

Black Holes and Particle Species

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Outline

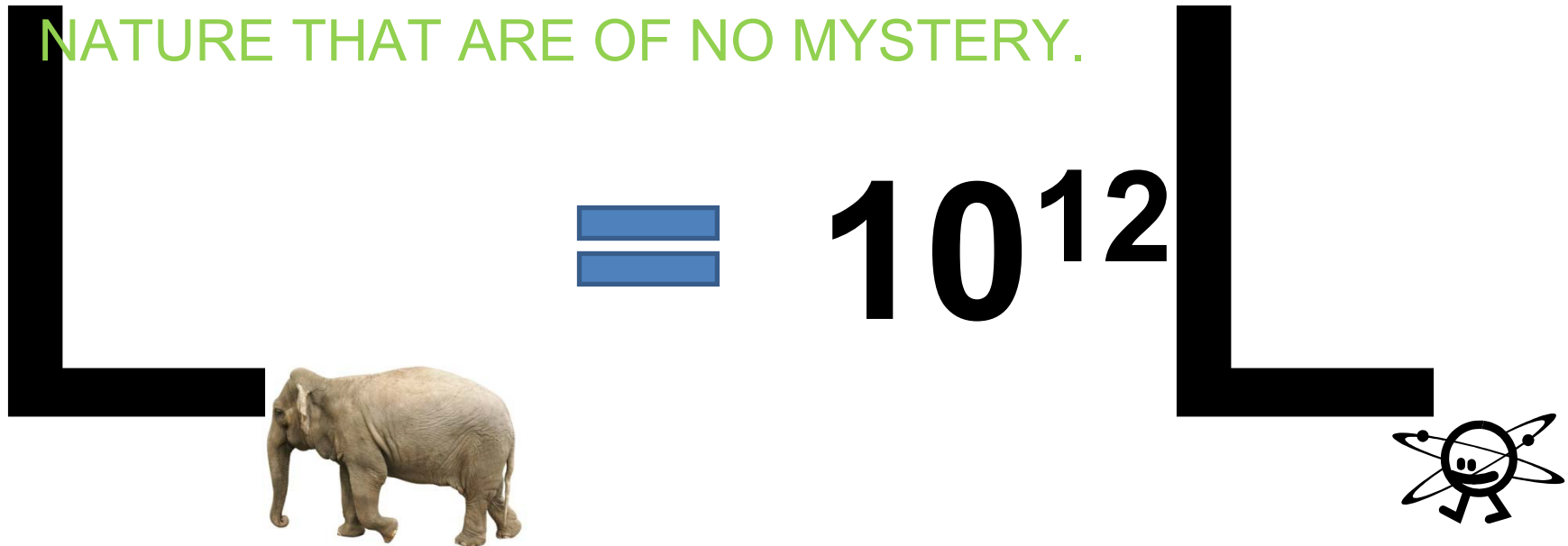
- 1) **The Hierarchy Problem and Dark Matter** motivation for Beyond the Standard Model Physics at **LHC**.
- 2) The Idea of a **TeV-scale** quantum gravity.
- 3) Large Extra Dimensions.
- 4) Power of the black hole physics: What lowers the quantum gravity scale is the **number of particle species**.
- 5) Pandora's box of possibilities.
- 6) Experimental signatures at LHC: Production of mini black holes, with hair.
- 7) Cosmology of Species: **up to 10^{32} New Dark Sectors?**
- 8) Conclusions.

THE SEARCHES OF THE NEW (BEYOND THE STANDARD MODEL) PHYSICS AT THE LARGE HADRON COLLIDER (LHC) ARE MOTIVATED BY THE PROBLEM OF THE HIERARCHY OF THE STABILITY OF THE WEAK INTERACTION SCALE ($M_W = 10^2$ GeV) VERSUS THE PLANCK MASS ($M_P = 10^{19}$ GeV),

WHY IS $M_W^2/M_P^2 = 10^{-34}$?

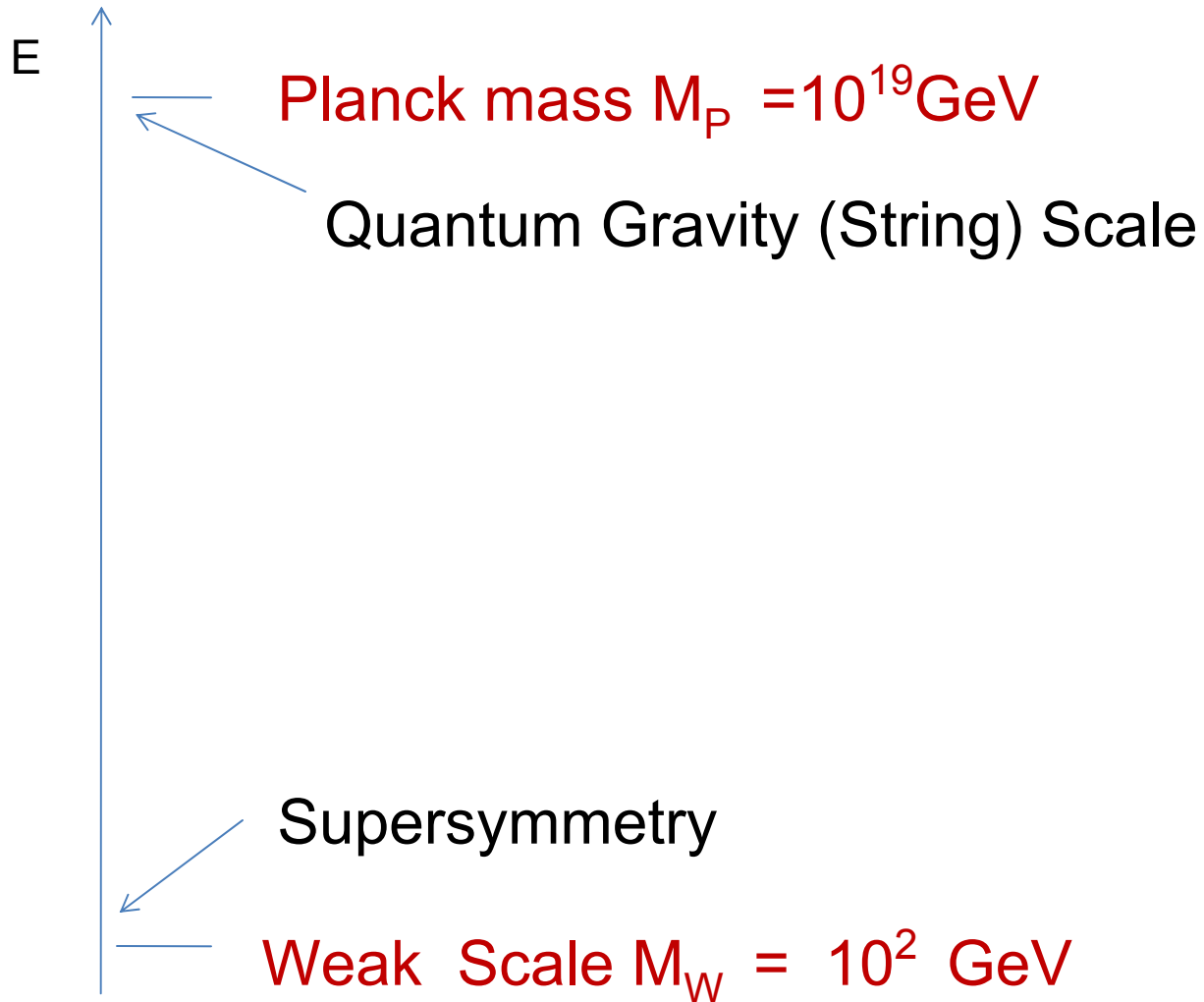
THE HIERARCHY PROBLEM IS NOT ABOUT BIG/SMALL NUMBERS!

THERE ARE PLENTY OF BIG/SMALL NUMBERS IN NATURE THAT ARE OF NO MYSTERY.



ELEPHANTS (OR HUMANS) ARE BIG,
BECAUSE THEY CARRY A HUGE
RADIOACTIVE NUMBER

Standard Paradigm '74 - '98



It is well established, that for the energies $E < M_W$ the world of (known) elementary particles is described by the STANDARD MODEL

GAUGE FORCES  $SU(3) \times SU(2) \times U(1)$

MATTER:

QUARKS : (u,d) (c,s) (t,b), LEPTONS: (e, ν_e) (μ , ν_μ) (τ , ν_τ)

HIGGS: H

The weak scale is set by the vacuum expectation value of the Higgs

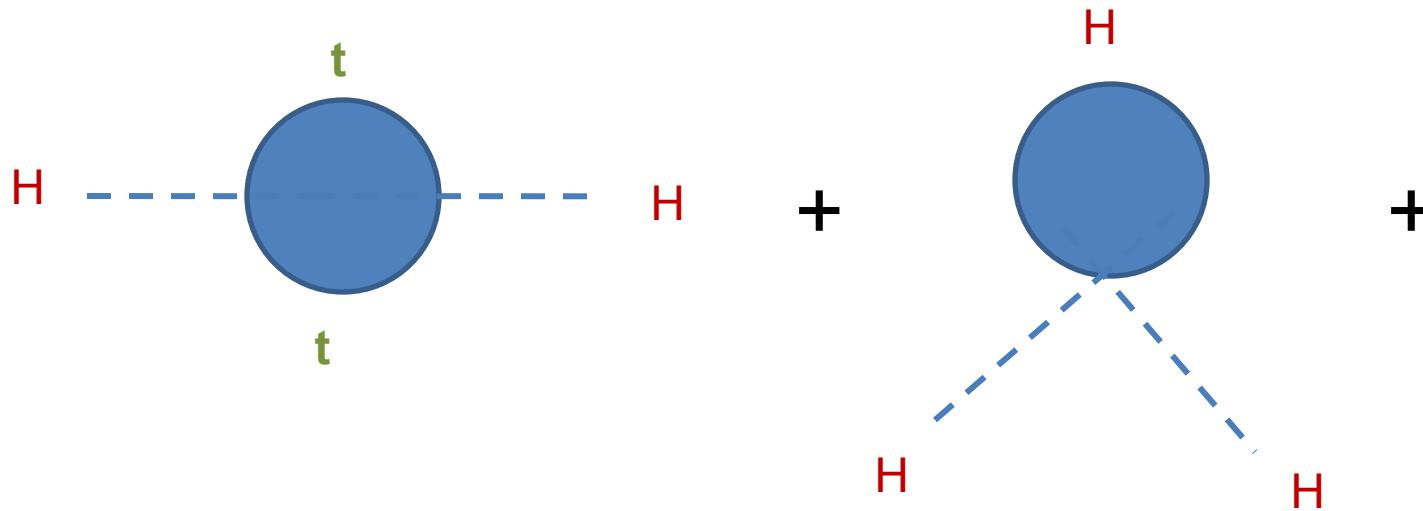
field, which is related to the mass of the Higgs boson, m_H .

This mass is UV-unstable!

THE HIERARCHY PROBLEM IS ABOUT
THE UV STABILITY OF THE VERY
SMALL NUMBER

$$M_W^2/M_P^2 = 10^{-34}$$

UV-instability of the Higgs mass



$$\delta m^2_H \approx \Lambda^2 !$$

The natural cutoff is the gravity scale $\Lambda = M_P$

Without gravity the problem could have been less severe, but with gravity there is no way out:

The particles running in the loop cannot have arbitrarily high energies without becoming big black holes.

THUS, THERE MUST BE SOME NEW PHYSICS NOT FAR ABOVE THE SCALE, THAT STABILIZES THE HIGGS MASS, AND LHC SHOULD PROBE IT.

WHAT IS THIS NEW PHYSICS?

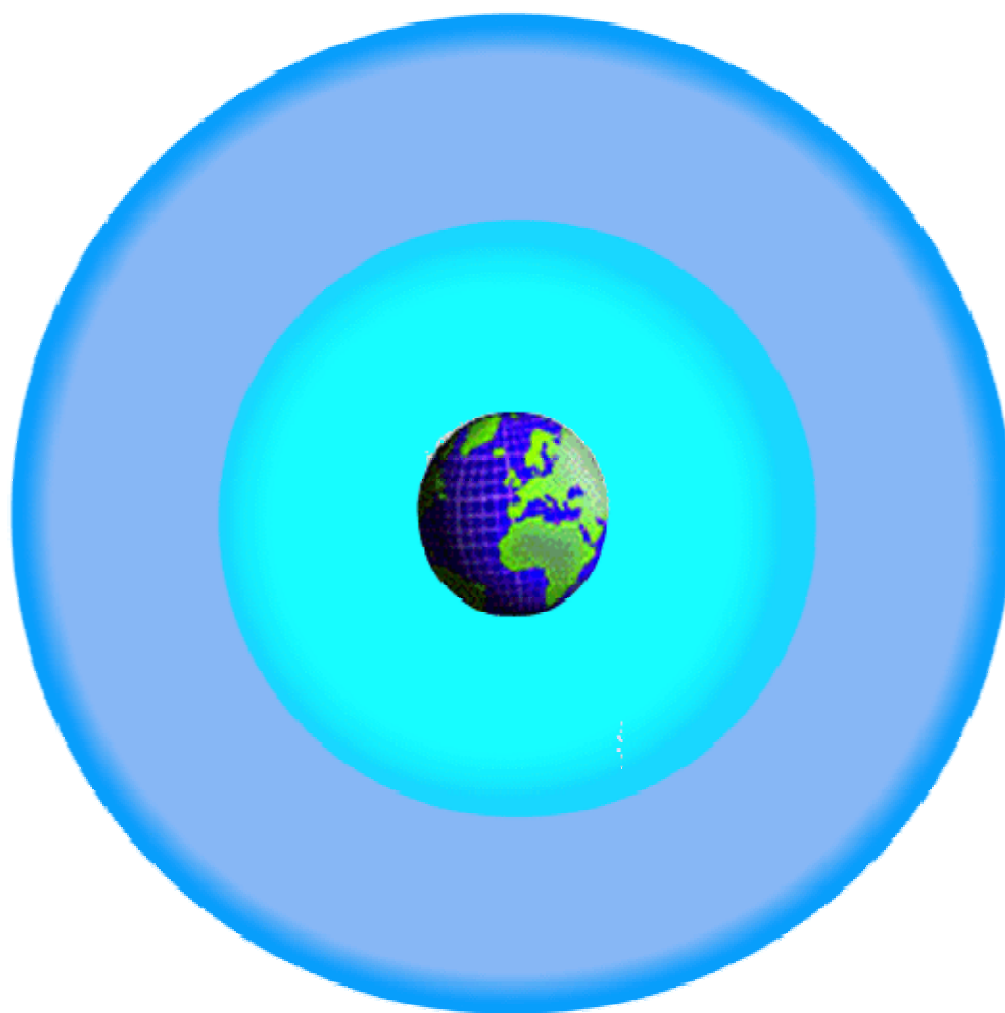
‘98 ADD (Arkani-Hamed, Dimopoulos, G.D.) idea:

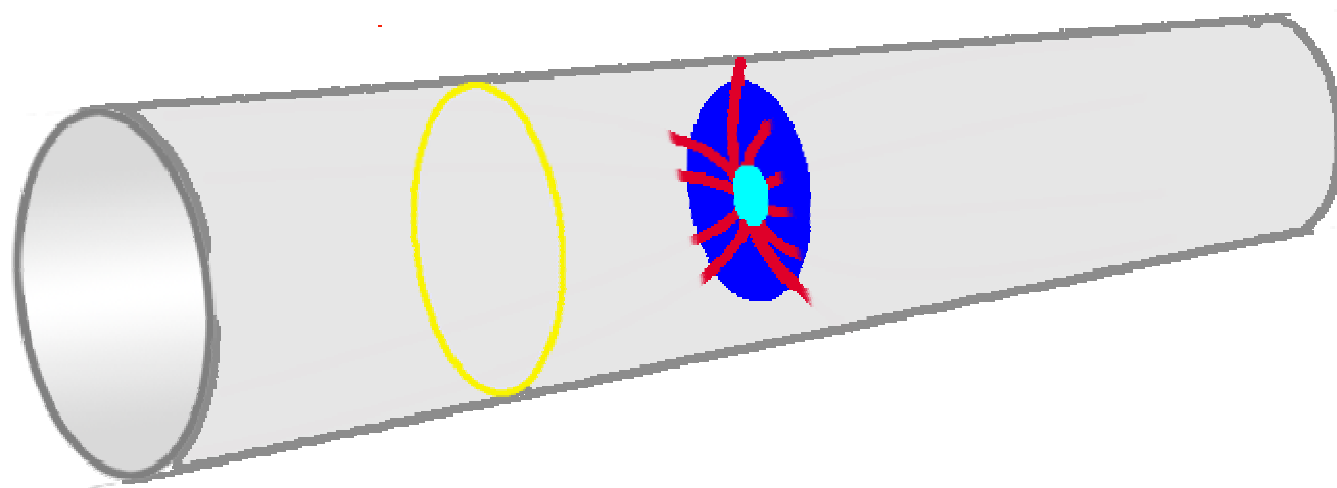
Weak scale is stable, because the quantum gravity scale $M_* \approx \text{TeV}$!

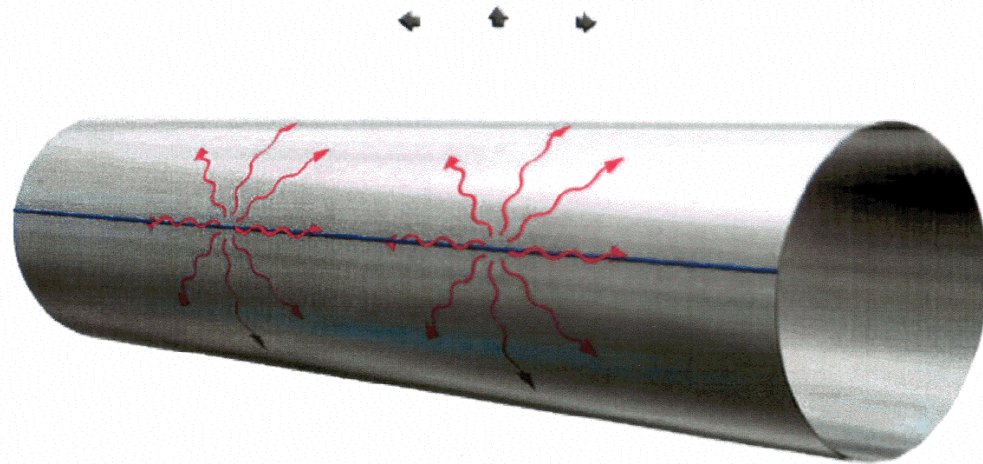
But, if gravity becomes strong around the TeV scale, why is the large distance gravity so much weaker than all the other forces of nature?

For example, gravitational attraction between the two protons at 1 m distance is 10^{37} times weaker of their Coulomb repulsion!

Original Realization: Extra Dimensions








$$G_N = G_{NF} / V_{\text{EXTRA}}$$

As a result of the dilution, there is a simple relation between the true quantum gravity scale and the Planck mass measured at large distances:

$$M_P^2 = M_*^2 (M_* R)^n$$


Volume of extra
space

Notice, that the above relation can be rewritten as,

$$M_P^2 = M_*^2 N,$$

Where N is the number of Kaluza-Klein species. This is very important, because the latter expression turns out to be more general than the former:

What matters is the number of species!

It was understood recently that the class of low scale quantum gravity theories is much wider and is **not**, a priori, limited by the large extra dimensional models.

In any theory with large number ($N \gg 1$) of species the scale of quantum gravity is inevitably lowered, relative to the Planck mass [C.D. Meda, '07]

$$M_P^2 = M_*^2 N !$$

This follows from the consistency of the black hole physics and can be proven by the following black hole thought experiment .

THE BLACK HOLE PROOF:

Consider N species of the quantum fields.

Φ_j $j = 1, 2, \dots, N$
of mass Λ .

Assume that this system is invariant under an exact (gauged) discrete symmetry

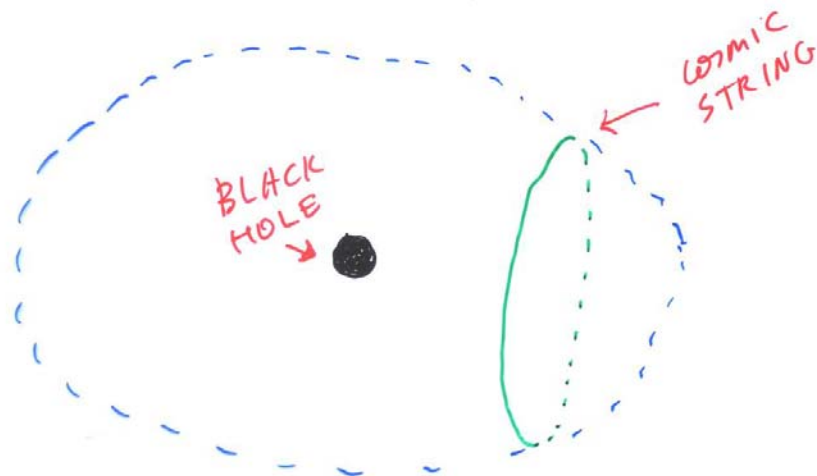
$$\mathbb{Z}_2^N \equiv \mathbb{Z}_2^{(1)} \times \mathbb{Z}_2^{(2)} \times \dots \times \mathbb{Z}_2^{(N)}$$

$$\mathbb{Z}_2^{(j)} \rightarrow \Phi_j \rightarrow -\Phi_j$$

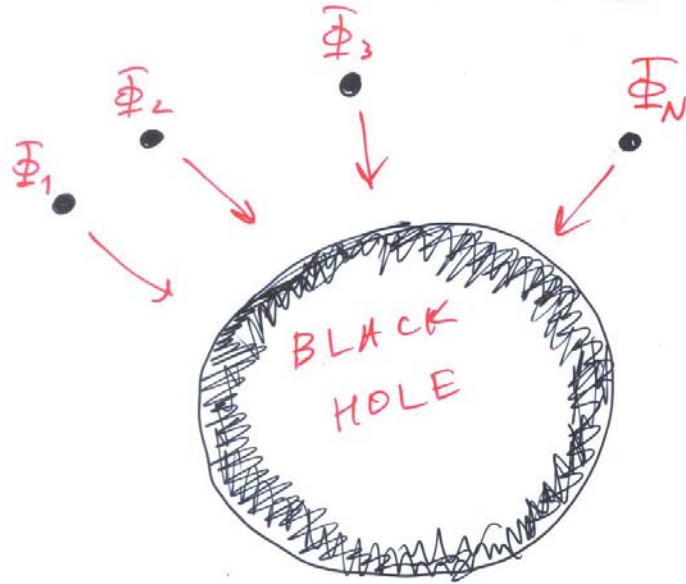
Because \mathbb{Z}_2^N is gauged, it is respected by the black hole physics.

This is because black holes can carry a \mathbb{Z}_N quantum mechanical hair, which can be measured at infinity by the Aharonov-Bohm effect.

Krauss & Wilczek.



Now, ~~we~~ let us prepare an
arbitrarily-large black hole that
carries a maximal Z_2^N -charge



and wait.

Because Hawking evaporation is thermal, for

$$T_H = \frac{M_P^2}{M_{BH}} \ll \Lambda,$$

the emission probability of 1-species is Boltzmann-suppressed by

$$\sim e^{-\frac{\Lambda}{T_H}}.$$

So no matter how large is N , the black hole can only start "giving back" the Z_2^N -charge after

$$T_H \gtrsim T_H^* \sim \Lambda.$$

At this point the mass is:

$$M_{BH}^* = \frac{M_P^2}{\Lambda}$$

Now use conservation of energy.
Then, the maximum number of
species that can be returned is

$$N_{\max} = \frac{M_p^2}{\lambda^2}.$$

Because by \mathbb{Z}_2^N -conservation,

$$N_{\max} \geq N,$$

we prove the bound

$$M_p^2 \geq N \lambda^2$$

In fact, in a theory with N particle species, the quantum gravity scale is

$$M_*^2 = M_P^2 / N$$

This can be seen by number of arguments, perhaps the most elegant being, that black holes of size

$R_g = M_*^{-1}$, have the lifetime

$$t_{BH} = M_*^{-1}$$

and thus, cannot be regarded as semi-classical states of the Hawking temperature $T_H = M_*$!

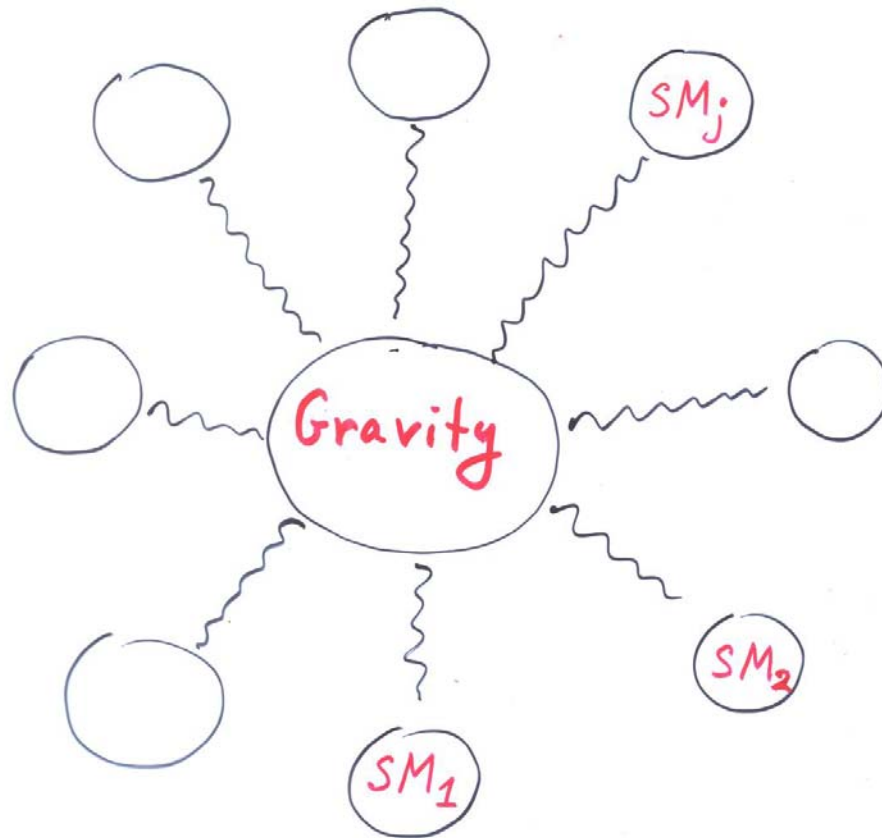
Thus, black holes of this size are quantum objects.

The black hole arguments show, that the class of theories which solve the Hierarchy Problem by TeV quantum gravity scale, is much larger.

In particular, any theory with $N = 10^{32}$ particle species, will do this.

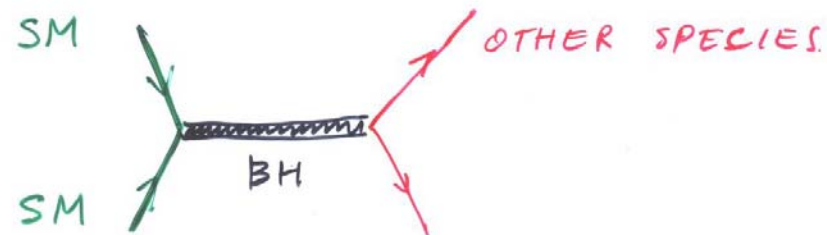
The role of these 10^{32} species, can equally well be played by 10^{32} Kaluza-Klein gravitons from large extra dimensions, or by 10^{32} copies of the Standard Model!

$N \sim 10^{32}$ Copies of the Standard Model



Gravity becomes weak by $\frac{1}{N}$
because of "Spreading" in the
space of Species!

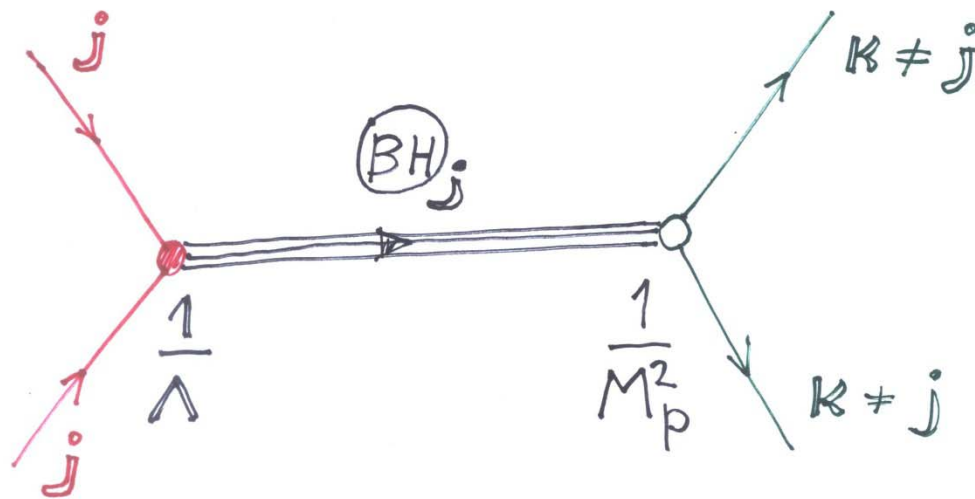
BUT IF Λ IS THE SCALE
OF QUANTUM GRAVITY,
LHC MUST SEE PRODUCTION
OF THE BLACK HOLES.



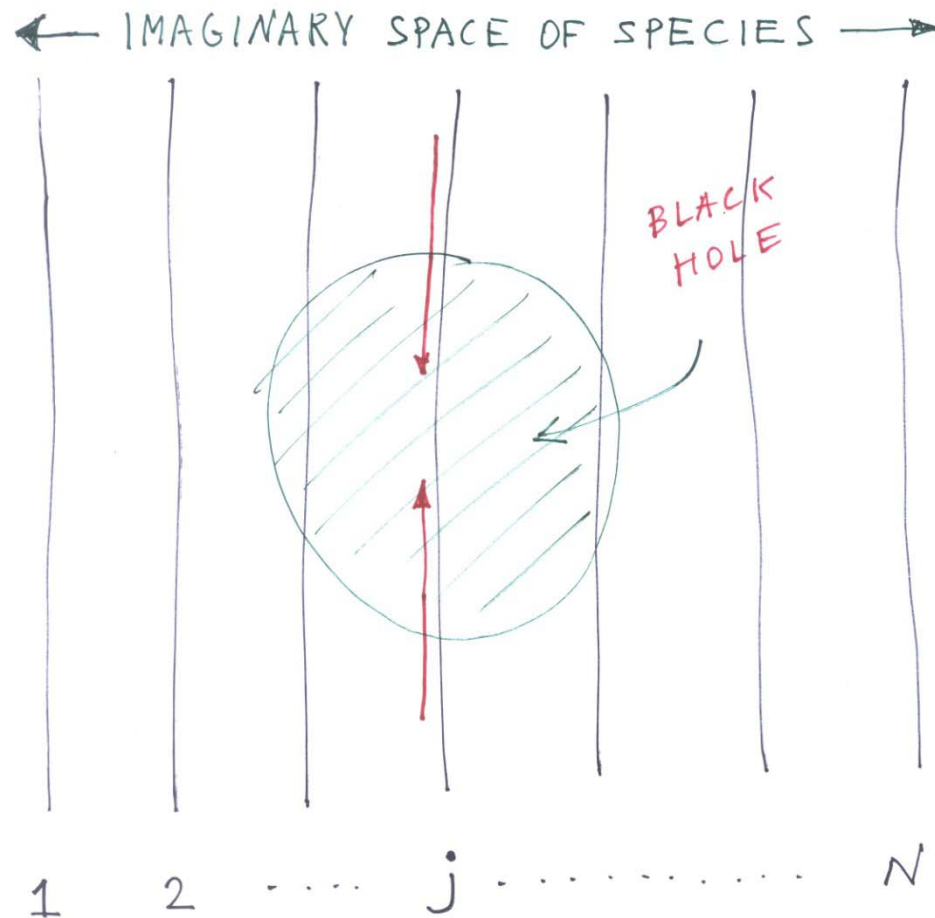
IN FACT, THE BH PRODUCED
AT LHC MUST HAVE A
MEMORY OF THEIR "SPECIES OF
ORIGIN".

THE ONLY CONSISTENT POSSIBILITY
IS THAT SMALL BH-S HAVE A
"MEMORY OF THE PLACE OF ORIGIN"
IN THE SPACE OF SPECIES.

THAT IS, THEY CARRY N FLAVORS
OF HAIR



WITH THE GROWING SIZE OF A BH,
THE MEMORY BECOMES SHORTER AND
SHORTER.



Experimental signatures of low scale quantum gravity theories are pretty spectacular.

One model-independent prediction is the formation of mini black holes in particle collisions. The small black holes carry ``hair'', which becomes ``shorter'' with their increasing size. In the same time the cross-sections soften out with the increase of the collision energy. This is very different from supersymmetry.

In some realizations, the black holes can be semi-classical (G.D., Sibiryaev, '08), and live very long. For us, such black holes will look as very long lived charged states, with continuously decreasing mass, that at the final stage explode in very energetic Standard Model particles.

Another signature is production of string vibrations, and emission of particles in Extra Dimensions.



LHC at CERN



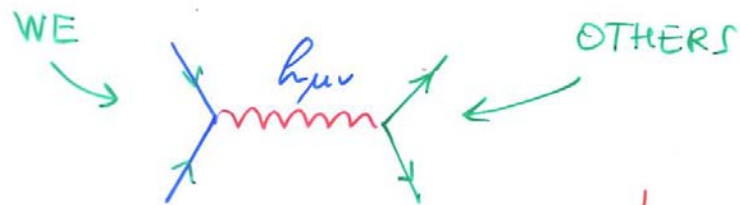
Cosmology of Species

Normalcy temperature.

Imagine we start out hot at temperature T and all the other sectors are empty.

The production rate of other species:

$$\Gamma_{\text{WE} \rightarrow \text{OTHERS}} = \frac{T^5}{M_P^4} N = \frac{T^5}{M_P^2 \Lambda^2}$$



$$\text{At } T_* = (M_P \Lambda^2)^{\frac{1}{3}} \sim 10^8 \text{ GeV}$$

$$\Gamma_{\text{WE} \rightarrow \text{OTHERS}} = H = \frac{T^2}{M_P}$$

For $T < T_*$, we cool down
as normal (due to Universe's
expansion).

For $T > T_*$ we cool because
of decay into the other
species!

Because $T_* \gg T_{\text{BBN}} \sim 10 \text{ MeV}$,
 $T \gg T_*$ is not a problem.

In fact, the baryons in the
other sectors can be
a dark matter.

For being dark matter,
there must be $\sim 10^{80}$ baryons
of the other copies.

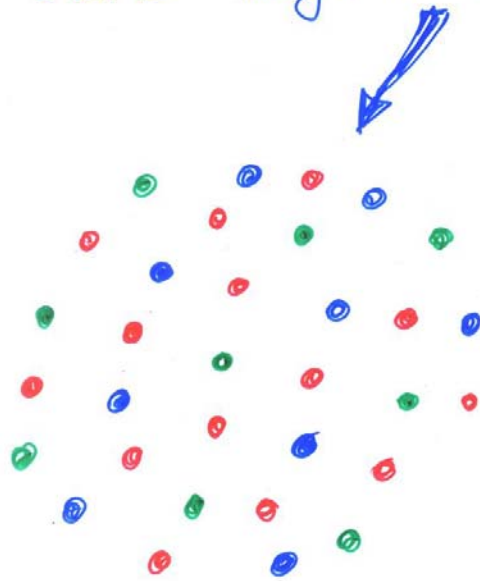
10^{48} baryons per SM copy.

This is 10^{31} times less than
the density of the normal
baryons.

So the "hidden" baryons
never interact and are
the perfect DM candidate!

SM ⊗ SM ⊗ SM ⊗

Dark baryon cloud



$$N_{\text{TOTAL}} = 10^{31} \times 10^{48} = 10^{80}$$

④ This solutions will be tested by LHC, or else there is a BIG puzzle.

⑤ We shall discuss some interesting open questions, and implications for other hierarchies

$$\frac{M_{\text{GUT}}}{M_p}, \quad \frac{M_{\text{STRING}}}{M_p} \dots$$

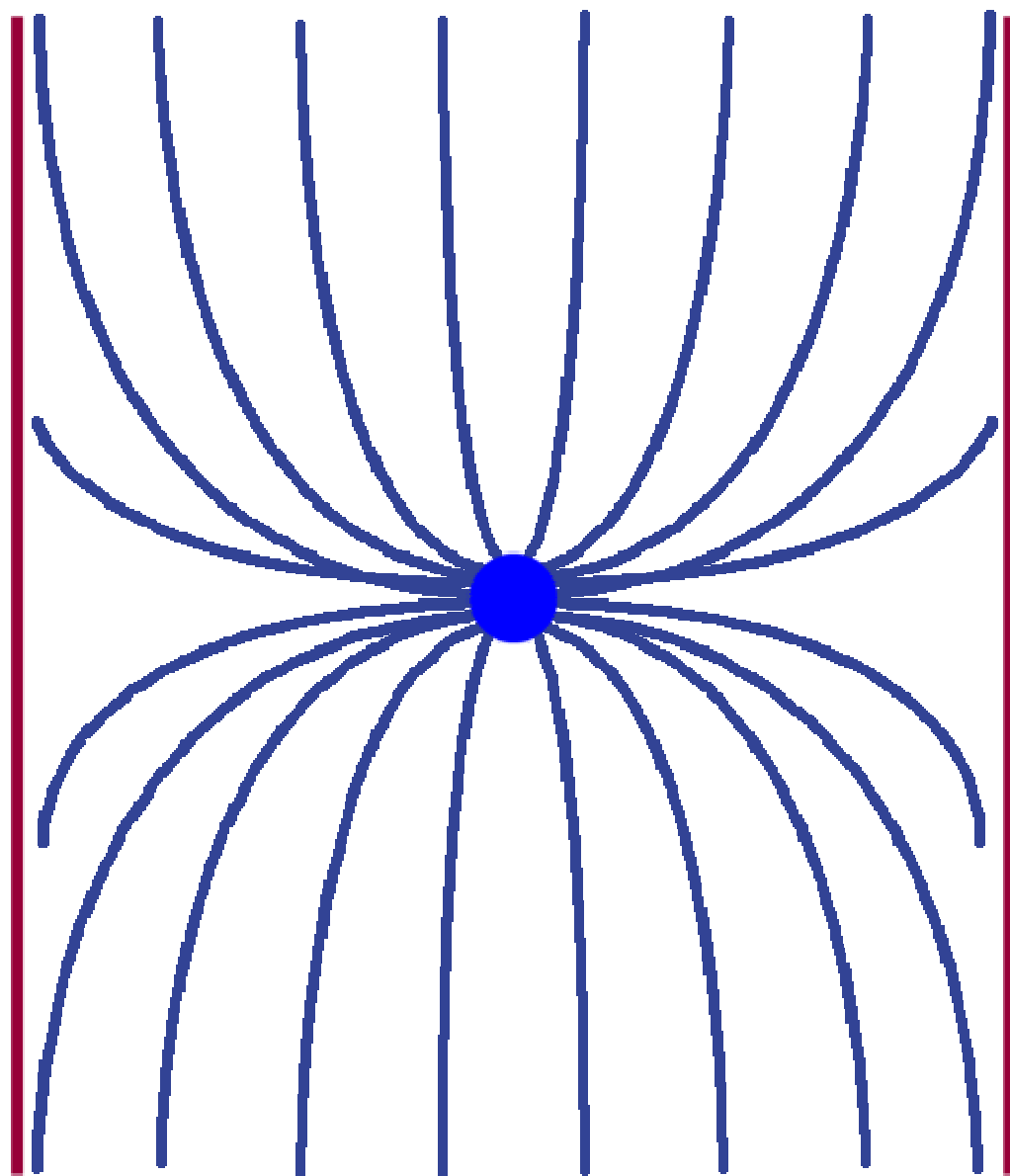
Conclusions

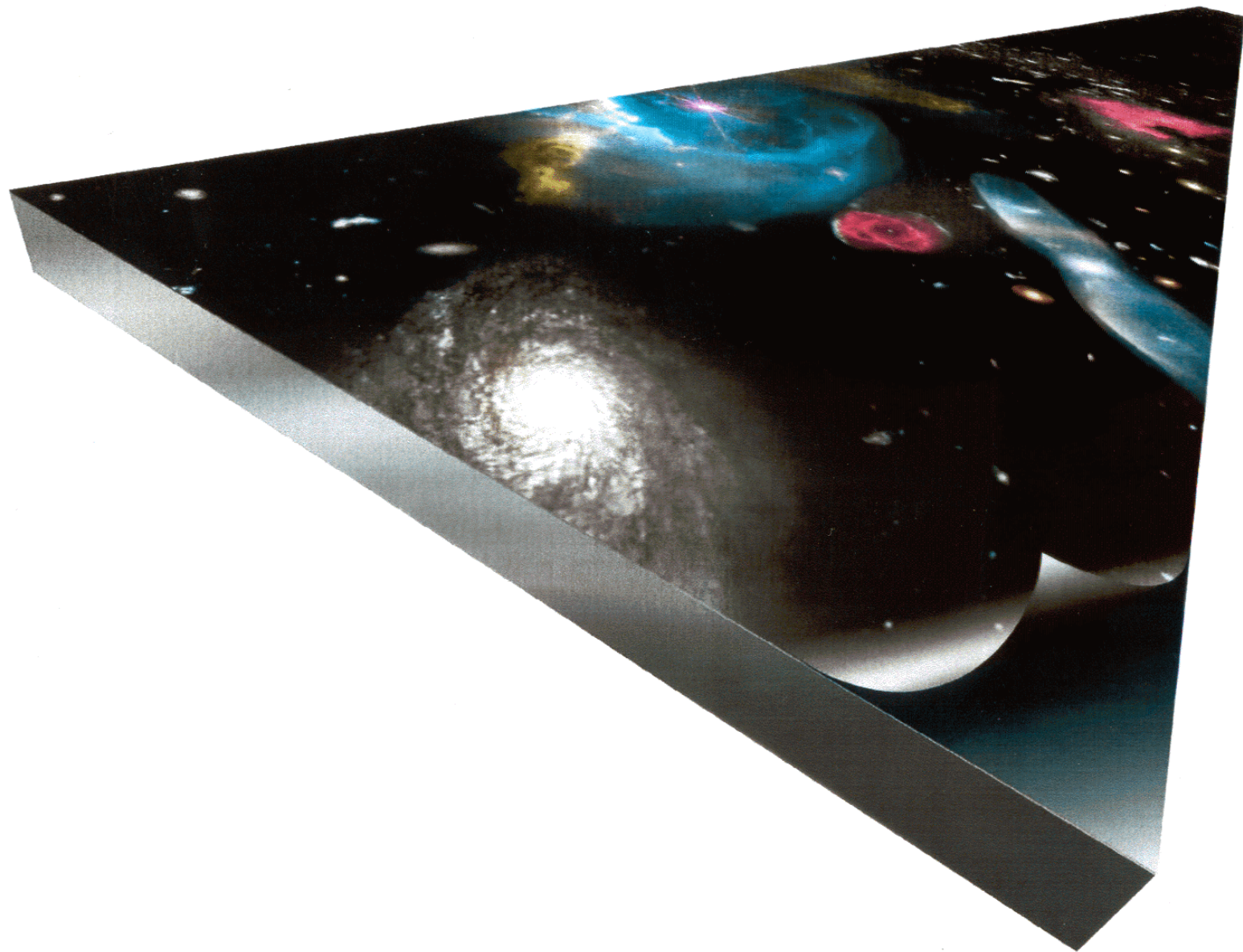
This is an exciting time for the particle physics community.

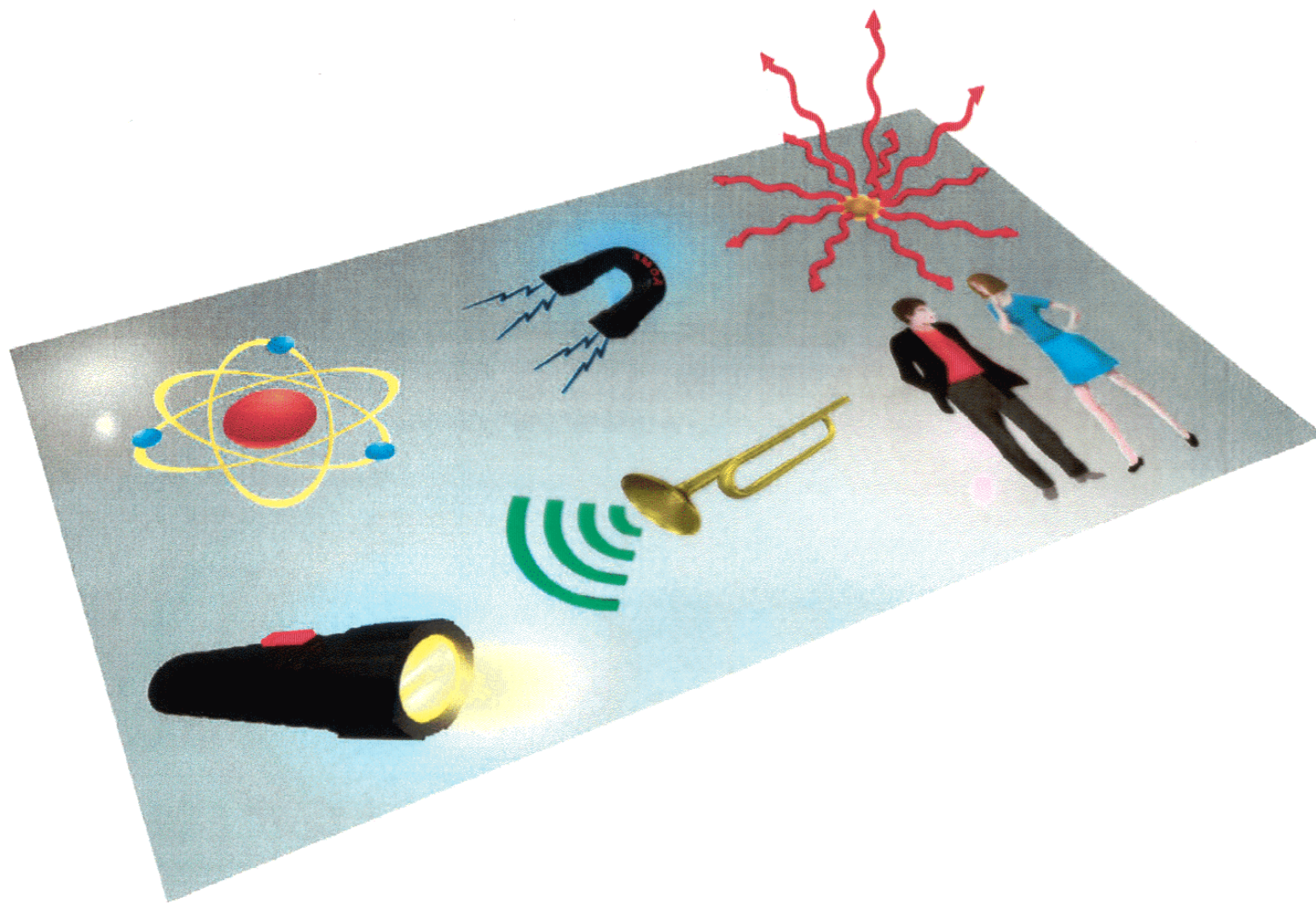
LHC will directly probe the mechanism which is responsible for generating the weak interaction scale and masses of the elementary particles.

And, there is a strong theoretical indication, that LHC will also probe physics that is behind the stability of the above scale.

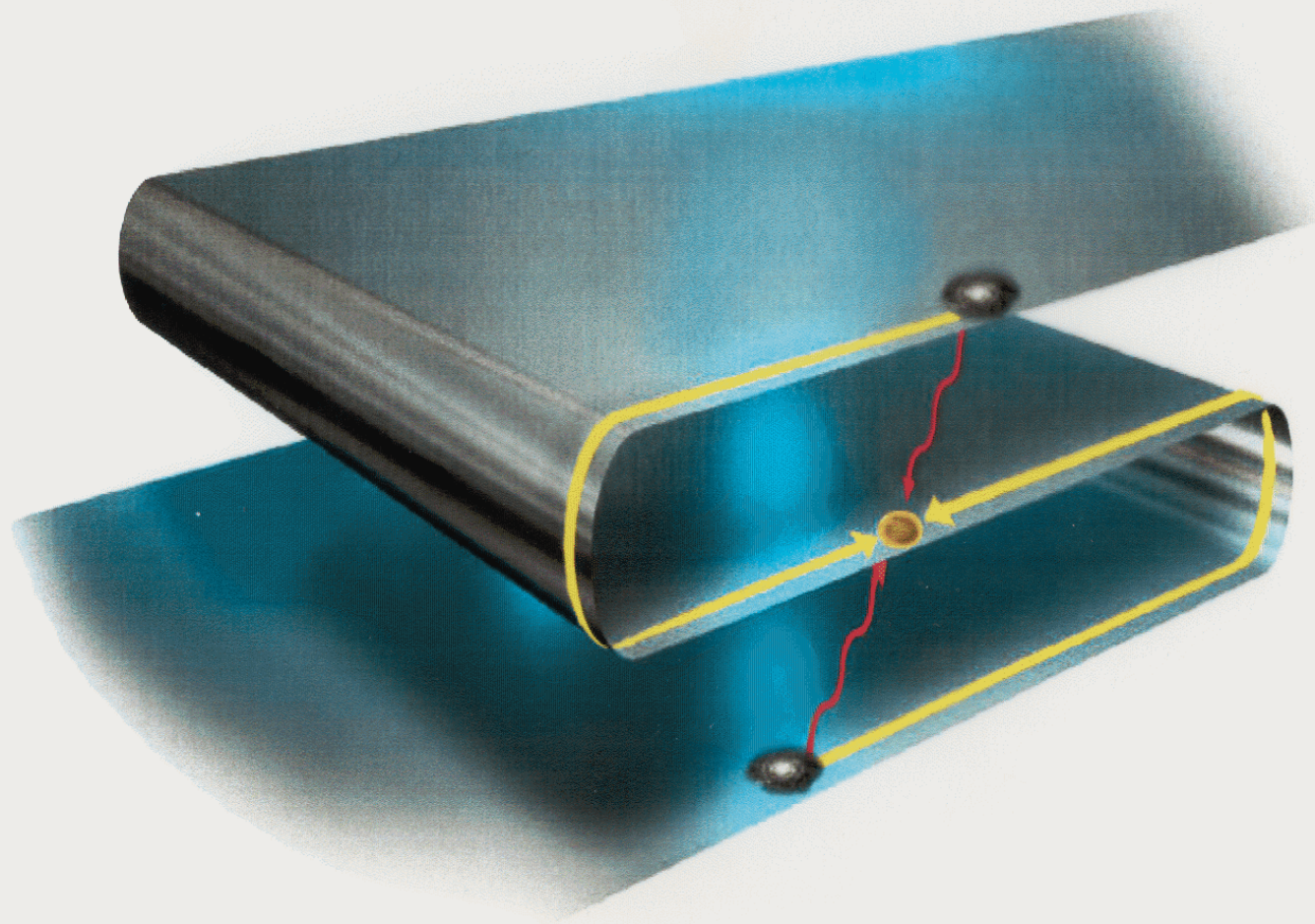
If the ideas presented in this talk have anything to do with nature, LHC has an exceptional chance of experimentally discovering and studying the nature of quantum gravity.



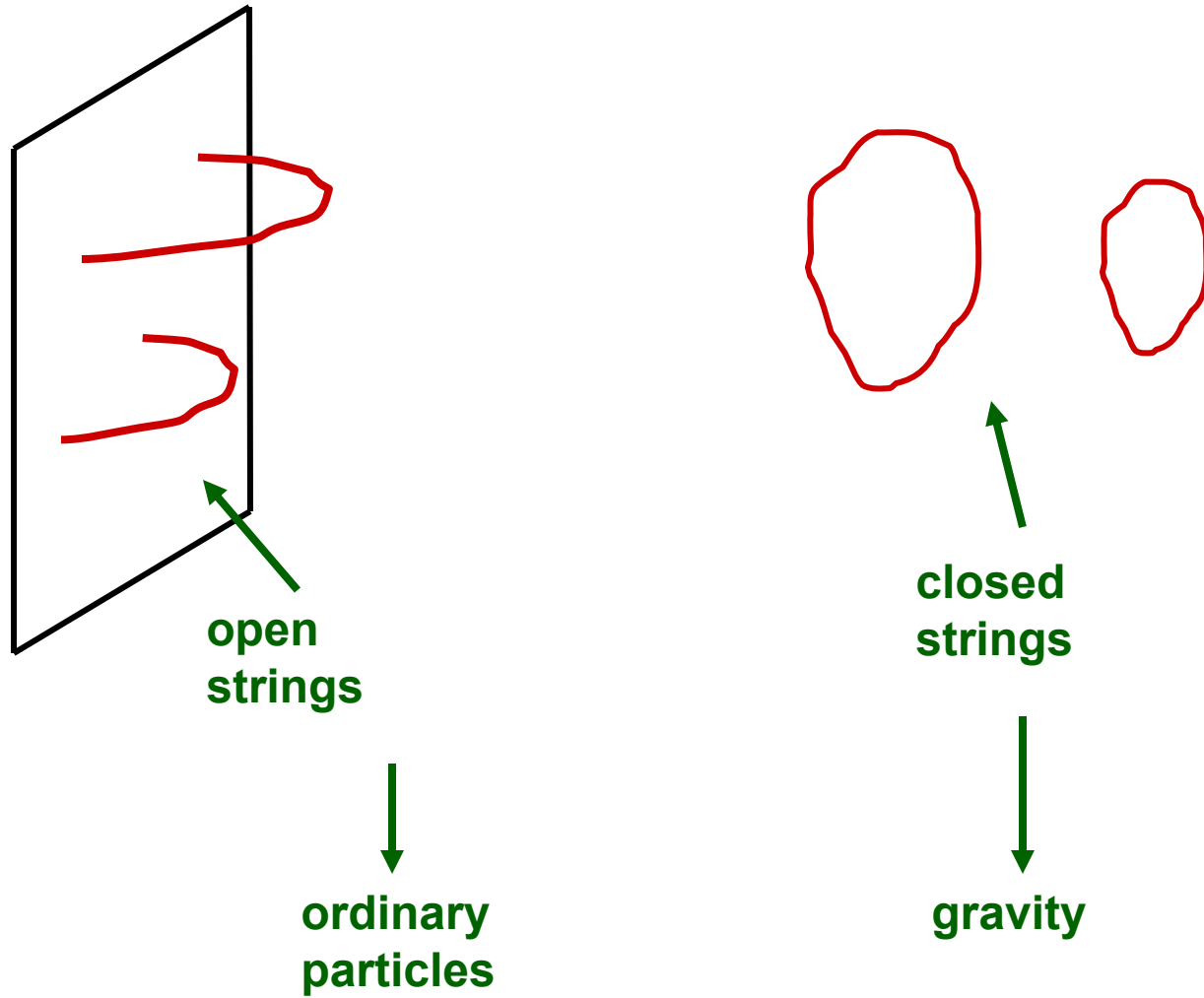


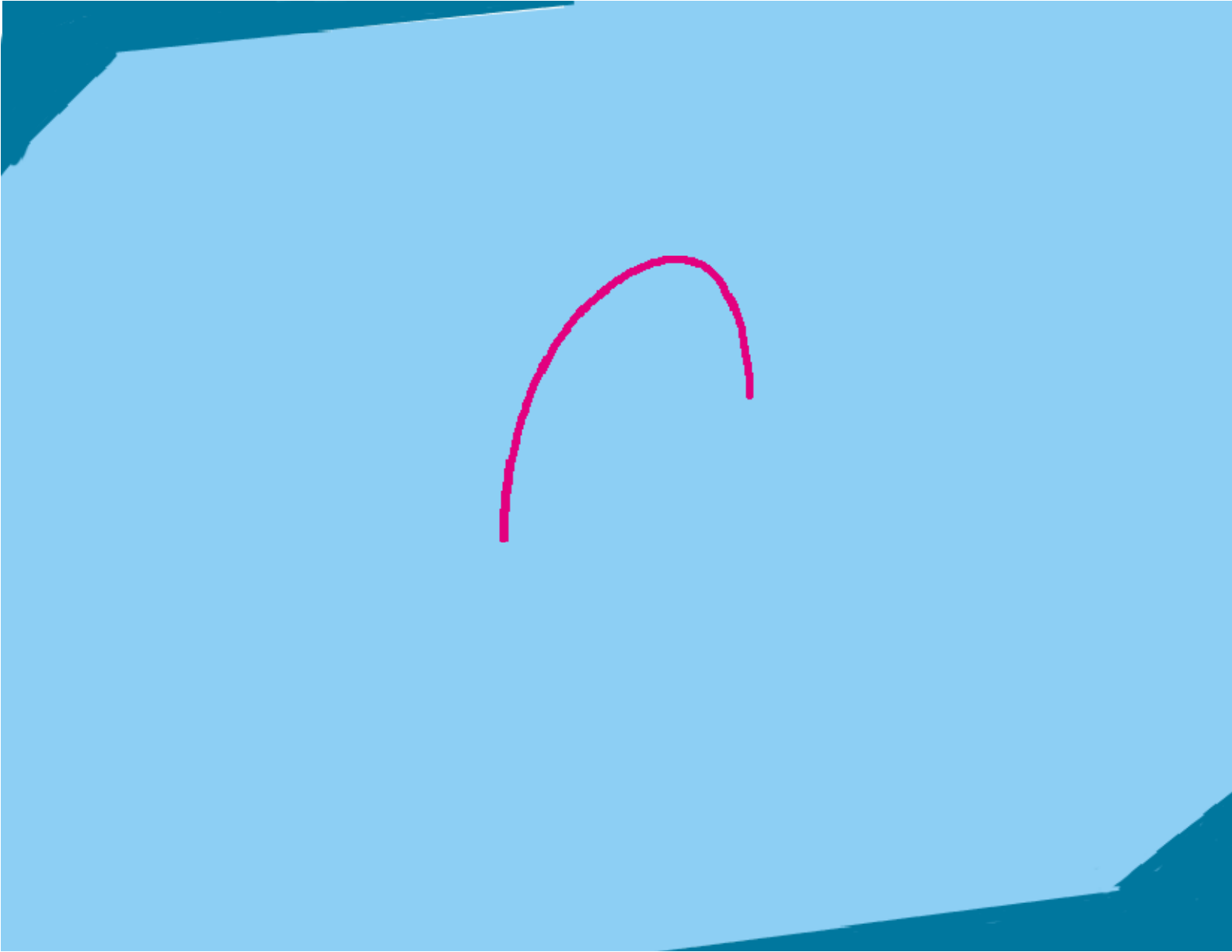


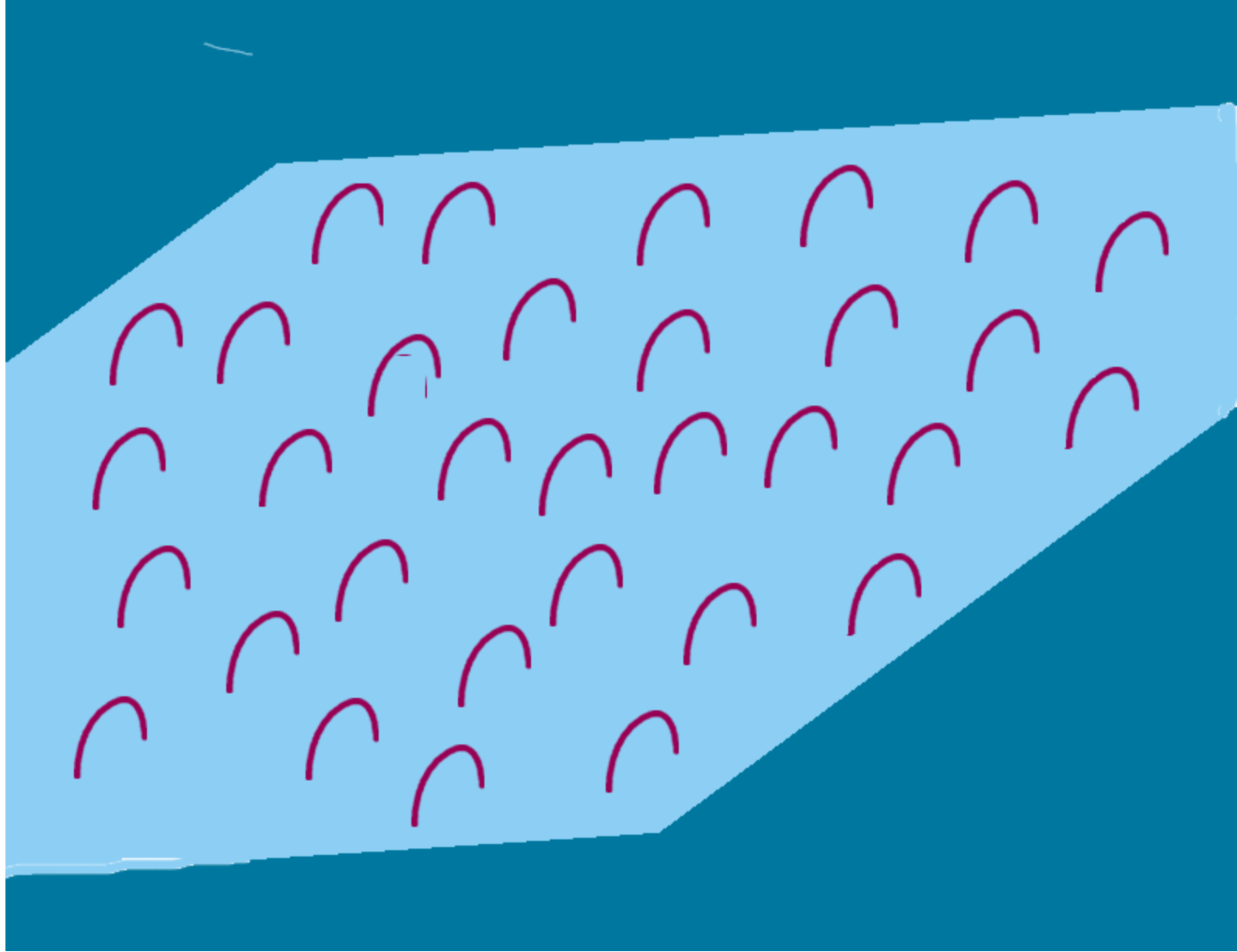
Gravitational shortcut

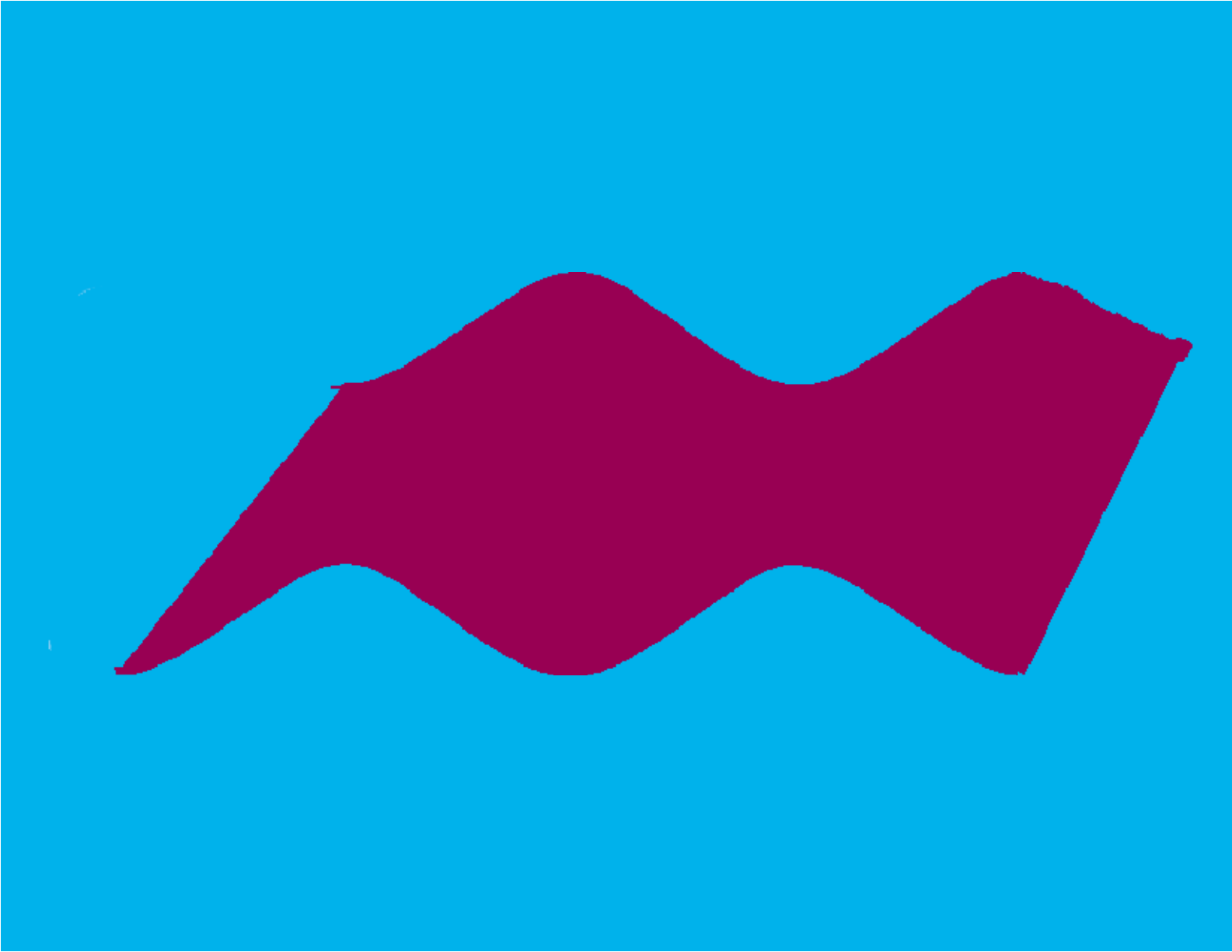


STRING THEORY PICTURE









THE SMALL BLACK HOLES CARRY
HAIR!

BH PRODUCED IN COLLISION OF OUR
STANDARD MODEL PARTICLES
AT ENERGY $\sim \Lambda$,

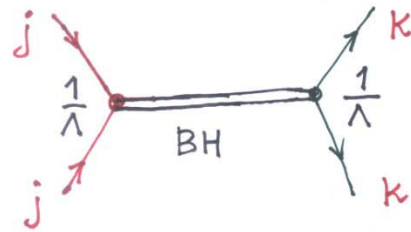
WILL DECAY WITH THE RATE

$$\Gamma_{\text{BH} \rightarrow \text{SM}} \sim \Lambda$$

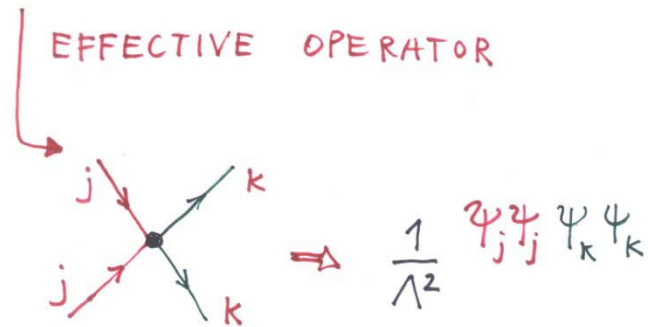
BACK INTO THE STANDARD MODEL
SPECIES, AND ONLY WITH VERY
SUPPRESSED RATE INTO THE
OTHER INDIVIDUAL COPIES

$$\Gamma_{\text{BH} \rightarrow \text{OTHERS}} \sim \frac{\Lambda^5}{M_{\text{Pl}}^4}$$

INDEED, IF SMALL BLACK HOLES
COULD DECAY DEMOCRATICALLY,
WE WOULD RUN INTO A FIELD-THEORETIC
CONTRADICTION.



EFFECTIVE OPERATOR



RATE OF TRANSITION:

$$\sum_K \Gamma_{j \rightarrow k} \sim \frac{E^5}{\Lambda^4} N \sim \frac{E^5 M_P^2}{\Lambda^6}$$

WOULD BLOW UP AT:

$$E_* \sim \Lambda \sqrt{\frac{\Lambda}{M_P}} \ll \Lambda !$$

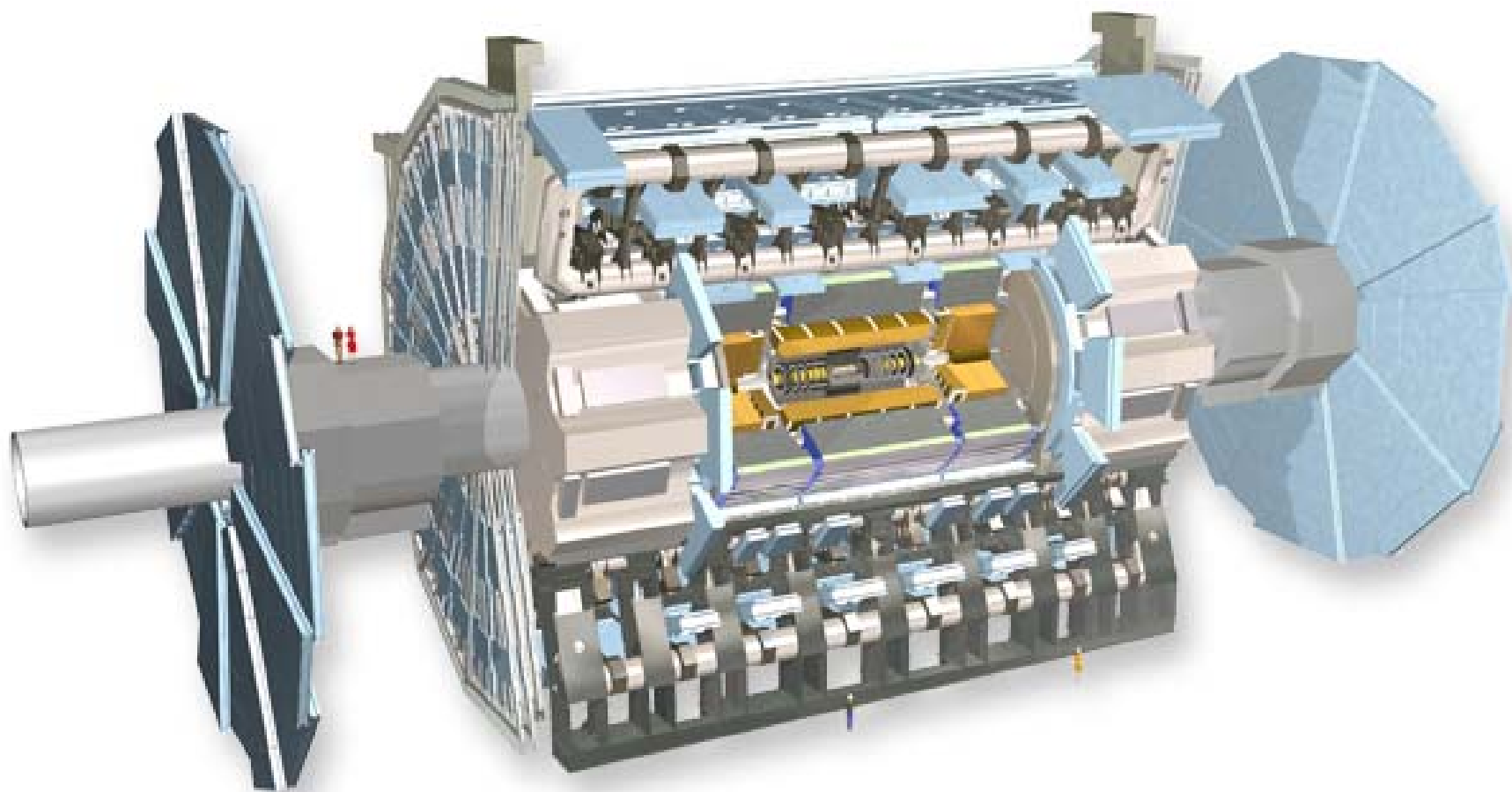
RENORMALIZATION OF SM KINETIC
TERMS WOULD BE HUGE:

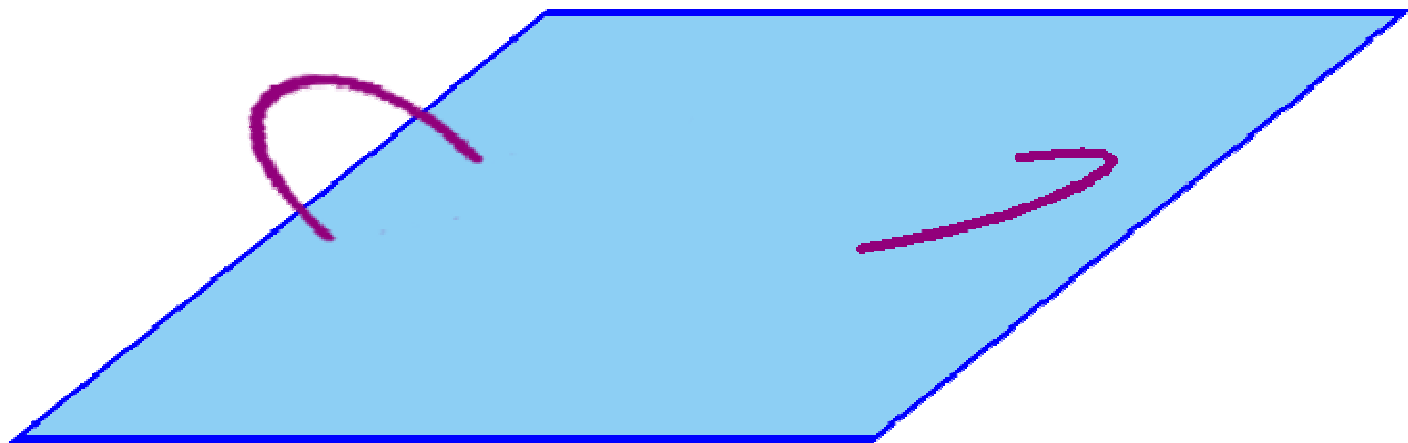
$$\sum_k \text{ (loop diagram) } \Rightarrow \left(\frac{M_P}{\Lambda} \right)^2 \bar{\psi}_j \not{\partial} \psi_j$$

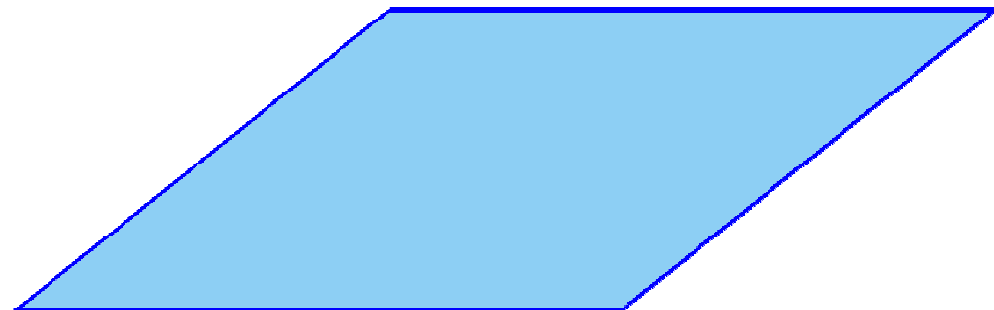
The diagram shows a summation over k of a loop diagram. The loop is a circle with two external lines labeled j . The loop momentum is k . The diagram is equated to a term proportional to $\left(\frac{M_P}{\Lambda} \right)^2 \bar{\psi}_j \not{\partial} \psi_j$.

SM PARTICLES WOULD BE
EXTREMELY WEAKLY COUPLED!









Missing energy signals, see, e.g., Vacavant, Hinchliffe.

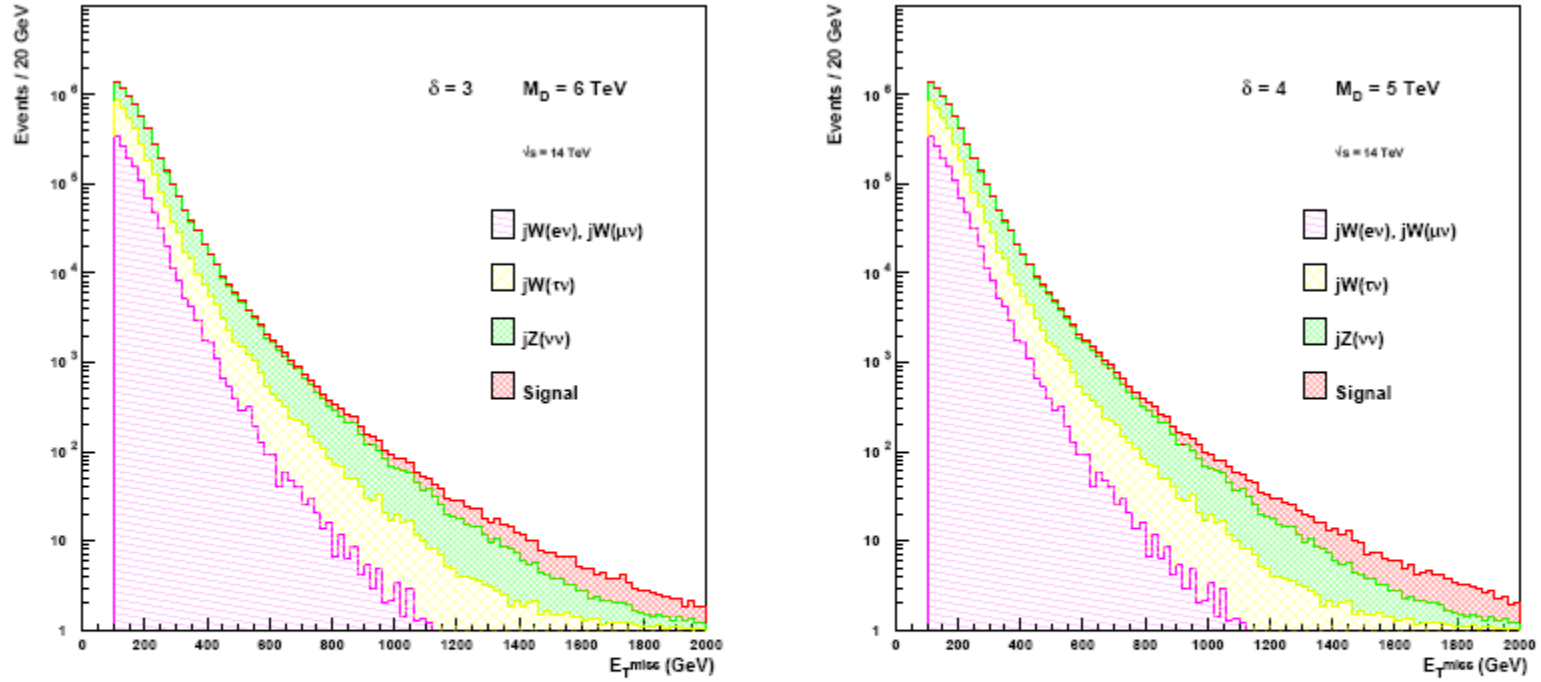


Figure 11: Distributions of the missing transverse energy in signal and in background events after the selection and for 100 fb^{-1} of integrated luminosity. Various cases (δ, M_D) for the signal are shown.