Il futuro della fisica delle particelle e il Bosone di Higgs

INFN Roma

Barbara Mele

Outline

* very exciting (and challenging) time for particle physics !

* Theory : present status

* Experiments : main strategies

* quite a few great options for "beyond HL-LHC" Physics !

* a few (personal) remarks

WHERE ARE WE ?

[THEORY + EXP's]

SM works !

- Higgs boson (the last piece of the SM) found !
- huge amount of LHC data fits SM predictions with amazing (unplanned) level of accuracy

nevertheless...

great (although hazy) expectations
for new BSM phenomena at colliders !

* two kinds of issues with the SM :

* existence of "external" phenomena :

(quantum ?) Gravity

+ empirical evidences :

Dark Matter

Barion asymmetry

neutrino masses

. . .

* "internal" poor consistency :

mainly connected to the EWSB/Higgs sector

what's so problematic about the Higgs (TH)

$$\mathcal{L}_{\rm Higgs} = (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger\phi) - \bar{\psi}_L\Gamma\psi_R\phi - \bar{\psi}_R\Gamma^\dagger\psi_L\phi^\dagger$$

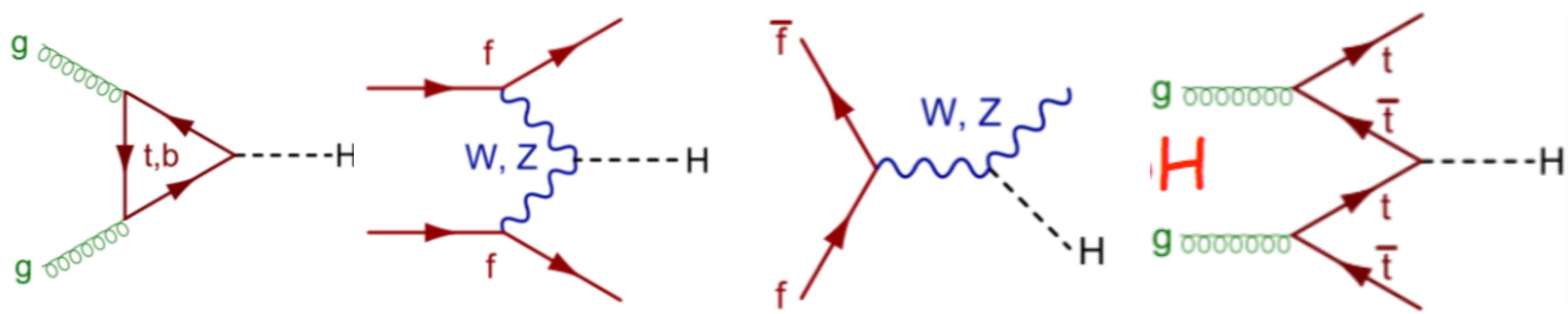
$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \frac{1}{2}\lambda(\phi^\dagger\phi)^2$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

- the only "fundamental" scalar particle (microscopic interpretation ?)
- not protected by symmetries (the less constrained SM sector):
  - naturalness problem : $m_H \sim g \times \Lambda_{cutoff}$
- many different couplings all fixed by masses (?)
  - proliferation of parameters historically leads to breakdown in TH models
- fermion masses/Yukawa's hierarchy (?)
  - have neutrinos a special role ?!!!
- λ determines shape and evolution of Higgs potential → cosmology !

what's so problematic about the Higgs (EXP)

- very challenging experimental studies in general
  - tiny x-sections in direct production from light states
    → must excite heavy states (t,W,Z) radiating Higgs
    → small cross sections → harsh separation from backgrounds



- the measured (and unpredicted) m_H value comes as a bonus, since it opens many explorable decay channels (with relatively unsuppressed production x-sections)

a comment on Naturalness

* the naturalness/hierarchy problem is a robust one !

* one might say : SM theory is self-consistent by itself
  → it is a complete framework !

renormalizable,
UV-complete

* BUT :
  * "external" phenomena unavoidably introduces extra M scales (M_{pl}, ...)
  * in a unified description this inevitably drives the Higgs-mass scale up to the extra M scales well above observed m_H value,
  * generating puzzling mass hierarchies (many many orders of magnitude for "desert" hypothesis up to M_{pl} or so)
  * typical of fundamental scalar fields !

LHC is just the right machine to explore this issue !

* theorists suggested a few elegant paths to solve m_H hierarchy

→ look for new heavy (~1TeV) states predicted in :

* SUSY (particularly far-reaching)
* Composite Higgs
* Extra Dims ...

* on the other hand :

* LHC already excluded their minimal versions
* but minimal versions not well motivated if not by allowing manageable predictions of new models that in general involve a large number of new parameters (>100 for MSSM !)
* Nature might well have chosen different paths than the theorists' ones to solve the hierarchy problem
* relevant new energy scale must anyway be connected to m_H !

presently four strategies
to advance in HEP
at colliders →→

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* by exploring the characteristics of the Higgs sector and confirming/spoiling the SM picture
  (primary relevance since the Higgs sector is so critical !)

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- by looking for new "DARK" states (i.e.,uncoupled to SM at tree level) either in production or/and heavy-state (H,top…) decays (elusive signatures, may be long-lived p.les)

four paths to advance in HEP at colliders:

* Higgs
* new particles
* indirect effects
* "Dark" signals

every single method is of fundamental importance to make progress !

(unplanned !) EW precision at LHC !

if new physics is heavy →

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \dots$$

BSM effects SM particles

model independent
way to probe BSM couplings !

* deviations (δ) from SM via $O_i^{d=6}$ can grow with energy :

amplitudes ratio:

$$\frac{\mathcal{A}_{\mathrm{SM+BSM}}}{\mathcal{A}_{\mathrm{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

enters SM-BSM
interference terms !!

* LHC can match LEP sensitivity
by looking at larger (< Λ) Energy !!!

then, δ ~ 0.1% at E_{LEP} ~ 100 GeV

matches δ ~ 10% at E_{LHC} ~ 1 TeV

Higgs distribut.s as lever arm on BSM effects

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

* in inclusive production :

  $\delta\, \kappa_i = \delta g_{Hii} / g_{SM} \sim (v/\Lambda)^2 \sim 6\%\, (\mathrm{TeV}/\Lambda)^2$

  $\sim 1\%$ for $\Lambda \sim 2.5$ TeV

* at large momentum transfer $O_i^{d=6}$ may induce a grow:

  $\delta\, [d\sigma/dp_T] \,/\, [SM] \sim (p_T/\Lambda)^2$

  $\sim 16\%$ at $p_T \sim 1$TeV

  for $\Lambda \sim 2.5$ TeV

kinematic features can probe same Λ scales as inclusive ones requiring smaller accuracy !

λH^3 coupling most exposed to BSM

(impact on vacuum stability, Baryogenesis from cosmological EWPT ?)

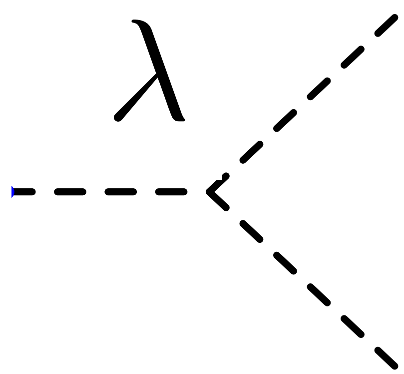
- in the SM :

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda' H^4$$

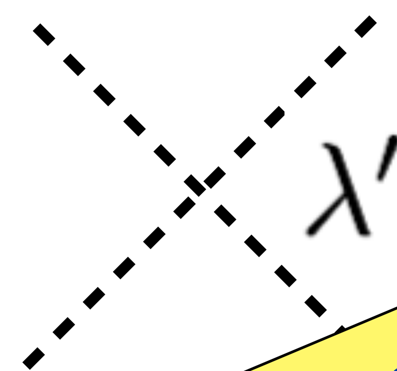
$$\lambda = \lambda' = M_H^2/(2v^2) = 0.13$$

➡ m_H directly related to Higgs dynamics !

- direct exploration needs HH in final states (tiny x-sections)



or HHH



out of reach ??

- BSM : Max λ deviations compatible with no other BSM observation:

➡ few % to ~20%

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

- target for both TH and EXP accuracies !

WHAT after HL-LHC ???

four paths to advance in HEP at colliders:

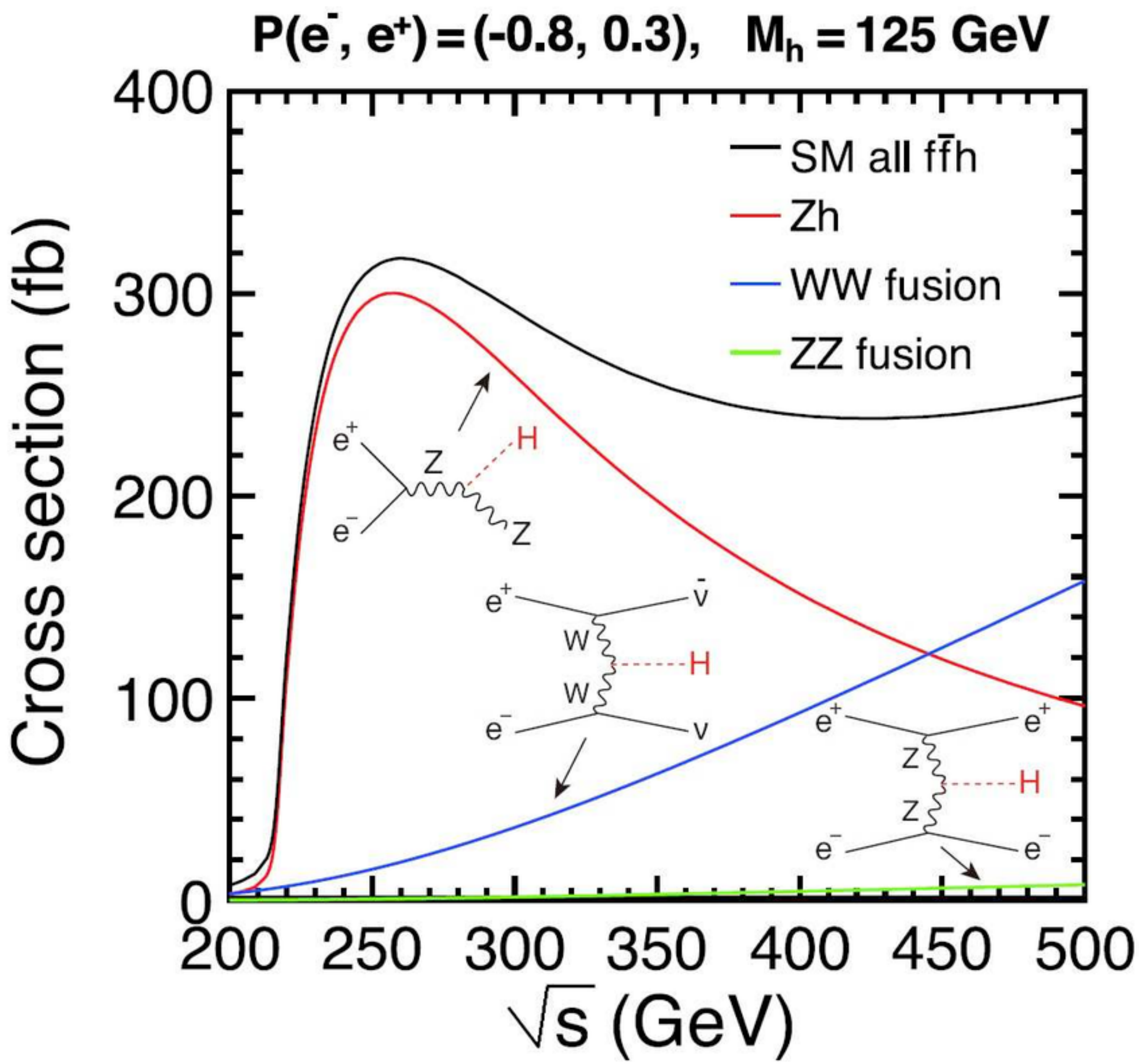
* Higgs
* new particles
* indirect effects
* "Dark" signals

* e^+e^- colliders great opportunities in all sectors (cleanness [→ model independence], accuracy…)

* focus on e^+e^- Higgs factories

general consensus by now on next machine

250GeV e+e- Higgs Factory



Next Big Machine should be an e+e- collider “Higgs Factory”

But …

Which Higgs Factory?

Geoffrey Taylor, LP2019, Toronto, CA 10th August, 2019 17

Snowmass summary on expected $\delta g_{Hii}/g_{SM}$

Energy Frontier Higgs Factory First Stages

EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings: Tree	Gauge Couplings: Loop induced	Higgs Width	λ_3
LHC/HL-LHC	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.1)$	$\mathcal{O}(1)$
Higgs Factory + HL-LHC: ILC/C^3 250	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$ *	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$
CLIC 380	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$
FCC-ee 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$
CEPC 240	$> \mathcal{O}(1)$	$> \mathcal{O}(1)$	?	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$> \mathcal{O}(1)$	$\mathcal{O}(.1)$	$\mathcal{O}(.01)$	$\lesssim \mathcal{O}(10^{-3})$	$\mathcal{O}(.01)$	$\mathcal{O}(.01)$	$\mathcal{O}(1)$

Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ ◆ $\mathcal{O}(.01)$ ◆ $\mathcal{O}(.1)$ ◆ $\mathcal{O}(1)$ □ $> \mathcal{O}(1)$

assume we find a deviation in H couplings…

- Deviation from SM: $\delta \sim v^2/M^2$
  - M scale of new physics
  - $M \sim 1 - 10$ TeV → $\delta \sim 6 - 0.06\%$

* in order to figure out what's going on we will need an energy-frontier facility to explore the corresponding M scale in a direct way.

* R&D for future high-energy colliders (new technologies ?)
  hadron collider beyond LHC ?
  higher energy linear collider ? multi-TeV muon collider ?
  plasma acceleration ?

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

LHC ➜ 150 MW, 4 GCHF

ESPP2020

updated list after Snowmass discussion (2022)

Snowmass 2021: EF Benchmark Scenarios

Higgs-boson factories (up to 1 TeV c.o.m. energy)

timelines

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2	2028	2038
		350 GeV	$\pm 80/\pm 30$	0.2		
		500 GeV	$\pm 80/\pm 30$	4		
		1 TeV	$\pm 80/\pm 20$	8		
CLIC	ee	380 GeV	$\pm 80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

Multi-TeV colliders (> 1 TeV c.o.m. energy)

timelines

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5	2052	2058
		3.0 TeV	$\pm 80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

new entries

Timelines are taken from the ITF report (AF)

how to assess a large-scale project

project → [beam species, energy, lumi, technology]

- * Physics potential (direct, indirect) *(mainly discussed here)*
- * feasibility → maturity → technical risk
- * innovation
- * construction/operation costs (vs constrains from fund. agencies)
- * power consumption
- * start-up time
- * total operation time (staging, expandibility)
- * location vs infrastructures vs politics (global context !)
- * HEP (both regional and global) community support
- * fraction of present HEP community involved

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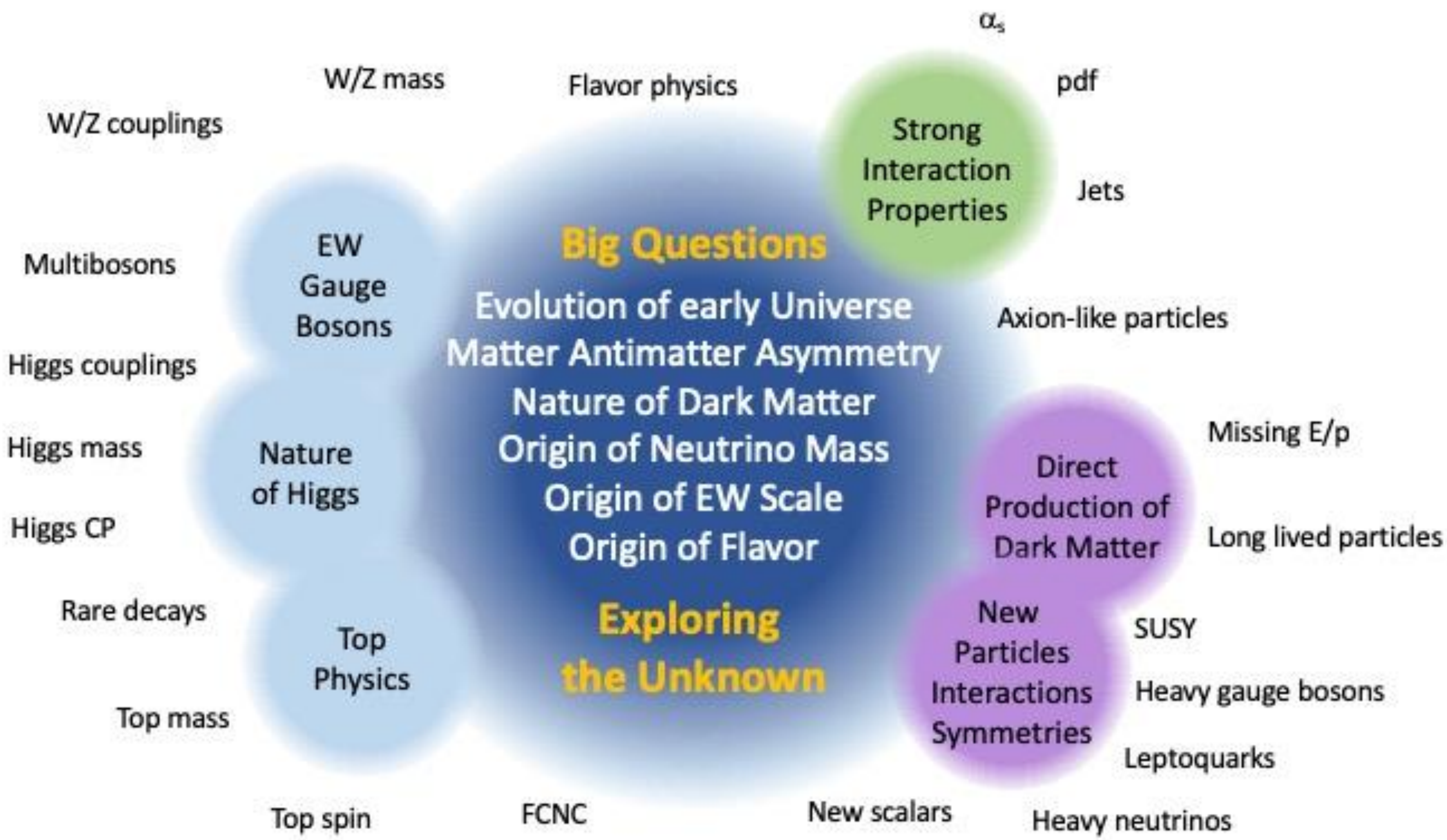
a global affair !

Probes and Signatures of new physics at colliders

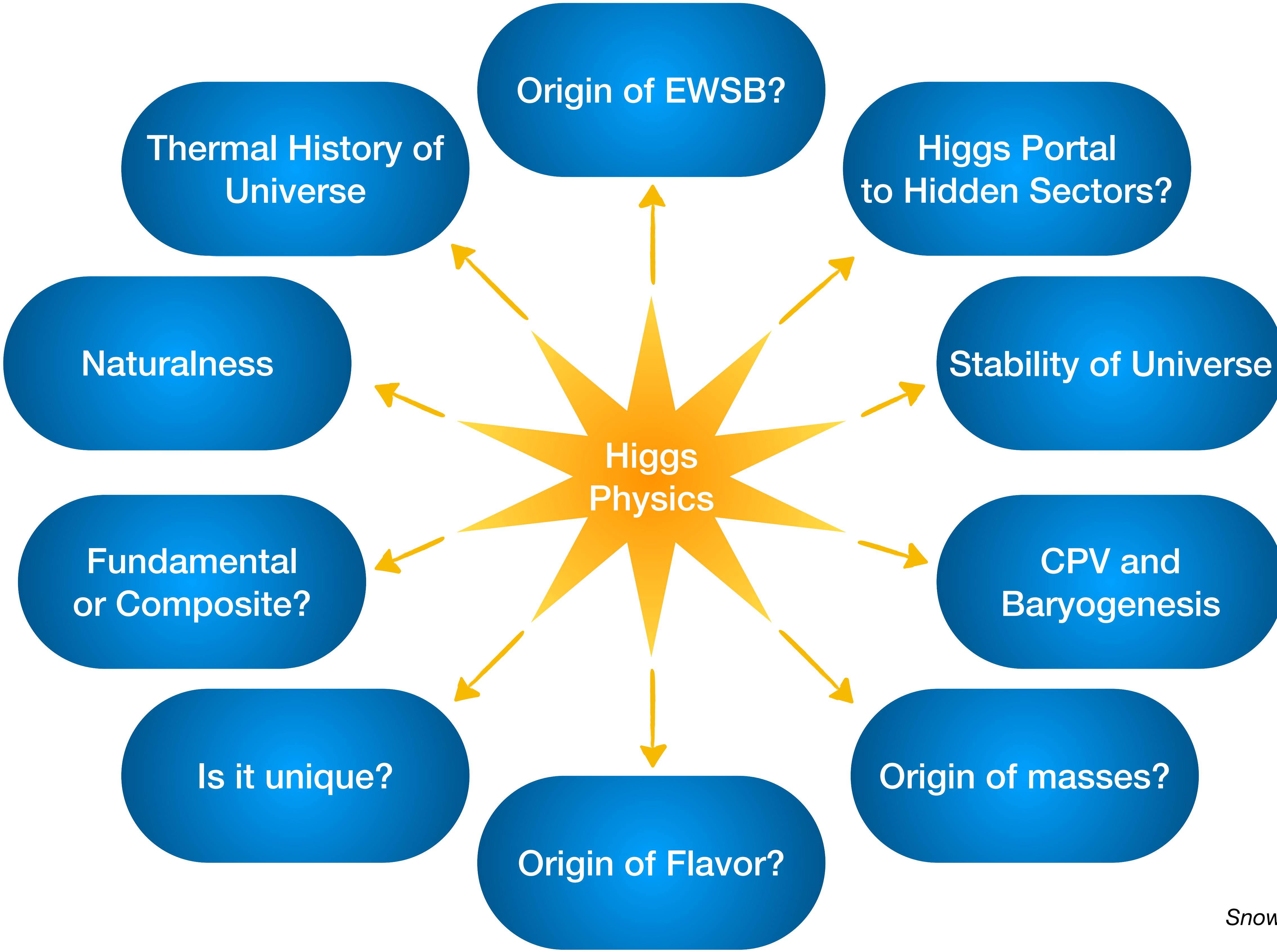
With such an exciting and vast landscape of $^{TH}_{\vee}$ possibilities,
the **breadth of the experimental program** is of paramount importance



Pagan Griso, Snowmass 2022

Colliders offer the unique ability to probe, with a single experimental setup, all sectors of the SM and its extensions

Higgs is a fantastic probe to unravel current HEP mysteries !



Snowmass 2022