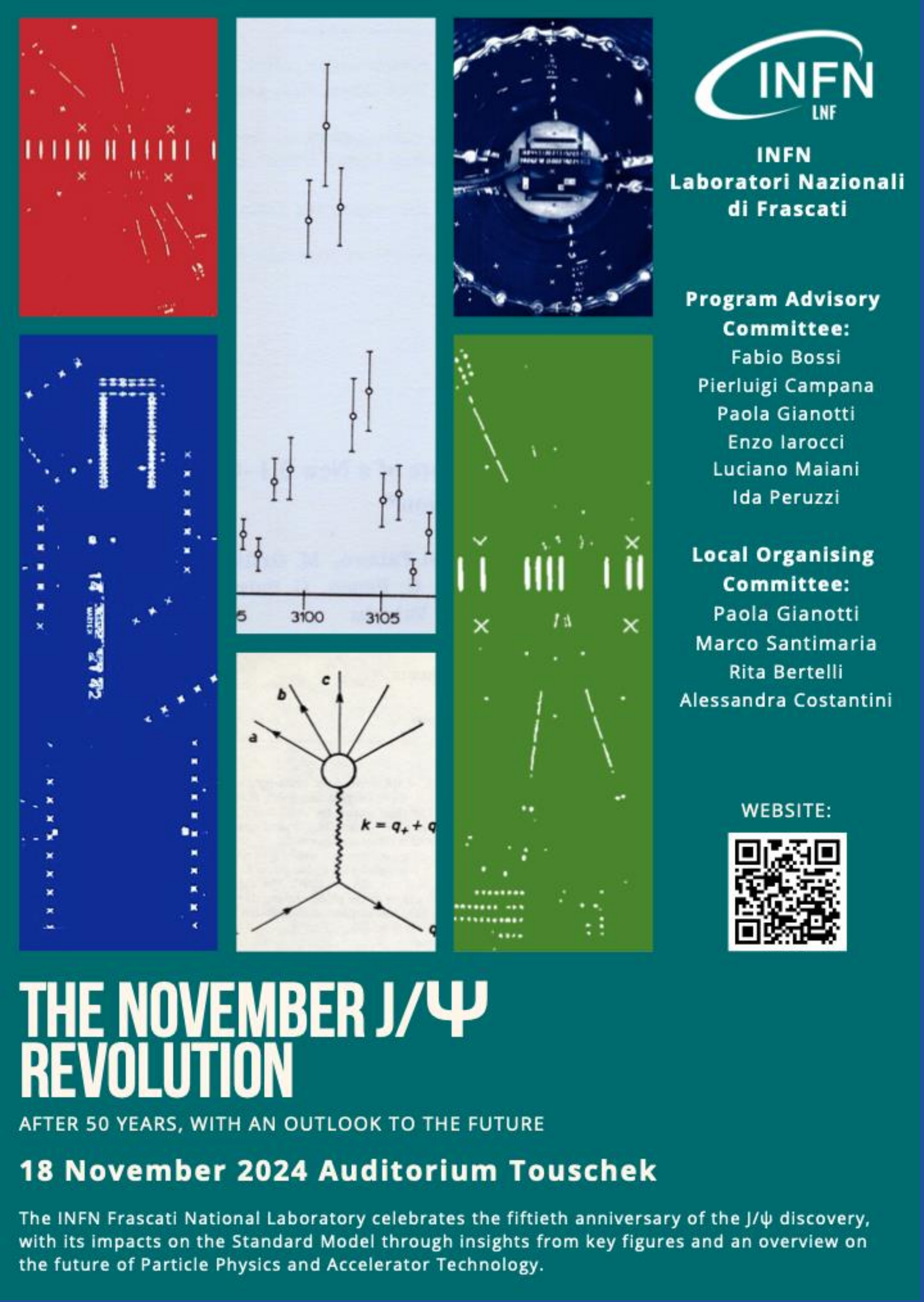

INFN LNF

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Laboratori Nazionali
di Frascati

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THE NOVEMBER J/Ψ REVOLUTION

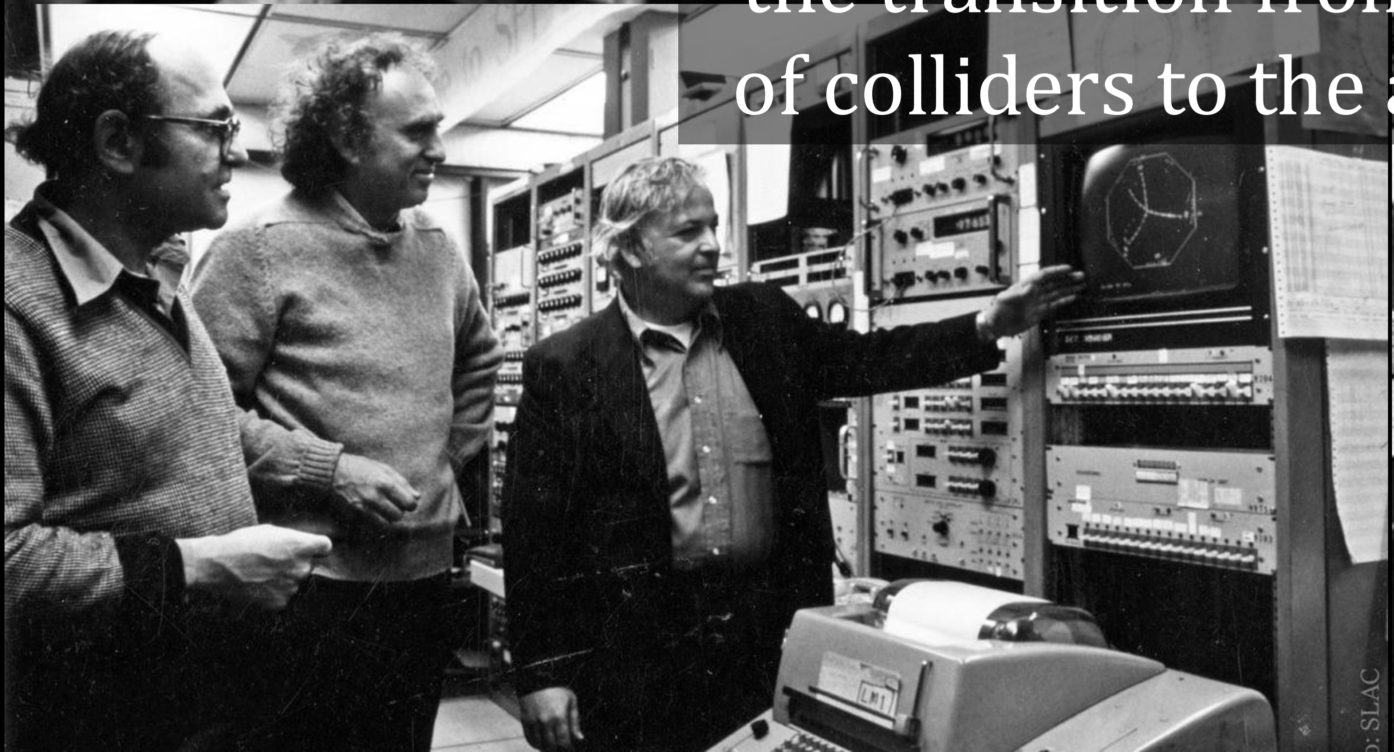
AFTER 50 YEARS, WITH AN OUTLOOK TO THE FUTURE

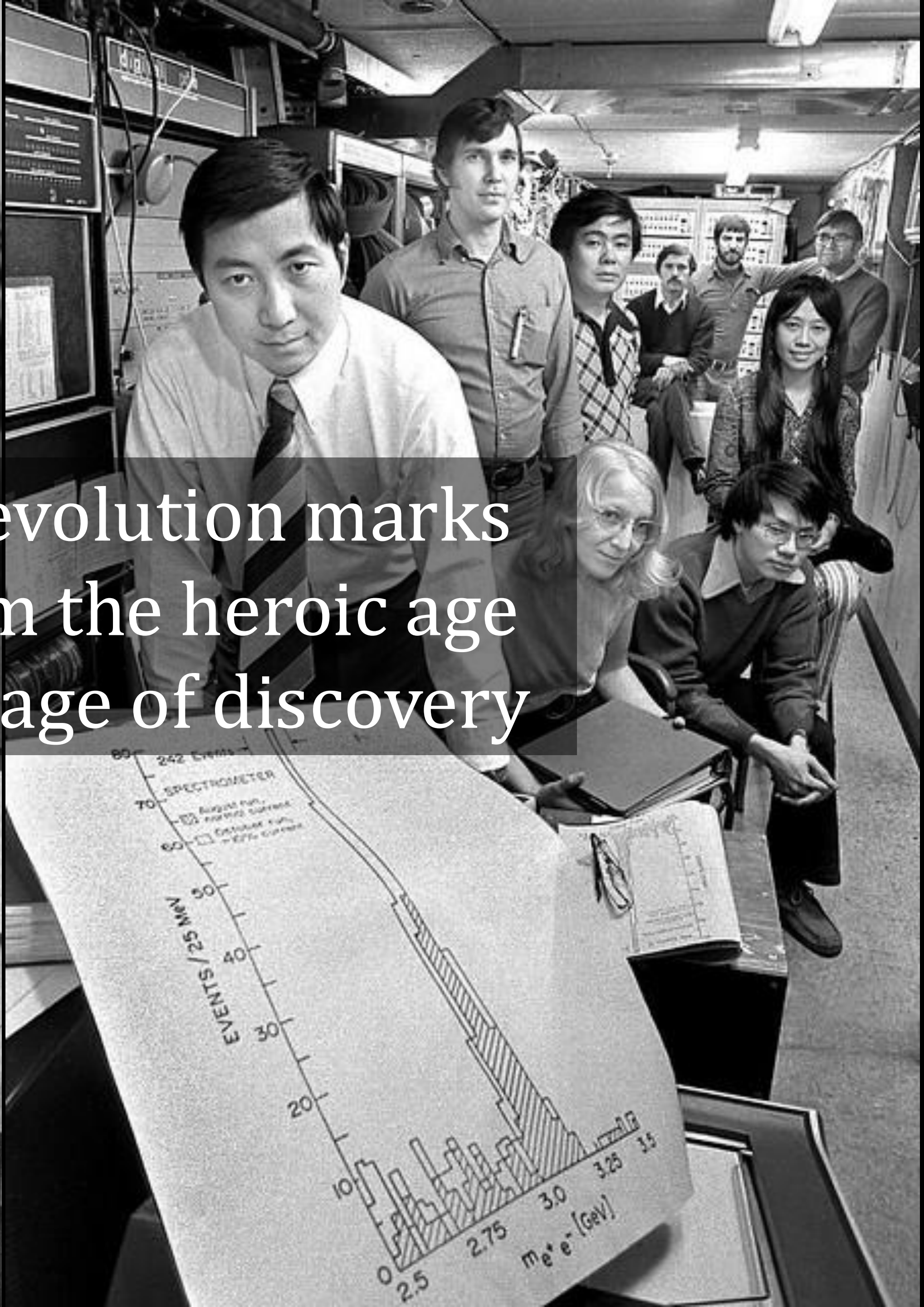
18 November 2024 Auditorium Touschek

The INFN Frascati National Laboratory celebrates the fiftieth anniversary of the J/ψ discovery, with its impacts on the Standard Model through insights from key figures and an overview on the future of Particle Physics and Accelerator Technology.

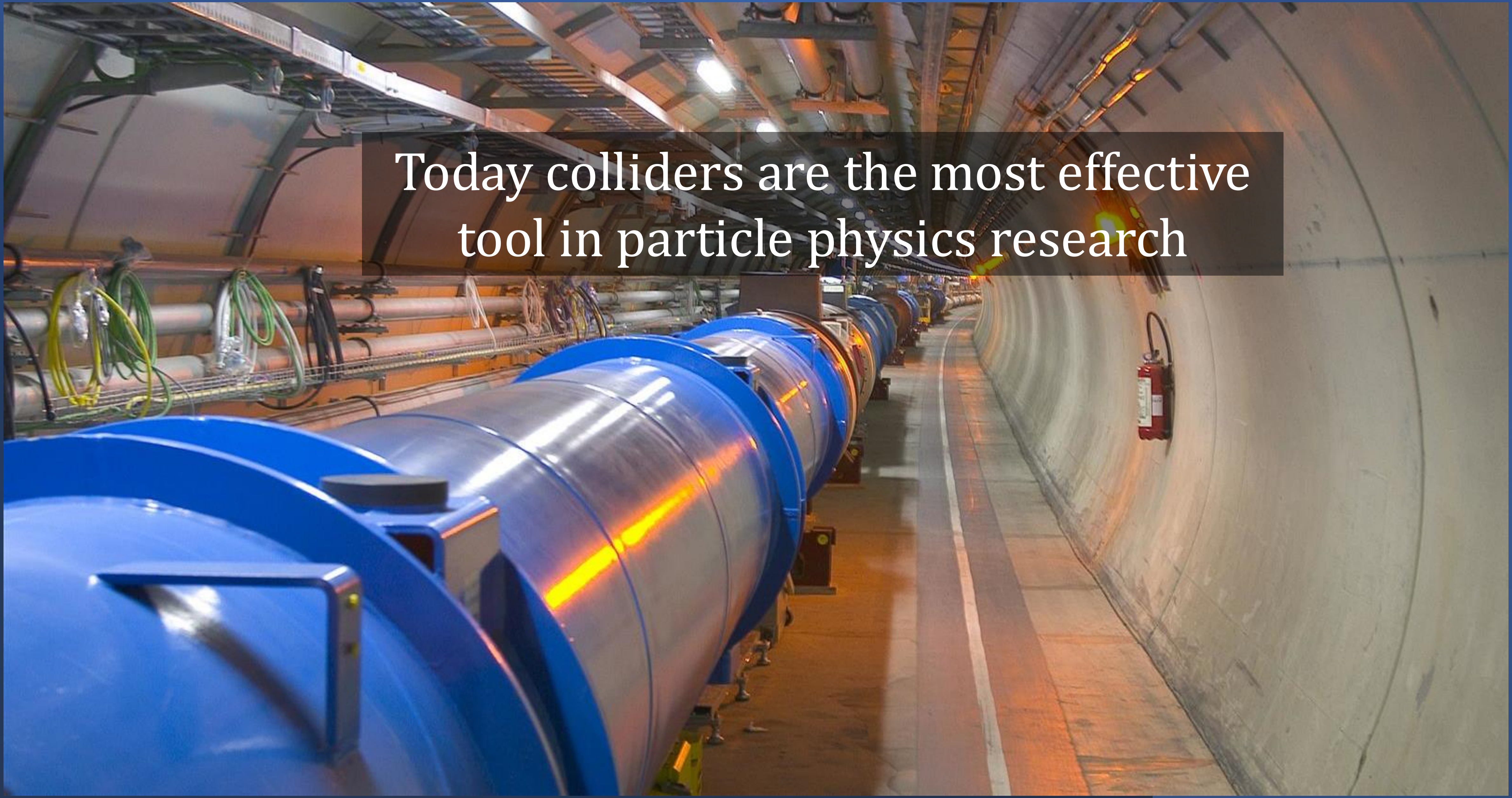
The future of collider physics

Gian Francesco Giudice



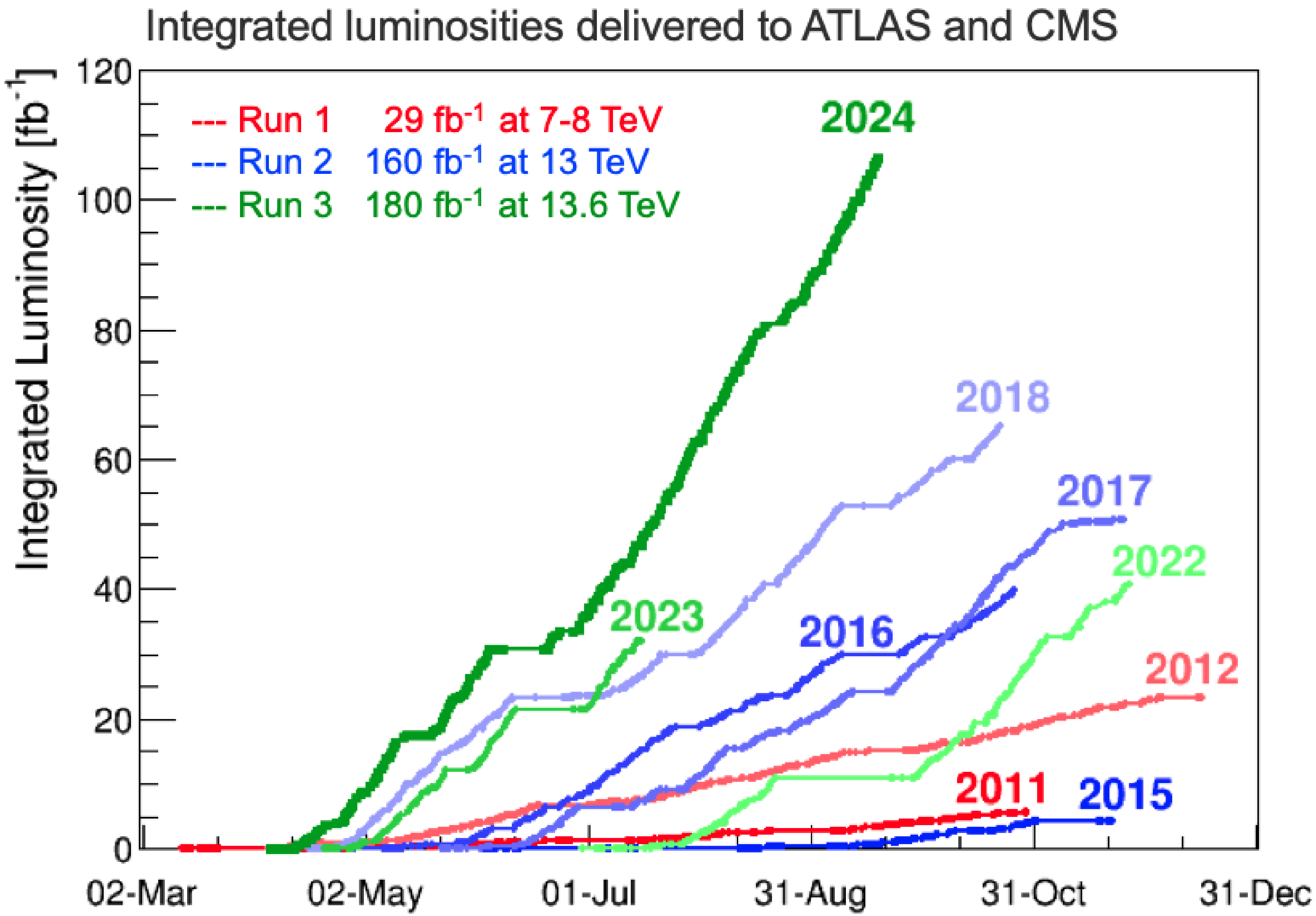


The November Revolution marks the transition from the heroic age of colliders to the age of discovery



Today colliders are the most effective tool in particle physics research

The success of the LHC

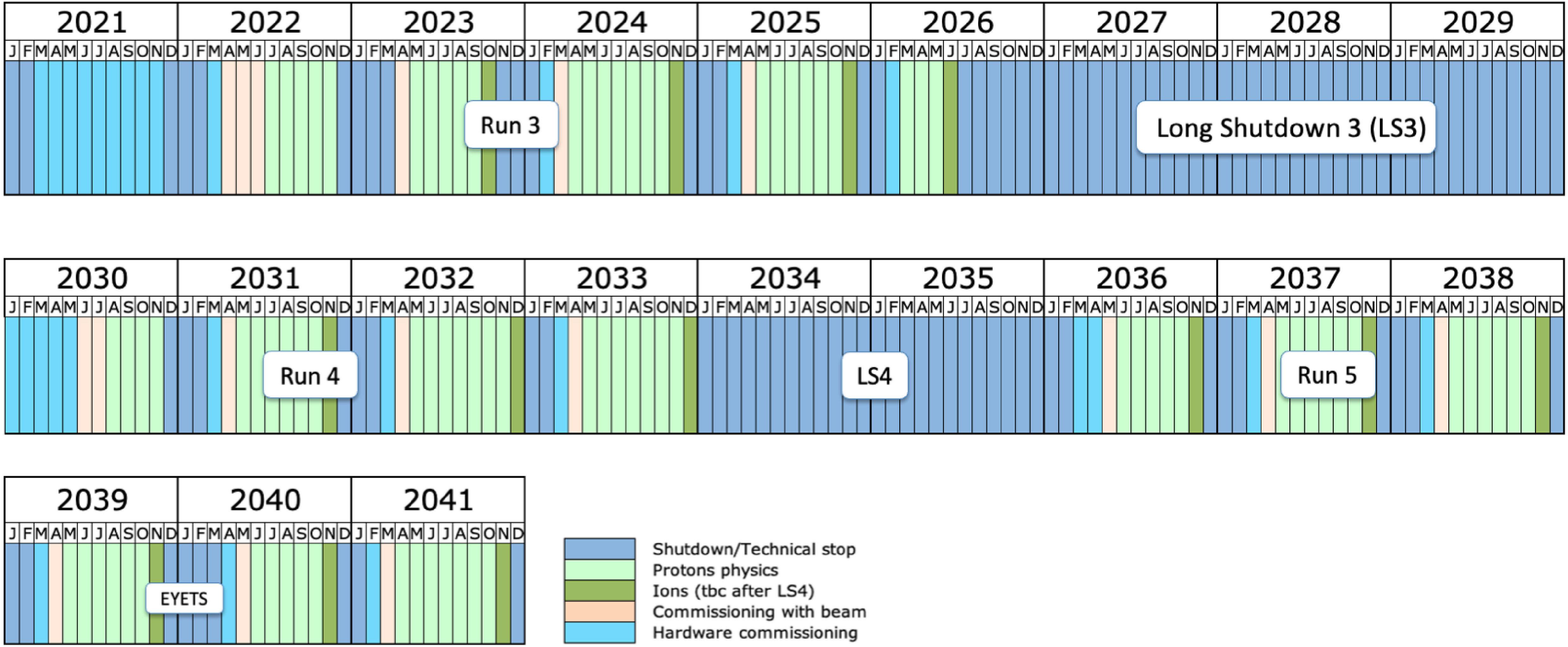


Integrated luminosities delivered to ATLAS and CMS

→ goal of the year (110 fb^{-1} to ATLAS, CMS) achieved 2.5 weeks ahead of schedule!

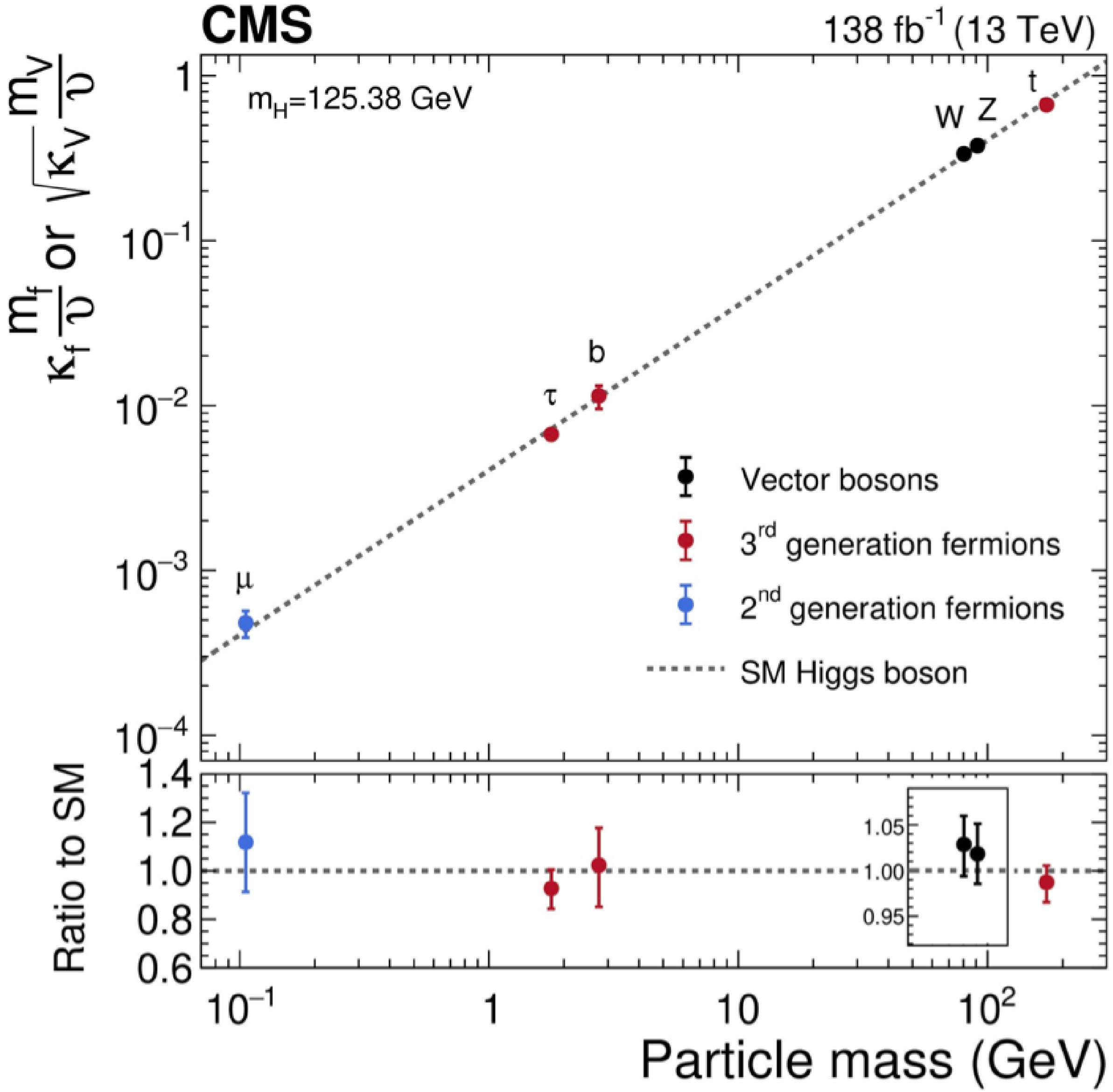
→ on track to surpass ~ 120 fb^{-1} at the end of this year’s pp run

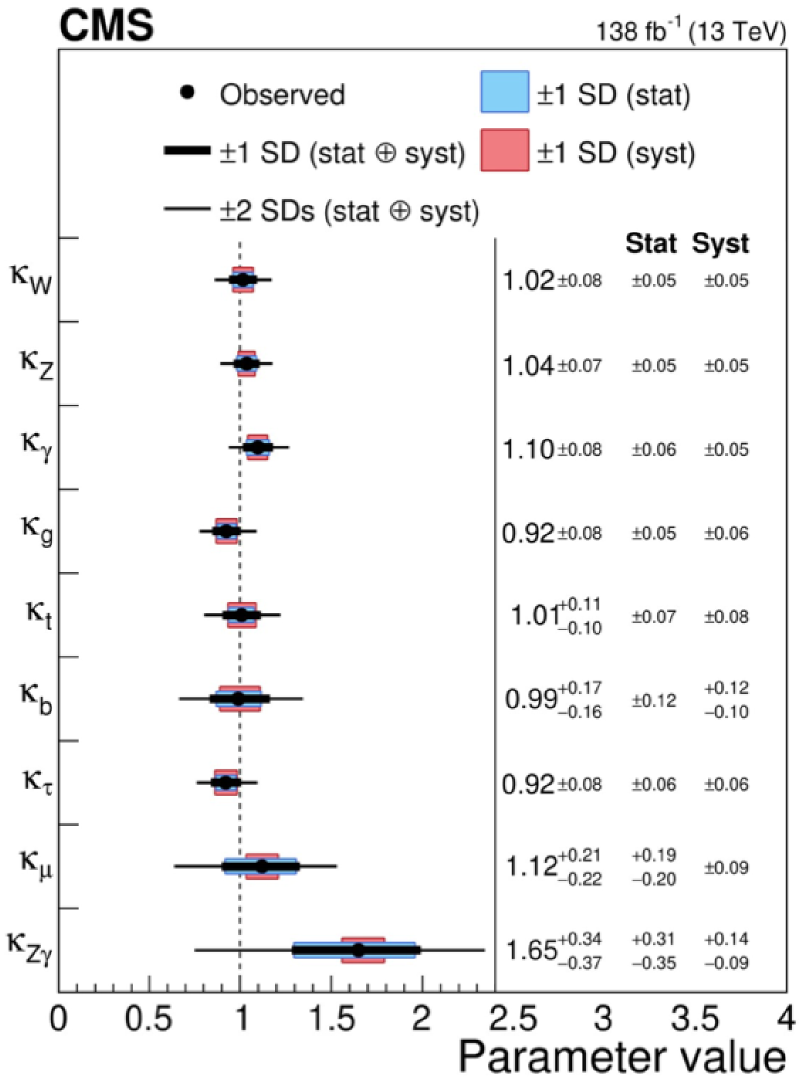
LHC Schedule



- LS3 start delayed by 7.5 months
- LS3 length (beam to beam) increased by 4.5 months

Lots of new results: Higgs





$$\kappa = \frac{g}{g_{SM}}$$

~7-8%

~10%

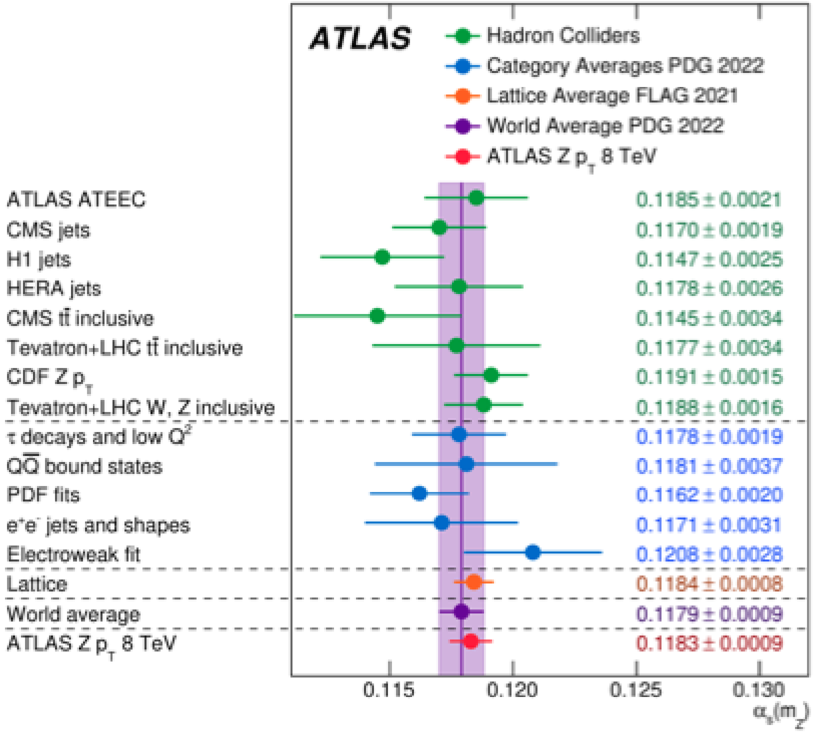
~15%

~ 8%

~20%

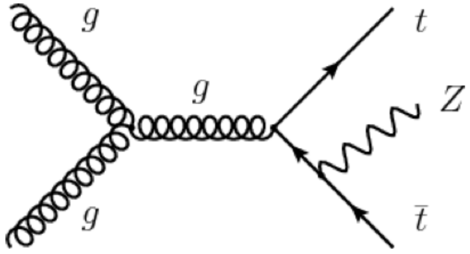
~35%

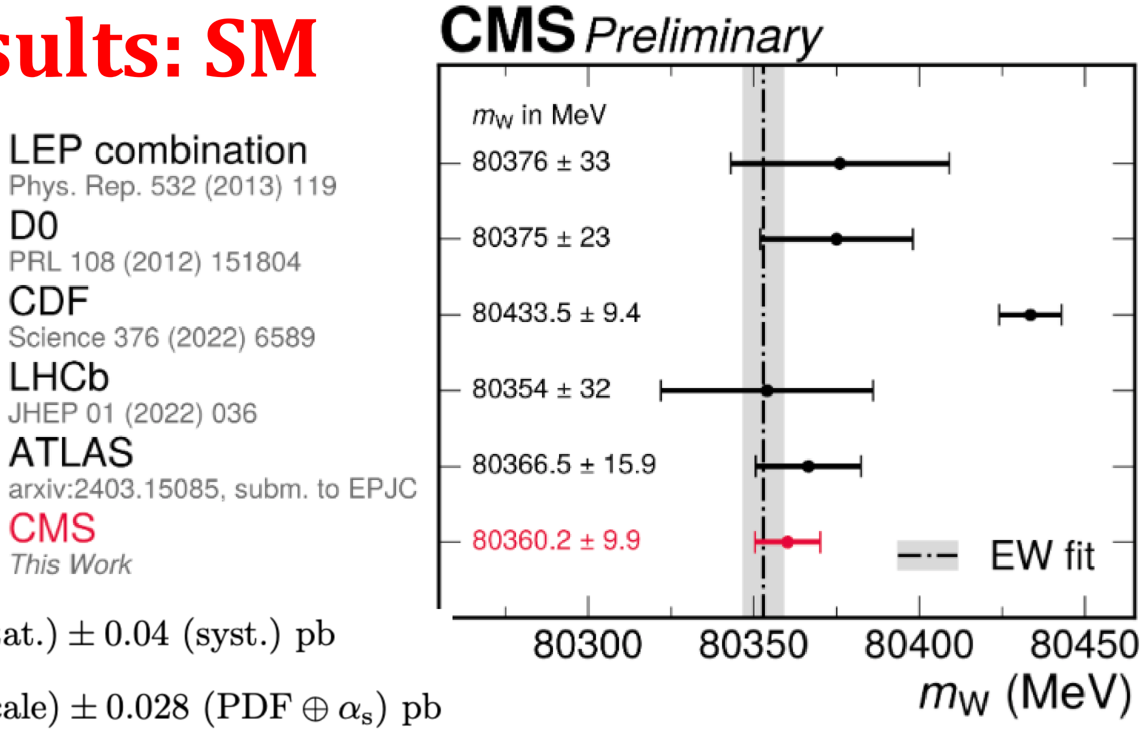
Lots of new results: SM



arXiv:2402.08713

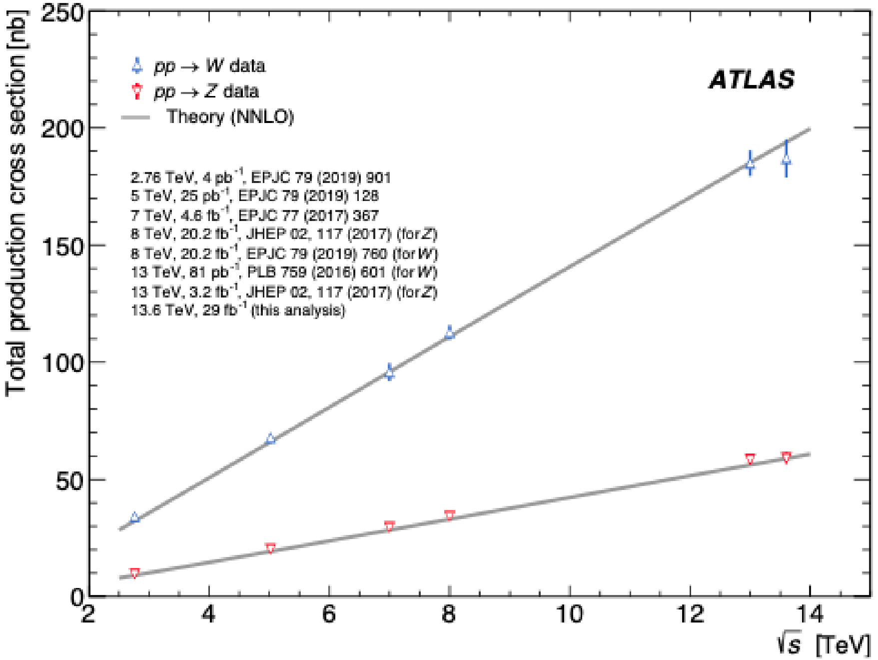

0.8% precision on strong force couplings at Z mass

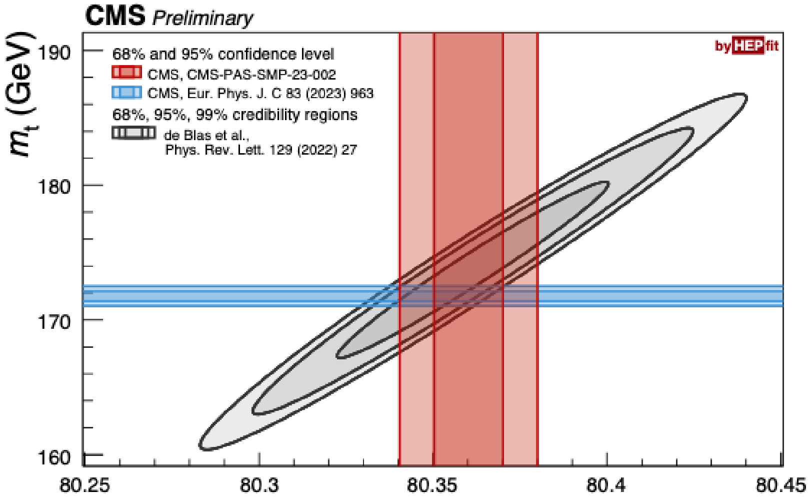




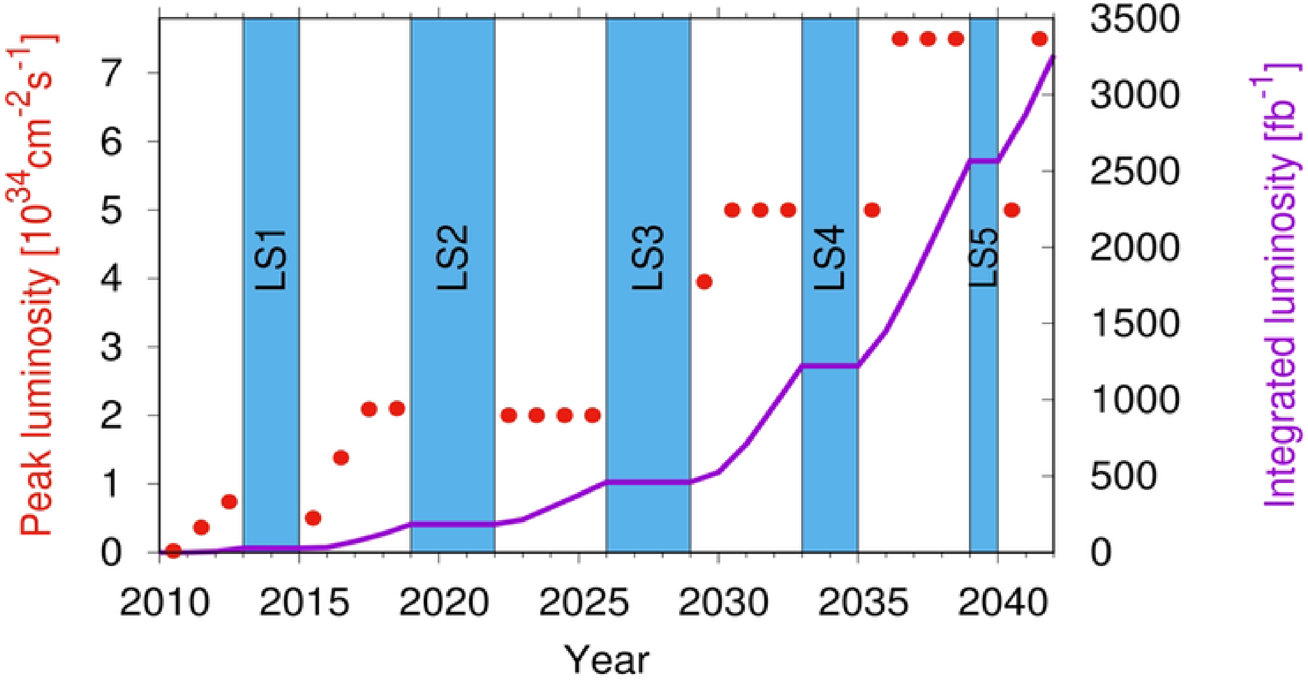
Measured $\sigma_{t\bar{t}Z} = 0.86 \pm 0.04\ \text{(stat.)} \pm 0.04\ \text{(syst.)}\ \text{pb}$

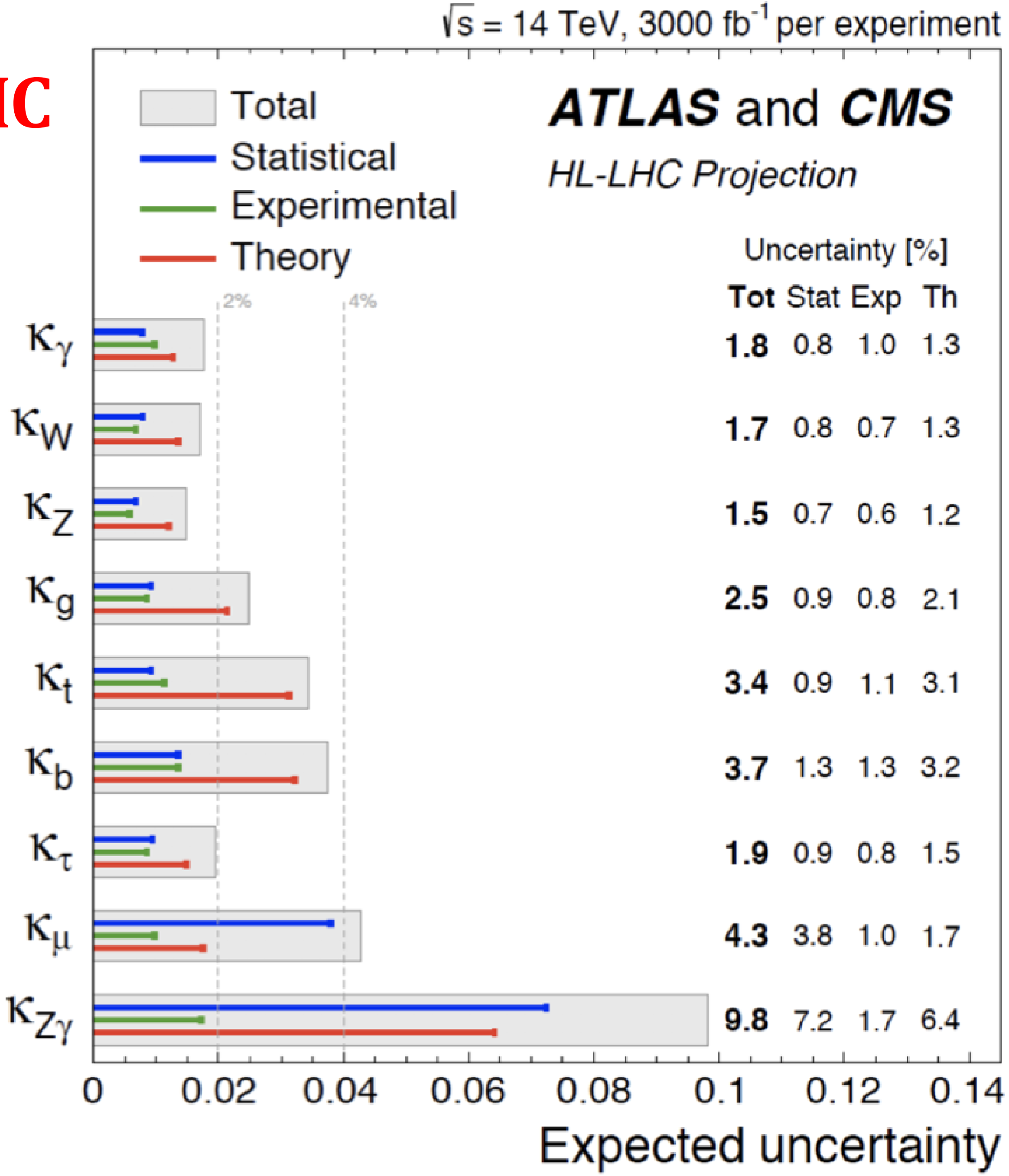
Prediction $\sigma_{t\bar{t}Z} = 0.863^{+0.073}_{-0.085}\ \text{(scale)} \pm 0.028\ (\text{PDF} \oplus \alpha_s)\ \text{pb}$





New precision frontier with HL-LHC





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

What’s next?

Timeline for the update of the European Strategy for Particle Physics

End September 2024
Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024
Council decision on the venue for the **ESG** **Strategy Drafting Session**

31 March 2025
Deadline for the submission of main input from the community

26 May 2025
Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025
Open Symposium

End September 2025
Submission of the “Briefing Book” to the **ESG**

14 November 2025
Deadline for the submission of final national input in advance of the **ESG** **Strategy Drafting Session**

1-5 December 2025
ESG Strategy Drafting Session

End January 2026
Submission of the draft strategy document to the Council

March and June 2026
Discussion of the draft strategy document by the Council and **updating of the Strategy**

Why do we need to go beyond LHC?

1) The Higgs mystery

Gauge sector $i\overline{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$

Higgs sector

$$D^{\mu}H^{\dagger}D_{\mu}H - (\overline{\psi}\,Y H\,\psi + \text{h.c.}) - \lambda|H|^4 + \mu^2|H|^2$$

The SM Higgs potential is today one of the best measured quantities in particle physics:

$$V_{\text{SM}}(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4 = M_h^2\left(\sqrt{2}G_F\,|H|^2 - 1\right)\frac{|H|^2}{2}$$

0.1% 0.001%

And yet, it looks like a parametrisation, just like Landau-Ginzburg for superconductivity before BCS.

Unprecedented phenomenon in particle physics:

- Does the Higgs sector lack the “uniqueness” of the gauge sector?
- Non-gauge fundamental forces?
- Naturalness problem?
- Fundamental or composite particle?
- Flavour problem?
- Portal to new sectors? (Only Lorentz and gauge invariant term with d<4)

Deeply related to the history of our universe:

- Spacetime vacuum structure
- Metastability and ultimate fate of the universe
- Prototype for inflation
- Prototype for early-universe phase transitions (GW)

Addressing these mysteries is a not-to-be missed experimental program

Why do we need to go beyond LHC?

2) The flavour mystery

➔ See Gino Isidori's talk

- Flavour is one of the most puzzling features of the SM.
- Flavour parameters are well measured, but their microscopic origin remains mysterious.
- The Higgs shows that the flavour problem is related to the rest of the theory: EW data, Higgs couplings, flavour measurements are not independent.
- Unlike Higgs naturalness, it is difficult to anchor the flavour problem to a well-defined energy scale.
- Almost any theory that addresses Higgs naturalness disrupts the fragile flavour properties of the SM.

Why do we need to go beyond LHC?

3) The mystery of the unknown

- Despite its successes, there are many theoretical and cosmological considerations suggesting that the SM is incomplete.
- The paradox is that naturalness suggests a new physics scale below TeV, while conservation laws suggest a very high scale.
- This paradox must be addressed experimentally.
- Exploration of the unknown has always been the driving force in particle physics.
- Indirect exploration through EW precision data.

Approaches towards the unknown

The traditional (pre-Higgs-discovery) strategy: **top-down approach**

- Identify the guiding principles to address some of SM problems.
- Construct a theory that provides a solution.
- Identify its consequences and test its predictions.

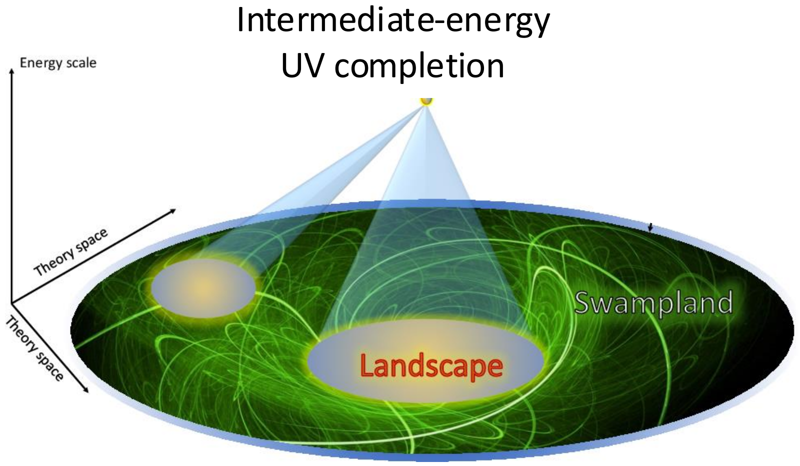
The lack of new physics at the LHC has challenged most of these theories and is suggesting a separation of scales. This motivates a different strategy: **bottom-up approach**

- Forget about any theoretical motivation or bias.
- Parametrise new physics using the most general basis of higher-dimensional operators (SMEFT).
- Take one operator at a time and test its consequences.

Both approaches have good motivations. However...

The pitfalls of SMEFT

The SMEFT Swampland



- A large portion of SMEFT is not populated by any reasonable UV completion.
- It misses important correlations between signals.
- Although superficially more “general”, it can be misleading in defining priorities, motivating searches for non-existing theories.

As written in the US Declaration of Independence,
“not all SMEFT operators are created equal.”

CONGRESS. July 4. 177

Declaration of the thirteen united States of

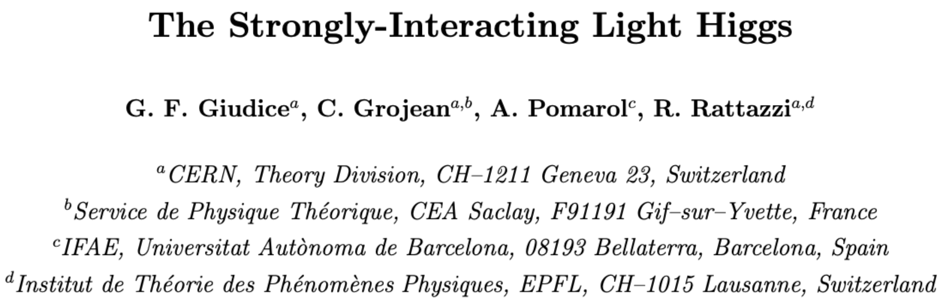
The fallacies of SMEFT culture

- Experimental searches are valued not by the knowledge that can be extracted from measurements, but by the number of operators that can be tested or the value of their scales.
- Examples: HIKE at CERN; testing EW baryogenesis using HHH or EDM; flat directions.

No magic recipe: only theory intuition.

From MSSM to SMEFT...

Example: SILH



The Strongly-Interacting Light Higgs

G. F. Giudice[a], C. Grojean[a,b], A. Pomarol[c], R. Rattazzi[a,d]

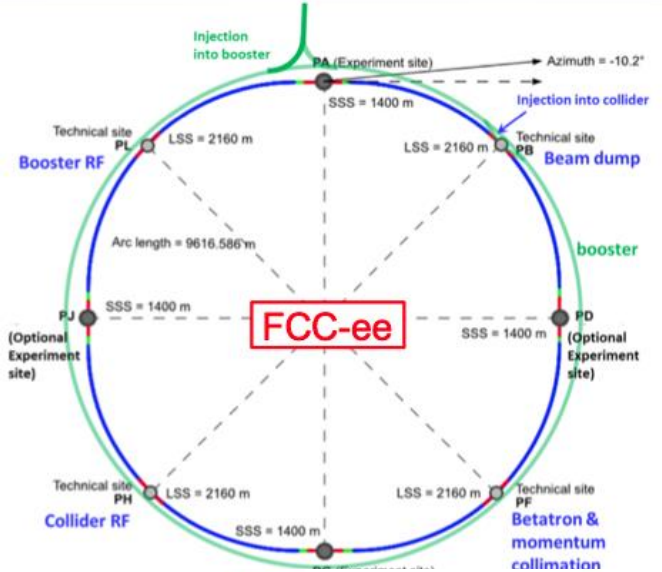
[a] *CERN, Theory Division, CH–1211 Geneva 23, Switzerland*
[b] *Service de Physique Théorique, CEA Saclay, F91191 Gif–sur–Yvette, France*
[c] *IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain*
[d] *Institut de Théorie des Phénomènes Physiques, EPFL, CH–1015 Lausanne, Switzerland*

- Define a class of theories (strongly-interacting theory with Higgs as a pseudo-Goldstone)
- Characterise coefficients of higher-dim operators in terms of selection rules and dimensional analysis of couplings and masses.
- Derive consequences and predictions.

Example: build a theory of composite supersymmetry with the lowest possible scale

(K. Agashe, GFG, R. Rattazzi, R. Sundrum)

Plan A: FCC



~ 91 km ring with potentially two sequential colliders

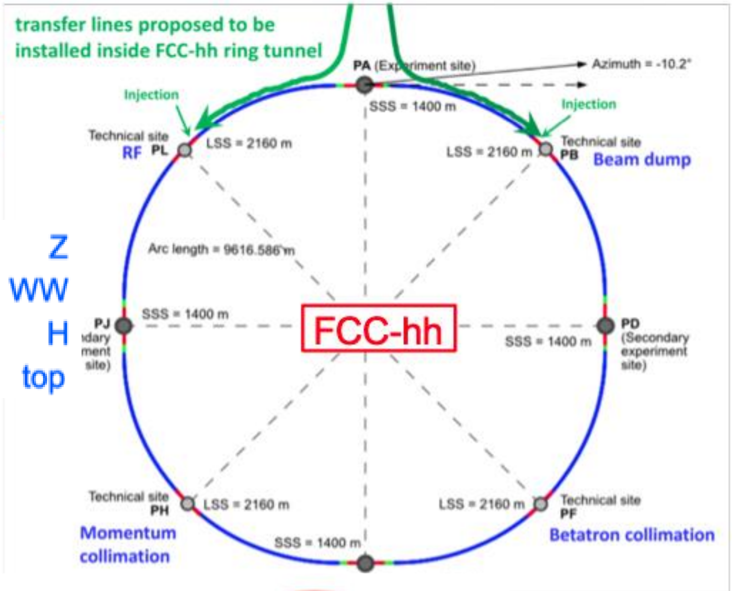
1st stage collider FCC-ee:

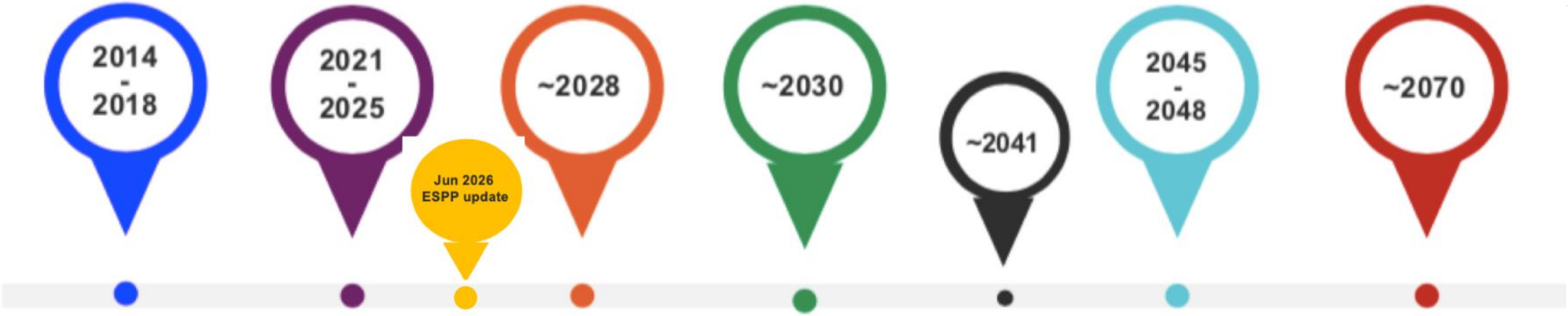
- ☐ electron-positron collisions 90-360 GeV
- ☐ best of all proposed electroweak and Higgs factories up to HZ energies

~90 GeV	Z
160	WW
240	H
~365	top

2nd stage collider FCC-hh:

- ☐ proton-proton collisions at ~ 100 TeV
- ☐ <u>direct</u> exploration of the 10-40 TeV E-scale





2014 - 2018

Conceptual Design Study
(Conceptual Design Report end 2018)

2021 - 2025

Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

Jun 2026 ESPP update

~2028

Project approval by CERN Council

~2030

Construction of tunnel and FCC-ee starts

~2041

HL-LHC ends

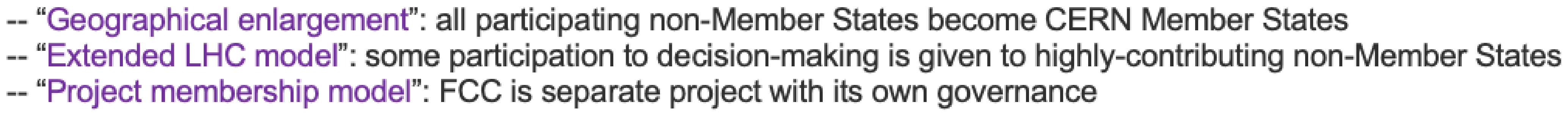
2045 - 2048

Operation of FCC-ee
(15 years physics exploitation)

~2070

Operation of FCC-hh
(~ 20 years of physics exploitation)

FCC Governance



-- “Geographical enlargement”: all participating non-Member States become CERN Member States
-- “Extended LHC model”: some participation to decision-making is given to highly-contributing non-Member States
-- “Project membership model”: FCC is separate project with its own governance

FCC-*ee* Cost

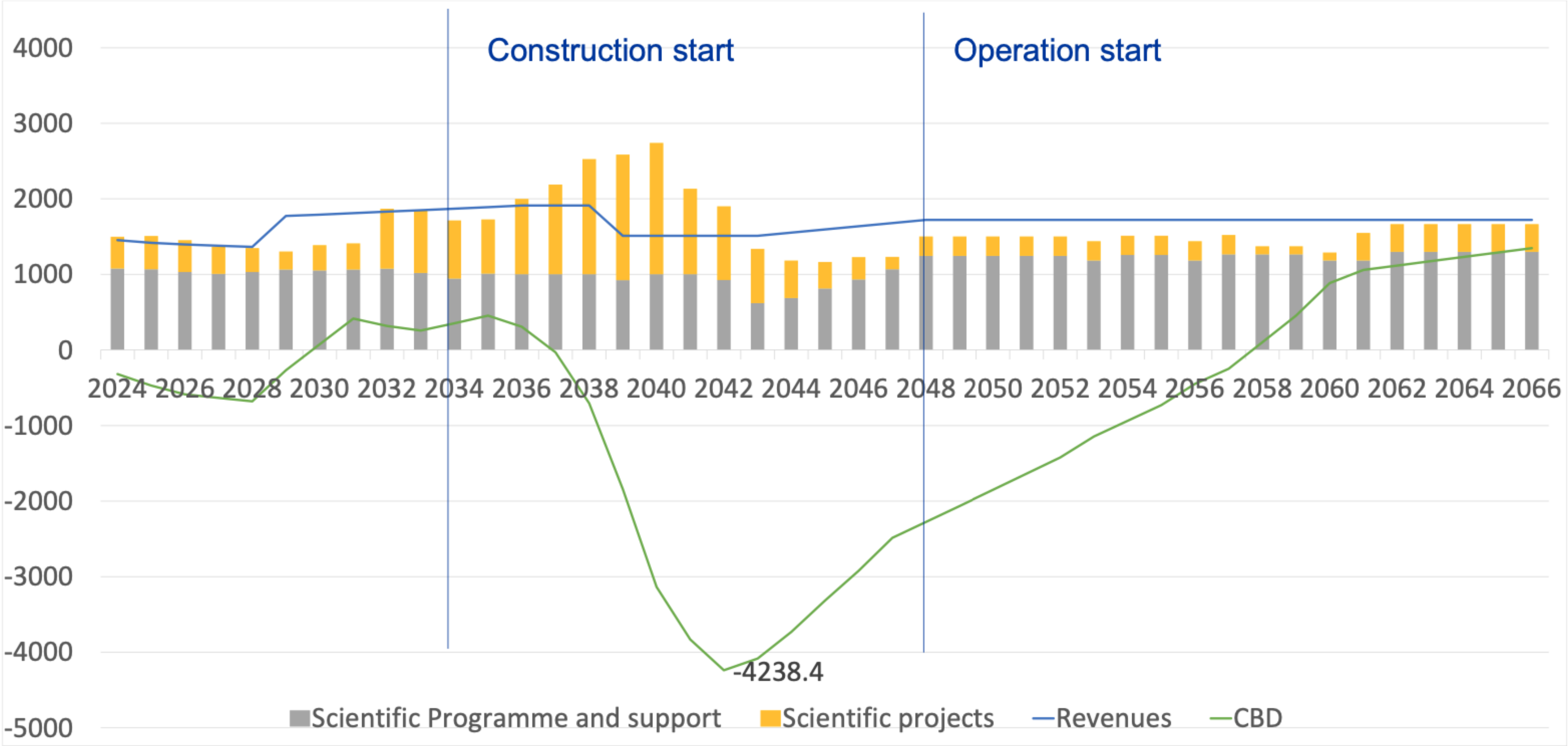
Civil engineering	5,538 MCHF
Territorial development	191 MCHF
Technical infrastructures	2,490 MCHF
Injection & transfer lines	585 MCHF
Accelerators	3,847 MCHF
Experiments	150 MCHF
Total	**12,801 MCHF**
4 IP for experiments instead of 2 IP	710 MCHF
Total	**13,511 MCHF**
RF and cryogenics to operate at *tt*	1,465 MCHF
Total	**14,976 MCHF**

FCC-*hh* Cost

$\sim$ 17 BCHF (13 BCHF for magnets)
if built after FCC-*ee*
$\sim$ 24 BCHF (if standalone)

Baseline Funding Scheme

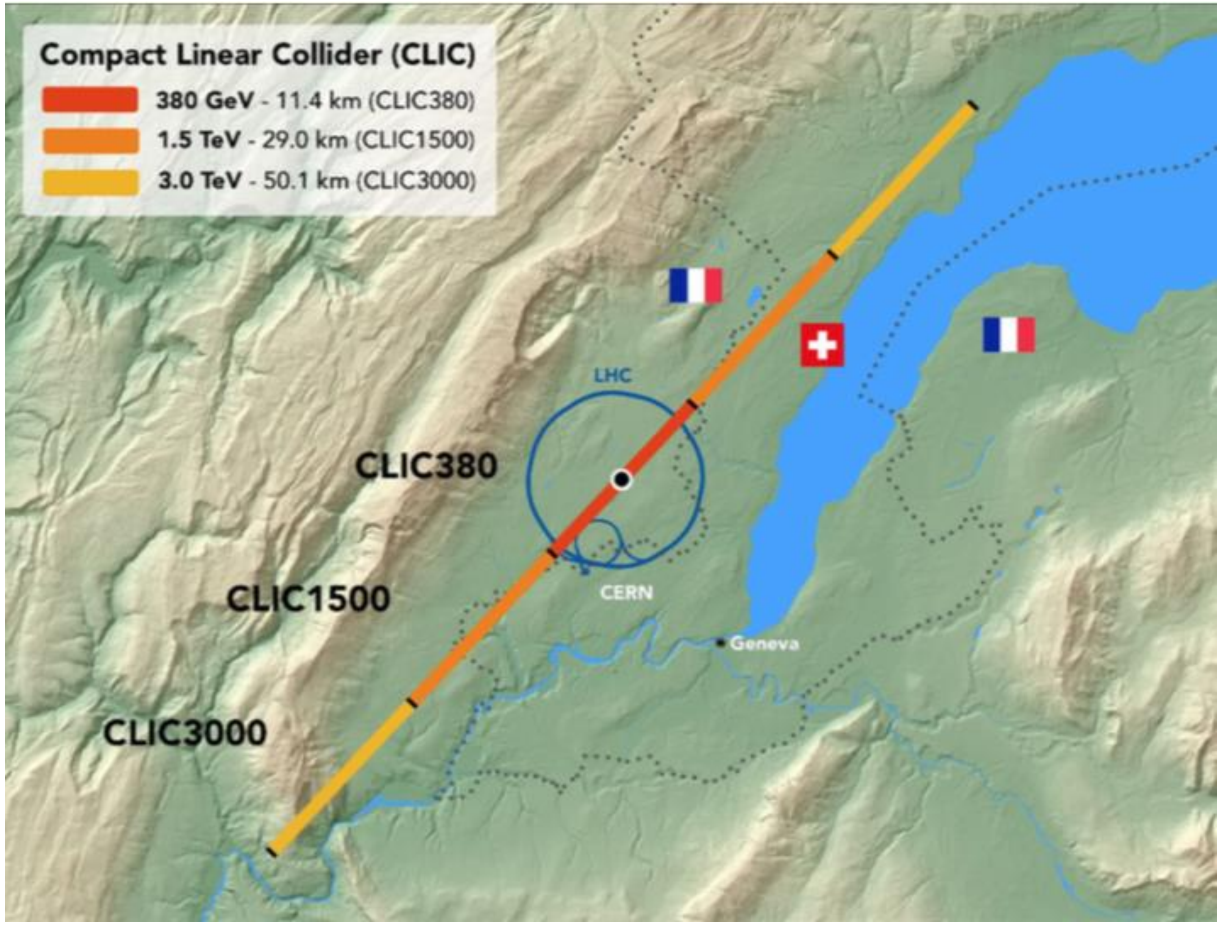
- Increase of MS annual contribution to CERN budget by 1.5% p.a. for 8 yrs as of 2029 for a total of 12.6%
- 4 BCHF special contribution from outside CERN budget
  - 1.5 BCHF from NMS
  - 1.0 BCHF from private donors
  - 1.5 BCHF from special MS contributions (host states and in-kind)
- 2-3 BCHF from EU possible but not included



Alternative funding schemes have been proposed, but have a significant scientific impact

Plan B: CLIC, SLHC, ILC@CERN, ... Long-term: μ collider, plasma wakefield acceleration, ...

Parameter	Unit	Stage 1	Stage 2	Stage 3
$\sqrt{s}$	GeV	380	1500	3000
Tunnel length	km	11	29	50
Gradient	MV/m	72	72/100	72/100
Pulse length	ns	244	244	244
Luminosity (above 99% of $\sqrt{s}$)	10^{34} cm^{-2}s^{-1}	1.5 0.9	3.7 1.4	5.9 2
Repetition frequency	Hz	50	50	50
Bunches per train		352	312	312
Bunch spacing	ns	0.5	0.5	0.5
Particles/bunch	10^9	5.2	3.7	3.7
Beam size at IP (σ_y/σ_x)	nm	2.9/149	1.5/60	1/40
Annual energy consumption	TWh	0.8	1.7	2.8
Construction cost	BCH	5.9	+5.1	+7.3



- A notable example of the remarkable returns from the joint collaboration of European countries is the creation of the European Organization for Nuclear Research (CERN) in 1954.
- Its collaborative effort has yielded remarkable successes.
- One of CERN’s most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC).
- Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority, given the objective of maintaining European prominence in this critical area of fundamental research, which is expected to generate significant business spillovers in the coming years.

- Today, CERN is a magnet for top scientists from all continents.
- Basically, every physicist in the world wants to work at CERN.
- I am proud that we have financed the feasibility study for CERN's Future Circular Collider. This could preserve Europe's scientific edge, and it could push the boundaries of human knowledge even further.
- CERN is the living proof that science fosters innovation and that innovation fosters competitiveness.
- Your story is one of progress against all odds, just like the story of Europe. You were born to discover. And I cannot wait to see what you will discover next because I am sure that once again, CERN will change the world.

Conclusions

- The LHC results have changed our perspective on the particle world.
- To go beyond LHC, we need a diversified experimental approach that includes large- and small-scale projects with different goals and techniques, bridging across fields.
- High-energy colliders remain the most powerful microscope at our disposal to explore nature at small distances and an irreplaceable tool to study the fundamental laws that govern the Universe.
- Colliders are not single-purpose projects but are, in themselves, a diversified physics programme.