Non-supersymmetric extensions of the SM

(Alternatives to the MSSM)

Alex Pomarol (Univ. Autonoma Barcelona)

In most people's mind:

- Are there really serious alternatives to the MSSM?
- The MSSM is the perfect candidate for physics beyond the SM

It has become the orthodoxy

The MSSM gained its present status after LEP I,

where EWPT left behind its main competitors (e.g. technicolor)

Veneziano SUSY 98 summary talk:

To conclude, the score on precision tests puts the SSM first, with the SM itself (with a light Higgs and some additional intermediate scale) a close second. Technicolour theories appear to lag far behind and... there is not much else in the race. I would conclude that, if

But after LEP I , it came LEP II and Tevatron...

In the MSSM the Higgs or the sparticles were expected to be seen!

But Nothing was seen!

→ MSSM must be tuned (1% to 10%) to survive

Is there something else in the "race"?

Is there something else in the "race"?

1) Large extra dimensions

2) Randall-Sundrum model

Exotic signatures $\longrightarrow$ Gravitons, BH, string modes

But, do not give a clue on the origin of EWSB

3) Higgs as a composite state ~ PNGB

Is there something else in the "race"?

1) Large extra dimensions

2) Randall-Sundrum model

Exotic signatures ⟶ Gravitons, BH, string modes

But, do not give a clue on the origin of EWSB

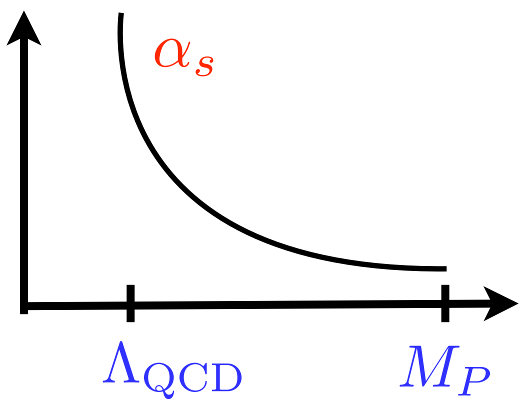
3) Higgs as a composite state ~ PNGB

does not suffer from naturalness problems

Example in QCD:

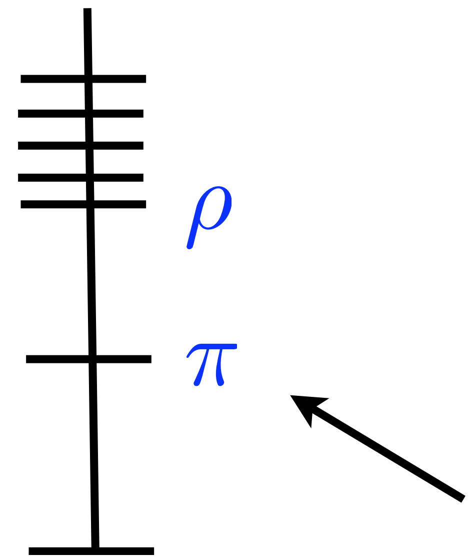
$$m_\pi << M_P$$

spin=0 composite states at $\Lambda_{\rm QCD} << M_P$

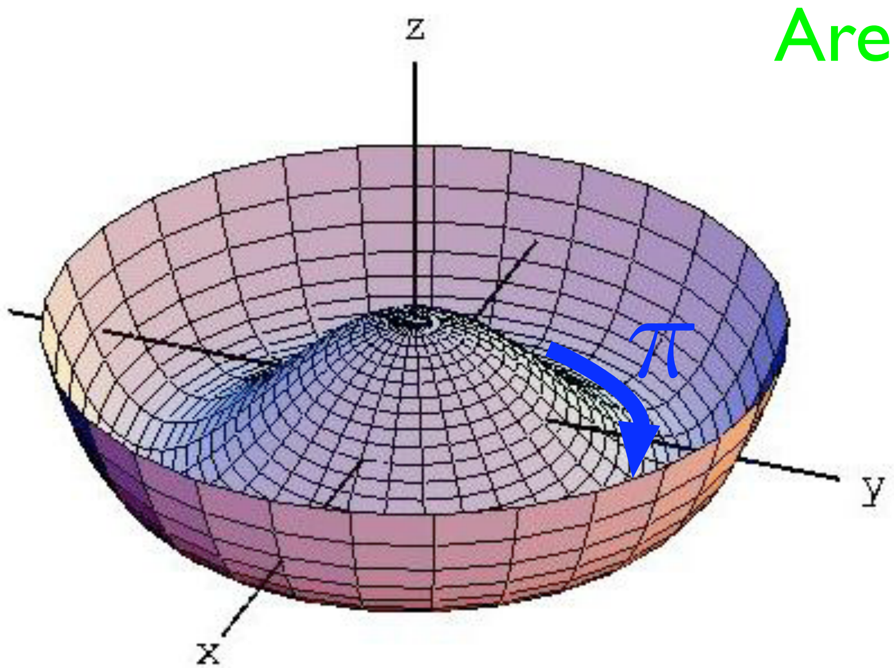


Composite Higgs scenario is inspired by QCD where one observes that the (pseudo) scalar are the lightest states

Spectrum:



Are Pseudo-Nambu-Goldstone bosons (PNGB)

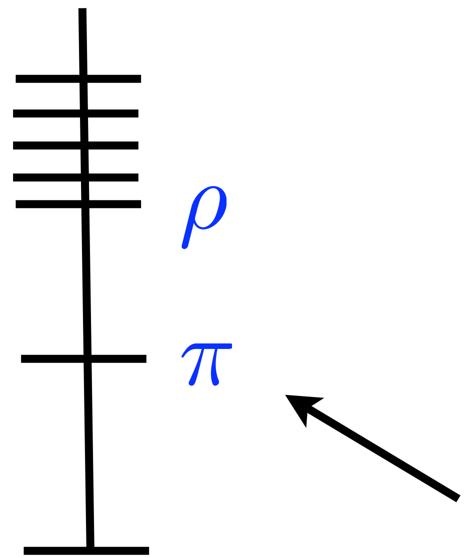


Mass protected by the global QCD symmetry!

$$\pi \longrightarrow \pi + \alpha$$

Composite Higgs scenario is inspired by QCD where one observes that the (pseudo) scalar are the lightest states

Spectrum:

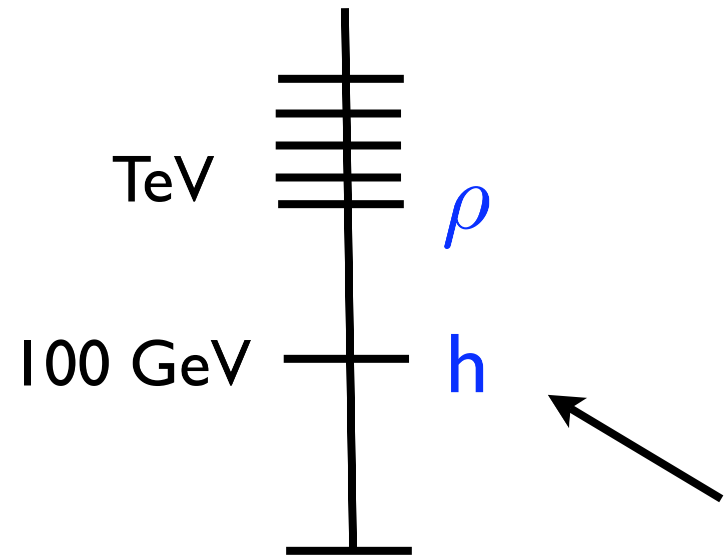


Are Pseudo-Nambu-Goldstone bosons (PNGB)

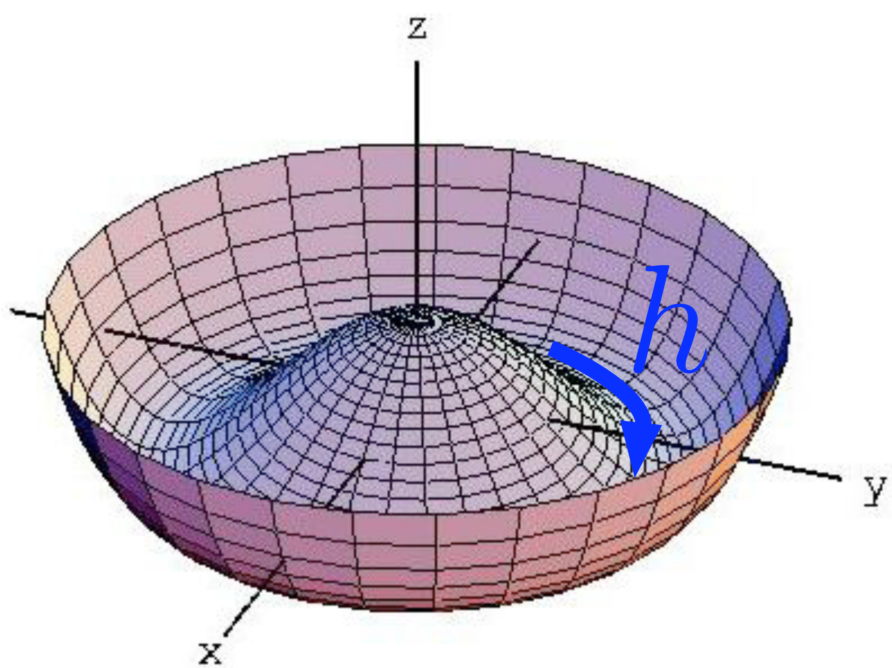
Mass protected by the global QCD symmetry!

→ Can the light Higgs be a kind of a pion from a new strong QCD-like sector?

Spectrum of the new QCD-like sector:



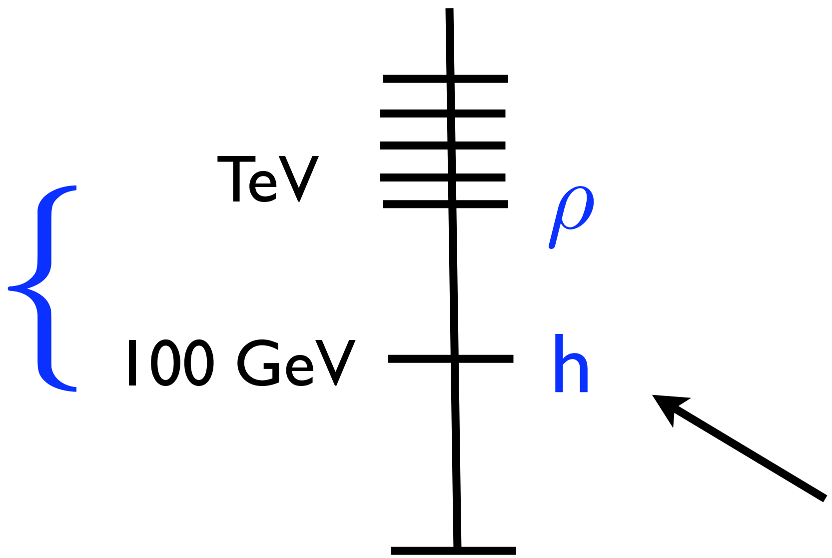
Pseudo-Nambu-Goldstone bosons (PNGB)



Mass protected by a global symmetry G

$$h \to h + \alpha$$

Spectrum of the new QCD-like sector:



Mass gap: Would explain the absence of new states at colliders before the LHC

Pseudo-Nambu-Goldstone bosons (PNGB)

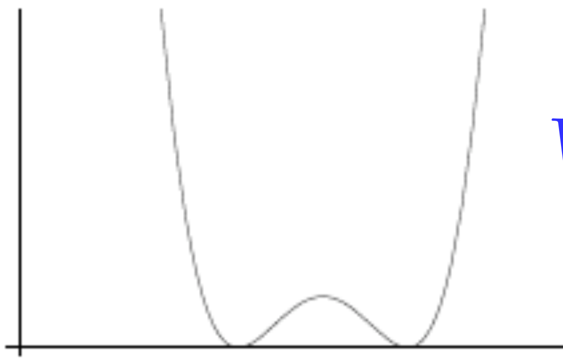
Mass protected by a global symmetry G

Although clashes with EWPT unless new states are around 3 TeV

Origin of EWSB

SM interactions break the global symmetry G

Higgs potential induced by gauge loops + top loops



$$V(h) = -m^2 h^2 + \ldots$$

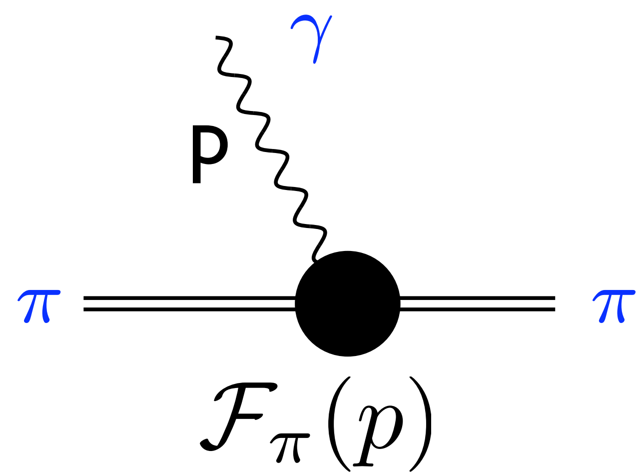
One finds EWSB minimums thanks to the fact that the SM have a heavy top: **EWSB $\leftrightarrow$ heavy top**

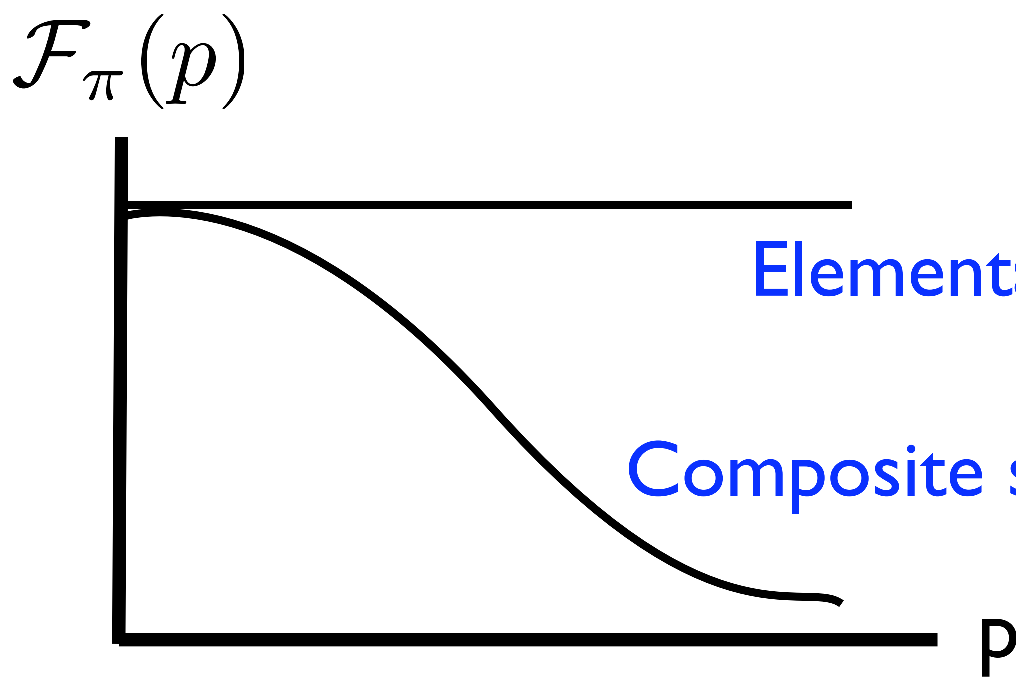
The Higgs will be light since its mass arises at the one-loop level (mass ~ 100-200 GeV)

How to unravel the composite nature of the Higgs?

Easy in an ideal collider:

As we do it with pions in QCD:

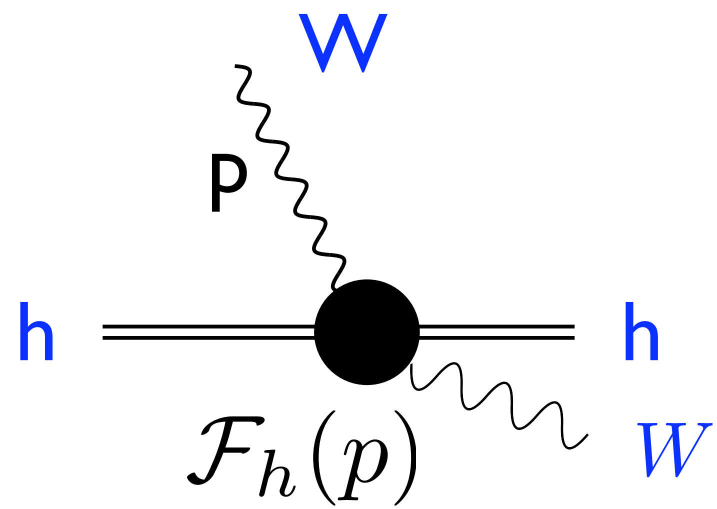


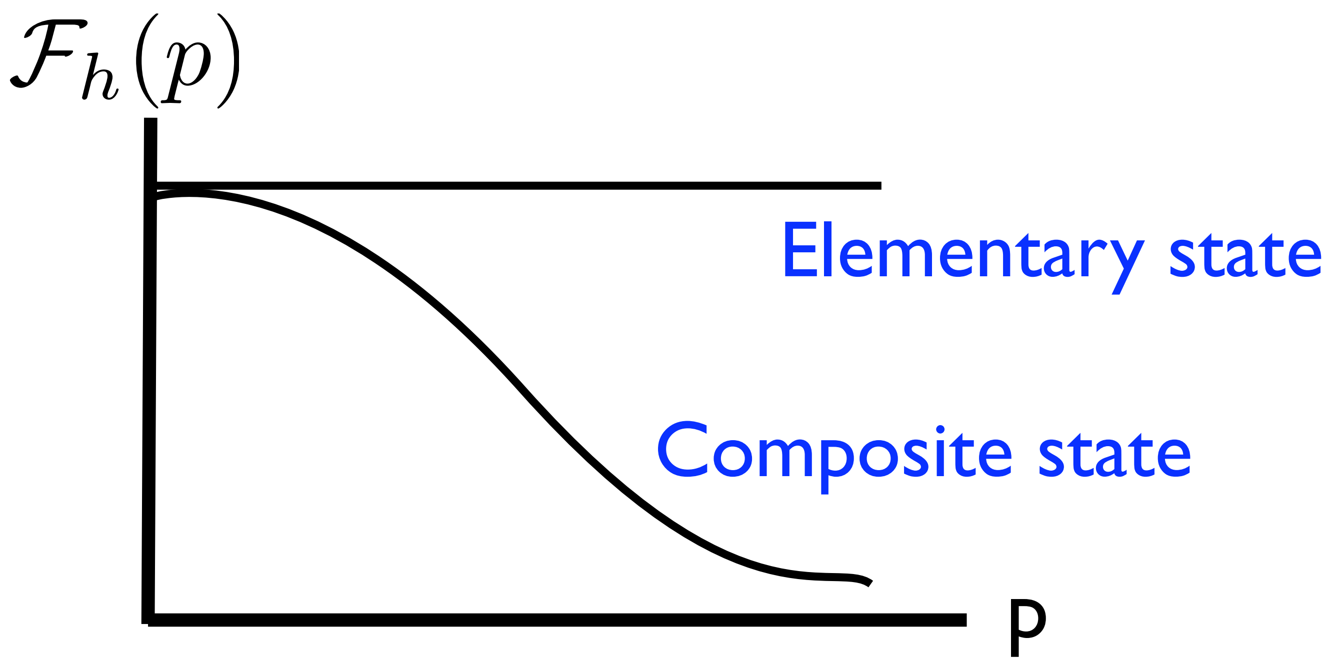


How to unravel the composite nature of the Higgs?

Easy in an ideal collider:

Similarly for the Higgs:

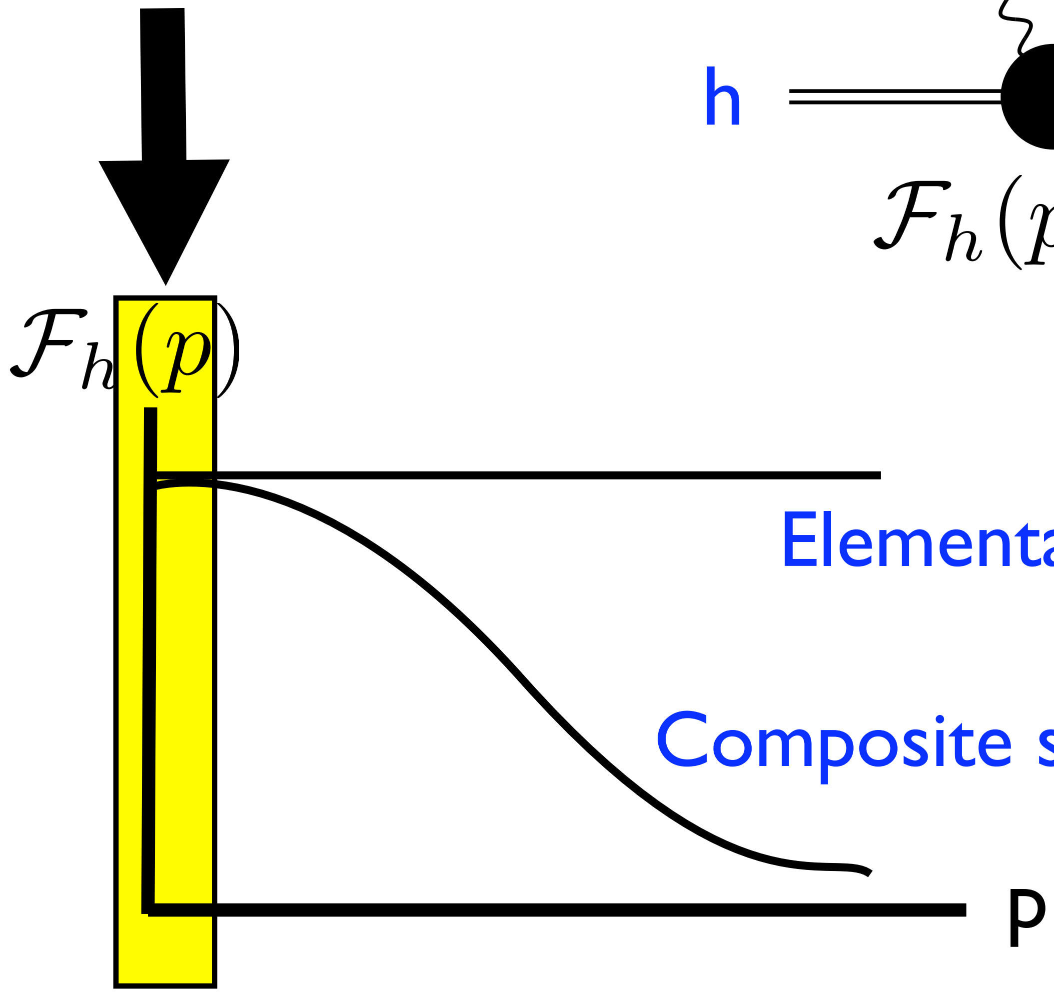


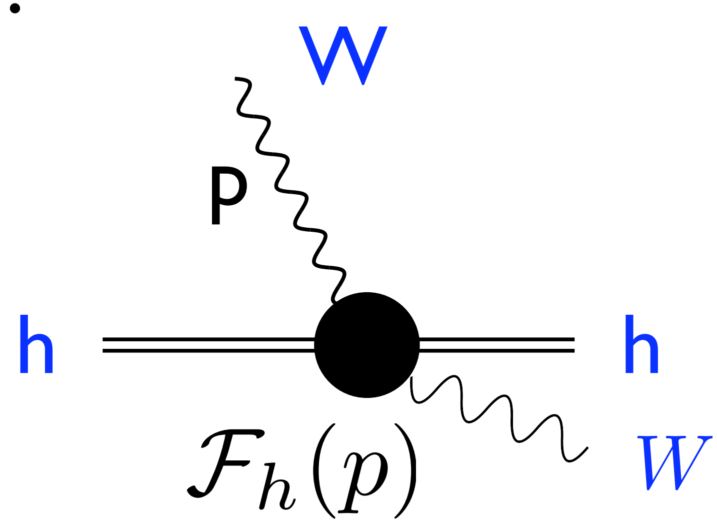


How to unravel the composite nature of the Higgs?

But in a real collider (LHC):

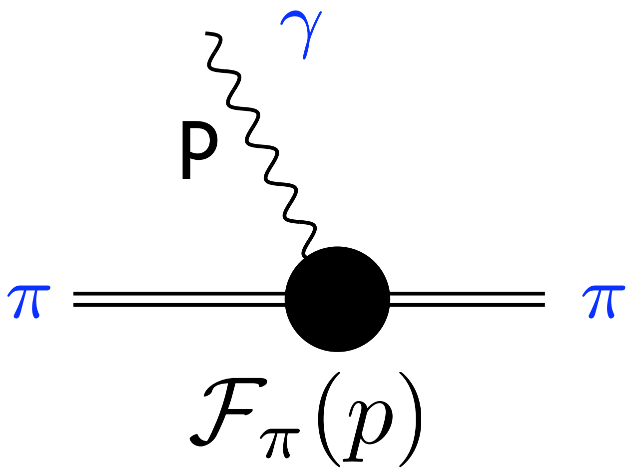
Only access up to few TeV





Another signature of compositeness:

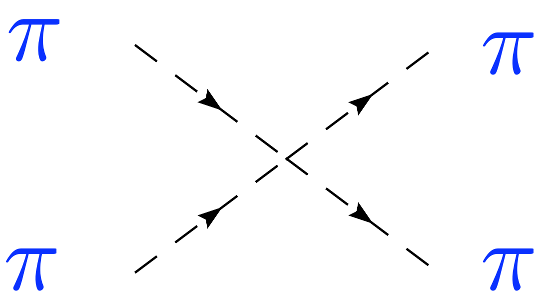
Lesson from QCD:



at small momentum

$$\mathcal{F}_\pi(p) \simeq 1 - \frac{p^2}{m_\rho^2}$$

m_ρ → ~ 1 GeV

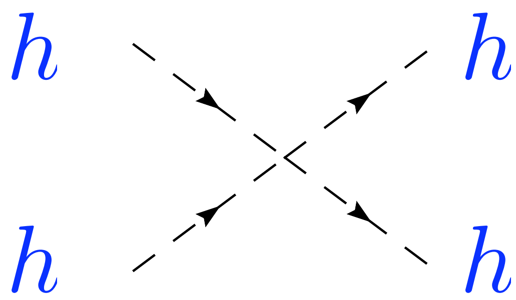


$$\sim \frac{p^2}{F_\pi^2}$$

F_π → ~ 100 MeV

Bigger effects at low-energies!

Similarly, in composite Higgs (f =Higgs decay constant):

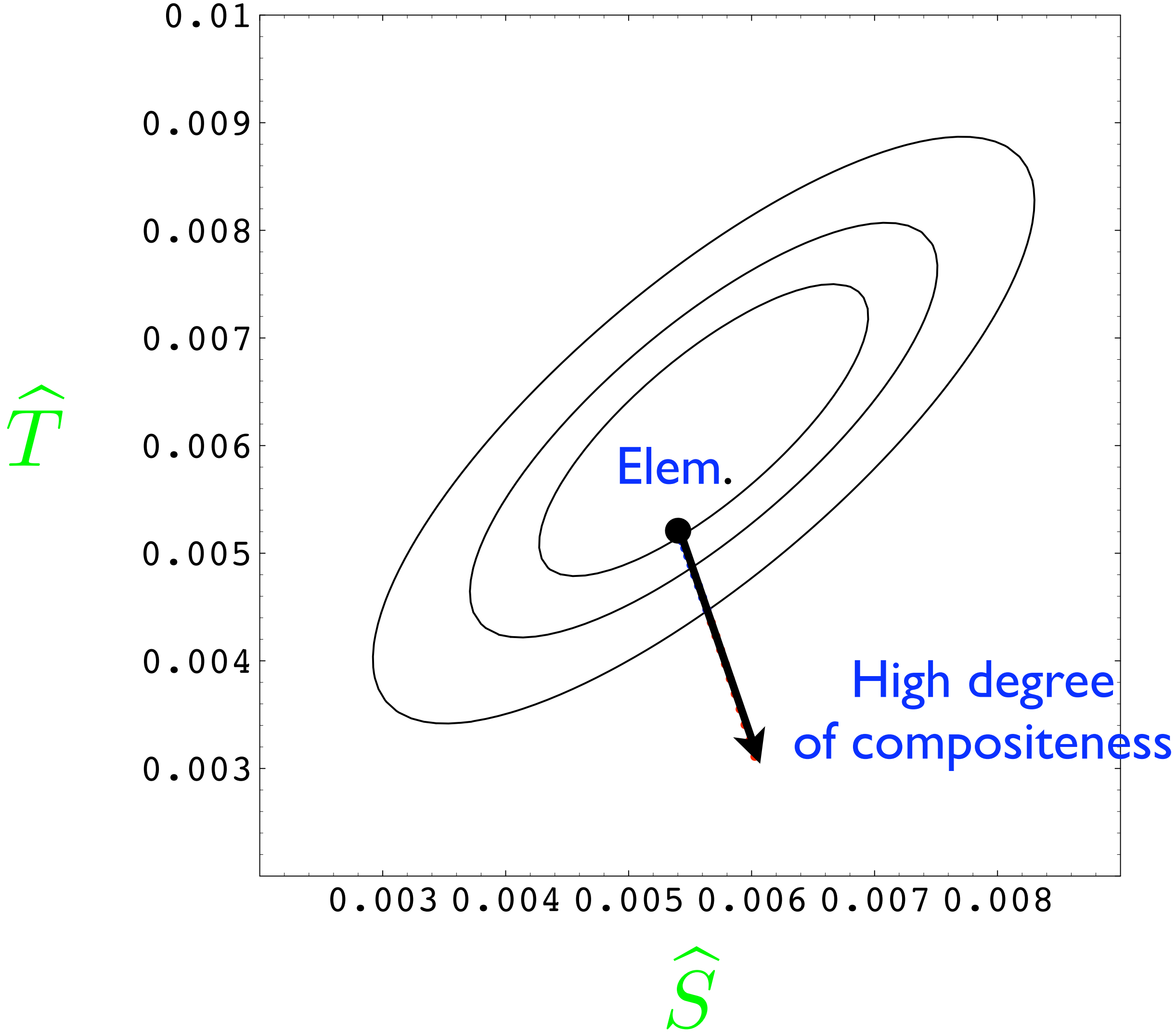


$$\sim \frac{p^2}{f^2}$$

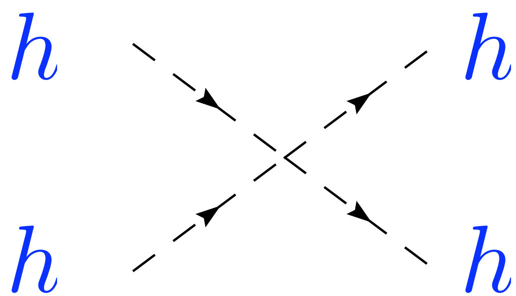
can be as low as ~500 GeV

Bound from EWPT

The more composite, the more goes out of the S-T ellipse



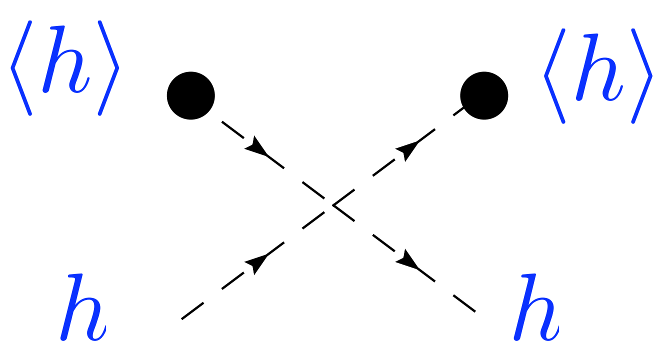
Similarly, in composite Higgs:



$$\sim \frac{p^2}{f^2}$$

can be as low as ~500 GeV

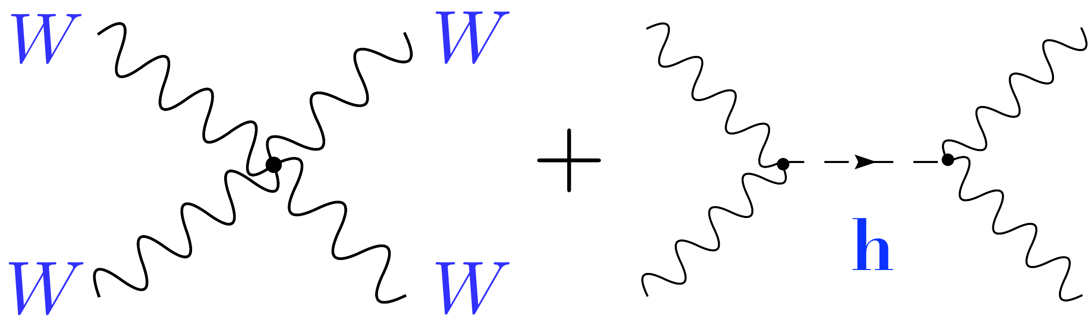
Impact on the Higgs propagator:



Effects on WW-scattering,
Higgs production, ...

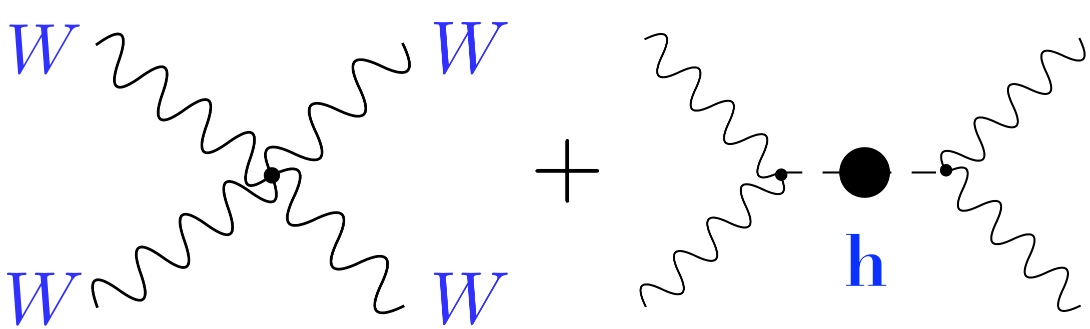
Example: WW-scattering

In the SM with an elementary Higgs unitarize the WW-amplitude



$$\sim E^0$$

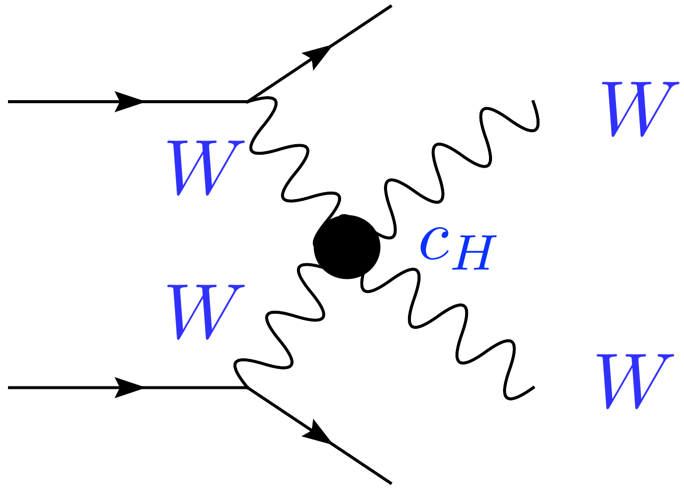
In the SM with a composite Higgs



$$\sim \frac{E^2}{f^2}$$

Gets large at high-energies!

Best test of composite Higgs: WW-scattering



even that the Higgs is light,
it grows with s

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H s}{f^2},$$

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2},$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0.$$

Difficult to see. From Higgsless studies Bagger et al
possible to see if

$$\frac{c_H v^2}{f^2} \sim 0.5 - 0.7$$

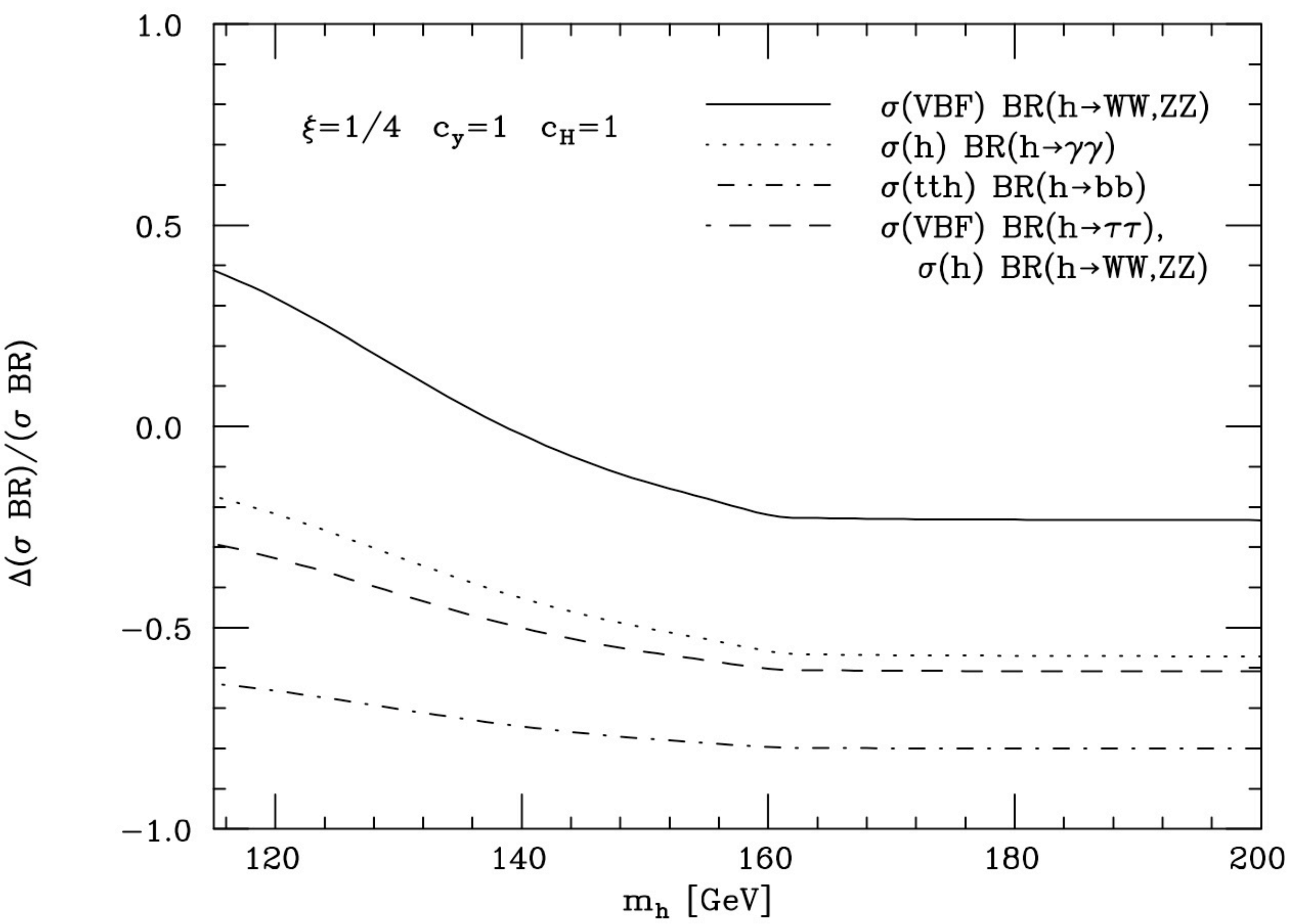
Giudice,Grojean,AP,Rattazzi

Giudice,Grojean,AP,Rattazzi

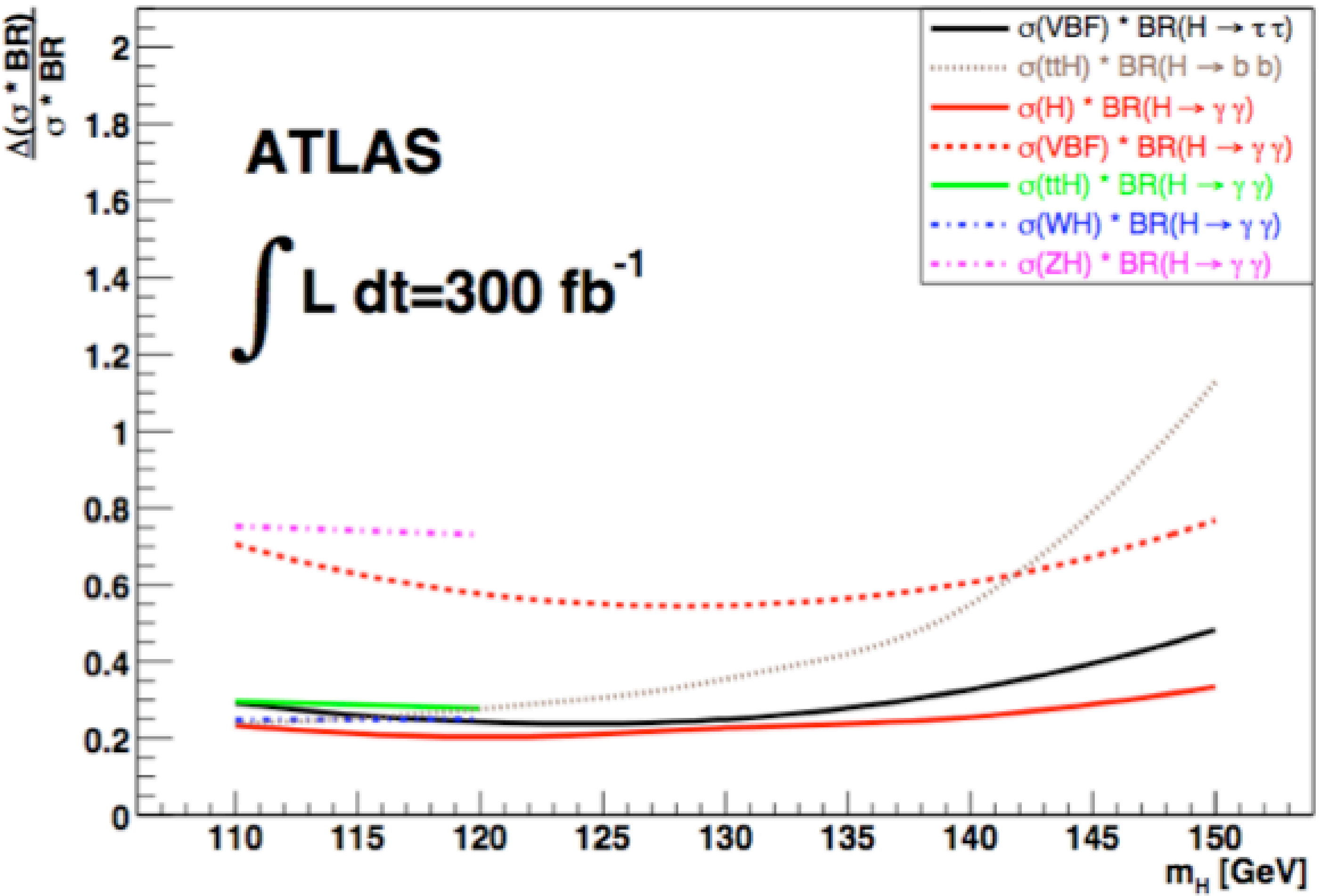
Other effects: Modifications of Higgs production σ x BR at the 20% level

→ Large luminosity to see them!

Deviations from the SM:



Visible at LHC?



Duhrssen 03

...certainly if they are of order 20-40%

ILC would be a perfect machine to test these scenarios:
effects could be measured up to a few %

What about indirect signatures?

As in QCD, detecting other hadrons was an indication of pion compositeness

Difficult to calculate the spectrum in strongly interacting theories ➡ Very difficult to find the underlying theory of the constituents

Recent progress:

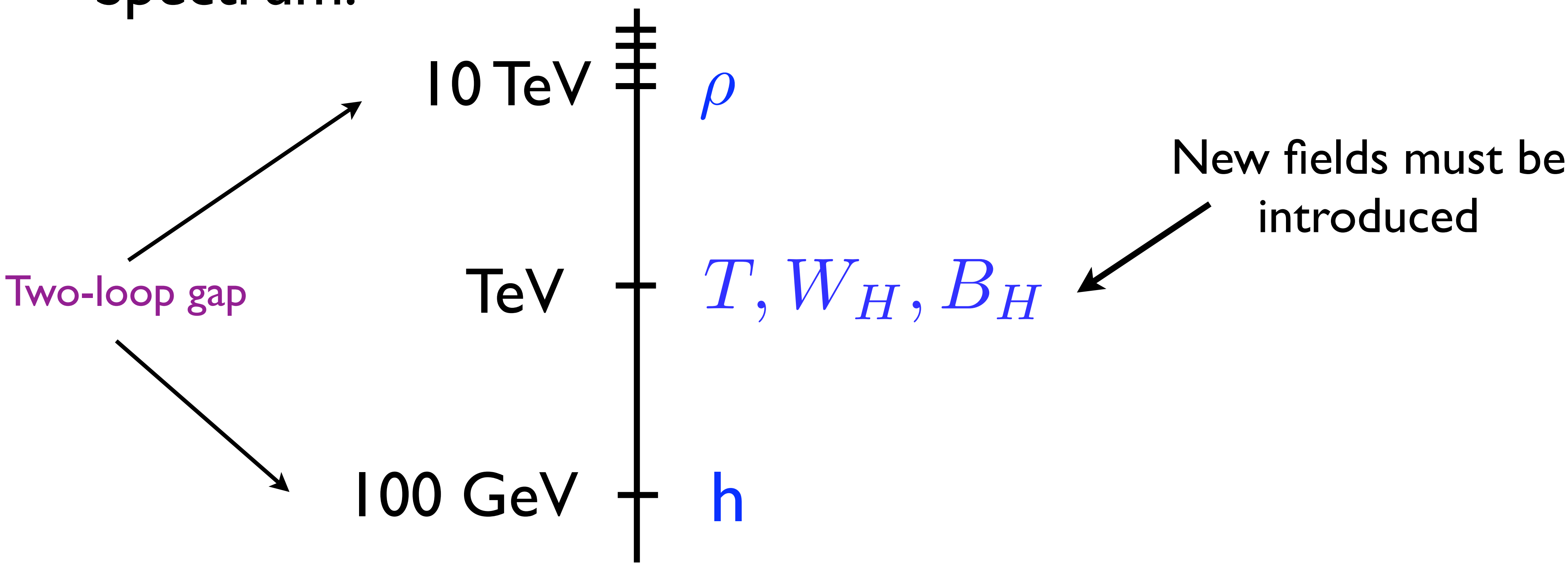
Explicit weakly-coupled approaches to PGB Higgs

- Little Higgs — Arkani-Hamed, Cohen, Katz, Nelson
- Holographic Higgs: Extra dimensional Composite Higgs models — Agashe, Contino, AP

1) Little Higgs:

Engineer a model where a PGB Higgs do not get a mass at one-loop but at two-loops

Spectrum:

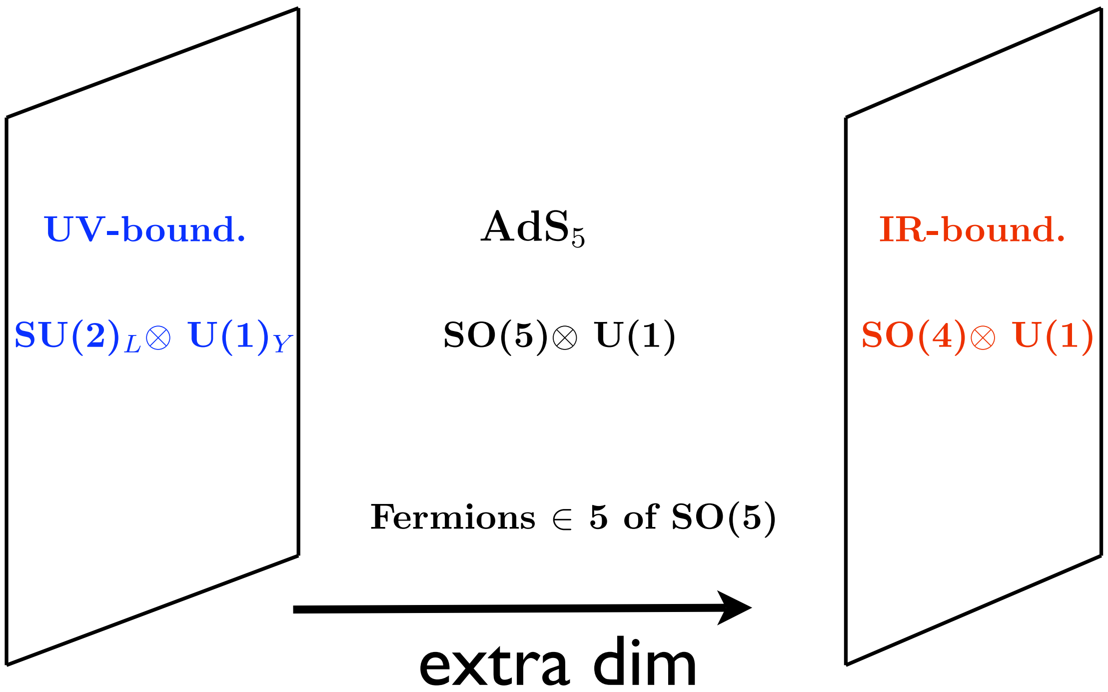


2) Holographic composite Higgs:

Maldacena

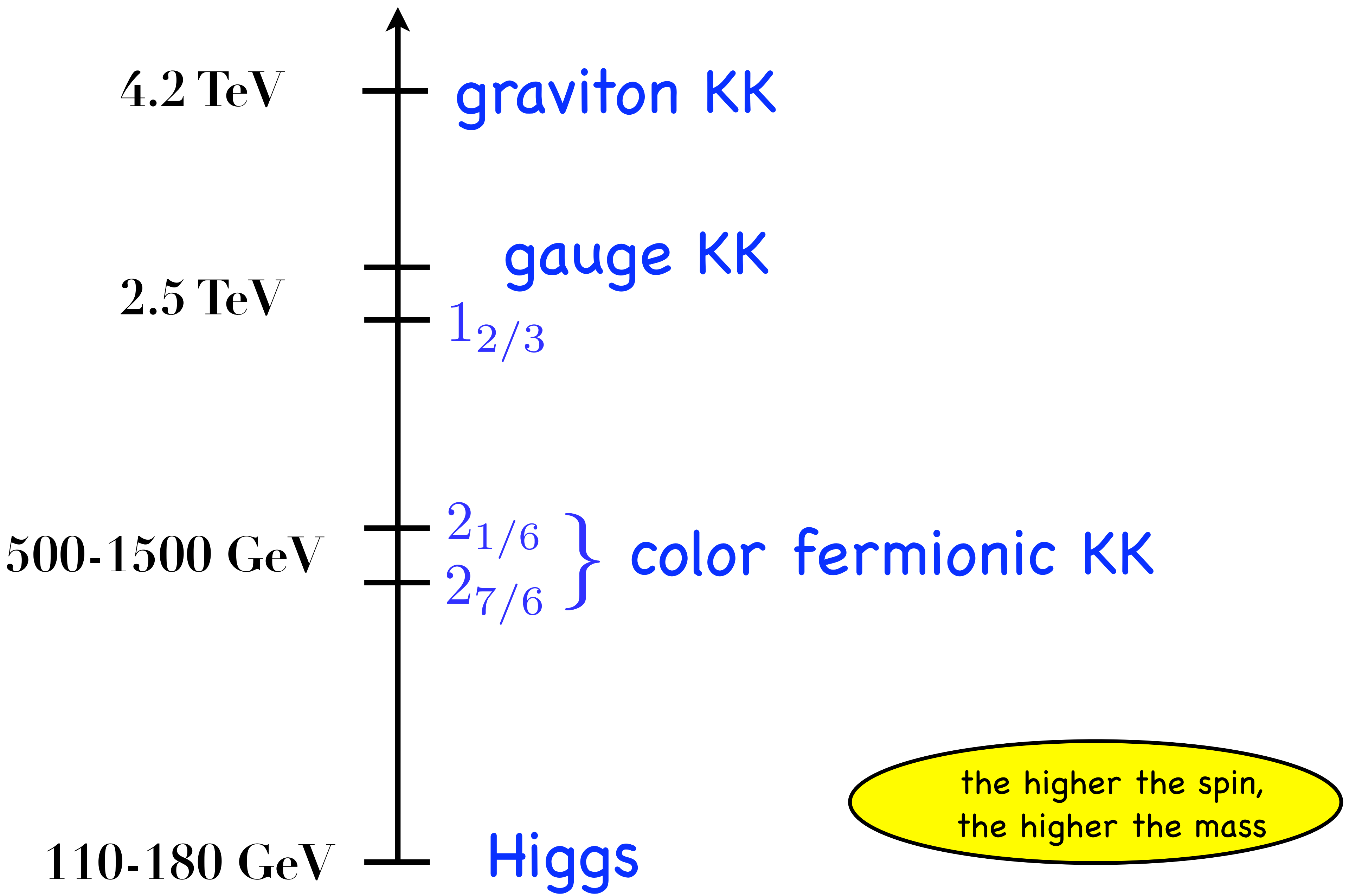
Using the AdS/CFT correspondence that relates some strongly-coupled theories in 4D to extra dimensional models

Models of 5D composite Higgs:



Agashe,Contino,A.P.

Spectrum


4.2 TeV
graviton KK
gauge KK
2.5 TeV
$1_{2/3}$
$2_{1/6}$
500-1500 GeV
color fermionic KK
$2_{7/6}$
110-180 GeV
Higgs
the higher the spin,
the higher the mass

Predictions

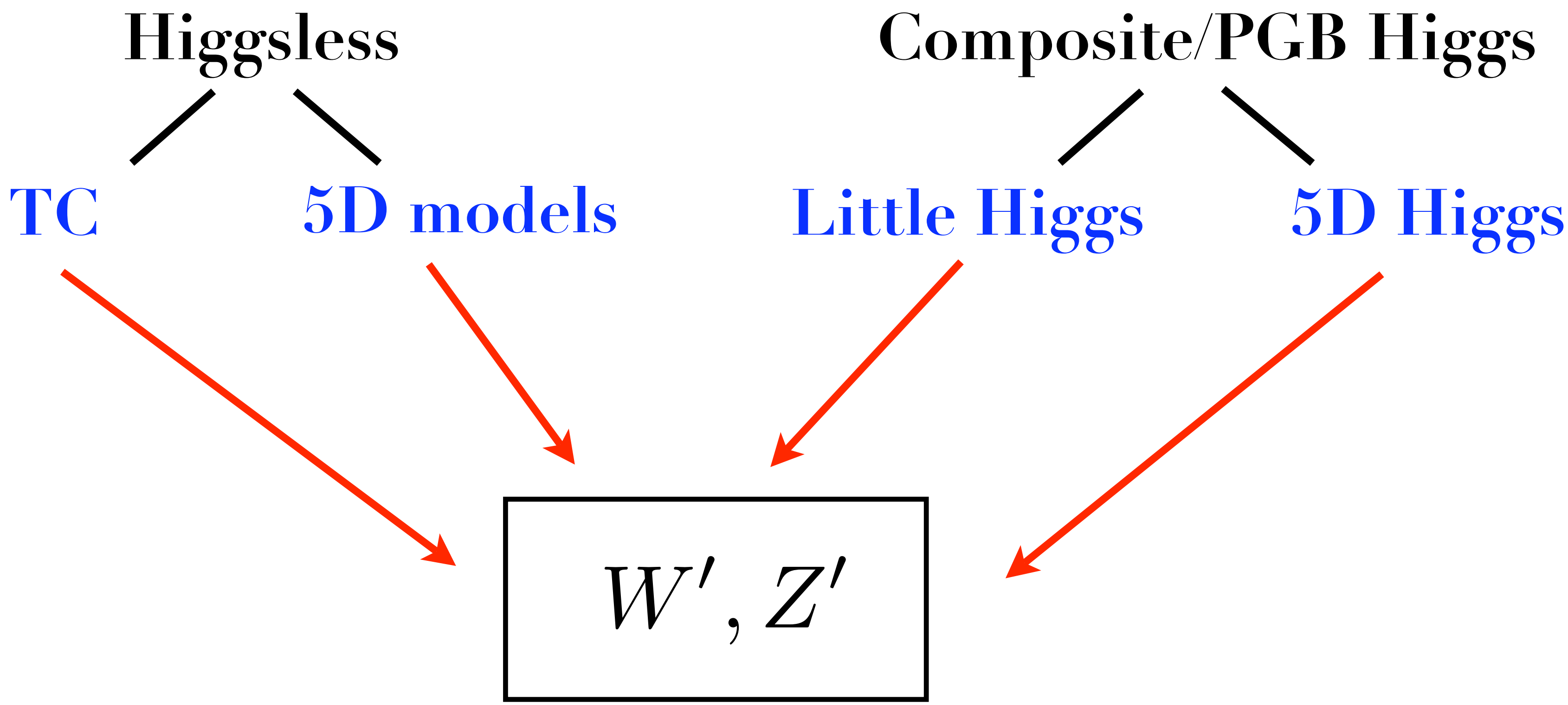
Both model give similar signatures
(and also similar to Technicolor models)

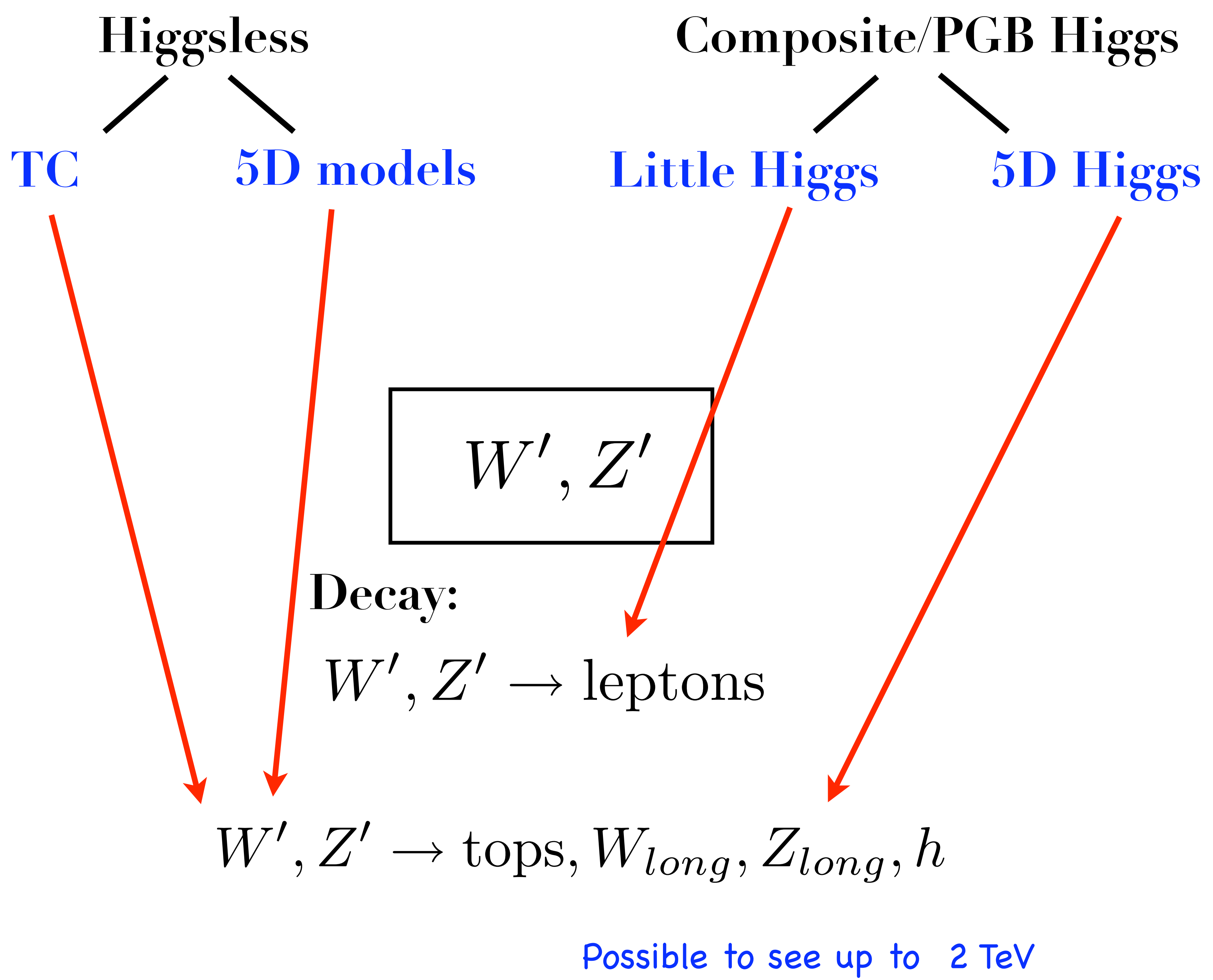
Higgsless

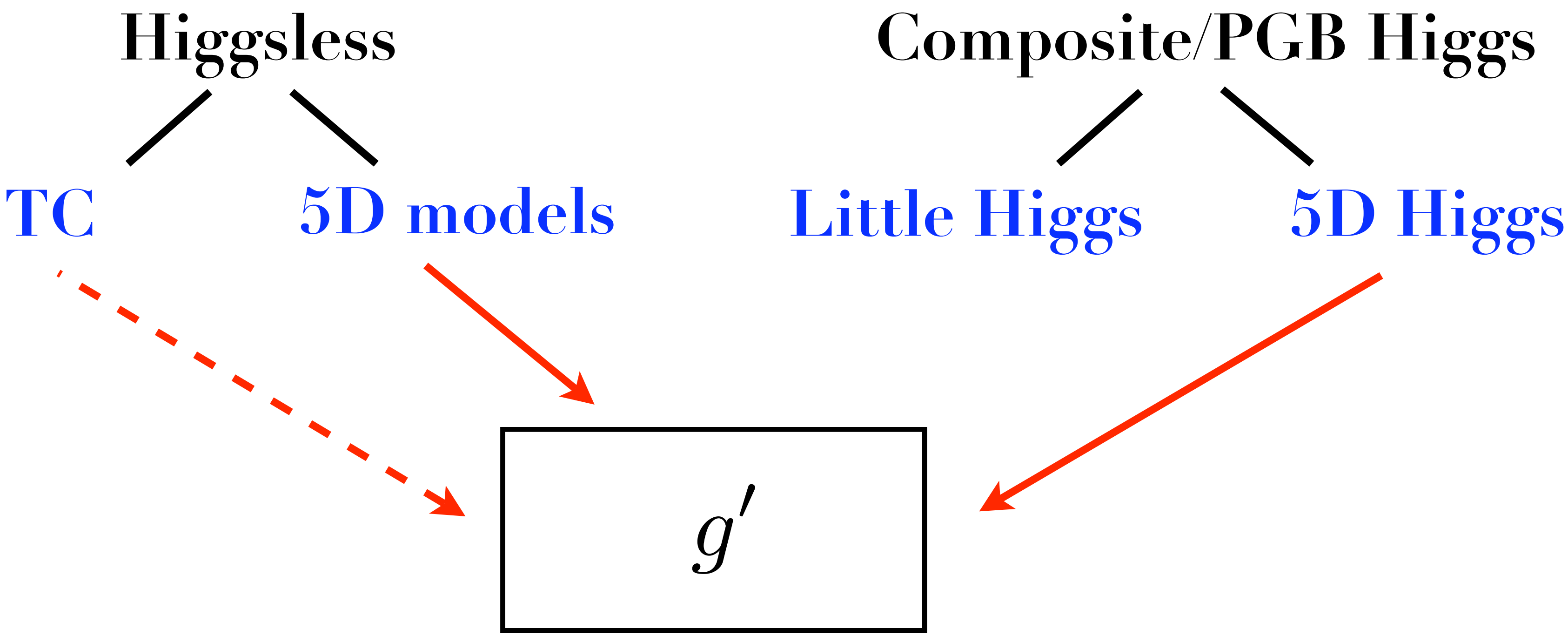
- TC
- 5D models

Composite/PGB Higgs

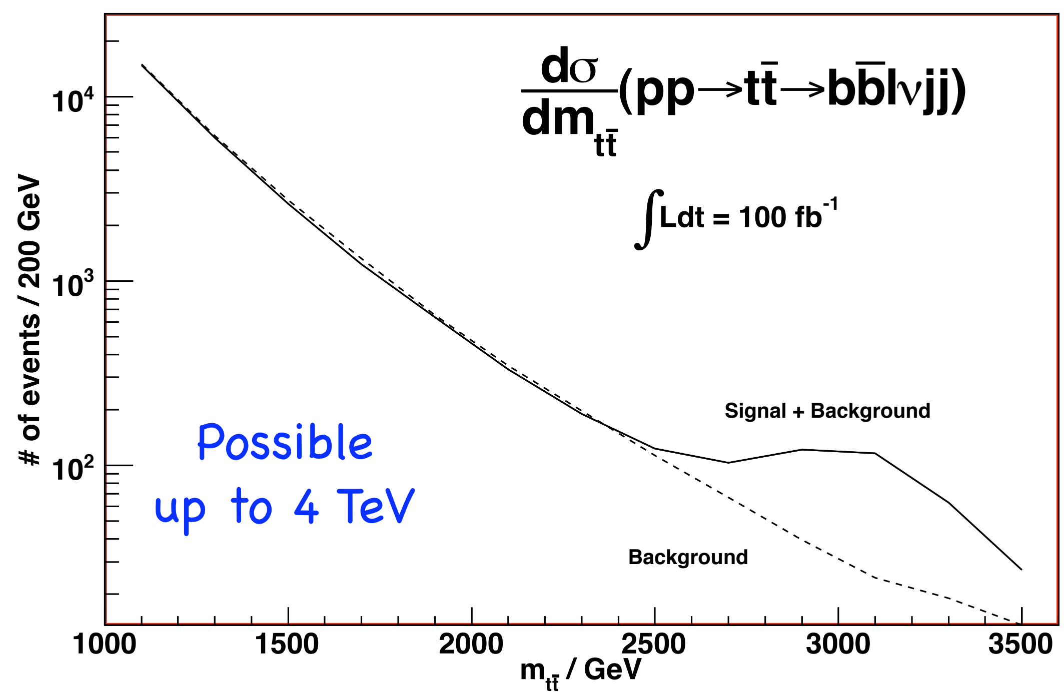
- Little Higgs
- 5D Higgs


Higgsless
Composite/PGB Higgs
TC
5D models
Little Higgs
5D Higgs
W', Z'

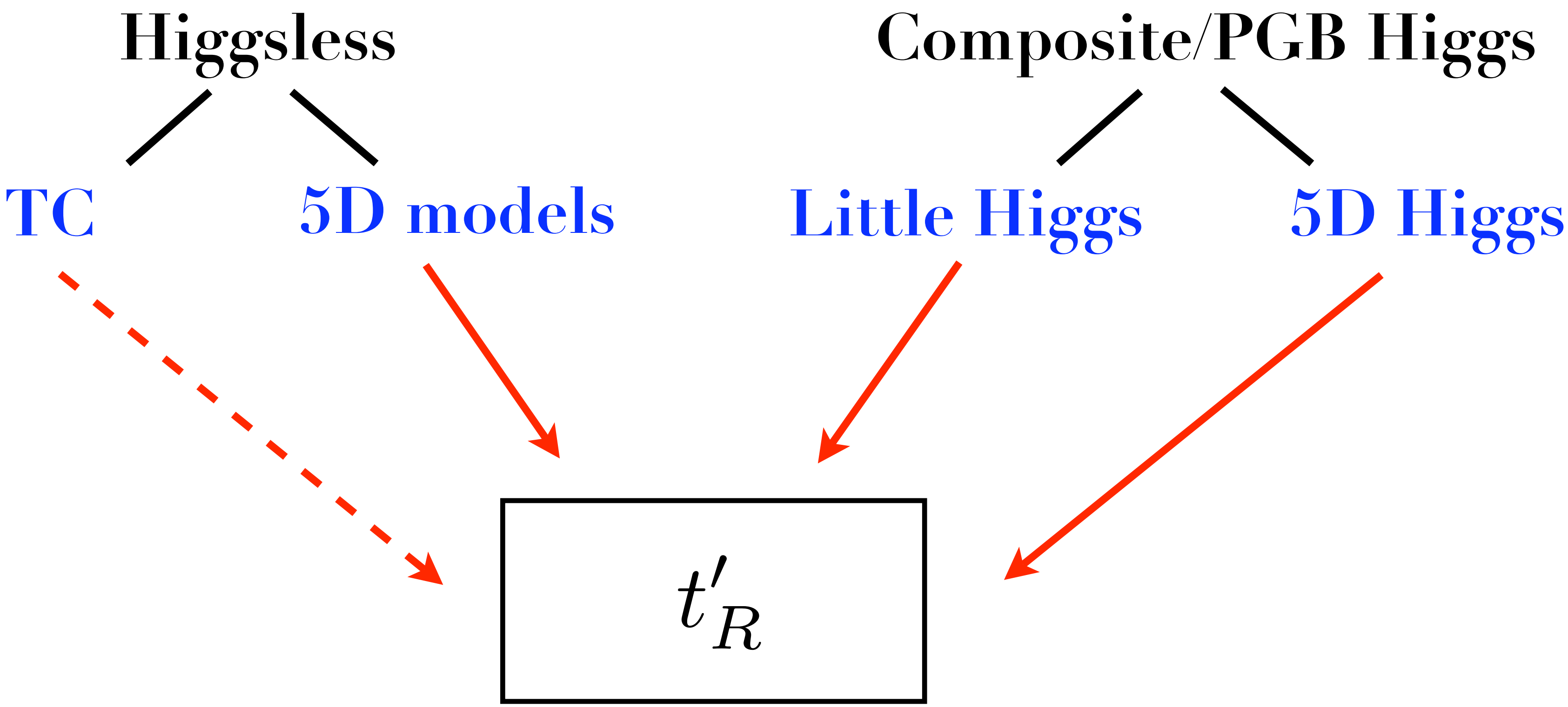

Higgsless
Composite/PGB Higgs
TC
5D models
Little Higgs
5D Higgs
W', Z'
Decay:
$W', Z' \rightarrow$ leptons
$W', Z' \rightarrow \text{tops}, W_{long}, Z_{long}, h$
Possible to see up to 2 TeV



Decay: $g' \rightarrow t\bar{t}$

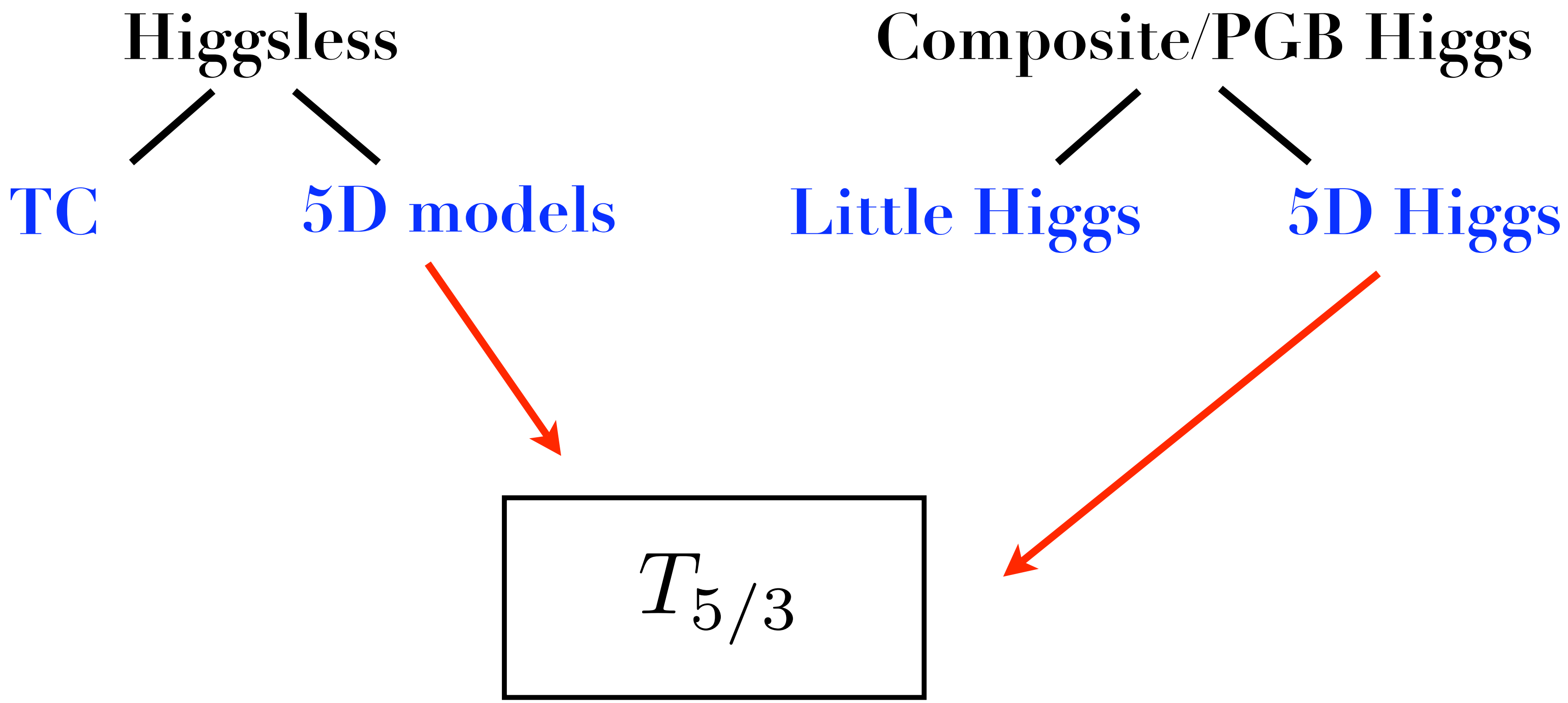


Agashe et al



Decay: $t'_R \to W_{long} b$

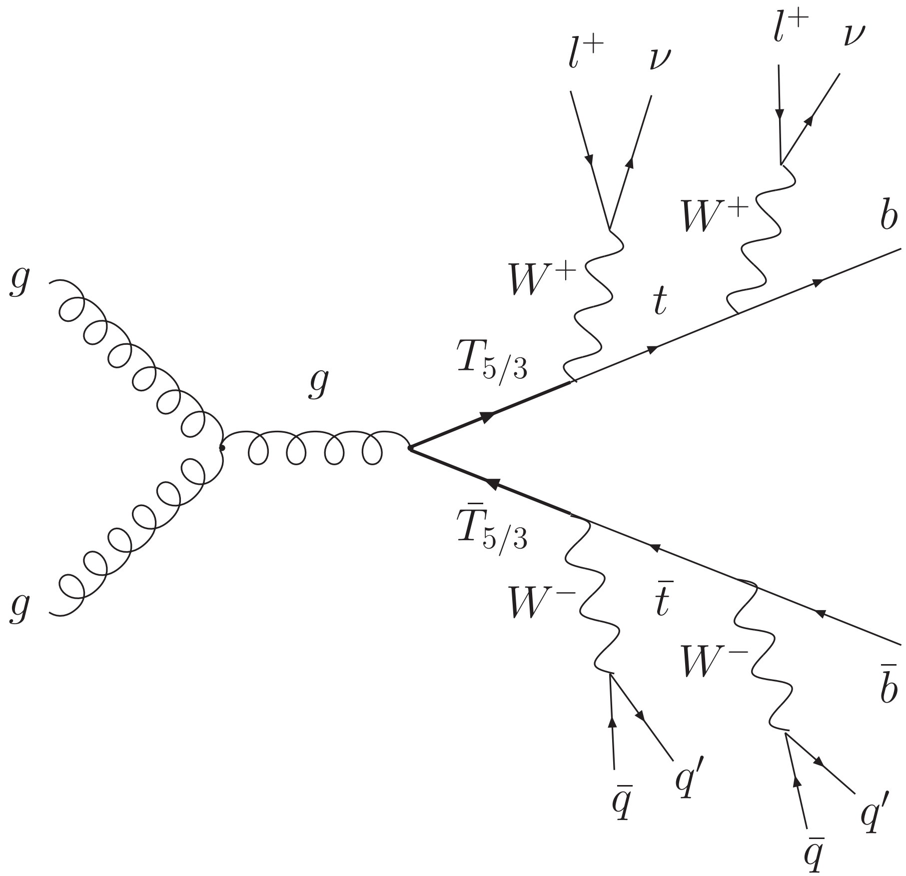
feasible to see up to 1-2 TeV



Decay: $T_{5/3} \longrightarrow W_{long} t$

feasible to see up to 1-2 TeV

If this fermion is light, it can be double produced:



two like-sign leptons

masses up to 1 TeV reached with an integrated luminosity of 20/fb

Contino,Servant

Other possibilities: More PGB scalars:

Gripaios, AP, Riva, Serra

Example: G=SO(6) broken to SO(5) delivers 5 PGB:

One Higgs doublet (h) + Singlet (η)

Possibility for a new Higgs decay:

$$h \longrightarrow \eta\eta \longrightarrow b\bar{b}b\bar{b} \text{ or } \tau\bar{\tau}\tau\bar{\tau}$$

(depending on the η-mass)

In these cases, Higgs h can be lighter than LEP bound 114 GeV

Chang, Dermisek, Gunion, Weiner

Conclusions

There are alternatives to the MSSM:

e.g. composite/PNGB Higgs

→ Worthy to be explored at the LHC

Signals:

- Higgs couplings different from the SM, and strong WW-scattering at high E
- W',Z'-type resonances: Quite generic
- Gluonic resonances: Cleanest signature
- Fermionic resonances: Lightest states "partners" of the top → although also exotic states, e.g. Q=5/3
- Extra PNGB