Future Colliders: why? what?

LHC Outreach Group meeting
6 April 2023

Michelangelo L. Mangano
Theory Department,
CERN, Geneva

The important questions HEP is seeking an answer to

- **What is the origin of:**
  - Dark Matter ?
  - Neutrino masses ?
  - Matter vs antimatter asymmetry ?
  - Dark energy ?
  - …

Remark

there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

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  - **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*** to explore, to find the right clues

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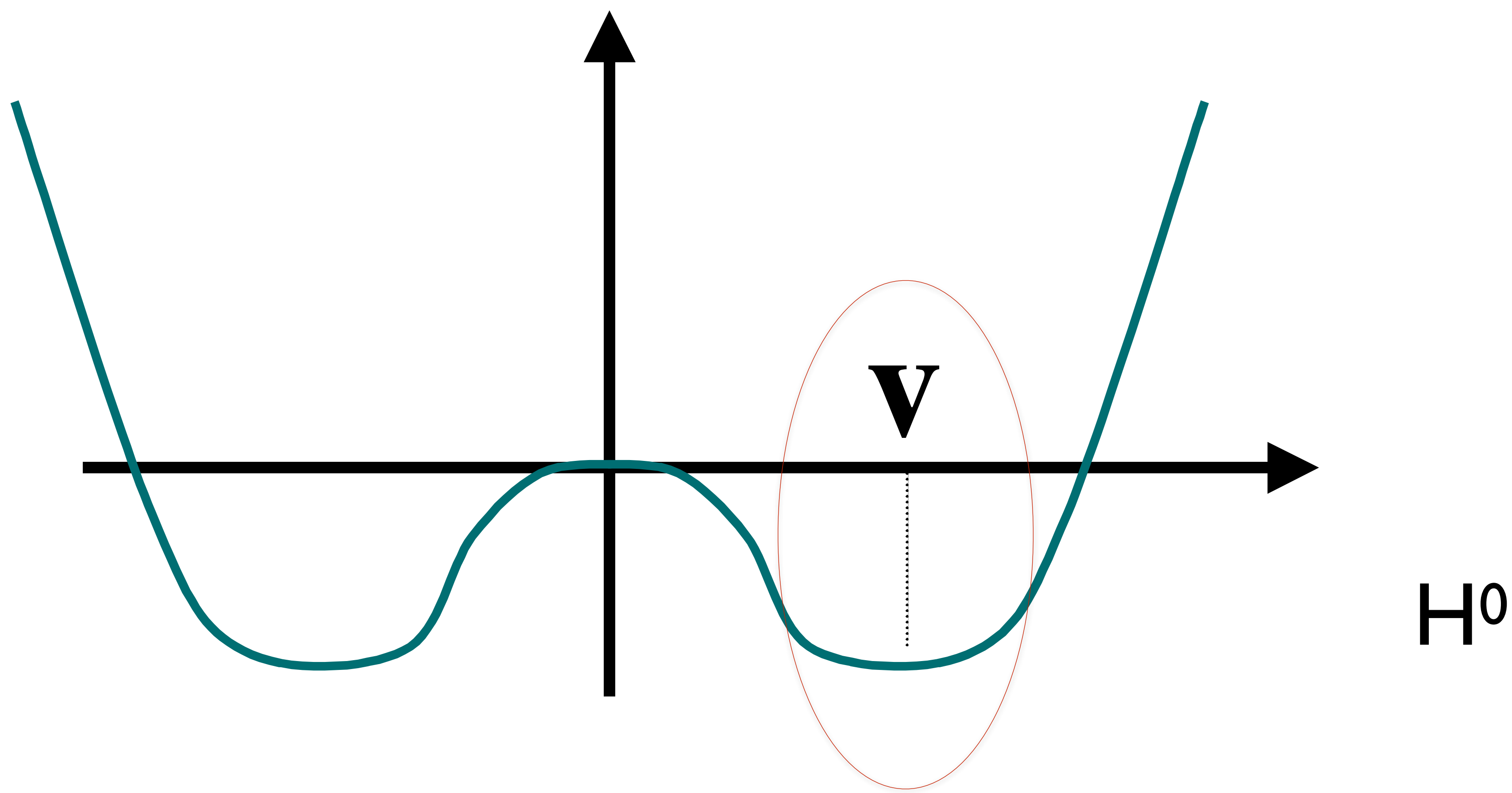

$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Where does this come from?

What's the origin of the Higgs phenomenon?

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Finding the origin of the Higgs boson will take us beyond the SM, and collider experiments are the only way we know how to do that

Having understood the "how" and "what", we're now moving to explore the "why" and "what else"

see e.g. the road from electromagnetism to Maxwell's eqs, to QED and then gauge theories…

Examples of open questions emerging in a beyond-the-SM Higgs context

- Is the Higgs the only (fundamental?) scalar field, or **are there other Higgs-like states** (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do **Higgs couplings conserve flavour?** $H\rightarrow\mu\tau$? $H\rightarrow e\tau$? $t\rightarrow Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
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➡ ***the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can only rely on a future generation of colliders***

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- The study of the Higgs is the "guaranteed deliverable" that by itself motivates and requires a future collider

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

The discussion of the relevance/implications of achieving this precision in Higgs measurements at future colliders goes beyond the scope of this presentation …

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  - *NB: these challenges are what makes an ambitious project interesting, and are an important component of the motivation by young researchers*

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- Timescale and young scientists engagement
  - *remarks in the next few slides*

symmetry
dimensions of particle physics

topics | follow +

A joint Fermilab/SLAC publication

LHC experiments see four top quarks

03/24/23 | By Sarah Charley

The ATLAS and CMS experiments have observed a process 4,000 times rarer than the production of Higgs bosons.

“When I was a high school student in Taiwan, I was attracted by the discovery of the Higgs boson,” **Tsai*** says. “Even though I didn’t know what exactly a Higgs boson was, I was thrilled and wished that I would be able to come to Geneva and join the collaboration in CERN one day, working with physicists there to discover new physics. And now, everything has come true.”

* Meng-ju **Tsai**, a graduate student at the University of Michigan

From my "LHC legacy" talks:

I have a broad concept of "*new physics*", which includes SM phenomena, emerging from the data, that are unexpected, surprising, or simply poorly understood.

I consider as "new", and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

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> **“New physics” is emerging every day at the LHC!**

- Discovery of B(s) $\rightarrow \mu\mu$
- Discovery of D mixing and CP violation in the D system
- Discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in “small” systems (pA and pp)
- Discovery of super-rare processes $pp \rightarrow 3W,\ 4t,\ \ldots$
- Discovery of the odderon in elastic pp vs $p\bar{p}$ elastic scattering
- …

From my contribution to this issue:

“[…] Space for initiative, creativity and flexibility have been pillars of HEP and CERN’s culture for decades; joint with the intellectual challenge of exploring the universe, this cocktail made our field the most attractive among all sciences for young researchers.

Properly filling EDH forms and compliance to strict protocols better not become the leading intellectual challenges we leave to the next generation of scientists, whom we need to attract to carry out our long- term scientific vision! … “

https://staff-association.web.cern.ch/sites/default/files/PROTON-SPECIAL-2022-What-future-for-CERN.pdf

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- The driving force for all of us (old and young) should not be the vague expectation of a paradigm-shifting discovery, N years down the line, but the concrete prospect of creative and exciting research, with daily progress/rewards/satisfaction, working at the edge of all scientific and technological frontiers, in an unmatchable environment such as CERNs