

# Higgs Factory

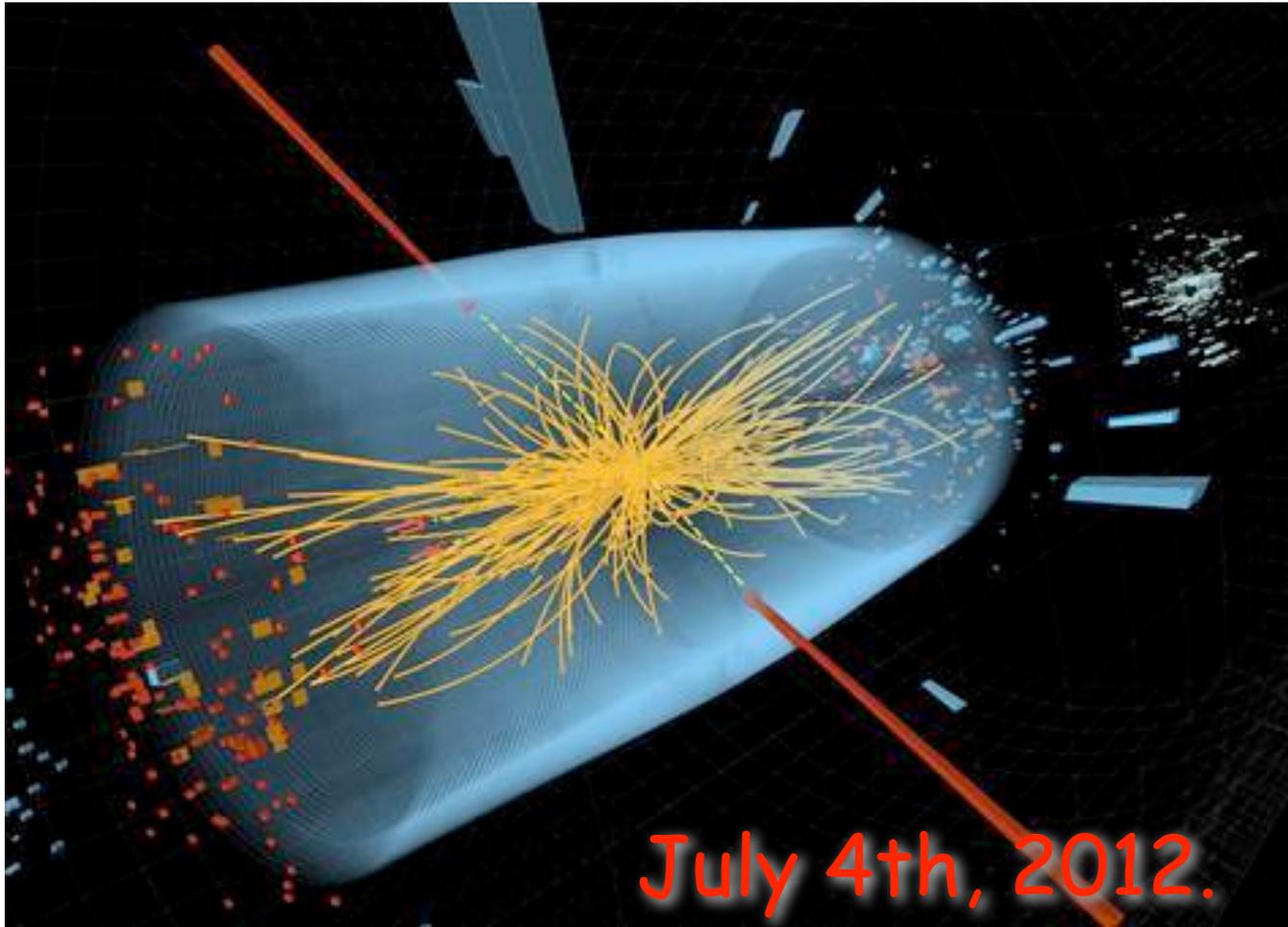
## Why, How, What?



Shufang Su • U. of Arizona

OSU, October 26, 2022

# Higgs discovery



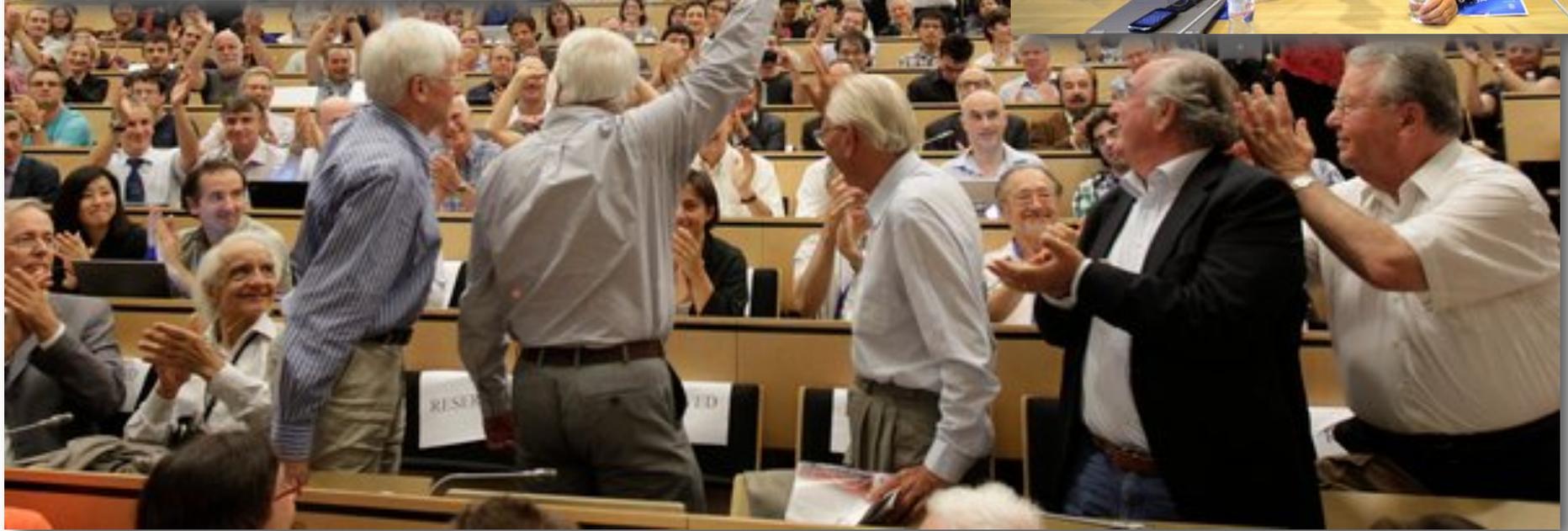
# “BREAKTHROUGH of the YEAR” - Science



Mosaic of the CMS and ATLAS detectors (as in 2007), part of the Large Hadron Collider at CERN. In 2012, research teams used these detectors to fingerprint decay products from the long-sought Higgs boson and determine its mass, successfully testing a key prediction of the standard model of particle physics.

Photos: Maximilien Brice and Claudia Marcelloni/CERN

# Celebration!



# Hunting the Last Missing Particle of the Standard Model



Shufang Su • Caltech

Feb 14, 2003

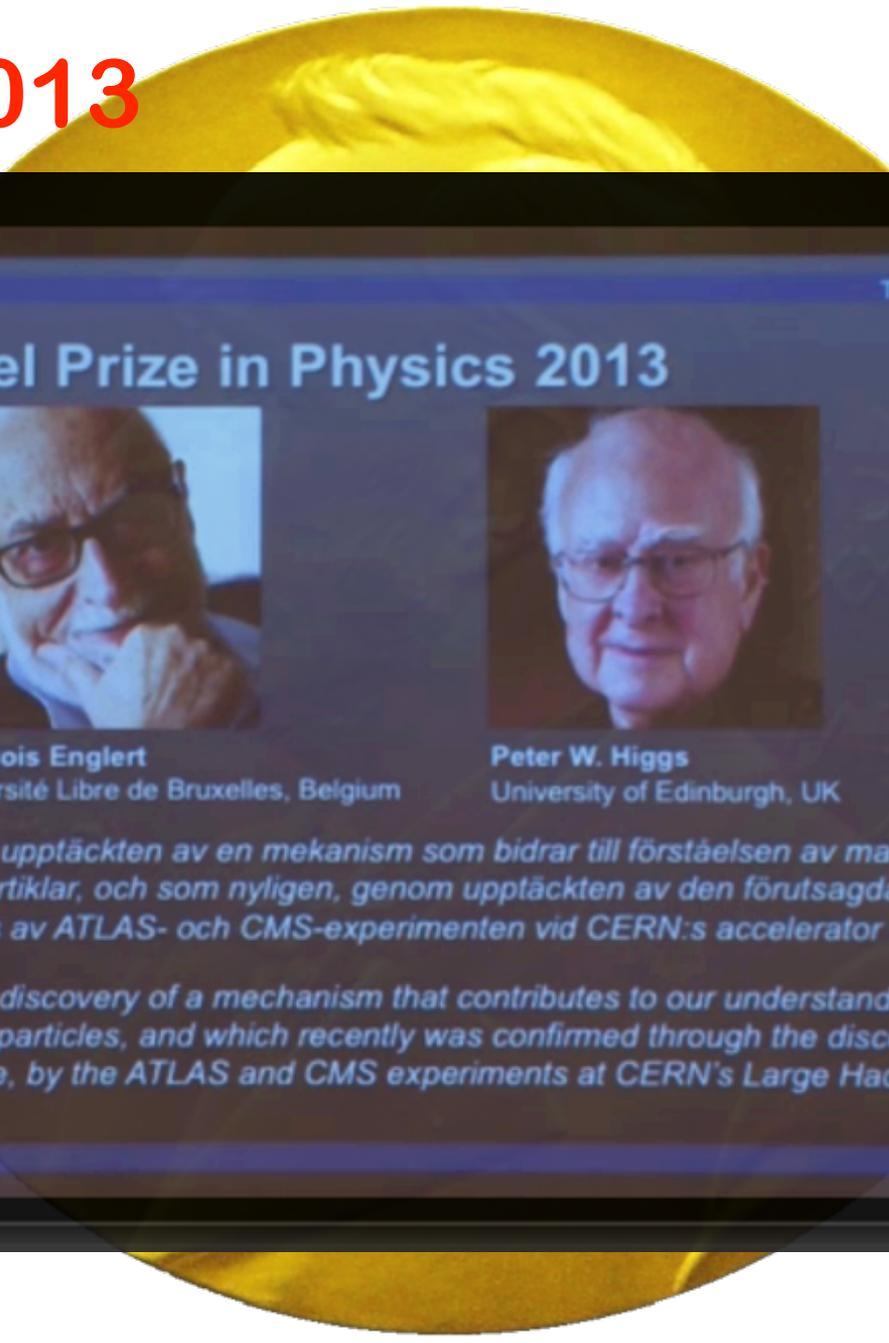
U Arizona Colloquium

Job Interview

# First Hint: Dec 13, 2011



Oct 8, 2013



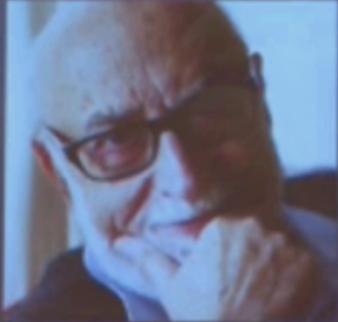
Nobelpriset 2013

The Nobel Prize 2013

# The Nobel Prize in Physics 2013



KUNGL. VETENSKAPS AKADEMIEN  
THE ROYAL SWEDISH ACADEMY OF SCIENCES



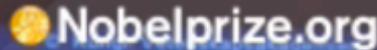
**François Englert**  
Université Libre de Bruxelles, Belgium



**Peter W. Higgs**  
University of Edinburgh, UK

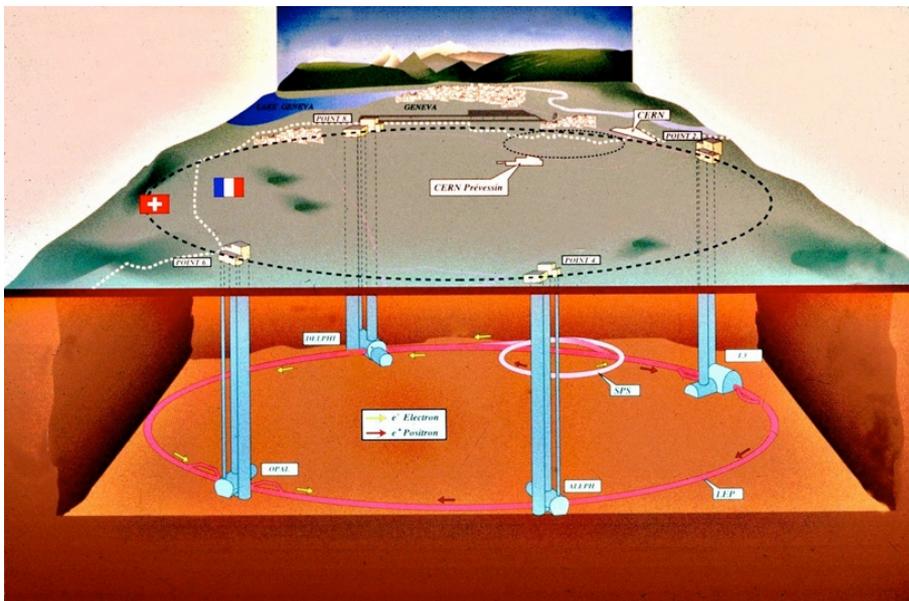
*"För den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid CERN:s accelerator LHC."*

*"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."*

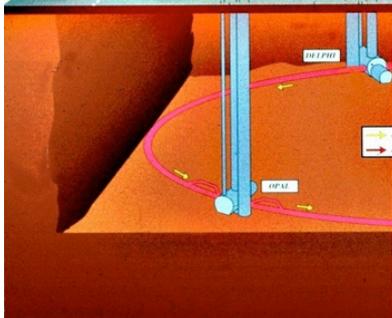
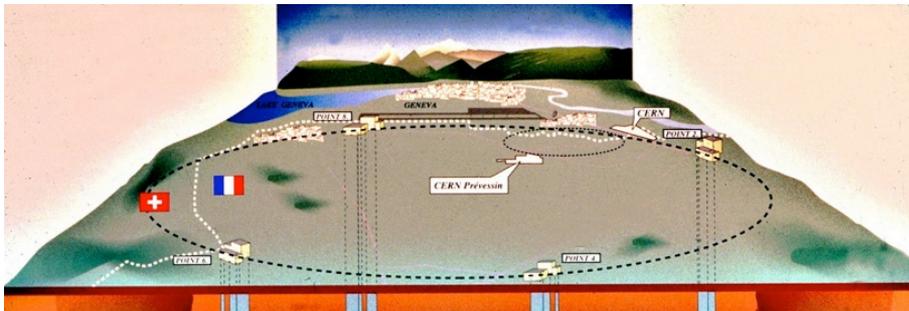
 Nobelprize.org

02.07.2013 22

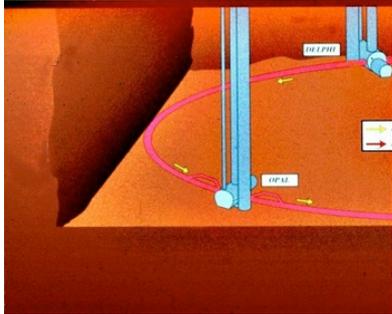
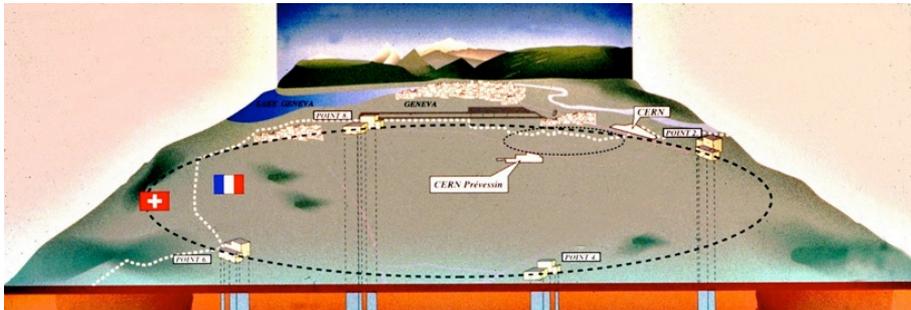
# 25 Yrs' Work by thousands experimentalists



# 25 Yrs' Work by thousands experimentalists



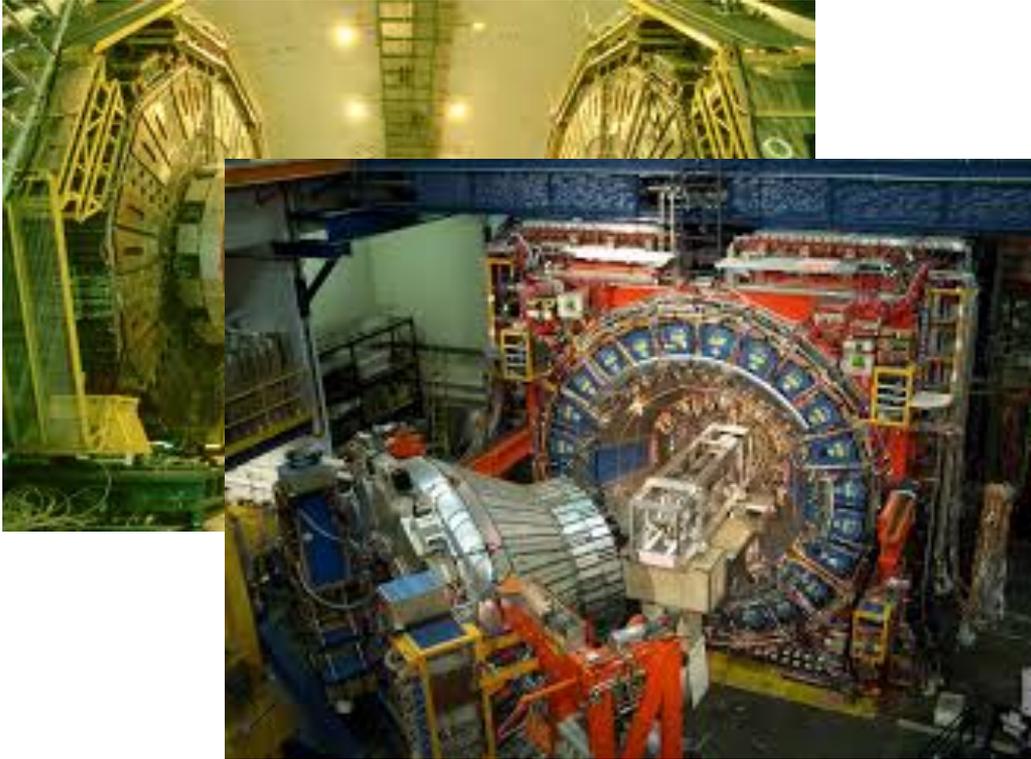
# 25 Yrs' Work by thousands experimentalists



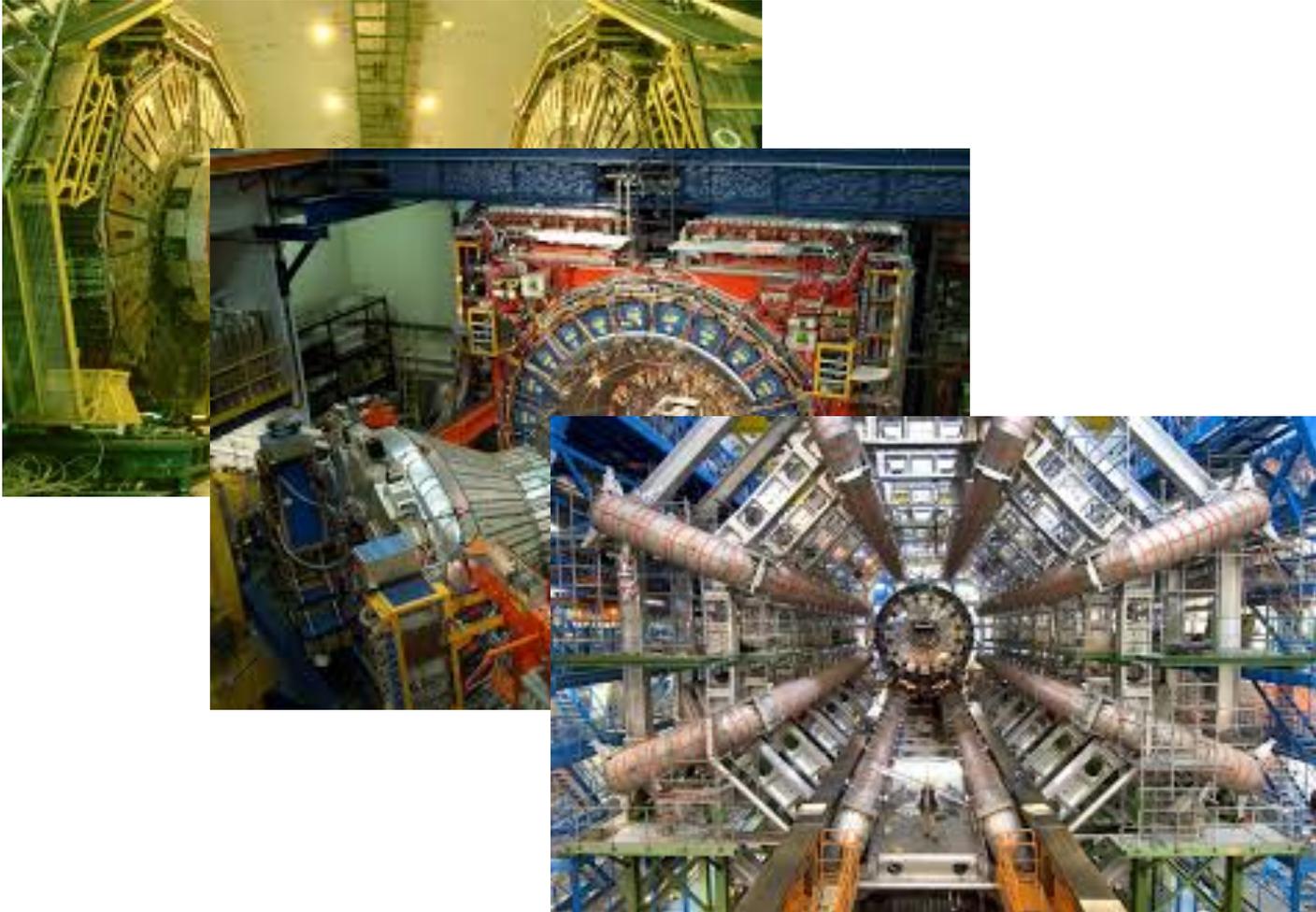
# 25 Yrs' work by thousands experimentalists



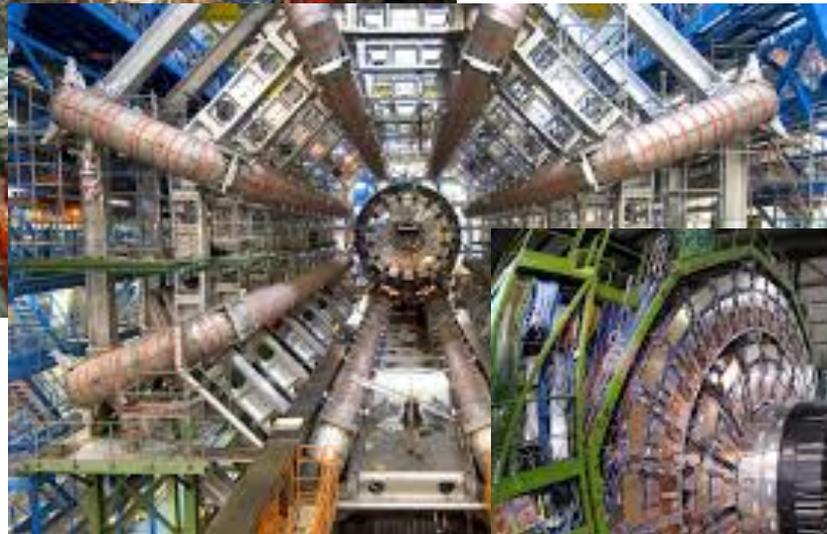
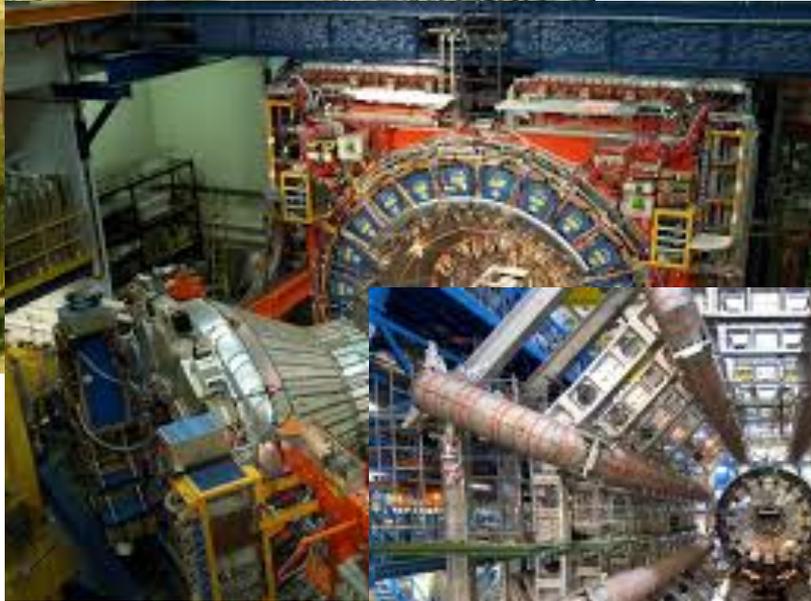
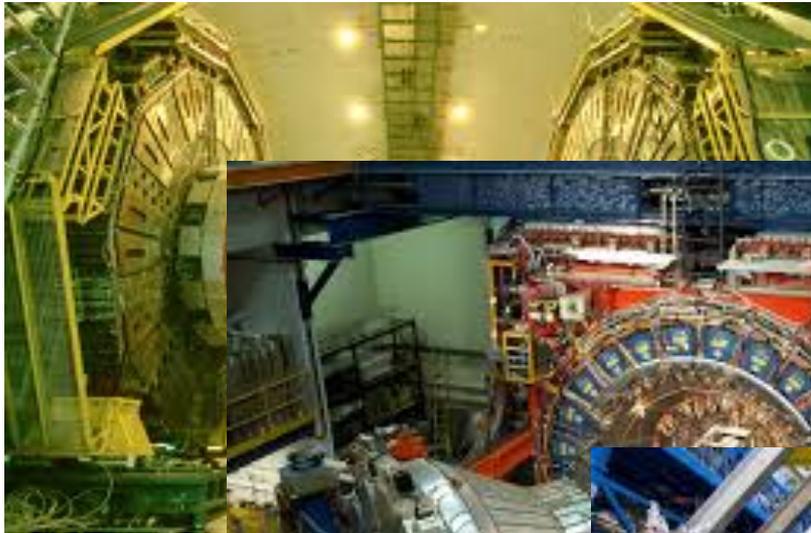
# 25 Yrs' work by thousands experimentalists

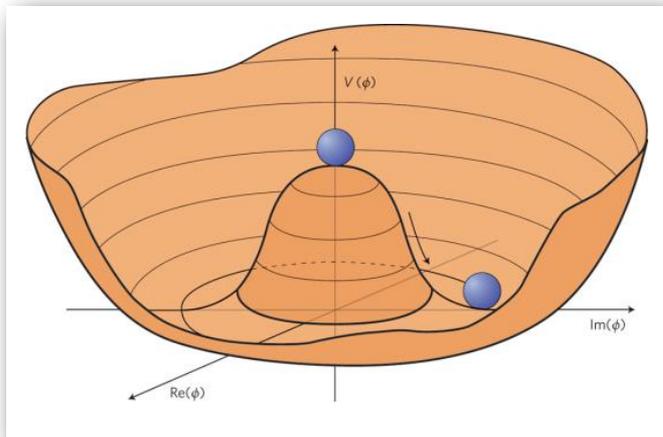
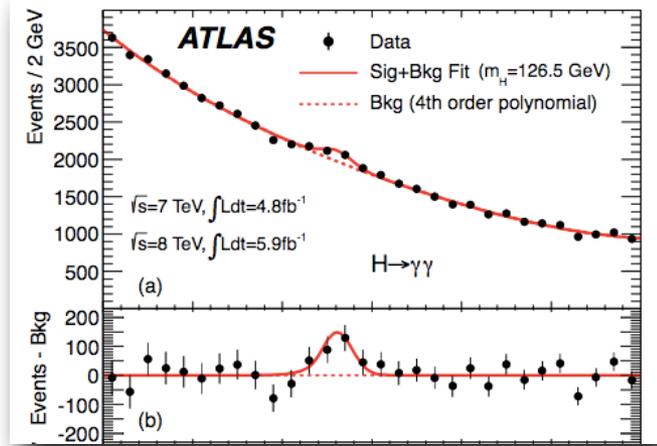


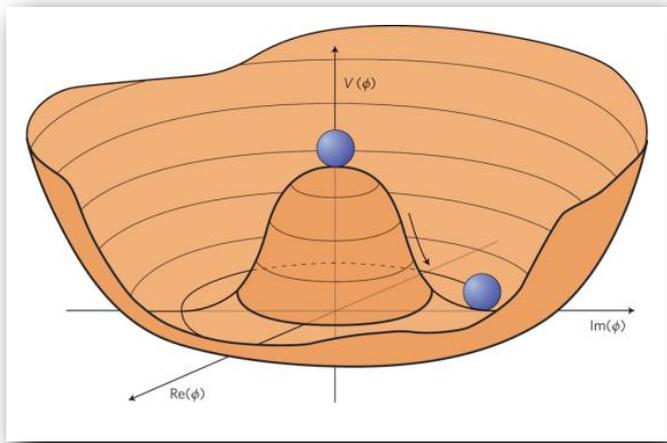
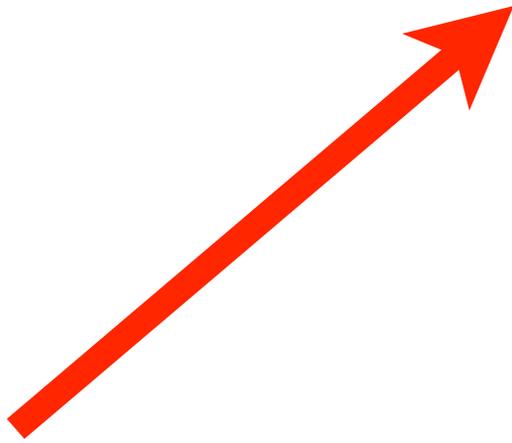
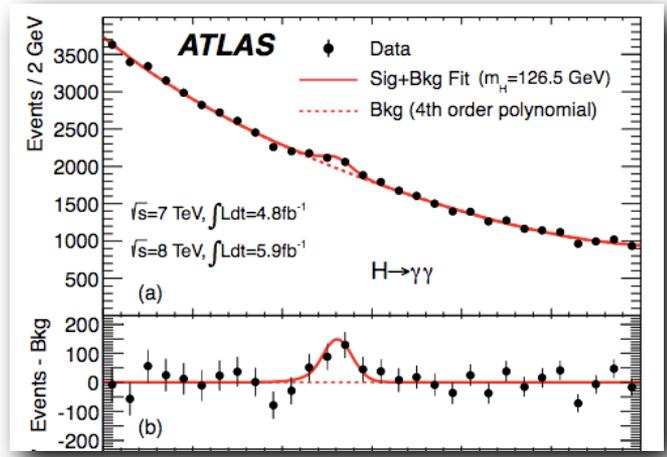
# 25 Yrs' work by thousands experimentalists



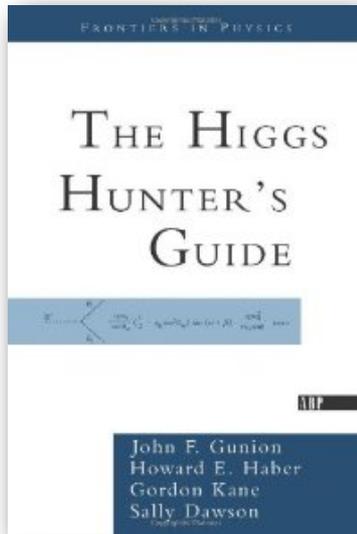
# 25 Yrs' work by thousands experimentalists



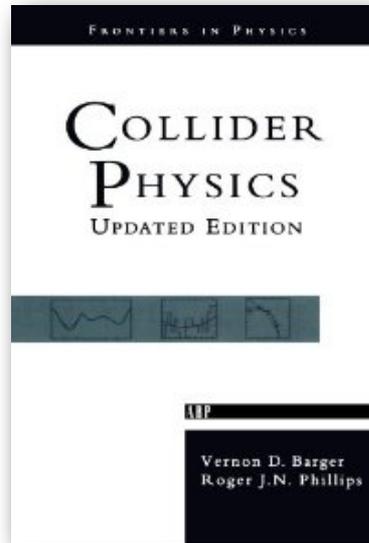
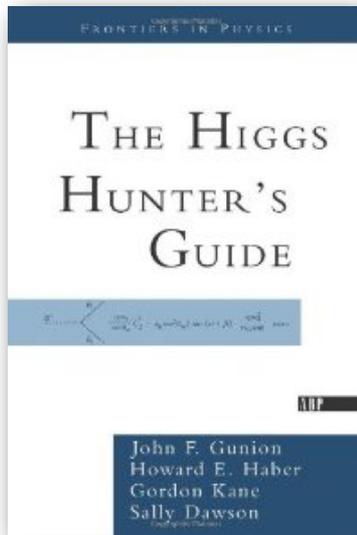




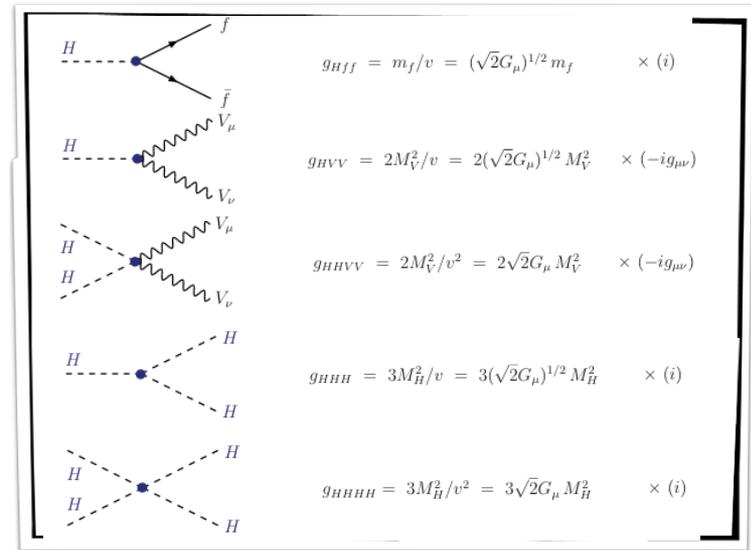
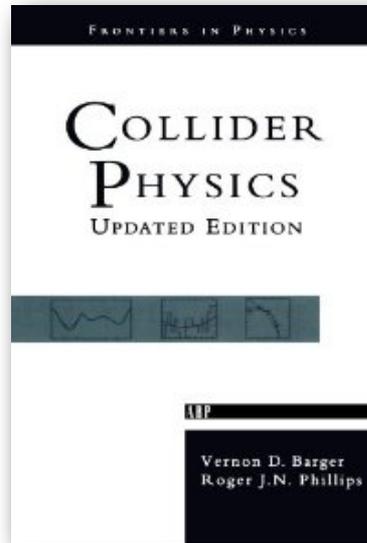
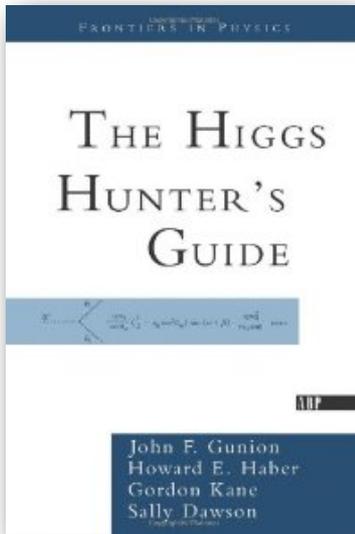
# 50 Years' work by numerous theorists



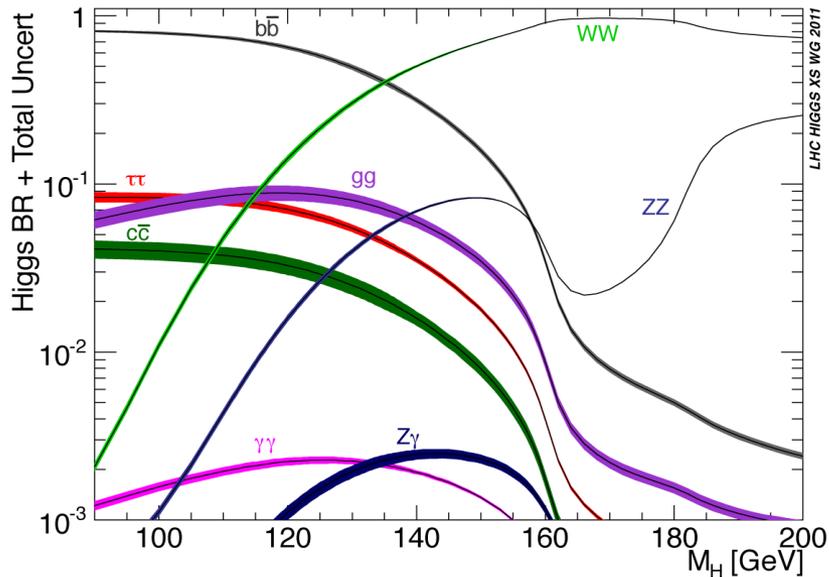
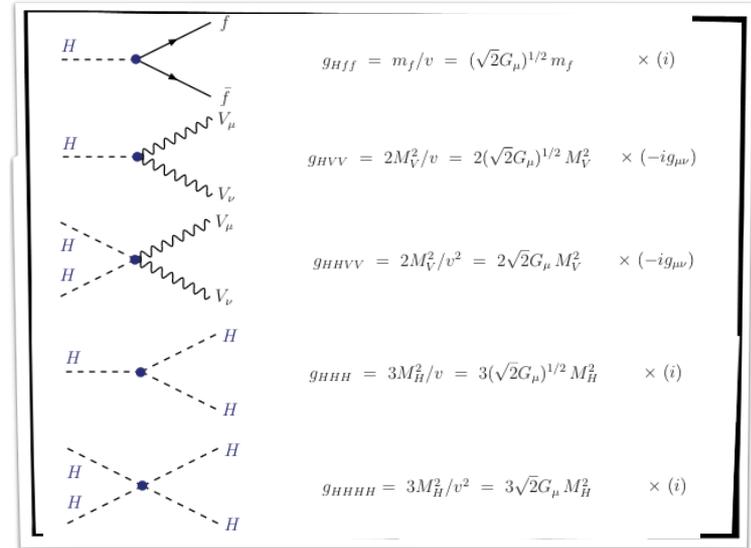
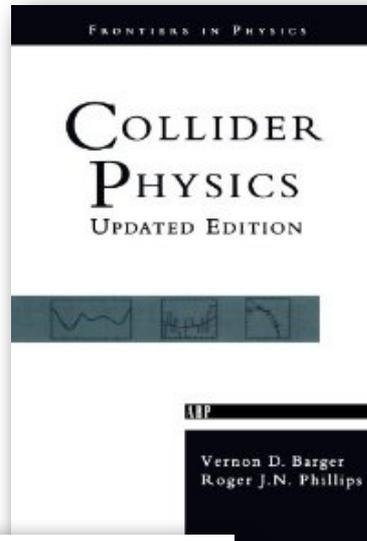
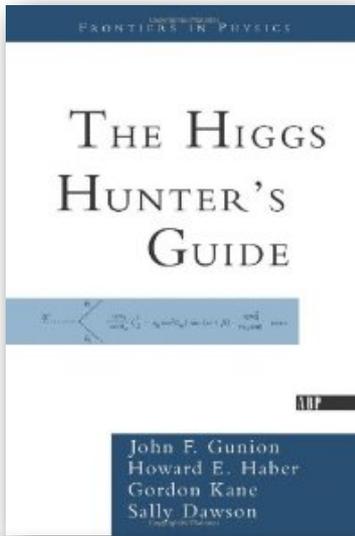
# 50 Years' work by numerous theorists



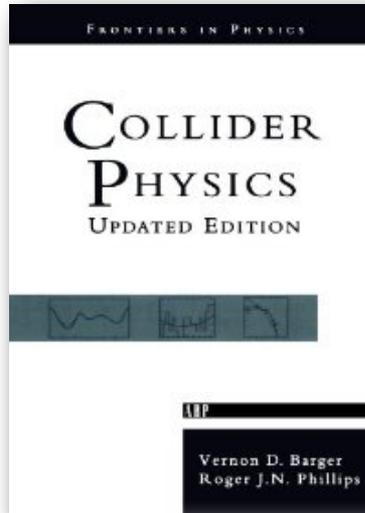
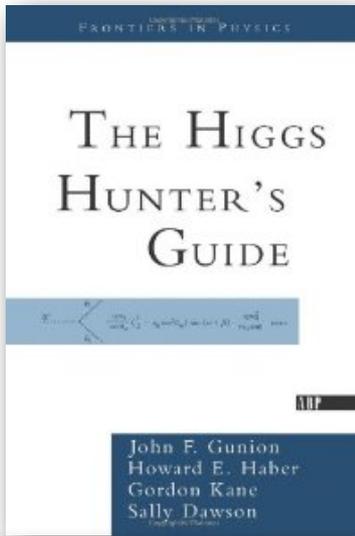
# 50 Years' work by numerous theorists



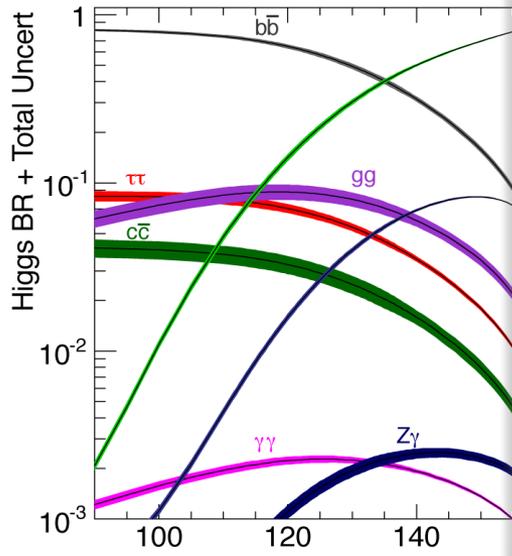
# 50 Years' work by numerous theorists



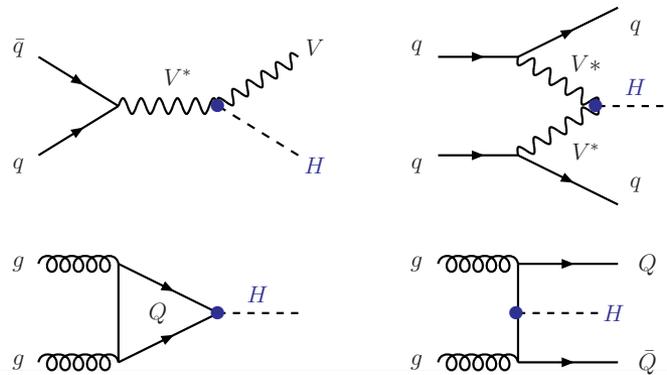
# 50 Years' work by numerous theorists



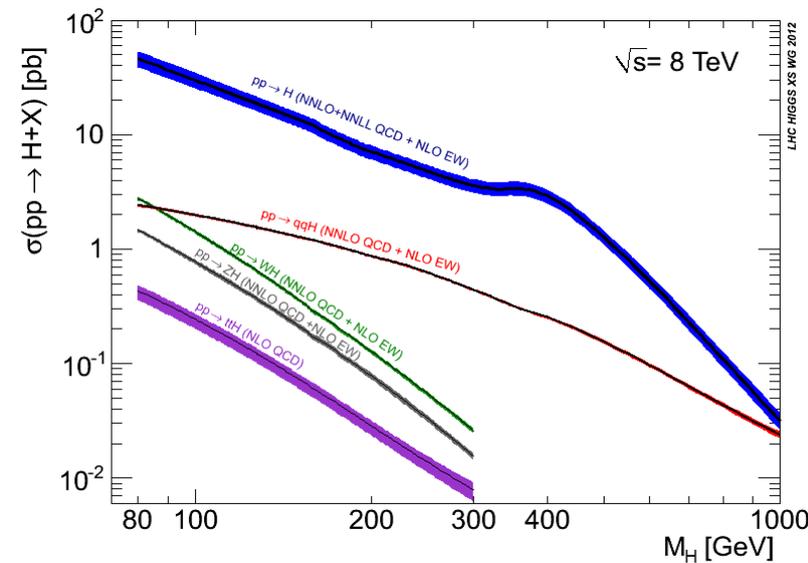
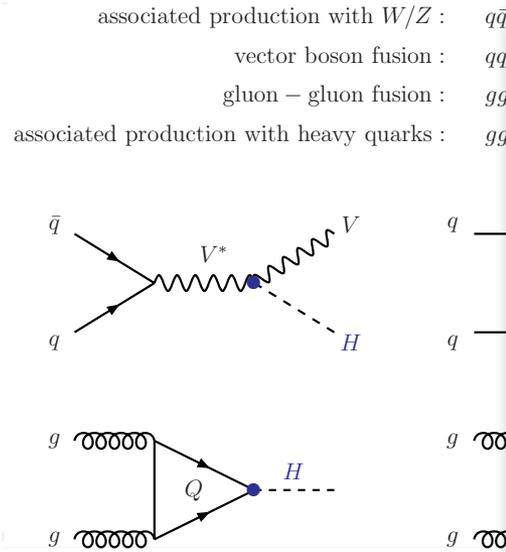
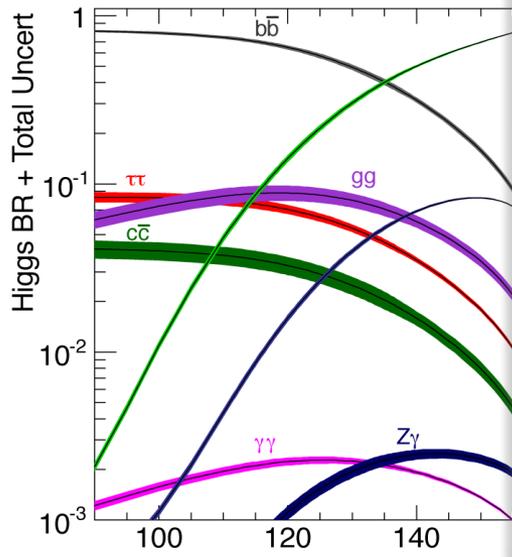
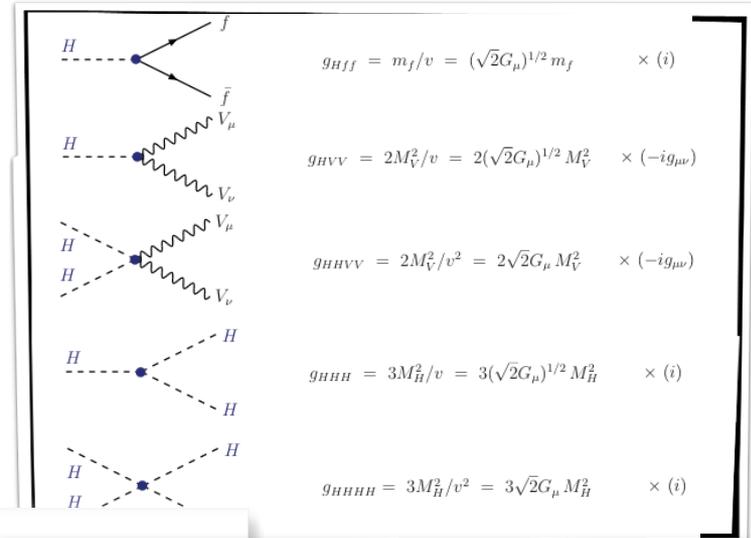
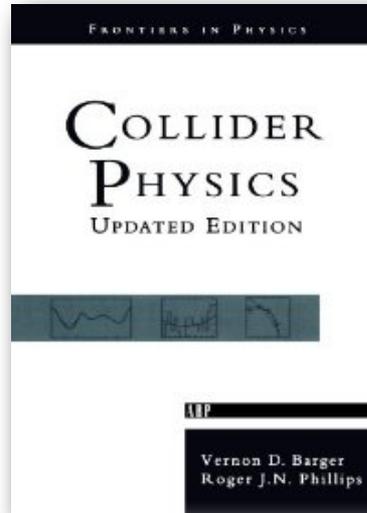
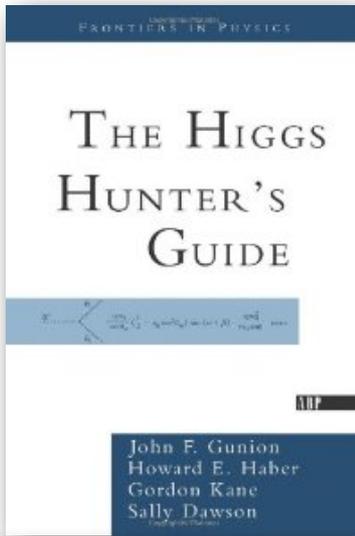
$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \quad \times (i)$   
 $g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \quad \times (-ig_{\mu\nu})$   
 $g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu M_V^2 \quad \times (-ig_{\mu\nu})$   
 $g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \quad \times (i)$   
 $g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu M_H^2 \quad \times (i)$



associated production with  $W/Z$  :  $q\bar{q} \rightarrow V + H$   
 vector boson fusion :  $qq \rightarrow V^*V^* \rightarrow qq + H$   
 gluon - gluon fusion :  $gg \rightarrow H$   
 associated production with heavy quarks :  $gg, q\bar{q} \rightarrow Q\bar{Q} + H$



# 50 Years' work by numerous theorists

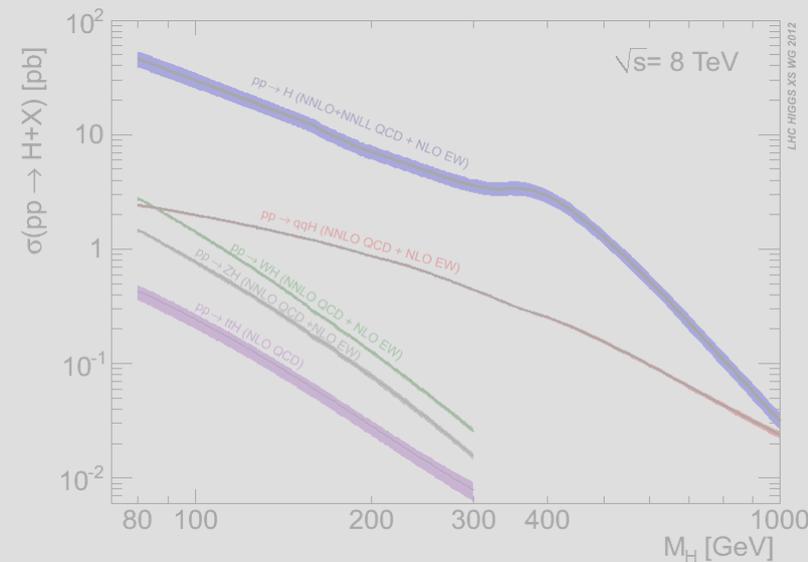
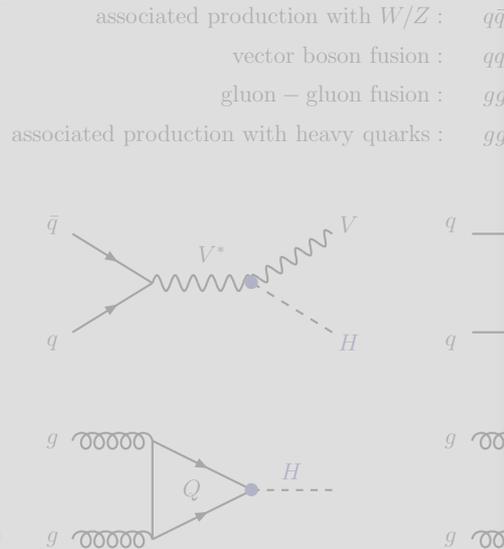
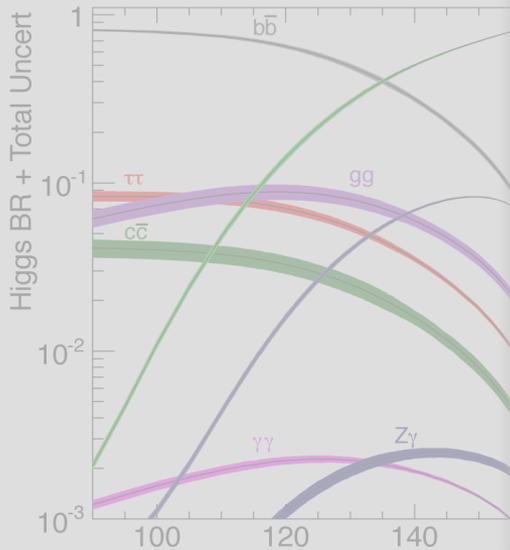
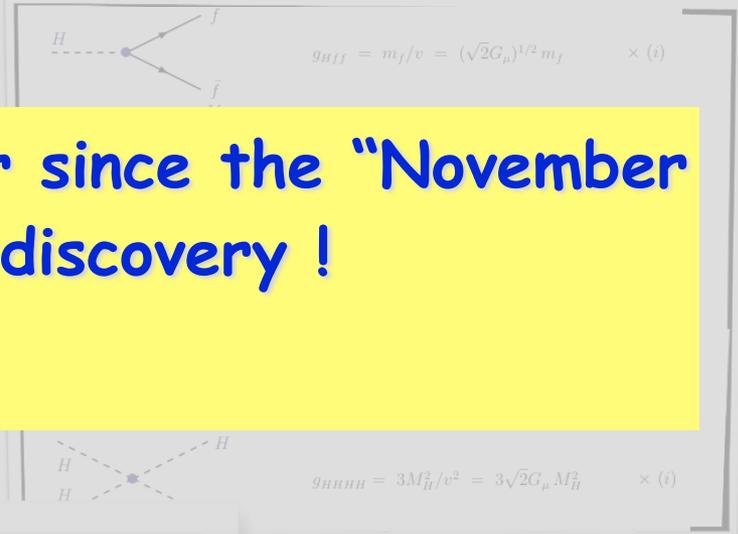


# 50 Years' work by numerous theorists

- Truly an "LHC Revolution" ever since the "November Revolution" in 1974 for the  $J/\psi$  discovery !
- Truly a monumental triumph.

Howard E. Haber  
Gordon Kane  
Sally Dawson

Vernon D. Barger  
Roger J.N. Phillips



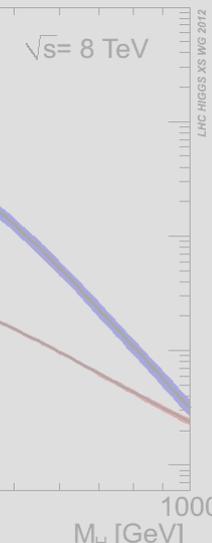
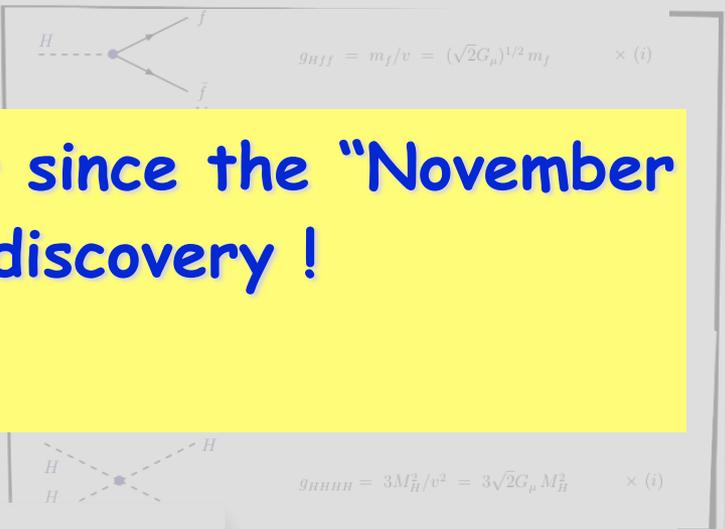
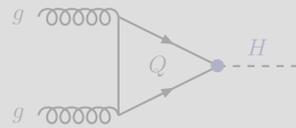
# 50 Years' work by numerous theorists

- ◎ Truly an "LHC Revolution" ever since the "November Revolution" in 1974 for the  $J/\psi$  discovery !
- ◎ Truly a monumental triumph.

SM Higgs does not have to be there...

Now that it actually IS...

Reached a deep understanding of nature !



# Outline

---

- **Why** we need a Higgs factory?
- **How** to make a Higgs factory?
- **What** we can learn with a Higgs factory?

# Why we need a Higgs Factory?

# Why we need a Higgs Factory?

**To study Higgs, of course!**

**Why we need a Higgs Factory?**

**To study Higgs, of course!**

**Why is it important to study Higgs?**

# Quiz!!!

---

# Quiz!!!

---

- © Higgs is responsible for the mass of Universe

# Quiz!!!

---

- ⦿ ~~Higgs is responsible for the mass of Universe~~

# Quiz!!!

---

- ⦿ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)

# Quiz!!!

---

- ⊙ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ⊙ Higgs is responsible for the mass of your and me  
(and 4% of the Universe)

# Quiz!!!

---

- ⦿ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ⦿ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe)

# Quiz!!!

---

- ⊙ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ⊙ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!

# Quiz!!!

- ⊙ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ⊙ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
- ⊙ Higgs is needed for the mass of elementary particles

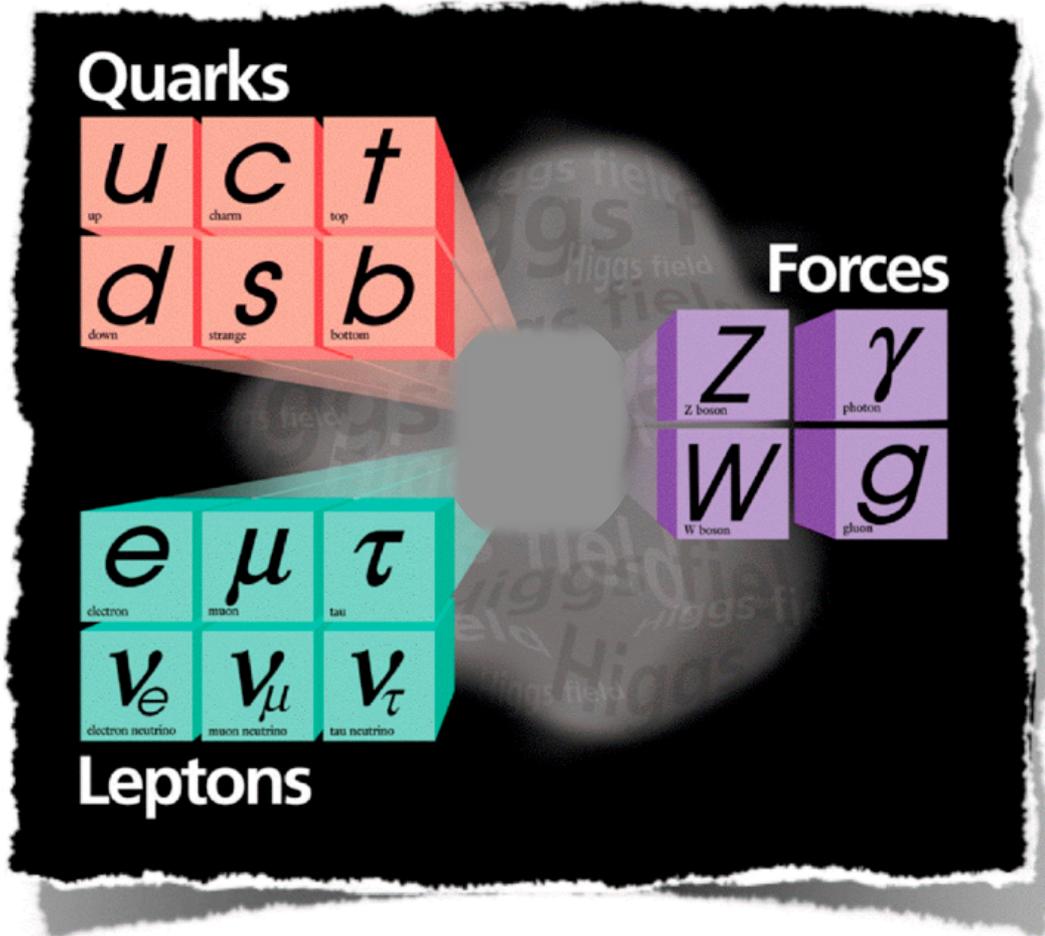
# Quiz!!!

- ⊙ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ⊙ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
- ⊙ Higgs is needed for the mass of elementary particles  
Higgs mechanism: **Yes**. Higgs particle: **No**.

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

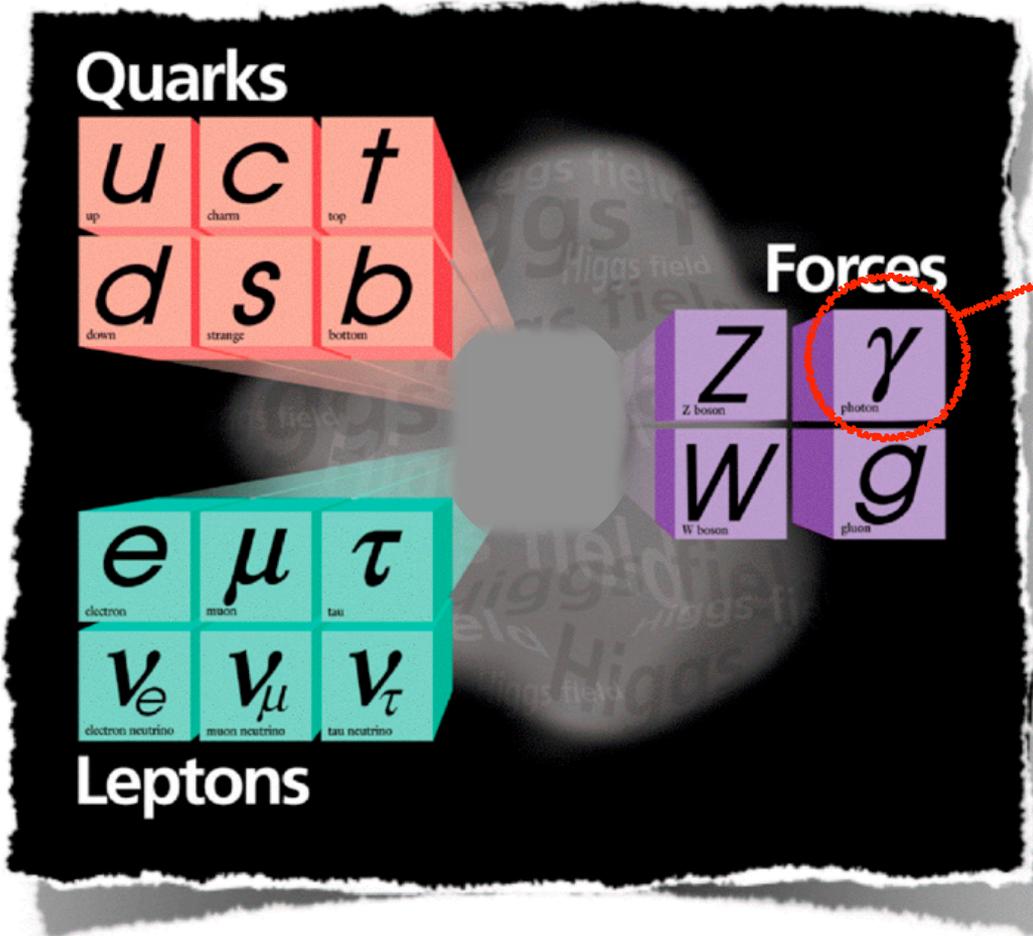
The successful  
"Standard Model"



# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The successful  
"Standard Model"



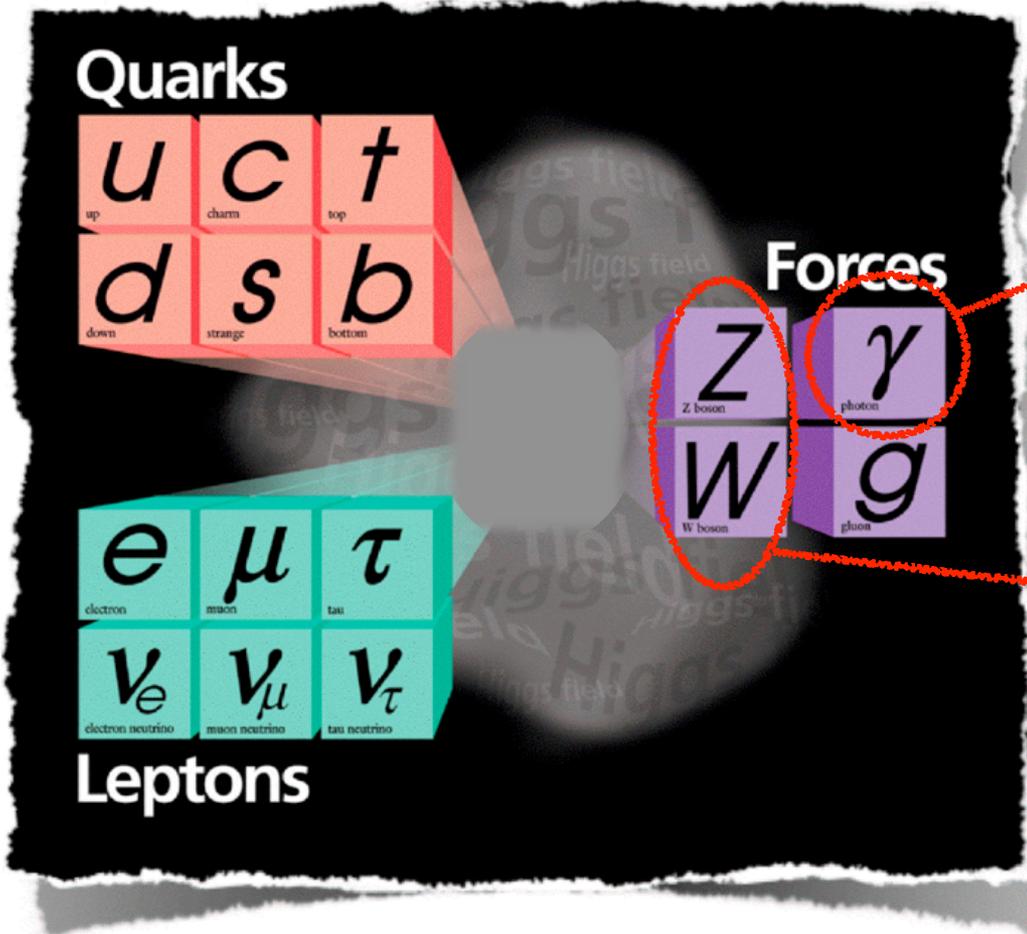
$$m_\gamma = 0$$

EM: long range force

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The successful  
"Standard Model"



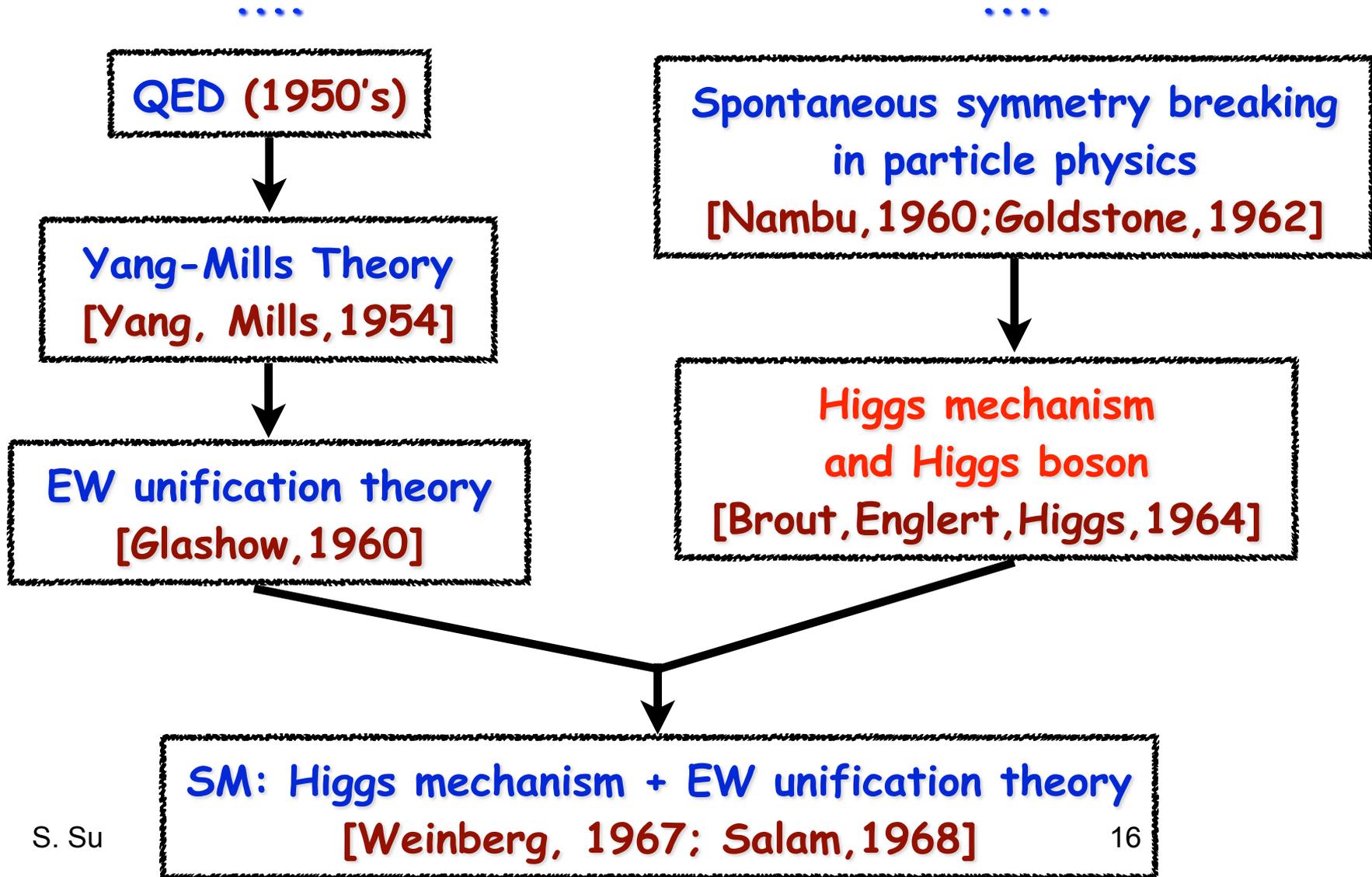
$$m_\gamma = 0$$

EM: long range force

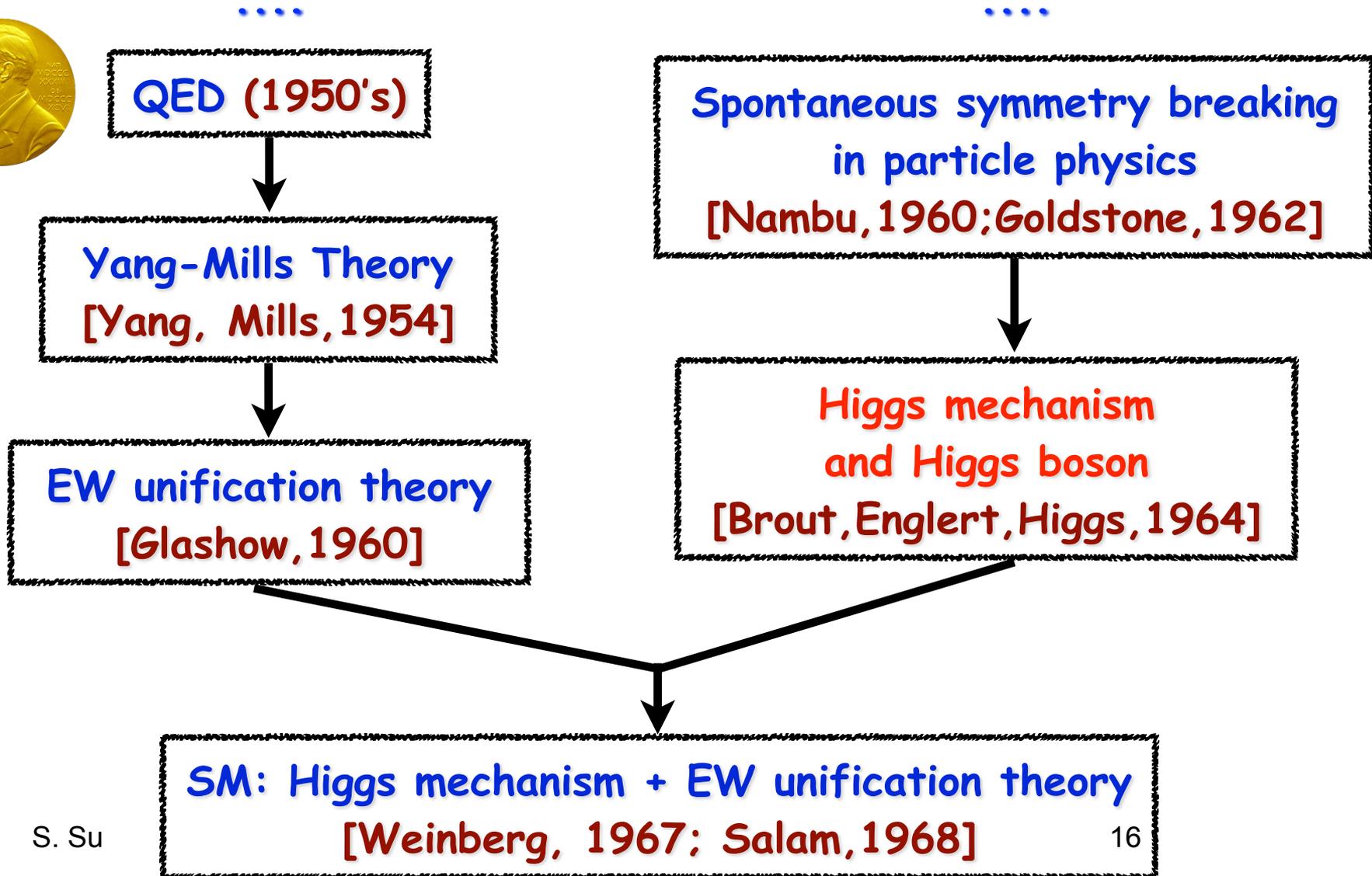
$$m_{W,Z} \sim 100 \text{ GeV}$$

weak interaction: short range force

# Higgs mechanism: historical profile



# Higgs mechanism: historical profile



# Higgs mechanism: historical profile



....

QED (1950's)

Yang-Mills Theory  
[Yang, Mills, 1954]

EW unification theory  
[Glashow, 1960]

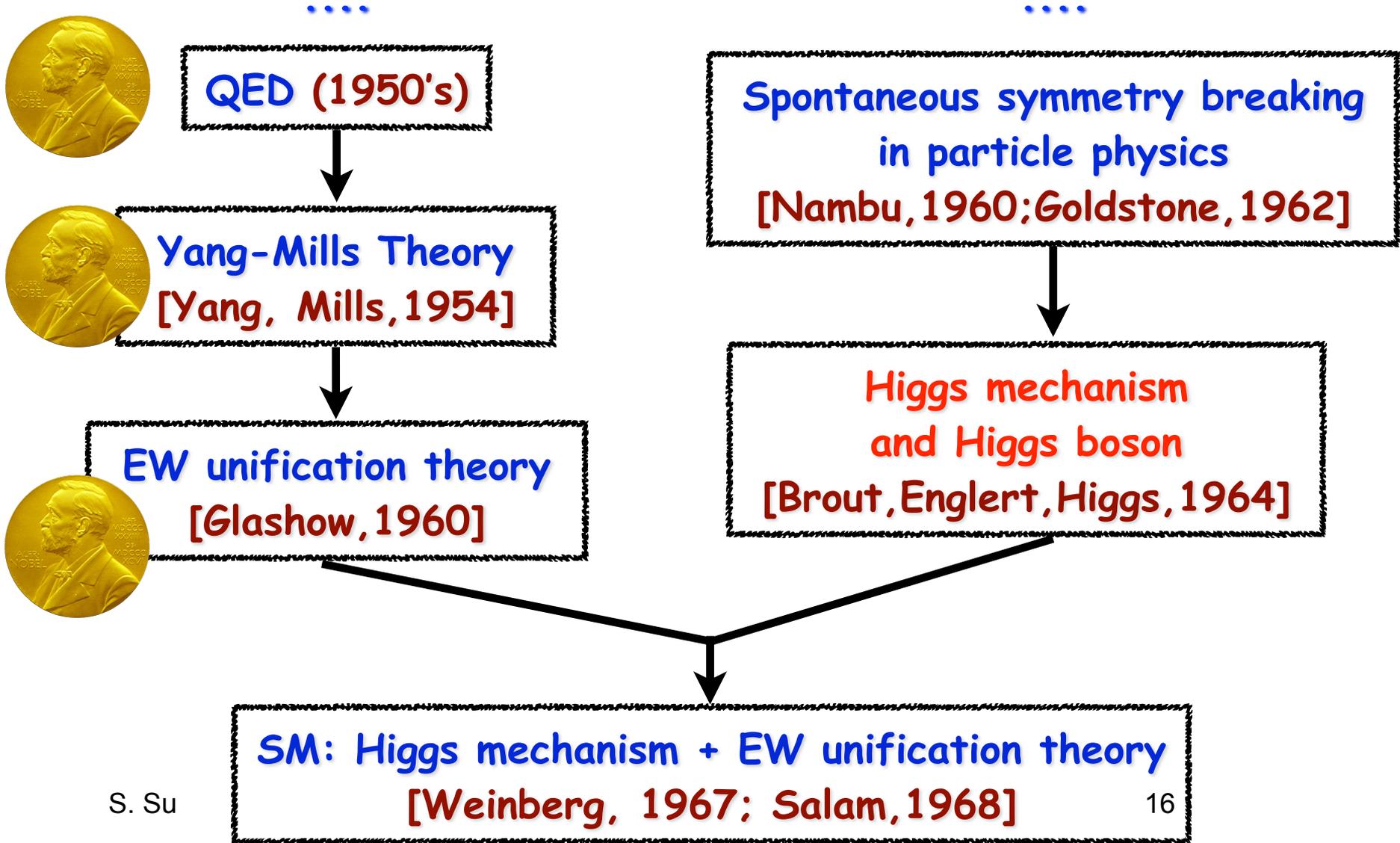
....

Spontaneous symmetry breaking  
in particle physics  
[Nambu, 1960; Goldstone, 1962]

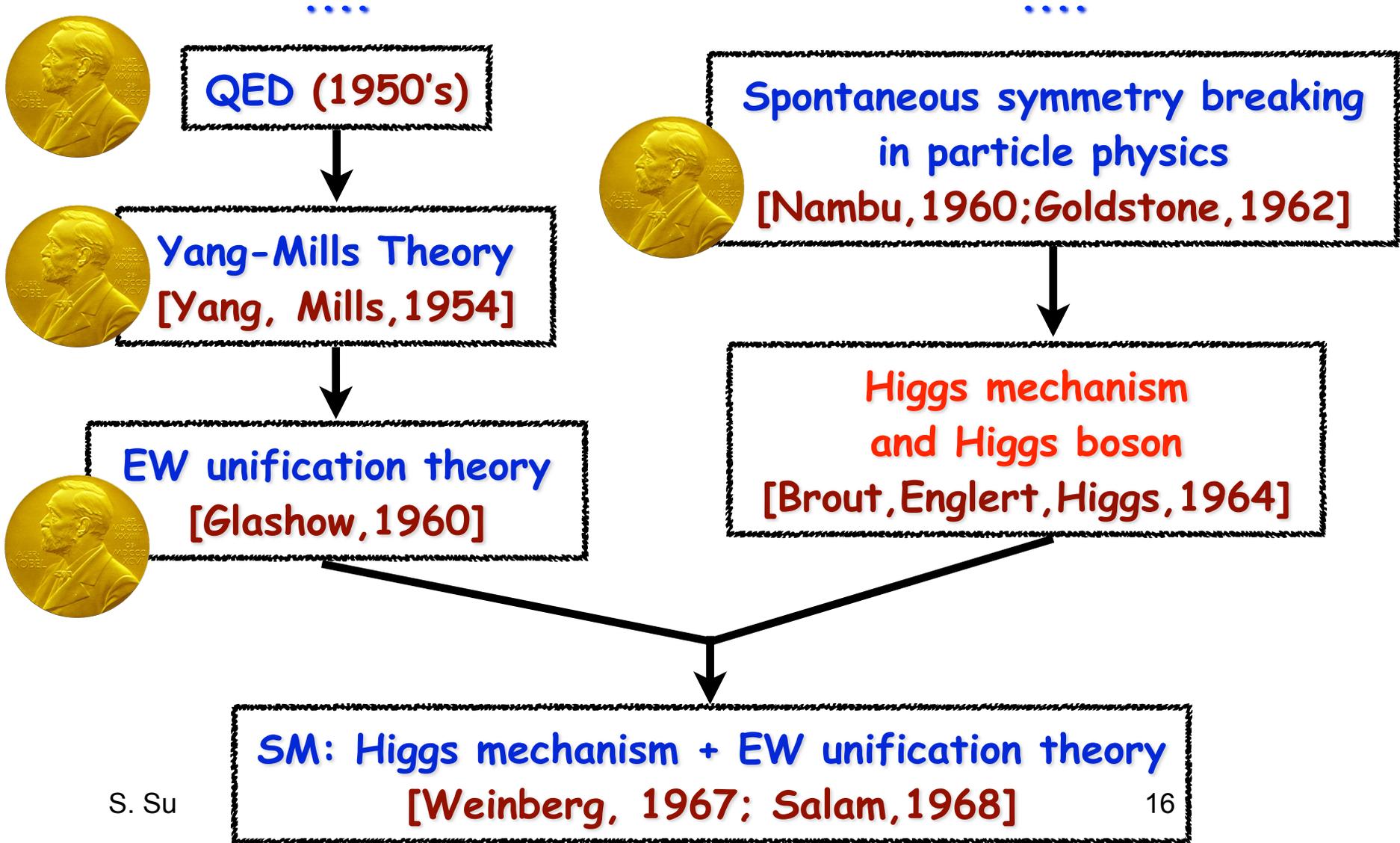
Higgs mechanism  
and Higgs boson  
[Brout, Englert, Higgs, 1964]

SM: Higgs mechanism + EW unification theory  
[Weinberg, 1967; Salam, 1968]

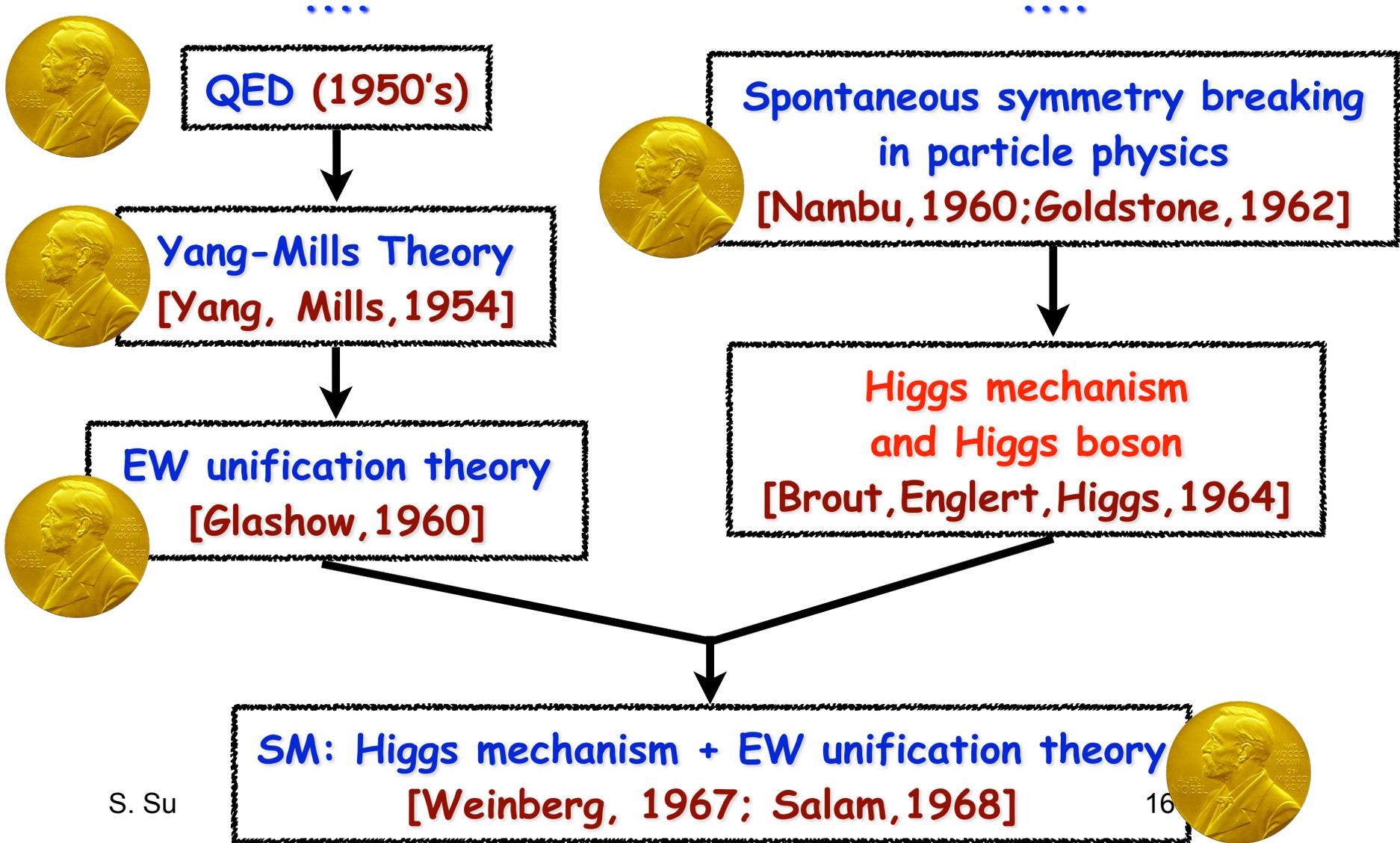
# Higgs mechanism: historical profile



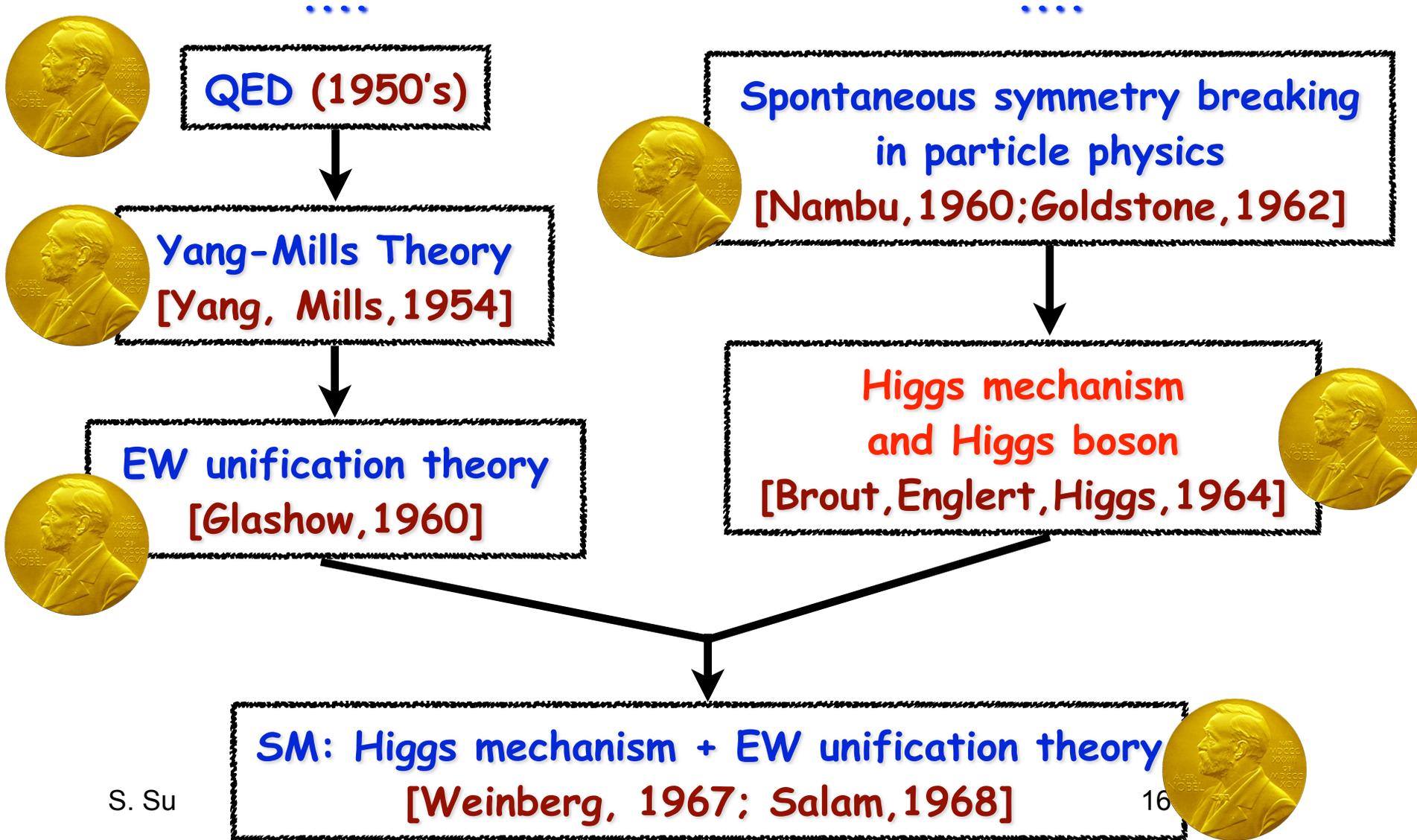
# Higgs mechanism: historical profile



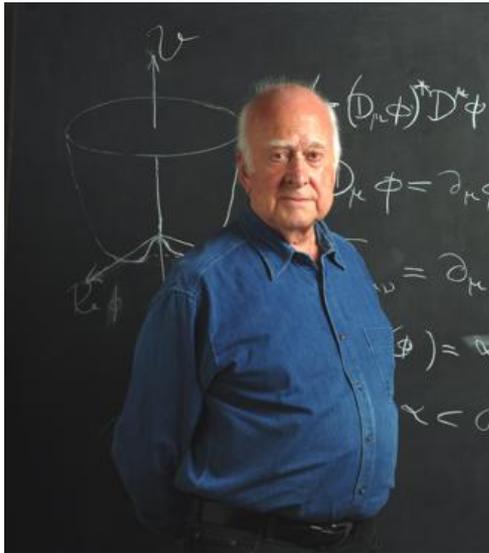
# Higgs mechanism: historical profile



# Higgs mechanism: historical profile

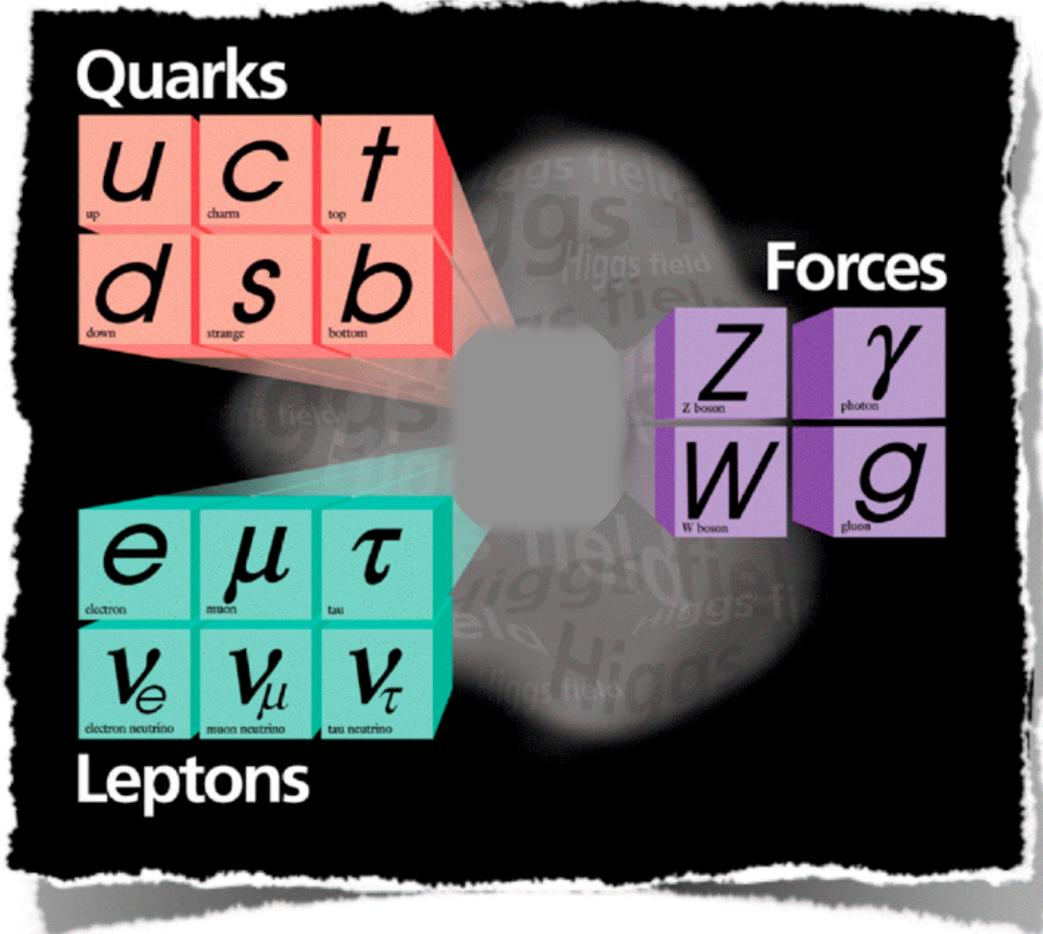


# Higgs Mechanism (1964)



# Elementary particles

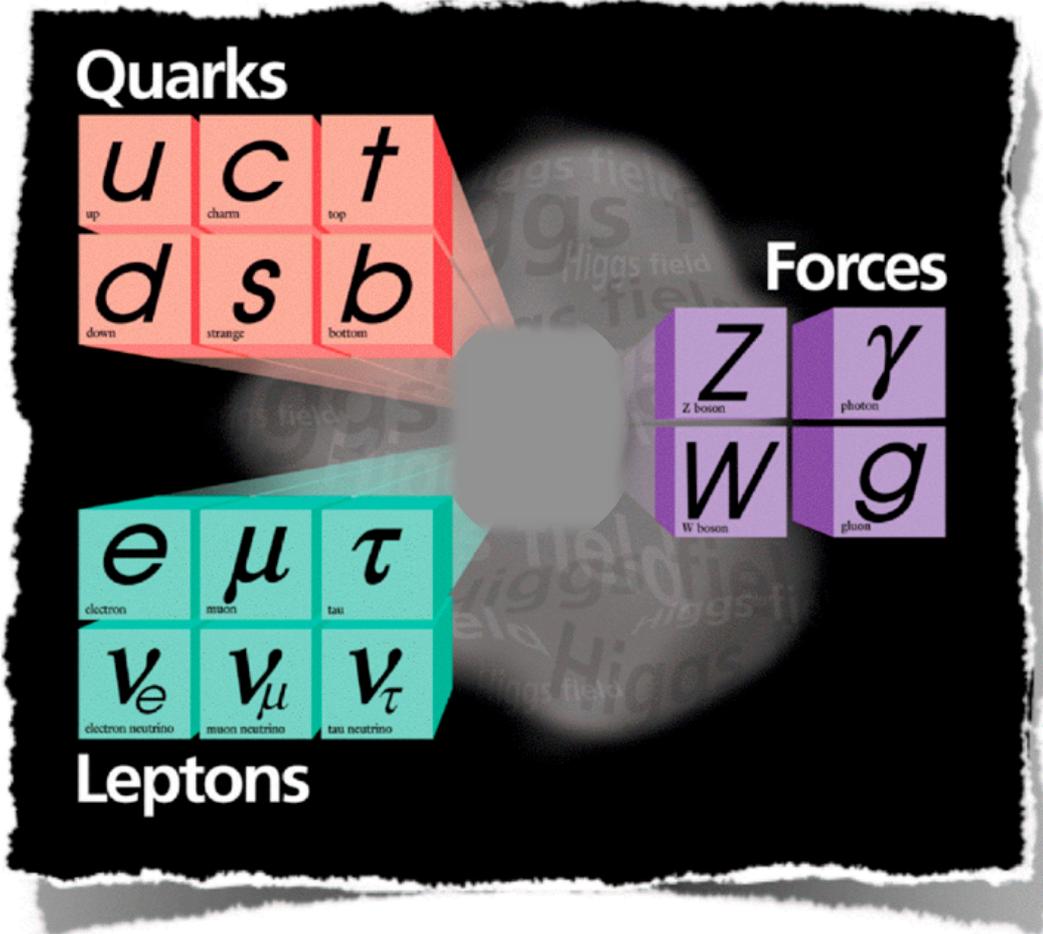
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



# Elementary particles

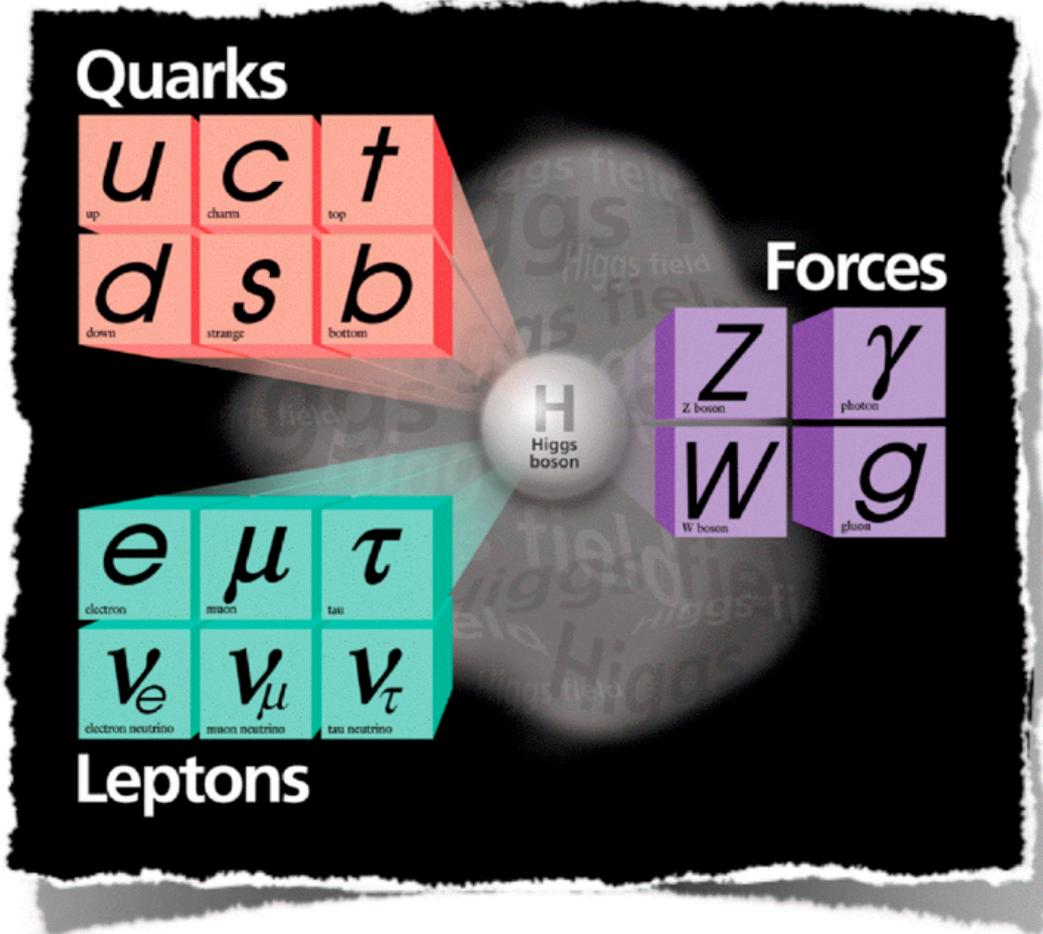
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Higgs (mechanism) !



# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

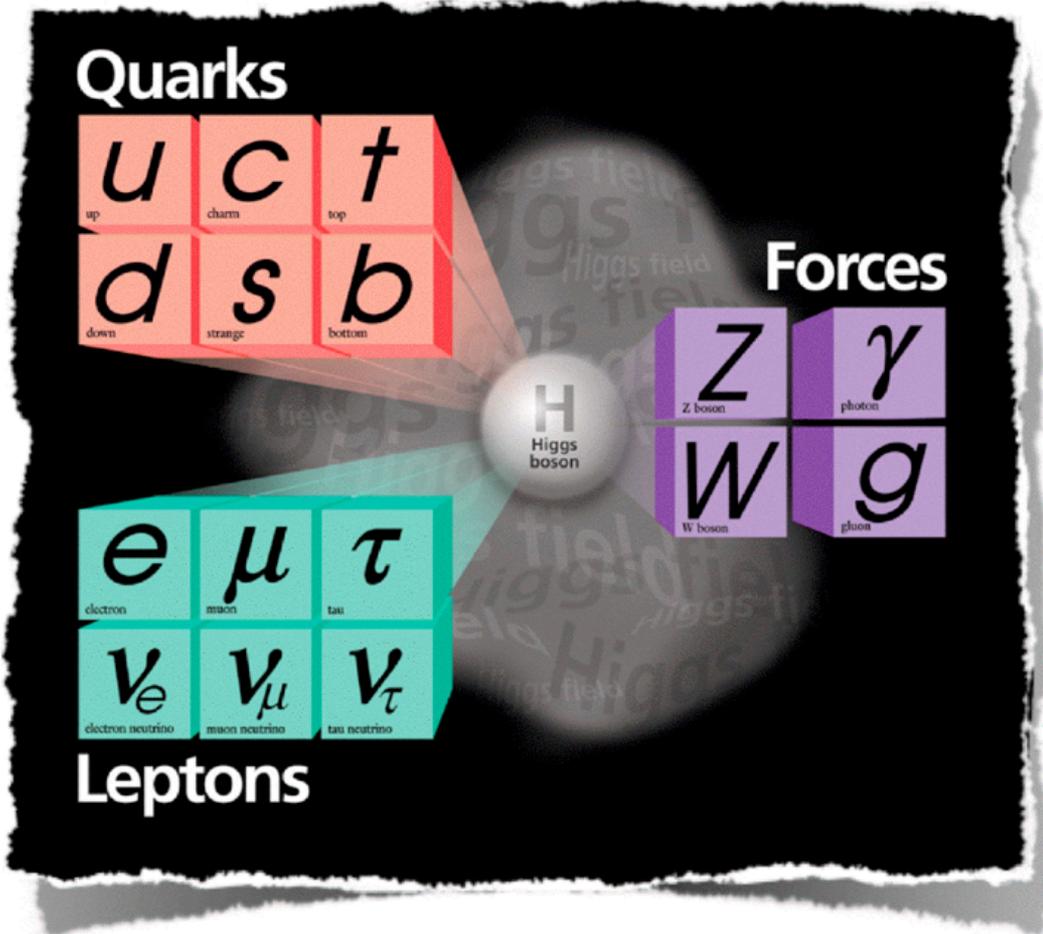


## Higgs (mechanism) !

- Higgs mechanism

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

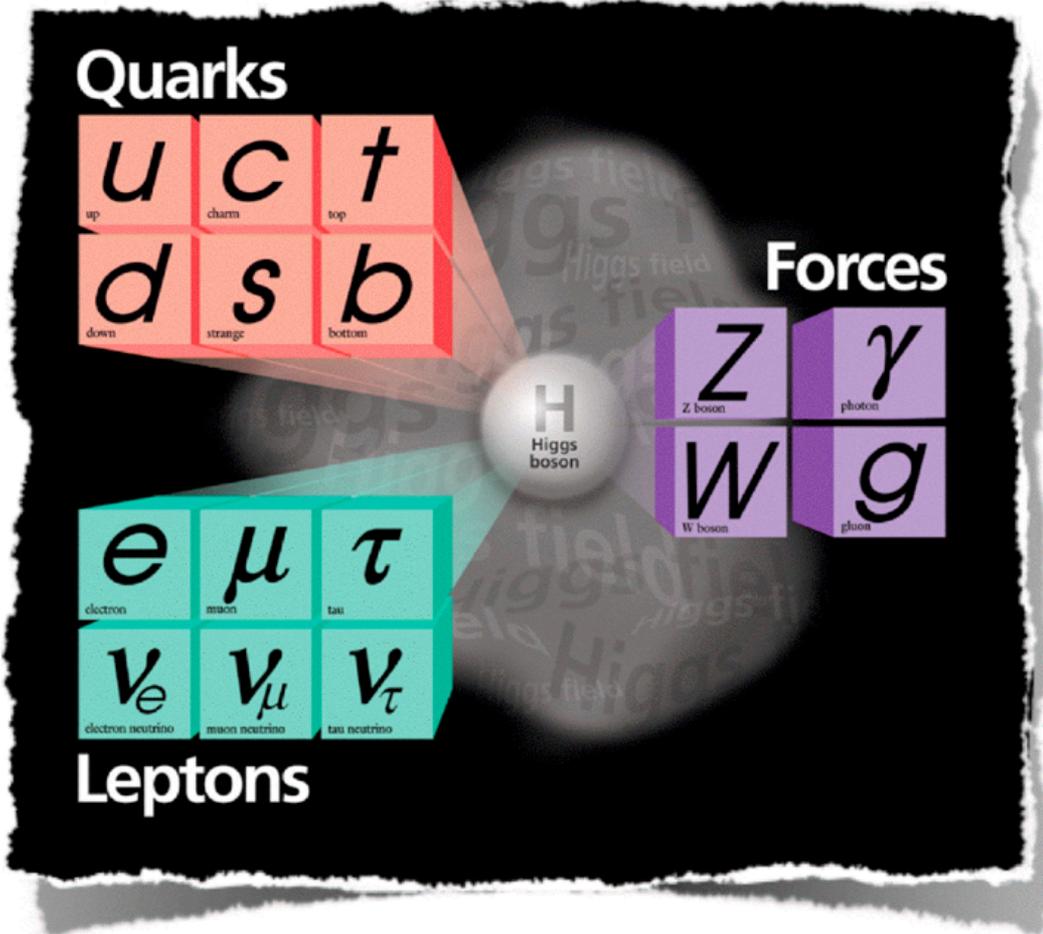


## Higgs (mechanism) !

- Higgs mechanism  
break electroweak symmetry  
spontaneously.

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

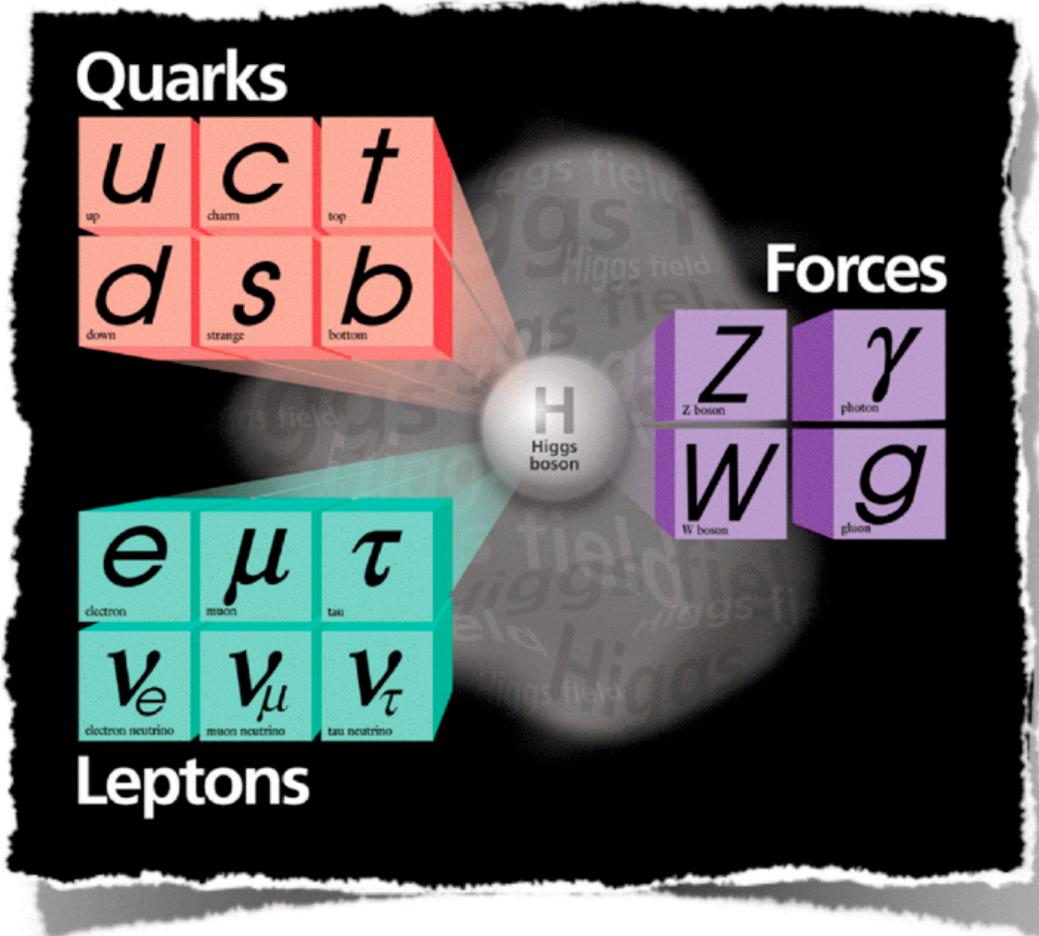


## Higgs (mechanism) !

- Higgs mechanism  
break electroweak symmetry  
spontaneously.

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

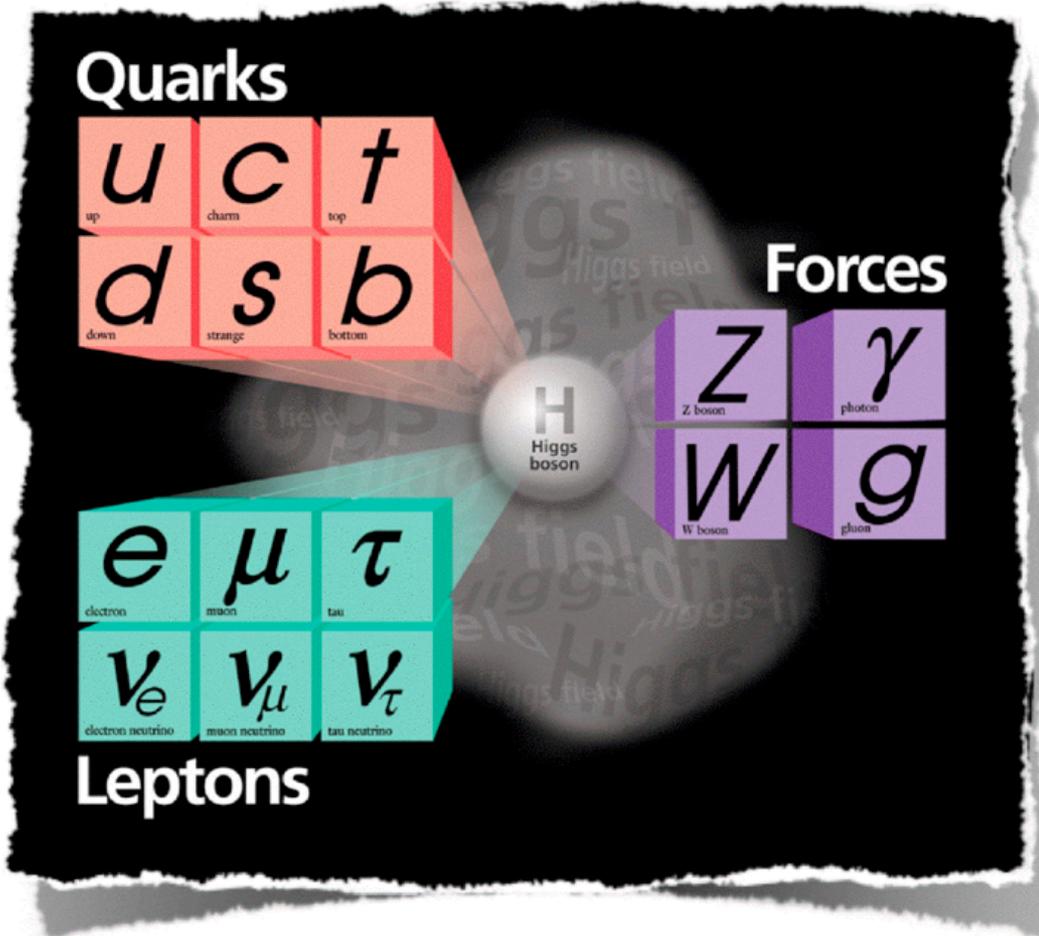


## Higgs (mechanism) !

- Higgs mechanism  
break electroweak symmetry  
spontaneously.
- Higgs field gives mass to  $e$ ,  
 $W$ ,  $Z$ , ...

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

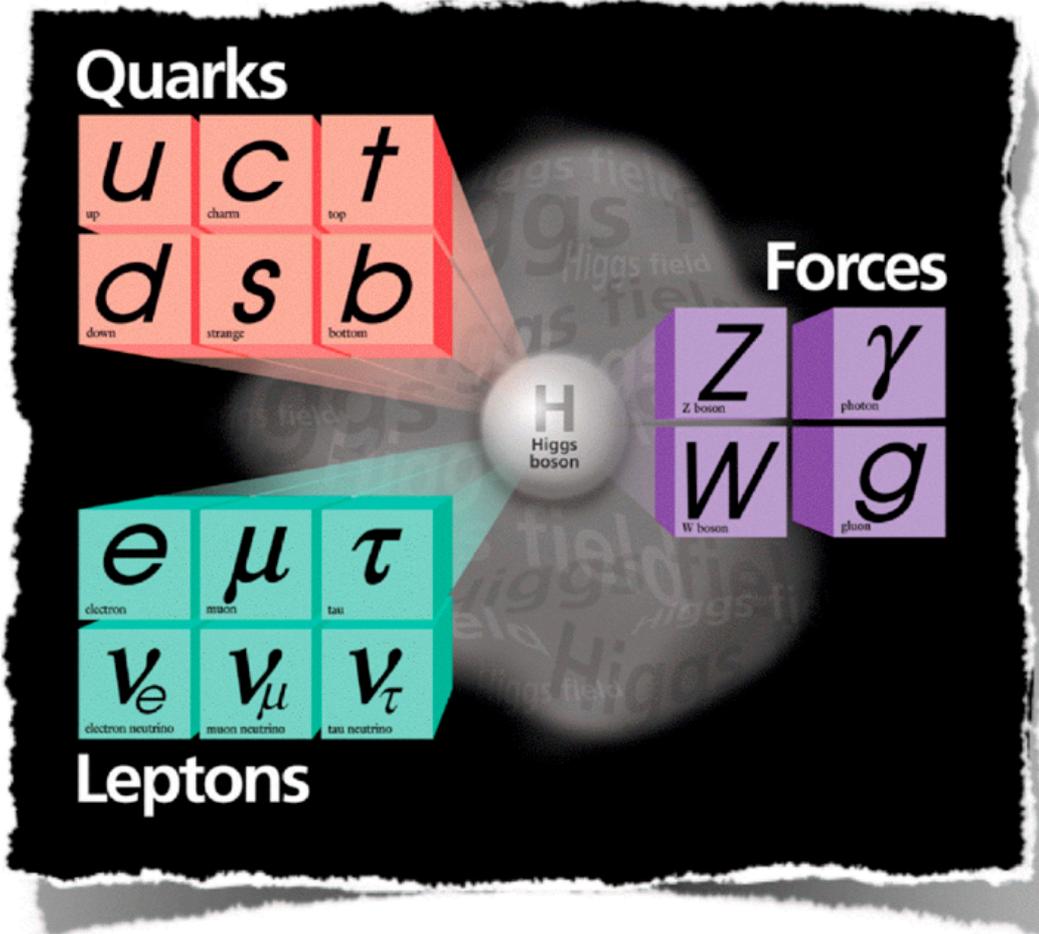


## Higgs (mechanism) !

- Higgs mechanism  
break electroweak symmetry  
spontaneously.
- Higgs field gives mass to  $e$ ,  
 $W$ ,  $Z$ , ...

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

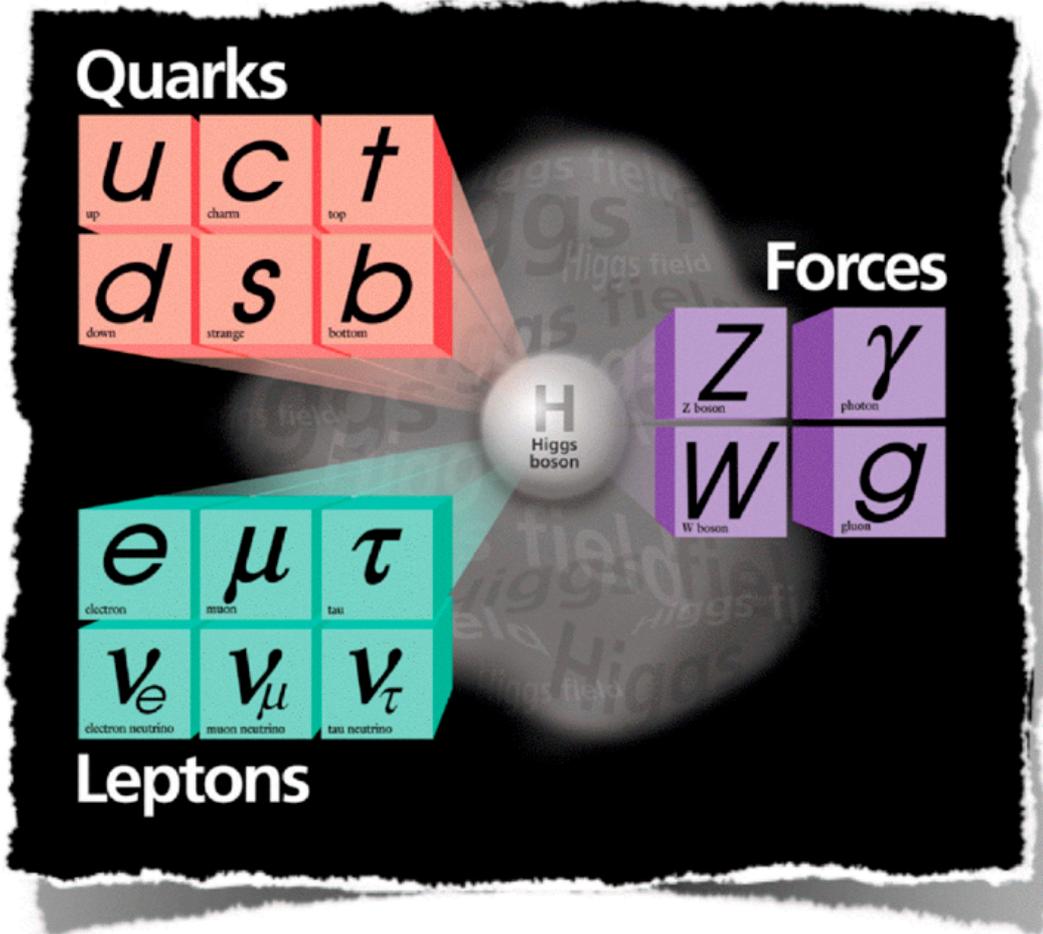


## Higgs (mechanism) !

- Higgs mechanism  
break electroweak symmetry  
spontaneously.
- Higgs field gives mass to  $e$ ,  
 $W$ ,  $Z$ , ...
- The remaining Higgs boson

# Elementary particles

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



## Higgs (mechanism) !

- Higgs mechanism  
break electroweak symmetry  
spontaneously.
- Higgs field gives mass to  $e$ ,  
 $W$ ,  $Z$ , ...
- The remaining Higgs boson  
spin 0 scalar

# Mass generation

---

Higgs Mechanism **DOES NOT** require a Higgs boson!

# Mass generation

Higgs Mechanism **DOES NOT** require a Higgs boson!

Higgs Mechanism: If a **LOCAL gauge symmetry** is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.

# Mass generation

Higgs Mechanism **DOES NOT** require a Higgs boson!

Higgs Mechanism: If a **LOCAL gauge symmetry** is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.

The predicted Higgs boson is the left-over particle!

# Mass generation

Higgs Mechanism **DOES NOT** require a Higgs boson!

Higgs Mechanism: If a **LOCAL gauge symmetry** is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.

The predicted Higgs boson is the left-over particle!

Higgs field  $\rightarrow 4 =$

# Mass generation

Higgs Mechanism **DOES NOT** require a Higgs boson!

Higgs Mechanism: If a **LOCAL gauge symmetry** is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.

The predicted Higgs boson is the left-over particle!

$$\text{Higgs field} \rightarrow 4 = 3$$

longitudinal modes of  $W^+, W^-, Z$

# Mass generation

Higgs Mechanism **DOES NOT** require a Higgs boson!

Higgs Mechanism: If a **LOCAL gauge symmetry** is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.

The predicted Higgs boson is the left-over particle!

$$\begin{array}{c} \text{Higgs} \\ \text{field} \end{array} \rightarrow 4 = 3 + 1$$

↑                    ↑

longitudinal modes of  $W^+, W^-, Z$       physical Higgs Boson

# THE HIGGS MECHANISM

① TO UNDERSTAND THE HIGGS MECHANISM, IMAGINE THAT A ROOM FULL OF PHYSICISTS QUIETLY CHATTERING IS LIKE SPACE FILLED ONLY WITH THE HIGGS FIELD.

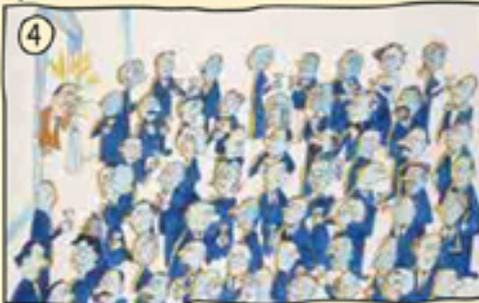


A WELL KNOWN SCIENTIST, ALBERT EINSTEIN, WALKS IN, CREATING A DISTURBANCE AS HE MOVES ACROSS THE ROOM, AND ATTRACTING A CLUSTER OF ADMIRERS WITH EACH STEP.

THIS INCREASES HIS RESISTANCE TO MOVEMENT - IN OTHER WORDS, HE ACQUIRES MASS, JUST LIKE A PARTICLE MOVING THROUGH THE HIGGS FIELD.



IF A RUMOUR CROSSES THE ROOM ...



IT CREATES THE SAME KIND OF CLUSTERING, BUT THIS TIME AMONG THE SCIENTISTS THEMSELVES. IN THIS ANALOGY, THESE CLUSTERS ARE THE HIGGS PARTICLES.

# Quiz!!!

- ⊙ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ⊙ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
- ⊙ Higgs is needed for the mass of elementary particles  
Higgs mechanism: **Yes**. Higgs particle: **No**.

# Quiz!!!

- ◉ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ◉ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
- ◉ Higgs is needed for the mass of elementary particles  
Higgs mechanism: Yes. Higgs particle: No.
- ◉ SM is now complete with the discovery of the Higgs

# Quiz!!!

- ◉ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
  - ◉ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
  - ◉ Higgs is needed for the mass of elementary particles  
Higgs mechanism: Yes. Higgs particle: No.
  - ◉ SM is now complete with the discovery of the Higgs
- ..... THE END.

# Quiz!!!

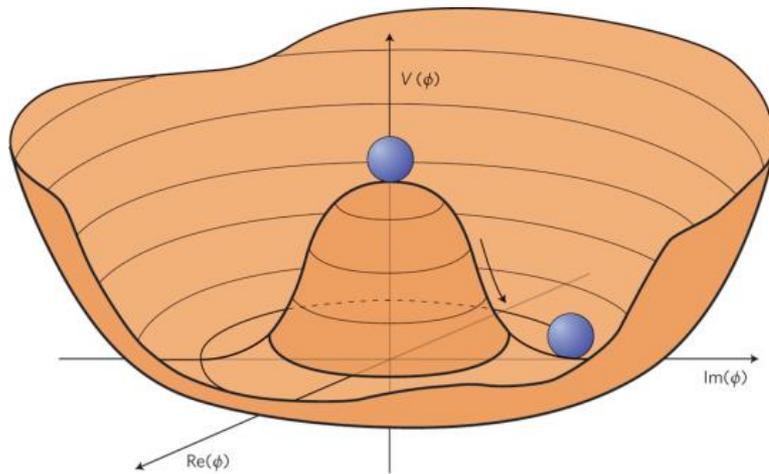
- ◉ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
  - ◉ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
  - ◉ Higgs is needed for the mass of elementary particles  
Higgs mechanism: Yes. Higgs particle: No.
  - ◉ SM is now complete with the discovery of the Higgs
- ..... ~~THE END.~~

# Quiz!!!

- ◉ ~~Higgs is responsible for the mass of Universe~~  
dark matter and dark energies (96% of the Universe)
- ◉ ~~Higgs is responsible for the mass of your and me~~  
(and 4% of the Universe) QCD does it!
- ◉ Higgs is needed for the mass of elementary particles  
Higgs mechanism: Yes. Higgs particle: No.
- ◉ SM is now complete with the discovery of the Higgs  
..... ~~THE END.~~ Beginning of a new Era !!!

# On the theory side...

light, weakly coupled boson:  $m_h = 125-126 \text{ GeV}$ ,  $\Gamma < 1 \text{ GeV}$



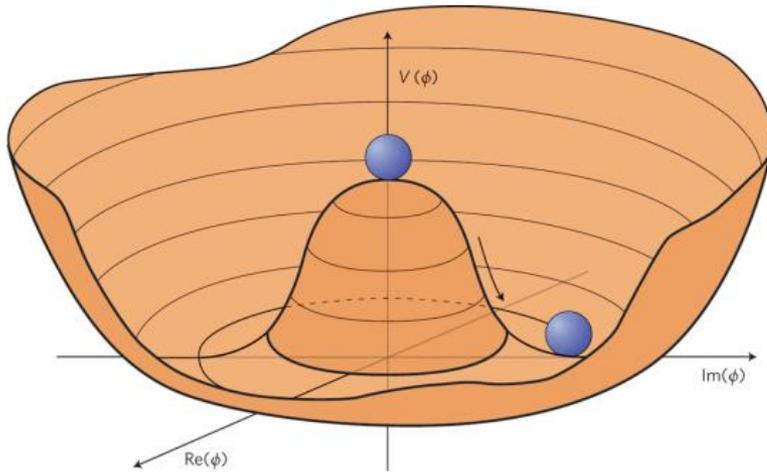
$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

# On the theory side...

light, weakly coupled boson:  $m_h = 125-126$  GeV,  $\Gamma < 1$  GeV



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

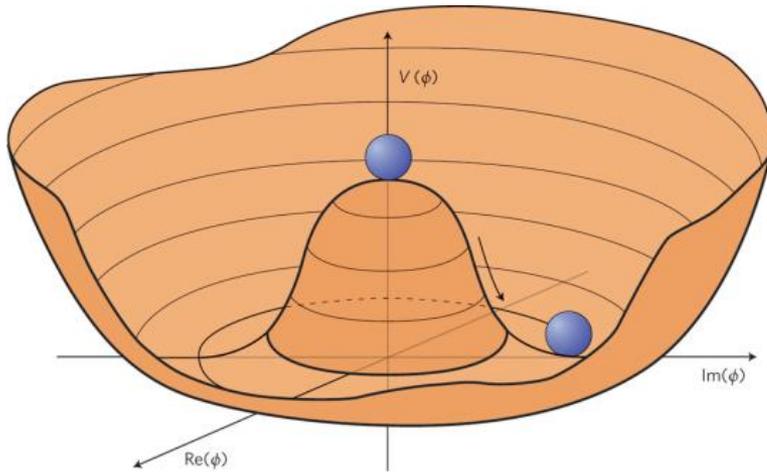
$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

- $\mu_h, \lambda$  measured, not predicted.  $\lambda \sim 1/8$ , A new force?

# On the theory side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

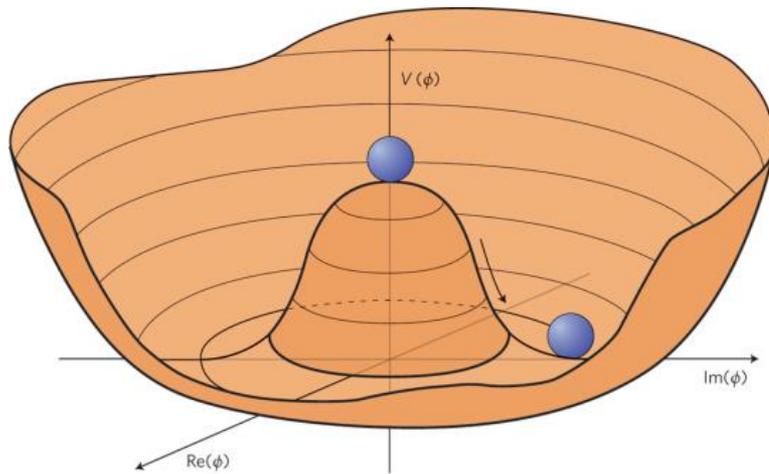
$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

- $\mu_h, \lambda$  measured, not predicted.  $\lambda \sim 1/8$ , A new force?
- like phase-transition in superconductor, however,

# On the theory side...

light, weakly coupled boson:  $m_h = 125-126 \text{ GeV}$ ,  $\Gamma < 1 \text{ GeV}$



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

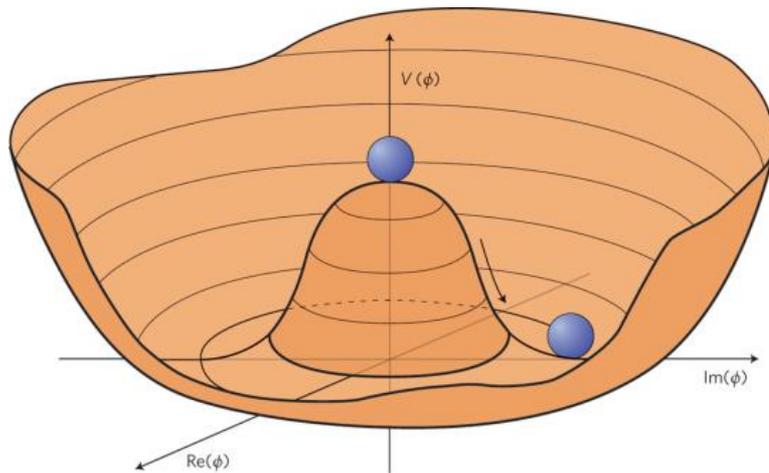
$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

- ⊙  $\mu_h, \lambda$  measured, not predicted.  $\lambda \sim 1/8$ , A new force?
- ⊙ like phase-transition in superconductor, however,  
→ not in known material

# On the theory side...

light, weakly coupled boson:  $m_h = 125-126 \text{ GeV}$ ,  $\Gamma < 1 \text{ GeV}$



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

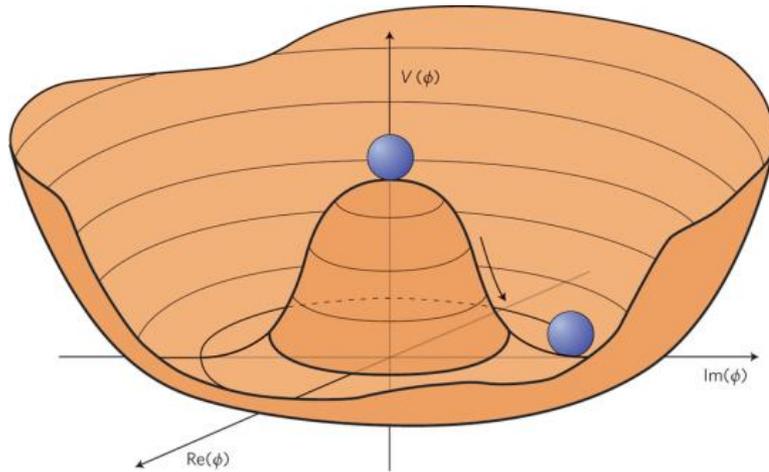
$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

- $\mu_h, \lambda$  measured, not predicted.  $\lambda \sim 1/8$ , A new force?
- like phase-transition in superconductor, however,
  - not in known material
  - nobody dials the temperature from outside

# On the theory side...

light, weakly coupled boson:  $m_h = 125-126 \text{ GeV}$ ,  $\Gamma < 1 \text{ GeV}$



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

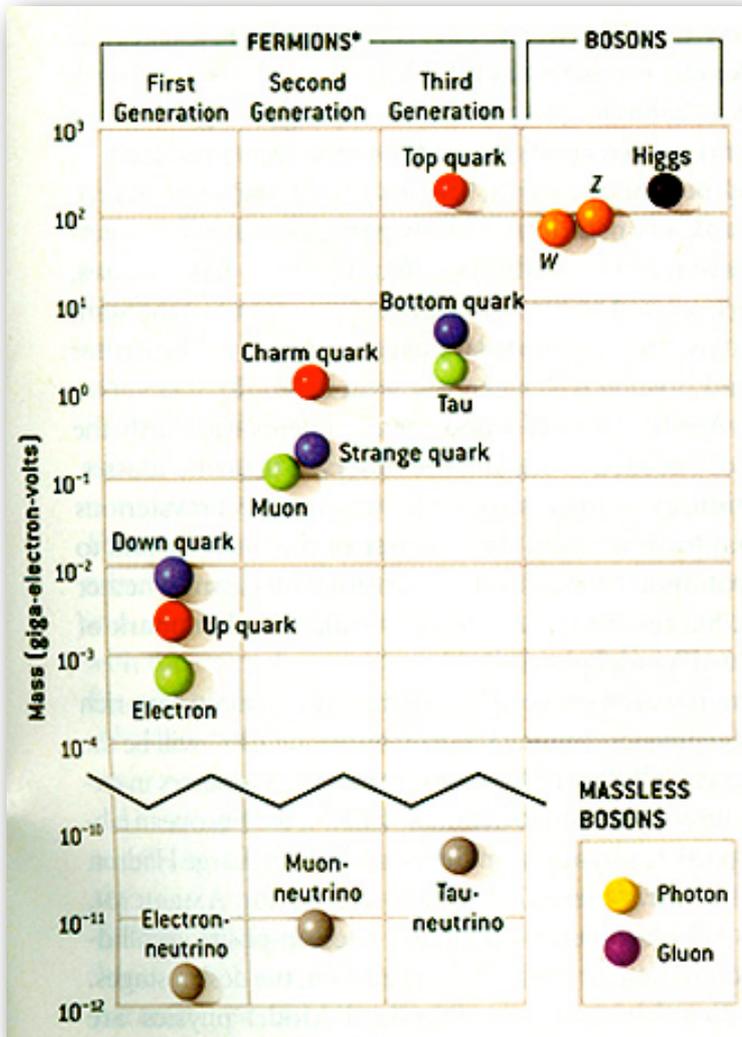
$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

- $\mu_h, \lambda$  measured, not predicted.  $\lambda \sim 1/8$ , A new force?
- like phase-transition in superconductor, however,
  - not in known material
  - nobody dials the temperature from outside
- parameters in  $V$  need to come from an (unknown) fundamental theory

# Standard Model

Image credit: Gordon Kane, Scientific American, June 2003.



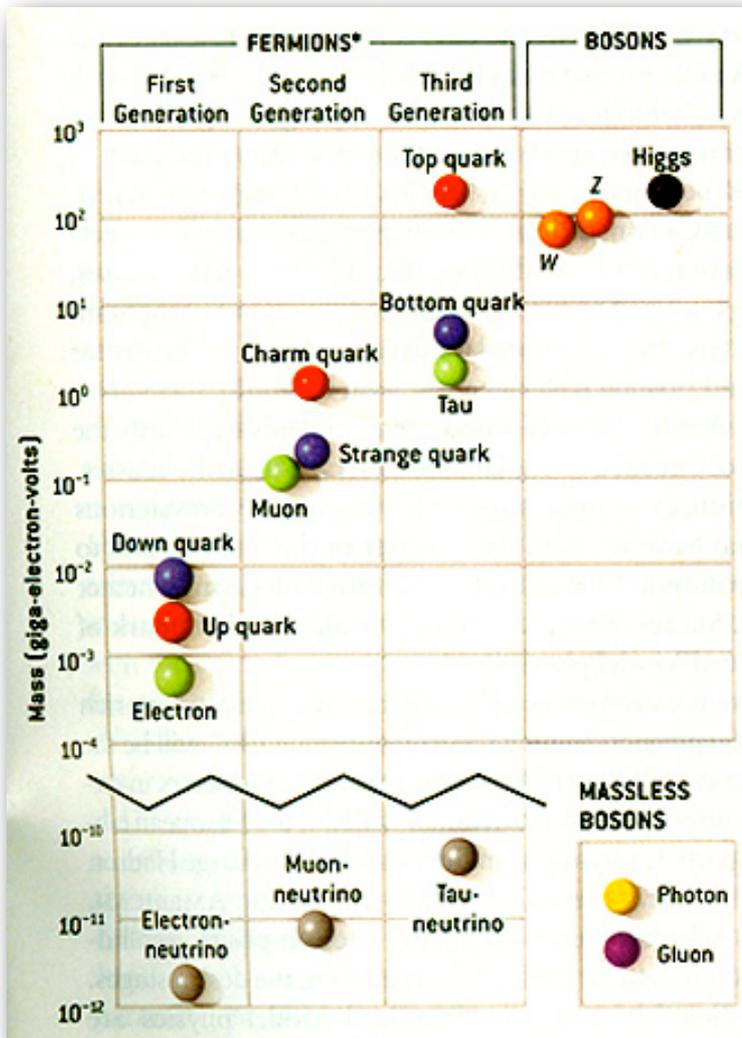
$$\lambda_q \sim m_q/v$$

All couplings and parameters of the Higgs sector is determined in the SM.



# Standard Model

Image credit: Gordon Kane, Scientific American, June 2003.



$$\lambda_q \sim m_q/v$$

All couplings and parameters of the Higgs sector is determined in the SM.

To compare with measurements high precise needed!

- clean environments
- lots of Higgs

→ Higgs factory!

# A light SM Higgs is puzzling...

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
<b>Higgs</b>	<b>0</b>

# A light SM Higgs is puzzling...

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
<b>Higgs</b>	<b>0</b>

**Higgs: a new kind of elementary particle!**

# A light SM Higgs is puzzling...

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
<b>Higgs</b>	<b>0</b>

**Higgs: a new kind of elementary particle!**

**Nothing protects its mass.**



# A light SM Higgs is puzzling...

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
<b>Higgs</b>	<b>0</b>

**Higgs: a new kind of elementary particle!**

**Nothing protects its mass.**



**New physics beyond the SM**

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126 \text{ GeV}$ ,  $\Gamma < 1 \text{ GeV}$

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$

Experimentally ...

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$

Experimentally ...

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$

Experimentally ...

- © Is it a SM Higgs? Mass, width, spin, coupling, CP, ...

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$

Experimentally ...

- Is it a SM Higgs? Mass, width, spin, coupling, CP, ...
- Is there more than one Higgs boson?

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$

Experimentally ...

- Is it a SM Higgs? Mass, width, spin, coupling, CP, ...
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?

# On the exp side...

light, weakly coupled boson:  $m_h = 125\text{-}126\text{ GeV}$ ,  $\Gamma < 1\text{ GeV}$

Experimentally ...

- Is it a SM Higgs? Mass, width, spin, coupling, CP, ...
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Can we use H to look for new physics?

# On the exp side...

light, weakly coupled boson:  $m_h = 125-126$  GeV,  $\Gamma < 1$  GeV

Experimentally ...

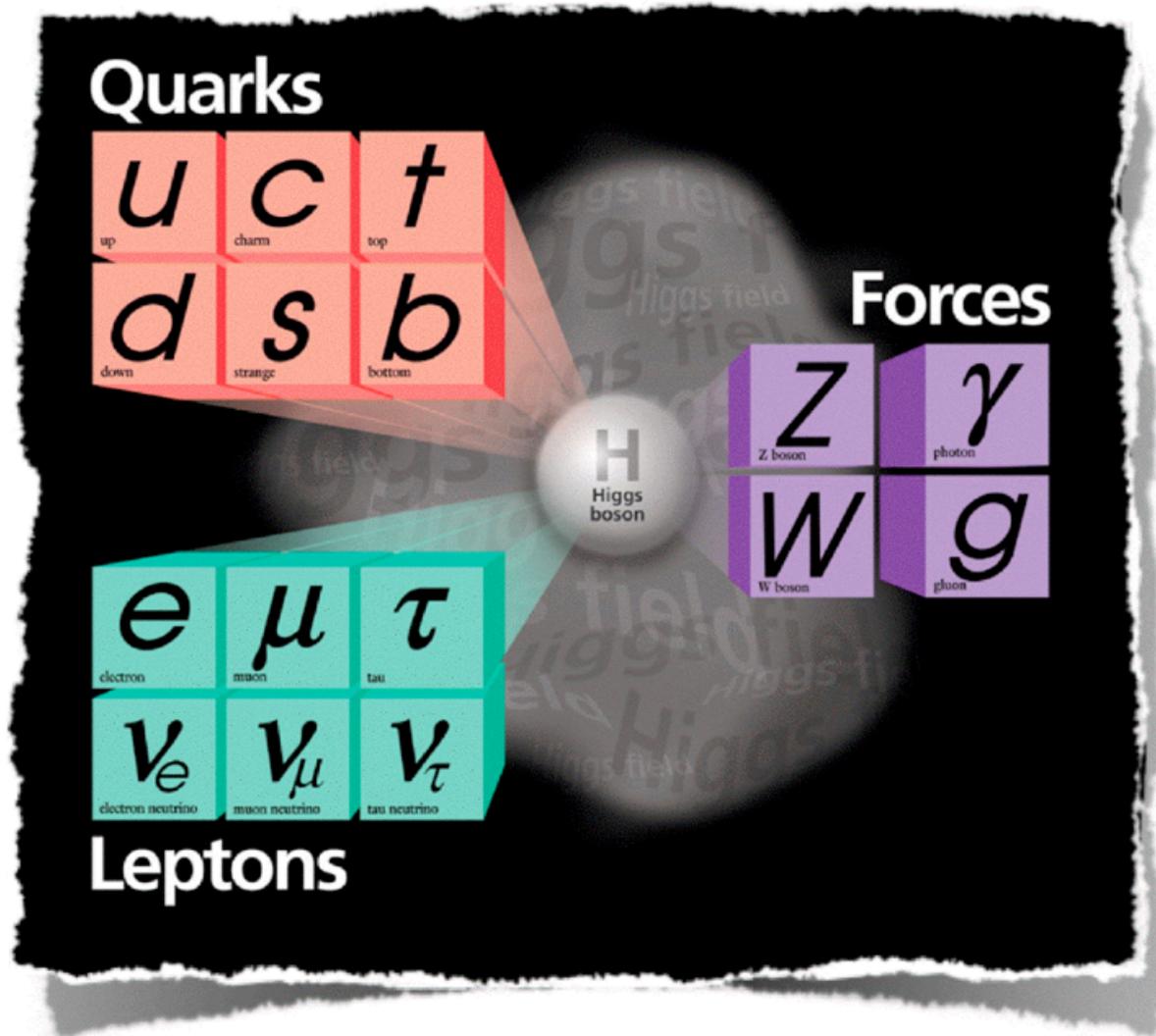
- Is it a SM Higgs? Mass, width, spin, coupling, CP, ...
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Can we use H to look for new physics?
- Where is new physics? top partners? Dark matter?

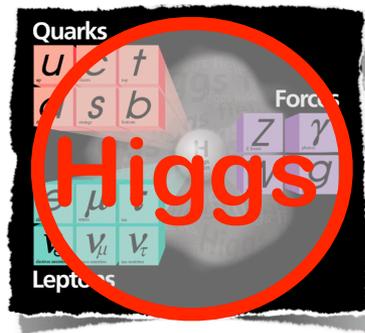
# On the exp side...

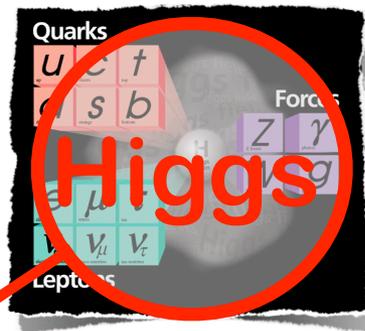
light, weakly coupled boson:  $m_h = 125-126$  GeV,  $\Gamma < 1$  GeV

Experimentally ...

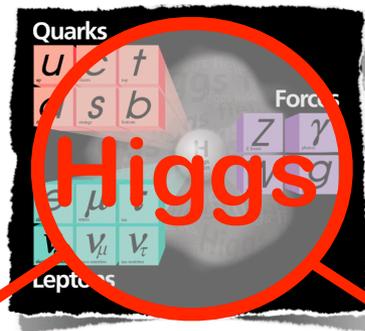
- Is it a SM Higgs? Mass, width, spin, coupling, CP, ...
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Can we use H to look for new physics?
- Where is new physics? top partners? Dark matter?
- ...







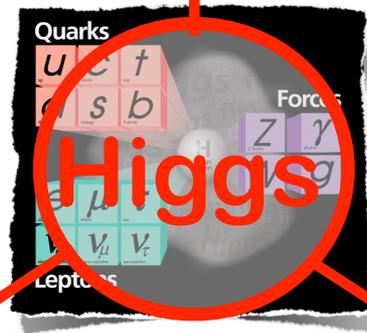
syblings  
H, A, H<sup>±</sup>,  
...



syblings  
H, A, H $^\pm$ ,  
...

partners  
Higgsinos  
...

friends  
stop,  
...



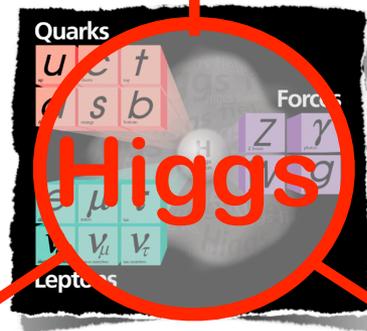
Higgs

syblings  
H, A, H $^{\pm}$ ,  
...

partners  
Higgsinos  
...

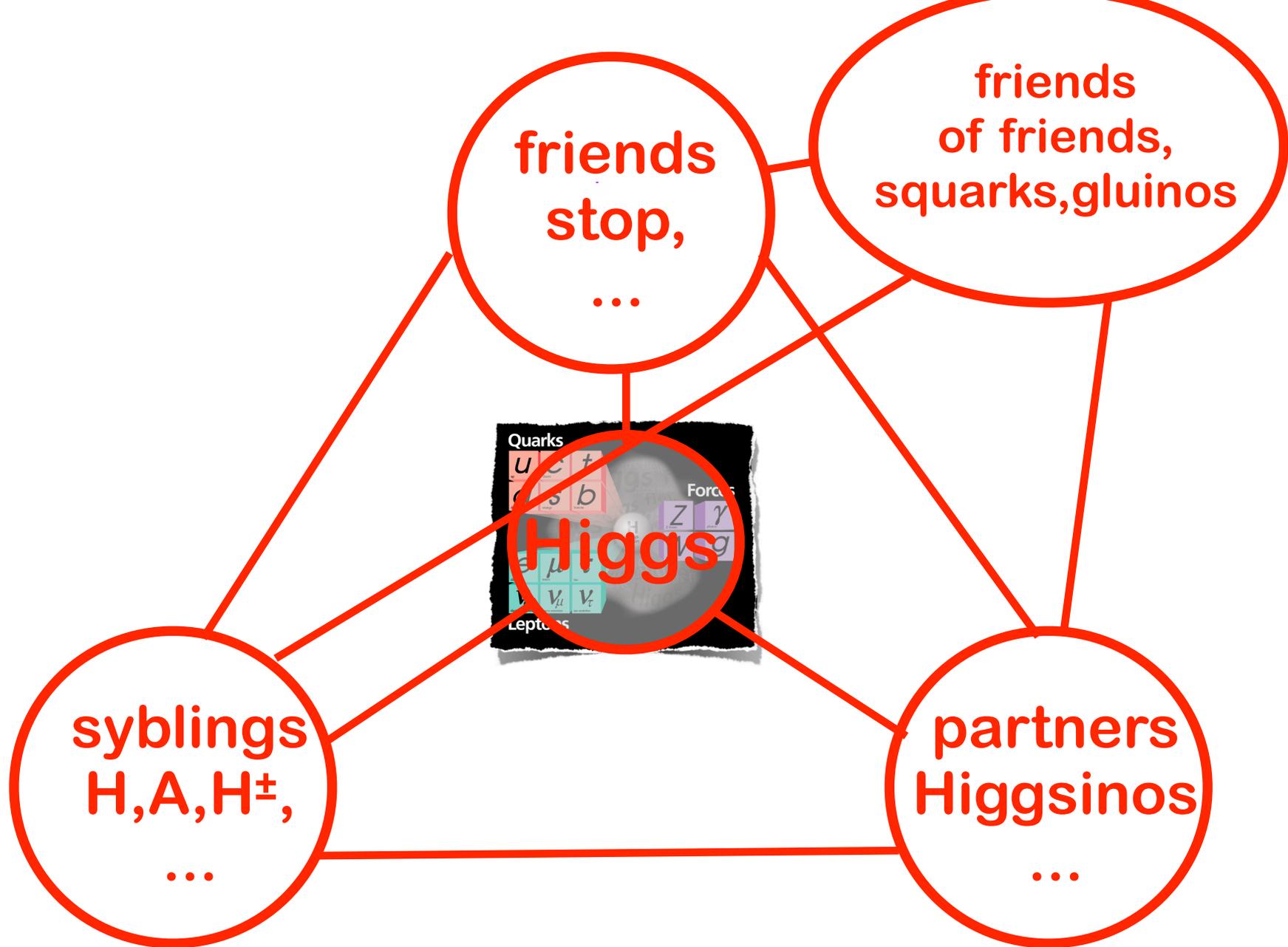
friends  
stop,  
...

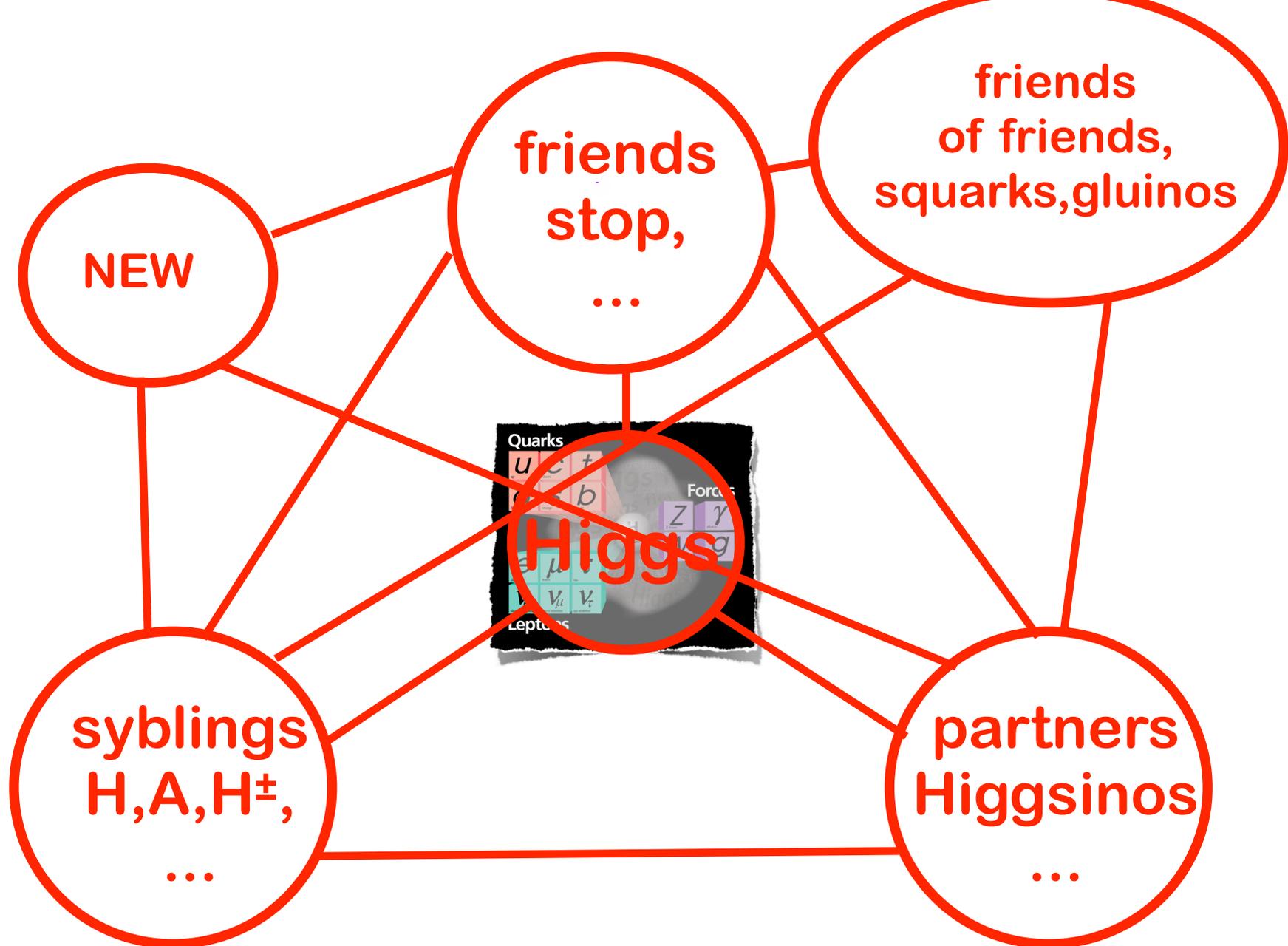
friends  
of friends,  
squarks, gluinos



syblings  
H, A, H $\pm$ ,  
...

partners  
Higgsinos  
...





# facebook

NEW

friends  
stop,  
...

friends  
of friends,  
squarks, gluinos

Higgs

syblings  
 $H, A, H^\pm,$   
...

partners  
Higgsinos

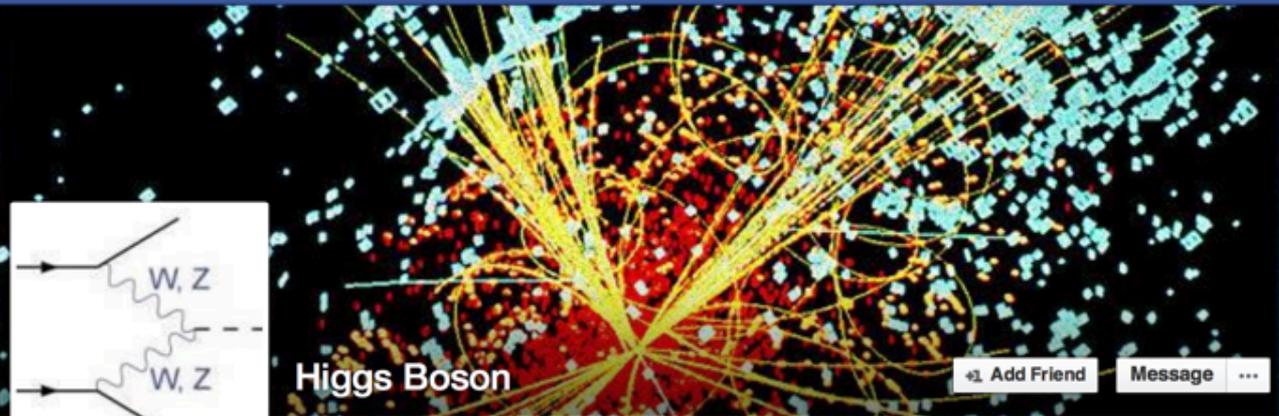


# facebook

friends

friends  
of friends,  
quinos

N



Higgs Boson

Add Friend

Message

Timeline

About

Photos

Friends 9 Mutual

More

## About

To see what he shares with friends, send him a friend request.

Add Friend



9 Mutual Friends

### Work and Education



CERN

Scalar elementary particle · Geneva, Switzerland · Jan 1980 to present



Fermi National Accelerator Laboratory



European Center for Nuclear Research



CERN

### Places Lived



Geneva, Switzerland

Hometown

### Basic Information

Birthday

September 29, 1954

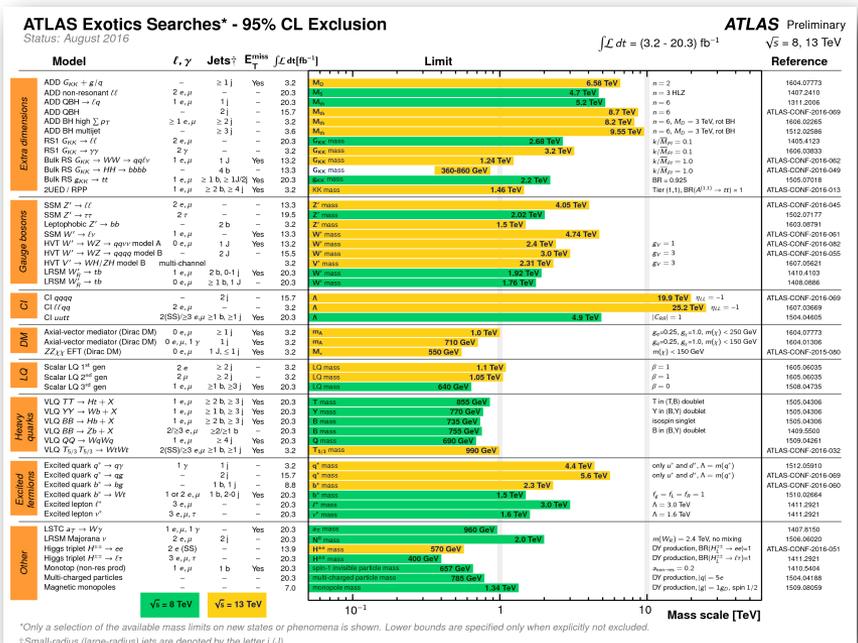
Gender

Male

S  
H

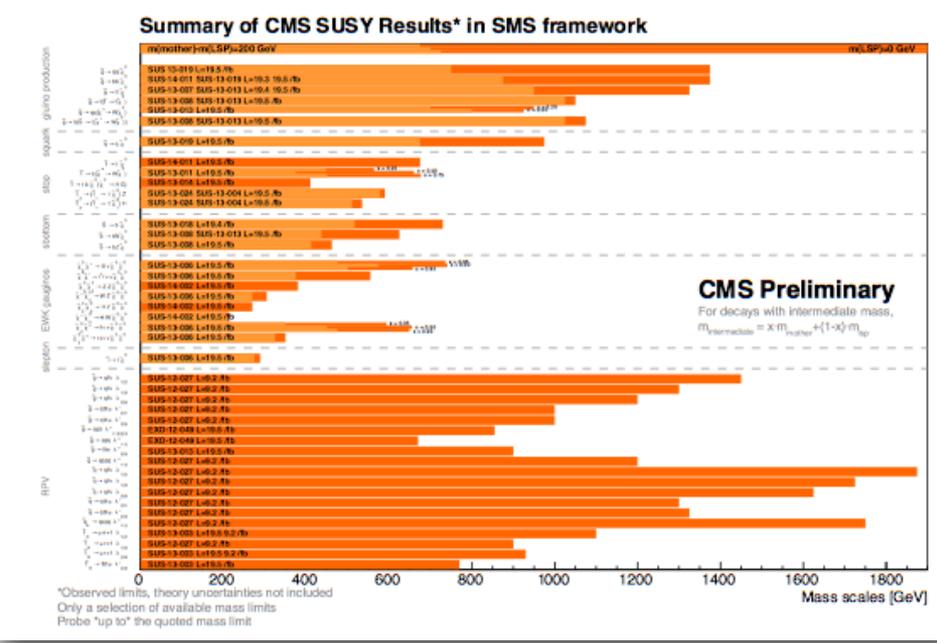
rs  
OS

# New Physics Searches



## ATLAS exotic

S. Su



## CMS SUSY

27

# New Physics Searches

**ATLAS Exotics Searches\* - 95% CL Exclusion**  
Status: August 2016

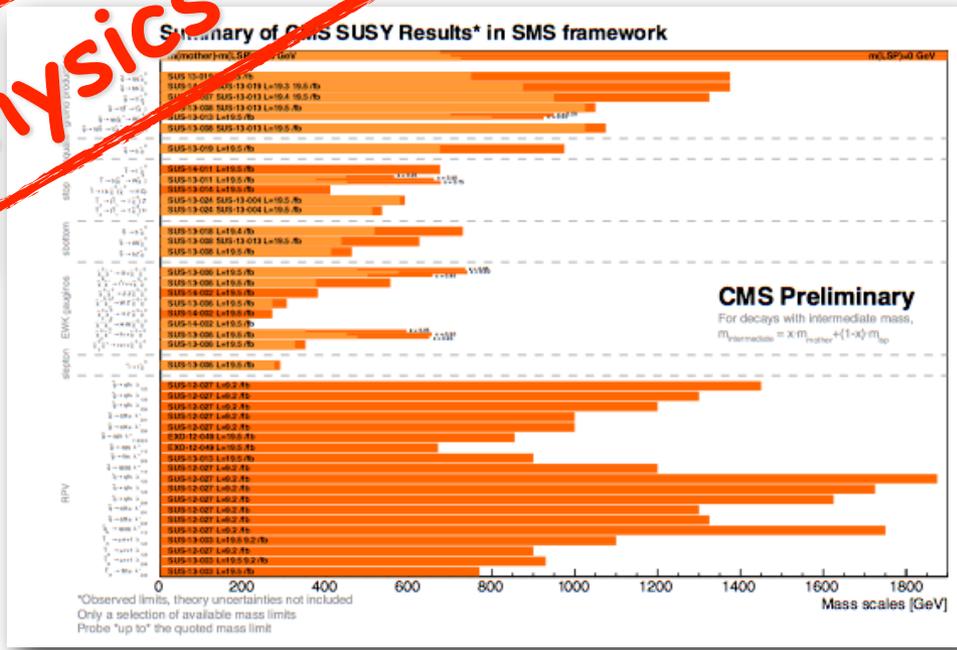
ATLAS Preliminary  
 $\sqrt{s} = 8, 13 \text{ TeV}$

$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$

Model	$\ell, \gamma$	Jets <sup>b</sup>	$E_{\text{miss}}^c$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
<b>Extra dimensions</b>						
ADD $G_{KK} \rightarrow g/d$	-	$\geq 1$	Yes	3.2	$M_{KK} > 4.50 \text{ TeV}$	$n=2$ 1604.07773
ADD non-resonant $\ell\ell$	$2, e, \mu$	-	-	20.3	$M_{KK} > 4.7 \text{ TeV}$	$n=3 \text{ HZ}$ 1407.2410
ADD OBH $\rightarrow g$	$1, e, \mu$	1	-	20.3	$M_{KK} > 5.2 \text{ TeV}$	$n=6$ 1311.2006
ADD OBH	$1, e, \mu$	2	-	15.7	$M_{KK} > 4.7 \text{ TeV}$	$n=6$ 1606.00265
ADD BH high $\gamma$	$\geq 1, e, \mu$	$\geq 2$	-	3.2	$M_{KK} > 8.7 \text{ TeV}$	$n=6, M_0 = 3 \text{ TeV, rot BH}$ 1512.02666
ADD BH midjet	$\geq 1, e, \mu$	$\geq 3$	-	2.6	$M_{KK} > 9.55 \text{ TeV}$	$n=6, M_0 = 3 \text{ TeV, rot BH}$ 1405.123
RS1 $G_{KK} \rightarrow \ell\ell$	$2, e, \mu$	-	-	20.3	$M_{KK} \text{ mass} > 2.86 \text{ TeV}$	$k/M_0 = 0.1$ 1606.09003
RS1 $G_{KK} \rightarrow \gamma\gamma$	$2, \gamma$	-	-	3.2	$G_{KK} \text{ mass} > 3.2 \text{ TeV}$	$k/M_0 = 0.1$ 1606.09003
Bulk RS $G_{KK} \rightarrow WW \rightarrow \text{qq}\nu$	$1, e, \mu, \tau$	1, J	Yes	13.2	$G_{KK} \text{ mass} > 1.24 \text{ TeV}$	ATLAS CONF 2016.062
Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}bb$	-	4b	-	13.3	$G_{KK} \text{ mass} > 360-660 \text{ GeV}$	ATLAS CONF 2016.049
Bulk RS $G_{KK} \rightarrow tt$	$1, e, \mu, \tau$	$\geq 1, b, \geq 1, J$	Yes	20.3	$G_{KK} \text{ mass} > 2.2 \text{ TeV}$	BR-0325 1505.07016
ZUED / RPP	$1, e, \mu, \tau$	$\geq 2, b, \geq 4$	Yes	3.2	$RPP \text{ mass} > 1.46 \text{ TeV}$	Tar(1,1), BR( $d^{(1)}$ ) = $m = 1$ ATLAS CONF 2016.013
<b>Gauge bosons</b>						
SSM $Z' \rightarrow \ell\ell$	$2, e, \mu, \tau$	-	-	13.3	$Z' \text{ mass} > 4.05 \text{ TeV}$	ATLAS CONF 2016.045
SSM $Z' \rightarrow \gamma\gamma$	$2, \gamma$	-	-	19.5	$Z' \text{ mass} > 2.06 \text{ TeV}$	1502.07177
Leptoophobic $Z' \rightarrow b\bar{b}$	$2, b$	-	-	3.2	$Z' \text{ mass} > 1.3 \text{ TeV}$	1603.00781
SSM $W' \rightarrow \ell\nu$	$1, e, \mu, \tau$	-	Yes	13.3	$W' \text{ mass} > 4.74 \text{ TeV}$	ATLAS CONF 2016.061
HVT $W' \rightarrow WZ \rightarrow \text{qq}\nu$ model A	$0, e, \mu, \tau$	1, J	Yes	13.2	$W' \text{ mass} > 2.4 \text{ TeV}$	$\beta = 1$ ATLAS CONF 2016.062
HVT $W' \rightarrow WZ \rightarrow \text{qq}\nu$ model B	$0, e, \mu, \tau$	2, J	Yes	15.5	$W' \text{ mass} > 3.0 \text{ TeV}$	$\beta = 3$ ATLAS CONF 2016.055
HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	Yes	3.2	$V' \text{ mass} > 2.31 \text{ TeV}$	$\beta = 3$ 1607.59021
LRSM $W'_2 \rightarrow \ell\nu$	$1, e, \mu, \tau$	$2, b, 0, 1, J$	Yes	20.3	$W'_2 \text{ mass} > 1.96 \text{ TeV}$	1418.0103
LRSM $W'_2 \rightarrow \ell b$	$0, e, \mu, \tau$	$\geq 1, b, 1, J$	Yes	20.3	$W'_2 \text{ mass} > 1.76 \text{ TeV}$	1408.0886
<b>CI</b>						
CI $\ell\ell\ell\ell$	-	2	-	15.7	$I_A > 19.9 \text{ TeV}$	$\theta_{12} = -1$ ATLAS CONF 2016.069
CI $\ell\ell\ell\gamma$	$2, e, \mu, \tau$	-	-	3.2	$I_B > 25.2 \text{ TeV}$	$\theta_{12} = -1$ 1607.00699
CI $\ell\nu\ell\nu$	$2(SS) \geq 3, e, \mu, \tau \geq 1, b, \geq 1$	Yes	20.3	$I_C > 4.9 \text{ TeV}$	$ I_{\text{cut}}  = 3$ 1504.04605	
<b>DM</b>						
Axial-vector mediator (Dirac DM)	$0, e, \mu, \tau$	$\geq 1$	Yes	3.2	$m_A > 25, m_{\nu} < 250 \text{ GeV}$	1604.07773
Axial-vector mediator (Dirac DM)	$0, e, \mu, \tau$	1, J	Yes	3.2	$m_A > 25, m_{\nu} < 150 \text{ GeV}$	1604.01306
$ZZ_{\text{eff}}$ EFT (Dirac DM)	$0, e, \mu, \tau$	$1, b, \geq 1, J$	Yes	3.2	$m_A < 300 \text{ GeV}$	ATLAS CONF 2015.090
<b>LO</b>						
Scalar $LQ^{1st}$ gen	$2, e, \mu, \tau$	$\geq 2, 1$	-	3.2	$LQ \text{ mass} > 1.1 \text{ TeV}$	$\beta = 1$ 1605.06035
Scalar $LQ^{2nd}$ gen	$2, e, \mu, \tau$	$\geq 2, 1$	-	3.2	$LQ \text{ mass} > 1.05 \text{ TeV}$	$\beta = 1$ 1605.06035
Scalar $LQ^{3rd}$ gen	$1, e, \mu, \tau$	$\geq 1, b, \geq 3$	Yes	20.3	$LQ \text{ mass} > 646 \text{ GeV}$	$\beta = 0$ 1504.0725
<b>Heavy quarks</b>						
VLO $YY \rightarrow Hg \rightarrow X$	$1, e, \mu, \tau$	$\geq 2, b, \geq 3$	Yes	20.3	$V \text{ mass} > 699 \text{ GeV}$	$\Gamma \text{ (B)} \text{ doublet}$ 1505.04396
VLO $YY \rightarrow Wg \rightarrow X$	$1, e, \mu, \tau$	$\geq 1, b, \geq 3$	Yes	20.3	$V \text{ mass} > 776 \text{ GeV}$	$\Gamma \text{ (BY)} \text{ doublet}$ 1505.04396
VLO $BB \rightarrow Hg \rightarrow X$	$1, e, \mu, \tau$	$\geq 2, b, \geq 3$	Yes	20.3	$V \text{ mass} > 726 \text{ GeV}$	isospin singlet 1505.04396
VLO $BB \rightarrow Wg \rightarrow X$	$2(S) \geq 3, e, \mu, \tau$	$\geq 2, 1, b$	Yes	20.3	$V \text{ mass} > 785 \text{ GeV}$	$\Gamma \text{ (BY)} \text{ doublet}$ 1505.04396
VLO $QQ \rightarrow Wg \rightarrow X$	$1, e, \mu, \tau$	$\geq 4$	Yes	20.3	$V \text{ mass} > 690 \text{ GeV}$	$\Gamma \text{ (BY)} \text{ doublet}$ 1505.04396
VLO $Tg \rightarrow Wg \rightarrow X$	$2(S) \geq 3, e, \mu, \tau \geq 1, b, \geq 1, J$	Yes	3.2	$V \text{ mass} > 990 \text{ GeV}$	ATLAS CONF 2016.052	
<b>Excluded fermions</b>						
Excluded quark $q' \rightarrow q\gamma$	$1, \gamma$	1	-	3.2	$q' \text{ mass} > 4.4 \text{ TeV}$	only $q' \text{ and } d', A = 0$ 1512.05010
Excluded quark $q' \rightarrow qZ$	-	2	-	15.7	$q' \text{ mass} > 5.6 \text{ TeV}$	only $q' \text{ and } d', A = 0$ ATLAS CONF 2016.069
Excluded quark $q' \rightarrow qg$	-	$1, b, 1, J$	-	8.8	$q' \text{ mass} > 2.3 \text{ TeV}$	ATLAS CONF 2016.069
Excluded quark $q' \rightarrow W\nu$	$1, e, \mu, \tau$	$1, b, 2, 0, 1$	-	20.3	$q' \text{ mass} > 1.3 \text{ TeV}$	$\beta = 1$ 1411.01001
Excluded lepton $\ell'$	$3, e, \mu, \tau$	-	-	20.3	$\ell' \text{ mass} > 3.0 \text{ TeV}$	$\beta = 1$ 1411.01001
Excluded lepton $\ell'$	$3, e, \mu, \tau$	-	-	20.3	$\ell' \text{ mass} > 1.8 \text{ TeV}$	$\beta = 1$ 1411.01001
<b>Other</b>						
LSTC $\mu\mu \rightarrow W\nu$	$1, e, \mu, \tau$	2	Yes	20.3	$W' \text{ mass} > 900 \text{ GeV}$	$m(W') = 2.4 \text{ TeV, no mixing}$ 1407.00000
LRSM Majorana $\nu$	$2, e, \mu, \tau$	2	Yes	20.3	$M \text{ mass} > 570 \text{ GeV}$	$\Delta Y \text{ production, BR}(W) \rightarrow \nu\bar{\nu} = 1$ ATLAS CONF 2016.061
Higgs triplet $H^{\pm} \rightarrow ee$	$2, e$ (SS)	-	-	13.9	$H^{\pm} \text{ mass} > 806 \text{ GeV}$	$\Delta Y \text{ production, BR}(H^{\pm}) \rightarrow \nu\bar{\nu} = 1$ 1411.01001
Higgs triplet $H^{\pm} \rightarrow \ell\nu$	$3, e, \mu, \tau$	-	-	20.3	$H^{\pm} \text{ mass} > 697 \text{ GeV}$	$A_{\text{mix}} = 0.2$ 1410.0404
Monopole (non-res prod)	$1, e, \mu, \tau$	1, b	Yes	20.3	$M \text{ mass} > 785 \text{ GeV}$	$\Delta Y \text{ production}$ 1504.04186
Multi-charged particles	-	-	-	7.0	$M \text{ mass} > 1.34 \text{ TeV}$	$\Delta Y \text{ production}$ 1509.06059
Magnetic monopoles	-	-	-	7.0	$M \text{ mass} > 1.34 \text{ TeV}$	$\Delta Y \text{ production}$ 1509.06059

\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly stated.  
†Small-radius (large-radius) jets are denoted by the letter (L) (J).

No New Physics Yet!



ATLAS exotic

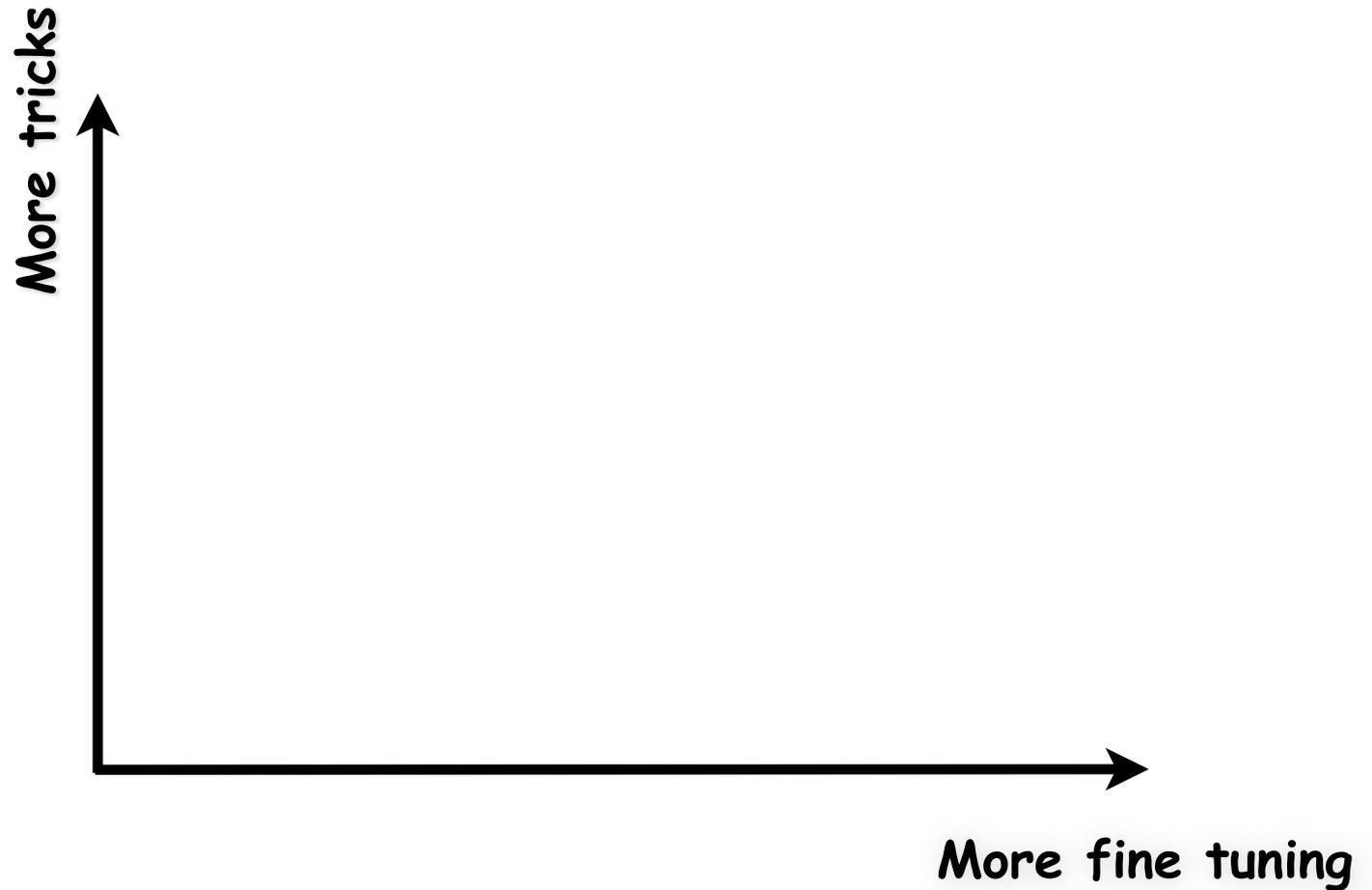
# Where Are We Now?

---

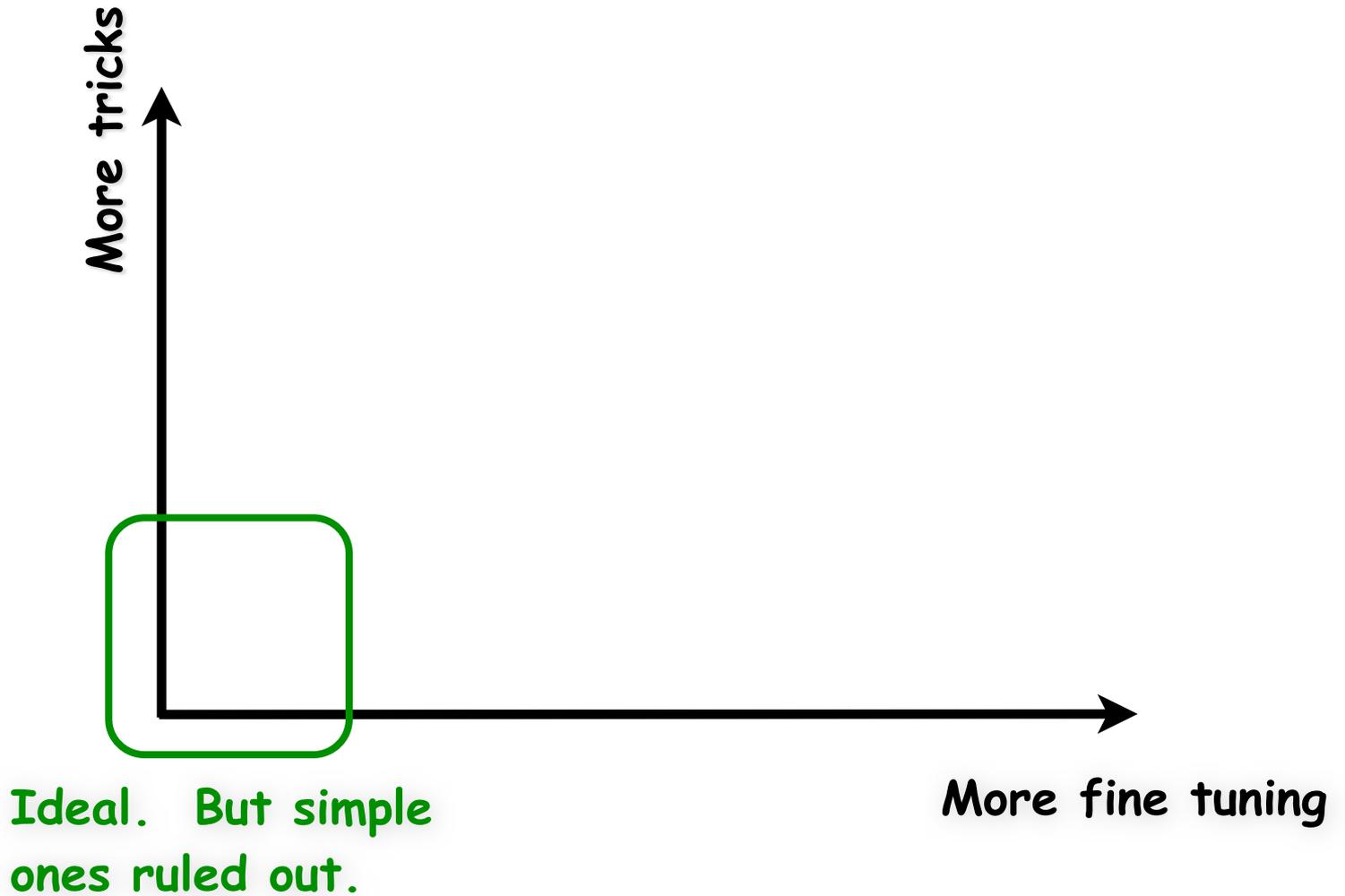
- ◎ Our wish list has not change much from 10 years ago.
- ◎ Discovery of Higgs
  - ➔ Exclude technicolor
  - ➔ Narrow down parameter space
- ◎ Non-discovery of anything else
  - ➔ New physics gets heavier
  - ➔ A bit uncomfortable, big picture unchanged

# What Do Theorists Say?

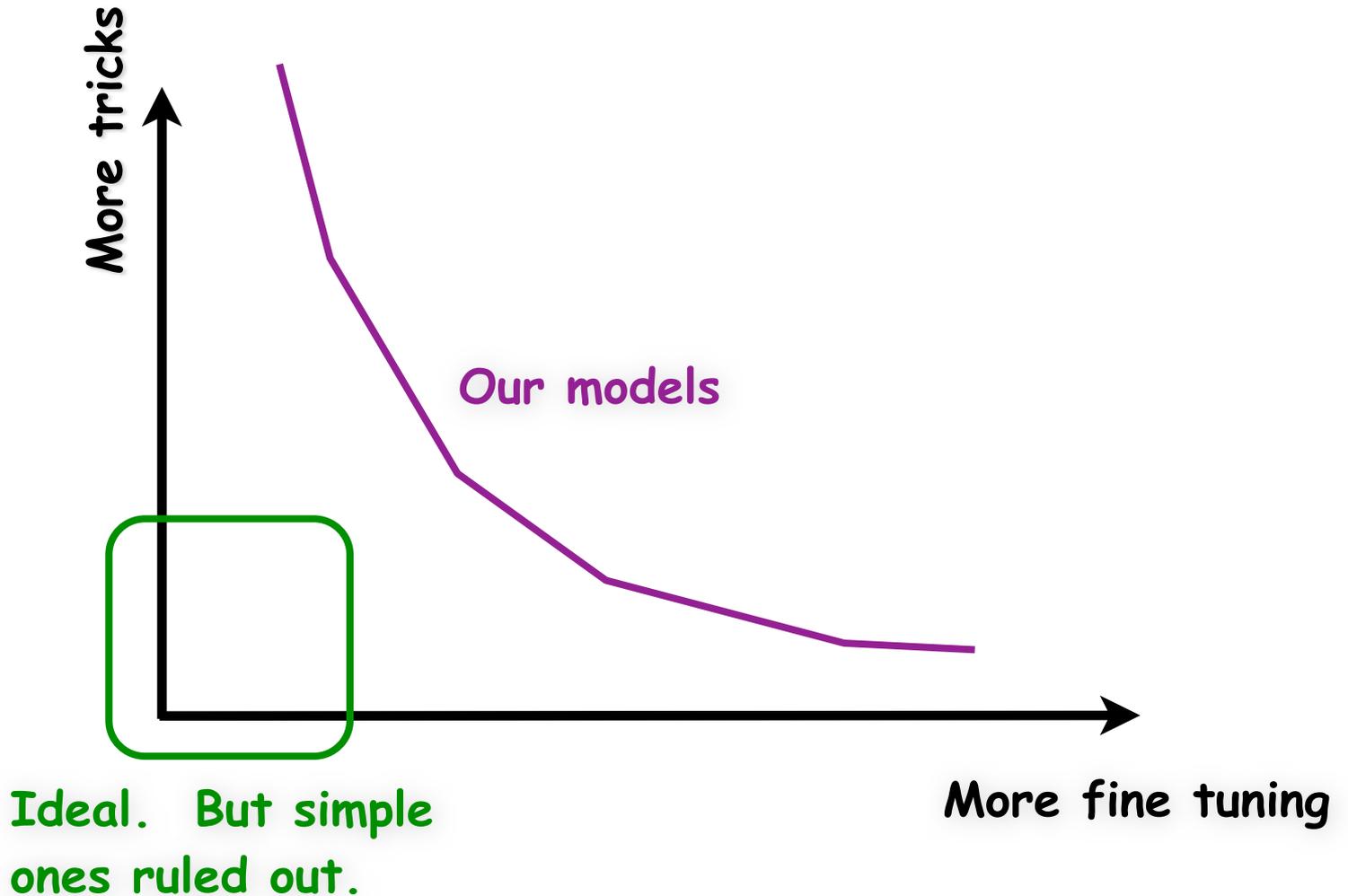
---



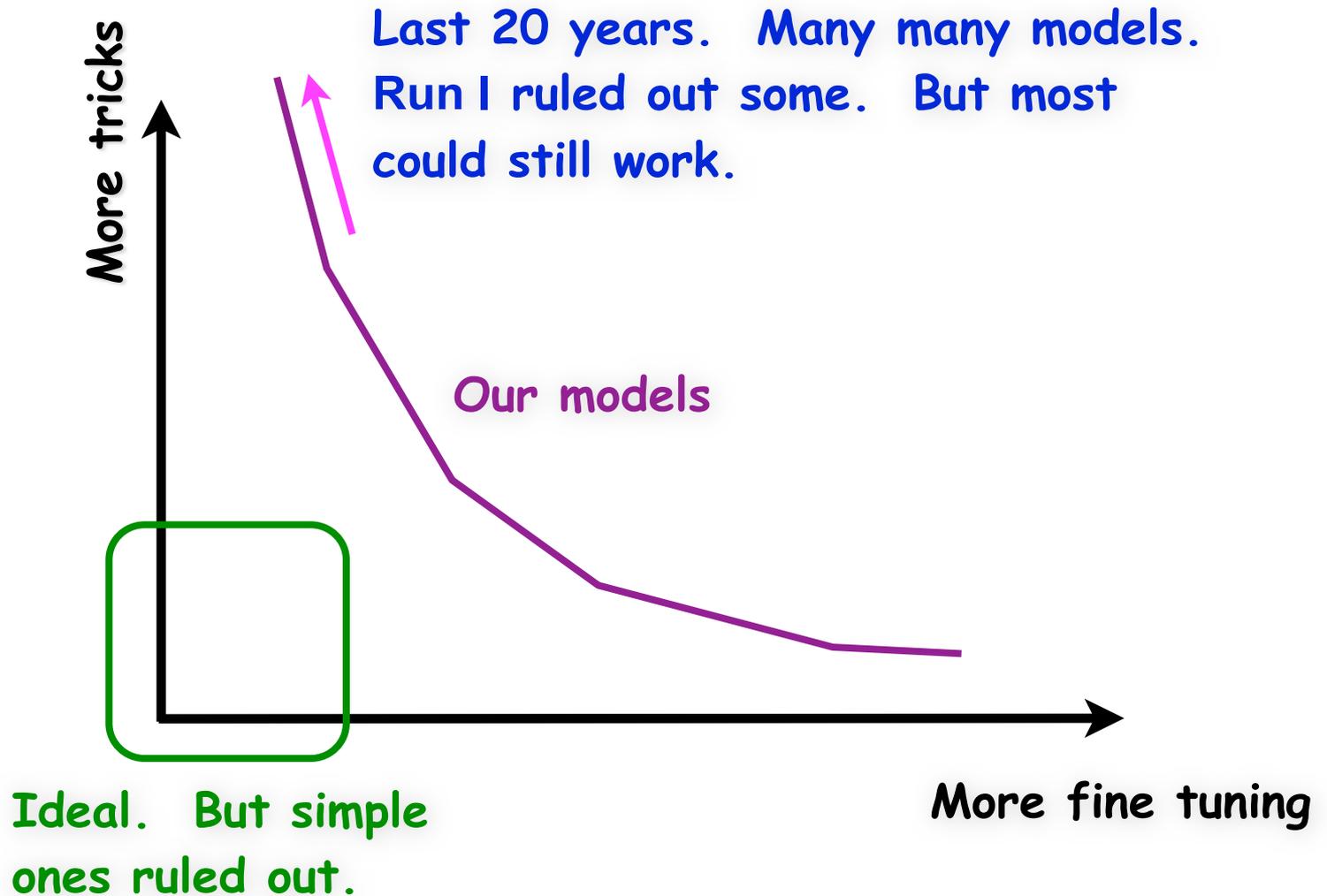
# What Do Theorists Say?



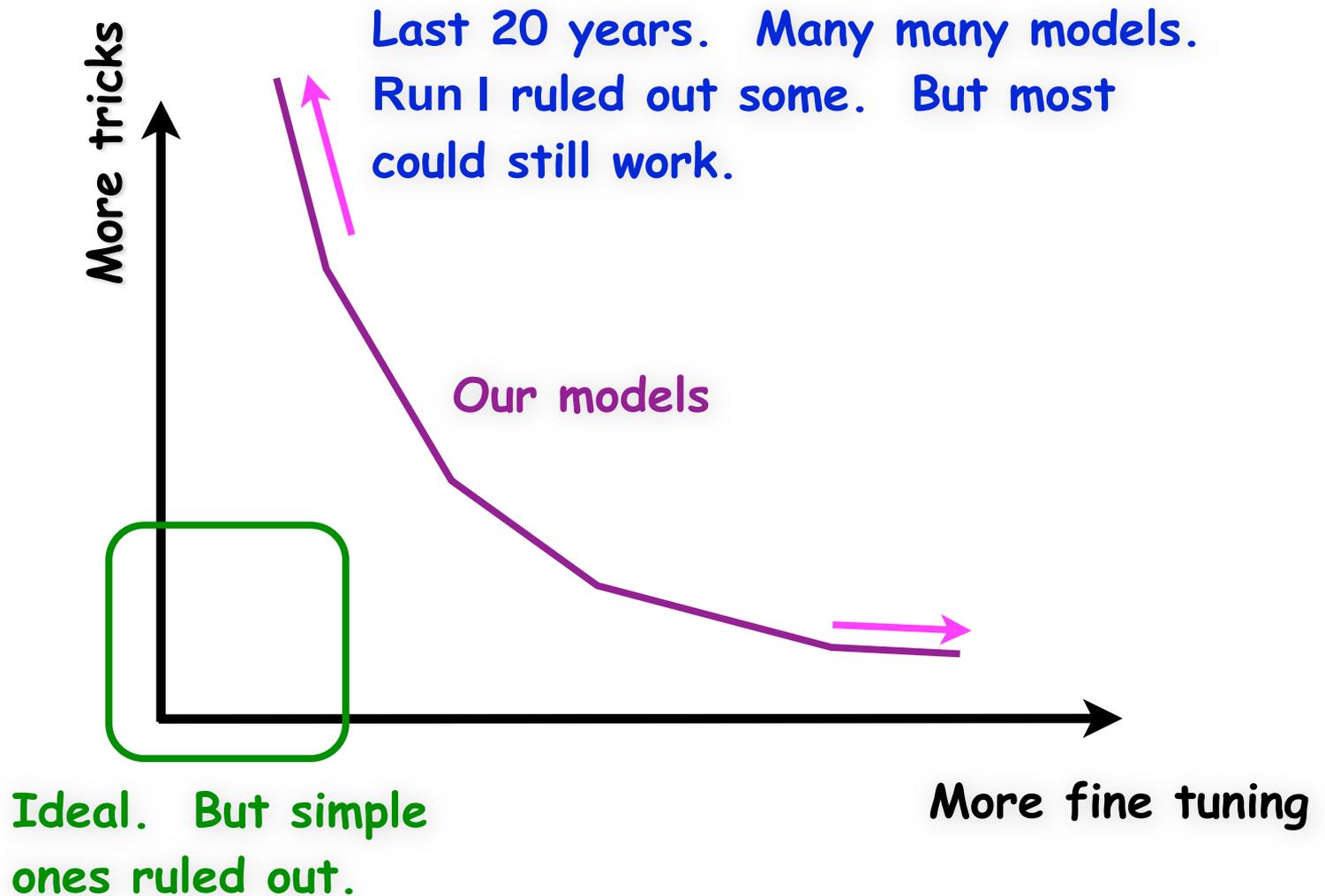
# What Do Theorists Say?



# What Do Theorists Say?



# What Do Theorists Say?



# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

⦿ Indirect search

**e<sup>+</sup>e<sup>-</sup>**

⦿ direct search

**pp**

# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

**e<sup>+</sup>e<sup>-</sup>**

● direct search

**pp**



# Current and Future Colliders

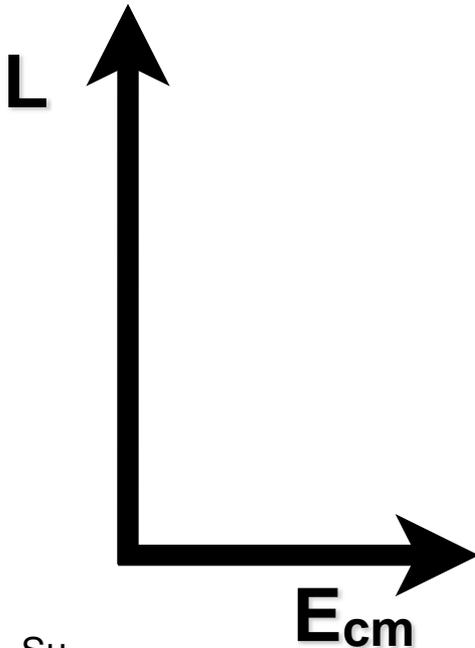
Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

**e+e-**

● direct search

**pp**



# Current and Future Colliders

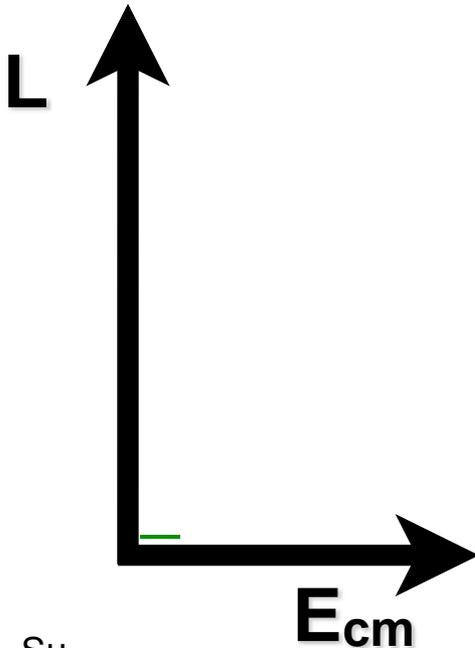
Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

**e+e-**

● direct search

**pp**



# Current and Future Colliders

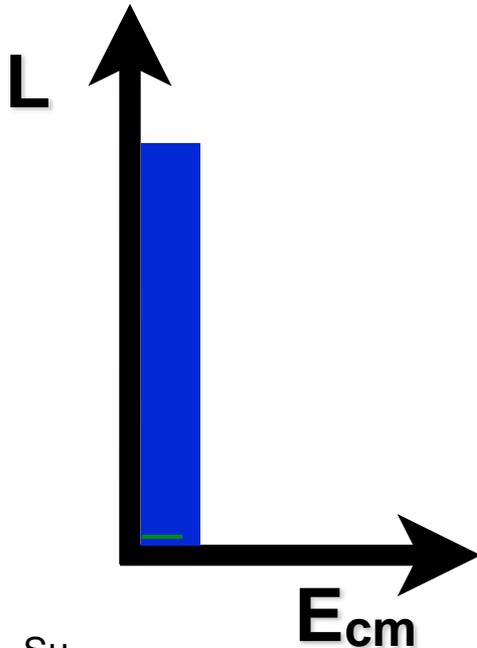
Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

**e+e-**

● direct search

**pp**



# Current and Future Colliders

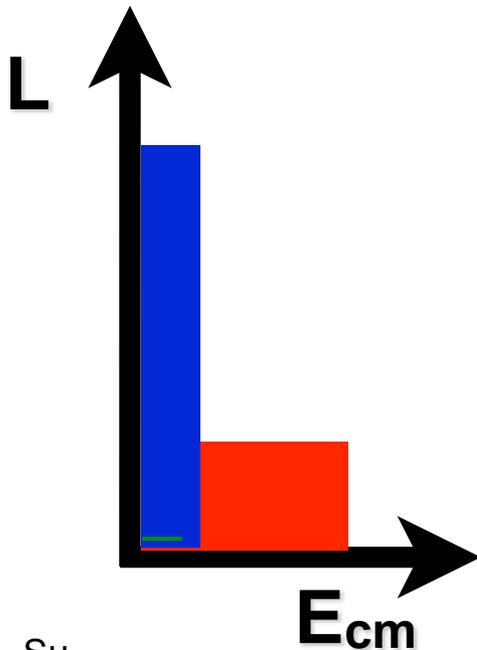
Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

**e+e-**

● direct search

**pp**



# Current and Future Colliders

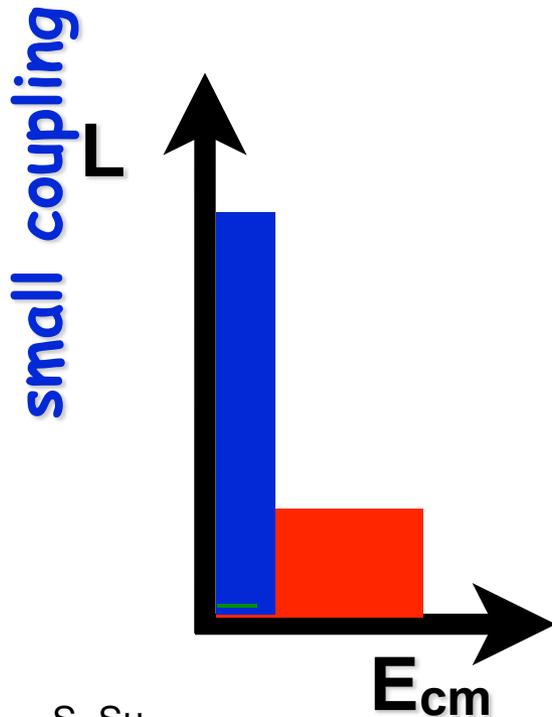
Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

● direct search

**e+e-**

**pp**



# Current and Future Colliders

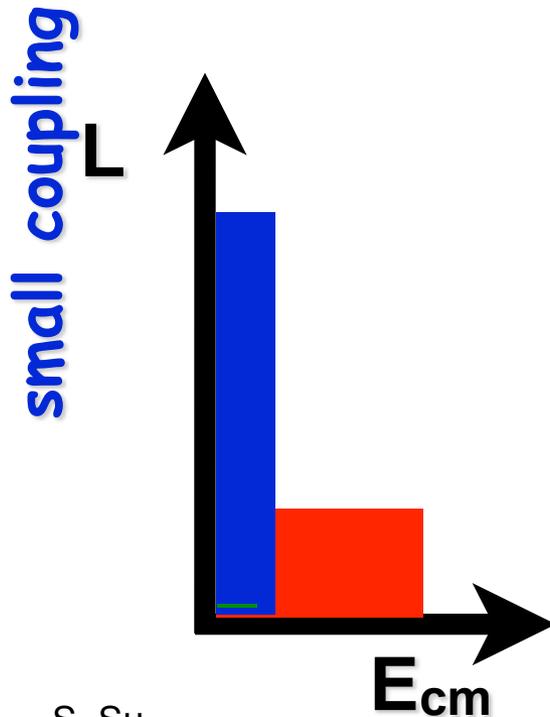
Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

e<sup>+</sup>e<sup>-</sup>

● direct search

pp

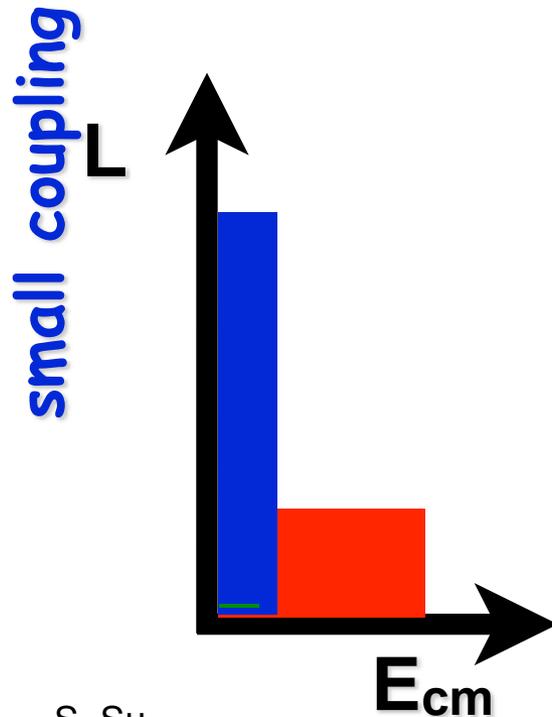


# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

● Indirect search

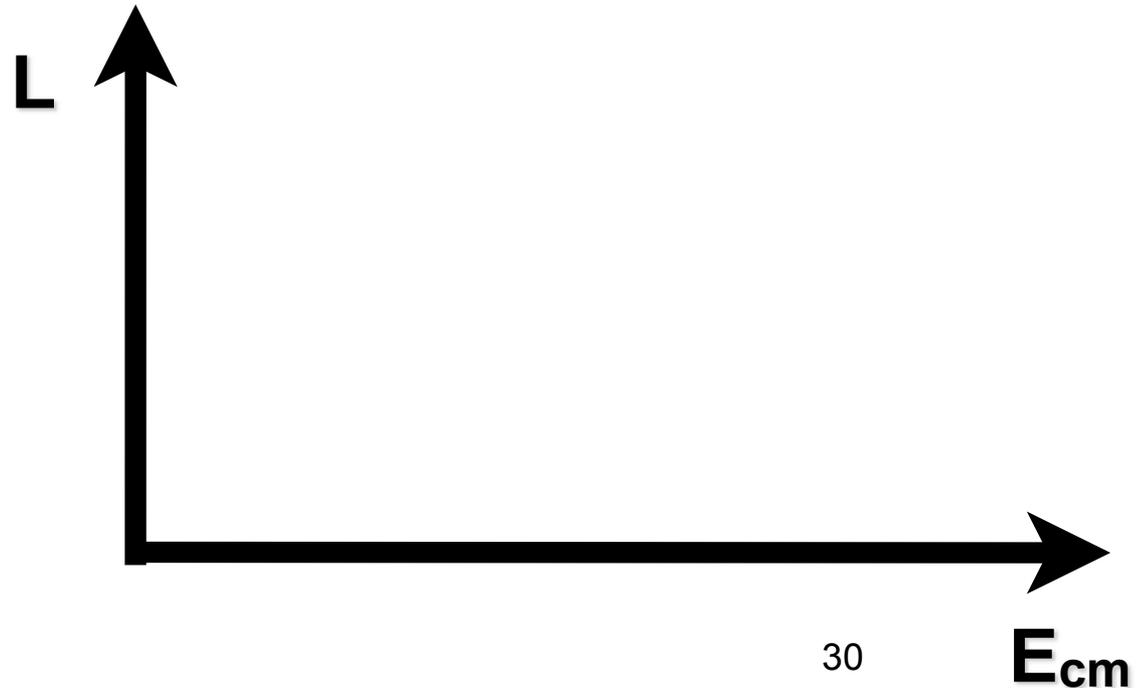
**e+e-**



S. Su

● direct search

**pp**



30

$E_{cm}$

# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

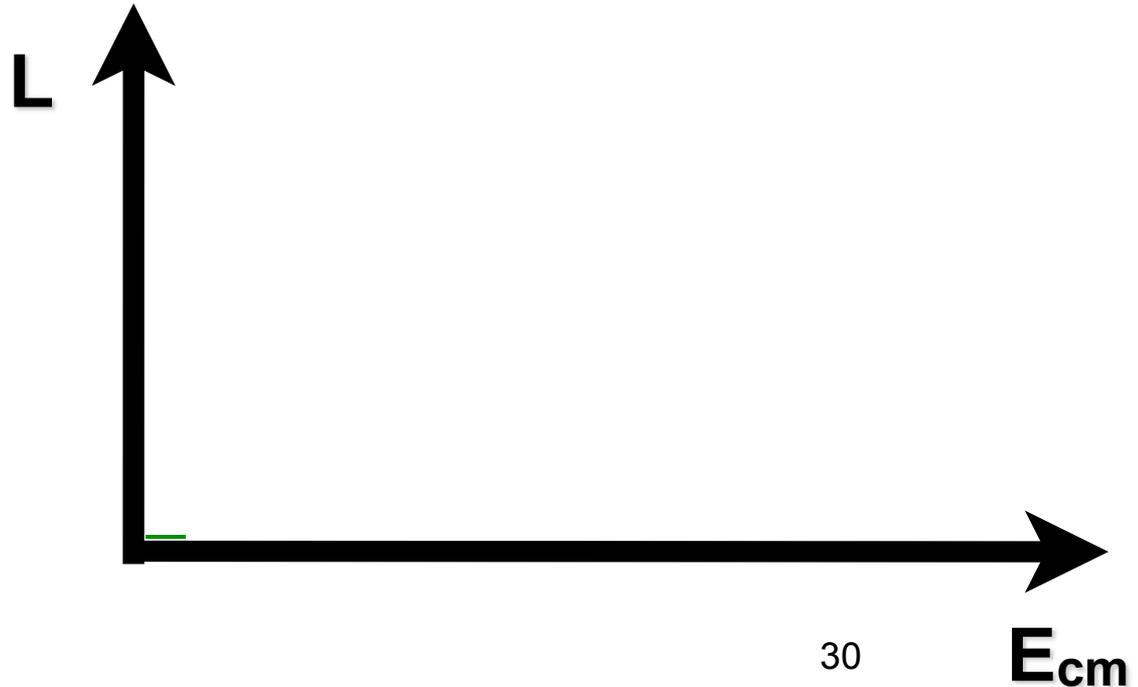
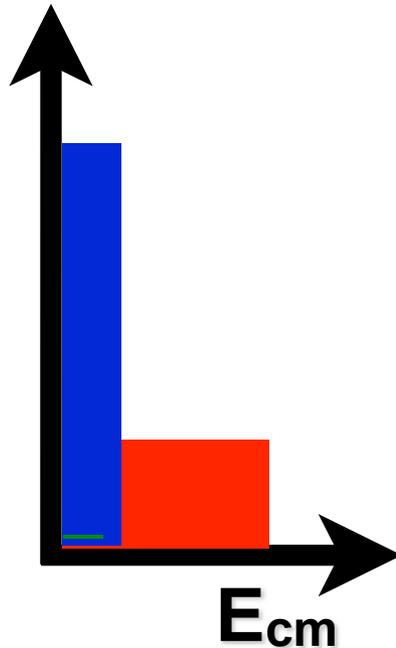
● Indirect search

● direct search

**e+e-**

**pp**

small coupling

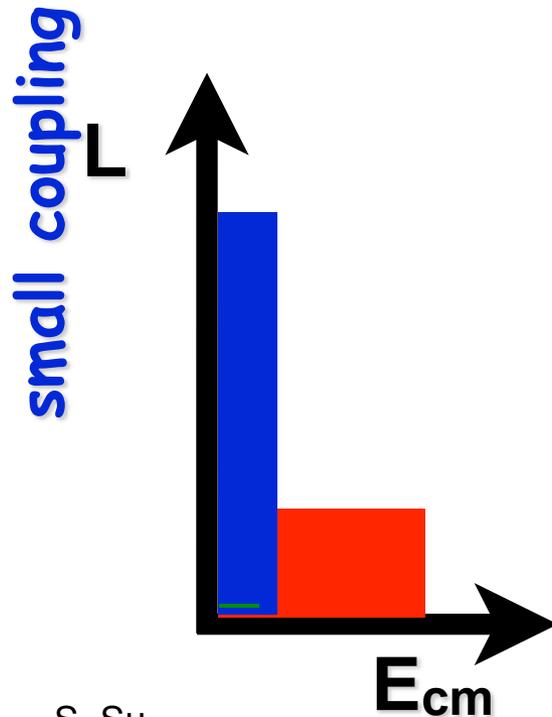


# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

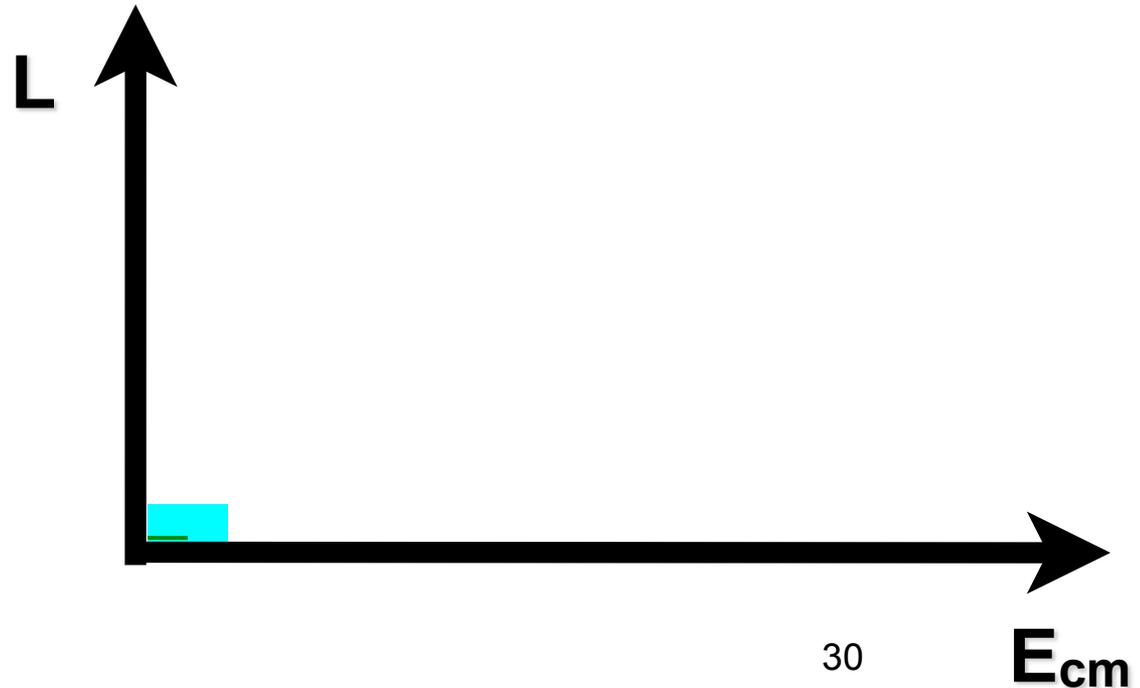
● Indirect search

**e+e-**



● direct search

**pp**



# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

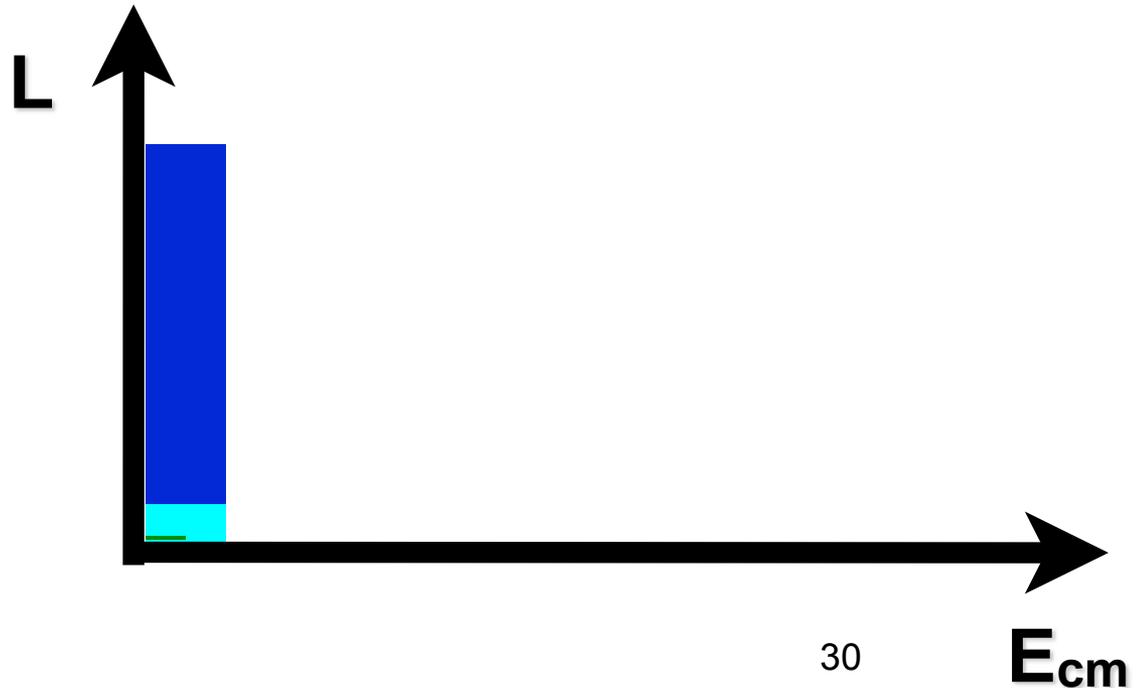
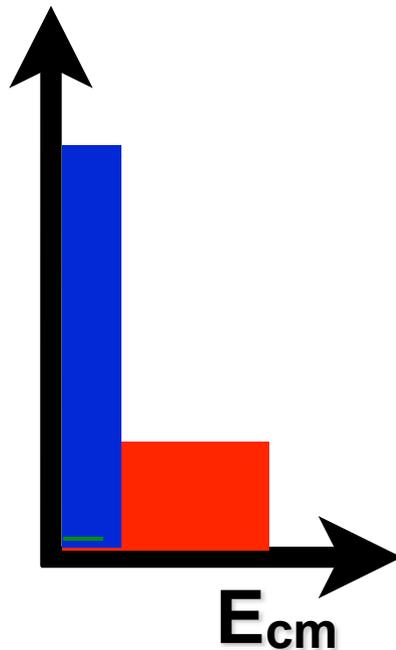
● Indirect search

● direct search

**e+e-**

**pp**

small coupling



# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

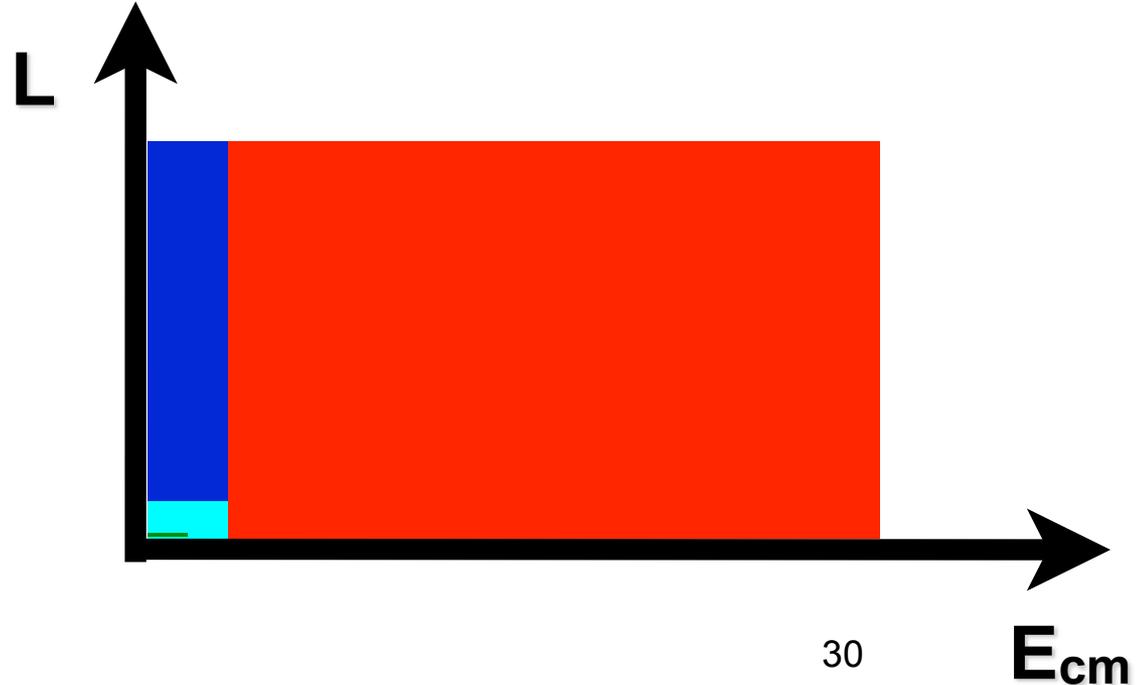
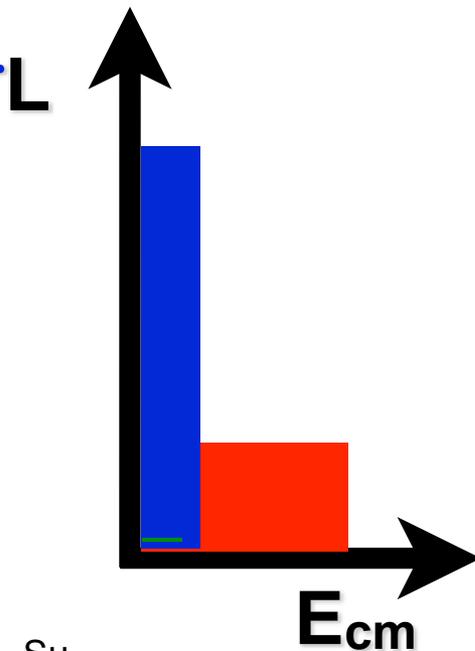
● Indirect search

● direct search

**e+e-**

**pp**

small coupling



# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

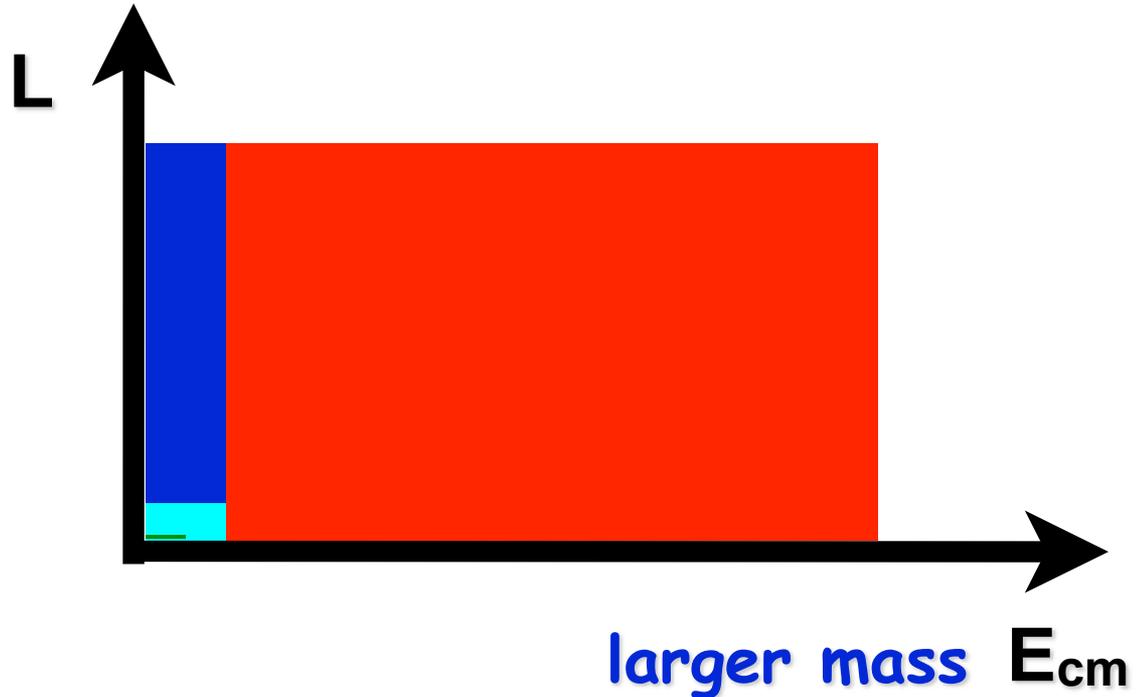
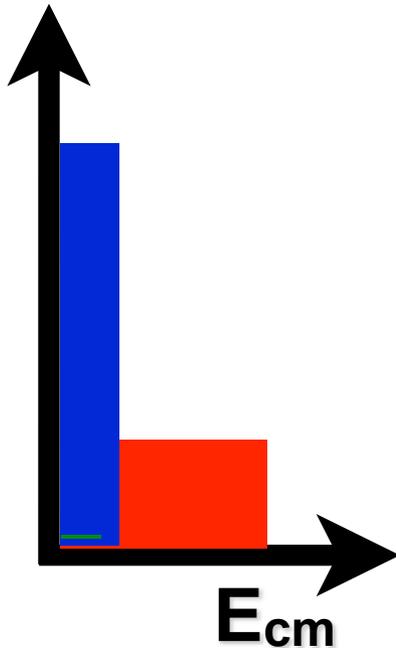
● Indirect search

● direct search

**e+e-**

**pp**

small coupling



# Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

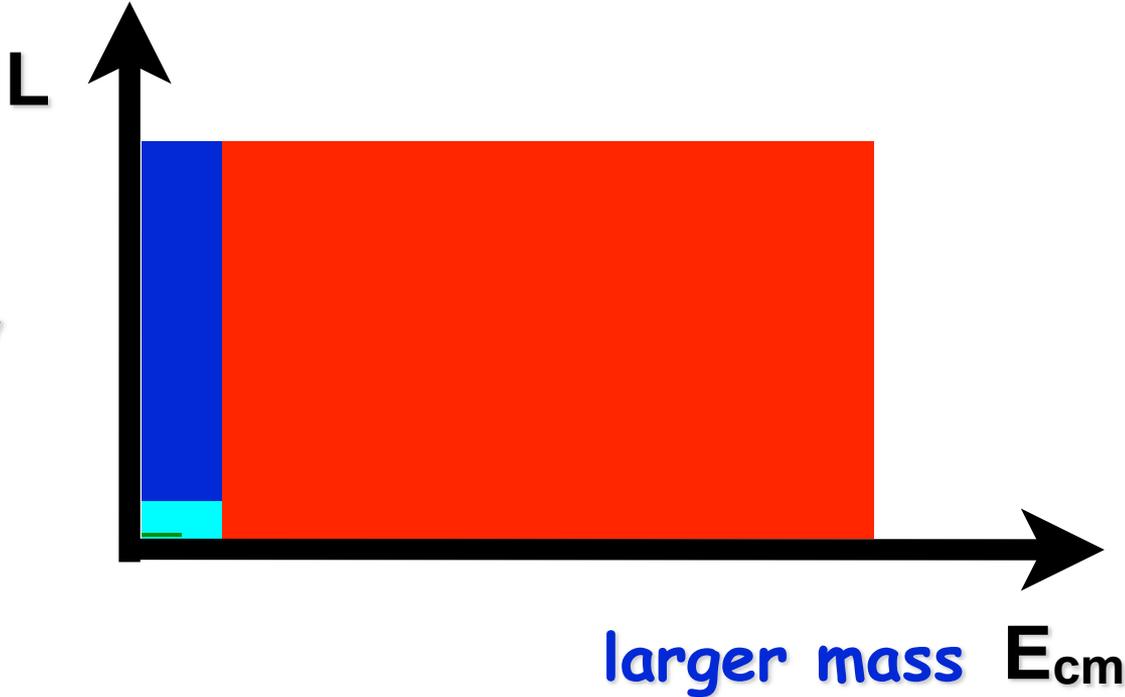
● Indirect search

● direct search

**e+e-**

**pp**

small coupling



# How to Make a Higgs Factory?

# LHC



- ◎ pp collider, 27 km

- ◎ 7 TeV beam  
0.999999999 c

- ◎ stored energy:  
~ Giga Joule

# LHC



- ⦿ **stored energy:**  
**~ Giga Joule**

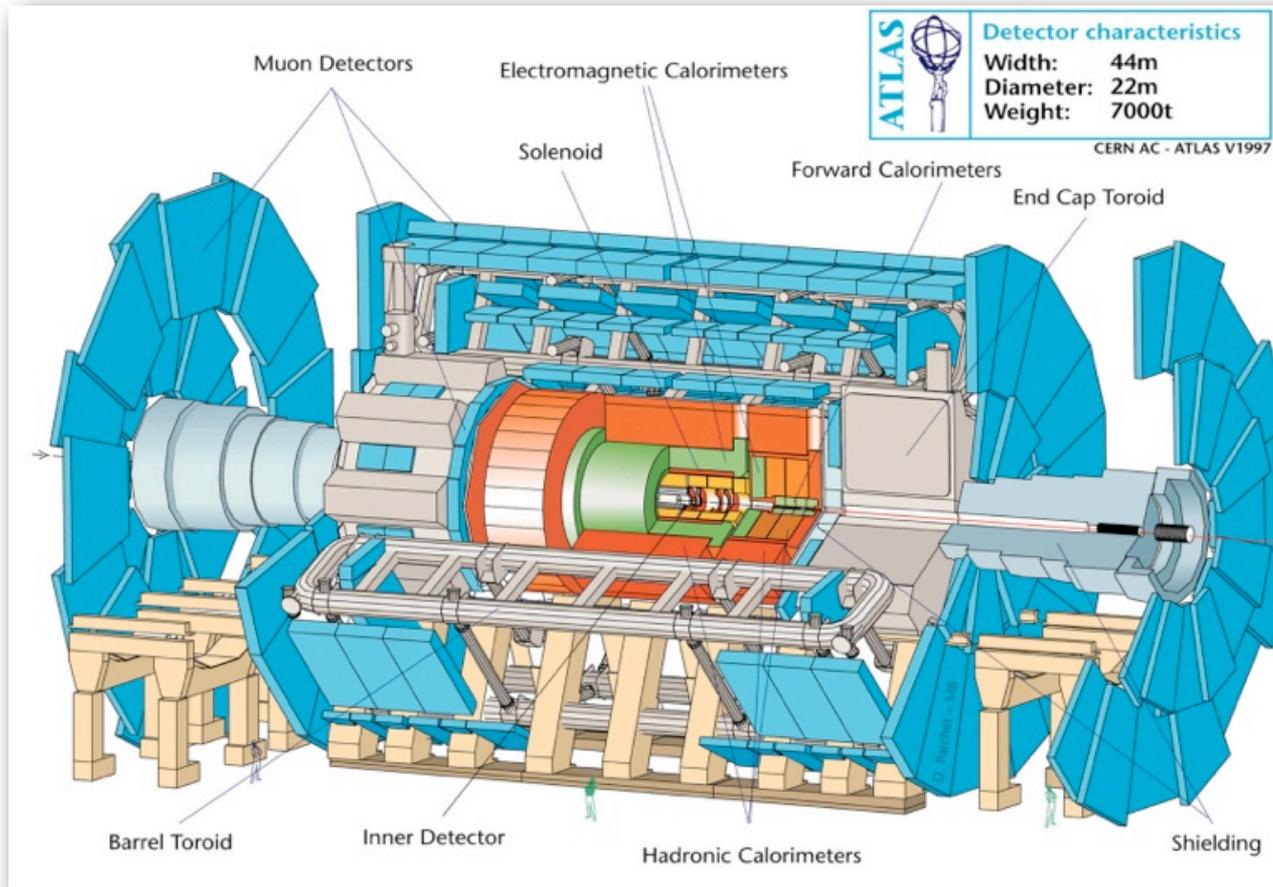
# LHC



- ⦿ **stored energy:**  
**~ Giga Joule**

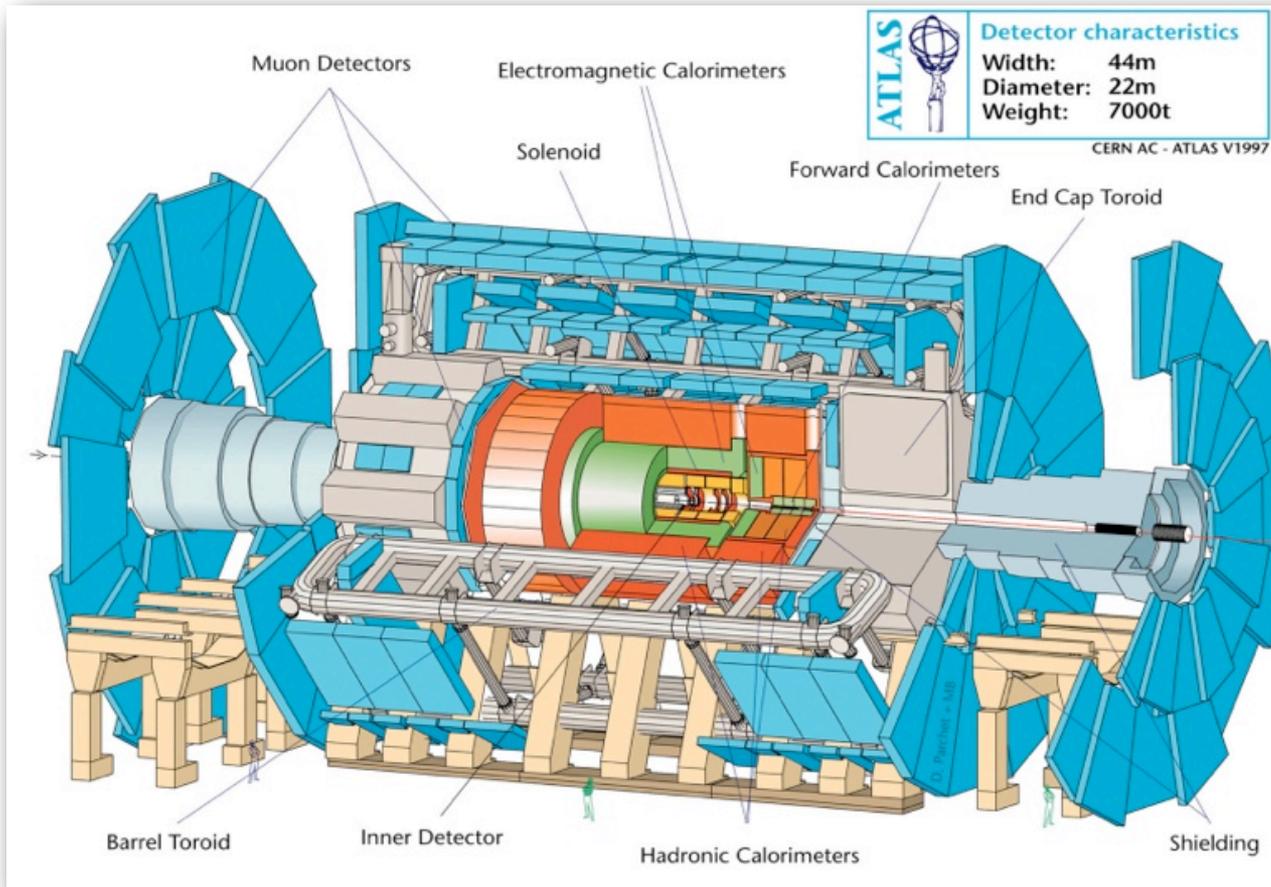
**Highest energy, probing smallest distance ( $10^{-10}$  nm)**

# Particle Detector



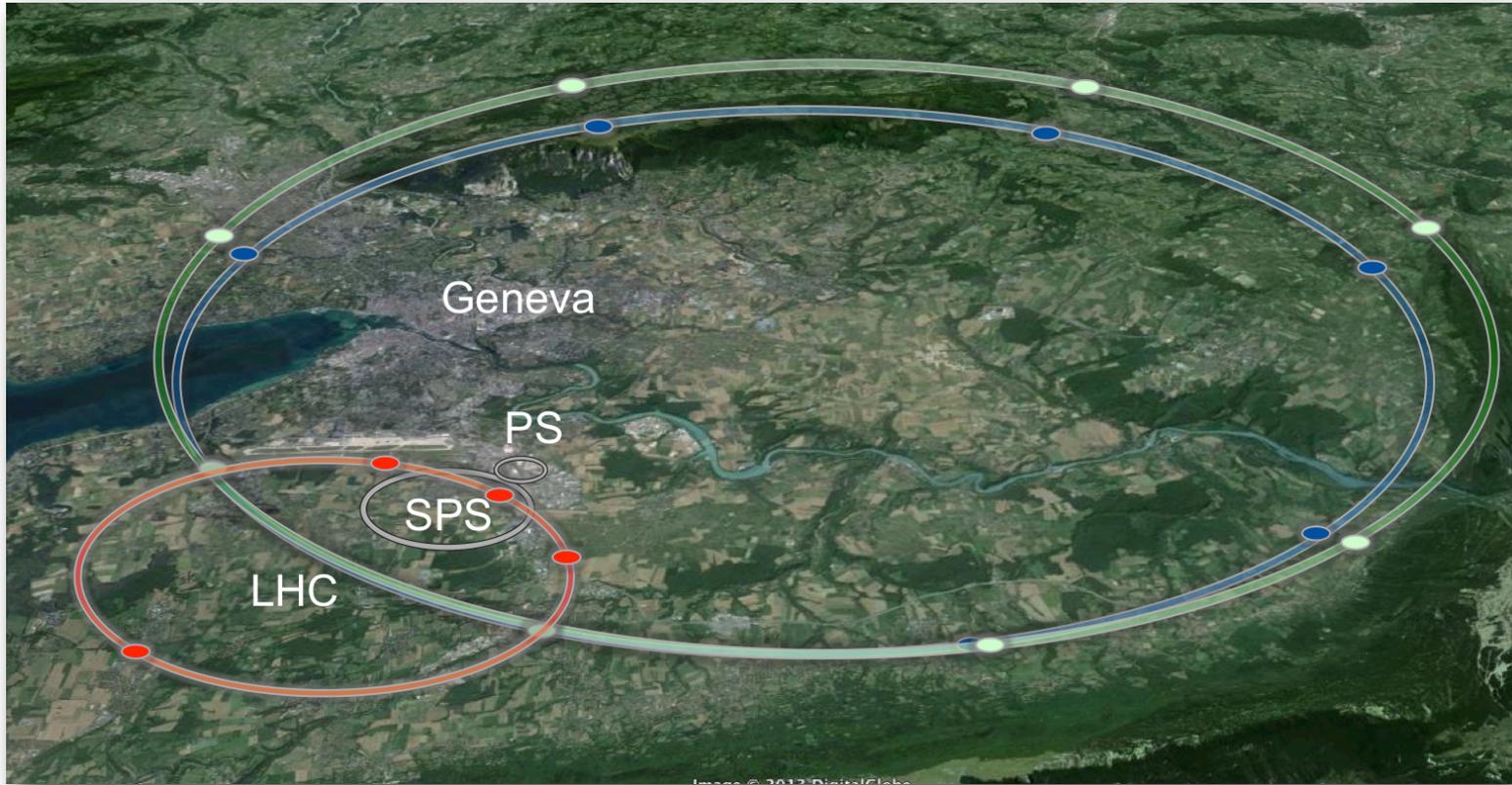
- 150 MP
- 600 million snapshots / second

# Particle Detector



- 150 MP
- 600 million snapshots / second
- 7000 scientists
- \$10 billion

# FCC



**HE-LHC**  
**27 km, 20T**  
**33 TeV**

**FCC-ee**  
**80/100 km**  
**90 - 400 GeV**

**FCC-hh**  
**80 /100 km, 16/20T**  
**100 TeV**



# CEPC-SPPC

IHEP-CEPC-DR-2018-02

IHEP-EP-2018-01

IHEP-TH-2018-01

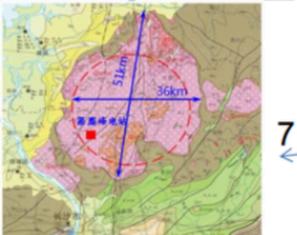
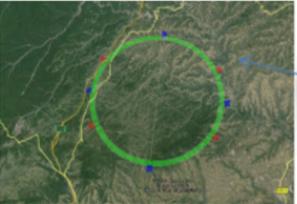
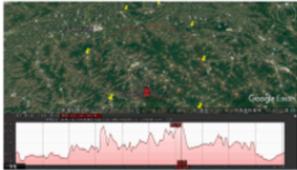
## CEPC

### *Conceptual Design Report*

Volume II - Physics & Detector

The CEPC Study Group

October 2018



- 1) Qinhuangdao, Hebei Province
- 2) Huangling, Shanxi Province
- 3) Shenshan, Guangdong Province
- 4) Baoding (Xiongan), Hebei Province
- 5) Huzhou, Zhejiang Province
- 6) Chuangchun, Jilin Province
- 7) Changsha, Hunan Province

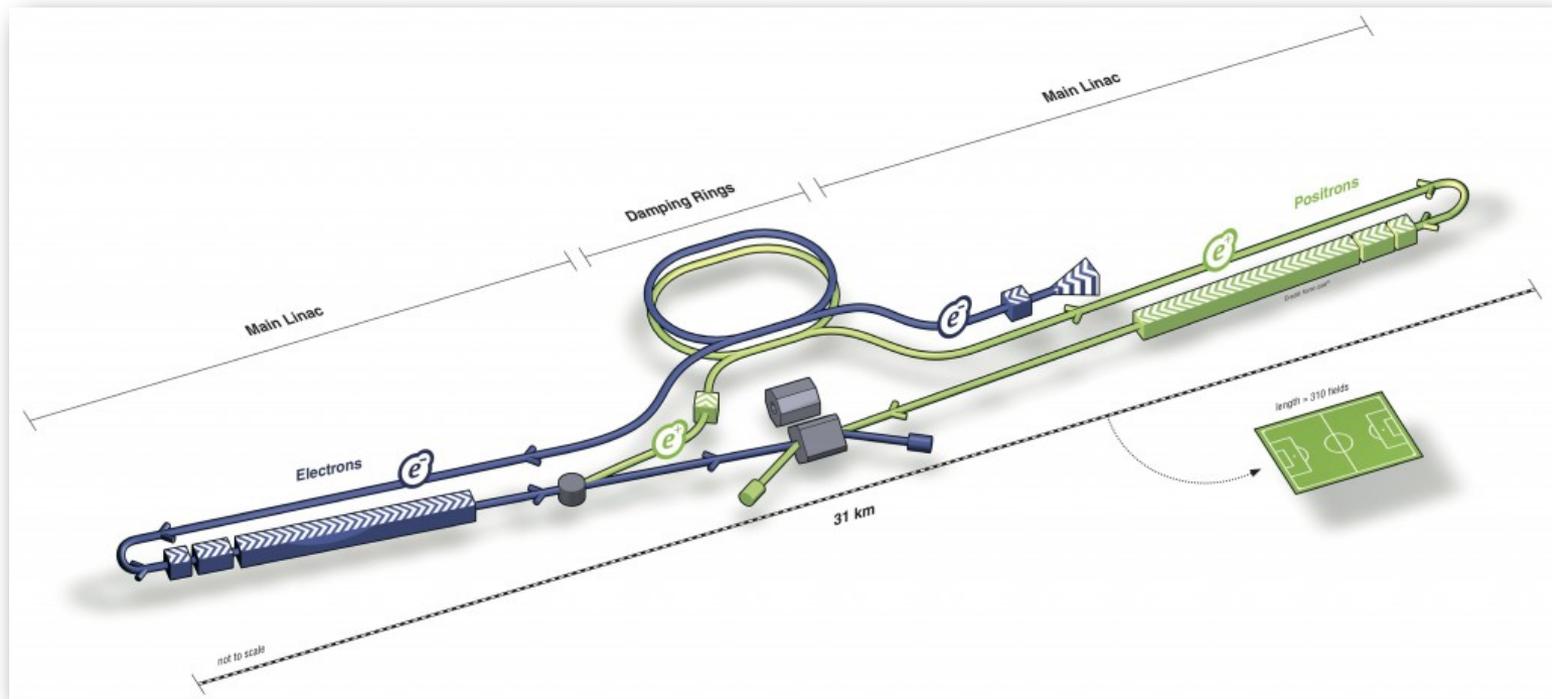
**CEPC**

**e+e-: 240 GeV**

**SPPC**

**pp: 70-100 TeV**

# ILC

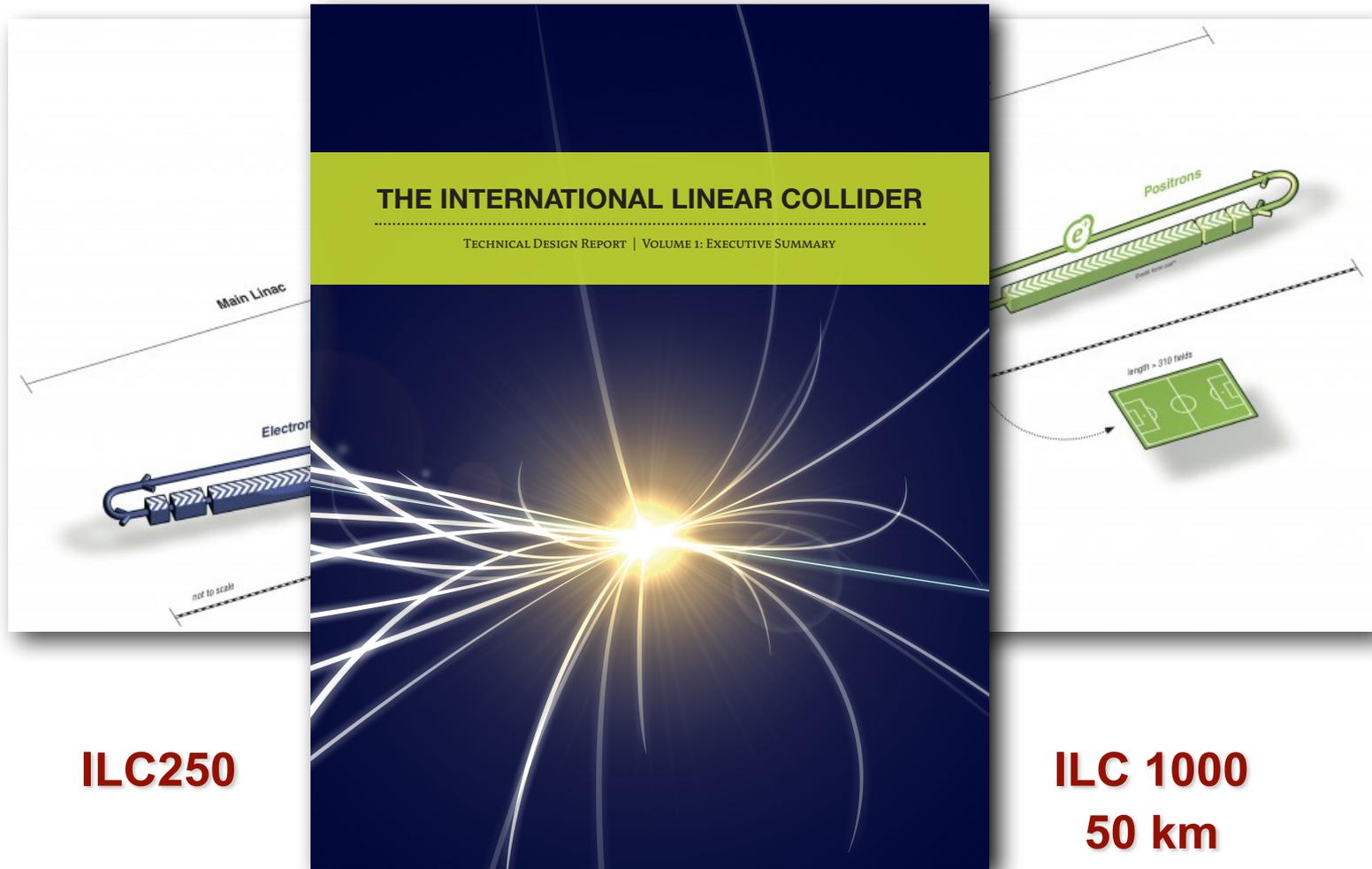


**ILC250**

**ILC 500**  
**31 km**

**ILC 1000**  
**50 km**

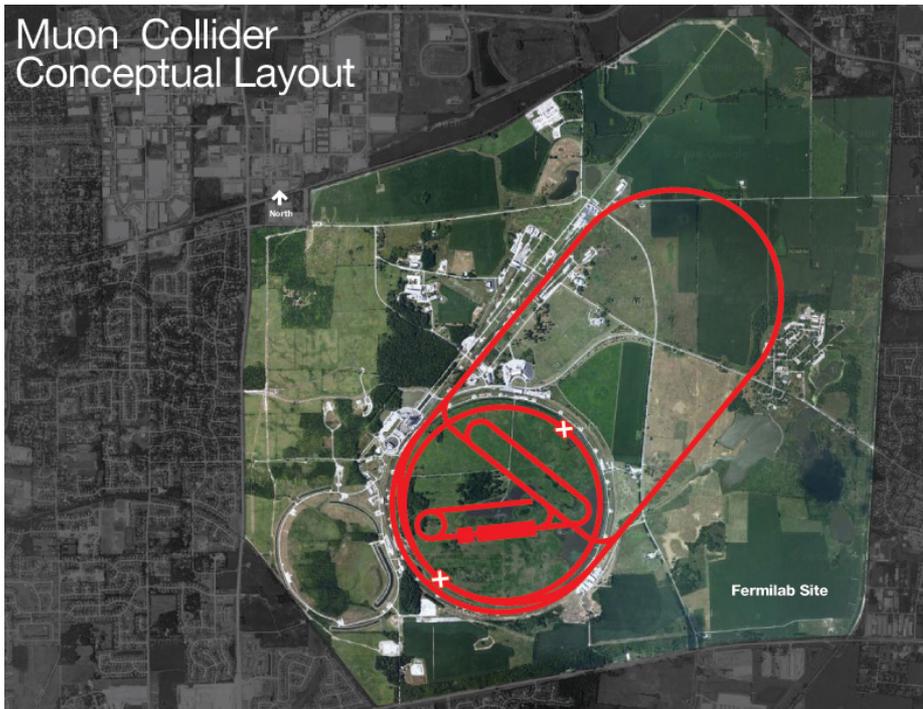
# ILC



**ILC250**

**ILC 1000  
50 km**

# Muon Collider



$$m_{\mu} \sim 200 m_e$$

- ⦿ unique combination of higher energy and clean environment
- ⦿ smaller ring

# How to make a Higgs

---

**$e^+e^-$  collider**

**$\mu^+\mu^-$  collider**

# How to make a Higgs

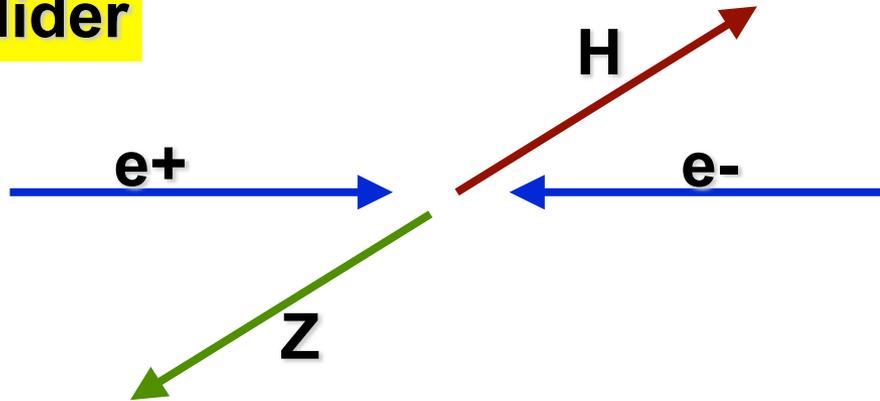
**$e^+e^-$  collider**



**$\mu^+\mu^-$  collider**

# How to make a Higgs

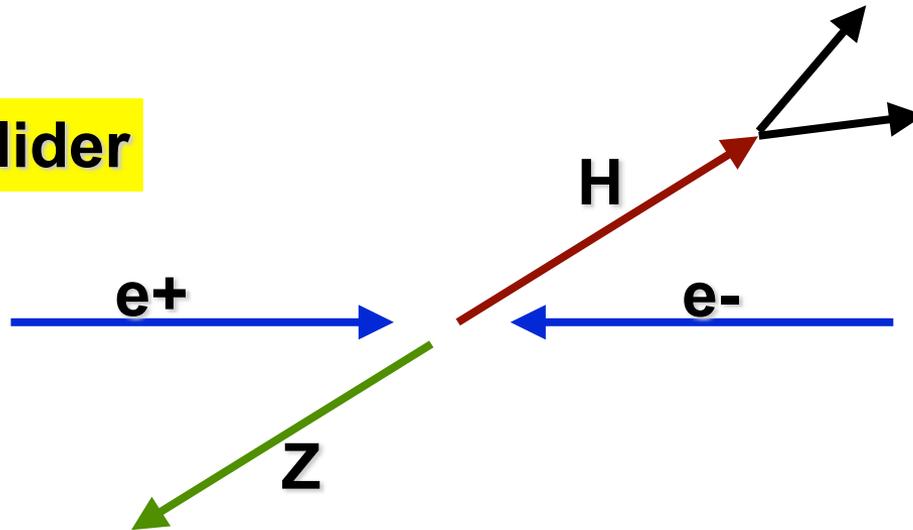
**$e^+e^-$  collider**



**$\mu^+\mu^-$  collider**

# How to make a Higgs

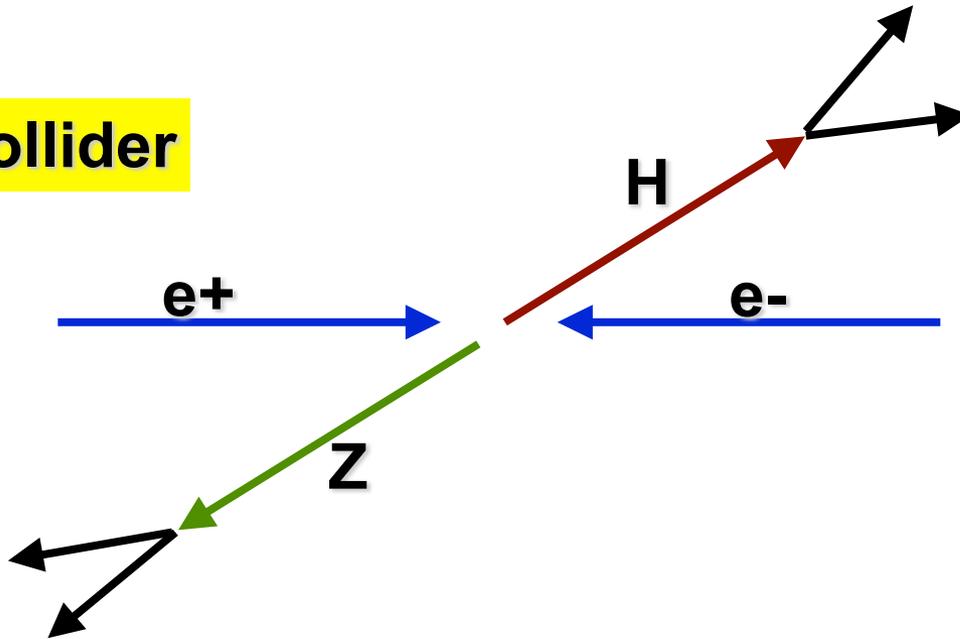
**$e^+e^-$  collider**



**$\mu^+\mu^-$  collider**

# How to make a Higgs

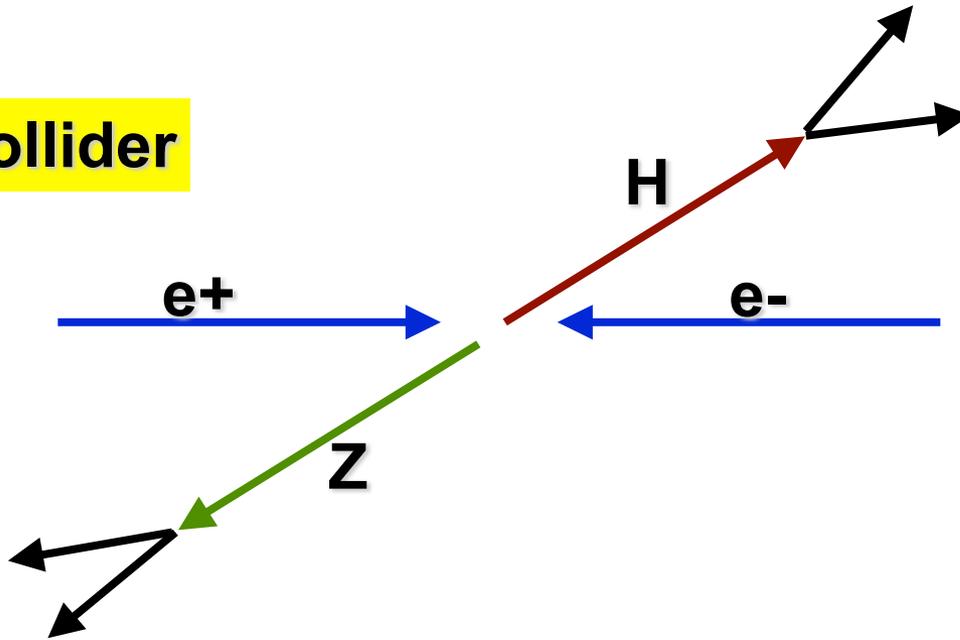
**$e^+e^-$  collider**



**$\mu^+\mu^-$  collider**

# How to make a Higgs

**$e^+e^-$  collider**

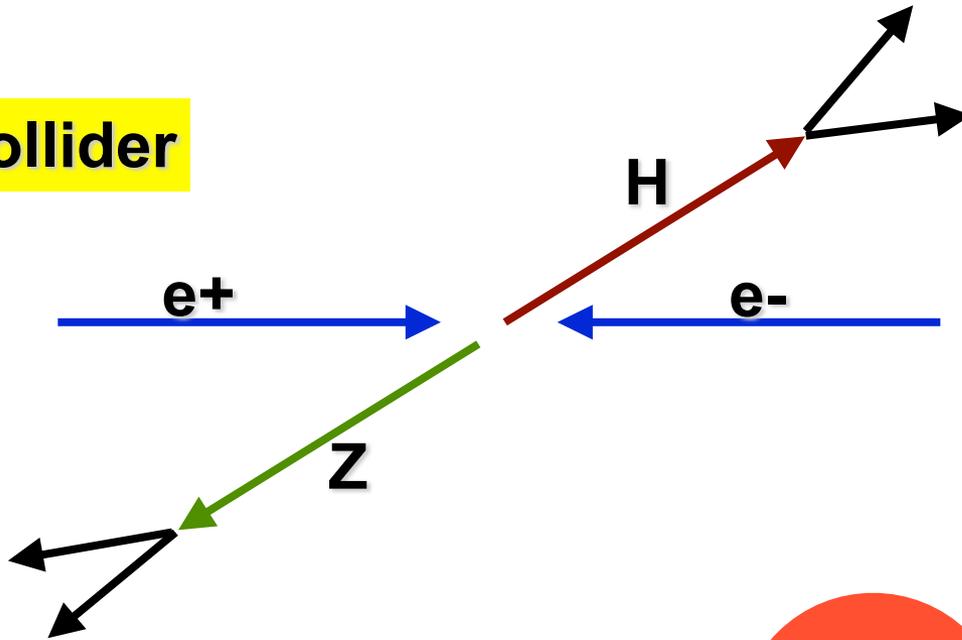


**$\mu^+\mu^-$  collider**

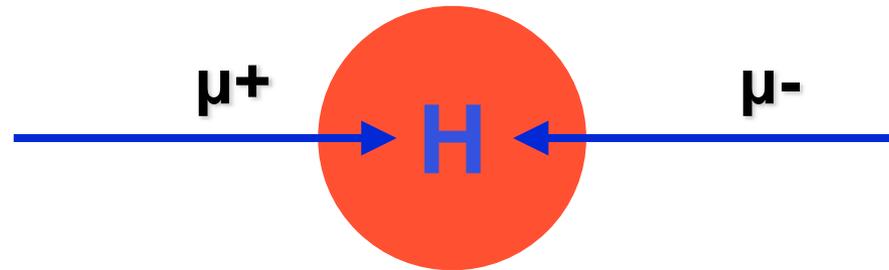


# How to make a Higgs

**$e^+e^-$  collider**

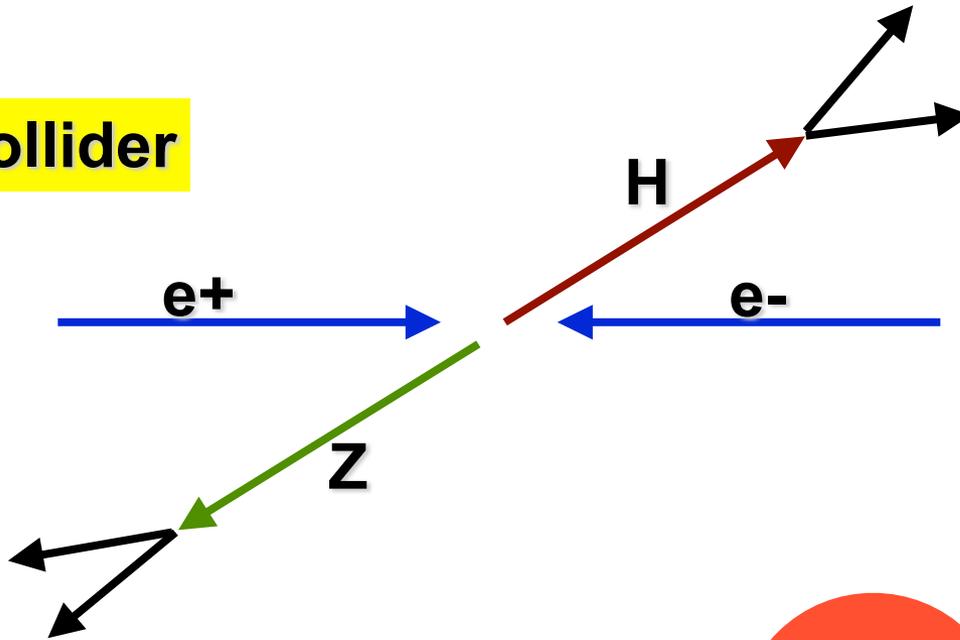


**$\mu^+\mu^-$  collider**

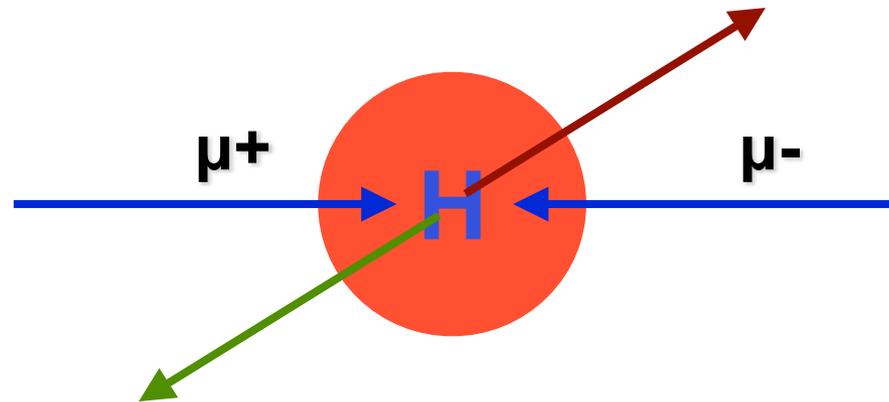


# How to make a Higgs

**$e^+e^-$  collider**



**$\mu^+\mu^-$  collider**

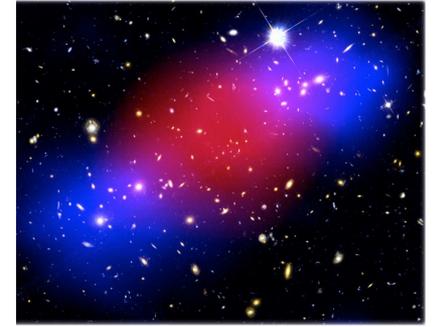


# What we can learn with a Higgs Factory?

◎ SM physics

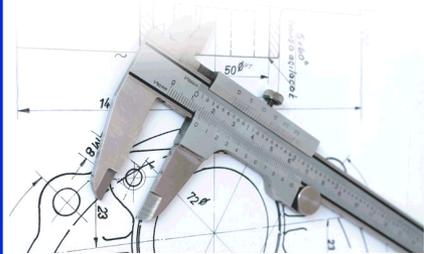


◎ dark matter

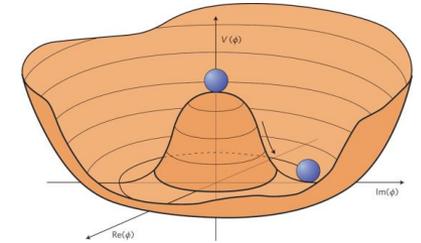


Higgs  
Factory

◎ precision  
tests



◎ Cosmo  
connection



◎ Higgs-related



◎ other BSM



◎ SM physics

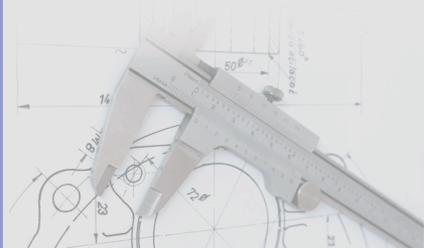


◎ dark matter

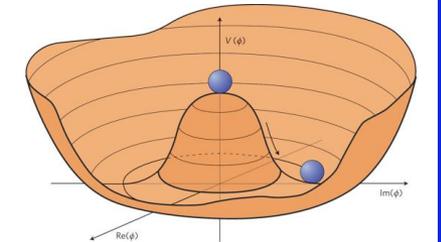


# Higgs Factory

◎ precision tests



◎ Cosmo connection



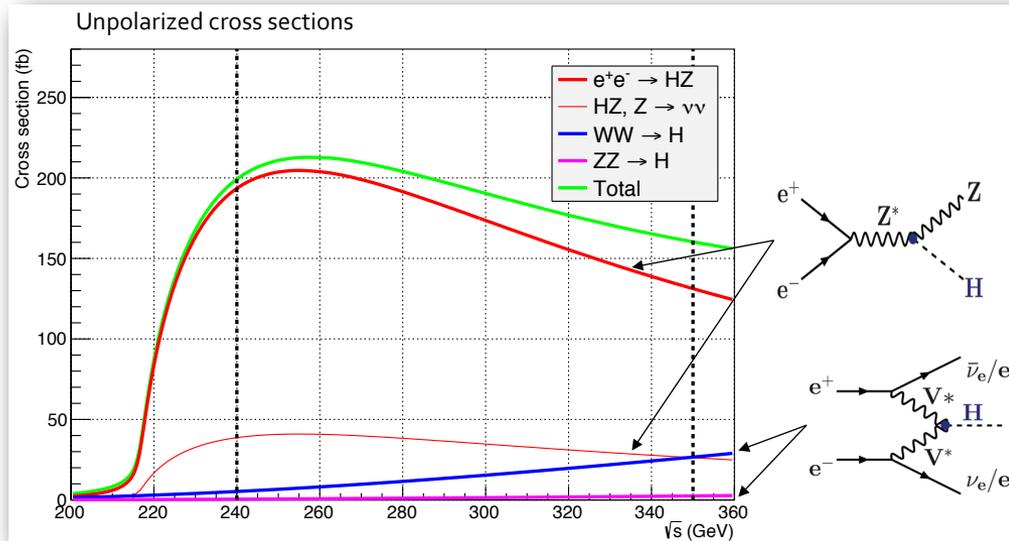
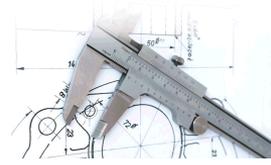
◎ Higgs-related



◎ other BSM



# Higgs Production @ e+e-

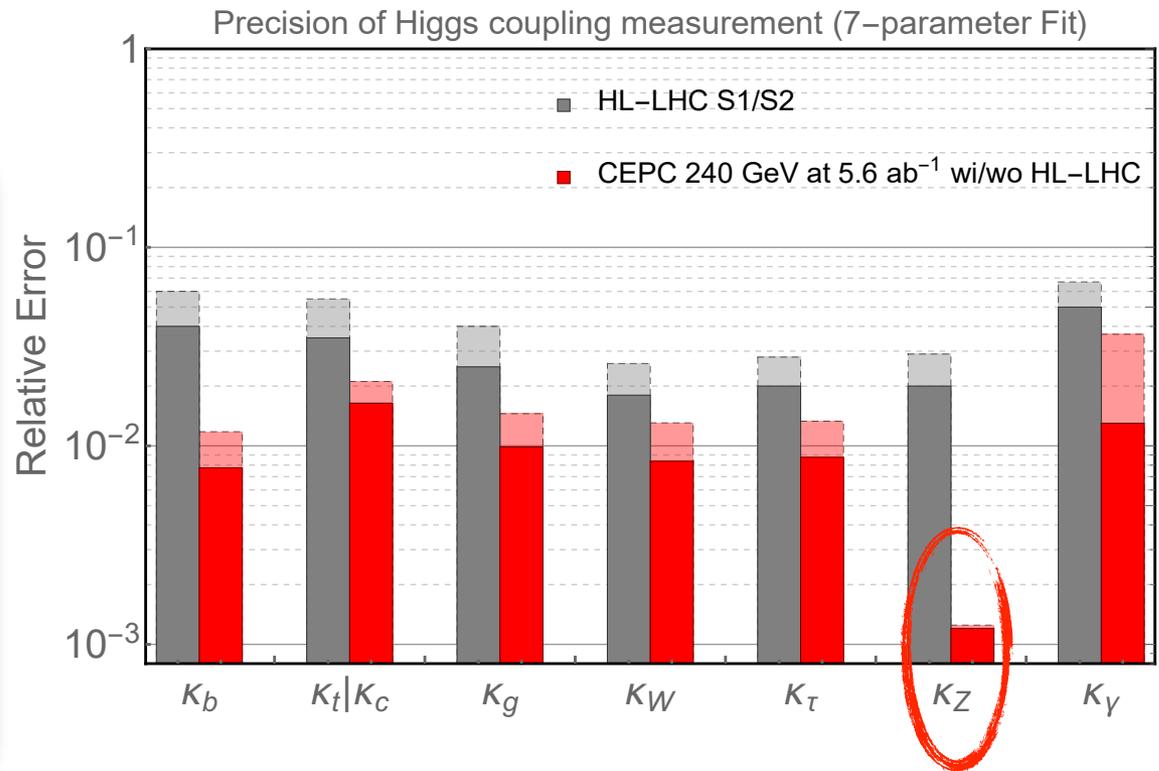
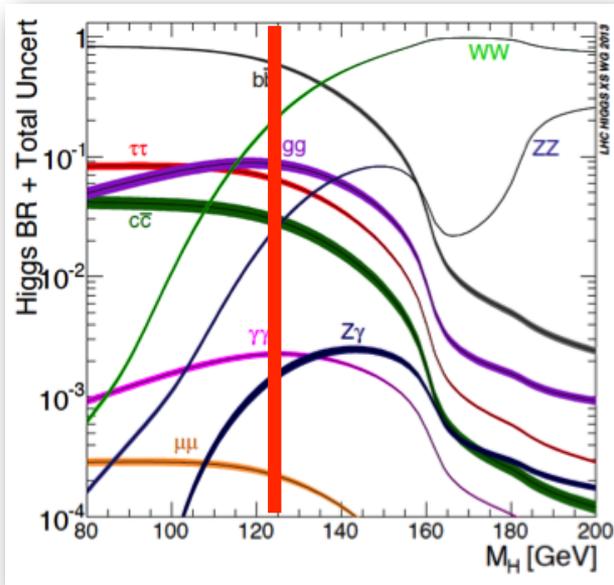
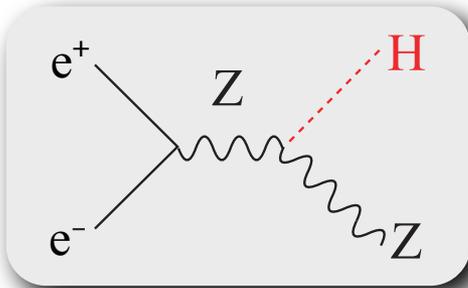
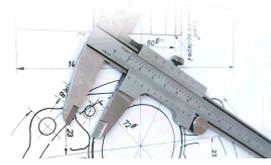


$$\sigma(e^+e^- \rightarrow H + X) \times BR(H \rightarrow YY)$$

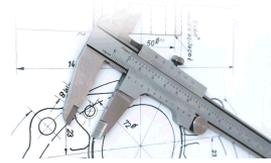
**Y=b,c,g,W,Z, $\gamma$ , $\tau$ , $\mu$**

- ⦿ Determine all Higgs couplings (model-independent)
- ⦿ Infer Higgs total decay width
- ⦿ probe invisible Higgs decay

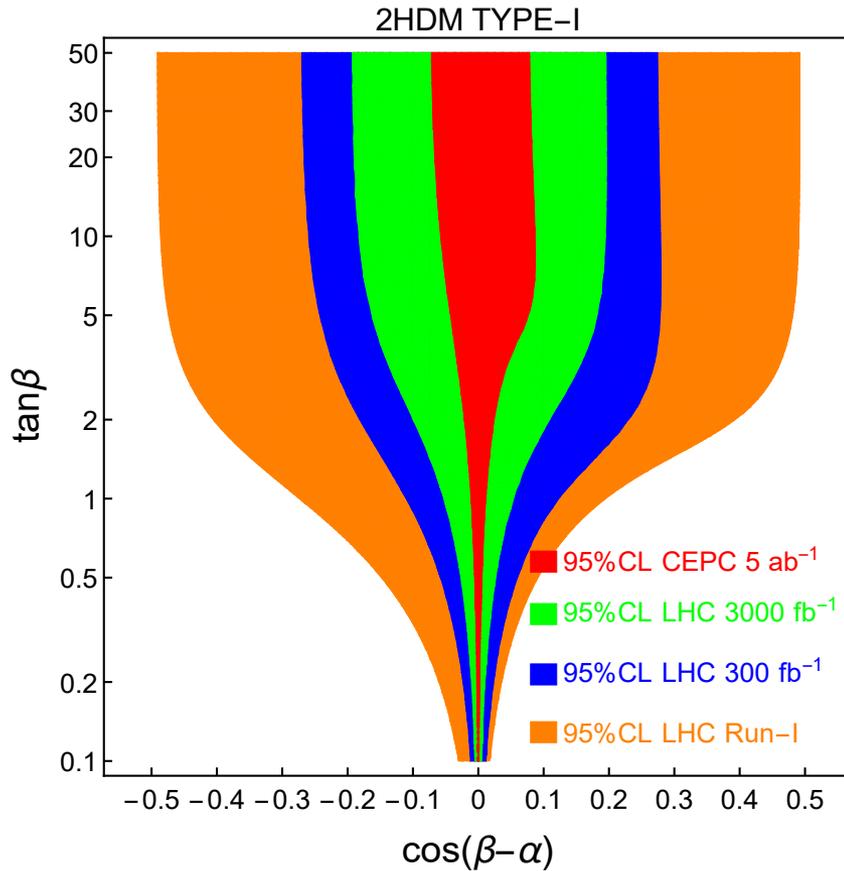
# Higgs Precision Measurement



# Tree-level 2HDM fit

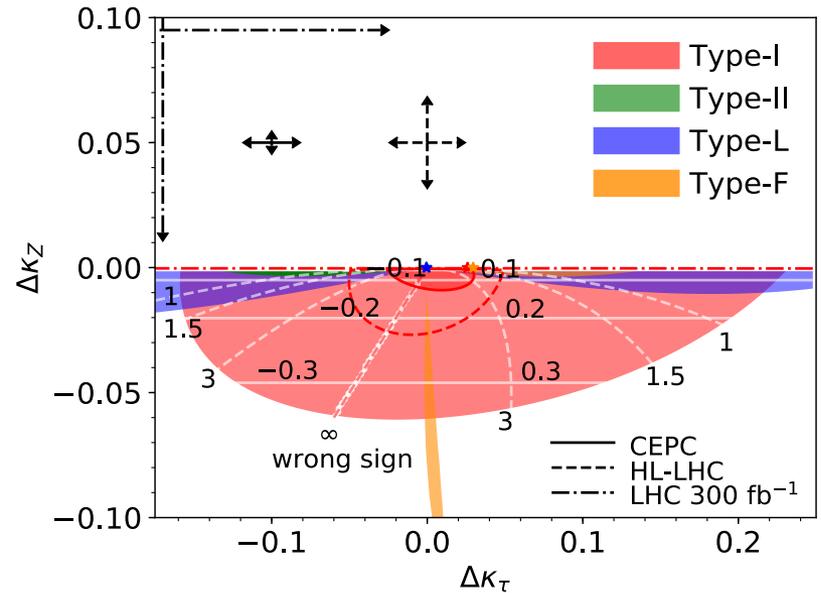


## 2HDM, LHC/CEPC fit



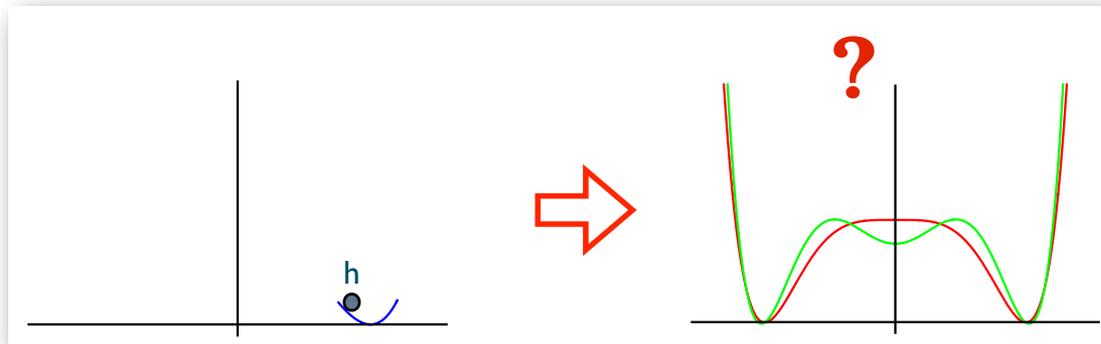
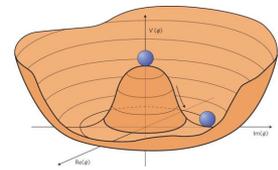
S. Su

Gu, Li, Liu, SS, Su (2017)

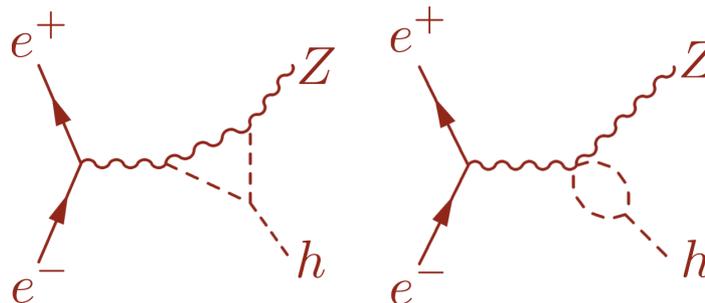


Han, Li, SS, Su, Wu (2020)

# EW baryogenesis



- ⊙ baryon asymmetry ← baryogenesis ← strong 1st order EWPT
- ⊙ **SM: 125 GeV, 2nd order EWPT ⇒ no EW baryogenesis**
- ⊙ **BSM with strong 1st order EWPT ⇒ large deviation in HHH**
  - ➔ HHH > 20% or more, 100 TeV pp
  - ➔ ggH coupling, LHC
  - ➔ HZZ coupling,  $e^+e^-$



# Conclusion

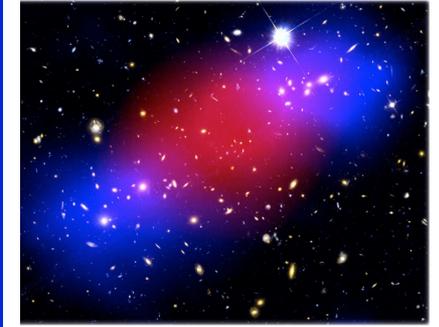
---

- ⦿ The discovery of Higgs is a remarkable triumph in particle physics
- ⦿ A light weakly coupled Higgs argues for new physics beyond SM
- ⦿ Search for new physics calls for both high precision machine and high energy machine
- ⦿ Higgs factory: precise measurement of Higgs properties
  - Higgs coupling to sub-percent level
  - indirect approach for new physics beyond the SM
  - cosmo connection, dark matter, SM physics...

◎ SM physics

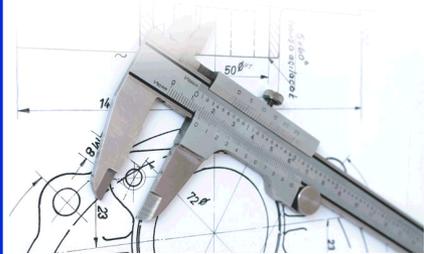


◎ dark matter



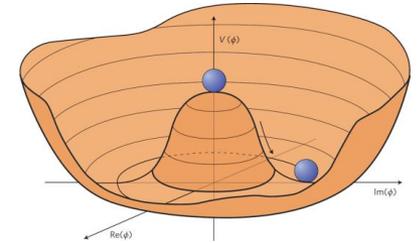
# Higgs Factories

◎ precision  
tests



An exciting journey ahead of us!

◎ Cosmo  
connection



◎ Higgs-related



◎ other BSM





## DPF community planning exercise

Snowmass Frontiers

Energy Frontier

Neutrino Physics Frontier

Rare Processes and Precision

Cosmic Frontier

Theory Frontier

Accelerator Frontier

Instrumentation Frontier

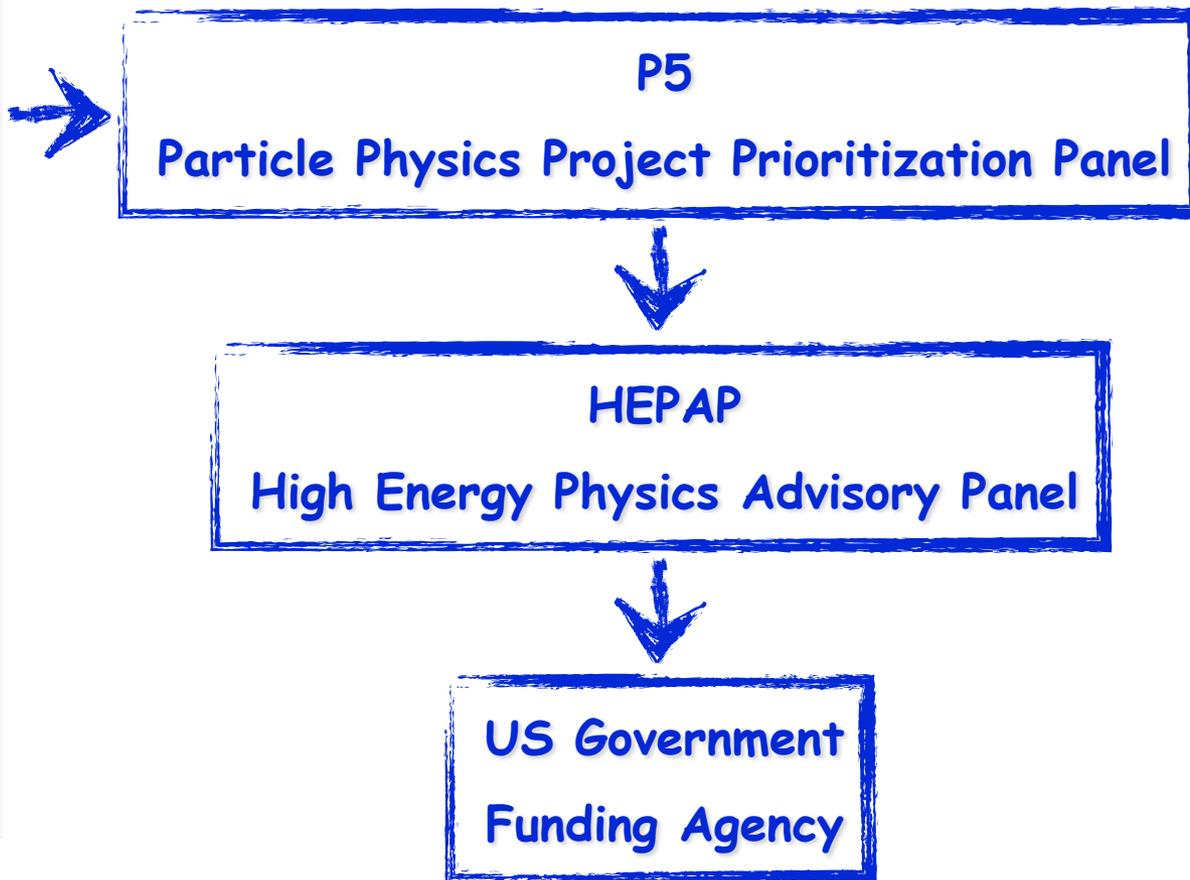
Computational Frontier

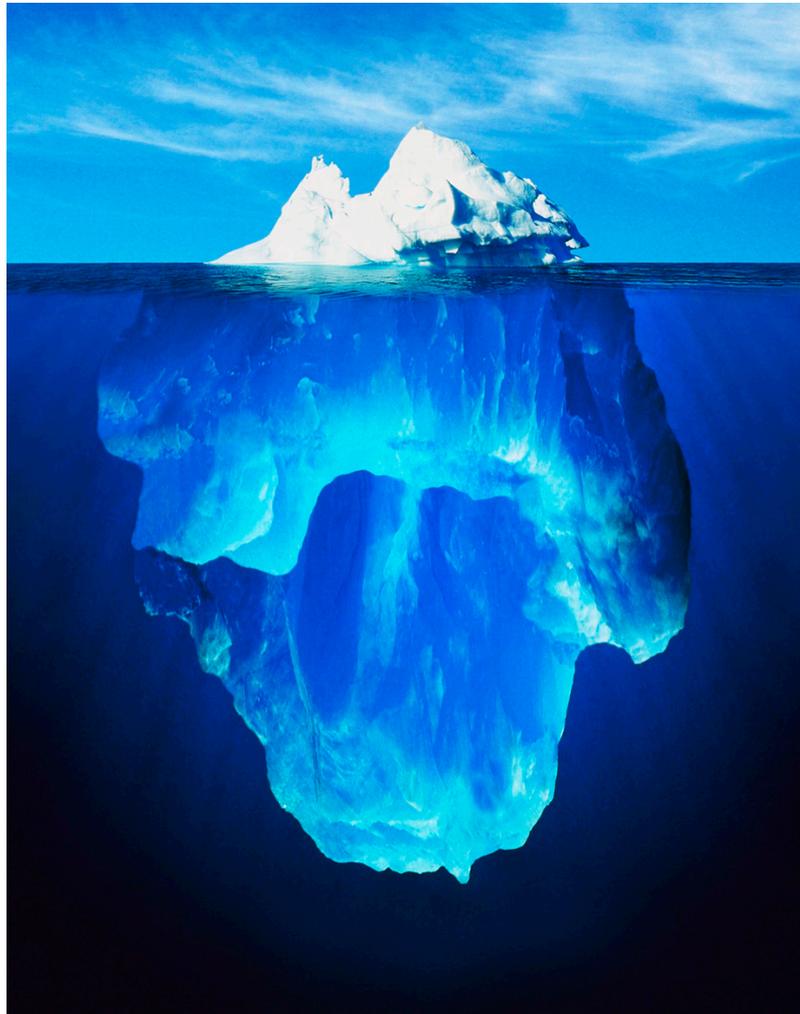
Underground Facilities

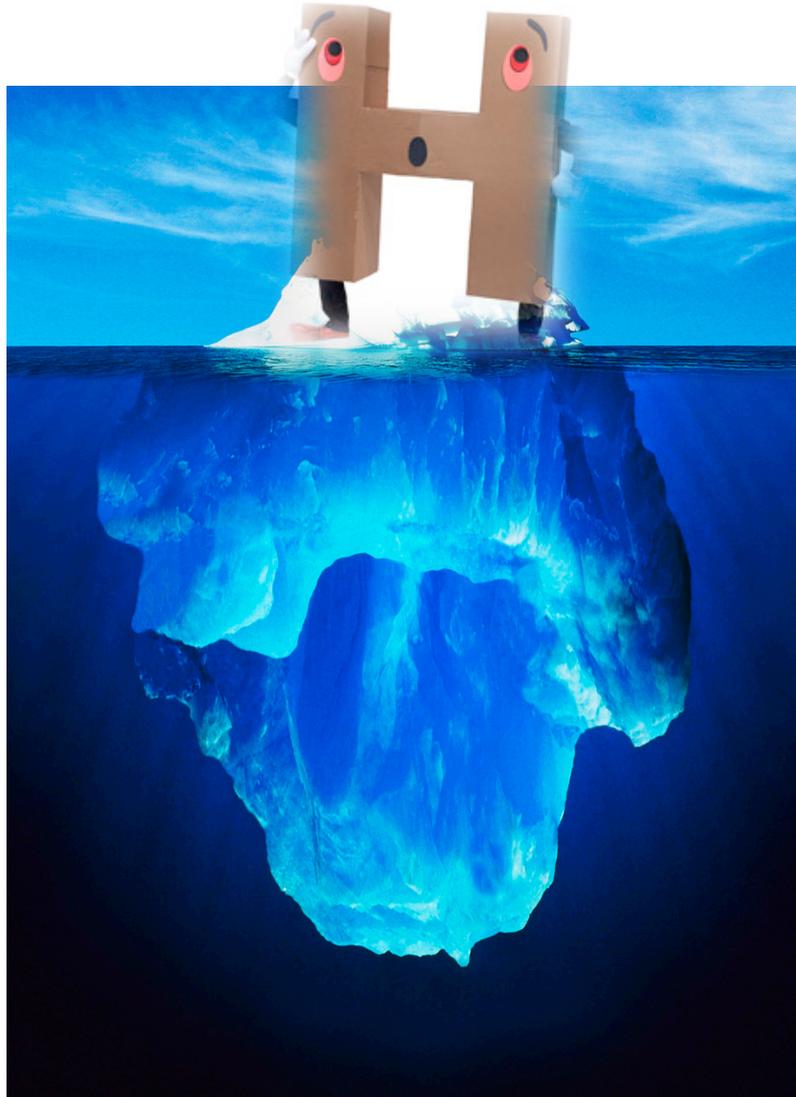
Community Engagement

Snowmass Liaisons

**Physics**









Beginning of new era ...



Beginning of new era ...

Thank you !