

From Pisa



Higgs Physics

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Few words about me

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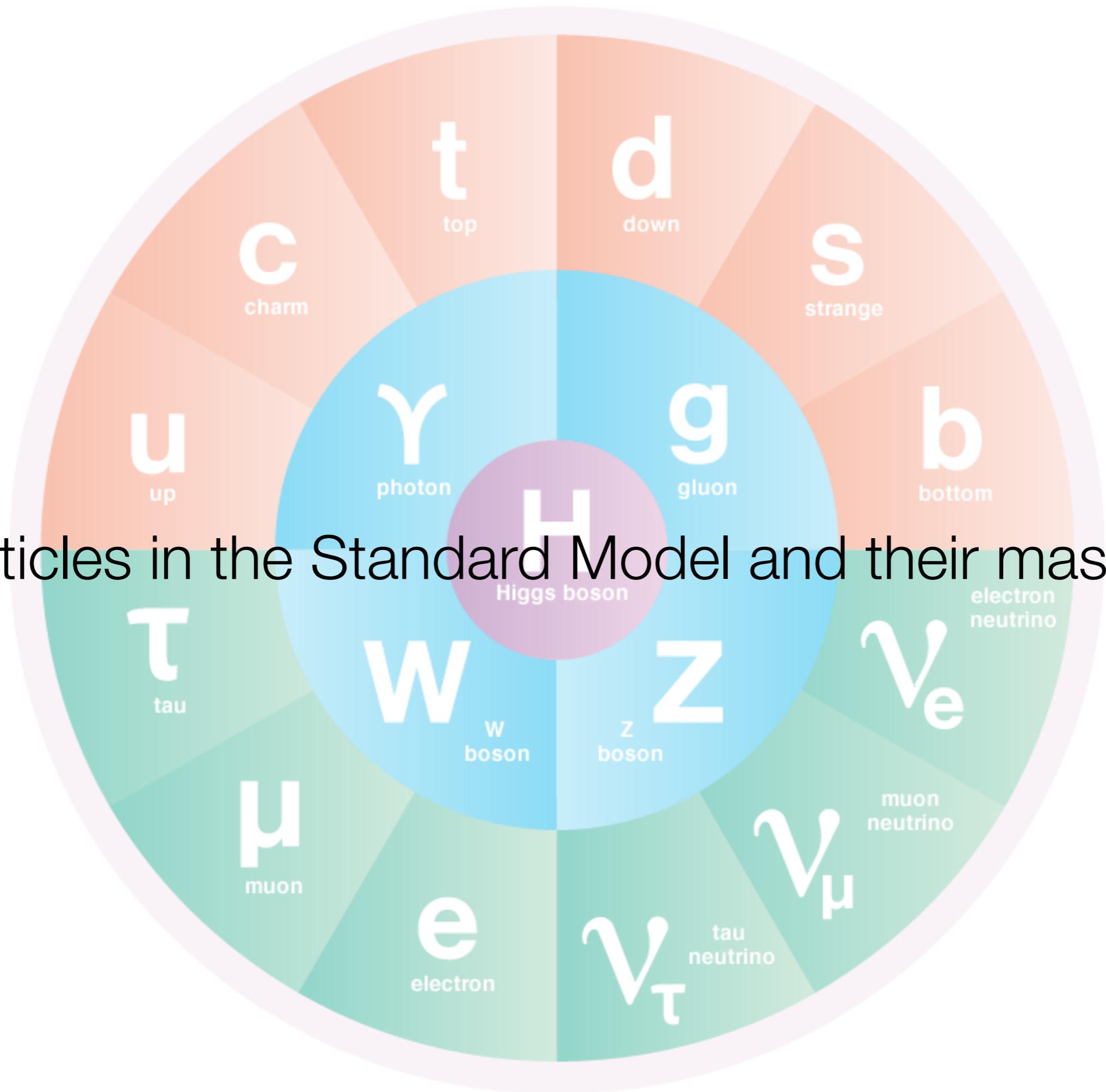


- Master's thesis in Pisa (Italy)
- Summer Student at CERN (Switzerland)
- PhD in Pisa (Italy)
 - Short term studentship with MCnet @ CERN (Switzerland) & Lund Universitet (Sweden)
- Post-doc in Barcelona IFAE (Spain)
 - First time in HASCO in 2012
- Post-doc in Paris ILP-LPNHE (France)
- Permanent Research (INFN) in Pisa since 2017
- Member of the ATLAS since 2005
- Enthusiast in Higgs physics, statistics for HEP, and, lately, Custom High Performance Computing (FPGA+ASICs)

Outline

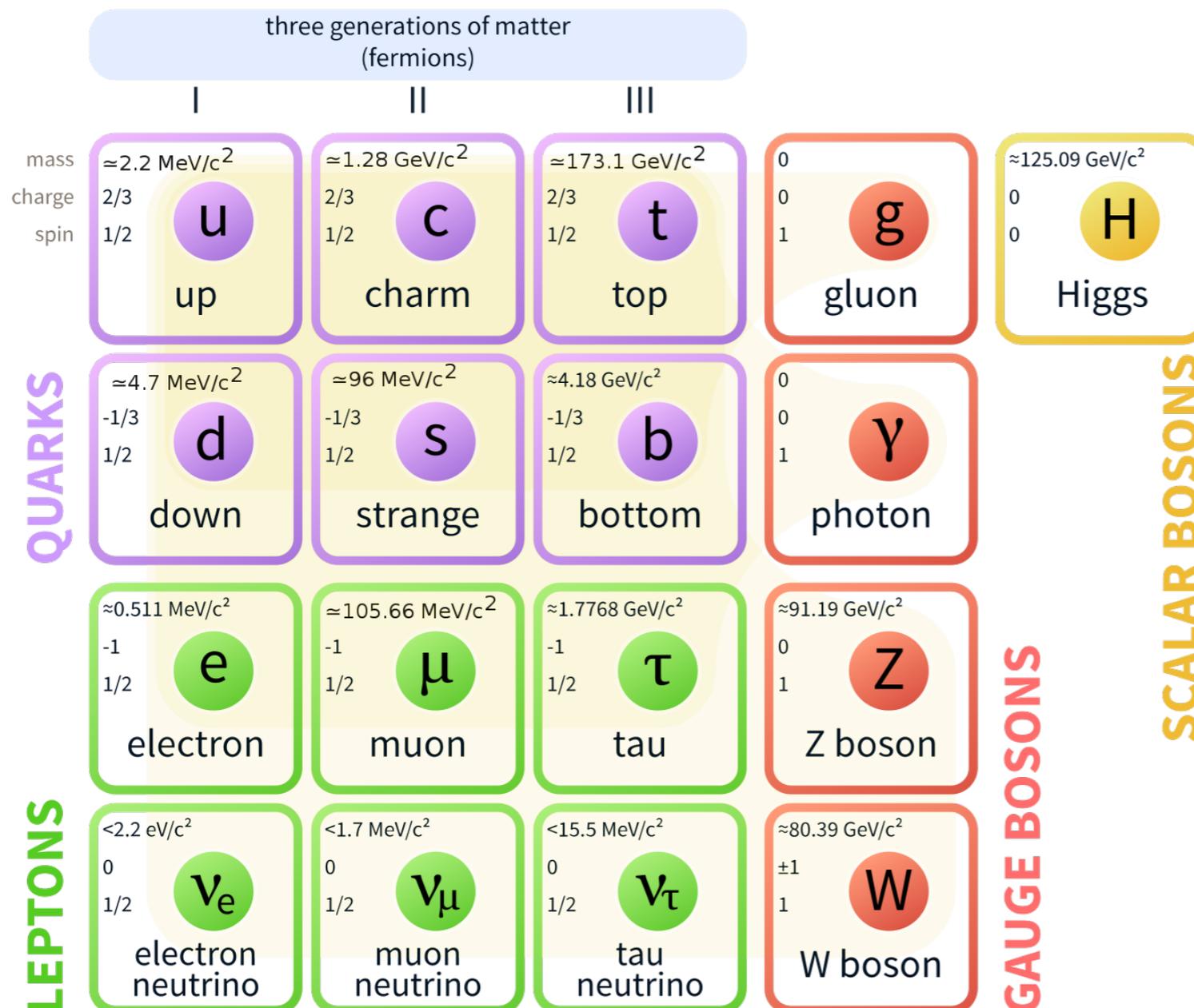
- **Particles in the Standard Model and their masses**
- **Condensate and the spontaneous breaking of symmetry**
- **Masses and the condensate**
- **Higgs boson**
- **Discovering the Higgs boson at the LHC**
- **Selected news from Run2**
- **Higgs Properties**
- **Bonus: Some important questions...**
- **Bonus: Back to the future**

Particles in the Standard Model and their masses



Particles in the Standard Model

Standard Model of Elementary Particles



Imagine we see this for the first time
What we would learn?

- Some organised way to map particles;
- Some coherency in spin and charge, with very well defined values;
- Mass is a mess...

Which is the allowed range for the mass of a fundamental particle?



Photons have 0 mass* \Rightarrow Our scale starts from 0

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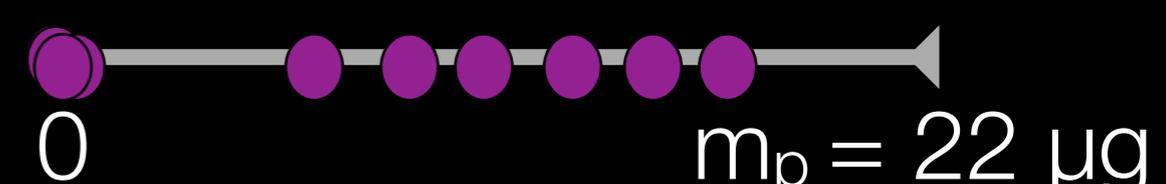
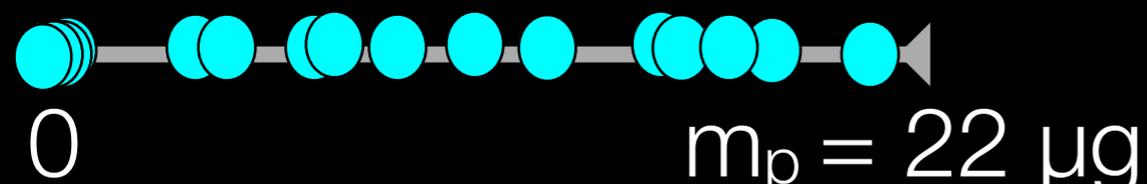
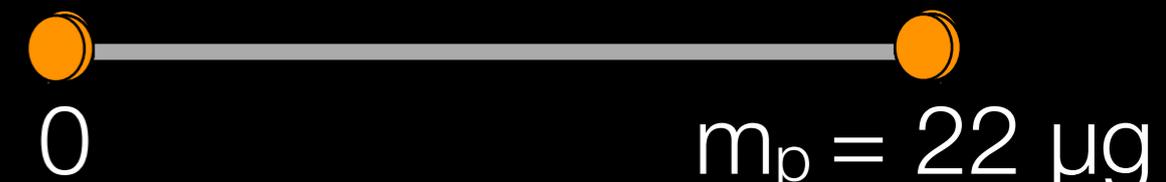
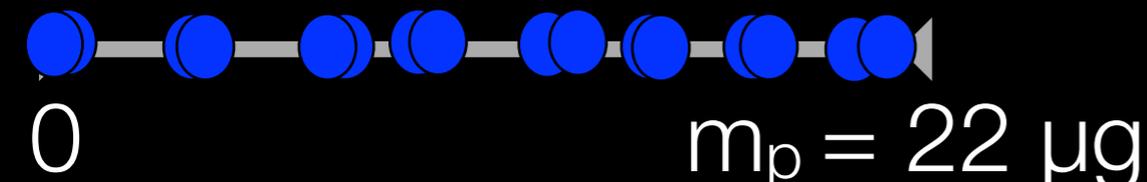
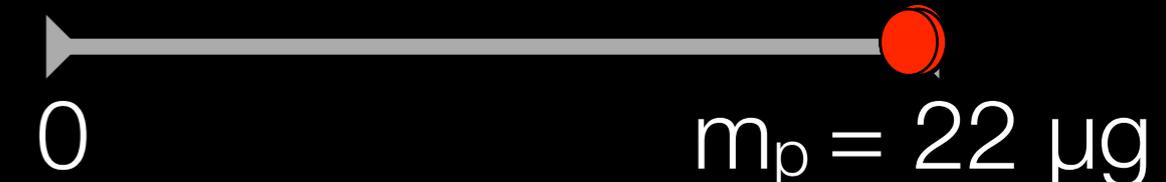
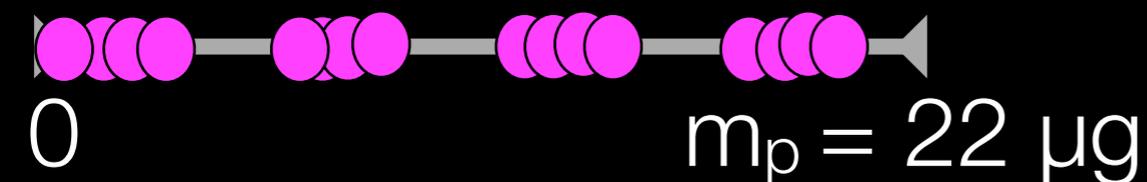
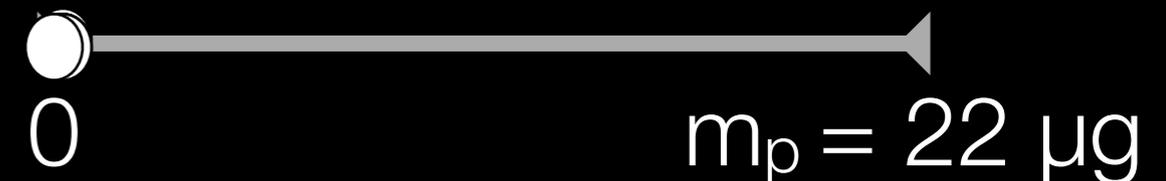
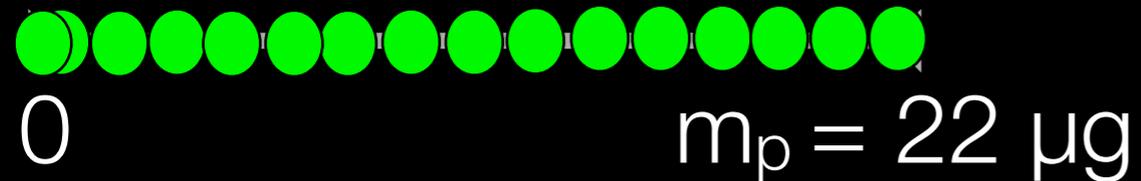


Approaching the Plank mass, the gravitational effects
will be more and more important
Black Holes, so an object with different properties(?!)

1% of the mass of a mosquito

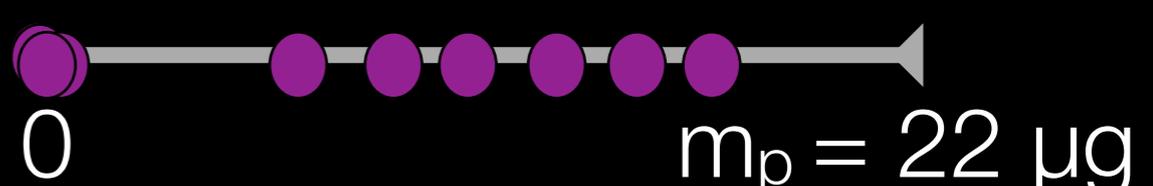
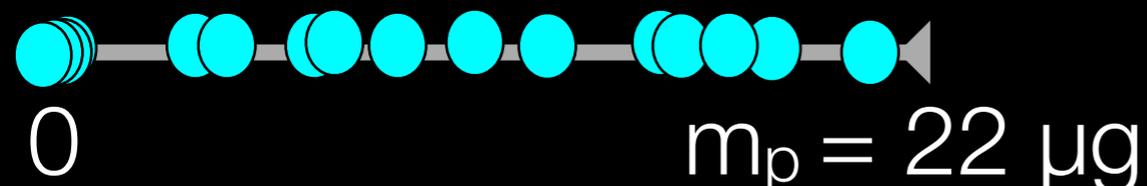
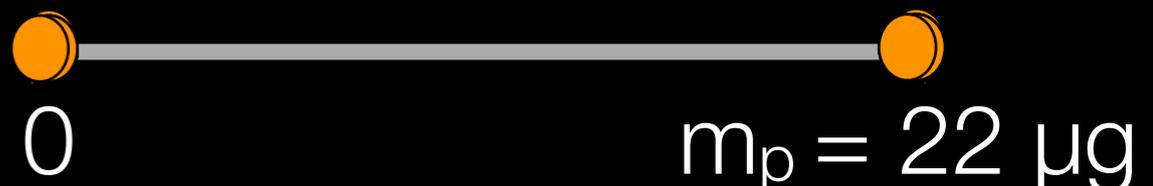
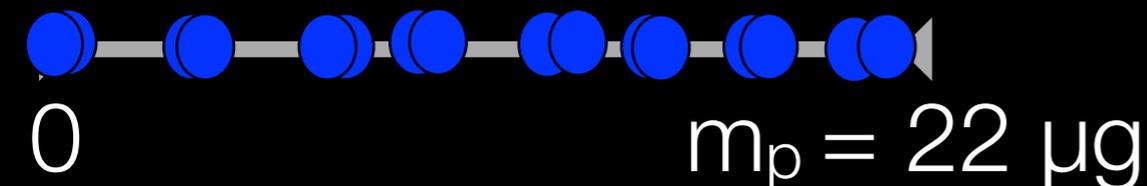
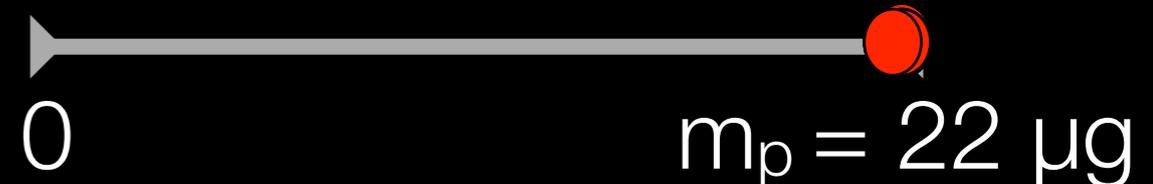
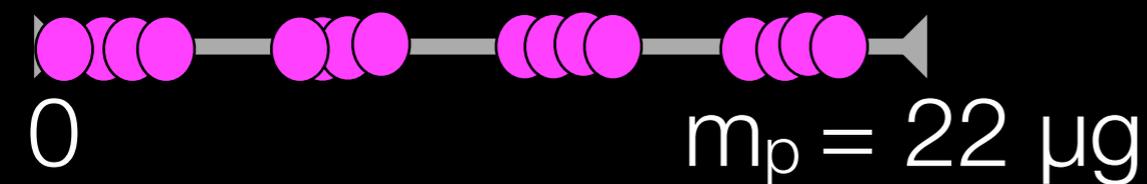
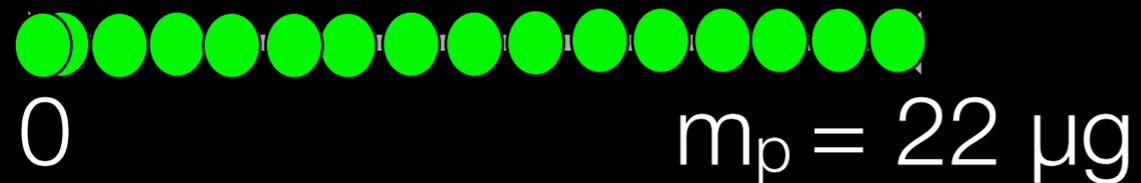
Question time!!!

We have 16 particles (+ Higgs boson),
between 0 and $22 \mu\text{g}$. Where are they?



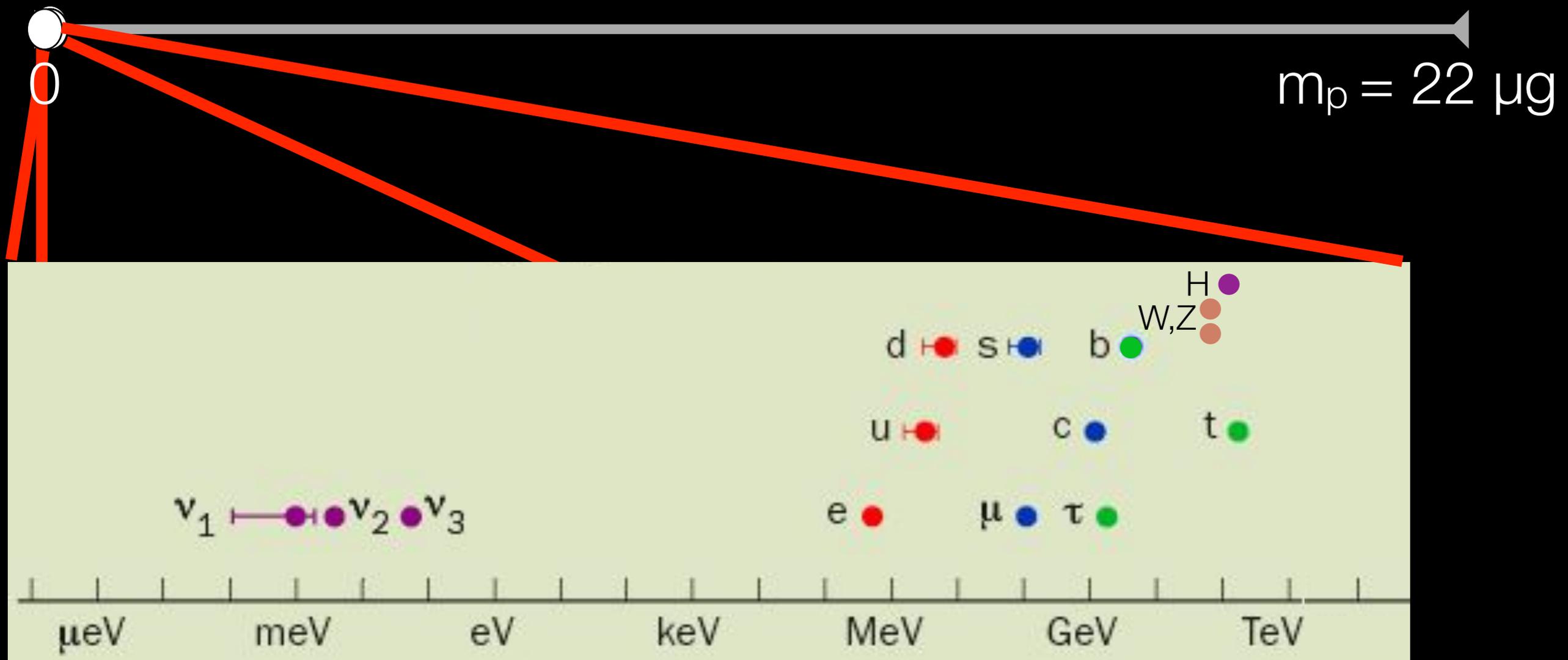
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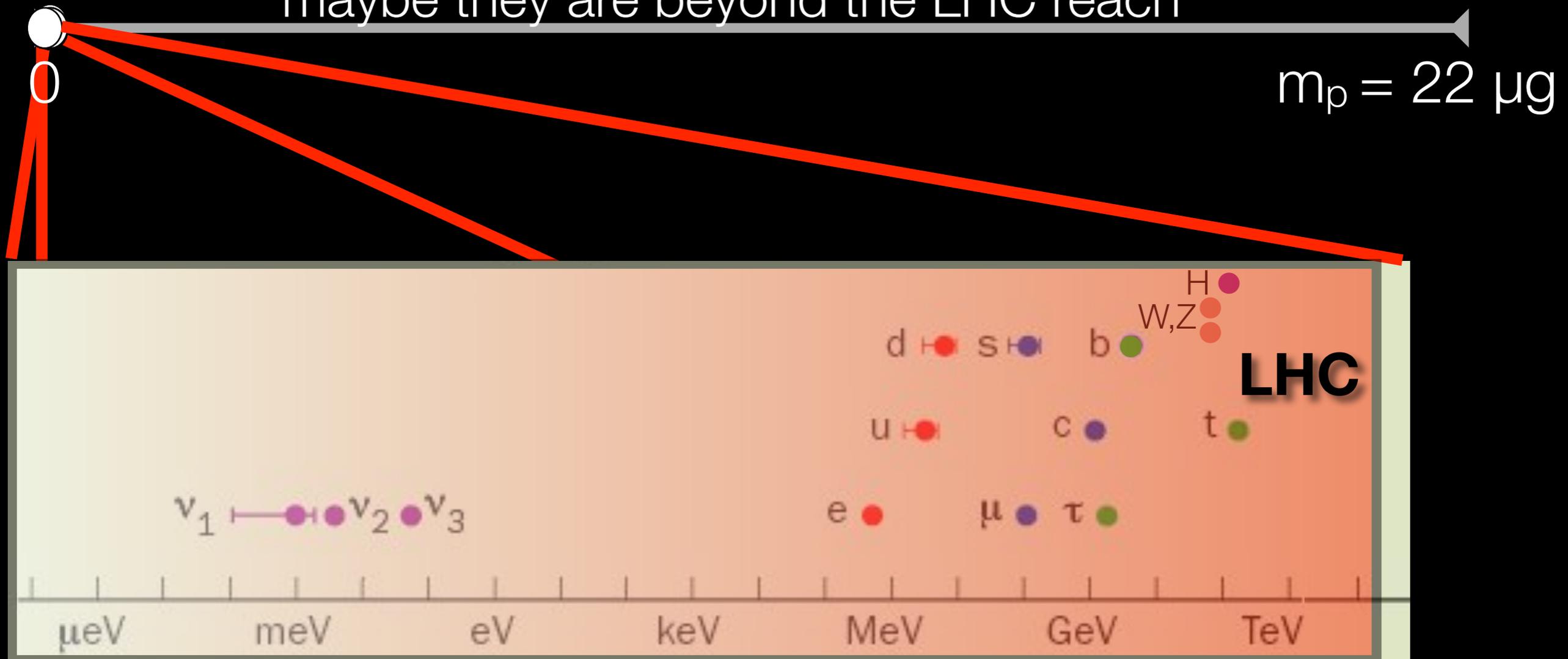
Why?

known particles are in the range $0-10^{-17} m_p$



Why?

Maybe other particles out here,
maybe we will find them in the coming years,
maybe they are beyond the LHC reach

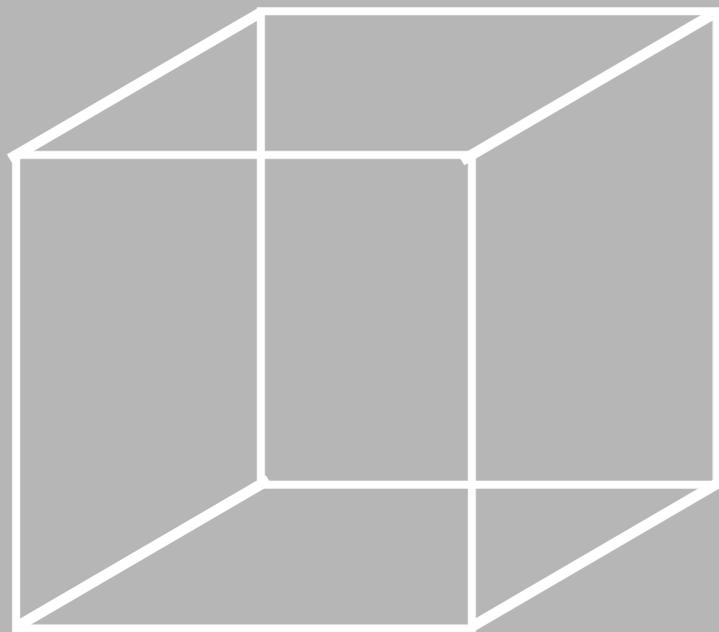


What is special with these particles and their masses?

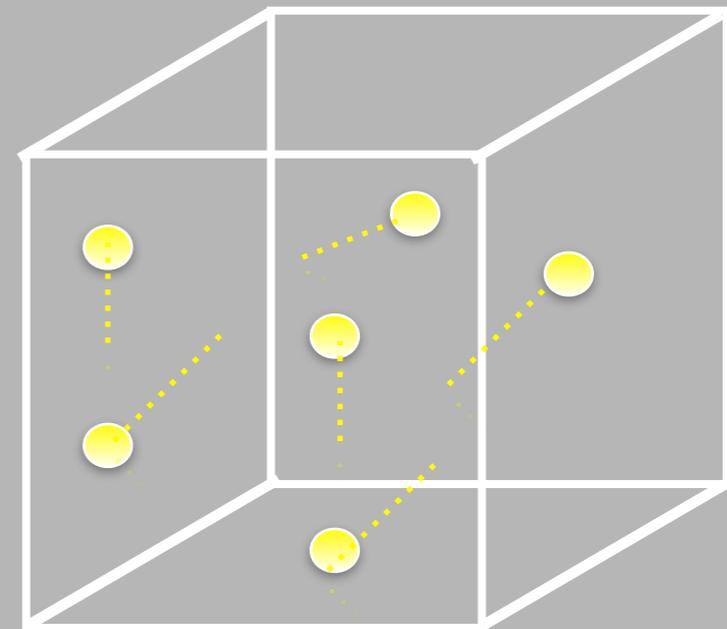
- We can write a version of the SM with all the fermions and vector bosons (without the Higgs boson/mechanism) in which all the particles are massless.
- This theory has all the nice features a theory could need (but one)
- and in part that could explain why they have a mass so small (it is like a small correction from 0)
- BUT:
 - it is not describing nature because particles have masses...

Going back: what is mass?

empty box



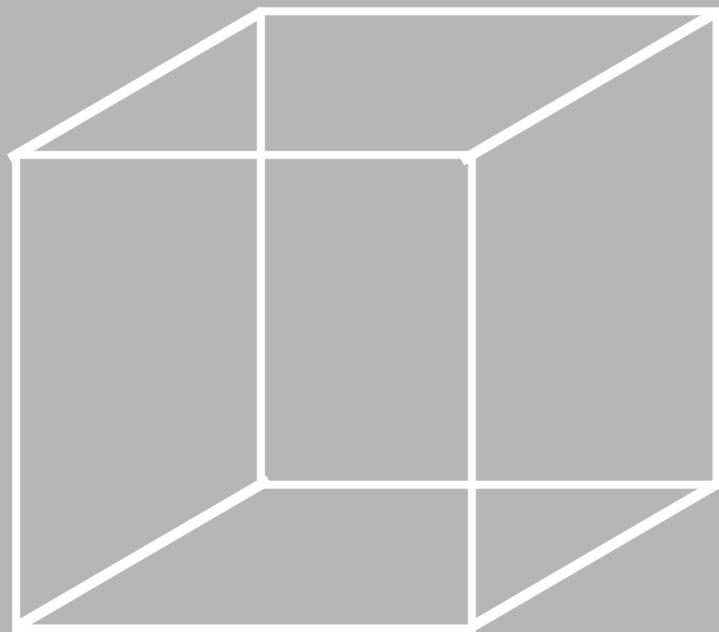
box filled with photons



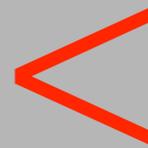
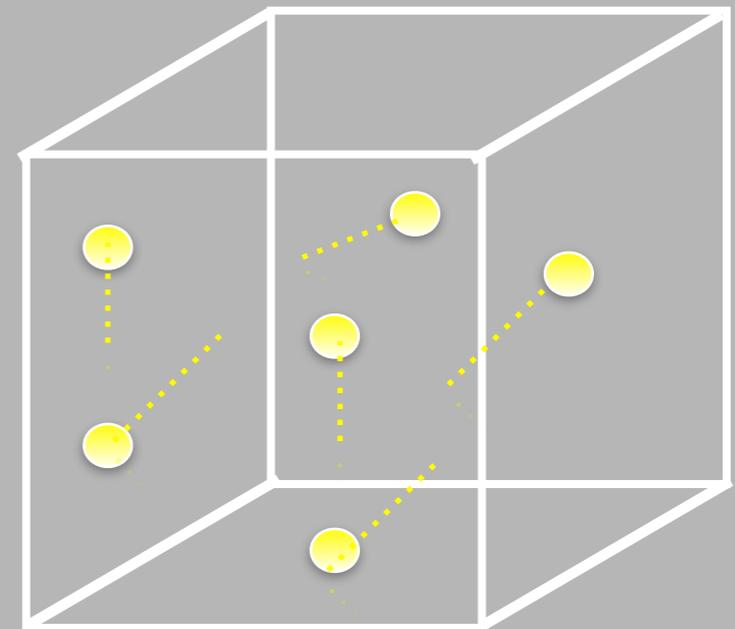
Going back: what is mass?

A system of massless constituents could have a mass
In this case, it is an emergent phenomena

empty box



box filled with photons

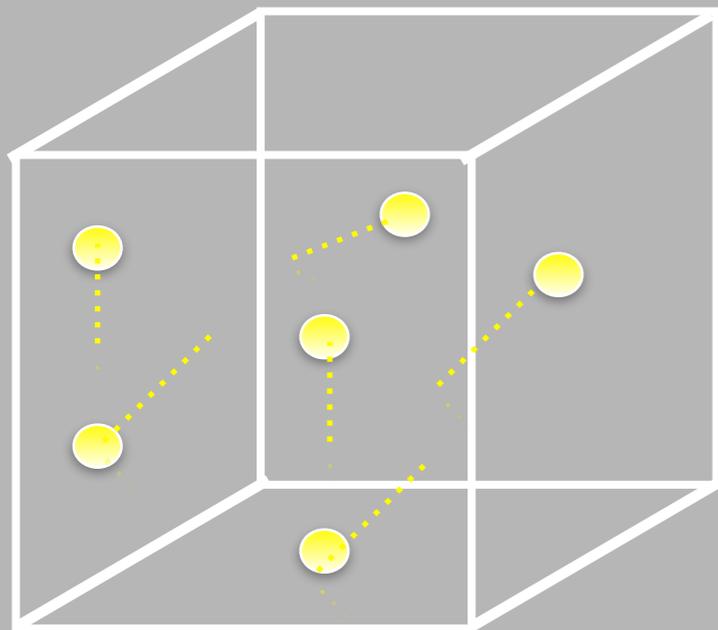


$$m = E/c^2$$

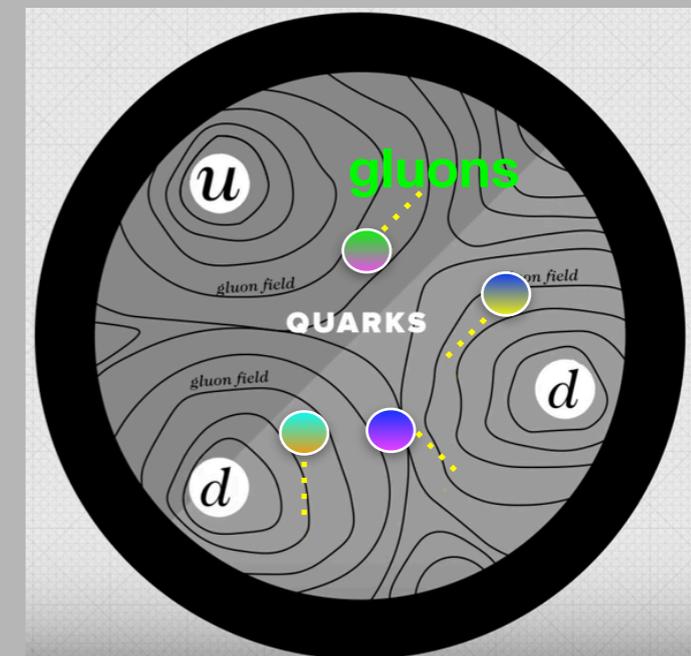
which, by the way, is how Einstein wrote it in his paper ¹⁵

In the real World...

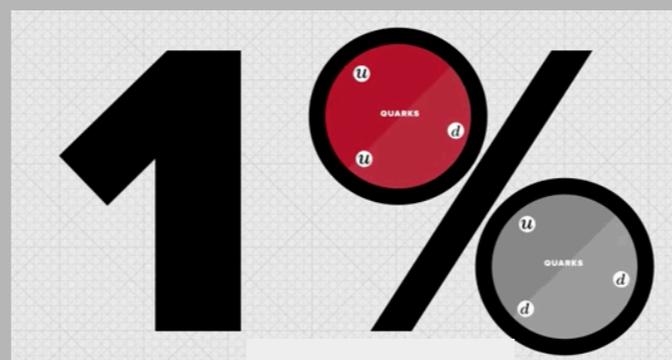
box filled with photons



neutron



Mass of the quarks is



of the mass of
protons/neutrons

**~99% of our mass dynamically emerging from
strong interactions**

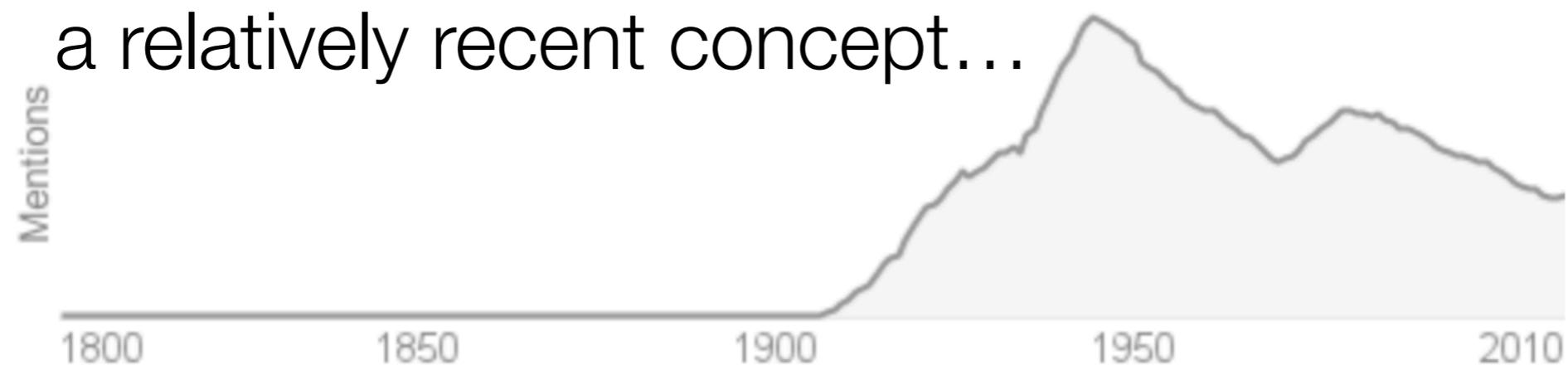
Particles in the Standard Model and their masses

- Compared to the Plank mass, the elementary particles are almost massless
- The mass can be an emergent property of a system
- It may be related to some underlying dynamics

Condensate and the spontaneous breaking of symmetry

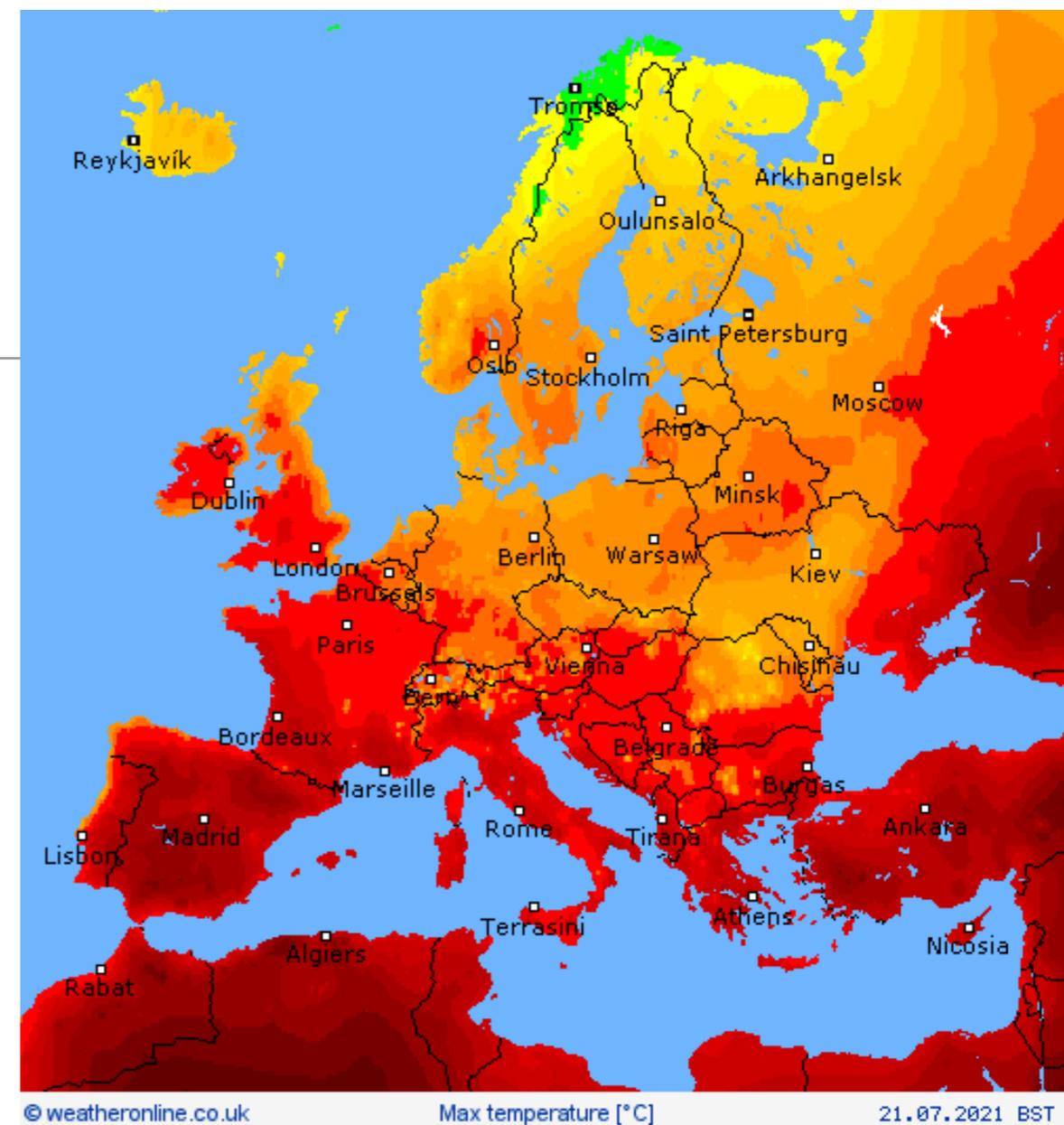
Use over time for: condensate

a relatively recent concept...



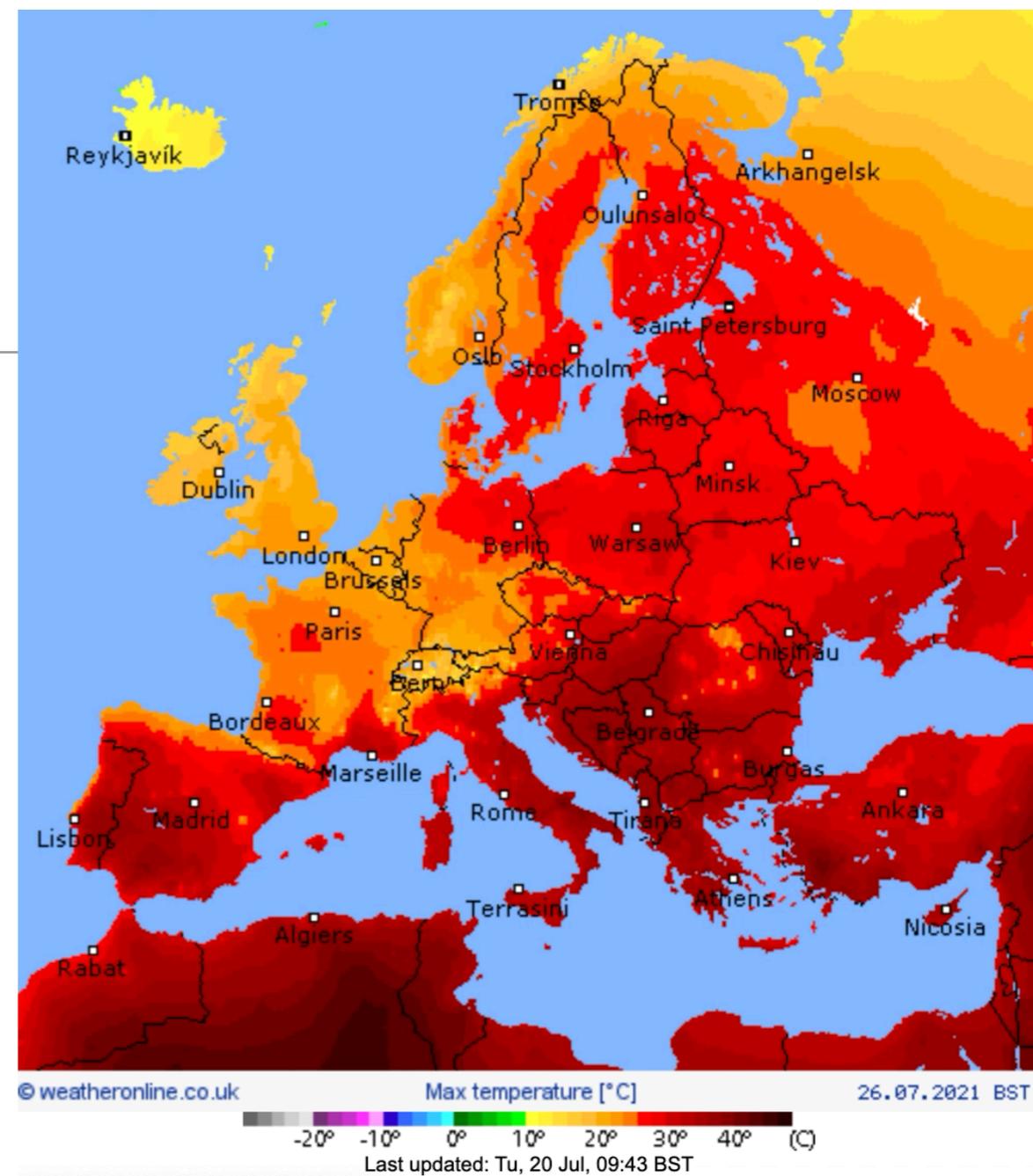
Fields

- Fields characterises the behaviour of a quantity in that moment in that place
- They can vary from place to place, and they can evolve in time
- They could effect how things are moving, for example electric field
- Space can be filled with fields



Fields

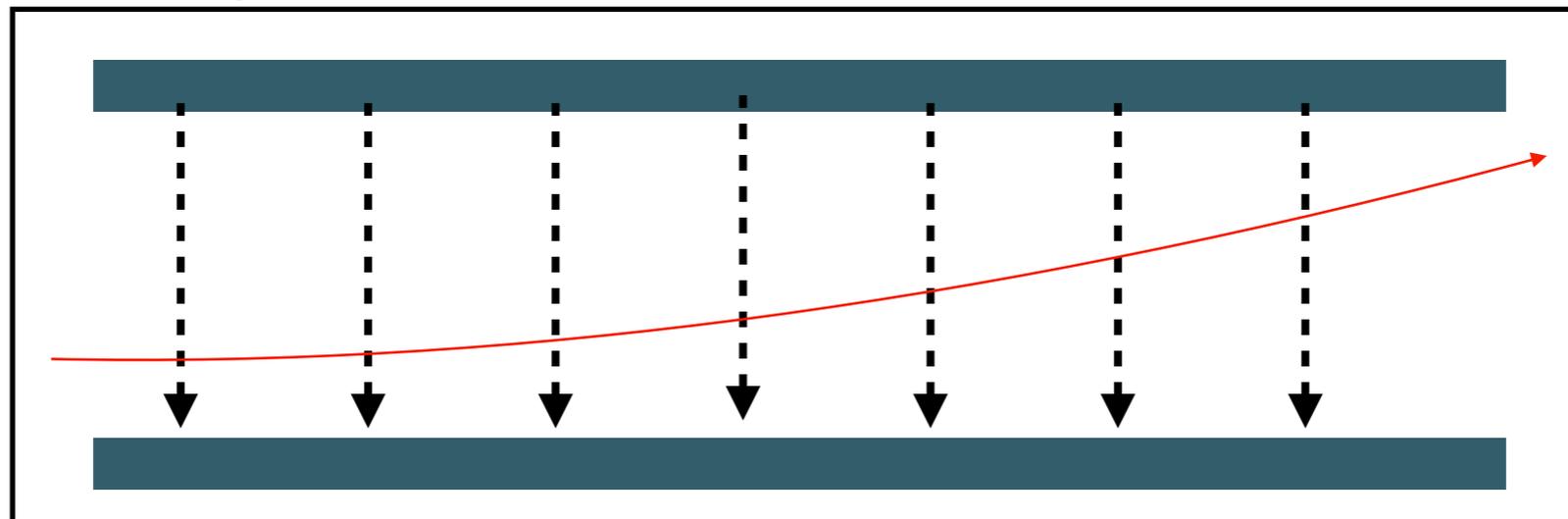
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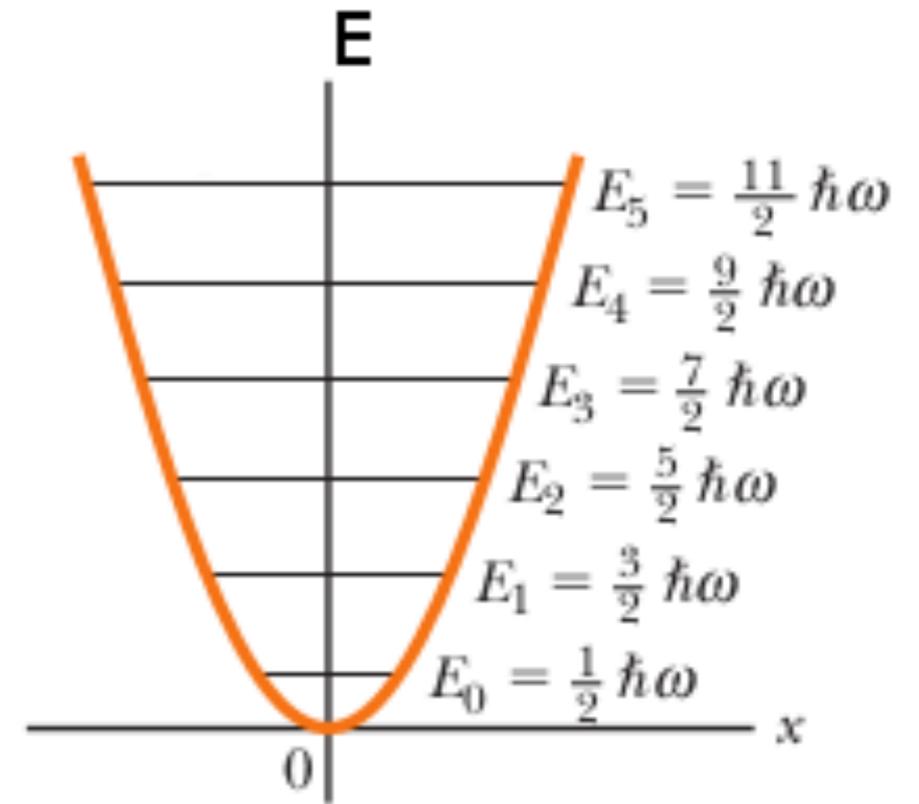
Vacuum

- Ordinarily we think that fields are zero in empty space
- Is there a requirement in physics that says that this should be the case?
- What if our universe was filled with electric field?
 - i.e. capacitors placed infinitely far from us?
 - The electric field would just be there
 - We would experience charged particles moving in some peculiar way, but that would be just a fact of nature



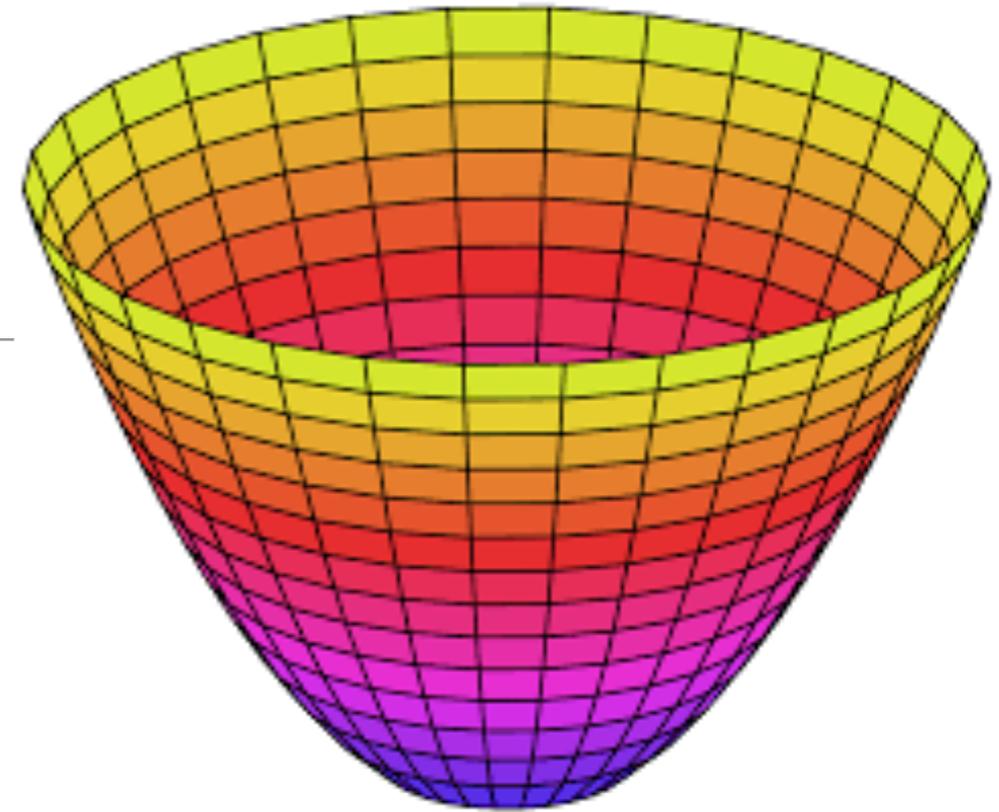
Energy of a field and vacuum

- In general, fields cost energy
- Space without an electric field has 0 energy
- Energy density of the electric field:
 - $u \propto E^2$
- From the Quantum Mechanical point of view, the vacuum is a state: the state of lowest energy...
- and the quanta of vibration of a field are particles



Multiple fields

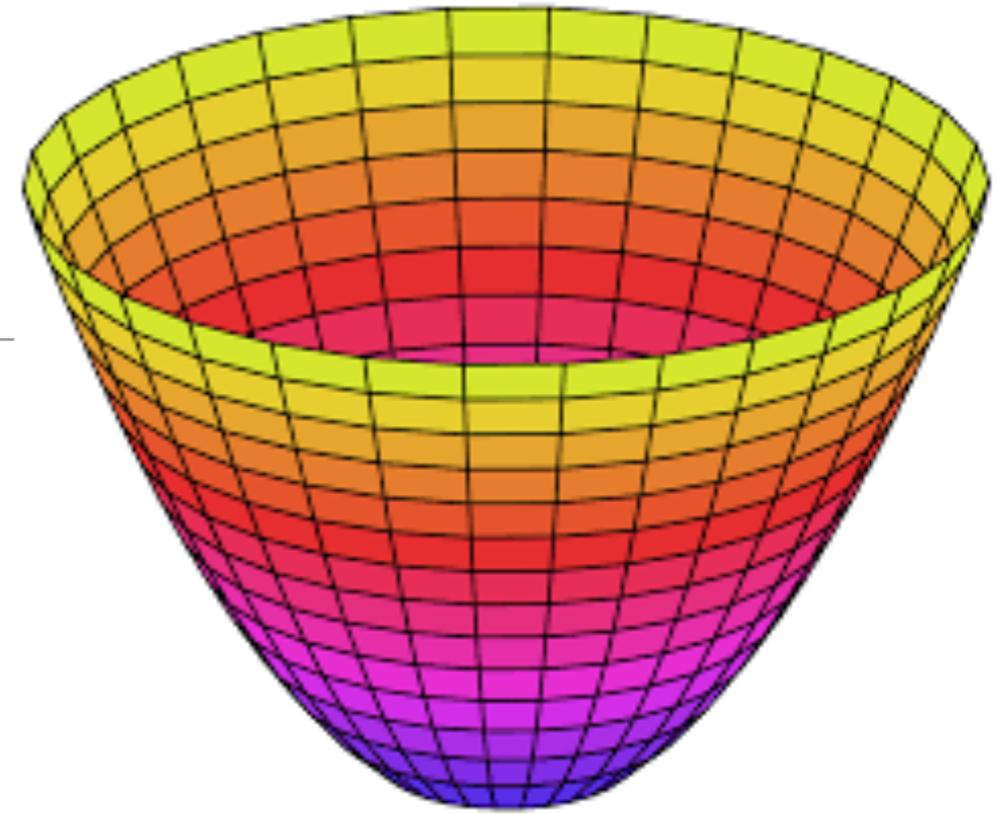
- Let's imagine we have 2 dim field :
 $\Phi = (\phi_1, \phi_2)$



- The energy would depend on both the components
- No matter in which direction we displace the field, it costs energy
- If we have a paraboloid, to minimize the energy, the components of the field would be at the bottom of the “potential”.
- Must all the fields respect this parabolic shape?

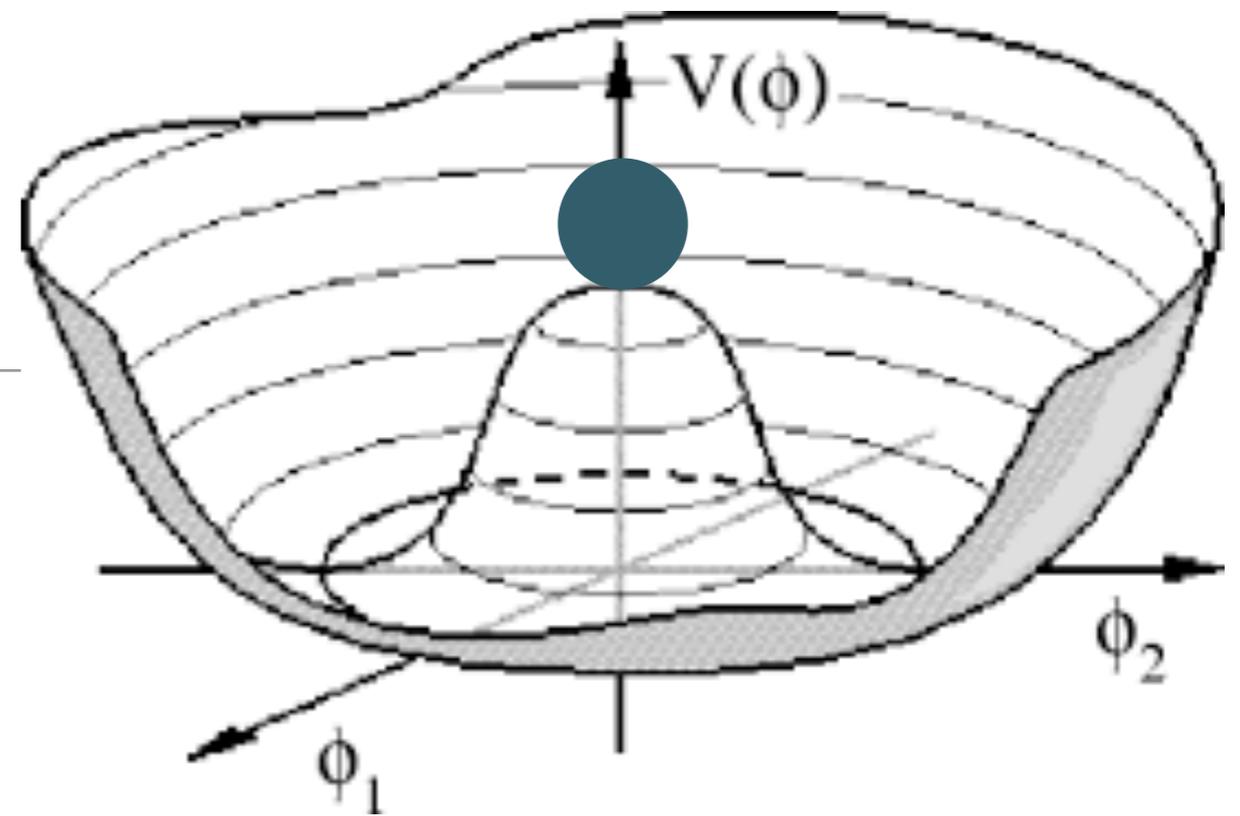
Paraboloid potential

- If the potential is symmetric, we could “move” the field in a circle.
- This motion of the field is very similar to angular momentum
 - It is not in space, it is in the internal field space
- But as the angular momentum, this is quantised.
- This corresponds to the quantisation of charge for that field.
- What if the potential energy is not a paraboloid?



Mexican hat potential

- Maximum at the top of the hat.
So, $\boldsymbol{\phi} = (0,0)$ is not the stable equilibrium
 - un-stable equilibrium
- The brim of the hat is where a ball placed on the top of the hat is going to go.
- The lowest energy state for the field would not be at zero field, but it would be in the brim.
- Interesting!!! The zero energy of the field is not at $\boldsymbol{\phi} = (0,0)$, but on the brim
- Interesting vacuum: the value of the field in each point in space is not zero.
- How would we notice if we have this configuration?
- It may effect other things, and indeed it does...



Something interesting is happening to the “spin”

- In the paraboloid, we had to excite the field to get it in rotation
 - This means that creating charged particle costs some energy
- And in the mexican hat?
 - We do not have to ride up the side of the hat to make a rotation.
 - it is for free in terms of potential energy!!!
 - With this potential, the field could “spin” for free in terms of potential energy in each place of the space.
 - This again correspond to a charge.
 - The entire space would have charge density for essentially no potential energy
 - This is known as condensate in space of charge



Properties of this condensate

- **What if we want to find the lowest energy that the vacuum can have?**

- Best bet: make the field not move with time

- Remember, ride up the potential cost energy,

- but there is still some “kinetic” energy in moving in circle.

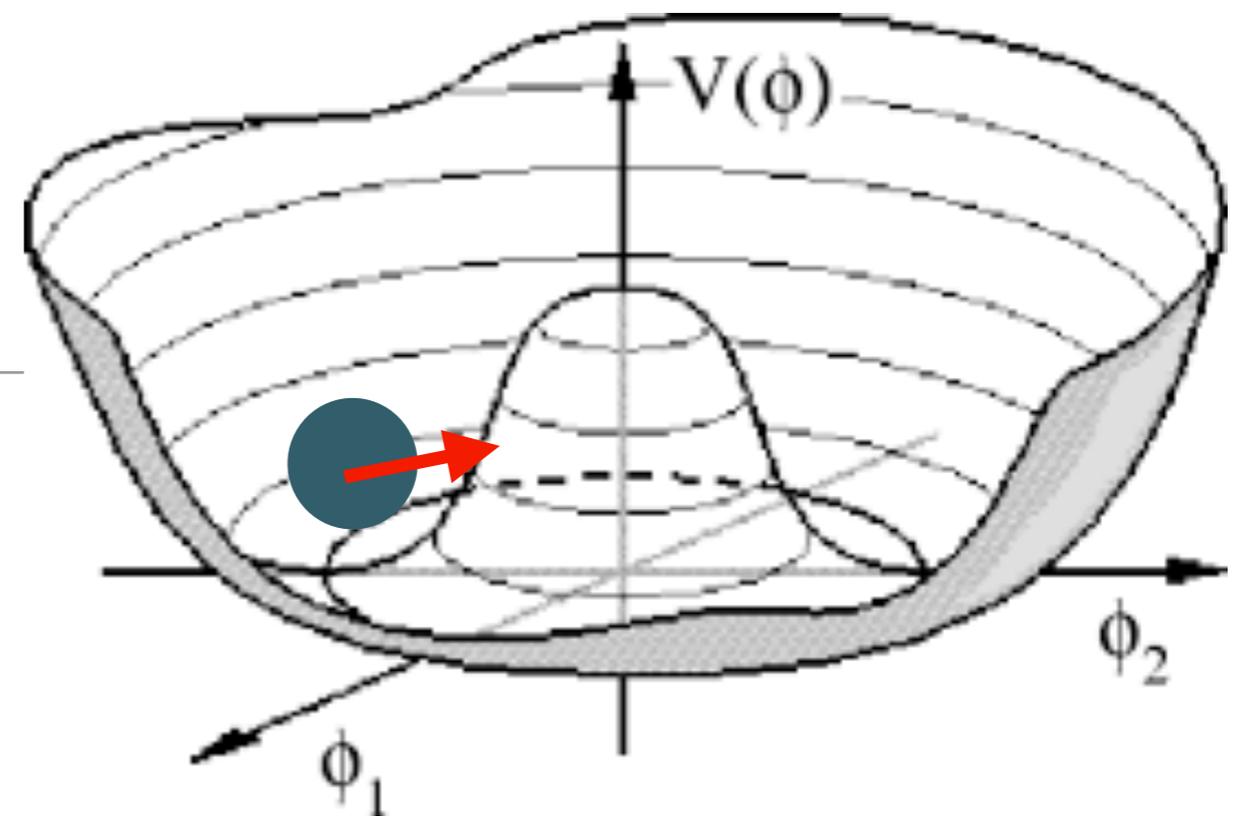
- *So minimum is should be standing steel?*

- **Problem:** uncertainty principle

- We know where the field is in the potential, but for the uncertainty principle, large uncertainty on how fast it is moving around the circle.

- **This means that in a condensate, we cannot have empty space with no charge in it**

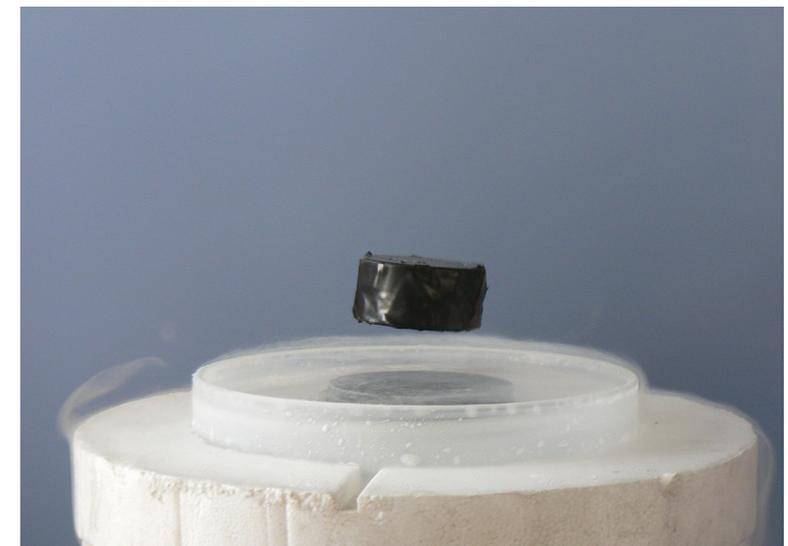
- **Empty space is filled with a totally uncertain amount of charge.**



$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Condensates

- What does it mean that the empty space is filled with a totally uncertain amount of charge?
 - Equal probability for the charge in a place in space to be 0, 1, 2, -1, -2, etc...
- What happens if we have an extra charged particle, and we trow it in?
 - It is not changing the probability of having a certain amount of charge.
 - It is the same from where we stated with.
- What if we take one charge out of this thing?
 - Again same status as before.
- In a condensate we would not really realise if we are putting a charge in or we are taking a charge out.
- The real world is not like that with respect to electric charge.
 - But this is what happens in superconductors! They are exactly like this!
- So, in nature, there are regions where the charge is totally uncertain, and we have condensate!



Condensate and the spontaneous breaking of symmetry

- The vacuum can be filled with a condensate
- The condensate has a totally uncertain amount of charge
- It is a very weird beast....

Masses and the condensate



Dirac theory of fermions:
few "naive" considerations

$$\psi_L \equiv \frac{1}{2}(1 - \gamma_5)\psi$$

$$\psi_R \equiv \frac{1}{2}(1 + \gamma_5)\psi$$

Dirac Lagrangian

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

$$\psi = \psi_L + \psi_R$$

Spinor represented
with the chiral spinors

For massless fermions, the Dirac Lagrangian becomes:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}_L(i\cancel{\partial})\psi_L + \bar{\psi}_R(i\cancel{\partial})\psi_R$$

It seems like these are two independent degrees of freedom in
the particle zoo...

Dirac theory of fermions: few "naive" considerations

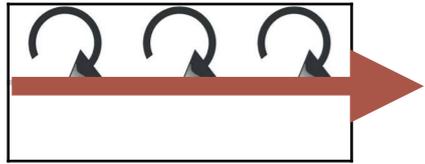
- For 0 mass fermions, the two chiral spinors have a well defined physical meaning:
- They are the two possible projections of the spin in the direction of motion of the fermion - helicity.
(This is not true anymore for massive fermions)

Right Handed

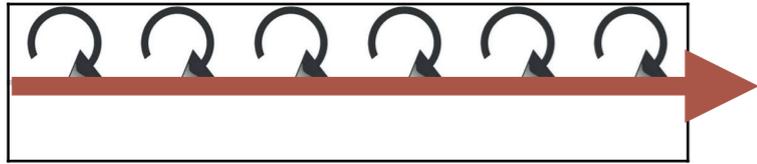
Left Handed



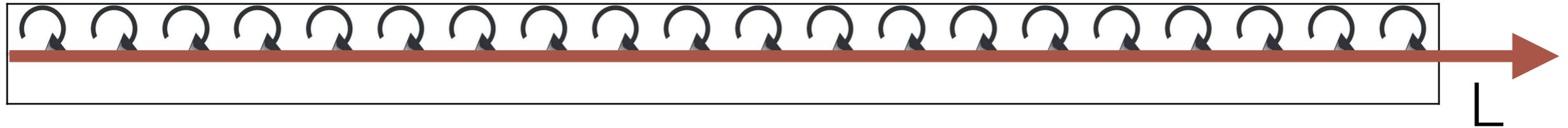
Following the massless fermions



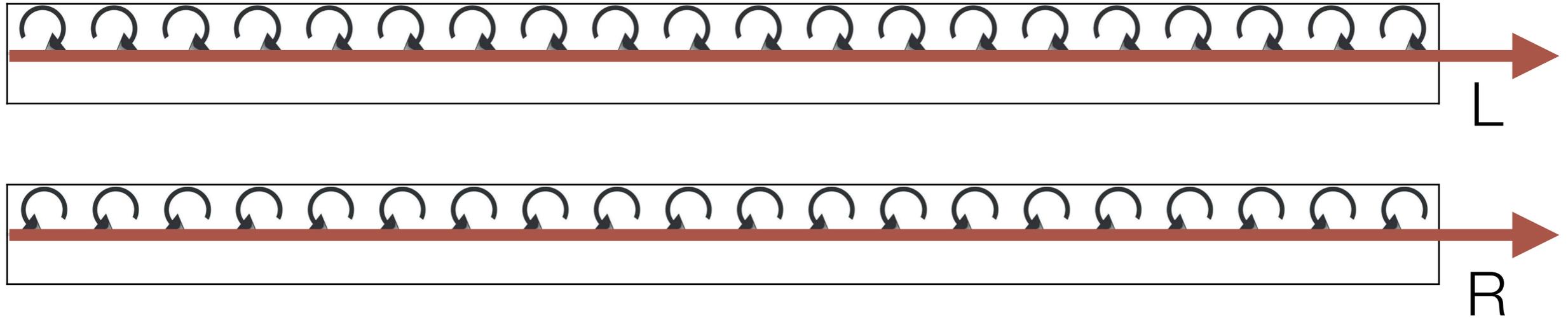
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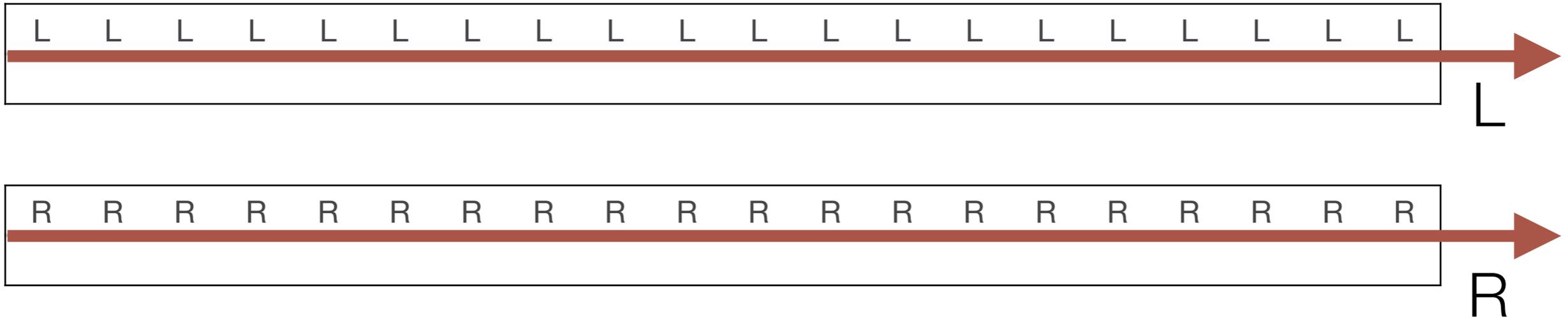
Following the massless fermions



Following the massless fermions



Following the massless fermions



- Are the LH and RH fermions completely equivalent in terms of interactions?

- NO!!!!

- LH are charged for SU(2) weak isospin interaction

- RH are neutrals for SU(2) weak isospin interaction*

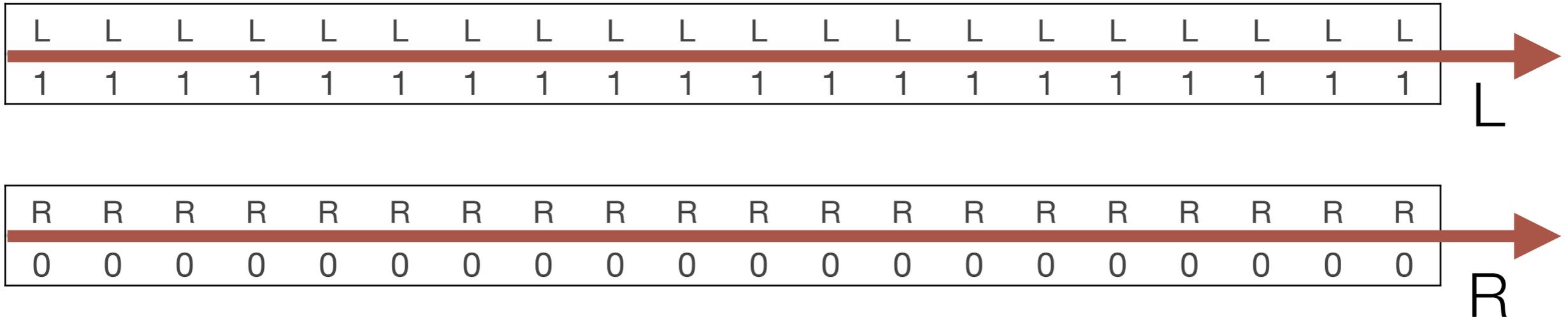
$$\mathcal{L}_{CC} = g W_{\mu}^1 \bar{L}_L \gamma^{\mu} \frac{\sigma_1}{2} L_L + g W_{\mu}^2 \bar{L}_L \gamma^{\mu} \frac{\sigma_2}{2} L_L$$

$$\mathcal{L}_{NC} = \frac{g}{2} W_{\mu}^3 [\bar{\nu}_{eL} \gamma^{\mu} \nu_{eL} - \bar{e}_L \gamma^{\mu} e_L] + \frac{g'}{2} B_{\mu} \left[Y(L) (\bar{\nu}_{eL} \gamma^{\mu} \nu_{eL} + \bar{e}_L \gamma^{\mu} e_L) \right. \\ \left. + Y(\nu_{eR}) \bar{\nu}_{eR} \gamma^{\mu} \nu_{eR} + Y(e_R) \bar{e}_R \gamma^{\mu} e_R \right]$$

- Why? One of the big mysteries....

*Note: After EWSB, RH are coupling with the Z^0 as a result of the mixing of $(W^0, B) \rightarrow (Z^0, A)$

Following the massless fermions



- Are the LH and RH fermions completely equivalent in terms of interactions?

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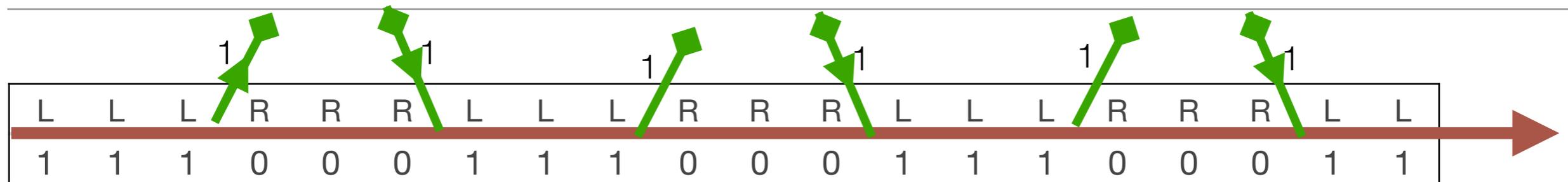
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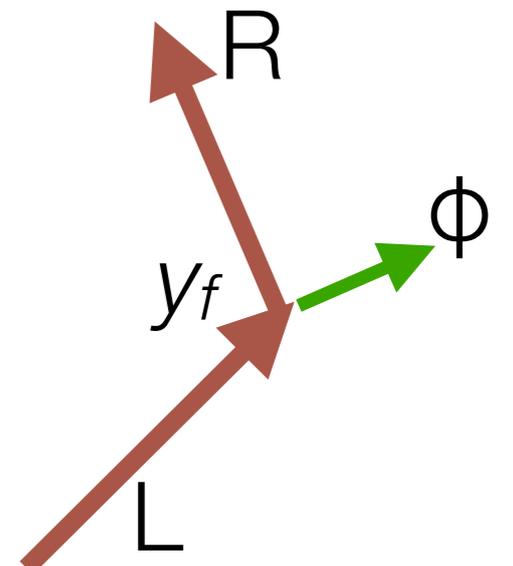
The condensate

- If we have a condensate, empty space is filled with a totally uncertain amount of (weak) charge.
- The LH will interact with the condensate and the (weak) charge is continuously exchanged with the empty space for free.

The chiral symmetry breaking



- New ingredient: a boson (not yet the Higgs) from the condensate
- Recall, we can add one more to the condensate, or take one out, without changing the state of the condensate.
- So, the LH fermion can emit one of these bosons which carries its (weak) charge out.
- Where does this boson go?
 - To the condensate!
- And the fermion can borrow a charge back from the condensate...



We are introducing an interaction which couple LH and RH fermions

Following a fermion



Following a fermion



- the first fermion is flipping more often:
 - it's interaction with the condensate is stronger
- the second fermion is flipping less often:
 - it's interaction with the condensate is weaker

The Lagrangian is proportional to $\mathbf{y}_f \langle \boldsymbol{\phi} \rangle (\psi_L \psi_R + \psi_R \psi_L)$

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$$\psi = \psi_L + \psi_R$$

Spinor represented
with the chiral spinors

For massive fermions, the Dirac Lagrangian becomes:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}_L(i\partial\!\!\!/)\psi_L + \bar{\psi}_R(i\partial\!\!\!/)\psi_R - m(\psi_L\psi_R + \psi_R\psi_L)$$

- The mass is in practise this interaction between LH and RH fermions.
- The rate of flipping from LH to RH and back to LH is proportional to the mass.

Vector bosons from local symmetries: Recap

- We can start from the lagrangian of the fermions we have seen before.

$$\mathcal{L}_0 = \bar{\psi}(x) (i\partial - m) \psi(x)$$

- We require this to be invariant under a certain local symmetry

$$\psi(x) \rightarrow e^{iq\theta(x)} \psi(x)$$

(for the easier case $U(1)$)

- What happens if we do a derivative of $\psi(x)$?

$$\partial_\mu \psi(x) \rightarrow e^{iq\theta(x)} \partial_\mu \psi(x) + iq e^{iq\theta(x)} \psi(x) \partial_\mu \theta(x)$$

- We introduce a field \mathbf{A} to reabsorb this term

$$\bar{\psi}(x) (i\partial - m) \psi(x) - q \bar{\psi}(x) \gamma_\mu \psi(x) A^\mu(x)$$

- To do so, \mathbf{A} must satisfy $A_\mu \rightarrow A_\mu - \partial_\mu \theta(x)$ (for the easier case $U(1)$)

- We introduce the lagrangian for \mathbf{A} : $-\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x)$

Vector bosons from local symmetries:

1 slide recap

- The lagrangian for **A cannot contain a term proportional to $A_\mu A^\mu$**

- **This term is not gauge invariant!**

- But this is the kind of term needed to describe a massive vector boson

- We are again back to massless particles.

- Again 2 possible polarisations

Polarisation: recap

$$A_\mu = \epsilon_\mu e^{ik_\mu x^\mu}$$
$$\epsilon^\mu \epsilon_\mu = -1 \quad k^\mu \epsilon_\mu = 0$$

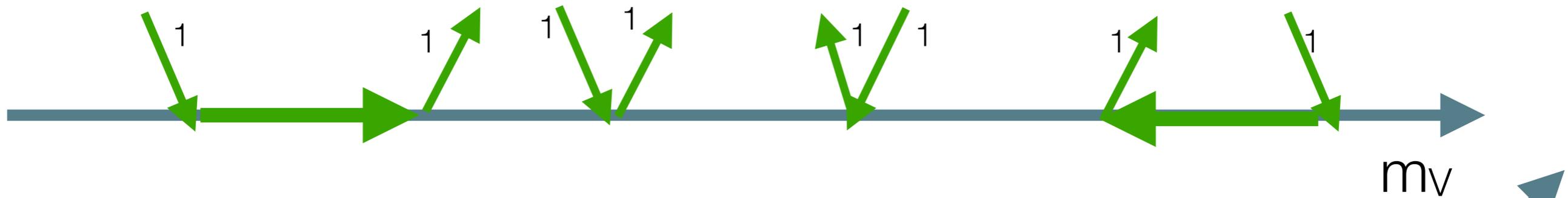
$$k^\mu = (E, 0, 0, k)$$

$$\text{with } k_\mu k^\mu = E^2 - k^2 = M^2$$

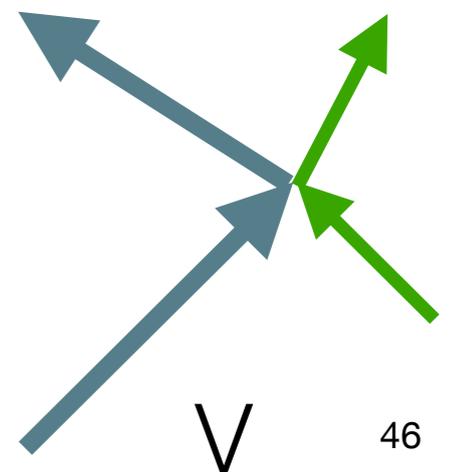
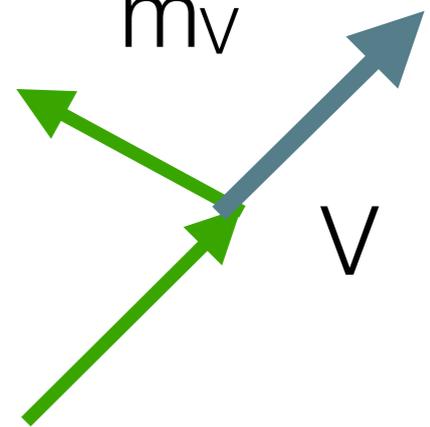
✱ 2 transverse:
$$\begin{cases} \epsilon_1^\mu = (0, 1, 0, 0) \\ \epsilon_2^\mu = (0, 0, 1, 0) \end{cases}$$

✱ 1 longitudinal:
$$\epsilon_{||}^\mu = \left(\frac{k}{M}, 0, 0, \frac{E}{M}\right) \approx \frac{k^\mu}{M} + \mathcal{O}\left(\frac{E}{M}\right)$$

The Brout-Englert-Higgs Mechanism



- How the V boson get a mass? Something very similar to fermion
- The V boson can interact with particles with (weak) charge, so it can interact with these new bosons.
- How?
- **The Brout-Englert-Higgs mechanism**
- NOTE: if there was a condensate of ordinary charged particles, this would have happen to the photon...



The Brout-Englert-Higgs Mechanism

The diagram illustrates the Higgs mechanism in two stages. The top stage shows a gauge boson A^μ interacting with a Higgs field $\langle \phi_1 \rangle$ via a vertex $e^2 g_{\mu\nu}$. The bottom stage shows the same gauge boson interacting with the Higgs field via vertices $e q_\mu$ and $-e q_\nu$ with a propagator $1/q^2$. The resulting mass m_V and velocity V are shown as vectors. A portrait of F. Englert and a Nobel Prize medal are also present.

*F. Englert
Séminaire Poincaré 2014*

The Brout-Englert-Higgs Mechanism

NOTE: if $\langle \phi_1 \rangle = 0$, the gauge boson would have zero mass.

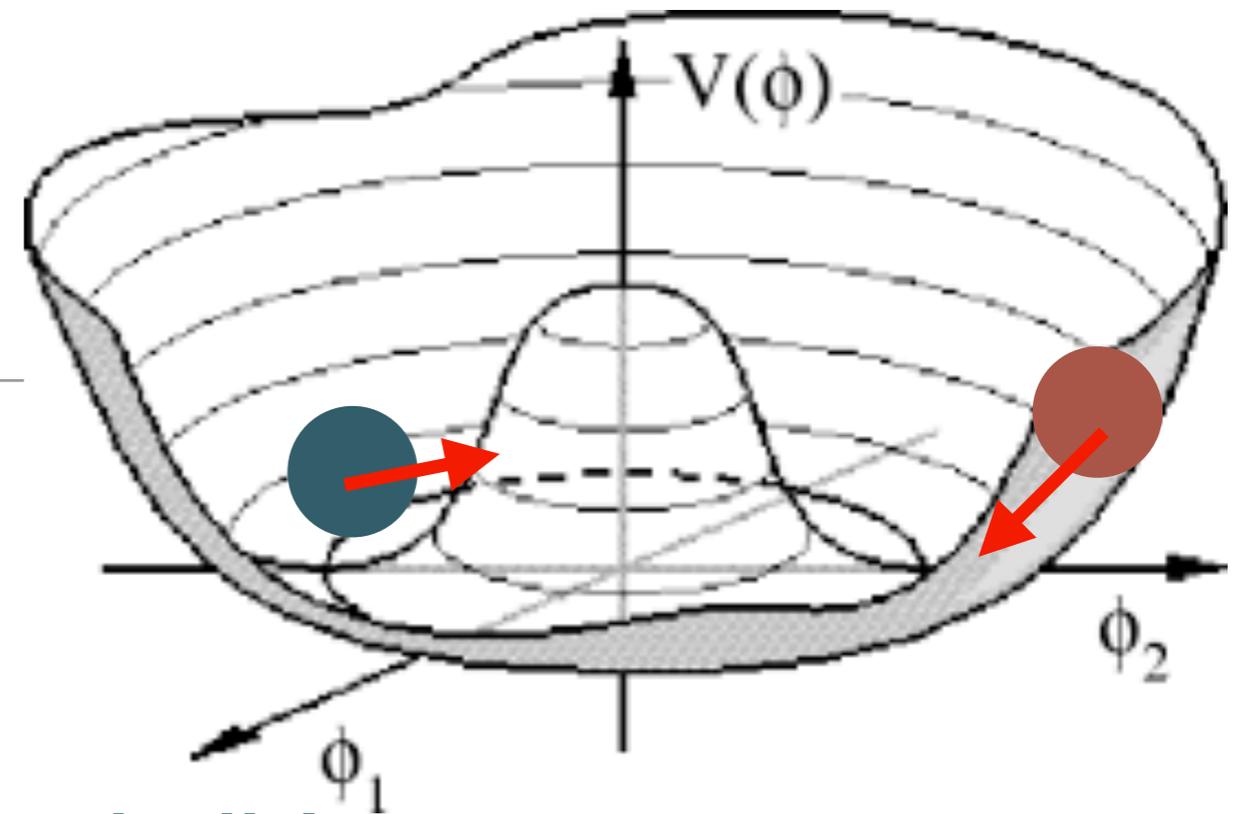
$$\Pi_{\mu\nu} = \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) e^2 \langle \phi_1 \rangle^2$$

$$D_{\mu\nu} = \frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - e^2 \langle \phi_1 \rangle^2}$$

$$M_V^2 = e^2 \langle \phi_1 \rangle^2$$

Back to the Mexican hat

- We have two modes for the field in this potential:



- **Rotating on the brim, with no cost in potential energy**
 - This is causing our condensate, and the bosons related to this mode are the bosons entering in the mechanism seen before
- **Oscillating up-down hill**
 - This costs energy \rightarrow create this boson cost energy
 - This mode is like a “sound” wave of the density of the condensate
- **THE HIGGS BOSON**

Masses and the condensate

- Thanks to the exchange of charges with the condensate, we have a way to give mass to the elementary particles:
 - It works for fermions
 - It works for bosons
- The model predicts the existence of a sound wave of the condensate:
The Higgs boson

Higgs boson

THE HIGGS BOSON



The Standard Model

Հիմնական սկզբնական հասկացությունները
հիմնական սկզբնական հասկացությունները

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

• Kinematic term of the gauge bosons

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

• Kinematic term of the fermions, and interaction between fermions and gauge bosons

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

• Higgs-fermions interaction

$$+ |D_\mu \phi|^2 - V(\phi)$$

• Kinematic term of the Higgs boson, and interaction with the gauge bosons

• Higgs potential and self interaction

The Standard Model

Հիմնական հասկացությունները: Գրգռվածություն, Կապակցվածություն, Կապակցվածություն, Կապակցվածություն

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

- Kinematic term of the gauge bosons
- Kinematic term of the fermions, and interaction between fermions and gauge bosons

$$+ \bar{\psi}_i \gamma_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

- Higgs-fermions interaction
- Kinematic term of the Higgs boson, and interaction with the gauge bosons
- Higgs potential and self interaction

Higgs sector in the Standard Model

- Probably the less elegant sector
 - Largest number of parameters

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + \text{h.c.}$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs sector in the Standard Model

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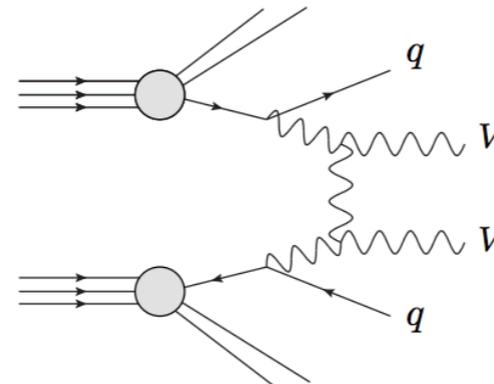
- However:
 - It solves the issue of how masses in the standard model
 - Predict the relation between the masses and couplings of the gauge bosons
 - Predict the existence of the Higgs boson

Higgs sector in the Standard Model

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- It solves another big issue:
The unitarity of the longitudinal vector boson scattering.

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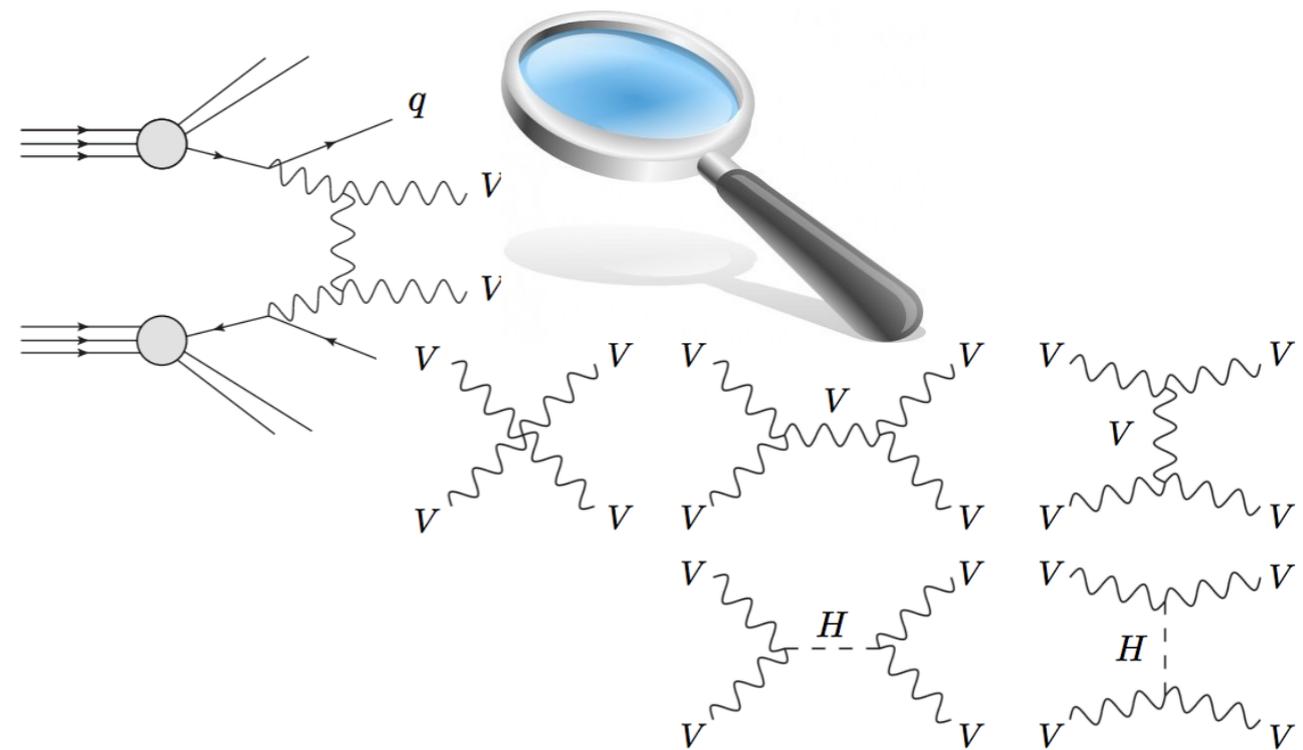


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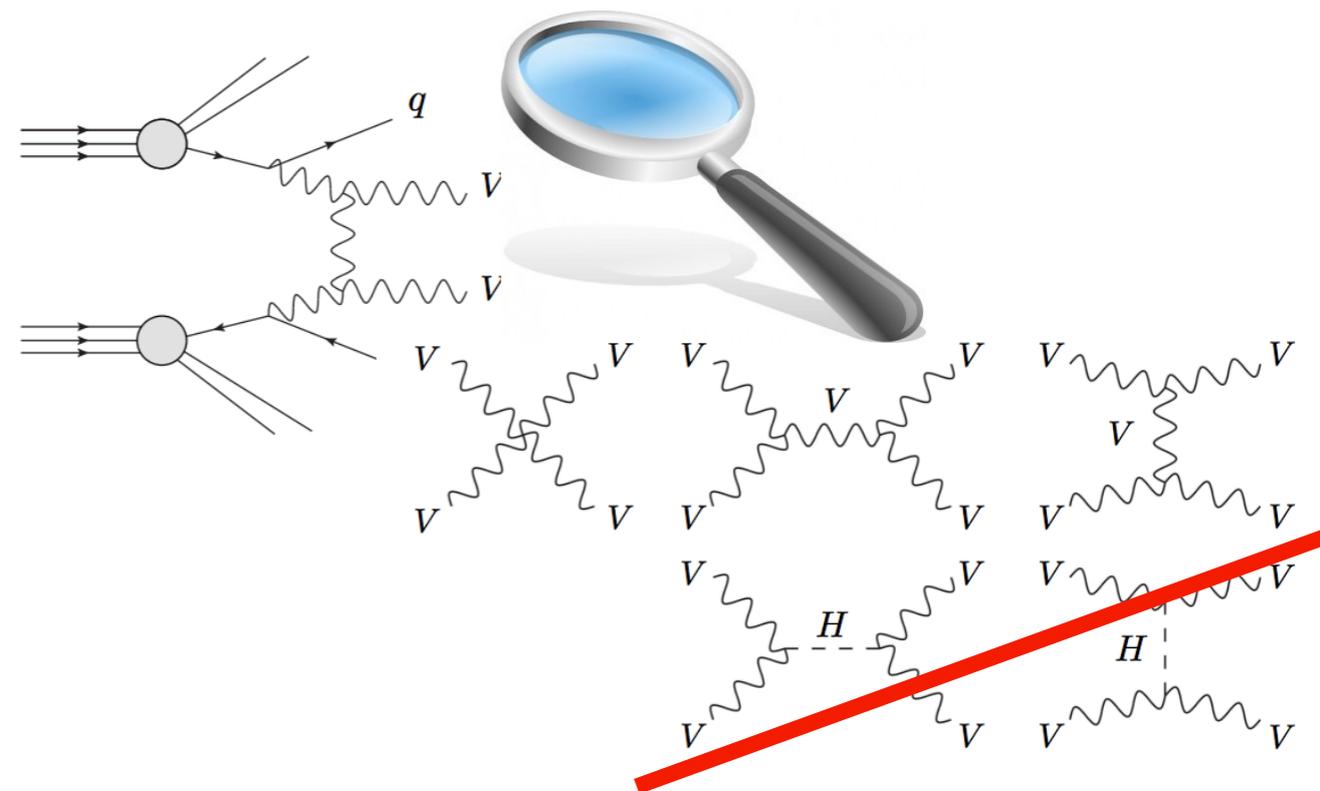
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- It solves another big issue:
The unitarity of the longitudinal vector boson scattering.



In absence of a Higgs boson with $m_H < 1$ TeV, would imply a strong dynamics which could be produced in the WW process

Higgs sector in SM Lagrangian $\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$

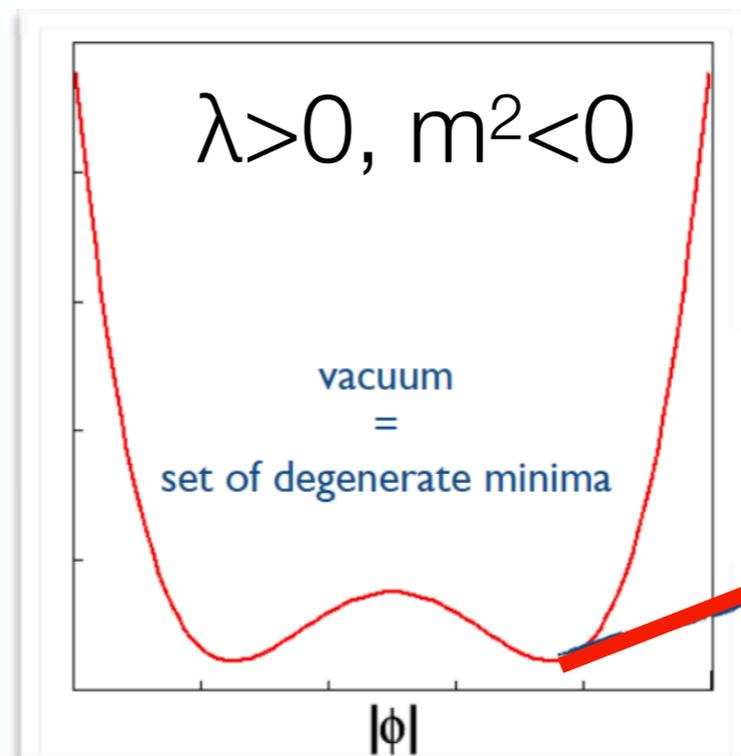
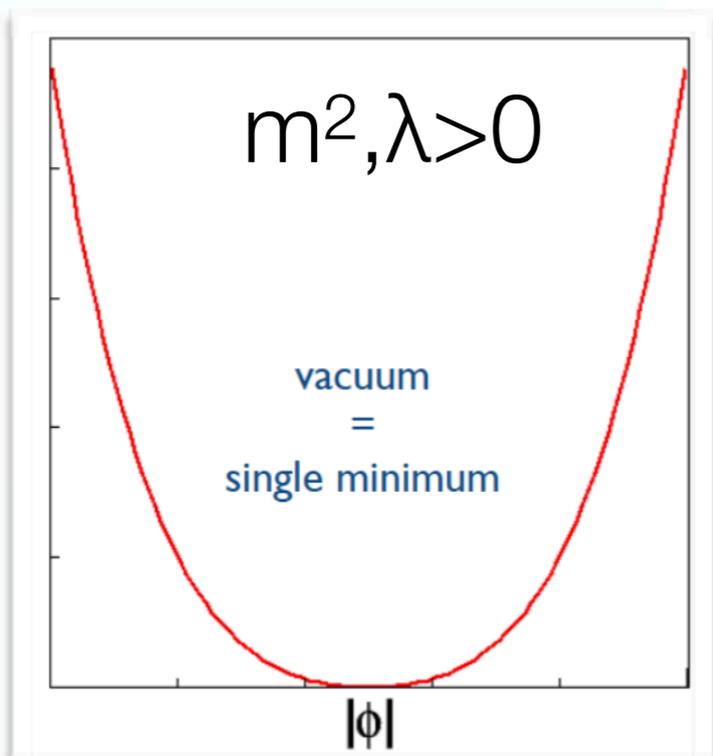
- In what we discussed, we had some simplifications, being a bit more precise :)
- A new SU(2) doublet of spin-0 particles is added to the lagrangian, and interact with the W and B bosons

$$D_\mu \Phi = (\partial_\mu + ig\sigma^a W_\mu^a/2 + ig'Y B_\mu/2)\Phi$$

- 4 new degrees of freedom: doublet+anti-particles
- It has a very specific potential

$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

couplings for the EW sector



around the minimum:

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$$\sqrt{-m^2/2\lambda} = v/2 > 0$$

Some calculations

$$\begin{aligned}
 D^\mu \Phi &= \left(\partial^\mu - igW_i^\mu \frac{\sigma^i}{2} - ig' \frac{1}{2} B^\mu \right) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \\
 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \partial^\mu H \end{pmatrix} - \frac{i}{2\sqrt{2}} \left[g \begin{pmatrix} W_3^\mu & W_1^\mu - iW_2^\mu \\ W_1^\mu + iW_2^\mu & -W_3^\mu \end{pmatrix} + g' B^\mu \right] \begin{pmatrix} 0 \\ v + H \end{pmatrix} \\
 &= \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 0 \\ \partial^\mu H \end{pmatrix} - \frac{i}{2} (v + H) \begin{pmatrix} g(W_1^\mu - iW_2^\mu) \\ -gW_3^\mu + g' B^\mu \end{pmatrix} \right] \\
 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \partial^\mu H \end{pmatrix} - \frac{i}{2} \left(1 + \frac{H}{v} \right) \begin{pmatrix} gvW^{\mu+} \\ -v\sqrt{(g^2 + g'^2)/2} Z^\mu \end{pmatrix}
 \end{aligned}$$

$$(D^\mu \Phi)^\dagger D_\mu \Phi = \frac{1}{2} \partial^\mu H \partial_\mu H + \left[\left(\frac{gv}{2} \right)^2 W^{\mu+} W_\mu^- + \frac{1}{2} \frac{(g^2 + g'^2) v^2}{4} Z^\mu Z_\mu \right] \left(1 + \frac{H}{v} \right)^2$$

$$V = \frac{1}{2} (2\lambda v^2) H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4$$

Consequences - the masses of the bosons

- Two massive charged vector bosons

$$m_W^2 = \frac{g^2 v^2}{4}$$

Corresponding to the observed charged currents

$$\frac{G_F}{\sqrt{2}} = \left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{m_W^2} \quad \Rightarrow \quad v = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246.22 \text{ GeV}$$

- One massless vector boson

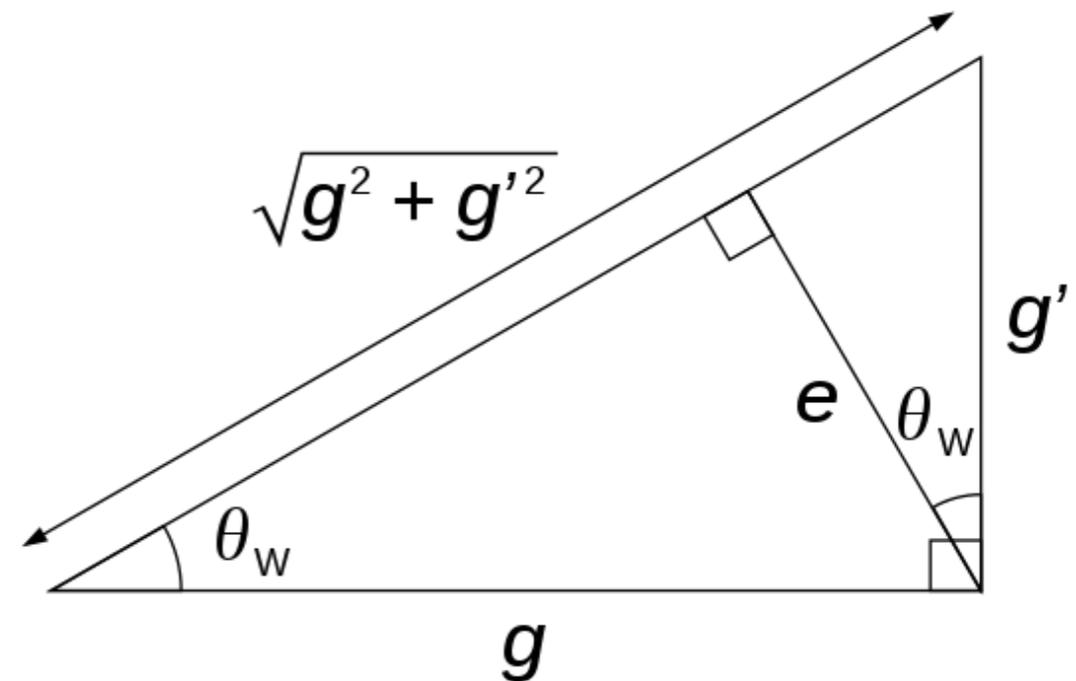
$$m_\gamma = 0$$

- One massive neutral vector boson Z

$$m_Z^2 = (g^2 + g'^2)v^2/4$$

- One massive scalar particle: The Higgs Boson

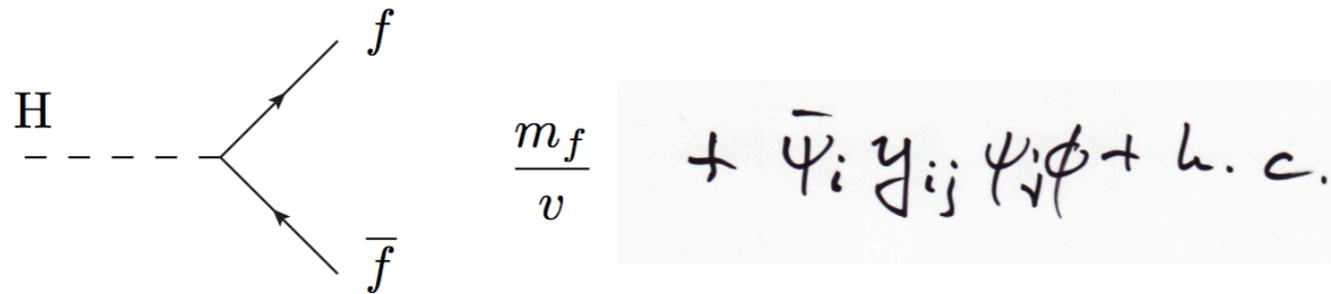
$$m_H^2 = \frac{4\lambda(v)m_W^2}{g^2}$$



Whose mass is an unknown parameter of the theory as the quartic coupling λ

Higgs Boson couplings in the SM

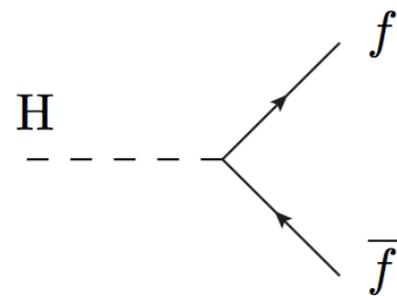
- All the couplings of the Higgs boson to SM particles (except itself) known before the discovery



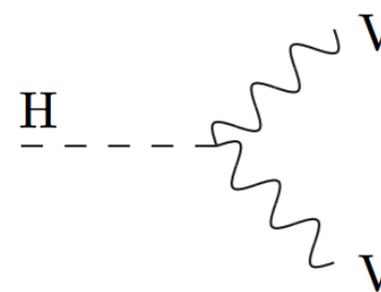
Is the H responsible for the fermion masses?
For all the fermion masses?
Why are the families so different?

Higgs Boson couplings in the SM

- All the couplings of the Higgs boson to SM particles (except itself) known before the discovery



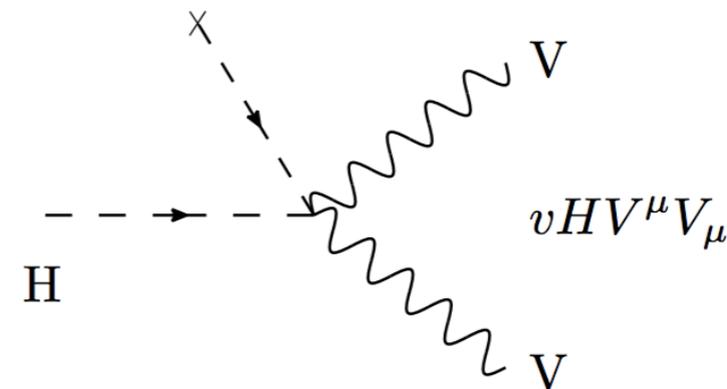
$$\frac{m_f}{v} + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$



$$\frac{2m_V^2}{v} + |D_\mu \phi|^2$$

This term could not exist without a vev

How do we proof there is a condensate?



$$vHV^\mu V_\mu$$

Higgs Boson couplings in the SM

- All the couplings of the Higgs boson to SM particles (except itself) known before the discovery

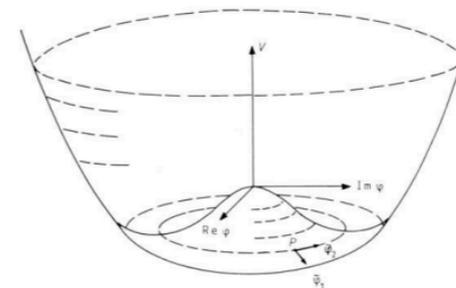
$\frac{m_f}{v}$
 $+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$

$\frac{2m_V^2}{v}$
 $+ |\partial_\mu \phi|^2$
 This term could not exist without a vev

$\frac{3m_H^2}{v}$
 $\frac{3m_H^2}{v^2}$
 $V(\phi)$

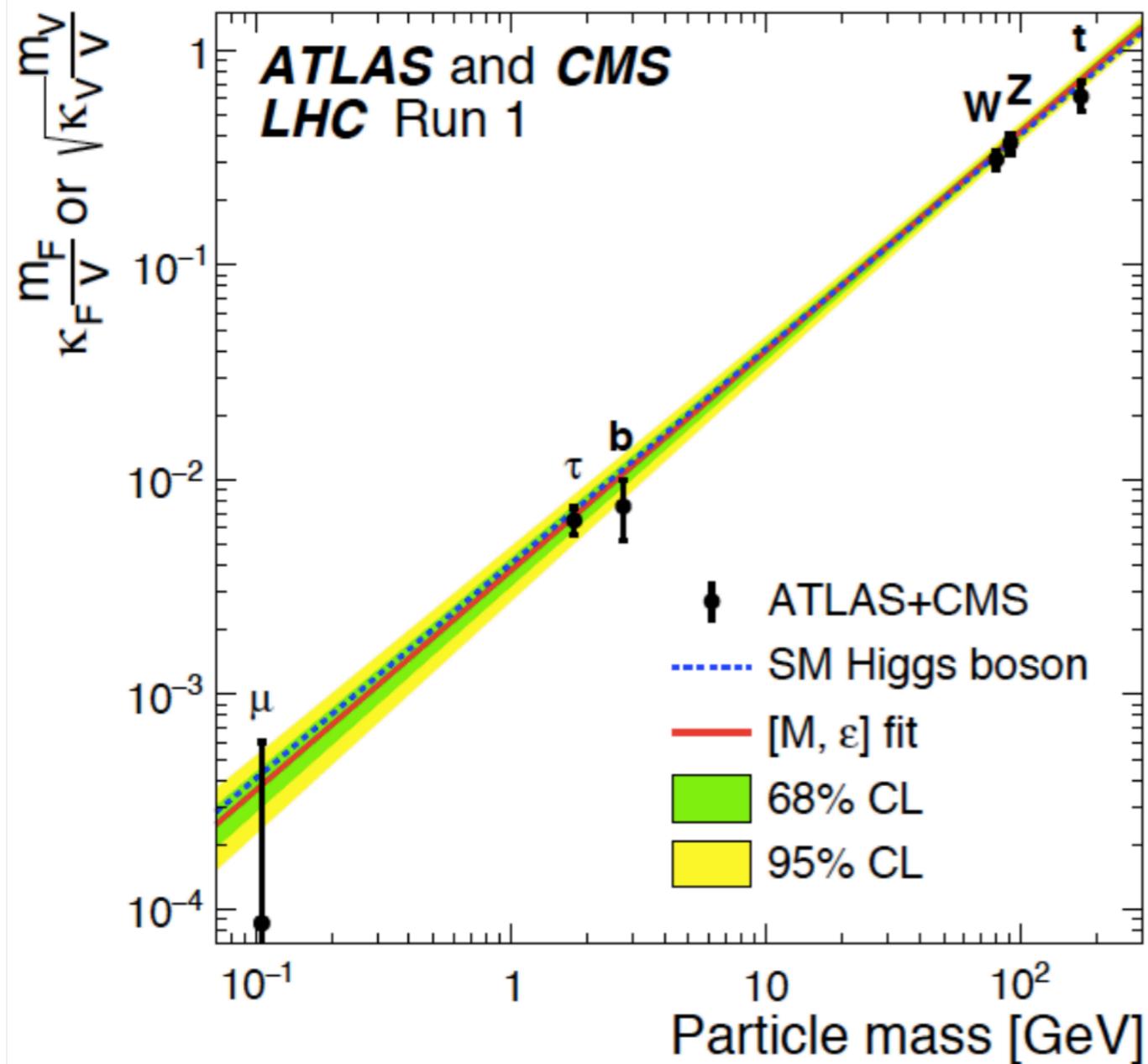
What do we know of the real shape of the potential?

$$V = \frac{1}{2} (2\lambda v^2) H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4$$



Higgs Couplings - measurements

Where we are

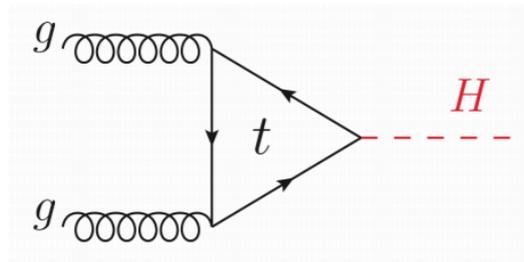


Measurements of vector bosons and 3rd generation fermions

2nd and 1st generation?

Self couplings?

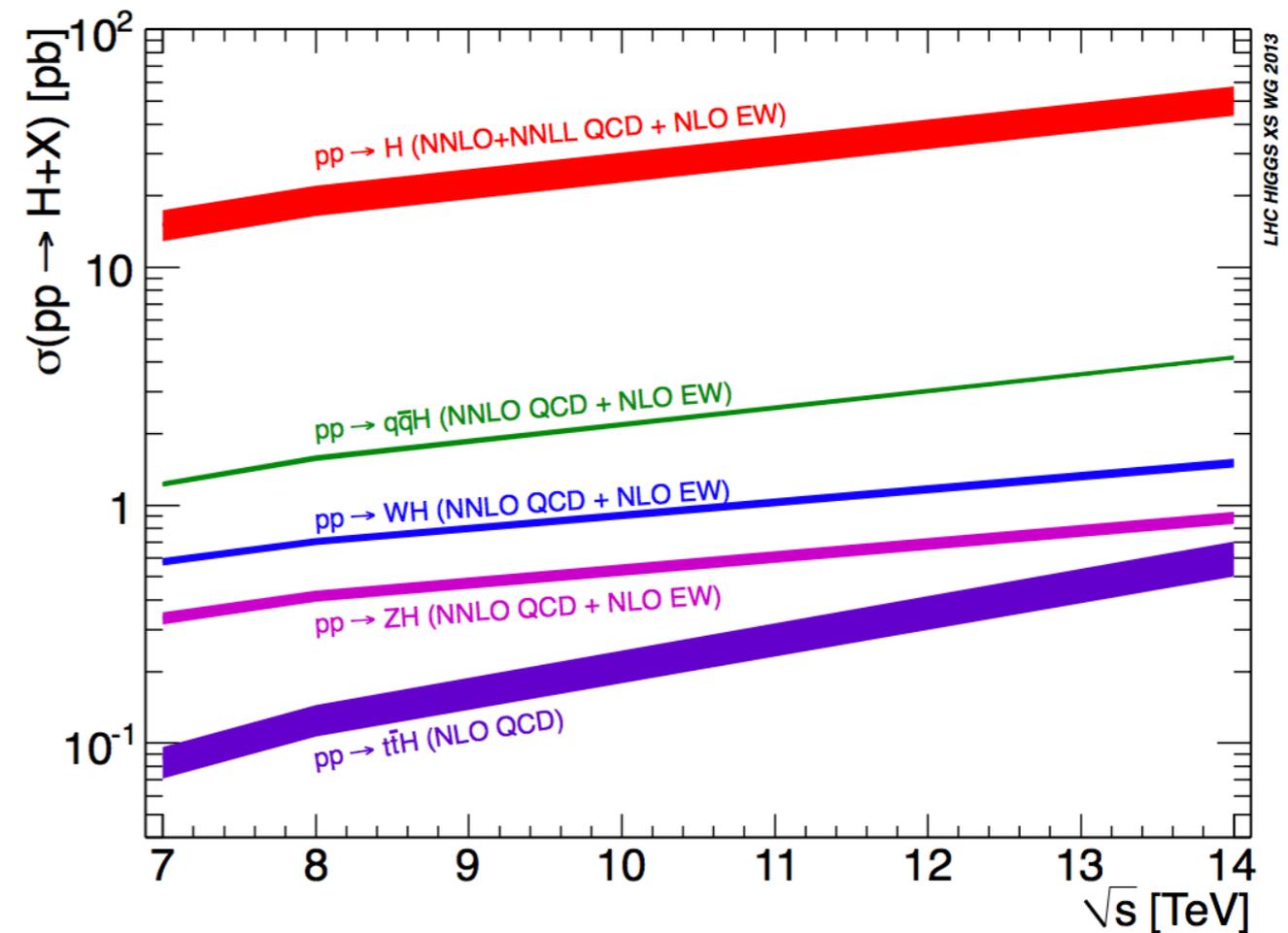
(Main) Higgs boson production modes



**Production for
140fb⁻¹ in Run2**

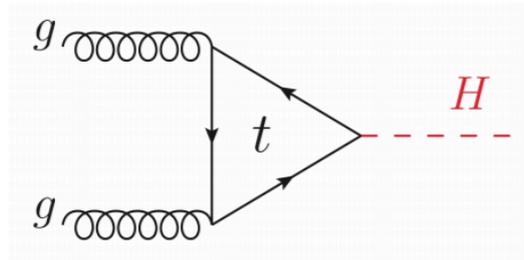
Gluon Fusion

~7M events produced



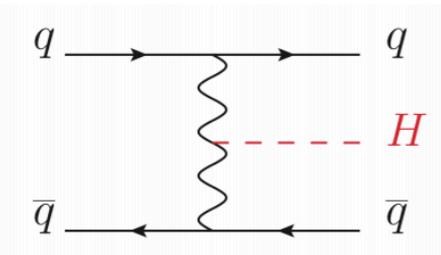
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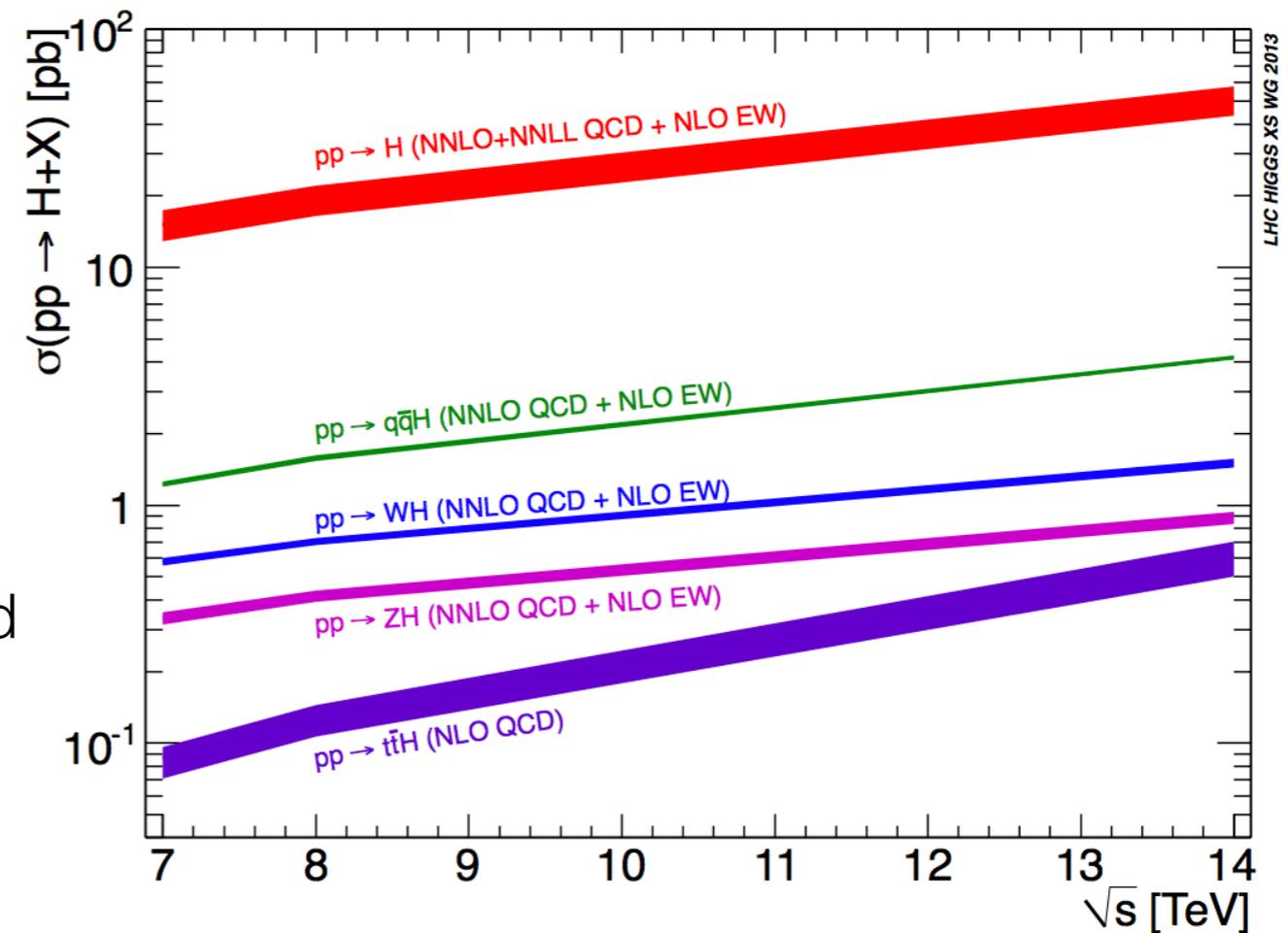
Gluon Fusion

~7M events produced



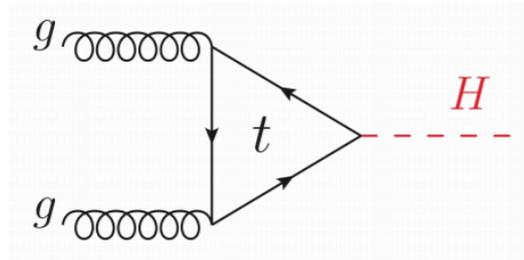
Vector boson Fusion

~0.5M events produced



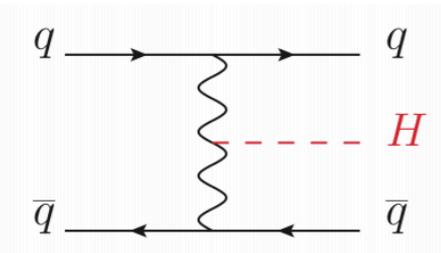
(Main) Higgs boson production modes

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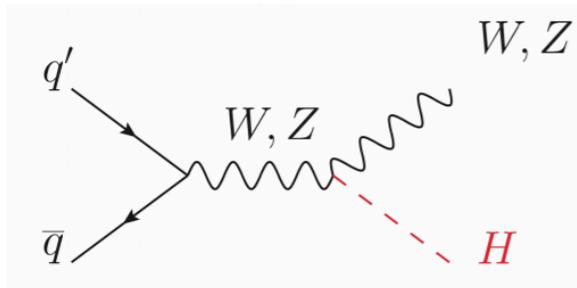
Gluon Fusion

~7M events produced



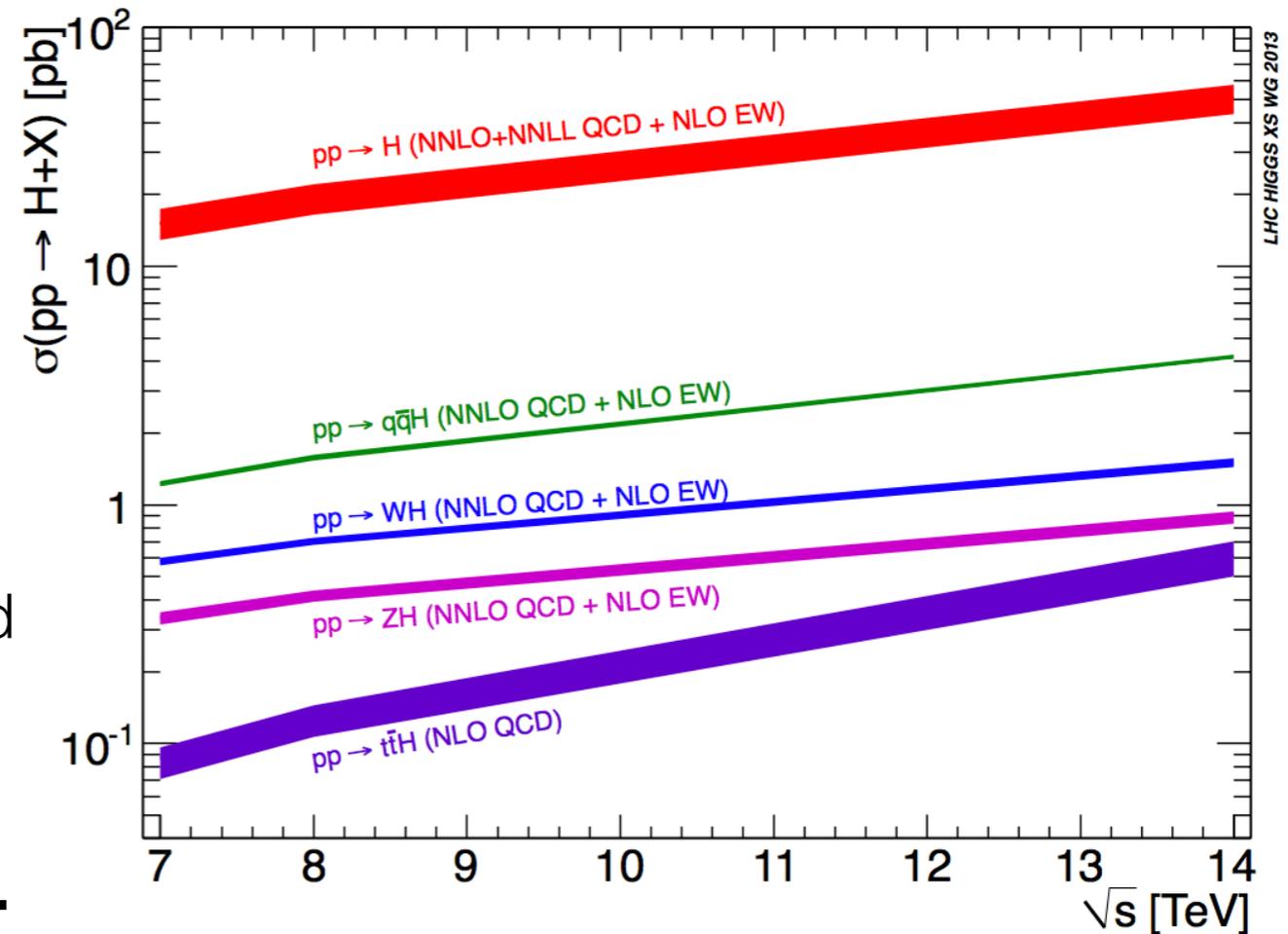
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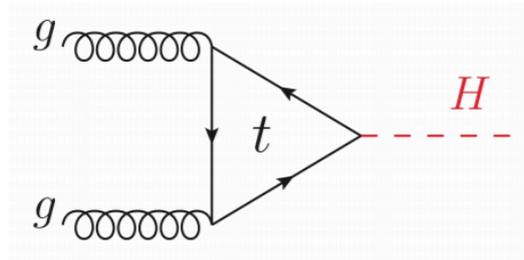
W and Z Assoc. Prod.

~0.35M events prod.



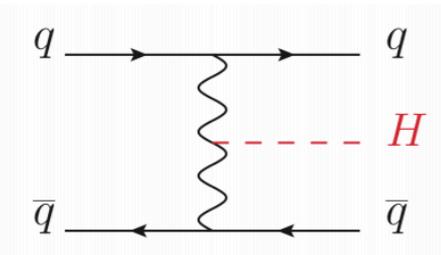
(Main) Higgs boson production modes

Production for 140fb⁻¹ in Run2



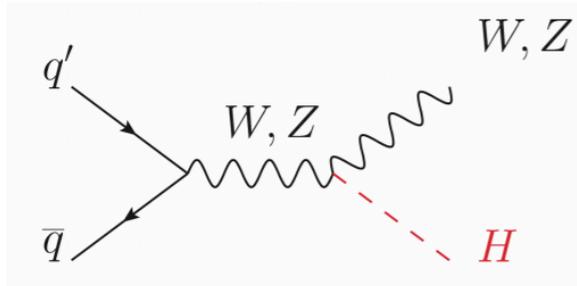
Gluon Fusion

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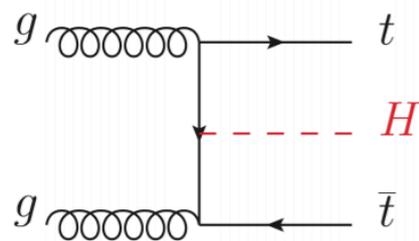
Vector boson Fusion

~0.5M events produced



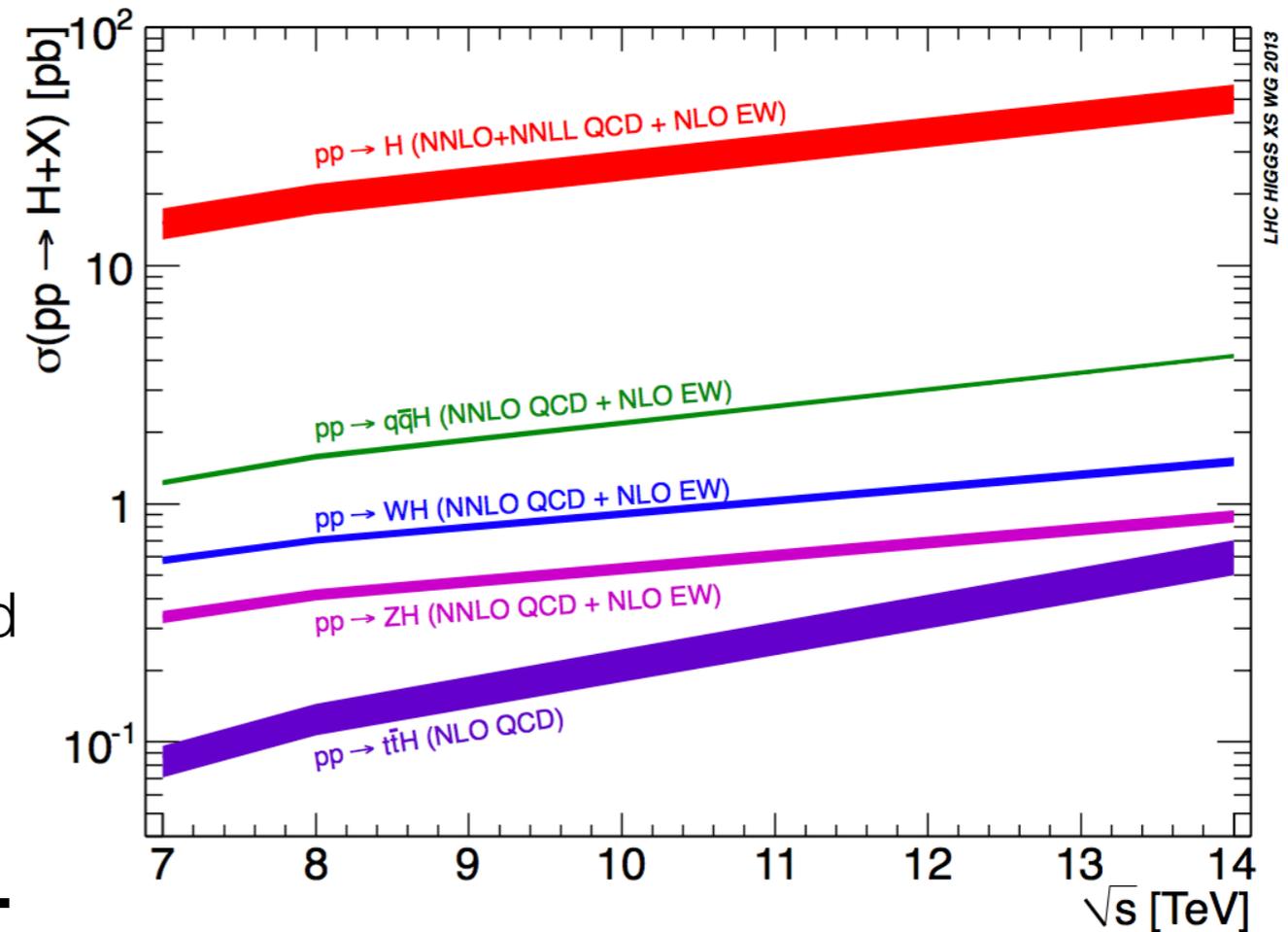
W and Z Assoc. Prod.

~0.35M events prod.



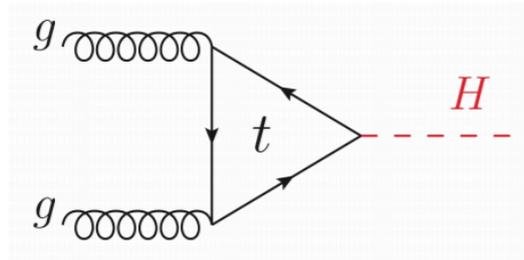
Top Assoc. Prod.

~70k events produced



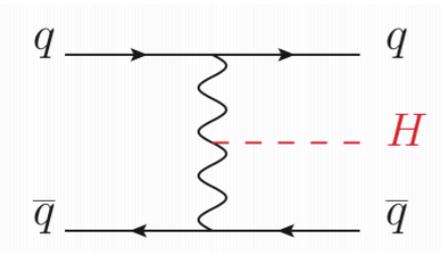
(Main) Higgs boson production modes

**Production for
140fb⁻¹ in Run2**



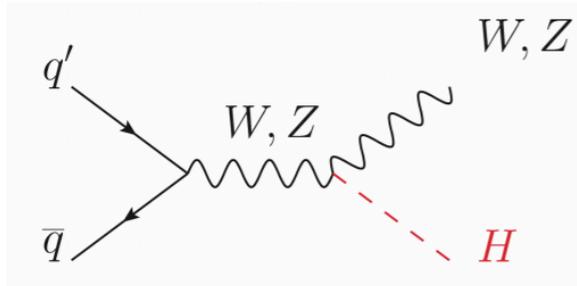
Gluon Fusion

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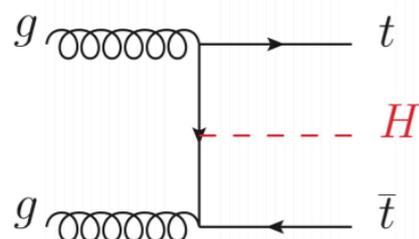
Vector boson Fusion

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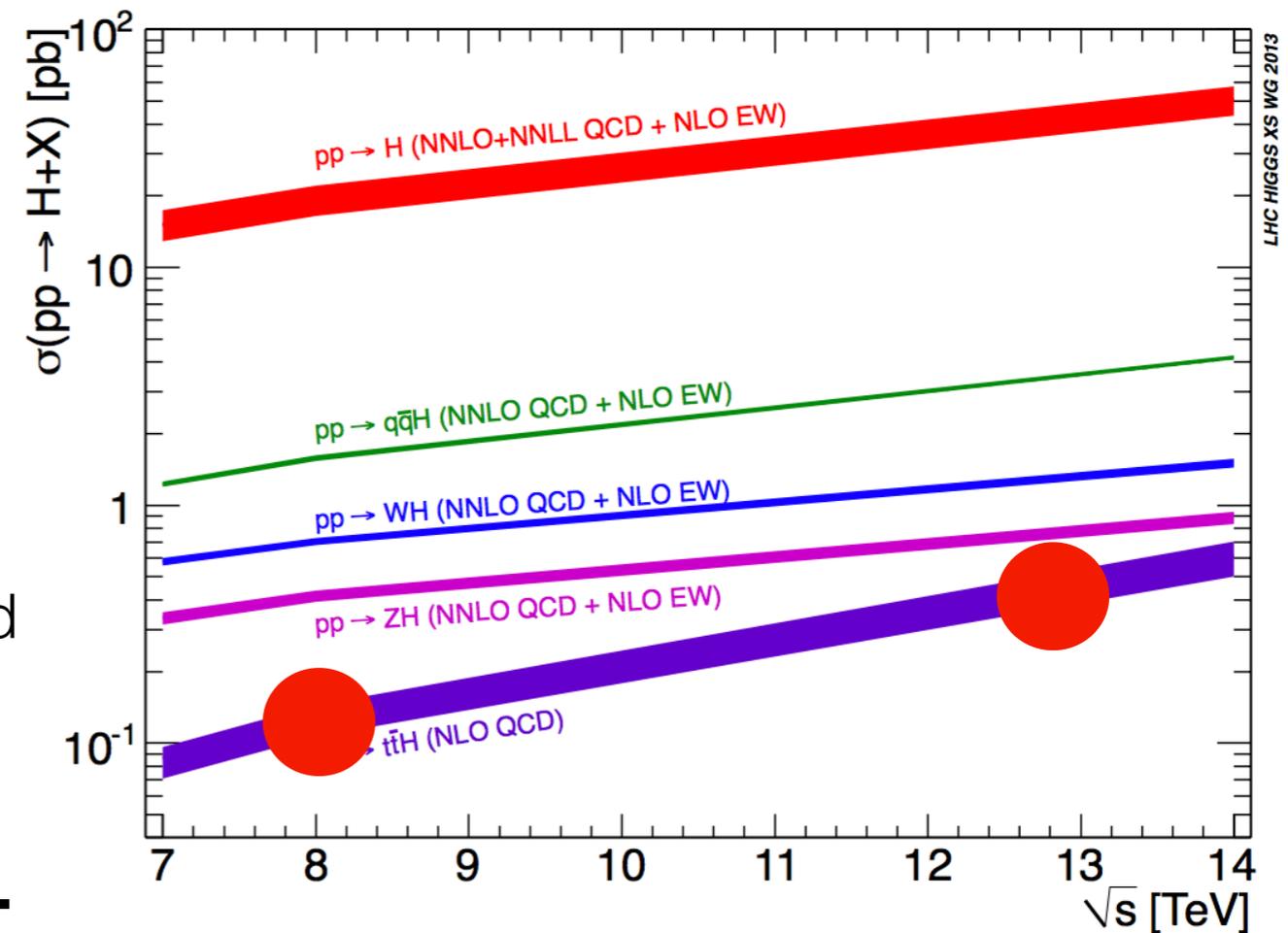
W and Z Assoc. Prod.

~0.35M events prod.



Top Assoc. Prod.

~70k events produced



**Cross sections increase with
center of mass energy.
Note ttH!!**

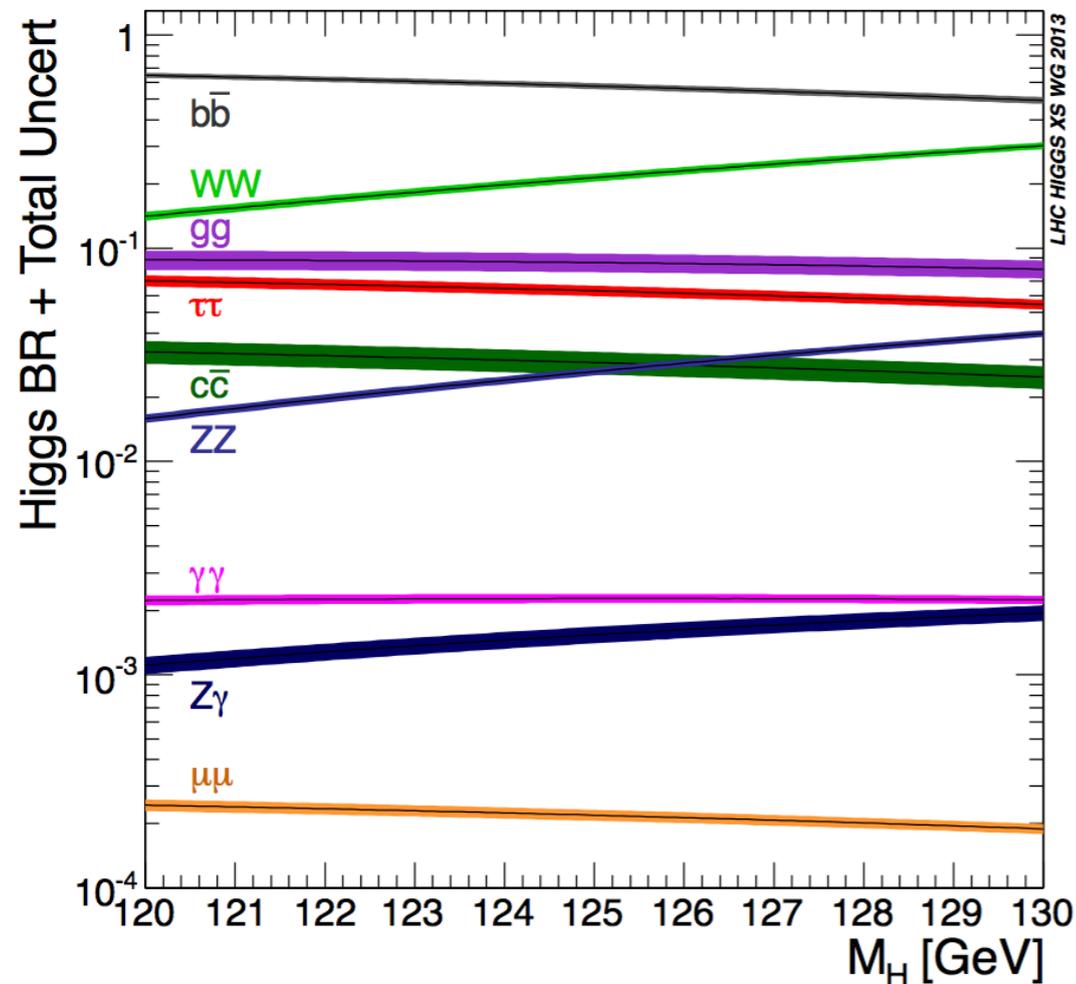
Higgs boson decay channels

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Third generation quarks

Decay mode	Expected BR for $m_H=125$ GeV
bb	57%



$$\Gamma_{H \rightarrow bb} \propto \sum_{\text{colors}} \left| \begin{array}{c} \text{H} \\ \text{---} \\ \text{---} \end{array} \begin{array}{l} \nearrow f \\ \searrow \bar{f} \end{array} \right|^2$$

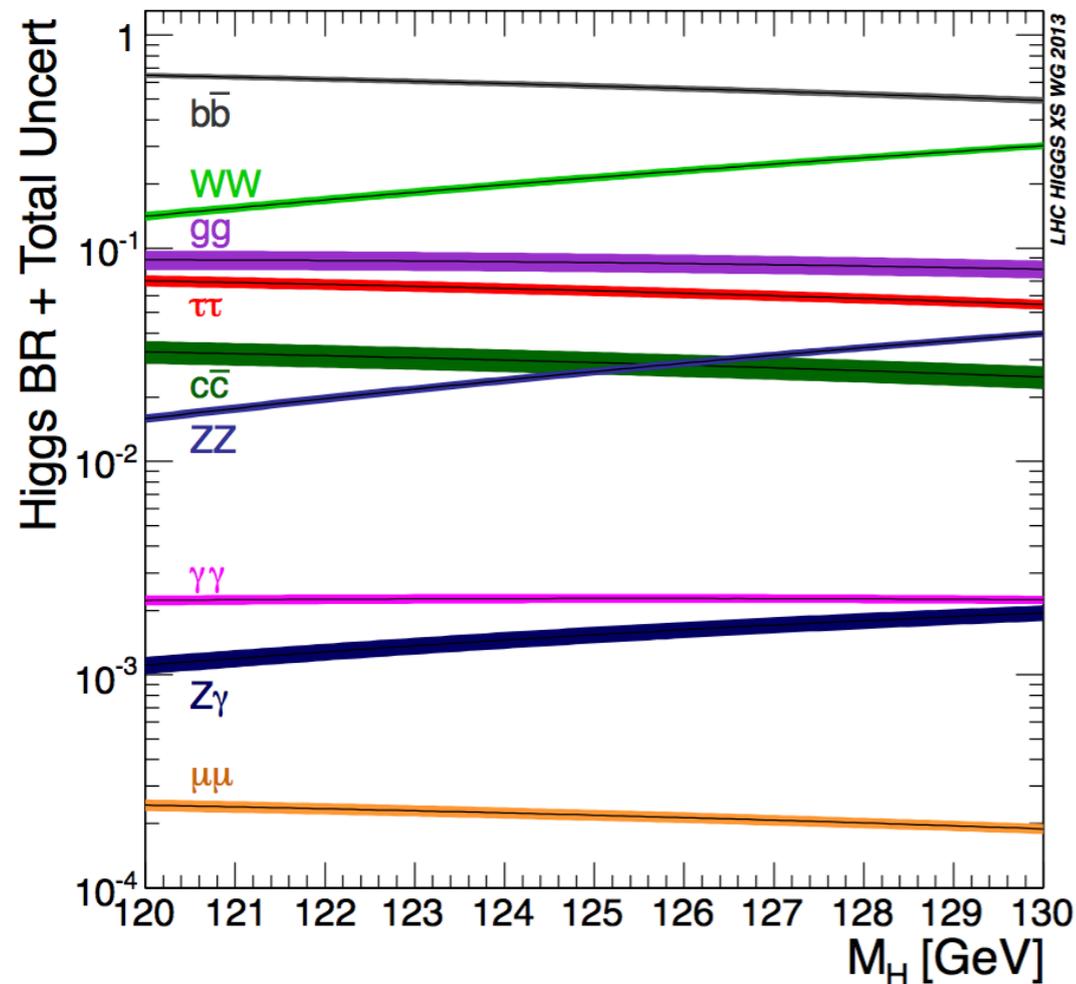
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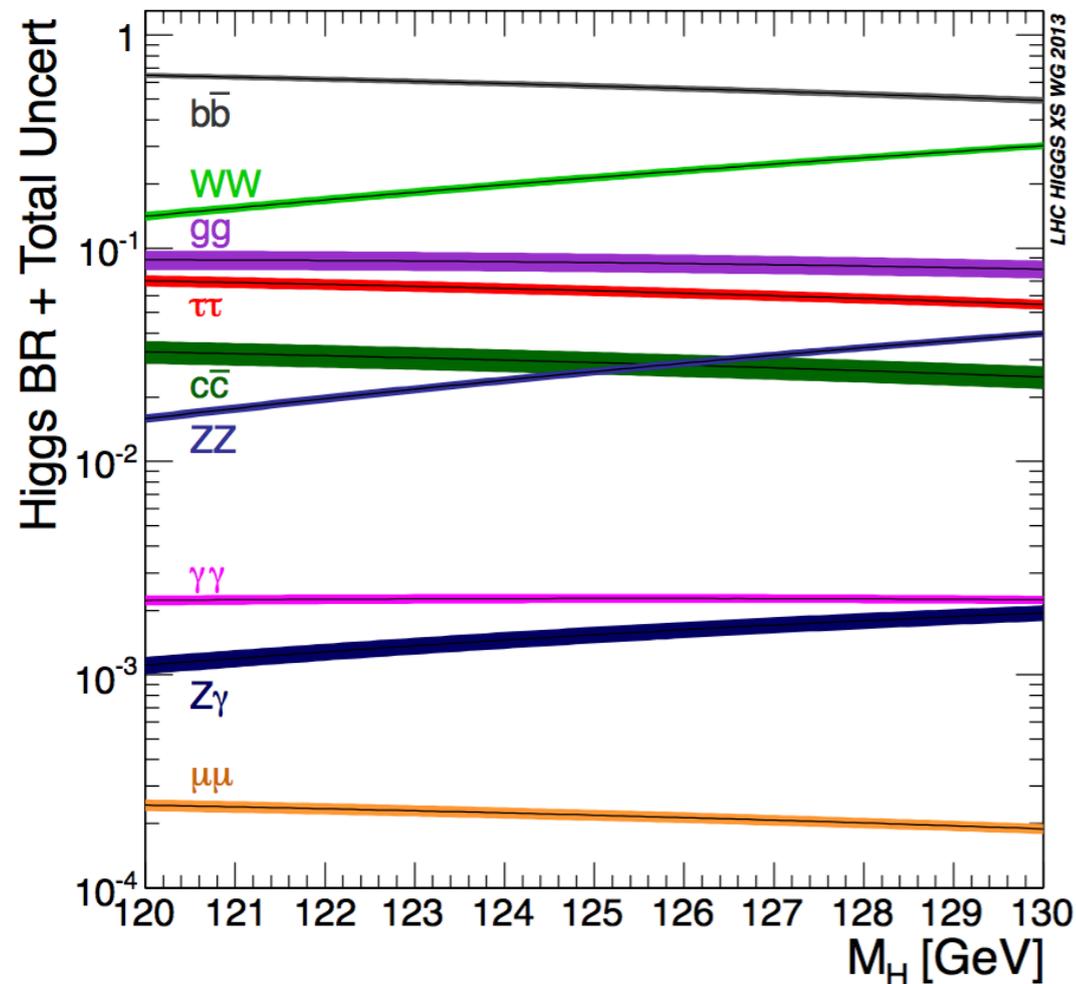
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$$\sim k \boxed{N_c} m_f^2(m_H)(1 + \Delta_{\text{QCD}})$$

↑
3

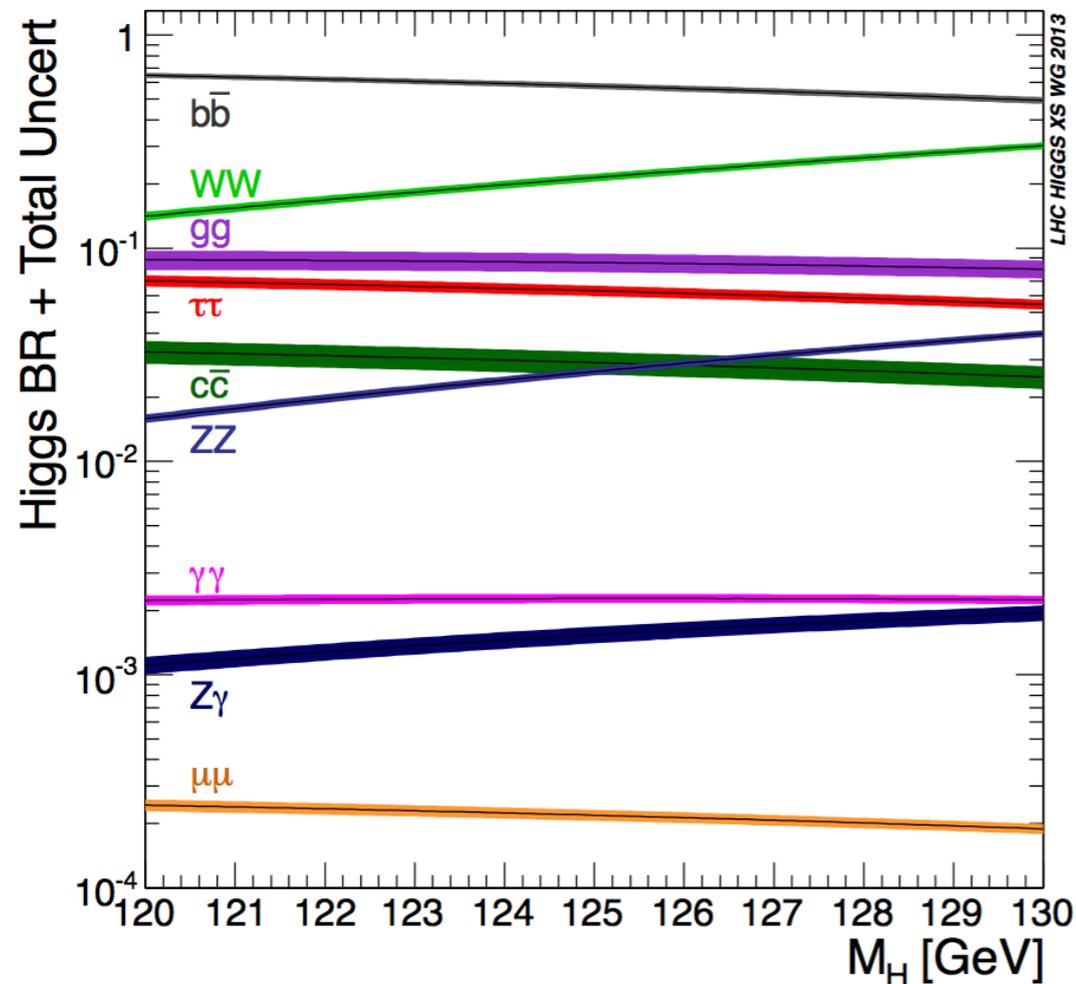
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$$\sim k N_c \boxed{m_f^2(m_H)} (1 + \Delta_{\text{QCD}})$$

\uparrow 3
 \uparrow 2.8 GeV

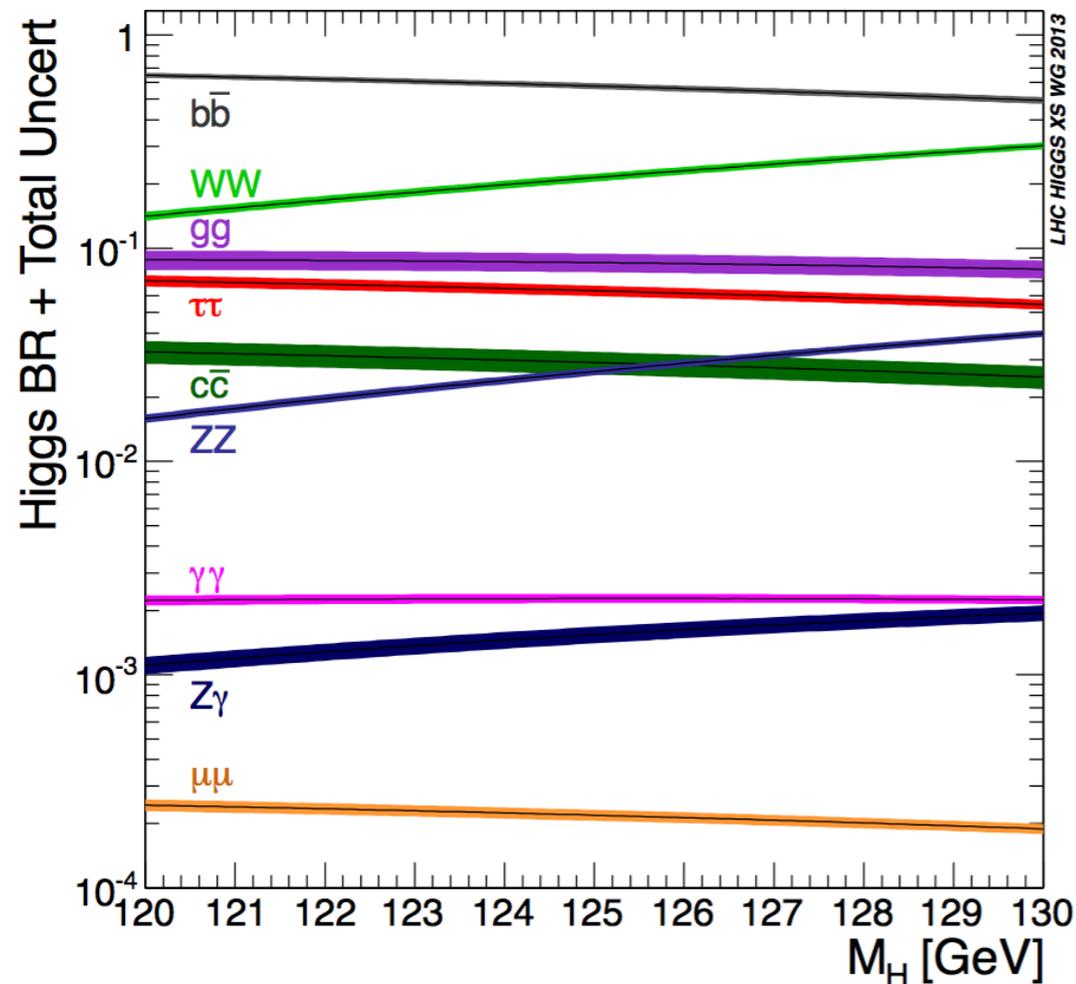
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QCD corr.

$$\sim k \underbrace{N_c}_{3} \underbrace{m_f^2(m_H)}_{2.8 \text{ GeV}} \underbrace{(1 + \Delta_{\text{QCD}})}_{0.2}$$

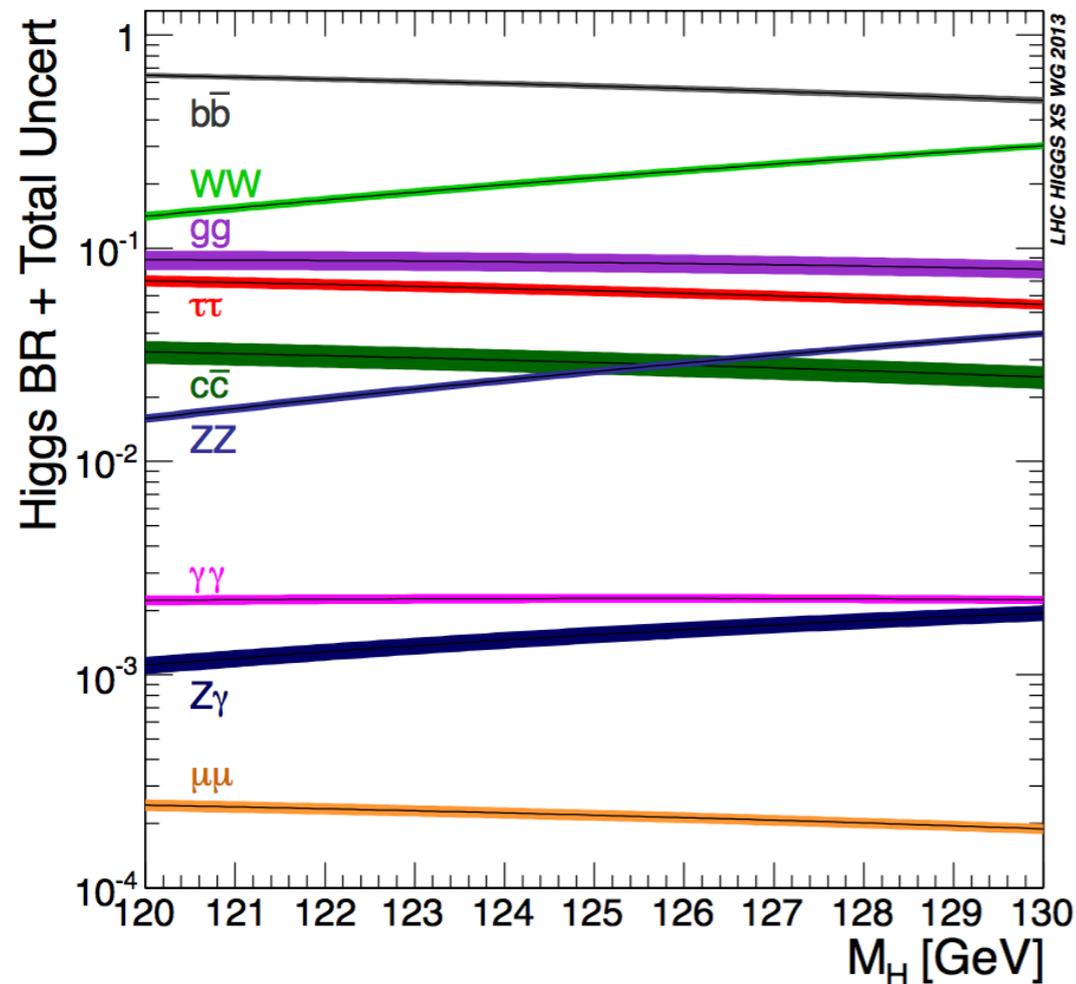
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$$\Gamma_{H \rightarrow bb} \propto \sum_{\text{colors}} \left| \begin{array}{c} H \\ \vdots \\ f \\ \swarrow \\ \bar{f} \end{array} \right|^2 \frac{m_f}{v}$$

QCD corr.

$$\sim k N_c m_f^2(m_H)(1 + \Delta_{\text{QCD}})$$

$8 \times 10^{-5} / \text{GeV}$ (points to $\sim k$)
 3 (points to N_c)
 2.8 GeV (points to m_f)
 0.2 (points to Δ_{QCD})

Total width Γ_{tot} : 4.1 MeV

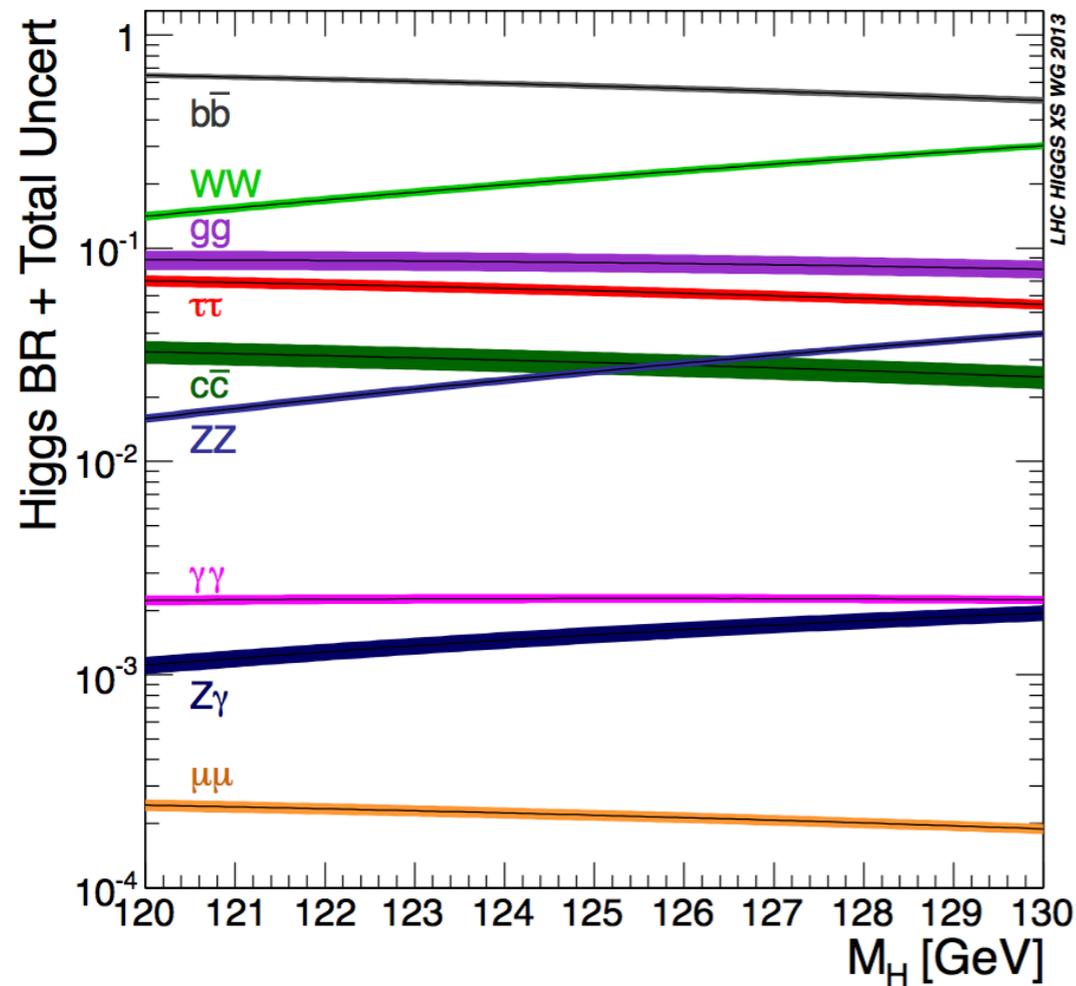
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$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

W bosons

Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%

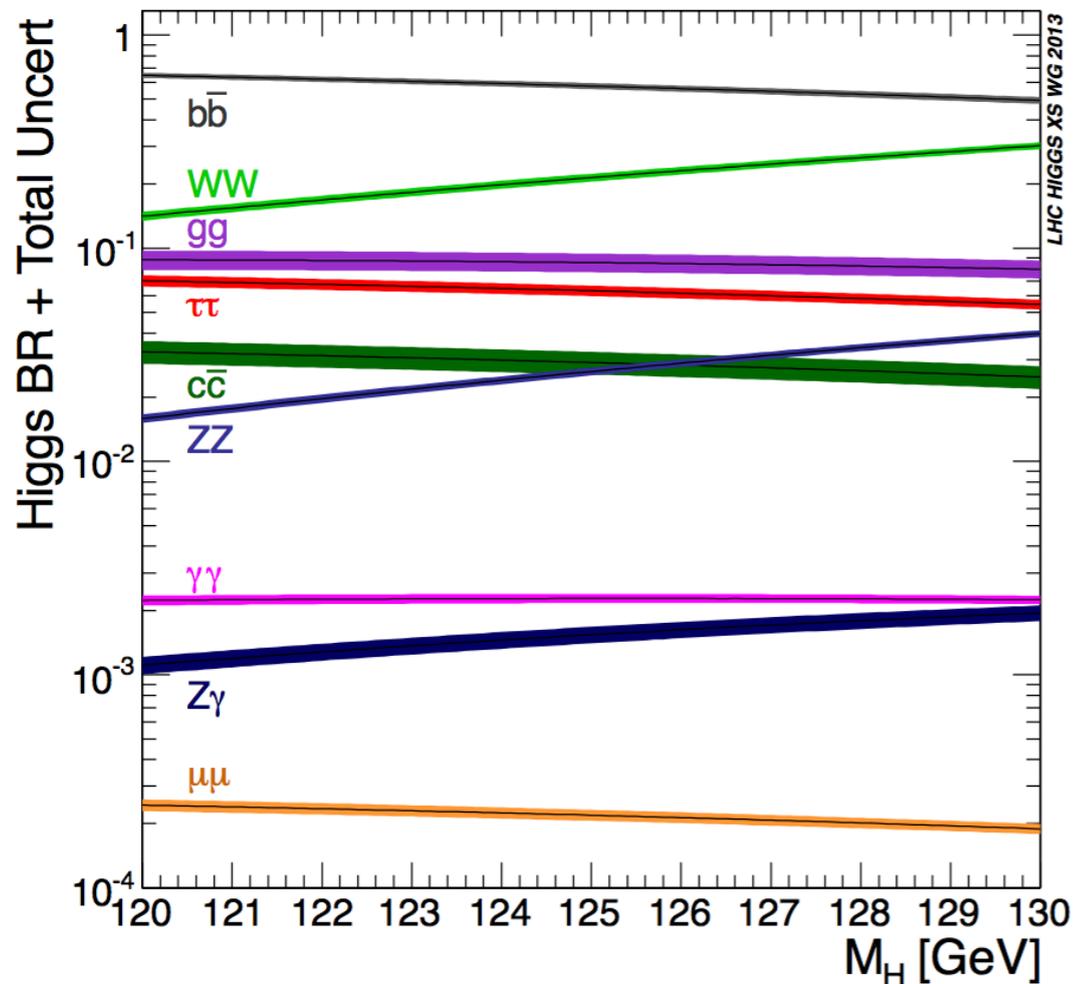


Higgs boson decay channels

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Third generation fermions



Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %

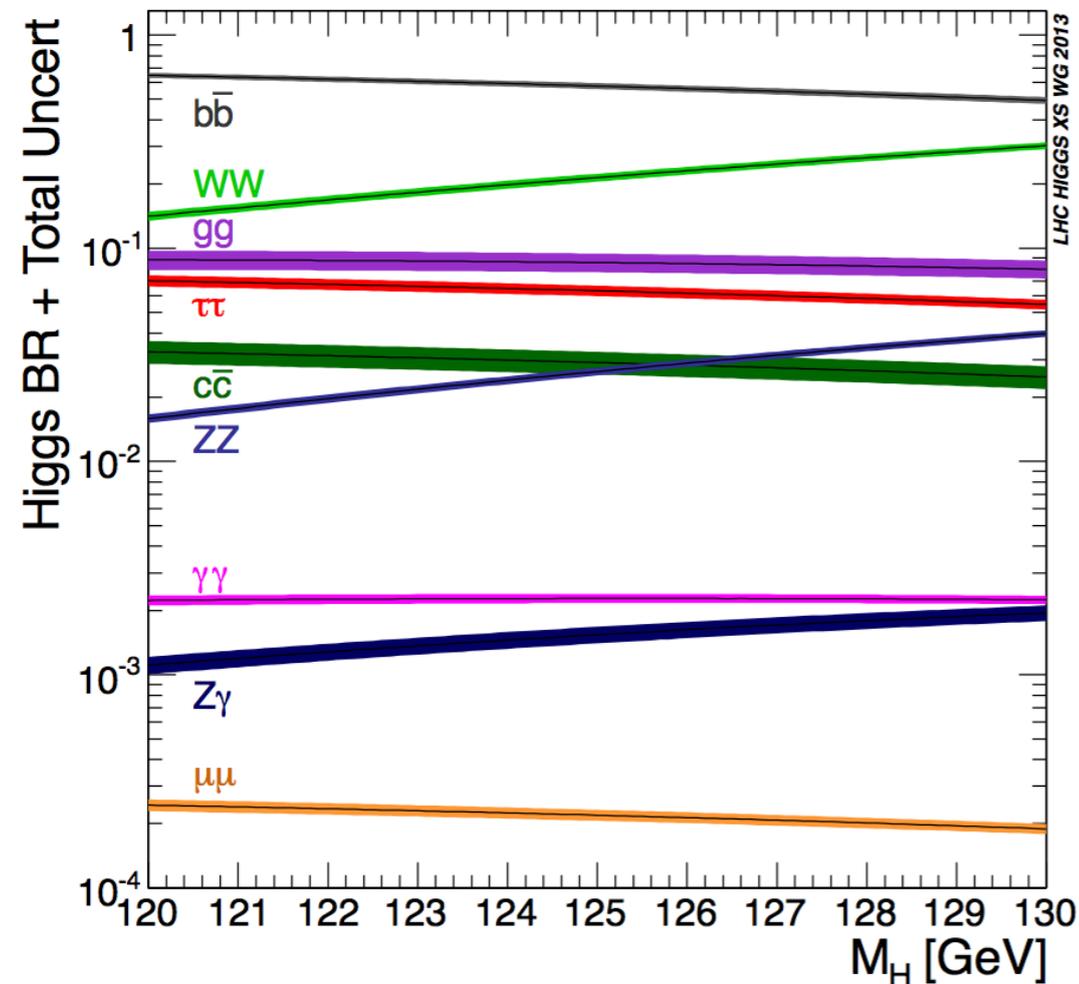
$$\Gamma_{H \rightarrow \tau\tau} \sim [8 \times 10^{-5} / \text{GeV}] m_f^2$$

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Higgs boson decay channels

Z bosons



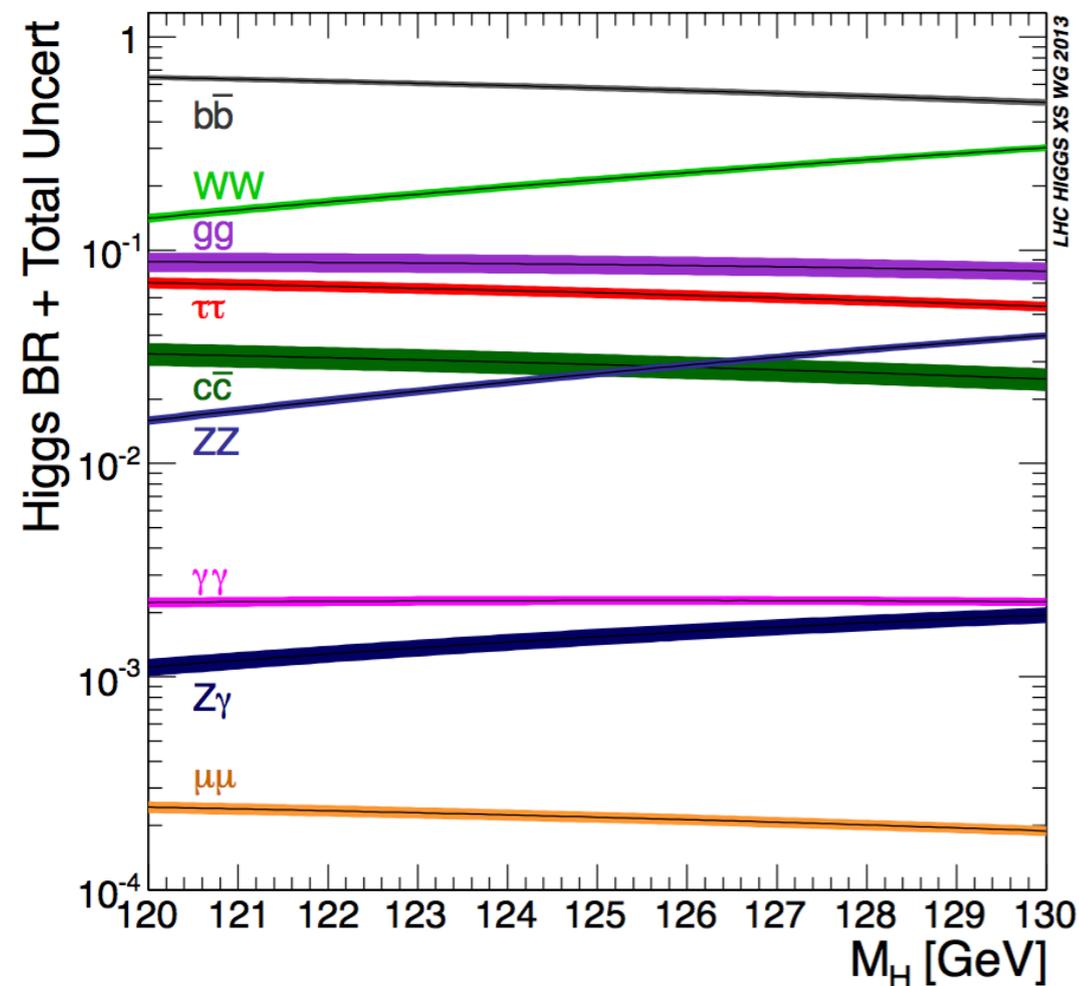
Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %
ZZ	3%

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Higgs boson decay channels

Second generation quarks



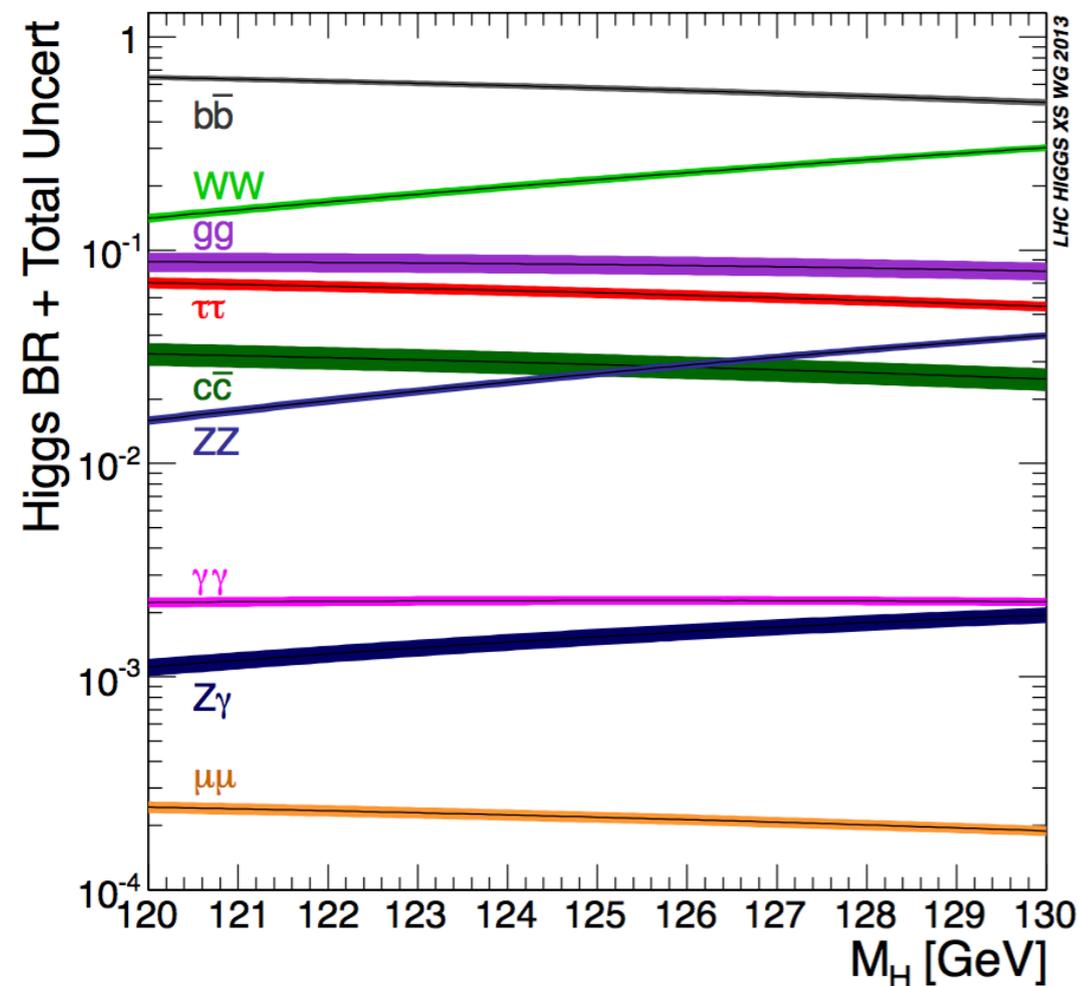
Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %
ZZ	3%
cc	3%

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Higgs boson decay channels

Photons ?? How?



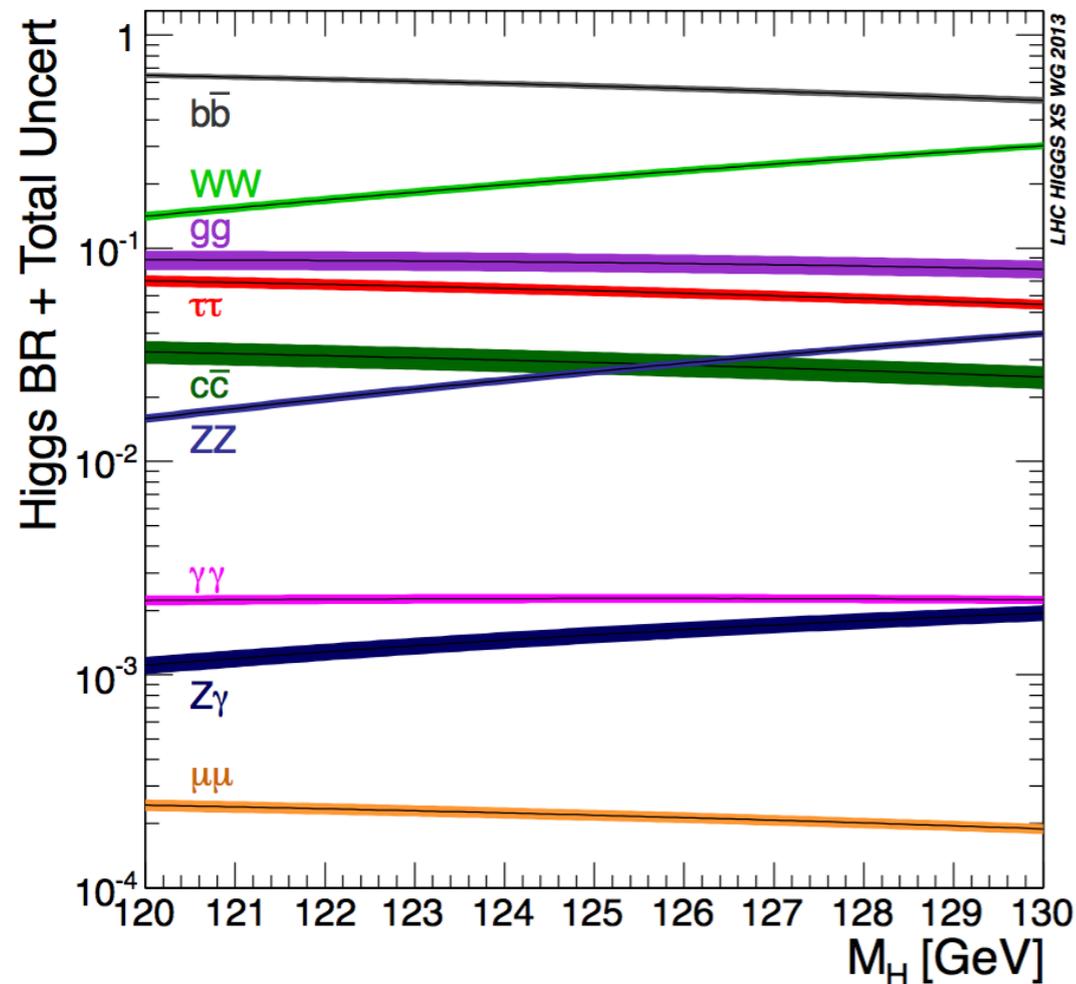
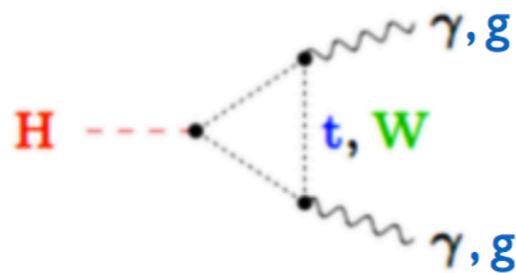
Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %
ZZ	3%
cc	3%
$\gamma\gamma$	0.2 %

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Higgs boson decay channels

Photons ?? How?



Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %
ZZ	3%
cc	3%
$\gamma\gamma$	0.2 %

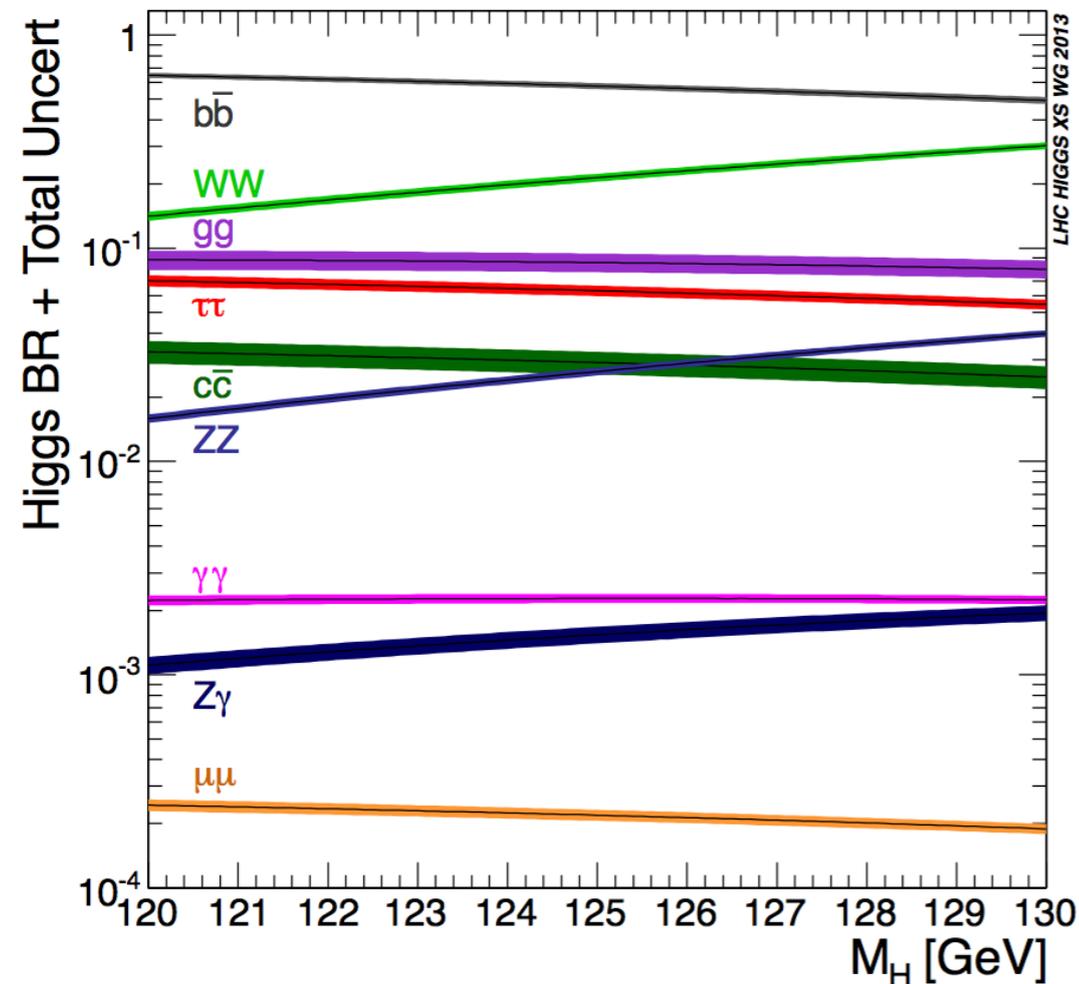
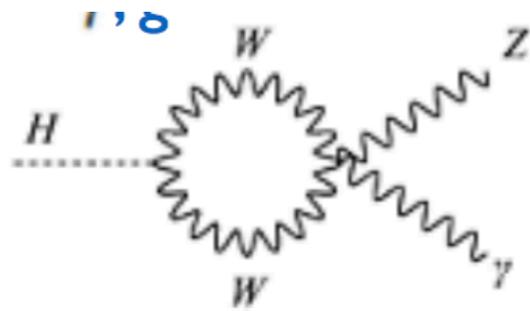
Possible through loops
 What if we have some new particle in the loop?

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Higgs boson decay channels

Zγ?? How?



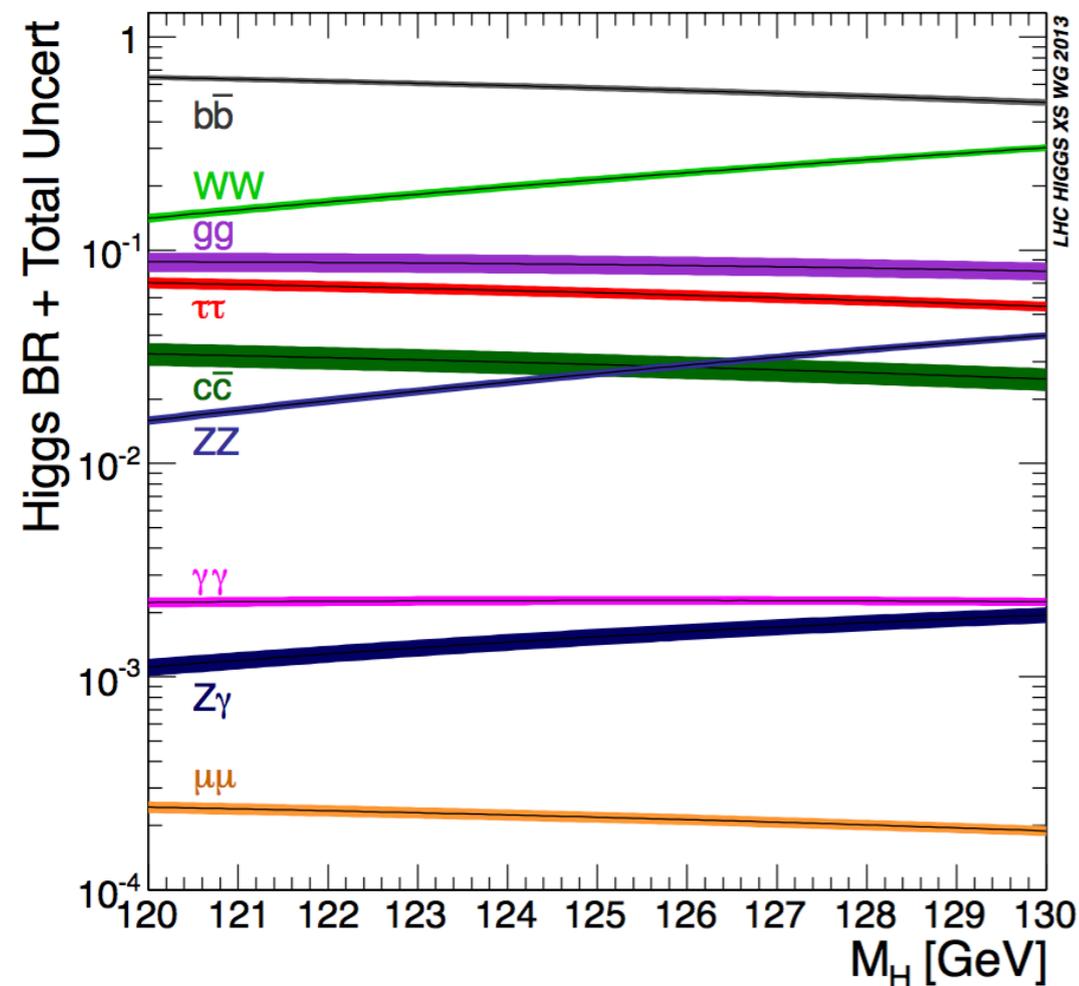
Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %
ZZ	3%
cc	3%
$\gamma\gamma$	0.2 %
$Z\gamma$	0.2 %

$$BR_i = \Gamma_i / \Gamma_{\text{tot}}$$

$$\Gamma_{\text{tot}} = \sum \Gamma_i$$

Higgs boson decay channels

Second generation fermions



Decay mode	Expected BR for $m_H=125$ GeV
bb	57%
WW	22%
$\tau\tau$	6.3 %
ZZ	3%
cc	3%
$\gamma\gamma$	0.2 %
$Z\gamma$	0.2 %
$\mu\mu$	0.02 %

Higgs boson

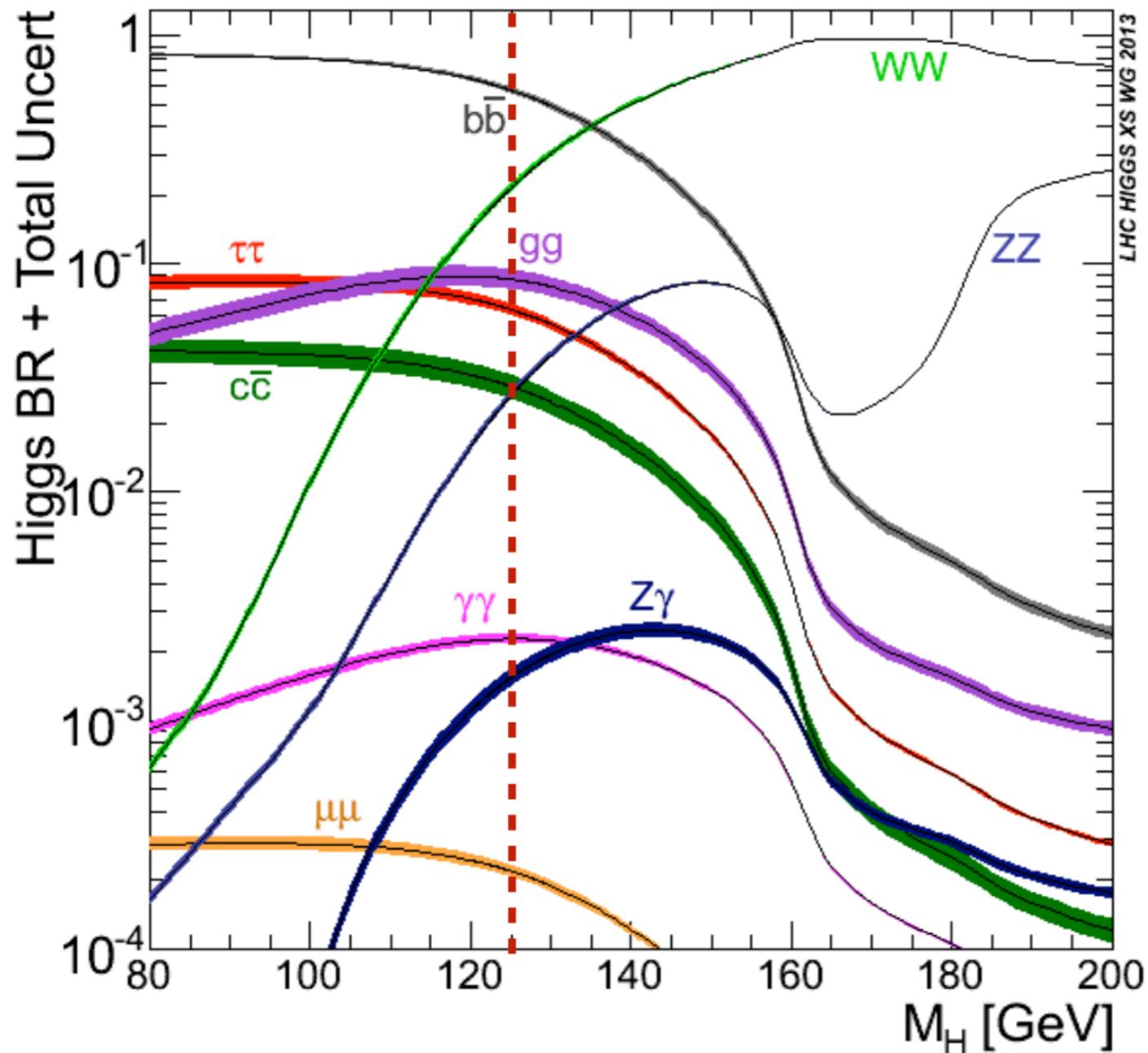
- Couplings with the SM particles
- Production modes
- Decay Branching Ratio
 - NOTE: for fermions
 - $\Gamma_{H \rightarrow ff} \sim k N_c m_f^2 (m_H) (1 + \Delta_{\text{QCD}})$

And now.... some fresh air...

Discovering the Higgs boson at the LHC

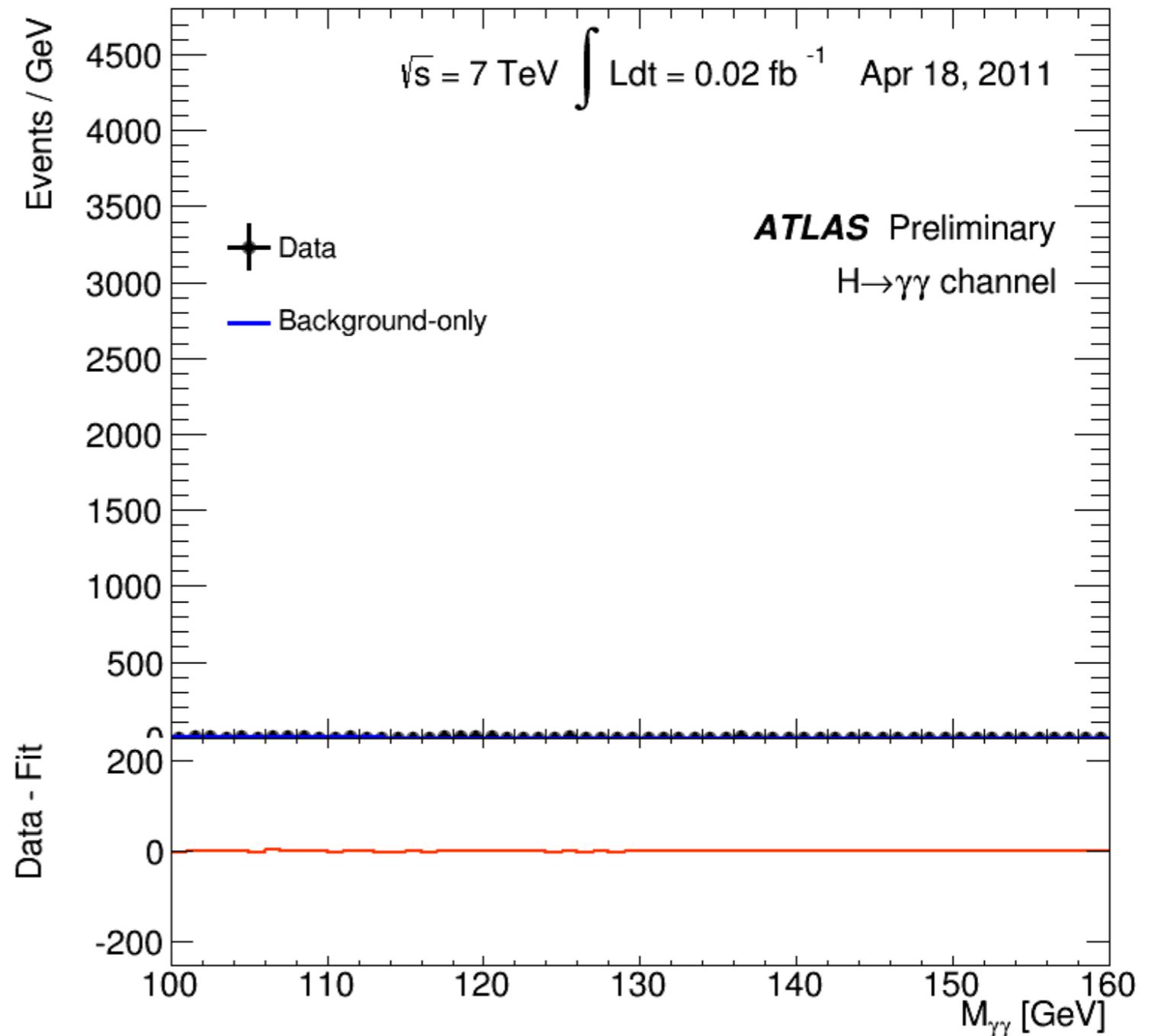
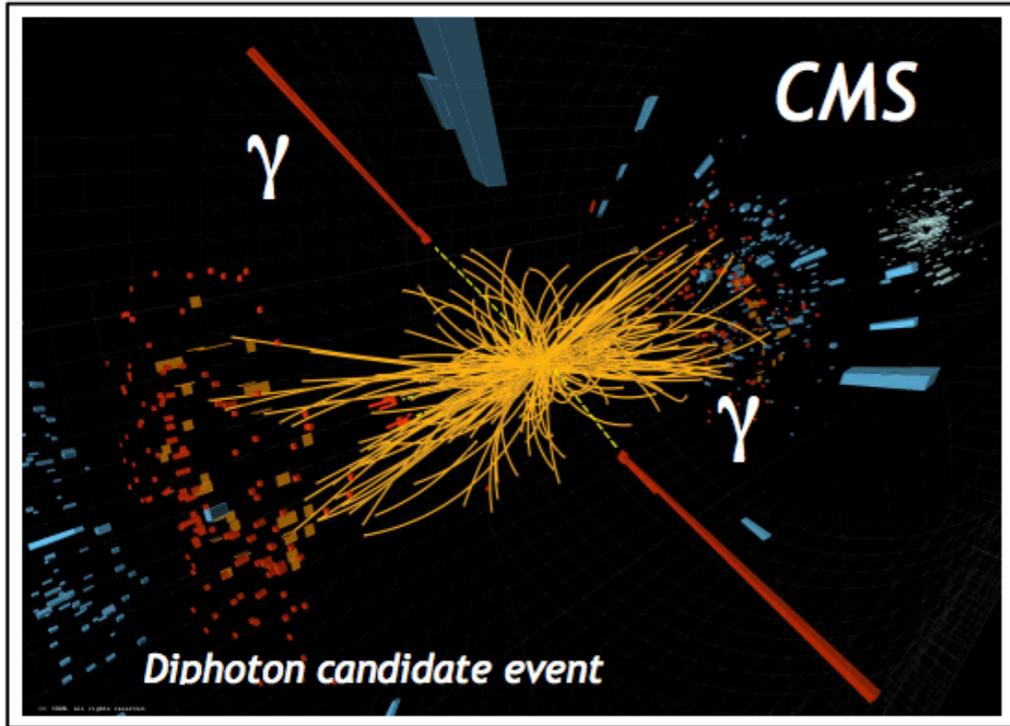


Which are the needed performances for our detector?



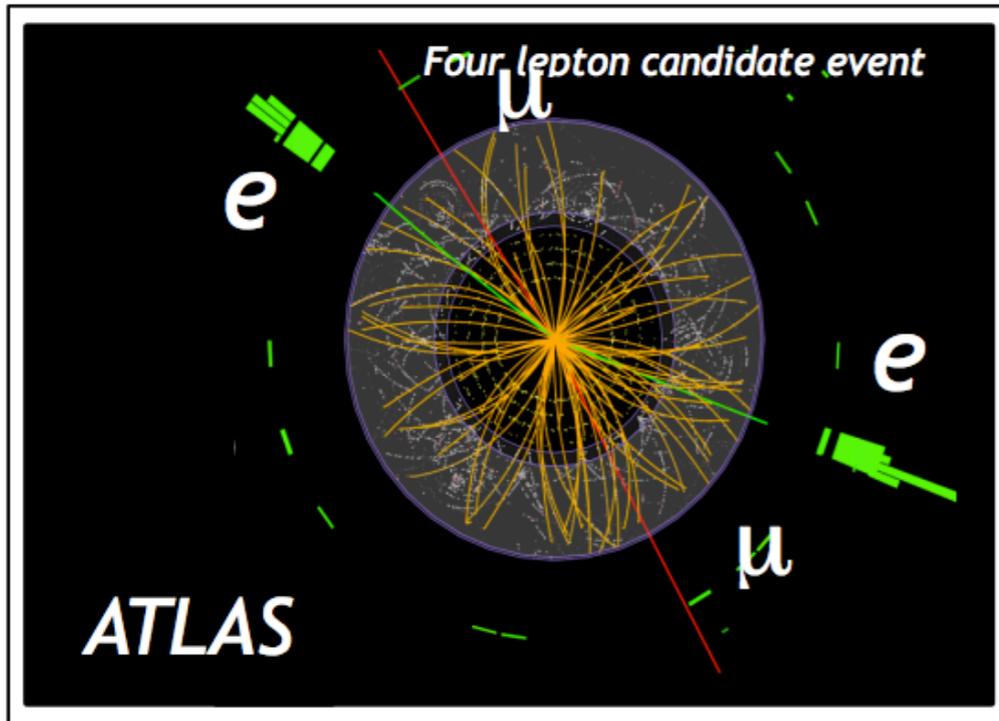
- $\gamma\gamma$: identification and measurement of **photons**
- ZZ, WW : identifications and measurement of **muons, electrons**
- $WW, \tau\tau$: measurement of **missing transverse momentum** (requiring momentum measurement up to very forward - $|\eta| \sim 5$)
- $bb, \tau\tau$, efficient and pure **b-tagging** and **τ identification**
- **VBF**: Capability to detect **forward jets** (for vector boson fusion processes)

$$H \rightarrow \gamma\gamma$$



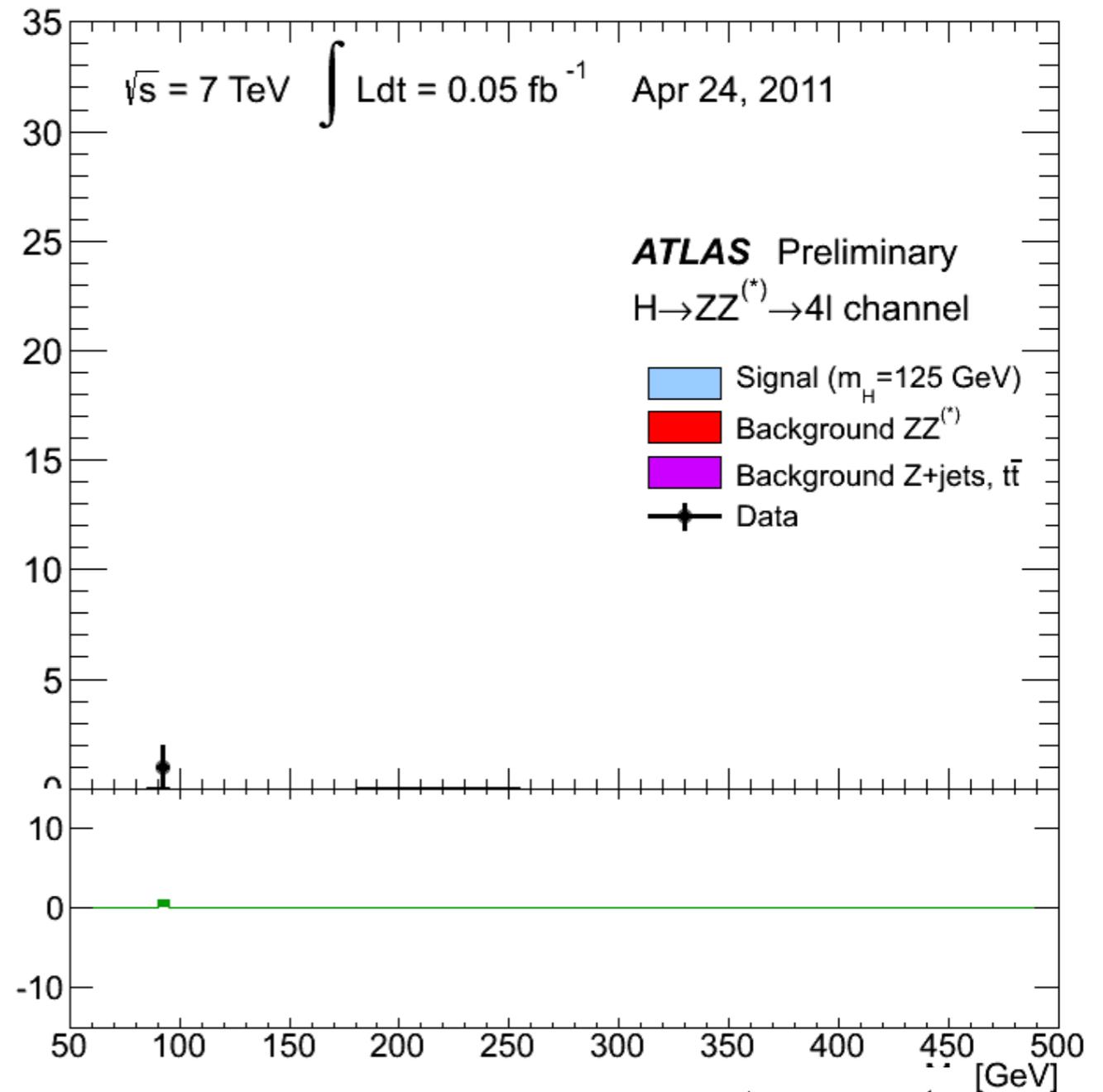
- Low S/B, but relatively high statistics for the signal
Signal: ~300 events in Run1 Background: Largest contribution from jets
- Very simple selection, quality of detector response and performance play a crucial role
- Main production modes and decay mode occur through loop. Probe for new physics

$$H \rightarrow ZZ^* \rightarrow 4l$$

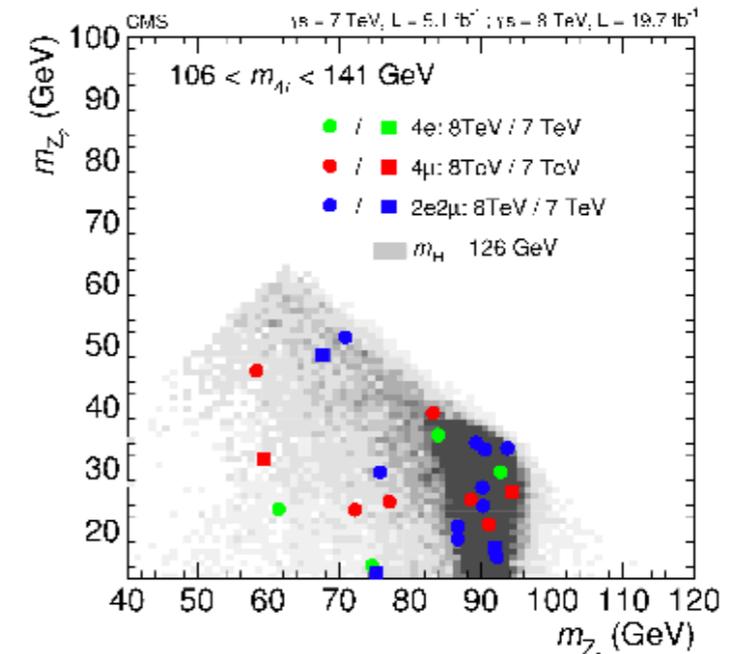


Events / 5 GeV

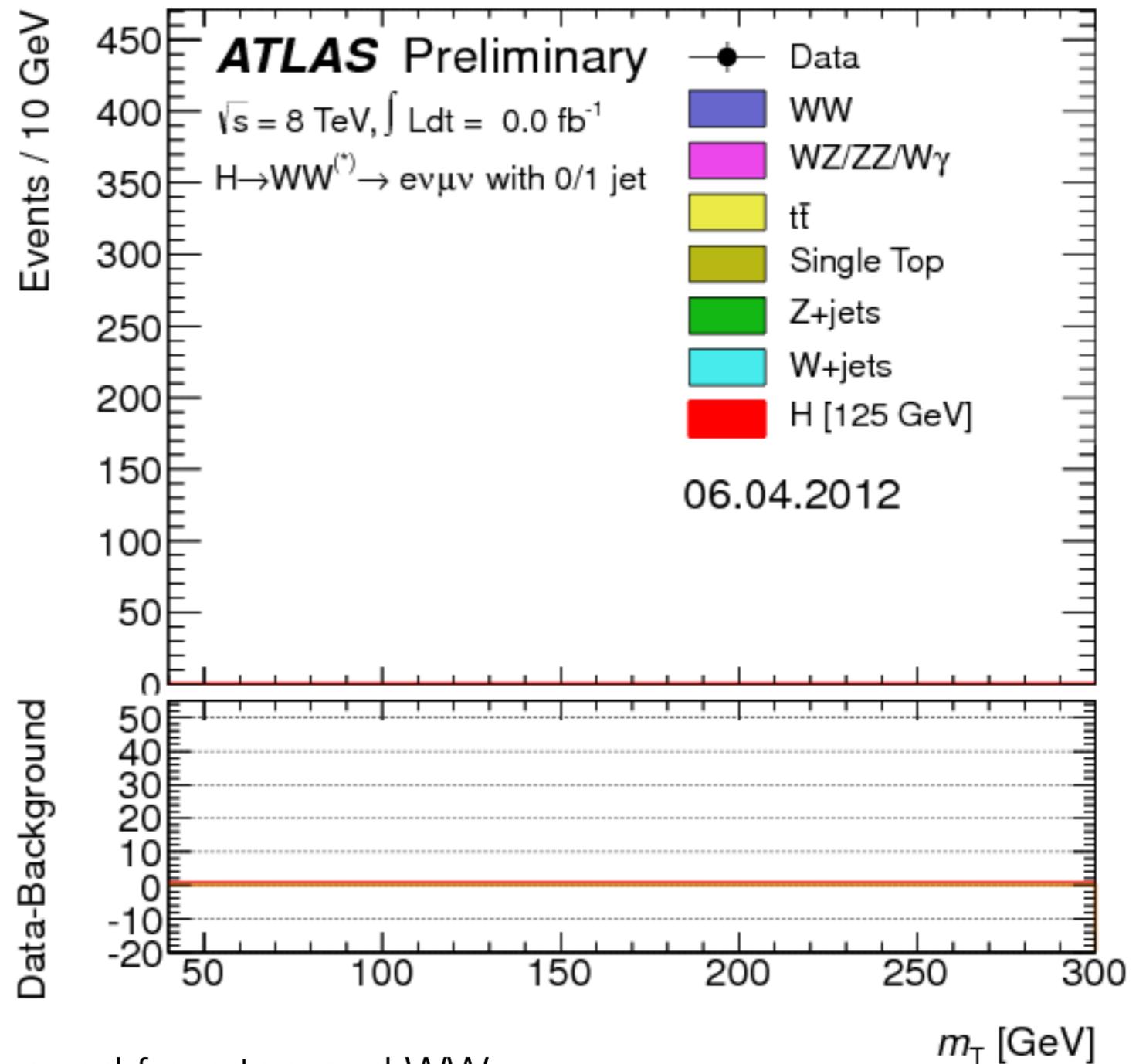
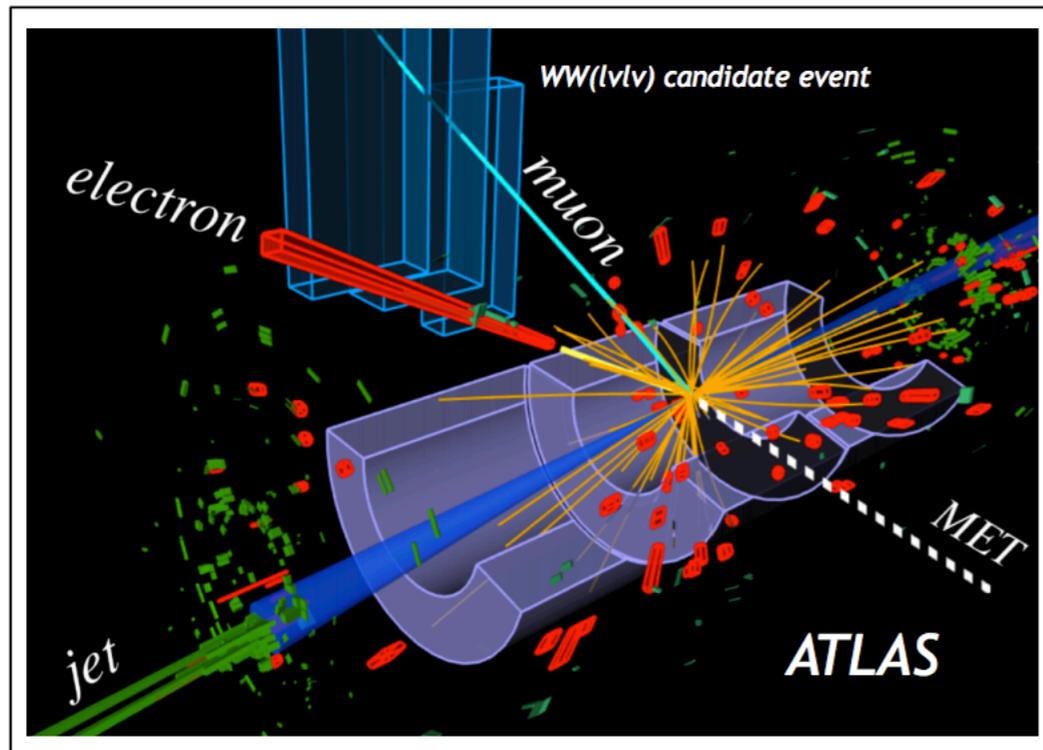
Data - Background



- High S/B (2-10), but relatively low statistics
 Background: $pp \rightarrow ZZ$ estimated by MC
- Typically one Z is on-mass shell
- Note: $BR(H \rightarrow ZZ) \sim 3\%$, $BR(Z \rightarrow ee) + BR(Z \rightarrow \mu\mu) \sim 6.7\%$

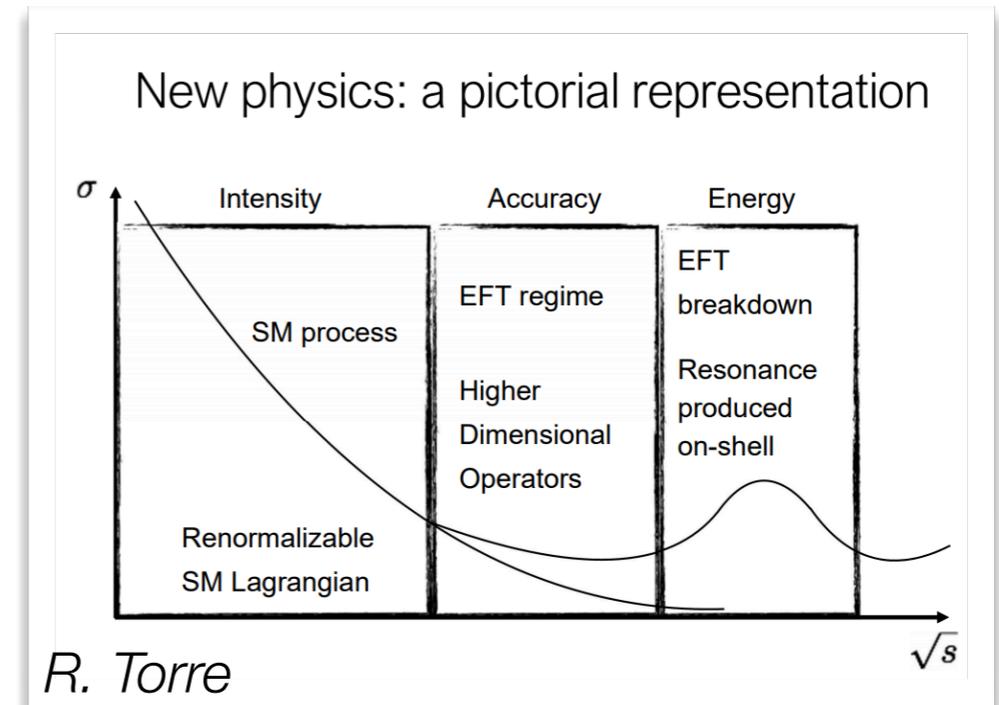
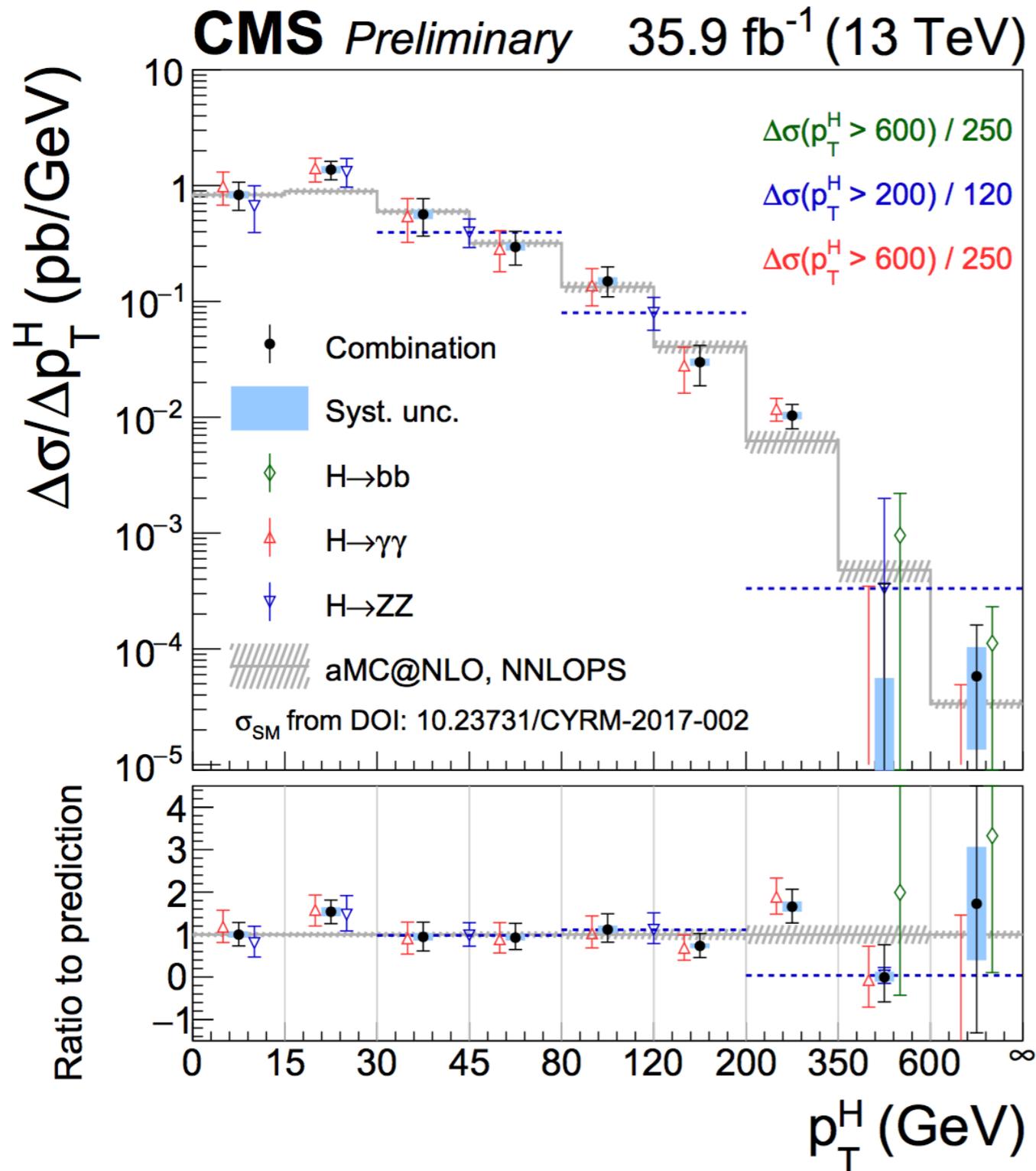


$$H \rightarrow WW^* \rightarrow 2l2\nu$$



- Large signal event rate, but large background from top and WW
- Requires a very good understanding of the background in simulations and with control regions
- The presence of neutrinos spoil the mass resolution

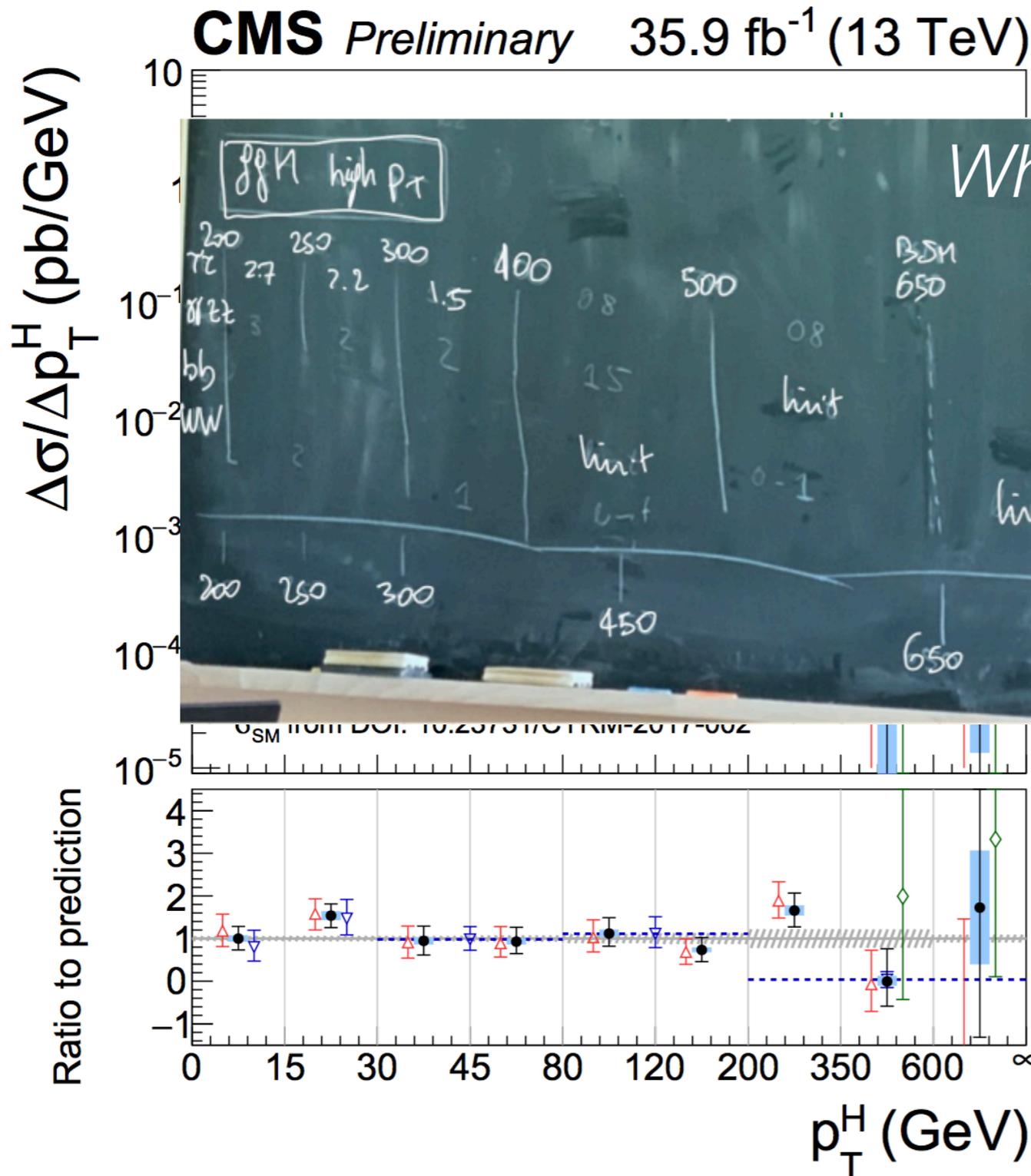
A new era - differential measurements



What if New physics exist, but just beyond the reach of the LHC?

We should start having “anomalies”

A new era - differential measurements



New physics: a pictorial representation

Where can we arrive?
Les Houches 2019

1 jet
≥ 2 jet
proposed
alternative (some get)

@ $\sqrt{s}=0,2$
?

but just
?!

We should start having
“anomalies”

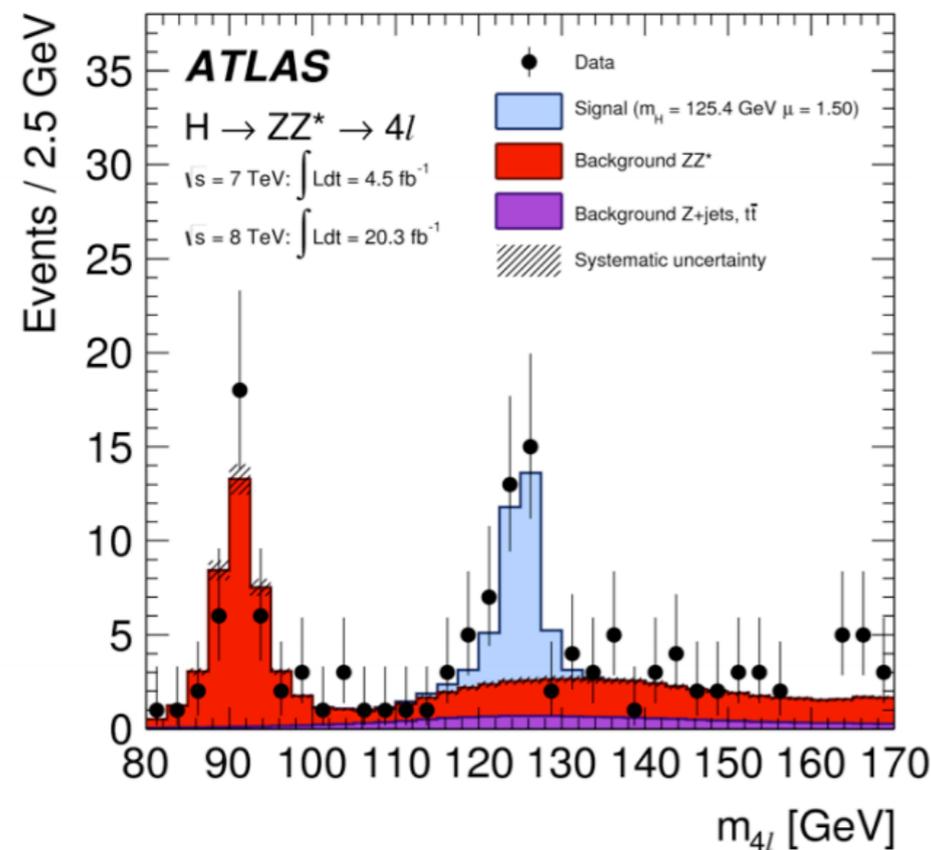
Discovering the Higgs boson at the LHC

- Detector needs for the discovery
- Short review of $H \rightarrow \gamma\gamma$
- Short review of $H \rightarrow ZZ$
- Short review of $H \rightarrow WW$
- Measurement of the differential cross sections

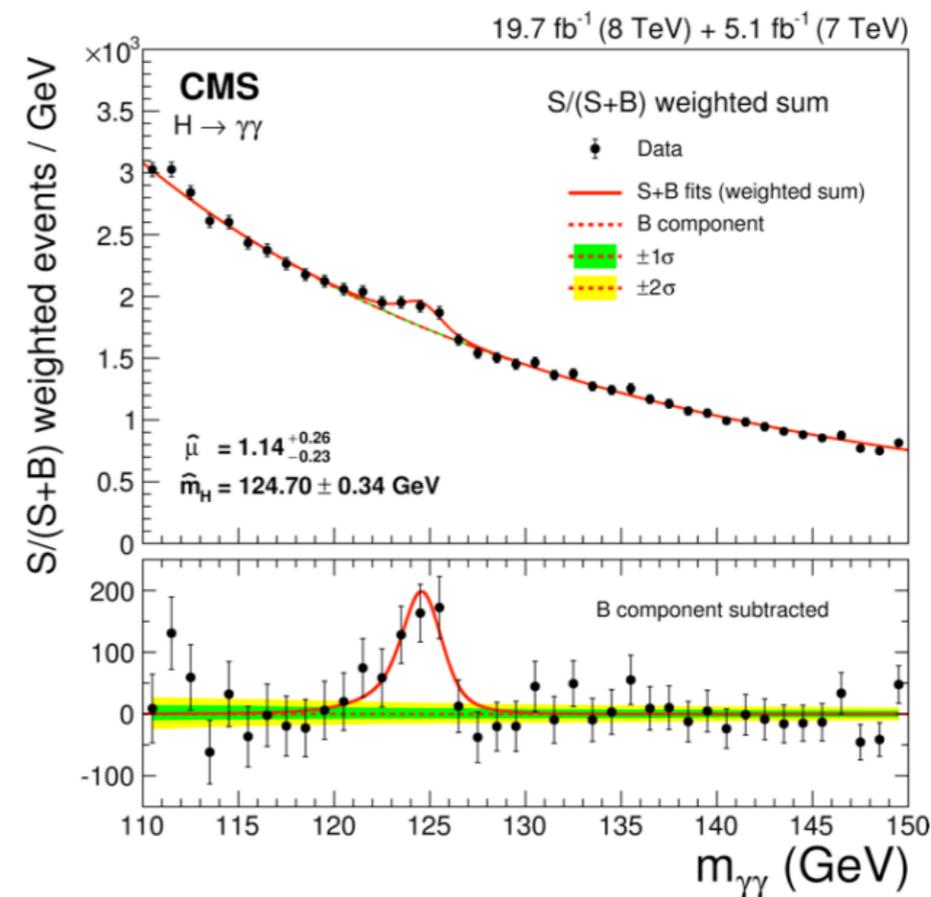
Higgs Properties

Higgs boson mass

- Higgs mass is the only parameter unconstrained by SM
- Crucial in SM prediction of production and decay modes
- Measurement based on $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ final states, for which invariant mass can be reconstructed with high precision



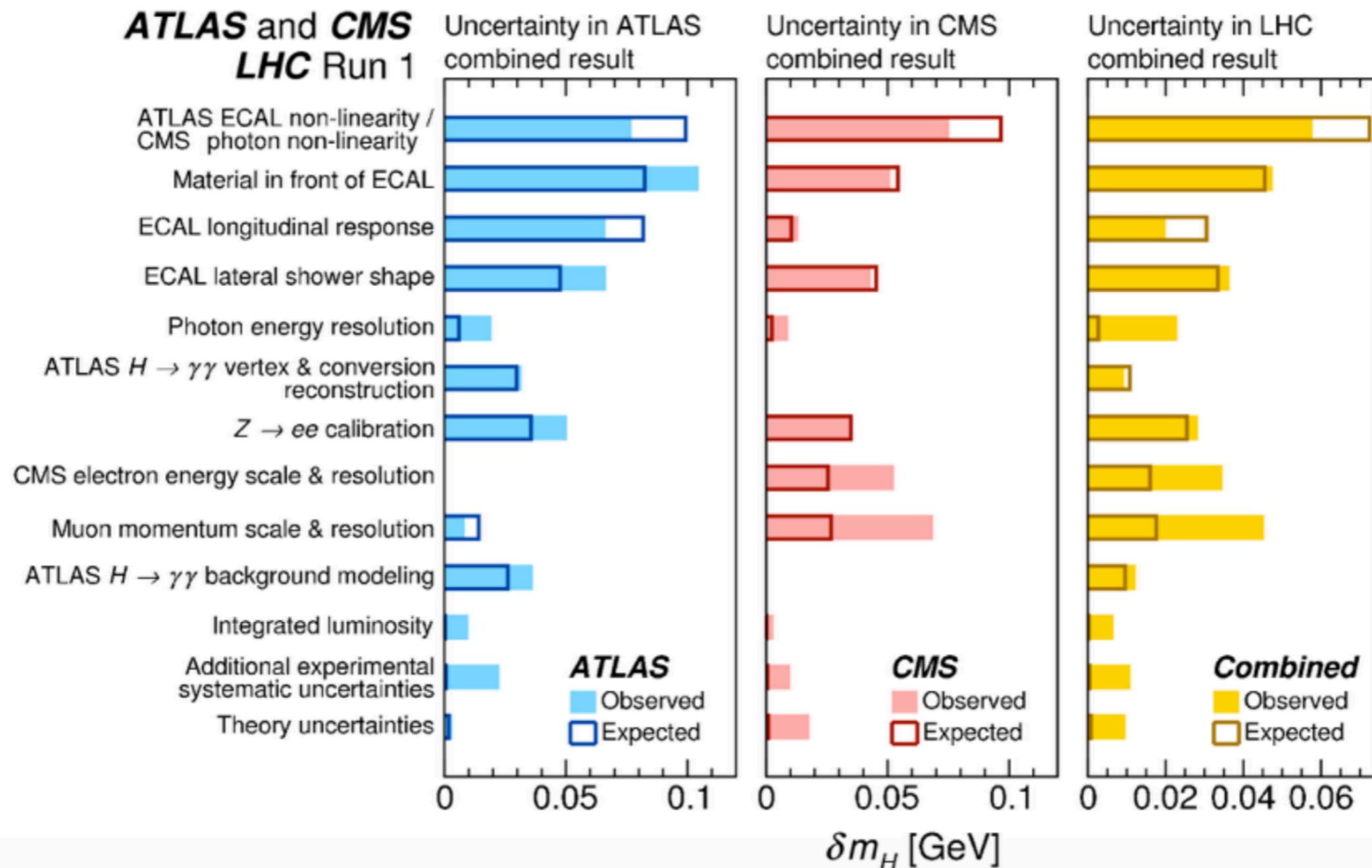
[Phys. Rev. D 90, 052004 \(2014\)](#)



[Eur. Phys. J. C 74 \(2014\) 3076](#)

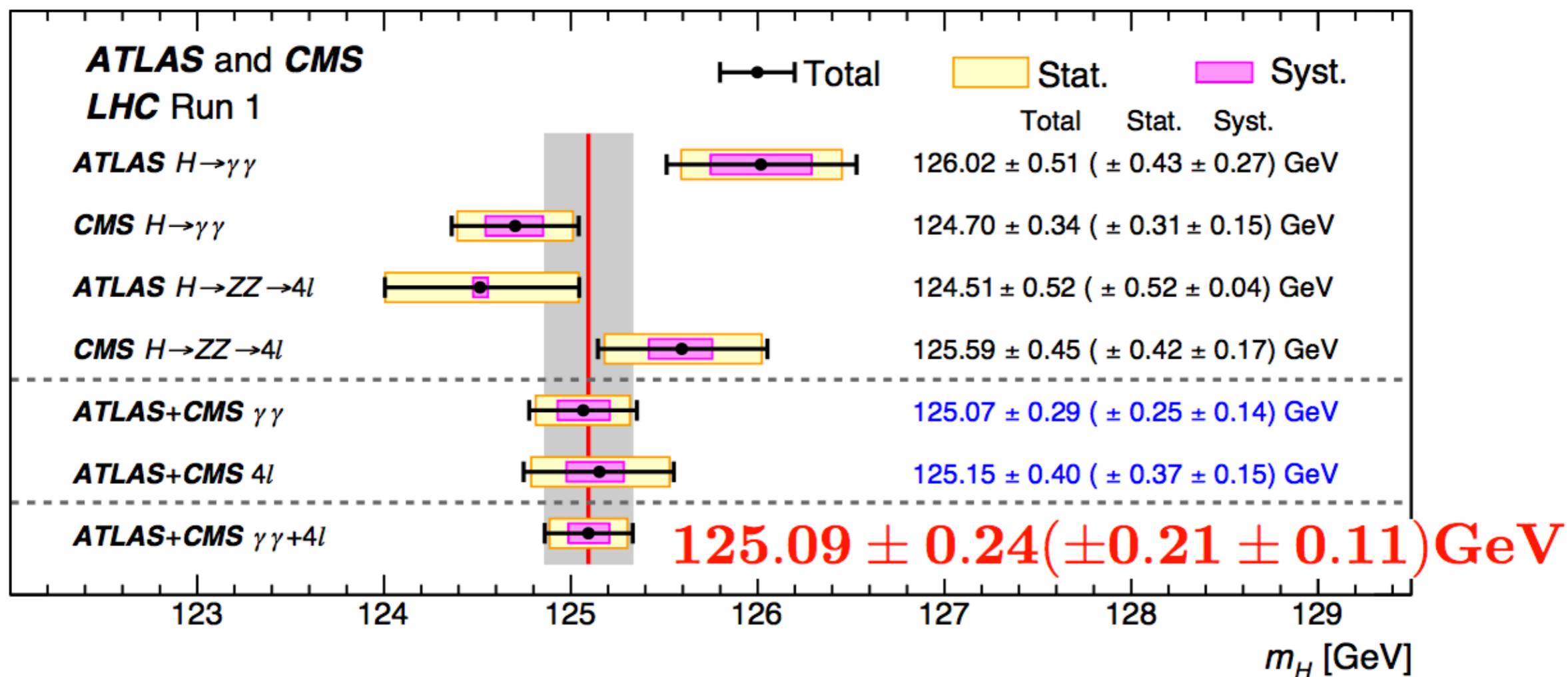
Measurement of the Higgs boson mass - Systematic impact on the measurements

Largest impact from energy scale - as expected...



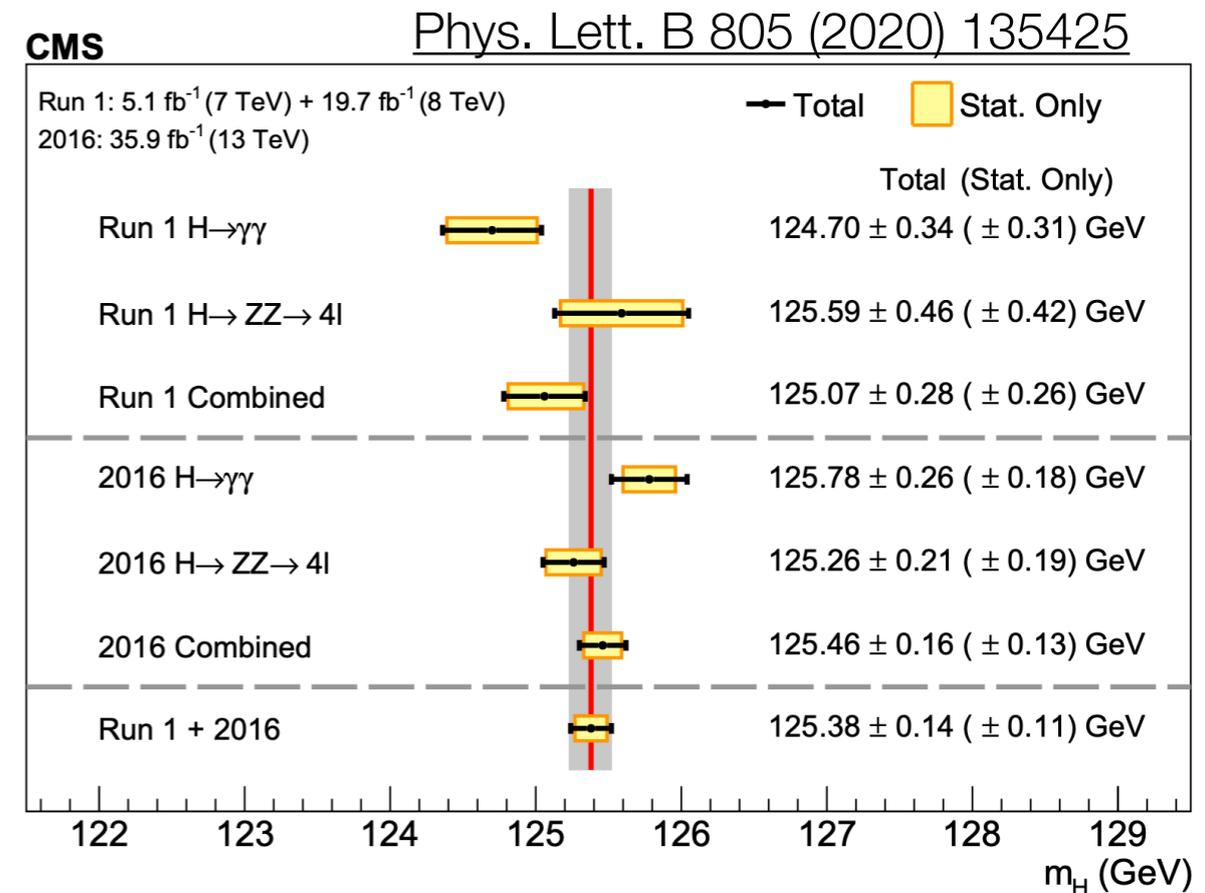
Measurement of the Higgs boson mass

- Mass of Higgs boson measured with $<0.2\%$ precision
- $M_H = 125.09 \pm 0.24 \text{ GeV} [\pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)}]$
- Dominant systematics: energy or momentum scale and resolution for γ, e, μ

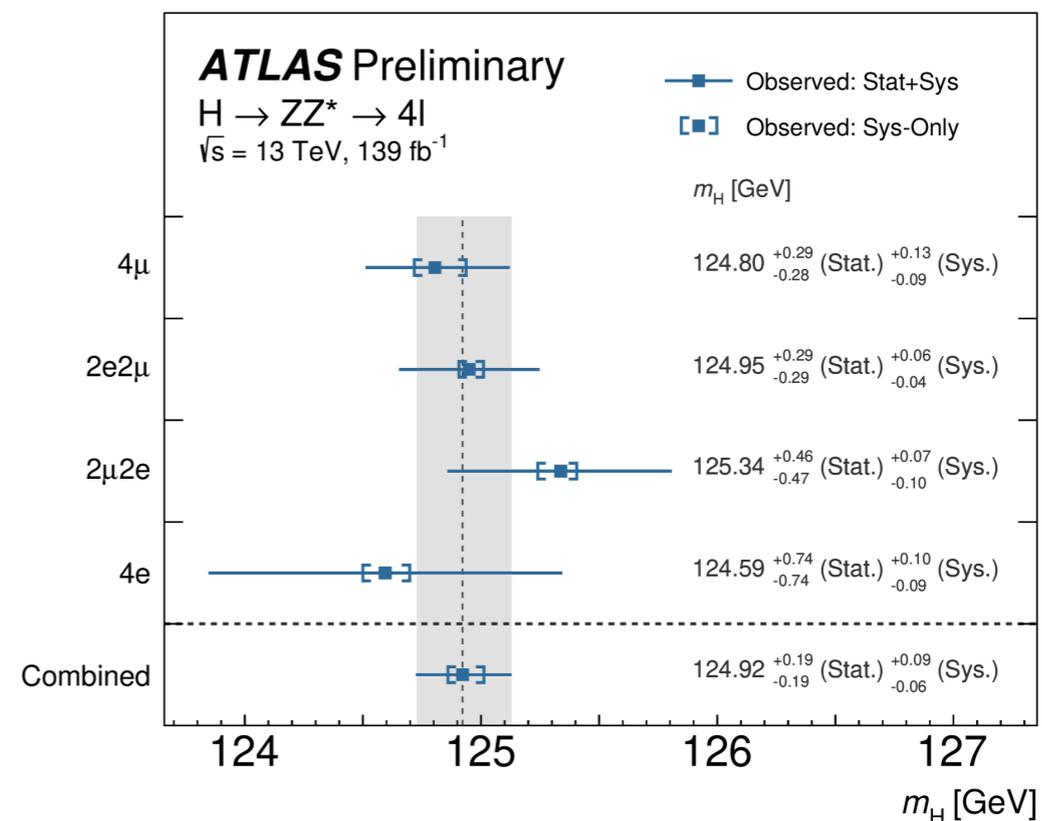


Measurement of the Higgs boson mass

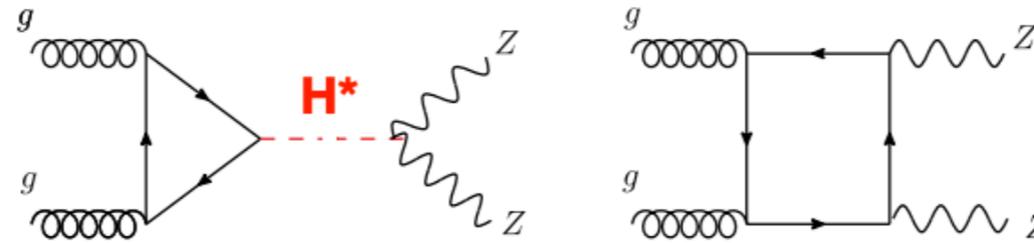
- ATLAS+CM Run1 combination:
 $m_H = 125.09 \pm 0.24 \text{ GeV}$
- CMS Combination
 Run1+2016:
 $m_H = 125.38 \pm 0.14 \text{ GeV}$
 (Most precise to date)
- ATLAS Full statistics in
 $H \rightarrow ZZ \rightarrow 4l$:
 $m_H = 124.92 \pm 0.19 \text{ GeV}$



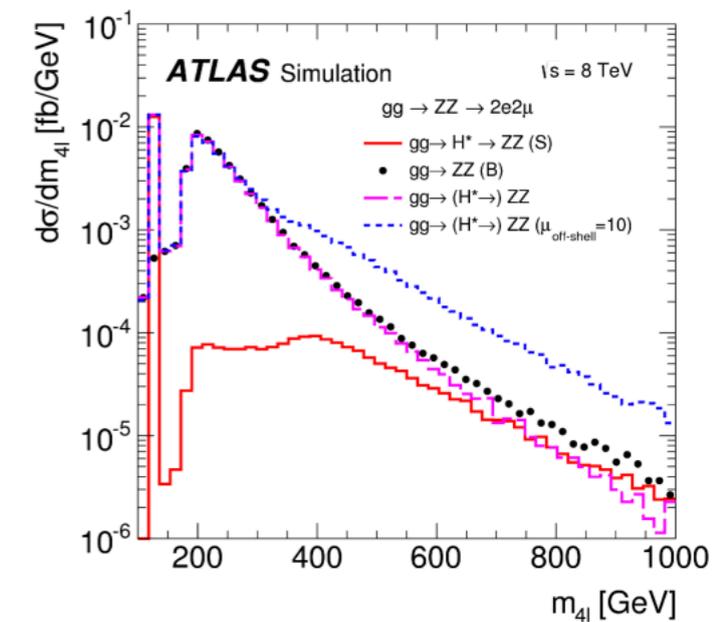
ATLAS-CONF-2020-005



Off shell Higgs

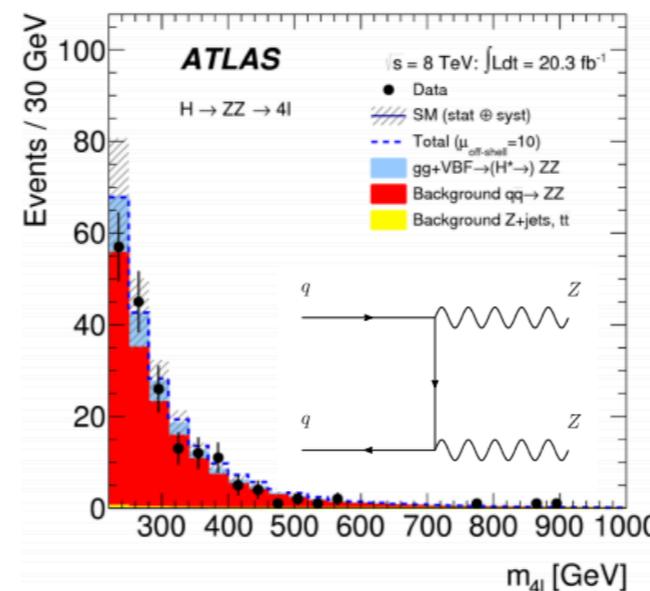


- Study of the 4-lepton spectrum in the high mass regime where the Higgs boson acts as a propagator
- Measurement of the Higgs contribution is independent of the total width of the Higgs boson
- Assuming that the Higgs couplings run as in the Standard Model



- Highly non trivial due to:
 - the negative interference
 - the large backgrounds

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

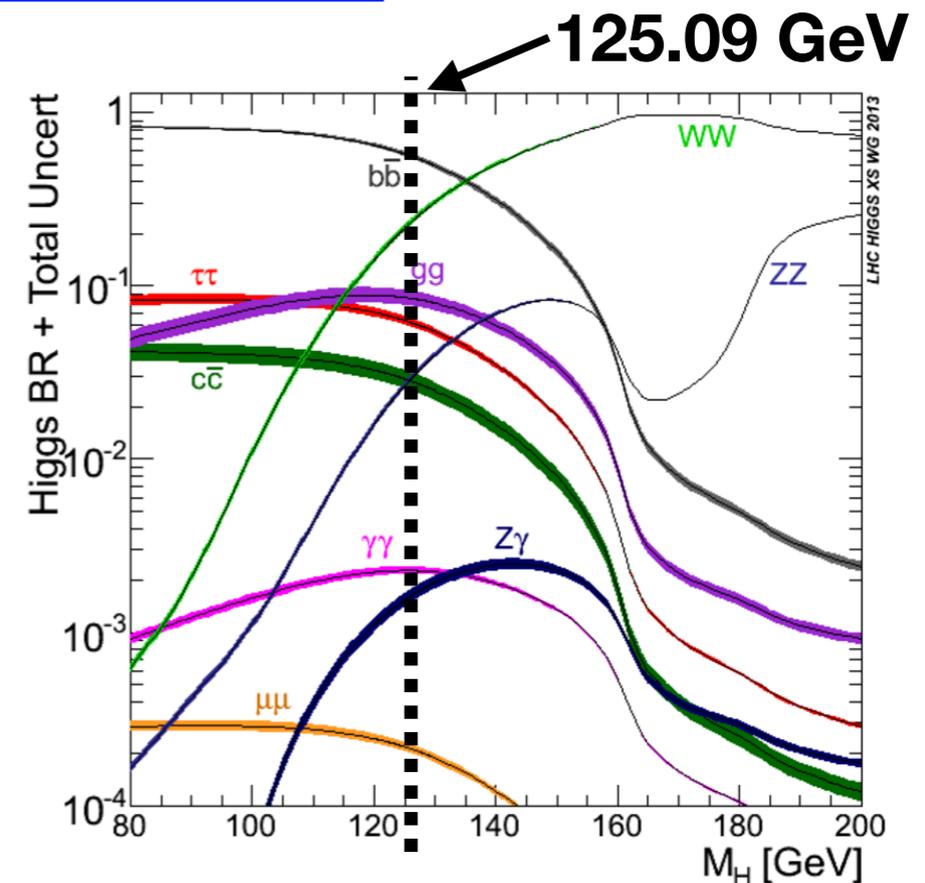
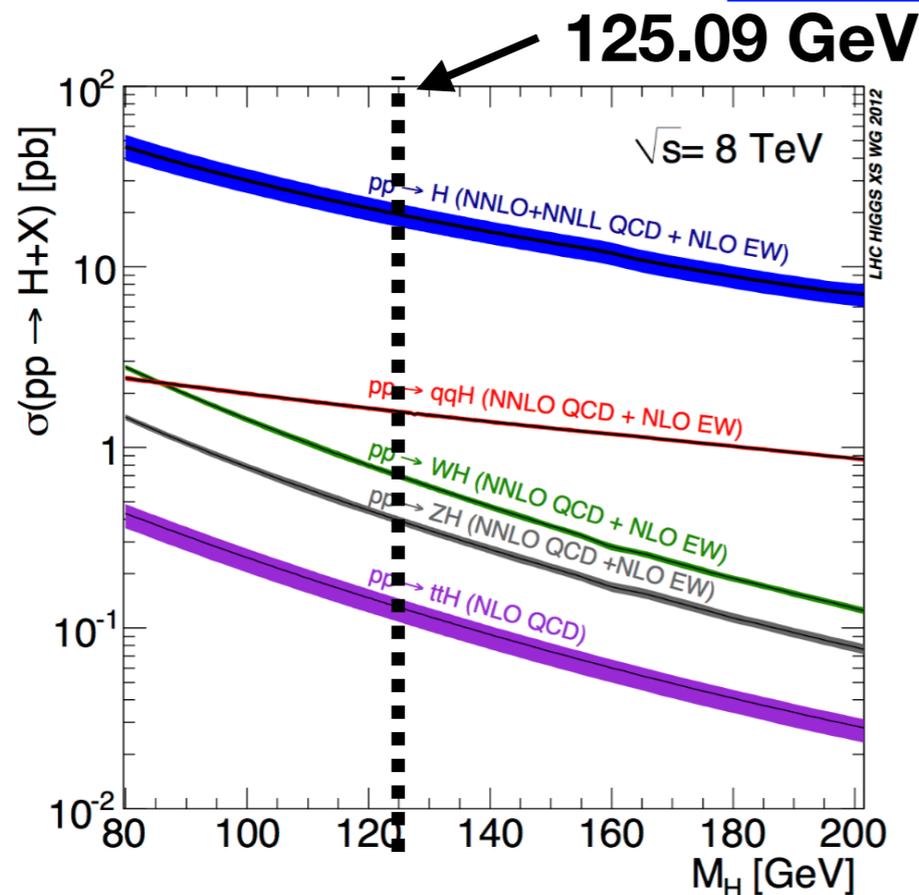


obs. 95% CL on Γ_H	
ATLAS 4l+2l2μ (36/fb Run2)	$\Gamma_H < 14.4$ MeV
CMS 4l (Run1 + 77/fb Run2)	$0.08 < \Gamma_H < 9.16$ MeV

Knowing the mass....

- SM predictions for production mode cross sections and decay BR fully determined

[CERN-2013-004, FERMILAB-CONF-13-667-T](#)



- Combining measurements and searches by ATLAS and CMS collaborations

Run1 - Measurements in ATLAS and CMS

- Integrated luminosities per experiment:
 $\sim 5 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ $\sim 20 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \rightarrow \gamma\gamma$	[91]	[92]	1.14 ^{+0.27} _{-0.25} (+0.26) (-0.24)	1.11 ^{+0.25} _{-0.23} (+0.23) (-0.21)	5.0 (4.6)	5.6 (5.1)
$H \rightarrow ZZ$	[93]	[94]	1.52 ^{+0.40} _{-0.34} (+0.32) (-0.27)	1.04 ^{+0.32} _{-0.26} (+0.30) (-0.25)	7.6 (5.6)	7.0 (6.8)
$H \rightarrow WW$	[95,96]	[97]	1.22 ^{+0.23} _{-0.21} (+0.21) (-0.20)	0.90 ^{+0.23} _{-0.21} (+0.23) (-0.20)	6.8 (5.8)	4.8 (5.6)
$H \rightarrow \tau\tau$	[98]	[99]	1.41 ^{+0.40} _{-0.36} (+0.37) (-0.33)	0.88 ^{+0.30} _{-0.28} (+0.31) (-0.29)	4.4 (3.3)	3.4 (3.7)
$H \rightarrow bb$	[100]	[101]	0.62 ^{+0.37} _{-0.37} (+0.39) (-0.37)	0.81 ^{+0.45} _{-0.43} (+0.45) (-0.43)	1.7 (2.7)	2.0 (2.5)
$H \rightarrow \mu\mu$	[102]	[103]	-0.6 ^{+3.6} _{-3.6} (+3.6) (-3.6)	0.9 ^{+3.6} _{-3.5} (+3.3) (-3.2)		
ttH production	[77, 104, 105]	[107]	1.9 ^{+0.8} _{-0.7} (+0.7) (-0.7)	2.9 ^{+1.0} _{-0.9} (+0.9) (-0.8)	2.7 (1.6)	3.6 (1.3)

off-shell analyses not in combination

	Untagged	VBF	VH	ttH
$H \rightarrow \gamma\gamma$	✓	✓	✓	✓
$H \rightarrow ZZ \rightarrow 4l$	✓	✓	✓	✓
$H \rightarrow WW \rightarrow 2l2\nu$	✓	✓	✓	✓
$H \rightarrow \tau\tau$	✓	✓	✓	✓
$H \rightarrow bb$			✓	✓
$H \rightarrow \mu\mu$	✓	✓		
$H \rightarrow Z\gamma$				
$H \rightarrow \text{inv}$				

overwhelming multijet BKG

not yet in combination

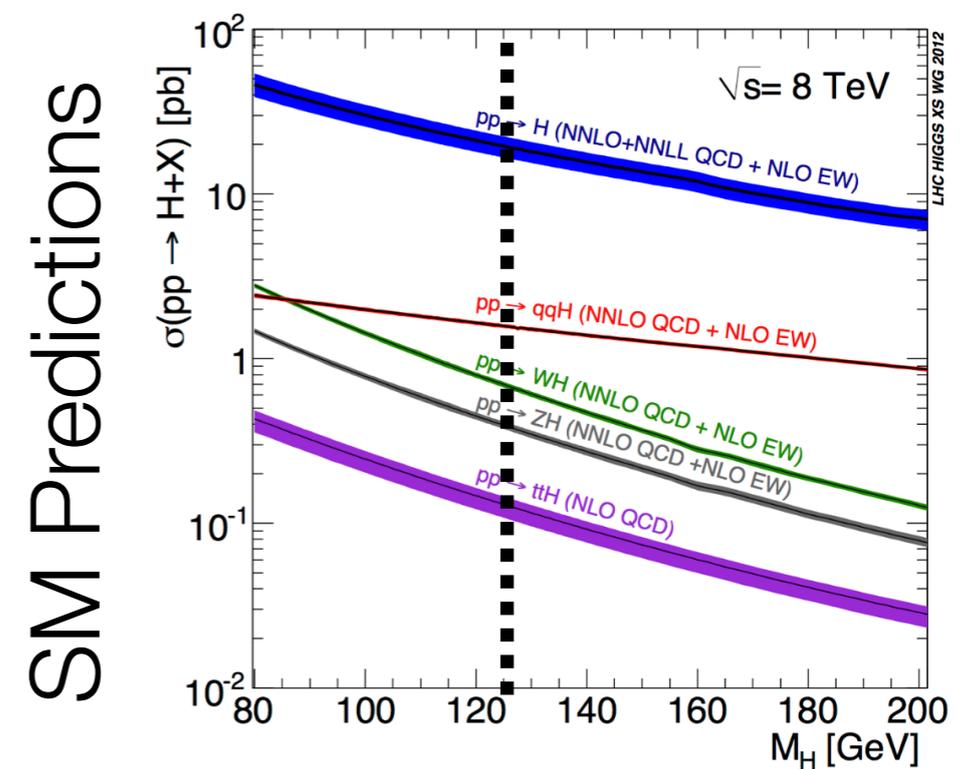
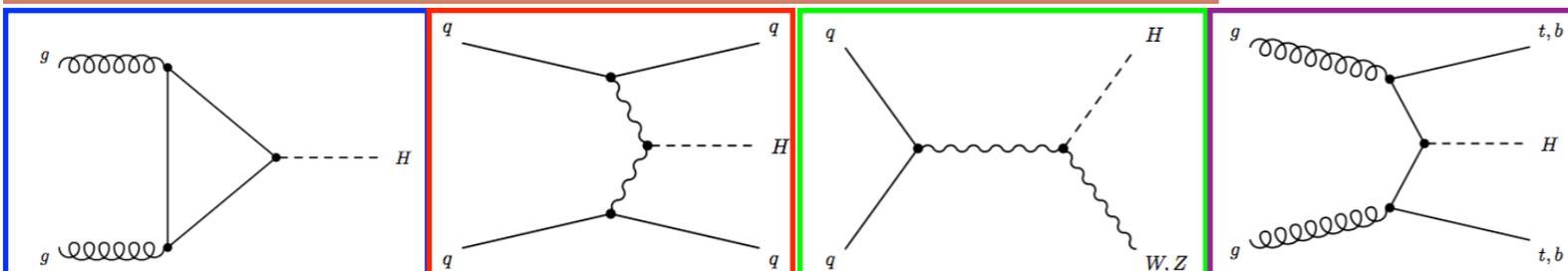
extremely low $\sigma_i \times B_{\mu\mu}$

From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k)** also based on **multi variate techniques**
- Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot B^f \right\}$$

Inclusive SM cross-section for production mode i i.e. gluon-gluon fusion

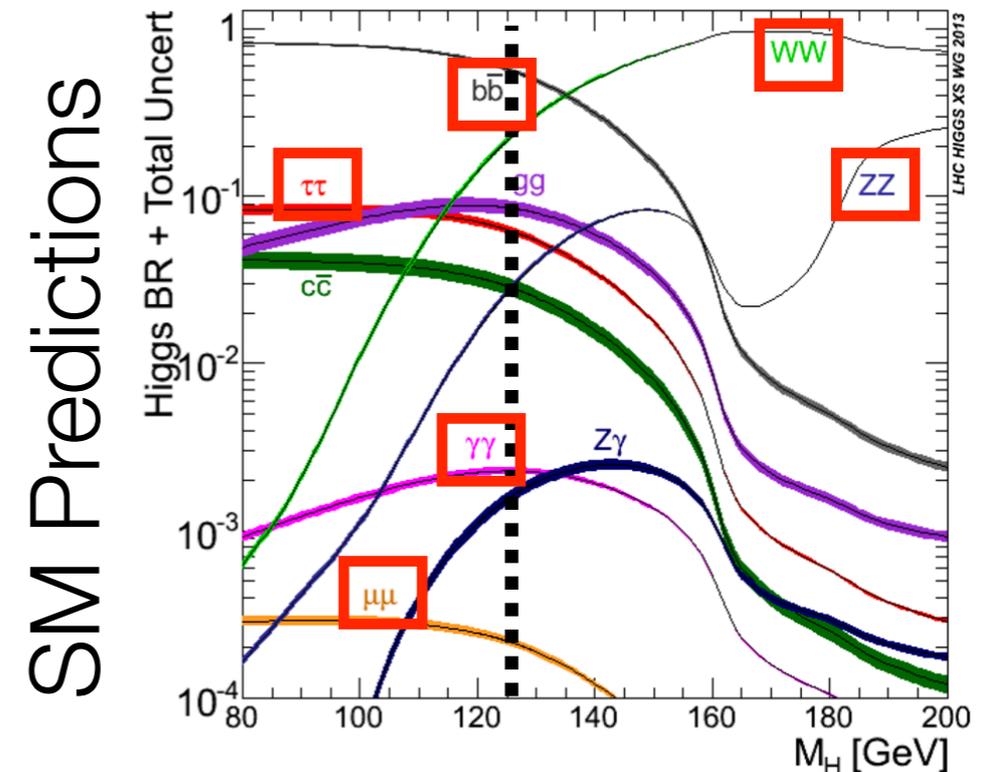
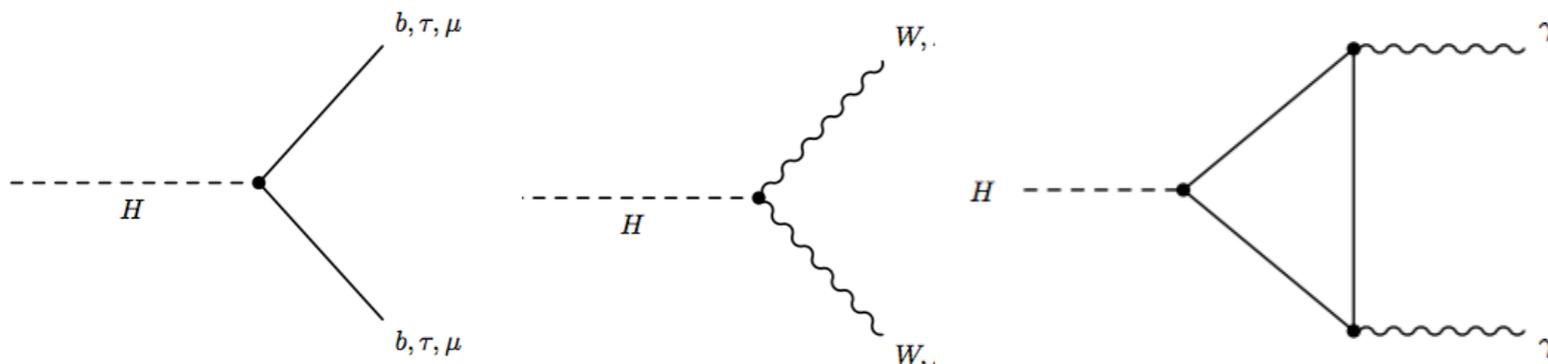


From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k)** also based on **multi variate techniques**
- Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot \boxed{\mathbf{B}^f} \right\}$$

Branching Fractions
i.e.: $H \rightarrow ZZ$



From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k) also based on multi variate techniques**
- **Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot \boxed{A_i^{f,SM}(k) \cdot \varepsilon_i^f(k)} \cdot B^f \right\}$$

Acceptances and efficiencies, from MC assuming SM

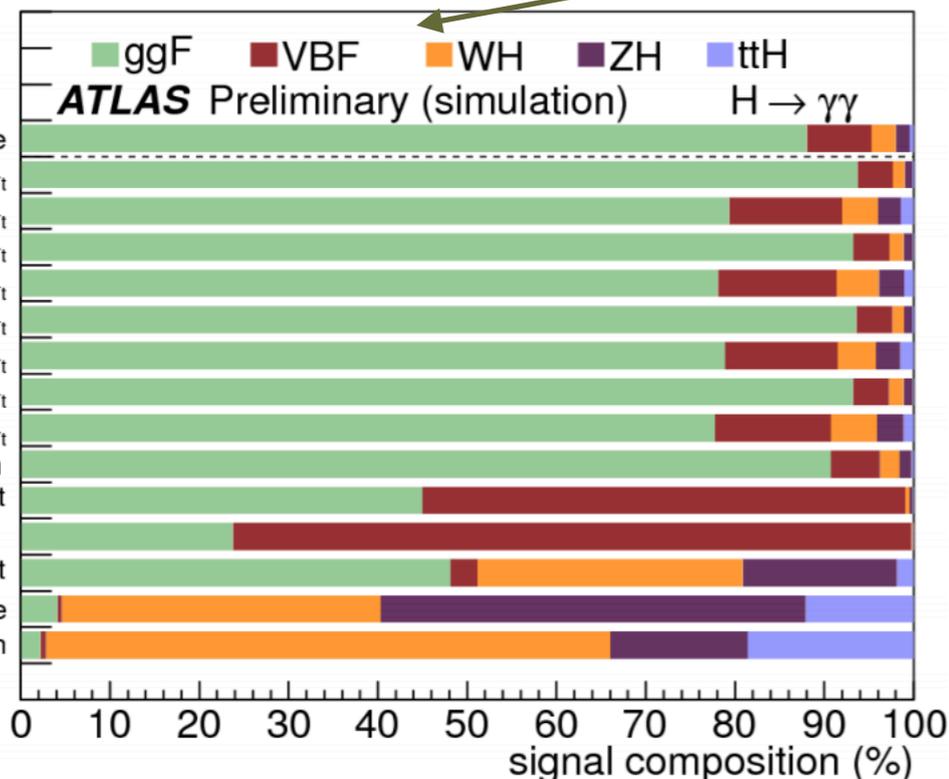
Production process	Event generator	
	ATLAS	CMS
<i>ggF</i>	POWHEG [79–83]	POWHEG
<i>VBF</i>	POWHEG	POWHEG
<i>WH</i>	PYTHIA8 [84]	PYTHIA6.4 [85]
<i>ZH (qq → ZH or qg → ZH)</i>	PYTHIA8	PYTHIA6.4
<i>ggZH (gg → ZH)</i>	POWHEG	See text
<i>ttH</i>	POWHEL [87]	PYTHIA6.4
<i>tHq (qb → tHq)</i>	MADGRAPH [89]	AMC@NLO [78]
<i>tHW (gb → tHW)</i>	AMC@NLO	AMC@NLO
<i>bbH</i>	PYTHIA8	PYTHIA6.4, AMC@NLO

From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k)** also based on **multi variate techniques**
- Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot B^f \right\}$$

Example: ttH, H → multilepton



Category	Higgs boson decay mode			
	WW*	ττ	ZZ*	Other
2ℓ0τ _{had}	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
2ℓ1τ _{had}	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
1ℓ2τ _{had}	4%	93%	0%	3%

From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k) also based on multi variate techniques**
- **Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot B^f \right\}$$

Run1 Full combination: **~600 signal regions & control regions**

Grand total of ~4200 nuisance parameters:

related to (systematic) uncertainties

Correlation scheme: strategy of nuisance parameters a delicate and complicated task (would deserve a separate lecture)

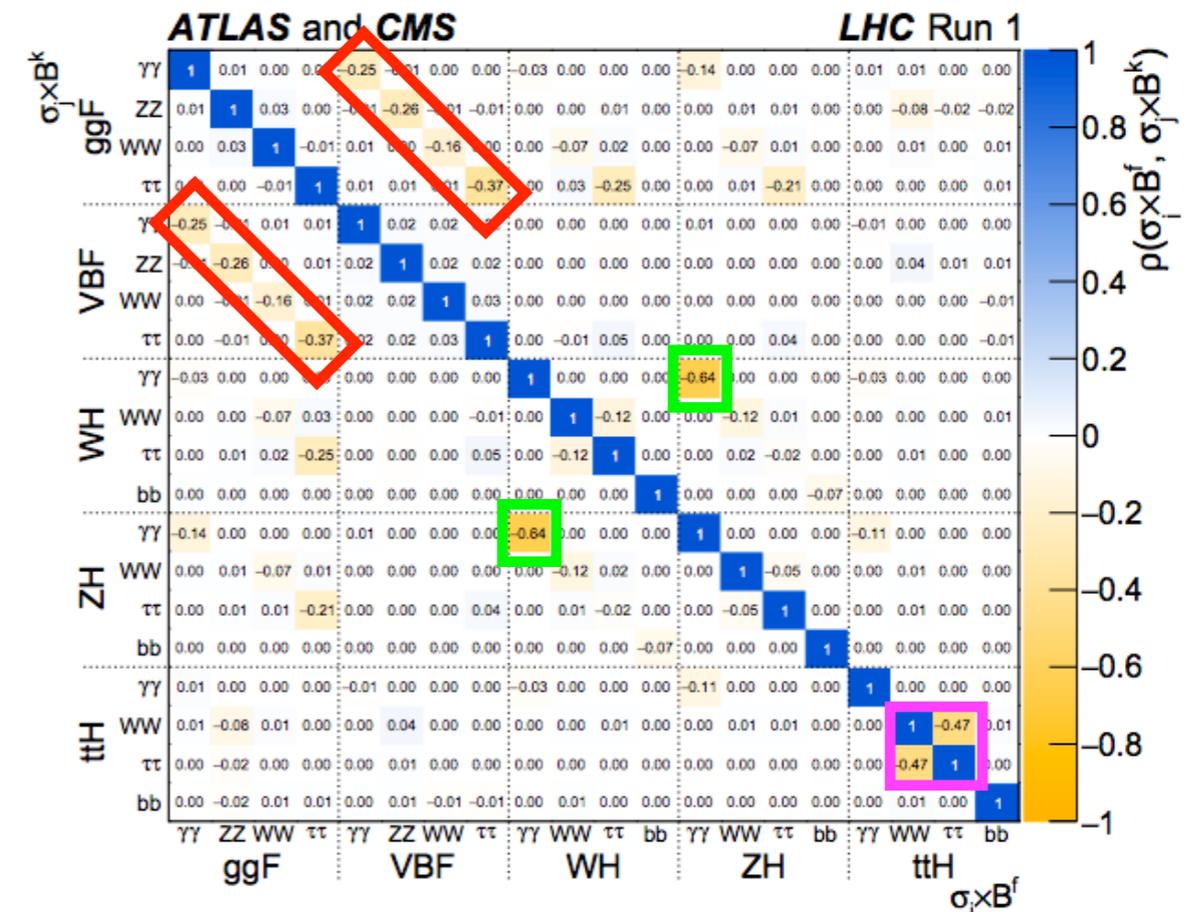
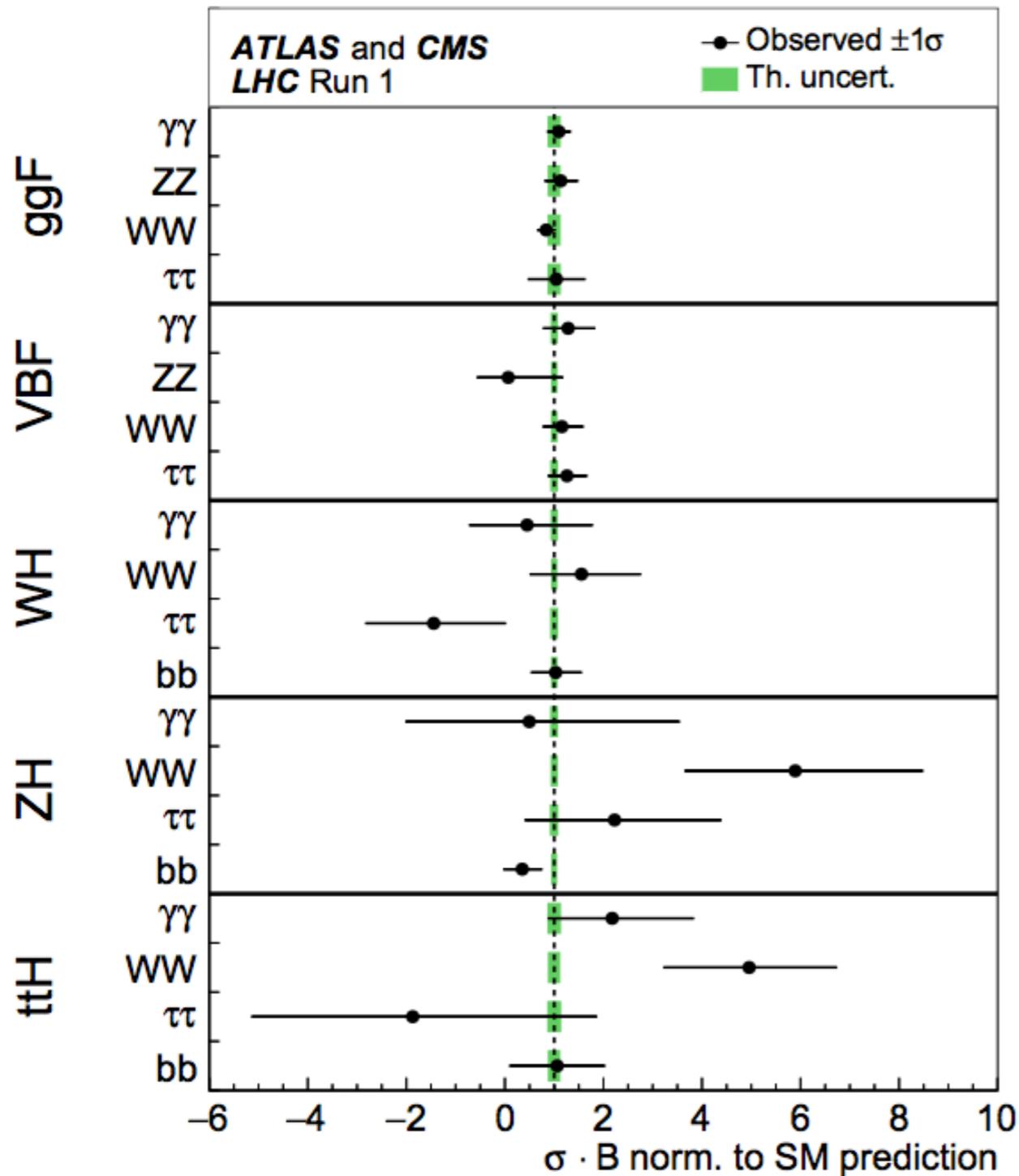
From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k) also based on multi variate techniques**
- **Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot A_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot B^f \right\}$$

- **What to measure?**
- **To reduce as much as possible the assumptions on the SM nature of the Higgs boson, we can measure $\sigma_i B^f$.
SM assumption only on A ε and $\sigma_i(7\text{TeV})/\sigma_i(8\text{TeV})$**

Cross Sections times Branching Ratios



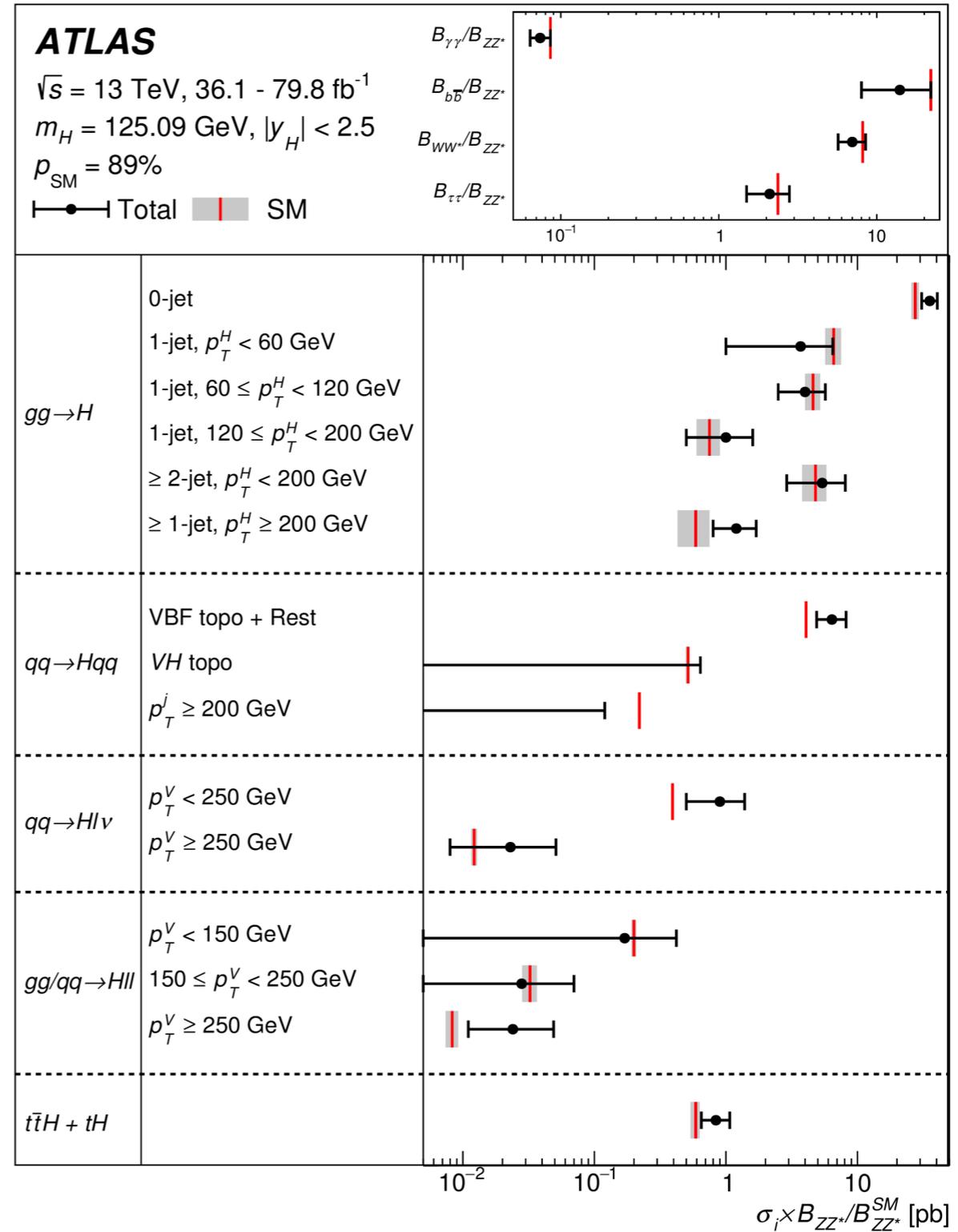
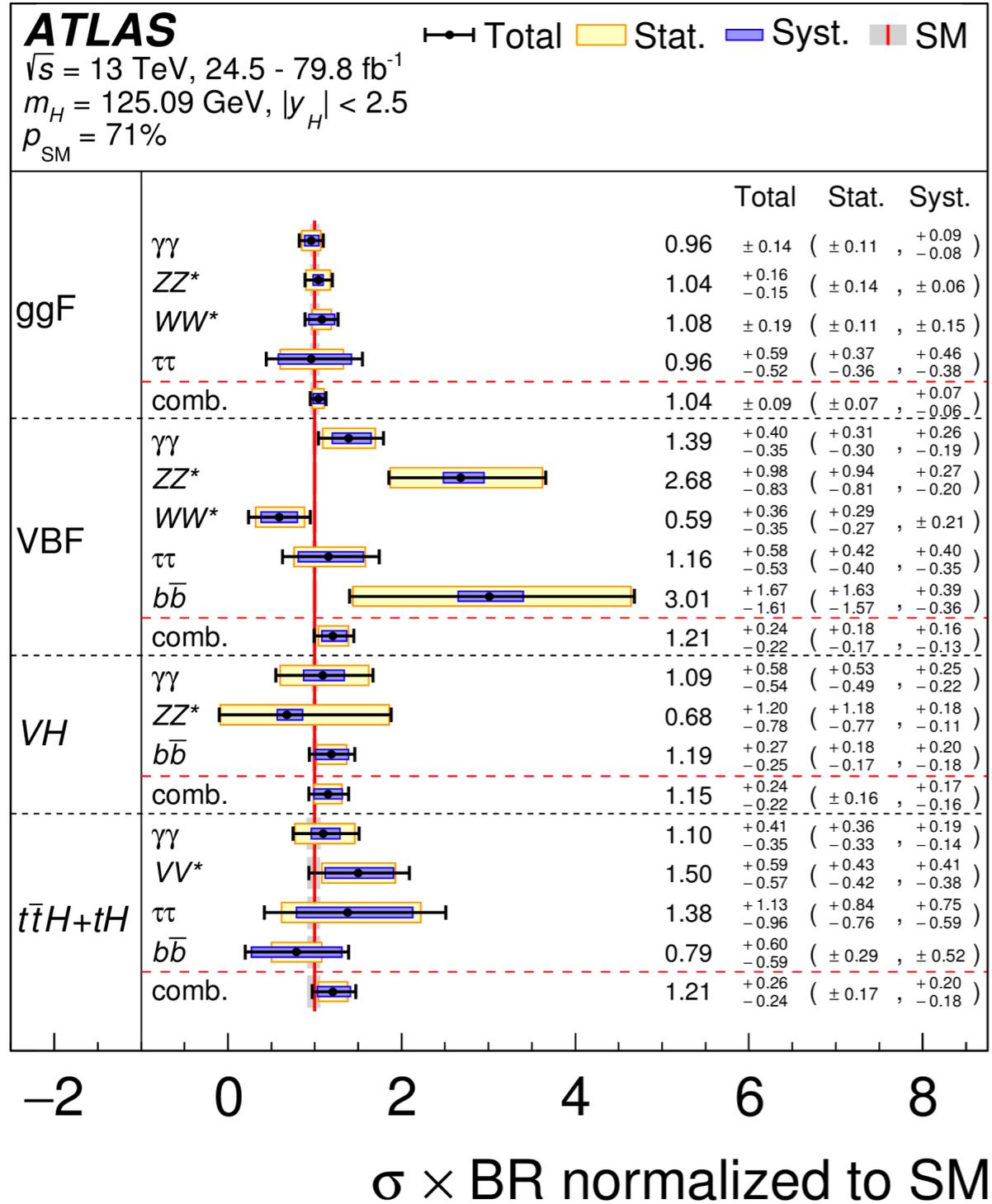
• As expected, correlations due to signal **mix** of **production modes** in the analysis categories:

- ggF VS VBF (in 2-jet selections)
- or WH VS ZH ($V \rightarrow \text{hadrons}$) in $H \rightarrow \gamma\gamma$;

and **decay modes**:

- $\tau\tau$ VS WW in ttH (in multileptons)

Cross Sections times Branching Ratios - STXS



$$\sigma_i \cdot \mathbf{B}^f = \frac{\sigma_i(\vec{k}) \cdot \Gamma^f(\vec{k})}{\Gamma_H}$$

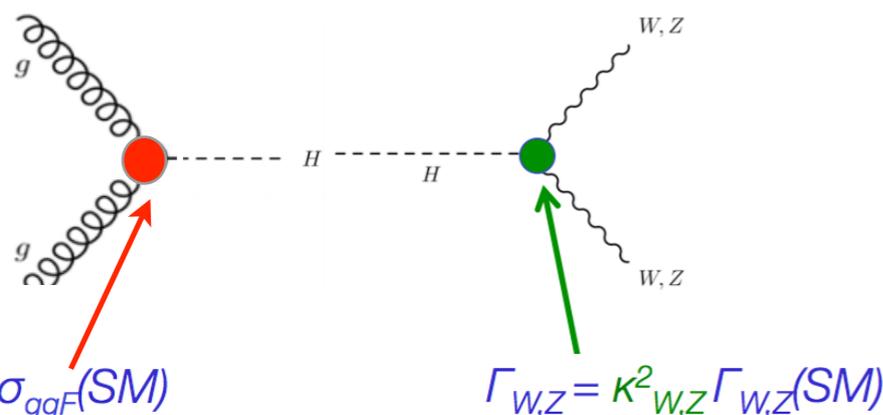
$$\kappa_j^2 = \sigma_j / \sigma_j^{\text{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma_{\text{SM}}^j$$

Coupling modifiers

- σ^{SM}_j and Γ_{SM}^j are calculated using the status of art theoretical SM predictions
- Higgs vertexes scales by a factor k
 - Recover the SM if $k=1$

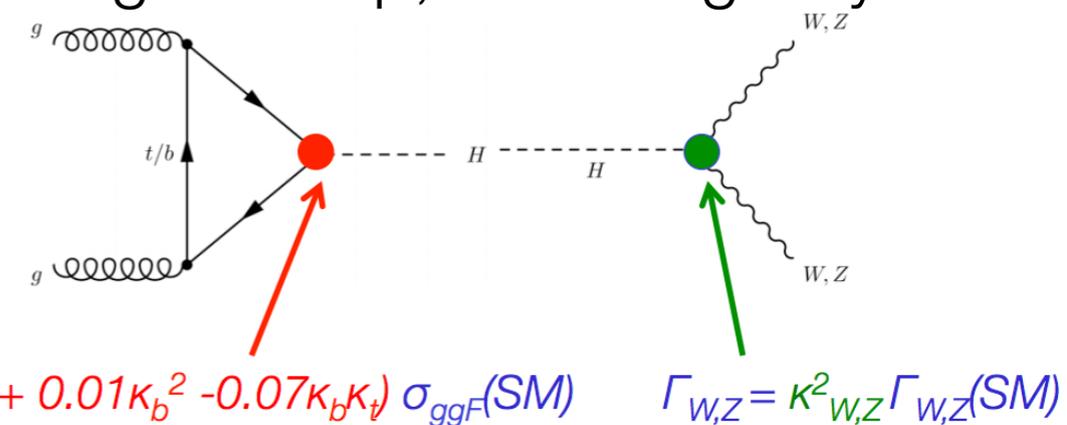
Example: $ggF \rightarrow H \rightarrow WW$ (or ZZ)

Effective κ



Resolving the loop, assuming only SM

or



- and Γ_H ?

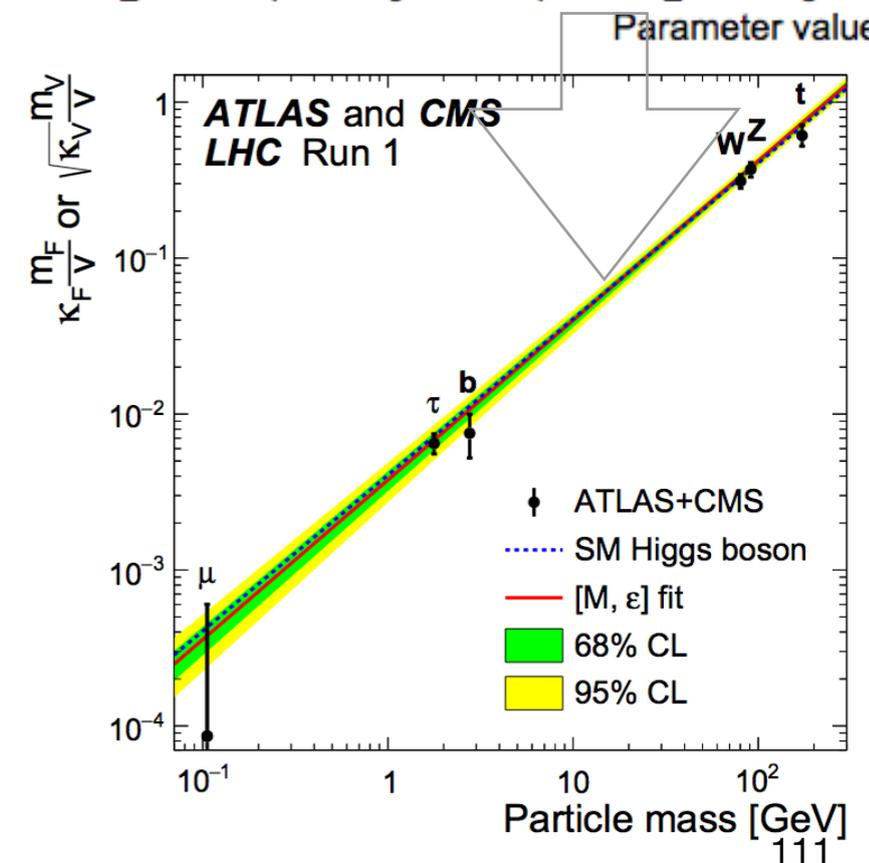
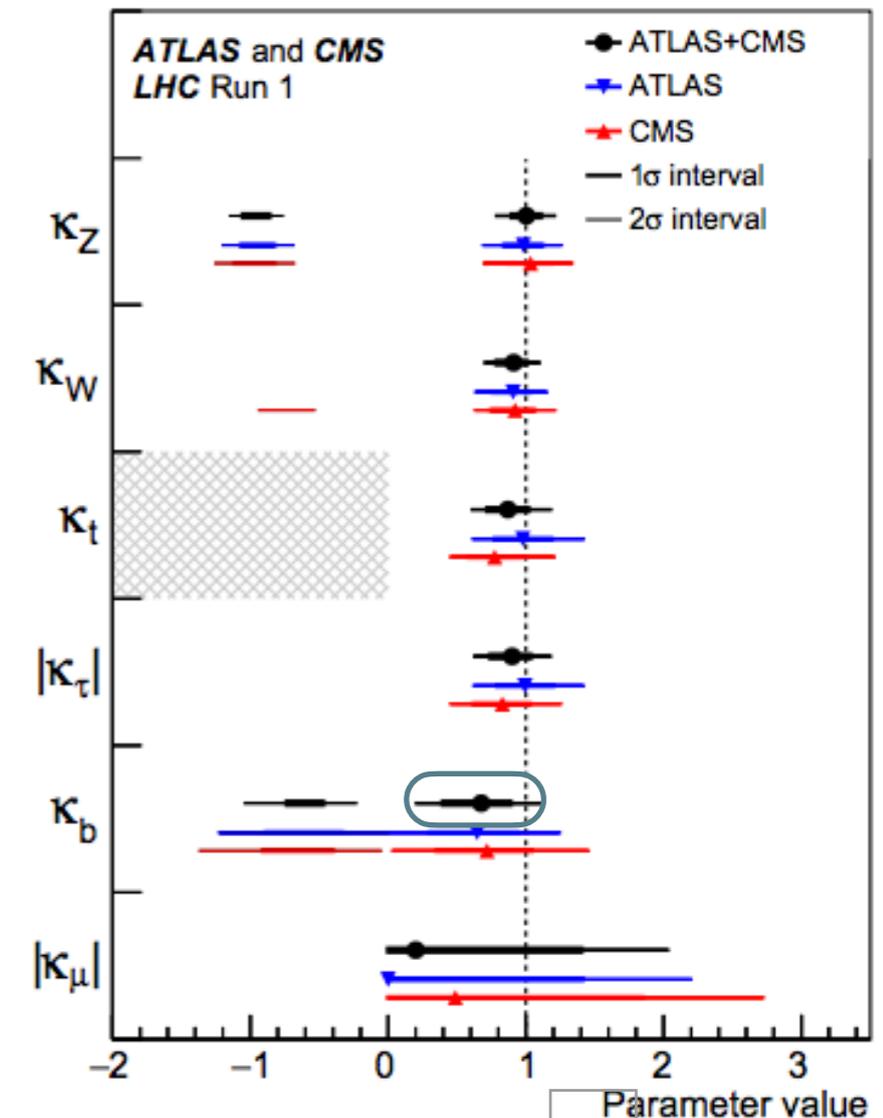
- Option 1: assume only SM decay modes $\Gamma_H = \sum_j \mathbf{B}_{\text{SM}}^j \kappa_j^2 \cdot \Gamma_H^{\text{SM}}$

- Option 2: allow for an additional branching fractions in BSM $\Gamma_H = \frac{\sum_j \mathbf{B}_{\text{SM}}^j \kappa_j^2 \cdot \Gamma_H^{\text{SM}}}{1 - \mathbf{B}_{\text{BSM}}}$

Resolving the loops and assuming coupling with only SM particles

- **Interferences** help to resolve the sign (*NB*: κ_τ and κ_μ)
- *NB*: in this fit model, low measured value of **κ_b** reduces total width $\Gamma_H \Rightarrow$ all κ_i measured low

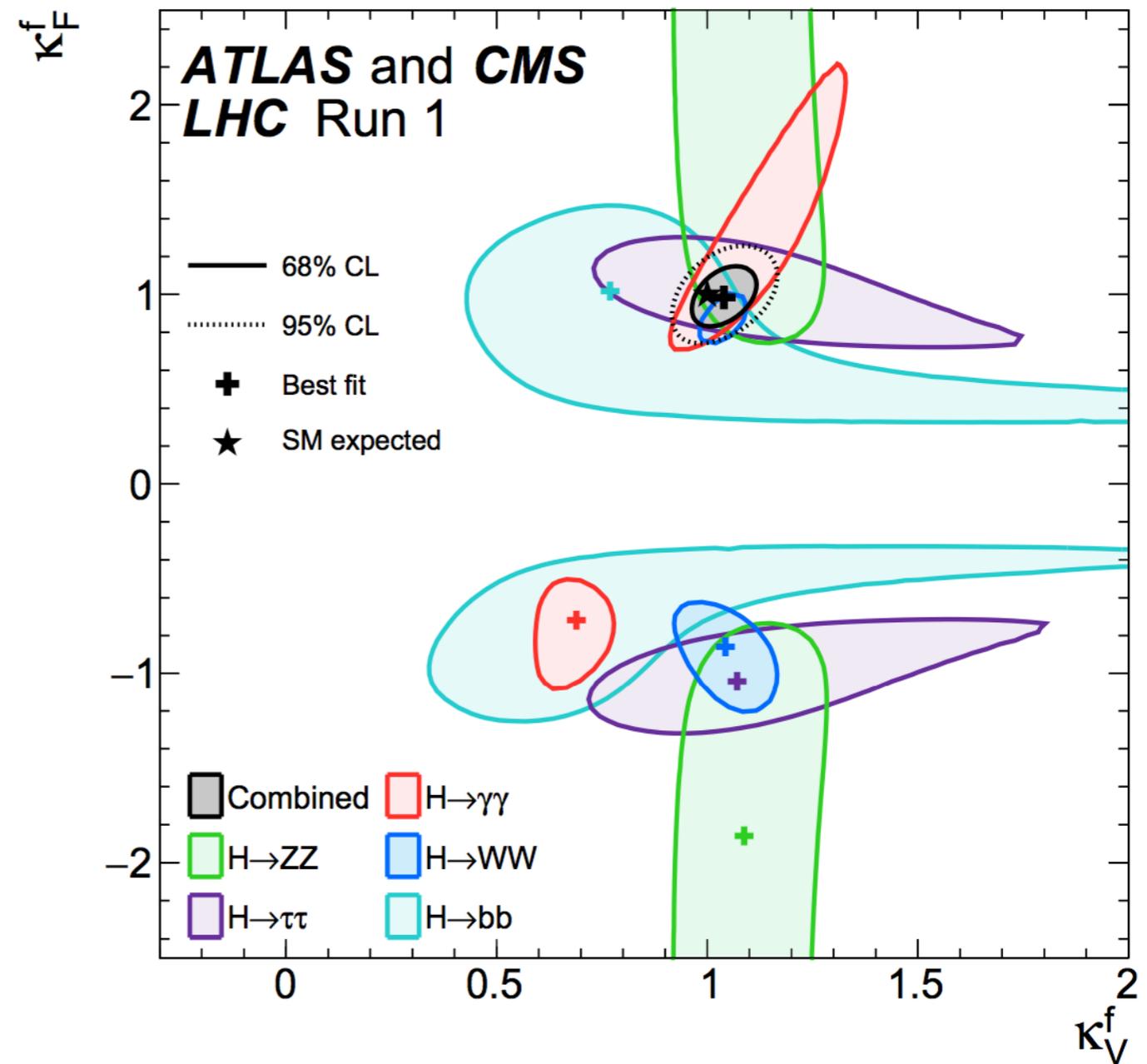
Production	Loops	Interference	Resolved scaling factor
$\sigma(ggF)$	✓	$t-b$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	κ_W^2
$\sigma(qq/qg \rightarrow ZH)$	-	-	κ_Z^2
$\sigma(gg \rightarrow ZH)$	✓	$t-Z$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	-	-	κ_t^2
$\sigma(gb \rightarrow tHW)$	-	$t-W$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \rightarrow tHq)$	-	$t-W$	$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	-	-	κ_b^2
Partial decay width			
Γ^{ZZ}	-	-	κ_Z^2
Γ^{WW}	-	-	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$t-W$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	-	-	κ_τ^2
Γ^{bb}	-	-	κ_b^2
$\Gamma^{\mu\mu}$	-	-	κ_μ^2
Total width ($B_{BSM} = 0$)			
Γ_H	✓	-	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



Fermions and bosons

- Testing the intrinsic difference between couplings to
 - W/Z: EW Symmetry Breaking
 $\kappa_Z = \kappa_W = \kappa_V$
 - fermions: Yukawa couplings
 $\kappa_t = \kappa_\tau = \kappa_b = \kappa_F$
- Sensitivity to the relative sign between κ_V and κ_F through interference terms
- Large asymmetry between the positive and negative coupling ratios for $H \rightarrow \gamma\gamma$

$$\Gamma^{\gamma\gamma}_{t-W} = 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$



- Fits on individual channels have slight preference for negative κ_F
- Combined result converges to positive κ_F

Fermions and bosons

- Testing the intrinsic difference between couplings to

- W/Z: EW Symmetry Breaking

$$K_Z = K_W = K_V$$

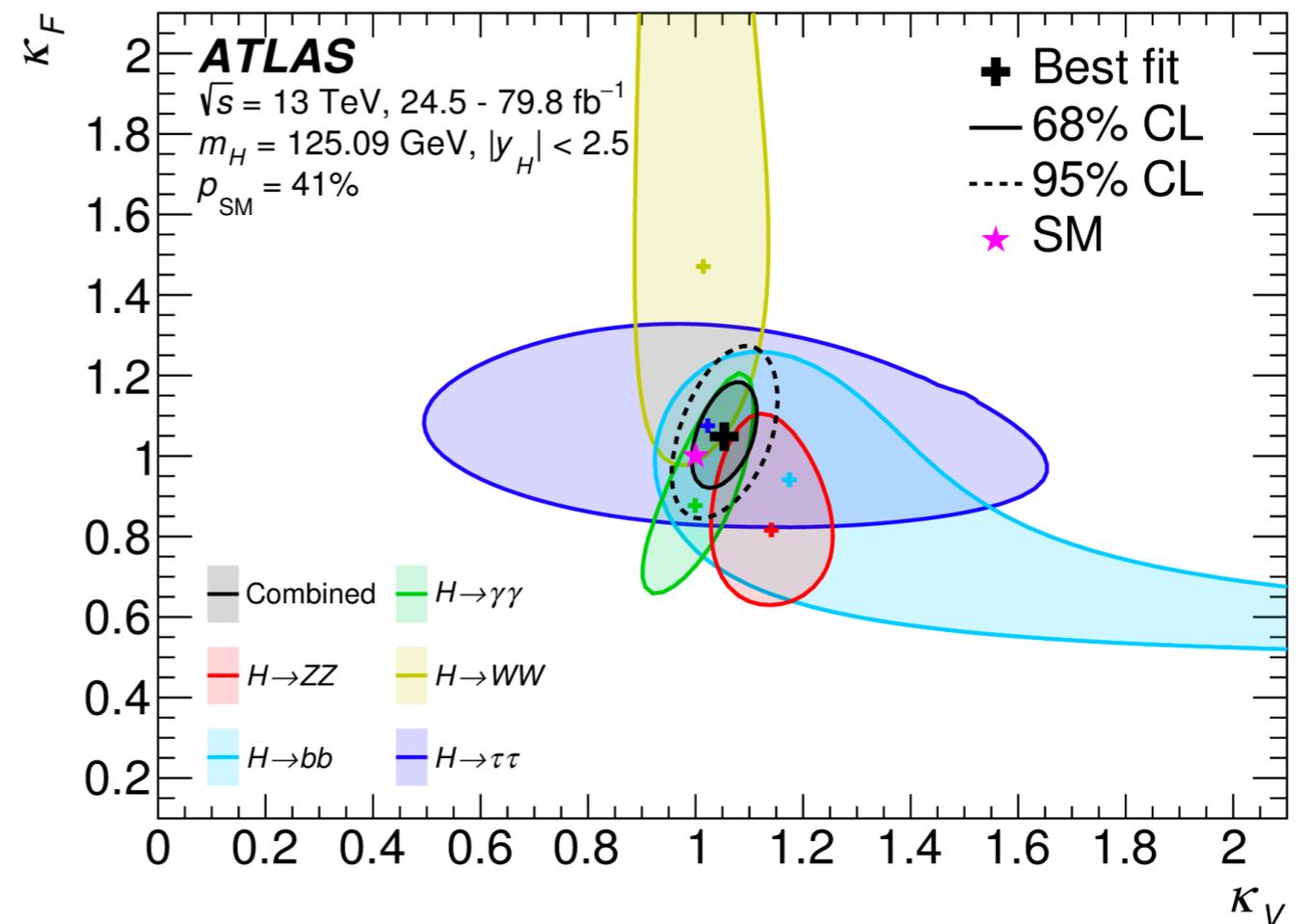
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Higgs Properties

- Higgs Mass
- Higgs production XS times BR and STXS
- Higgs couplings

Two quarks for Muster Higgs

Since the big discovery of 2012, the Large Hadron Collider at CERN has been accumulating data and making steady progress. Two recent results establish the origins of the mass of the two heaviest quarks



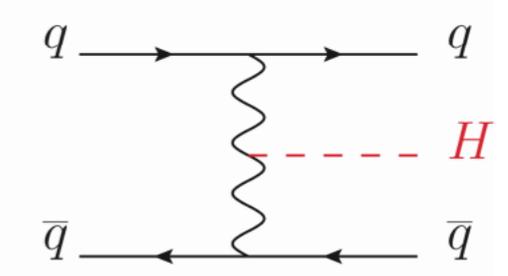
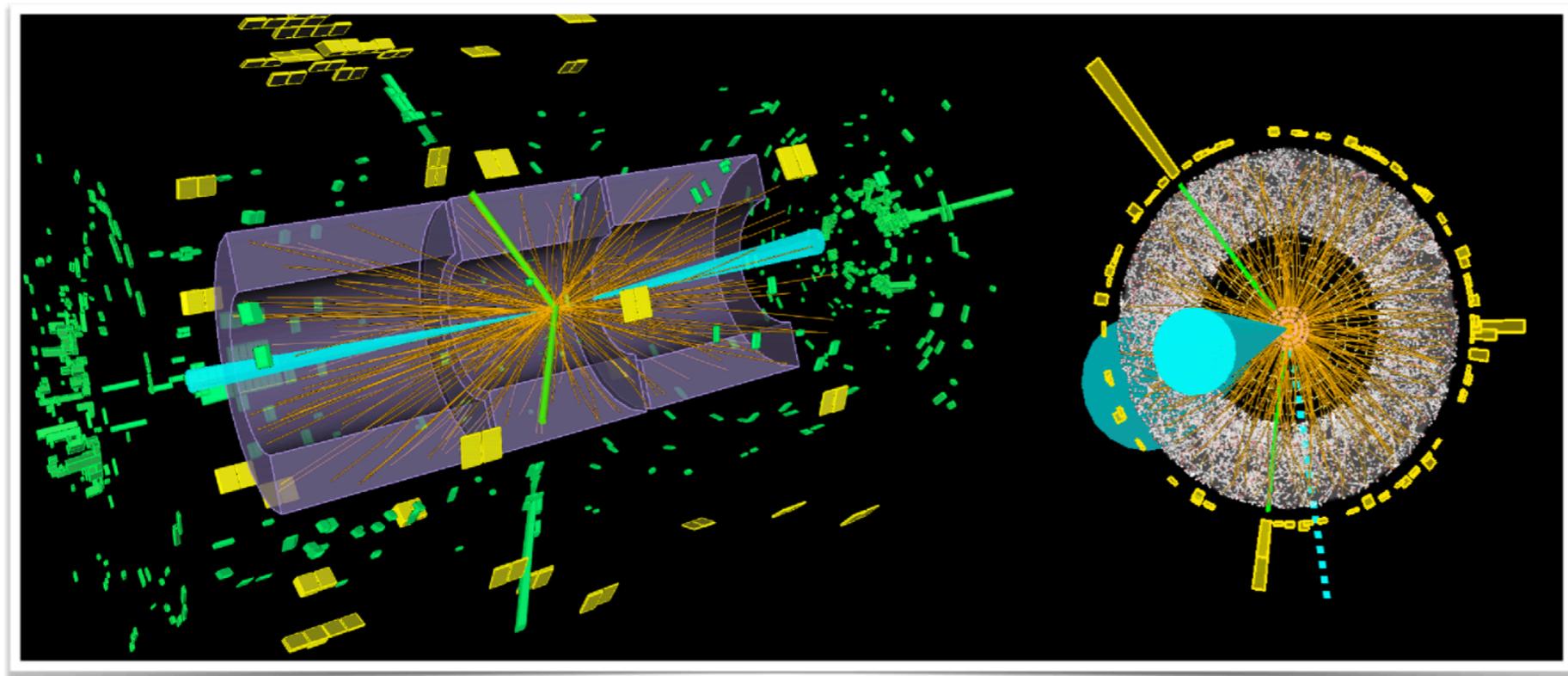
Selected news from Run2

▲ The visitor centre at the ALICE experiment on the CERN Large Hadron Collider Photograph: Jon Butterworth

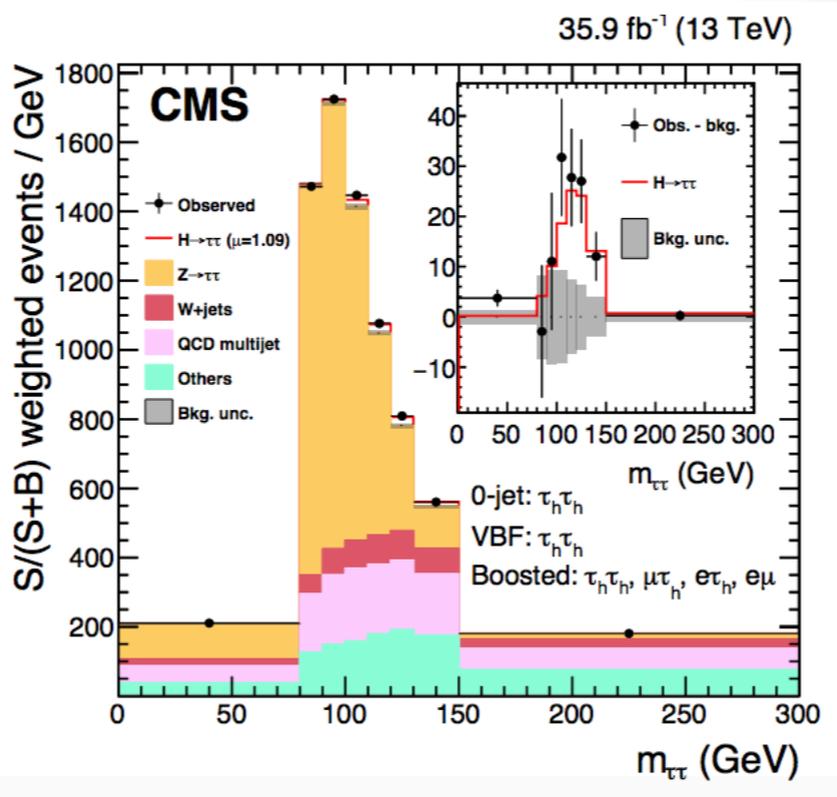
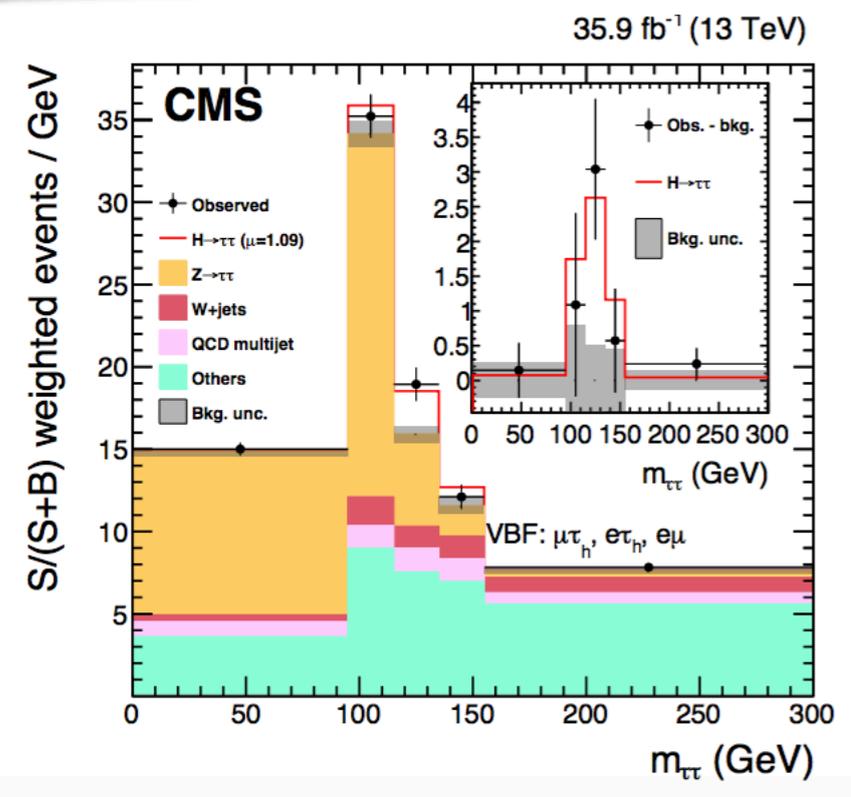
Observed!



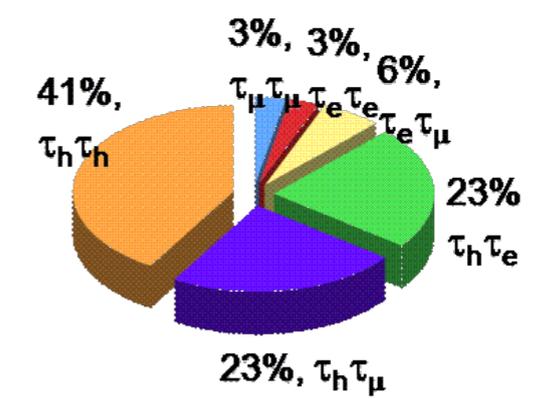
The Big news (1): τ -Higgs interaction



VBF
 With two forward jets and a large rapidity gap between the jets



Analysis based on several channels depending on the decay mode of the τ .

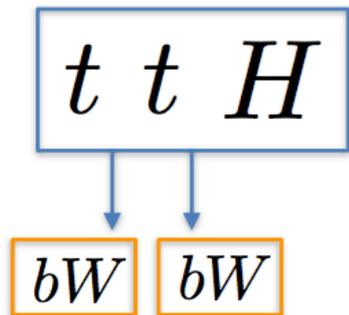


Background is Z production with two jets

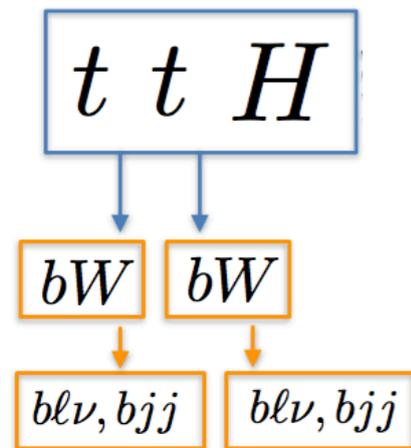
The Big news (2): Top -Higgs interaction

$$t \ t \ H$$

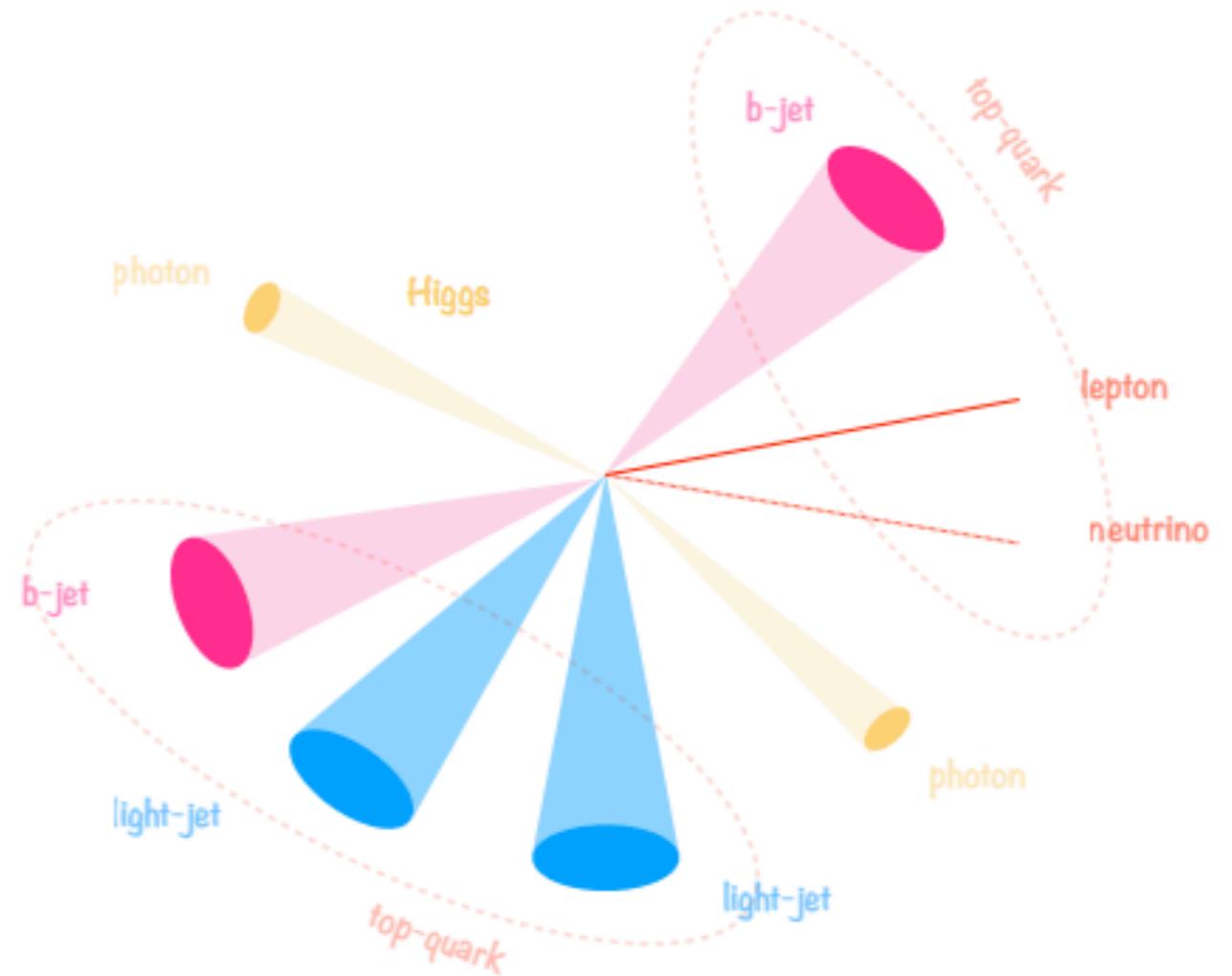
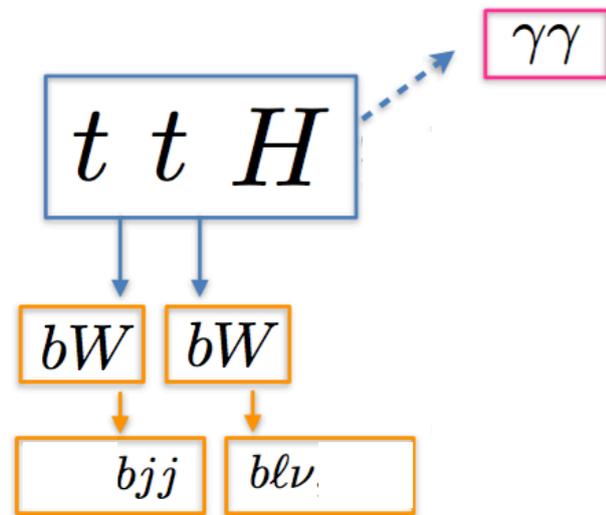
The Big news (2): Top -Higgs interaction



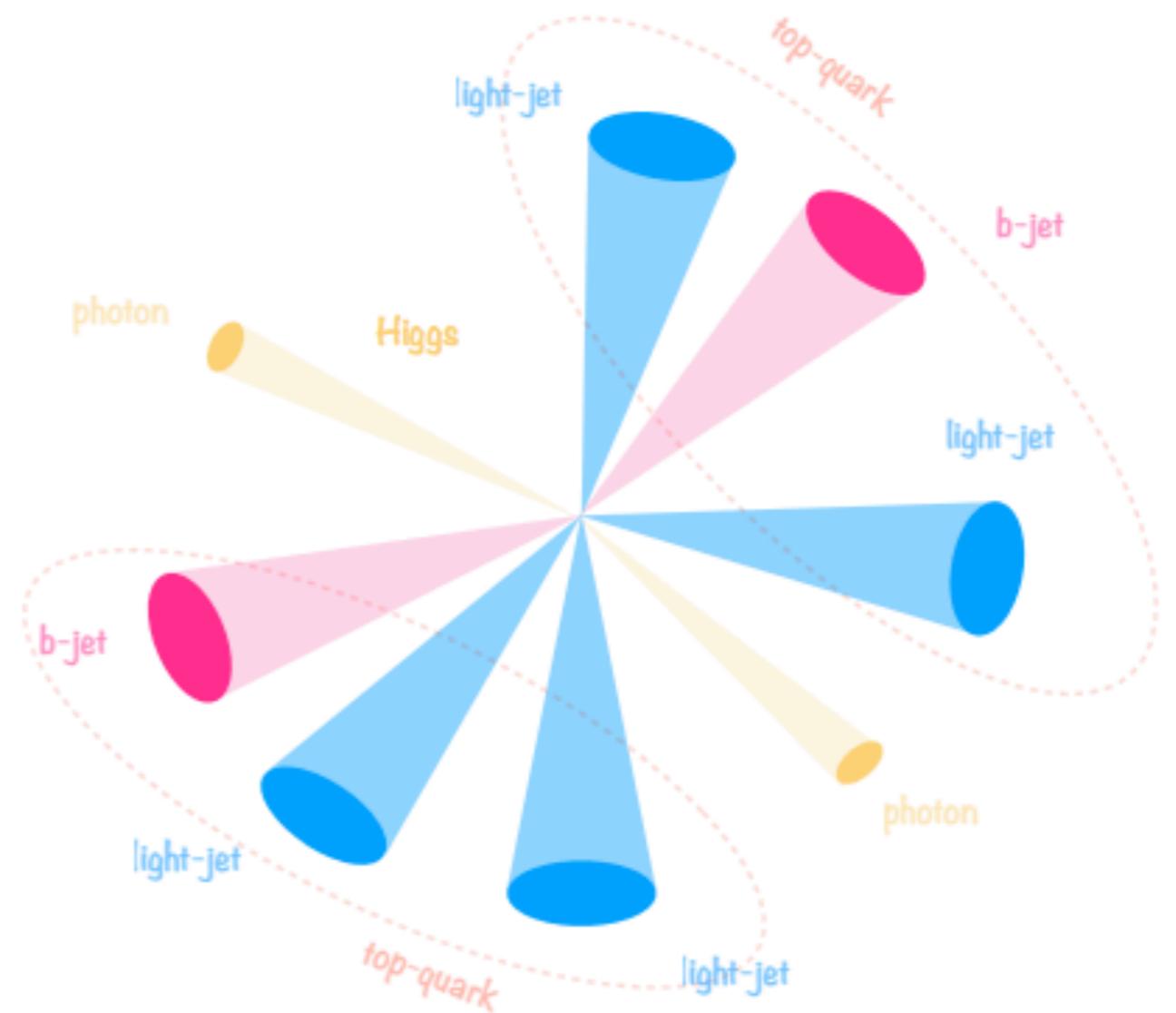
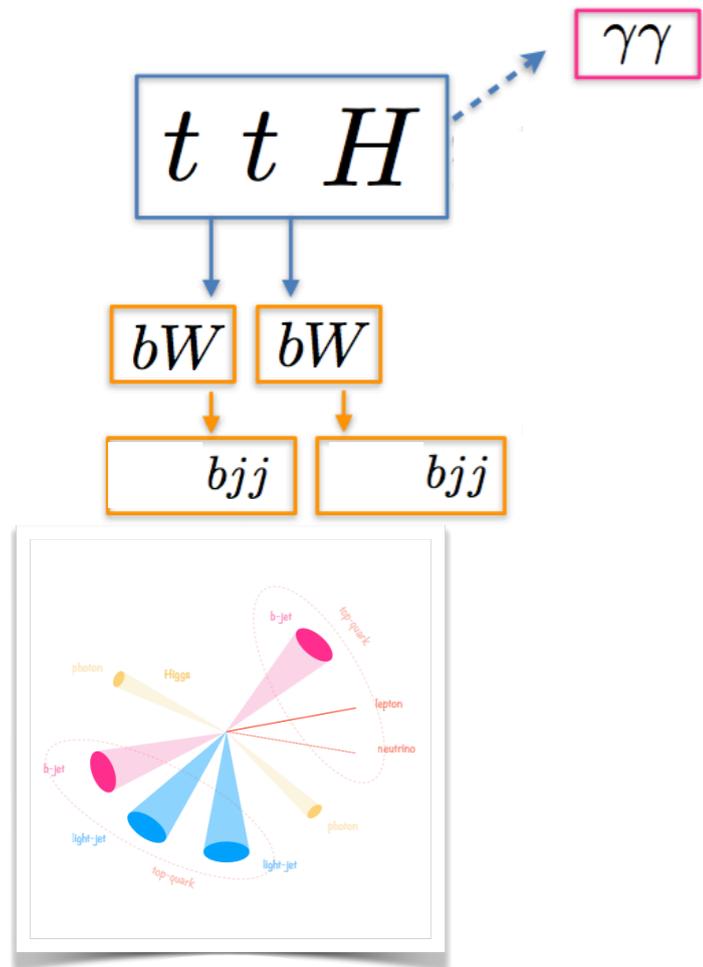
The Big news (2): Top -Higgs interaction



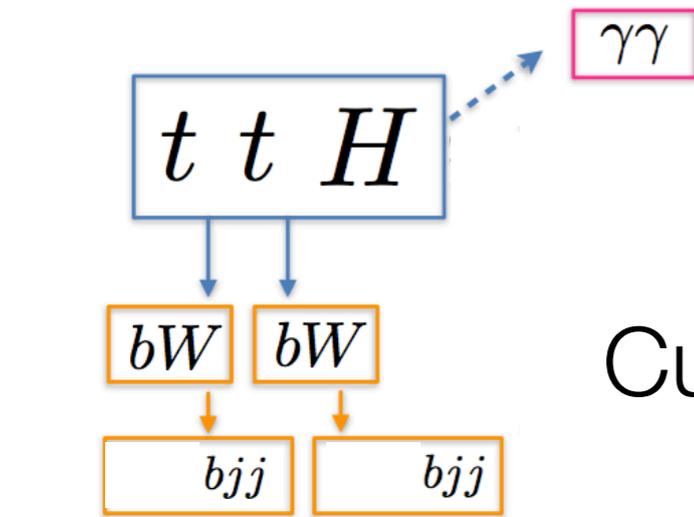
The Big news (2): Top -Higgs interaction



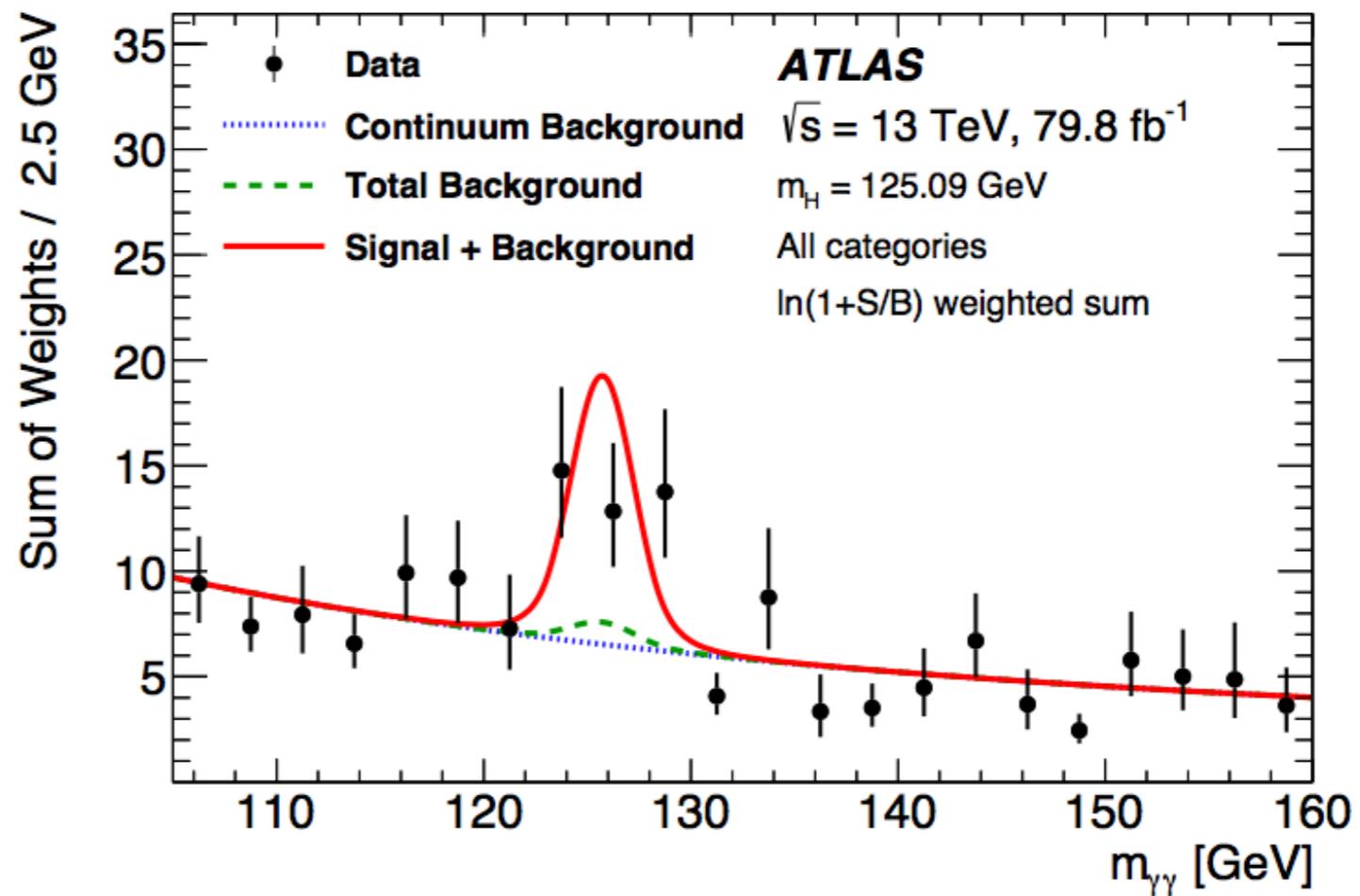
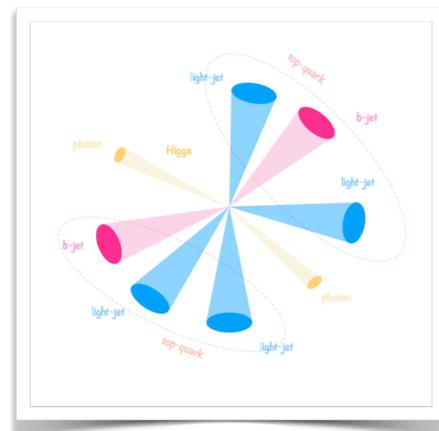
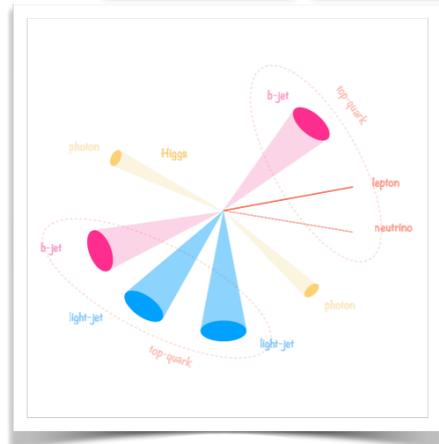
The Big news (2): Top -Higgs interaction



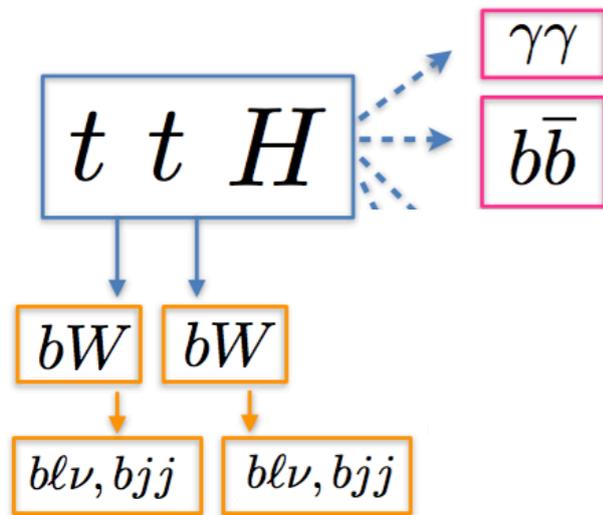
The Big news (2): Top -Higgs interaction



Currently cleanest and most sensitive channel

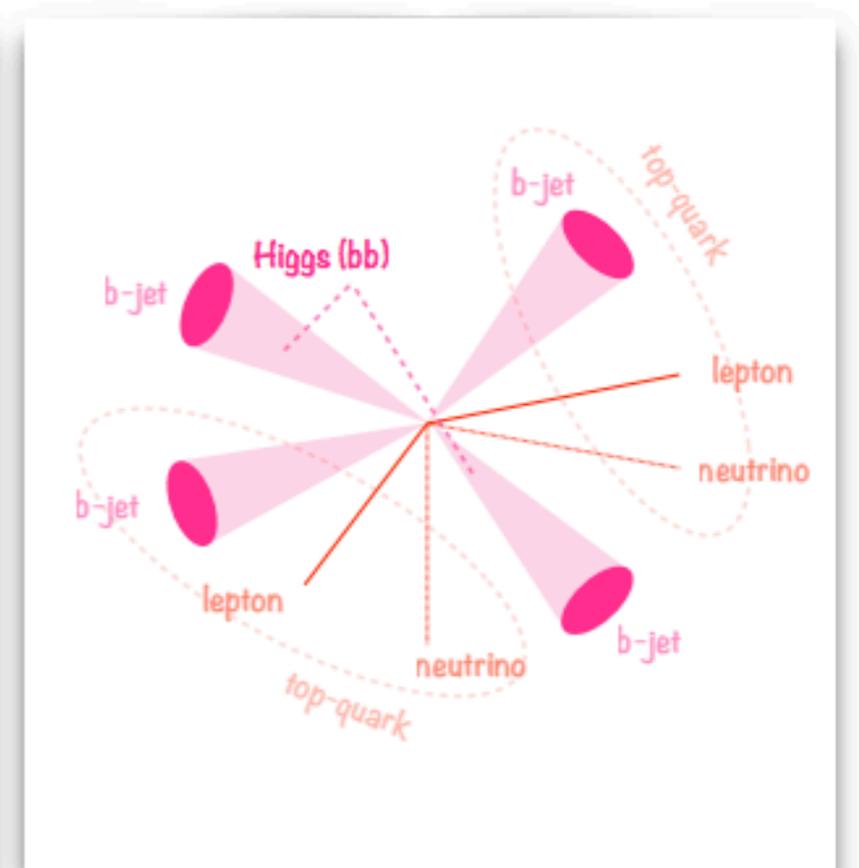
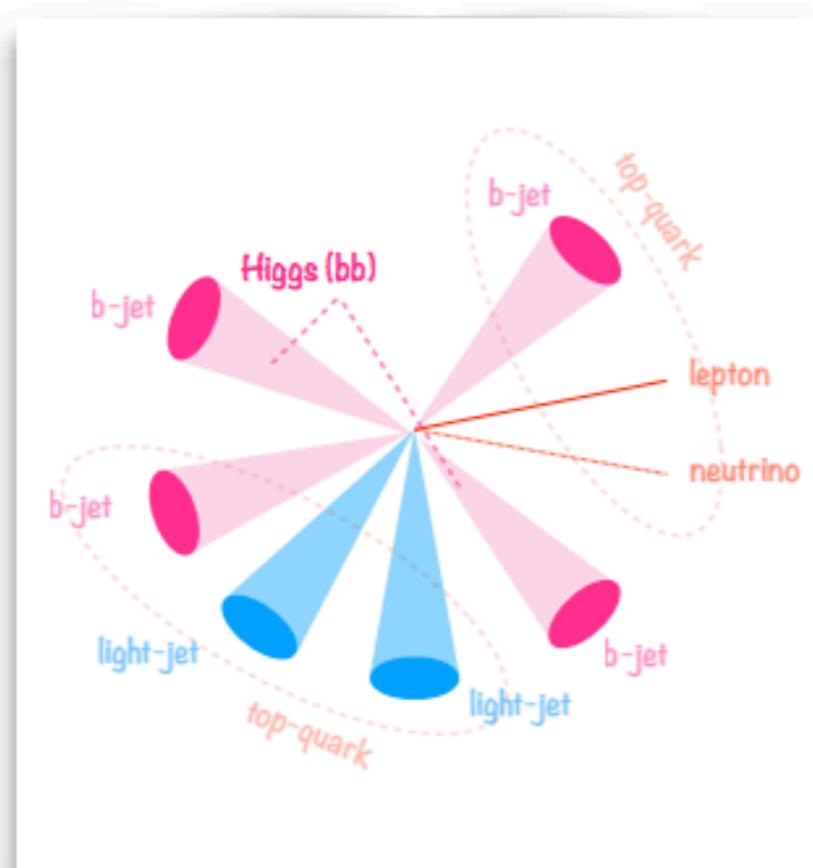
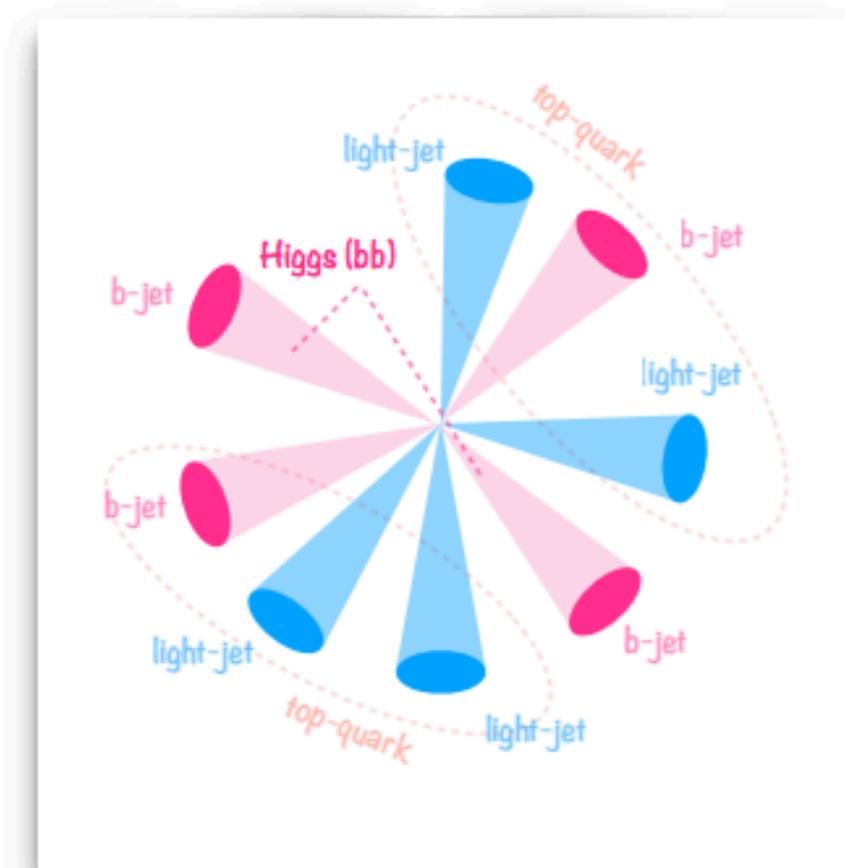


The Big news (2): Top -Higgs interaction

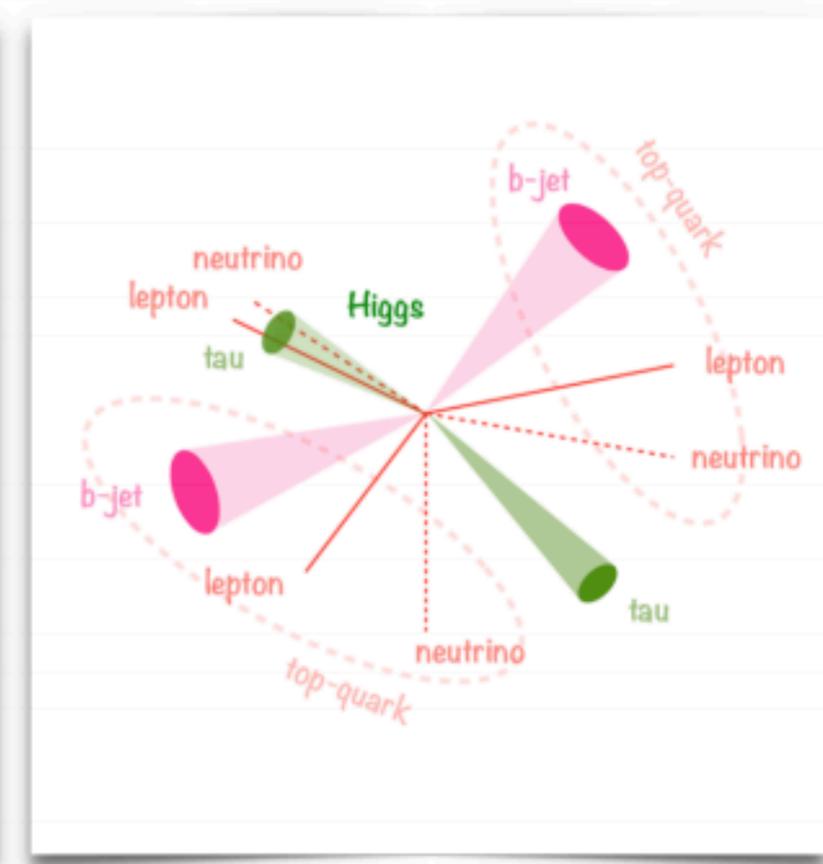
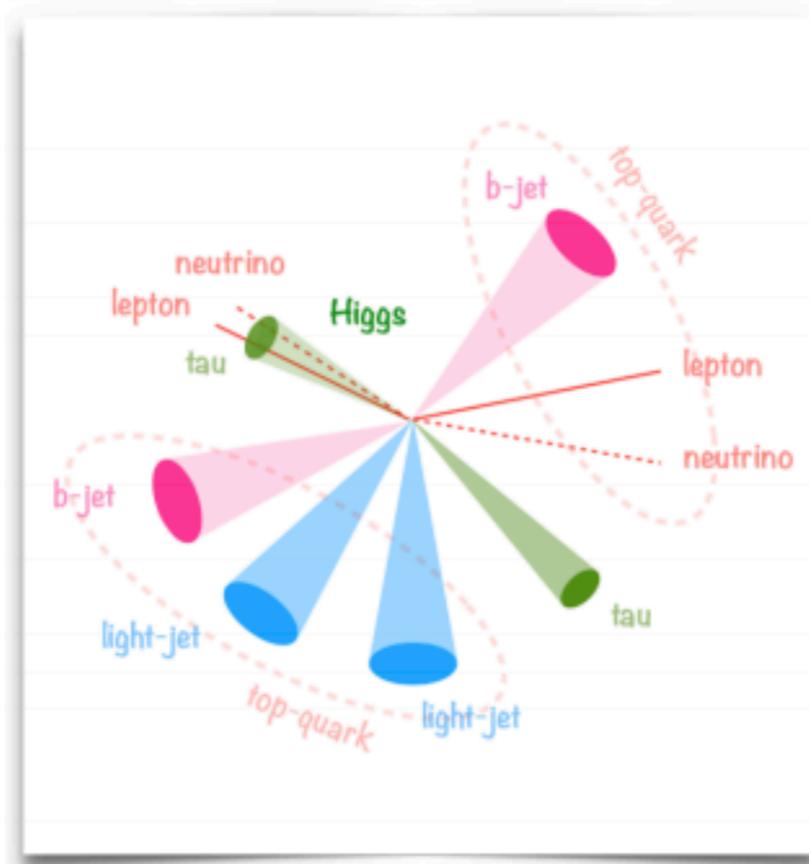
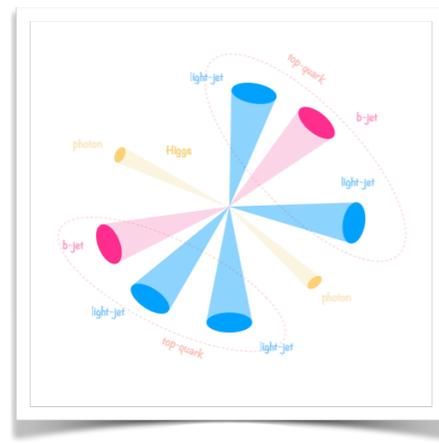
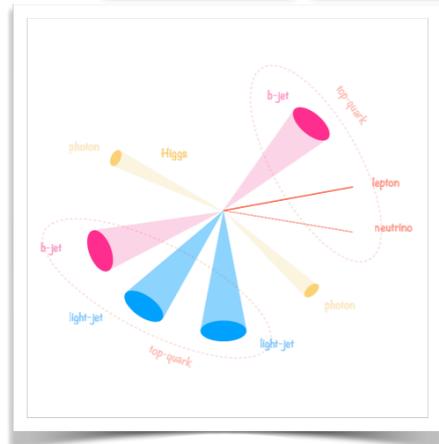
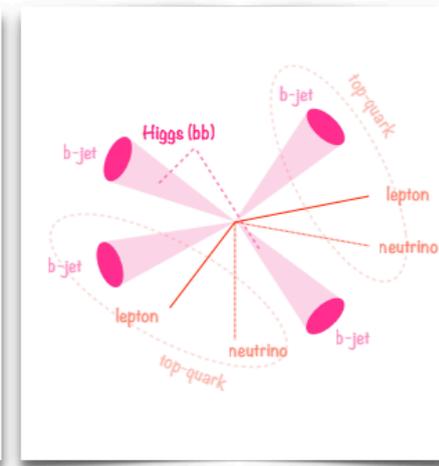
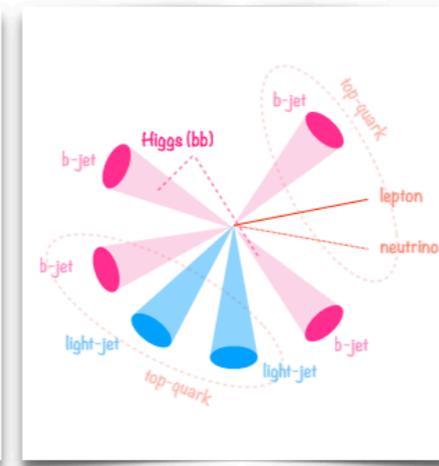
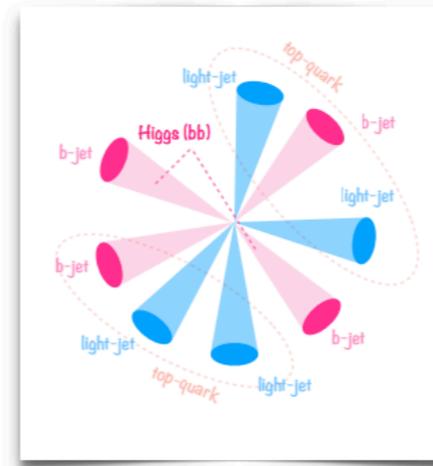
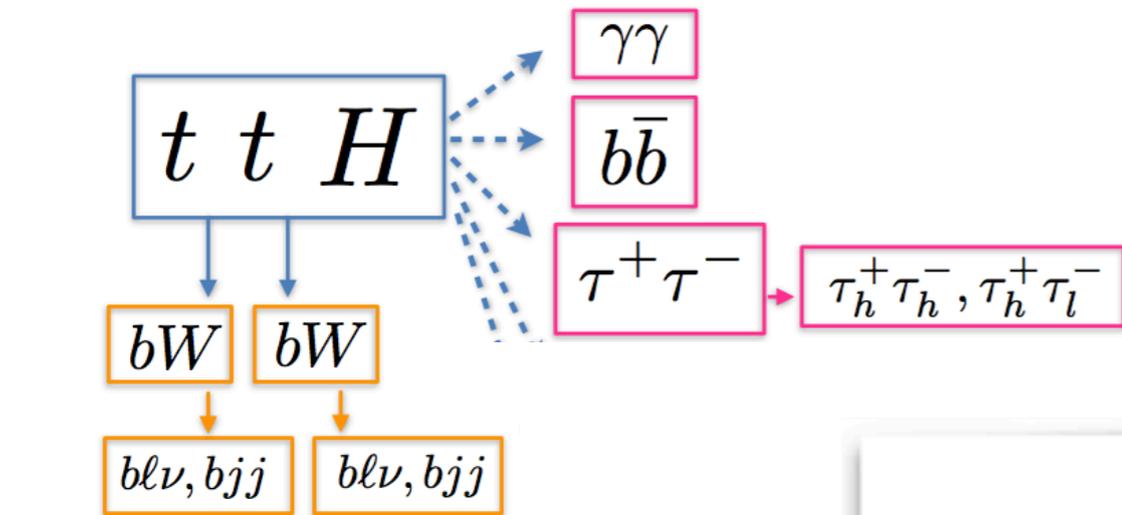


$ttH(bb)$

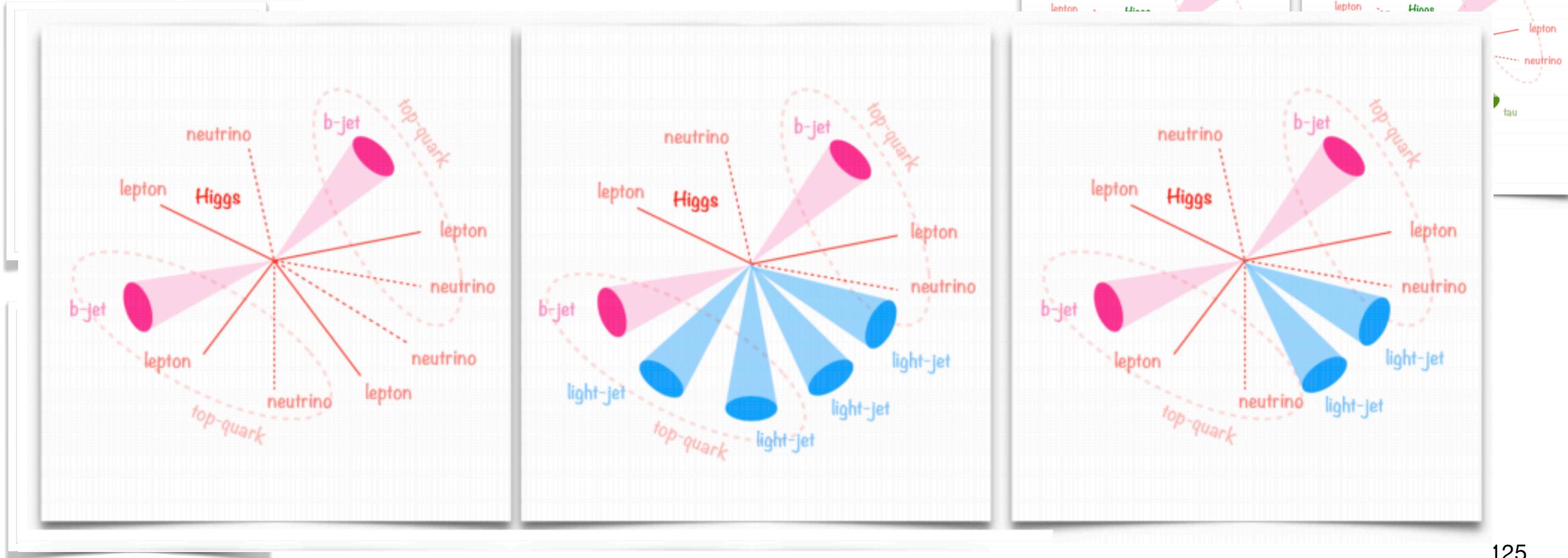
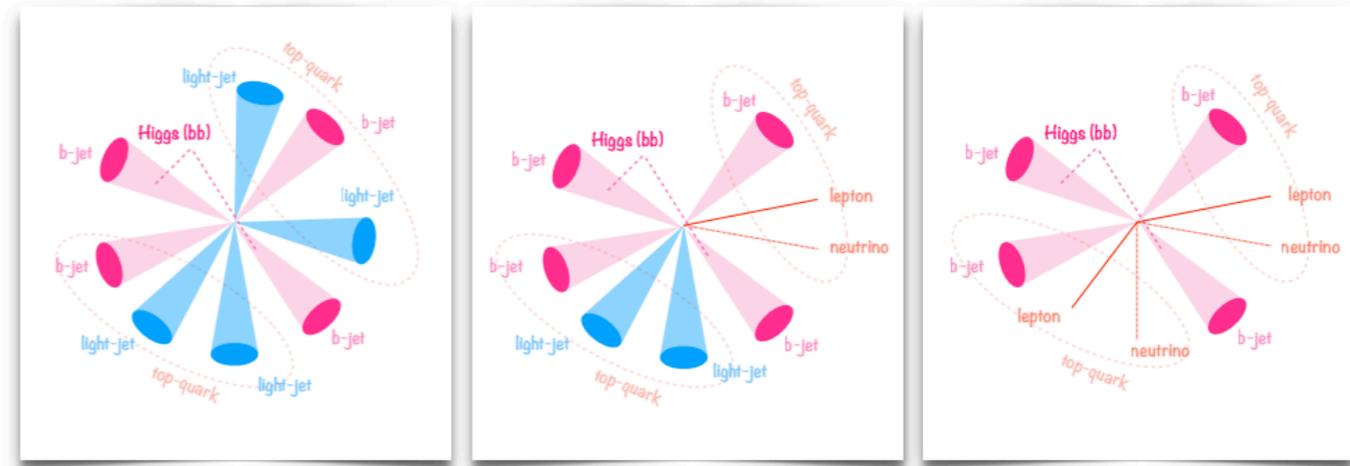
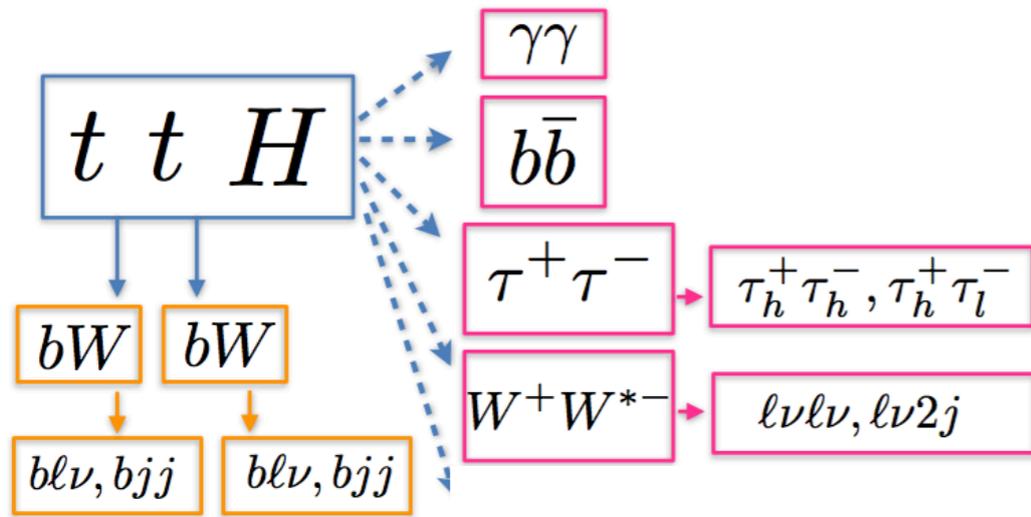
Very large backgrounds of top pair production associated with b jets



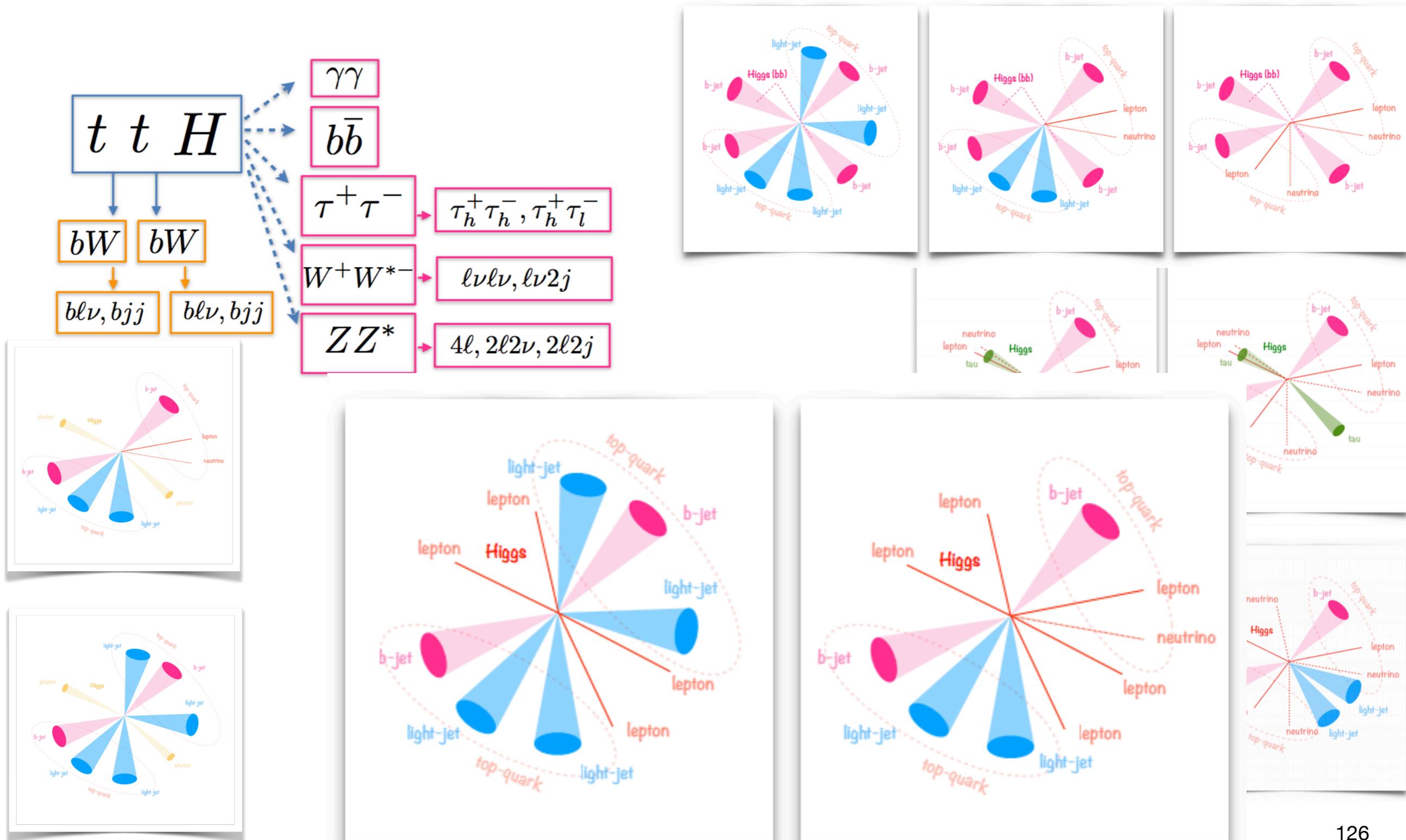
The Big news (2): Top -Higgs interaction



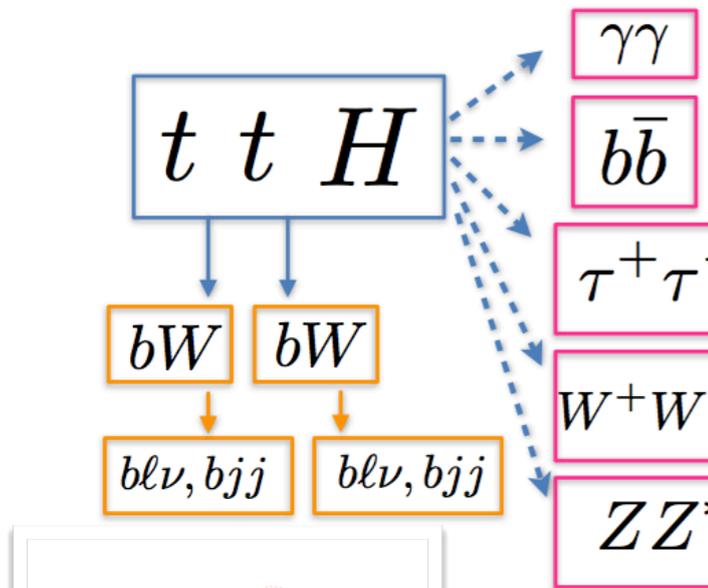
The Big news (2): Top -Higgs interaction



The Big news (2): Top -Higgs interaction

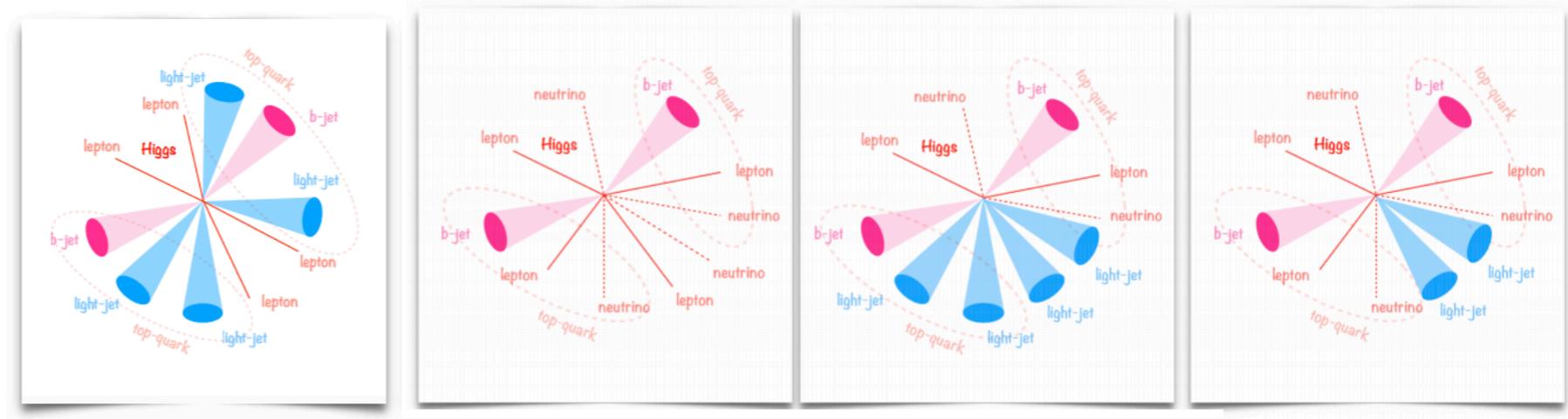
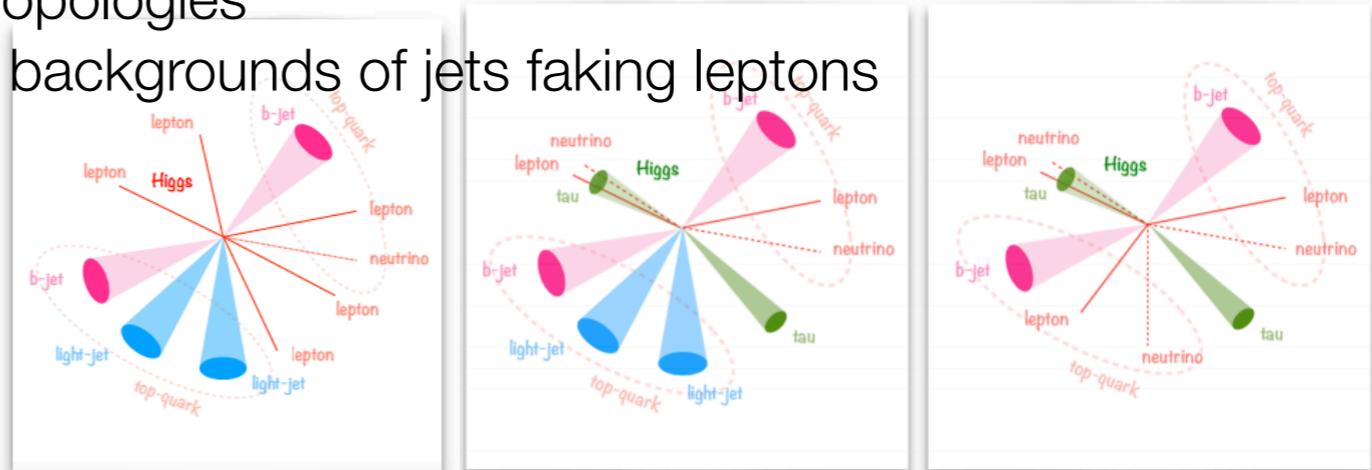
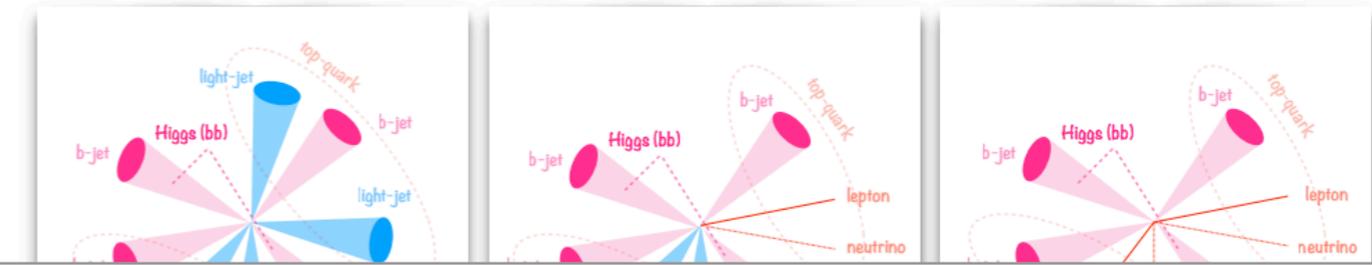
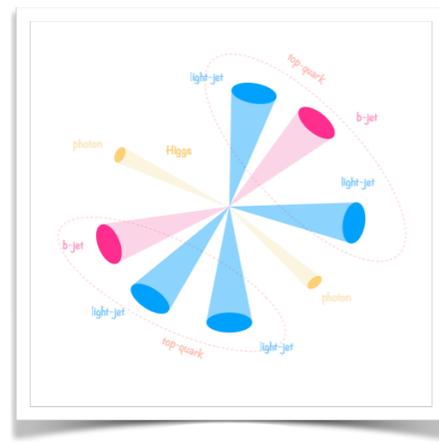
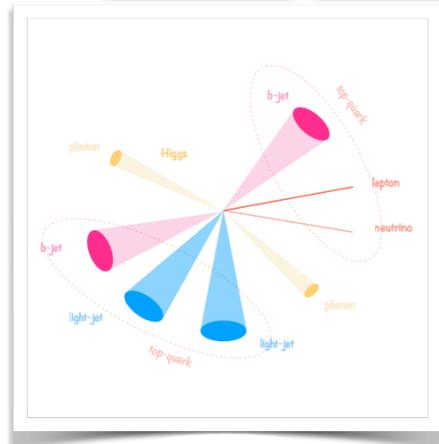


The Big news (2): Top -Higgs interaction



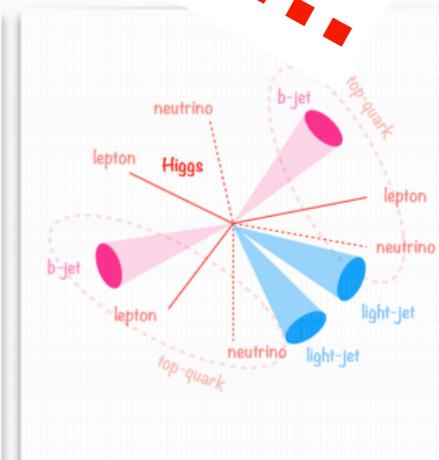
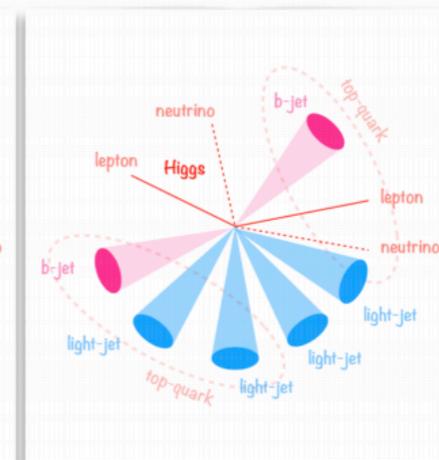
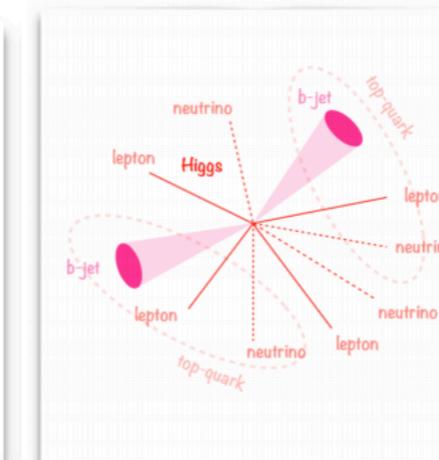
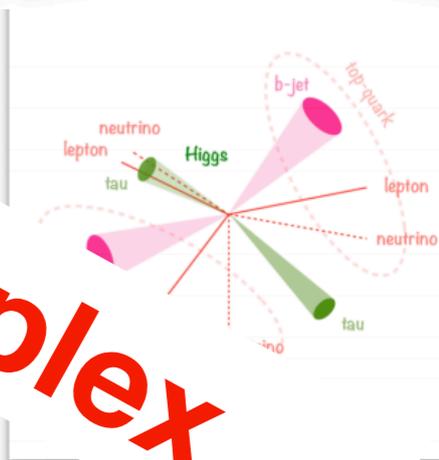
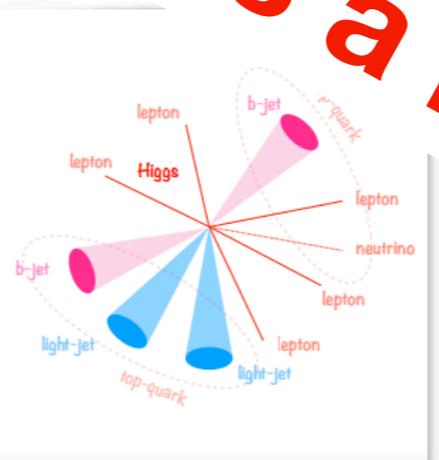
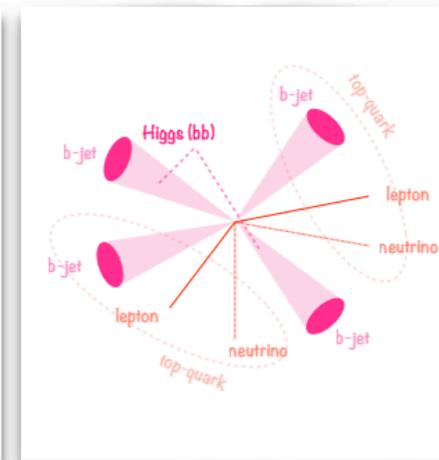
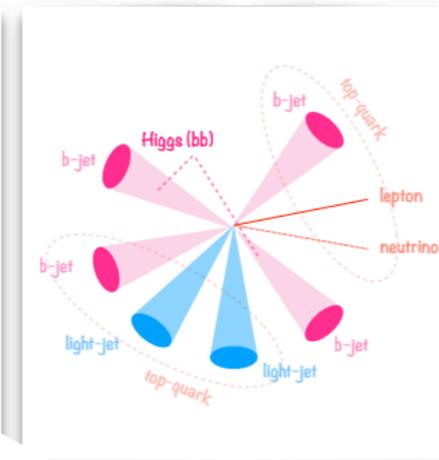
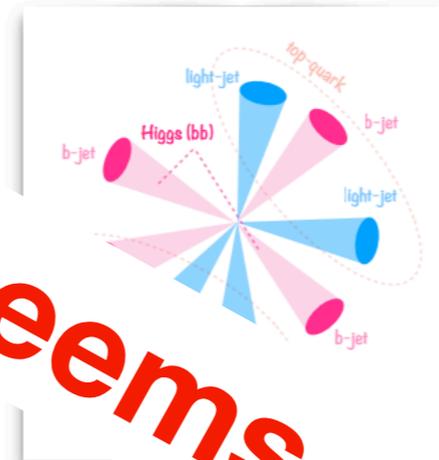
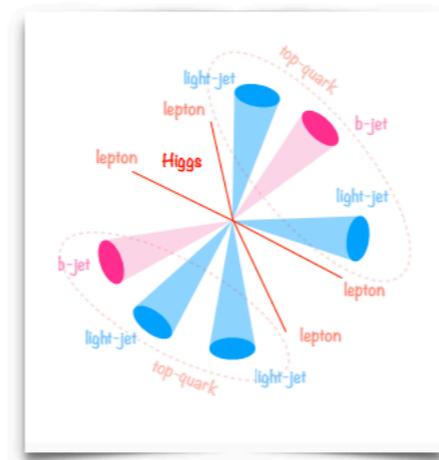
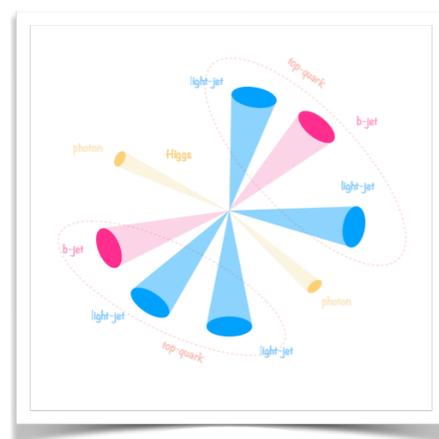
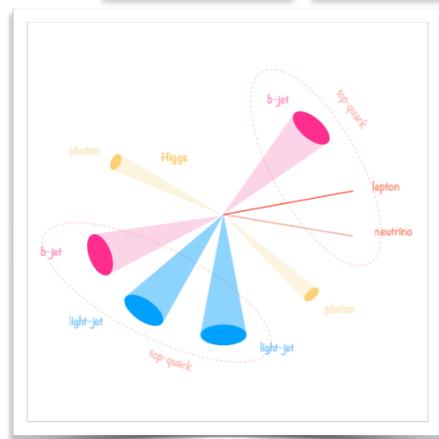
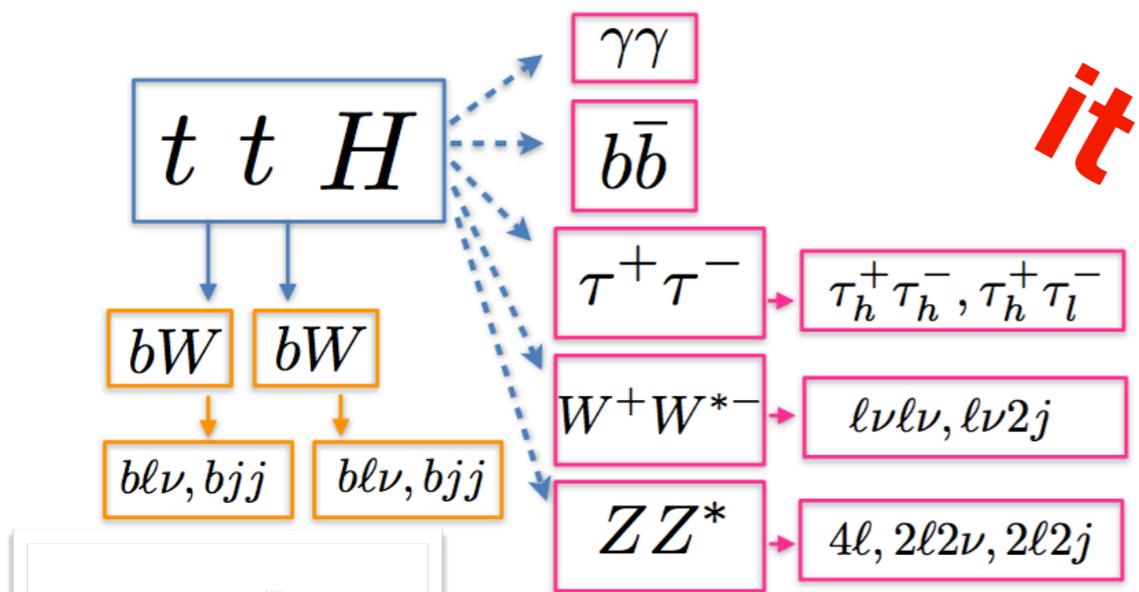
Multi lepton channel

Large number of topologies
intricate reducible backgrounds of jets faking leptons



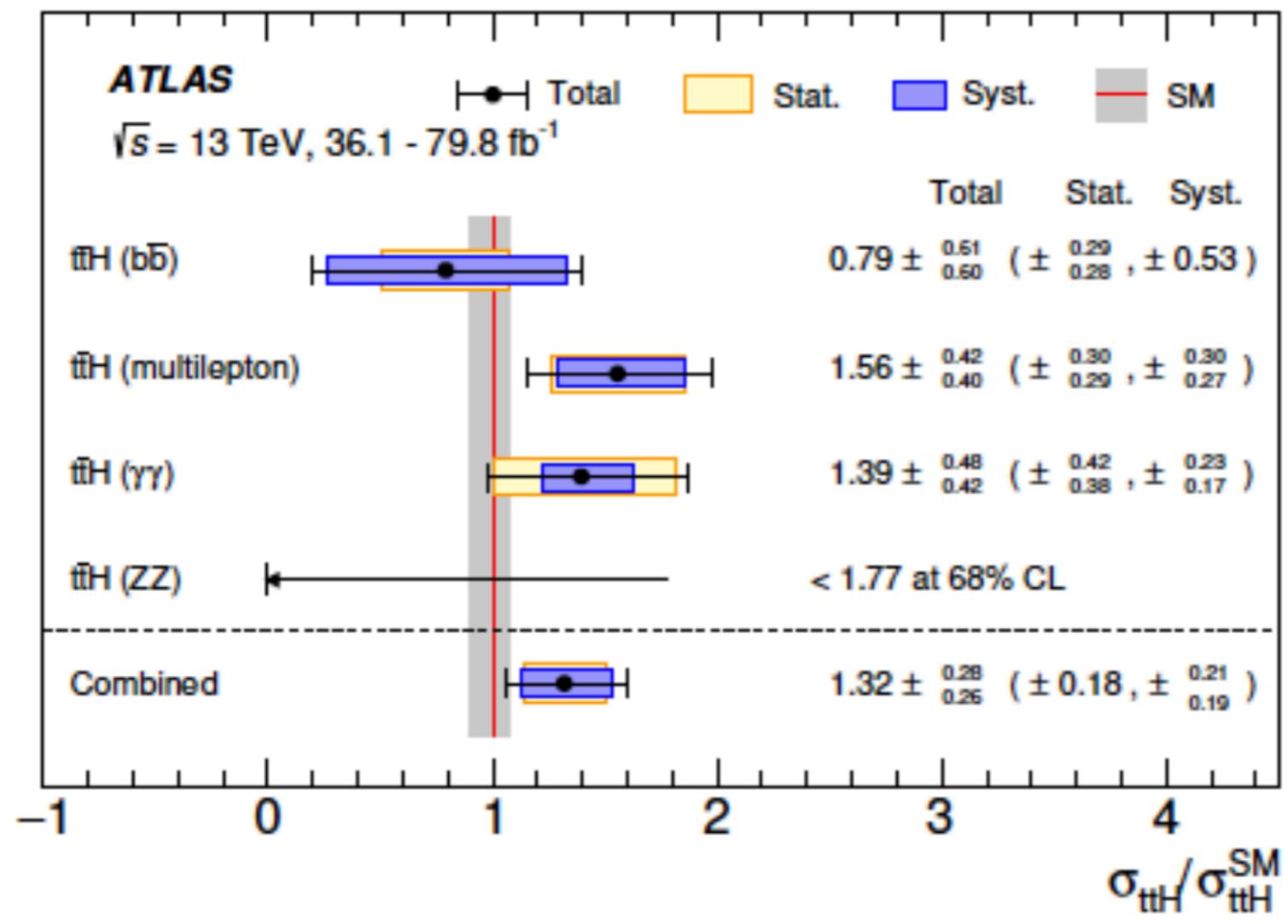
The Big news (2): Top -Higgs interaction

it seems a bit complex...



Observed!

The Big news (2): Top -Higgs interaction

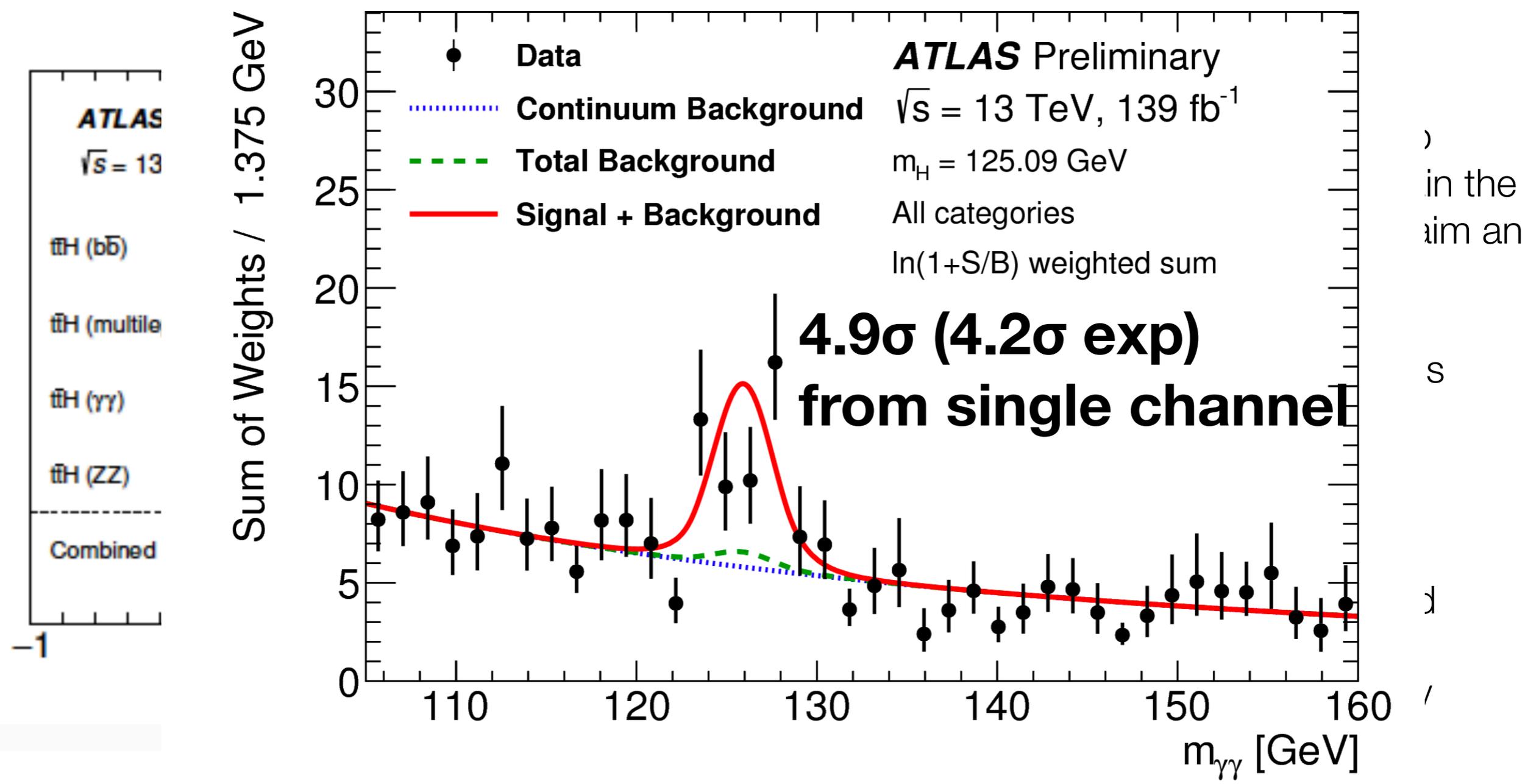


- CMS and ATLAS results presented at LHCP2018
- Both collaborations had to combine channels to obtain the sensitivity necessary to claim an observation
- All possible advanced tools were used
 - Multi Variate Analysis
 - Matrix Element Method
 - Status of the art theory predictions

Observed!



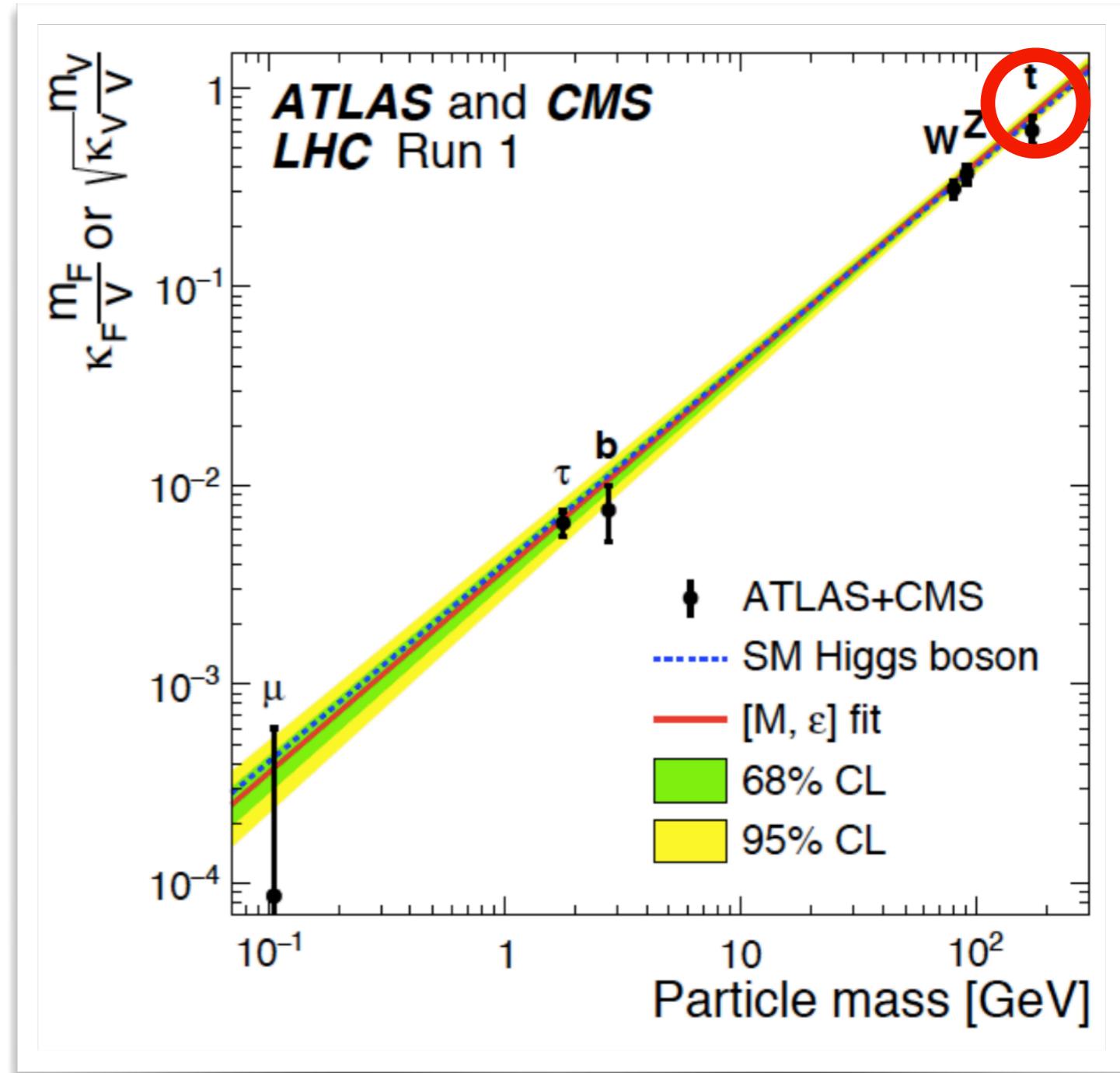
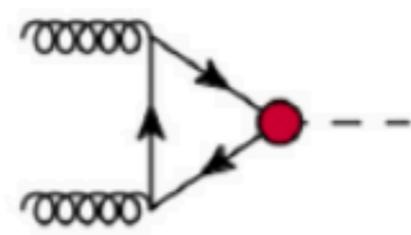
The Big news (2): Top -Higgs interaction



Observed!

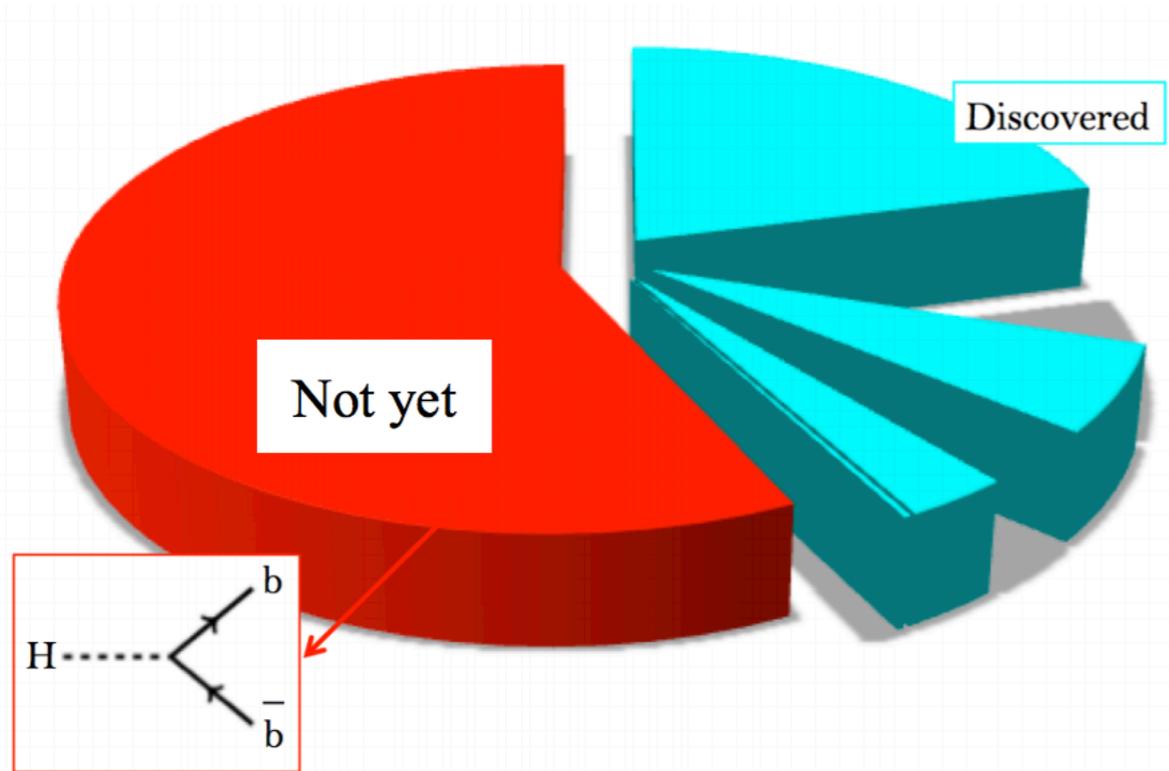
The Big news (2): Top -Higgs interaction

- Why important:
 - We have a proof that top and H interact...
 - ...and they interact strongly
 - Is this because of some new dynamics?
 - Is this strong coupling indicating something more than the SM?
 - We have an handle to know what happens in the gluon-gluon fusion loop.



The Big news (3): Bottom -Higgs interaction

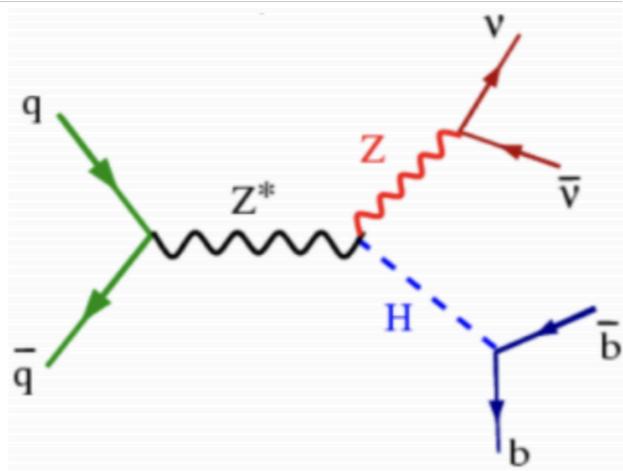
- ATLAS presented the $H \rightarrow bb$ observation in ICHEP 2018
- In addition to probing coupling to b-quarks:
 - $H \rightarrow bb$ drives the uncertainty on the total decay width, and thus on measurement of absolute couplings
 - It also drives the indirect limit on “undetected/ invisible” decays



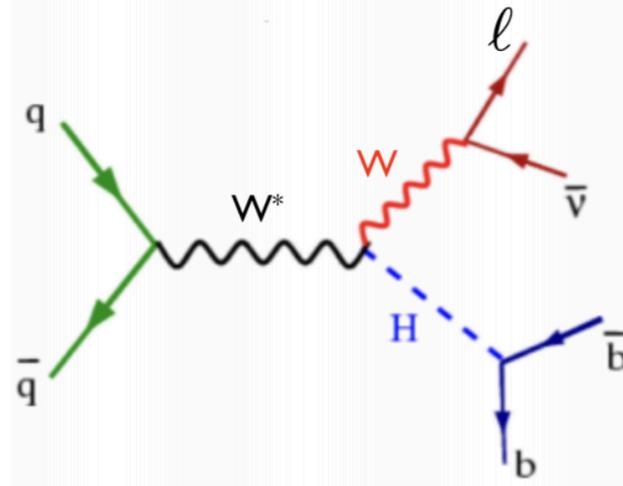
The Big news (3): Bottom -Higgs interaction

G. Piacquadio - ICHEP 2018

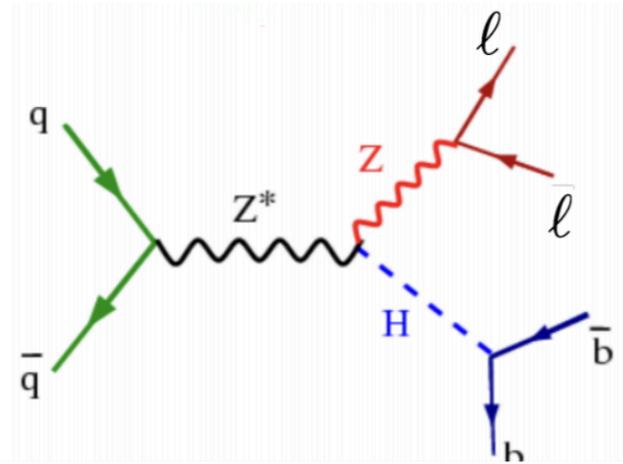
0-lepton



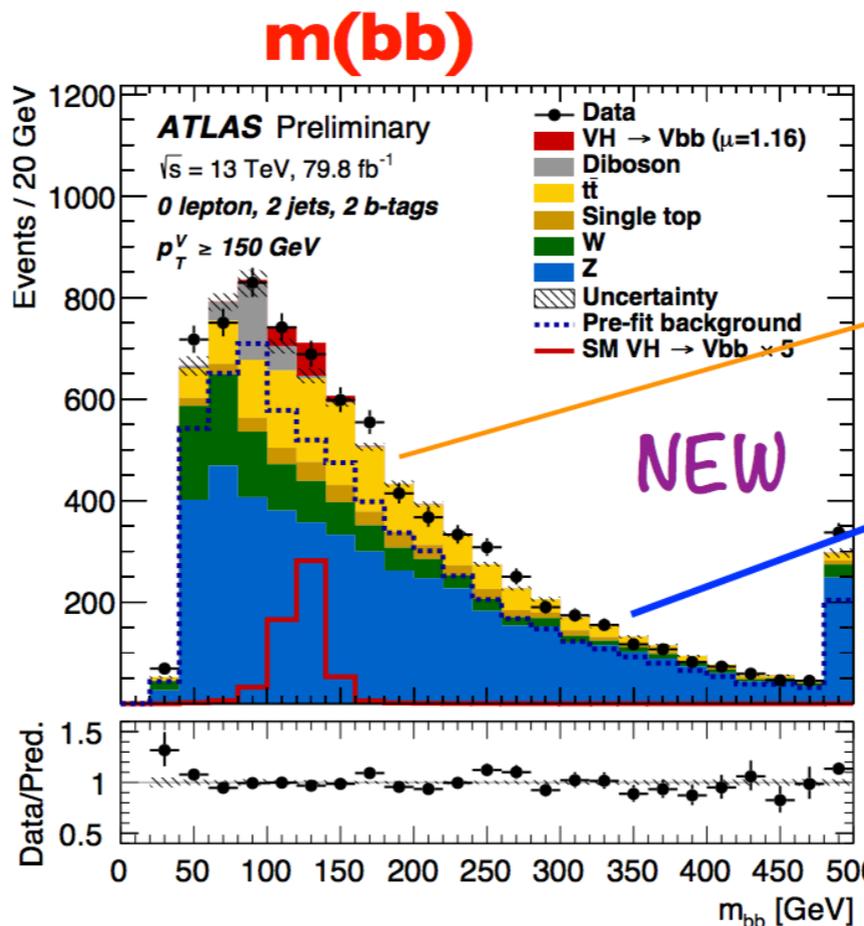
1-lepton



2-lepton



- VH production most sensitive mode for $H \rightarrow bb$ at the LHC
- 3 channels (0-, 1-, 2 charged leptons from $V=W/Z$ boson)
- Select 2 b-tagged jets and $p_T(V) > 75$ or 150 GeV
- Main discriminant variables $m(bb)$, $p_T(V)$ and $\Delta R(bb)$ (combined into a Boosted Decision Tree)



Non-resonant backgrounds:
ttbar,
single top
 (NLO, PowHeg)

W+jets
Z+jets
 (NLO for up to 2 extra jets, Sherpa 2.2.1)

Overall strategy:
 normalization from data, shapes from MC

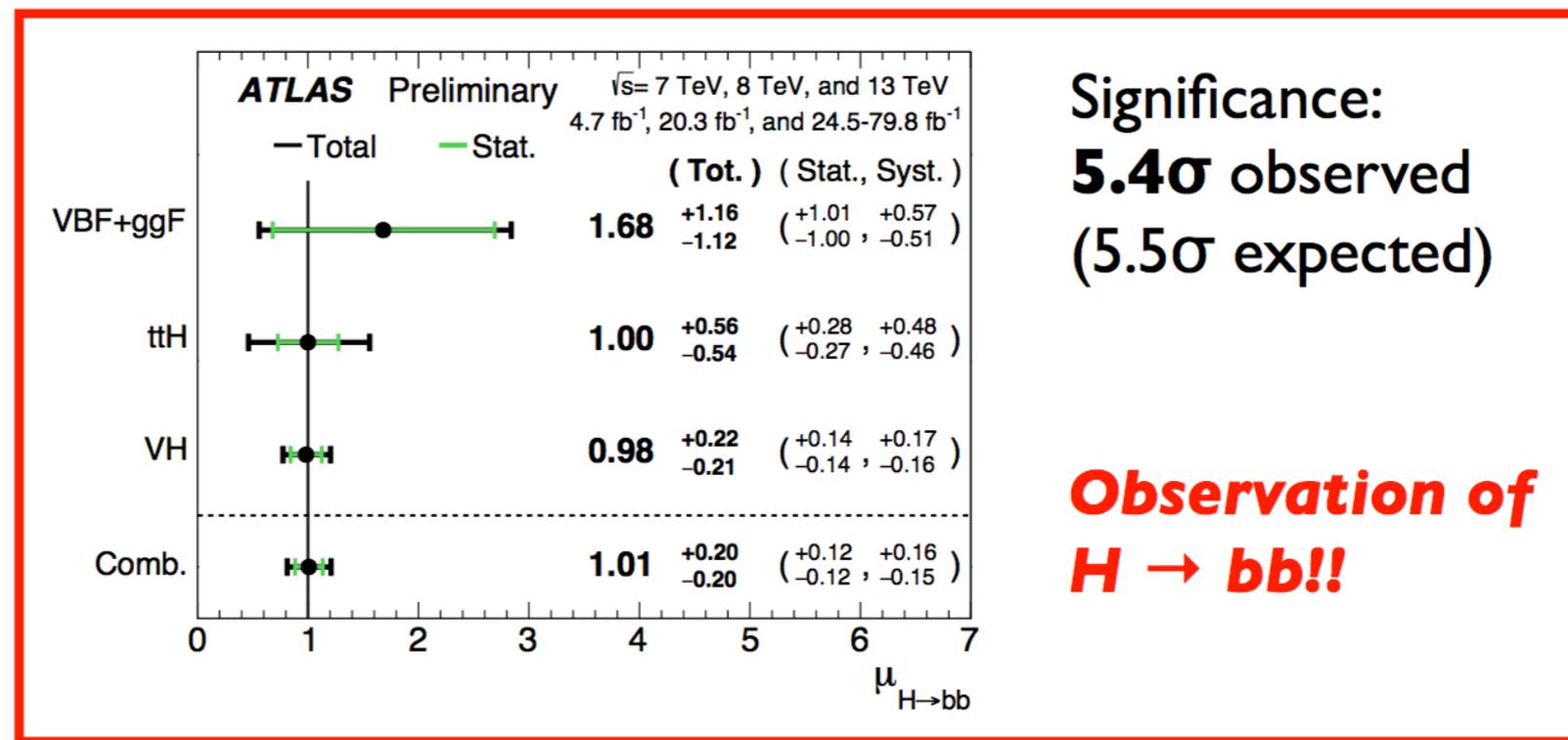
Observed!

The Big news (3): Bottom -Higgs interaction AND VH production mode!!!

H → bb combination

NEW

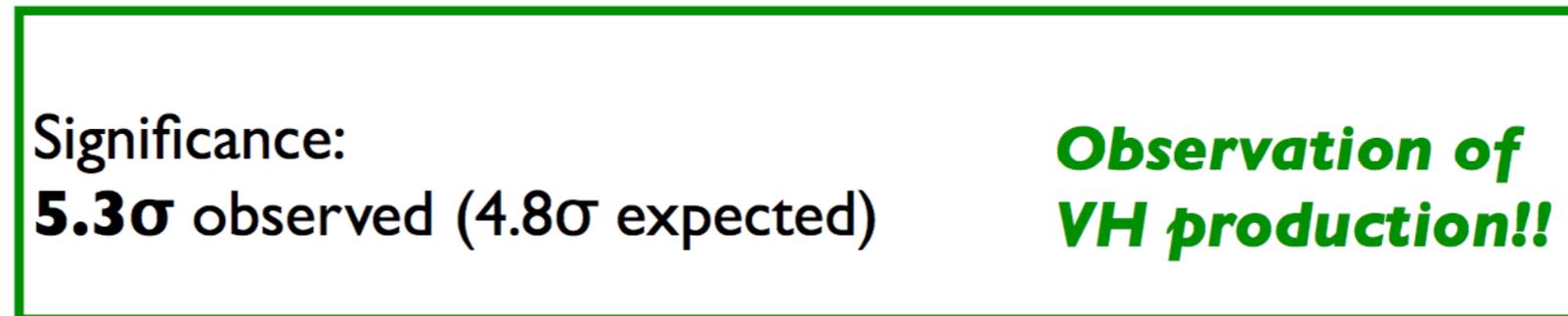
- Run-1+Run-2
 - VH, H → bb
 - VBF(+ggF), H → bb
 - ttH, H → bb



VH combination

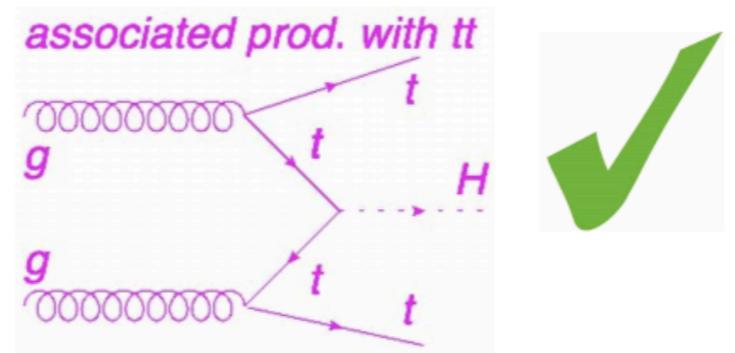
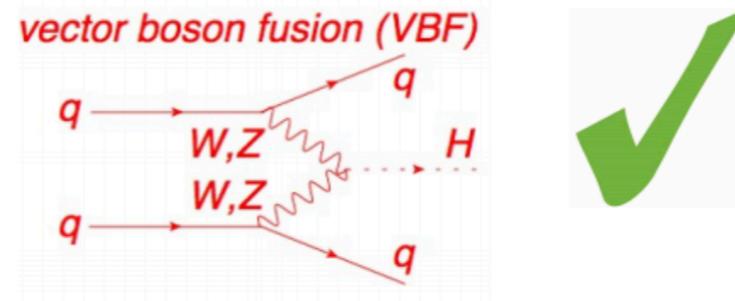
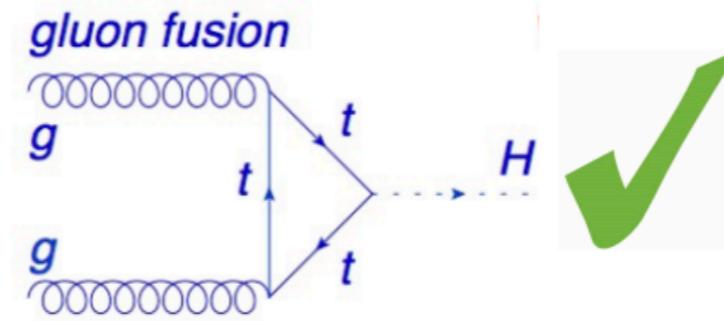
NEW

- Run-2
 - VH, H → bb
 - VH, H → γγ
 - VH, H → ZZ*



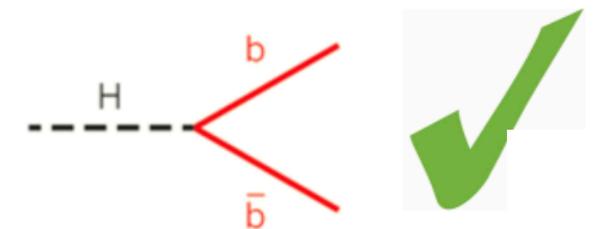
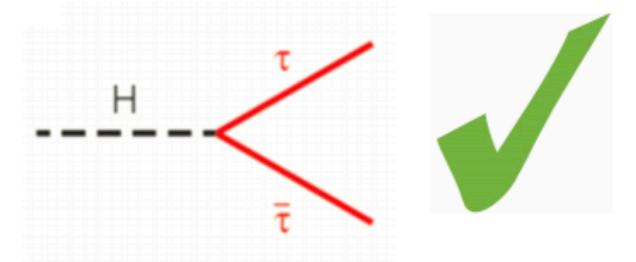
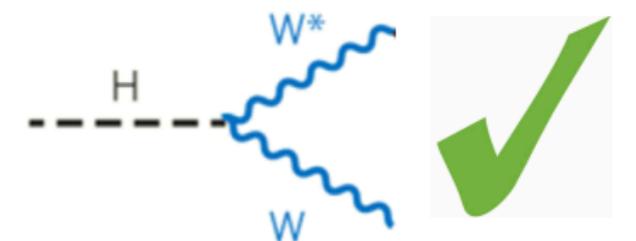
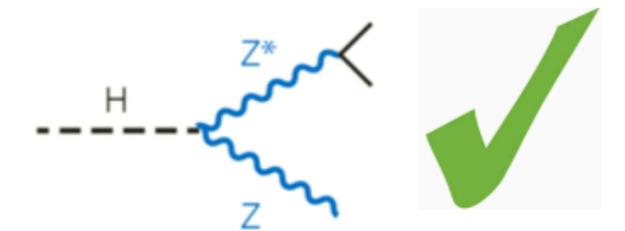
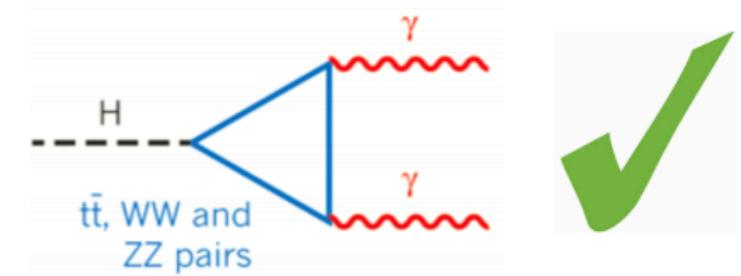
Where we are today

Production

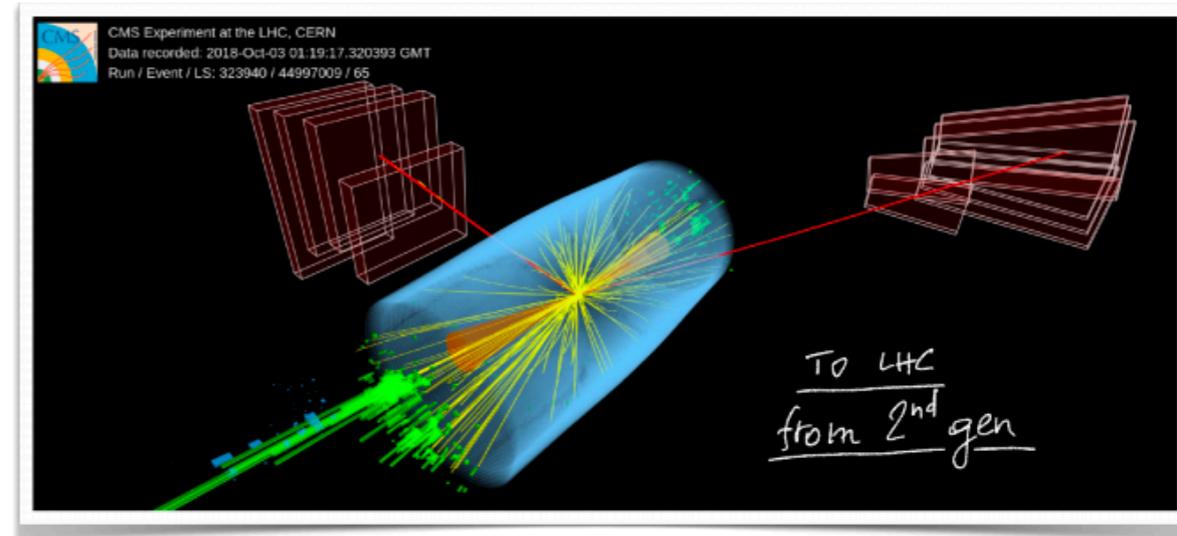


✓ = observed

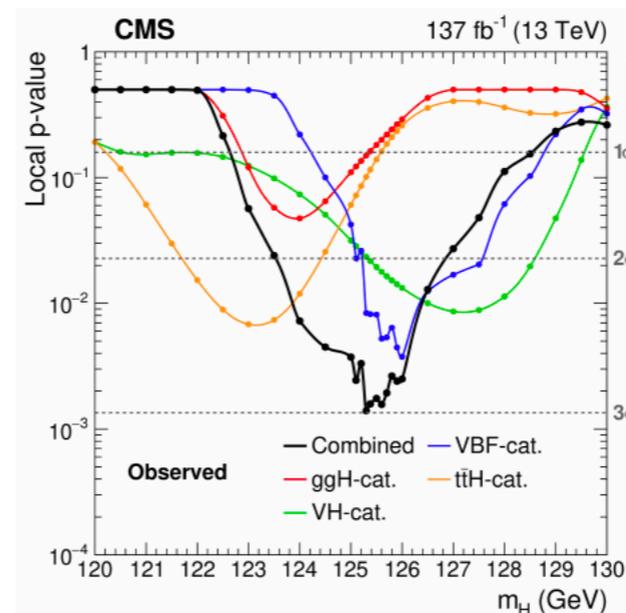
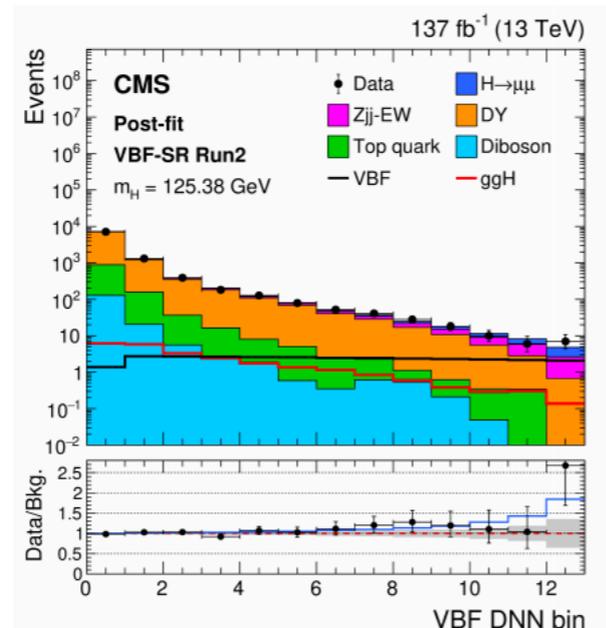
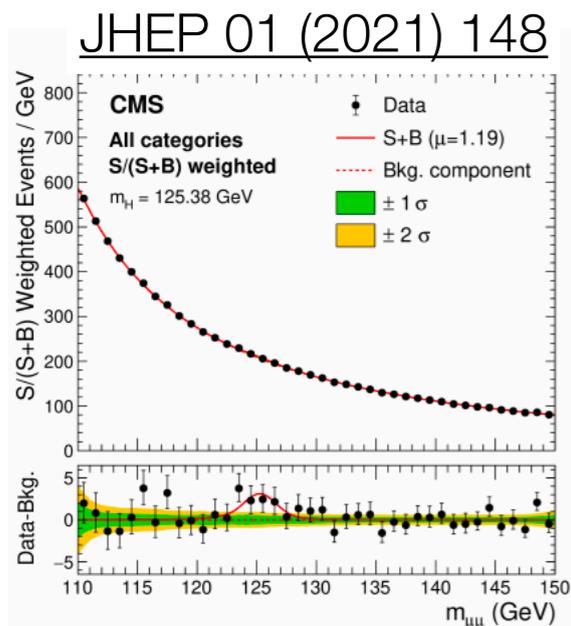
Decays



Evidence for Second Generation: $H \rightarrow \mu\mu$



- Direct evidence of the Higgs decaying to second generation fermions
- Included all main production modes (ggF, VBF, VH, ttH)
- Boosted decision trees and Deep Neural Networks are used to improve signal classification



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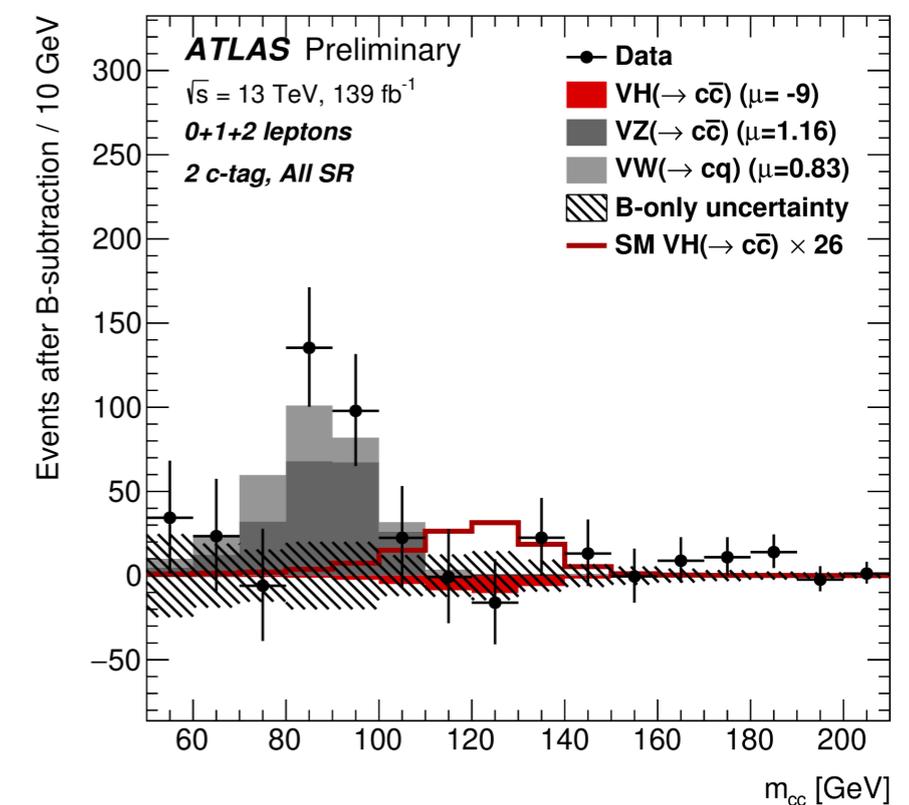
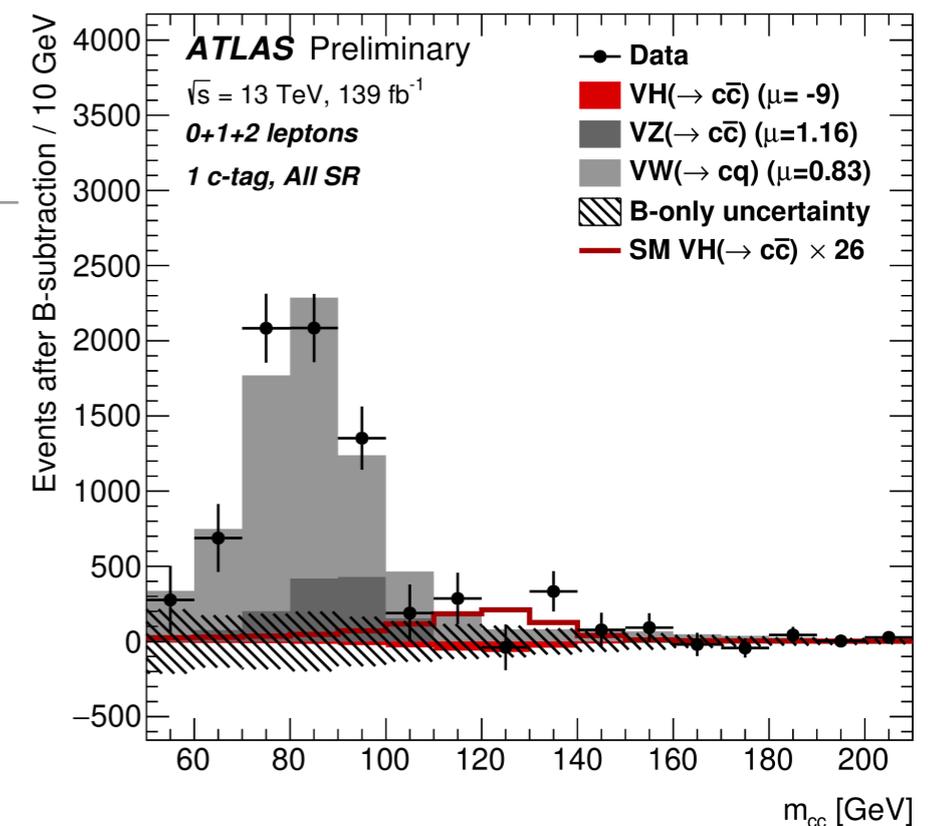
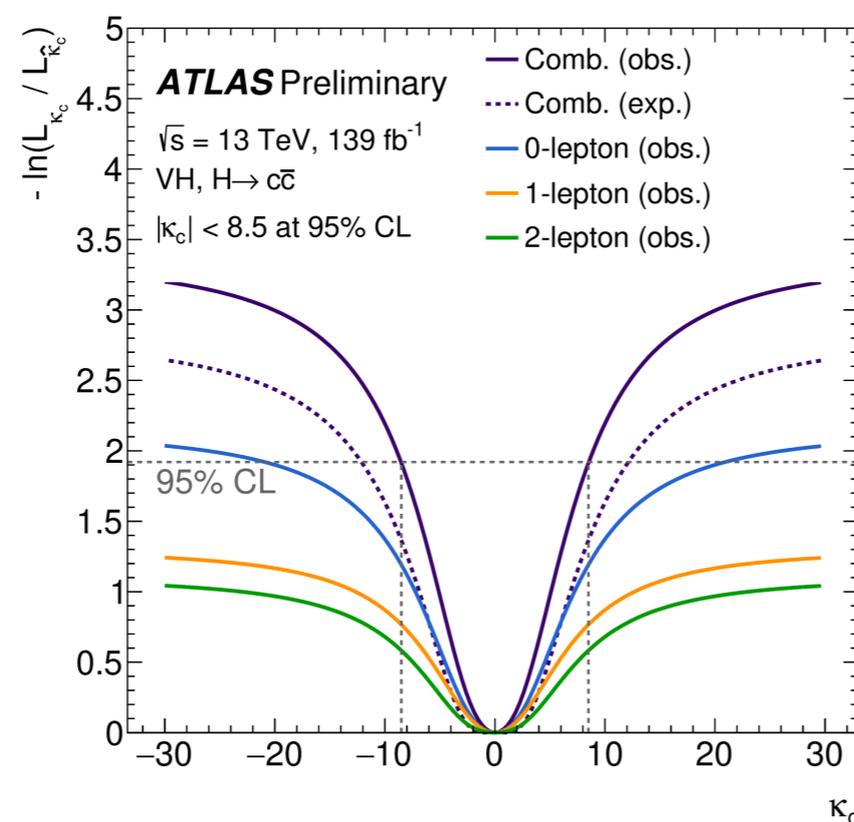
ATLAS
Significance of 2.0 (1.7) σ
 $\mu = 1.2 \pm 0.6$

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CMS
Significance of 3.0 (2.5) σ
 $\mu = 1.19^{+0.40}_{-0.39} \text{ (stat)}^{+0.15}_{-0.14} \text{ (syst)}$

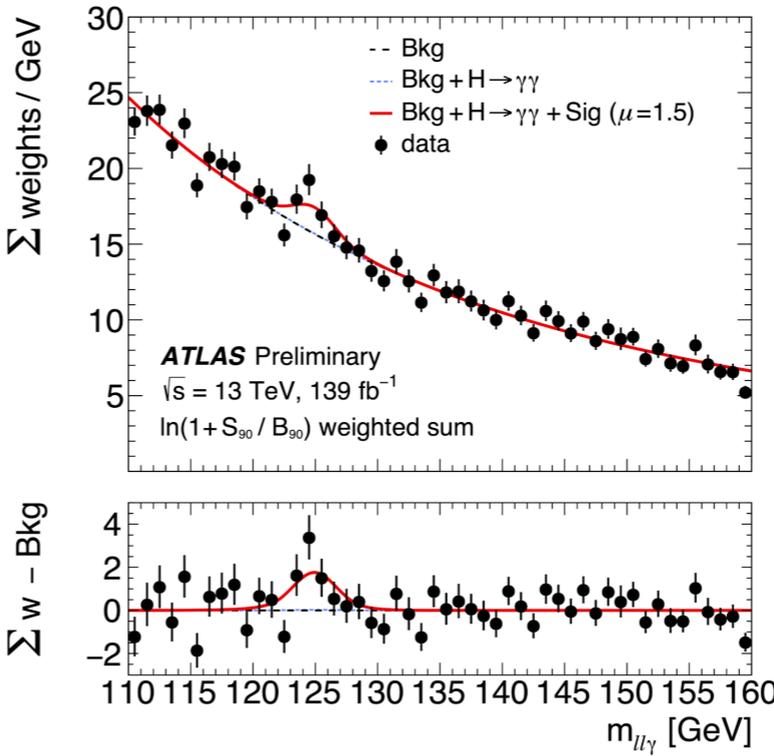
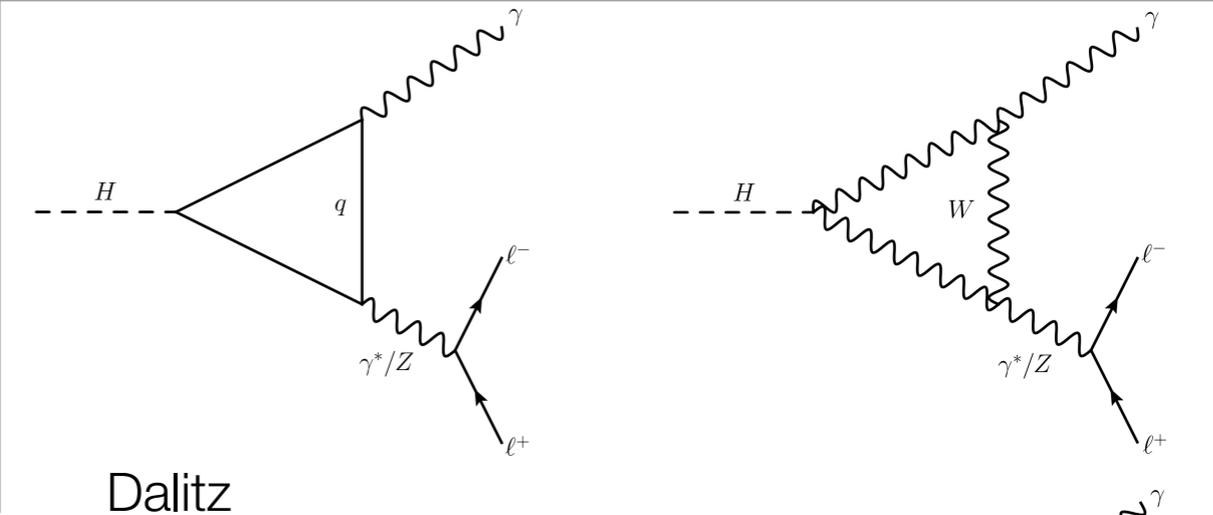
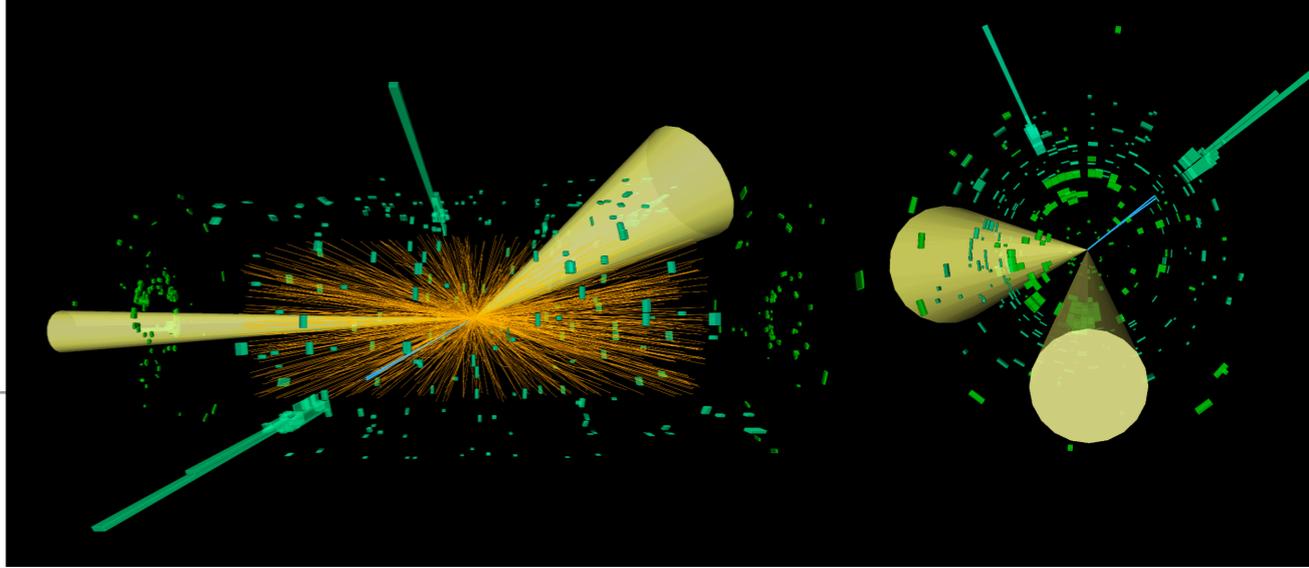
Search for Second Generation: $H \rightarrow c\bar{c}$

- Next milestone to study the second generation couplings
- Analysis mimic the $H \rightarrow b\bar{b}$ search:
- $Z(\ell\ell)H$, $Z(\nu\nu)H$, $W(\ell\nu)H$
- Observed (expected) signal strength $\mu < 26$ (31) @95% CL
- Observed (expected) $|\kappa_c| < 8.4$ (12.4)@95% CL



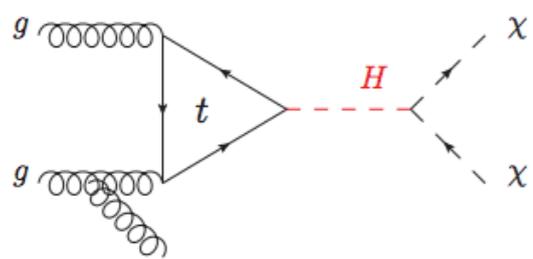
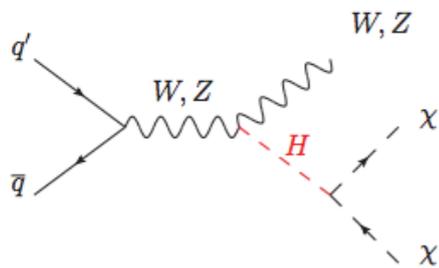
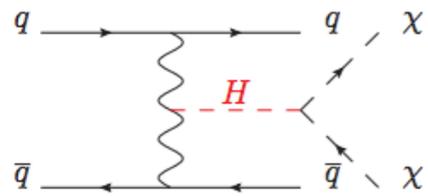
Evidence for $H \rightarrow l\bar{l}\gamma$

- Different diagrams contribute to $H \rightarrow l\bar{l}\gamma$
- Low mass ($m_{ll} < 30$ GeV) targets Dalitz
- First evidence of $H \rightarrow l\bar{l}\gamma$ with $l = e$ or μ
- Includes all main production modes (ggF, VBF, VH, ttH)
- Categories based on lepton flavour ($ee, \mu\mu$) and event topology (VBF-like, etc...)
- Observed (expected) significance is $3.2 (2.1) \sigma$
- Signal strength $\mu = 1.5 \pm 0.5$

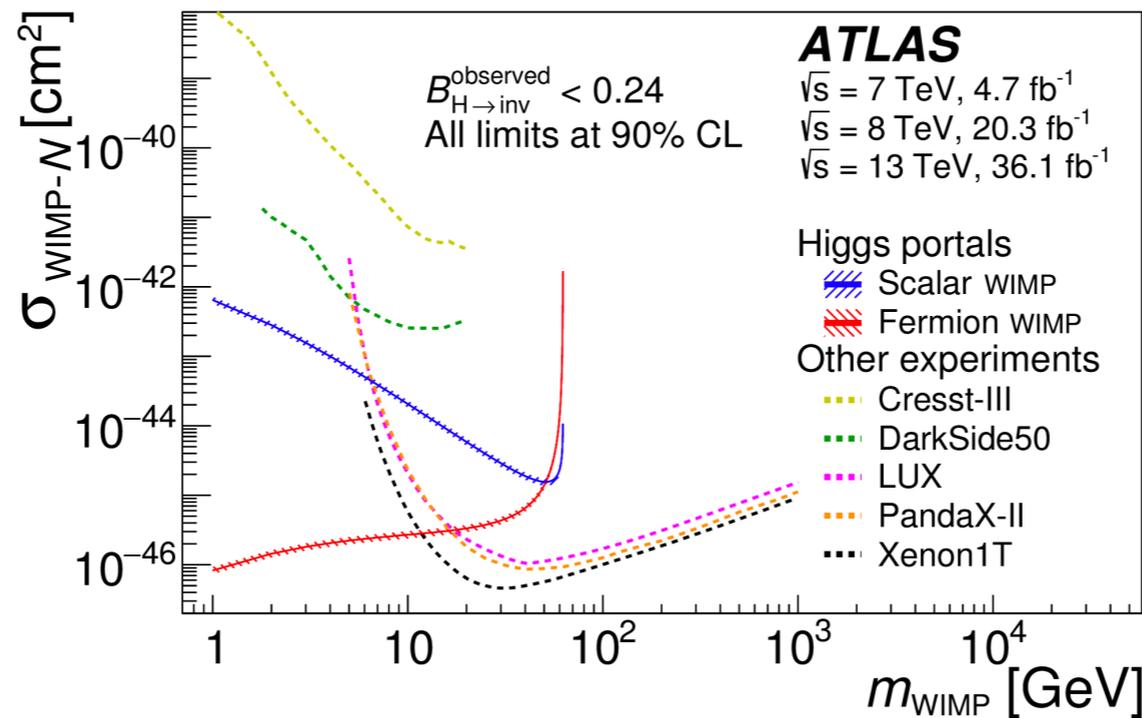
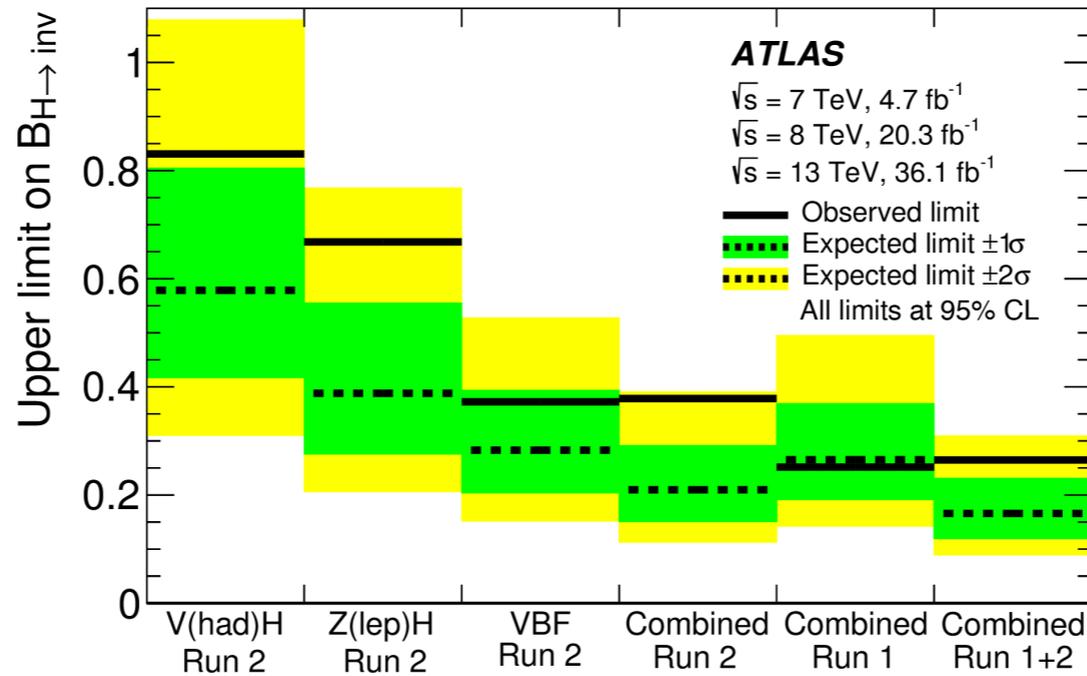


... more rare options....

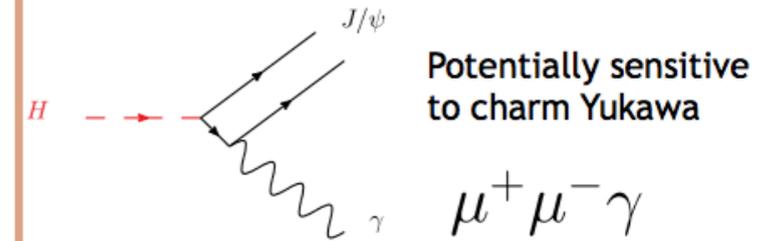
Invisible decays



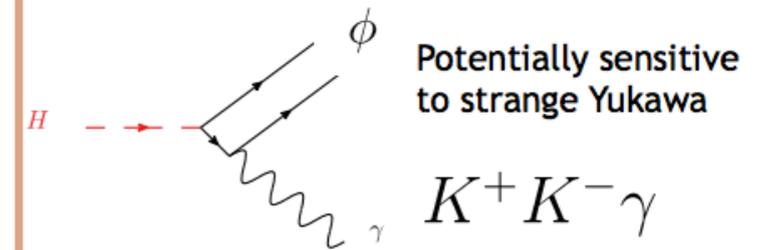
$BR_{inv} < 0.26$ (0.17)
at 95% CL



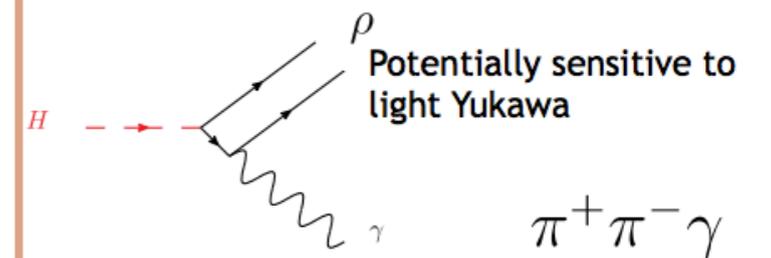
Quarkonia-photon



Higgs $\sim 400 \times$ SM



Higgs $\sim 200 \times$ SM



Higgs $\sim 50 \times$ SM

CP in Hff and HVV

- Stringent constraints on the JCP using H-VW coupling in Run1
- Pure pseudo scalars Higgs state excluded
- Small non-SM anomalous coupling or mixed state of scalar and pseudo scalar are not excluded yet.
- H-VV couplings: CP-odd contributions suppressed by $1/\Lambda^2$ factor

$$A(HV_1V_2) = \frac{1}{v} \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV} (q_{V1} + q_{V2})^2}{(\Lambda_Q^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

- H-ff: CP even and CP odd could be of the same order

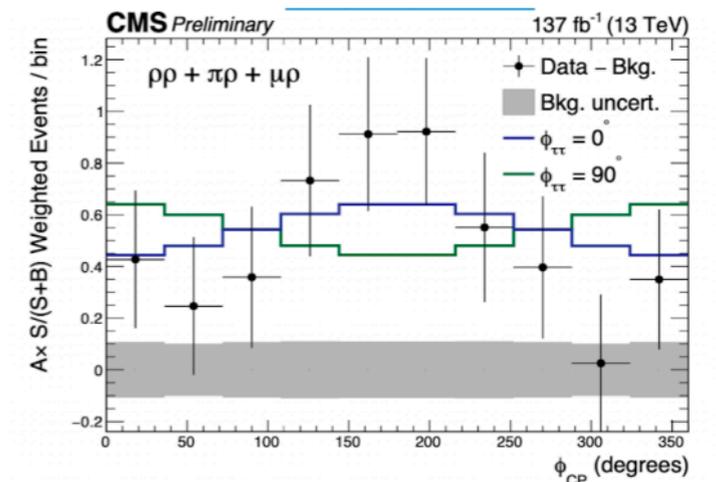
$$A(Hff) = -\frac{m_f}{v} \bar{\psi}_f (\kappa_f + \underbrace{i\tilde{\kappa}_f \gamma_5}_{\text{CP-odd}}) \psi_f,$$

ttH+tH, Hγγ: excluded at 3 σ pure CP odd

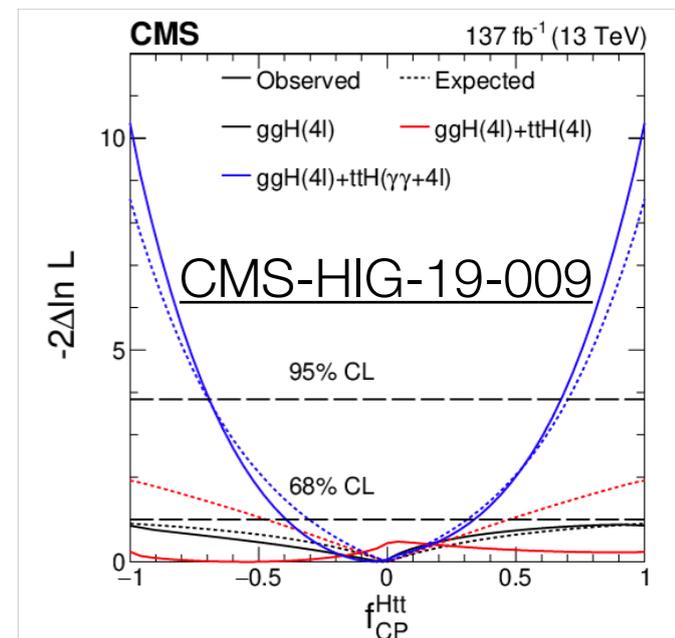
Hττ: First measurement of CP structure of τ Yukawa

Based on angular distribution of hadronic τ decays. Excluded at 3.2 σ pure CP odd

CMS-HIG-20-006



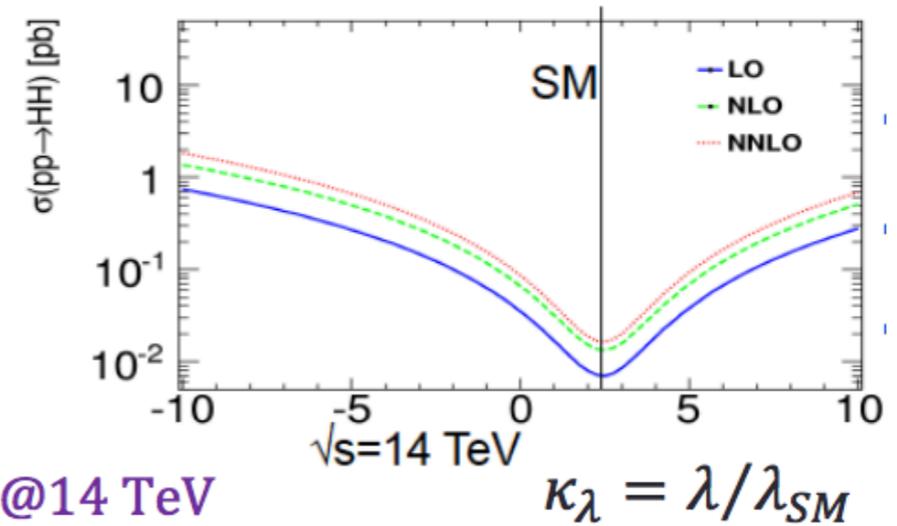
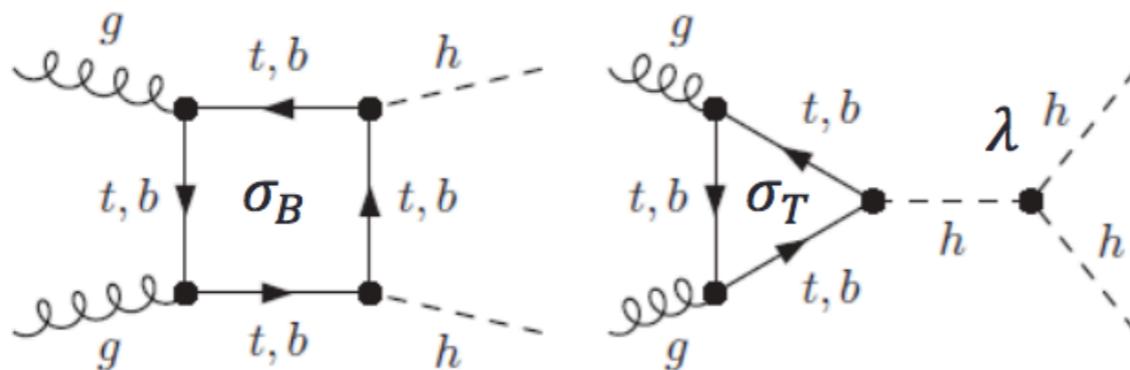
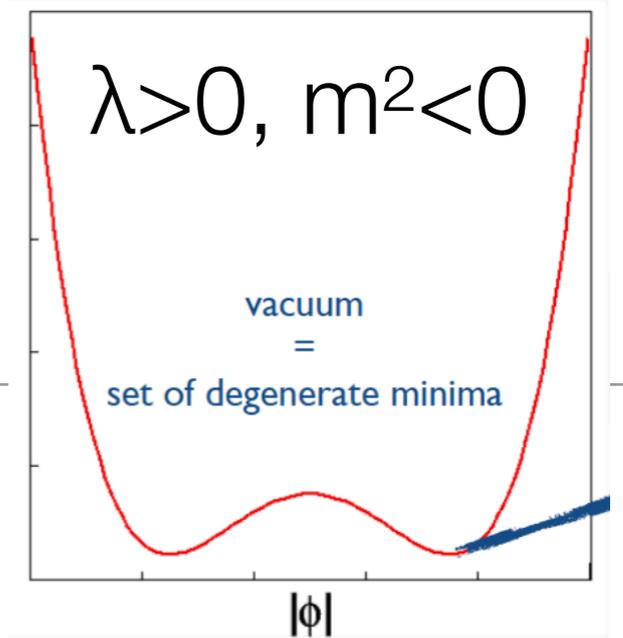
HVV: Study tensor structure, including all anomalous couplings, with contributions from H-gg and H-tt.



No deviations from SM

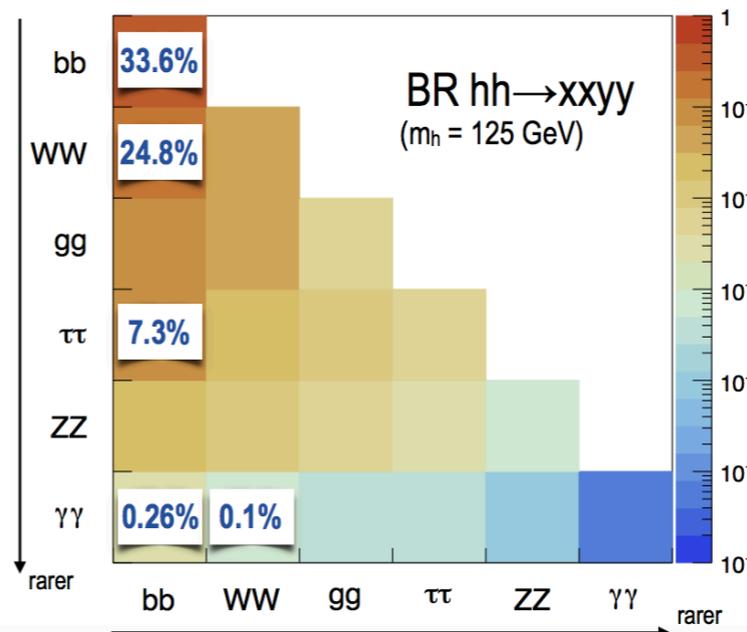
...and the big challenge: Double Higgs production!

- The nature of the Higgs potential is one of the big open question in EW symmetry breaking. In SM potential is determined by G_F and m_H
- Direct measurement of Higgs self coupling is the big challenge in the EWSB.



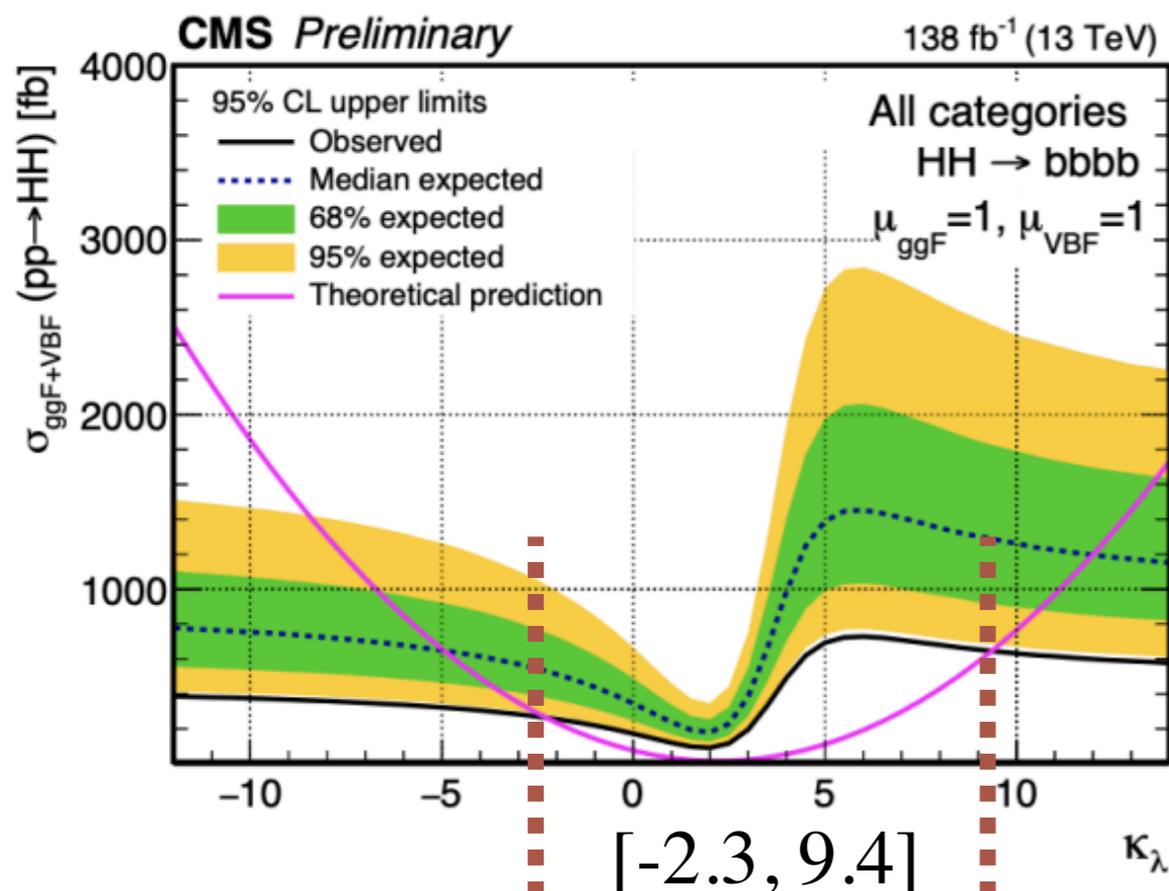
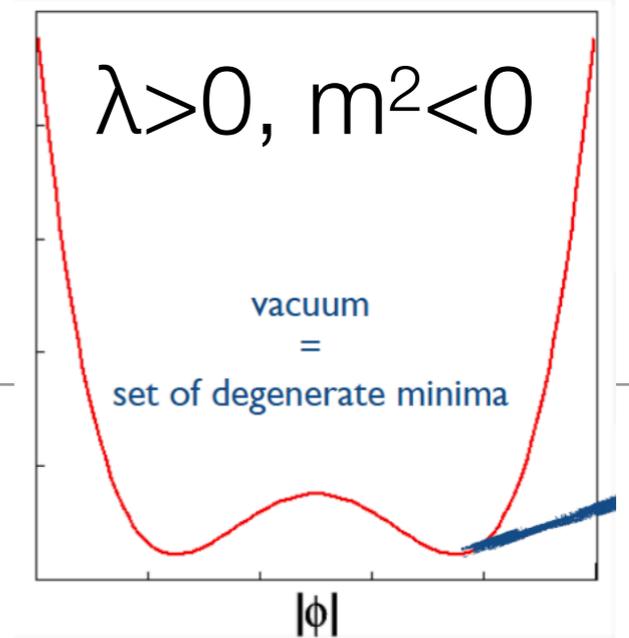
- Destructive interference** $\rightarrow \sigma_{hh} \approx \frac{\sigma_T + \sigma_B}{2.5} \rightarrow \sigma_{hh} = 39.5 \text{ fb @ 14 TeV}$

- Deviations from SM because of BSM?
- Resonances?
- Which channels? which machines?



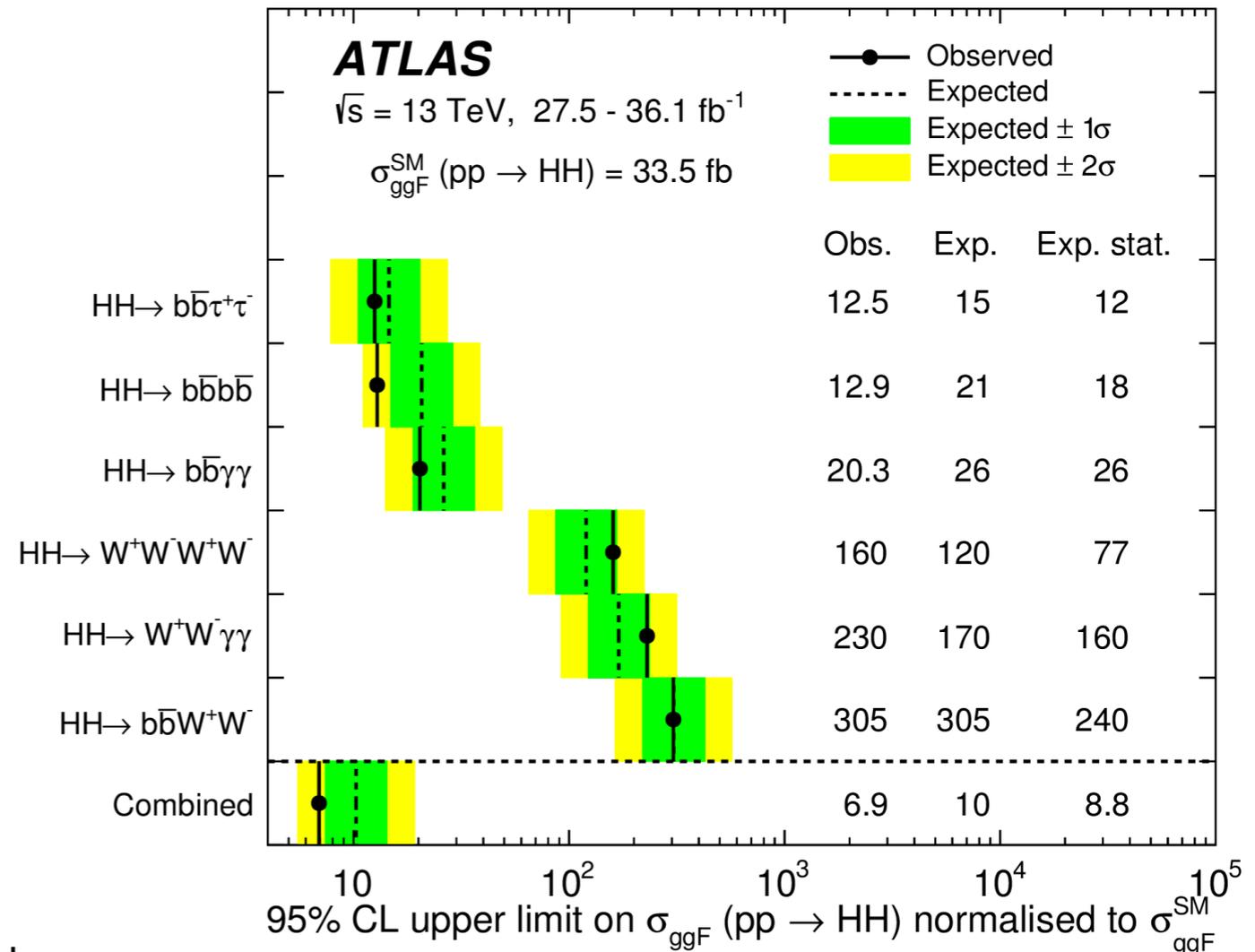
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← excluded
@ 95% CL

→ excluded
@ 95% CL



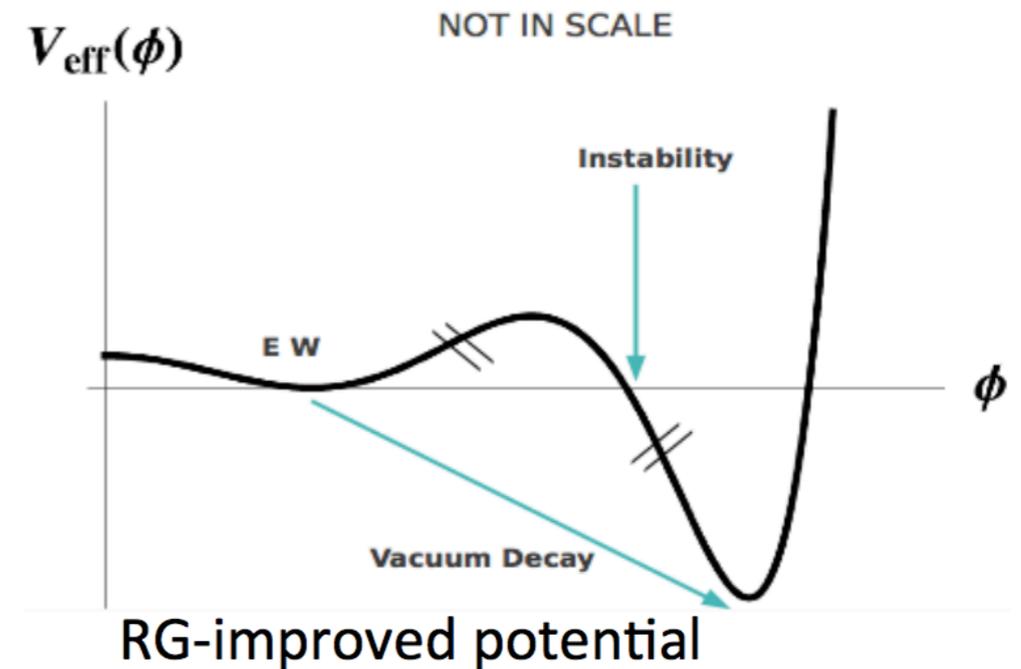
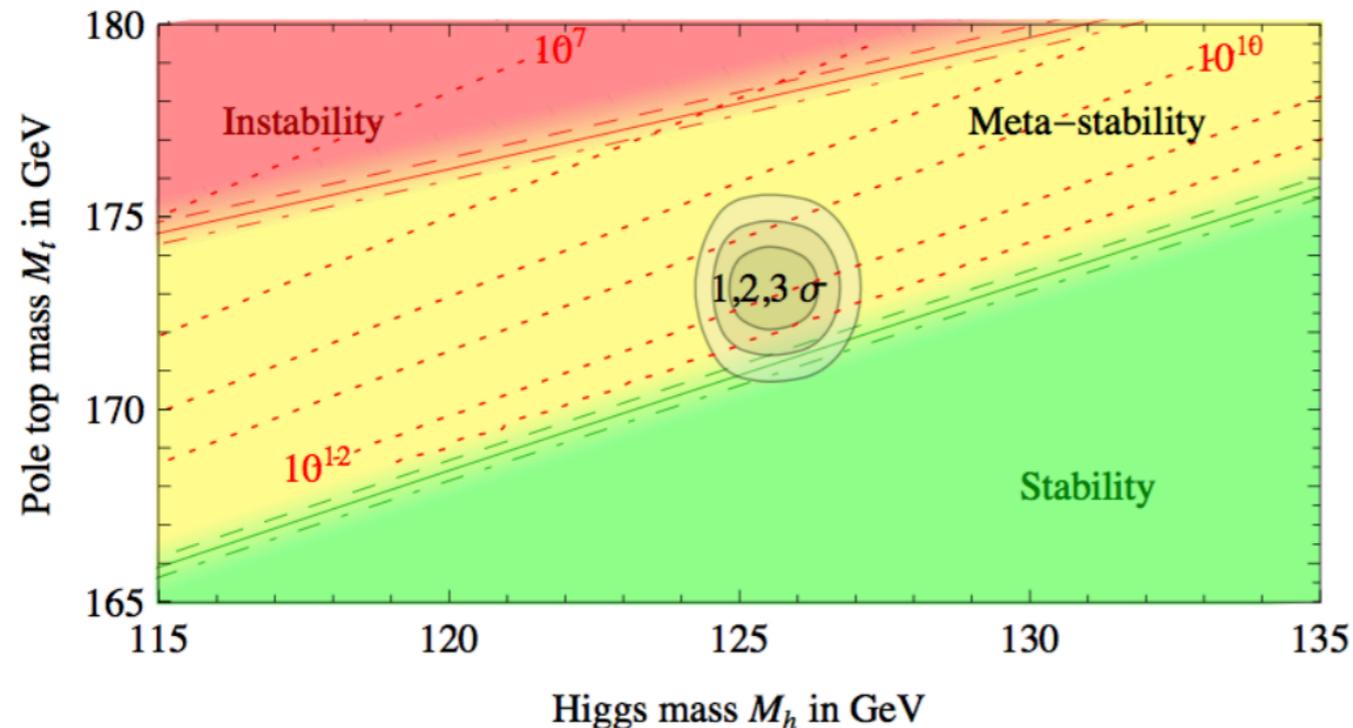
Selected news from Run2

- Observation of $H \rightarrow \tau\tau$
- Observation of $pp \rightarrow ttH$
- Observation of $H \rightarrow bb$
- Observation of $pp \rightarrow VH$
- Evidence of $H \rightarrow \mu\mu$
- Evidence of $H \rightarrow l\bar{l}\gamma$
- Search of $H \rightarrow cc$
- Search of $H \rightarrow inv$
- CP in H - ff and H - VV
- Beginning of the quest for $pp \rightarrow HH$ and constrains on λ

BONUS

Some important questions...

Some more considerations: back to the potential, and the fate of the Universe



- What if the the EW minimum is a local and not the absolute minimum of the potential?
- Couplings use to run.... What about the self coupling λ ?
- It depends on the mass of the Higgs boson and of the Top quarks
- If at some scale, λ changes sign, the vacuum is not stable... Maybe we are safe if some new dynamics enters. For the time being, the only new dynamics we know is related to gravity, and it has a scale of the order of the Plank mass 10^{19} GeV.

Some more considerations: back to the potential, and the fate of the Universe

*slide from
R. Goncalo*

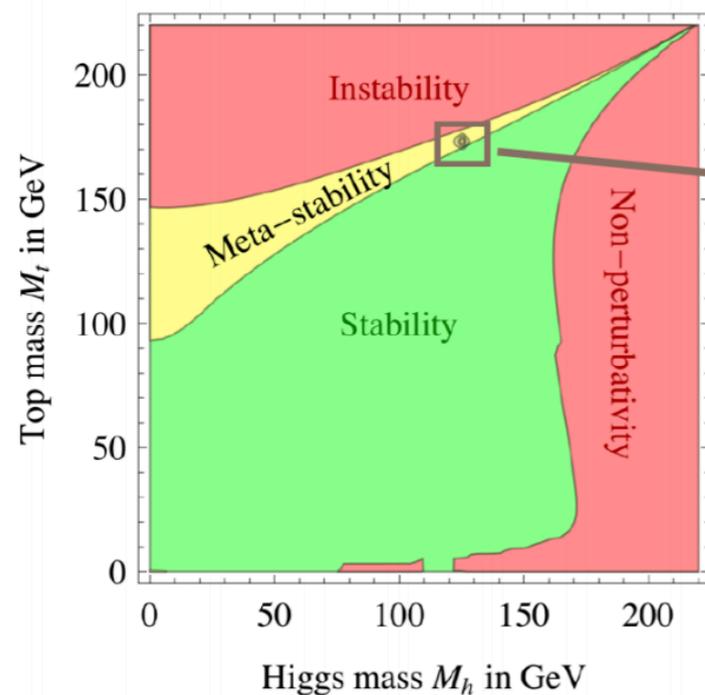
The universe seems to live
near a critical condition

JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?



Higgs boson and cosmology

- The mexican hat potential expanded around the vacuum state becomes:

$$V = \frac{1}{2} (2\lambda v^2) H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 - \frac{\lambda}{4} v^4$$

- The last term is constant and it is irrelevant for the SM
- This term can have an impact on gravity: it define the curvature of the vacuum.
- Experimentally this is flat, and the upper limit is: $\rho_{\text{vac}} \leq 10^{-46} \text{ GeV}^4$
- The expected value for the SM Higgs is: $\rho_H \geq 10^8 \text{ GeV}^4$
- 54 order of magnitude of difference!!! Why?

Is the Standard Model complete?

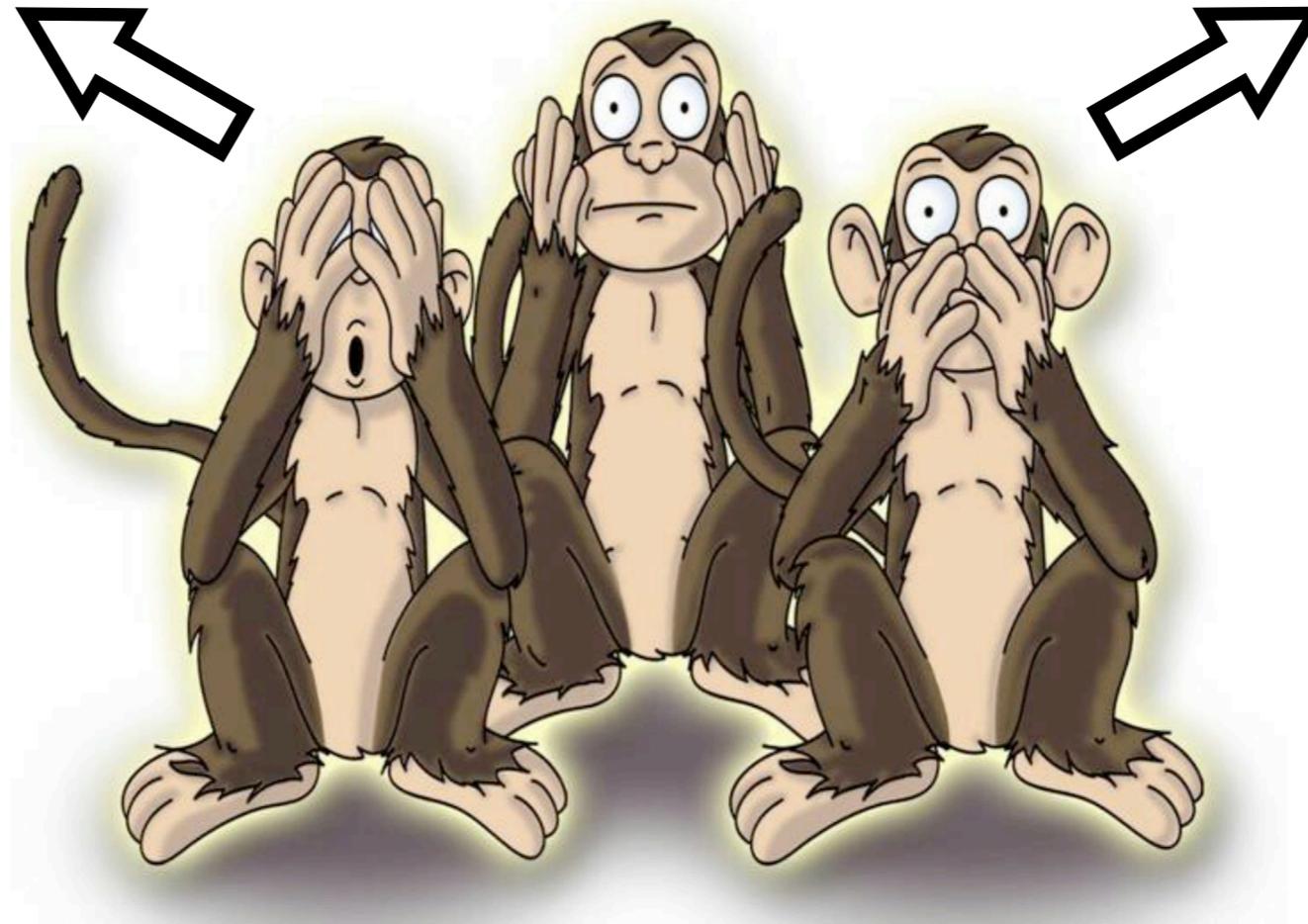
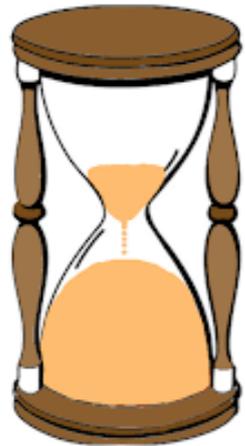
- mmm... a lot of open question...
- Why do we observe matter and almost no antimatter, if we believe there is a symmetry between the two in the universe?
- What is the “dark matter” that we can’t see, but it has visible gravitational effect in the cosmos?
- Are quarks and leptons actually fundamental, or made up of more fundamental particles?
- Why are there exactly three generations of quarks and leptons?
- What is the explanation for the observed pattern for the particle masses?

no hint of new physics at the LHC yet...

Where is everybody?

Option 1: **New physics at TeV exist**, we (you) will discover it soon!

Option 3: **No new physics at the TeV** scale we need to understand better the questions we are asking



Option 2: New physics exist, **but just beyond the reach of the LHC.**

But we should start having “**anomalies**”

An example: Models with two Higgs doublets

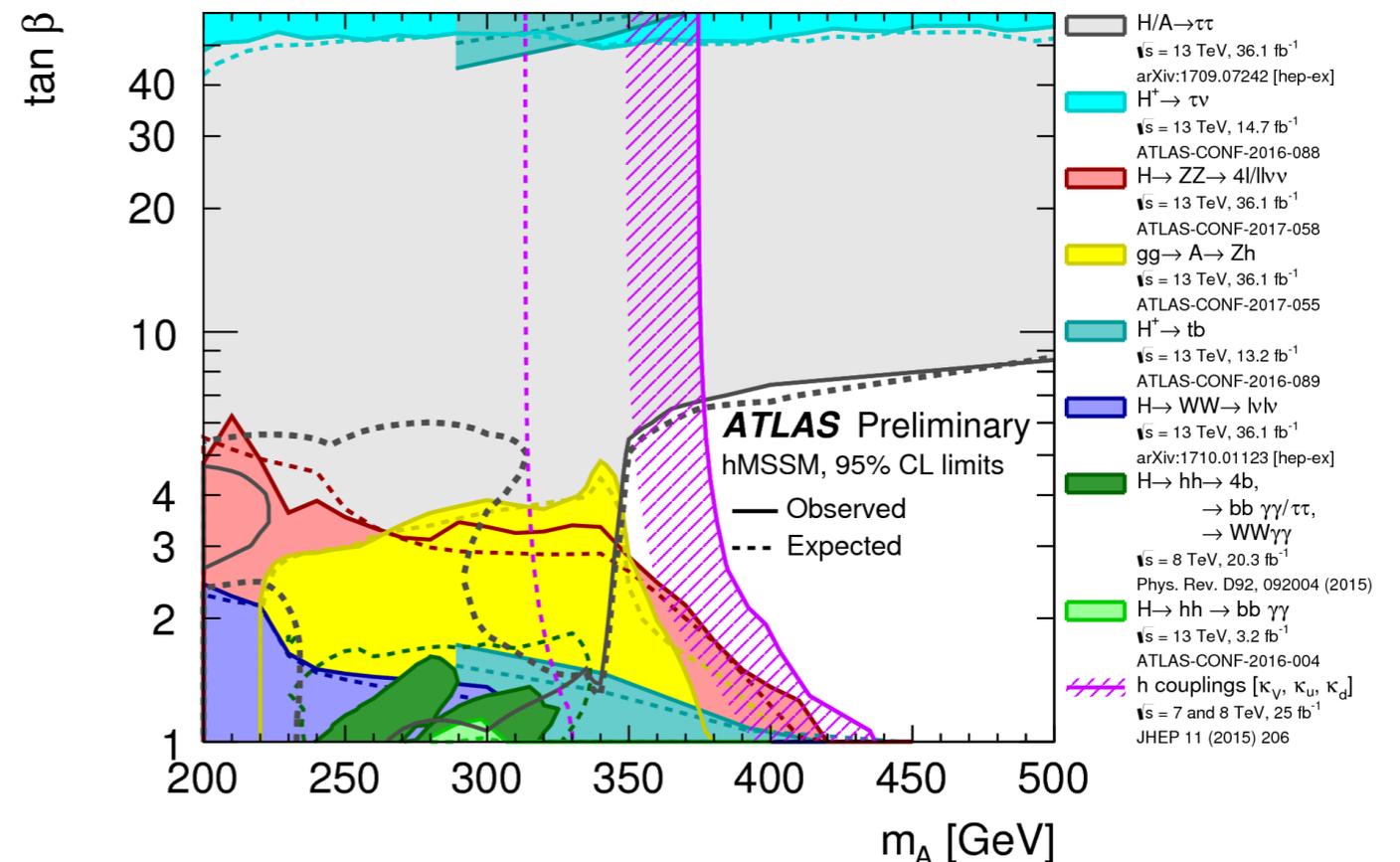
- Why just one doublet for the Higgs Sector?
- It is the more economical, but no limitation to the presence of other scalar doublets.
- Example: hMSSM
(some configuration of SUSY models, with two Higgs doublets)

- This leads to 5 different Higgs Bosons

- CP even (scalar): h, H
- CP odd (pseudoscalar): A
- Charged : $H^+ H^-$

- We can search these new particles...

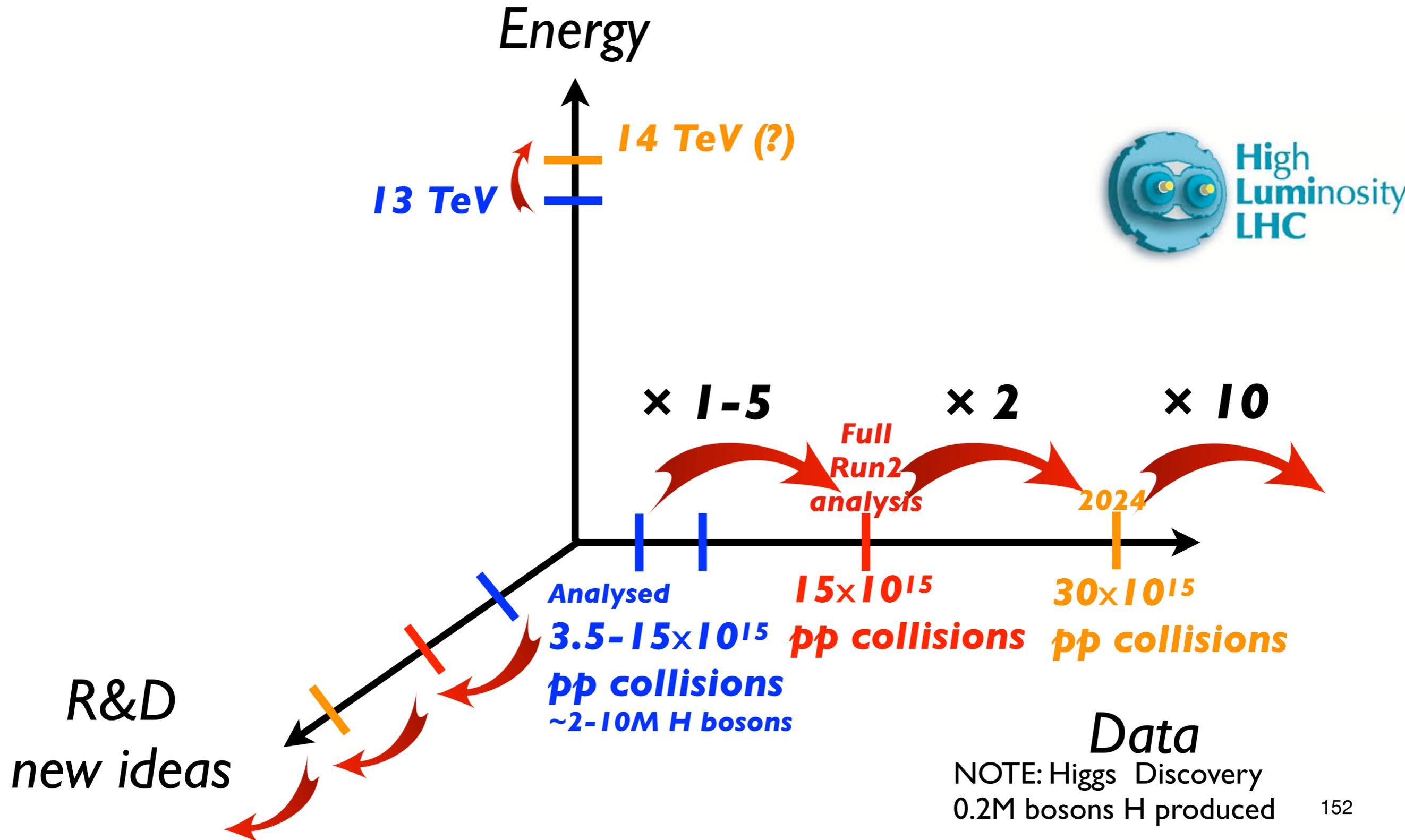
- ...or we can check if they leave some anomaly in the couplings of the boson we observed...



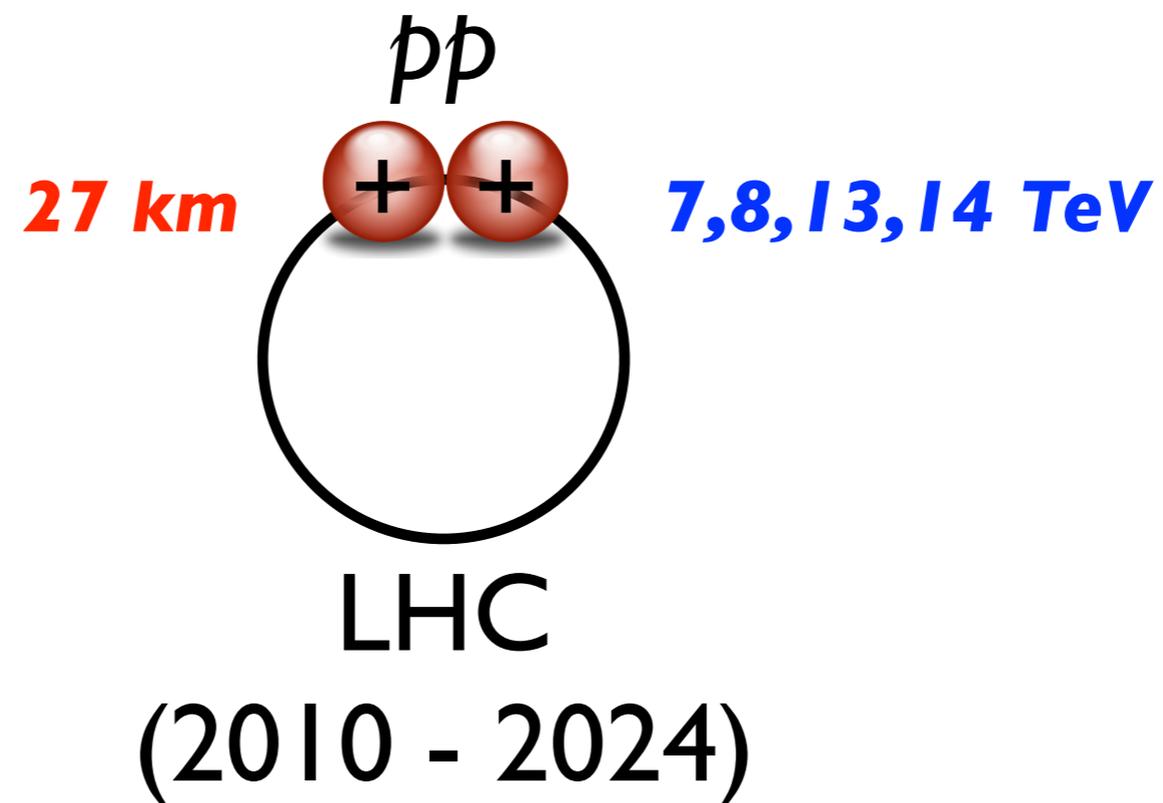
BACK TO THE FUTURE



The reach of the LHC

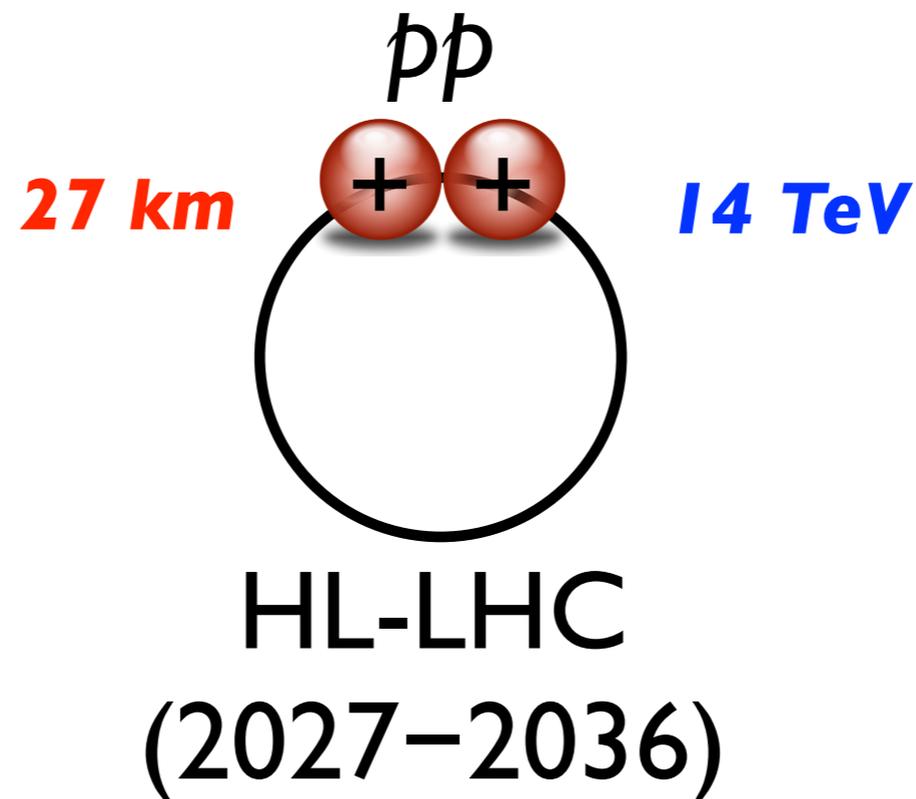


Future colliders



Future colliders

HL-LHC = same energy, but collision rate 2÷3 time higher



Future colliders

FCC-ee (?) **90–350 GeV**

→ FCC-hh (?) **100 TeV**

100 km

CepC (2028 ?) **240 GeV**

→ SppC (2042 ?) **70 TeV**

54 km

27 km

HL-LHC (2027–2036)

14 TeV

CLIC (?) **380 GeV – 3 TeV**

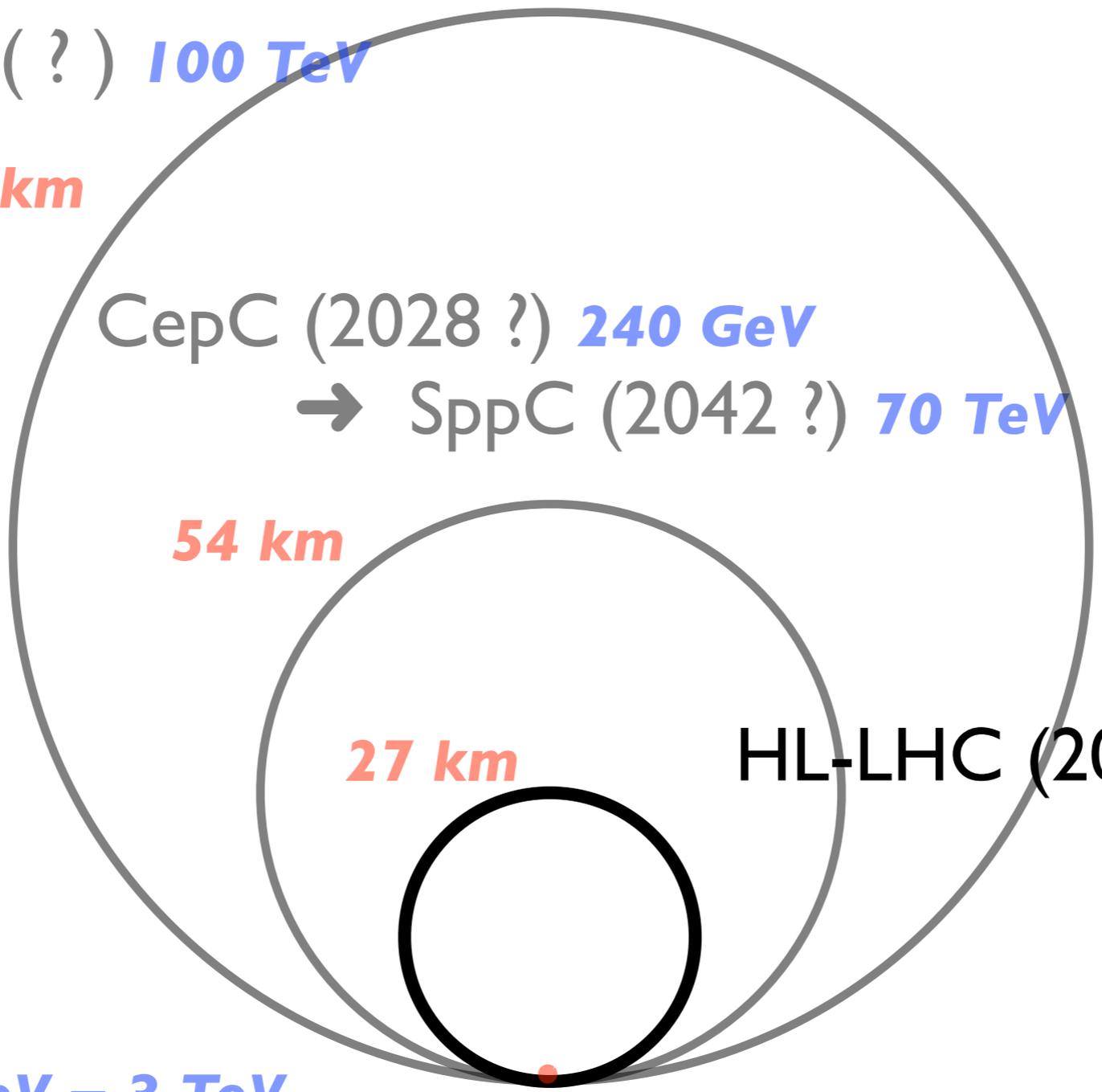
48 km

11 km

31 km

50 km

ILC (?) **250–500 GeV**



Ideas for new Future Colliders

		Begin -end data taking		L[ab-1] @ \sqrt{s} [GeV]				L[ab-1] @ \sqrt{s} [TeV]						Total L[ab-1] at $\sqrt{s}>240$ GeV	#years	#H events
				90	~240	350-380	500	1.5	3	7-14	27	70	100			
LHC	pp	2010	2024							0.3				0.3	14	15M
HL-LHC	pp	2027	2036							3				3	~10	150M
CepC	ee	2028?	2038?		5									5	~10	1M
ILC	ee	2030?	2050?		2	0.2	4							6.2	~20	1.6M
CLIC	ee	2035?	2055?			0.5		1.5	3					4	~20	1.5-2M
FCC-ee	ee	2039?	2055?	150	5	2								13	~15	1-2M
HE-LHC	pp	2040?	2060?								>10			>10	~20	1B
FCC-hh	pp	2043? (FCC-ee?)	2063?										40	40	~25	40B
SppC	pp	2045?	2060?									30		30	~10-15	30B

LHC → HL-LHC: 10 times more H (50-100x analysed data)

HL-LHC → HE-LHC: ~10 times more H (500-1000x analysed data)

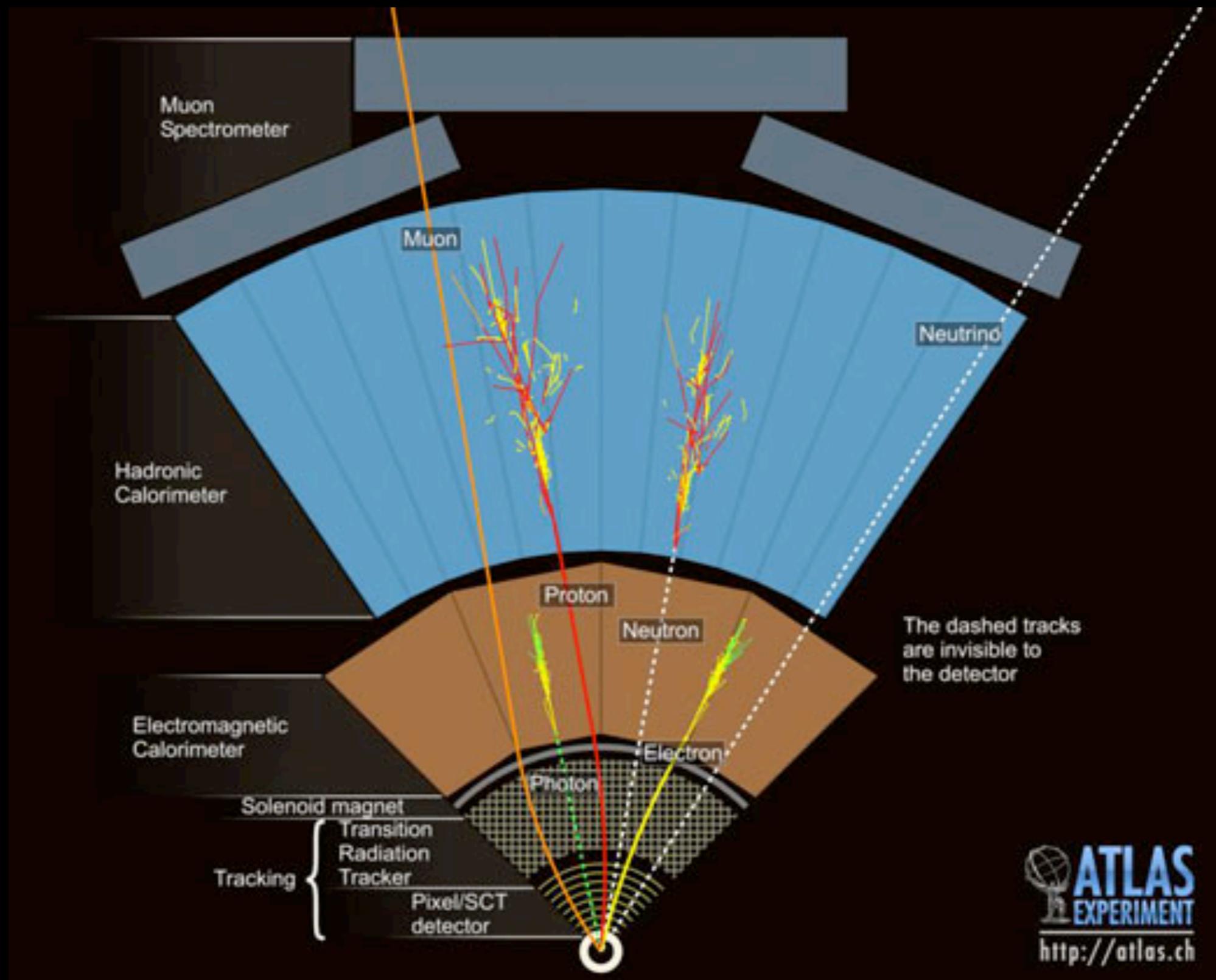
HE-LHC → FCC-hh: ~40 times more H (20000-40000x analysed data)



That's all Folks!

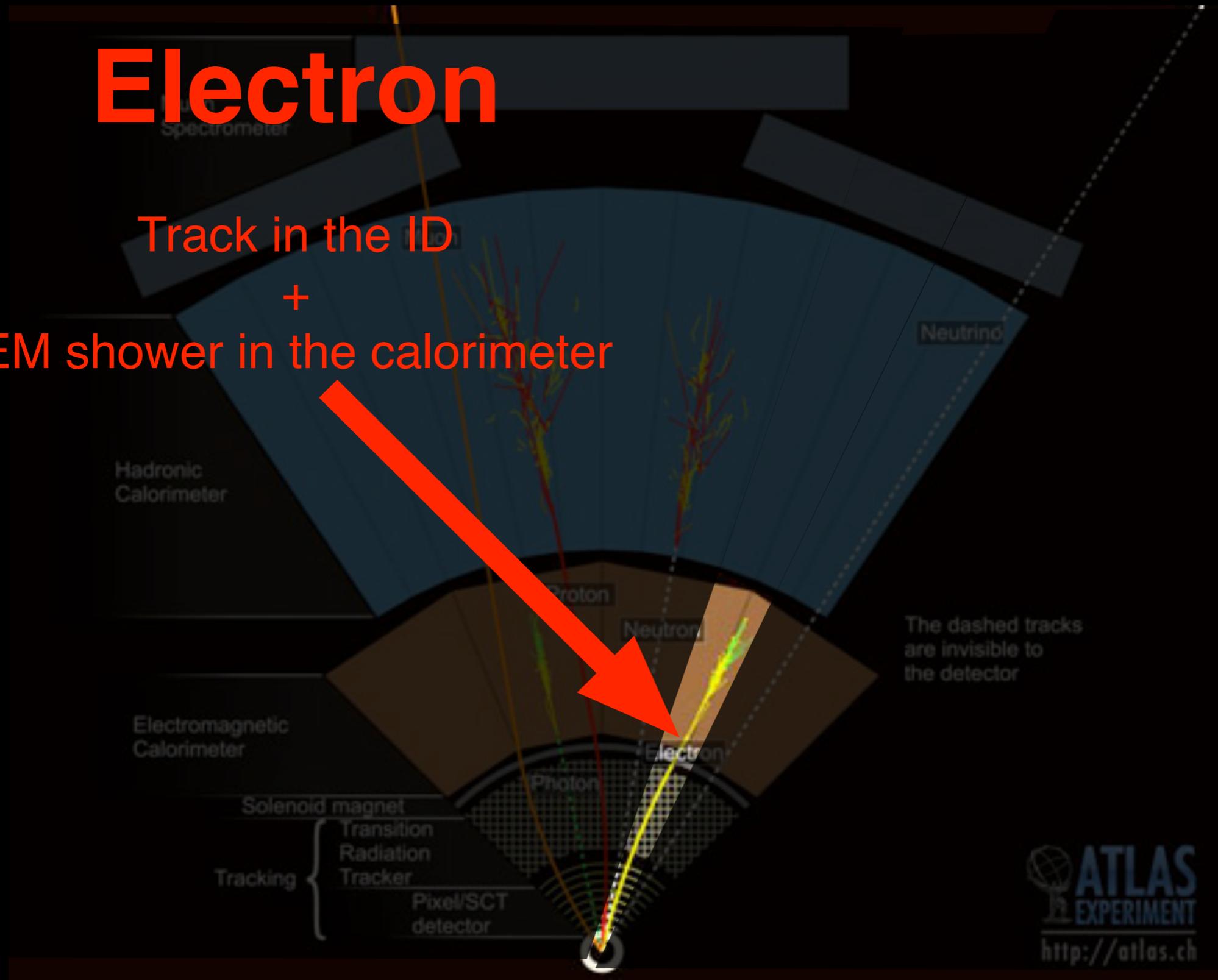
Backup

Concept

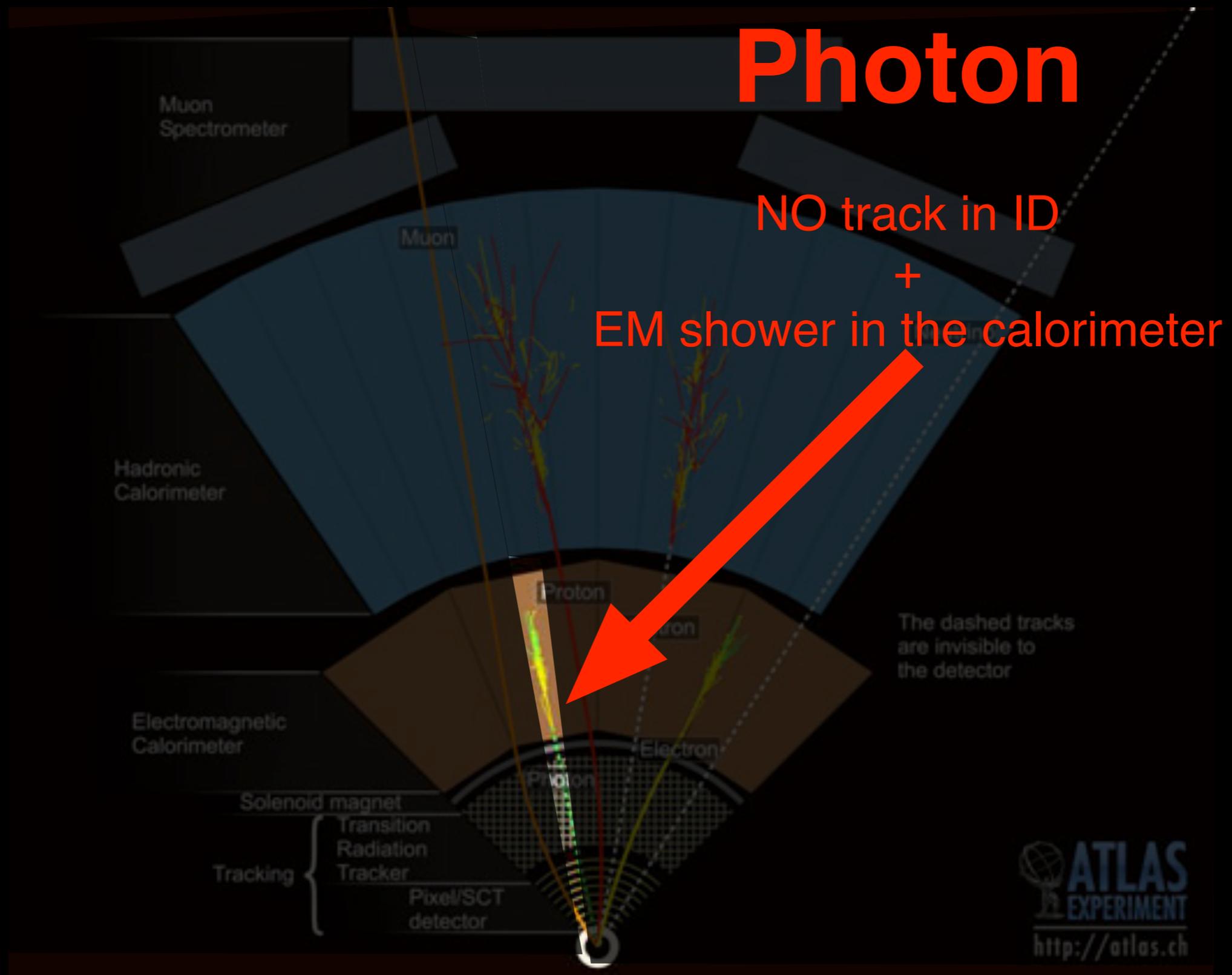


Concept

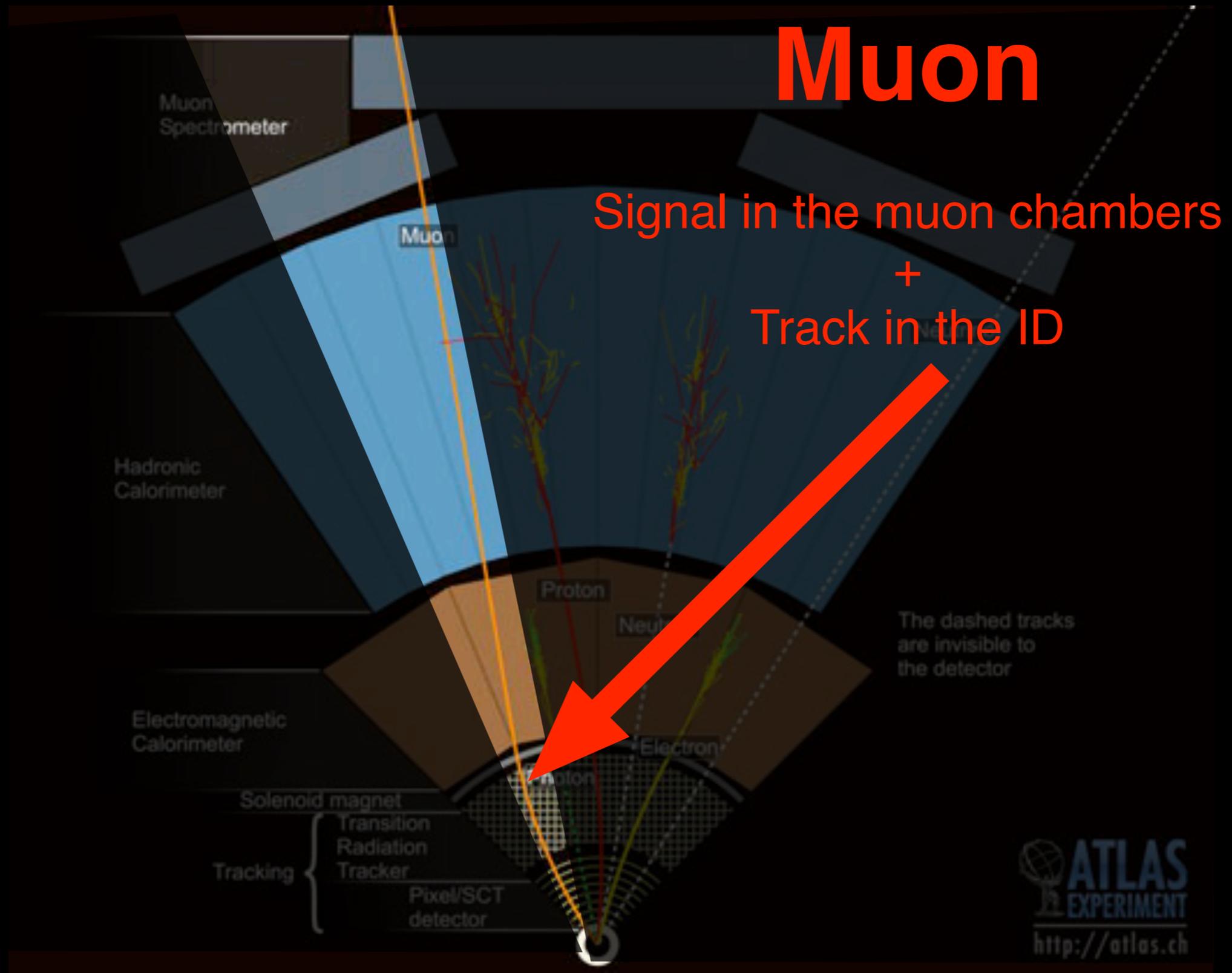
Electron
Track in the ID
+
EM shower in the calorimeter



Concept



Concept

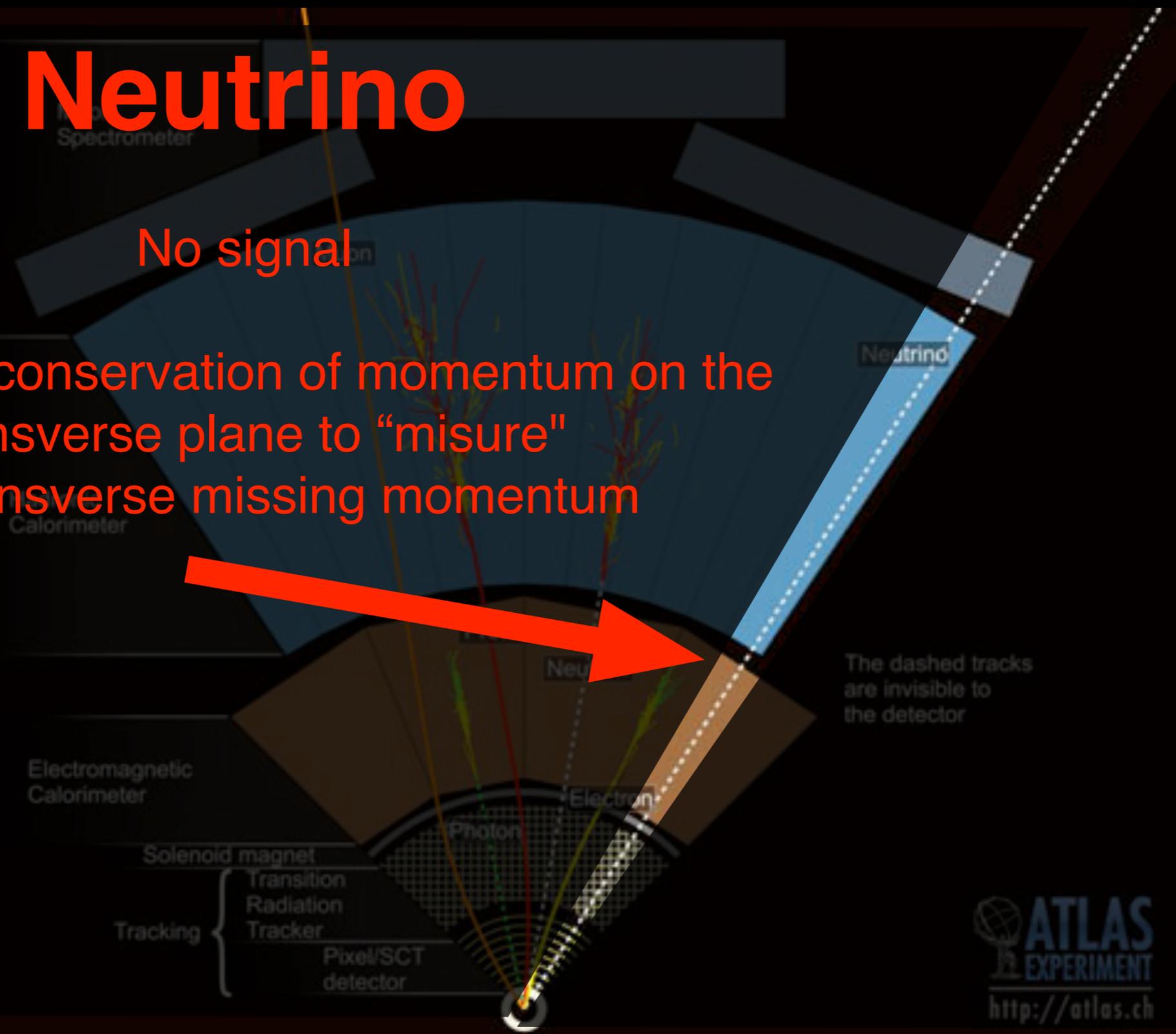


Concept

Neutrino

No signal

We use the conservation of momentum on the transverse plane to "measure" the transverse missing momentum



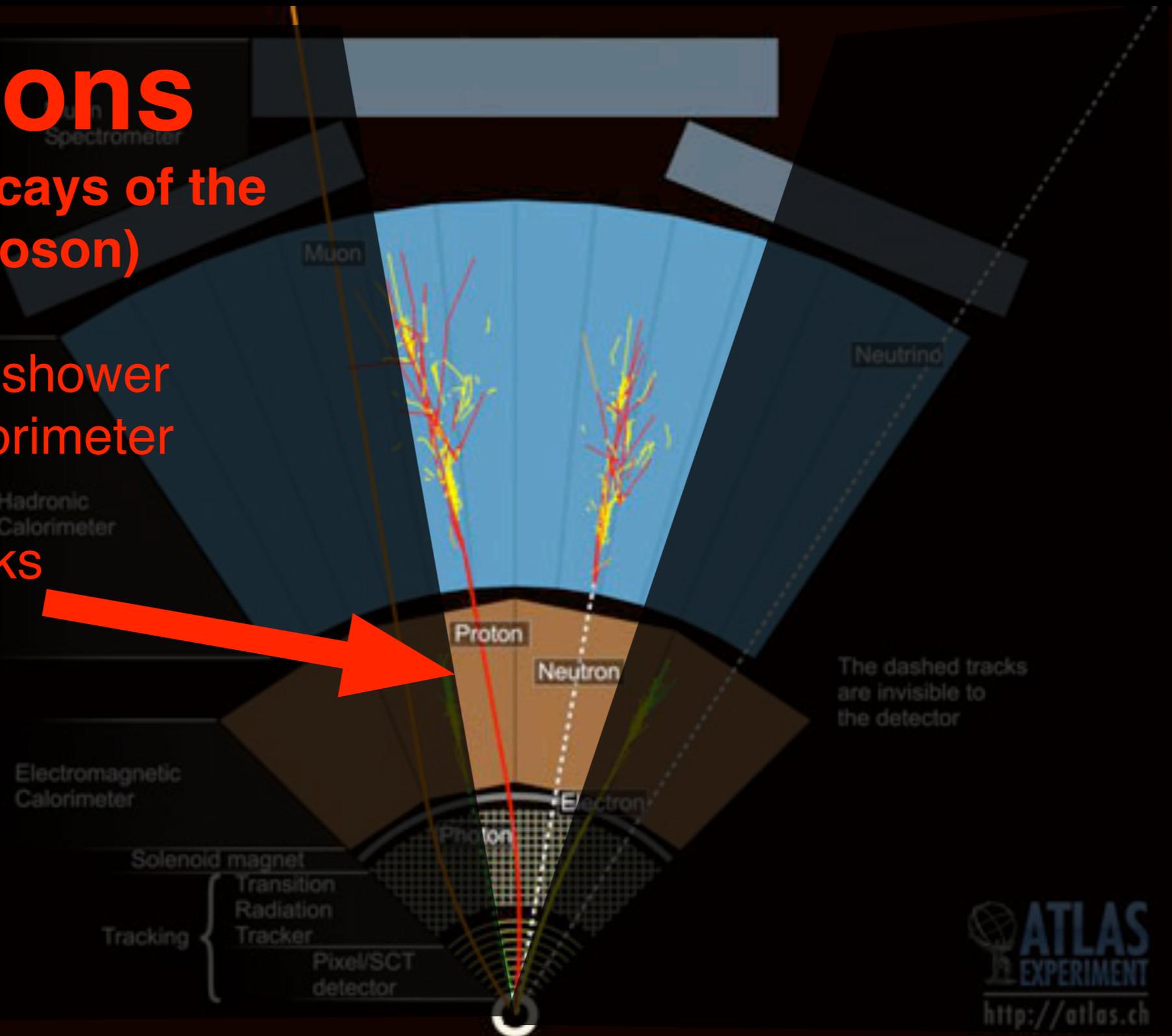
Concept

Hadrons

(in b - or τ -decays of the Higgs boson)

Hadronic shower
in the calorimeter

+ Hadronic
Calorimeter
tracks

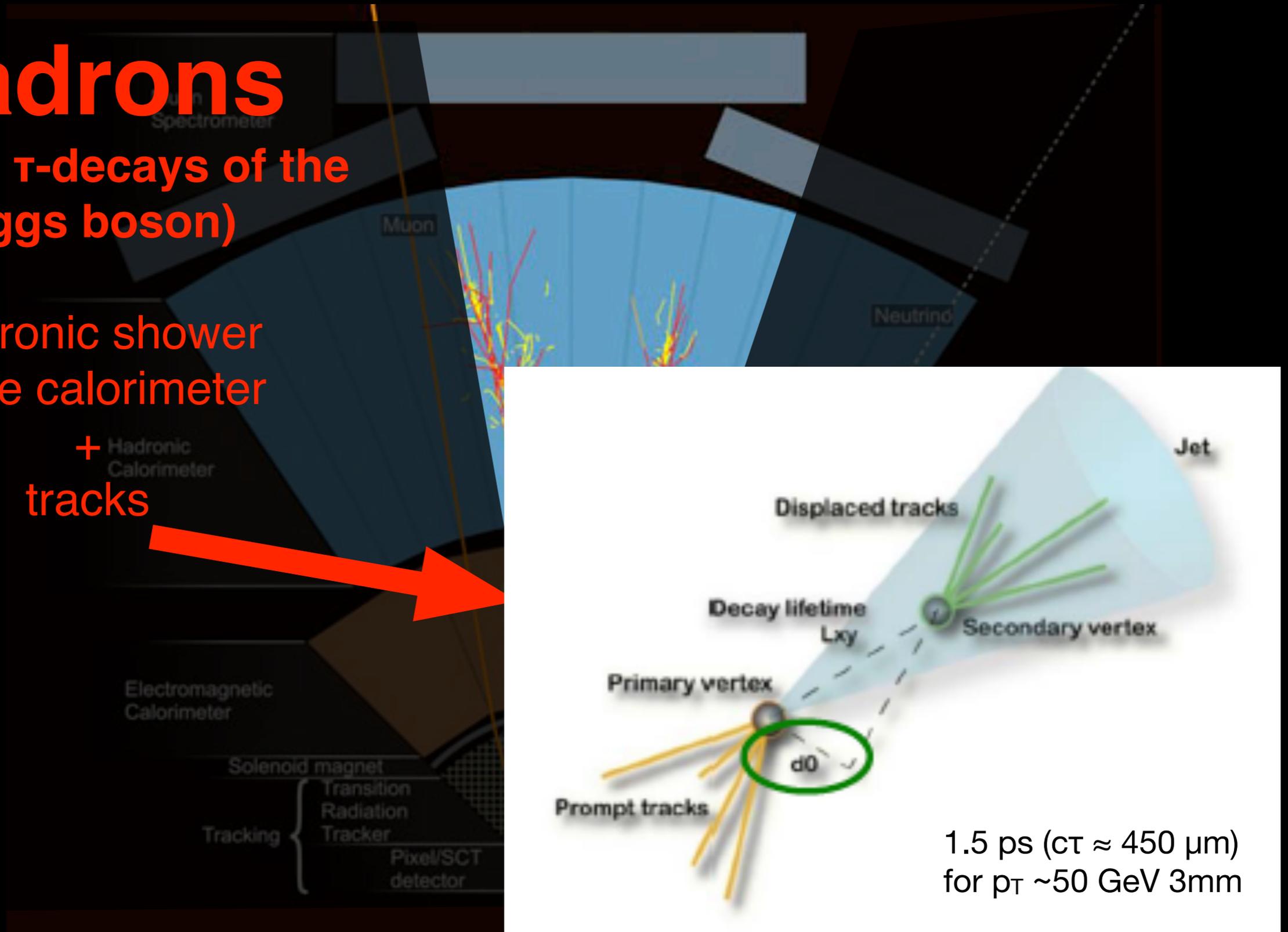


Concept

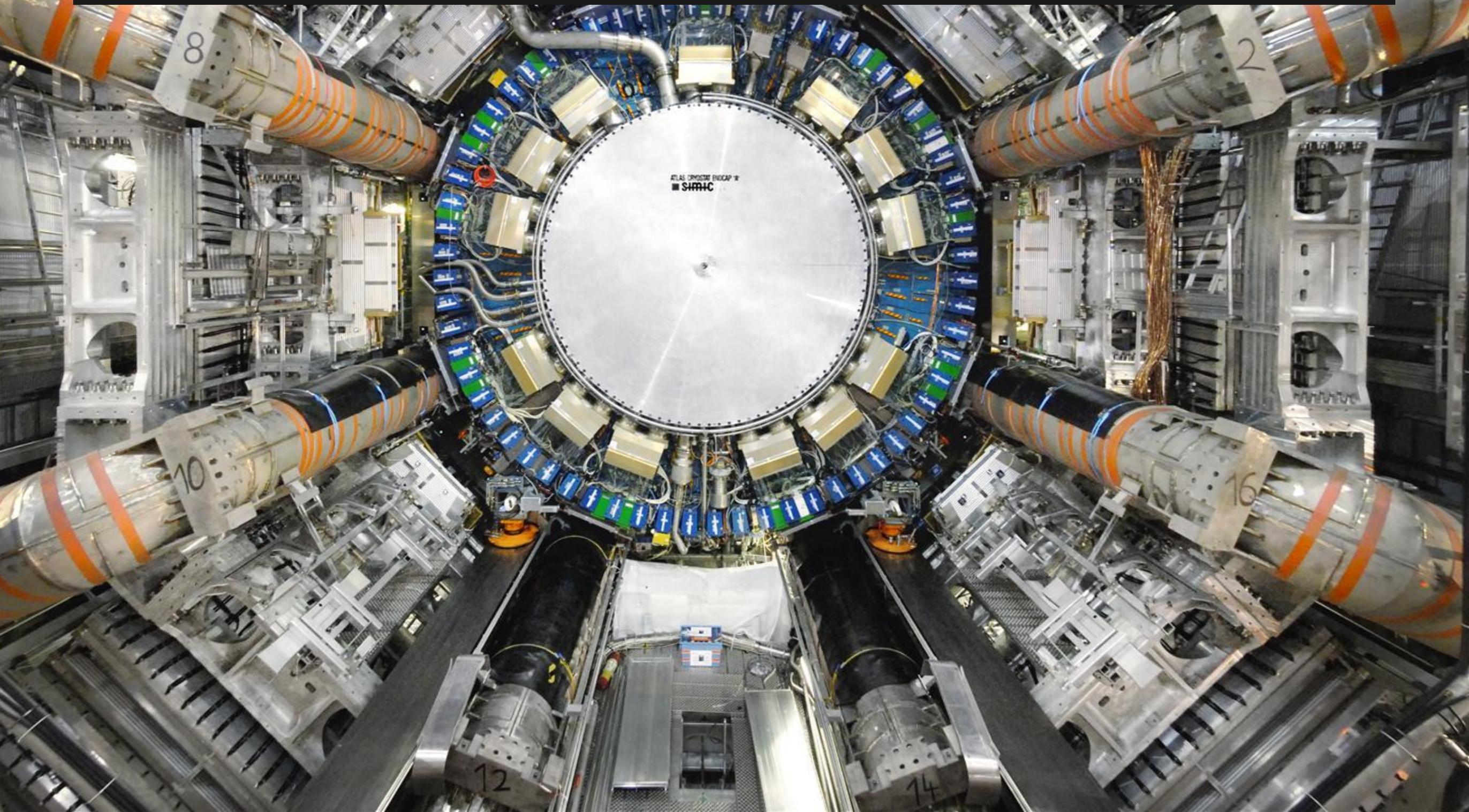
Hadrons (in b - or τ -decays of the Higgs boson)

Hadronic shower
in the calorimeter

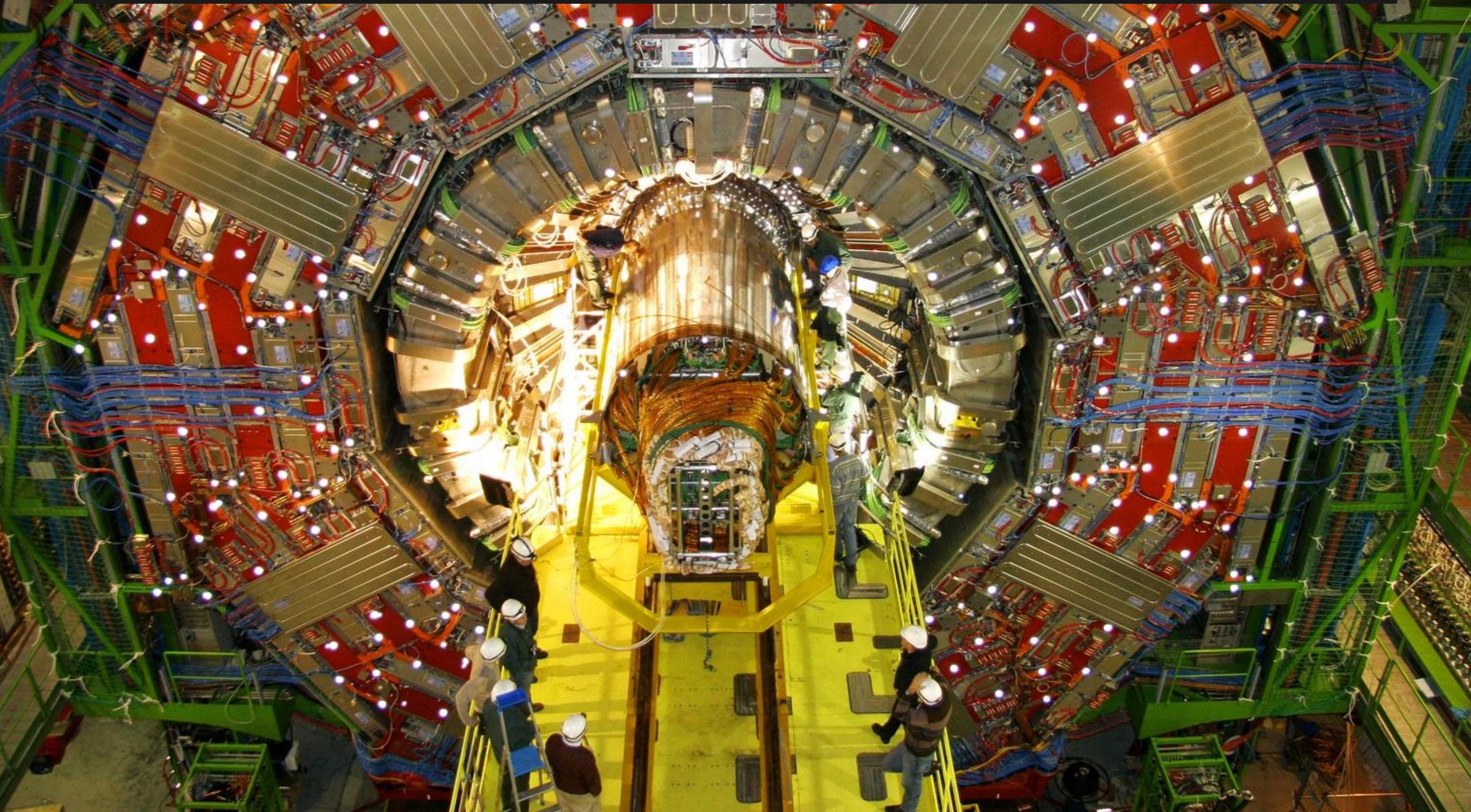
+ Hadronic
Calorimeter
tracks



ATLAS



CMS



Object Resolution

