Higgsinoless SUSY and Hidden Gravity

Ryuichiro Kitano (Tohoku U.)

Ref.: Michael Graesser, RK, Masafumi Kurachi, JHEP 0910:077,2009 (arXiv:0907.2988)

Seminar at IPMU, Dec. 17, 2009

Role of the Higgs field:

Non-vanishing VEV

\+ → masses

Coupling to quark/lepton/gauge

We think there is a (strong) dynamics behind this mechanism.

Role of the Higgs field:

Single dynamics at TeV? (extended technicolor, extra dim....)

Non-vanishing VEV

\+

Coupling to quark/lepton/gauge

→ masses

→ Usually cause too large FCNC.

Role of the Higgs field:

A dynamics for VEV only. (technicolor..)

Non-vanishing VEV

\+ → masses

Coupling to quark/lepton/gauge

→ Difficulty in writing the Yukawa interactions.

Role of the Higgs field:

Non-vanishing VEV

\+ → masses

Coupling to quark/lepton/gauge

A dynamics for Yukawa only.

→ Hierarchy problem remain unsolved.

Role of the Higgs field:

Weakly coupled Supersymmetry (elementary Higgs)

+ dynamics to break supersymmetry + messengers

Non-vanishing VEV

+ → masses

Coupling to quark/lepton/gauge

→ μ-problem (naturalness problem unsolved).

(difficulty in SUSY breaking transmission to the Higgs field)

or FCNC problems

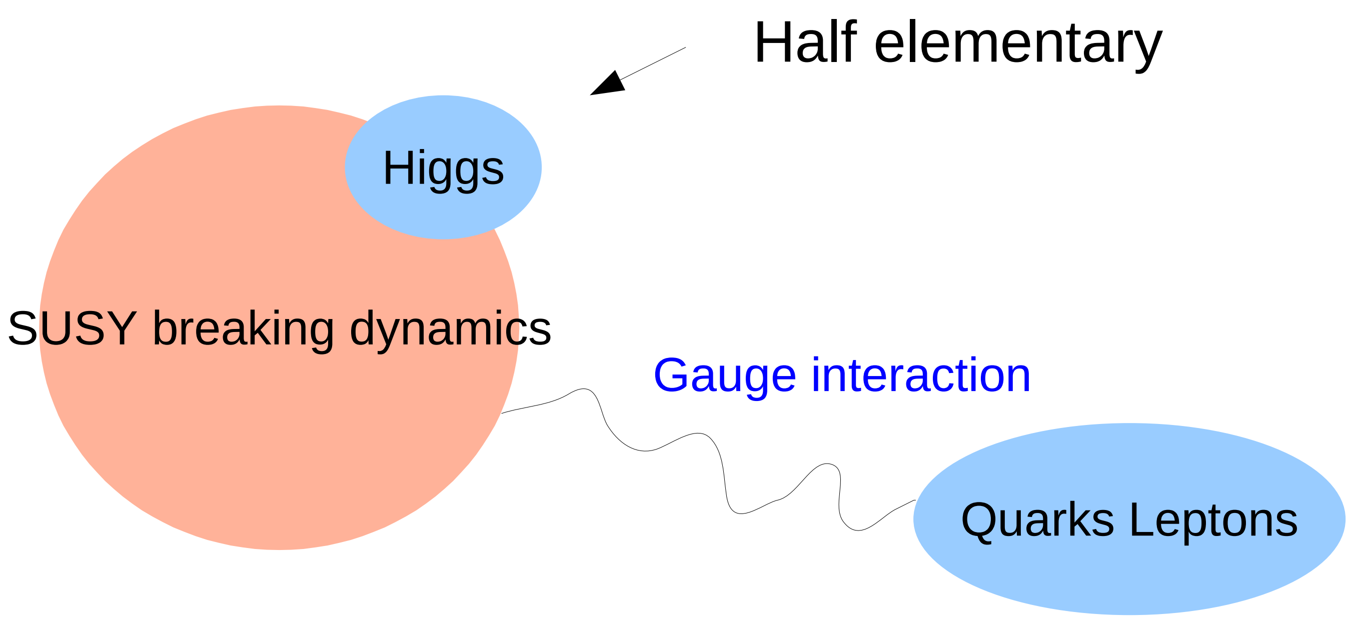
We need the Higgs field to have two different features:

Composite + elementary

Naturally small VEV

O(1) Yukawa interactions
without FCNC.

A pretty picture emerges: Supersymmetric Technicolor



That is SUSY breaking at (a few) TeV and the Higgs gets VEV triggered by the same dynamics. Some weak interactions provide mass splittings in the matter sector.

[Dine, Fischler, Srednicki '81, Dimopulos, Raby '81, Affleck, Dine, Seiberg '85]

What's the motivation of SUSY? [Dine, Fischler, Srednicki '81]

Isn't TeV dynamics enough?

The weak point of technicolor is the Yukawa interaction.

↓

Maybe in the UV, we need an elementary Higgs field for Yukawa.

↓

We want SUSY to naturalize it.

↓

Even with SUSY, we have naturalness problem, the μ-problem, in the Higgs sector. Also, we need to break SUSY.

↓

Maybe there is a complicated dynamics at TeV which is directly coupled to the Higgs field.

↓

SUSY technicolor!

If you are a string theorist/SUSY believer,

There is SUSY. We need to break it.

↓

We need a dynamics to break SUSY.

↓

The most natural (economical) scale to break SUSY is TeV.

↓

Unification of EW and SUSY breaking dynamics.

If you are an experimentalist,

SUSY is a well-motivated/beautiful framework.

↓

In an extreme scenario, SUSY breaking dynamics is accessible at the LHC experiments.

↓

We may be able to directly see a SUSY breaking dynamics in addition to superpartners!

If you are a cosmologist,

Gravitino is a very bad particle in the early universe.

↓

They are harmless if they are light enough such as lighter than O(10eV). [M. Viel et al. 05]

↓

Low energy SUSY breaking!

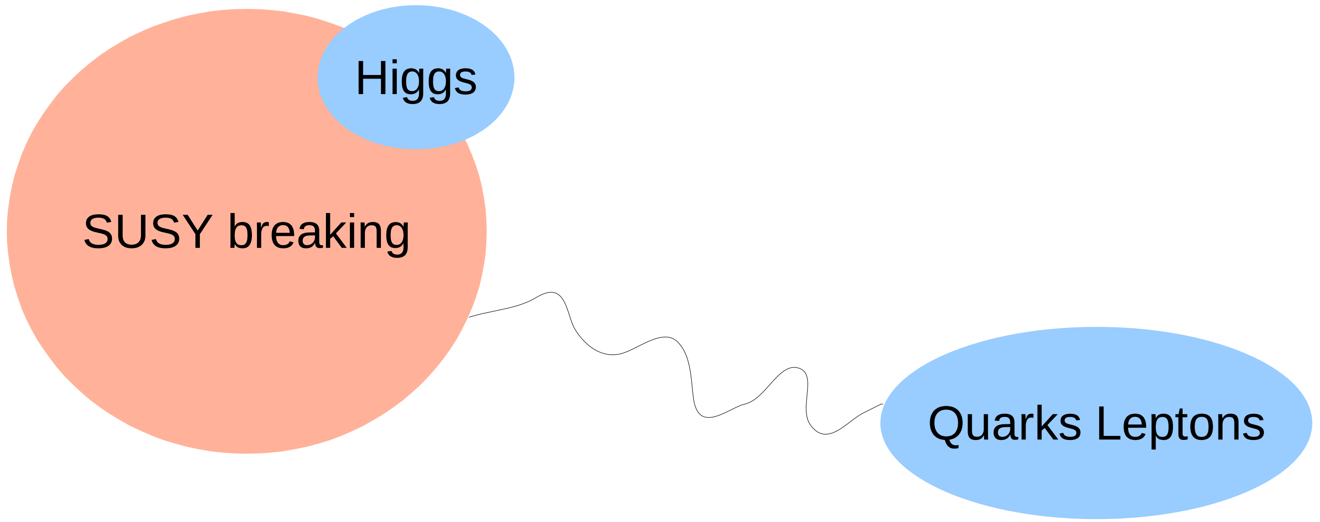
All right. Let's proceed.

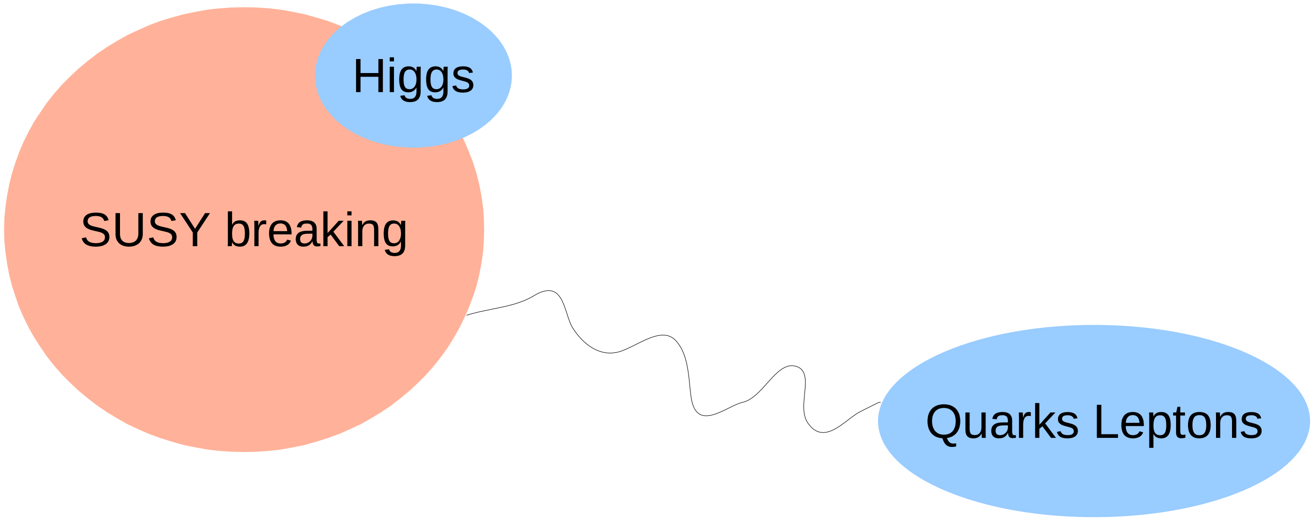
Now, can we build a dynamical model of TeV scale SUSY breaking which triggers EWSB?

→ Maybe. But before having data, the discussion is better to be general.

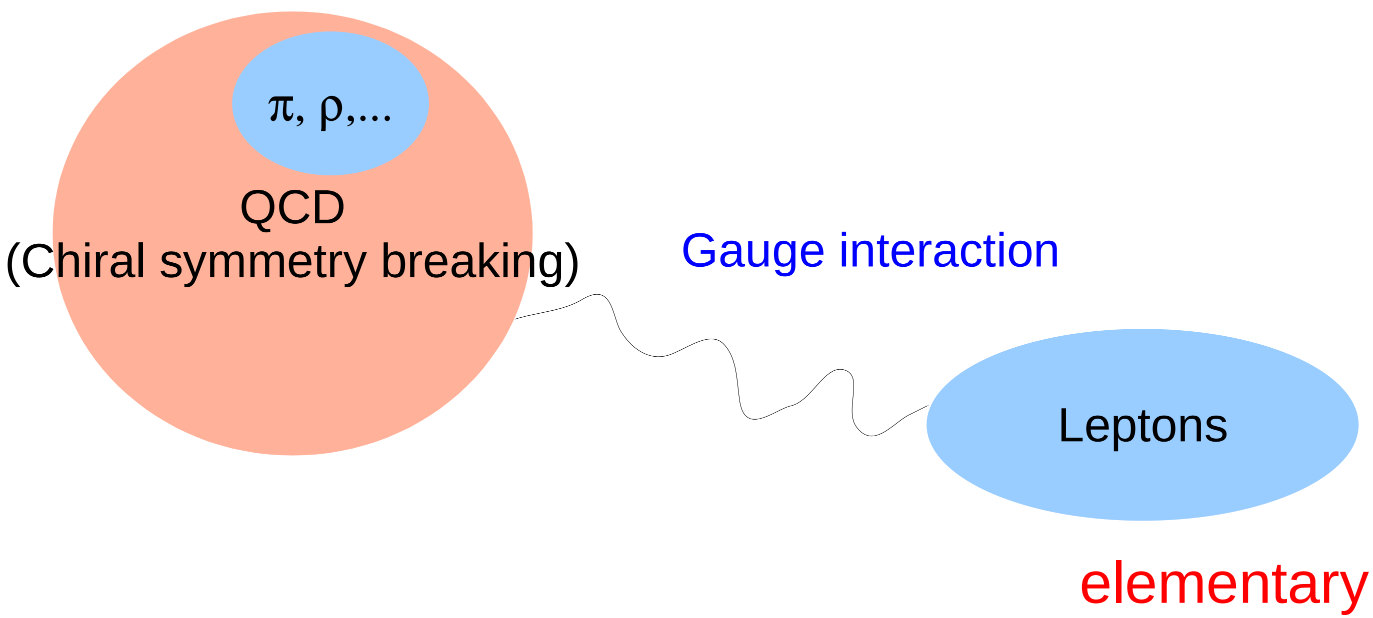
It is like trying to build QCD before observing any hadrons.

What we know is just this picture:





QCD analogy:



We know that there is a powerful tool to describe low-energy physics with dynamically broken symmetry. That is the nonlinear σ-model.

Nonlinear SUSY

[Volkov and Akulov '73]

Akulov and Volkov found a funny symmetry in the Dirac equation for a massless fermion λ and wrote down an invariant action:

$$S = -\frac{1}{2}\int d^4x \det A$$

where $A_\mu{}^a \equiv \delta_\mu{}^a - i\lambda\sigma^a\partial_\mu\bar{\lambda} + i\partial_\mu\lambda\sigma^a\bar{\lambda}$

This action is invariant under

$$x^\mu \longrightarrow x^\mu + i\eta\sigma^\mu\bar{\lambda}(x) - i\lambda(x)\sigma^\mu\bar{\eta}$$

$$\lambda(x) \longrightarrow \lambda(x) + \eta$$

η is a fermionic parameter.

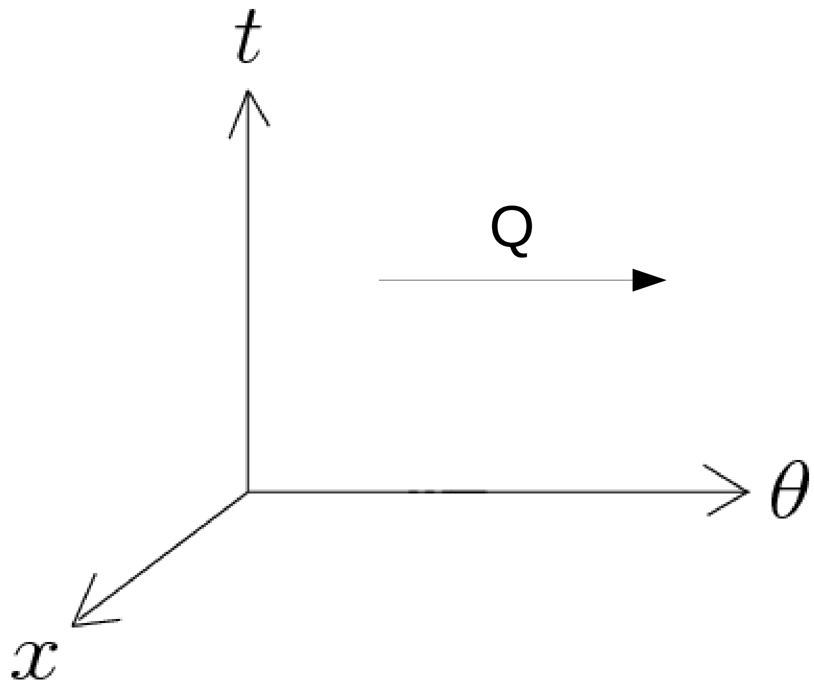
→ This is supersymmetry. λ(x) is the Goldstino field.

What's that?

A simple formulation of SUSY.

SUSY is a translational invariance of the superspace.

[Salam, Strathdee, '78]

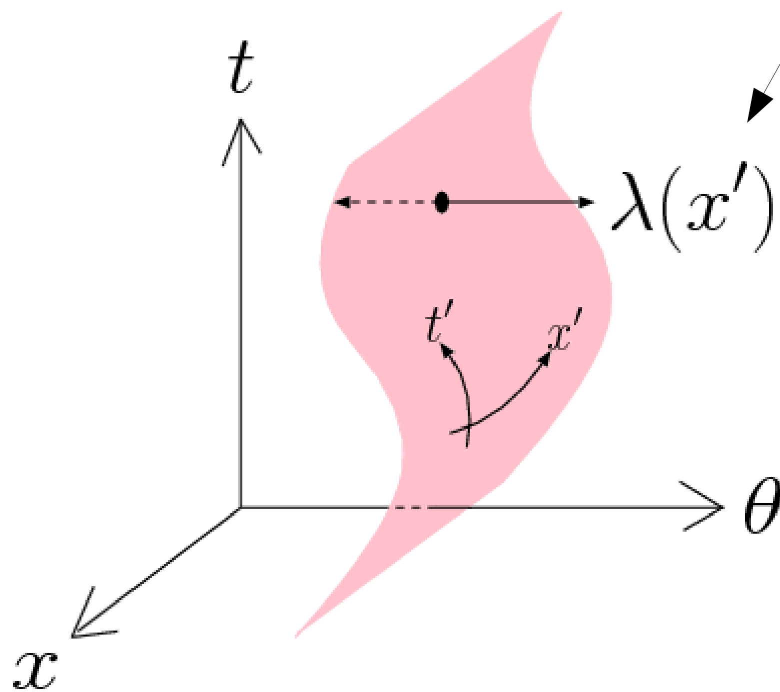


In order to break the symmetry spontaneously, what we need to do is just...

What's that?

A simple formulation of SUSY.

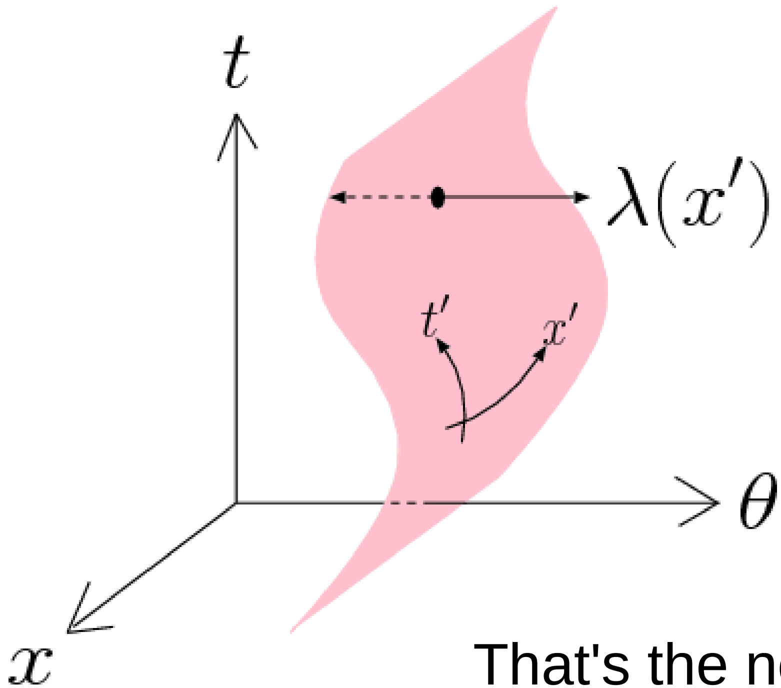
SUSY is a translational invariance of the superspace.



Goldstino
coordinate of
SuperPoincare/Poincare

(See [Clark, Love '04] for a construction of non-linear SUSY by using the coset space.)

In order to break the symmetry spontaneously, what we need to do is just putting a brane in the superspace.



Translation of θ axis induces a coordinate transformation on the brane.

$$x'^{\mu} \to x'^{\mu} + i\eta\sigma^{\mu}\bar{\lambda}(x') - i\lambda(x')\sigma^{\mu}\bar{\eta}$$

$$\lambda(x') \to \lambda(x') + \eta$$

That's the nonlinear transformation of Volkov-Akulov.

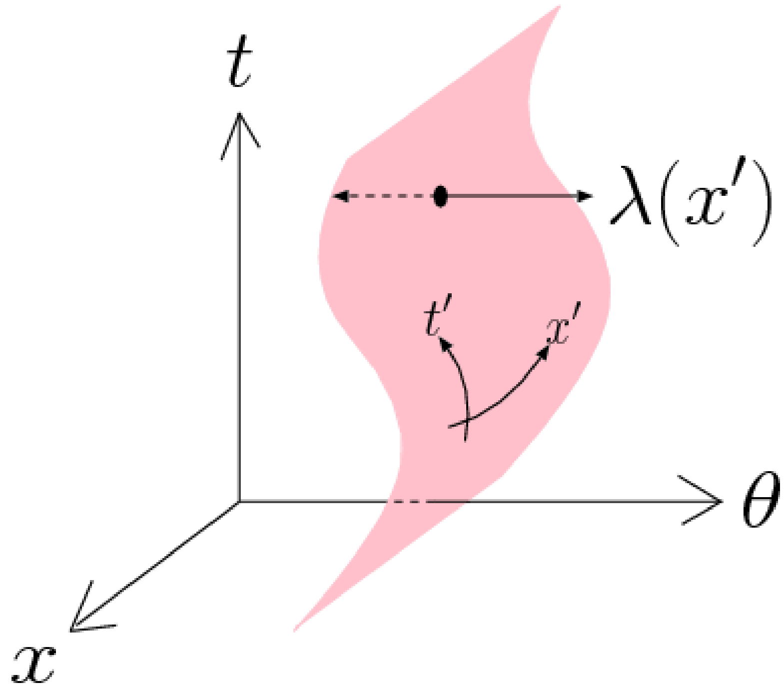
The matrix $$A_{\mu}{}^{a} \equiv \delta_{\mu}{}^{a} - i\lambda\sigma^{a}\partial_{\mu}\bar{\lambda} + i\partial_{\mu}\lambda\sigma^{a}\bar{\lambda}$$

is the induced metric (like?) on the brane.

This transforms as the vielbein under the SUSY transformation.

$$A_{\mu}{}^{a} \to \frac{\partial x'^{\rho}}{\partial y'^{\mu}} A_{\rho}{}^{a} \longrightarrow \int d^4x' \det A(x')$$ is invariant.

Now let's go back to the model. We can formulate the setup in this way.



Elementary fields:

Quarks and leptons are superfields (living in the bulk)

Hadron fields: nonlinearly transform under SUSY

Brane localized field. ⟶ No superpartners!

We can introduce the Higgs boson as a brane localized field.

⟶ Higgsinoless Supersymmetry! [Graesser, RK, Kurachi '09]

Let's be a bit rigorous.

Linear SUSY --> Superfields

[Salam, Strathdee, '78]

$$S_K = \int d^4x d^2\theta d^2\bar{\theta}\ K(\Phi, \Phi^\dagger, V)$$

$$S_W = \int d^4x d^2\theta\ W(\Phi) + \text{h.c.}$$

Non-linear SUSY

[Volkov and Akulov '73][Ivanov, Kapustnikov '77]

$$S_{\rm NL} = \int d^4x' \det A\ \mathcal{L}(\phi)$$

↑ Scalar under “coordinate transformation.”

Linear + non-linear

(by the way.. It has been tried to formulate non-linear SUSY by superfields.
[Rocek '78][Ivanov, Kapstnikov '82][Samuel, Wess '83]
[komargodski, Seiberg '09])

We need interaction terms between Φ and ϕ, but they are living in different spaces.

SUSY invariant identification of two space-times: [Ivanov, Kapustnikov '77]

$$x = x' + i\lambda(x')\sigma^\mu\bar\theta - i\theta\sigma^\mu\bar\lambda(x')$$

(gauge fixing of hidden general covariance)

→ One can construct invariant action by using

$$\int d^4x d^4\theta d^4x' \det X \delta^4(x - x' - i\lambda\sigma\bar\theta + i\theta\sigma\bar\lambda)$$

↑ Jacobian

$$X_\mu{}^a = \eta_\mu{}^a - i\theta\sigma^a\partial_\mu\bar\lambda + i\partial_\mu\lambda\sigma^a\bar\theta$$

Volkov-Akulov action:

$$S_{\mathrm{VA}} =$$

Invariant measure

$$-\frac{f^4}{2}\int d^4x d^4\theta d^4x' \det X \delta^4(x - x' - i\lambda\sigma\bar{\theta} + i\theta\sigma\bar{\lambda})$$

$$\times \delta^4(\theta - \lambda)$$

Brane location

This is also an SUSY invariant delta function.

$$= -\frac{f^4}{2}\int d^4x' \det A(x')$$

VA action (brane volume)

SUSY invariant Lagrangian

For elementary fields such as gauge fields and quarks/leptons, the Lagrangian is the same as the usual MSSM Lagrangian:

$$S = \int d^4x d^2\theta \frac{1}{2} \left[\mathrm{Tr} W^\alpha W_\alpha + \mathrm{h.c.} \right] + \int d^4x d^4\theta \Phi^\dagger e^{-2gV} \Phi$$

← Kinetic terms

We can also write down brane localized kinetic terms:

$$S = \int d^4x' d^2\theta \det A \cdot \delta^2(\theta - \lambda(x')) \frac{1}{2} \left[\mathrm{Tr} W^\alpha W_\alpha(x', \lambda, \bar{\lambda}) + \mathrm{h.c.} \right] + \int d^4x' d^4\theta \det A \cdot \delta^4(\theta - \lambda(x')) \; \Phi^\dagger e^{-2gV} \Phi$$

← $(\theta - \lambda)^2$

These are nothing but the soft SUSY breaking terms.

(gauge? mediation)

=Spurion formalism

SUSY invariant Lagrangian 2

For the Higgs boson, one can write down an invariant action:

Invariant delta function

Brane localization

$$S = \int d^4x d^4x' d^4\theta \det A \cdot \delta^4(x - x' - i\lambda\sigma^\mu\bar\theta + i\theta\sigma^\mu\bar\lambda)\delta^4(\theta - \lambda)$$

$$\times\Big[(D_\mu\phi(x'))^\dagger e^{-2gV} D^\mu\phi(x')$$

Kinetic term

$$-m^2\phi^\dagger(x')e^{-2gV}\phi(x') - \frac{k}{4}\left(\phi^\dagger(x')e^{-2gV}\phi(x')\right)^2\Big]$$

Higgs potential

Covariant derivative made of the vielbein $A_\mu{}^a$. The action needs to be invariant under general coordinate transformation induced by global SUSY.

$$D_\mu \equiv \nabla_\mu - ig\mathcal{A}_\mu + g(\nabla_\mu\lambda)^\alpha\mathcal{A}_\alpha$$

$$\left(\begin{array}{l} \nabla_\mu \equiv (A^{-1})_\mu{}^\nu \dfrac{\partial}{\partial x'^\nu} \\ g\mathcal{A}_\mu \equiv \dfrac{1}{4}\bar D e^{2gV}\bar\sigma_\mu D e^{-2gV}, \qquad g\mathcal{A}_\alpha \equiv e^{2gV}D_\alpha e^{-2gV} \end{array}\right)$$

SUSY invariant Lagrangian 2

For the Higgs boson, one can write down an invariant action:

Invariant delta function — Brane localization

$$S = \int d^4x d^4x' d^4\theta \det A \cdot \delta^4(x - x' - i\lambda\sigma^\mu\bar{\theta} + i\theta\sigma^\mu\bar{\lambda})\delta^4(\theta - \lambda)$$

$$\times\Big[(D_\mu\phi(x'))^\dagger e^{-2gV} D^\mu\phi(x')$$ ← Kinetic term

$$-m^2\phi^\dagger(x')e^{-2gV}\phi(x') - \frac{k}{4}\left(\phi^\dagger(x')e^{-2gV}\phi(x')\right)^2\Big]$$ ← Higgs potential

→ We don't have to deal with the μ-problem because there is no Higgsino!

(Note: we don't claim we solved the μ-problem. But we could avoid to deal with the problem in a consistent (supersymmetric) framework.)

The Higgs boson mass is a free parameter. No relation to the gauge coupling.

SUSY invariant Lagrangian 3

Bulk to brane interaction –Yukawa interactions.

$$S = \int d^4x d^4x' d^4\theta \det A \cdot \delta^4(x - x' - i\lambda\sigma^\mu\bar{\theta} + i\theta\sigma^\mu\bar{\lambda})\delta^4(\theta - \lambda)$$

$$\times \left[y_u^{ij}\phi(x') \cdot \left(\frac{1}{2}D^2_{(\mathrm{cov})}U_j^c Q_i\right)\right.$$

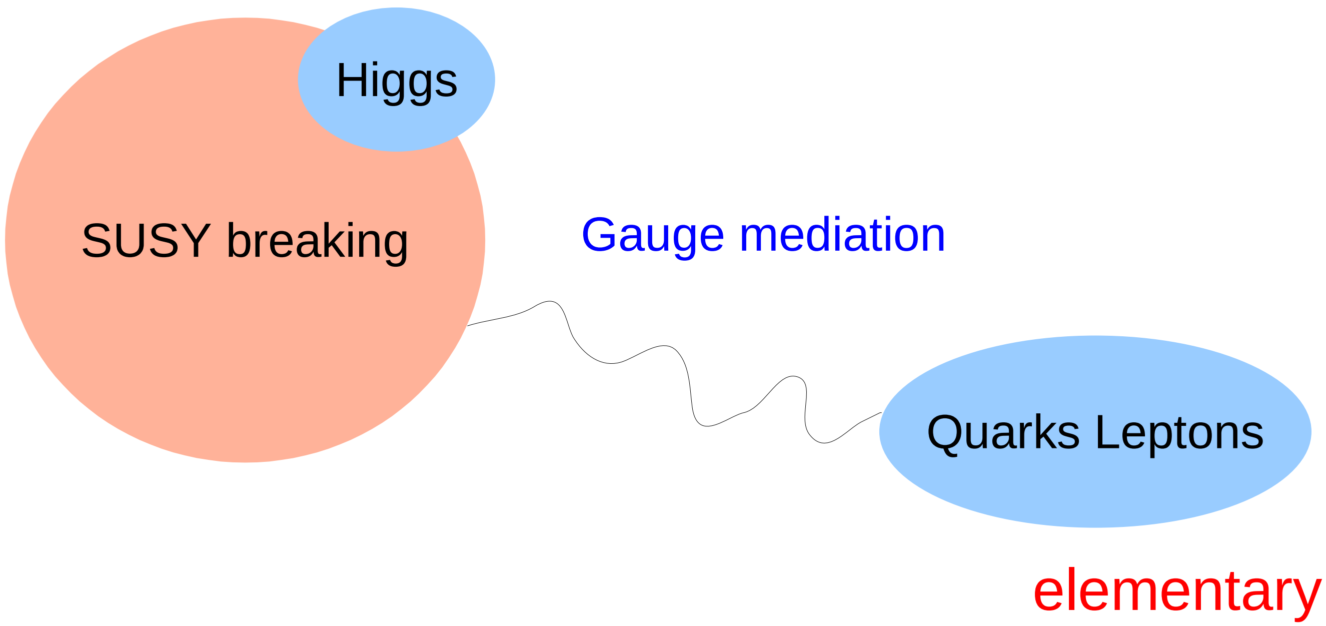
$$\left. + y_d^{ij}\phi^\dagger(x')e^{-2gV}\left(\frac{1}{2}D^2_{(\mathrm{cov})}D_j^c Q_i\right) + y_e^{ij}\phi^\dagger(x')e^{-2gV}\left(\frac{1}{2}D^2_{(\mathrm{cov})}E_j^c L_i\right)\right]$$

$$D^2_{(\mathrm{cov})} \equiv e^{2gV}D^2 e^{-2gV}$$

We don't need two kinds of Higgs fields to write down the Yukawa interactions.

We could write down a SUSY invariant action without Higgsinos
by compensating the SUSY transformation by the Goldstino.

This action serves as the effective theory of the framework:



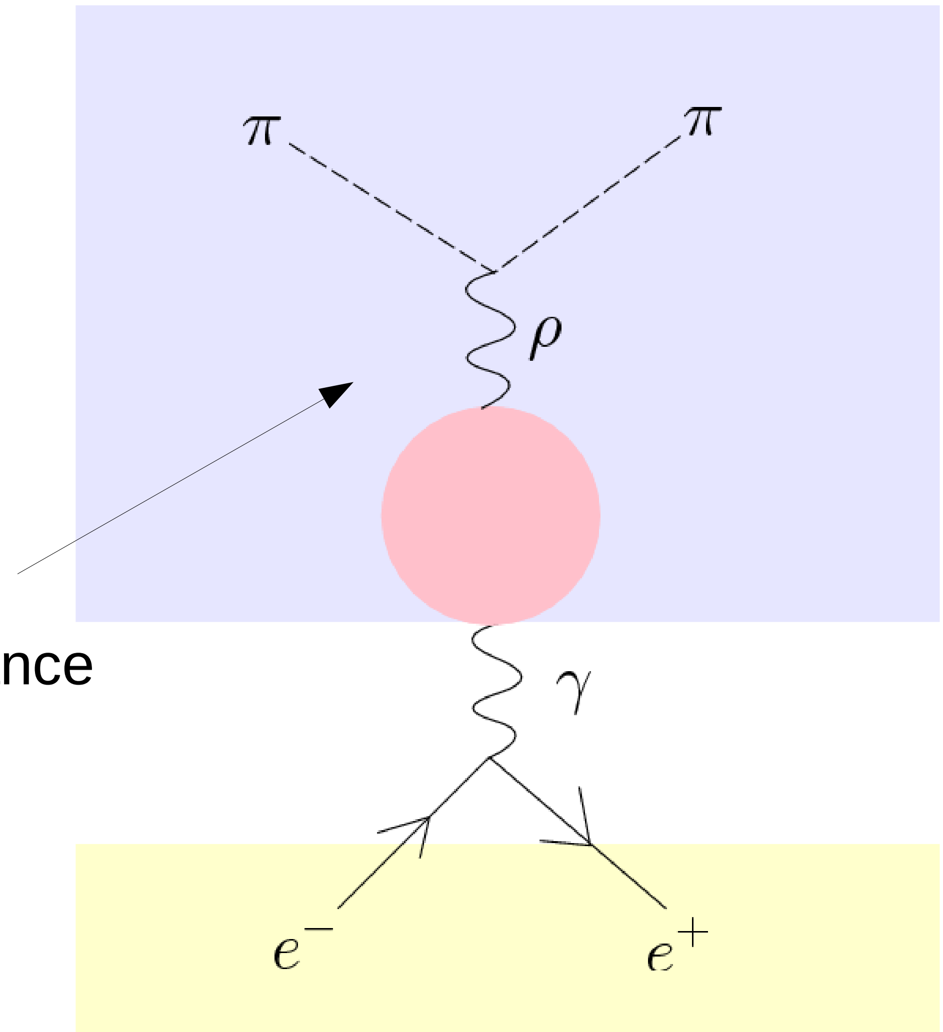
One can see many relations in the Lagrangian such as mass vs coupling
(Goldberger-Treiman relations).

Hidden Gravity

The most interesting feature of this scenario is that we may be able to access the SUSY breaking sector directly at the LHC.

What kind of resonances do we expect to see?

In QCD,



Composite

resonance

elementary

In the nonlinear sigma model of chiral symmetry breaking, there is a formulation for the vector resonance (the ρ meson), called

Hidden Local Symmetry

[Bando, Kugo, Uehara, Yamawaki, Yanagida '85]

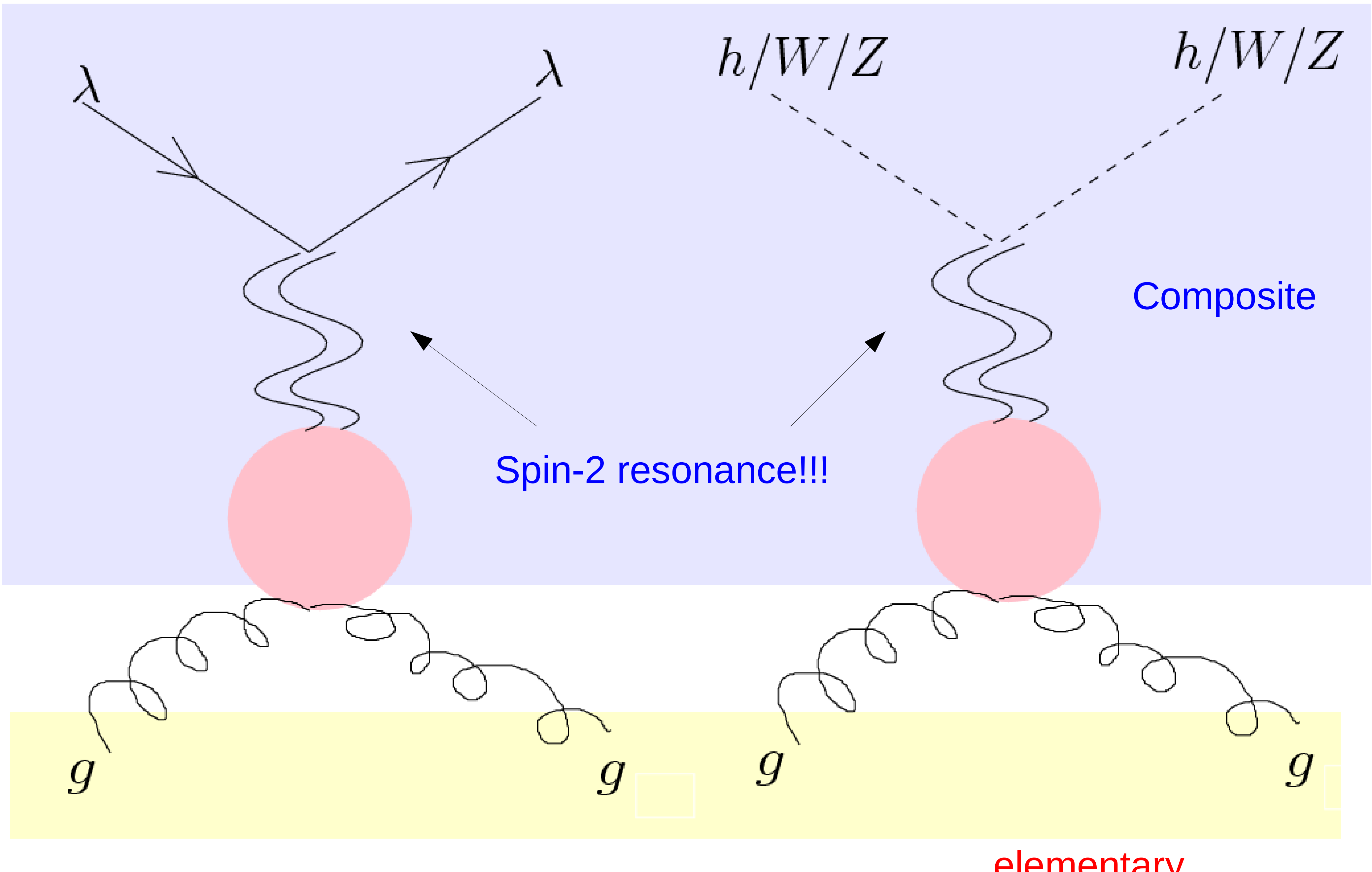
in which the resonance (massive vector boson) is consistently introduced as a **gauge boson of the unbroken global symmetry** ($SU(2)_V$).

The SUSY version of that is

Hidden Gravity
(massive spin-2 resonance)

because the unbroken global symmetry is the Poincare symmetry.

Production of composite particles in the SUSY breaking sector



We can follow exactly the same procedure of introducing the ρ meson in the chiral Lagrangian.

As we have seen, there is an operator made of Goldstino which transforms as a metric under the global SUSY transformation (induced metric).

(don't be confused!)

One can easily introduce a massive graviton field on the brane by using the "metric."

mass term

$$S = \int d^4x \left[-\frac{1}{2} \det A - \frac{m_{\rm P}^2}{2} \sqrt{g} R - \frac{m_{\rm P}^2 m^2}{8} \sqrt{g} g^{\mu\nu} g^{\alpha\beta} \left(H_{\mu\alpha} H_{\nu\beta} - H_{\mu\nu} H_{\alpha\beta} \right) \right],$$

[Fierz, Pauli '39]

$$H_{\mu\nu} = g_{\mu\nu} - G_{\mu\nu}, \quad G_{\mu\nu} = A_\mu{}^a A_\nu{}^b \eta_{ab}$$

← "metric"

graviton

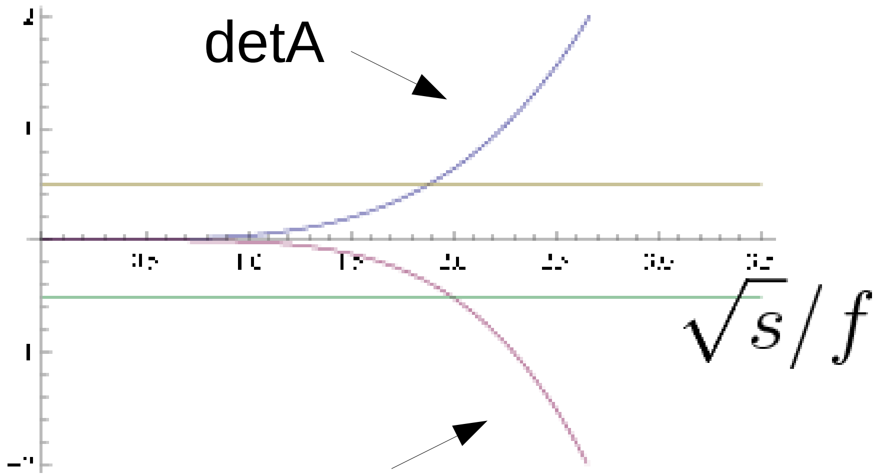
This is invariant under general coordinate transformation even though there is a mass term.

→ Global SUSY invariant formulation of the massive graviton.

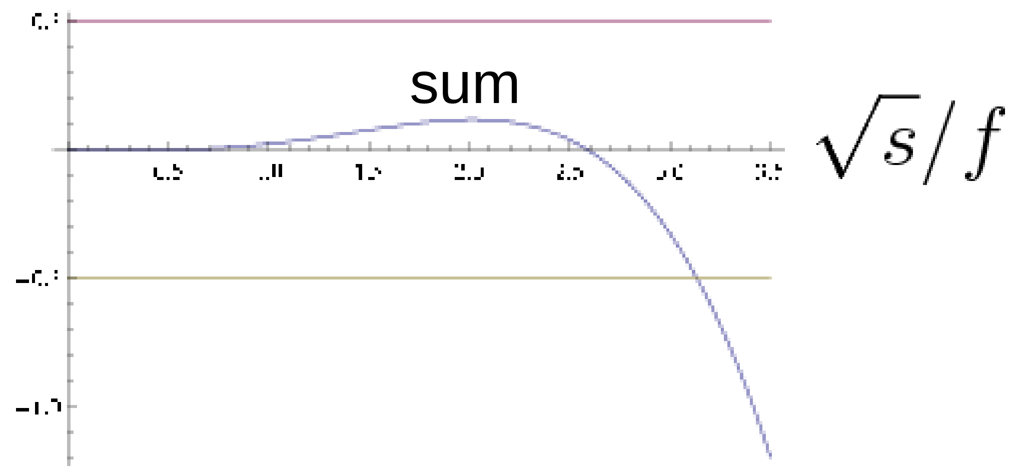
Is that a good particle?

Well, at least one can consistently introduce it without spoiling the calculability (perturbative unitarity).

s-wave amplitude



s-wave amplitude



$$m_{\mathrm{P}} = 0.7f, \quad m = 1.2f$$

(f: decay constant)

The spin-2 particle partially cancel the grow of the scattering amplitude of λλ --> λλ.

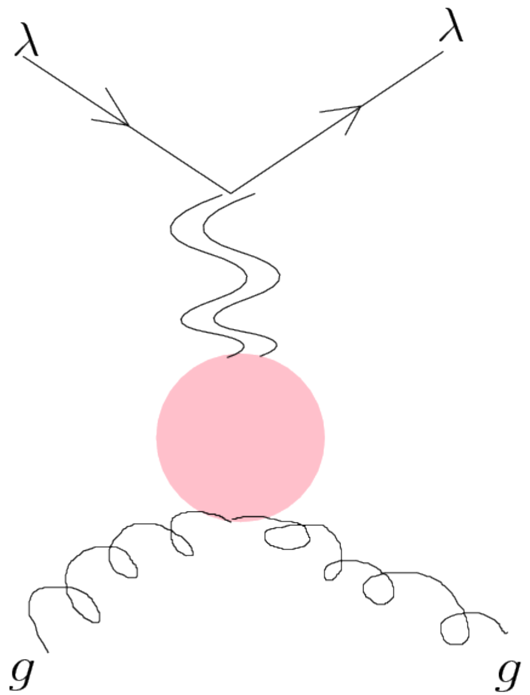
That's the same property as the ρ meson in HLS.

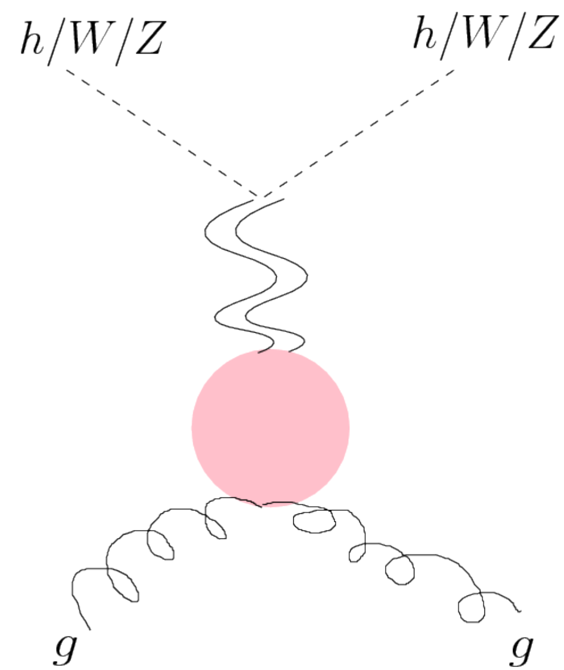
Massive Graviton (SUSY version) at the LHC

The resonance couples strongly to hadrons (Goldstino, Higgs boson).

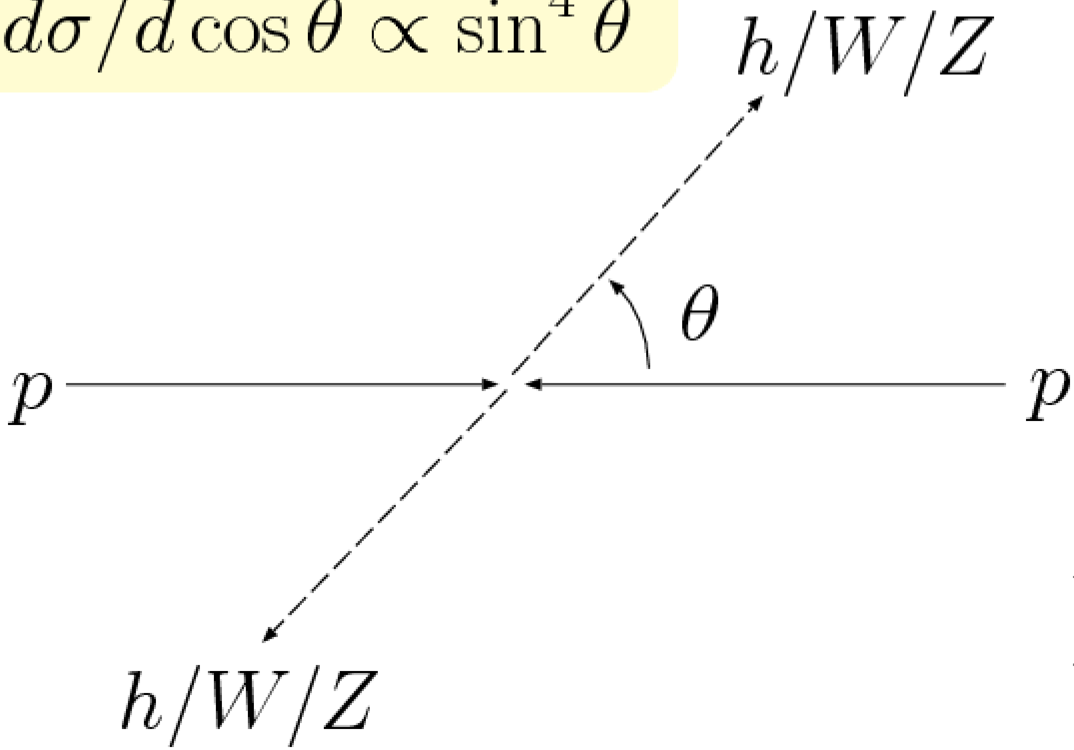
invisible

hh/ZZ/WW modes

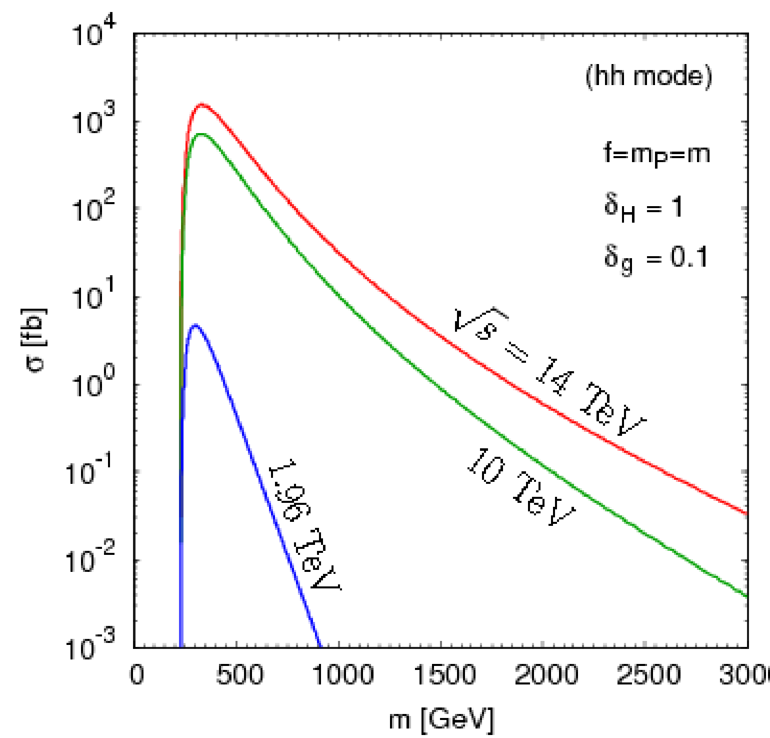




$$d\sigma/d\cos\theta \propto \sin^4\theta$$



Br(Graviton -->hh) ~ 0.1



σ(pp-->Graviton-->hh)

These are typical signatures for

The Large Extra Dimension (invisible mode)

The Randall-Sundrum model (hh/ZZ/WW modes)

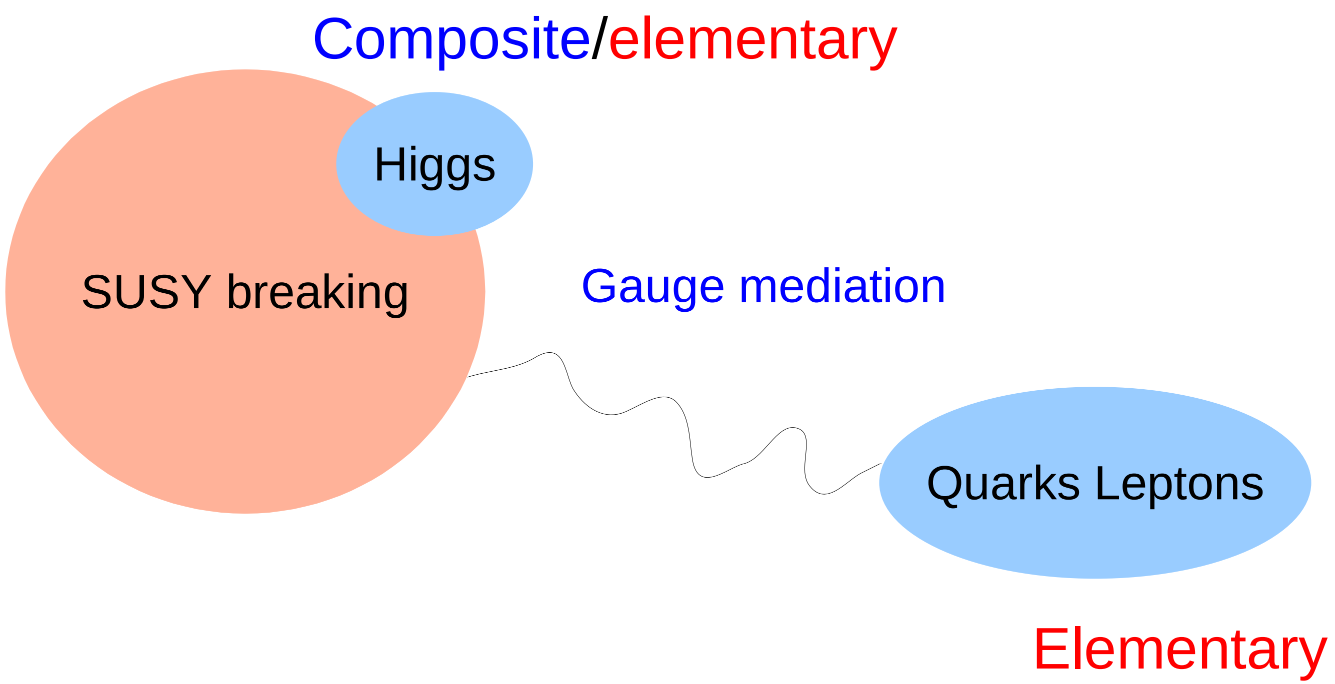
Well, it is probably true that the spin-2 resonance is a signature of the enlarged spacetime. So,

Discovery of graviton (massive spin-2) → **It can be SUSY!**

Don't be confused that we find both SUSY and extra-dim. Yes, SUSY is an extra-dim!

Summary

I think this is a good framework.



We may see many unconventional SUSY signals at the LHC.