Strong Dynamics and “New” Electroweak Models

Alex Pomarol (Univ. Autonoma Barcelona)

At 2011, still two paradigm for EWSB:

- Weakly coupled (Elementary) Higgs = SM

  Naturalness ➠ Supersymmetric SM

- Strongly-coupled "Higgs" ➠ Composite Higgs or Higgsless (e.g. Technicolor)

At present, <u>no serious hints</u> for one or the other!

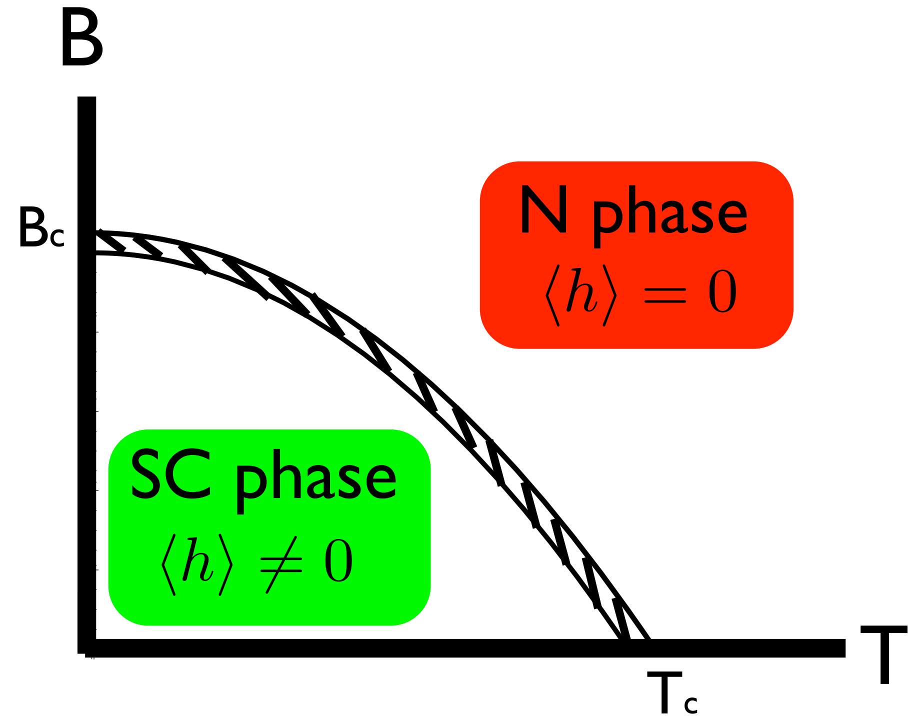
Symmetry Breaking by a non-elementary Higgs

Nature uses it often...

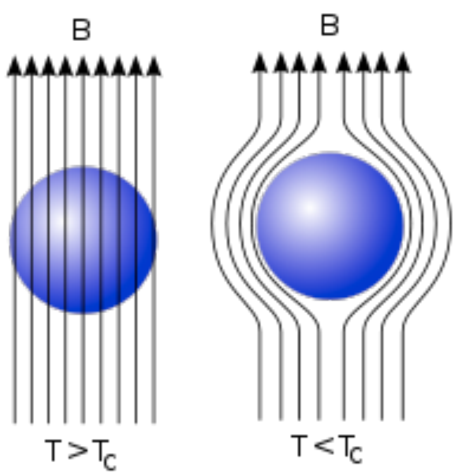
1) Superconductors:

Breaking of $U(1)_{EM}$ inside the material by a "cooper pair":

$$\langle h \rangle = \langle e^- e^- \rangle$$



Explains:



2) QCD: Symmetry Breaking of the Chiral Symmetry

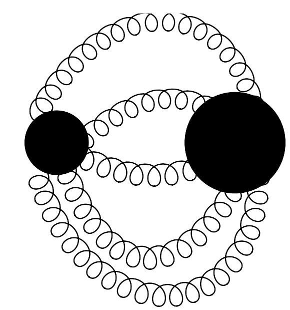
Considering only two quarks in the massless limit,

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

QCD has an accidental global symmetry (Chiral Symmetry):

$SU(2)_L \times SU(2)_R$

It's broken by the quark condensate: $h \equiv \langle q\bar{q} \rangle \neq 0$



$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ *Isospin*

3 Goldtones:

π^+, π^-, π^0

EW symmetry broken by the QCD condensate!

Symmetry Breaking by a non-elementary Higgs

Apply similar ideas for EWSB:

There is a new Strong Sector at the TeV responsible for EWSB

"Simple minded" option:

Technicolor = Replica of QCD at E~TeV

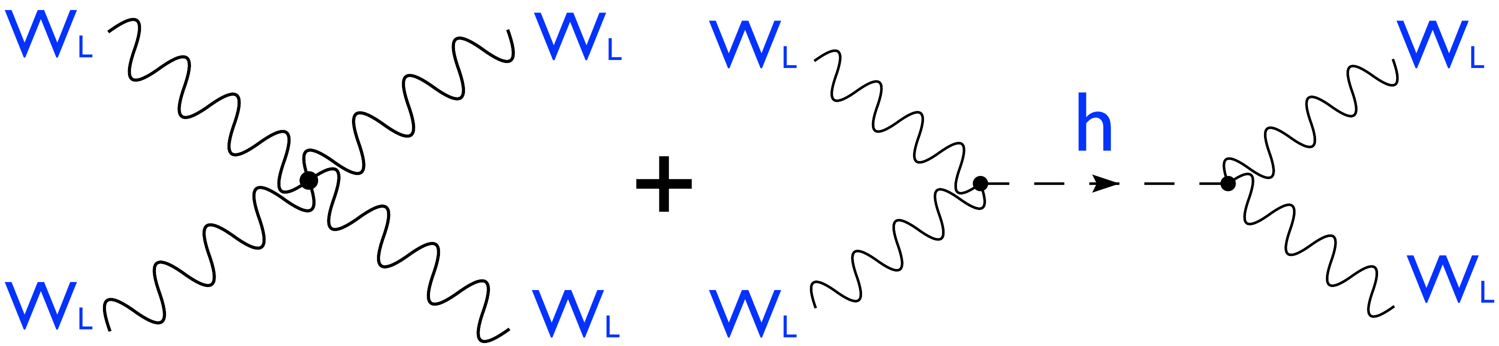
"Higgs" = composite object $\langle Q'\bar{Q}'\rangle$

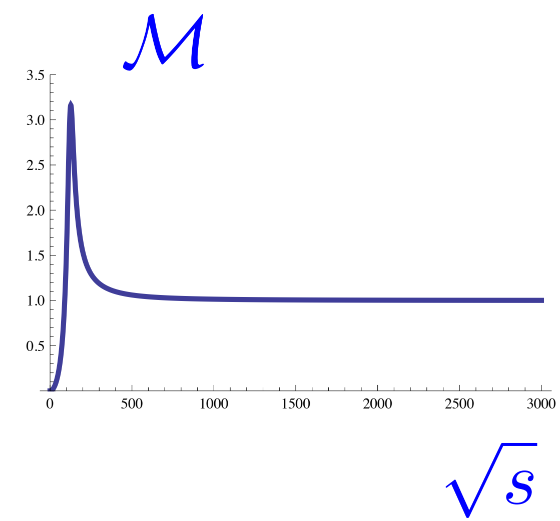
But no light scalar playing the role of the SM Higgs

➥ **Higgsless models**

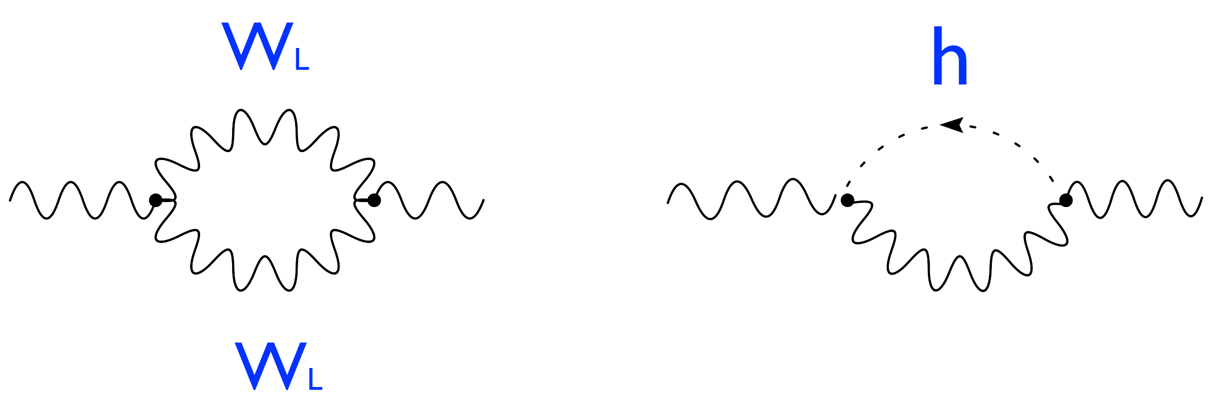
Role of the **SM Higgs**:

1) Unitarization: Amplitudes do not grow with E





2) Crucial to give one-loop finite results:



Higgsless theories must contain extra spin=0,1,... **resonances** (as in QCD)

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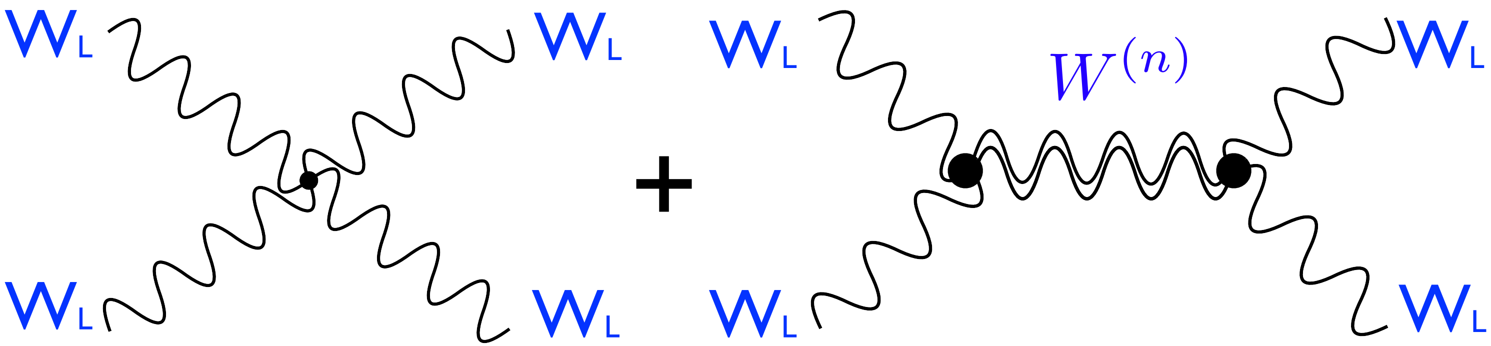

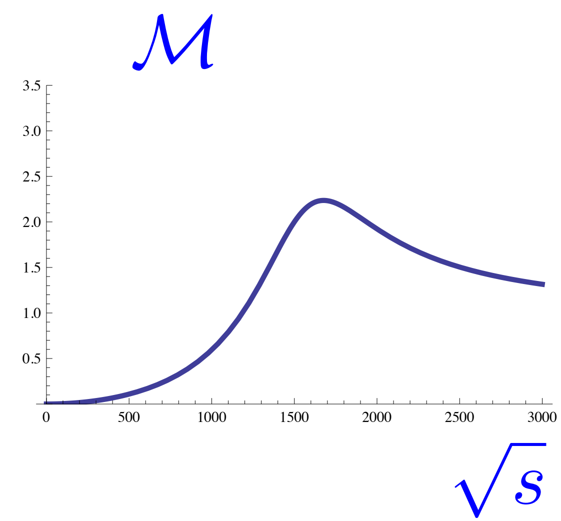

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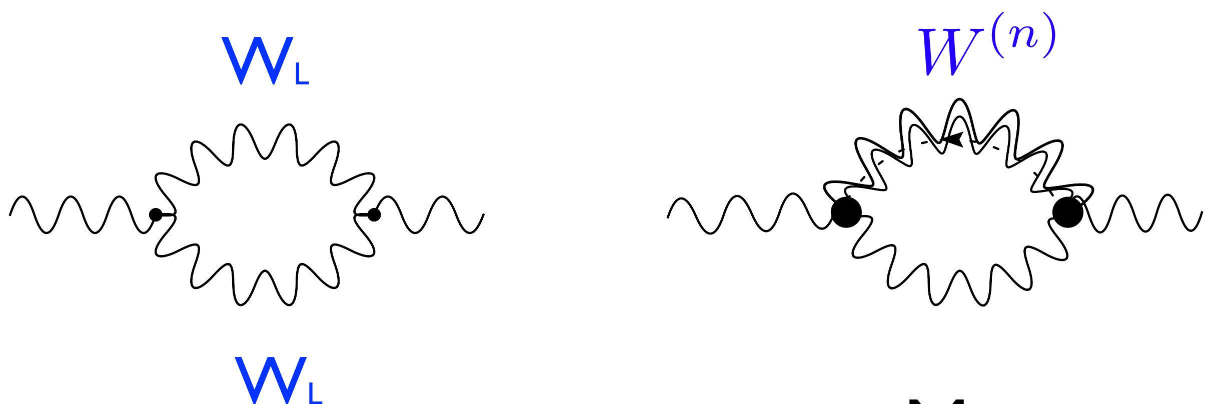


Masses of $W^{(n)}$ ~ TeV

Main objection to these scenarios → EWPT

Sizable effects on the W and Z propagators
(highly constrained by LEP & Tevatron)

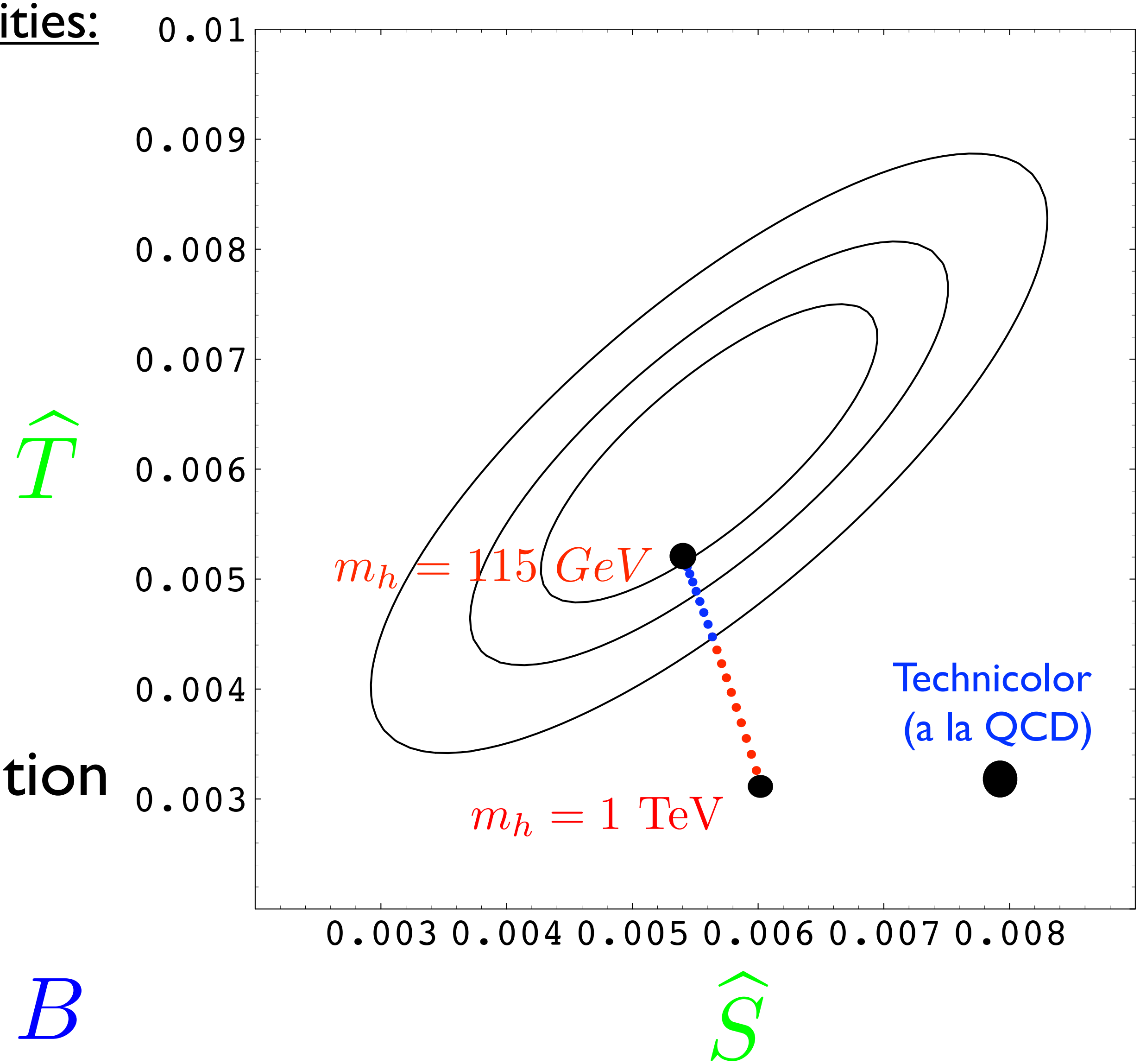
<u>Effects parametrized by two quantities:</u>

$$\hat{S} \quad = \quad g^2 \, \Pi'_{W_3B}(0)$$

$$\hat{T} \quad = \quad \frac{g^2}{M_W^2} \, [\Pi_{W_3}(0) - \Pi_{W^+}(0)]$$

Peskin, Takeushi

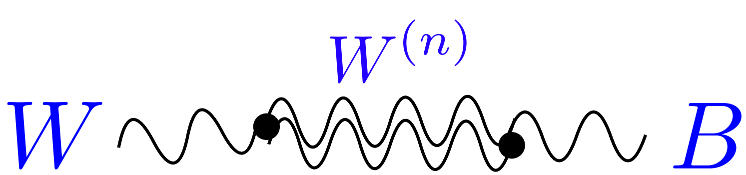
Barbieri, AP, Rattazzi, Strumia



Two main contributions:

a) No light Higgs

b) Extra tree-level contribution from resonances:



Two attitudes:

1) Extra contributions (vertex effects, extra fermions, presence of a dilaton,...) will put the Higgsless models inside the S-T ellipse

2) Precision EW data points towards the existence of a light Higgs... but not necessarily elementary

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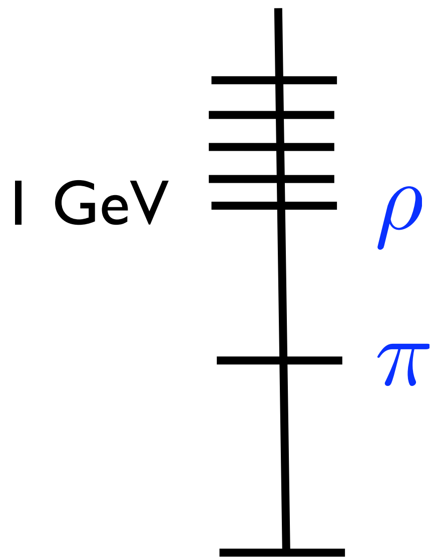
➥ **Composite light Higgs**

First question for this scenario:
Why the Higgs is going to be lighter than the other resonances of M~ TeV?

We can again get some inspiration from QCD:
There one observes that the (pseudo) scalar are the lightest states

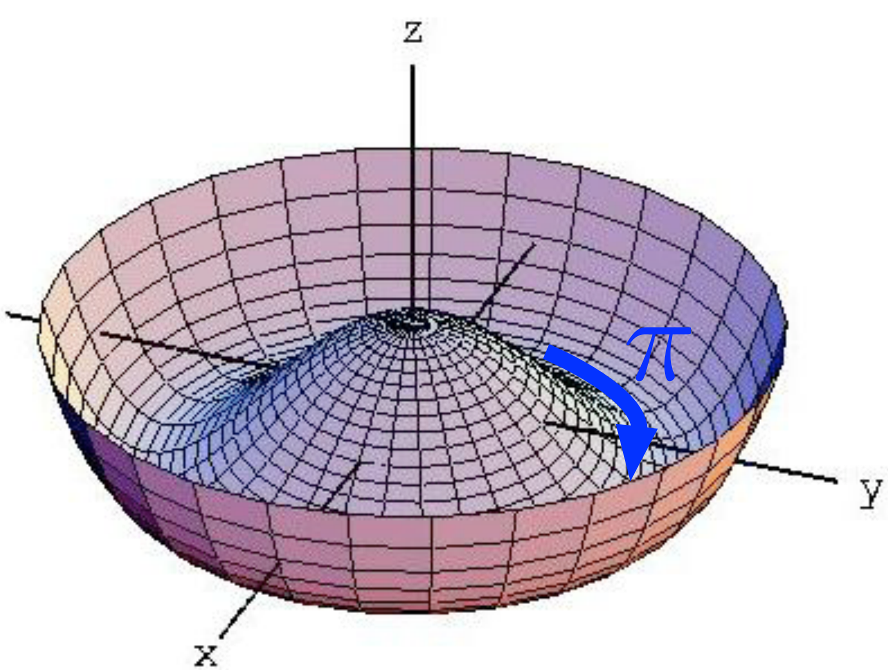
Spectrum:



Are Pseudo-Goldstone bosons (PGB):

From the spontaneous breaking
$SU(2)_L \times SU(2)_R \to SU(2)_V$

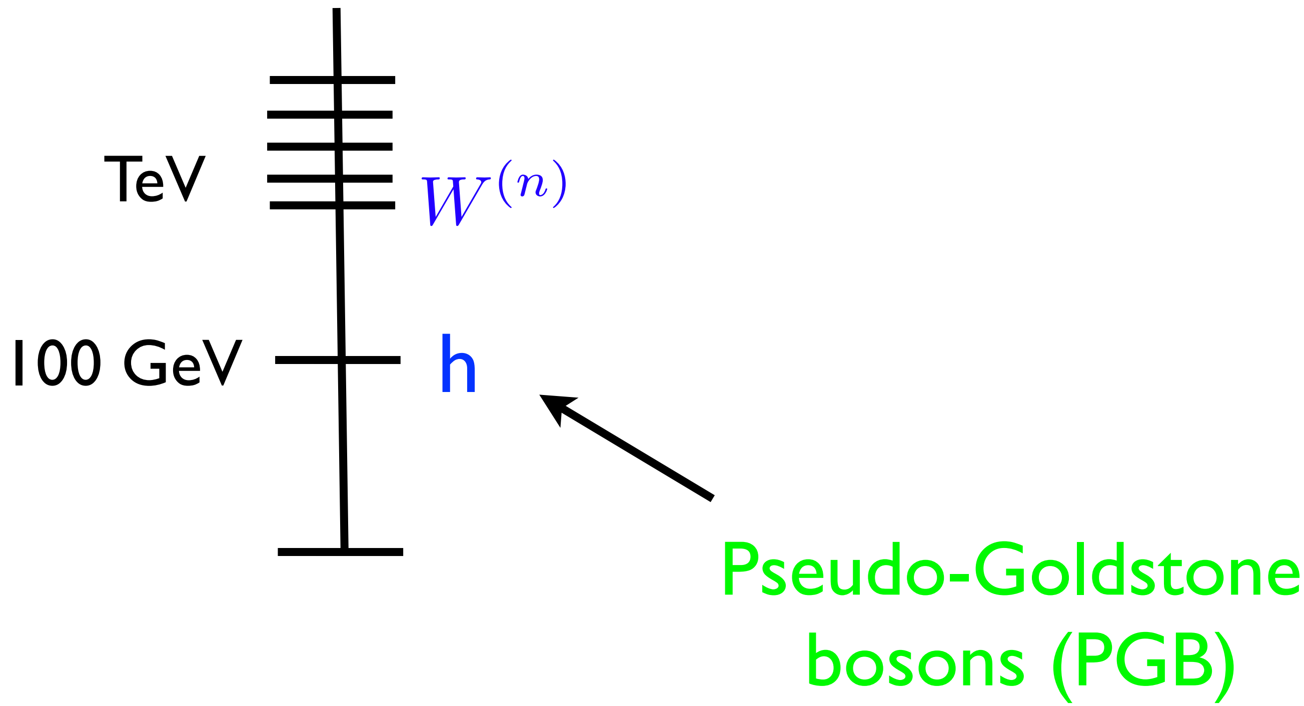
3 Goldtones:
π^+, π^-, π^0



massless up to explicit breaking terms

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

We'd like the spectrum of the new strong sector to be:



Quantum numbers of the Goldstones fixed by the Symmetry Breaking Pattern in the new Strong sector:

G→H

Possible symmetry patterns:

G	H	PGB
SO(5)	O(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	O(4)xO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

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Agashe, Contino, AP

one doublet

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Gripaios, AP, Riva, Serra

One doublet
+ Singlet

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Two doublets

J.Mrazek, A. P., R. Rattazzi, M. Redi, J. Serra and A. Wulzer, in preparation

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Good: Scalar (PGB) spectrum fixed by symmetries

Bad: Not clear which G/H should be considered

➡ **Not clear that minimality is a good guide**

Fermionic Sector: Couplings of the Higgs to SM fermions

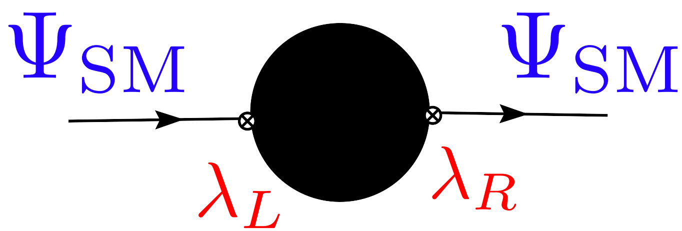
Recent proposal: Assume that elementary SM fermions mix with fermionic resonances of the strong sector:

"Partial-compositeness"

Agashe,Contino,A.P.
early work by D.Kaplan

$$\mathcal{L}_{\rm int} = \lambda \Psi_{\rm SM} \Psi_{compo}$$

Generation of masses from mixing:



$\sim \lambda_L \lambda_R$

Relatively safe from FCNC!

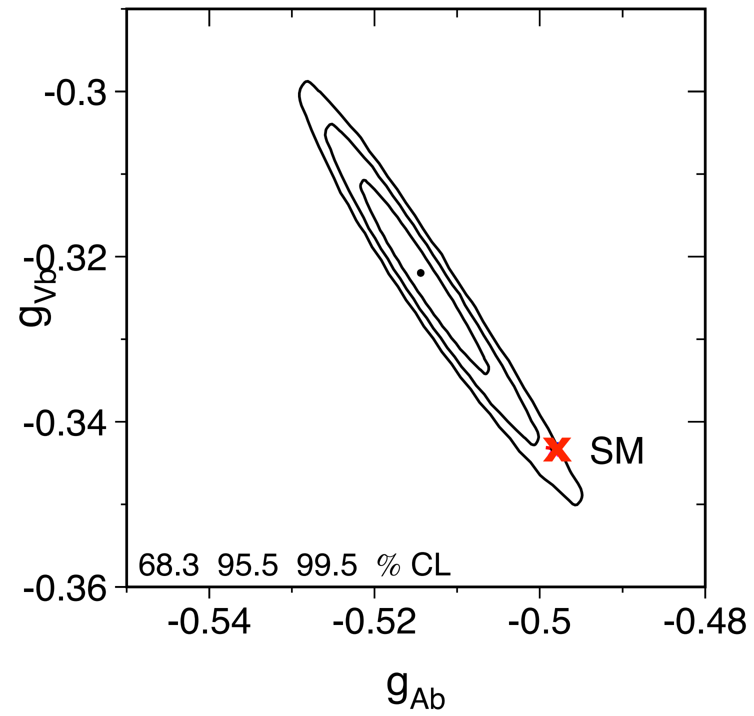
Implications:

- Fermionic partners for all SM fermions
- The larger λ, the larger the mixing, the larger the mass:

3rd family most sensible to Strong Dynamics ➡ Expected deviations in their couplings

Certain experimental hints for compositeness in the 3rd family:

~3 sigma discrepancy for the Forward-Backward Asymmetry of the bottom from LEP/SLD experiment



~3 sigma discrepancy for the Forward-Backward Asymmetry in Top production at Tevatron

time will tell us...

Full model? What's the strong sector made of?

Not has been possible yet!

At 2011, LHC must be our guide from now on...

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Nevertheless, calculable models can be obtained by the AdS/CFT correspondence:

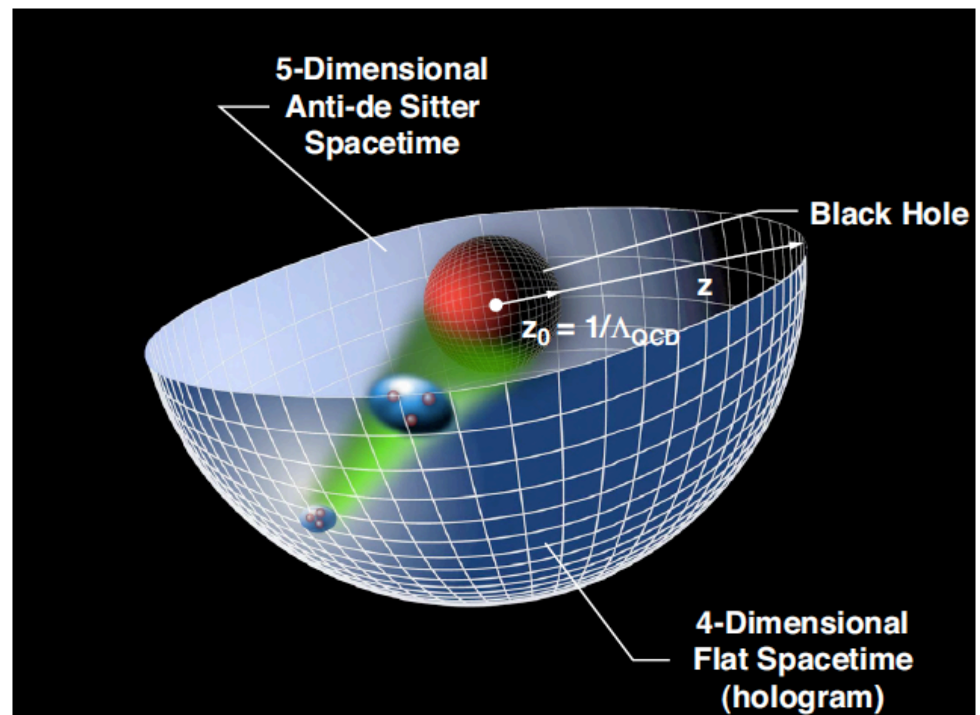
Maldacena 98

Strongly-coupled theories $\approx$ Models with extra warped dimensions

The 4D composite properties of the Higgs are due to its 5D nature

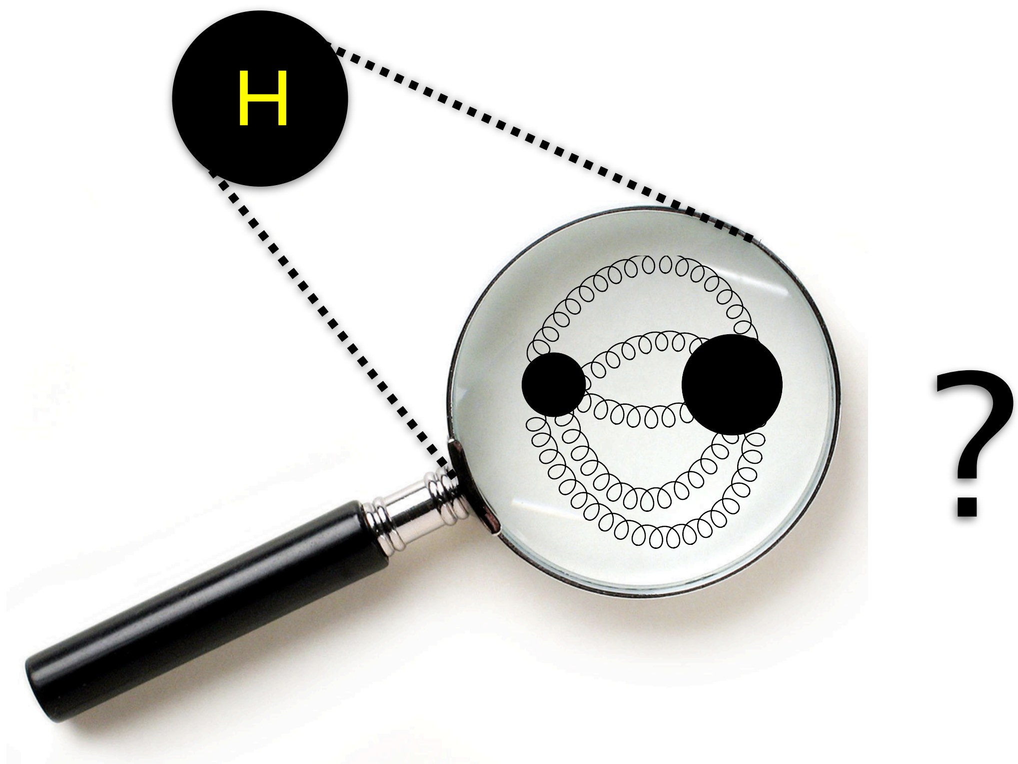
Higgs as an "hologram"

Contino,Nomura,AP 03



Picture from
G.F. de Teramond

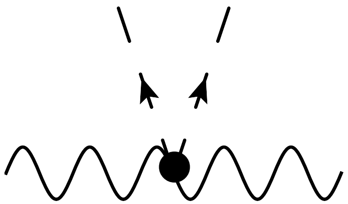
How to unravel the composite nature of the Higgs?



Look for deviations on Higgs couplings

Couplings can be very different for a composite Higgs

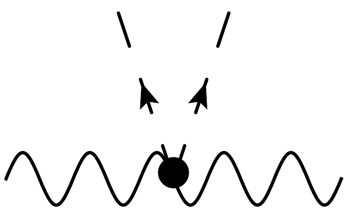
For example, for an elementary Higgs:



$$gWWh^2 \underset{\text{EWSB}}{\longrightarrow} gWW(v^2 + 2vh + h^2)$$

$$h \to v + h$$

For a composite Higgs:



$$gWWf(h) \underset{\text{EWSB}}{\longrightarrow} gWW(f(v) + f'(v)h + \cdots)$$

E.g. For a Pseudo-Goldstone Higgs:

$$f = \sin h\,,\ f' = \cos h: \quad \text{If} \quad f \to 1\ , \quad f' \to 0\ !!$$

➥ Non-zero W masses but no coupling of h to WW

Parametrization of deviations from SM Higgs couplings

Contino et al 10

$$\mathcal{L} = \frac{M_V^2}{2} V_\mu^2 \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_f \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right) + \cdots$$

SM Higgs: $a = b = c = 1$

Minimal Composite Higgs:

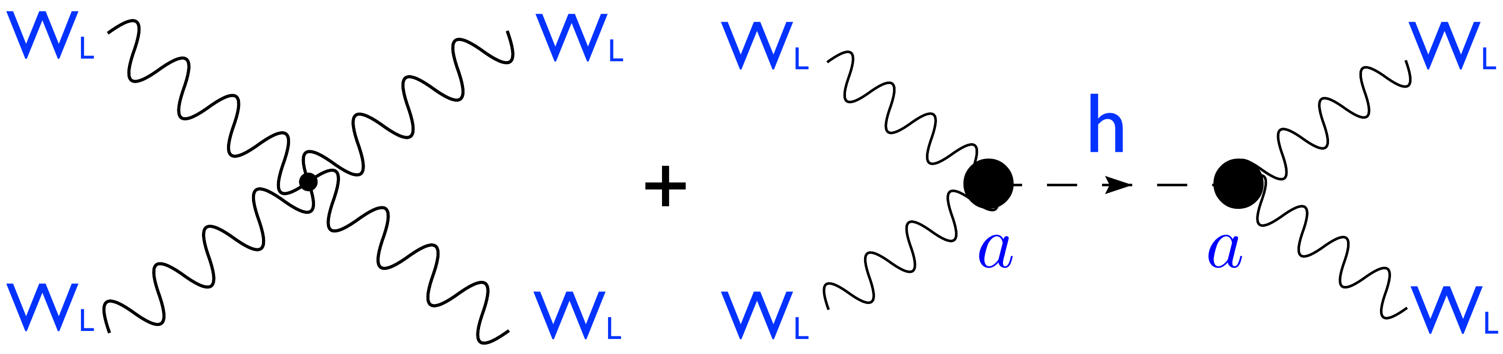
Giudice,Grojean,AP,Rattazzi 07

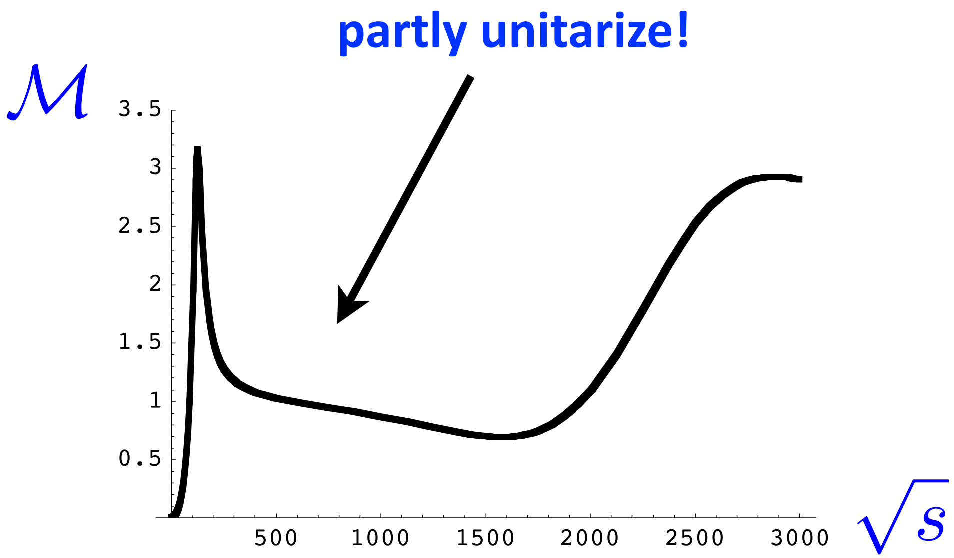
$$a = \sqrt{1 - \frac{v^2}{f^2}} \qquad b = 1 - \frac{2v^2}{f^2} \qquad c = \sqrt{1 - \frac{v^2}{f^2}}$$

Scale related to the composite-scale

expected value: f ~ v

Composite Higgs only partly does the job of a **true** Higgs





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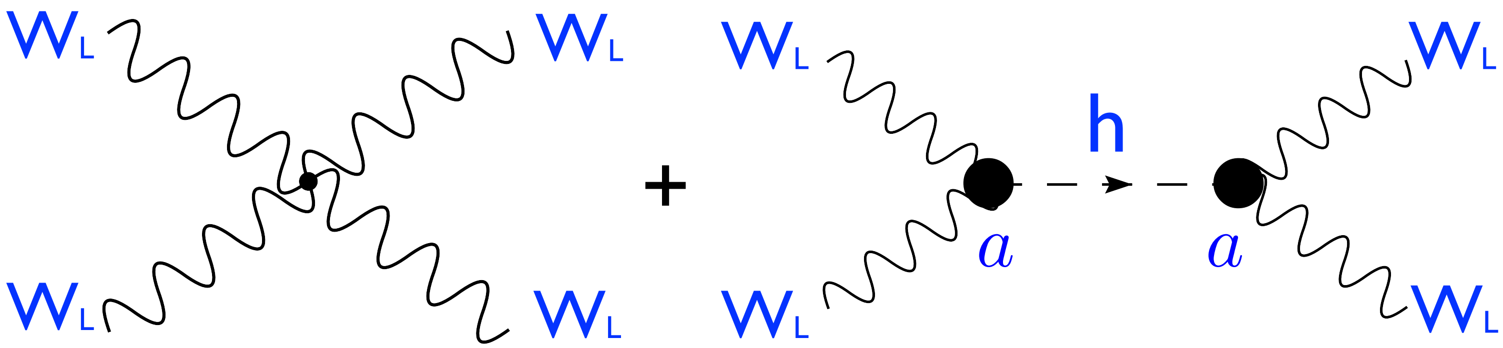

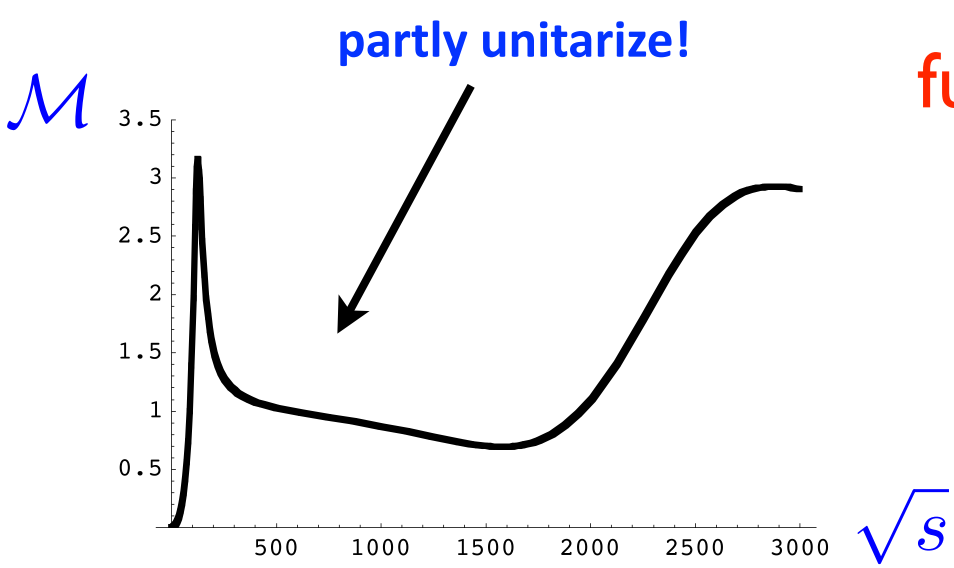

Extra states needed to fully unitarize (for consistency)!

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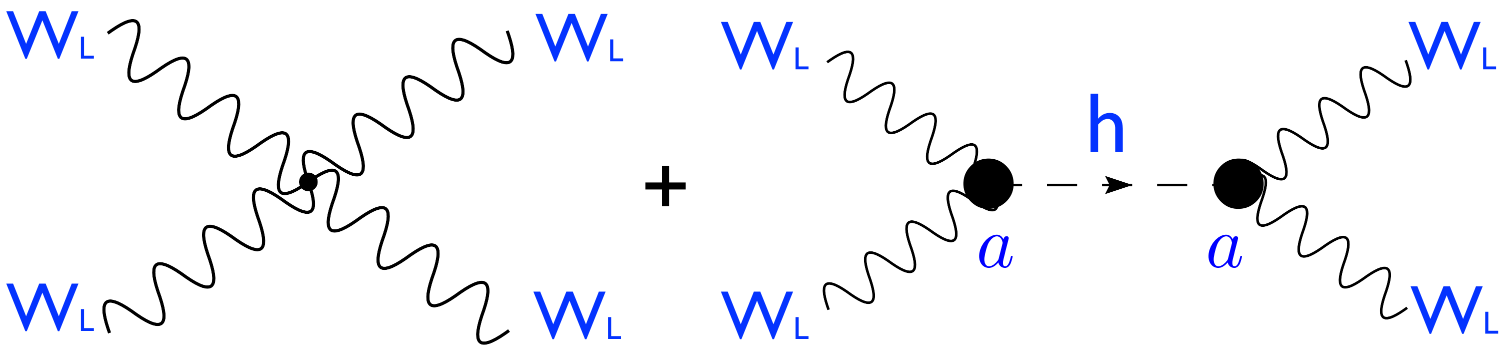

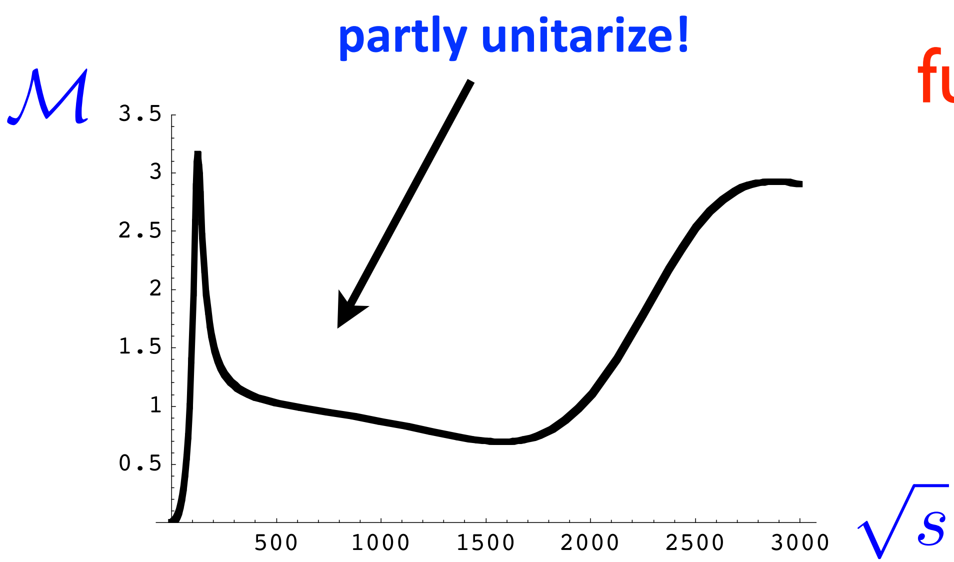

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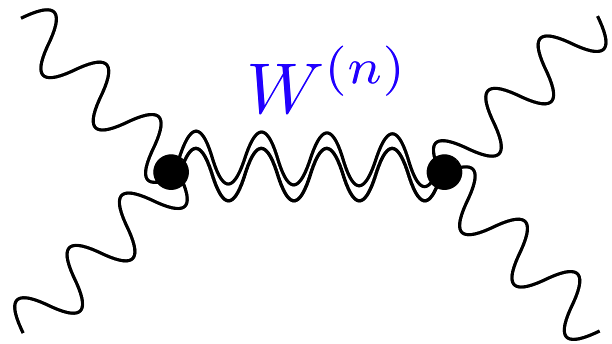

Extra resonances

(as in QCD)

$$M_{W^{(n)}} \simeq \frac{2\ \mathrm{TeV}}{\sqrt{1-a^2}}$$

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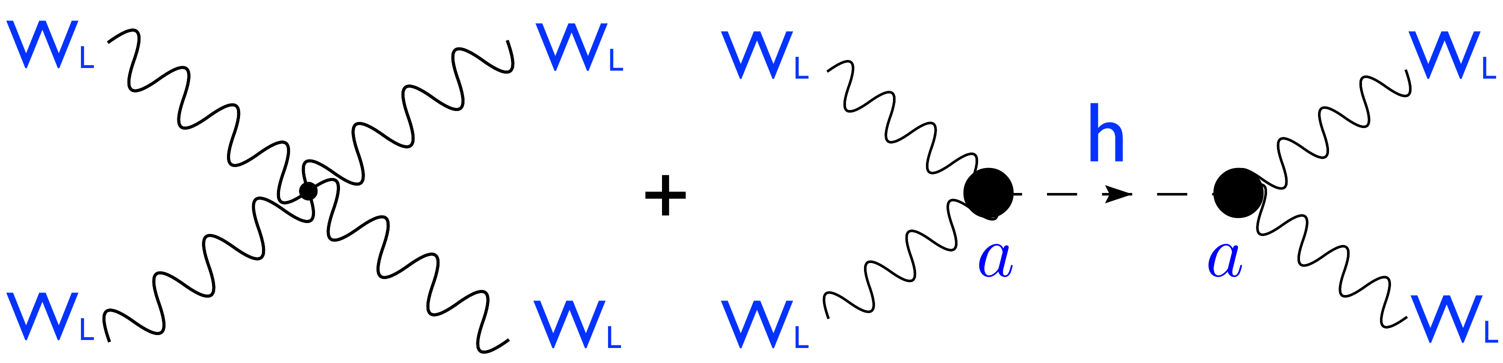

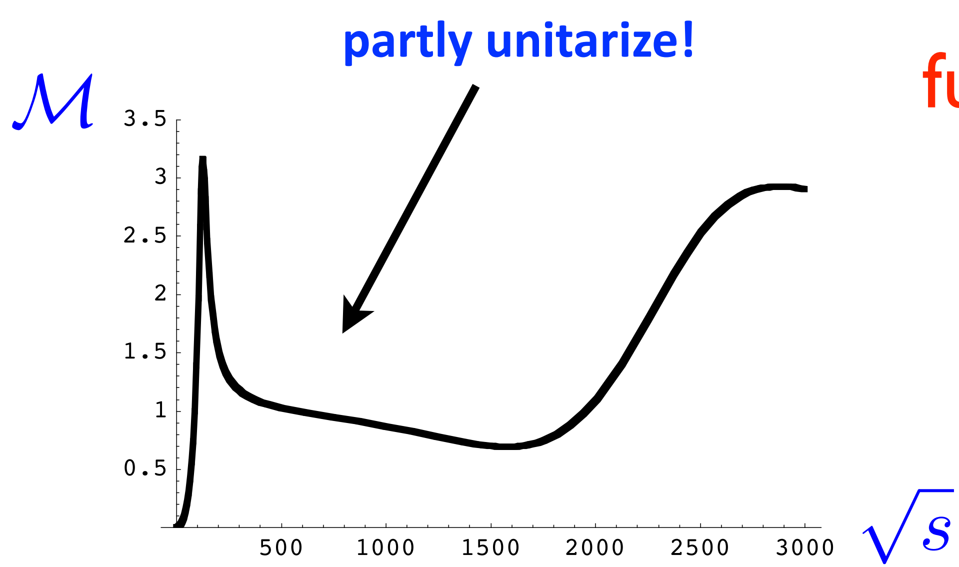

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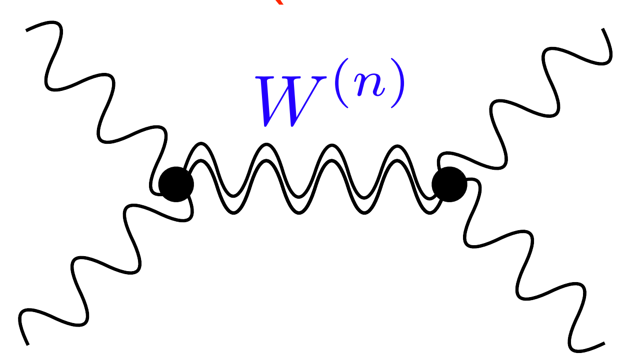
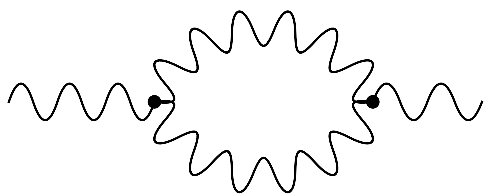


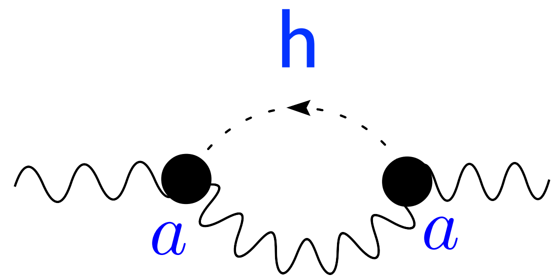
Extra resonances
(as in QCD)

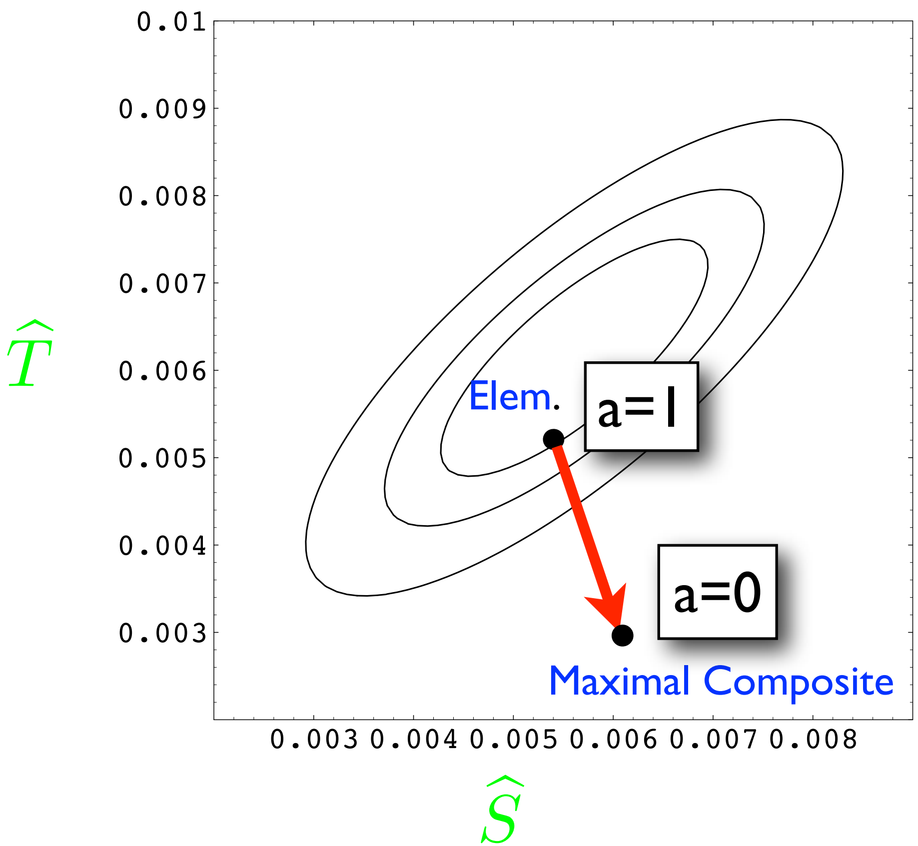
$$M_{W^{(n)}} \simeq \frac{2\ \mathrm{TeV}}{\sqrt{1-a^2}}$$

In the limit a=0 (~ **Higgsless**)
composite Higgs not at all a Higgs
Resonances do all the job!

Maximal degree of compositeness (a~0) not allowed by EWPT







$$\hat{T} = \frac{g^2}{M_W^2}\left[\Pi_{W_3}(0) - \Pi_{W+}(0)\right]$$

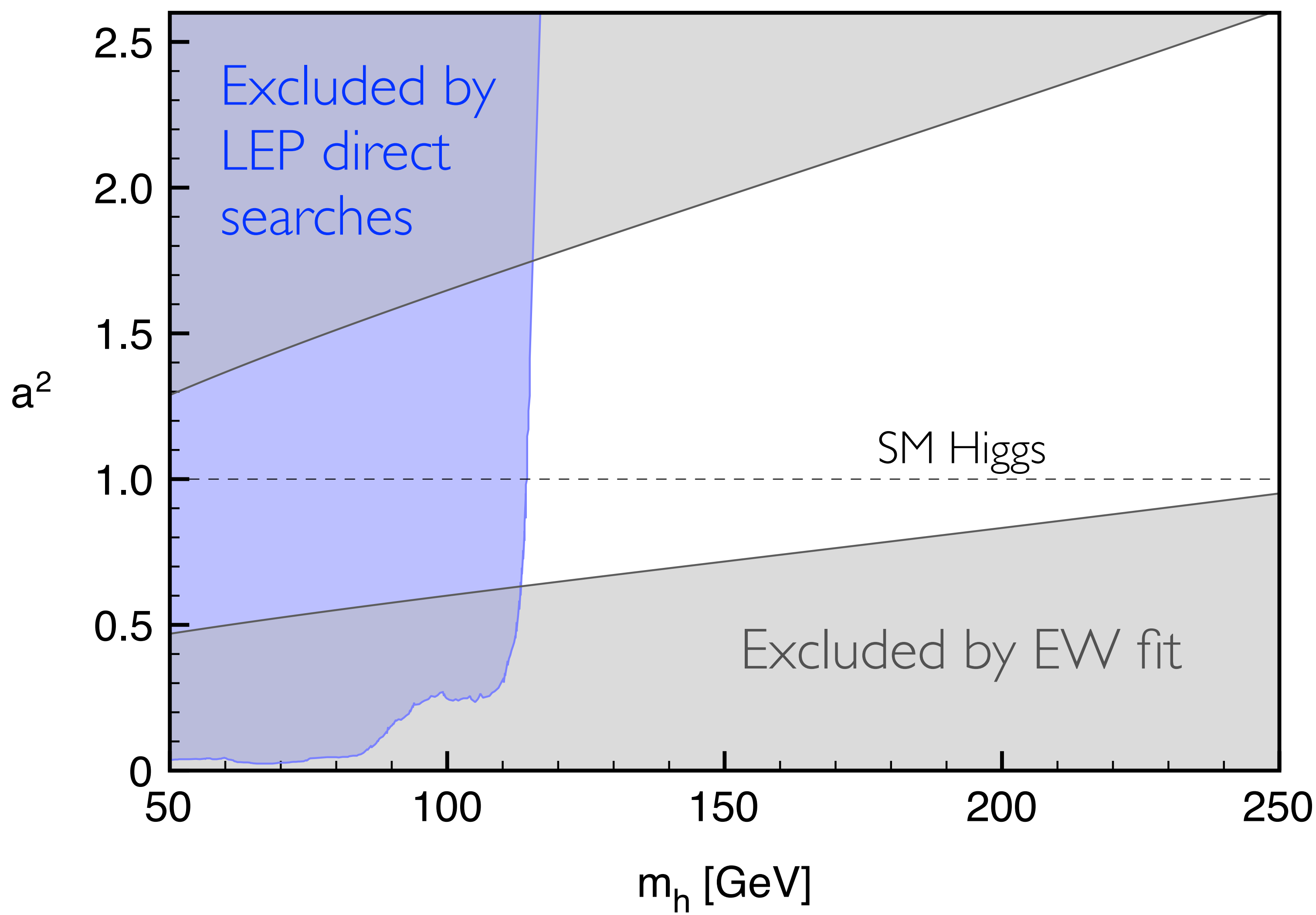
$$\hat{S} = g^2\, \Pi'_{W_3 B}(0)$$

➡ a > 0.86

Put a bound on the scale of compositeness: f>500 GeV

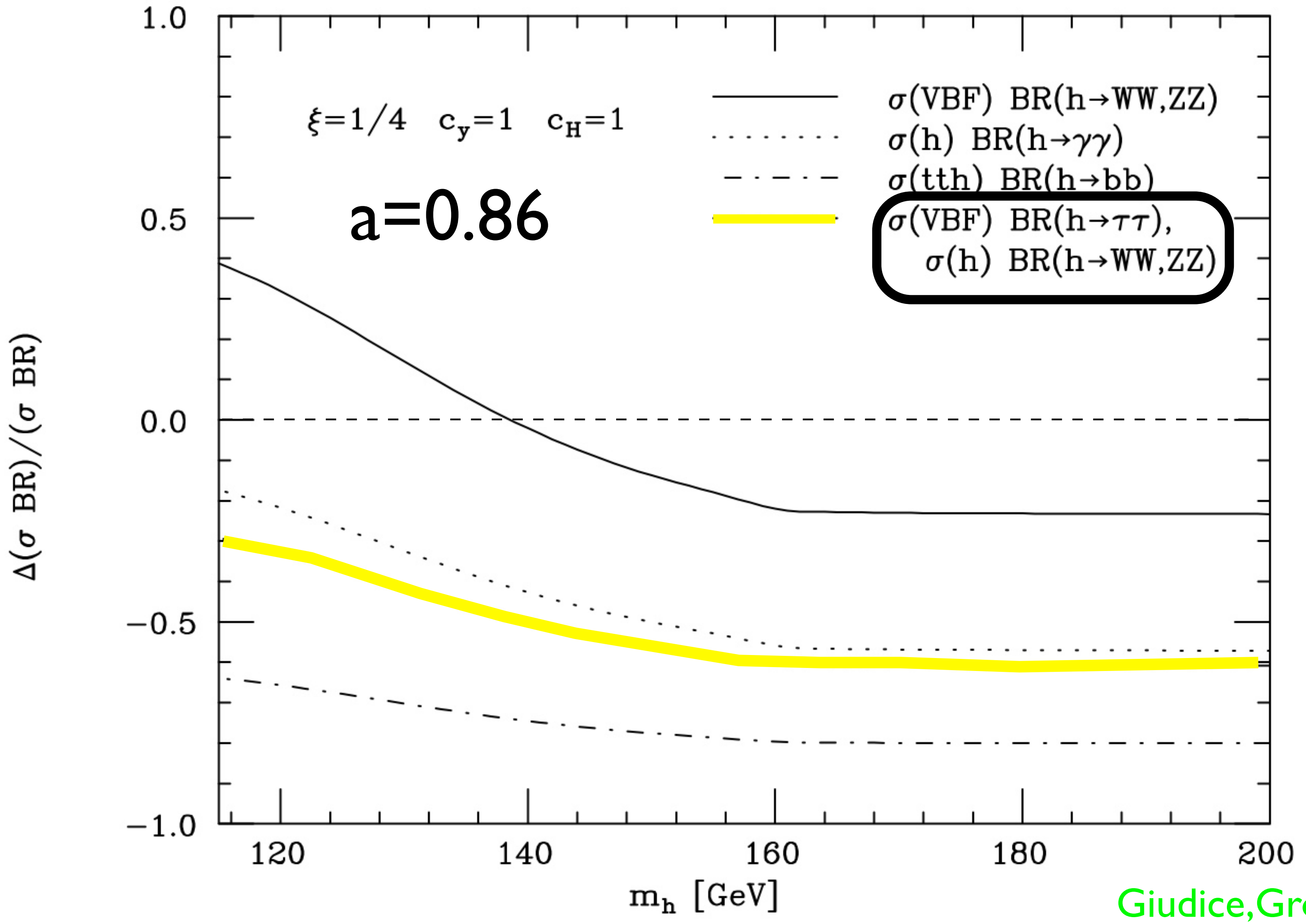
More precise:

Contino at Planck10



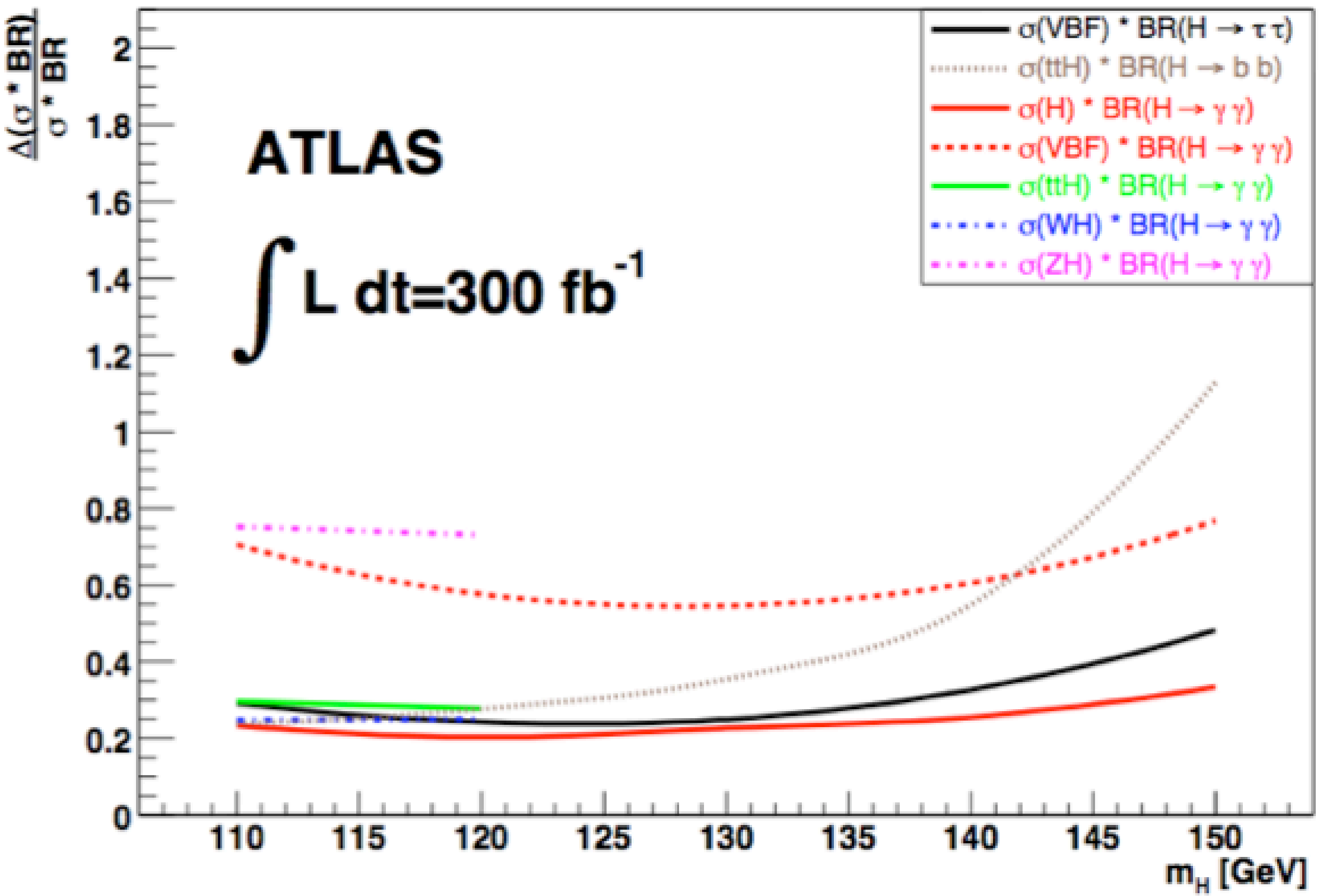
If the Higgs is **composite**, how it will change LHC predictions?

Bad news: Reduction of rates!



Giudice,Grojean,AP,Rattazzi 07

see also, Grojean,Espinosa,Muhlleitner 10



Duhrssen 03

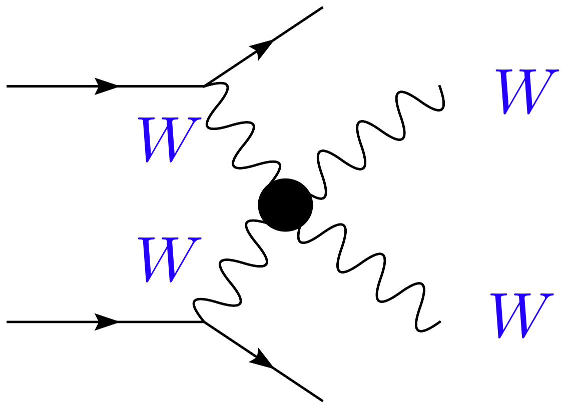
Higgs coupling measurements ~ 20-40%

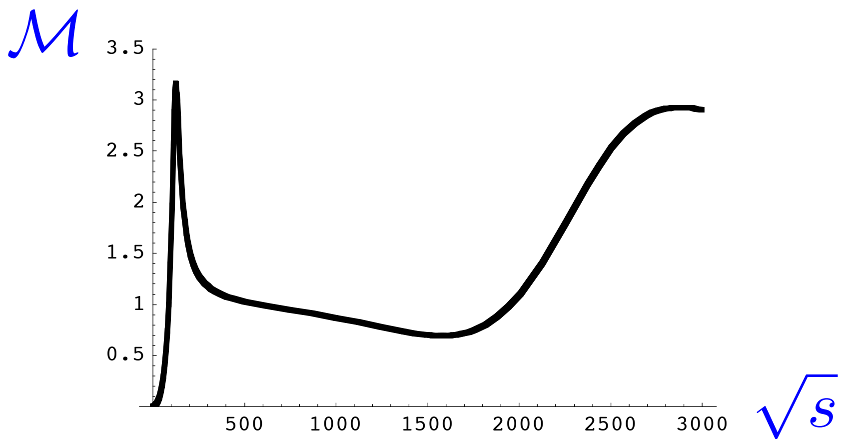
recent studies Lafaye,Plehn,Rauch,Zerwas,Duhrssen 09

ILC would be a perfect machine to test this scenario:
effects could be measured up to a few %

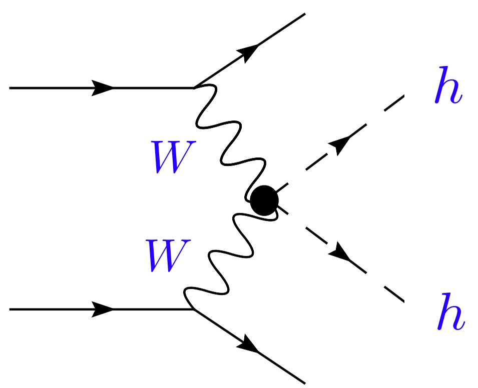
Genuine properties of the **composite** nature of the Higgs

1) W_LW_L -scattering grows at high energy





2) Double-Higgs production grows at high energy



In the best cases "3σ signal significance with 300/fb collected at a 14 TeV LHC"

Contino et al 10

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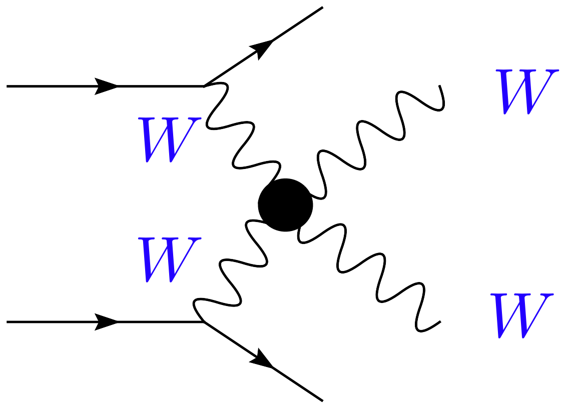

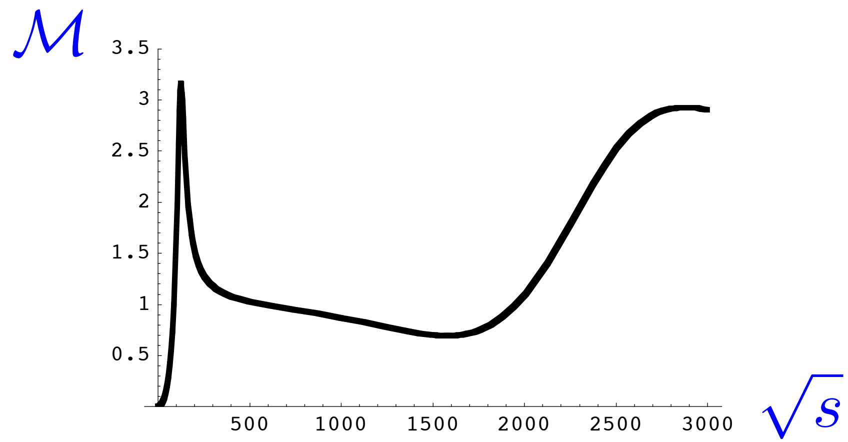

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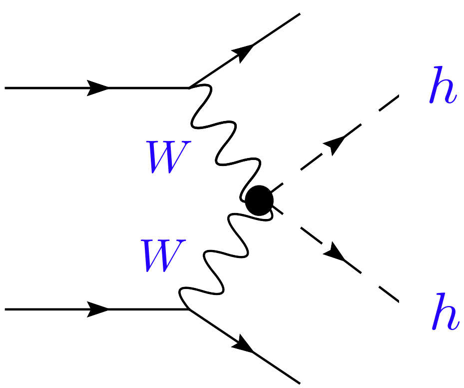

$$pp \to hhjj \to 4Wjj \to \begin{cases} l^+l^+l^-l^- \not{E}_T + 2j \\ l^+l^-l^\pm \not{E}_T + 4j \\ l^{+(-)}l^{+(-)} \not{E}_T + 5j\,(6j) \end{cases}$$

Contino et al 10

In the best cases "3σ signal significance with 300/fb collected at a 14 TeV LHC"

If SO(6)→SO(5) breaking pattern: Doublet h +Singlet η

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$$\frac{f^2}{8}\,\mathrm{Tr}|D_\mu\Sigma|^2 = \frac{f^2}{2}(\partial_\mu h)^2 + \frac{f^2}{2}(\partial_\mu \eta)^2 + \frac{f^2}{2}\frac{(h\partial_\mu h + \eta\partial_\mu\eta)^2}{1-h^2-\eta^2}$$

$$+\frac{g^2 f^2}{4}h^2\left[W^{\mu+}W^-_\mu + \frac{1}{2\cos^2\theta_W}Z^\mu Z_\mu\right]$$

Gripaios, AP, Riva, Serra

$h\eta\eta$ coupling:

$$-\frac{f^2\langle h\rangle}{2}\eta^2\partial_\mu^2 h$$

Fixed by symmetries !!

Possibility for a new Higgs decay:

(depending on the η-mass)

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

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

Chang, Dermisek, Gunion, Weiner

What about indirect signatures of composite Higgs?

As in QCD, detecting other hadrons was an indication of pion compositeness → **Look for resonances**

(Kaluza-Klein-states)

Predictions:

W'
Z'
γ'
t'
.
.
.

} Extra heavy copies of the SM states
M~ TeV

Not have been accessible yet

Waiting for the LHC!

From AdS/CFT, predictions can be made:

Spectrum

the higher the spin,
the higher the mass

Mass	State
4 TeV	graviton resonance
2.5 TeV	gauge resonance: W′,Z′
500-1500 GeV	top fermionic resonances with exotics: (color=**3**, weak=**2**,Y=7/6)
100-200 GeV	Higgs

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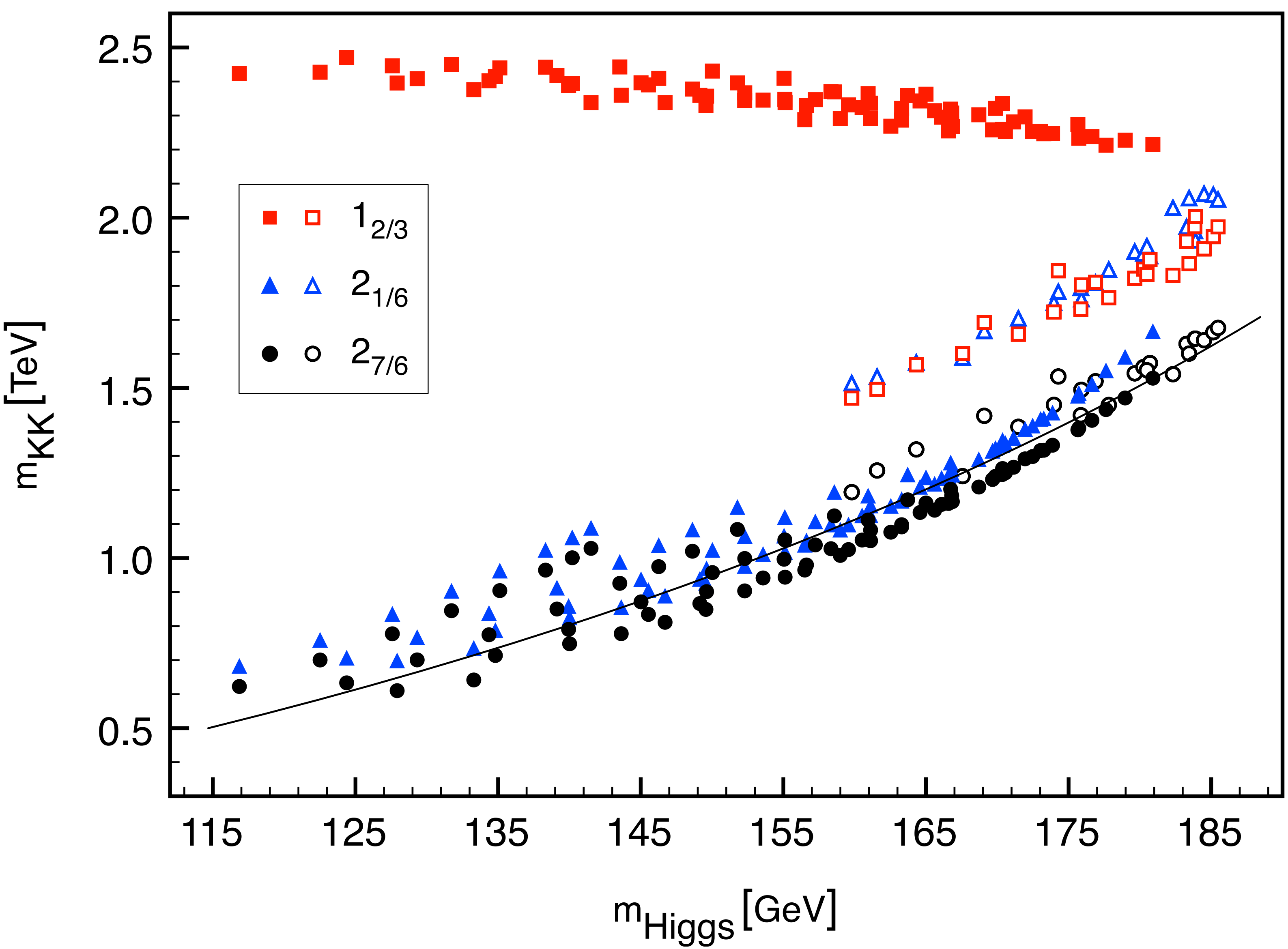
500-1500 GeV — top fermionic resonances with exotics: (color=**3**, weak=**2**,Y=7/6)

100-200 GeV — Higgs

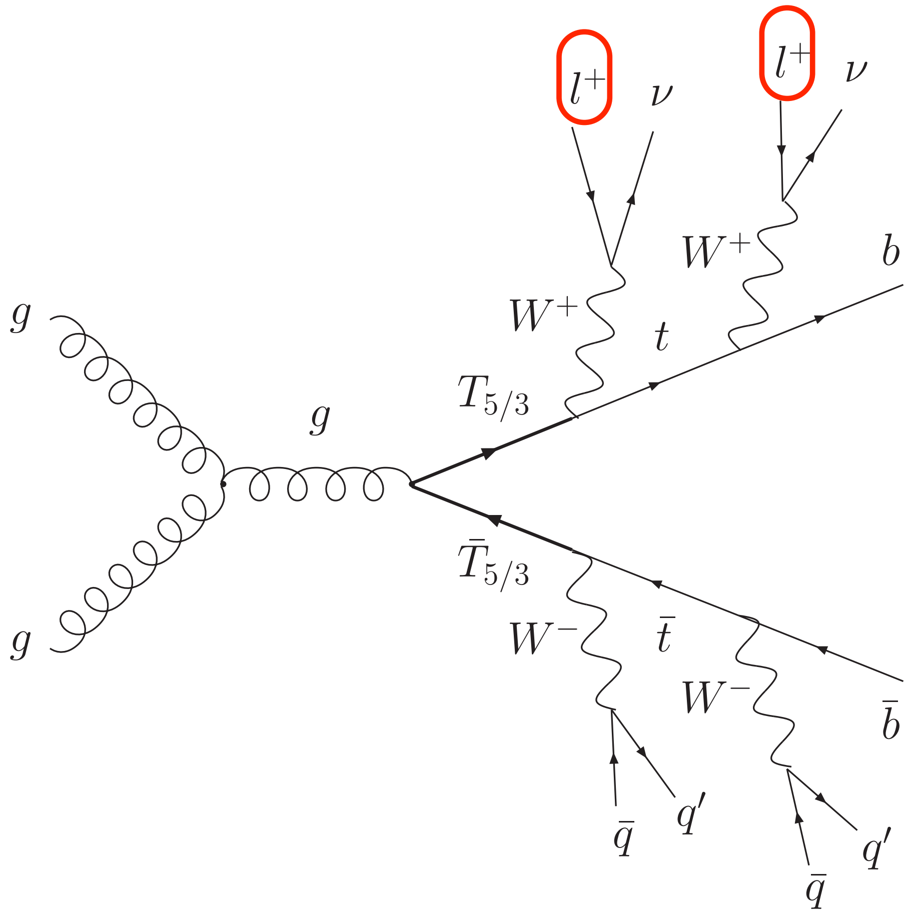
“Smoking Gun” possible at first LHC run

Correlation between the Higgs mass and the mass of the fermionic resonances:



Color vector-like fermions with charge 5/3:

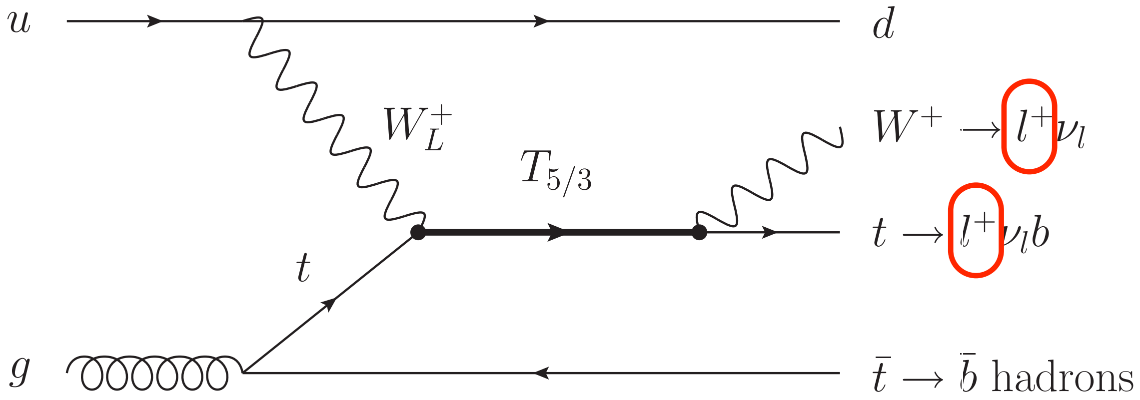
If this fermion is light, it can be double produced:

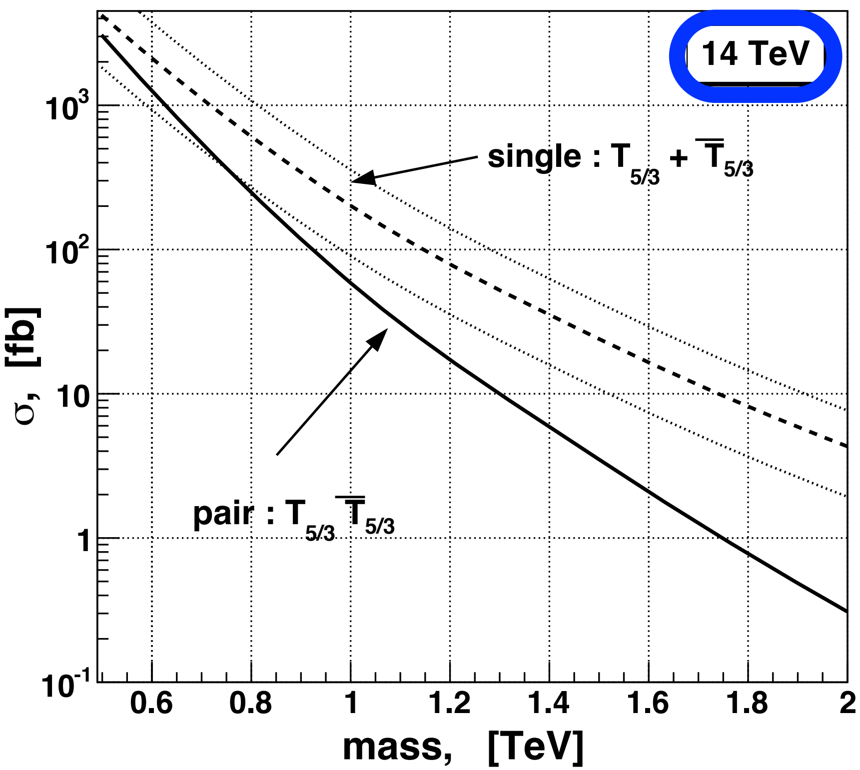


same-sign di-leptons

Contino,Servant
Mrazek, Wulzer
Aguilar-Saavedra,
Dissertori, Furlan,Moorgat,Nef

If too heavy, it can be single produced:





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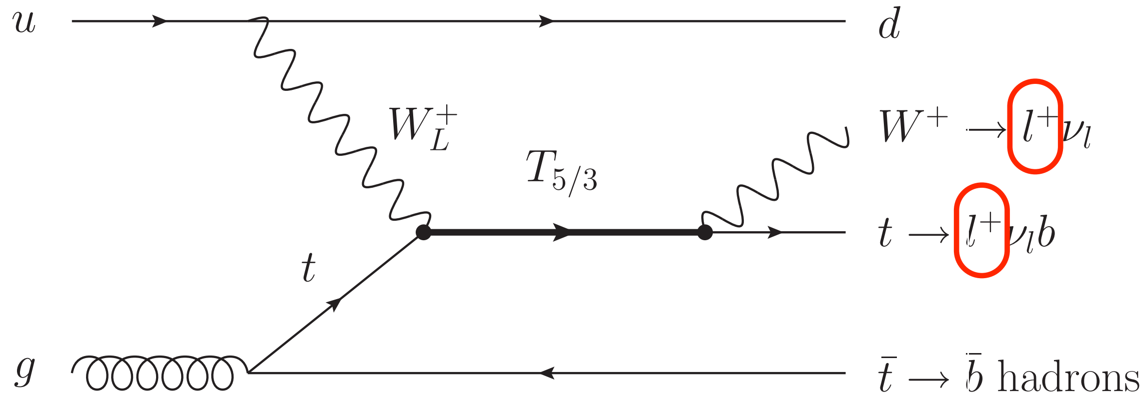
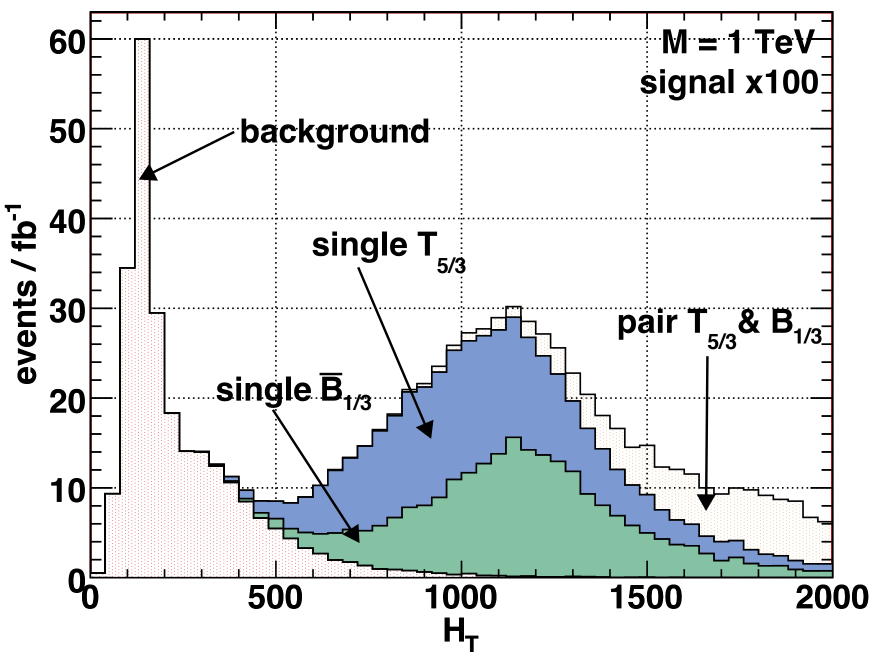
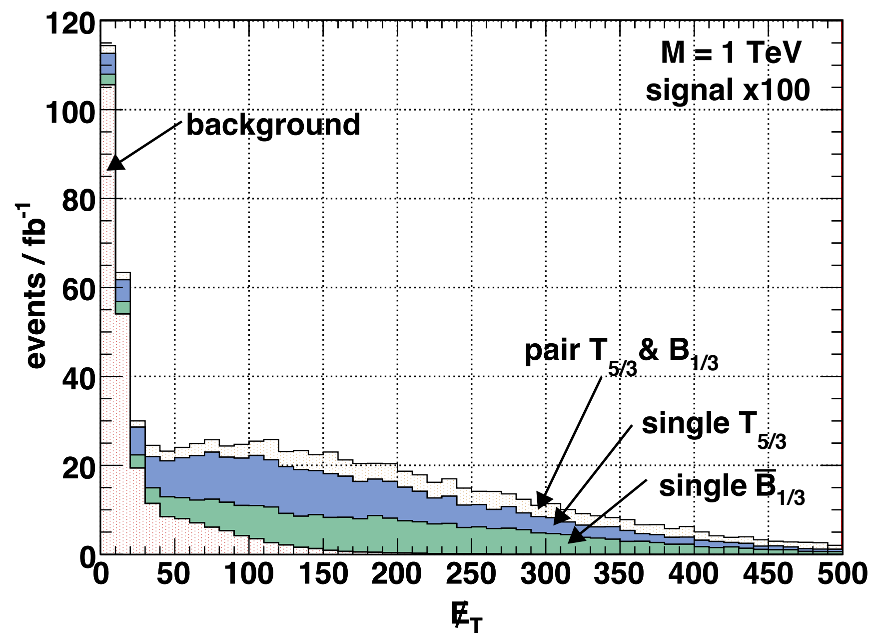


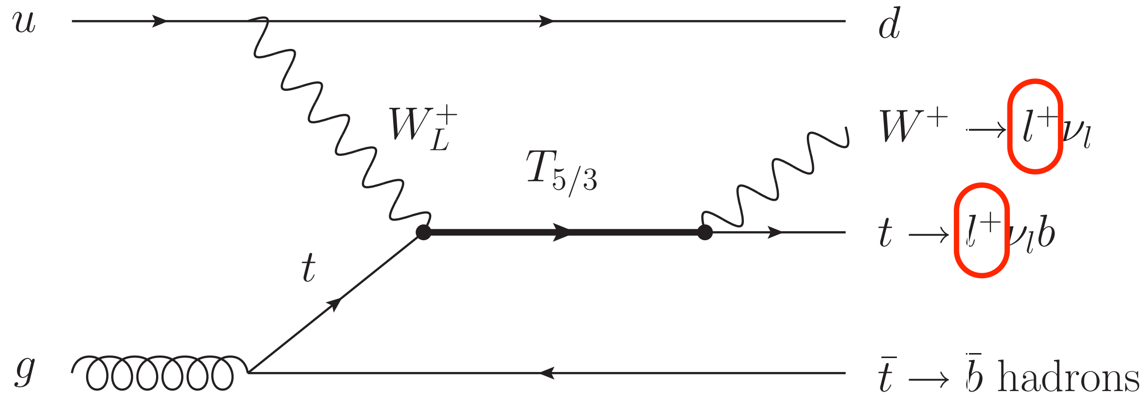
Mrazek, Wulzer





$$H_T = \sum_{J,L,\not{E}_T} |\vec{p_T}| \, .$$

If too heavy, it can be single produced:



Mrazek, Wulzer

Mass, [TeV]	$L_{\text{discovery}}$, [fb^{-1}]	# signal	# background
0.5	0.024	5	0
1.0	1.103	8	2
1.5	26.40	17	11
2.0	326.7	28	31

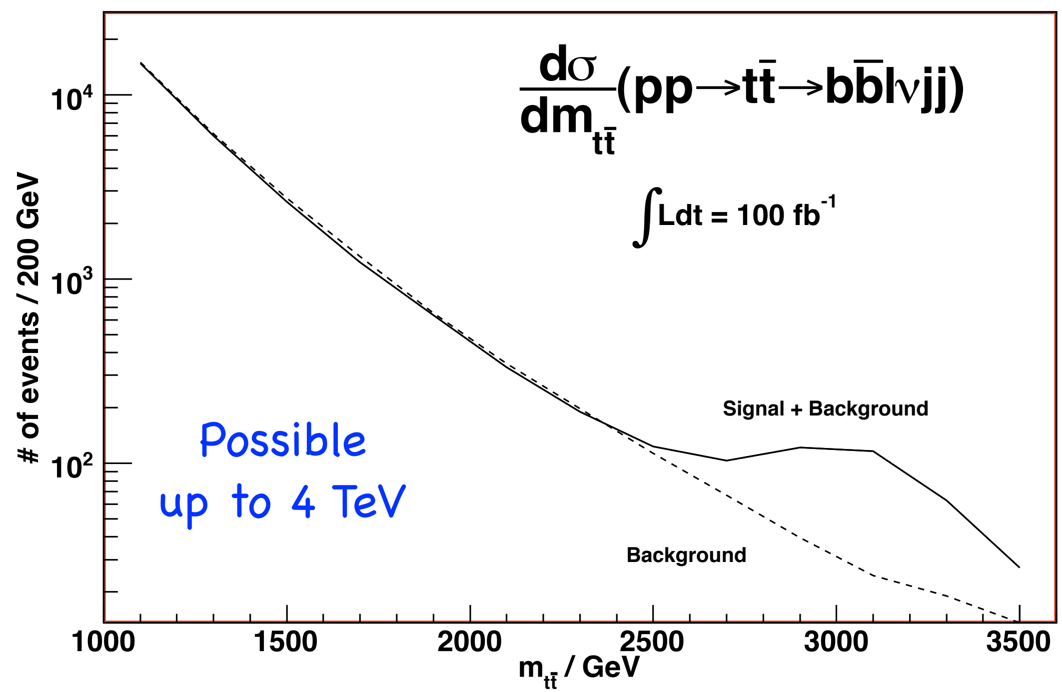
Dissertori, Furlan,Moorgat,Nef

At $\sqrt{s}$=7 TeV with 200/pb, one can reach masses ~ 300-400 GeV

Other “easy” signature: Gluonic resonances

$$pp \to g' \to t\bar{t}$$

Expected to decay mainly into tops since they have a sizable coupling to the Strong Sector



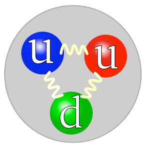
Agashe et al

Other issues:

- Dark Matter:
- Unification:
- Proton decay:
- Flavor physics:
- Neutrino masses:
- ...

Dark Matter

Most natural candidate:



TechniBaryon

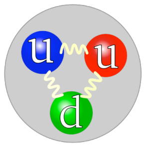
The lightest can be stable
by TechniBaryon
Number Conservation

(as Baryons in QCD)

M~ TeV

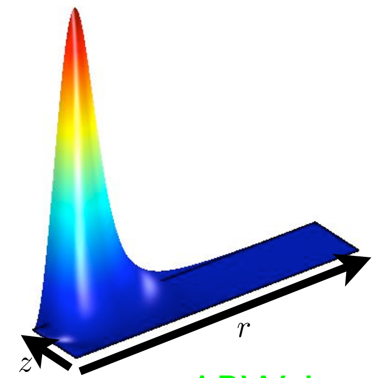
Dark Matter

Most natural candidate:



TechniBaryon ≈ A soliton in 5D

AdS/CFT



AP,Wulzer

The lightest can be stable by TechniBaryon Number Conservation

(as Baryons in QCD)

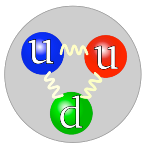
M~ TeV

The lightest can be stable by Topological Number Conservation

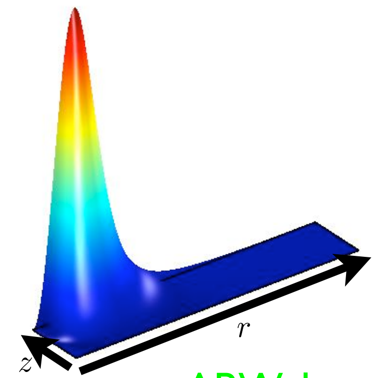
$$M_N \simeq 3\ TeV \left(\frac{F}{246\ GeV}\right)^2 \left(\frac{1\ TeV}{M_{KK}}\right)$$

Dark Matter

Most natural candidate:



TechniBaryon $\approx$ A soliton in 5D



AP,Wulzer

AdS/CFT

The lightest can be stable by TechniBaryon Number Conservation

(as Baryons in QCD)

M~ TeV

The lightest can be stable by Topological Number Conservation

$$M_N \simeq 3\ TeV \left(\frac{F}{246\ GeV}\right)^2 \left(\frac{1\ TeV}{M_{KK}}\right)$$

Not a WIMP: Must be produced non-thermally (via Sphalerons?) as Baryons

Must be neutral but could couple to the SM via dipole moments

Conclusions

If Nature chooses Strong Dynamics
to break EW symmetry, we will have to be patient.
It will take time to see:

1) Expected deviations on Higgs couplings
but also on 3rd family couplings (maybe already seen)

2) TeV-resonances. Color fermion (Q=5/3) being the lightest

But when dealing with Strong Dynamics,
as in the case of Superconductors and QCD,
experiments have always been the driven force
most of the time ahead of theory

Similarly, we expect in the next years
LHC will take a crucial role !