SUSY Breaking, Composite Higgs and Hidden Gravity

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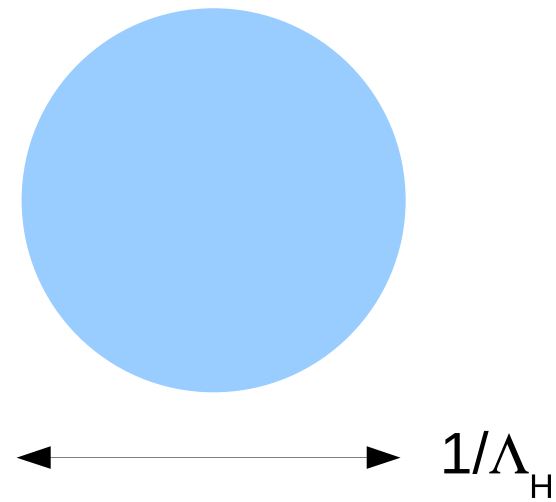
What's Higgs?

Elementary particle?

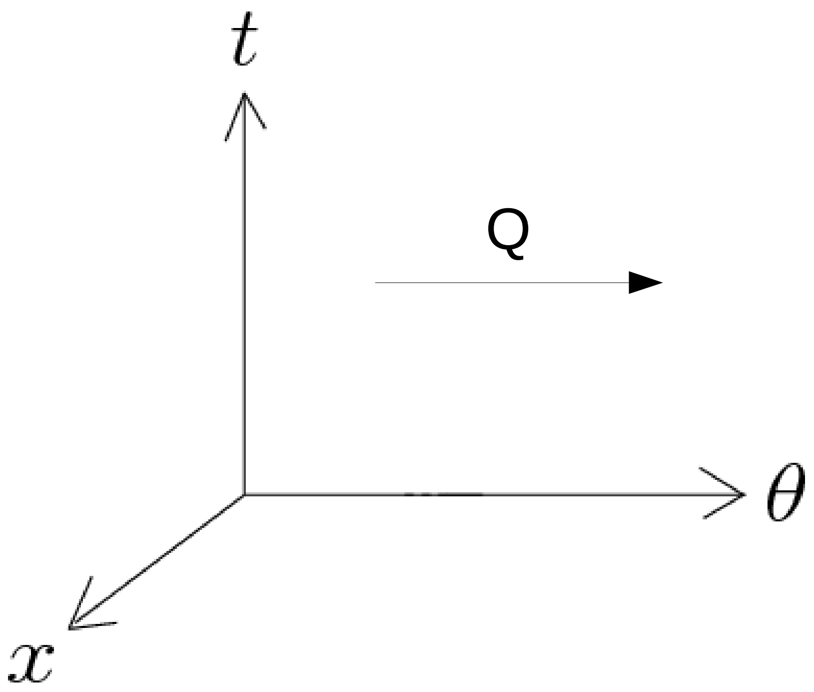


Something else?

Composite, technicolor,
unparticle, string, D-brane...

We can use the quantum field theory to describe a particle, but not something else. The scale Λ_H is the cut-off of the theory.

Where is SUSY?



SUSY is symmatry of superspace.

How is it broken? Where are we in this space?

Hints (problems) that we have:

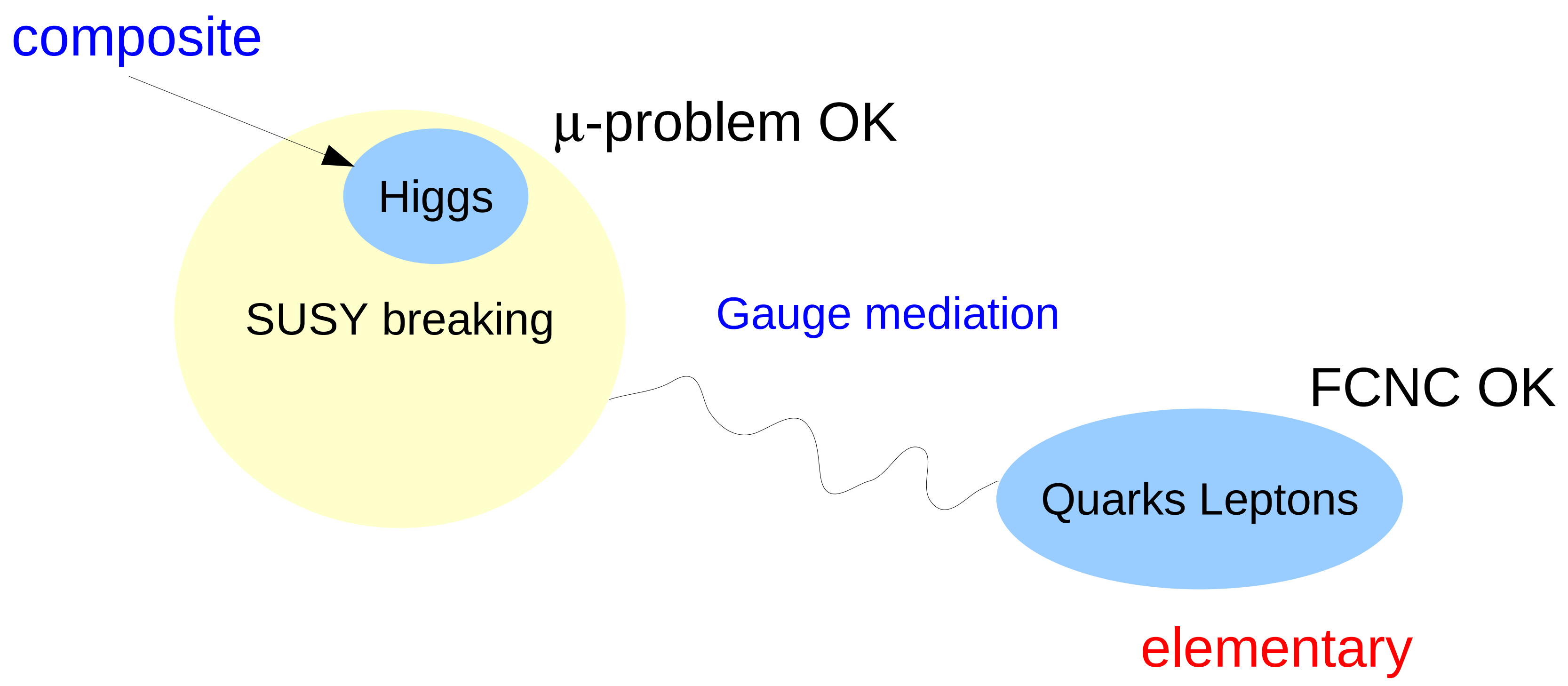
naturalness	→	Gravity Mediation	→	composite
FCNC	→	Gauge or Anomaly Mediation	→	elementary

at the messenger scale physics.

The composite vs elementary problem....

Supersymmetry is not a solution to the naturalness problem?

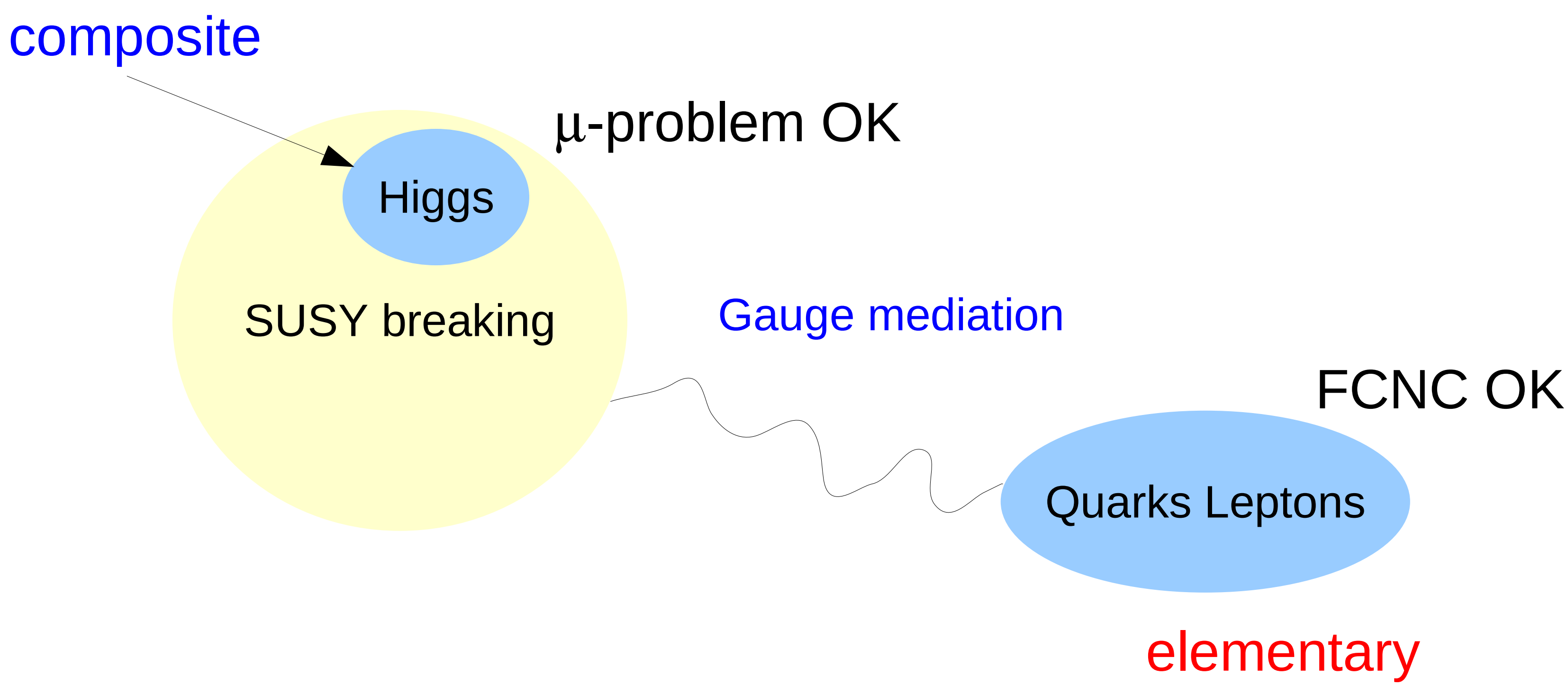
Not really. Naturalness and FCNC are problems in different sectors.
It naturally leads us to this picture:



The dynamics to break SUSY contains the Higgs fields.

OK. What's the model?

I think the simplest setup of the framework of

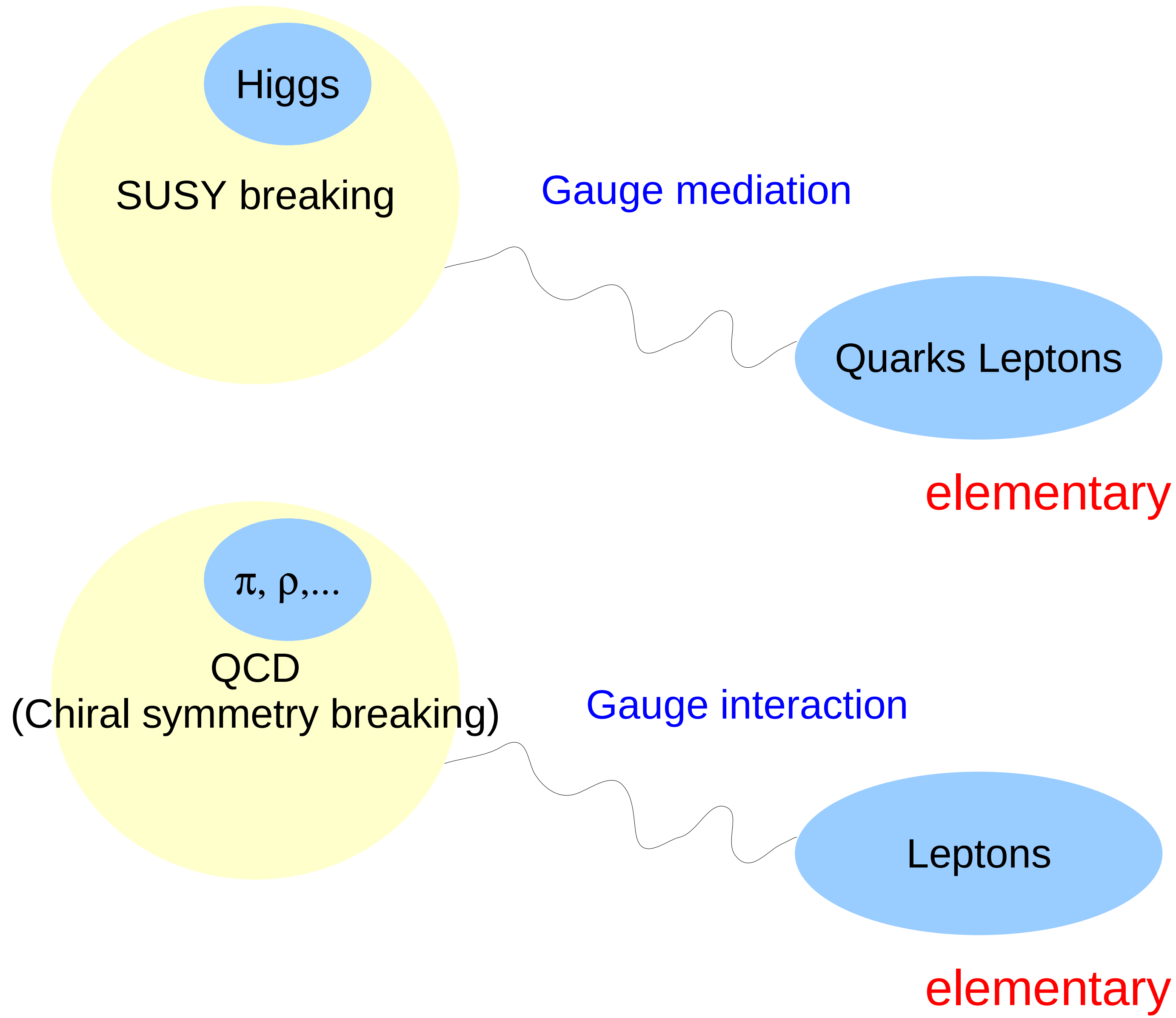


is to take the extreme limit of this scenario.

That is SUSY breaking at (a few – 10) TeV and the Higgs boson comes out as a composite particle. Direct gauge mediation provides mass splittings in the matter sector.

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

Very similar to the QCD.



We know that there is a powerful tool to describe physics of hadrons at low energy. 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

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

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

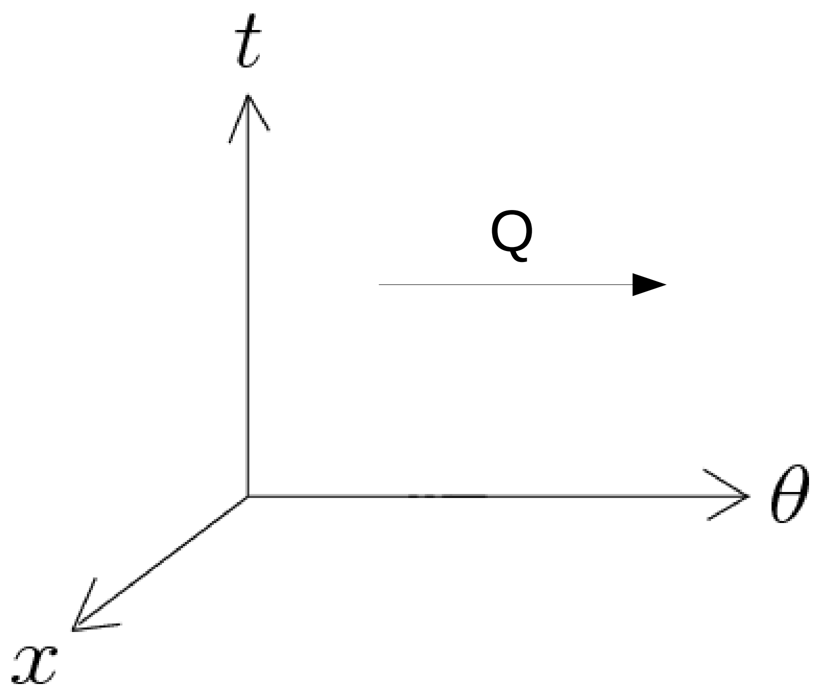
η is a fermionic parameter.

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

What's that?

A simple formulation of nonlinear SUSY.

SUSY is a translational invariance of the superspace.

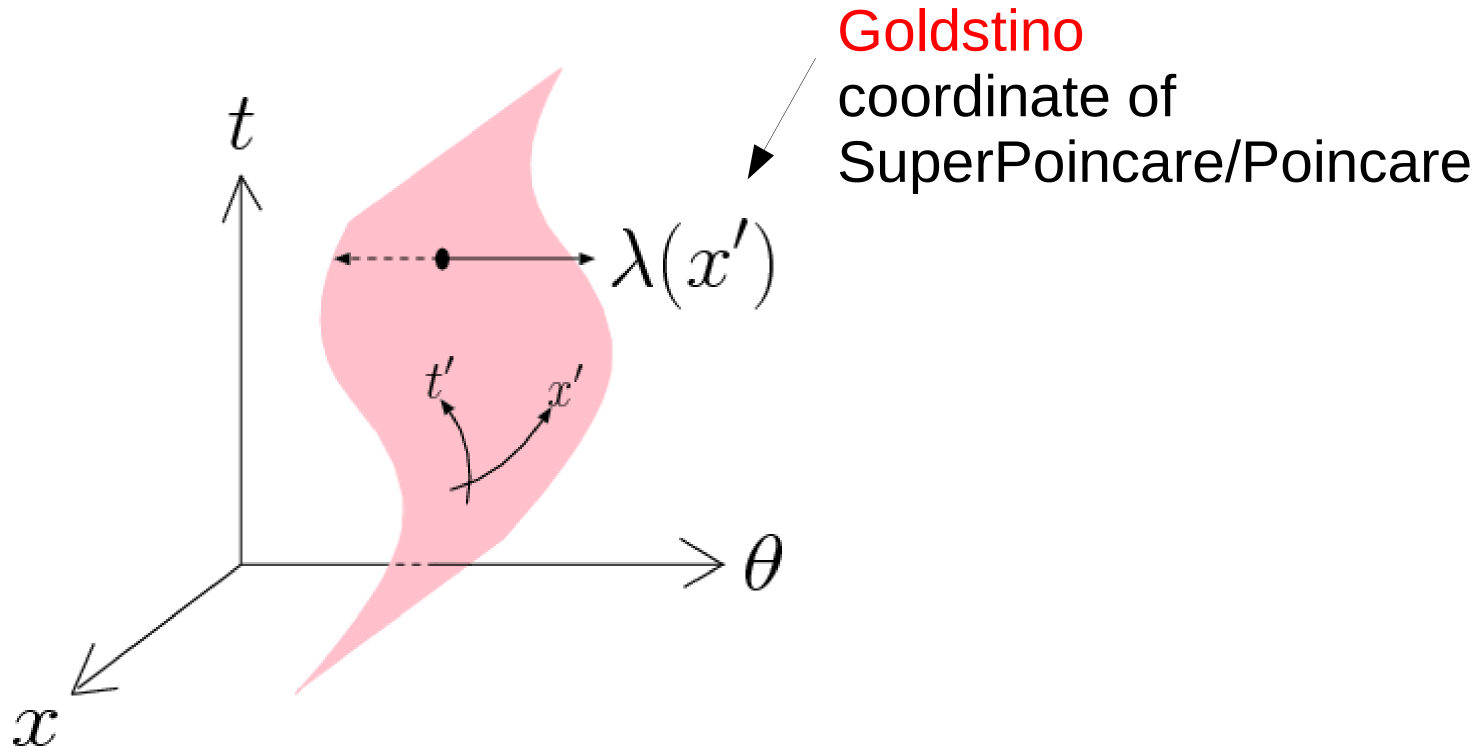


In order to break the symmetry spontaneously, what we need to do is just...

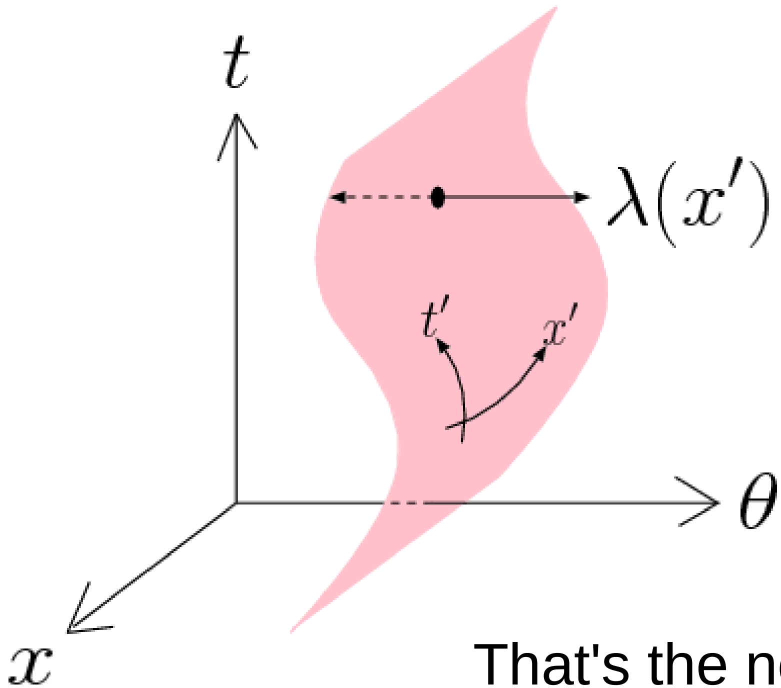
What's that?

A simple formulation of nonlinear SUSY.

SUSY is a translational invariance of the superspace.



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.

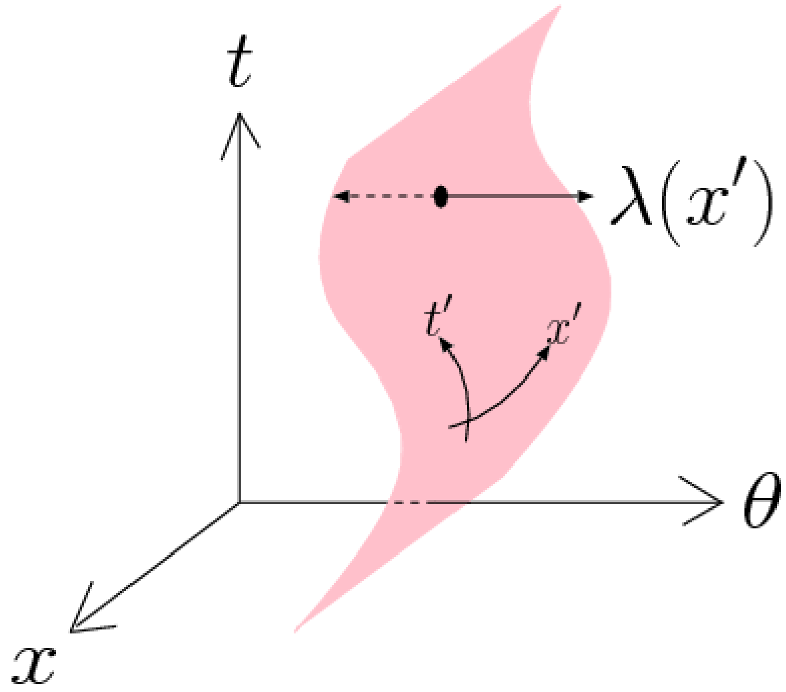
The matrix $$A_{\mu}{}^{a} \equiv \delta_{\mu}{}^{a} - i\lambda\sigma^{a}\partial_{\mu}\bar{\lambda} + i\partial_{\mu}\lambda\sigma^{a}\bar{\lambda}$$

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)

Composite 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 in progress]

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.

SUSY invariant Lagrangian 2

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

Brane location

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

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

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 SUSY.

→ There is no μ-problem because there is no Higgsino!

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

→ No SUSY finetuning problem.
(actually I hide it in the unknown dynamics.)

SUSY invariant Lagrangian 3

Bulk to brane interaction –Yukawa interactions.

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

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

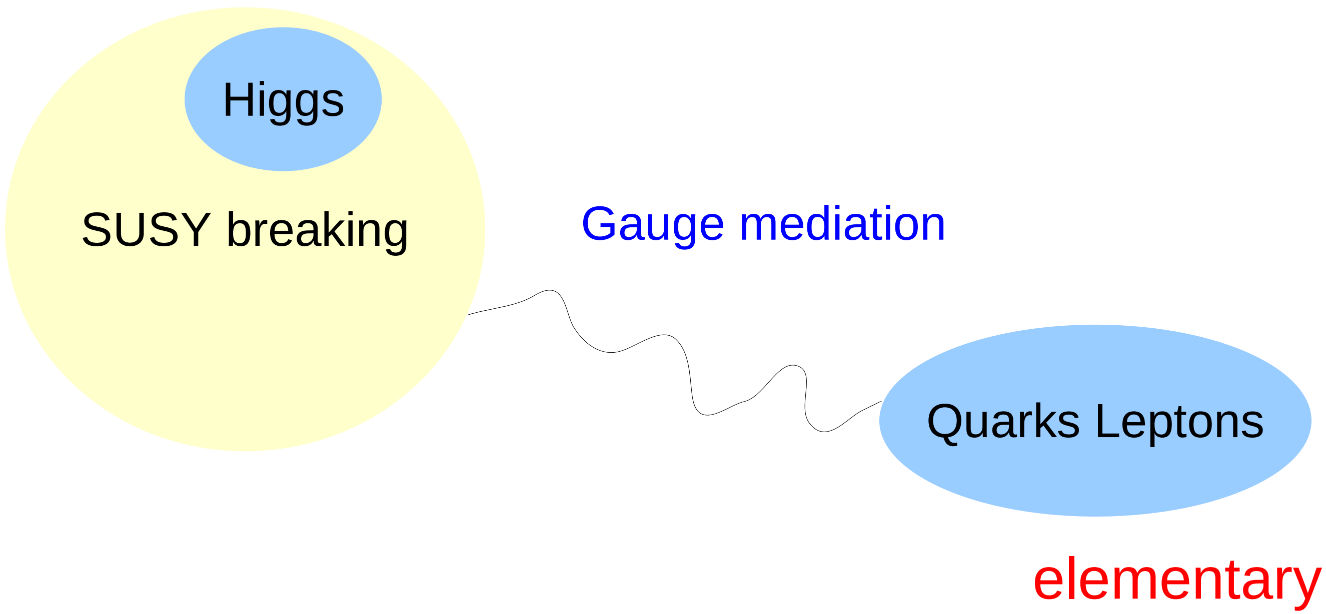
$$\left. + y_d^{ij}\phi^\dagger(x')e^{-2gV}\left(\frac{1}{2}D^2_{(\mathrm{cov})}D^c_j Q_i\right) + y_e^{ij}\phi^\dagger(x')e^{-2gV}\left(\frac{1}{2}D^2_{(\mathrm{cov})}E^c_j L_i\right)\right]$$

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

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:



But.... SO WHAT?

Isn't there any interesting prediction other than there isn't Higgsino?

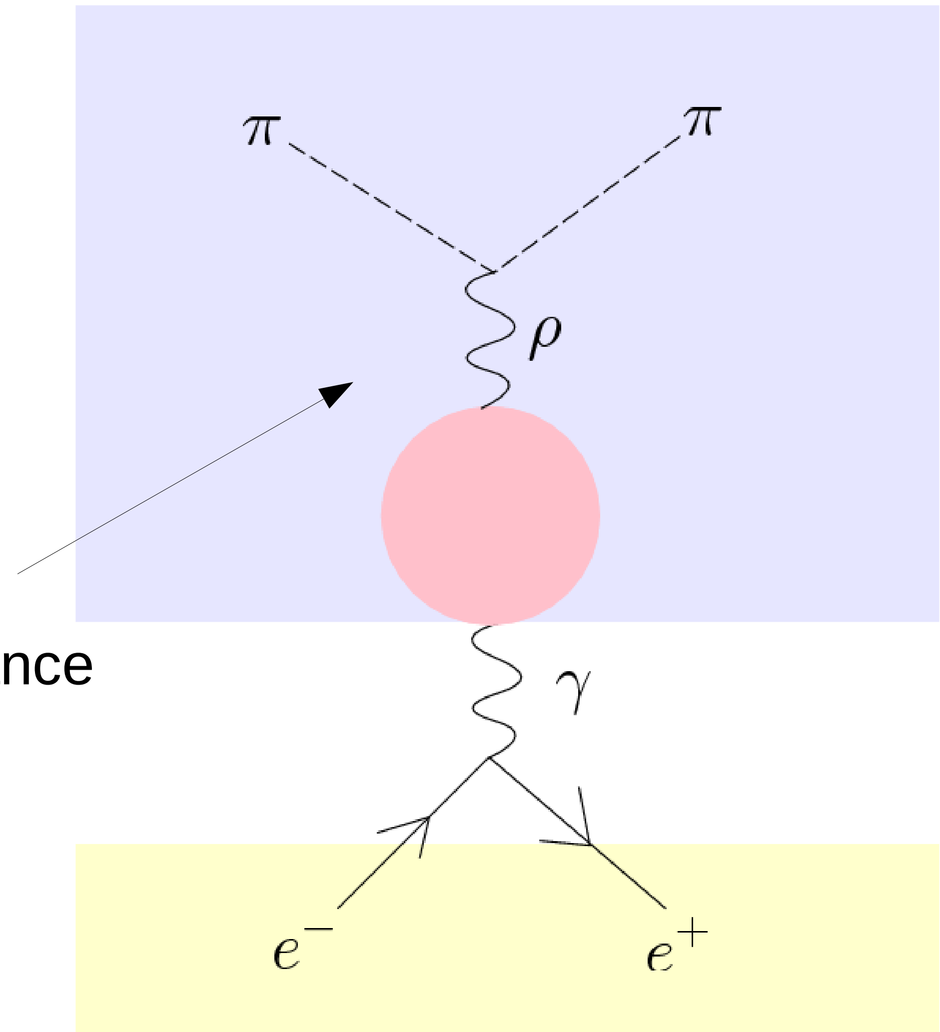
The Higgs mass, mass spectrum are all free parameters.....

Hidden Gravity

The most interesting possibility 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,



resonance

Composite

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]

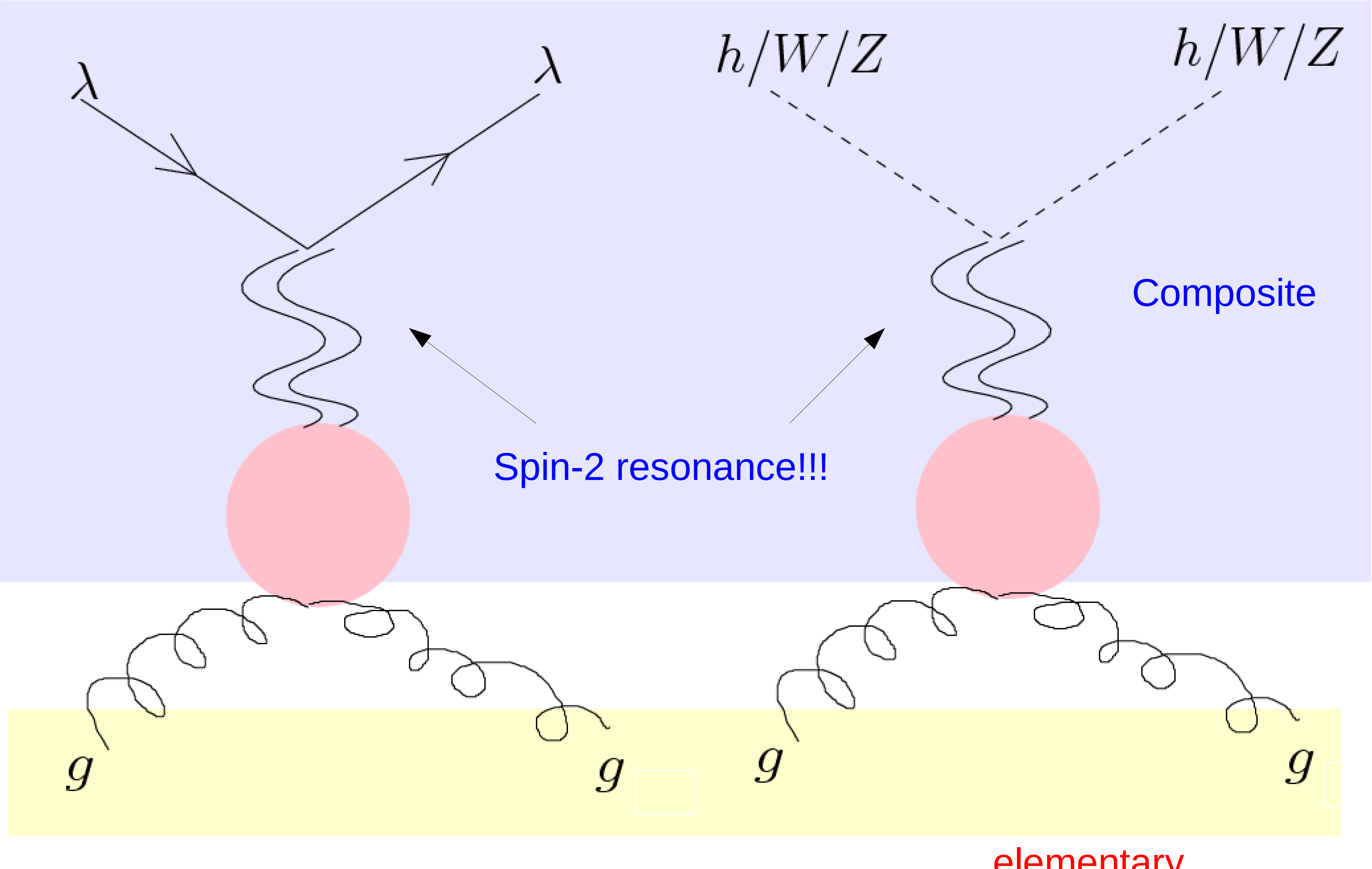
in which the resonance (massive vector boson) is consistently introduced as a **gauge boson of the unbroken global symmetry** ($SU(2)_V$).

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.

(don't be confused!)

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

mass term

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

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

← "metric"

graviton

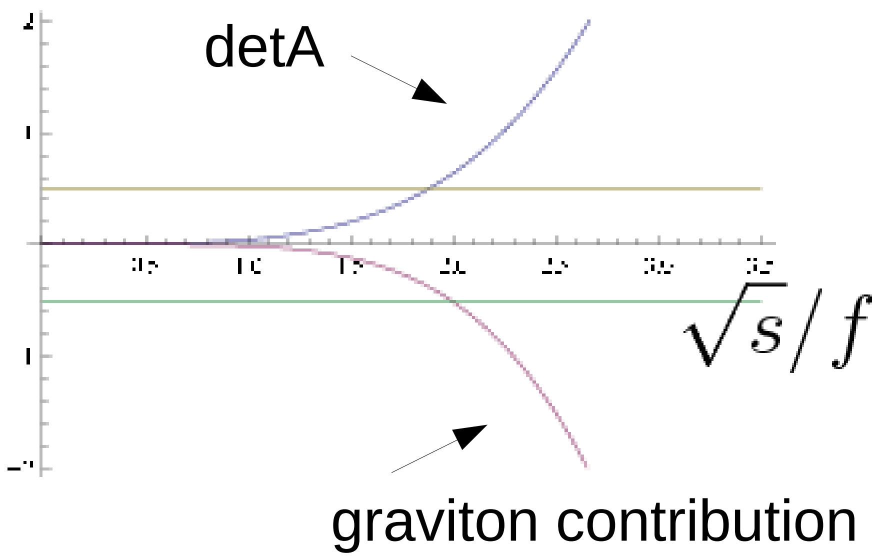
This is invariant under general coordinate transformation even though there is a mass term.

→ Global SUSY invariant formulation of the massive graviton.

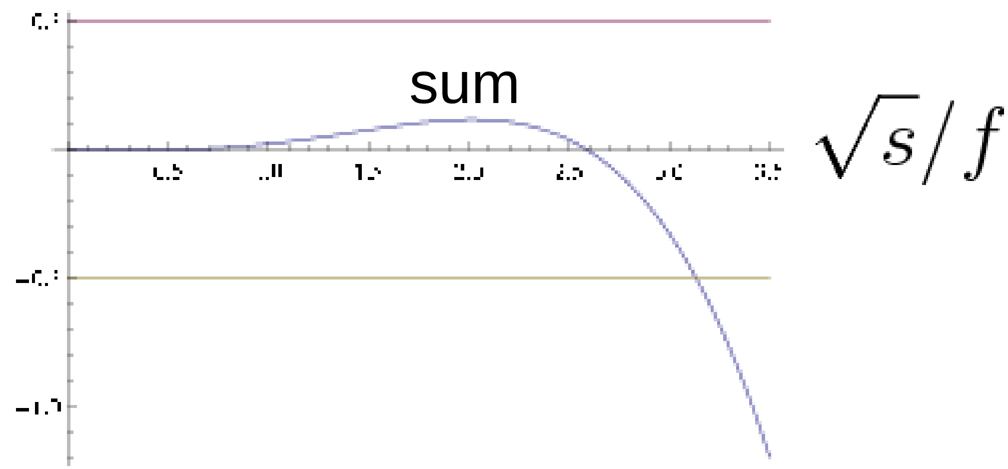
Is that a good particle?

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.

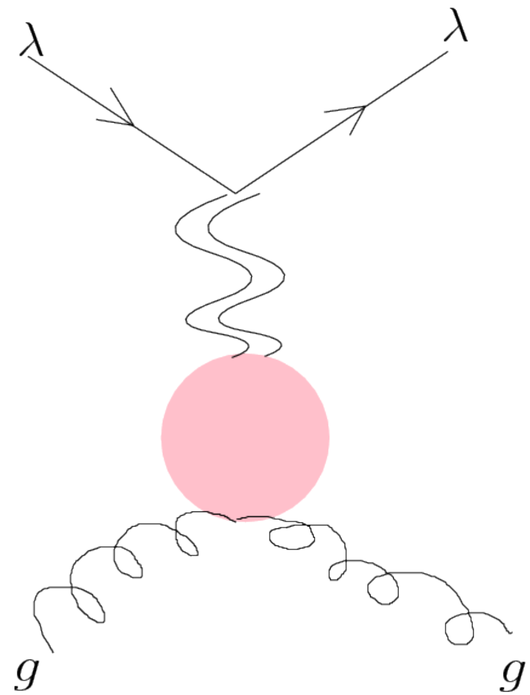
That's the same property as the ρ meson.

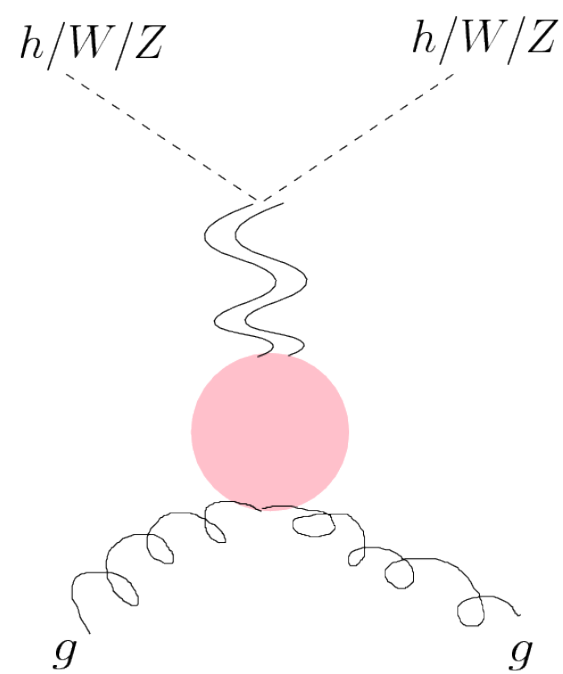
Massive Graviton (SUSY version) at the LHC

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

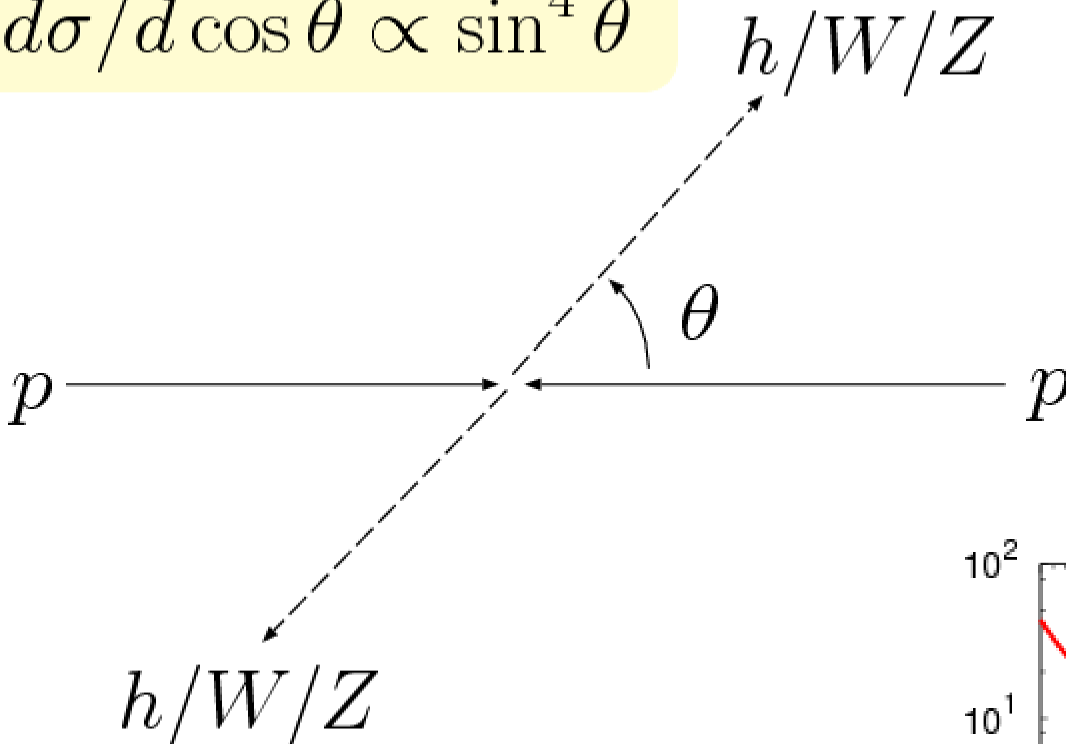
invisible

hh/ZZ/WW modes

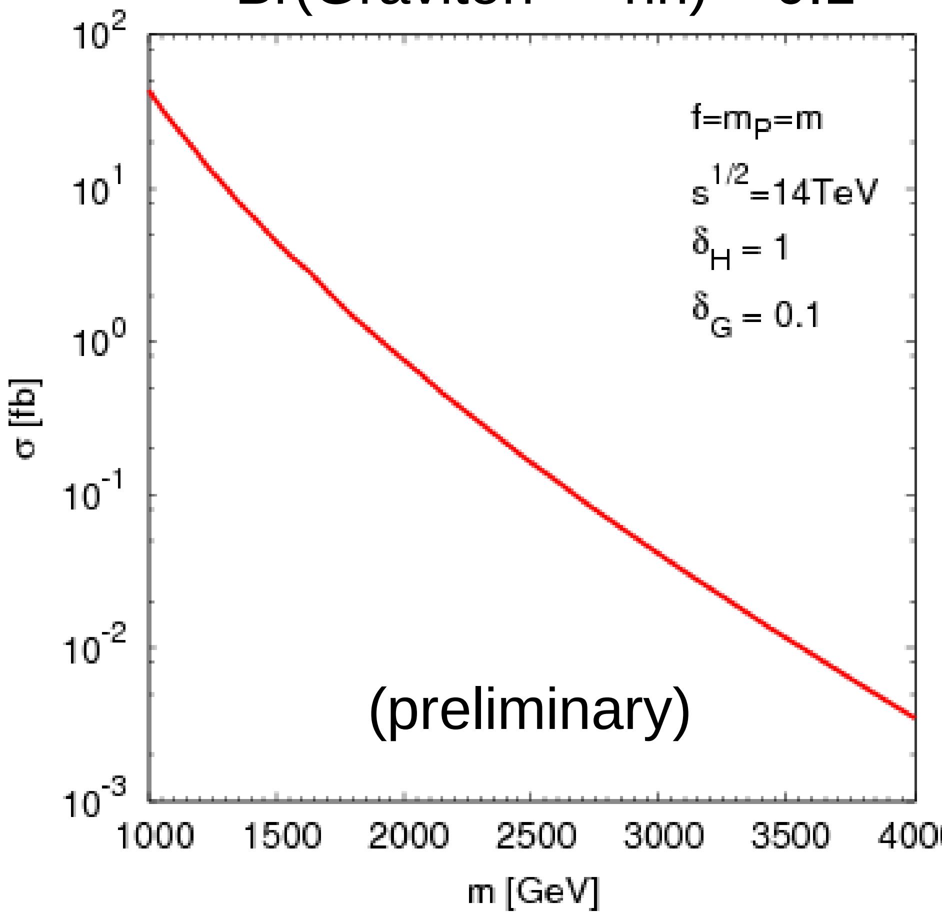




$$d\sigma/d\cos\theta \propto \sin^4\theta$$



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)

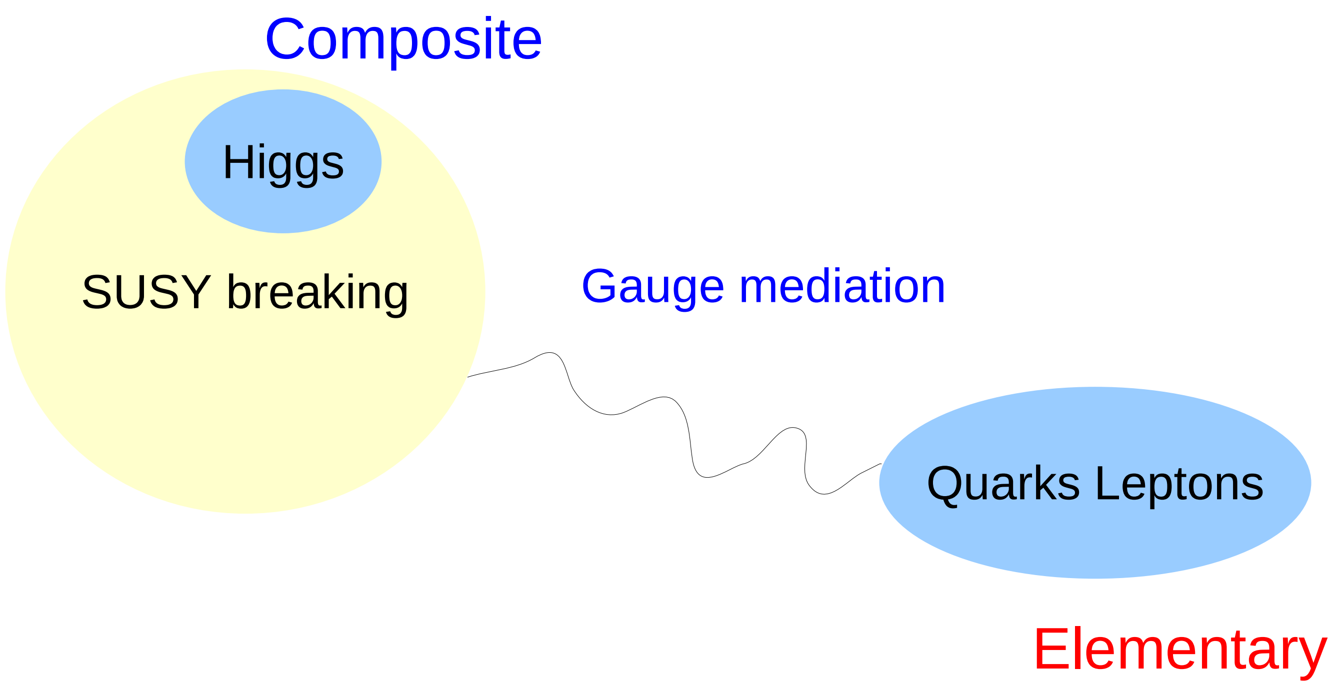
Well, it is probably true that the spin-2 resonance is a signature of the enlarged spacetime. So,

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.