Where is Susy?

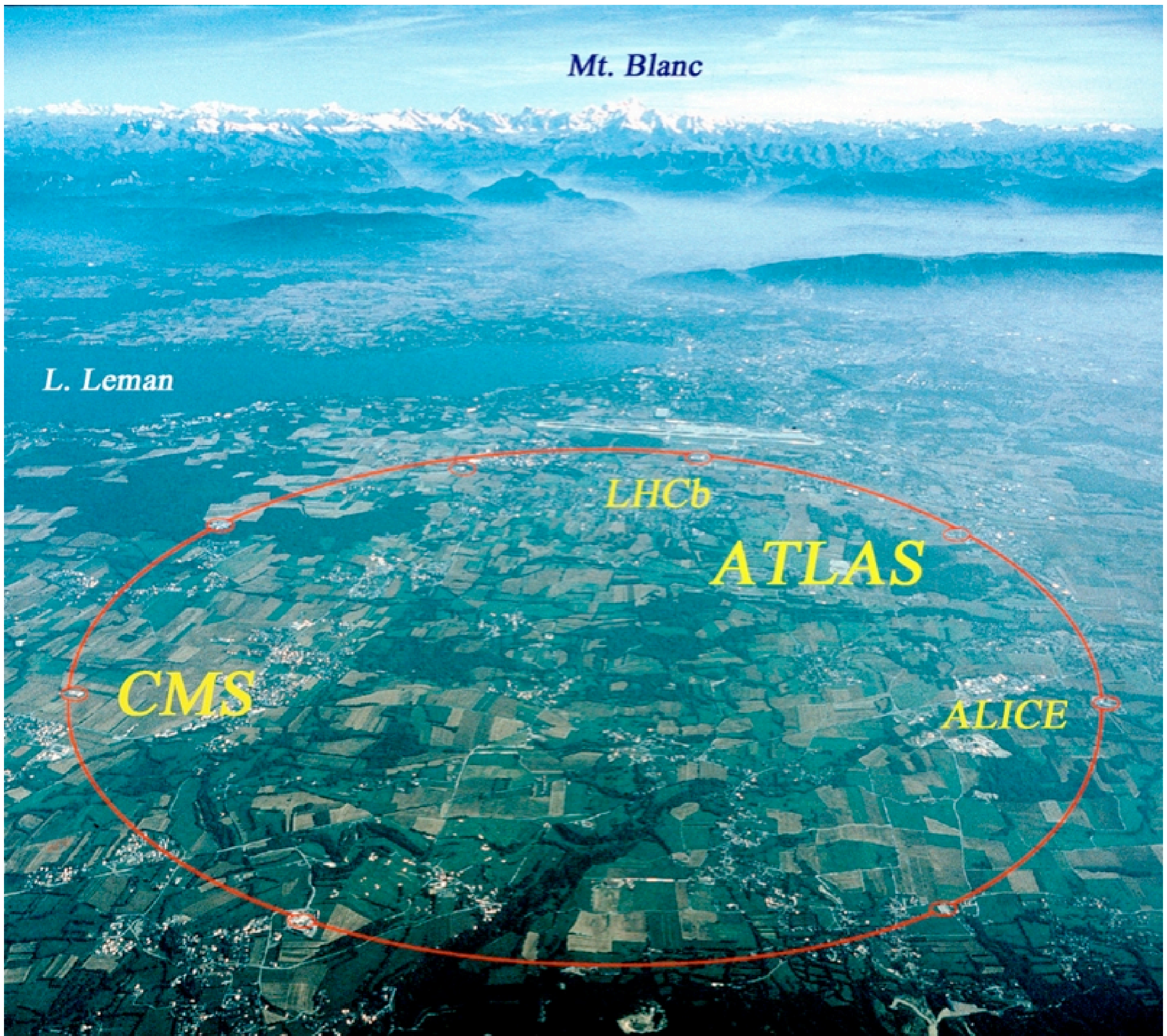
Savas Dimopoulos
Stanford University

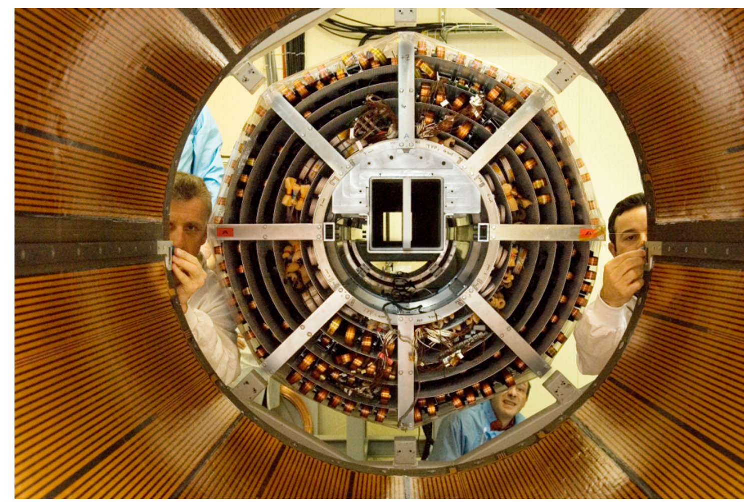
October 16, 2006

SUGRA 30

Large Hadron Collider

Coming Soon in 2008





February 22, 2006:
ATLAS inner tracker

Large Hadron Collider

Will push the

Energy Frontier 2 TeV $\longrightarrow$ 14 TeV

Luminosity Frontier 2 fb^{-1}/yr $\longrightarrow$ 30 fb^{-1}/yr

Will find the last piece of the Standard Model,
the Brout, Englert, Higgs particle

May find weak-scale SUSY

Adventures in Model Building

70's	Early Developments
80's	Soft Susy Breaking and Unification
90's	LEP Rollercoaster
00's	Questioning Naturalness

Omissions

Because of space-time limitations I had to leave out many important topics. More complete coverage and references in:

"Soft Supersymmetry and the Supersymmetric Standard Model"
Presented at 30 Years of Supersymmetry
Minneapolis, Minnesota, October 2000
Nucl.Phys.Proc.Suppl.101, 183-194, 2001
hep-th/0105034

"Supersymmetric Unification"
Presented at the conference on the history of original ideas and basic discoveries in particle physics, Erice, July 1994.
Plenum: London. NATO Asi series B, Physics, vol 352, 1996
hep-ph/9412297

70's

Mathematical Breakthroughs

1974 Supersymmetry Wess and Zumino

1976 Supergravity Ferrara, Freedman and van Nieuwenhuizen
Deser and Zumino

lots more ...

particle ⟷ sparticle

Model Building Insights

Fayet 1975 -1978

Features

2 Higgs Doublets

~Massless LSP Gravitino $m_{\frac{3}{2}} \sim 10^{-5}$ eV

Unbroken R-symmetry⇒ ~Massless Gluinos: $m_{\frac{1}{2}} \cong 0$

R-Hadrons at a GeV

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Obstacles

Color & Charge broken $m^2_{\text{scalar}} < 0$

$m_{\text{photon}} \sim m_{\text{scalar}}$

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Supertrace Theorem S. Ferrara, L. Girardello, F. Palumbo 1979

m^2_{fermion} $m^2_{\text{scalar}\,+}$ $m^2_{\text{scalar}\,-}$

Model Building Insights

Fayet 1975 -1978

Features

2 Higgs Doublets

~Massless LSP Gravitino $m_{\frac{3}{2}} \sim 10^{-5}$ eV

Unbroken R-symmetry⇒ ~Massless Gluinos: $m_{\frac{1}{2}} \simeq 0$

R-Hadrons at a GeV

Obstacles

Color & Charge broken $m^2_{\rm scalar} < 0$

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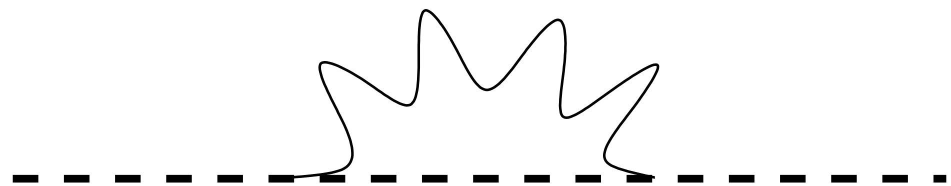
Tree Level Theorem

$m^2_{\rm fermion}$ $m^2_{\rm scalar\ +}$ $m^2_{\rm scalar\ -}$

1981: Hierarchy Problem comes to the rescue!



$$\delta m^2_{\text{scalar}} = \alpha M^2$$

Radiative corrections are large,

can make masses positive

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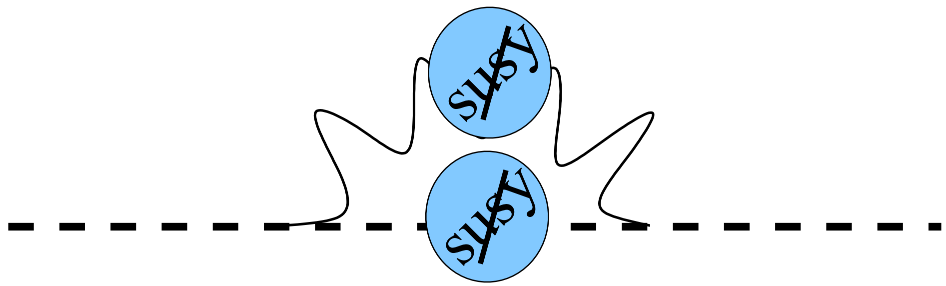

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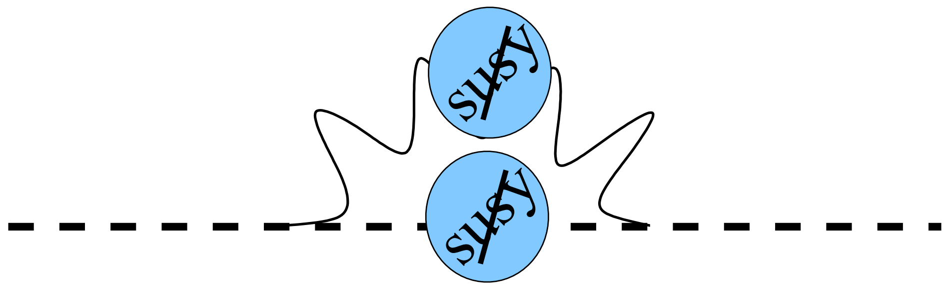

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can make masses positive

Lesson: If the susy particles only feel susy breaking at loop level, no charge or color breaking

Most Importantly:

The hierarchy problem fixes the Sparticle masses to 100 GeV !

80's

Soft Terms

S. D., Georgi (81)
Girardello, Grisaru (82)

parametrize susy breaking

just as quark masses parametrize chiral breaking

Do accessible physics without knowing inaccessible short-distance details

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Mediated Susy Breaking

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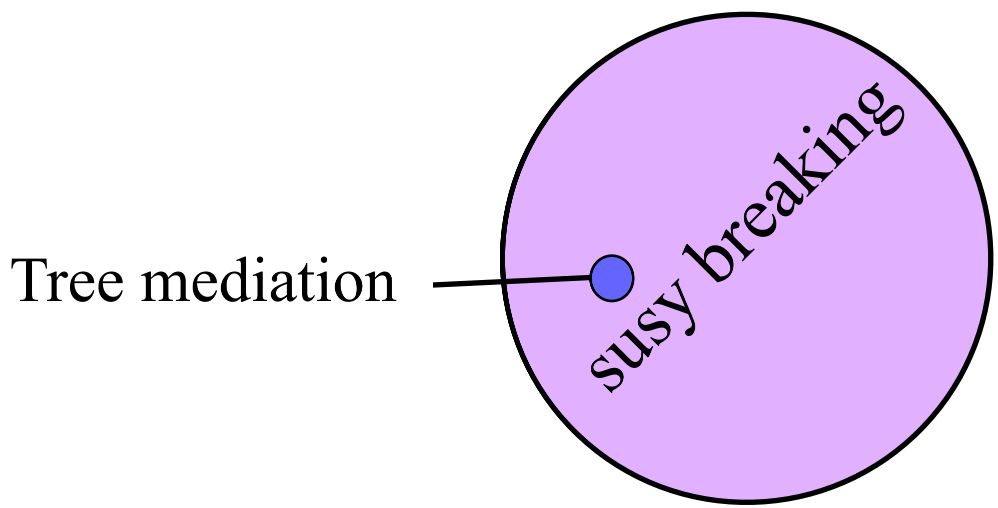

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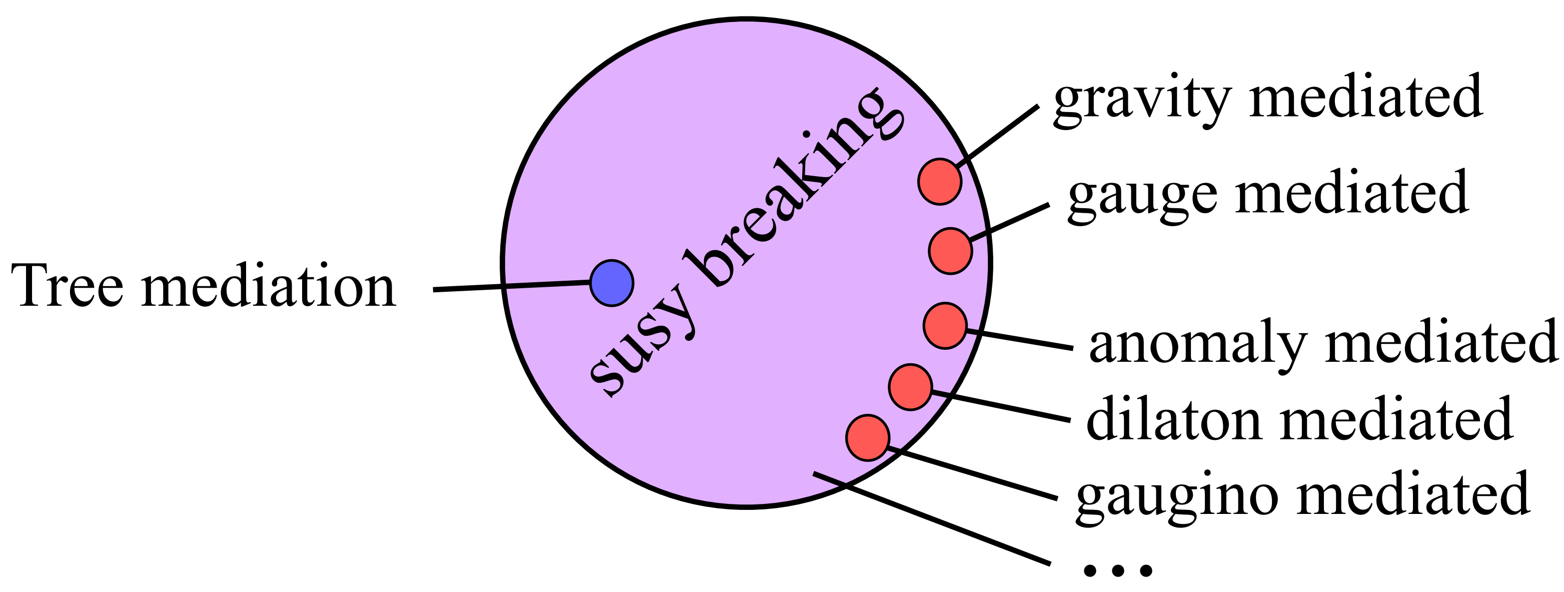

Why first focus on general soft terms?

1) To make model-independent predictions.

Insensitive to the UV details of the SUSY breaking theory.
Approximate flavor conservation already suggested the universality and proportionality of the soft terms.

2) The cosmological constant problem.

It raises doubts on the predictions of any *specific* SUSY breaking mechanism that fails to address it.
It favors a *general* approach that can adapt to the correct SUSY breaking mechanism that will address it.

Supersymmetric Standard Model (S.D., Georgi 1981)

Pillars:

1) Softly broken SUSY at a TeV

2) Unification

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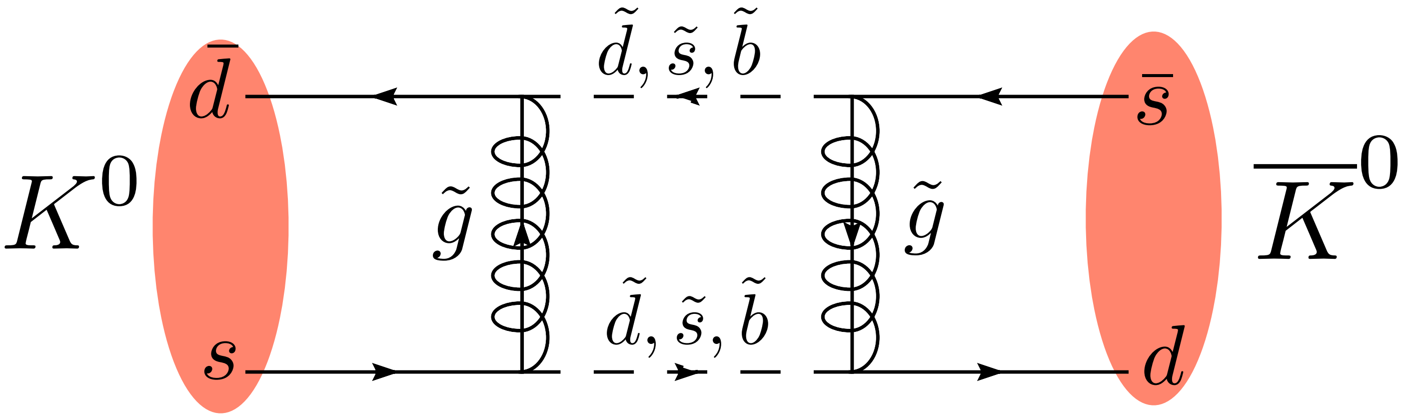
Stable 100 GeV LSP

Soft SUSY Breaking

Universality of soft terms

Super Glashow-Iliopoulos-Maiani mechanism



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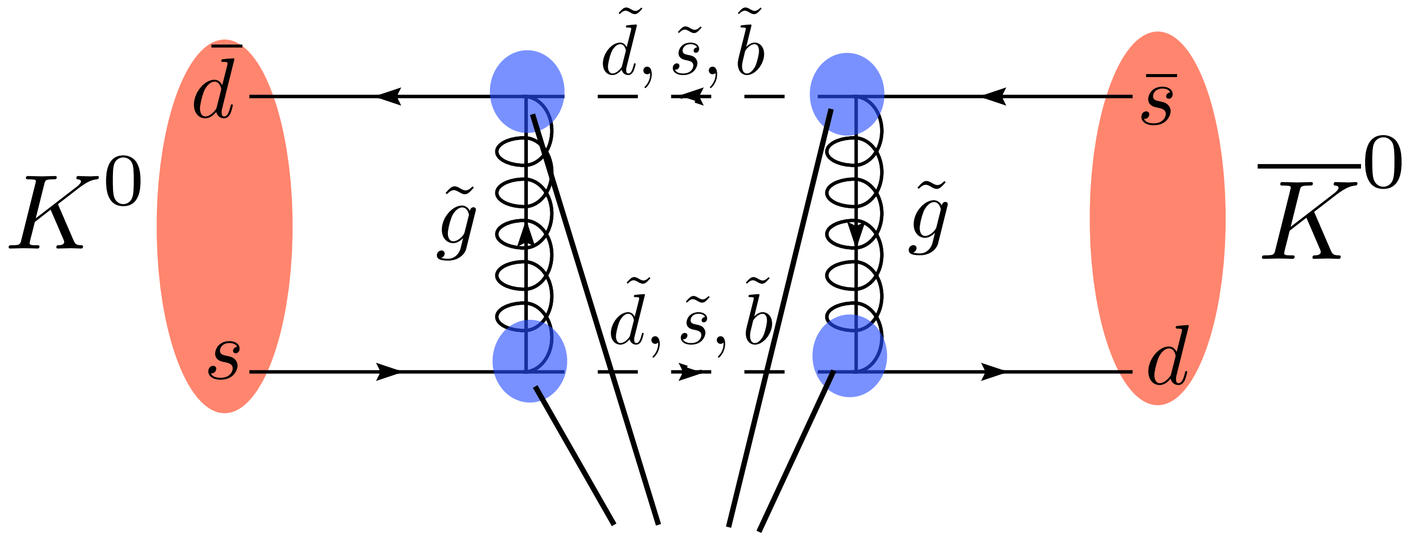

Need to be Flavor Universal Couplings

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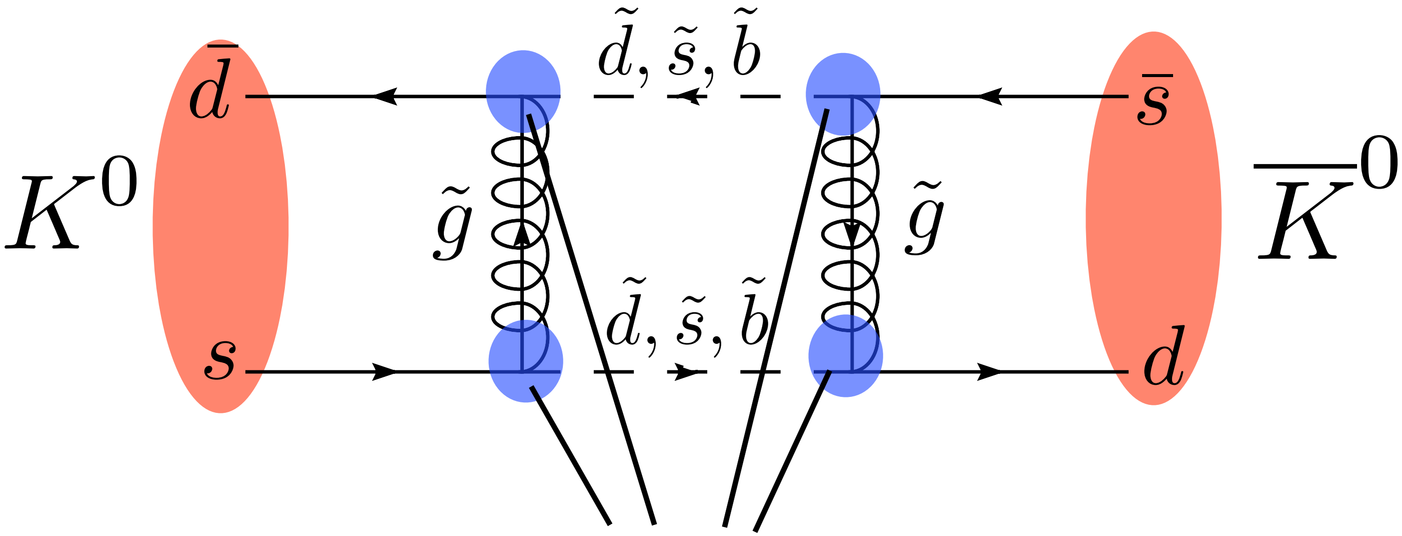

Need to be Flavor Universal Couplings

Scalar Masses $m_0^2 \propto \mathbb{1}$

Trilinear A-Terms $A \propto \mathbb{1}$

} No new directions in flavor space

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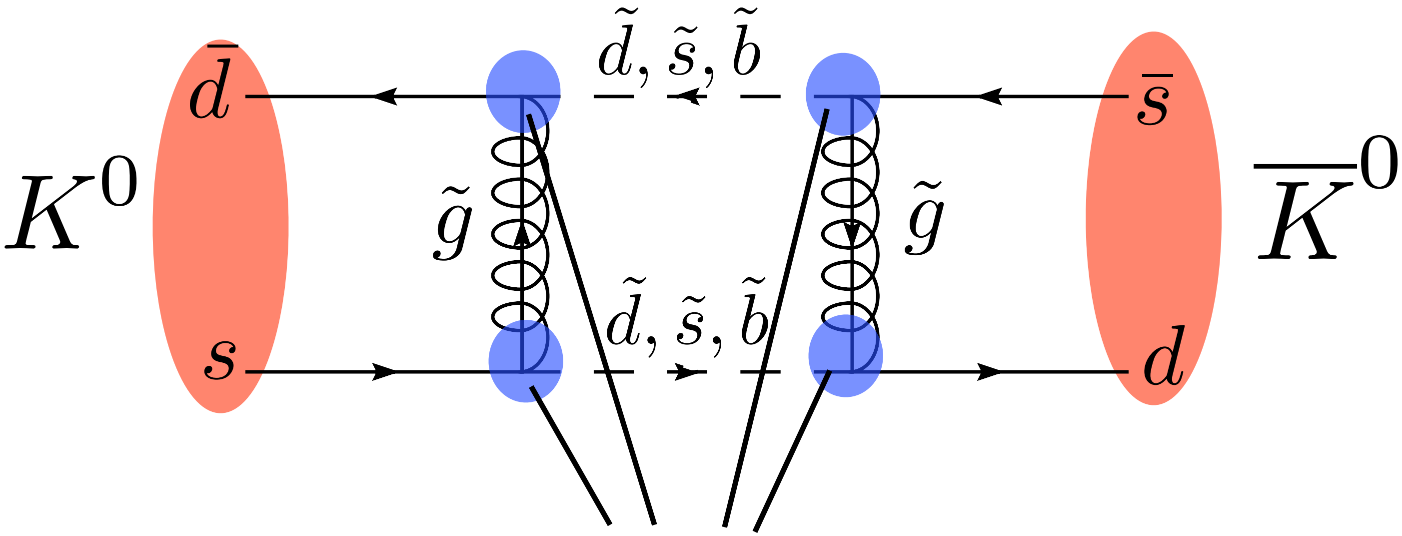

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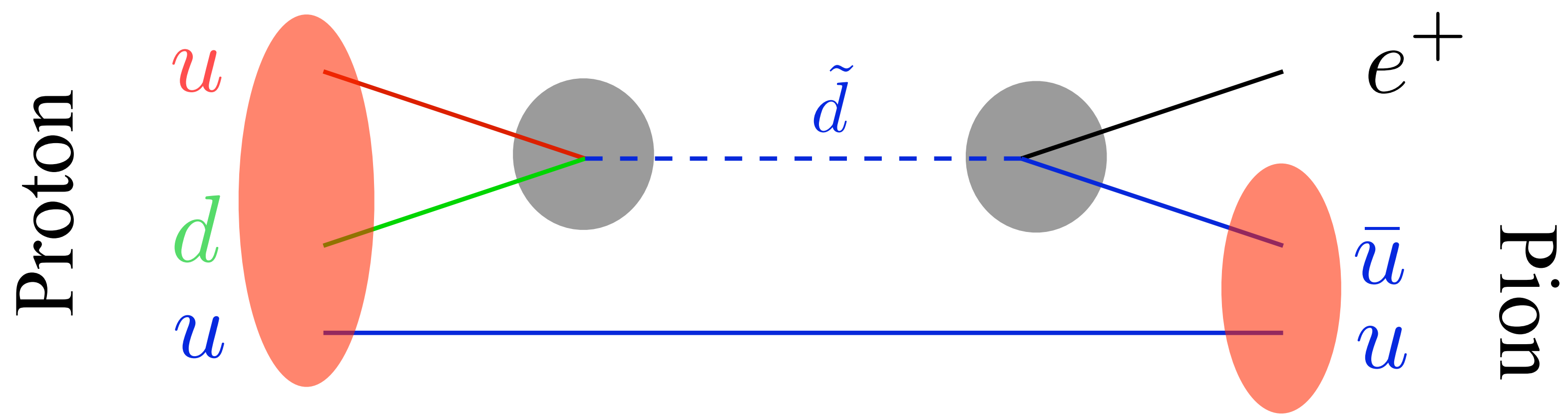
Approximate degeneracy of scalars

LHC: Lots of particles accessible!

Proton Stability

New particles ⇒

new ways to mediate proton decay



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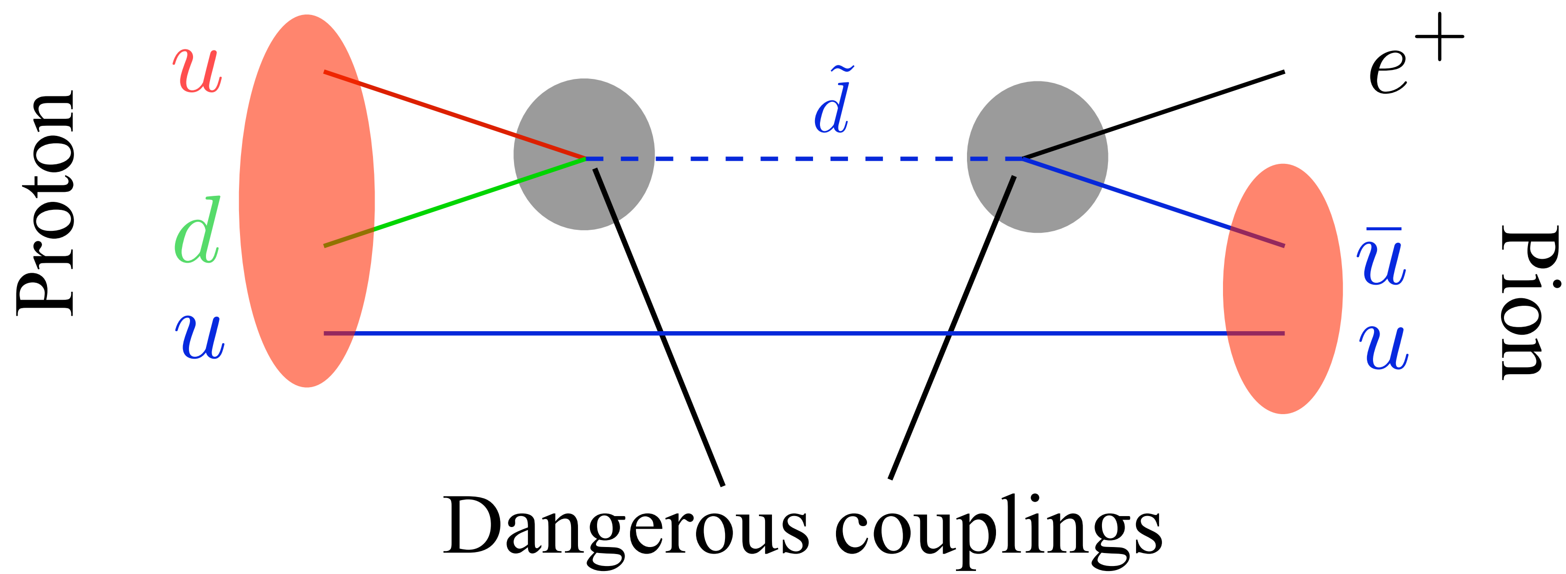

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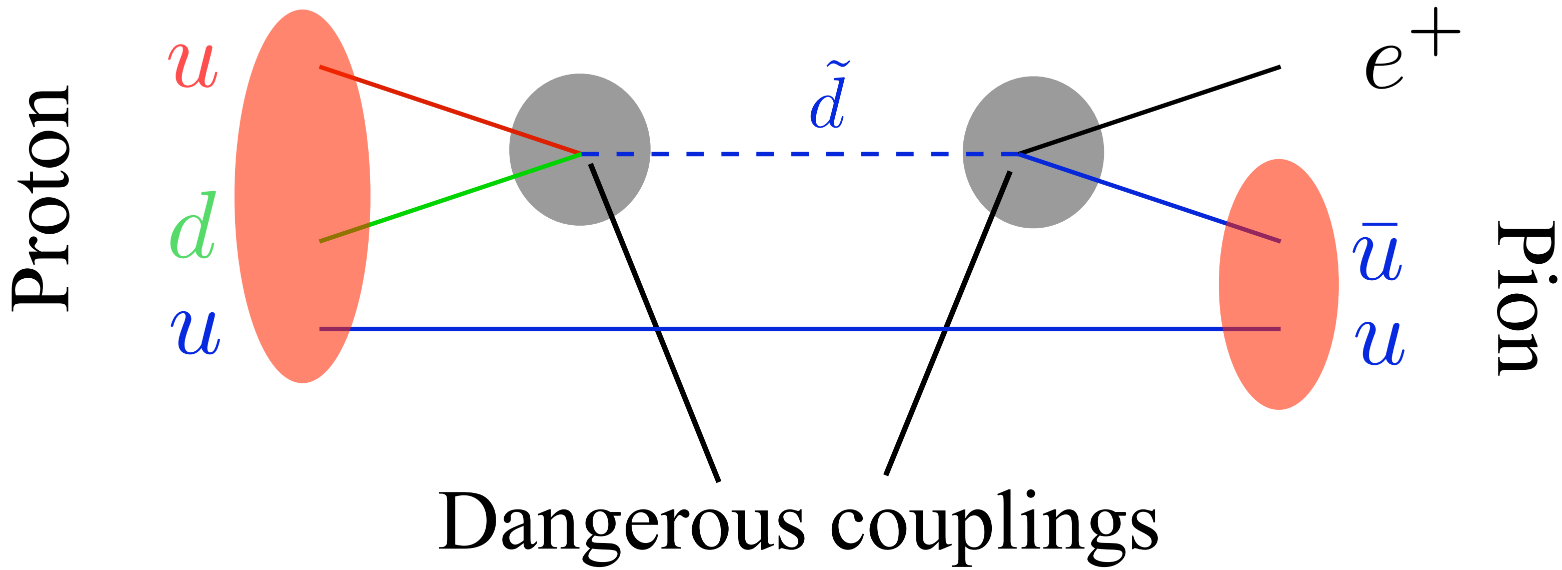

A new symmetry forbids these couplings: Family-parity

Proton Stability

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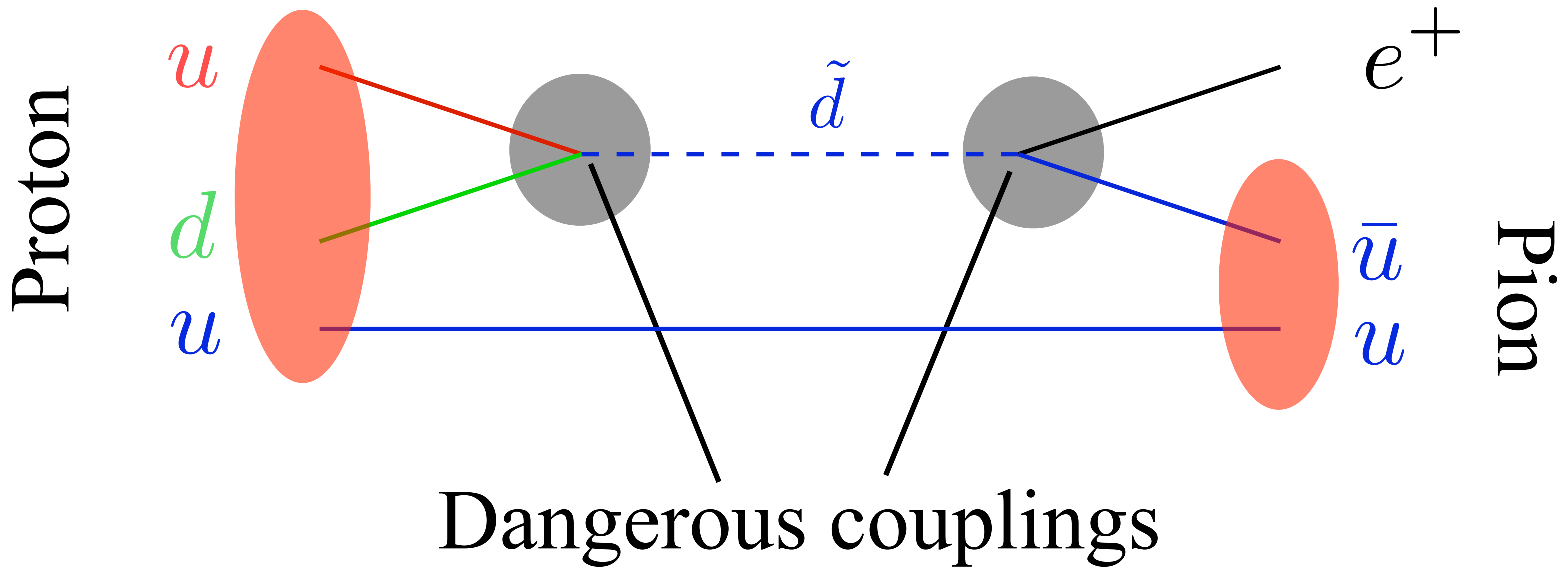

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Lightest Supersymmetric Particle is stable

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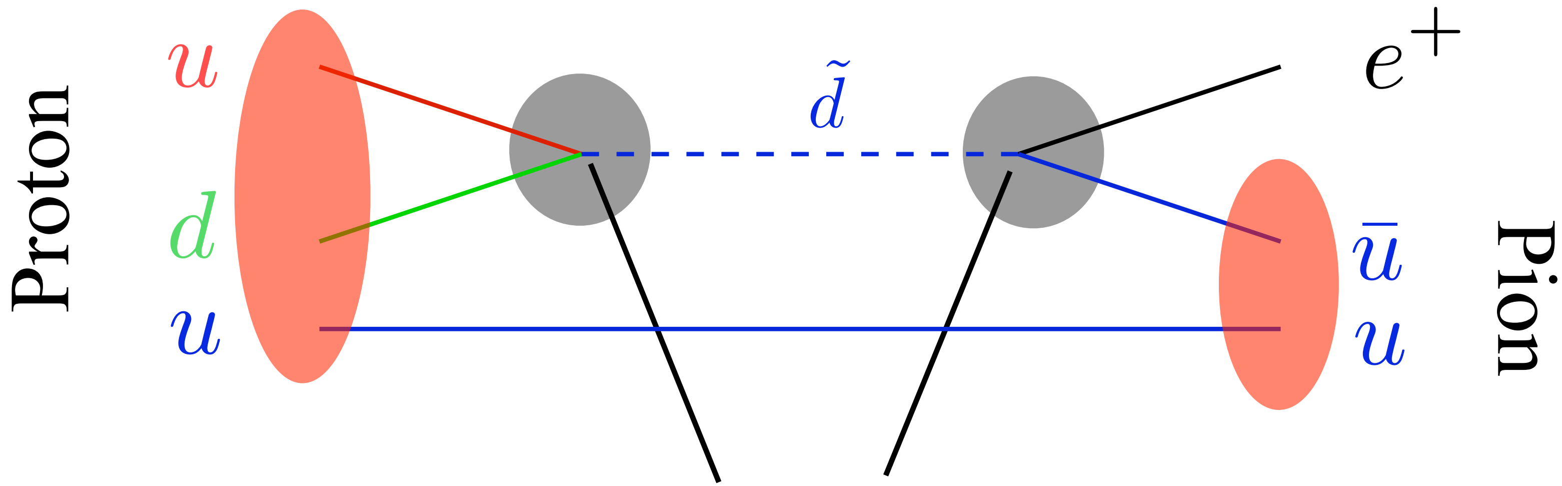


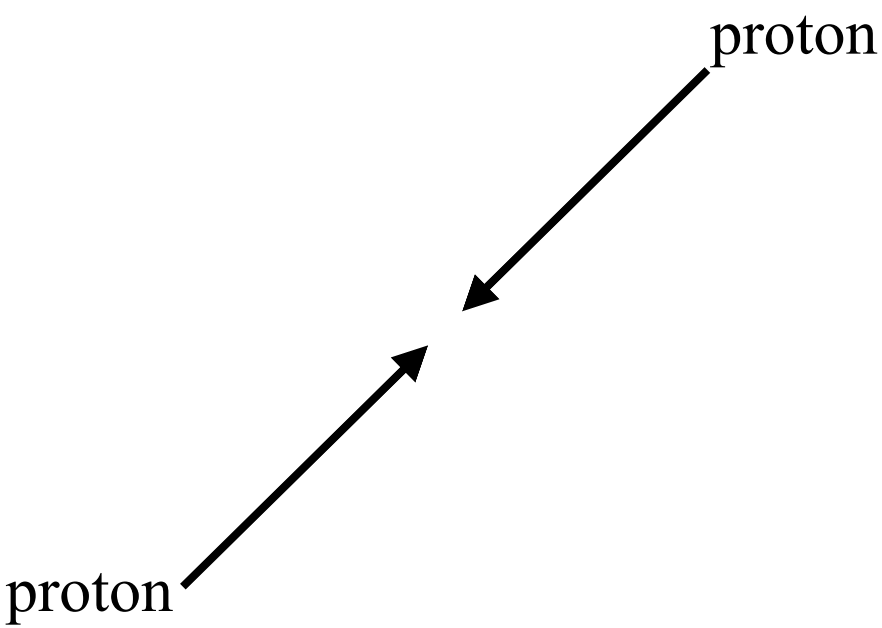
Dangerous couplings

A new symmetry forbids these couplings: Family-parity

Lightest Supersymmetric Particle is stable

If neutral and colorless -- Dark Matter

Dark Matter at the LHC



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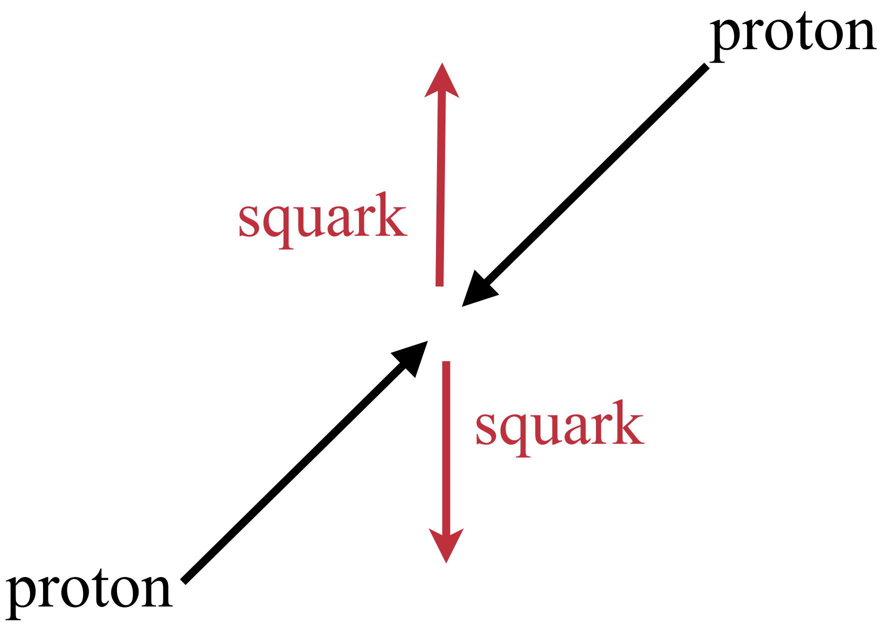

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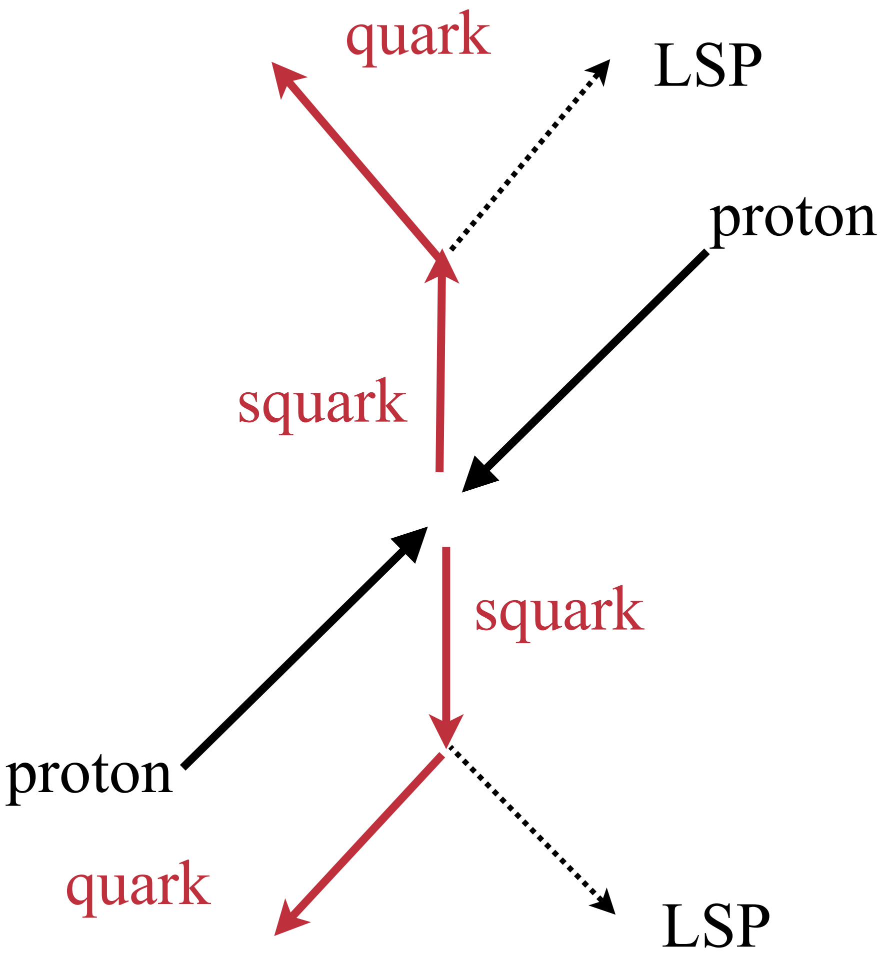

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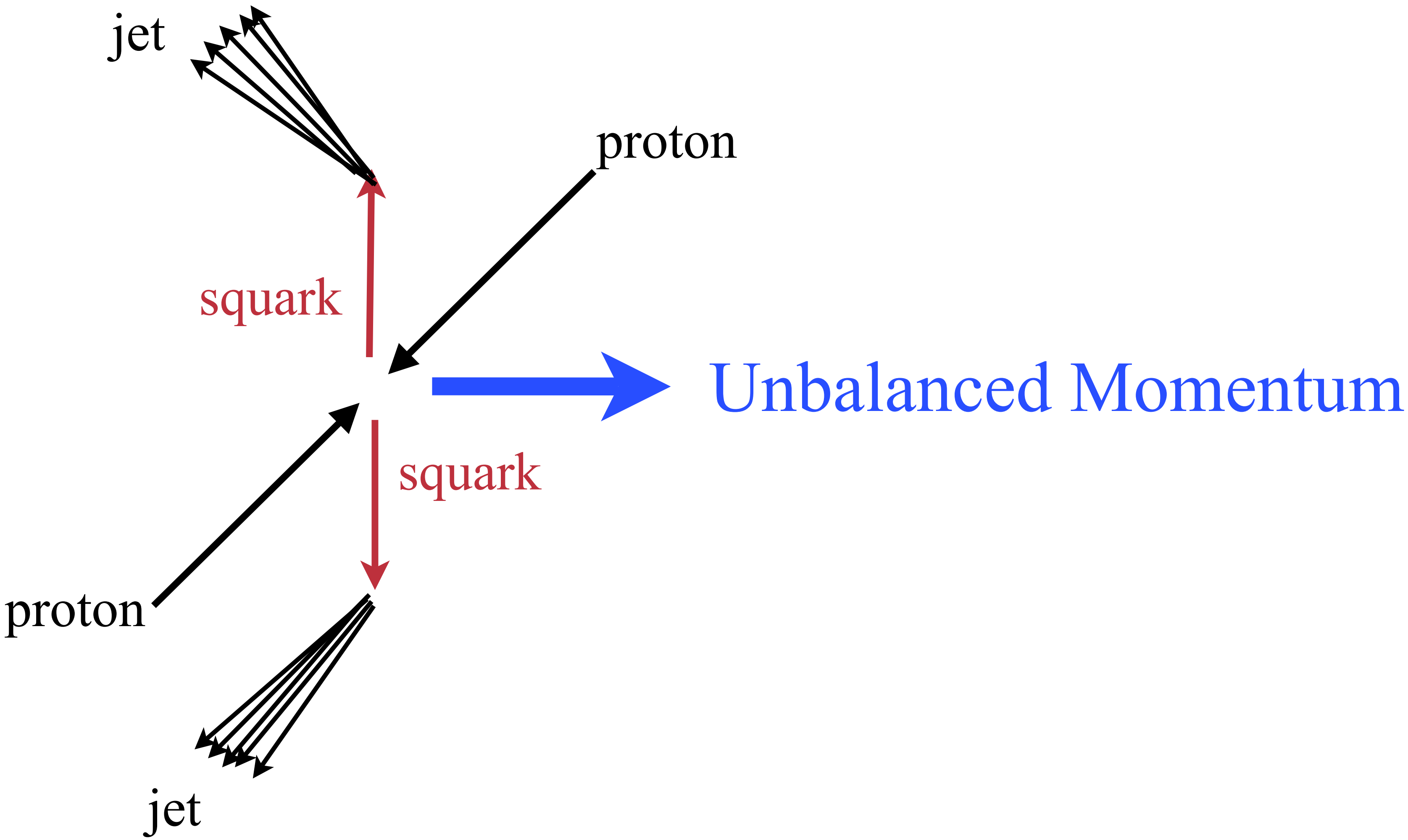
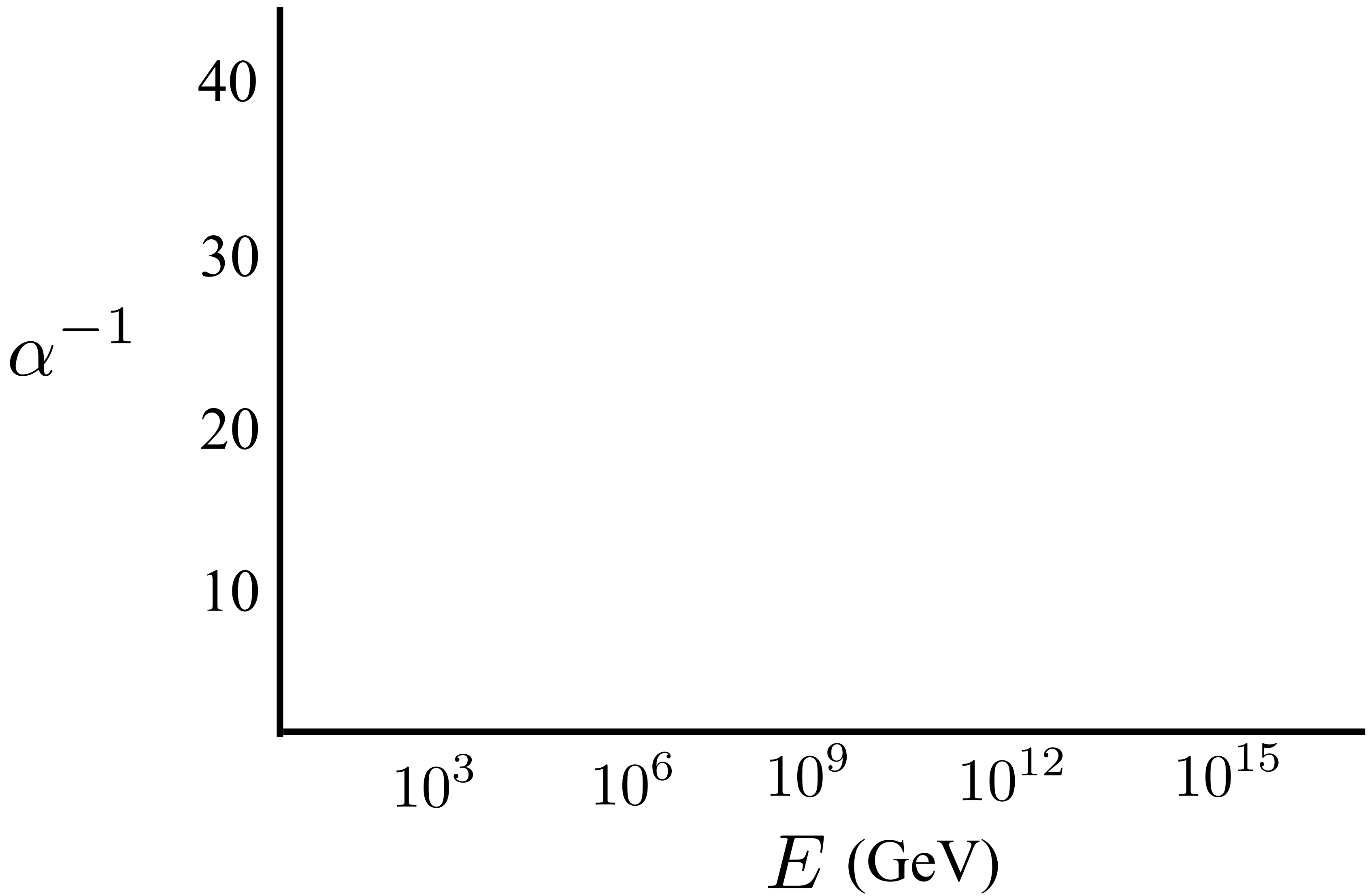


Smoking gun "Missing Energy" signatures at LHC

Gauge Coupling Unification



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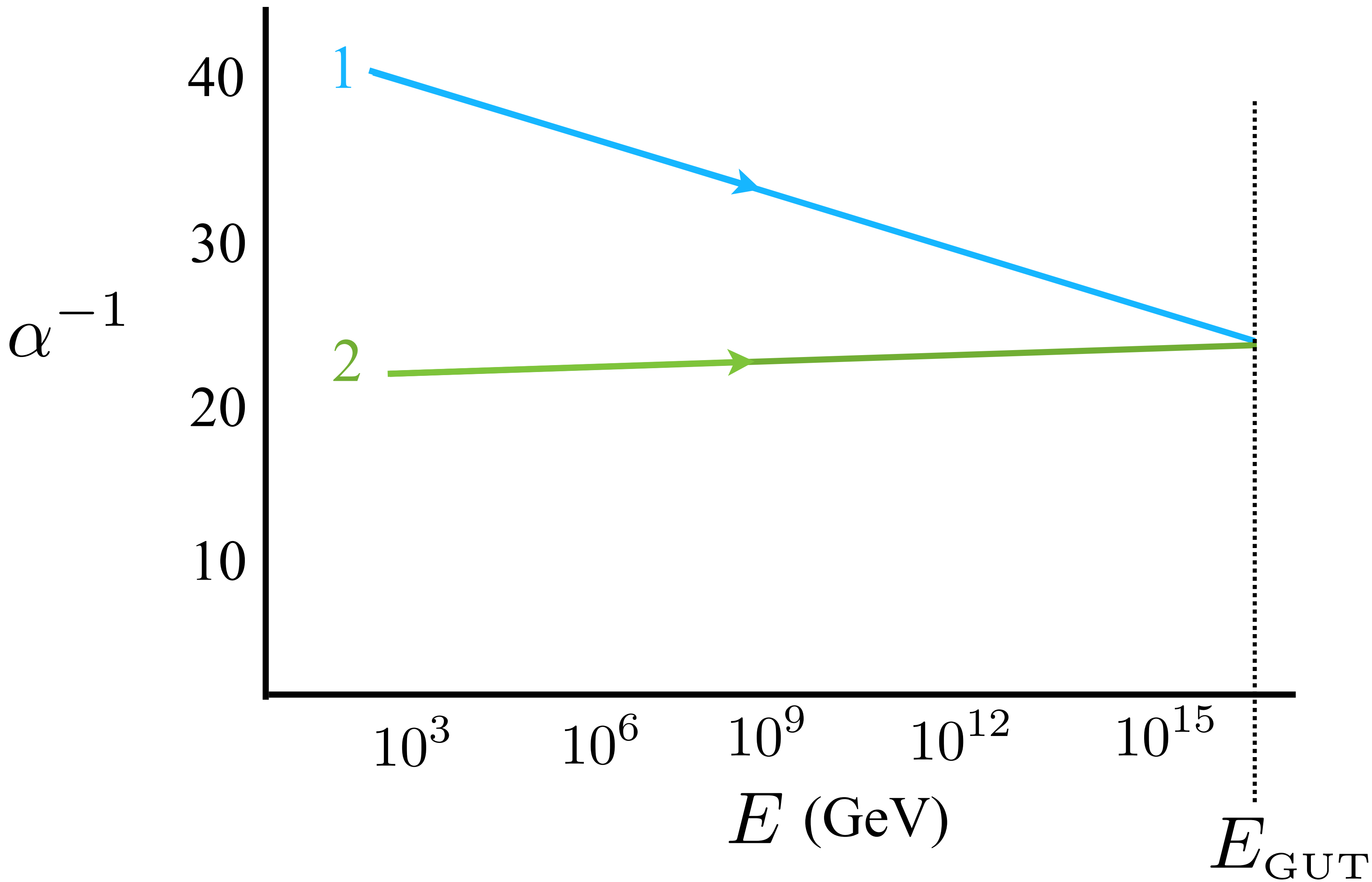

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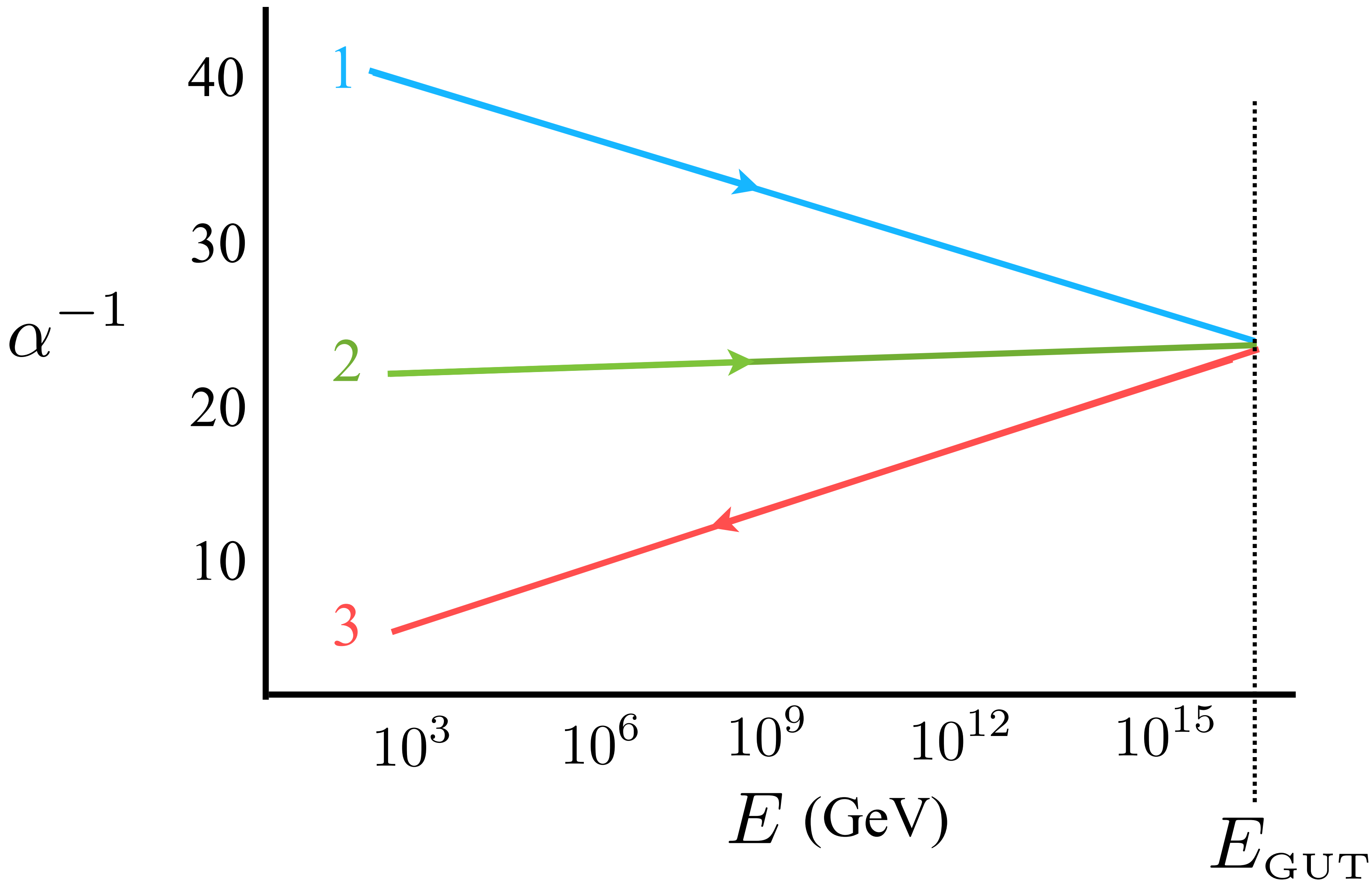

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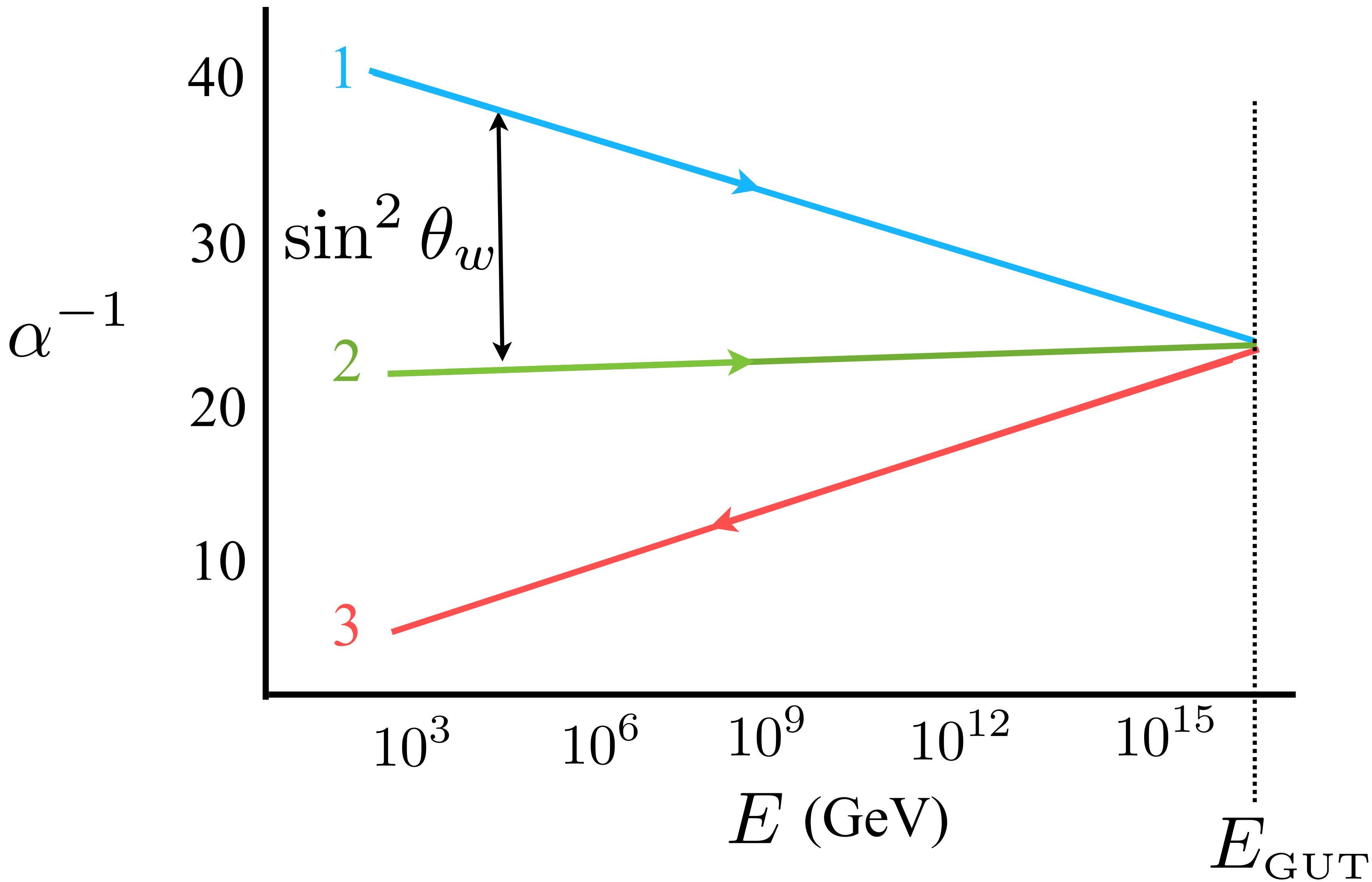

Unification scale goes up

S. D., Raby, Wilczek (81)

E_{GUT} $\quad 10^{14}\ \mathrm{GeV} \longrightarrow 10^{16}\ \mathrm{GeV}$

No dim-6 Proton decay

$$p \rightarrow \pi^0 e^+$$
$$p \rightarrow \pi^+ \nu$$

$$\tau_p \sim 10^{36}\ \mathrm{yr}$$

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Proton decay candidates in 1981!

$$p \to \pi^0 e^+ \qquad \tau_p \sim 10^{31}\ \mathrm{yr}$$

Kolar gold field, Homestake mine, Witwatersrand

Disproved MSSM!

Unification scale goes up

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dim 5 proton decay operators

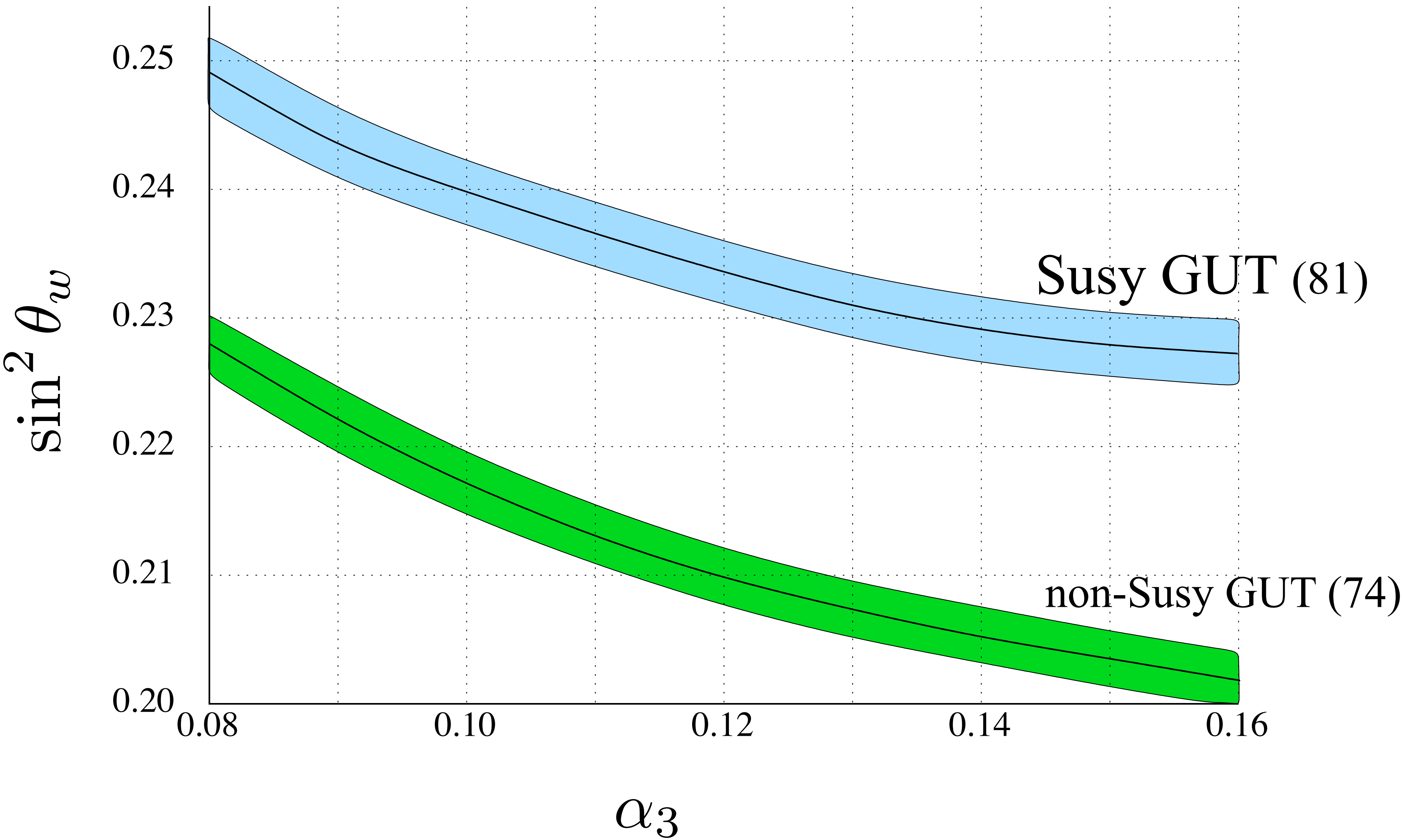
S.Weinberg; Sakai, Yanagida (1981)

flavor suppression

$p \to K^+ \nu$ $\tau_p \sim 10^{34}$ yr

S. D., Raby, Wilczek (81)
Ellis, Nanopoulos, Rudaz (81)

Unification



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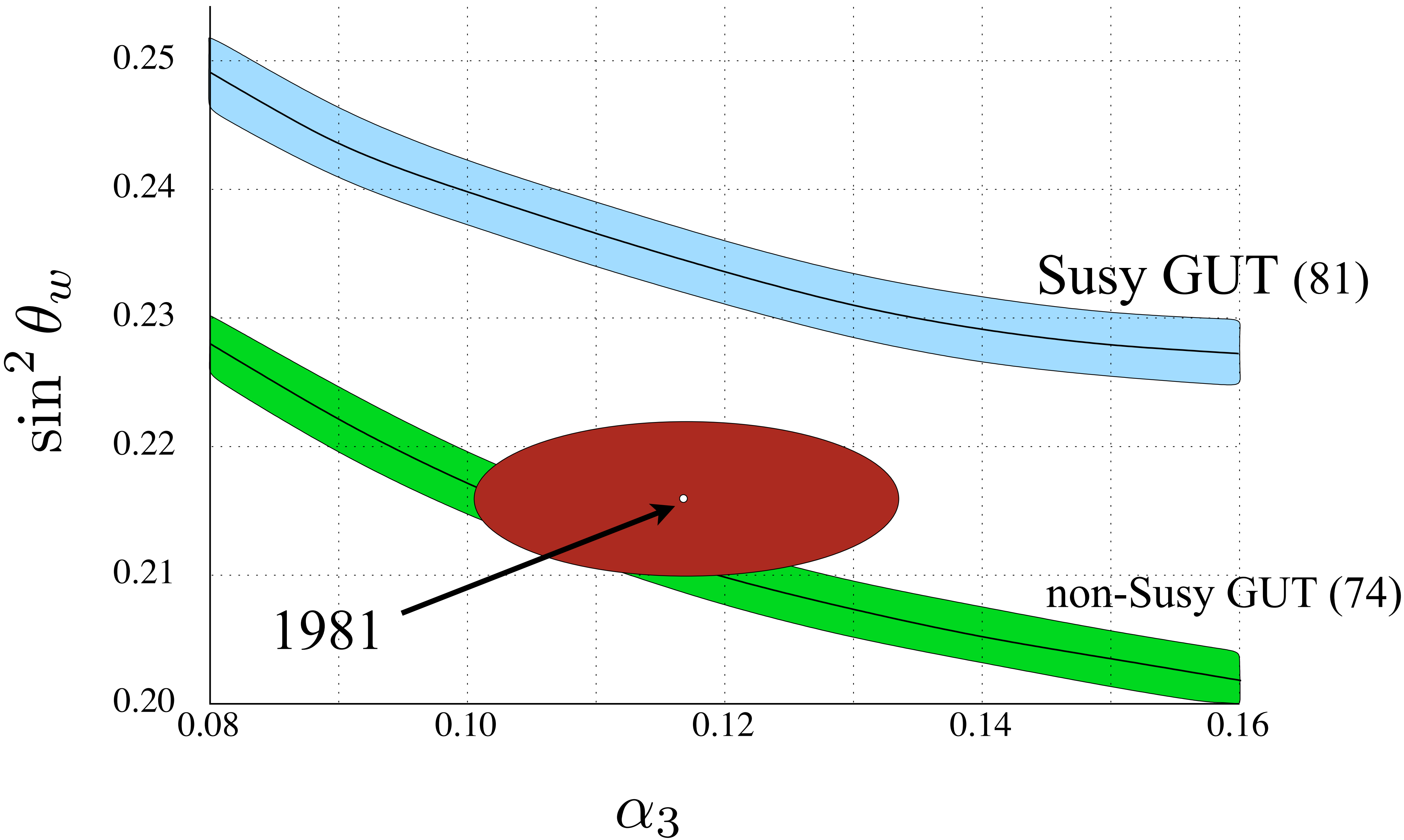

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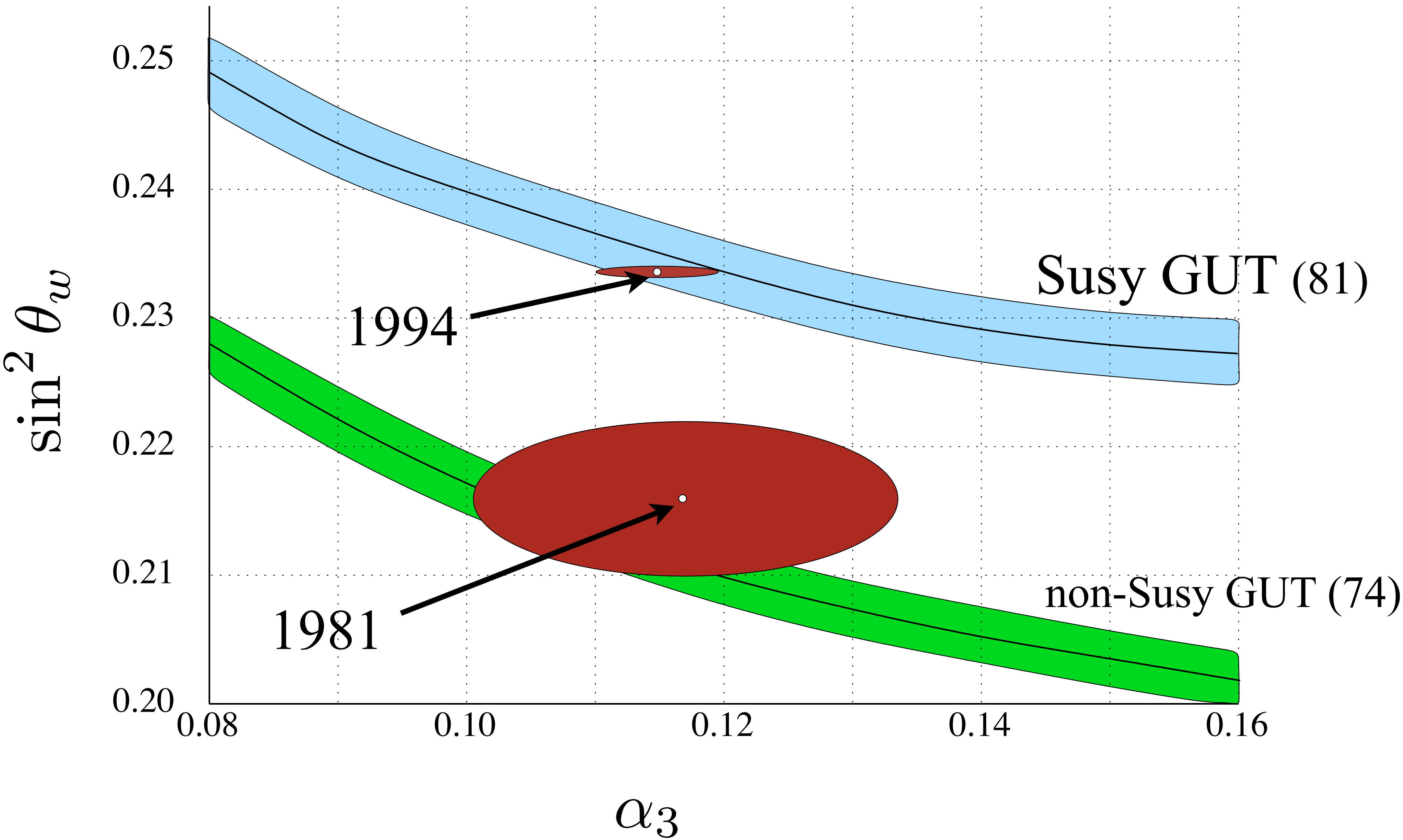

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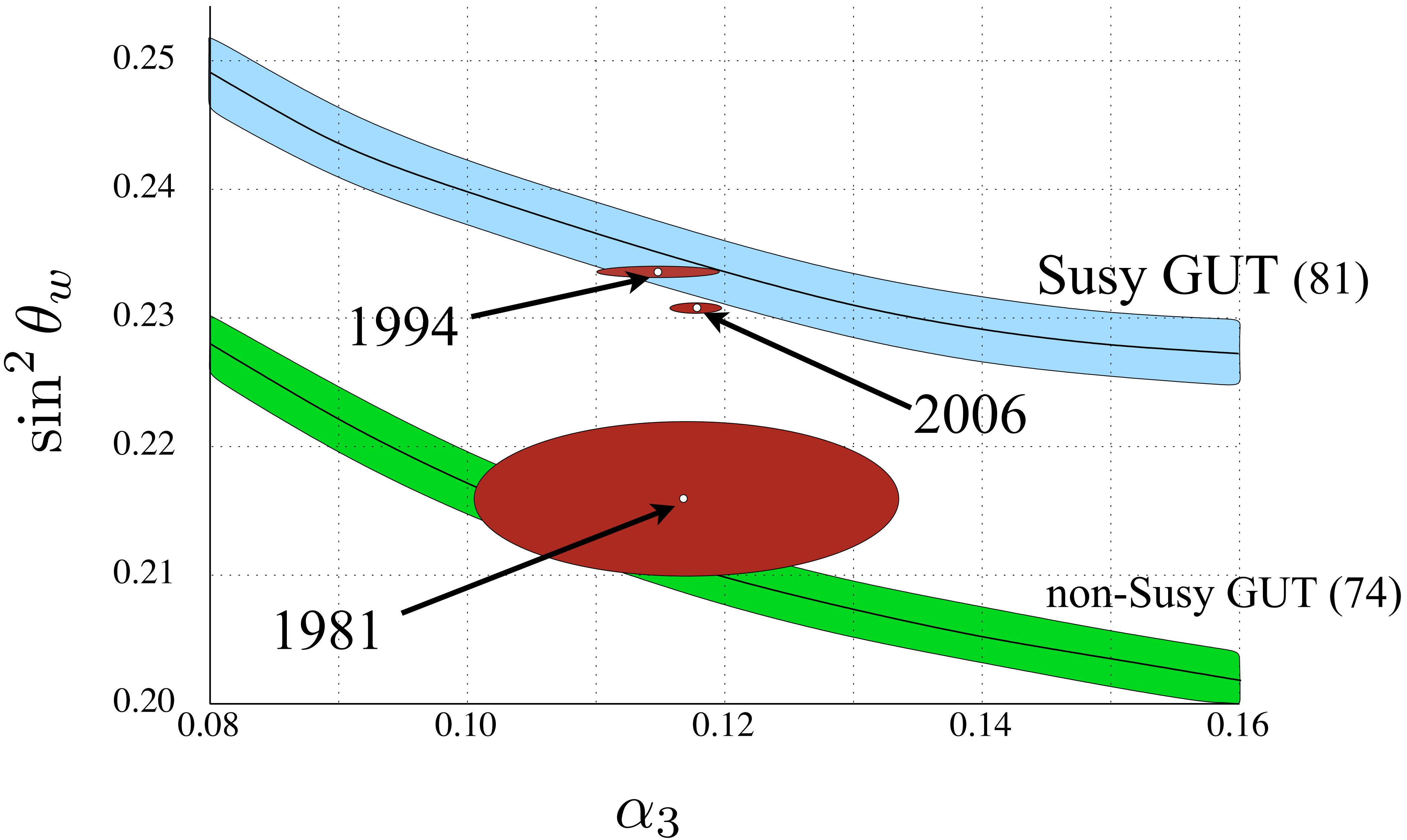

Summary of 1981 Predictions

S. D., Georgi

Degenerate Soft Terms

Many sparticles to be discovered at once

Stable 100 GeV LSP

Missing Energy at Colliders

WIMPs

Unification

New proton decay channels

$\sin^2 \theta_w$ vs $\alpha_3 \rightarrow$ already confirmed at LEP!

Late 90's

Everybody expected LEP2/Tevatron
to be discovery machines

Nothing discovered!

No sparticles or Higgs...

Supersymmetric Standard Model

Grade Report: Circa 2000

<u>Successes</u>	<u>Shortcomings</u>
	Higgs?
Unification	Sparticles?
Dark Matter	FCNC, GIM ~110 parameters
	Proton Decay, CP
	Gravitino & Moduli Problems

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Strategy for the last 30 years

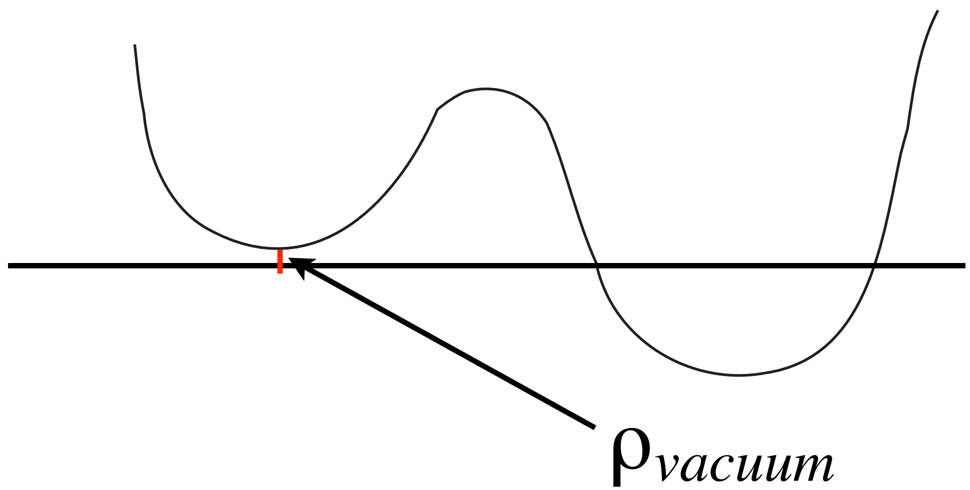
$$m_{\mathrm{weak}} \qquad\qquad\qquad \rho_{\mathrm{vacuum}}$$

↑ Focus on this

↑ Ignore this

This could be flawed

In theories with few vacua

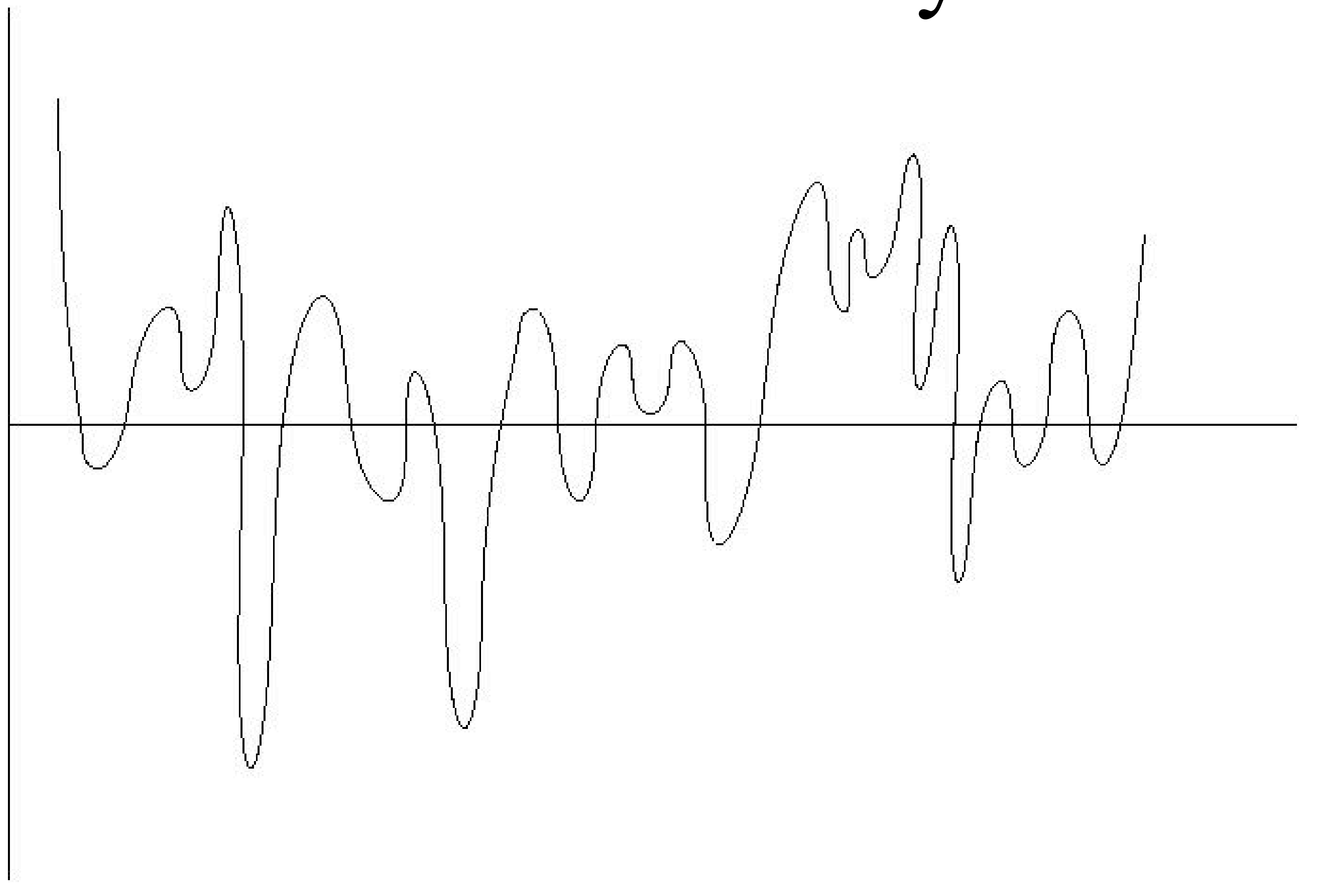


Getting $\rho_{vacuum} \sim (10^{-15} M_W)^4$

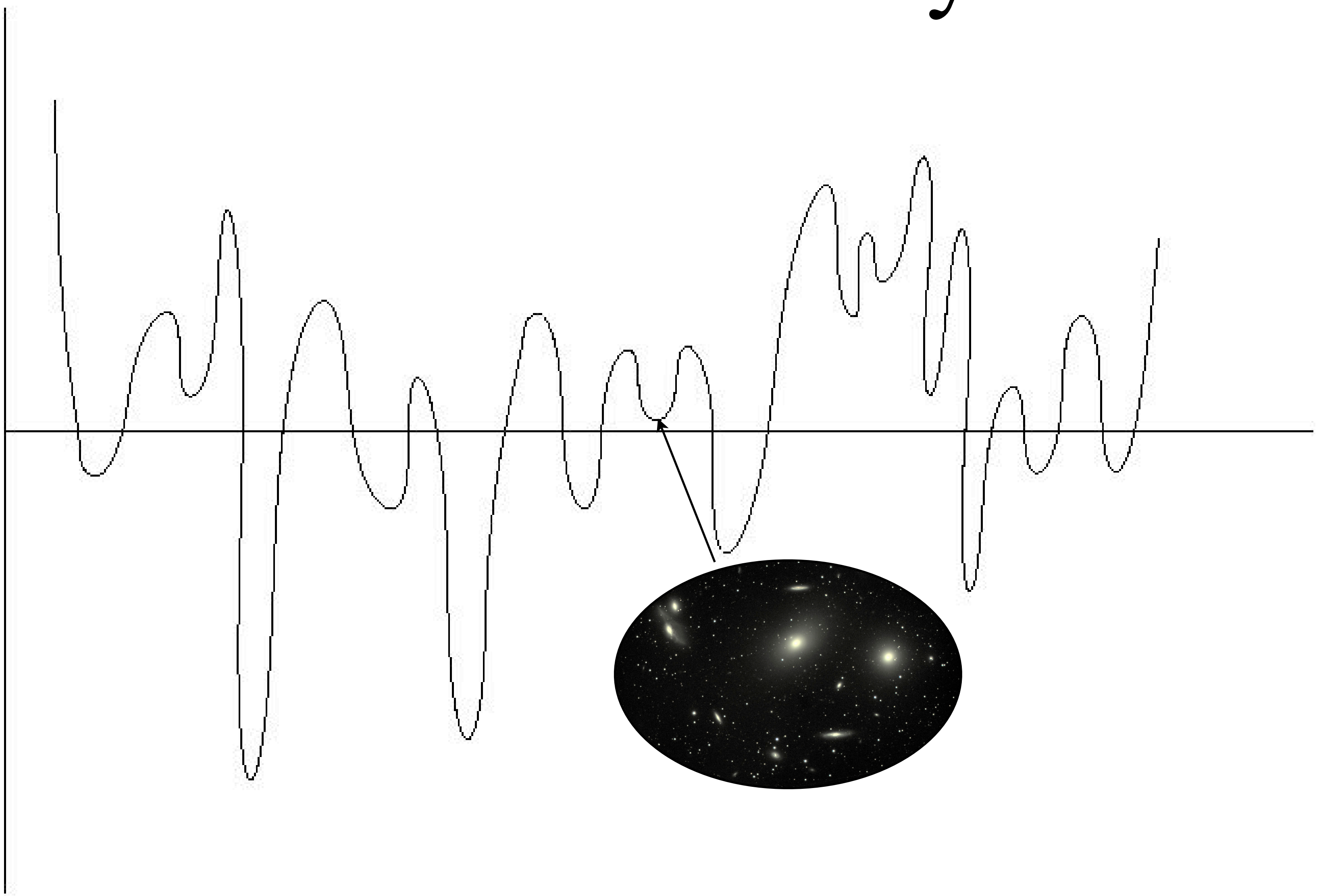
Looks like divine intervention!
Since any bigger value would rip apart galaxies

However... (Weinberg 1987)

In theories with many vacua



In theories with many vacua



Therefore, if there are enough vacua with different ρ_{vacuum}, the “structure” principle can explain why we live in a universe with small, but nonzero, ρ_{vacuum}

This reasoning correctly predicted a small ρ_{vacuum}

String theory may well have a vast "landscape" of metastable vacua

$$10^{100s}$$

Which can drastically affect what we consider natural.

If, for example, there are vastly more non-supersymmetric than supersymmetric vacua, then SUSY may not be favored

Notions of Naturalness in the Landscape

Standard Fine Tuning $$\frac{m_{h^0}^2}{m_{\rm susy}^2}$$ few-vacua measure

Tuning in the Landscape $$\left(\frac{m_{h^0}^2}{m_{\rm susy}^2}\right)\left(m_{\rm susy}^2\right)^N$$ multi-vacua measure

could favor high-scale SUSY

Motivates:

Ignoring the hierarchy problem,
like the cosmological constant problem.

Assume Higgs mass is fine-tuned,
like the cosmological constant.

Challenge:

Preserve the successes of SSM: DM + Unification

Just keep the fermions of the SSM!

Split Susy

Arkani-Hamed & S.D.
Giudice & Romanino
Wells

$M_{\mathrm{Pl.}}$ 10^{16} TeV

M_{susy}
M_{weak} 1 TeV

M_{CC} 10^{-15} TeV

Split Susy

Arkani-Hamed & S.D.
Giudice & Romanino
Wells

	$M_{\mathrm{Pl.}}$	10^{16} TeV
Scalars (Squarks, sleptons, ...)	M_{susy}	? { 10^{15} TeV / 10 TeV
	↑	
	M_{weak}	1 TeV
	M_{CC}	10^{-15} TeV

Split Susy

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$M_{\rm Pl.}$ — 10^{16} TeV

Scalars
(Squarks, sleptons, ...)

$M_{\rm susy}$? $\left\{ \begin{array}{l} 10^{15}\ \text{TeV} \\ 10\ \text{TeV} \end{array} \right.$

↓ Chiral symmetry

Fermions
(Higgsinos, gauginos)

$M_{\rm weak}$ — 1 TeV

↓ Fine tuned

SM Higgs

$M_{\rm CC}$ — 10^{-15} TeV

Split Susy

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$M_{\rm Pl.}$ 10^{16} TeV

Scalars
(Squarks, sleptons, ...)

$M_{\rm susy}$? { 10^{15} TeV / 10 TeV

Chiral symmetry

Fine tuned

Fermions
(Higgsinos, gauginos)

$M_{\rm weak}$ 1 TeV

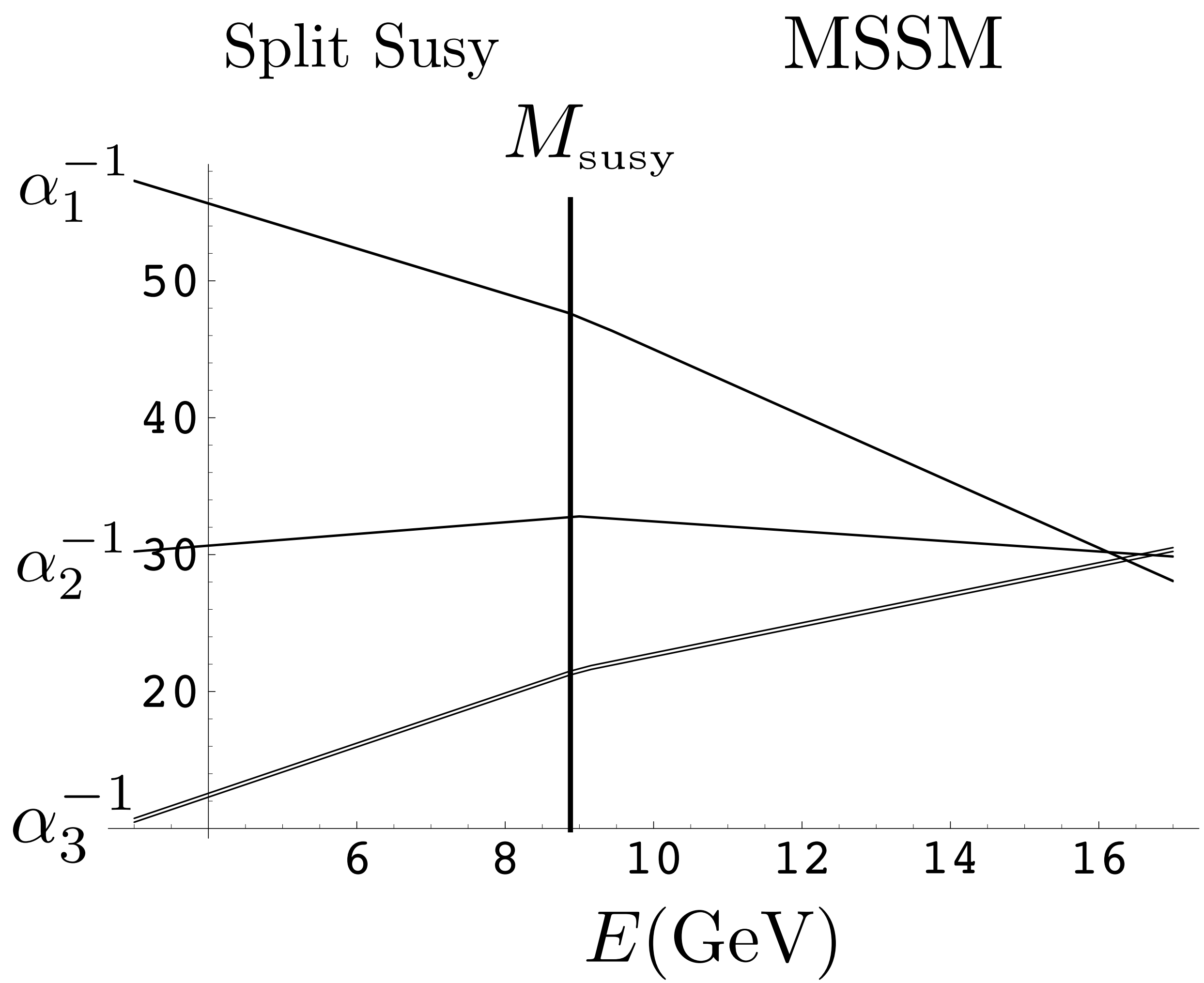
SM Higgs

$M_{\rm CC}$ 10^{-15} TeV

Dark Matter + Unification

Gauge Coupling Unification

Squarks and Sleptons don't alter unification

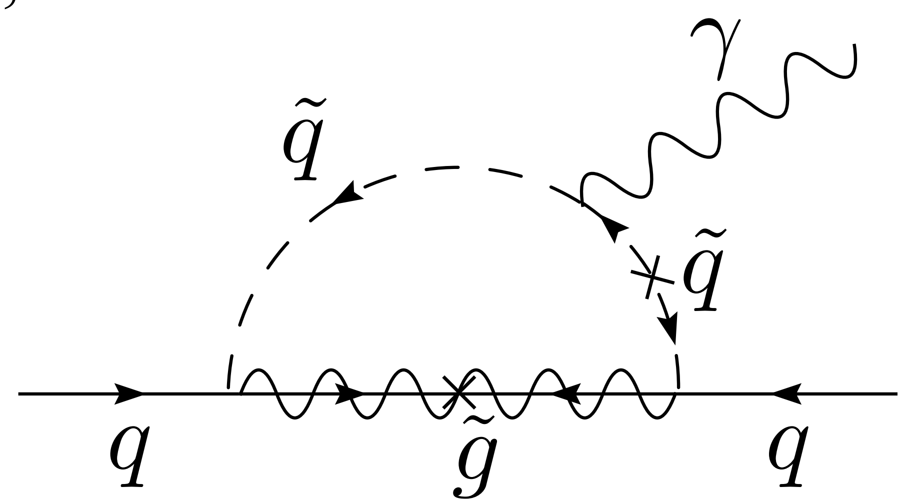


Problems solved in one stroke:

- Sparticles

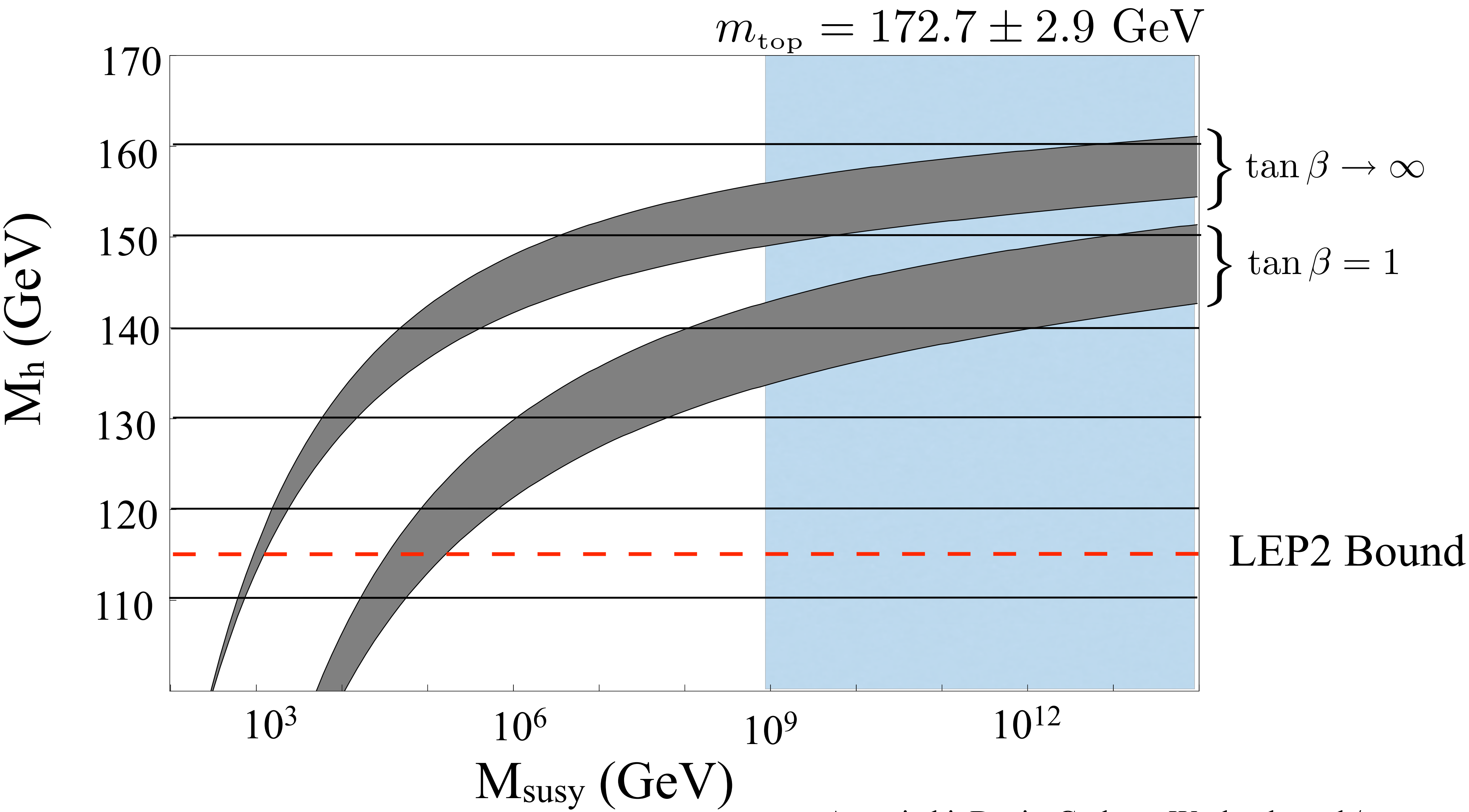
- Proton decay

- FCNC; CP; GIM



- Gravitino and Moduli problems also solved

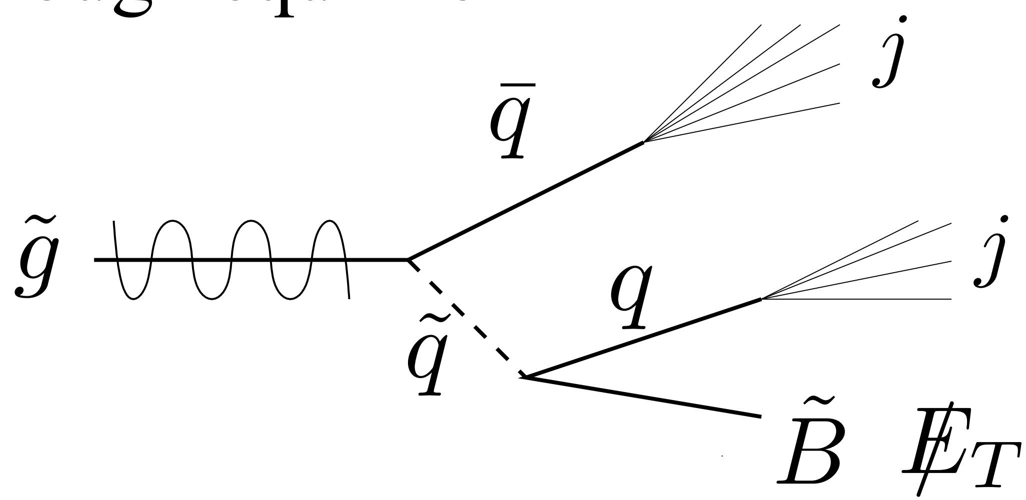
The Higgs Mass



Arvanitaki, Davis, Graham, Wacker hep-ph/0406034

Long-Lived Light Gluinos

Must decay through squarks



$$\tau_{\tilde{g}} \simeq 2 \text{ sec.} \left(\frac{350 \text{ GeV}}{m_{\tilde{g}}} \right)^5 \left(\frac{M_{\text{Susy}}}{10^6 \text{ TeV}} \right)^4$$

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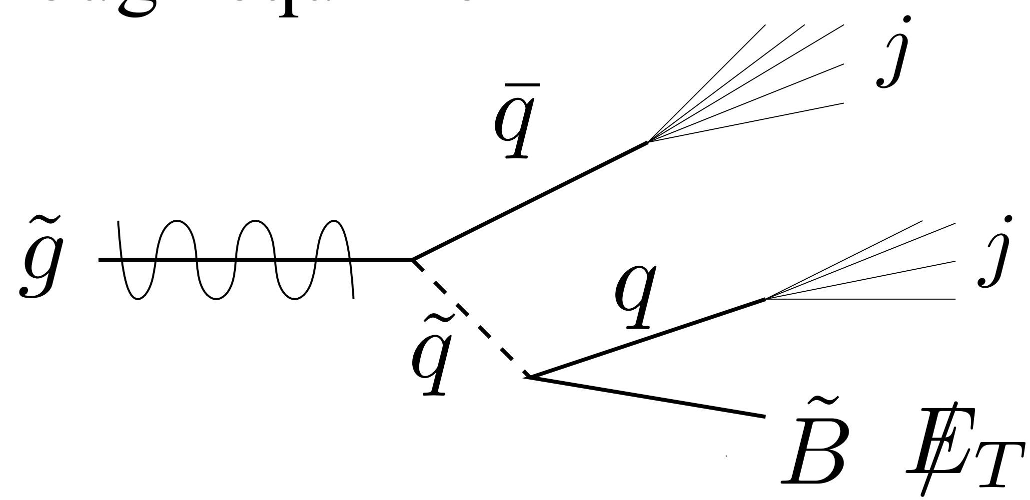

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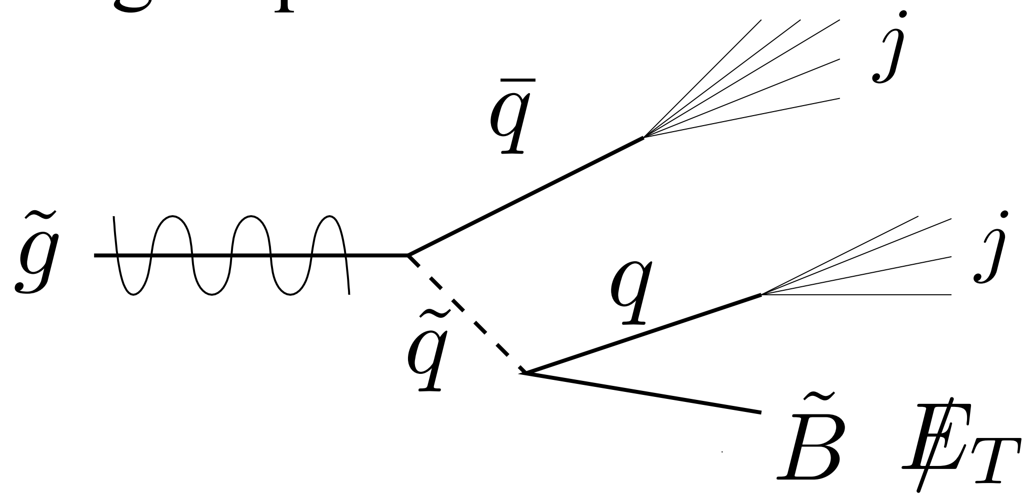
LHC: Gluino Factory, ~1 gluino/sec! (350 GeV)

Long-Lived Light Gluinos

Must decay through squarks



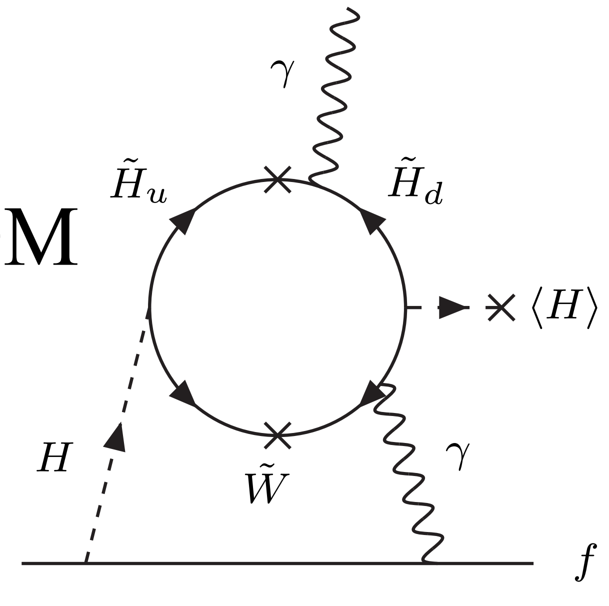
$$\tau_{\tilde{g}} \simeq 2 \text{ sec.} \left(\frac{350 \text{ GeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\text{Susy}}}{10^6 \text{ TeV}}\right)^4$$

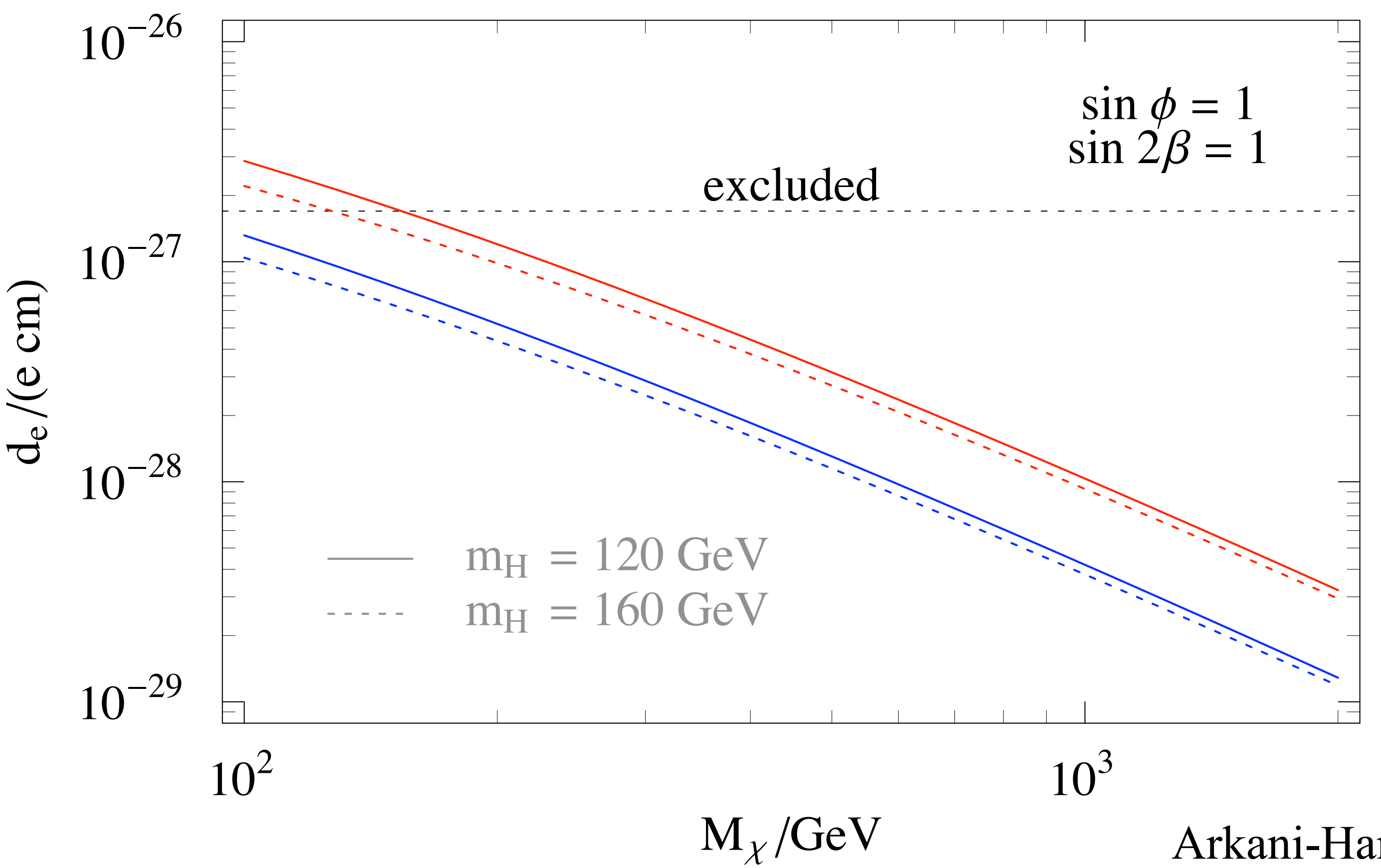
LHC: Gluino Factory, ~1 gluino/sec! (350 GeV)

Electric Dipole Moments

Three phases in split SUSY

Feeds in at 2 loops to neutron EDM





Arkani-Hamed, et al hep-ph/0409232

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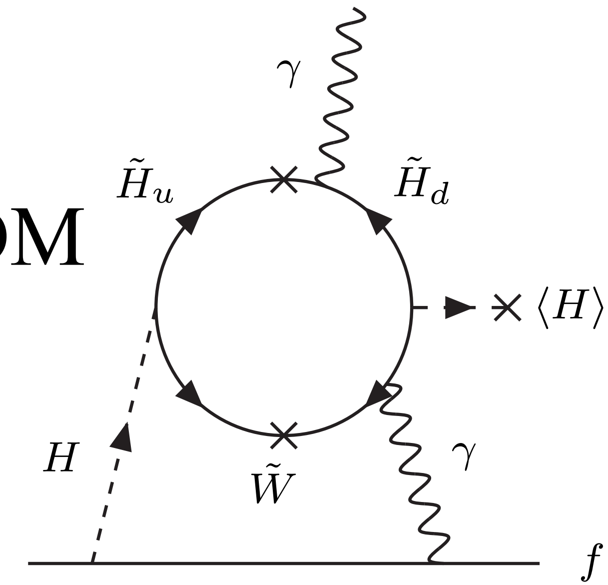

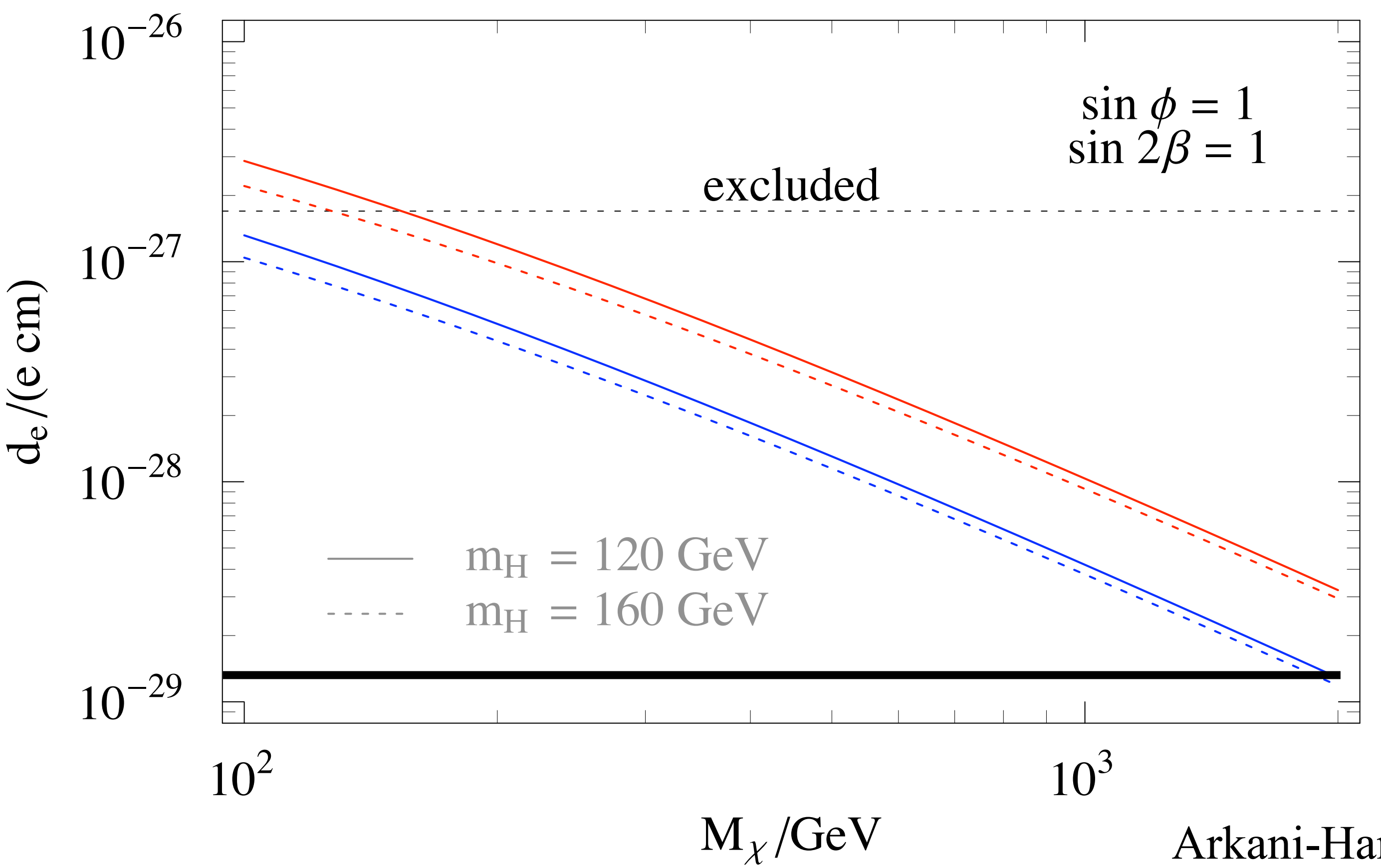

DeMille/Yale Groups by 2007

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Other Split SUSY Couplings

Higgs Quartic

$$\lambda|H|^4 - m^2|H|^2$$

$$\lambda(M_s) = \frac{1}{8}\left(g^2 + g'^2\right)\cos^2 2\beta$$

Gaugino Yukawas

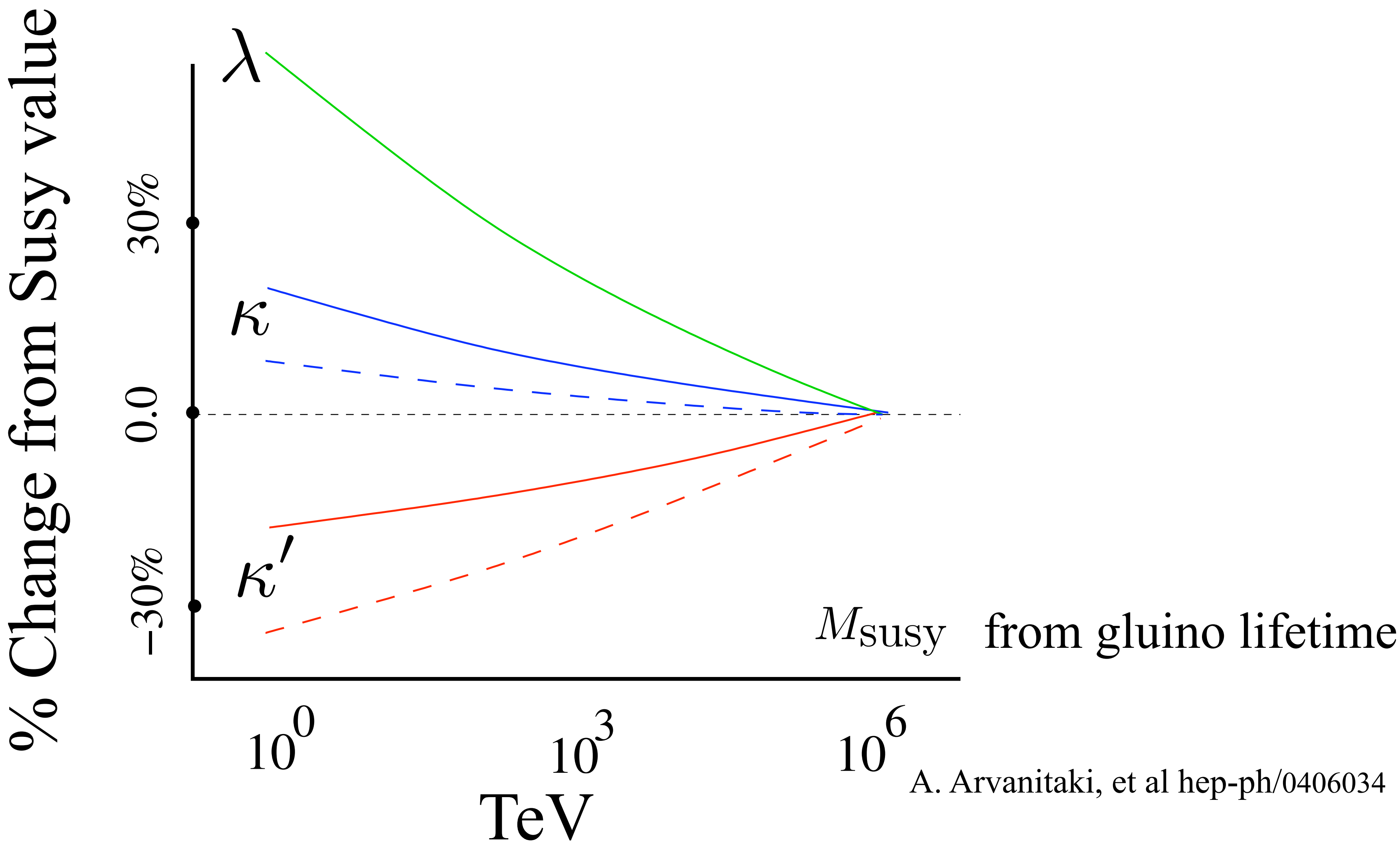
$$\kappa_u H \widetilde{H_u}\widetilde{W} + \kappa_d H^\dagger \widetilde{H_d}\widetilde{W}$$
$$\kappa'_u H \widetilde{H_u}\widetilde{B} + \kappa'_d H^\dagger \widetilde{H_d}\widetilde{B}$$

$$\kappa_u(M_s) = g\sin\beta$$
$$\kappa_d(M_s) = g\cos\beta$$

Run from the weak scale to M_s

Yukawa Couplings' Unification

$$\tan\beta \longrightarrow \lambda \;\; \kappa_u \;\; \kappa_d \;\; \kappa'_u \, \kappa'_d$$



A. Arvanitaki, et al hep-ph/0406034

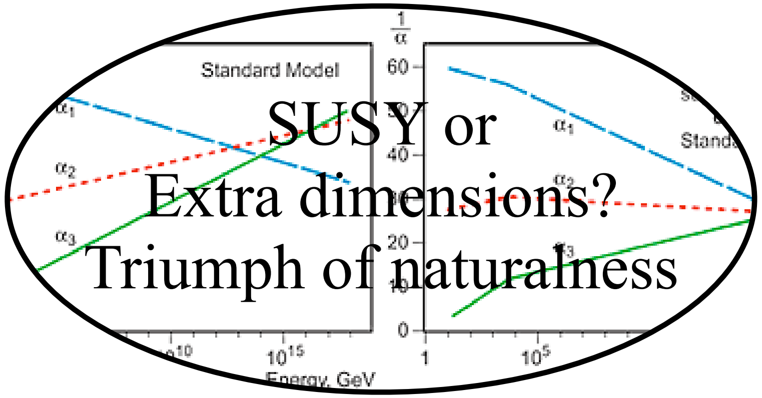
Tests of Split Supersymmetry

- Higgs Mass 120 - 160 GeV
- Gauginos and Higgsinos
- Dark Matter
- EDMs
- Gluino lifetime reveals m_{susy}
- κ's and λ in terms of $\tan\beta$ and m_{susy}

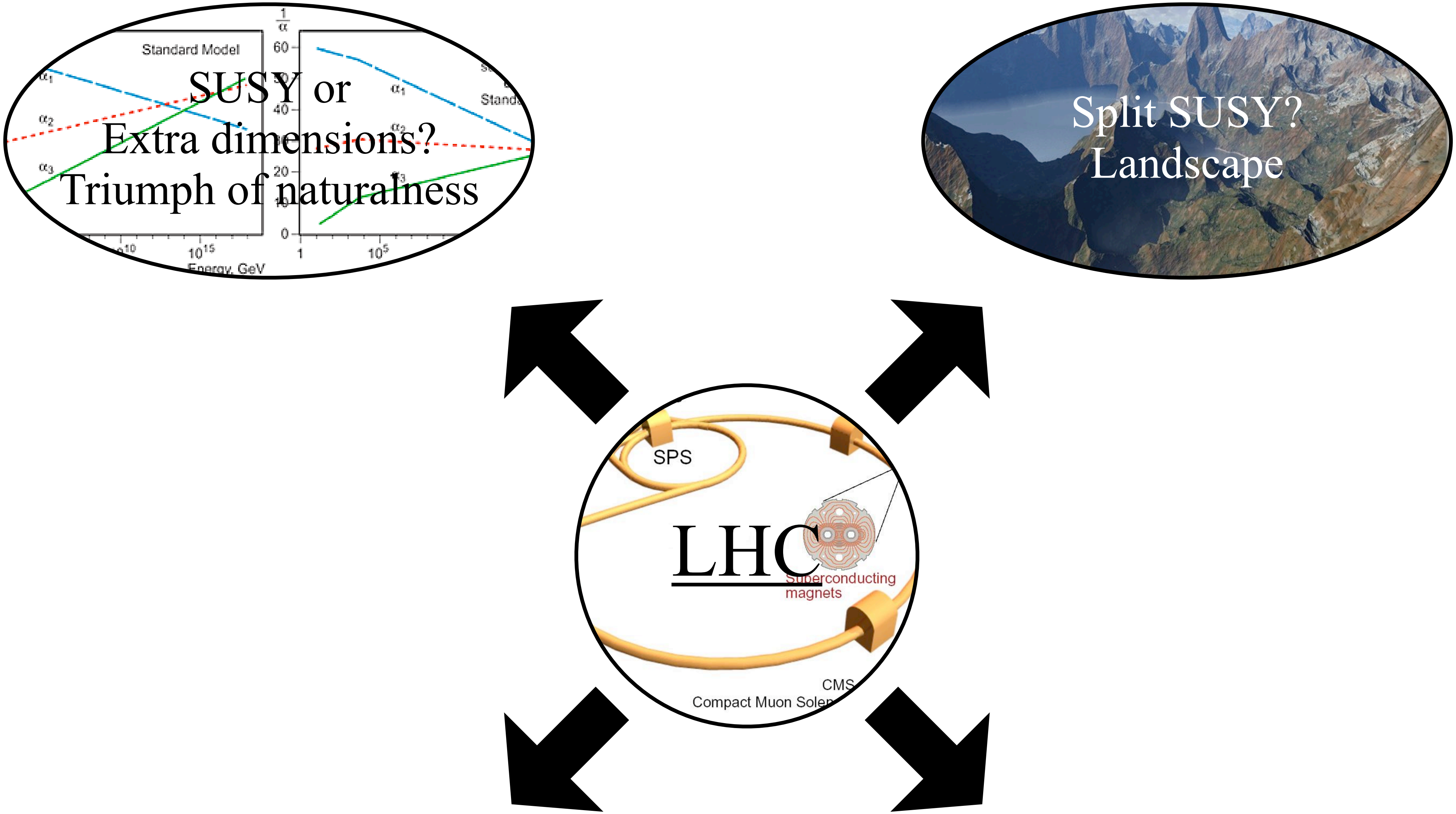
Four predictions,
four independent tests of high-scale SUSY !

Strong evidence for a fine tuning mechanism, in the EW sector. No subtleties of gravity.

Late 00's


SUSY or
Extra dimensions?
Triumph of naturalness
Standard Model
Energy, GeV


LHC
SPS
Superconducting
magnets
CMS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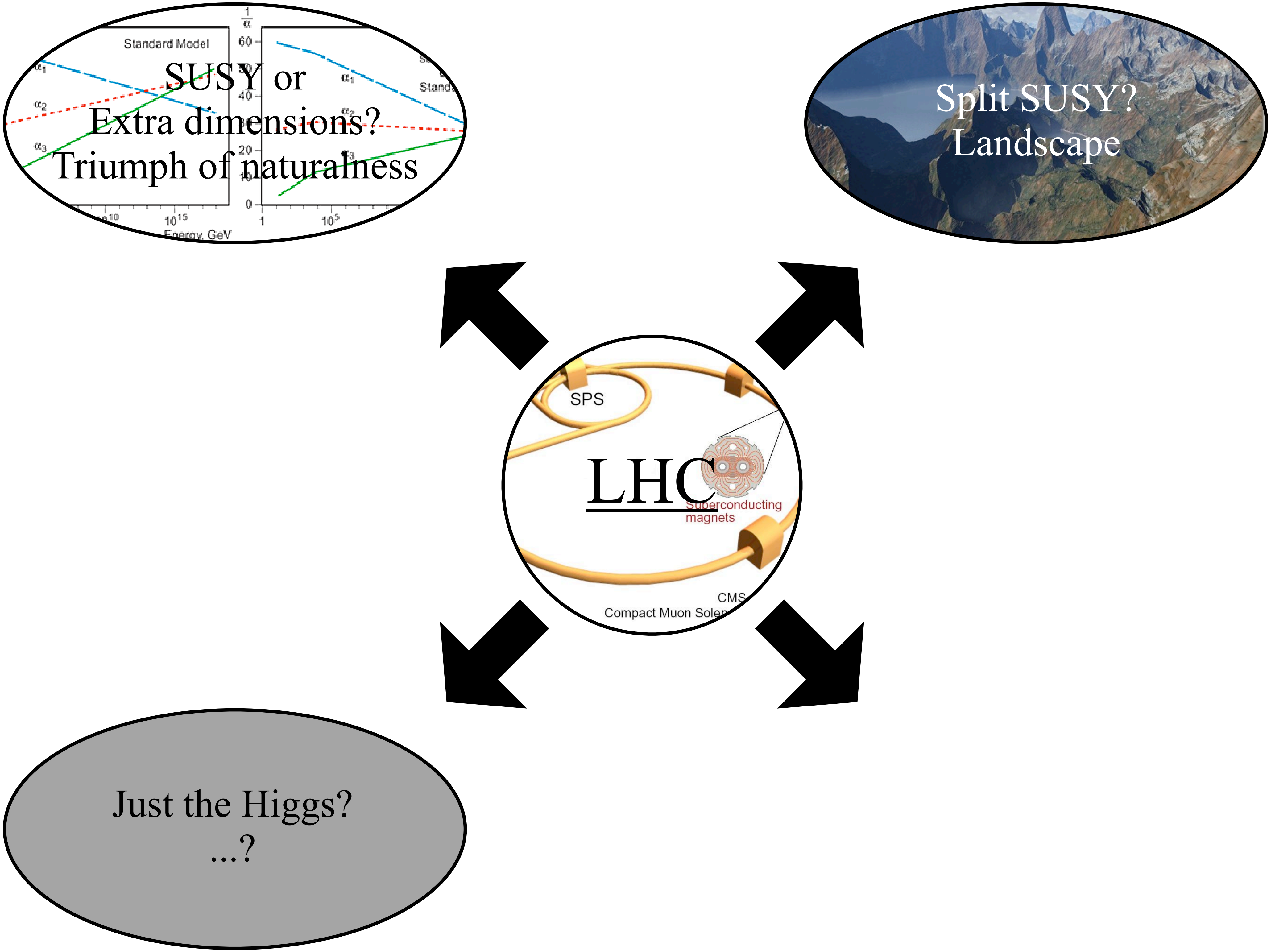
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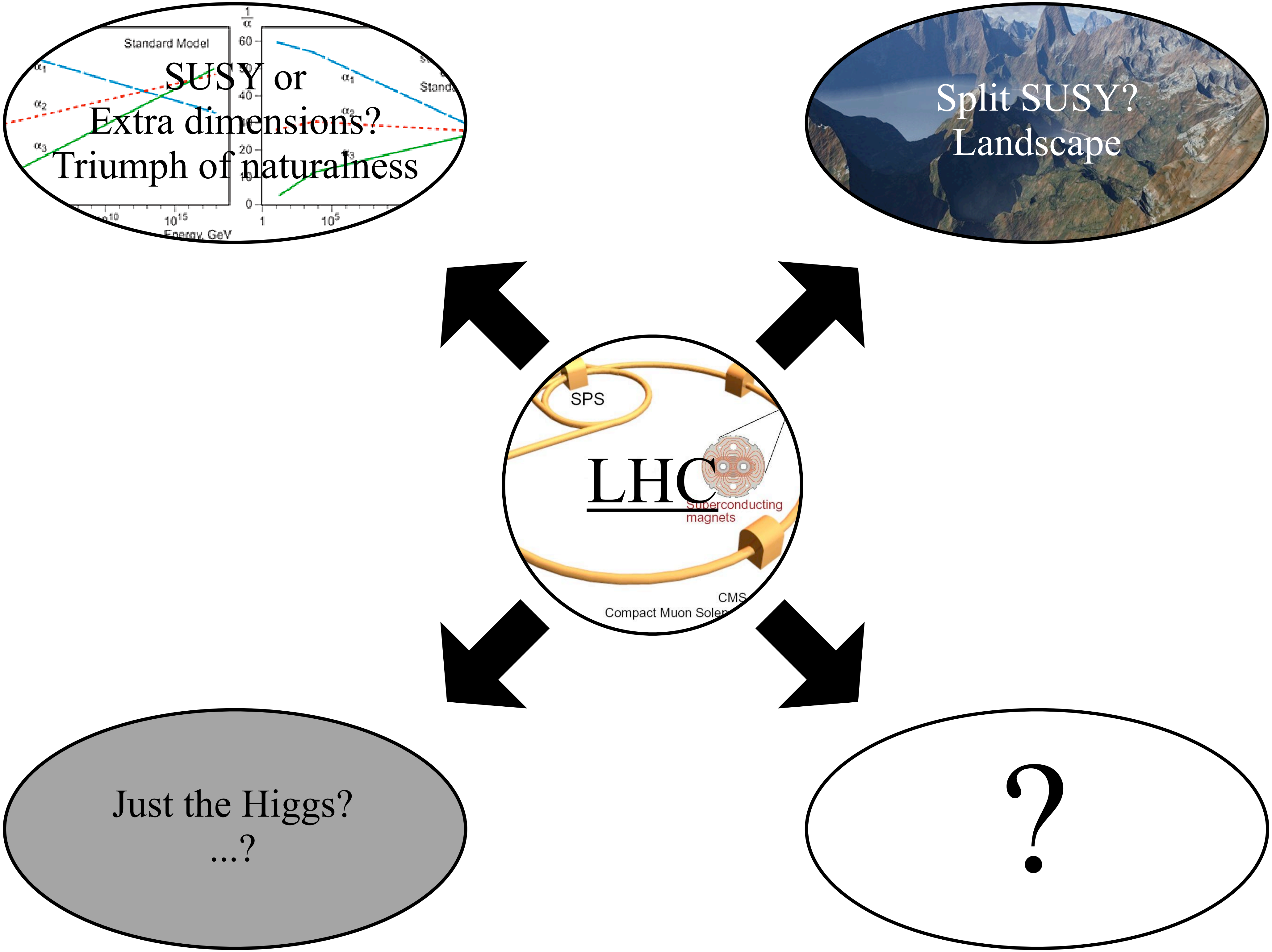
...?



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?