Physics at FCC: a perspective

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Why the FCC?

because!

the skeptical

- the technology skeptical ("*too ambitious, too $$*")
- the timescale skeptical ("*call me when you're ready*")
- the discovery skeptical ("*no guarantee*")
- the precision skeptical ("*how boring, who cares*")
- …

The challenge of sharing a vision

The next steps in HEP build on

- having important questions to pursue
- creating opportunities to answer them
- being able to constantly add to our knowledge, while seeking those answers

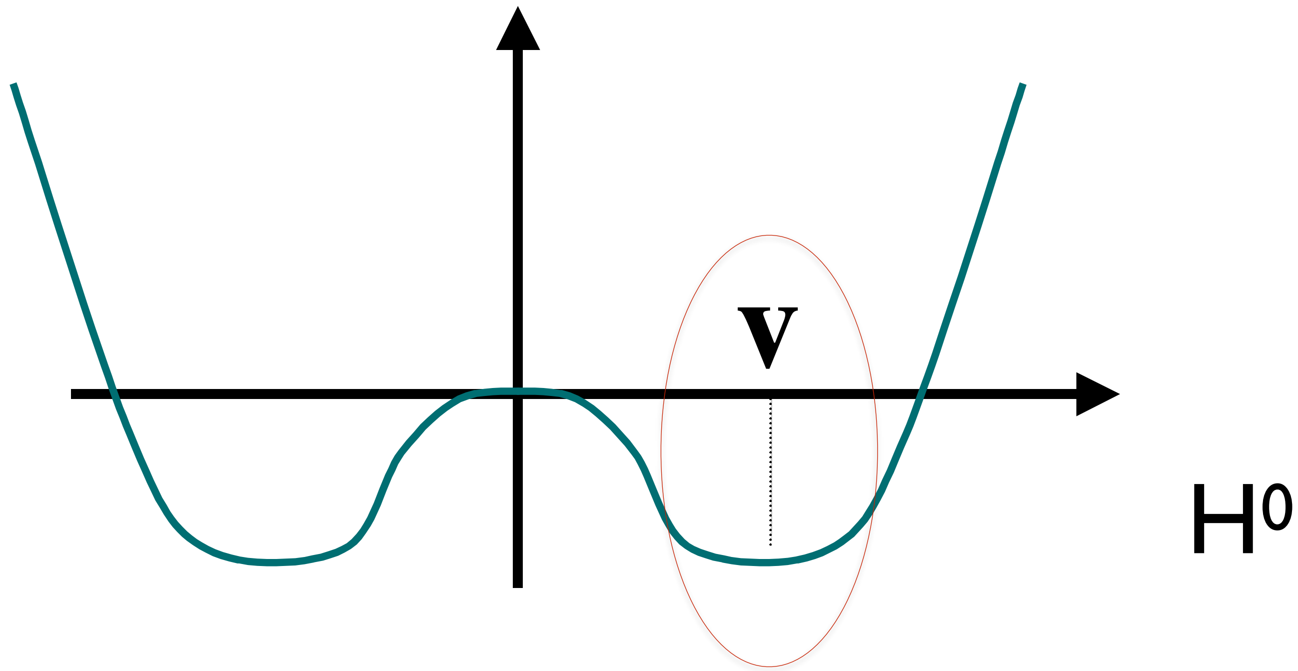
The important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - Neutrino masses: could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu\to e\gamma$, $H\to\mu\tau$, …): as for DM, ***a broad range of options***
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

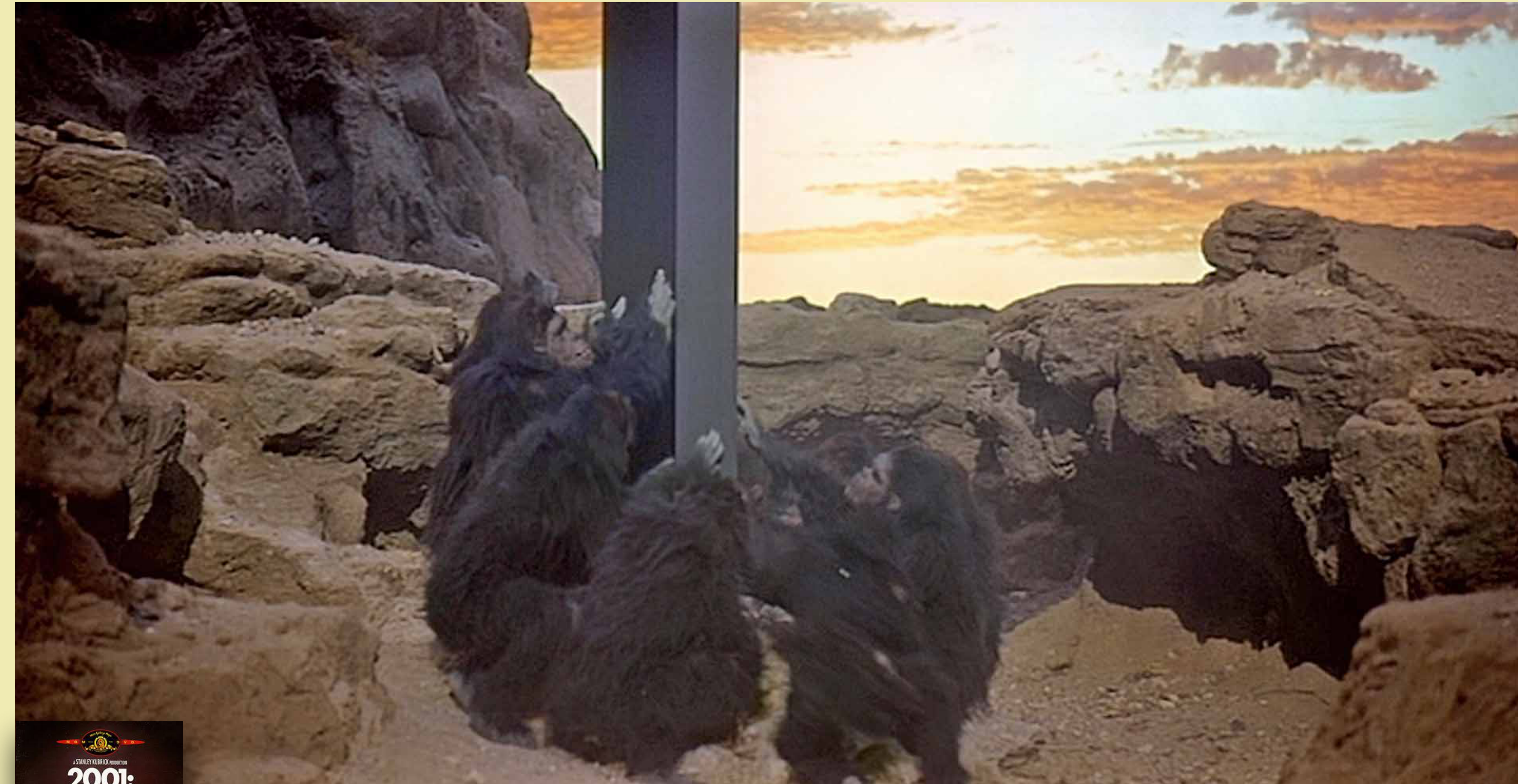
One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction….

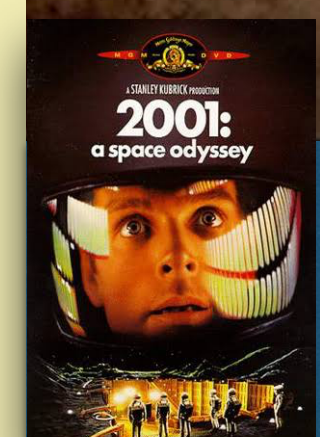


$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

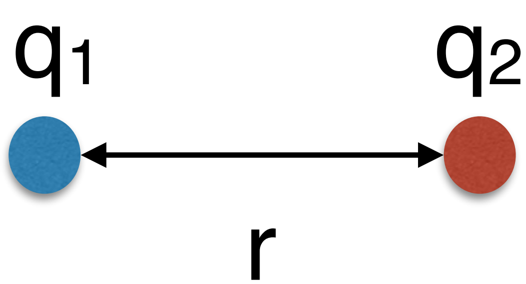
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics





Who put it there?

Electromagnetic vs Higgs dynamics

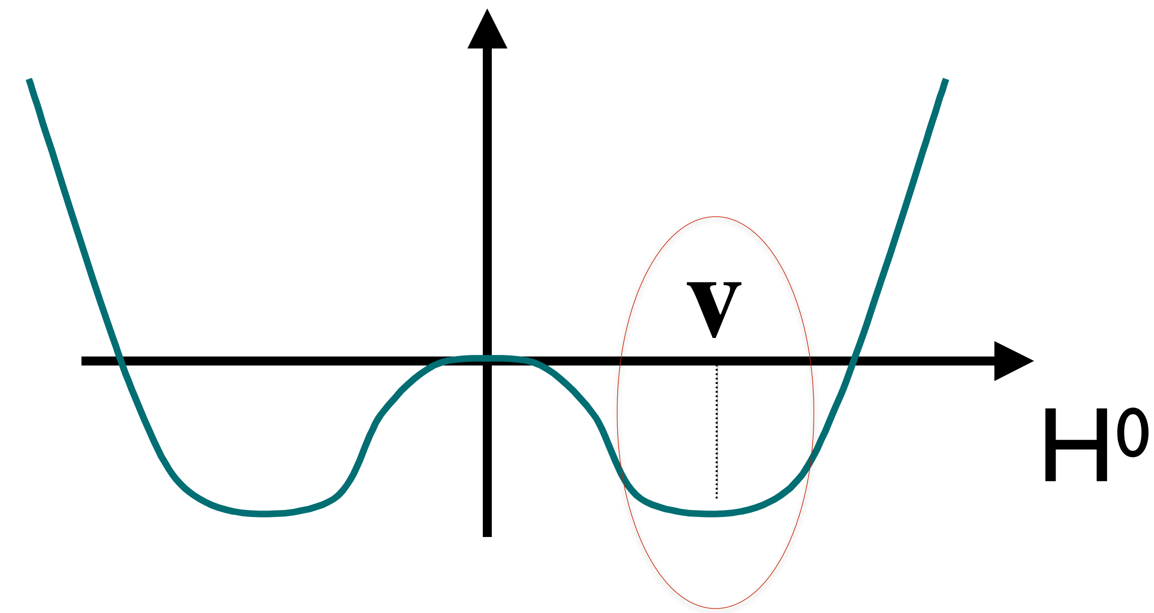


$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

quantized, in units of fixed charge

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem



any function of $|H|^2$ would be ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

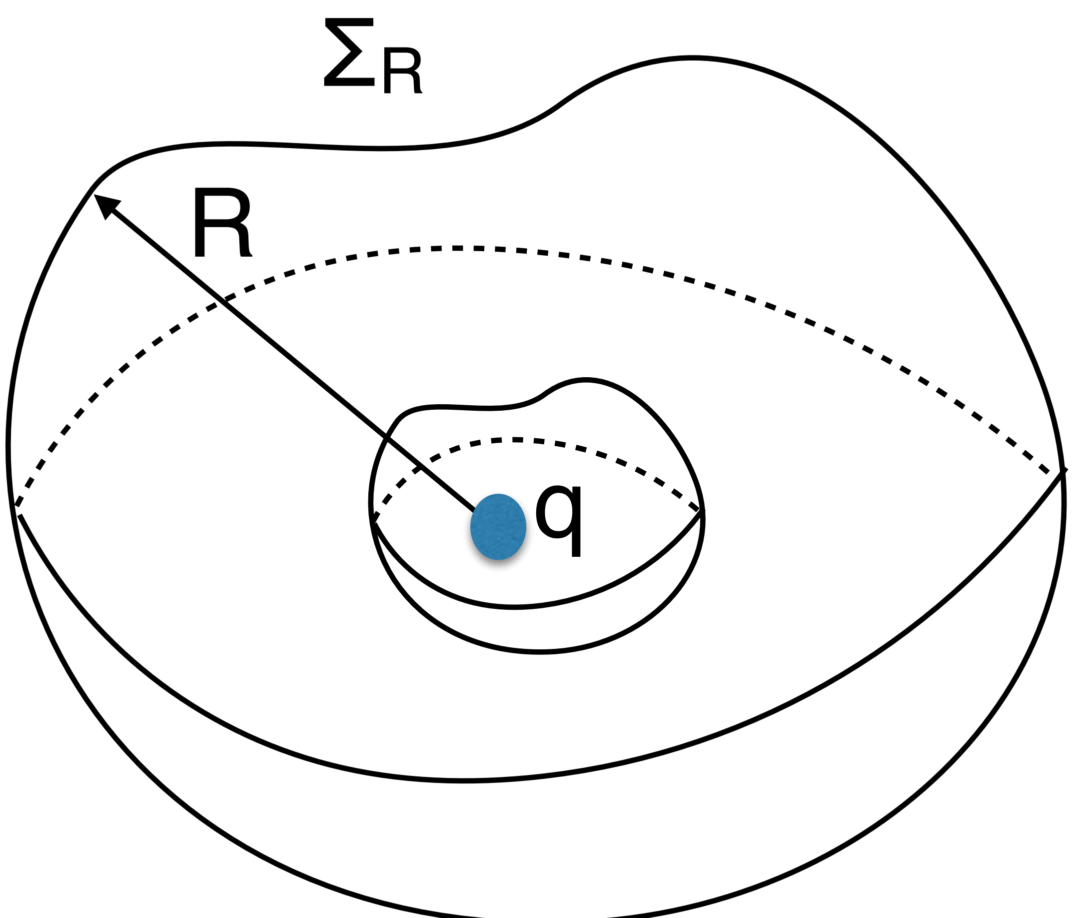
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either case we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Decoupling of high-frequency modes

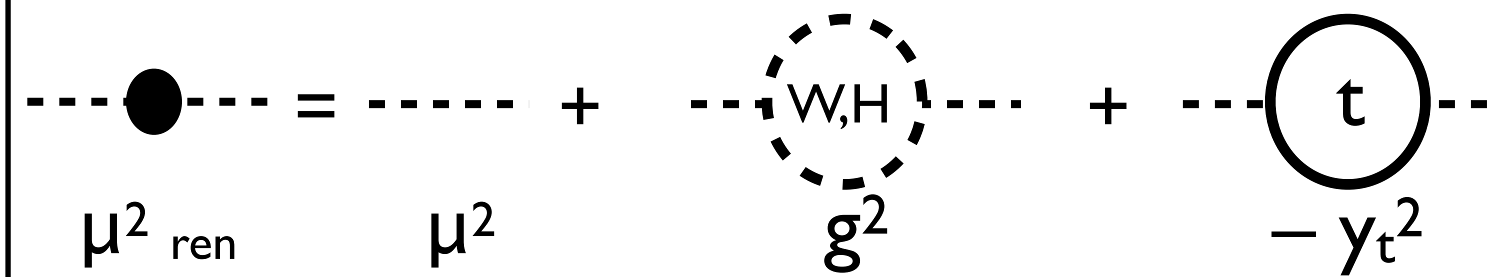
E&M



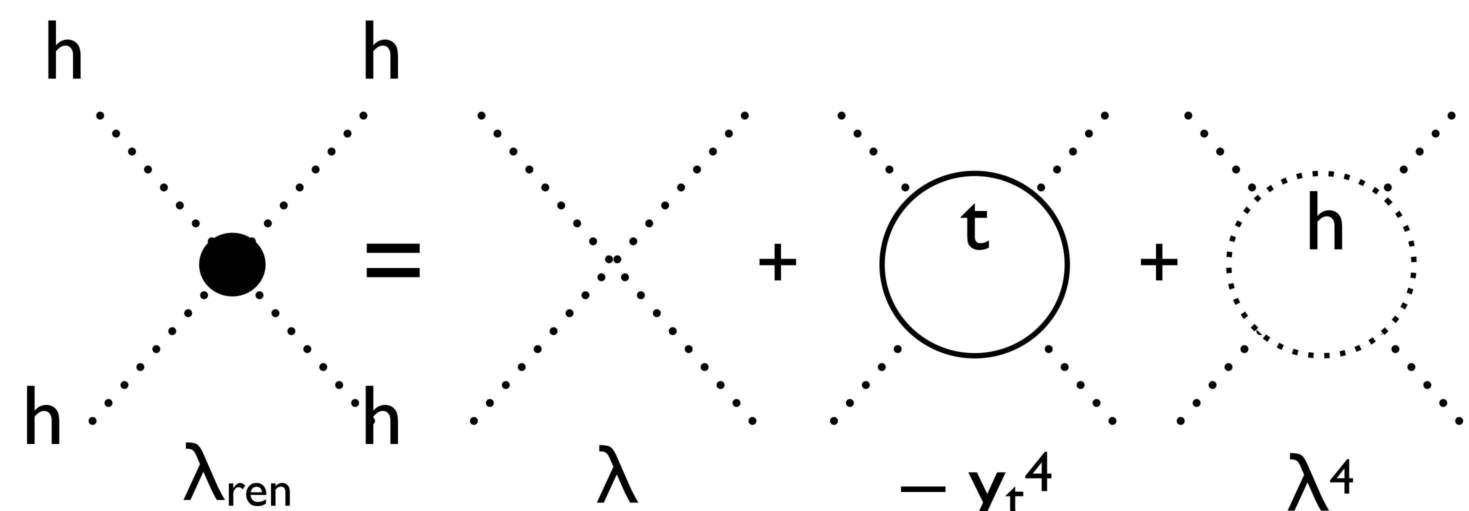
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter the charge seen at large scales

$$V_{SM}(H) = -\mu^2 \left|H\right|^2 + \lambda \left|H\right|^4$$



$$\Delta\mu^2 \sim (\, c_B\, m_B^2 - c_F\, m_F^2\,)\ \mathrm{x}\ (\,\Lambda / v)^2$$



$$\Longrightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a\, m_H^4 - b\, m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics

bottom line

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the "natural" scale defined by the measured parameters v and m_H

$\Rightarrow$ **naturalness**

message

- Naturalness and the origin of the Higgs go hand in hand, and are unavoidably tied to BSM physics. They have provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
  - again, "who ordered that?"
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted
  - what we've experimentally proven so far are basic properties, which, from the perspective of EFT and at the current level of precision of the measurements, could hold in a vast range of BSM EWSB scenarios

➡ ***the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, and relying on a future generation of colliders***

On the role of measurement

- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, it's about finding out how things work
- We do not measure Higgs couplings precisely to **find** deviations from the SM. We measure them to **know** them!
- LEP's success was establishing SM's amazing predictive power!
- *Precision for the sake of it is not necessarily justified. Improving X10 the precision on m(electron) or m(proton) is not equivalent to improving X10 the Higgs couplings:*
  - *m(e) => just a parameter; m(p)=> just QCD dynamics; Higgs couplings => ???*
- … but who knows how important a given measurement can become, to assess the validity of a future theory?
  - Tycho Brahe (data) => Kepler (phenomenology) => Newton (theory)
  - Mercury's perihelion precession measurements vs GR: Einstein did not develop GR to explain Mercury's orbit. But those data were crucial to validate his theory!
  - the day some BSM signal is found somewhere, the available precision measurements, whether they agree or deviate from the SM, will be useful to establish the nature of the signal

Criteria to judge a future facility

- <u>Guaranteed deliverables</u>
- <u>Extensive exploration potential</u>
- <u>Firm Yes/No answers to relevant questions</u>

The FCC targets

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**
- Exploration potential:
  - **enhanced mass reach** for direct exploration (pp@100TeV)
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
  - exploit both direct (large Q^2) and indirect (precision) probes
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Event rates: examples

FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←Z)
	10^{6}	$5\ 10^{12}$	10^{8}	10^{6}	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

FCC-hh	H	b	t	W(←t)	τ(←W←t)
	$2.5\ 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5\ 10^{6}$	$2\ 10^{7}$

The goals of the first FCC physics studies

- explore the measurement and discovery potential of the individual components of the programme
- guide the definition of accelerator layout/performance parameters (energies, luminosities, bunch structure, MDI, ...)
- identify the key experimental requirements, define the target detector performance parameters, provide benchmark studies for the evaluation of the detector performance
- identify targets for the progress of theoretical calculations
- take a broader look at the full programme, explore synergies and complementarities

Major events organized

FCC-ee

- 5th TLEP Workshop "TLEP physics and technology", Fermilab, 25-26 July 2013, https://indico.cern.ch/event/246137/
- 6th TLEP Workshop, CERN, 16-18 October 2013, https://indico.cern.ch/event/257713/
- FCC-ee/TLEP physics workshop (TLEP7), CERN, 19-21 June 2014, https://indico.cern.ch/event/313708/
- FCC-ee (TLEP) Physics Workshop (TLEP8), LPNHE Paris, 27-29 October 2014, https://indico.cern.ch/ event/337673/
- FCC-ee (TLEP) Physics Workshop (TLEP9), SNS Pisa, 3-5 February 2015, https://indico.cern.ch/event/357188/
- 1st FCC-ee mini-workshop on Detector Requirements, CERN, 17-18 June 2015, https://indico.cern.ch/event/393093/
- FCC-ee mini-workshop on "Precision Observables and Radiative Corrections", CERN, 13-14July 2015, https://indico.cern.ch/event/387296/
- First FCC-ee workshop on Higgs physics, CERN, 24-25 Sept. 2015, https://indico.cern.ch/event/401590/
- Workshop on high-precision α_S measurements: from LHC to FCC-ee, 12-13 October 2015, https://indico.cern.ch/event/392530/
- FCC-ee Mini-Workshop: "Physics Behind Precision", CERN, 2-3 February 2016, https://indico.cern.ch/event/469561/
- 10th FCC-ee Physics Workshop, CERN, CERN, 2-3 February 2016, https://indico.cern.ch/ event/469576/
- Parton Radiation and Fragmentation from LHC to FCC-ee, CERN, 21-22 Nov 2016, https://indico.cern.ch/event/557400/
- 2nd mini-workshop on FCC-ee detector requirements CERN, 23-24 November 2016, https://indico.cern.ch/event/570415/
- Mini workshop: Precision EW and QCD calculations for the FCC studies, CERN 12-13 January 2018, https://indico.cern.ch/ event/669224/
- FCC-ee mini-workshop on Flavours, CERN, 31 Jan.-1 Feb. 2018, https://indico.cern.ch/event/687191/
- 11th FCC-ee workshop: Theory and Experiments, CERN, 8 - 11 Jan 2019, https://indico.cern.ch/event/766859/

FCC-hh

- Ions at the Future Hadron Collider, Dec16-17 2013, https://indico.cern.ch/event/288576/
- BSM physics opportunities at 100 TeV, Febr 10-11 2014, https://indico.cern.ch/event/284800/
- 1st Future Hadron Collider Workshop, May 26-28 2014, https://indico.cern.ch/event/304759
- Ions at the Future Circular Collider, Sept 22-23 2014, https://indico.cern.ch/event/331669/
- Higgs & BSM at 100 TeV, March 11-13 2015, https://indico.cern.ch/event/352868/
- QCD, EW and tools at 100 TeV, Oct 7-9 2015, https://indico.cern.ch/event/437912/
- Dark Matter at a future hadron collider, Dec 4-6 2015, https://indico.cern.ch/event/445743/

FCC-eh

- LHeC and FCC-eh, CERN and Chavanne-de-Bogis, 24-26.6.2015, https://indico.cern.ch/ event/356714/
- LHeC and FCC-eh, CERN, 11-13.9.2017, https://indico.cern.ch/event/639067/
- Electrons for the LHC - LHeC/FCC-eh and PERLE, Orsay, 27-29.6.2018, https://indico.cern.ch/event/698368/

Joint

- LHC, FCC-ee, FCC-hh Interplay, 25 November 2016, https://indico.cern.ch/event/ 573689/
- 1st FCC Physics Workshop, January 16-20 2017, https://indico.cern.ch/event/550509/
- 2nd FCC Physics Workshop, January 15-19 2018, https://indico.cern.ch/event/618254/

… plus many events worldwide dedicated to physics at FCCs

Reports produced

FCC-ee

- First Look at the Physics Case of TLEP, https://arxiv.org/abs/1308.6176
- High-Precision αs Measurements from LHC to FCC-ee, Workshop report, https://arxiv.org/abs/1512.05194
- Physics Behind Precision, Workshop report, https://arxiv.org/abs/1703.01626
- Parton Radiation and Fragmentation from LHC to FCC-ee, Workshop report, https://arxiv.org/abs/1702.01329
- Standard Model Theory for the FCC-ee: The Tera-Z, Workshop report, https://arxiv.org/abs/1809.01830

FCC-hh

"Physics at 100 TeV", CERN Yellow Report:

- Standard Model processes https://arxiv.org/abs/1607.01831
- Higgs and EW symmetry breaking studies, https://arxiv.org/abs/1606.09408
- Beyond the Standard Model phenomena, https://arxiv.org/abs/1606.00947
- Heavy ions at the Future Circular Collider, https://arxiv.org/abs/1605.01389
- Physics Opportunities with the FCC-hh Injectors, https://arxiv.org/abs/1706.07667

... plus hundreds of articles inspired by the physics opportunities at FCCs

Future Circular Collider Study
Conceptual Design Report
Volume 1: Physics Opportunities
https://fcc-cdr.web.cern.ch

what's been left out of the CDR studies

- few examples. Eg
  - exhaustive study of opportunities with the injector complex (see https://arxiv.org/abs/1706.07667 for some examples)
  - systematic study of dedicated experiments at the two low-lumi pp IP, beyond FCC-eh (eg LHCb', HI, …)
  - more systematic studies of flavour physics at the Z peak, at 100 TeV, with injectors
  - studies of additional physics scenarios
  - etc.etc.

There is still plenty of work left, to unveil new physics opportunities, to characterize in more detail the physics potential already examined, to develop new detector concepts and optimize their designs, …