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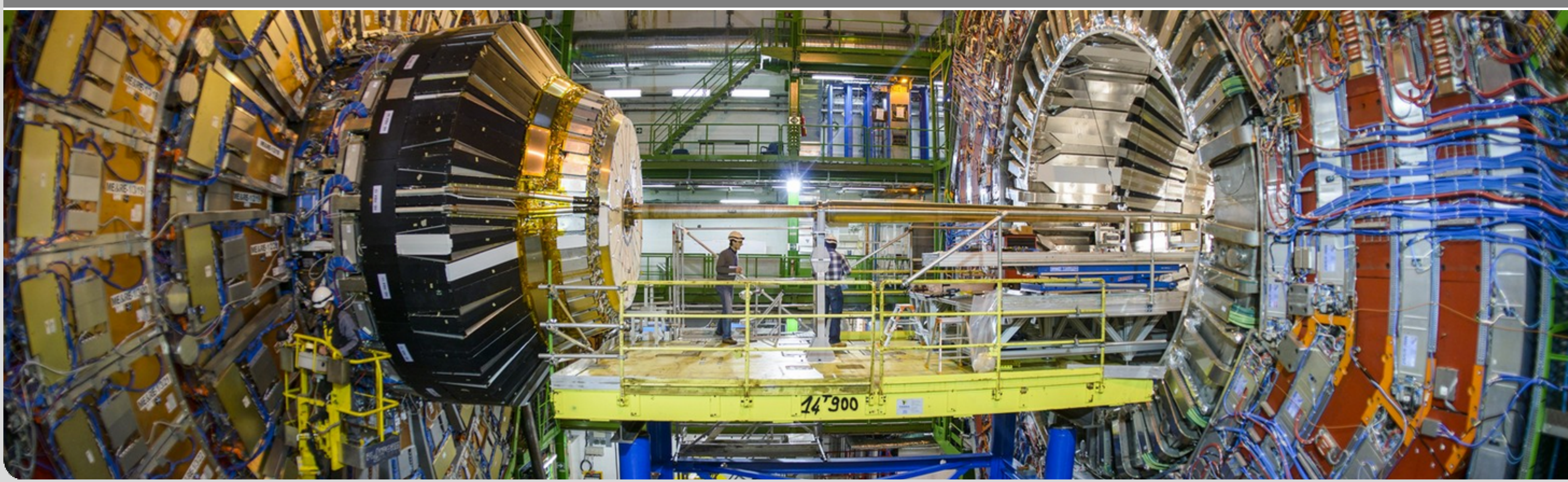
The Higgs Boson and its coupling to fermions

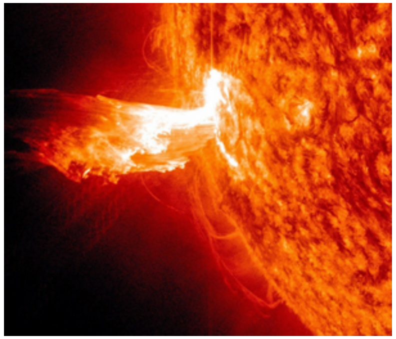
Raphael Friese
24. February 2016

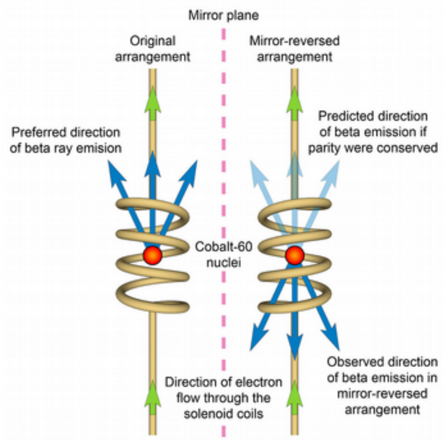
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

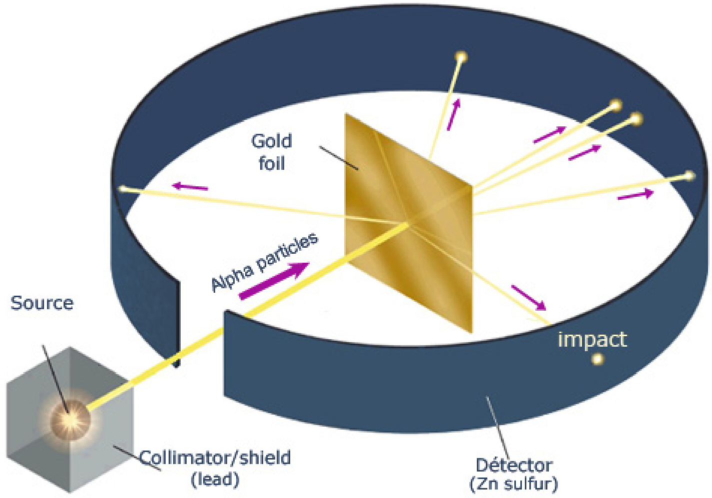


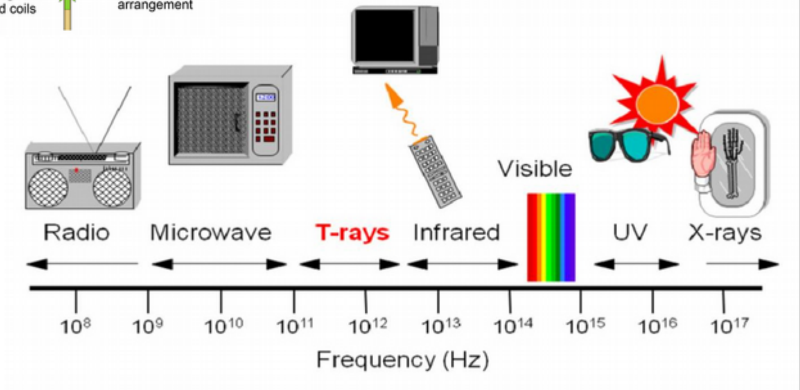
Particle Physics

investigates the irreducibly smallest detectable particles
and the irreducibly fundamental forces









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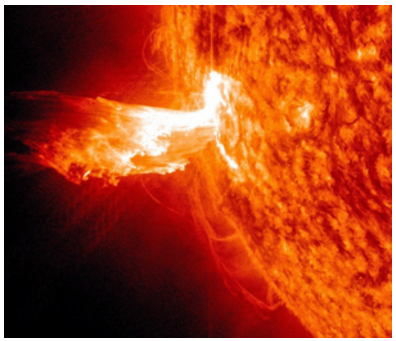
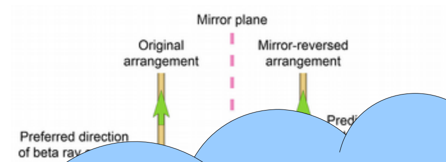
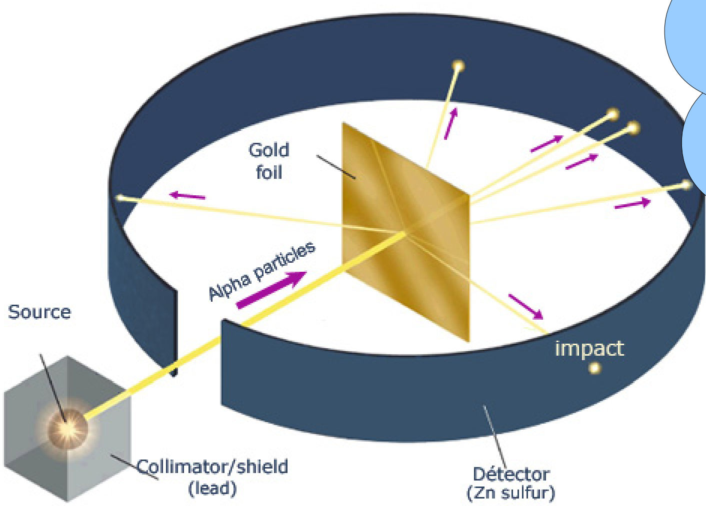
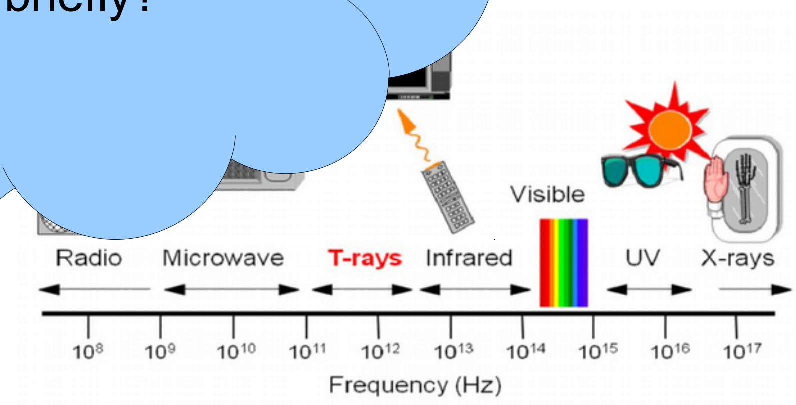
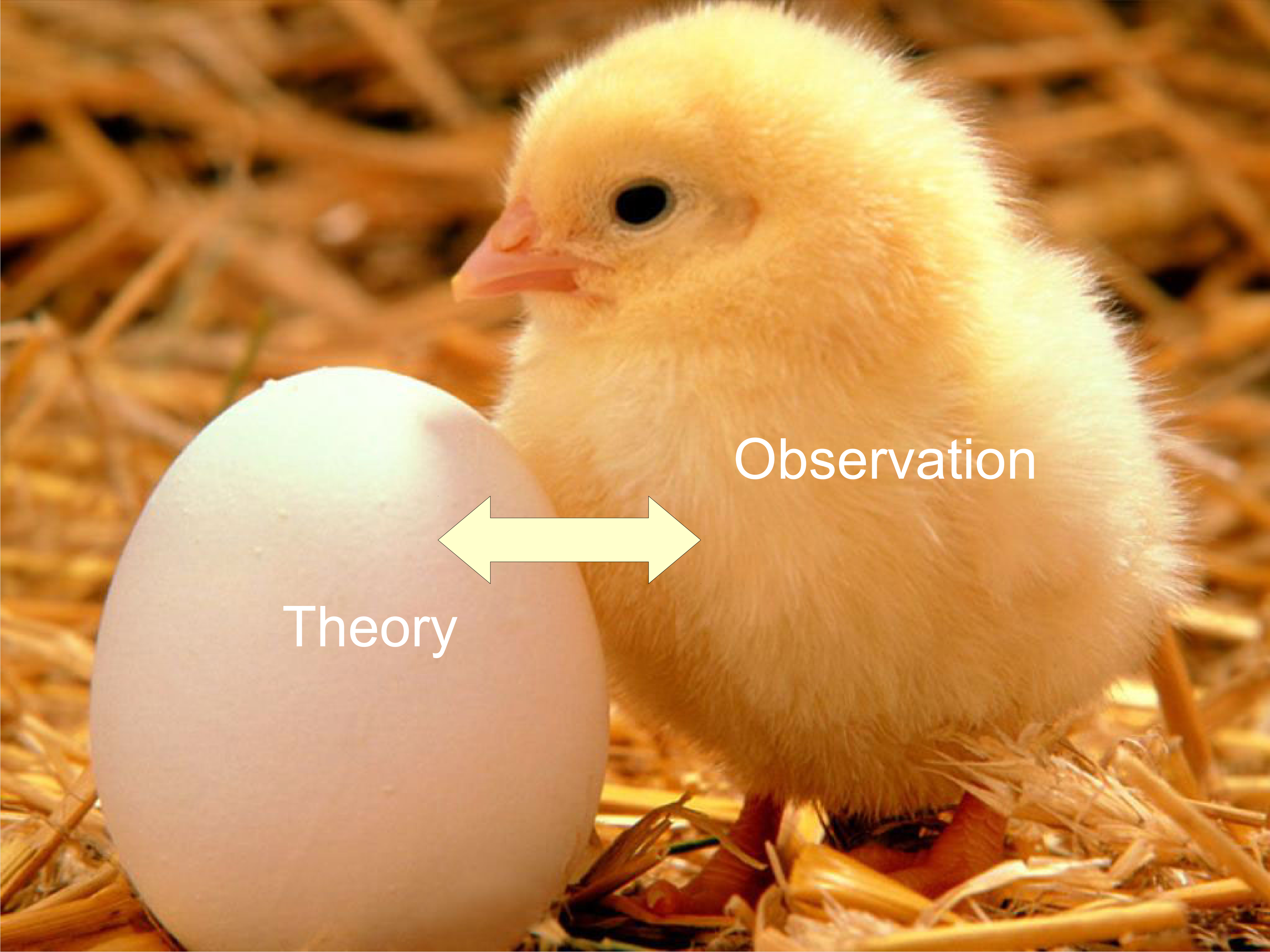




Can you write that down briefly?

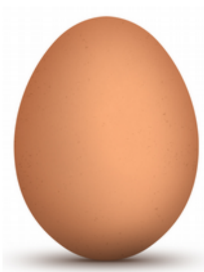





Observation
Theory

Two points of view

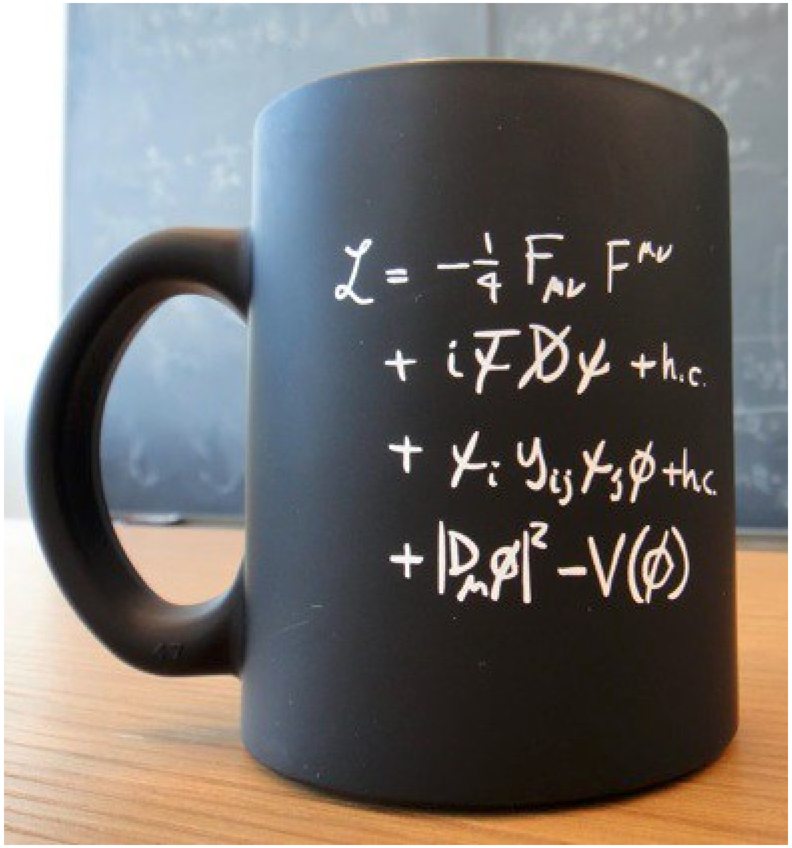
Theorists

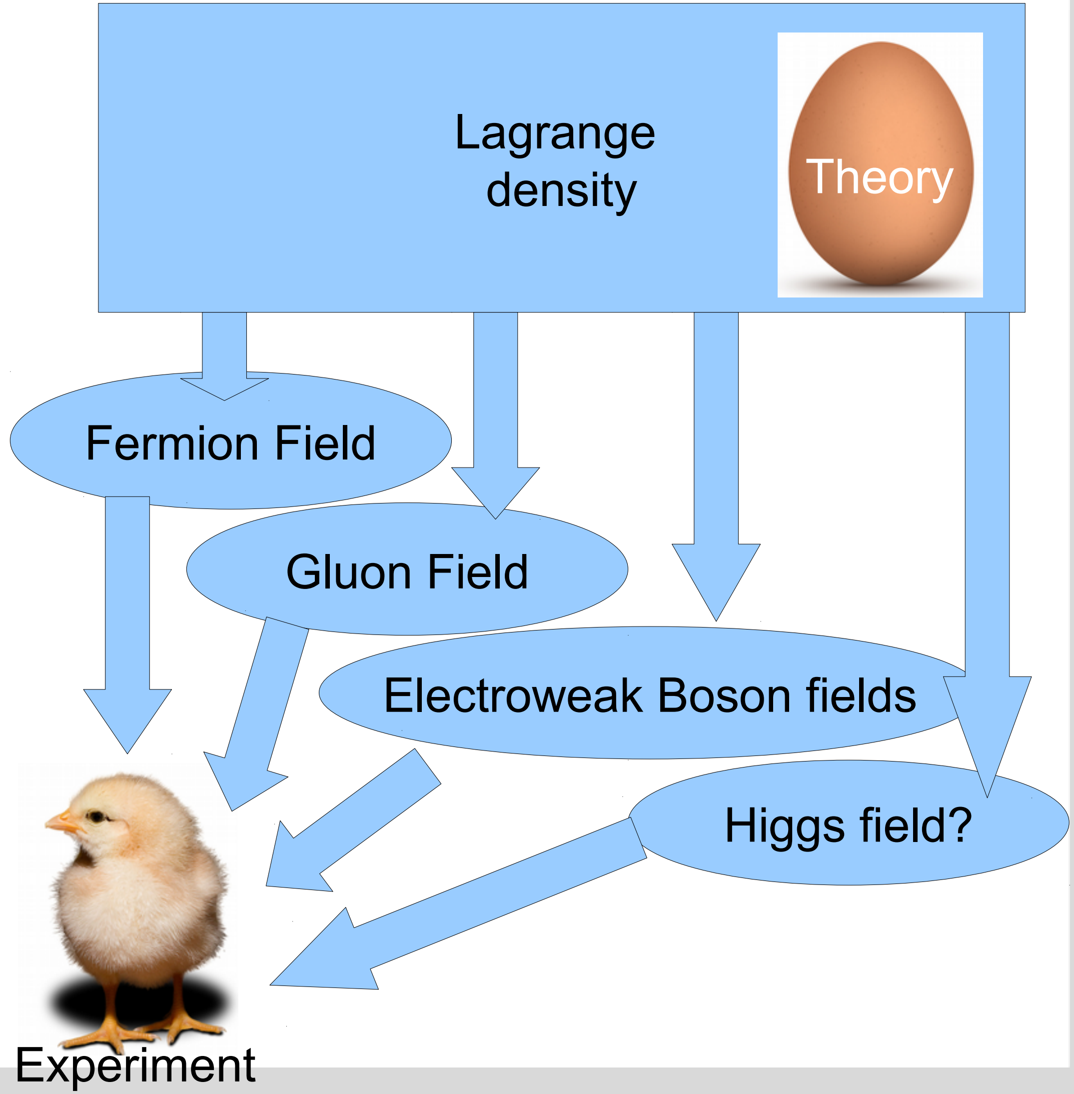


Experimentalists

Field equations ⟷ Particles

The "Standard Model of Particle Physics" - a quantum field theory





Lagrange Formalism

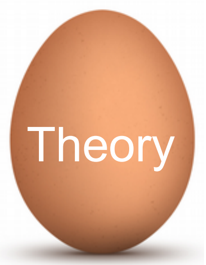
Lagrangian

The Lagrangian is a function of fields fully describing the kinematics of all known particles

Excitations of these fields are interpreted as particles

Classical observables become *expectation values of operators* that act on the fields

The Standard Model Lagrangian has some intrinsic degrees of freedom ("phases") that do not change the observables



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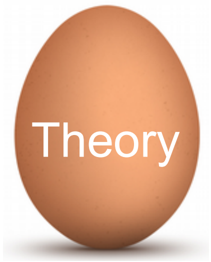

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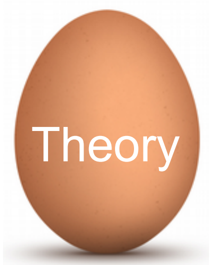

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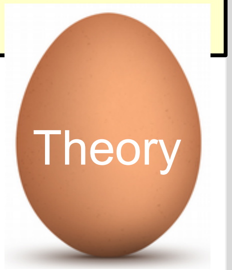

Comparison with observation

Constituents of Matter

- All matter we know off today is made up of six quark and six lepton flavors:

	Fermions		
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
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- All of them are fermions with spin $^1/_2$.
- They have no sub-structure, but most of them decay

Experiment

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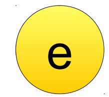

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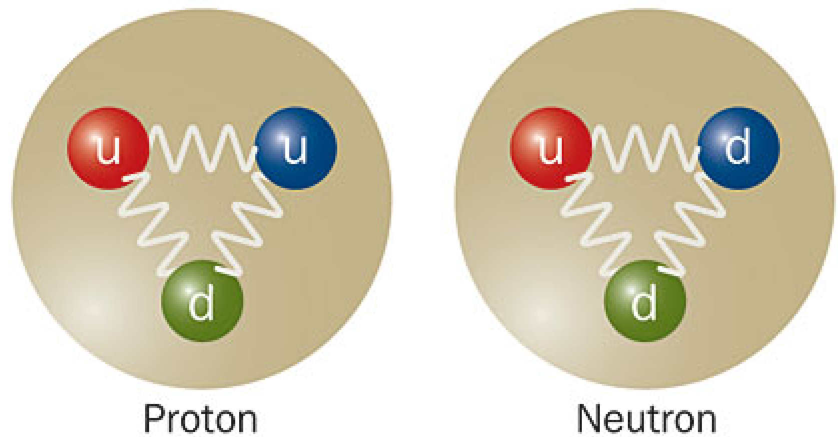

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Experiment

Fundamental Interactions

- We know four fundamental interactions, which act between them:

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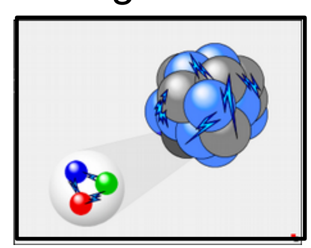
Gravitation:

Electromagnetic Force:

Weak Force:

Strong Force:



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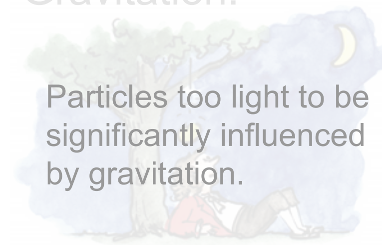
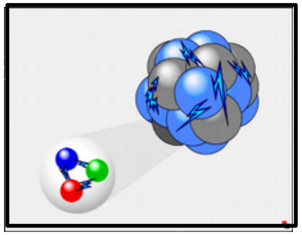


Particles too light to be significantly influenced by gravitation.

Weak Force:

Strong Force:



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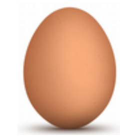

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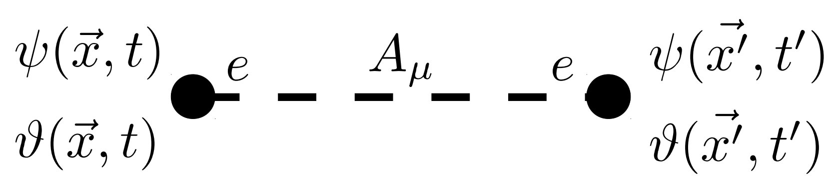
- Gauge: Can choose arbitrary phase ϑ for wave functions .

$$\psi(\vec{x}, t) \rightarrow \psi(\vec{x}, t) e^{i\vartheta}$$

- But phase must be the same at any point in space, at any time! ($\rightarrow$ global symmetry)

- Possible to allow arbitrary phase $\vartheta(\vec{x}, t)$ of $\psi(\vec{x}, t)$ at each point in space and any time. ($\rightarrow$ local symmetry)
- But this requires introduction of a mediating field A_μ, which transports phase information from point to point:



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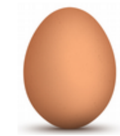

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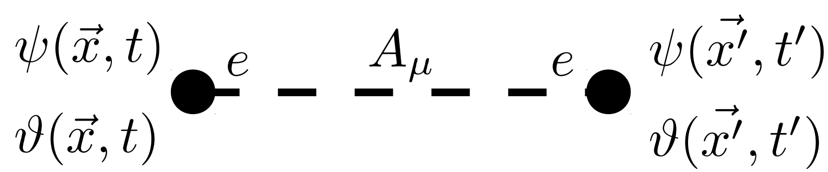

Local Gauge Symmetries

- Structure of fundamental interactions enforced by principle of local gauge symmetries:

	Fermions			Bosons
Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	Z Z boson
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
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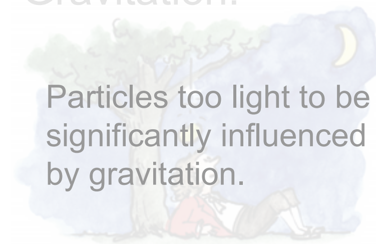

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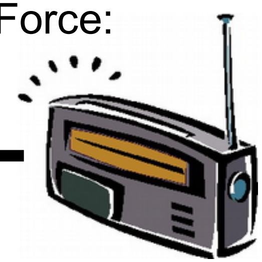

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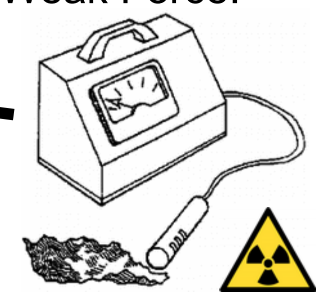

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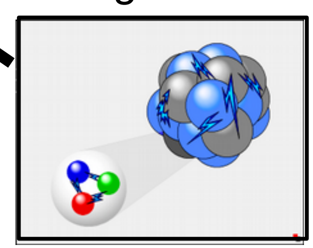
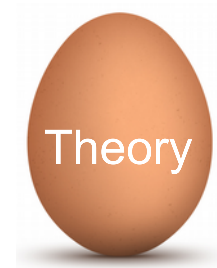


- Lead to introduction of force carrying particles (→ Bosons).
- Strictly requires to have $m = 0$!



Can this theory be confirmed by experiment?

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Experiment

Case of Electroweak Symmetry

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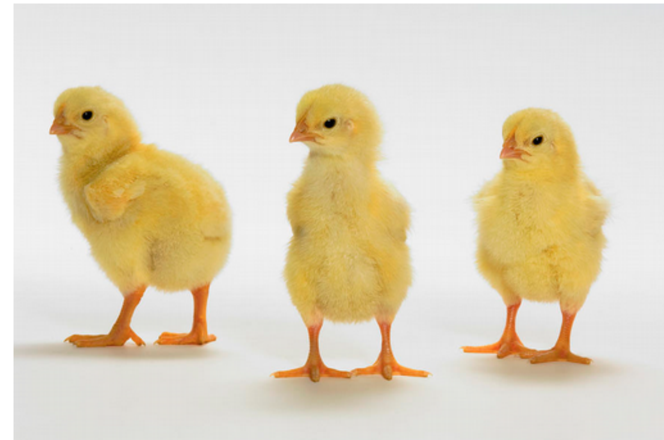
$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$
$$m_W = 85.385 \pm 0.015 \text{ GeV}$$



- Weak interactions are described by weak gauge symmetries! → symmetry exists.
- Force mediating particles are have which explicitly breaks symmetry! → symmetry not realized in nature.

Case of Electroweak Symmetry

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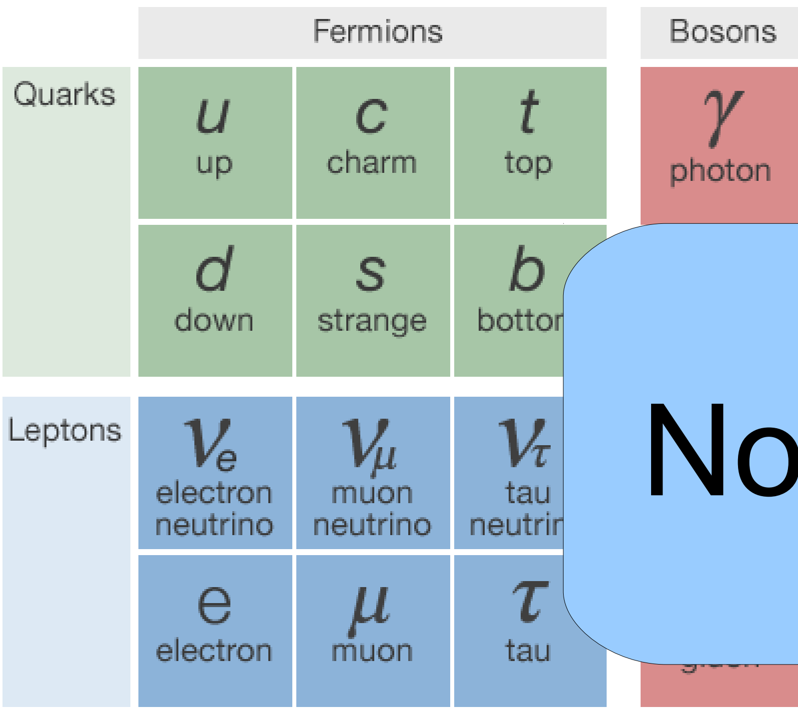

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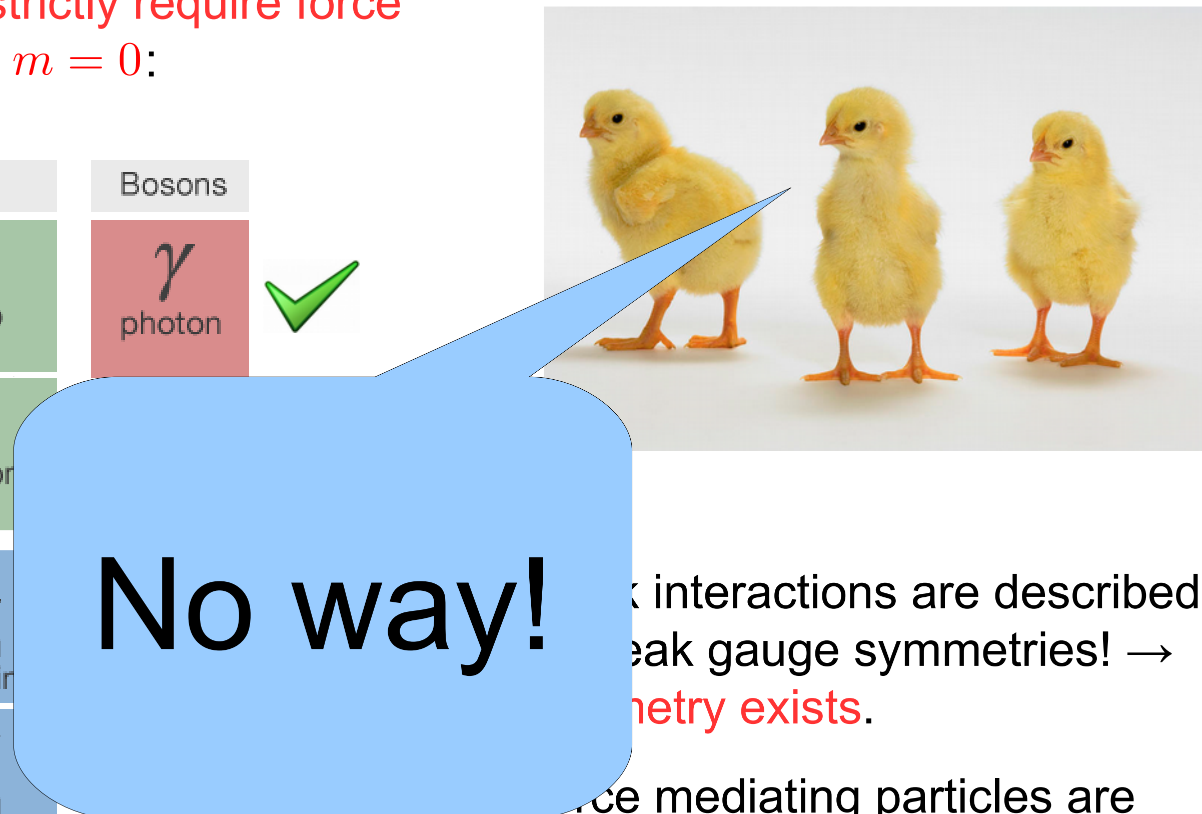

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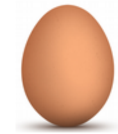
Higgs Mechanism - save the SM



The gauge mechanism depends on symmetry ⟷ The observations in not compatible with symmetry

Solution: Introduce new field ϕ with characteristic interaction potential.

- Symmetric (i.e. in Lagrangian density $\mathcal{L}$)
- BUT symmetry broken in energy ground state of the system (=quantum vacuum)

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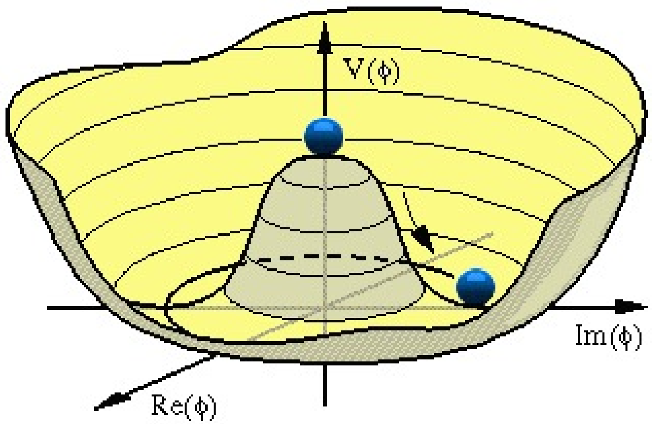
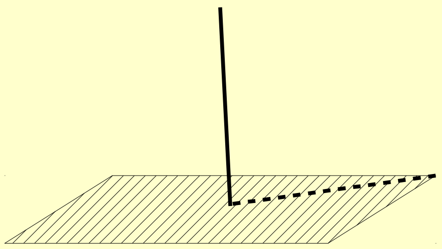
- Incorporation of spontaneous symmetry breaking in gauge field theory
  = Higgs mechanism:



Needle on point:



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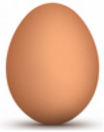
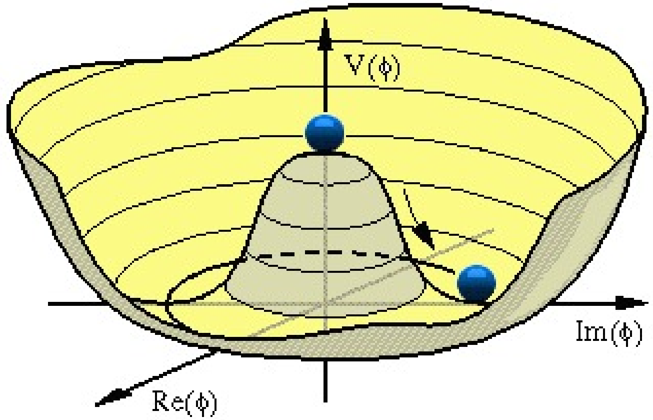


- New Field leads to prediction of new particle: → Higgs boson!
- Allows to incorporate mass terms in the theory.
- Gauge symmetry compromising mass terms compensated by characteristic couplings to Higgs particle

Higgs coupling is

$\propto m_v^2$ (for force mediating W & Z boson)

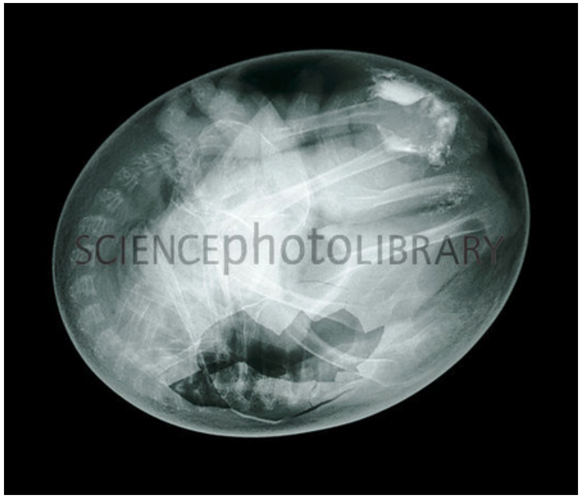
$\propto m_f$ (for weakly interacting fermions)



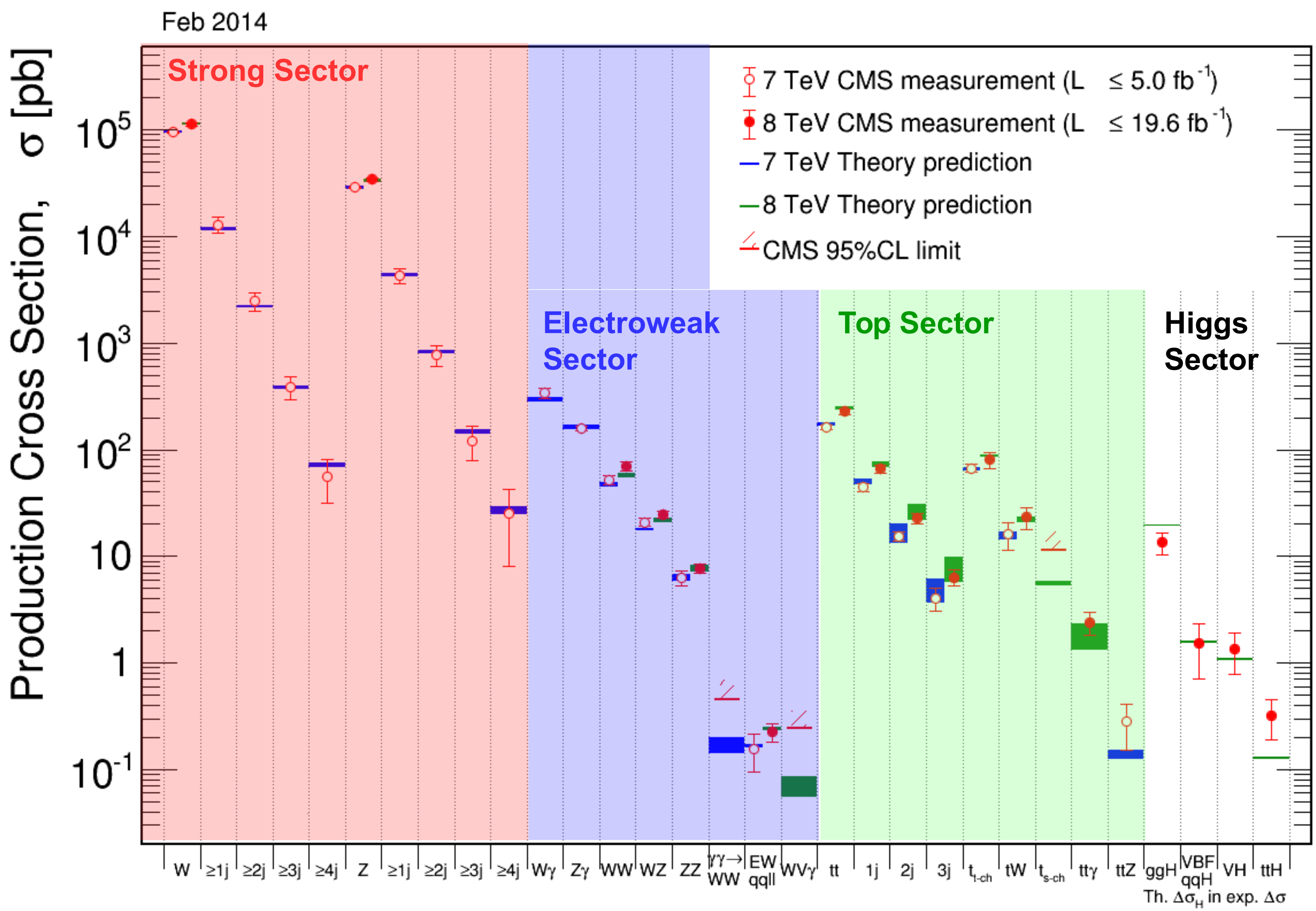
Where to search for the Higgs Boson?

- The standard model has many free but constrained parameters
- the only unconstrained parameter of the Higgs Boson was its mass

- Prediction from theory:
  - Production rate (cross section)
  - Couplings
  - branching ratio to final states of interest
  - signatures



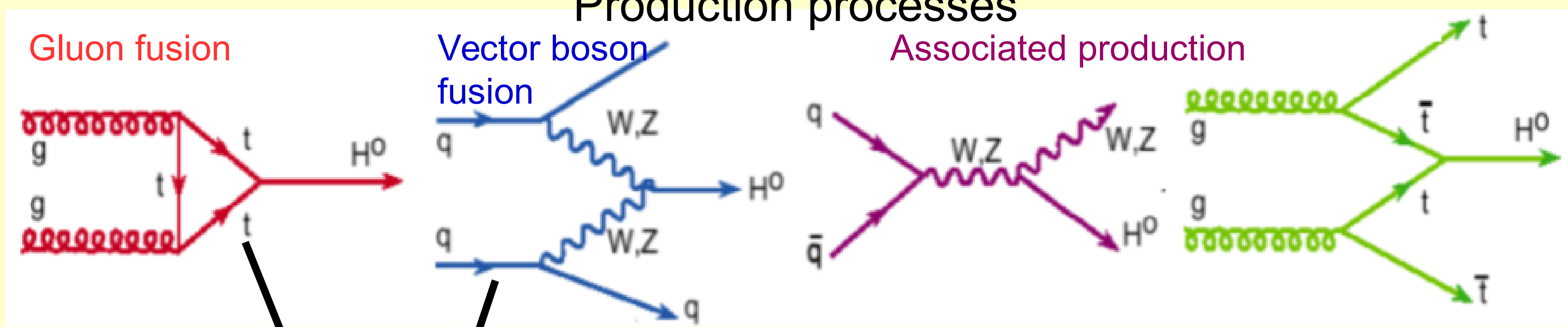
Snapshot of our Physics Understanding of Today



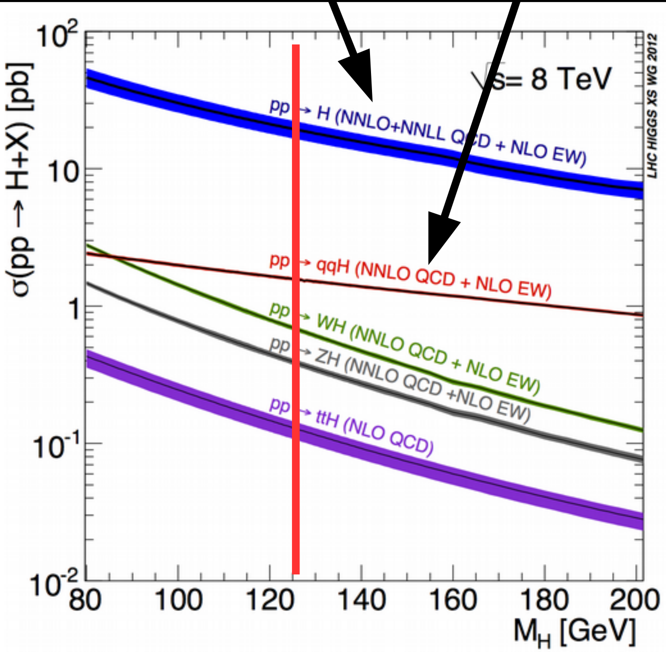
Where to search for the Higgs Boson?

- All properties of the (SM) Higgs boson are a function of m_H :

Production processes



Production (in proton proton collisions)



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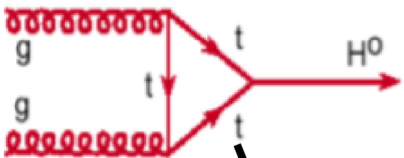
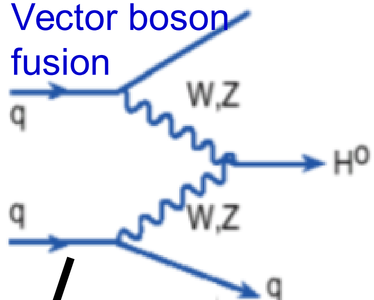
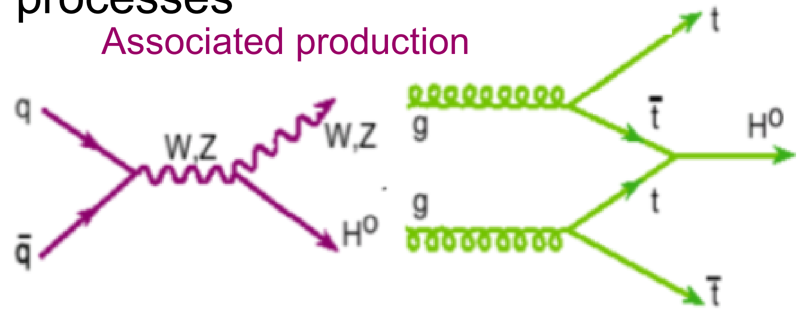
Gluon fusion



Vector boson fusion



Associated production



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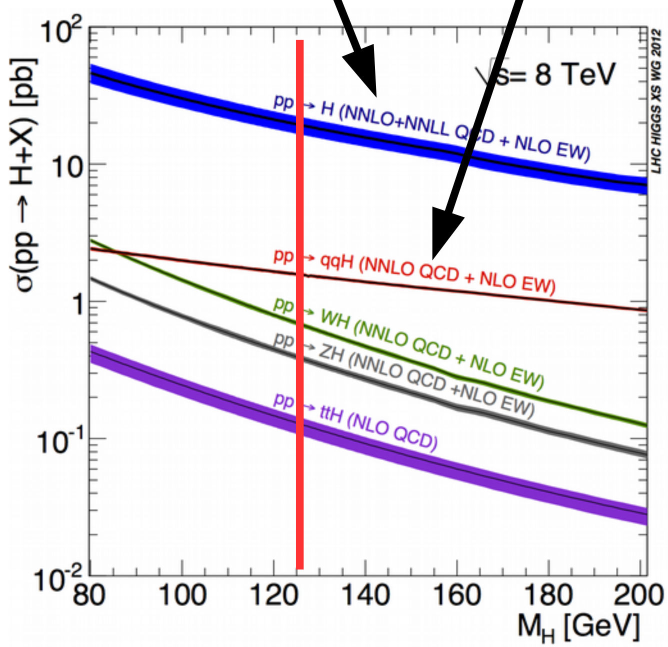
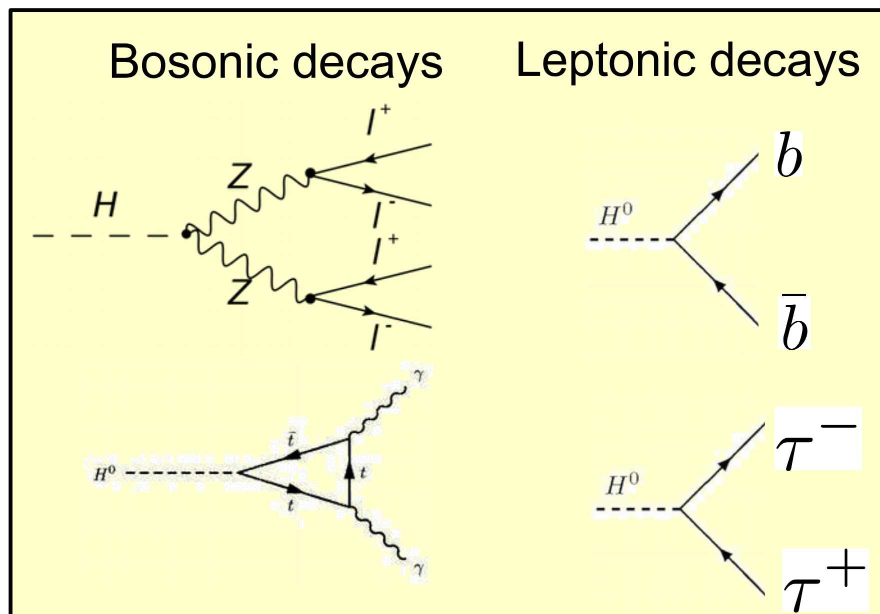
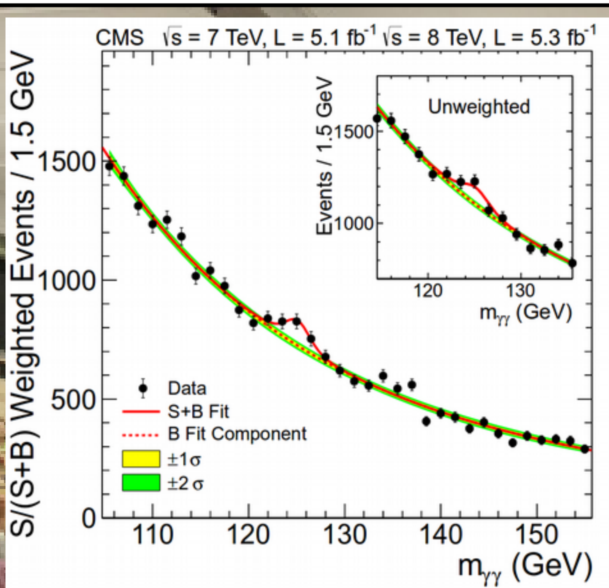
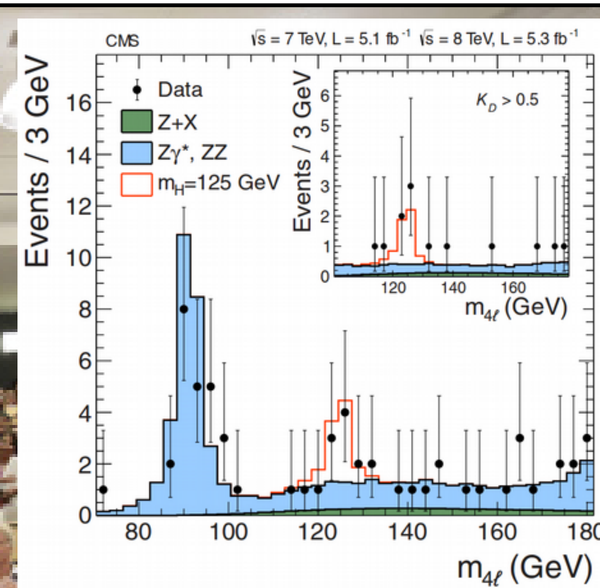




Discovery of a new particle 4th July 2012





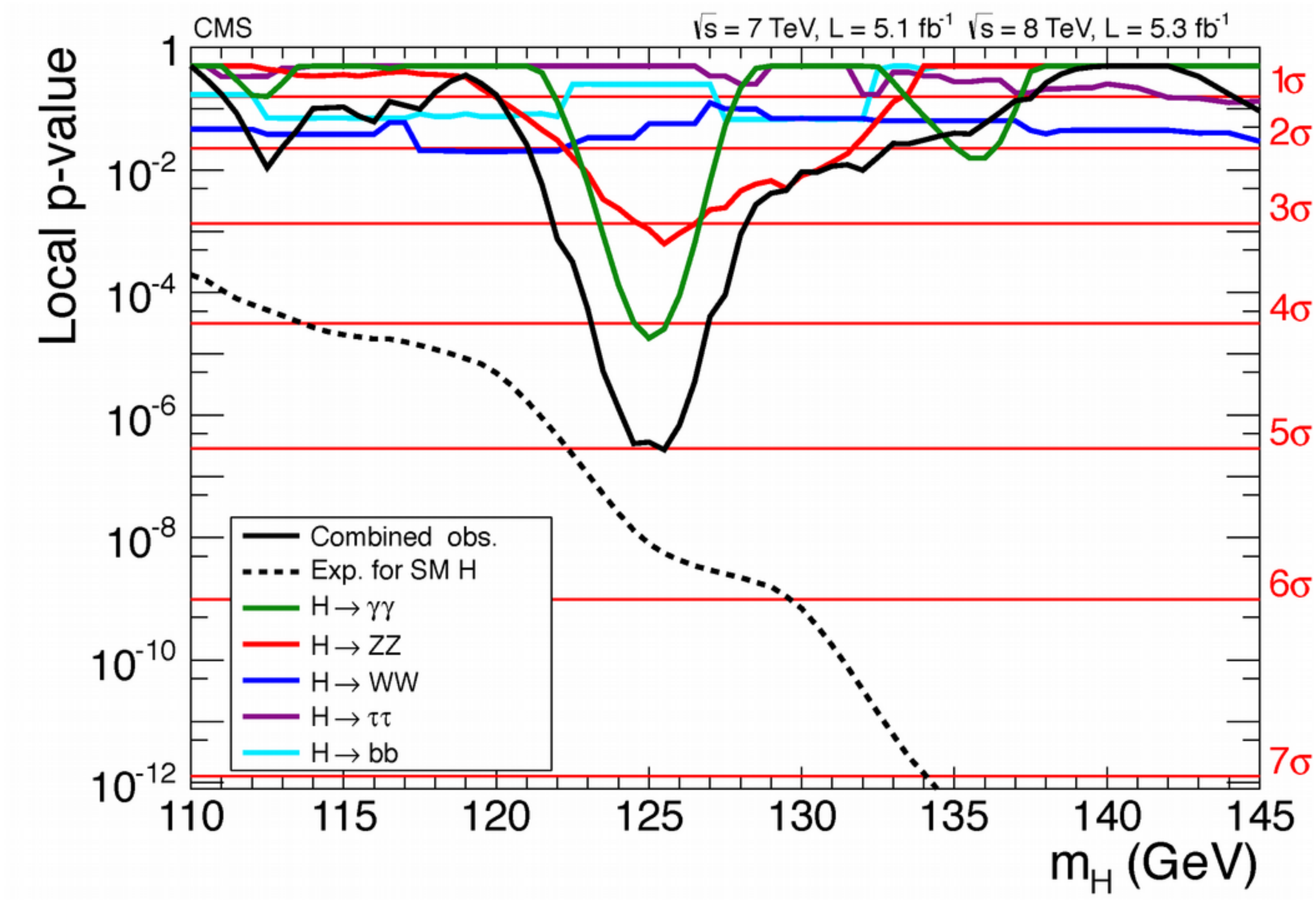
$$\kappa_{HVV} = \frac{2m_V^2}{\mathrm{v}} \qquad \kappa_{Hff} = \frac{m_f}{\mathrm{v}}$$

Channel	Resolution	S/B
$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
$H \to ZZ$	1-2%	$\mathcal{O}(>1)$
$H \to WW$	20%	$\mathcal{O}(1)$
$H \to b\bar{b}$	10%	$\mathcal{O}(0.1)$
$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

(κ_{HVV} applies to the $\gamma\gamma$, ZZ, WW channels; κ_{Hff} to $b\bar{b}$, $\tau\tau$.)

Discovery of a new particle 4th July 2012

- Scratching magic 5σ boundary.
- Discovery driven by high resolution channels ($H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ$).
- Broad moderate excesses for $H \rightarrow WW$.
- No signal seen in fermionic decay channels.



Does the new particle couple to fermions?

Higgs to leptons experimentally

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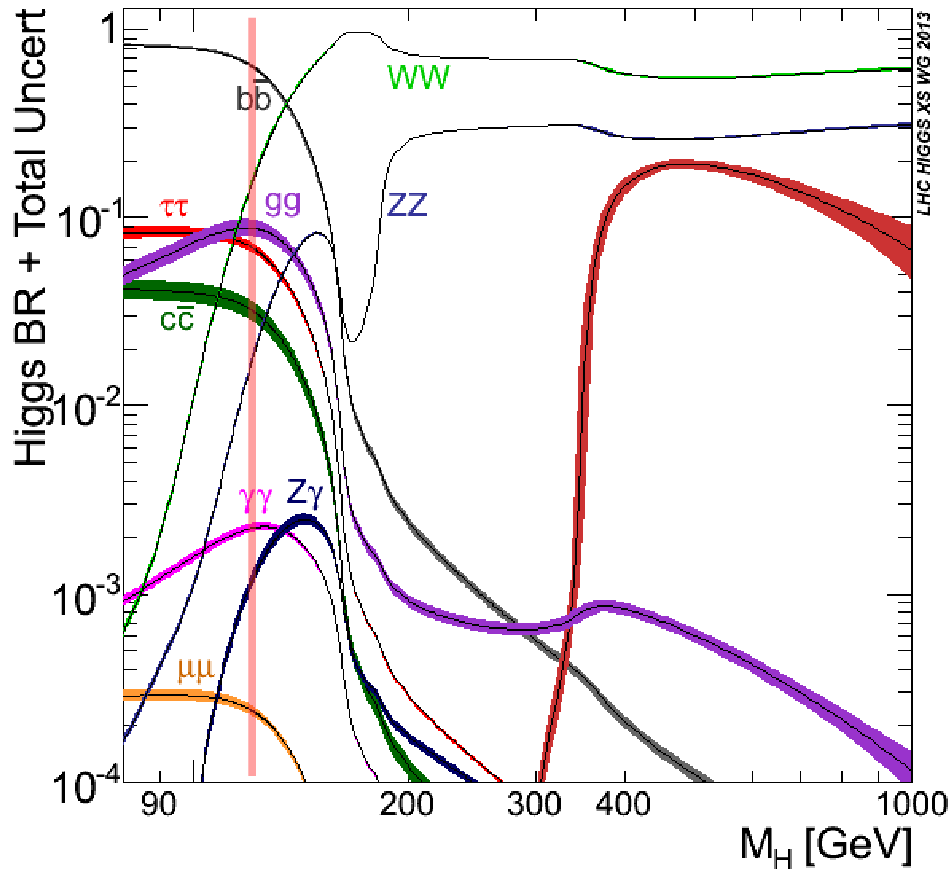
Quarks	*u* up	*c* charm	*t* top
	d down	*s* strange	*b* bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

too heavy

hopeless

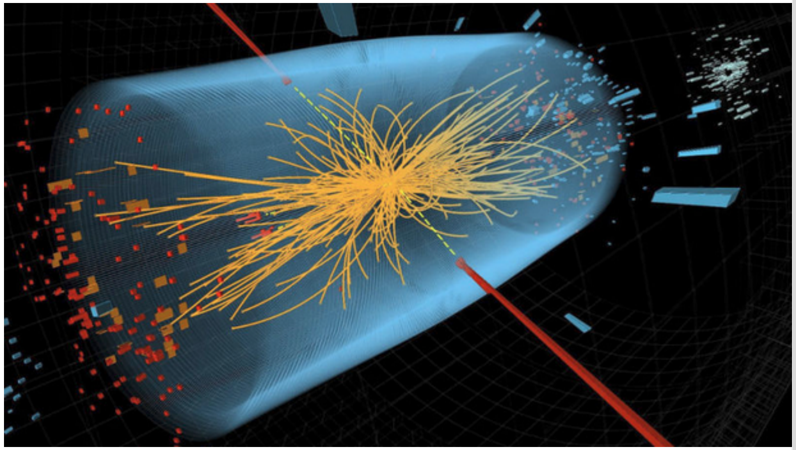
massless

perfect!



How modern particle physics experiments work

- Accelerating protons very close the the speed of light
- Colliding them and see what is happening
- 40 million collisions / second
- Each one is considered an “Event”
- Measured: Hits and Calorimetry deposits
  - Reconstruction of high-level objects (muons, electrons ..)
  - Clustering of several particles to “Jets”
- Only further consider events with special kinematic properties and sort the remaining ones into categories
- Do the statistical evaluation on a final distribution



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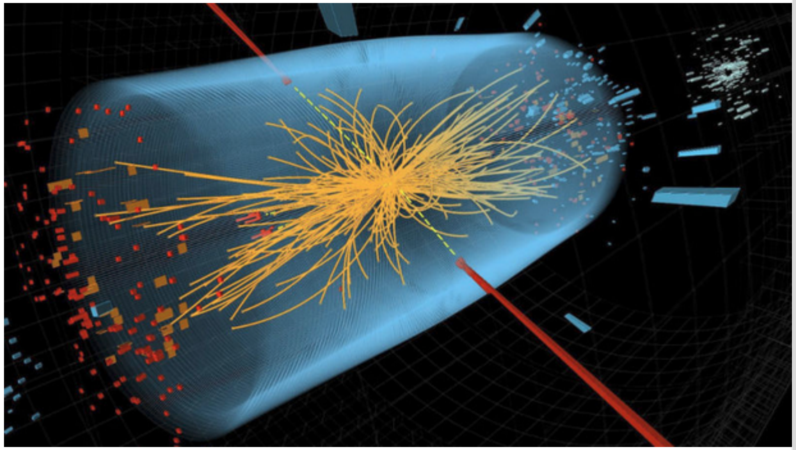

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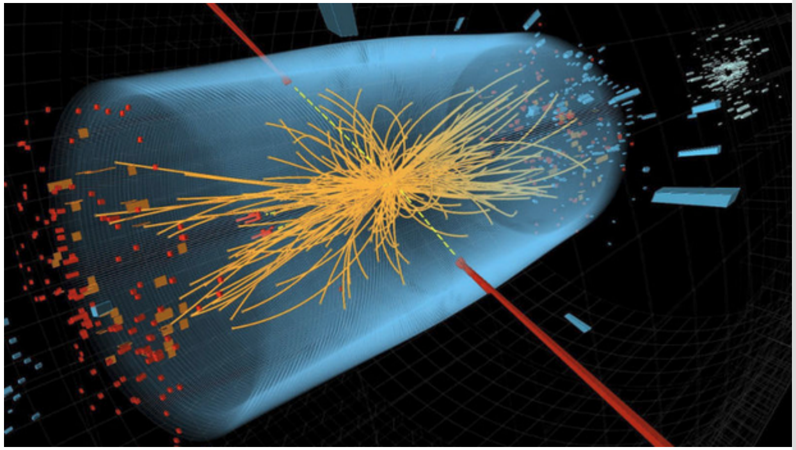

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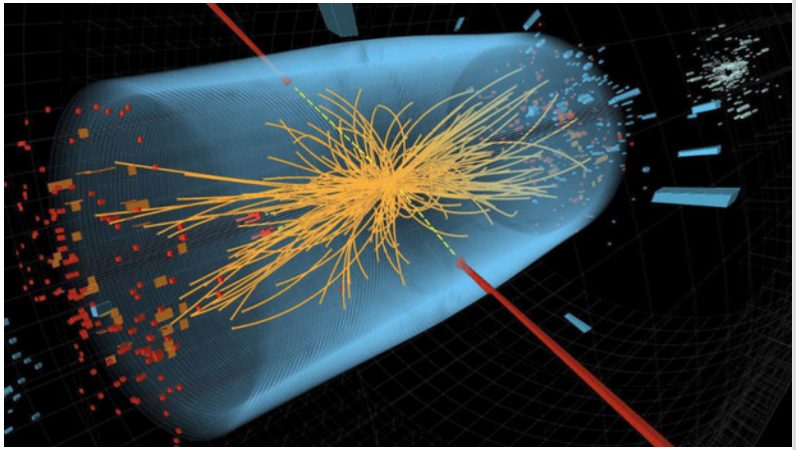

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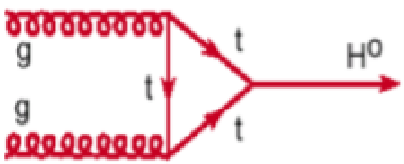
Analysis

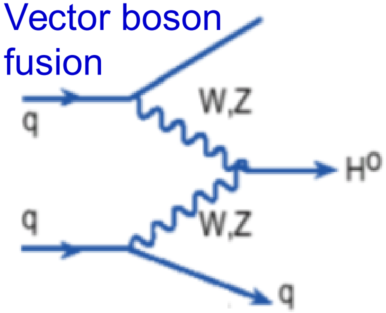
Higgs to two tauons

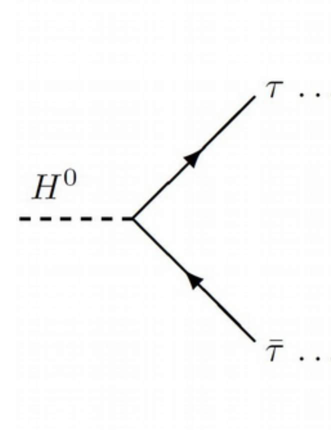
- If m_H is given all properties of the (SM) Higgs boson are known:

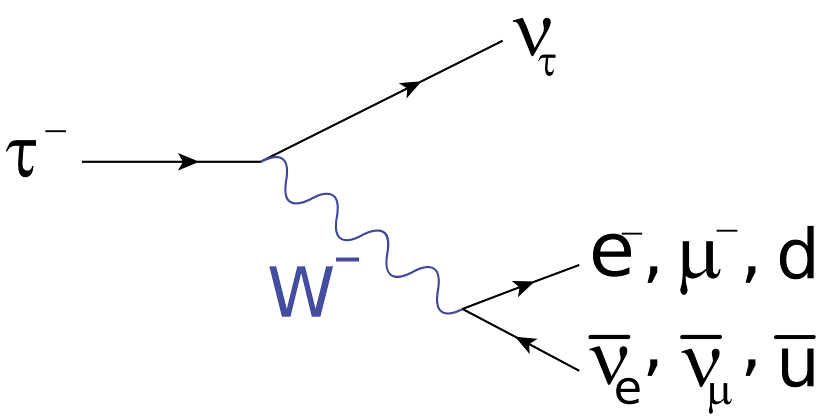
Gluon fusion



Vector boson fusion





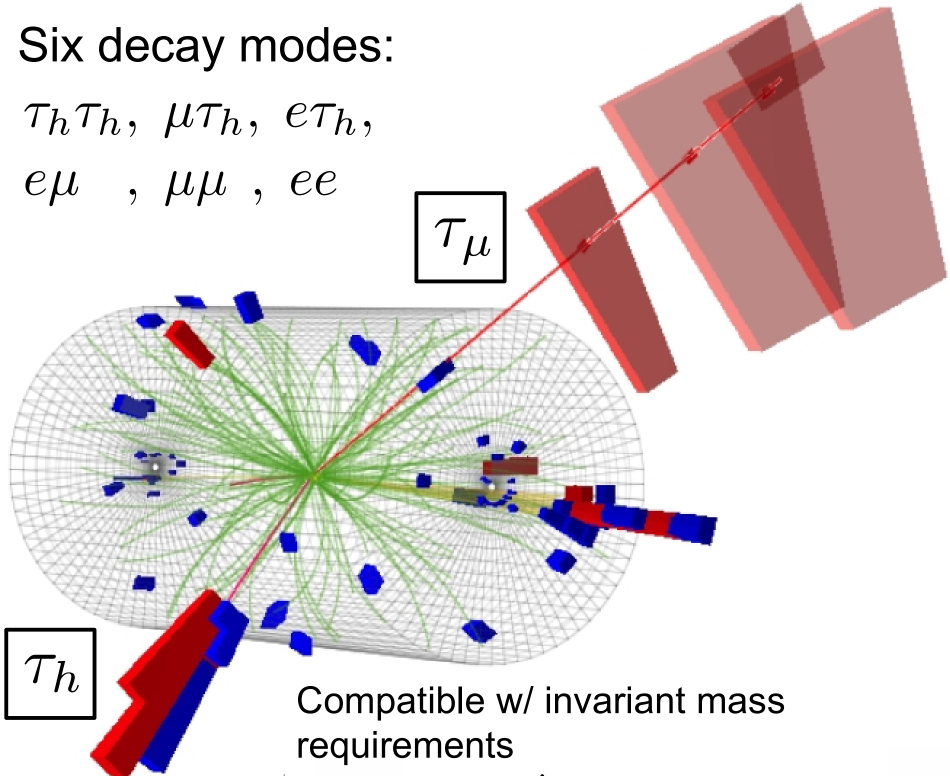


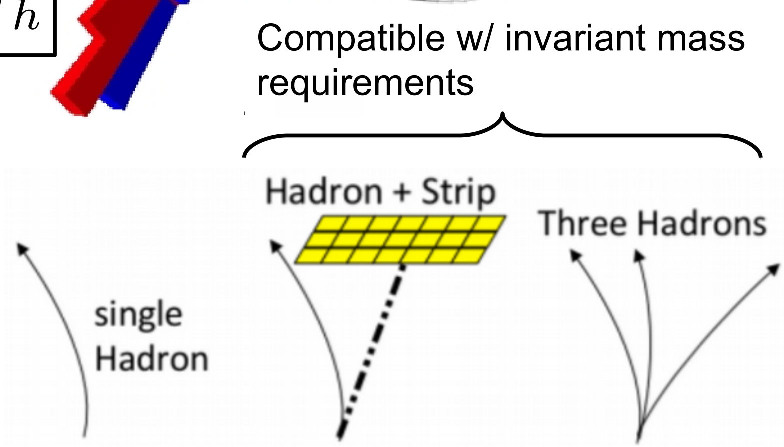
Decay Mode	BR
$\tau \to e\nu_e\nu_\tau$	17.83%
$\tau \to \mu\nu_\mu\nu_\tau$	17.41%
$\tau \to$ 1-prong ν_τ	37.10%
$\tau \to$ 3-prong ν_τ	15.20%

$H \rightarrow \tau\tau$ Decay Channel

Six decay modes:

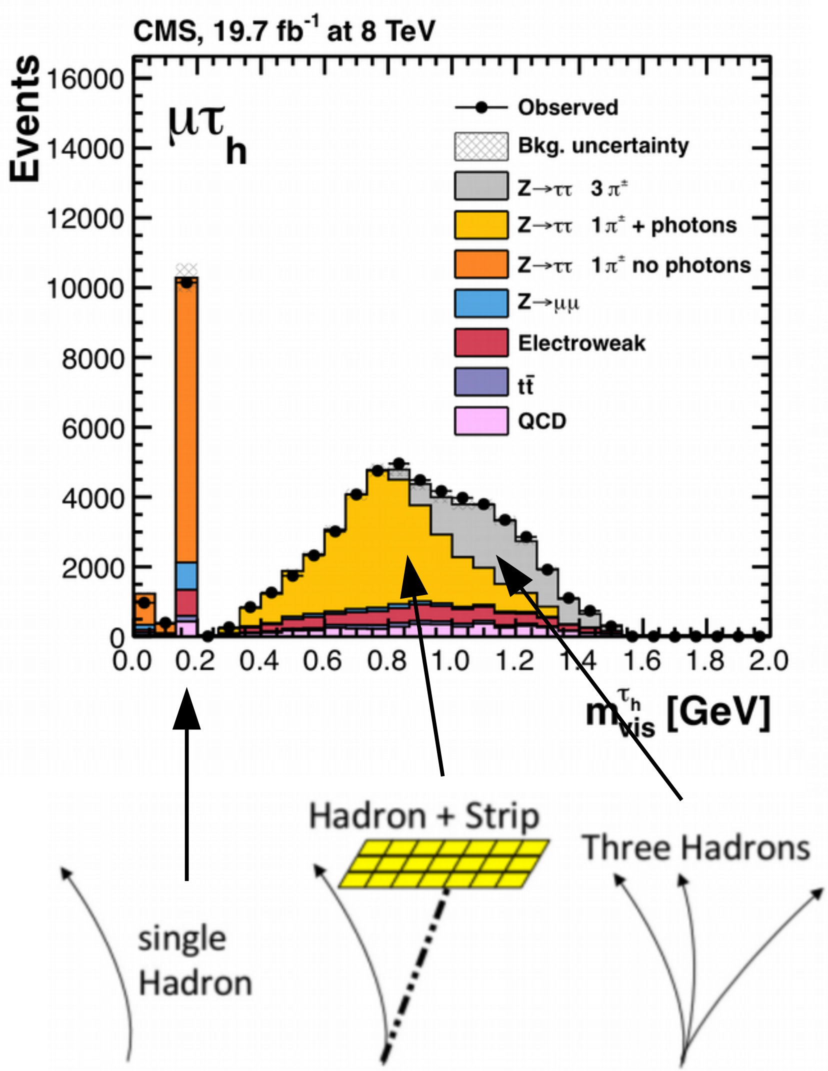
$\tau_h\tau_h,\ \mu\tau_h,\ e\tau_h,$
$e\mu\ ,\ \mu\mu\ ,\ ee$



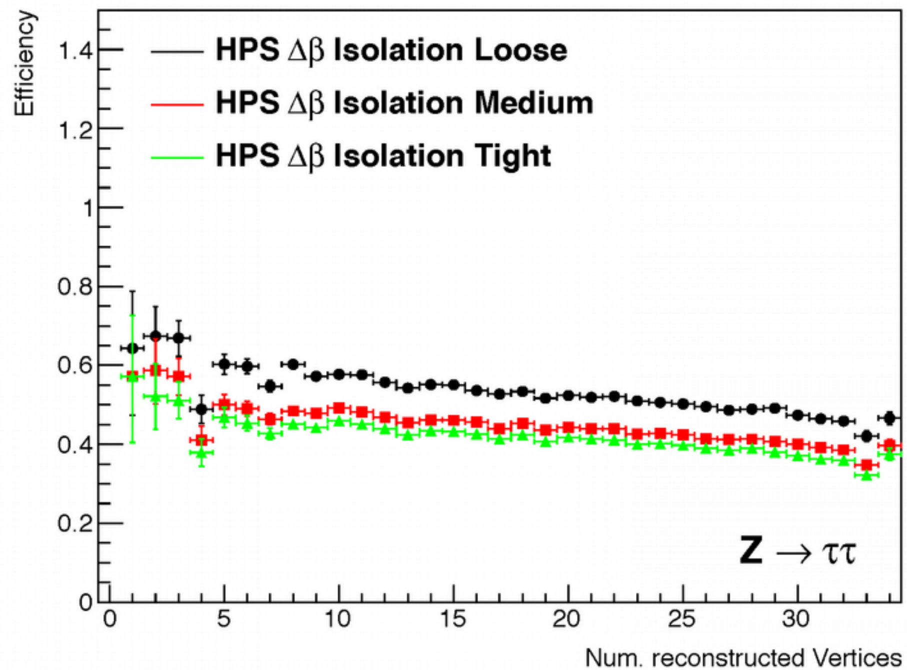


- Isolation (based on energy τ_h deposits in vicinity of reconstructed candidate).
- Discrimination against electrons (based on shower shape & E/p).
- Discrimination against muons.

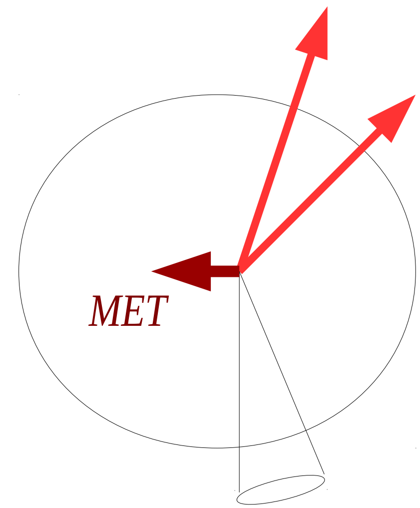
Performance of Hadronic τ Reconstruction



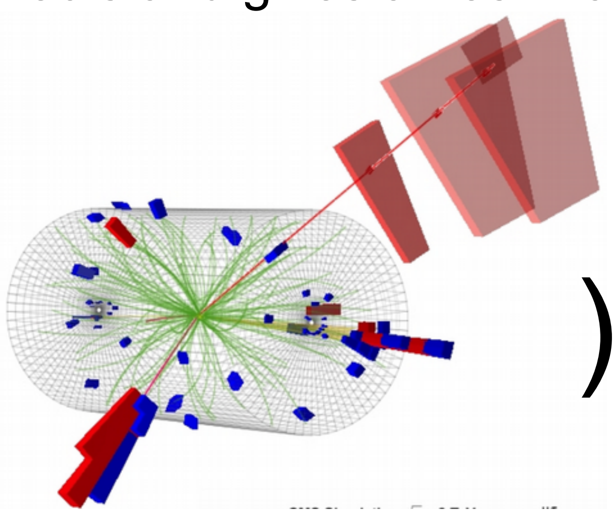
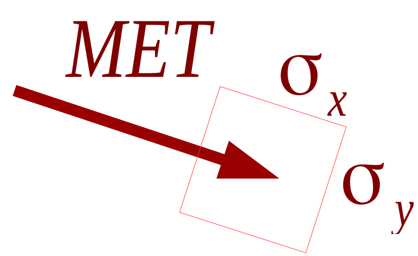
- Efficiency $\approx 60\%$ ($\approx 3\%$ fakerate), flat for $p_T(\tau) > 30\ \mathrm{GeV}$ & independent from pileup events.



Reconstruction of the missing energy

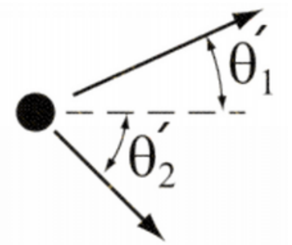
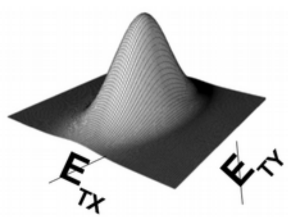


- Missing transverse energy (MET):
  - momentum in plane perpendicular to beam axis, in theory equivalent to neutrino momentum
- Sum over all reconstructed and energy-corrected particles in the event in x-y-plane together with MET is 0 by definition
- A multivariate regression technique removes biasing effects and gives an estimation of phase space of

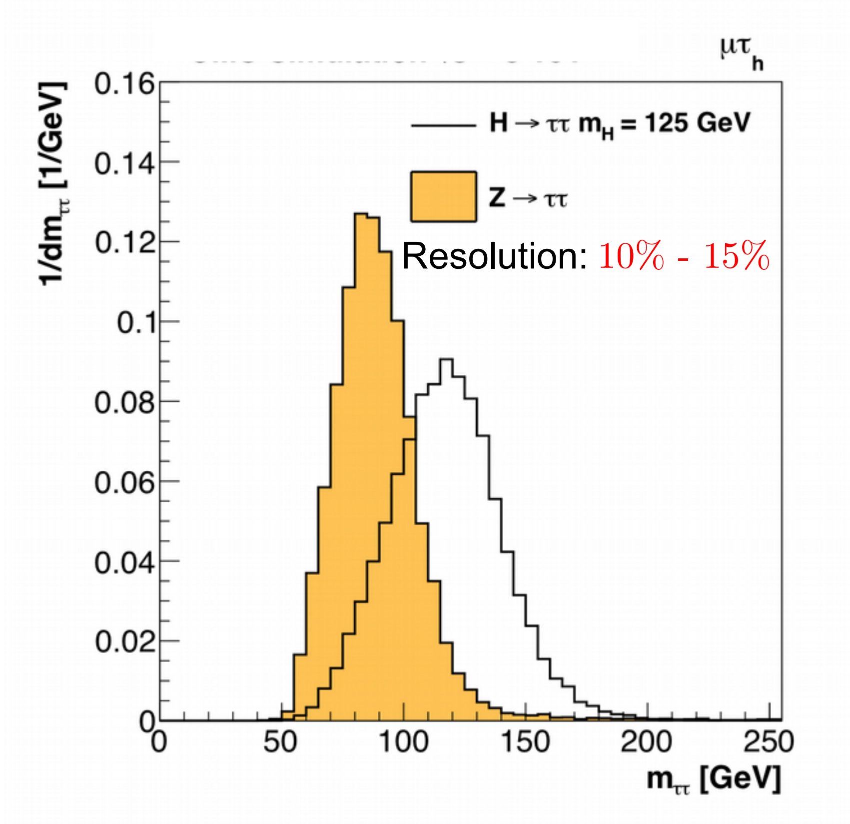
f (Σ ) = 

Analysis Strategy

- Analyze all six inclusive decay channels ($\tau_h\tau_h,\ \mu\tau_h,\ e\tau_h,\ e\mu,\ \mu\mu,\ ee$) & many more exclusive decay channels for VH production ($Z \to \ell\ell,\ W \to \ell\nu$).
- Select two isolated leptons ($\tau_h,\ \mu,\ e$).
- Restrict $\not{E}_T$ to reduce background from $W + \text{jets}$ events.
- Use fully reconstructed $m_{\tau\tau}$ as discriminating variable:

$\mathcal{L} =$  $\times$ 

- Use further kinematic properties of the event to improve sensitivity



Background Control

$Z \rightarrow \tau\tau$

- Embedding (in $Z \rightarrow \mu\mu$ replace μ by sim τ).
- Norm from $Z \rightarrow \mu\mu$.

$Z \rightarrow \ell\ell$

- From simulation
- Corrected for $jet \rightarrow \tau$ or $e/\mu \rightarrow \tau$ fakerate.

tt

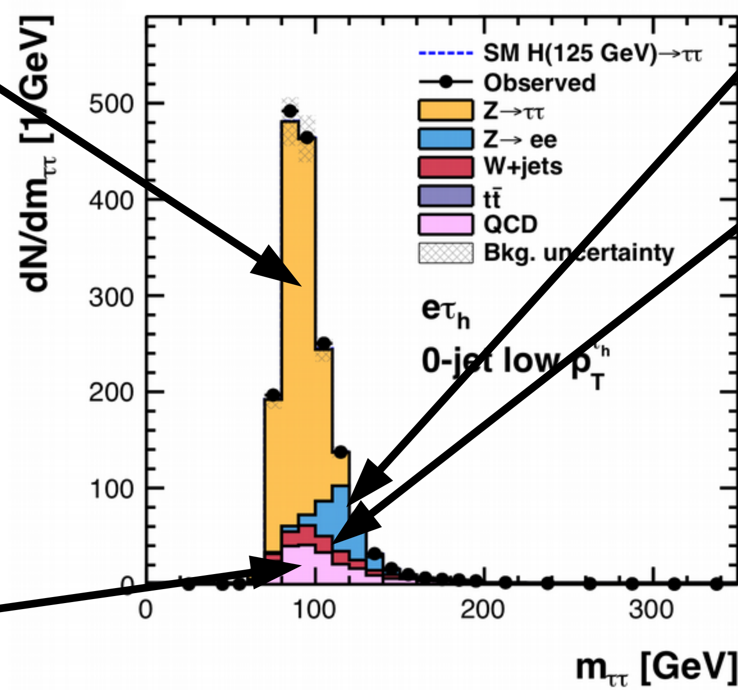
- From simulation.
- Normalization from sideband.

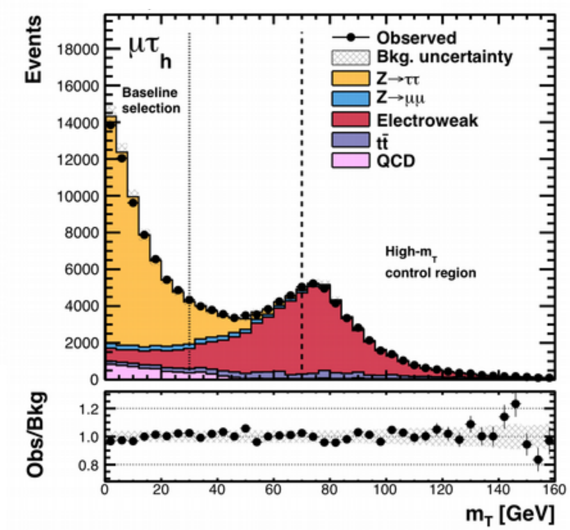
$W + jets$, Diboson

- From simulation
- Normalization from sidebands.

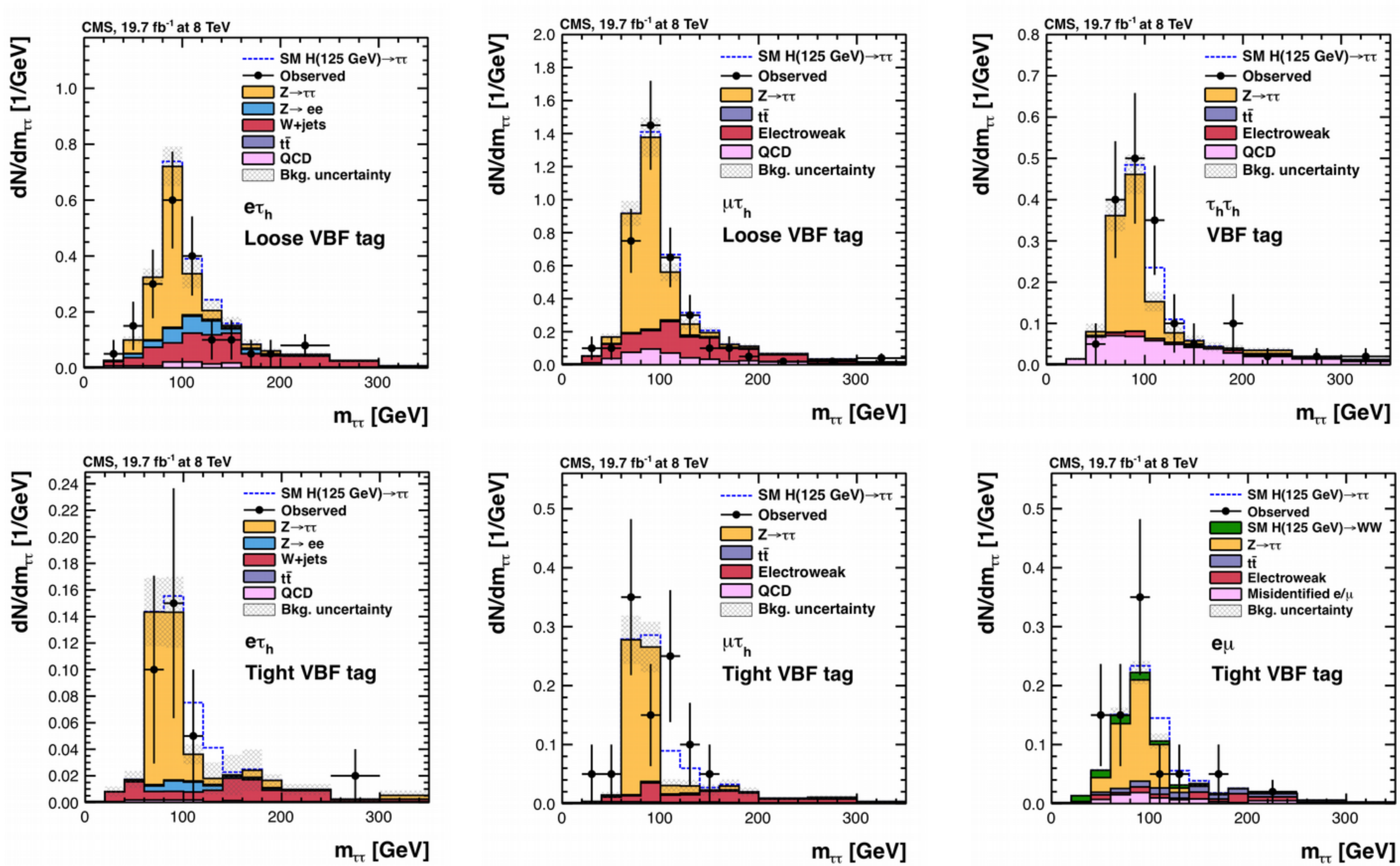
QCD multijet

- Normalization & shape taken from SS/OS or fakerate.

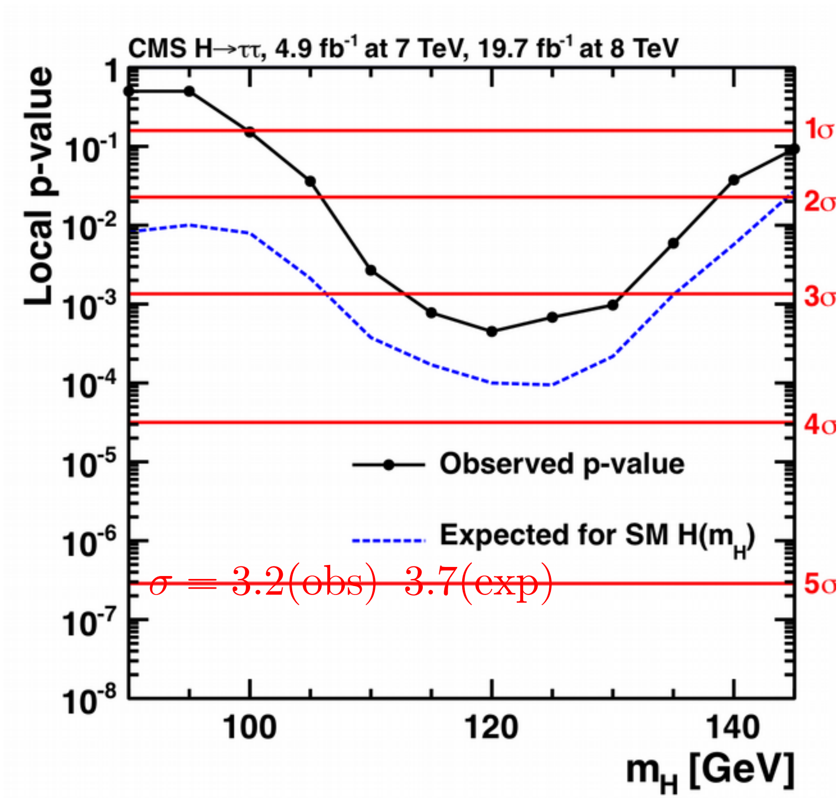


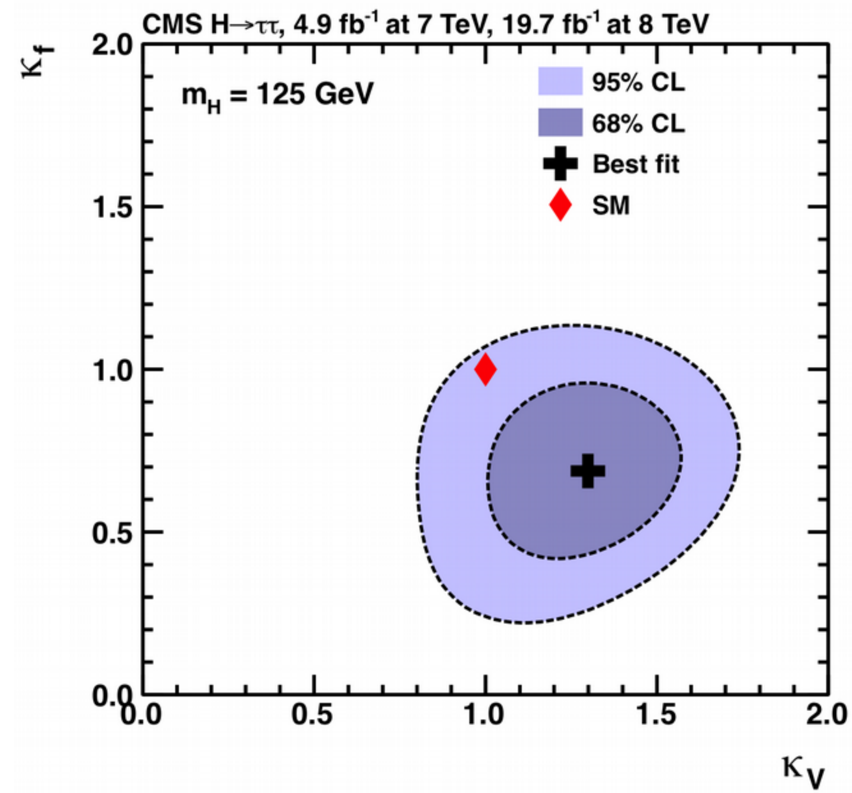


Distribution of $m_{\tau\tau}$



3σ Evidence of Higgs Coupling to Fermions

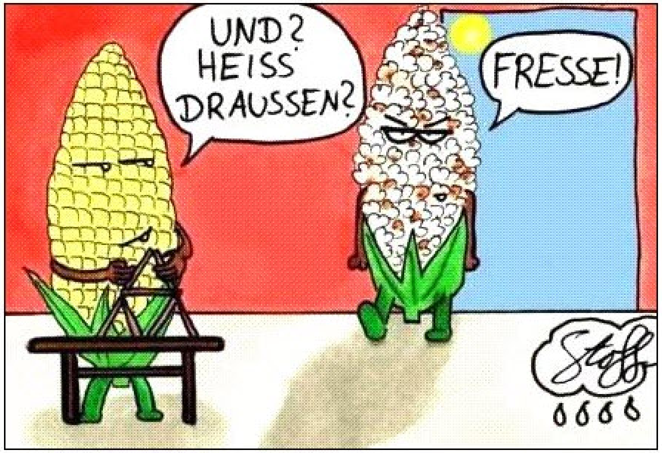




Couplings normalized to Standard Model expectations

Quo Vadis $H \rightarrow \tau\tau$

- Why is $H \rightarrow \tau\tau$ still hot?
  - Most promising channel to have direct access to Higgs fermion couplings.
  - $H \rightarrow \tau\tau$ needs to be reestablished in 2016 data.
  - 3σ need to be turned into an unquestionable 5σ discovery.



  - $H \rightarrow \tau\tau$ is the only channel to measure direct CP violation in the Higgs sector.
  - Exciting: H-tautau opens the windows to probe physics beyond the standard model

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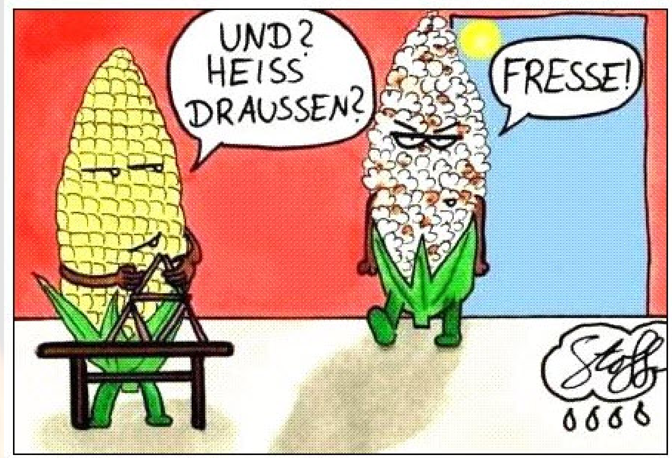


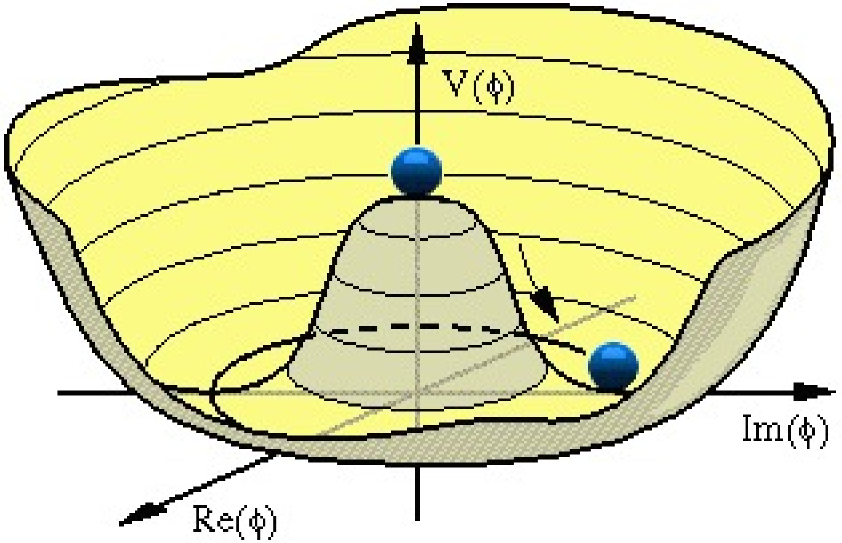
What will be next?

Backup

Application to Particle Physics

- *Goldstone* Potential:

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$
$$\mathcal{L}(\phi) = \partial_\mu\phi\partial^\mu\phi^* - V(\phi)$$



- invariant under $U(1)$ transformations (i.e. φ symmetric).
- metastable in $\phi = 0$.
- ground state breaks $U(1)$ symmetry, BUT at the same time all ground states are in-distinguishable in φ .

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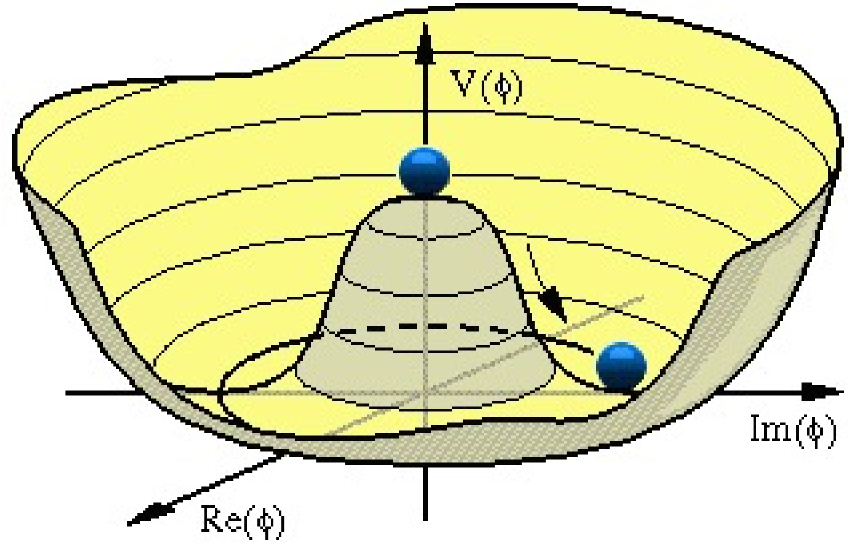

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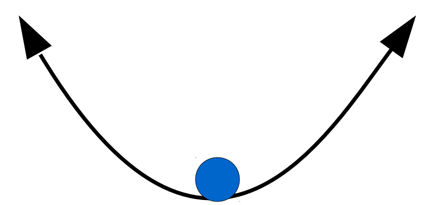
- ϕ has radial excitations in the potential $V(\phi)$.



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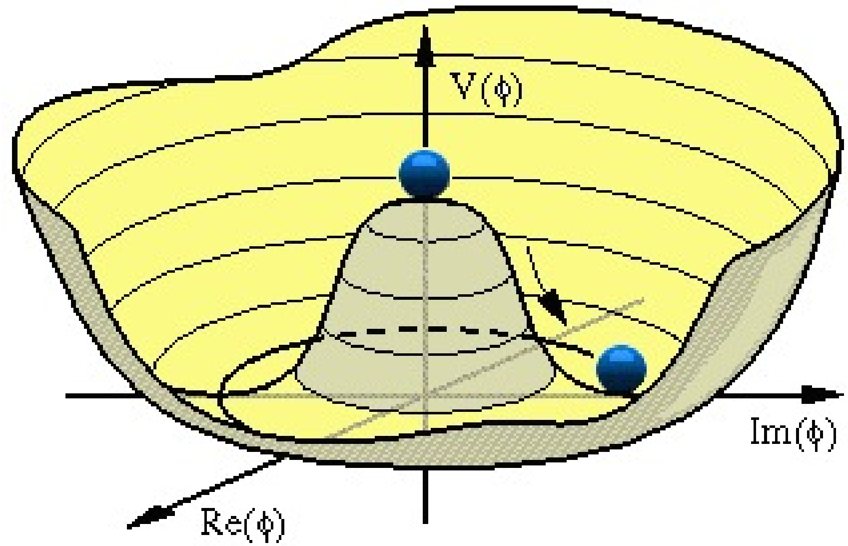

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- ϕ can move freely in the circle that corresponds to the minimum of $V(\phi)$.