APS physics

APS Mid-Atlantic Senior Physicists Group

Supersymmetry

S. James Gates, Jr.

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http://umdphysics.umd.edu/people/faculty/135-gates.html

SYMMETRY PRINCIPLES IN SELECTED PROBLEMS OF FIELD THEORY

by

SYLVESTER JAMES GATES, JR.

B.S., Massachusetts Institute of Technology
(June 1973)

B.S., Massachusetts Institute of Technology
(September 1973)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(June 1977)

$$M^2_{F^\bullet} \cong g^2 M^2_G \left[d^2 + \tfrac{1}{2}\left(1 + \tfrac{1}{2}\alpha^2\right)\right]$$

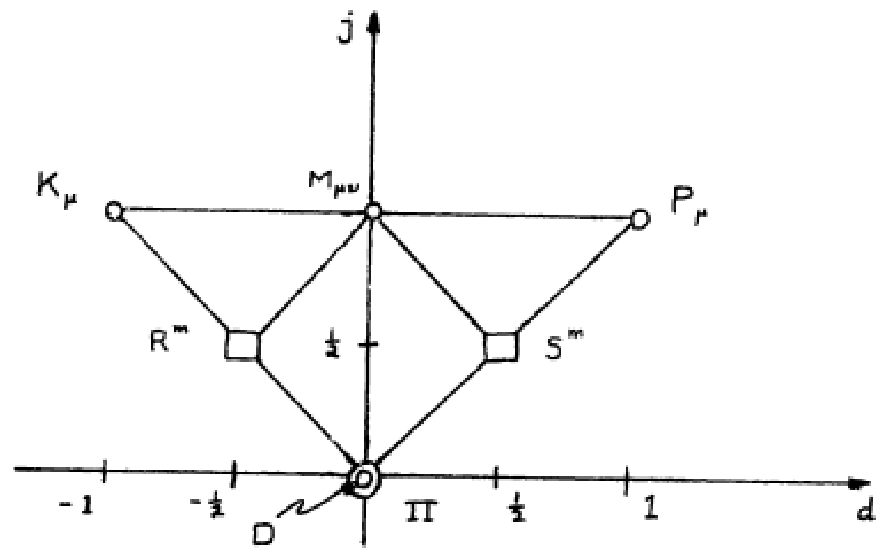
$$M^2_{F^\pm} \cong g^2 M^2_G \left(\tfrac{1}{\alpha}\right)^2$$

$$M^2_{G^\bullet} \cong g^2 M^2_G \left[b^2 + \tfrac{5}{18}\left(1 + \tfrac{1}{2}\alpha^2\right)\right]$$

$$M^2_{Z^\bullet} \cong 5 g^2 M^2_G \left(1 + \tfrac{1}{2}\alpha^2\right)$$

$$M^2_W \cong g^2 M^2_G \left(1 + \tfrac{1}{2}\alpha^2\right)$$

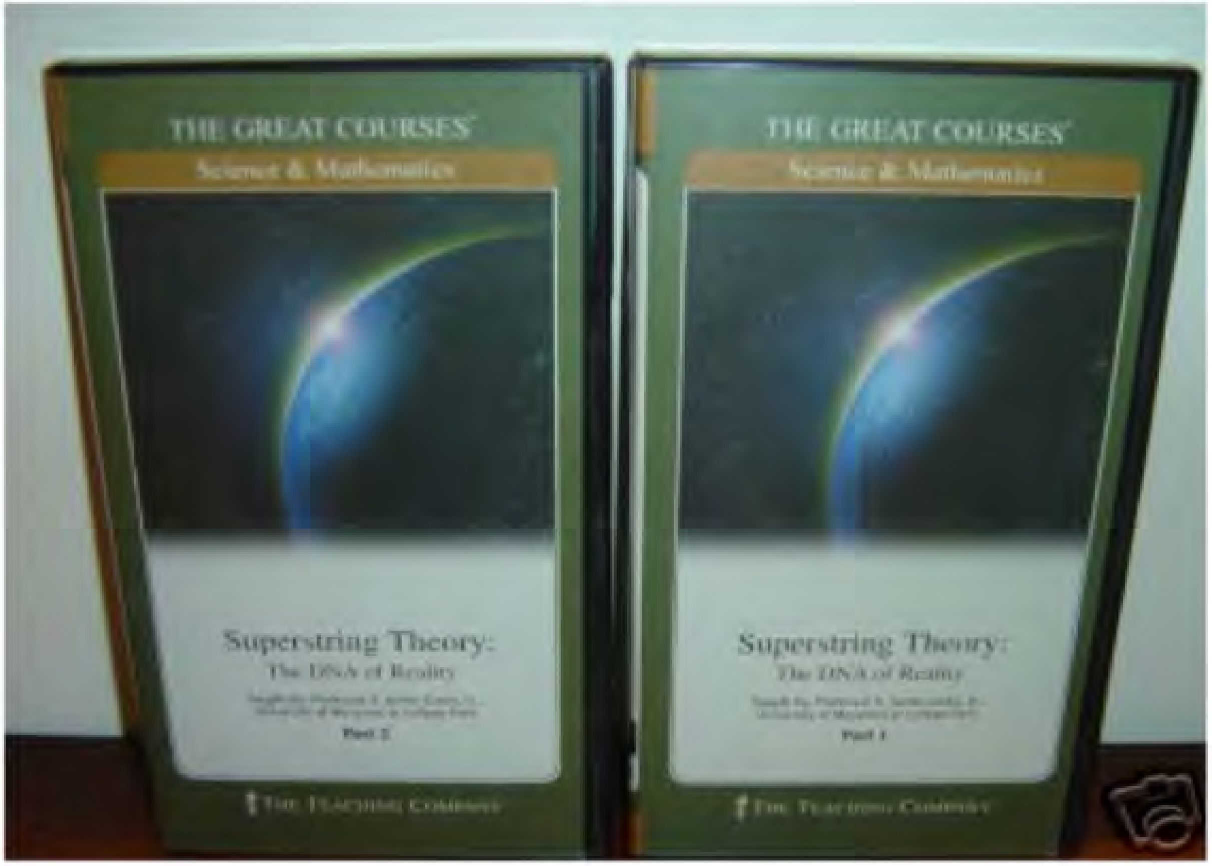
$$M^2_A$$



○ ≡ Bosonic generator

□ ≡ Fermionic generator

Diagram illustrating the generators of the superconformal group. The classification of these operators has been made according to intrinsic spin and dimensionality.



Superstring Theory: The DNA of Reality

Web:
http://www.teach12.com/ttcx/coursedesclong2.aspx?cid=1284

One Theorist's Bucket List

(a.) Higgs Boson
(b.) Gravitational Waves
(c.) Superpartners
(d.) Evidence of Superstrings

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One Theorist's Bucket List

(a.) Higgs Boson
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From The
SM To The
With Higgs

The Standard Model (SM)

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

The Standard Model (SM)

FERMIONS

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BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0
H^0	125	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
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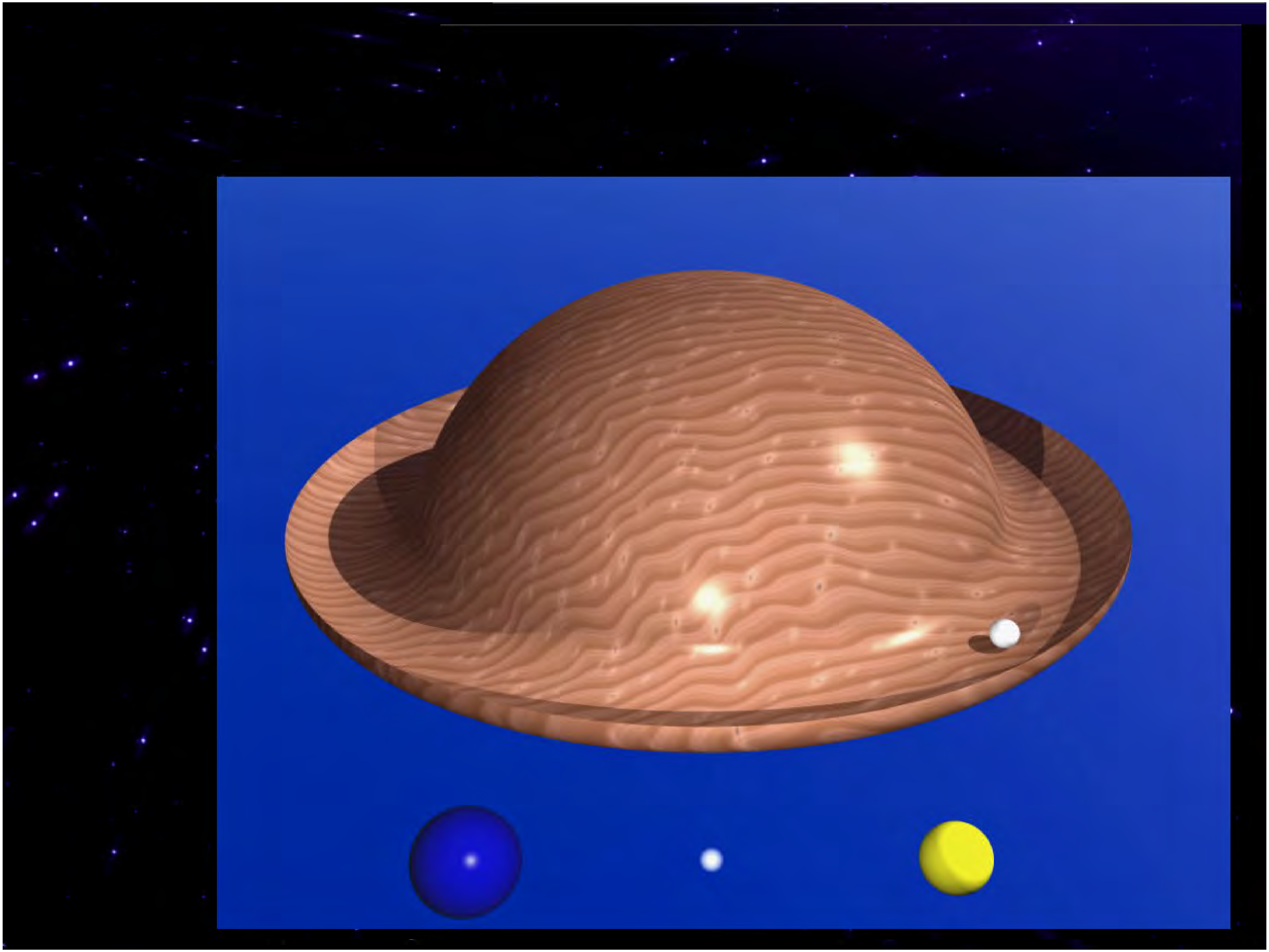
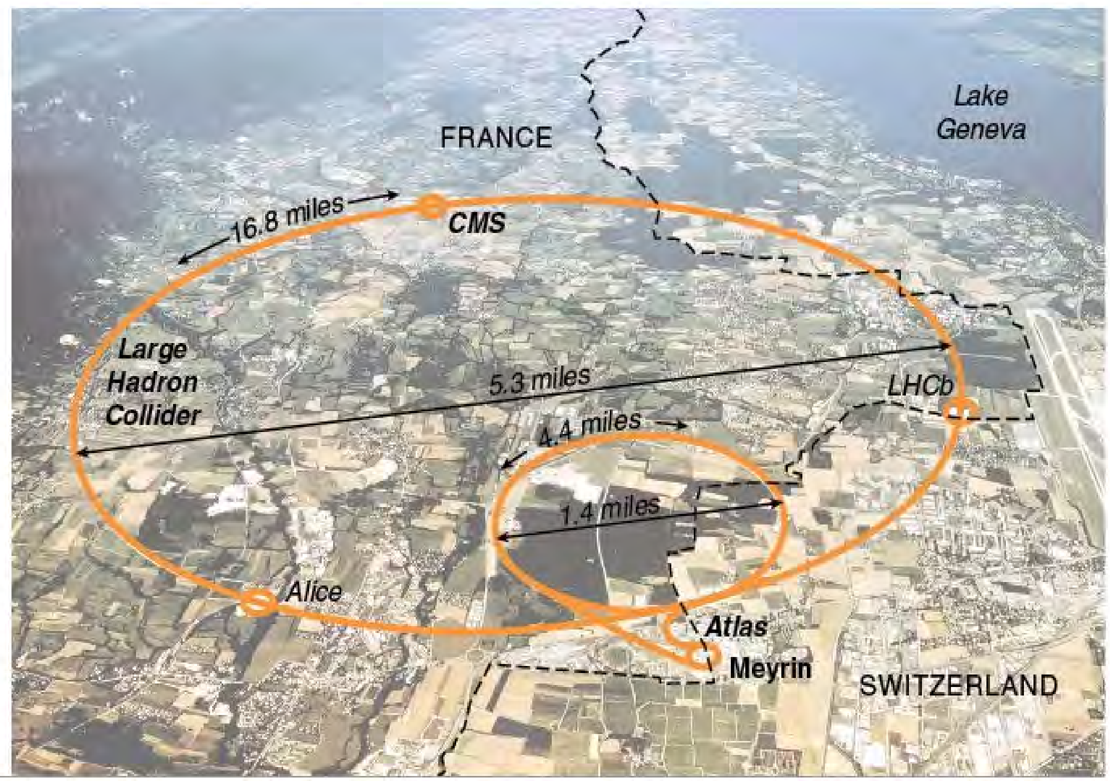
The Higgs
And
The LHC

Higgs, Carrier Mass & Goldstone Bosons



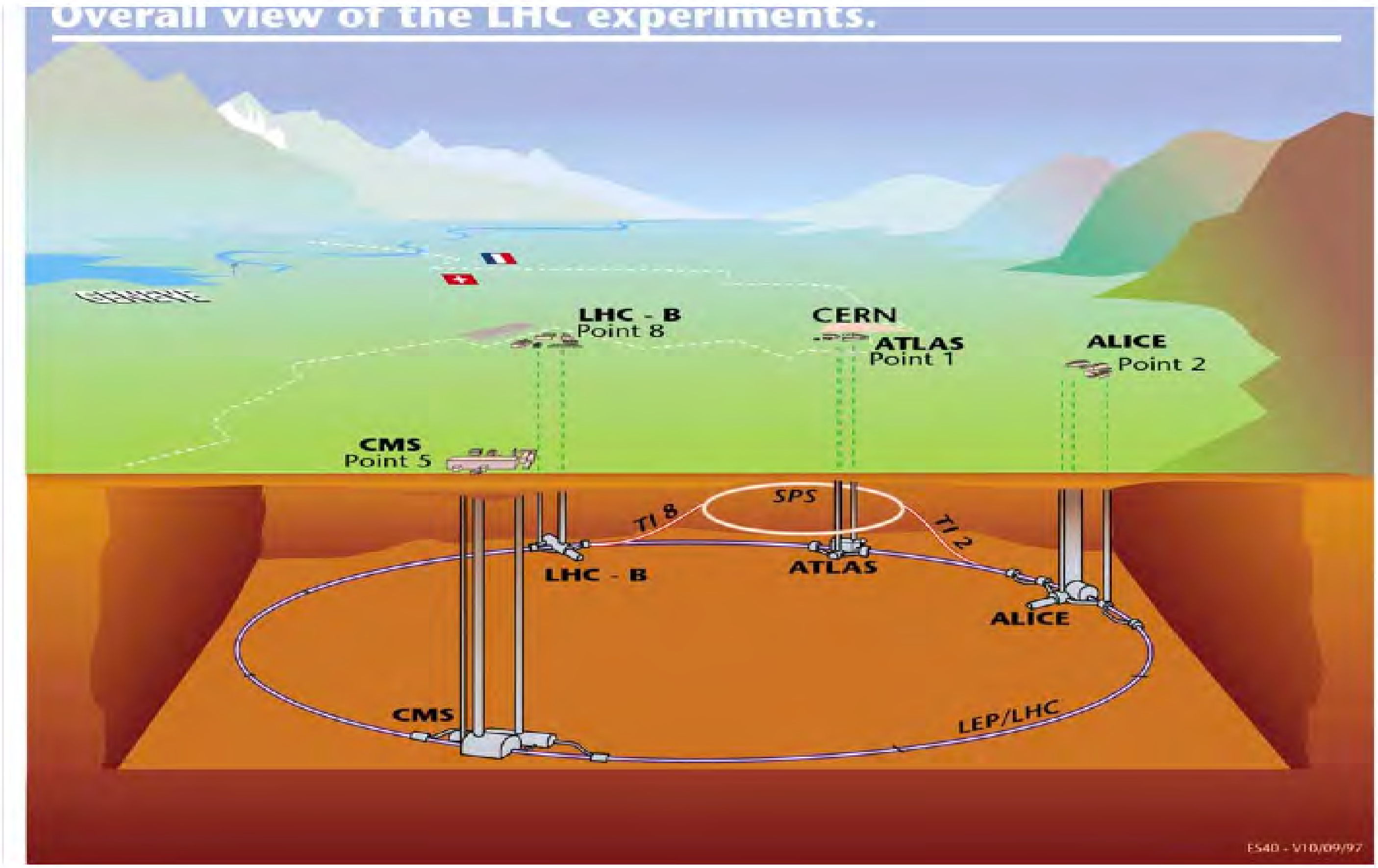
The Large Hadron Collider of Cern (European Organization for Nuclear Research)

In a tunnel 300 feet below Switzerland and France, scientists are putting the final touches on a 16.8-mile long particle accelerator that will smash protons together in an attempt to create forces and particles that existed shortly after the Big Bang and rarely, if ever, today.



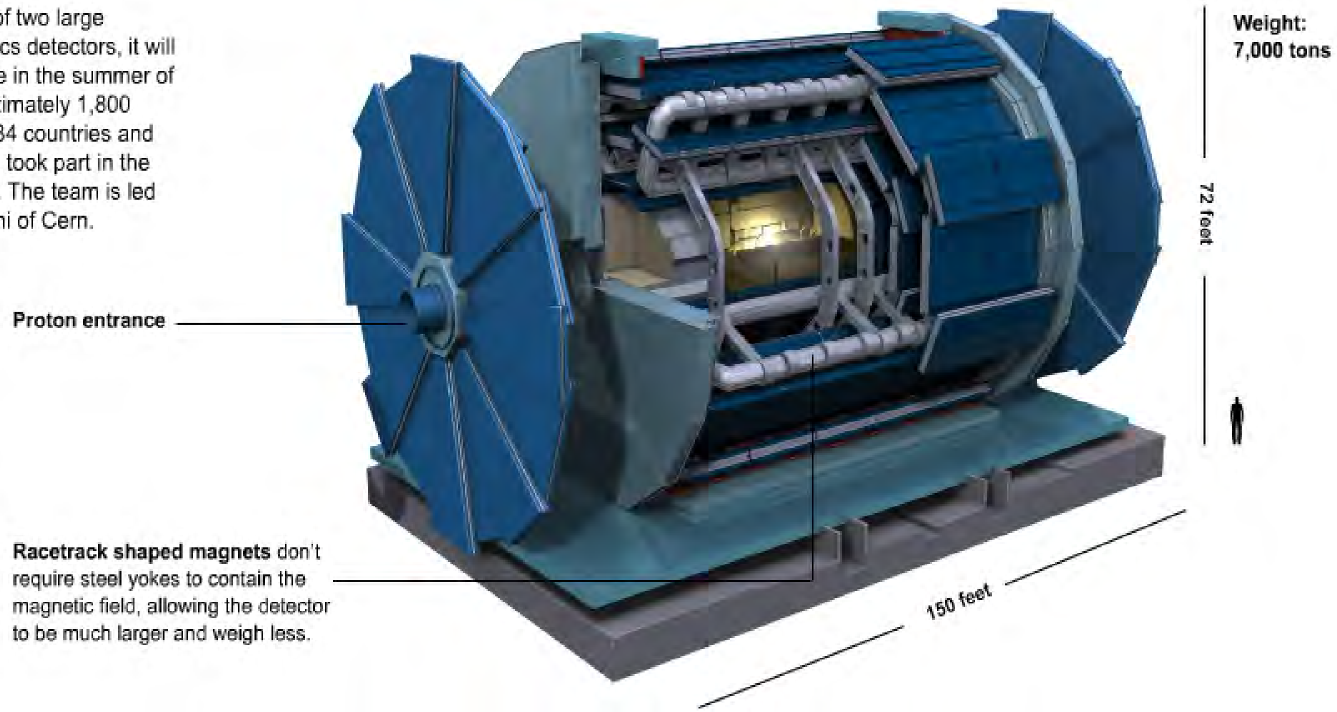
Source: Cern; Physics World, Sept. 2004; Lawrence Berkeley National Laboratory

Graham Roberts, David Constantine, Mika Gröndahl, Erin Aigner/ The New York Times


Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

Atlas

The second of two large particle physics detectors, it will also go online in the summer of 2008. Approximately 1,800 people from 34 countries and 150 institutes took part in the collaboration. The team is led by Peter Jenni of Cern.



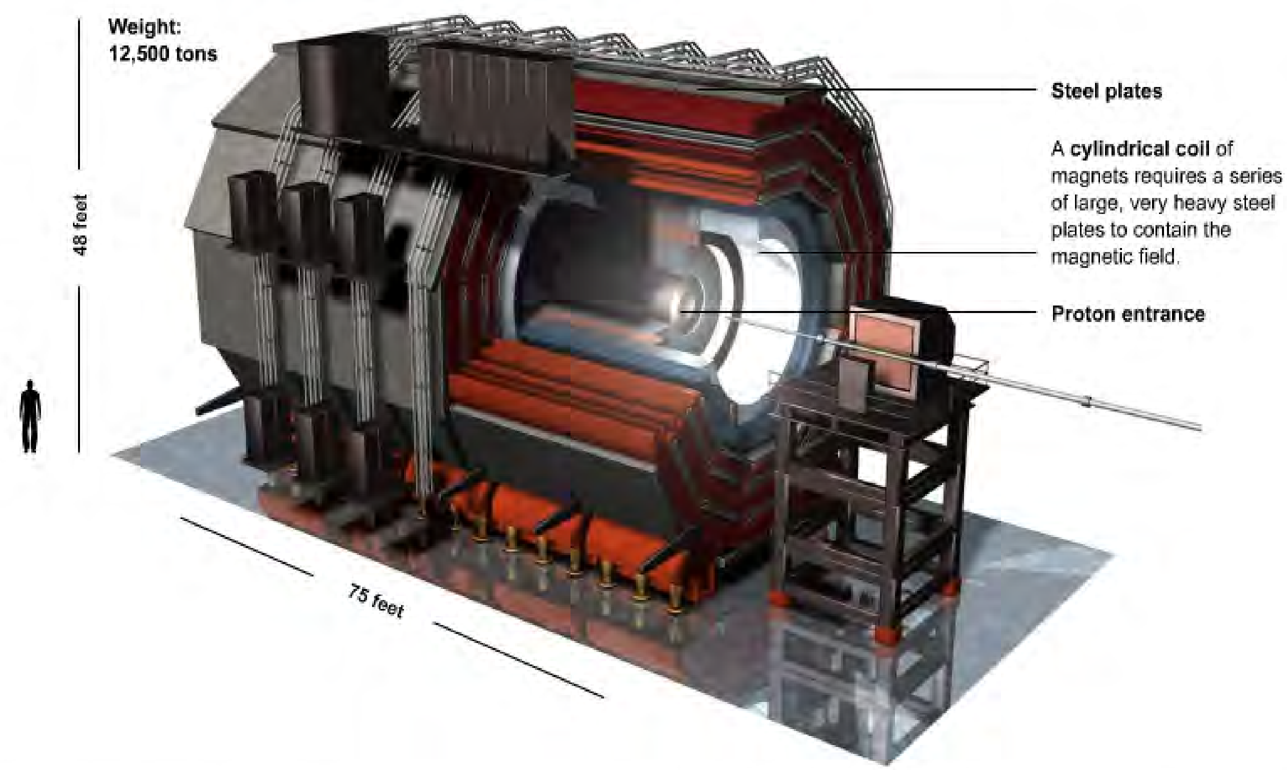
Racetrack shaped magnets don't require steel yokes to contain the magnetic field, allowing the detector to be much larger and weigh less.

Source: Cern; Physics World, Sept. 2004; Lawrence Berkeley National Laboratory

Graham Roberts, David Constantine, Mika Gröndahl, Erin Aigner/ The New York Times

Compact Muon Solenoid (CMS)

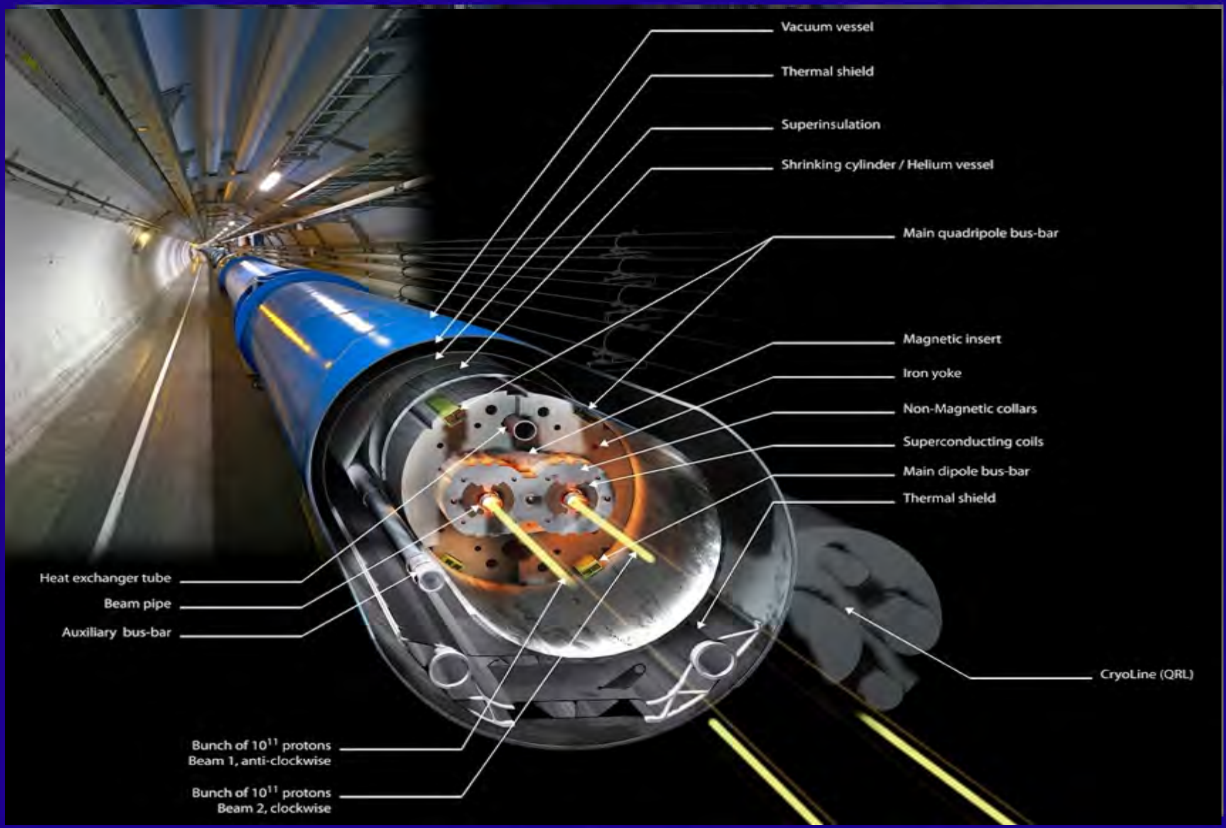
One of two large general-purpose particle physics detectors to go online in 2008. Approximately 2,500 people from 37 countries and 155 institutes form the collaboration building it. The team is led by Jim Virdee of Imperial College London and Cern.



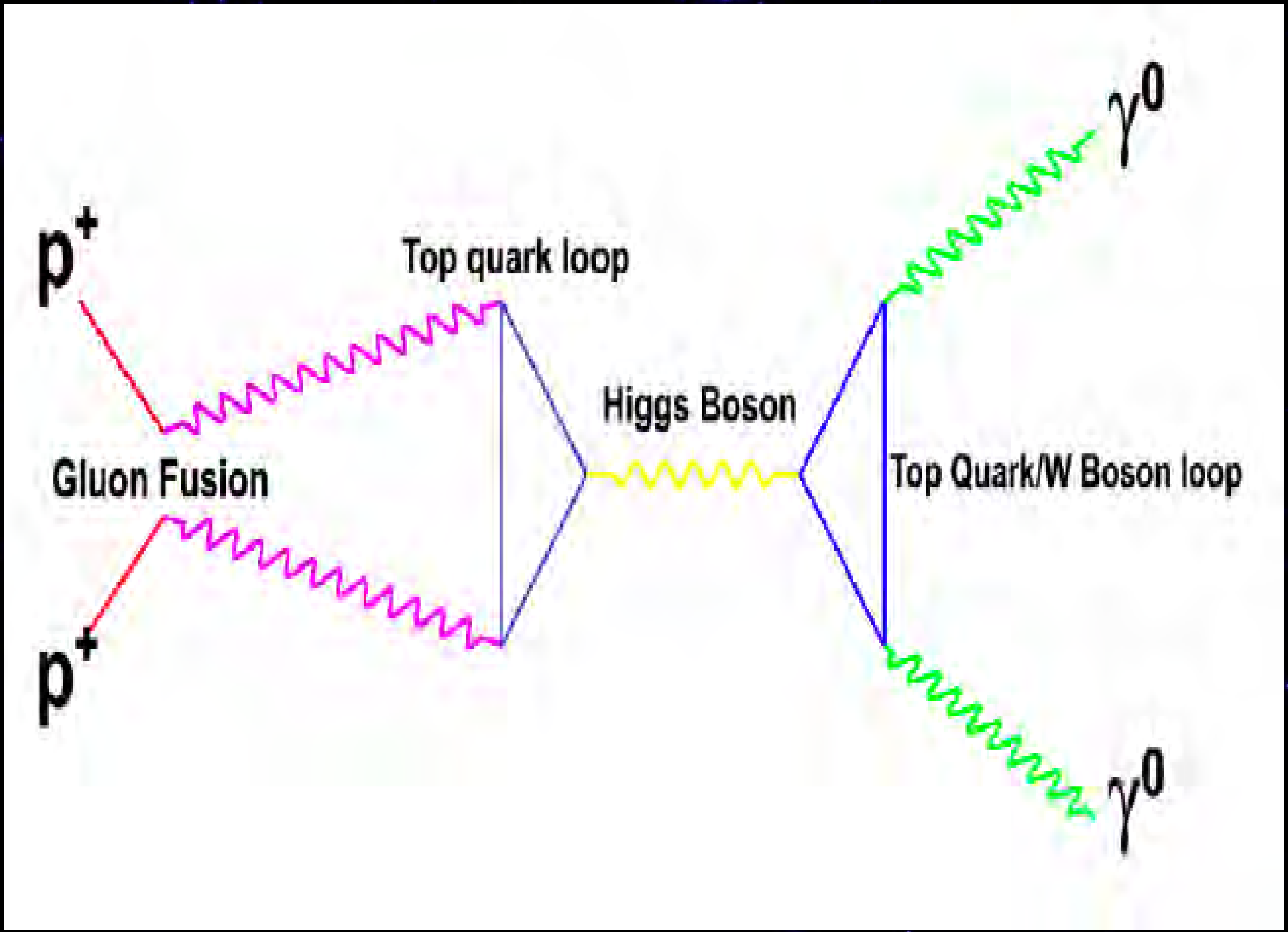
Source: Cern; Physics World, Sept. 2004; Lawrence Berkeley National Laboratory

Graham Roberts, David Constantine, Mika Gröndahl, Erin Aigner/ The New York Times

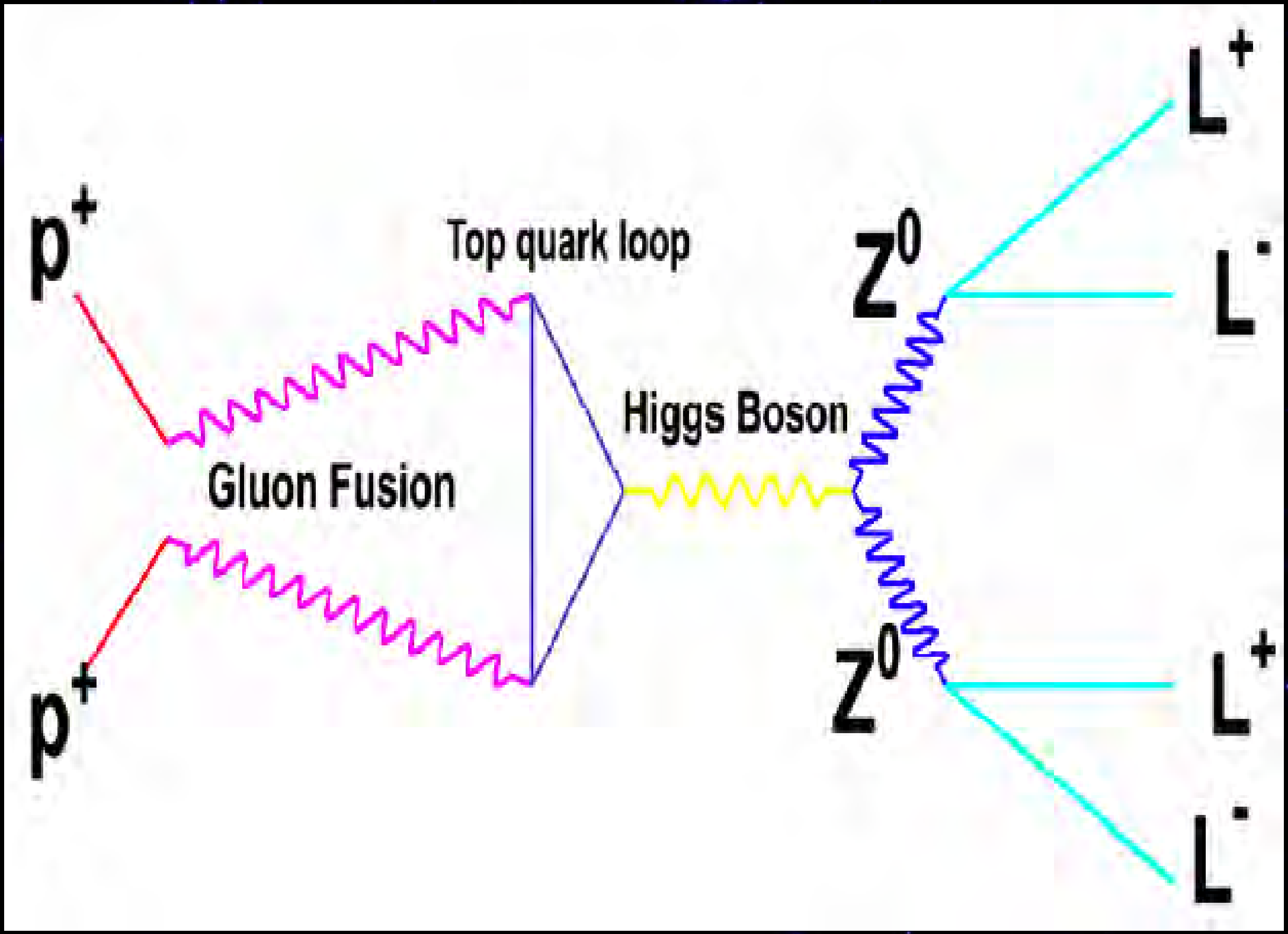
Overview of LHC Higgs Production Factory



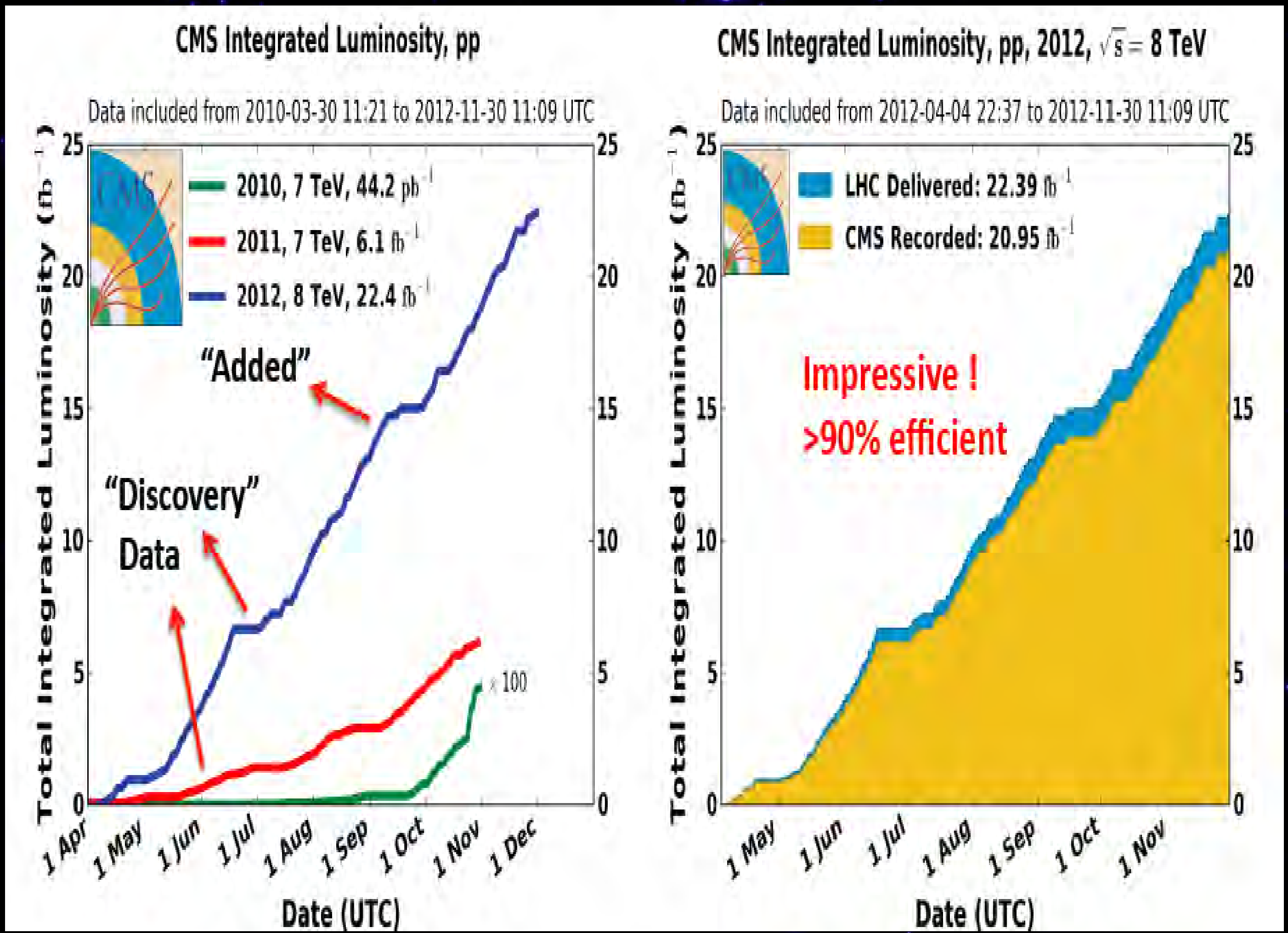
A Higgs Production & Decay Process



A Higgs Production & Decay Process



Productivity & Performance



‘Born’ On The Fourth of July

In 2012, there was an announcement of the discovery of a previously unknown boson where:

(a.) the ATLAS collaboration measured at a mass of 126.5 GeV/c^2 and

(b.) the CMS collaboration measured at a mass 125.3 ± 0.6 GeV/c^2

and using both ‘channels’ this is a ‘five sigma’ event – i.e. less than a 1-in-a-million chance of error.

From: Rolf Heuer <rolf.heuer@cern.ch>
Date: 14 March 2013 11:29:54 AM SAST
To: "cern-personnel (CERN Personnel - Members and Associate Members)" <cern-personnel@cern.ch>
Subject: CERN Press Release: New results indicate that particle discovered at CERN is a Higgs boson

La version française sera disponible ultérieurement ici: http://press.web.cern.ch/fr/press-releases

New results indicate that particle discovered at CERN is a Higgs boson

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, **or possibly the lightest of several bosons** predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Whether or not it is a Higgs boson is demonstrated by how it interacts with other particles, and its quantum properties. For example, a Higgs boson is postulated to have no spin, and in the Standard Model its parity – a measure of how its mirror image behaves – should be positive. CMS and ATLAS have compared a number of options for the spin-parity of this particle, and these all prefer no spin and positive parity. This, coupled with the measured interactions of the new particle with other particles, strongly indicates that it is a Higgs boson.

From The SM
To The
MSSM

	FERMION	BOSON
ENERGY		g, γ, Z^0, $W^{\pm}$; H^0
MATTER	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$; e_R μ_R τ_R; ν_{eR} $\nu_{\mu R}$ $\nu_{\tau R}$; $\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$; u_R c_R t_R; d_R s_R b_R	

	FERMION	BOSON
ENERGY	$\tilde{g}$, $\tilde{\gamma}$, $\tilde{Z}^0$, $\tilde{W}^\pm$ $\tilde{H}^0$, $\tilde{h}^0$, $\tilde{A}^0$, $\tilde{H}^\pm$	g, γ, Z^0, $W^\pm$ H^0, h^0, A^0, $H^\pm$
MATTER	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$ e_R, μ_R, τ_R ν_{e_R}, ν_{μ_R}, ν_{τ_R} $\begin{pmatrix}u\\ d\end{pmatrix}_L \begin{pmatrix}c\\ s\end{pmatrix}_L \begin{pmatrix}t\\ b\end{pmatrix}_L$ u_R, c_R, t_R d_R, s_R, b_R	$\begin{pmatrix}\tilde{\nu}_{e_L}\\ \tilde{e}_L\end{pmatrix} \begin{pmatrix}\tilde{\nu}_{\mu_L}\\ \tilde{\mu}_L\end{pmatrix} \begin{pmatrix}\tilde{\nu}_{\tau_L}\\ \tilde{\tau}_L\end{pmatrix}$ $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_R$ $\tilde{\nu}_{e_R}$, $\tilde{\nu}_{\mu_R}$, $\tilde{\nu}_{\tau_R}$ $\begin{pmatrix}\tilde{u}_L\\ \tilde{d}_L\end{pmatrix} \begin{pmatrix}\tilde{c}_L\\ \tilde{s}_L\end{pmatrix} \begin{pmatrix}\tilde{t}_L\\ \tilde{b}_L\end{pmatrix}$ $\tilde{u}_R$, $\tilde{c}_R$, $\tilde{t}_R$ $\tilde{d}_R$, $\tilde{s}_R$, $\tilde{b}_R$

Bohr 1913

$$|\vec{L}| = 2\pi\hbar n \quad .$$

Wilson-Sommerfeld 1916

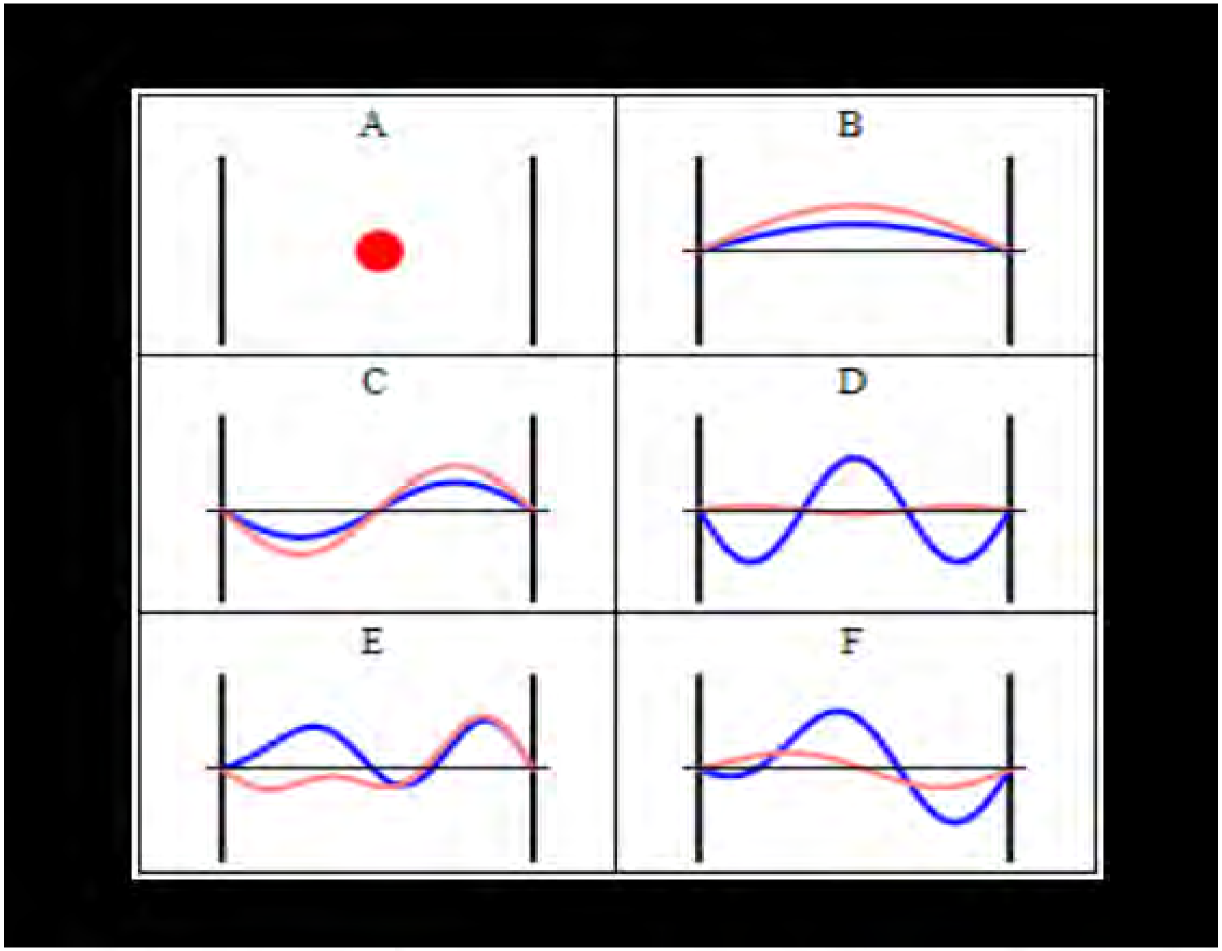
$$\int P\,dq = 2\pi\hbar n \quad .$$

de Broglie 1924

$$\vec{p} = \hbar\vec{k} \quad .$$

Schroedinger 1925

$$i\hbar\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + V(\vec{r})\Psi$$



https://en.wikipedia.org/wiki/Particle_in_a_box#/media/File:InfiniteSquareWellAnimation.gif

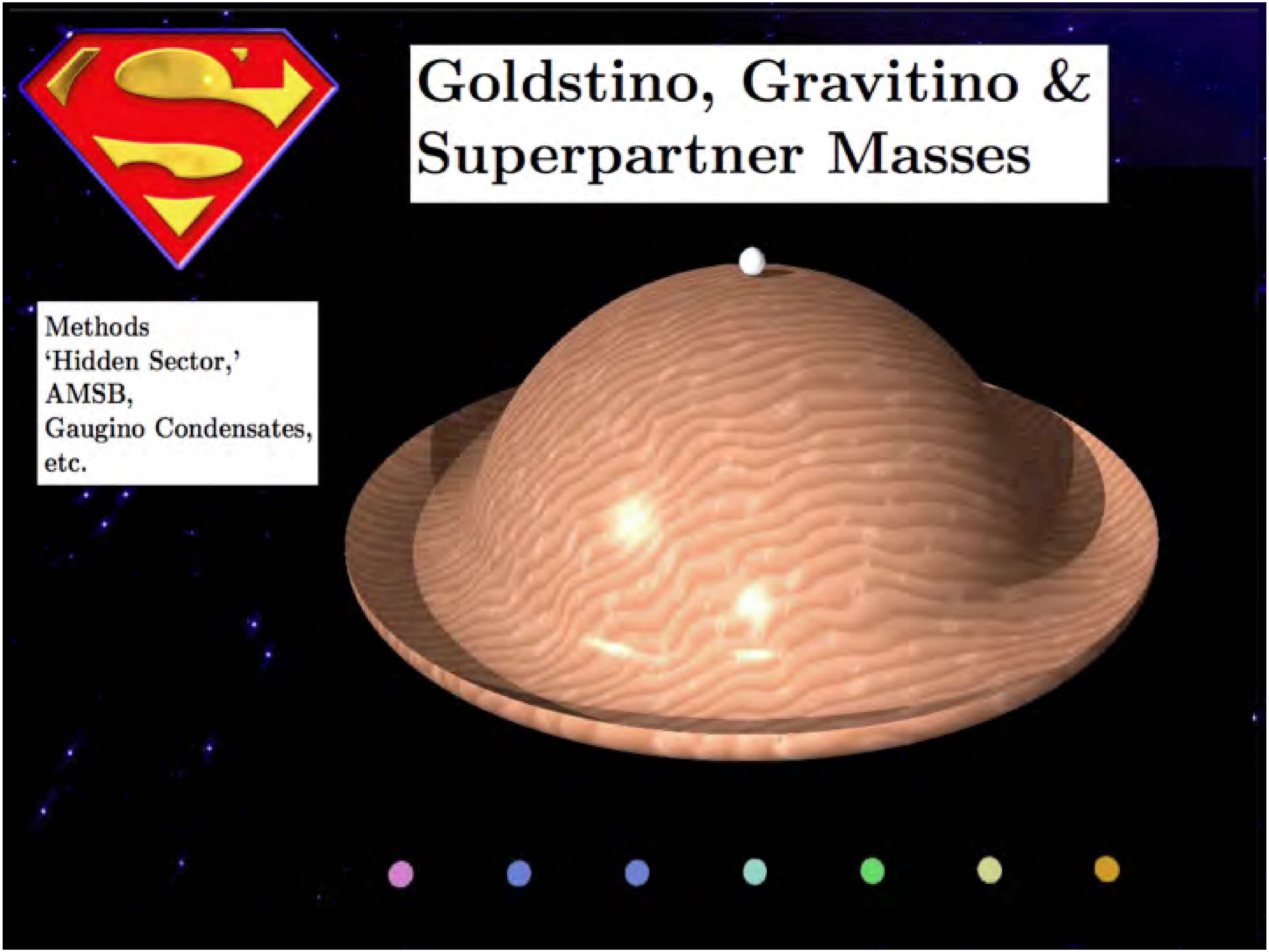
Two Identical Particles In A Box

$$E_{n_1, n_2} = \frac{\hbar^2 \pi^2}{2 M_0 L^2} [n_1 + n_2]$$

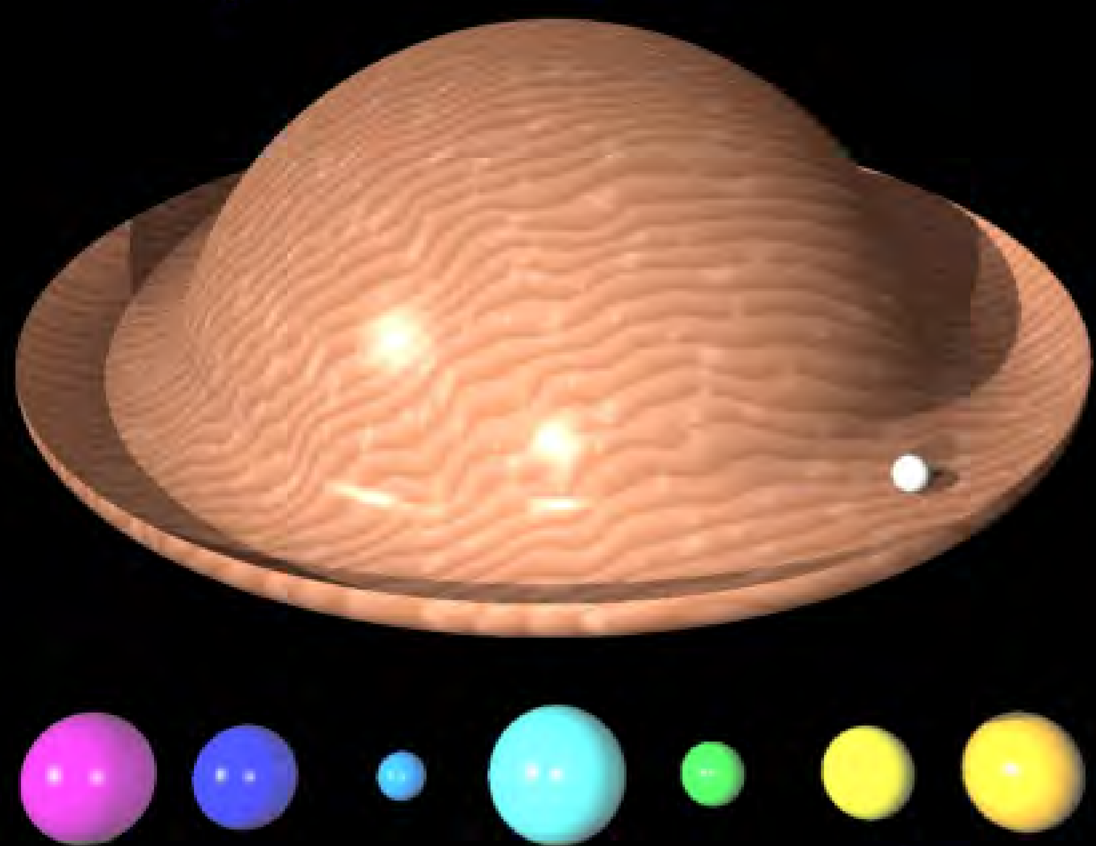
Two Identical Bosons Ground State : $n_1 = n_2 = 1$

Two Identical Fermions Ground State : $n_1 = 1, n_2 = 2$ *OR*

$n_1 = 2, n_2 = 1$


Goldstino, Gravitino &
Superpartner Masses
Methods
'Hidden Sector,'
AMSB,
Gaugino Condensates,
etc.

Superpartner Mass & The Goldstino



Force Carriers (Gauge Particles)

	M	Q	S	
$g_{\mu\upsilon}$ (graviton)	0	0	2	
Ψ_μ^d (gravitino)	0	0	3/2	
	80.6	+1	1	(charged IVB) W_μ^+
	?	+1	1/2	(+charged Wino) $\tilde{W}^+$
G_μ^i (gluon)	0	0	1	
$\tilde{\lambda}^i$ (gluino)	0	0	1/2	
	91.2	0	1	(neutral IVB) Z_μ^0
	?	0	1/2	(neutral Zeno) $\tilde{Z}$
A_μ (photon)	0	0	1	
$\tilde{\lambda}$ (photino)	?	0	1/2	
	80.6	-1	1	(charged IVB) W_μ^-
	?	-1	1/2	(-charged Wino) $\tilde{W}^-$

SQuarks & Quarks

	M	Q	S
u	4×10^{-3}	2/3	1/2
$\tilde{u}$ (up-squark)	?	2/3	0
d	7×10^{-3}	-1/3	1/2
(down-squark) $\tilde{d}$	?	-1/3	0
c	1.5	2/3	1/2
$\tilde{c}$ (charmed-squark)	?	2/3	0
s	0.15	-1/3	1/2
(strange-squark) $\tilde{s}$	?	-1/3	0
t	173	2/3	1/2
$\tilde{t}$ (top-squark)	?	2/3	0
b	4.7	-1/3	1/2
(bottom-squark) $\tilde{b}$	?	-1/3	0

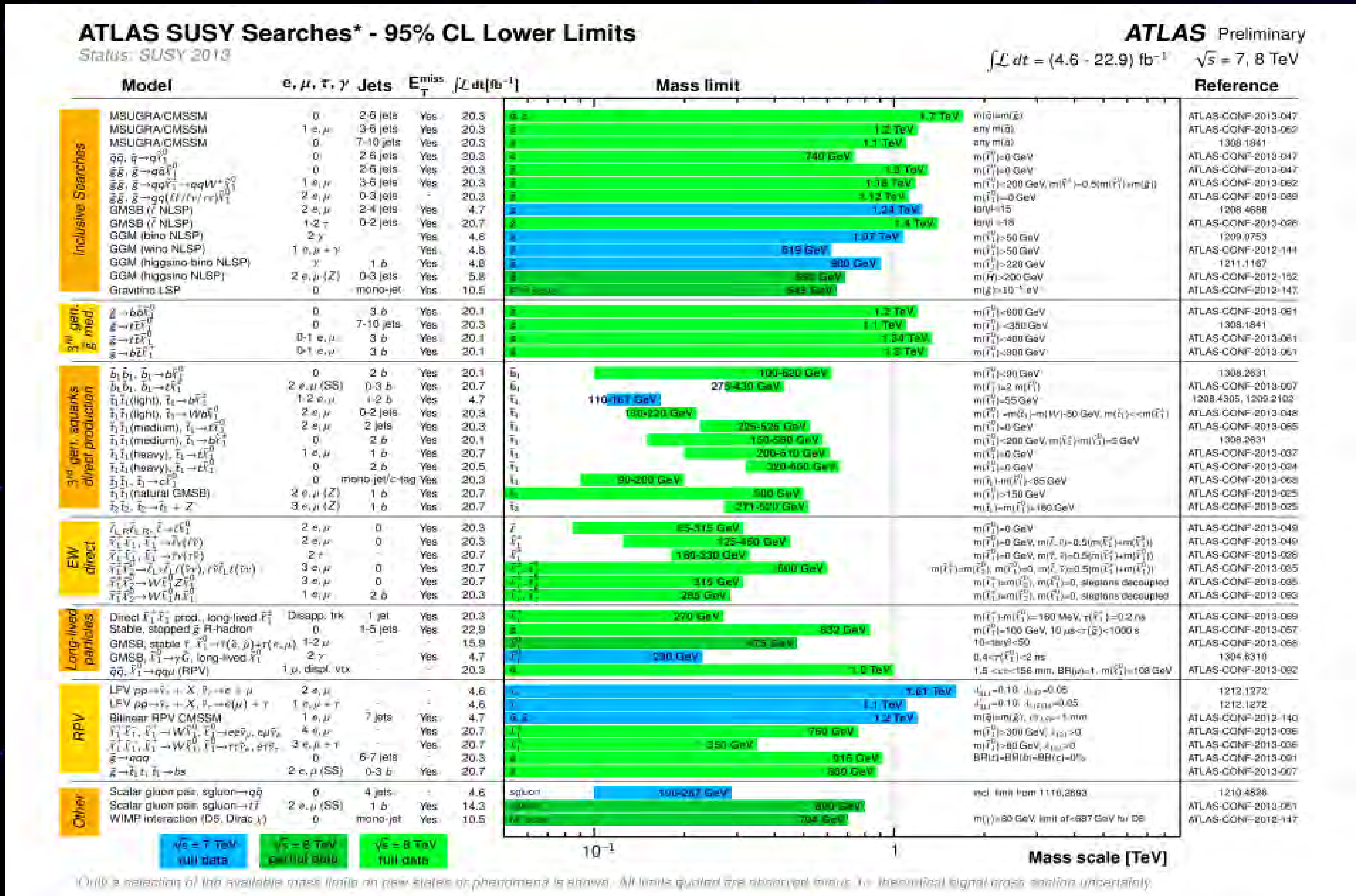
SLeptons & Leptons

mass unit $\frac{GeV}{c^2}$

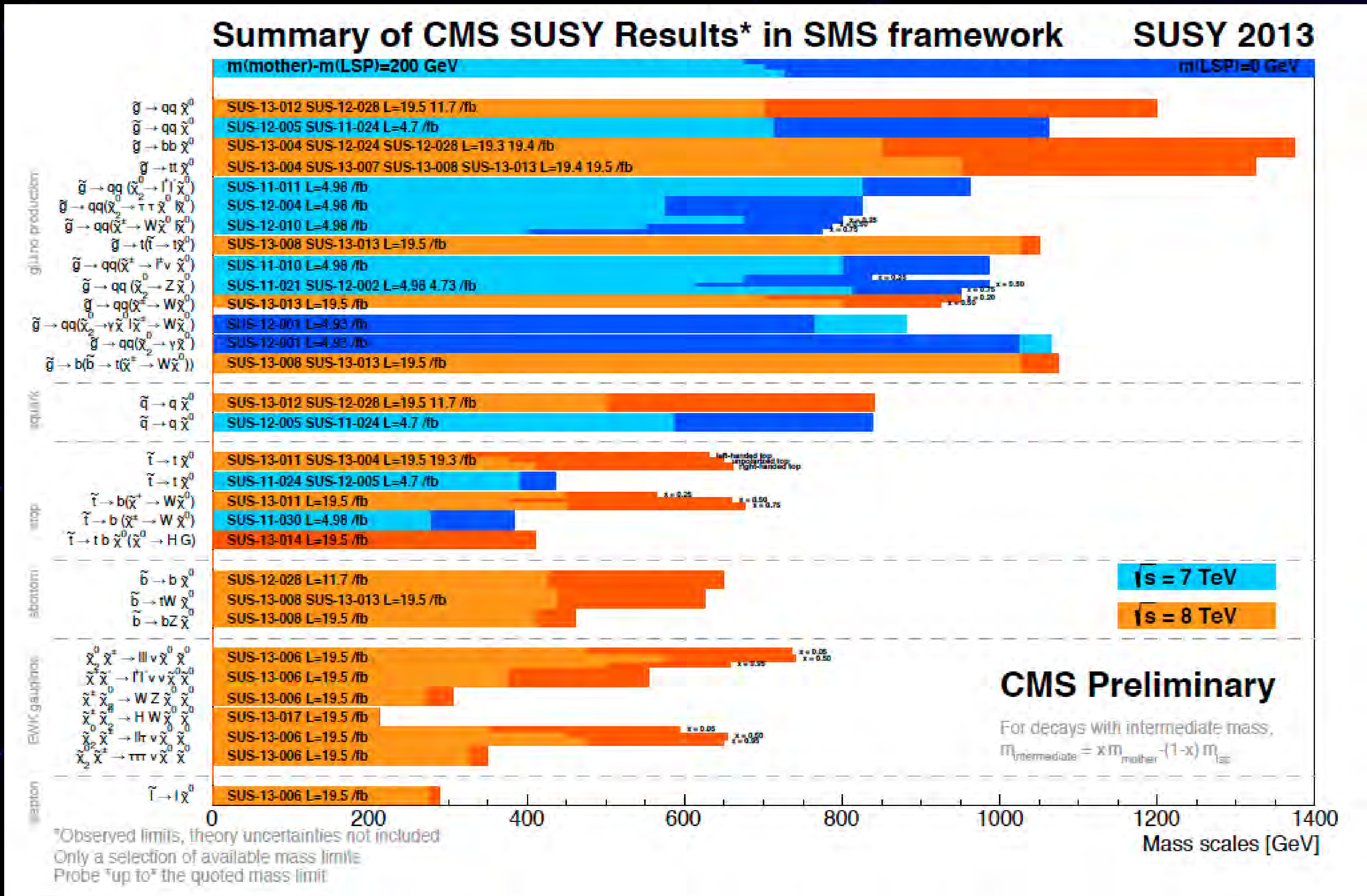
$m_\upsilon \rightarrow 10^{-8}/10^{-4}/10^{-2}$

	M	Q	S
υ_e	~0	0	1/2
$\tilde{\upsilon}_e$ (e-sneutrino)	?	0	0
e	5×10^{-4}	-1	1/2
(selectron) $\tilde{e}$	?	-1	0
υ_μ	~0	0	1/2
$\tilde{\upsilon}_\mu$ (μ -sneutrino)	?	0	0
μ	0.106	-1	1/2
(smuon) $\tilde{\mu}$	?	-1	0
υ_τ	~0	0	1/2
$\tilde{\upsilon}_\tau$ (τ-sneutrino)	?	0	0
τ	1.784	-1	1/2
(staon) $\tilde{\tau}$	?	-1	0

LHC Search For The MSSM (Sci Run-1)



ATLAS SUSY Searches* - 95% CL Lower Limits
Status: SUSY 2013
ATLAS Preliminary
∫L dt = (4.6 - 22.9) fb⁻¹
√s = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^miss
∫L dt[fb⁻¹]
Mass limit
Reference
Inclusive Searches
3rd gen. g̃ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
√s = 7 TeV full data
√s = 8 TeV partial data
√s = 8 TeV full data
10⁻¹
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
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SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
gluino production
squark
stop
sbottom
EWK gauginos
slepton
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x) m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Constrained Minimal Supersymmetric Standard Model (CMSSM)

G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D 49 (1994) 6173

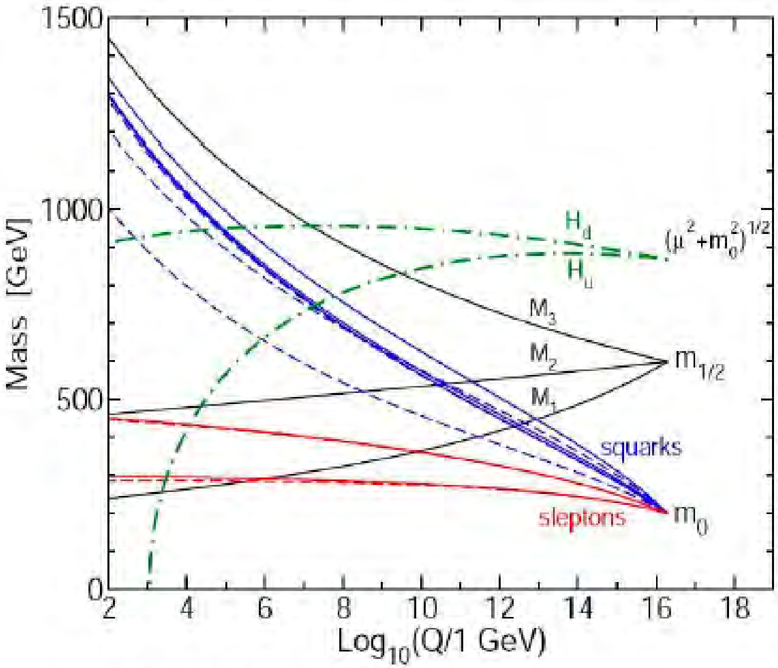


figure from hep-ph/9709356

At $M_{\rm GUT} \simeq 2\times 10^{16}\,\rm GeV$:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars
  $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m_0^2$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB
  $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t}\tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$
- five independent parameters:
  $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ {\rm sgn}(\mu)$
- well developed machinery to compute masses and couplings

Bayes FITS

In general supersymmetric SM too many free parameters

Phenomenological Minimal Supersymmetric

Symbol	Description	number of parameters
$\tan\beta$	the ratio of the vacuum expectation values of the two Higgs doublets	1
M_A	the mass of the pseudoscalar Higgs boson	1
μ	the higgsino mass parameter	1
M_1	the bino mass parameter	1
M_2	the wino mass parameter	1
M_3	the gluino mass parameter	1
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}$	the first and second generation squark masses	3
$m_{\tilde{l}}, m_{\tilde{e}_R}$	the first and second generation slepton masses	2
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$	the third generation squark masses	3
$m_{\tilde{L}}, m_{\tilde{\tau}_R}$	the third generation slepton masses	2
A_t, A_b, A_τ	the third generation trilinear couplings	3

…and from the media…

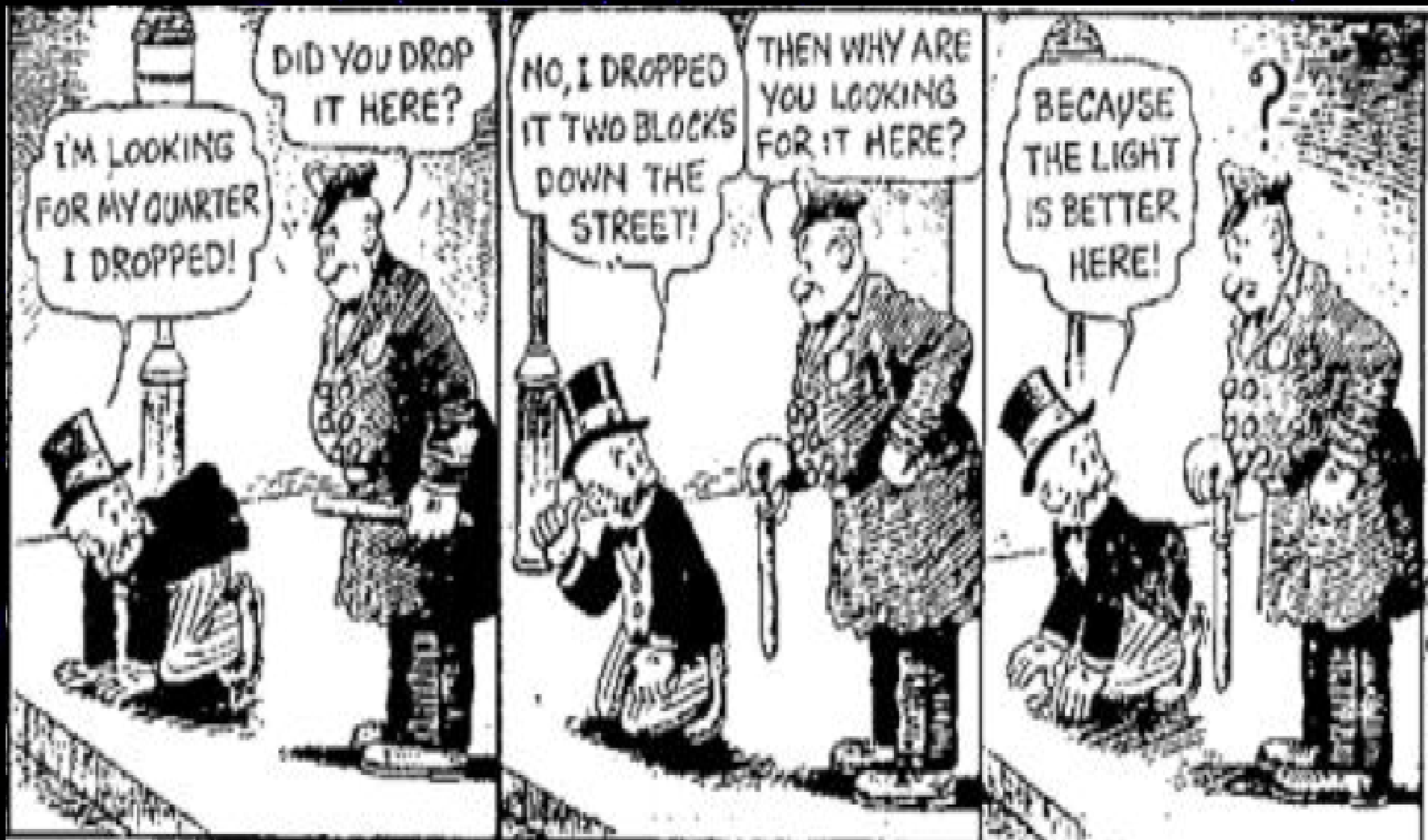
Is Supersymmetry Dead?

The grand scheme, a stepping-stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

SCIENTIFIC AMERICAN™

April 2012


Wrong!


I'M LOOKING FOR MY QUARTER I DROPPED!
DID YOU DROP IT HERE?
NO, I DROPPED IT TWO BLOCKS DOWN THE STREET!
THEN WHY ARE YOU LOOKING FOR IT HERE?
BECAUSE THE LIGHT IS BETTER HERE!
?

Physics World October 2014

Sticking with SUSY

In my view, the current situation is akin to that ofan explorer who, having scoured the eastern seaboard of North America, concludes that no groves of Sequoiadendron giganteum exist in the entire continental USA.

As with this hypothetical hunt for giant sequoia trees, finding evidence for SUSY depends on the observer looking in the right place.

Another example concerns the possible extension of something similar to quark–lepton symmetry. This occurs between quarks and the family of particles known as leptons, which includes the electron and its heavier cousins, the muon and the tau. When this symmetry – which explains why pairs of leptons appear in the Standard Model alongside pairs of quarks – is applied to a version of the Standard Model that possesses SUSY, the implication is that the Higgs boson discovered at the LHC is not the only one. Instead, there must be a minimum of five Higgs bosons. This might seem like an embarrassment of riches, but if at some future point a second Higgs boson is observed, it could be a sign of SUSY appearing in nature.

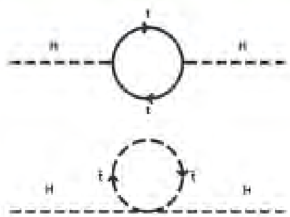
The 125 GeV Higgs Boson and SUSY

A curse…

In SUSY Higgs mass is a calculated quantity

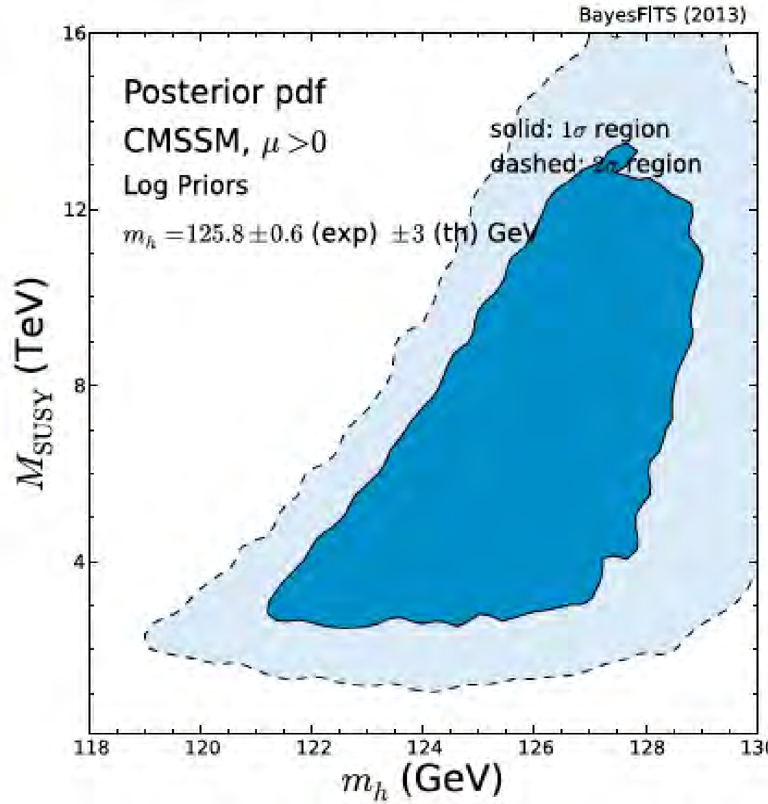
➢ 1 loop correction

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$



$$X_t = A_t - \mu \cot\beta$$

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$$



Only m_h~125 GeV and CMS lower bounds on SUSY applied here.

$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\ {\rm GeV})^2}{\sigma^2+\tau^2}}$$

$\sigma = 0.6$ GeV, $\tau = 2$ GeV

125 GeV Higgs -> multi-TeV SUSY

L. Roszkowski, PACIFIC-2014, 19 Sep. 2014

Effects:

MSSM vs. SM

Five Higges

Q: Why Would Nature Possess More Than One Higgs?

A: More Local Symmetries or …

$$L_{\ell_1} \equiv \frac{1-\gamma^5}{2} \begin{bmatrix} \nu_{e_1} & \nu_{\mu_1} \\ e_1 & \mu_1 \end{bmatrix}_{Y=-1 \quad H=-1}$$

$$R_{e_1} \equiv \tfrac{1}{2}(1+\gamma^5)\, e_1 \quad Y=-2 \quad H=0$$

$$R_{\mu_1} \equiv \tfrac{1}{2}(1+\gamma^5)\, \mu_1 \quad Y=-2 \quad H=0$$

$$L_{\ell_2} \equiv \frac{1-\gamma^5}{2} \begin{bmatrix} e_2 & \mu_2 \\ \nu_{e2} & \nu_{\mu2} \end{bmatrix}_{Y=1 \quad H=1}$$

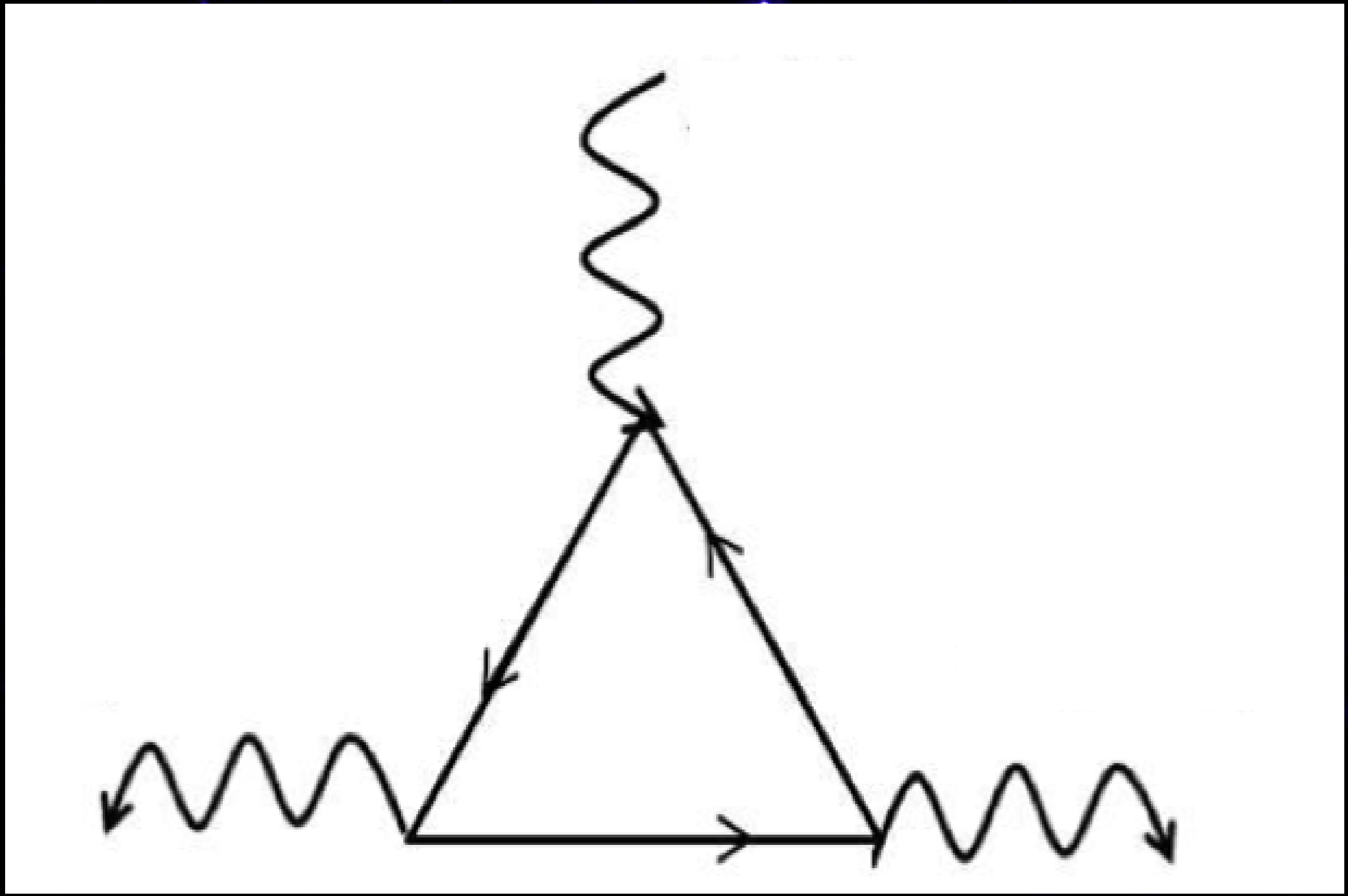
$$R_{e_2} \equiv \tfrac{1}{2}(1+\gamma^5)\, e_2 \quad Y=2 \quad H=0$$

$$R_{\mu_2} \equiv \tfrac{1}{2}(1+\gamma^5)\, \mu_2 \quad Y=2 \quad H=0$$

Q: Why Does SUSY Possess More Than One Higgs?

A: Anomalies!

But There Are Quantum Dangers: Anomalies



But There Are Quantum Dangers: Anomalies

Anomalies and Anomaly-Freedom Conditions

$$Q_u = Q_d + 1 = \frac{1}{2}\left[1 - \frac{1}{3}\left(2Q_e + 1\right)\right]$$

$$Q_c = Q_s + 1 = \frac{1}{2}\left[1 - \frac{1}{3}\left(2Q_\mu + 1\right)\right]$$

$$Q_t = Q_b + 1 = \frac{1}{2}\left[1 - \frac{1}{3}\left(2Q_\tau + 1\right)\right]$$

"g_e - 2"

The Best Known Theoretical Number in All of Science

Electron Anomalous Magnetic Moment

Measurement

$$g_e = 2.0023193038$$

Uncertainty

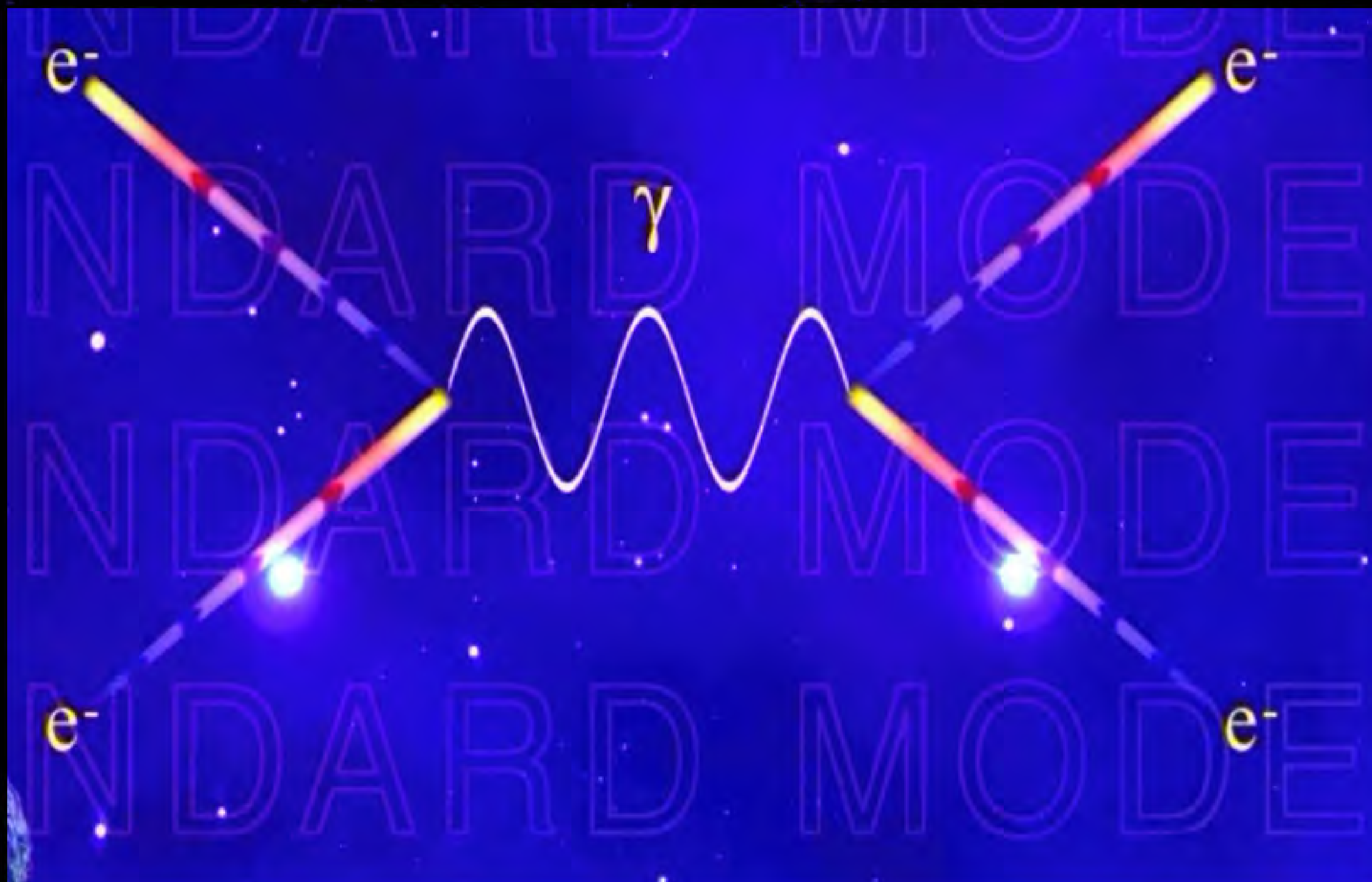
$$\Delta g_e = \pm 0.0000000040$$

Theory

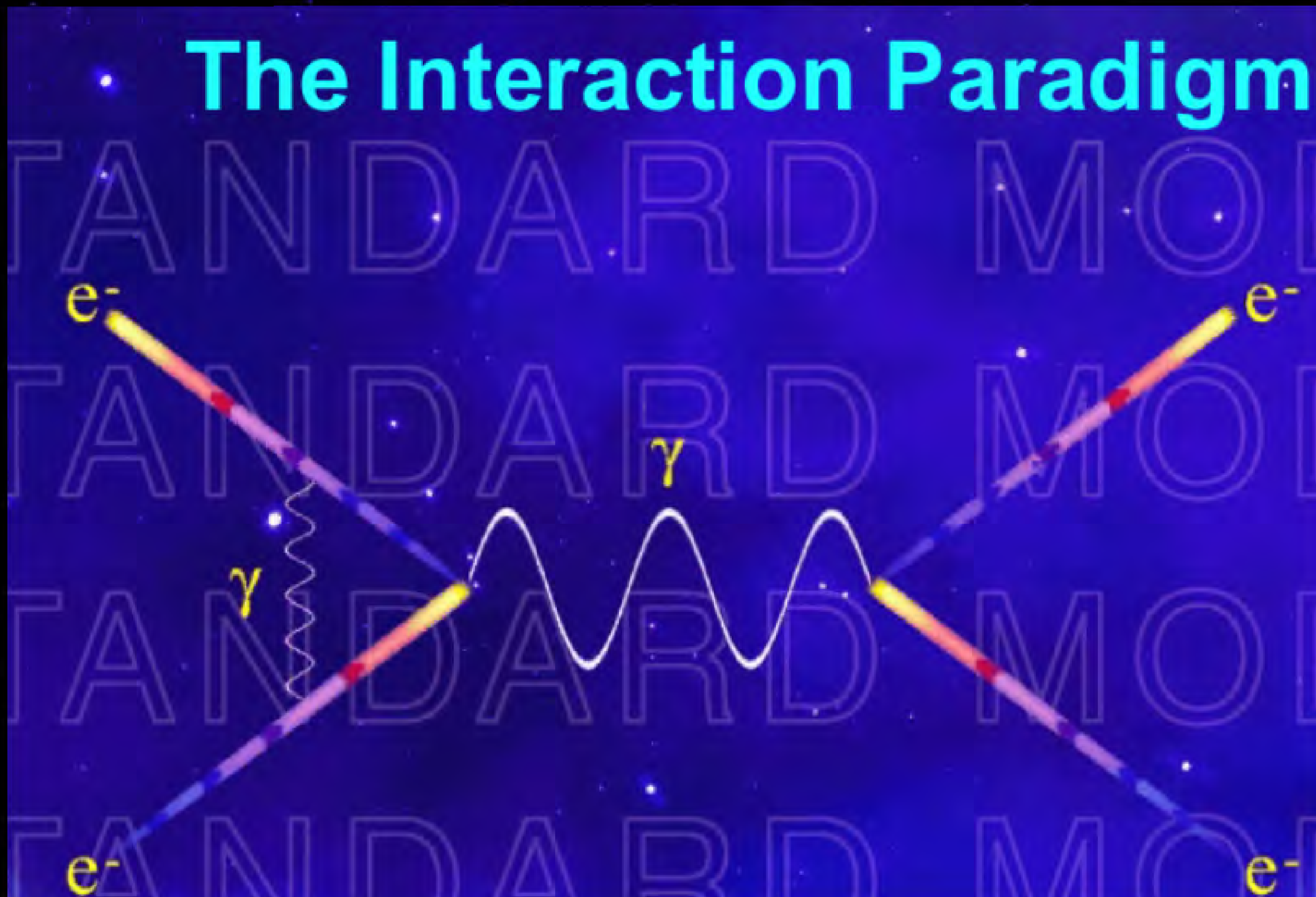
$$g_e = 2.0023193044$$

Quantum Loops &

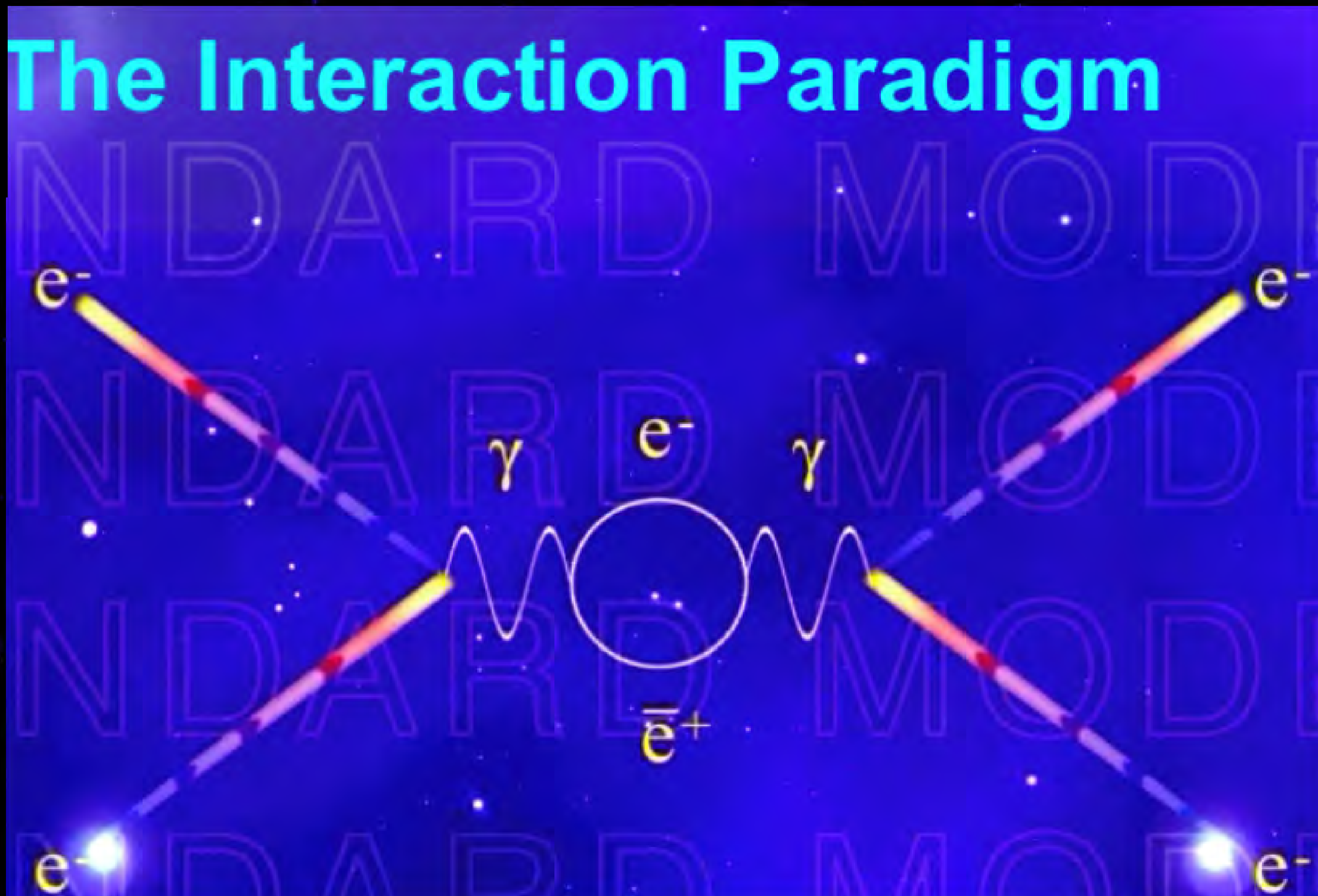
The Interaction Paradigm



Quantum Loops

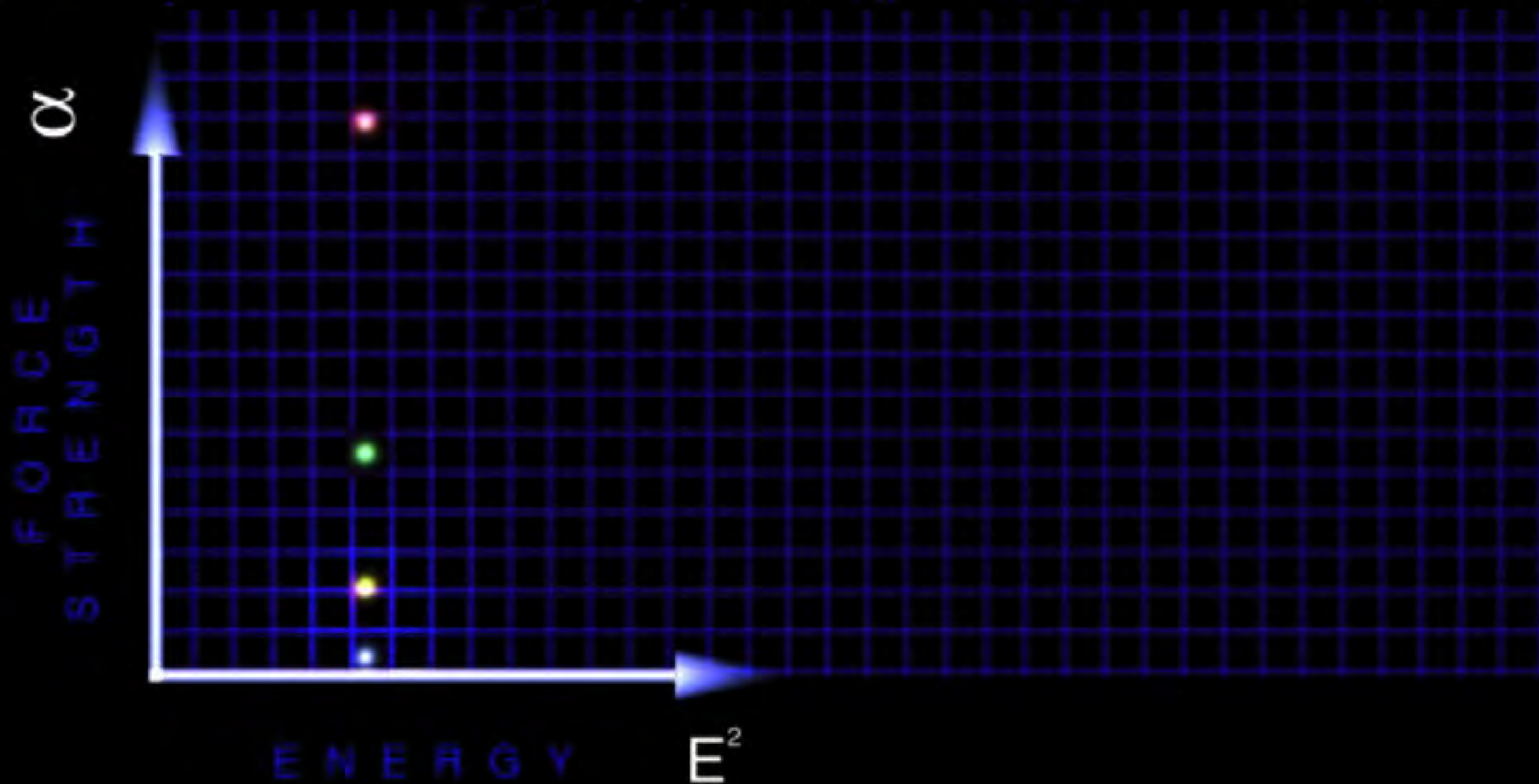


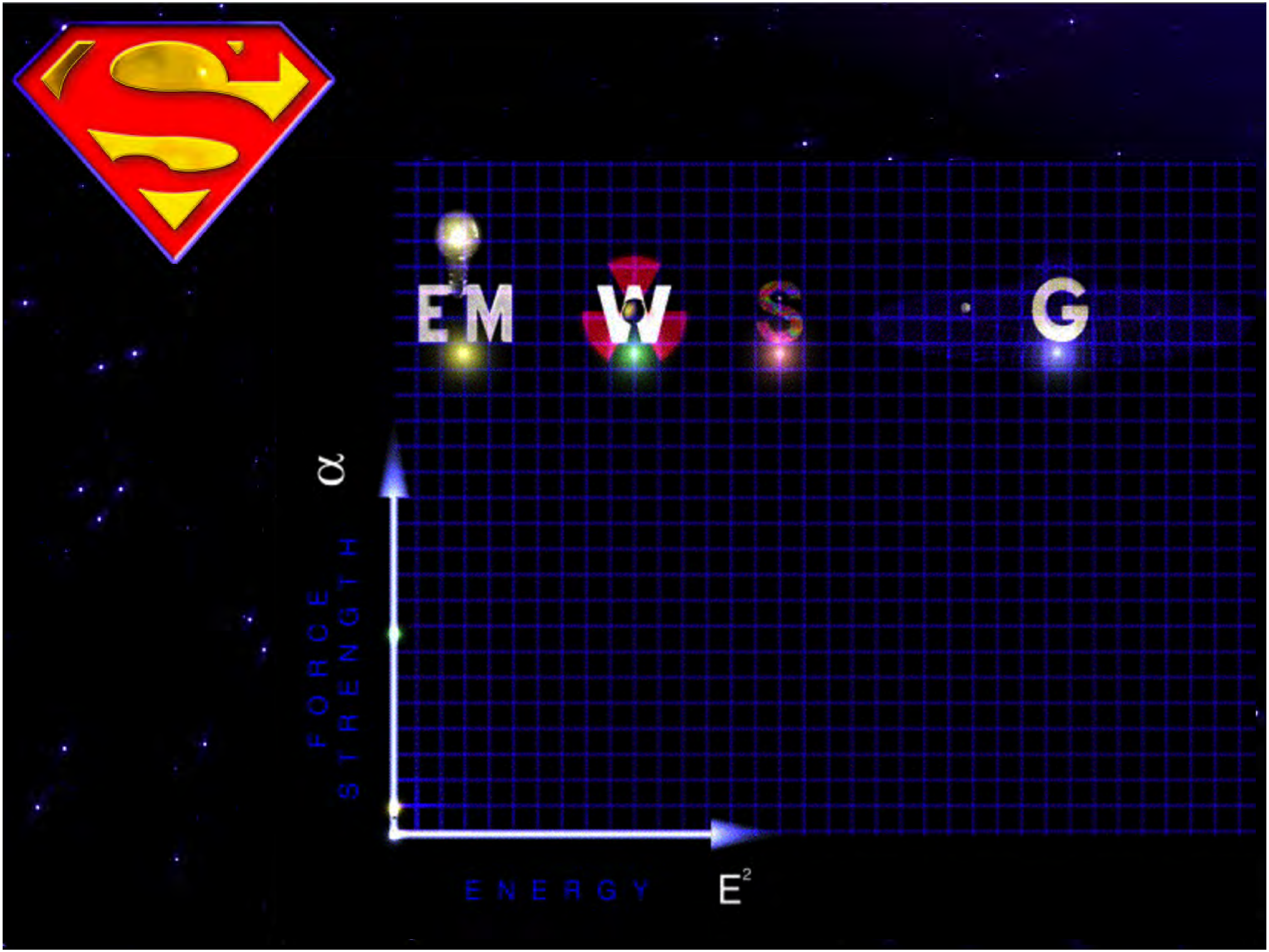
Quantum Loops



Effects: MSSM vs. SM Couplings

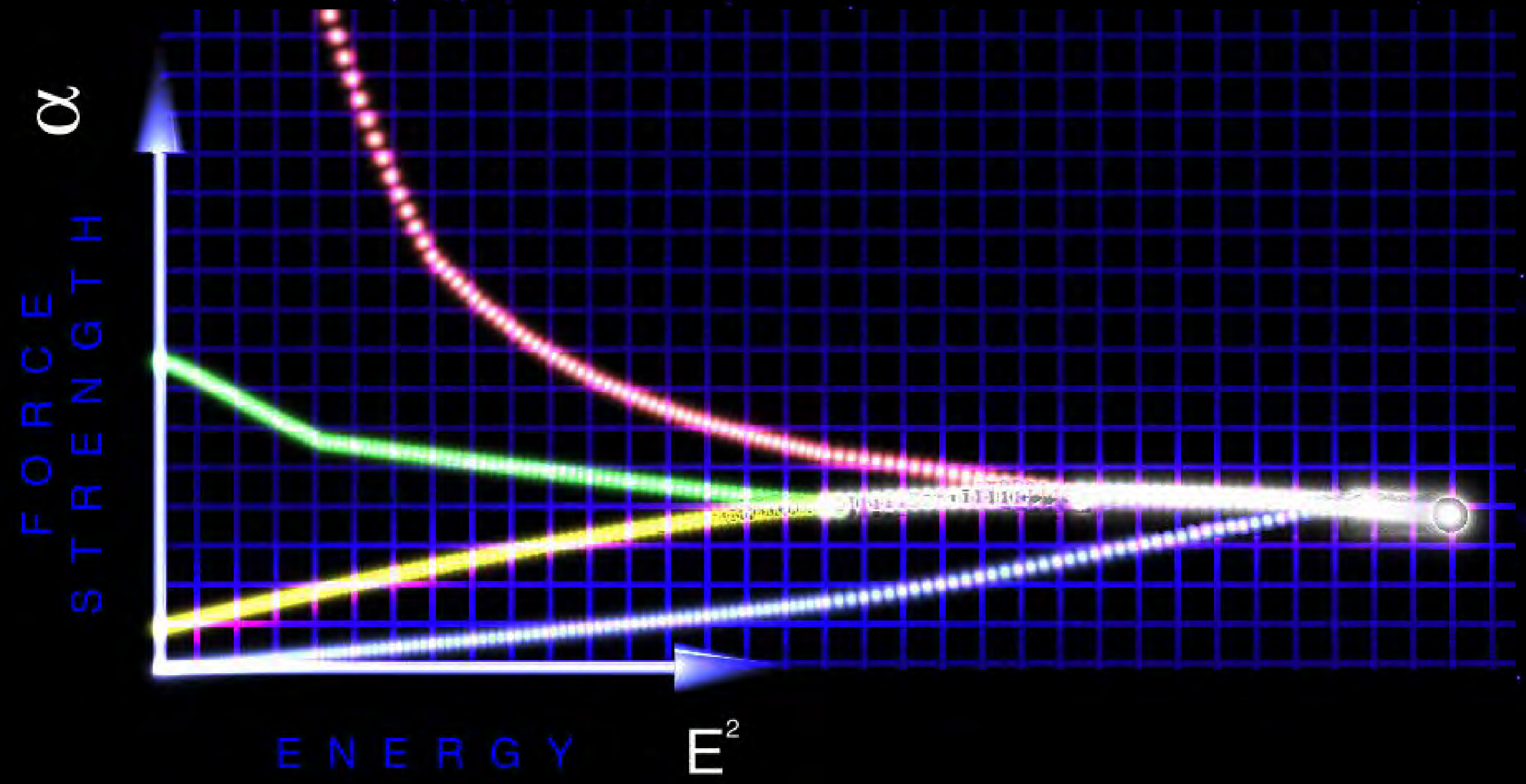
'Running Constants' with Superpartners

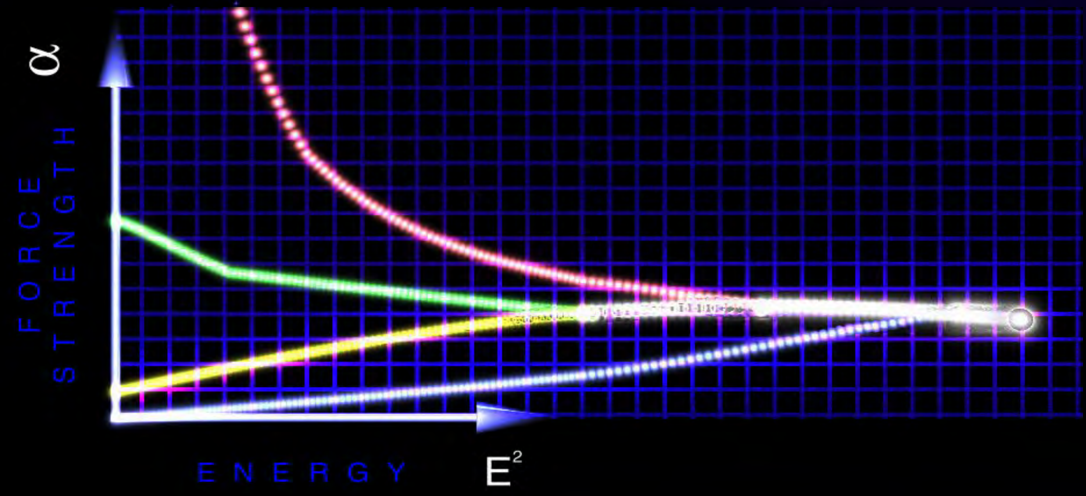




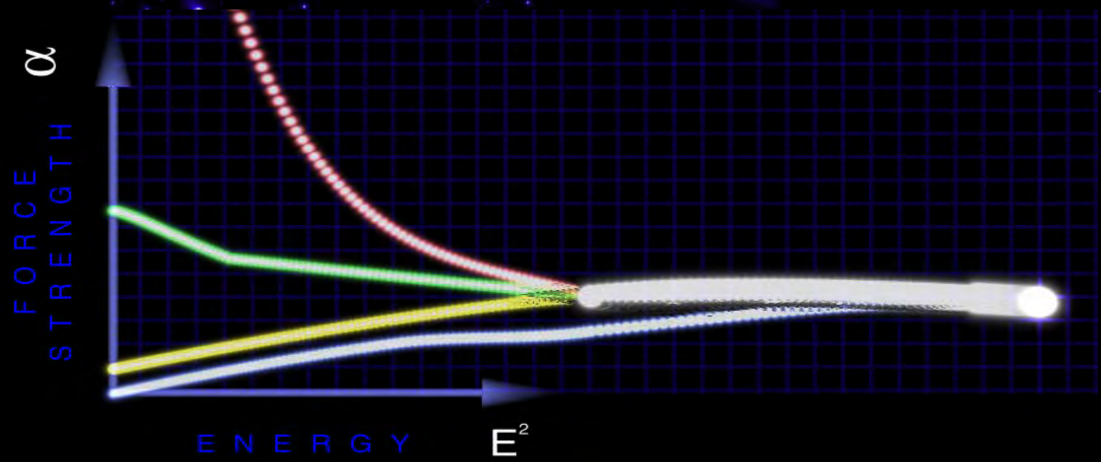
EM
W
S
G
α
FORCE
STRENGTH
ENERGY
E²

‘Running Constants’





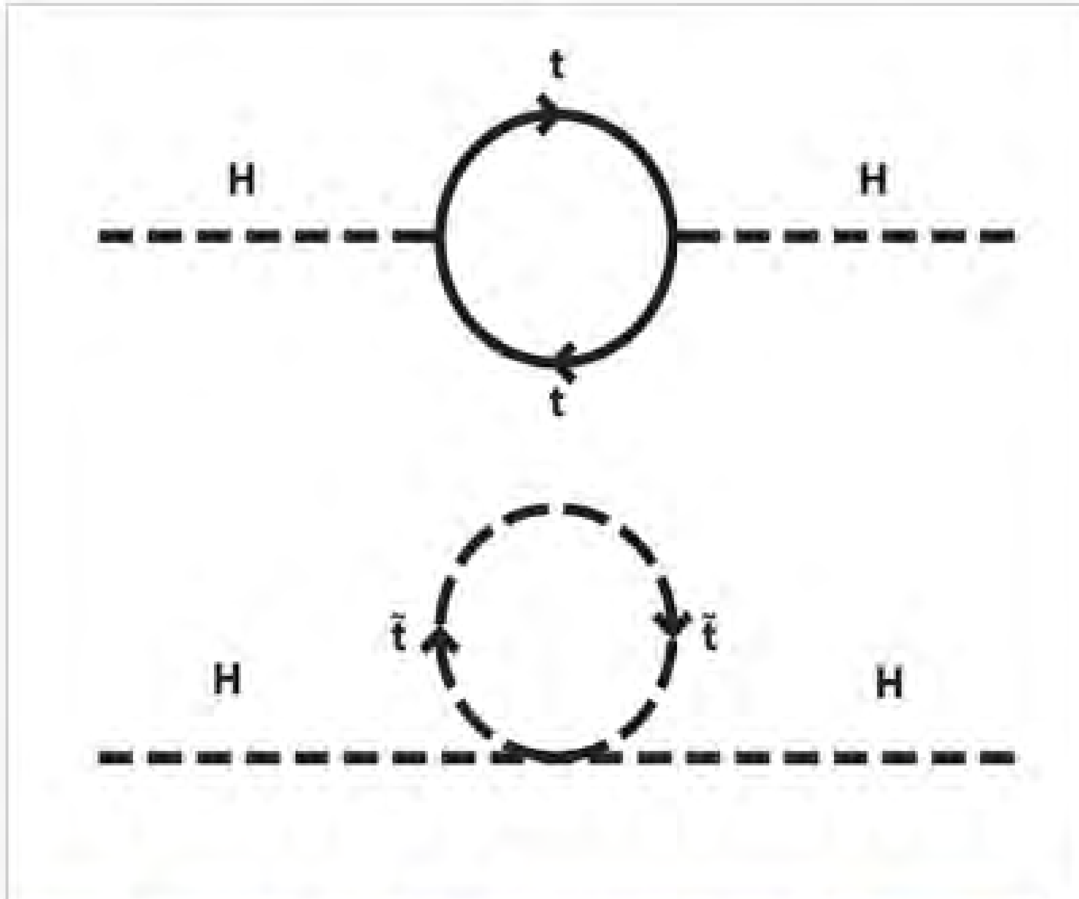
A Comparison



Effects:

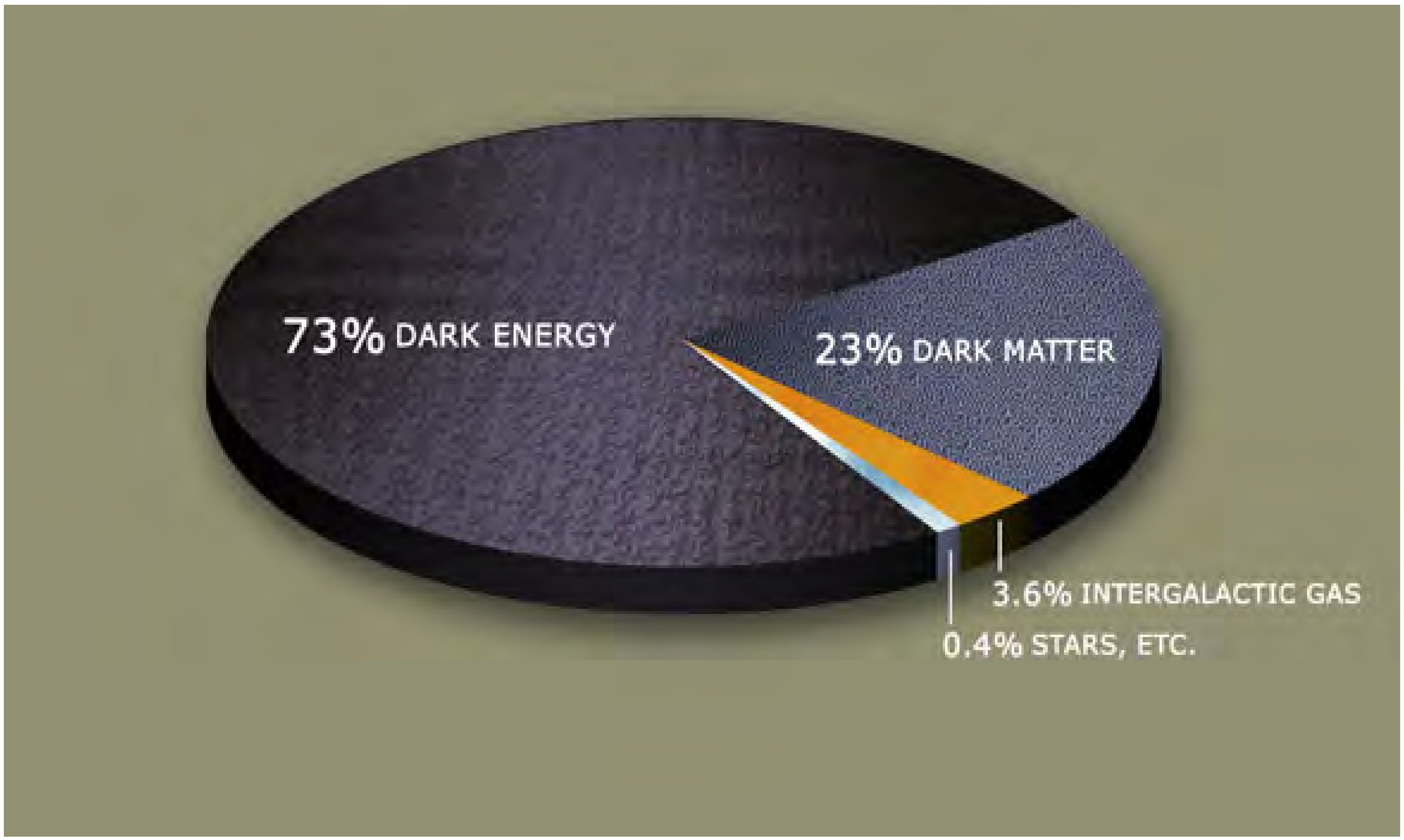
MSSM vs. SM

Naturalness



Cancellation of the Higgs boson quadratic mass renormalization between fermionic top quark loop and scalar top squark Feynman diagrams in a supersymmetric extension of the Standard Model

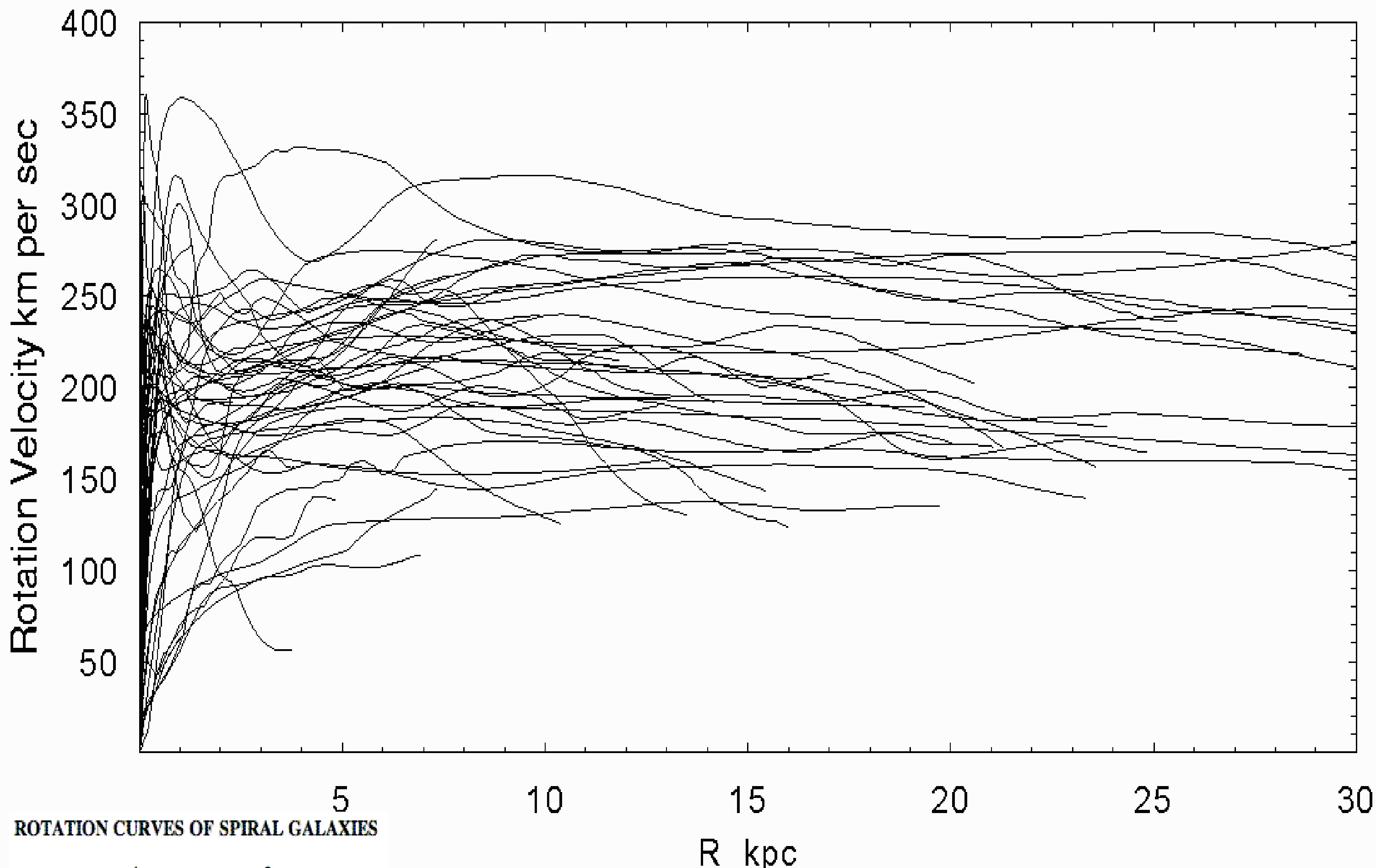
Effects:
MSSM vs. SM
Dark Matter


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Lightest Supersymmetric Particle

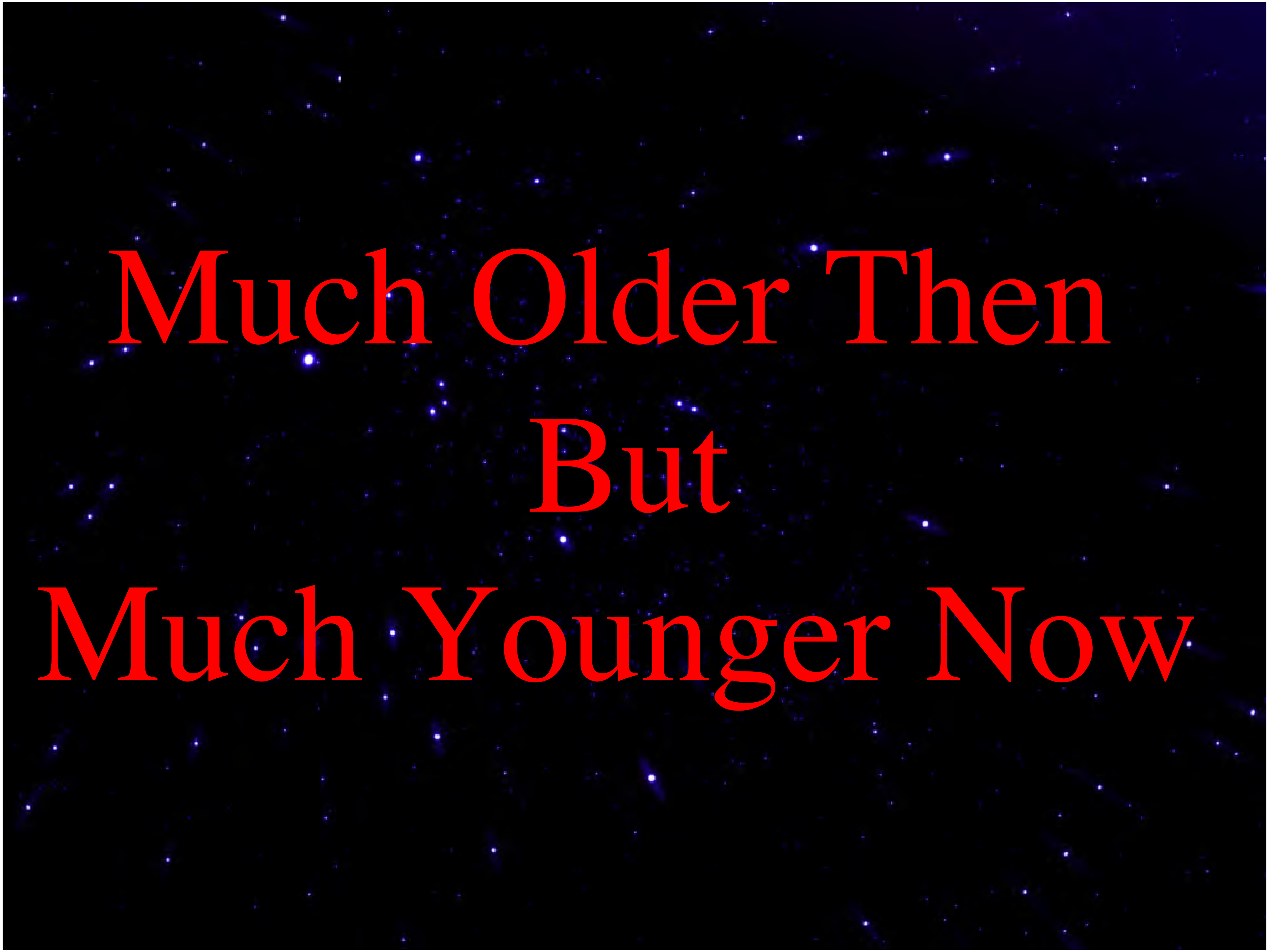
From Wikipedia, the free encyclopedia

In particle physics, the **lightest supersymmetric particle** (**LSP**) is the generic name given to the lightest of the additional hypothetical particles found in supersymmetric models. In models with R-parity conservation, the LSP is stable. There is extensive observational evidence for an additional component of the matter density in the Universe that goes under the name dark matter. The LSP of supersymmetric models is a dark matter candidate and is a Weakly interacting massive particle (WIMP).[1]



ROTATION CURVES OF SPIRAL GALAXIES

Yoshiaki Sofue[1] and Vera Rubin[2]



Much Older Then
But
Much Younger Now

Is string theory phenomenologically viable?

S. James Gates Jr

String theory is entering an era in which its theoretical constructs will be confront-ed by experimental data. Some cherished ideas just might fail to pass the test.

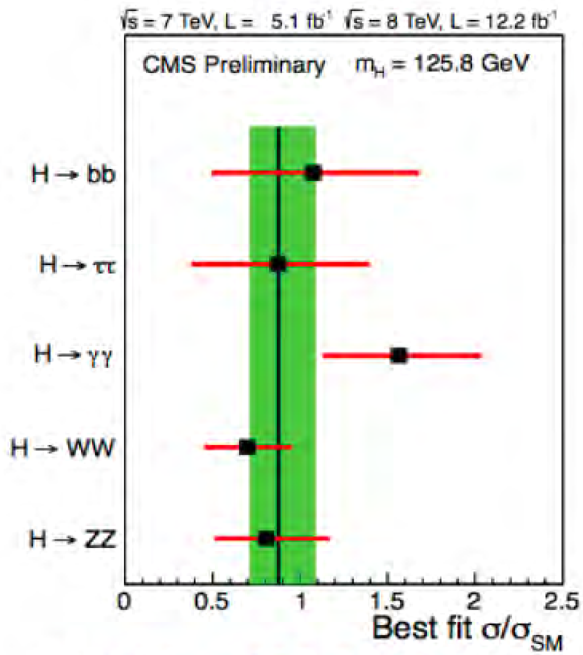
June 2006 Physics Today

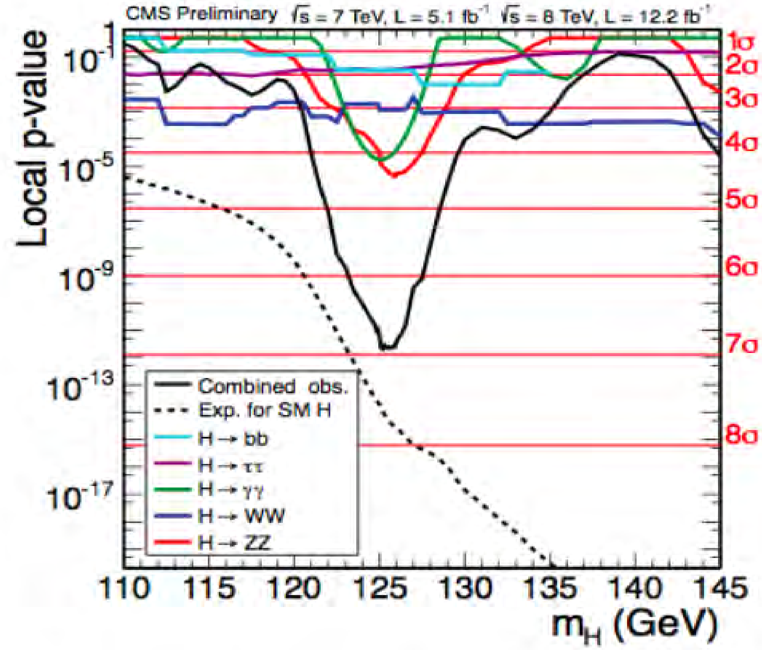
However, it will take great good fortune for a superparticle to be directly observable. The range of masses discussed in the literature is something like 1,000 to 30,000 times the mass of the proton, which is roughly 1 GeV/c^2

With the dates of discovery and masses of the neutron and W bosons as benchmarks, one can crudely estimate the rate at which humanity is progressing in its ability to detect massive particles: about 1.5 GeV/c^2 year. Thus, if Nature is kind enough to provide light superpartners, one might still expect about a century to pass before a superparticle is directly observed.

Much more likely, evidence for supersymmetry will emerge by indirect means. Such evidence might be provided by precision measurements of the rates of change of the coupling constants, anomalies in lifetimes or branching ratios in decays of known particles, and so forth.

Combined Limit & Global Picture





For M_H = 125.8 GeV

Observed: 6.9; Expected: 7.8 ➔ Signal strength: 0.88 ± 0.21

PHYSICS HIGHLIGHTS - PLAIN ENGLISH SUMMARIES

See also LHCb public webpage: http://lhcb-public.web.cern.ch/lhcb-public/

LHCb photo gallery https://cdsweb.cern.ch/collection/LHCb%20Photos?ln=en

Discovery of Ultra-Rare Decay at LHC

July 24th 2013

Summary: The LHC experiments LHCb and CMS have announced the observation of one of the rarest processess in fundamental physics, concluding a search that has lasted almost 30 years.

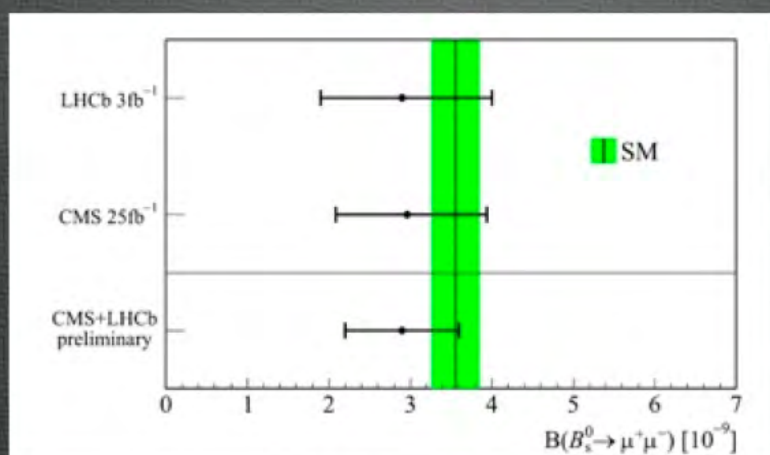


Image: Results of the LHCb and CMS experiments and the combination of these. By combining the results the threshold to announce discovery is passed. *(Credit LHCb and CMS)*

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2015-314
LHCb-PAPER-2015-051
December 14, 2015

Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

The LHCb collaboration[†]

On the anomalies in the latest LHCb data

T. Hurth[*,a], F. Mahmoudi[†,b,c], S. Neshatpour[‡,d]

[a]*PRISMA Cluster of Excellence and Institute for Physics (THEP)*
Johannes Gutenberg University, D-55099 Mainz, Germany

[b]*Univ Lyon, Univ Lyon 1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon*
UMR5574, F-69230 Saint-Genis-Laval, France

[c]*Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

[d]*School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM)*
P.O. Box 19395-5531, Tehran, Iran

If the ‘anomalies in the branching ratios’ grow after more analysis of data, then the post-Standard Model Era will have begun -- a rich spectrum of Higgs-like fields could be the avatars for the existence of symmetries beyond those of the SM…

maybe even SUPERSYMMETRY.

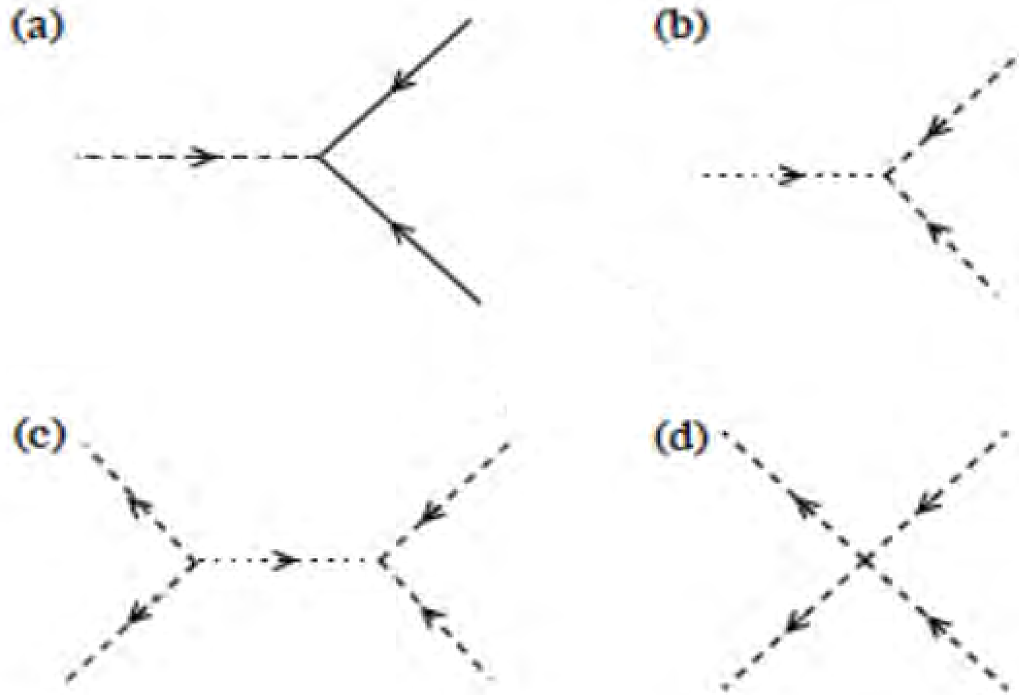
Effects: Taming The Quantum Vacuum

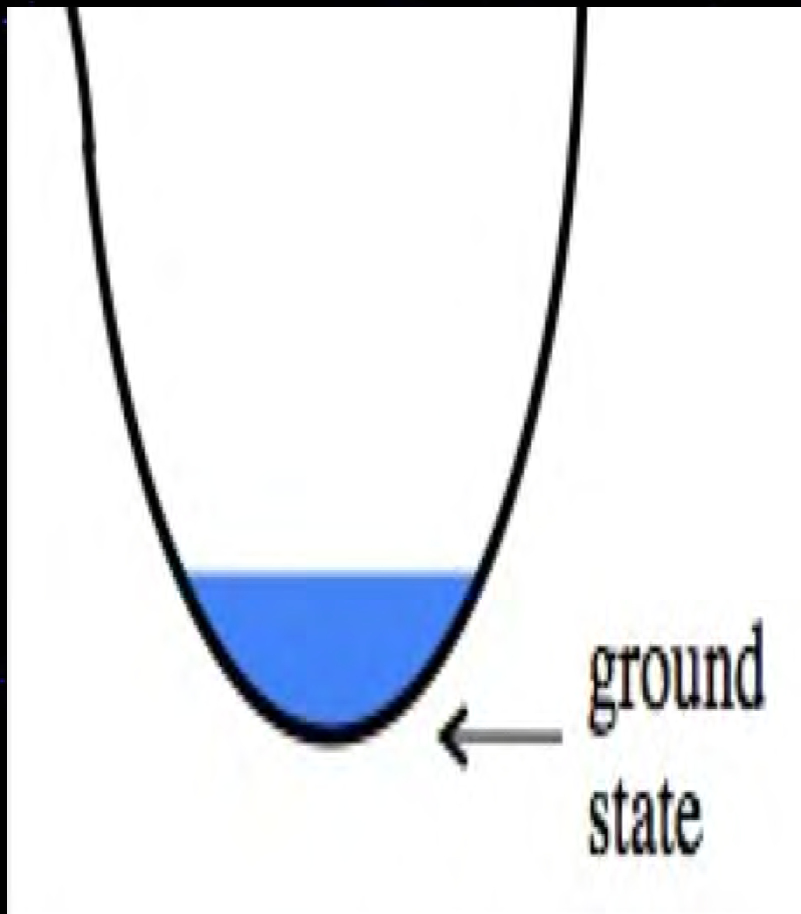
N = 4 supersymmetric Yang–Mills theory

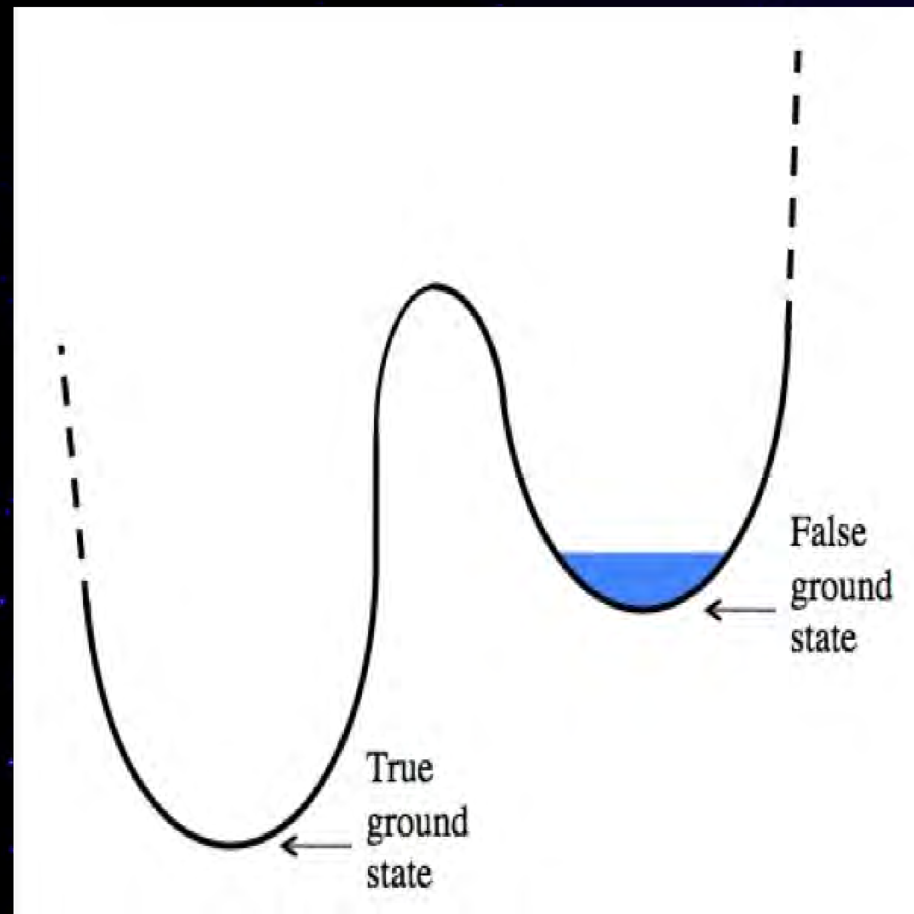
$$L = \mathrm{tr}\left\{ -\frac{1}{2g^2} F_{\mu\nu} F^{\mu\nu} + \frac{\theta_I}{8\pi^2} F_{\mu\nu} \bar{F}^{\mu\nu} - i \overline{\lambda}^a \overline{\sigma}^\mu D_\mu \lambda_a - D_\mu X^i D^\mu X^i \right.$$

$$\left. + g C_i^{ab} \lambda_a [X^i, \lambda_b] + g \overline{C}_{iab} \overline{\lambda}^a [X^i, \overline{\lambda}^b] + \frac{g^2}{2} [X^i, X^j]^2 \right\}$$

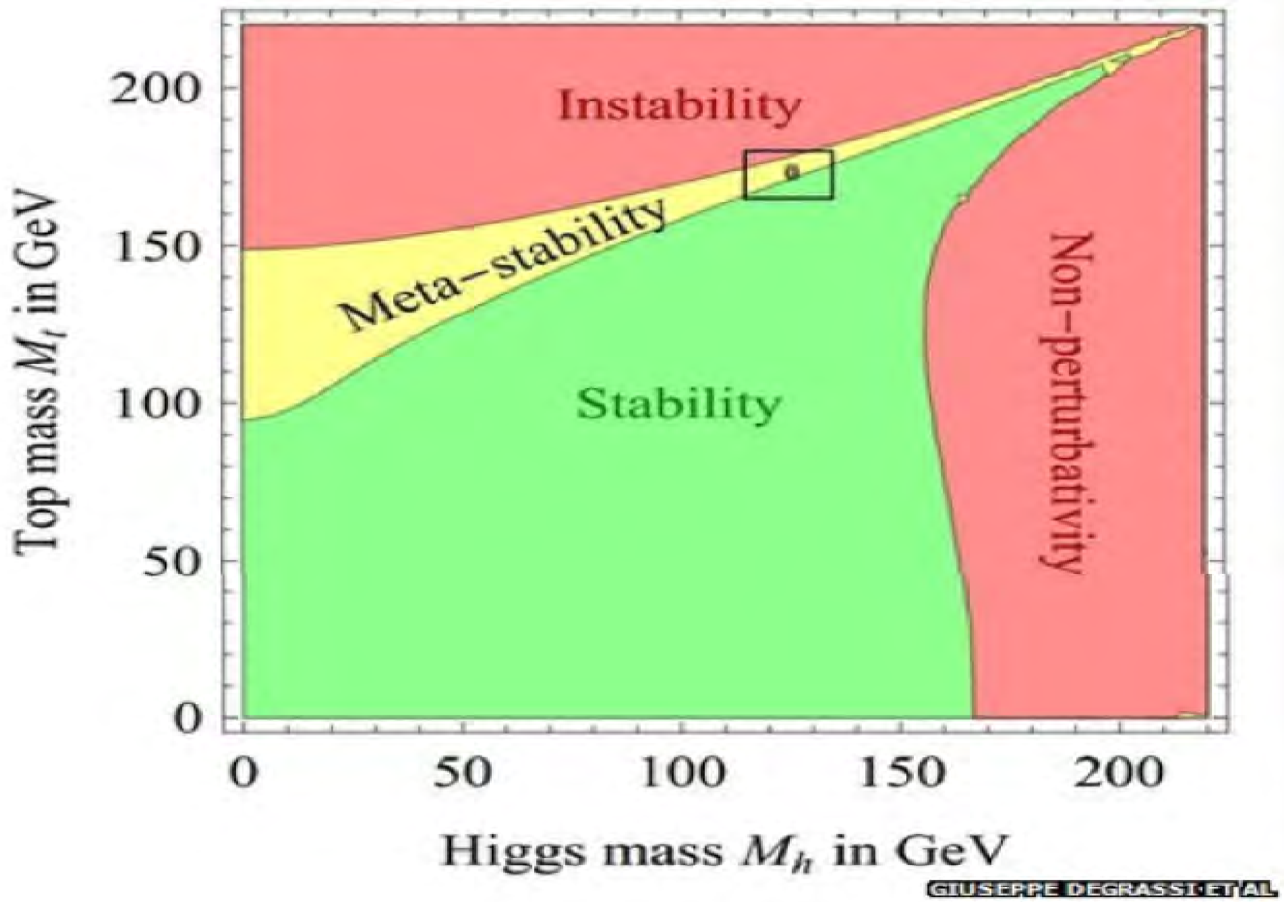
$N = 4$ supersymmetric Yang–Mills theory





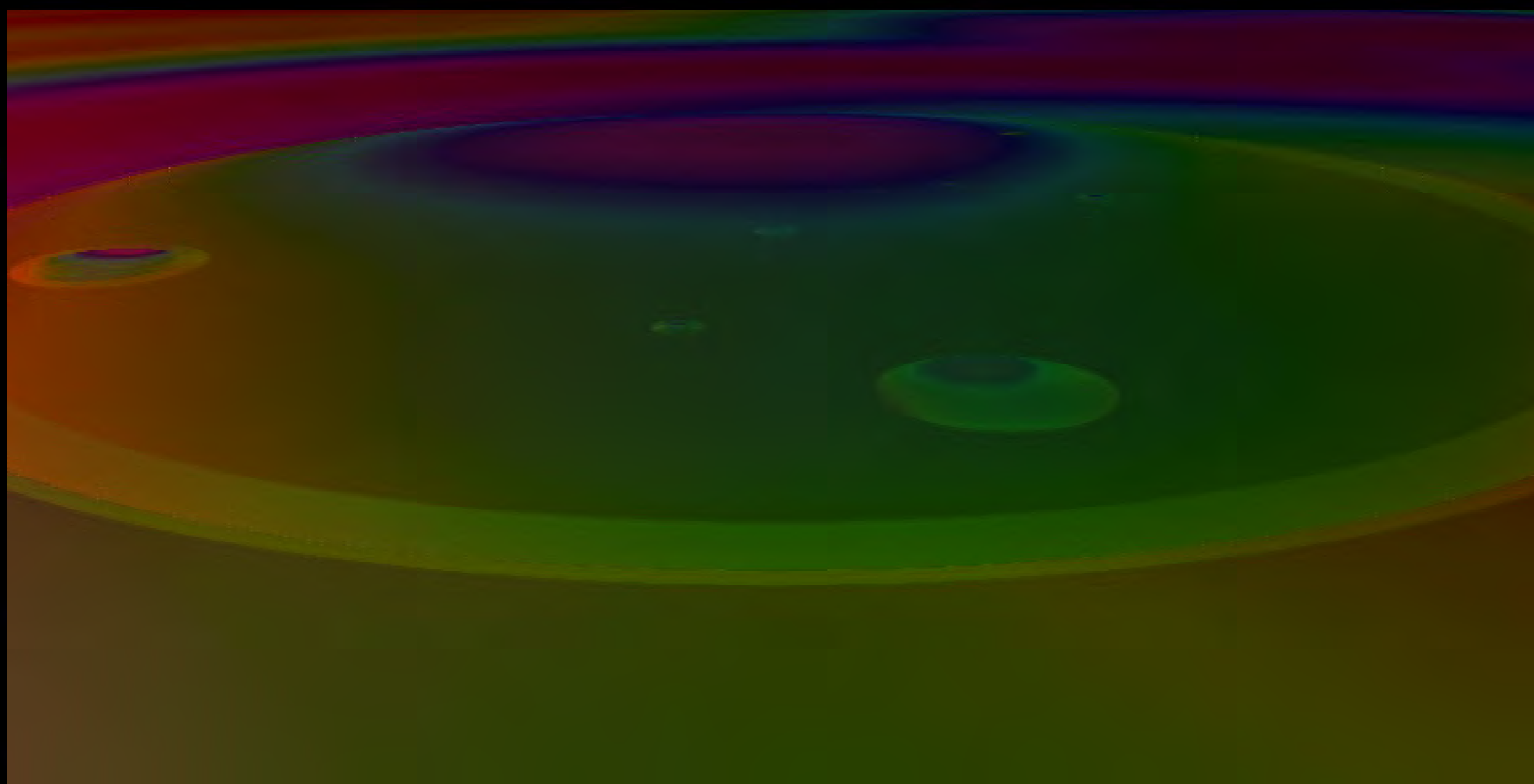


Ask a Mathematician / Ask a Physicist



Higgs mass and vacuum stability in the Standard Model at NNLO

Giuseppe Degrassi[a], Stefano Di Vita[a], Joan Elias-Miró[b], José R. Espinosa[b,c],
Gian F. Giudice[d], Gino Isidori[d,e], Alessandro Strumia[g,h]



SUSY & The Quantum Vacuum Energy

$$E_{vacuum} = \frac{1}{2}\sum_{\vec{p},\, bosons} \sqrt{|\vec{p}|^2 + M_{boson}^2} - \frac{1}{2}\sum_{\vec{p},\, fermions} \sqrt{|\vec{p}|^2 + M_{fermion}^2}$$

$$\sqrt{|\vec{p}|^2 + M^2} = |\vec{p}| \left[1 + \frac{1}{2}\frac{M^2}{|\vec{p}|^2} - \frac{1}{8}\frac{M^4}{|\vec{p}|^4} + \ldots \right]$$

$$\sum_{bosons} M_{boson}^2 - \sum_{fermions} M_{fermion}^2 = 0$$

$$\sum_{bosons} M_{boson}^4 - \sum_{fermions} M_{fermion}^4 = 0$$

THANK

YOU

Acknowledgment

Prof. Gates also wishes to acknowledge The Teaching Company for the use of some CGI units that appear in

“Superstring Theory: The DNA of Reality.”