Higgs Beyond the SM and SUSY

Adam Martin
CERN/Notre Dame
(adam.martin@cern.ch)

YETI Winter School, IPPP Durham UK, 2013

Outline

Lecture #1

- Where are we now and where do we go from here?
- Did it have to be a Higgs?
- EFT for beyond the SM
- Composite Higgs (Higgs as a Goldstone Boson)

Lecture #2

- more Composite Higgs (Higgs as a Goldstone Boson)
- where & how to look at LHC

Where are we now?

- massive $W^{\pm}/Z^0$ fermions, massless γ, g:
  ‘electroweak symmetry is broken’

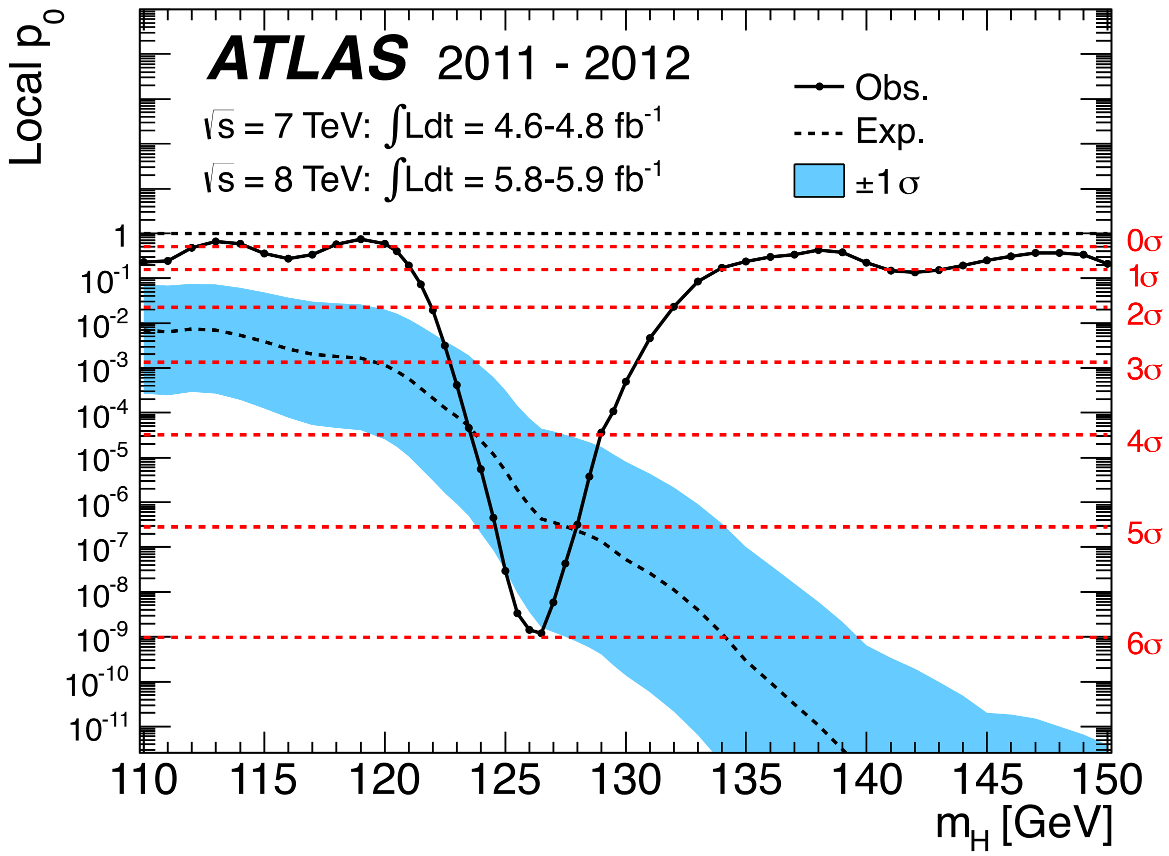
Where are we now?

- massive $W^{\pm}/Z^{0}$ fermions, massless γ, g:
  ‘electroweak symmetry is broken’

- As of July 4th, 2012...

we have a new boson **X**, with mass ~125 GeV

likely spin-0,
likely CP-even



X is observed in channels and with rates similar to what we expect for a SM Higgs boson

What now?

- To what extent are EWSB and **X** related?

  Meaning what are the similarities & differences between **X** and SM Higgs?

- What is the bigger picture?

Is there a bigger picture?

- LOTS we don't know.. many things we observe are not in the SM.

baryon vs. anti-baryon asymmetry

Dark Matter

neutrino masses

generations, charge assignments

- Scale/properties of these other phenomena is unknown.

- Hope that understanding EWSB (& connection w/ **X** boson) will shed some light on these other topics

Did it have to be Higgs?

Was finding a Higgs-like boson inevitable? Is that the only path in nature for what we see?

Did it have to be Higgs?

Was finding a Higgs-like boson inevitable? Is that the only path in nature for what we see?

NOPE

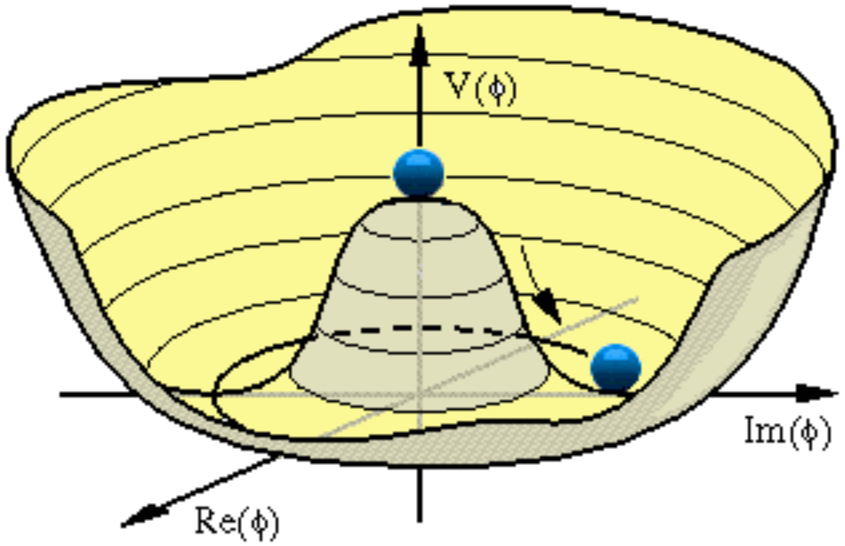
Did it have to be Higgs?

Was finding a Higgs-like boson inevitable? Is that the only path in nature for what we see?

NOPE

we know how Higgs works

(see lectures by Mück,Englert,Duehrssen)



$H \in (2, 1/2)$ of $SU(2)_W \otimes U(1)_Y$

$$|D_\mu H|^2 - \lambda(H^\dagger H - \frac{v^2}{2})^2$$

Did it have to be Higgs?

Instead lets add a field Σ(x):

Pauli matrices

$$\Sigma(x) = \exp\left(\frac{i\,2\pi^a\,\tau_a}{v}\right) = \mathbf{1}_{2\times 2} + 2\,i\,\frac{\pi_a\,\tau^a}{v} - 2\,\frac{\pi_a\pi_b\,\tau^a\tau^b}{v^2} + \cdots$$

3 “pion” fields

EW scale

Did it have to be Higgs?

Instead lets add a field Σ(x):

Pauli matrices

$$\Sigma(x) = \exp\left(\frac{i\,2\pi^a\,\tau_a}{v}\right) = \mathbf{1}_{2\times 2} + 2\,i\,\frac{\pi_a\,\tau^a}{v} - 2\,\frac{\pi_a\pi_b\,\tau^a\tau^b}{v^2} + \cdots$$

3 “pion” fields

EW scale

expanding out, we get a (2x2) matrix

$$\Sigma = \begin{pmatrix} \cos(\hat{\pi}/v) + i\hat{\pi}_3 \sin(\hat{\pi}/v) & i(\hat{\pi}_1 - i\hat{\pi}_2)\sin(\hat{\pi}/v) \\ i(\hat{\pi}_1 + i\hat{\pi}_2)\sin(\hat{\pi}/v) & \cos(\hat{\pi}/v) - i\hat{\pi}_3 \sin(\hat{\pi}/v) \end{pmatrix}$$

$$\hat{\pi} = \sqrt{\pi_a^2}, \quad \hat{\pi}_a = \pi_a/\hat{\pi}$$

remember, the SM Higgs doublet

$$H(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} h_1 + i\,h_2 \\ h_0 + i\,h_3 \end{pmatrix}$$

has 4 fields, our
Σ has 3

Did it have to be Higgs?

under $SU(2)_W \times U(1)_Y$: $U_L\, \Sigma\, U^{\dagger}_R$

$$D_\mu \Sigma = \partial_\mu \Sigma - ig \vec{W}_\mu \Sigma + ig' \Sigma B_\mu \tau_3$$

how is this different than H? (forget $U(1)_Y$ for now..)

U_L is a 2 x 2 matrix: $U_L = \exp\left(i\alpha_a(x)\tau^a\right)$

acting on the Higgs vs. on Σ:

$U_L\, H(x)$: mixes up the 4 components h_i

ex.) $h_3 \rightarrow h_3 + i\, h_0\, \alpha_3 - i\, h_1\, \alpha_1 + i\, h_2\, \alpha_2$

$U_L\, \Sigma(x)$: shifts the π_a fields, $\pi_3 \rightarrow \pi_3 + \alpha_3$

Did it have to be Higgs?

out of Σ, we have:

$$\mathcal{L}_\Sigma = \frac{v^2}{4}\mathrm{tr}(D^\mu \Sigma\, D_\mu \Sigma^\dagger) + \cdots$$

more derivatives,
etc.

by a gauge transformation:

$$U_L = \Sigma^\dagger,\ \Sigma \to \Sigma^\dagger \Sigma = \mathbf{1}\,,\ \ iD_\mu\,\Sigma = (g\,\vec{W}_\mu - g'\,B_\mu)$$

$$\mathcal{L}_\Sigma = \frac{v^2}{4}\,(g\,\vec{W}_\mu - g'\,B_\mu)^2 = m_W^2\,W_\mu^+ W^{\mu -} + m_Z^2\,Z^\mu Z_\mu$$

so with only **3** degrees of freedom, we can give mass to W±/Z (fermions too: $y_t\,v\,Q\,\Sigma\,u_R^*$, etc.).

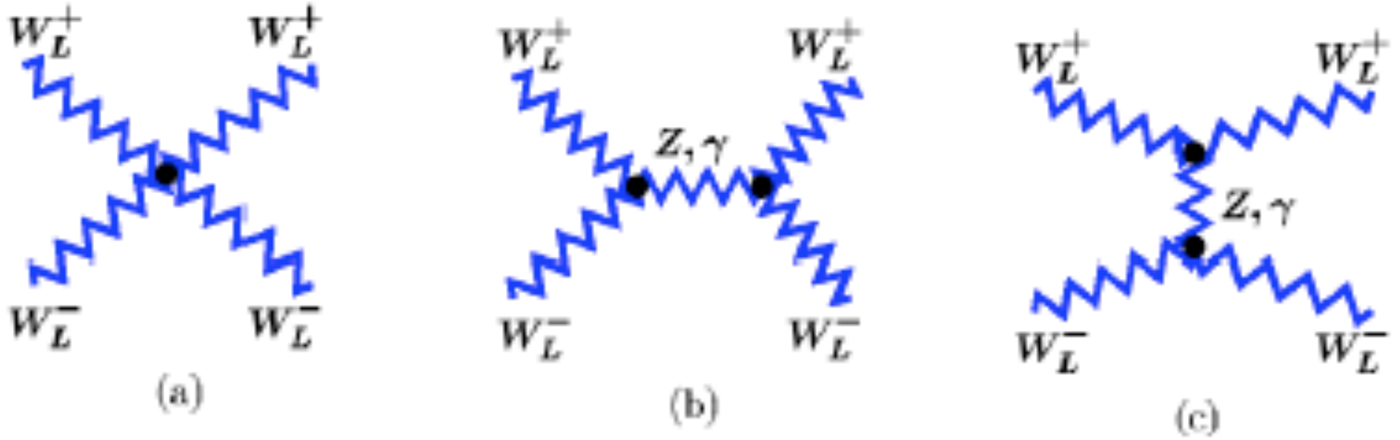
‘Higgsless’ EWSB

we haven’t explained what dynamics gives Σ ...
but no explanation for V(H) in SM.

So what's the difference?

Look at $W_L W_L \rightarrow W_L W_L$ scattering in the H & Σ theories
(at tree level)

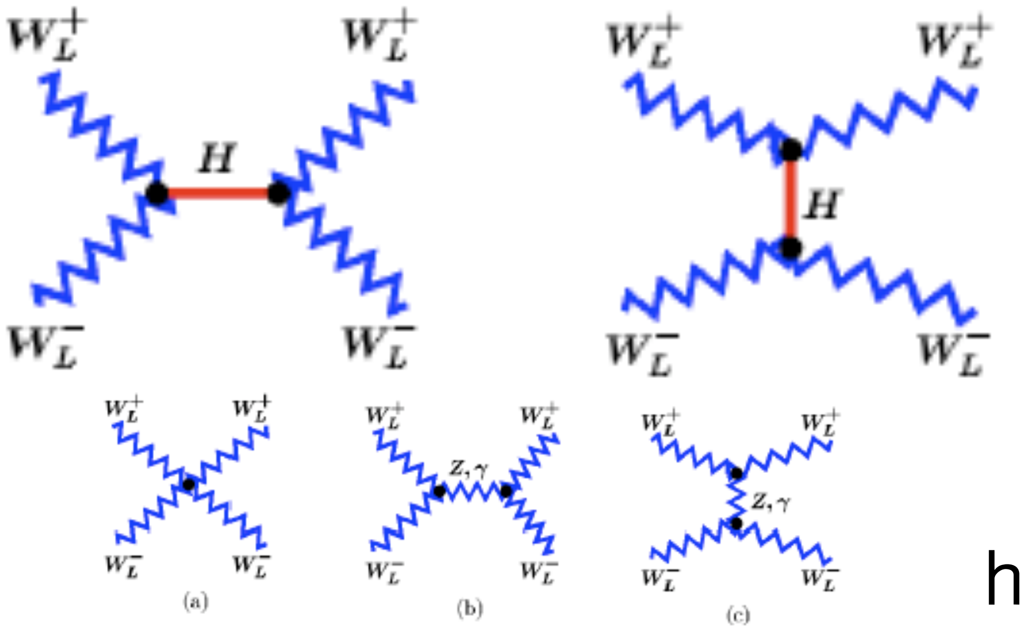
in the Σ theory:



$$A \sim \frac{s}{v^2}$$

amplitude grows with energy

in the SM:



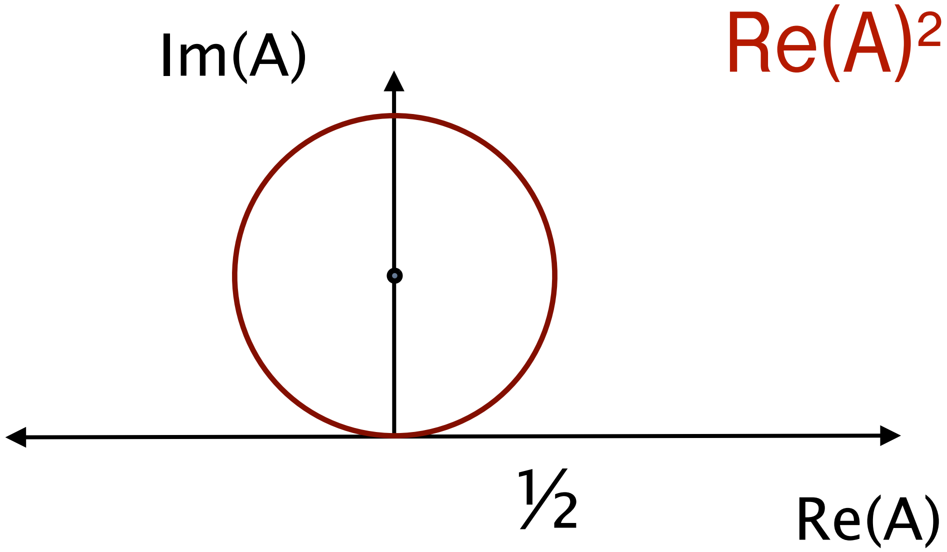
extra contributions coming from Higgs exchange. amplitude → constant

$$A \sim \frac{m_H^2}{s}$$

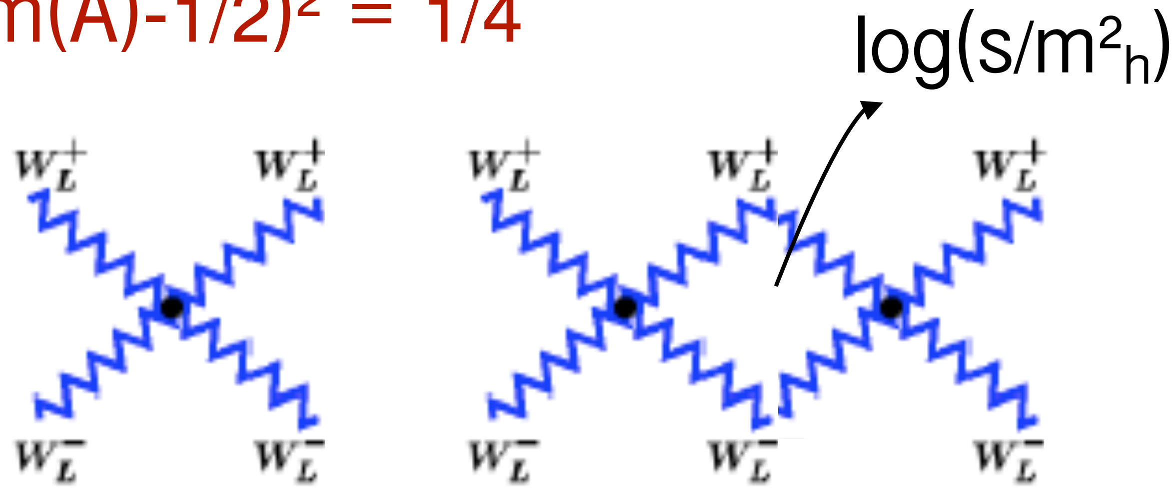
hW^+W^-, etc. couplings set by gauge invariance

So what?

Unitarity imposes relations on QM amplitudes



$\mathrm{Re}(A)^2 + (\mathrm{Im}(A)-1/2)^2 = 1/4$



tree level amplitude is real, at loop level A gets an imaginary part

Σ theory: A $\sim s/v^2$, Re(A) grows with energy

bigger Re(A) is, bigger Im(A) must get to keep unitary relation.

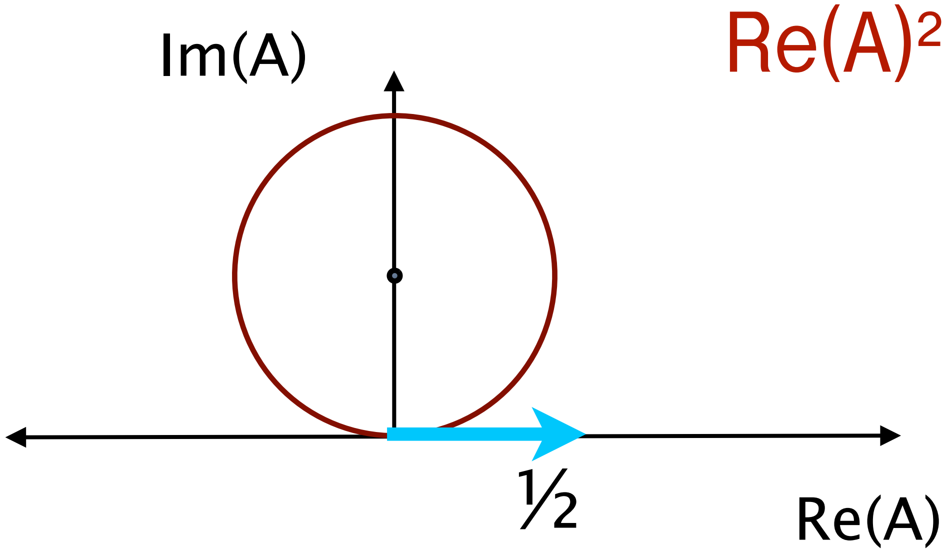
If Im(A) = Re(A) then 1–loop is same size as tree level
= loss of perturbativity = **theory is strongly coupled**

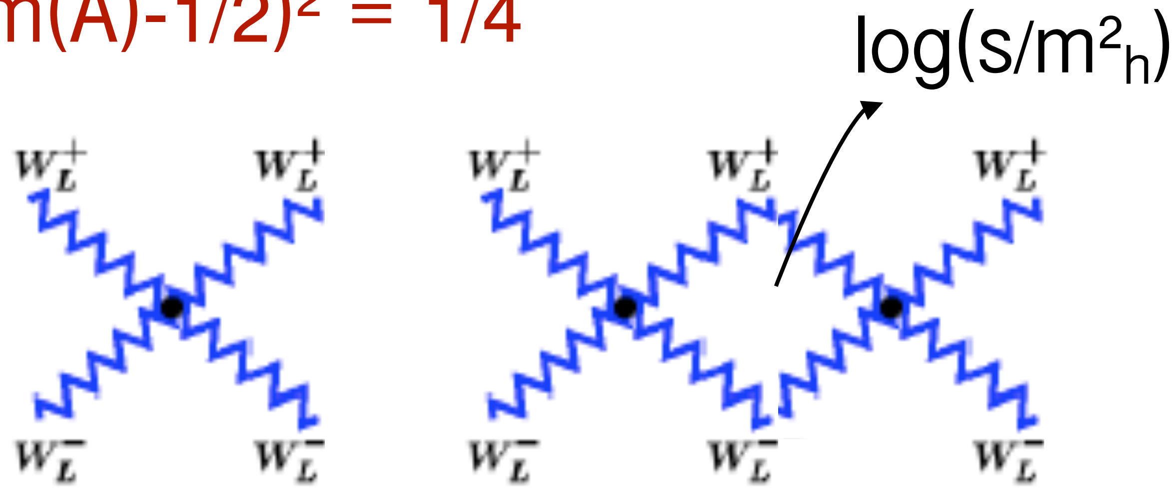
SM theory: A $\sim m^2_H/s$, perturbativity retained for all s

So what?

Unitarity imposes relations on QM amplitudes

$$\mathrm{Re}(A)^2 + (\mathrm{Im}(A)-1/2)^2 = 1/4$$





tree level amplitude is real, at loop level A gets an imaginary part

Σ theory: $A \sim s/v^2$, Re(A) grows with energy

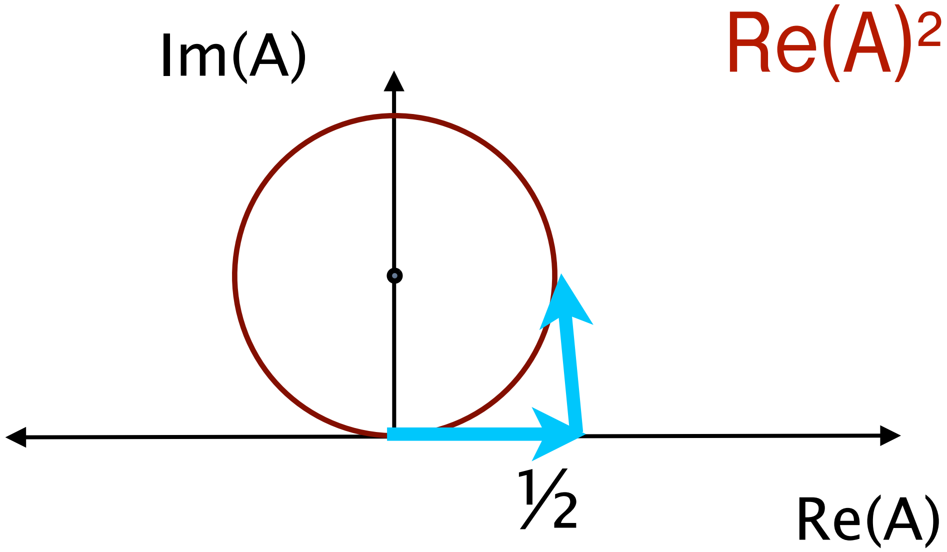
bigger Re(A) is, bigger Im(A) must get to keep unitary relation.

If Im(A) = Re(A) then 1-loop is same size as tree level
= loss of perturbativity = **theory is strongly coupled**

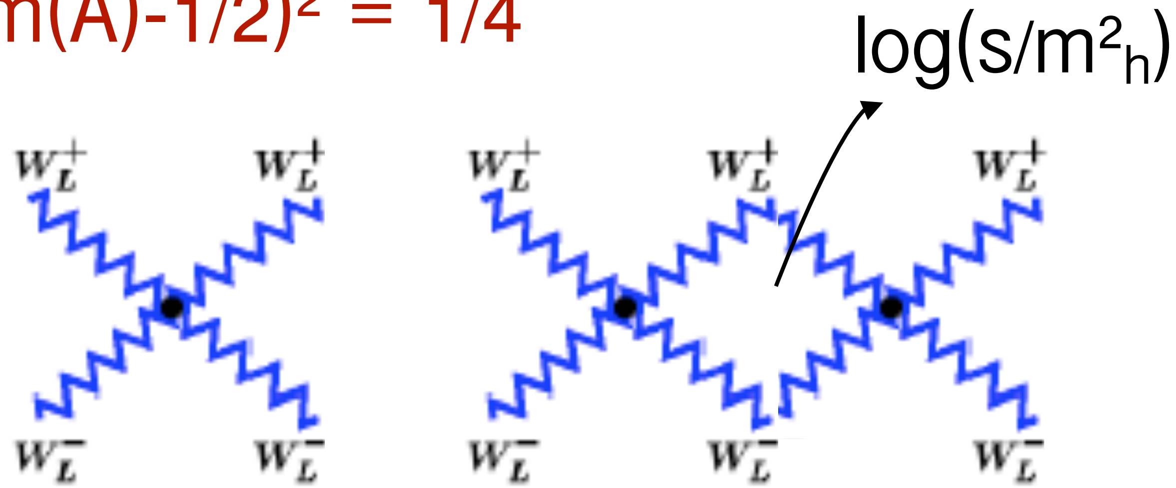
SM theory: $A \sim m^2_H/s$, perturbativity retained for all s

So what?

Unitarity imposes relations on QM amplitudes



$\mathrm{Re}(A)^2 + (\mathrm{Im}(A)-1/2)^2 = 1/4$



tree level amplitude is real, at loop level A gets an imaginary part

Σ theory: $A \sim s/v^2$, Re(A) grows with energy

bigger Re(A) is, bigger Im(A) must get to keep unitary relation.

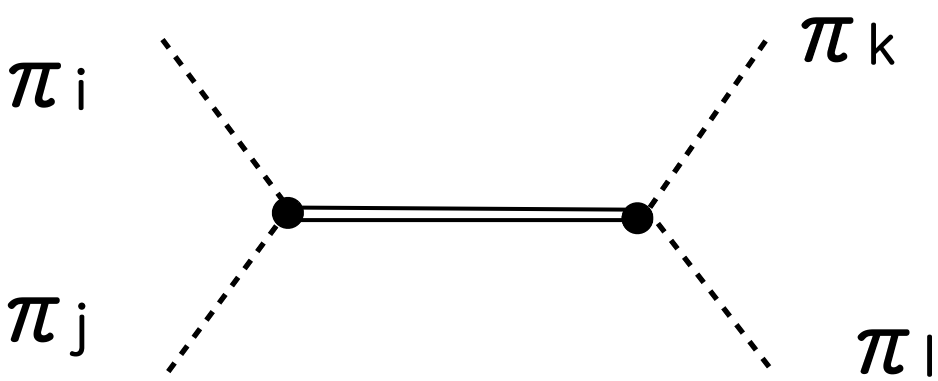
If Im(A) = Re(A) then 1-loop is same size as tree level
= loss of perturbativity = **theory is strongly coupled**

SM theory: $A \sim m^2_H/s$, perturbativity retained for all s

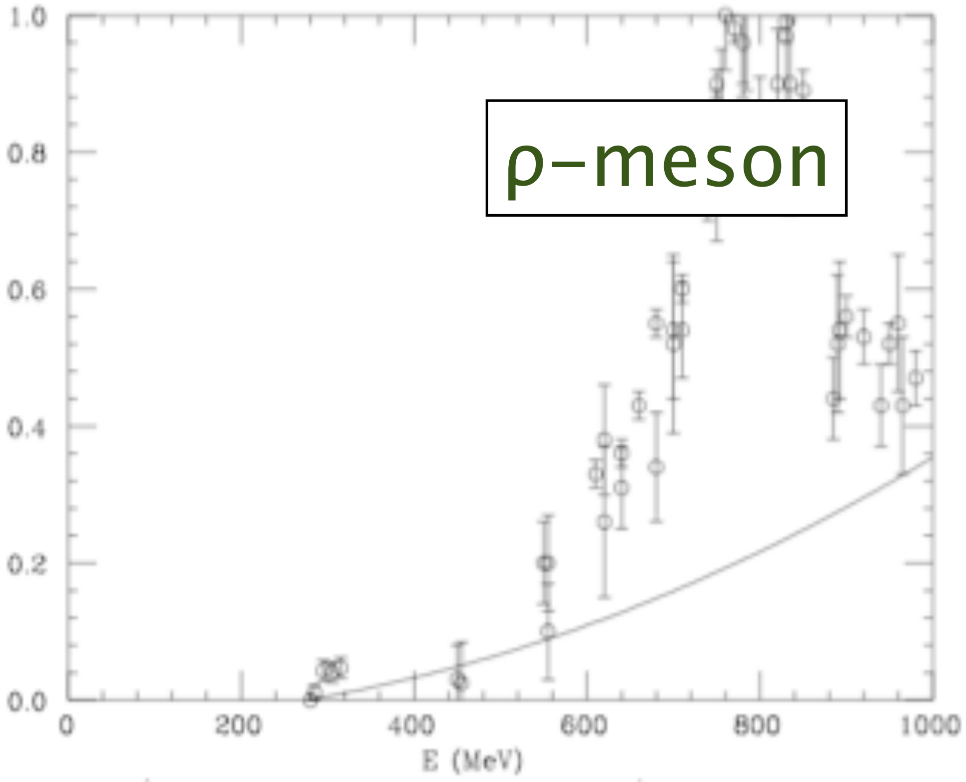
So what?

we’ve seen strong coupling before: QCD in the ~ 100 MeV – 1 GeV range

π π → π π scattering



strong coupling manifests in exchange of resonances: ρ, a_1, ρ’, etc., other $\bar{q}q$ bound states



in QCD, strong coupling tells us that above a certain energy there is a transition and quarks & gluons are the right degrees of freedom

But...

$\mathcal{L}_\Sigma$ has massive particles, but no new scalar state (X, or h) ... so it needs to be augmented

$$\mathcal{L}_\Sigma = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{tr}(D_\mu\Sigma\, D^\mu\Sigma^\dagger)\left(1 + a\frac{2\,h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{m_H^2}{2}h^2 + y_{ij}v\,Q_i\,\Sigma\,u^*_{R\,j}\left(1 + c\,\frac{h}{v} + \cdots\right) \text{ + h.c.}$$

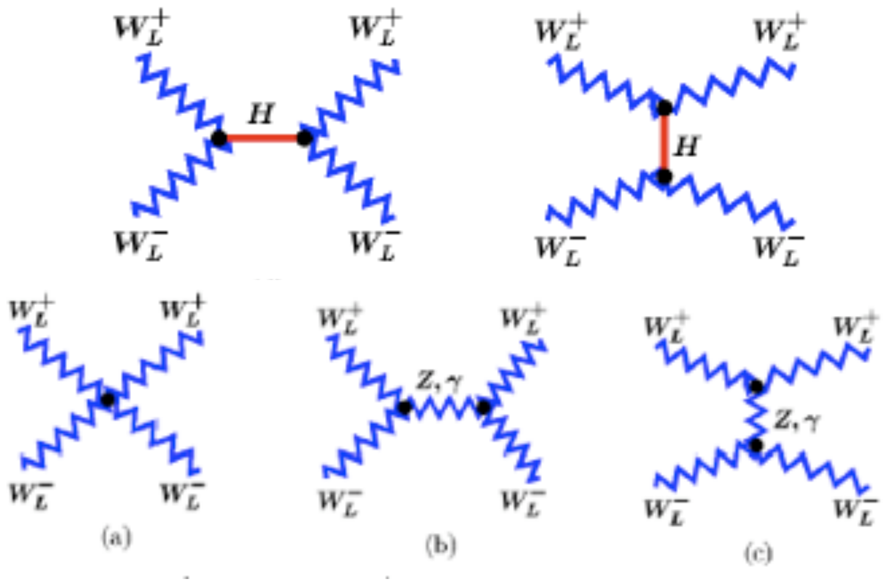
+ analogous terms for other fermions, + terms with more derivatives

Looks familiar? a = b = c = 1 → SM Higgs Lagrangian, where three π_a fields + h combine to the H doublet

but that is just a special case, L_Σ is more general: triplet of states eaten by $W^\pm/Z^0$ + real scalar = **EFT for LHC Higgs**

Higgs EFT

What is the meaning of a, b, c ≠ 1?



$$A \sim \frac{(s+t)}{v^2}(1-a) + O\left(\frac{m_H^2}{s}\right)$$

for a ≅ 1, energy growth

in A is suppressed

pert. lost when Re(A) ≈ 1/2

partial wave A_l

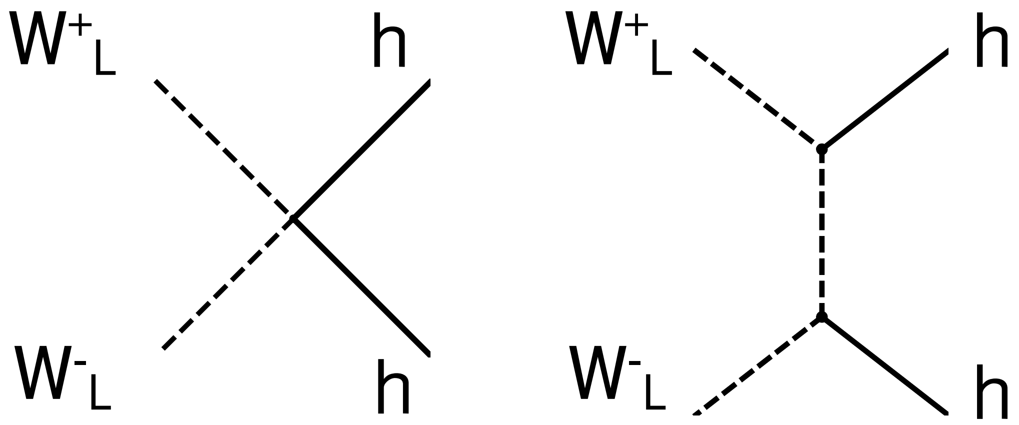
$$A_0 = \frac{E^2\,(1-a)}{32\pi\,v^2} = \frac{1}{2} \longrightarrow E_{lim} = \frac{4\sqrt{\pi}v}{\sqrt{1-a}}$$

above this scale (& without other terms), strong dynamics

- a=0, strong dynamics ~ TeV scale (Technicolor)
- a=1, theory stays perturbative (SM Higgs)
- a≅1, strong dynamics scale pushed higher

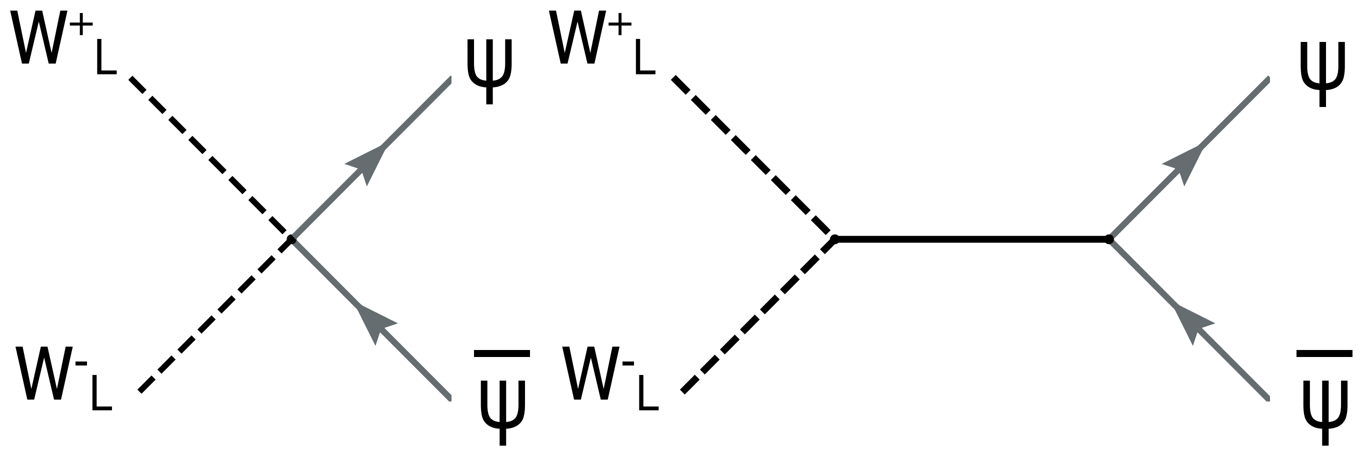
Higgs EFT

there are processes other than W_LW_L → W_LW_L that can grow with energy



$$A(W_L^+W_L^- \to hh) \sim \frac{s}{v^2}(b - a^2) + O\Big(\frac{m_H^2}{s}\Big)$$

b≠1, c≠1 also lead to ill-behaved amplitudes

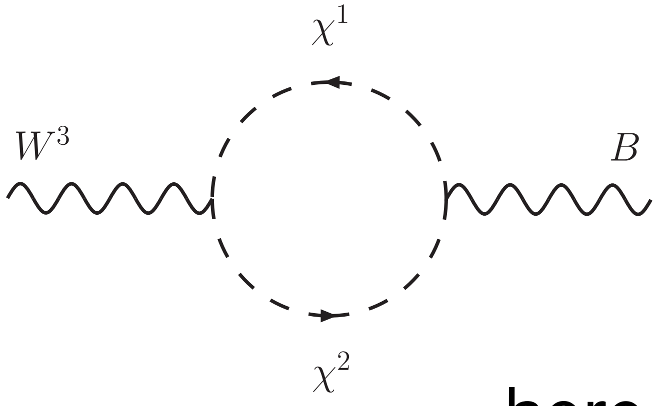


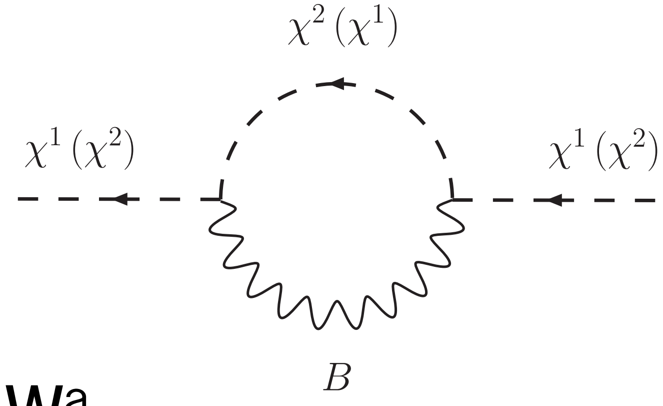
$$A(W_L^+W_L^- \to \bar\psi\psi) \sim \frac{m_\psi\sqrt{s}}{v^2}(1 - a\,c) + O\Big(\frac{m_H^2}{s}\Big)$$

Higgs EFT

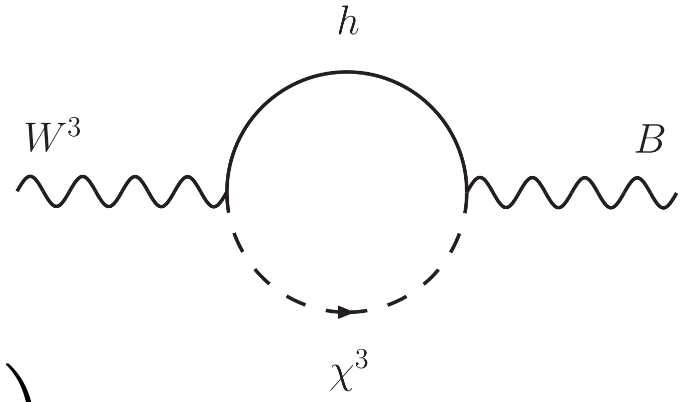
there are existing, indirect constraints on a,b,c

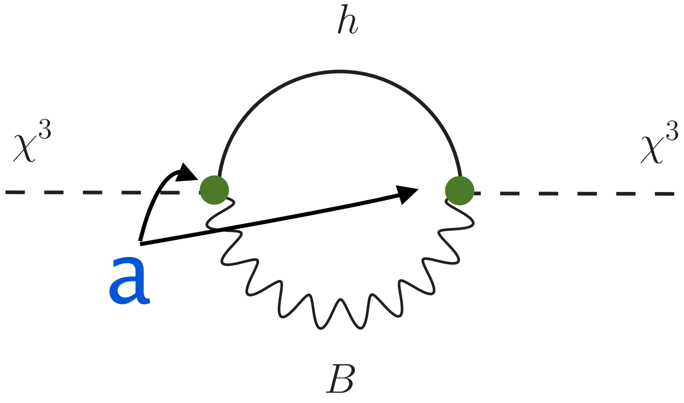
ex.) loop level contributions
to
S,T parameters





here $\chi^a = W^a_L$





$$\Delta S = +\frac{1}{12\pi}(1 - a^2)\log\left(\frac{\Lambda^2}{m_H^2}\right)$$

$$\Delta T = -\frac{3}{16\pi\ \cos^2\theta_W}(1 - a^2)\log\left(\frac{\Lambda^2}{m_H^2}\right)$$

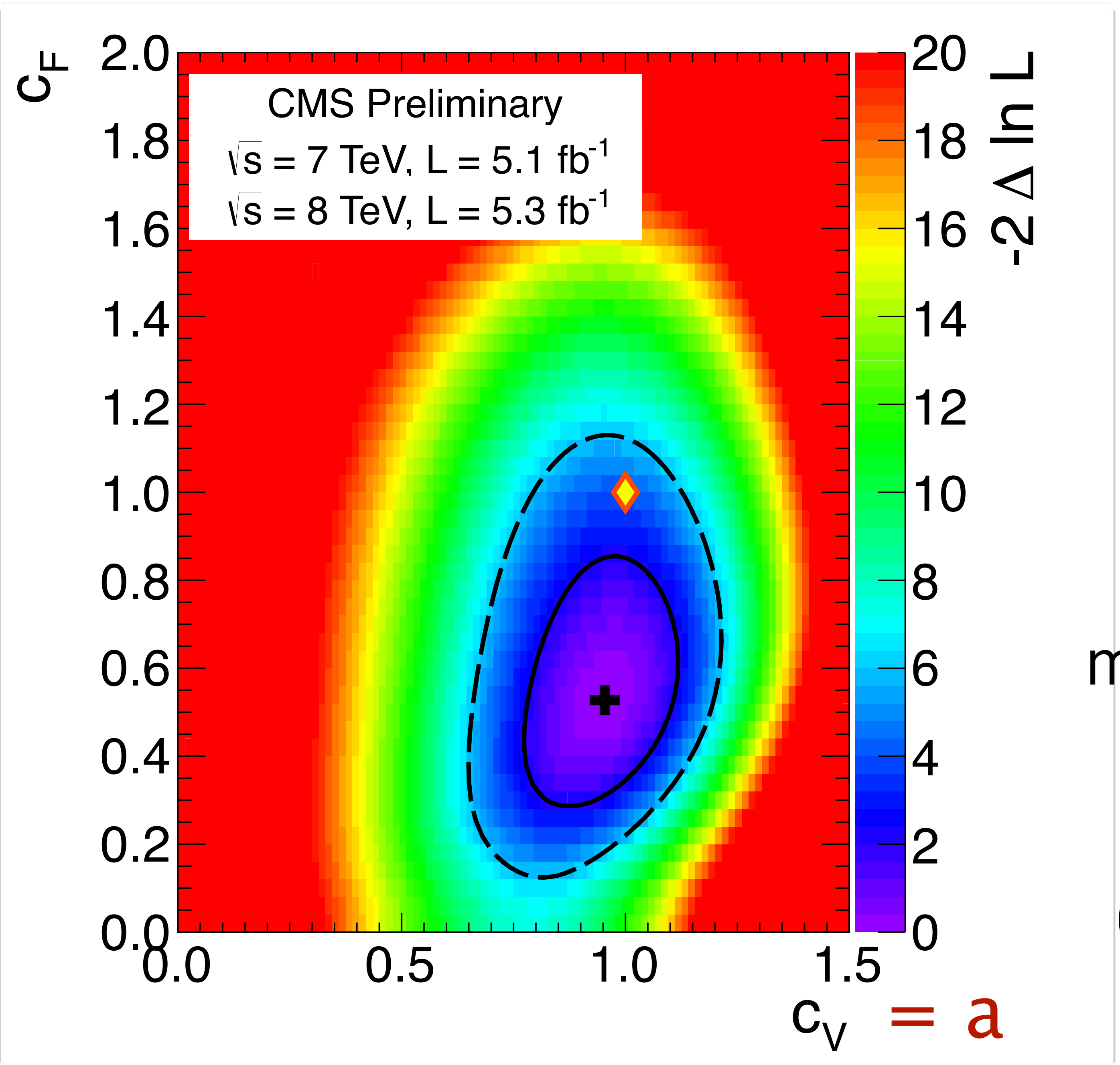
roughly constrains
$0.75 \leq a \leq 1.5$,
depending on assumptions

similarly, off-diagonal c_{ij} strongly constrained by flavor physics

diagonal c_{ii}, b are less constrained

Higgs EFT in action

several groups (theory & experiment) are already looking at LHC Higgs data in the a,b,c space



c = c_F

c_V **= a**

many subtleties! care required in interpretation (talk by Duehrssen)

Recap

- to fit observation, we need massive $W^{\pm}/Z^{0}$/fermions + extra scalar
- general setup: L_{Σ} .. contains L_{SM} in special $a = b = c = 1$ limit
- for $a,b,c \neq 1$, L_{Σ} becomes strongly coupled at some energy E_{lim} ... expect (from QCD experience) some new dynamics to enter at that scale
- useful framework for LHC Higgs data
- BUT: What UV dynamics actually leads to L_{Σ}? What else (other states, couplings) is present in those scenarios?

Light scalar fields

$\frac{m_H^2}{2} h^2$ masses of scalar fields are sensitive to the highest scales of a theory: $\delta m^2_H \sim \Lambda^2$

Having a scalar mass << theory cutoff requires delicate ‘unnatural’ cancellations = “hierarchy problem”. Many BSM scenarios try to address this problem

who cares about natural?

UK, LEAD BY NEW PLAYER HIGGS, DEFEATS GERMANY IN WORLD CUP FINAL

1000 - 0

theoretically possible, but hard to imagine within the rules we trust...

either Higgs is unlike the other particles/players we know, or there is more going on

Light scalar fields

$\frac{m_H^2}{2} h^2$ masses of scalar fields are sensitive to the highest scales of a theory: $\delta m^2_H \sim \Lambda^2$

Having a scalar mass << theory cutoff requires delicate 'unnatural' cancellations = "hierarchy problem". Many BSM scenarios try to address this problem

- links scalars to fermions via a symmetry. chiral symmetry protects mass = SUSY (lectures by Slavich)
- shift symmetry: $h \to h + c$, then h^2 forbidden = Higgs as a Goldstone boson

making these symmetries approximate, rather than exact -> light scalar (Higgs)

Higgs as a pseudo-Goldstone Boson

For starters: let’s study a simpler setup, 2 flavor QCD. As we’ll see, the pion of QCD is a pNGB, so many lessons from L_π will carry over to LH.

At high energy, QCD is quarks and gluons

$$\mathcal{L} = i\bar{u}_L \not{D} u_L + i\bar{d}_L \not{D} d_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R$$

this theory is invariant under rotations of LH, RH quarks among themselves

$$\begin{pmatrix} u'_L \\ d'_L \end{pmatrix} = U_L \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{pmatrix} u'_R \\ d'_L \end{pmatrix} = U_R \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

global symmetry is $SU(2)_L \otimes SU(2)_R$

Higgs as a pseudo-Goldstone Boson

at E ~ 1 GeV, the strong force becomes confining, quarks & antiquarks get bound together.. only color singlet states allowed

color-singlet condensates form: $\langle \bar{Q}_L Q_R \rangle \neq 0$

under global symmetry: $\langle \bar{Q}_L Q_R \rangle \to \langle \bar{Q}_L \, U_L^\dagger U_R \, Q_R \rangle$

only invariant when $U_L = U_R$, the ‘vectorial’ subgroup

so, as a result of the strong dynamics, symmetry has been broken: $SU(2)_L \otimes SU(2)_R \to SU(2)_V$

Goldstone’s theorem: for each generator of a spontaneously broken, continuous, global symmetry
→ a massless scalar (a Goldstone boson)

Higgs as a pseudo-Goldstone Boson

at E ~ 1 GeV, the strong force becomes confining, quarks & antiquarks get bound together.. only color singlet states allowed

color-singlet condensates form: $\langle \bar{Q}_L Q_R \rangle \neq 0$

under global symmetry: $\langle \bar{Q}_L Q_R \rangle \to \langle \bar{Q}_L \, U_L^\dagger U_R \, Q_R \rangle$

only invariant when $U_L = U_R$, the ‘vectorial’ subgroup

so, as a result of the strong dynamics, symmetry has been broken: $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$

+3 NGB

Goldstone’s theorem: for each generator of a spontaneously broken, continuous, global symmetry
→ a massless scalar (a Goldstone boson)

Higgs as a pseudo–Goldstone Boson

the interactions of the NGB can be described by the 'chiral lagrangian'

introduce: $U = \exp\left(\frac{2\,i\vec{\pi}}{f_\pi}\right)$

$\vec{\pi} = \pi_a\,\tau_a$

pion decay constant = 93 MeV

fix U → $U_L\, U\, U^\dagger_R$ then **U** has the same transformation properties as $<Q_L\bar{Q}_R>$

$UU^\dagger$ = 1, so terms in L_π must involve derivatives

$$\mathcal{L}_\pi = \frac{f_\pi^2}{4}\mathrm{tr}(\partial_\mu U\,\partial^\mu U^\dagger) + c_1\,\mathrm{tr}(\partial_\mu U\,\partial^\mu U^\dagger)^2 + \cdots$$

other 4-deriv. terms

expanded out:

$$\mathcal{L}_\pi = \frac{1}{2}(\partial_\mu\pi_a)^2 + \cdots$$

multiple–π interactions $(\pi\,\partial_\mu\pi)^2$, etc.

Higgs as a pseudo-Goldstone Boson

Look familiar? it should! same setup as triplet of fields in L_Σ, but with v → f_π. Setup is the same because the symmetry (& symmetry breaking) is the same

but remember: our goal is to have a setup where triplet PLUS h are ALL NGBs.. needs more work

First, some more observations of L_π & QCD:

- number of π_a is set by the amount of symmetry broken
- the transformation properties of π_a under unbroken symmetry (SU(2)V) also set by pattern of symmetry breaking
- all interactions of π_a involve ∂_μ

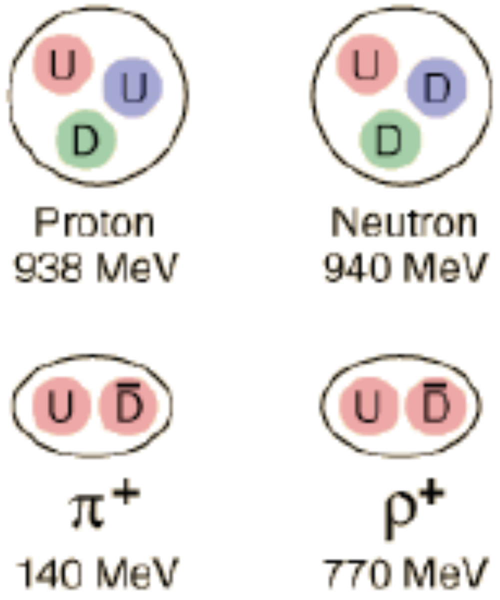
Higgs as a pseudo-Goldstone Boson

more observations of L_π & QCD:

- there is more to QCD than just π_a...

There are other bound states of quarks = resonances like ρ, a_1, ω. These resonances have various JPC, & interact strongly with the π_a.

$$M_\rho = 770\,\mathrm{MeV},\ J^{PC} = 1^{--}$$
$$M_\omega = 782\,\mathrm{MeV},\ J^{PC} = 1^{--}$$
$$M_{a_1} = 1230\,\mathrm{MeV},\ J^{PC} = 1^{++}$$
$$M_\eta = 539\,\mathrm{MeV},\ J^{PC} = 0^{-+} \quad \ldots$$



They are not contained in L_π.. no first-principles way to include them, instead must use phenomenological models

Higgs as a pseudo-Goldstone Boson

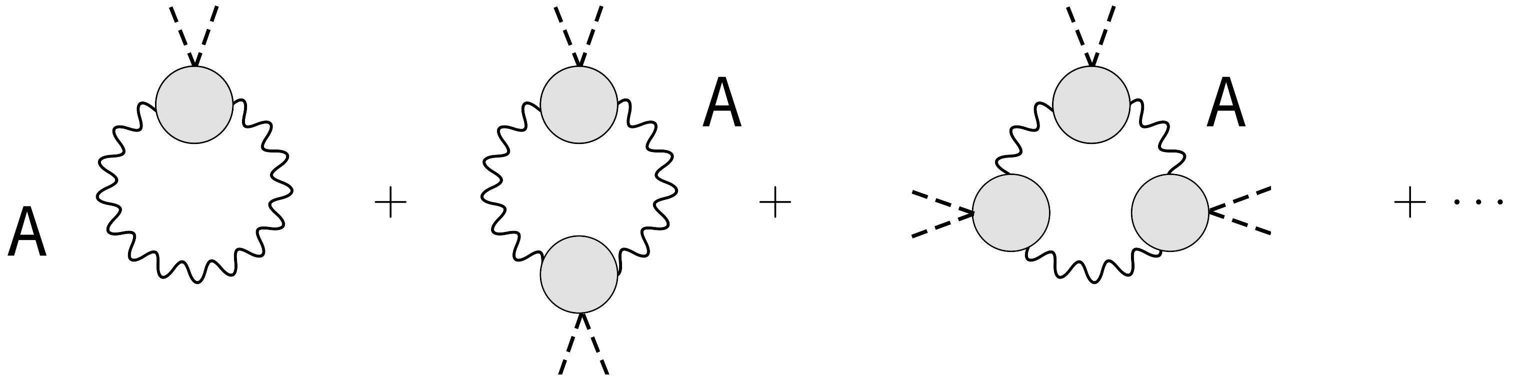
adding electromagnetism:

- U(1)$_{em}$ is part of the SU(2)$_V$ that remains unbroken (LH, RH quarks have the same EM charge). What if we turn on this gauge interaction?

$$\partial_\mu U \to D_\mu U,\, D_\mu U = \partial_\mu U + ieA_\mu \hat{Q}\, U \qquad \hat{Q} = \begin{pmatrix} \frac{2}{3} & \\ & -\frac{1}{3} \end{pmatrix}$$

we get new interactions of pions and photons, some of which have no derivatives

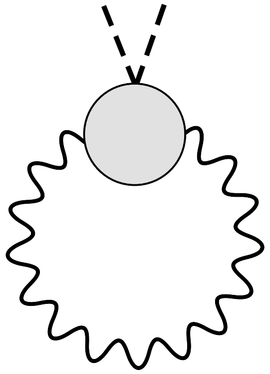
loops of photons generate V(π)



Higgs as a pseudo-Goldstone Boson

cutoff: typically Λ = O(4πf)

mass term:



$$\sim c_2 \frac{e^2}{16\pi^2} \Lambda^2 \, \pi_a^2$$

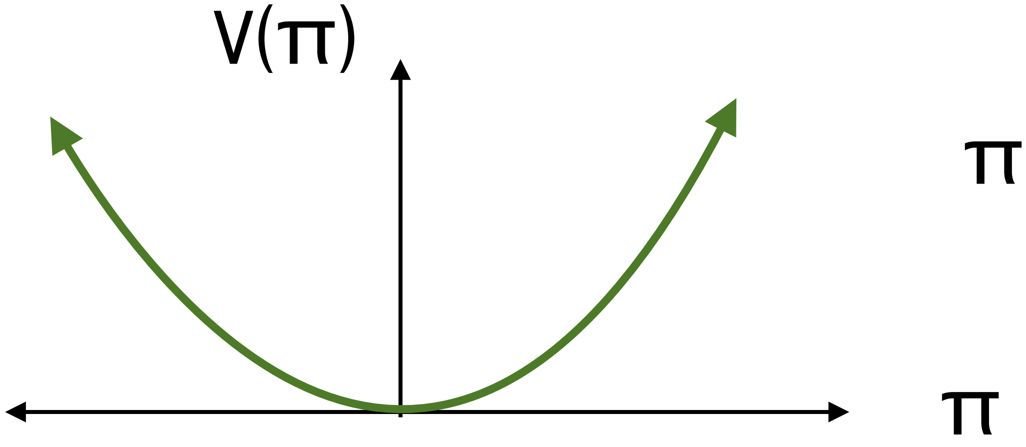
coeff.

loop factor

other terms in V(π) generated similarly.

Above is just an estimate... loops of strongly coupled particles involved. For more rigorous calculation, see: Contino 1005.4269 + ref. therein

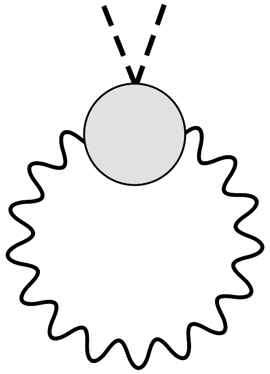
With full calculation, can show V(π) has a min at π = 0



π^+, π^- get mass, π^0, γ stay massless

Higgs as a pseudo–Goldstone Boson

mass term:



cutoff: typically Λ = O(4πf)

$$\sim c_2 \frac{e^2}{16\pi^2} \Lambda^2 \, \pi_a^2$$

coeff.

loop factor

is there a mπ “hierarchy problem”: unnatural for mπ ≪ Λ ?

NO...we can’t take Λ arbitrarily high

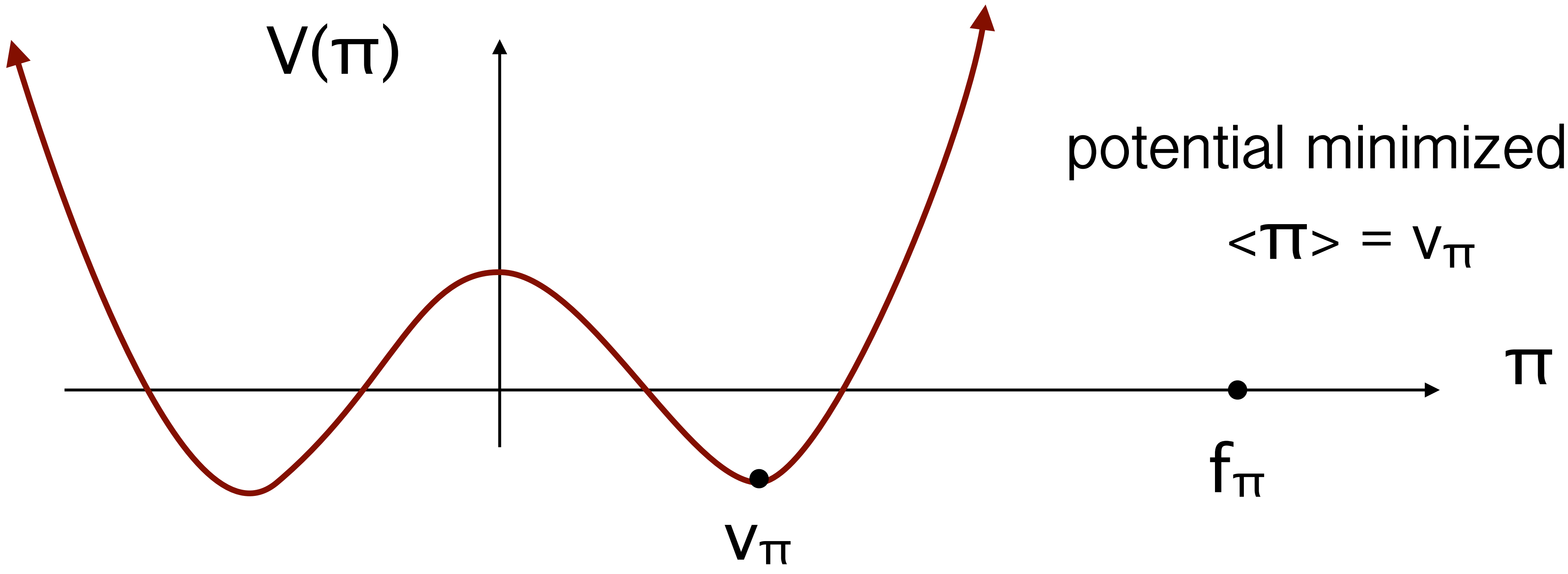
above a certain scale, π description no longer makes sense, the π falls apart into its quark constituents

Higgs as a pseudo-Goldstone Boson

thought experiment: what if π interacted with fields other than the photon (some fermions, other gauge interactions, etc.)?

these other interactions would also affect V(π). Shape of V(π) no longer set...

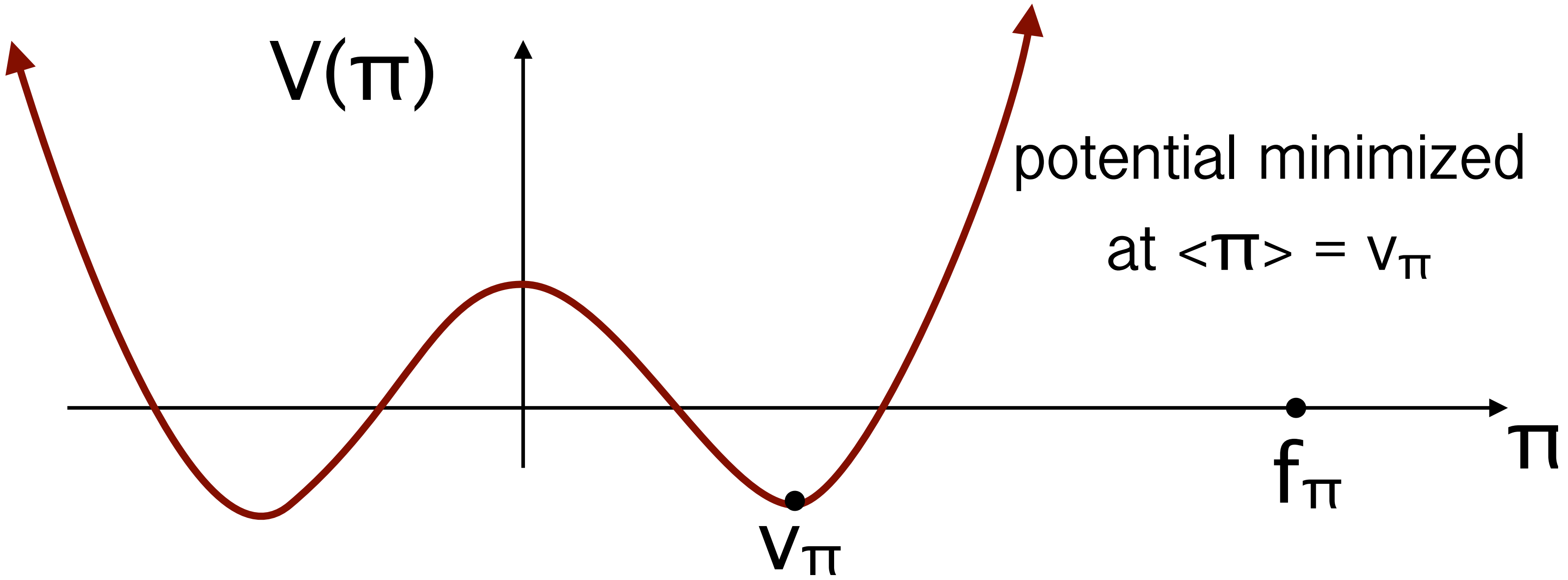
What if V(π) developed a non-trivial minima?



potential minimized at

$\langle \pi \rangle = v_\pi$

Higgs as a pseudo-Goldstone Boson



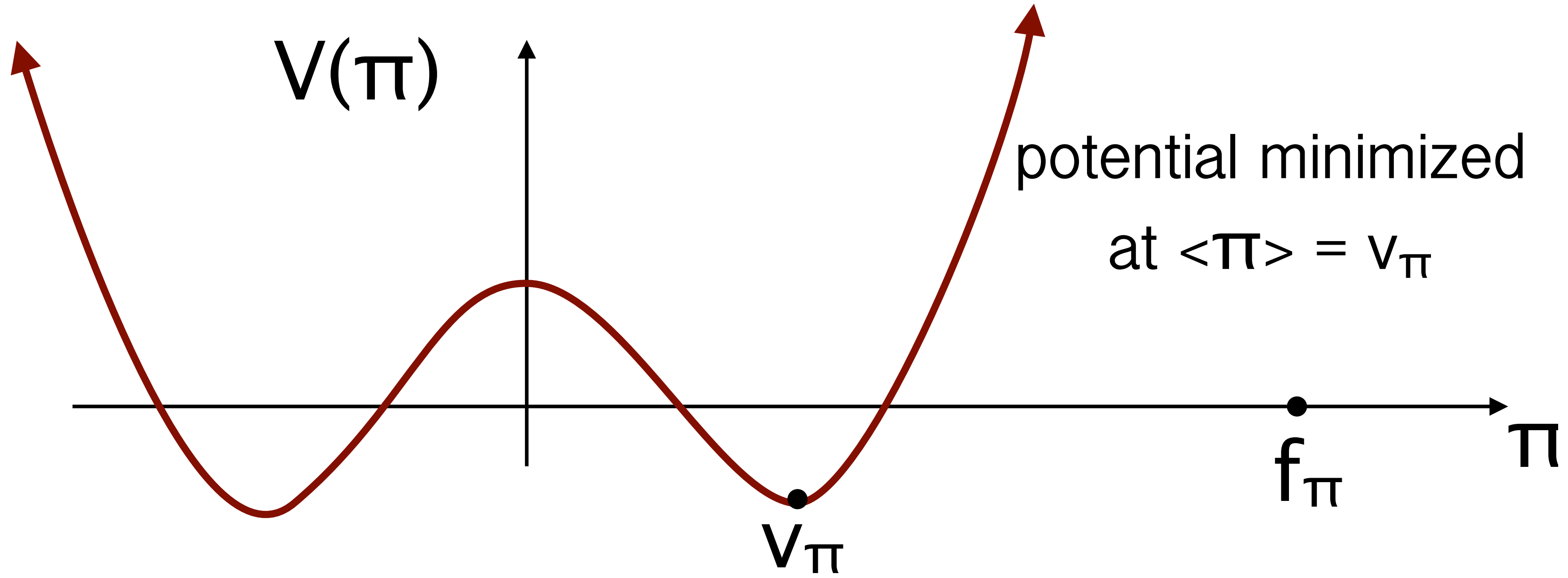
then <π> ≠ 0 breaks $U(1)_{em}$

$$e^2 A^\mu A_\mu \pi^+\pi^- \to e^2 v_\pi^2 A^\mu A_\mu$$ photon gets a mass

scale of the breaking is $v_\pi < f_\pi$

clearly this is not a situation we want for QCD!

Higgs as a pseudo-Goldstone Boson



potential minimized

at <π> = v$_\pi$

then <π> ≠ 0 breaks U(1)$_{em}$

$$e^2 A^\mu A_\mu \pi^+ \pi^- \to e^2 v_\pi^2 A^\mu A_\mu$$

photon gets a mass

scale of the breaking is $v_\pi < f_\pi$

clearly this is not a situation we want for QCD!

BUT: shows that NGB interactions lead to a potential, and can lead to breaking of symmetries the strong dynamics respected. New scale v$_\pi$ develops

Higgs as a pseudo-Goldstone Boson

based on our QCD analogy, we have a recipe for a Goldstone Higgs scenario:

- assume some strong dynamics at a high scale **f**.
  EWS should remain unbroken: $\mathbf{G} \rightarrow \mathbf{H} \supset SU(2)_W \otimes U(1)_Y$
- that dynamics generates a bunch of Goldstone bosons, including the Higgs (4-plet of particles), as a doublet.
- interactions exterior to strong dynamics lead to V(h).
  Choose interactions such that $V(h)_{min}$ is at $h \neq 0$.
  Instead $h_{min} = \mathbf{v}$

- Higgs is a composite particle → no hierarchy problem
- **v** < **f** means EWSB happens at a scale lower than the strong dynamics

Higgs as a pseudo-Goldstone Boson

based on our QCD analogy, we have a recipe for a Goldstone Higgs scenario:

step 1:

- assume some strong dynamics at a high scale **f**.
  EWS should remain unbroken: **G** → **H** ⊃ $SU(2)_W \otimes U(1)_Y$

- that dynamics generates a bunch of Goldstone bosons, including the Higgs (4-plet of particles), as a doublet.

- interactions exterior to strong dynamics lead to V(h).
  Choose interactions such that $V(h)_{min}$ is at $h \neq 0$.
  Instead h_{min} = **v**

- Higgs is a composite particle → no hierarchy problem

- **v** < **f** means EWSB happens at a scale lower than the strong dynamics

Higgs as a pseudo-Goldstone Boson

based on our QCD analogy, we have a recipe for a Goldstone Higgs scenario:

step 1:

- assume some strong dynamics at a high scale **f**.
  EWS should remain unbroken: $\mathbf{G} \rightarrow \mathbf{H} \supset SU(2)_W \otimes U(1)_Y$

- that dynamics generates a bunch of Goldstone bosons, including the Higgs (4-plet of particles), as a doublet.

step 2:

- interactions exterior to strong dynamics lead to V(h).
  Choose interactions such that $V(h)_{min}$ is at $h \neq 0$.
  Instead h_{min} = **v**

- Higgs is a composite particle → no hierarchy problem

- **v** < **f** means EWSB happens at a scale lower than the strong dynamics

Higgs as a pseudo-Goldstone Boson

step 1: the art in these models is picking the right pattern of symmetry breaking...

the (global) group left unbroken by the strong dynamics:

- must contain SU(2) ⊗ U(1)...
- actually SU(2)⊗ SU(2) ≅ SO(4) works better (T parameter)

Higgs as a pseudo-Goldstone Boson

step 1: the art in these models is picking the right pattern of symmetry breaking...

the (global) group left unbroken by the strong dynamics:

- must contain $SU(2) \otimes U(1)$...
- actually $SU(2)\otimes SU(2) \cong SO(4)$ works better (T parameter)

starting group must be bigger than ending group:
choice that works: SO(5)

$$\frac{\mathbf{SO(5)}}{\mathbf{SO(4)}} : \quad 10 \text{ generators} \rightarrow 6 \text{ generators}$$

$$= 4 \text{ broken generators} = 4 \text{ NGB}$$

just enough!

Higgs as a pseudo-Goldstone Boson

step 1: the art in these models is picking the right pattern of symmetry breaking...

the (global) group left unbroken by the strong dynamics:

- must contain SU(2) ⊗ U(1)...
- actually SU(2)⊗ SU(2) ≅ SO(4) works better (T parameter)

starting group must be bigger than ending group:
choice that works: SO(5)

$$\frac{\mathbf{SO(5)}}{\mathbf{SO(4)}} :$$

10 generators → 6 generators

= 4 broken generators = 4 NGB

just enough!

assemble: $$\Sigma = \exp\left(\frac{2i\,\chi_a T^a}{f}\right)\Sigma_0$$

broken generator

symmetry-breaking ‘vev’

strong scale

NGB

Higgs as a pseudo-Goldstone Boson

Huh? use SU(3)/(SU(2)⊗U(1)) as an explicit example:

$$\Sigma_{ex} = \exp\left\{\frac{i}{f}\begin{pmatrix} & & \chi_4 - i\chi_5 \\ & & \chi_6 - i\chi_7 \\ \chi_4 + i\chi_5 & \chi_6 + i\chi_7 & \end{pmatrix}\right\}\underbrace{\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}}_{\Sigma_0}$$

Higgs as a pseudo-Goldstone Boson

Huh? use SU(3)/(SU(2)⊗U(1)) as an explicit example:

$$\Sigma_{ex} = \exp\left\{\frac{i}{f}\begin{pmatrix} & & \chi_4 - i\chi_5 \\ & & \chi_6 - i\chi_7 \\ \chi_4 + i\chi_5 & \chi_6 + i\chi_7 & \end{pmatrix}\right\}\underset{\uparrow\,\Sigma_0}{\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}}$$

SU(2)⊗ U(1) correspond to these (unbroken) generators

Higgs as a pseudo-Goldstone Boson

Huh? use SU(3)/(SU(2)⊗U(1)) as an explicit example:

$$\Sigma_{ex} = \exp\left\{\frac{i}{f}\begin{pmatrix} & & \chi_4 - i\chi_5 \\ & & \chi_6 - i\chi_7 \\ \chi_4 + i\chi_5 & \chi_6 + i\chi_7 & \end{pmatrix}\right\}\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Σ_0

SU(2)⊗ U(1) correspond to these (unbroken) generators

NGB come with broken generators.

The set of 4: $\chi_{4,5,6,7}$ form a doublet under the $SU(2)_W \otimes U(1)_Y$

Higgs as a pseudo-Goldstone Boson

Huh? use SU(3)/(SU(2)⊗U(1)) as an explicit example:

$$\Sigma_{ex} = \exp\left\{\frac{i}{f}\begin{pmatrix} & & \chi_4 - i\chi_5 \\ & & \chi_6 - i\chi_7 \\ \chi_4 + i\chi_5 & \chi_6 + i\chi_7 & \end{pmatrix}\right\}\underbrace{\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}}_{\Sigma_0}$$

SU(2)⊗ U(1) correspond to these (unbroken) generators

NGB come with broken generators.

The set of 4: $\chi_{4,5,6,7}$ form a doublet under the $SU(2)_W \otimes U(1)_Y$

$$\mathcal{L}_\Sigma = \frac{f^2}{4}\mathrm{tr}(D^\mu \Sigma_{ex}\, D_\mu \Sigma_{ex}^\dagger) + \cdots$$

contains interactions of $\chi_{4,5,6,7}$ with W/Z/γ and each other

Higgs as a pseudo-Goldstone Boson

Now for the real thing: SO(5)/SO(4)

$$\mathcal{L}_\Sigma = \frac{f^2}{4}\mathrm{tr}(D^\mu \Sigma\, D_\mu \Sigma^T) + \cdots$$

after LOTS of ugly group theory & algebra

$$\mathcal{L}_\Sigma = \frac{(\partial_\mu h)^2}{2} + \frac{g^2\, f^2}{4}\sin^2\left(\frac{h}{f}\right) W^+_\mu W^{-\mu} + \frac{g^2\, f^2}{8\cos^2\theta}\sin^2\left(\frac{h}{f}\right) Z^0_\mu Z^{0\mu}$$

Higgs as a pseudo-Goldstone Boson

Now for the real thing: SO(5)/SO(4)

$$\mathcal{L}_\Sigma = \frac{f^2}{4} \mathrm{tr}(D^\mu \Sigma \, D_\mu \Sigma^T) + \cdots$$

after LOTS of ugly group theory & algebra

$$\mathcal{L}_\Sigma = \frac{(\partial_\mu h)^2}{2} + \frac{g^2 f^2}{4} \sin^2\left(\frac{h}{f}\right) W^+_\mu W^{-\mu} + \frac{g^2 f^2}{8\cos^2\theta} \sin^2\left(\frac{h}{f}\right) Z^0_\mu Z^{0\mu}$$

ASSUMING: <h>≠0 (have to justify later with V(h))

set h → h + <h> in above, and expand

define: $v = f \sin\left(\frac{< h >}{f}\right)$

EW scale v < scale of strong dynamics f

Higgs as a pseudo-Goldstone Boson

Keep expanding: $\frac{g^2 f^2}{4} \sin^2\left(\frac{h}{f}\right) W_\mu^+ W^{-\mu}$

$$f^2 \sin^2\left(\frac{h}{f}\right) = v^2 + 2\, v\, h \sqrt{1-\xi} + h^2\, (1-2\xi) + \cdots$$

where: $\xi = \frac{v^2}{f^2}$

recall our Higgs EFT: $m_W^2 \left(1 + a \frac{2\,h}{v} + b \frac{h^2}{v^2} + \cdots\right)$

$\therefore$ in the SO(5)/SO(4) composite Higgs model

$$a = \sqrt{1 - \frac{v^2}{f^2}} \quad , \quad b = 1 - 2\frac{v^2}{f^2}$$

Higgs as a pseudo-Goldstone Boson

bad behavior in W_LW_L amplitudes delayed by a factor of

$$(1-a)^{-1/2} \sim \frac{f^2}{v^2}$$

recall: precision EW bounds a require $\frac{v}{f} \lesssim 0.5$

so strong coupling scale pushed to ~ 10 TeV (at least)

other patterns of symmetry breaking would have different values for a,b,c, as well as more states

ex.) SO(6)/SO(5) has 5 NGBs,
4 ∊ H + 1 extra scalar η

many other possibilities

Higgs potential

How do we get <h> ≠ 0 in the first place?

right now our h_i interact with gauge fields, but we know from QCD experience that V(h) generated from these interactions alone has a minimum at h = 0

Solution: Yukawa couplings

even forgetting V(h), our theory was incomplete, because it **did not explain how fermion masses arise**

we can write $y\, f\, Q_L\, \Sigma\, u_R^* + h.c.$

but why does such a term exist? for gauge bosons, gauge invariant demanded W, Z talk to h. No such reason for the fermion mass term

Higgs potential

Also: If we imagine Σ is a bound state of more fundamental fermions (the things that the composite Higgs is made of), analogous to QCD pion = $<\bar{q}\gamma_5 q>$

$$y\, f\, Q_L\, \Sigma\, u_R^* \rightarrow y\frac{(Q_L u_R^*)(\bar{\psi}\psi)}{\Lambda^2}$$

previous term is dimension-6, suppressed by some scale

need Λ low to make fermion masses big enough (m_t!), but low Λ would cause large flavor problems

i.e.) $$\frac{(Q_L d_R^*)^2}{\Lambda^2}$$

leads to large K^0 - $\overline{K}^0$, B^0-$\overline{B}^0$ mixing, etc.

So, try a different approach: ‘partial compositeness’

Partial Compositeness

- new strong dynamics makes mesons (including the h), so it can make 'baryons' = composite fermions too
- composite baryons are massive even without EWSB, just as proton would have mass even without quark masses.
- proton interacts strongly with QCD pion ∴ composite fermions will interact strongly with composite higgs.

Partial Compositeness

- new strong dynamics makes mesons (including the h), so it can make ‘baryons’ = composite fermions too

- composite baryons are massive even without EWSB, just as proton would have mass even without quark masses.

- proton interacts strongly with QCD pion ∴ composite fermions will interact strongly with composite higgs.

- by mixing the SM fermions with the composite fermions, the SM fermions can acquire mass

Partial Compositeness

- new strong dynamics makes mesons (including the h), so it can make ‘baryons’ = composite fermions too

- composite baryons are massive even without EWSB, just as proton would have mass even without quark masses.

- proton interacts strongly with QCD pion ∴ composite fermions will interact strongly with composite higgs.

- by mixing the SM fermions with the composite fermions, the SM fermions can acquire mass

- the price we pay for massive SM fermions is new states, the composite fermions. New states -> new LHC signals

Partial Compositeness

in practice (schematically)

composite fermions

mass terms for composites

$$\mathcal{L}_F = \Delta_L Q_L \mathcal{Q}_R + \Delta_R t_R \mathcal{T}_L + \mathcal{M}_Q \mathcal{Q}_L \mathcal{Q}_R + M_T \mathcal{T}_L \mathcal{T}_R + Y_T\, \mathcal{Q}_L\, \Sigma\, \mathcal{T}_R + h.c.$$

composite + higgs couplings

blue terms: come from strong sector & therefore obey same SO(5) symmetry

there are several choices for what representations composite fermions sit in (4, 5, 10, etc.), leading to slightly different structure of the interactions

Note: $\mathcal{Q}_L$, $\mathcal{Q}_R$, etc. must be colored particles

Partial Compositeness

Undo the mixing

$$\mathcal{L}_F = \Delta_L Q_L \mathcal{Q}_R + \Delta_R t_R \mathcal{T}_L + \mathcal{M}_Q \mathcal{Q}_L \mathcal{Q}_R + M_T \mathcal{T}_L \mathcal{T}_R + Y_T\, \mathcal{Q}_L\, \Sigma\, \mathcal{T}_R + h.c.$$

$$\begin{pmatrix} \mathcal{Q}_H \\ q_L \end{pmatrix} = \begin{pmatrix} \Delta_L & \mathcal{M}_Q \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Q_L \\ \mathcal{Q}_L \end{pmatrix}$$

+ similar for t_R $T_{L,R}$

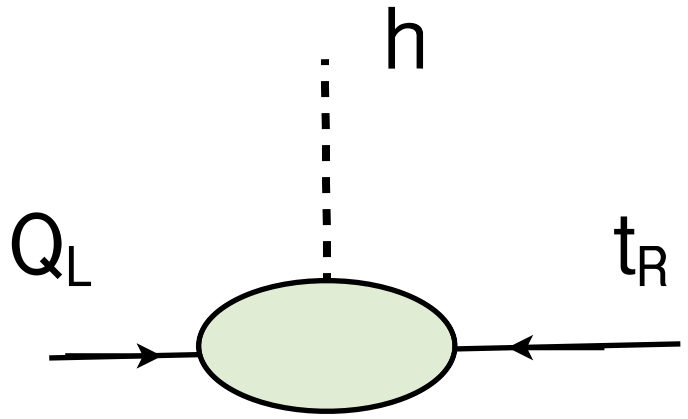
$$\mathcal{Q}_L = \cos(\phi_L)\, \mathcal{Q}_H + \sin(\phi_L)\, q_L$$

$$Q_L = -\sin(\phi_L)\, \mathcal{Q}_H + \cos(\phi_L)\, q_L$$

+ similar for t_R $T_{L,R}$

yields

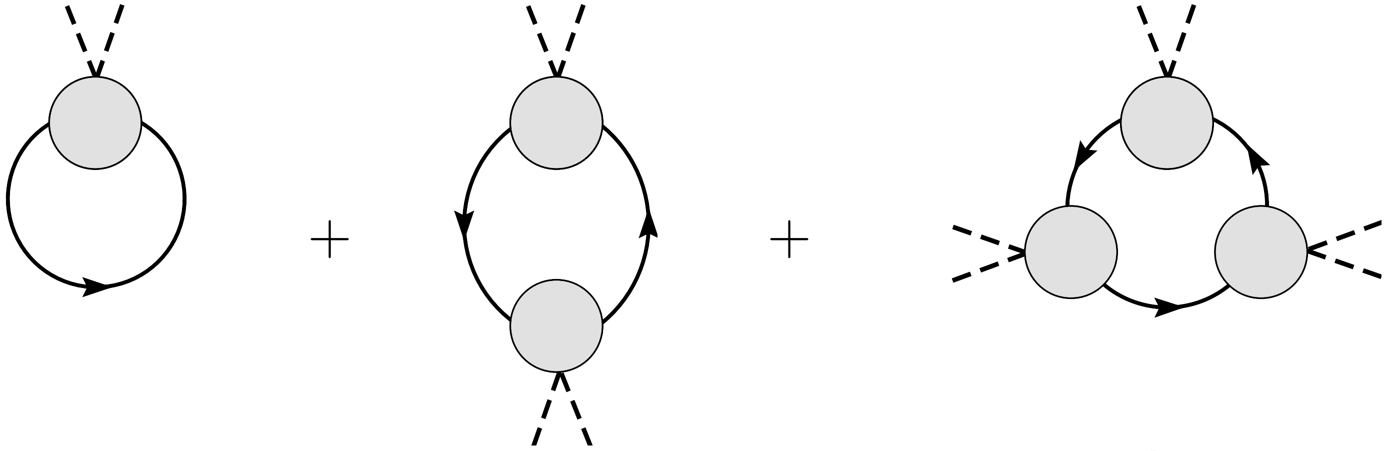
$$(q_L\, h\, t_R^*)\, Y_T \sin(\phi_L) \sin(\phi_R)$$



SM fermions get mass by
mixing with composites

About that potential

within this setup, we can calculate the V(h) from loops of fermions, in same fashion as done before



contribution to V(h = 0) is negative

V_{min} at h≠0 is possible, requires delicate balance between +ve and −ve contributions to obtain v « f = requires some ‘tuning’ of parameters

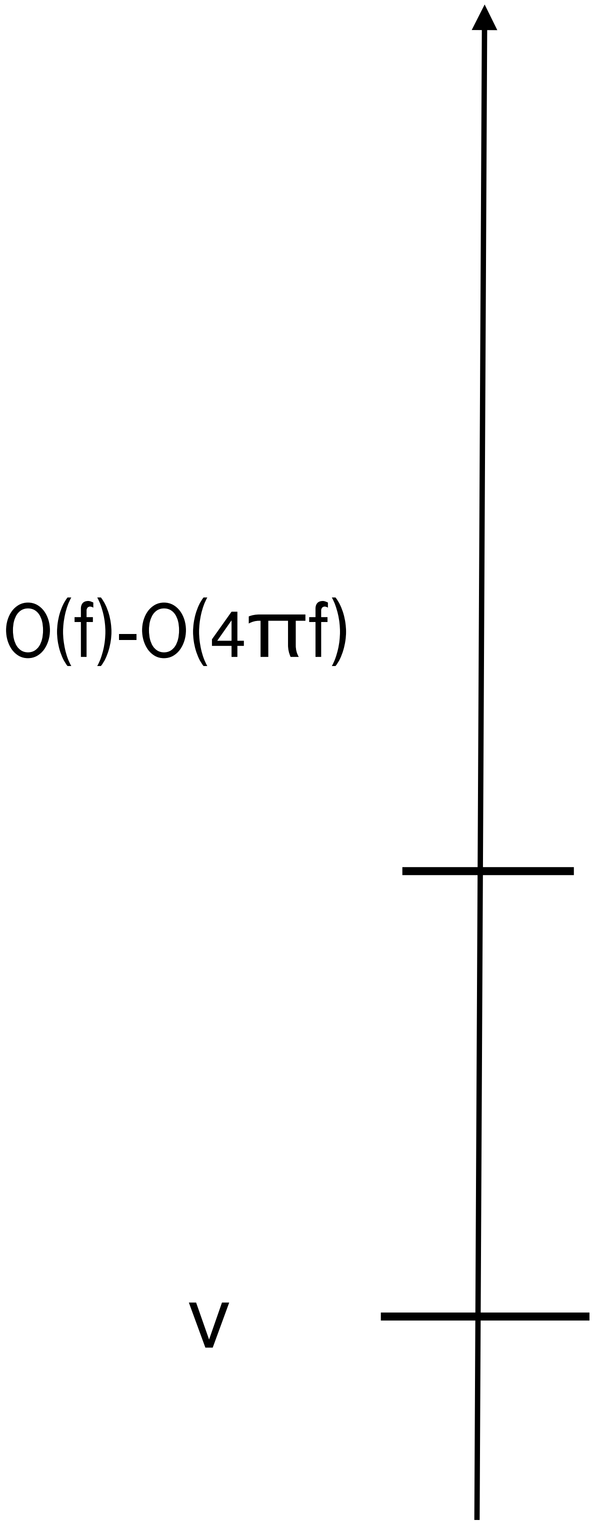
expanding h about vev, find c*:

$$c = \sqrt{1 - \frac{v^2}{f^2}}$$

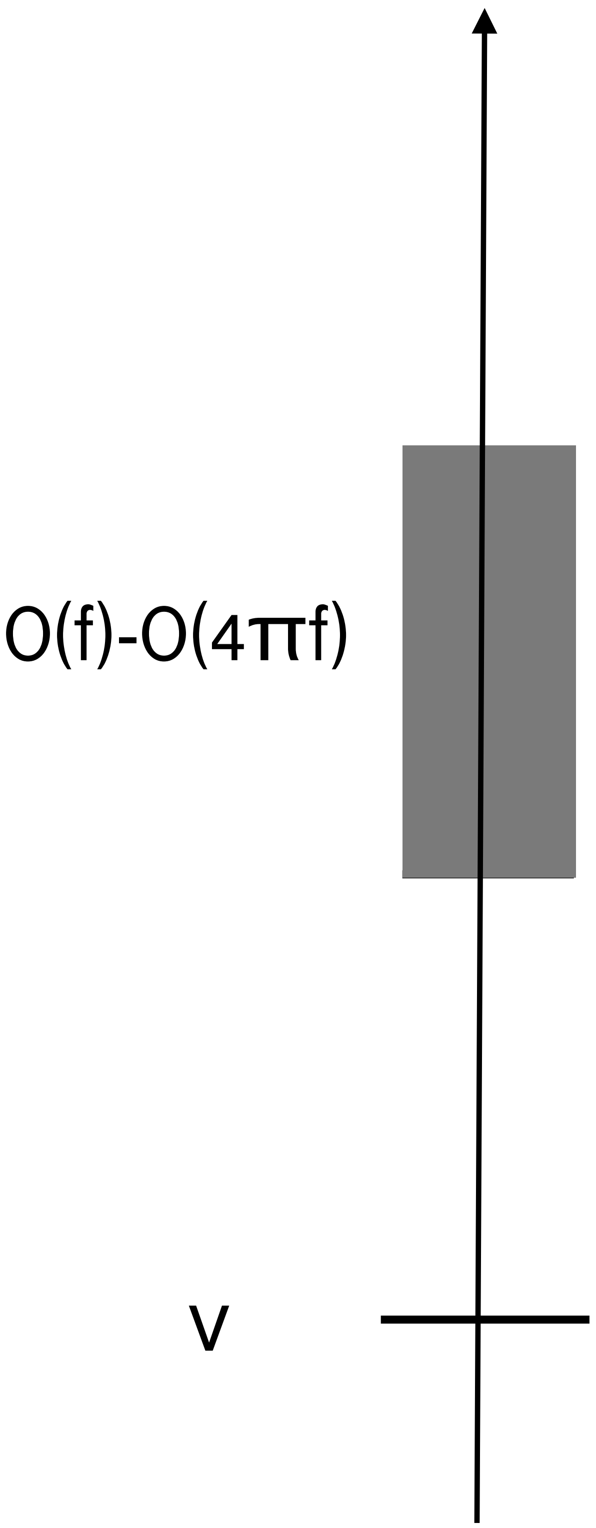
*depends on representation of $\mathcal{Q}_L$, $\mathcal{Q}_R$,etc.

Review

high energies: constituents rather than composites are relevant d.o.f, analog of q, g of QCD



Review

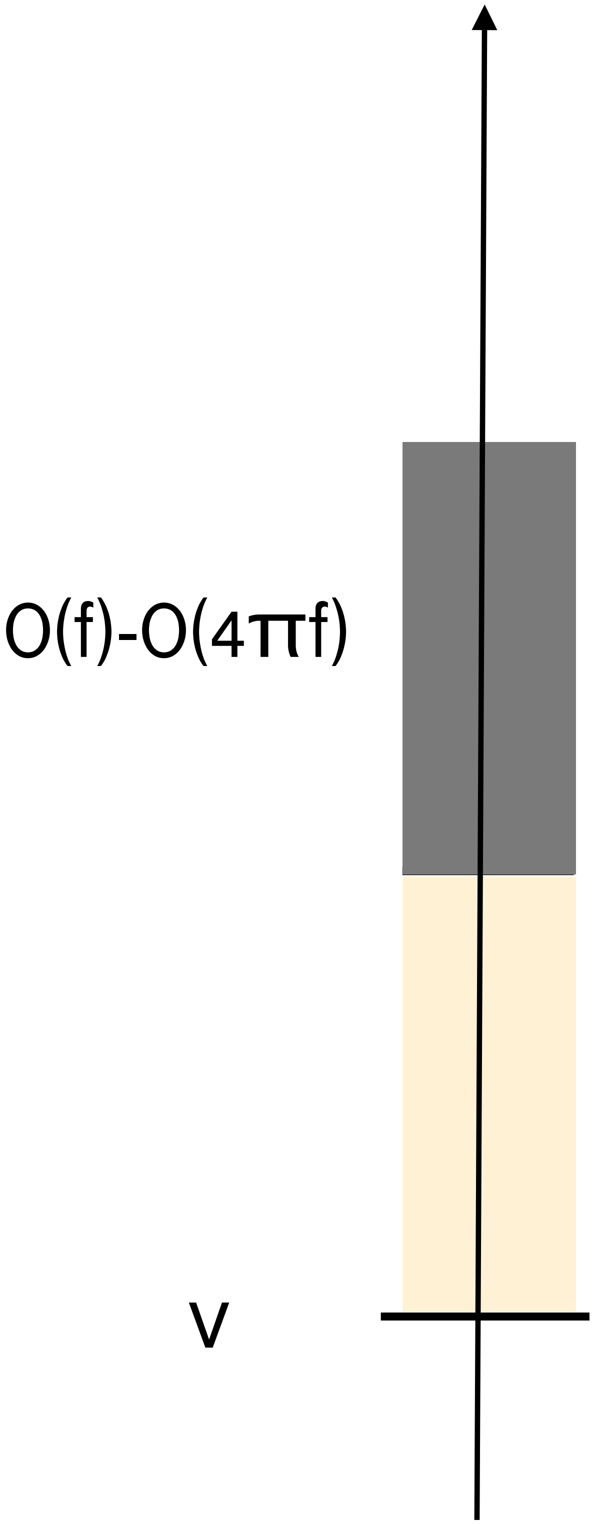


high energies: constituents rather than composites are relevant d.o.f, analog of q, g of QCD

strong dynamics kick in, constituents confined, breaks SO(5) → SO(4). EWS unbroken

not: $\langle \bar{q}_L q_R \rangle$ instead: $\langle \epsilon^{ij} \psi_i \psi_j \rangle$

Review



high energies: constituents rather than composites are relevant d.o.f, analog of q, g of QCD

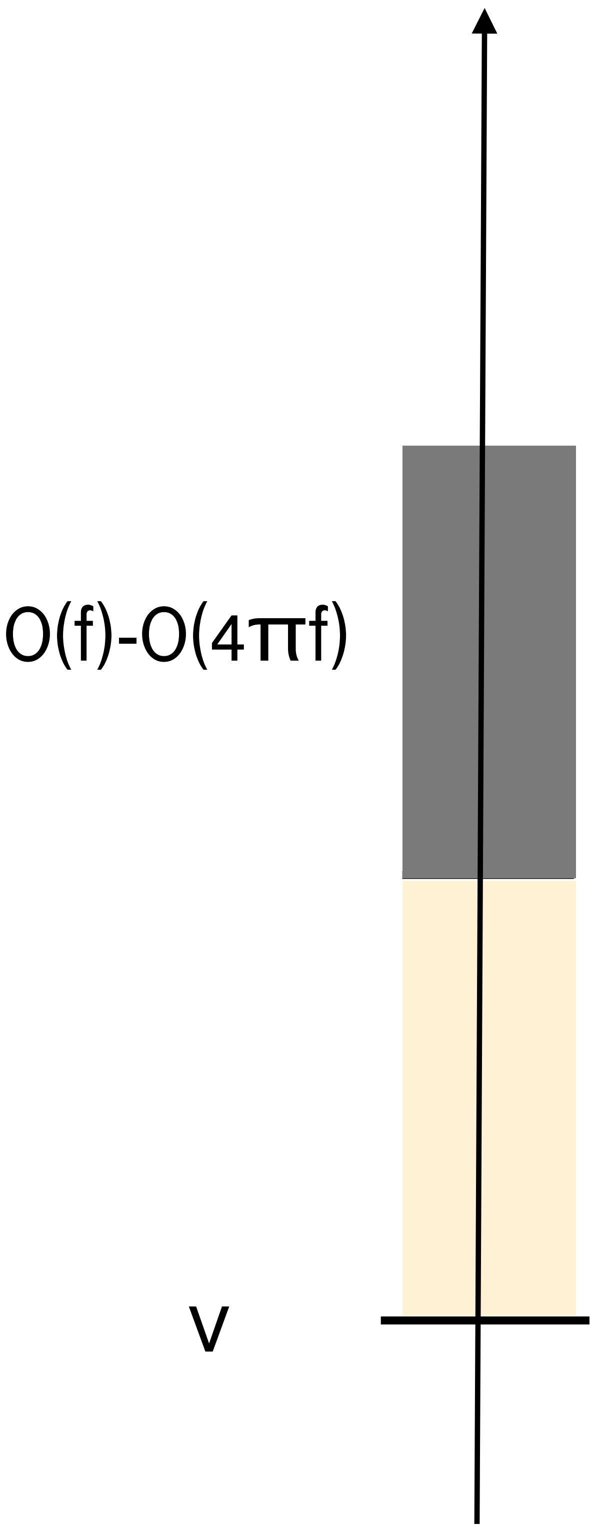
strong dynamics kick in, constituents confined, breaks SO(5) → SO(4). EWS unbroken

not: $\langle \bar{q}_L q_R \rangle$ instead: $\langle \epsilon^{ij} \psi_i \psi_j \rangle$

NGB + massless gauge fields, described by L_Σ

loop-level gauge, Yukawa interactions generate V(h)

Review



high energies: constituents rather than composites are relevant d.o.f, analog of q, g of QCD

strong dynamics kick in, constituents confined, breaks SO(5) → SO(4). EWS unbroken

not: $\langle \bar{q}_L q_R \rangle$ instead: $\langle \epsilon^{ij} \psi_i \psi_j \rangle$

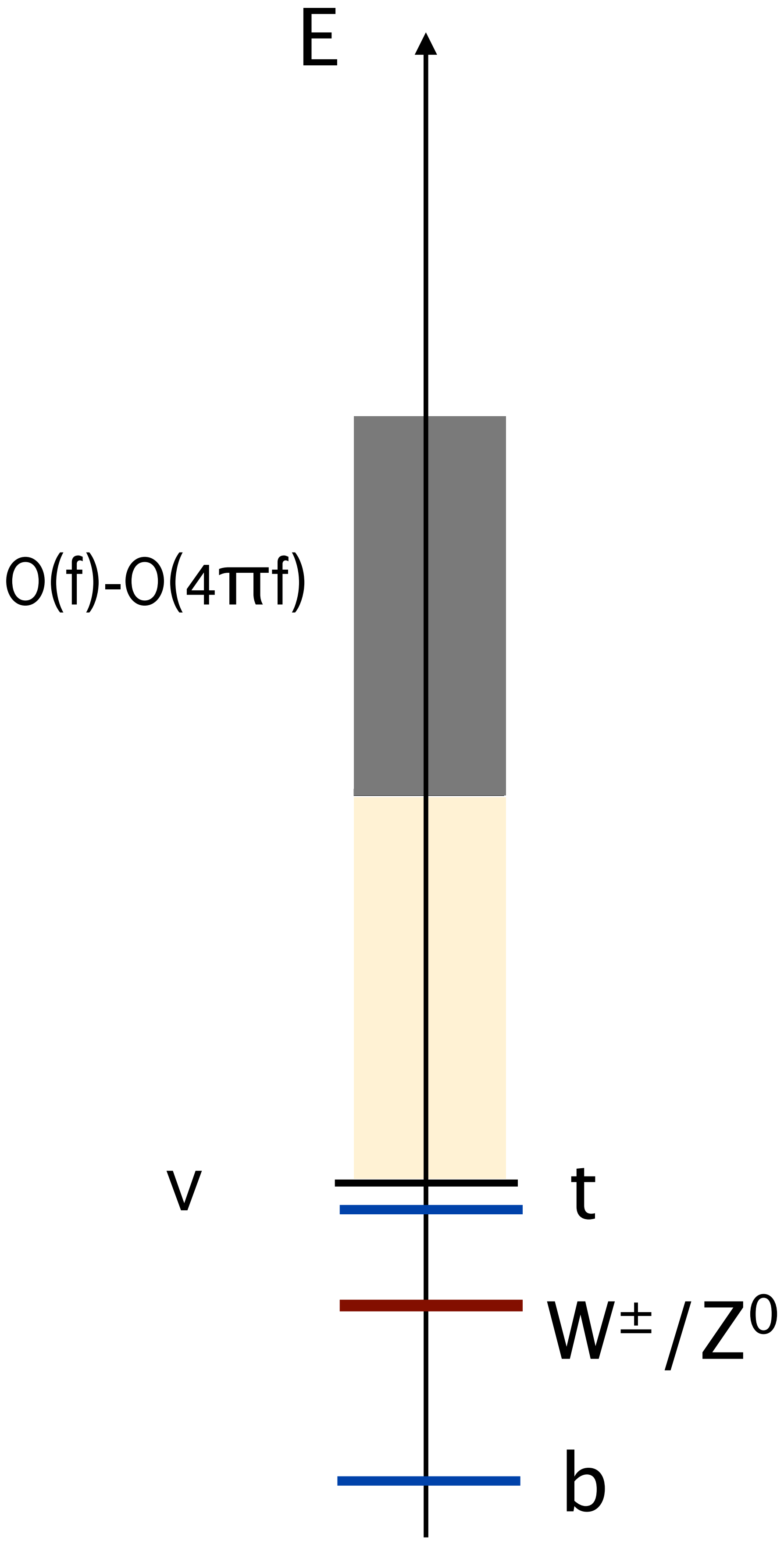
NGB + massless gauge fields, described by L_Σ

loop-level gauge, Yukawa interactions generate V(h)

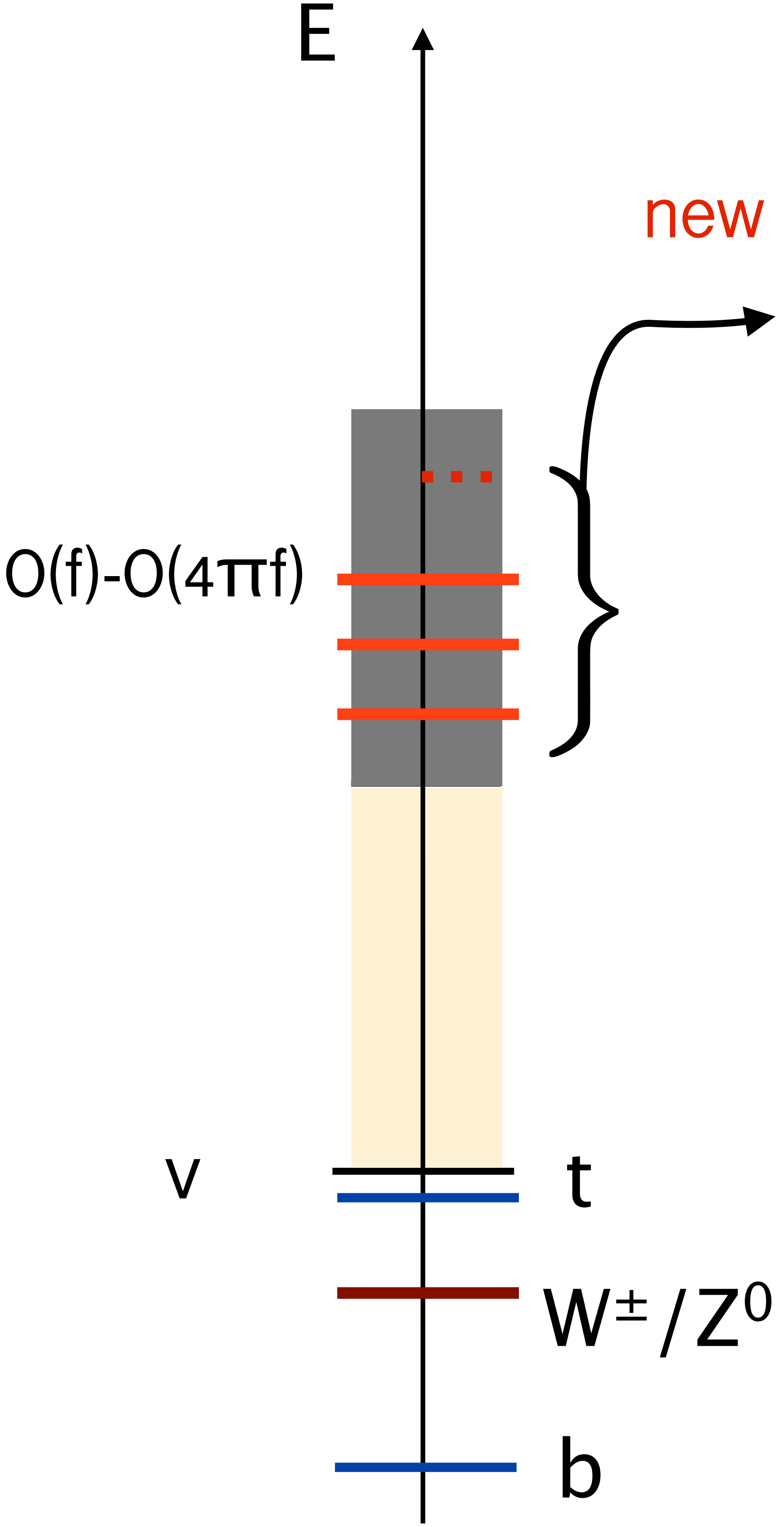
V(h) has nontrivial minima,<h>≠0, EWSB

bigger separation: f ≫ v, more SM-like

Review



Review

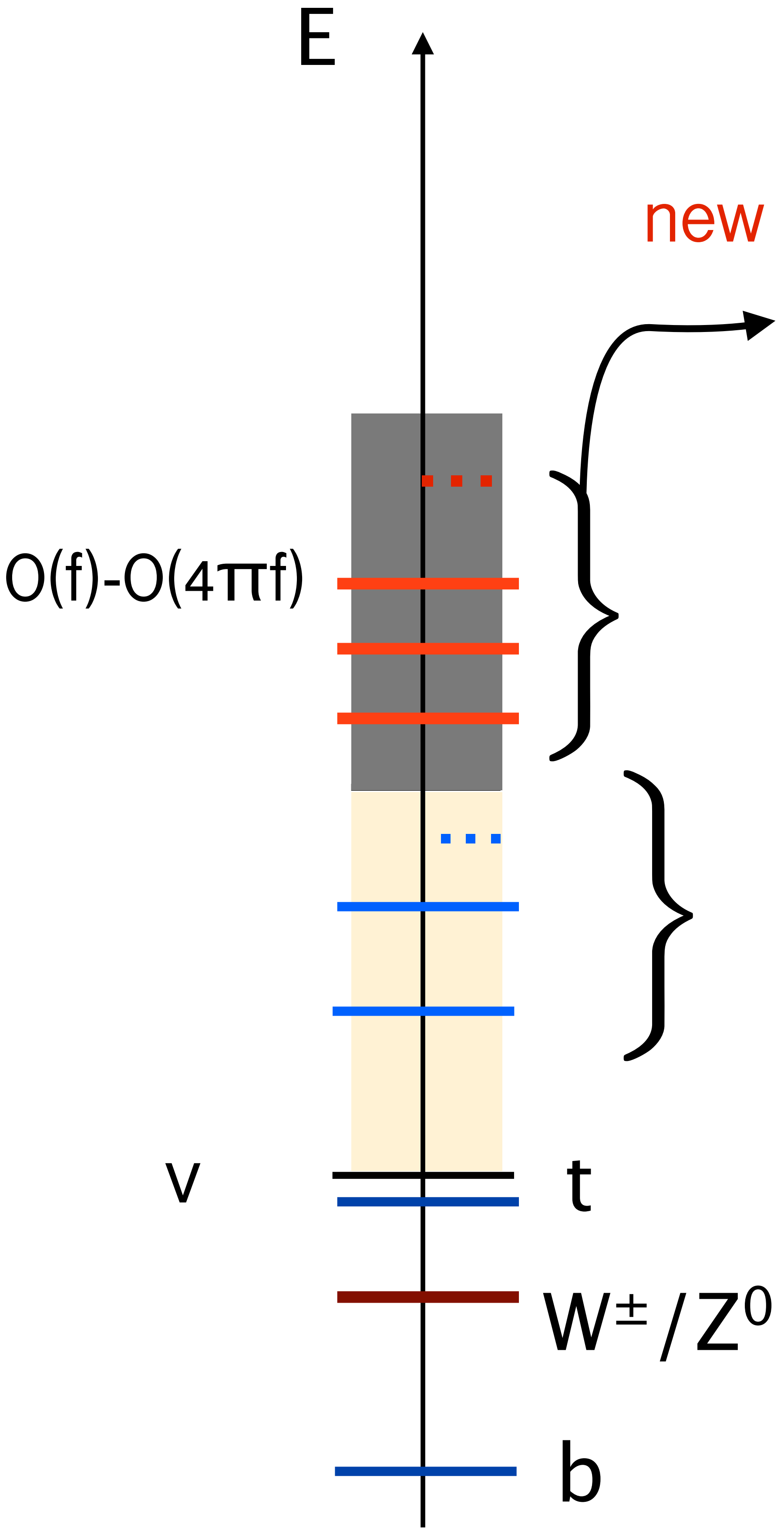


new vector resonances: other composites of strong dynamics with different spin, parity.

W', Z', W'', ...

Analog of ρ, a_1, etc. of QCD

Review



new vector resonances: other composites of strong dynamics with different spin, parity.

W', Z', W'', ...

Analog of ρ, a_1, etc. of QCD

fermion resonances: 'baryons' that mix with SM fermions

T', B', etc.

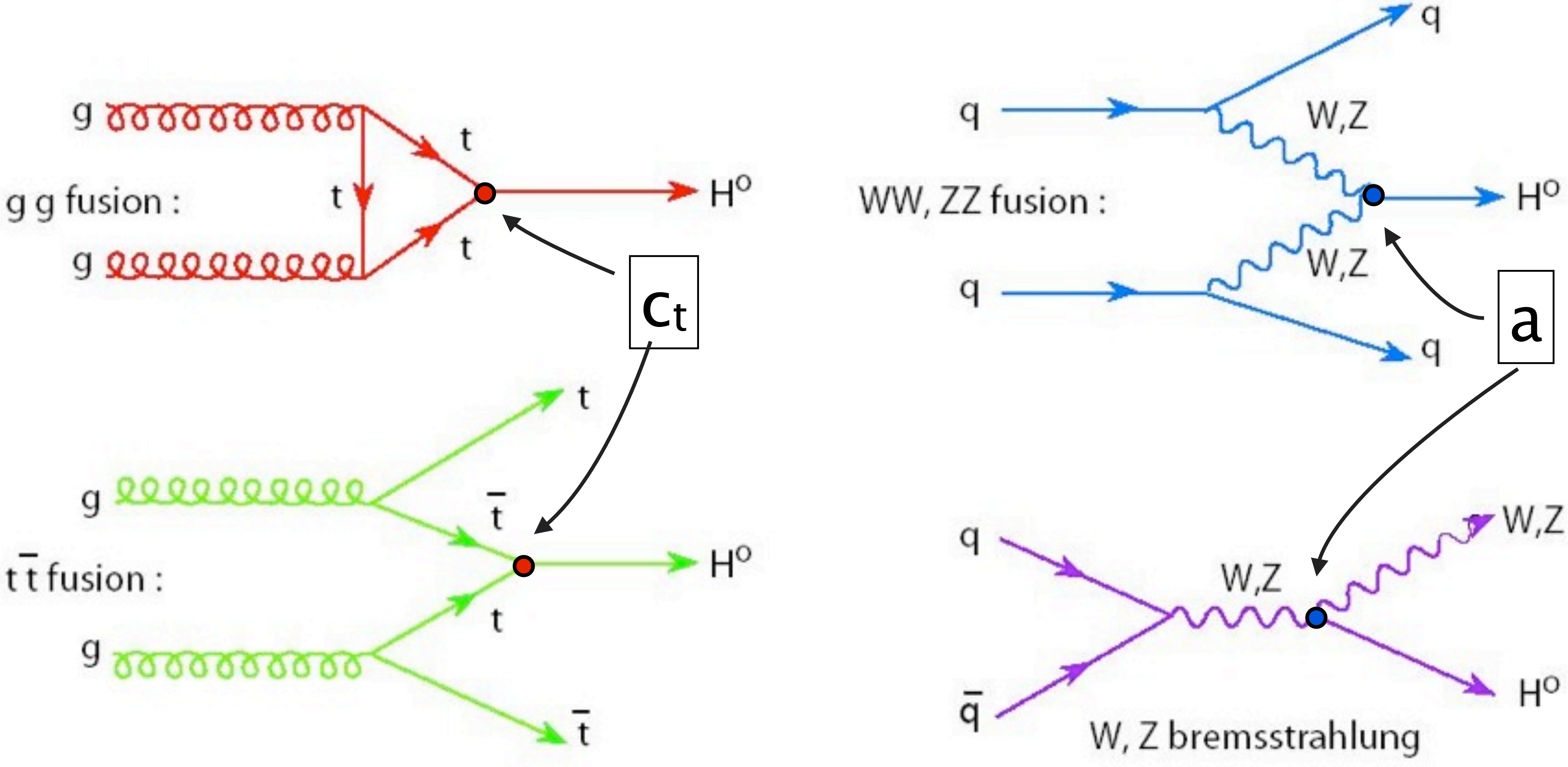
$\overline{T'}_L H T'_R$ interactions + mixing → SM mass terms

LHC signals

1.) Higgs couplings: a, b, c

study all possible Higgs production and decay process to extract a, c

intricate process, as different production mechanisms scale differently with a, c, and contribute differently to each final state



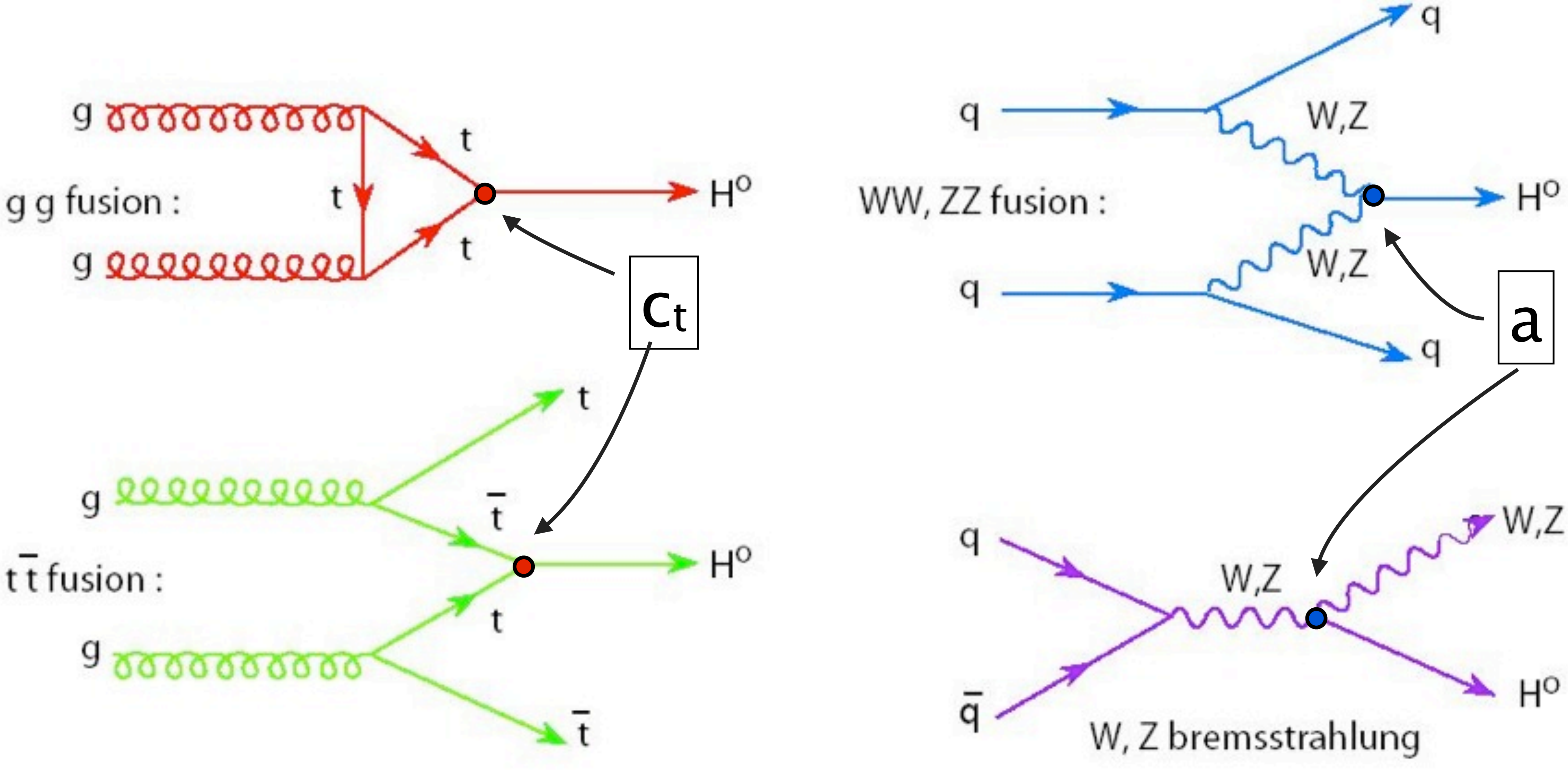
LHC signals

relevant NOW

1.) Higgs couplings: a, b, c

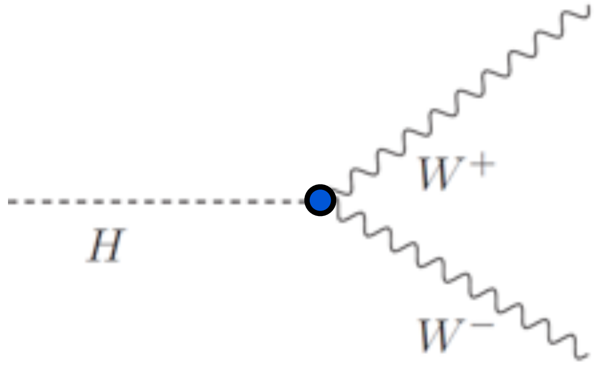
study all possible Higgs production and decay process to extract a, c

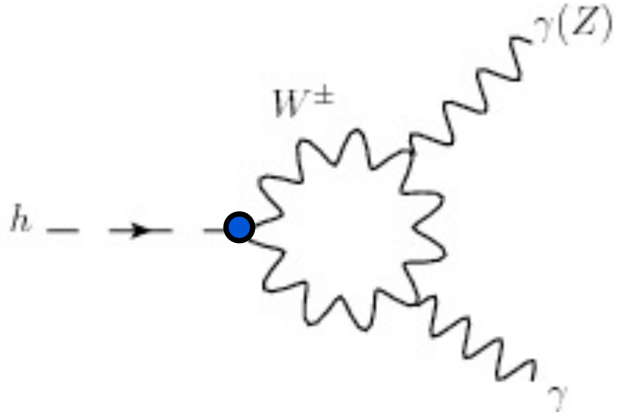
intricate process, as different production mechanisms scale differently with a, c, and contribute differently to each final state

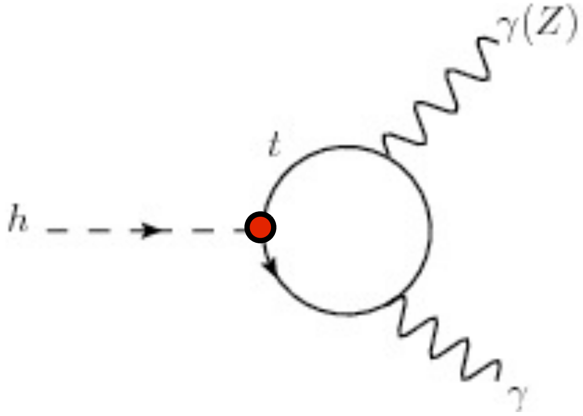


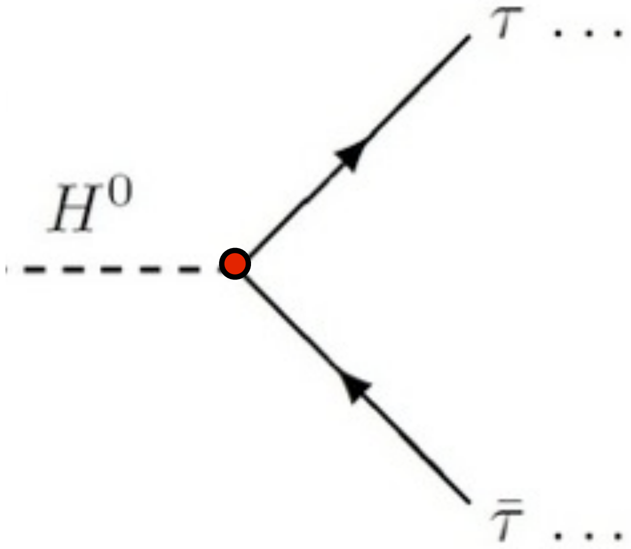
LHC signals

different composite Higgs models → different a, c, possibly even extra Higgs decay modes from new particles









ex.) $gg \to h \to W_\mu^+ W_\mu^- \sim a\, c_t/\Gamma_H$

$\text{VBF } pp \to h \to \tau^+ \tau^- \sim a\, c_\tau/\Gamma_H$

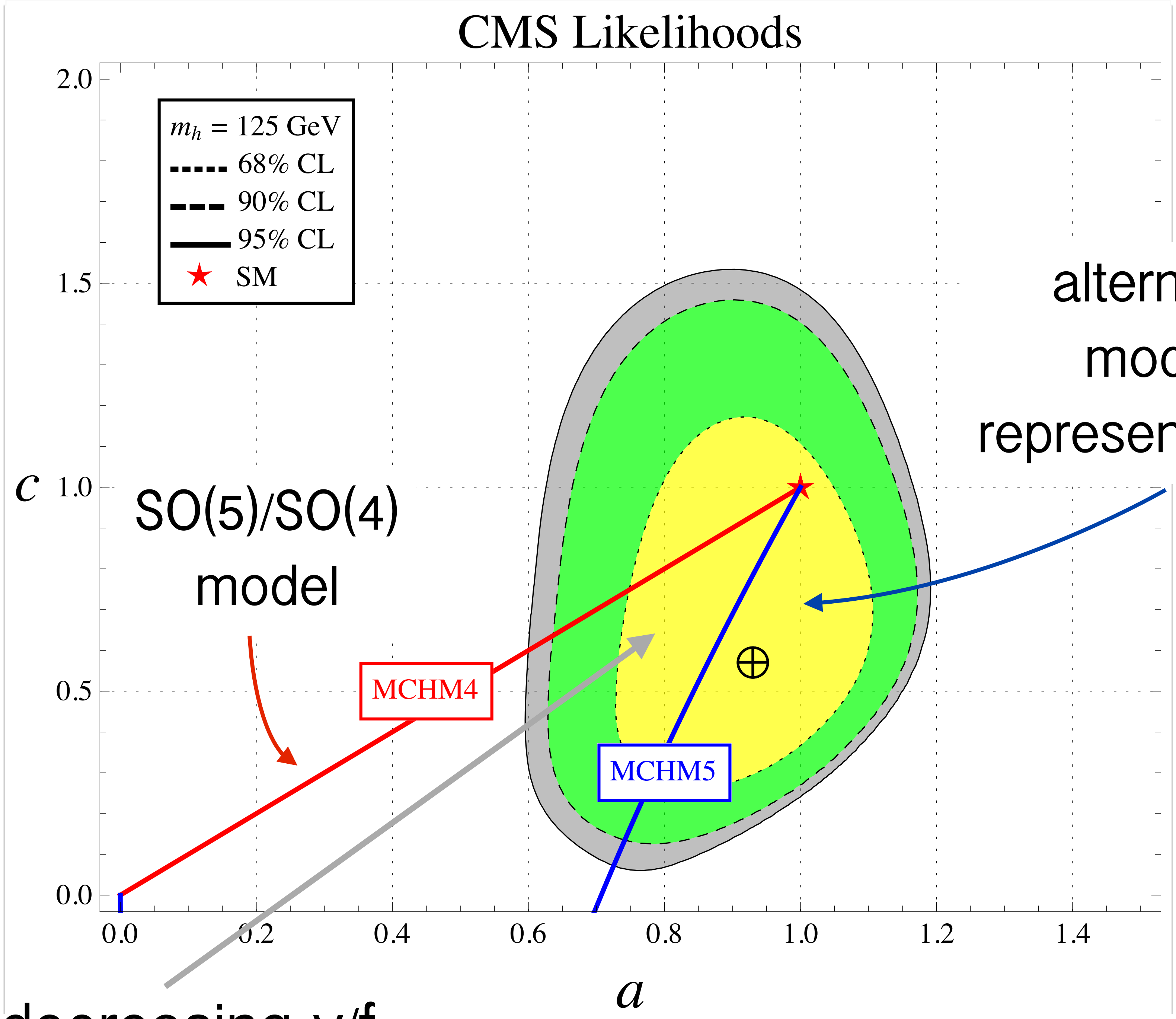
$gg \to h \to \tau^+\tau^- \sim c_t\, c_\tau/\Gamma_H$

BUT, careful: H + jj is not VBF alone, H+0j is not just gg → H

also, Γ_H knows about all c_i

LHC signals

compiling Higgs data (prior to HCP)



SO(5)/SO(4) model

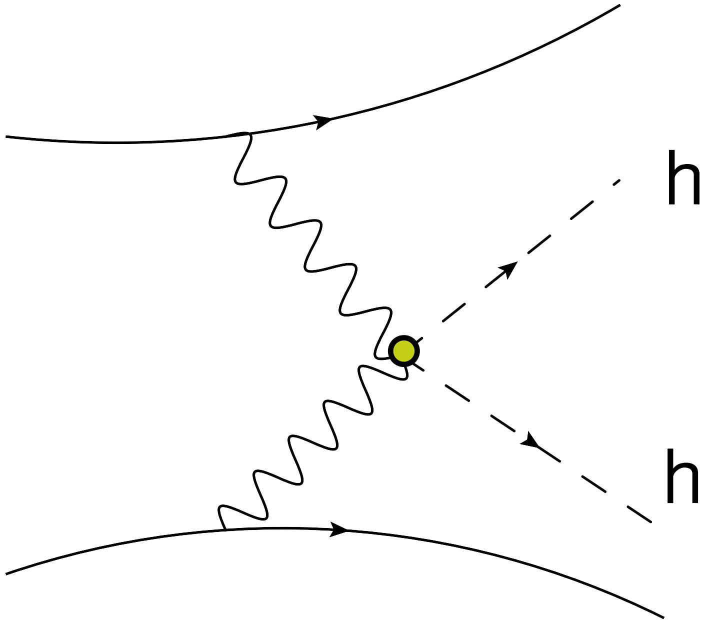
alternate SO(5)/SO(4) model w/ different representation for fermions

decreasing v/f

[from J. Galloway]

LHC signals

coupling b is trickier.. requires studying multi-Higgs production in detail

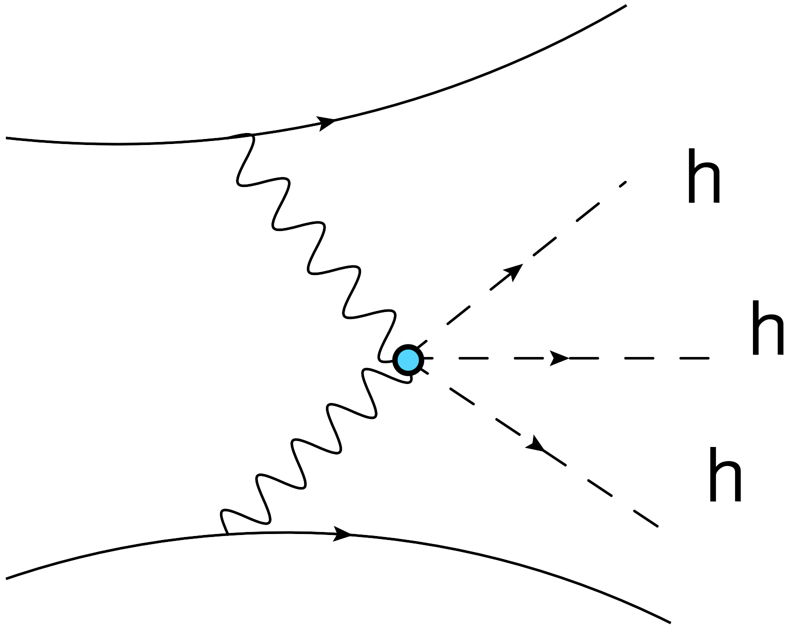


low cross section and b must be disentangled from other hh production diagrams

see ex.) [Dolan, Englert, Spannowsky 1206.5001,1210.8166]

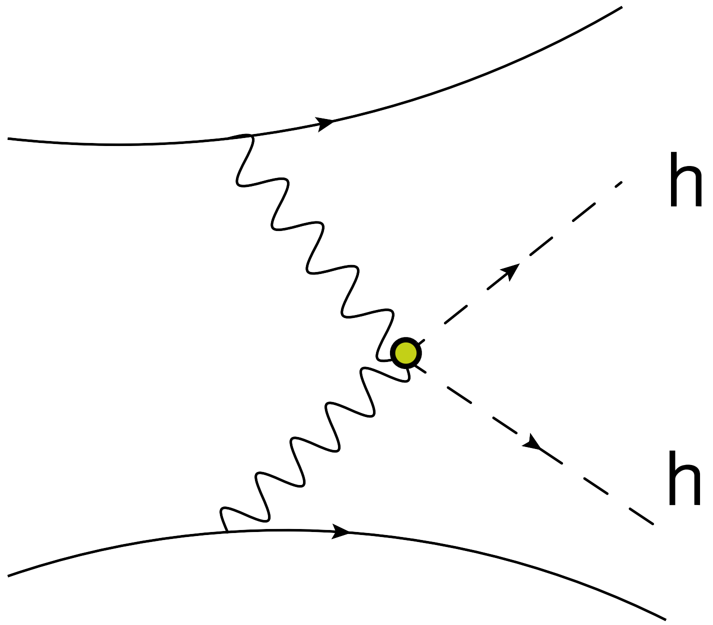
$W^+W^- h^3$ signal .. from further expansion of $f \sin^2(h/f)$

doesn't exist at tree level in the SM



LHC signals

coupling b is trickier.. requires studying multi-Higgs production in detail



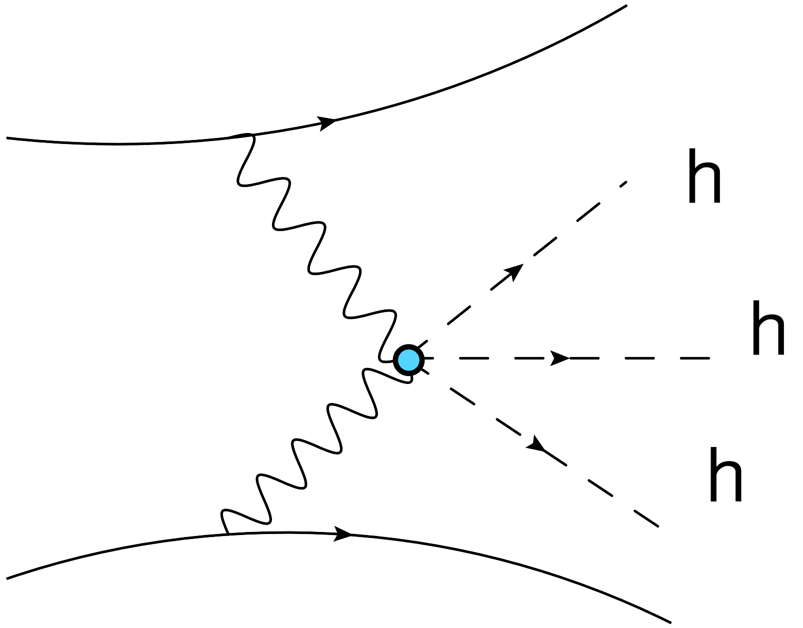
low cross section and b must be disentangled from other hh production diagrams

high-luminosity needed!

see ex.) [Dolan, Englert, Spannowsky 1206.5001,1210.8166]

$W^+W^- h^3$ signal .. from further expansion of $f \sin^2(h/f)$

doesn’t exist at tree level in the SM



LHC signals

2.) production of new particles

we’ve seen that composite Higgs models generically have new vector (spin-1: W’, Z’,W’’) and fermion (T’, B’) resonances

- interactions of Higgs with W/Z set by choice of symmetry breaking... much more model dependence for resonances & their interactions
- additional complication: we know the theory is strongly coupled.. no obvious ‘best’ way to proceed.

One idea: rescale properties of QCD resonances

$$\rho \to W', \, M_{W'} = \sqrt{\frac{3}{N_C}}\frac{f}{f_\pi}M_\rho$$ ~ 4 TeV for f = 2 v

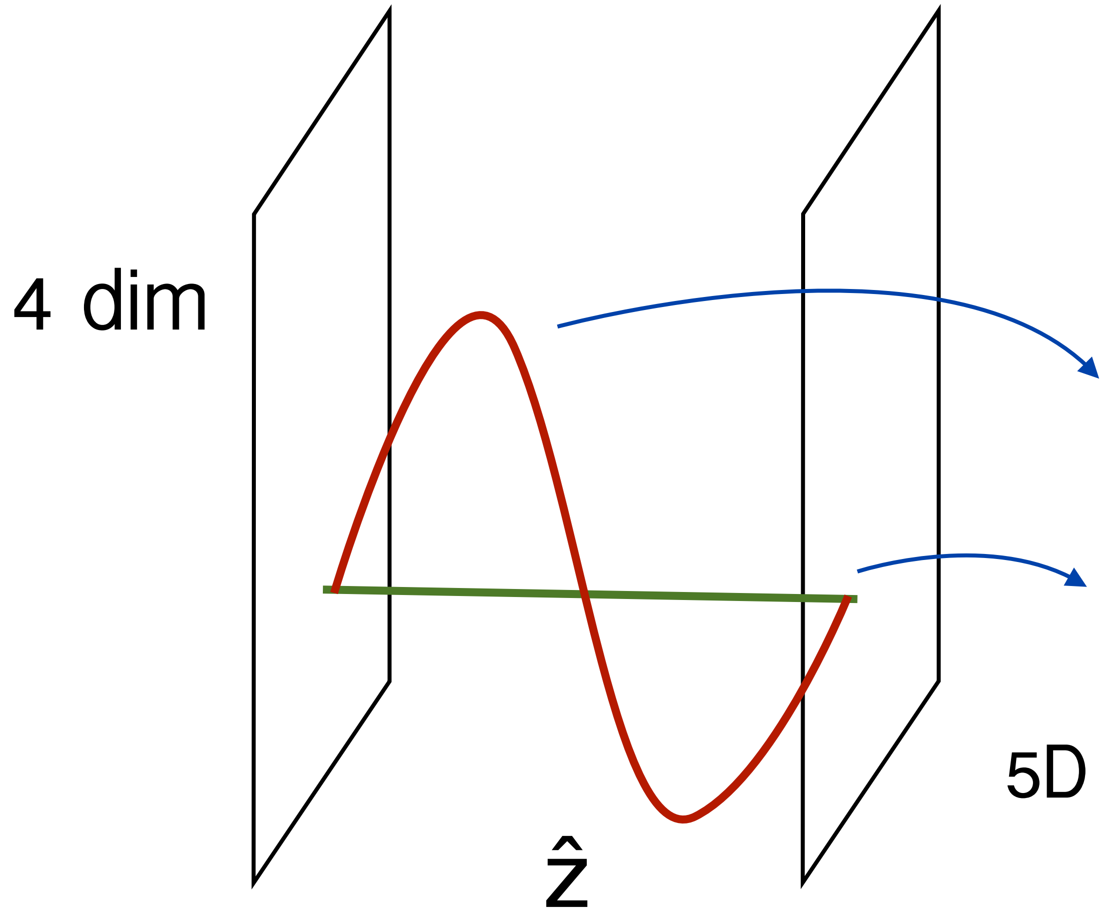
not very quantitative

Extra dimensional models on a slide

One way to model the strong dynamics is with an extra dimension

$$\partial^2\phi = \Box\phi + \partial_z^2\phi$$

4-d deriv.   deriv. along ẑ



$$\Box\phi + X^2\phi$$ ‘massive’ field

$$\Box\phi$$ ‘massless’ field

5D field = whole tower of 4D fields of increasing mass, interpret as SM field + resonances

couplings among fields = integral over ẑ of overlapping profiles

$$\int_0^L dz\, \phi_1(z)\phi_2(z)\phi_3(z)$$

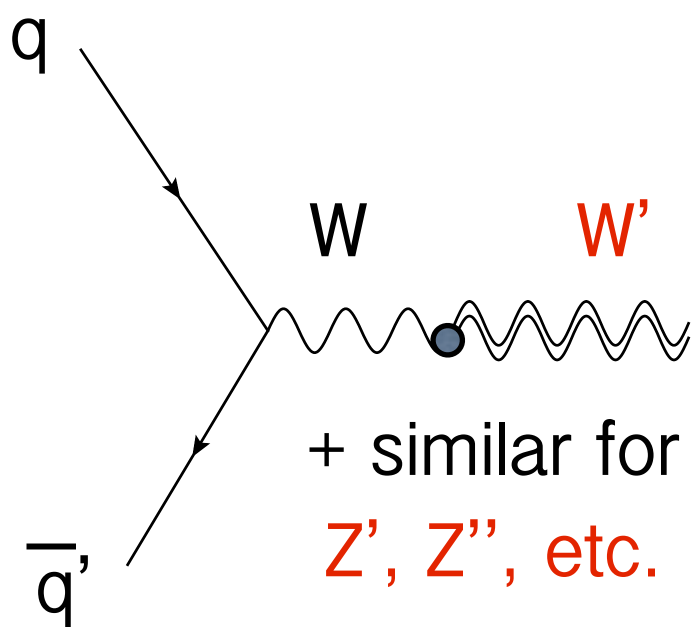
masses, interactions set by few parameters: size, geometry of 5th dimension

but not fundamental, just a model

LHC signals

spin-1 resonances:

slight mixing between W’, Z’ and W, Z, means new resonances produced most easily in $\hat{s}$-channel



+ similar for Z’, Z’’, etc.

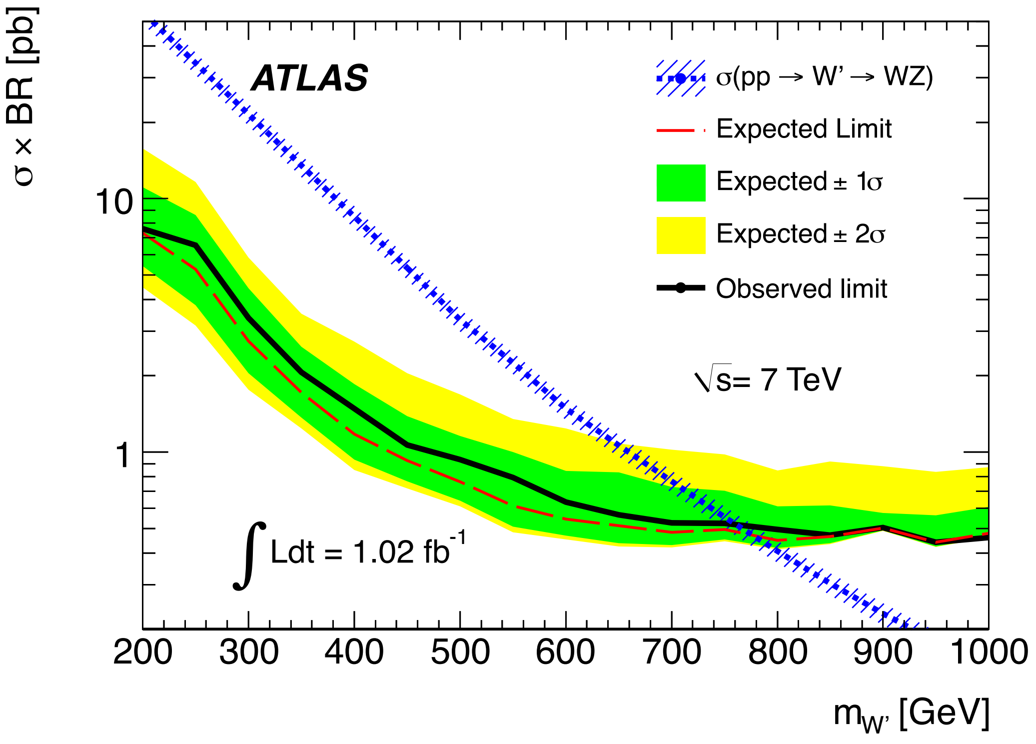
may look like usual W’, Z’

BUT: W’,Z’ couple strongest to other strong-sector states, like the longitudinal W, Z & h (even t). Big couplings mean $\Gamma_{W'}$, etc. can be big.

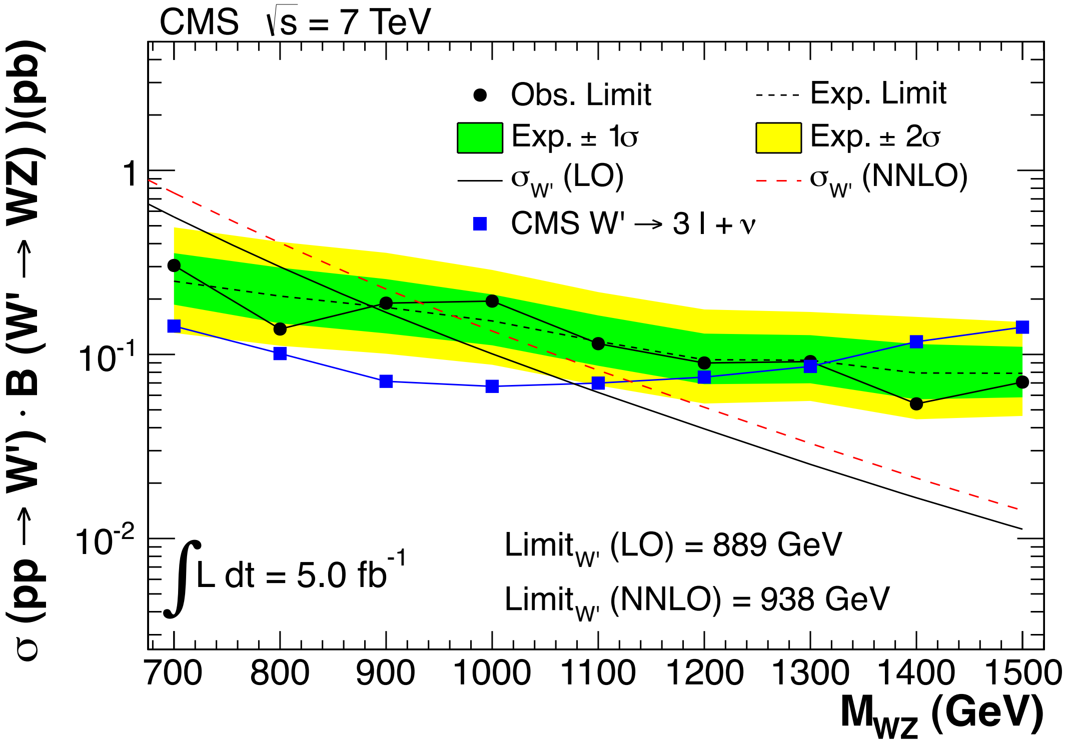
usual W’, Z’ LHC searches assume zero (or very small) W’WZ interactions... these **need to be reinterpreted** for particles w/ strong interactions with W, Z, etc.

LHC signals

cleanest signal for W/Z decay products is the fully leptonic mode: W’ → WZ → 3 ℓ + ν



ATLAS 1.02 fb^{-1}



CMS 5 fb^{-1}

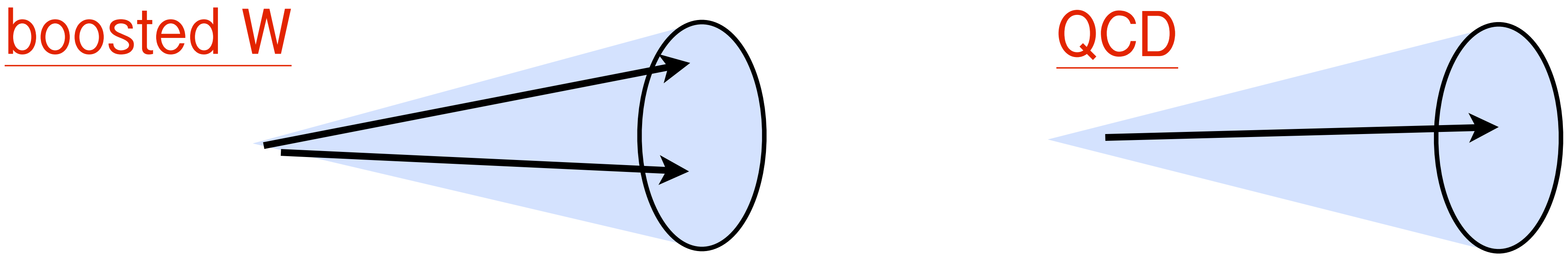
leptonic modes have small BR .. combined with small production cross section, rate will be a problem as mW’ increases

LHC signals

semi-leptonic modes ($\ell\ell$ + jj, $\ell\nu$+jj) look swamped by background (W/Z + jets) ...

but we can use the fact that W, Z from a ~few TeV W' will be **highly boosted**

angular sepn. of W→jj ~ 2 m_W/p_T ~ 0.3 for p_T ~ 500 GeV .. both decay products fall into the same 'jet'



jet 'substructure' will be an essential tool for uncovering such signals

[Butterworth et al '08, Kaplan et al '08, ...]

more in tutorial session!

LHC signals

fermionic resonances = new heavy fermions

exactly what states are present & their masses depends on details of the composite fermions (masses M, representations)

simple example, to show some general features:

t_R mixing with composites T, $T^c \in (3,1)_{2/3}$

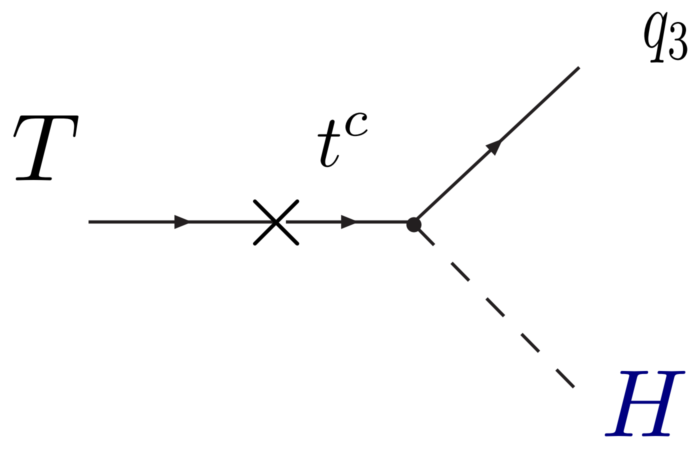
$$y_t\, Q_3\, H\, t^c + M\, T\, T^c + \delta\, T\, t^c + h.c.$$

$$(t \;\; T)\begin{pmatrix} m & 0 \\ \delta & M \end{pmatrix}\begin{pmatrix} t^c \\ T^c \end{pmatrix}$$

$$\begin{aligned}\mathcal{L} \supset\; & \frac{m_t\, \cos^2\theta_l}{v} h\, \bar{T}_D(\tan\theta_r\, P_L + \tan\theta_l\, P_R)\, t_D \\ & + \frac{g_2 \sin\theta_l\, \cos\theta_l}{2\, \cos\theta_W} Z_\mu \left(\bar{T}_D\gamma^\mu\, P_L t_D + \bar{t}_D\gamma^\mu\, P_L T_D\right) \\ & + \frac{g_2 \sin\theta_l}{\sqrt{2}} \left(W^+_\mu \bar{T}_D\gamma^\mu P_L b_D + W^-_\mu \bar{b}_D\gamma^\mu\, P_L T_D\right)\end{aligned}$$

LHC signals

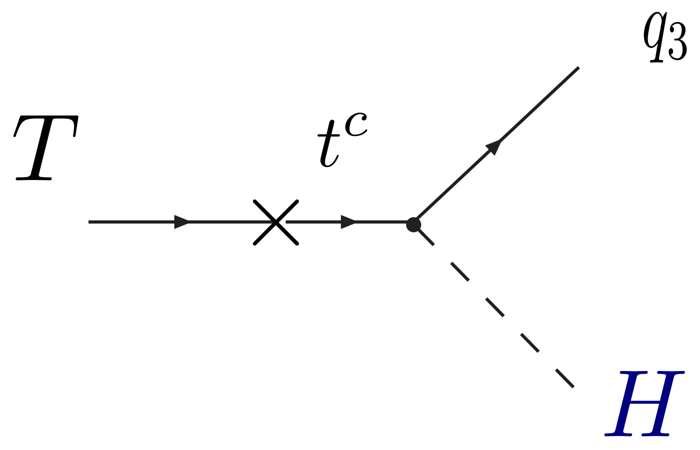
new interaction



Branching ratio, up to small corrections,
set by Goldstone equivalence:

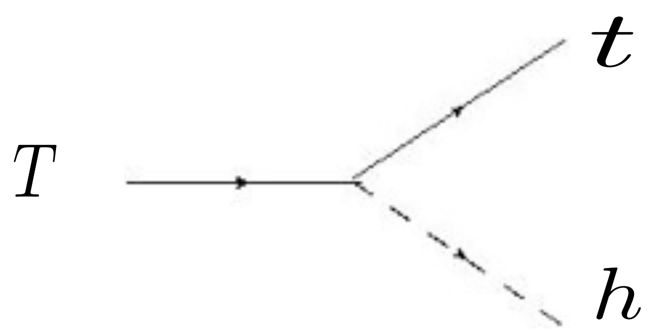
LHC signals

new interaction

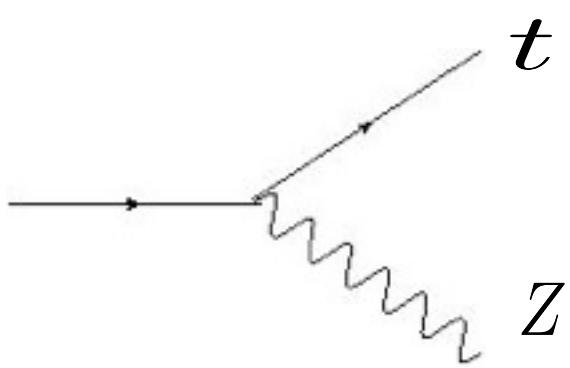


Branching ratio, up to small corrections,
set by Goldstone equivalence:

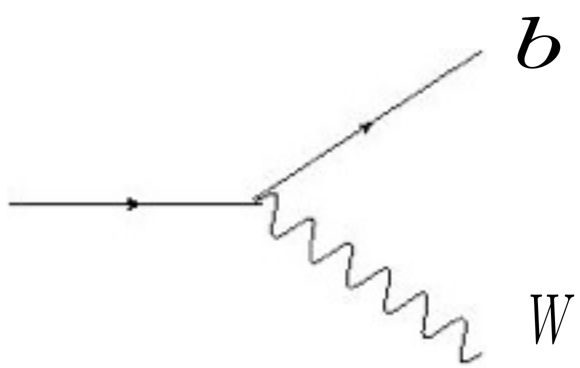
T decay modes



$\sim 25\%$



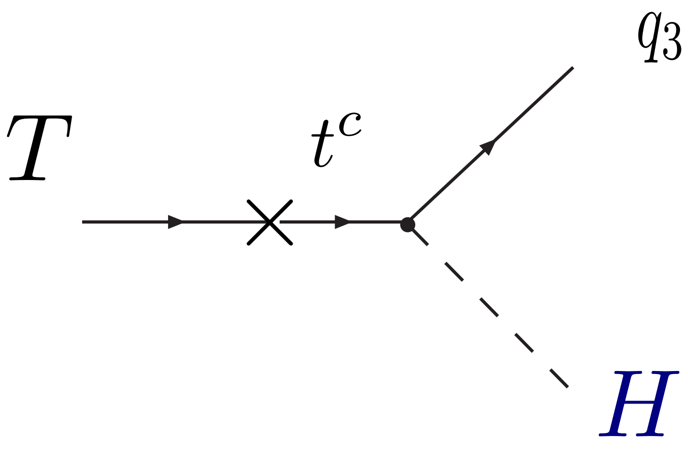
$\sim 25\%$



$\sim 50\%$

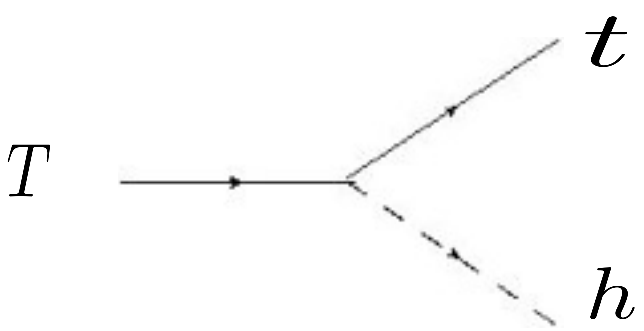
LHC signals

new interaction

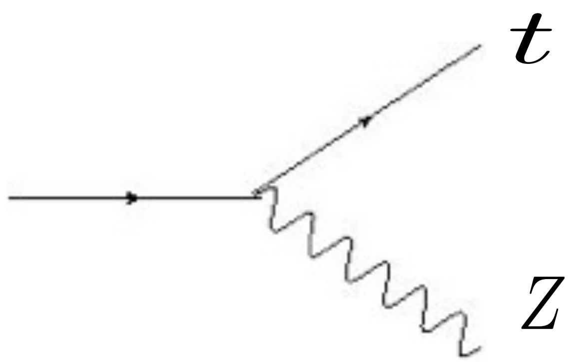


Branching ratio, up to small corrections,
set by Goldstone equivalence:

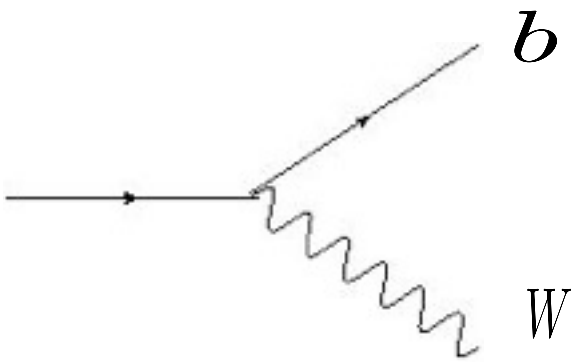
T decay modes



$\sim 25\%$



$\sim 25\%$

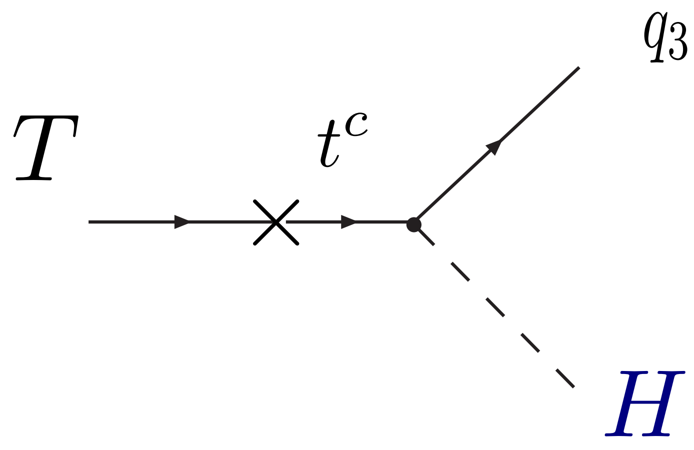


$\sim 50\%$

in large mass limit,
only parameter is M_T

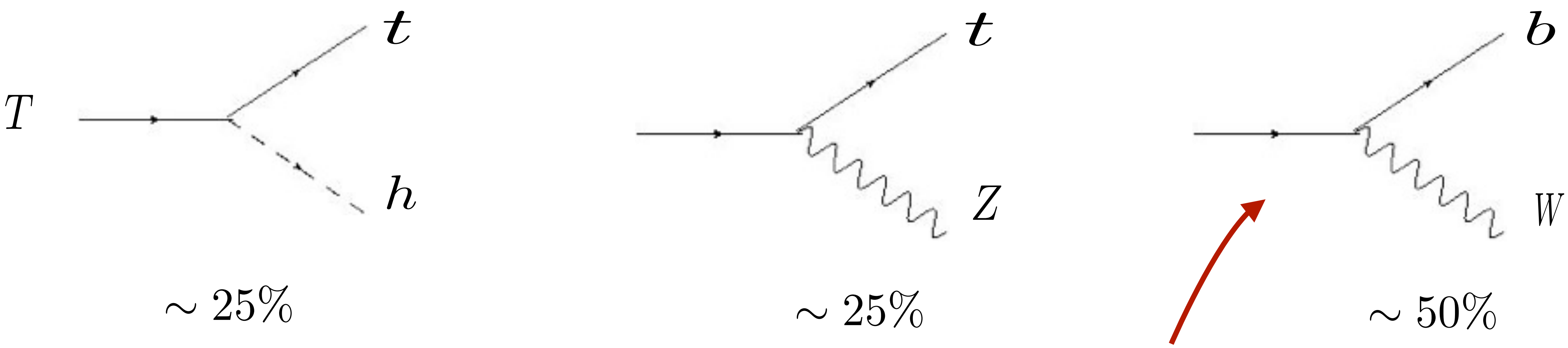
LHC signals

new interaction



Branching ratio, up to small corrections,
set by Goldstone equivalence:

T decay modes

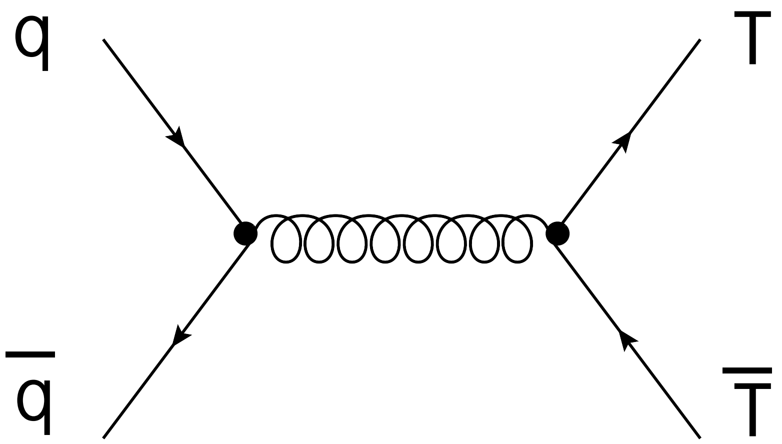


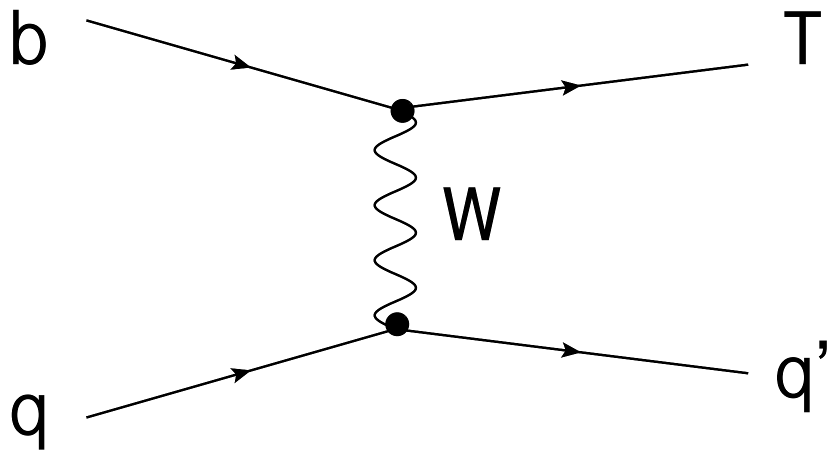
in large mass limit,
only parameter is M_T

extra 'chiral' quarks
(4th generation)
only have this decay mode

LHC signals

both pair-production (T $\overline{\text{T}}$) and single production possible. Pair production dominates for $M_T \lesssim 1$ TeV

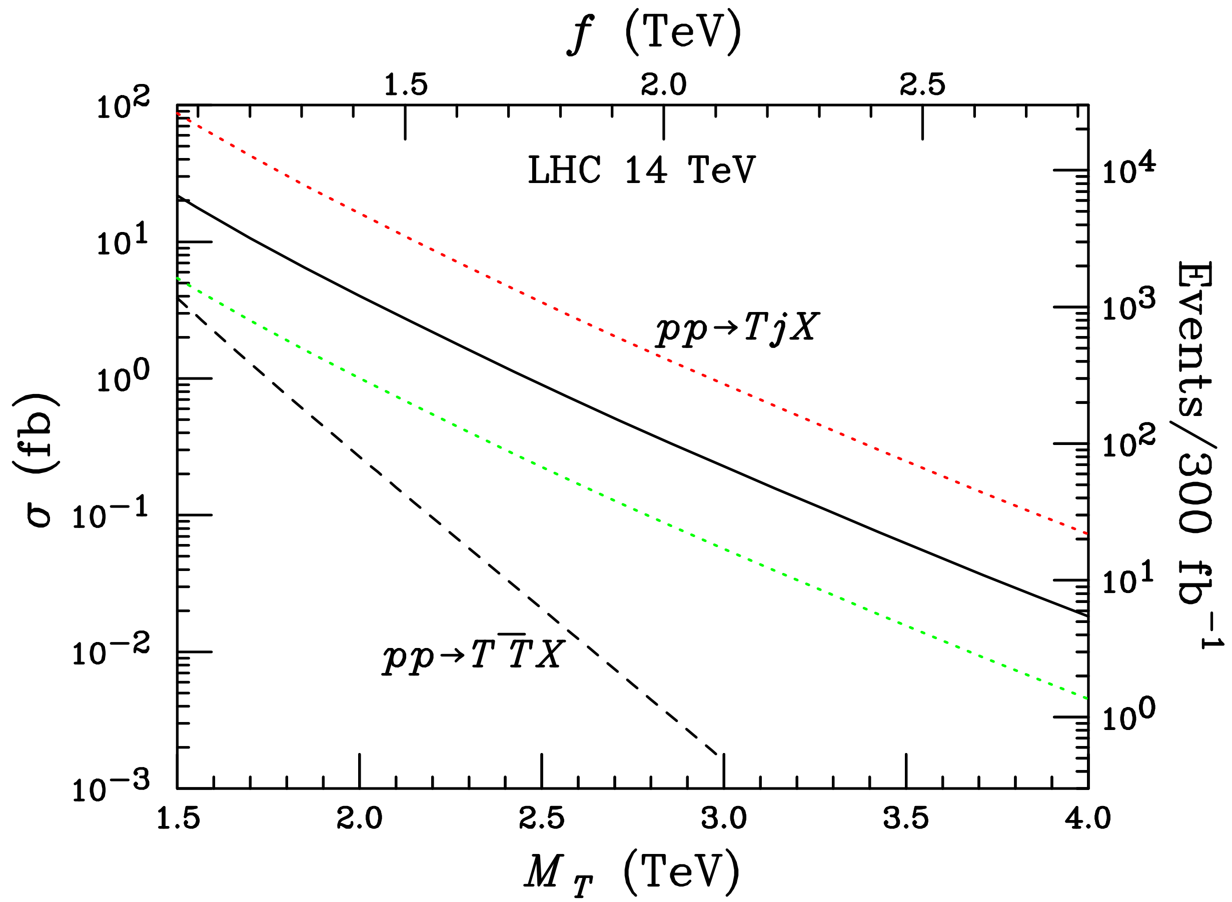




- fairly large cross section
- lots of W,Z,h, b in the final state

$$\begin{aligned} T\overline{T} &\to tZ^0\bar{b}W^- + c.c. \\ &\to bjj\ell^+\ell^- b + (W) \end{aligned}$$

$$\begin{aligned} T\overline{T} &\to tZ^0\bar{t}h^0 + c.c. \\ &\to bjj\ell^+\ell^- b\ell\nu bb \end{aligned}$$



LHC signals

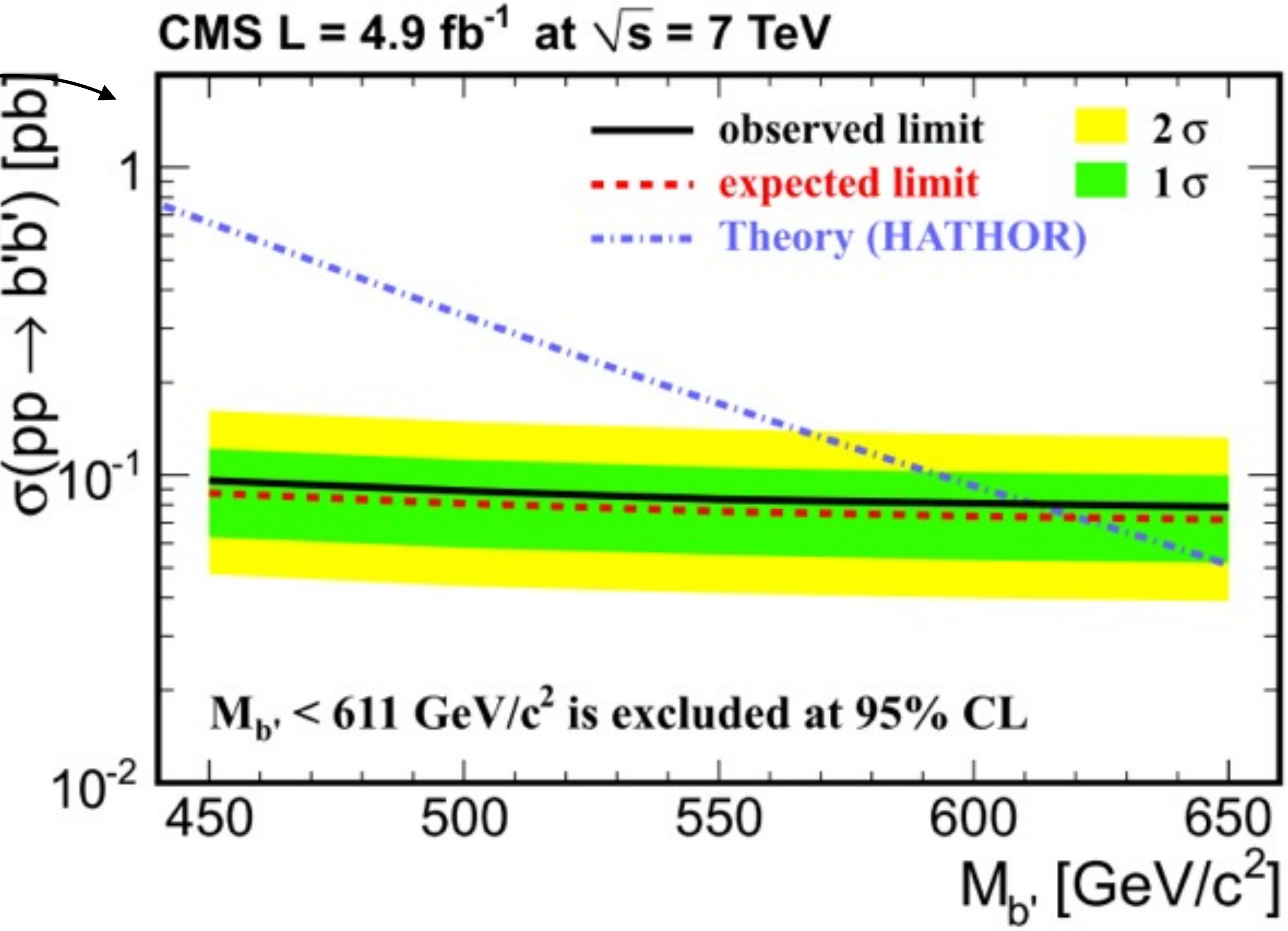
existing limits on T’, B’:

assume 100% BR into one mode: T→ W b (4th gen), T → t Z

B’→ t W
CMS 1109.4985

also
ATLAS 1204.1265

recent
counterexamples
Rao, Whiteson
1204.4504, 1203.6642
De Simone et al
1211.5663



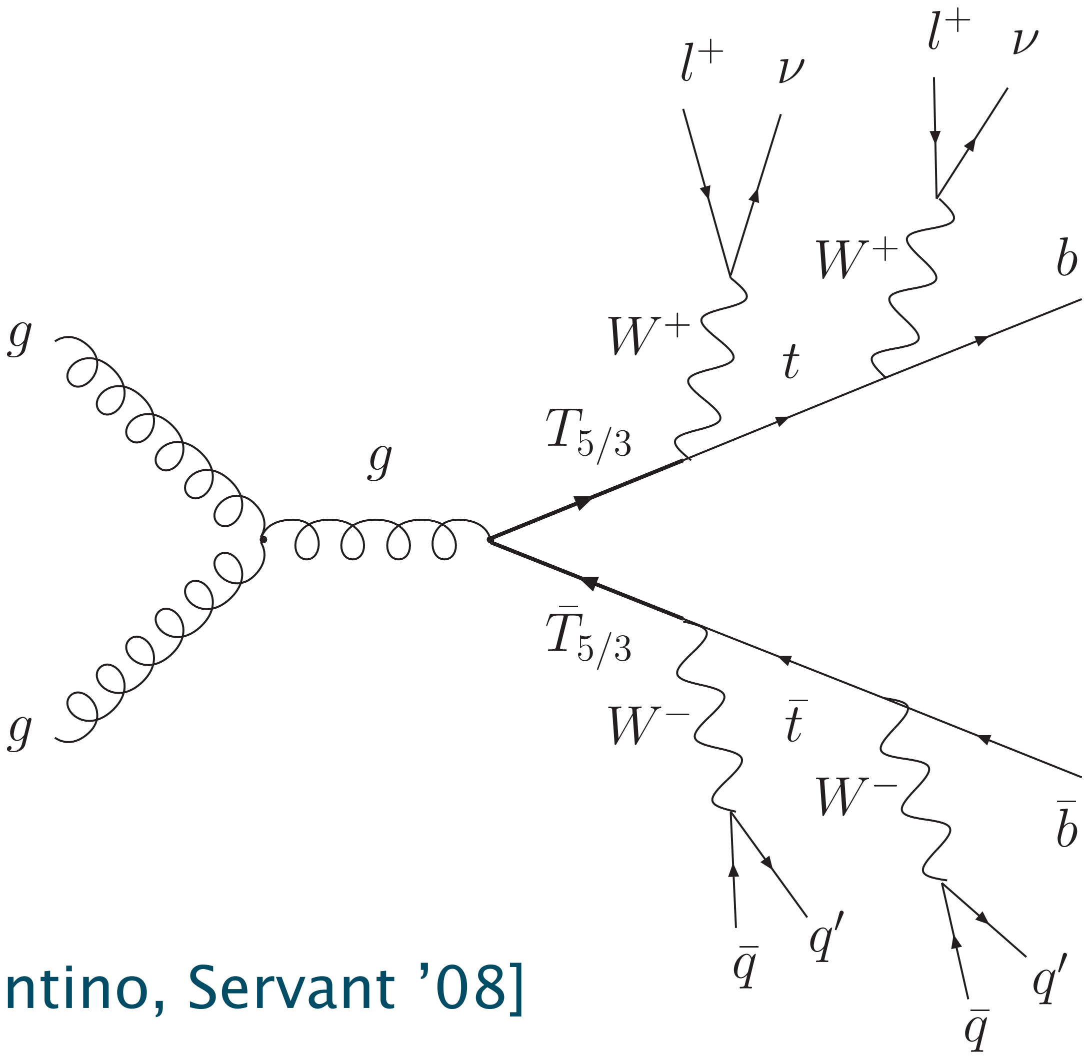
so, limits need to be reinterpreted. Mixed modes likely to yield stronger constraints.

substructure could be useful for identifying hadronic W/Z

LHC signals

more exotic possibilities:

In some scenarios, Q_{3L} doublet is extended & includes higher charge states: $X_{5/3}$, or $X_{7/6}$



[Contino, Servant '08]

cascade decays of
X → t W→ W b
gives like-sign
dileptons

low SM background

LHC signals: summary

- the era of precision Higgs: composite-ness of the Higgs is encoded in deviations of couplings from their SM values

mass scale of new particles ~f is constrained via Higgs coupling measurements. More SM-like couplings → smaller v/f → heavier new states

- direct production of new particles:

both spin-1 and fermionic resonances have large couplings to W/Z/h/t: W/Z/h/t-rich final states

W'/Z'/T' have different properties than LHC searches usually assume -- care required in interpreting limits

Conclusions:

immediate LHC focus: how Higgs-like is X(125)?

L_Σ EFT is the right framework to use, look for deviations a,b,c≠1

a,b,c≠1 indicate strong coupling enters at some scale

Composite Higgs: Higgs as a Goldstone boson. UV setup that gives light Higgs + a,b,c≠1

gauge and Yukawa interactions generate nontrivial V(h) and lead to EWSB. tuning of different contributions to get $v \ll f$

other composites (spin-1, fermions) in spectra, possible targets for LHC searches.

different than ‘generic’ W’Z’/T’: large couplings to W/Z/h/t