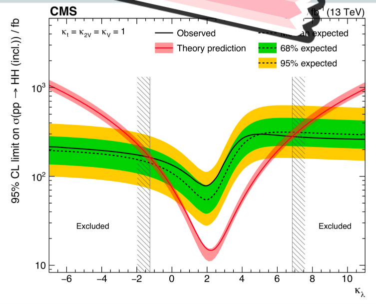
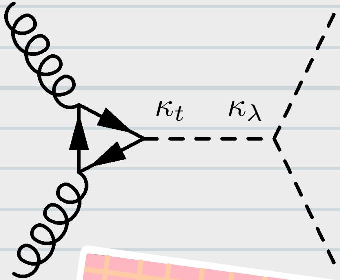
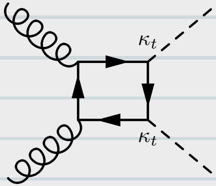
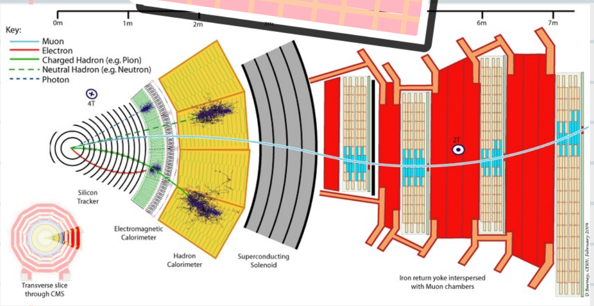




Higgs pair production at the LHC



Agni Bethani, 19th July 2022



In this talk

01 Elementary particles

The Standard Model of elementary particles and their role.

02 Physics in Colliders

What do we do at particle colliders?

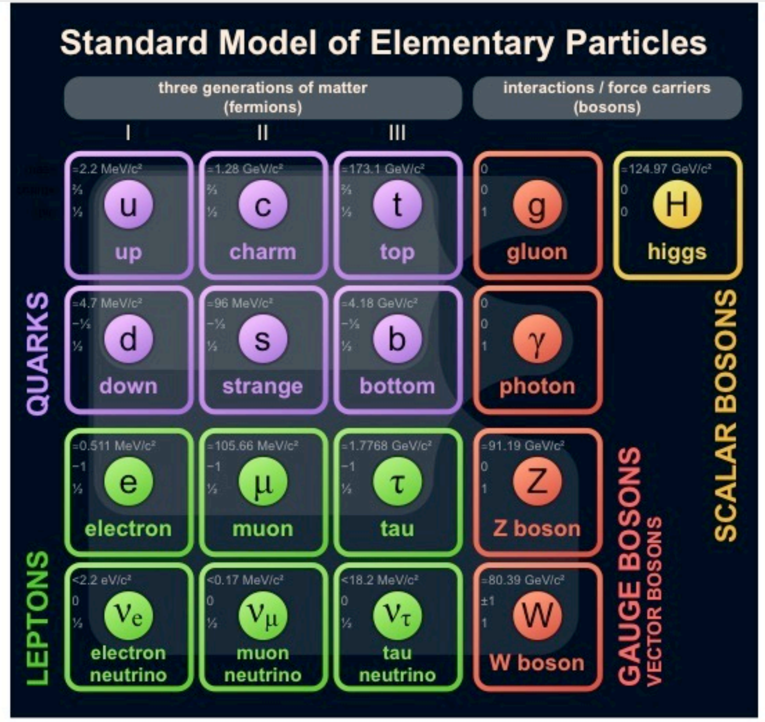
03 Higgs physics

Why is it important to study Higgs and in particular HH physics?

04 Analysis methods

How do we extract results out of our data?

Elementary particles



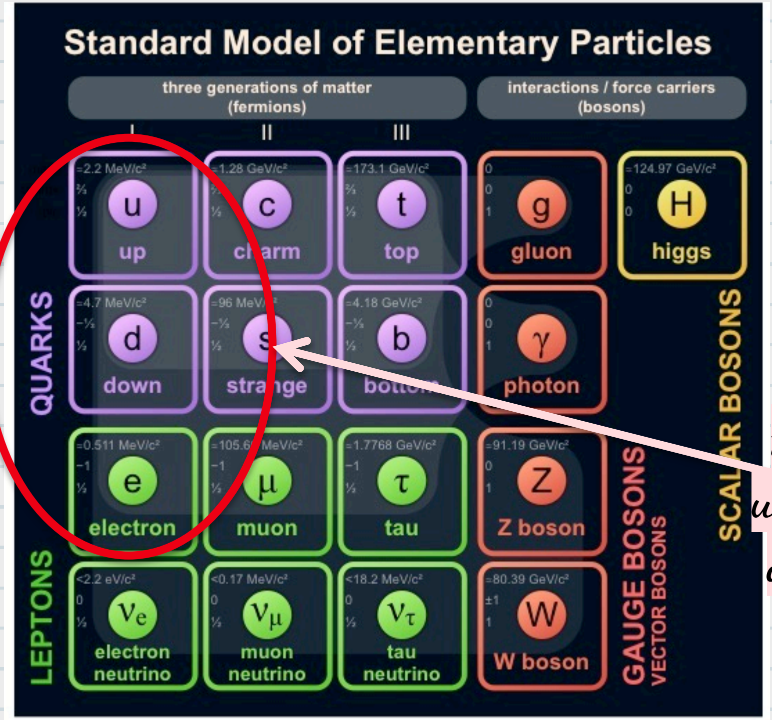
Fermions

leptons and quarks
make up all matter

Bosons

Carriers of forcers
eg. photon carrier of electromagnetic interactions and gluon is the carrier of the strong force!

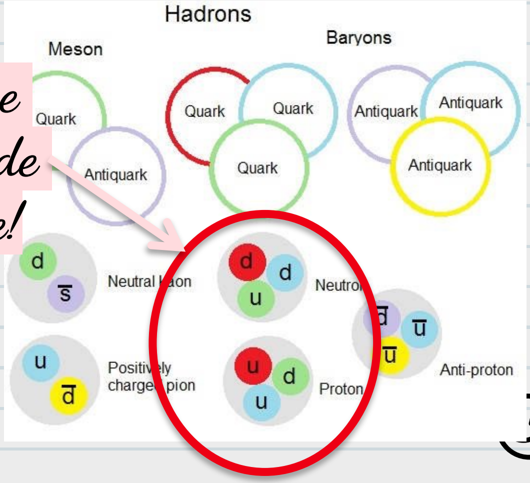
Elementary particles



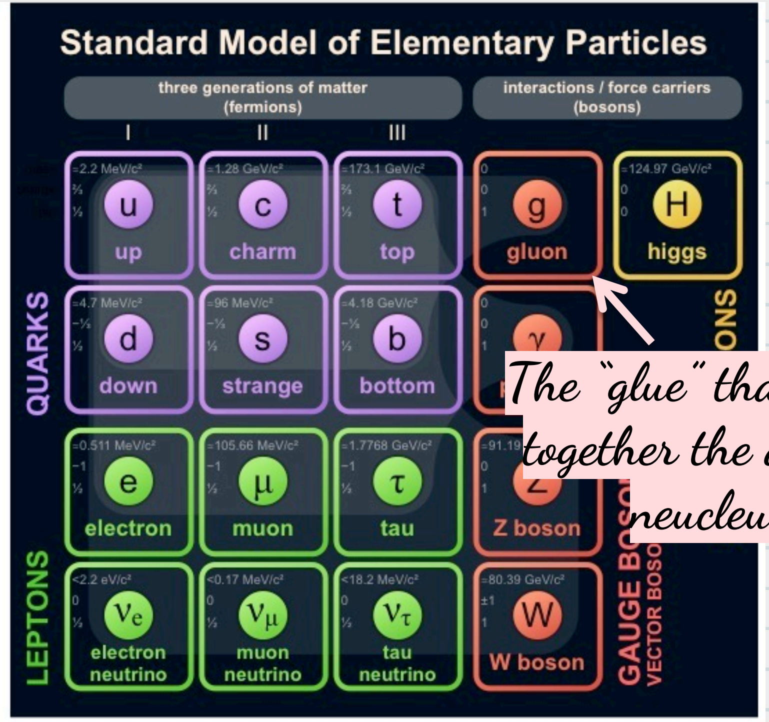
All atoms in the universe are made out of just these!

Fermions

leptons and quarks make up all matter



Elementary particles



The "glue" that holds together the atomix neucleus

Fermions

leptons and quarks
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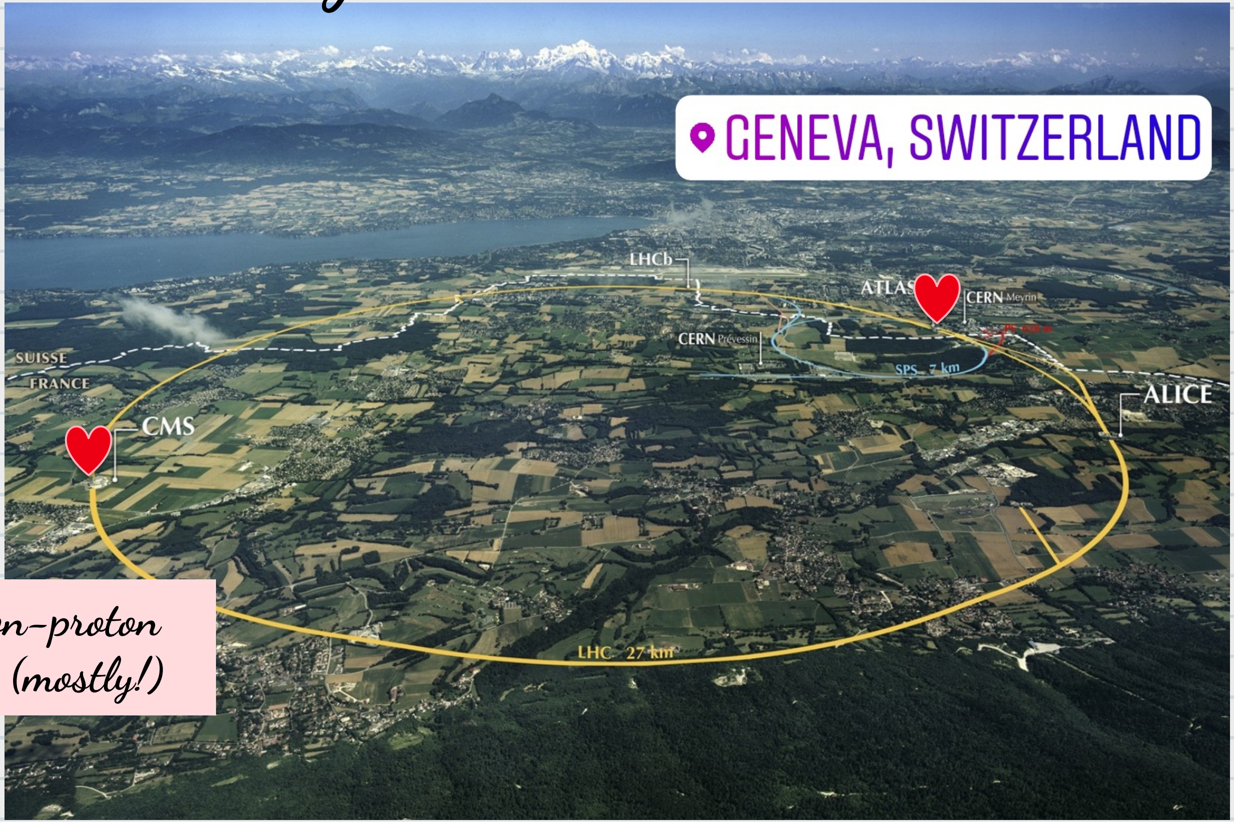
Bosons

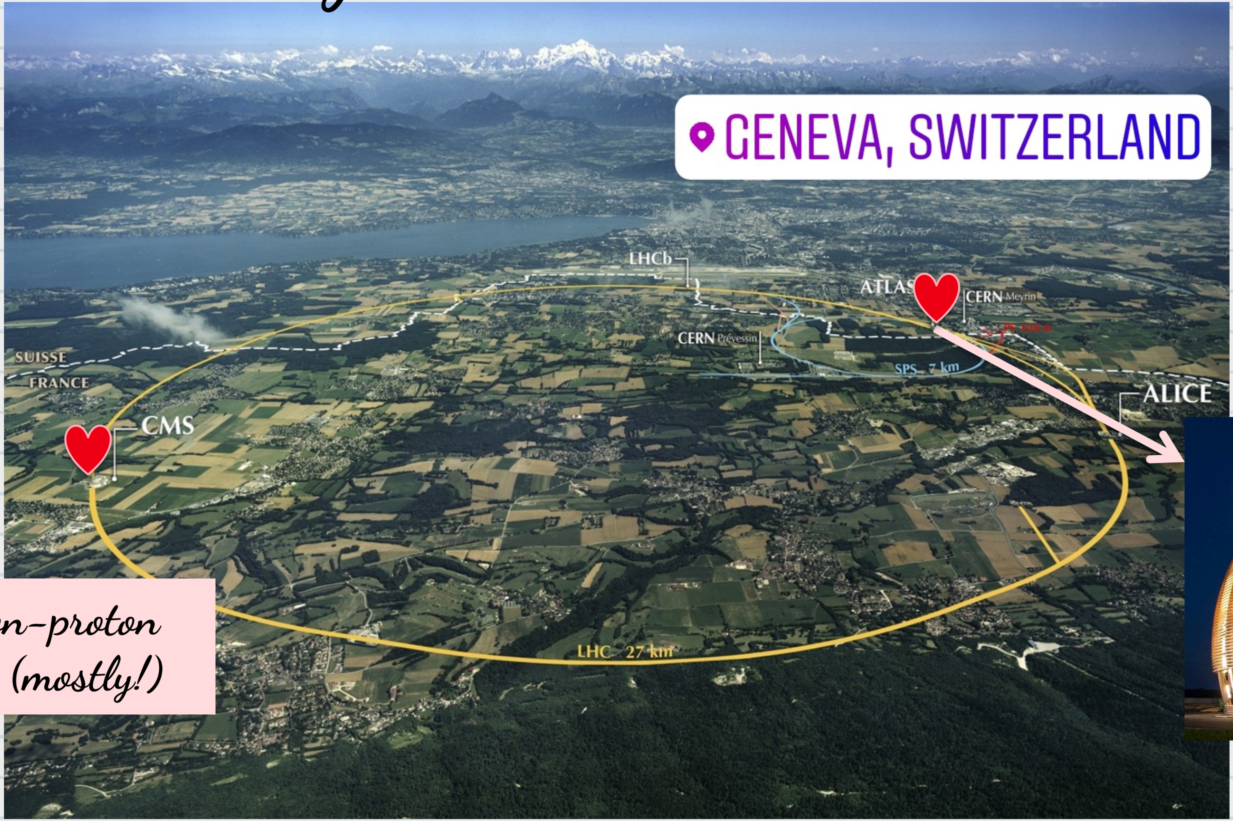
Carriers of forcers
eg. photon carrier of electromagnetic interactions and gluon is the carrier of the strong force!

The Lharge hadron collider (LHC)



A proton-proton collider (mostly!)

The Lharge hadron collider (LHC)



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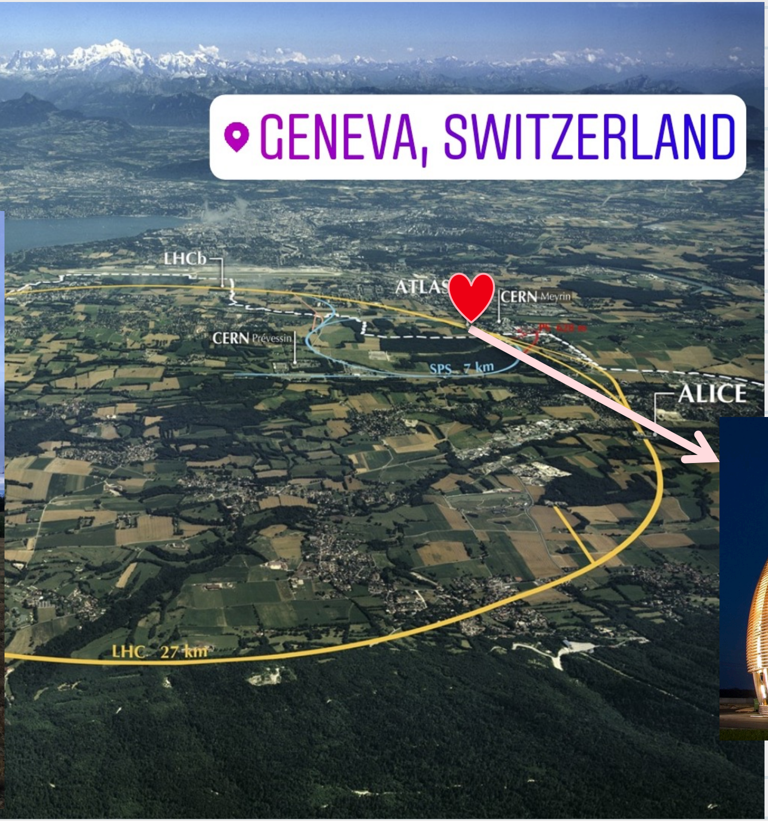
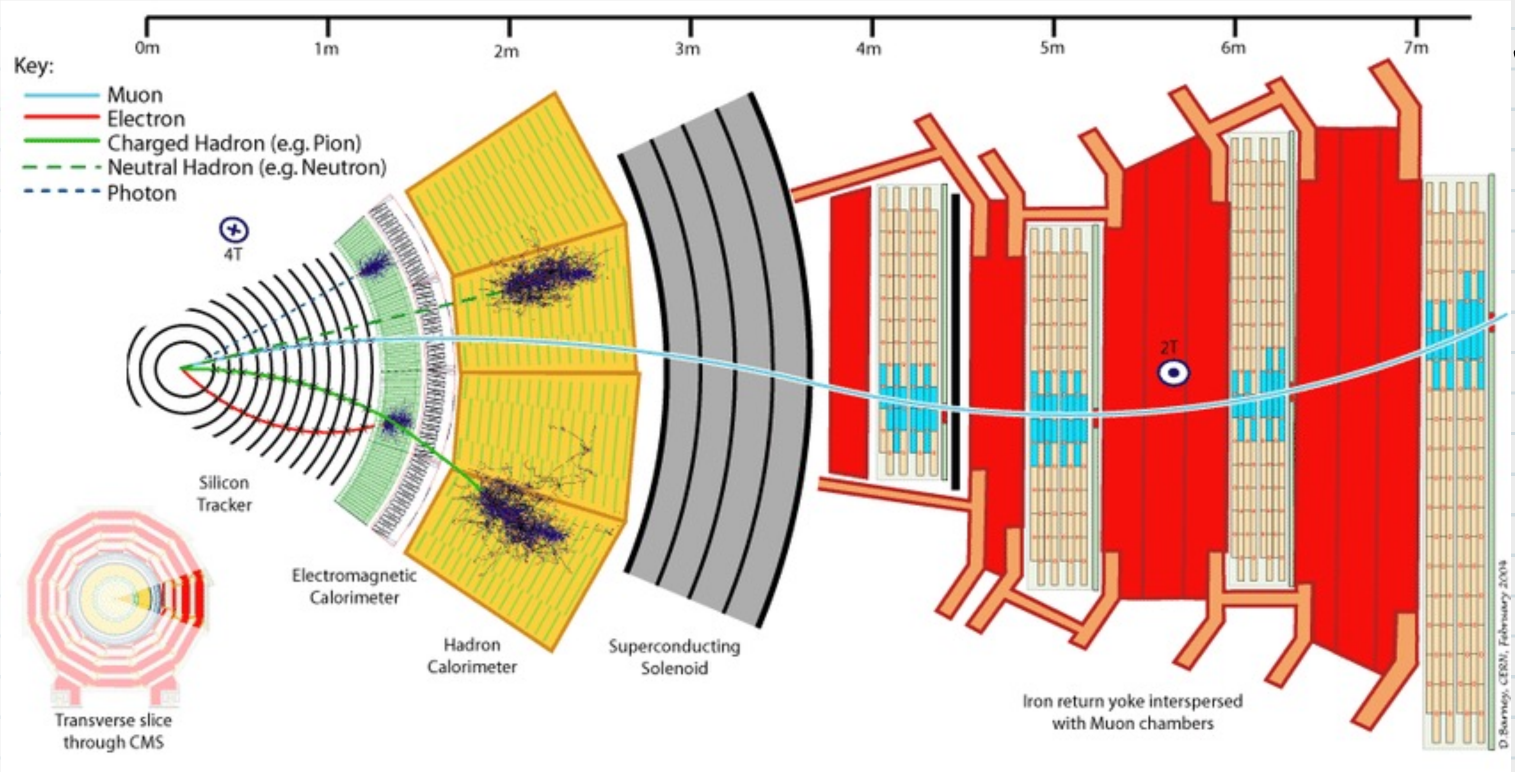
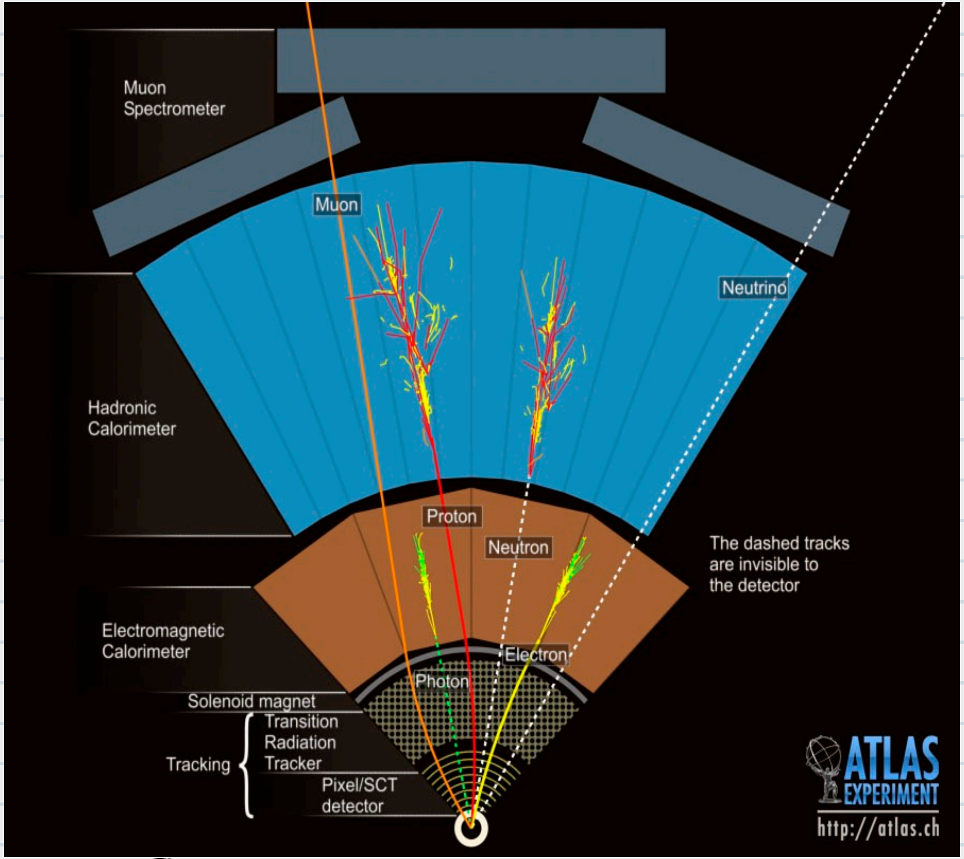


CMS: general purpose detector



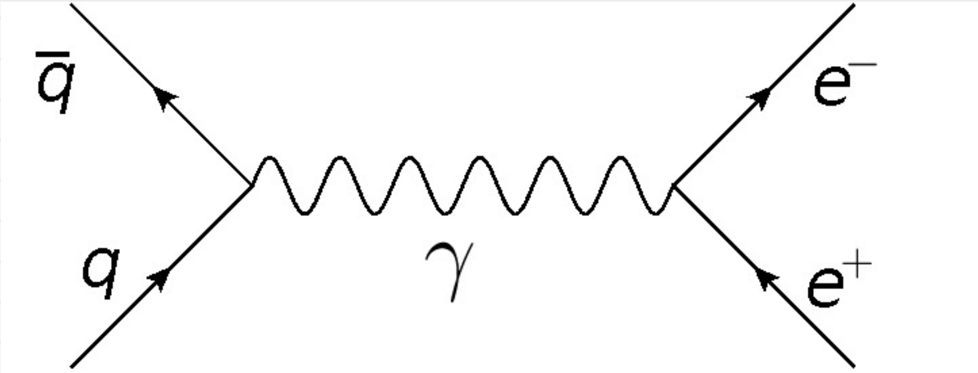
ATLAS : general purpose detector



How do we study particle collisions and decays

Colliders

Initial state
Production mechanism
Cross-section
(how frequent a process is)



we call these feynnman diagrams

Detectors

Final state
Decay products
Branching Ratio
(what % of the decays result in this final state)

How do we study particle collisions and decays

Colliders

Initial state
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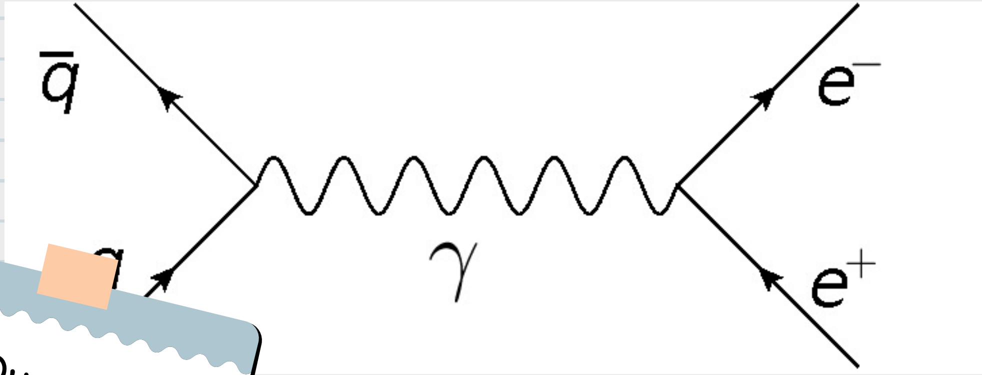


Detectors

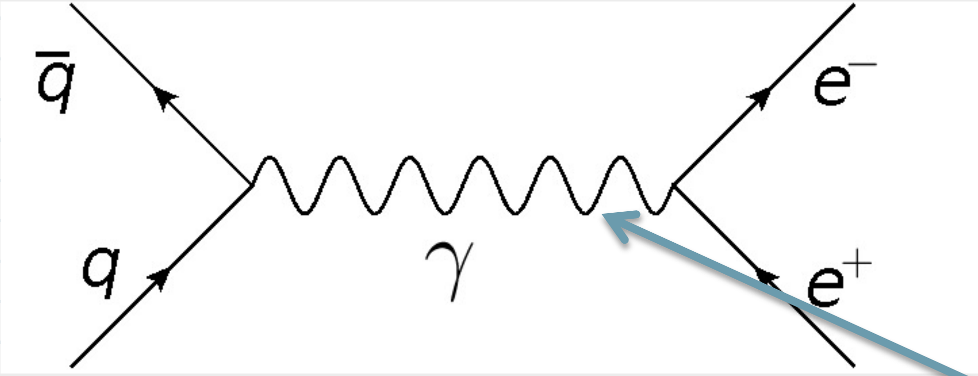
Final state
Decay products
Branching Ratio
(what % of the decays result in this final state)

Question:
What are the initial state particles at the Large Hadron Collider?
(proton-proton collisions)

How do we study particle collisions and decays

Colliders

Initial state
Production mechanism
Cross-section
(how frequent a process is)



we call these feynnman diagrams

Detectors

Final state
Decay products
Branching Ratio
(what % of the decays result in this final state)

Mediator of interaction
in this case a photon

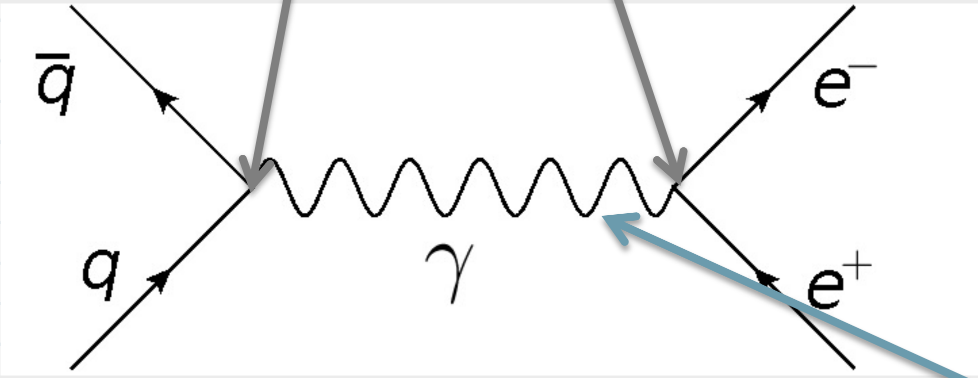
How do we study particle collisions and decays

the "couplings" tell us how particles interact with each other!

Couplings!

Colliders

Initial state
Production mechanism
Cross-section
(how frequent a process is)



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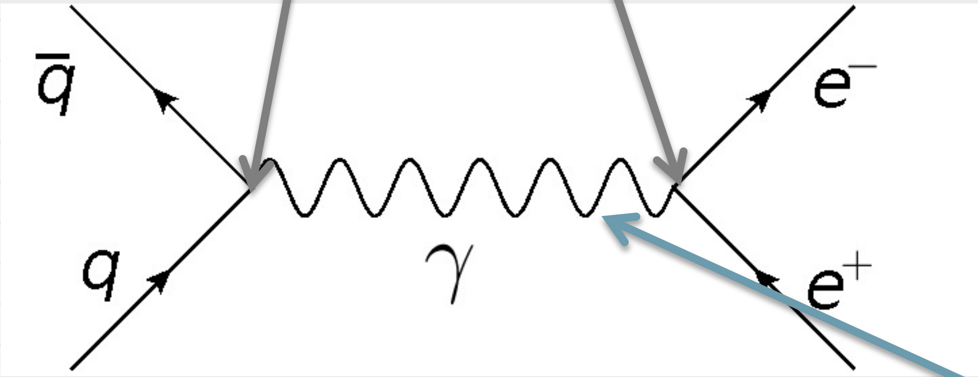

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Detectors

Final state
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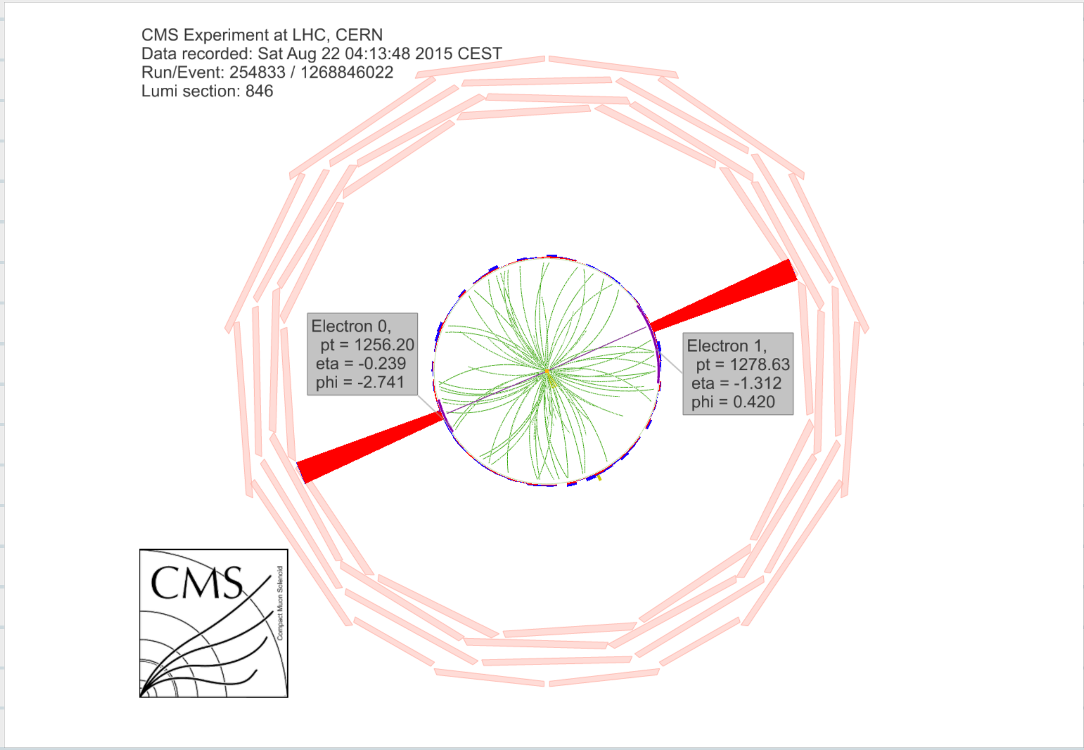
(what % of the decays result in this final state)

Mediator of interaction

This is what it looks like in real life!



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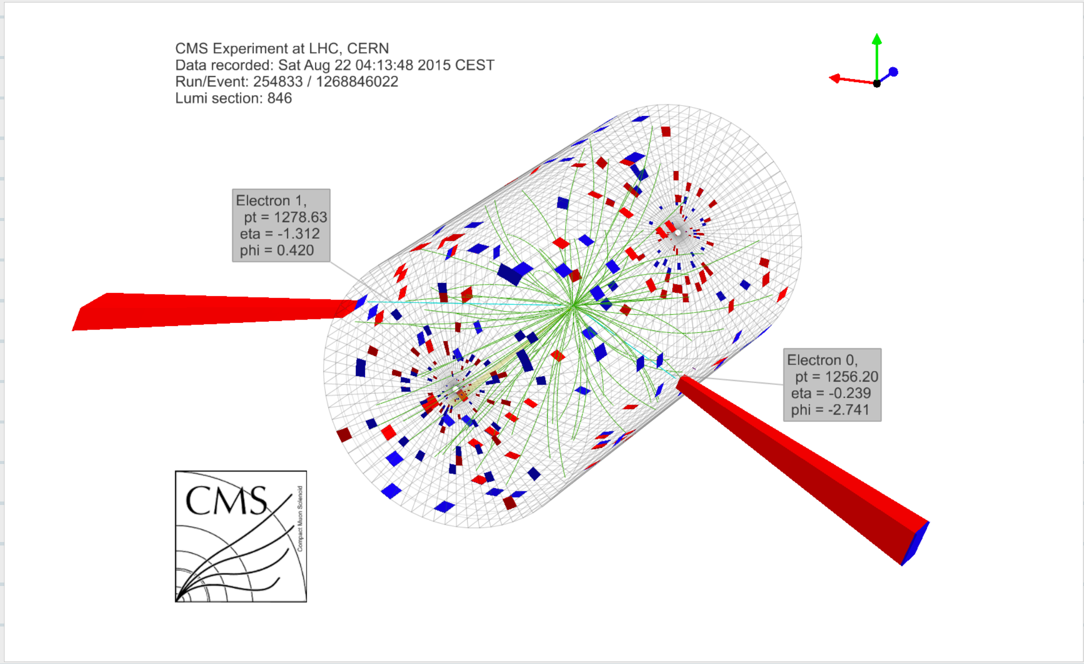
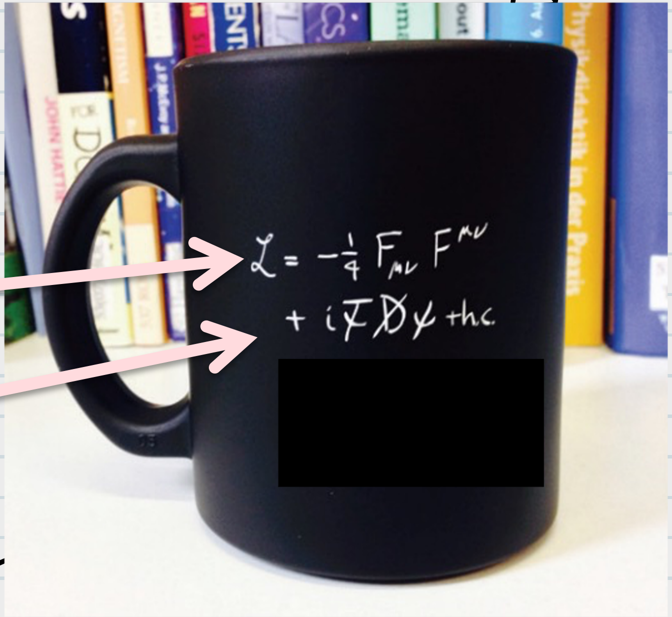


The Standard Model(SM) Lagrangian

- The mathematical formulation of the SM is complex.
- The Lagrangian fills several pages
- Ultra-short version

Describes all bosons and their interactions to each other. (except the Higgs boson)

Boson interactions with fermions. The fields ψ describe quarks and leptons



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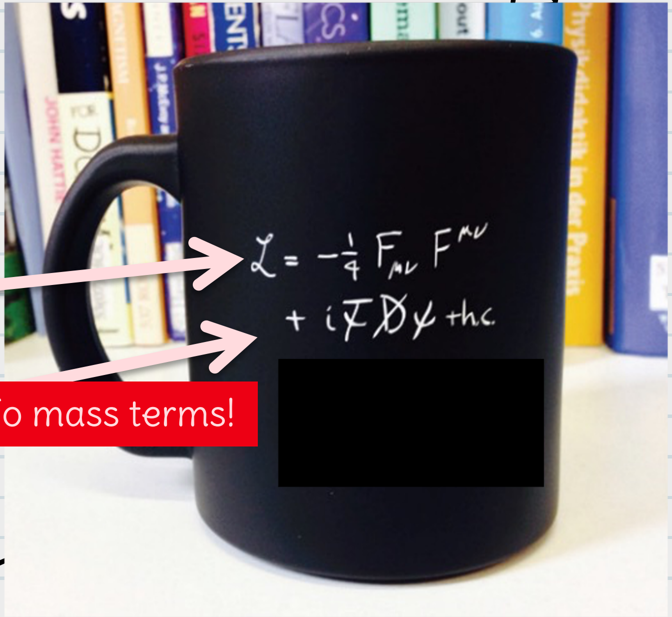
Describes all bosons and their interactions to each other. (except the Higgs boson)

Boson interactions with fermions. The fields ψ describe quarks and leptons

No mass terms!



The Standard Model(SM) Lagrangian

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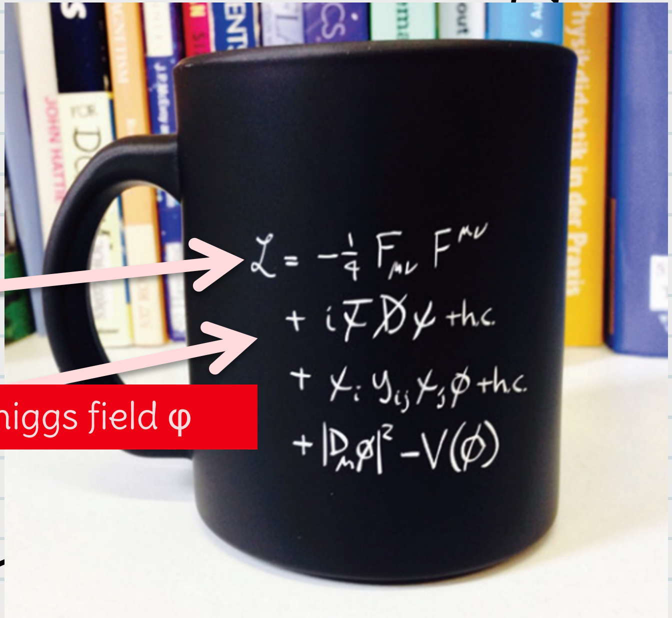
Describes all bosons and their interactions to each other. (except the Higgs boson)

Adding higgs field φ

Boson interactions with fermions. The fields ψ describe quarks and leptons



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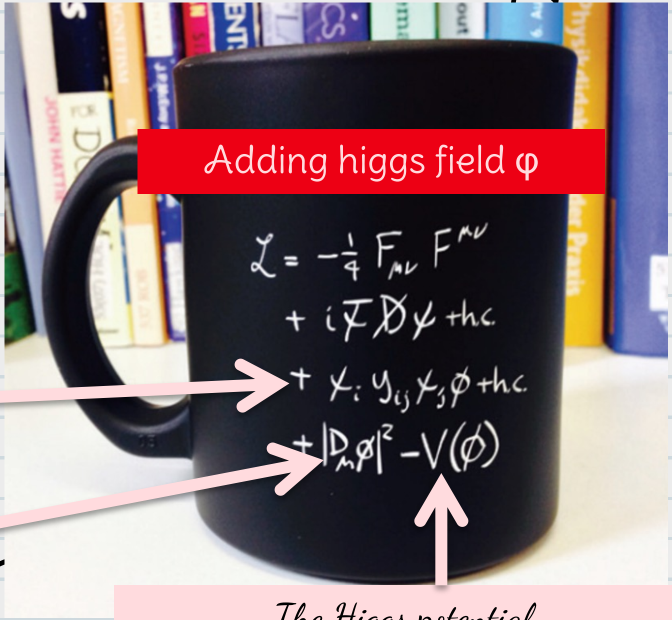

Fermions couple to the Higgs field φ and obtain mass.
Have you heard of Yukawa y_{ij} couplings?

Bosons couple to the Higgs field

The Higgs potential

10 years ago

Higgs boson discovery!

- first measurement of its mass and spin
- Observed only the most common production mechanisms
- Only two decay final states

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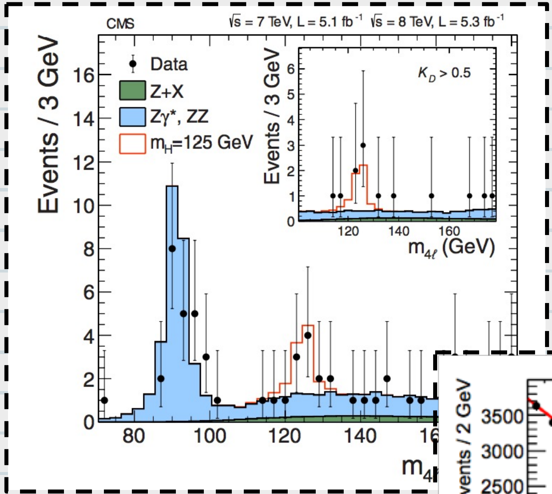
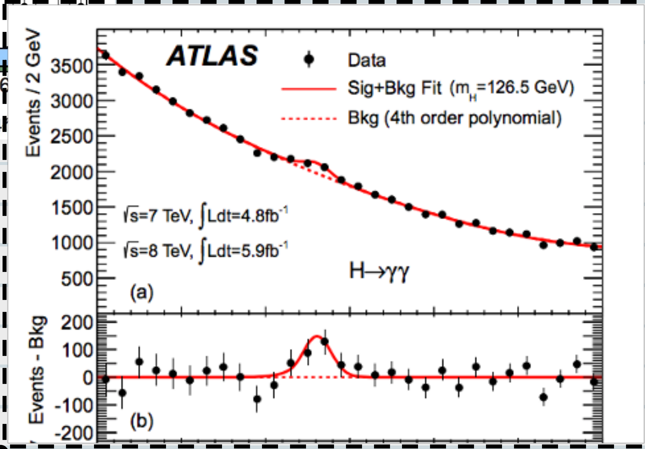
CMS Higgs discovery paper



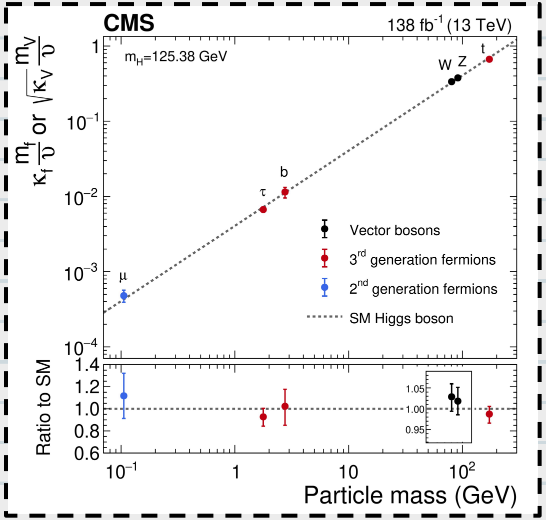


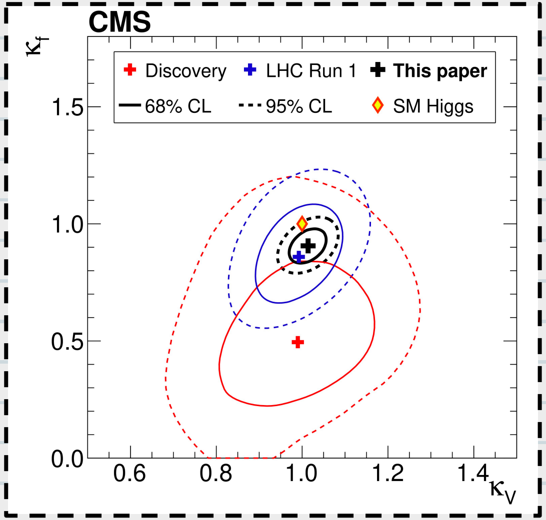
ATLAS Higgs discovery paper

Now

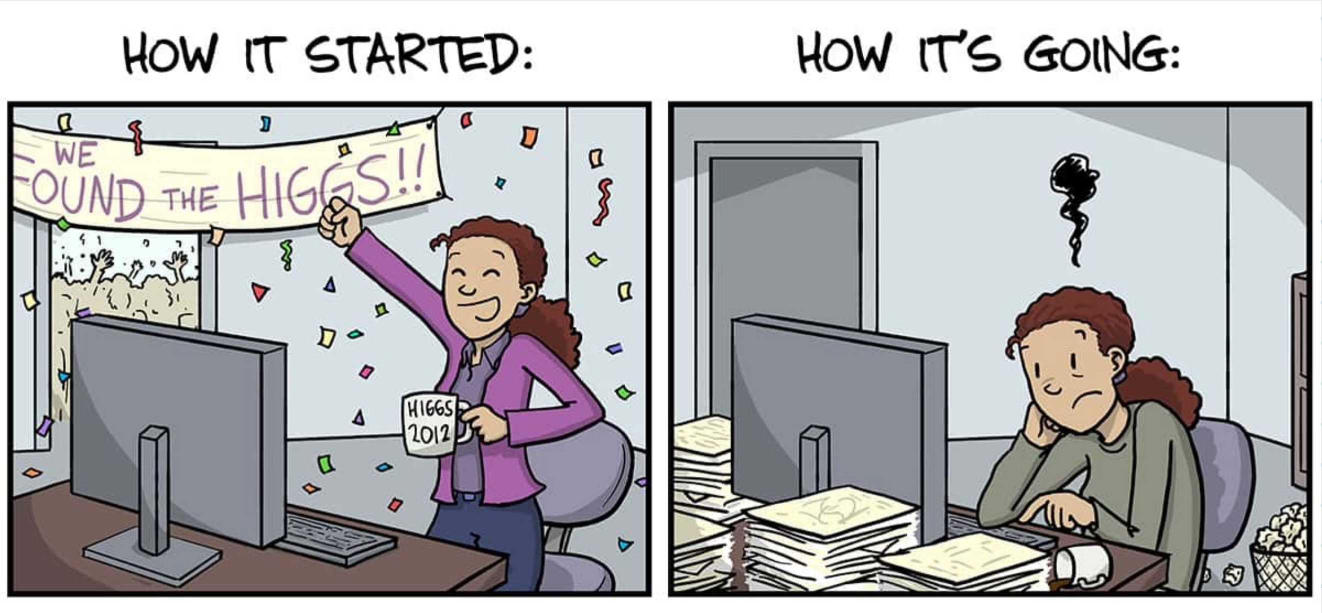
Precision measurements of the Higgs mass
Measurements of Higgs couplings to other particles
There is a lot we still don't know!

"A portrait of the Higgs boson by the CMS experiment ten years after the discovery"
published recently in Nature
Includes latest measurements on Higgs properties





In other words...



❀ The Higgs potential

- Higgs potential: $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$
- Expand around the vacuum expectation value: $V(\varphi) \rightarrow V(v + h)$
- $V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \cdots$
- $V(h) = V_0 + \frac{1}{2}{m_h}^2 h^2 + \frac{{m_h}^2}{2v^2} v h^3 + \frac{1}{4}\frac{{m_h}^2}{2v^2} h^4 + \cdots$

Mass term

Higgs trilinear self-coupling

Higgs quadratic self-coupling

$v = \frac{\mu}{\sqrt{\lambda}}$ and $\mu = \frac{{m_h}^2}{2}$

In the SM υ=246 GeV and λ=0.13

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Mass term

Higgs trilinear self-coupling

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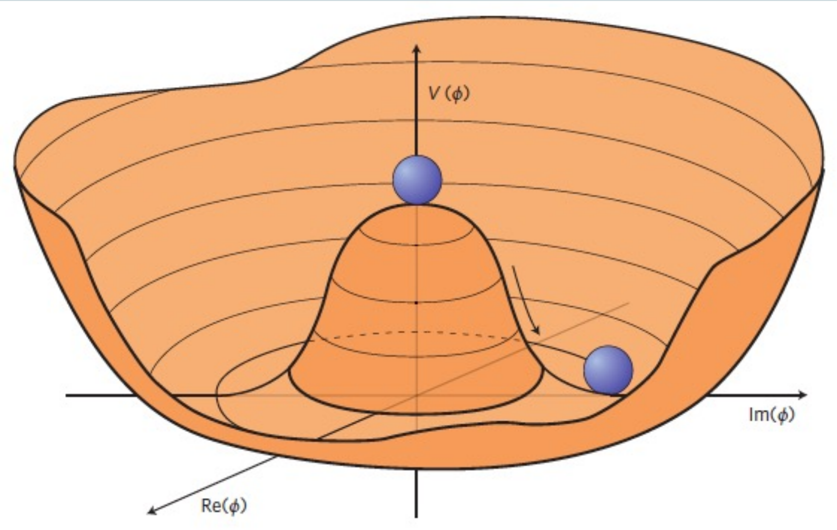

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In the SM v=246 GeV and λ=0.13

Mass term

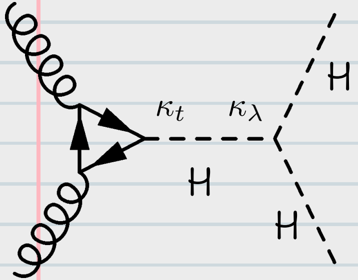
talk by Guenach

Higgs trilinear self-coupling

Higgs quadratic self-coupling

Self-coupling==self-interaction

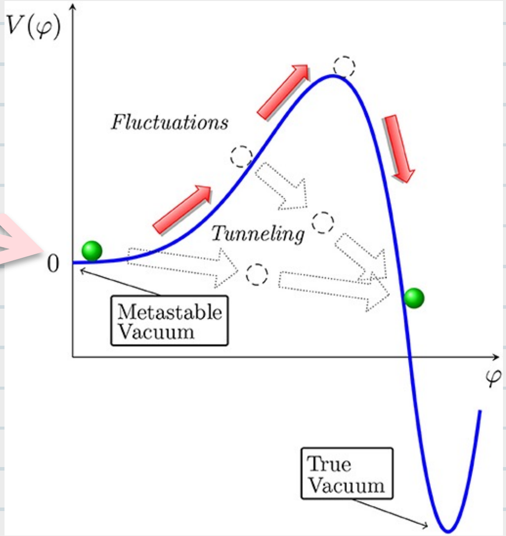
Study Higgs pair production!



this talk! ☺

Why is the Higgs self-coupling so important?

- **The least explored part of the Standard Model!**
- The Higgs sector is sensitive to new physics BSM
- Cosmological consequences:
  a. Jnflation
  b. **Vacuum stability**
  c. Baryogenesis
  d. ...?



“If the Universe was infinitely old, even an arbitrarily low vacuum decay rate would be incompatible with our existence.”

https://doi.org/10.3389/fspas.2018.00040

"If the Universe was infinitely old, even an arbitrarily low vacuum decay rate would be incompatible with our existence."

in other words...

Just by existing we have evidence about the nature of our universe

https://doi.org/10.3389/fspas.2018.00040

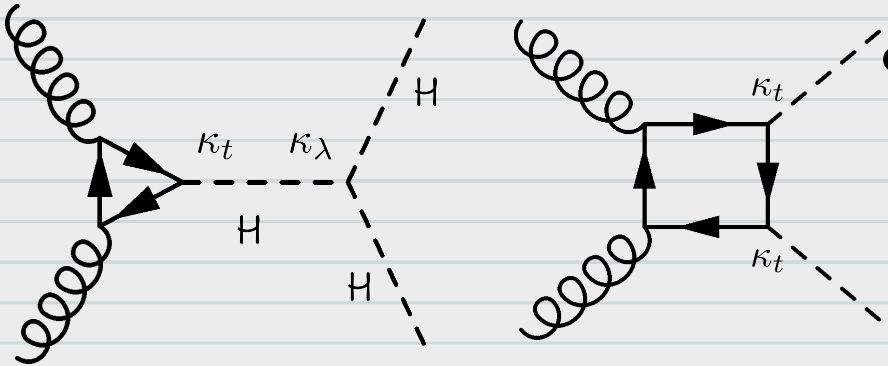
"If the Universe was infinitely old, even an arbitrarily low vacuum decay rate would be incompatible with our existence."

But we can't get all the answers that way!
We have to do some work!

https://doi.org/10.3389/fspas.2018.00040

How can we study Higgs pair production?

- We have to analyse the data from the proton colisions collected by our detectors
- Find two Higgs boson decays at the same time
- Finding two Higgs bosons produced at the same time is 1000 more rare than finding one Higgs boson

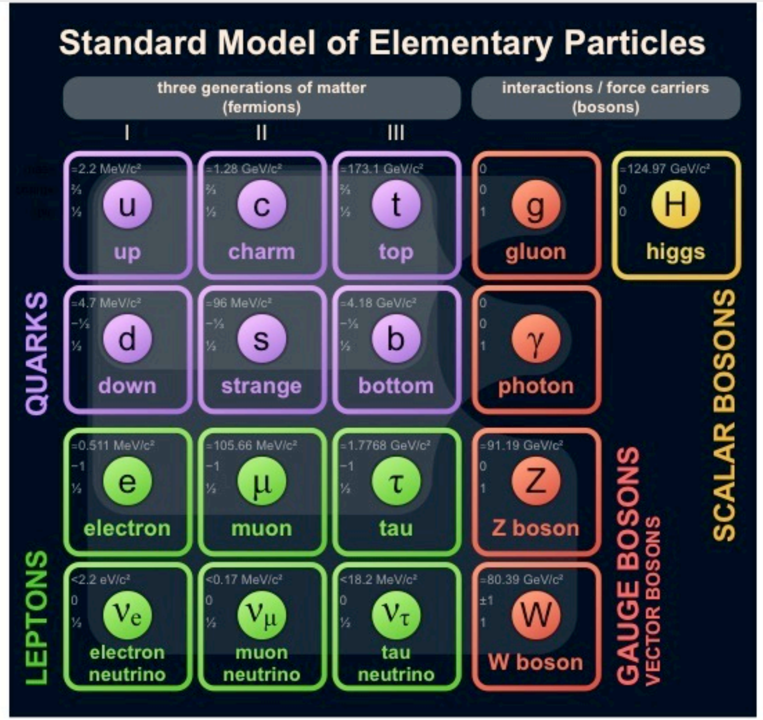


What will we see in the data?

Higgs and HH decays

Higgs decays

- H->bb highest BR (why?)
- H->γγ clear signature
- H->ZZ clear 4 lepton final states
- H->ττ high BR and cleaner than bb
- H->μμ very clean but tiny BR



Higgs and HH decays

Higgs decays

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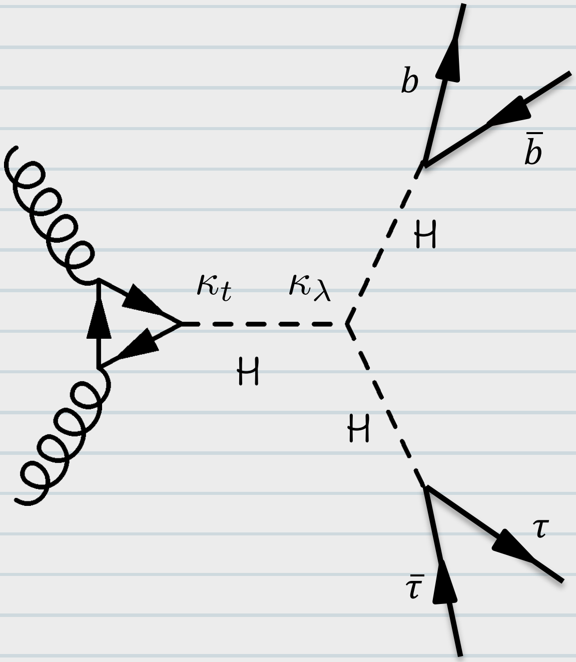
HH decays

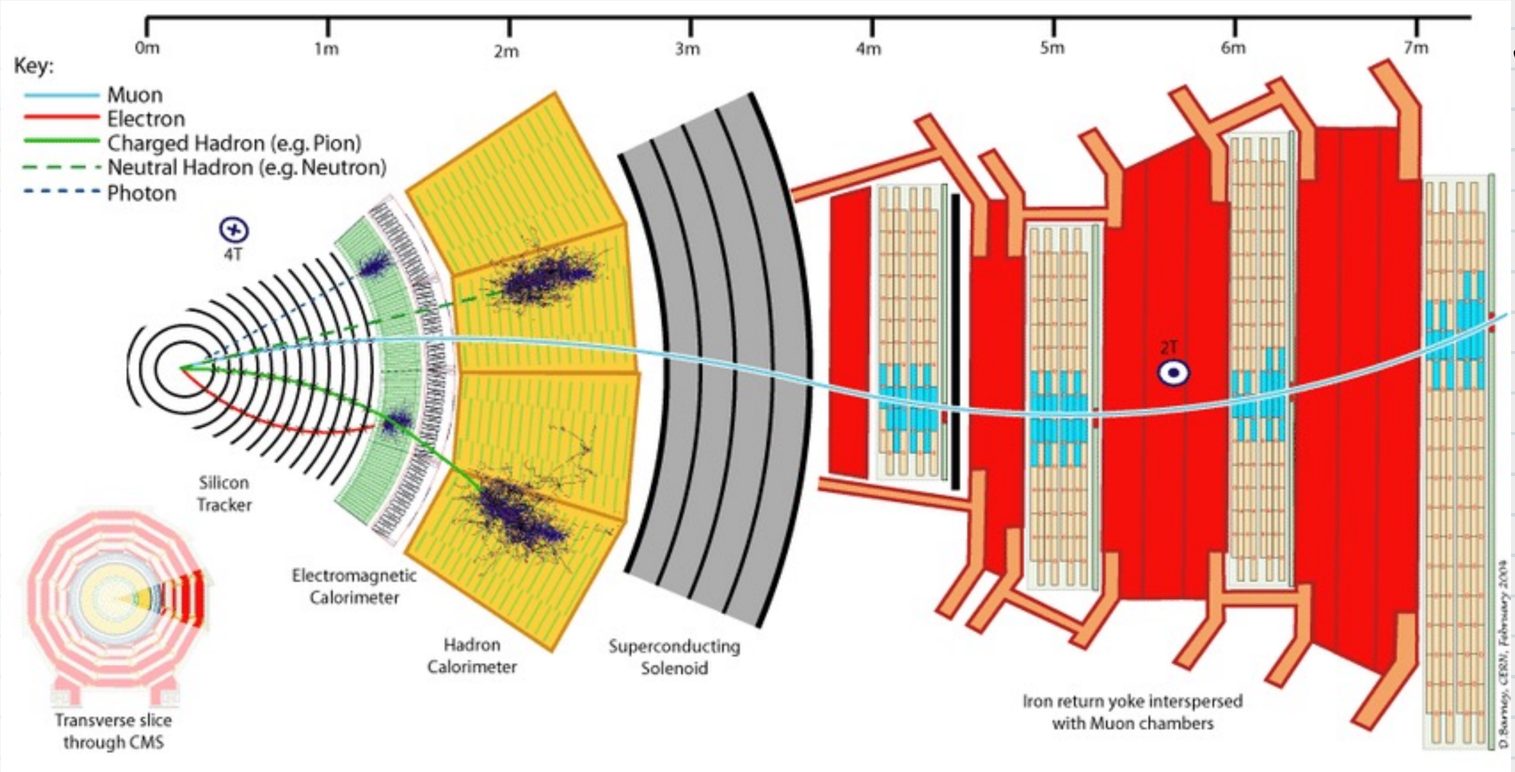
- Each Higgs decays independently
- So the final states will be the same as Higgs but double e.g. HH->bbbb, HH->bbγγ, HH->bbττ

HH decays

For example HH->bbττ



Remember each particle leaves a unique signature in the detector.



HH decays

All HH decay pairs:

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%

three best decays to look for HH

bbbb:
the highest branching fraction, large QCD background

bbττ:
relatively large branching fraction, clear signature but large background from $\bar{t}t$

bbγγ:
small branching fraction, clean $h \rightarrow \gamma\gamma$ mass peak

What do we mean by "background"?

When protons collide a lot of particles are produced and interact.
But only a subset of them are interesting.

From the small number of interesting events
our HH signal is even smaller!!

Despite the unique signature of the HH signal, there are still many events that will look very similar to our signal events.

Data analysis process in particle physics

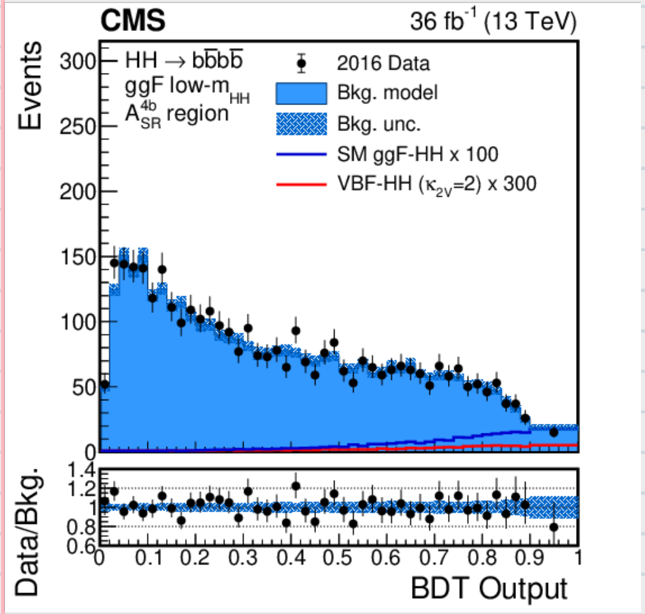
Signal selection

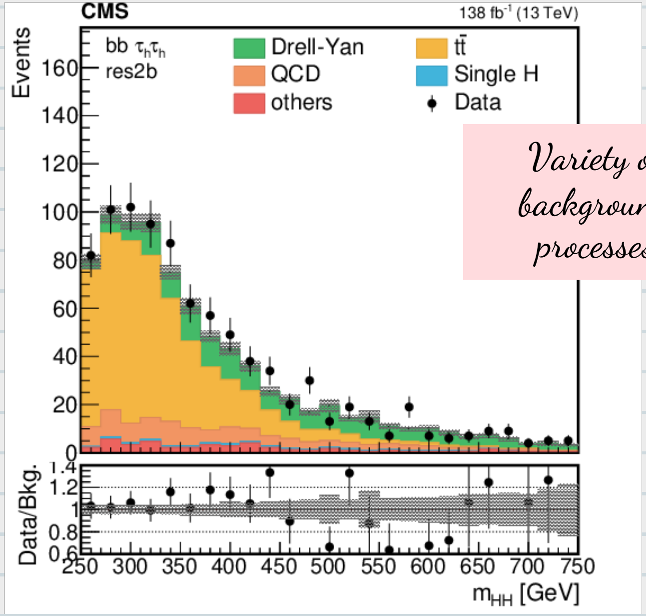
- Simply selecting some events and rejecting others based on various criteria (nominally kinematic features of the particles in the event.)
- Training multivariate and machine learning algorithms to identify the features of the signal.

Background estimation

- Accurately estimate the number of background events to expect
- Using simulation or real data
- Compare to observed data and check for an excess of data wrt expectation!

Examples

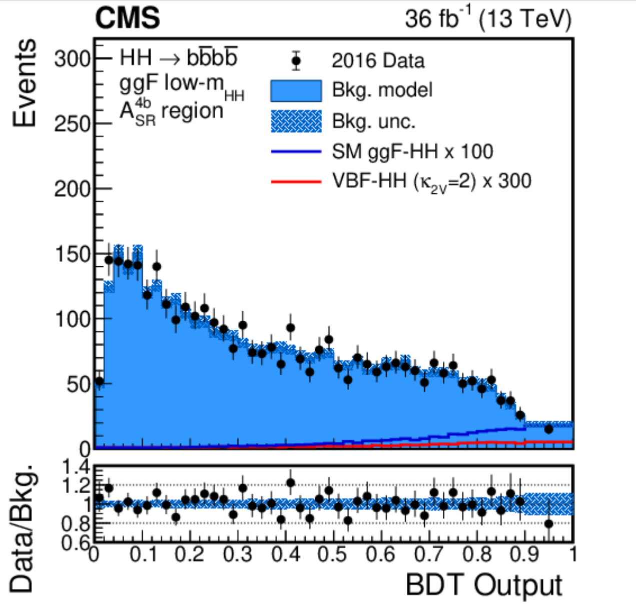




Variety of background processes

Boosted Decision Tree (BDT)
A multivariate algorithm used often in particle physics

Examples



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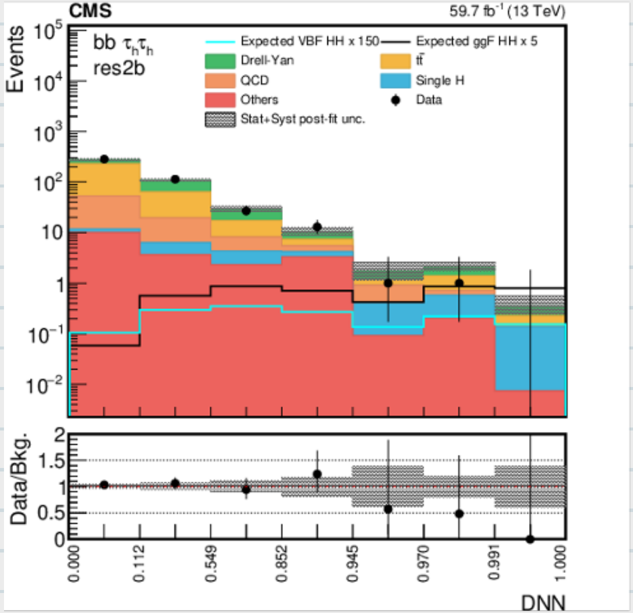

Deep Neural networks (DNN) are machine learning algorithms often used.

Analysis process summary

- Select particles according to the final state of the Higgs decays
- Apply selection on events based on various criteria
- Estimate background
- Machine learning (optional but common!)
- Statistical analysis

Statistical analysis means that we compare our expectation to the observed data and we check what is the likelihood they match according to our hypotheses

Analysis process summary

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Statistical analysis means that we compare our expectation to the observed data and we check what is the likelihood they match according to our hypotheses

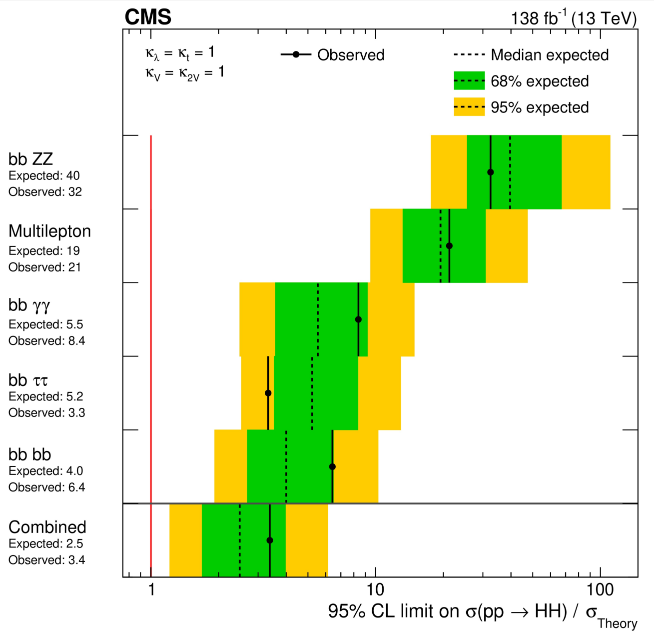
Common interpretations are exclusion limits, maximum likelihood, significance

Results!

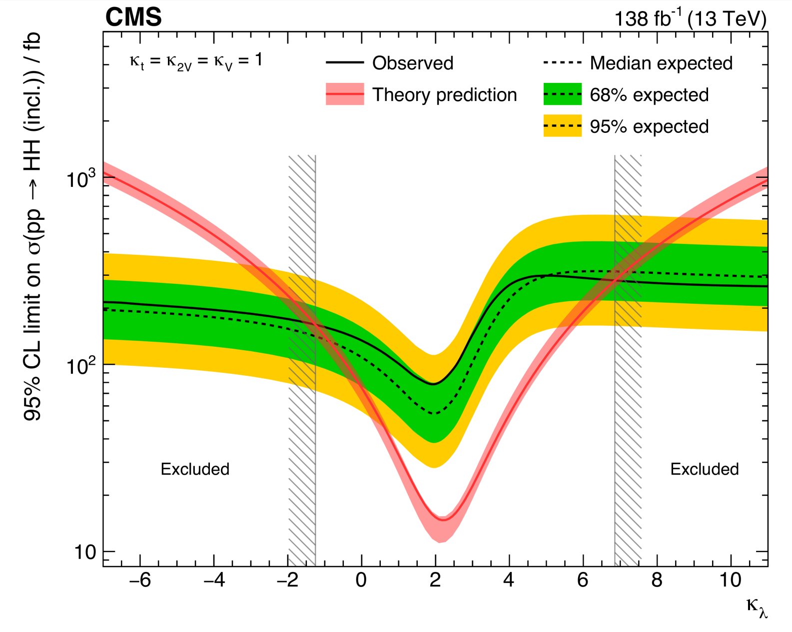
latest HH results by CMS

Results!

Exclusion limits



Higgs self-coupling

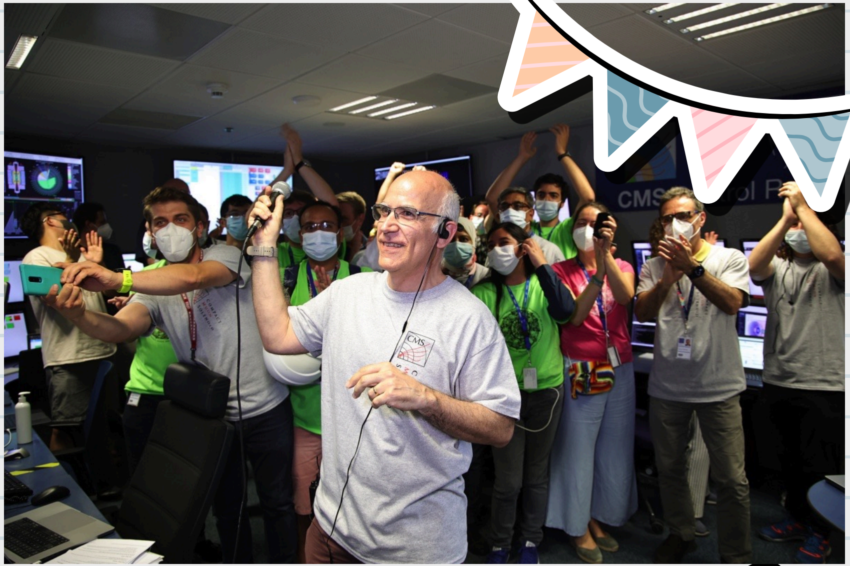


What is next?

Future colliders!
e.g. FCC

Run 3 just started!

July 5th 2022



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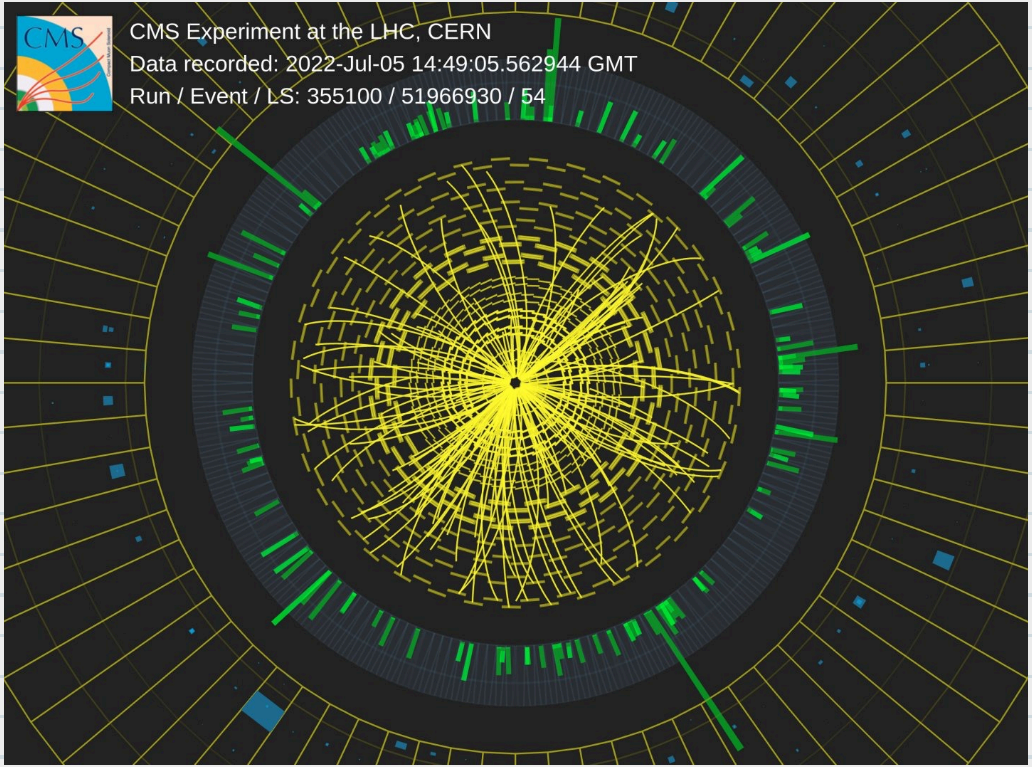


Take away points!

Thank you for listening!

- Higgs physics is important and exciting!
- HH searches is one of the hottest topics for the LHC right now
- A little better understanding of how we study collisions and decays
- An idea of how we do data analysis
- Long future ahead!
  (at some point we need to measure the Higgs quadratic self-coupling remember?)

Back up

What is a jet?

Short answer

- Jets are the signatures of quarks and gluons produced in high-energy collisions such as the proton-proton interactions at the Large Hadron Collider (LHC)
- A jet is a narrow cone of hadrons and other particles
- They are produced by a process called hadronization *

*topic for another lecture!

What is a Gauge theory ?

- Quantum field theories (QFT) describe the behaviour of particles.

What is a Langrangian??

A quantity that characterizes the state of a physical system.
e.g. In classical mechanics, the Lagrangian function is the kinetic energy minus the potential energy

theory a gauge theory

- The quanta of the gauge fields are called gauge bosons.

What is a Gauge theory ?

- Quantum field theories (QFT) describe the behaviour of particles. Written in the form of a Lagrangian.
- A gauge theory is a type of field theory in which the Lagrangian is invariant under a group of local transformations. (symmetry groups)
- Gauge fields are vector fields included in the Lagrangian to make a theory a gauge theory
- The quanta of the gauge fields are called gauge bosons.

What is special about symmetries?

The SM is a Gauge theory invariant under

$SU(3) \times SU(2) \times U(1)$

$$SU_c(3) \rightarrow 8G^{\alpha}_{\mu}, \quad \alpha = 1, \ldots, 8$$

Strong interactions

gluons!

$$SU_L(2) \rightarrow 3W^{\alpha}_{\mu}, \quad \alpha = 1, 2, 3$$

W+/- and Z

$$U_Y(1) \rightarrow B_{\mu}$$

γ (photon)

Why do we need the Higgs field?

$SU_c(3)$

$\downarrow$

$8G^{\alpha}_{\mu}$

$\alpha = 1$

Strong interactions

gluon

$SU_L(2)$

$\downarrow$

V^{α}_{μ}

$= 1, 2, 3$

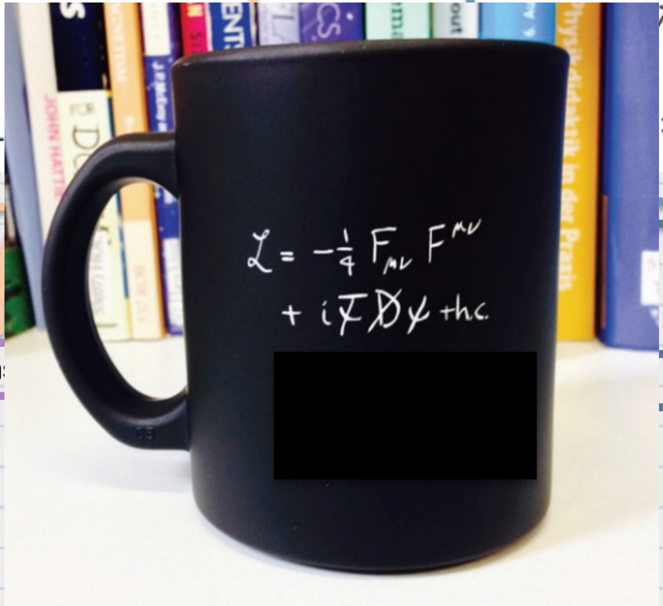
W+/- and Z

$U_Y(1)$

$\downarrow$

B_{μ}

γ (photon)



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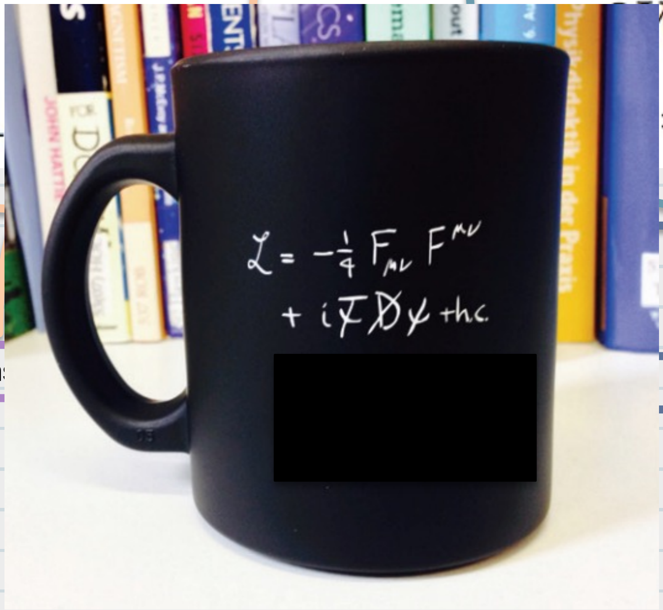


Experiments show that W+/- and Z have mass!
Not only they have mass!
The fermions have mass also!
No mass terms in this Lagrangian

Why do we need the Higgs field?

$SU_c(3)$ → $8G_\mu^\alpha$, $\alpha = 1$ …

Strong interactions

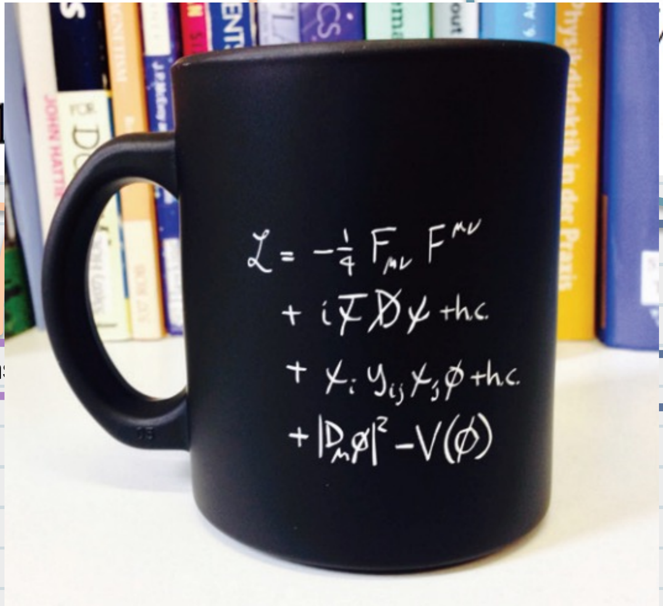
gluon…

$SU_L(2)$ → W_μ^α, … $= 1, 2, 3$

W+/- and …

$U_Y(1)$ → B_μ

γ (photon)



The SM Langrangian without the Higgs field would be symmetric under SU(3)xSU(2)xU(1)
–> no massive bosons!

We need the Higgs field to spontaneously break the symmetry