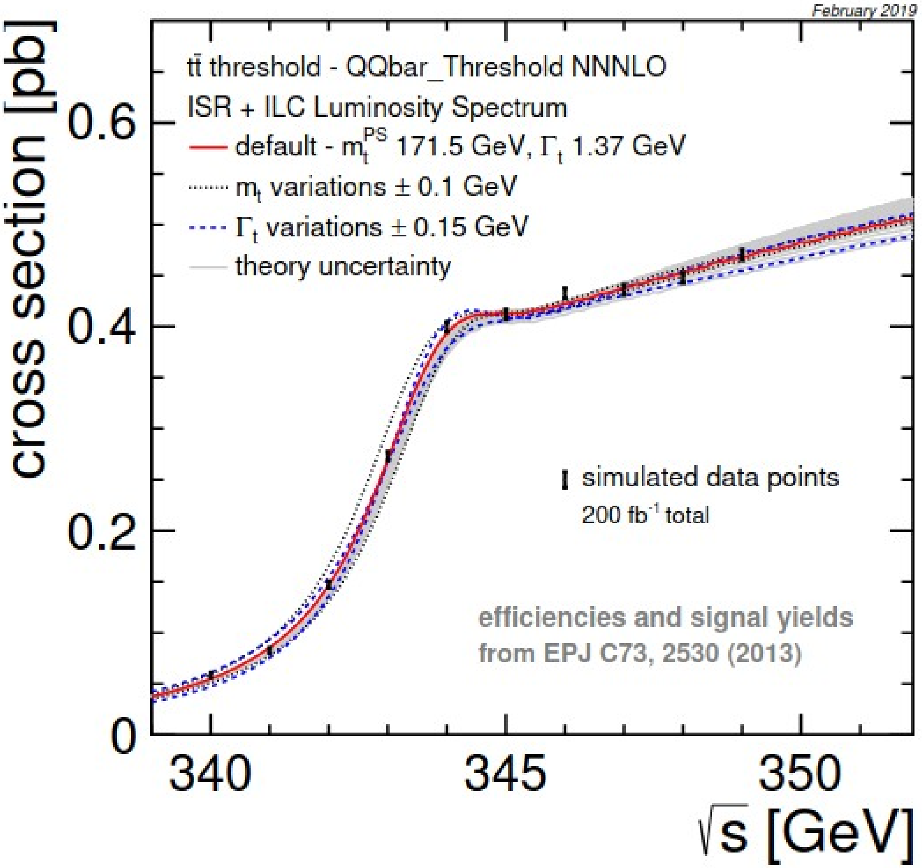


EW couplings (2-fermion operators) order of magnitude better than HL-LHC
4-fermion operators (eett) extremely precise with two runs at sqrt(s) above the top pair production threshold

Top quark mass

Threshold scan yields well-understood top mass measurement, with < 50 MeV uncertainty

My favourite subject: ask me during the Q&A or the discussion session



The Higgs factory: when and where?

Scientists have handed in our homework; now it’s politics

✔ CERN investigates “financial feasibility” of the FCCee tunnel (CLIC as backup)

✔ Japanese government to pronounce itself on the ILC (soon?)

(“The timely realisation of the electron-positron ILC in Japan would be compatible with [the European] strategy and, in that case, the European particle physics community would wish to collaborate.”)

✔ Chinese government to announce plan for CEPC (soon?)

The process should converge before the next strategy update, and culminate in at least(*) one Higgs/EW/top factory operating on the planet

(*) See: Blondel & Janot, Circular and linear e^+e^- colliders: another story of complementarity, arXiv:1912.1177

The next-to-next collider

The 2020 update of the European Strategy for Particle Physics approved by the CERN council in May 2020 (and similar roadmaps from China, Japan and the US) thinks about the long-term future:

“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”


2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy
Update

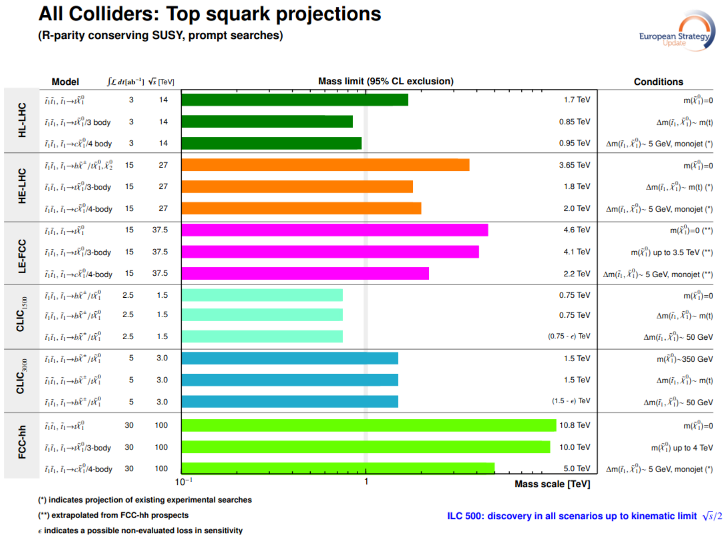
https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

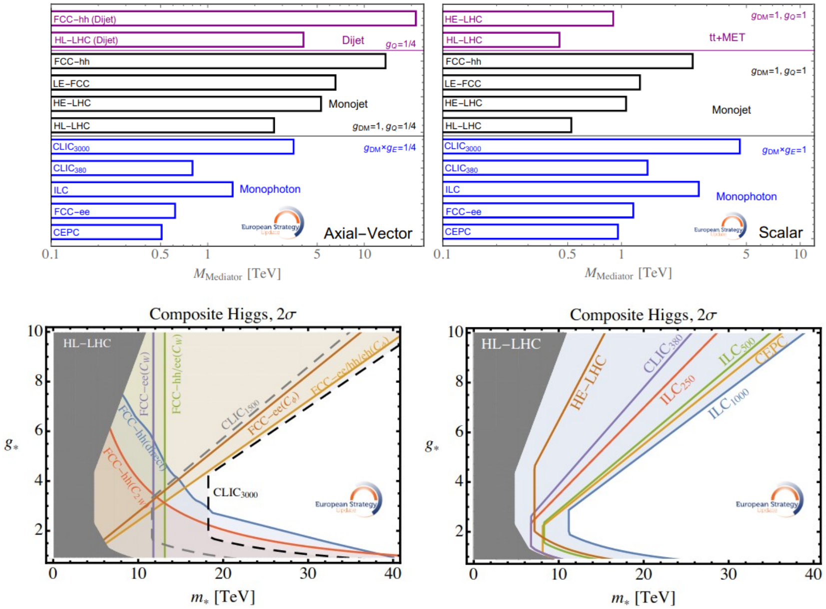
Exploration

European strategy update: “For the longer term, the European particle physics community [note: and China] has the ambition to operate a proton-proton collider at the highest achievable energy.”

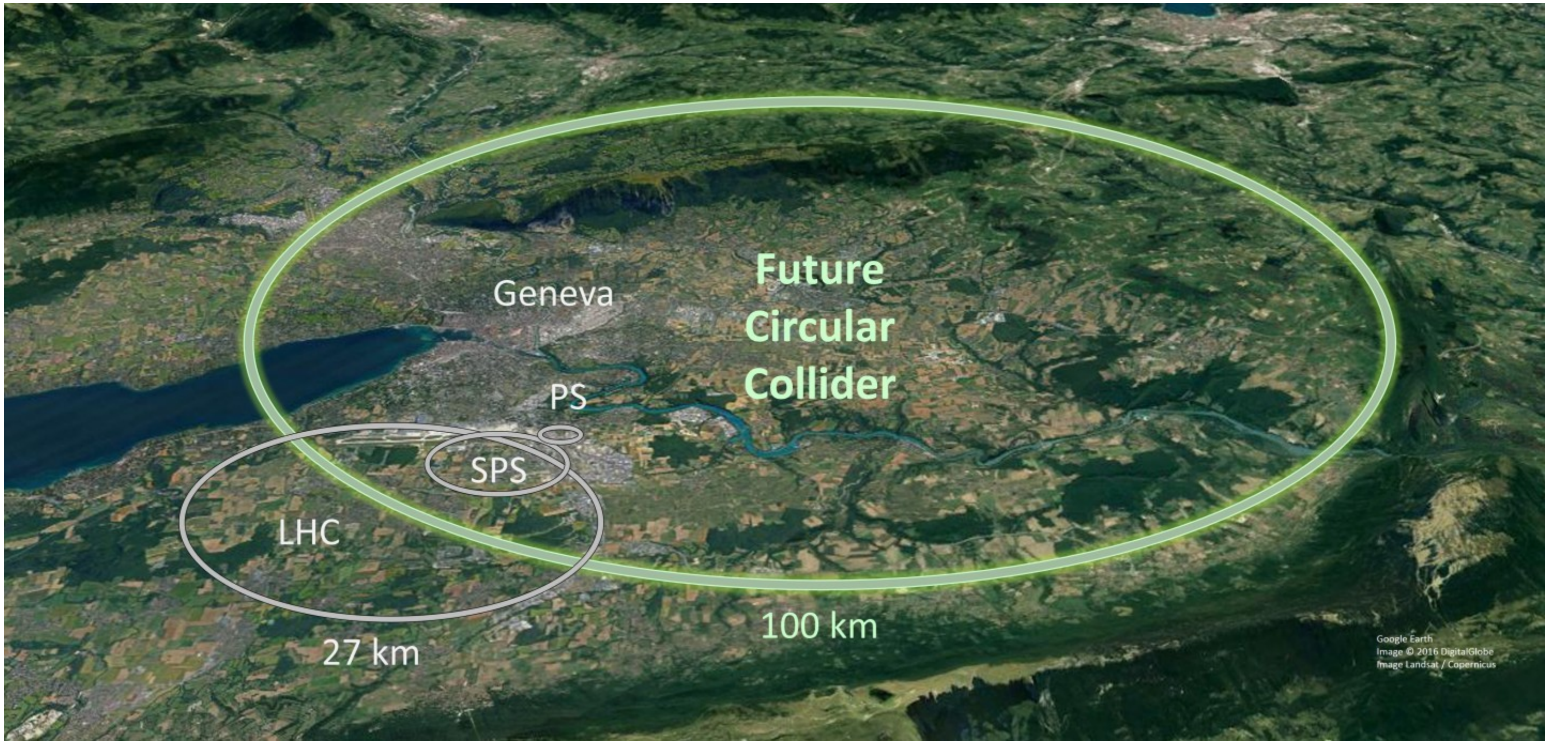
The energy frontier has never let us down so far. A 100 TeV pp collider represents a big enough leap for exploration.

Pick your benchmark! Hints of new physics before the Planck scale are welcome!





Advanced energy-frontier options



Proven concept on a grand scale: a new 100 km-100 TeV pp collider
Viability FCChh under study at CERN (CDR2018), SPPC in China
Advantage: synergy with FCCee/CEPC
Challenge: keep the size/prize tag in check with Nb3Sn or HTS magnets

The next-to-next collider

“The European particle physics community must intensify accelerator R&D and sustain it with adequate resources.”

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

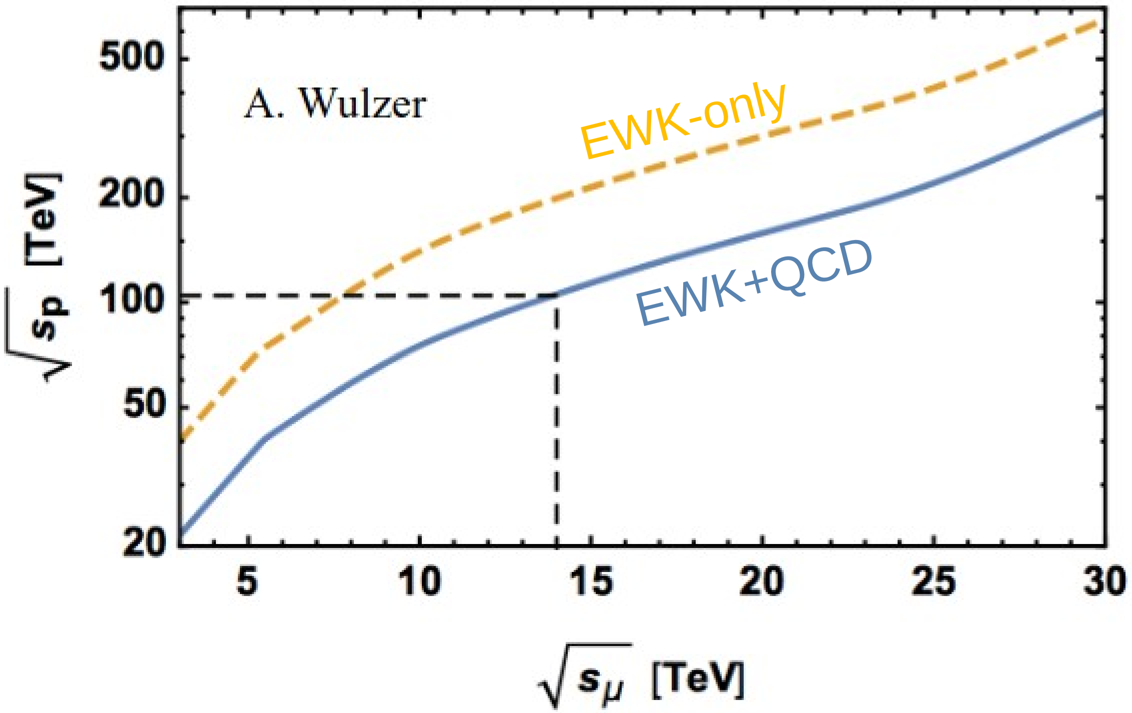
Novel acceleration techniques: muon collider, up to 3-30 TeV $\mu^+\mu^-$

Novel acceleration techniques: wakefield acceleration, 10 TeV e^+e^-

Muon collider

Colliding muons is interesting because: muons are elementary particles

Total beam energy is avialable for collisions; a factor 7-14 gain in effective energy



Colliding muons is challenging because: muons decay (τ~2 μs)

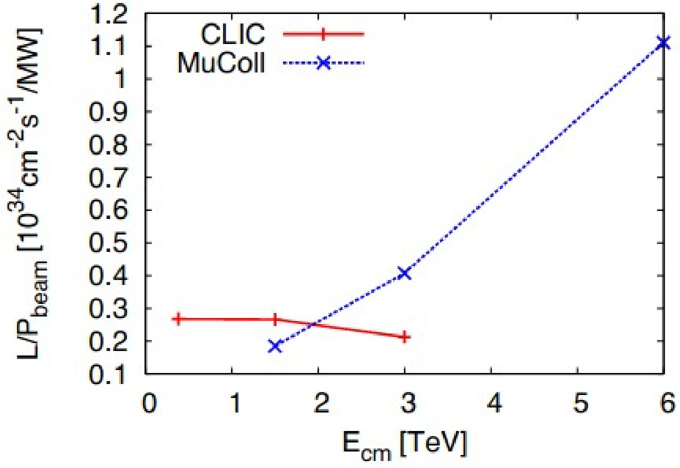
Muon collider

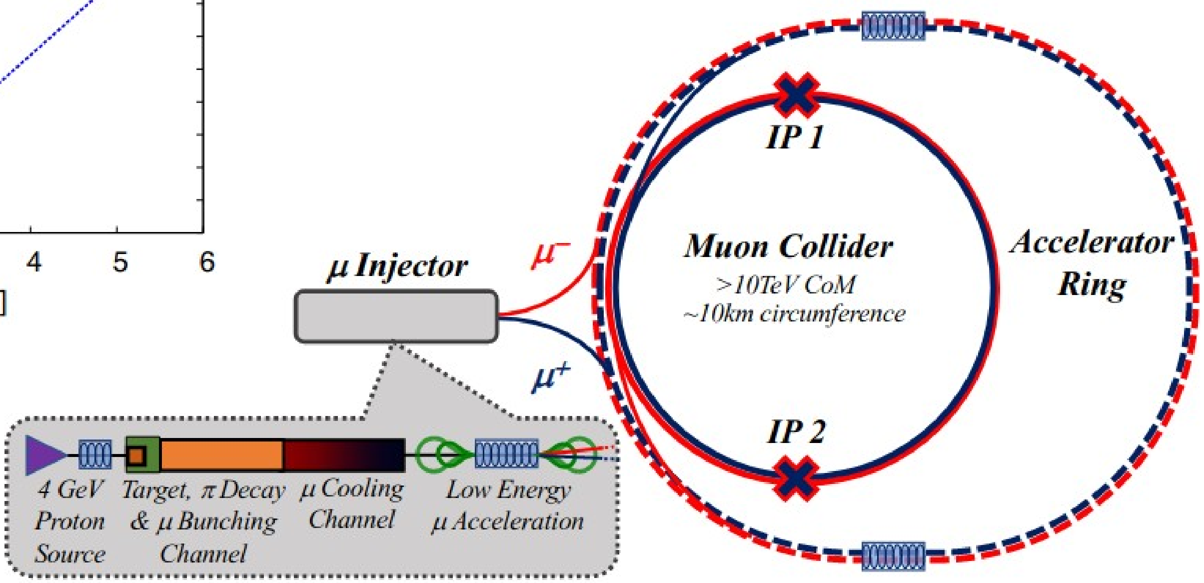
Goal: establish feasibility by next strategy update

Muon colliders enables relatively compact circular machine

Advantages: better scaling of power, cost and size

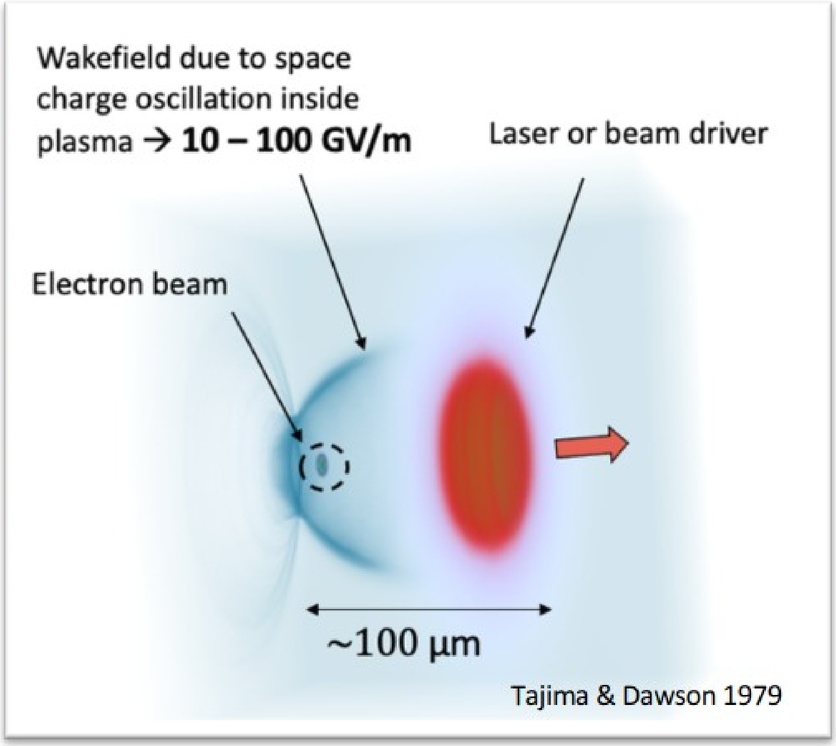
Challenges: muon source and cooling, backgrounds from muon decay





Plasma/wakefield acceleration

Avoid limitation RF system accelerating in plasma or dielectric (accelerator-on-chip)
Inject power from laser pulse or drive beam; electrons “surf” the shock wave
Gradient can be 10-100 GV/m (cf. 30-150 MV/m for RF cavities)
Accelerator facility can be kept very compact (and possibly cheap)



Tajima & Dawson 1979

Illustration from EuPRAXIA, A. Ferran Pousa et al

Plasma/wakefield acceleration

Rapid (exponential) progress in maximum beam energy from 1980 to 2020
Demonstrator planned for accelerators: EUPRAXIA aims for 5 GeV in 60 m

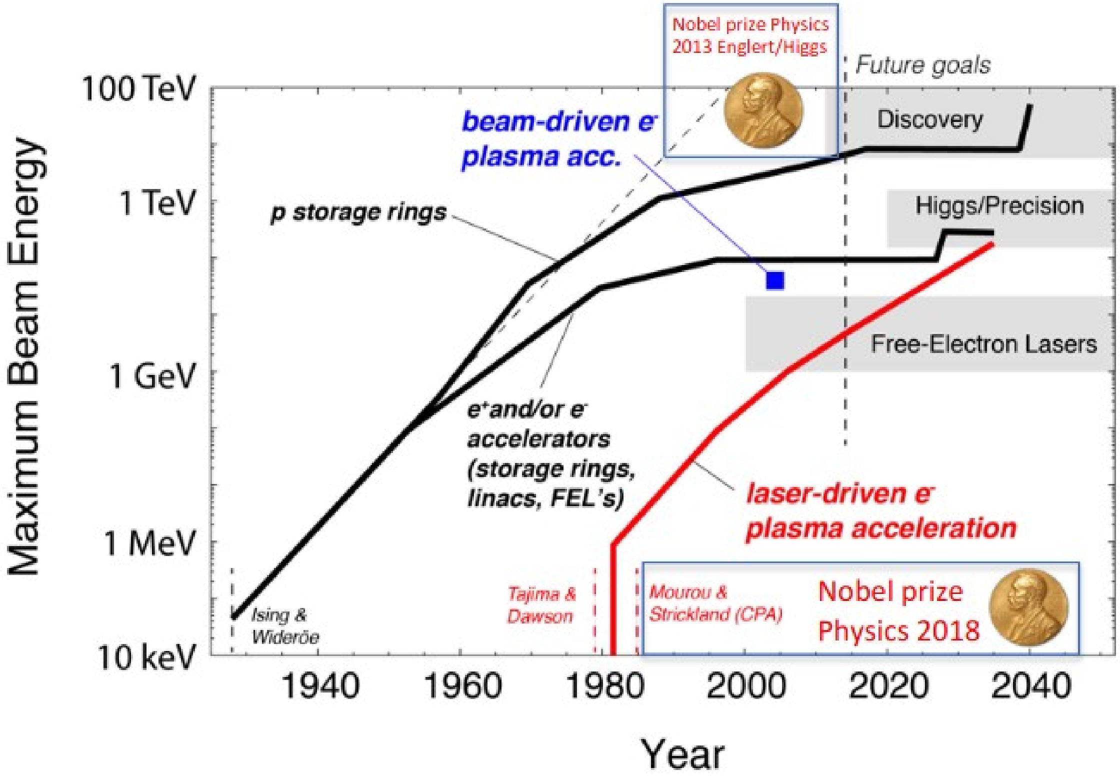


Image from R. Assmann

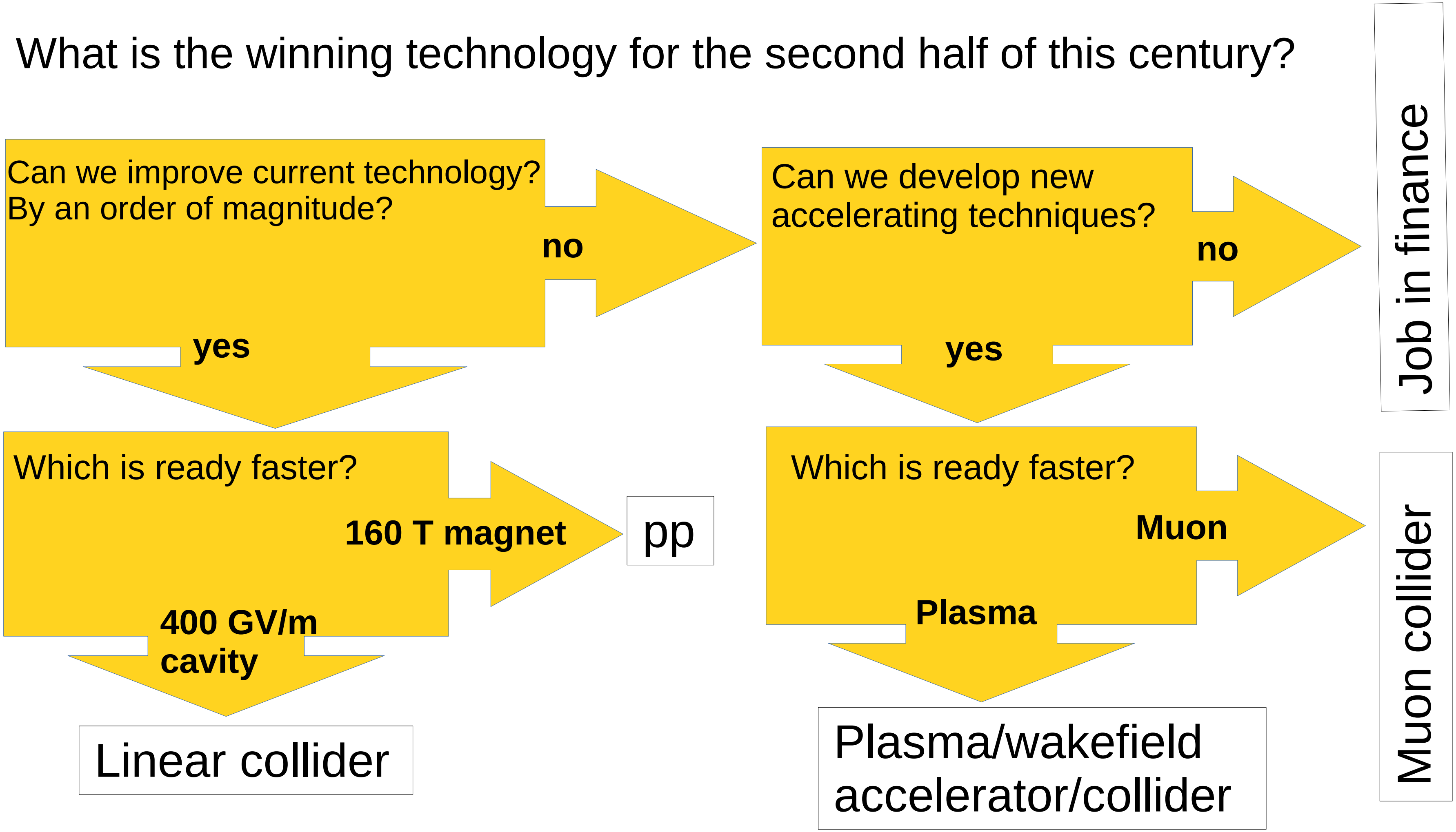
Collider-specific work by ALLEGRO (laser), AWAKE (beam driven)
Challenges: collider, beam quality & luminosity, anti-particles

Long-term future of colliders

Remember Livingston: a factor 10 increase every 6 years!

Circular (hadron) colliders have dominated HEP in the last decades.

What is the winning technology for the second half of this century?



Can we improve current technology? By an order of magnitude?

no

yes

Can we develop new accelerating techniques?

no

yes

Job in finance

Which is ready faster?

160 T magnet

pp

400 GV/m cavity

Linear collider

Which is ready faster?

Muon

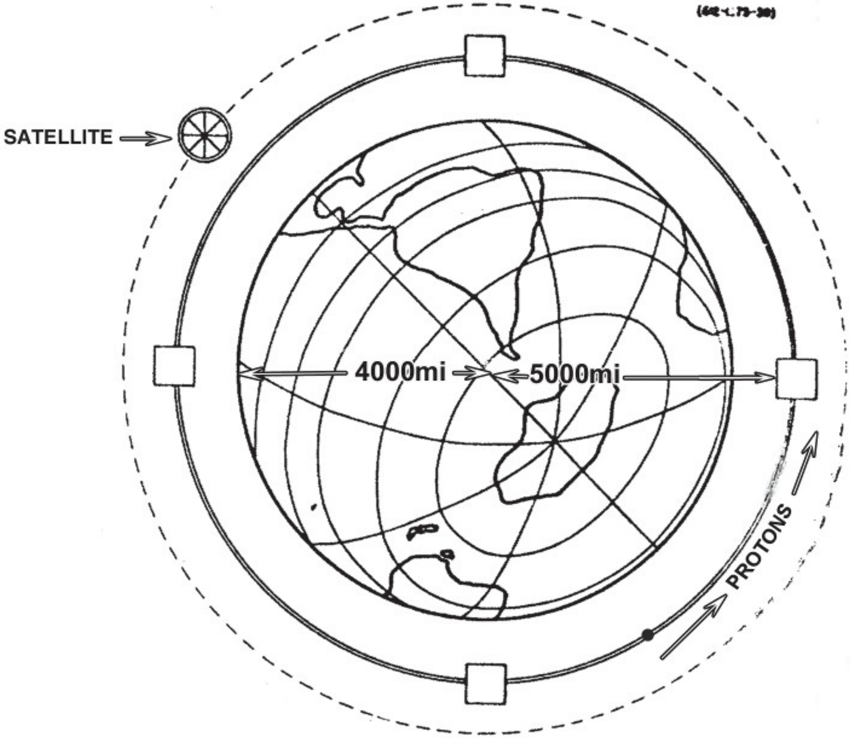
Muon collider

Plasma

Plasma/wakefield accelerator/collider

Scaling

The last resort in designing energy-frontier colliders: *make ‘m bigger*



Fermi, in 1954, speculated that in 1994 we might build a planet-sized accelerator

Note: we didn’t. But if the size of the LHC is a deception, its center-of-mass is close to what Fermi hoped for

The future is hard to predict, even for a Nobel-prize-winning genius

See also: Beacham & Zimmermann, A very high-energy hadron collider on the moon, New J. Phys. 24 (2022)

11.000 km, 20 T magnets, 14 PeV pp
“an attractive prospect for the (next-to-) next-to-next-generation of particle physics project”

Summary

High-energy collisions are a key tool to advance knowledge of the constituents of matter and their interactions at the most fundamental level

The LHC program has opened the TeV regime and delivered a long series of discoveries of previously unobserved processes, with or without Higgs boson

Much more to come in the the next two decades:
- more LHC, with an important luminosity upgrade
- the start of an e^+e^- Higgs factory
- feasibility studies for energy frontier
- and R&D on novel acceleration techniques

Stay tuned: https://home.cern/feeds

Dedication to the memory

Last Saturday, Esteban Fullana, member of the ATLAS group in Valencia and of the top group, passed away. His sudden death has shocked everyone around him.
We wish everyone the strength to cope, especially his wife Belén, and his daughters

Biography

Marcel Vos is an experimental physicist at the particle physics institute IFIC (UVEG/CSIC) in Valencia, Spain He is active in the ATLAS experiment at the LHC and in the ILC and CLIC projects for a linear electron-positron collider. His work focuses on jets and the top quark, and on Silicon detectors for charged-particle detection. Dutch by birth and education (U. Utrecht, U. Twente), he is a staff member of the Spanish research council CSIC