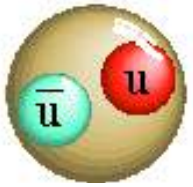
Composite Higgs

H = 

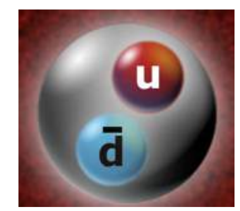
"dead dogs don't bite":

If no elementary Higgs, μ^2 not anymore a fundamental parameter

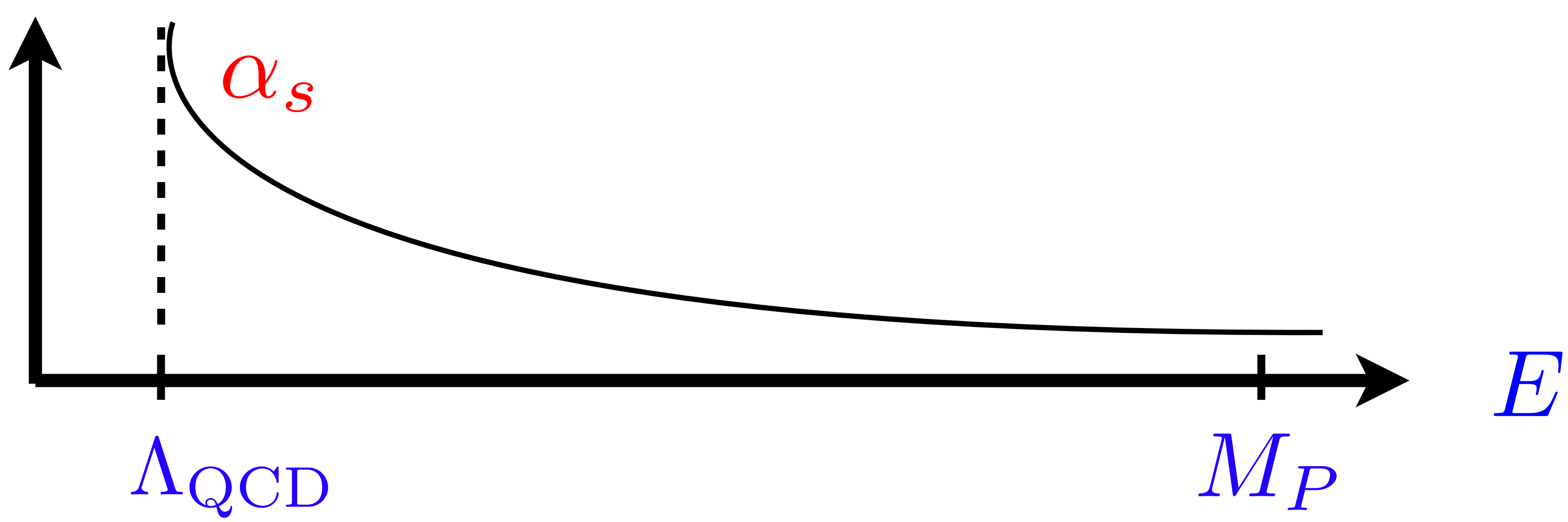
Indeed, in **QCD** we see **light scalars** without problems of naturalness:

$$m_\pi,\ m_K,\ m_{a_0}, \dots << M_P$$

Reason: they are <u>composite</u> states at $\Lambda_{\rm QCD} << M_P$,



defined by the scale at which the strong gauge-coupling becomes large:

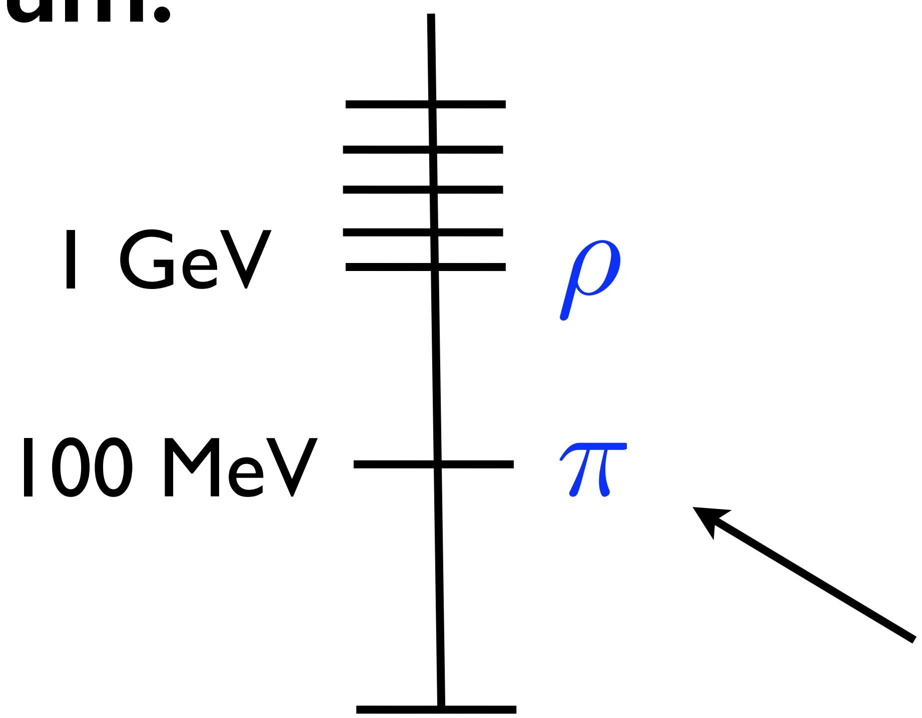


Furthermore,

the lightest states in **QCD** are the (pseudo) **scalars**

(spin=0 particles like the Higgs)

QCD Spectrum:



Why the lightest?

Because they are
Pseudo-Goldstone bosons (PGB)

Pseudo-Goldstone bosons (PGB) in QCD

QCD, considering only two quarks in the massless limit,

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

has an accidental global symmetry:

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

It is broken by the quark condensate: $\langle q\bar{q} \rangle \neq 0$

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

3 Goldtones:

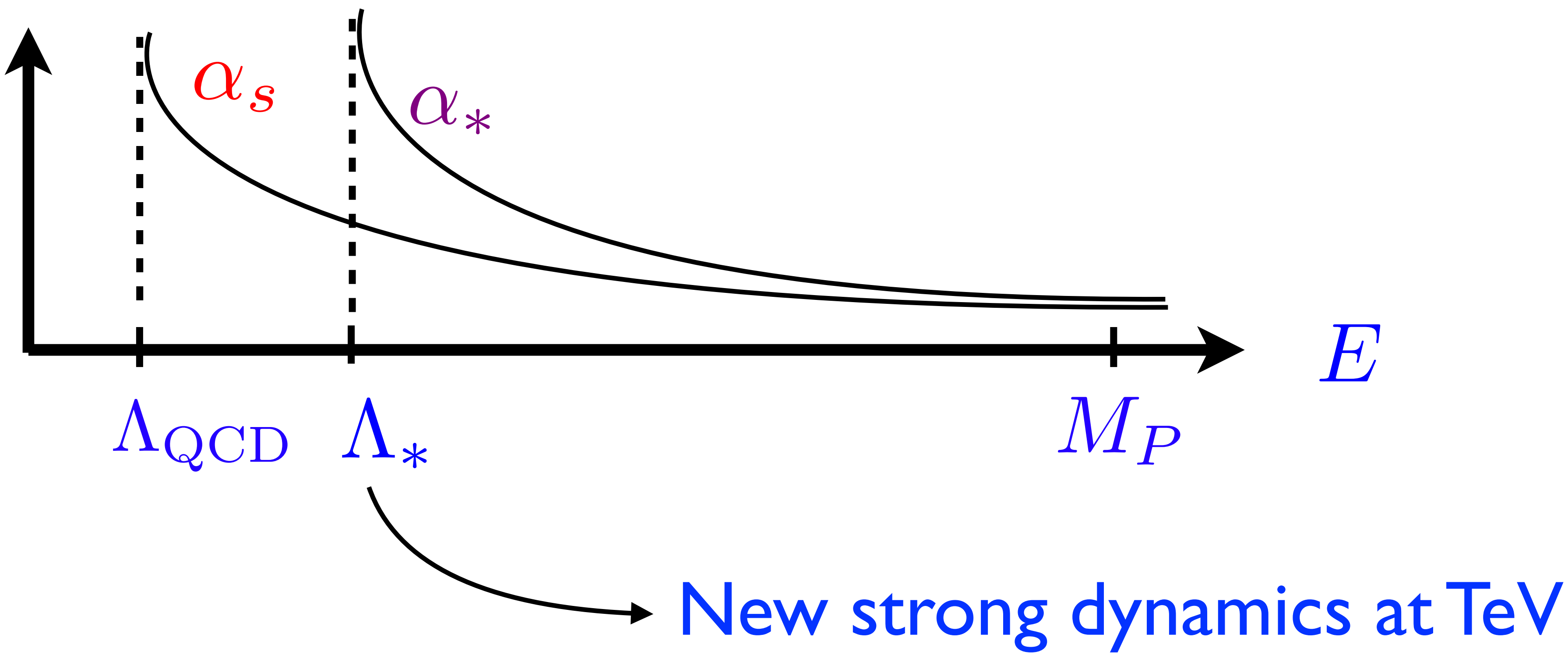
π^+, π^-, π^0 **Massless!!**

In reality, they are not massless since quark masses break explicitly $SU(2)_L \times SU(2)_R$ giving the pions a mass:

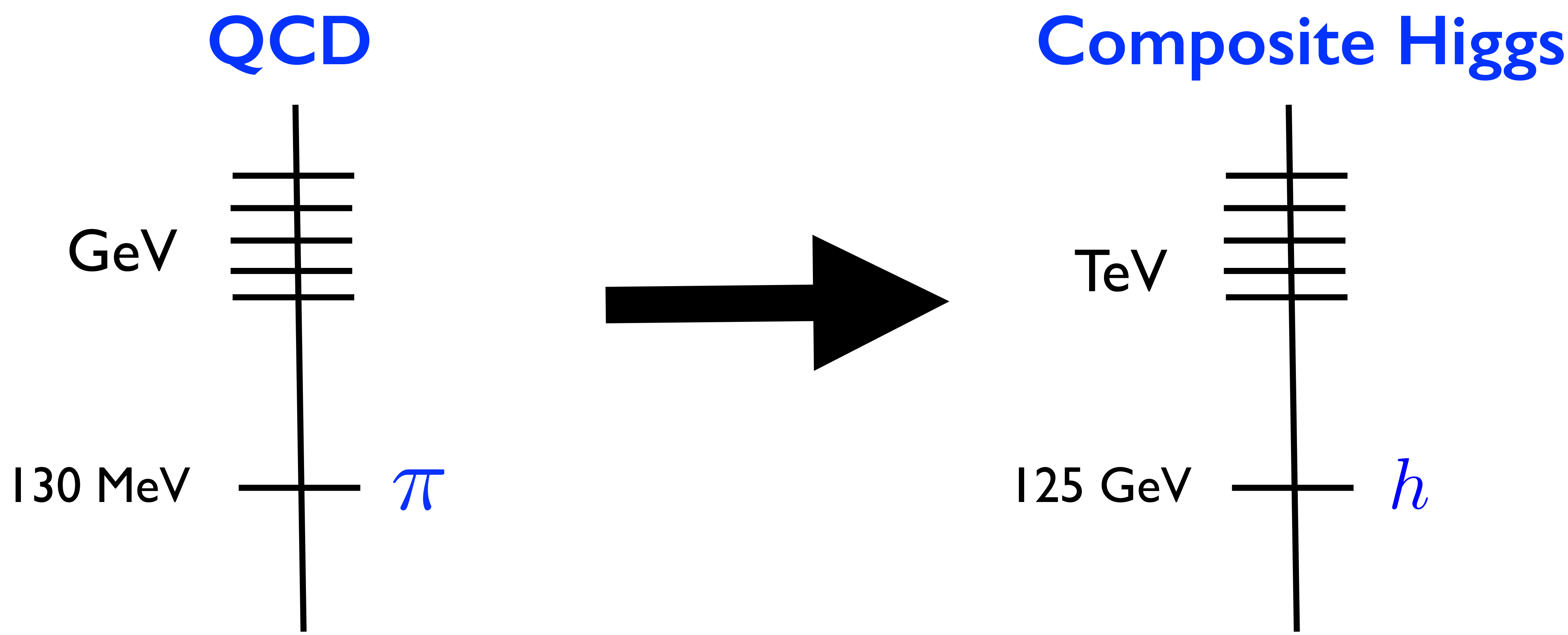
$$m_\pi^2 \propto m_q$$

Lets try the same for the Higgs

➠ Assume that there is a **New Strong sector** (QCD-like) at around the TeV-scale:



The **Higgs, the lightest** of the new strong resonances, as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)



E.g.: **SO(6) → SO(4)**

5 Goldstones = Higgs doublet
+ Singlet

Galloway, Evans, Luty, Tacchi 10

Example: Just take QCD (with two flavors)
replace **$SU(3)_c$** by **$SU(2)_c$**

	$SU(3)_c$	$SU(2)_c$
Global symmetry:	$SU(2)_L \otimes SU(2)_R$	$SU(4) \sim SO(6)$
	↓ $\langle\psi\psi\rangle \neq 0$	↓ $\langle\psi\psi\rangle \neq 0$
	$SU(2)_V$	$SP(4) \sim SO(5)$
	3 Golstones = π^0, π^+, π^-	5 Goldstones = **Higgs doublet + singlet**

since $2 \sim \bar{2}$

$4 = 2_L + 2_R$

ψ_L, ψ_R^c

Fermion masses

Simplest possibility

1) bilinear-mixing:

$$\mathcal{L}_{\rm bil} \sim \bar{f}_i \mathcal{O}_H f_j \;\; \frac{1}{\Lambda_{\rm UV}^{d_H-1}} \qquad \langle 0|\mathcal{O}_H|H\rangle \neq 0$$

e.g. $\mathcal{O}_H \sim \bar{q}' q'$

$$Yukawa \sim \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{d_H-1}$$

too small for the top!

Suggesting an alternative possibility

1) linear-mixing:

$$\mathcal{L}_{\rm lin} = \epsilon_{f_i} \, \bar{f}_i \, \mathcal{O}_{f_i}$$

must have a dimension close to 5/2

arXiv:1502.00390

e.g. SU(4) strong sector

Fermions:
a) three $\Psi_{L,R} \in$ **4** (fundamental)
b) five $\Upsilon \in$ **6** (antisym. matrix)

$$\Psi \Upsilon \Psi = \mathcal{O}_{\text{top}}$$

Operator that can be coupled to the top:

$$\mathcal{L}_{\text{mixing}} = t\ \mathcal{O}_{\text{top}}$$

Global sym.

$$G = SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)'$$

↓

$$H = SO(5) \times SU(3)_{\text{color}} \times U(1)_X$$

dimension at weak coupling: 9/2

↓

dimension needed at strong coupling: 5/2 arXiv:1502.00390

e.g. SU(4) strong sector

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$$\downarrow$$

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dimension at weak coupling: 9/2

↓

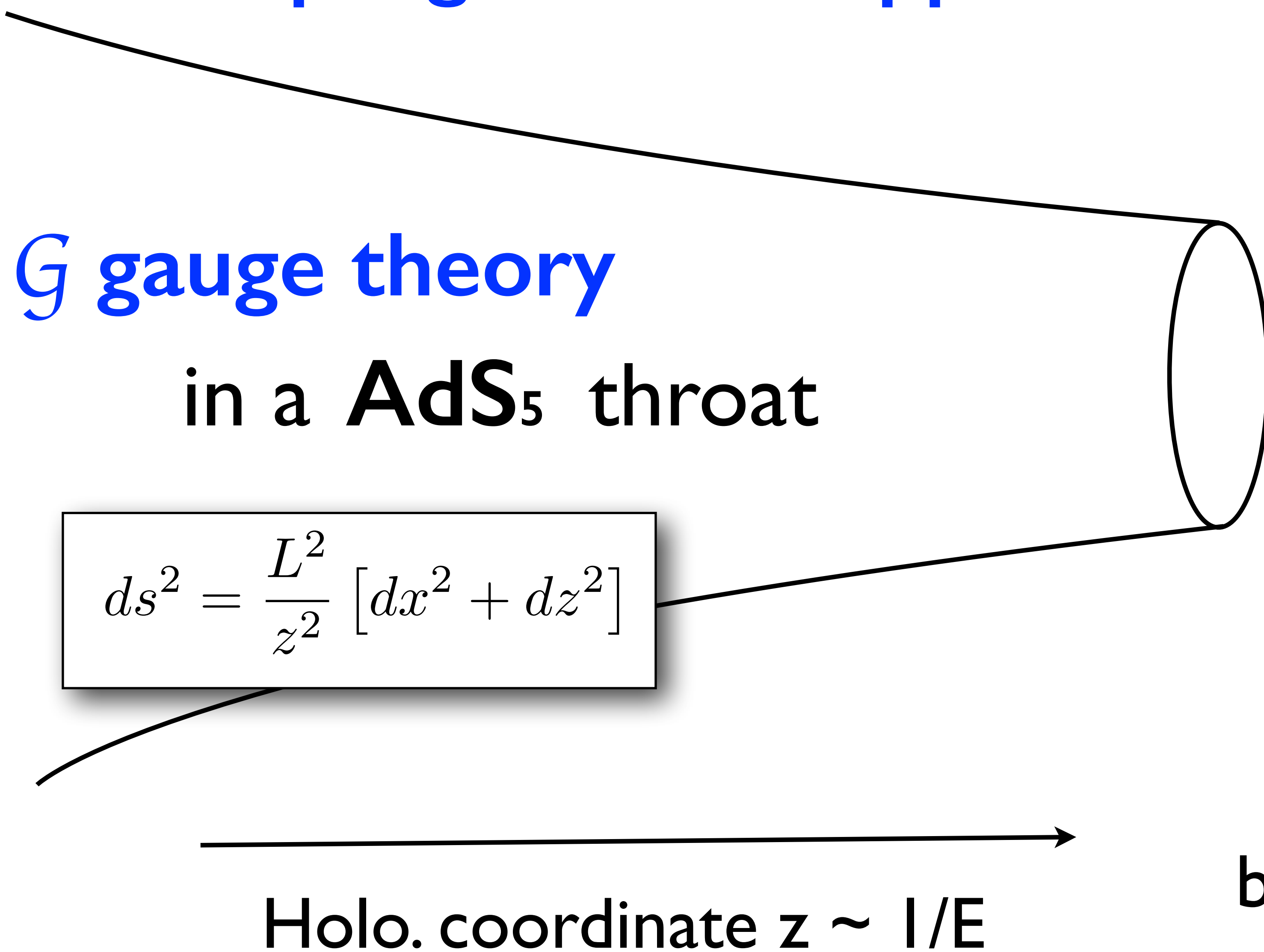
dimension needed at strong coupling: 5/2

Possible?

Inspiration from holography:

Simple geometric approach to fermion masses

Agashe,Contino,A.P.



hard/soft wall

Mass gap ~ TeV

Symmetry : $\mathcal{H}$

Breaking of symmetry by boundary conditions

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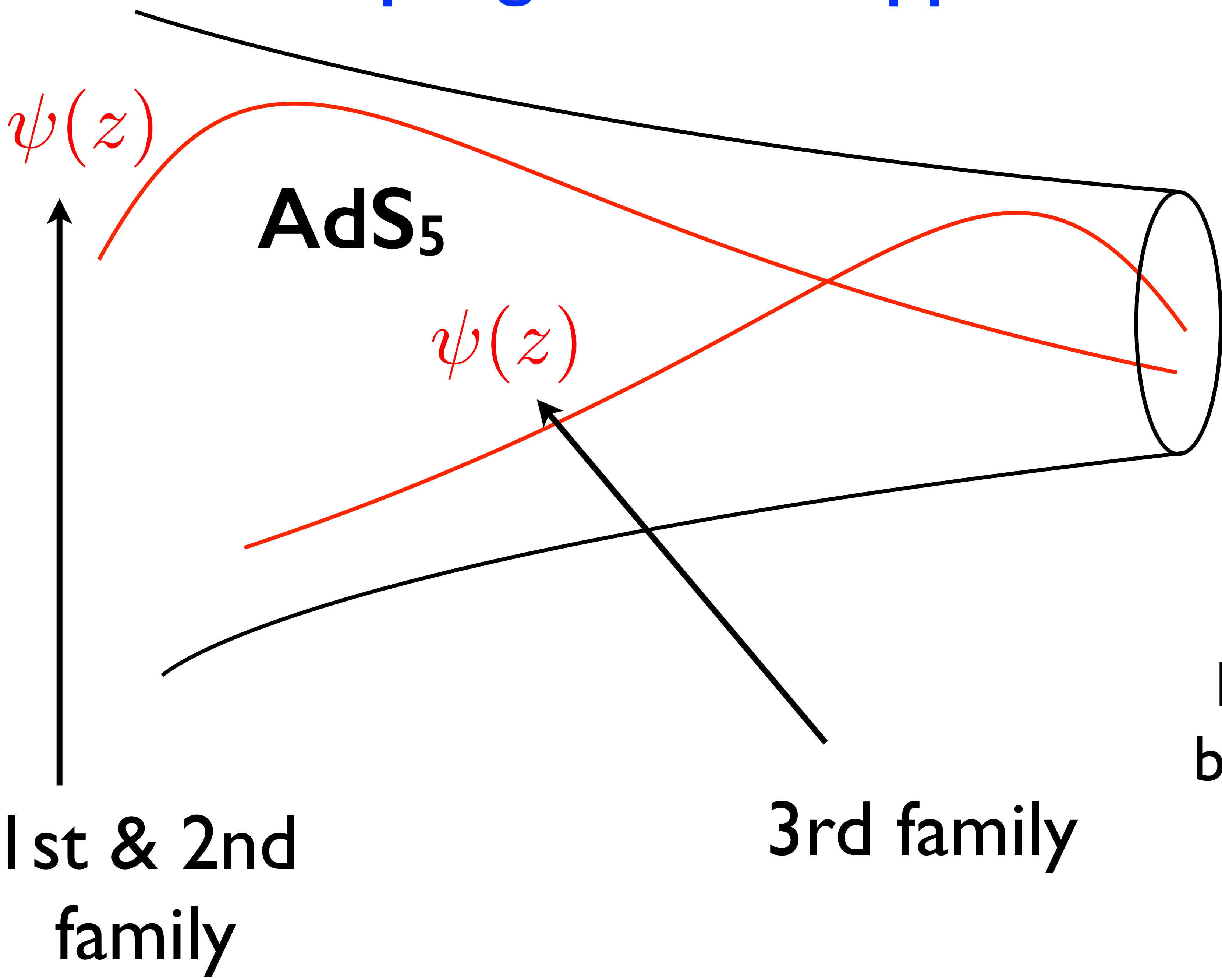


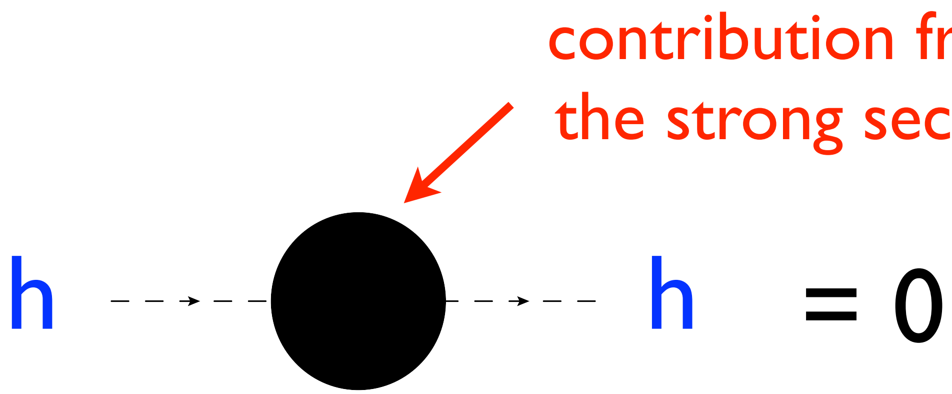
hard/soft wall

Mass gap ~ TeV

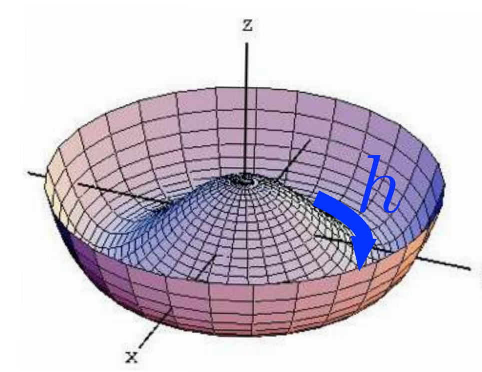
Symmetry : $\mathcal{H}$

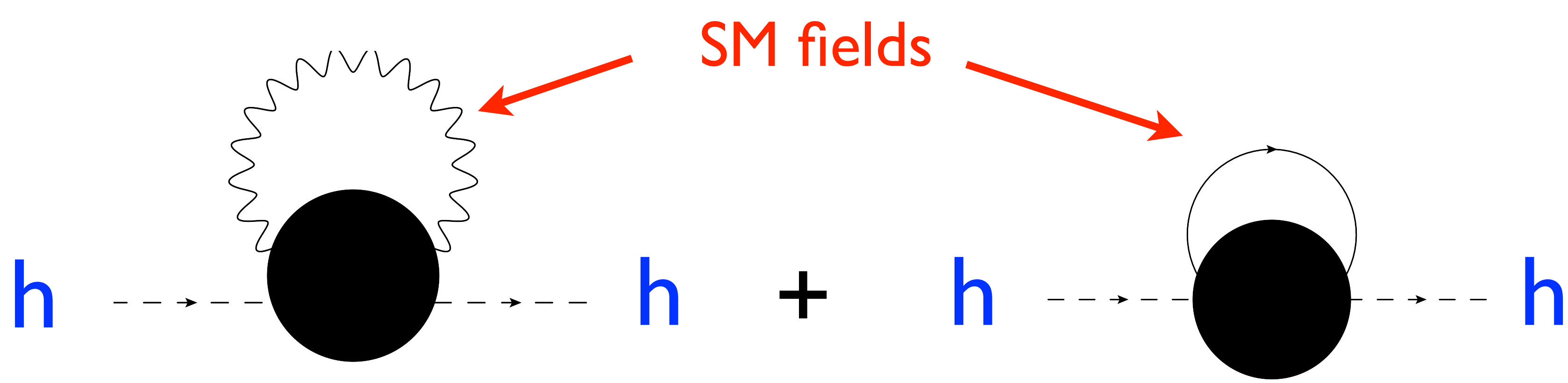
Breaking of symmetry by boundary conditions

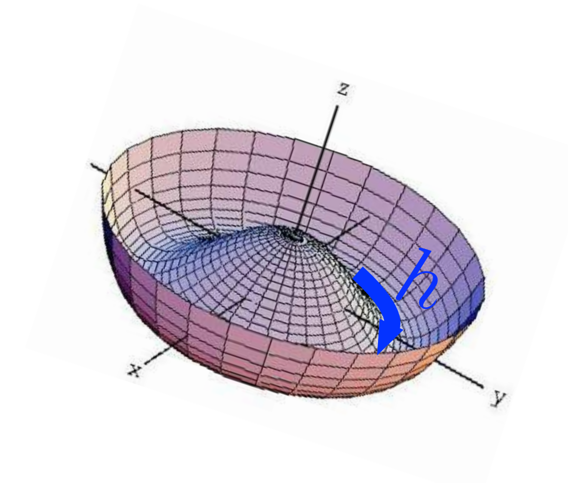
Higgs potential



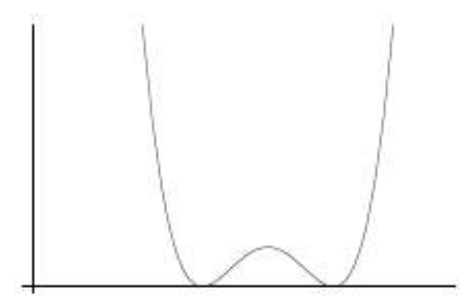
it's a Goldstone







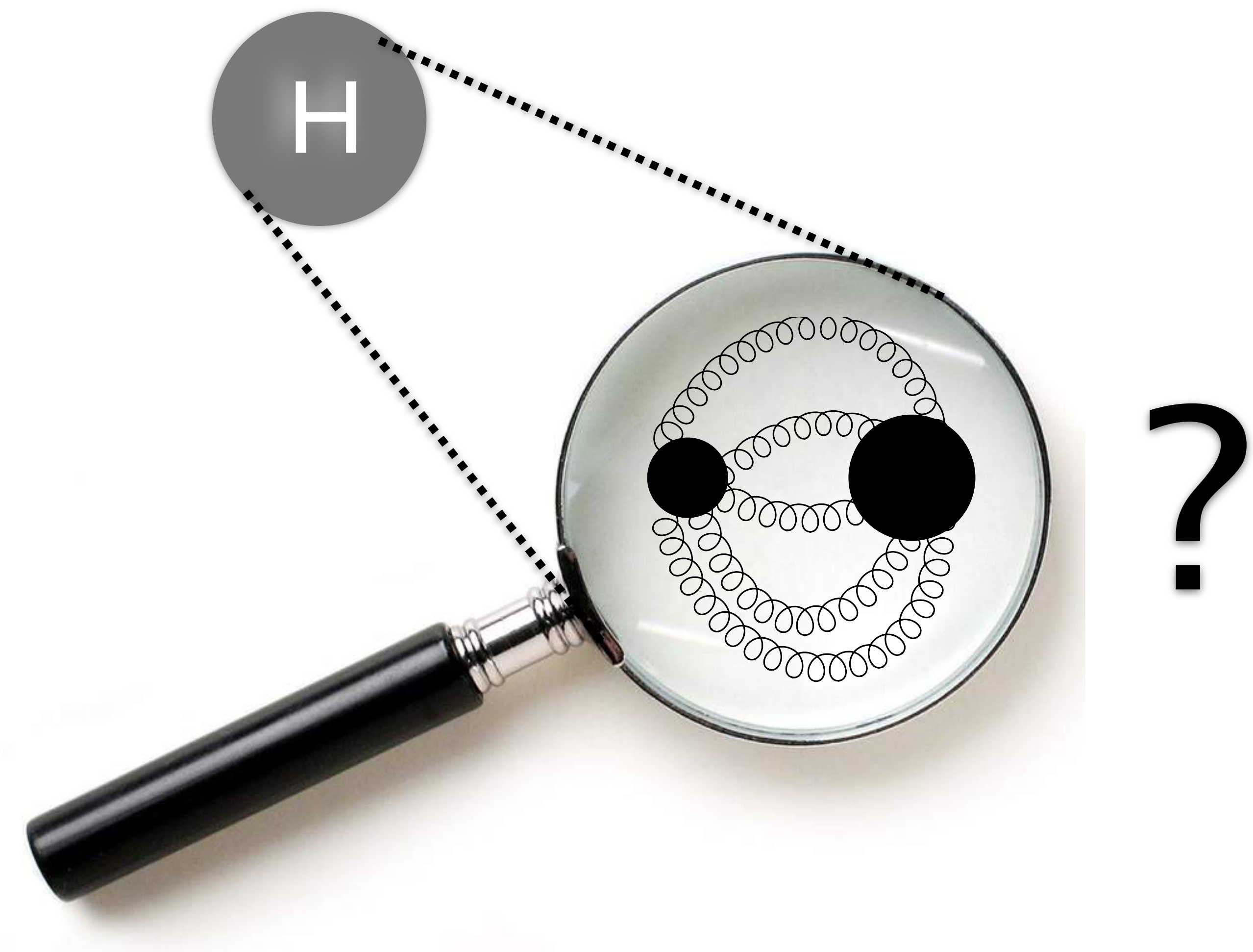
- **Top needed to achieve EWSB!**



$$v \sim f \sim \langle \bar{q}' q' \rangle$$

- **Mass at the one-loop level ☛ Light Higgs expected!**

How to unravel the composite nature of the Higgs?



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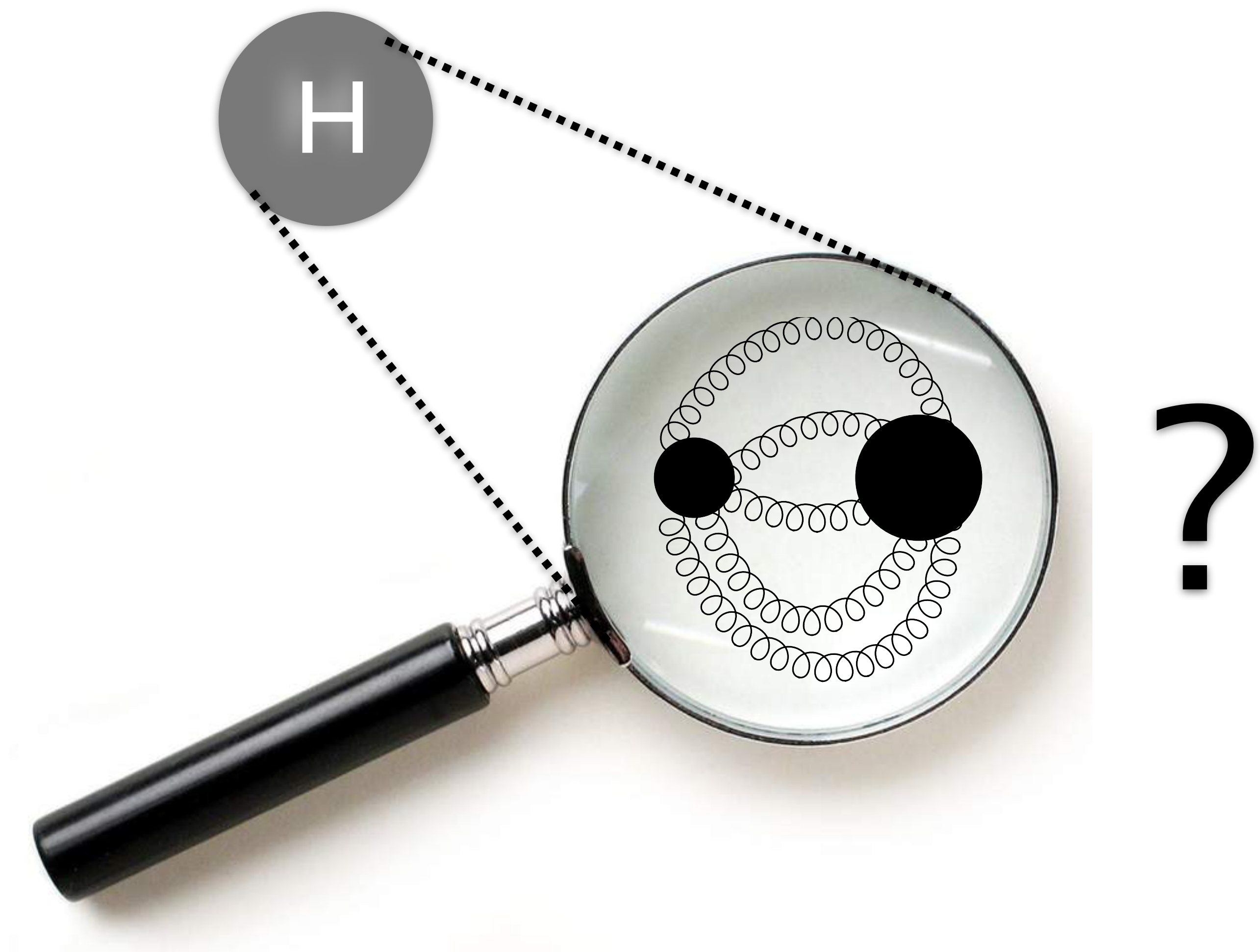


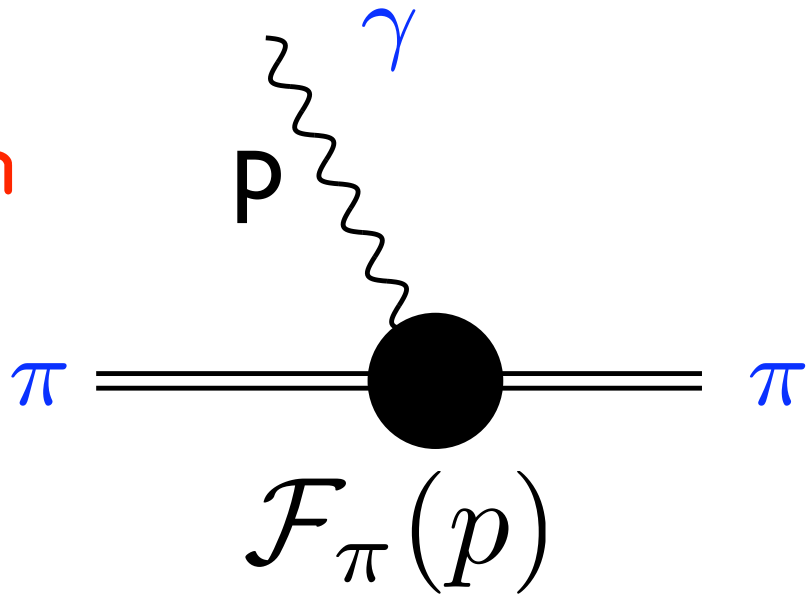
Measuring its couplings!

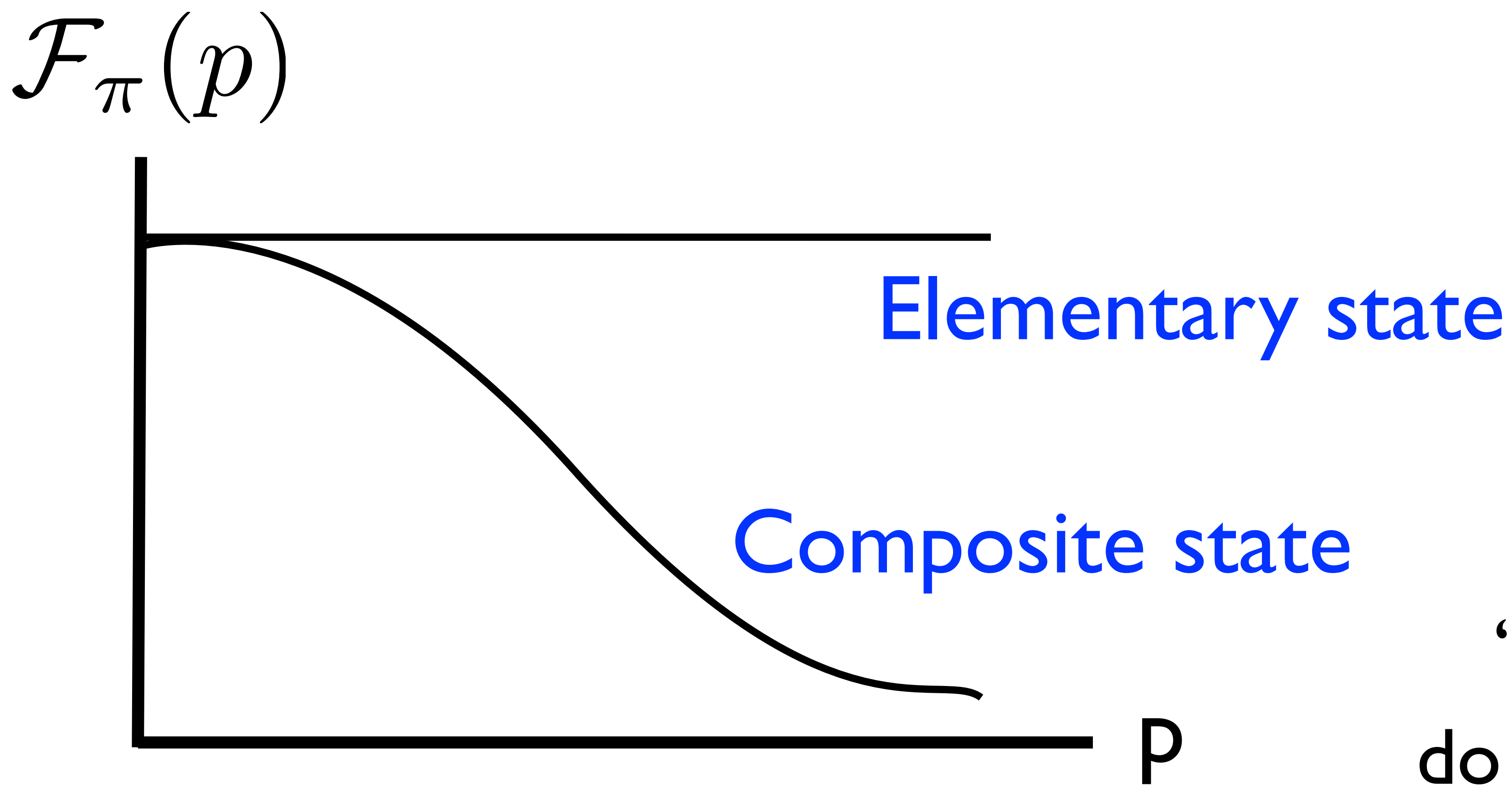
The higher the energy, the better

How to unravel the composite nature of the Higgs?

Easy in an ideal collider:

Do it as we do with pions in QCD:
probe it with photons at high-momentum



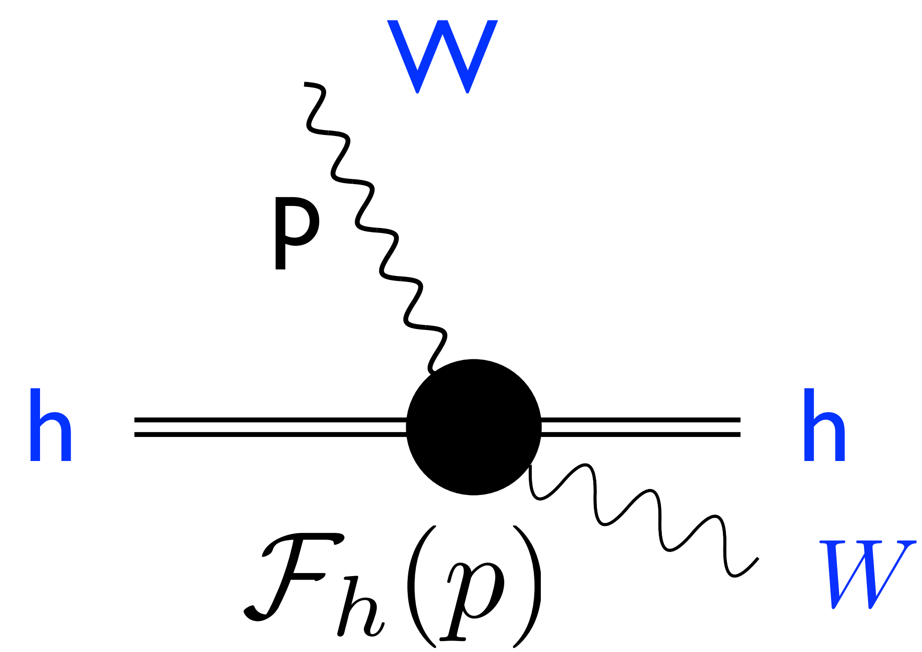


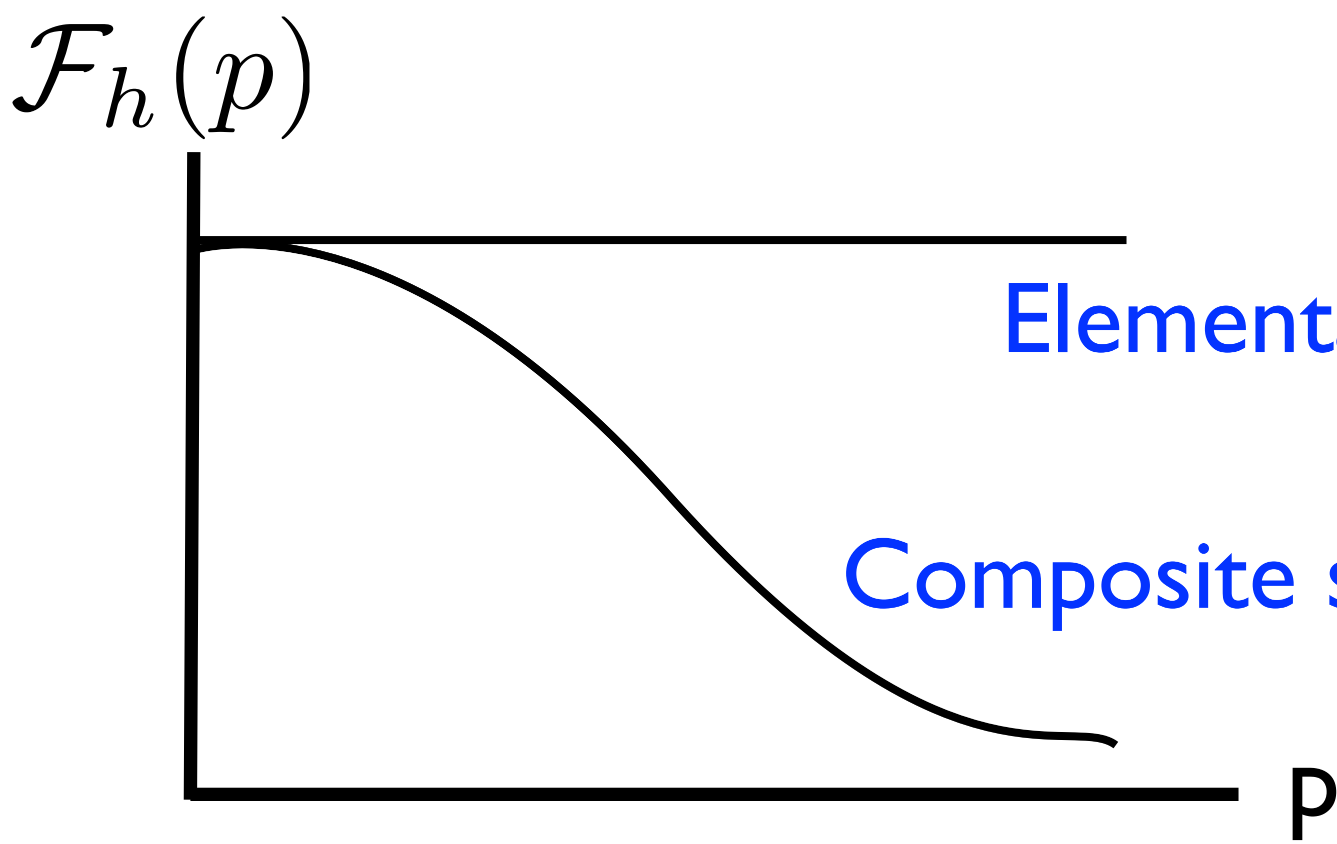
→ QM analog of
"High-frequency waves
do not see big soft objects"

How to unravel the composite nature of the Higgs?

Easy in an ideal collider:

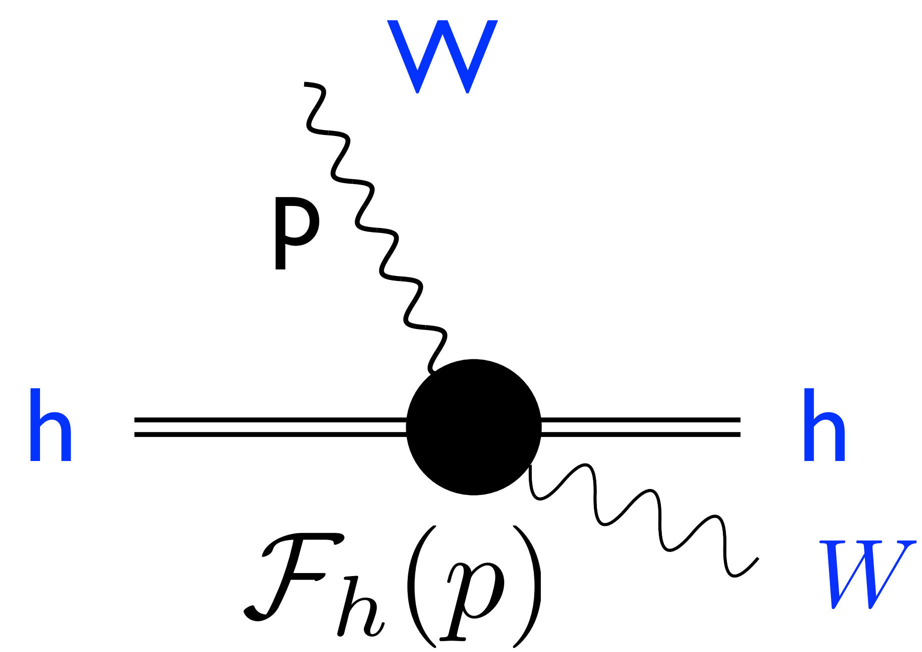
Similarly for the Higgs:

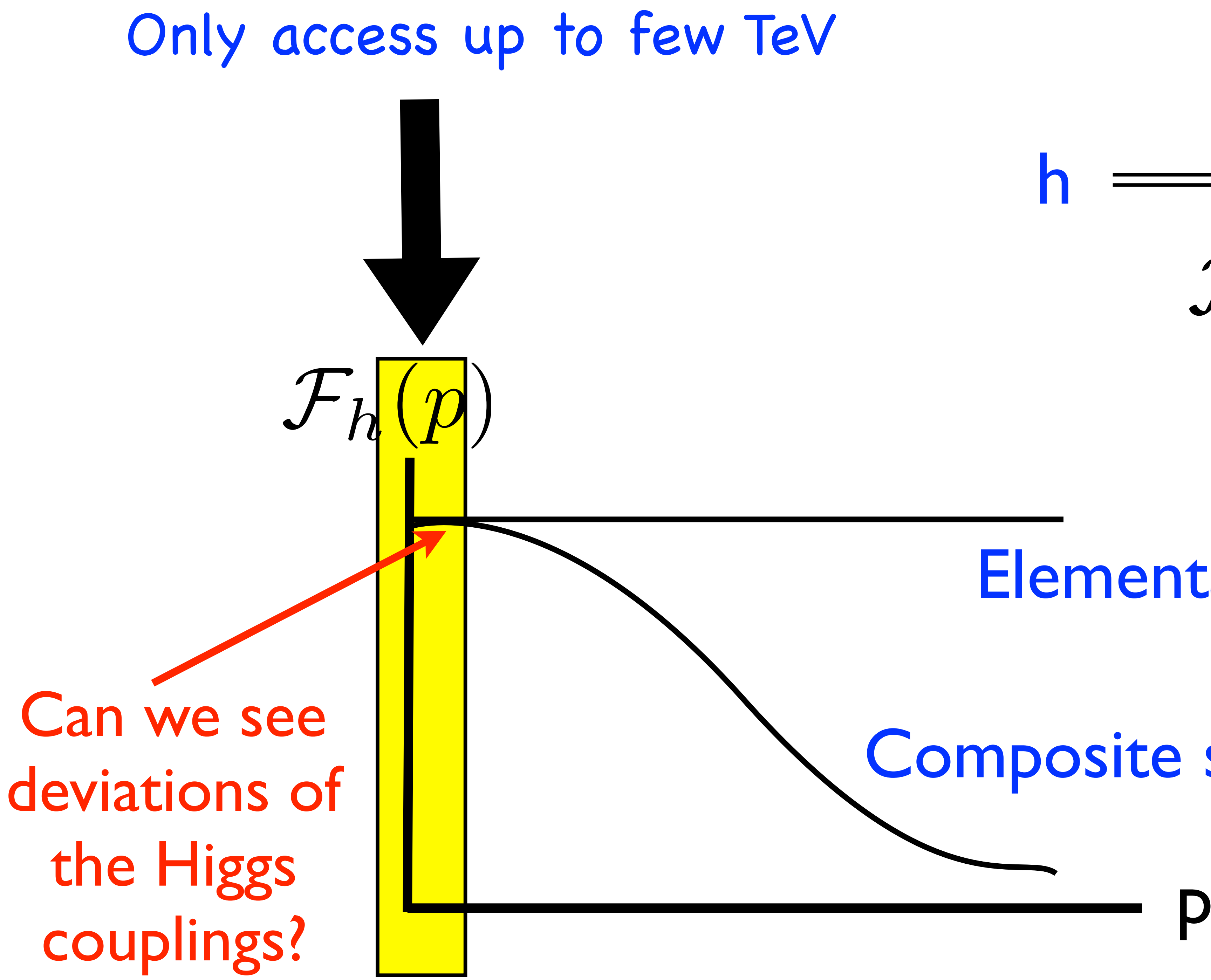




How to unravel the composite nature of the Higgs?

But in a real collider (LHC):





Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07

AP,Riva 12

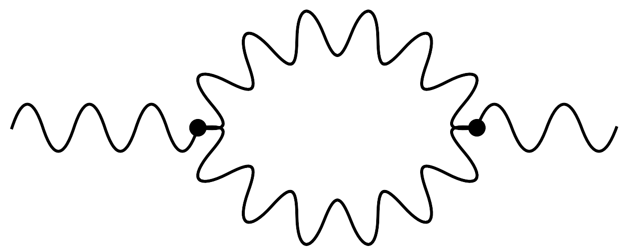
$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}} \quad \longrightarrow \quad f \sim \langle \bar{q}' q' \rangle$$

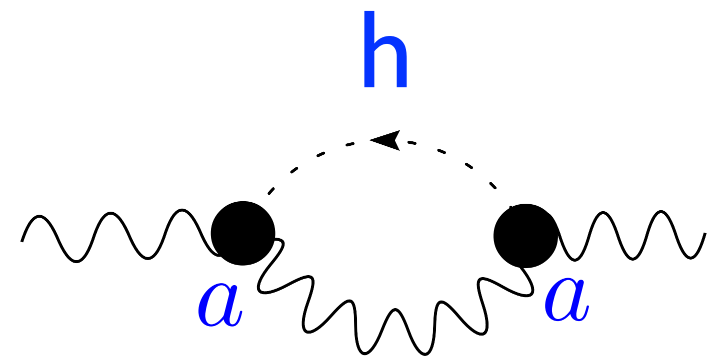
$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}} \qquad n = 0, 1, 2, \ldots$$

$n=0$: MCHM4, $n=1$: MCHM5

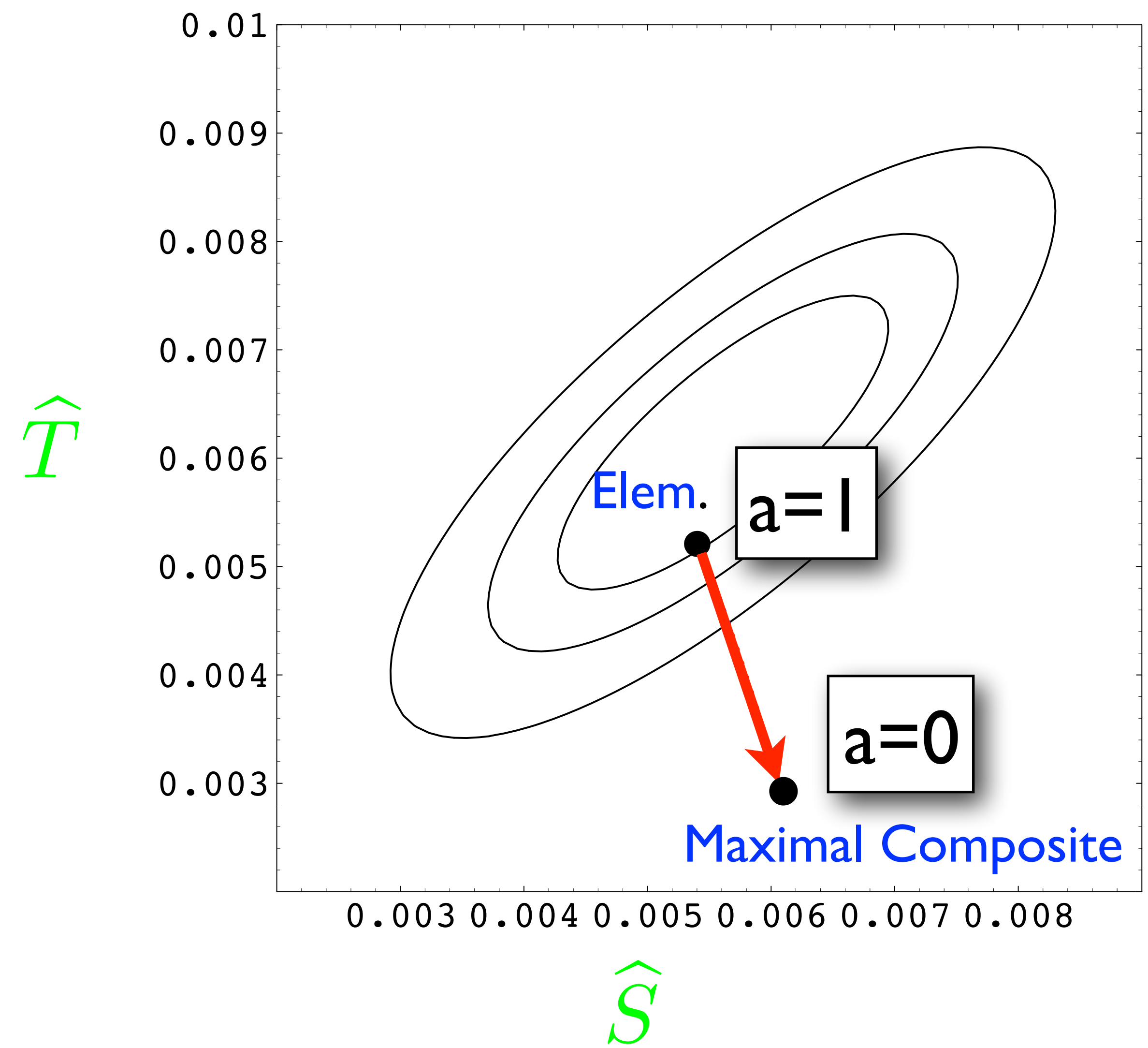
small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs

Maximal degree of compositeness not allowed by EWPT





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

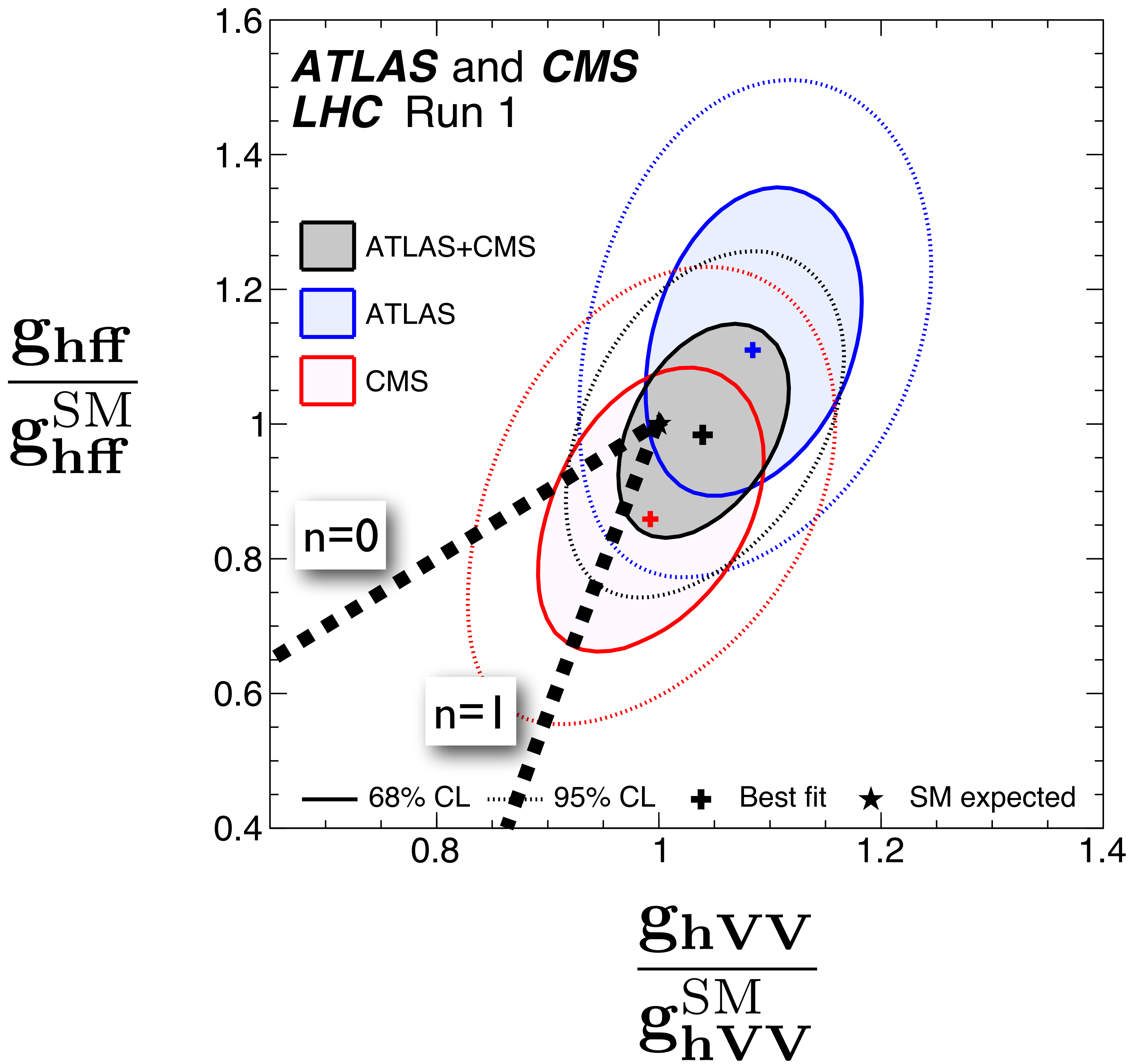


$$\hat{\mathrm{T}} = \frac{\mathrm{g}^2}{\mathrm{M}_\mathrm{W}^2} \left[\Pi_{\mathrm{W}_3}(0) - \Pi_{\mathrm{W}^+}(0)\right]$$

$$\hat{\mathrm{S}} = \mathrm{g}^2\, \Pi'_{\mathrm{W}_3\mathrm{B}}(0)$$

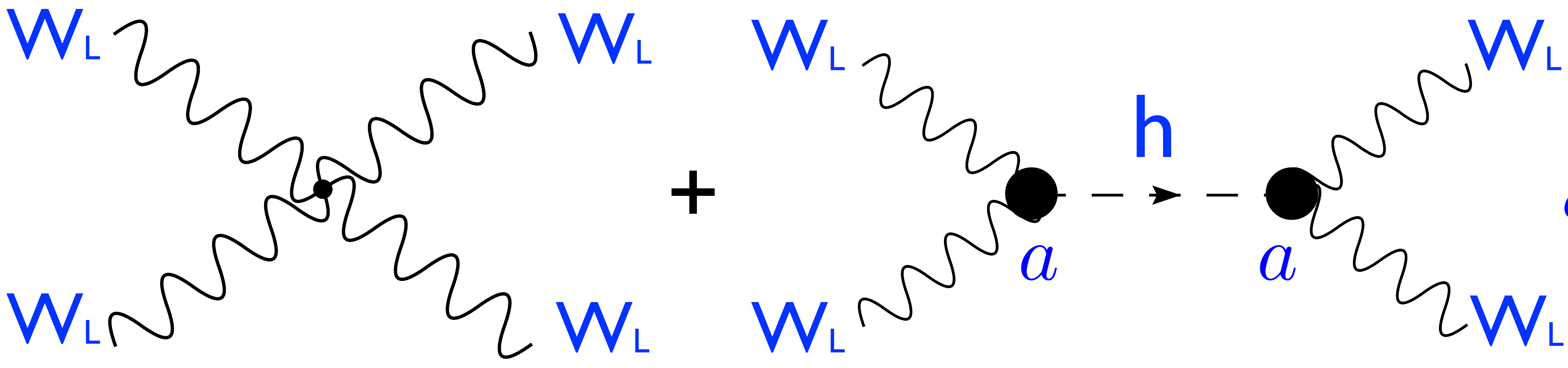
$\Rightarrow$ a > 0.86

Signs of compositeness of the Higgs



Entering the interesting region: bounds getting below 10%!

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



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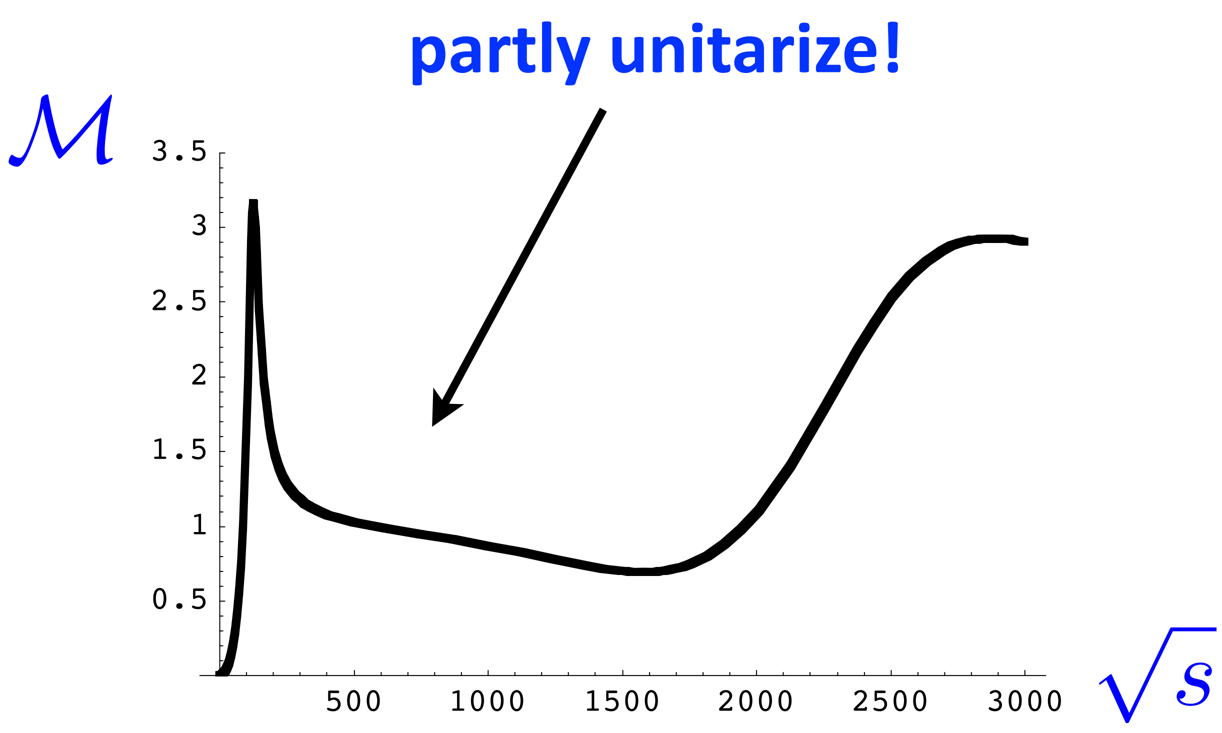
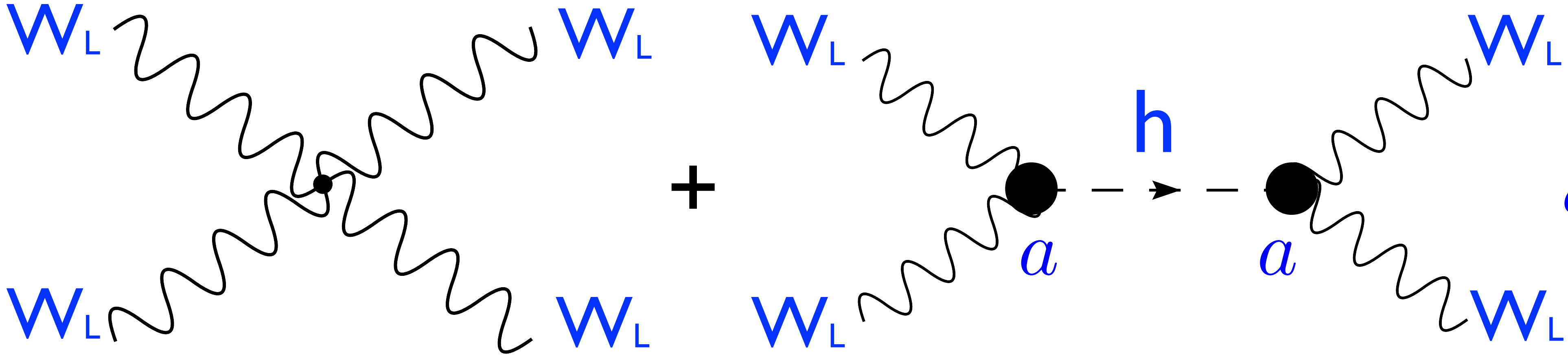
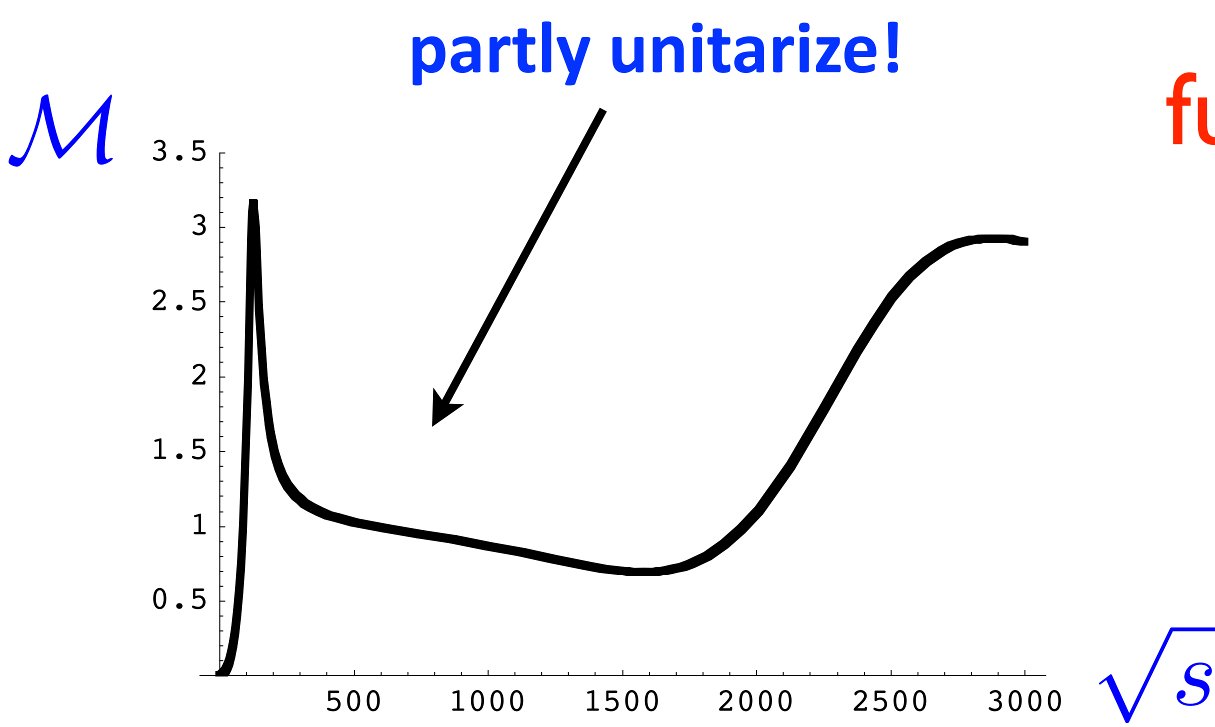


Composite Higgs only partly does the job of a **true** Higgs



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

Extra states needed to
fully unitarize (for consistency)!



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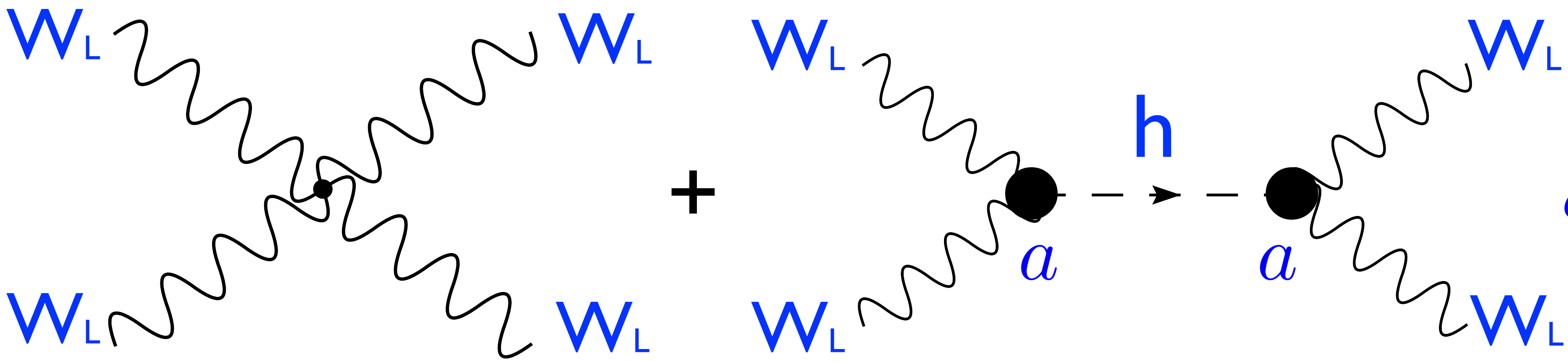
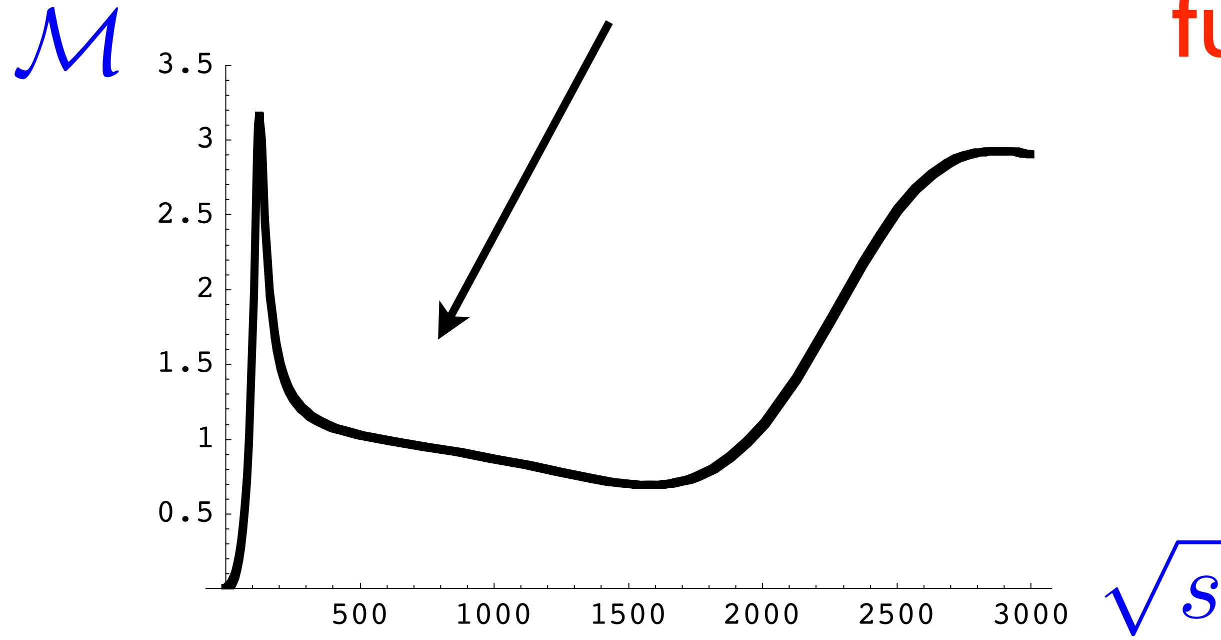


$a = \sqrt{1 - \frac{v^2}{f^2}}$

partly unitarize!



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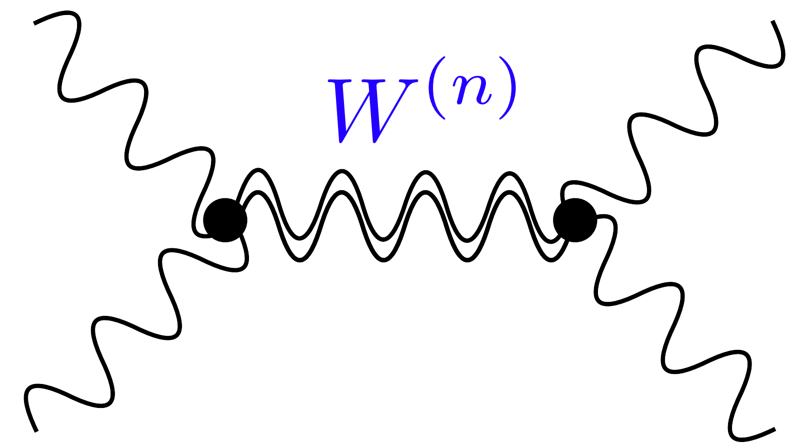
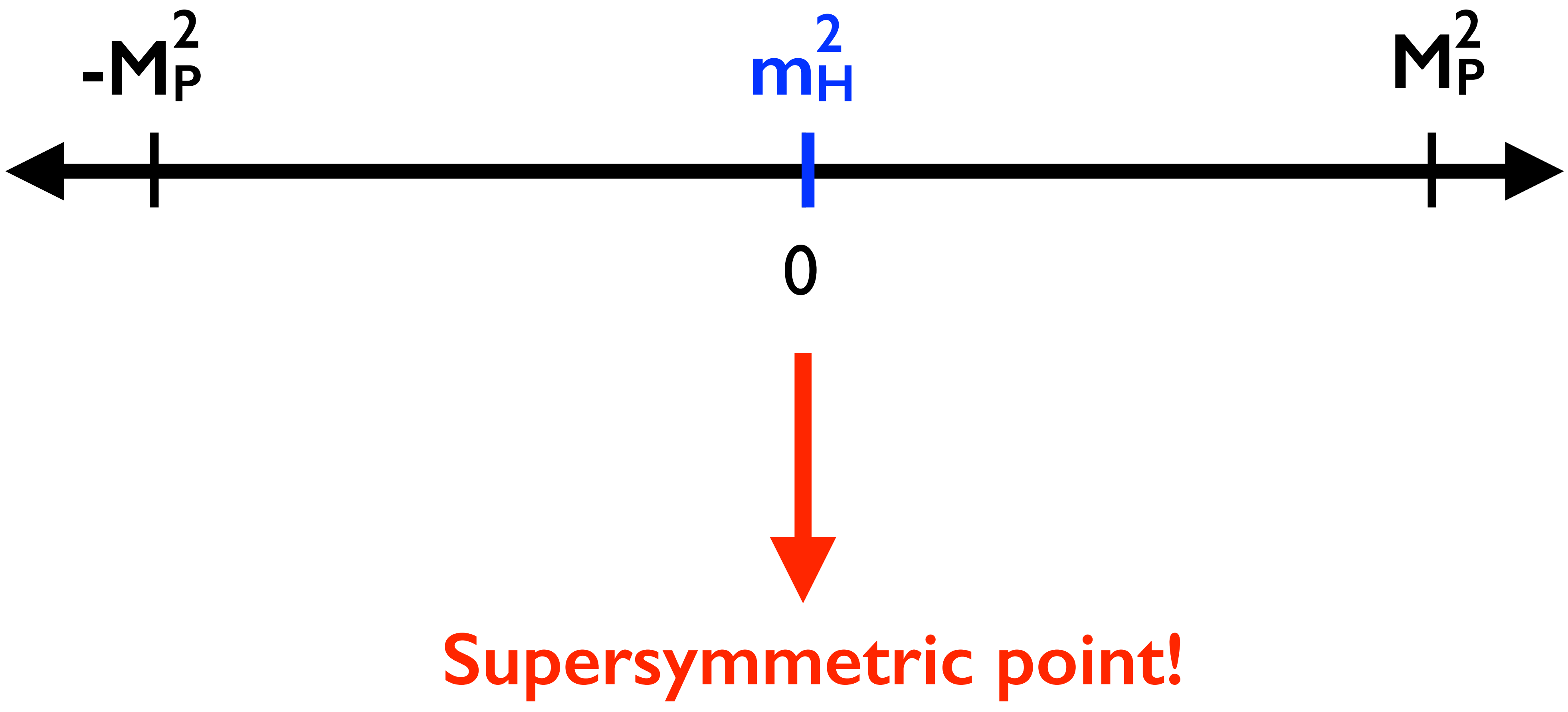


Extra resonances

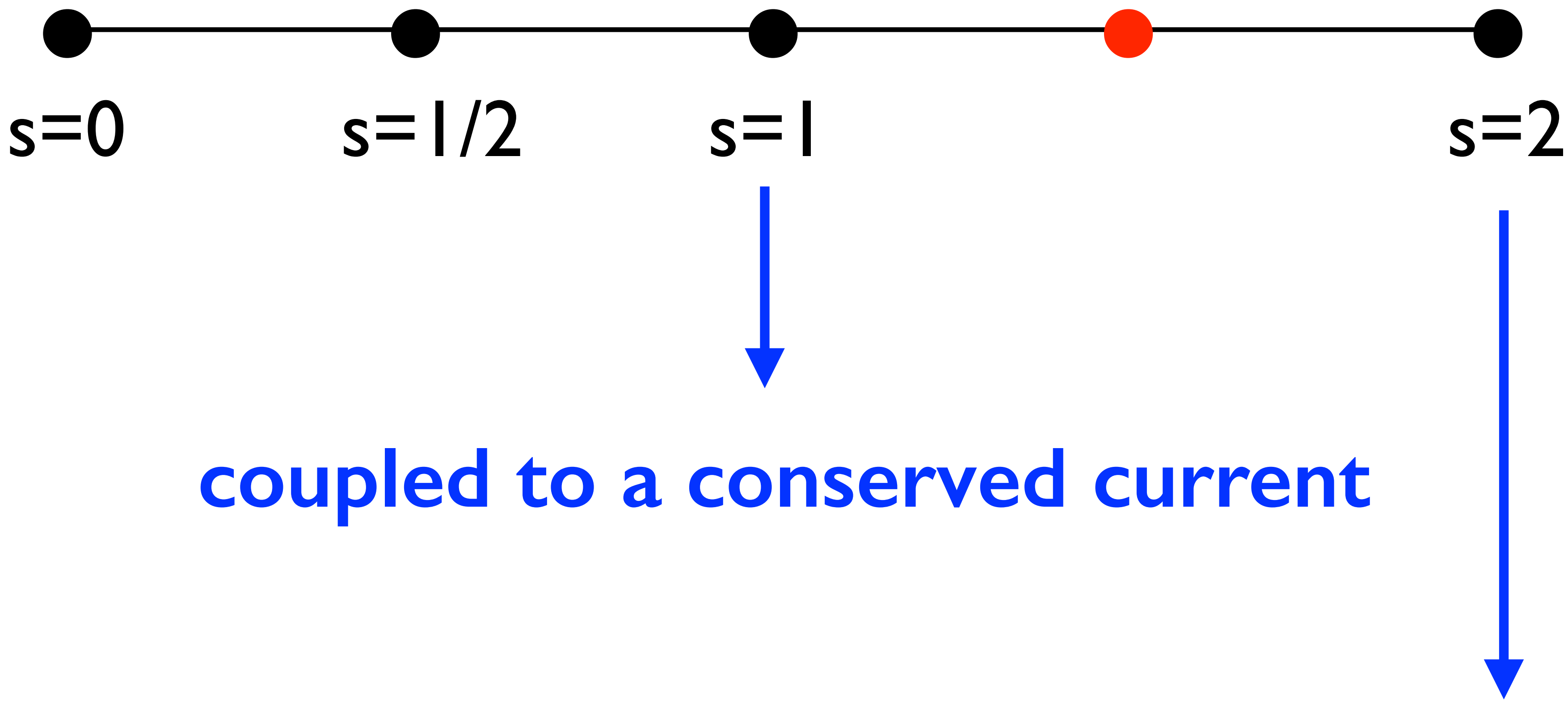
(as in QCD)

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

Supersymmetry



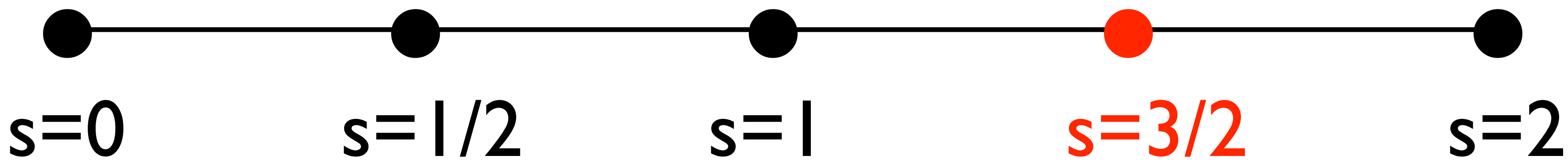
Requirements of consistent theories:



coupled to a conserved current

coupled to the energy-momentum tensor

Requirements of consistent theories:



coupled to a conserved current

coupled to the energy-momentum tensor

coupled to a conserved fermionic current:

SUPERSYMMETRY!

Simplest supersymmetric model: free theory of a scalar and fermion

(hep-ph/9709356)

$$S = \int d^4x \, (\mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{fermion}}) \, ,$$

$$\mathcal{L}_{\text{scalar}} = -\partial^\mu \phi^* \partial_\mu \phi, \qquad \mathcal{L}_{\text{fermion}} = i\psi^\dagger \overline{\sigma}^\mu \partial_\mu \psi.$$

→ 2-component Weyl fermion

$$\begin{cases} \delta\phi = \epsilon\psi, \\ \delta\psi_\alpha = -i(\sigma^\mu \epsilon^\dagger)_\alpha \, \partial_\mu \phi, \end{cases}$$

→ 2-component Weyl fermion (anti-commuting) parametrizing the infinitesimal transformation

Supersymmetry Algebra

(Maximal extension of Poincare in a QFT)

Minimal SUSY (*N*=*1*): One extra generator Q

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

Schematic form:

$$\begin{aligned}
&[Q, M_{\mu\nu}] = Q \\
&\{Q, Q^\dagger\} = P^\mu, \\
&\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0, \\
&[P^\mu, Q] = [P^\mu, Q^\dagger] = 0,
\end{aligned}$$

Q commutes with P^2 and any generator of the gauge symmetries:

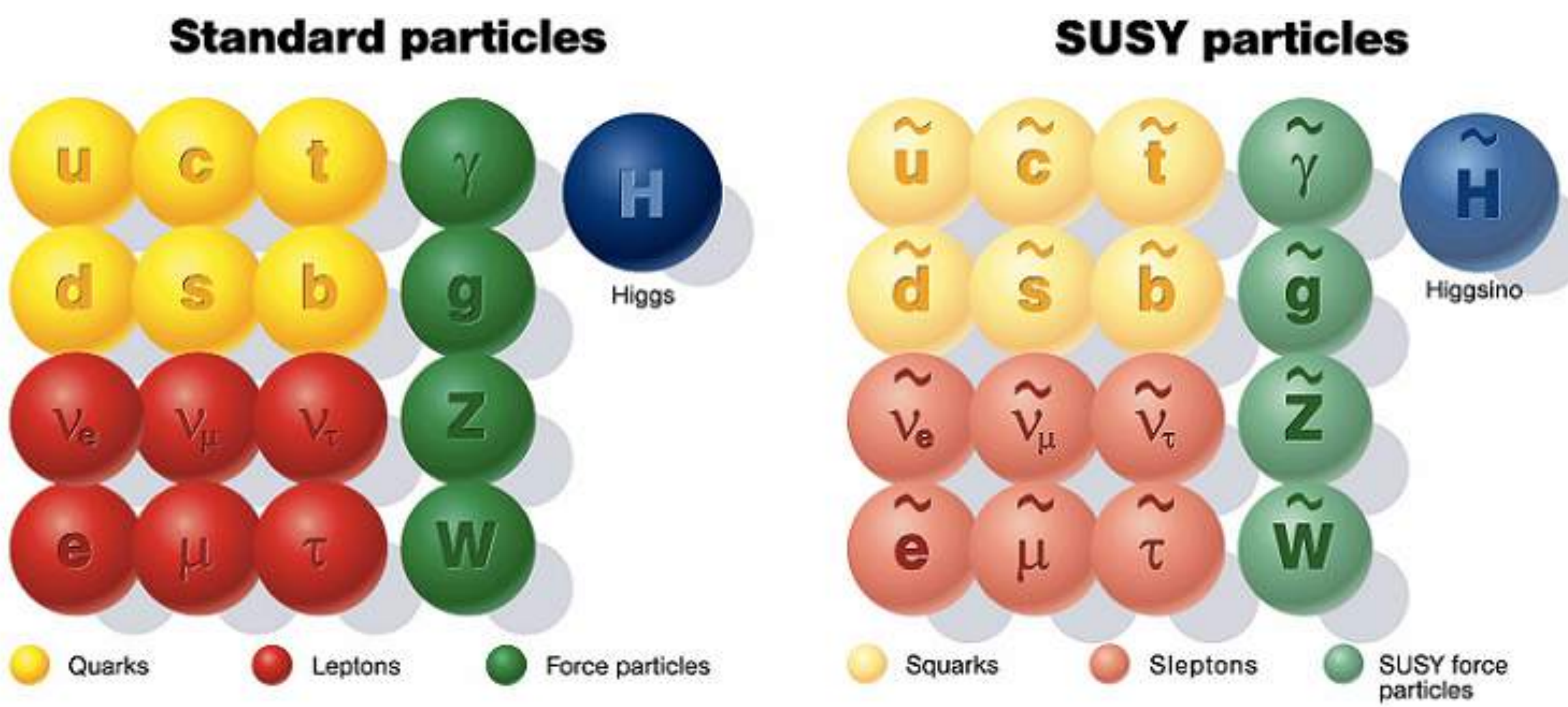
The Fermion and Boson have <u>equal</u> masses and charges

Minimal Supersymmetric SM (MSSM)

Imposing supersymmetry to the **SM** ➡ **MSSM**

The spectrum is doubled:

SM fermion ➡ New scalar (s-”...”)
SM boson ➡ New majorana fermion (“ ...“-ino)



... but not yet realistic:

The model has a quantum anomaly (due to the Higgsino) and the down-quarks and leptons are massless

Extra Higgs needed

➡ Two Higgs doublets:

$H_u : \ (1, 2, 1)$ → give mass to the up quarks

$H_d : \ (1, 2, -1)$ → give mass to the down quarks and leptons

+ two Higgsino doublets:

$\widetilde{H}_u : \ (1, 2, 1)$

$\widetilde{H}_d : \ (1, 2, -1)$

MSSM Spectrum

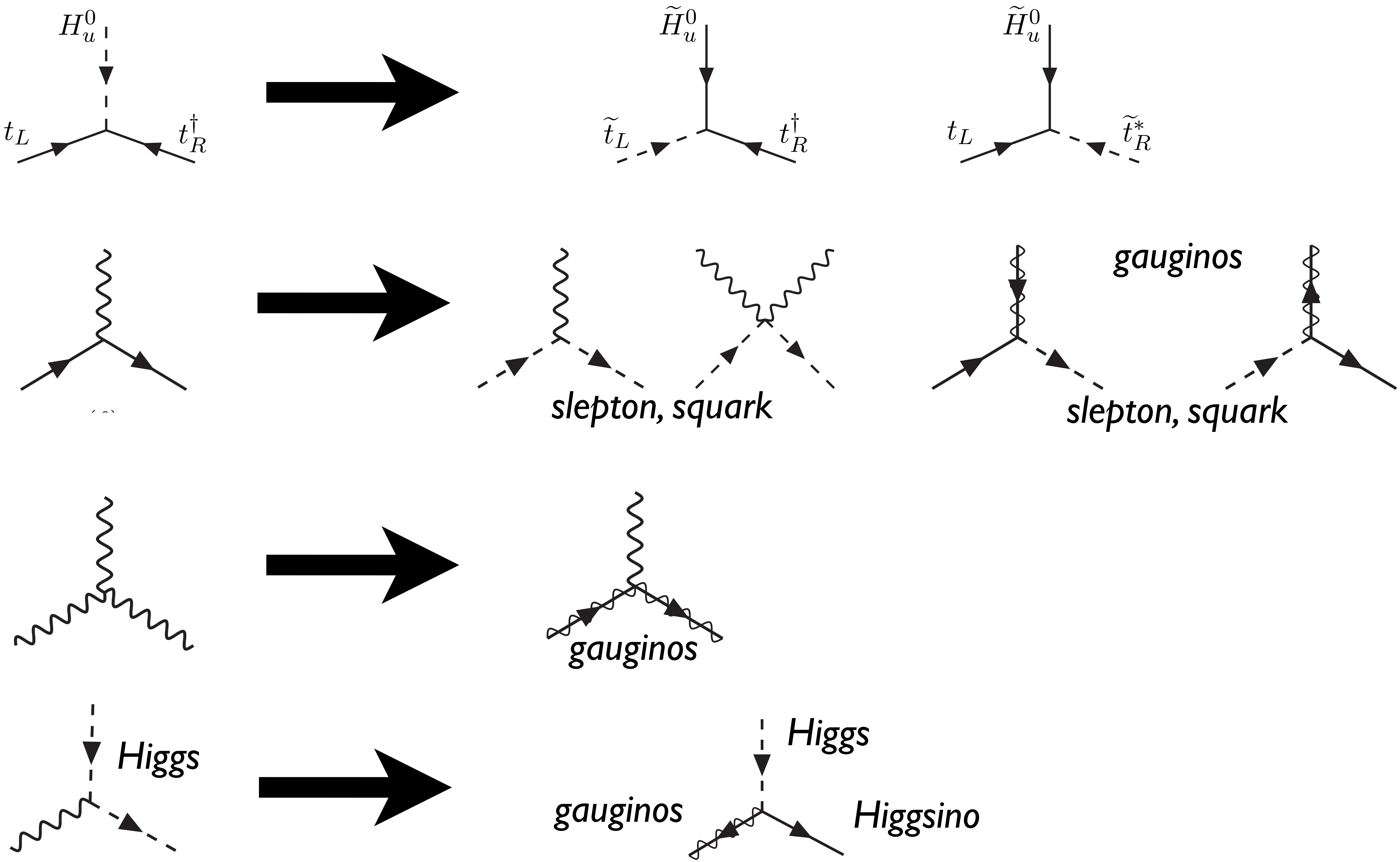
Squarks	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	
	$\widetilde{u}^*_R$	$u^\dagger_R$	
	$\widetilde{d}^*_R$	$d^\dagger_R$	
Sleptons	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	
	$\widetilde{e}^*_R$	$e^\dagger_R$	
	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	Higgsinos
	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	
Gauginos	$\widetilde{g}$	g	
	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$	
	$\widetilde{B}^0$	B^0	

- particles: *R-parity* = 1
- superpartners: *R-parity* = -1

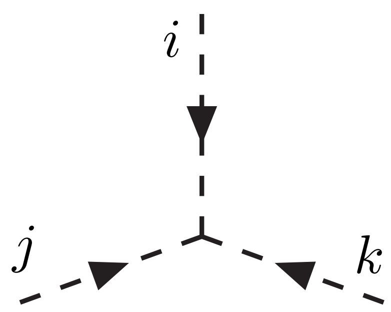
1) Superpart. interact in pairs
2) Lightest superpart. stable

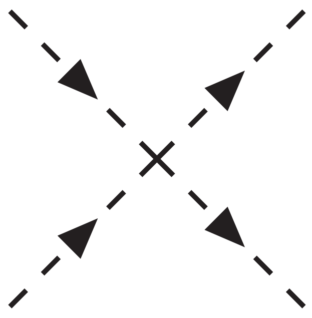
Type of interactions

Getting them from “supersymmetrization”:

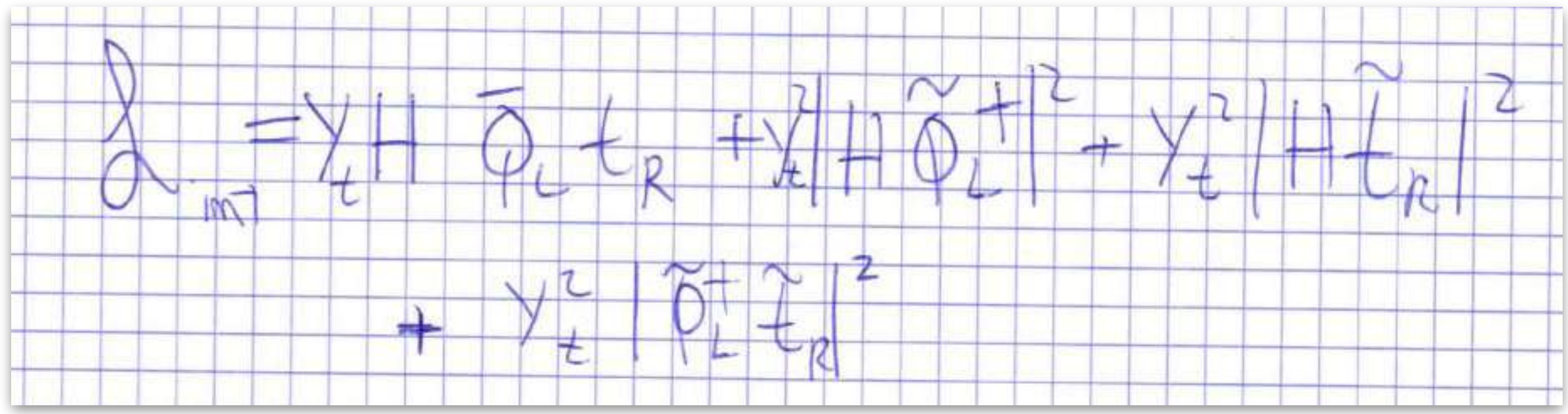


Up to scalar trilinear and quartics:

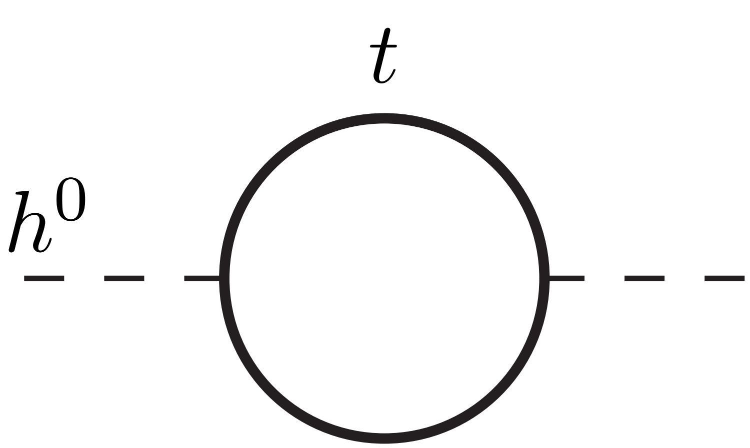




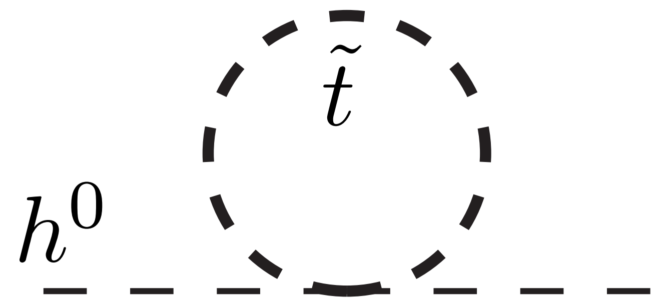
How supersymmetry works?



$$\mathcal{L}_{int} = y_t H \bar{Q}_L t_R + y_t^2 |H \tilde{Q}_L^\dagger|^2 + y_t^2 |H \tilde{t}_R|^2 + y_t^2 |\tilde{Q}_L^\dagger \tilde{t}_R|^2$$



+



Fermion loop

Boson loop

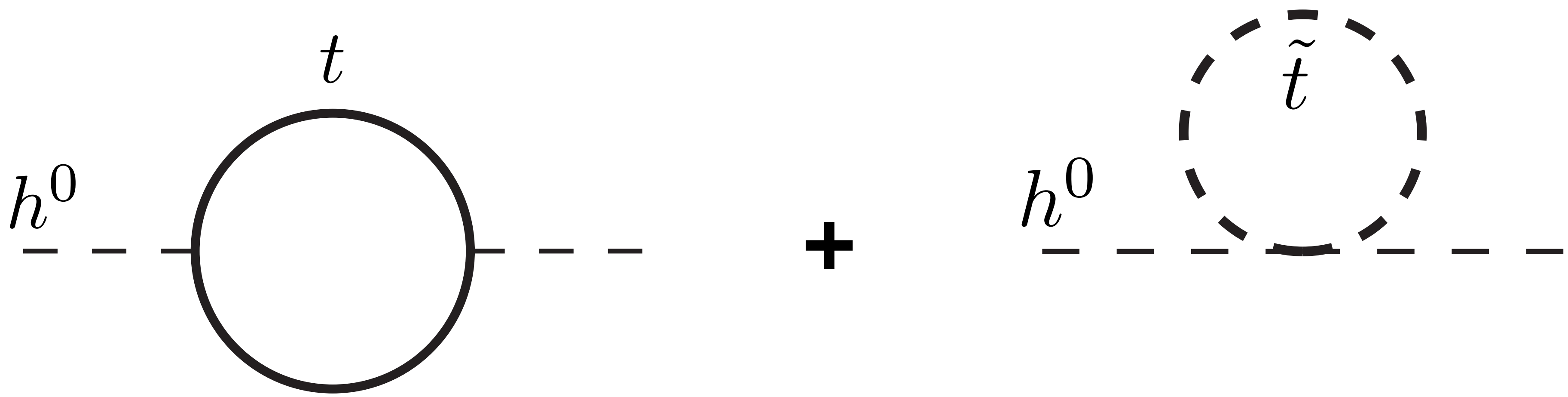
$m_H^2 = + A$

$m_H^2 = - A$

$m_H^2 = 0$

How supersymmetry works?

(if stops gets a susy-breaking mass)



Fermion loop | **Boson loop**

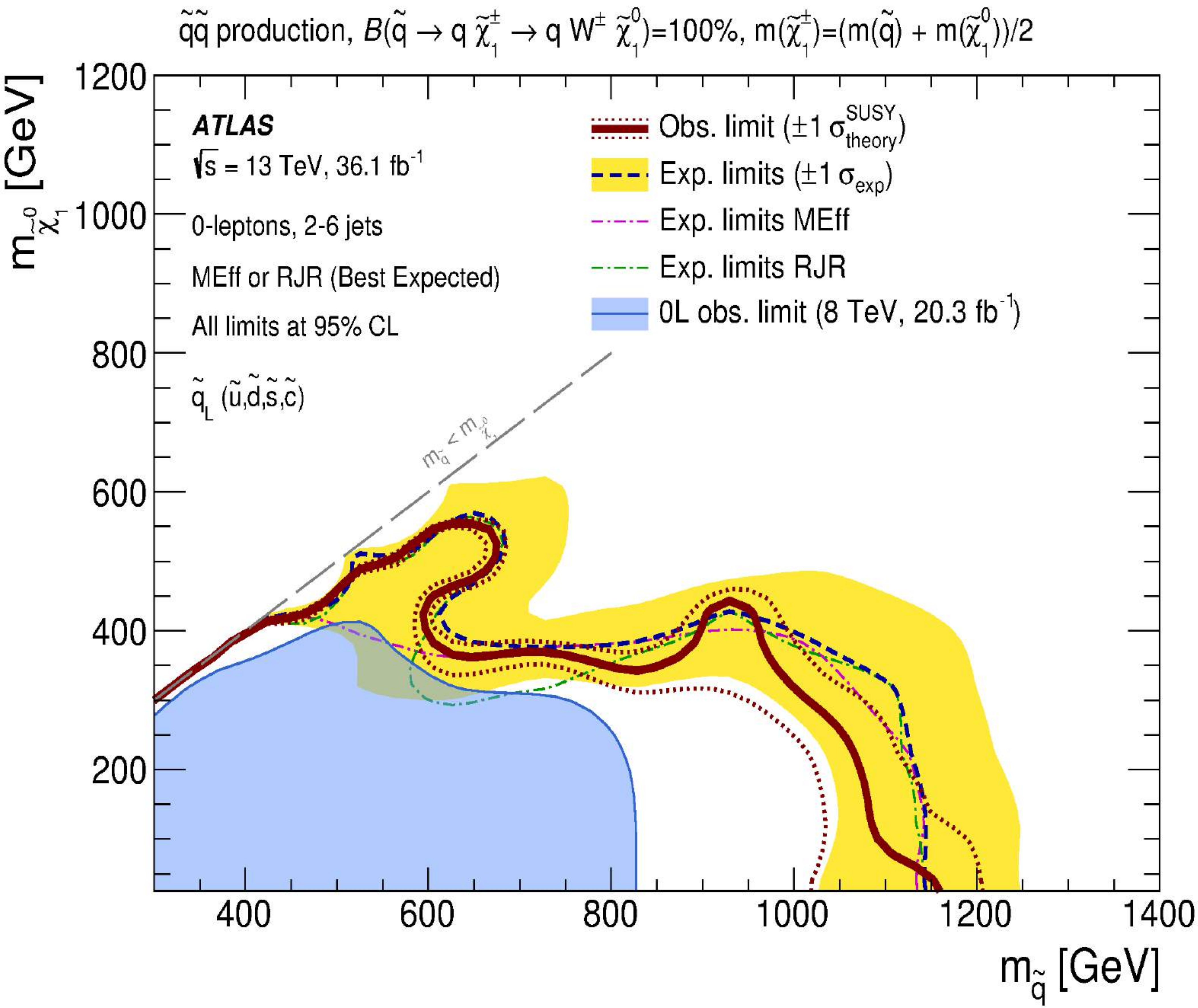
$m_H{}^2 = +A$

$m_H{}^2 = -A + m_{stop}{}^2 \; B$

$$\mathbf{m_H^2 \simeq -\frac{3Y_t^2}{8\pi^2}\left(m^2_{\tilde{Q}_L} + m^2_{\tilde{t}_R}\right) \ln \frac{M_{SSB}}{m_{\tilde{t}_R}} + \cdots}$$

scale at which the susy-breaking terms are generated

~ 400 GeV



$\tilde{q}\tilde{q}$ production, $B(\tilde{q} \rightarrow q\, \tilde{\chi}_1^{\pm} \rightarrow q\, W^{\pm}\, \tilde{\chi}_1^0)$=100%, $m(\tilde{\chi}_1^{\pm})=(m(\tilde{q}) + m(\tilde{\chi}_1^0))/2$
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
0-leptons, 2-6 jets
MEff or RJR (Best Expected)
All limits at 95% CL
$\tilde{q}_L$ ($\tilde{u},\tilde{d},\tilde{s},\tilde{c}$)
Obs. limit ($\pm 1\, \sigma^{SUSY}_{theory}$)
Exp. limits ($\pm 1\, \sigma_{exp}$)
Exp. limits MEff
Exp. limits RJR
0L obs. limit (8 TeV, 20.3 fb^{-1})
$m_{\tilde{q}} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{q}}$ [GeV]

Higgs sector

Only 3 parameters:

$$
\begin{aligned}
V = & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\
& + [b(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}] \\
& + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2} g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 .
\end{aligned}
$$

quartic coupling
related to gauge-couplings

Spectrum:

2 x 4 = 8 scalars = 3 Goldstones (eaten by W, Z)

+3 neutral Higgs = h, H, A

+ Charged Higgs = H^+, H^-

2 unknown parameters (since $v^2 = \langle H_u \rangle^2 + \langle H_d \rangle^2$):

1) $\tan\beta = \dfrac{\langle H_u \rangle}{\langle H_d \rangle}$ 2) m_A

At tree-level:

$$\begin{cases} m^2_{H^+} = m^2_A + m^2_W \\ m^2_{h,H} = \frac{1}{2}\left\{ m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 - m_Z^2)^2 + 4\sin^2 2\beta\, m_A^2 m_Z^2} \right\} \end{cases}$$

$$m_h \leq m_Z$$

Was a great prediction for Higgs hunters at LEP!

There is a nice prediction from supersymmetry:

The Higgs quartic is related to gauge couplings!

$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

➥ susy breaking term (at one-loop)

There is a nice prediction from supersymmetry:

The Higgs quartic is related to gauge couplings!

$$\mathbf{M_h^2 \leq M_Z^2 + \Delta m^2}$$

➥ susy breaking term (at one-loop)

$\mathbf{(125\ GeV)^2}$

$\mathbf{(91\ GeV)^2}$

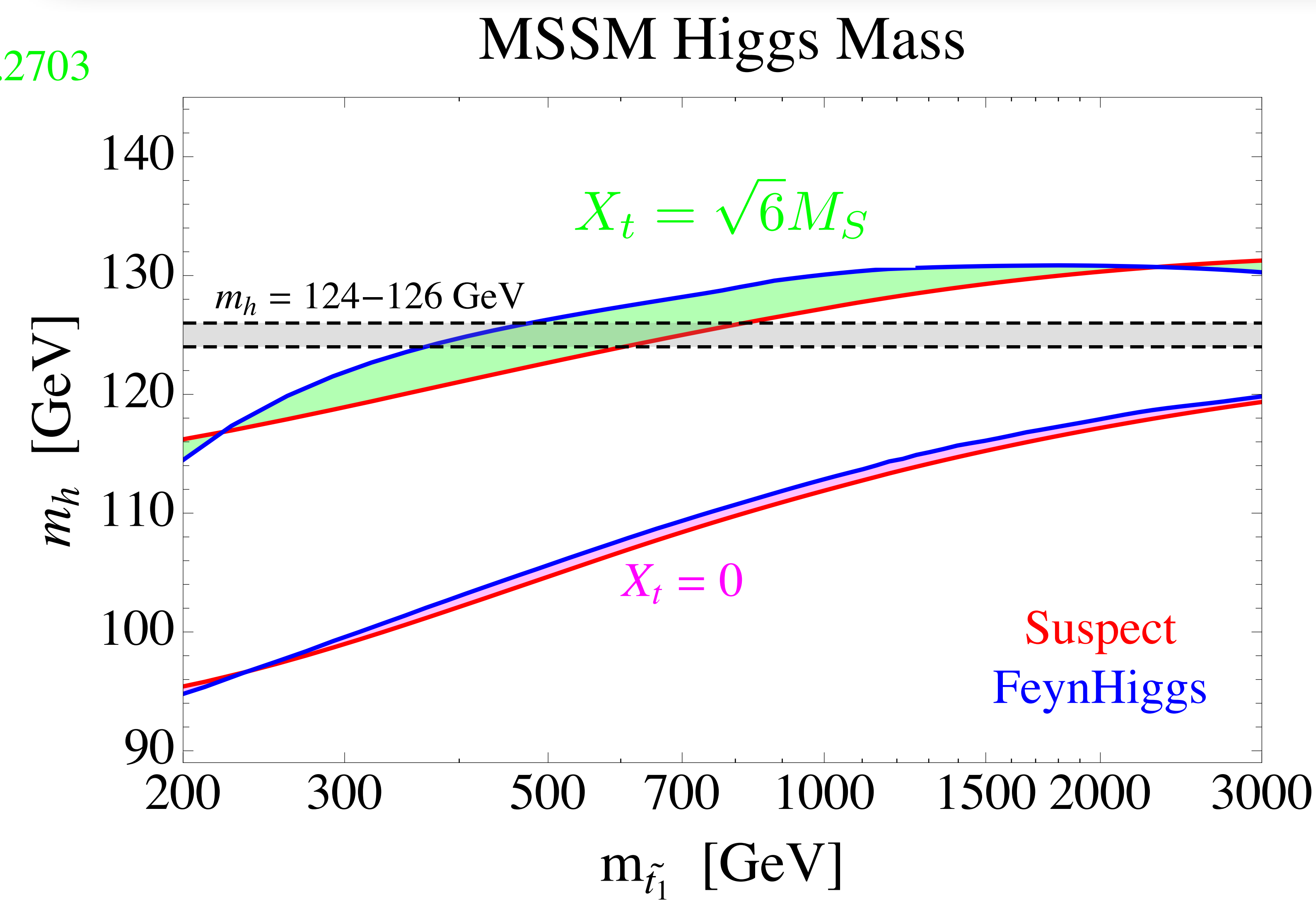
$\mathbf{(86\ GeV)^2}$

both have similar size:

Non-small Susy breaking effects

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

arXiv:1112.2703



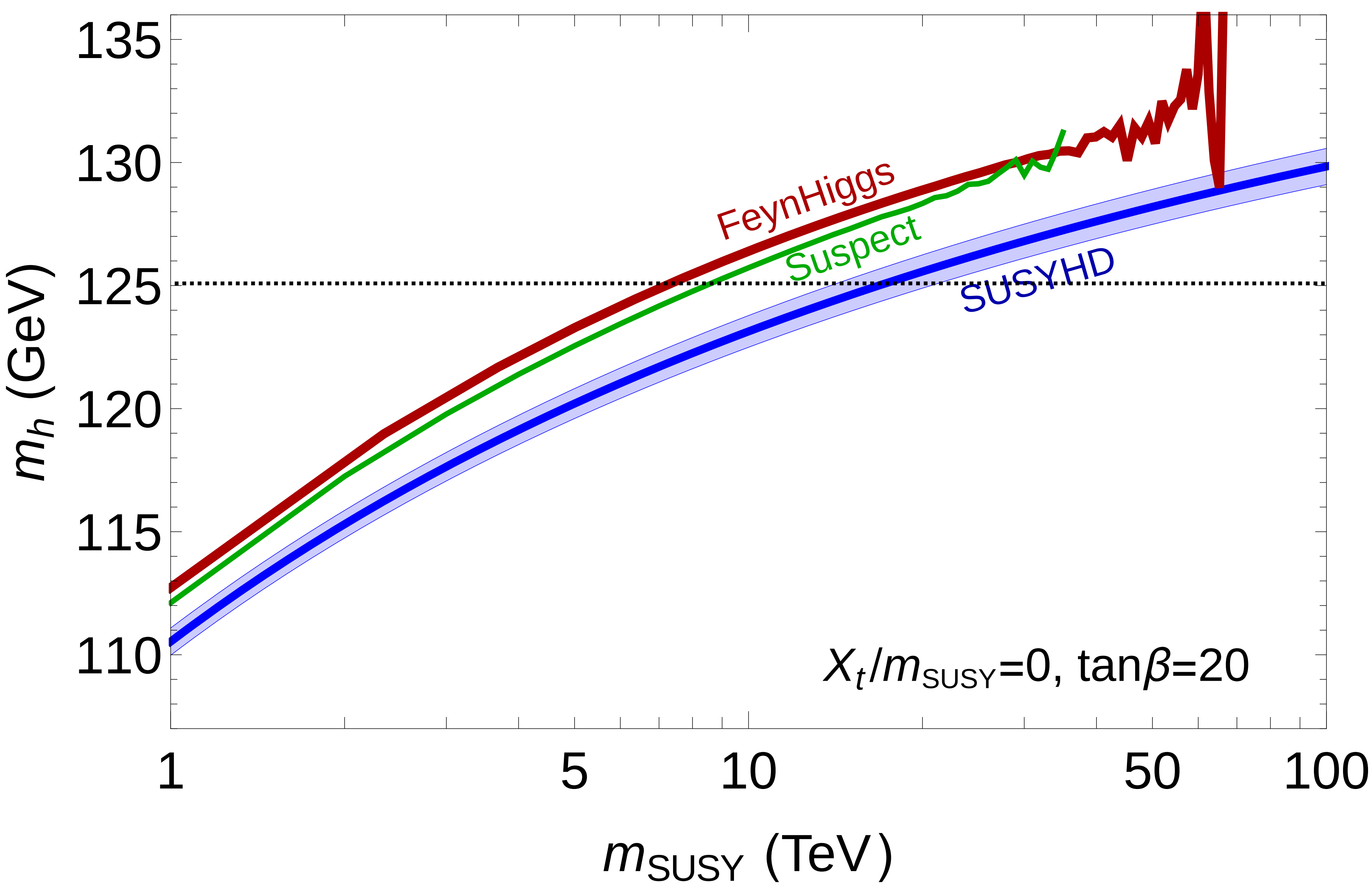
$$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

$$M_S \equiv \left(m_{\tilde{t}_1} m_{\tilde{t}_2}\right)^{1/2}$$

$$X_t \equiv A_t - \mu \cot\beta$$

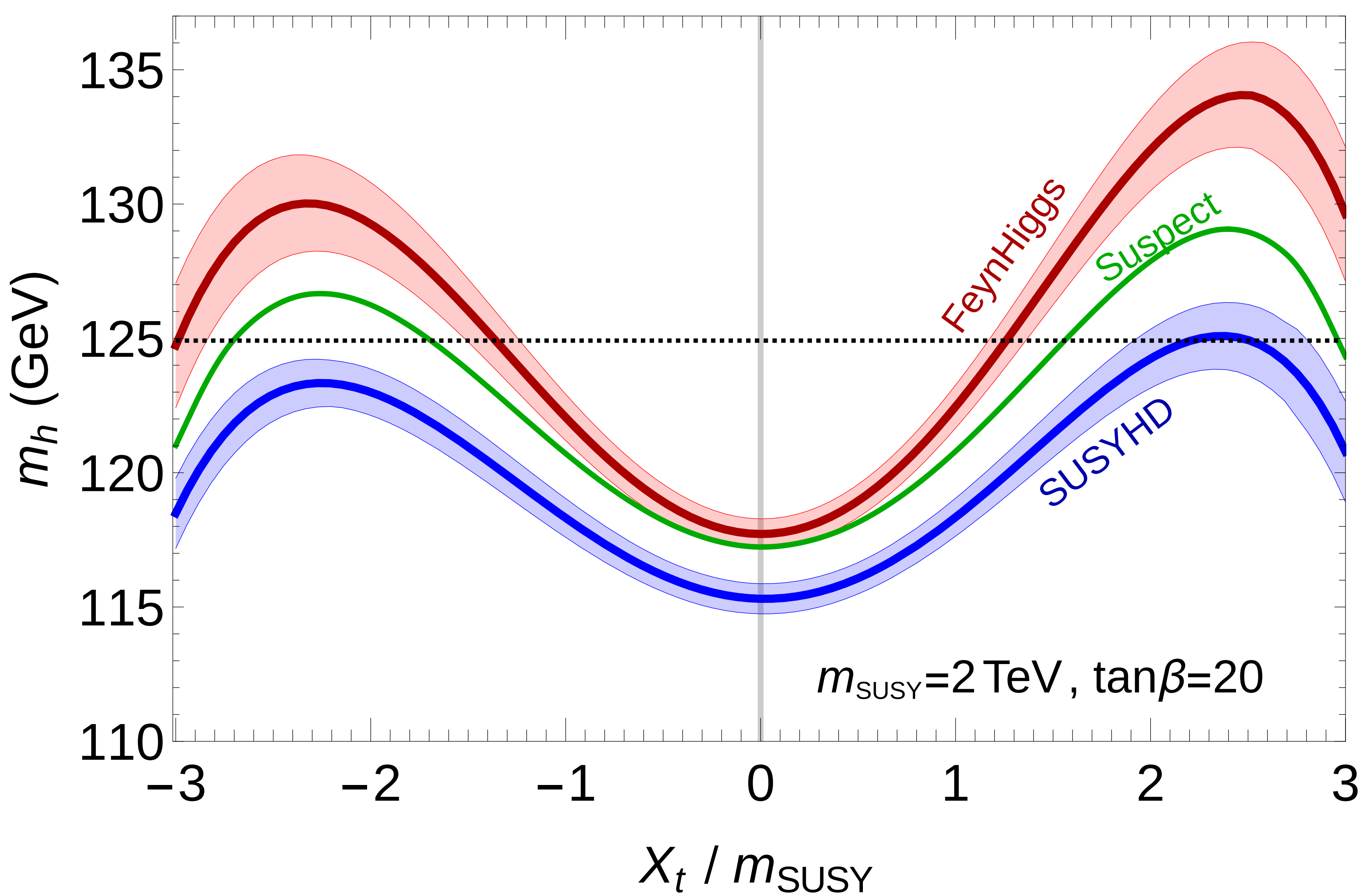
Implications: Large tanβ, large stop masses or trilinears

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$



1504.05200

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

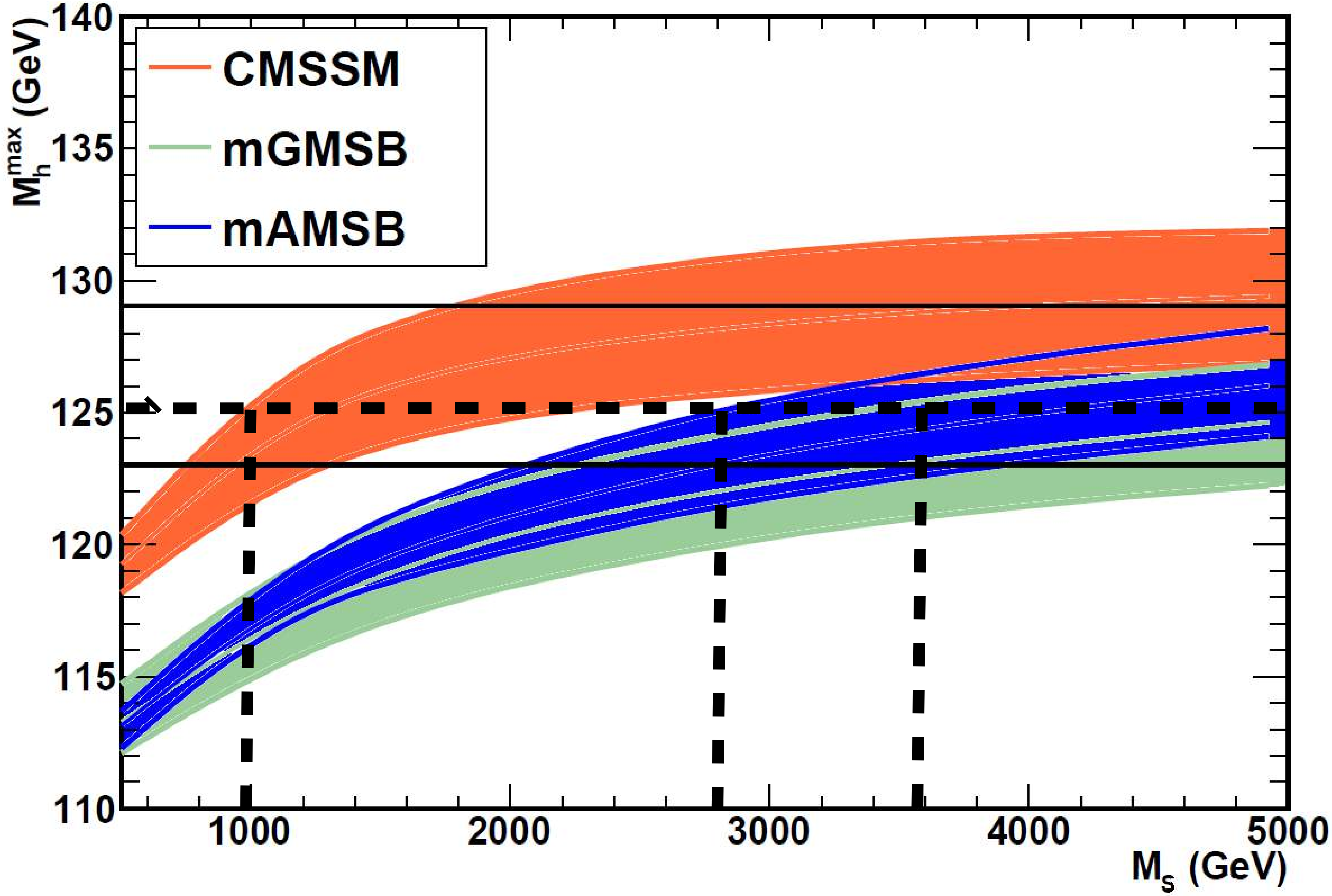


1504.05200

Implications in particular models of susy-breaking

Higgs mass in particular models of susy breaking:

from arXiv:1207.1348



This implies that most superpartners are beyond present LHC searches!

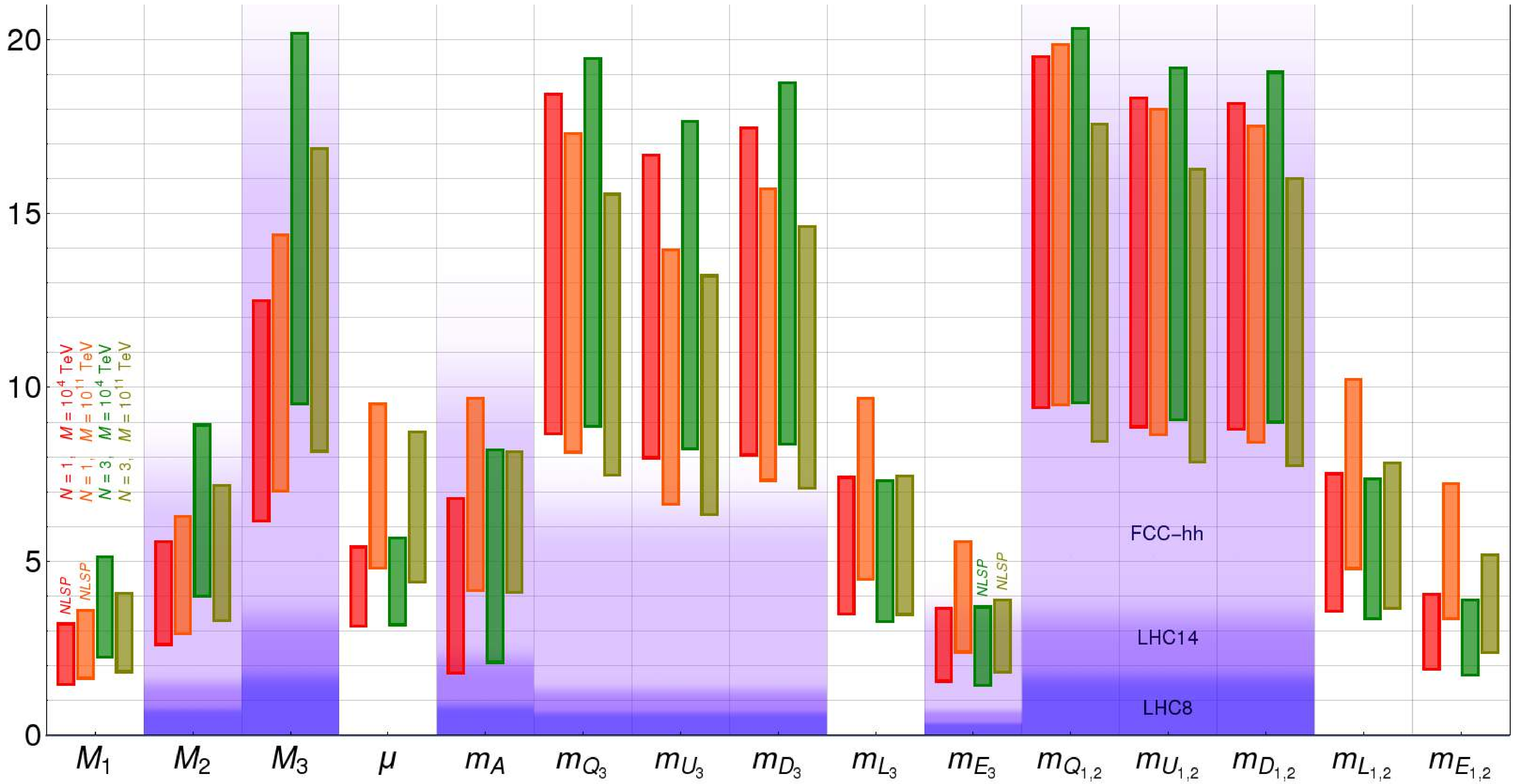


Figure 8: *Prediction for the spectrum of MGM after imposing the constraint from the Higgs mass (or better from the top mass). For each superpartner we plot the allowed range of masses (in TeV) for four different combinations of* $N = 1(3)$ *and* $M = 10^4(10^{11})$ *TeV. For each mass the lowest (highest) value corresponds to increasing (decreasing) the value of the top mass by* 2σ *with respect to its experimental central value. The values of* $\tan\beta$ *at the bottom (top) side of each of the four bands, from left to right, are 58 (42), 49 (45), 56 (29) and 44 (46) respectively. The three differently shaded areas represent "pictorially" the existing LHC8 bounds and the expected reach at LHC14 and at a future 100 TeV collider, respectively from the bottom.*