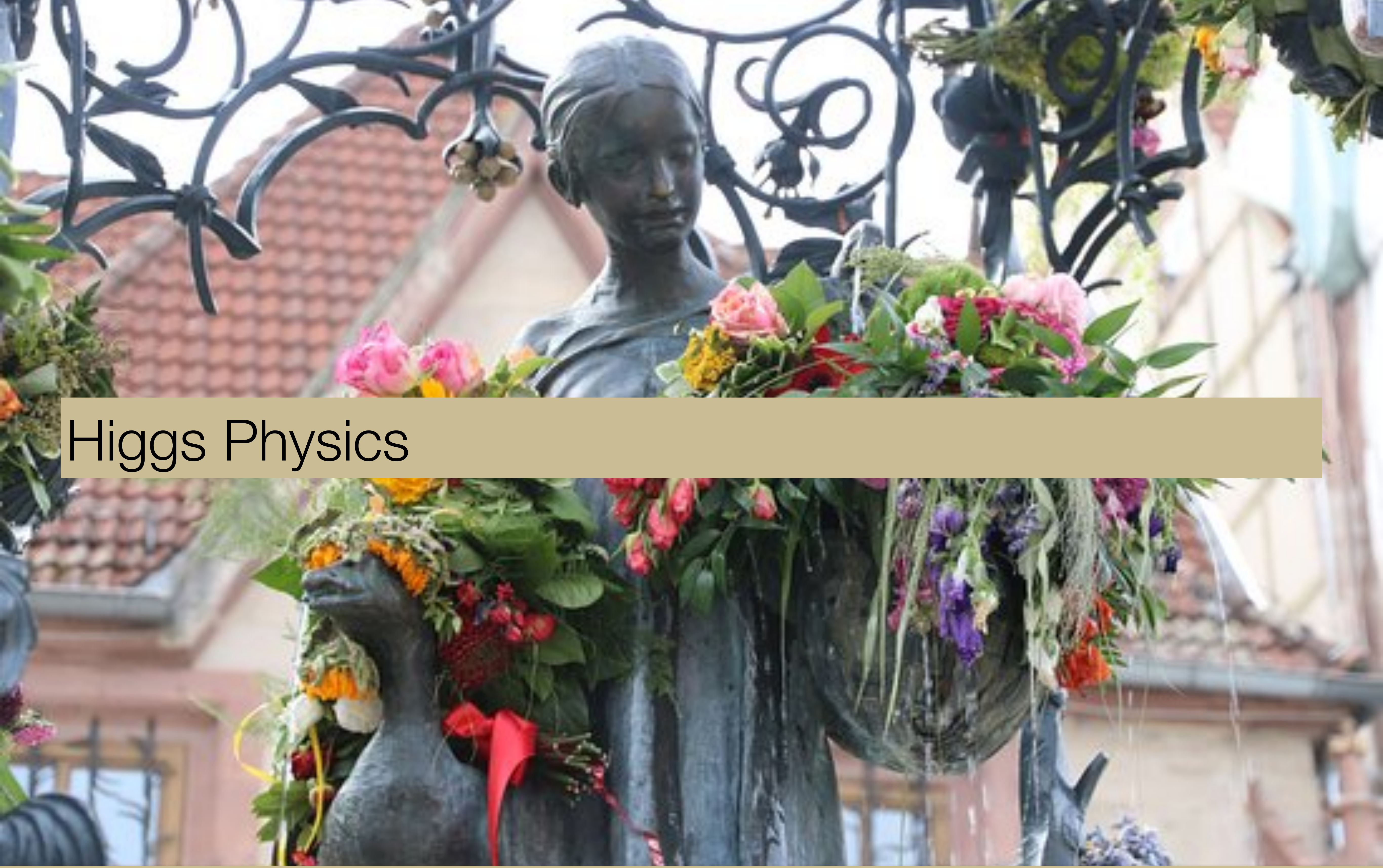
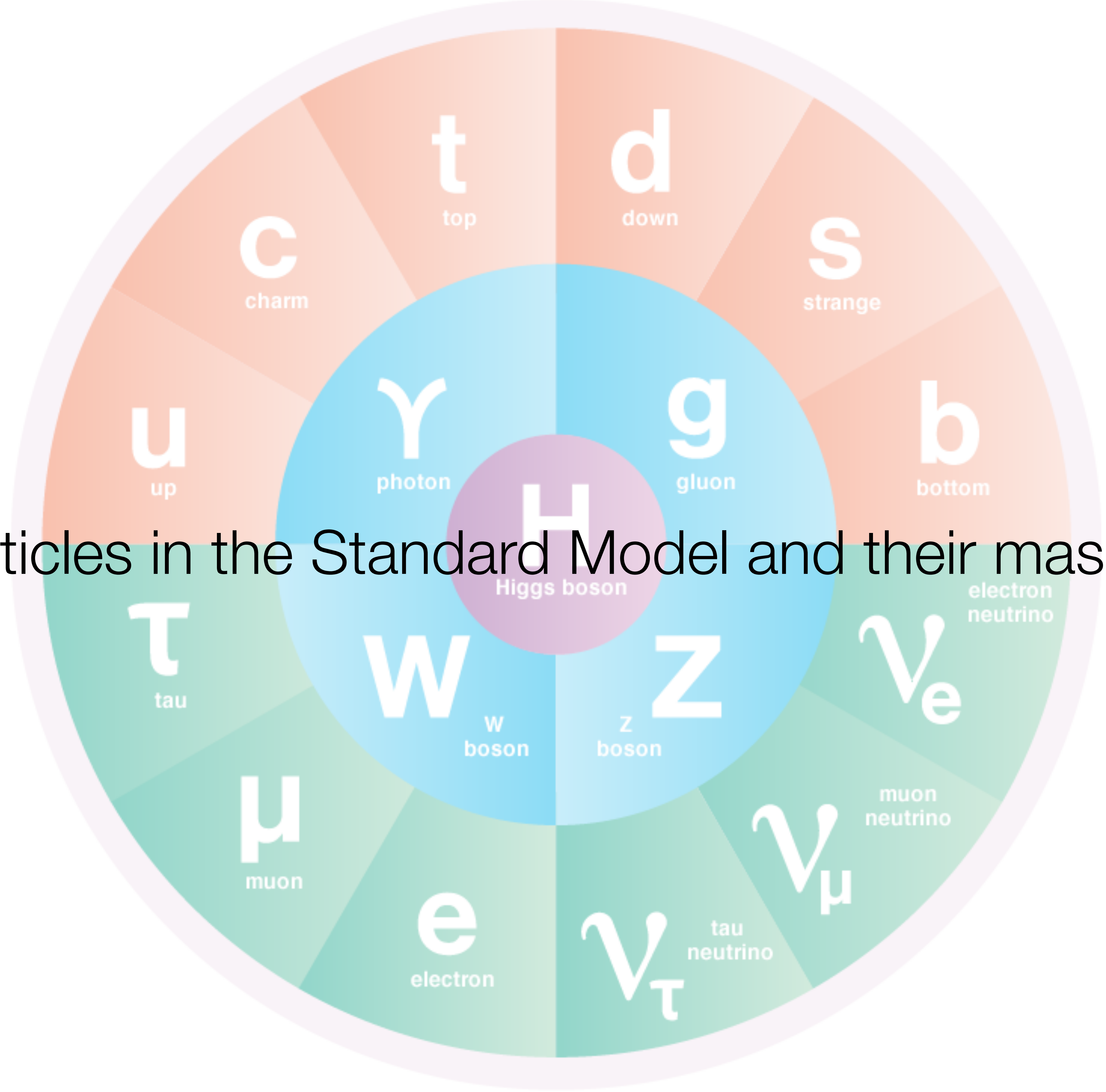


Higgs Physics

Paolo Francavilla - Istituto Nazionale di Fisica Nucleare, Pisa
24/7/2019 - HASCO 2019 - Göttingen

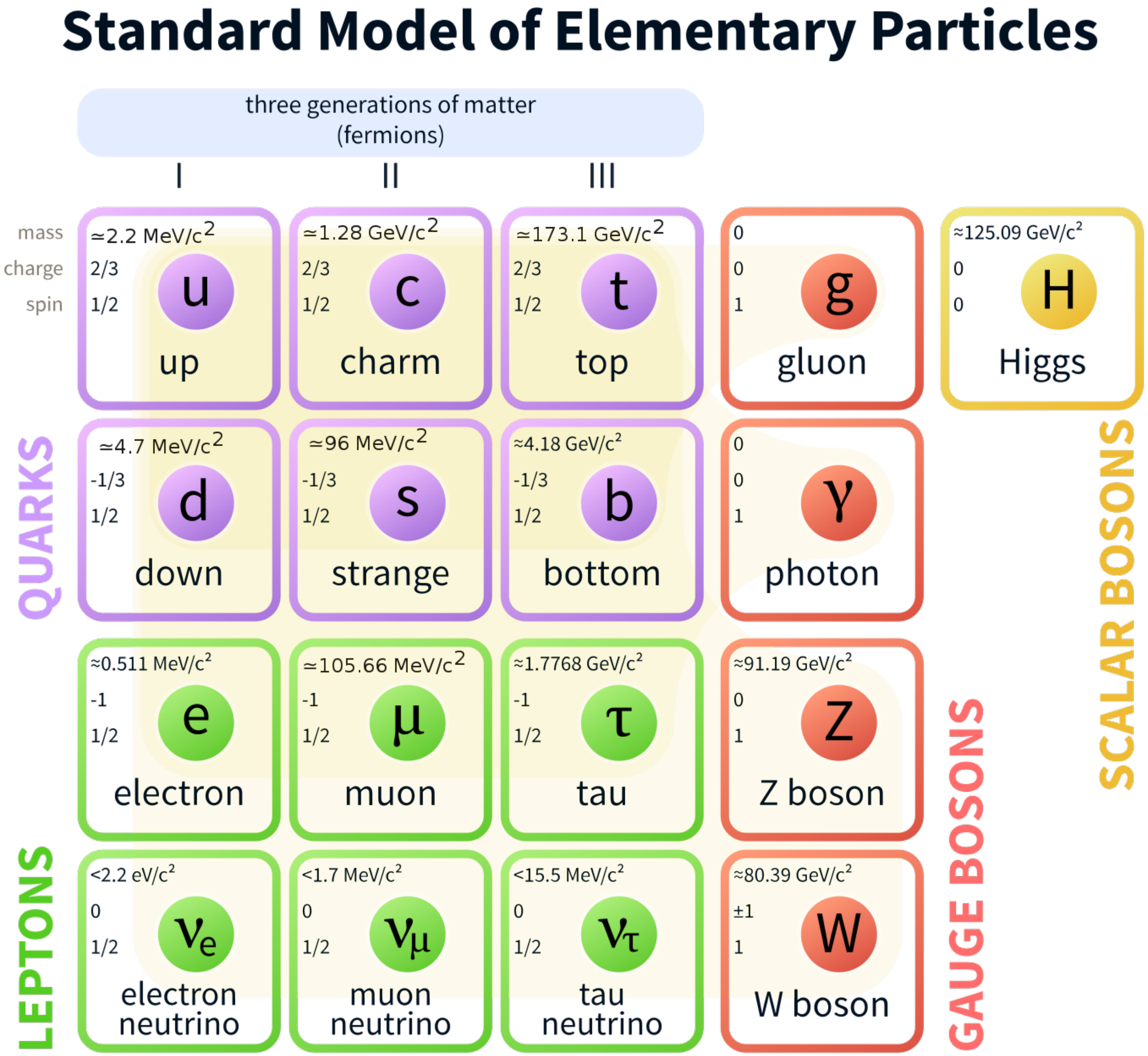
Outline

- **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

		three generations of matter (fermions)				
		I	II	III		
QUARKS	mass charge spin	≃2.2 MeV/c^2 2/3 1/2 u up	≃1.28 GeV/c^2 2/3 1/2 c charm	≃173.1 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
		≃4.7 MeV/c^2 -1/3 1/2 d down	≃96 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS		≈0.511 MeV/c^2 -1 1/2 e electron	≃105.66 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
		<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	

Immagine 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* ⇒ Our scale starts from 0

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

Photons have 0 mass* ⇒ Our scale starts from 0

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

0

$m_p = 22\ \mu g$

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 µg. Where are they?

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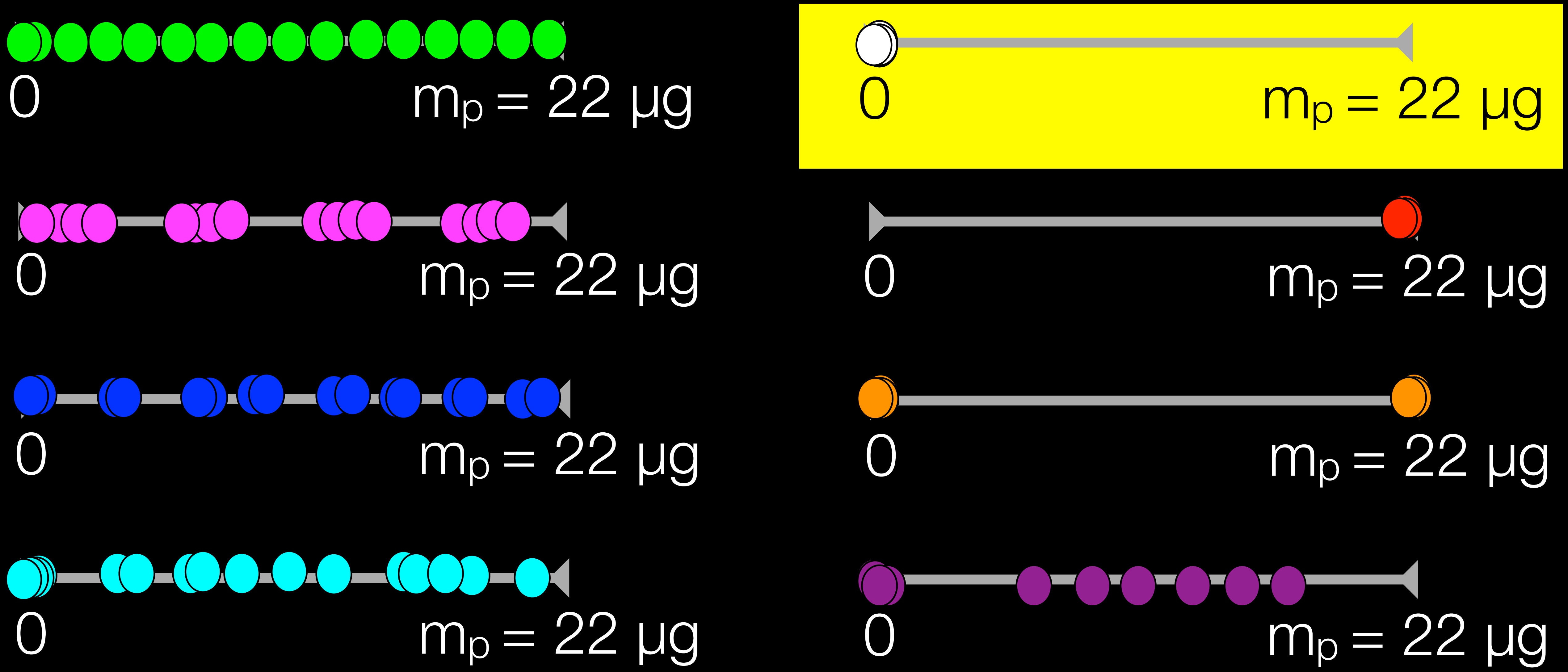
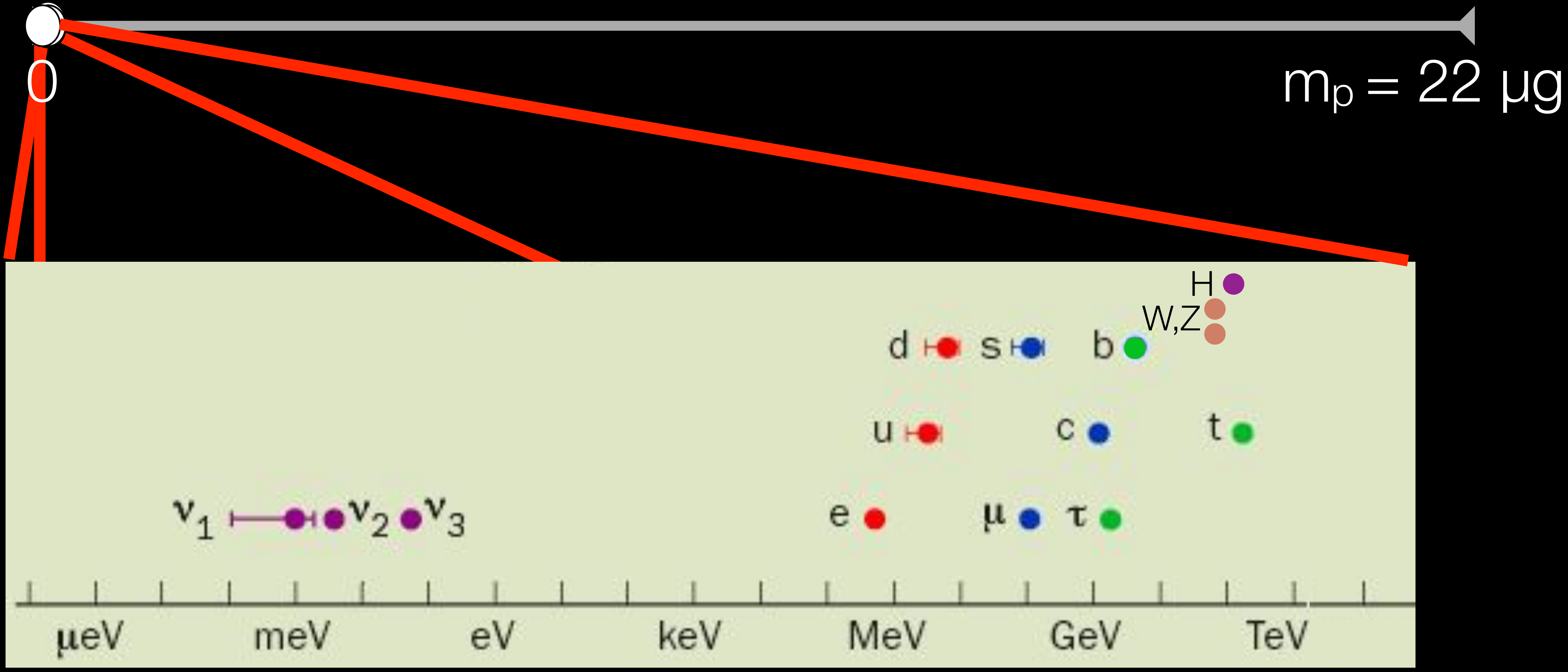


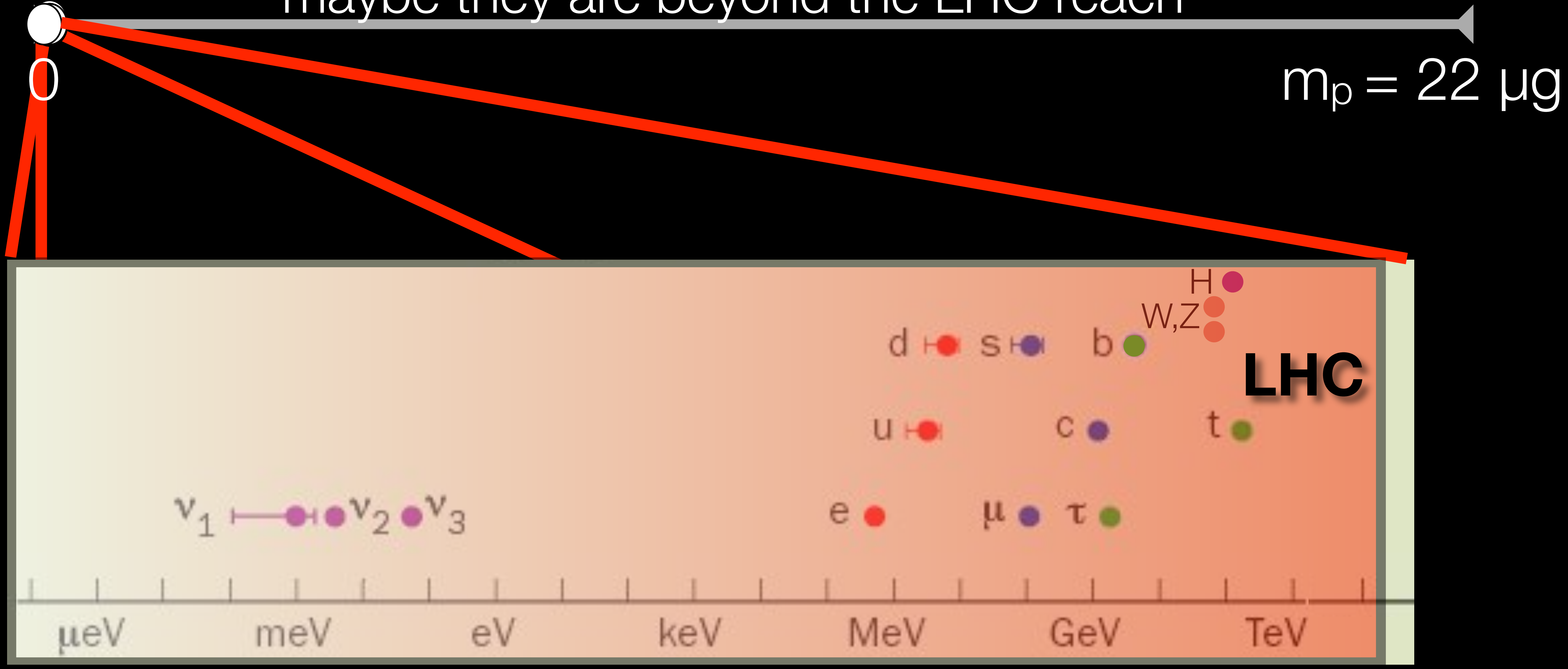
Why?

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.

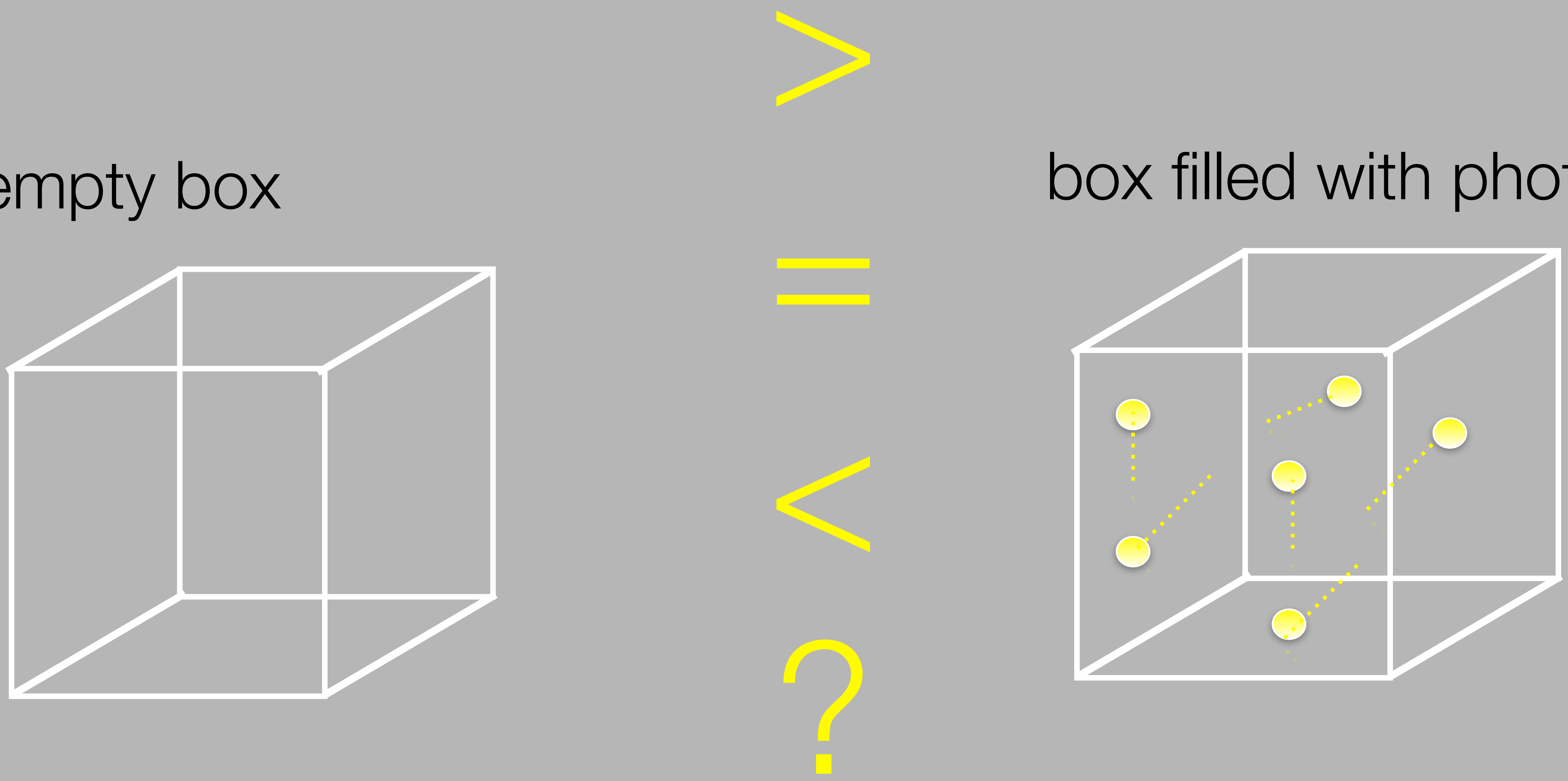
- This theory has all the nice features a theory could need (but one)

- 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

>

=

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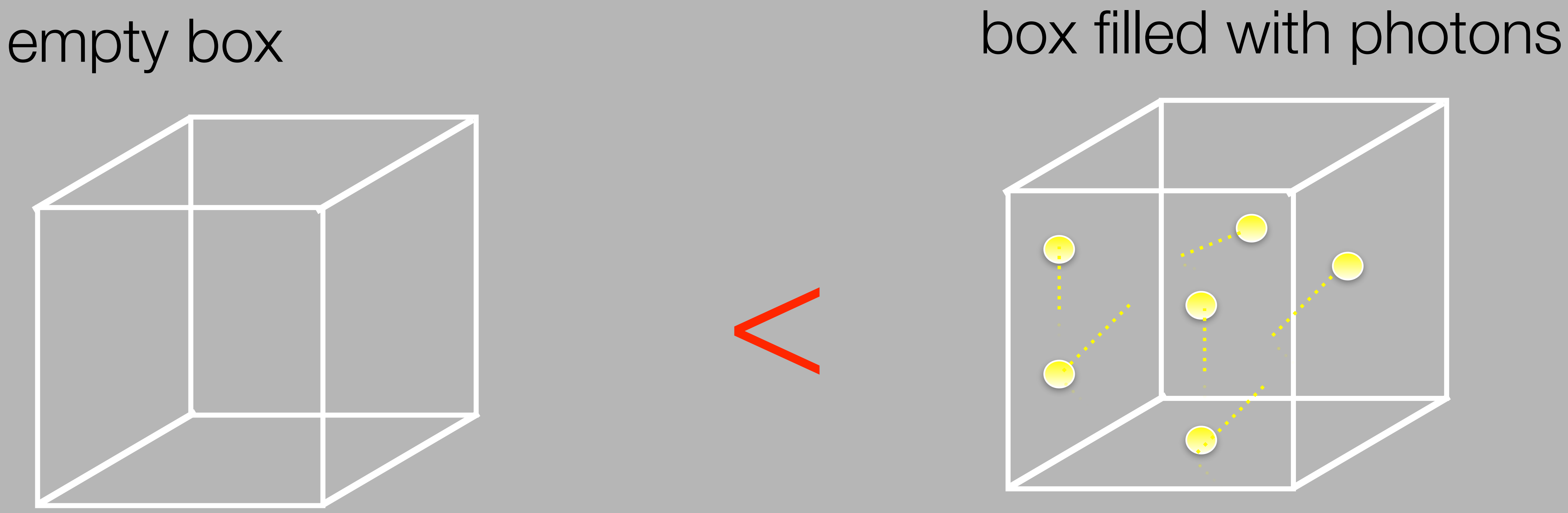
?

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

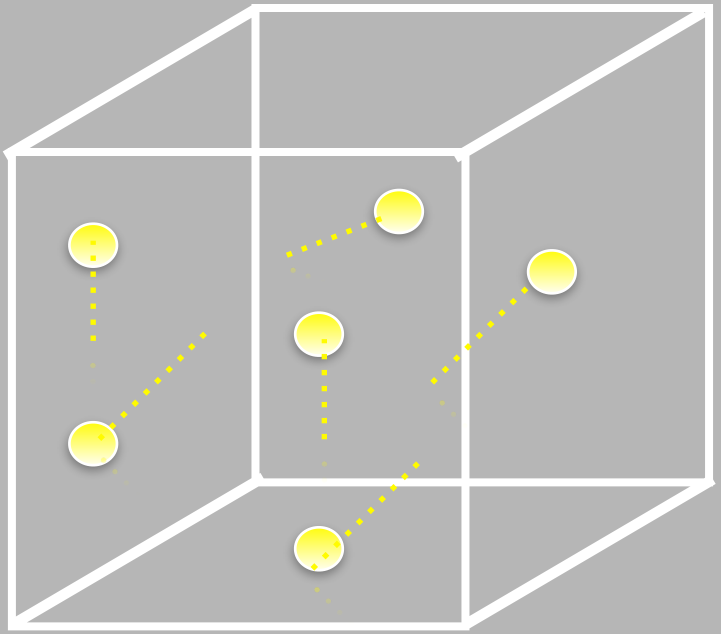


$$m = E/c^2$$

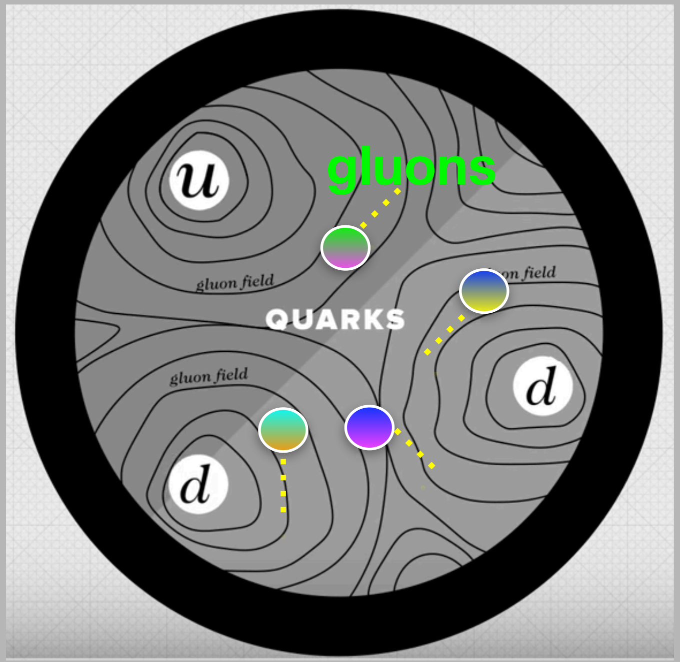
which, by the way, is how Einstein wrote it in his paper

In the real World…

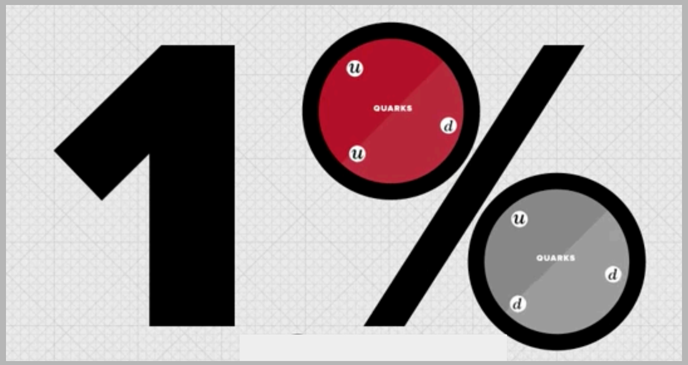
box filled with photons



neutron



Mass of the quarks is



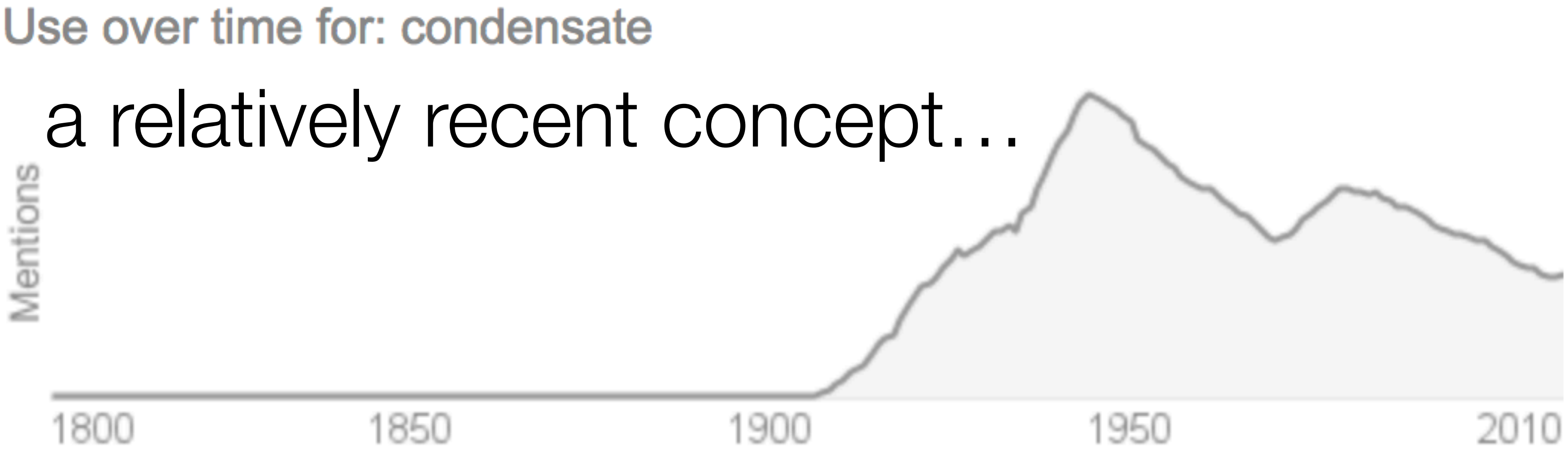
of the mass of protons/neutrons

~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

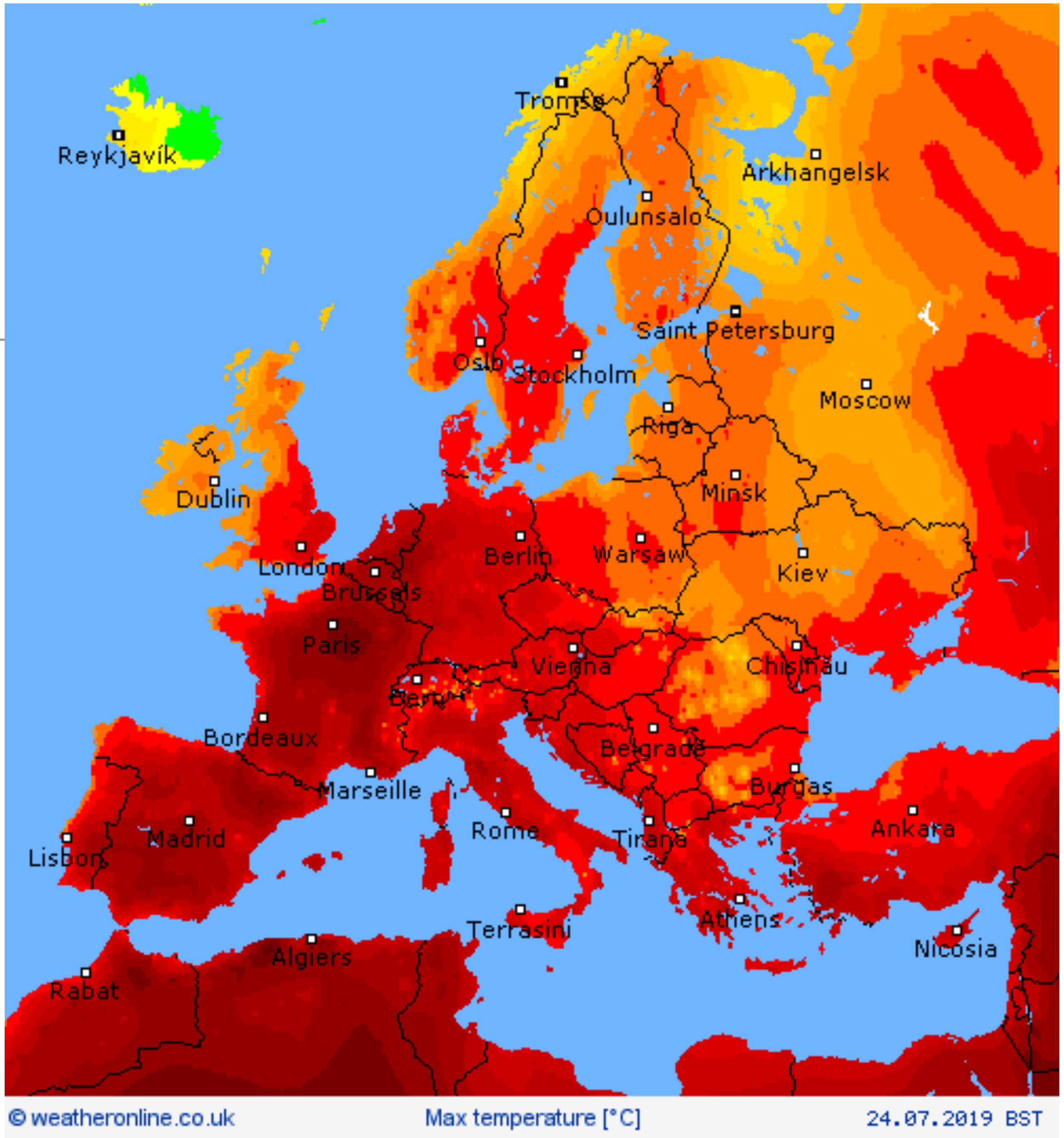
Condensate and the spontaneous breaking of symmetry



a relatively recent concept…

Fields

- Fields characterises the behaviour of a quantity
  in that moment in that place



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- 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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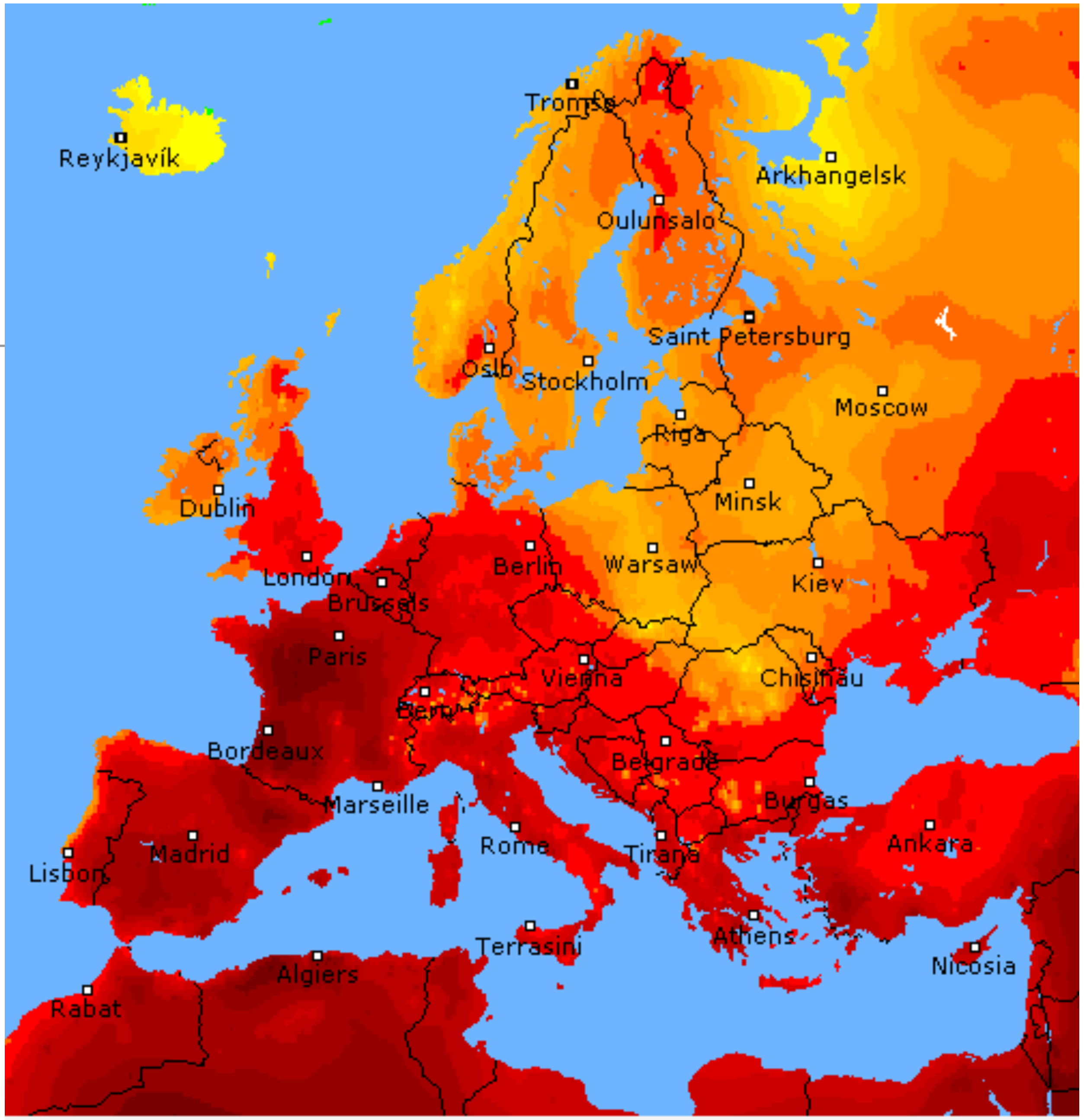

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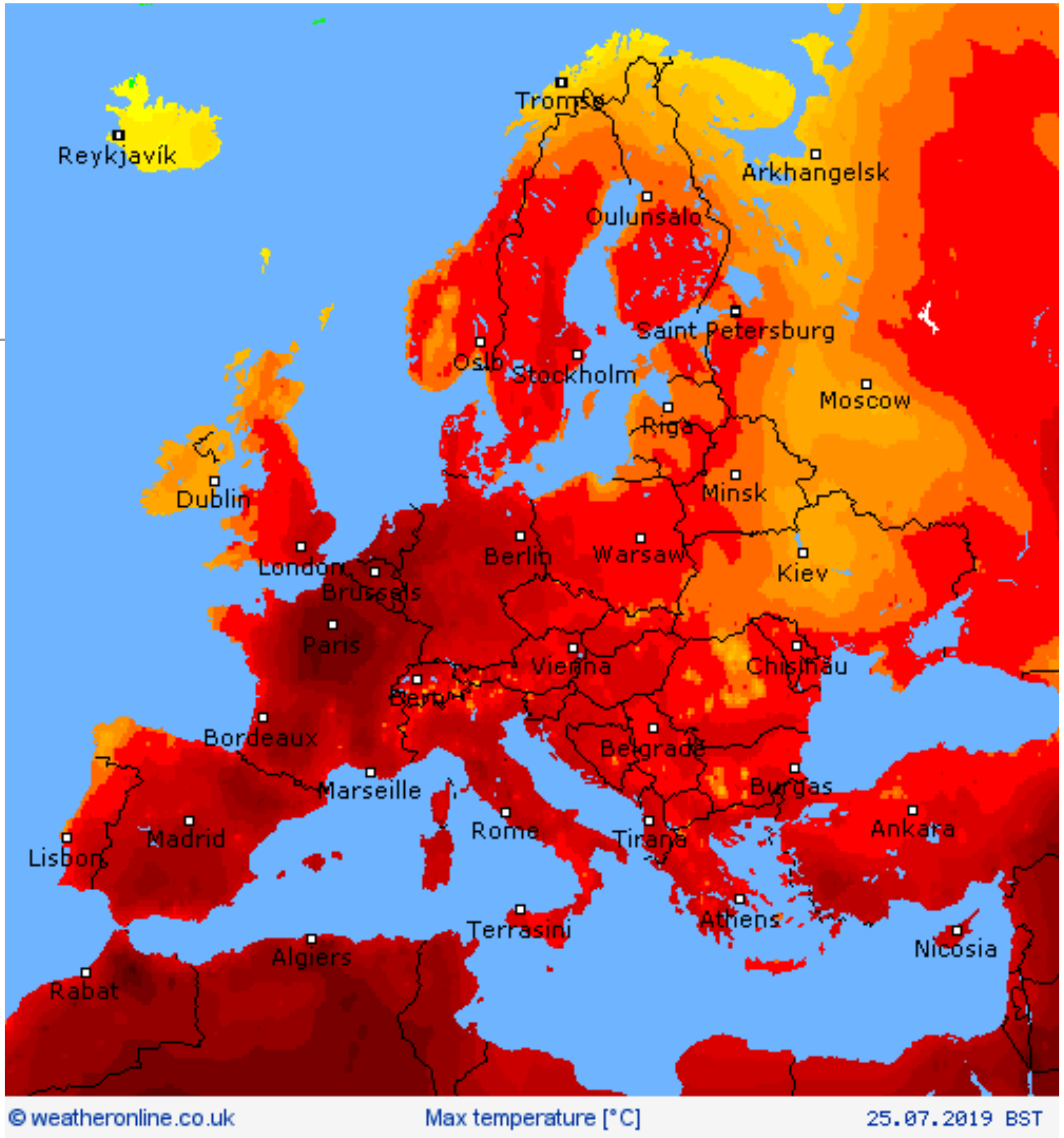

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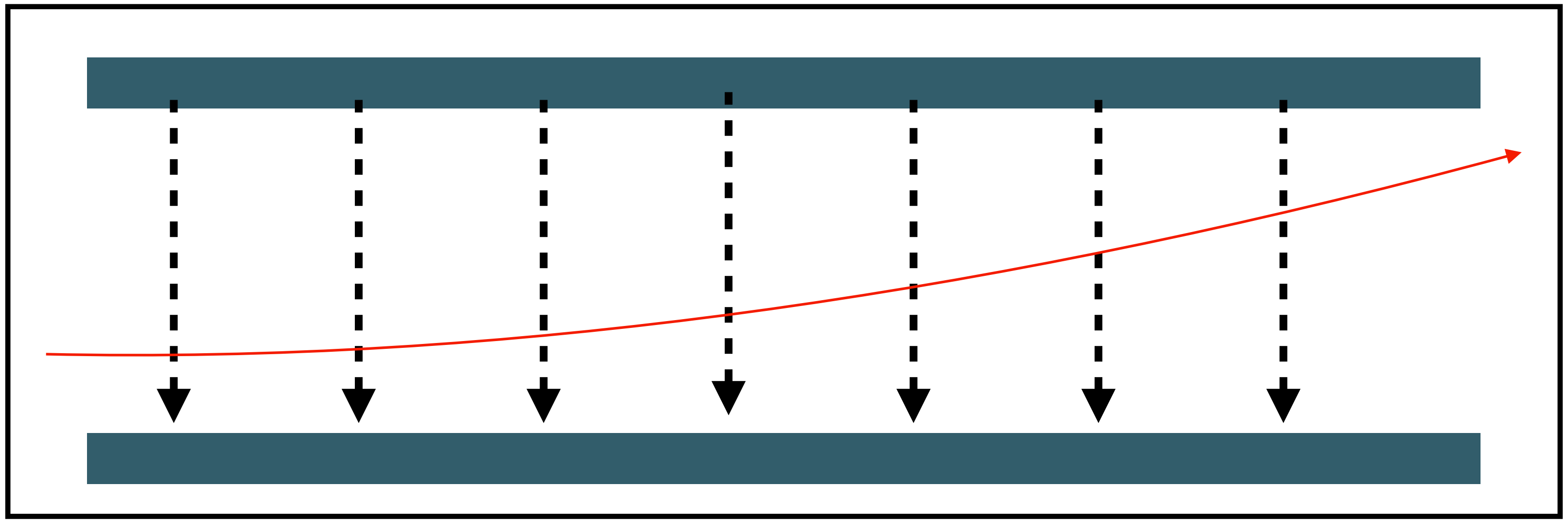
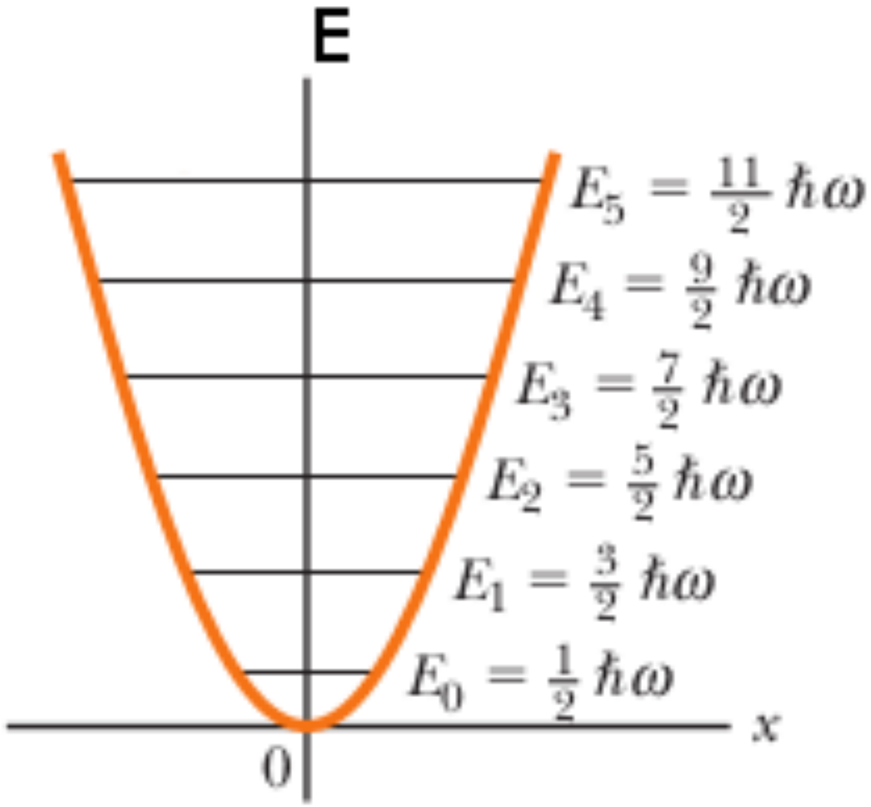
  - They could effect how things are moving, for example electric field
- Space can be filled with fields

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

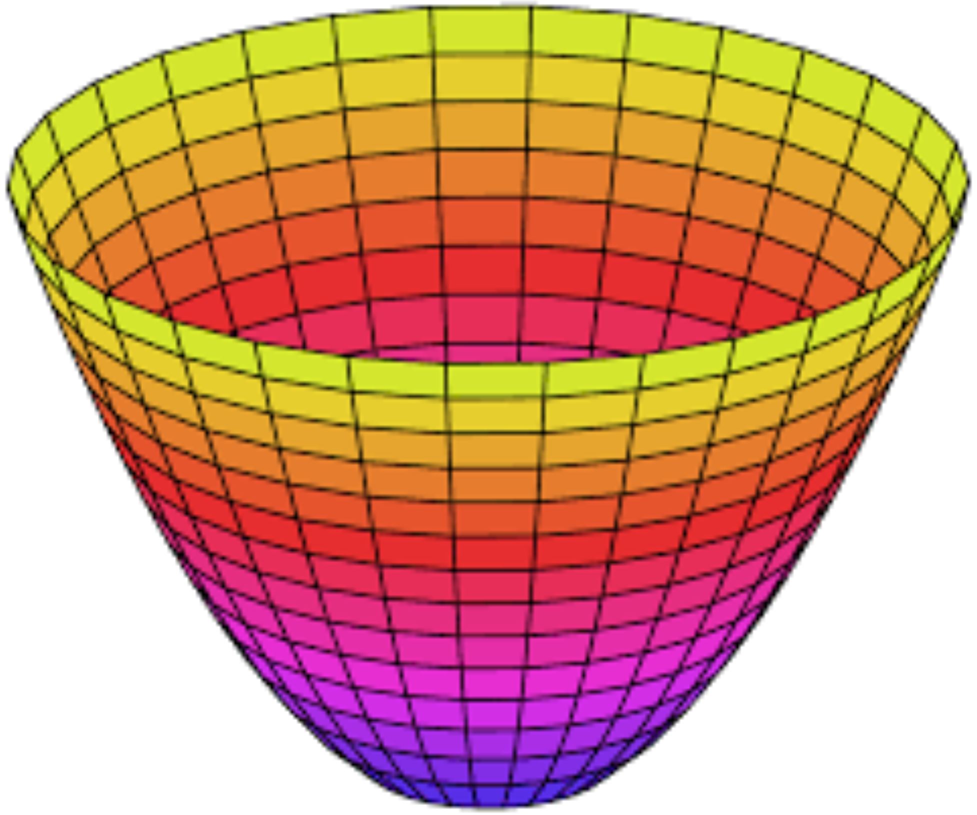


Energy of a field and vacuum



- 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 immagine we have 2 dim field : $\boldsymbol{\Phi}$ =(ϕ_1,ϕ_2)

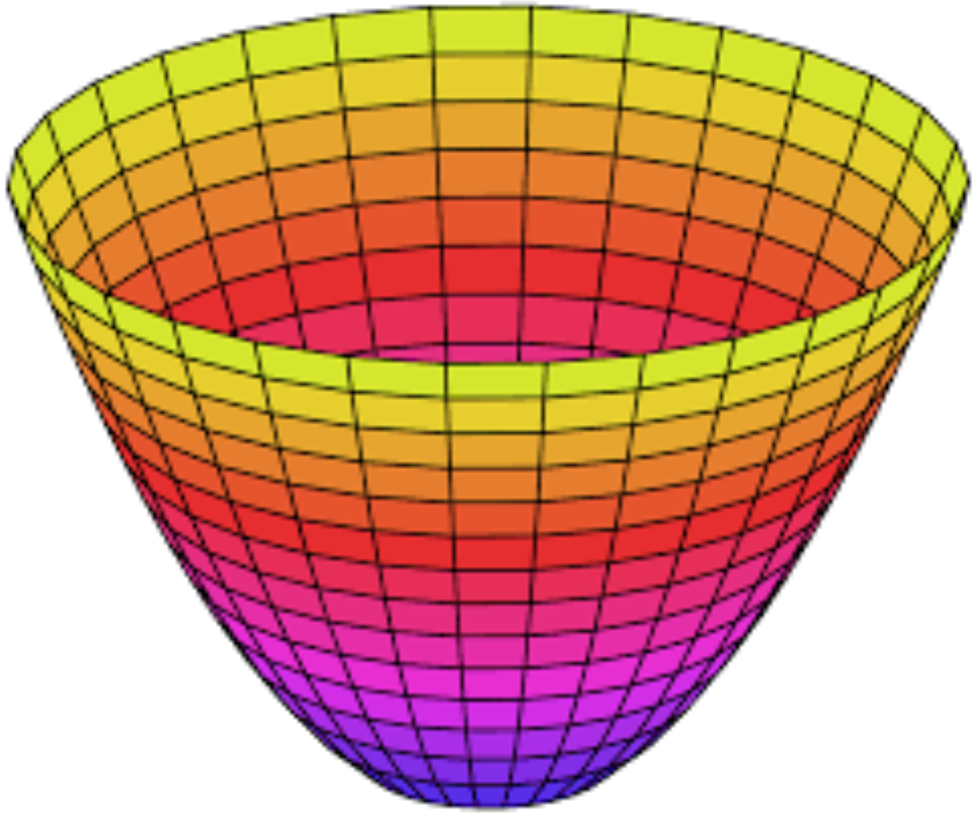
- The energy would depends on both the components

- No matter in which direction we displace the field, it costs energy

- If we have a paraboloid, to minimise the energy, the components of the field would be at the bottom of the "potential".

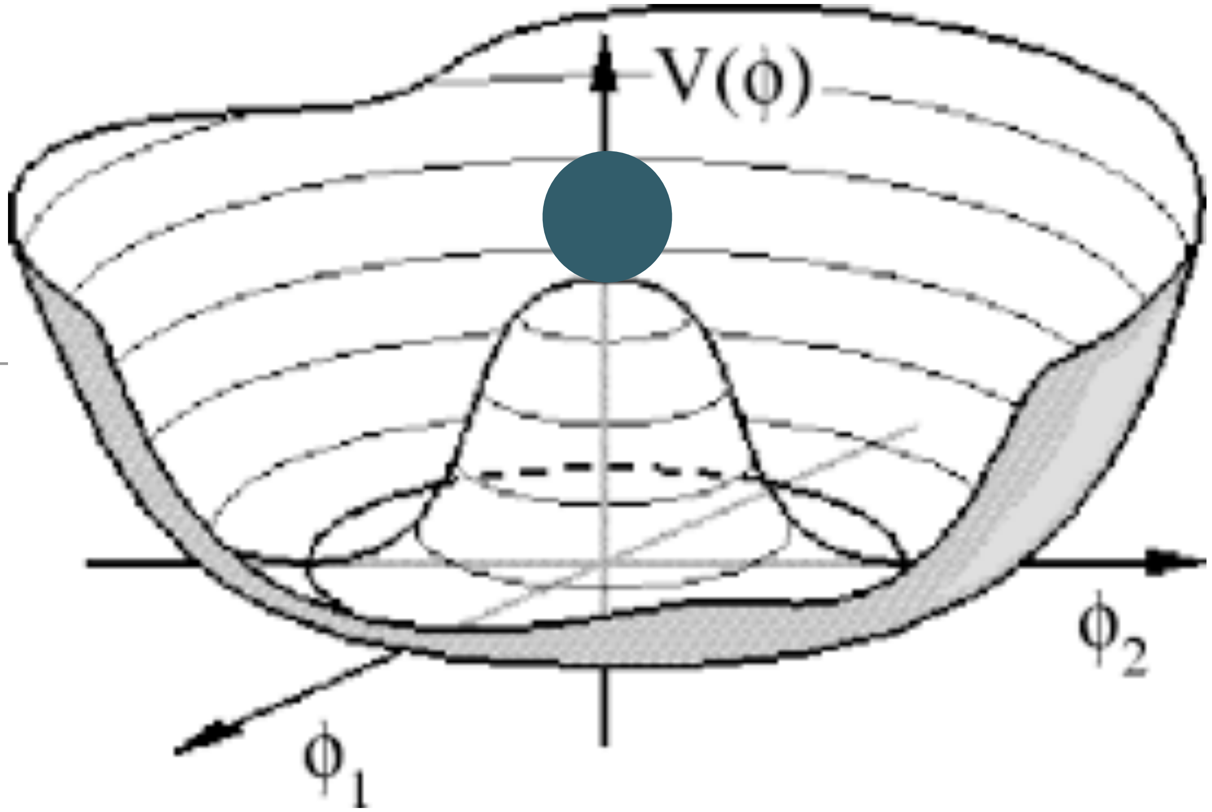
- Must all the fields respect this parabolic shape?

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

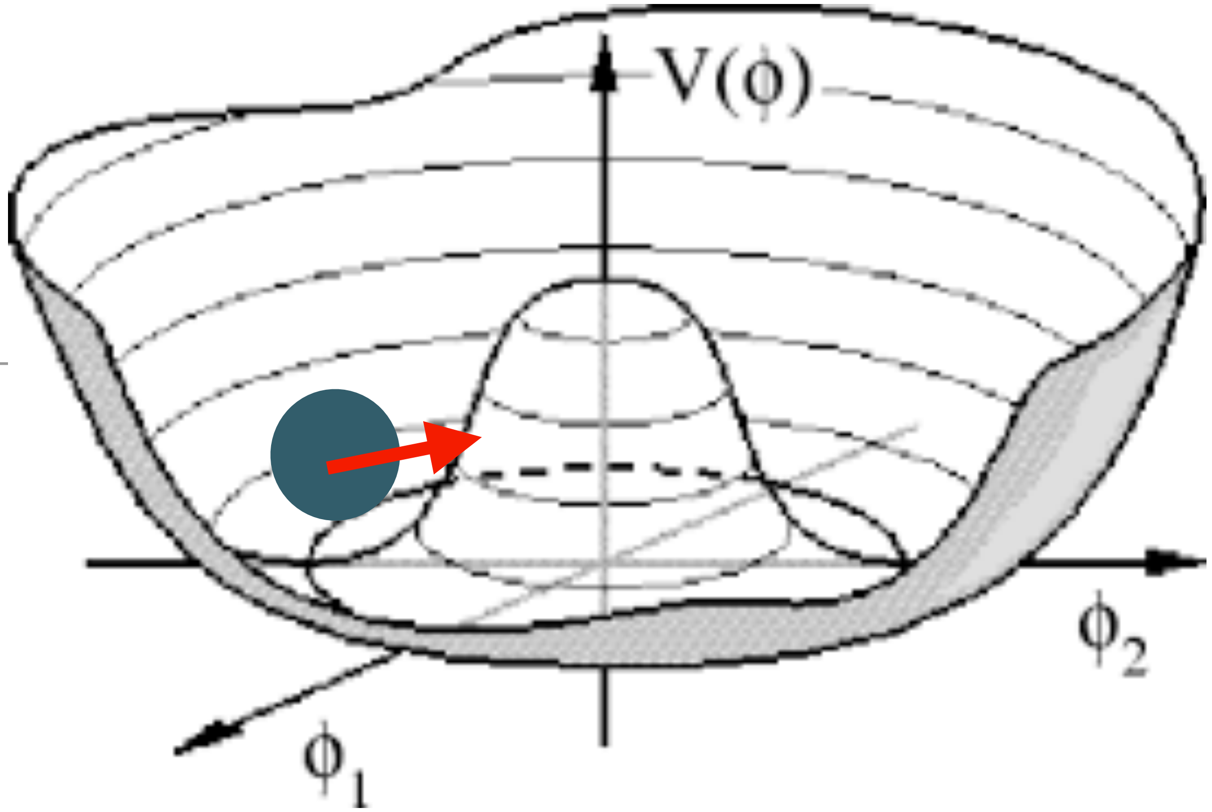


- Maximum at the top of the hat.
  So, **ϕ** =(0,0) is not the stable equilibrium
    - un-stable equilibrium
- The brim of the hat is where a ball placed on the top of the hat is going to go.
- The lowest energy state for the field would not be at zero field, but it would be in the brim.
- Interesting!!! The zero energy of the field is not at **ϕ** =(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



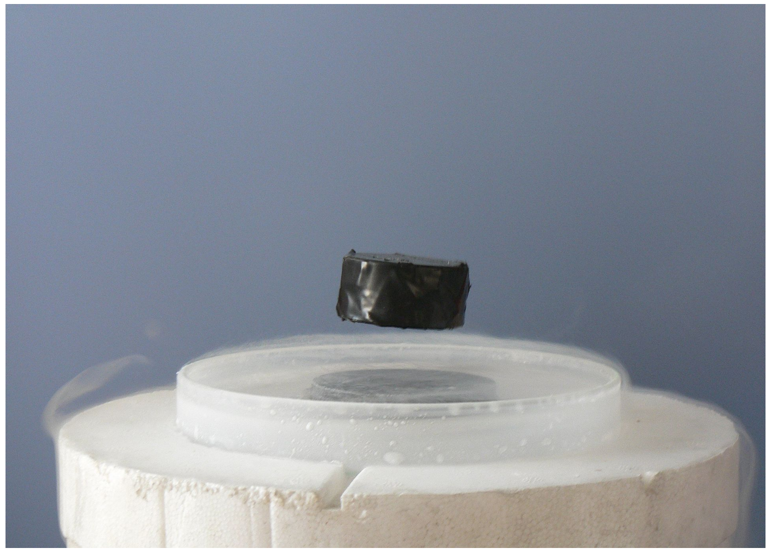
- **What if we want to find the lowest energy that the vacuum can have?**
  - Best bet: make the field not move with time
- Remember, ride up the potential cost energy,
  - but there is still some “kinetic” energy in moving in circle.
- *So minimum is should be standing steel?*
- **Problem:** uncertainty principle

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

- 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 empt space with no charge in it**
- **Empty space is filled with a totally uncertain amount of charge.**

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 trough 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 word 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:

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

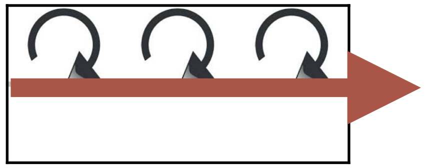
It seems like these are two independent degrees of freedom in the particle zoo…

Dirac theory of fermions: few “naive" considerations

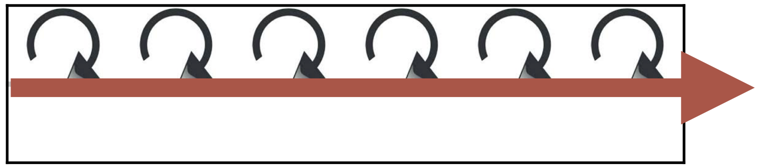
- For 0 mass fermions, the two chiral spinors have a well defined physical meaning:

- 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)

Following the massless fermions



Following the massless fermions



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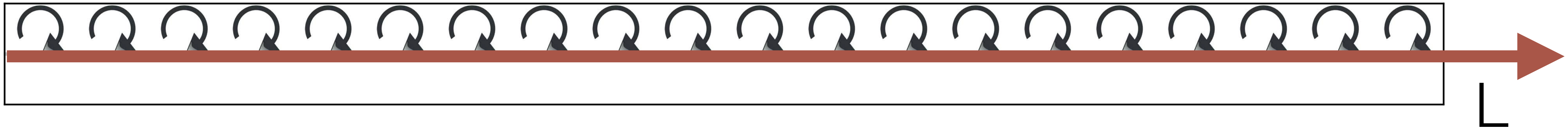
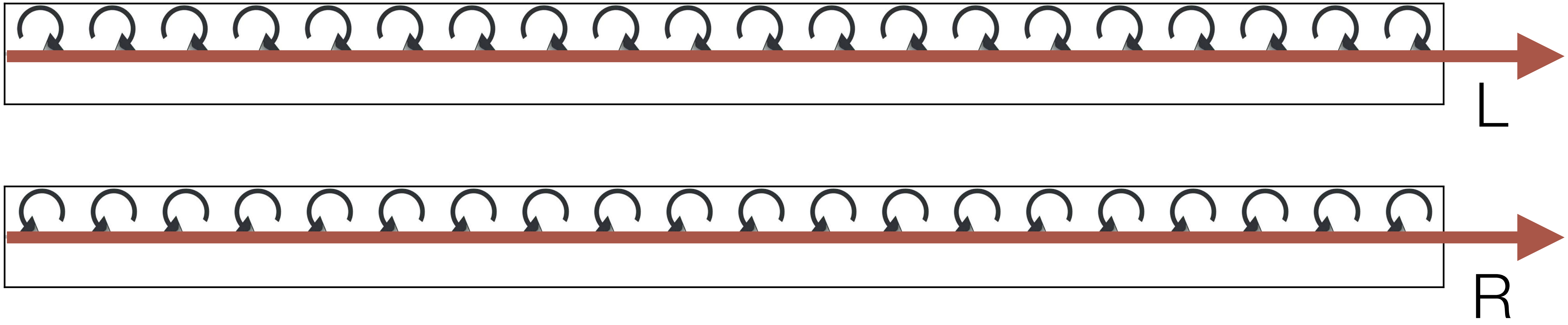


Following the massless fermions



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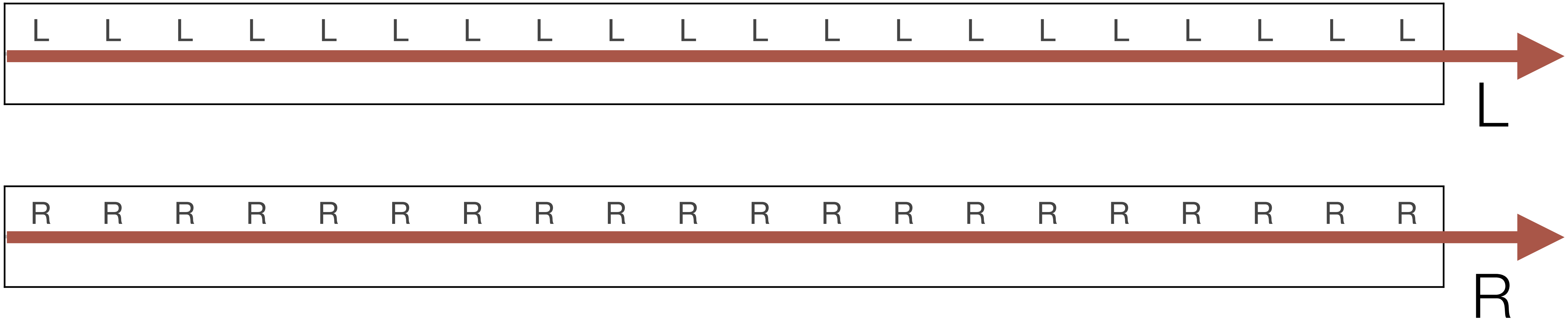


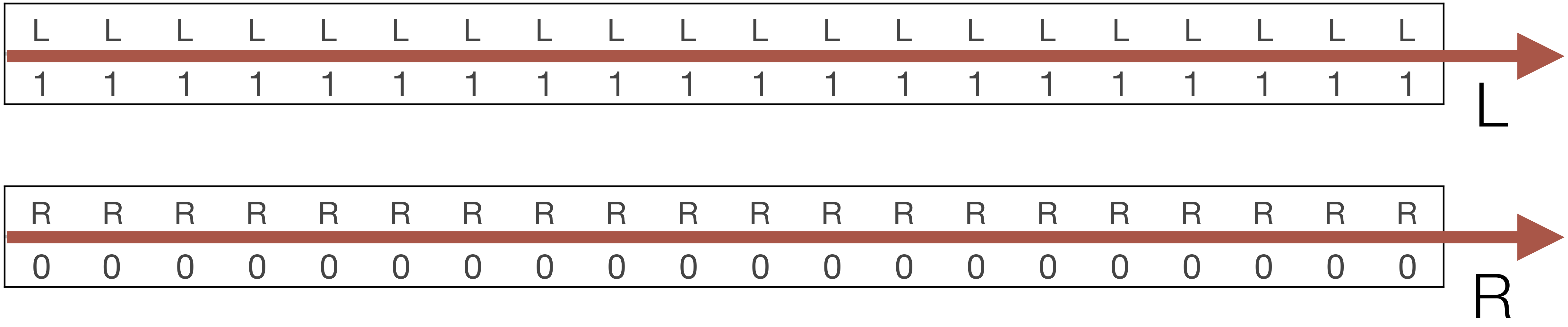
- Are the LH and RH fermions completely equivalent in terms of interactions?
  - NO!!!!
- LH are charged for SU(2) weak isospin interaction
- RH are neutrals for SU(2) weak isospin interaction*

$$\begin{aligned}
\mathcal{L}_{CC} &= g\,W^1_\mu\,\bar{L}_L\,\gamma^\mu\,\frac{\sigma_1}{2}\,L_L + g\,W^2_\mu\,\bar{L}_L\,\gamma^\mu\,\frac{\sigma_2}{2}\,L_L \\
\mathcal{L}_{NC} &= \frac{g}{2}\,W^3_\mu\,[\bar{\nu}_{eL}\,\gamma^\mu\,\nu_{eL} - \bar{e}_L\,\gamma^\mu\,e_L] + \frac{g'}{2}\,B_\mu\Big[Y(L)\,(\bar{\nu}_{eL}\,\gamma^\mu\,\nu_{eL} + \bar{e}_L\,\gamma^\mu\,e_L) \\
&\quad + Y(\nu_{eR})\,\bar{\nu}_{eR}\,\gamma^\mu\,\nu_{eR} + Y(e_R)\,\bar{e}_R\,\gamma^\mu\,e_R\Big]
\end{aligned}$$

- Why? One of the big mysteries….

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

Following the massless fermions



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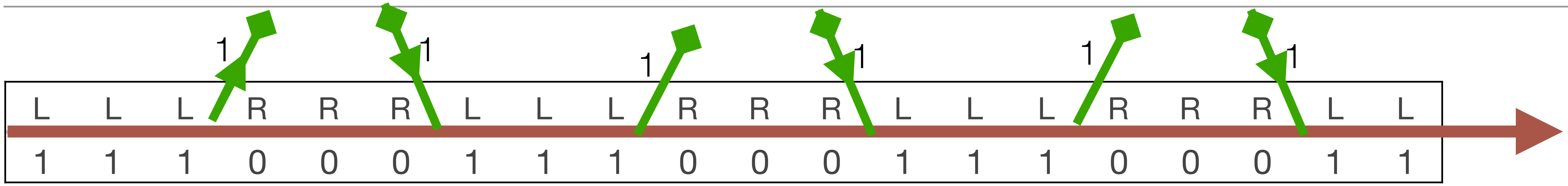
- Why? One of the big mysteries.

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

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

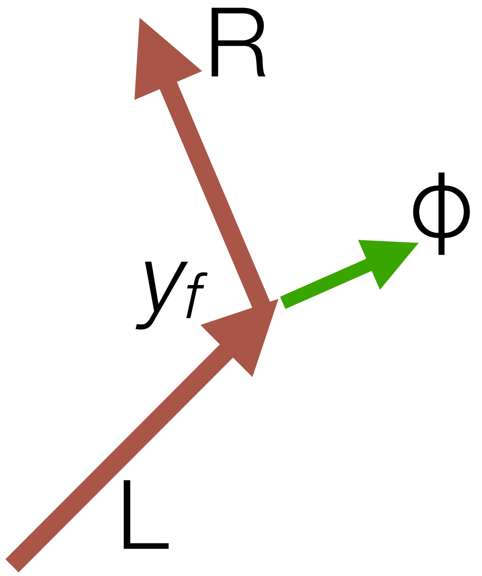
- Recall, we can add one more to the condensate, or take one out, without changing the state of the condensate.

- 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

L R L R L R L R L R L R L R L R L R L R

f_1

L L L R R R L L L R R R L L L R R R L L

f_2

Following a fermion

L R L R L R L R L R L R L R L R L R L R

f_1

L L L R R R L L L R R R L L L R R R L L

f_2

- 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 $\boldsymbol{y_f \langle \phi \rangle} (\psi_L \psi_R + \psi_R \psi_L)$

Dirac theory of fermions: few “naive" considerations

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

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

Spinor represented with the chiral spinors

Dirac Lagrangian

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

For massive fermions, the Dirac Lagrangian becomes:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}_L(i\not{\partial})\psi_L + \bar{\psi}_R(i\not{\partial})\psi_R - \boxed{m(\psi_L\psi_R + \psi_R\psi_L)}$$

- 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

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

(for the easier case U(1))

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

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

- We introduce a field ***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, ***A*** must satisfy $A_\mu \rightarrow A_\mu - \partial_\mu\theta(x)$ *(for the easier case U(1))*

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

Vector bosons from local symmetries:
1 slide recap

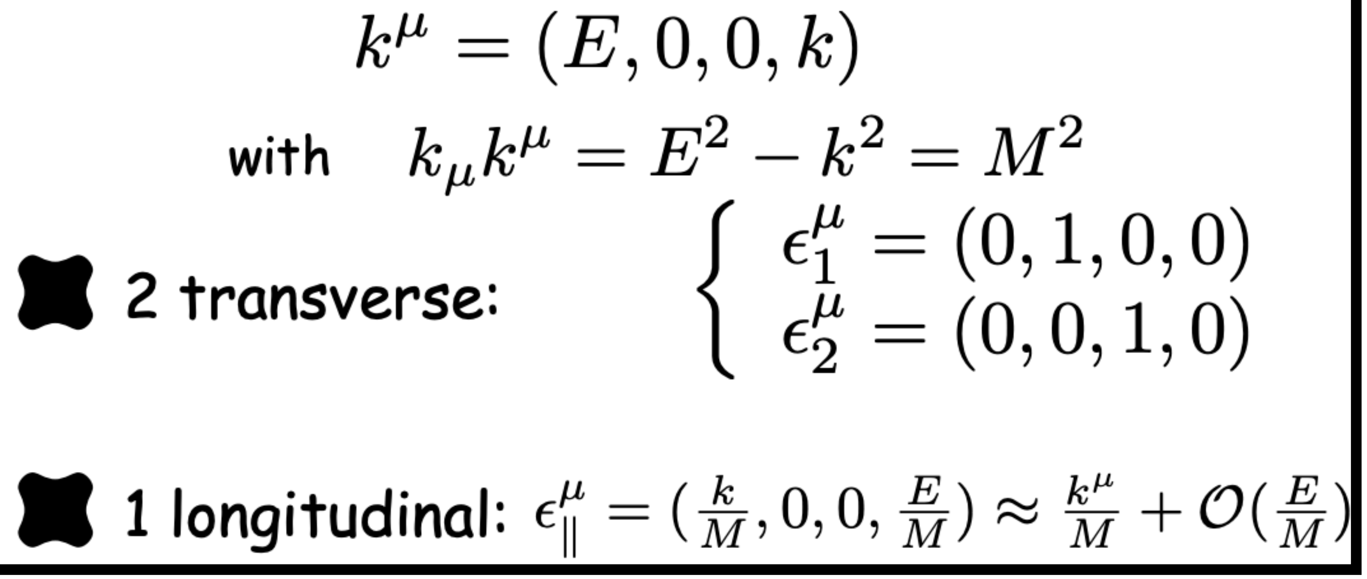
- The lagrangian for **A cannot contain a term proportional to** $A_\mu A^\mu$
- **This term is not gauge invariant!**
- But this is the kind of term needed to describe a massive vector boson
- We are again back to massless particles.
- Again 2 possible polarisations

Polarisation: recap

$$A_\mu = \epsilon_\mu \; e^{ik_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

……



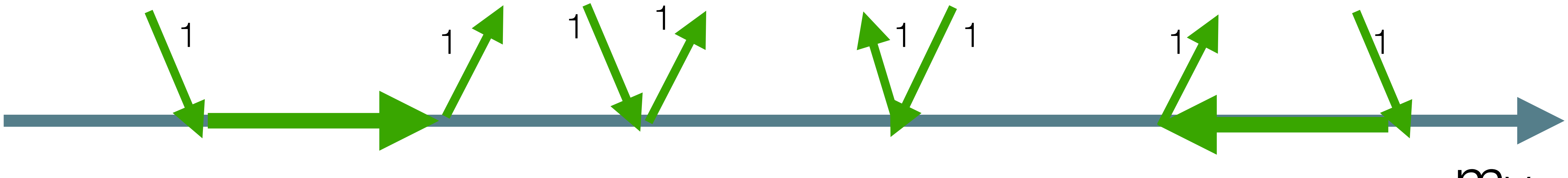
$$k^\mu = (E, 0, 0, k)$$

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

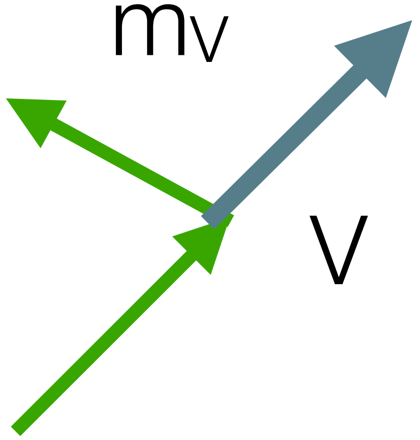
■ 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$

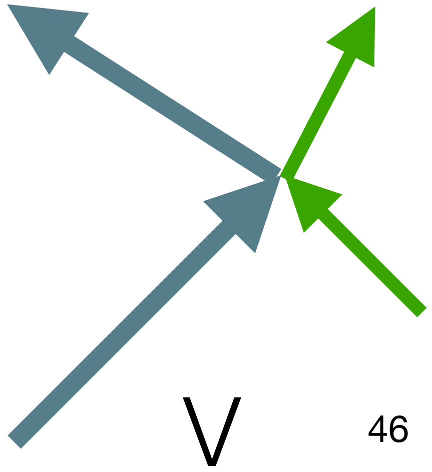
■ 1 longitudinal: $\epsilon_\parallel^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

The Brout-Englert-Higgs Mechanism

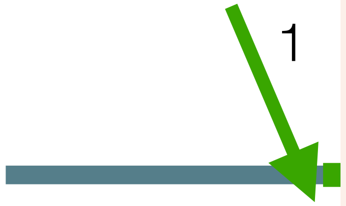


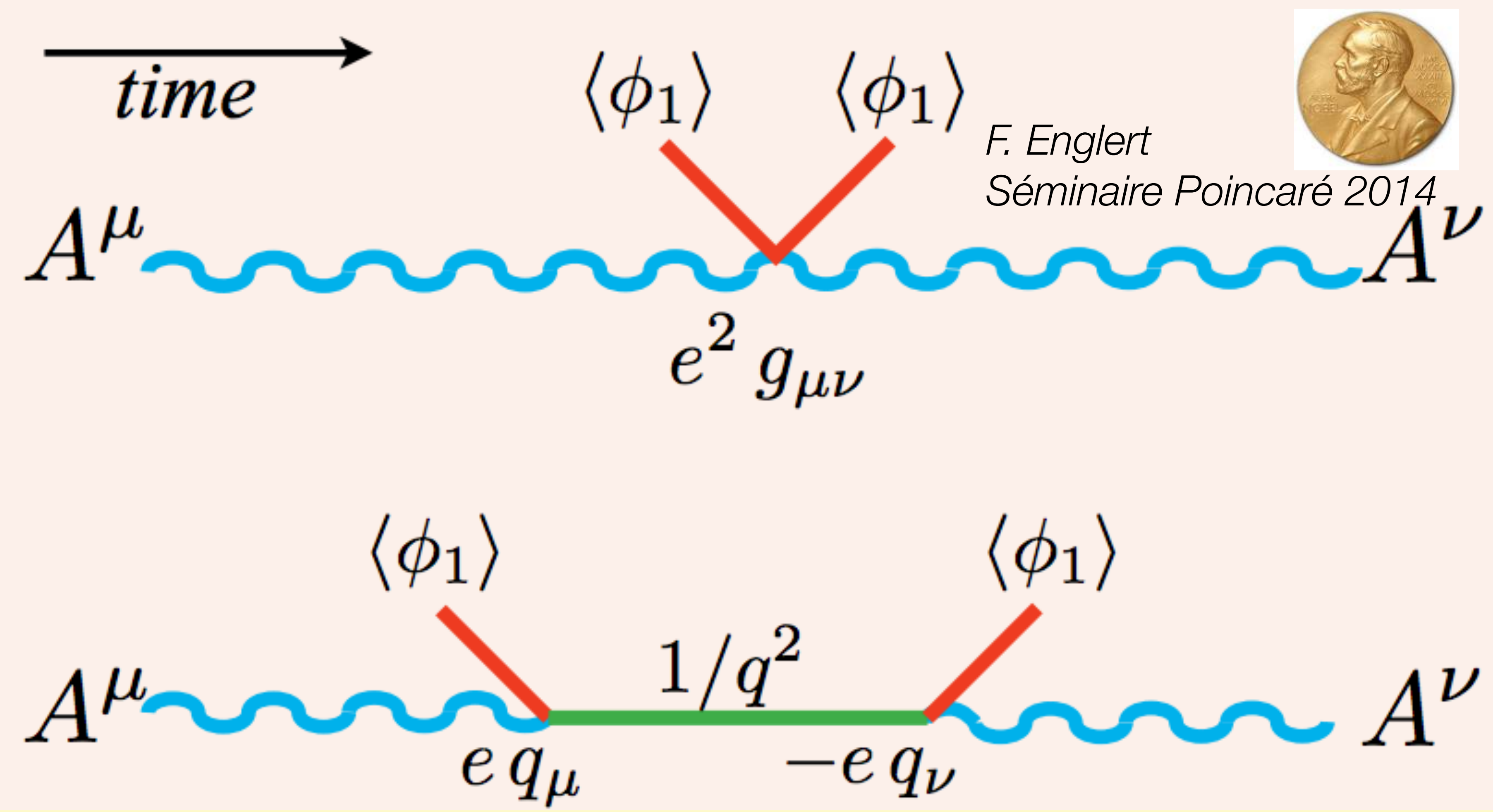
- How the V boson get a mass? Something very similar to fermion
- The V boson can interact with particles with (weak) charge, so it can interact with these new bosons.
- How?
- **The Brout-Englert-Higgs mechanism**
- NOTE: if there was a condensate of ordinary charged particles, this would have happen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





The Brout-Englert-Higgs Mechanism



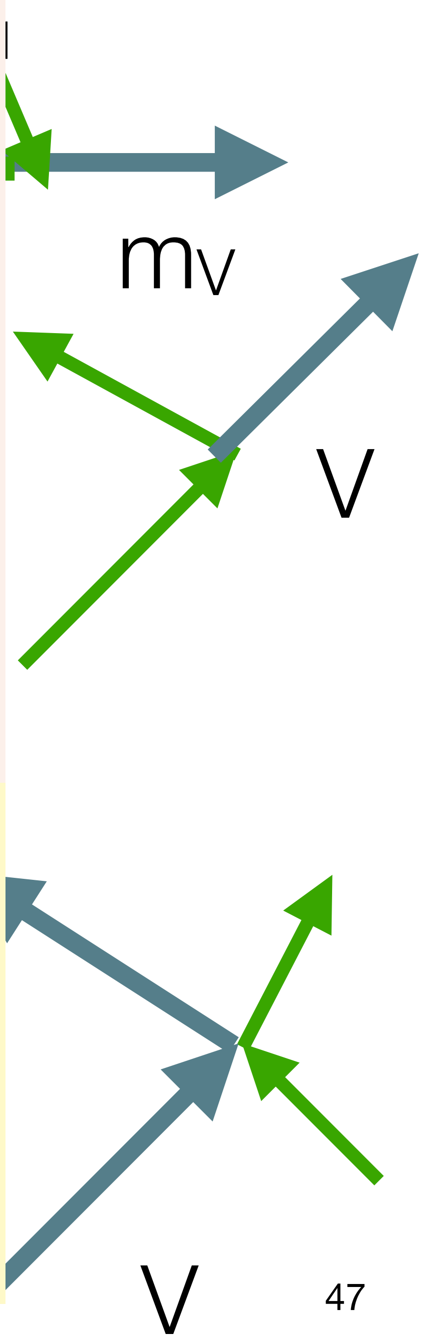


F. Englert
Séminaire Poincaré 2014

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

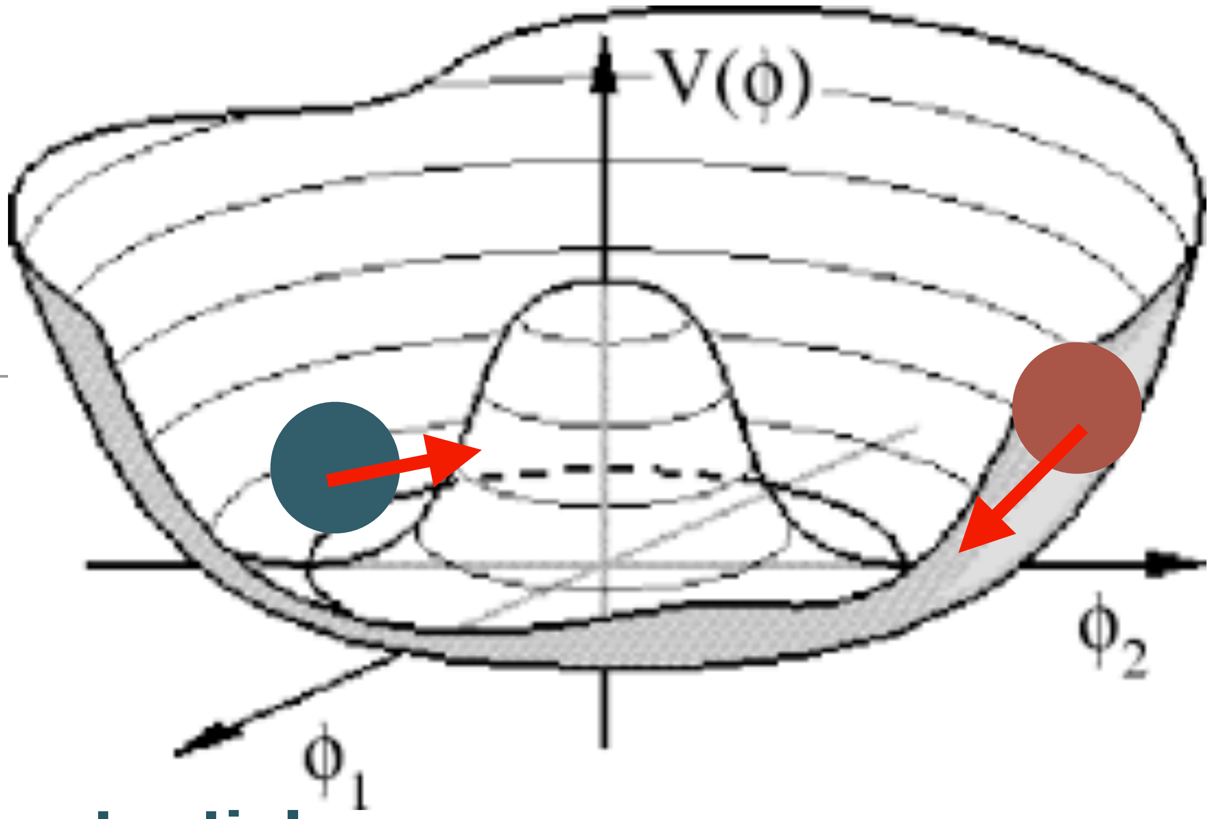
$$D_{\mu\nu} = \frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - e^2\langle\phi_1\rangle^2}$$

$$\boxed{M_V^2 = e^2\langle\phi_1\rangle^2}$$



- How the
- The V bo
  interact w
- How?
- **The Brou**
- NOTE: if
  would ha

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 -> 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

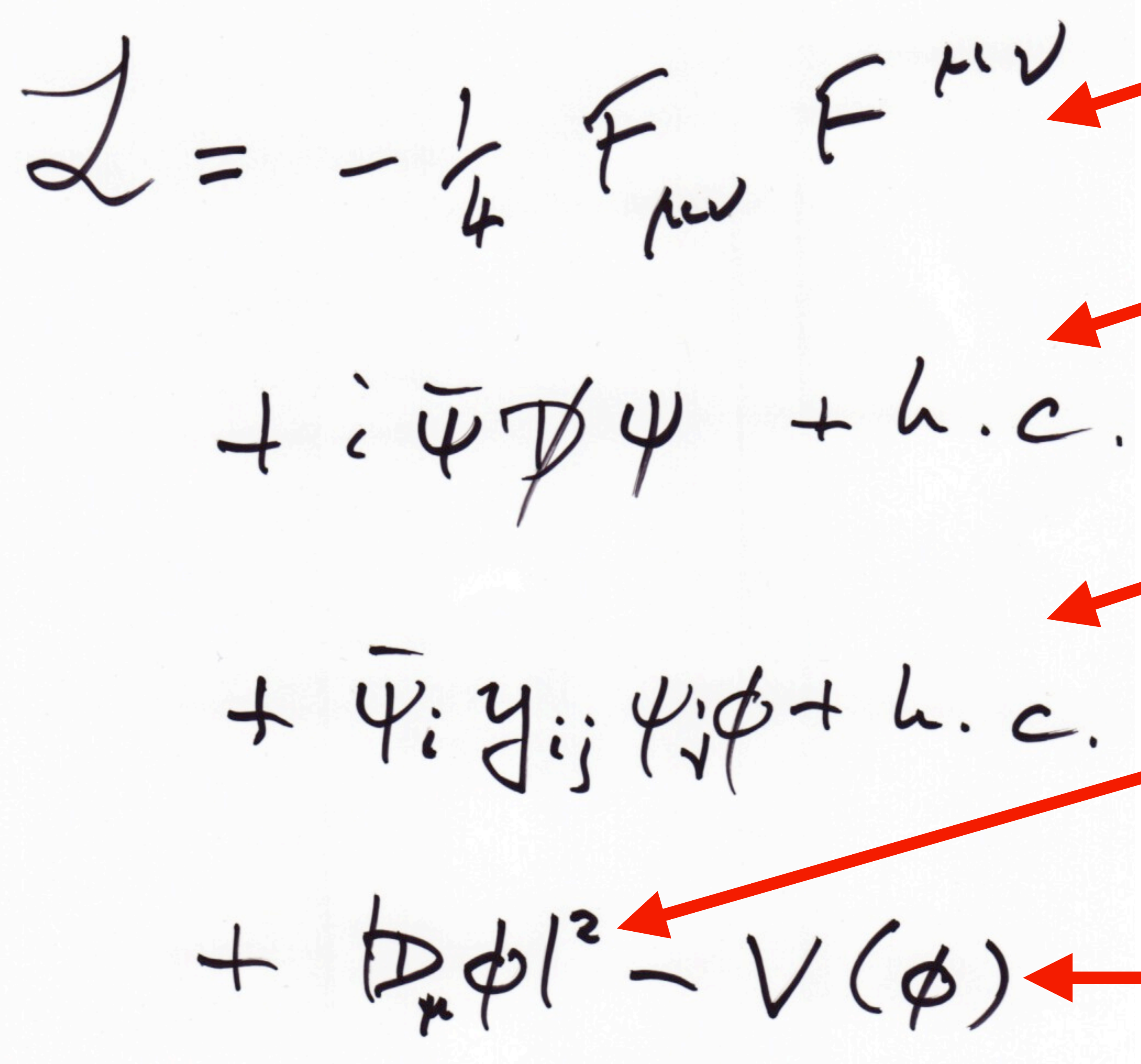
- Thanks to the exchange of charges with the condensate, we have a way to give mass to the elementary particles:

  - 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 Standard Model



$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

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

The Standard Model

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Higgs sector in the Standard Model

- Probably the less elegant sector
    - Largest number of parameters

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

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

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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

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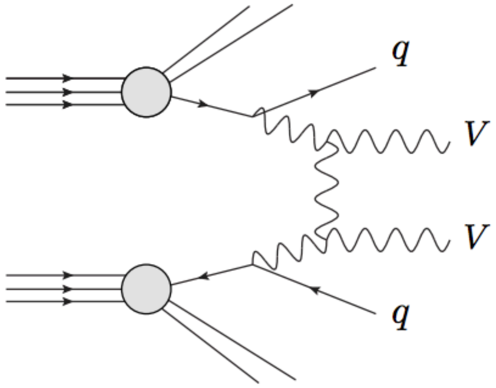
  The unitarity of the longitudinal vector boson scattering.



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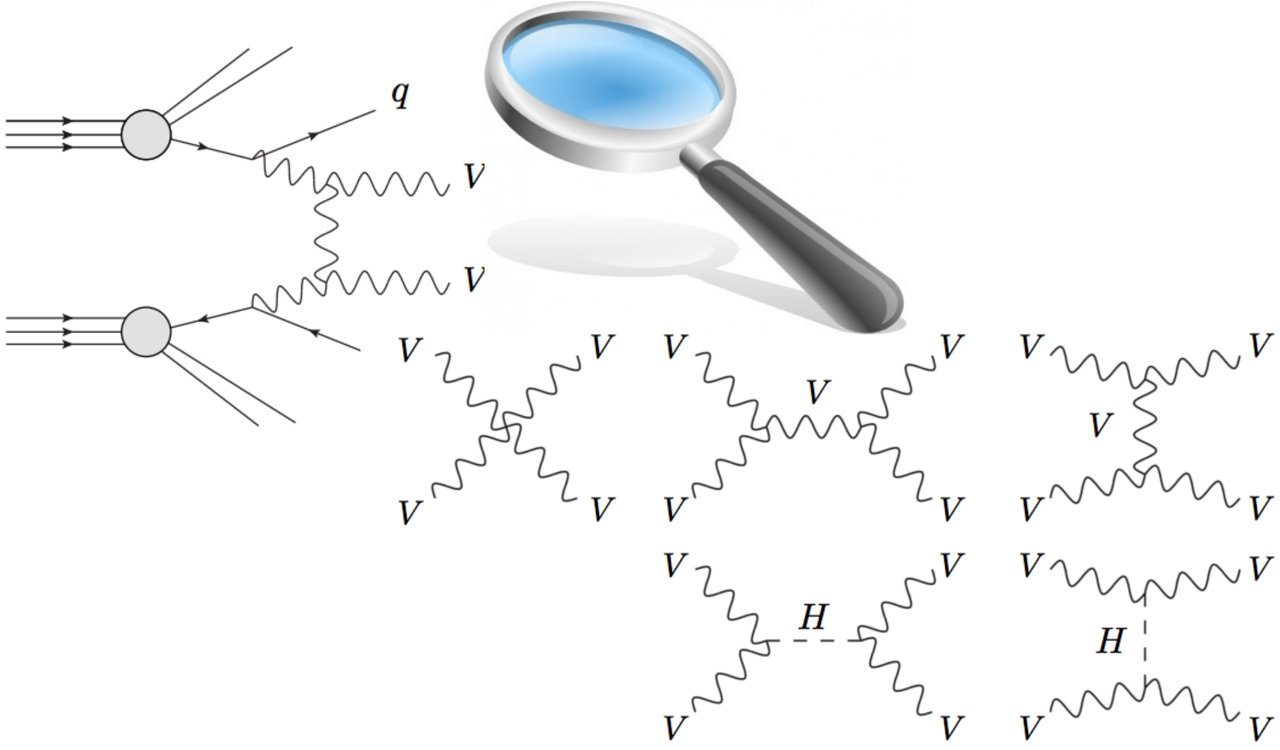

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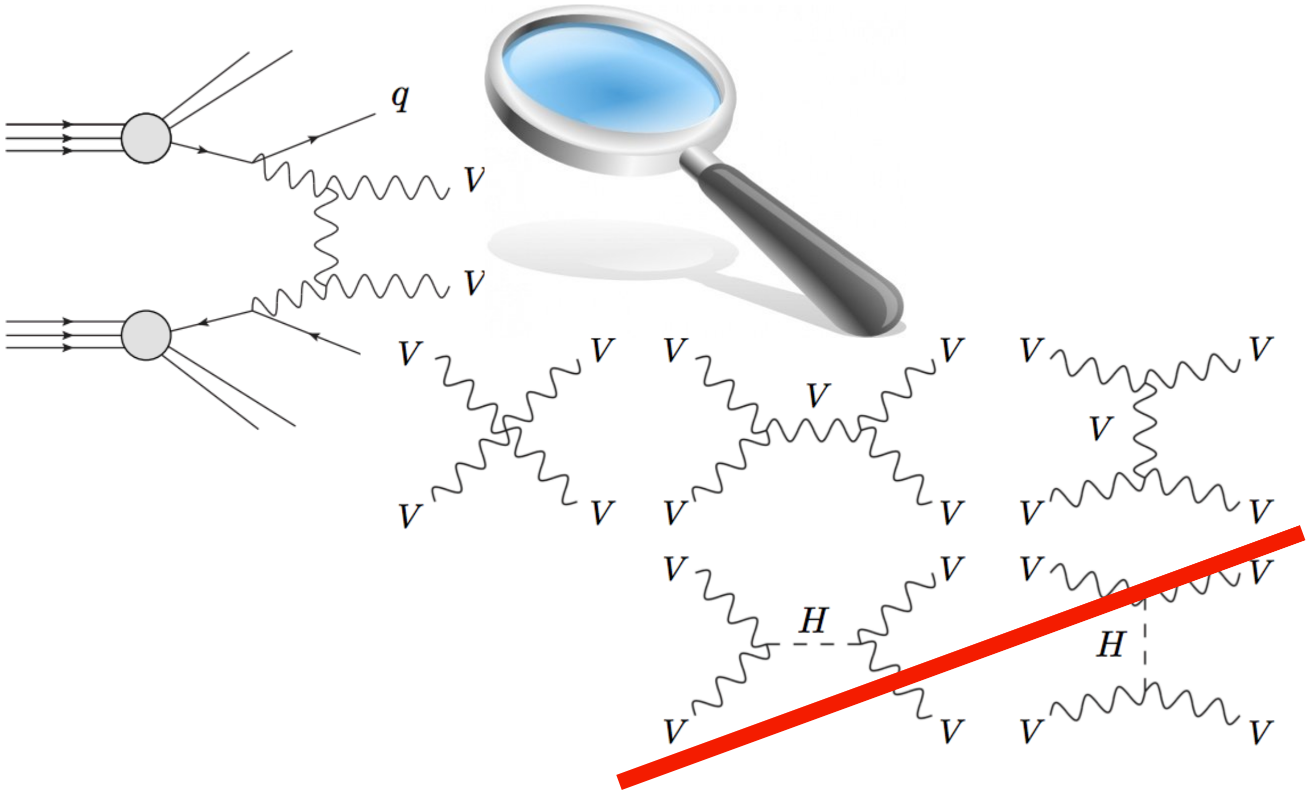


In absence of a Higgs boson with m_H<1 TeV, would imply a strong dynamics which could be produced in the WW process

Higgs sector in SM Lagrangian

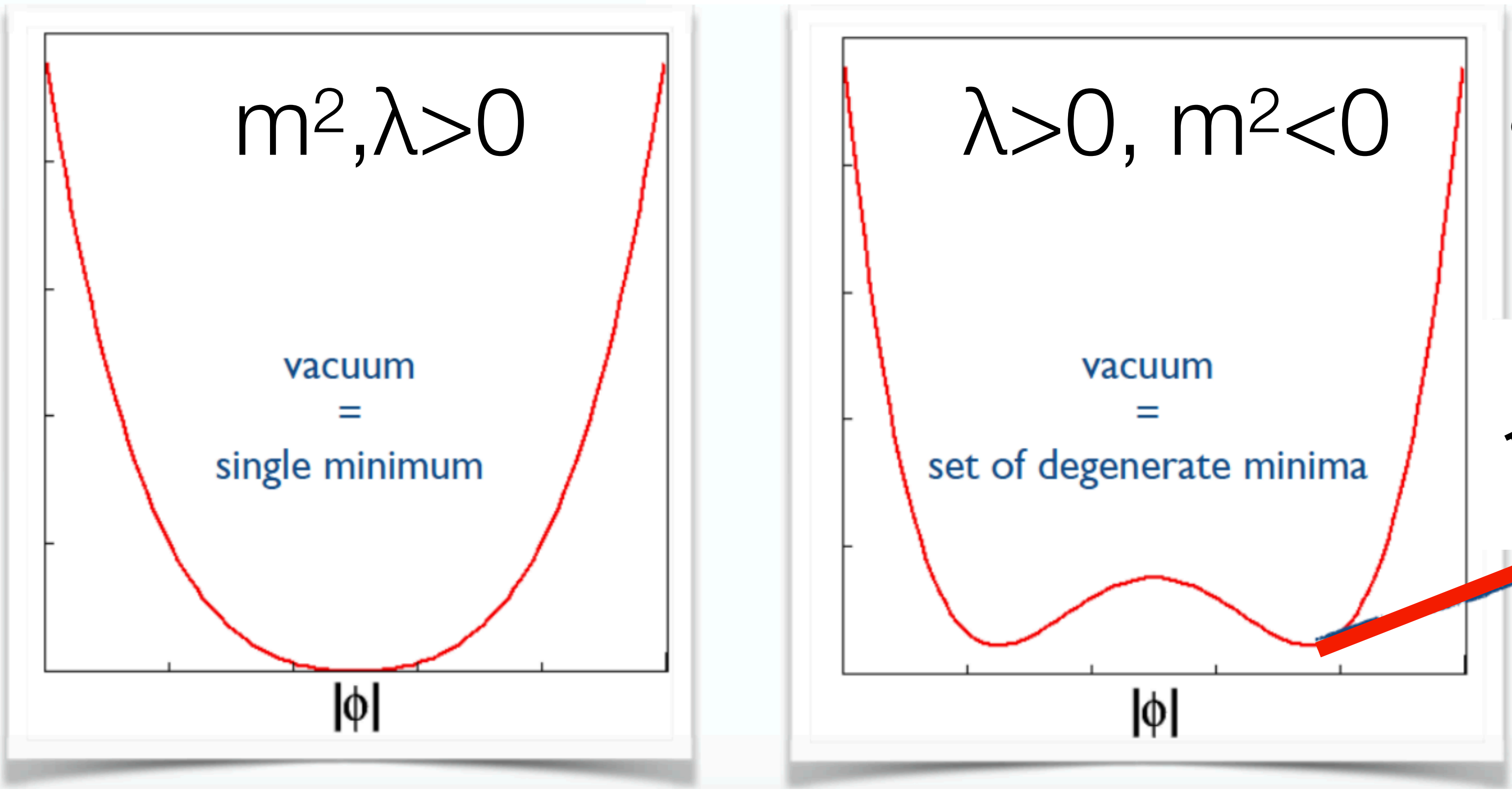
$$\mathcal{L}_{\text{Higgs}} = (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi)$$

- 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

$$D_\mu\Phi = (\partial_\mu + ig\sigma^a W^a_\mu/2 + ig'YB_\mu/2)\Phi$$

couplings for the EW sector

- 4 new degrees of freedom: doublet+anti-particles
- It has a very specific potential $V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$



around the minimum:

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

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

stolen from C. Oleari: link

Some calculations

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

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

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

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

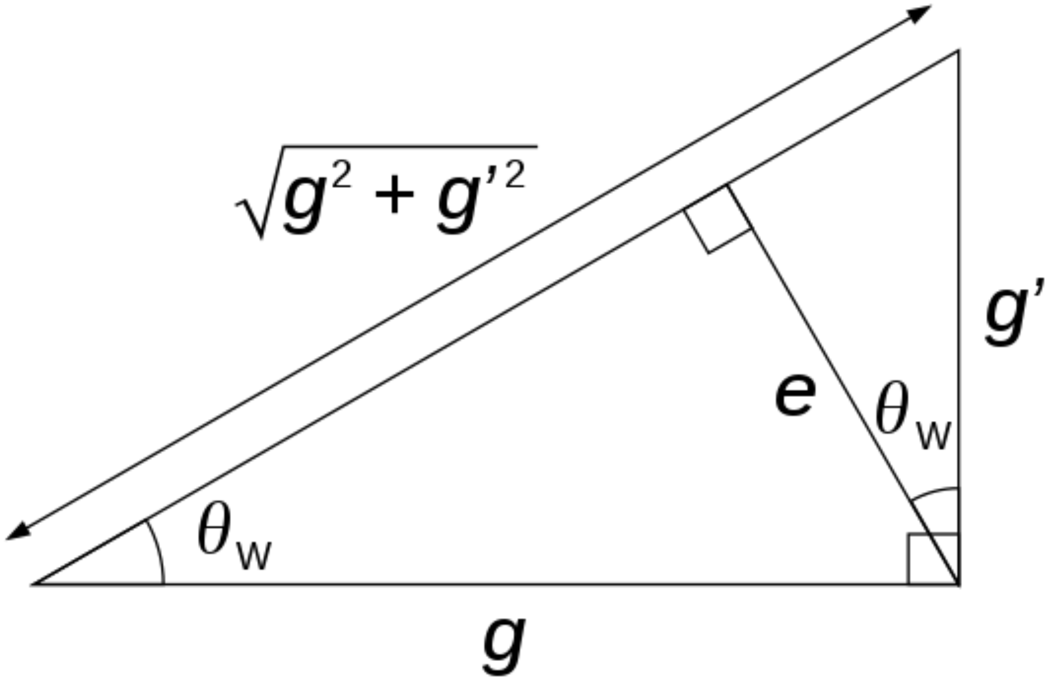
$$\frac{G_F}{\sqrt{2}} = \left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{m_W^2} \quad \Longrightarrow \quad v = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246.22\ \mathrm{GeV}$$

- One massless vector boson

$$m_\gamma = 0$$

- One massive neutral vector boson Z

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



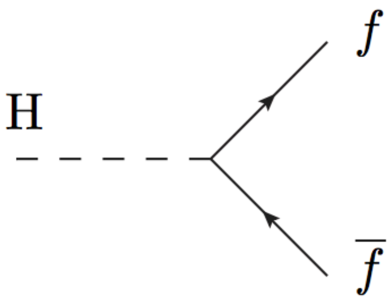
- One massive scalar particle: The Higgs Boson

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

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



$$\frac{m_f}{v}$$

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

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

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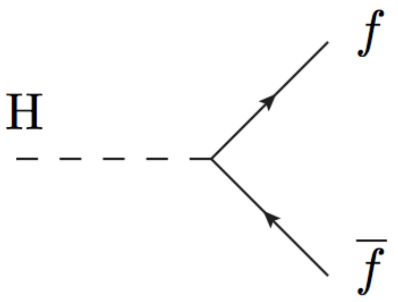

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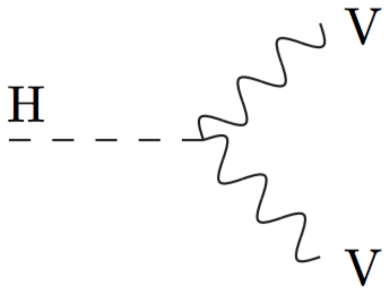
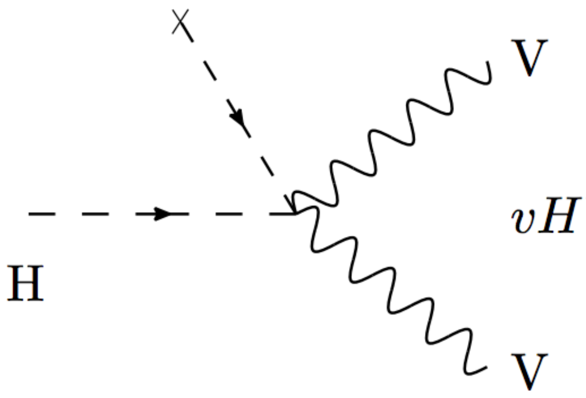


$$\frac{2m_V^2}{v}$$

$$+ |D_\mu \phi|^2$$

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

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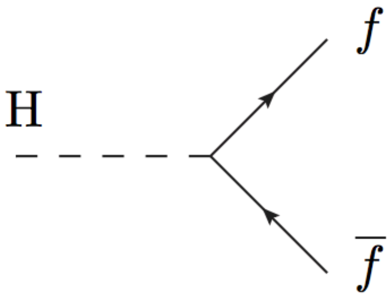

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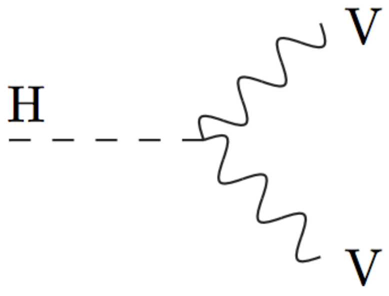

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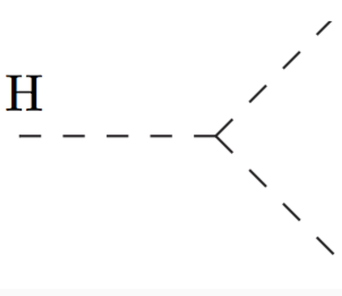
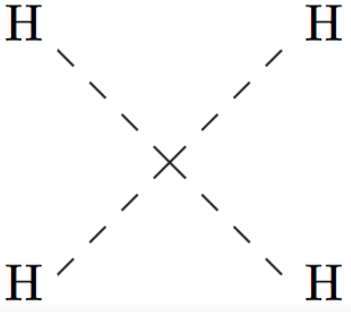


$\frac{3m_H^2}{v}$

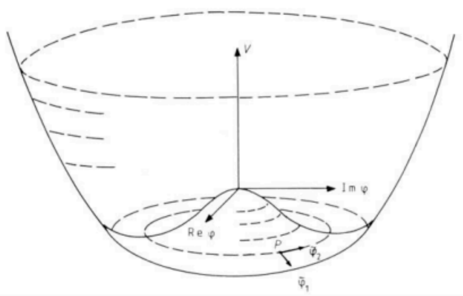


$\frac{3m_H^2}{v^2}$

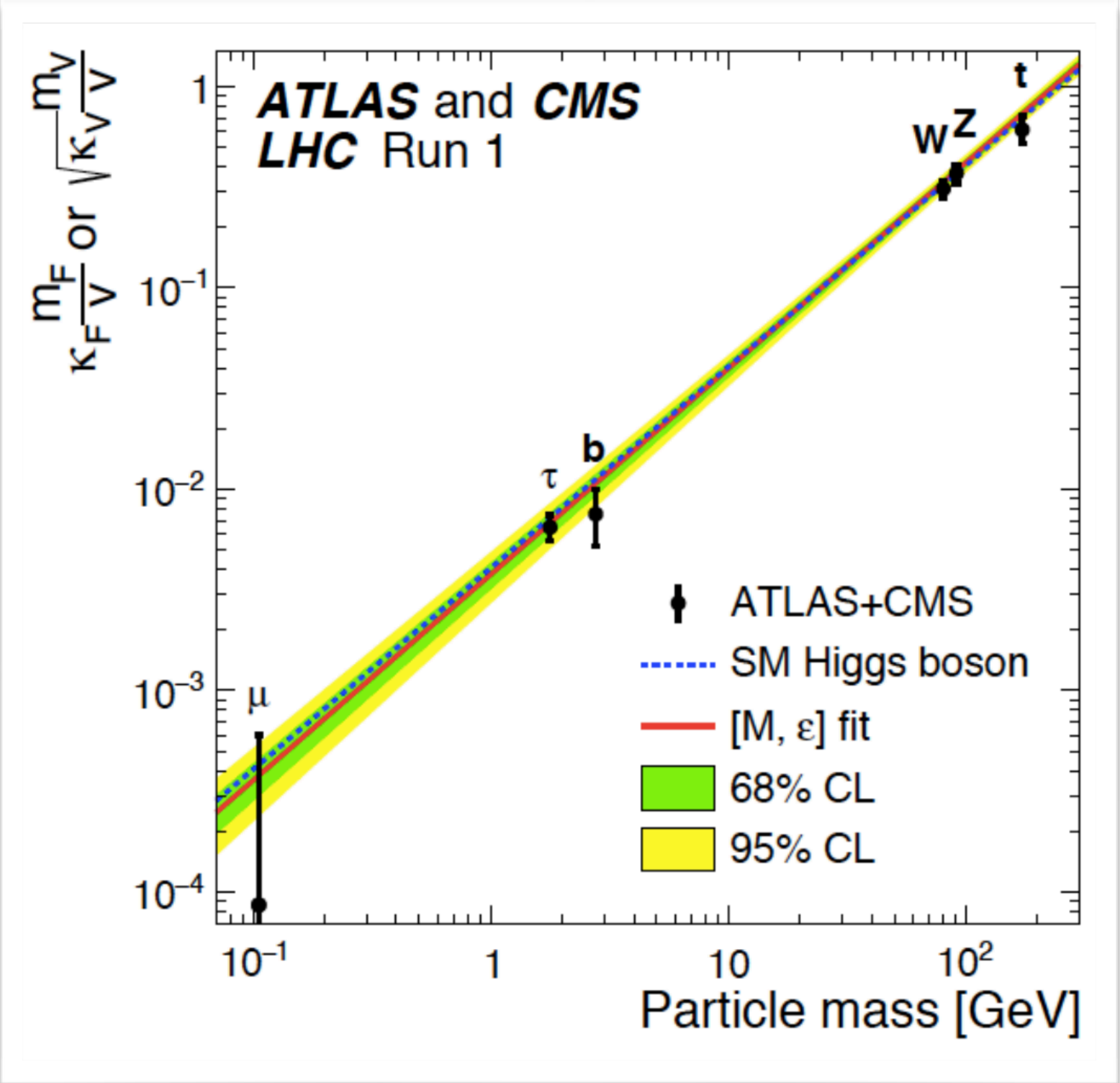
$V(\phi)$

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

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



Higgs Couplings - measurements
Where we are

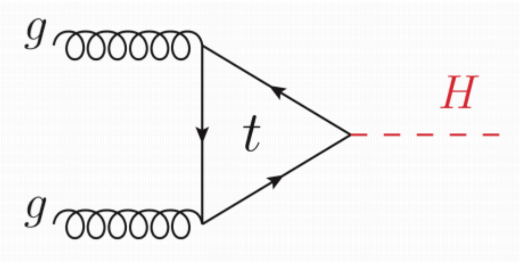


Measurements of vector bosons and 3rd generation fermions

2nd and 1st generation?

Self couplings?

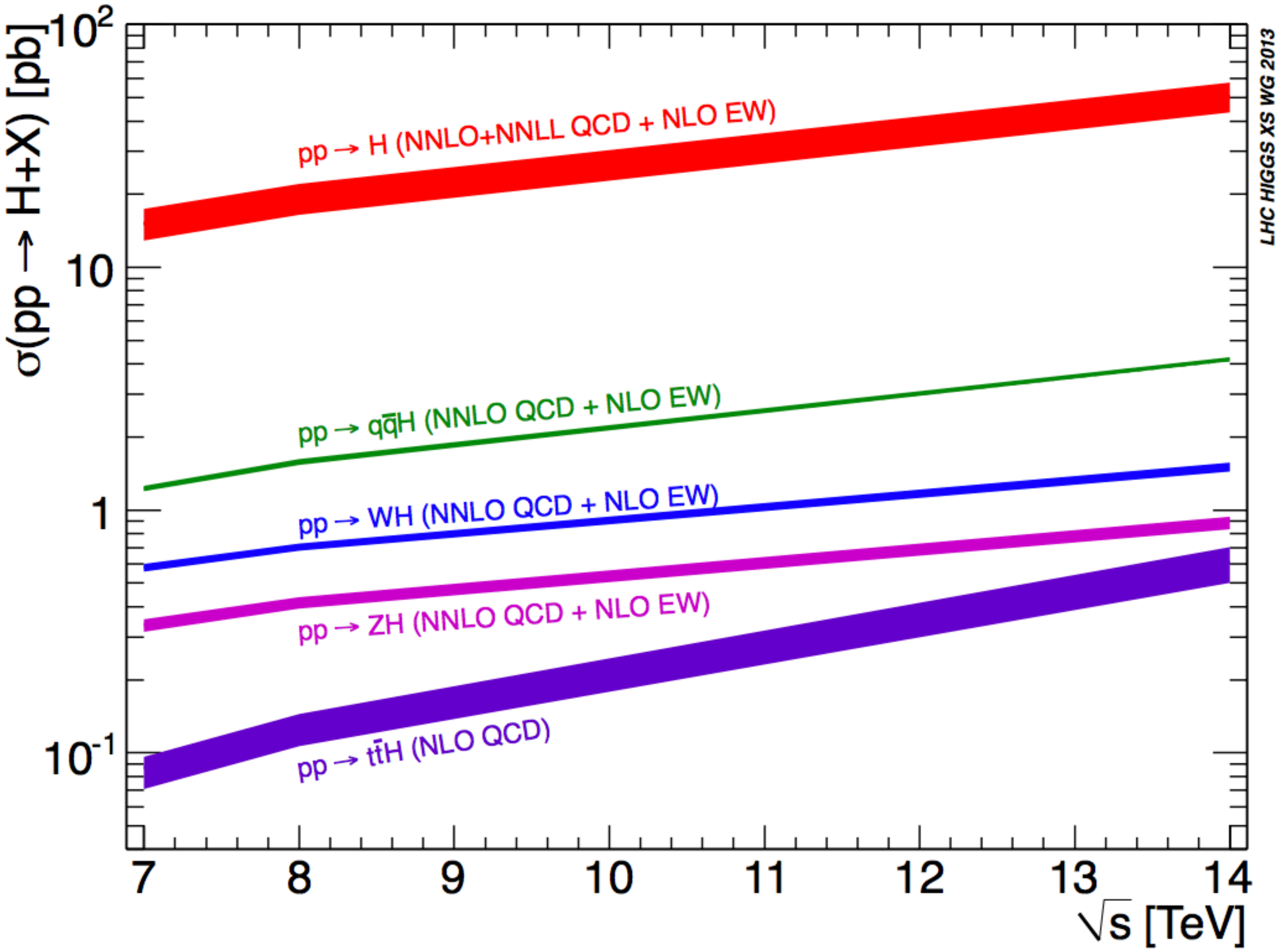
(Main) Higgs boson production modes



Production for $140fb^{-1}$ in Run2

Gluon Fusion

~7M events produced



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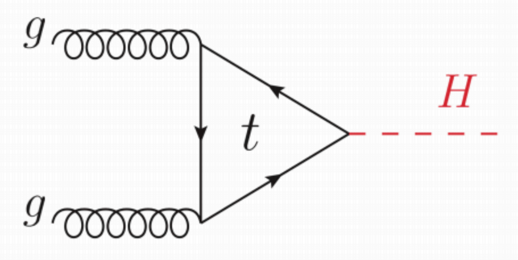

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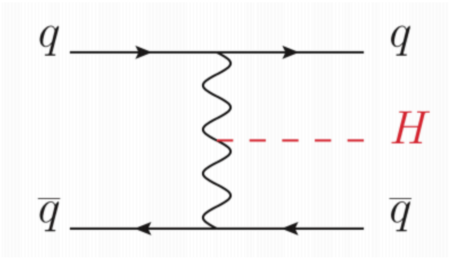

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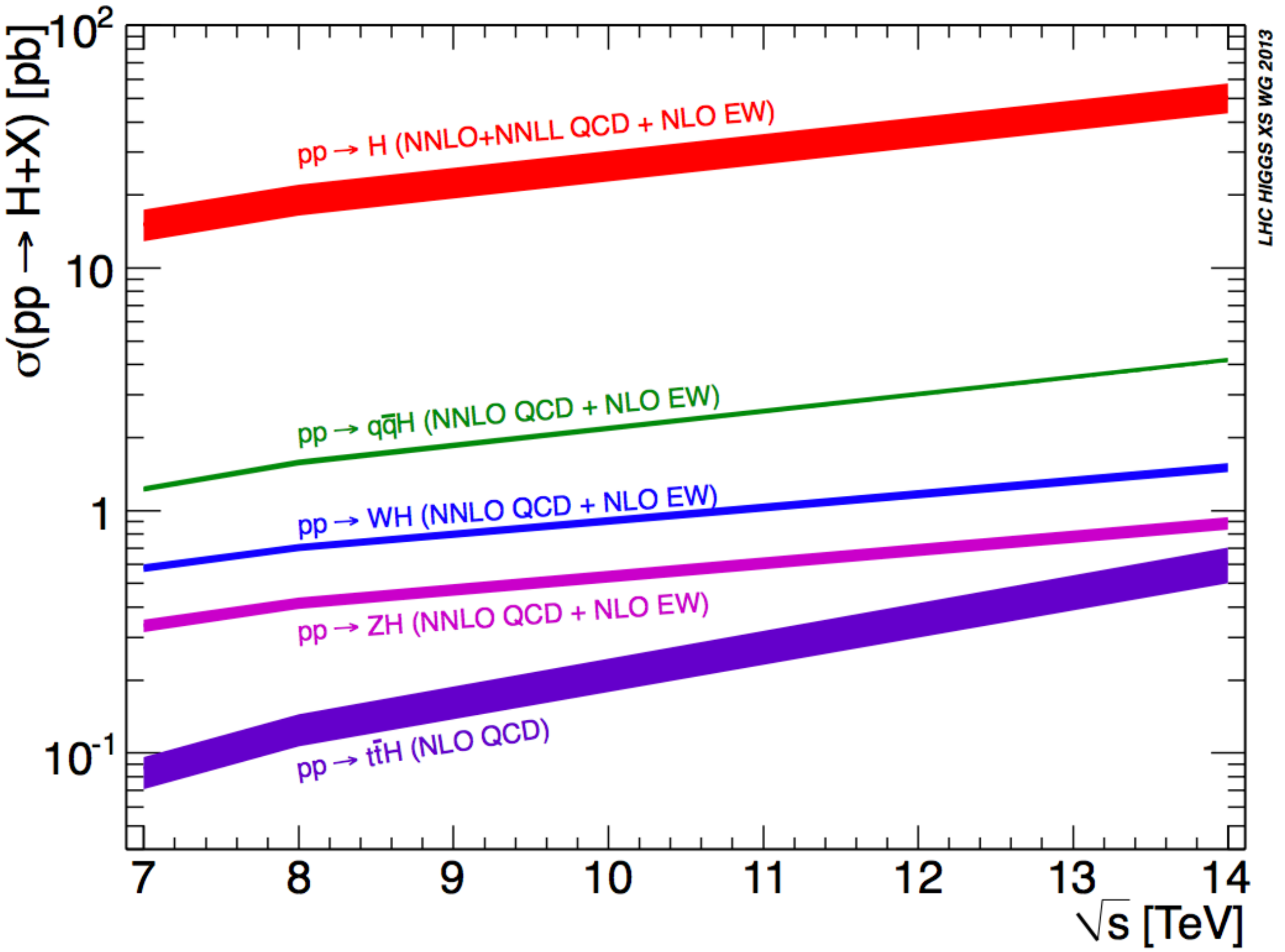

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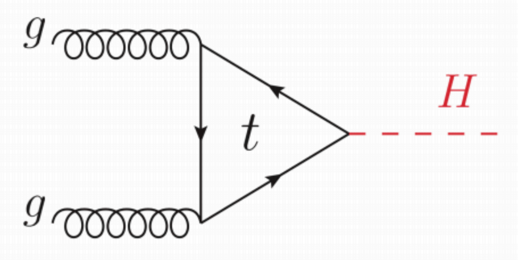

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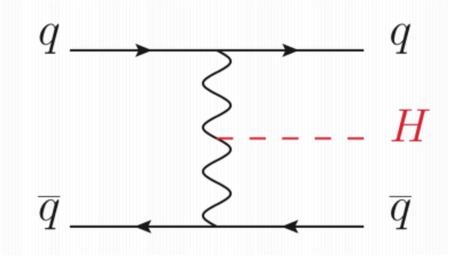

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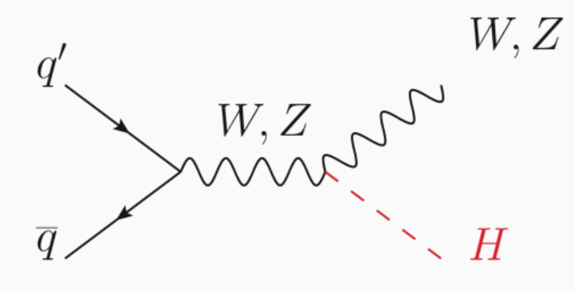
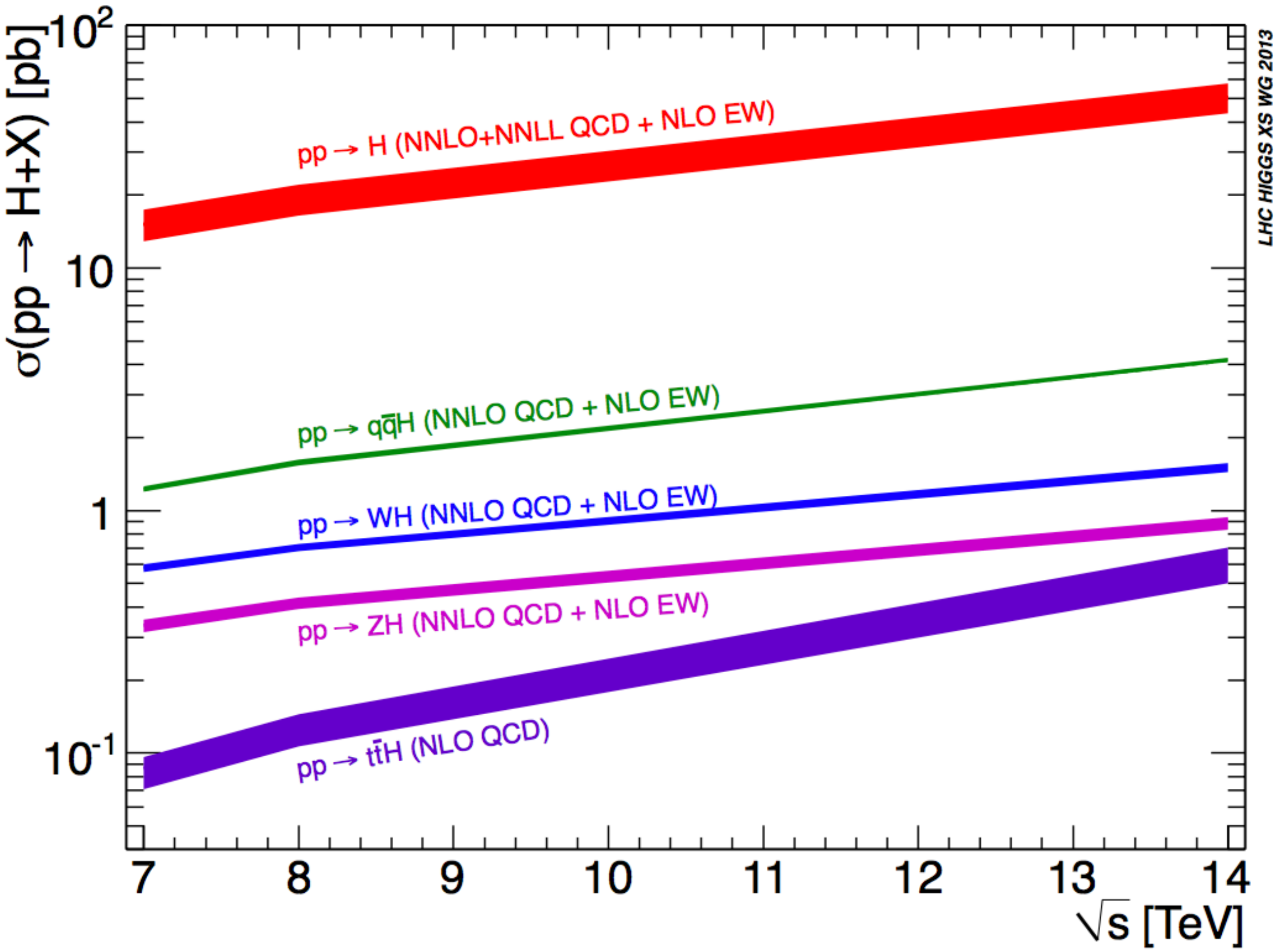


W and Z Assoc. Prod.

~0.35M events prod.



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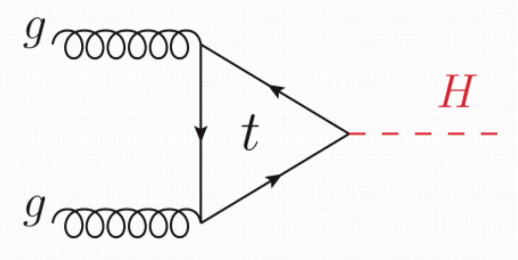

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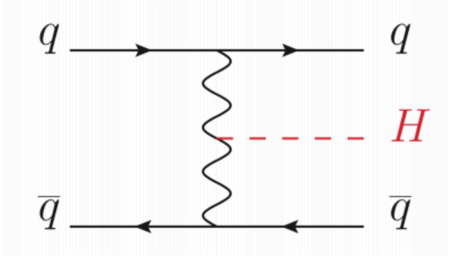

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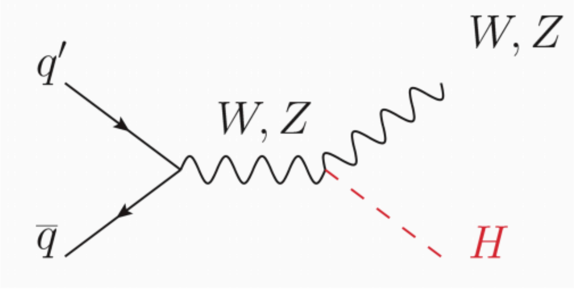

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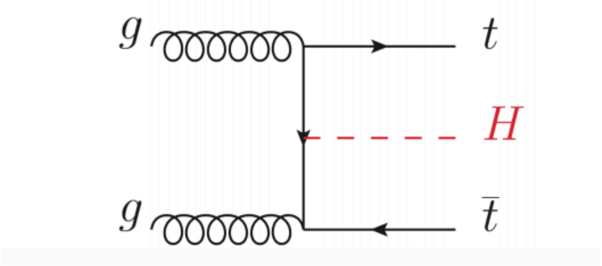
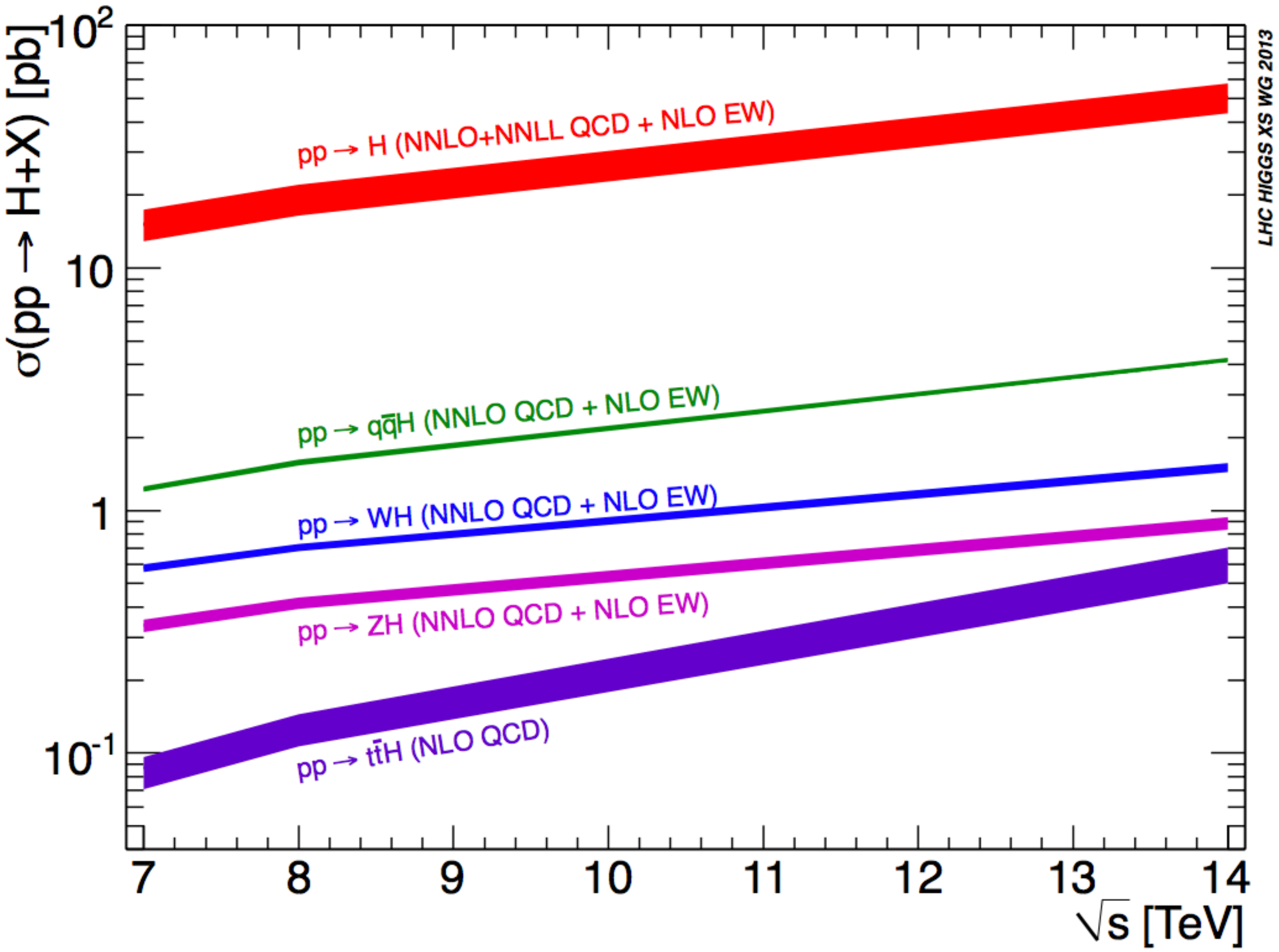


Top Assoc. Prod.

~70k events produced



(Main) Higgs boson production modes

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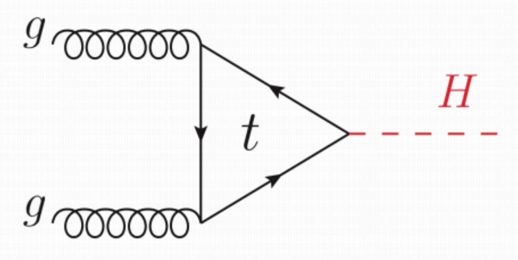

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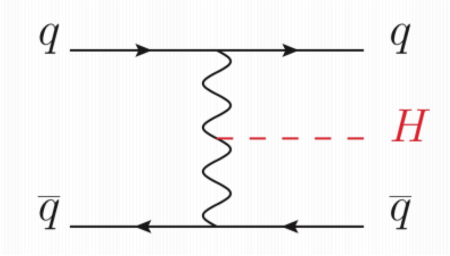

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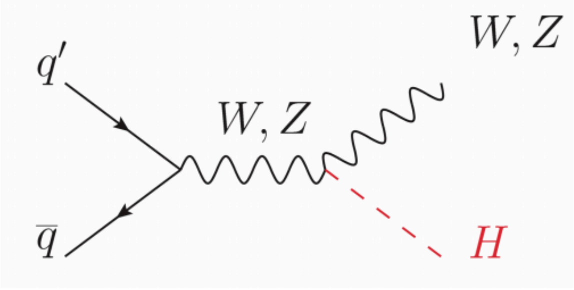

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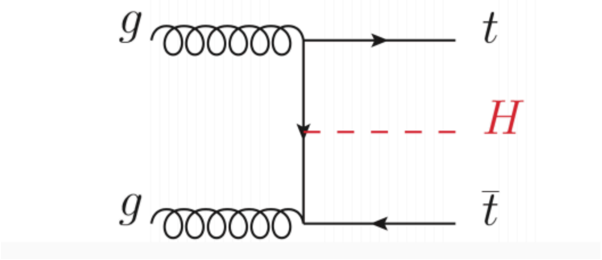

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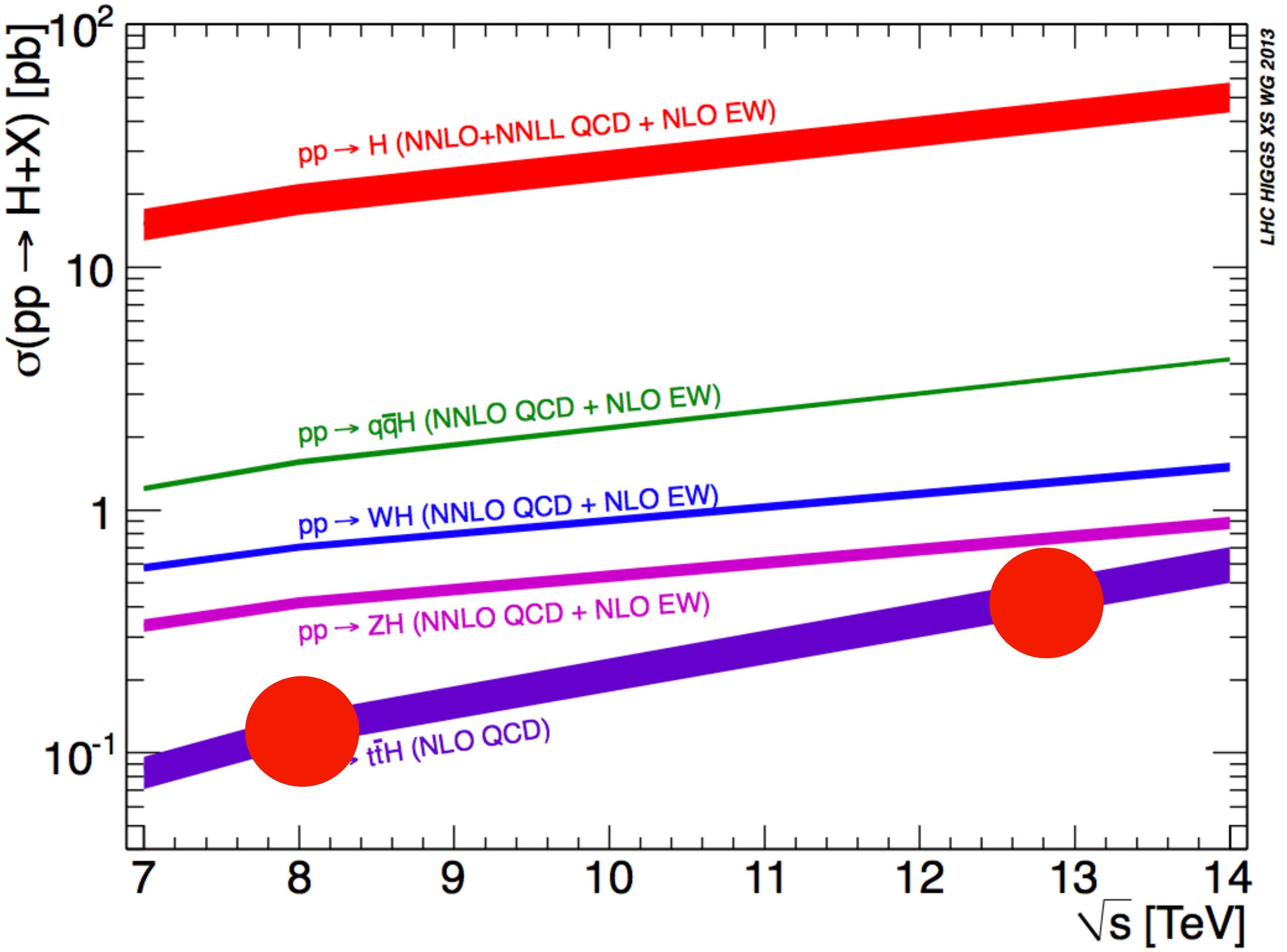


Cross sections increase with center of mass energy.
Note ttH!!

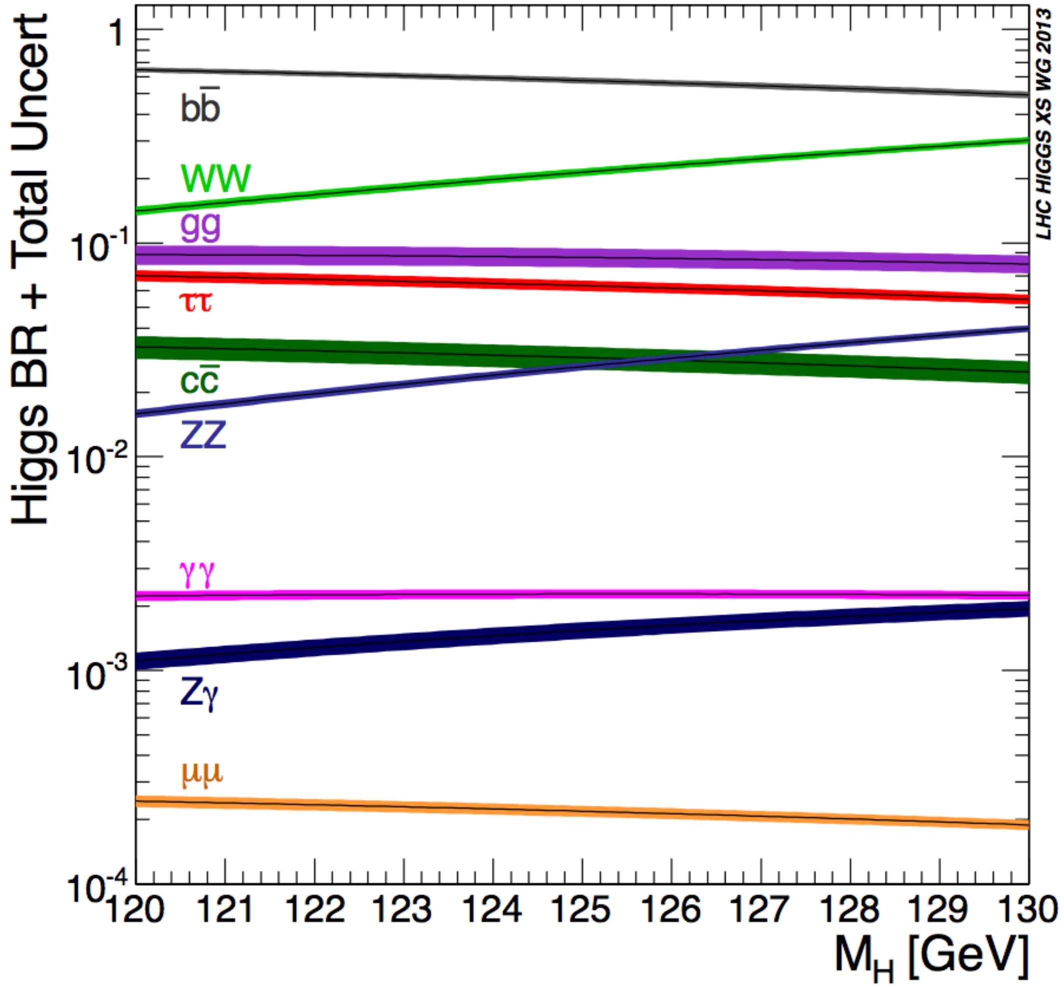
$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$

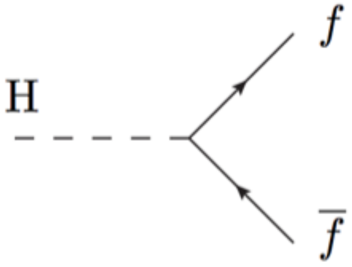
Higgs boson decay channels

Third generation quarks

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



$\Gamma_{H\to bb} \propto \Sigma_{colors}$ |



$|^2$

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

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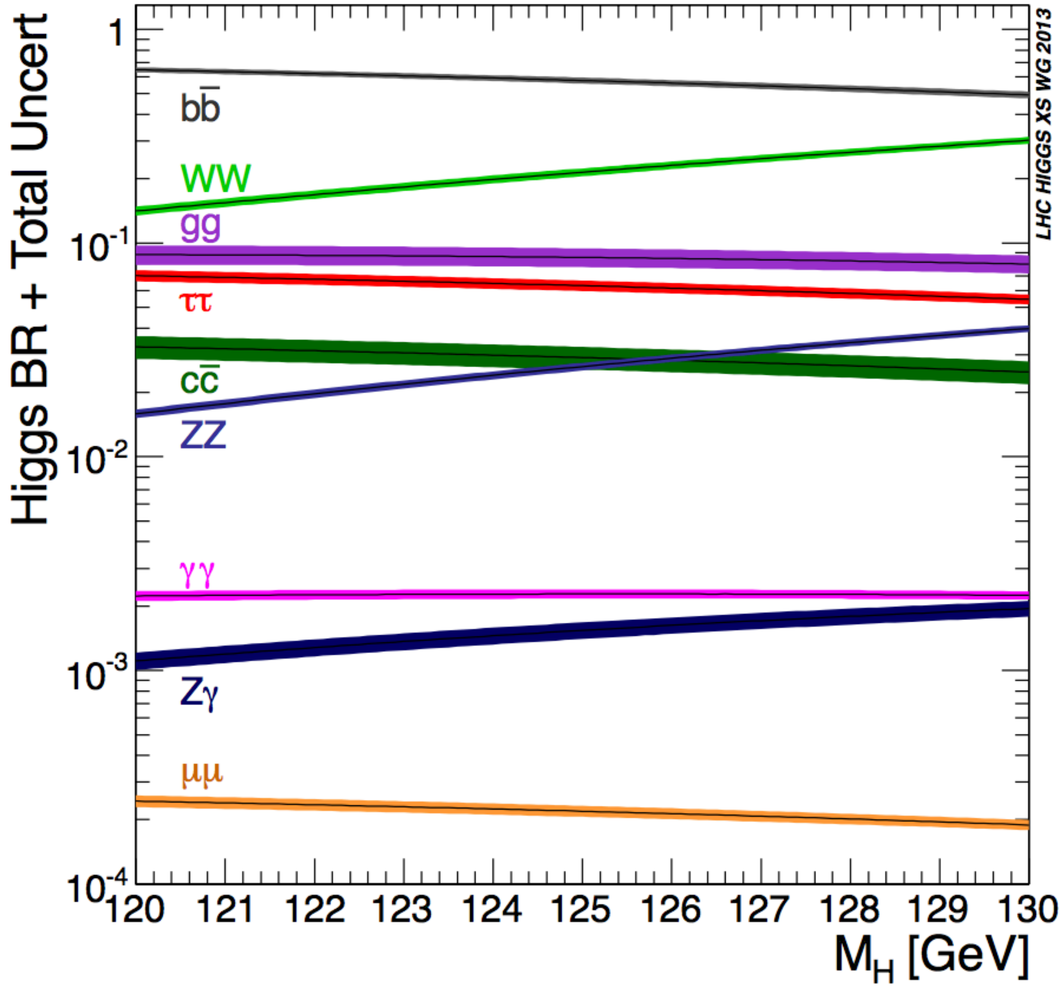
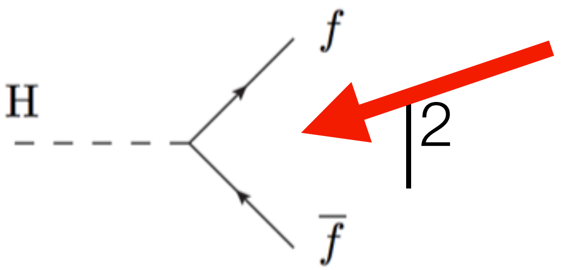


$$\Gamma_{H\to bb} \propto \Sigma_{\text{colors}} \left| \quad \right|^2$$



$$\frac{m_f}{v}$$

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

$\Gamma_{tot} = \Sigma\, \Gamma_i$

Higgs boson decay channels

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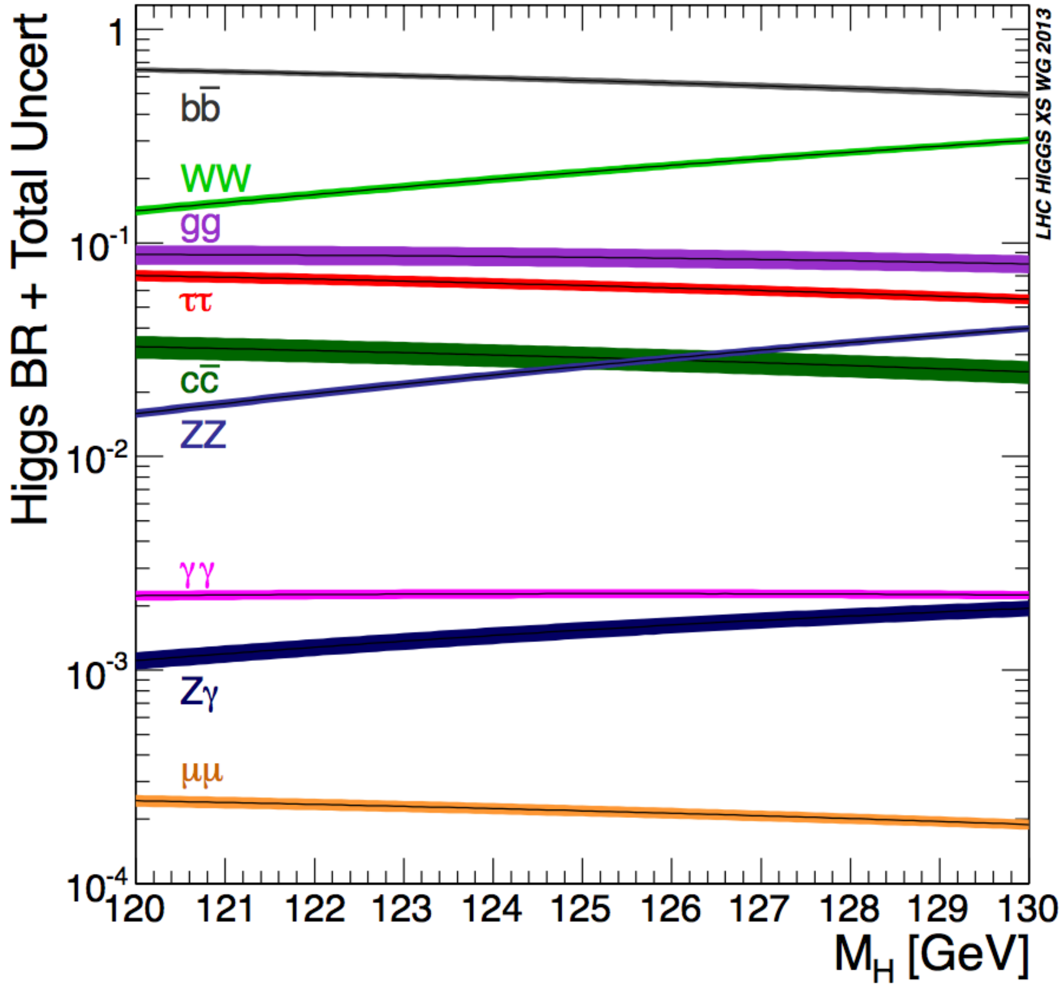
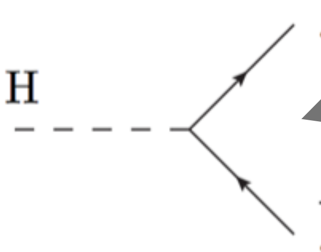
Decay mode	Expected BR for m_H=125 GeV
bb	57 %



$\Gamma_{H\to bb} \propto \Sigma_{colors}\,|$



$|^2$

$$\frac{m_f}{v}$$

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

3

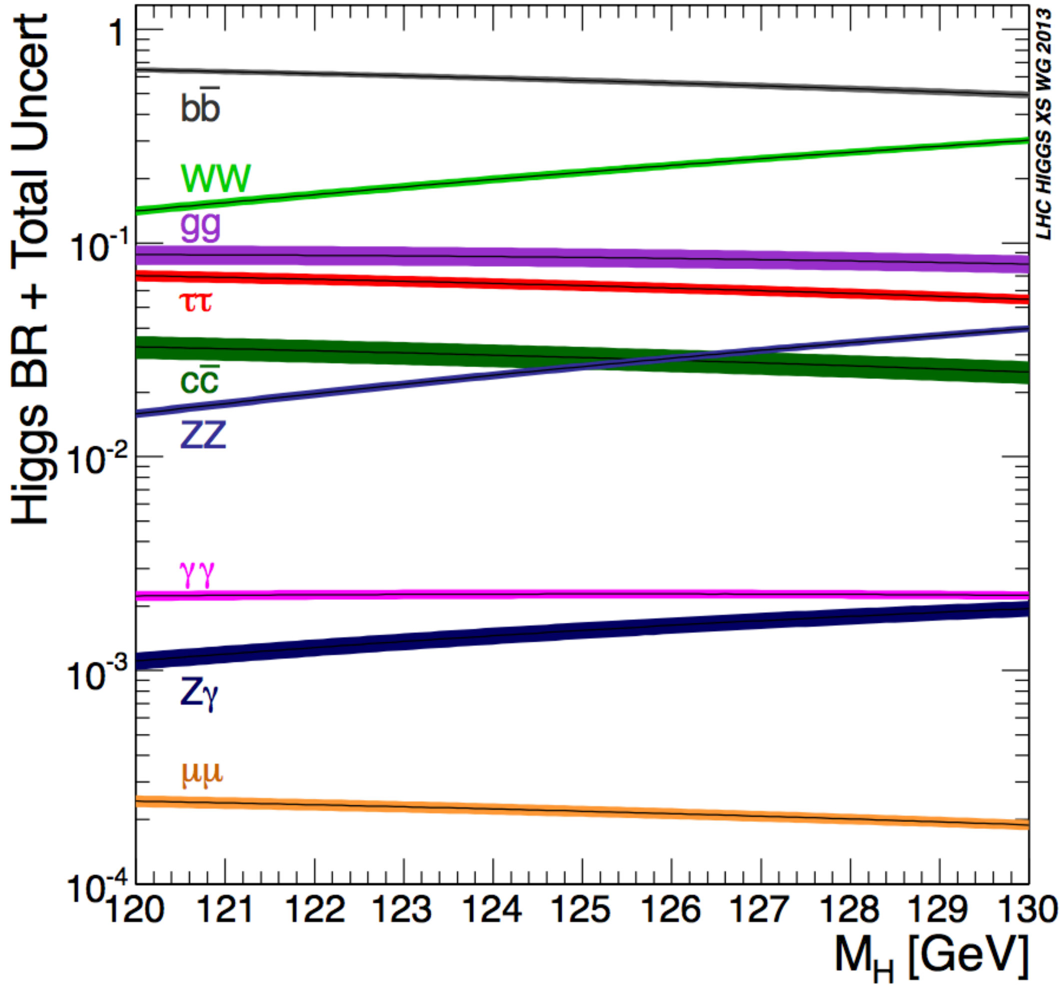
$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$

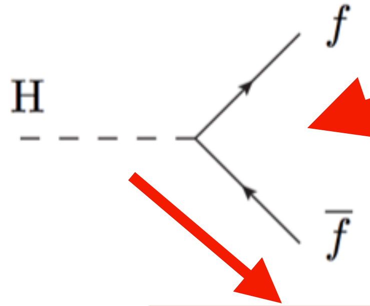
Higgs boson decay channels

Third generation quarks

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



$\Gamma_{H\to bb} \propto \Sigma_{\text{colors}}$ |



$|^2$

$$\frac{m_f}{v}$$

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

3

2.8 GeV

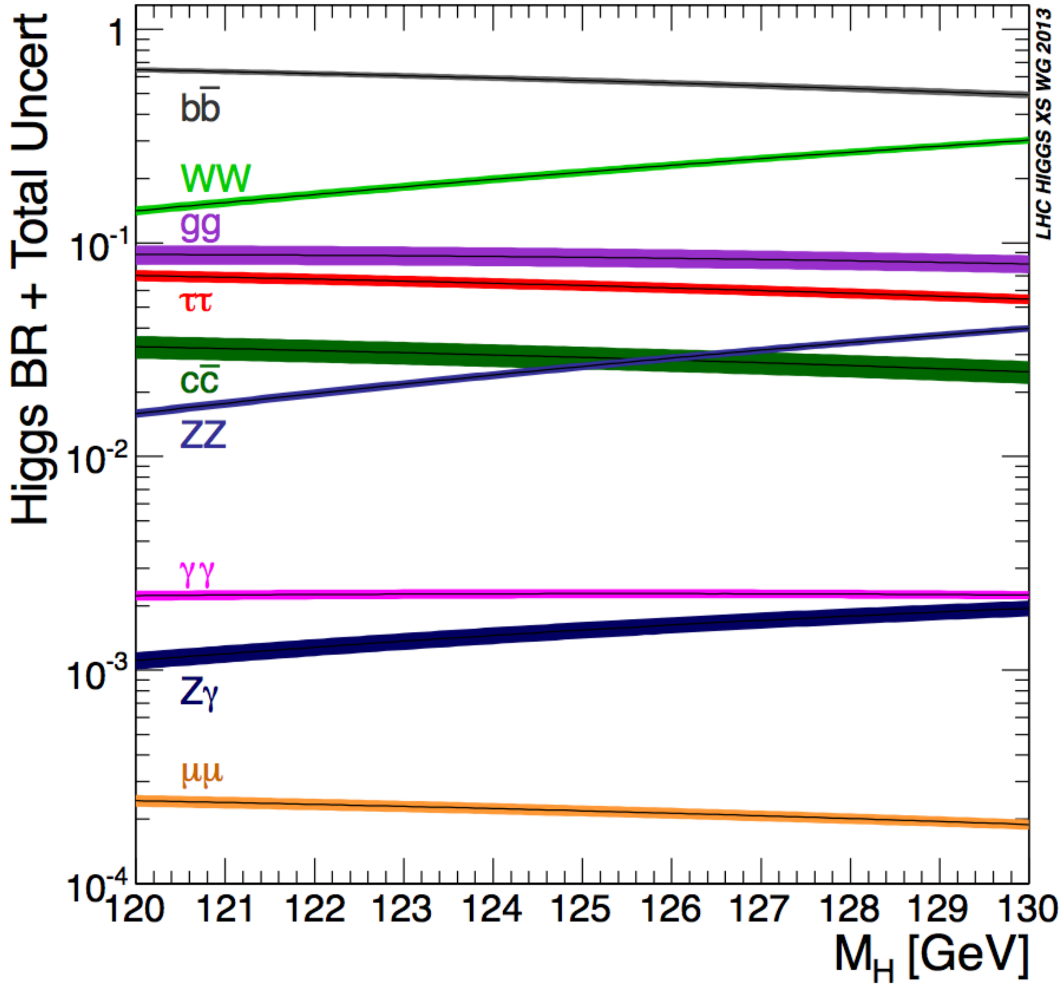
Higgs boson decay channels

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

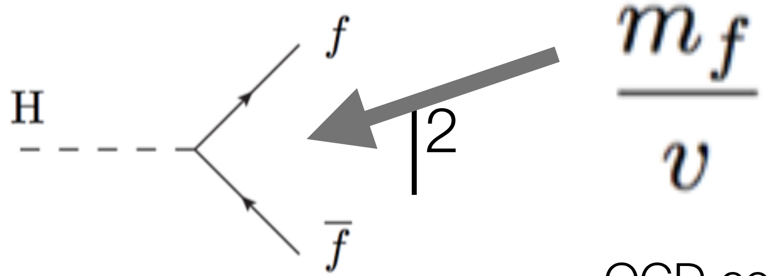
$\Gamma_{tot} = \Sigma\, \Gamma_i$

Third generation quarks

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



$\Gamma_{H\to bb} \propto \Sigma_{\text{colors}} \left| \quad \right|^2$



$\frac{m_f}{v}$

$$\sim k\, \underset{3}{N_c}\, \underset{2.8\text{ GeV}}{m_f^2(m_H)}\, \underset{0.2}{\overset{\text{QCD corr.}}{\boxed{(1+\Delta_{QCD})}}}$$

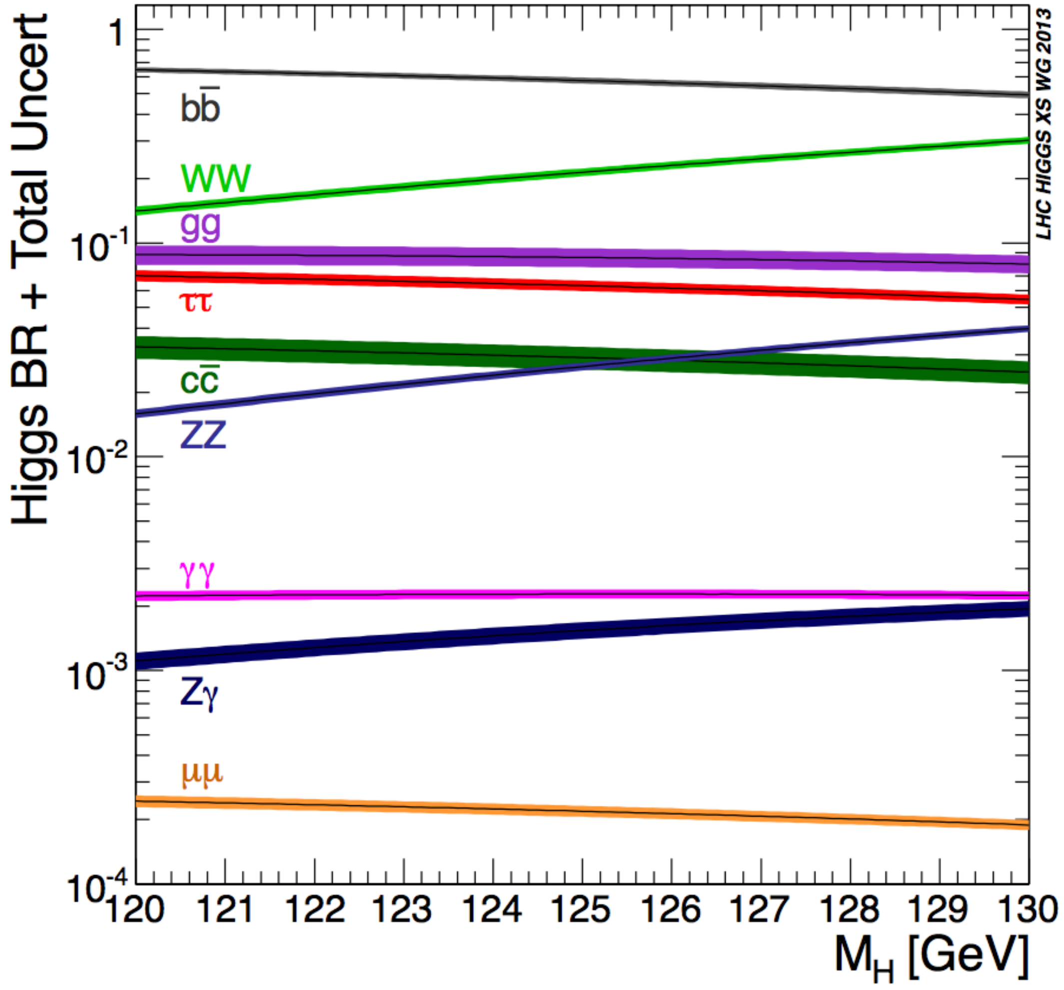
$BR_i = \Gamma_i / \Gamma_{tot}$

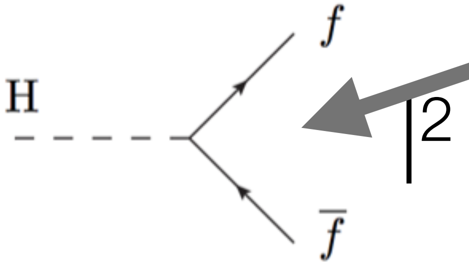
$\Gamma_{tot} = \Sigma\, \Gamma_i$

Higgs boson decay channels

Third generation quarks

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





$$\Gamma_{H\to bb} \propto \Sigma_{colors} \left| \quad \right|^2 \qquad \frac{m_f}{v}$$

QCD corr.

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

3

0.2

8x10^{-5} /GeV

2.8 GeV

Total width Γ_{tot}: 4.1 MeV

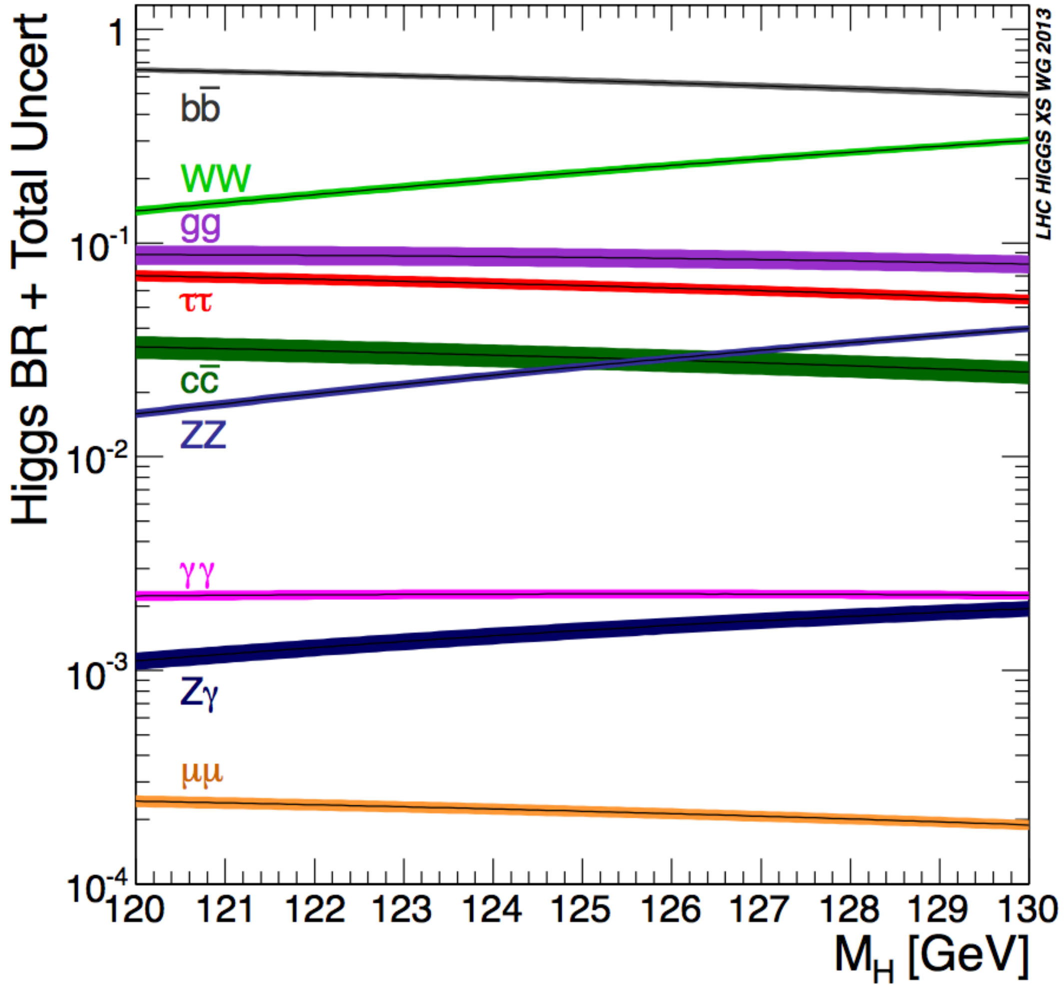
$BR_i=\Gamma_i / \Gamma_{tot}$

$\Gamma_{tot}=\Sigma \Gamma_i$

Higgs boson decay channels

W bosons

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



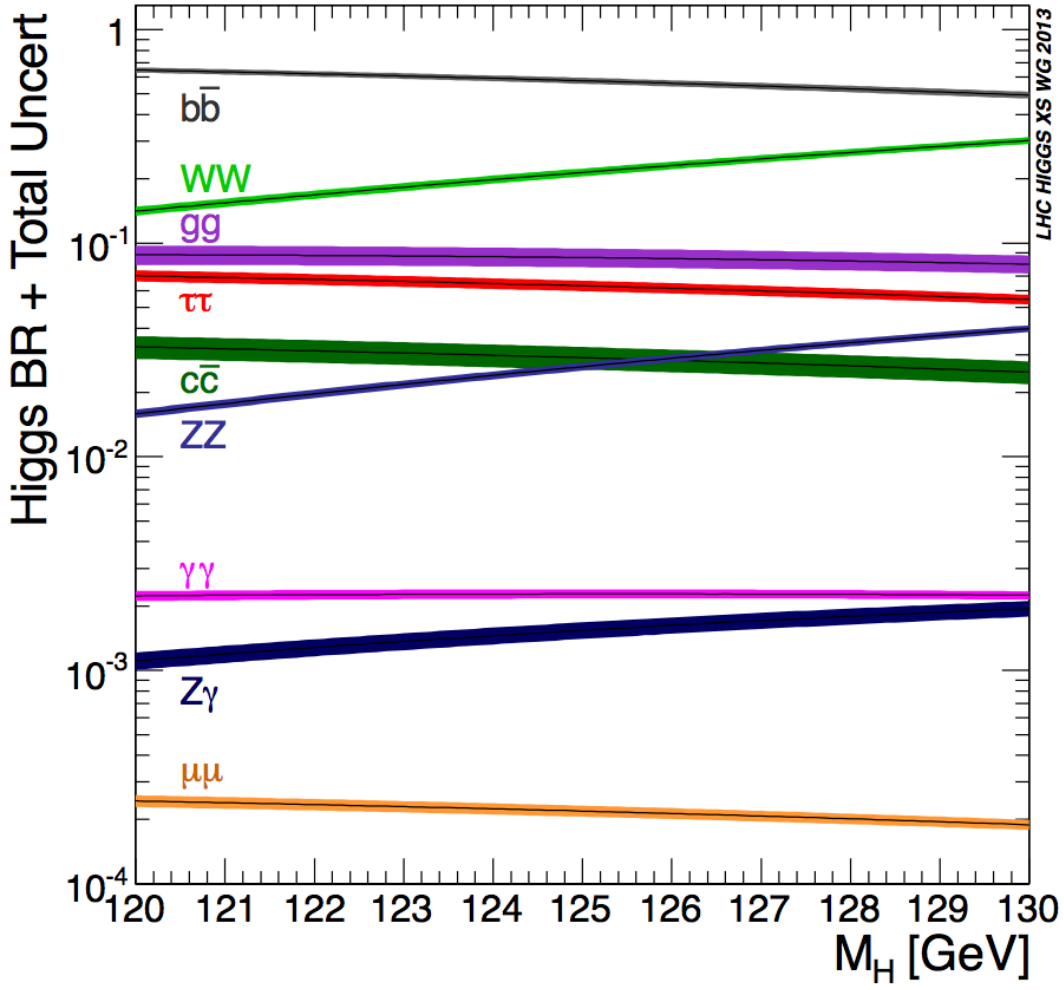
$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$

Higgs boson decay channels

Third generation fermions

Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %



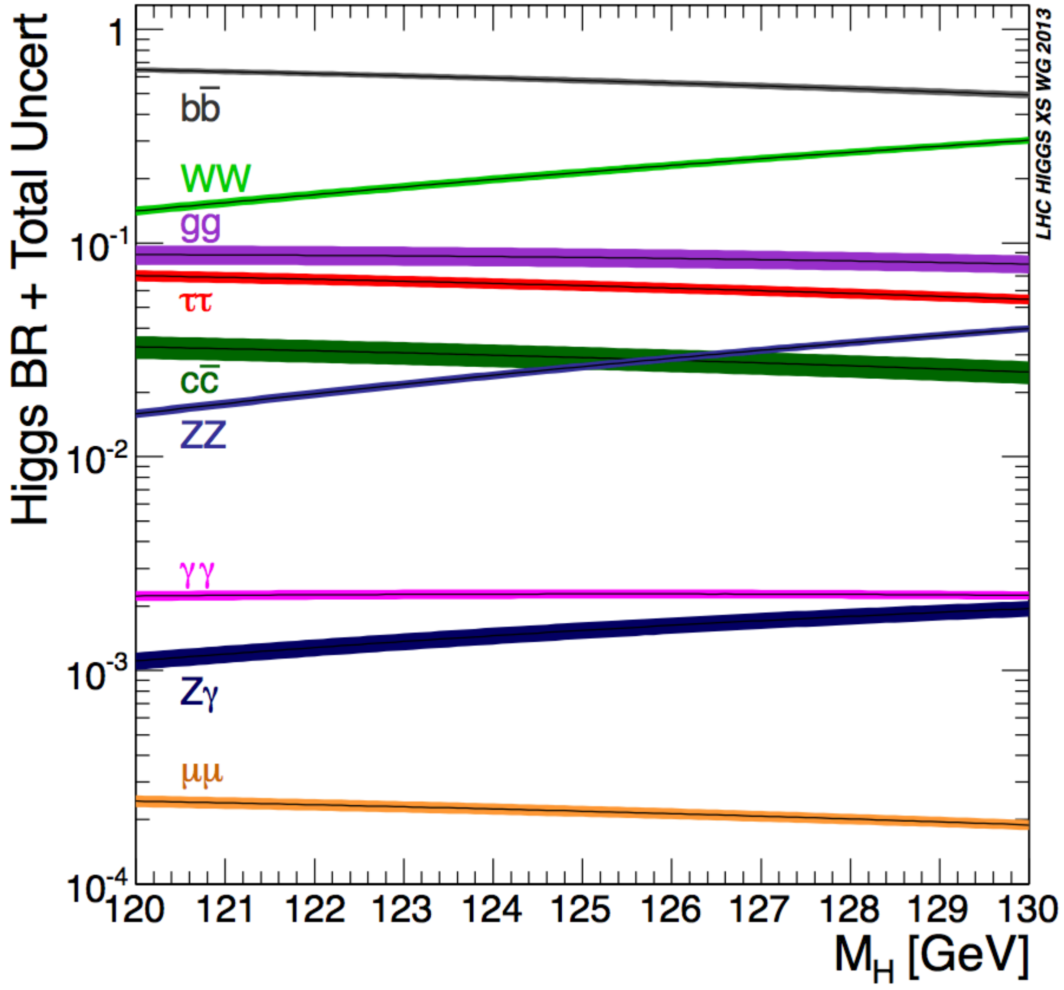
$\Gamma_{H\rightarrow\tau\tau} \sim [8\text{x}10^{-5}\ /\text{GeV}]\ m_f^2$

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

$\Gamma_{tot} = \Sigma\, \Gamma_i$

Higgs boson decay channels

Z bosons



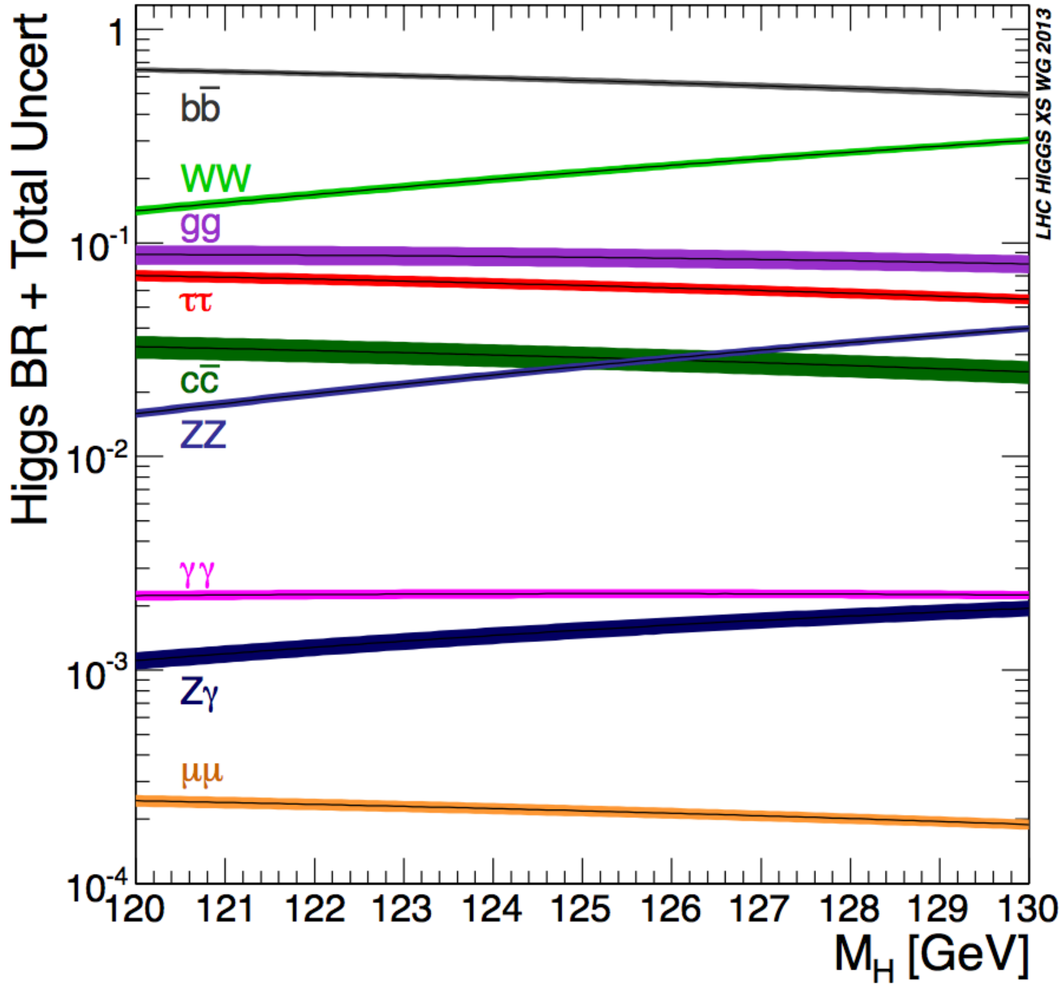
Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %
ZZ	3 %

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

$\Gamma_{tot}=\Sigma \Gamma_i$

Higgs boson decay channels

Second generation quarks



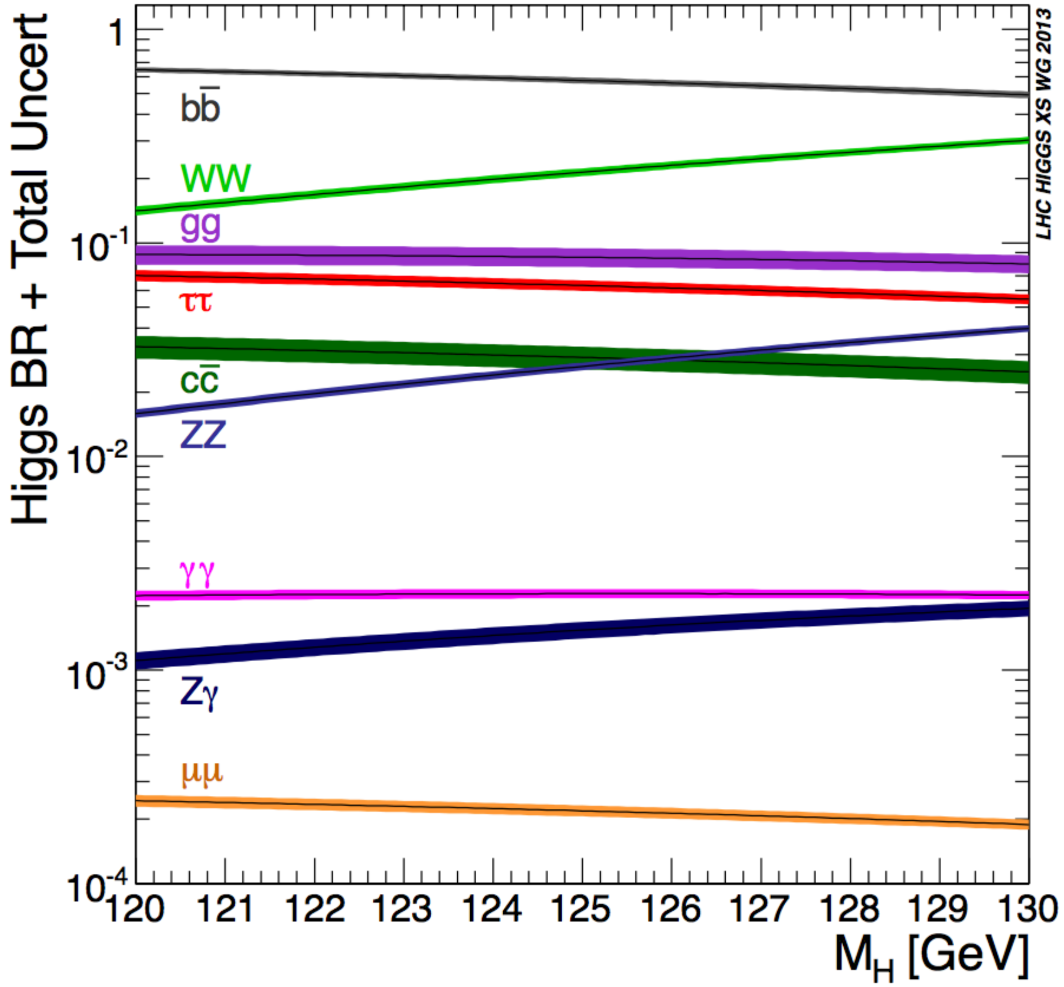
Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %
ZZ	3 %
cc	3 %

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

$\Gamma_{tot}=\Sigma\, \Gamma_i$

Higgs boson decay channels

Photons ?? How?



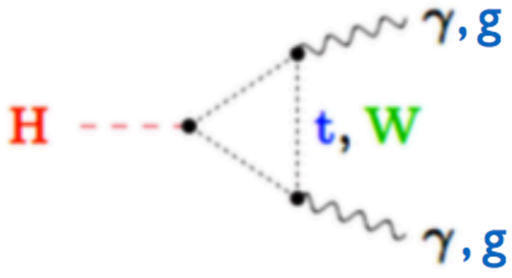
Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %
ZZ	3 %
cc	3 %
γγ	0.2 %

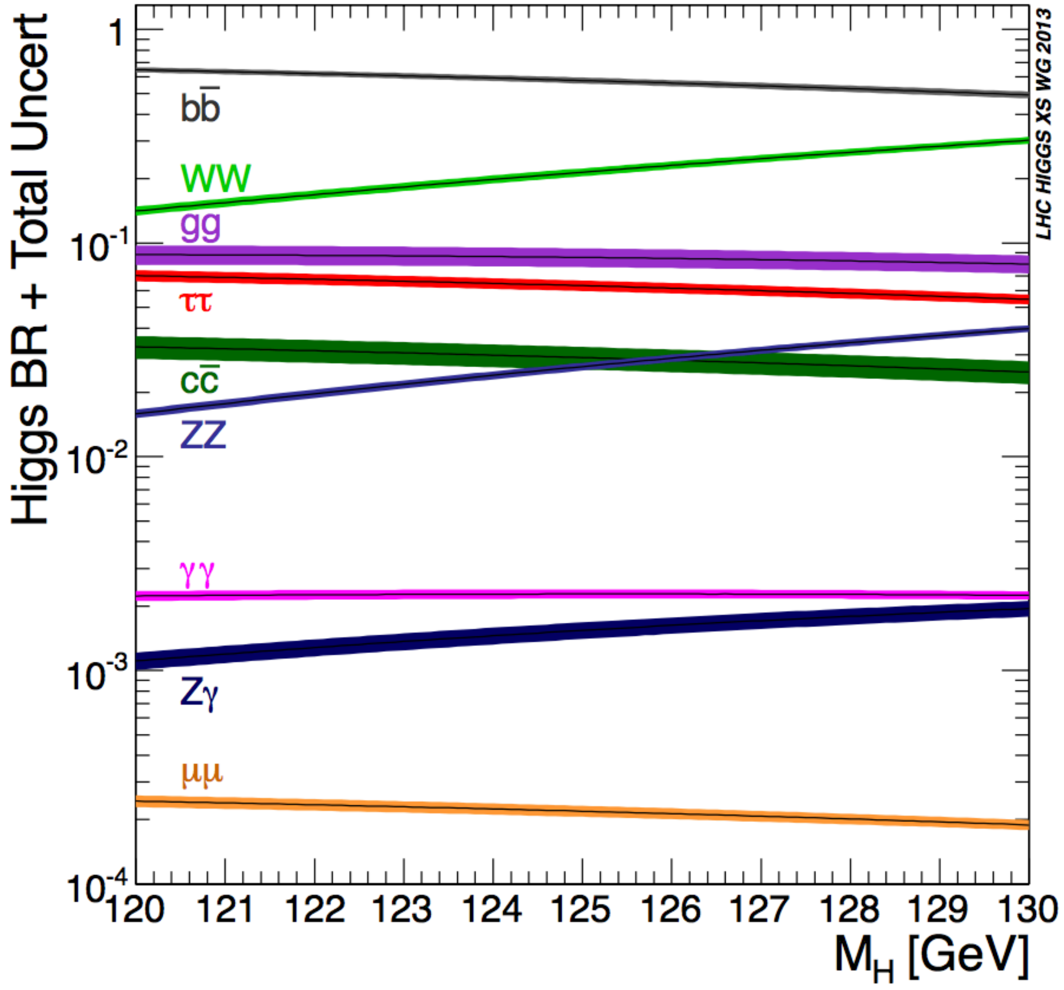
$BR_i = \Gamma_i / \Gamma_{tot}$

$\Gamma_{tot} = \Sigma\, \Gamma_i$

Higgs boson decay channels

Photons ?? How?





Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %
ZZ	3 %
cc	3 %
γγ	0.2 %

Possible trough loops

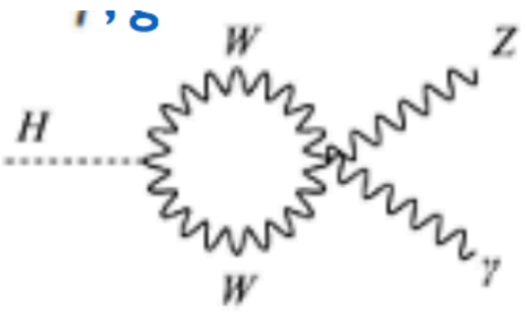
What if we have some new particle in the loop?

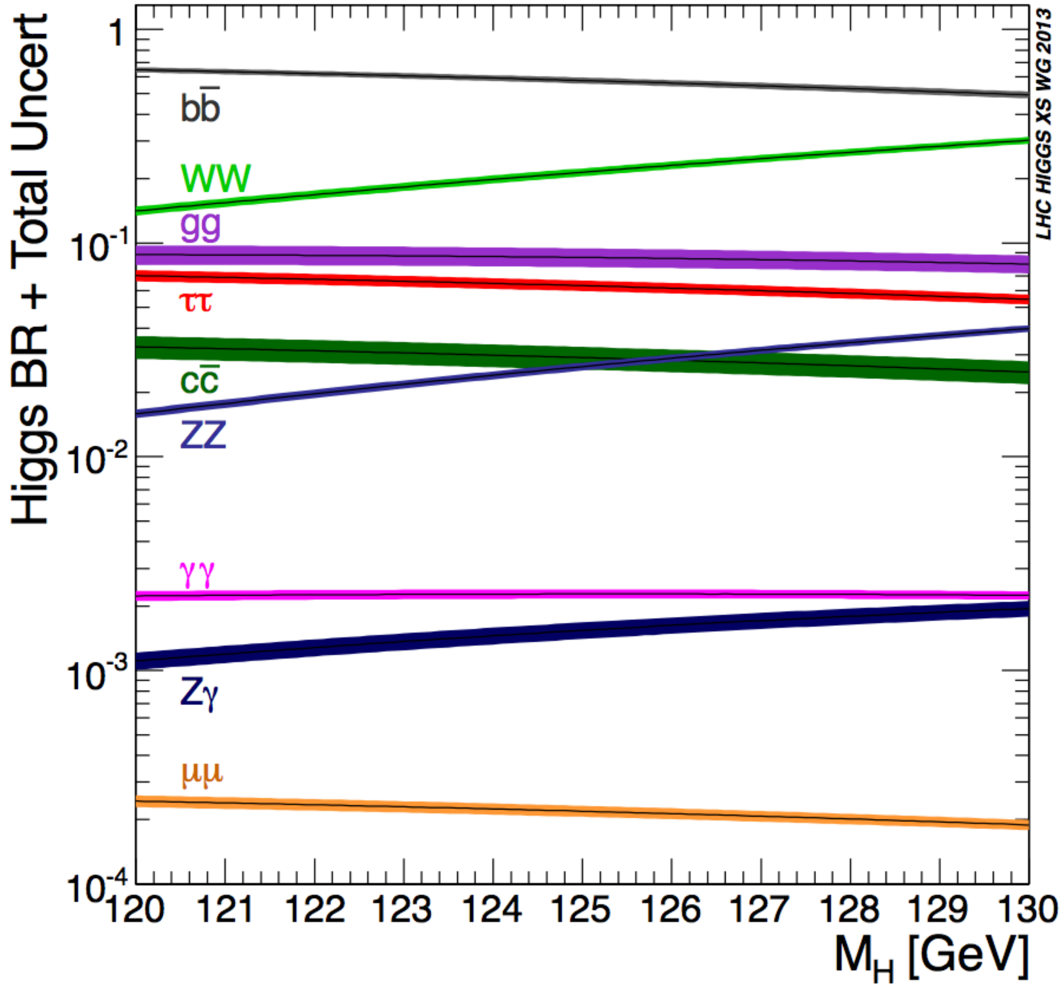
Higgs boson decay channels

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

$\Gamma_{tot} = \Sigma\, \Gamma_i$

Zγ?? How?



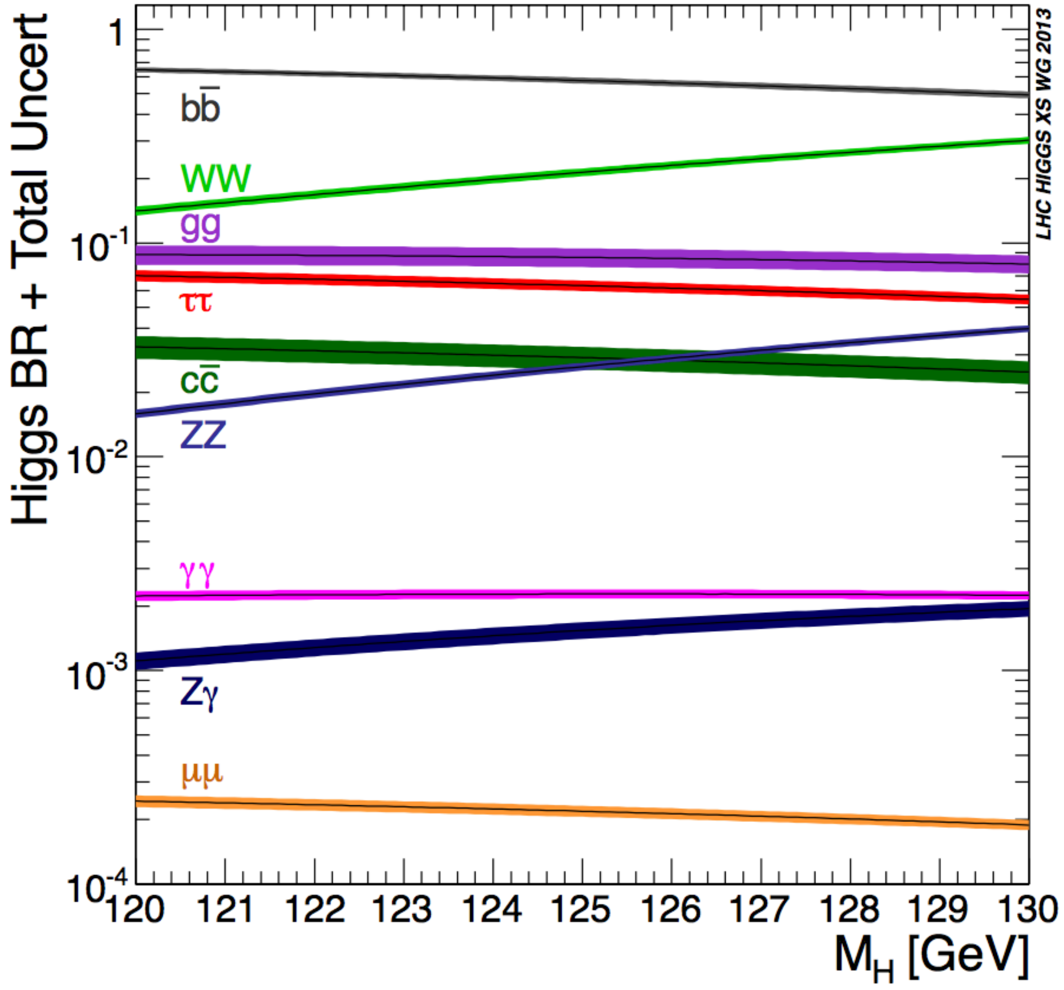


Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %
ZZ	3 %
cc	3 %
γγ	0.2 %
Zγ	0.2 %

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

Higgs boson decay channels

Second generation fermions



Decay mode	Expected BR for m_H=125 GeV
bb	57 %
WW	22 %
ττ	6.3 %
ZZ	3 %
cc	3 %
γγ	0.2 %
Zγ	0.2 %
μμ	0.02 %

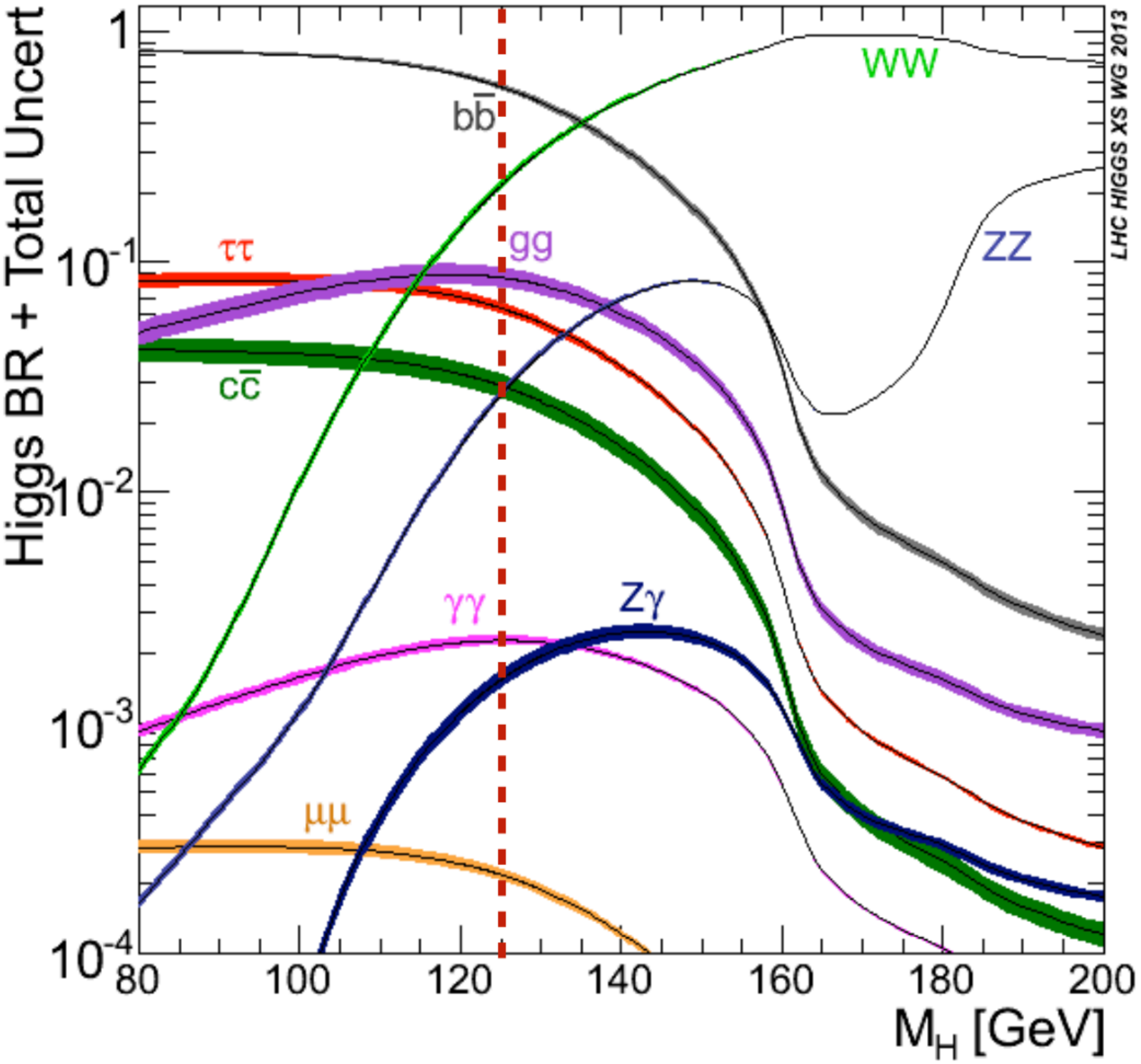
Higgs boson

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

And now…. some fresh air…

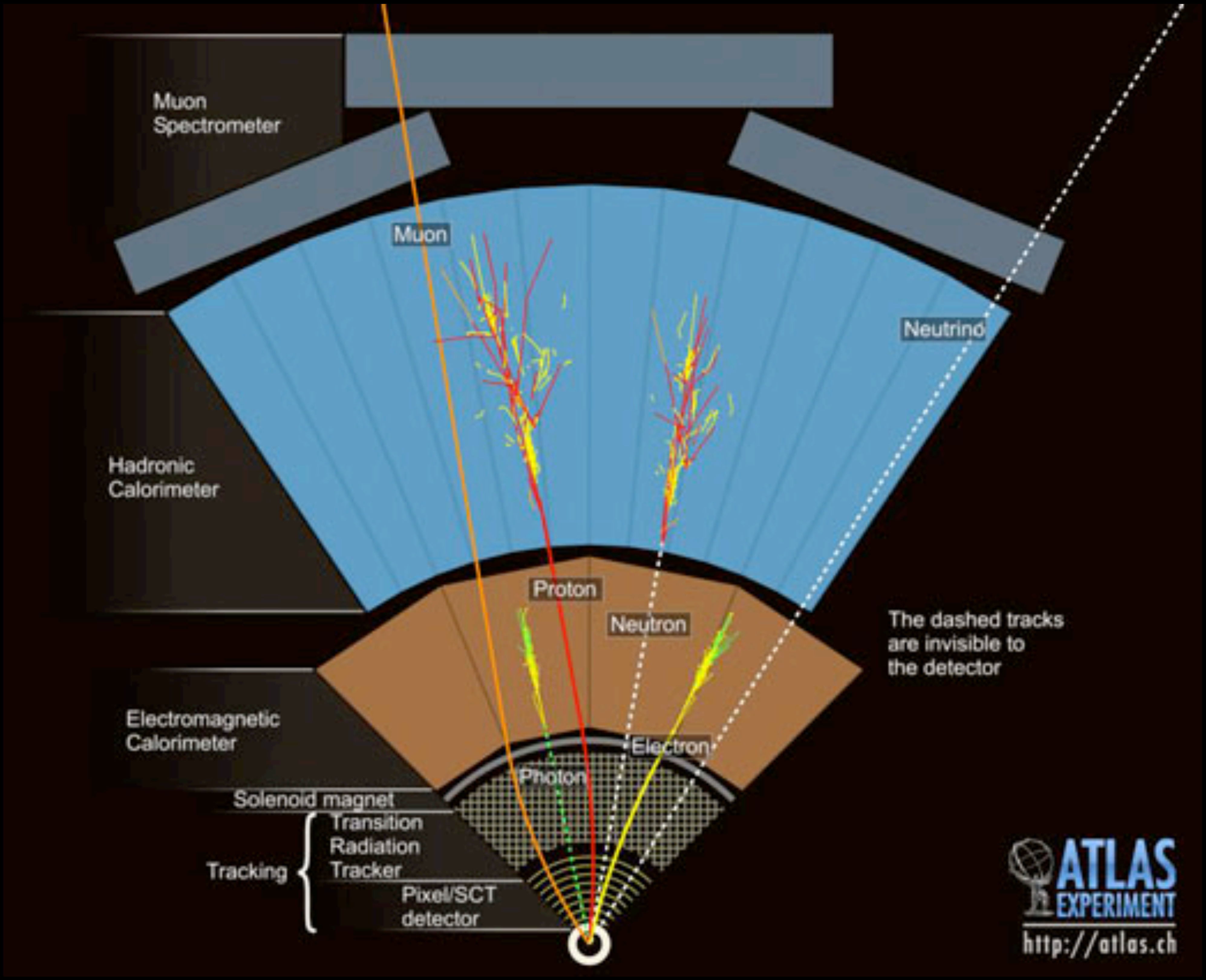
Discovering the Higgs boson at the LHC

Which are the needed performances for our detector?

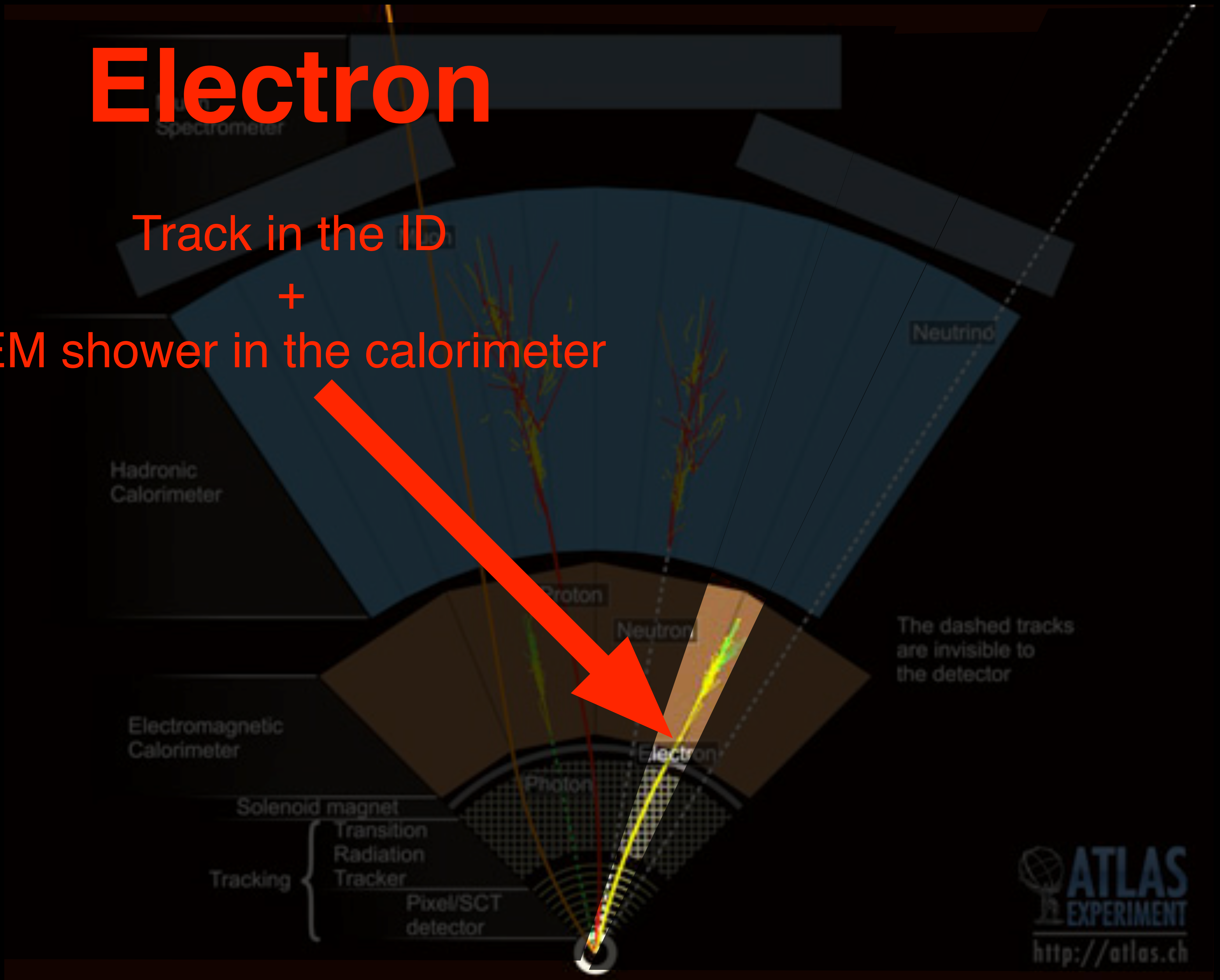


- **γγ**: identification and measurement of **photons**
- **ZZ,WW**: identifications and measurement of **muons**, **electrons**
- **WW**,**ττ**: measurement of **missing transverse energy** (requiring energy measurement up to very forward - |η|~5)
- **bb**,**ττ**, efficient and pure **b-tagging** and **τ identification**
- **VBF**: Capability to detect **forward jets** (for vector boson fusion processes)

Concept


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

Concept



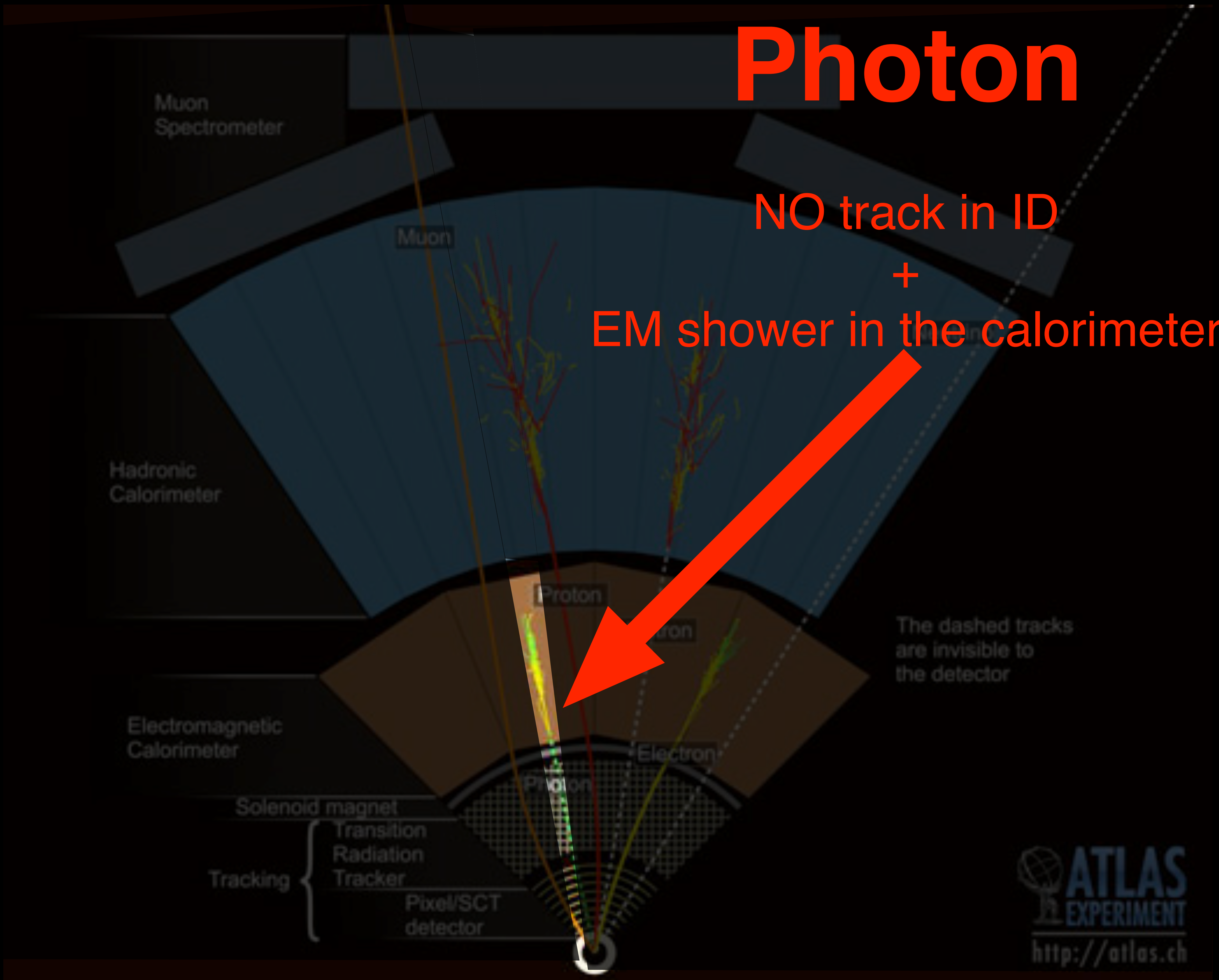
Electron

Track in the ID

\+

EM shower in the calorimeter

Concept



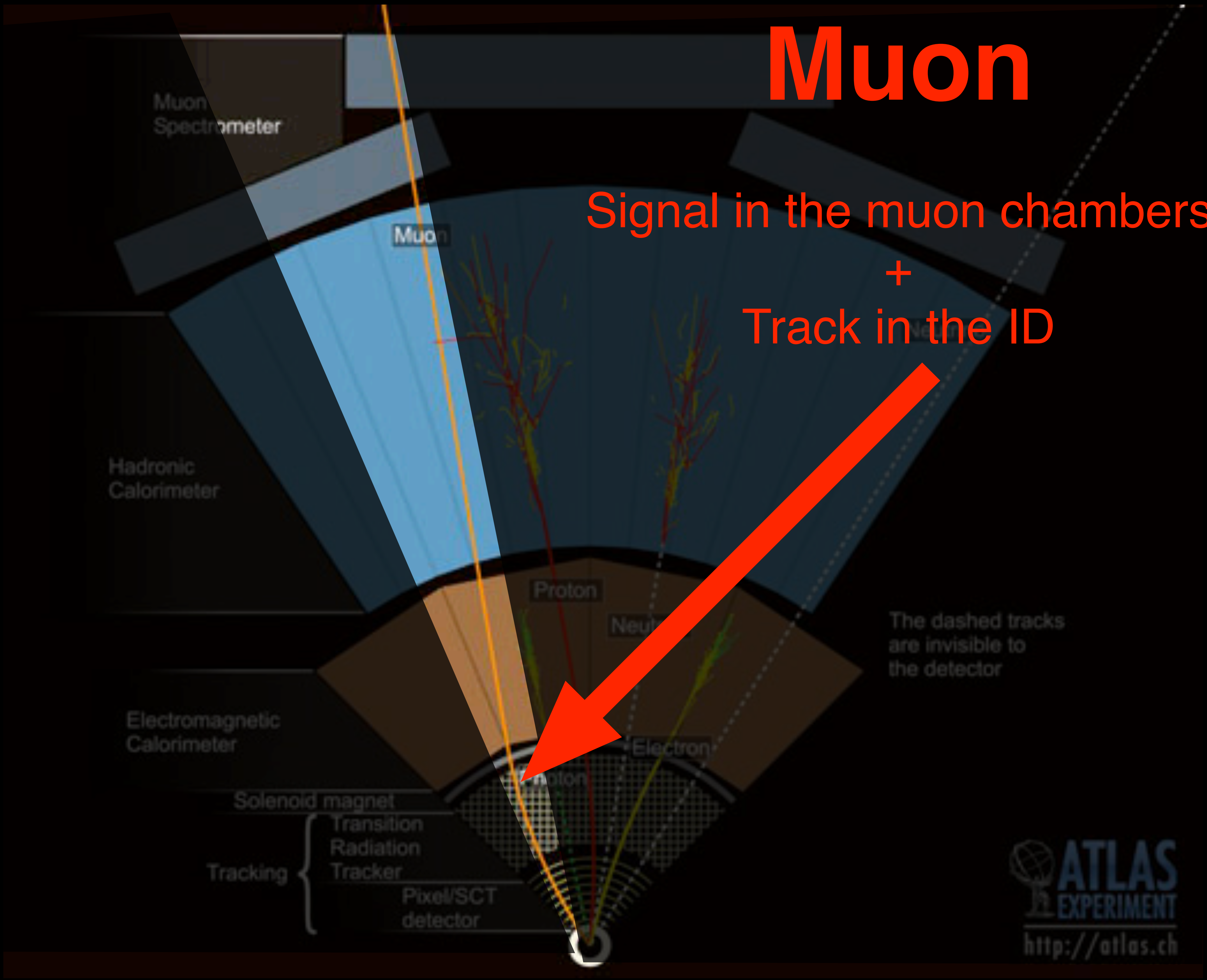
Photon

NO track in ID

+

EM shower in the calorimeter

Concept



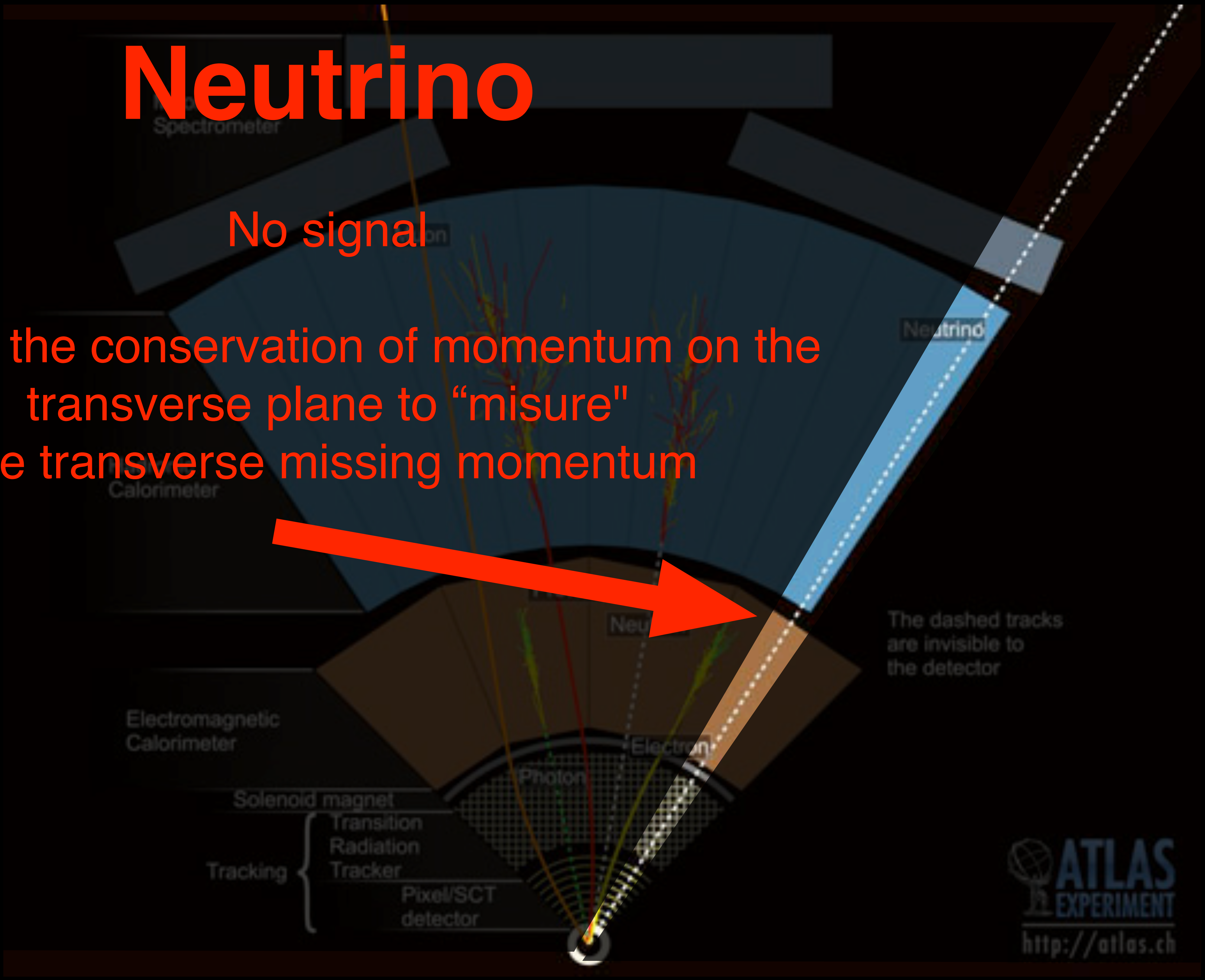
Muon

Signal in the muon chambers

+

Track in the ID

Concept

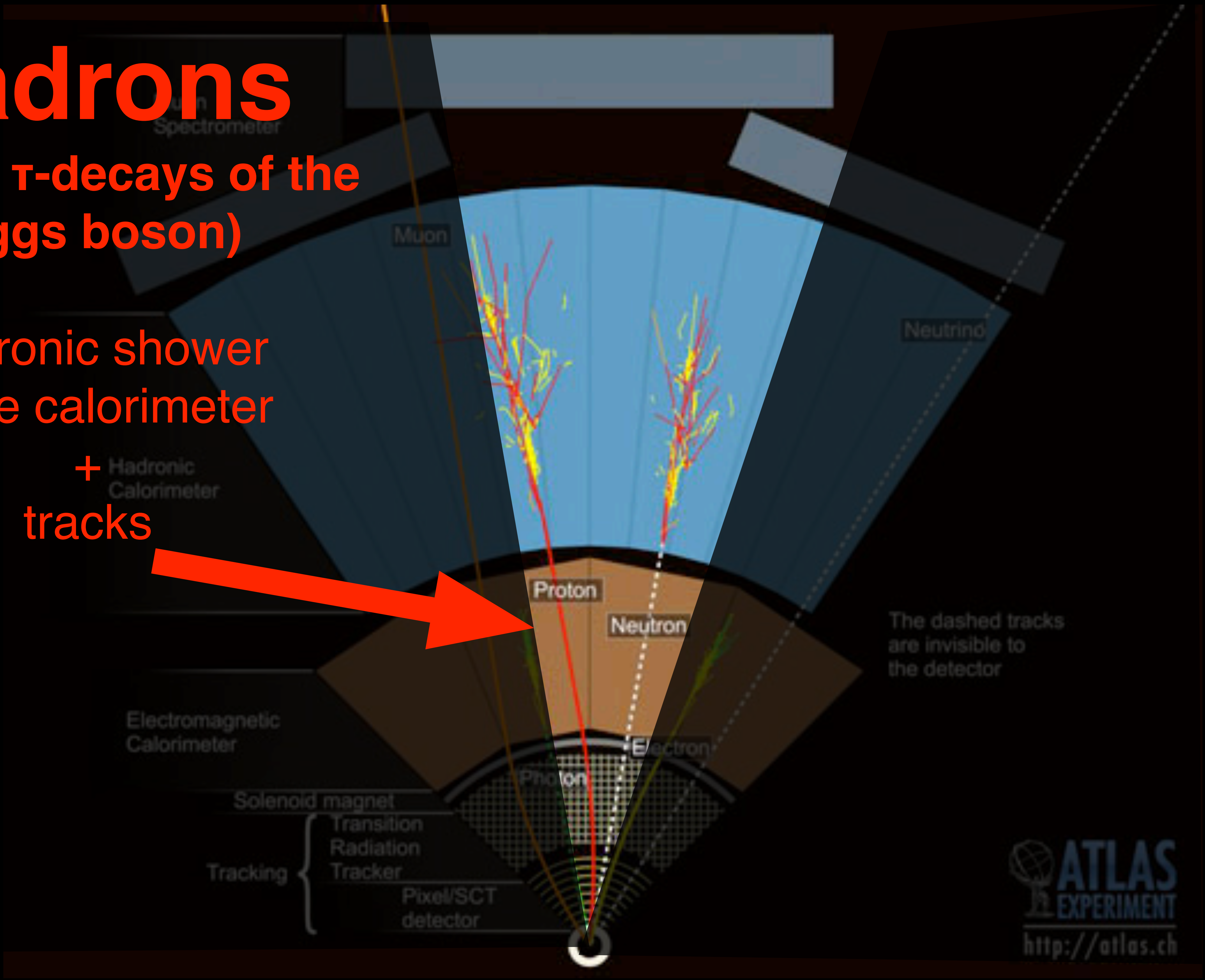


Neutrino

No signal

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

Concept



Hadrons

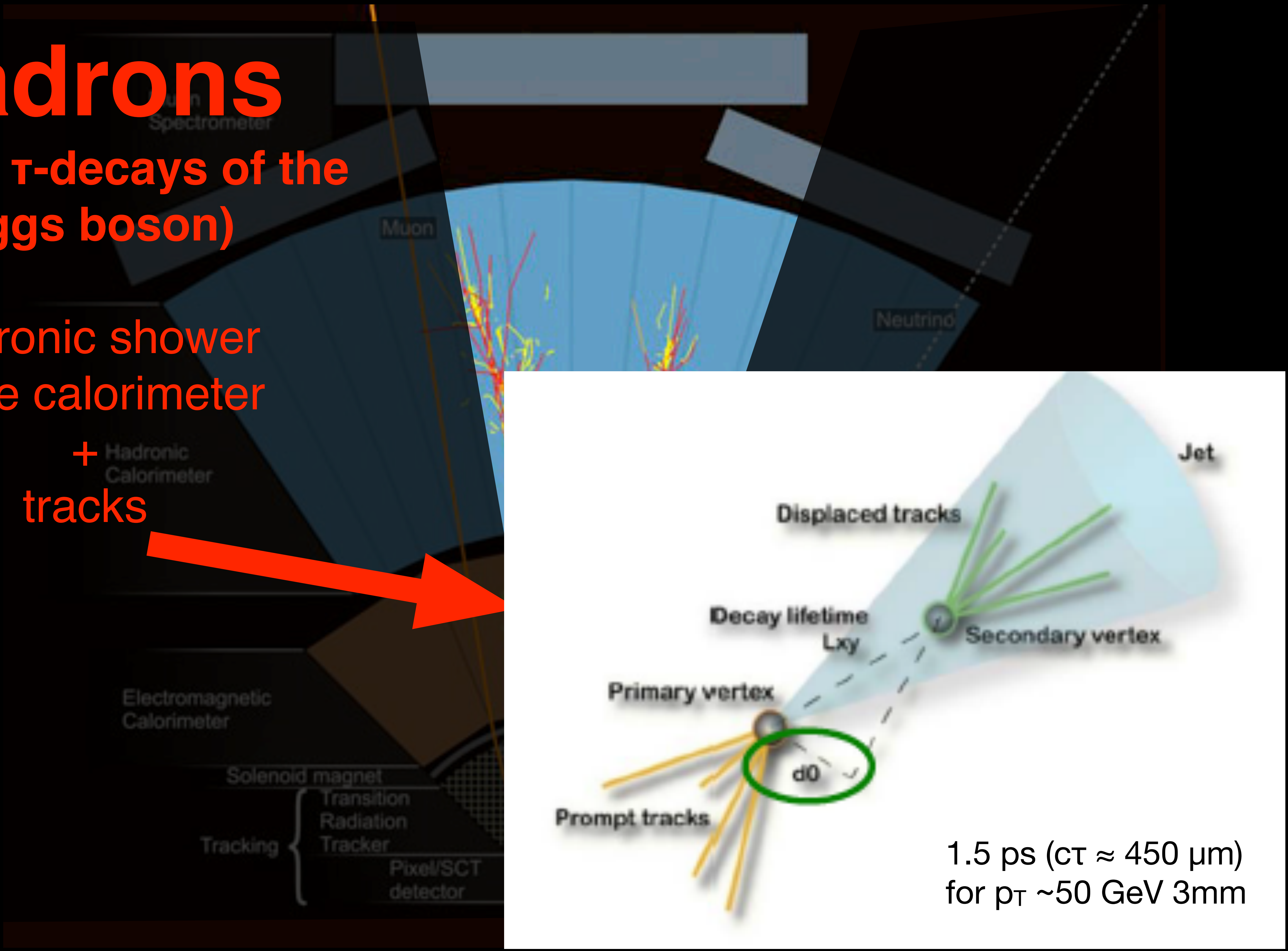
(in b- or τ-decays of the Higgs boson)

Hadronic shower in the calorimeter

+

tracks

Concept



Hadrons

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

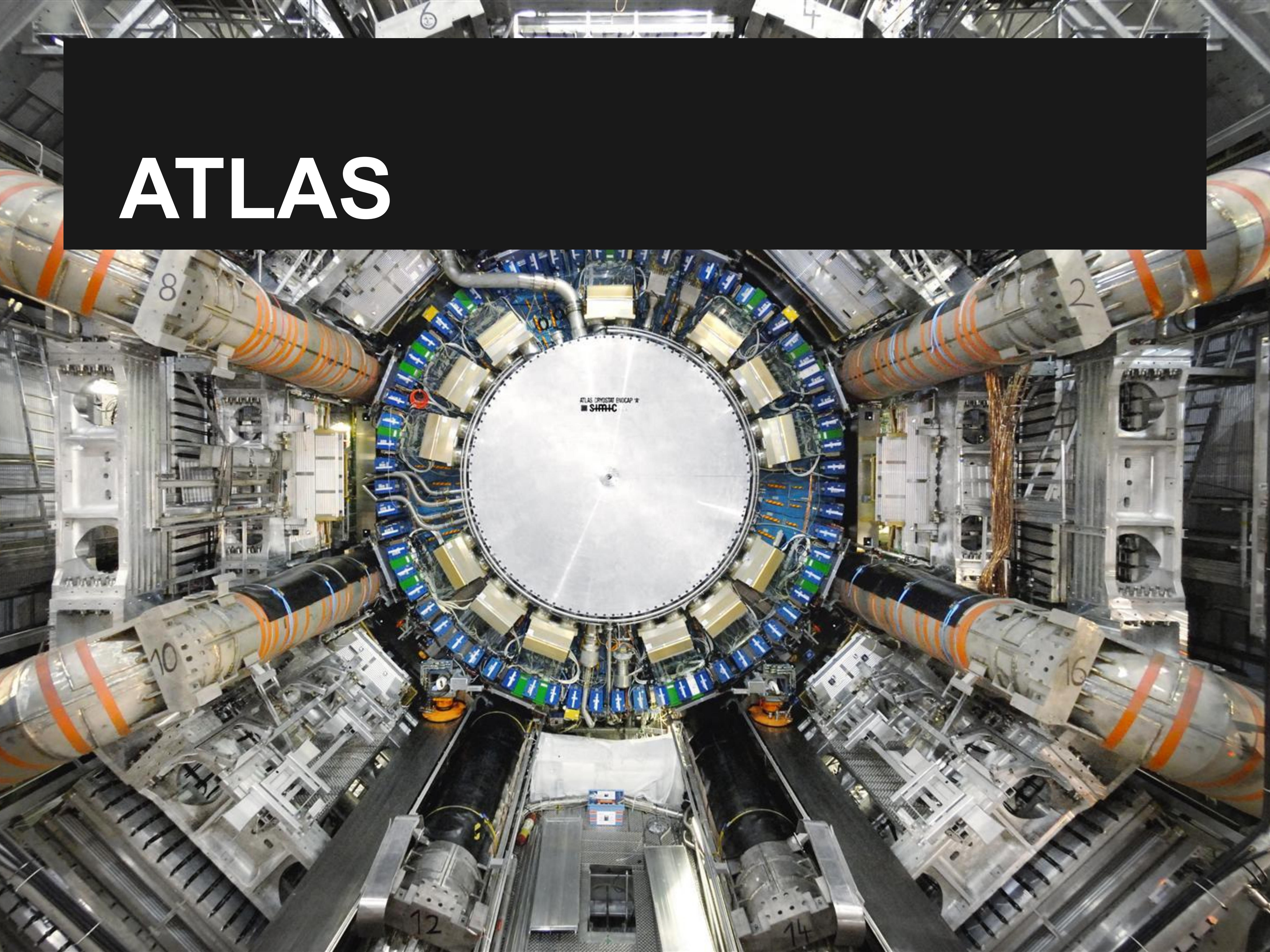
Hadronic shower in the calorimeter

+

tracks

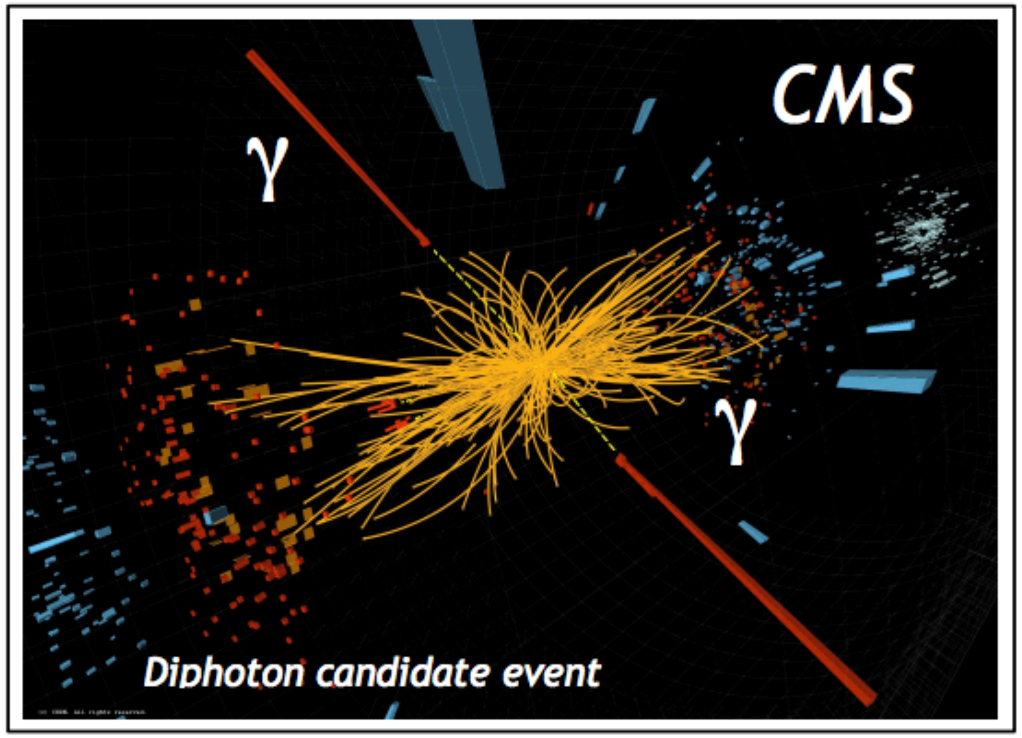
1.5 ps (cτ ≈ 450 μm)
for p_T ~50 GeV 3mm

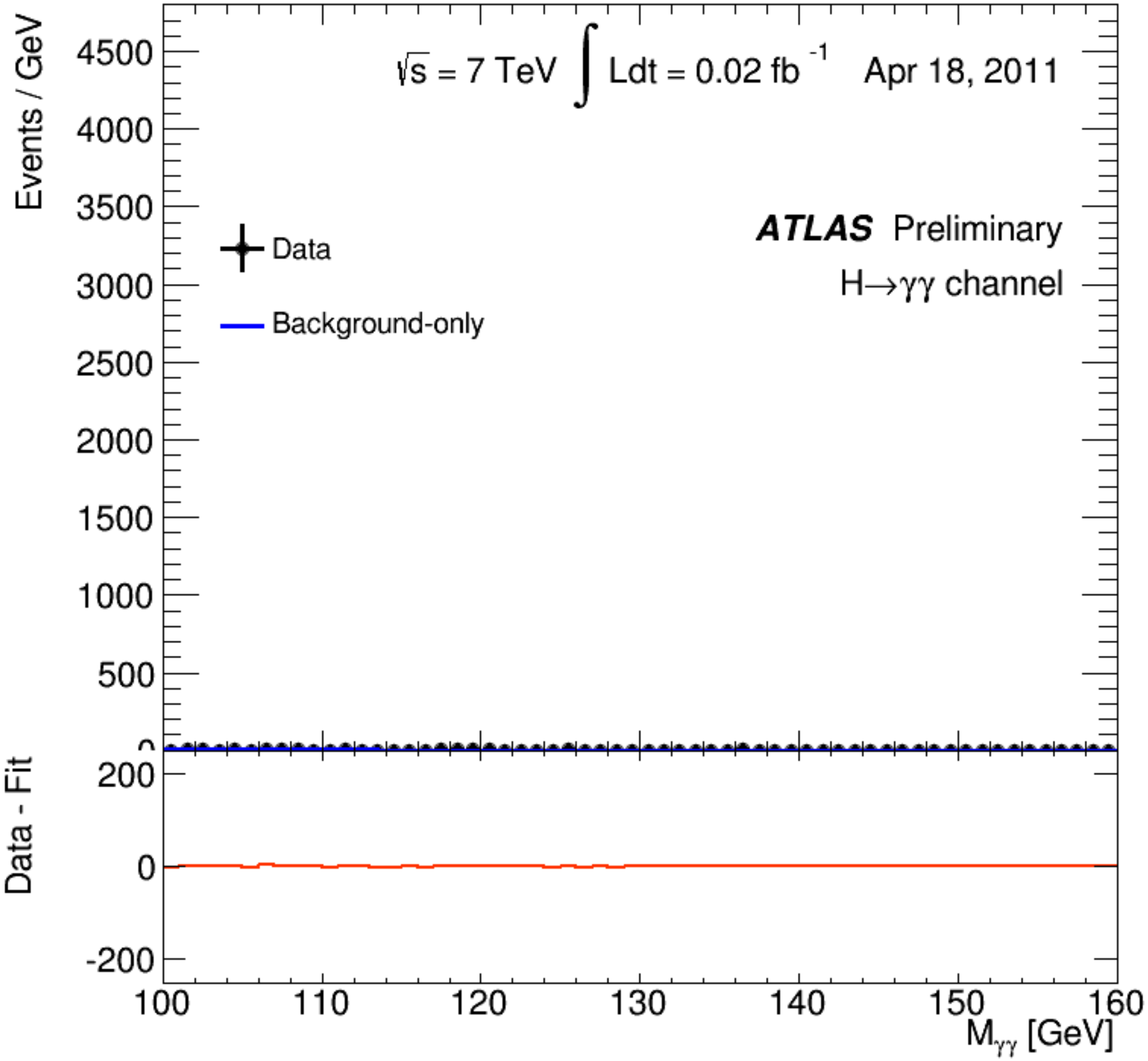
ATLAS



CMS

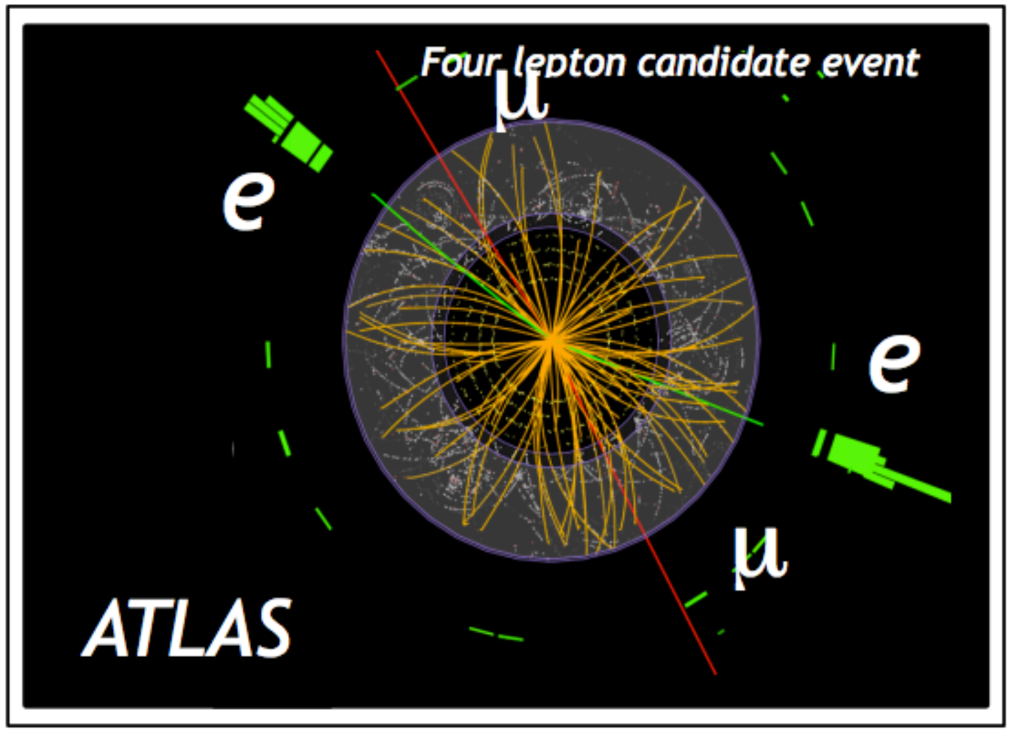
H→γγ

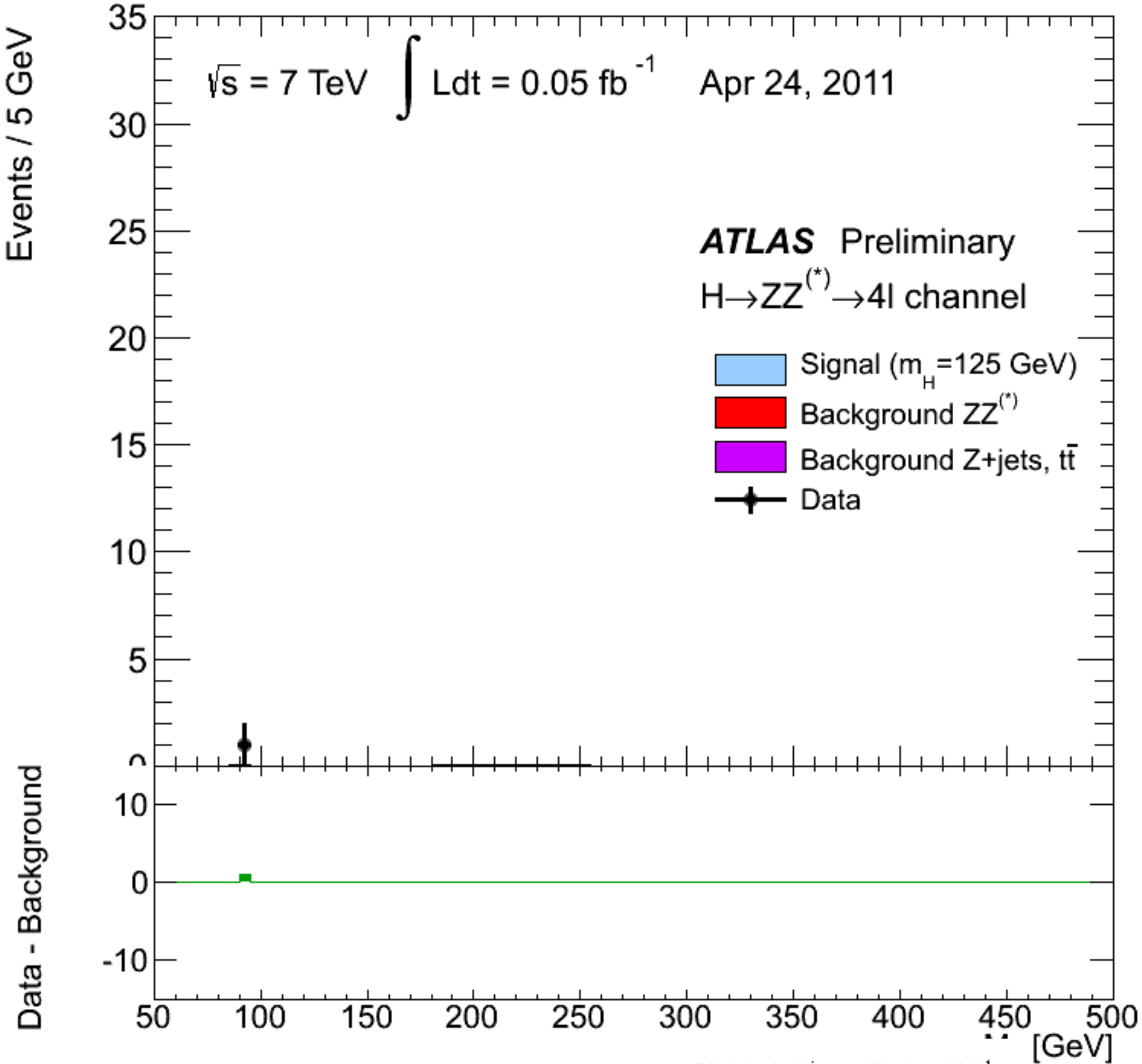




- Low S/B, but relatively high statistics for the signal
  Signal: ~300 events in Run1 Background: Largest contribution from jets
- Very simple selection, quality of detector response and performance play a crucial role
- Main production modes and decay mode occur trough loop. Probe for new physics

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



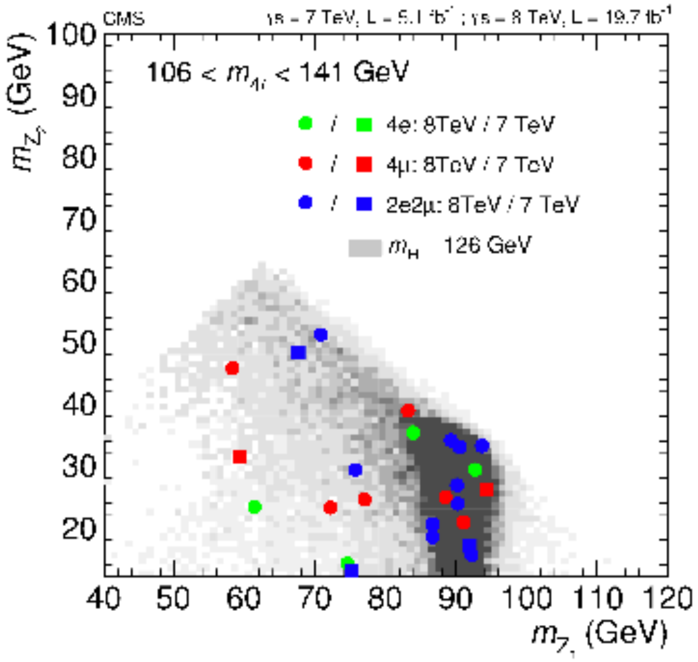


- High S/B (2-10), but relatively low statistics

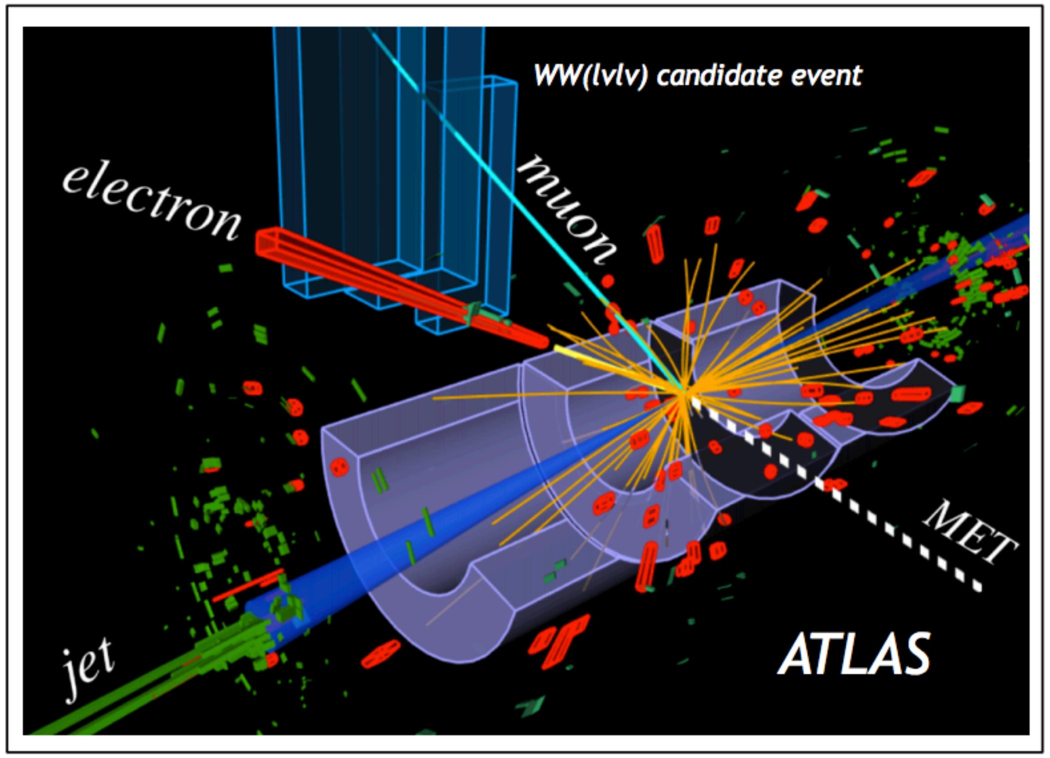
Background: pp->ZZ estimated by MC

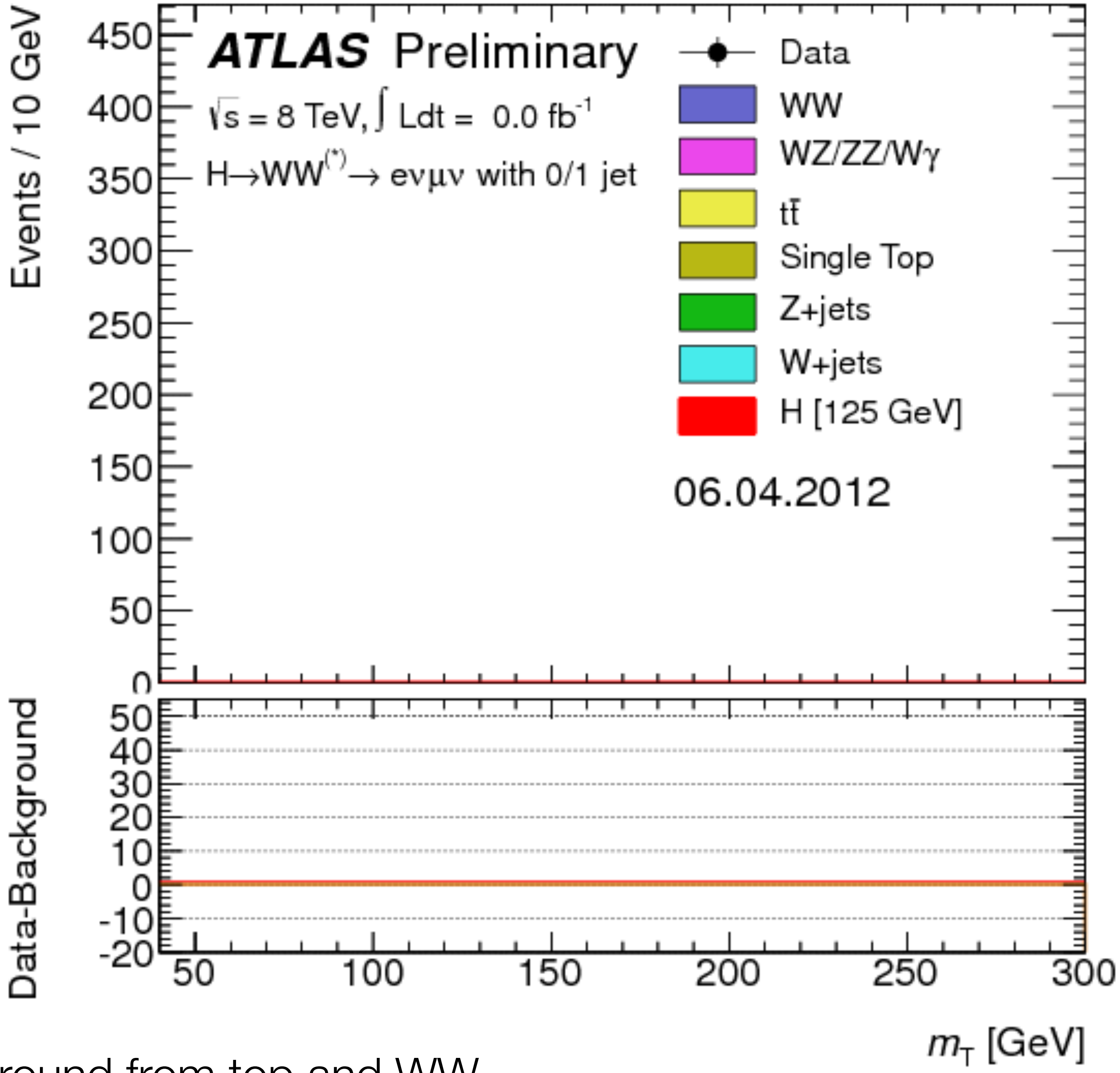
- Typically one Z is on-mass shell

- Note: BR(H→ZZ)~3%, BR(Z→ee)+BR(Z→μμ)~6.7%



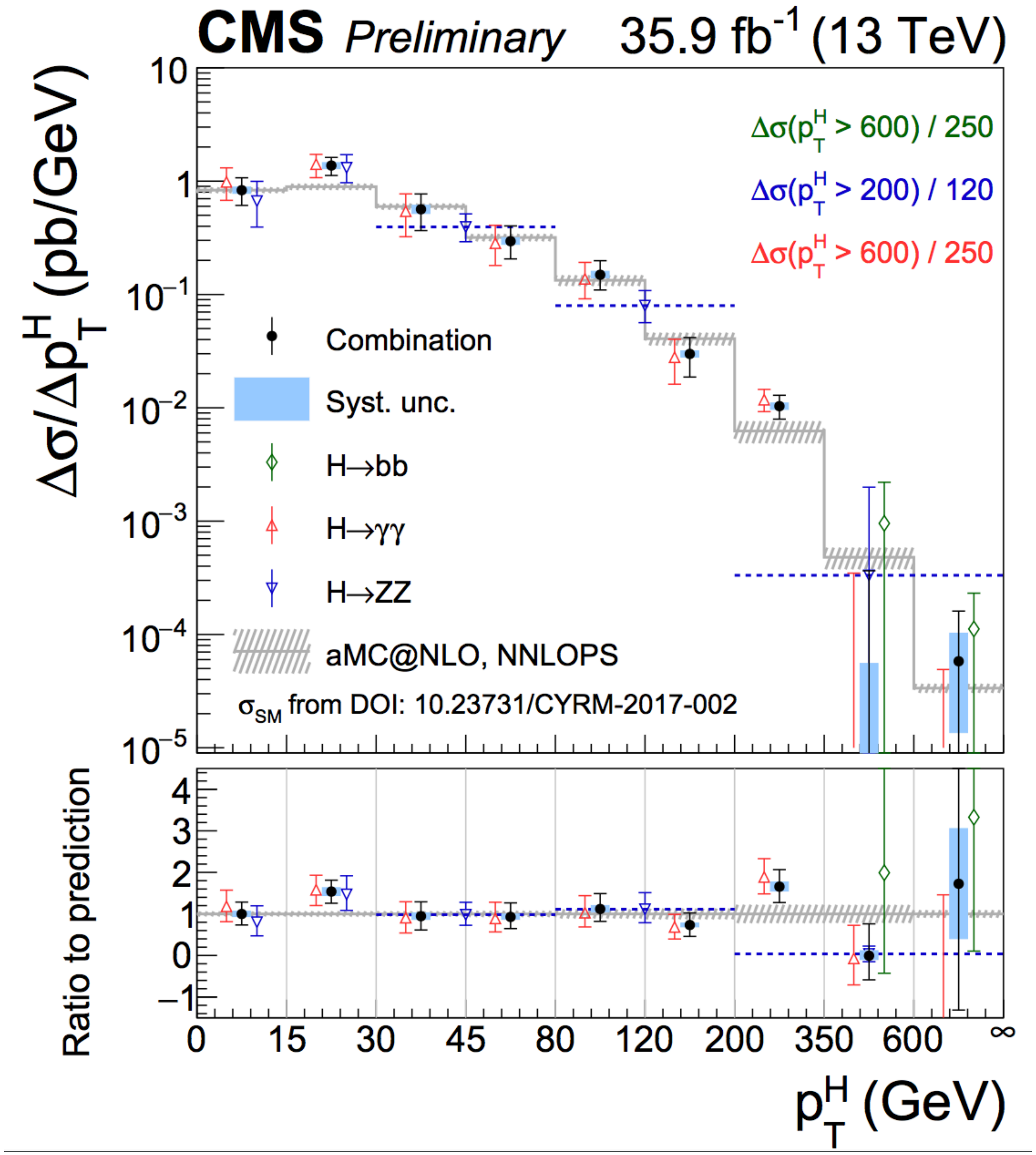
$H \rightarrow WW^* \rightarrow 2l2\nu$

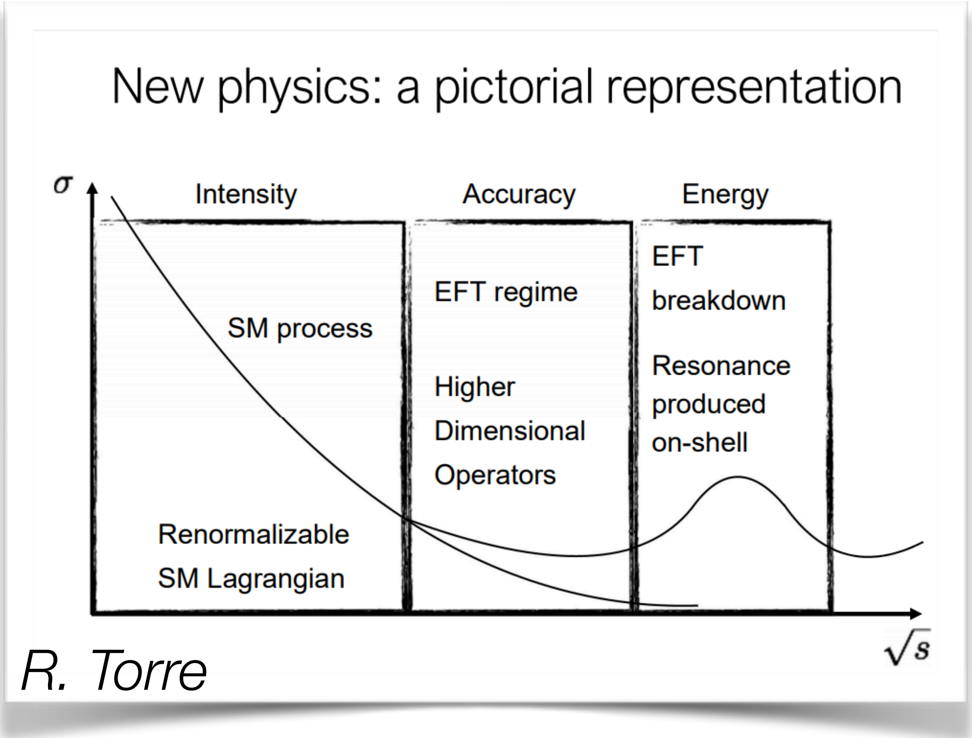




- Large signal event rate, but large background from top and WW
- Requires a very good understanding of the background in simulations and with control regions
- The presence of neutrinos spoil the mass resolution

A new era - differential measurements



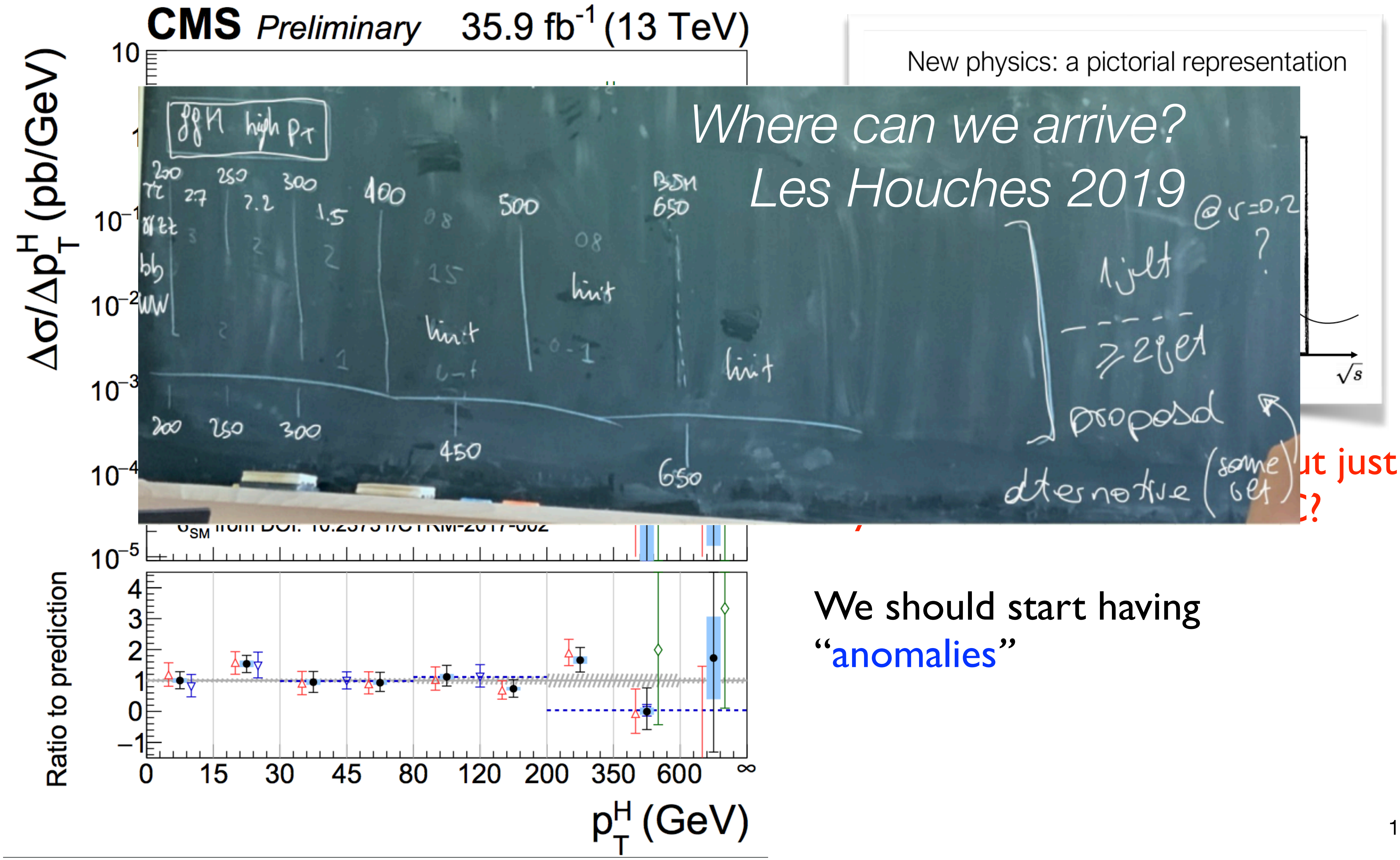


R. Torre

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

We should start having "anomalies"

A new era - differential measurements



Where can we arrive?

Les Houches 2019

ut just

C?

We should start having “anomalies”

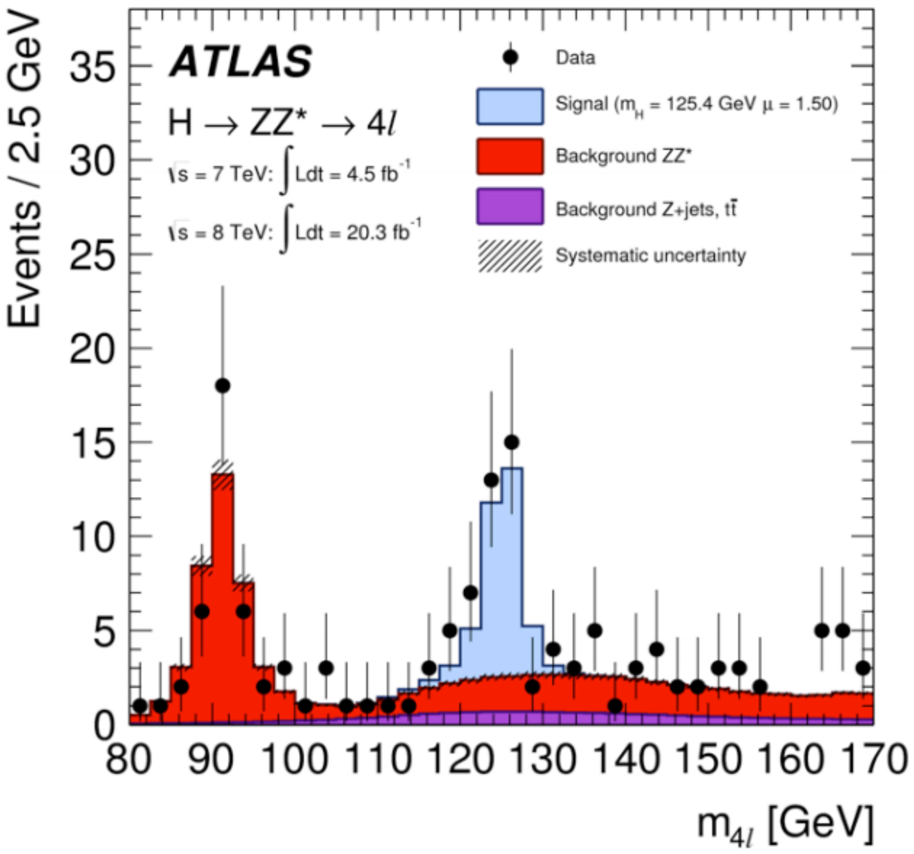
Discovering the Higgs boson at the LHC

- 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

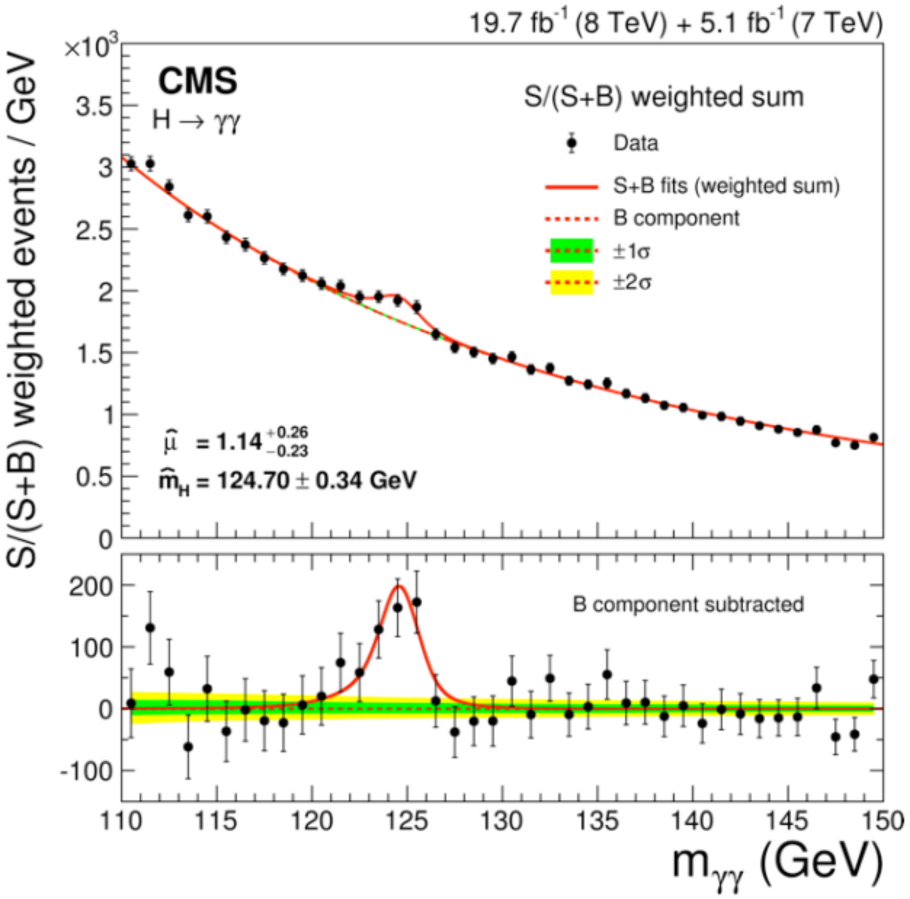
Higgs Properties

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→ZZ*→4l and H→γγ final states, for which invariant mass can be reconstructed with high precision



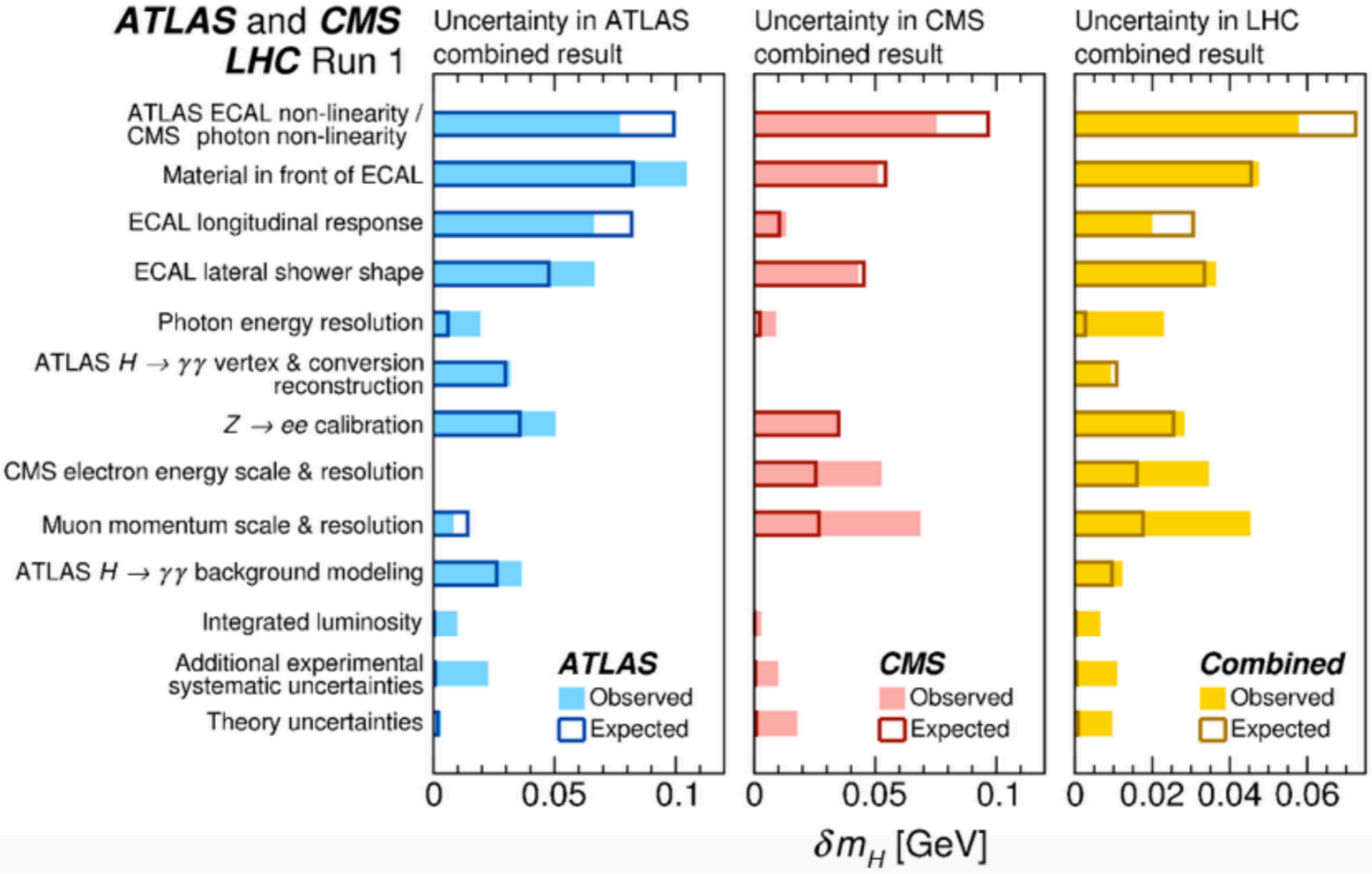
Phys. Rev. D 90, 052004 (2014)



Eur. Phys. J. C 74 (2014) 3076

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

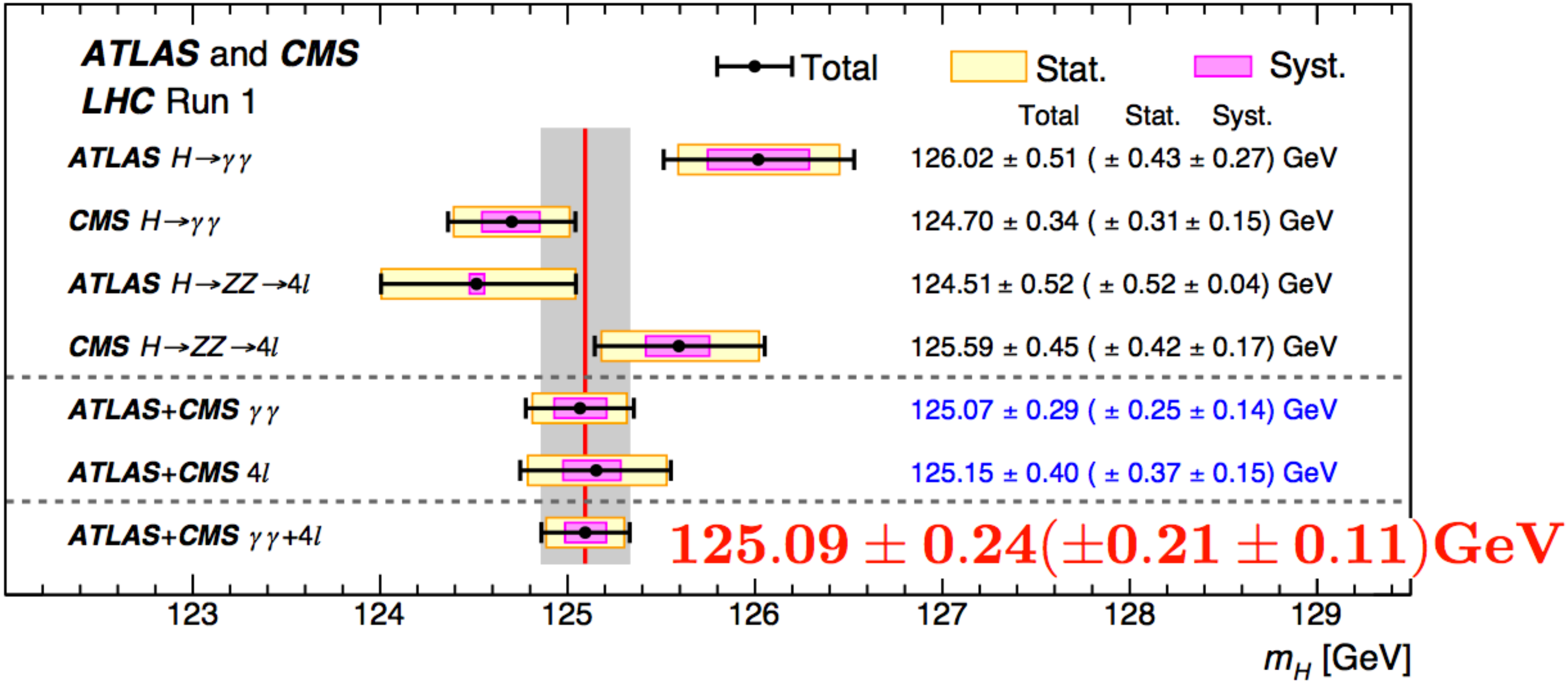
Largest impact from energy scale - as expected…



Phys. Rev. Lett. 114, 191803 (2015)

Measurement of the Higgs boson mass

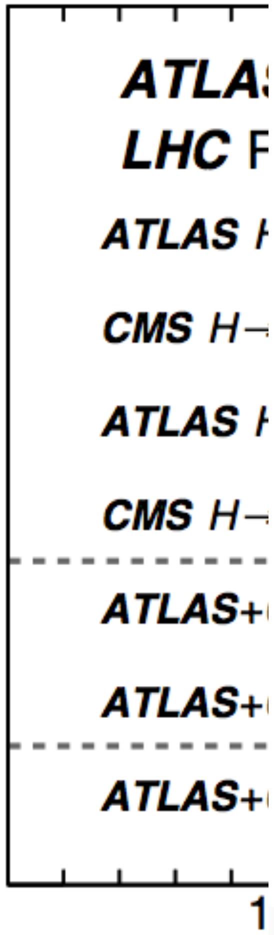
- Mass of Higgs boson measured with <0.2% precision
- MH = 125.09 ± 0.24 GeV [±0.21 (stat.) ±0.11(syst.)]
- Dominant systematics: energy or momentum scale and resolution for γ,e,μ

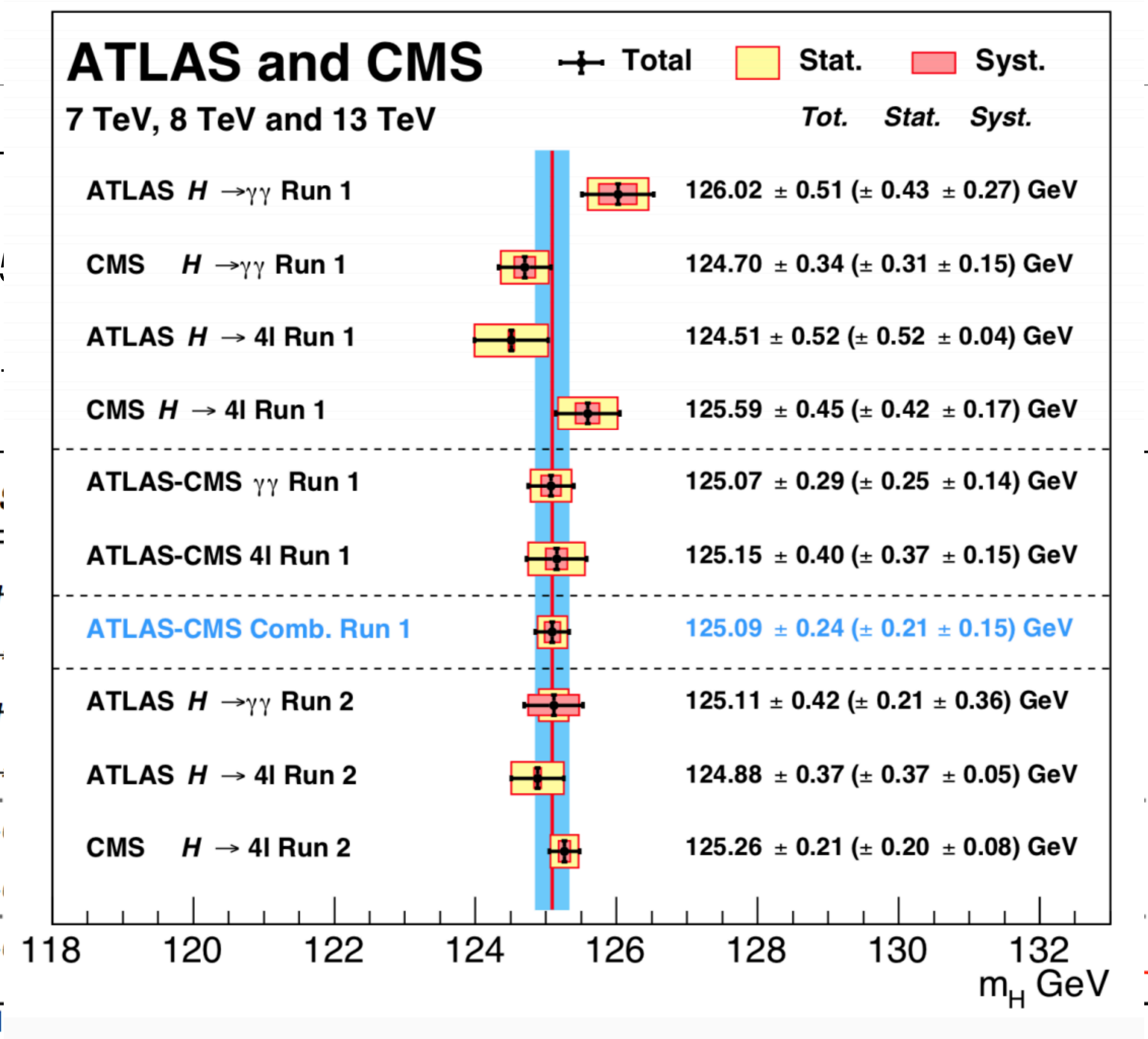


Phys. Rev. Lett. 114, 191803 (2015)

Measurement of the Higgs boson mass

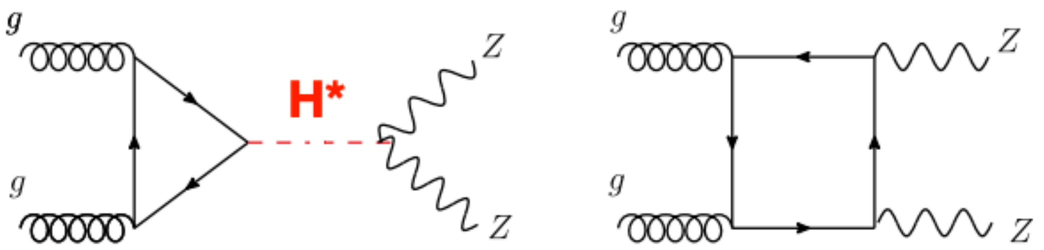
- Mass of H
- MH = 12
- Dominan

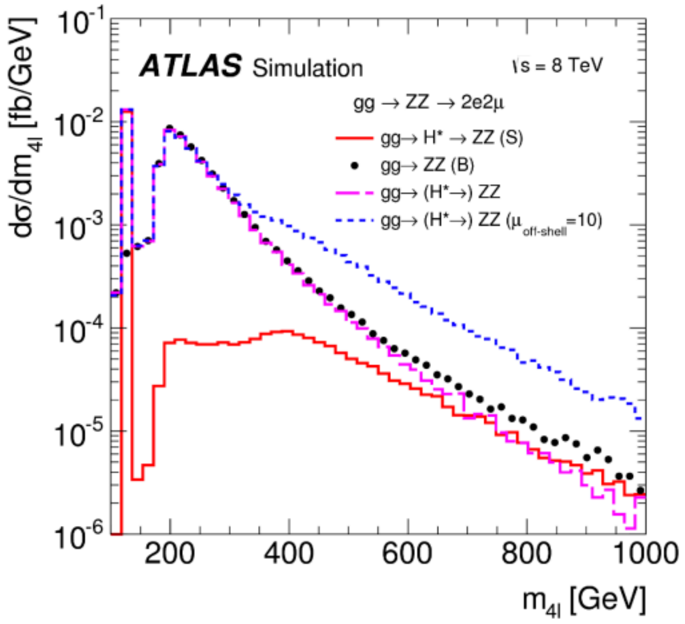




for γ,e,μ

Off shell Higgs





- Study of the 4-lepton spectrum in the high mass regime where the Higgs boson acts as a propagator

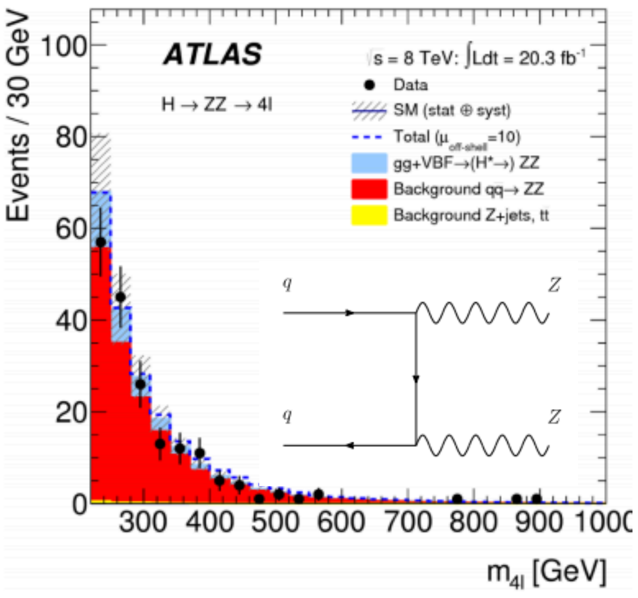
- Measurement of the Higgs contribution is independent of the total width of the Higgs boson

- Assuming that the Higgs couplings run as in the Standard Model

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

	obs. 95% CL on Γ_H
4ℓ+2ℓ2ν (36/fb Run2)	$\Gamma_H < 14.4$ MeV
4ℓ (Run1 + 77/fb Run2)	$0.08 < \Gamma_H < 9.16$ MeV

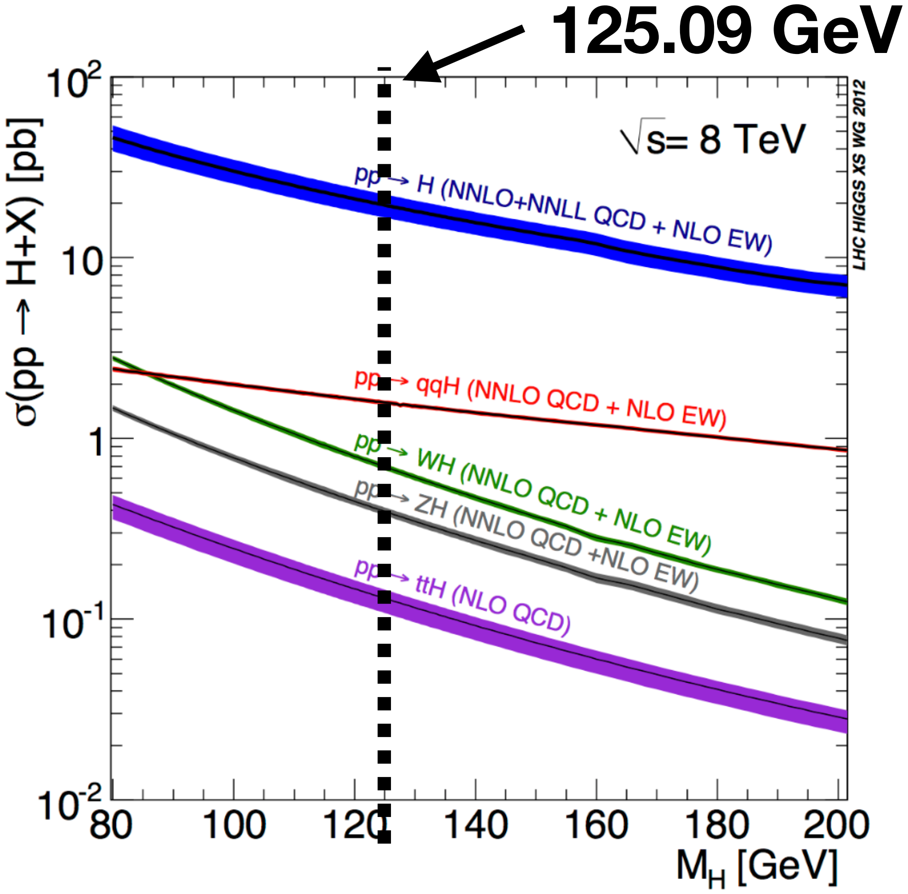
- Highly non trivial due to:
  - the negative interference
  - the large backgrounds



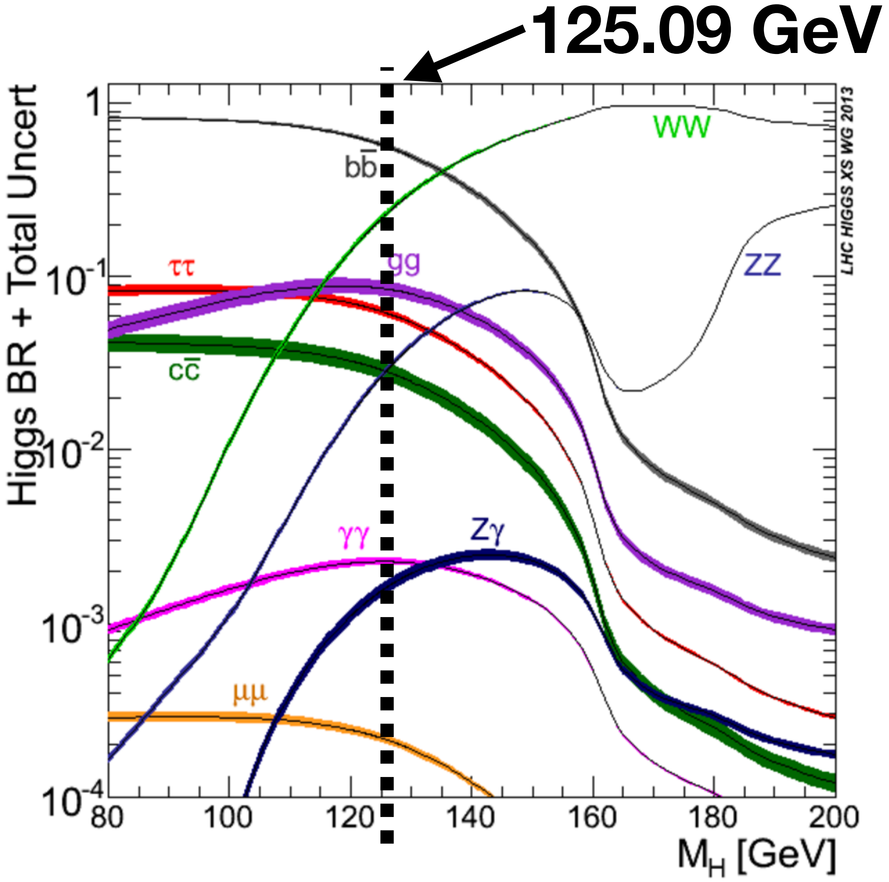
Knowing the mass….

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

CERN-2013-004, FERMILAB-CONF-13-667-T



125.09 GeV

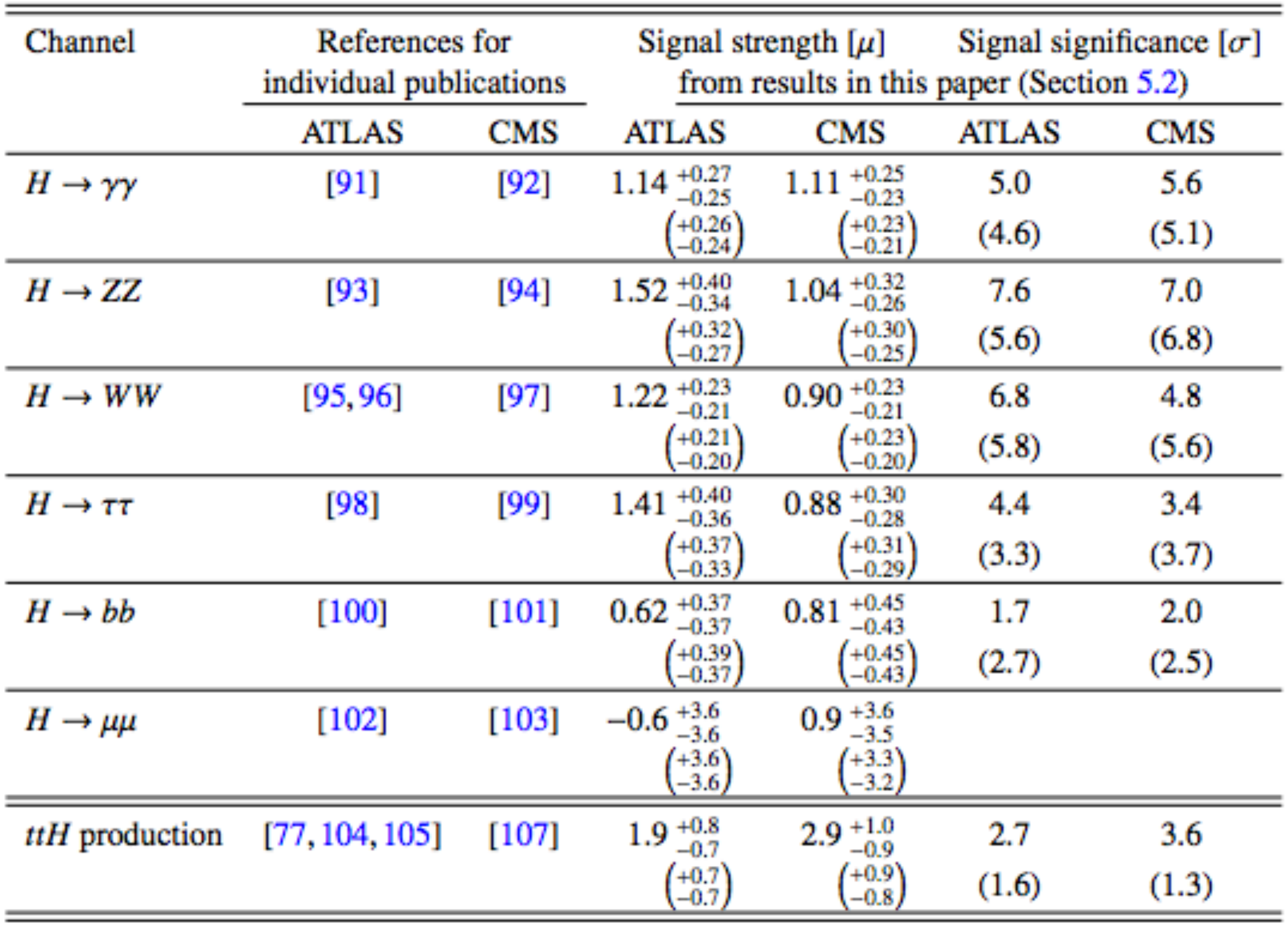


125.09 GeV

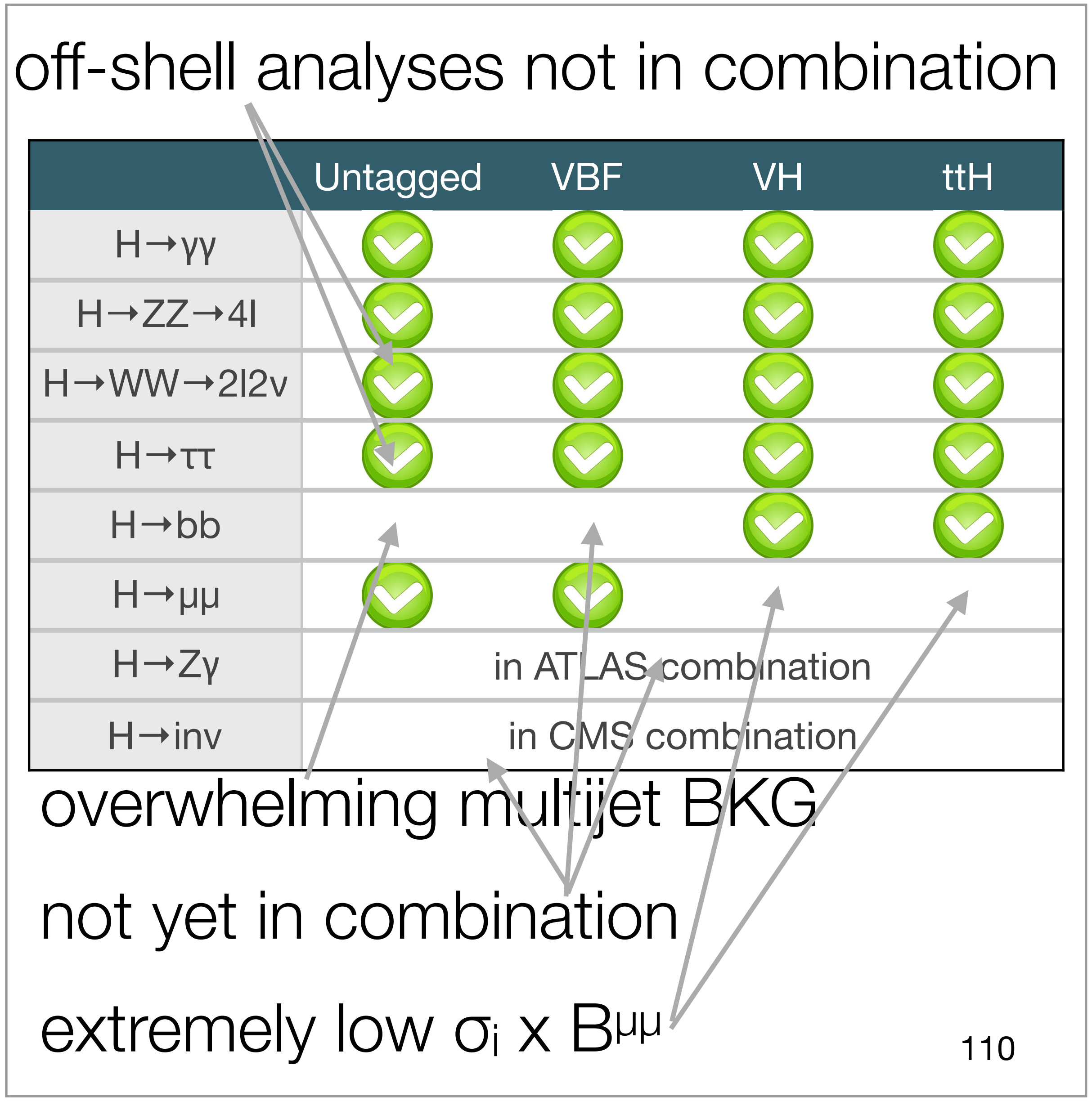
- Combining measurements and searchers by ATLAS and CMS collaborations

Run1 - Measurements in ATLAS and CMS

- Integrated luminosities per experiment:
  ~5 fb^{-1} at $\sqrt{s}$ = 7 TeV ~20 fb^{-1} at $\sqrt{s}$ = 8 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
$H \to \gamma\gamma$	[91]	[92]	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[93]	[94]	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[95,96]	[97]	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[98]	[99]	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[100]	[101]	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[102]	[103]	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[77,104,105]	[107]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)



off-shell analyses not in combination

	Untagged	VBF	VH	ttH
H→γγ	✓	✓	✓	✓
H→ZZ→4l	✓	✓	✓	✓
H→WW→2l2ν	✓	✓	✓	✓
H→ττ	✓	✓	✓	✓
H→bb			✓	✓
H→μμ	✓	✓		
H→Zγ	in ATLAS combination			
H→inv	in CMS combination			

overwhelming multijet BKG

not yet in combination

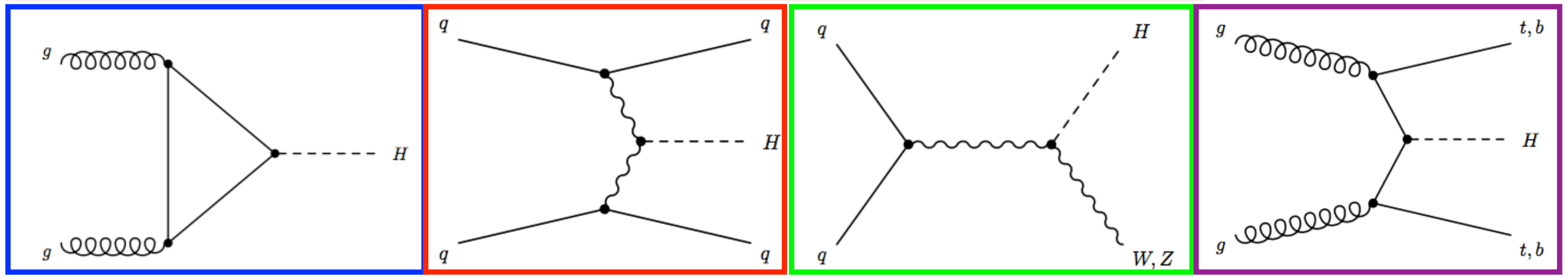
extremely low $\sigma_i \times B^{\mu\mu}$

From single channel, to combined results

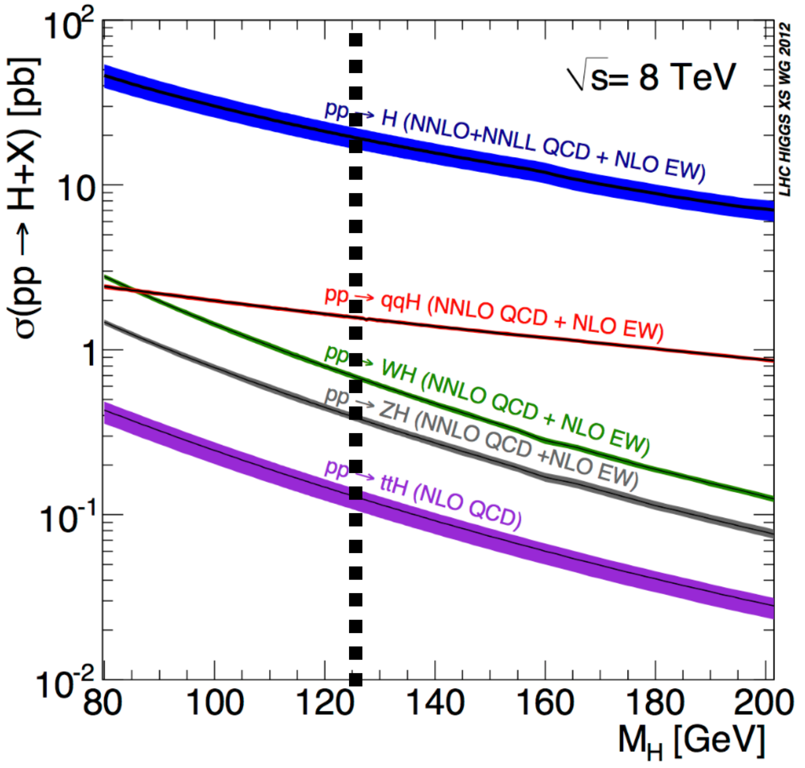
- To **enhance the sensitivity**, the experimental analysis uses **event categories(k) also based on multi variate techniques**
  - **Sensitivity to different production modes**

$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_{i} \sum_{f} \left\{ \boxed{\sigma_i \cdot} \mathrm{A}_i^{f,SM}(k) \cdot \varepsilon_i^{f}(k) \cdot \mathrm{B}^{f} \right\}$$

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



SM Predictions



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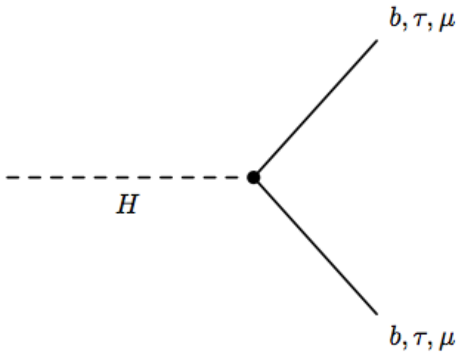
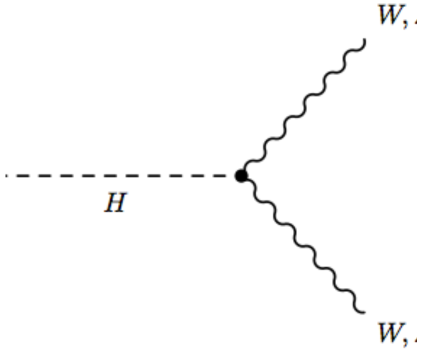
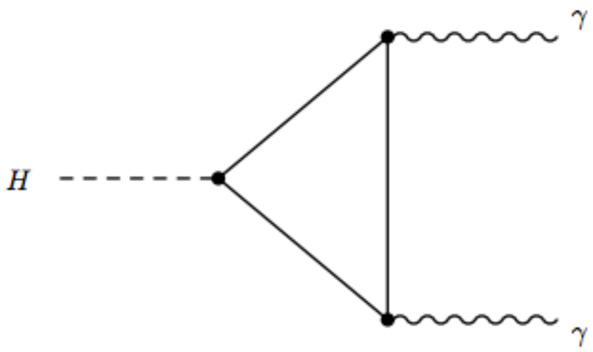
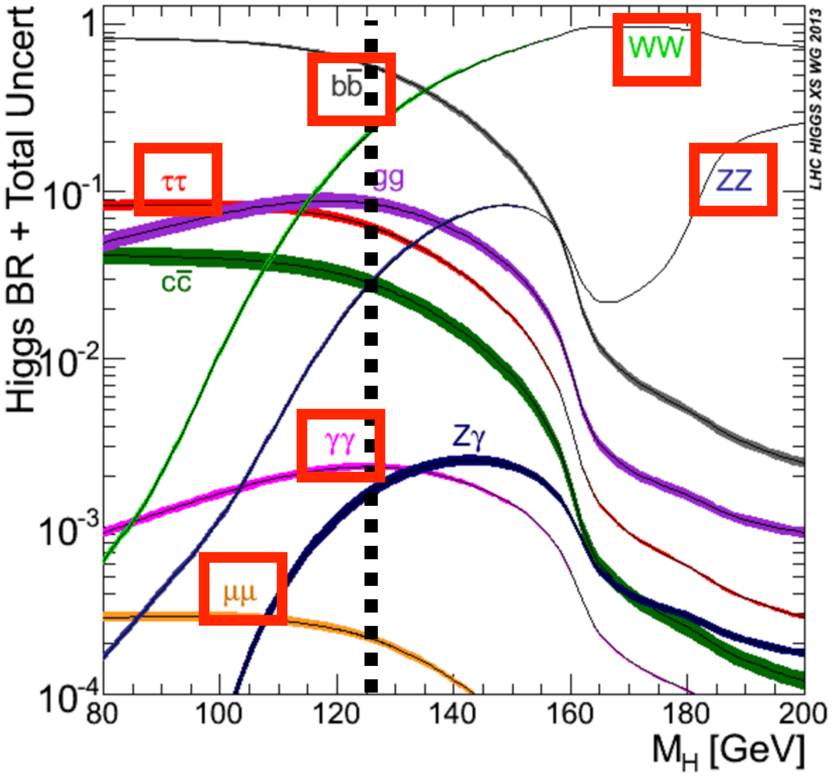
Branching Fractions
i.e.: H→ZZ







SM Predictions

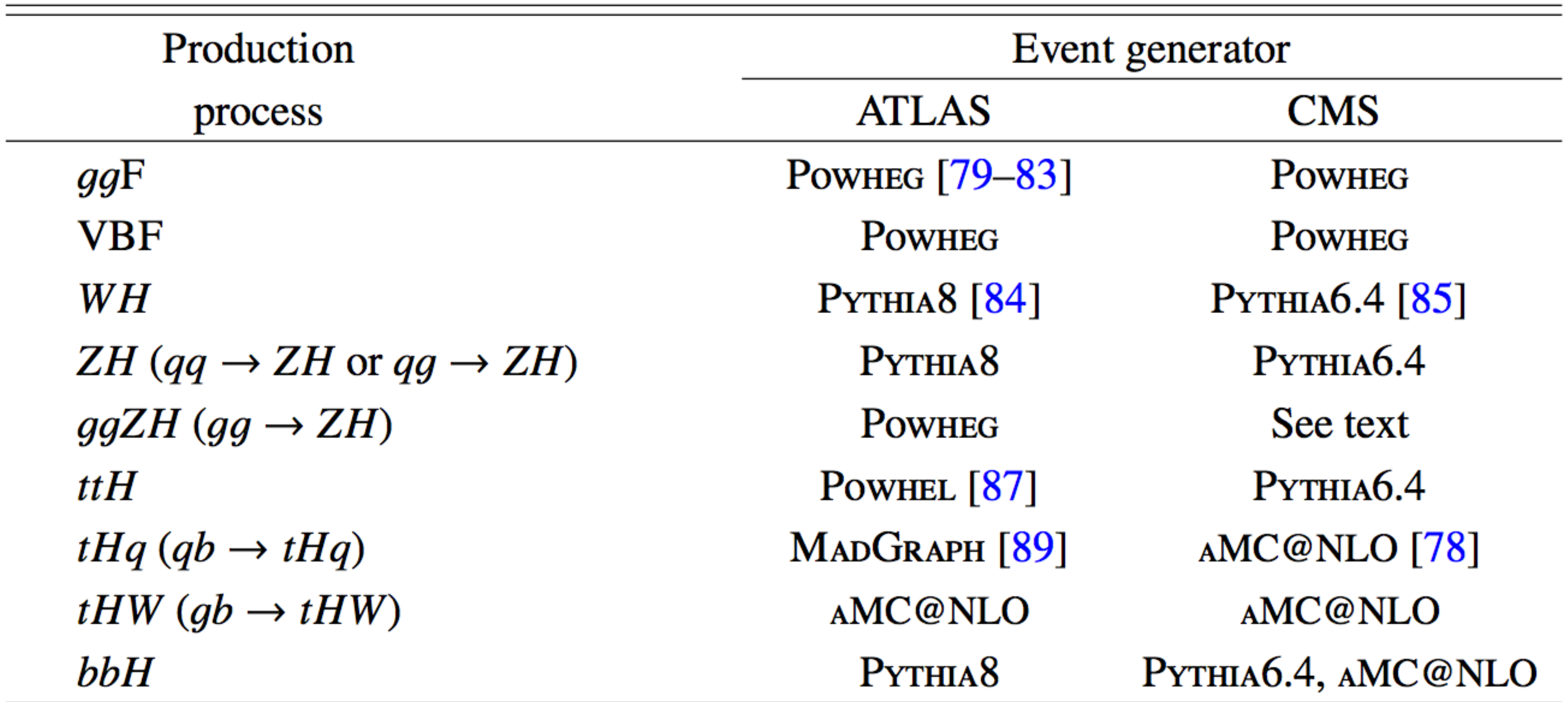


From single channel, to combined results

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

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

Acceptances and efficiencies, from MC assuming SM

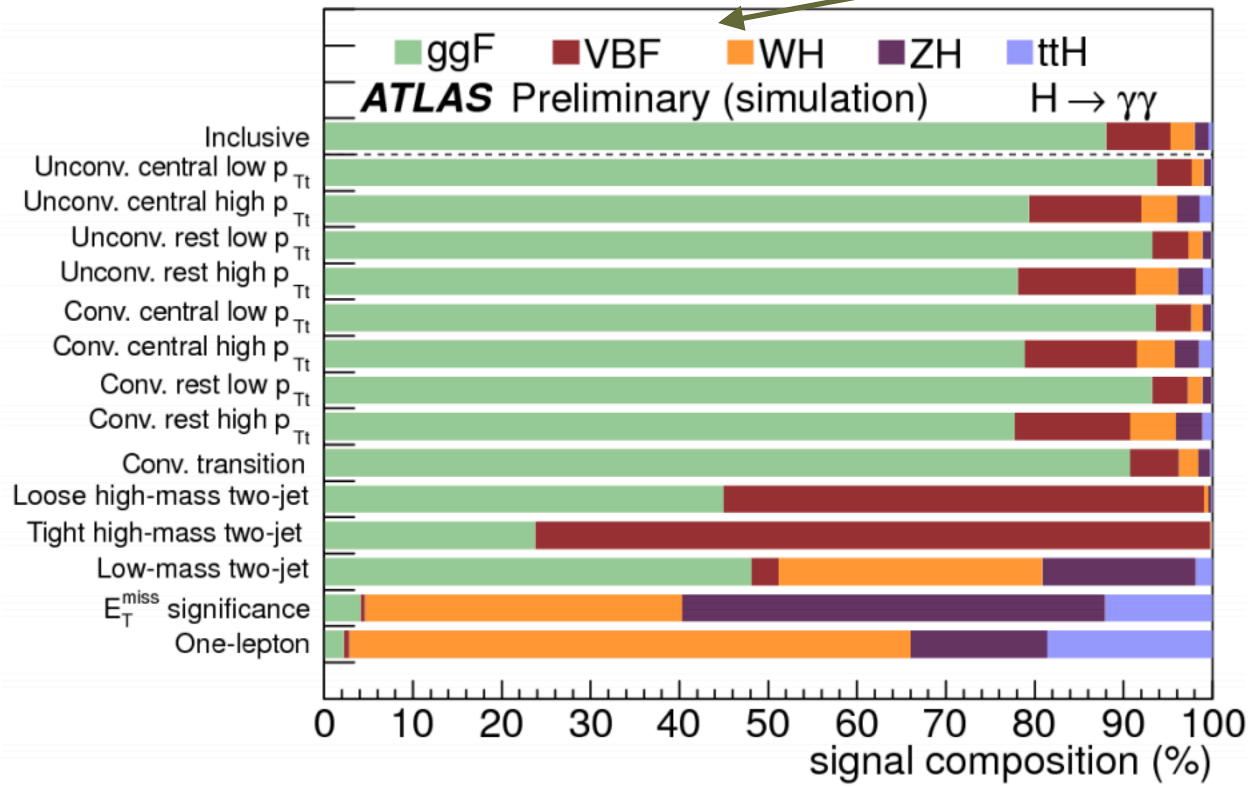


Production process	Event generator ATLAS	Event generator CMS
ggF	Powheg [79–83]	Powheg
VBF	Powheg	Powheg
WH	Pythia8 [84]	Pythia6.4 [85]
ZH ($qq \to ZH$ or $qg \to ZH$)	Pythia8	Pythia6.4
ggZH ($gg \to ZH$)	Powheg	See text
ttH	Powhel [87]	Pythia6.4
tHq ($qb \to tHq$)	MadGraph [89]	aMC@NLO [78]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	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**

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



Example: ttH, H→multilepton

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\text{had}}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\text{had}}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\text{had}}$	4%	93%	0%	3%

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From single channel, to combined results

- To **enhance the sensitivity**, the experimental analysis uses **event categories(k) also based on multi variate techniques**
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$$n_{\mathrm{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \left\{ \sigma_i \cdot \mathrm{A}_i^{f,SM}(k) \cdot \varepsilon_i^f(k) \cdot \mathrm{B}^f \right\}$$

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)

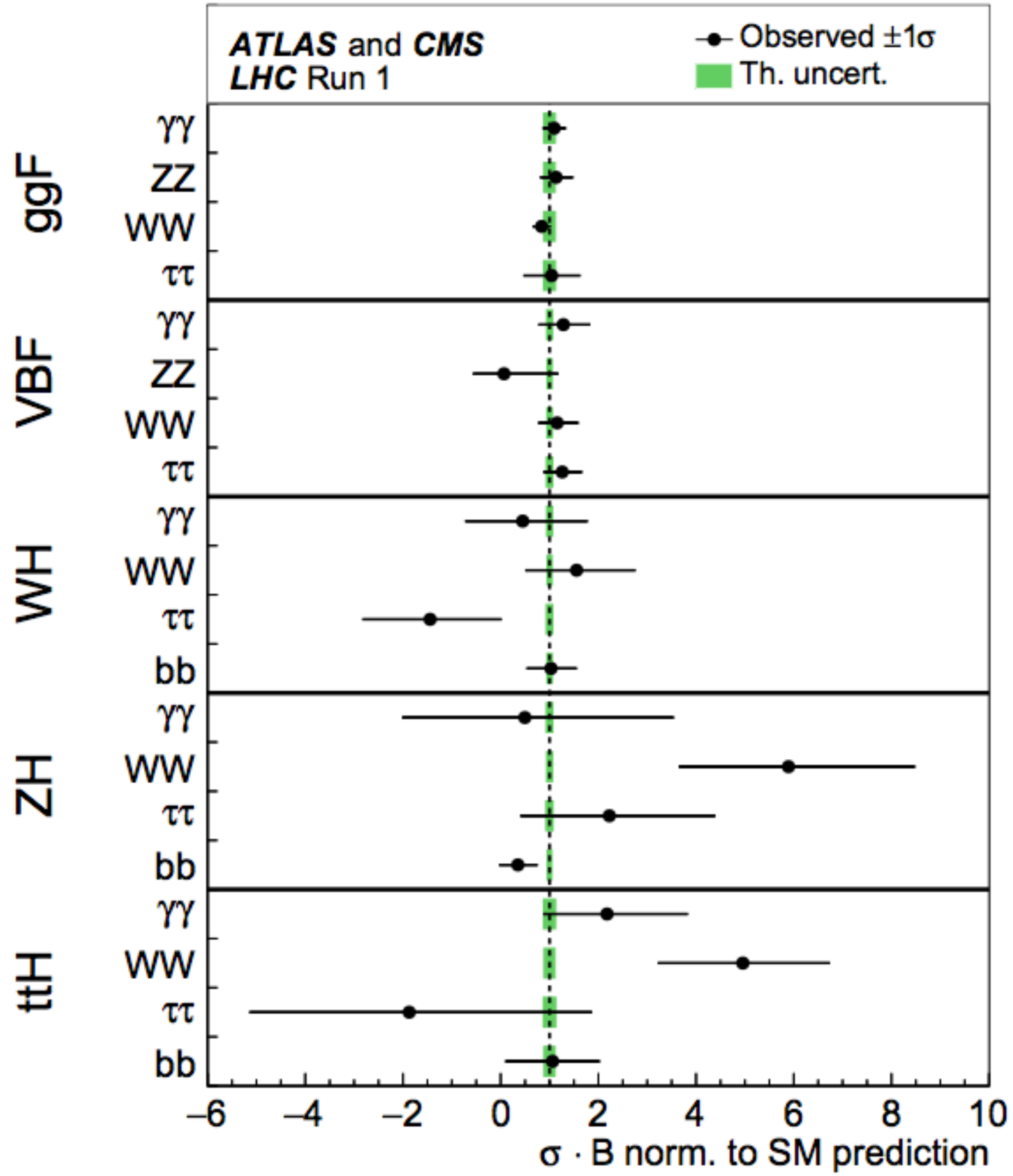
From single channel, to combined results

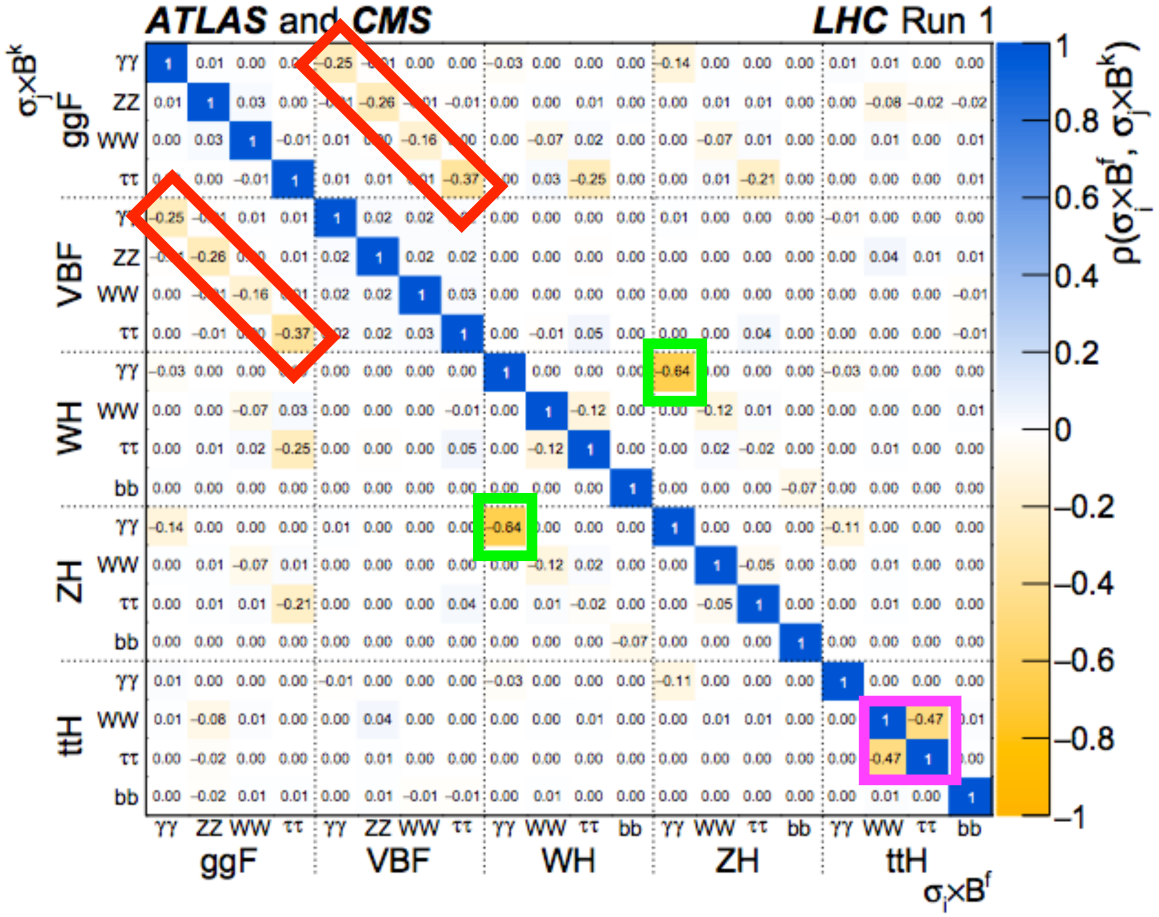
- To **enhance the sensitivity**, the experimental analysis uses **event categories(k) also based on multi variate techniques**
  - **Sensitivity to different production modes**

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

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

Cross Sections times Branching Ratios



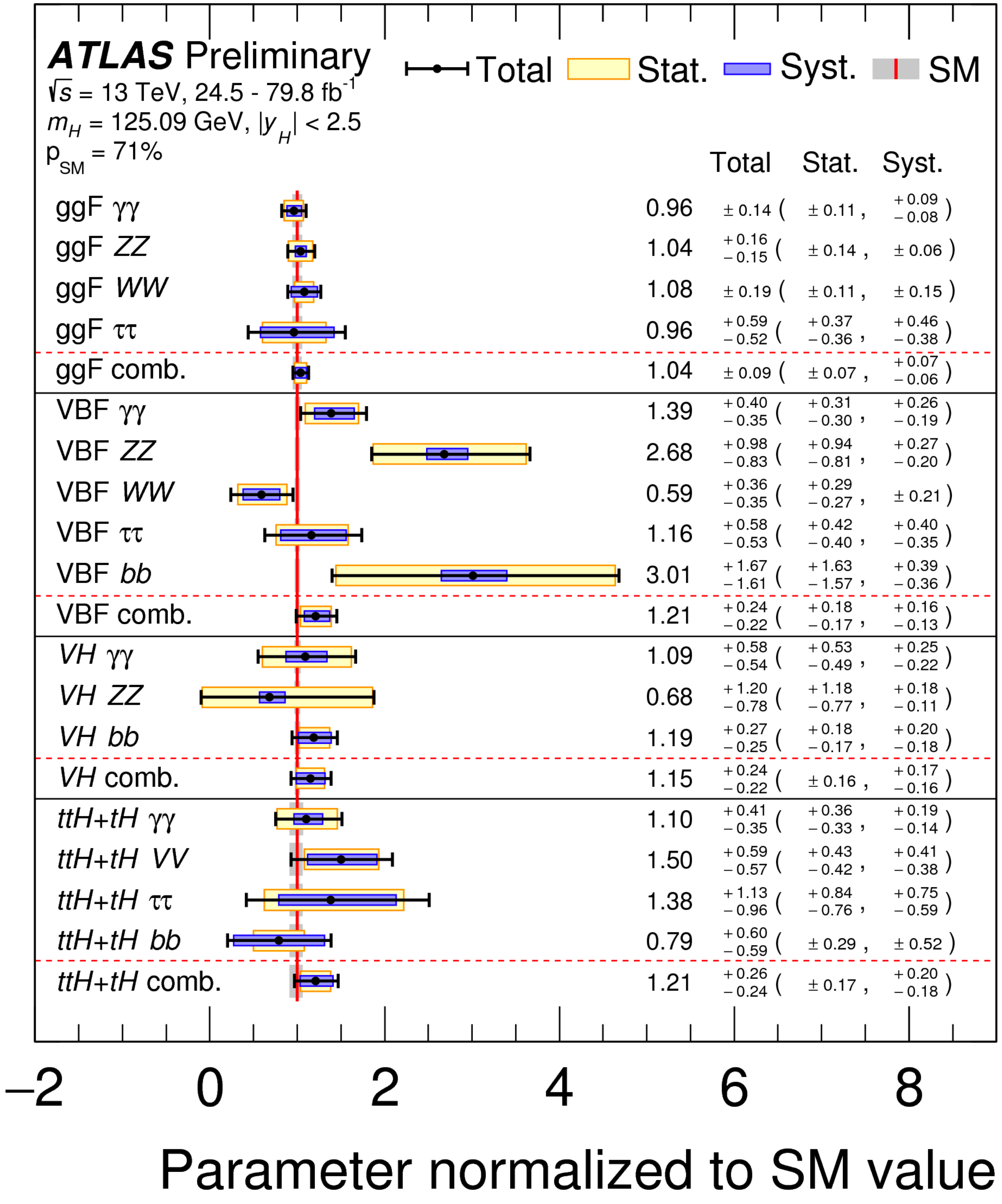


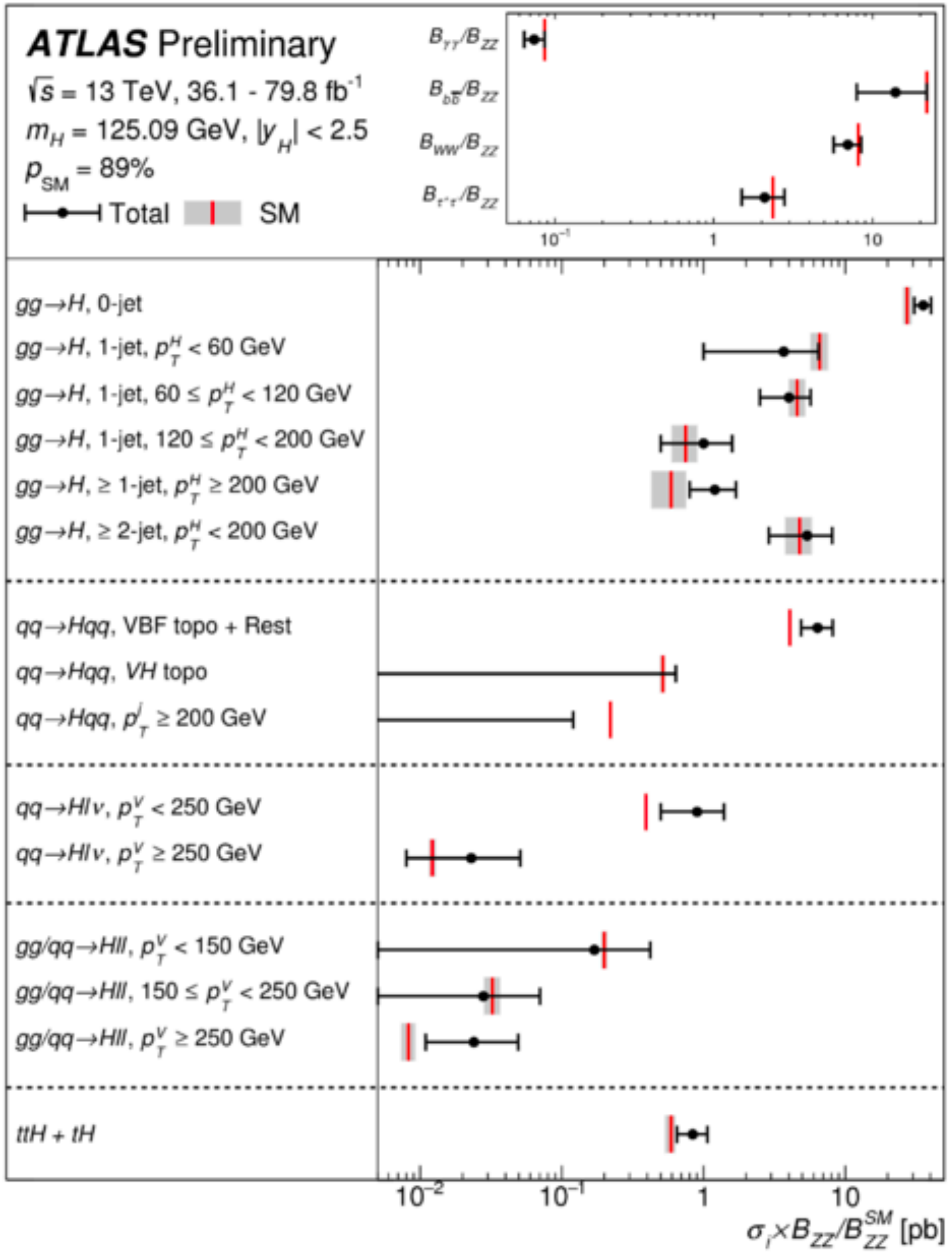
- As expected, correlations due to signal **mix** of **production modes** in the analysis categories:
  - ggF VS VBF (in 2-jet selections) or WH VS ZH (V→hadrons) in H→γγ;

and **decay modes**:

  - ττ VS WW in ttH (in multileptons)

Cross Sections times Branching Ratios





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

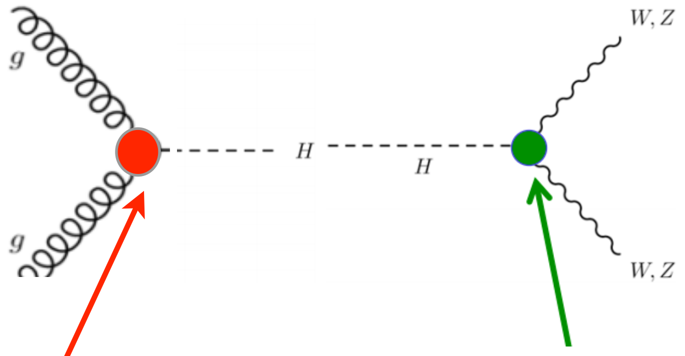
Coupling modifiers

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

- $\sigma^{\mathrm{SM}}{}_j$ and $\Gamma_{\mathrm{SM}}{}^j$ 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→H→WW (or ZZ)

Effective κ

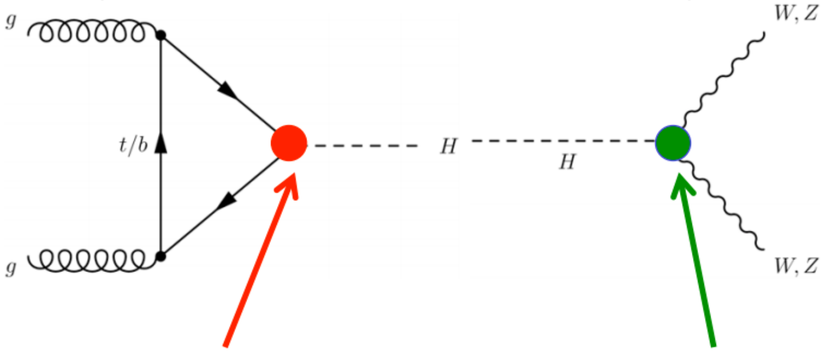


$\sigma_{ggF} = \kappa_g^2\ \sigma_{ggF}(SM)$

$\Gamma_{W,Z} = \kappa^2_{W,Z} \Gamma_{W,Z}(SM)$

or

Resolving the loop, assuming only SM



$\sigma_{ggF} = (1.06\ \kappa_t^2 + 0.01\kappa_b^2\ -0.07\kappa_b\kappa_t)\ \sigma_{ggF}(SM)$

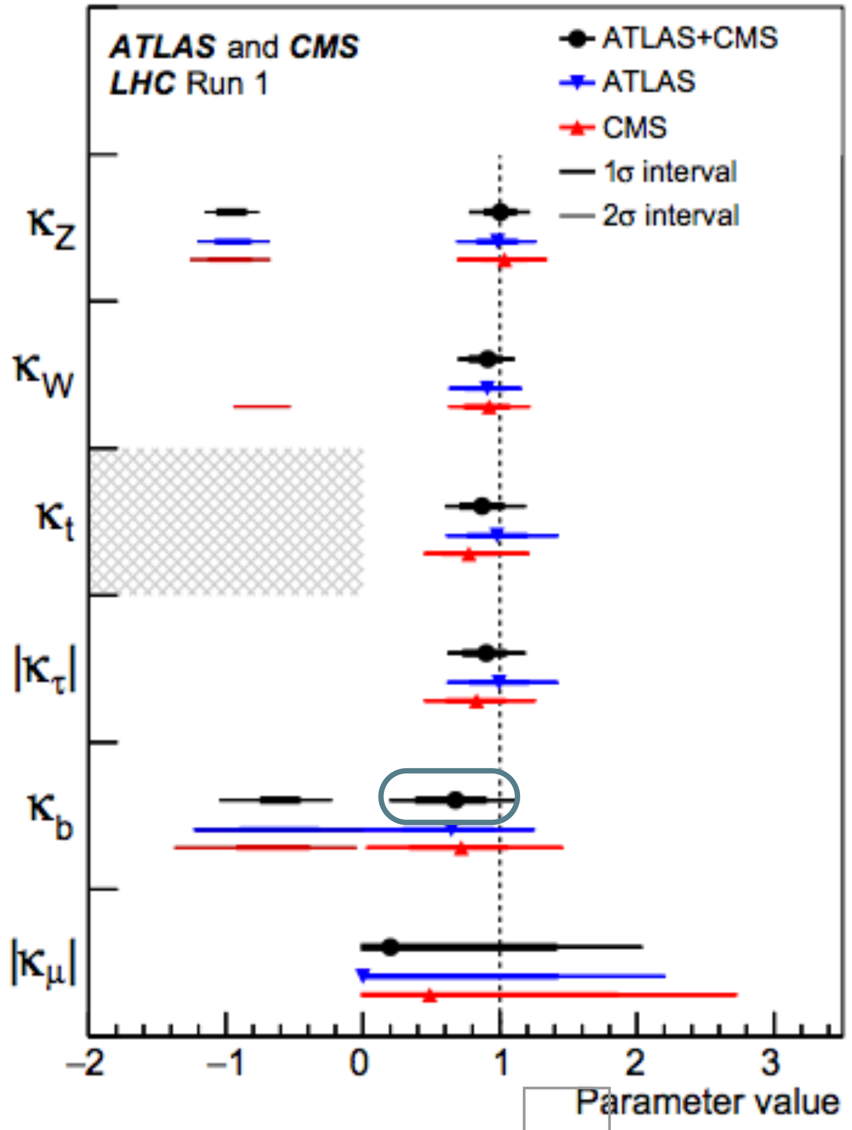
$\Gamma_{W,Z} = \kappa^2_{W,Z} \Gamma_{W,Z}(SM)$

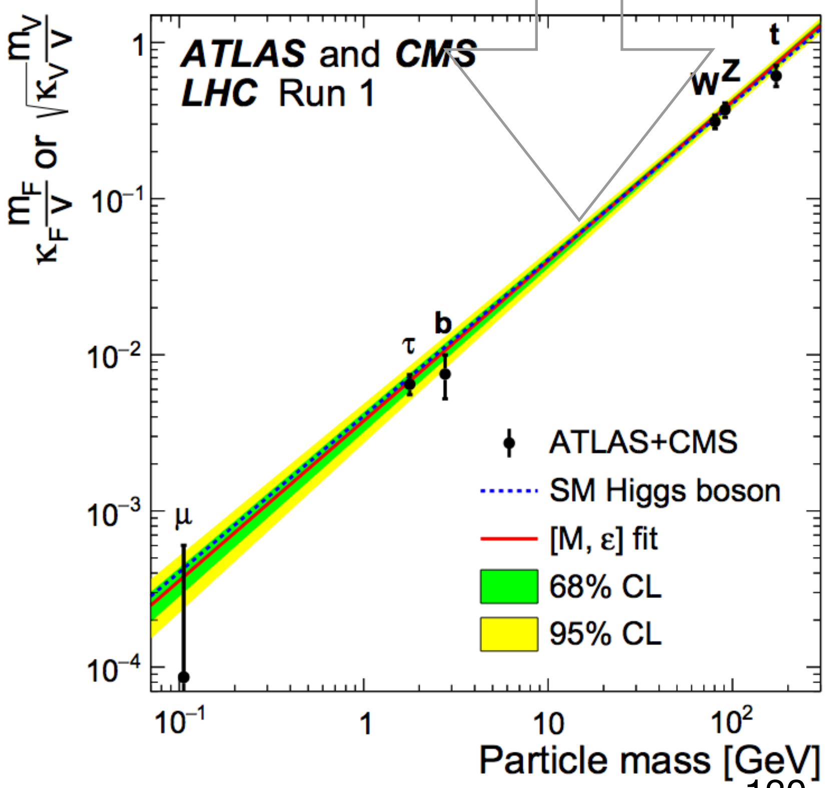
- and Γ_H?
  - Option 1: assume only SM decay modes $\Gamma_H = \sum_j \mathrm{B}^j_{\mathrm{SM}} \kappa_j^2 \cdot \Gamma_H^{\mathrm{SM}}$
  - Option2: allow for an additional branching fractions in BSM $\Gamma_H = \dfrac{\sum_j \mathrm{B}^j_{\mathrm{SM}} \kappa_j^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{B}_{\mathrm{BSM}}}$

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 **κb reduces total width Γ_H => 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
$\sigma(qq/qg \to ZH)$	–	–	κ_Z^2
$\sigma(gg \to ZH)$	✓	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
$\sigma(gb \to tHW)$	–	t–W	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	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	✓	–	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$





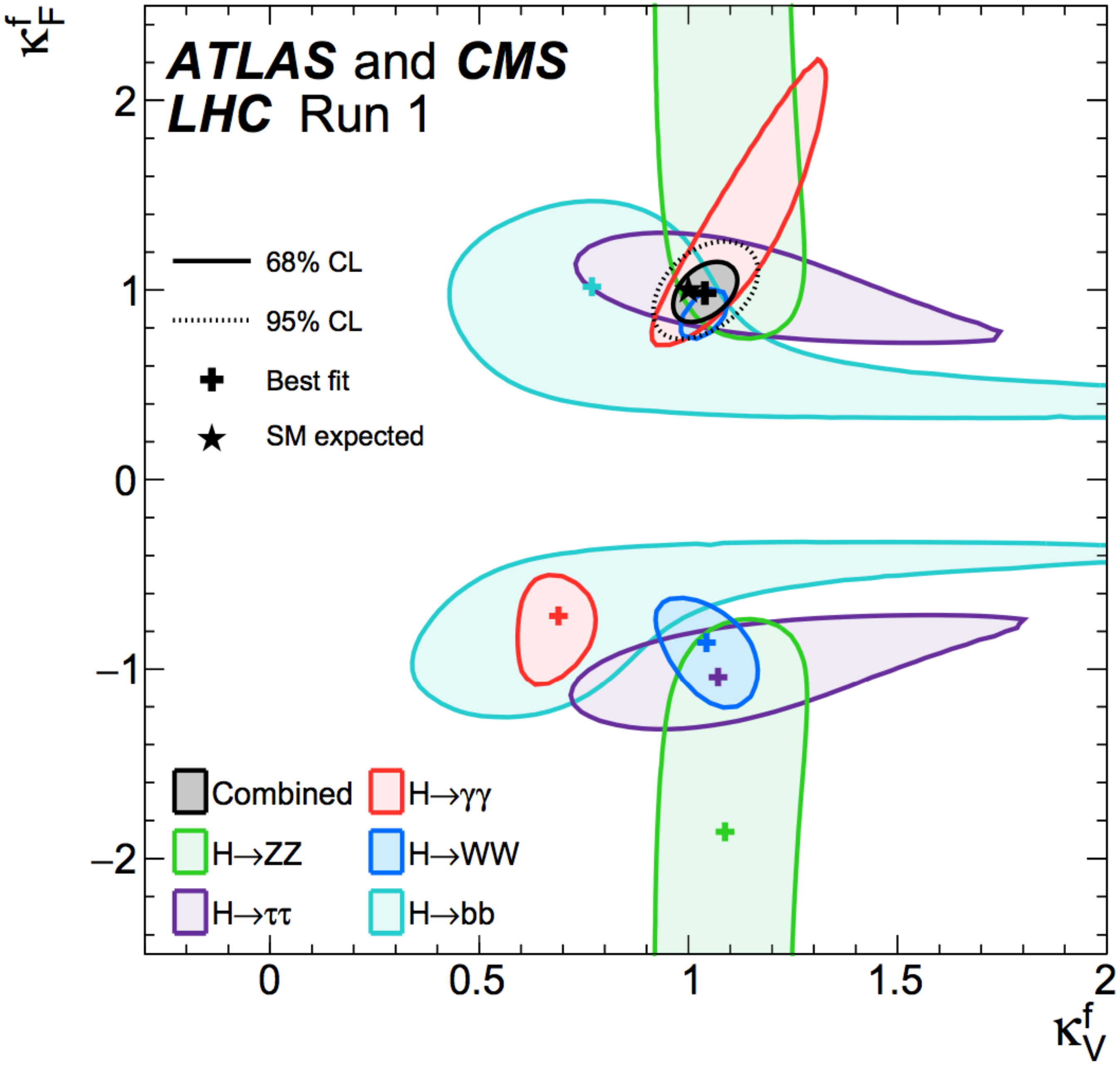
Fermions and bosons

- Testing the intrinsic difference between couplings to
  - W/Z: EW Symmetry Breaking

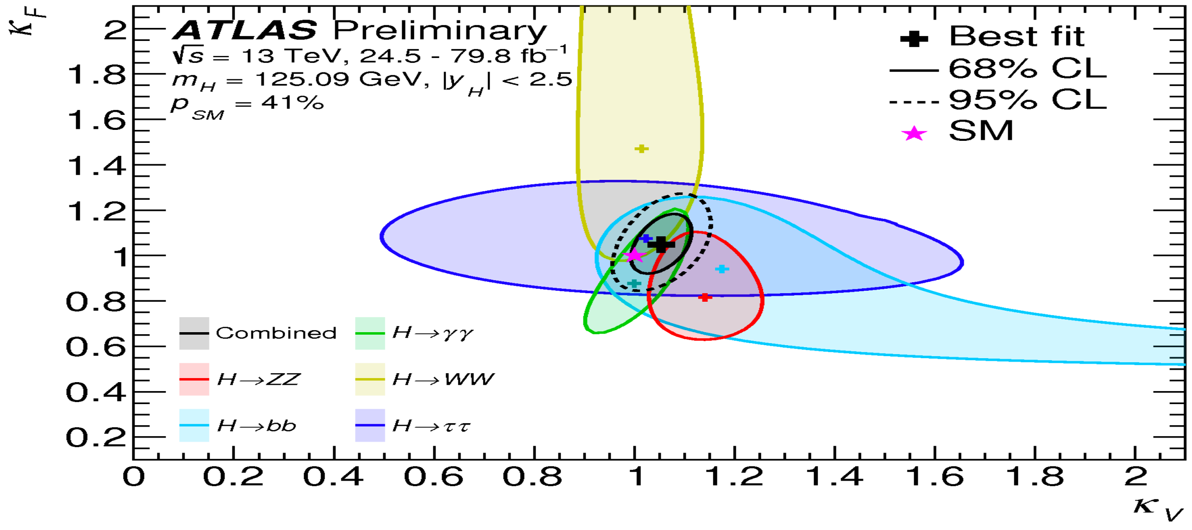
    $\kappa_Z = \kappa_W = \kappa_V$
  - fermions: Yukawa couplings

    $\kappa_t = \kappa_\tau = \kappa_b = \kappa_F$
- 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→γγ

$$\Gamma^{\gamma\gamma} \qquad t\text{–}W \qquad 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$



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



Fermions and bosons

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Higgs Properties

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

Selected news from Run2

International edition

The Guardian

Two quarks for Muster Higgs

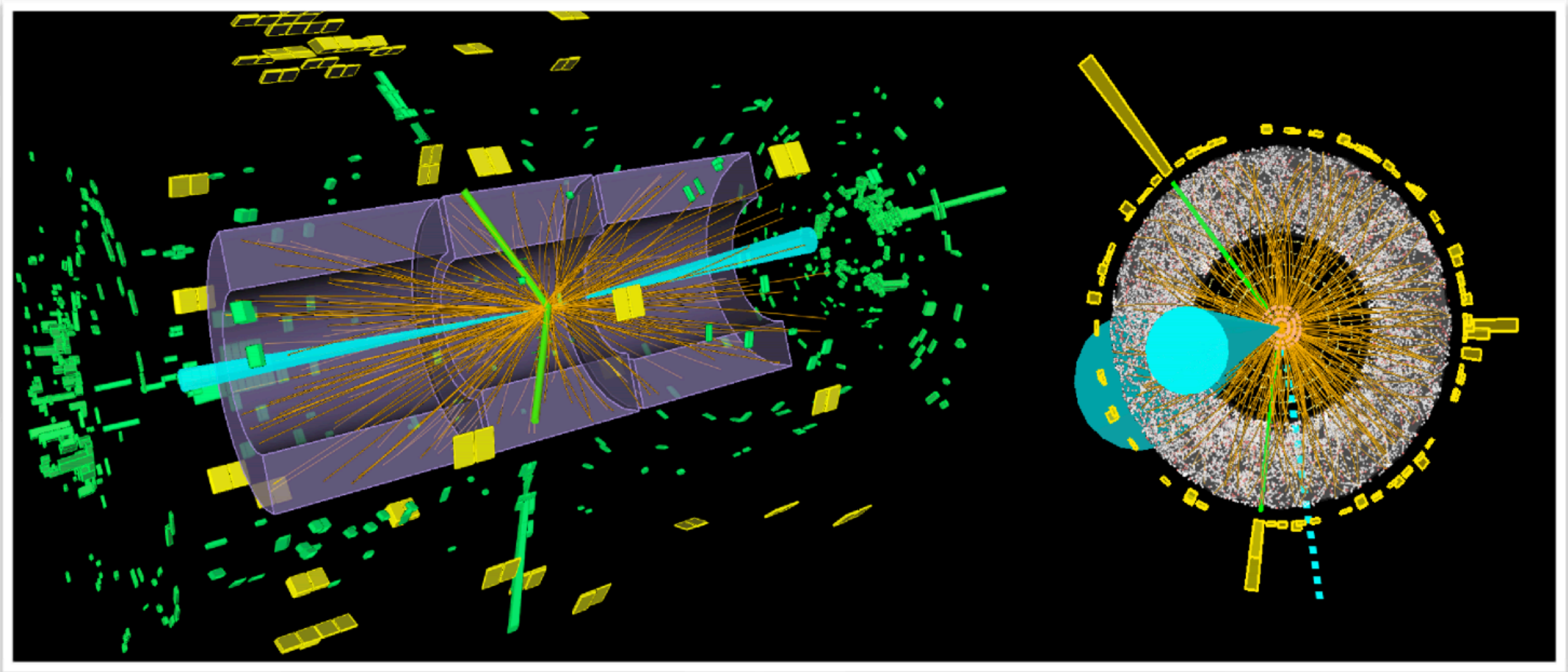
Since the big discovery of 2012, the Large Hadron Collider at CERN has been accumulating data and making steady progress. Two recent results establish the origins of the mass of the two heaviest quarks

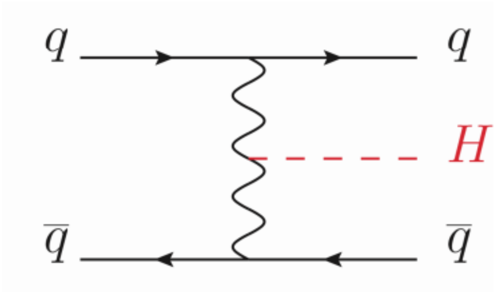
▲ The visitor centre at the ALICE experiment on the CERN Large Hadron Collider Photograph: Jon Butterworth

Observed!

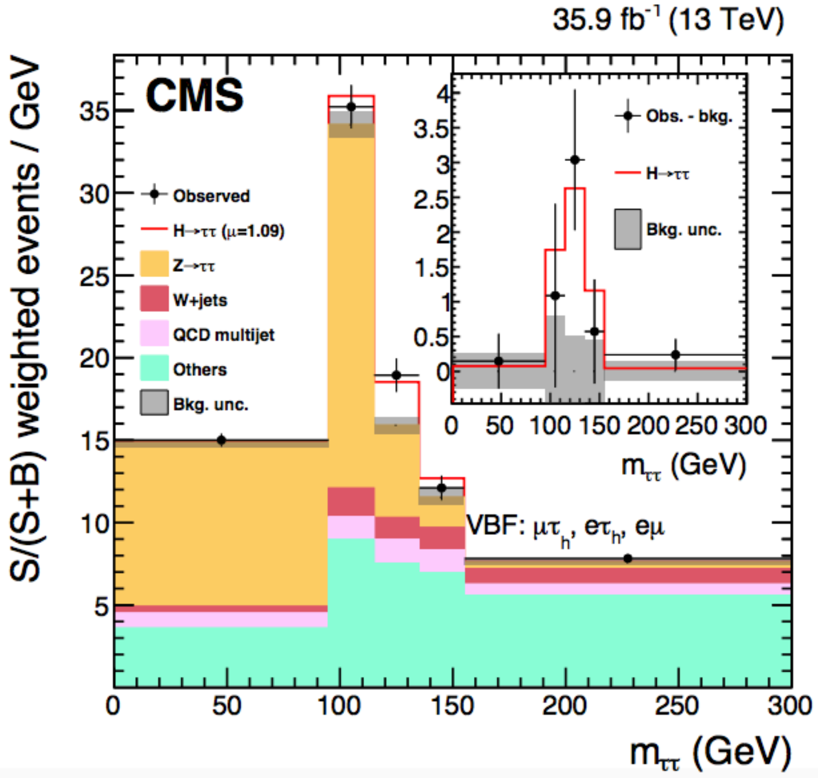
The Big news (1): τ -Higgs interaction

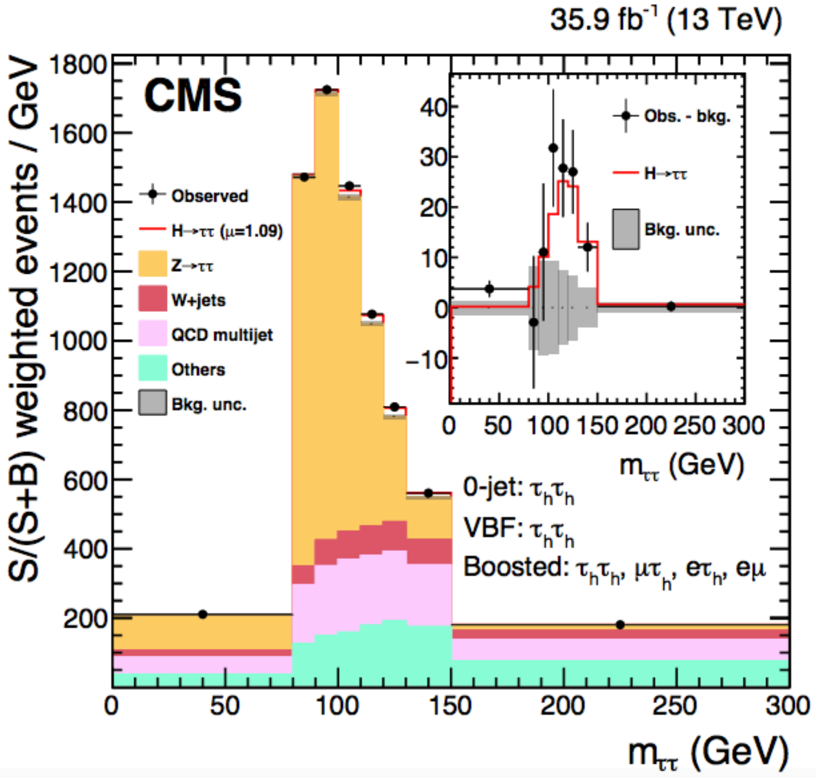
EUROPEAN PHYSICAL SOCIETY HEP2017



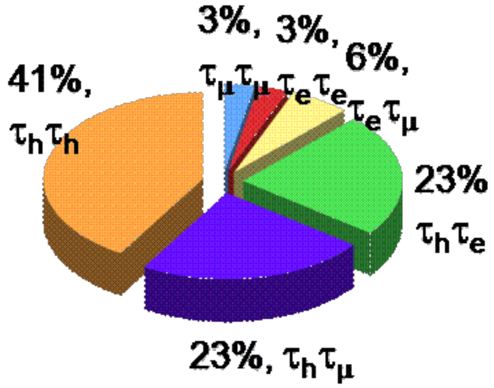


VBF
With two forward jets and a large rapidity gap between the jets





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

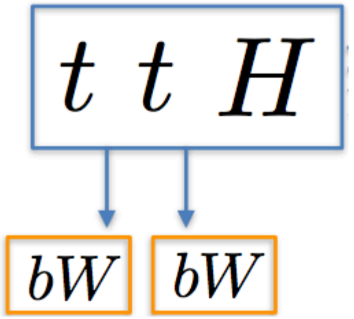


Background is Z production with two jets

The Big news (2): Top -Higgs interaction

$$\boxed{t \; t \; H}$$

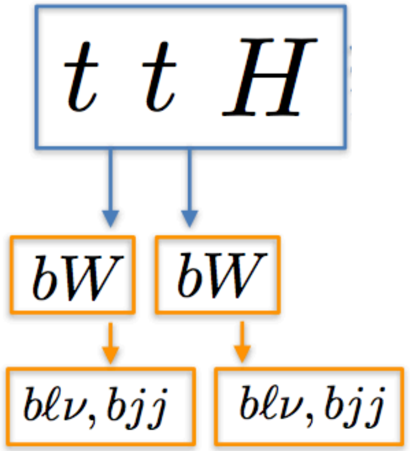
The Big news (2): Top -Higgs interaction



$t\ t\ H$

bW bW

The Big news (2): Top -Higgs interaction

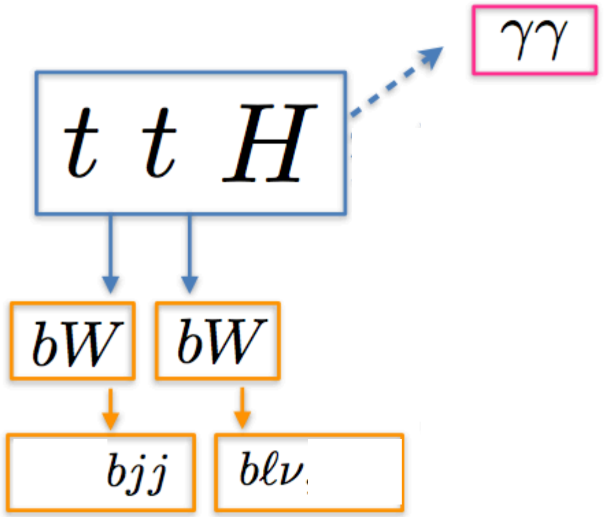


$t\ t\ H$

bW bW

$b\ell\nu, bjj$ $b\ell\nu, bjj$

The Big news (2): Top -Higgs interaction

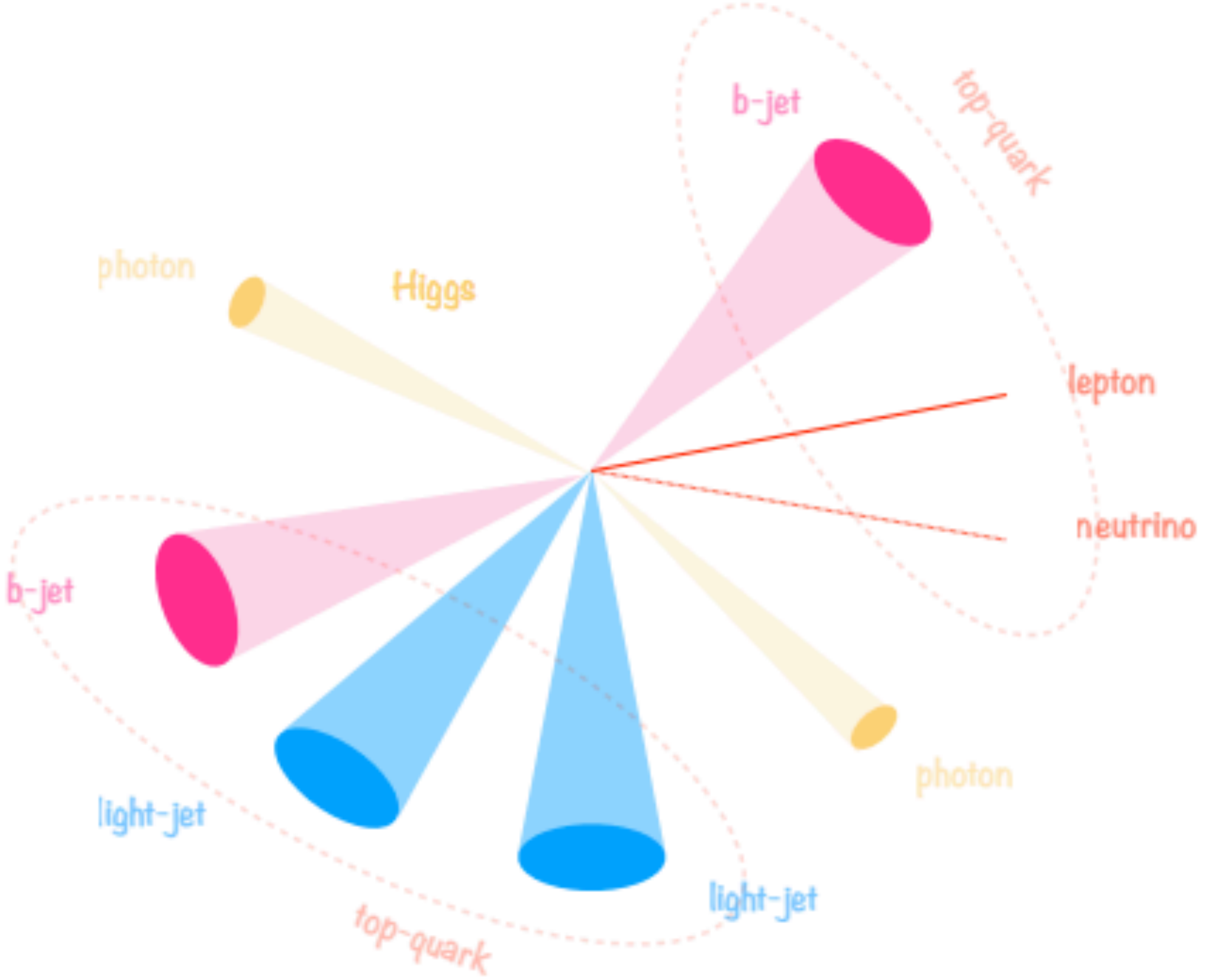


$\gamma\gamma$

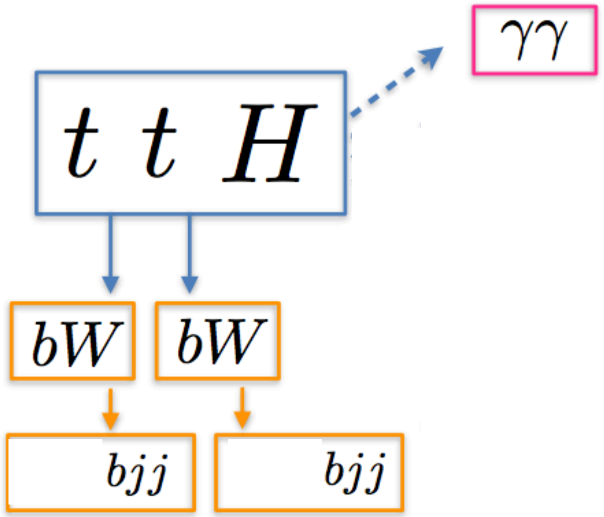
$t\ t\ H$

bW bW

bjj $b\ell\nu$



The Big news (2): Top -Higgs interaction

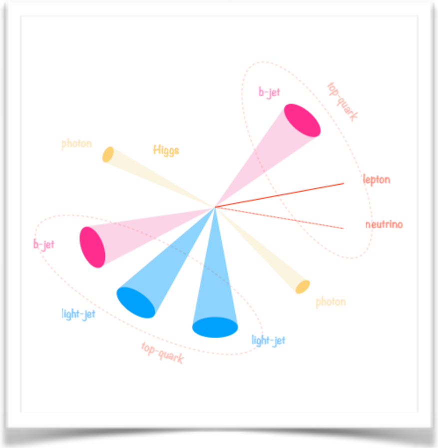


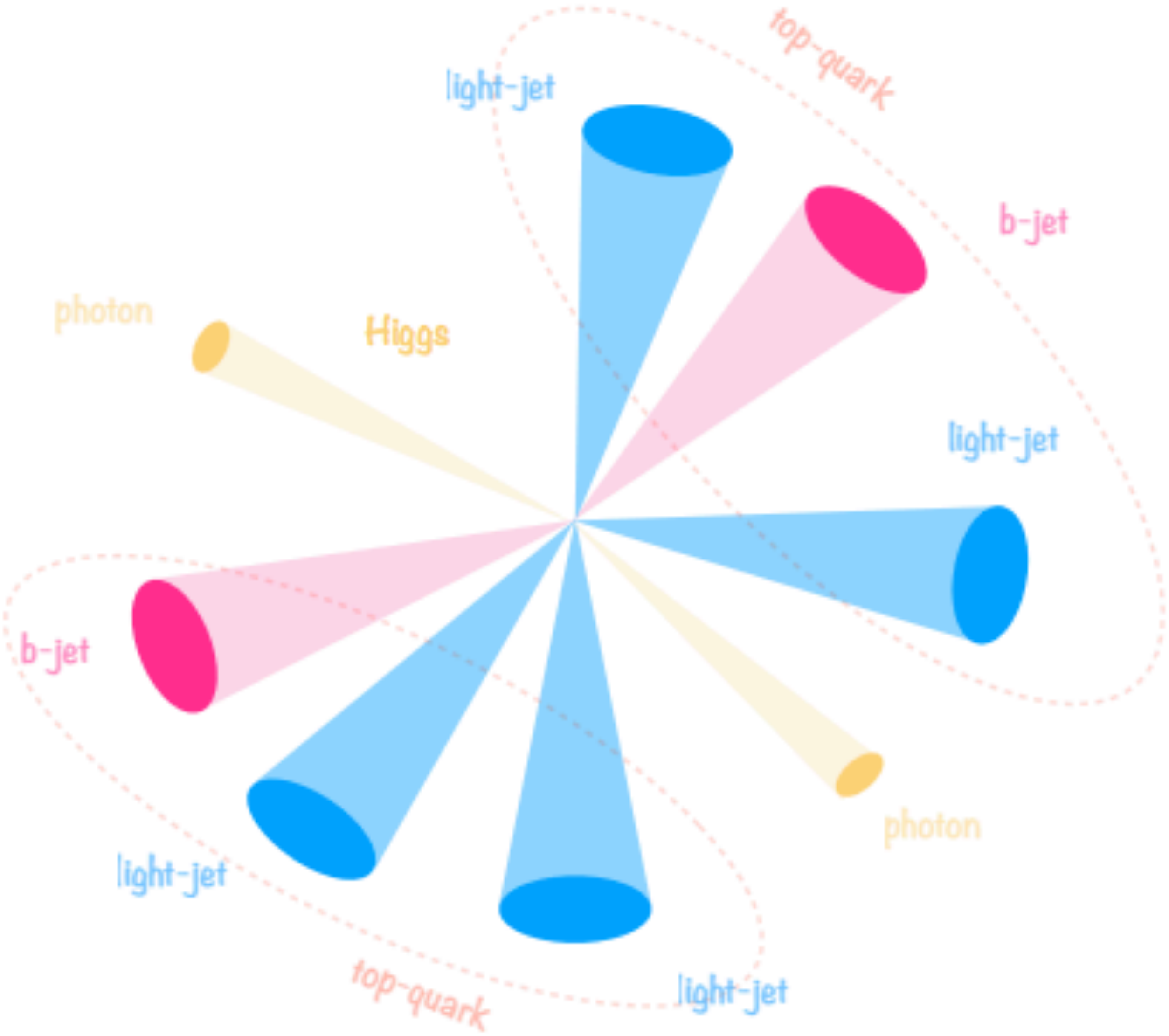
$\gamma\gamma$

$t\ t\ H$

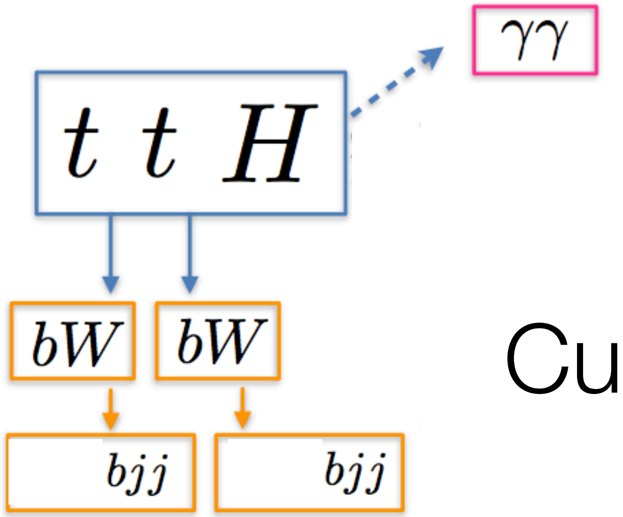
bW bW

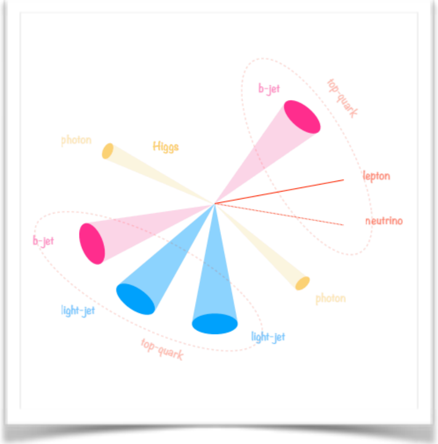
bjj bjj

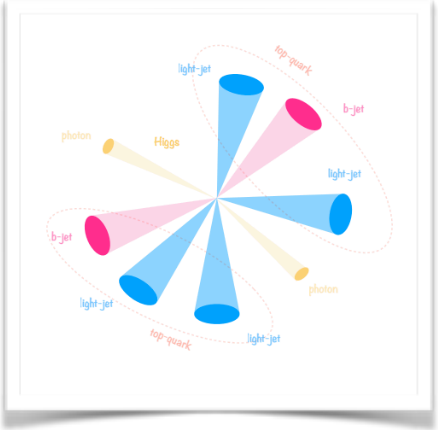




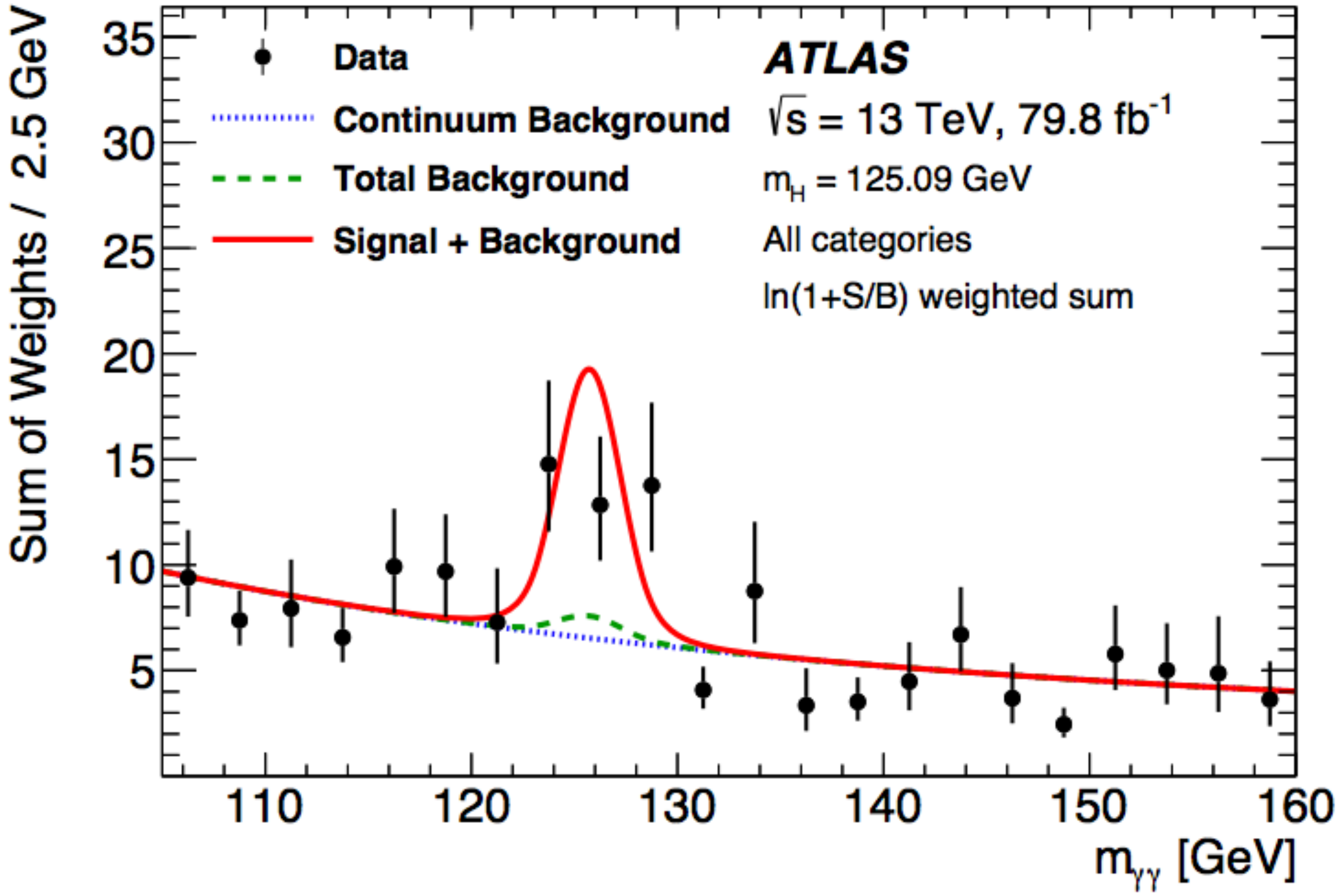
The Big news (2): Top -Higgs interaction



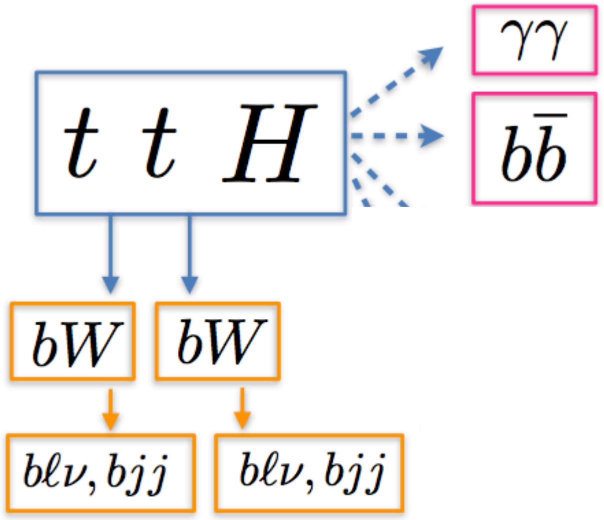




Currently cleanest and most sensitive channel



The Big news (2): Top -Higgs interaction



$t\ t\ H$

$\gamma\gamma$

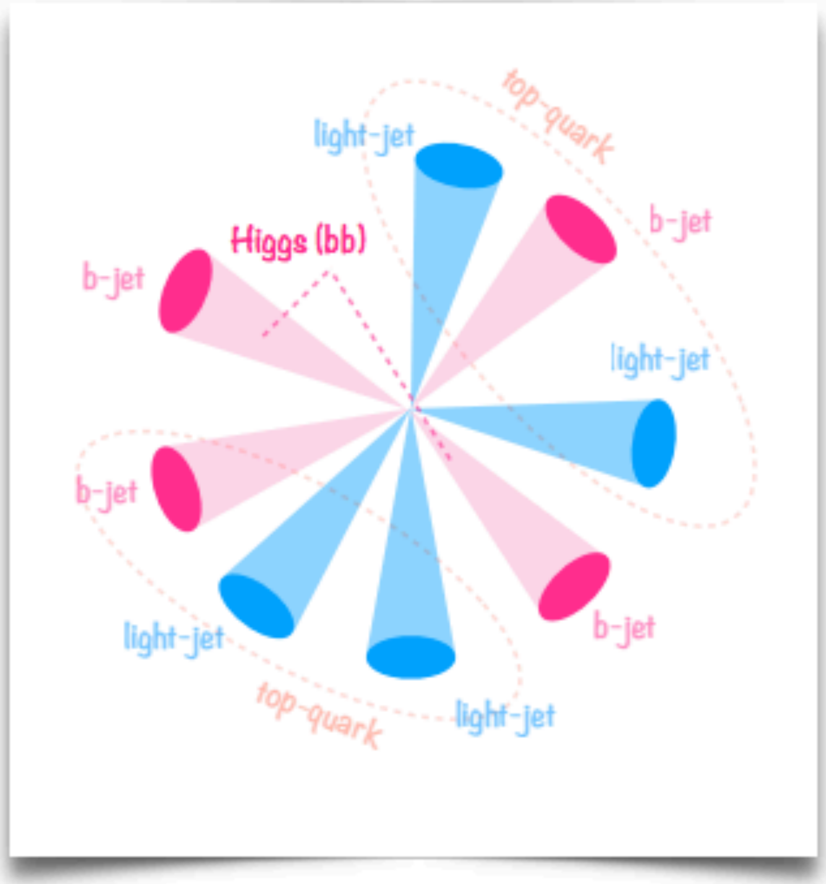
$b\bar{b}$

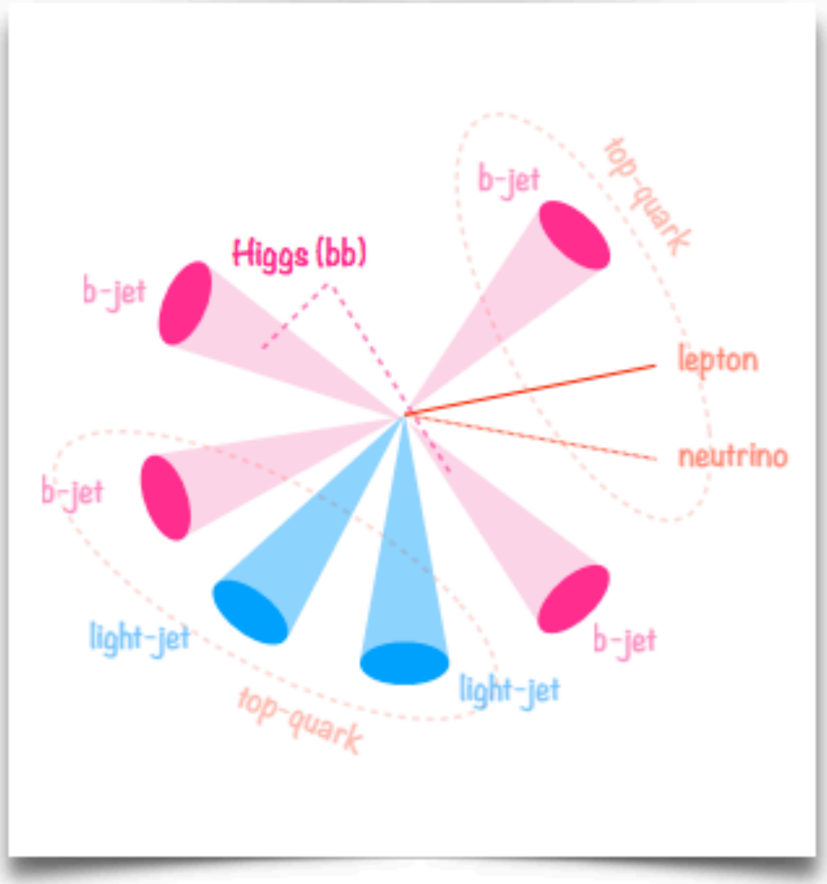
bW bW

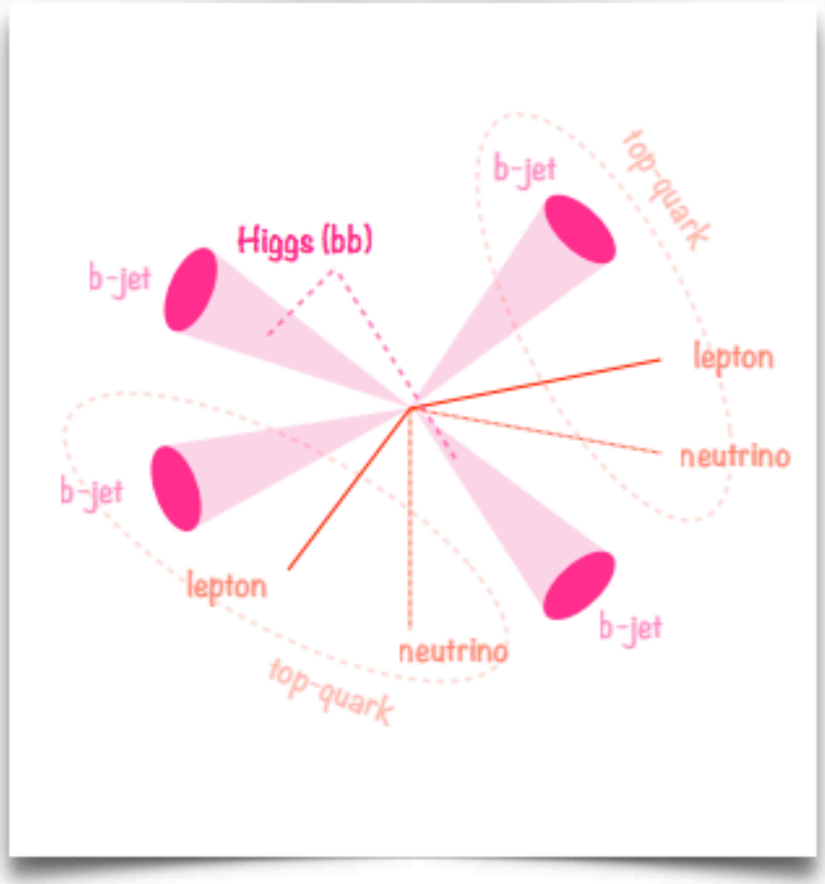
$b\ell\nu, bjj$ $b\ell\nu, bjj$

ttH(bb)

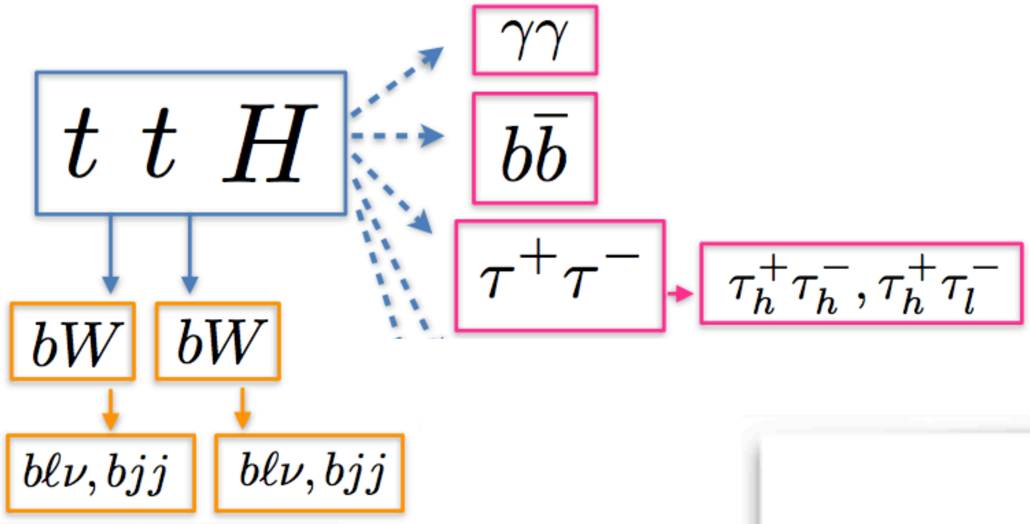
Very large backgrounds of top pair production associated with b jets







The Big news (2): Top -Higgs interaction



$t\ t\ H$

$\gamma\gamma$

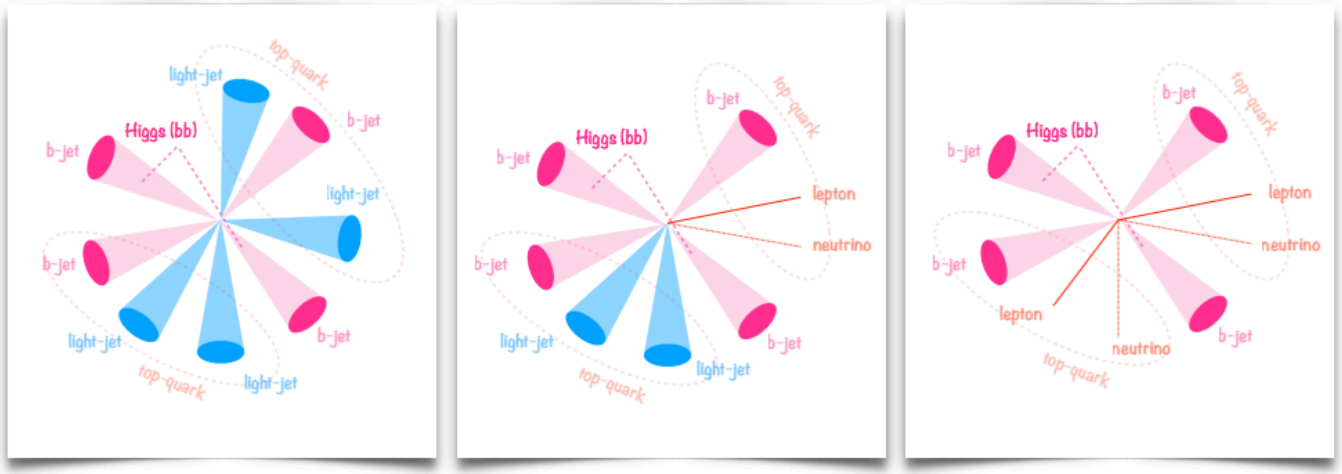
$b\bar{b}$

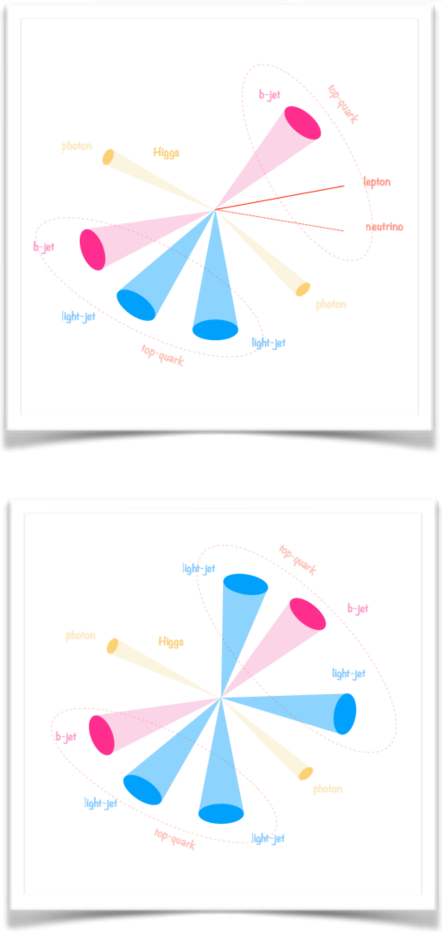
$\tau^+\tau^-$

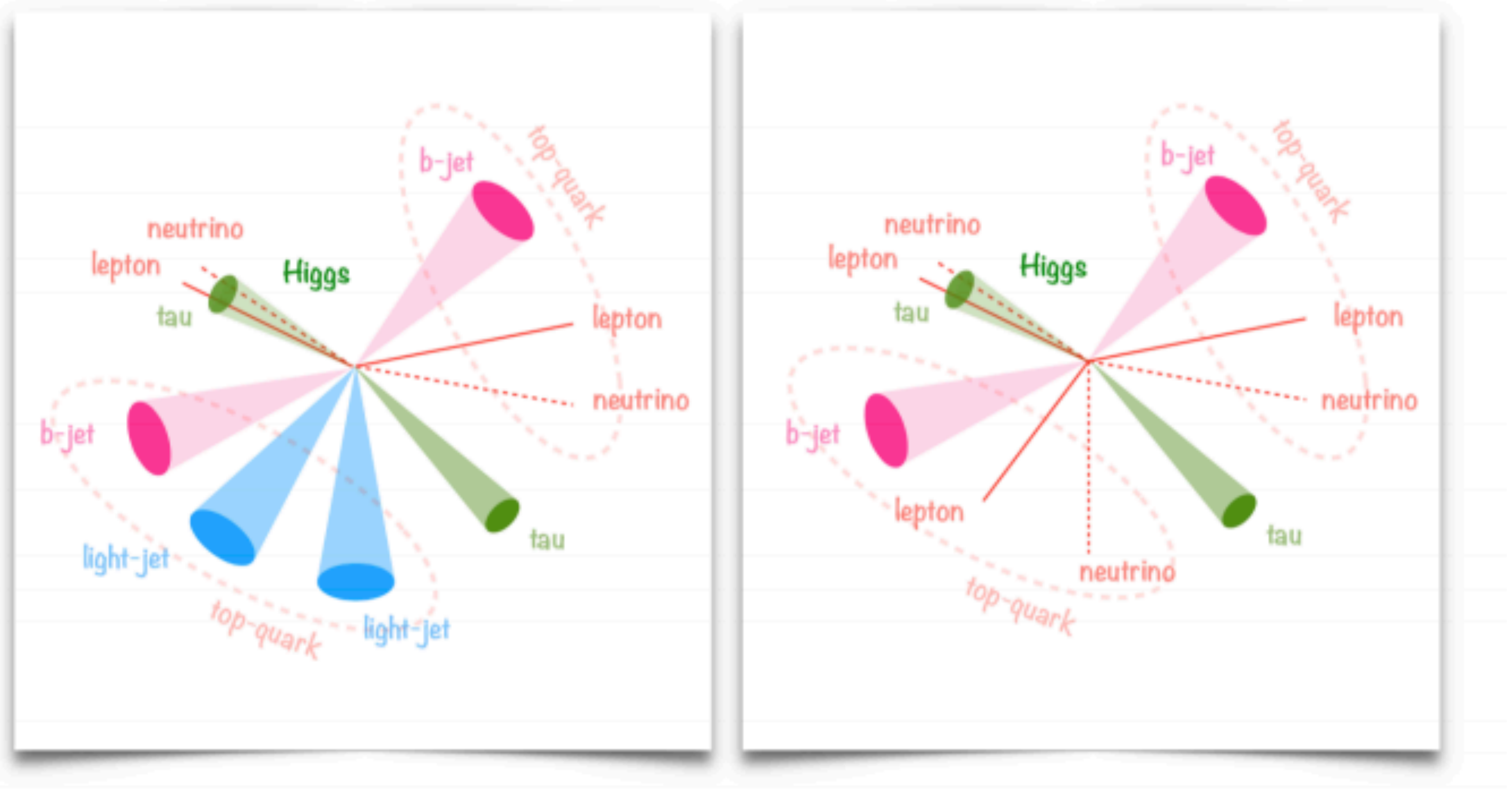
$\tau_h^+\tau_h^-, \tau_h^+\tau_l^-$

bW bW

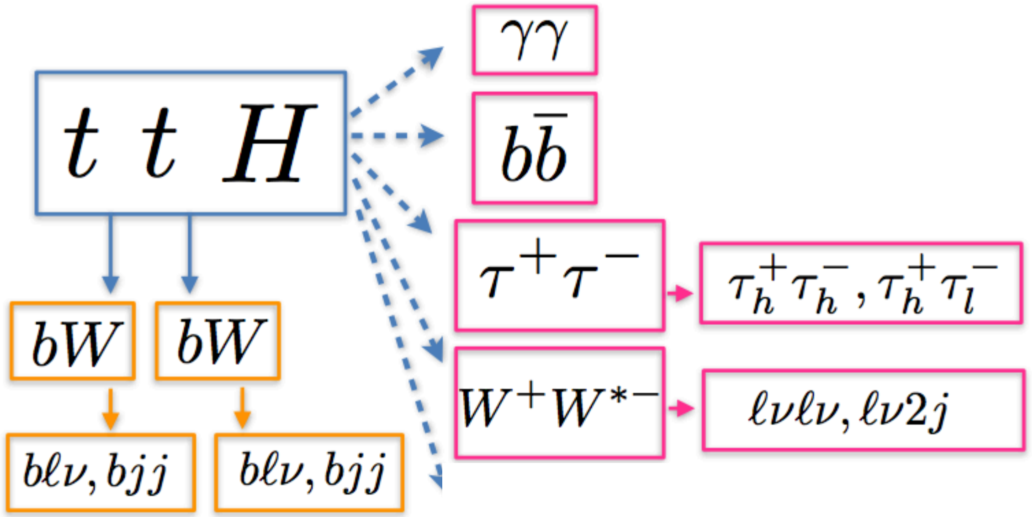
$b\ell\nu, bjj$ $b\ell\nu, bjj$







The Big news (2): Top -Higgs interaction



$t\ t\ H$

bW bW

$b\ell\nu, bjj$ $b\ell\nu, bjj$

$\gamma\gamma$

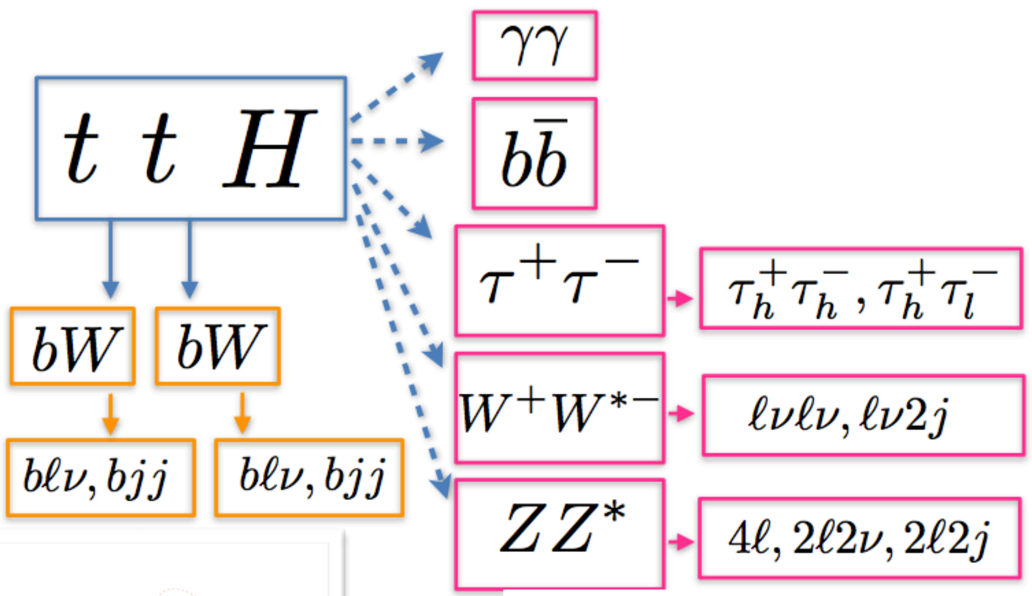
$b\bar{b}$

$\tau^+\tau^-$ → $\tau_h^+\tau_h^-, \tau_h^+\tau_l^-$

W^+W^{*-} → $\ell\nu\ell\nu, \ell\nu 2j$

The Big news (2): Top -Higgs interaction

LHCP Bologna 2018



$t\ t\ H$

$\gamma\gamma$

$b\bar{b}$

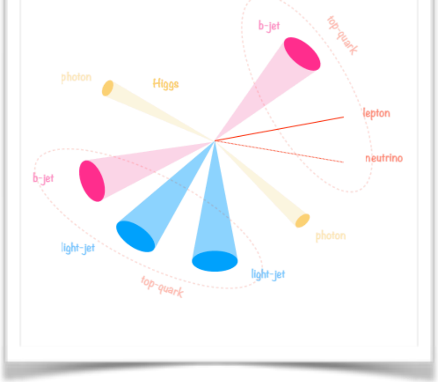
$\tau^+\tau^-$ → $\tau_h^+\tau_h^-, \tau_h^+\tau_l^-$

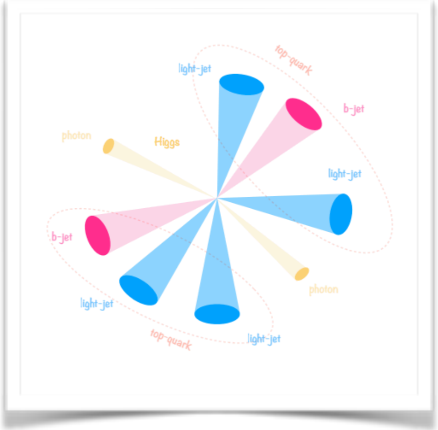
W^+W^{*-} → $\ell\nu\ell\nu, \ell\nu 2j$

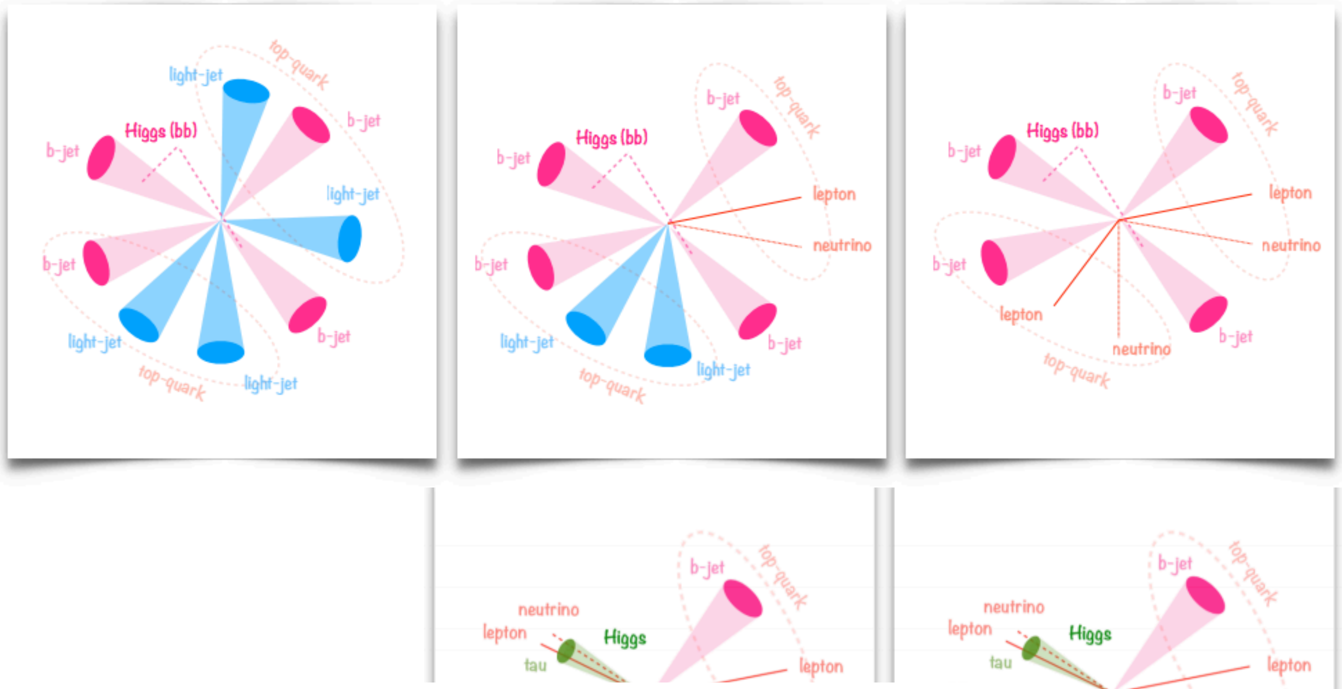
ZZ^* → $4\ell, 2\ell 2\nu, 2\ell 2j$

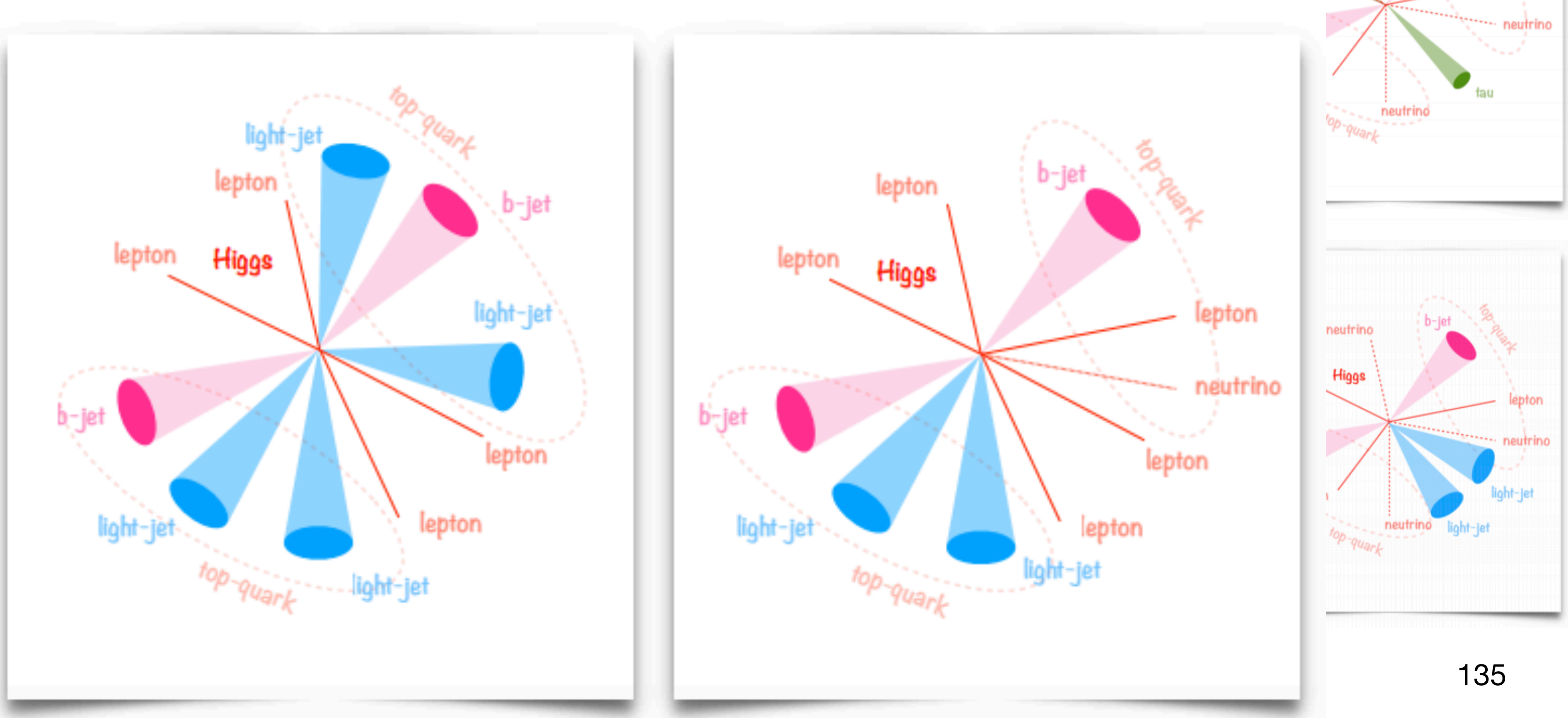
bW → $b\ell\nu, bjj$

bW → $b\ell\nu, bjj$

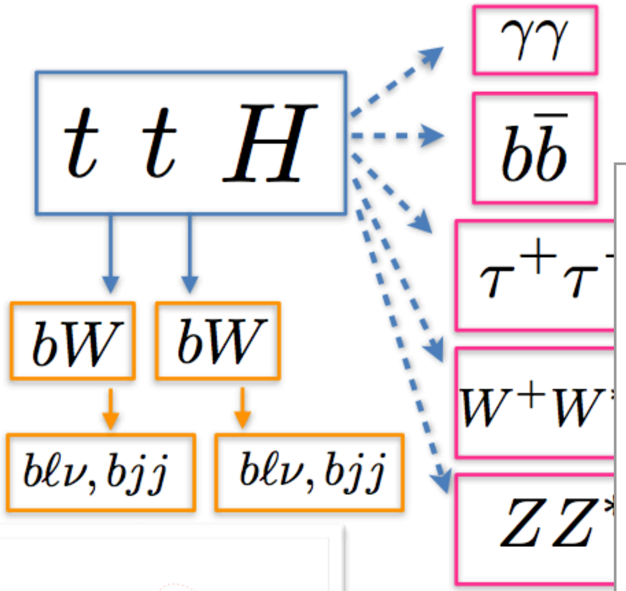








The Big news (2): Top -Higgs interaction



$t\ t\ H$

bW bW

$b\ell\nu, bjj$ $b\ell\nu, bjj$

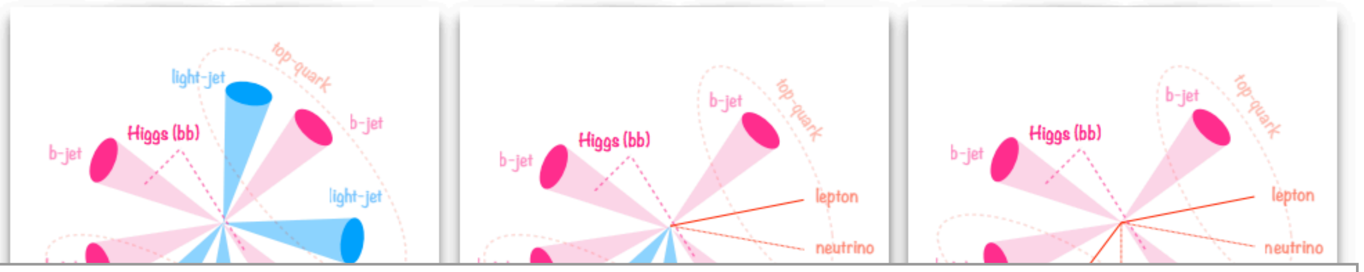
$\gamma\gamma$

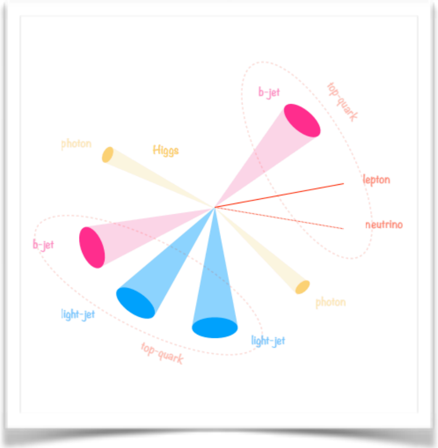
$b\bar{b}$

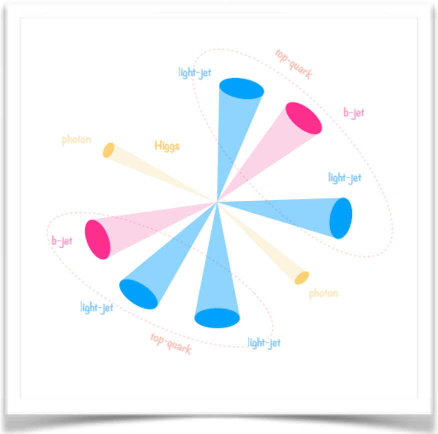
$\tau^+\tau$

W^+W

ZZ



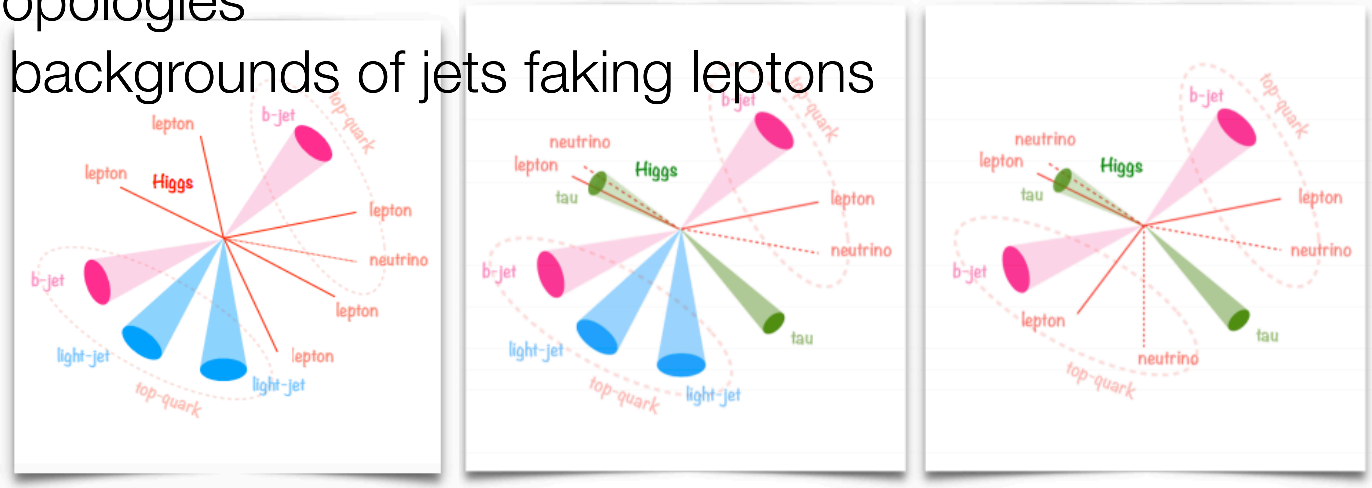


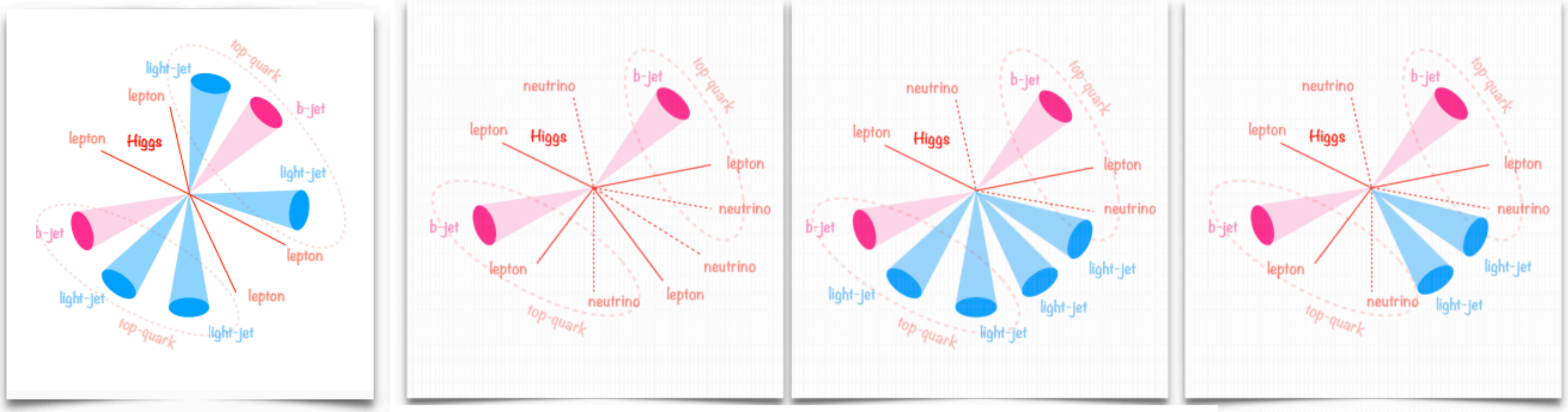


Multi lepton channel

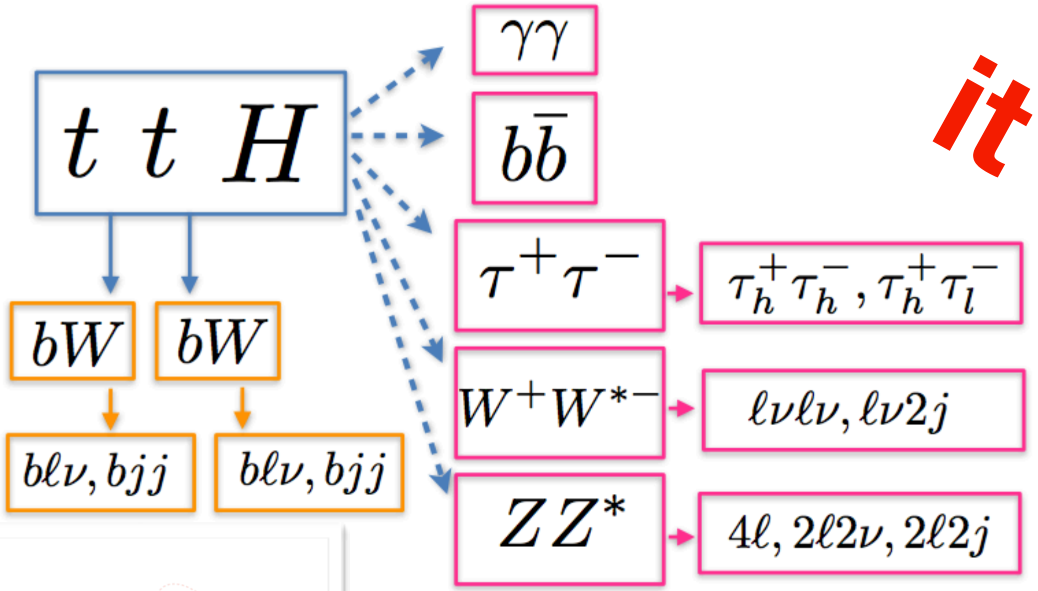
Large number of topologies

intricate reducible backgrounds of jets faking leptons





The Big news (2): Top -Higgs interaction



$t\ t\ H$

bW → $b\ell\nu, bjj$

bW → $b\ell\nu, bjj$

$\gamma\gamma$

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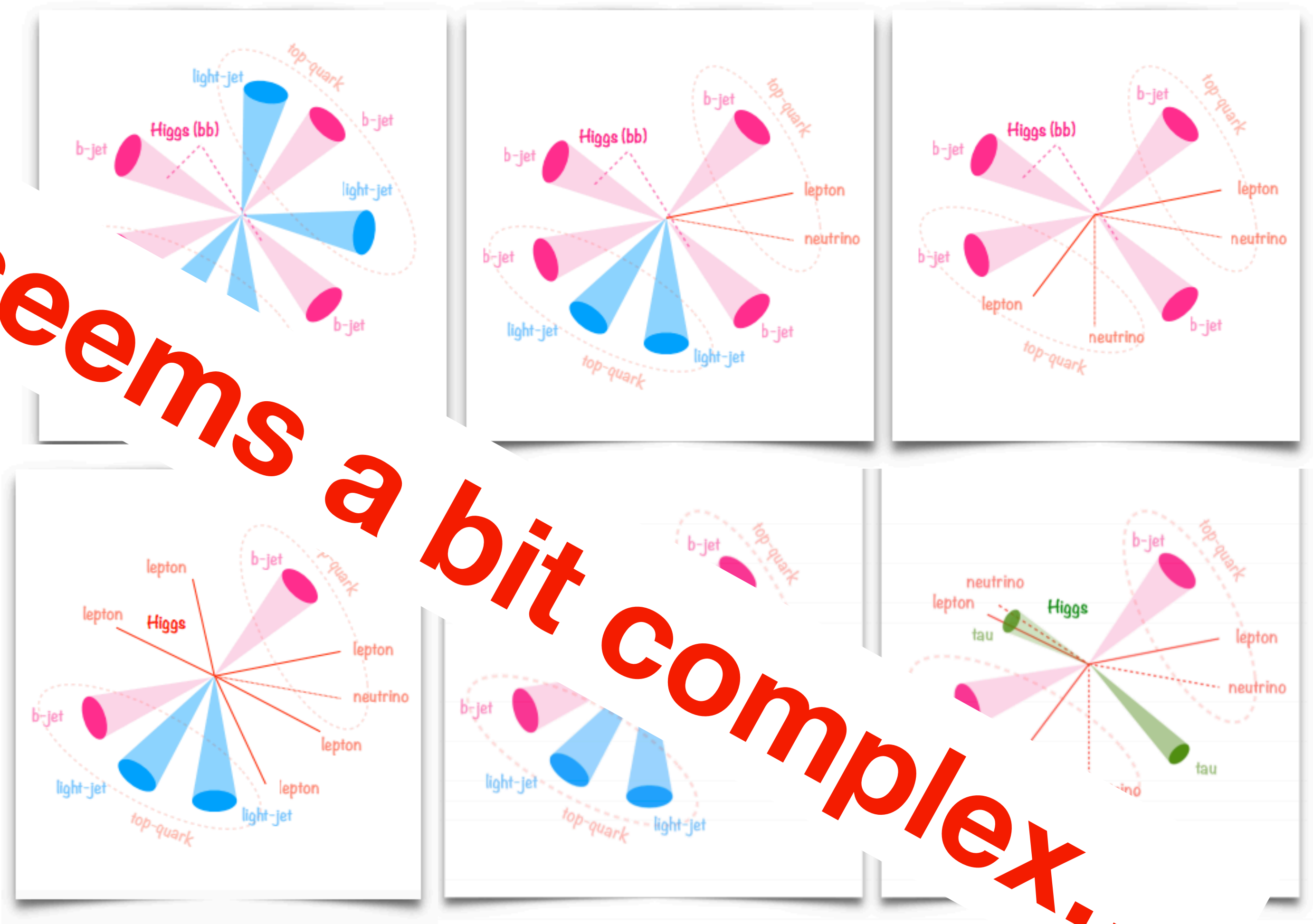
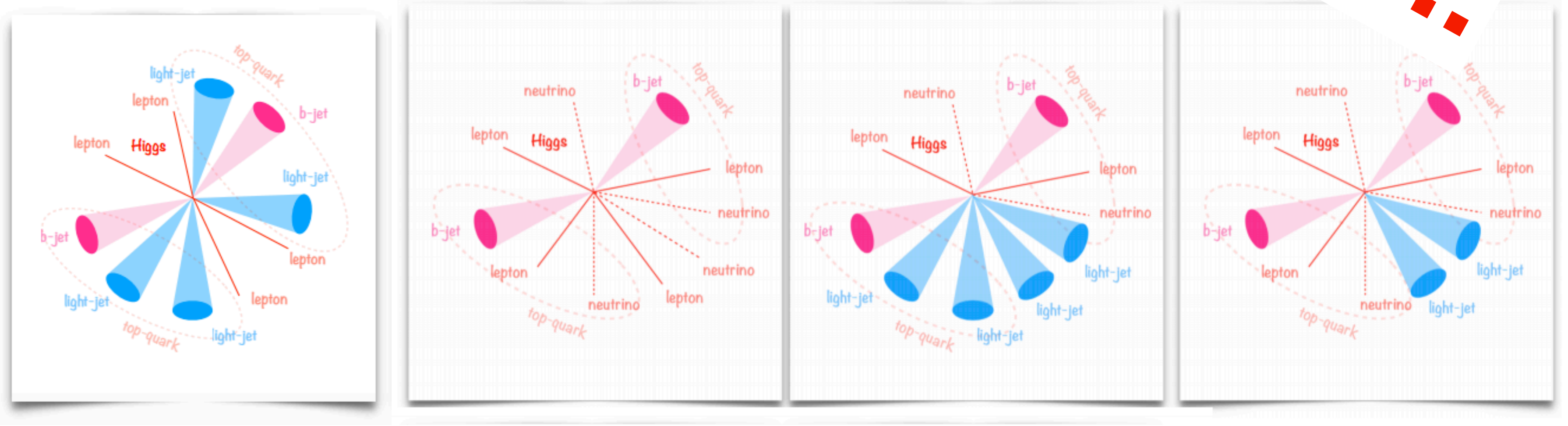
$\tau^+\tau^-$ → $\tau_h^+\tau_h^-, \tau_h^+\tau_l^-$

W^+W^{*-} → $\ell\nu\ell\nu, \ell\nu 2j$

ZZ^* → $4\ell, 2\ell 2\nu, 2\ell 2j$



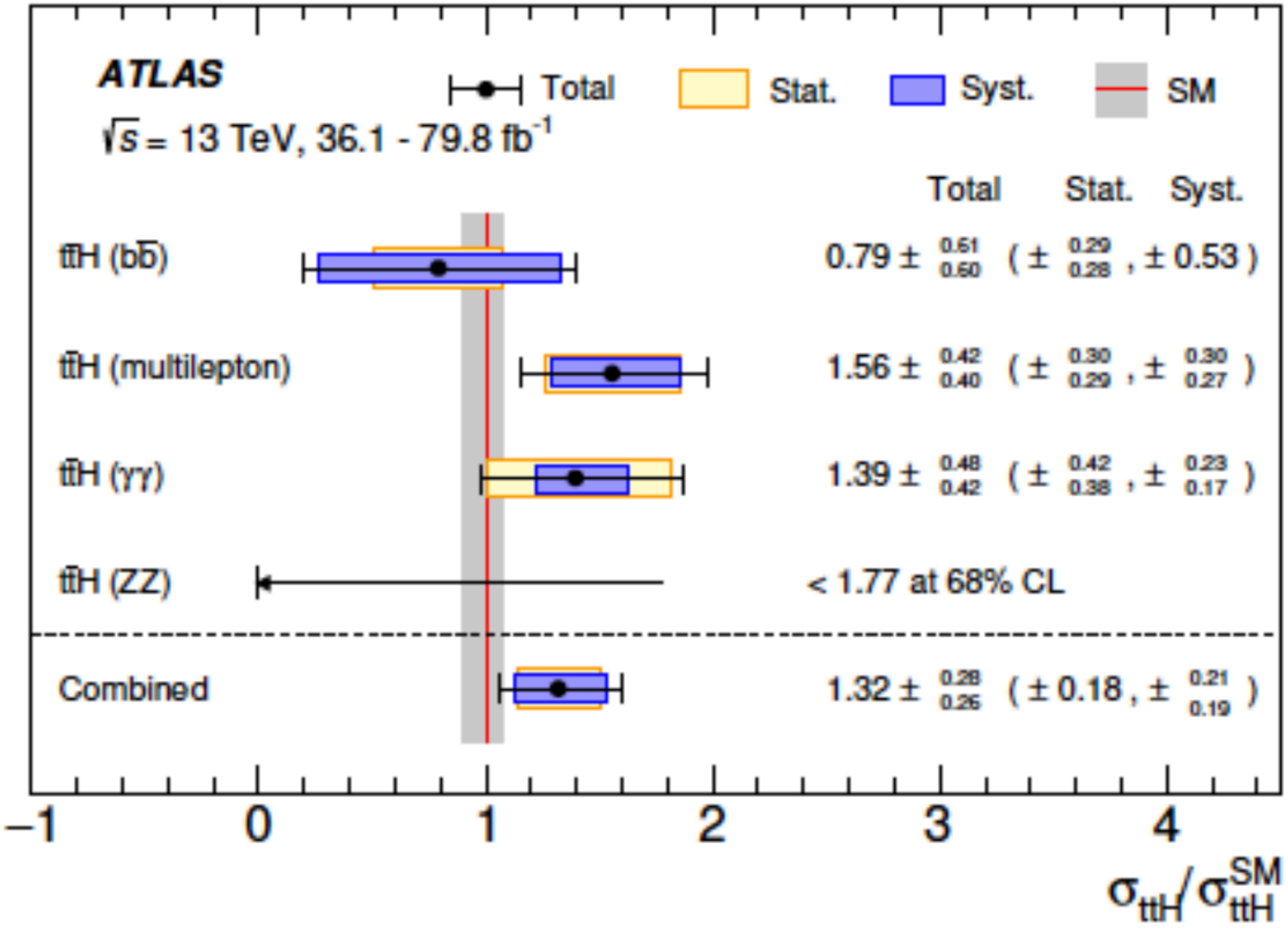
it seems a bit complex....



Observed!

LHCP
Bologna
2018

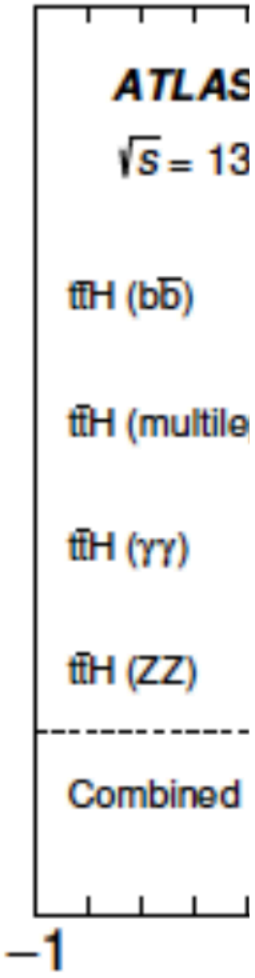
The Big news (2): Top -Higgs interaction

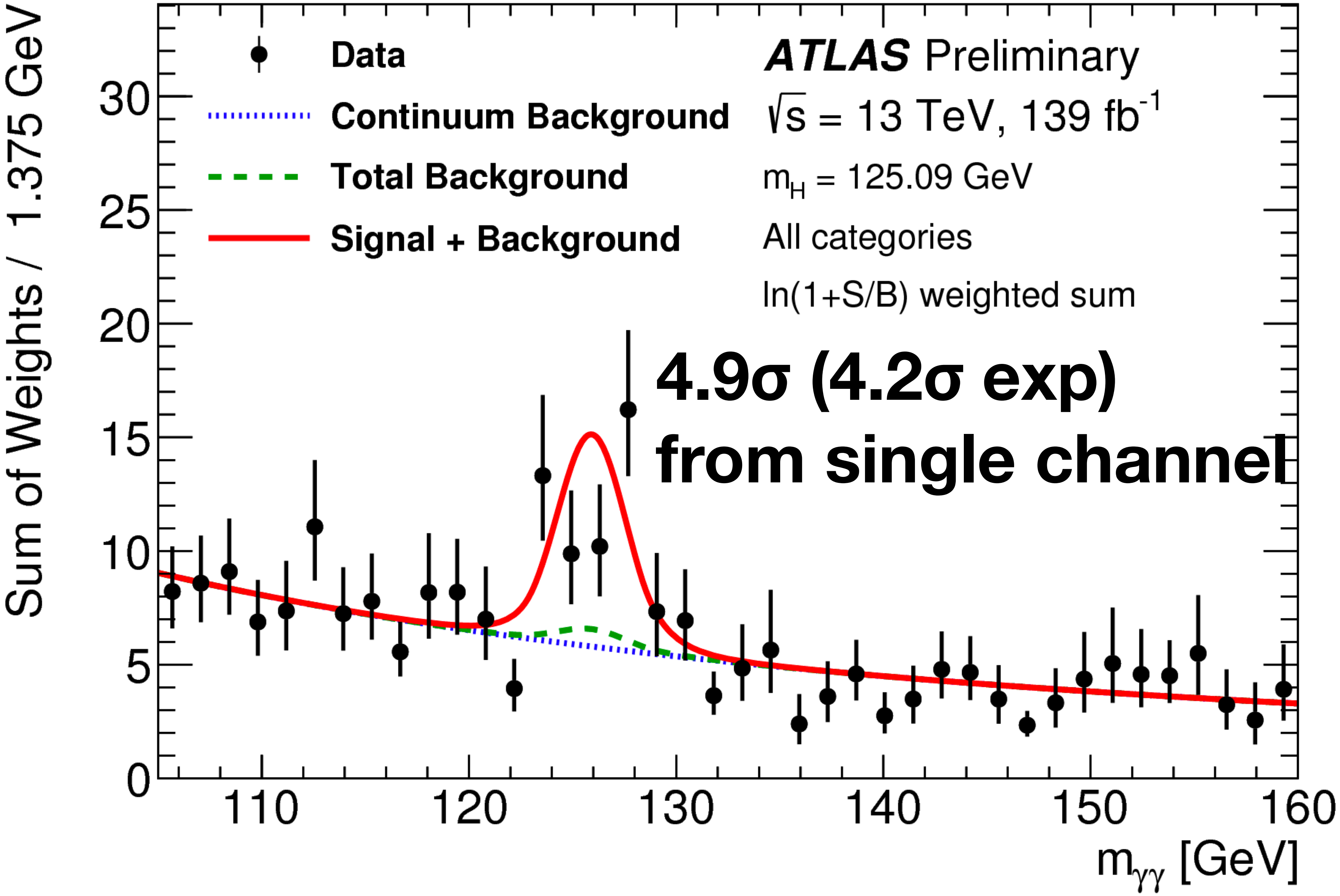


- CMS and ATLAS results presented at LHCP2018
- Both collaborations had to combine channels to obtain the sensitivity necessary to claim an observation
- All possible advanced tools were used
  - Multi Variate Analysis
  - Matrix Element Method
  - Status of the art theory predictions)

The Big news (2): Top -Higgs interaction

Observed!





4.9σ (4.2σ exp) from single channel

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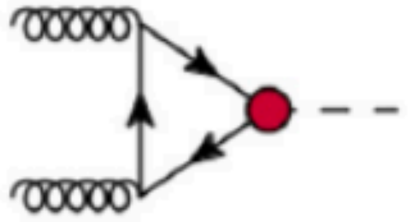
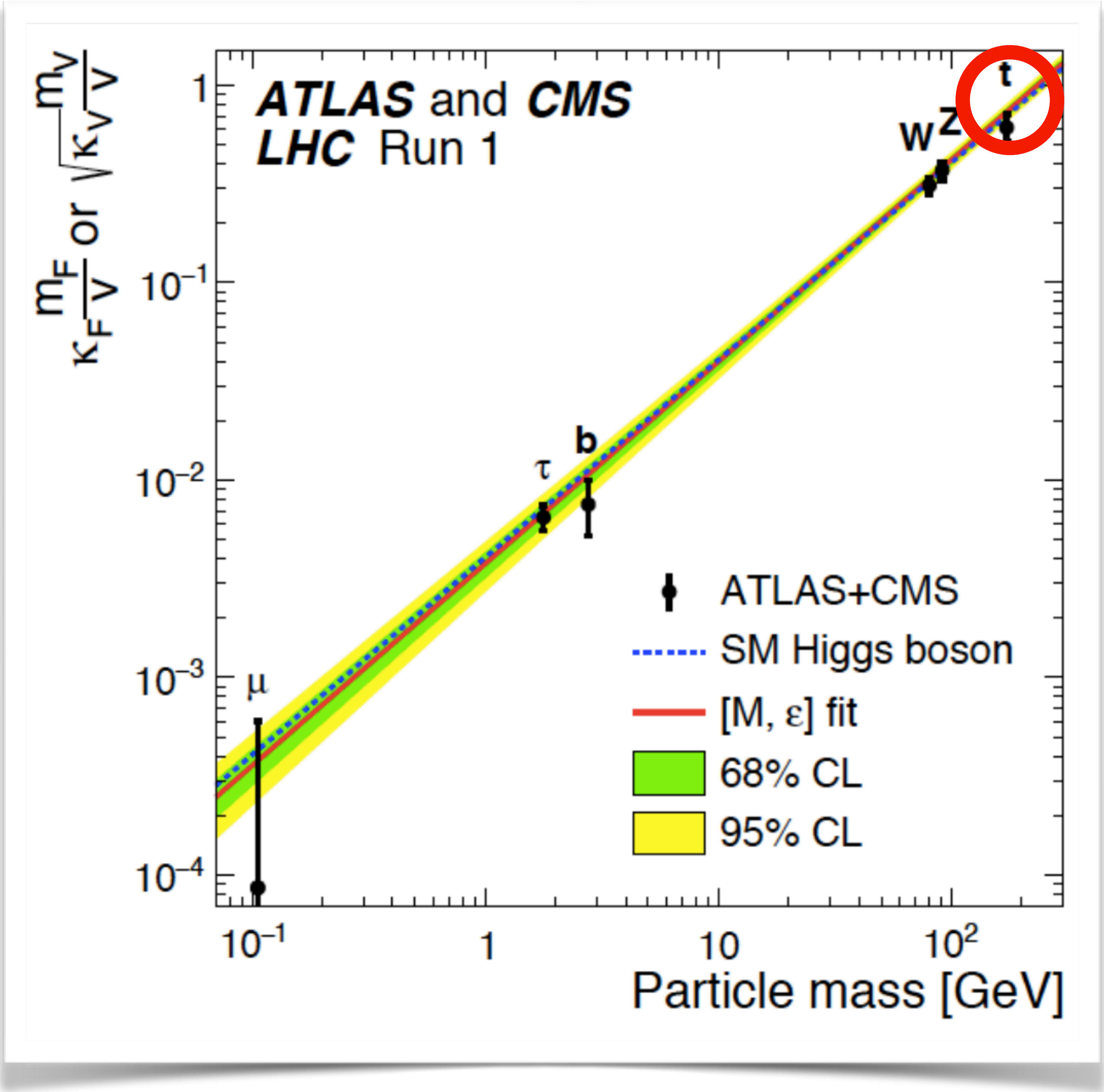
Observed!

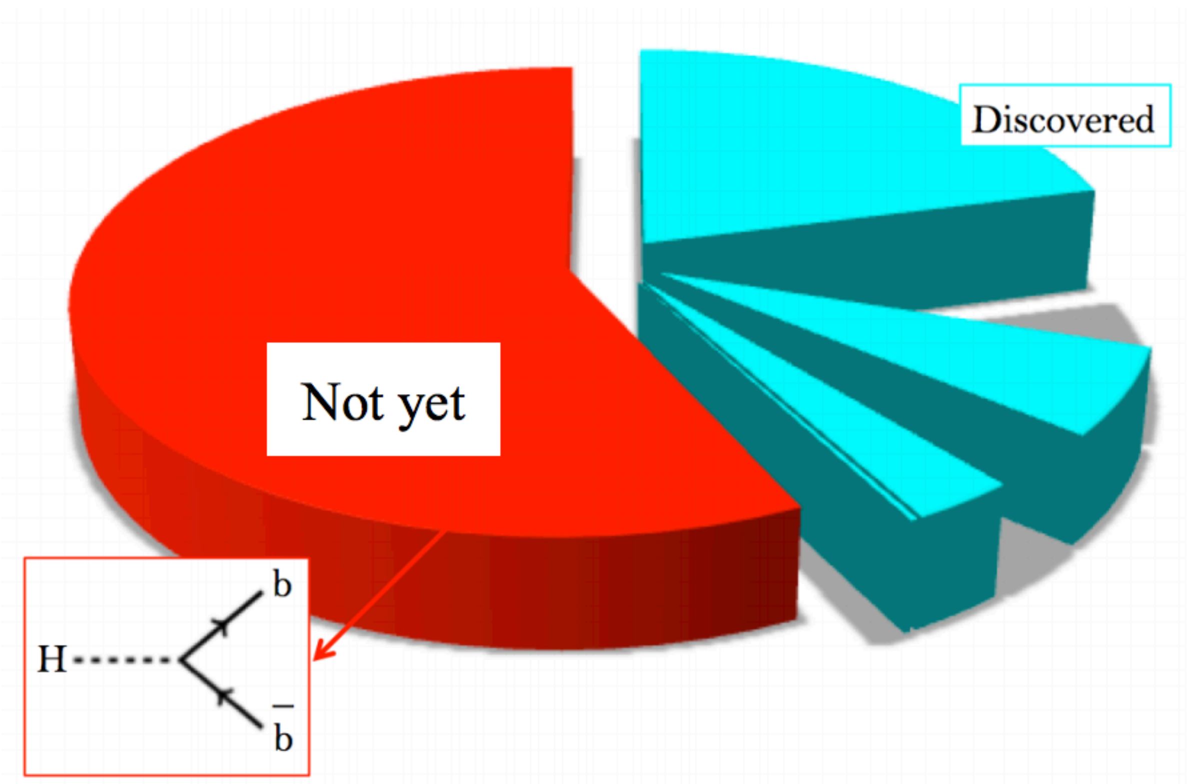
The Big news (2): Top -Higgs interaction

- 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→bb observation in ICHEP 2018

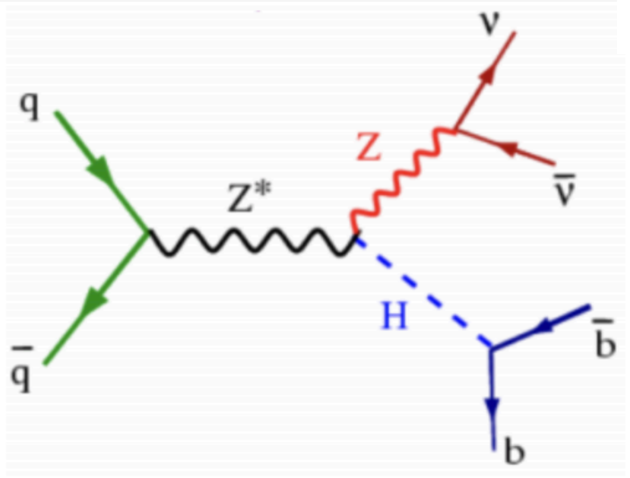
- In addition to probing coupling to b-quarks:
  - H→bb drives the uncertainty on the total decay width, and thus on measurement of absolute couplings
  - It also drives the indirect limit on “undetected/ invisible” decays

The Big news (3): Bottom -Higgs interaction

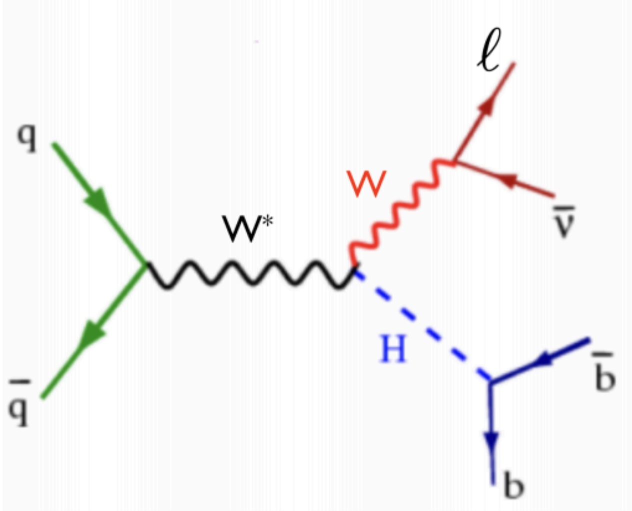
G. Piacquadio - ICHEP 2018

- VH production most sensitive mode for H → 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 ΔR(bb) (combined into a Boosted Decision Tree)

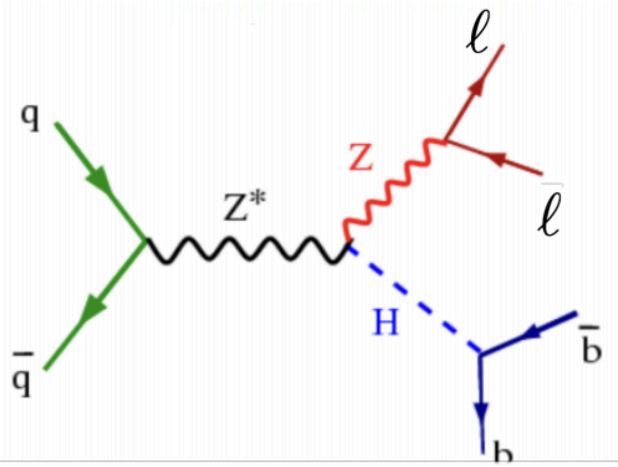
0-lepton



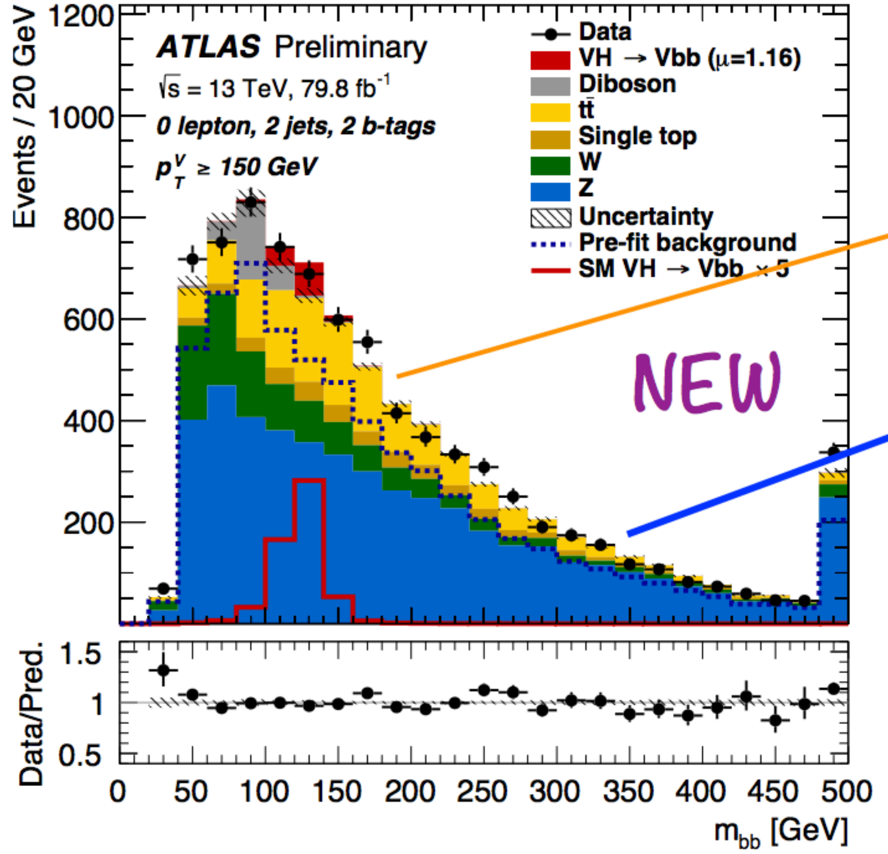
1-lepton



2-lepton



m(bb)



Non-resonant backgrounds:

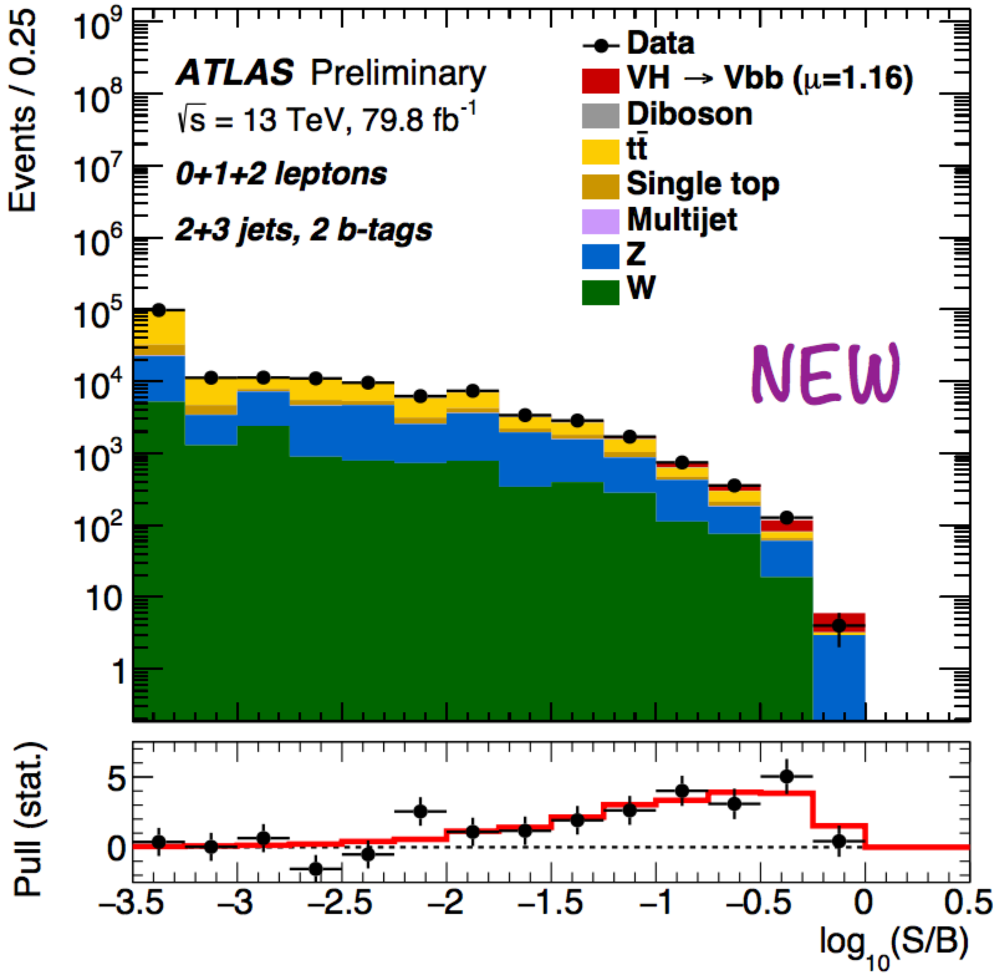
ttbar,
single top
(NLO, PowHeg)

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

Overall strategy: normalization from data, shapes from MC

The Big news (3): Bottom -Higgs interaction

[ATLAS-CONF-2018-036]



G. Piacquadio - ICHEP 2018

Fit result with 79.8 fb^{-1} of Run-2 data

$$\mu = \sigma_{\text{meas}} / \sigma_{\text{SM}} = 1.16^{+0.27}_{-0.25}$$

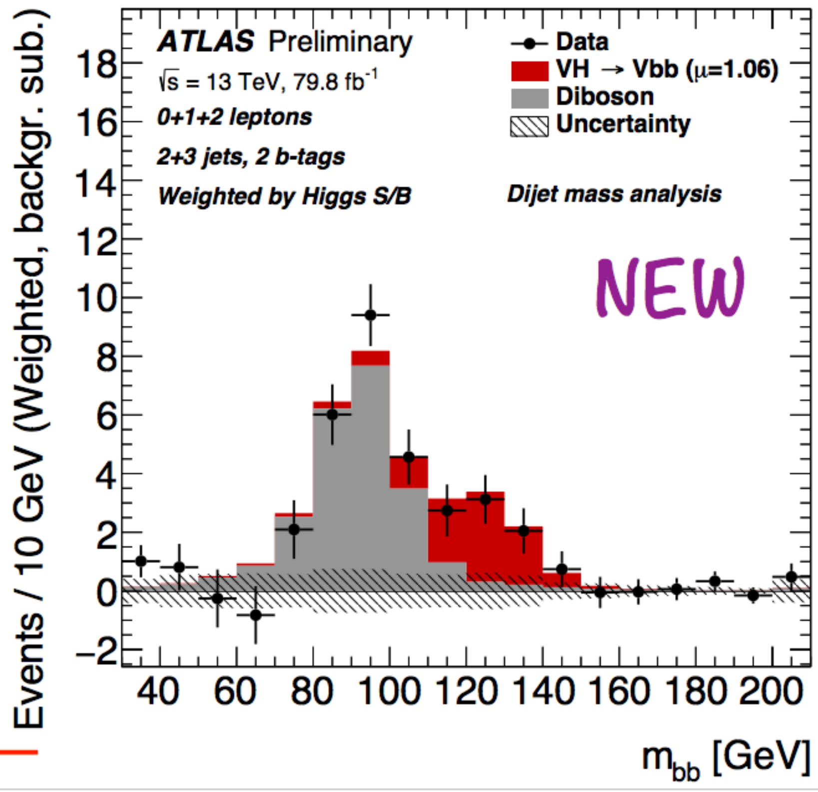
Significance: **4.9σ** (4.3σ expected)

Combination with Run-1:

$$\mu = 0.98 \pm 0.14(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})$$

Significance: **4.9σ** (5.1σ expected)

- Detailed validation of analysis:
  - Fit to diboson VZ, Z → bb: $\mu = 1.20^{+0.20}_{-0.18}$ (9.6σ)
  - m(bb) fit for VH, H → bb: $\mu = 1.06^{+0.36}_{-0.33}$ (**3.6σ**)



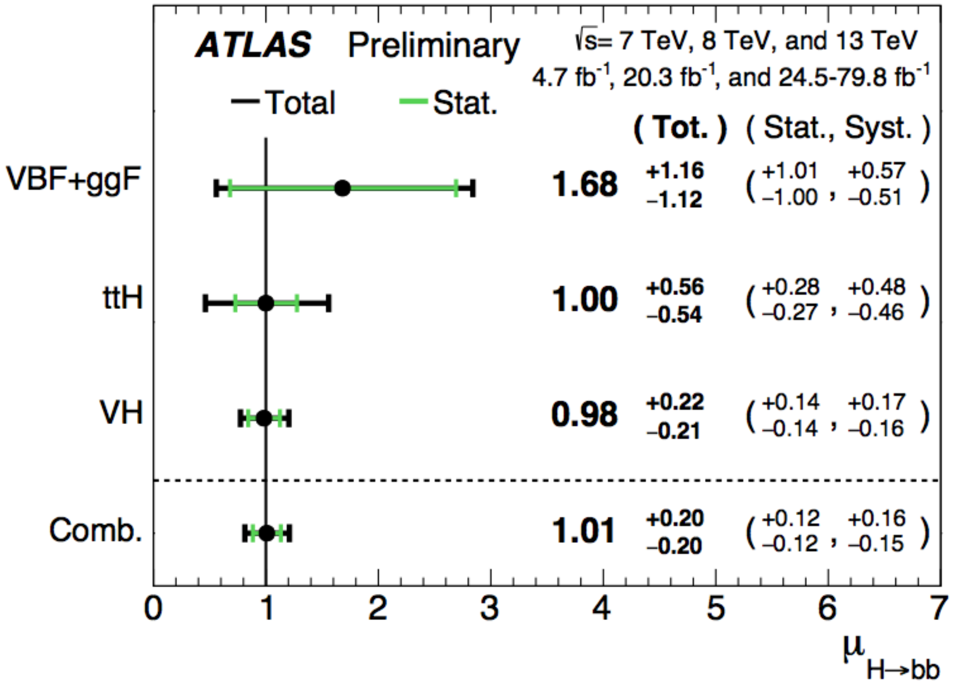
Observed!

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

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

H → bb combination

NEW



Significance:
5.4σ observed
(5.5σ expected)

Observation of H → bb!!

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

VH combination

NEW

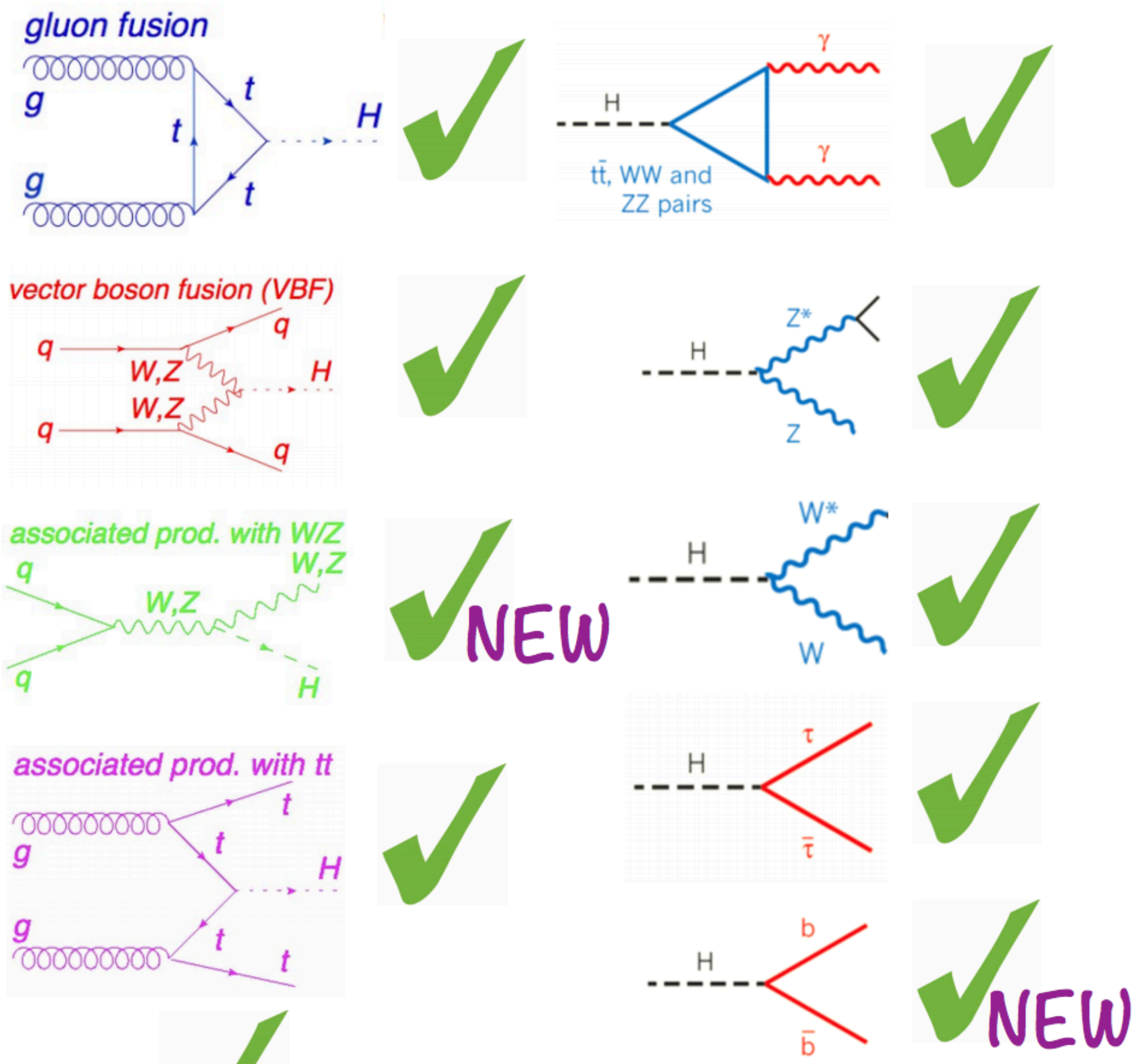
Significance:
5.3σ observed (4.8σ expected)

Observation of VH production!!

G. Piacquadio - ICHEP 2018

Where we are today

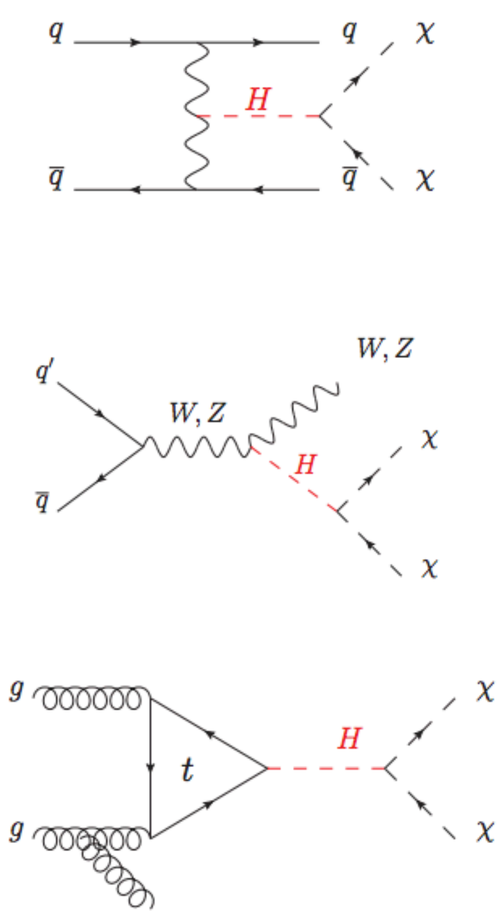
Production **Decays**



✓ = observed

… more rare options….

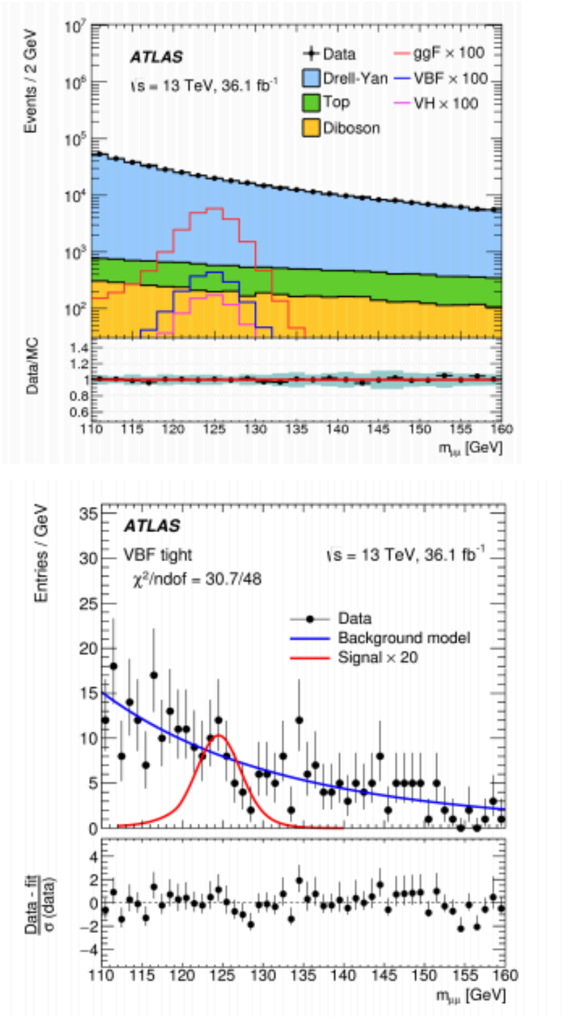
Invisible decays



$B r_{inv} < 0.24\ (0.23)$

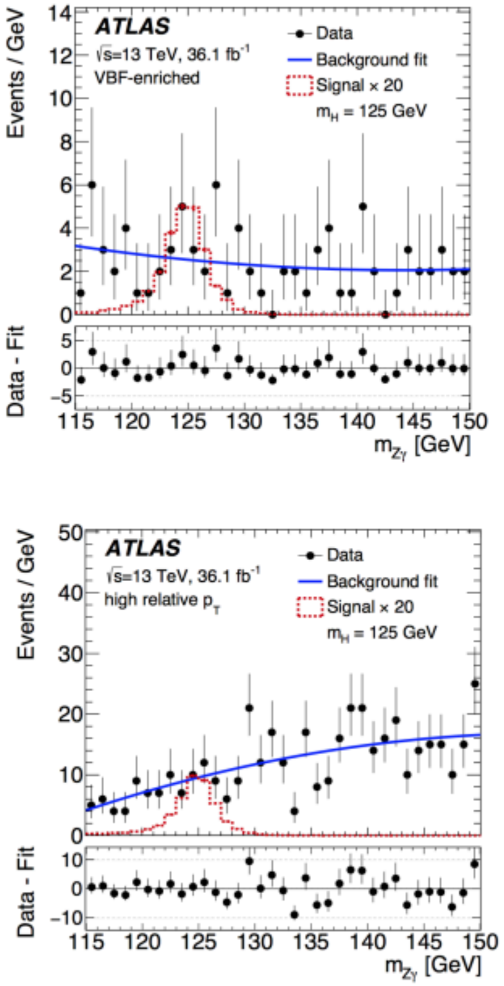
at 95% CL

di-muons



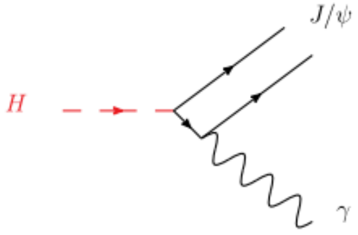
Limits currently ~2 x SM

Z-photon



Limits currently ~6 x SM

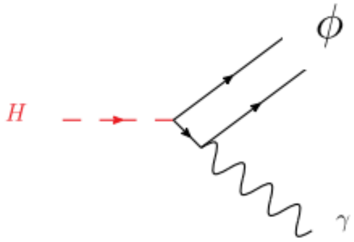
Quarkonia-photon



Potentially sensitive to charm Yukawa

$\mu^+\mu^-\gamma$

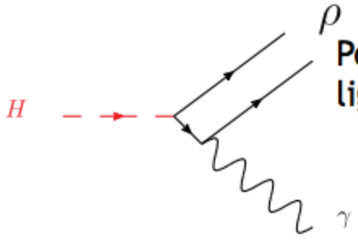
Higgs ~400 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

Higgs ~200 x SM

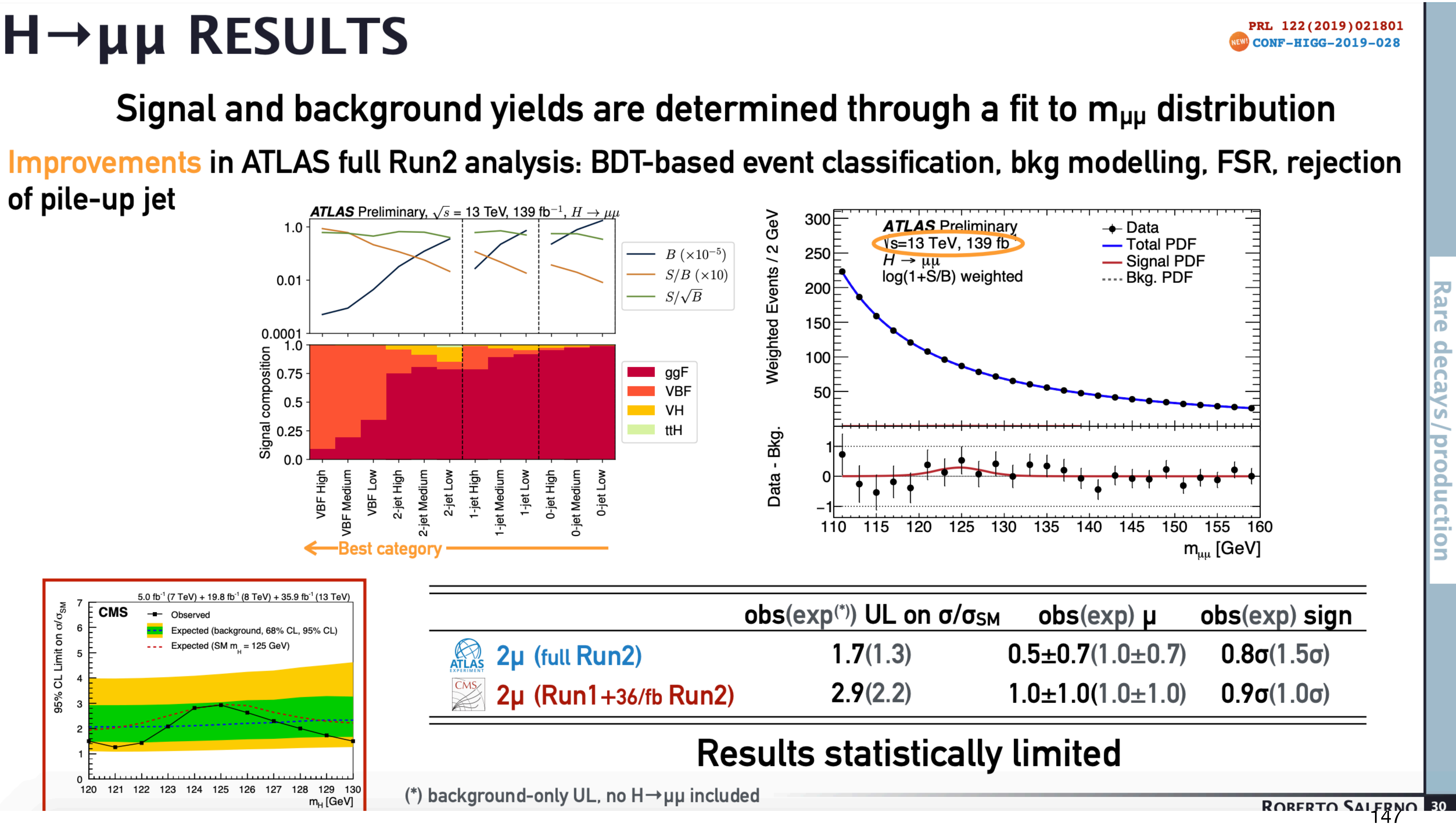


Potentially sensitive to light Yukawa

$\pi^+\pi^-\gamma$

Higgs ~50 x SM

From EPS 2019 (last week)



H→μμ RESULTS

PRL 122(2019)021801
NEW! CONF-HIGG-2019-028

Signal and background yields are determined through a fit to $m_{\mu\mu}$ distribution

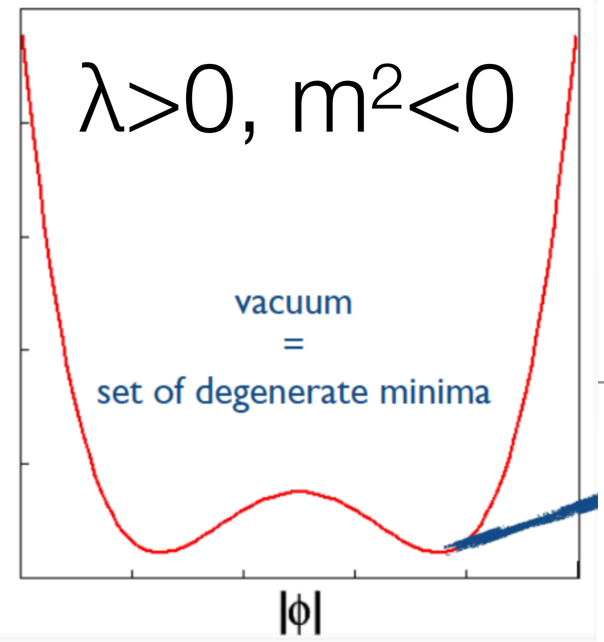
Improvements in ATLAS full Run2 analysis: BDT-based event classification, bkg modelling, FSR, rejection of pile-up jet

	obs(exp$^{(*)}$) UL on σ/σ_{SM}	obs(exp) μ	obs(exp) sign
ATLAS 2μ (full Run2)	1.7(1.3)	0.5±0.7(1.0±0.7)	0.8σ(1.5σ)
CMS 2μ (Run1+36/fb Run2)	2.9(2.2)	1.0±1.0(1.0±1.0)	0.9σ(1.0σ)

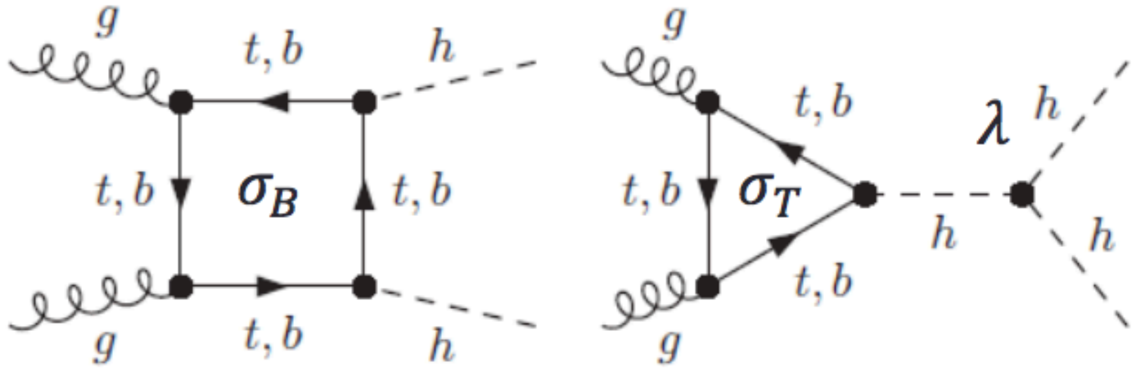
Results statistically limited

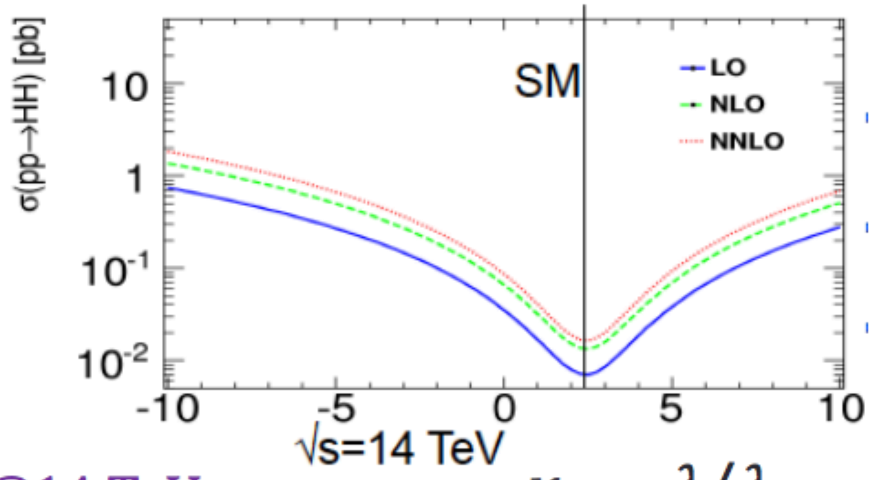
(*) background-only UL, no H→μμ included

…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.

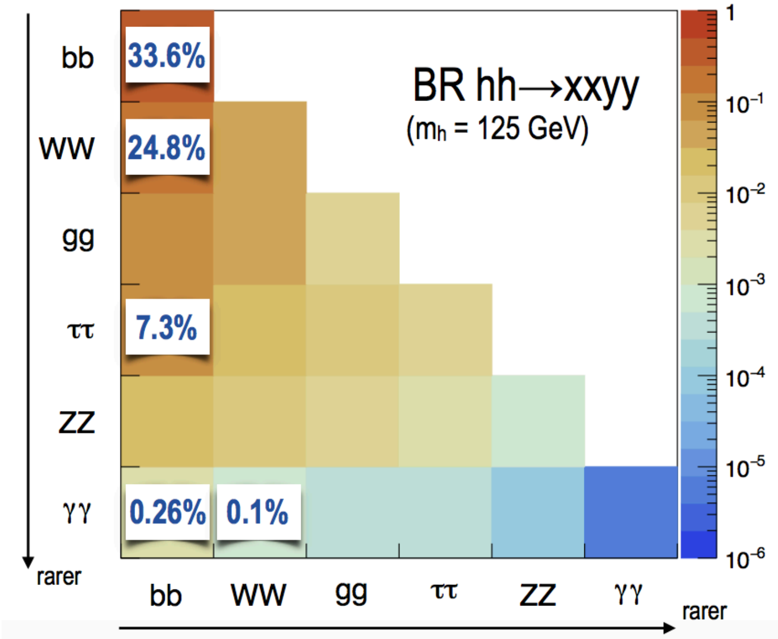




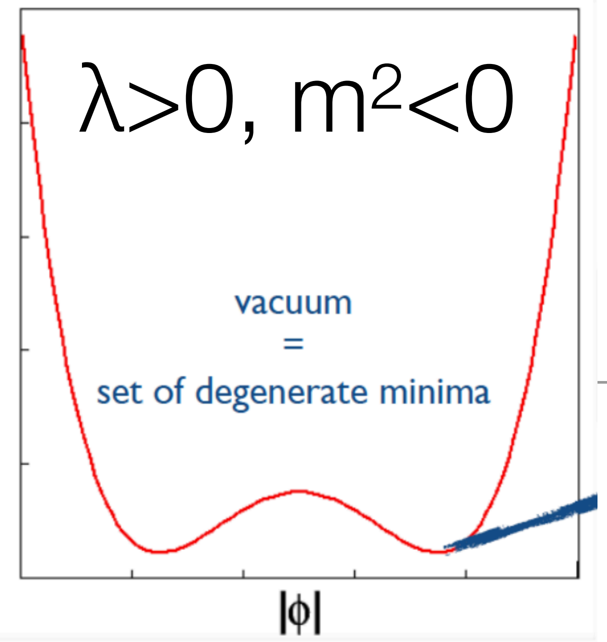
- **Destructive interference ➔ $\sigma_{hh} \approx \frac{\sigma_T+\sigma_B}{2.5}$ ➔ $\sigma_{hh} = 39.5$ fb @14 TeV**

$\kappa_\lambda = \lambda/\lambda_{SM}$

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



…and the big challenge: Double Higgs production!



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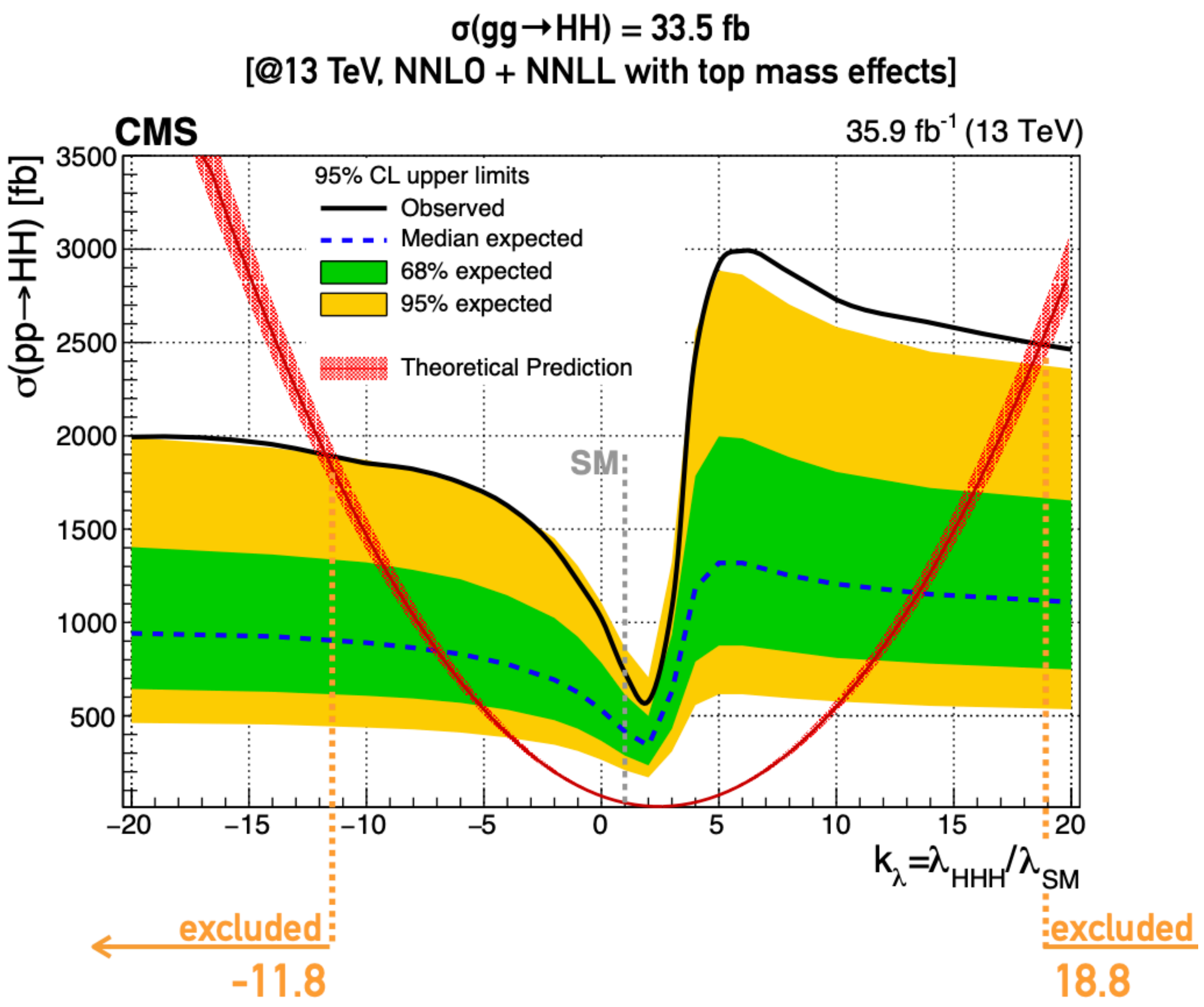
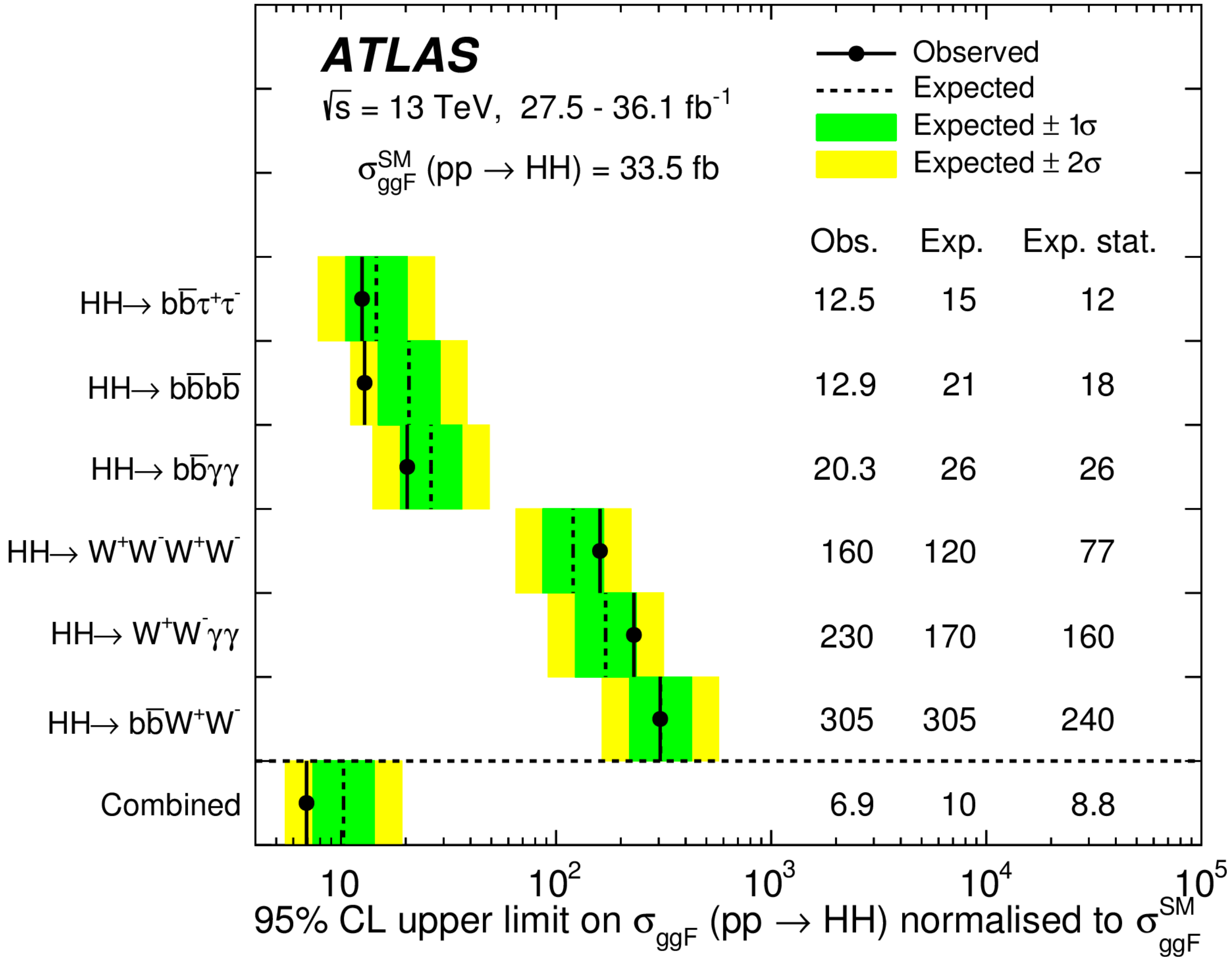


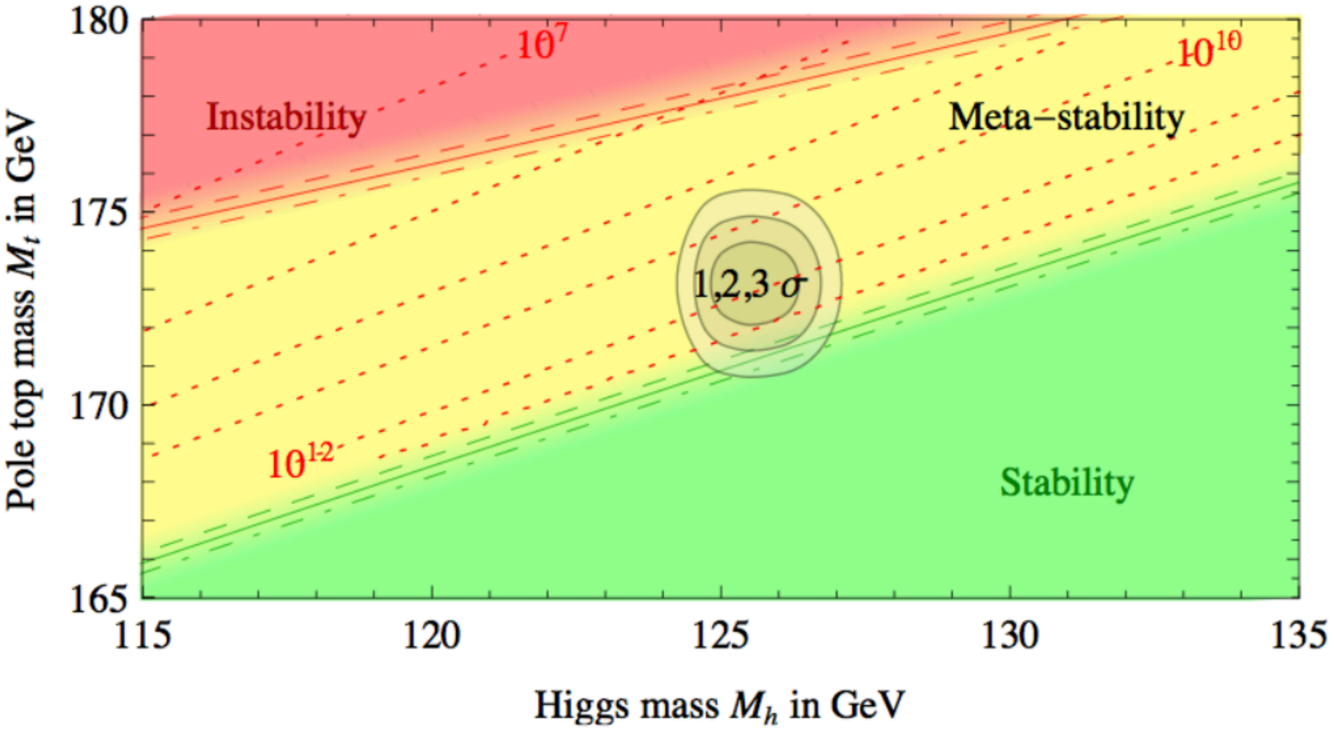


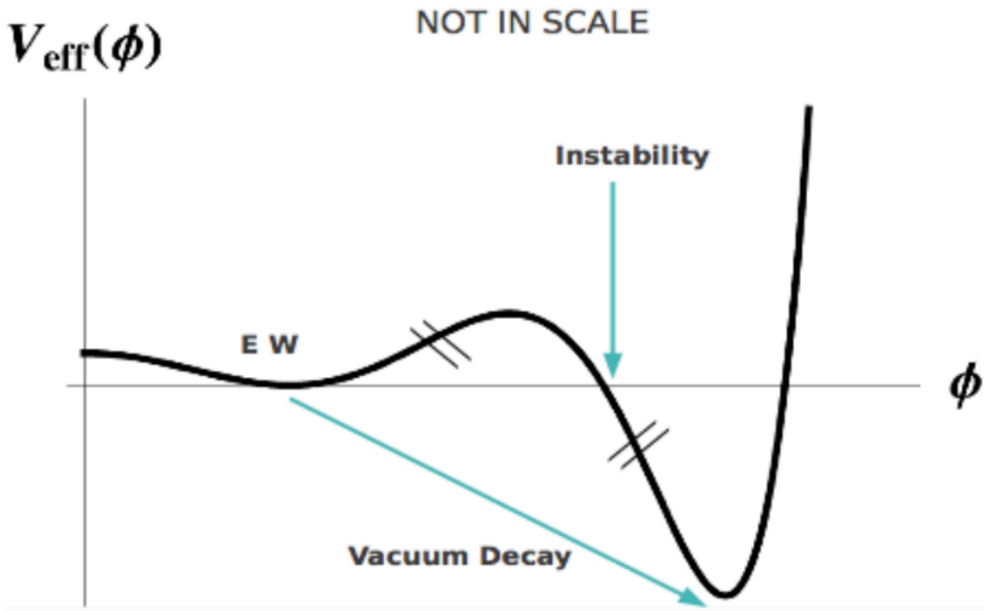
Selected news from Run2

- Observation of $H \to \tau\tau$
- Observation of $pp \to ttH$
- Observation of $H \to bb$
- Observation of $pp \to VH$
- Beginning of the quest for $pp \to HH$ and constrains on λ

BONUS
Some important questions…

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



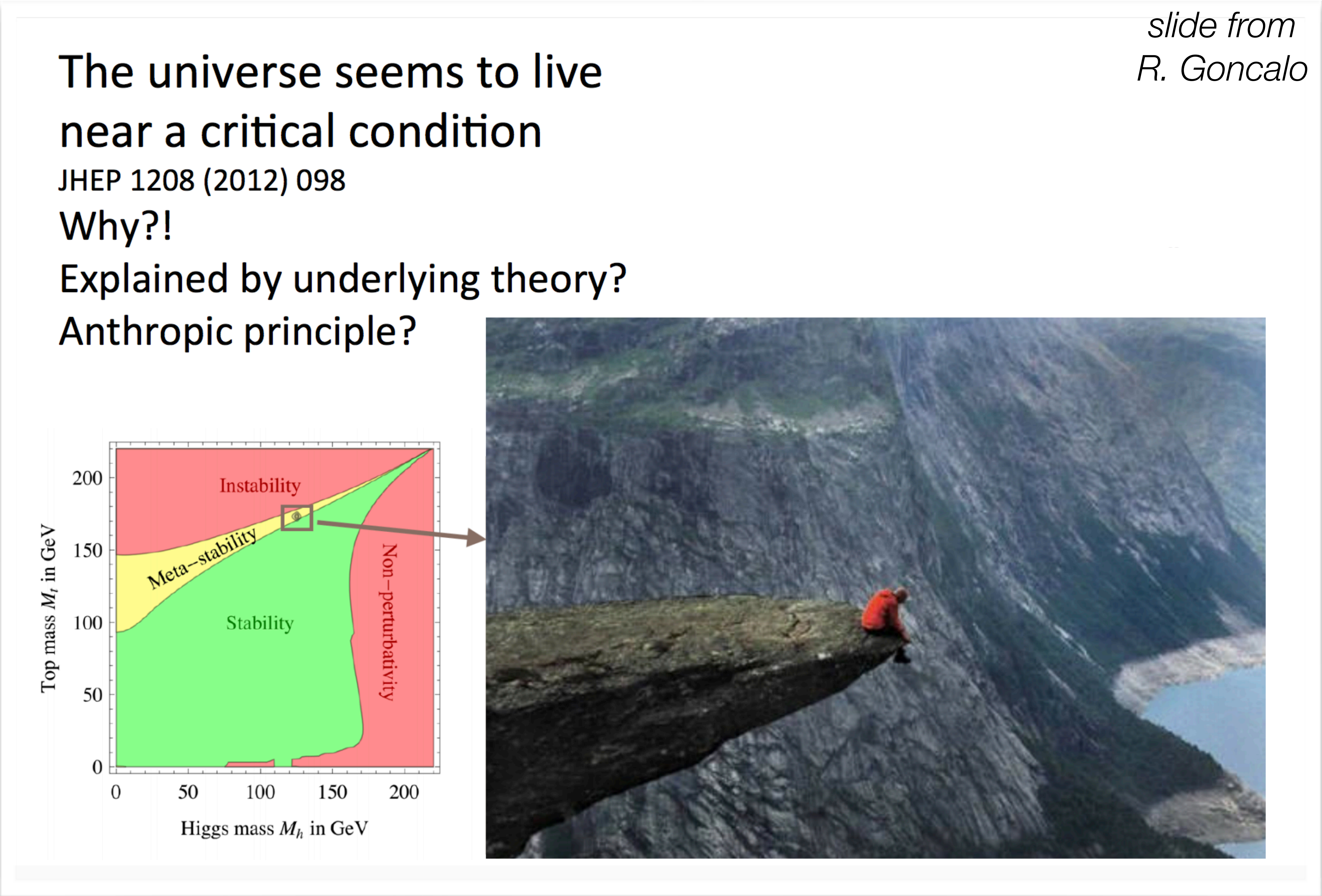


RG-improved potential

- 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:

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

- 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?

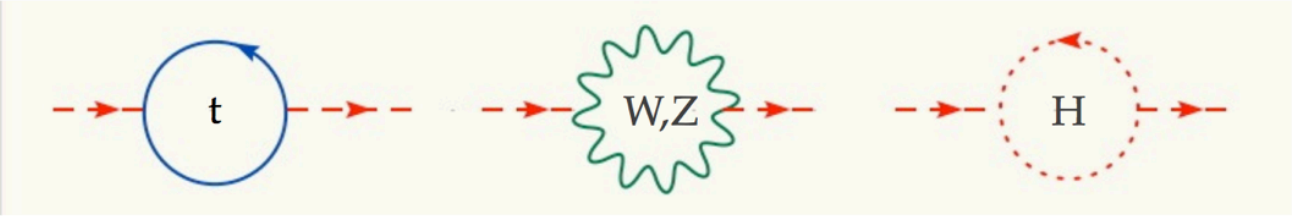
no hint of new physics at the LHC yet…

Some more considerations: hierarchy and naturalness

- Plank Scale
  - ~10^{19} GeV

- Grand Unification Scale:
  - ~10^{16} GeV

- Scale at which λ becomes negative : vacuum instability (with current measured m_{top} and m_H)
  - ~10^{16} GeV
- Mass of the particles (other than Higgs): 0-100 GeV
  - They should be 0 for gauge symmetries , with a “small" correction from the Higgs condensate
- But why the condensate is at 250 GeV and the mass of the Higgs is at 125 GeV?
  - Just by chance?



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Quantum correction to m_H, assuming as cut off scale due to new physics Λ

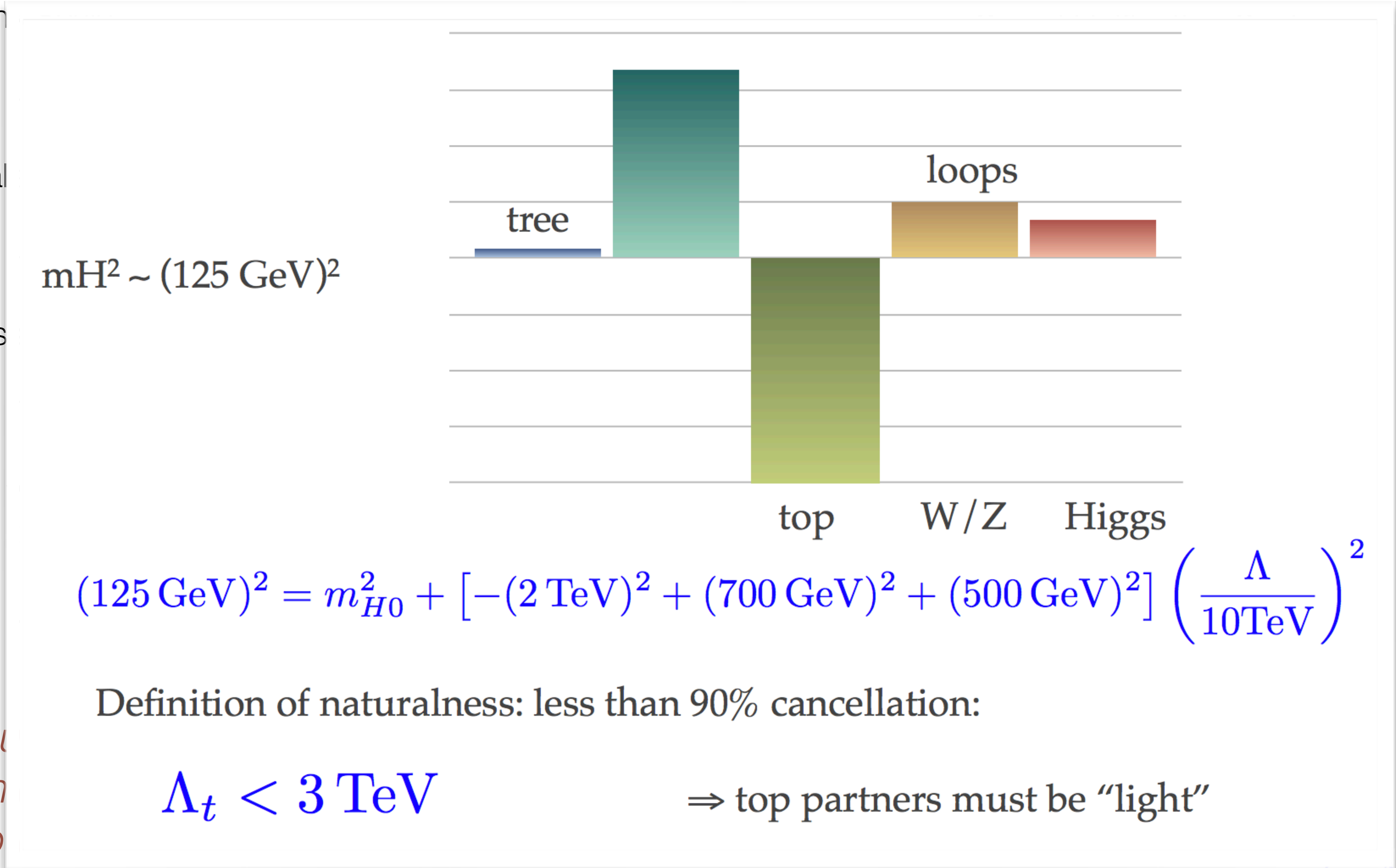
Putting numbers, one gets:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Some more considerations:
hierarchy and naturalness

- Plan
    -
- Scal
    -
- Mas
    -
- But and
    -

Quant assum due to



mH² ~ (125 GeV)²

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Definition of naturalness: less than 90% cancellation:

$$\Lambda_t < 3\,\mathrm{TeV}$$

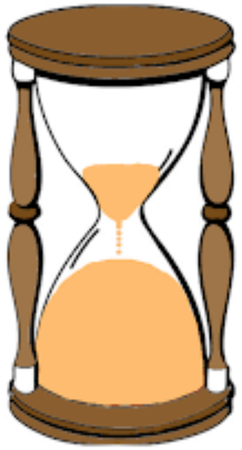
⇒ top partners must be “light”

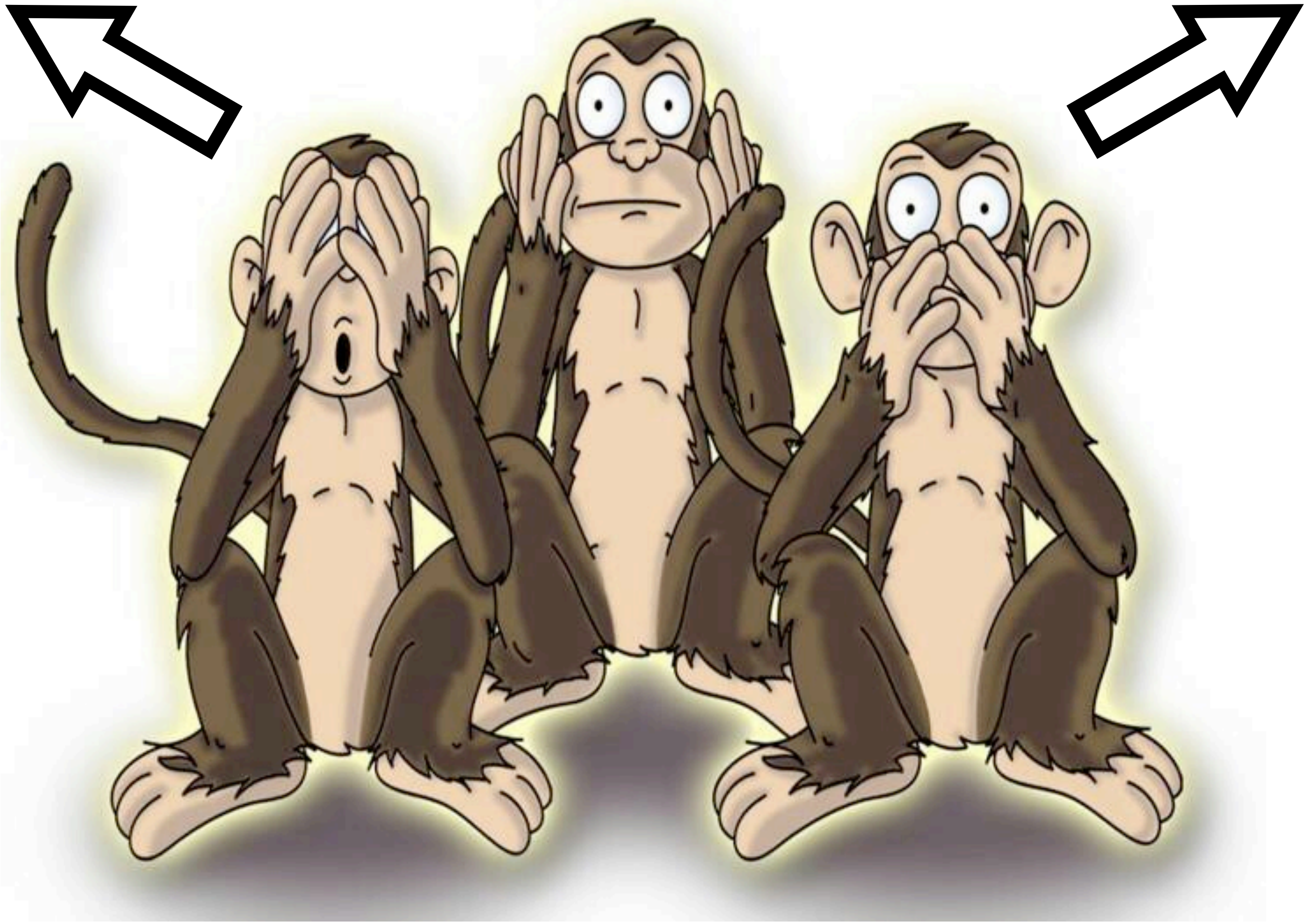
$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

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



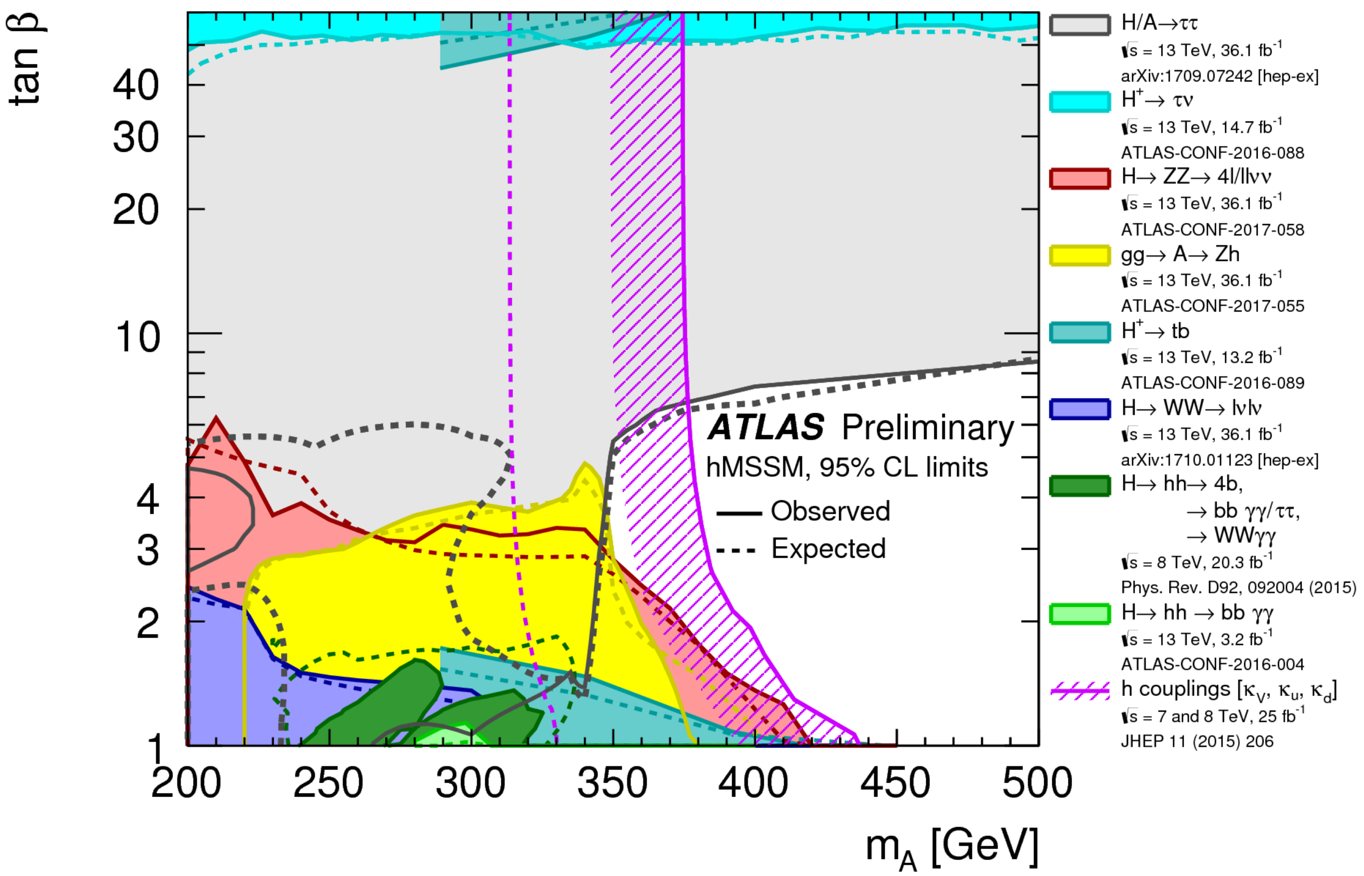


Option 2: New physics exist, but just beyond the reach of the LHC.

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

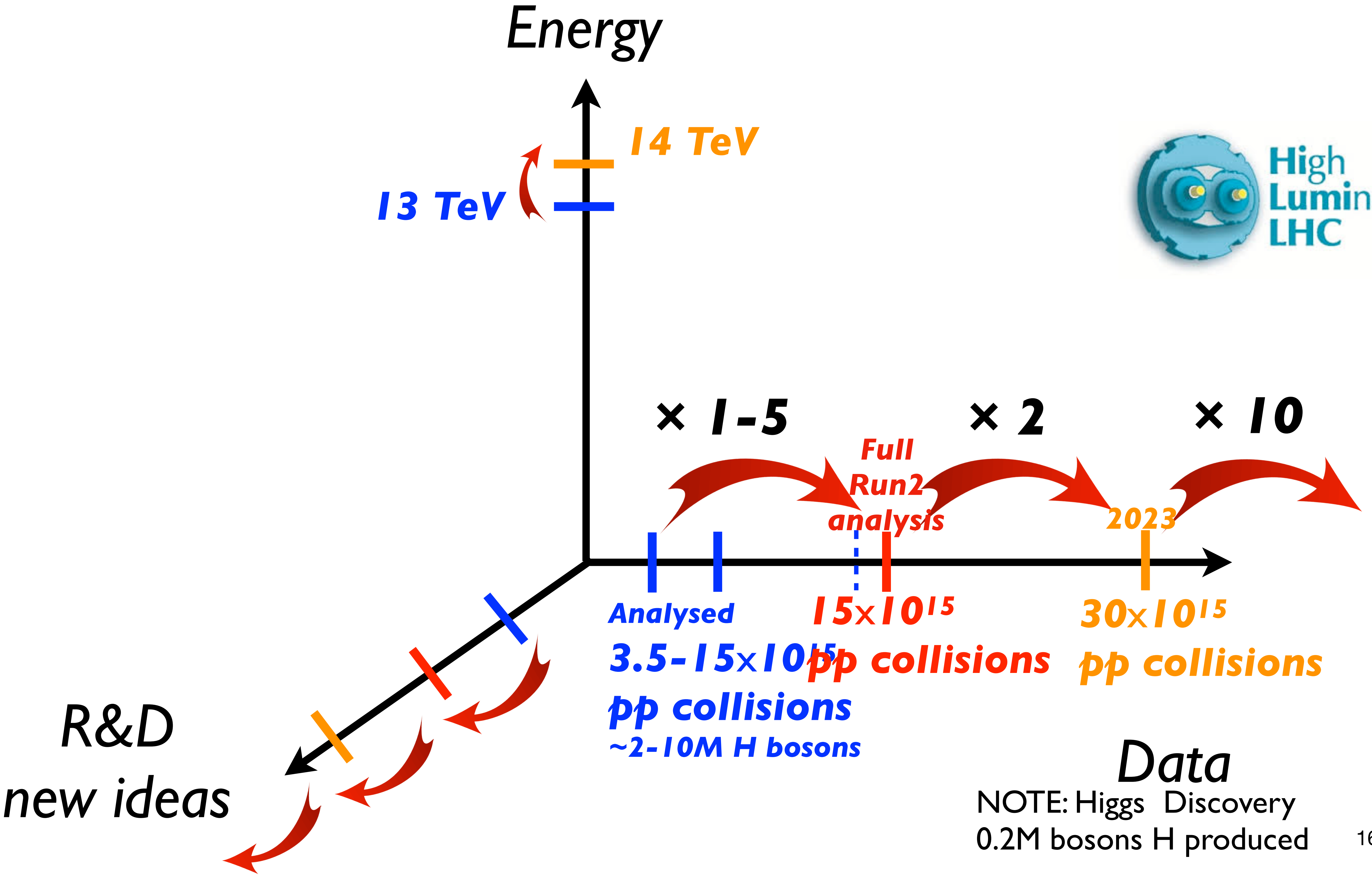
some advertisement :)

PISA SCHOOL ON FUTURE COLLIDERS

PISA, ITALY

September 17th - 21st, 2018

The reach of the LHC



Energy

14 TeV

13 TeV

High
Luminosity
LHC

× 1-5

× 2

× 10

Full
Run2
analysis

2023

Analysed
3.5-15×10^{15}
pp collisions
~2-10M H bosons

15×10^{15}
pp collisions

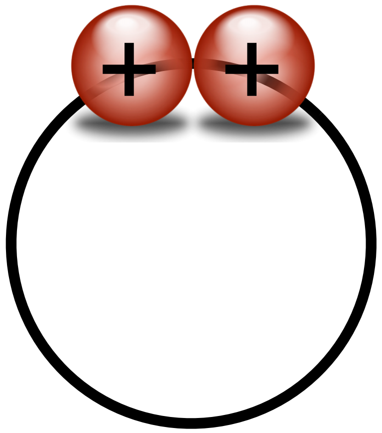
30×10^{15}
pp collisions

Data

R&D
new ideas

NOTE: Higgs Discovery
0.2M bosons H produced

Future colliders



pp

27 km

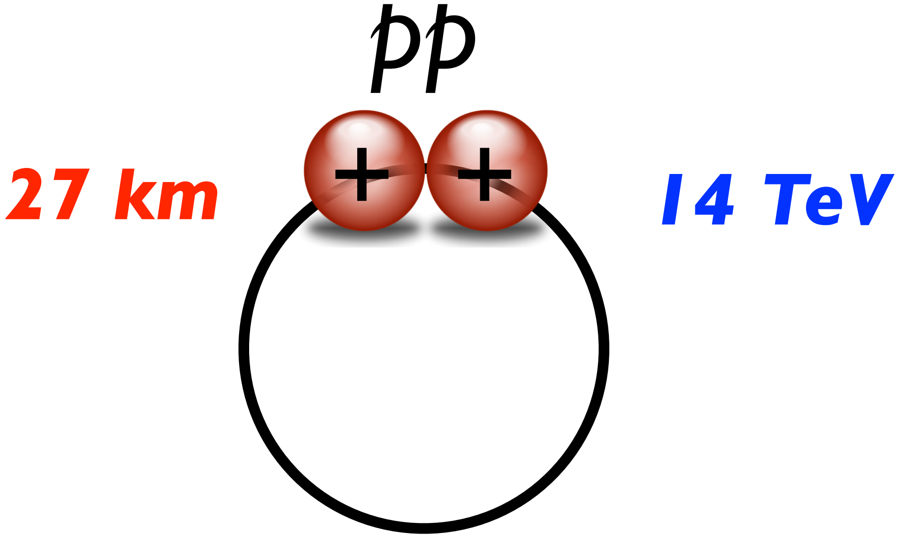
7,8,13,14 TeV

LHC

(2010 - 2023)

Future colliders

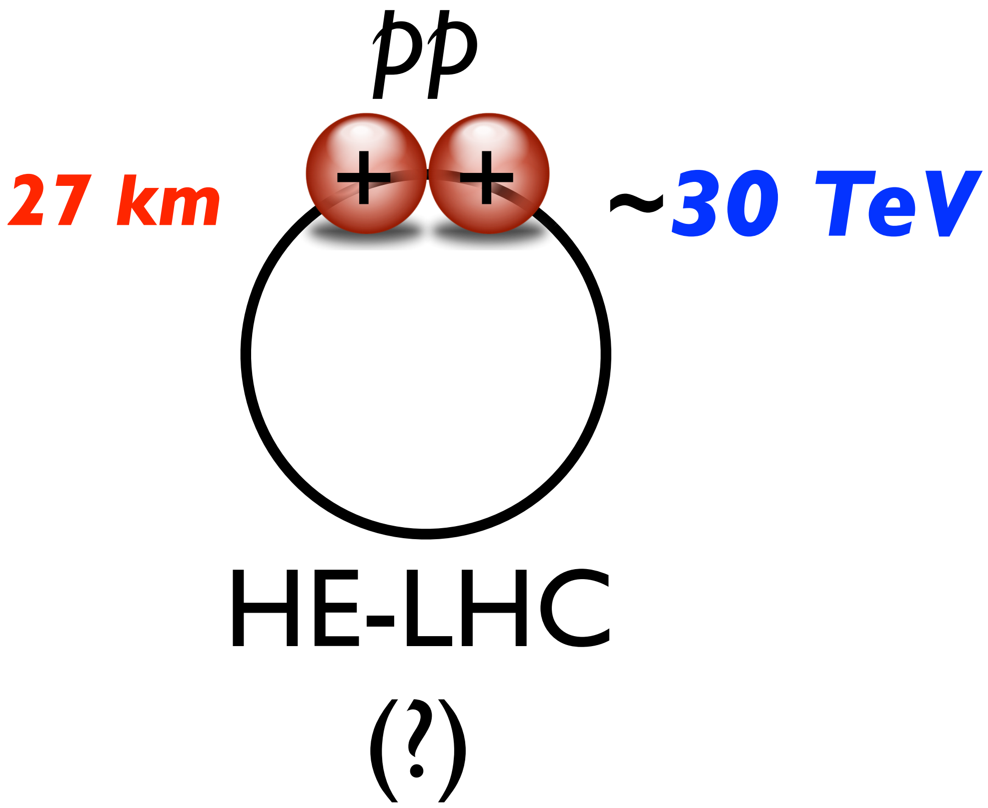
HL-LHC = same energy, but collision rate 2÷3 time higher



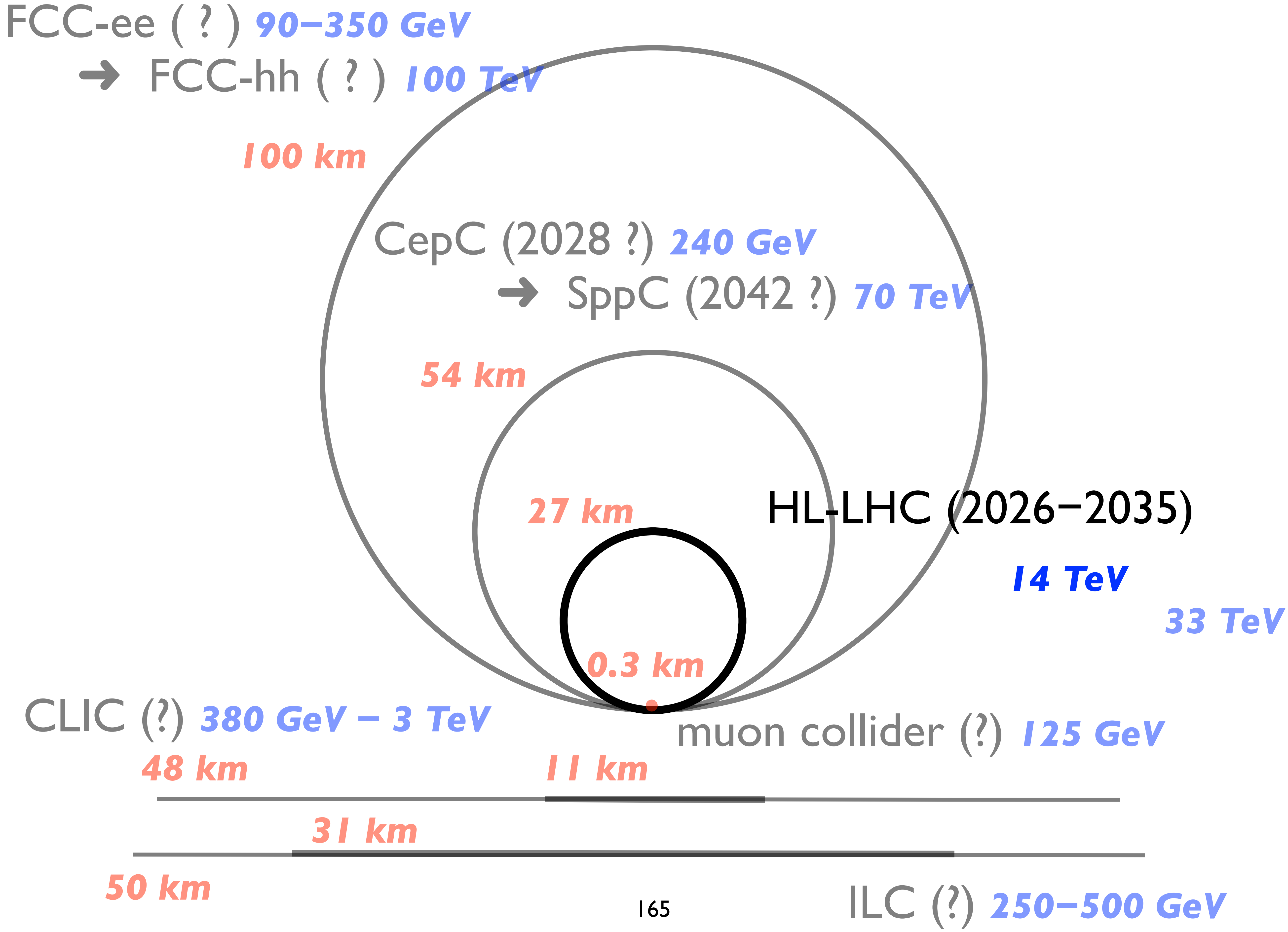
HL-LHC
(2026−2035)

Future colliders

HE-LHC = 2 times the center of mass energy?



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 (2026−2035)

14 TeV

33 TeV

0.3 km

CLIC (?) **380 GeV − 3 TeV**

muon collider (?) **125 GeV**

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	2023							0.3				0.3	13	**15M**
HL-LHC	pp	2026	2035							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)

Backup

Going beyond the SM

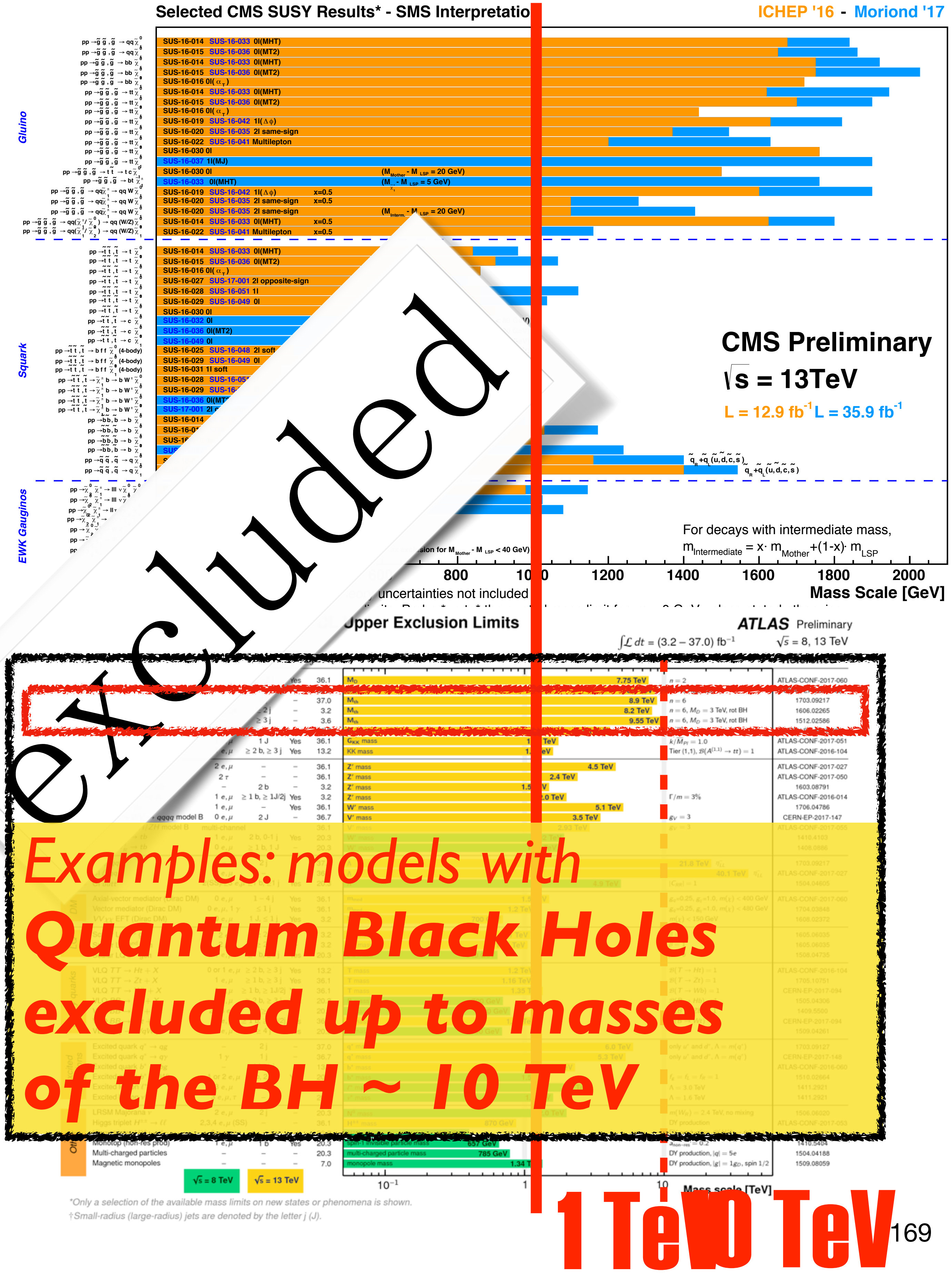
BSM: Direct Searches

Direct searches of new physics gave non positive results so far

Some examples

Supersymmetry (MSSM) ⇒

Top-partners
Composite Higgs
Extra-dimensions
Excited Quark
… ⇒



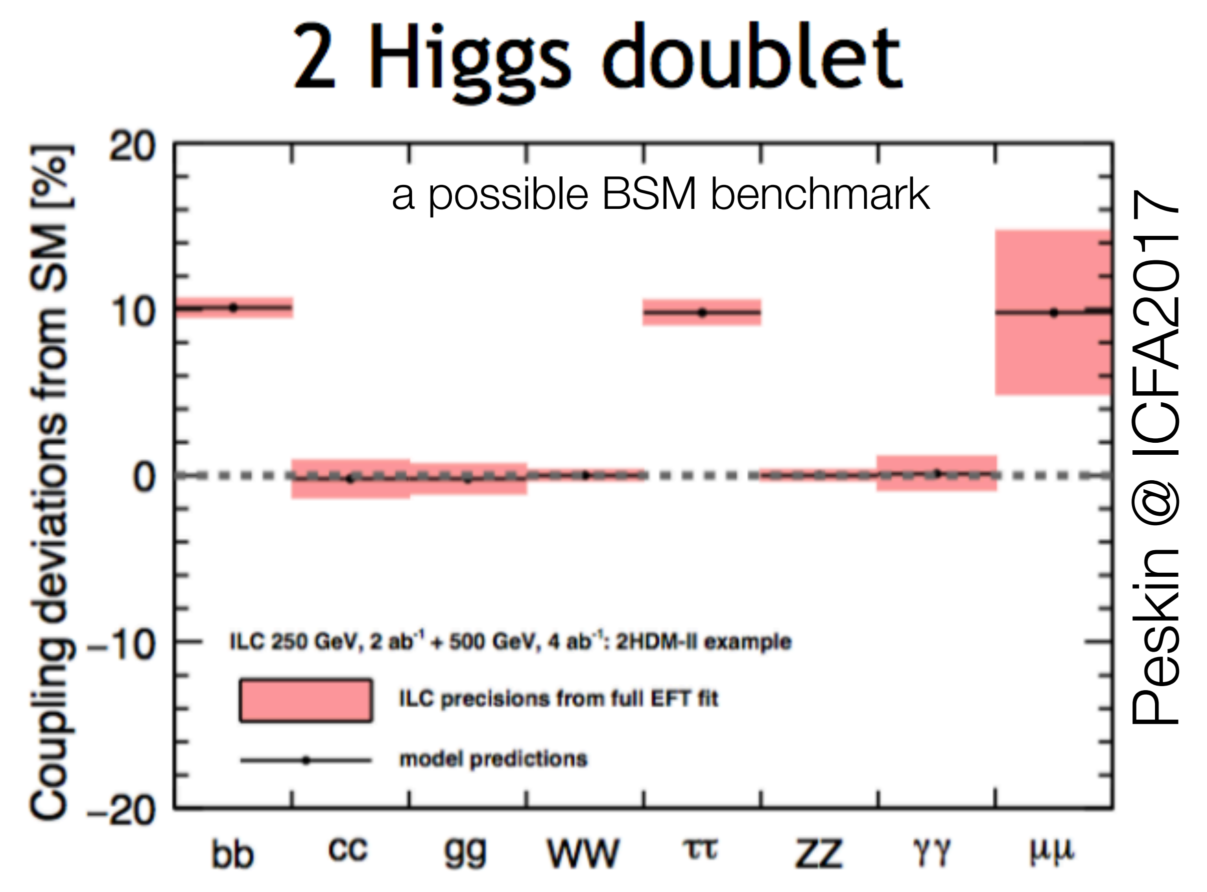
Examples: models with
Quantum Black Holes excluded up to masses of the BH ~ 10 TeV

An example: Models with two Higgs doublets

Another possible benchmark with two Higgs doublets

Deviations in couplings up to 10%

We can expect deviations, even if we do not see directly the new particles

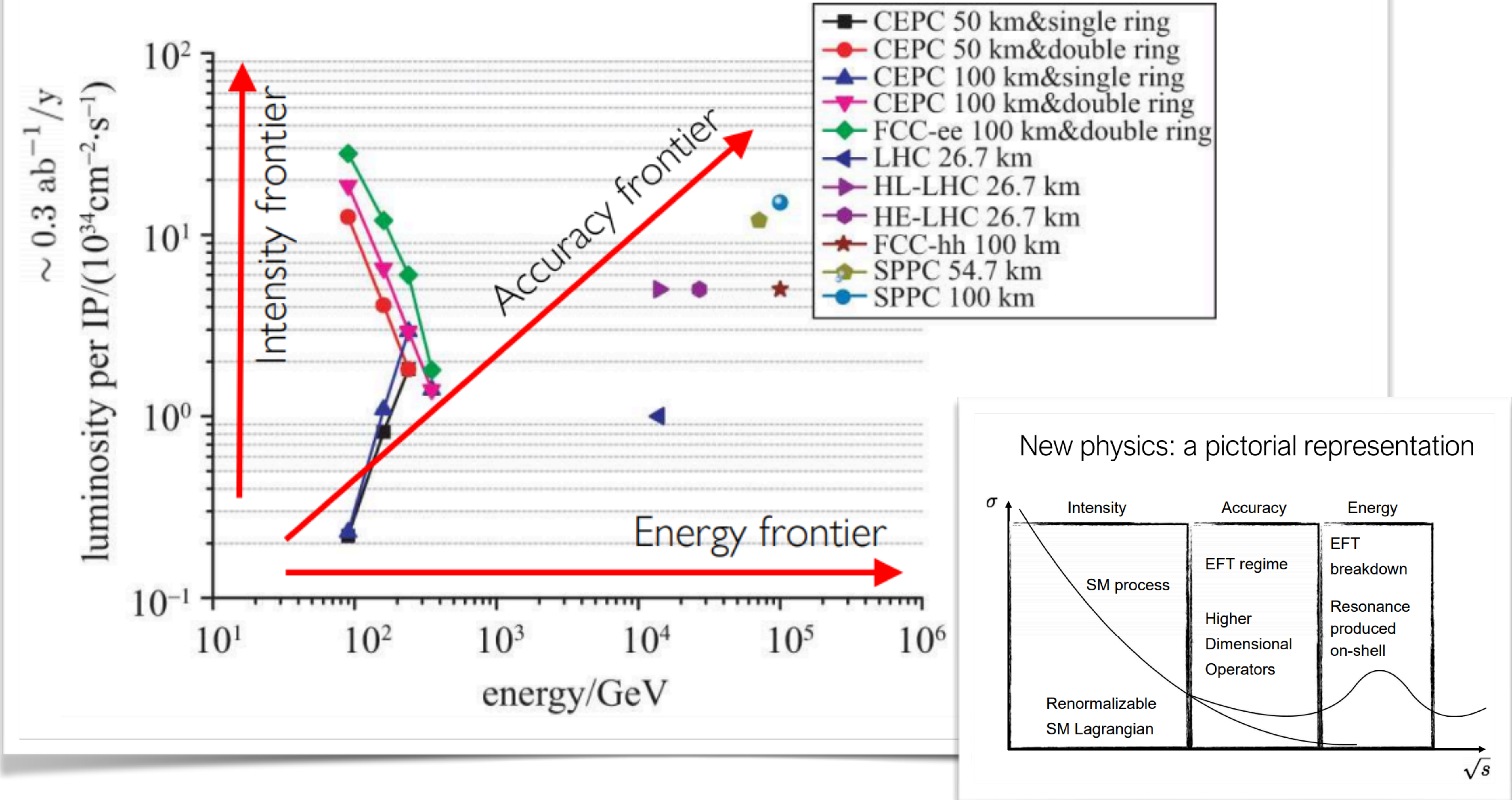


Peskin @ ICFA2017

Higgs sector is new, and weird…. we must do our best to measure all the properties in the best way we can

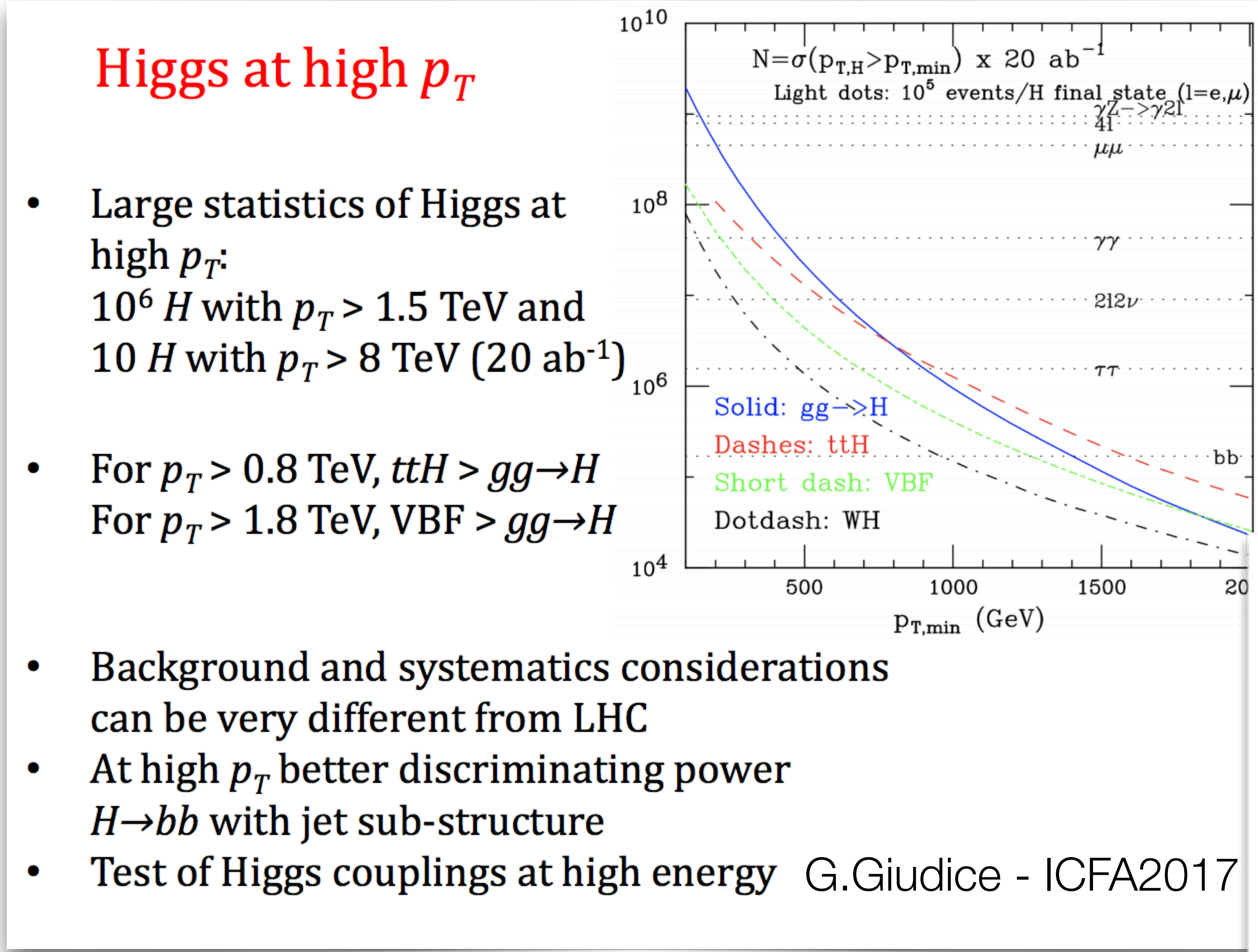
Energy, intensity, and accuracy frontiers

R. Torre HL/HE LHC workshop



New physics: a pictorial representation

High p_T Higgs

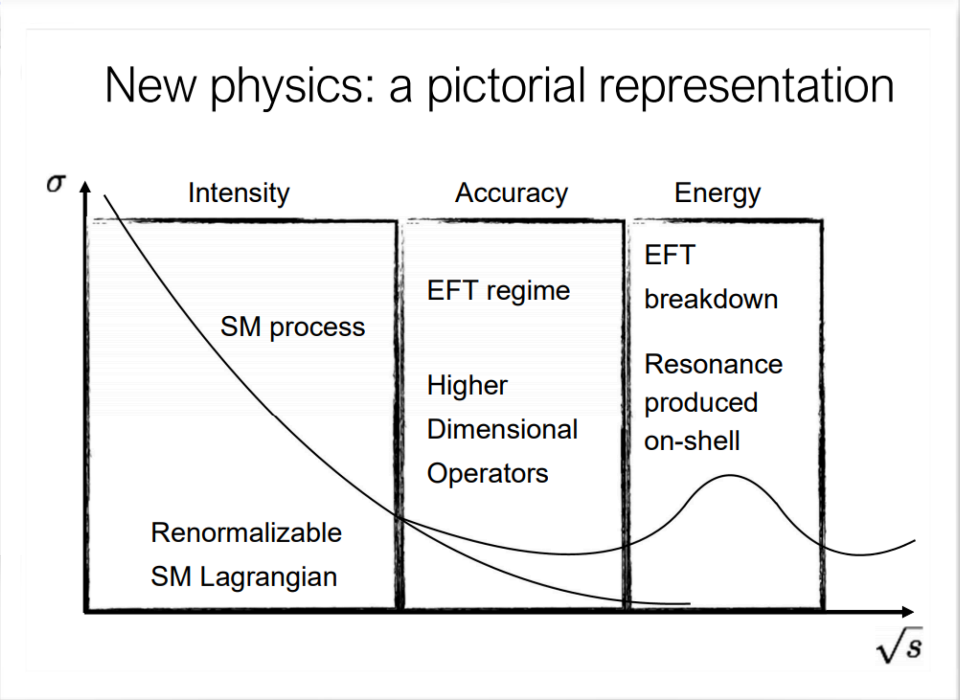


Higgs at high p_T

- Large statistics of Higgs at high p_T:
  10^6 H with $p_T > 1.5$ TeV and
  10 H with $p_T > 8$ TeV (20 ab^{-1})
- For $p_T > 0.8$ TeV, $ttH > gg \to H$
  For $p_T > 1.8$ TeV, VBF > $gg \to H$
- Background and systematics considerations can be very different from LHC
- At high p_T better discriminating power $H \to bb$ with jet sub-structure
- Test of Higgs couplings at high energy

G.Giudice - ICFA2017

10% precision at E = TeV probes New Physics as much 0.1% precision in Higgs decays



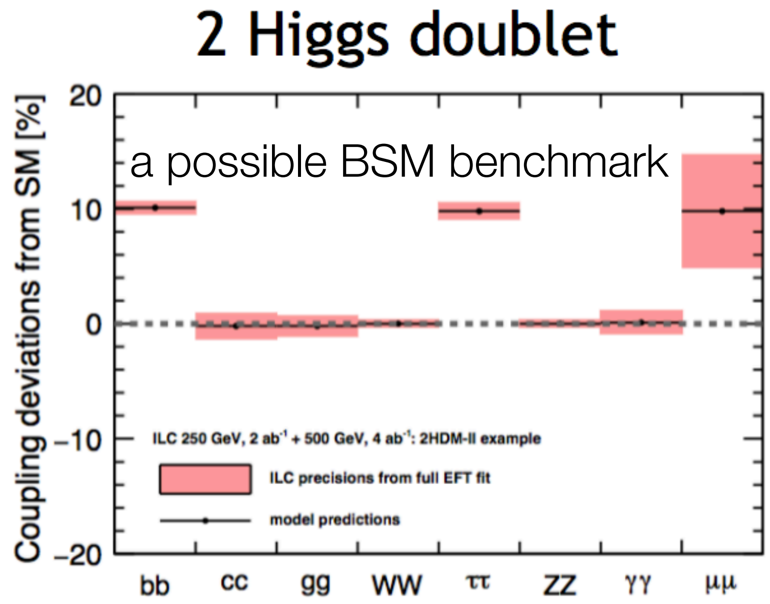
New physics: a pictorial representation

Higgs couplings

- LHC coupling measurements at the order of 10-20%
- Projections for HL-LHC: O(5%)
    - based on Run1 experience - iper-conservative?
- e^+e^- colliders can provide model independent measurements for the Higgs couplings O(1%)

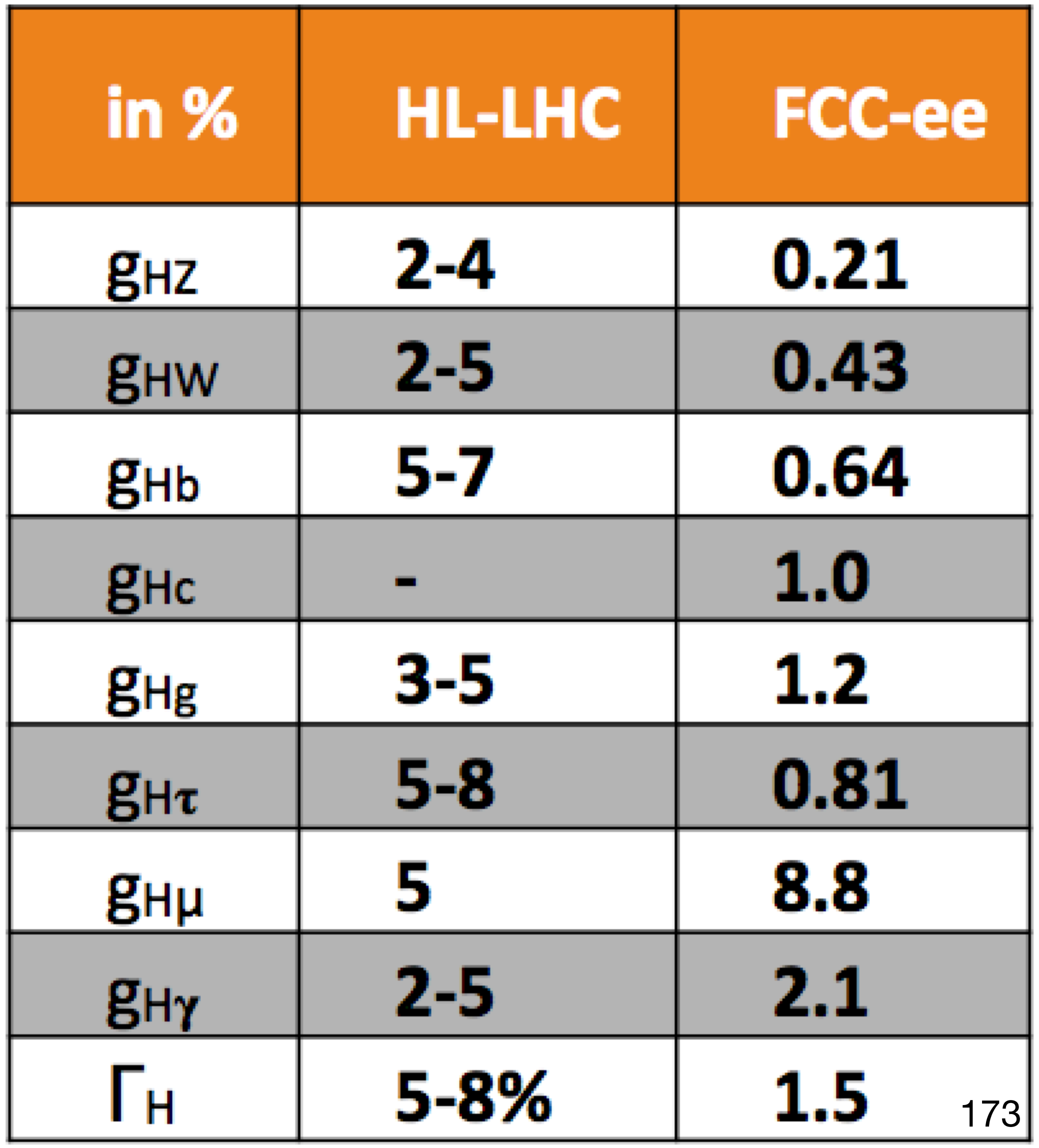
- What can the HL/HE-LHC program say about coupling with first and second generation?
    - If SM, Hμμ can be observed in HL-LHC
    - Which options for Hcc at LHC? Direct searches? Wh asymmetries?
- and self-coupling?

Peskin @ ICFA2017



(HL- LHC measurements are model dependent)

Tenchini @ FCC week 2017



in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.0
g_{Hg}	3-5	1.2
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.8
$g_{H\gamma}$	2-5	2.1
Γ_H	5-8%	1.5

up/down-type fermion and lepton/quark asymmetries

Asymmetries in Higgs couplings

- between up-type and down-type fermion
- between lepton and quark

predicted by several BSM physics models

Parameterise model in terms of ratios of coupling strength modifiers

$$\boxed{\lambda_{du} = \kappa_d/\kappa_u}$$

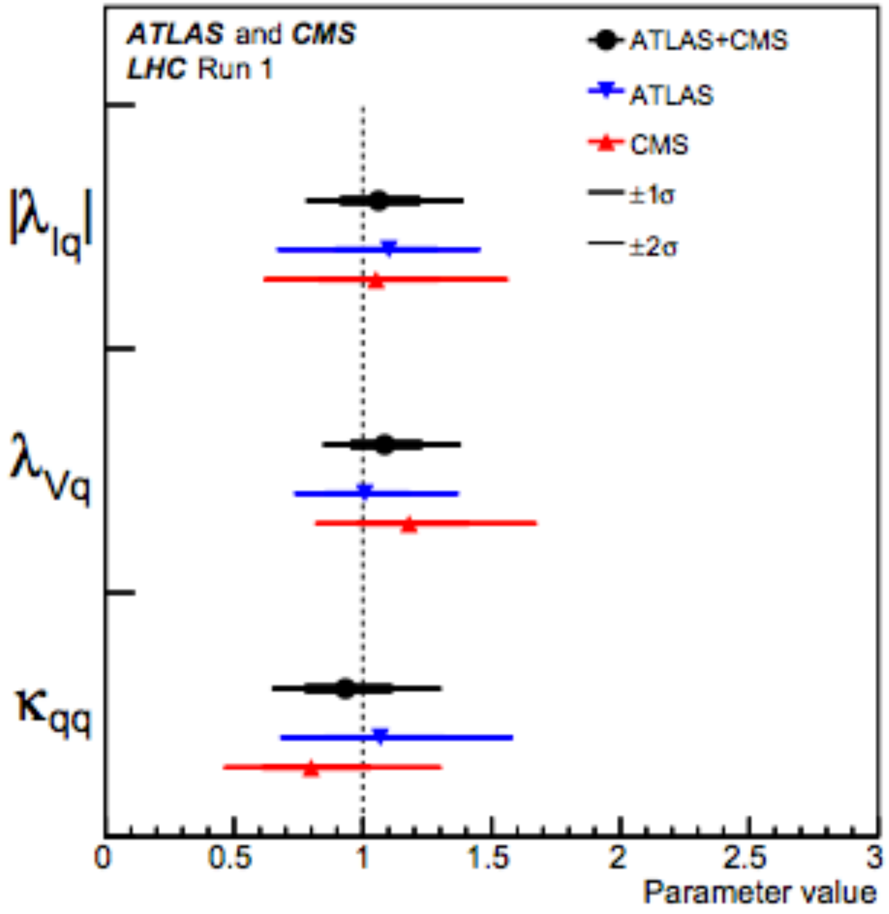
$$\lambda_{Vu} = \kappa_V/\kappa_u$$

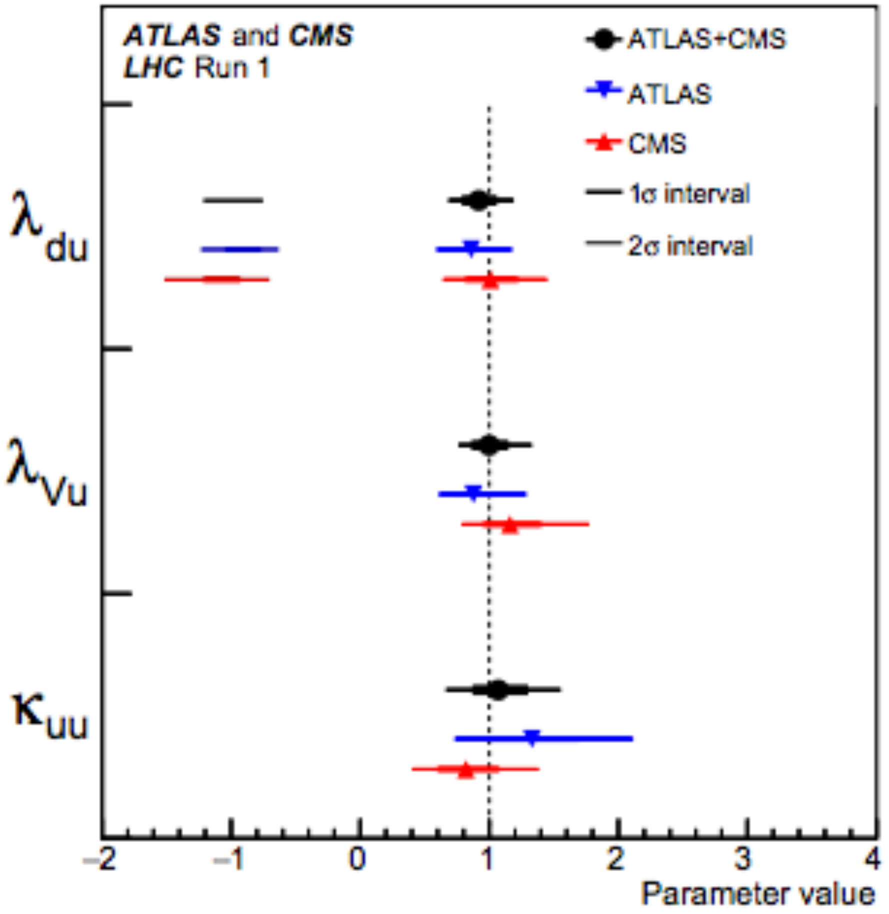
$$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H.$$

$$\boxed{\lambda_{\ell q} = \kappa_\ell/\kappa_q}$$

$$\lambda_{Vq} = \kappa_V/\kappa_q$$

$$\kappa_{qq} = \kappa_q \cdot \kappa_q/\kappa_H$$

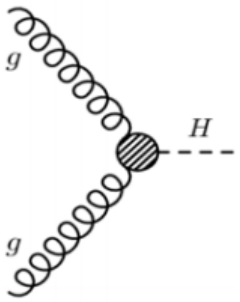


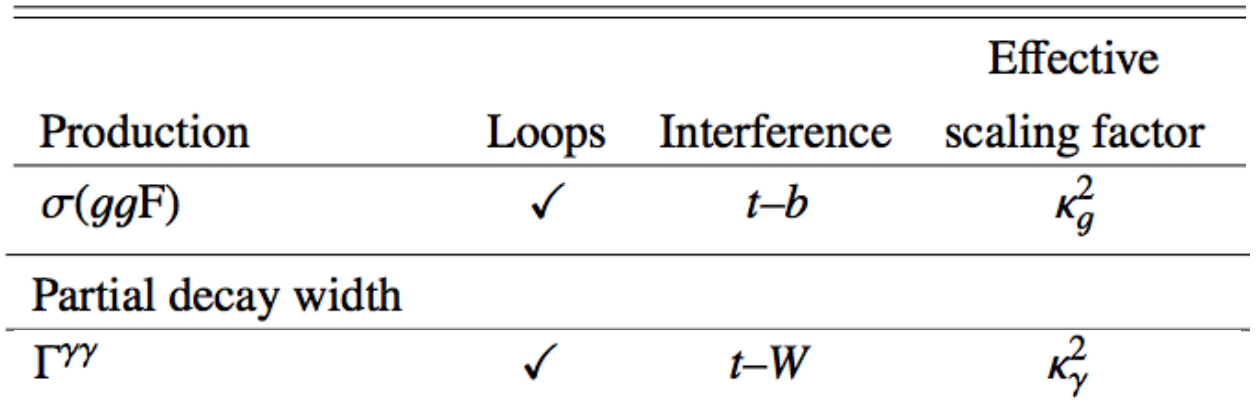


Effective couplings and BSM BR

- What if we have new particles in the loops?

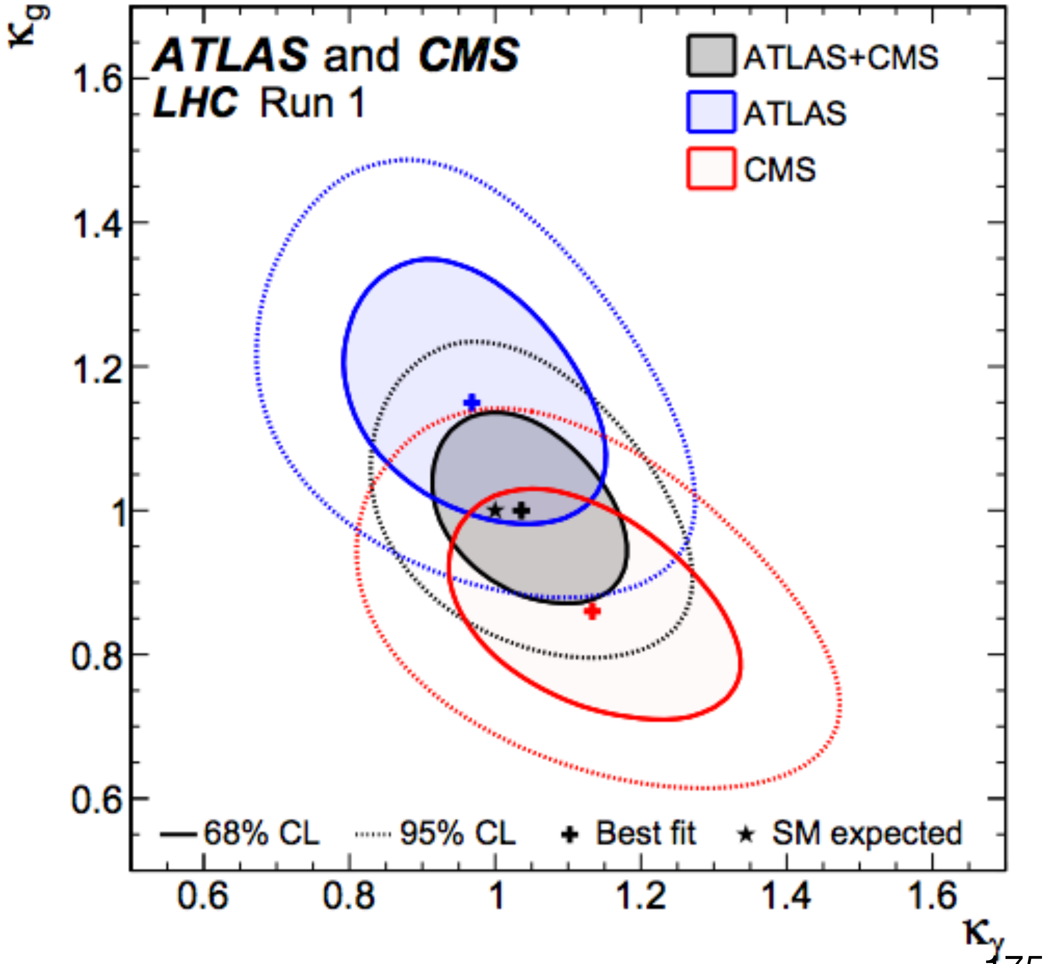
- Specific fit not resolving the loops, but use effective couplings κg and κγ





Production	Loops	Interference	Effective scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2
Partial decay width			
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2

- Fix all tree-level Higgs couplings to SM ($\kappa_W,\kappa_Z,\kappa_b,\kappa_t,\kappa_\mu,\kappa_\tau=1$) and $B_{BSM}=0$



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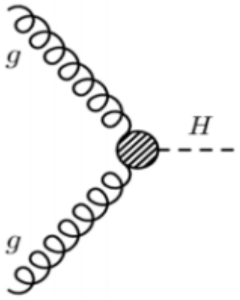

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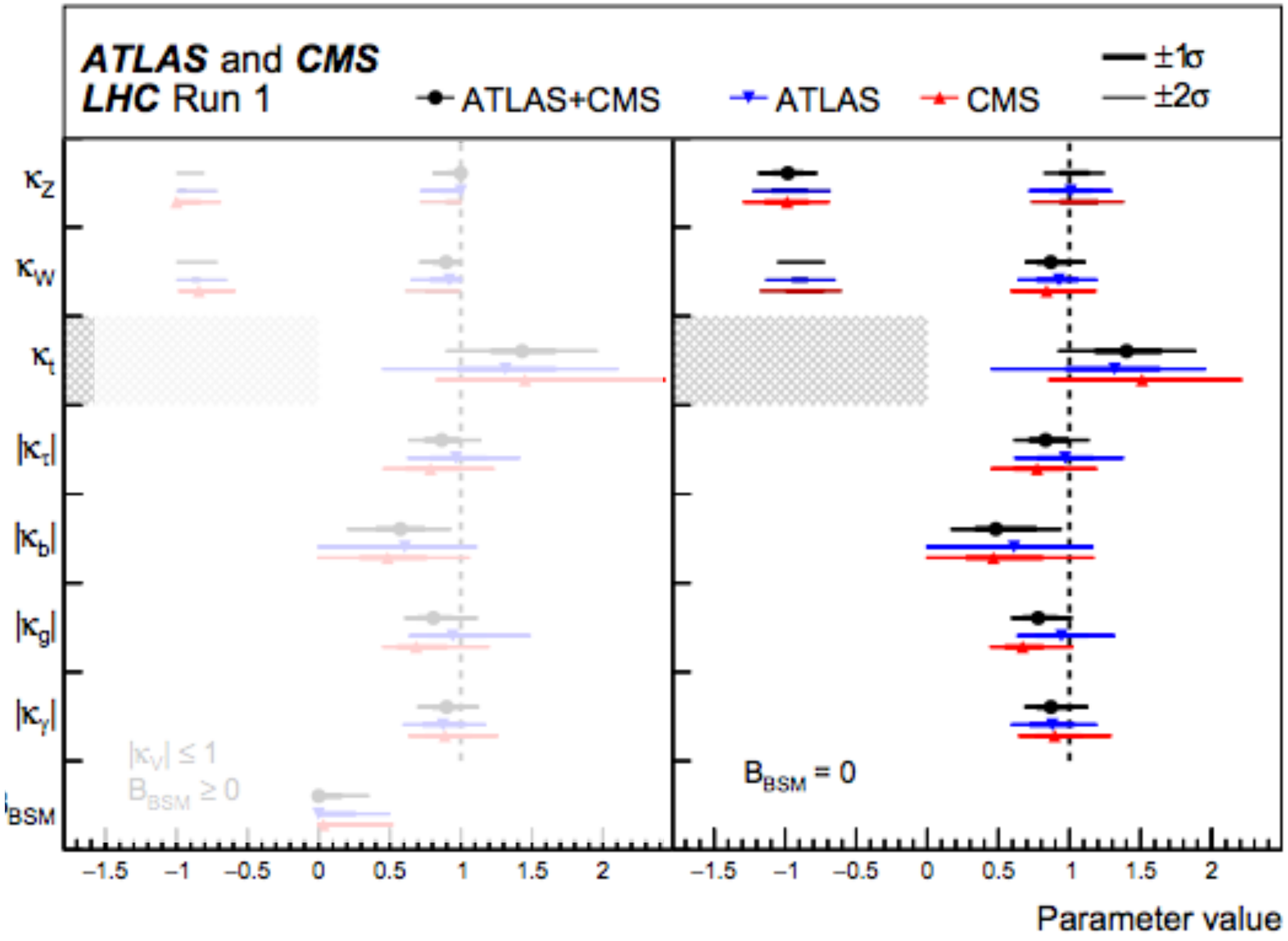


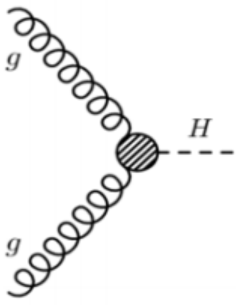
Effective couplings and BSM BR

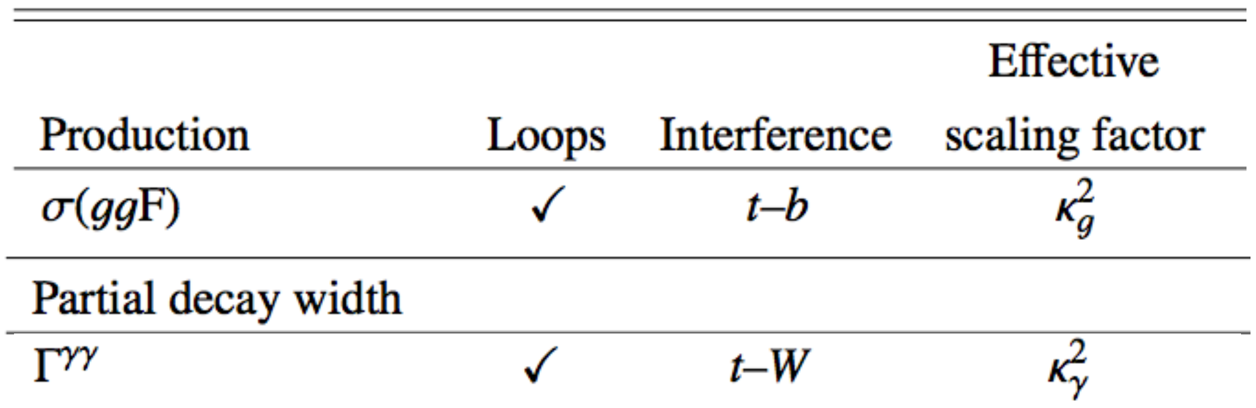
- What if we have new particles in the loops?

- Specific fit not resolving the loops, but use effective couplings κg and κγ

- And if the Higgs boson decays in some other mode we did not detect yet?

  - Constrain $B_{BSM} \geq 0$ and $|\kappa_V| \leq 1$





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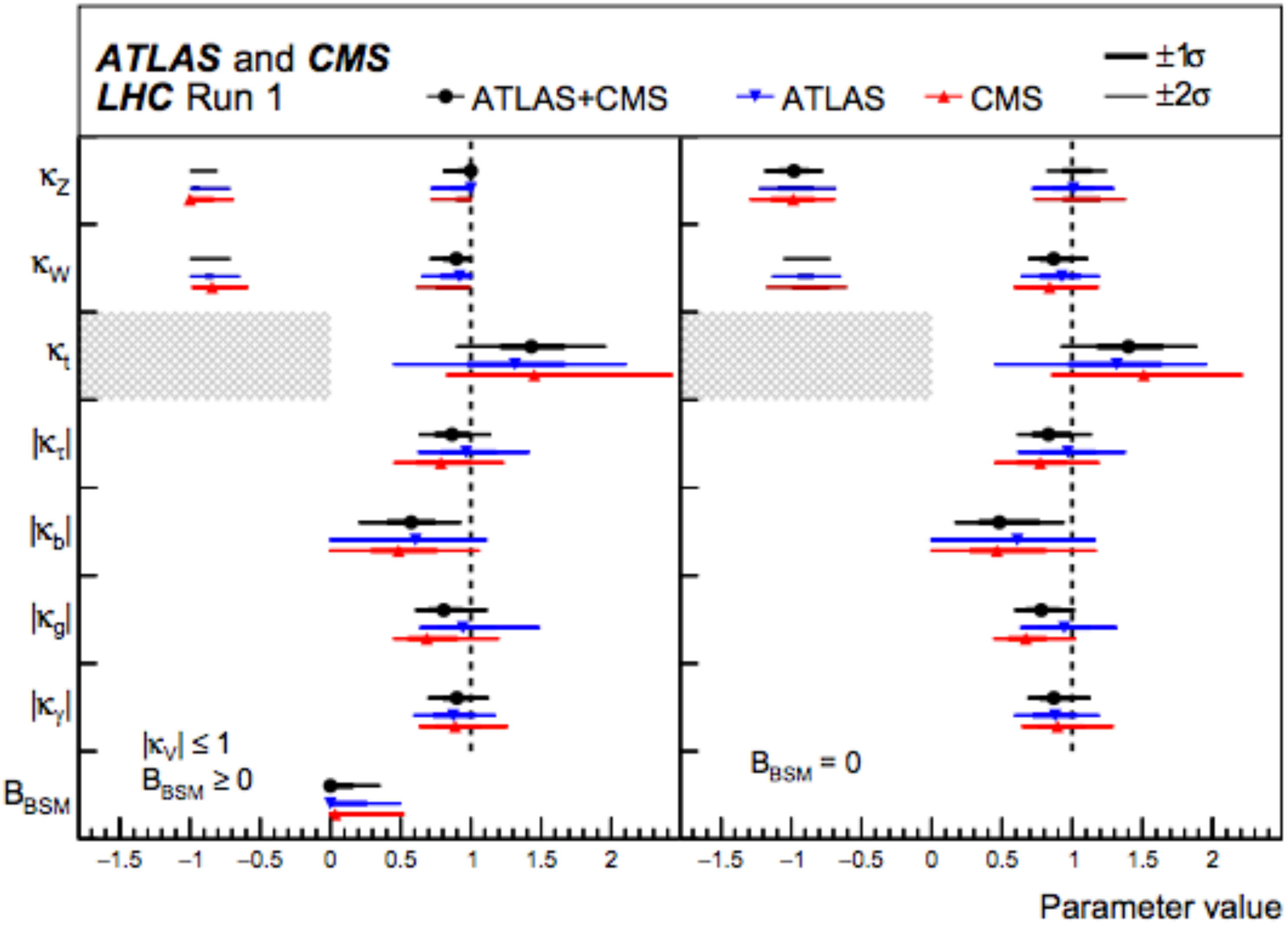
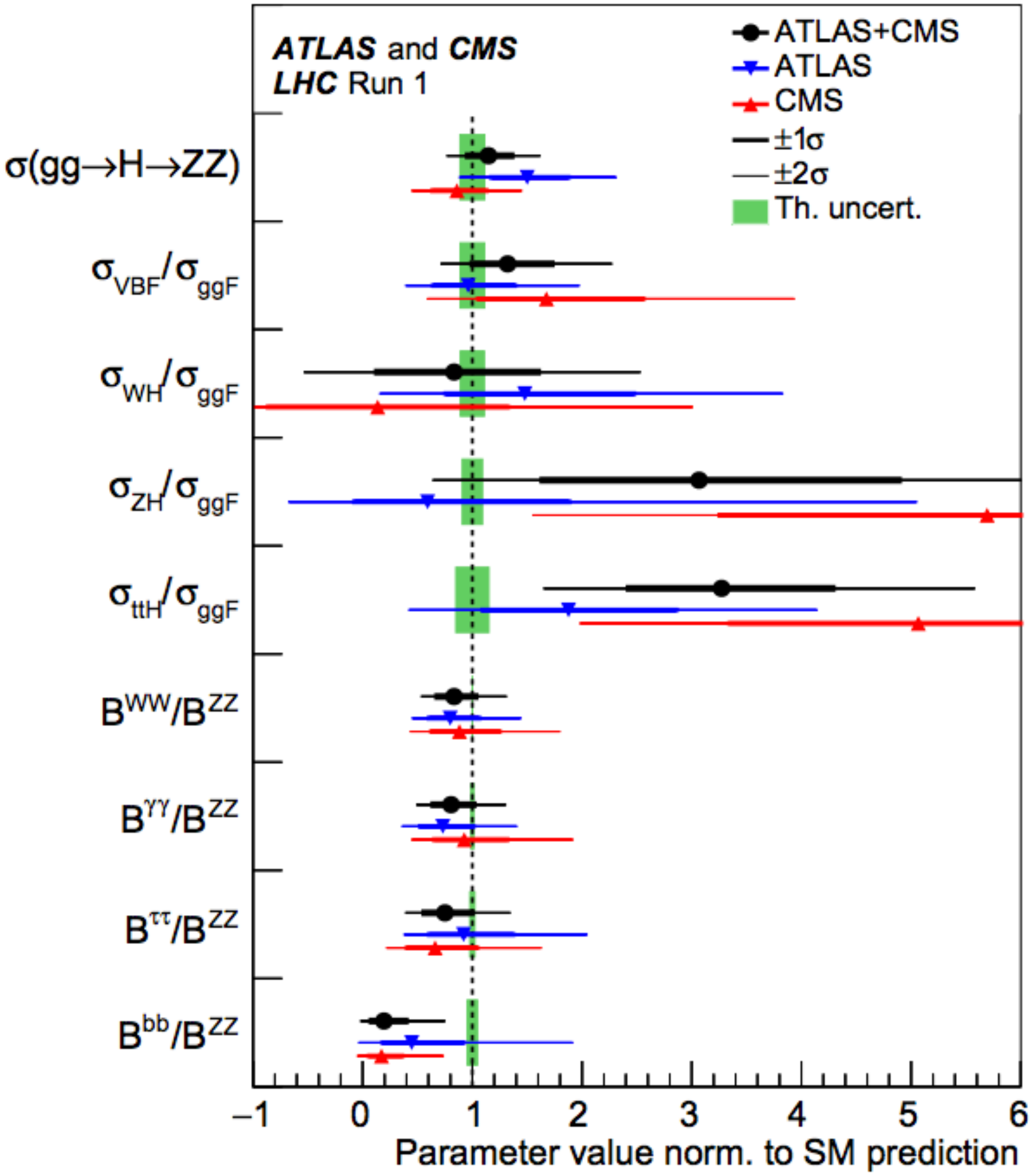


Ratios of production Cross Sections and BR

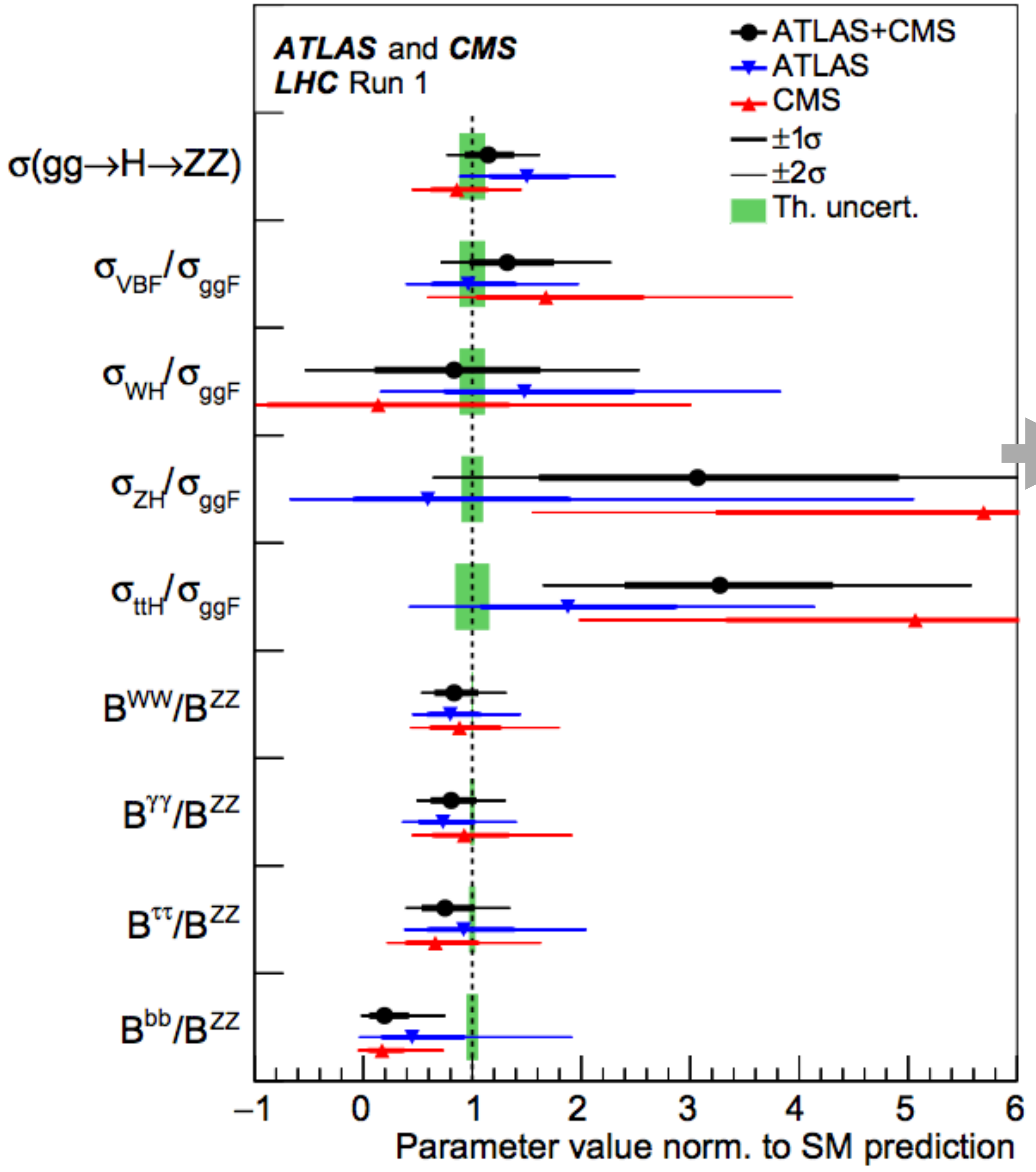


- Measuring ratios of production cross sections and BR

$$\sigma_i \cdot \mathrm{B}^f = \sigma(gg \to H \to ZZ) \cdot \left(\frac{\sigma_i}{\sigma_{gg\mathrm{F}}}\right) \cdot \left(\frac{\mathrm{B}^f}{\mathrm{B}^{ZZ}}\right)$$

- No additional SM assumption on these measurements
- p-value(SM) = 16% (~1σ)

Ratios of production Cross Sections and BR



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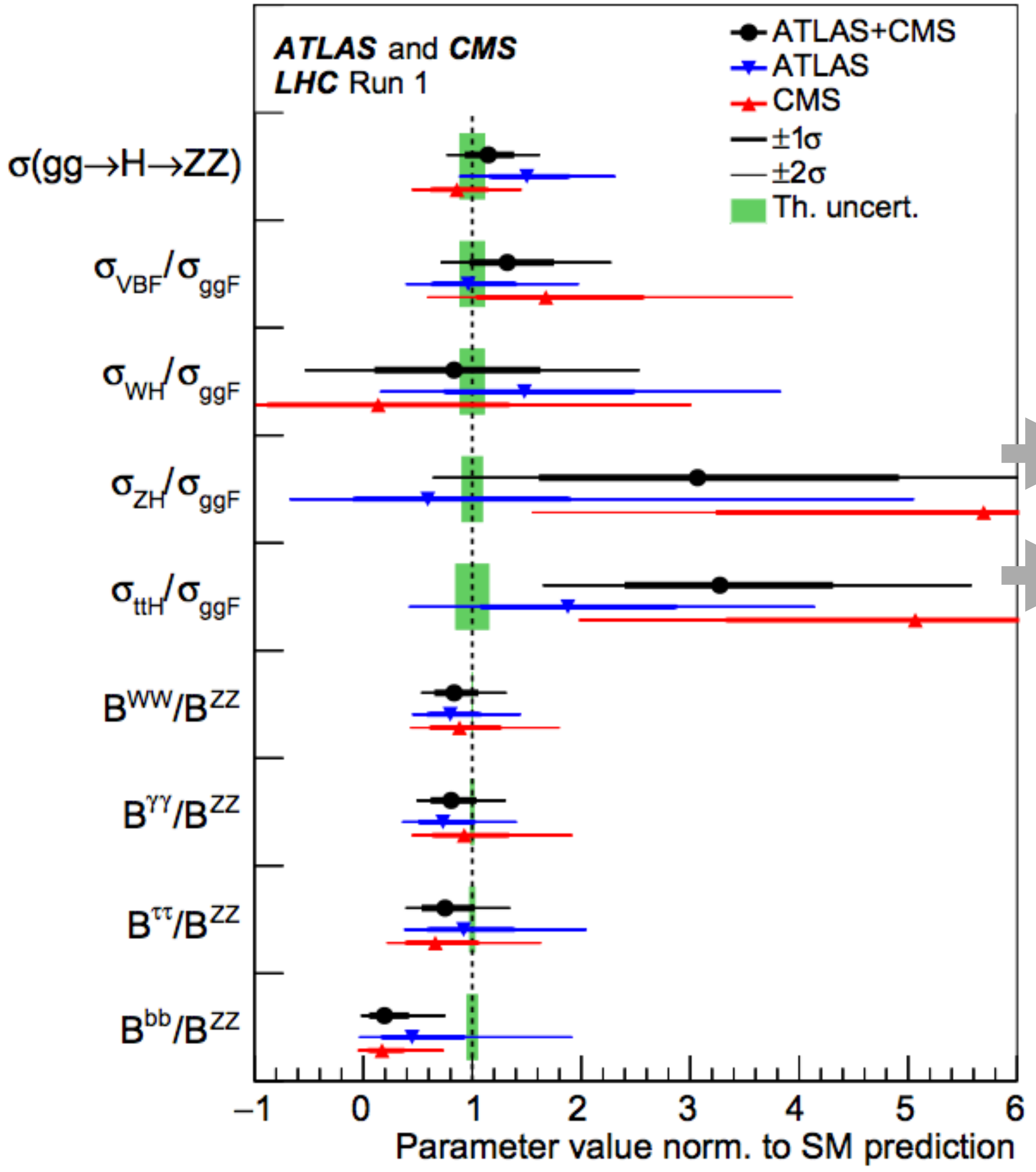

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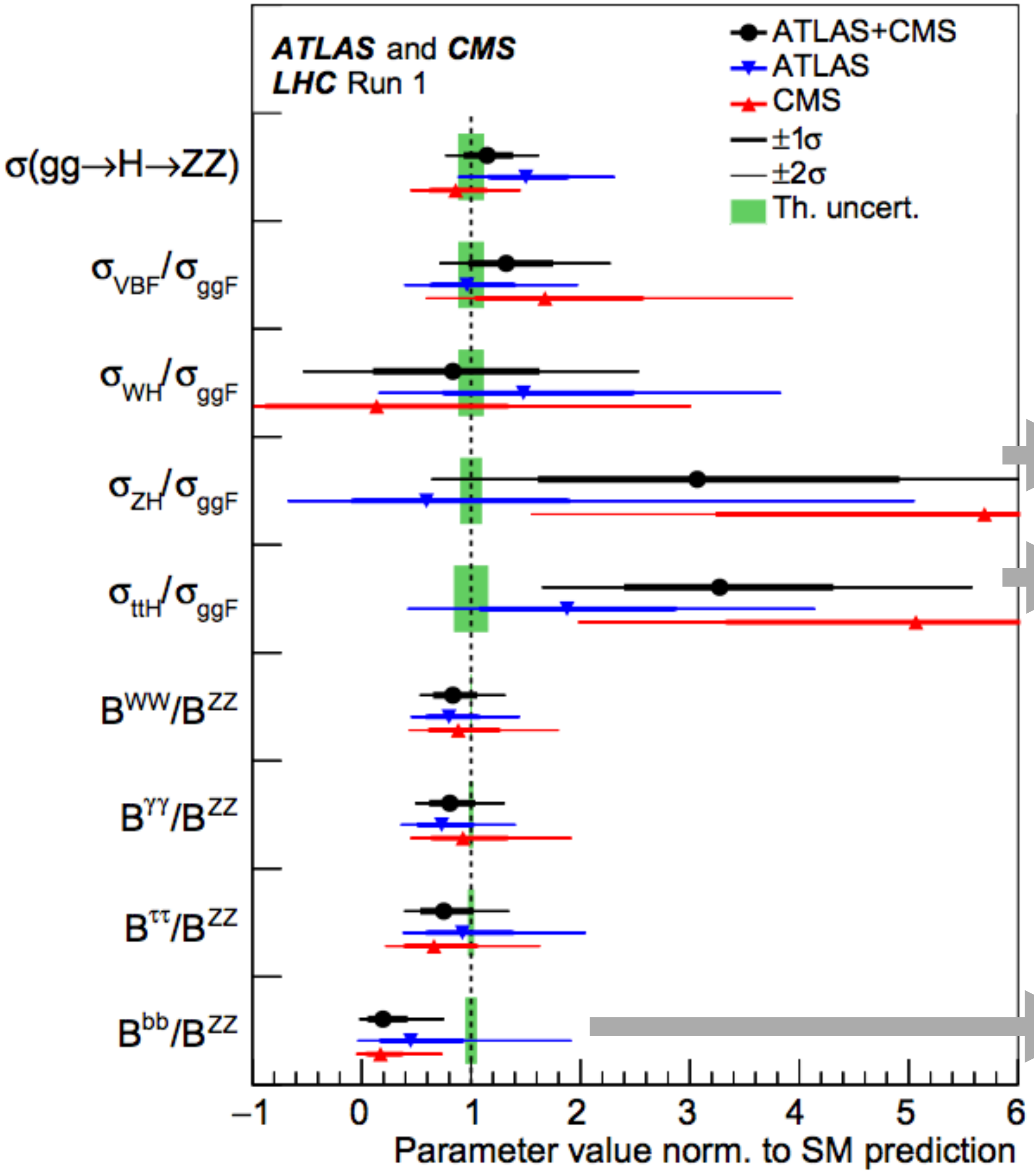

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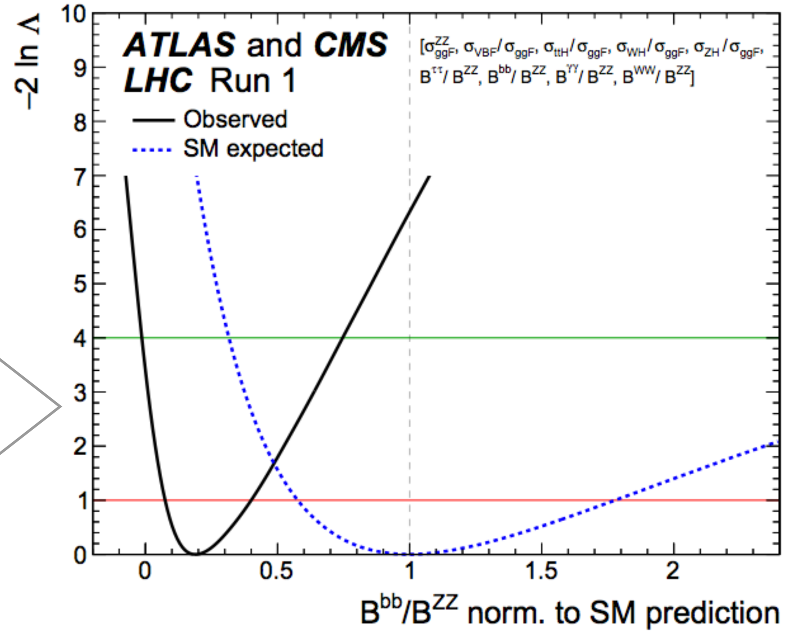
High ZH, H → WW ,
High ttH, H → multi lept
Low ZH, H → bb
contribute to…

- B^{bb}/B^{ZZ}:
  deficit ~ 2.5σ
  with respect to SM



Signal strengths at the end of Run1

- Measurements of signal strengths μ for each production mode and for each decay mode by fixing the relative B^f or the σ_i to the SM prediction.

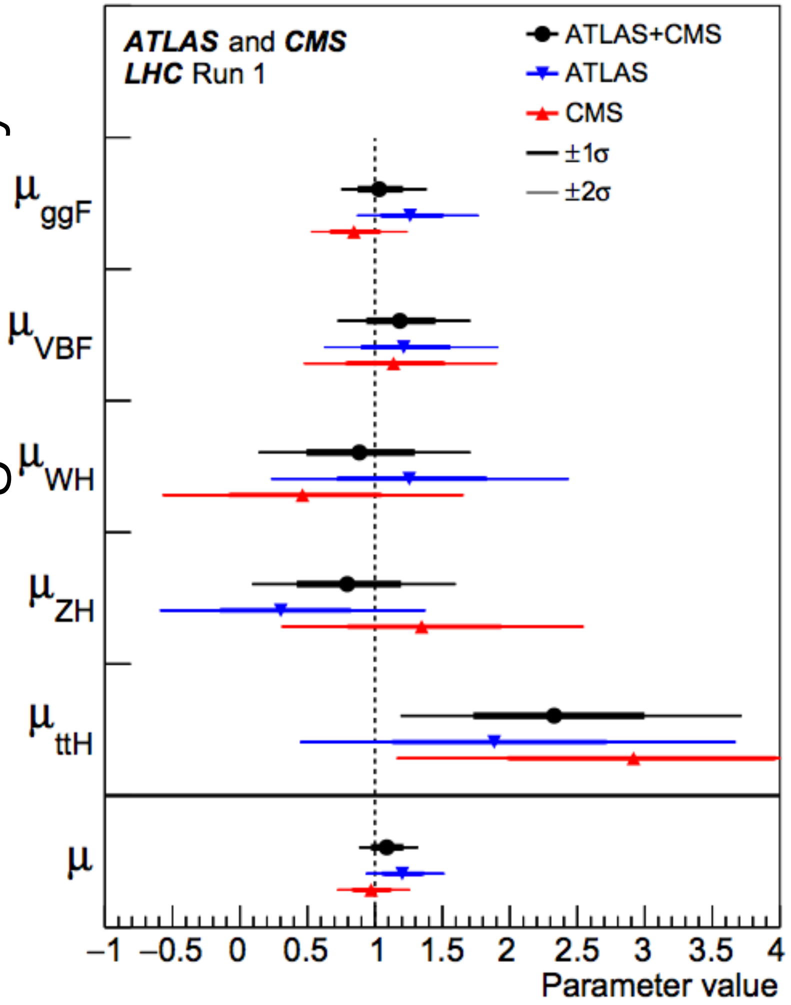
$$n_{\text{signal}}(k) = \mathcal{L}(k) \cdot \sum_i \sum_f \mu_i \mu^f \left\{\sigma_i^{\text{SM}} \cdot A_i^{f,\text{SM}}(k) \cdot \varepsilon_i^f(k) \cdot \text{B}^f_{\text{SM}}\right\}$$

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

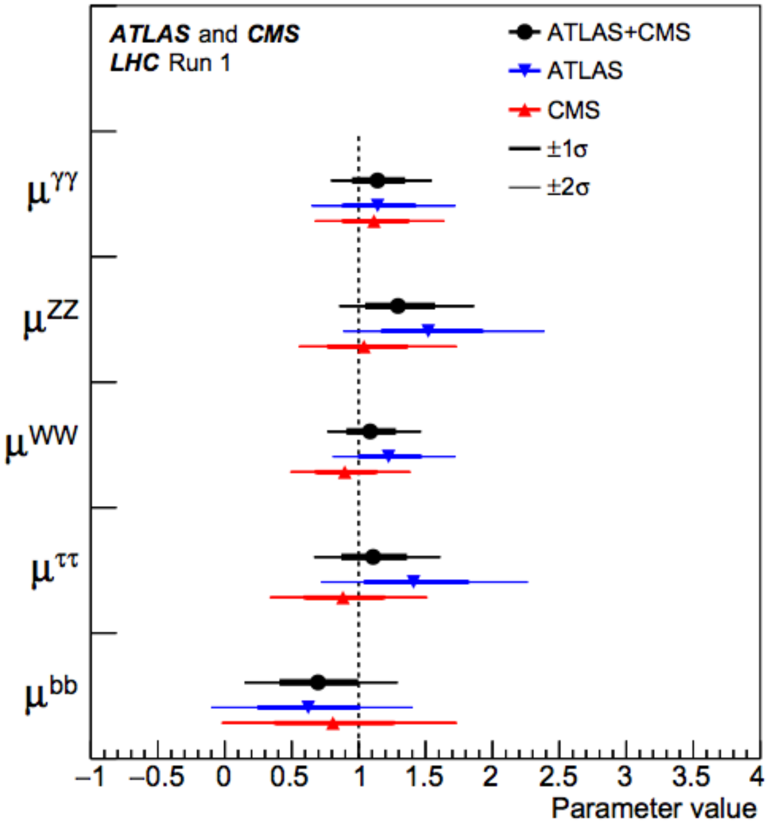
- By fixing all the B^f and σ_i to the SM prediction, and allowing for only one global signal strength, one gets:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

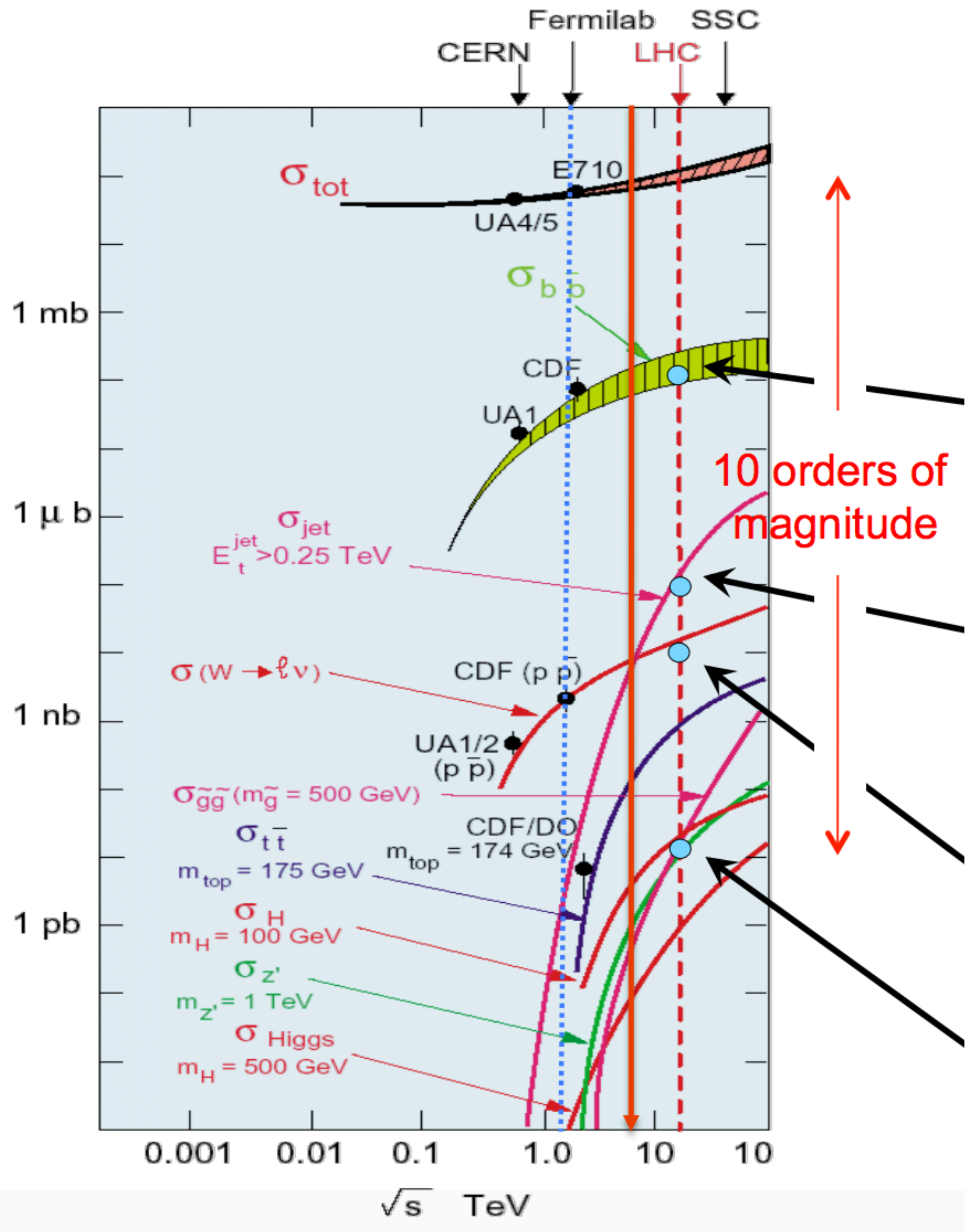
Assuming SM Decay BR



Assuming SM Production XS



Physics backgrounds at hadron colliders



LHC experiments need to be able to select every second the O(200) most interesting events out of 10^9 collisions that took place

jets

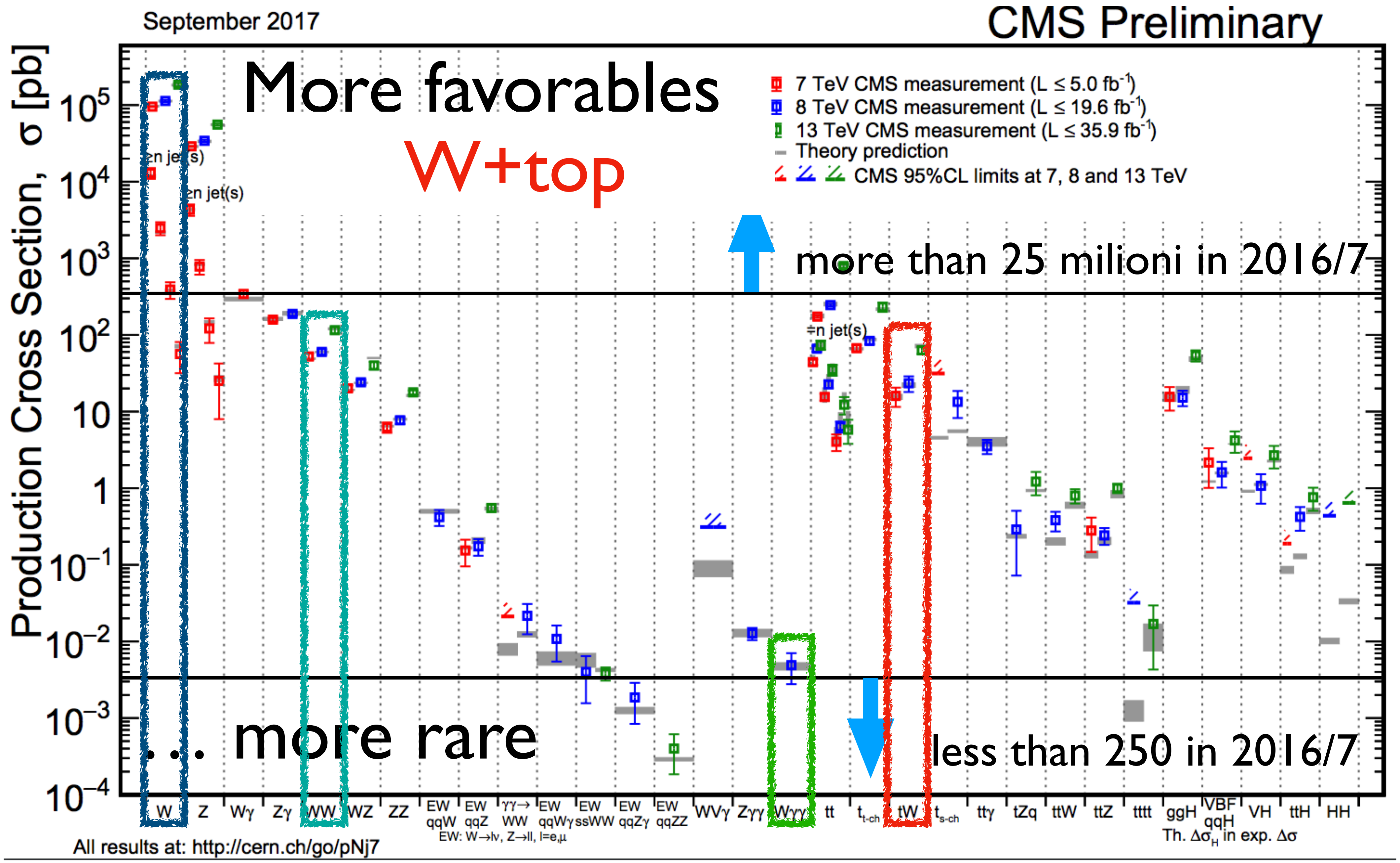
high-p_T jets

W production

H production

Verifying the SM,
Preparing the ground for a discovery

~ Production Probability



More favorables

W+top

more than 25 milioni in 2016/7

… more rare

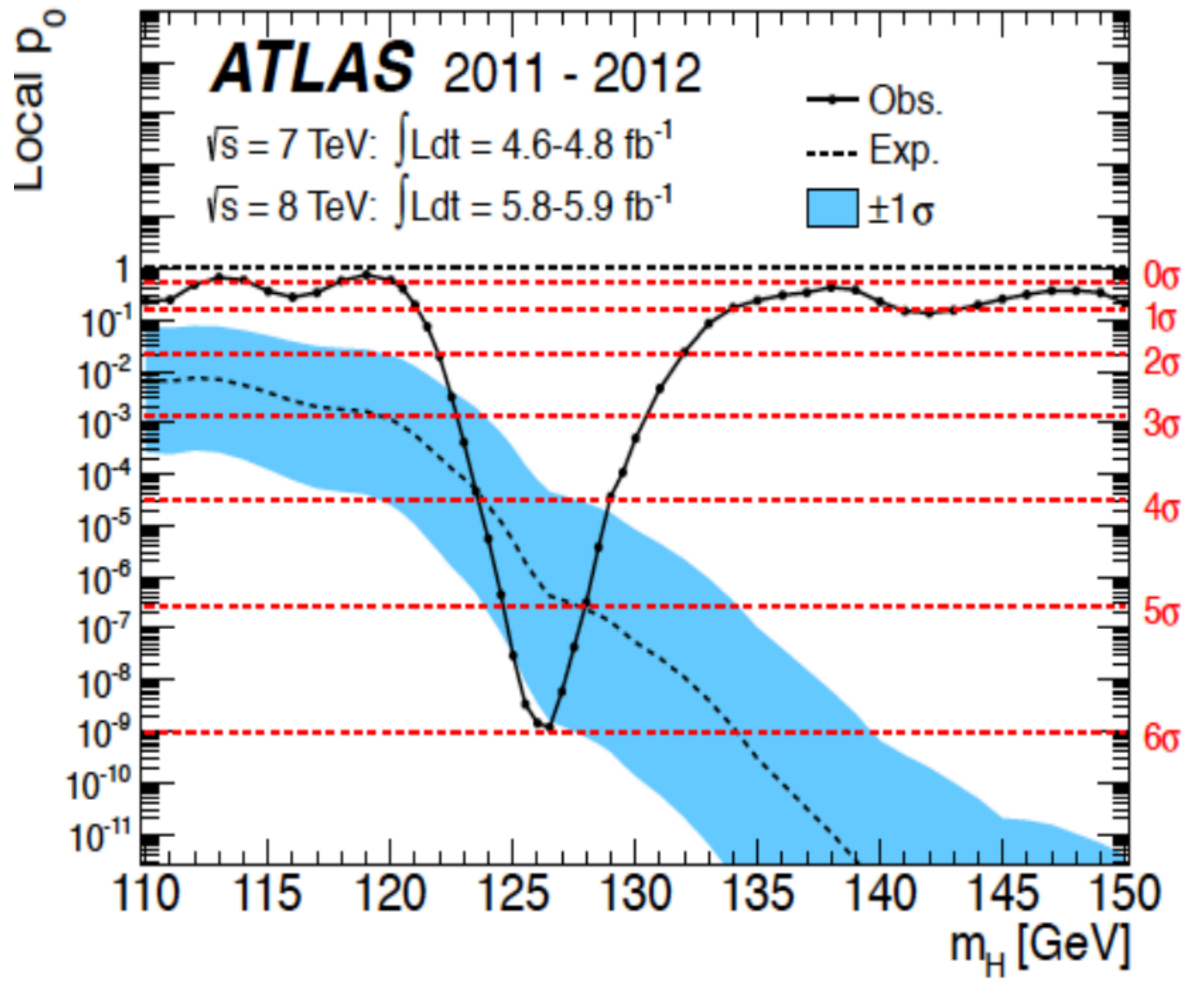
less than 250 in 2016/7

Combination of the results

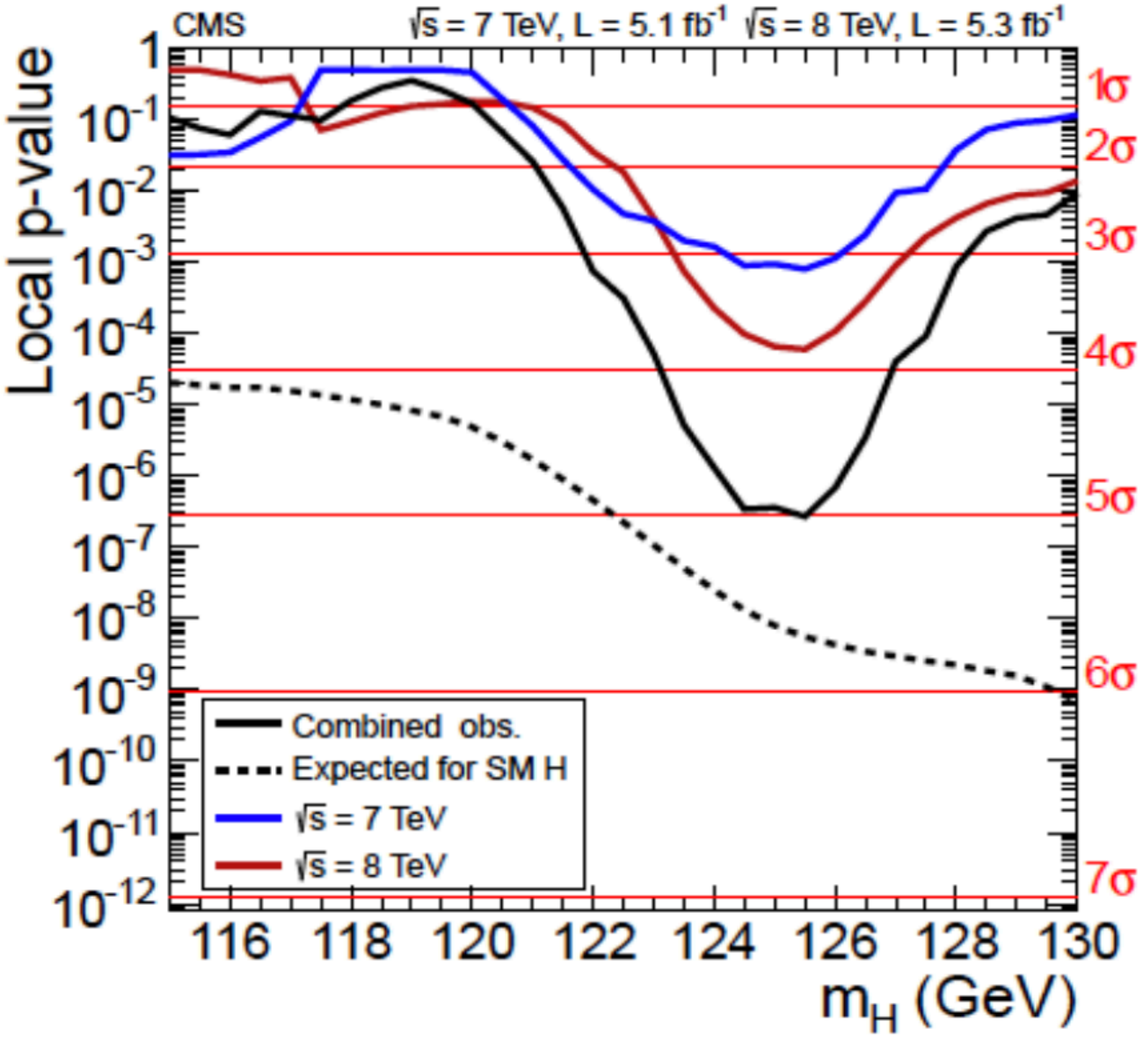
- p_0: probability that the data could come from a model with no Higgs boson.
- Very high standards:

  Evidence benchmark ➔ $p_0 = 0.00135$ (3 Gaussian standard deviations)

  Discovery benchmark ➔ $p_0 = 2.6 \times 10^{-7}$ (5 Gaussian standard deviations)



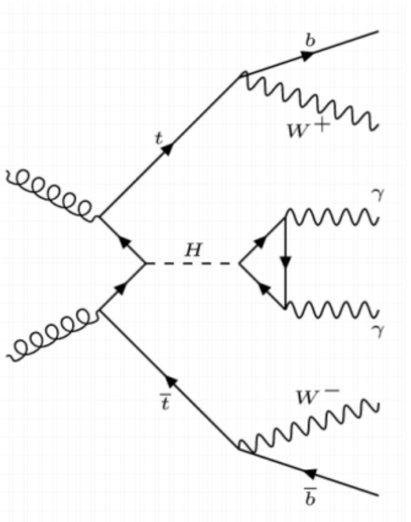
5.9 s.d. at m_H=126.5 GeV



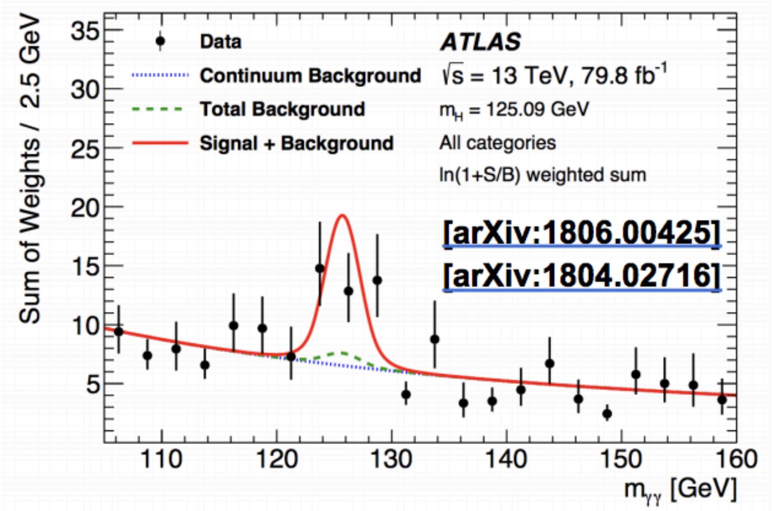
5.0 s.d. at m_H=125.5 GeV

(The analysis of more data since July 4, 2012 has further strengthened the significance)

The Big news (1): Top -Higgs interaction

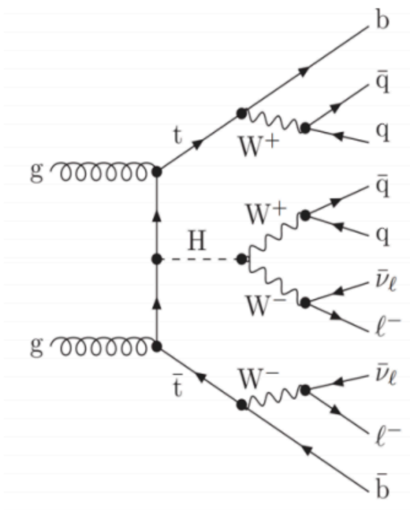


$$H \to ZZ^* \to 4\ell$$
$$H \to \gamma\gamma$$



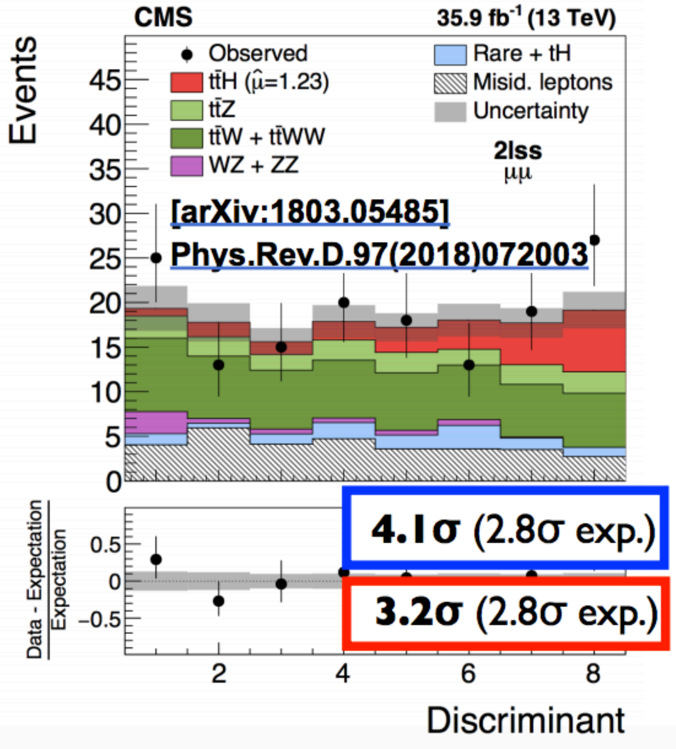
ATLAS 4.1σ (3.7σ exp.) (80fb^{-1})

CMS 1.4σ (1.5σ exp.)



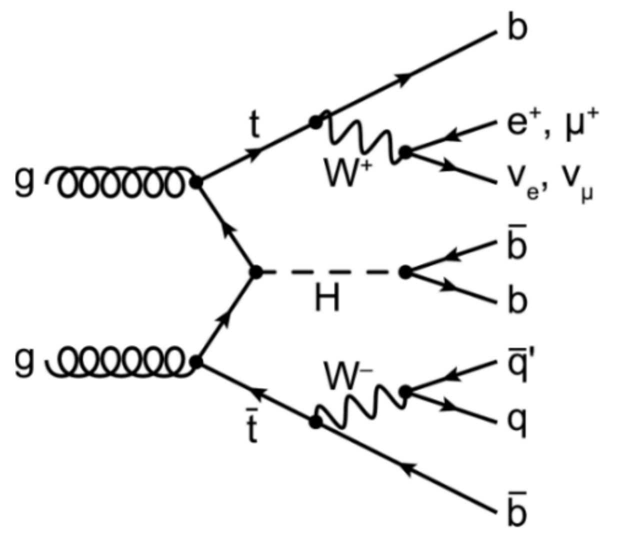
$$H \to WW^* \to \ell\nu\ell\nu$$
$$H \to \tau\tau$$

(multi-leptons)



4.1σ (2.8σ exp.)

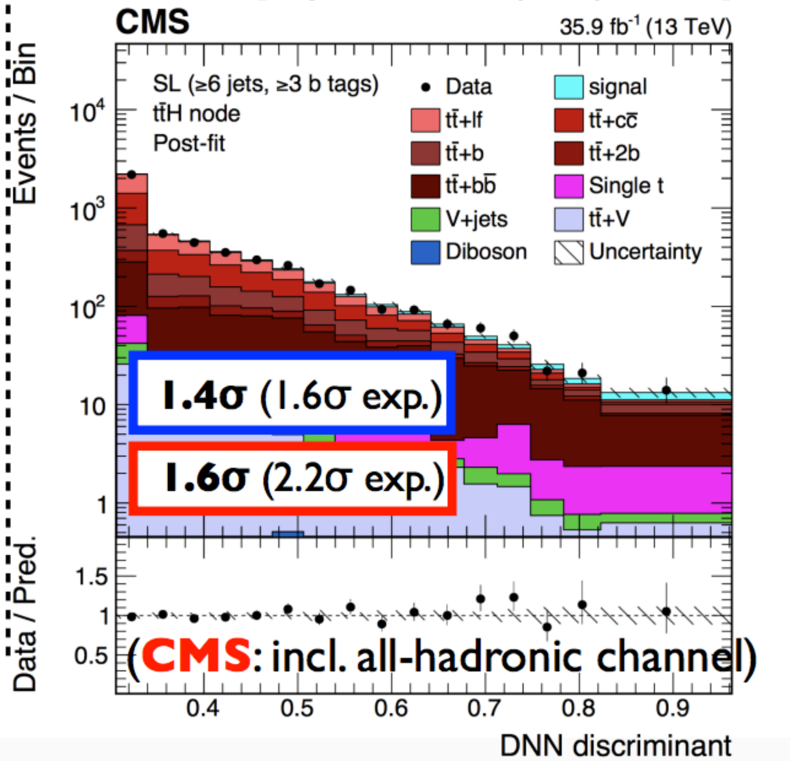
3.2σ (2.8σ exp.)



$$H \to b\bar b$$

[arXiv:1804.03682]

[Phys. Rev. D 97 (2018) 072016]



1.4σ (1.6σ exp.)

1.6σ (2.2σ exp.)

(**CMS**: incl. all-hadronic channel)

Object Resolution