Standard Model 4/4

Andreas Weiler (TU Munich)

CERN, 7/2024

Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2013 beslutat att med det
NOBELPRIS
som detta år tillerkännes den
som inom fysikens område gjort den
viktigaste upptäckten eller uppfinningen
gemensamt belöna

Peter W Higgs
och François Englert

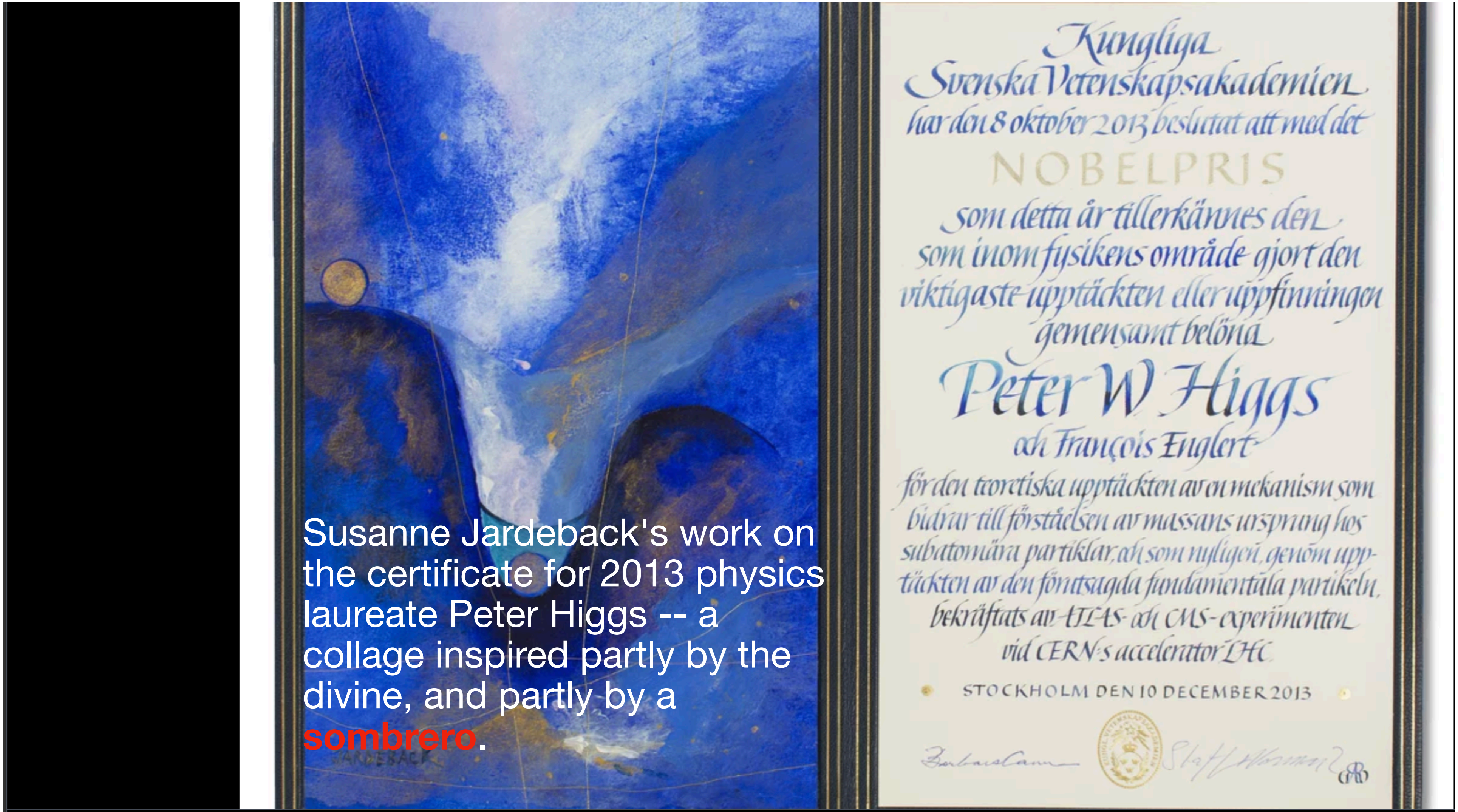
för den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid CERN:s accelerator LHC

STOCKHOLM DEN 10 DECEMBER 2013

Barbara Cannon Staffan Normark

The certificate for 2013 physics laureate Peter Higgs — who shared the prize with Francois Englert — with original artwork by Susanne Jardeback.

Lovisa Engblom/Courtesy of and copyright (c) The Nobel Foundation



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STOCKHOLM DEN 10 DECEMBER 2013

Susanne Jardeback's work on the certificate for 2013 physics laureate Peter Higgs -- a collage inspired partly by the divine, and partly by a sombrero.

The certificate for 2013 physics laureate Peter Higgs — who shared the prize with Francois Englert — with original artwork by Susanne Jardeback.

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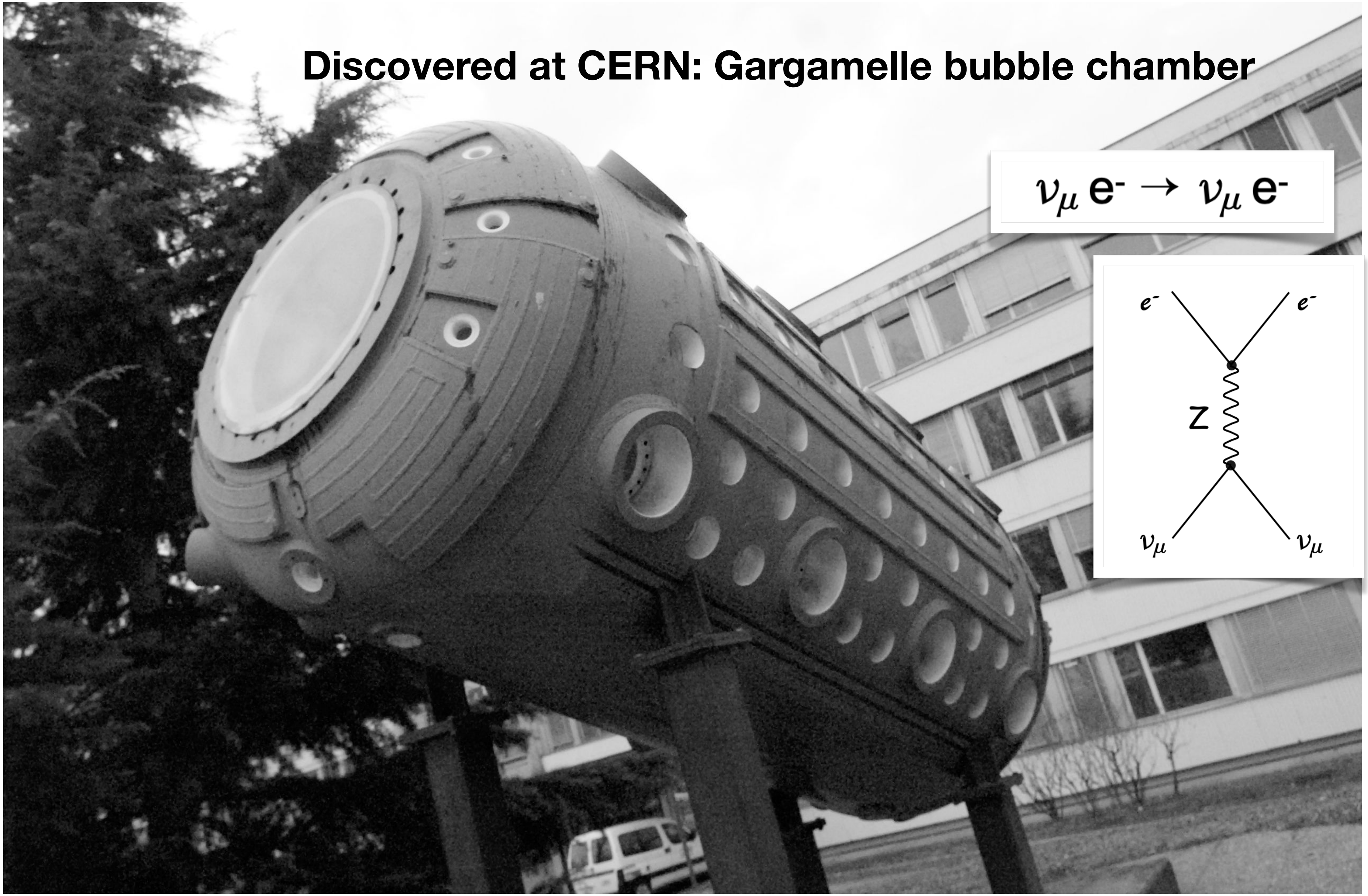
First: some further discussion on the Gargamelle discovery from last lecture.

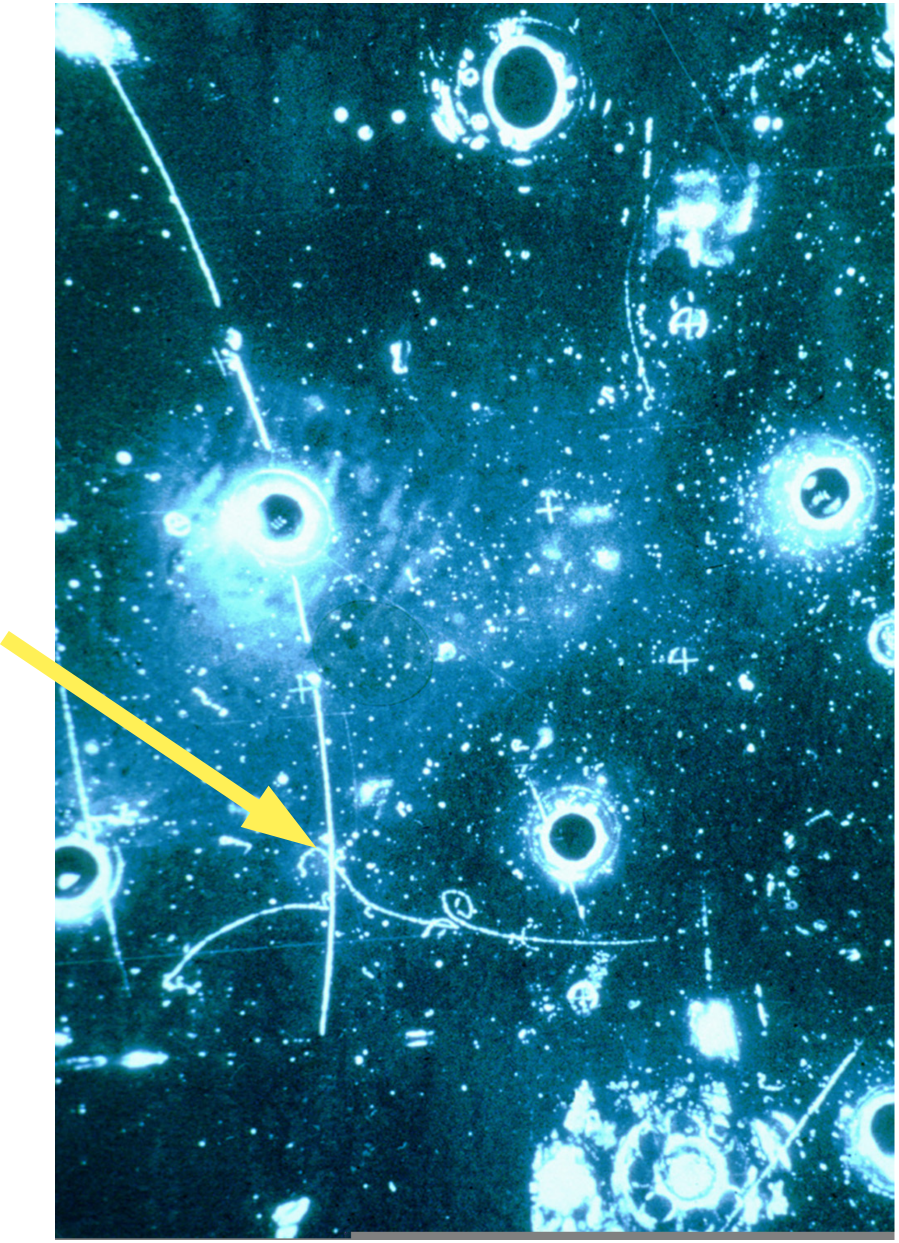
Discovered at CERN: Gargamelle bubble chamber

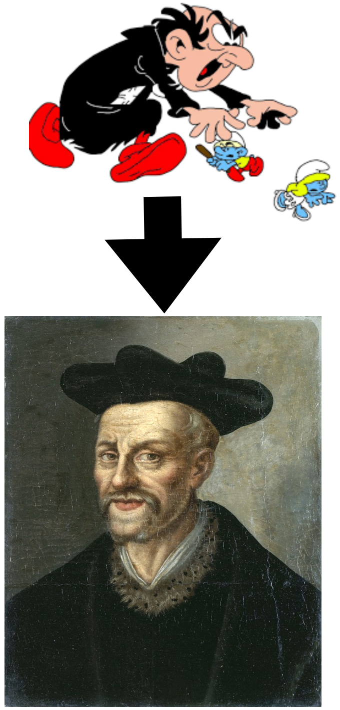


$$\nu_\mu \, e^- \rightarrow \nu_\mu \, e^-$$

In front of the CERN theory group.

- Obviously weak currents



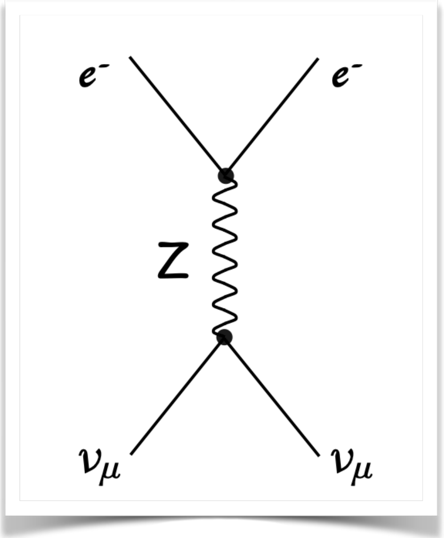


Let us understand the Gargamelle experiment

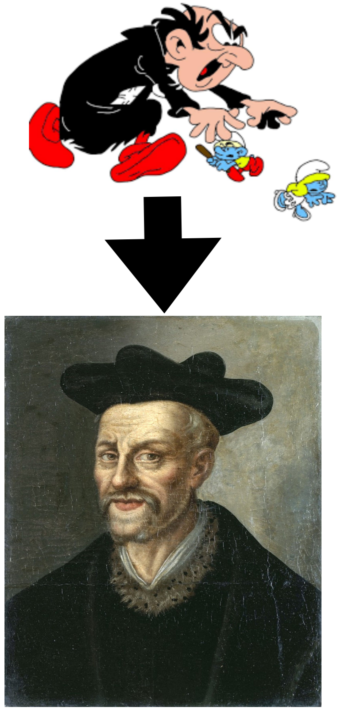
Shows existence of neutral current

- How did they know it is a muon-neutrino?!

Gargamelle



- Why is not a charge current process? (mediated by W-boson)



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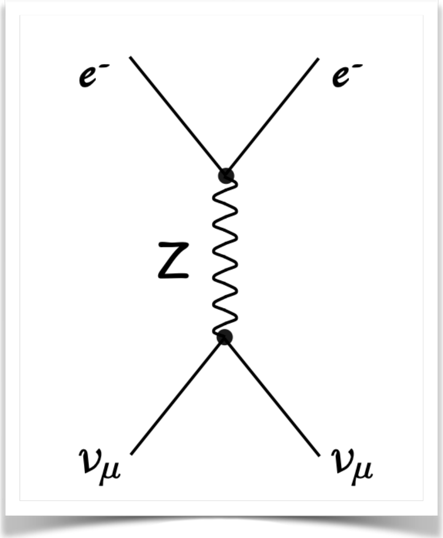
Gargamelle



- How did they know it is a muon-neutrino?!

  Do you know of a particle that prefers to decay to muon neutrinos? ***cough*** π^+ *** cough***

$$\frac{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)}{\Gamma(\pi^- \to e^- \bar{\nu}_e)}|_{EXP} \approx 10^4$$

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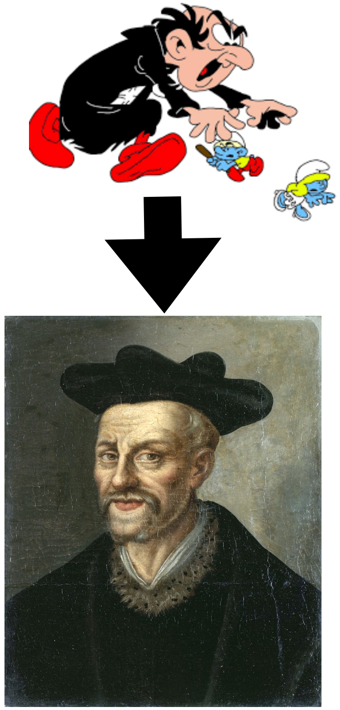

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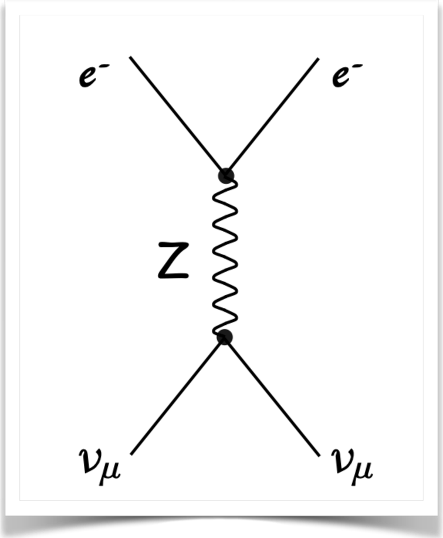

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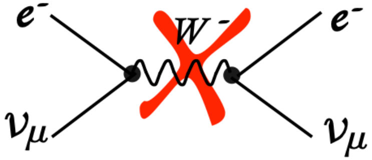
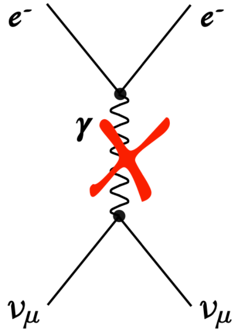
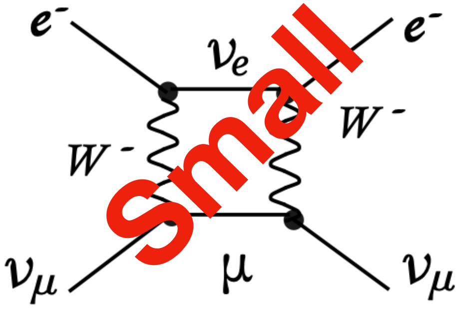
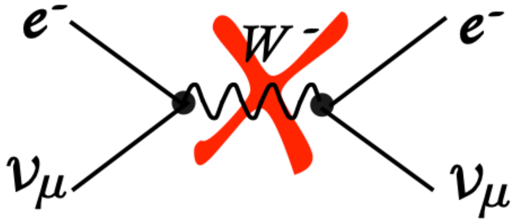






suppressed since
higher order in expansion
~ g^4/(16 pi^2) ~ 0.001



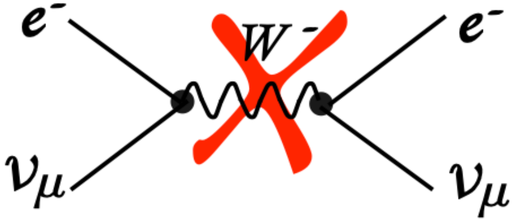
This would jump generations (change the “flavor” from electron to muon)

We know this transition must be possible, since we know that neutrinos change flavor in neutrino oscillations!

But the effect is tiny! It is proportional to the neutrino mass

$$m_\nu < 1\,\mathrm{eV} \ll m_e = 511\,\mathrm{keV}$$

(We will see that for quarks these flavor changes can be much bigger!)



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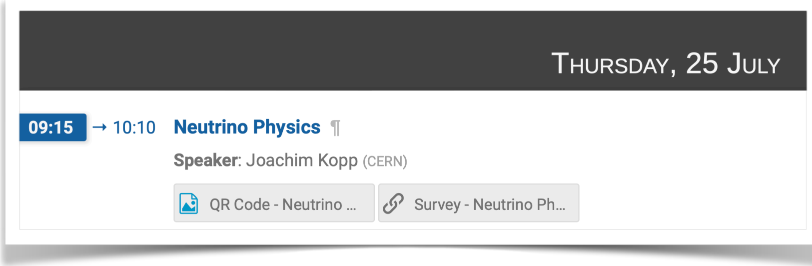

THURSDAY, 25 JULY

09:15 → 10:10 **Neutrino Physics** ¶

Speaker: Joachim Kopp (CERN)

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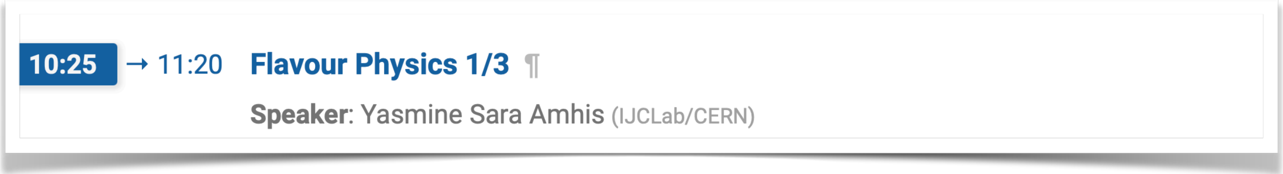
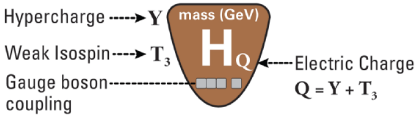


10:25 → 11:20 **Flavour Physics 1/3** ¶

Speaker: Yasmine Sara Amhis (IJCLab/CERN)

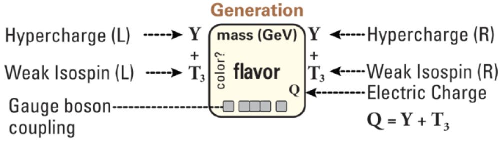
Higgs

Spin 0
(Higgs Boson)



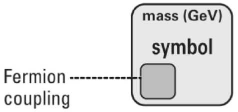
Matter

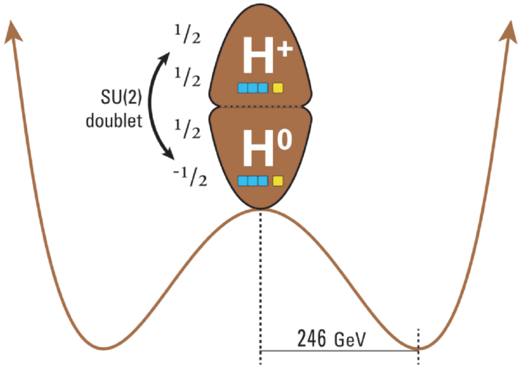
Spin 1/2
(Fermions)

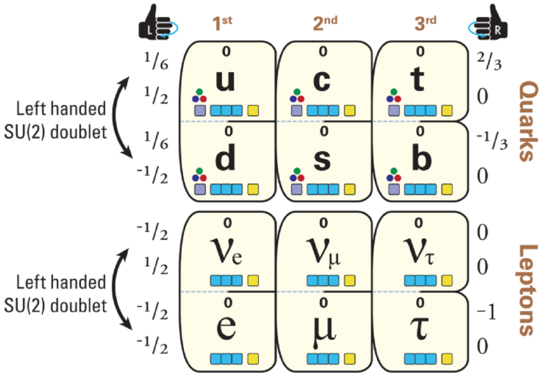


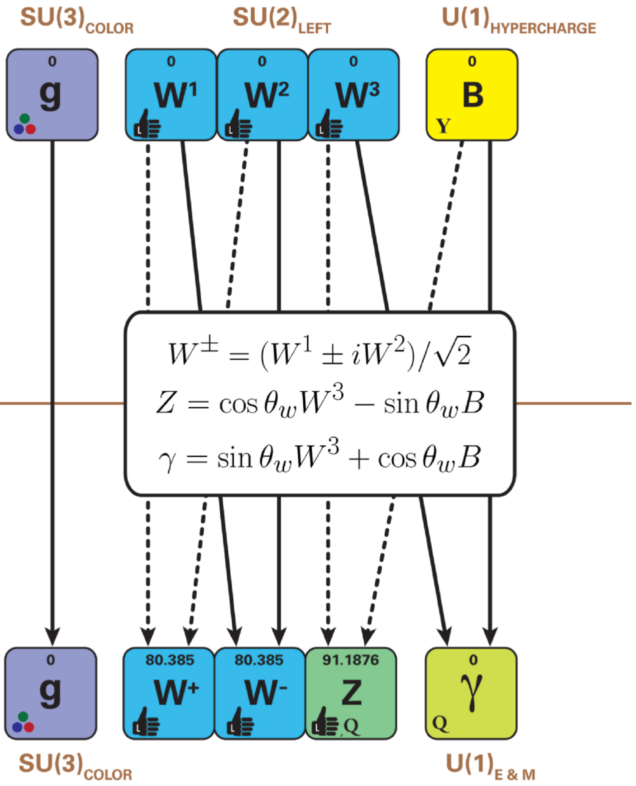
Forces

Spin 1
(Gauge Bosons)





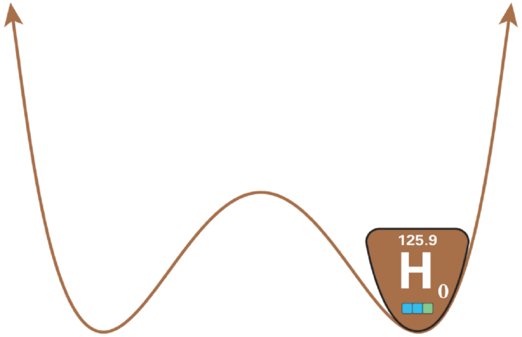


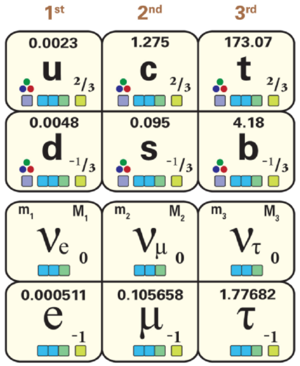


$$W^{\pm} = (W^1 \pm iW^2)/\sqrt{2}$$
$$Z = \cos\theta_w W^3 - \sin\theta_w B$$
$$\gamma = \sin\theta_w W^3 + \cos\theta_w B$$

Unbroken Symmetry

Broken Symmetry

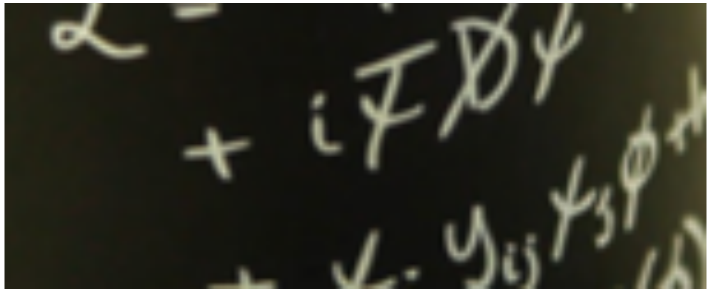


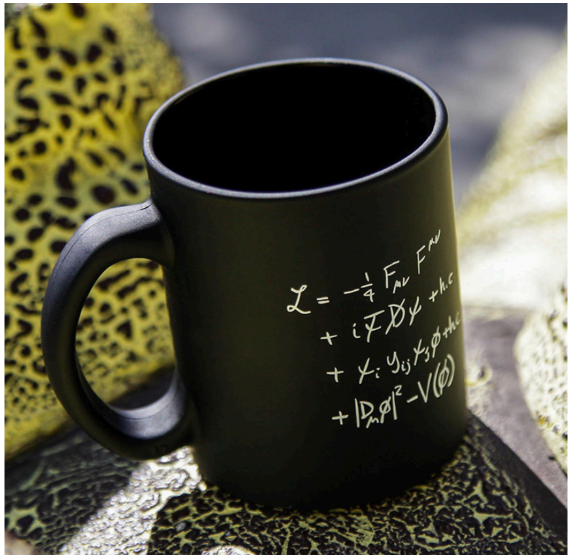


1st	2nd	3rd
0.0023 u 2/3	1.275 c 2/3	173.07 t 2/3
0.0048 d -1/3	0.095 s -1/3	4.18 b -1/3
m_1 M_1 ν_e 0	m_2 M_2 ν_μ 0	m_3 M_3 ν_τ 0
0.000511 e -1	0.105658 μ -1	1.77682 τ -1

Matter quantum fields: full form

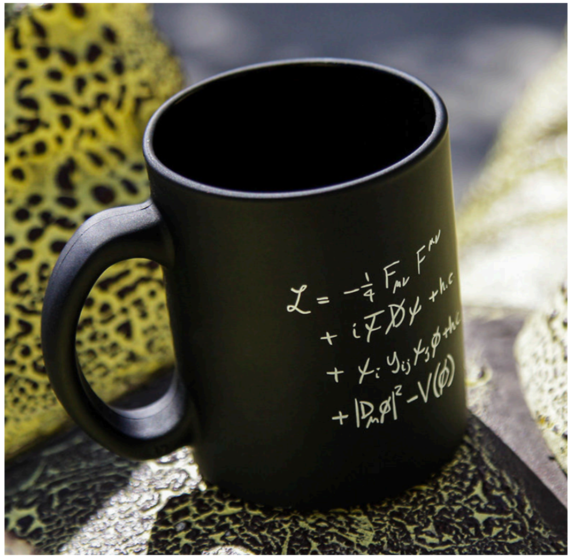
Meaning of the mug?

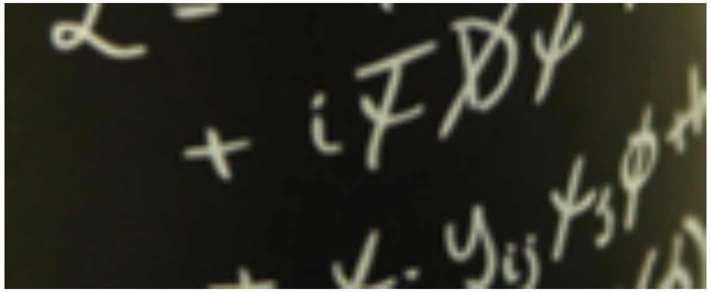




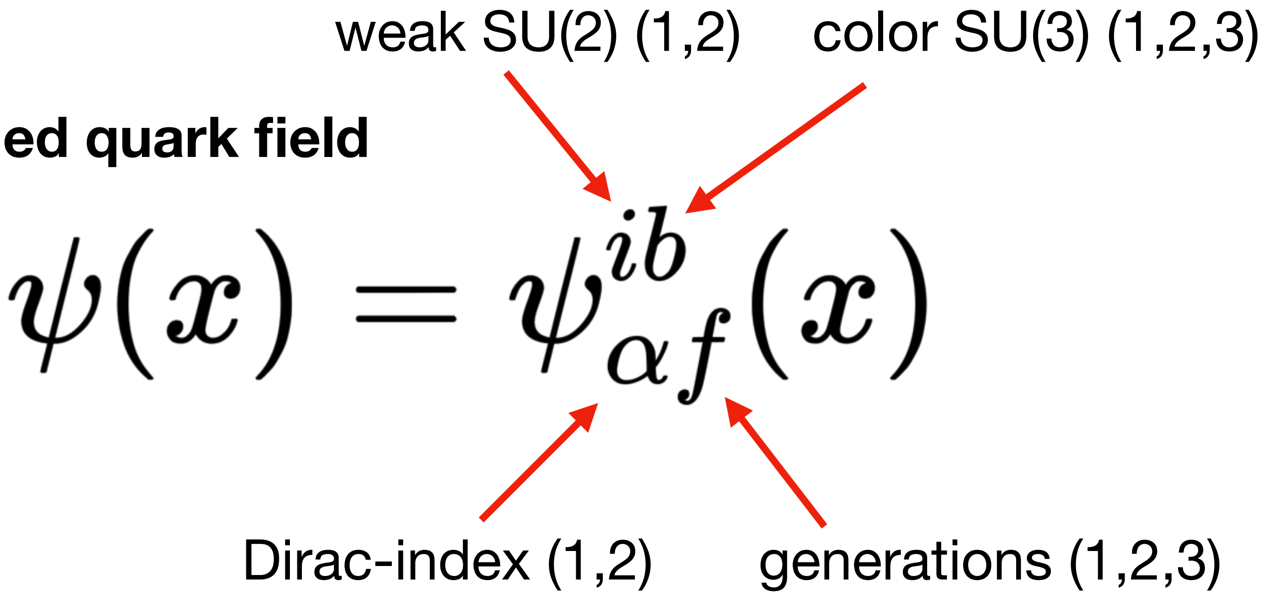
Matter quantum fields: full form

Meaning of the mug?





Left-handed quark field



weak SU(2) (1,2)

color SU(3) (1,2,3)

$$\psi(x) = \psi^{ib}_{\alpha f}(x)$$

Dirac-index (1,2)

generations (1,2,3)

Weak interactions paradoxes

We need non-abelian gauge theory, but gauge bosons need to be massive!
How can we save SU(2) gauge invariance?

$$M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu$$

Since the weak interactions are chiral (only the **left-handed** particles are charged), the **left-handed** and **right-handed** particles are fundamentally different.
How can they have a mass term?

SU(2) $\begin{pmatrix} u \\ d \end{pmatrix}_L$ u_R d_R

vs. $m(\bar{u}_L u_R + \bar{u}_R u_L)$ **not** SU(2) invariant !

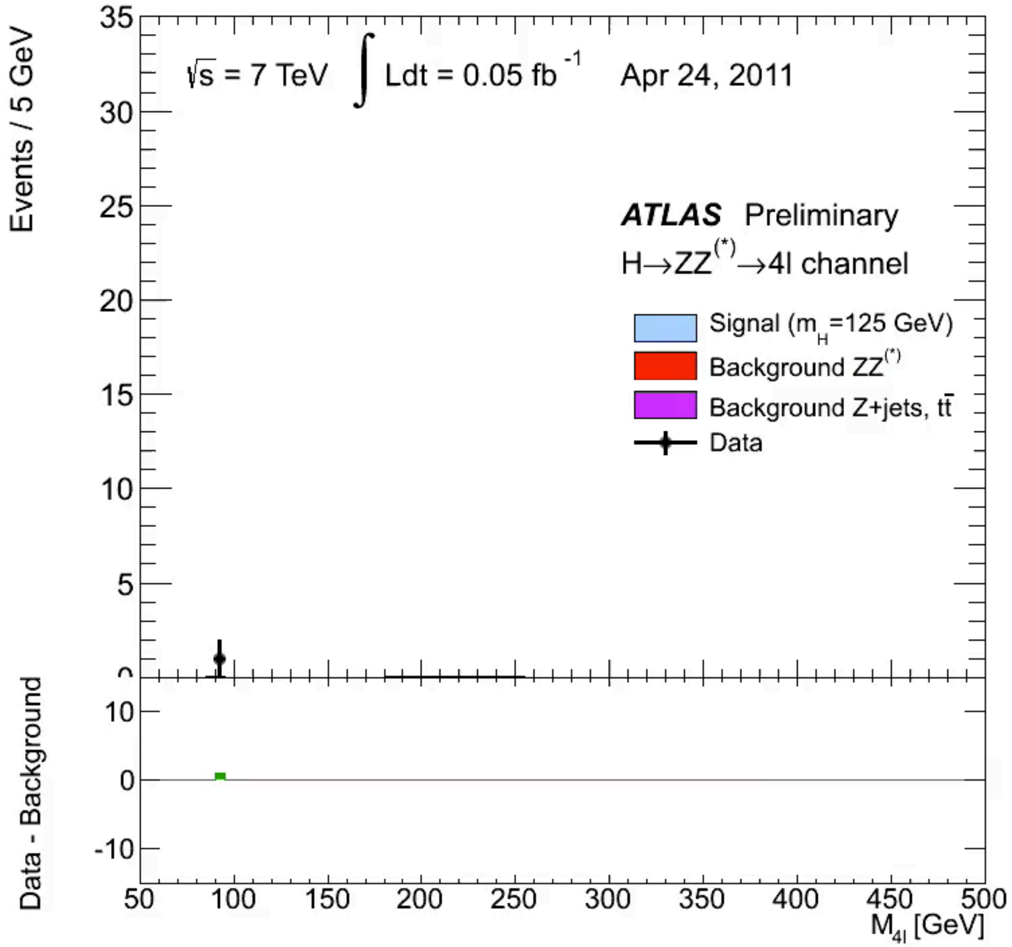
Avengers of the SM assemble

Peter Higgs

Francois Englert

Robert Brout

4th of July 2012
Genf (CH)

Events / 5 GeV
35
30
25
20
15
10
5
0
√s = 7 TeV ∫ Ldt = 0.05 fb⁻¹ Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
10
0
-10
50
100
150
200
250
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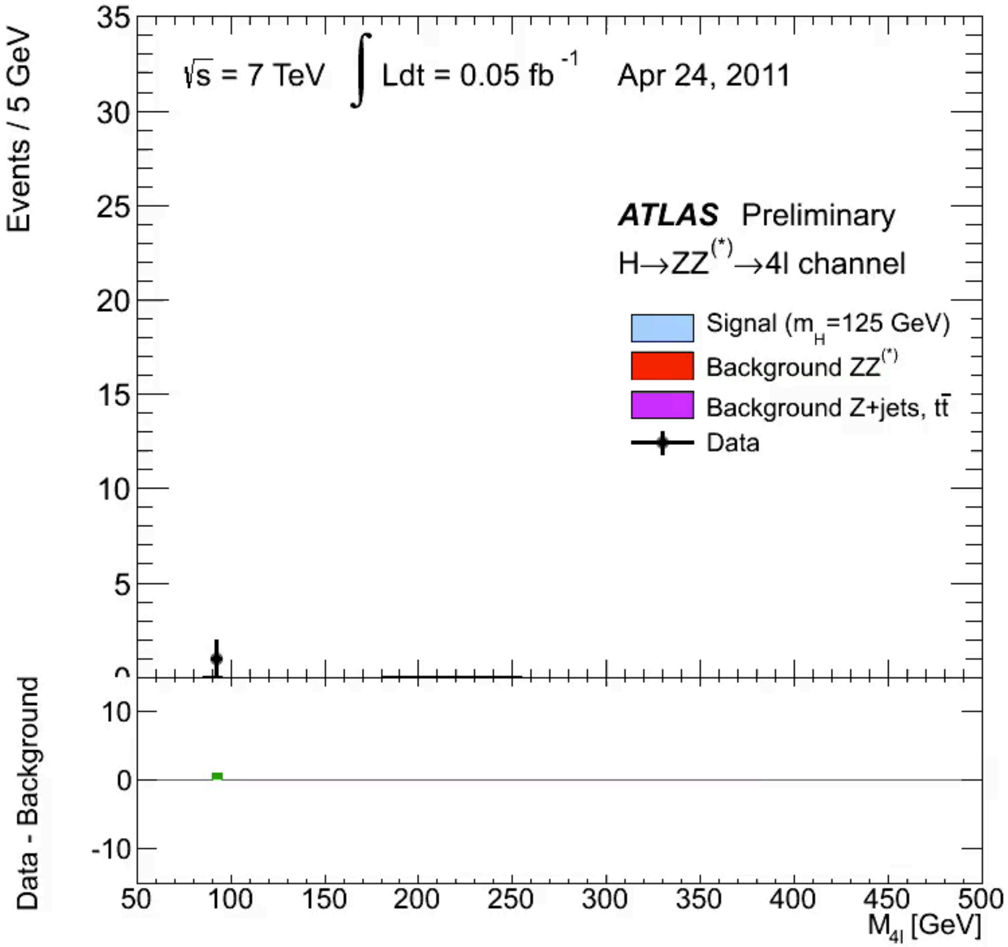
400
450
500
M4l [GeV]


$\sqrt{s}$ = 7 TeV
$\int$ Ldt = 0.05 fb^{-1}
Apr 24, 2011
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H→ZZ$^{(*)}$→4l channel
Signal (m_H=125 GeV)
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Data
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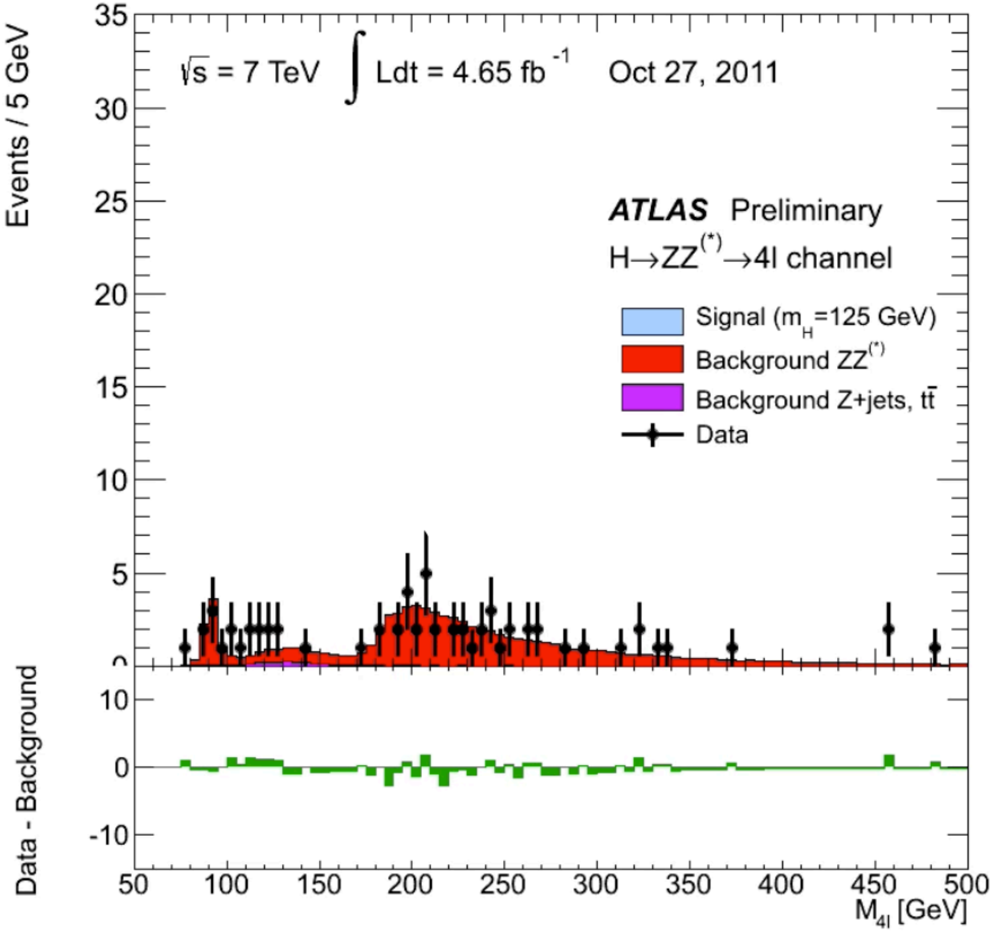
500
M_{4l} [GeV]


$\sqrt{s}$ = 7 TeV
$\int$ Ldt = 4.65 fb^{-1}
Oct 27, 2011
ATLAS Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel
Signal (m_H=125 GeV)
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Data
Events / 5 GeV
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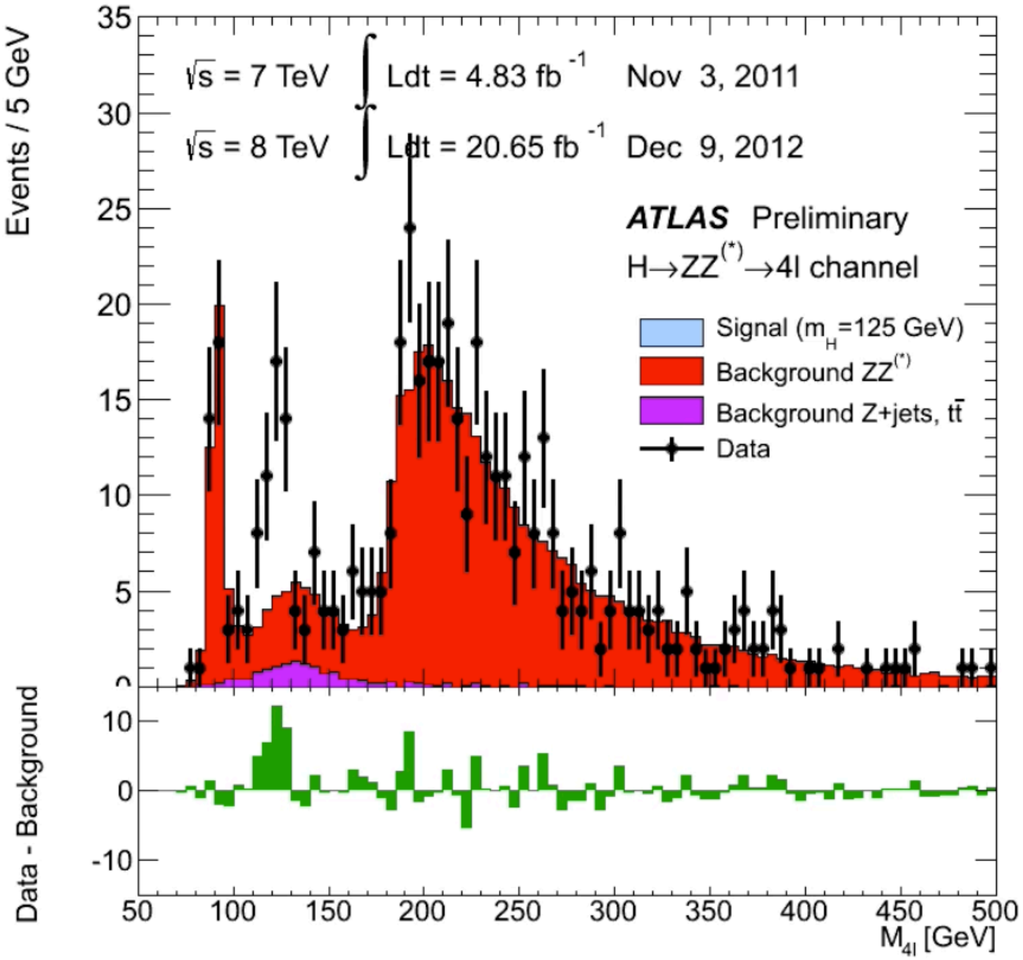
M_{4l} [GeV]


√s = 7 TeV ∫ Ldt = 4.83 fb⁻¹ Nov 3, 2011
√s = 8 TeV ∫ Ldt = 20.65 fb⁻¹ Dec 9, 2012
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]
0
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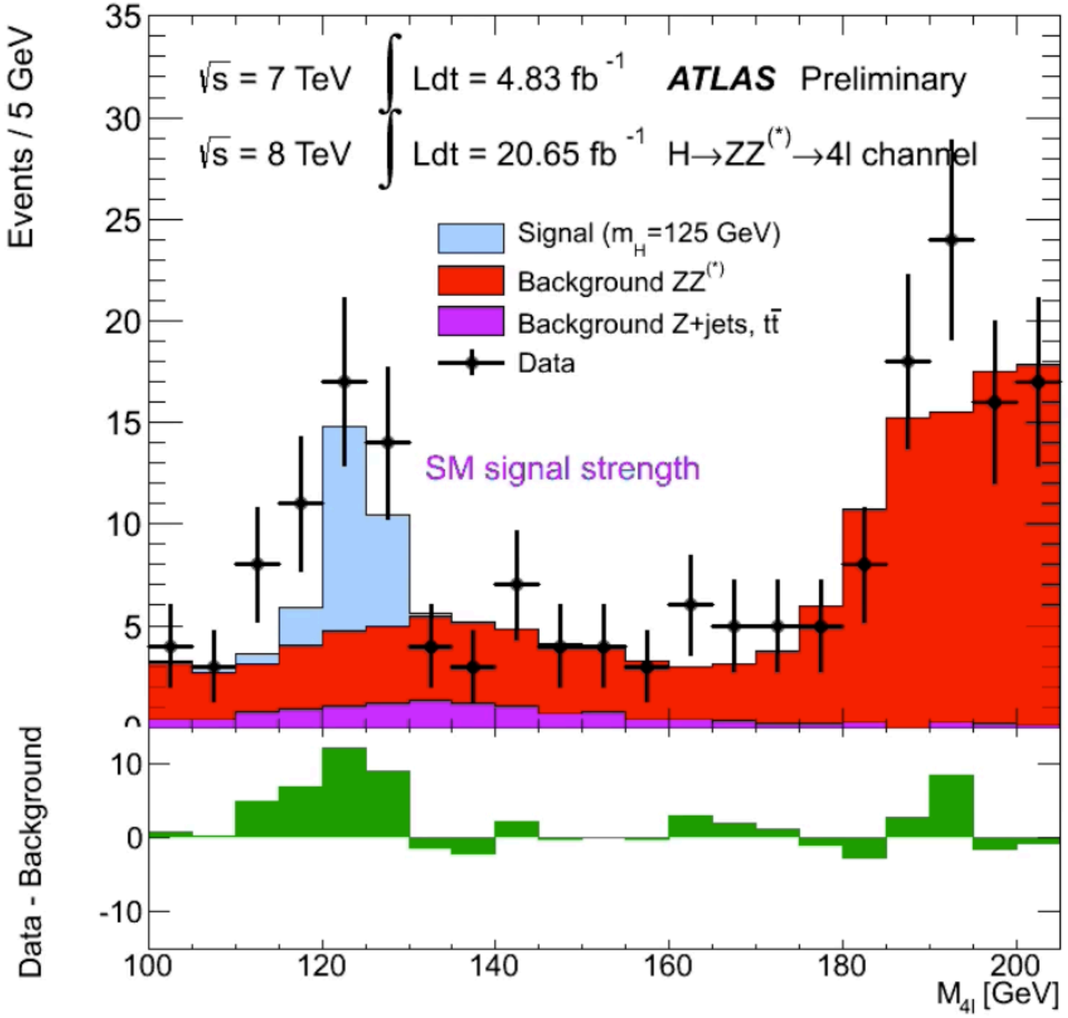
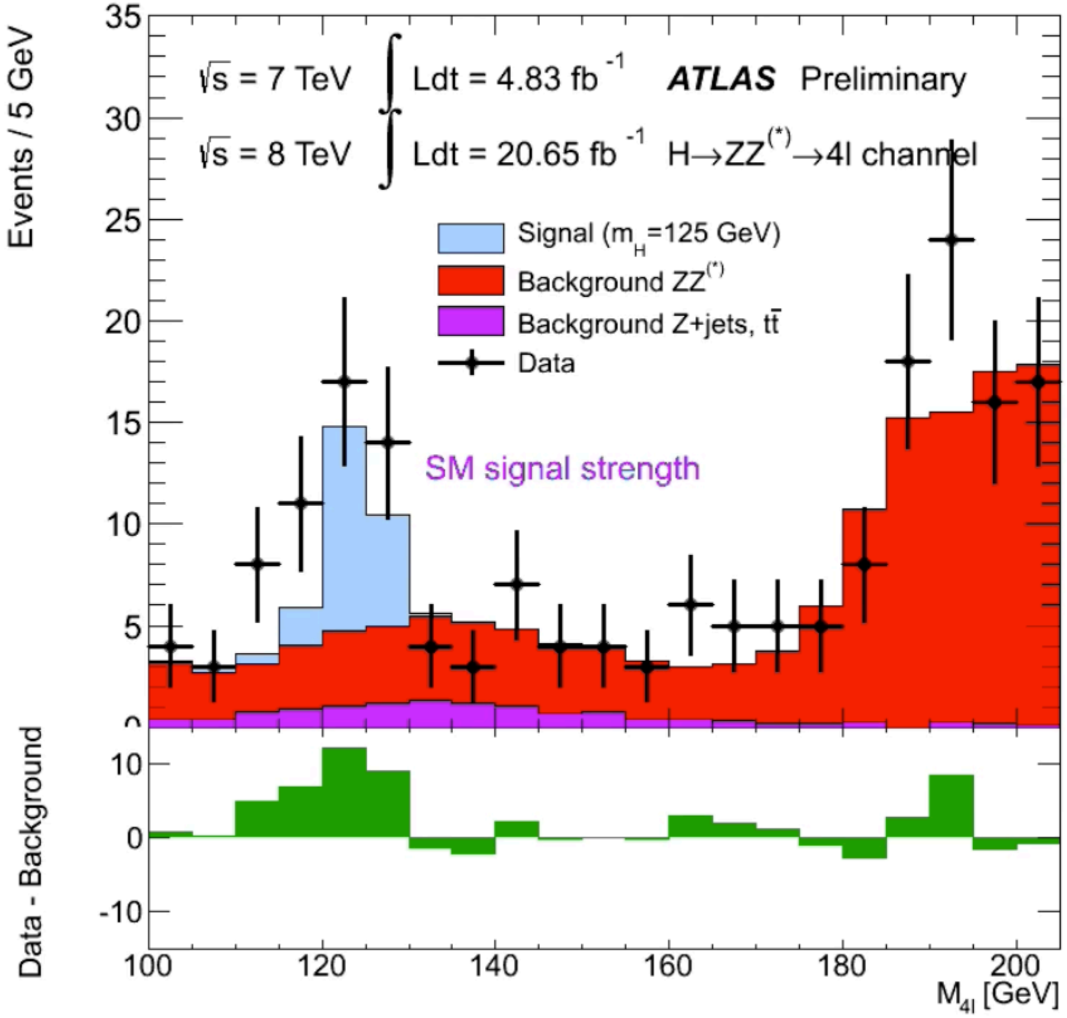


SM signal strength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Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
SM signal strength
Data - Background
10
0
-10
100
120
140
160
180
200
M_4l [GeV]

4/7/2012 discovery of the Higgs

theory : 1964

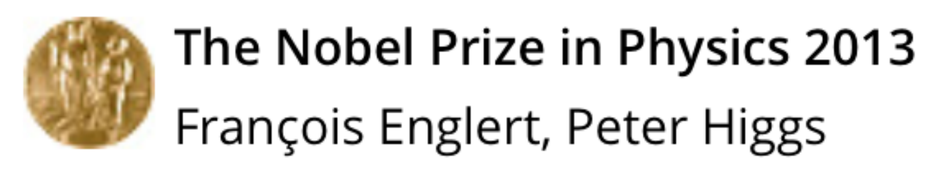
design : 1984

construction : 1998

One year later in the theory group at CERN…

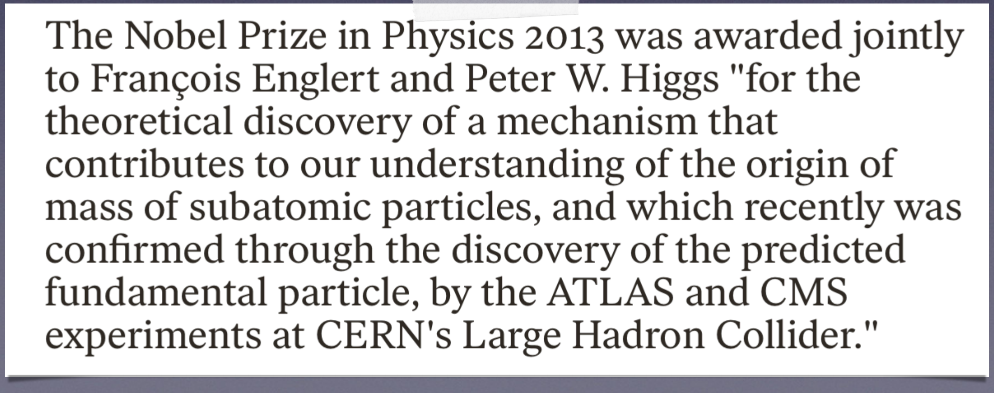

COMING UP
Announcement of the
Nobel Prize in Physics


Announcement of the
Nobel Prize in Physics



The Nobel Prize in Physics 2013

François Englert, Peter Higgs



The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "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."

Higgs is at the center of SM

- the only particle that talks to everybody*
- the only elementary particle that doesn't spin
- the only particle that is condensed in the universe
- the source of all masses of elementary particles
- We don't know why all of this is the case
- important & special particle!

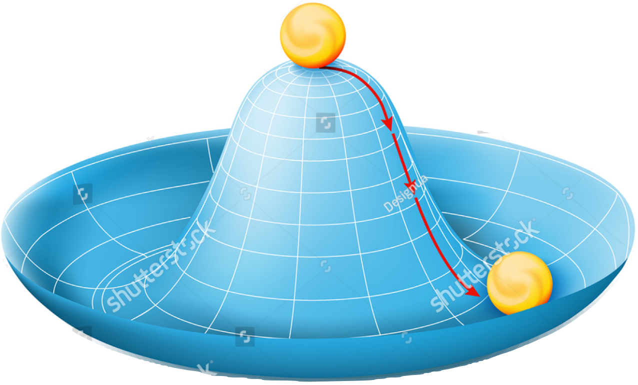
* if we ignore the graviton

Plan

Model building the SM — requirements

- Explain the 3 massive weak bosons ($W^+,\ W^-, Z$), SU(2) structure
- Two types of massless gauge bosons (photon, 8 gluons)
- Explain why the left-handed and right-handed particles can have different quantum numbers (= are different particles) while being massive
- Make some predictions we can test.

Higgs mechanism!



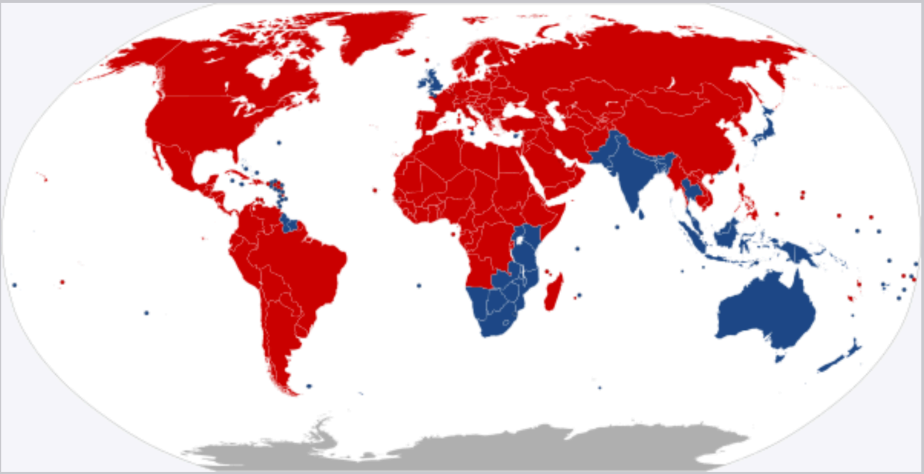
Spontaneous symmetry breaking

Countries by direction of road traffic, c. 2020

🟦 ⇅ Left-hand traffic

🟥 ⇵ Right-hand traffic

Spontaneous symmetry breaking



Countries by direction of road traffic, c. 2020

🟦 ⇅ Left-hand traffic

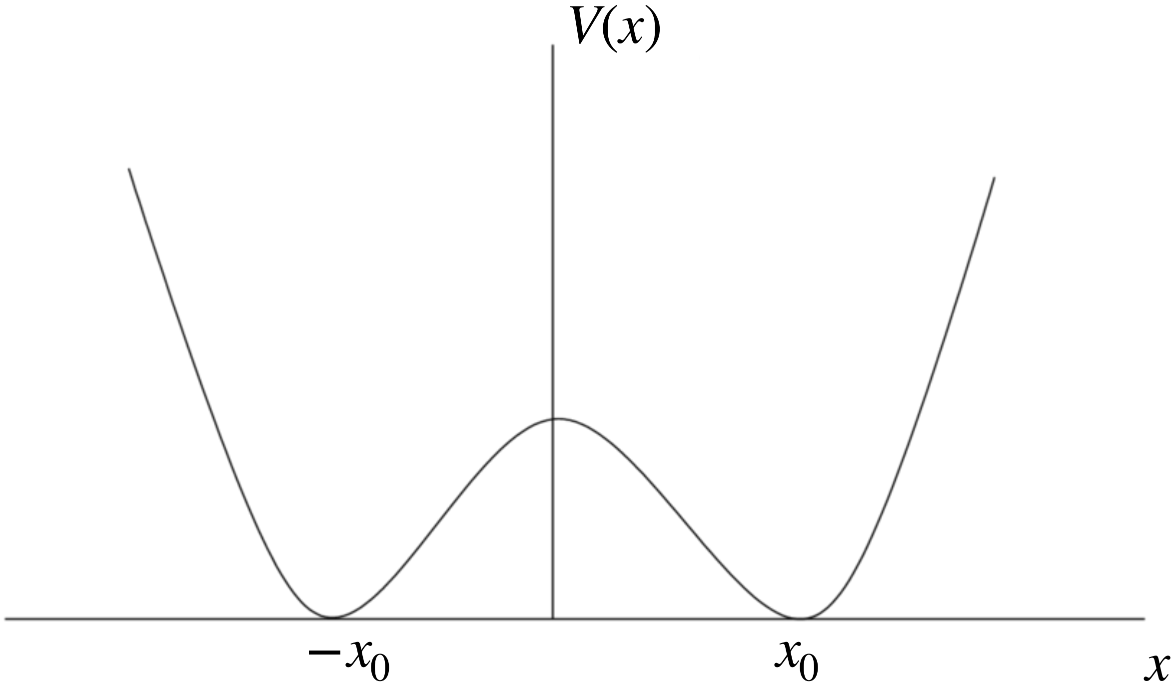
🟥 ⇵ Right-hand traffic

(a) The ferromagnet for $T > T_c$. The global rotational symmetry is unbroken.

(b) The ferromagnet for $T < T_c$. The global rotational symmetry is spontaneously broken.

Classical mechanics

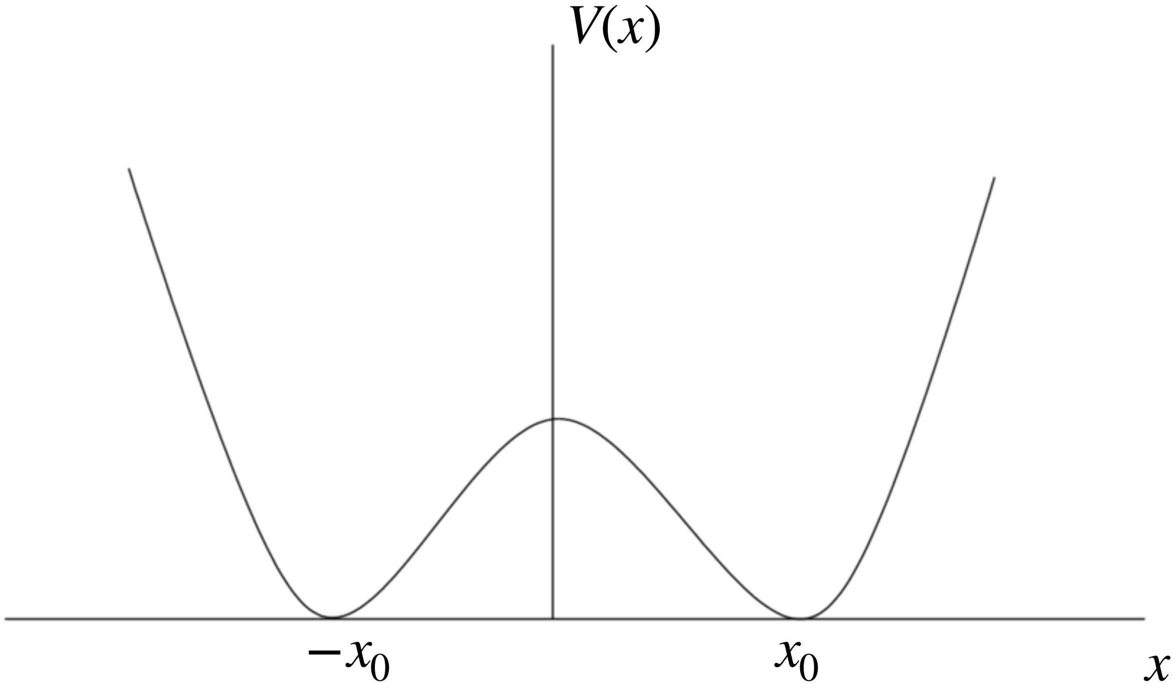
Symmetries? what is the ground state?



Classical mechanics

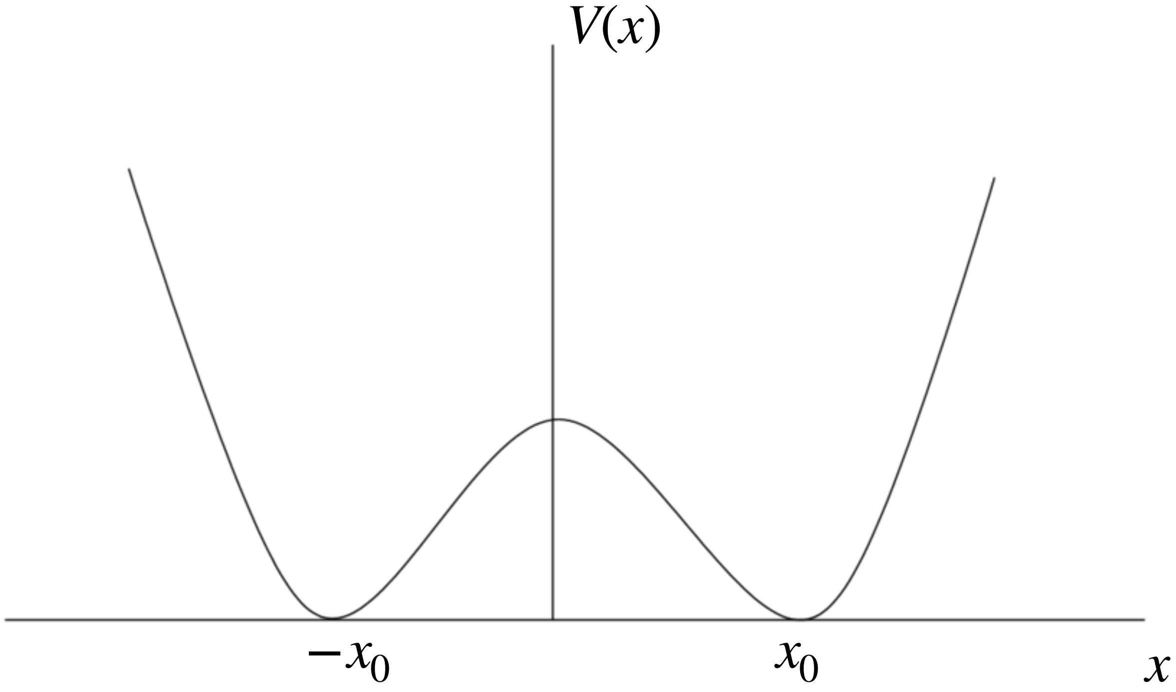
Symmetries? what is the ground state?

$$x \to -x$$



Quantum mechanics

Symmetries? what is the ground state?



Quantum mechanics

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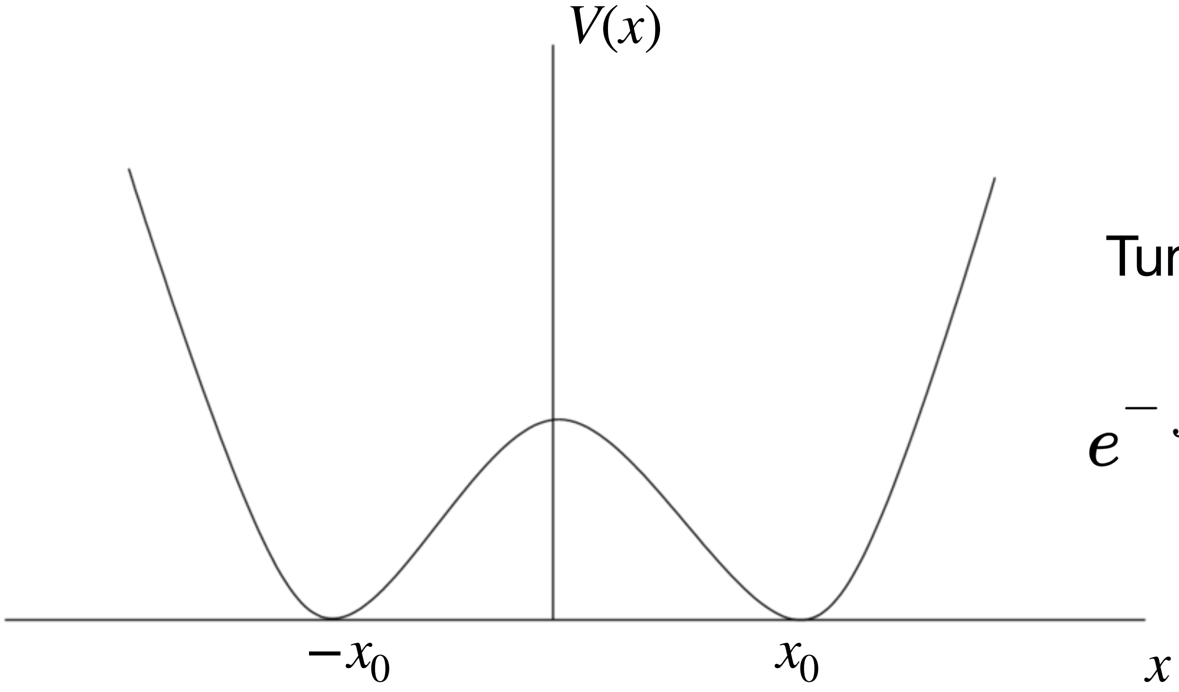
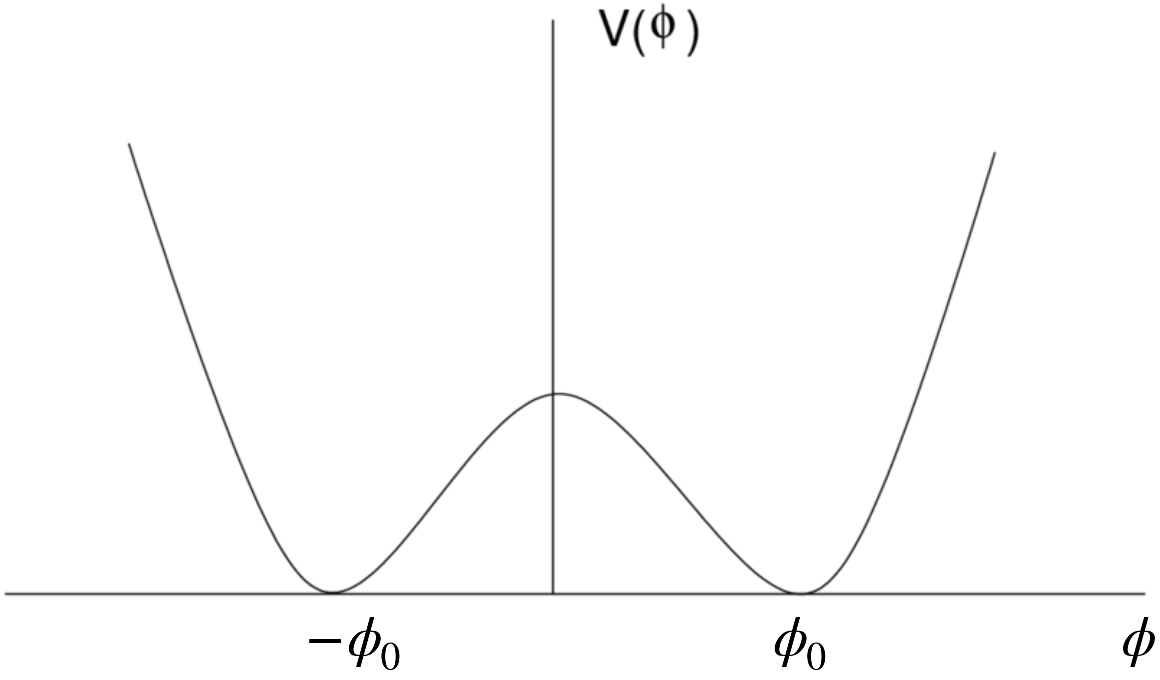


Tunneling amplitude

$$e^{-\int dx \sqrt{\frac{2m}{\hbar^2}(V(x)-E)}}$$

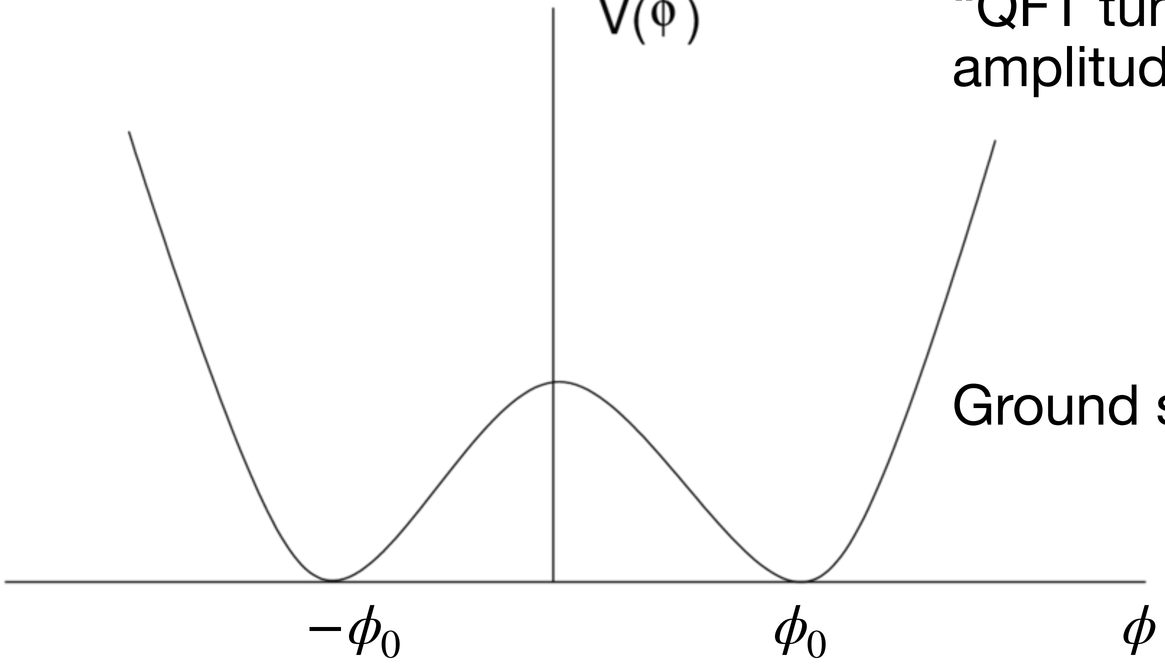
Quantum Field Theory

Symmetries? what is the ground state?



Quantum Field Theory

Symmetries? what is the ground state?



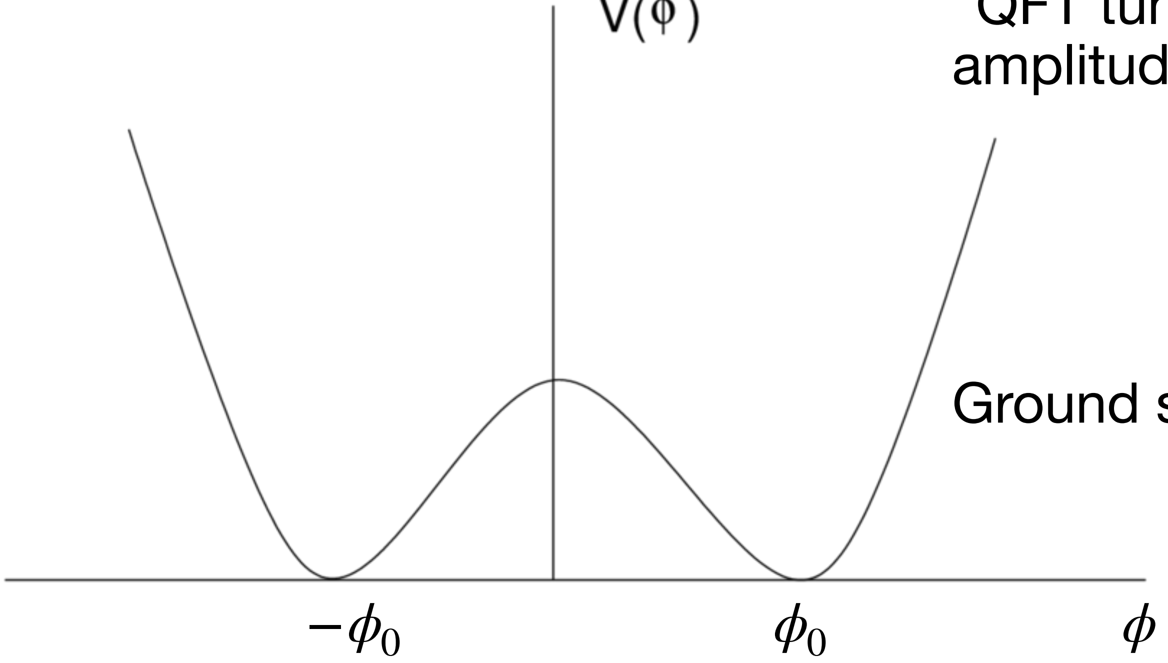
"QFT tunneling amplitude" $\propto \exp\left(-\Omega \int_{-\phi_0}^{\phi_0} \sqrt{2V(\phi)}d\phi\right) \to 0$

$\Omega =$ volume of space

Ground state is **not** combination of ϕ_0 and -ϕ_0

Quantum Field Theory

Symmetries? what is the ground state?

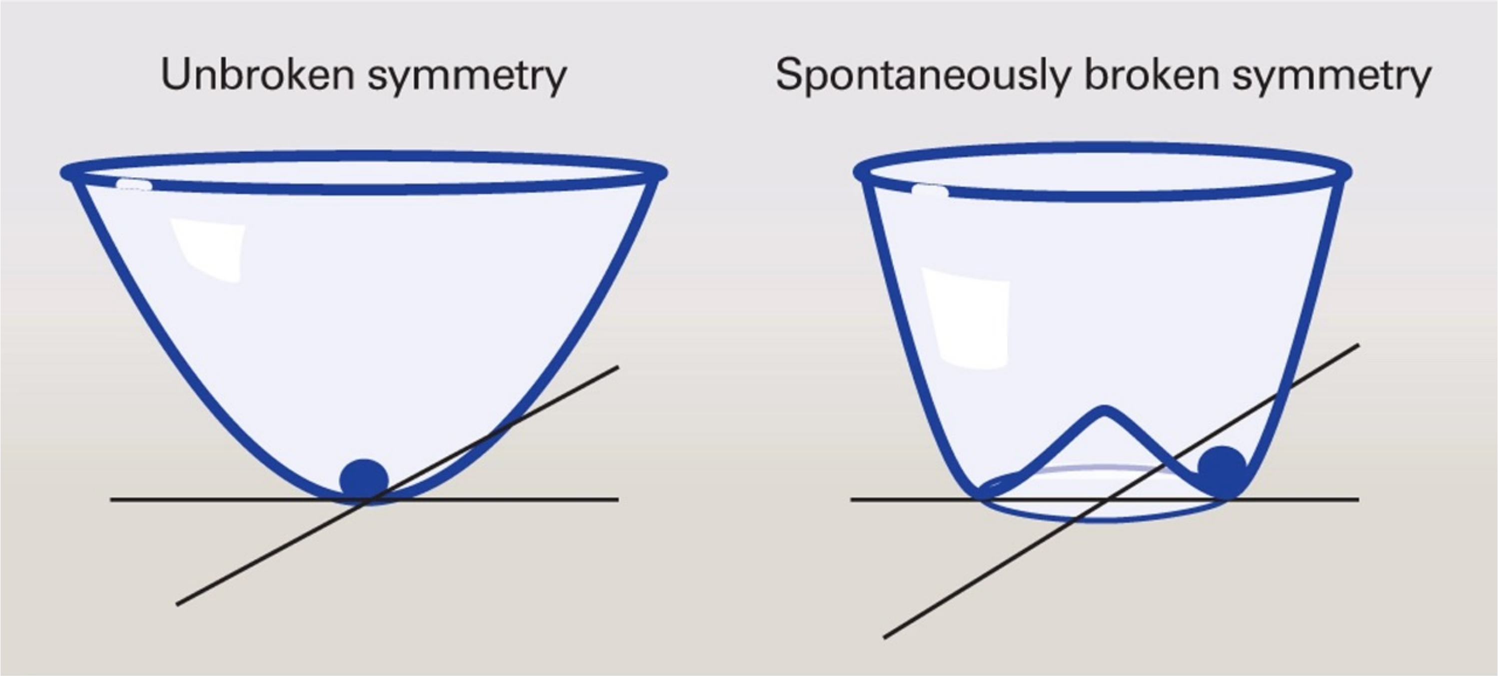


"QFT tunneling amplitude" $\propto \exp\left(-\Omega\int_{-\phi_0}^{\phi_0}\sqrt{2V(\phi)}d\phi\right) \to 0$

$\Omega =$ volume of space

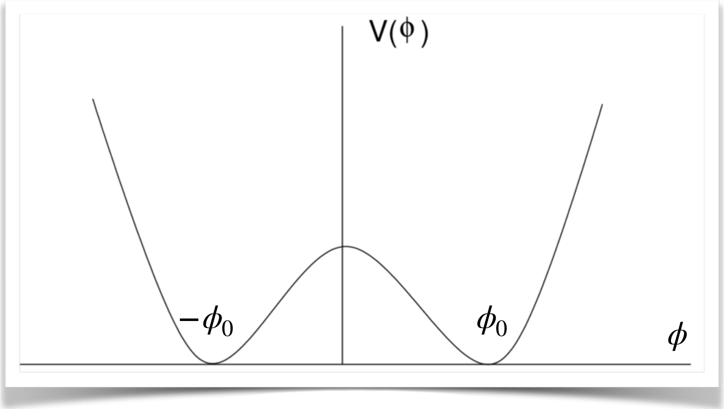
Ground state is **not** combination of ϕ_0 and -ϕ_0

Ground state solution has **fever symmetries** than the potential.


Unbroken symmetry
Spontaneously broken symmetry

Spontaneous symmetry breaking

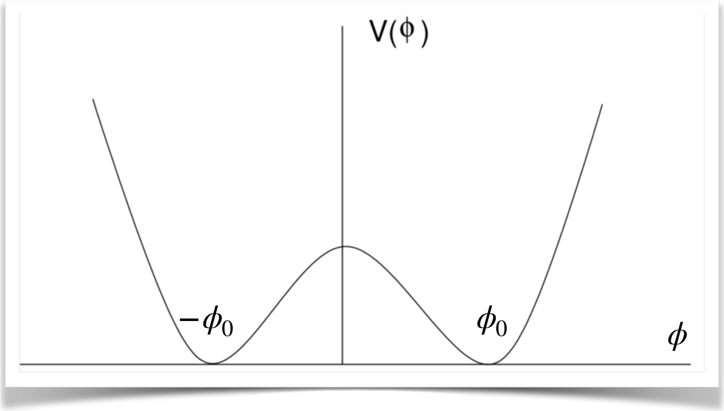
Real scalar field (see Tim's lectures)



$$\mathscr{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)$$

$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

Spontaneous symmetry breaking



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Minimum at: $$\frac{\partial V}{\partial \phi} = 0 \Leftrightarrow -\mu^2\phi + \lambda\phi^3 = 0$$

Spontaneous symmetry breaking

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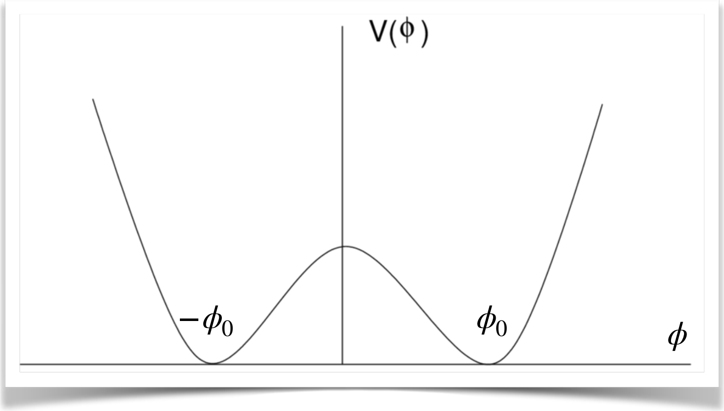

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➡ $$\phi_0 = \pm\frac{\mu}{\sqrt{\lambda}} = \pm v.$$

Scalar field develops "**vacuum expectation value**" (v = vev).

Spontaneous symmetry breaking

Real scalar field (see Tim’s lectures)

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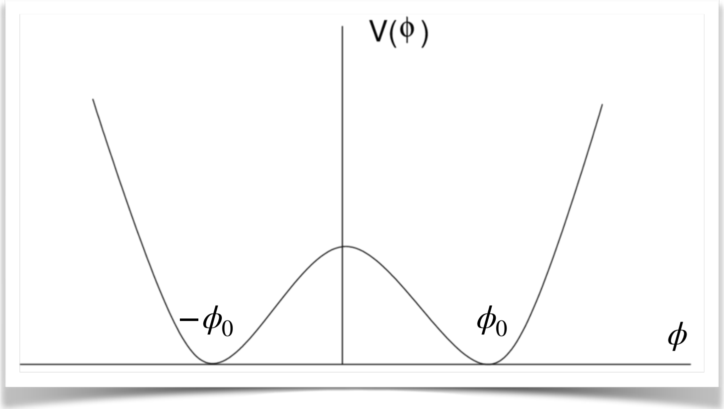

Pick one!

Minimum at: $\frac{\partial V}{\partial\phi} = 0 \Leftrightarrow -\mu^2\phi + \lambda\phi^3 = 0$

$$\Rightarrow \quad \phi_0 = \pm\frac{\mu}{\sqrt{\lambda}} = \pm v.$$

Scalar field develops “**vacuum expectation value**” (v = vev).

Anderson-Higgs mechanism

Couple complex scalar field to a photon

gauge symmetry:

$$\phi(x) \to e^{i\alpha(x)}\phi(x)$$

$$A_\mu(x) \to A_\mu + \frac{1}{g}\partial_\mu\alpha(x).$$

➡

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$$\partial_\mu\phi \quad \text{becomes} \quad D_\mu\phi = (\partial_\mu - igA_\mu)\phi$$

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➡ $$\mathscr{L} = D_\mu\phi^\dagger D_\mu\phi + \mu^2\phi^\dagger\phi - \frac{\lambda}{2}\left(\phi^\dagger\phi\right)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

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Groundstate $A_\mu^{(0)} = 0$ $\phi^{(0)} = v = \frac{\sqrt{\mu}}{\lambda}$ (vev)

(Would it have been problematic if the photon developed a vacuum value?)

Higgs-Anderson Mechanism

Particle spectrum

vev

real scalar fields

Expand around minimum:

$$\phi(x) = \overset{\text{vev}}{v} + \frac{1}{\sqrt{2}}\Big(\chi(x) + i\theta(x)\Big)$$

Higgs-Anderson Mechanism

Particle spectrum

vev

real scalar fields

Expand around minimum:

$$\boxed{\phi(x) = v + \frac{1}{\sqrt{2}}\left(\chi(x) + i\theta(x)\right)}$$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu\phi^\dagger D_\mu\phi + \mu^2\phi^\dagger\phi - \frac{\lambda}{2}\left(\phi^\dagger\phi\right)^2$$

$$\Downarrow$$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}^2 + e^2v^2A_\mu A^\mu + \frac{1}{2}(\partial_\mu\chi)^2 - \mu^2\chi^2 + \dots$$

Higgs-Anderson Mechanism

Particle spectrum

vev

real scalar fields

Expand around minimum:

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$$\Downarrow$$

Higgs particle

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}^2 + e^2v^2A_\mu A^\mu + \frac{1}{2}(\partial_\mu\chi)^2 - \mu^2\chi^2 + \dots$$

m_A^2 the gauge boson became **massive.**

Higgs-Anderson Mechanism

Particle spectrum

vev

real scalar fields

Expand around minimum: $\boxed{\phi(x) = v + \frac{1}{\sqrt{2}}\left(\chi(x) + i\theta(x)\right)}$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu\phi^\dagger D_\mu\phi + \mu^2\phi^\dagger\phi - \frac{\lambda}{2}\left(\phi^\dagger\phi\right)^2$$

$$\Downarrow$$

Higgs particle

$$\mathscr{L} = -\frac{1}{4}F^2_{\mu\nu} + \underbrace{e^2v^2}_{m_A^2}A_\mu A^\mu + \frac{1}{2}(\partial_\mu\chi)^2 - \mu^2\chi^2 + \ldots$$

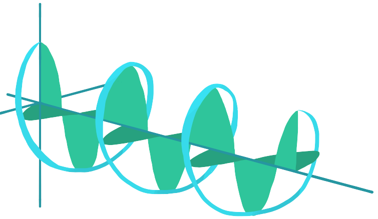
the gauge boson became **massive.**

What happened to the $\theta(x)$ field? It got **eaten by the gauge boson**!

Count physical degrees of freedom

$$\boxed{\phi(x) = v + \frac{1}{\sqrt{2}}\big(\chi(x) + i\theta(x)\big)}$$

massless photon



2 polarizations

(2 transverse)

complex scalar:

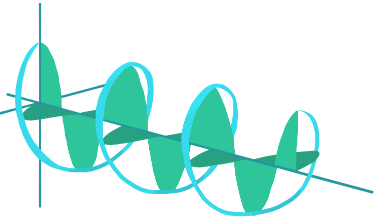
2 real degrees of freedom

$\sum$ **2**+**2** = **4**

Count physical degrees of freedom

$$\boxed{\phi(x) = v + \frac{1}{\sqrt{2}}\left(\chi(x) + i\theta(x)\right)}$$

massless photon



2 polarizations

(2 transverse)

$$\langle\phi(x)\rangle = v$$

➡

massive spin s=1

(2s+1) = **3** polarizations

(2 transverse + 1 longitudinal)

complex scalar:

2 real degrees of freedom

$\sum$ **2**+**2** = **4**

before SSB

real scalar

1 degree of freedom

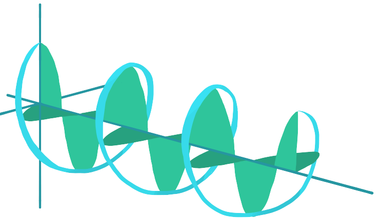
$\sum$ **3**+**1** = **4**

after SSB

Count physical degrees of freedom

$$\phi(x) = v + \frac{1}{\sqrt{2}}\big(\chi(x) + i\theta(x)\big)$$

massless photon



2 polarizations

(2 transverse)

$$\langle \phi(x) \rangle = v$$

➡

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(2s+1) = **3** polarizations

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complex scalar:

2 real degrees of freedom

$\sum$ **2**+**2** = **4**

before SSB

✓

real scalar

1 degree of freedom

$\sum$ **3**+**1** = **4**

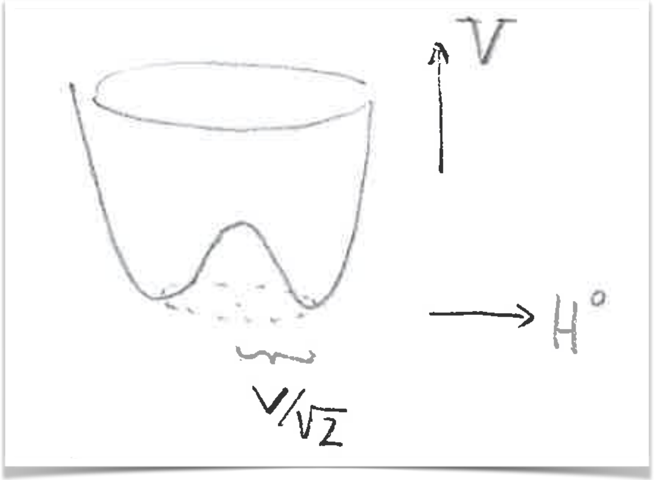
after SSB

Warm-up: Higgs for a SU(2) gauge boson

Higgs must couple to SU(2) bosons:

Complex 2 vector $H(x) = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ $$H(x) \rightarrow e^{i\sigma^a \alpha^a(x)} H(x)$$

$$\mathscr{L}_H = D_\mu H^\dagger D^\mu H - \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$$



$$H(x) = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \frac{1}{\sqrt{2}} e^{i\theta^a(x)\sigma^a} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

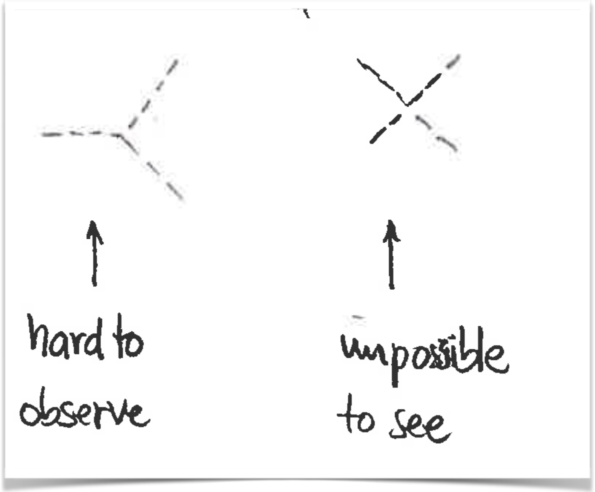
get eaten

Higgs potential

probe at LHC and future machines!

$$V \rightarrow + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

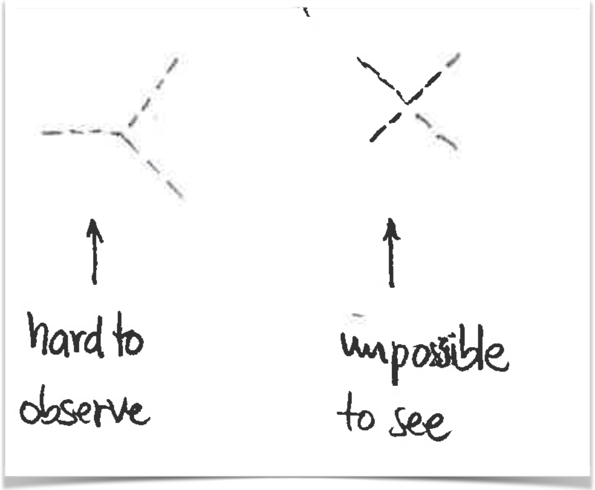
$$m_h^2 = 2\lambda v^2$$



Higgs potential

probe at LHC and future machines!

$$V \to + \overset{\checkmark}{\underset{\substack{\uparrow \\ m_h^2 = 2\lambda v^2}}{\lambda v^2} h^2} + \lambda v h^3 + \frac{\lambda}{4} h^4$$



Higgs potential

probe at LHC and future machines!

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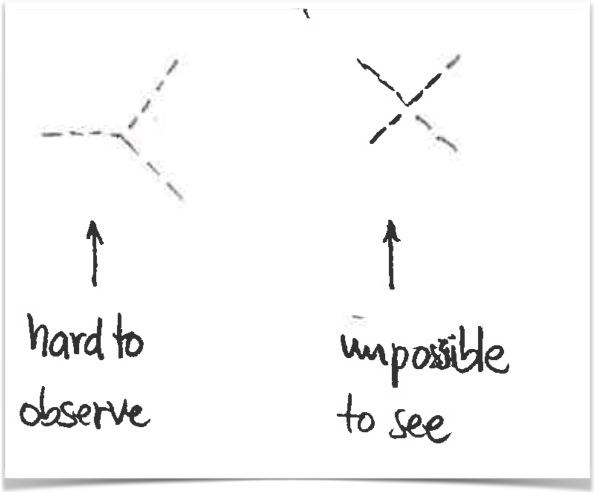
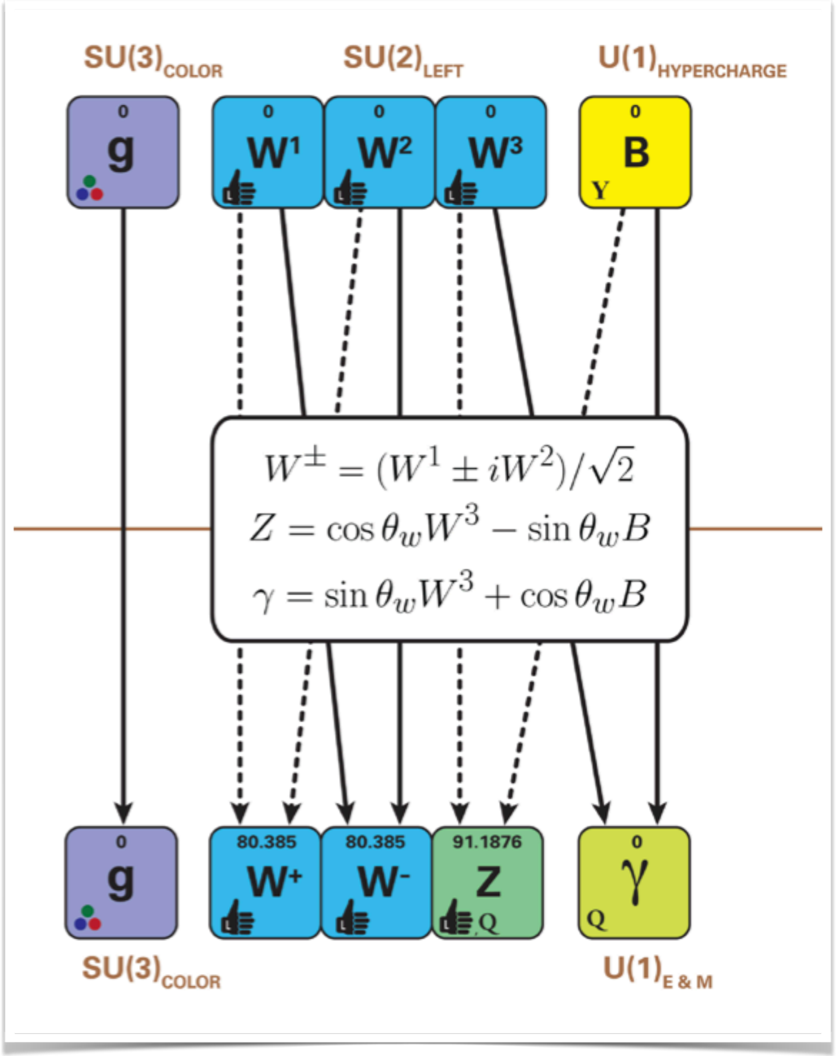


Higgs mechanism for W,Z masses



$$W^{\pm} = (W^1 \pm iW^2)/\sqrt{2}$$
$$Z = \cos\theta_w W^3 - \sin\theta_w B$$
$$\gamma = \sin\theta_w W^3 + \cos\theta_w B$$

To arrive at $W^+, W^-, Z,$ and γ

propose: $SU(2)_L \times U(1)_Y$

Glashow, Salam, Weinberg (Nobel '73)

Higgs mechanism for W,Z masses

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -\mathrm{i} \\ \mathrm{i} & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Gauge structure: $$H(x) \to e^{i\beta(x)}\, e^{i\sigma^a \alpha^a(x)}\, H(x)$$

$U(1)_Y$ $SU(2)_L$

$$D_\mu H = \left(\partial_\mu - ig'\frac{1}{2}B_\mu - ig\frac{\sigma^a}{2}W_\mu^a\right)H$$

Higgs mechanism for W,Z masses

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U(1)Y SU(2)L

$$D_\mu H = \left(\partial_\mu - ig'\frac{1}{2}B_\mu - ig\frac{\sigma^a}{2}W^a_\mu\right)H$$

in components:

$$D_\mu H = \partial_\mu H - \frac{i}{2}\begin{pmatrix} gW^3_\mu + g'B_\mu & \sqrt{2}gW^+_\mu \\ \sqrt{2}gW^-_\mu & -gW^3_\mu + g'B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \tfrac{1}{\sqrt{2}}\left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu\right)$$

Higgs mechanism for W,Z masses

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$U(1)_Y$ $SU(2)_L$

$$D_\mu H = \left(\partial_\mu - i g' \frac{1}{2} B_\mu - i g \frac{\sigma^a}{2} W^a_\mu \right) H$$

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$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\left|D_\mu H\right|^2 = \tfrac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \tfrac{1}{8} \left(W^3_\mu \; B_\mu\right) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

Higgs mechanism for W,Z masses

Gauge structure: $H(x) \to e^{i\beta(x)}\, e^{i\sigma^a \alpha^a(x)}\, H(x)$

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$U(1)_Y$ *$SU(2)_L$*

$$D_\mu H = \left(\partial_\mu - i g' \frac{1}{2} B_\mu - i g \frac{\sigma^a}{2} W^a_\mu \right) H$$

Diagonalize

in components:

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} g W^3_\mu + g' B_\mu & \sqrt{2} g W^+_\mu \\ \sqrt{2} g W^-_\mu & -g W^3_\mu + g' B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \tfrac{1}{\sqrt{2}} \left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu \right)$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$|D_\mu H|^2 = \tfrac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \tfrac{1}{8} \left(W^3_\mu \, B_\mu \right) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

Higgs mechanism for W,Z masses

Diagonalize

$$A = \sin\theta_W W_3 + \cos\theta_W B$$

$$Z = \cos\theta_W W_3 - \sin\theta_W B$$

$$M_A^2$$

$$D_\mu H^\dagger D^\mu H \to \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} + \frac{\left(g^2 + g'^2\right) v^2}{4} \frac{1}{2} Z_\mu Z^\mu + 0 \cdot A_\mu A^\mu$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$M_W^2 \qquad M_Z^2$$

$$\sin\theta_w = \frac{g'}{\sqrt{g^2 + g'^2}}$$

Higgs mechanism for W,Z masses

Diagonalize

$$A = \sin\theta_W W_3 + \cos\theta_W B$$

$$Z = \cos\theta_W W_3 - \sin\theta_W B$$

$$D_\mu H^\dagger D^\mu H \to \frac{g^2 v^2}{\underset{\overset{\uparrow}{M_W^2}}{4}} W_\mu^+ W^{-\mu} + \frac{\left(g^2 + g'^2\right) v^2}{\underset{\overset{\uparrow}{M_Z^2}}{4}} \frac{1}{2} Z_\mu Z^\mu + \overset{\overset{M_A^2}{\downarrow}}{0} \cdot A_\mu A^\mu$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \nearrow$$

$$v = 246\,\text{GeV}$$

$$g = 0.65, \quad g' = 0.36$$

$$M_W = 80.38\,\text{GeV}$$

$$M_Z = 90.19\,\text{GeV}$$

$$\sin^2\theta_w = 0.231$$

$$\sin\theta_w = \frac{g'}{\sqrt{g^2 + g'^2}}$$

Electro-weak unification

$$e = \frac{g\,g'}{\sqrt{g^2 + g'^2}}$$

The electro-magnetic coupling is derived from a more fundamental theory!

Higgs mechanism for W,Z masses

U(1)Y SU(2)L

$$D_\mu H = \left(\partial_\mu - ig'\frac{1}{2}B_\mu - ig\frac{\sigma^a}{2}W_\mu^a\right)H$$

$$D_\mu H^\dagger D^\mu H \to \frac{g^2v^2}{4}W_\mu^+W^{-\mu} + \frac{\left(g^2 + g^2\right)v^2}{4}\frac{1}{2}Z_\mu Z^\mu$$

M_W^2 M_Z^2

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v\end{pmatrix}$$

$$\sin\theta_w = \frac{g}{\sqrt{g^2 + g'^2}}$$

$$W^\pm = \frac{W_1 \mp iW_2}{\sqrt{2}}$$

$$A = \sin\theta_W W_3 + \cos\theta_W B$$

$$Z = \cos\theta_W W_3 - \sin\theta_W B$$

Fermion masses

The SM is chiral. Left- and right-handed electrons are different particles. But m

$$m_e(\bar{e}_L e_R + \bar{e}_R e_L)$$

Not gauge invariant!

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \to e^{i\sigma^a \alpha^a(x)} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$e_R \to e^{-i\beta(x)} e_R$$

Fermion masses

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$$m_e(\bar{e}_L e_R + \bar{e}_R e_L)$$

?

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Fermion masses

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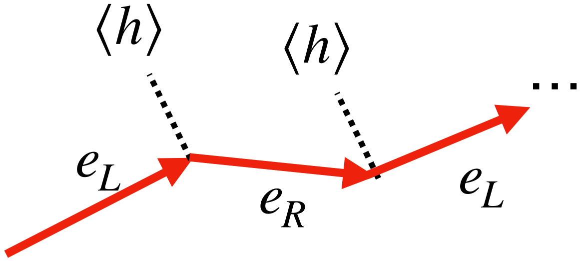
$$e_R \rightarrow e^{-i\beta(x)} e_R$$

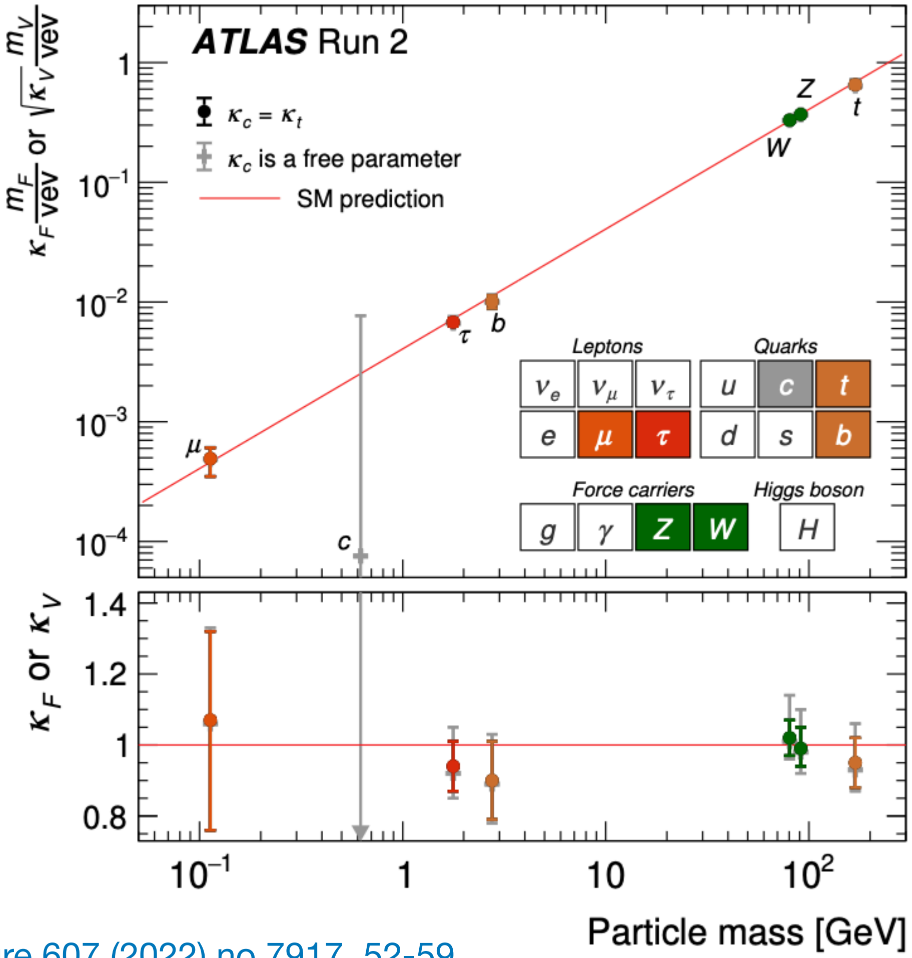
Higgs to the rescue! Fermion masses are emergent and are a result of interacting with the Higgs vacuum expectation value.

$$y_e \begin{pmatrix} \bar{\nu}_L \\ \bar{e}_L \end{pmatrix} \cdot \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} e_R = \frac{y_e v}{\sqrt{2}} \left(\bar{e}_L e_R + \frac{1}{v} \bar{e}_L e_R h \right)$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

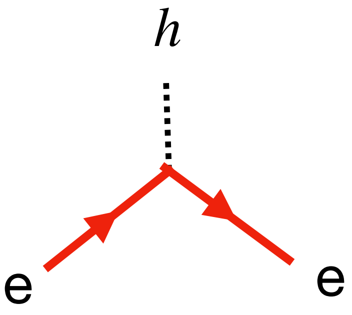


Is the Higgs coupling proportional to mass of particle?



Nature 607 (2022) no.7917, 52-59

$$\frac{y_e v}{\sqrt{2}}\left(\bar{e}_L e_R + \frac{1}{v}\bar{e}_L e_R h\right) = m_e\left(\bar{e}_L e_R + \frac{1}{v}\bar{e}_L e_R h\right)$$



$$= \frac{m_e}{v}$$

?

Flavor in the SM

Higgs matter interactions are matrices, introduce generation hopping interactions (flavor change)

$$\mathscr{L}_{yukawa} = Y_L^{ij} \begin{pmatrix} \bar{\nu}_L \\ \bar{l}_L \end{pmatrix}^i H\, l_R^j + Y_U^{ij} \begin{pmatrix} \bar{u}_L \\ \bar{d}_L \end{pmatrix}^i \tilde{H}\, u_R^j + Y_D^{ij} \begin{pmatrix} \bar{u}_L \\ \bar{d}_L \end{pmatrix}^i H\, d_R^j$$

Flavor in the SM

Higgs matter interactions are matrices, introduce generation hopping interactions (flavor change)

$$\mathscr{L}_{yukawa} = Y_L^{ij} \begin{pmatrix} \bar{\nu}_L \\ \bar{l}_L \end{pmatrix}^i H\, l_R^j + Y_U^{ij} \begin{pmatrix} \bar{u}_L \\ \bar{d}_L \end{pmatrix}^i \tilde{H}\, u_R^j + Y_D^{ij} \begin{pmatrix} \bar{u}_L \\ \bar{d}_L \end{pmatrix}^i H\, d_R^j$$

$$Y_U \approx \begin{pmatrix} 6 \cdot 10^{-6} & -0.001 & 0.008 + 0.004i \\ 1 \cdot 10^{-6} & 0.004 & -0.04 + 0.001 \\ 8 \cdot 10^{-9} + 2 \cdot 10^{-8} i & 0.0002 & 0.98 \end{pmatrix}$$

$$Y_D \approx \mathrm{diag}\begin{pmatrix} 2 \cdot 10^{-5} & 0.0005 & 0.02 \end{pmatrix}$$

Flavor in the SM

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What is the reason for this ?

compare to:

$g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{Higgs} \sim 1$

$$Y_D \approx \mathrm{diag}\left(2 \cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

Flavor in the SM

Higgs matter interactions are matrices, ir
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Flavor in the SM

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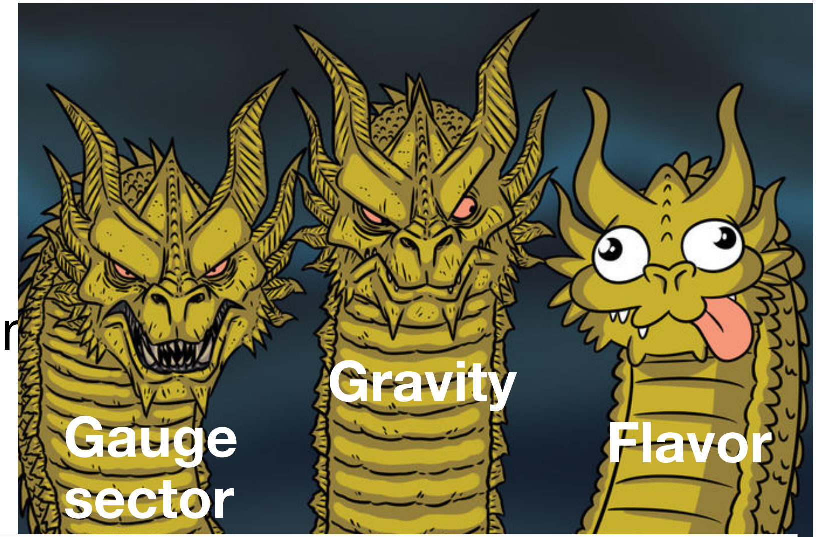

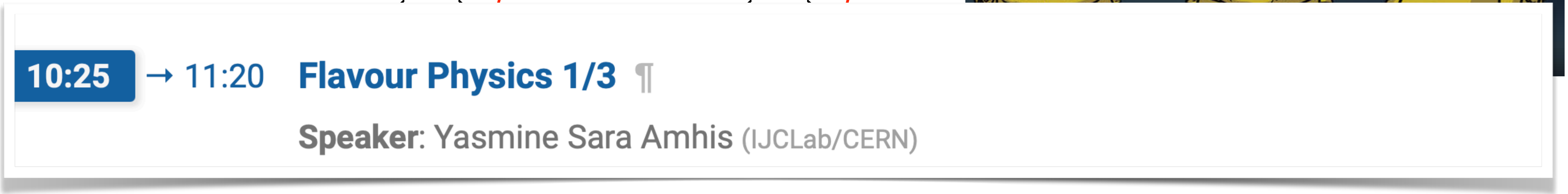
10:25 → 11:20 **Flavour Physics 1/3** ¶

Speaker: Yasmine Sara Amhis (IJCLab/CERN)

$$Y_U \approx \begin{pmatrix} 6\cdot 10^{-6} & -0.001 & 0.008+0.004i \\ 1\cdot 10^{-6} & 0.004 & -0.04+0.001 \\ 8\cdot 10^{-9}+2\cdot 10^{-8}i & 0.0002 & 0.98 \end{pmatrix}$$

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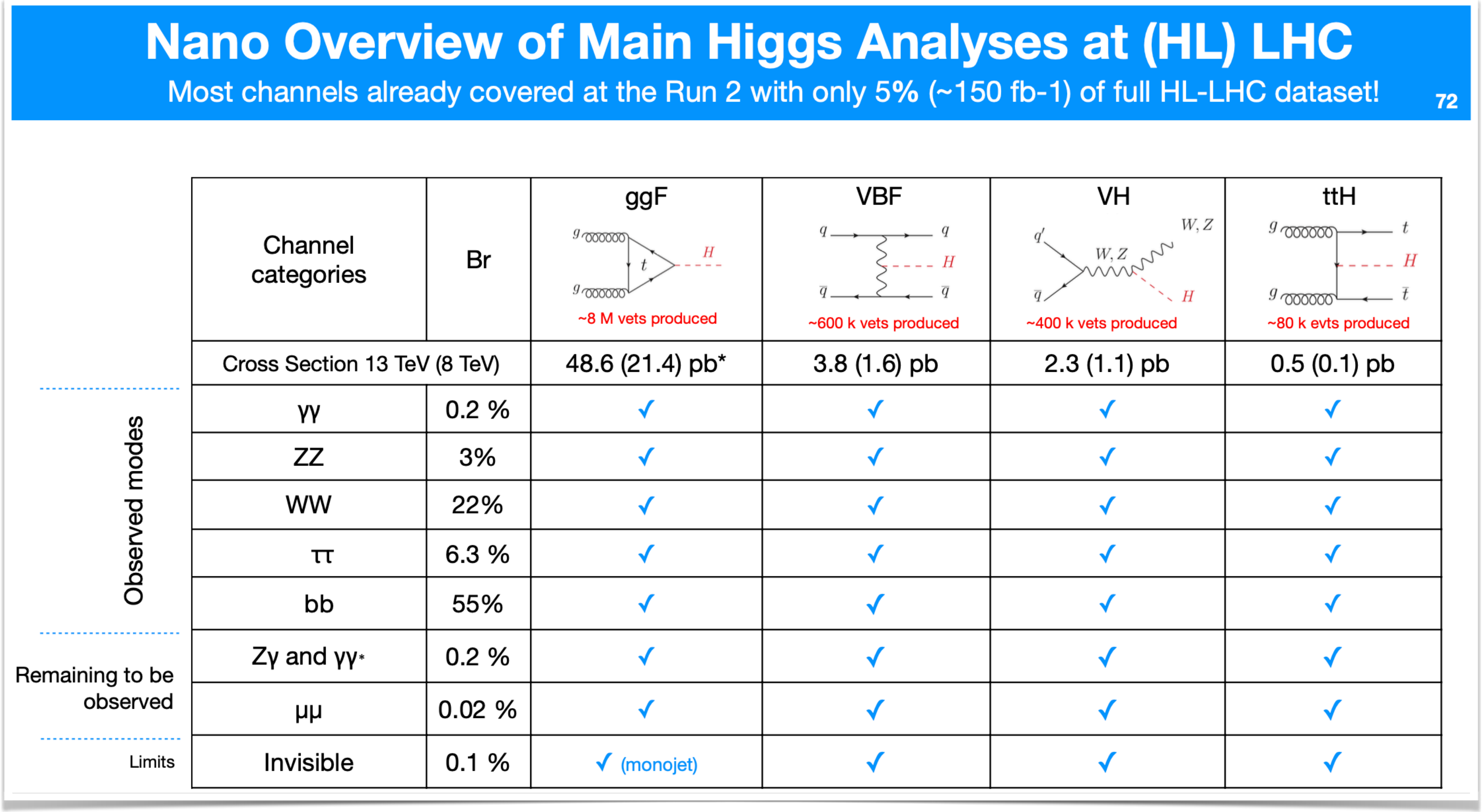
LHC is pinning down the Higgs (> 8 Million produced)



Nano Overview of Main Higgs Analyses at (HL) LHC

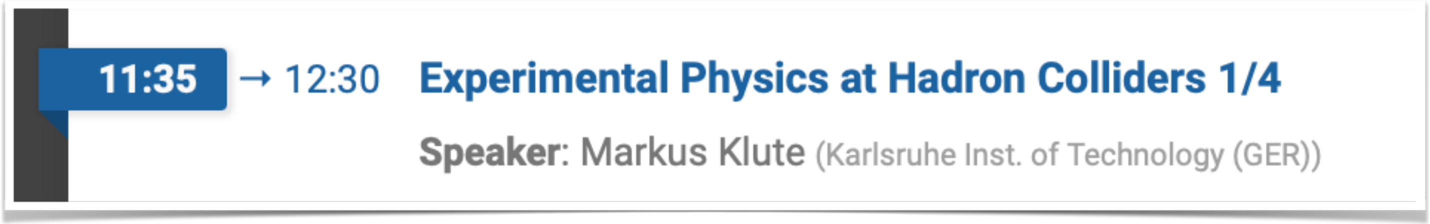
Most channels already covered at the Run 2 with only 5% (~150 fb-1) of full HL-LHC dataset!

72

	Channel categories	Br	ggF ~8 M vets produced	VBF ~600 k vets produced	VH ~400 k vets produced	ttH ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

courtesy Marumi Kado

much more on the Higgs searches here:



11:35 → 12:30 **Experimental Physics at Hadron Colliders 1/4**

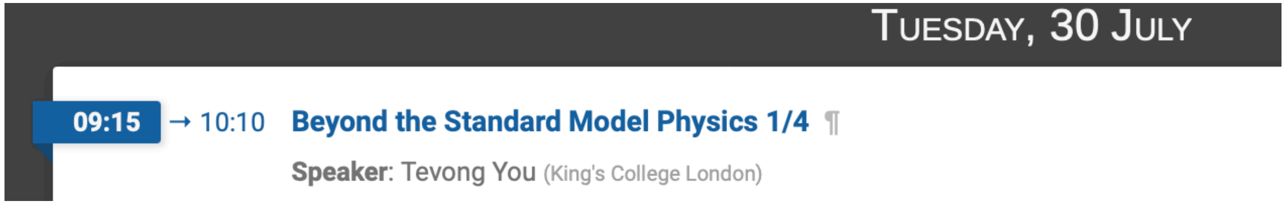
Speaker: Markus Klute (Karlsruhe Inst. of Technology (GER))

Good news: SM is incomplete

At least five missing pieces in the SM

- non-baryonic dark matter
- neutrino mass
- dark energy
- inflation
- baryon asymmetry

We don't know their energy scales.

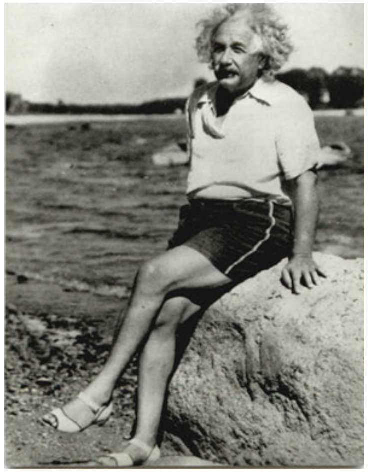


TUESDAY, 30 JULY

09:15 → 10:10 **Beyond the Standard Model Physics 1/4** ¶

Speaker: Tevong You (King's College London)

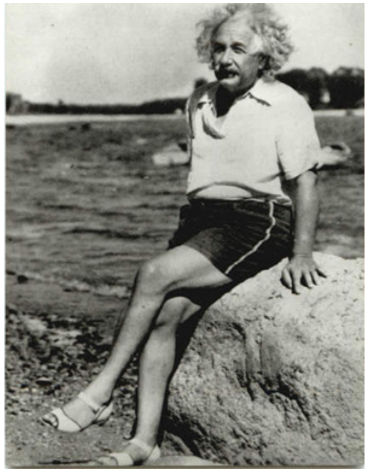
–Henri Poincaré's recommendation letter for A. Einstein, 1911



"I do not mean to say that all these anticipations will withstand the test of experiment on the day such a test would become possible. Since he seeks in all directions one must, on the contrary, expect most of the trails […] to be blind alleys.

—Henri Poincaré's recommendation letter for

A. Einstein, 1911



"I do not mean to say that all these anticipations will withstand the test of experiment on the day such a test would become possible. Since he seeks in all directions one must, on the contrary, expect most of the trails […] to be blind alleys.

But one must hope at the same time that one of the directions he has indicated may be the right one, and that is enough. This is indeed how one should proceed. The role of mathematical physics is to ask the right questions, and experiment alone can resolve them. "

Enjoy the rest of your summer at CERN!

Office hours: 2:00-3:00 (today)

Office: 4/2-026

andreas.weiler@tum.de