Composite Higgs models, the LHC, and Lattice

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before ~ July 2012

elementary Higgs (tuned SM, supersymmetry)

composite Higgs

no Higgs

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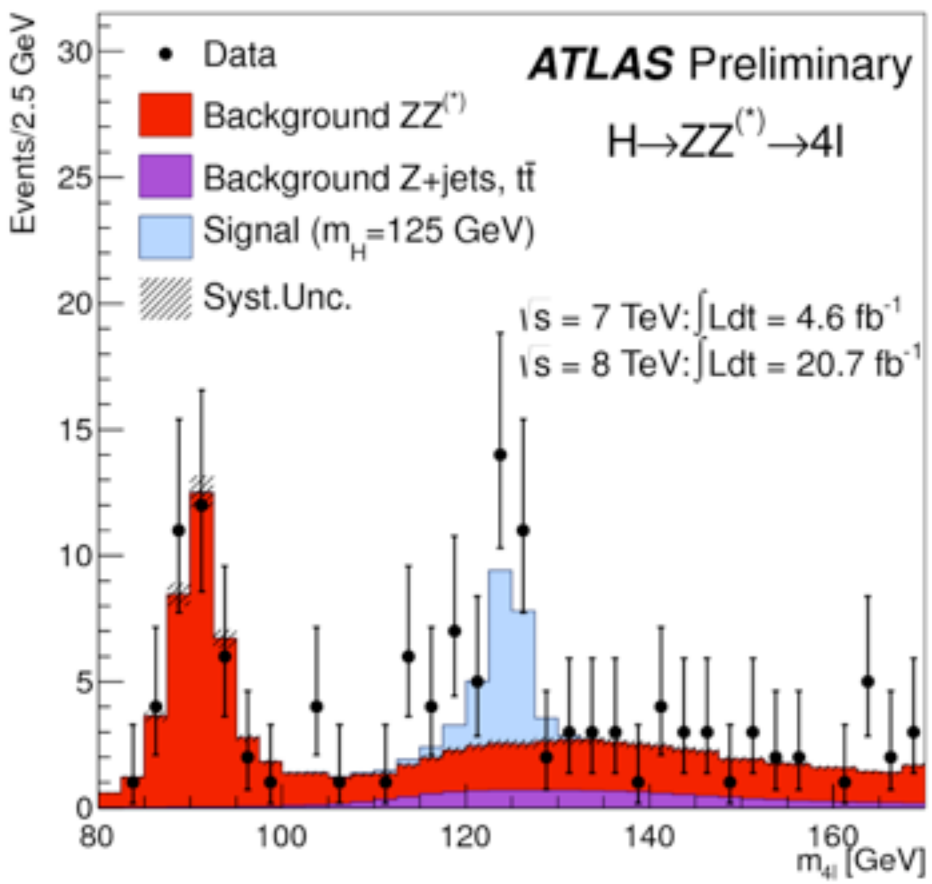

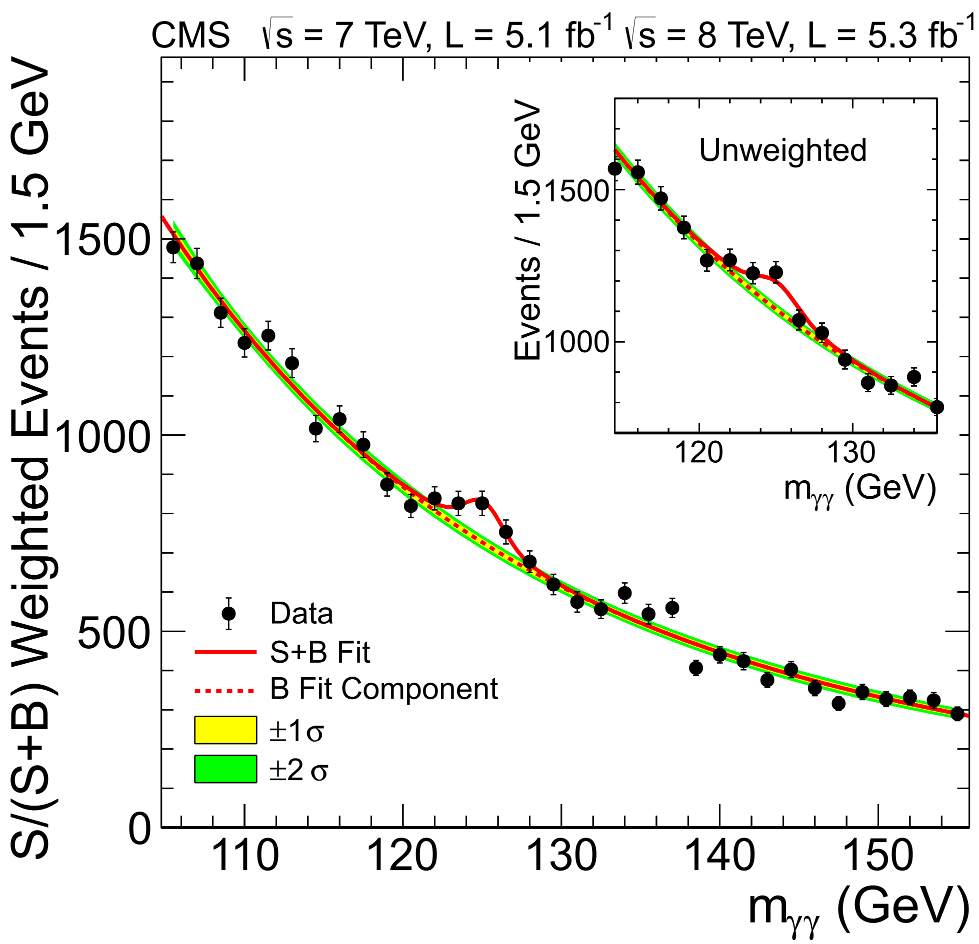

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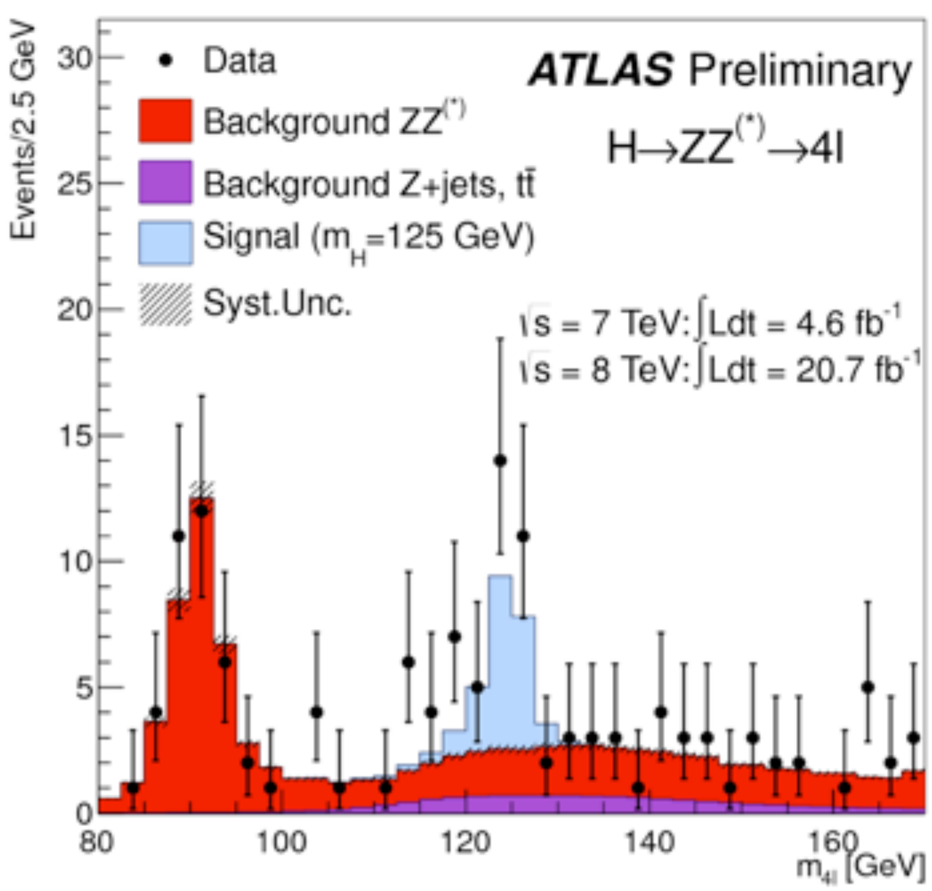
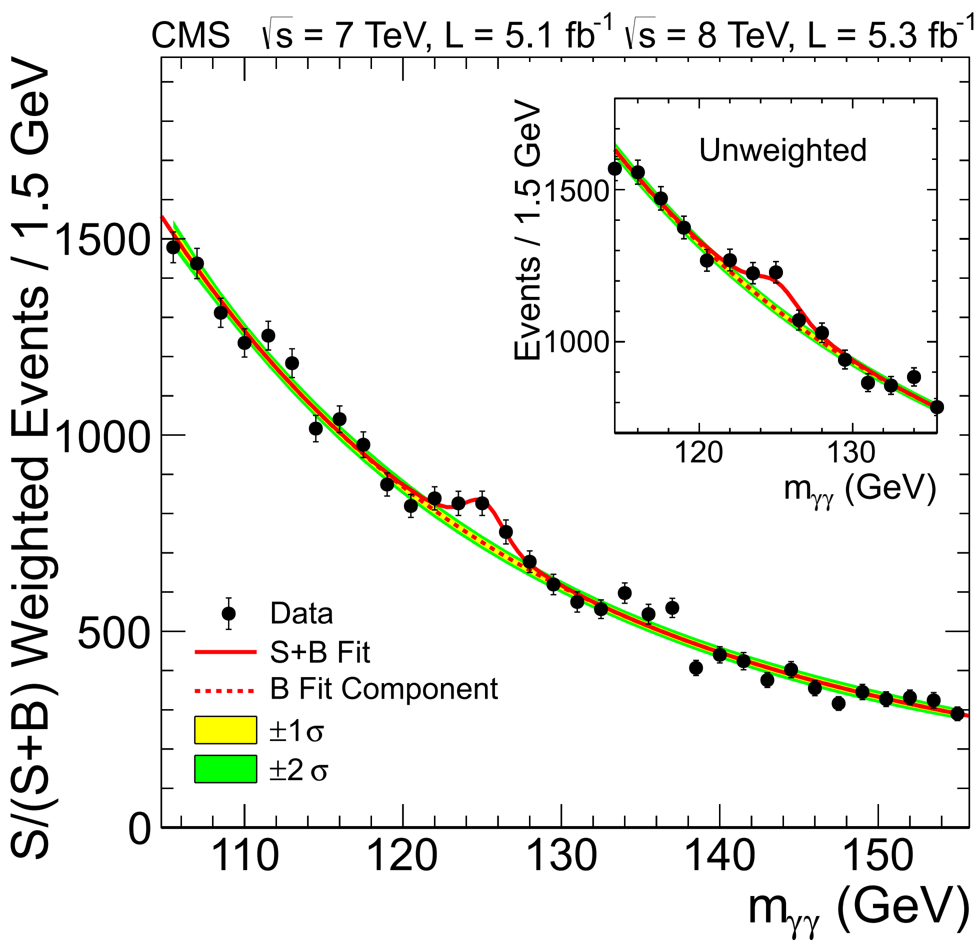
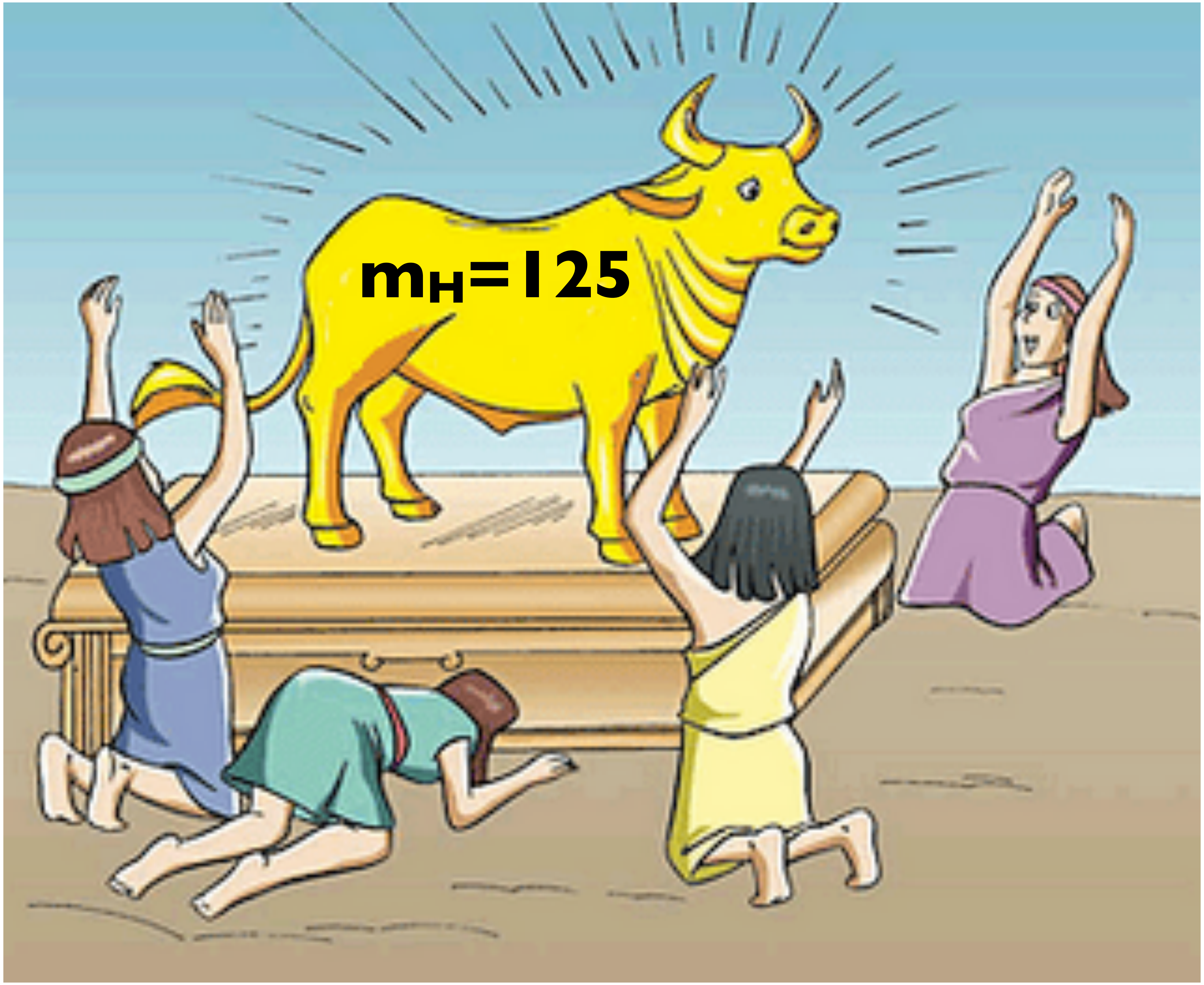




... so lets not get carried away



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from AM, USQCD 5/4/12

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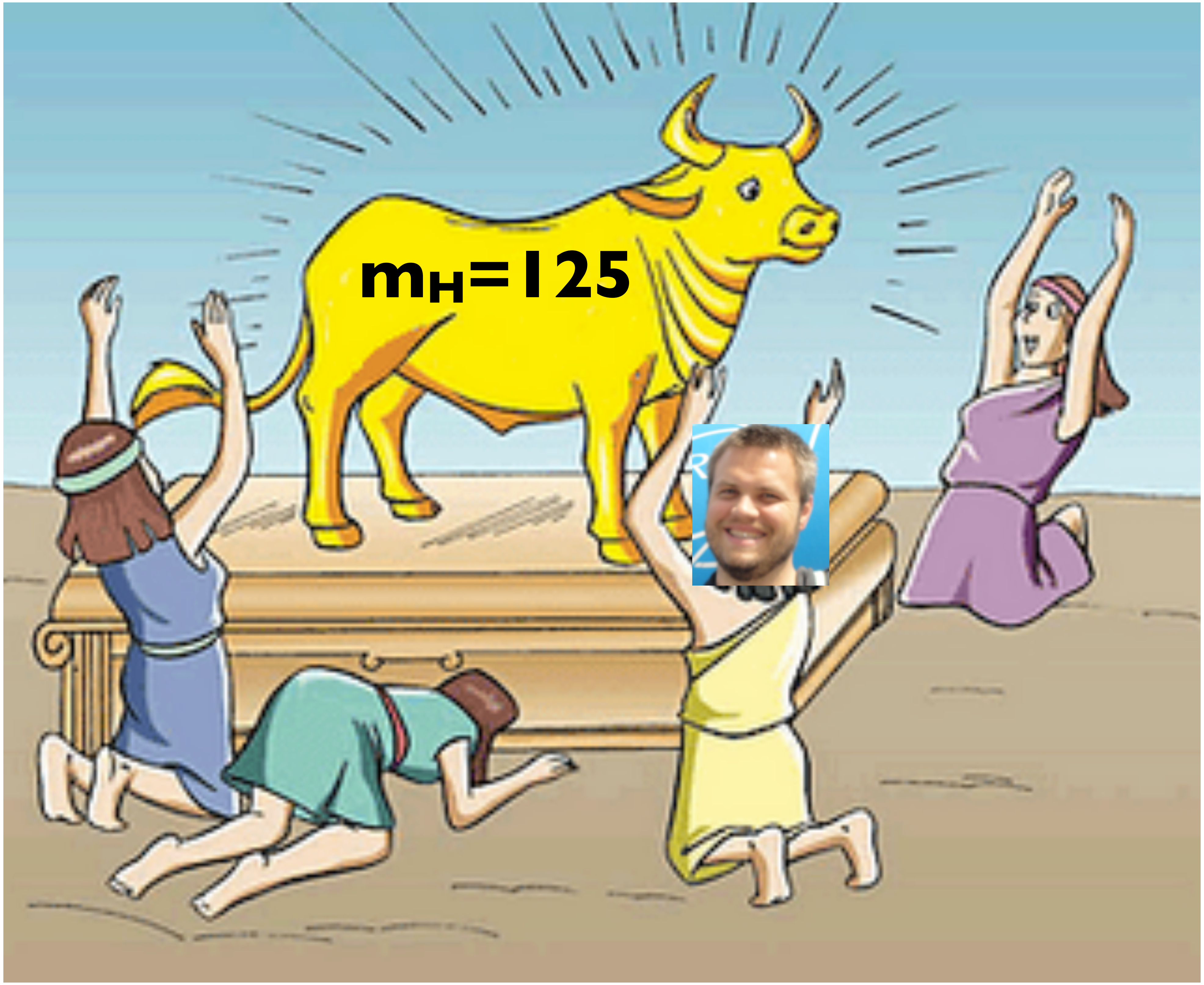

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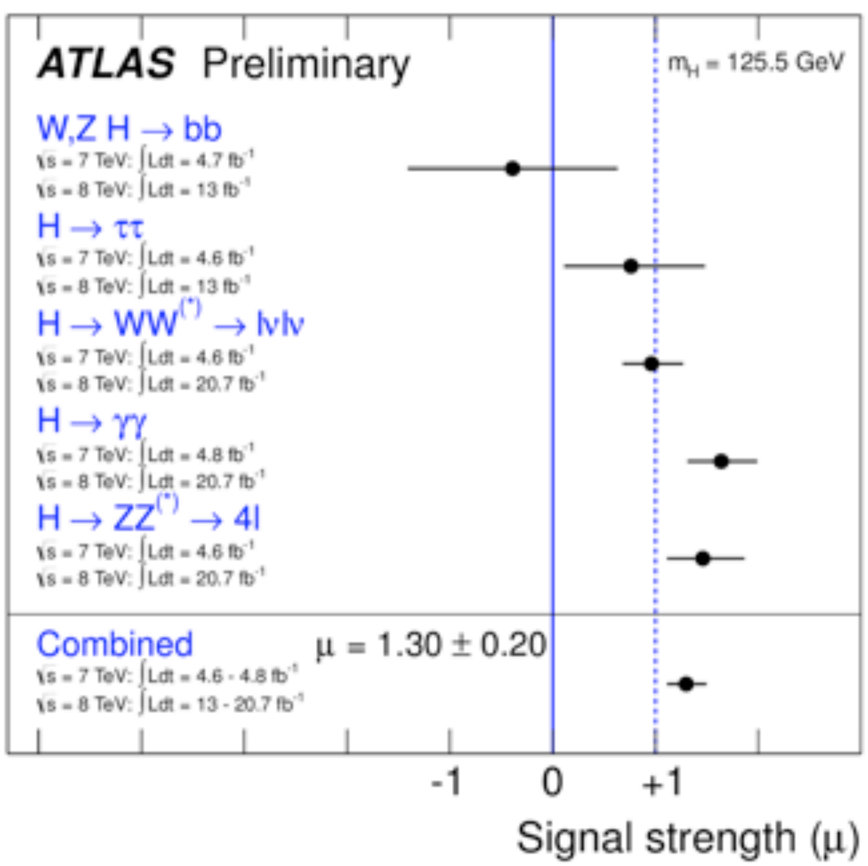

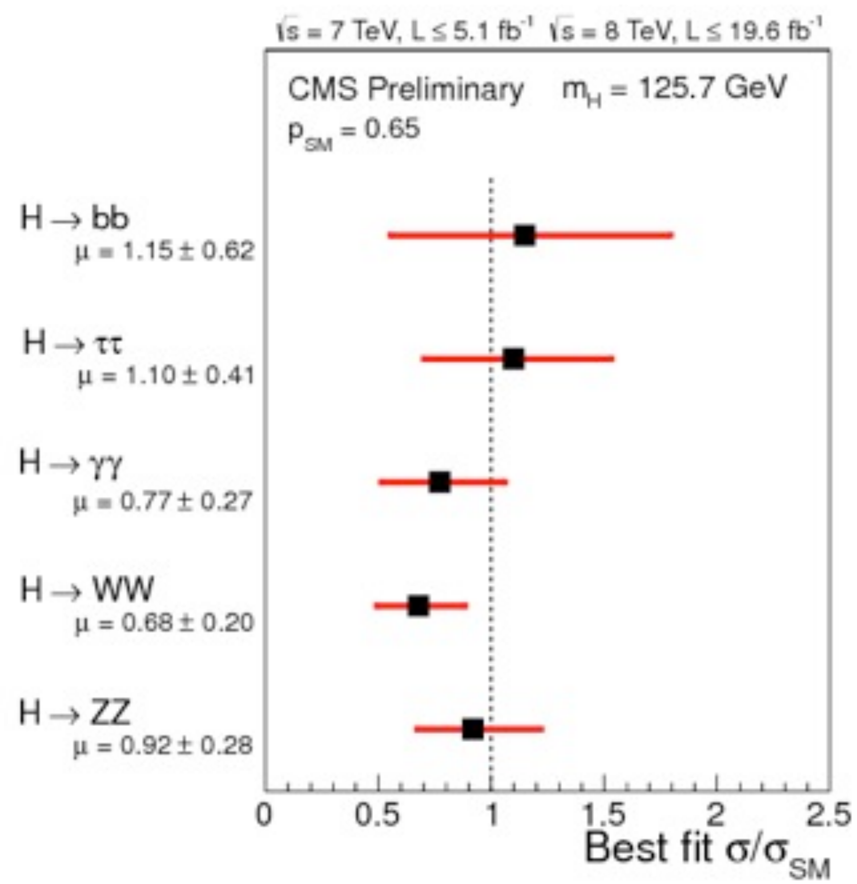

Composite Higgs

basic idea: Higgs doublet (2, 1/2) is a pNGB .. that is why it is lighter than other new physics

just as $m^2_\pi \ll m^2_\rho$

at some high scale: **f**

G → G' + NGBs   from some new <u>strong dynamics</u>

unbroken group G' contains SU(2)⊗ U(1)

NGB come in reps. of G', arrange such that

NGBs contain a doublet H of EWS: $$\frac{G}{G'} \supset H(2, \frac{1}{2})$$

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lattice!

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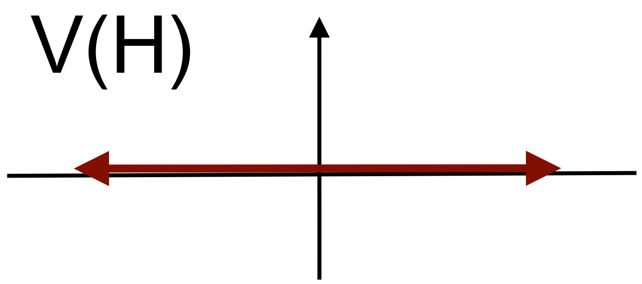
Composite Higgs

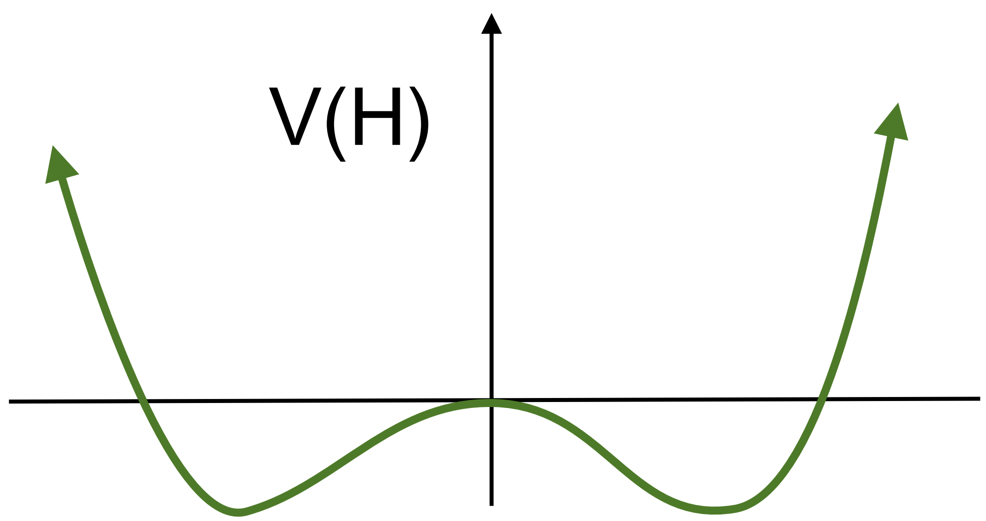
at tree-level:



EWS unbroken

loop-level:

induced by interactions that explicitly break G (gauge, Yukawa)



$v \neq 0$ → EWSB

new scale generated

- need v ≠ 0, but also v ≪ f

- $m_H^2 = \frac{d^2V(h)}{d^2h}\Big|_{h=v}$ Higgs mass also needs to be small

Composite Higgs

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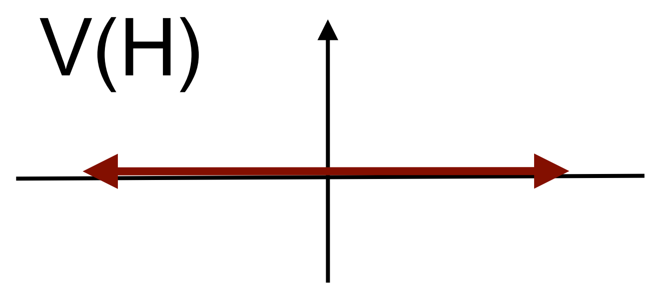

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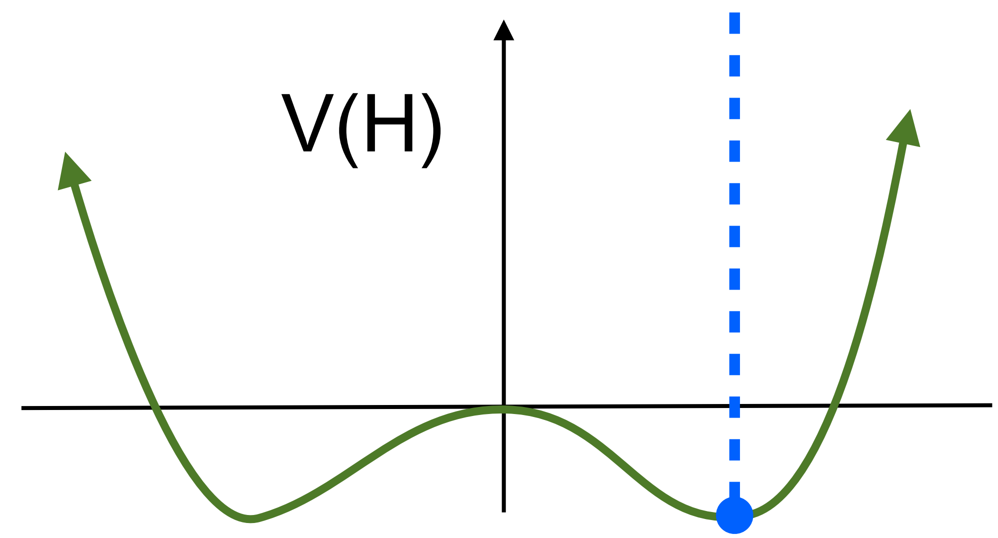

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Composite Higgs in action

$\frac{SO(5)}{SO(4)}$: 10 generators → 6 generators
= 4 broken generators = 4 NGB

just enough!

phenomenologically, G' ⊃ SU(2)⊗ SU(2) ≅ SO(4) works
better than just SU(2) ⊗ U(1)... (T parameter)

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

broken generator

symmetry-
breaking 'vev'

strong scale

NGB

start writing terms with Σ, $D_\mu\Sigma$ ...

Composite Higgs in action

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

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

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

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

Composite Higgs in action

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

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

expand, do lots of algebra...

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

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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

Composite Higgs in action

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

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

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Composite Higgs in action

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: $\xi = \dfrac{v^2}{f^2}$

reshuffling things... $$m_W^2 \left(1 + a\,\frac{2\,h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$

$\therefore$ 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 couplings deviate from SM values

Composite Higgs in action

$a \neq 1$: eventual bad behavior in $W_L W_L \to W_L W_L$ amplitudes

at $$\frac{4\sqrt{\pi}v}{\sqrt{1-a}} \sim 4\sqrt{\pi}v\,\frac{f^2}{v^2}$$

eventual strong dynamics...

∴ expect **resonances** at scale

~f in analogy with to QCD

ρ', a', ω', etc.

want strong coupling scale pushed to ~ few TeV (at least)

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

ex.) SO(6)/SO(5) has 5 NGBs,

$4 \in H$ + 1 extra scalar η

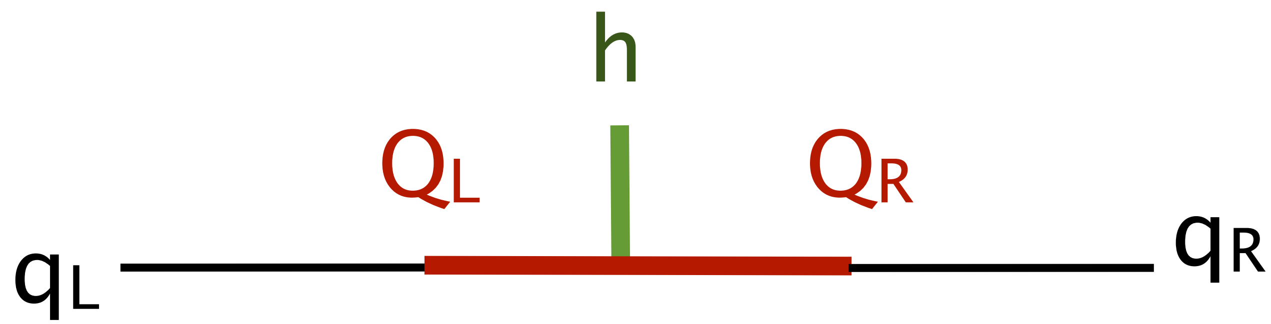
many other possibilities

Partial Compositeness

How do fermions get mass?

they mix with composite fermions ~ baryons of the new strong interaction

- 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.



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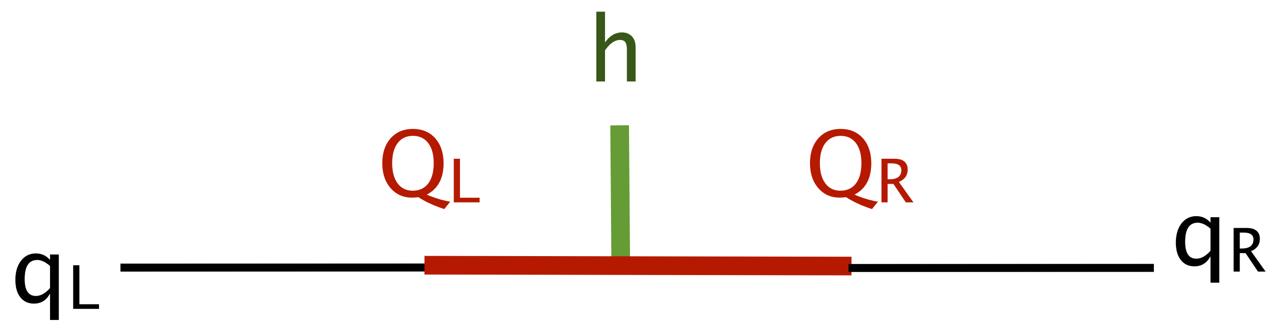

- the price we pay is new states, the composite fermions..

new states -> new LHC signals

Partial Compositeness

in practice:

composite fermions

mass terms for composites

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

SM fields

composite + higgs couplings

Undo the mixing:

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

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

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

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

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exact form depends on how composites transform under G

Partial Compositeness

in practice:

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

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Recap:

Composite Higgs models are characterized by two scales: f and v

- Higgs couplings deviate from SM values at $O(v^2/f^2)$

i.e. for SO(5)/SO(4) “MCHM”

$$\frac{g_{hVV}}{g_{hVV,SM}} = \sqrt{1-\frac{v^2}{f^2}}\,, \qquad \frac{g_{hhVV}}{g_{hhVV,SM}} = 1 - 2\frac{v^2}{f^2}\,, \qquad \frac{g_{t\bar{t}h}}{g_{t\bar{t}h,SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

set by G/G’ pattern

set by composite fermion rep.

- new dynamics at f, new states at O(f-4π f)

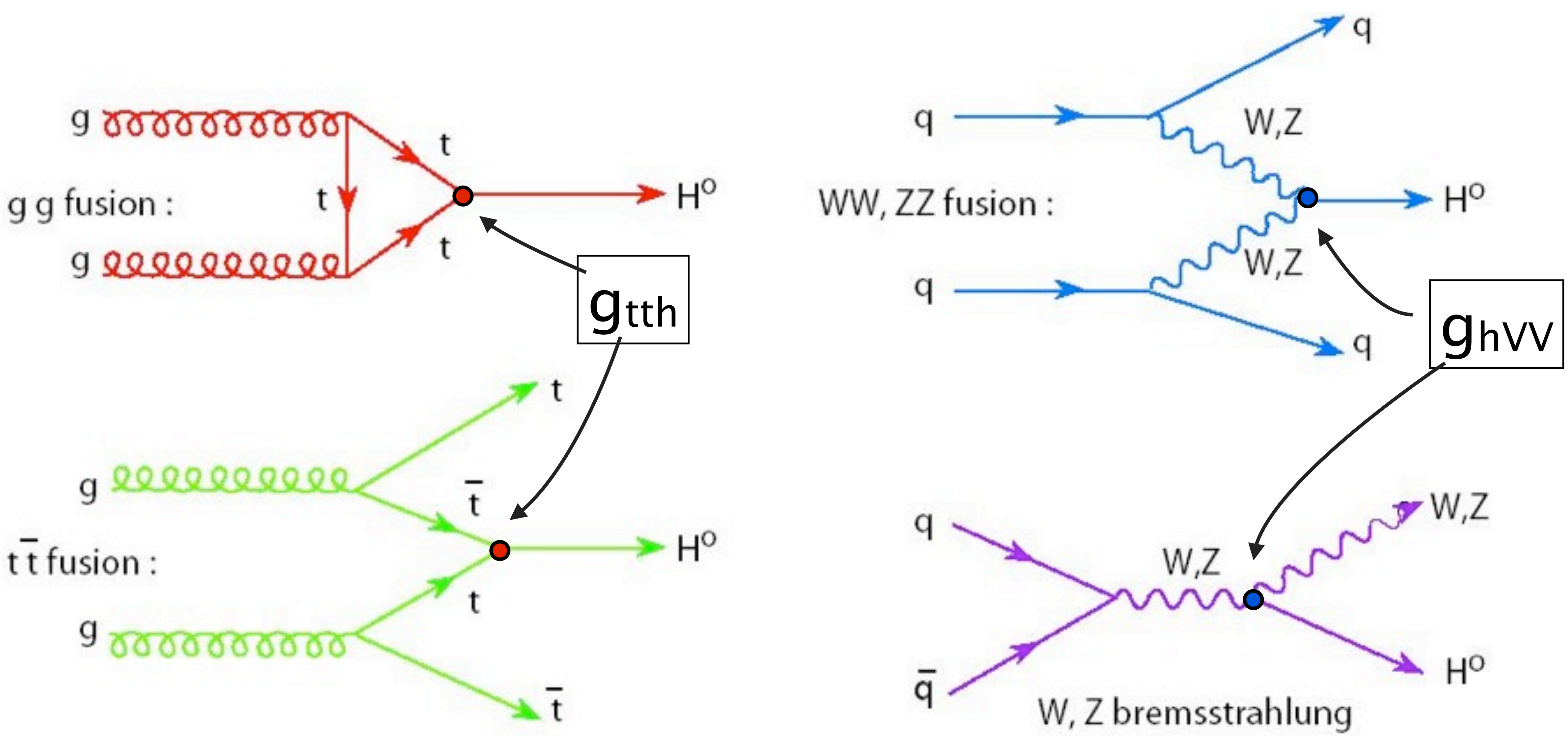
new spin-1 resonances: ρ’, a’, etc.

new spin-1/2 resonances: composite fermions

LHC signals: Higgs couplings

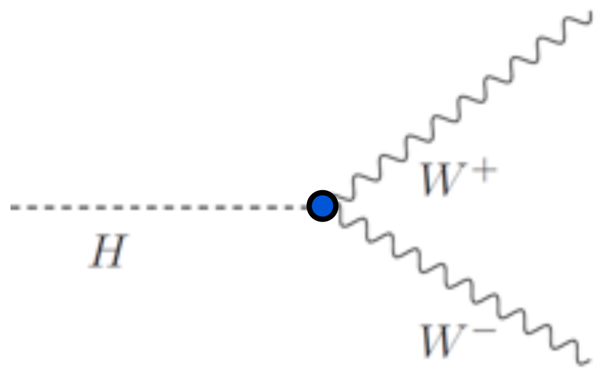
study all possible Higgs production and decay process to extract g_{hVV}, g_{tth}

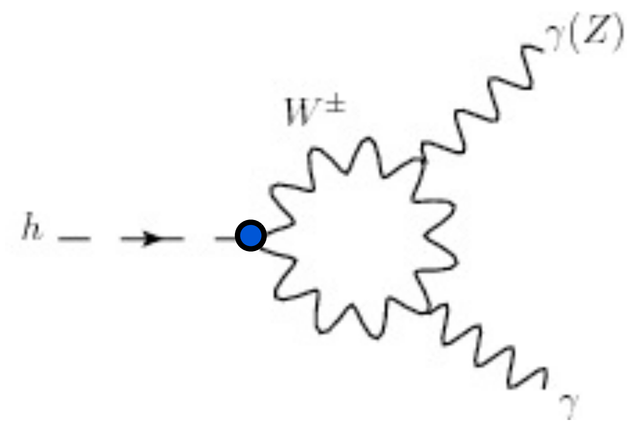
intricate process, as different production mechanisms scale differently with g_{hVV}, g_{tth} and contribute differently to each final state

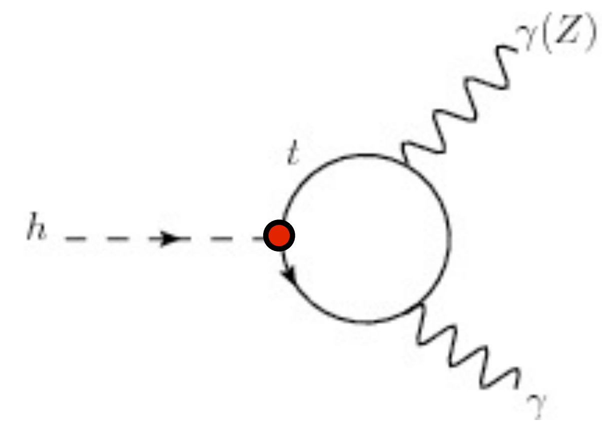


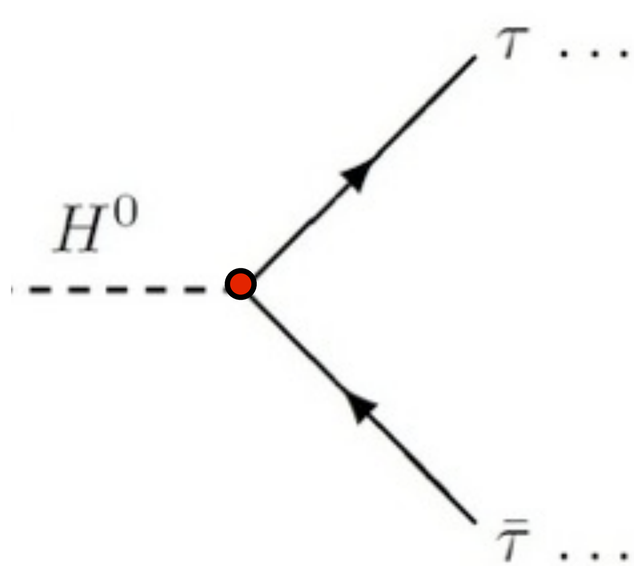
LHC signals: Higgs couplings

different composite Higgs models → different g_{hVV}, g_{htt}, possibly even extra Higgs decay modes from new particles









ex.) $gg \to h \to W_\mu^+ W_\mu^- \sim g_{hVV}\, g_{tth}/\Gamma_H$

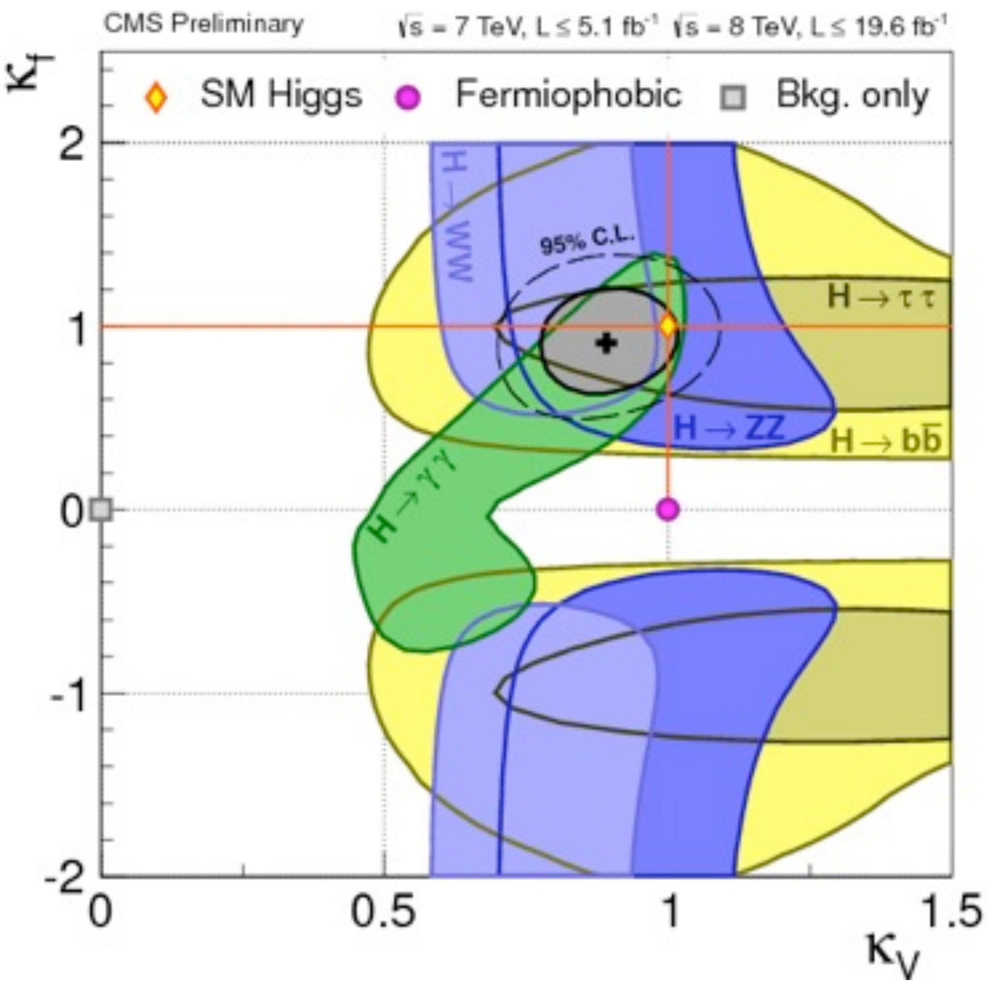
VBF $pp \to h \to \tau^+ \tau^- \sim g_{hVV}\, g_{\tau\tau h}/\Gamma_H$

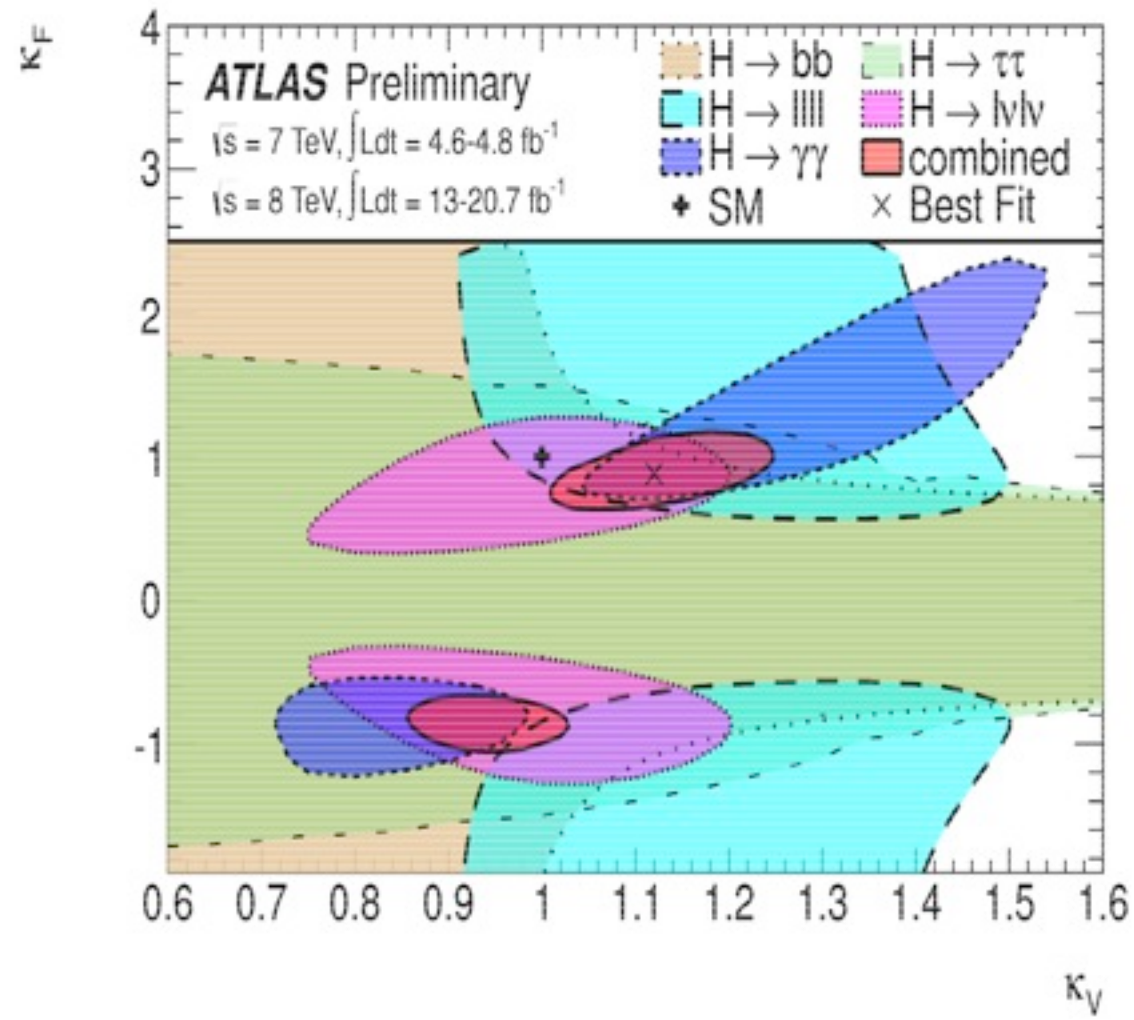
$gg \to h \to \tau^+\tau^- \sim g_{tth}\, g_{\tau\tau h}/\Gamma_H$

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

also, Γ_H knows about all g_{ffh}

LHC signals: Higgs couplings





both LHC expts. already cast results in space of

$$\kappa_V = \frac{g_{hVV}}{g_{hVV,SM}}, \quad \kappa_f = \frac{g_{t\bar{t}h}}{g_{t\bar{t}h,SM}}$$

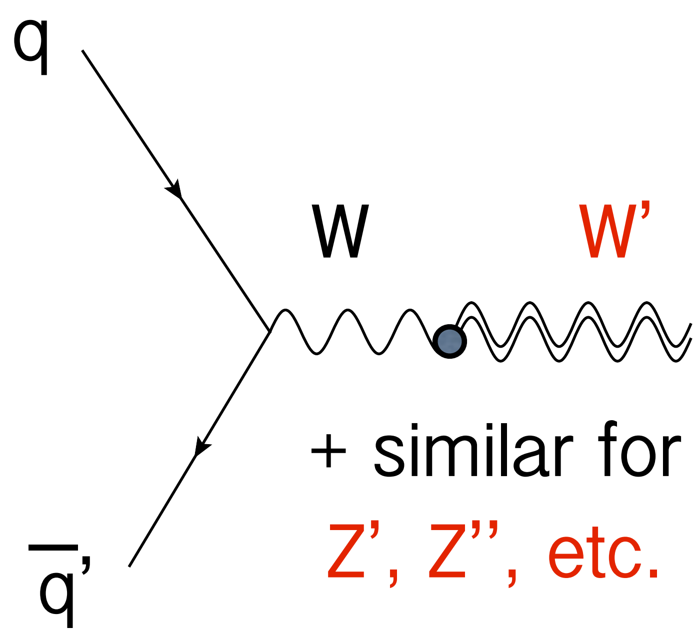
roughly, $|\kappa_V - 1| \lesssim 0.2$, $v \gtrsim 550$ GeV (though caveats remain)

improvements? $|\kappa_V - 1| \simeq 0.1$ possible...

hard to get much better due to uncertainties (PDF/σ_h/vetoes)!

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'

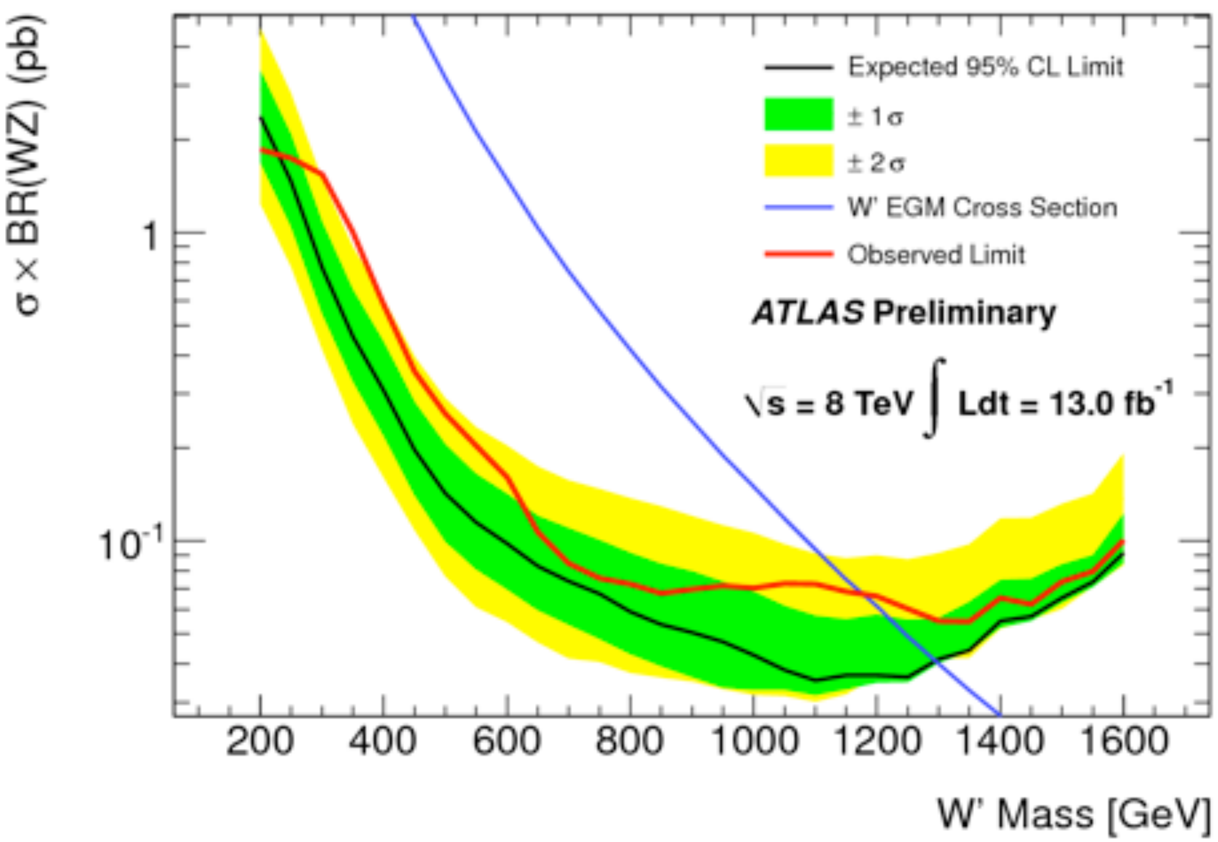
BUT: W',Z' couple strongest to other strong-sector states, like the longitudinal W, Z & h (even t). Big couplings mean $\Gamma_{W'}$, etc. can be big.

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.

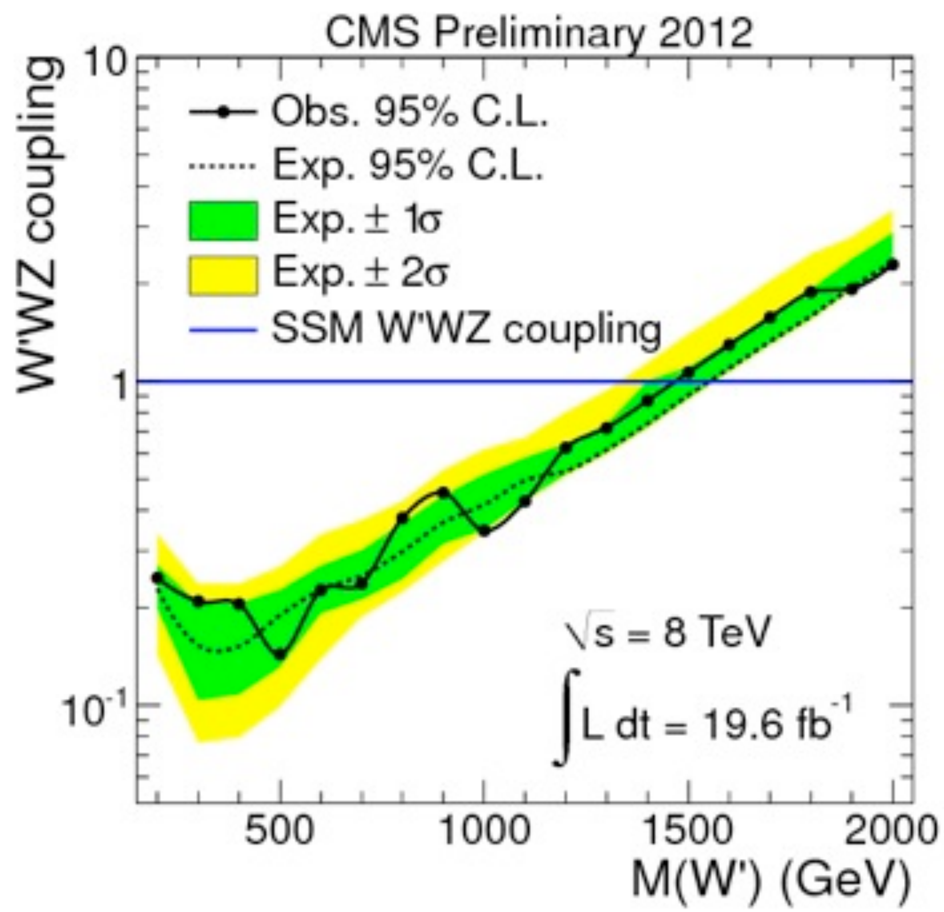
LHC signals: spin-1 resonances

cleanest signal for W/Z decay products is the fully leptonic mode:

$W' \to WZ \to 3\ell + \nu$



ATLAS 13.0 fb^{-1}



CMS 19.6 fb^{-1}

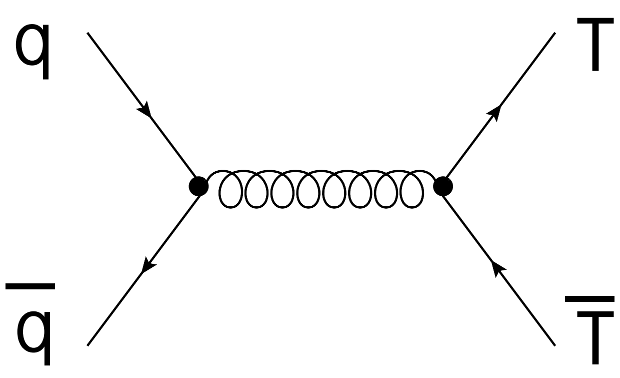
existing studies assume small W'WZ coupling!

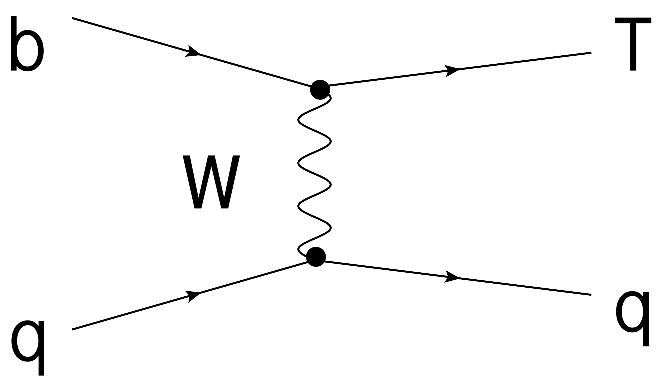
leptonic modes have small BR .. combined with small production cross section, rate will be a problem as $m_{W'}$ increases

LHC signals: fermionic resonances

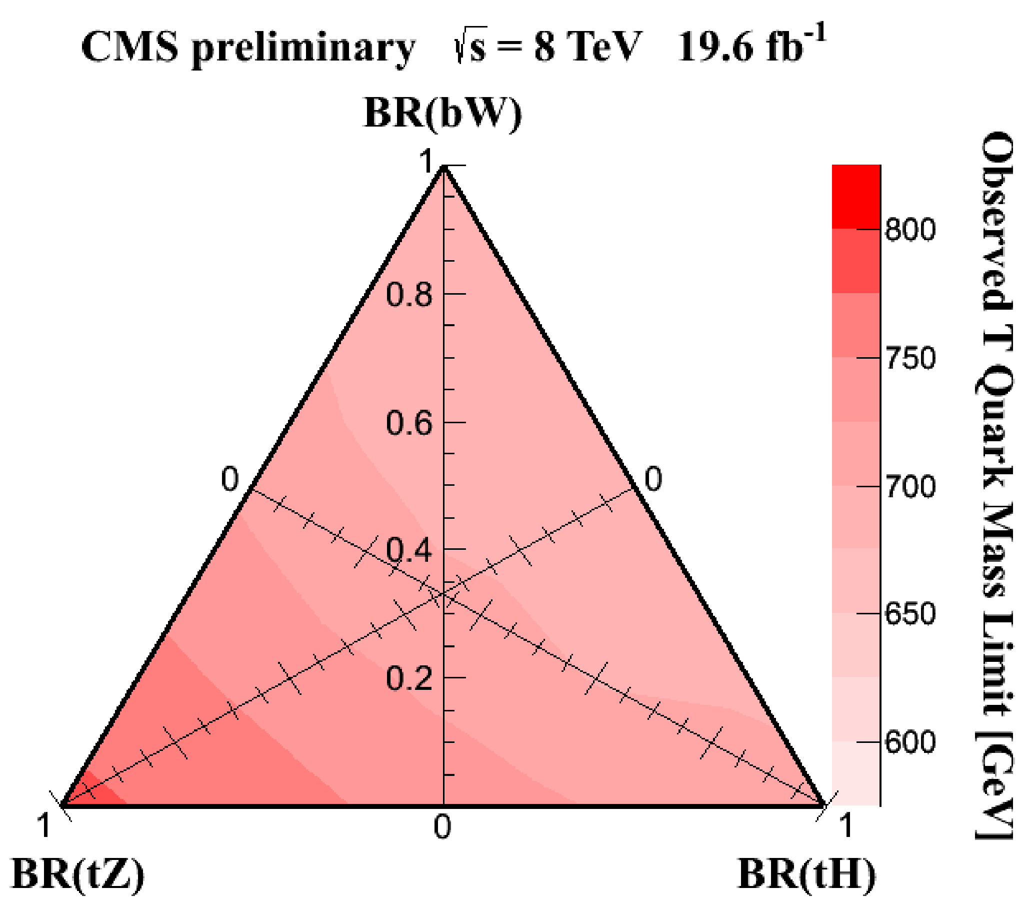
top/bottom-partners usually lightest new fermions

can be pair- or singly-produced





often decay to W/Z/H + t/b...
exact modes, BR depend on the model

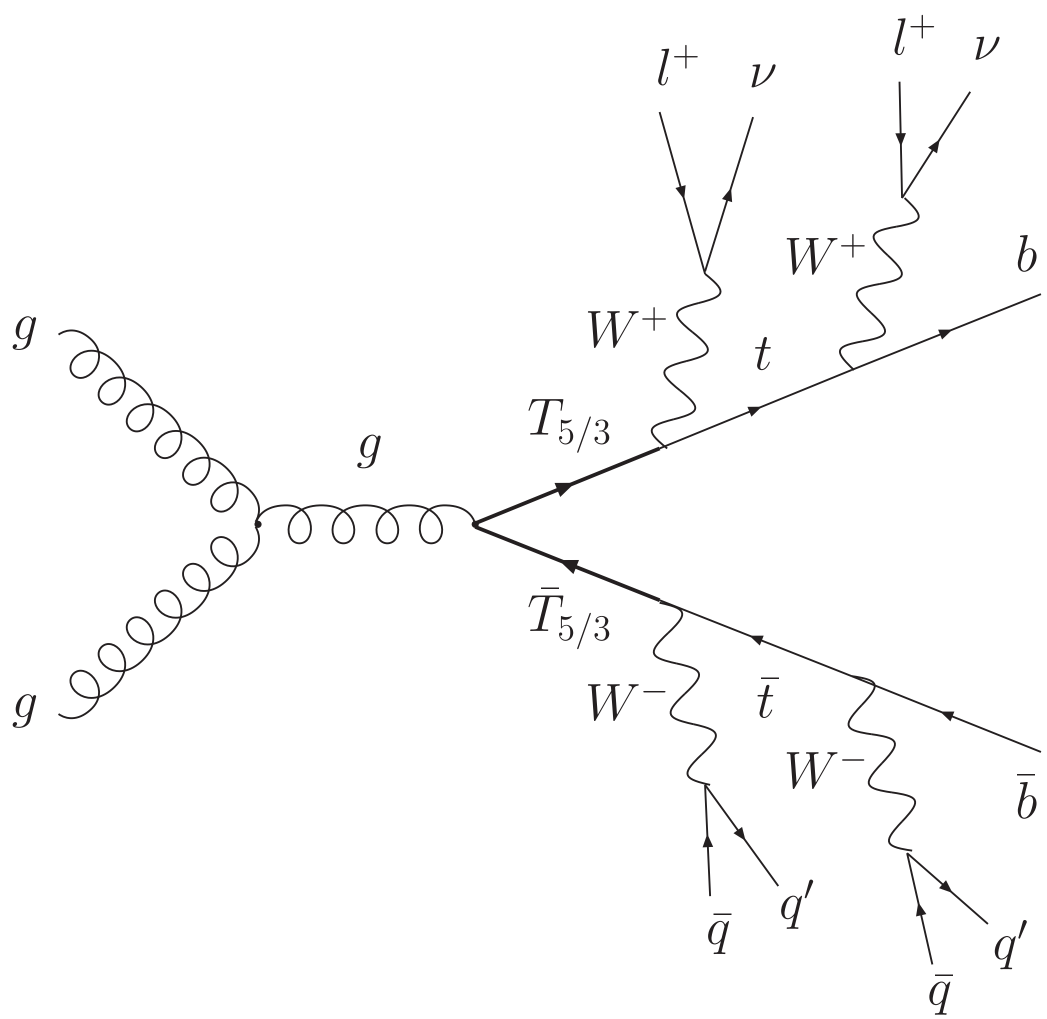


[CMS B2G-12-015,
ATLAS-CONF-2013-056, -058, -018]

LHC signals: fermionic resonances

stronger bounds from exotically charged new fermions

t_L partner ~ part of larger SU(2) rep. containing $X_{5/3}$ (helps w/ $Zb\bar{b}$)



pair-production of $X_{5/3}$ generates SSL signal

very little SM background → strong limit

$m_X \gtrsim 770$ GeV

[CMS PAS B2G-12-012, ATLAS-CONF-2013-051]

limit pulls up mass of whole multiplet

about that Higgs potential...

new f-scale dynamics impact Higgs through potential (v, m^2_H)

rewrite L_{CH} differently...

$$\mathcal{L} = \frac{1}{2}(P_T)^{\mu\nu}\Big[\left(\Pi_0^X(q^2) + \Pi_0(q^2) + \frac{\sin^2(h/f)}{4}\Pi_1(q^2)\right) B_\mu B_\nu + \left(\Pi_0(q^2) + \frac{\sin^2(h/f)}{4}\Pi_1(q^2)\right) A_\mu^{a_L} A_\nu^{a_L} + 2\sin^2(h/f)\,\Pi_1(q^2)\,\hat{H}^\dagger T^{a_L} Y \hat{H}\, A_\mu^{a_L} B_\nu\Big],$$

form factors Π_0, Π_1 encapsulate strong dynamics

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$$\mathcal{L} = \frac{1}{2}(P_T)^{\mu\nu}\Big[\Big(\Pi_0^X(q^2) + \Pi_0(q^2) + \frac{\sin^2(h/f)}{4}\Pi_1(q^2)\Big)B_\mu B_\nu + \Big(\Pi_0(q^2) + \frac{\sin^2(h/f)}{4}\Pi_1(q^2)\Big)A_\mu^{a_L}A_\nu^{a_L} + 2\sin^2(h/f)\,\Pi_1(q^2)\,\hat{H}^\dagger T^{a_L} Y \hat{H}\, A_\mu^{a_L} B_\nu\Big],$$

form factors Π_0, Π_1 encapsulate strong dynamics

$$\langle J_\mu^a(q) J_\nu^a(-q)\rangle = \Pi_0(q^2)(P_T)_{\mu\nu}$$

2-pt function of unbroken (SO(4)) currents

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difference of unbroken-broken currents

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know some properties of Π_0, Π_1 at $q^2 = 0, \infty$

i.e. $\Pi_0(0) = 0$, $\Pi_1(0) = f^2$

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$S \propto \Pi'_1(0)$

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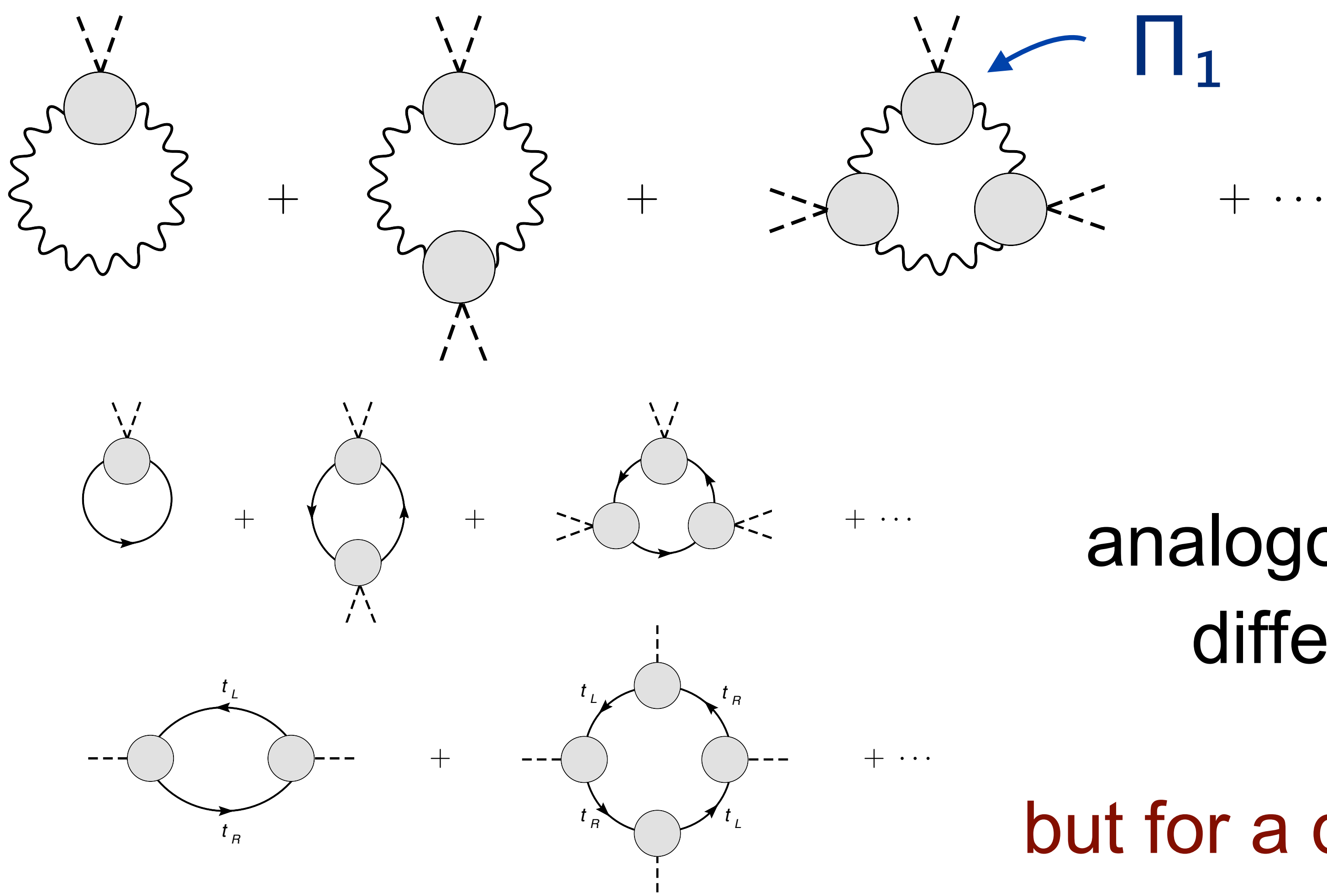
similarly, in
fermion sector

$$\mathcal{L} = \bar{q}_L \not{p} \left(\Pi_0^q(p) + \Pi_1^q(p) \cos(h/f) \right) q_L$$
$$+ \bar{t}_R \not{p} \left(\Pi_0^u(p) - \Pi_1^u(p) \cos(h/f) \right) t_R$$
$$+ \sin(h/f)\, M_1^u(p)\, \bar{q}_L \hat{H}^c t_R + h.c.$$

form V(H) by resumming...



analogous to π± - π0 mass
difference in QCD...

but for a different χSB pattern,
different underlying strong dynamics

about that Higgs potential...

without really knowing Π_i, etc. model-builders resort to

vector-meson-dominance

large-N_c

"AdS/CFT"-inspired extra-dimensions

NDA

important since Π_i modeling ties new resonances to V(h) and thereby to EWSB and m^2_h

modeling

$$m_h^2 = 2N_c \frac{y_t^2}{8\pi^2} m_*^2 \xi \quad , \quad \xi = \frac{v^2}{f^2}, \; m^* = \kappa\, m_T$$

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but are these assumptions any good? generic?

help from the lattice!

about that Higgs potential...

big questions for composite Higgs after 20 fb^{-1} LHC data:

- can we get v, $m_h \ll m_{W'}$, m_T in CH setup?
- what are the properties of those theories?

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know from $SU(N)^2/SU(N)$ lattice studies that different N_F, representation, etc. lead to behavior different from vanilla QCD.

what happens with different χSB pattern?

conclusions

composite Higgs = Higgs as a pNGB, formed from new strong dynamics at f

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

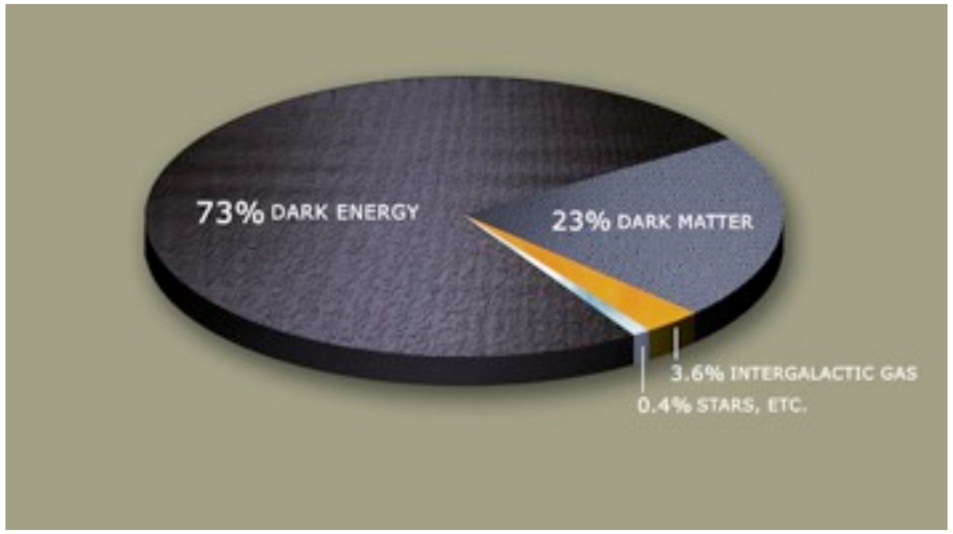
$O(v^2/f^2)$ Higgs coupling deviations, new heavy resonances (spin-1, fermions) in spectra, all targets for LHC searches

resonance ↔ Higgs interplay requires understanding/ modeling strong dynamics.

lattice insight needed

other directions

<u>new composite sector & Dark Matter:</u>



- lightest `techni'baryon can be stable by analog of $U(1)_B$

- an initial matter/anti-matter asymmetry gets shared among baryons, leptons, `techni'baryons via sphalerons

(Chivukula, Barr, Fahri, Nussinov)

- can get observed $\Omega_{DM}/\ \Omega_B$ easily for ~ TeV scale DM

must be electrically neutral, EW singlets to avoid direct detection

Then leading operators are charge radius and polarizability:

ex.) $$\frac{B^* B\, v_\mu\, \partial_\nu F^{\mu\nu}}{\Lambda_{TC}^2}\,,\ \frac{B^* B\, F_{\mu\nu} F^{\mu\nu}}{\Lambda_{TC}^3}$$

lattice input?