Beyond the Standard Model

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Outline:

- **Electroweak symmetry breaking (Lecture 1)**
- **Quark and lepton masses; vectorlike quarks (Lecture 2)**
- **New gauge bosons (Lecture 3)**
- **WIMPs and cascade decays (Lecture 4)**
- **How to search for new phenomena (Lecture 5)**

September 2011 - European School of HEP

High Energy Physics has established that all known natural phenomena can be described by a local quantum field theory which is invariant under:

- 3+1 dimensional Lorentz transformations $SO(3,1)$ and translations
- $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge transformations

High Energy Physics has established that all known natural phenomena can be described by a local quantum field theory which is invariant under:

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$\Longrightarrow$ *all elementary particles belong to certain representations of the Lorentz and gauge groups:*

Spin-1 bosons

$$\begin{cases} G^\mu : & (8,1,\ 0) \\ W^\mu : & (1,3,\ 0) \\ B^\mu : & (1,1,\ 0) \end{cases}$$

Spin-1/2 fermions

$$3 \times \begin{cases} q_L : & (3,2,\ +1/6) \\ u_R : & (3,1,\ +2/3) \\ d_R : & (3,1,\ -1/3) \\ l_L : & (1,2,\ -1/2) \\ e_R : & (1,1,\ -1) \end{cases}$$

Spin-2: graviton

Dark matter particle (spin =?)

Electroweak symmetry breaking

We know that $SU(2)_W \times U(1)_Y \rightarrow U(1)_Q$

$\Rightarrow W^{\pm}$ **and** Z **have not only transverse polarizations, but also longitudinal ones: three spin-0 states have been eaten.**

What is the origin of EWSB?

Electroweak symmetry breaking

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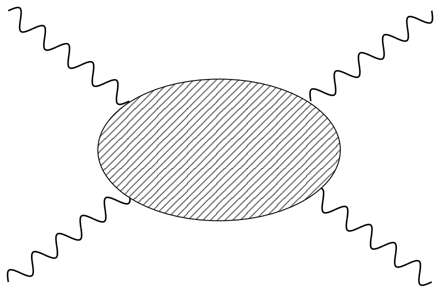
but also longitudinal ones: three spin-0 states have been eaten.

What is the origin of EWSB?

We don't know:

- **what unitarizes** $W_L^+ W_L^-$ **scattering?**
- **why is there a VEV that breaks** $SU(2) \times U(1)$ **?**
- **what has a VEV that breaks** $SU(2) \times U(1)$ **?**

$W_L^+ W_L^-$ scattering:



Perturbatively:

$$\sigma \left(W_L^+ W_L^- \to W_L^+ W_L^- \right) \approx \frac{G_F^2\, s}{16\pi}$$

This makes sense only up to $\sqrt{s} \sim 1$ TeV *(see Lecture 5 of E. Dudas).*

At higher energy scales:

⋆ **A new particle: Higgs boson**

OR

⋆ **New strong interactions (perturbative expansion breaks down)**

OR

⋆ **Quantum field theory description breaks down**

Homework 1.1

Draw the Feynman diagrams for $WW \to WW$ *and* $WZ \to WZ$ *in the standard model which are relevant in the* $M_h \gg M_W$ *limit.*

Devise experimental searches for the Higgs boson using these processes.

Hint: the LHC is not only a gg or gq or qq collider, but also a WW and a WZ collider!

Alternative to Higgs boson: **spin-1 particles (ρ_T) coupled to WW.**

Unitarity in WW scattering may be restored by ρ_T exchange.

However, $\rho_T\rho_T$ and $\rho_T W$ scattering are then non-unitary, unless some other particles exist.

$\rightarrow$ a whole tower of heavy particles is needed .... it sounds like QCD, but at a scale 10^3 higher!

"Technicolor": a new gauge interaction which becomes strong at the TeV scale.

Techni-fermion condensate breaks electroweak symmetry (same as chiral symmetry breaking in QCD).

ρ_T is the techni-rho.

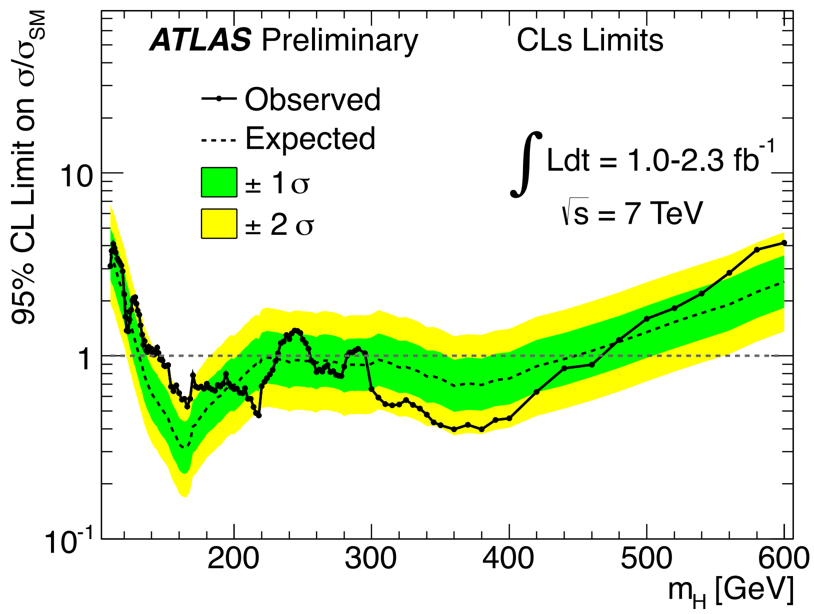
Technicolor has problems with the fits to the electroweak observables. However, strongly coupled field theories are poorly understood, so it is hard to make precise predictions.

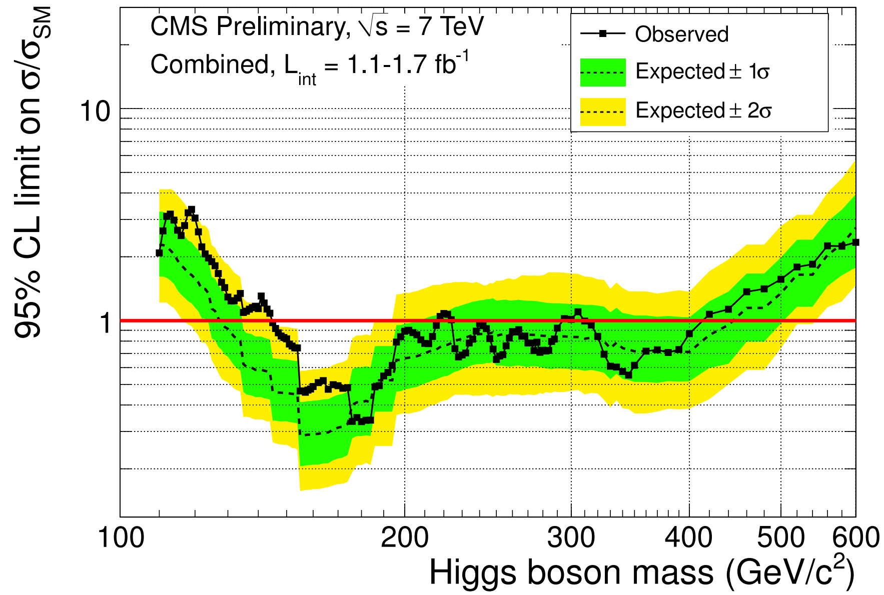
Another example of spin-1 particles that unitarize WW scattering: Kaluza-Klein modes in a model with one extra dimension where the electroweak symmetry is broken by boundary conditions:

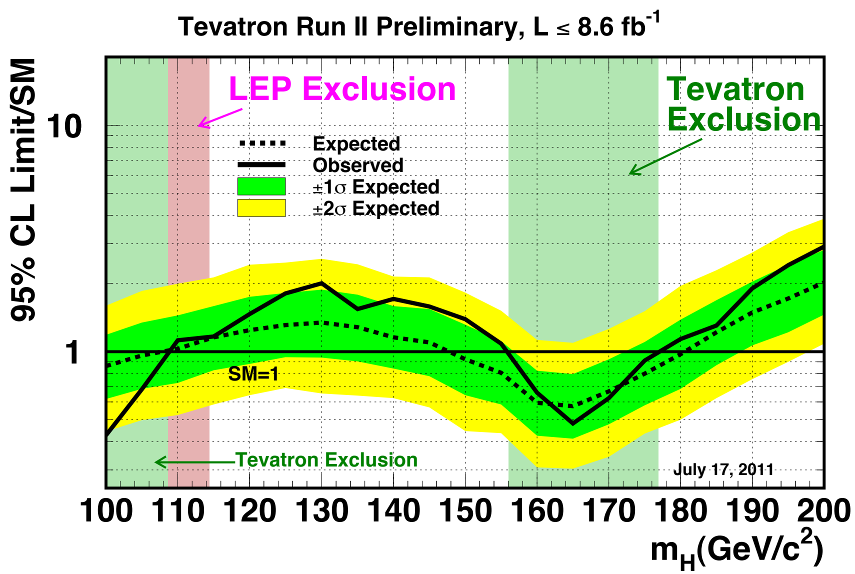
"Higgsless models" *Csaki, Grojean, Pilo, Terning: hep-ph/0308038*

$\longrightarrow$ lightest spin-1 resonances around 1.2 TeV

Searches for the standard-model Higgs boson:



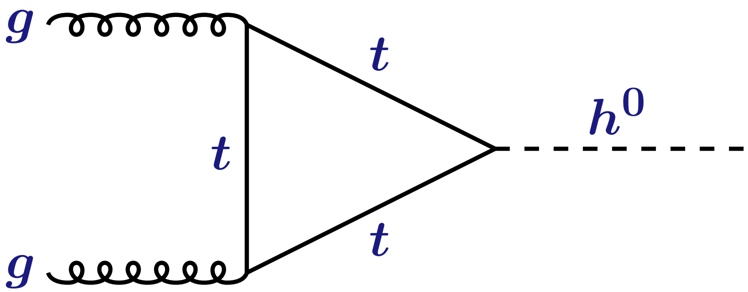




Room for SM Higgs boson has shrank dramatically this summer!

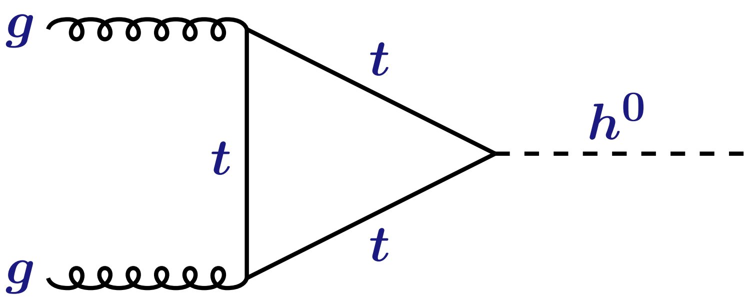
Hidding the Higgs boson

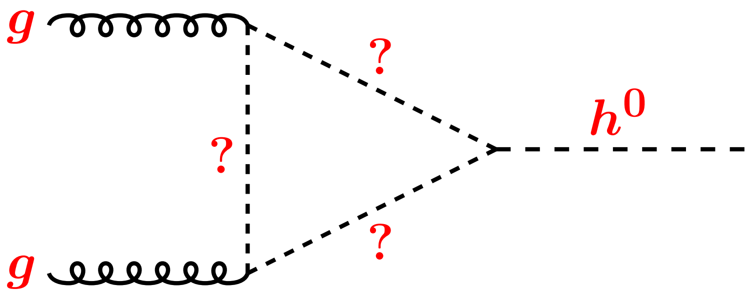
SM gluon fusion

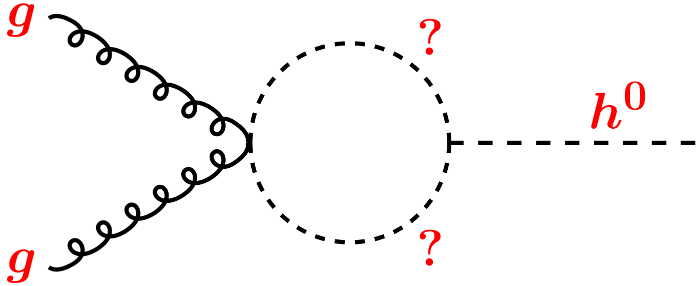


Hidding the Higgs boson

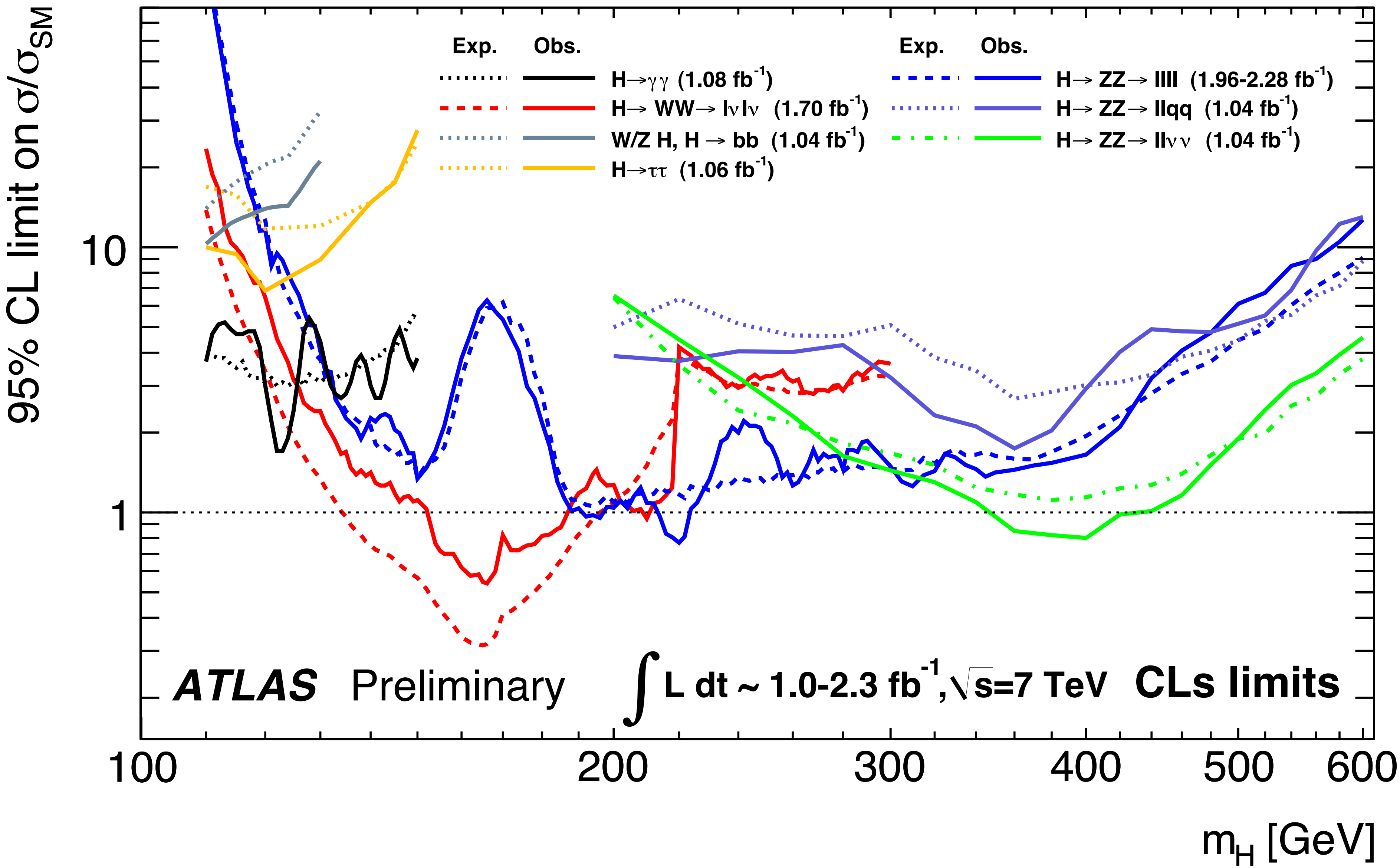
SM gluon fusion $\pm$ **non-standard production**







The cross section for gluon fusion may be reduced, but only if there are new colored particles at the electroweak scale.



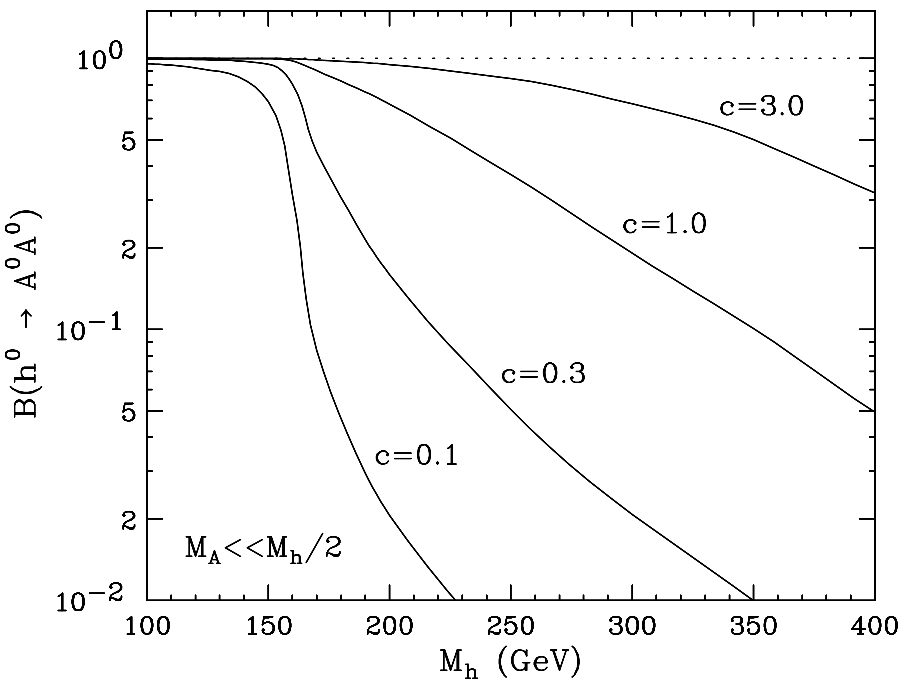
Homework 1.2: *What other channels can be used?*

Nonstandard Higgs decays: a case study

Standard model + a scalar singlet S: $\quad cH^\dagger H S^\dagger S$

$$S = \frac{1}{\sqrt{2}}\left(\varphi_S + \langle S\rangle\right) e^{iA^0/\langle S\rangle}$$, A^0 is a CP-odd spin-0 particle (axion)

$$\frac{c\,v}{2} h^0 A^0 A^0 \ \text{coupling} \ \Rightarrow \ \Gamma(h^0 \to A^0 A^0) = \frac{c^2 v^2}{32\pi M_h}\left(1 - 4\frac{M_A^2}{M_h^2}\right)^{1/2}$$

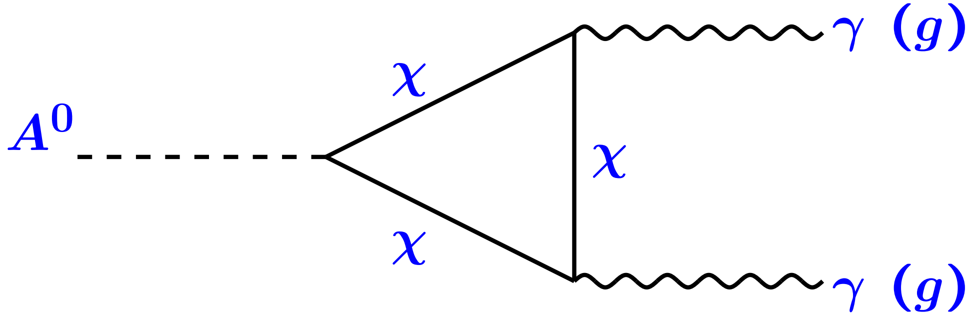


Dobrescu, Landsberg, Matchev,

hep-ph/0005308

The subsequent decays of A^0 are model dependent.

Example: $\mathcal{L} = \xi S \overline{\chi}_L \chi_R + \mathrm{h.c.} - V(H, S)$, χ is a new fermion

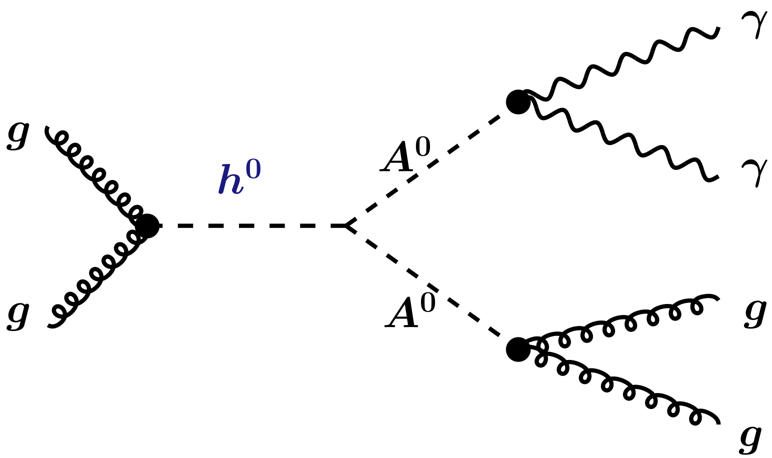


Effective coupling of the axion to pairs of gluons and photons:

$$\frac{-\sqrt{2}}{16\pi\langle S\rangle} A^0 \epsilon^{\mu\nu\rho\sigma} \left[T_2(\chi)\alpha_s \, \mathrm{G}_{\mu\nu}\mathrm{G}_{\rho\sigma} + N_c e_\chi^2 \alpha \, F_{\mu\nu}F_{\rho\sigma} \right]$$

If χ is both colored and electrically charged: $\dfrac{B(A^0 \to \gamma\gamma)}{B(A^0 \to gg)} \approx 10^{-3}$.

$h \to A^0 A^0 \to (\gamma\gamma)(jj)$ **may be the most interesting decay, with the diphoton and dijet peaks having same mass.** *(Chang, Fox, Weiner, hep-ph/0608310, ...)*

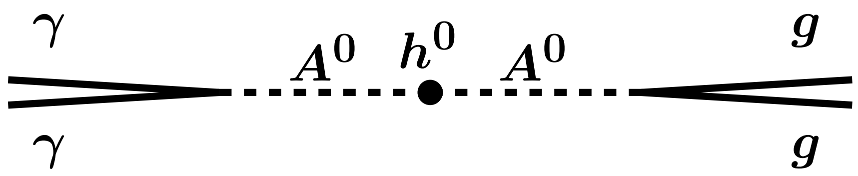


Homework 1.3:

Draw the Feynman diagrams for $pp \to Wh \to W\gamma\gamma jj$.

Roughly estimate the LHC cross section for this signal and identify the main backgrounds. *(Hint: see A. Martin, hep-ph/0703247)*

For a light A^0, this may appear in the detector as
$h \to A^0 A^0 \to (\gamma\gamma) j$ or $h \to A^0 A^0 \to$ "γ" j.



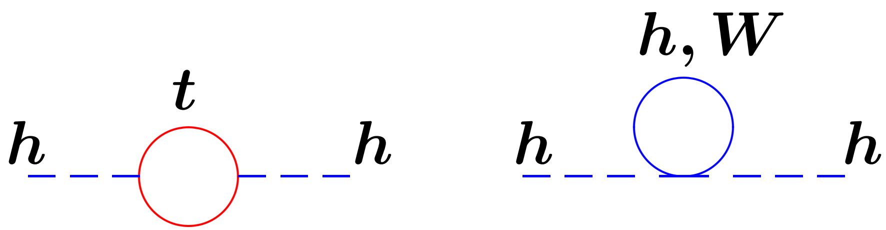
Homework 1.4:

Estimate M_A such that: a) the jets overlap; b) the photons overlap.
(assume $M_h = 120$ GeV)

If χ is electrically-neutral but carries color $\Rightarrow B(A^0 \to jj) \approx 100\%$
$h \to A^0 A^0 \to 4j$ is the main decay mode for $M_h < 2M_W$
$\Rightarrow$ huge background at the LHC,
Higgs boson will be hard to discover ... (use jet substructure?)

Hierarchy problem

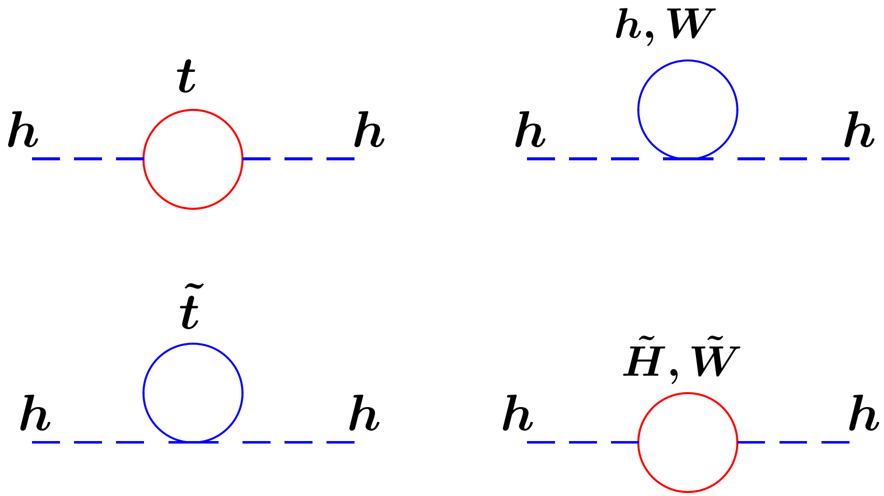
Quantum fluctuations tend to increase the vacuum expectation value of the Higgs field.



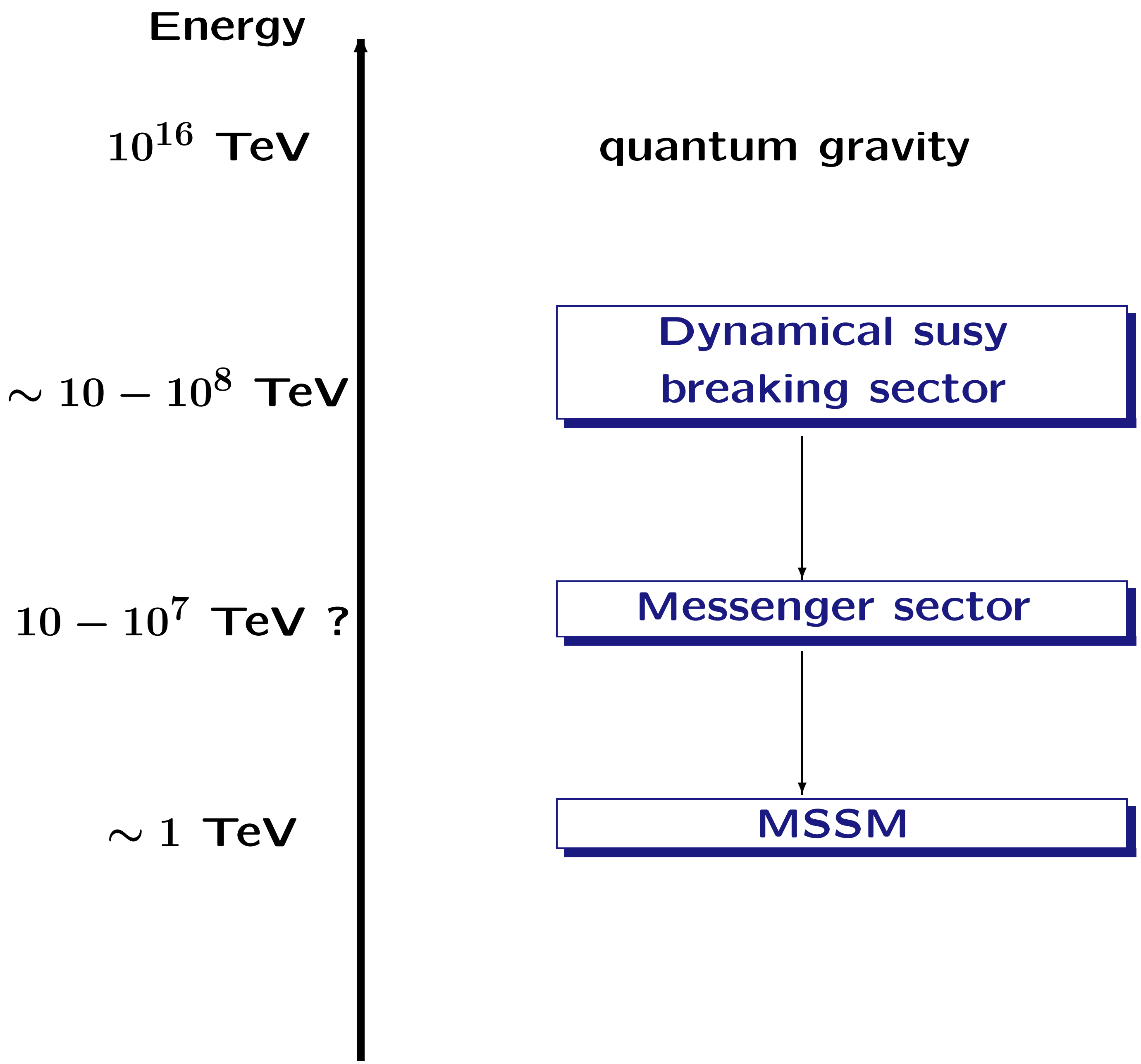
Stability of the electroweak scale requires a modification of the standard model at scales above ~ 1 TeV.

Solution #1: Supersymmetric Standard Model

No quadratic divergences because loops with superpartners partially cancel the SM loops



Additional structures required to explain why $\langle H \rangle \sim M_{\mathrm{SUSY}}$, μ.


Energy
10^{16} TeV
quantum gravity
$\sim 10 - 10^8$ TeV
Dynamical susy breaking sector
$10 - 10^7$ TeV ?
Messenger sector
~ 1 TeV
MSSM

Solution #2: Technicolor

Energy

10^{16} **TeV** — **quantum gravity**

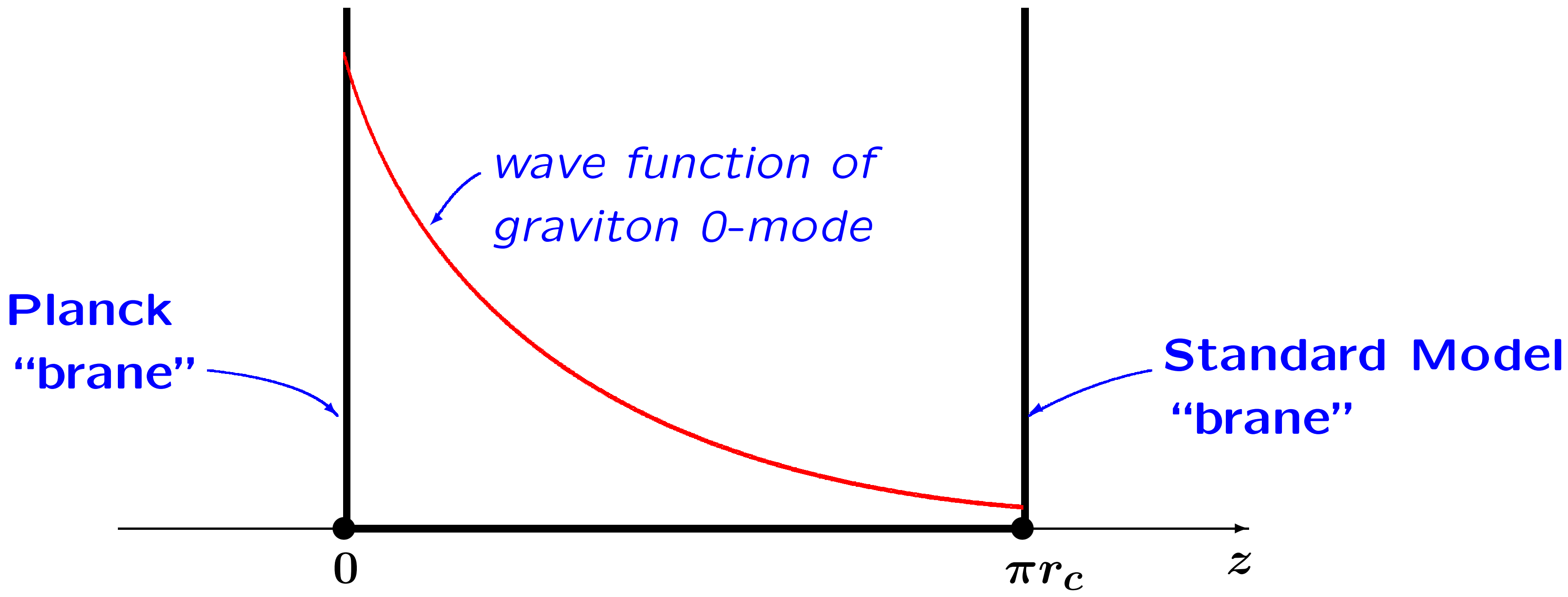
Technicolor gauge coupling: $g_{\mathrm{TC}} \sim O(1)$

logarithmic running of g_{TC}
(increases at lower scales,
just as in QCD)

~ 1 **TeV** — $\boxed{g_{\mathrm{TC}} \sim O(4\pi) \Rightarrow \textbf{Technifermions condense} \Rightarrow \textbf{electroweak symmetry is broken}}$

Solution #3: A warped extra dimension

L. Randall, R. Sundrum, hep-ph/9905221



Interaction of the graviton 0-mode (the massless 4D spin-2 field) with Standard Model particles is suppressed by its exponentially small wave function at the SM brane.

Hierarchy between the Planck and electroweak scales is explained!

Scales of RS1 model (measured on the SM brane):

Energy

~ 1 **TeV**

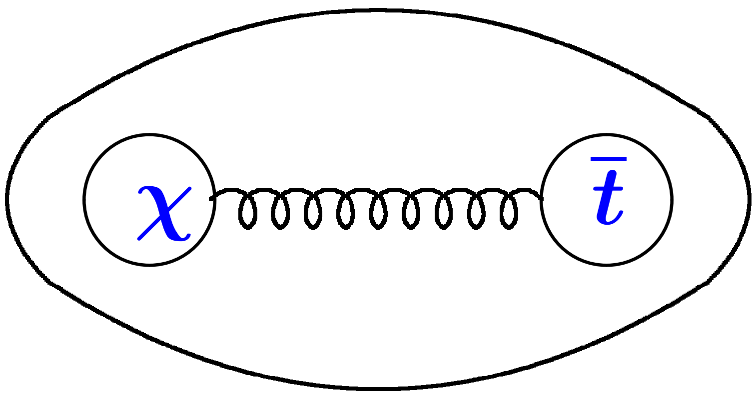
$\boxed{\textbf{Graviton KK modes are strongly coupled}}$

Standard Model

Solution #4: Composite Higgs models

Higgs boson is a bound state of top quark with a new quark χ.
"Top seesaw model" *(Chivukula et al, hep-ph/9809470)*

Binding may be due to some strongly-interacting heavy gauge bosons



Scale of Higgs compositeness may be as low as a few TeV.

Homework 1.5: *What are quantum numbers of χ? How would you search for this hypothetical particle?*

Solution (?) #5: Large extra dimensions (ADD)

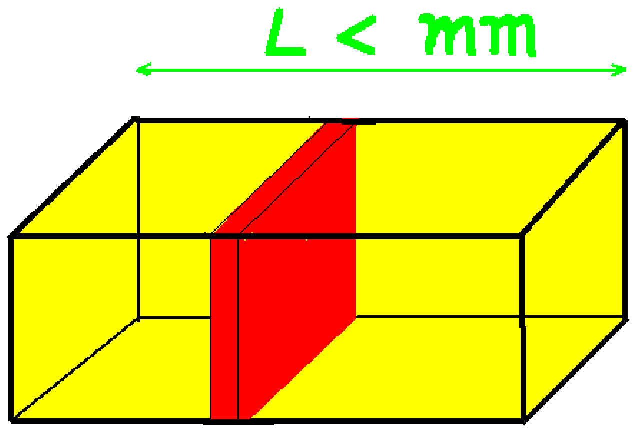
Graviton only in flat extra dimensions

Gravitational interactions measured at distances $\gtrsim 10^{-3}$cm:

$$F_N = \frac{m_1 m_2}{M_{\rm Planck}^2 r^2}$$

We may live on a wall in extra dimensions!

(Arkani-Hamed, Dimopoulos, Dvali, 1998)

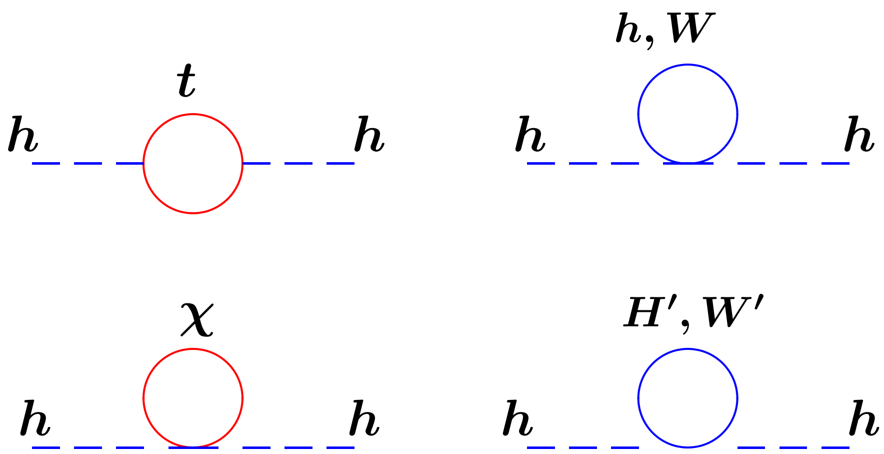


Newton's law in extra dimensions: $$F_N = \frac{m_1 m_2}{(M_s r)^{2+n}}$$

Scale of quantum gravity may be as low as $\sim$ 10 TeV: $$M_s = \left(\frac{M_{\rm Planck}^2}{L^n}\right)^{1/(2+n)}$$

(Partial) Solution #6: Little Higgs

1-loop quadratic divergences cancelled by partners carrying the same spin. *(Arkani-Hamed et al, hep-ph/0206021)*



Effective theory valid up to scales of order ~ 5 TeV, where some unspecified new dynamics takes over.

(Partial) Solution #7: Twin Higgs

Z. Chacko, H. S. Goh and R. Harnik, hep-ph/0506256

1-loop quadratic divergences are cancelled if there is a parity which interchanges each SM particle with a new particle that transforms under a twin SM gauge group.

If the new particles are neutral under the SM gauge group, than these partners would be very hard to see at the LHC .

This is unlike all other known solutions, where the a $\tilde{t}$ squark or a χ quark or something else is visible at the TeV scale.

Effective theory valid again only up to scales of order ~ 5 TeV...

Comparison between solutions to the hierarchy problem:

1. **Dynamically-broken supersymmetry**

Susy breaking scale is exponentially suppressed compared to $M_{\rm Planck}$ *due to gauge dynamics.*

Problem: μ term (the Higgsino mass) is supersymmetric.

Why $\mu \sim v$? (some solutions exist)

2. **Technicolor**

Exponential hierarchy between $M_{\rm Planck}$ *and the scale where the technicolor gauge interaction becomes strong.*

Problem: fit to the electroweak data? (some solutions exist)

3. **RS1**

$1/M_{\rm Planck}$ *is exponentially suppressed compared to* $1/v$.

Conclusions to Lecture #1

EWSB argument for new phenomena:

unitarity of $W_L W_L$ scattering requires a Higgs boson or new strong interactions or something more exotic.

Only in the presence of other light new particles it may be hard to discover the Higgs boson at the LHC+Tevatron.

Hierarchy argument for new phenomena:

naturalness requires new physics at the TeV scale,

but there are many possibilities and it may not be easy to pin down its nature even at the LHC.