European School on High Energy Physics 2015

HIGGS PHYSICS

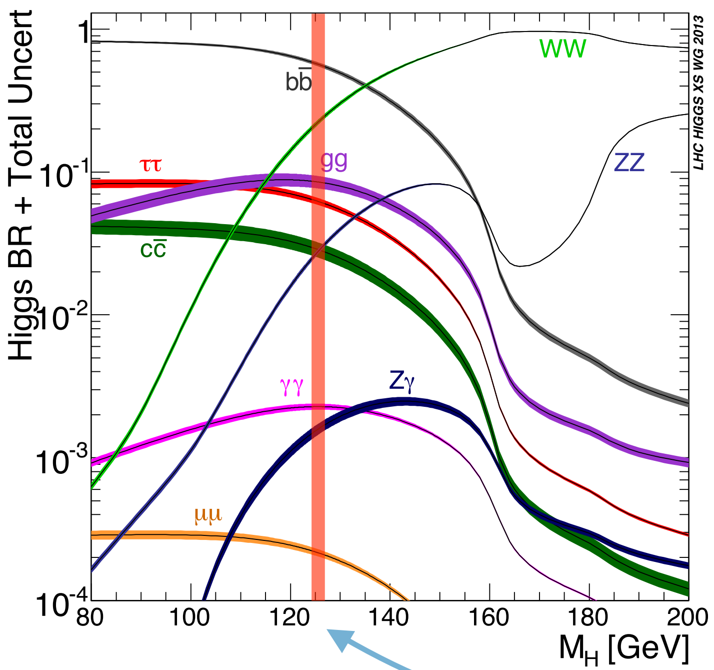
FRANCESCO RIVA - CERN

Motivations

Why Stop Worrying and Love the Higgs...

* From a physicist's point of view:

The Higgs is an exhibitionist...



Most decay channels have a large enough width to be visible

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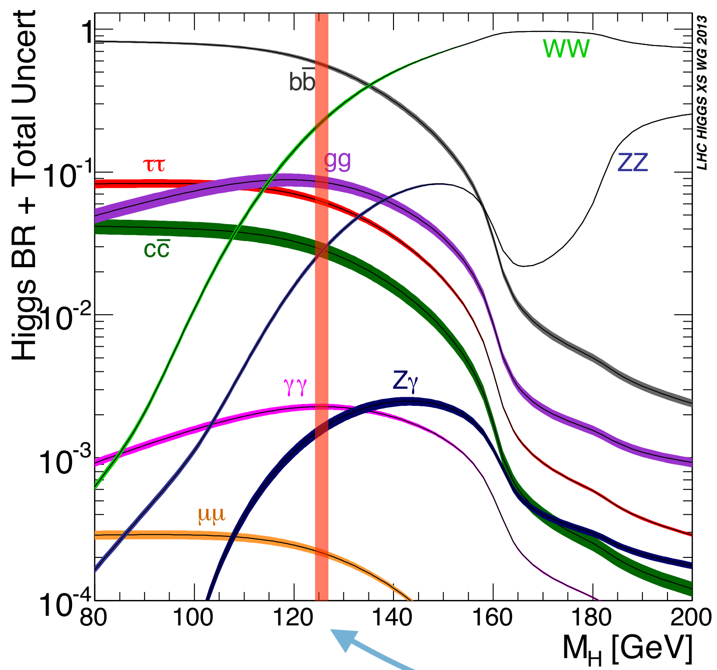

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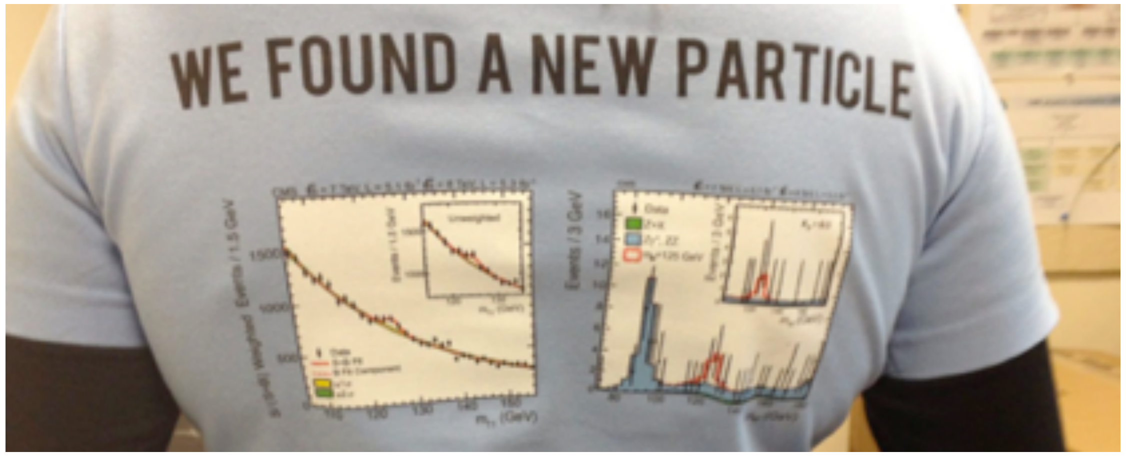
* From a young physicist's point of view:

The Higgs boson has been discovered in our lifetime



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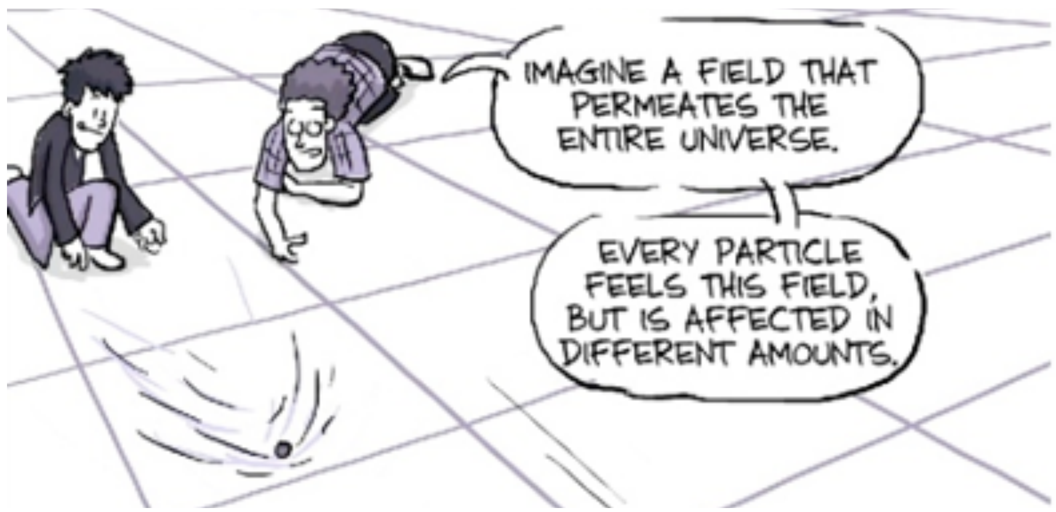

It is everywhere...

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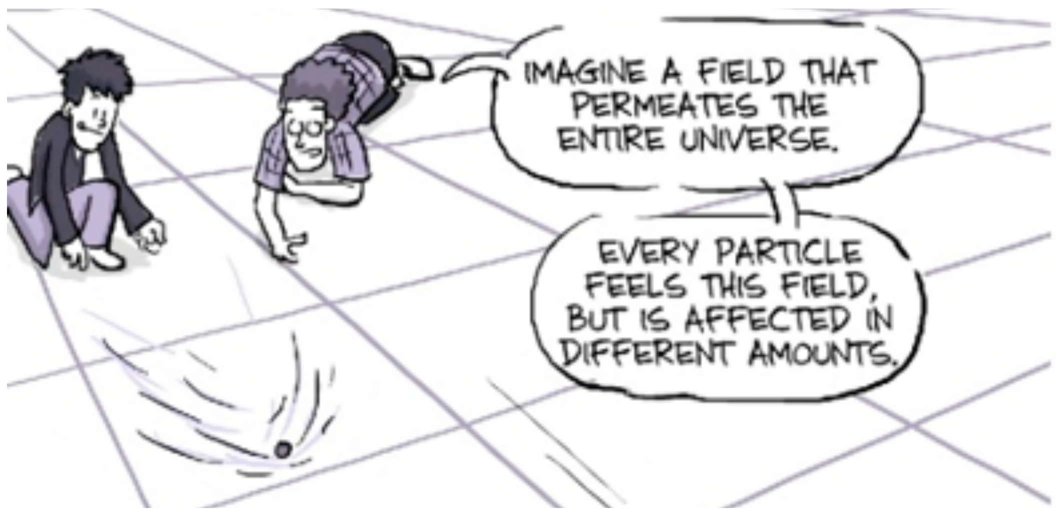
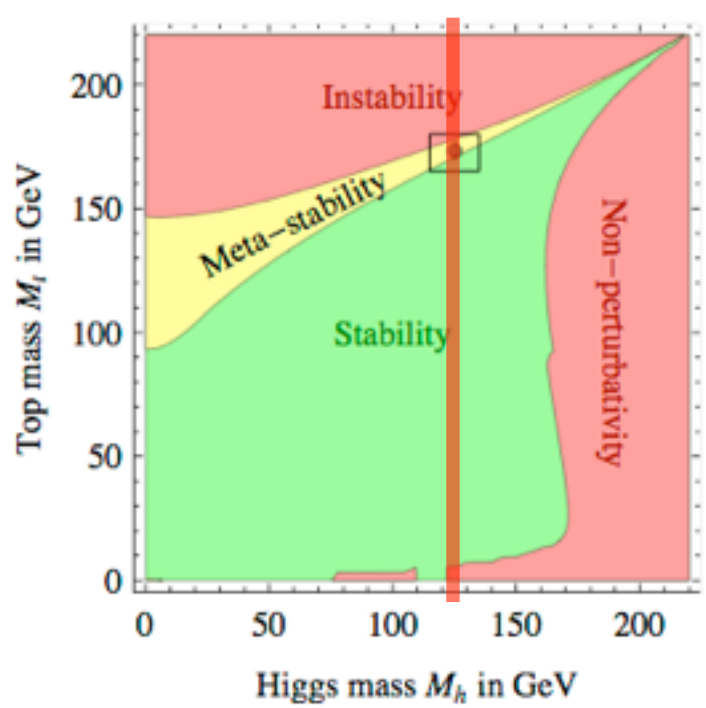


* From our children's point of view:

The Higgs boson might hold the key for the fate of the universe



Motivation

Why Stop Worrying and Love the Higgs...

* From a poet's point of view:

Cotton candy!

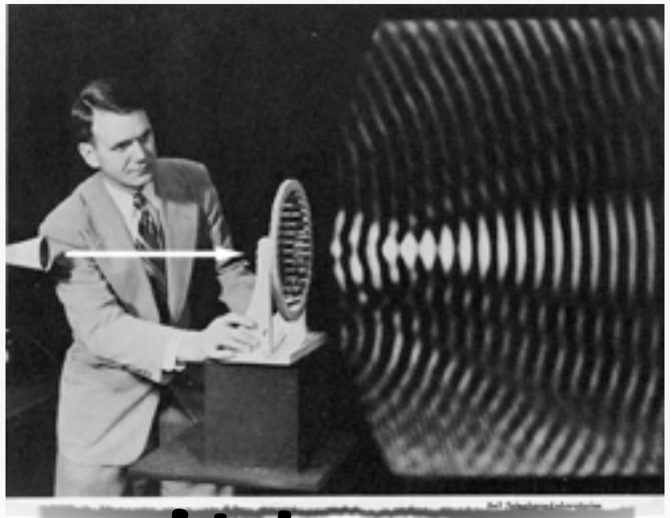
The Higgs field is like...

A crowded room!

P. Higgs

Snow!

Ellis



Air! Strassler

Water! Giudice

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Why Stop Worrying and Love the Higgs...

* From a heavy particle's point of view:

The Higgs discriminates between particles, and gives (some of them*) different masses

*=remember that 99% of the universe mass comes from QCD in the proton mass

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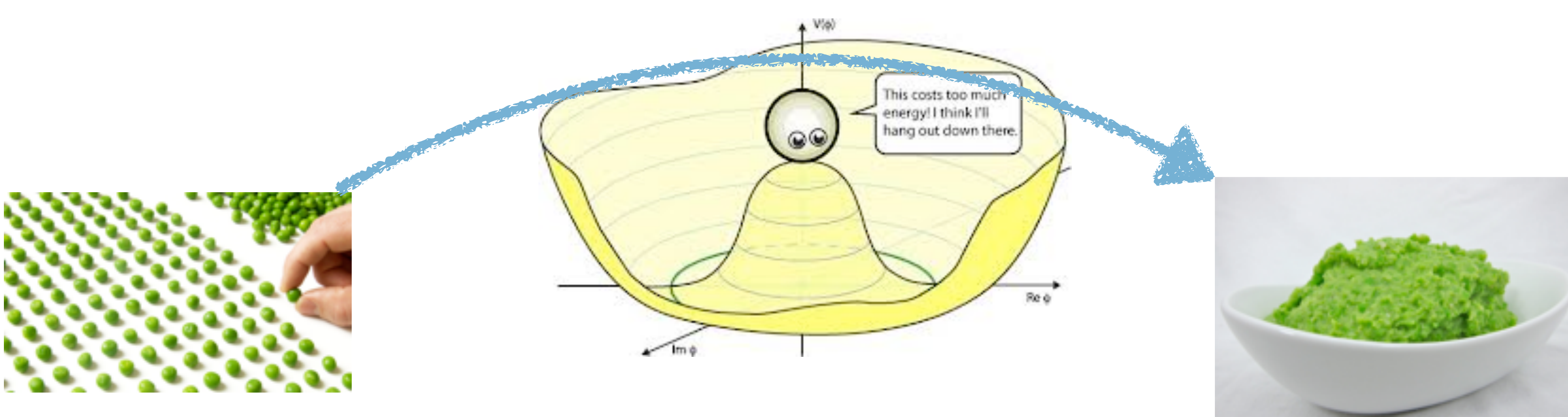
* From a perfectionist's point of view: The Higgs mechanism shows that things might be more ordered than they look



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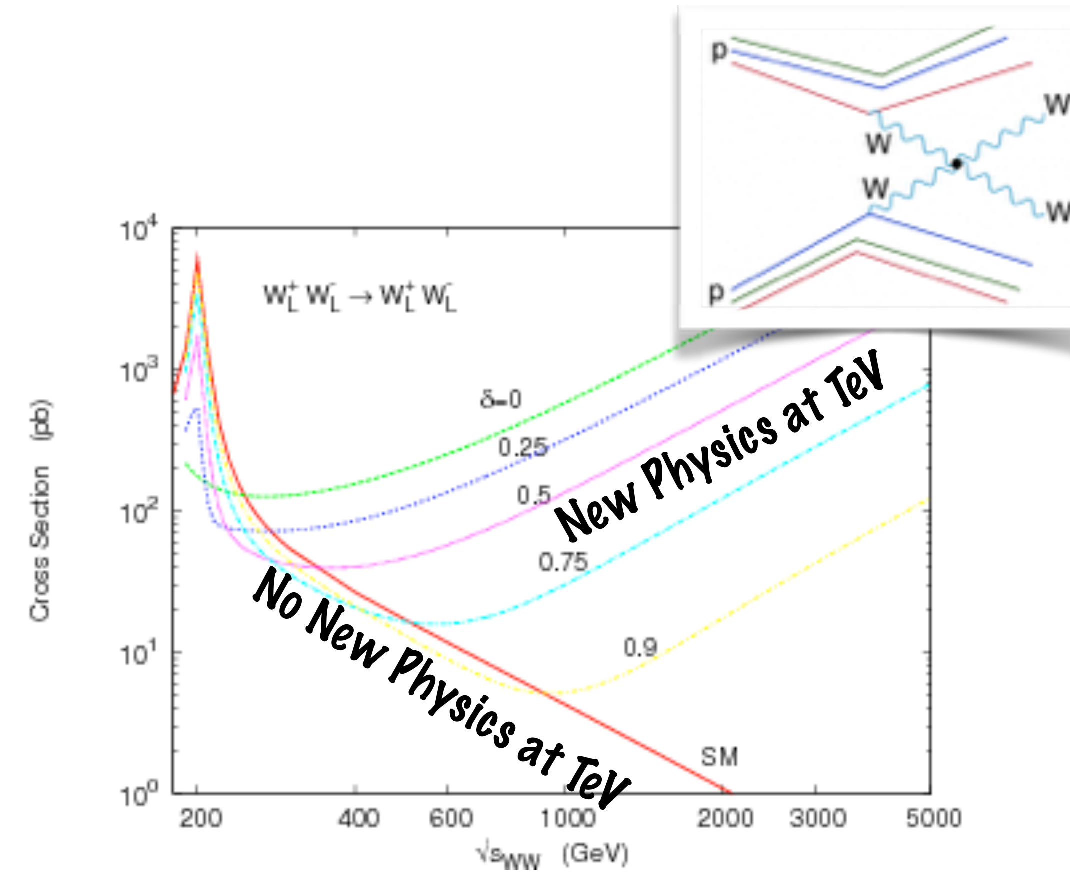
Why Stop Worrying and Love the Higgs...

* From a theorist's point of view:

The Higgs closes the door to what we know...



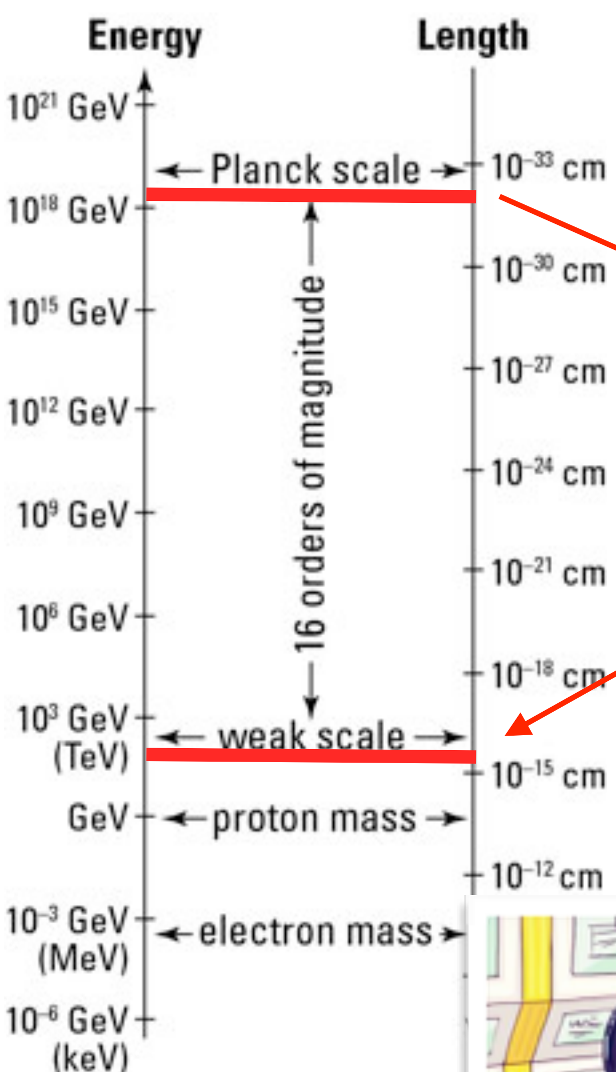
... but perhaps it will leave a window open into the unknown

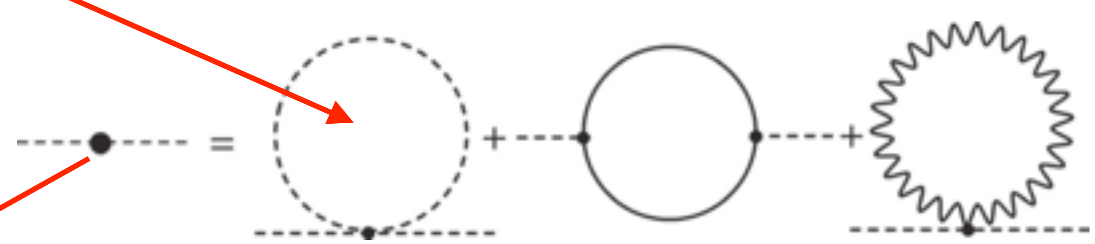
Motivation

Why Stop Worrying and Love the Higgs...

* Finally...

The Higgs hides a secret, the "hierarchy problem": Is it ok to have such a large separation of scales, given that scales mix with each other at the quantum level?





Is "Naturalness" a principle of Nature?

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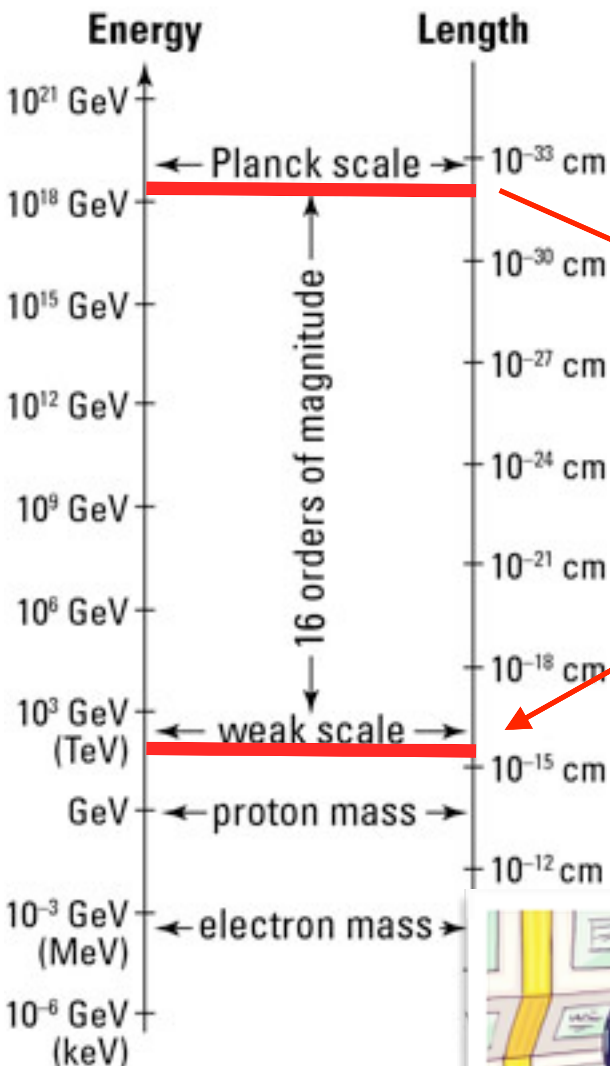
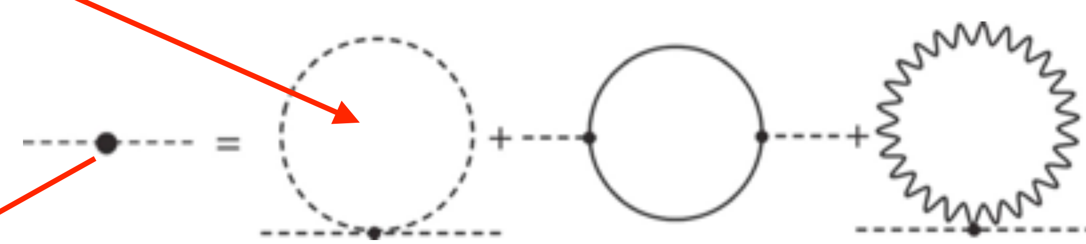
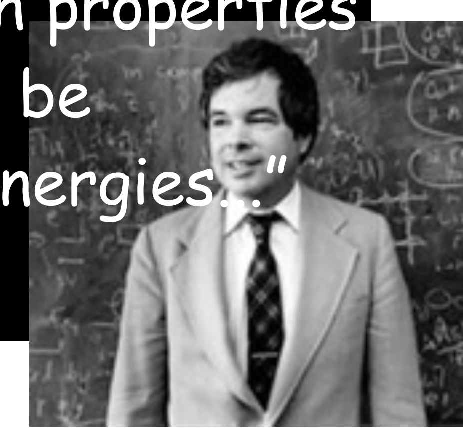




Is "Naturalness" a principle of Nature?

..."**elementary** particles with properties of the Higgs are unlikely to be observable at measurable energies..."
Wilson (Nobel 1936)



Outline

1. **Before the Standard Model (B^{-1}SM)**

   What do vectors need to be massive?

   The SM without Higgs boson?

   Why was LHC built?

2. **Standard Model (SM)**

   How predictive is it?

   How is it defined?

   How do we search for the Higgs boson?

3. **Beyond the Standard Model (BSM)**

   How has the Higgs discovery changed our picture of BSM?

   Hierarchy Problem?

   How can physics BSM impact Higgs phenomenology?

Part I

Before the Standard Model ($B^{-1}SM$)

(Higgs: the missing piece of what puzzle?)

A story of degrees of freedom - (2→3)

In Nature we observe both massless (γ) and massive vectors ($W^\pm$ Z)

...both mediate fundamental interactions, but differ in a crucial aspect:

Momentum: $k = (1,0,0,1) \quad k.k = 0$

Polarizations: $\epsilon_\mu = (a,b,c,d) = \epsilon^L_\mu + \epsilon^{T_1}_\mu + \epsilon^{T_2}_\mu$

$(\epsilon.k = 0)$ $\propto k_\mu$

(Arbuzov lectures)

In physical quantities (e.g. norm):

$\langle A|A\rangle \sim \epsilon_\mu \epsilon^\mu = \epsilon^T.\epsilon^T + 2\cancel{\epsilon^T.\epsilon^L} + \cancel{\epsilon^L.\epsilon^L}$

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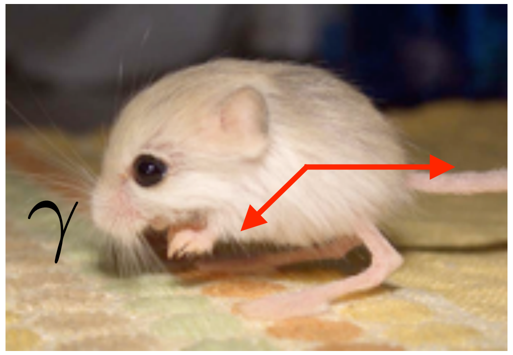

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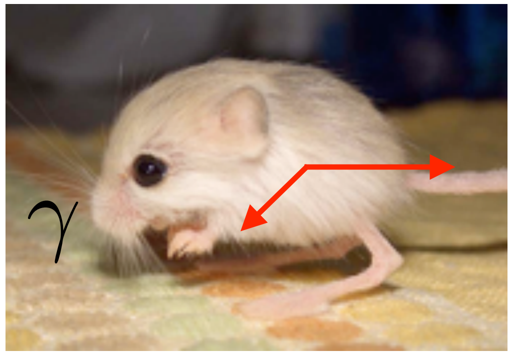

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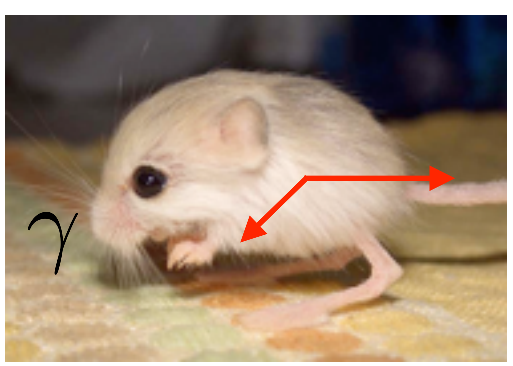

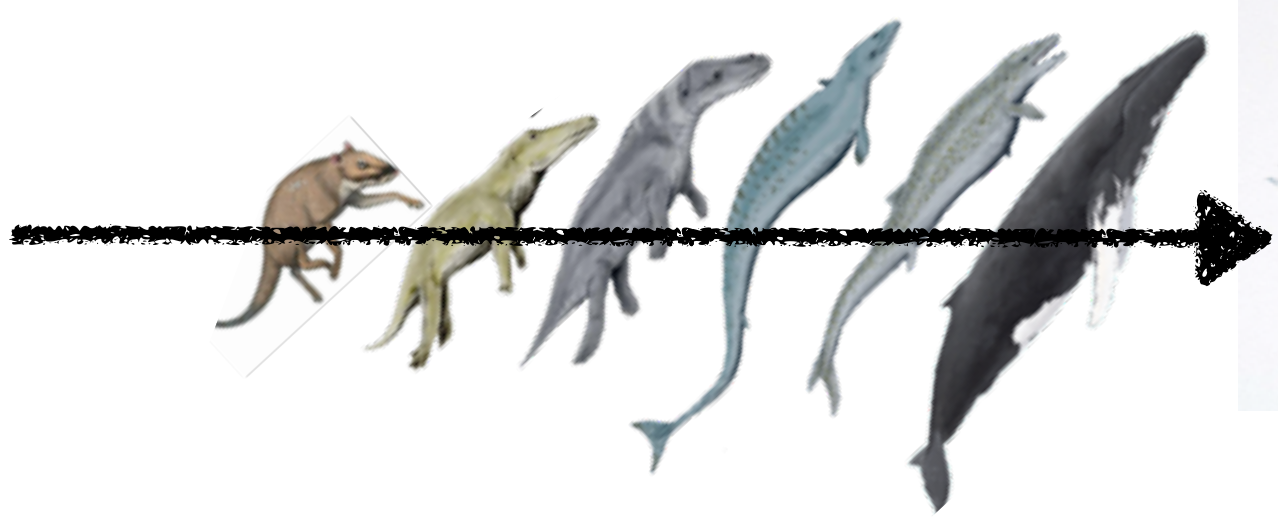

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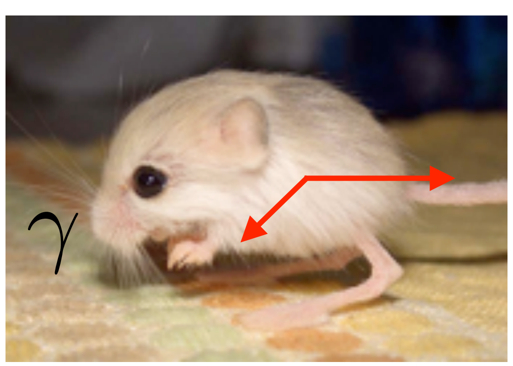

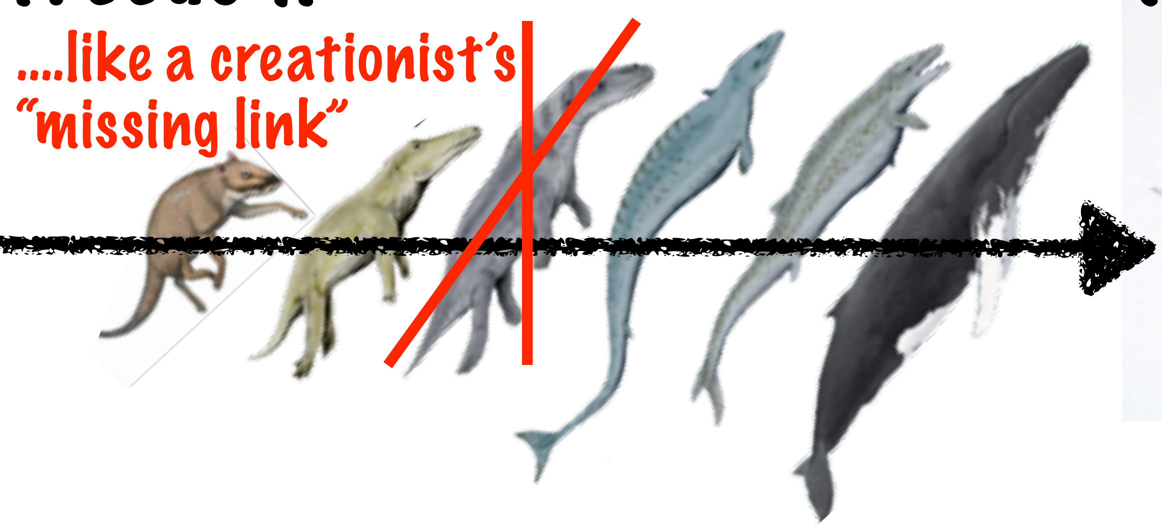

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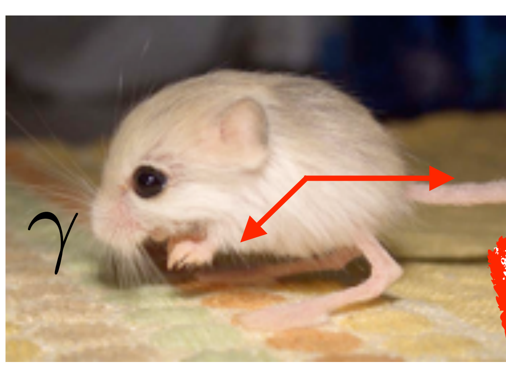

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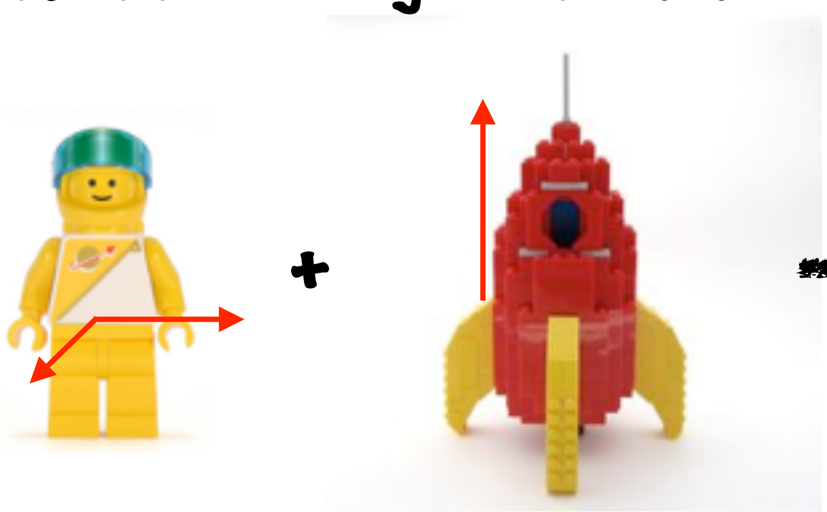

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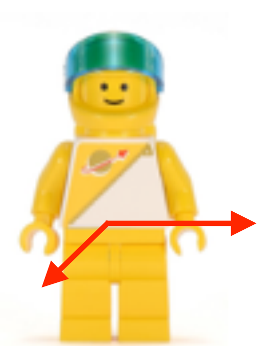
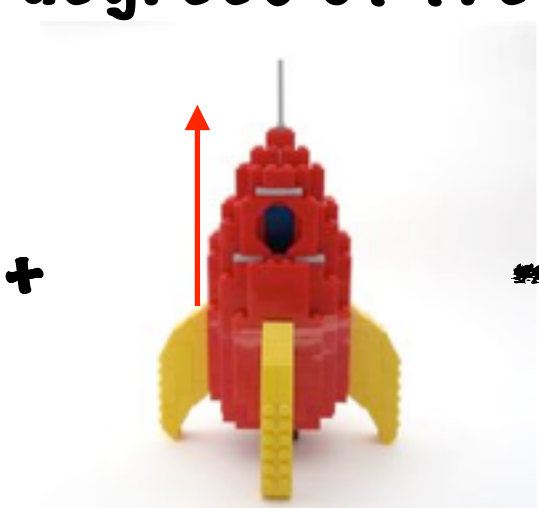
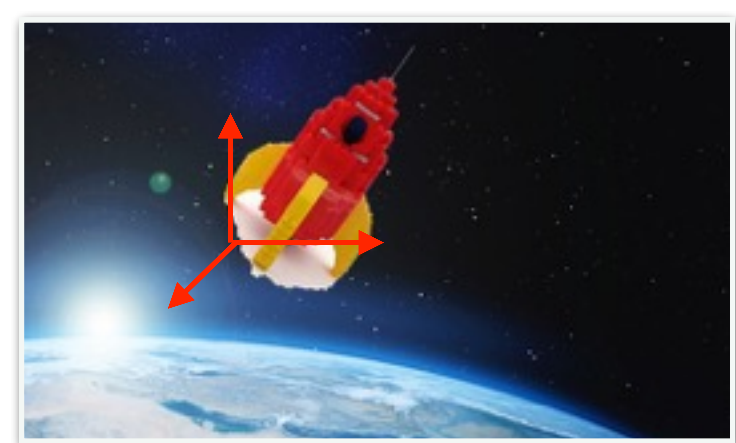
 +  → 

longitudinal pol.

1 massless vector + 1 scalar d.o.f. = 1 massive vector

(Eaten)

A story of degrees of freedom - (4→2)

Another important aspect: Gauge invariance

(or how democracy shows up in the mathematical world)

How could a $\overset{\text{2 d.o.f.}}{\gamma}$ be described by a Lorentz Vector $\overset{\text{4 d.o.f.}}{A_\mu}$?

4 Legs Good
2 legs better

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Same physical system
(e.g. translational invariance)

All animals
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2 d.o.f. 4 d.o.f.

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...some are more equal than others

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→ Action must be invariant under: $A_\mu \to A_\mu + \partial_\mu \alpha(x)$

($W_\mu \to U W_\mu U^{-1} + \partial_\mu U U^{-1}$ for $U \in G$ non-abelian)

(In fact, 1864 Maxwell's equations are gauge-invariant - although initially unnoticed)

Massive Vectors

$\boxed{4 \to 2 \to 3}$ ➔ massive vector = massless gauge vector + 1 scalar d.o.f.

A_μ ϕ

Massive Vectors

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Simplest gauge-redundant Lagrangian: $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{m^2}{2} (\partial_\mu \phi - A)^2$

(for $\alpha(x) = -\phi(x)$ is a mass term)

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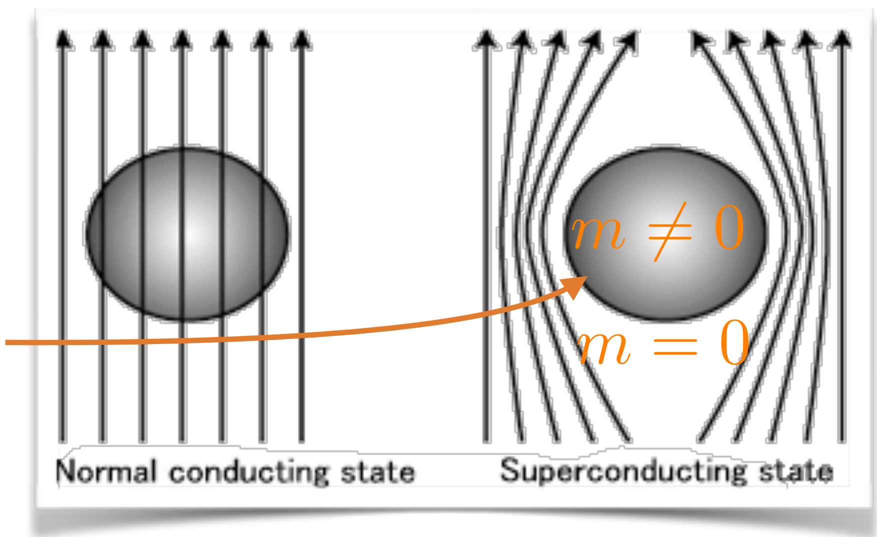
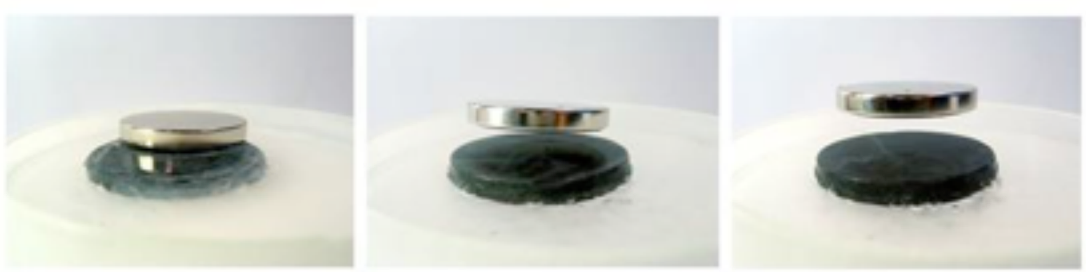
Exemple: Meissner effect

EM field decays exponentially inside superconductor

↓

Massive photon= photon + phase of Cooper ee pair





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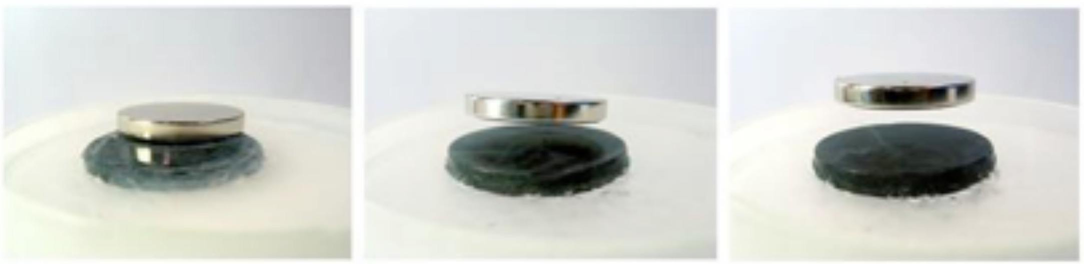
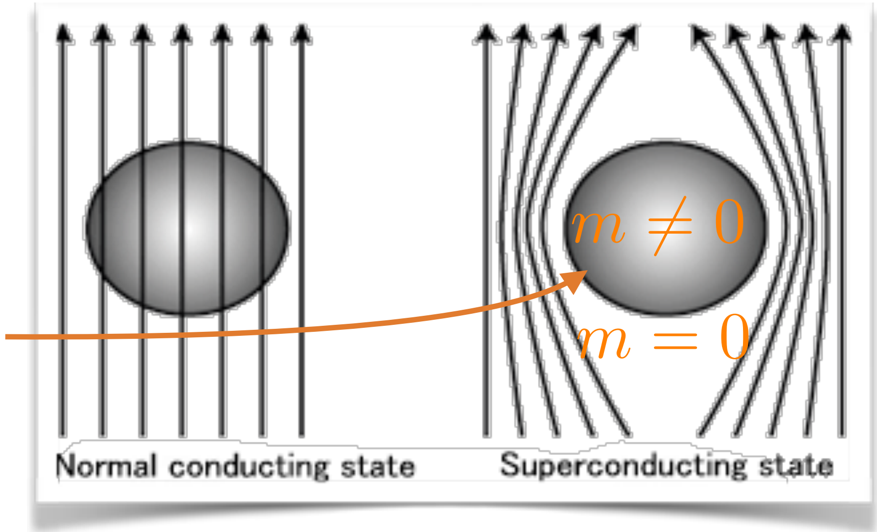
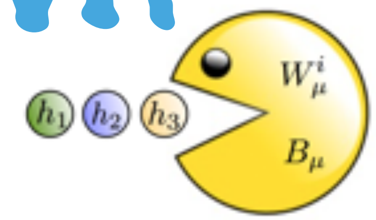




Can this work for the SM $SU(2)_L \times U(1)_Y$ symmetry?

Massive Vectors in the SM?



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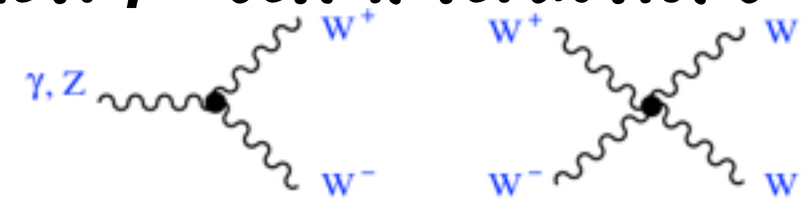
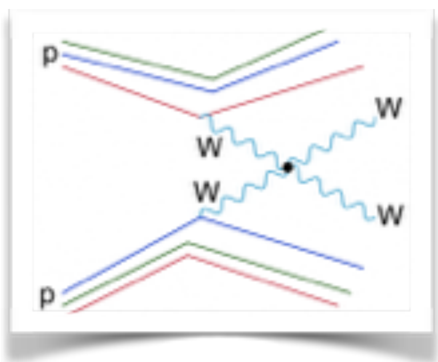
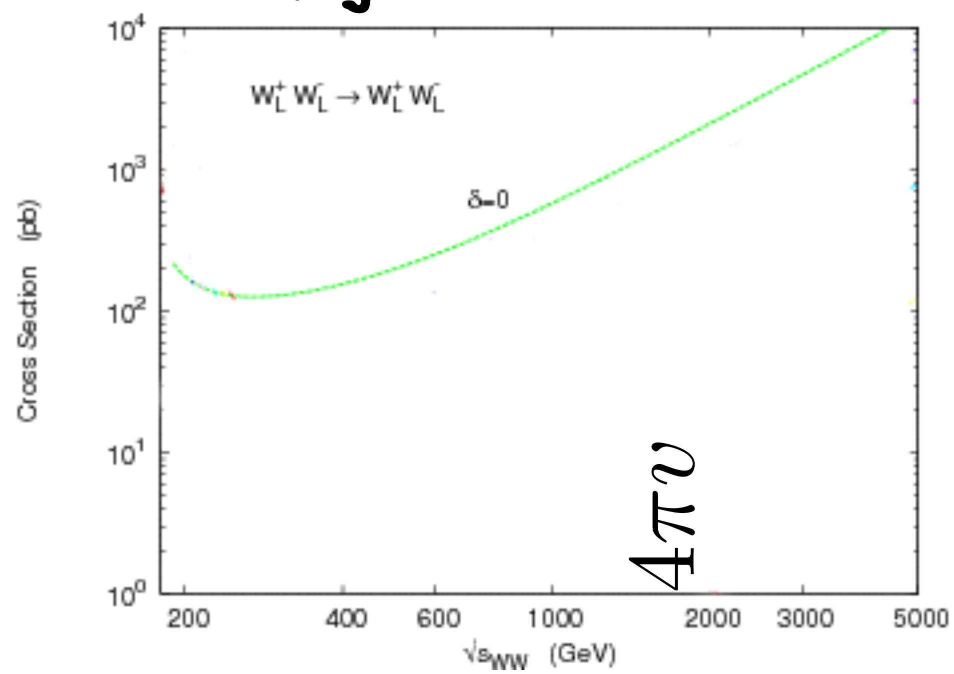
Non-abelian symmetry = self-interactions



Trouble in $W_L W_L$ scattering...





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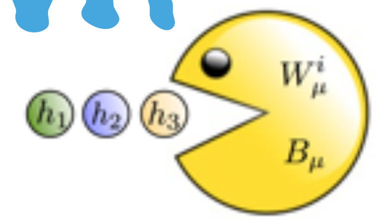
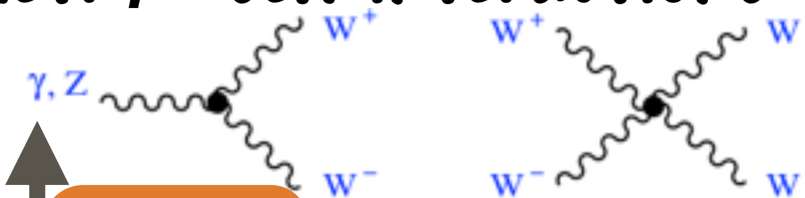


Non-abelian symmetry = self-interactions



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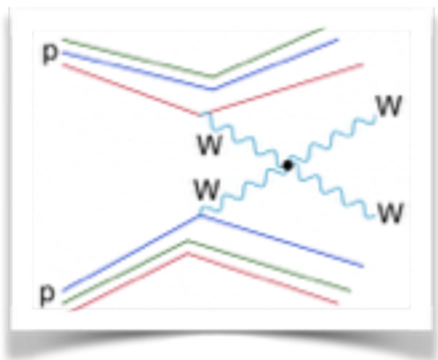

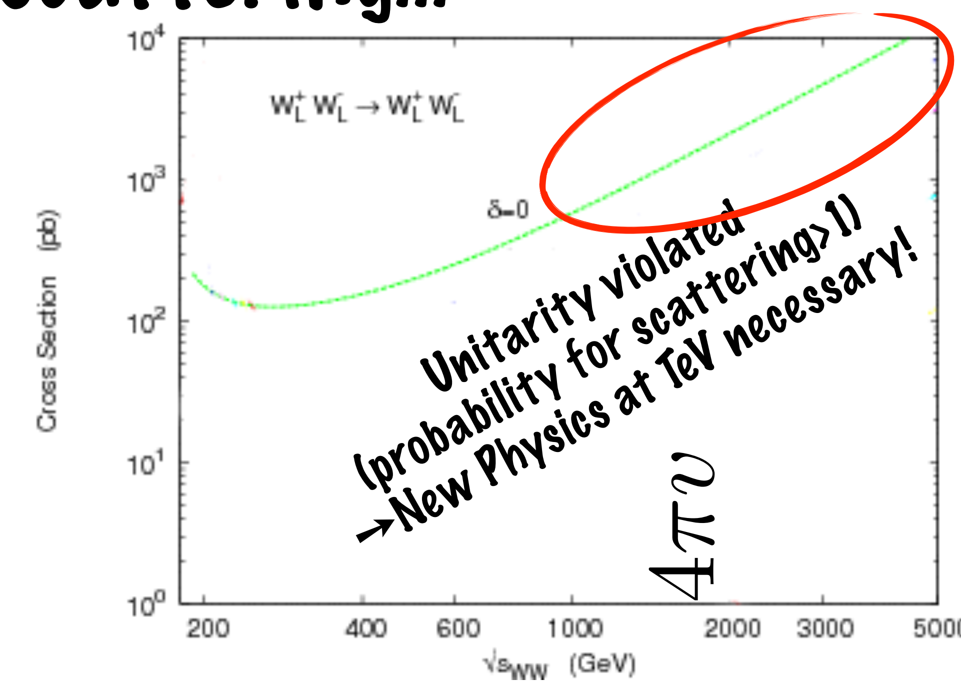

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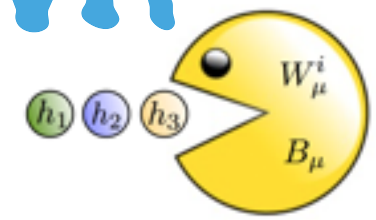

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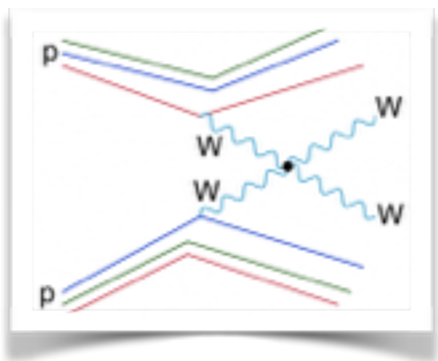
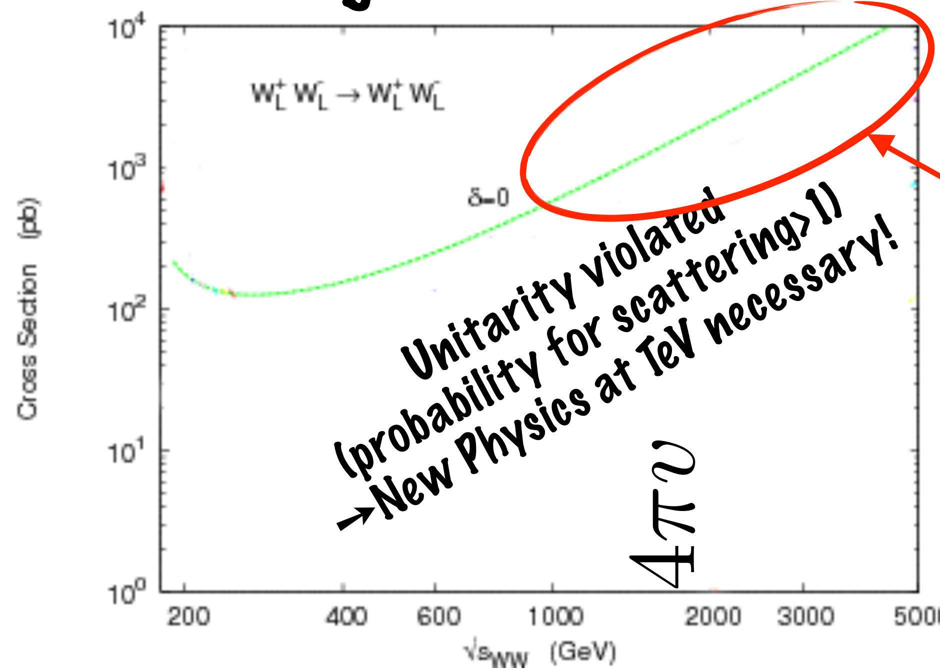
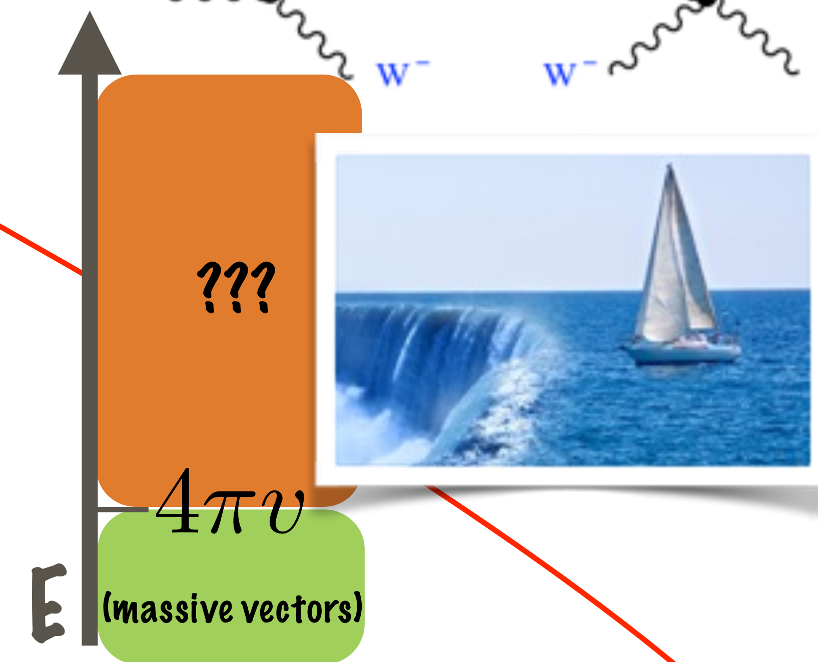


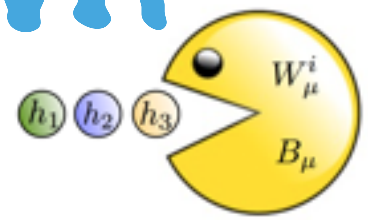




Why? Fields that transform as $\phi \to \phi + \alpha$ (non-linear transformation) are very special in physics: they are Goldstone bosons of a spontaneously broken symmetry

They appear with derivatives → their interactions grow with Energy

Massive Vectors in the SM?



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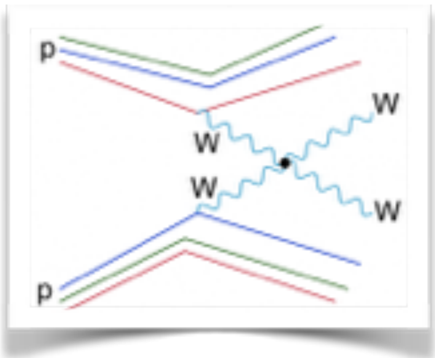

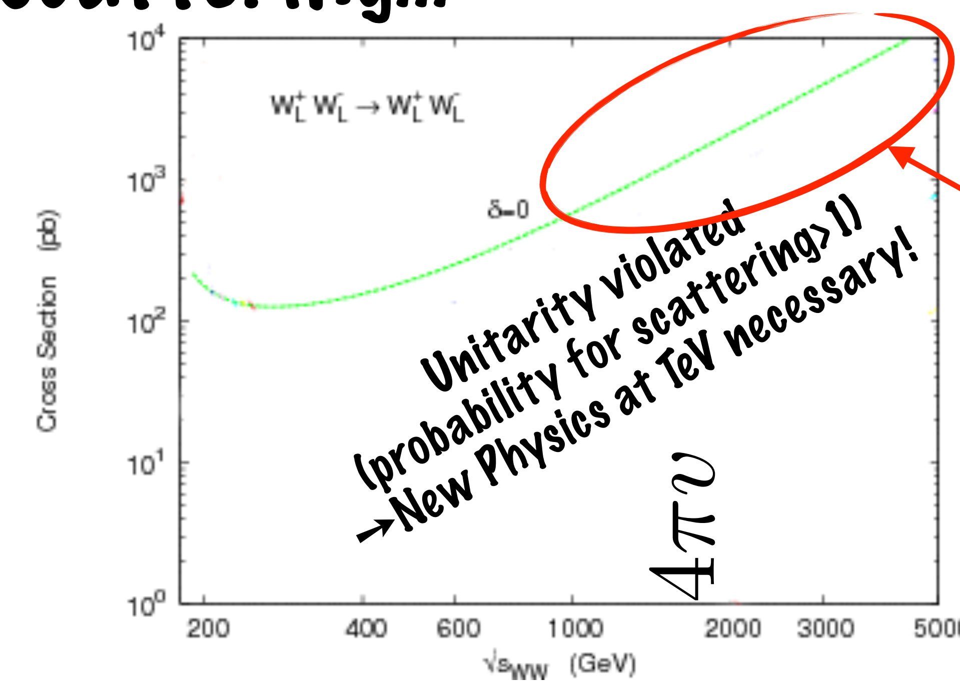

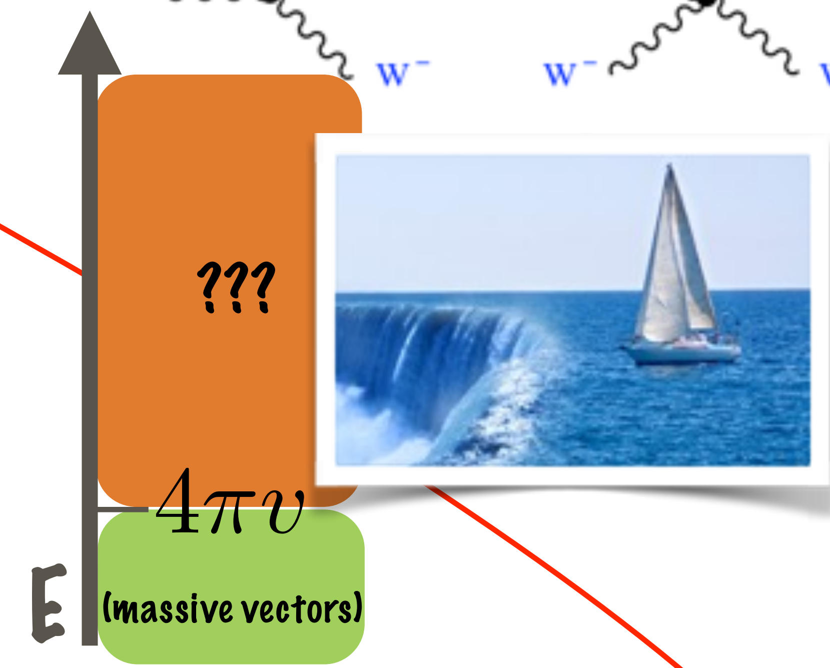

Why? (non-linear transformation)
Fields that transform as $\phi \to \phi + \alpha$ are very special in physics: they are Goldstone bosons of a spontaneously broken symmetry

They appear with derivatives → their interactions grow with Energy

So what's going on? They are necessarily only the low energy manifestation of a more complicated microscopic theory!

Exemples of Goldstone bosons

- **Pions in QCD:** Quarks $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} u_R \\ d_R \end{pmatrix}$ have $SU(2)_L \times SU(2)_R$ symm. (approximate)

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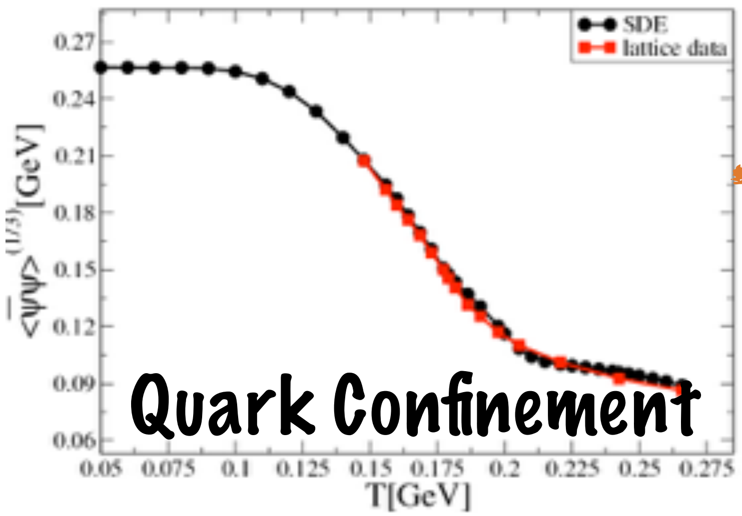

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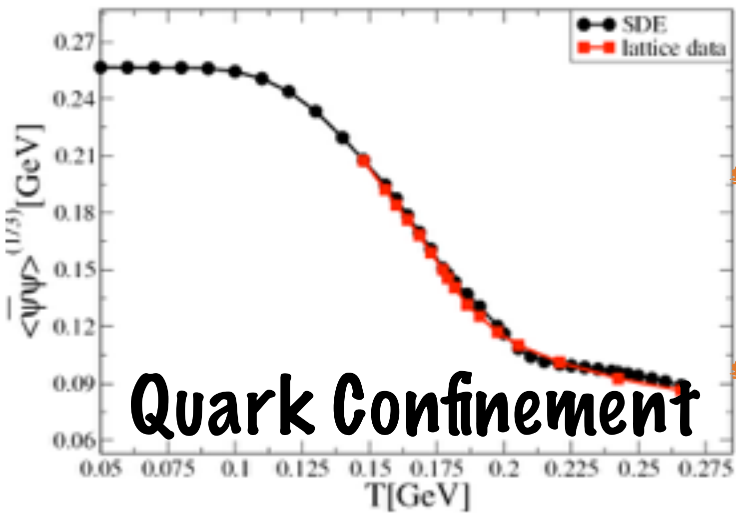

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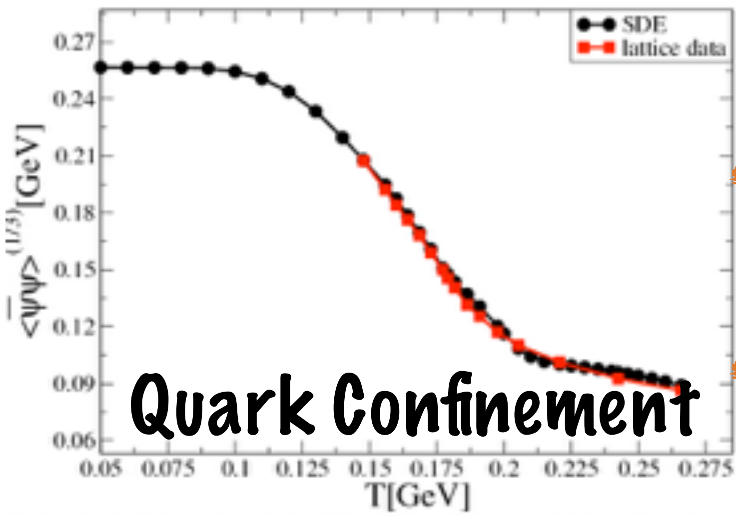

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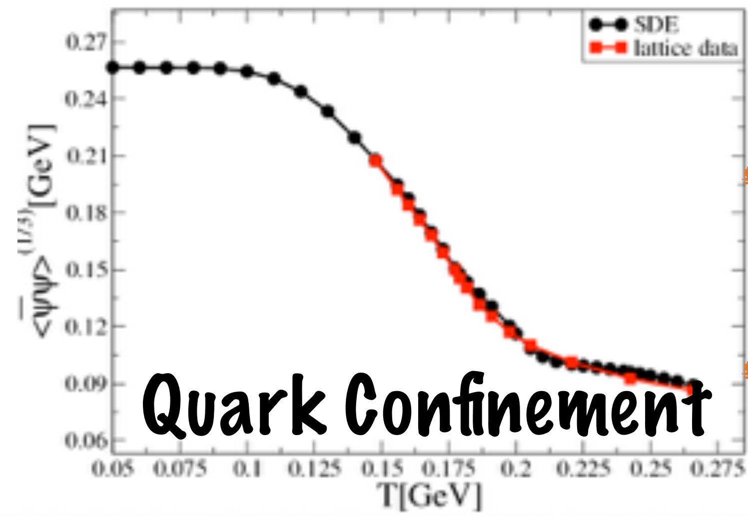

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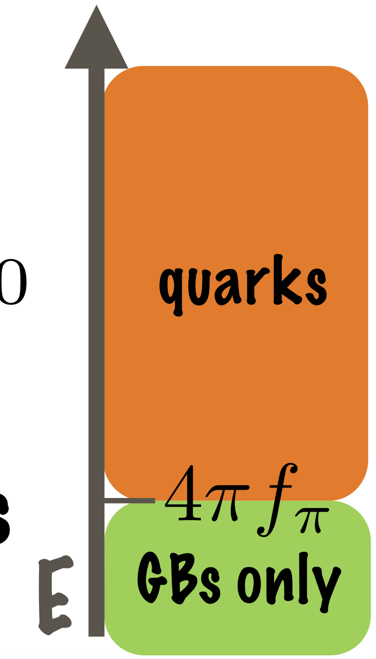

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$$\boxed{\Phi = \varphi e^{i\phi}}$$

non-linear (G.B.)

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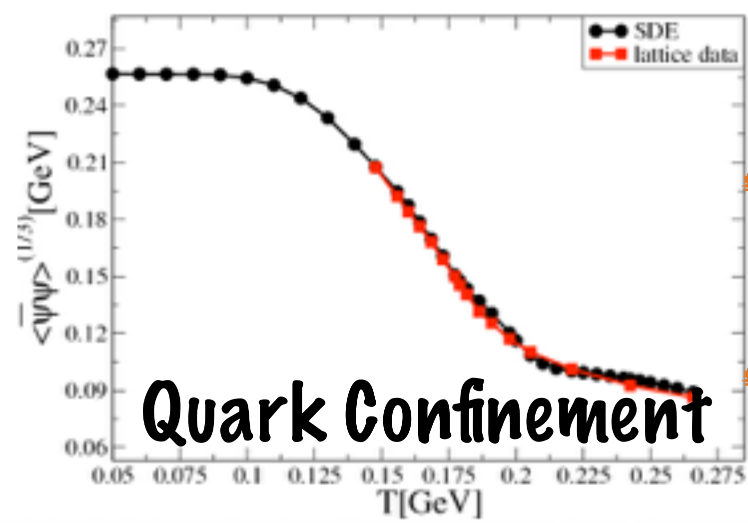

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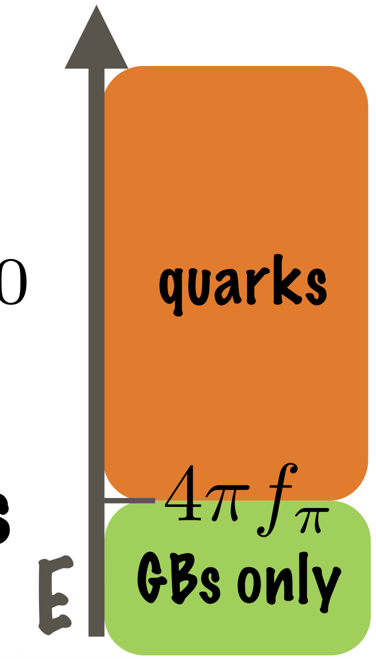

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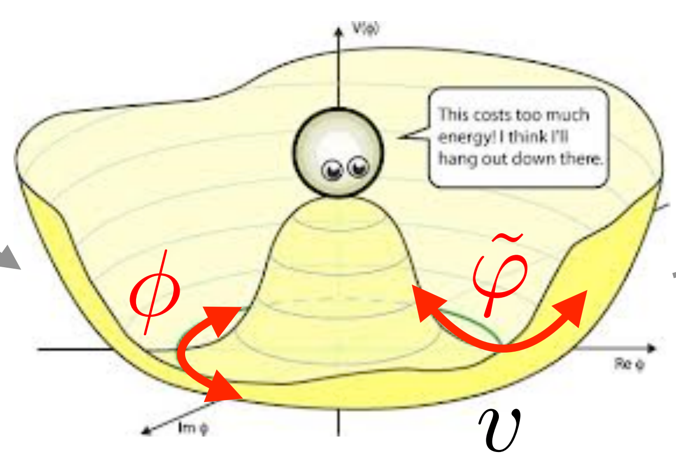

$$\varphi \to v + \tilde{\varphi}$$

Higgs boson

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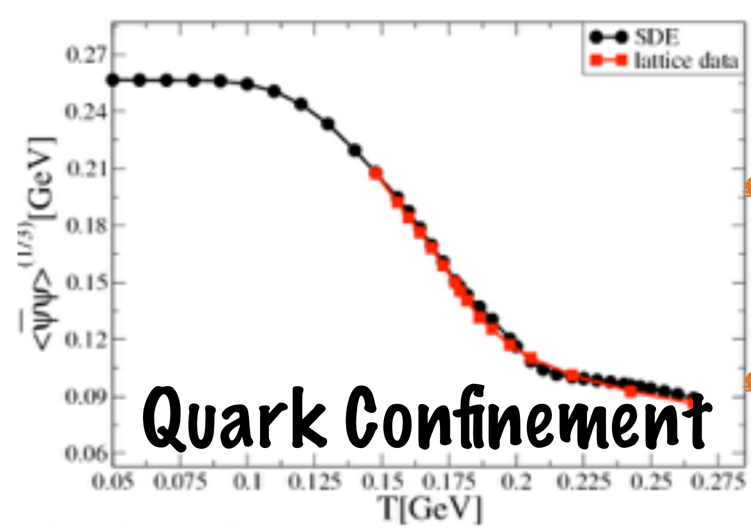

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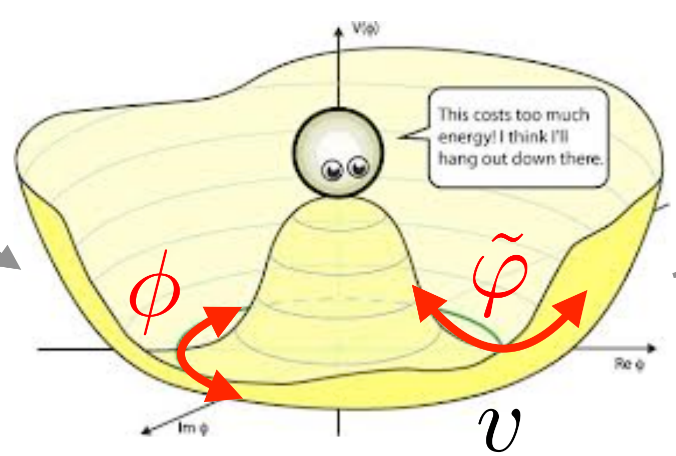

-Linear reps can be fundamental
(no problem with derivative couplings and E-growth)

-But an additional state necessary
(to extend non-linear into linear)

$$\varphi \to v + \tilde{\varphi}$$

Higgs boson

Extra States + Renormalizability

(=model can be extrapolated to arbitrary high energy)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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Higgs boson

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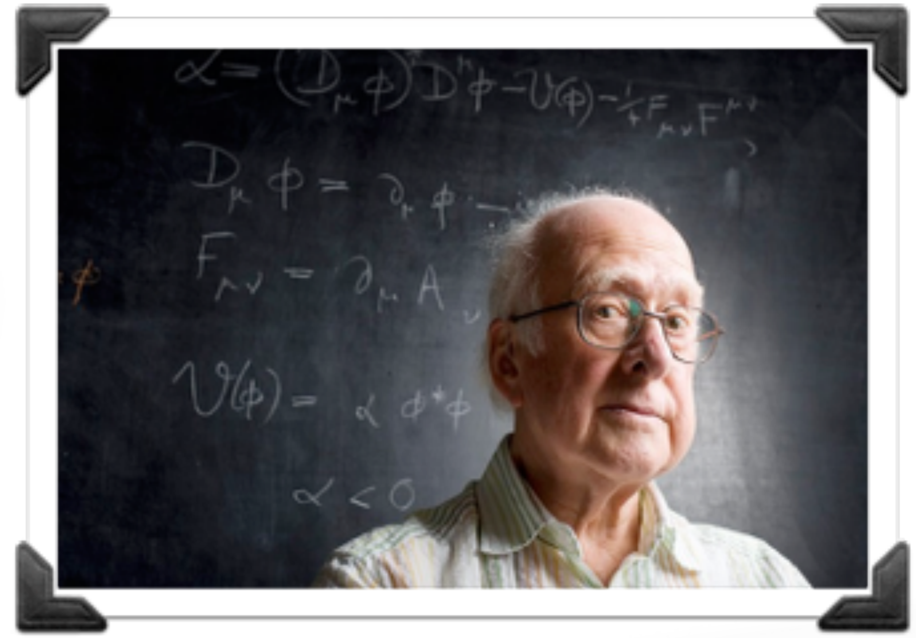

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
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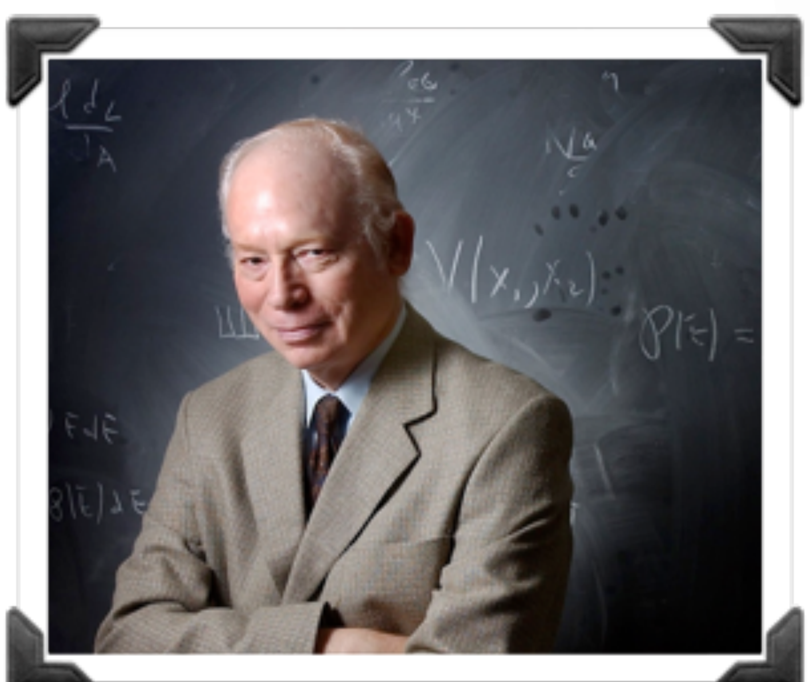

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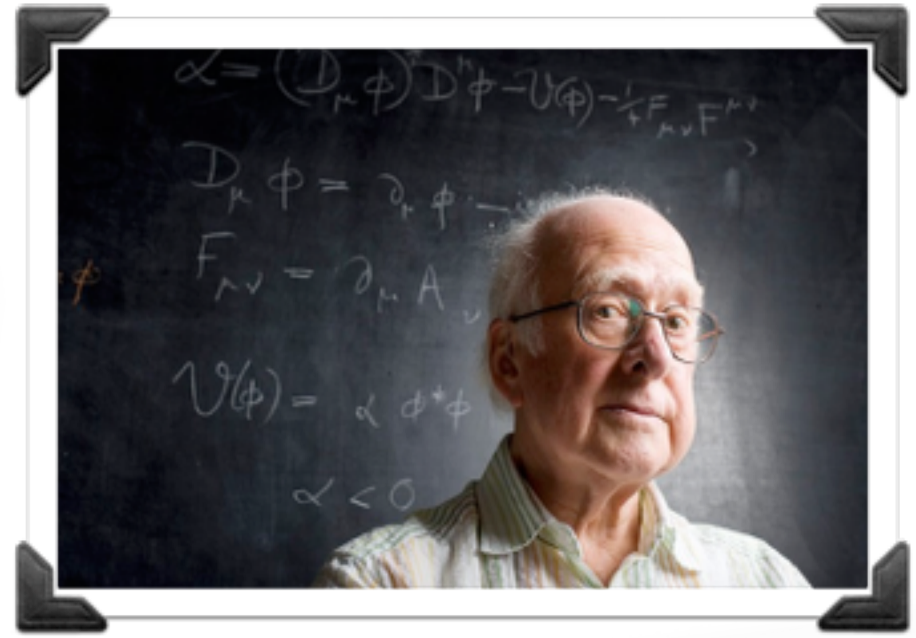

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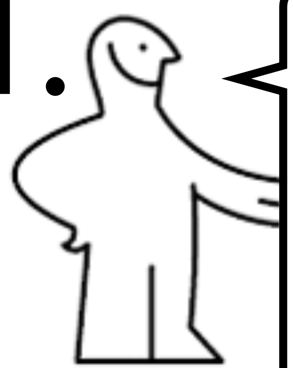

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(SM: smallest rep.>3)

$$\underset{(\mathbf{2},1/2)}{H} = (H^+, H^0) \qquad H^+ = h_1 + i h_2 \quad H^0 = h + i h_0$$

$$\cap$$

or equivalently SU(2)$_L$xSU(2)$_R$

(More technical, unusual,but more rewarding...)

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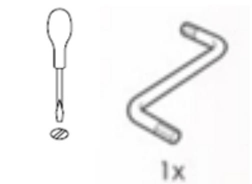

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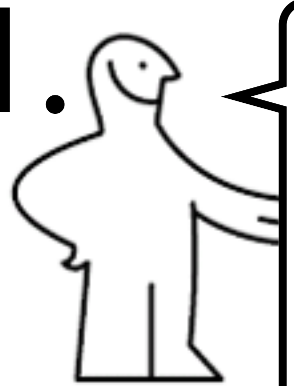
1. 

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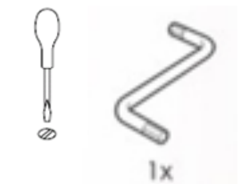
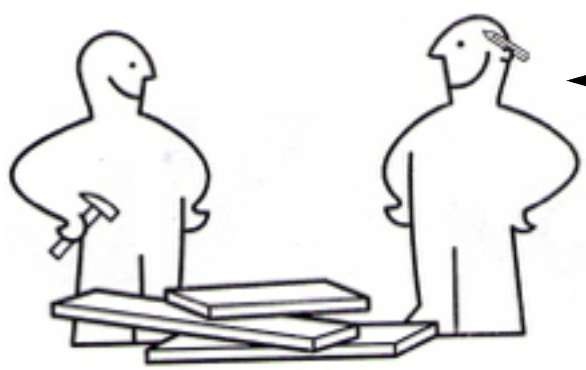


2. 

Build general symmetric Lagrangian

(See lecture 2 and Wulzer's)

$$\mathcal{L} = \mathcal{L}_{\rm kin}^{W,B,\Psi} + \underbrace{|D_\mu H|^2}_{\mathrm{Tr}(D_\mu \Sigma^\dagger D_\mu \Sigma)} - V(|H|) + (y \Psi_L H \Psi_R + \mathrm{h.c.}) + \sum_{d\geq 5} \frac{\mathcal{O}^d}{\Lambda^{d-4}}$$

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$\Lambda \to M_{\rm Pl}$

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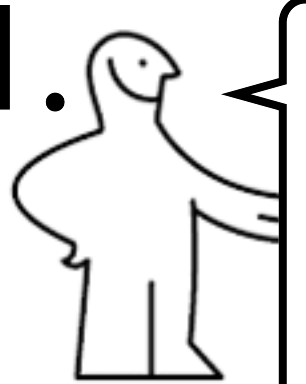

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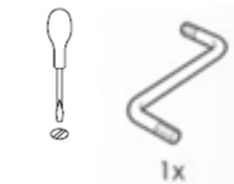

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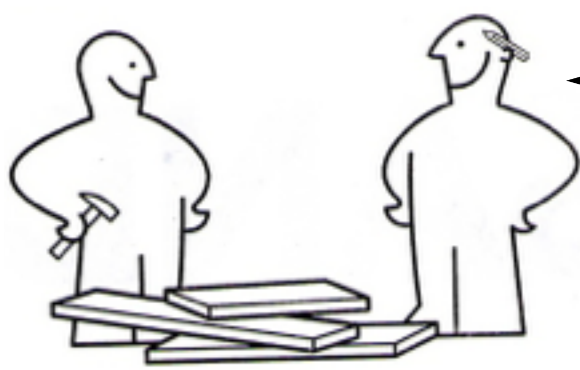

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$\mathrm{Tr}(D_\mu \Sigma^\dagger D_\mu \Sigma)$ $\quad\Sigma$

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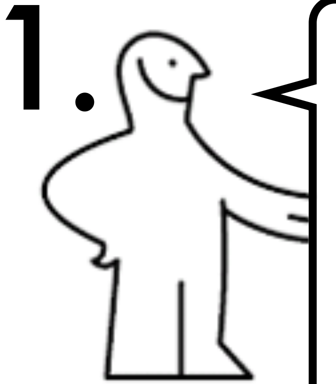

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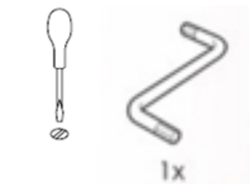

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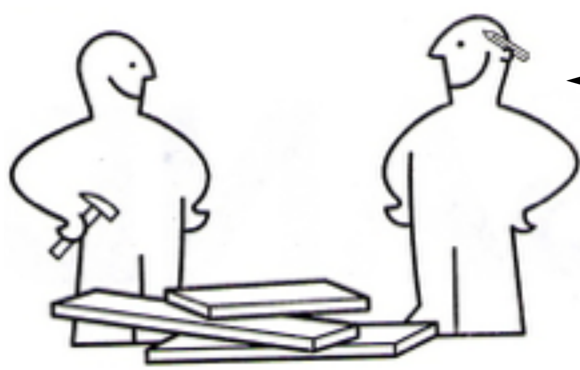

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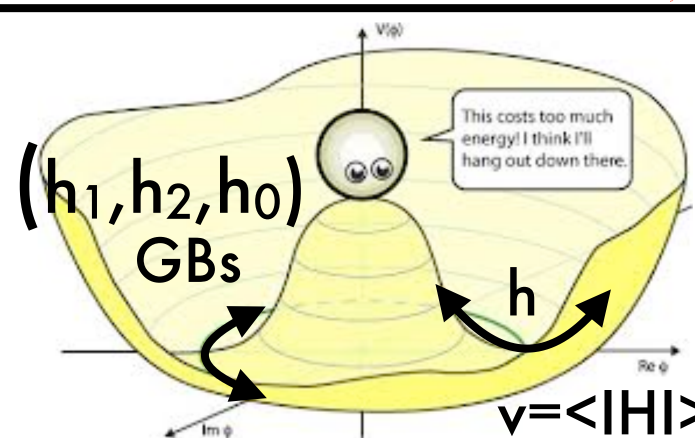
3.

Use Brout-Englert-Higgs potential to produce Goldstone Bosons (SSB)

$$V = -\mu^2 |H|^2 + \lambda |H|^4$$



SSB at minimum of energy:

$\langle H \rangle = (0, v)$ **SU(2)$_L$xU(1)$_Y$→U(1)$_{EM}$**

$\langle \Sigma \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix}$ **SU(2)$_L$xSU(2)$_R$→SU(2)$_C$ ⊃ U(1)$_{EM}$**

Custodial Symm (g'→0)

How to make the SM Valid to arbitrary High-E?

4. For physics at low energy, expand at minimum

$$\mathcal{L} = \mathcal{L}_{\rm kin}^{W,B,\Psi} - \frac{v^2}{4}\begin{pmatrix} W_\mu^1 \\ W_\mu^2 \\ W_\mu^3 \\ B_\mu \end{pmatrix}^T \begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & gg' \\ & & gg' & g^2 \end{pmatrix}\begin{pmatrix} W_\mu^1 \\ W_\mu^2 \\ W_\mu^3 \\ B_\mu \end{pmatrix}(1+\frac{h}{v})^2 \quad - \frac{m_h^2}{2}h^2(1+\frac{h}{v}+\frac{1}{4}\frac{h^2}{v^2}) - \sum_{f=u,d,e,..} m_f\bar{\psi}_f\psi_f(1+\frac{h}{v})$$

Custodial Symm → $\rho \equiv \dfrac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$

Also mass to fermions and Higgs boson!

How to make the SM Valid to arbitrary High-E?

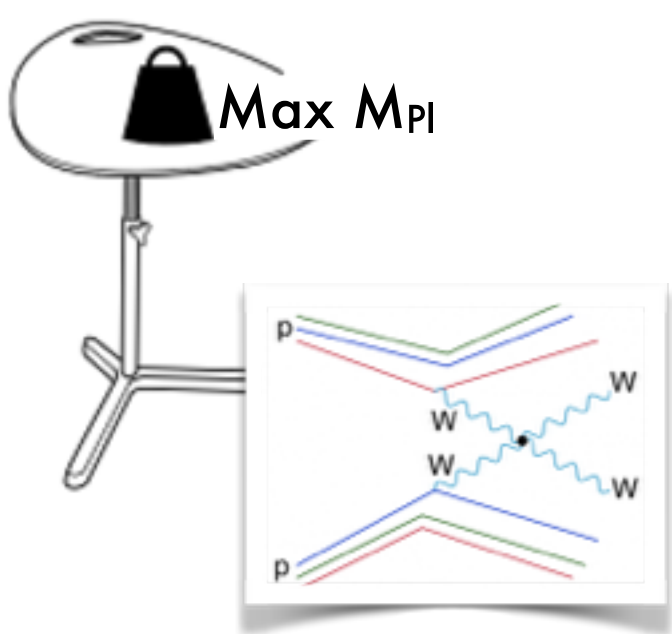
4. For physics at low energy, expand at minimum

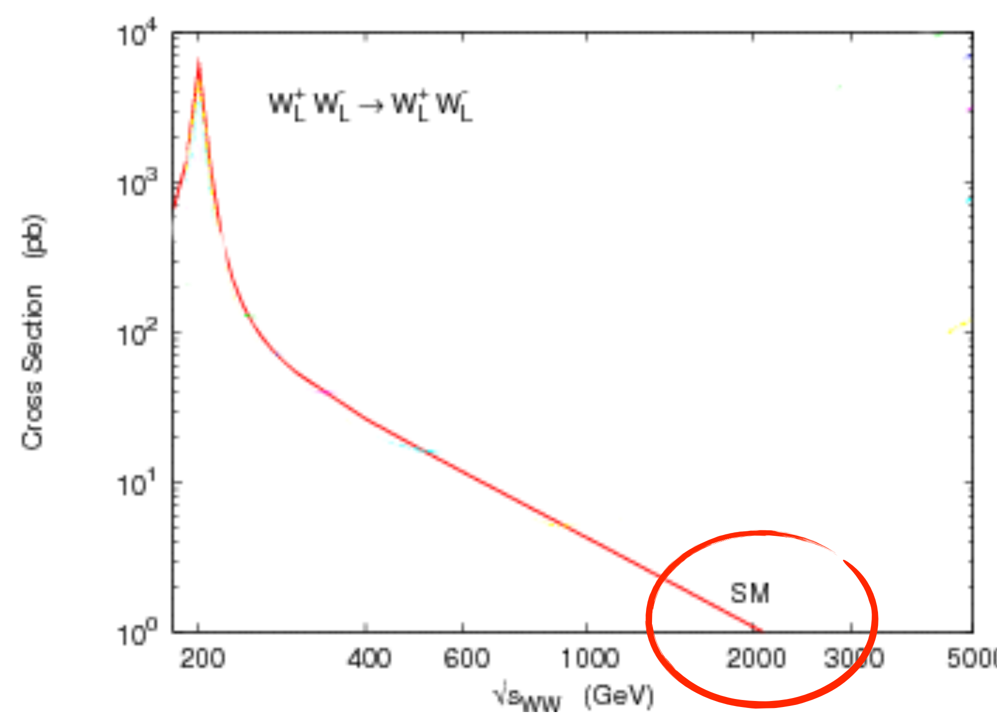
$$\mathcal{L} = \mathcal{L}_{\rm kin}^{W,B,\Psi} - \frac{v^2}{4}\begin{pmatrix} W_\mu^1 \\ W_\mu^2 \\ W_\mu^3 \\ B_\mu \end{pmatrix}^T \begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & gg' \\ & & gg' & g^2 \end{pmatrix}\begin{pmatrix} W_\mu^1 \\ W_\mu^2 \\ W_\mu^3 \\ B_\mu \end{pmatrix}(1+\frac{h}{v})^2 \;\; -\frac{m_h^2}{2}h^2(1+\frac{h}{v}+\frac{1}{4}\frac{h^2}{v^2}) - \sum_{f=u,d,e,..} m_f\bar{\psi}_f\psi_f(1+\frac{h}{v})$$

Custodial Symm $\rightarrow$ $\rho \equiv \dfrac{m_W^2}{m_Z^2\cos^2\theta_W} = 1$

Also mass to fermions and Higgs boson!

5. Test at High-Energy





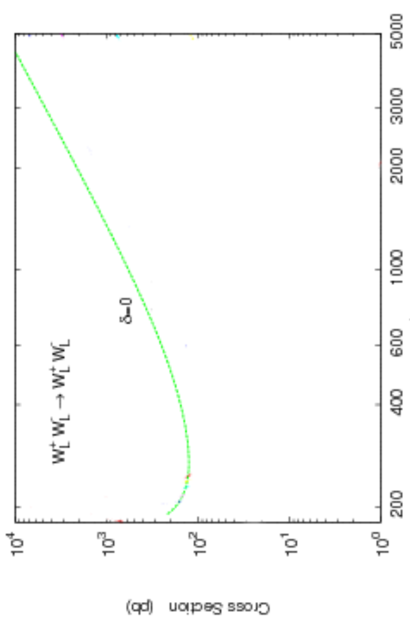
No energy growth!
→Model valid (in principle)
to arbitrary High E

Summary Part I - B^{-1}SM

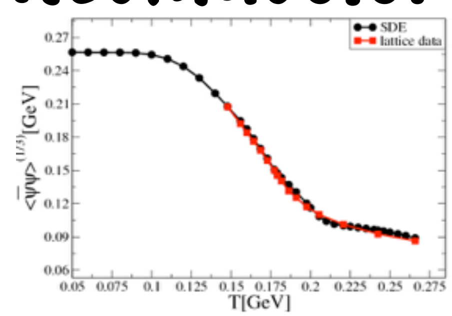
4→2 → Gauge Invariance

2→3 → Goldstone Boson

→ Spontaneous Symmetry Breaking



Like pions in QCD
(Technicolor?)



Strong Coupling

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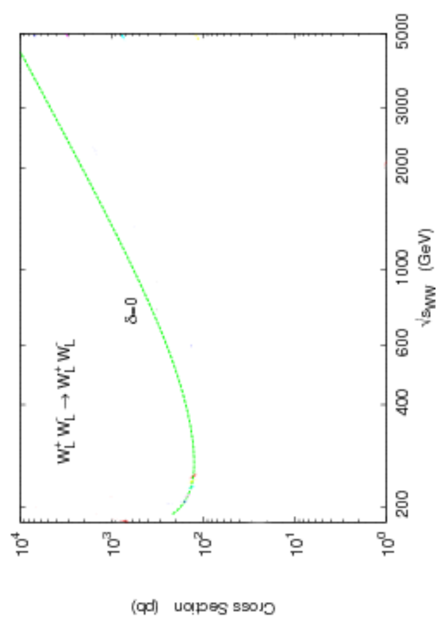

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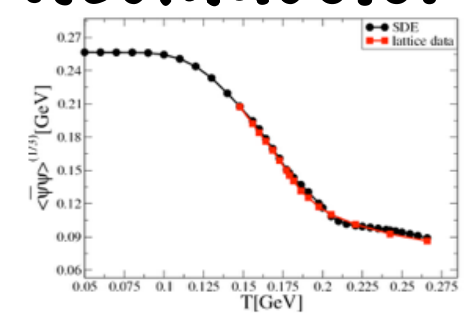
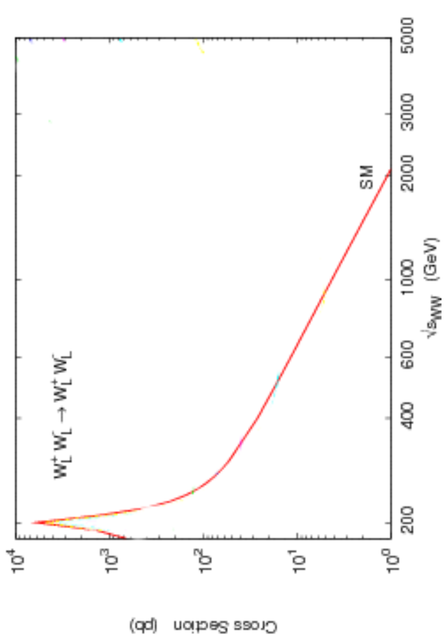
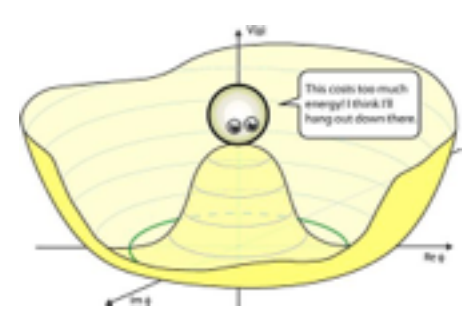


Strong Coupling



The Higgs Field



Weak Coupling

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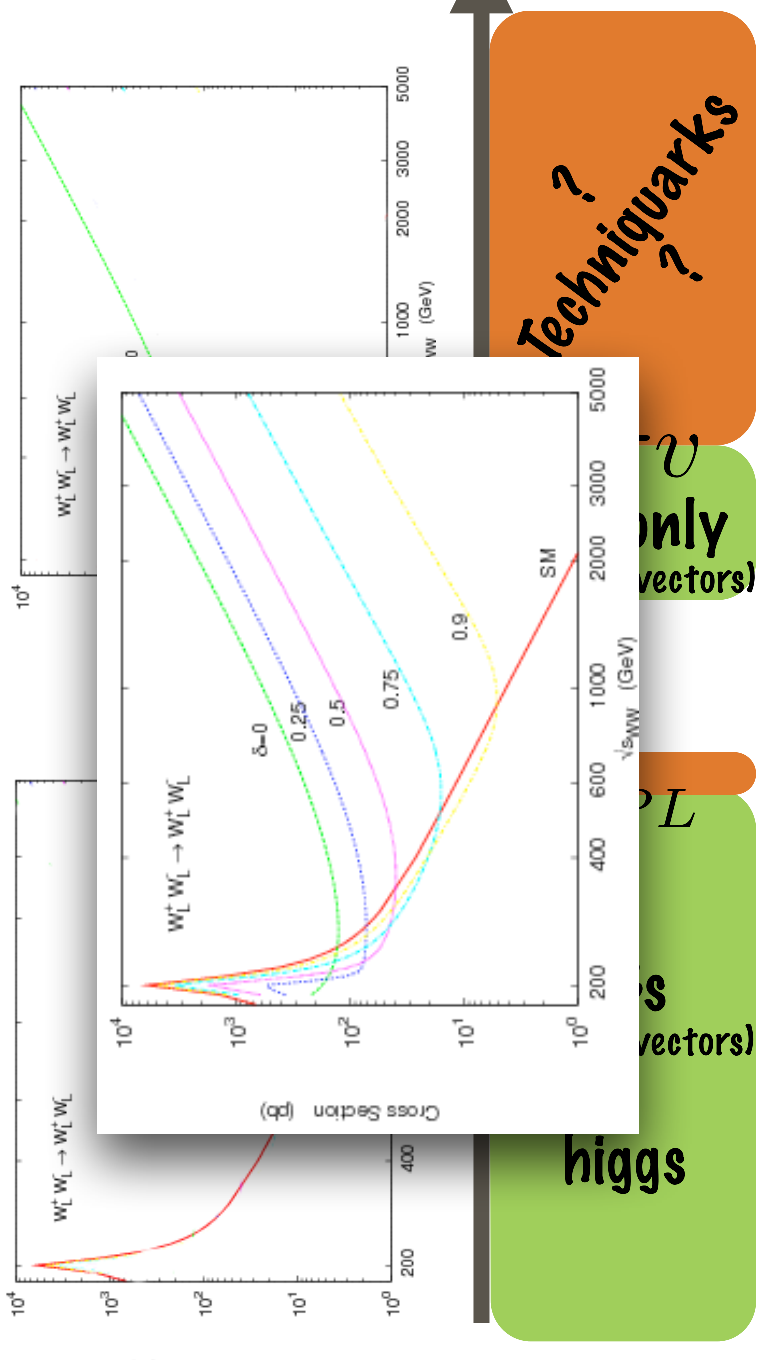
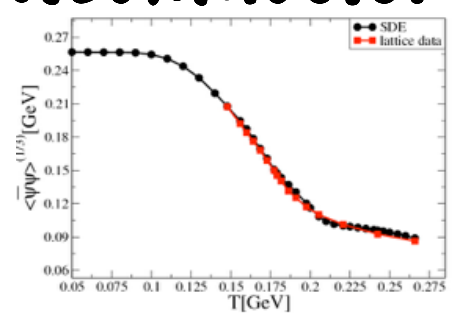


Like pions in QCD (Technicolor?)

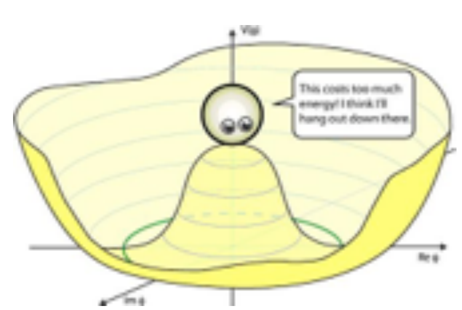


Strong Coupling

See Wulzer lecture/book

PNGB Higgs (SILH)

The Higgs Field



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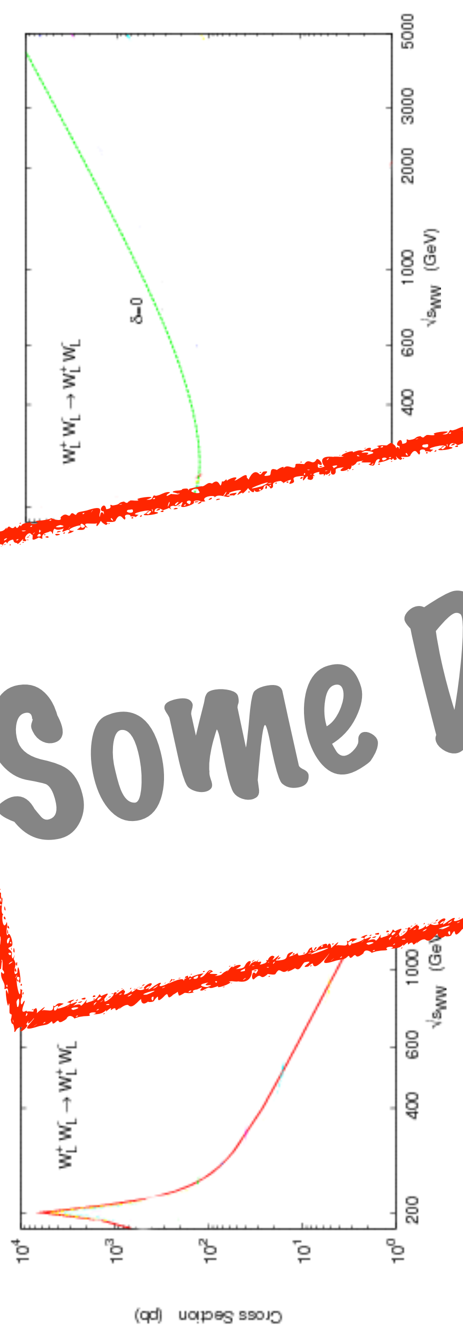


? Techniquarks ?

4π

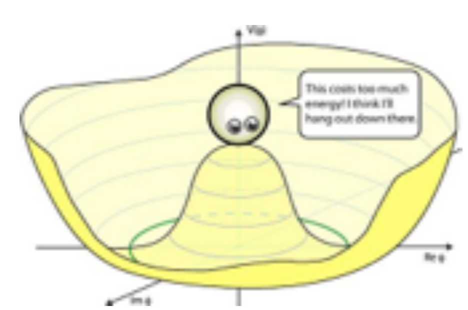
GBs
(massive vectors)
+
higgs

Like pions in QCD
(Technicolor?)

...cture/book ← PNGB Higgs (SILH)

Some Discovery Guaranteed

The Higgs Field



Weak Coupling

Part II

the Standard Model (SM)

Indeed...

the SM

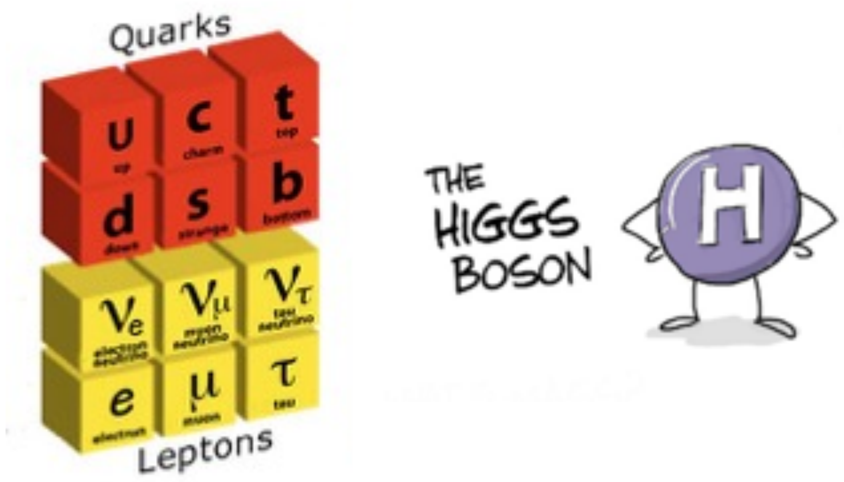
To complete the SM, the only piece of information that was missing was:

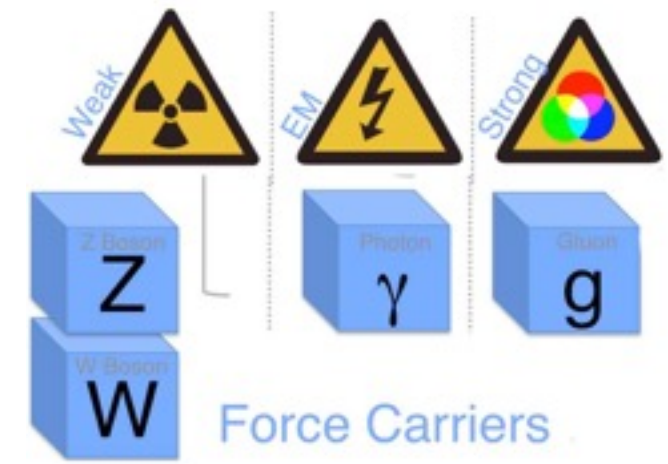
We found a Higgs boson with mass $m_h = 125$ GeV

$$B^{-1}SM \xrightarrow{m_h=125\ \text{GeV}} SM$$

the SM

Field Content: **Gauge Symmetry:** $SU(3)_C \times SU(2)_L \times U(1)_Y$





→ **Most general Lagrangian with these ingredients:**

$$\mathcal{L} = \Lambda^4 + \mathcal{L}_{d\leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots$$

the SM

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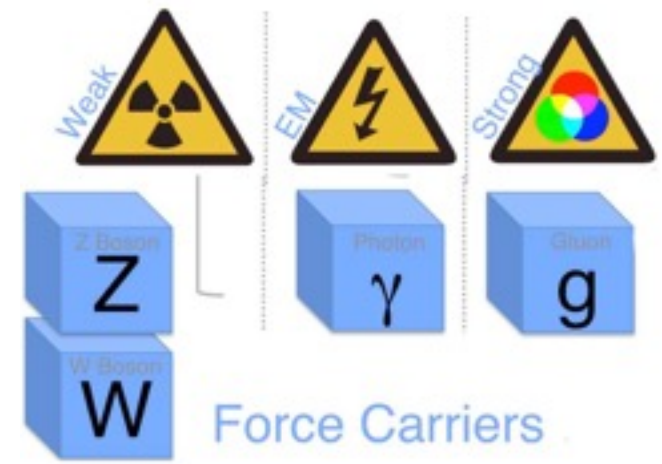

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Cosmological Constant
(see de Simone)

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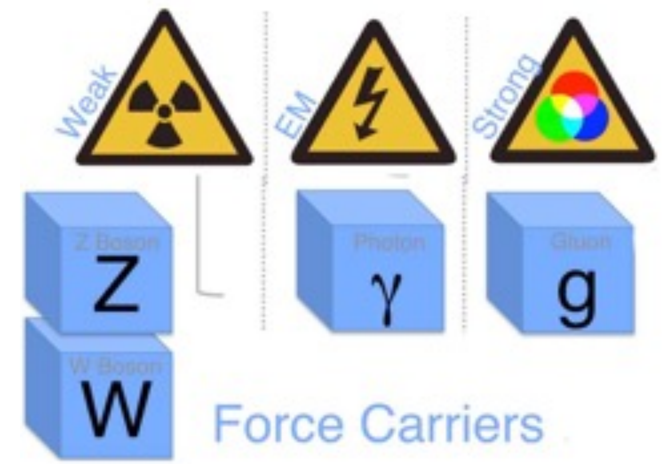

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For this lecture, take $\Lambda \simeq M_{Pl}$

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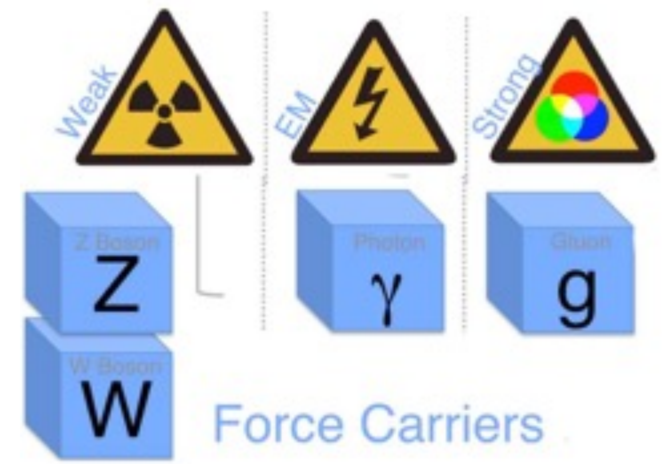

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This defines the Standard Model: only relevant and marginal operators with this field content and gauge symmetries

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j H + h.c. + |D_\mu H|^2 - V(H)$$

the SM

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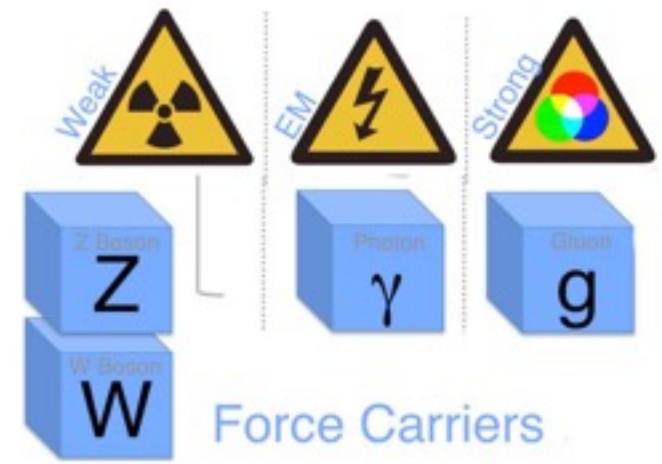

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the SM - tree level

Higgs Physics

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

Tree-level

the SM - tree level

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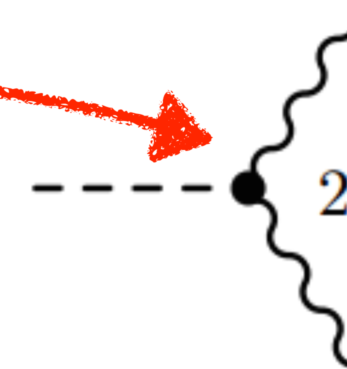
Tree-level

$$|D_\mu H|^2 \supset (m_W^2 W^{\mu+}W_\mu^- + \frac{m_Z^2}{2} Z_\mu Z^\mu)(1+\frac{h}{v})^2$$

m_Z, m_W



$$2i\frac{m_V^2}{v}g^{\mu\nu}$$

the SM - tree level

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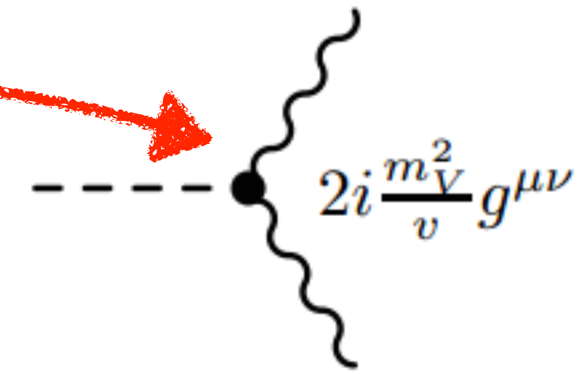
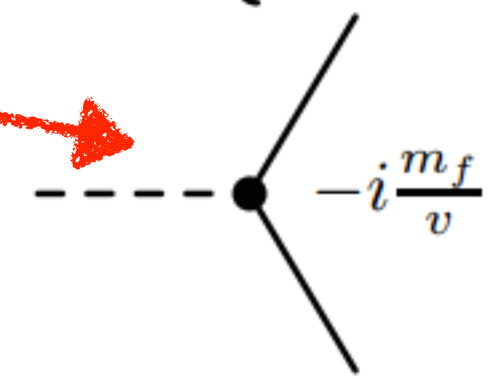


$$y_{ij} H \bar{\psi}_i \psi_j \supset - \sum_{f=u,d,e,..} m_f \bar{\psi}_f \psi_f (1+\frac{h}{v})$$

m_f



the SM - tree level

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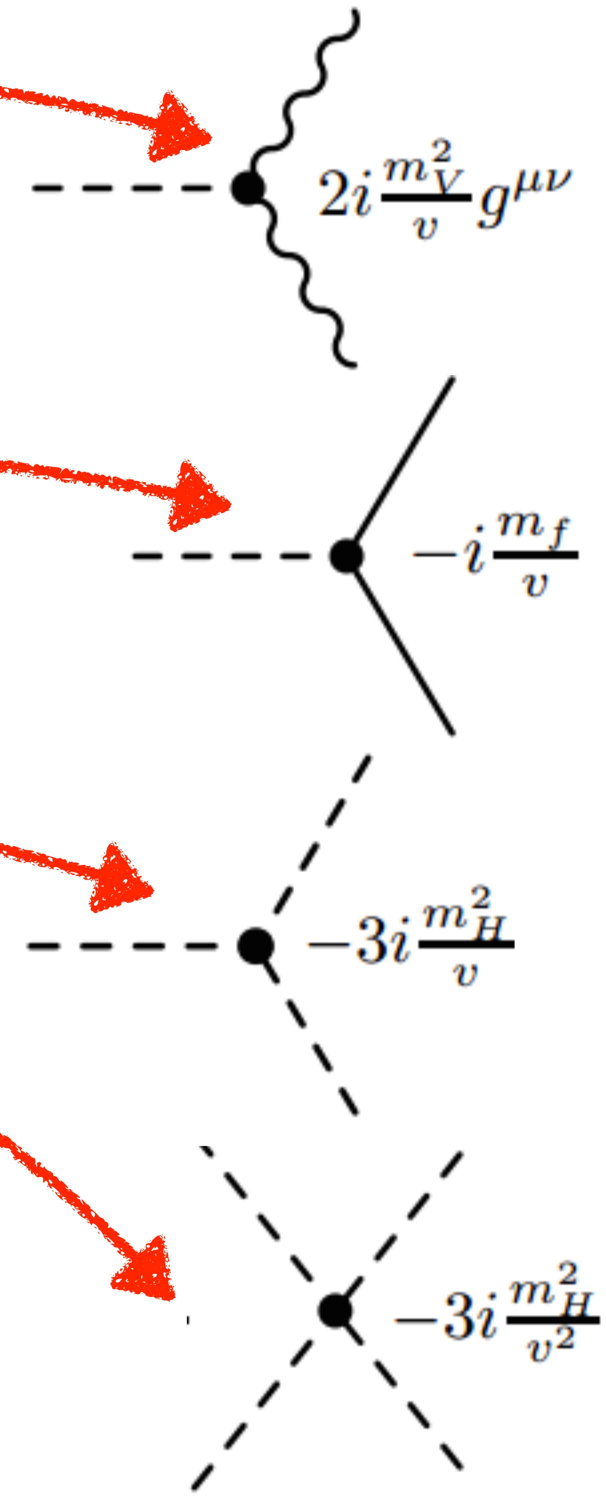
m_f

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

m_h



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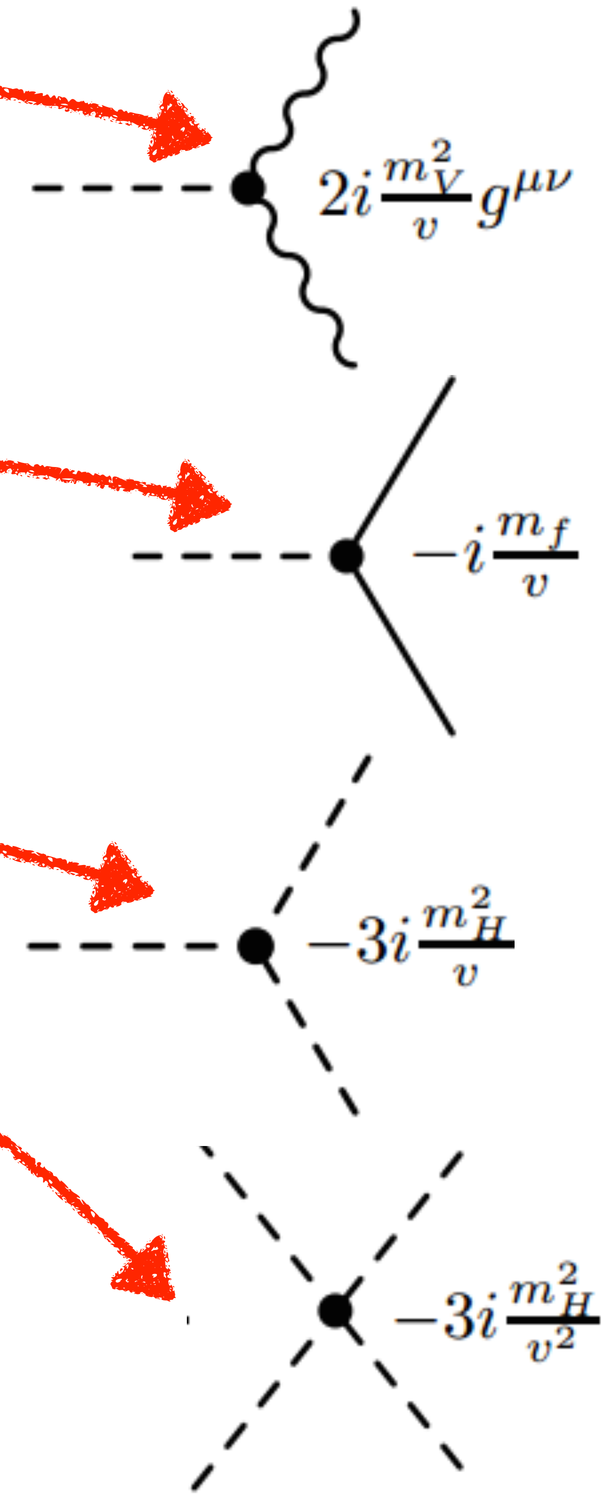

Higgs boson couples (at tree level) proportionally to mass

the SM - loop level

Higgs Physics

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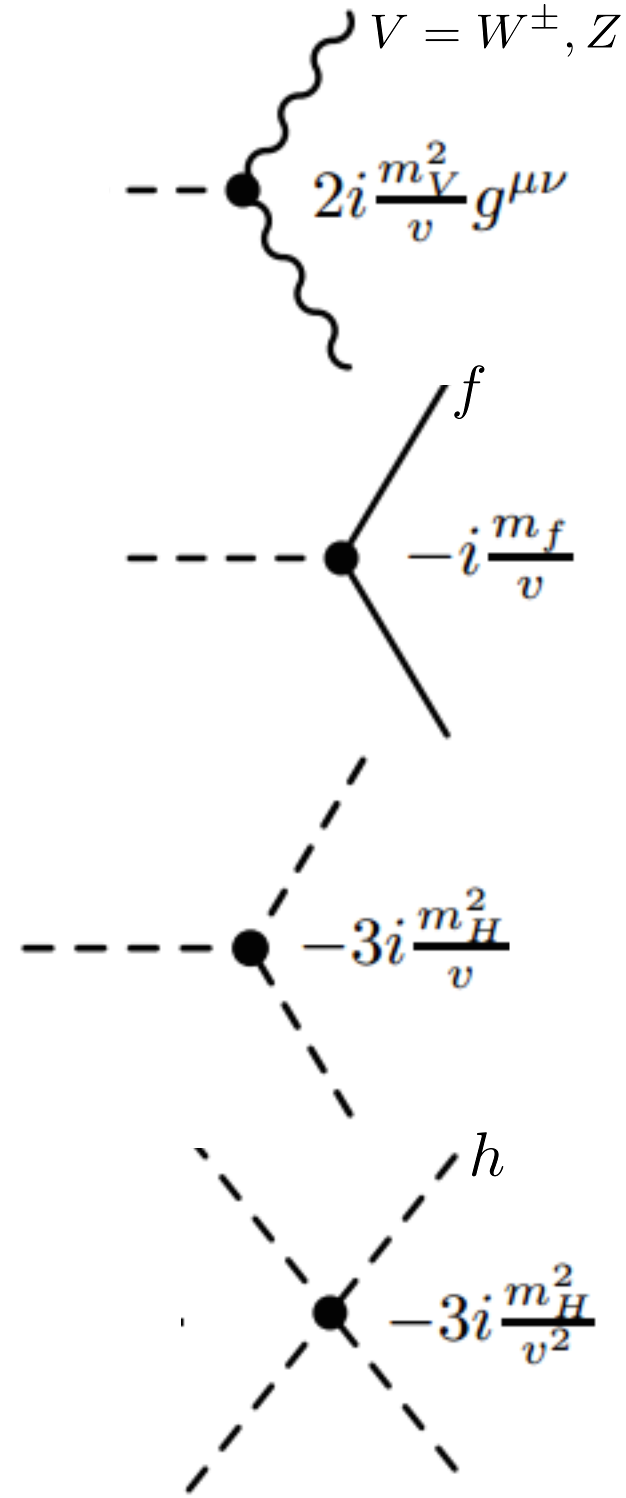
Tree-level



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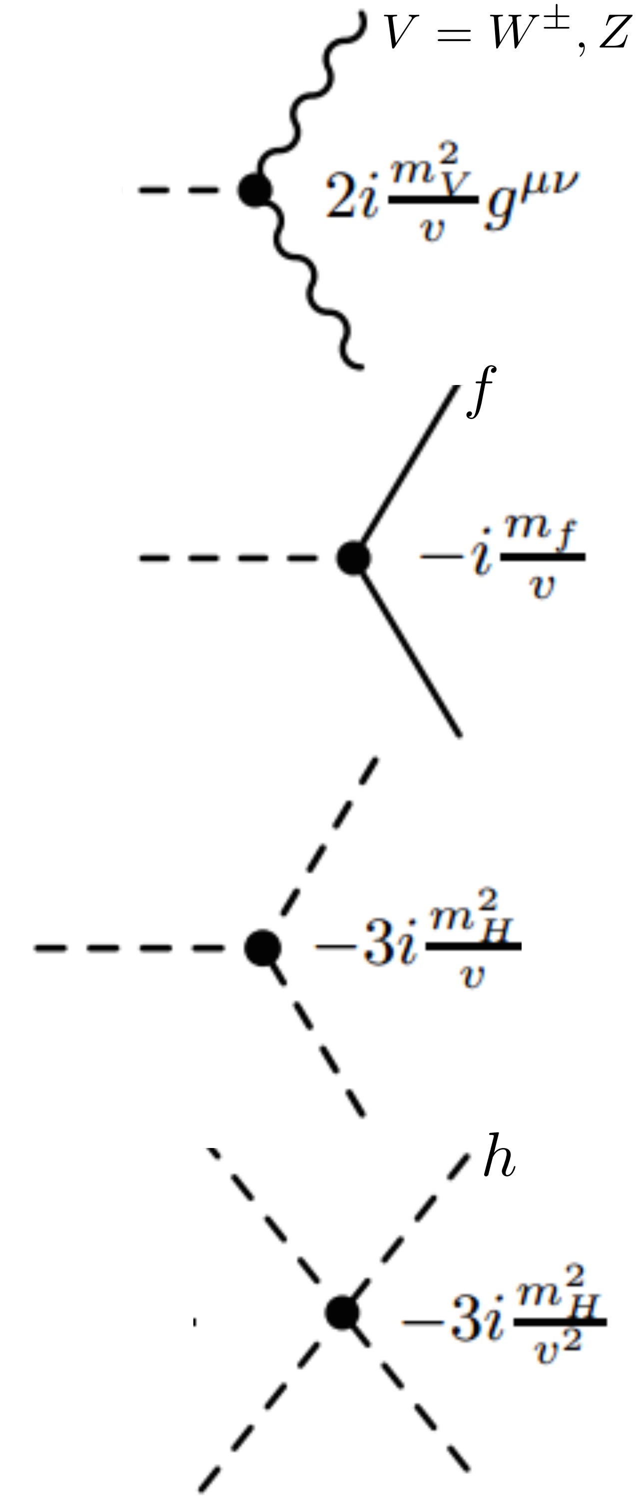
Loop-level

The SM is a renormalizable theory:
Infinite loops are unobservable,
but finite loops are measurable!

Tree-level



the SM - loop level

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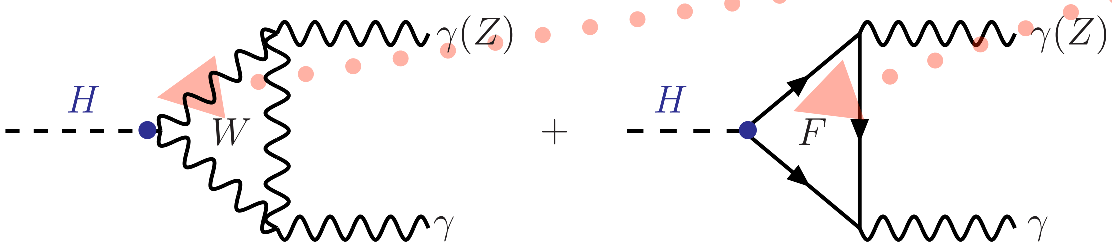
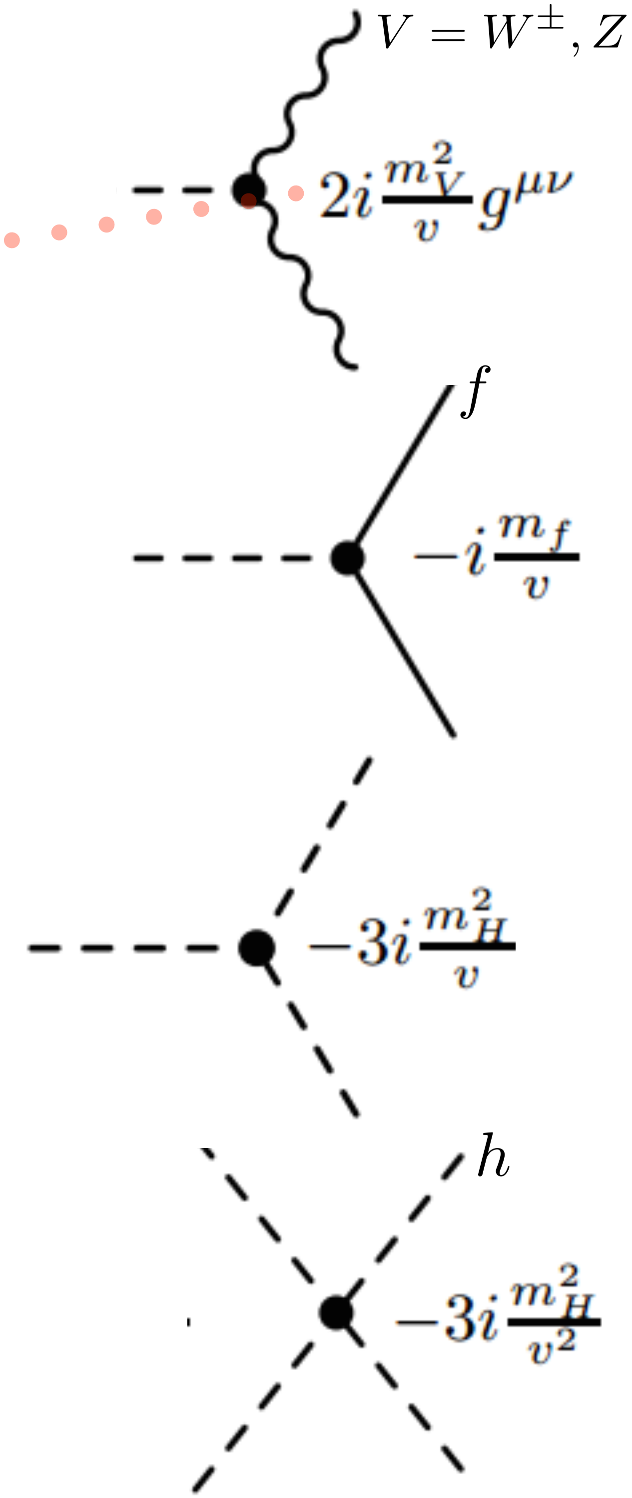


Tree-level



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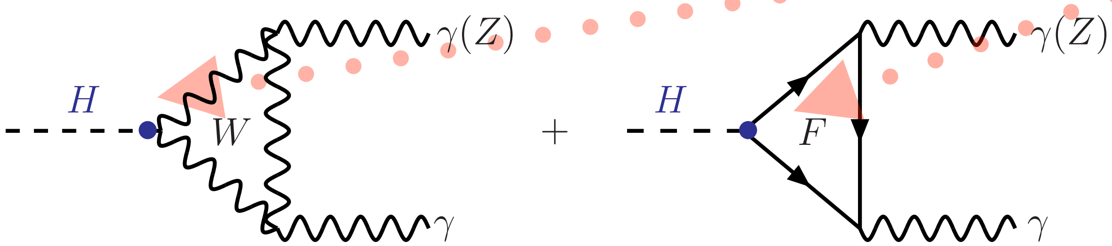
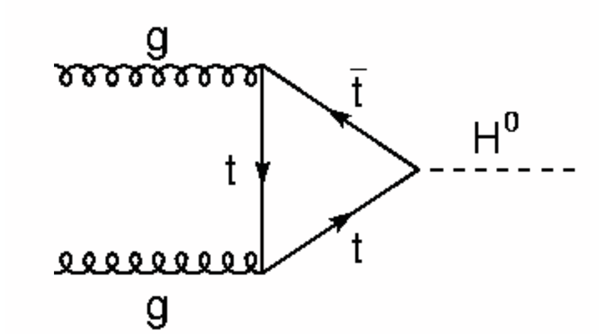
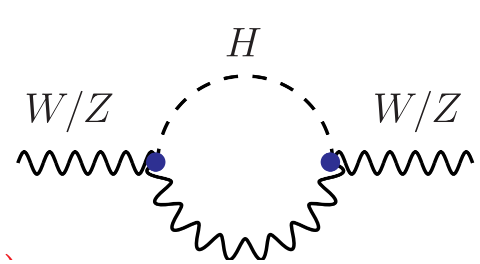
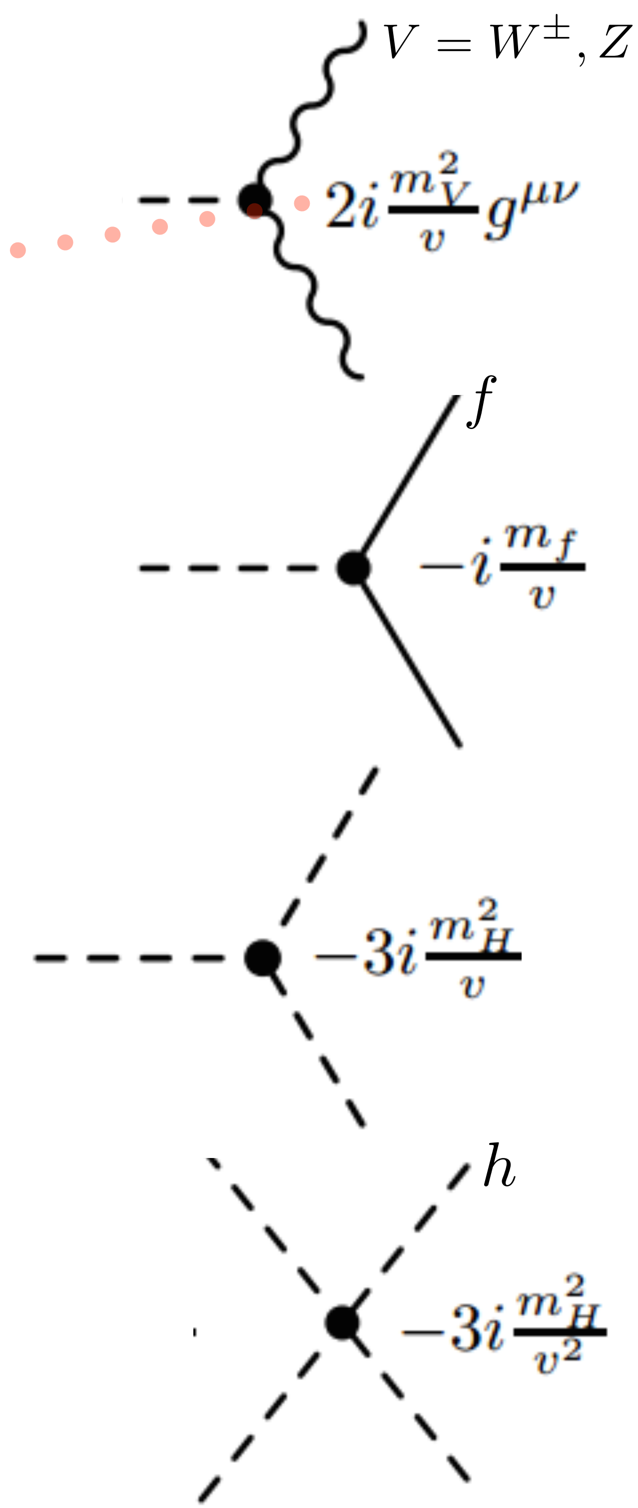






...

Tree-level



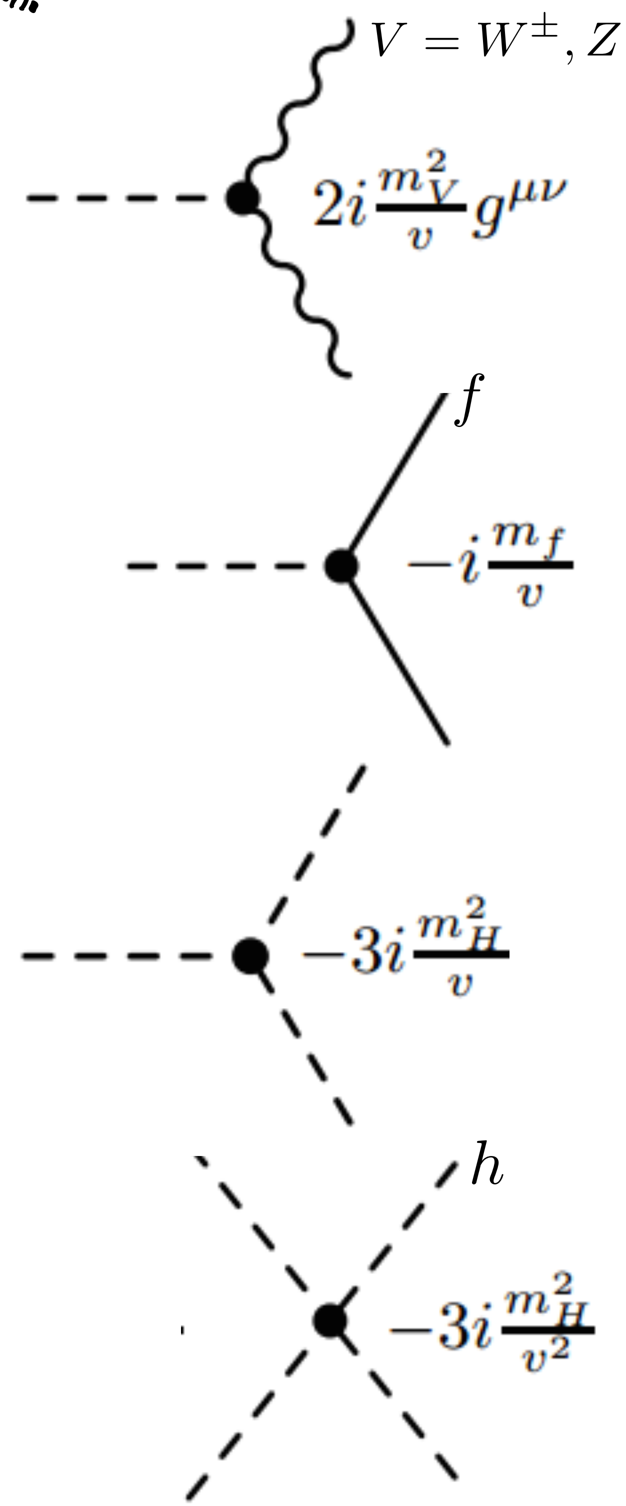
Predictions involving the Higgs

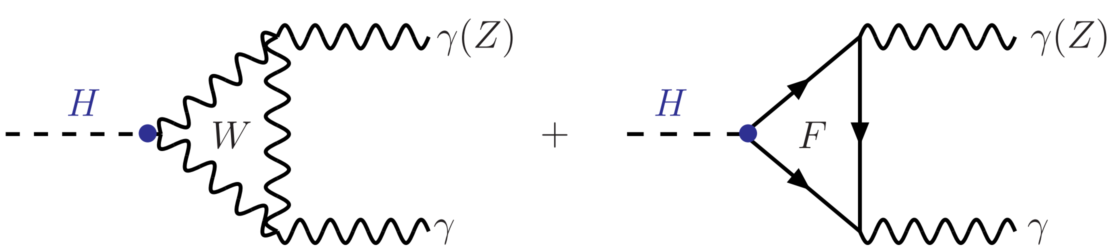
The SM is a very predictive theory:

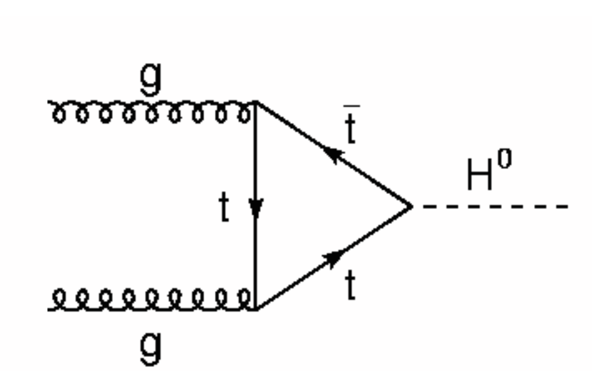
Measurement of only 19 input parameters is enough to define it!

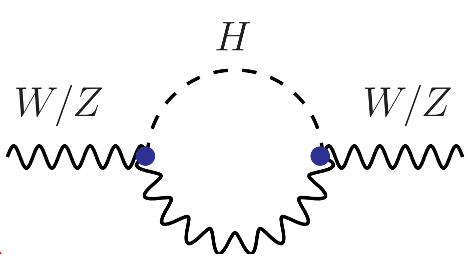
The only missing < 2012 was m_h!

→ Then, gauge symmetries and restriction to $d \leq 4$ fixes all couplings!









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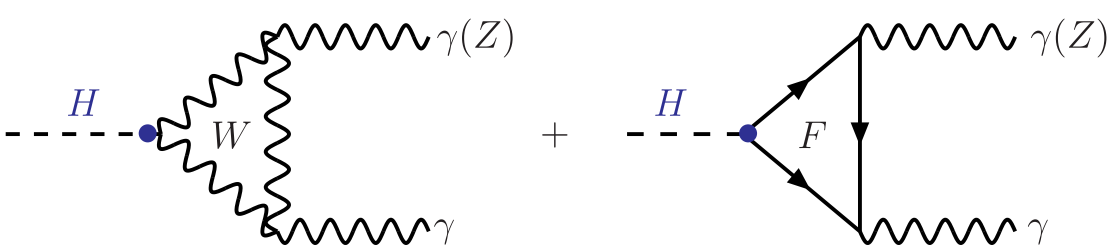
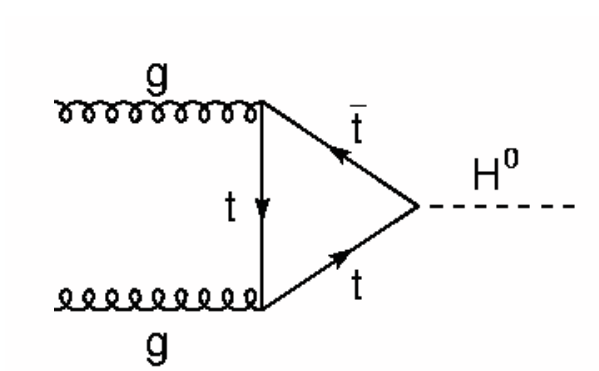
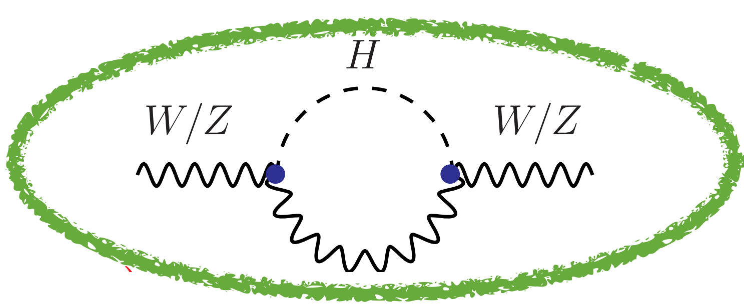
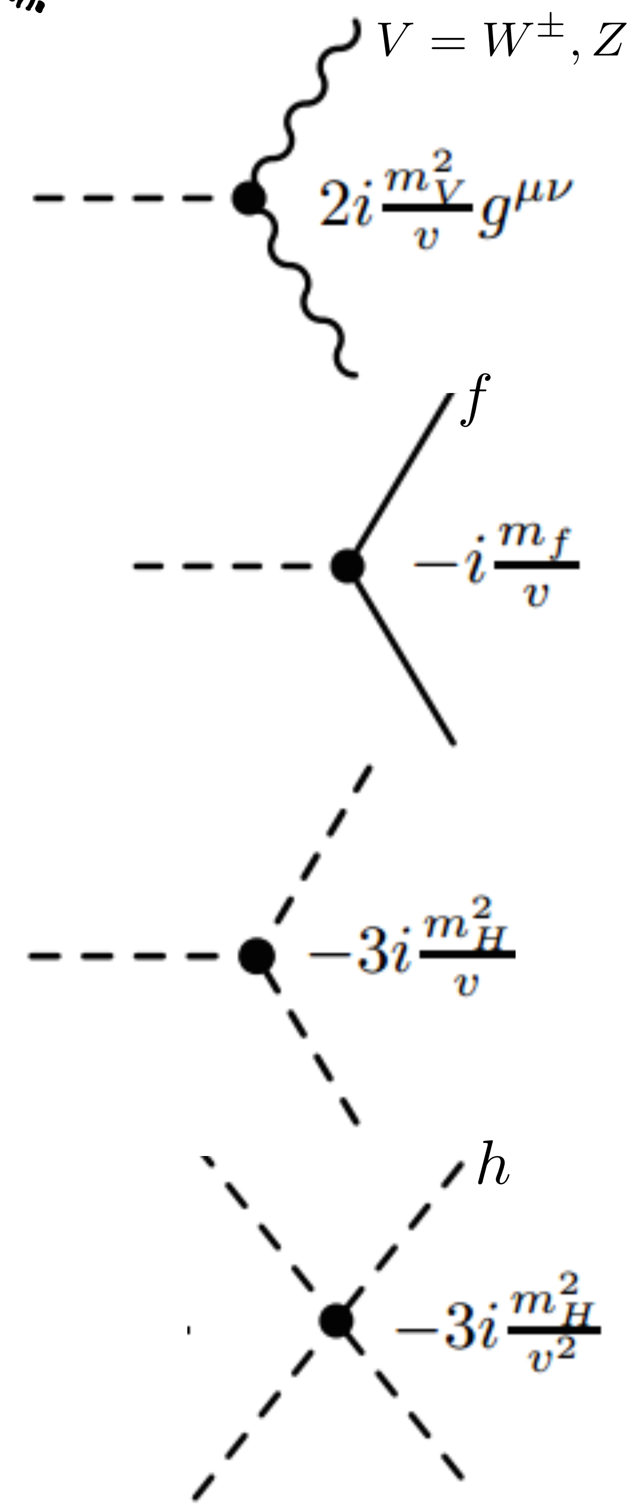






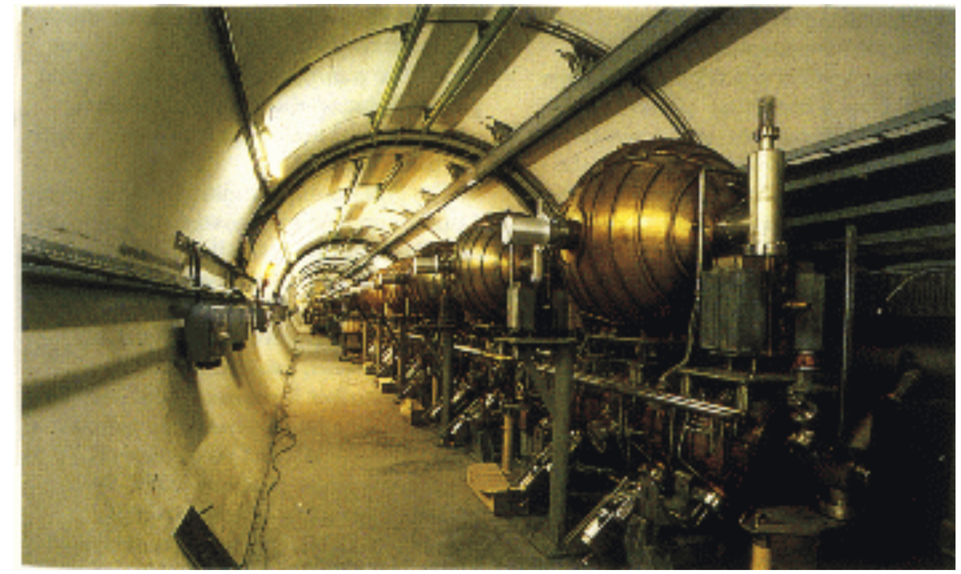
Observable also before Higgs discovery!

...

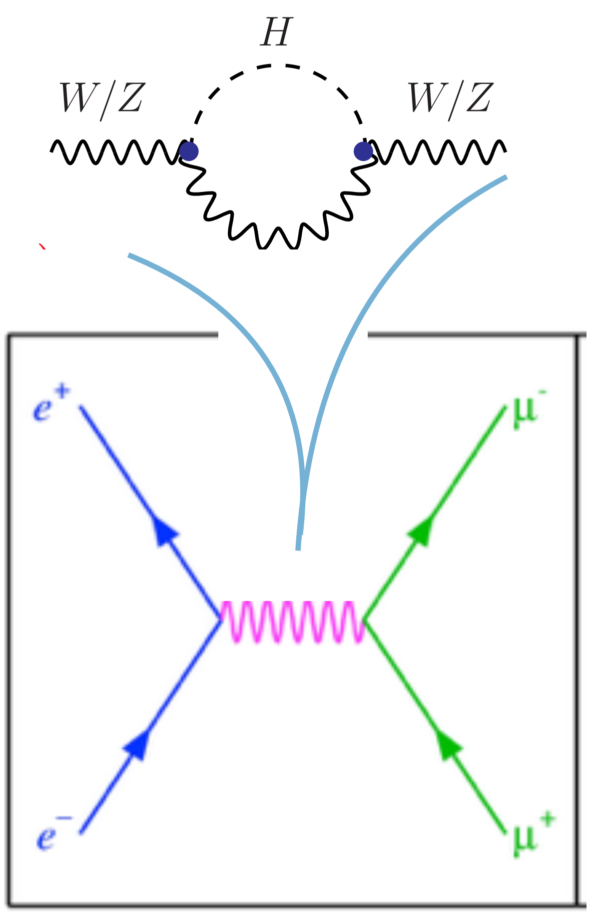


Predictions: Higgs before the Higgs

LEP



Predictions of the SM involving the Higgs Could be tested even before Higgs discovery: in Electroweak Precision Tests @ LEP (EWPT)



$$\propto \log \frac{m_h^2}{m_W^2}$$

Predictions: Higgs before the Higgs

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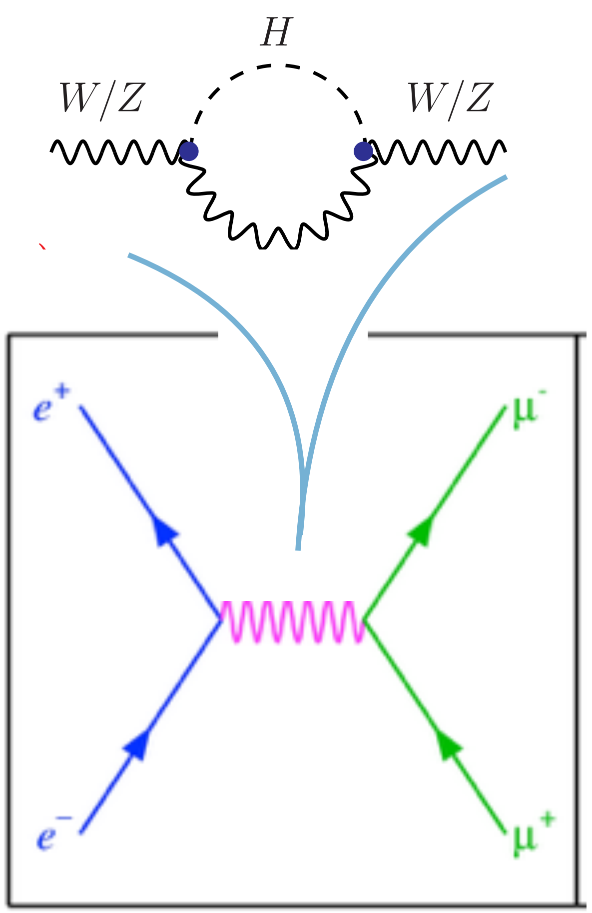

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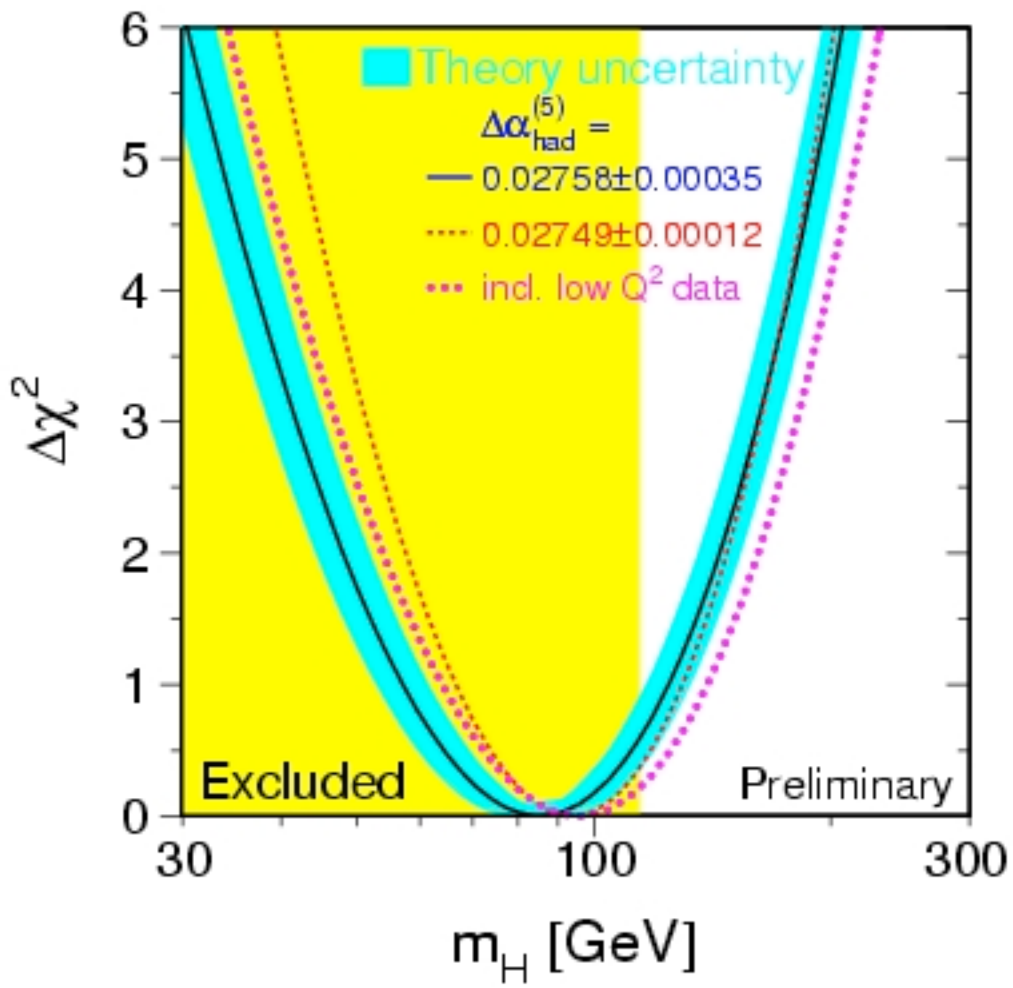
LEP



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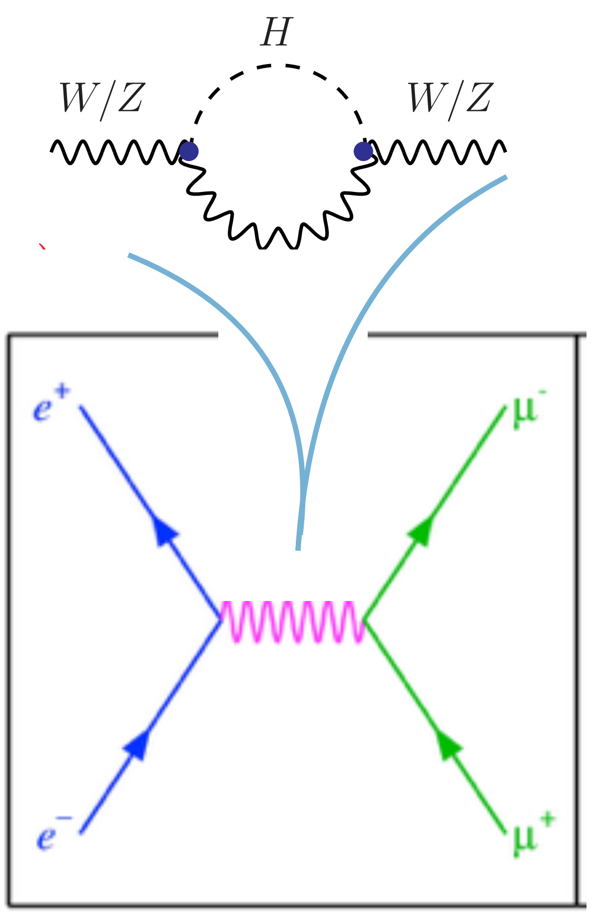
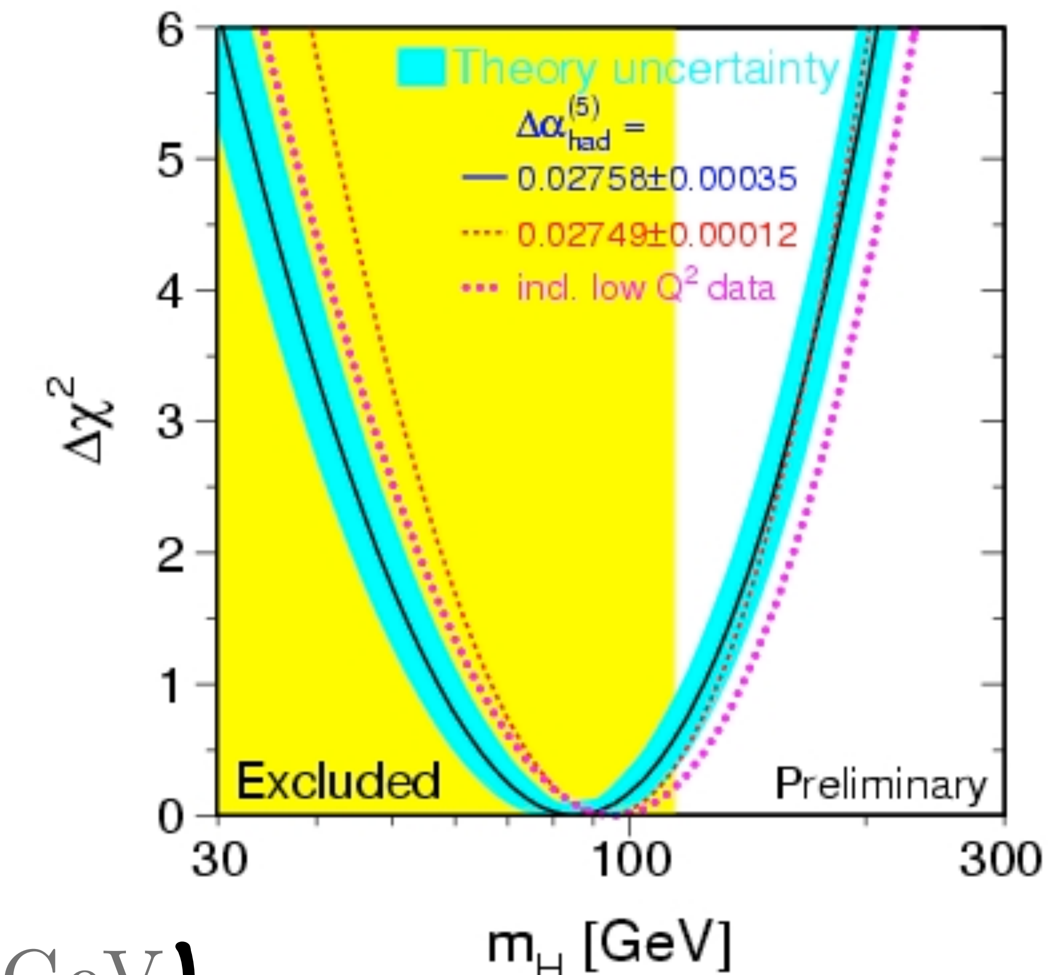
in Electroweak Precision Tests @ LEP (EWPT)

LEP



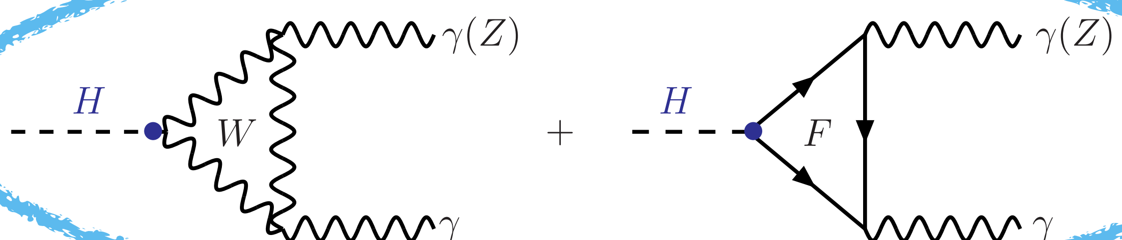
$$\propto \log \frac{m_h^2}{m_W^2}$$

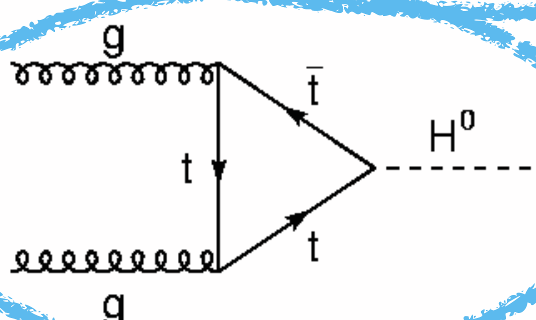


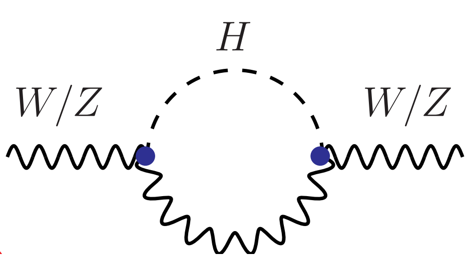
In SM Higgs mass $m_h = 94^{+29}_{-24}\mathrm{GeV}$
already from LEP*
(in contrast with LEP direct $m_h > 114.4\mathrm{GeV}$)

(*= BSM physics at TeV also contributes to EWPT and changes this conclusion)

Predictions for Higgs @ LHC

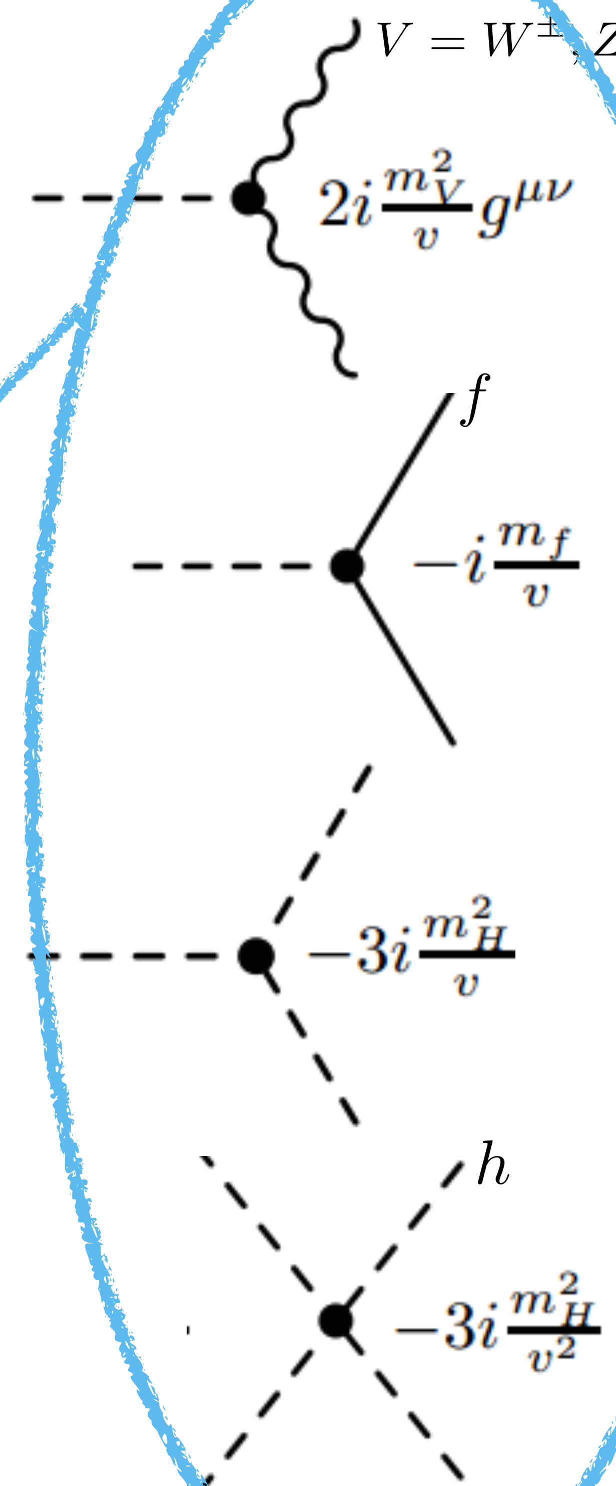






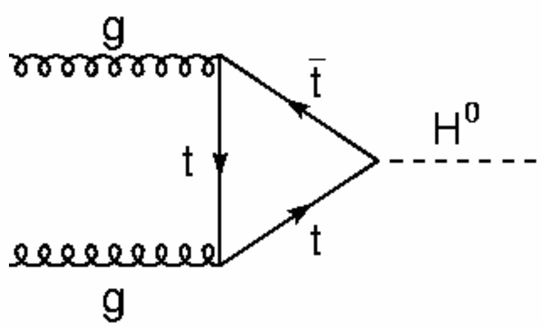
...

Given mh, all Higgs production cross-sections and Branching ratios are fixed in the SM!

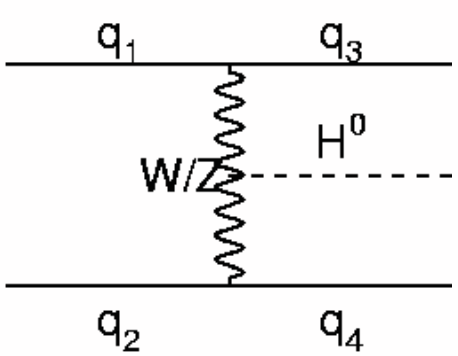


Higgs Production

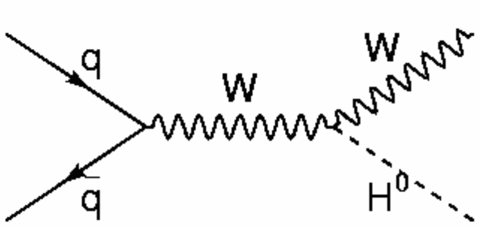
How to make a Higgs boson?



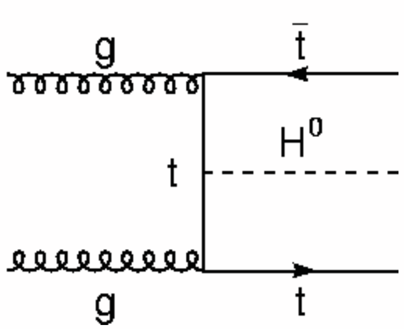
Gluon Fusion



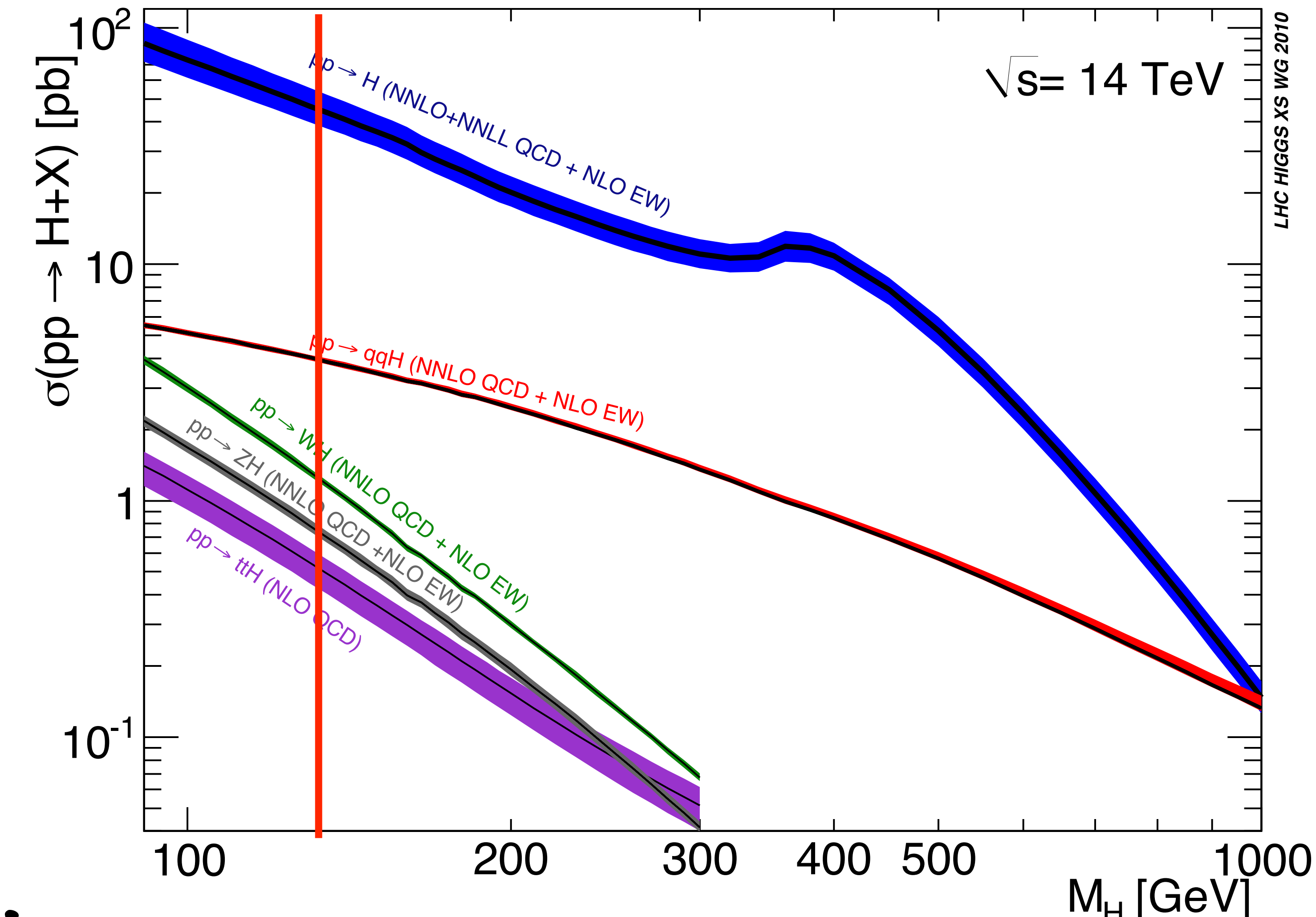
Vector Boson Fusion



Associated Production VH



Associated Production ttH



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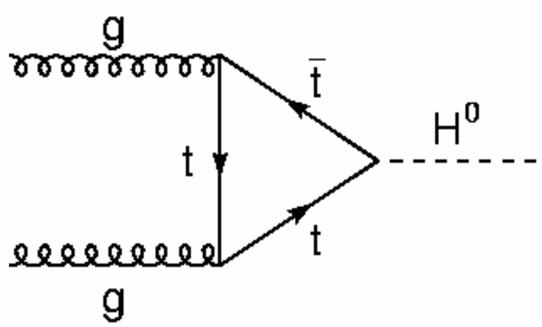
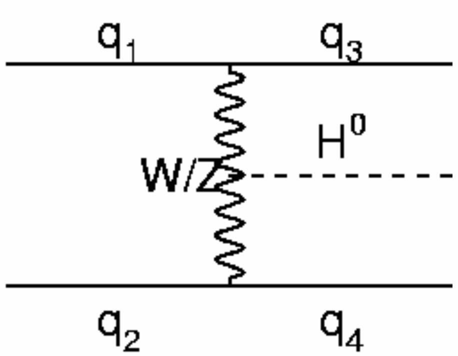


Gluon Fusion



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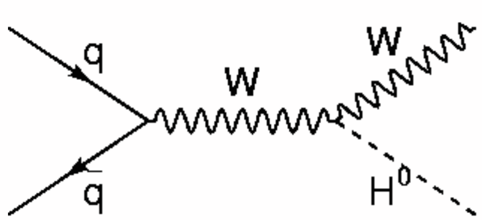
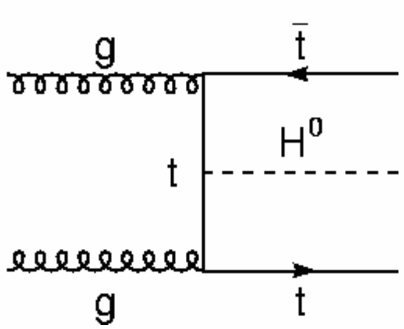


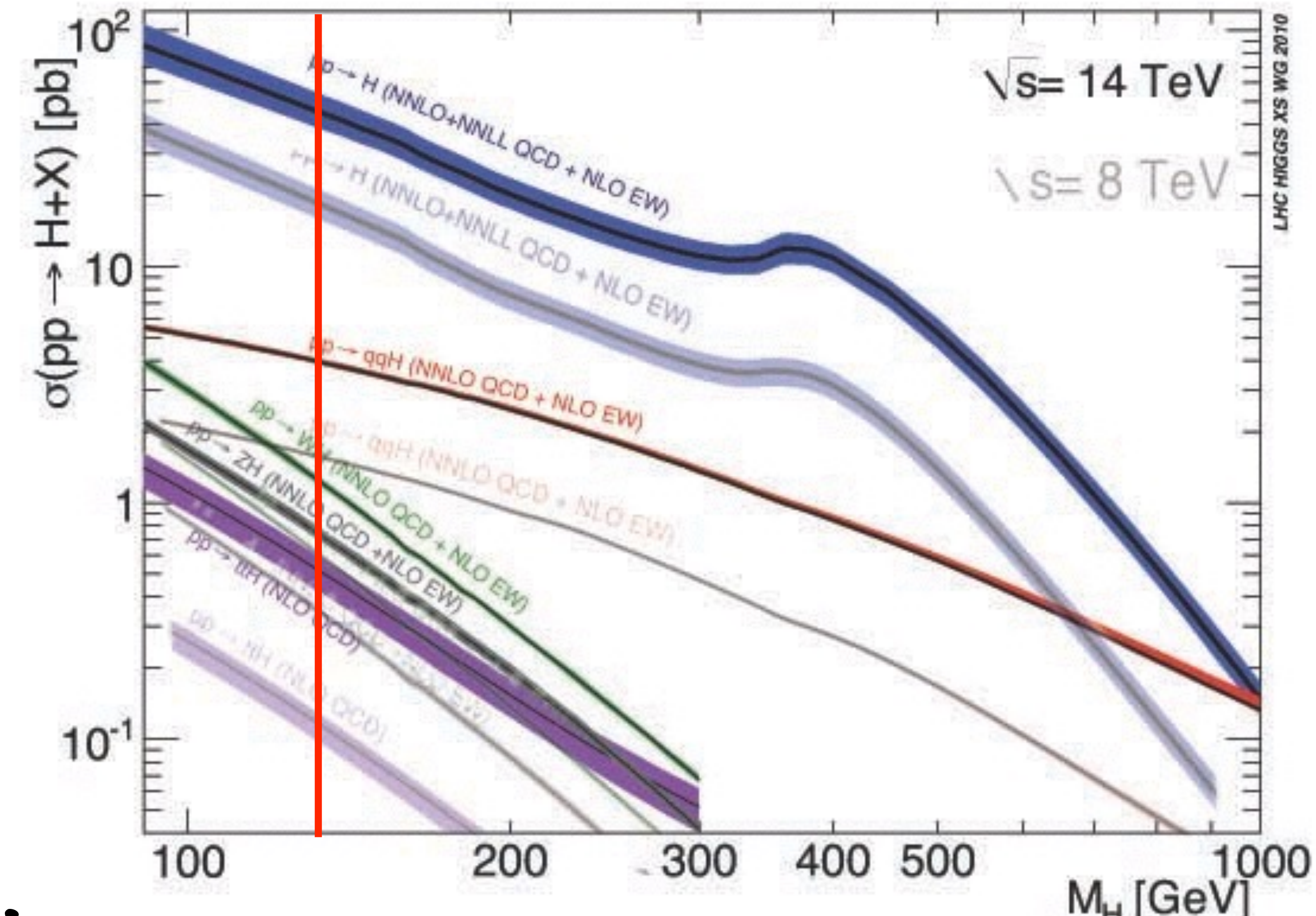
Associated Production VH



Associated Production ttH

	8 TeV	13 TeV
ggF	19 pb	44 pb
VBF	1.6 pb	3.7 pb
VH	1.1 pb	2.2 pb
ttH	0.13 pb	0.51 pb
tH	~20 fb	~90 fb

14 vs 8 TeV



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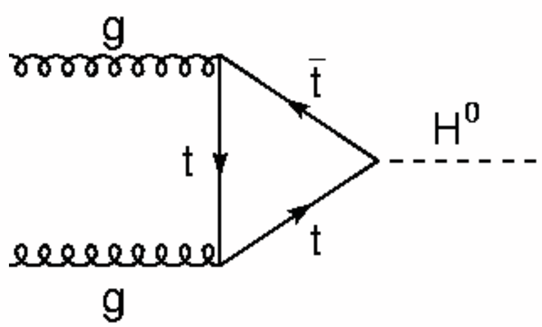
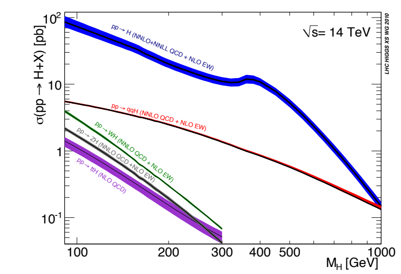
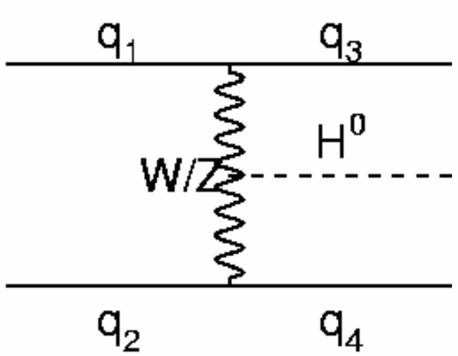


Gluon Fusion

Largest but no background discrimination

(useless for e.g. h->bb)





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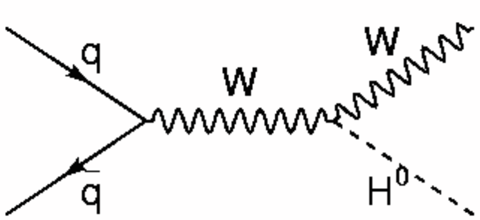
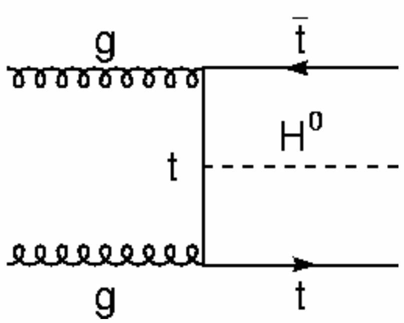


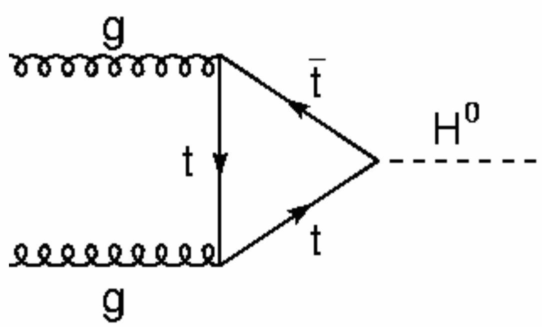
Associated Production VH



Associated Production ttH

Higgs Production

How to make a Higgs boson?



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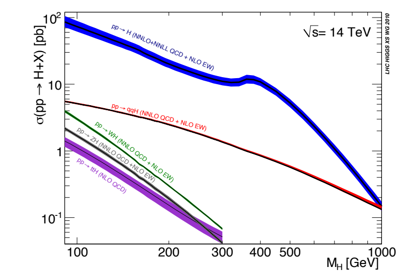
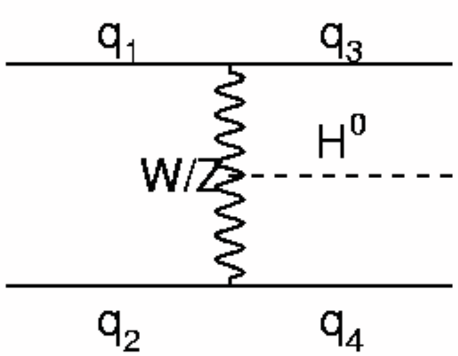
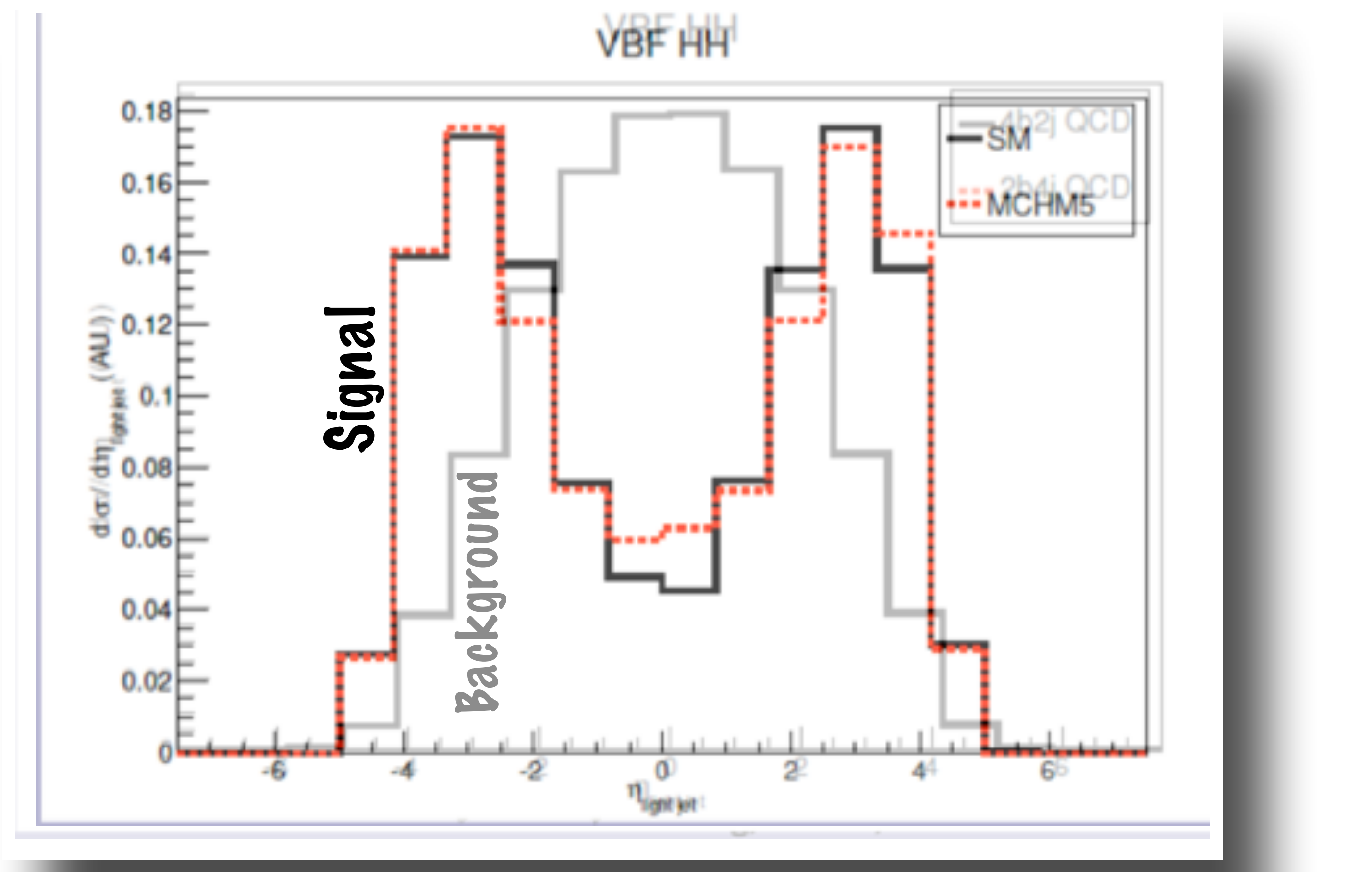
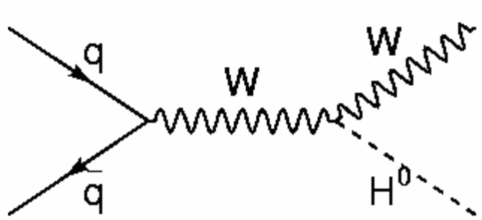




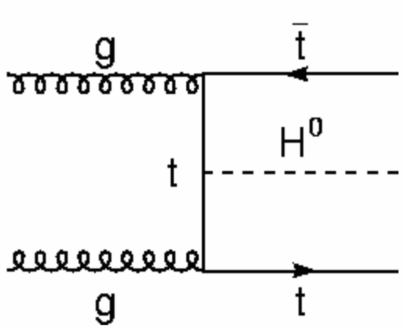
Vector Boson Fusion

Outcoming jets: kinematics collinear
(good background discrimination)





Associated Production VH



Associated Production ttH

Higgs Production

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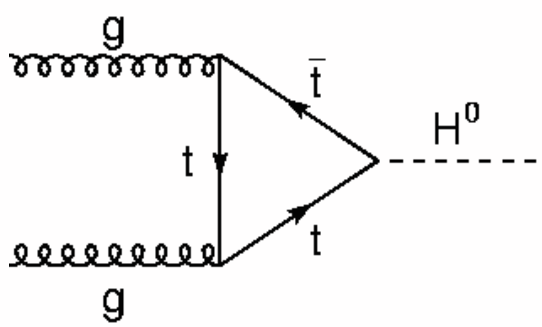

Gluon Fusion

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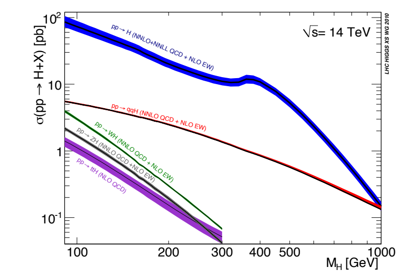
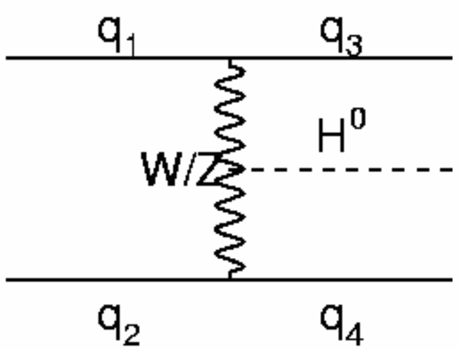
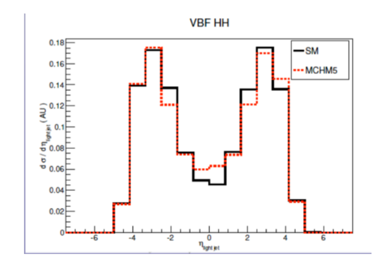
(useless for e.g. h->bb, see later)

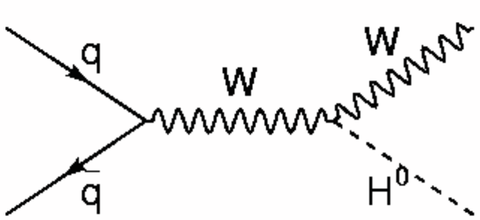




Vector Boson Fusion

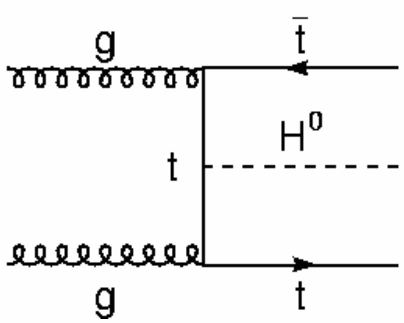
Outcoming jets: kinematics collinear
(good background discrimination)





Associated Production VH

Leptons in final state
(good background discrimination)

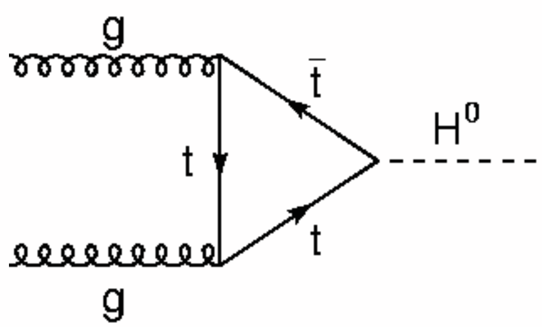


Associated Production ttH

Higgs Production

sometimes size matters not

How to make a Higgs boson?



Gluon Fusion

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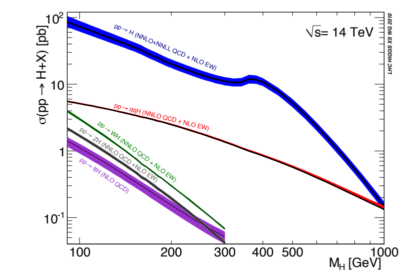
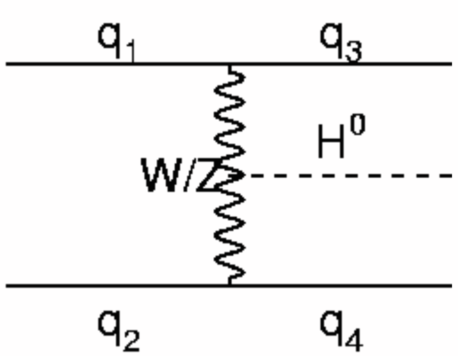
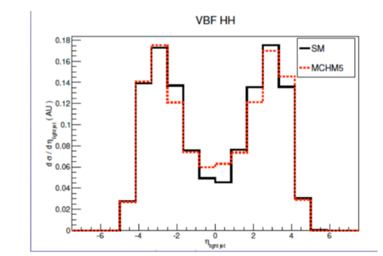


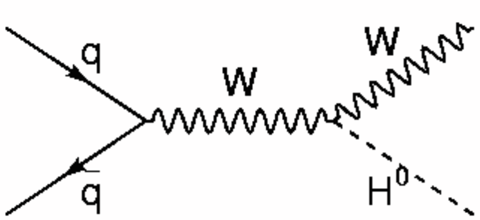


Vector Boson Fusion

Outcoming jets: kinematics collinear

(good background discrimination)





Associated Production VH

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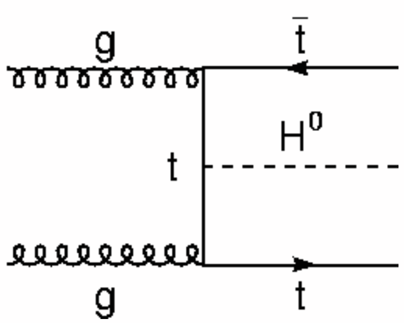
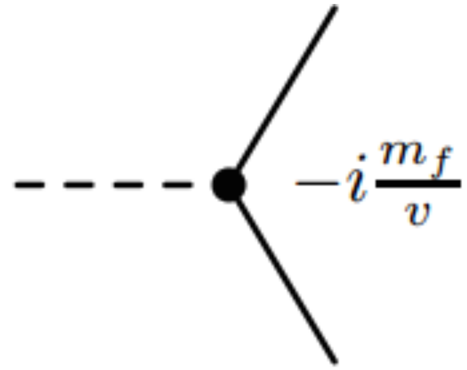


Associated Production ttH

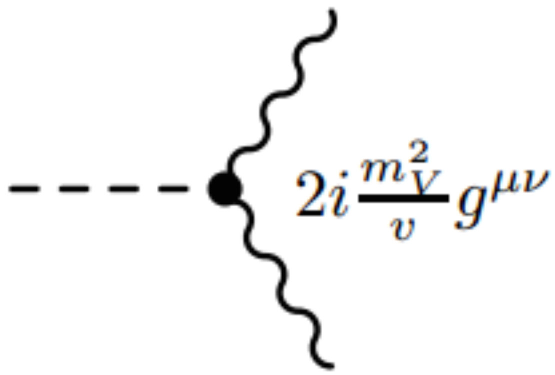
Independent test of tth coupling

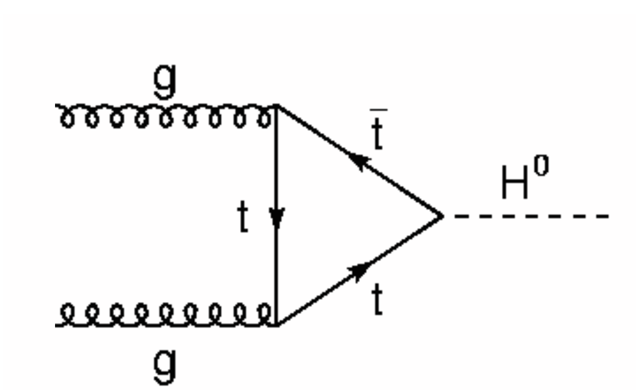
Higgs decays

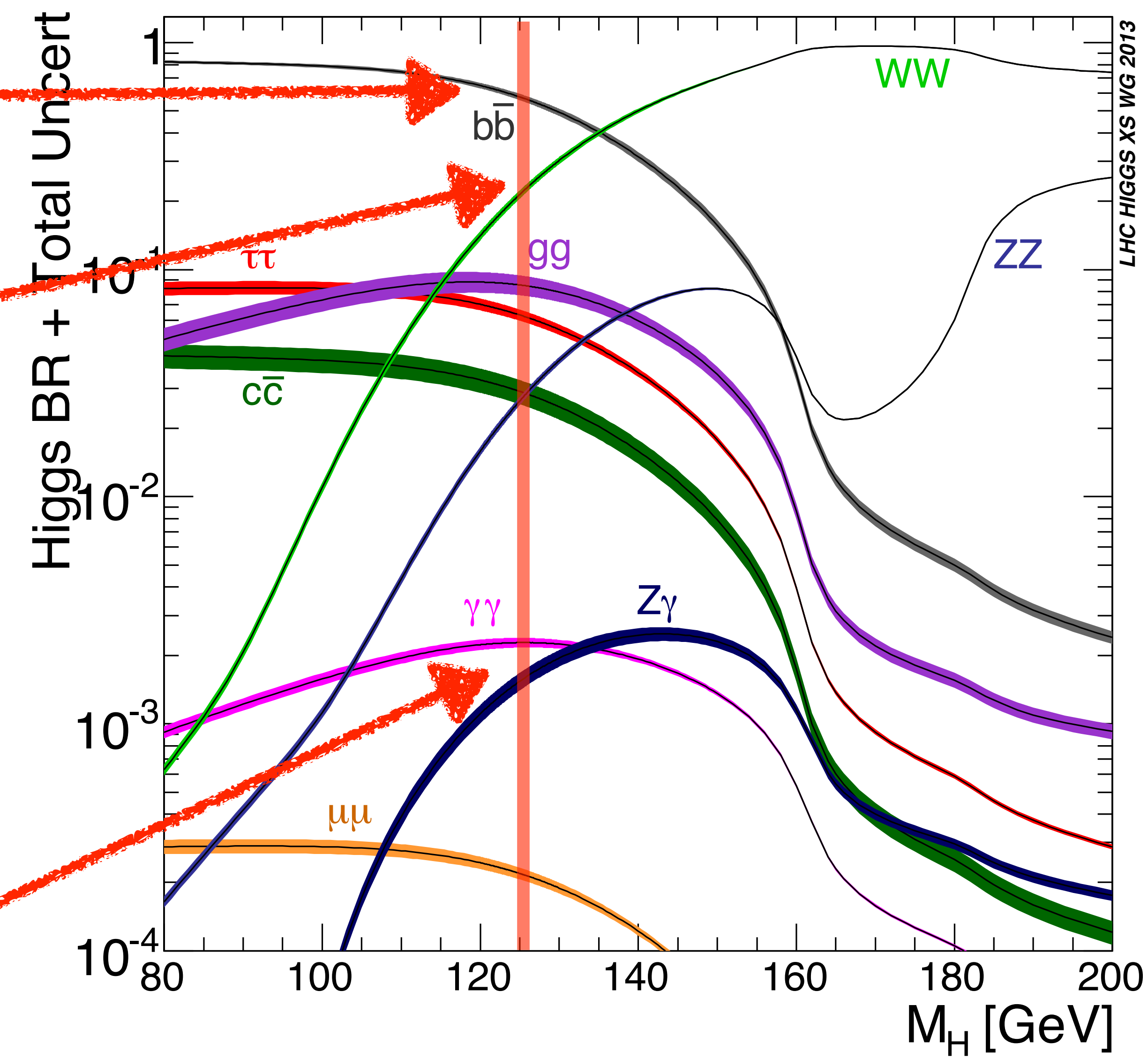
How to see a Higgs boson?

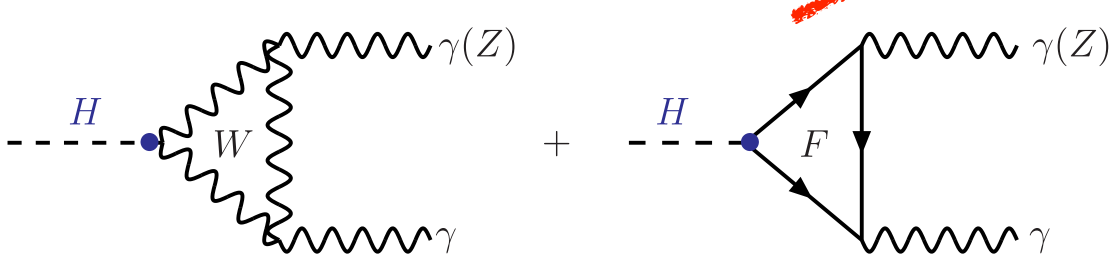


$f = b$-quark









Higgs decays

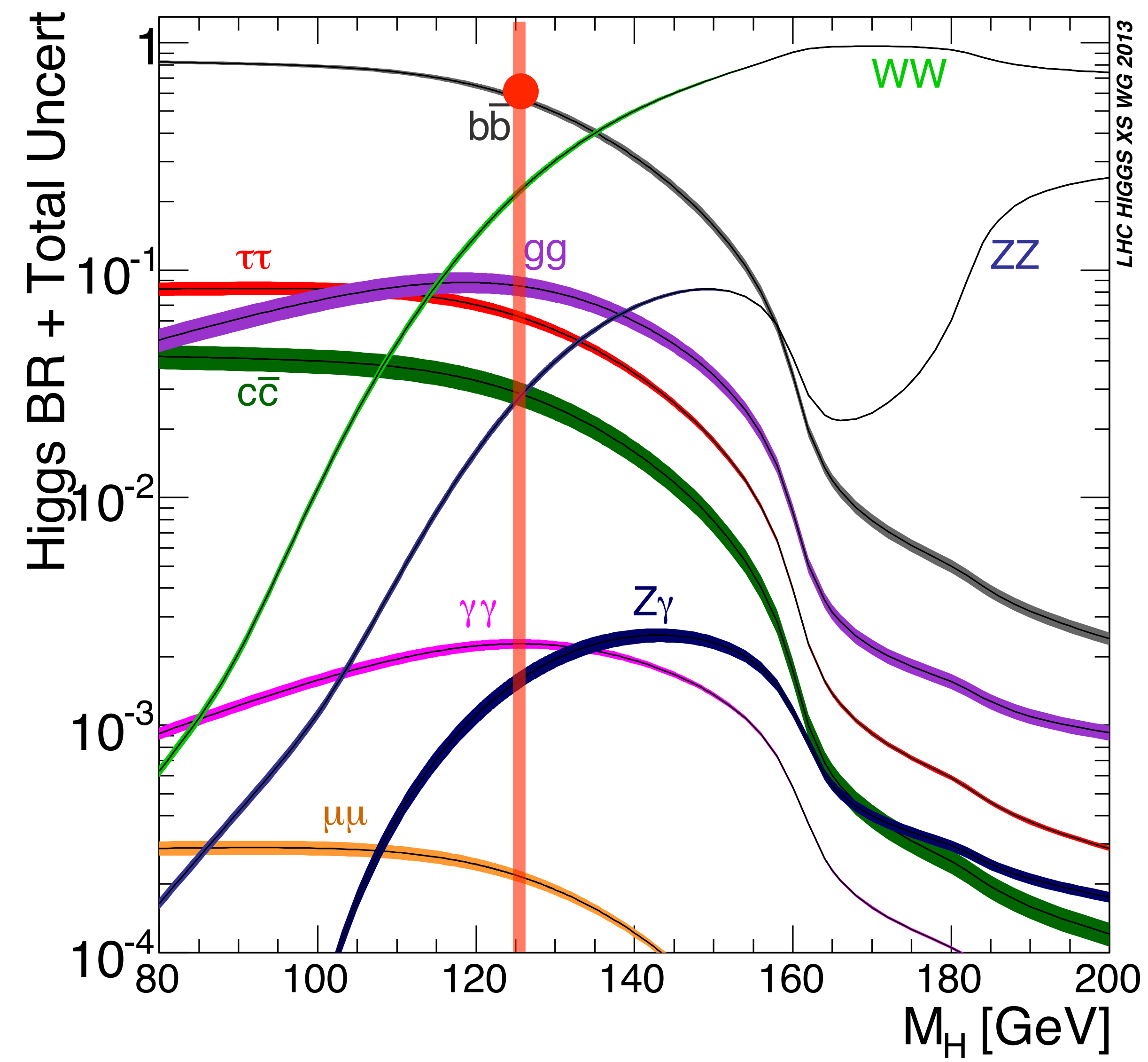
How to see a Higgs boson?

$\boxed{h \to \bar{b}b}$

Largest crossection

...but largest background

$$\sigma(pp \to \bar{b}b) \approx 10^8 \text{pb}$$



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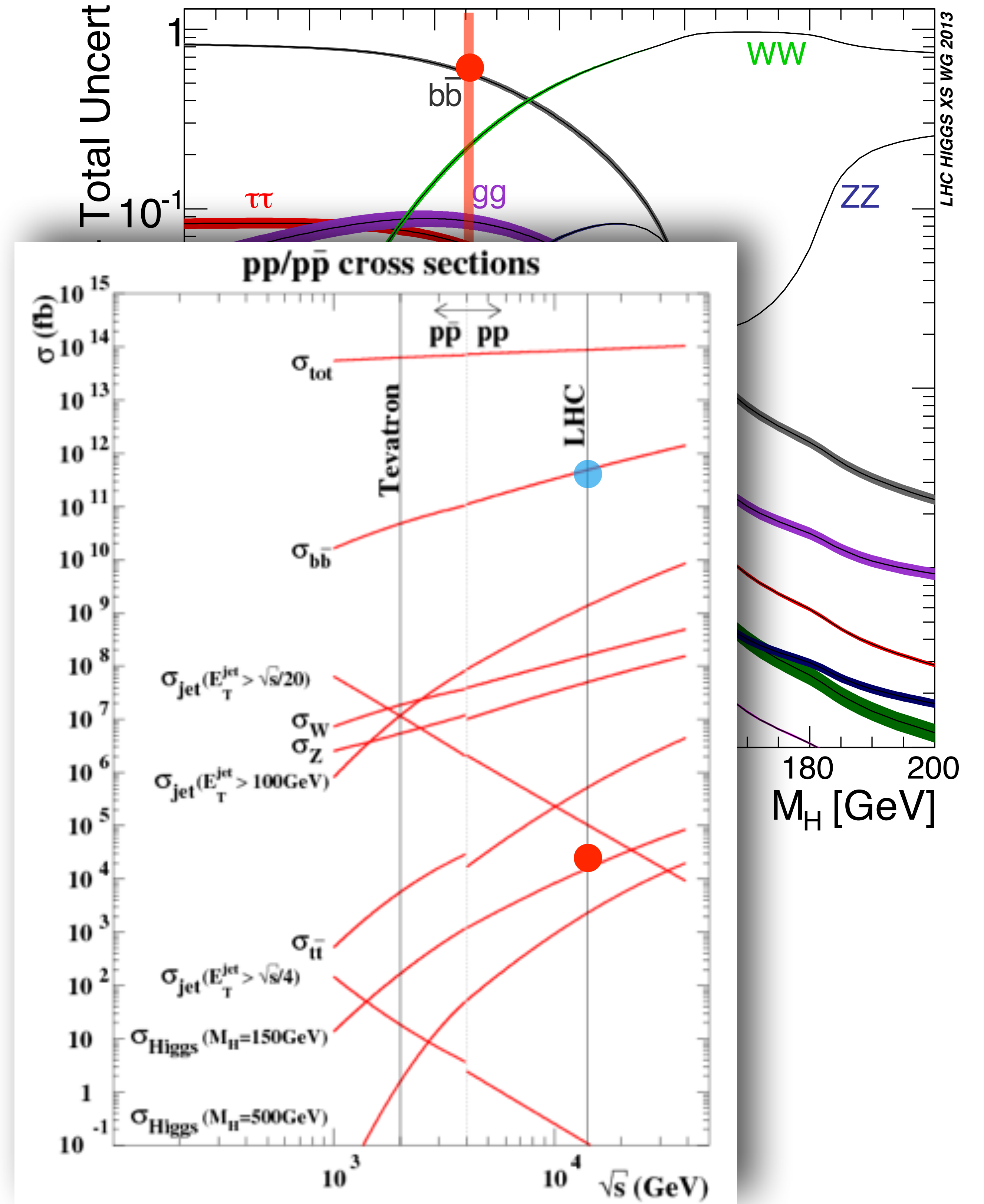

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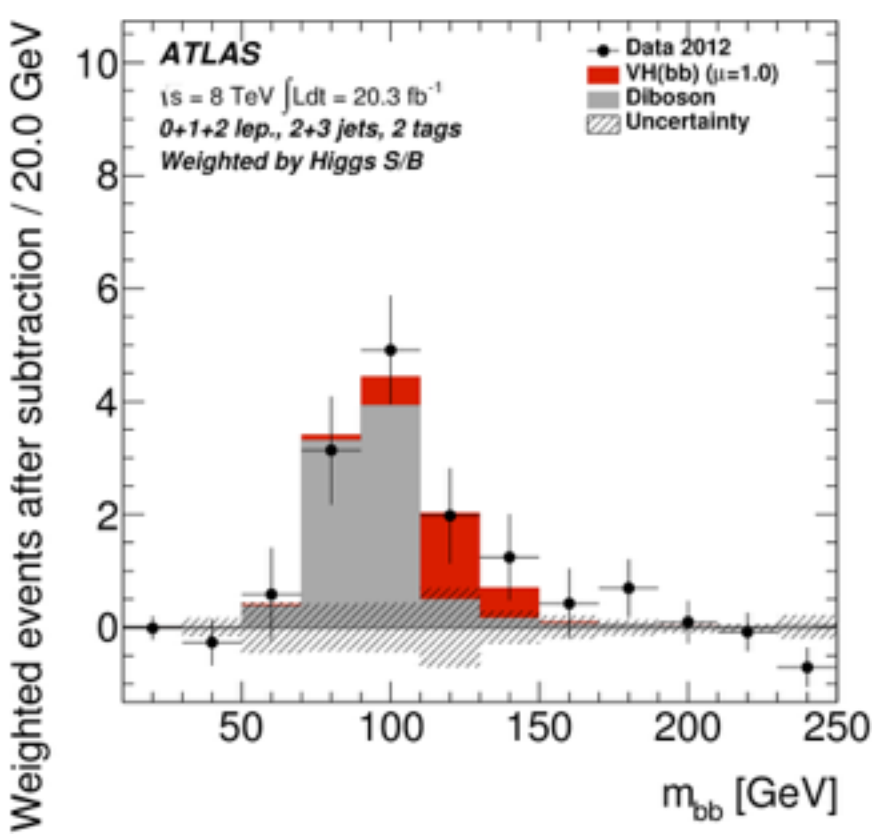
$\boxed{h \to \bar{b}b}$

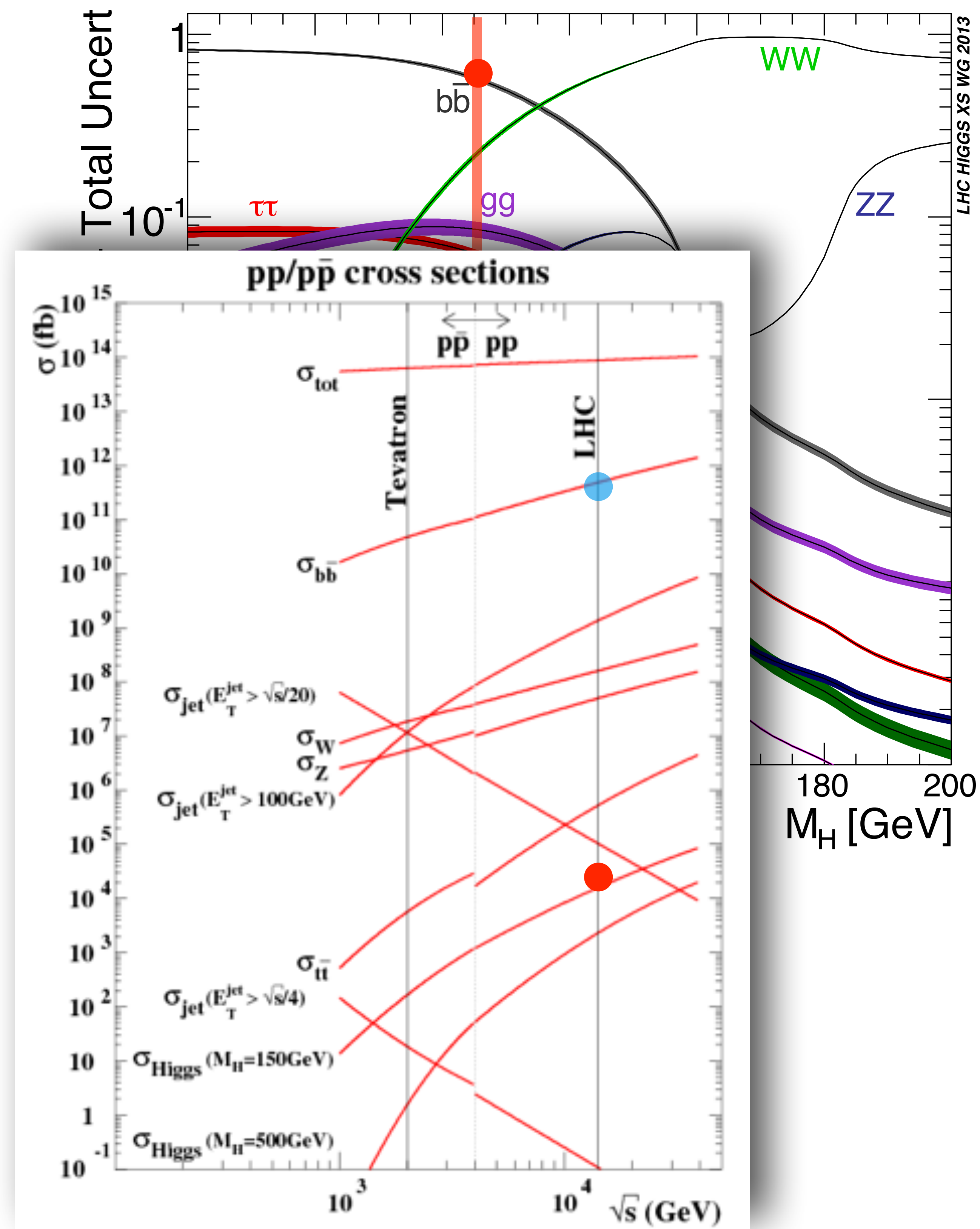
Largest crossection

...but largest background

$$\sigma(pp \to \bar{b}b) \approx 10^8 \text{pb}$$

Can only be used in VBF or VH production modes (to reduce background)





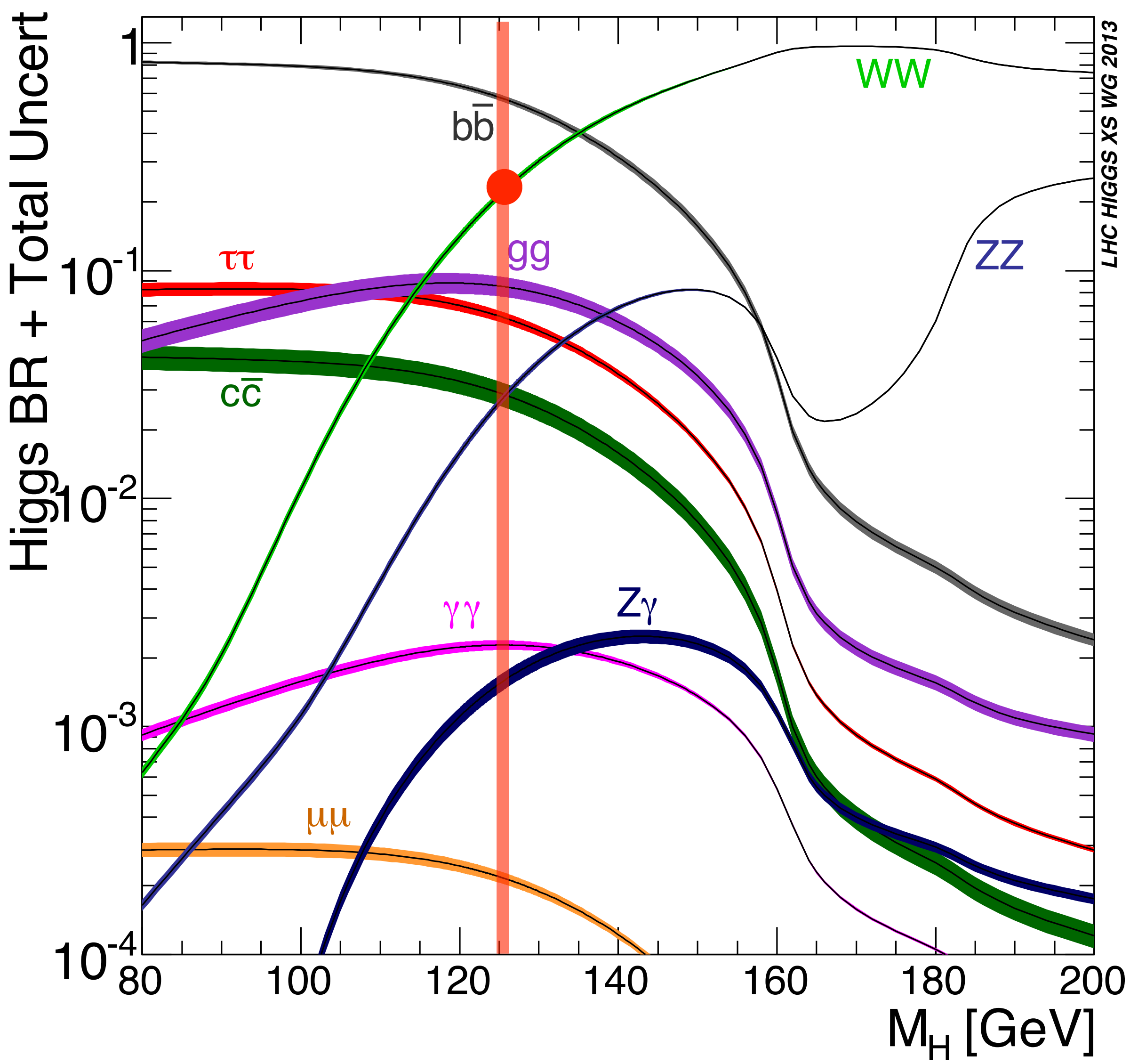
Higgs decays

How to see a Higgs boson?

$$\boxed{h \to W^+ W^{-*}}$$

Large cross-section,

... invisible neutrino steels some kinematic information (no mass reconstruction)



Higgs decays

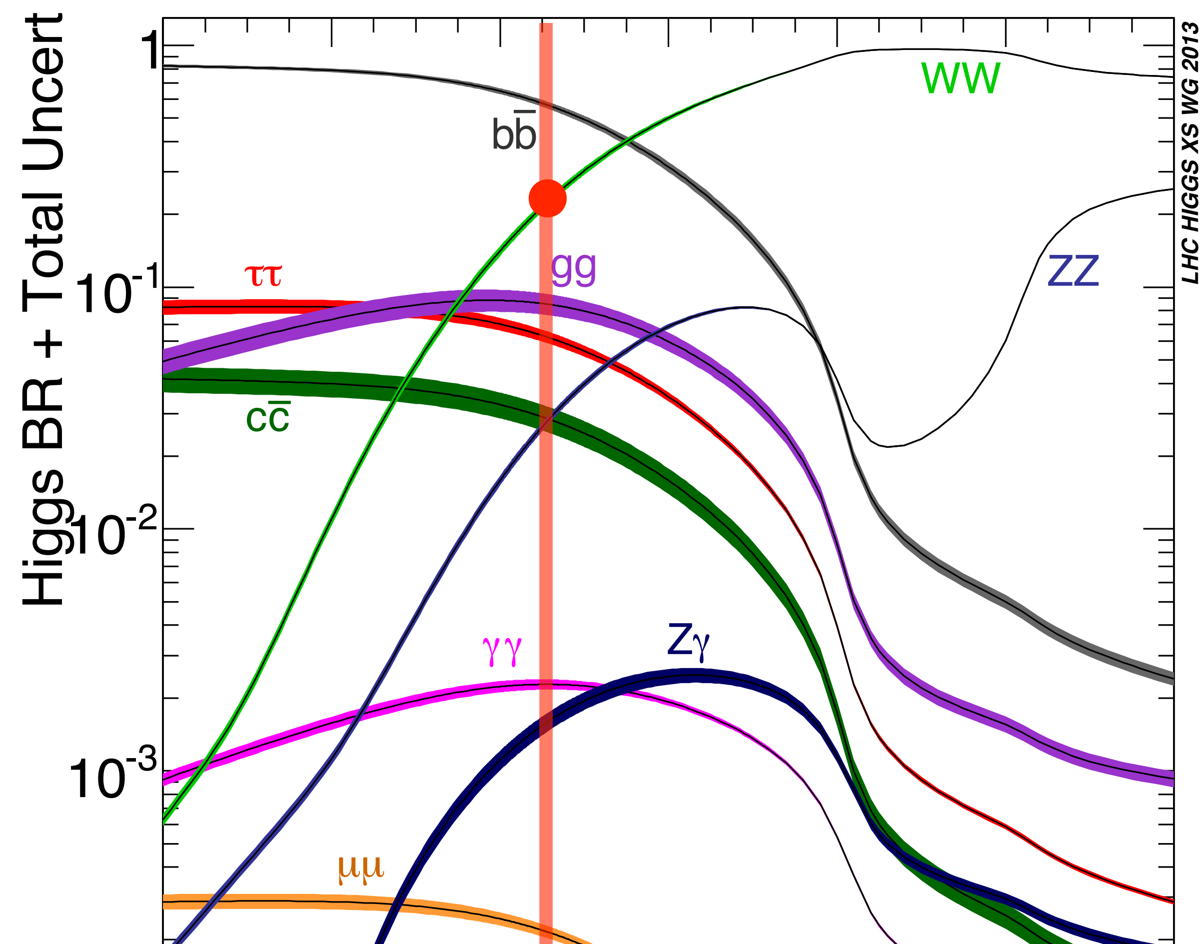
How to see a Higgs boson?

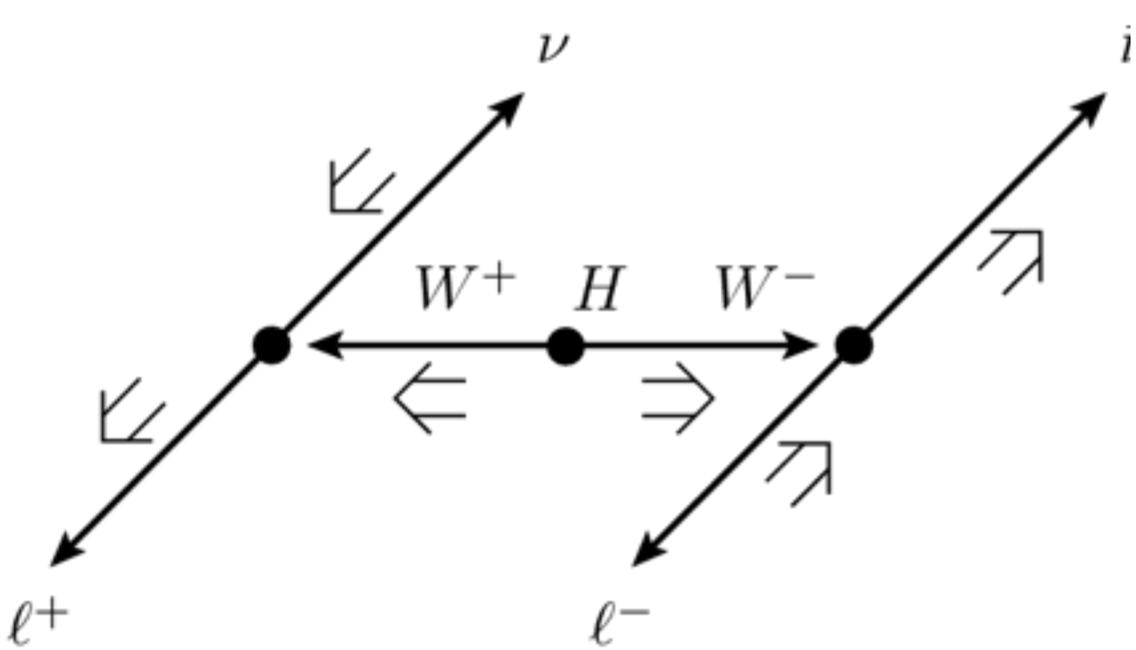
$h \to W^+W^{-*}$

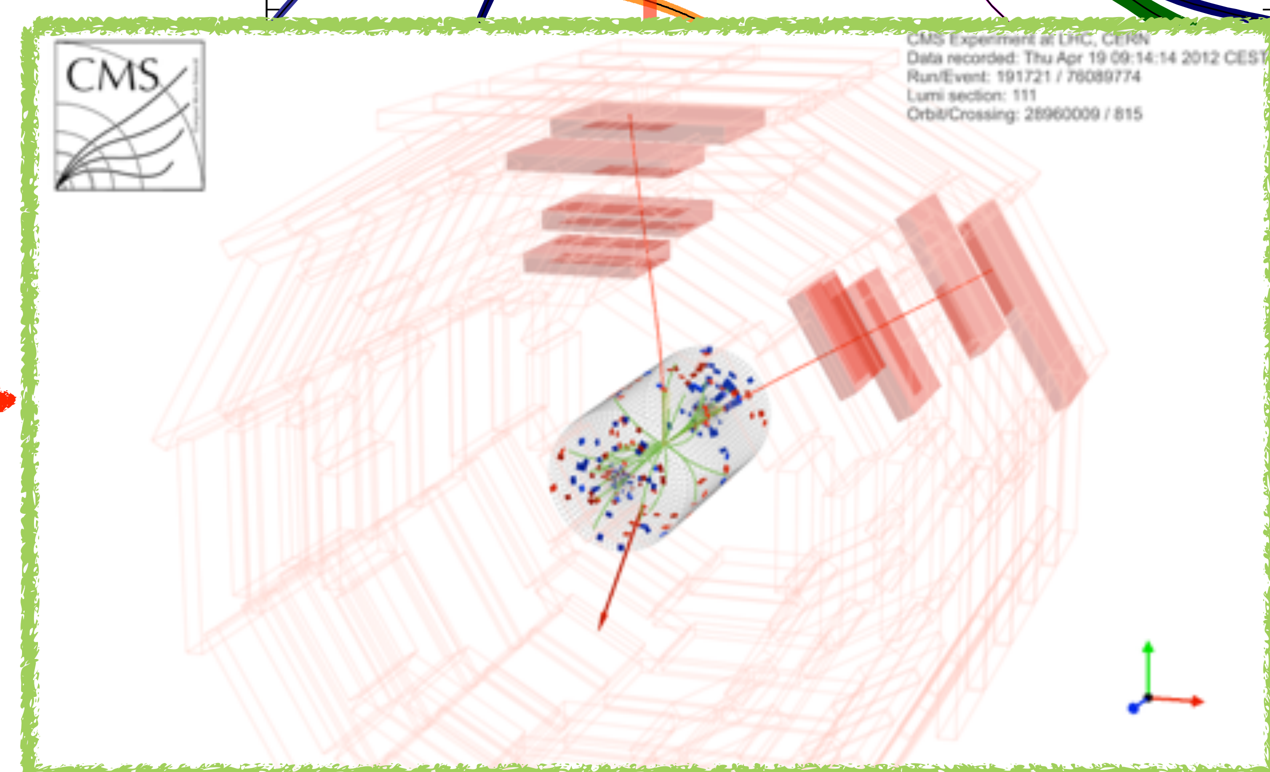
Large cross-section,

... invisible neutrino steels some kinematic information (no mass reconstruction)

...but distinctive kinematics due to chiral W couplings!



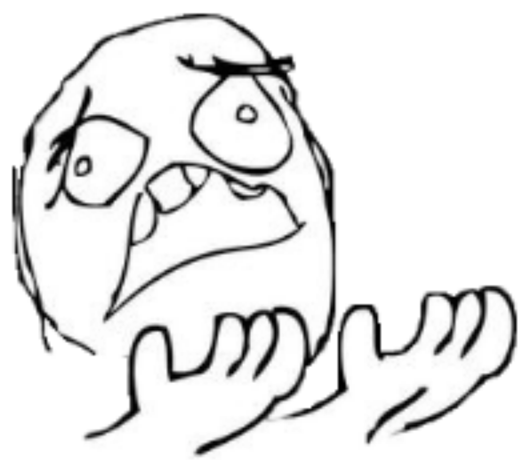


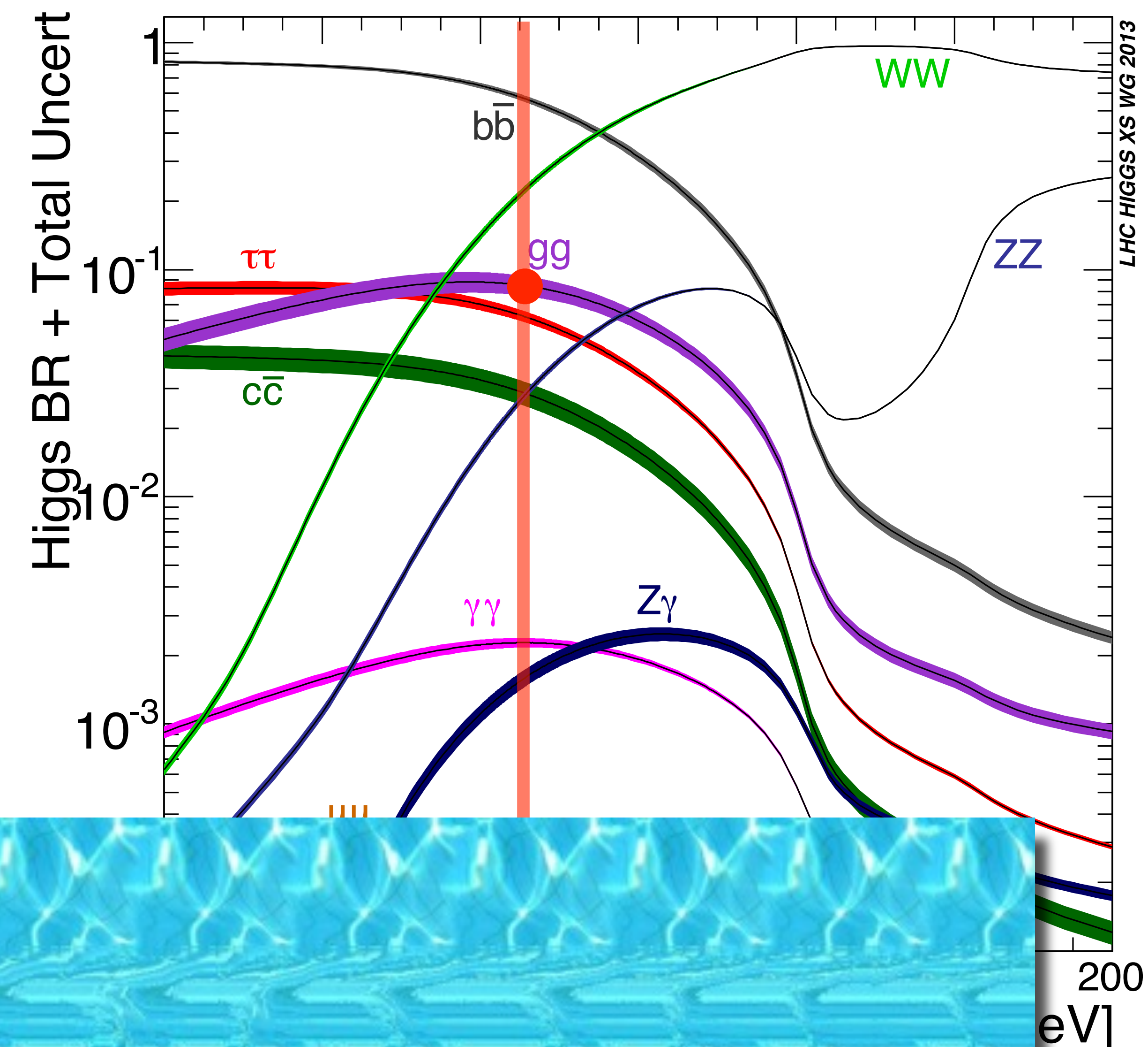


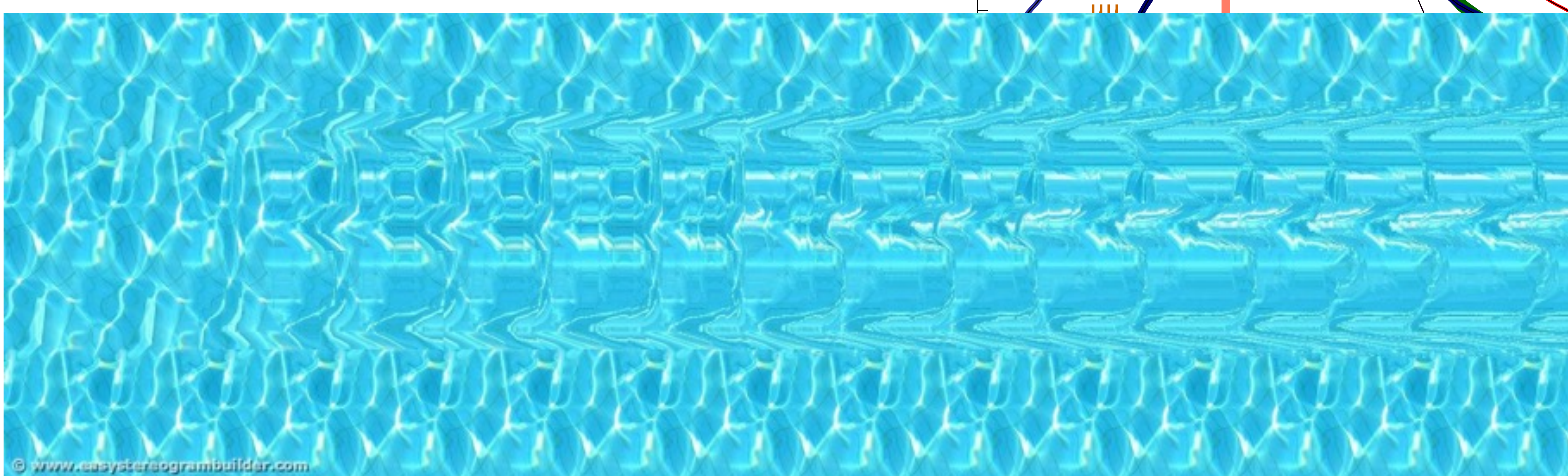
Higgs decays

How to see a Higgs boson?

$\boxed{h \to gg}$





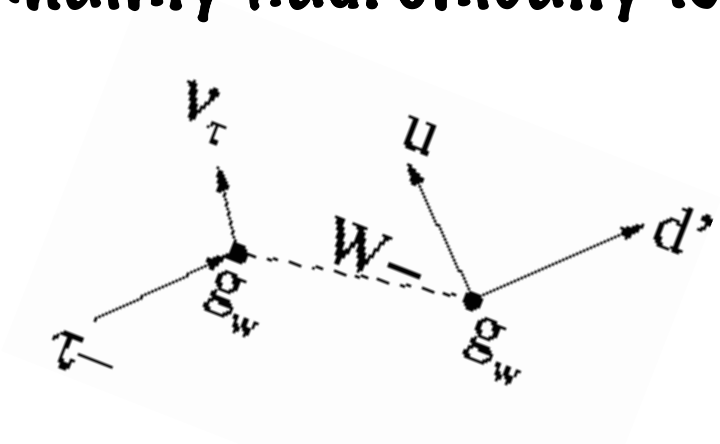


Higgs decays

How to see a Higgs boson?

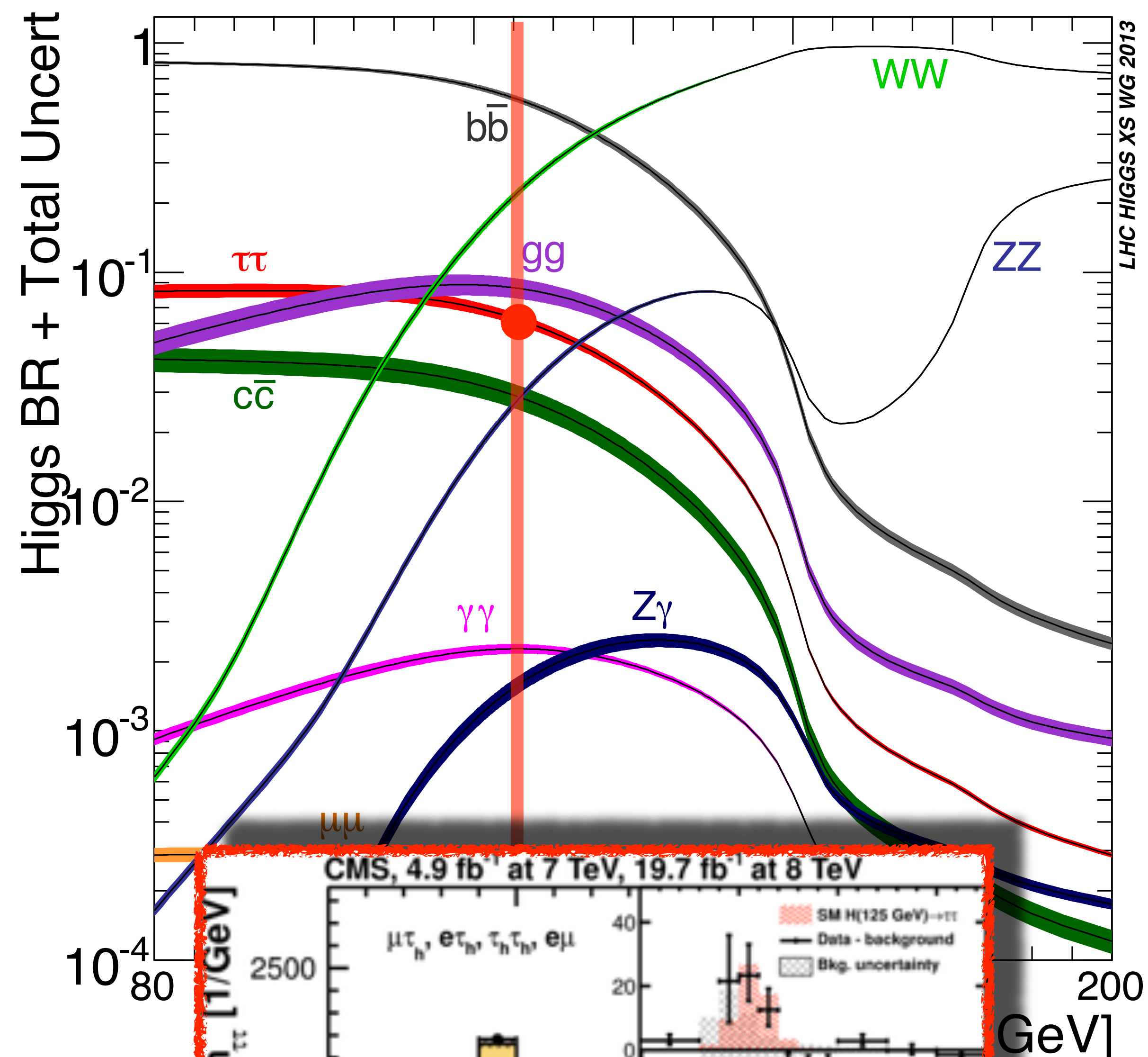
$\boxed{h \to \bar{\tau}\tau}$

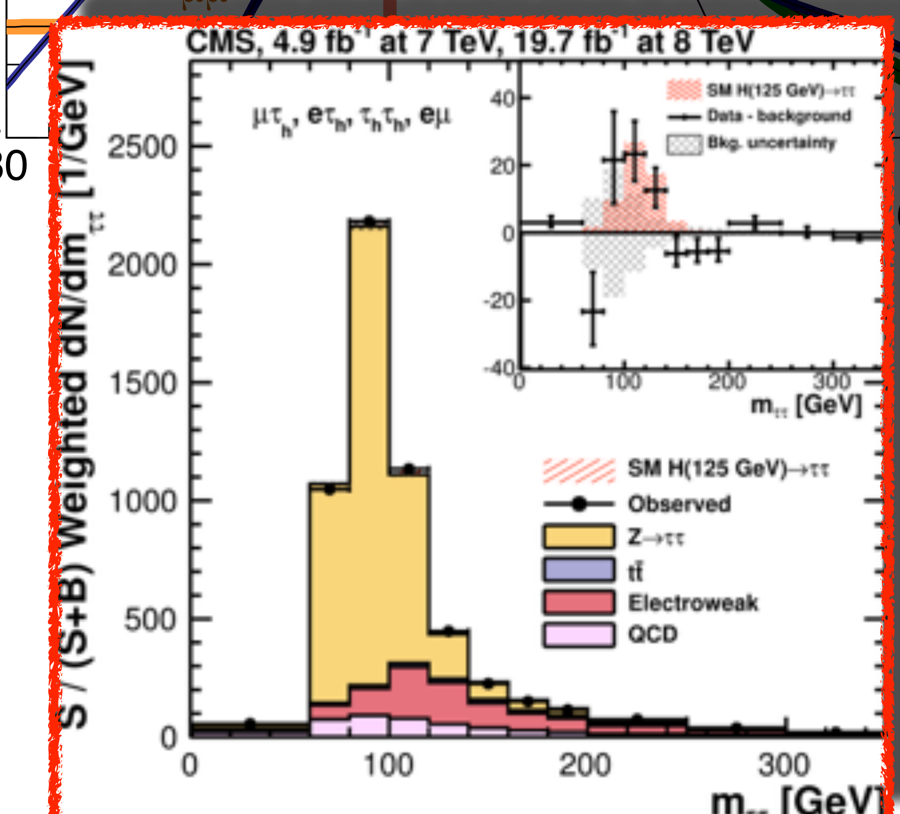
Although τ are leptons, for their large mass they decay mainly hadronically (65%)



This channel is similar to bb in terms of discovery potential... but smaller.

Nevertheless, it contains unique information on the $h\bar{\tau}\tau$ coupling





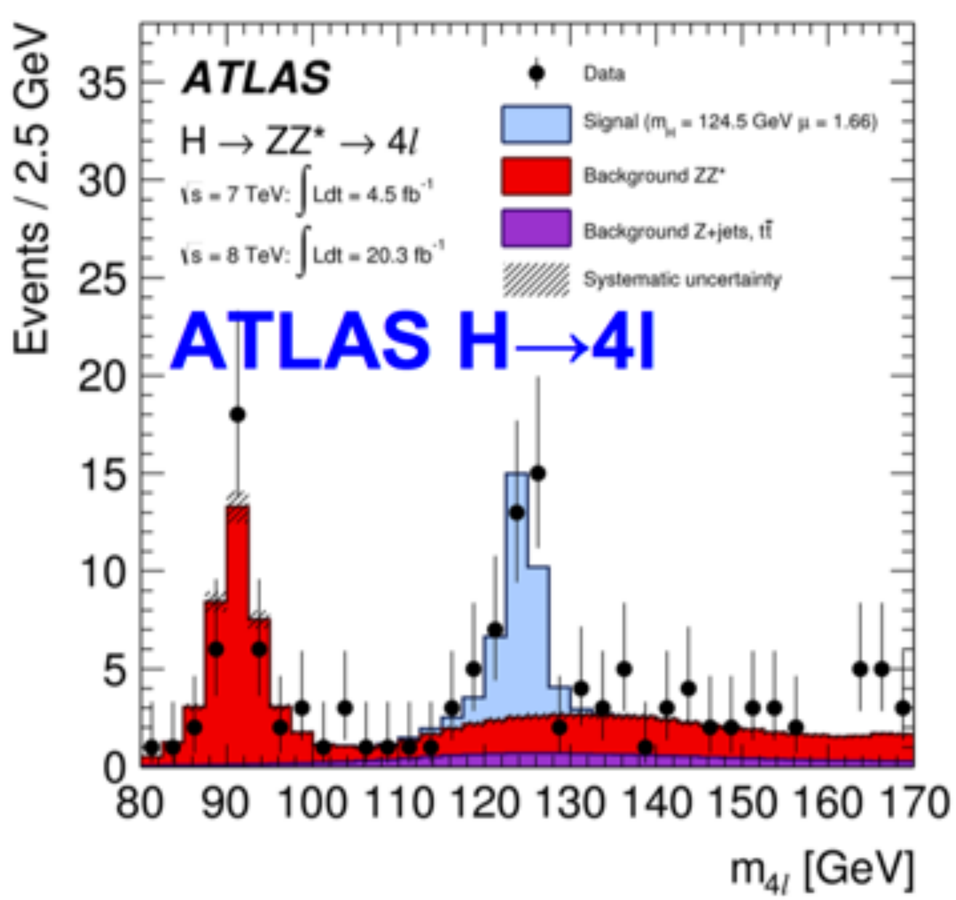
Higgs decays

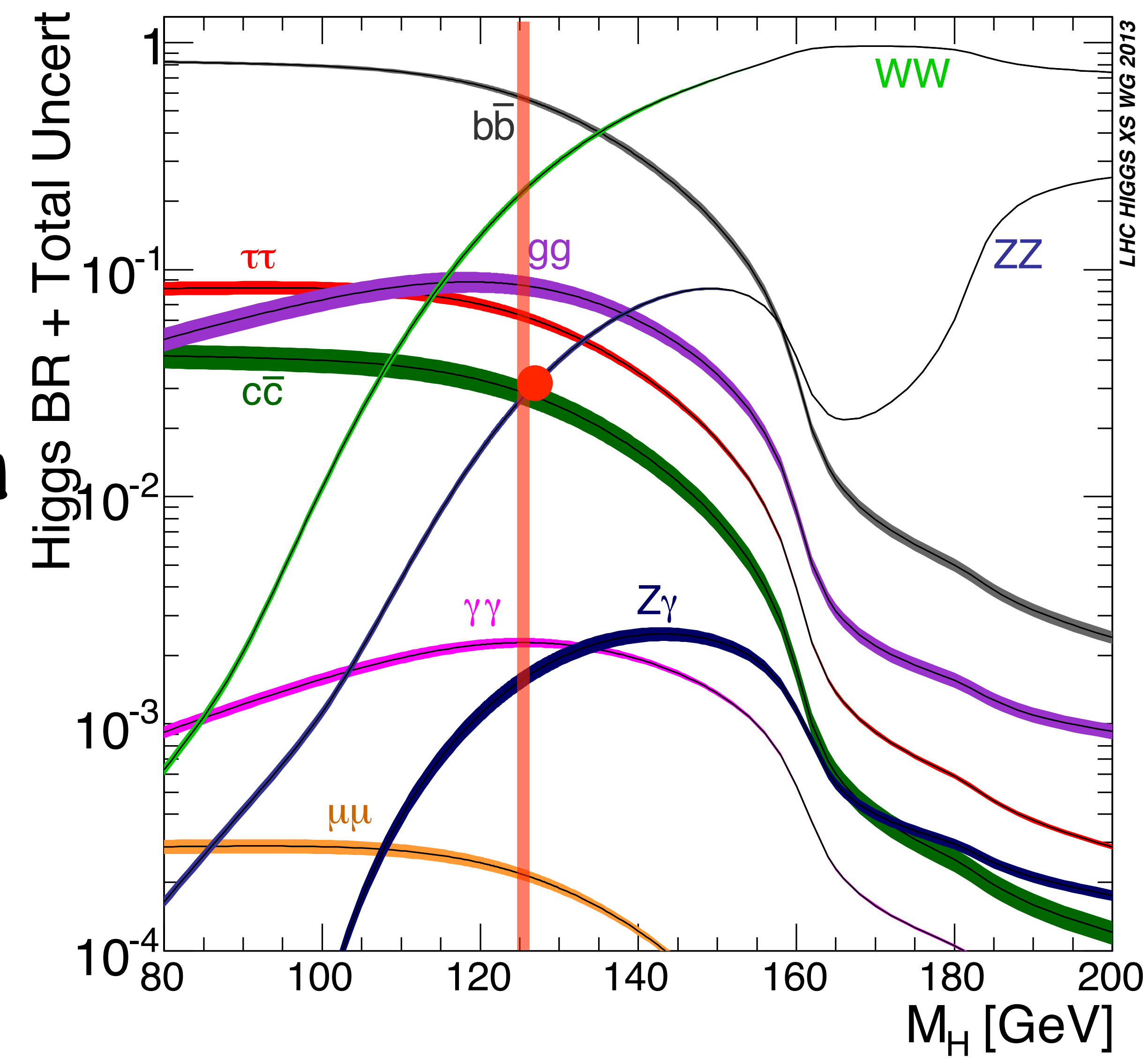
How to see a Higgs boson?

$\boxed{h \to ZZ^*}$ The Golden Channel!

≈ 7% of the times Z decays to e,μ

- Very good mass resolution
- Very good background discrimination
- At least one Z always off-shell



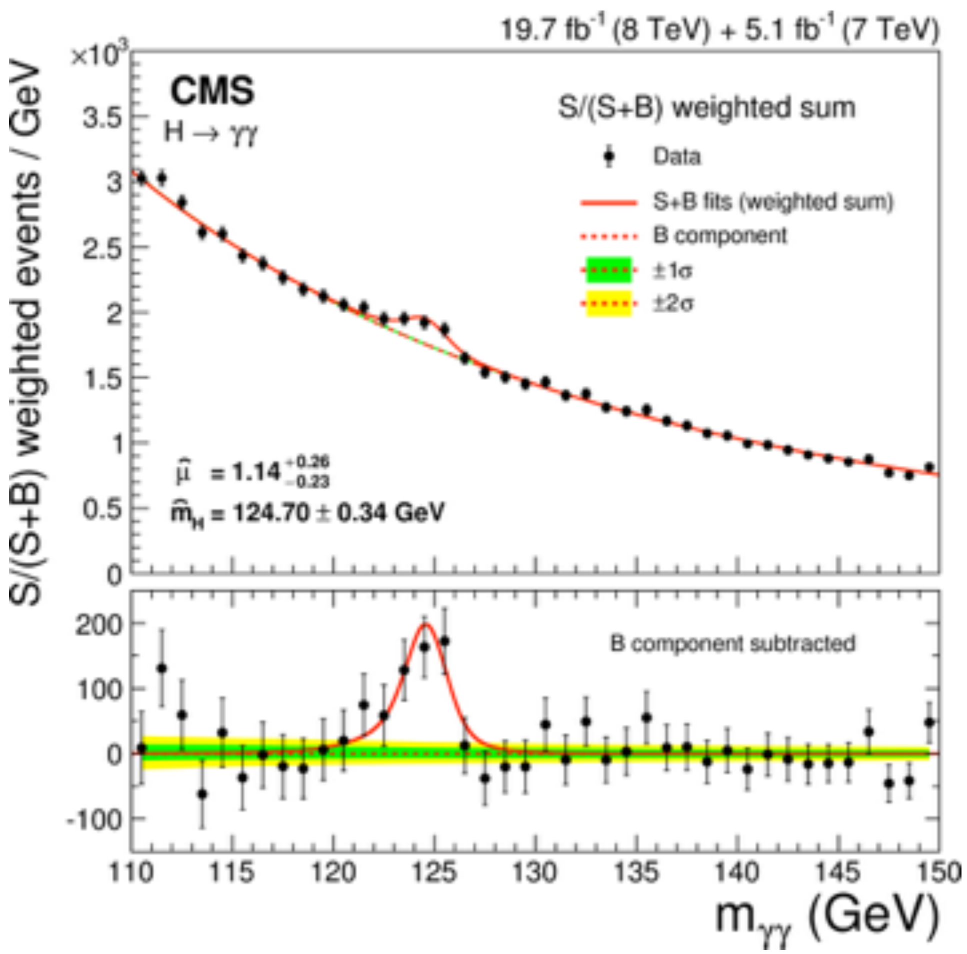


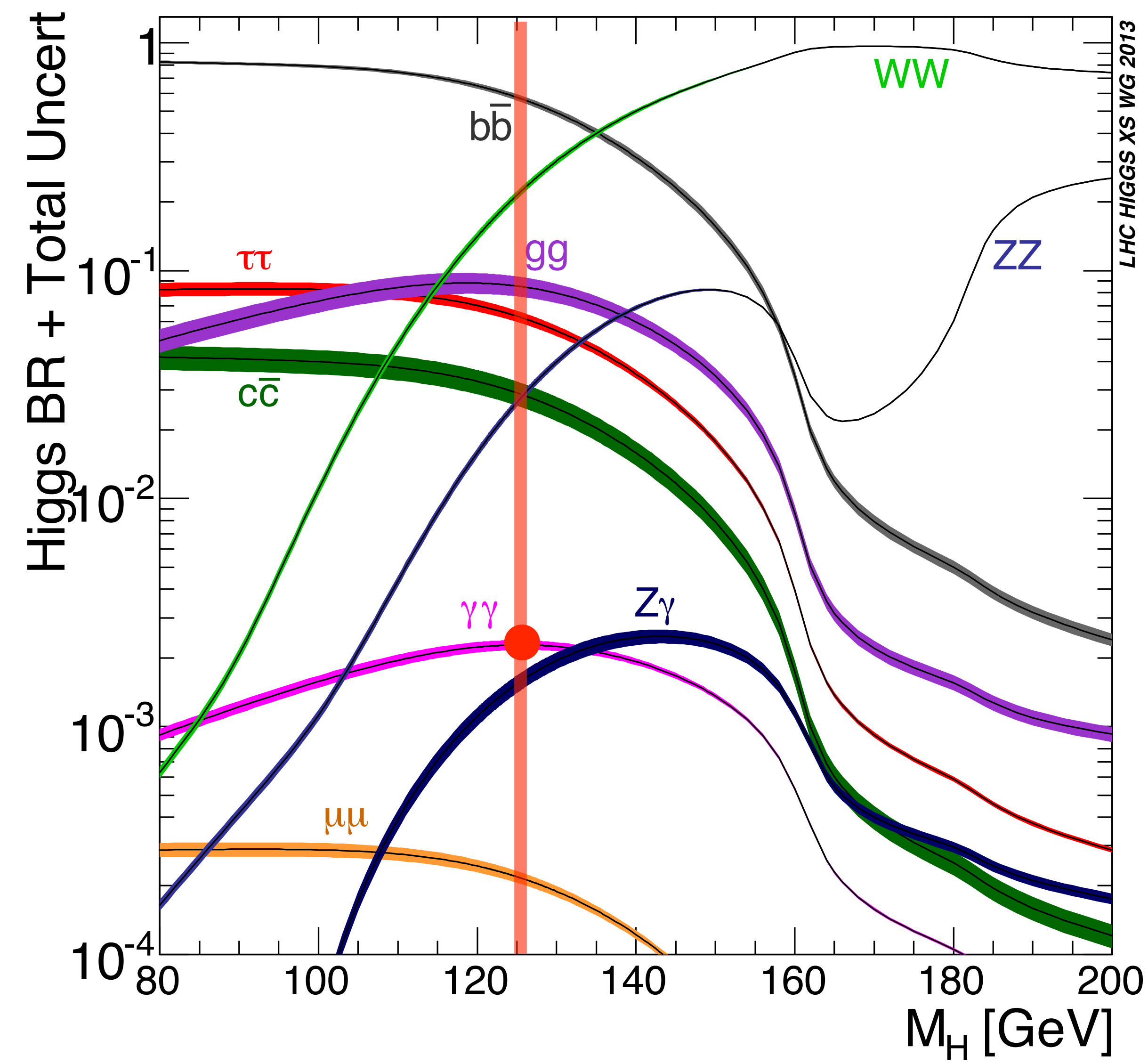
Higgs decays

How to see a Higgs boson?

$\boxed{h \to \gamma\gamma}$

- Very good mass-reconstruction
- Effective BR comparable to ZZ



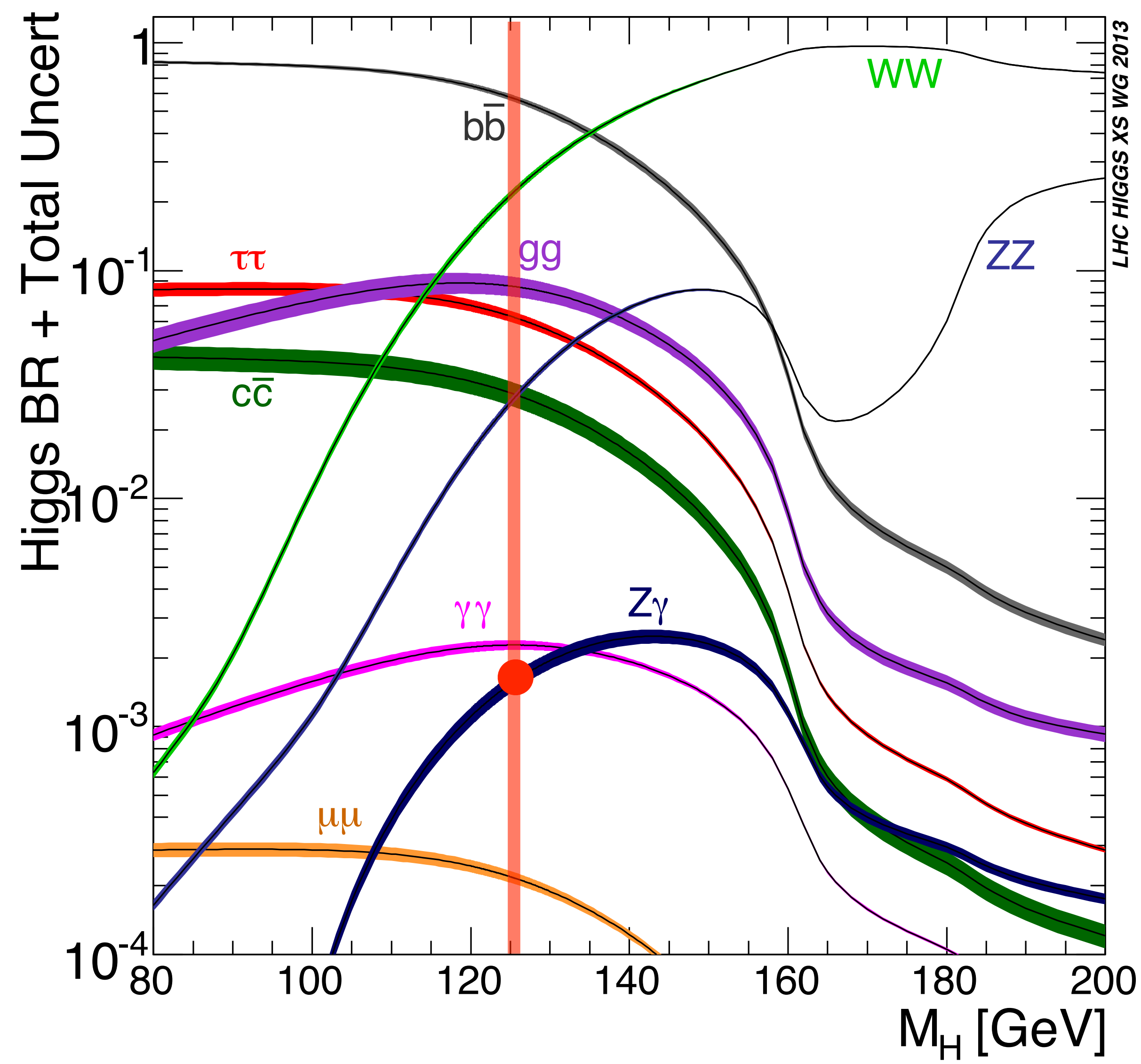


Higgs decays

How to see a Higgs boson?

$\boxed{h \to Z\gamma}$

- effectively smaller because of small Z leptonic BR

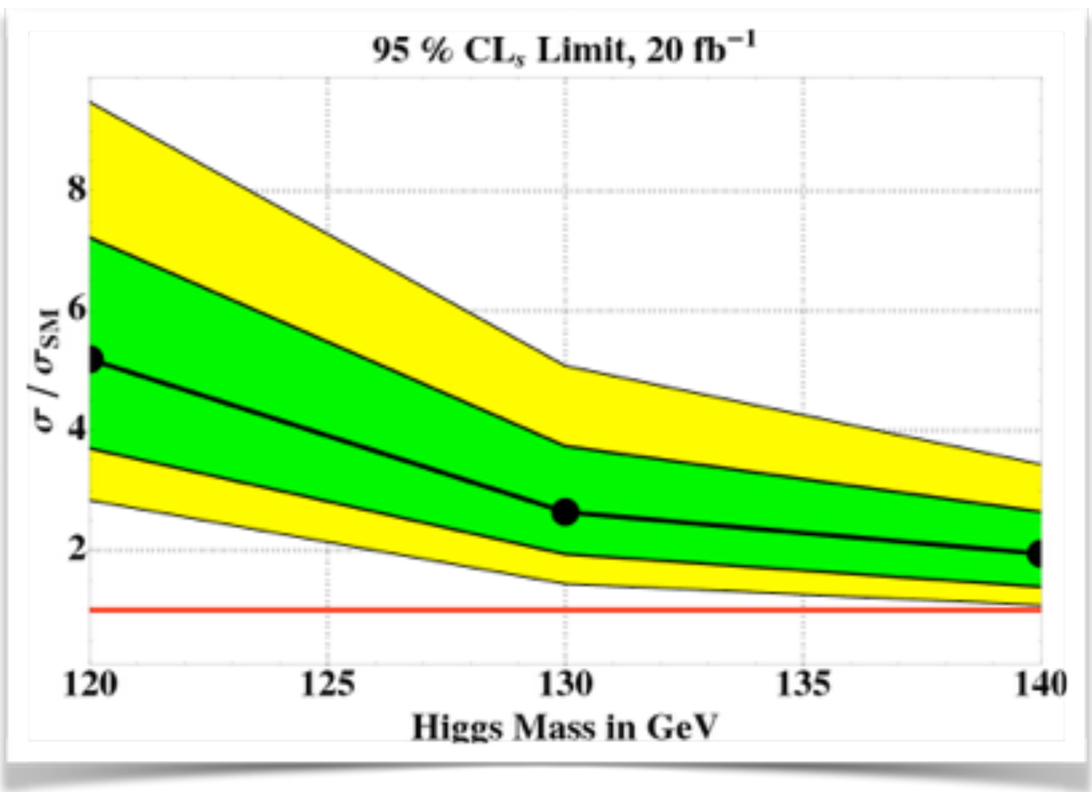


Higgs decays

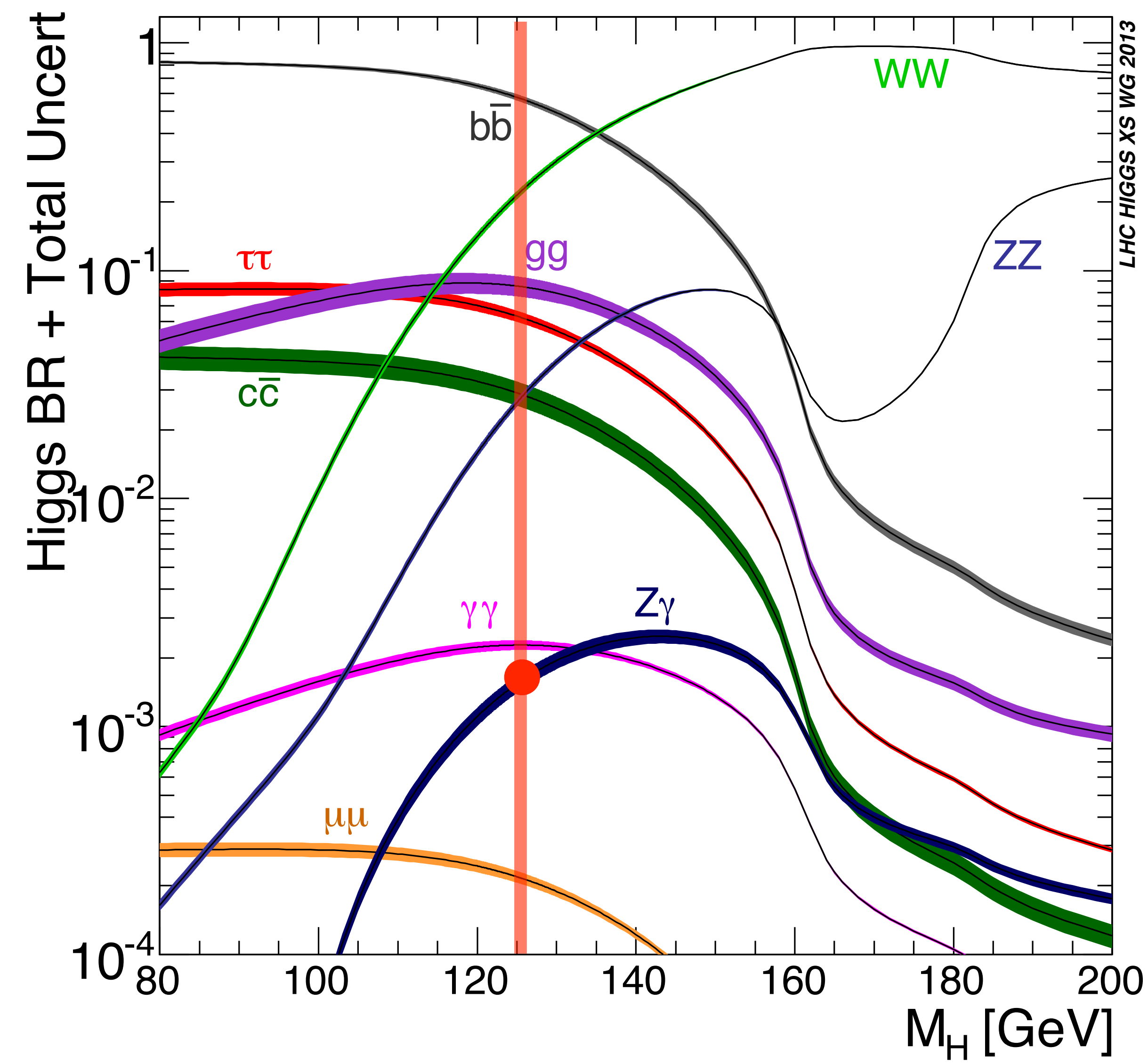
How to see a Higgs boson?

$h \to Z\gamma$

- effectively smaller because of small Z leptonic BR



Present searches are not sensitive to the SM, but only to BSM models in which the cross-section is enhanced by 3x ... still useful information!



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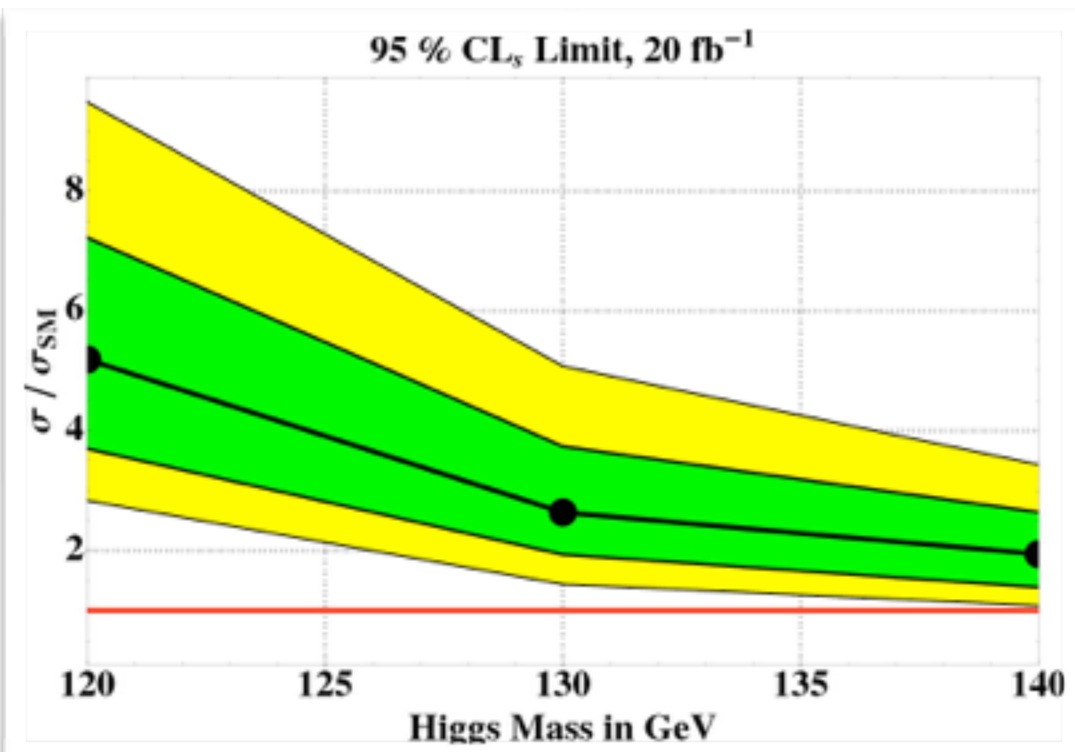
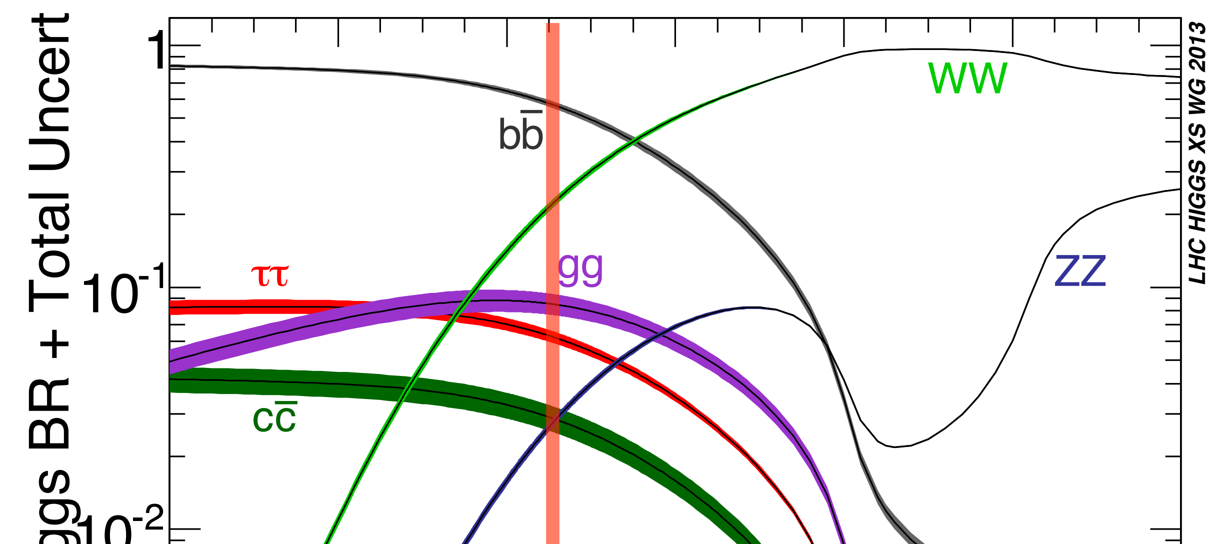
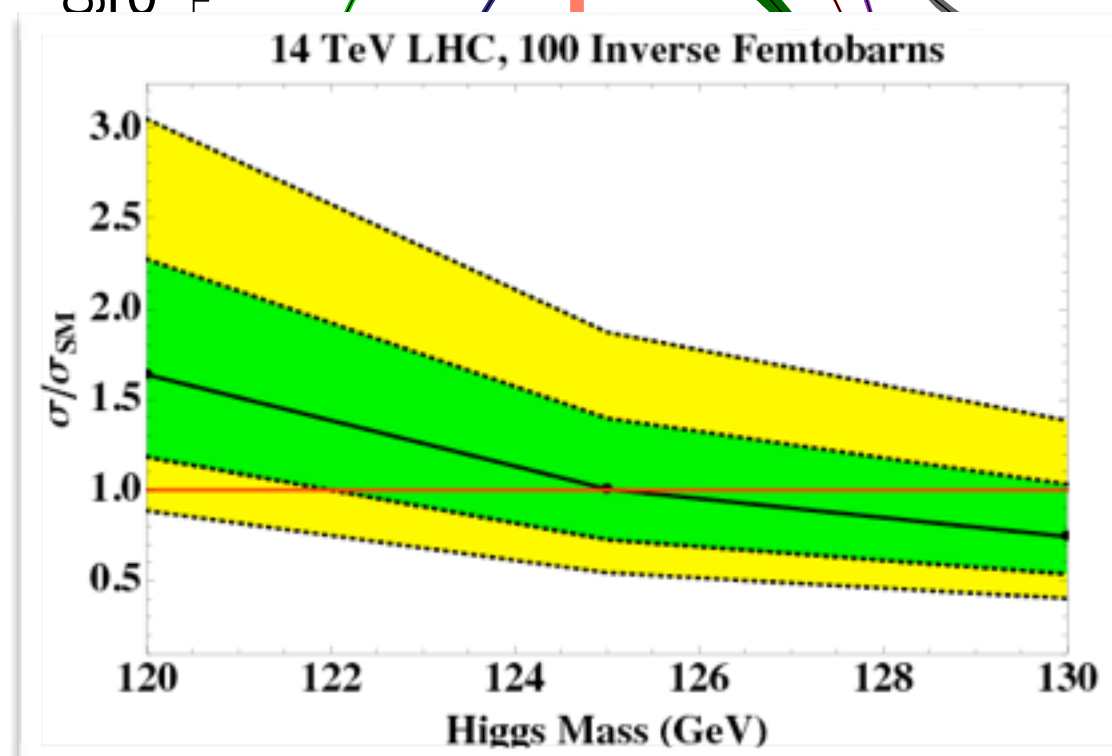
$h \to Z\gamma$

- effectively smaller because of small Z leptonic BR







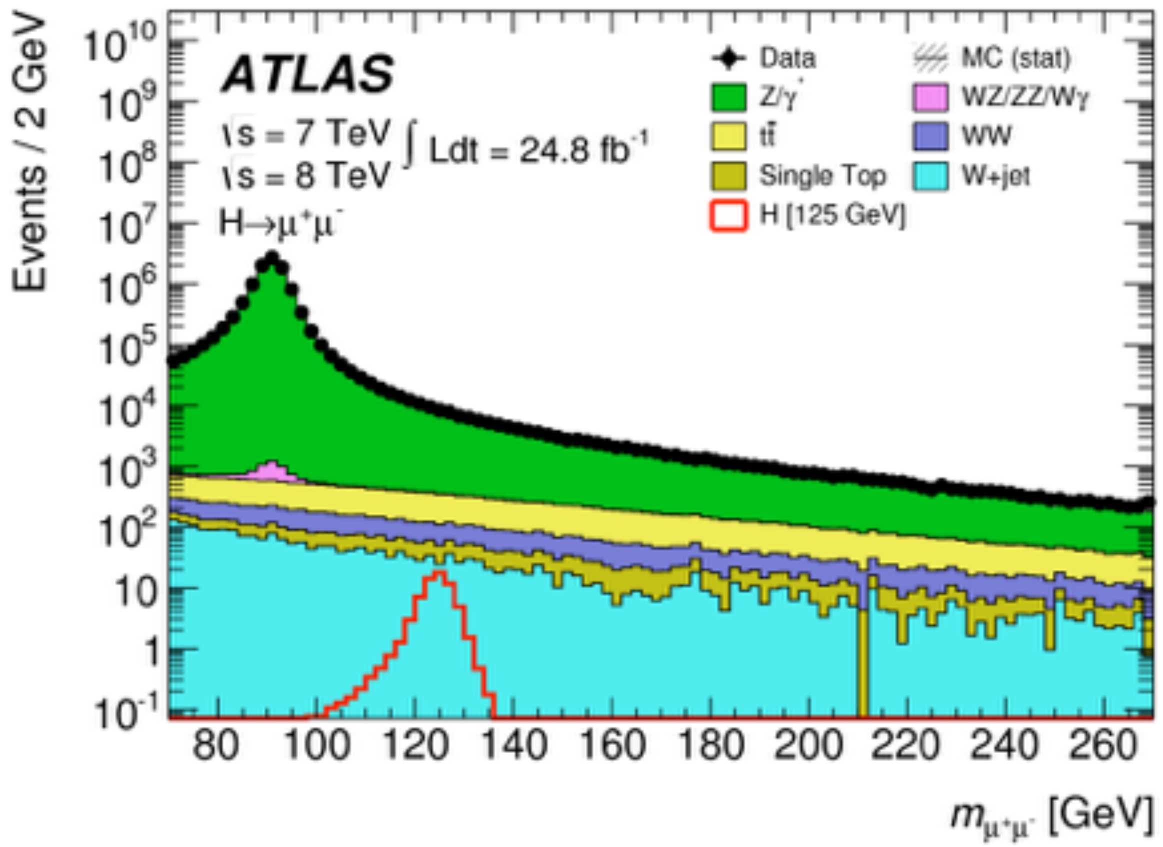
Present searches are not sensitive to the SM, but only to BSM models in which the cross-section is enhanced by 3x ... still useful information!

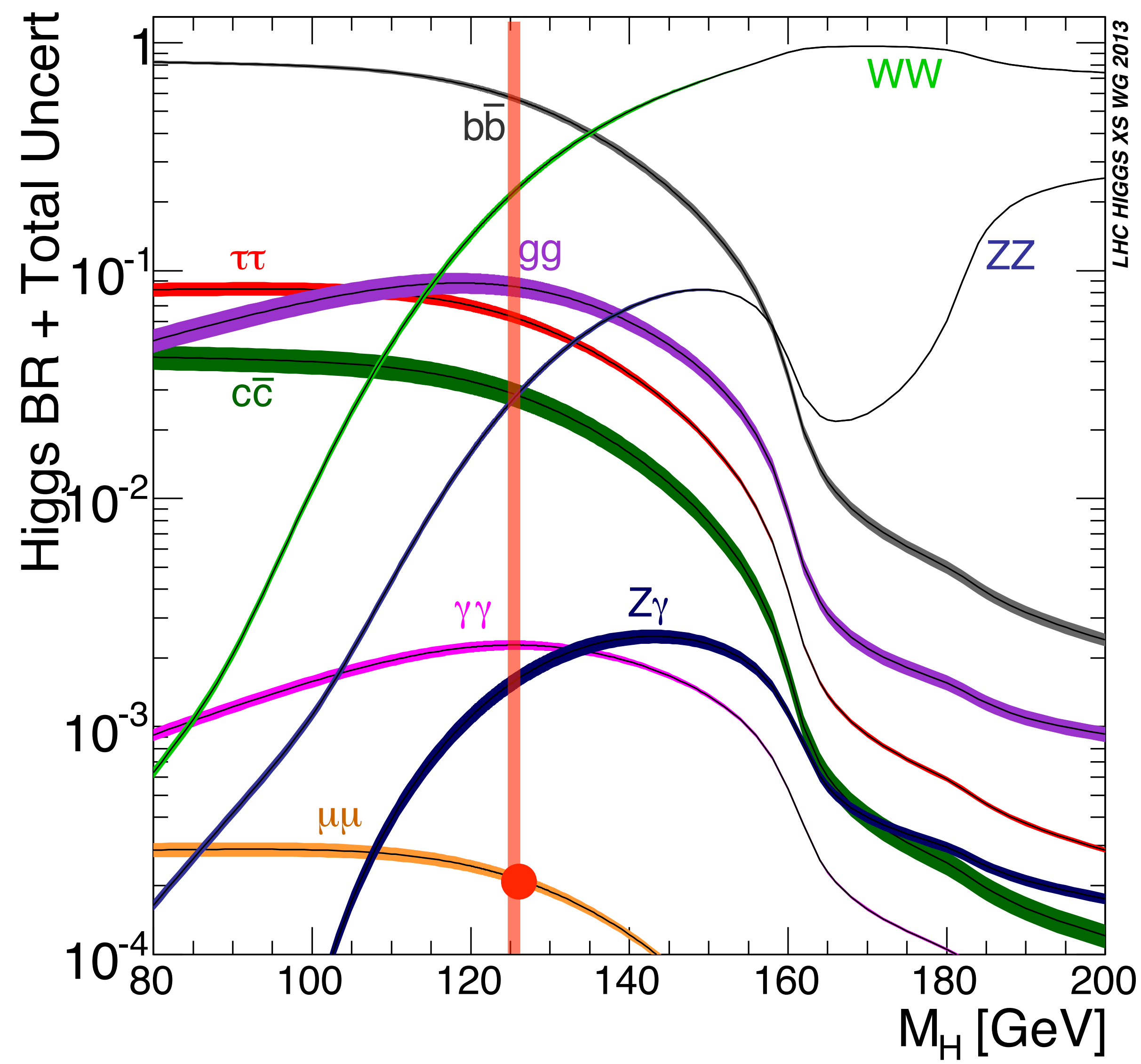
Higgs decays

How to see a Higgs boson?

$\boxed{h \to \bar{\mu}\mu}$

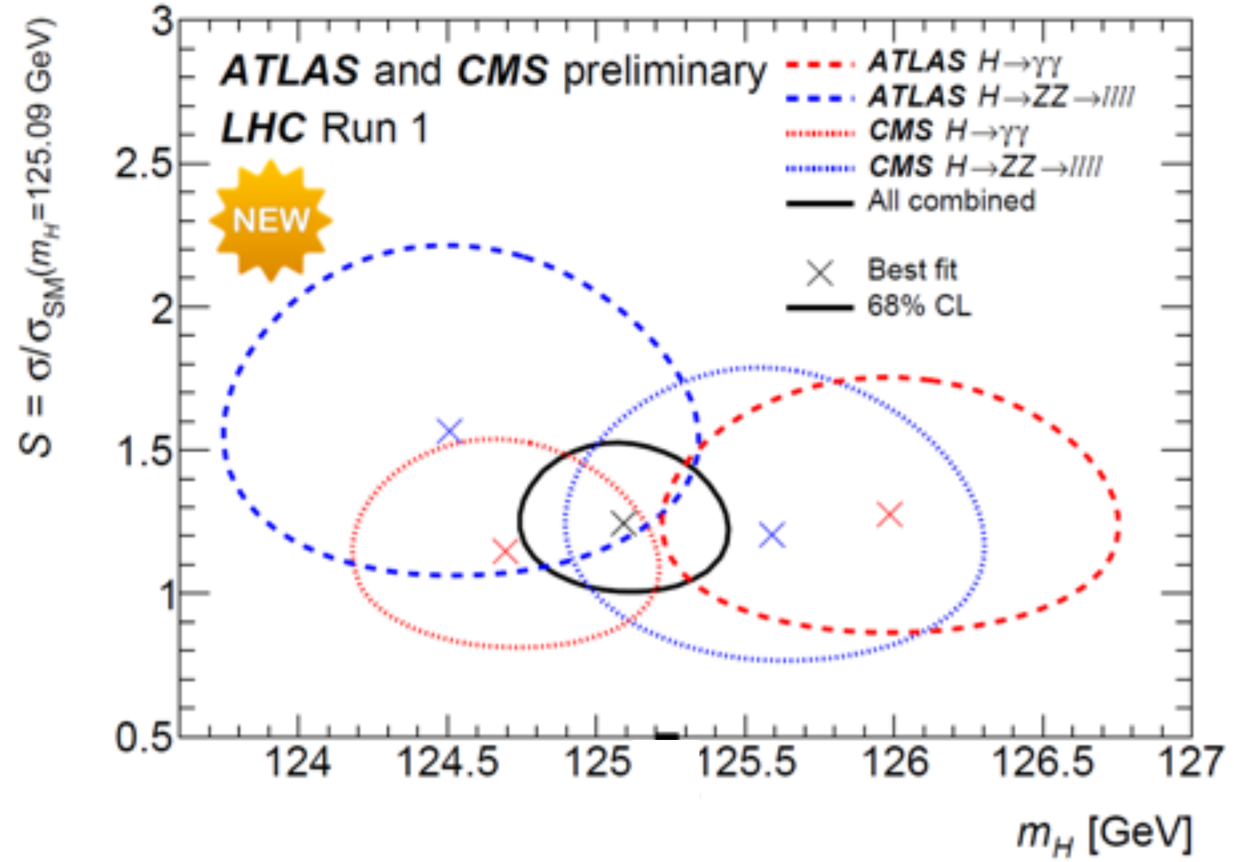
Very small rate ≈0.02%





Summary from RUN 1- mass

Combined Mass measurement:



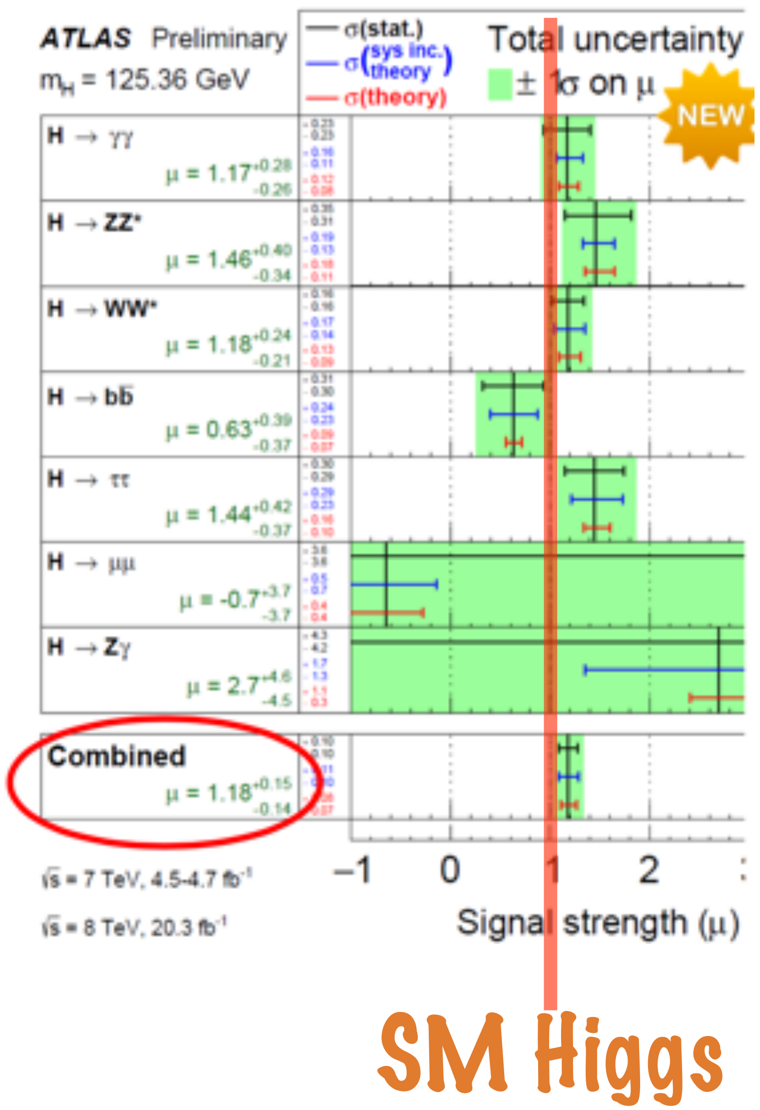
$$m_h = 125.09 \pm 0.24\mathrm{GeV}$$

A very precise measurement: *2‰*

This was the only missing piece of information, necessary to complete the SM: everything else is a prediction within the SM!

Summary from RUN 1- couplings

Coupling Measurements*:

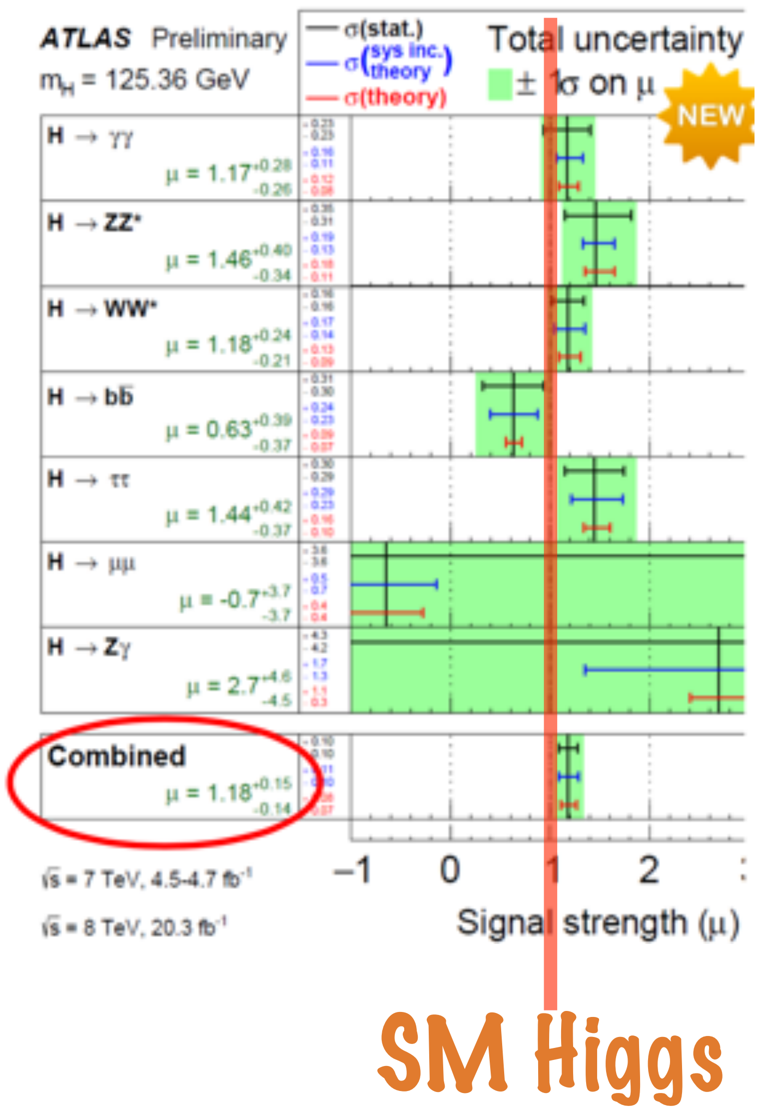


*Unlike m_h, couplings are not actually free parameters in the SM (remember they are proportional to known particle masses)…so what is this plot showing?

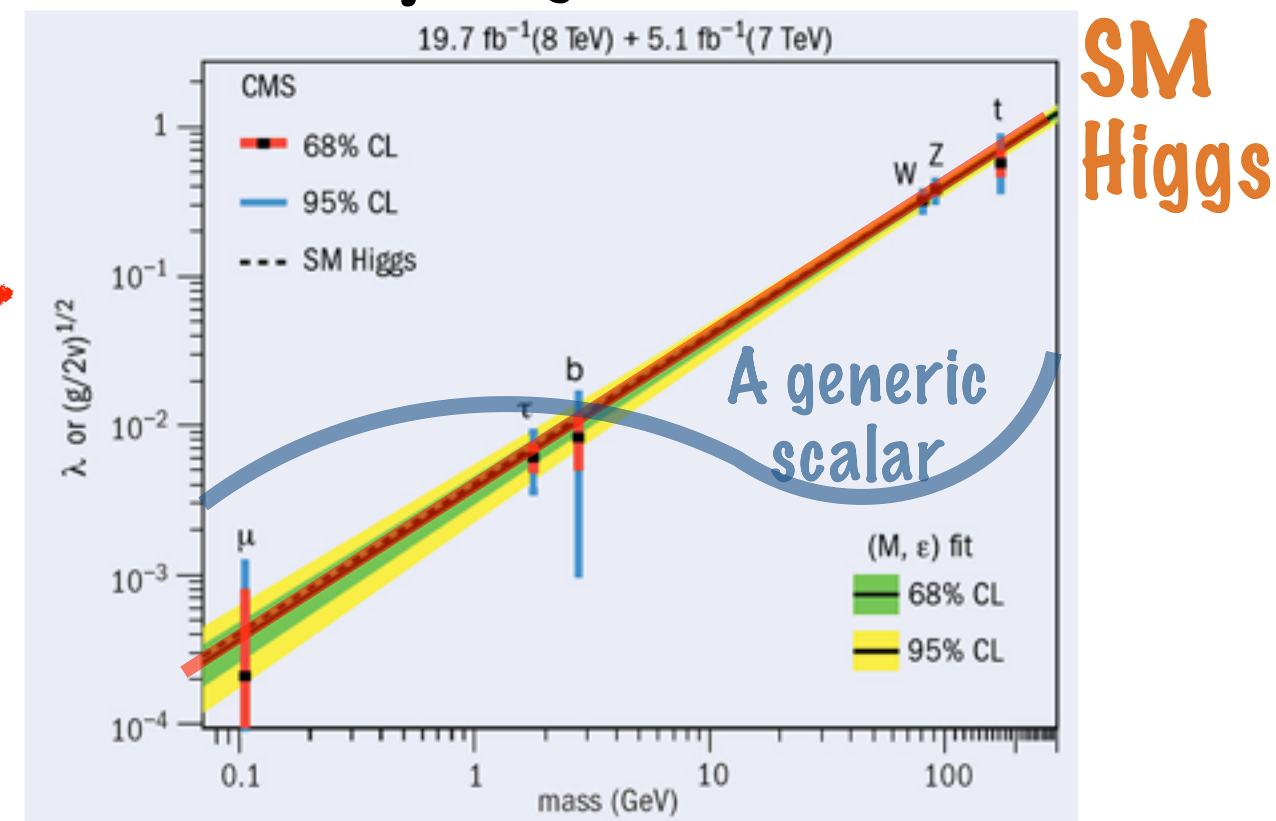
Every rate is rescaled by an independent factor (signal strength - μ), that is used in the fit to data.

Summary from RUN 1- couplings

Coupling Measurements*:



Mass/coupling relation:



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Summary from RUN 1- couplings

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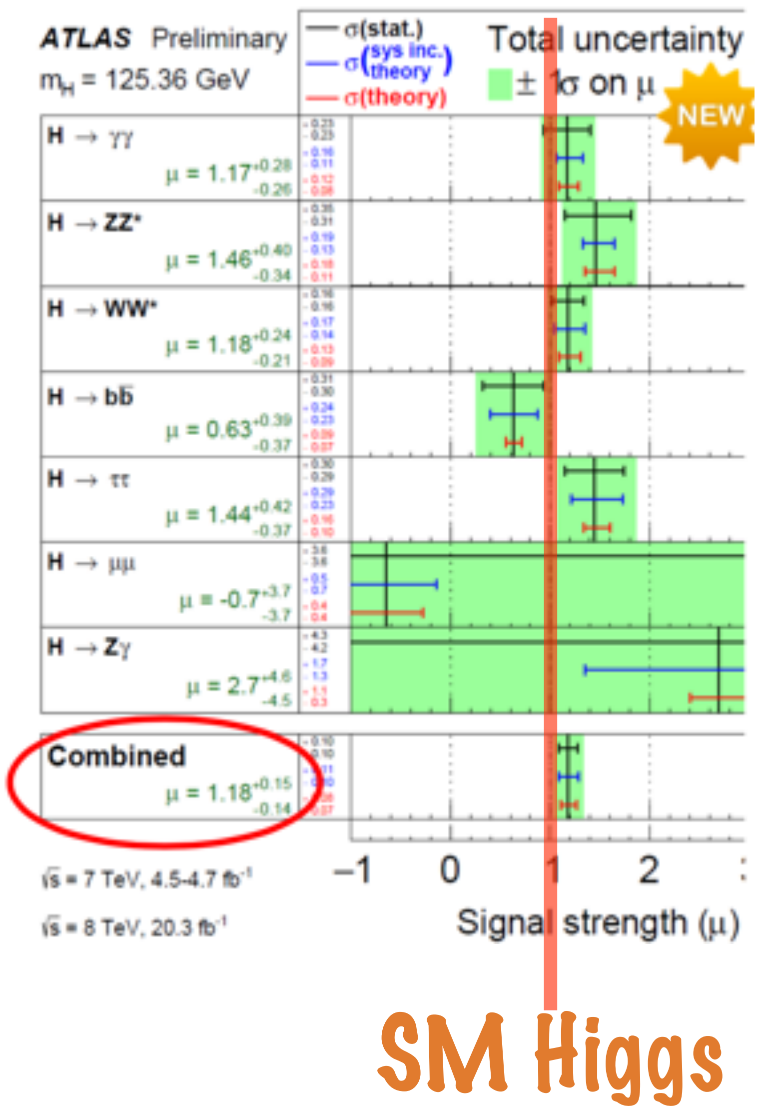

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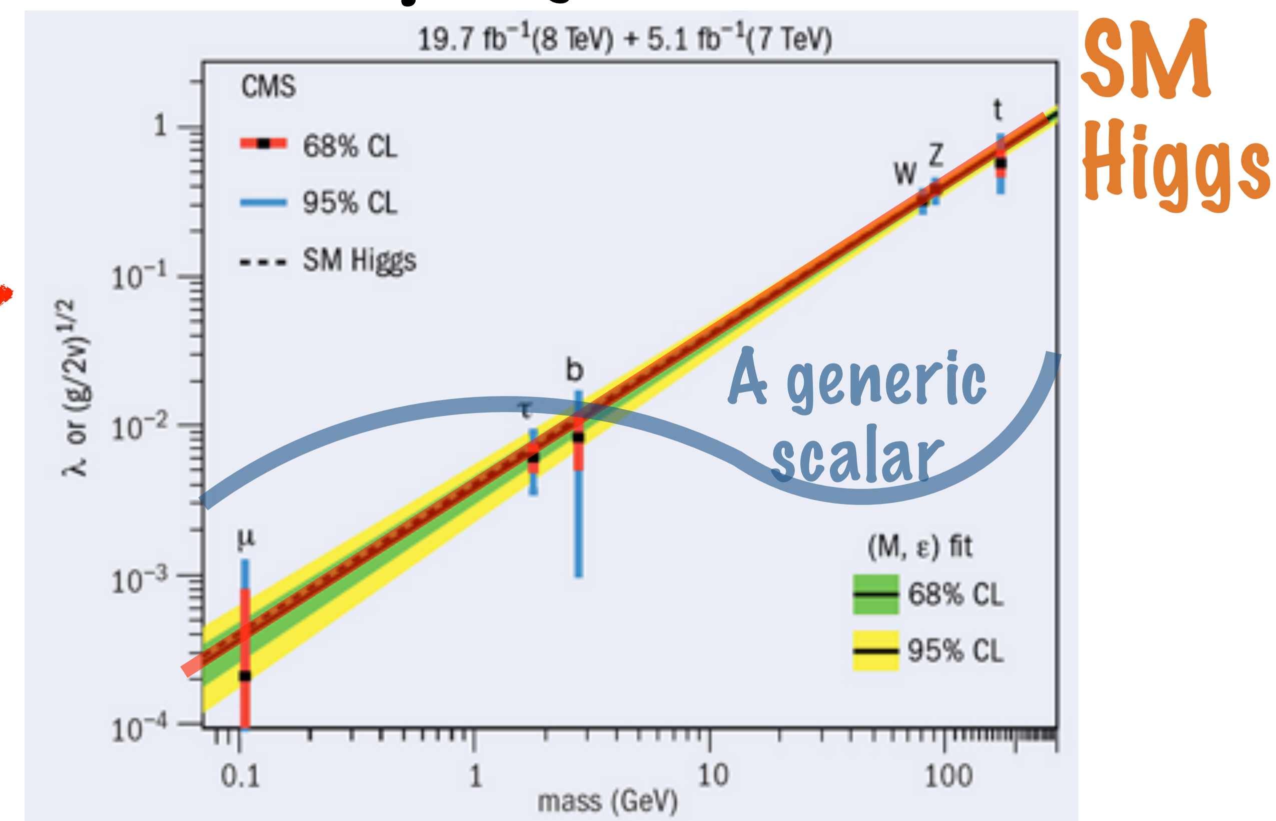

This is certainly a Higgs, responsible for EW symmetry breaking!

*Unlike m_h, couplings are not actually free parameters in the SM (remember they are proportional to known particle masses)...so what is this plot showing?

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