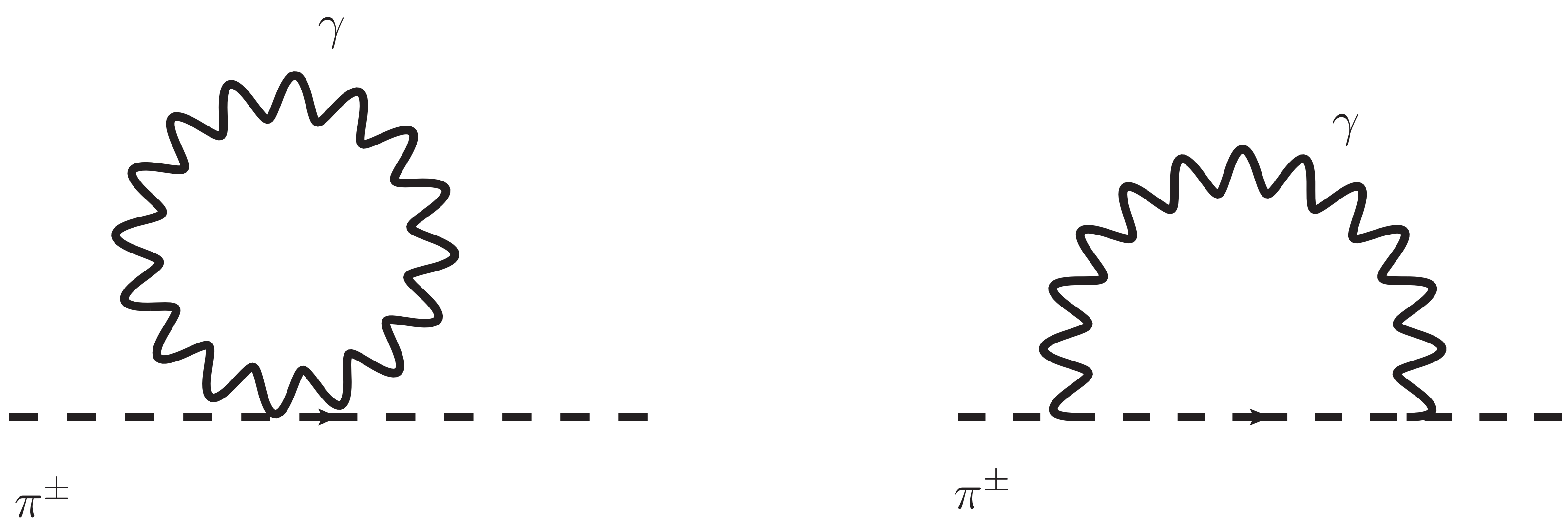
Compositeness

Recall:



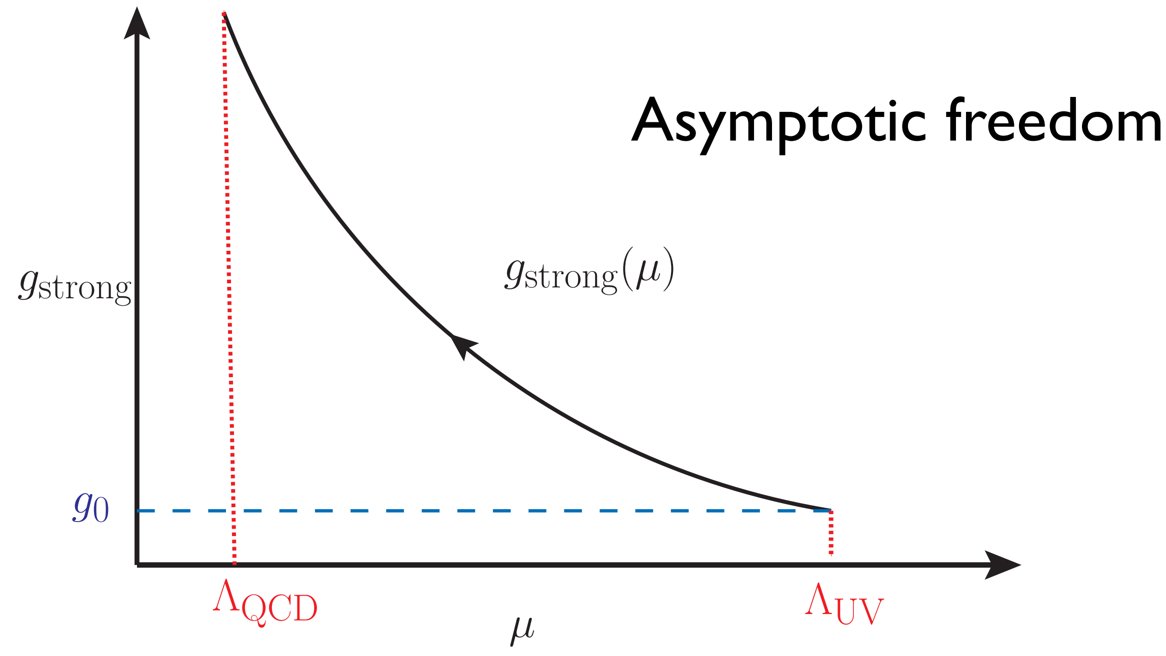
$$\delta m^2_{\pi^\pm} \simeq \frac{e^2}{16\pi^2}\Lambda^2$$

- Example: low energy QCD resonances: pion ....
- $m_\pi \sim$ 100 MeV.
- Naturalness requires $\Lambda \approx$ GeV.
  - Indeed, at GeV, QCD ⇒ theory of quark and gluon
  - Pion is not elementary.

Theory of strong interactions.

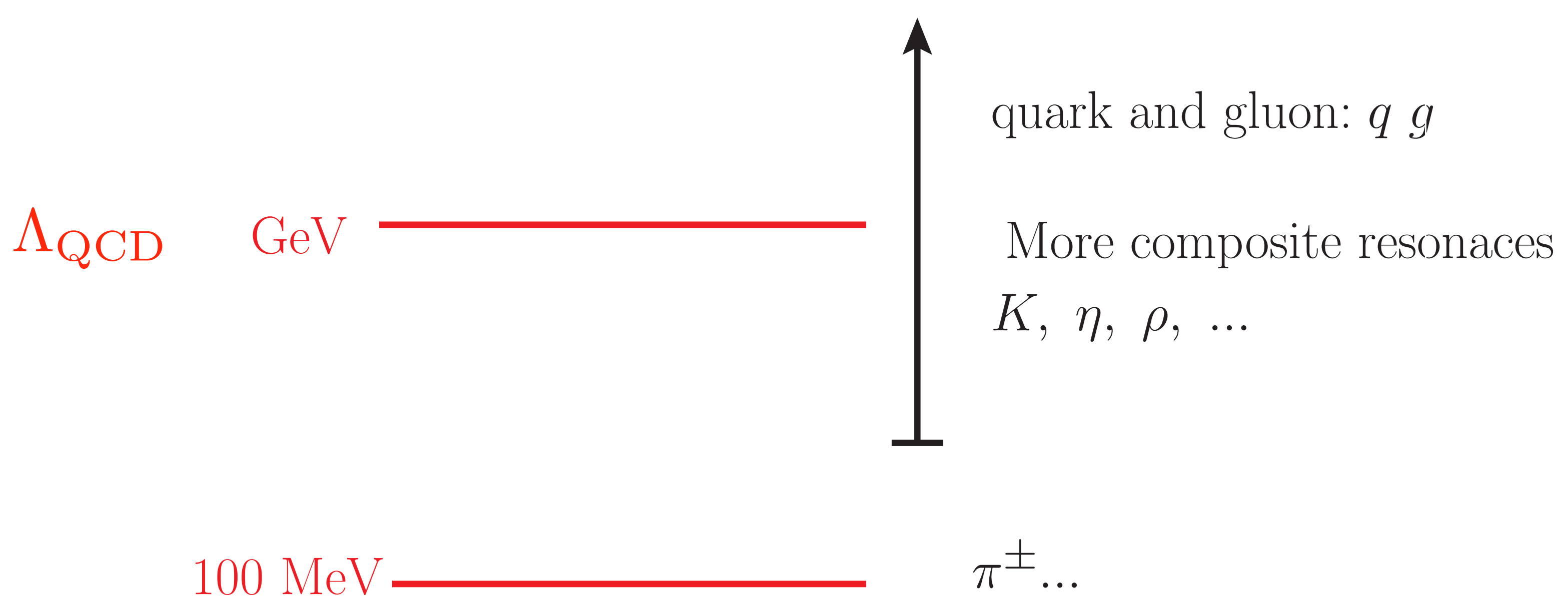
$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \ \Lambda_{\rm QCD} \leq \ \text{GeV}$$

$$b = 7$$



- Exponentially separated scales from the choice of an order one number g_0 .

- A strong coupling results in bound (composite) states.



QCD as a theory of EWSB

QCD phase transition

$$\langle \bar{q}_L q_R \rangle \simeq \Lambda^3_{\rm QCD} \sim \ ({\rm GeV})^3$$

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Can not be all the EWSB

How about another QCD?

- Another strong interaction, and a new set of quarks, q′.

- The new strong interaction becomes strong around TeV scale.
  - Just like QCD, it would have a phase transition breaking electroweak symmetry.

$$\langle \bar{q}'_L q'_R \rangle \sim \Lambda_{\rm TC}^3, \quad \Lambda_{\rm TC} \sim \ {\rm TeV}.$$

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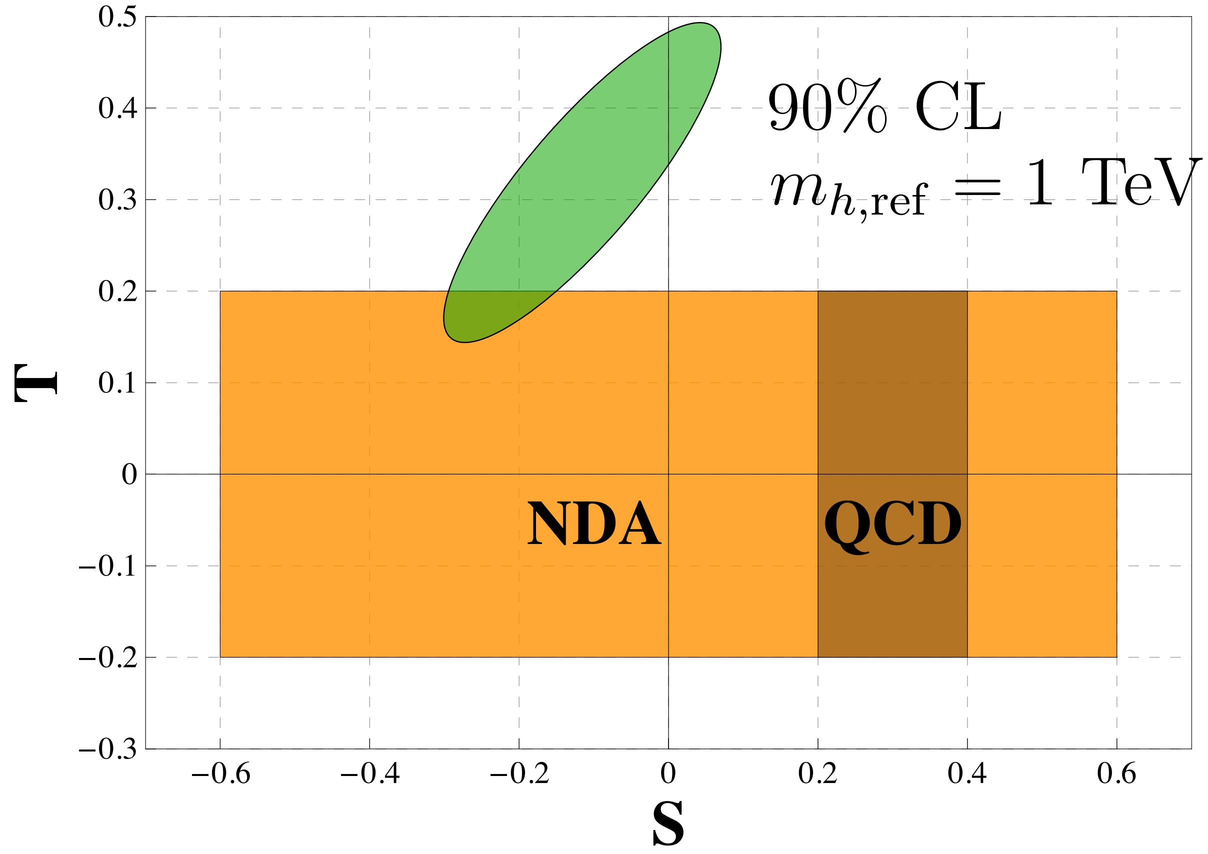
Technicolor, and its recent incarnations: Higgsless models
Very natural, reasonable idea.

However,



Luty

- Not really dead. Strong interaction, can't compute. Scaling up with QCD naive.

- Use AdS/CFT, due to a warped space, compute...
  - Complicated modes, might work

The Higgs problem

The Higgs problem

- Notice that although QCD break electroweak symmetry, there is no Higgs particle.
  - Not a surprise. After all, Higgs mechanism tells us that to give W/Z masses, we only need give them 3 Goldstone bosons $\Rightarrow W_L, Z_L$. There is no need for a Higgs boson.

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- Technicolor, by definition, has no Higgs boson.
- What about that 125 GeV resonance which walks and quacks like a Higgs?

Technicolor "dead"?

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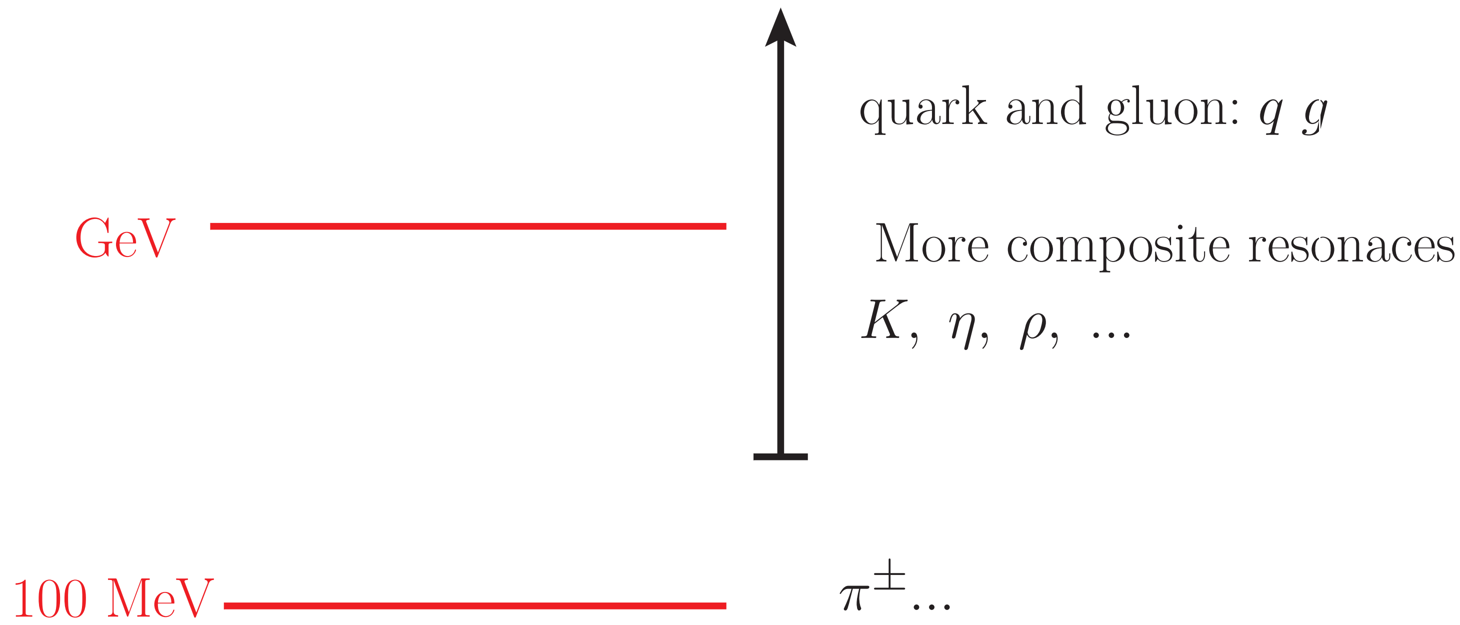
- Something else must be the 125 GeV resonance
  - dilaton, radion, spin-2.... must have couplings not very different from Higgs.

Technicolor "dead"?

- To resurrect:
- Something else must be the 125 GeV resonance
  - dilaton, radion, spin-2.... must have couplings not very different from Higgs.
- Something (a technicolor like theory) must break electroweak symmetry.
  - Its contribution to the S and T parameter must fool us to think it could come from a light Higgs boson.

Perhaps we can take another angle



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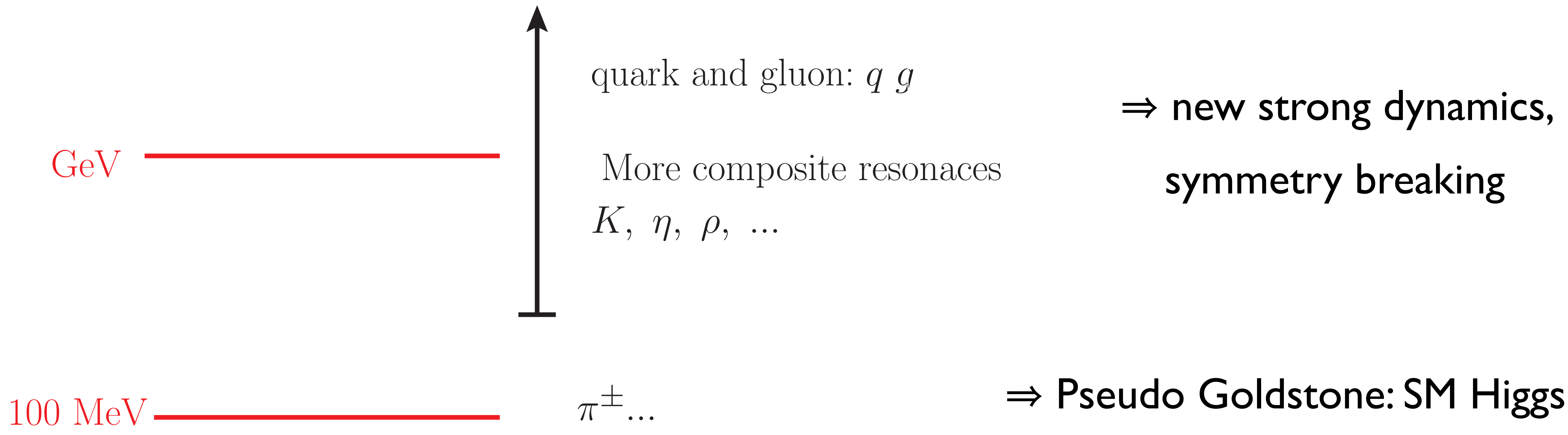
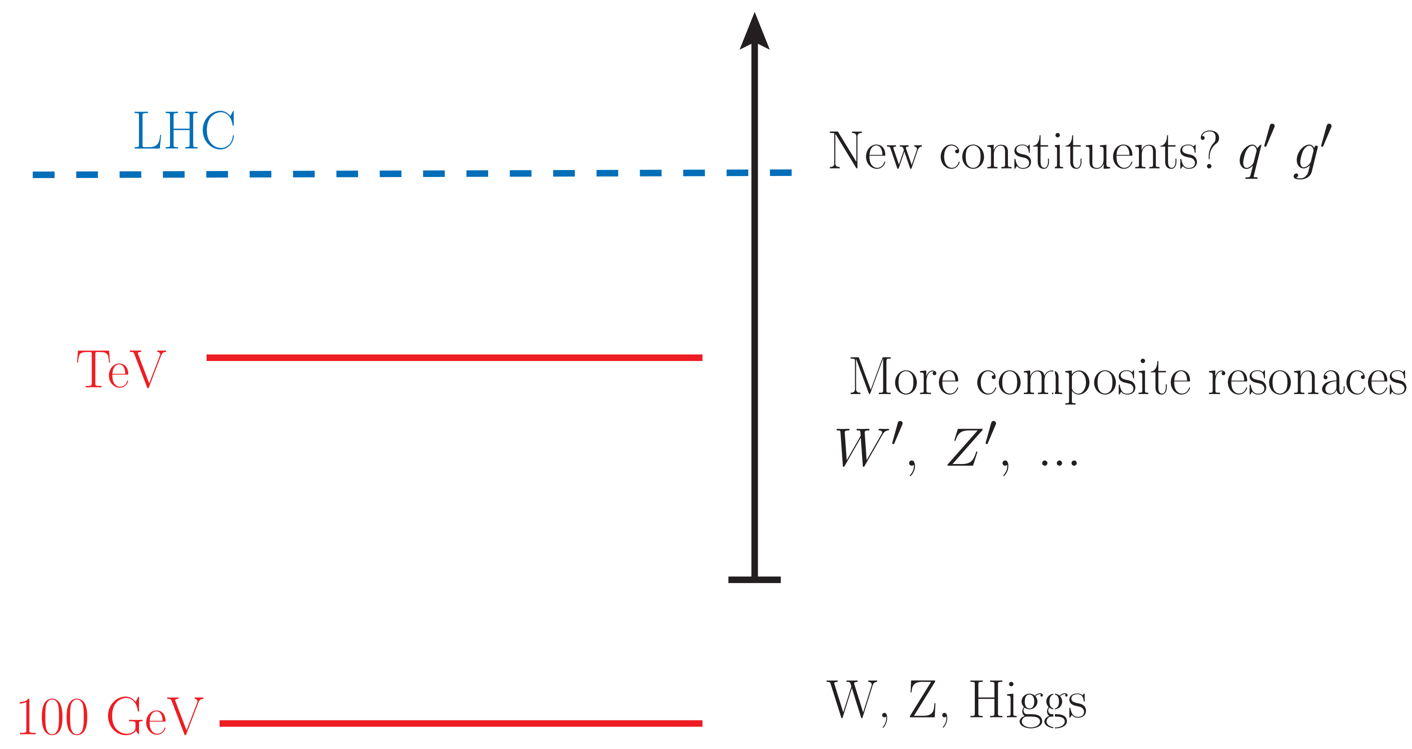


- Construct a new strong dynamics in which the low lying Goldstones will be the SM Higgs.
- Composite Higgs models. Still a natural theory.
  - Avoids the obvious problems of TC.

Composite Higgs



- Many many scenarios, models in this class.
- Little, fat, twin, holographic .... Higgs

– Similar scenarios: Randall-Sundrum, UED...

- Theories with Higgs + resonances.

Pseudo-Goldstone Boson (PGB)

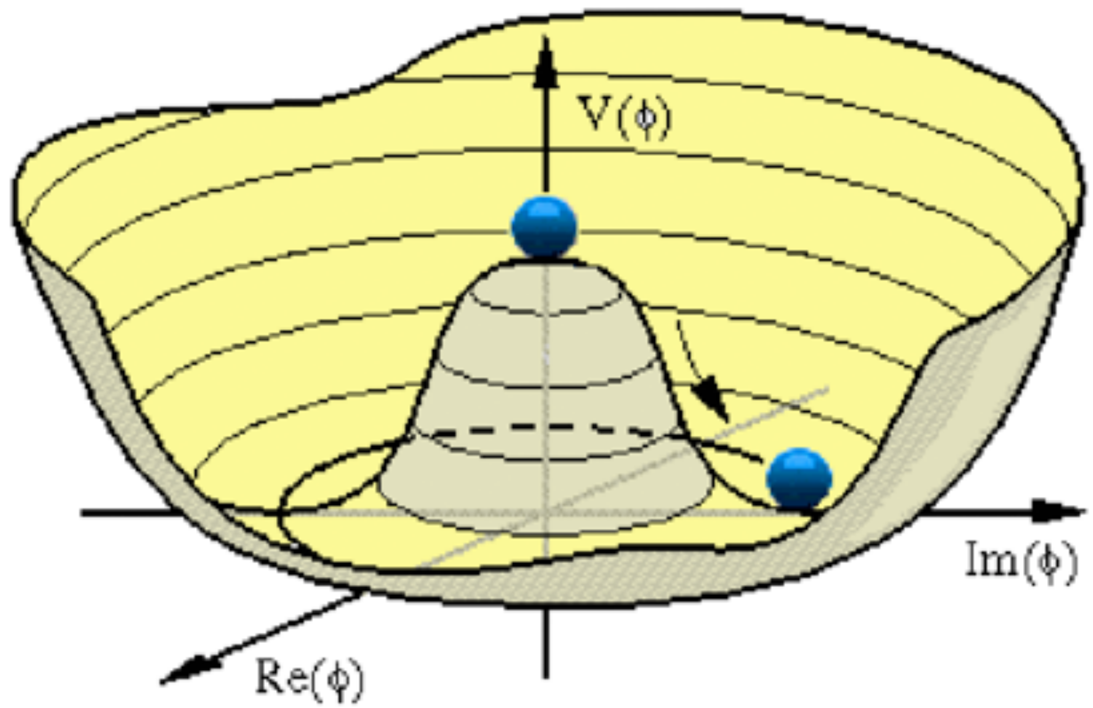
- Spontaneous Global symmetry breaking ⇒ massless goldstones.
- QCD with u and d quark (only light quarks)
  - Symmetry breaking $SU(2)_L \times SU(2)_R \Rightarrow SU(2)_V$
  - 3 Goldstones: $\pi^{\pm}$, π^0, massless.
  - Then small explicit breaking from quark masses $m_u \neq m_d$.
    - Small pion masses. (PGB)
- We would like to copy QCD this way.

Parameterizing Goldstone boson

- Example: spontaneously broken U(1)

$$\text{VEV: } \langle\phi\rangle = f$$

$$\phi = f \exp\left(i\frac{\pi}{f}\right)$$



Under U(1) rotation

$$\phi \to e^{i\alpha}\phi$$

$$\pi \to \pi + f\alpha$$

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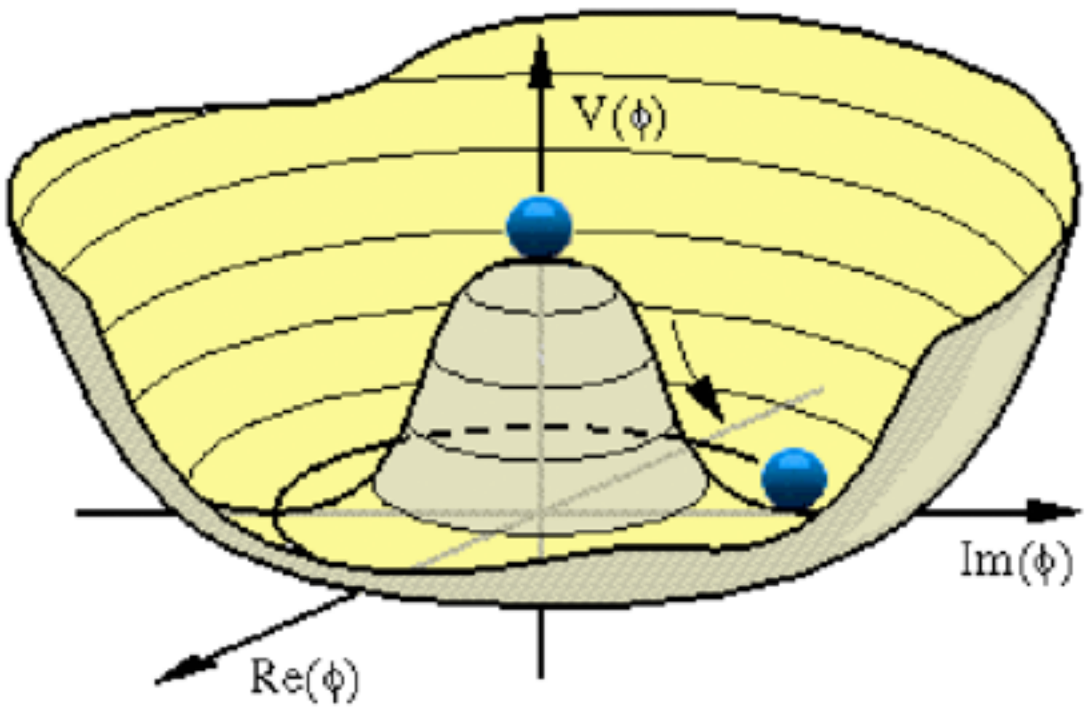


Under U(1) rotation

$$\phi \to e^{i\alpha} \phi$$

$$\pi \to \pi + f\alpha$$

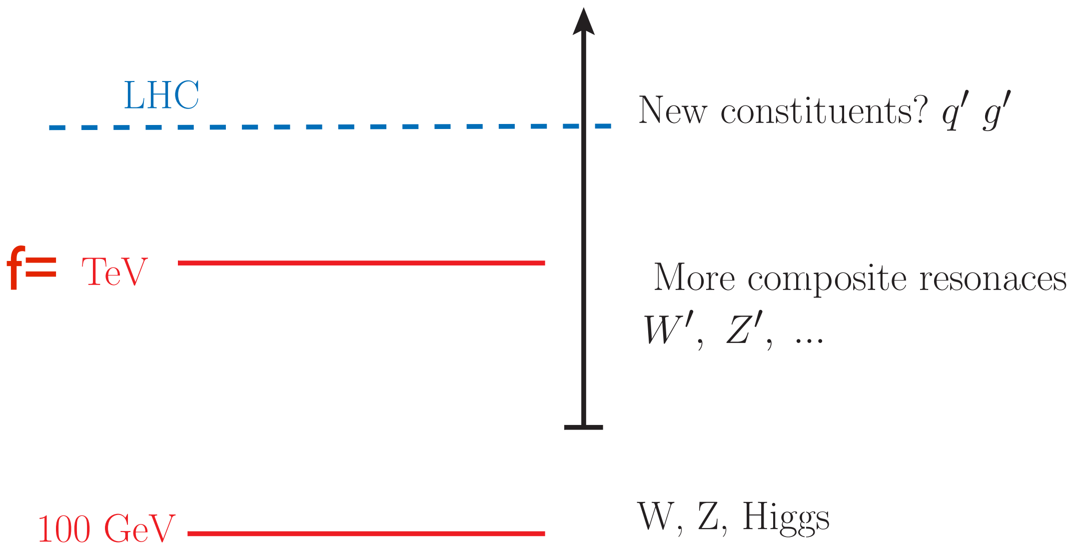
Theory still has shift symmetry ⇒ massless Goldston

since mass term $m^2 \pi^2$ breaks shift symmetry

PGB Higgs

- Using Goldstone as Higgs.

$$\phi = f \exp\left(i\frac{h}{f}\right)$$



- To generate a Higgs potential (mass, VEV), some (small) explicit breaking.

$$\epsilon_1 V_1\left(\frac{h}{f}\right)$$

- From this, $\langle h \rangle \approx f$. Simplest model would not work!

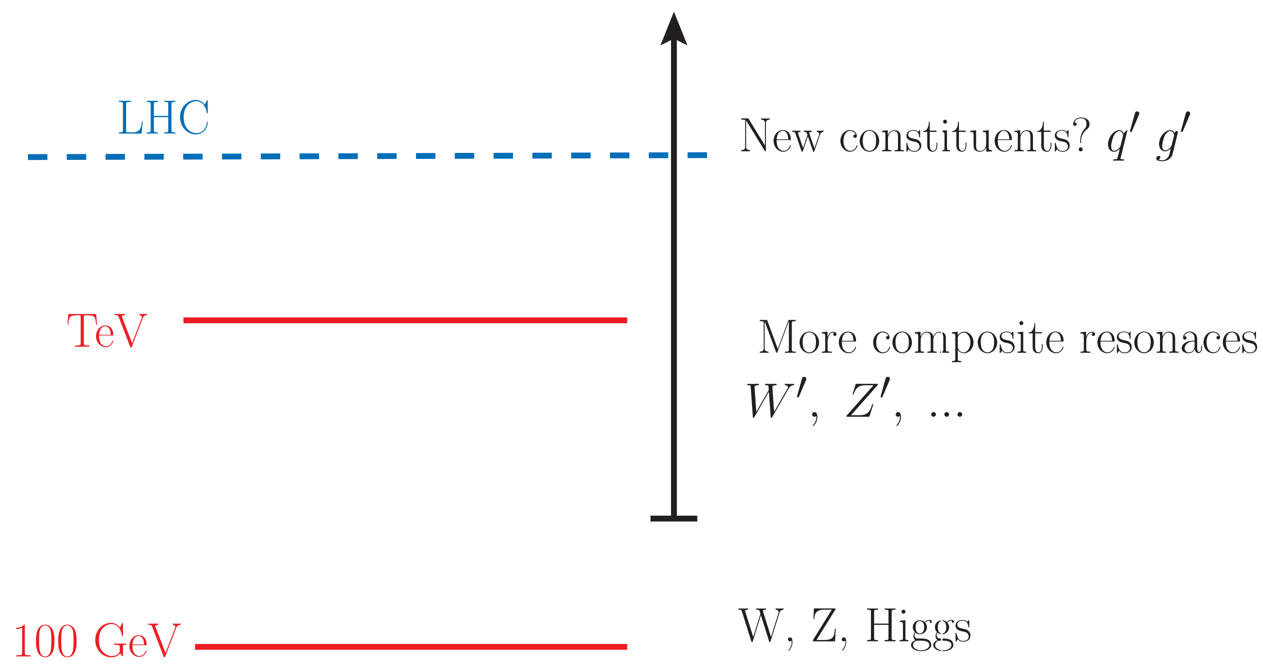
More complicated

- Say there are more than one source explicit symmetry breaking

$$\epsilon_1 V_1\left(\frac{h}{f}\right)+\epsilon_2 V_2\left(\frac{h}{f}\right)+\cdots$$

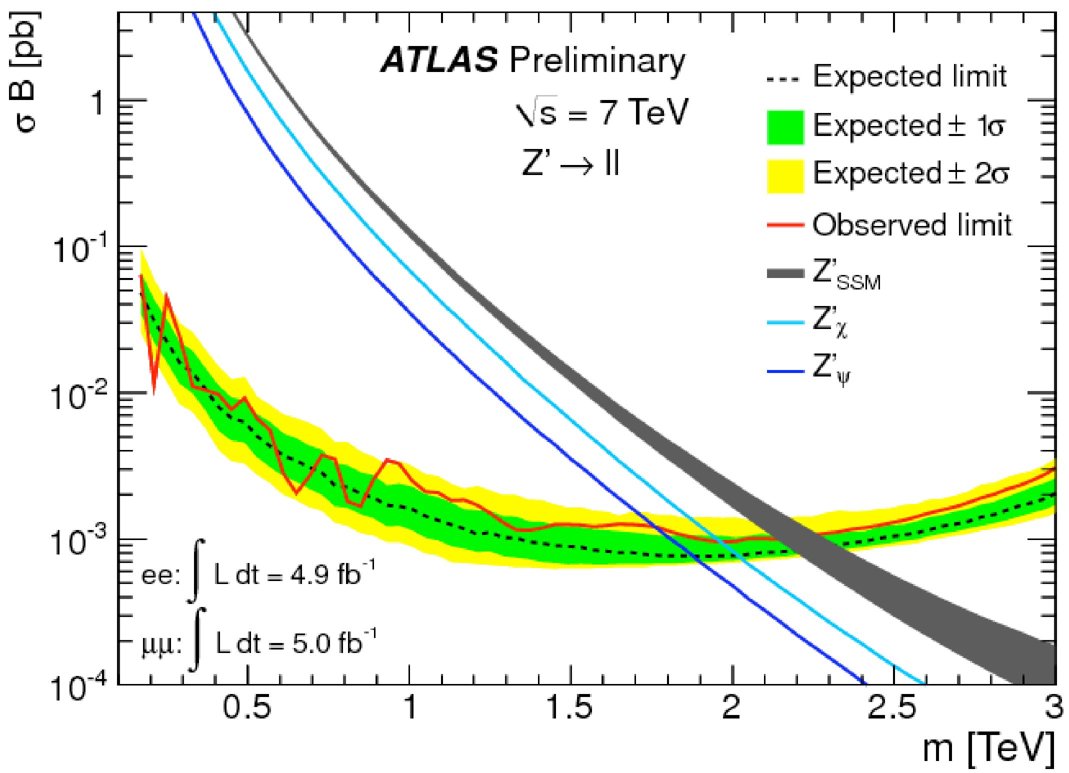
  - We can fine-tune to have $\langle h \rangle = v$.
  - Getting m_h = 125 GeV takes a little bit more work.
  - The potential not always calculable, due to strong dynamics.

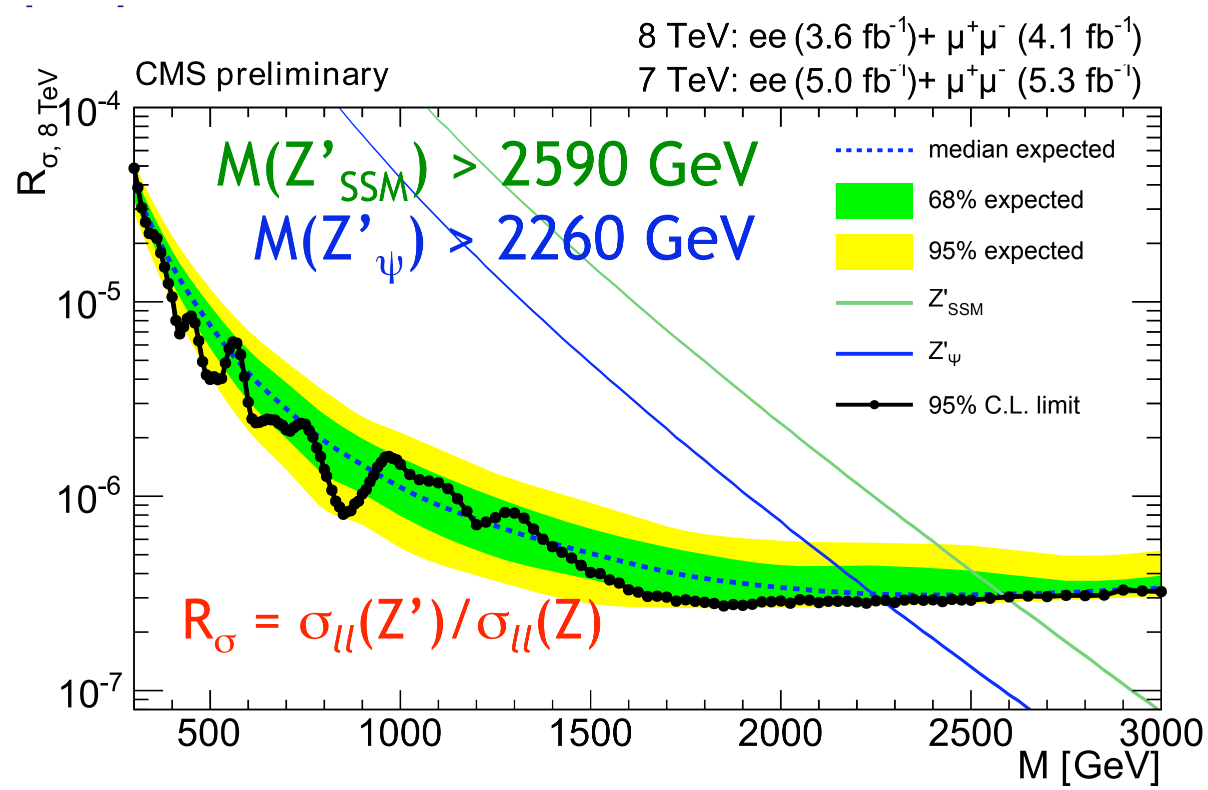
Collider Signal of compositeness



- Resonances.
- SM heavy particles (masses from EWSB) couples strongly to the resonances.
  - W, Z, top

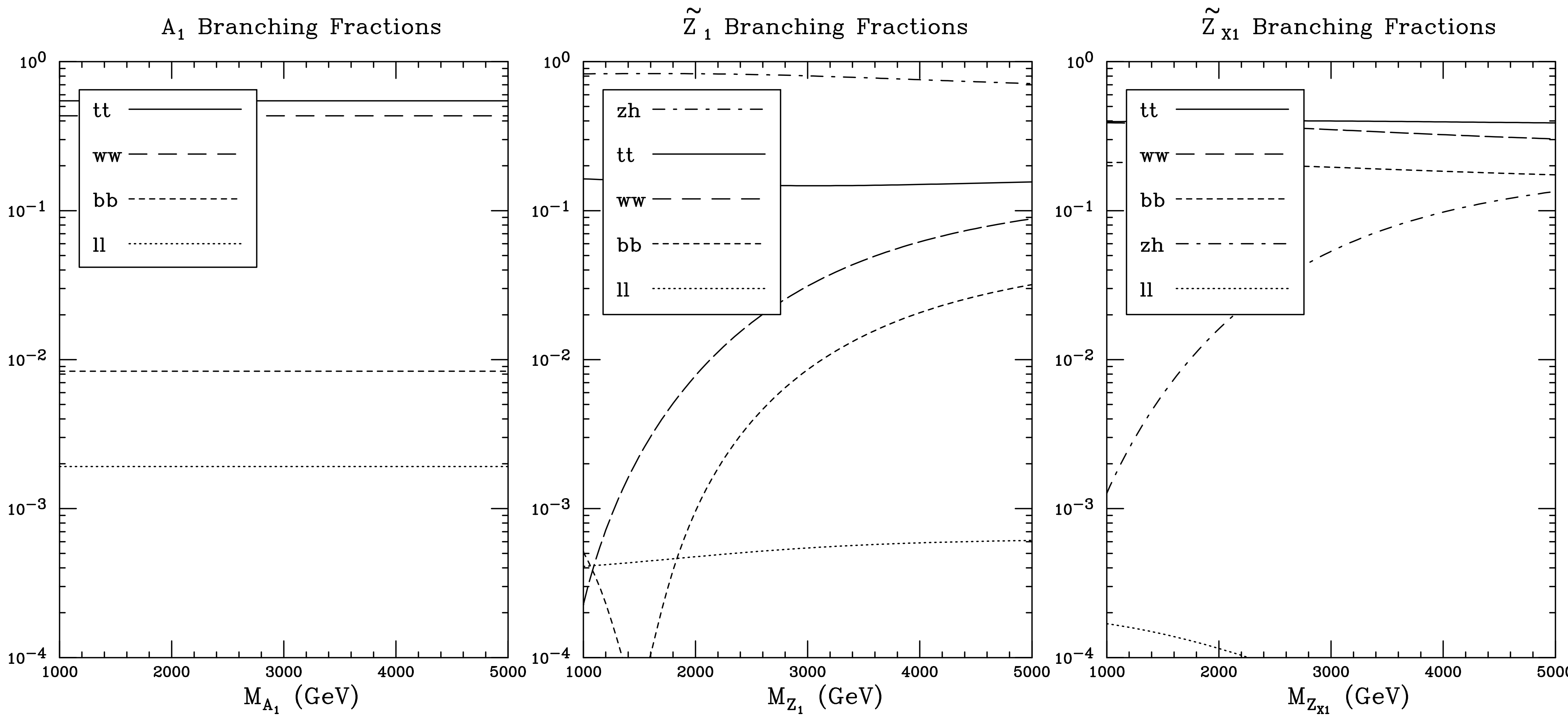
New resonance: Z′





- Rates model dependent. Can be suppressed.
- Generic Z′ (not necessarily composite), > 1.5 TeV.

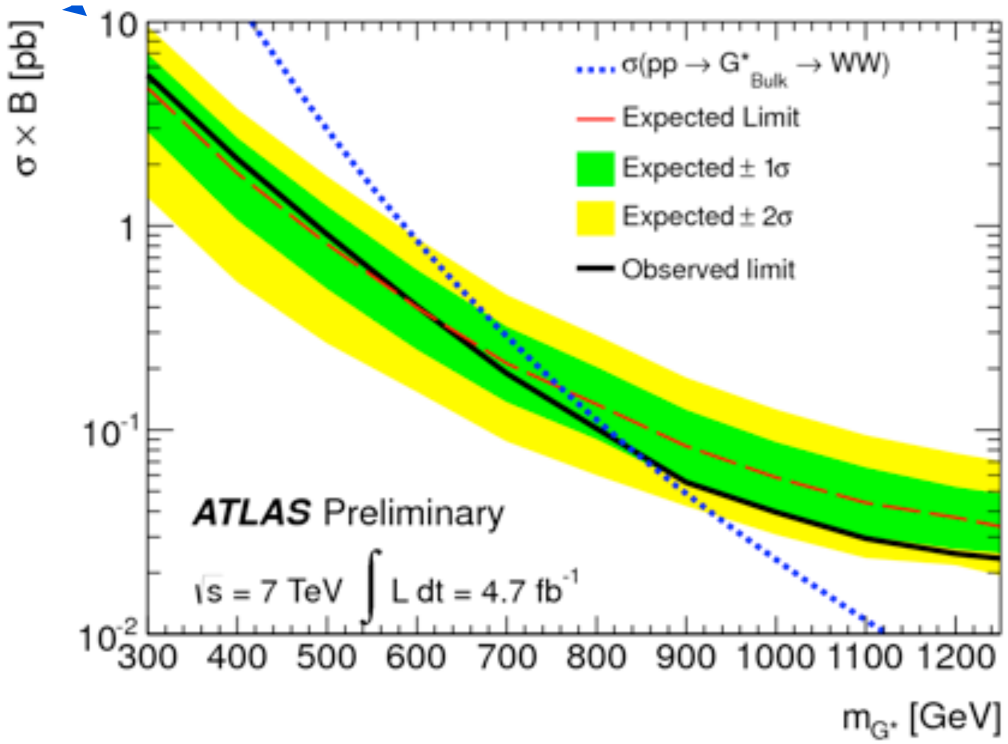
Composite resonance: Z′ → WW, Zh, tt

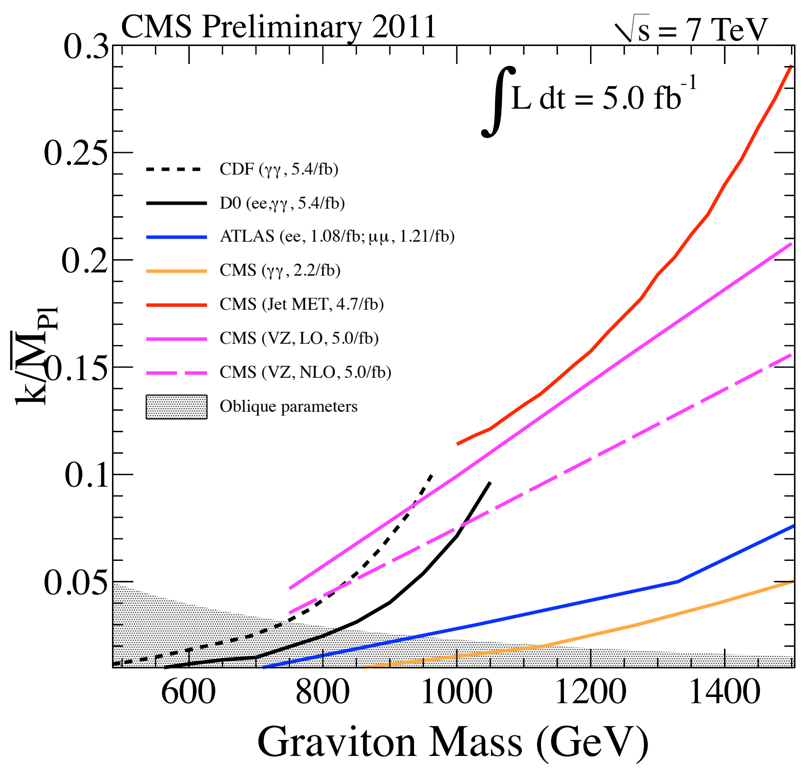


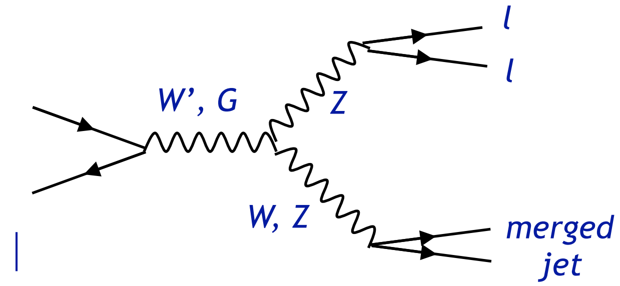
An example, Agashe et al, 0709.0007

- WW, Zh direct connection with EWSB.
- tt, top compositeness. (leptonic mode suppressed)

Composite Z'



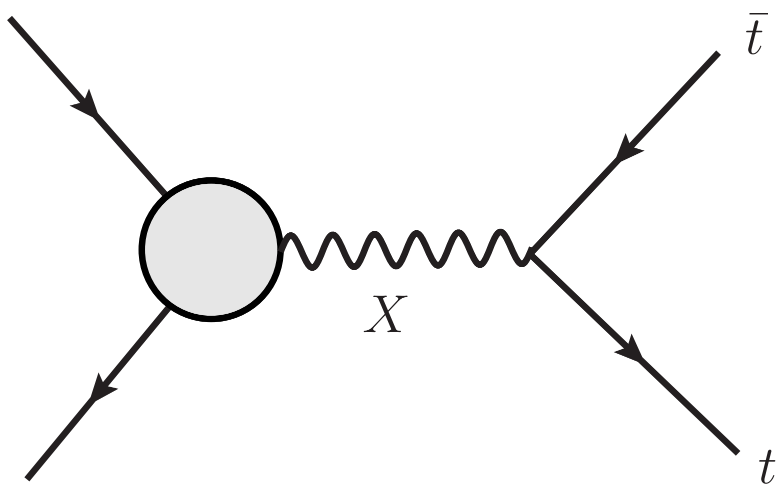




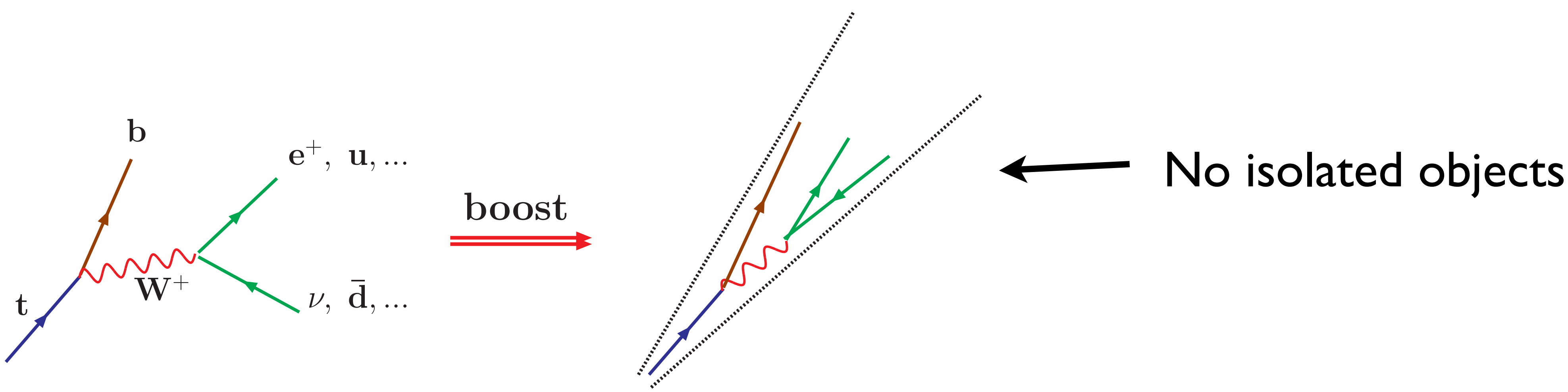
- Interesting limits, ~ TeV.
- Now we have Higgs, look for Zh final state!

Resonace → ttbar

- Heavy resonance decay.

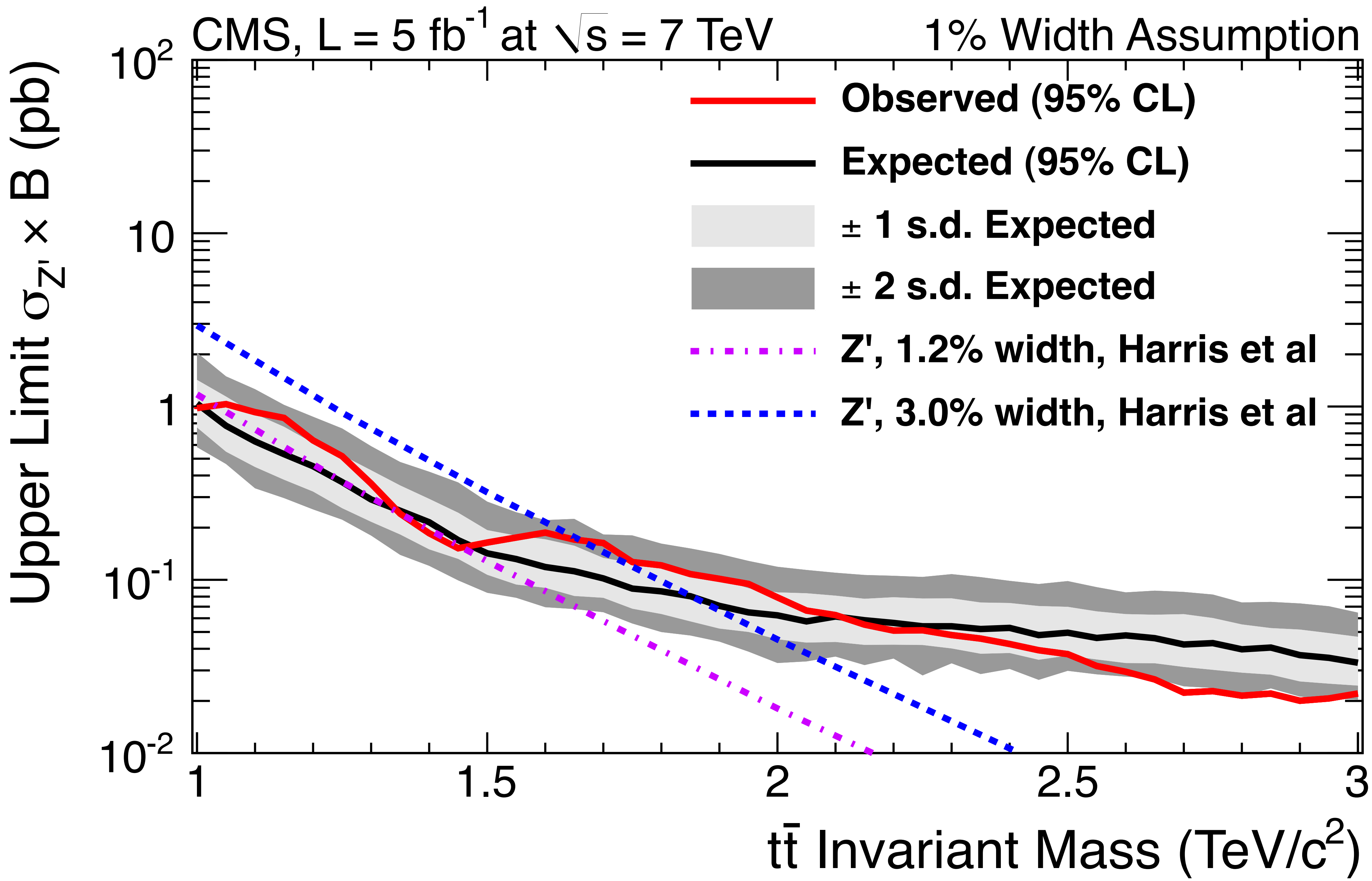


$$E_{\text{top}} \simeq \frac{M_X}{2}$$



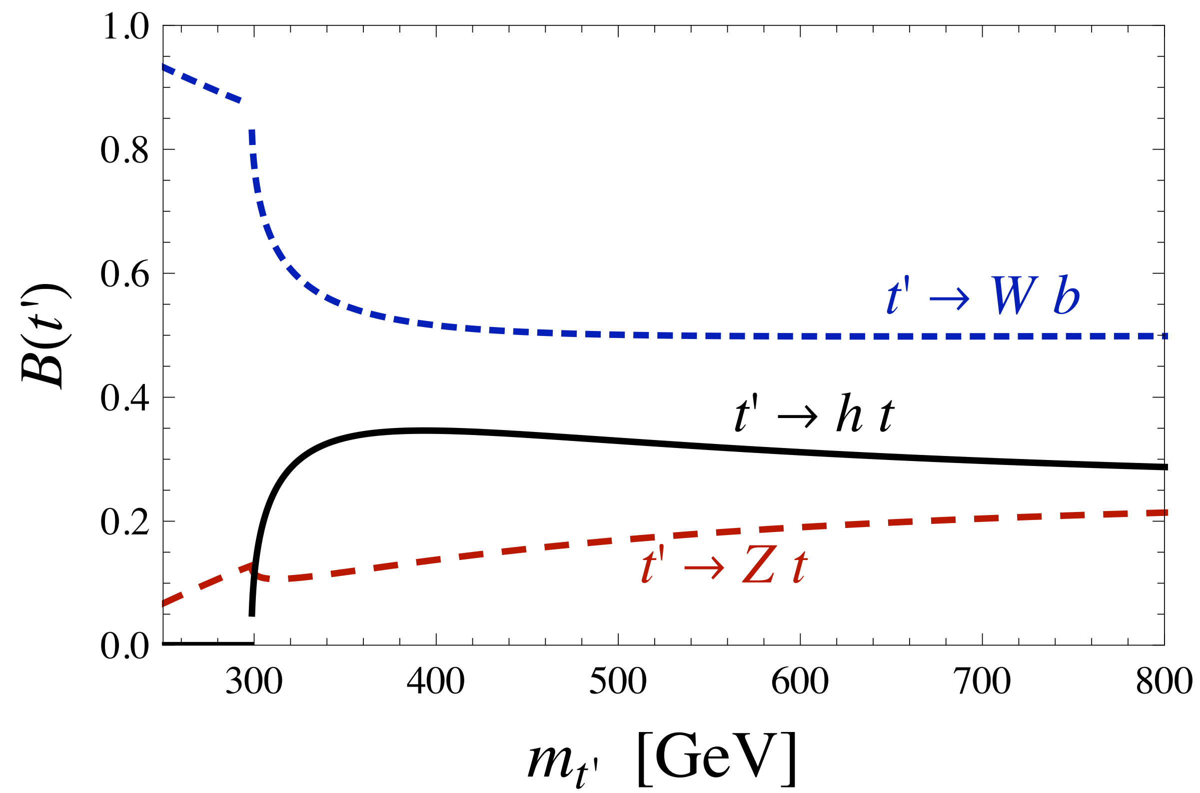
B. Lillie, L. Randall, and LTW, hep-ph/0701166

Use of boosted top taggers, 1201.0008



CMS, L = 5 fb^-1 at √s = 7 TeV
1% Width Assumption
Upper Limit σZ' × B (pb)
tt̄ Invariant Mass (TeV/c^2)
Observed (95% CL)
Expected (95% CL)
± 1 s.d. Expected
± 2 s.d. Expected
Z', 1.2% width, Harris et al
Z', 3.0% width, Harris et al
10^2
10
1
10^-1
10^-2
1
1.5
2
2.5
3

Composite resonace: t′

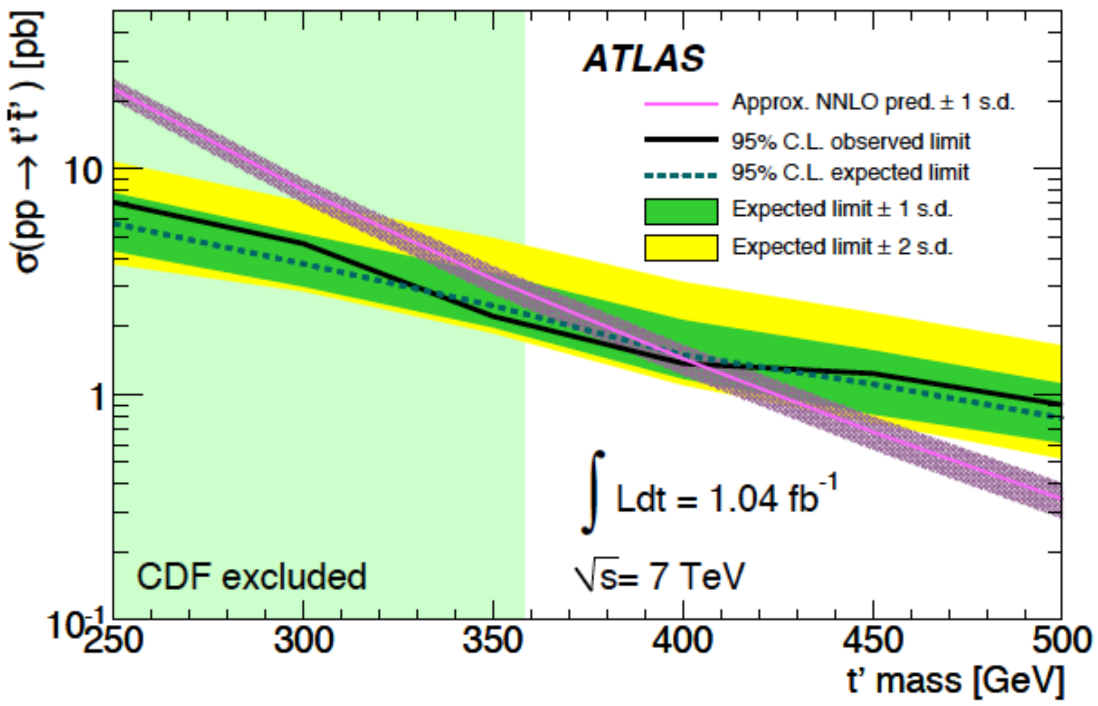


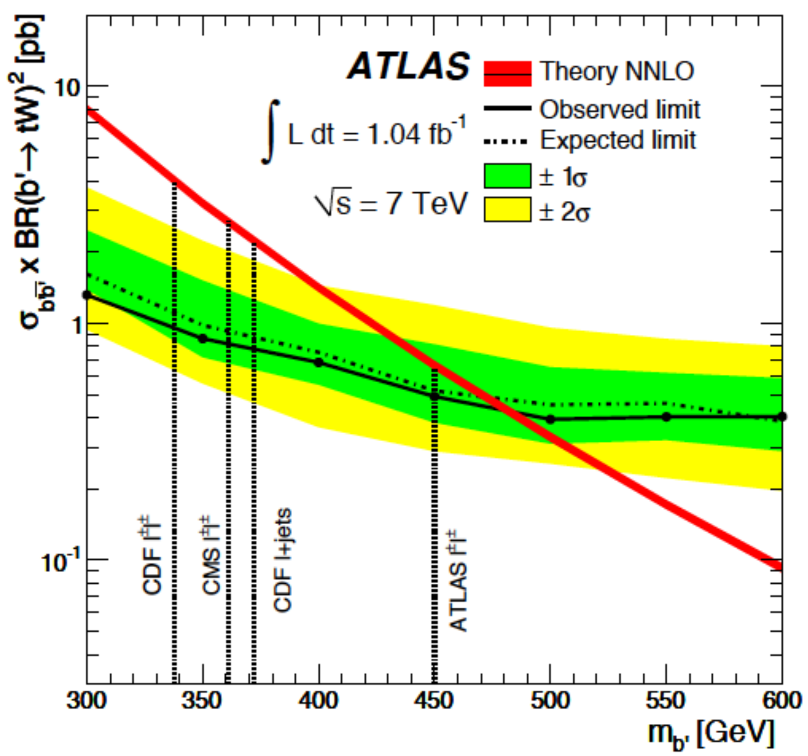
3 channels comparable

- Generic to expect a top partner to improve naturalness, e.g., little Higgs models.

- t′ can be 100s GeV to TeV-ish.

t′ searches





- Pair production, t′→ Wb
- Analogous b′ search, b′→ tW. (also bZ)
- Single production: bW→t′
  - Rate larger if $m_{t'}$ > 800 GeV.
  - Test bWt′ (related to t′th) coupling.

Perelstein, Peskin, Pierce 2003
Han, Logan, LTW 2003

Corrections to Higgs couplings.

- Era of precision Higgs physics.
  - Independent of whether other NP are found.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\,(V_\mu V^\mu)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] - m_i \bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \mathrm{h.c.}$$
$$+ \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$
$$+ c_g \frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma \frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$

Contino, Grojean, Moretti, Piccinini, RR '10

  - Measuring a, b, c, d reveal nature of Higgs and information of NP.
  - For example, in composite Higgs models, deviation on the order of $\frac{v^2}{f^2} \sim 10\% - \mathrm{ish}$

Better chance with resonance (m∼f∼ TeV) searches

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  - We now have top and W/Z partners (Same spin). Cancel quad divergence at 1-loop (in contrast, SUSY cancel quad divergence to all orders).
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- Sounds familiar? Similar signal to SUSY!

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  - Warped compactification, TeV extra Dim.
- In details, model can be complicated. Some tuning necessary.
  - Less predictive due to strong dynamics.
- Maybe less exciting then SUSY. Doesn't mean less likely.

The Higgs connection

Higgs couplings.

- Era of precision Higgs physics.
  - Independent of whether other NP are found.

$$
\begin{aligned}
\mathcal{L} \quad &= \quad \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\,(V_\mu V^\mu)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] - m_i\bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \text{h.c.} \\
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Contino, Grojean, Moretti, Piccinini, RR '10

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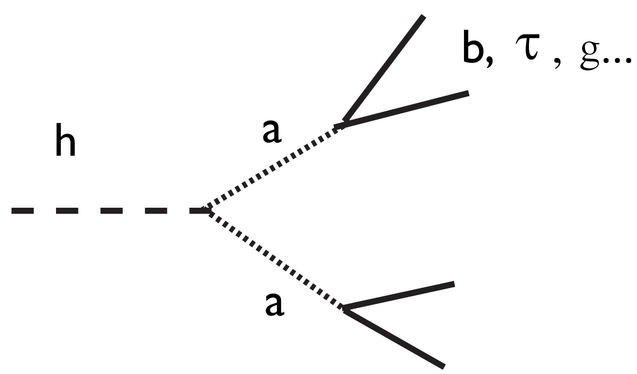
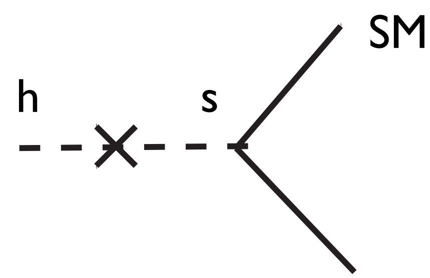
Higgs as a portal to new physics

– Modification of Higgs production and decay.

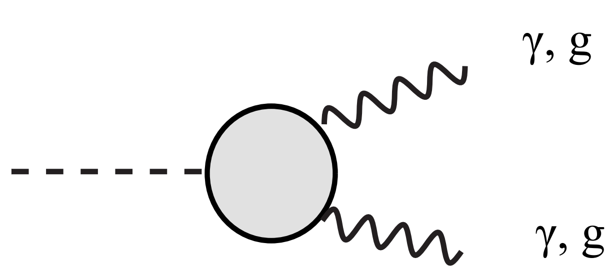
to new states



mixing



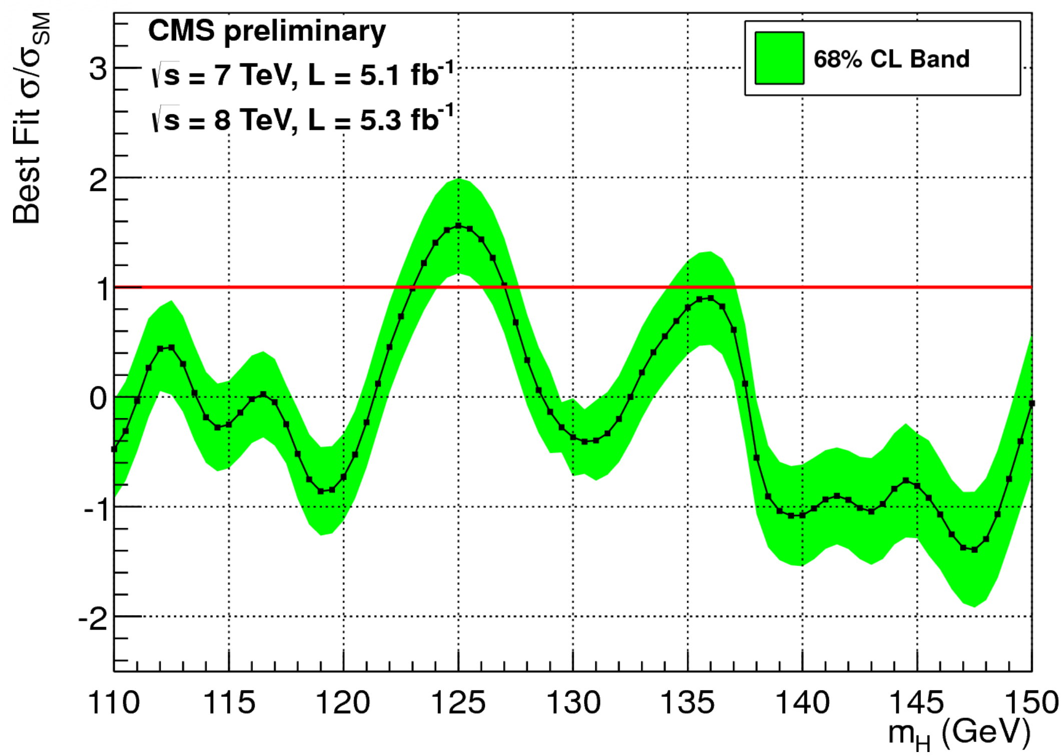
in the loop

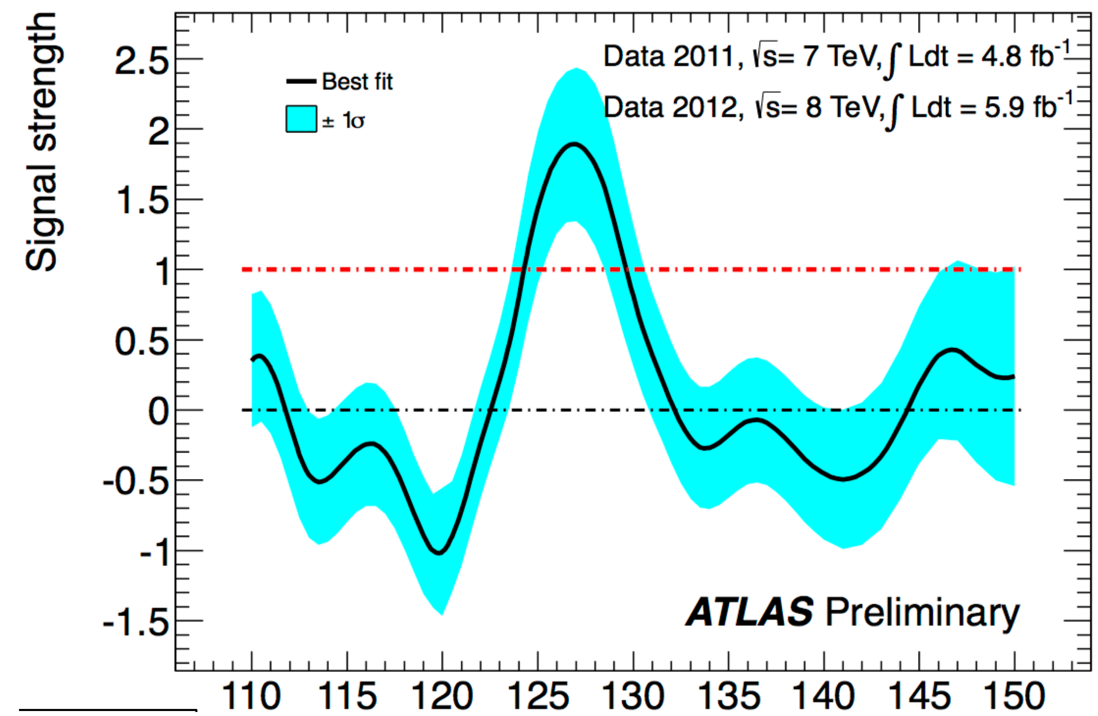


Loop of NP

In addition to measuring Higgs properties,
We can also look for the new states.

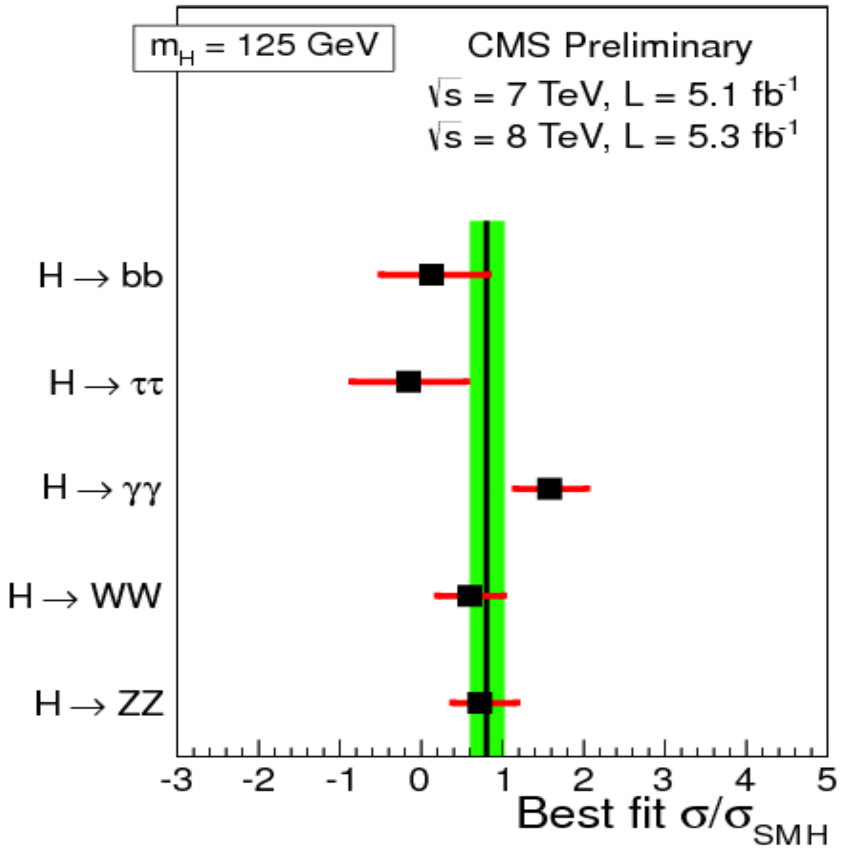
A hint, enhanced $h \to \gamma\gamma$?

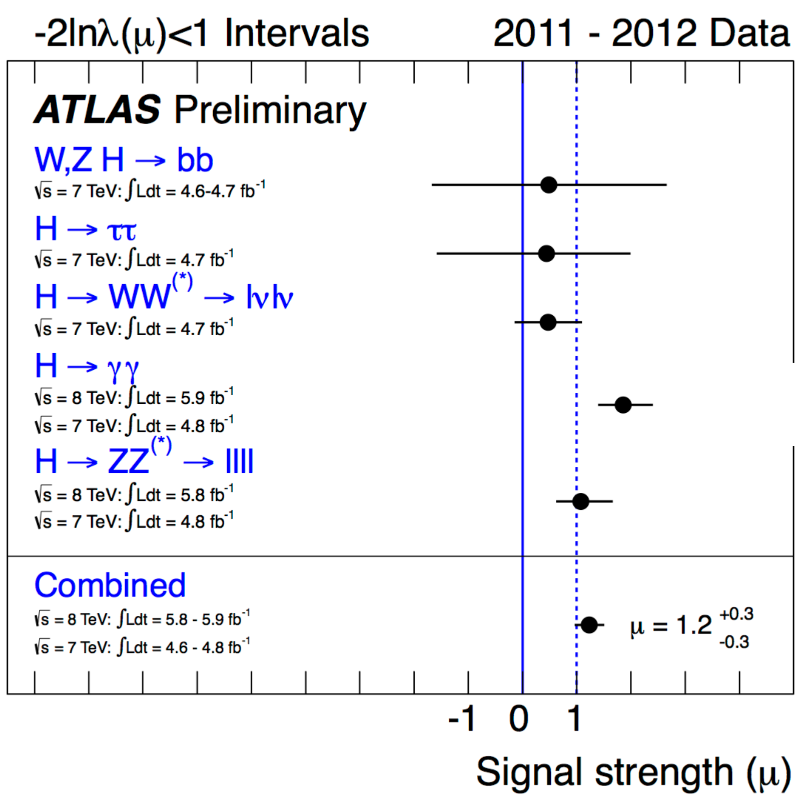




- Obviously, not significant.
- But, we could use this as an example for what kind of new physics opportunities Higgs physics may bring us.

Enhancement in ZZ/WW/ττ..?





- Perhaps $gg \to h \to WW/ZZ/\tau\tau$ not enhanced
  - only $h\gamma\gamma$ enhanced, new physics color neutral.

What if this is new physics

- SM $h \to \gamma\gamma$ is given by W and top loops.
  - W, t: light (~100 GeV), large coupling to the Higgs.
  - New states must be similar.
- New particles can be either fermion or boson.
  - Scalar: stau-like, special model. Carena, Gori, Shah, Wagner, 2011
  - New fermion: Yukawa like coupling: $h_{u,d}$ DN.
- Need to check EWPT.

Collider signal of such new physics

- If colored, should have strong constraint already.
- Not colored (preferred by data?)
  - Low cross section. 2 order of magnitude below colored NP rate.
  - But, they are light. Decent rates.
- Carries electric charge
  - decaying into: $W^{\pm}$, lepton, quarks
  - Signal similar to electroweak gaugino
- Similar to WZ, WW in the SM.

Couplings of the light states.

New doublet, Higgs, Higgsino-like

$$DQu^c \quad D^cQd^c$$

$$H_uH_uX^c \quad H_dH_uN^c$$

- Discovery in direct SUSY searches might be difficult.

- Modification of Higgs decay maybe their first signal.