# Overview of future directions of particle physics

LianTao Wang Univ. of Chicago

19th WIN Conference. July 2, Sun Yat-sen University, Zhuhai.

#### Where we are

#### Here, at last!

François Englert and Peter W. Higgs are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other (Englert together with his now deceased colleague Robert Brout). In 2012, their deas Were confirmed by the discovery of a so called Higgs particle at the CERN laboratory outside Geneva in Switzerland. The awarded mechanism is a central part of the Standard Model of particle physics that describes how the

world is constructed. According to the Standard Model, everything, from flowers and people to stars and would continue. planets, consists of just a few building blocks: *matter particles*. These particles are governed by forces medi-ated by *force particles* that make sure everything works as it should. ated by *force particles* that make sure everything works as it should.

force in the Standard Model was saved - the symmetry between the three heavy particles of the weak The entire Standard Model aftreares estimates inhora of the spectra plandtic force remains, only hidden from vi

of particle: the Higgs particle. It is connected to an invisible field that fills up all space. Even when our universe seems empty, this field i there. Had it not been there, electron stand apartes the average less just like photons, the light particles. And laboratories, Fermilab outs would, just as Einstein's theory predicts rush through space at the milab's Teva

speed of light, without any possibility progeta caugh CER Ntomsnorhmoly quiles in the world with the sea Nothing of what we know, not even devend we have a sea nothing of what we know, not even devend we have a sea nothing of what we know and sea not even devend we have a sea nothing of what we know and sea not even devend we have a sea nothing of what we know and sea not even devend we have a sea nothing of what we know and sea not even devend we have a sea nothing of what we know and sea not even devend we have a sea nothing of what we know a sea not even devend we have a sea nothing of what we know a sea nothing of we have a sea nothing of what we know a sea nothing a sea noth

physics that describes building blocks of the nuriverse

viert and Peter Higgs were young scientists when the in 1965, independently of each other put forward a theory that rescued the Stand d Model from collapse. Almost half a century ter, on Wolnesday 4 July / 012, they were both the European Laboratory of cea the audi Particle Physics, CERN, cueside Geneva, when THE BEH-1 the discovery of a Higgs particle that finally con-

irmed the theory was announced to the wor

The idea that the world care beies bained in ferthysics of the Royal Swedish Academy of Sciences at CFRN v of just a few building blocks is old. Already in 400 announced BC, the philosopher Democritus postulated that Photo: CER everything consists of atoms - átomos is Greek for indivisible. Today we know that atoms are not indivisible. The nucleus made up of neutrons and protons. And neutrons and pr

The Higgs particle, H, completes the Standard Model approved in an attempt to re CERN's grandest achievement, t t complex machin and the mos



survived. The other three were consumed by the weak force particles and one Z particle, which thereby got their mass. In t force in the Standard Model was saved – the symmetry between force and the massless photon of the electromagnetic force re

#### Extreme machines for extreme physics

The Nobel Laureates probably did not imagine that they we their lifetime. It took an enormous effort by physicists from laboratories, Fermilab outside Chicago, USA, and CERN or trying to discover the Higgs particle. But when Fermilab's ' couple of years ago, CERN became the only place in the wor

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wenty states, and about a hundred nations from all over the world collaborate on the projects? a train at full speed. In 2015 the energy



are v ible h Image: CER

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# simples Standard Model.





1961-1968

- The Higgs boson. Very successful. Many experimental tests. No cracks yet.

Spin O (scalar) 

#### Cosmos





A standard model of cosmology.

#### More than a century ago



#### Albert A. Michelson, 1899

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.

Are we in a similar situation?

#### More than a century ago



#### Albert A. Michelson, 1899

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.



Lord Kelvin, 1900"Two clouds"

Light propagation, ether (Michelson-Morley) Maxwell-Boltzmann, equipartition, specific heat

### We have many clouds



# Open questions in the Standard Moctoplest answer

Very nice, but it looks like chemistry to me.

Hierarchy, nautralness

Flavor structure

CP violation

- The Higgs boson.
  - Spin 0 (scalar)

Unification

- Higgs field gives masses to electron

Basically, what gives us the Standard Model?







None of above?

Dark world

In this case, we can't even start to look for them.





#### Vast gaps!

Need more lampposts.







# What is the future?

Where will be the next breakthrough?



# What is the future?

Where will be the next breakthrough?



Of course, I don't know.

# What is the future?

Where will be the next breakthrough?



Of course, I don't know.

I will focus on: Future experimental probes, and what we can learn from them The experimental probes

Energy frontier HL-LHC, Future colliders

Cosmological observations CMB, LSS, Gravitational wave

Table top exp, fixed target, ... Intensity frontier The experimental probes

Energy frontier HL-LHC, Future colliders

Cosmological observations CMB, LSS, Gravitational wave

Very briefly

Table top exp, fixed target, ... Intensity frontier



### Exciting news!

NANOGrav, June 29, 2023





Likely the beginning of a new era! Could be the first of observation of primordial GW!

### More data to come!



### The experimental probes

Energy frontier HL-LHC, Future colliders

Rest of the talk

Cosmological observations CMB, LSS, Gravitational wave

Table top exp, fixed target, ... Intensity frontier

### Current Energy frontier: HL-LHC

**HL-LHC** Still, 10 times more data to come.



The question: what will this data tell us?

#### As data accumulates



Progress on direct search will become slower, harder



## Precision: Higgs





#### HL-LHC as particle factories





 $> 10^{11}$  W and Zs

Expect a lot of progress in rare decay searches!

#### The portals

(SM) particle with small couplings to dark matter/dark sector.



#### Example: Higgs portal long lived particles



Potential to do better, BR(h $\rightarrow$ XX) < 10<sup>-5</sup>

More ideas?

Any new directions for the HL-LHC?

They really need HELP!

### Beyond the LHC: What should the next step?

#### 2014 P5: Higgs as a new tool for discovery

In summary, the EF supports a fast start for construction of an  $e^+e^-$  Higgs factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors. These projects have the potential to be transformative as they will push the boundaries of our knowledge by testing the limits of the SM, and indirectly or directly discovering new physics beyond the SM.

- 2021-2022 Snowmass EF report

For more details: <u>Snowmass reports</u> <u>European strategy update</u>

# Why focusing on Higgs?

#### Higgs is simple.



# Why focusing on Higgs?

Yet, Higgs is confusing.

Sure, the math is simple. It does not give us clues for a deeper understanding.

Different from other SM particles:

gauge boson (gauge symmetry), fermion (chiral symmetry)
# Why focusing on Higgs?

Yet, Higgs is confusing.

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Different from other SM particles: gauge boson (gauge symmetry), fermion (chiral symmetry)

Maybe not as simple as it seems?

Is it elementary (like electron) or composite (like proton or pion)?

Is the Higgs the only spin-0 particle, or there are similar ones?

#### What sets the masses?



Higgs mechanism sets the masses of the SM particles

#### What sets the masses?



Higgs mechanism sets the masses of the SM particles

However, we can't explain how this mass scale is set. Why is it around 100 GeV?

#### What do we know?

#### Higgs potential?

 $V(\phi)$ 



#### What do we know?

#### Higgs potential?



HL-LHC will make some progress. But it won't clarify the picture.





#### We need to know better!















## Physics output



Central theme: the electroweak scale

## The Higgs measurements

HL-LHC S2 + LEP/SLD	CEPC Z <sub>100</sub> /WW <sub>6</sub> /240GeV <sub>20</sub>	ILC 250GeV <sub>2</sub>	CLIC 380GeV <sub>1</sub>	MuC 3TeV <sub>1</sub> $\bigtriangledown$ w/FCC-ee
(combined in all lepton collider scenarios)	CEPC +360GeV <sub>1</sub>	$ILC + 350 \text{GeV}_{0.2} + 500 \text{GeV}_4$	CLIC +1.5TeV <sub>2.5</sub>	MuC 10TeV 10 MuC 125CoV 10ToV
no H exotic decay	FCC-ee +365GeV <sub>1.5</sub>	subscripts denote luminosity in ab <sup>-1</sup> , Z & WW denote Z-pole & WW threshold		



Z, W

Measuring crucial Higgs coupling up to  $10^{-3}$ 

# Is the Higgs composite?



# Is the Higgs composite?



# Is the Higgs boson alone?

#### **HL-LHC**



#### Maybe Higgs boson has some partners?

Will change Higgs behavior by interacting with it.

Simplest example: Higgs coupling to one other spin-0 boson





1. Self-coupling





#### EFT expectation

If there is a modification of the self-coupling from new physics, which can be parameterized by the operator

 $\frac{H^6}{\Lambda^2}$ 

We should expect other effect of such NP, e.g.

$$\frac{(\partial (HH^{\dagger}))^2}{\Lambda^2} \to \delta_{Zh} \sim \frac{v^2}{\Lambda^2}$$

Self-coupling measurement, typically harder, may not be the discovery channel.









## Comments on options

#### Circular



Higher luminosity. ⇒ more Higgs bosons!

More W (10<sup>6</sup>), Z (10<sup>12</sup>)

#### With more W, Zs

CircularHiggs factories: In comparison: 10<sup>12</sup> Zs 10<sup>6</sup> WW

LEP has 10<sup>7</sup> Zs



Precision on electroweak couplings:  $10^{-3} \Rightarrow 10^{-4}$ 

Search for NP in exotic Z decays (more later)

#### Linear



Longitudinal polarization. Better at resolving certain signals

Can go to higher energies

## At higher energies









#### Two excellent options!

Linear

Excellent Higgs factories!

Circular

Great performances for Higgs measurements.

Different in additional physics program and prospects

# Beyond the LHC:

Next energy frontier  $\sim 10$  TeV. How should we get there?

#### Energy frontier machines:







# High energy pp



Big gain with modest luminosity.

#### Muon collider

Lepton colliders (> 1 TeV). ITF Snowmass 2022



For generic new physics, such as top partner, the reach would be  $\approx 0.5$ E<sub>CM</sub>, with very low luminosity requirement.
## Muon collider

Lepton colliders (> 1 TeV). ITF Snowmass 2022



## Muon collider

Lepton colliders (> 1 TeV). ITF Snowmass 2022





## As Higgs factories



Hadron collider @ 100 TeV: 10<sup>10</sup> Higgses

Muon collider @ 10 TeV: 10<sup>7</sup> Higgses

## Performance

<i>к</i> -0	HL-	LHeC	HE-	LHC		ILC			CLIC	1	CEPC	FC	C-ee	FCC-ee/	$\mu^+\mu^-$
fit	LHC		S2	S2'	250	500	1000	380	1500	3000		240	365	eh/hh	10000
$\kappa_W$	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
$\kappa_Z$	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
$\kappa_g$	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
$\kappa_\gamma$	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98*	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	—	5.7	3.8	99 <b>*</b>	86*	$85\star$	$120\star$	15	6.9	8.2	81*	$75\star$	0.69	5.5
$\kappa_c$	—	4.1	—	—	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
$\kappa_t$	3.3	—	2.8	1.7	—	6.9	1.6	_	—	2.7	—	—	—	1.0	1.4
$\kappa_b$	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
$\kappa_{\mu}$	4.6	—	2.5	1.7	15	9.4	6.2	$320\star$	13	5.8	8.9	10	8.9	0.41	2.9
$\kappa_{ au}$	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

# Di-Higgs

#### 1910.00012





100 TeV pp, 40 times HL-LHC

Muon C @ 10 TeV: several x 10<sup>4</sup>



1. Self-coupling







## EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

## EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

## Comments on options

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All exciting possibilities, we should study all of them!!

### What energy is needed?

### What energy is needed?

As high as possible. Of course, limited by tech knowhow and resource.

A good next step should be about 10 TeV.

Some physics benchmark, such as WIMP dark matter. But mainly driven by other limitations.

We don't know. However,

We don't know. However,

We will probe nature at much shorter distances, with the potential of answering big open questions.

We don't know. However,

We will probe nature at much shorter distances, with the potential of answering big open questions.

We will understand the working of the Standard Model in a new regime: with unbroken EW symmetry, qcd at 10xLHC...

## An example for us





Big science project aiming at a better picture of how SM works under very different conditions.

## An example for us





Probing the strange world at short distances should be at least as exciting!



We get to a Higgs factory as soon as we can.

In the mean time, we (with a lot of R&D) to figure out the best way to get to higher energies (10 TeV).

## With all these possibilities



#### Let's figure out a way to do something ASAP!

## Extra



#### We get to a Higgs factory as soon as we can.



## Fastest way to get to a Higgs factory?







#### "Shovel ready" options

+ maybe LEP 3?

