Higgs Phenomenology

or: How I Learned to Stop Worrying and Love the Higgs Boson

Li Lin Yang
Peking University

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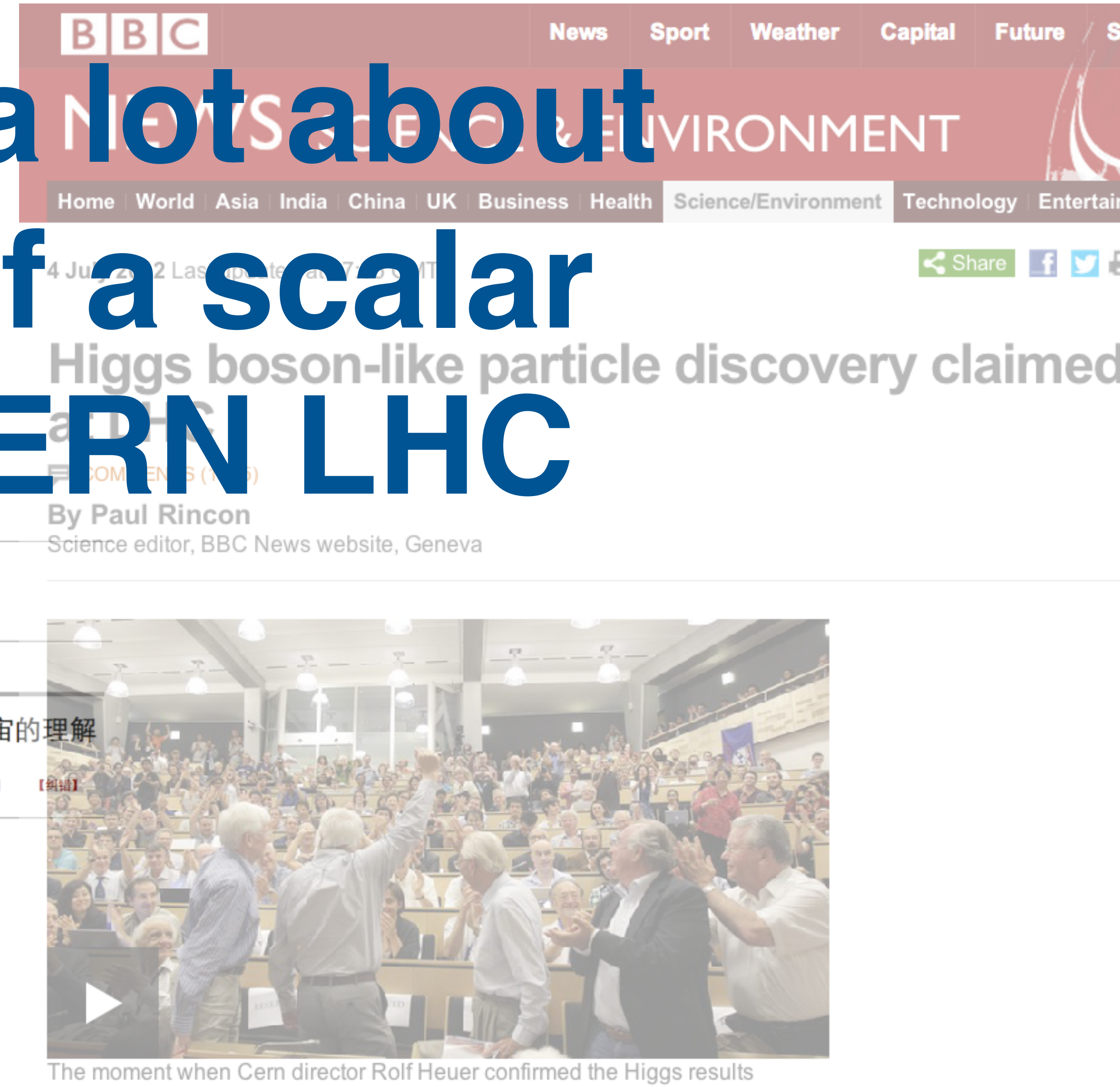
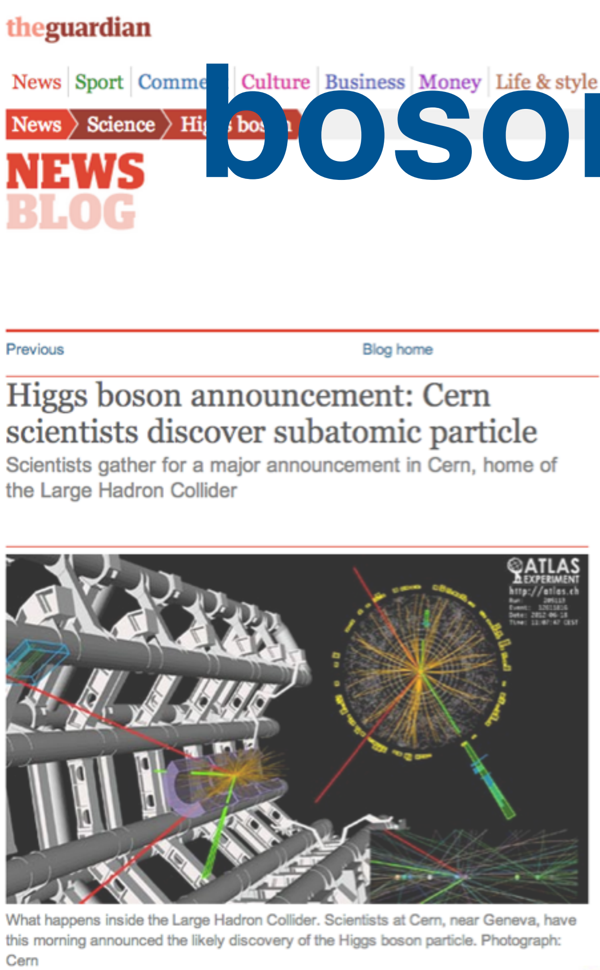
We've all heard a lot about the discovery of a scalar boson at the CERN LHC





And also:

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
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Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Question: why is the Higgs boson so important?

One of many answers in the market: it gives masses to elementary particles (hence the "God Particle")

However, consider the following:

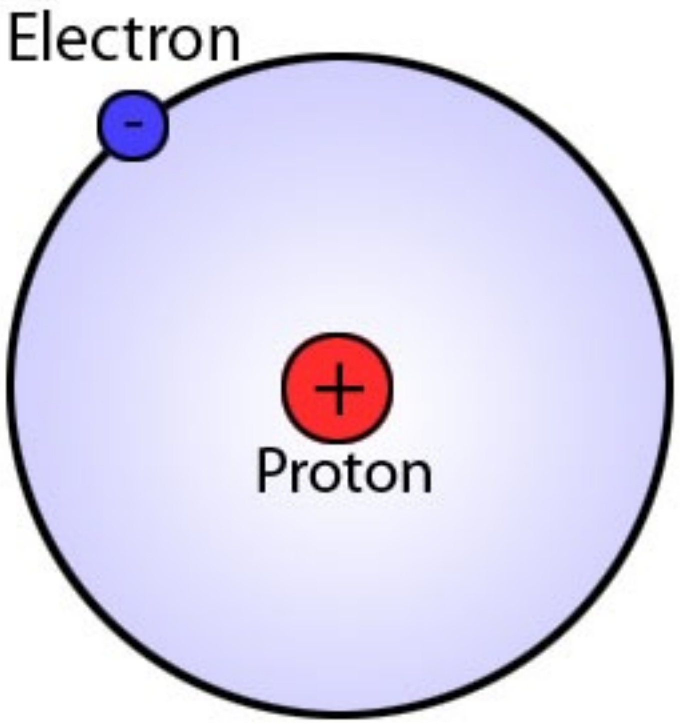
We don't understand where the mass of the dark matter comes from (85% of all matters in our universe)

In the remaining 15% (atoms), almost all masses are generated by strong interactions of quarks and gluons

So why are the masses from the Higgs boson of any particular importance?

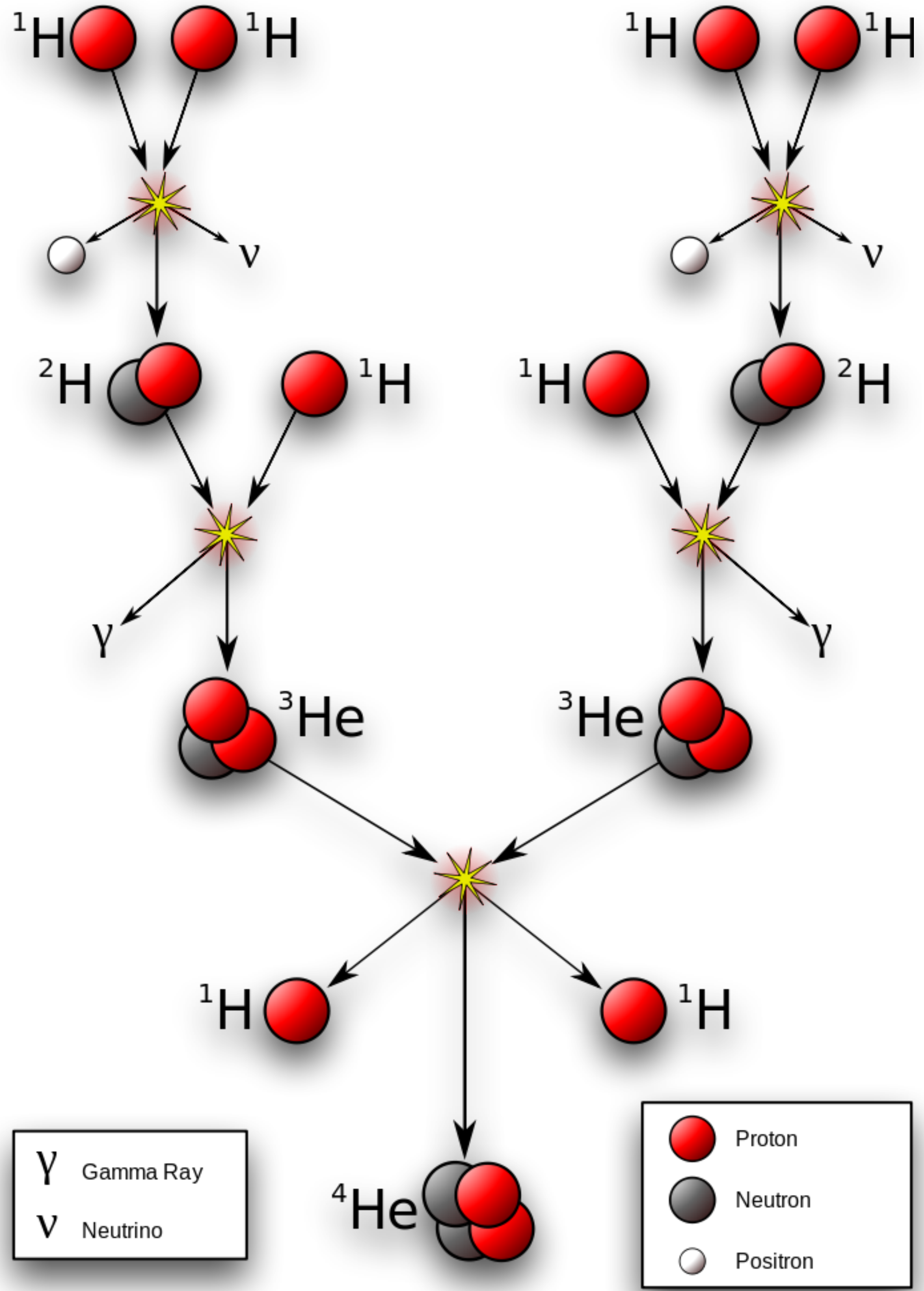
Reason 1

The electron mass, though tiny, ensures the very existence of atoms (and us)

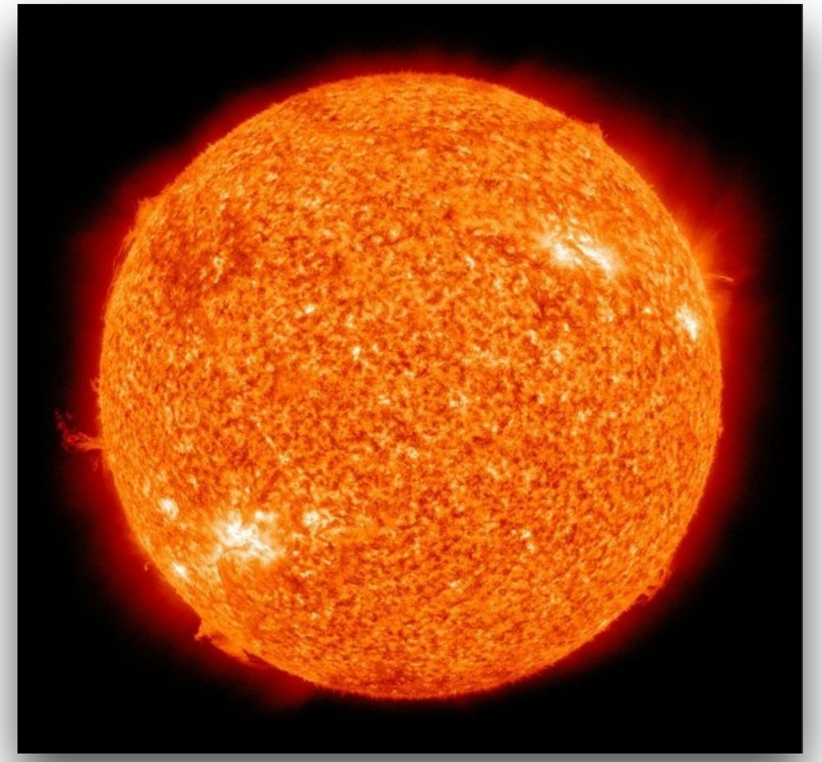


$$\text{Bohr radius} \propto \frac{1}{m_e}$$

If electrons were massless, they couldn't have been trapped within atoms

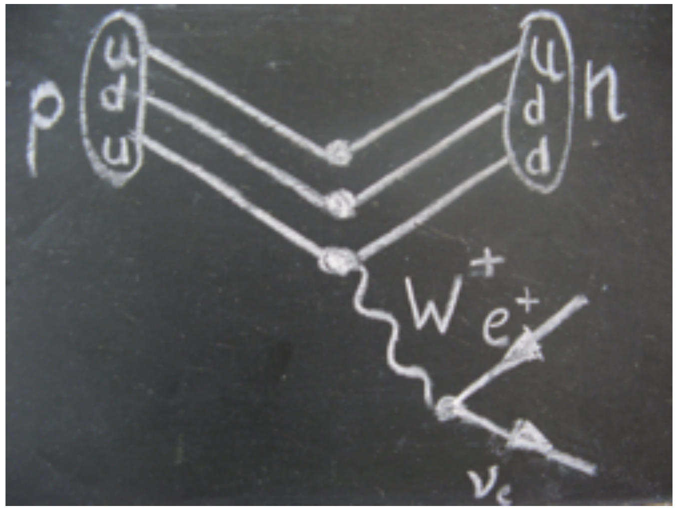


Reason 2



The sun wouldn't be shining now without the mass of the W boson

The speed of the reaction is mainly controlled by the beta-plus decay:



$$^1H + {}^1H \to {}^2H + e^+ + \nu_e$$

$$\text{rate} \propto G_F^2 \propto \frac{g^4}{m_W^4}$$

If the W boson were massless, the reaction could be so fast that the sun would have burnt out long before life could develop on the earth

How does the Higgs boson give masses to the electron and the W boson?

To answer that question, we should ask first: why the electron and the W boson cannot have masses without the Higgs boson?

Because our best model describing the weak interactions of electrons is a chiral gauge theory

The gauge symmetry

You should have heard a lot about it from Prof. Cao and Prof. Si

- A guiding principle to construct the standard model of particle physics

- Guarantees many desired properties of a realistic quantum field theory: unitarity, renormalizability, charge conservation…

- A property that is sometimes desired (for the photon) but sometimes not (for the W and Z bosons): **massless gauge bosons**

Do we need the gauge symmetry?

- Intermediate vector boson theory: massive W boson without gauge symmetry

Yukawa (1935); Schwinger (1957)

- Unitarity violating (probability > 1)
- Nonrenormalizable (infinite results when calculating quantum effects)

We can't give up gauge symmetry!

The chiral fermions

The Nobel Prize in Physics 1957
Chen Ning Yang, Tsung-Dao Lee

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The Nobel Prize in Physics 1957

Chen Ning Yang
Prize share: 1/2

Tsung-Dao (T.D.) Lee
Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

Chien-Shiung Wu Winner of Wolf Prize in Physics - 1978

Wolf Foundation · קרן וולף

THE 1978 WOLF FOUNDATION PRIZE IN PHYSICS

The Wolf Foundation Prize Committee for Physics unanimously chosen as the recipient of the first Wolf Prize in Physics;

Chien-Shiung Wu
Columbia University
New York, N.Y., USA

for her persistent and successful exploration of the weak interaction which helped establish the precise form and the non conservation of parity for this new natural force.

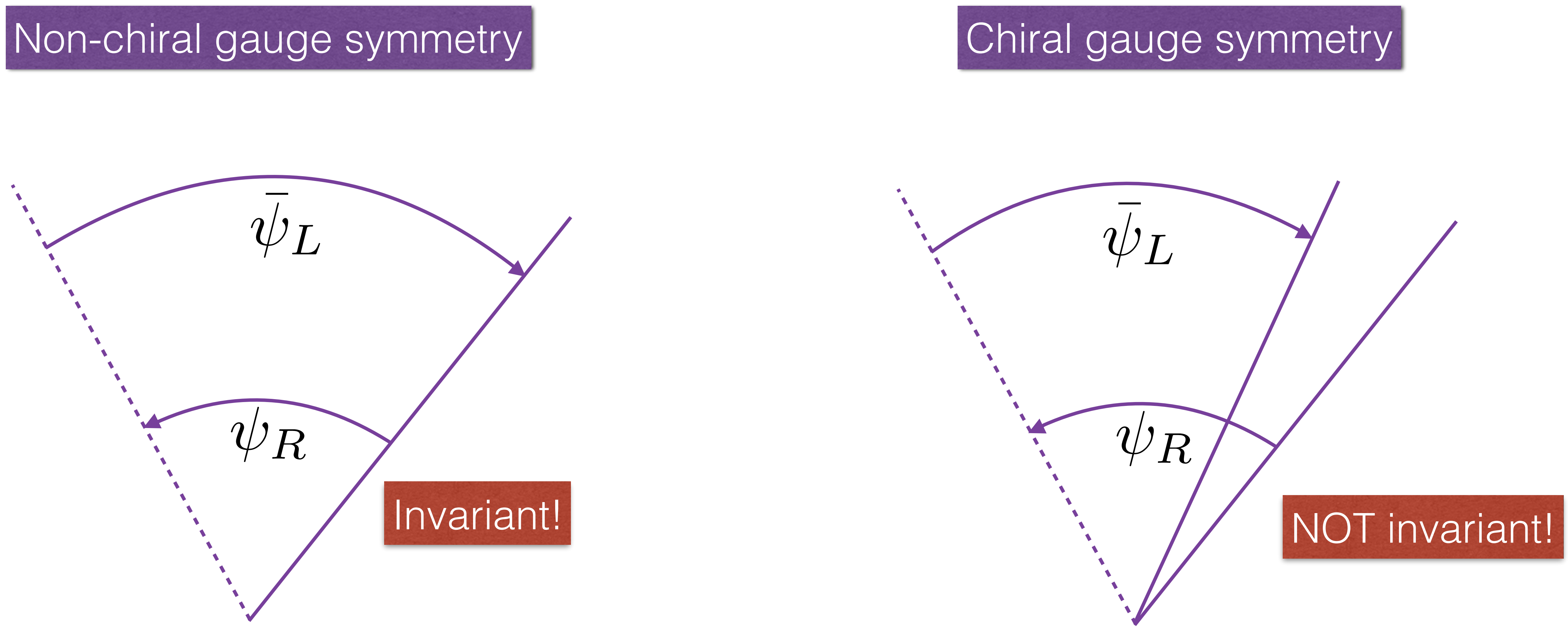
The insight of C. N. Yang and T. D. Lee, verified by C. S. Wu, tells us that the left-handed and right-handed fermions are different (with respect to weak interactions)

Consequences: V-A theory, chiral gauge symmetry

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

Fermion mass terms violate chiral gauge invariance!

Dirac mass term: $m\bar{\psi}_L\psi_R$

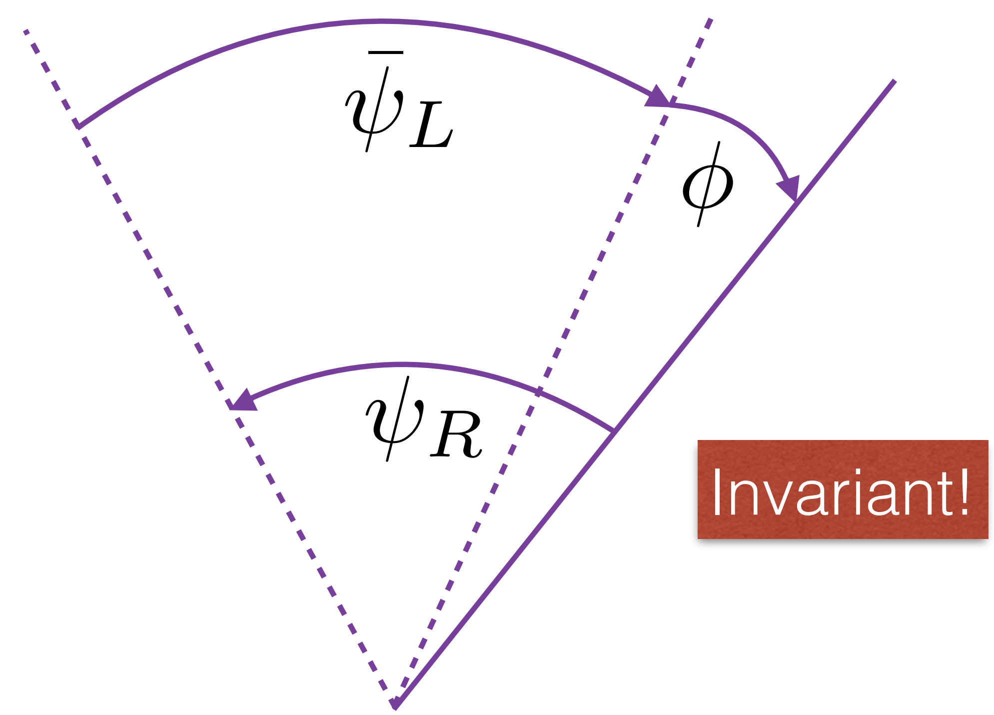


Solution for both problems: the Higgs field

$$(D_\mu \phi)^\dagger (D^\mu \phi)$$

$$\bar{\psi}_L \psi_R \phi$$

Gauge-invariant kinetic term containing interactions of the Higgs field with the W/Z bosons

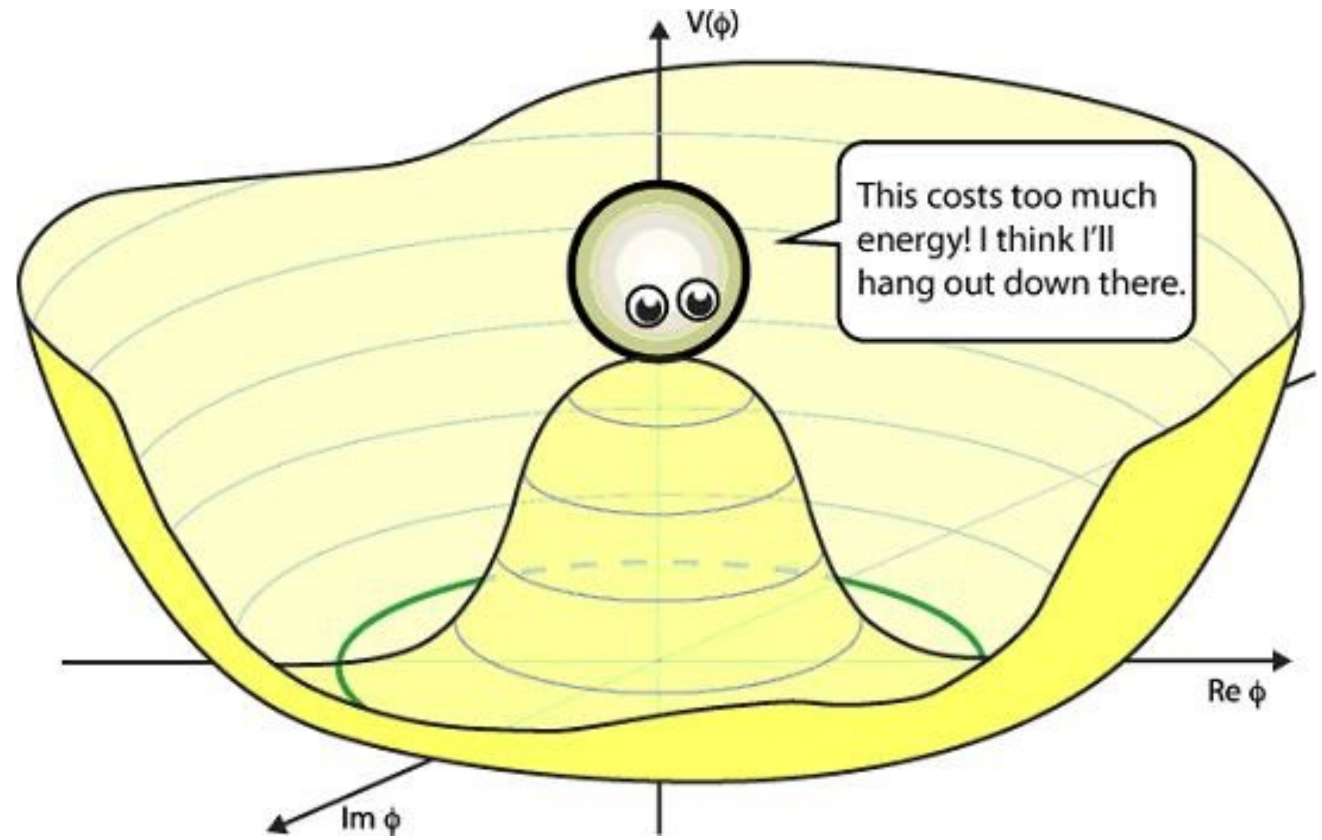


We need to go one step further…

Spontaneous symmetry breaking

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\mu^2 < 0$$



If you only want to remember one formula in this lecture, this is the one!

For more details, see Prof. Cao's lecture

The Higgs mechanism

The Higgs field acquires a vacuum expectation value

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

physical Higgs boson

The Higgs field interacts with the W boson with a strength g_2 → $m_W = \frac{g_2 v}{2}$

The Higgs field interacts with the electron with a strength y_e → $m_e = \frac{y_e v}{\sqrt{2}}$

In order to give the observed masses to the electron and the W/Z bosons, the Higgs boson must have a few properties:

- It must have the right quantum numbers (i.e., the right gauge interactions with the W/Z bosons)
- It must break the gauge symmetry following the correct pattern $SU(2)_L \otimes U(1)_Y \to U(1)_{\mathrm{EM}}$
- It must interact with the electron with the right strength (Yukawa coupling)

Applies to other massive chiral fermions

Higgs phenomenology I

- Verify the couplings of the Higgs boson with the W and Z bosons (crucial for the weak interactions)
- Verify the couplings of the Higgs boson to massive fermions (crucial for origin of fermion masses)
- Verify the Higgs potential (crucial for symmetry breaking and vacuum stability)

It's not the whole story!

Questions

- Flavor puzzle: why is the Yukawa coupling of the electron with the Higgs boson so tiny?

$$y_e = \frac{\sqrt{2}m_e}{v} \approx 3 \times 10^{-6}$$

compared to, e.g.,

$$y_t = \frac{\sqrt{2}m_t}{v} \approx 1$$

$$g_2 = \frac{2m_W}{v} \approx 0.65$$

- Extended Higgs sector: are we so lucky that the simplest model with only a single scalar boson is the correct one?

Remember the 12 fermions and 4 vector bosons!

Questions

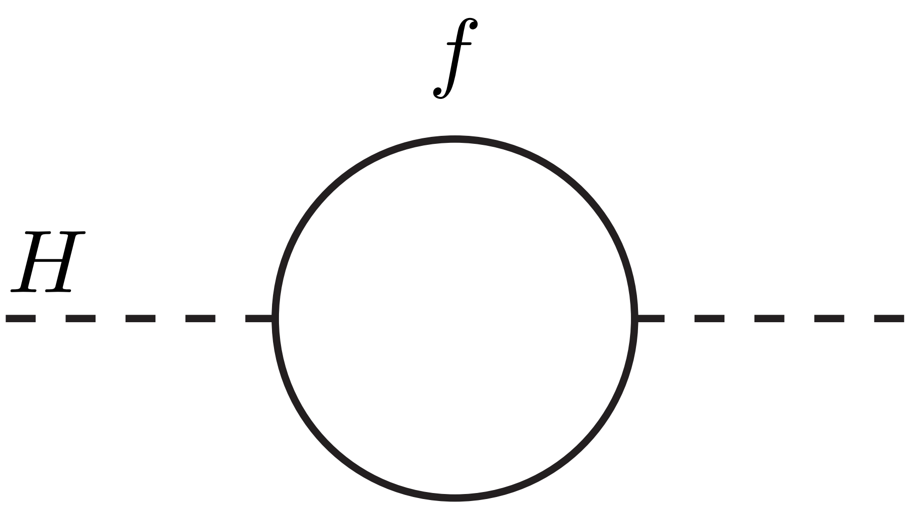
- Electroweak phase transition: how does the Higgs potential evolve from an unbroken phase in the early universe to a broken phase observed by us?

$$\mu^2 > 0 \quad \longrightarrow \quad \mu^2 < 0$$

- Naturalness: why is the Higgs boson so light compared to the Planck scale?

Hierarchy and naturalness

We are living in a quantum world, and the mass of the Higgs boson receives quantum corrections



These quantum effects (mostly from the top quark) tend to push the Higgs mass all the way up to the Planck scale

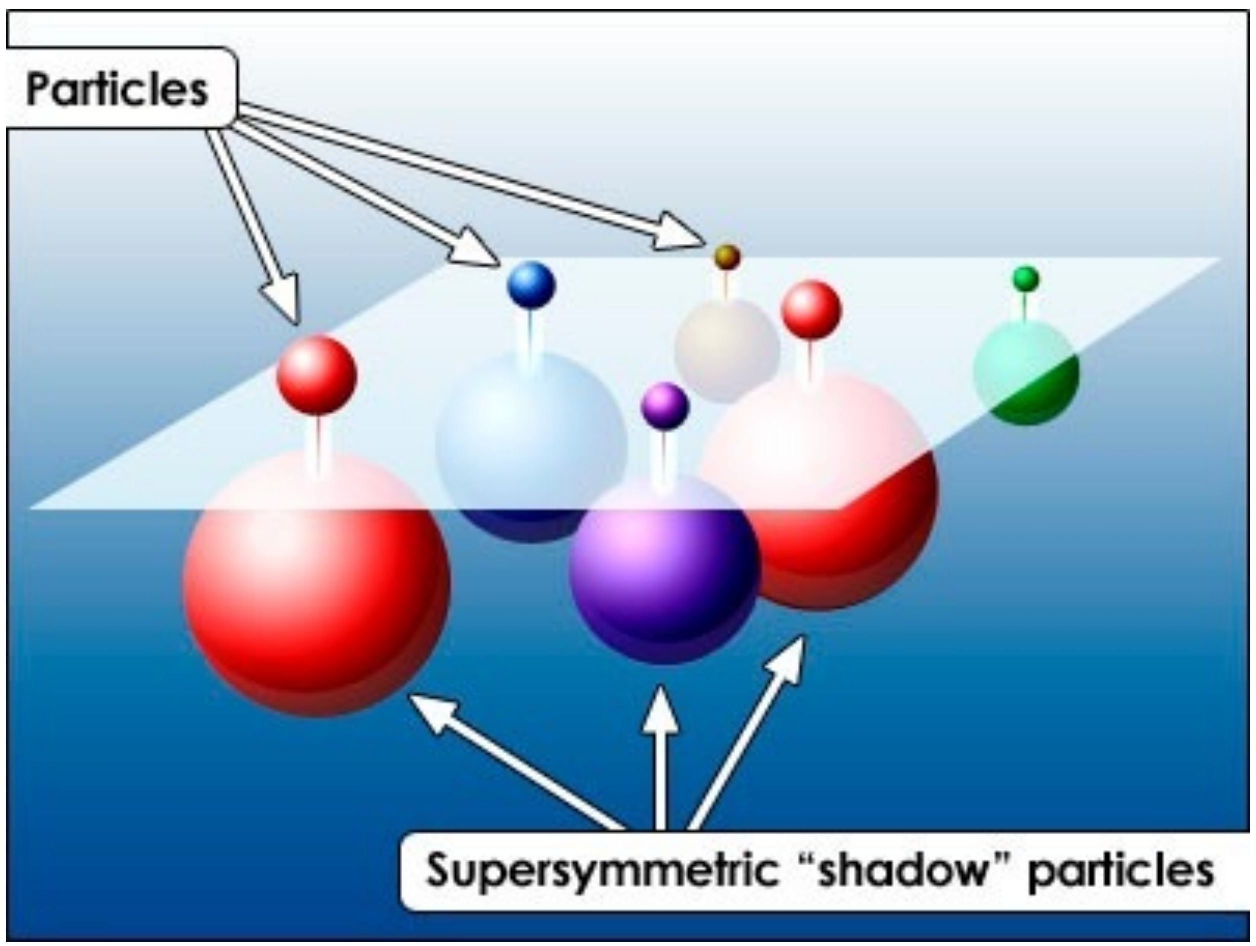
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots .$$

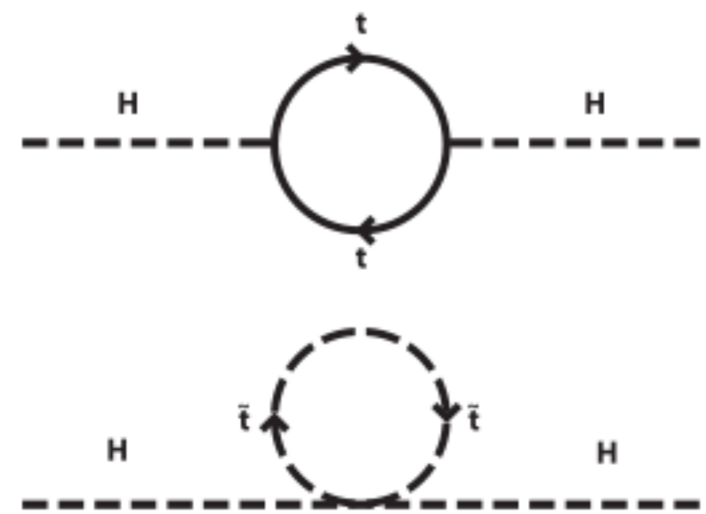
In order to get a light Higgs, one need to **fine-tune** the parameters to cancel these huge effects, which is considered highly **unnatural**

Higgs phenomenology II

- Look for possible solutions to the hierarchy problem
- Look for possible solutions to the flavor puzzle
- Look for possible extended Higgs sector
- Find out how the electroweak phase transition happened

A possible solution to the hierarchy problem: supersymmetry

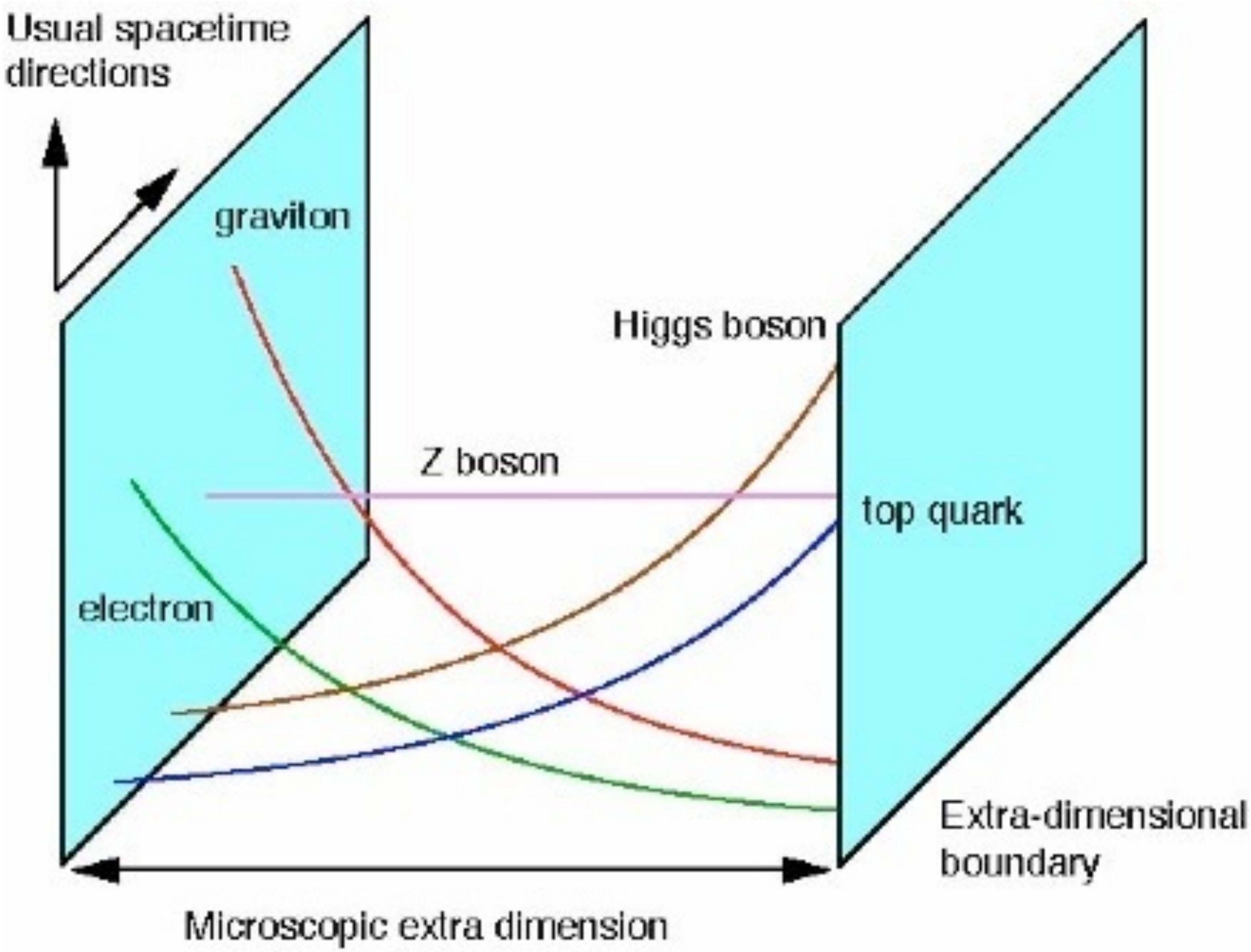




The quantum effects of a new particle cancel the dangerous quantum effects of the top quark

For more, see S. Martin: hep-ph/9709356

A possible solution to the flavor puzzle: the Randall-Sundrum model



Also solves the hierarchy problem!

A possible model for an extended Higgs sector: 2HDM

2HDM = 2 Higgs Doublet Model

5 physical Higgs bosons: $h^0, H^0, A^0, H^\pm$

Either of these two could be the 125 GeV scalar boson recently discovered!

Very rich phenomenology!

Required by supersymmetric models!

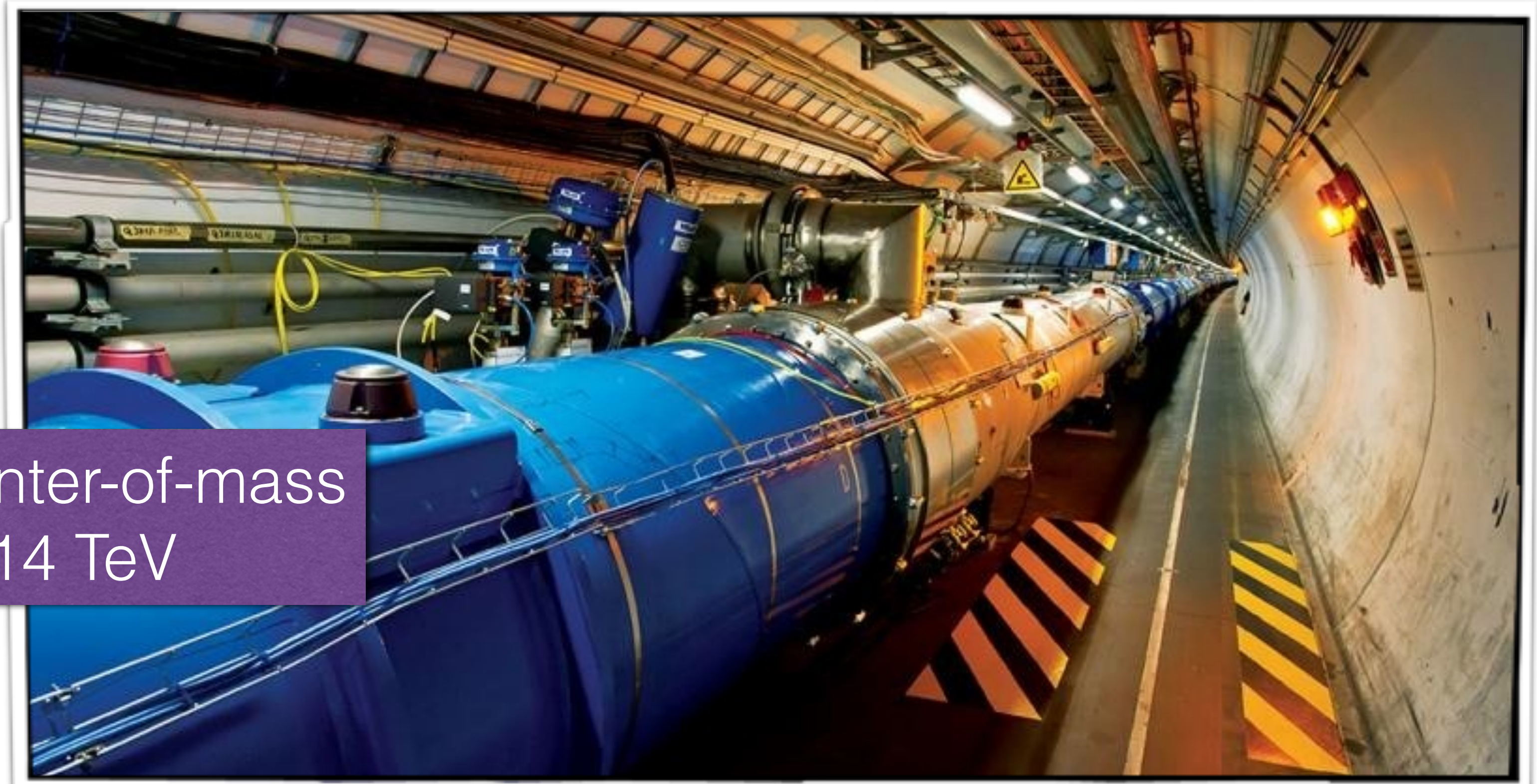
How do we do all these?

We should **make** a couple of Higgs bosons and **look** at them

How do we make Higgs bosons?

Not like this

We either need the LHC



A proton-proton collider running at center-of-mass energies ranging from 7 TeV to 14 TeV

Or a Higgs factory

A high-luminosity electron-positron collider running at a center-of-mass energy around 240-250 GeV

The Higgs boson couples to mass (at tree level)

However, the electrons, the positrons and the constitutes (up quarks, down quarks and gluons) of the protons are either massless or very light

We need some heavy mediators!

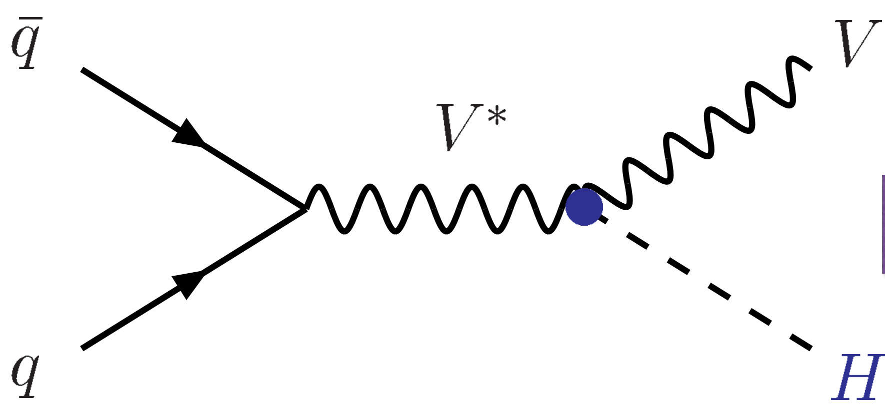
The Higgs boson couples to mass (at tree level)

We should look at the heavy guys:

4.5 GeV | 80 GeV | 91 GeV | 173 GeV

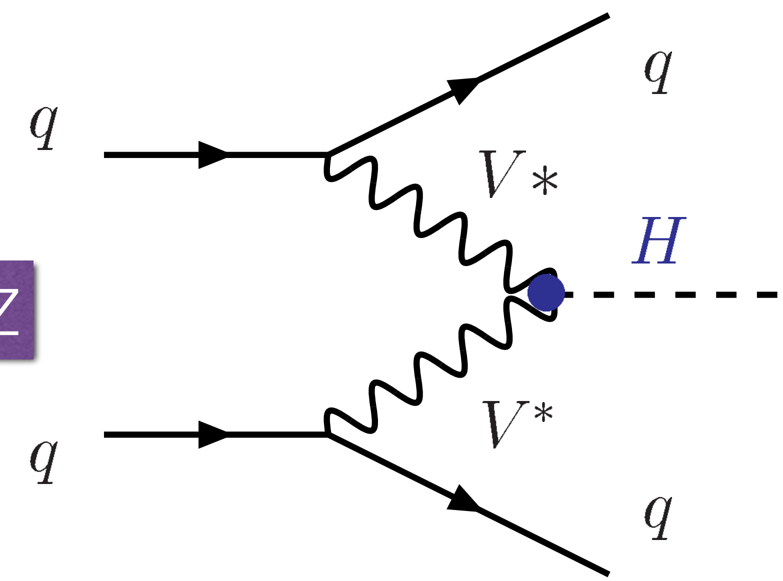
Production channels @ LHC

Higgs–strahlung

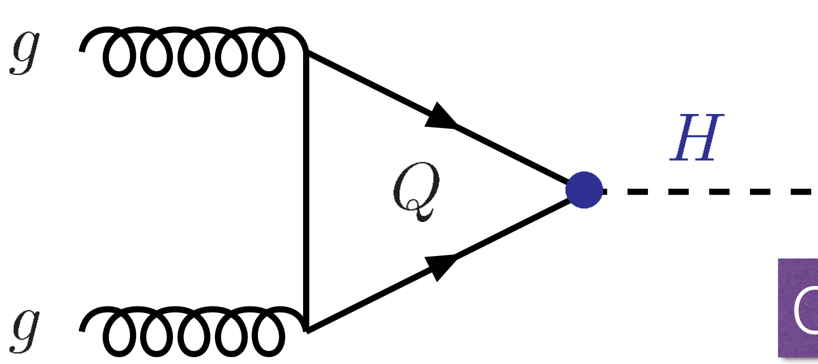


V = W,Z

Vector boson fusion

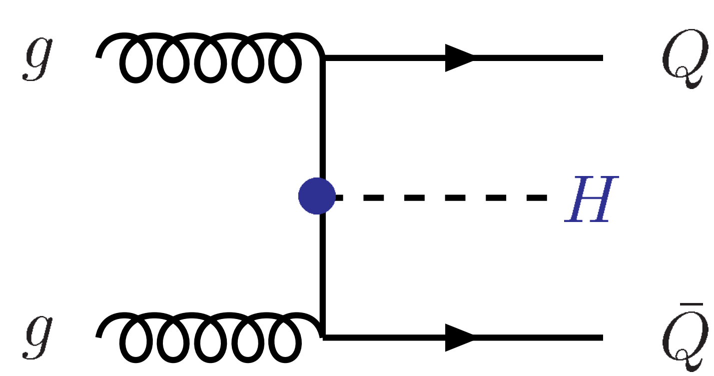


gluon–gluon fusion



Q = t, b

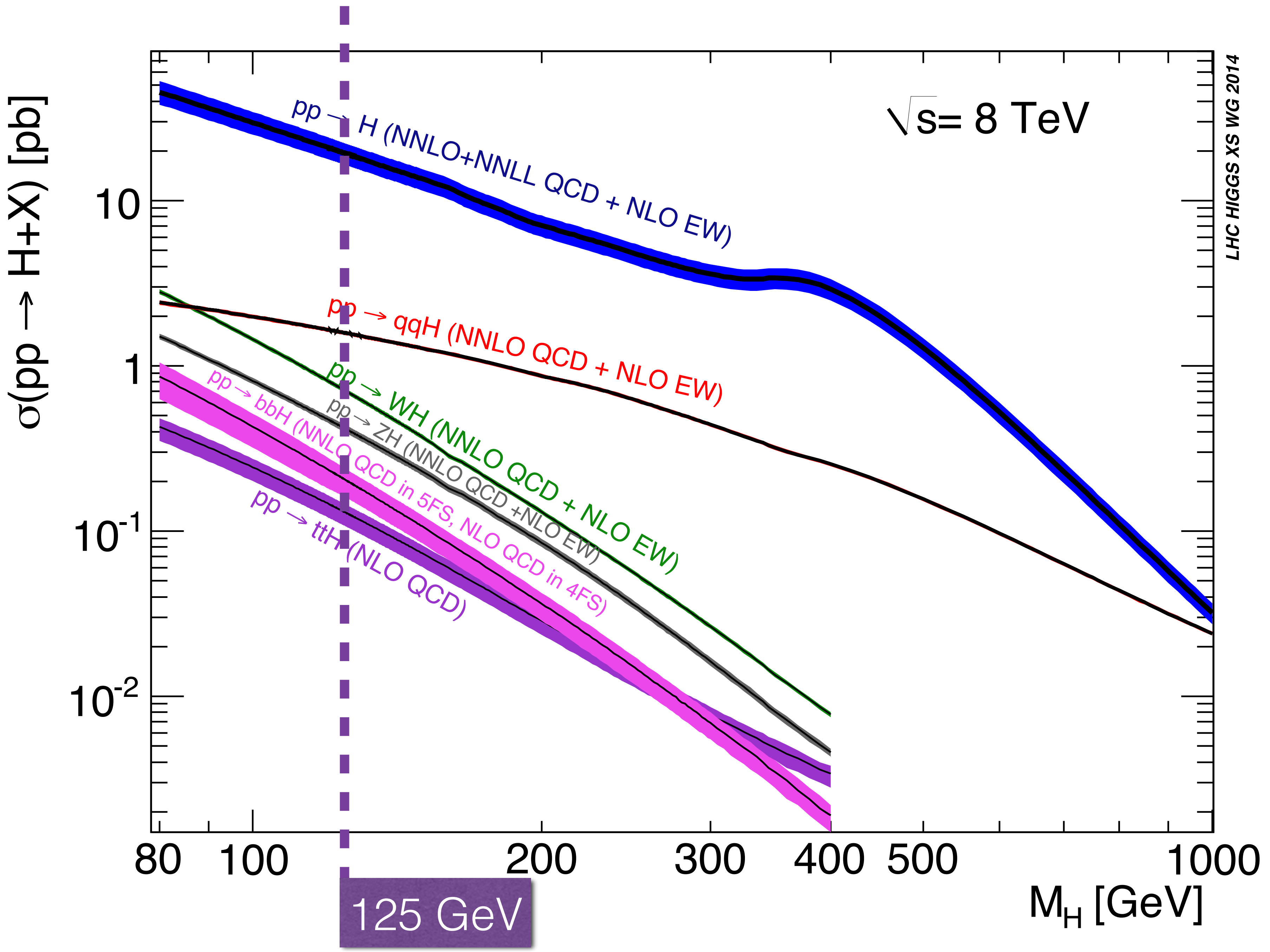
in associated with $Q\bar{Q}$



Diagrams from A. Djouadi, arXiv:1203.4199

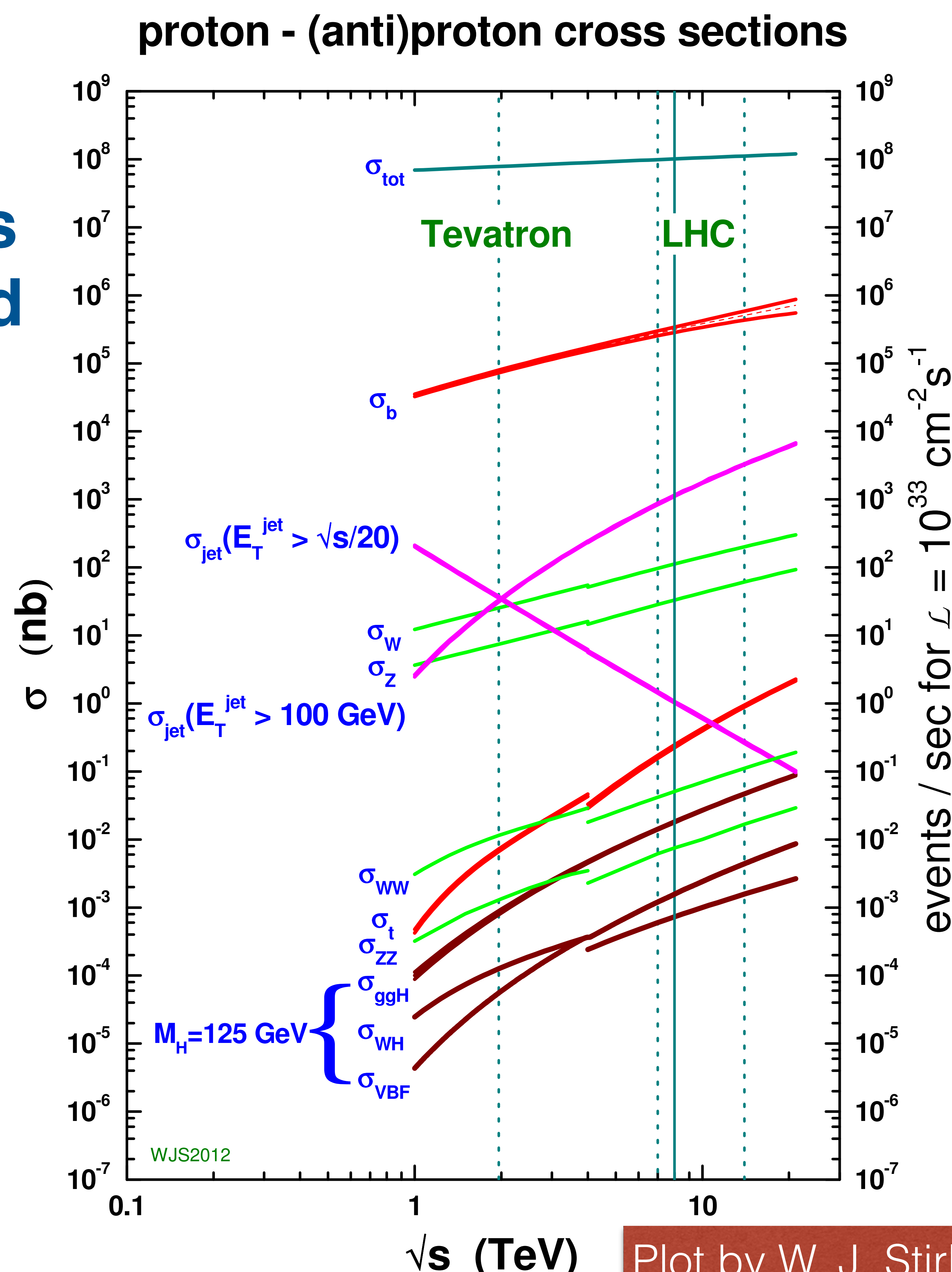
Cross sections @ LHC

Summary of the efforts of O(100) theorists over O(40) years



LHC Higgs Cross Section Working Group (arXiv:1307.1347)

The Higgs cross sections are really small compared to other processes!



Plot by W. J. Stirling

That's part of the reason why it took us so long to discover it

How do we look at a Higgs boson?

Not like this

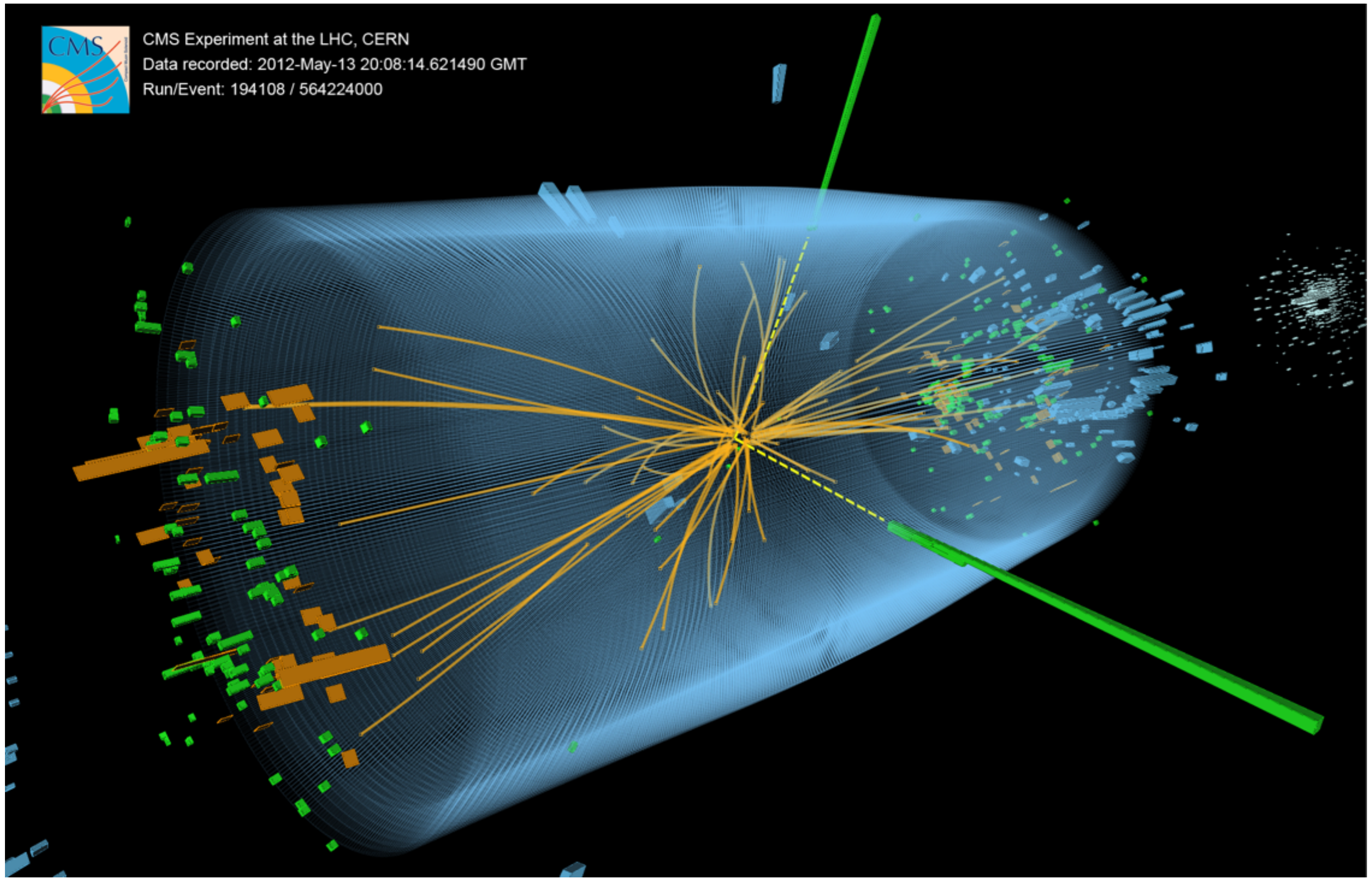
The life of a Higgs boson is extremely short

Mean lifetime ~ 10^{-22} second

In contrast to Professor Higgs

Lifetime > 85 years

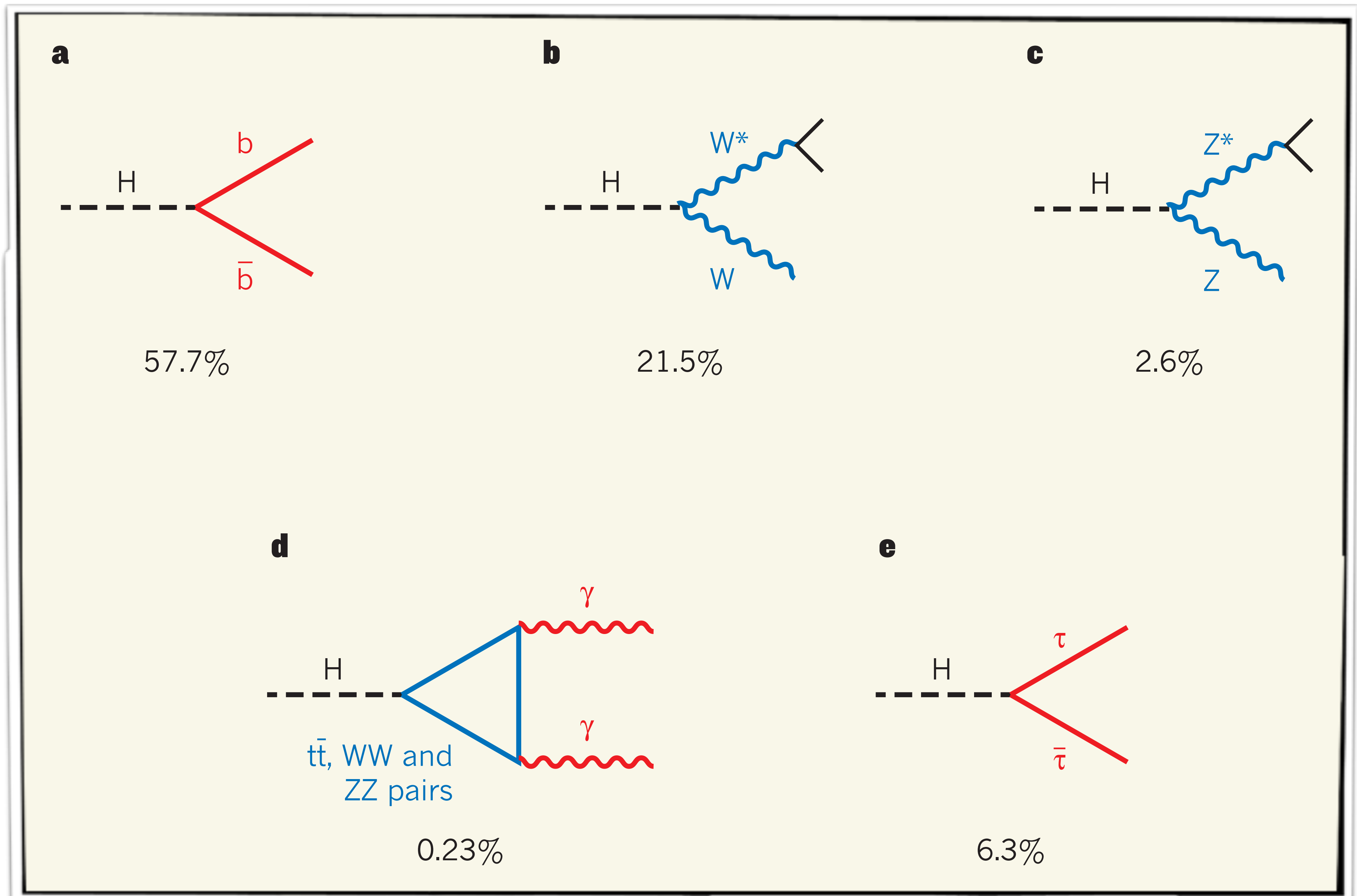
We can only look at the Higgs boson through its relics (decay products)



Decay Channels

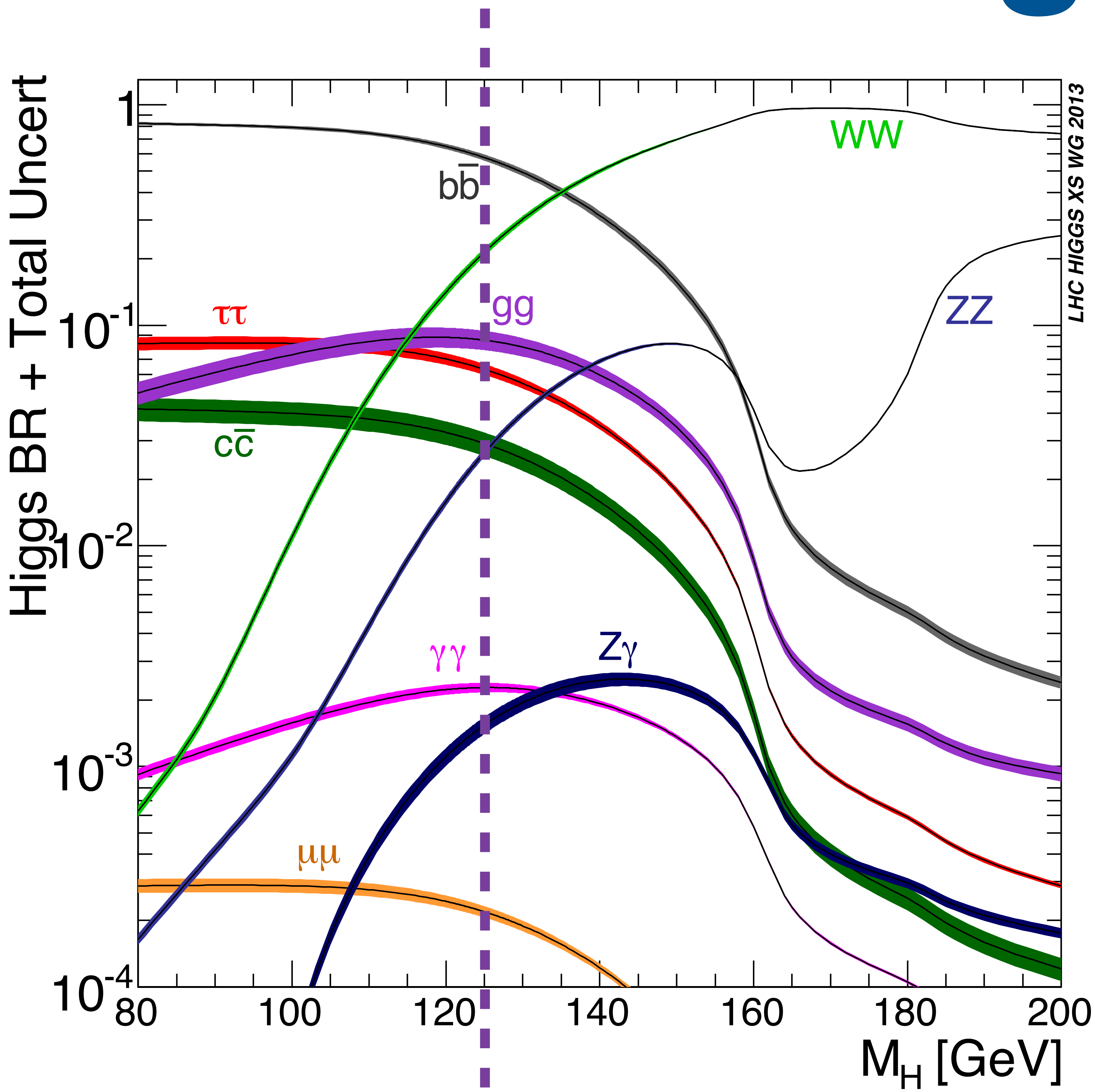
Again we should consider the heavy guys, and here we need to take into account limitations from energy-momentum conservation

125 GeV



Diagrams from F. Wilczek: Nature 496, 439-411 (2013)

Branching ratios



BR = probability to decay into a particular final state

LHC Higgs Cross Section Working Group (arXiv:1307.1347)

Question: A 125 GeV Higgs boson most likely decays into a pair of bottom quarks or a pair of W bosons. However, it was discovered firstly in the diphoton channel and the ZZ channel. Why?

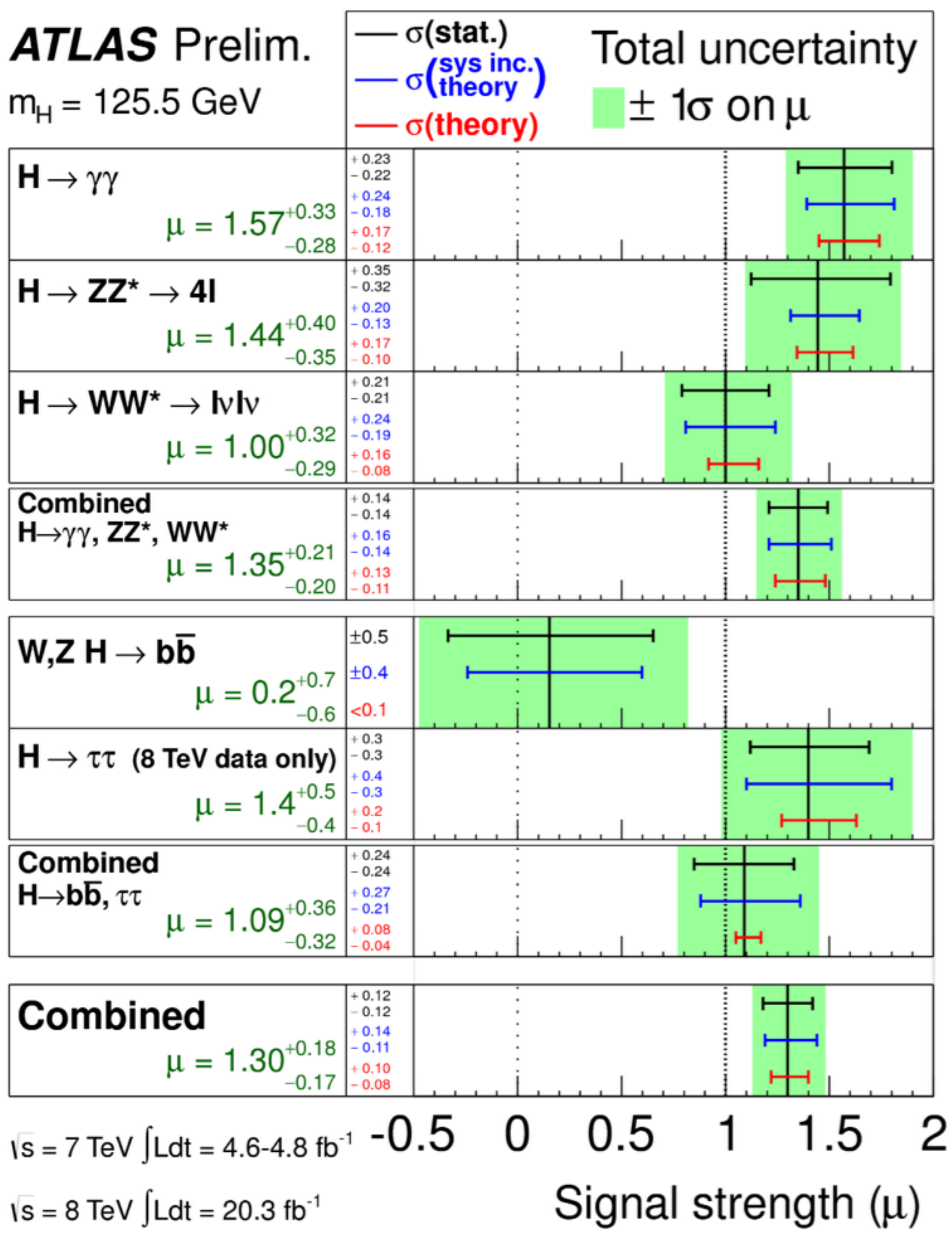
Background events (events not coming from the Higgs boson) are important!

Problem with bottom quarks: they are too easy to be created at a hadron collider via strong interactions

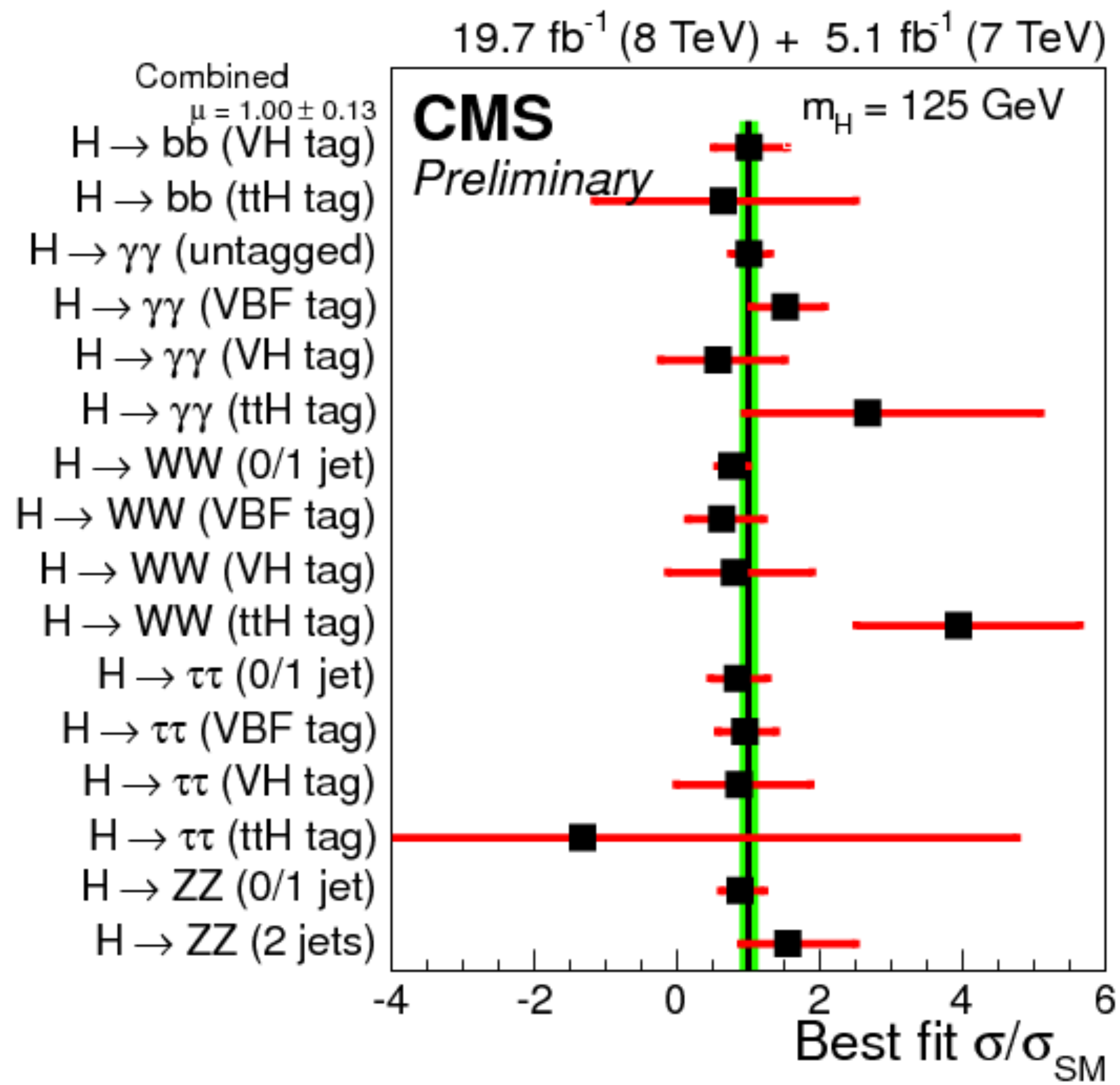
Problem with W bosons: they are also easy to create, and not so easy to identify (decaying to quarks or neutrinos)

Photons and Z bosons are "clean"

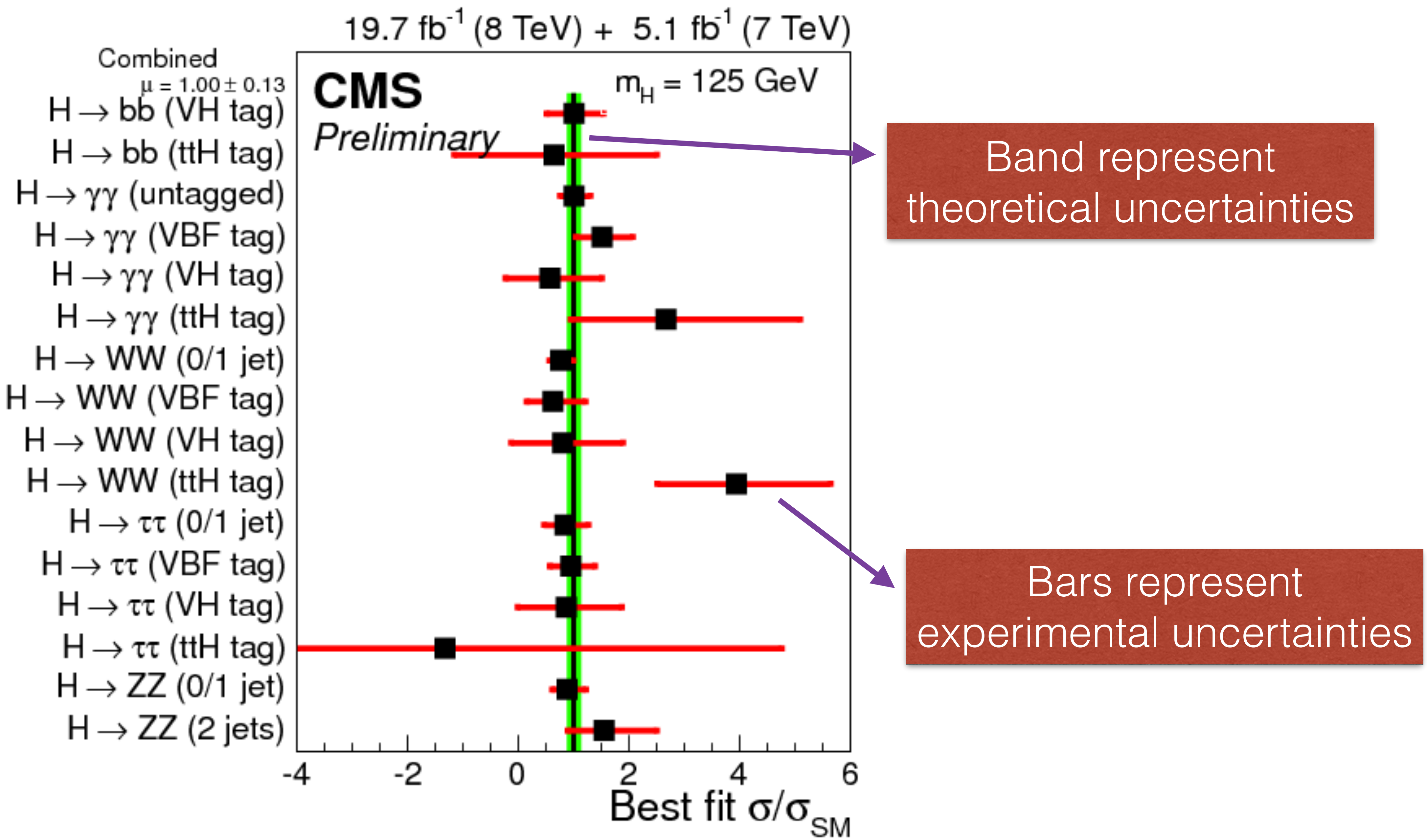
What we have seen?



ATLAS-CONF-2014-009



CMS-PAS-HIG-14-009



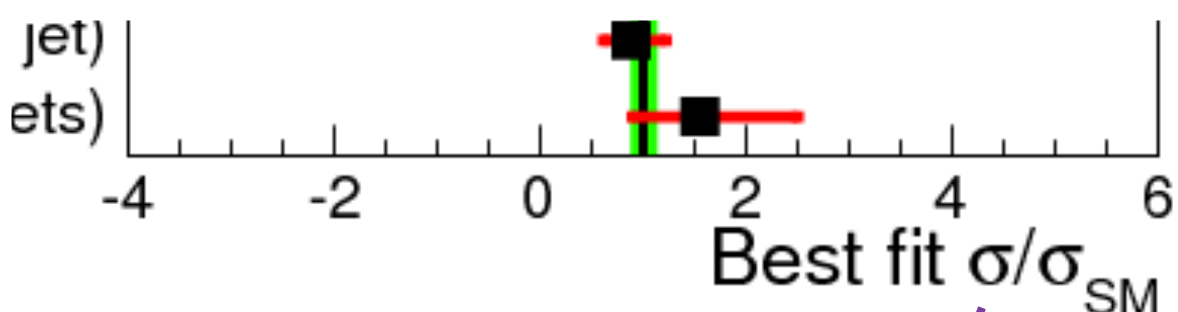
This plot contains a lot of information, so I'll spend some time to explain them

What goes into the x-axis?

What we can measure is:

production rate = cross section × branching ratio

functions of the couplings we want to know about



experimental measurement of the production rate

theoretical prediction in the SM

ratio = 1 means consistent with the SM

Perturbative calculations are important!

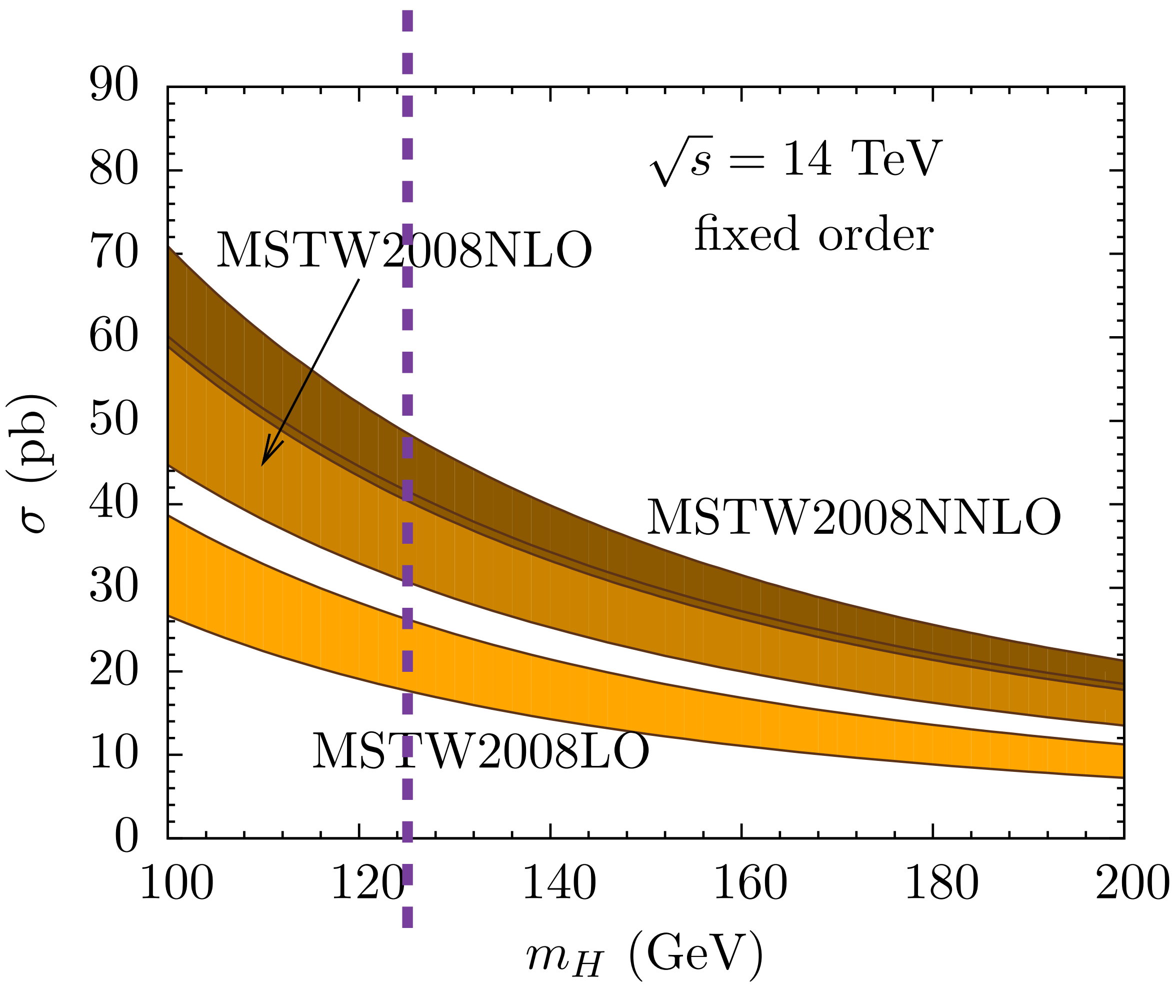
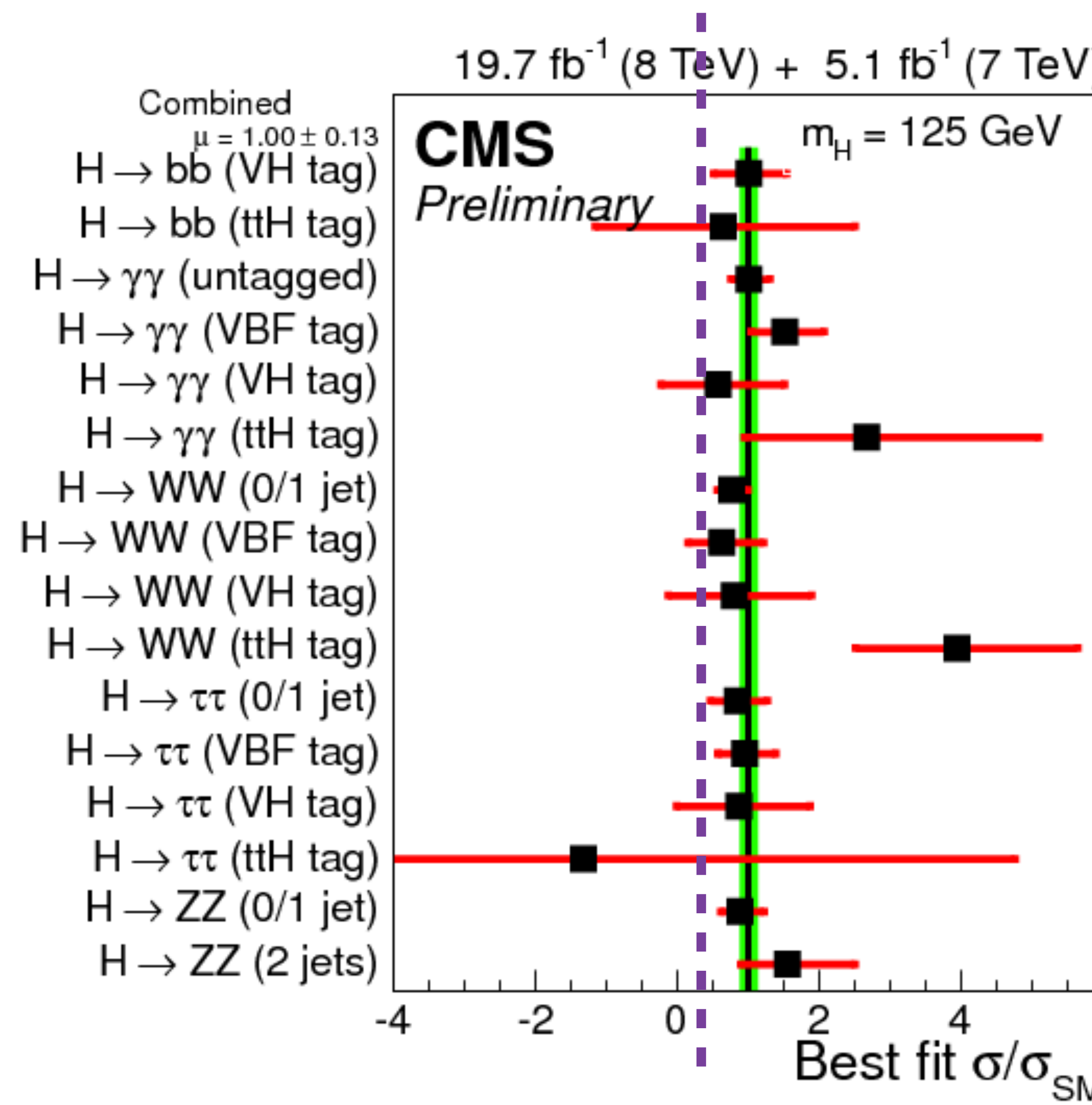
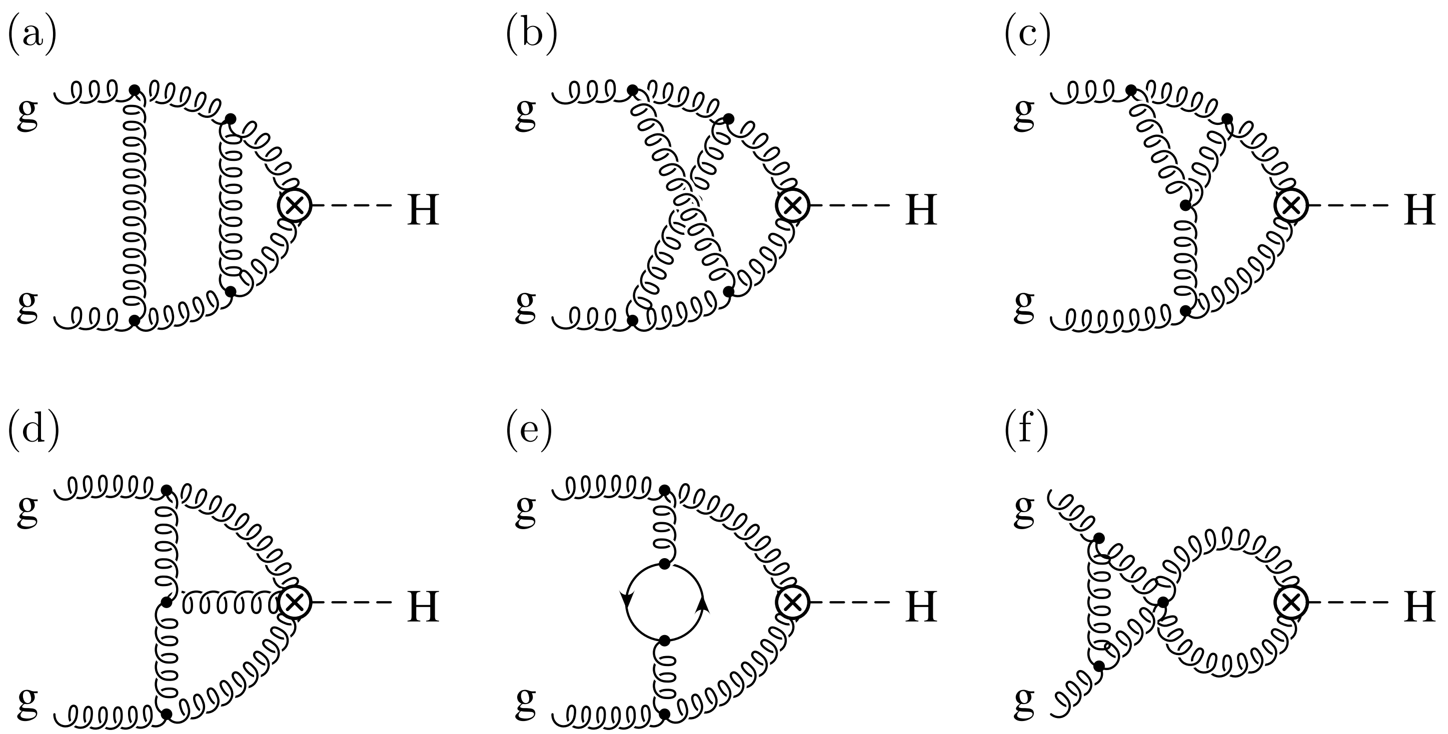


Figure from arXiv:0809.4283

If nobody ever did these calculations…



Higgs @ NNLO



Harlander: hep-ph/0007289

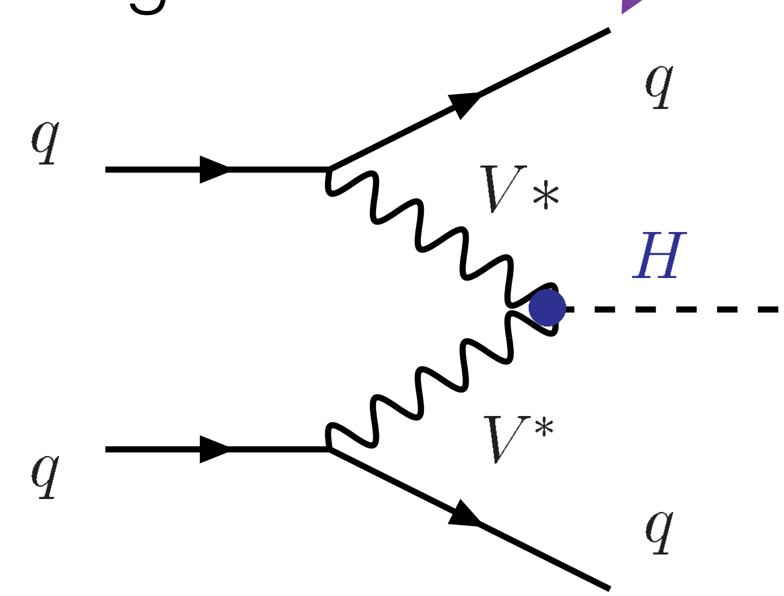
$$
\begin{aligned}
\Delta_{gg}^{(2)\mathrm{A}} = &\left(\frac{11399}{144} + \frac{133}{2}\zeta_2 - \frac{165}{4}\zeta_3 - \frac{9}{20}\zeta_2^2 + \frac{19}{8}L_t\right)\delta(1-x) + (133-90\zeta_2)\left[\frac{\ln(1-x)}{(1-x)}\right]_+ \\
&+\left(-\frac{101}{3} + 33\zeta_2 + \frac{351}{2}\zeta_3\right)\left[\frac{1}{(1-x)}\right]_+ - 33\left[\frac{\ln(1-x)^2}{(1-x)}\right]_+ + 72\left[\frac{\ln(1-x)^3}{(1-x)}\right]_+ \\
&+\frac{9(38x^2-20x^3+18x-39x^4+14+7x^5)}{1-x^2}\mathrm{Li}_3(x) - \frac{18(x^2+x+1)^2}{1+x}\mathrm{S}_{12}(x^2) \\
&+\frac{9(4x^4+8x^3+21x^2+14x+7)}{1+x}\mathrm{S}_{12}(-x) - \frac{9}{2}\frac{(5x^5-51x^4-57x^3+53x^2+59x-11)}{1-x^2}\mathrm{S}_{12}(x) \\
&-\frac{9}{2}\frac{(8x^4+8x^3-3x^2-2x-1)}{1+x}\mathrm{Li}_3(-x) - \frac{9}{2}\frac{(16+13x^5-40x^3-67x^4+64x^2+36x)}{1-x^2}\mathrm{Li}_2(x)\ln(x) \\
&+\frac{9}{2}\frac{(2x^4-15x^2-10x-5)}{1+x}\mathrm{Li}_2(-x)\ln(x) - \frac{9}{4}\frac{(59+177x^2-116x^3+59x^4-118x)}{1-x}\ln(x)\ln^2(1-x) \\
&+\frac{27(3x^2+2x+1)}{1+x}\mathrm{Li}_2(-x)\ln(1+x) + \frac{9(6-11x^3+18x^2-12x+6x^4)}{1-x}\ln^2(x)\ln(1-x) \\
&+\frac{9}{2}\frac{(3-8x^3+3x^4-6x+9x^2)}{1-x}\mathrm{Li}_2(x)\ln(1-x) - \frac{3}{2}\frac{(7x-7x^3+4+18x^2-17x^4+9x^5)}{1-x^2}\ln^3(x) \\
&+\frac{9}{2}\frac{(8x^4+16x^3+33x^2+22x+11)}{1+x}\zeta_2\ln(1+x) - \frac{36(x^2+x+1)^2}{1+x}\mathrm{Li}_2(x)\ln(1+x) \\
&-\frac{9}{4}\frac{(4x^4+8x^3+27x^2+18x+9)}{1+x}\ln(1+x)\ln^2(x) + (-21+\frac{63}{2}x^2-18x+\frac{33}{2}x^3)\ln(1+x)\ln(x) \\
&+\frac{27}{2}\frac{(3x^2+2x+1)}{1+x}\ln^2(1+x)\ln(x) - \frac{3}{4}\frac{(-280x^3+143x^4+394x-289+21x^2)}{(1-x)}\mathrm{Li}_2(x) \\
&+(-21+\frac{63}{2}x^2-18x+\frac{33}{2}x^3)\mathrm{Li}_2(-x) + (-\frac{2559}{4}x^3+\frac{1079}{2}x^2-\frac{2687}{4}x+\frac{2027}{4})\ln(1-x) \\
&-\frac{3}{8}\frac{(374x^4-389x+154+699x^2-827x^3)}{1-x}\ln^2(x) + (330x^3-348x^2+381x-297)\ln^2(1-x) \\
&+\frac{3}{4}\frac{(-1180x^3+641-1238x+1227x^2+605x^4)}{1-x}\ln(x)\ln(1-x) - 72(2-x+x^2)x\ln^3(1-x) \\
&-\frac{1}{8}\frac{(4318x^4-6955x^3+6447x^2-5611x+2333)}{1-x}\ln(x) + \frac{3}{4}\frac{(495x^4-886x^3+564x^2-200x+16)}{1-x}\zeta_2 \\
&+\frac{9(6x+18x^2+2+10x^5-6x^3-19x^4)}{1-x^2}\zeta_2\ln(x) - \frac{9}{2}\frac{(-48x^3+23x^4-46x+3+69x^2)}{1-x}\zeta_2\ln(1-x) \\
&+\frac{9}{2}\frac{(-36-15x^4-52x+19x^2+13x^3+33x^5)}{1-x^2}\zeta_3 + \frac{7539}{16}x^3 - \frac{24107}{48}x^2 + \frac{22879}{48}x - \frac{18157}{48},
\end{aligned}
$$

Anastasiou, Melnikov: hep-ph/0207004

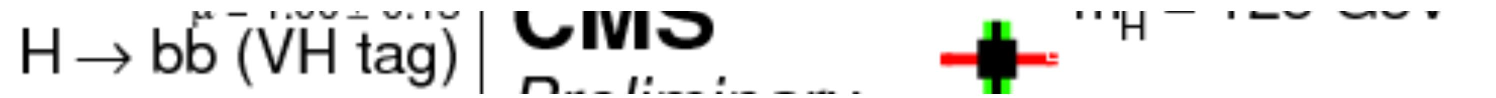
What are the labels on the y-axis?

decay mode of the Higgs boson

- VBF tag: selecting vector boson fusion production process (typically two forward jets with large rapidity gap and large invariant mass)
- VH and ttH tag: selecting corresponding production processes by identifying the W/Z boson or the top quark pair in the final state
- Untagged: mostly coming from gluon fusion production process
- 0/1 jet: mostly gluon fusion
- 2 jets: mostly VH or VBF



A subtlety in VH production with H decaying to bottom quarks



Backgrounds for this particular final state are huge (V+jets, top quark, etc.)

Many clever ideas were proposed by theorists, initiated by this work:

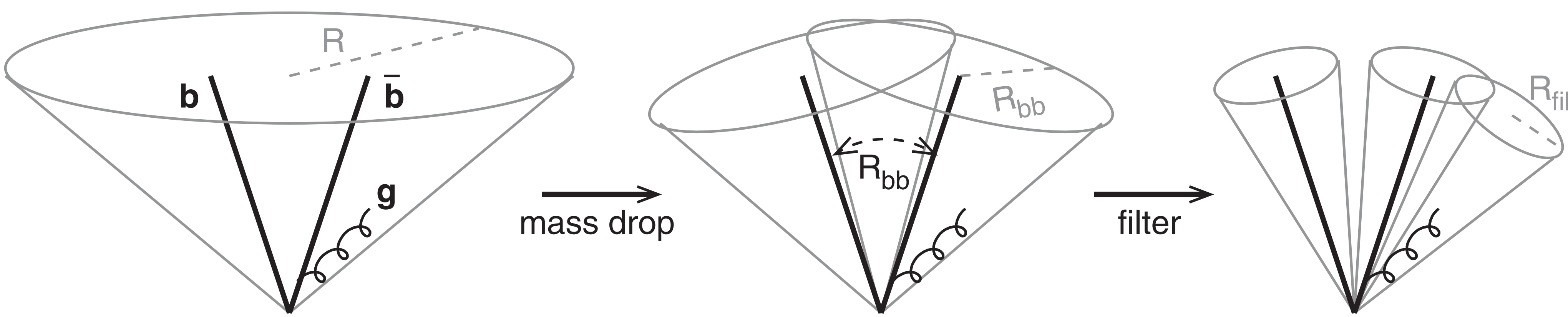
Butterworth, Davison, Rubin, Salam: arXiv:0802.2470

Bottom line: to suppress the huge backgrounds, we need to consider highly boosted V and H (i.e., those with large transverse momenta)

Boosted objects and jet substructure

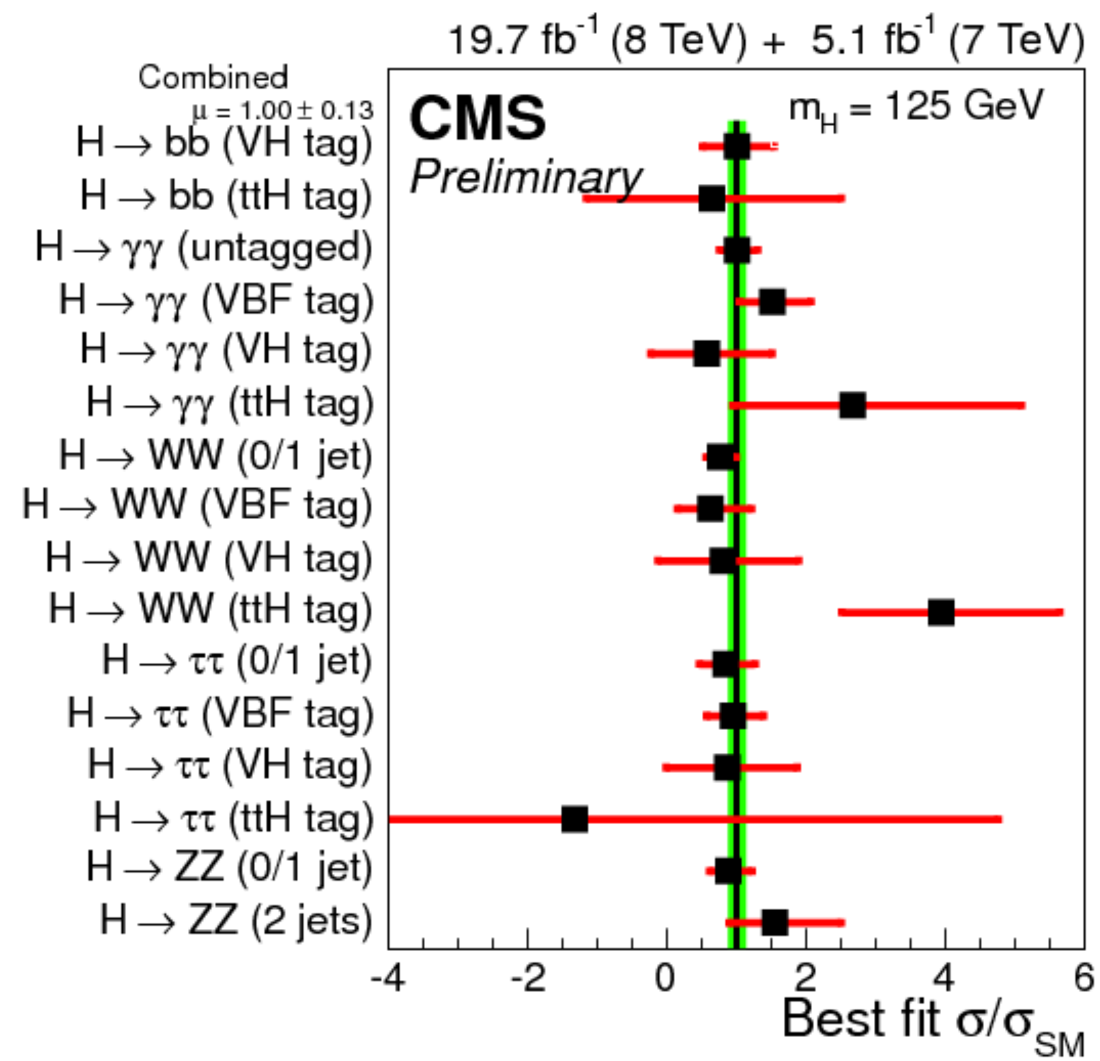
If the Higgs boson is boosted, the two bottom quarks from its decay will be very close to each other

The clever idea: "fat jet" and jet substructure



Checklist on our current knowledge about the couplings

- ☑ Couplings to the W and Z bosons: quite a lot of information
- ☑ Couplings to the bottom quark and the tau lepton: some rough information
- ☑ Couplings to the top quark: very rough information (indirectly from gluon fusion and directly from ttH production)
- ☐ Couplings to first/second generation fermions: largely no information
- ☐ Self-couplings in the Higgs potential: largely no information



Higgs self-couplings

Higgs potential

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

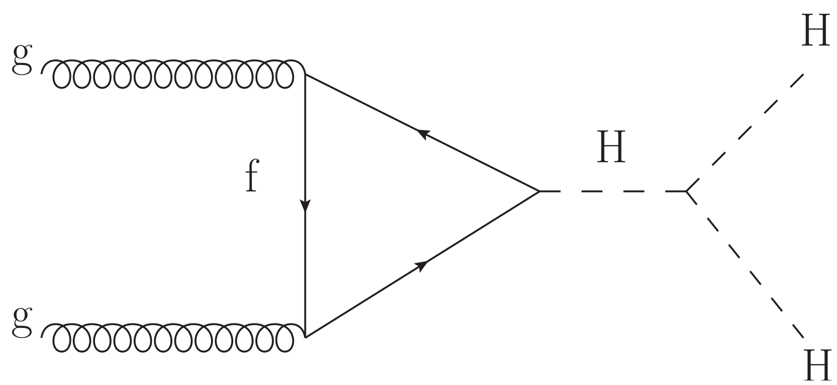
EWSB

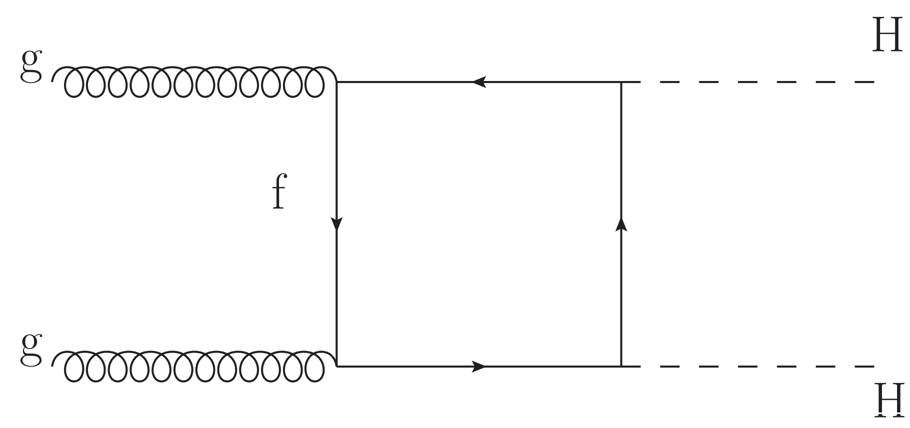
$$V(\phi) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

Can be probed by Higgs pair production

Can be probed by HHH production

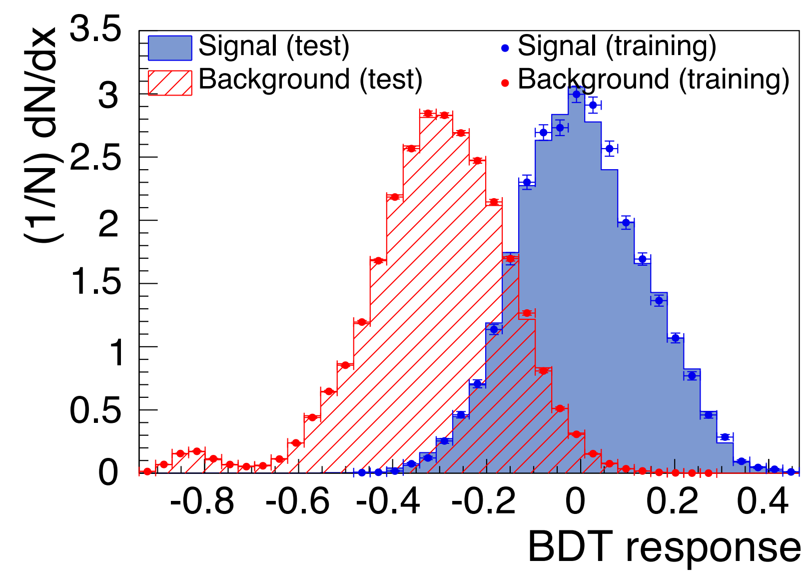
Higgs pair production





Cross section @ 14 TeV is 40 fb (very small!)

Will be a tough task for the LHC, requiring combination of jet substructure techniques and multivariate analysis



Papaefstathiou, Yang, Zurita: arXiv:1209.1489

Higgs coupling to electron?

Nobody knows how to measure this important one.
Waiting for clever ideas from you young people!

An example beyond the SM: the minimal supersymmetric standard model (MSSM)

2HDM embedded: $h^0, H^0, A^0, H^\pm$

Tree-level couplings to W/Z bosons and fermions are altered

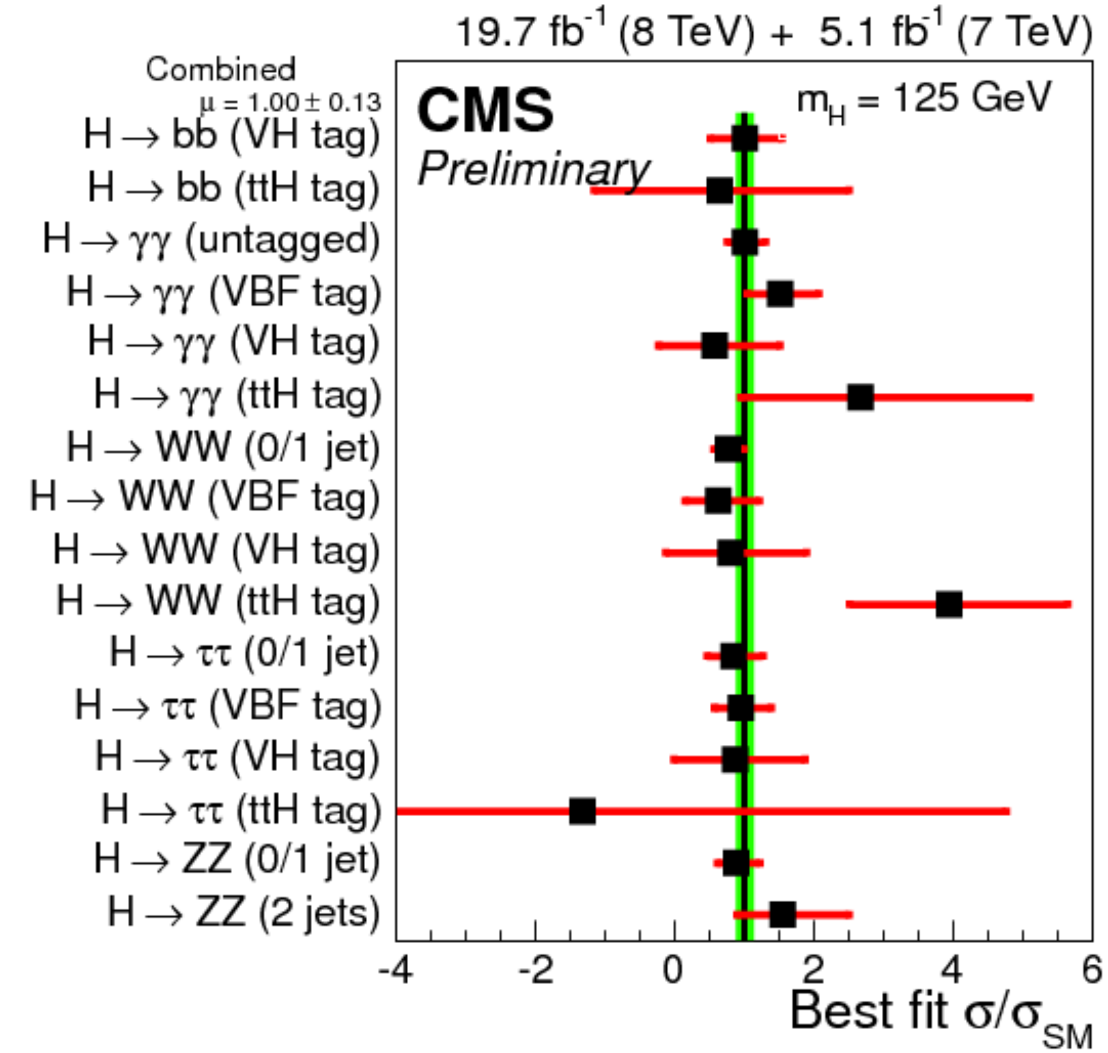
$$hVV : \sin(\beta - \alpha)\,, \quad HVV : \cos(\beta - \alpha)$$

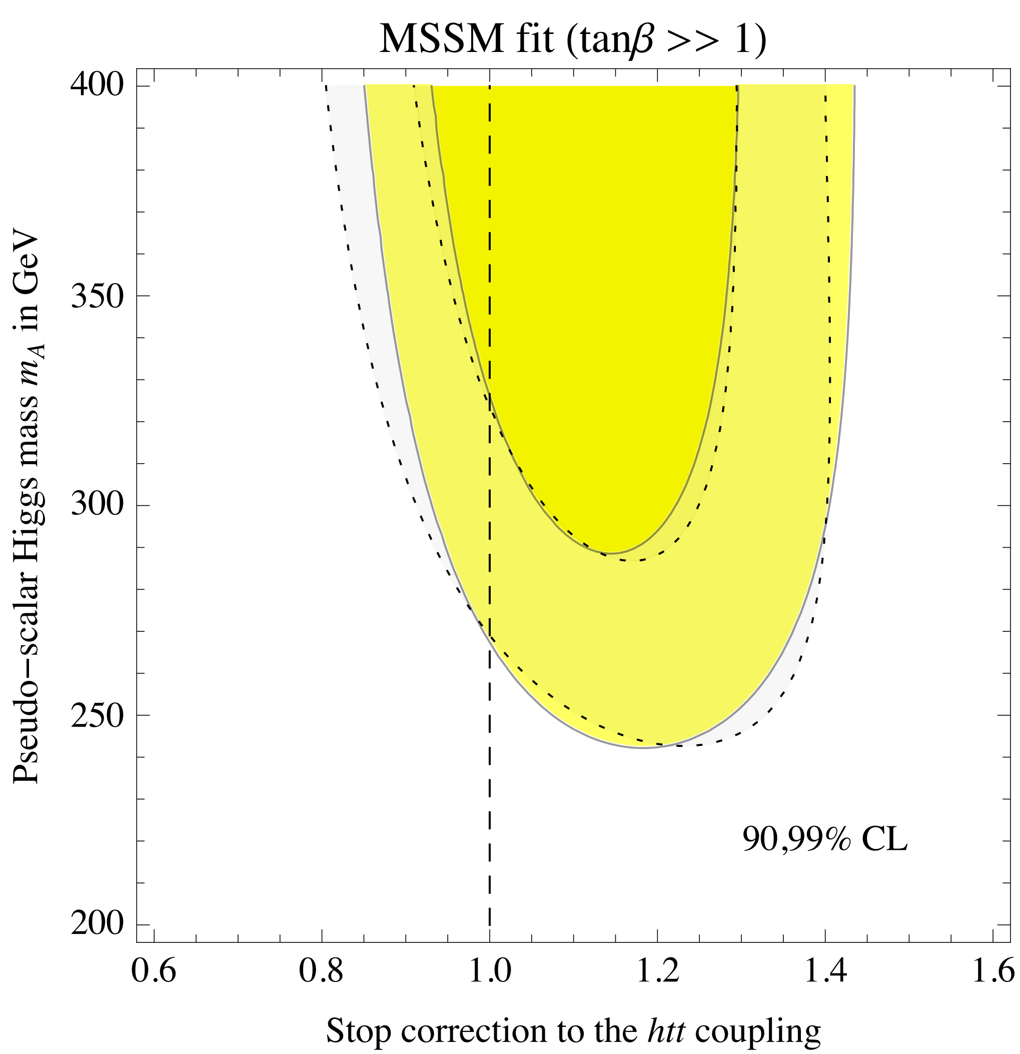
$$ht\bar{t} : \frac{\cos\alpha}{\sin\beta}\,, \quad Ht\bar{t} : \frac{\sin\alpha}{\sin\beta}$$

$$hb\bar{b} : -\frac{\sin\alpha}{\cos\beta}\,, \quad Hb\bar{b} : \frac{\cos\alpha}{\cos\beta}$$

New particles may enter the loop to change the gluon fusion process and the decay to diphoton

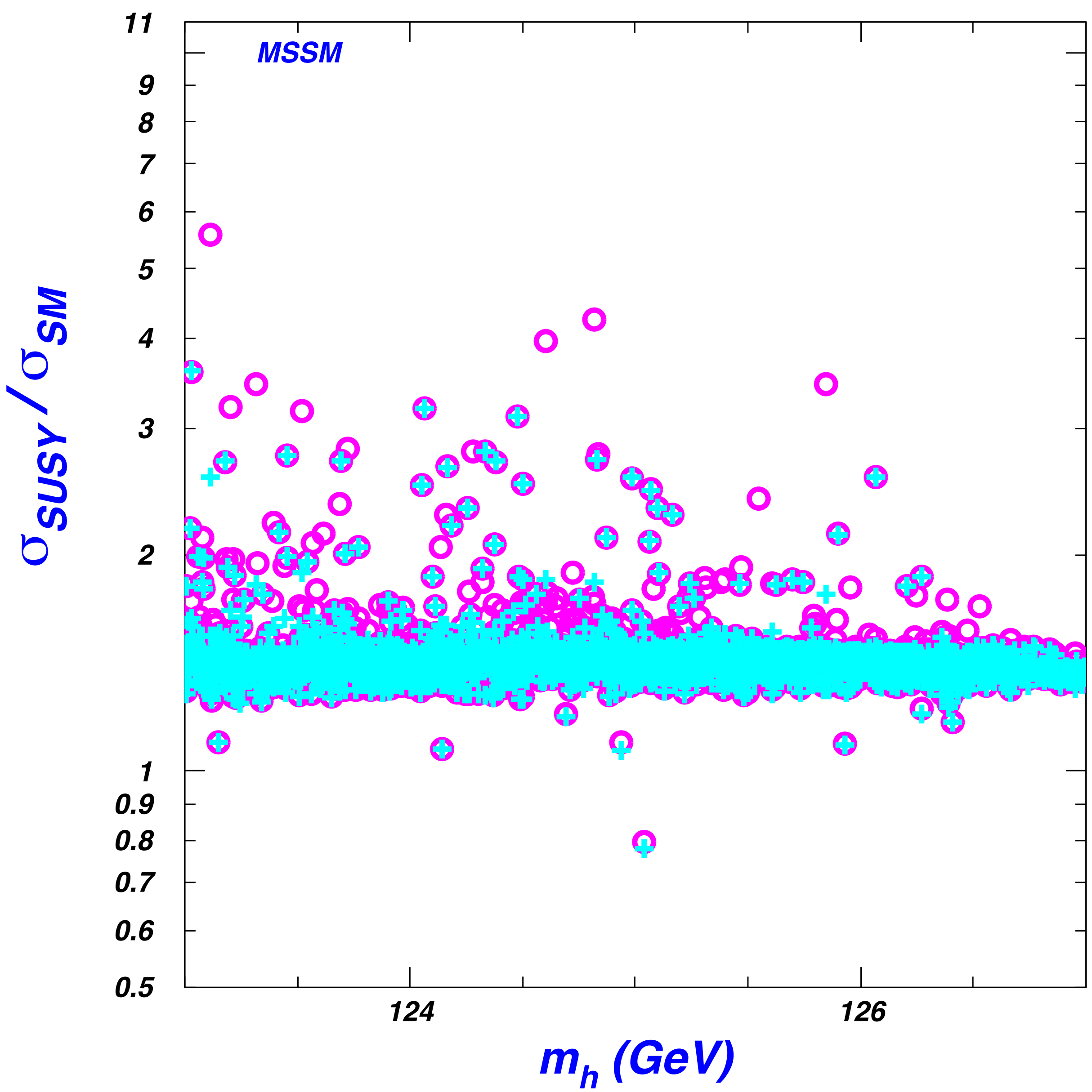
These changes should be reflected in this plot

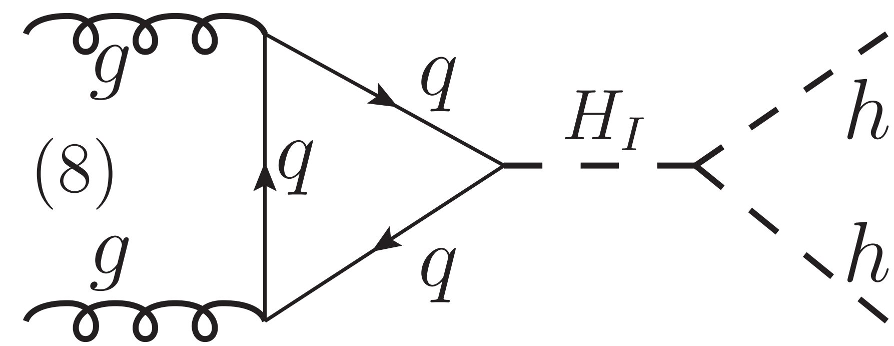




A simple fit done in arXiv:1303.3570

A heavy Higgs boson may enhance the production rate for a pair of light Higgs bosons

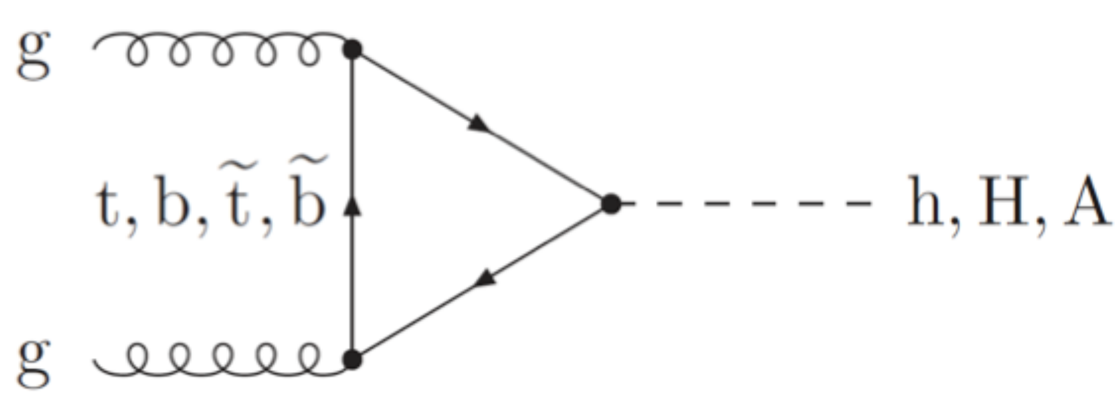


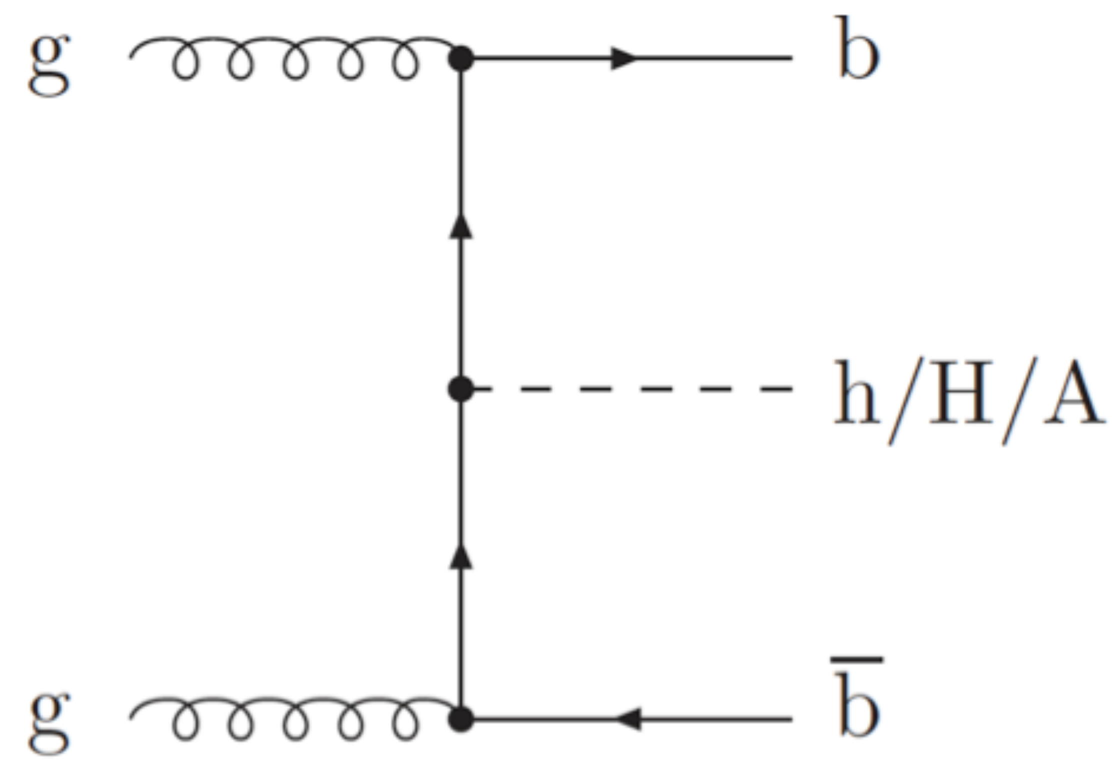


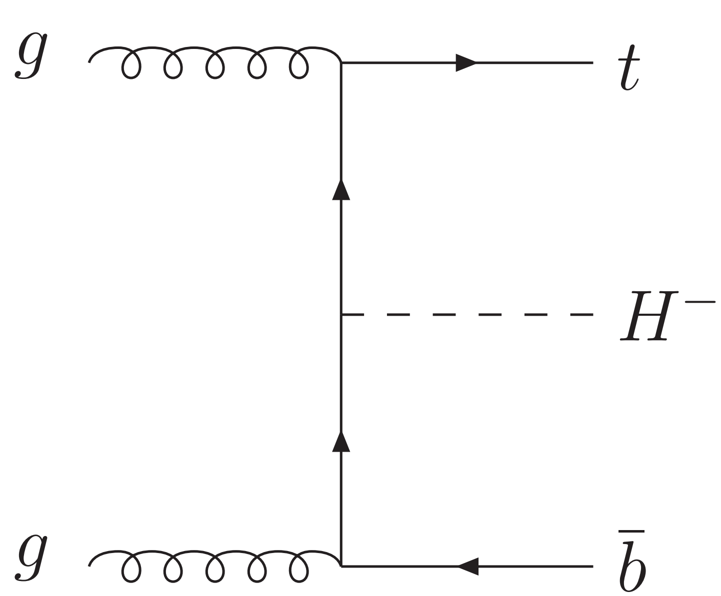
Possible to distinguish at the LHC?

Cao, Heng, Shang, Wan, Yang: arXiv:1301.6437

The additional Higgs bosons may also be directly produced



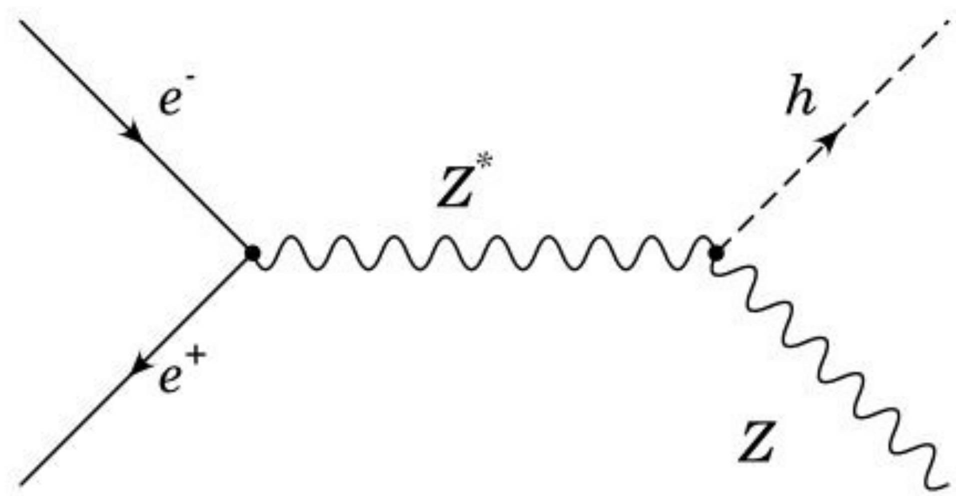




These will be striking guns for an extended Higgs sector beyond the SM!

The Higgs factory

An electron-positron collider dedicated to produce a lot of Higgs bosons via the process



Will certainly push our knowledge about the Higgs boson to a new frontier

CEPC

A great opportunity for you young people if it is built in China!

Further readings

- **The Higgs Hunter's Guide**
  by John F. Gunion, Howard E. Haber, Gordon Kane and Sally Dawson

- **Higgs Boson Theory and Phenomenology**
  hep-ph/0208209
  by Marcela Carena and Howard E. Haber

- **Searching for the Higgs boson**
  hep-ph/0702124
  by David Rainwater