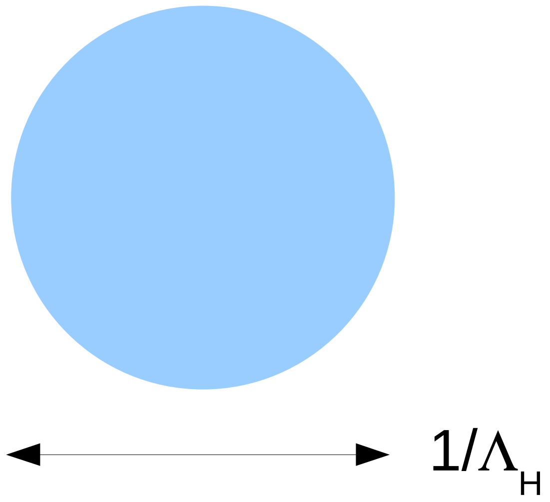
Higgsinoless SUSY and Hidden Gravity

Ryuichiro Kitano (Tohoku U.)

Talk at SUSY breaking '09, April 20-24, 2009, Durham, UK

What's Higgs?

Elementary particle?



Something else?

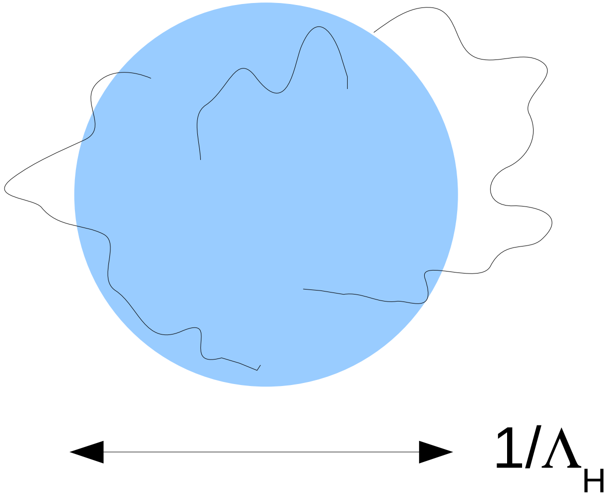
Composite, technicolor,
unparticle, string, D-brane...

I generically call those “composite”
in this talk.

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.

Naturalness

The quantum field theory suggests



Λ_H (cut-off) ~ v_H (VEV) ~ m_H (mass)

for a scalar field.

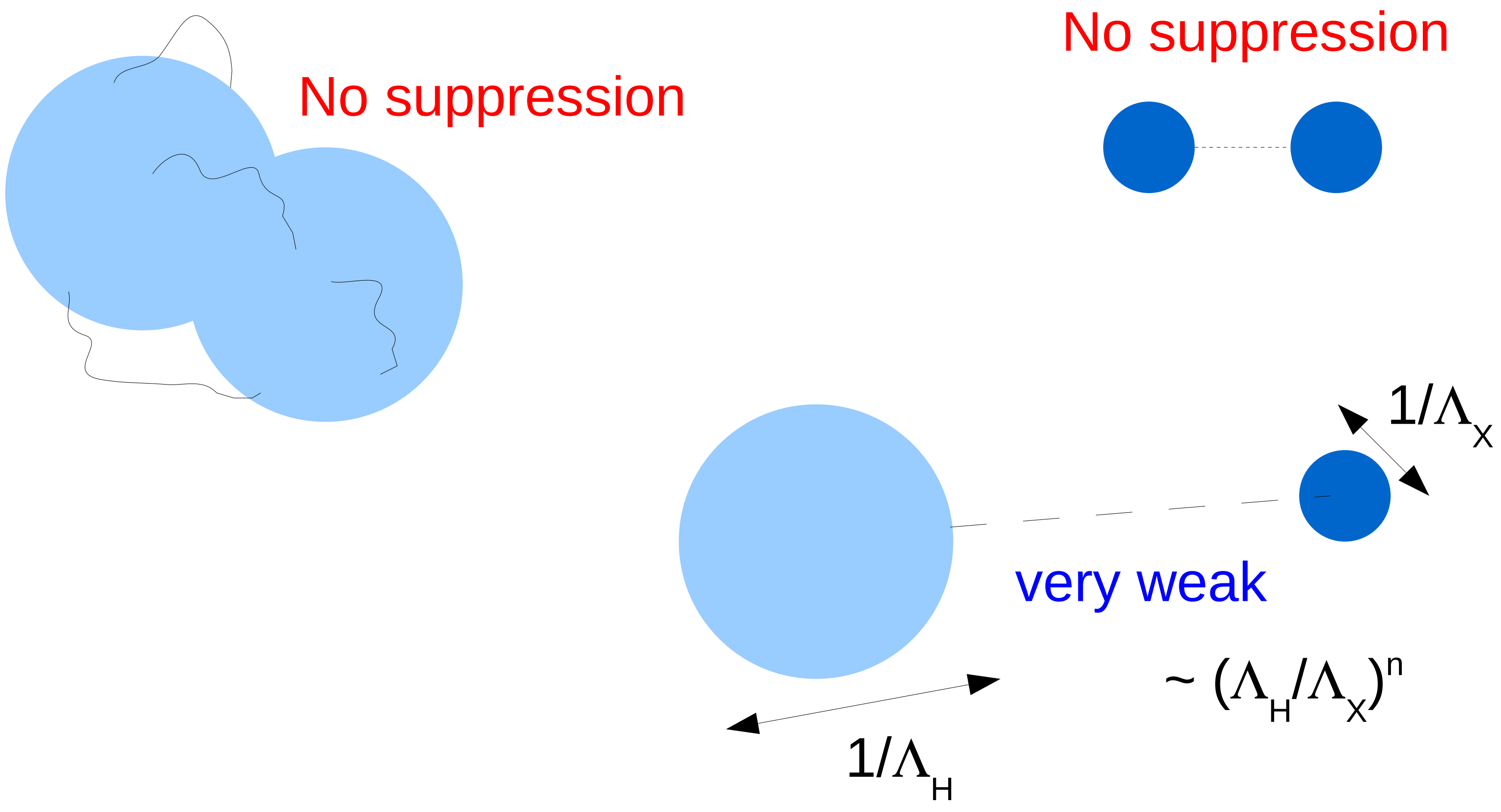
→ Therefore, “composite at TeV” is preferred!

This is exactly what's happening for chiral symmetry breaking.

naturalness → composite

Flavor Problem

Simply from a dimensional analysis,



No suppression

No suppression

$1/\Lambda_X$

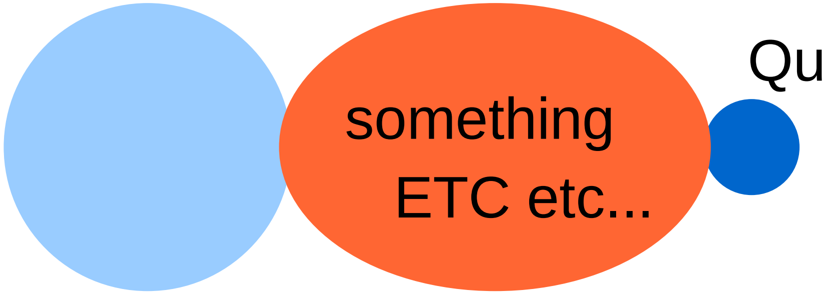
very weak

$\sim (\Lambda_H/\Lambda_X)^n$

$1/\Lambda_H$

Hadrons (composite) do not couple to elementary particles strongly. It is suppressed by a power of the ratio of the two cut-off's.

Therefore, in order to generate Yukawa interactions



Quark and leptons

something

ETC etc...

Composite Higgs

Generically, it also provides

Quark and leptons

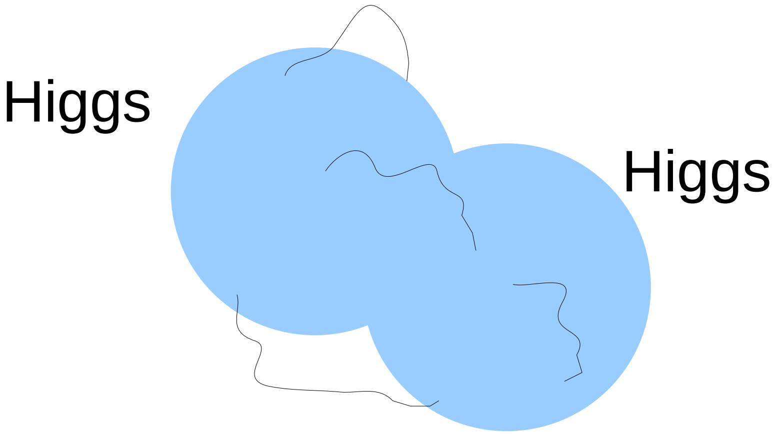
Quark and leptons

something

ETC etc...

FCNC!!!

There is also a constraint from the EW precision measurements, which prefer absence of new interactions for the Higgs field.



???

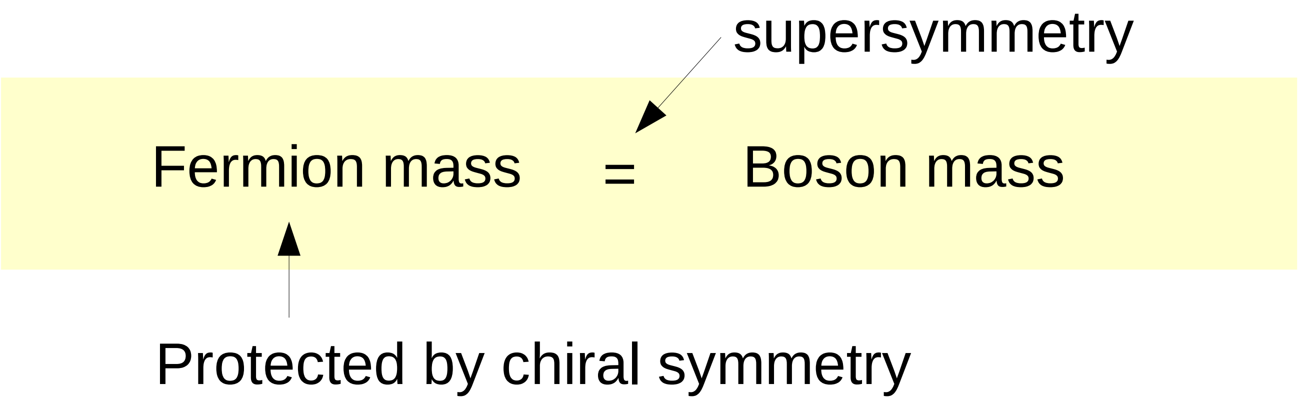
Therefore,

naturalness → composite

data → elementary

This is the composite vs elementary problem.

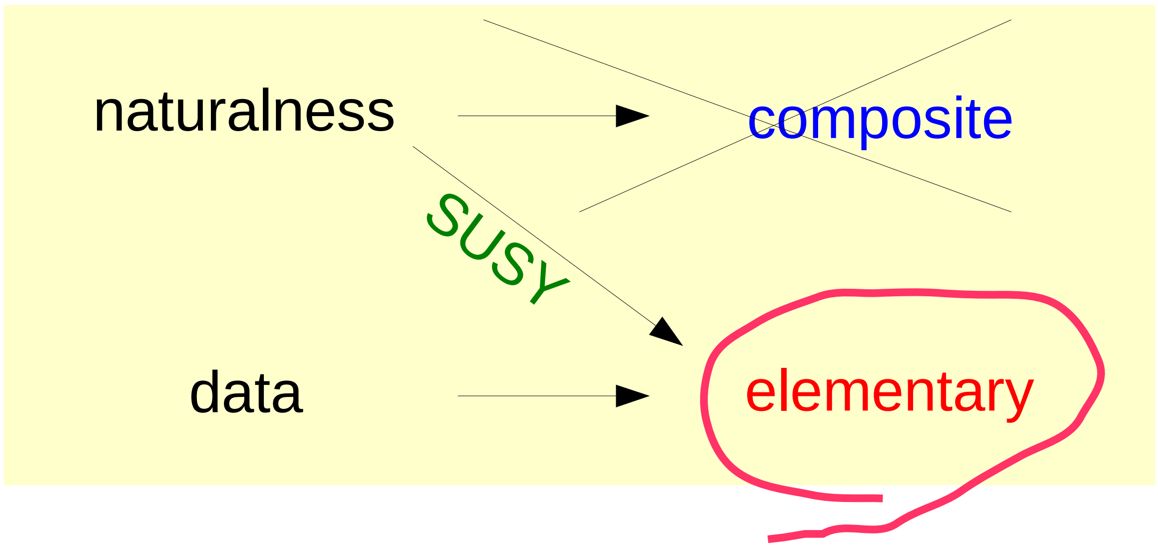
Supersymmetry is a trick to make an elementary scalar natural.



supersymmetry

Fermion mass = Boson mass

Protected by chiral symmetry



naturalness → ~~composite~~

SUSY

data → elementary

Great!!! But actually it isn't so simple. We will encounter exactly the same problem once we consider the SUSY breaking.

μ-problem

SUSY (Higgsino mass)

$$V(H) = (m_{H_u}^2 + \mu^2)|H_u|^2 + (m_{H_d}^2 + \mu^2)|H_d|^2$$

$$+B\mu H_u H_d + \text{h.c.}$$

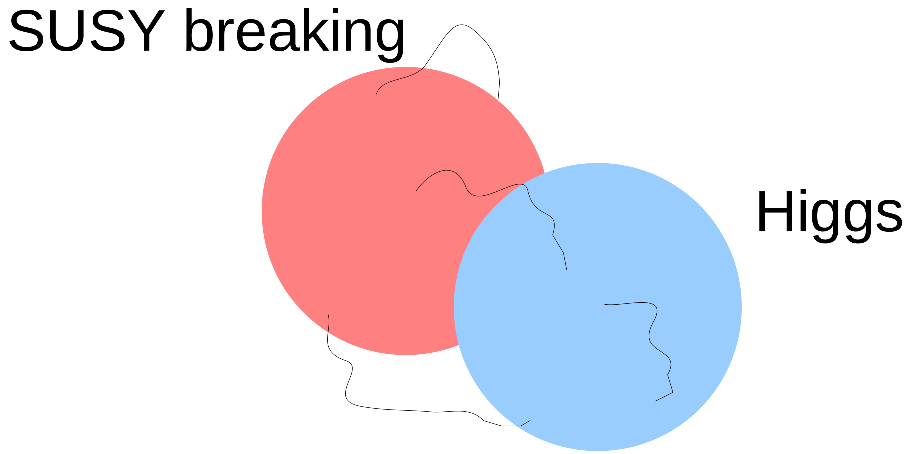
SUSY breaking

$$+\frac{g^2}{8}(|H_u|^2 - |H_d|^2)^2$$

We need $\mu^2 \sim \mu B \sim m_H^2 \sim m_W^2$

We need everything to be O(1) for naturalness.

That's easily realized in Gravity Mediation, because

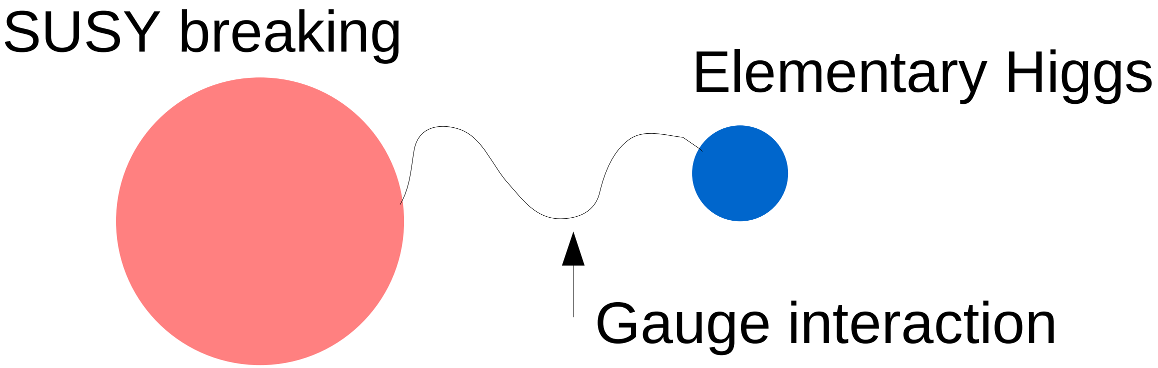


everything is strongly coupled (composite) at the Planck scale.

→ Everything is O(1).

That's the essence of the Giudice-Masiero mechanism.

In Gauge Mediation and Anomaly Mediation, two sectors are weakly coupled.


SUSY breaking

Elementary Higgs

Gauge interaction

In this situation, we encounter a problem in the Higgs sector, that is

1-loop

$$\frac{B\mu}{\mu^2} \sim 100 m_{1/2}$$

Gaugino mass

$(1\text{-loop})^2$

1-loop factor

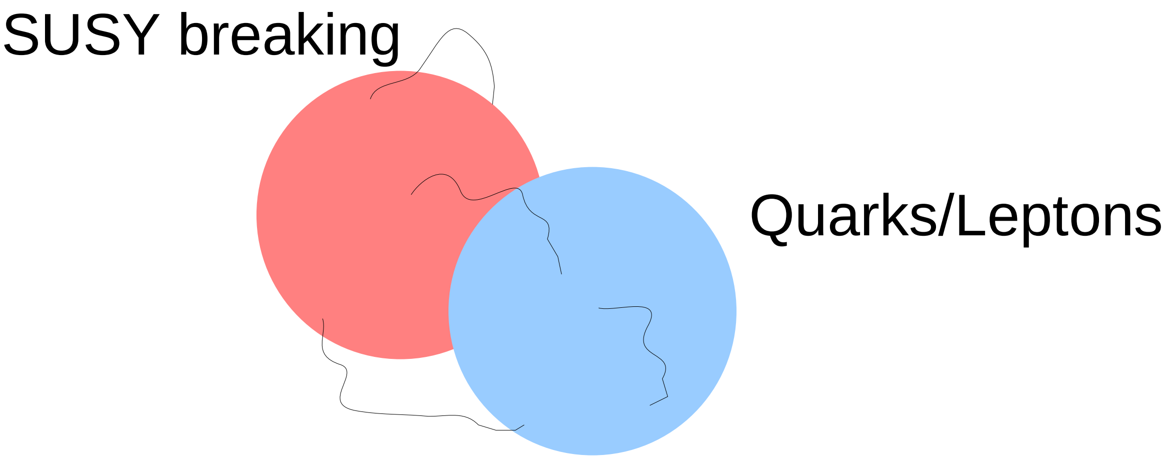
Essentially, we don't want any expansion parameter.

Therefore,

naturalness → composite

at the messenger scale.

On the other hand, constraints from FCNC processes prefer the Gauge Mediation or the Anomaly Mediation because



this will be problematic in Gravity Mediation.

In summary,

naturalness → Gravity Mediation → composite

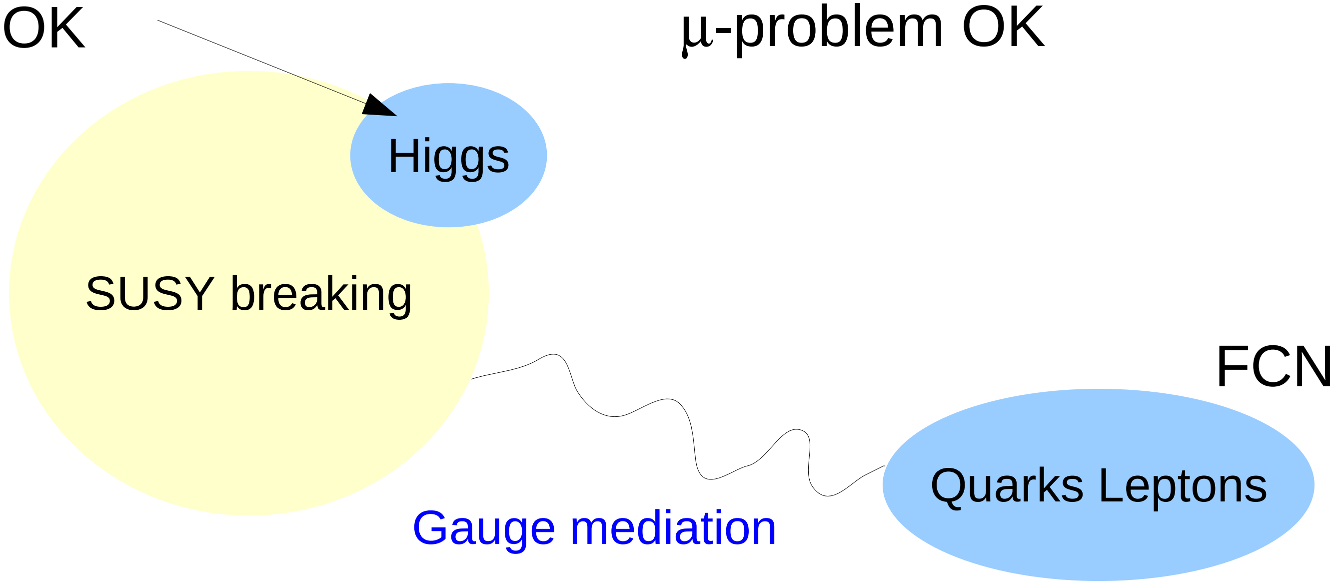
data → Gauge or Anomaly Mediation → elementary

at the messenger scale physics.

The composite vs elementary problem again....

Supersymmetry is not a solution to the naturalness problem?

Wait a minute. Naturalness and FCNC are problems in different sectors.
What about this picture?



elementary but directly coupled (composite).

Yukawa OK

μ-problem OK

Higgs

SUSY breaking

FCNC OK

Quarks Leptons

Gauge mediation

elementary

The dynamics to break SUSY directly couples to the Higgs fields.

OK. What's the model?

Sweet Spot SUSY:

(Linear sigma model)

SUSY breaking sector

$$
\begin{aligned}
K &= \boxed{S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}} \\
&\quad \boxed{+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}} \\
&\quad + \Phi^\dagger \Phi \quad ,
\end{aligned}
$$

coupling to Higgs sector
(direct communication
a la gravity mediation)

$$
W = W_{\text{Yukawa}}(\Phi) \boxed{+ m^2 S} + kS\bar{f}f + w_0 \ ,
$$

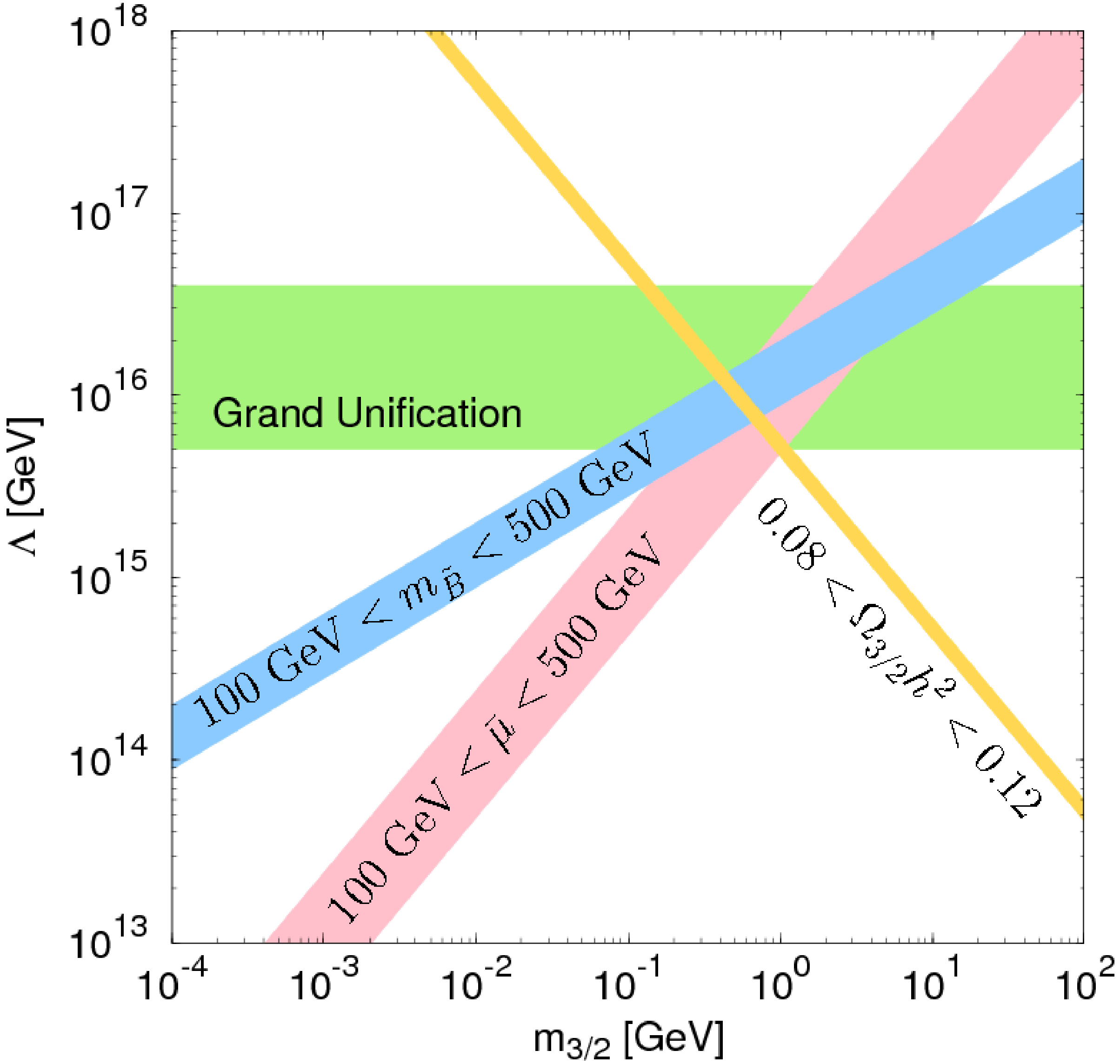
gauge mediation

Effective Lagrangian for the framework.

Sweet Spot Supersymmetry

[Ibe, Kitano '07]

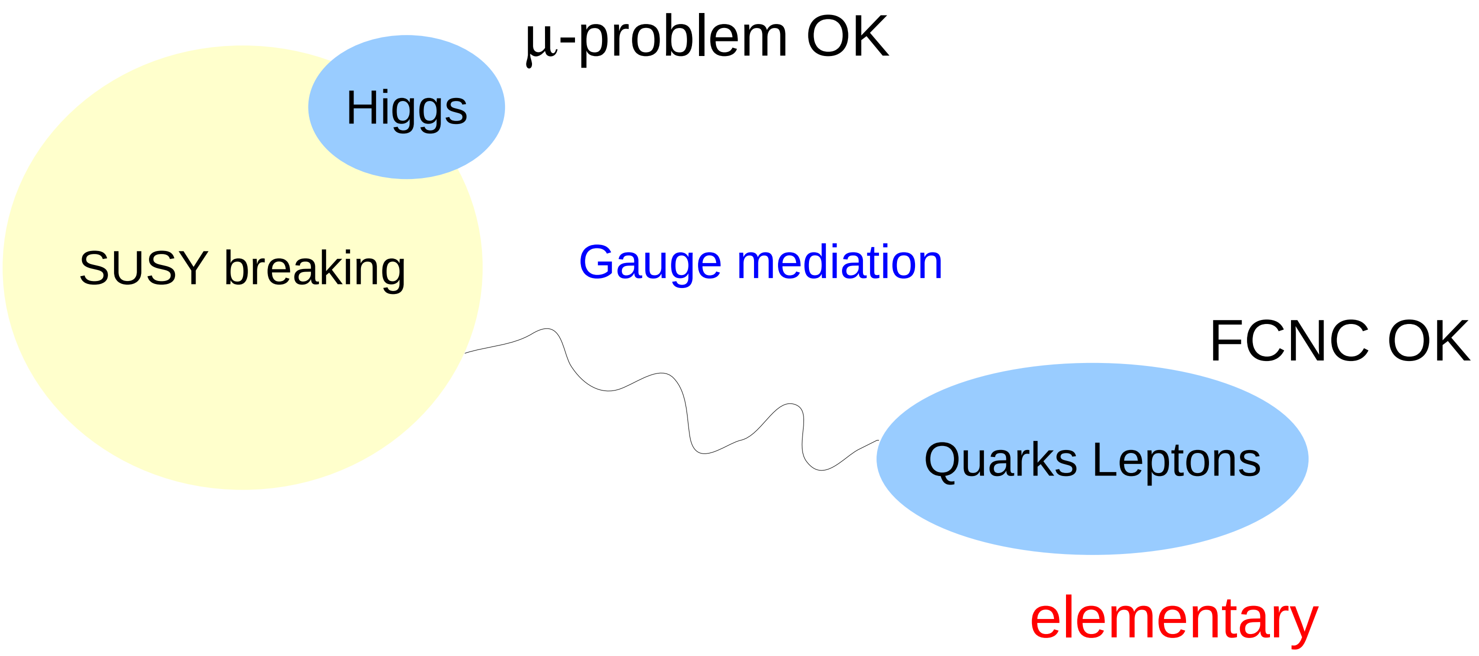
Two parameters Λ and $m_{3/2}$ ($\sim m^2/M_{Pl}$).



beautiful.

OK. What's next?

I think the simplest setup of the framework of



μ-problem OK

Higgs

SUSY breaking

Gauge mediation

FCNC OK

Quarks Leptons

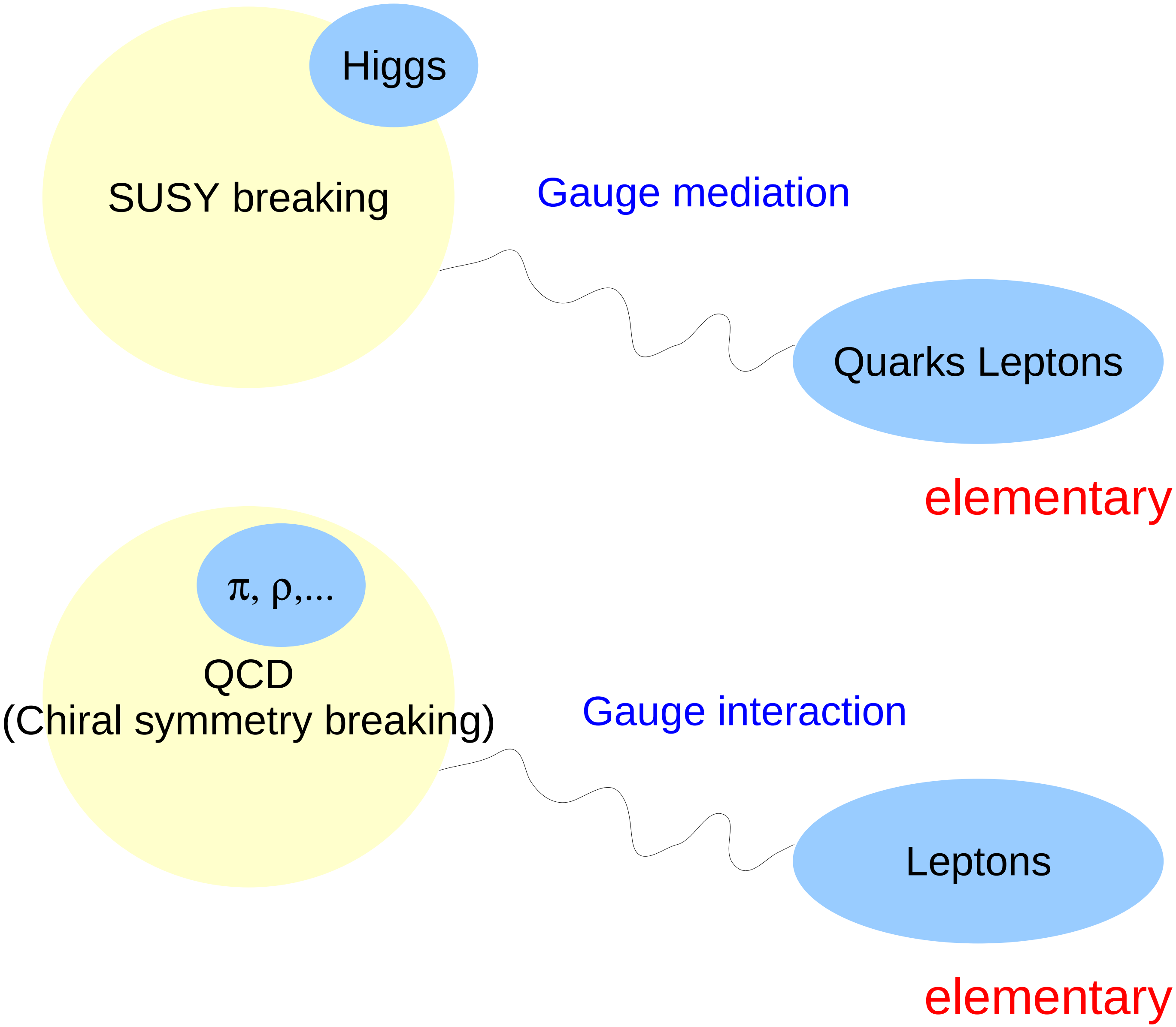
elementary

is to take the extreme limit of this scenario.

That is SUSY breaking at (a few – 10) TeV and the Higgs gets VEV triggered by the dynamics. 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.



Higgs

SUSY breaking

Gauge mediation

Quarks Leptons

elementary

π, ρ,...

QCD
(Chiral symmetry breaking)

Gauge interaction

Leptons

elementary

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

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

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

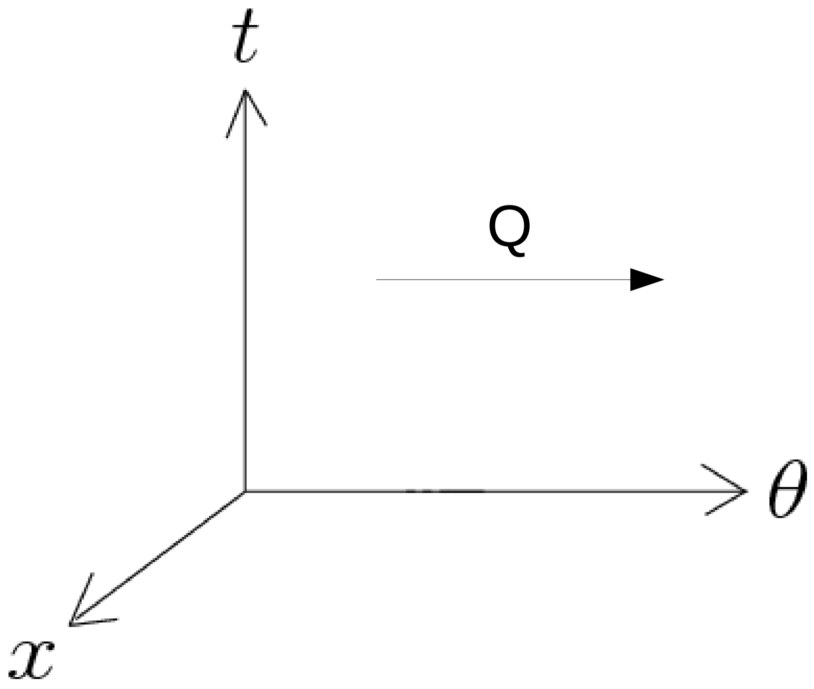
η is a fermionic parameter.

→ 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.

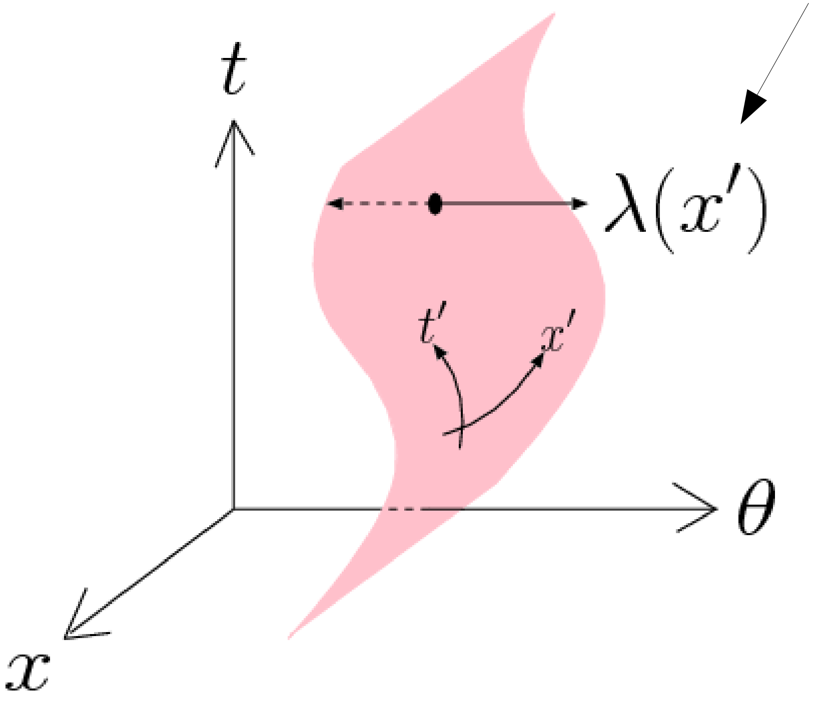


In order to break the symmetry spontaneously, what we need to do is just...

What's that?

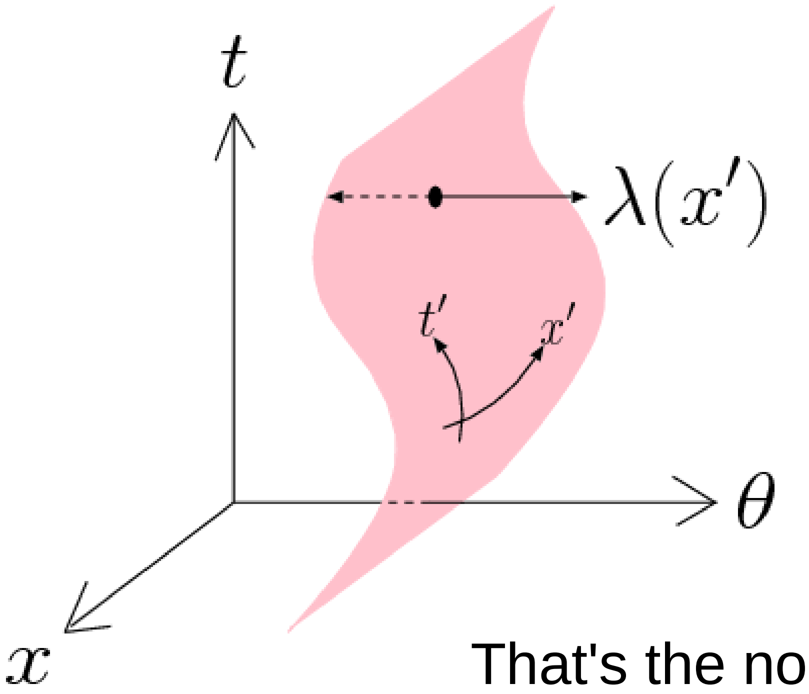
A simple formulation of nonlinear SUSY.

SUSY is a translational invariance of the superspace.



Goldstino
coordinate of
SuperPoincare/Poincare

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.

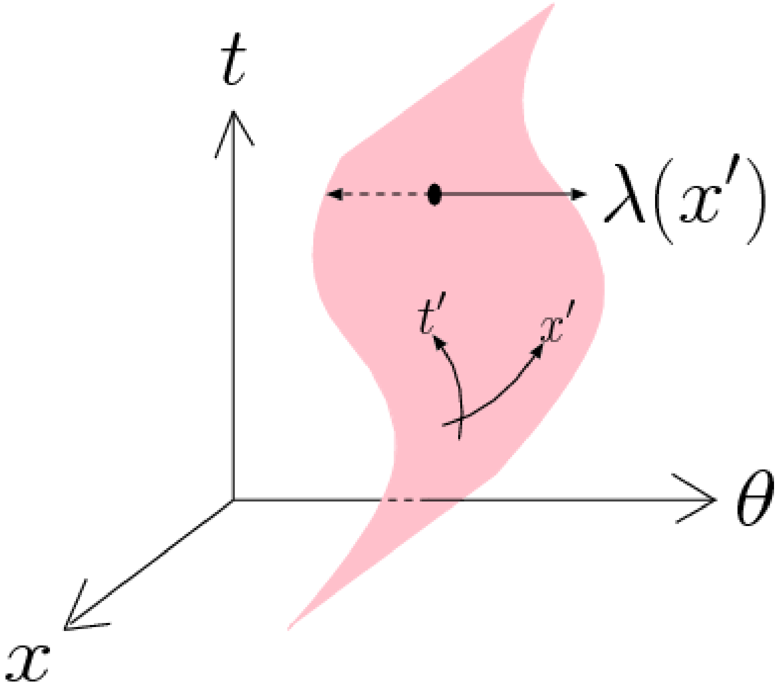
The matrix $$A_{\mu}{}^{a} \equiv \delta_{\mu}{}^{a} - i\lambda\sigma^{a}\partial_{\mu}\bar{\lambda} + i\partial_{\mu}\lambda\sigma^{a}\bar{\lambda}$$

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 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.
(gauge mediation)

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

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

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

Higgs potential

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

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

SUSY invariant Lagrangian 3

Bulk to brane interaction –Yukawa interactions.

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

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

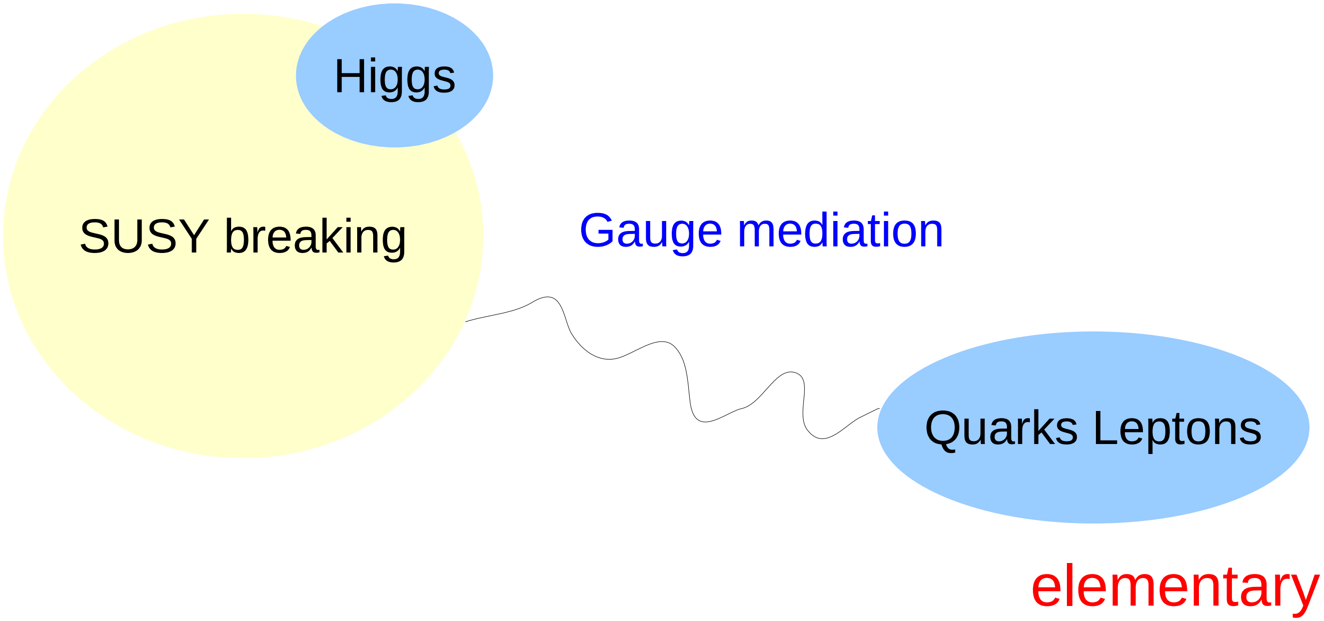
$$\left. + y_d^{ij}\phi^\dagger(x')e^{-2gV}\left(\frac{1}{2}D^2_{(\mathrm{cov})}D^c_j Q_i\right) + y_e^{ij}\phi^\dagger(x')e^{-2gV}\left(\frac{1}{2}D^2_{(\mathrm{cov})}E^c_j L_i\right)\right]$$

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

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:



Higgs

SUSY breaking

Gauge mediation

Quarks Leptons

elementary

But.... SO WHAT?

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

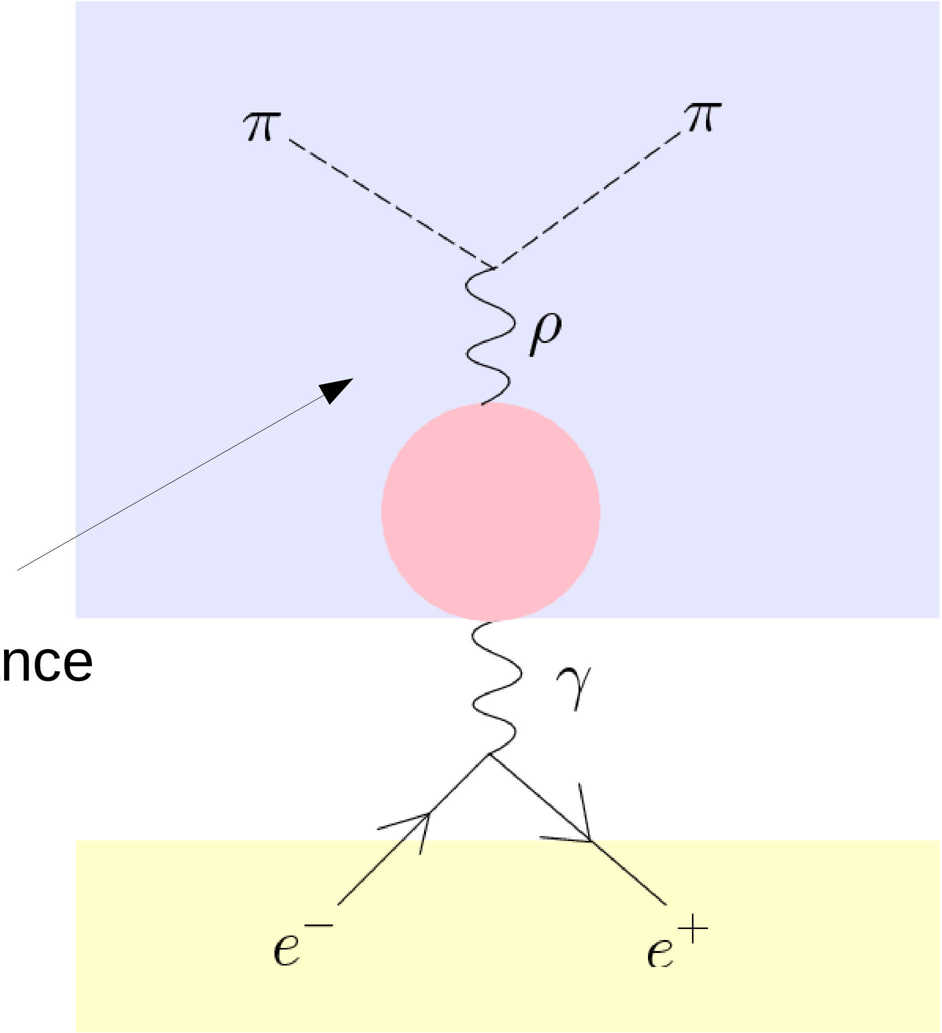
The Higgs mass, mass spectrum are all free parameters.....

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,



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]

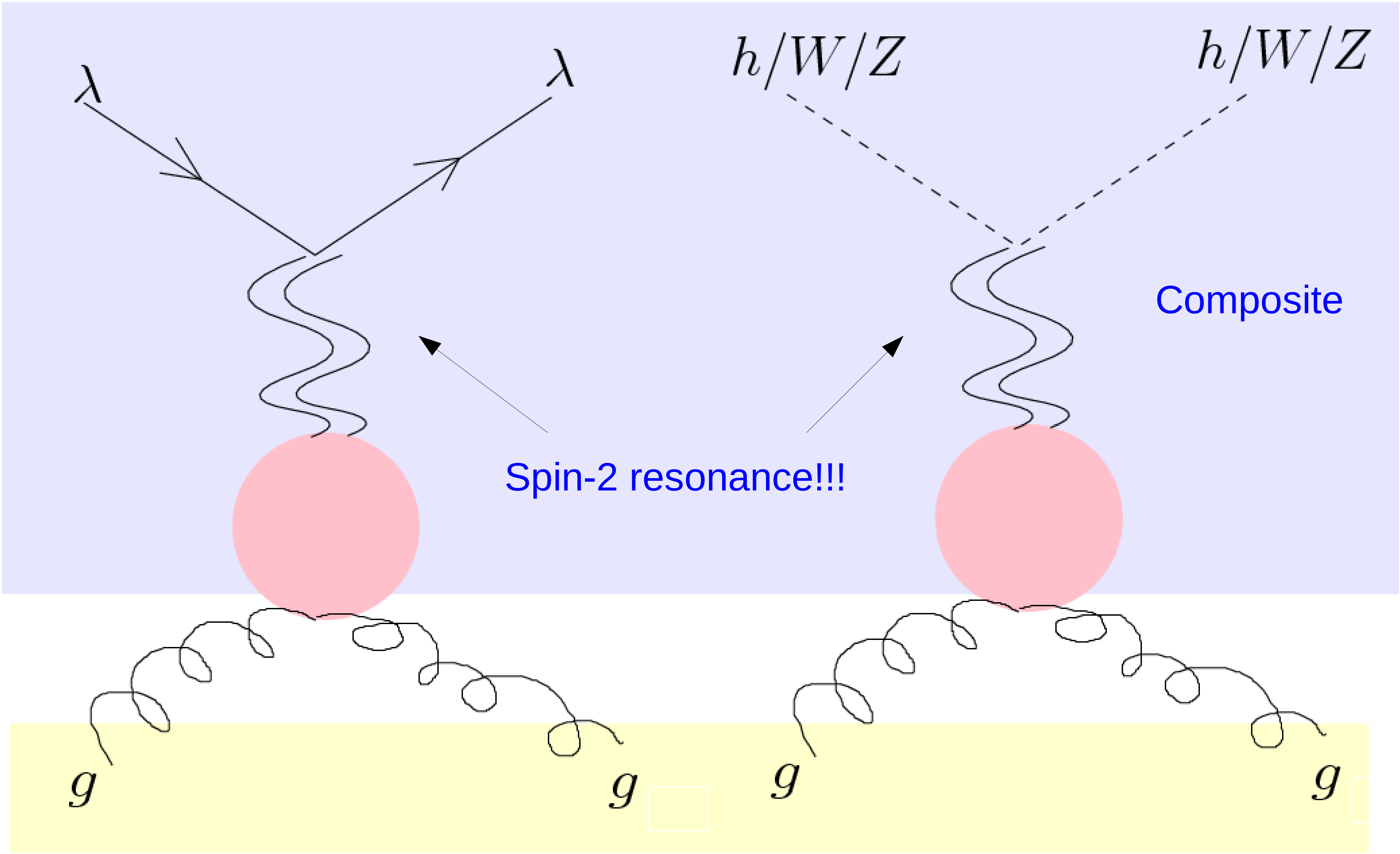
in which the resonance (massive vector boson) is consistently introduced as a **gauge boson of the unbroken global symmetry** ($SU(2)_V$).

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



Composite

Spin-2 resonance!!!

elementary

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

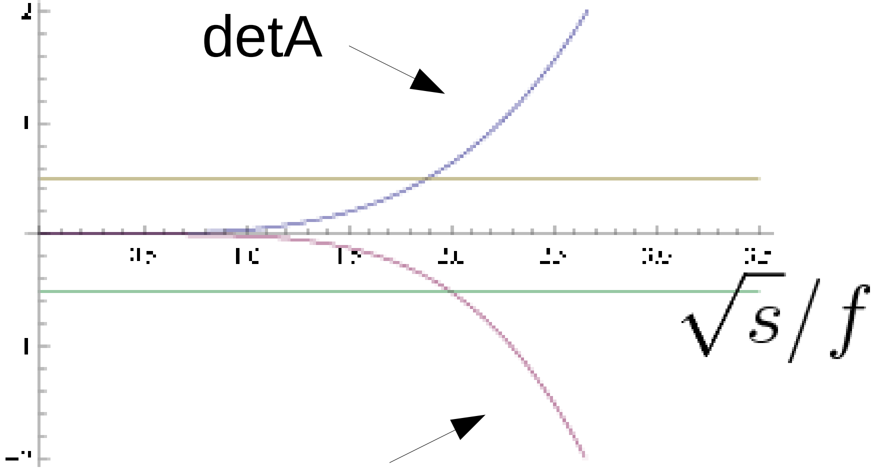
This is invariant under general coordinate transformation even though there is a mass term.

→ Global SUSY invariant formulation of the massive graviton.

Is that a good particle?

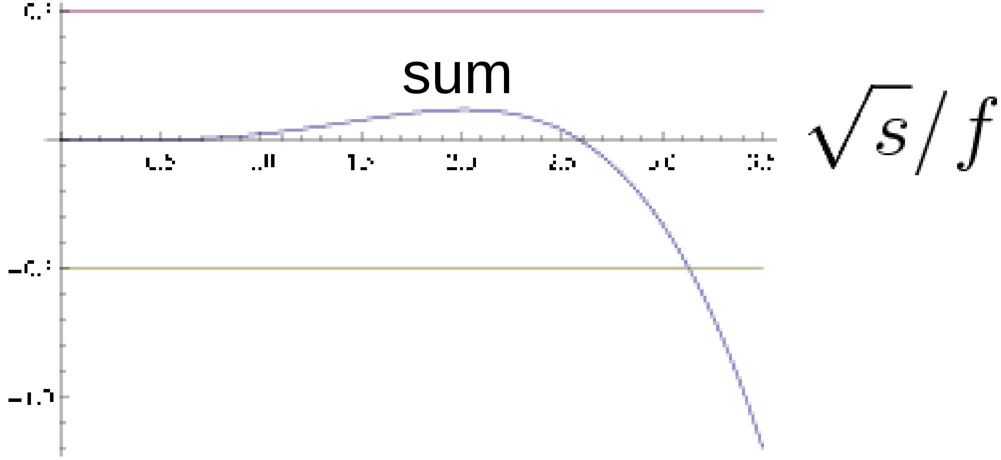
Well, at least one can consistently introduce it without spoiling the calculability (perturbative unitarity).

s-wave amplitude



graviton contribution

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.

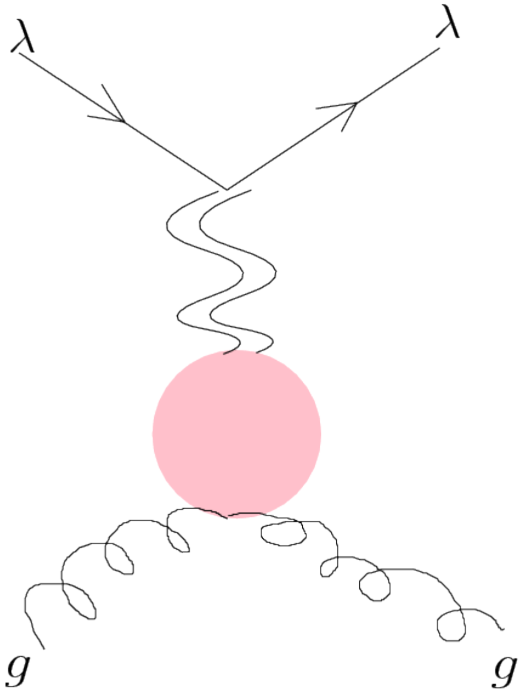
That's the same property as the ρ meson.

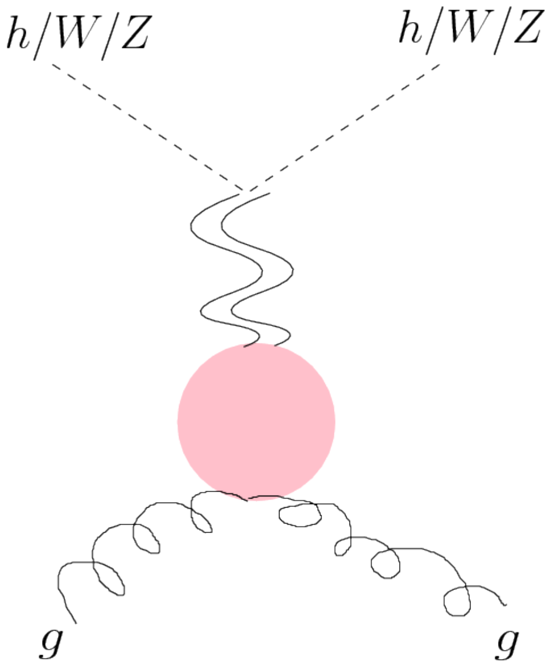
Massive Graviton (SUSY version) at the LHC

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

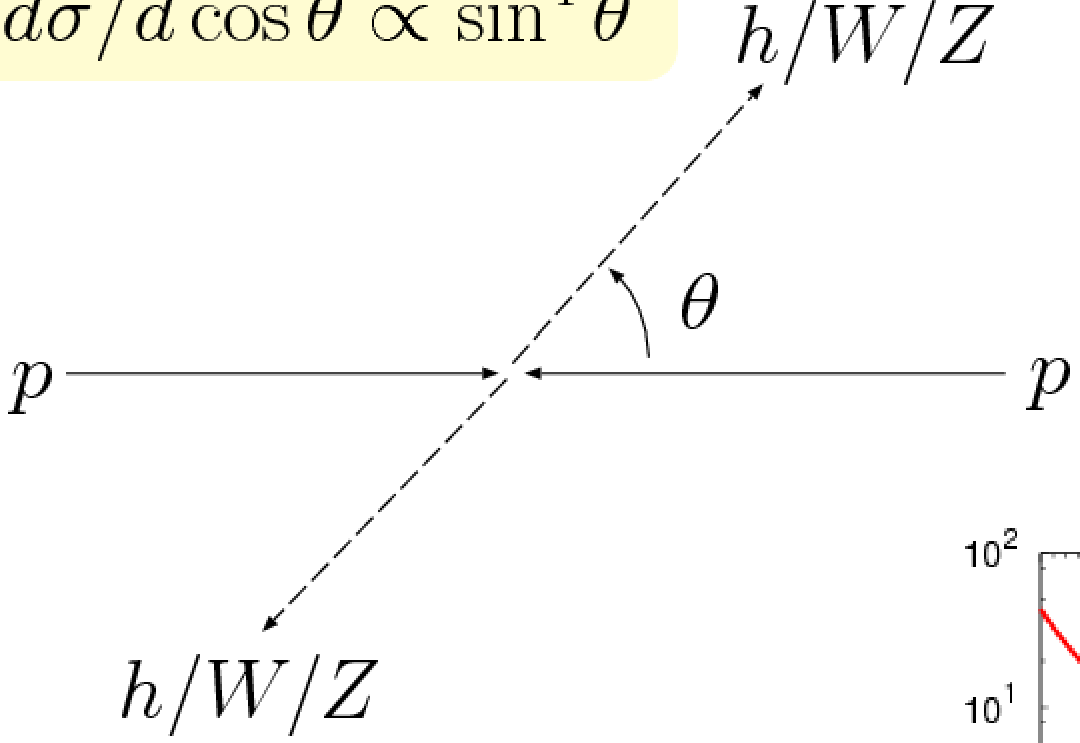
invisible

hh/ZZ/WW modes

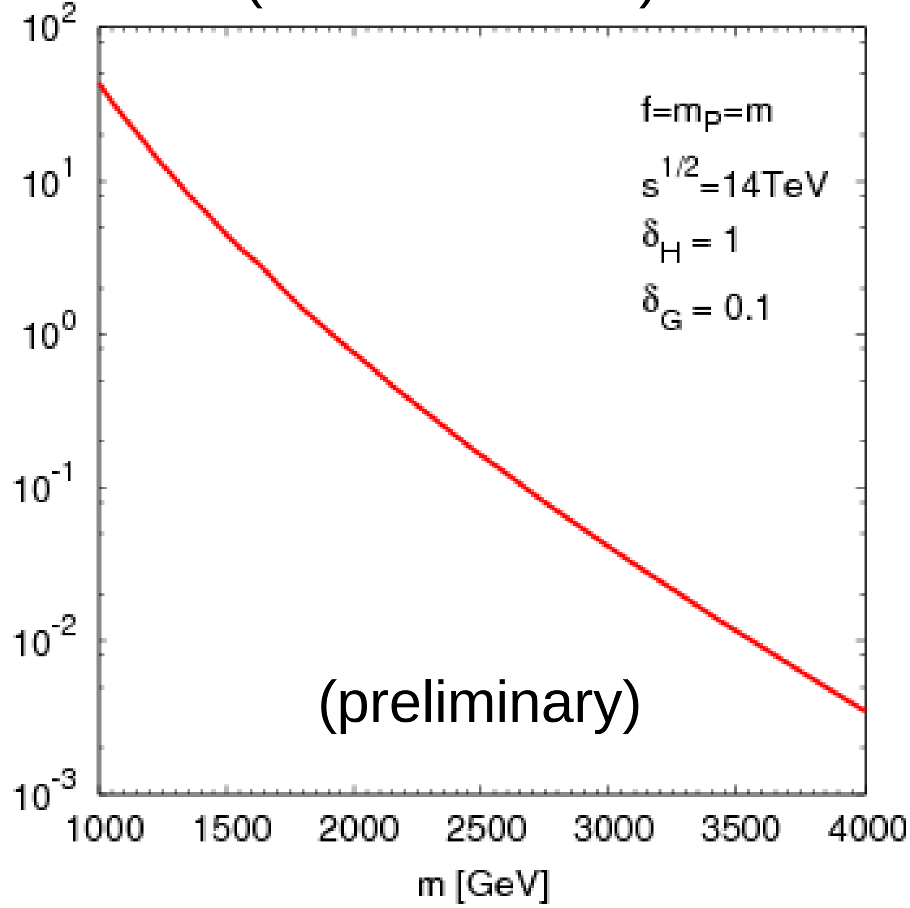




$$d\sigma/d\cos\theta \propto \sin^4\theta$$



Br(Graviton -->hh) ~ 0.1



(preliminary)

σ(pp-->Graviton-->hh)

These are typical signatures for

The Large Extra Dimension (invisible mode)

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

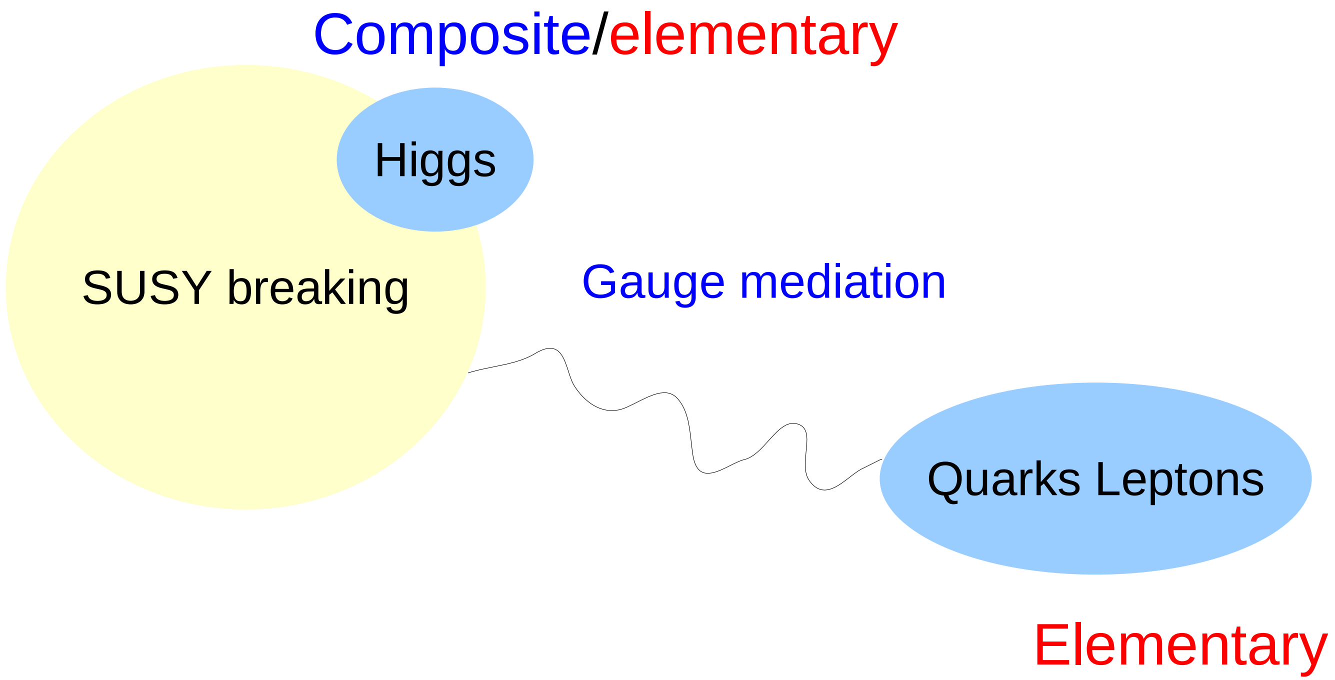
Well, it is probably true that the spin-2 resonance is a signature of the enlarged spacetime. So,

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.



Composite/elementary

Higgs

SUSY breaking

Gauge mediation

Quarks Leptons

Elementary

We may see many unconventional SUSY signals at the LHC.