Supersymmetry:
43 years of unrequited ♥

Pre-SUSY

Ioannina 2022

John Ellis

KING'S College LONDON

Before We Met

- 1967 – Coleman & Mandula: cannot combine Lorentz and internal symmetries
- 1970 – Berezin & Kac: anticommuting group parameters
- 1971 - Likhtman: supermultiplets, zero vacuum energy
- 1971 – Ramond, Neveu & Schwarz: 2-D supersymmetry (string theory)
- 1972 - Gol'fand & Likhtman: super-Poincaré, massive super-QED
- 1972 - Volkov & Akulov: neutrino as Goldstone particle (conjectured by Heisenberg in 1966)

First Stirrings

- 1973/4 – Wess & Zumino: 4-D supersymmetry
- 1974 – Ferrara, Iliopoulos & Zumino: no-renormalization theorems
- 1974 – Ferrara, Zumino & Wess: superfields
- 1974 - Salam & Strathdee: superspace
- 1974 - Volkov & Soroka: super-Higgs mechanism
- 1976 – Freedman, van Nieuwenhuizen & Ferrara, Deser & Zumino: supergravity
- 1977 – Polonyi: local supersymmetry breaking

Early Russian & Ukrainian Papers

Mat. Sbornik
Tom 82 (124) (1970), No. 3

Math. USSR Sbornik
Vol. 11 (1970), No. 3

LIE GROUPS WITH COMMUTING AND ANTICOMMUTING PARAMETERS

F. A. BEREZIN AND G. I. KAC

UDC 519.46

Abstract. In this paper we study analogs of Lie algebras and formal Lie grou
of groups differ from usual Lie groups, roughly speaking, in that they admit anticc
parameters. The analogs of Lie algebras differ from usual Lie algebras by proper
tator. In the definition of these objects an essential role is played by the gradient
ial they become Lie groups and algebras in the usual sense. To these generalize
over classical theorems on the connection between Lie groups and algebras and t
tation theory.

EXTENSION OF THE ALGEBRA OF POINCARE GROUP GENERATORS AND VIOLATION OF P INVARIANCE

Yu.A. Gol'fand and E.P. Likhtman
Physics Institute, USSR Academy of Sciences
Submitted 10 March 1971
ZhETF Pis. Red. 13, No. 8, 452 - 455 (20 April 1971)

POSSIBLE UNIVERSAL NEUTRINO INTERACTION

D.V. Volkov and V.P. Akulov
Physico-technical Institute, Ukrainian Academy of Sciences
Submitted 13 October 1972
ZhETF Pis. Red. 16, No. 11, 621 - 624 (5 December 1972)

PHYSICS LETTERS 3 September 1973

IS THE NEUTRINO A GOLDSTONE PARTICLE?

D.V. VOLKOV and V.P. AKULOV
Physico-Technical Institute, Academy of Sciences of the Ukrainian SSR, Kharkov 108, USSR

Received 5 March 1973

GAUGE FIELDS FOR SYMMETRY GROUP WITH SPINOR PARAMETERS

D. V. Volkov and V. A. Soroka

The inclusion of gauge fields for a symmetry group containing anticommuting parameters is considered. The Higgs effect is discussed for Goldstone fields with spin 1/2.

First attraction

Supersymmetry & Hierarchy Problem

Volume 105B, number 4 PHYSICS LETTERS 8 October 1981

MASS HIERARCHIES IN SUPERSYMMETRIC THEORIES

Edward WITTEN[1]
International Centre for Theoretical Physics, Trieste, Italy

Received 27 July 1981

It is argued that large gauge hierarchies occur naturally in some theories with supersymmetry spontaneously broken at the three level. Such theories may also lead to time-dependent values of the natural "constants".

GAUGE HIERARCHY IN A SUPERSYMMETRIC MODEL

Romesh K. KAUL
Centre for Theoretical Studies[1]*, Indian Institute of Science, Bangalore 560012, India and Tata Institute of Fundamental Research, Bombay 400005, India*

Received 13 August 1981
Revised manuscript received 31 August 1981

In a globally supersymmetric gauge theory with two distinct mass scales, the possible limitation on the gauge hierarchy due to the structure of the loop-corrected Higgs potential is shown to be absent. Also it has been demonstrated that the supersymmetry forces the large corrections to the two-point Greens functions of the light fields from the quadratic divergences and the logarithmic divergences with large coefficients to be zero *separately*. This would, therefore, allow a gauge hierarchy as large as desired.

No quadratic divergences, fewer logarithms

- 1979 – Maiani: Lectures at Gif-sur-Yvette School
- 1981 – Witten: "Mass hierarchies in supersymmetric theories"
- 1981 – Kaul: "Gauge hierarchy in a superysmmetric model"

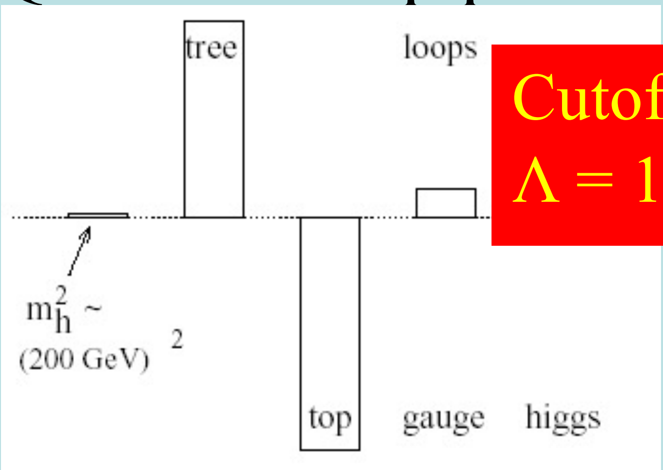
Theoretical worries about the Higgs boson

Elementary Higgs or Composite?

- Higgs field:

$<0|H|0> \neq 0$

- Quantum loop problems



Cutoff
$\Lambda = 10$ TeV

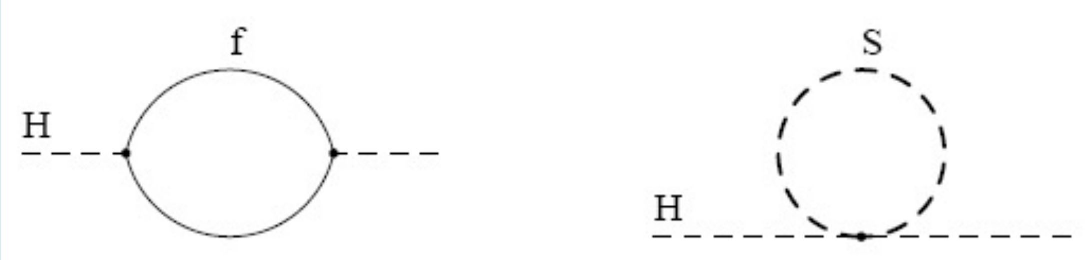
Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like π in QCD, BCS superconductivity
- New ‘technicolour’ force?

- Heavy scalar resonance?
- (Problems with precision electroweak data)
- Pseudo-Nambu-Goldstone boson?

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^\Lambda d^4k/k^2$

$$\Delta m_H^2 = -\frac{{y_f}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + \ldots]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

- Leading divergence cancelled if

$\lambda_S = y_f^2 \times 2$ **Supersymmetry!**

Our first dates

My Early Personal Efforts

- 1979 – Barbiellini, JE et al: Search for supersymmetric particles at LEP
- 1980 – JE, Gaillard & Zumino: A GUT from N=8 supergravity
- 1981 – JE, Campbell: Search for gluinos
- 1981 – JE, Nanopoulos & Rudaz: GUTs vs superGUTs
- 1982 – JE & Nanopoulos: Flavour-changing neutral interactions in broken supersymmetric theories
- 1982/3 – Electroweak symmetry breaking

Minimal Supersymmetric Extension of the Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

1981

We ♥ Supersymmetry

Volume 110B, number 1 PHYSICS LETTERS 18 March 1982

FLAVOUR-CHANGING NEUTRAL INTERACTIONS IN BROKEN SUPERSYMMETRIC THEORIES

John ELLIS and D.V. NANOPOULOS
CERN, Geneva, Switzerland

Super-GIM

Received 16 December 1981

We point out that in order to ensure an efficient "super-GIM" suppression of flavour-changing neutral interactions, the supersymmetric partners of conventional fermions (squarks and sleptons) must be almost degenerate in mass. The strongest constraints on squark mass differences of $\Delta m^2_{\mathrm{sq}}/m^2_{\mathrm{sq}} < O(10^{-3})$ come from the $K_1 - K_2$ mass matrix, while the non-observation of $\mu \to e\gamma$ imposes $\Delta m^2_{\mathrm{s}\ell}/m^2_{\mathrm{s}\ell} < O(10^{-3})$ if the supersymmetric partners of the SU(2) and SU(1) bosons have masses O(100) GeV. These results help motivate a susy gauge theory with an extra $\widetilde{\mathrm{U}}(1)$ symmetry spontaneously broken at low energy, perhaps of a non-minimal type.

$g_\mu - 2$ in Supersymmetry

- One-loop contribution from smuon/neutralino loop

$$\Delta(g-2)_\mu = -ab(\cos\alpha \sin\alpha / 4\pi^2)(m_\mu / m_{\tilde{G}})$$

$$\times \{1/(1-\eta_1) + 2\eta_1/(1-\eta_1)^2$$

$$+ [2\eta_1/(1-\eta_1)^3] \log\eta_1 - (\eta_1 \leftrightarrow \eta_2)\},$$

- and $\eta_i \equiv (m^2_{s\mu_i}/m^2_{\tilde{G}})$

$$\mathcal{L} = a\sqrt{2}\, s_\mu \bar{\mu}_L \tilde{G} + b\sqrt{2}\, t_\mu \bar{\mu}_R \tilde{G} + \text{h.c.}$$

Volume 116B, number 4 PHYSICS LETTERS (1982) 982

SPIN-ZERO LEPTONS AND THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

John ELLIS, John HAGELIN and D.V. NANOPOULOS
CERN, Geneva, Switzerland

Received 14 June 1982

The anomalous magnetic moment of the muon $(g-2)_\mu$ imposes constraints on the masses and mixing of spin-zero leptons (sleptons). We develop the predictions of models of spontaneous supersymmetry breaking for the slepton mass matrix, and show that they are comfortably consistent with the $(g-2)_\mu$ constraints.

During the present resurgence of interest in supersymmetry broken at low energies [1] new significance is attached to the classical phenomenological playgrounds of gauge theories such as the anomalous magnetic moments of the electron and muon [2], flavour-changing neutral interactions [3–5] parity [6] and *CP* violation [7,8] in the strong interactions. The three latter phenomena make life rather difficult [3,7] for the most general form of soft supersymmetry breaking, whereas simple models [9–11] of spontaneously broken supersymmetry naturally [3,4 7] respect the $\Delta F \neq 0$, *P* and *CP* violation constraints. As for the anomalous magnetic moments of the leptons, it has long been known that they vanish in an exactly supersymmetric theory [12], and Fayet [2] showed that in his model of supersymmetry breaking $(g-2)_\mu$ would be compatible with experiment if the spin-zero muon (smuon) masses were heavier than 15 GeV. Direct experimental searches [13] now exclude the existence of lighter smuons. Fayet's analysis [2] was in the context of a model with a very light photino $\tilde{\gamma}$ (see fig. 1a), and Grifols and Méndez [14] have recently made the interesting observation that his analysis is significantly altered for massive gauginos (see figs. 1b, 1c). They show that there are potentially nontrivial constraints on the smuon masses in models of broken supersymmetry.

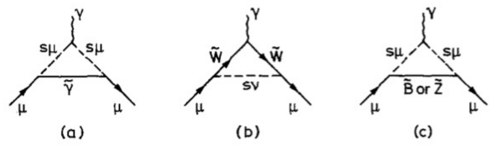


Fig. 1. One-loop diagrams contributing to $(g-2)_\mu$: (a) essentially massless photino $(\tilde{\gamma})$ exchange, (b) $\tilde{W}$ and sneutrino ($s\nu$) exchange, and (c) $\tilde{B}$ or $\tilde{Z}$ exchange.

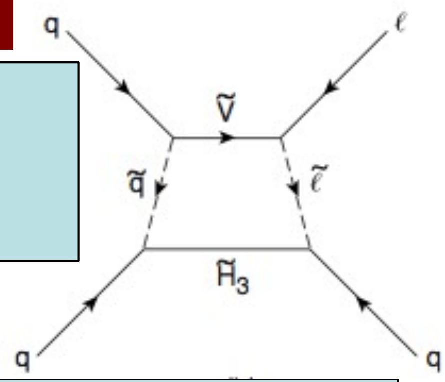
right transition operator there is a GIM [15]-like cancellation between the smuon mass eigenstates in fig. 1c which provides a potential suppression mechanism. We analyze recent models [10,11] of spontaneous supersymmetry breaking originating in the *D* and *F* sectors, respectively. We show that in the former case $(g-2)_\mu$ is suppressed by near degeneracy between the smuon mass eigenstates, while in the latter case $(g-2)_\mu$ is suppressed by small mixing angles between the left- and right-handed smuons. We close with some remarks about $(g-2)_e$ and about parity violation in the strong interactions.

When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\tilde{\gamma}$ diagram of fig. 1a and the $\tilde{W}$ diagram of fig. 1b as compared to the massive $\tilde{B}$ or $\tilde{Z}$ diagram of fig. 1c. The

1982

Dimopoulos, Raby & Wilczek

B Decay in Supersymmetric SU(5)



- B-violating operators of dimension 5 with squarks, sleptons: q̃q̃ql
- Dressed with Higgsino, Wino exchange ➔ operators of dimension 6 with quarks, sleptons

$$\mathcal{L}(p \to K^+\bar{\nu}_i) = C_{RL}(usd\nu_i)\left[\epsilon_{abc}(u_R^a s_R^b)(d_L^c \nu_i)\right] + C_{RL}(uds\nu_i)\left[\epsilon_{abc}(u_R^a d_R^b)(s_L^c \nu_i)\right]$$
$$+ C_{LL}(usd\nu_i)\left[\epsilon_{abc}(u_L^a s_L^b)(d_L^c \nu_i)\right] + C_{LL}(uds\nu_i)\left[\epsilon_{abc}(u_L^a d_L^b)(s_L^c \nu_i)\right]$$

- Coefficient $G_X \to \mathcal{O}\left(\frac{\lambda^2 g^2}{16\pi^2}\right)\frac{1}{m_{\tilde{H}_3}\tilde{m}}$ $m_X \simeq 2 \times 10^{16}$ GeV
- Antisymmetry in colour indices ➔u,d,s quarks
- Preferred decay modes: $p \to \bar{\nu}K^+\ ,\quad n \to \bar{\nu}K^0\ ,\quad \ldots$

JE, Nanopoulos & Rudaz

1982

Inflation Cries out for Supersymmetry

Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

COSMOLOGICAL INFLATION CRIES OUT FOR SUPERSYMMETRY

John ELLIS, D.V. NANOPOULOS, Keith A. OLIVE and K. TAMVAKIS
CERN, Geneva, Switzerland

Received 4 August 1982

We re-examine the inflationary scenario in the standard SU(5) model with Coleman–Weinberg symmetry breaking and point out difficulties which may be resolved in a broken supersymmetric model. Because of a partial cancellation at the one-loop level, the effective potential in a broken supersymmetric theory may be much flatter than in standard SU(5), thus permitting a greater amount of inflation.

One of our best-ever paper titles!

1982

Inflation Cries out for Supersymmetry

- Want “elementary” scalar field
  (at least looks elementary at energies << M_P)
- To get right magnitude of perturbations
  prefer mass << M_P
  (~ 10^{13} GeV in simple φ^2 models)
- And/or prefer small self-coupling λ << 1
- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive & Tamvakis 1982

Electroweak Symmetry Breaking

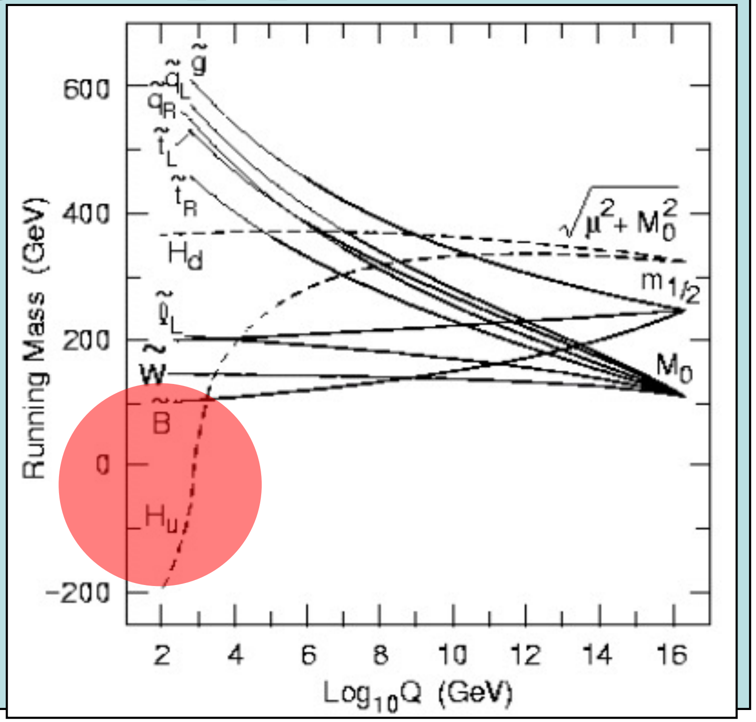
- Could be triggered by renormalization effects:

$$\frac{\partial m_{0_i}^2}{\partial t} = \frac{1}{16\pi^2}[\lambda^2(m_0^2 + A_\lambda^2) - g_a^2 M_a^2]$$

- Driven by large Yukawa coupling of top quark:

$$\frac{m_W}{m_P} = exp(\frac{-\mathcal{O}(1)}{\alpha_t}) : \alpha_t \equiv \frac{\lambda_t^2}{4\pi}$$

- Higgs mass^2 ⟶ negative
- Electroweak scale naturally ~ 100 GeV for m_t ~ 60 to 200 GeV



JE, Hagelin, Nanopoulos, & Tamvakis;
Alvarez-Gaumé, Polchinski & Wise, 1983

Volume 127B, number 3,4 PHYSICS LETTERS 28 July 1983

1983

SEARCH FOR SUPERSYMMETRY AT THE $\bar{p}p$ COLLIDER ☆

John ELLIS, John S. HAGELIN
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

and

D.V. NANOPOULOS and M. SREDNICKI
Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Received 25 April 1983

Many models of broken supersymmetry predict the existence of supersymmetric fermions $\chi^{\pm,0}$ with masses less than the $W^{\pm}$ and Z^0. Often there are two light neutral fermions χ^0, even in models with large gaugino masses. The $W^{\pm}$ have large branching ratios for decays into $\chi^{\pm} + \chi^0$, with the $\chi^{\pm}$ subsequently decaying into χ^0 plus hadrons or leptons. We propose looking at the CERN $\bar{p}p$ collider for $W^{\pm}$ production and decay into supersymmetric fermions, a likely signature being "zen" events with one broadened hadronic jet system recoiling against invisible missing transverse energy.

(One of) the first calculation(s) of
Electroweak SUSY production at hadron collider

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

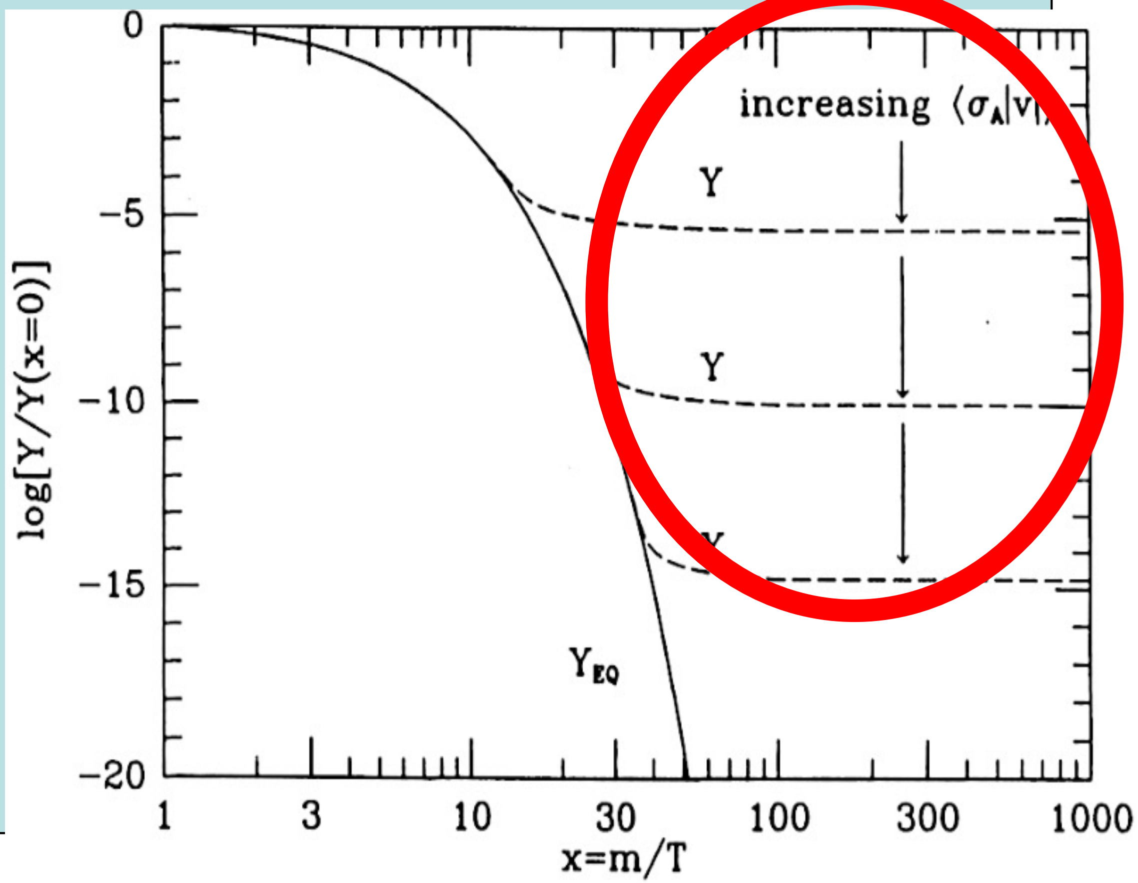
  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

- **Lightest supersymmetric particle (LSP) stable**

Weakly-Interacting Massive Particles (WIMPs)

- Numerous in primordial hot soup in primordial Universe when it was a fraction of a second old
- Would have cooled down as the Universe expanded
- Interactions would have weakened
- WIMPs decoupled from visible matter
- "Freeze-out"
- Larger σ → lower Y



Nuclear Physics B238 (1984) 453–476

1983

We ♥ Supersymmetric WIMPs

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE†, and M. SREDNICKI‡

CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

Volume 133B, number 1,2 PHYSICS LETTERS 8 December 1983

1983

NATURALLY VANISHING COSMOLOGICAL CONSTANT IN $N = 1$ SUPERGRAVITY

E. CREMMER
Ecole Normale Supérieure, Paris, France

and

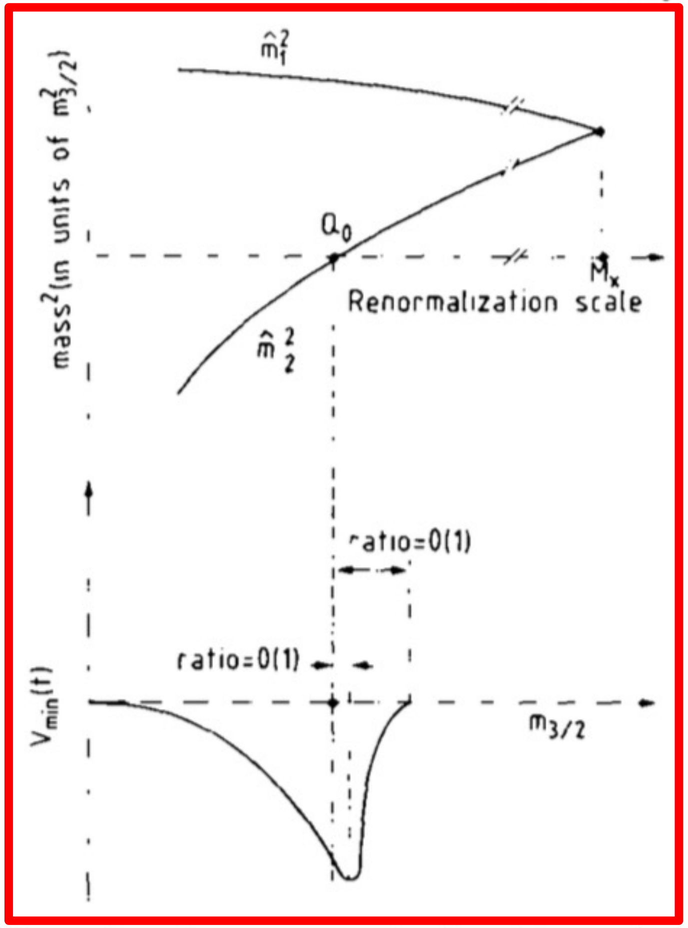
S. FERRARA, C. KOUNNAS and D.V. NANOPOULOS
CERN, Geneva, Switzerland

Received 5 September 1983

For $N = 1$ supergravity theories we show that the choice of a particular class of Einstein spaces for the Kähler manifold of the hidden sector leads to a vanishing cosmological constant without unnatural fine tuning. The total scalar potential from the hidden and physical sector is positive definite. The resulting low energy softly broken global supersymmetry for the matter fields is thus the same as in the case of factorized superpotential models with a flat Kähler metric.

Discovery of no-scale supergravity

1983



NO-SCALE SUPERSYMMETRIC STANDARD MODEL

John ELLIS, A.B. LAHANAS, D.V. NANOPOULOS
CERN, Geneva, Switzerland

and

K. TAMVAKIS
CERN, Geneva, Switzerland
and University of Ioannina, Ioannina, Greece

Received 7 November 1983

We propose a class of supergravity models coupled to matter in which the scales of supersymmetry breaking and of weak gauge symmetry breaking are *both* fixed by dimensional transmutation, *not* put in by hand. The models have a flat potential with zero cosmological constant before the evaluation of weak radiative corrections which determine $m_{3/2}, m_W = \exp[-O(1)/\alpha_t]\, m_P : \alpha_t = O(\alpha)$. These models are consistent with all particle physics and cosmological constraints for top quark masses in the range 30 GeV $< m_t <$ 100 GeV.

Application of no-scale supergravity:
SUSY-breaking scale also fixed dynamically

1984

Inflation cries out for Supergravity

- Stabilize ‘elementary’ scalar inflaton
  (needs mass << m_P and/or small coupling)
- **Supersymmetry**
- The only good symmetry is a local symmetry
  (cf, gauge symmetry in Standard Model)
- **Local supersymmetry = supergravity**
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = supergravity**

Volume 152B, number 3,4 PHYSICS LETTERS 7 March 1985

1984

No-Scale Inflation

SU(N, 1) INFLATION

John ELLIS, K. ENQVIST, D.V. NANOPOULOS
CERN, Geneva, Switzerland

K.A. OLIVE
Astrophysics Theory Group, Fermilab, Batavia, IL 60510, USA

and

M. SREDNICKI
Department of Physics, University of California, Santa Barbara, CA 93106, USA

Received 7 December 1984

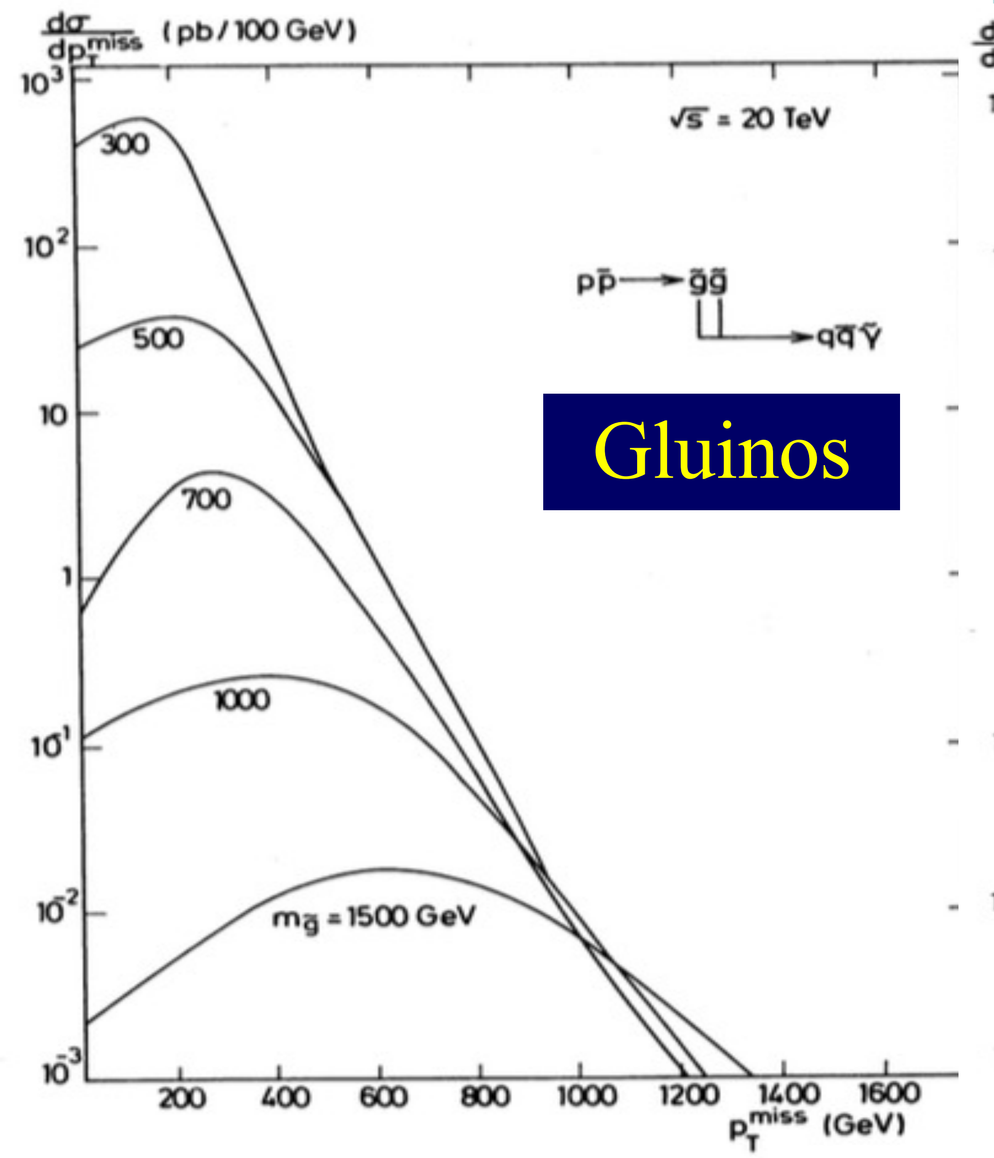
We present a simple model for primordial inflation in the context of SU(N, 1) no-scale $n = 1$ supergravity. Because the model at zero temperature very closely resembles global supersymmetry, minima with negative cosmological constants do not exist, and it is easy to have a long inflationary epoch while keeping density perturbations of the right magnitude and satisfying other cosmological constraints. We pay specific attention to satisfying the thermal constraint for inflation, i.e. the existence of a high temperature minimum at the origin.

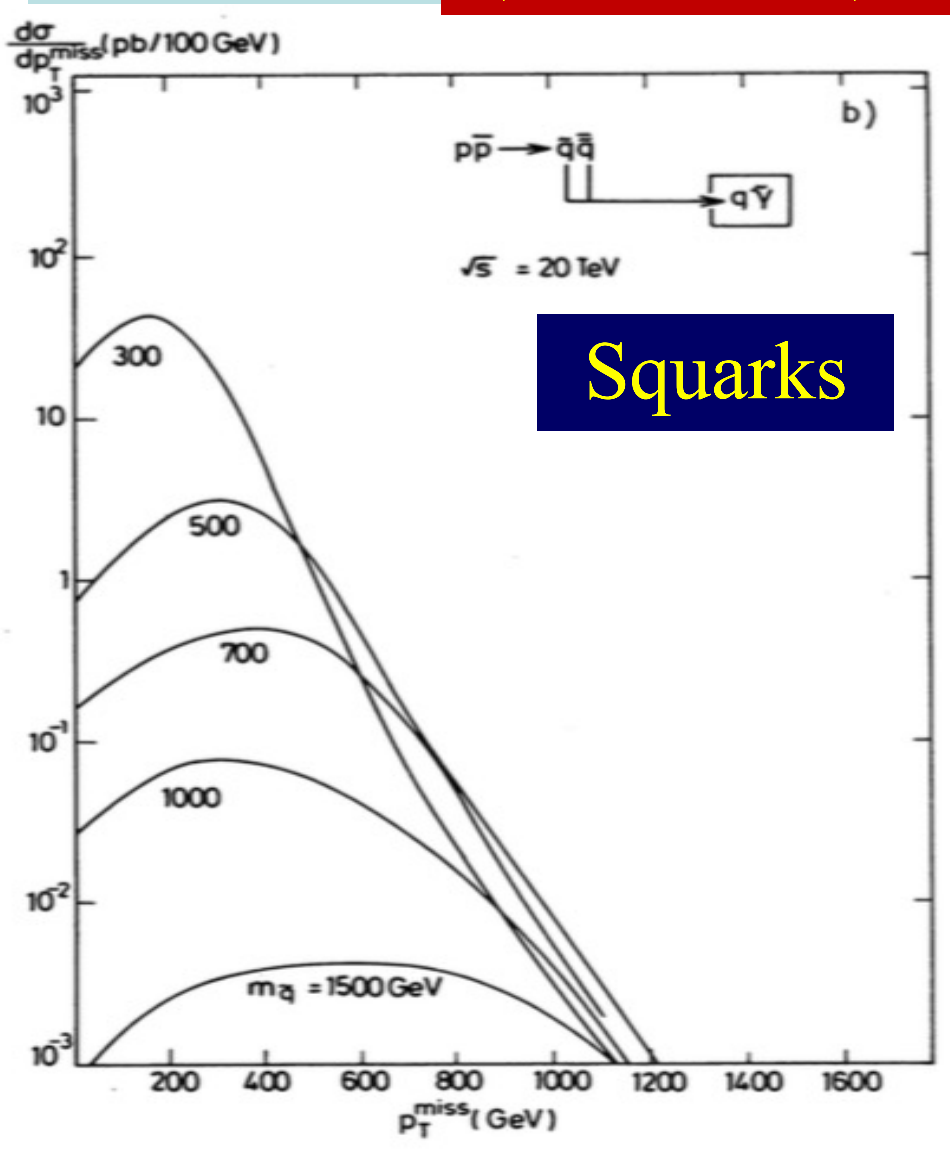
A love to which we returned recently

1984

A Preview of Supersymmetry @ LHC

JE, Gelmini & Kowalski, 1984





Modern Physics Letters A | Vol. 01, No. 01, pp. 57-69 (1986)

OBSERVABLES IN LOW-ENERGY SUPERSTRING MODELS

1986

JOHN ELLIS, K. ENQVIST, D.V. NANOPOULOS and F. ZWIRNER

https://doi.org/10.1142/S0217732386000105 | **Cited by:** 325

First Formulation of Naturalness

Abstract

We compile phenomenological constraints on the minimal low-energy effective theory which can be obtained from the superstring by Calabi-Yau compactification. Mixing with the single additional neutral gauge boson in this model reduces the mass of the conventional Z^0, Field vacuum expectation values are constrained by the experimental upper bound on this shift. Then, requiring the sneutrino mass squared to be positive constrains the scale of supersymmetry breaking more than do lower bounds on the masses of new charged particles and of sparticles. More model-dependent constraints follow from the "naturalness" requirement that observables do not depend sensitively on input parameters. We find a preference for the second neutral gauge boson to weigh ≲320 GeV, $m_{\tilde{g}} \lesssim 250$ GeV and $m_{\tilde{q}} \lesssim 500$ GeV. Dynamical generation of the gauge hierarchy is possible if $m_t \lesssim 70$ GeV, with lower values of m_t being favoured.

This requirement of "naturalness" is rather imprecise, and largely a matter of taste. Nevertheless, we have tried to quantify the concept as follows. We should worry that in a model with $m_W \ll m_{\frac{1}{2}}$, a small variation in the input parameters would produce a large change in the ratio $m_{\frac{1}{2}}/m_W$. We can replace this ratio by the alternative and essentially equivalent sensitivity indicator x/v. As input parameters which largely determine x/v we have α_k and α_λ. Therefore, we choose $S_{k,\lambda} \equiv \left|\partial \ln(x/v)/\partial \ln k,\lambda\right|_{\mu=\mu_f}$ as our measure of sensitivity, and require

$$S_{k,\lambda} \equiv \left| \frac{\partial \ln(x/v)}{\partial \ln k,\lambda} \right| \lesssim 5 \qquad (17)$$

as our criterion of "naturalness".

Volume 194, number 2 PHYSICS LETTERS B 6 August 1987

1987

SUPERSYMMETRIC FLIPPED SU(5) REVITALIZED

I. ANTONIADIS [1], J. ELLIS
CERN, CH-1211 Geneva 23, Switzerland

J.S. HAGELIN
Department of Physics, Maharishi International University, Fairfield, IA 52556, USA

and

D.V. NANOPOULOS
Physics Department, University of Wisconsin, Madison, WI 53706, USA

Received 16 May 1987

GUT derivable from string

We describe a simple $N=1$ supersymmetric GUT based on the group $SU(5)\times U(1)$ which has the following virtues: the gauge group is broken down to the $SU(3)_C\times SU(2)_L\times U(1)_Y$ of the standard model using just **10**, $\overline{\mathbf{10}}$ Higgs representations, and the doublet–triplet mass splitting problem is solved naturally by a very simple missing-partner mechanism. The successful supersymmetric GUT prediction for $\sin^2\theta_w$ can be maintained, whilst there are no fermion mass relations. The gauge group and representation structure of the model may be obtainable from the superstring.

Volume 208, number 2 PHYSICS LETTERS B 14 July 1988

1988

AN IMPROVED FLIPPED SU(5)×U(1) MODEL FROM THE FOUR-DIMENSIONAL STRING

I. ANTONIADIS, John ELLIS
CERN, CH-1211 Geneva 23, Switzerland

J. HAGELIN
Maharishi International University, Fairfield, IA 52556, USA

and

D.V. NANOPOULOS
University of Wisconsin, Madison, WI 53706, USA

Received 19 April 1988

GUT derived from string

We discuss a four-dimensional string model whose effective field theory is a supersymmetric flipped SU(5)×U(1) GUT with the following properties.
– The quark and lepton mass matrices have a hierarchical structure and all Cabibbo–Kobayashi–Maskawa mixing angles can be non-zero.
– There is a natural splitting of Higgs doublets and triplets. – A novel seesaw mechanism gives light left-handed neutrinos.
– The gauge group is reduced to the standard model $SU(3)_C \times SU(2)_L \times U(1)_Y$ at a large mass scale close to M_P.
Extensive use is made of non-renormalizable superpotential couplings which may arise from couplings to identifiable massive modes, and are restricted by an R symmetry and the requirements of flatness is some field directions.

Flipped SU(5) GUT

- Extend GUT SU(5) with additional U(1) [motivated by string theory]

Antoniadis, JE, Hagelin & Nanopoulos, 1987

- "Flipped" fermion assignments to representations:

$$\bar{f}_i(\bar{\mathbf{5}}, -3) = \{U_i^c, L_i\} \ , \quad F_i(\mathbf{10}, 1) = \{Q_i, D_i^c, N_i^c\} \ , \quad l_i(\mathbf{1}, 5) = E_i^c \quad i = 1, 2, 3$$

- Break GUT symmetry with 10-dimensional Higgses, electroweak symmetry with 5-dimensional Higgses:

$$H(\mathbf{10}, 1) = \{Q_H, D_H^c, N_H^c\} \ , \qquad \bar{H}(\bar{\mathbf{10}}, -1) = \{\bar{Q}_H, \bar{D}_H^c, \bar{N}_H^c\}$$

$$h(\mathbf{5}, -2) = \{T_{H_c}, H_d\} \ , \qquad \bar{h}(\bar{\mathbf{5}}, 2) = \{\bar{T}_{\bar{H}_c}, H_u\}$$

Lightest neutralino & lighter smuon can have small masses

- Superpotential:

$$W = \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{f}_j \bar{h} + \lambda_3^{ij} \bar{f}_i \ell_j^c h + \lambda_4 H H h + \lambda_5 \bar{H} \bar{H} \bar{h} + \lambda_6^{ia} F_i \bar{H} \phi_a + \lambda_7^a h \bar{h} \phi_a + \lambda_8^{abc} \phi_a \phi_b \phi_c + \mu_\phi^{ab} \phi_a \phi_b \, ,$$

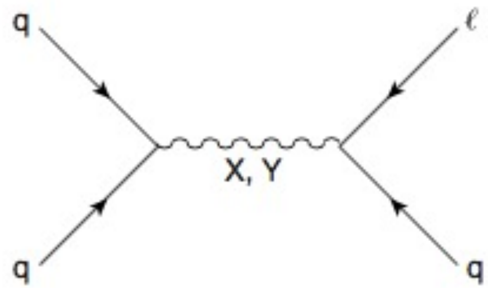
- Scan free parameters of model:

$$M_5, \ M_{X1}, \ m_{10}, \ m_5, \ m_1, \ \mu, \ M_A, \ A_0, \ \tan\beta$$

1987

Antoniadis, JE, Hagelin & Nanopoulos

B Decay in Flipped SU(5)



- Flip quark and lepton assignments in 5, $\overline{10}$

  u ←→ d, e,μ ←→ ν

- Dimension-5 operators suppressed
- Back to dimension-6, larger $m_X \simeq 2 \times 10^{16}$ GeV
- No prediction for m_b, could change multiplet assignments
- Dominant decay could be

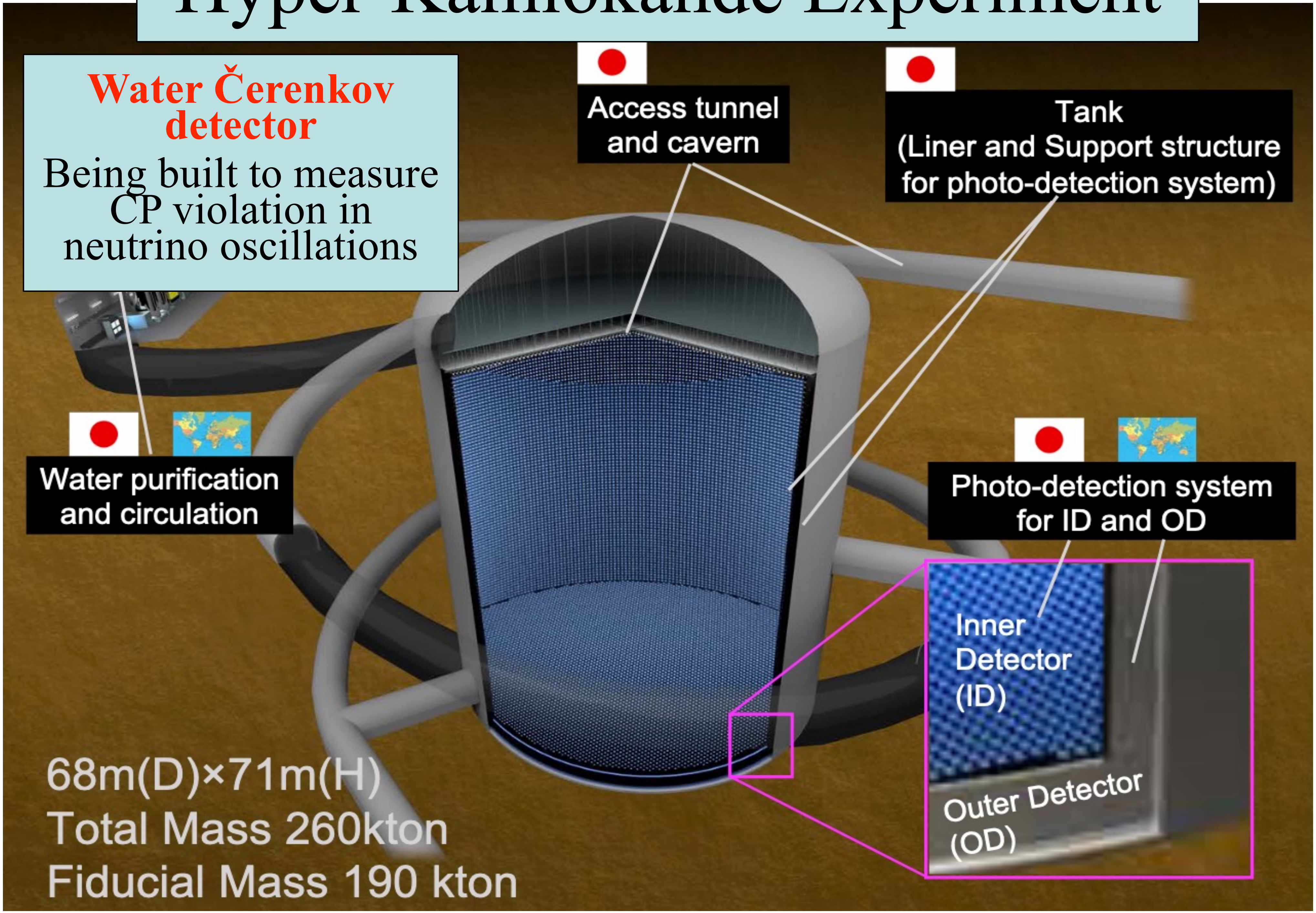
$p \to e^+ \pi^0$ or $p \to \mu^+ \pi^0$ or $p \to \mu^+ K^0$

2027

Hyper-Kamiokande Experiment

Water Čerenkov detector

Being built to measure CP violation in neutrino oscillations



1990/1

Higgs Bosons in Supersymmetry

- Need 2 complex Higgs doublets

  (cancel anomalies, form of SUSY couplings)

- 8 – 3 = 5 physical Higgs bosons

  Scalars h, H; pseudoscalar A; charged $H^{\pm}$

- Lightest Higgs < M_Z at tree level:

$$M^2_{\mathrm{H,h}} = \frac{1}{2}\left[M^2_{\mathrm{A}} + M^2_{\mathrm{Z}} \pm \sqrt{(M^2_{\mathrm{A}} + M^2_{\mathrm{Z}})^2 - 4M^2_{\mathrm{Z}}M^2_{\mathrm{A}}\cos^2 2\beta}\right]$$

- Important radiative corrections to mass:

$$G_\mu m^4_{\mathrm{t}} \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m^2_{\mathrm{t}}}\right)$$ $\Delta M_H|_{TH} \sim 1.5$ GeV

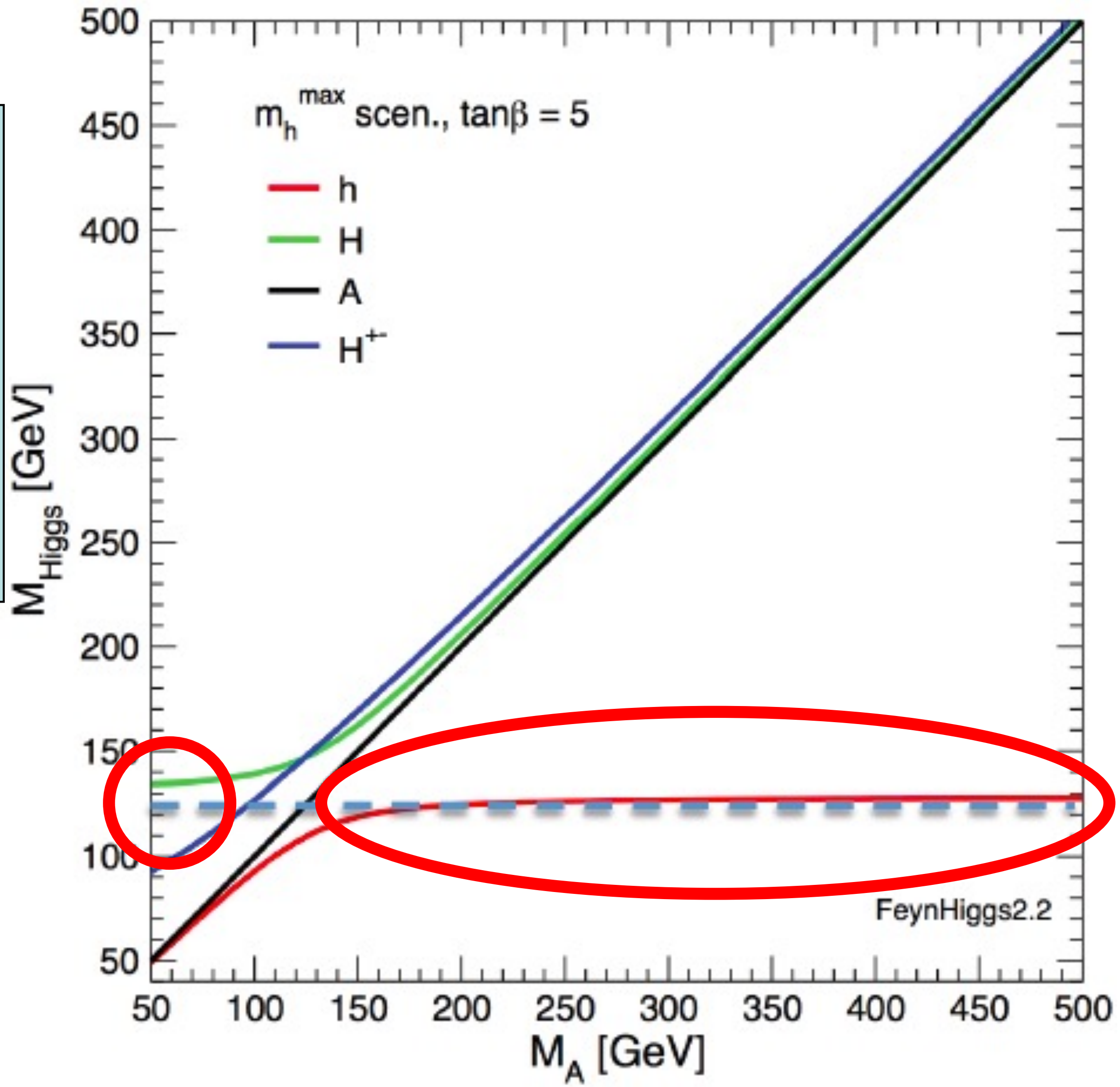
JE, Ridolfi & Zwirner,
Haber & Hempfling
Okada, Yamaguchi & Yanagida

1990/1

MSSM Higgs Masses & Couplings

Lightest Higgs mass
up to ~ 130 GeV
Heavy Higgs masses
quite close

Consistent
With LHC



1990-2011

Where are the top and Higgs?

Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\mathrm{G}_F}(1+\Delta r)$$

Veltman

- Sensitivity to top mass is quadratic: $\frac{3\mathrm{G}_F}{8\pi^2\sqrt{2}} m_t^2$

- Sensitivity to Higgs mass is logarithmic:

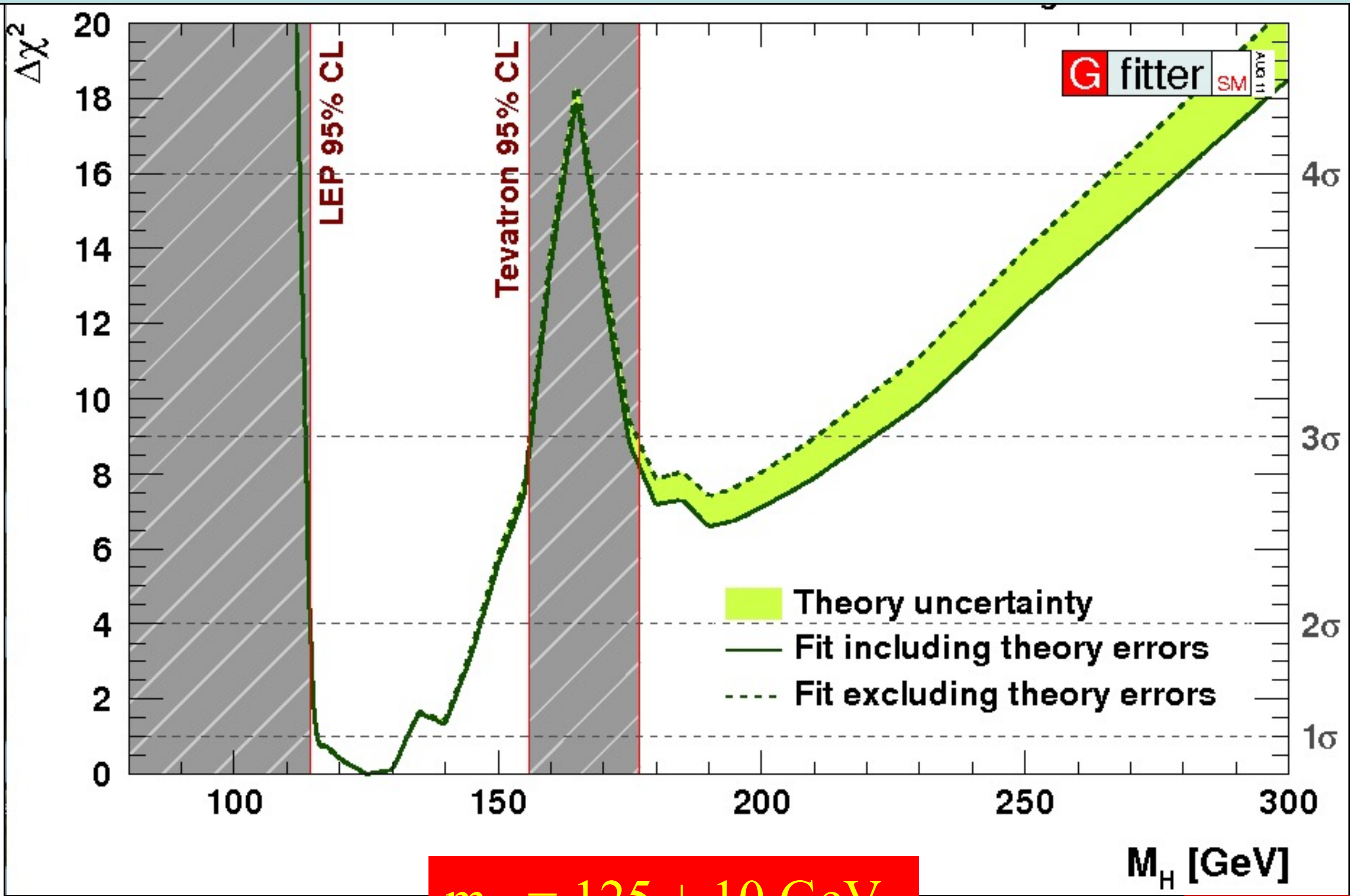
$$\frac{\sqrt{2}\mathrm{G}_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass

$$\Delta\rho = 0.0026\frac{M_t^2}{M_Z^2} - 0.0015\ln\left(\frac{M_H}{M_W}\right)$$

2011

Combining Information from Previous Direct Searches and Indirect Data



$m_H = 125 \pm 10$ GeV

Gfitter collaboration

1991

Grand Unification

- At one-loop order without/**with** supersymmetry:

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

$$b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ frac12 \\ 0 \end{pmatrix}$$

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Dimopoulos, Raby & Wilczek,
Ibanez & Ross, 1982

1991

Electroweak Mixing Angle

- Related to ratio of SU(2), U(1) couplings:

$$\sin^2\theta(m_Z) = \frac{g'^2}{g_2^2+g'^2} = \frac{3}{5}\frac{g_1^2(m_Z)}{g_2^2(m_Z)+\frac{3}{5}g_1^2(m_Z)}$$

- At one loop:

$$\sin^2\theta(m_Z) = \frac{1}{1+8x}\left[3x+\frac{\alpha_{em}(m_Z)}{\alpha_3(m_Z)}\right] = \frac{1}{5}\left(\frac{b_2-b_3}{b_1-b_2}\right)$$

- One-loop coefficients w'out/**with** supersymmetry:

$$\begin{aligned}
\frac{4}{3}N_G - 11 \leftarrow\ & b_3 \rightarrow 2N_G - 9 = -3\\
\frac{1}{6}N_H + \frac{4}{3}N_G - \frac{22}{3} \leftarrow\ & b_2 \rightarrow \frac{1}{2}N_H + 2N_G - 6 = +1\\
\frac{1}{10}N_H + \frac{4}{3}N_G \leftarrow\ & b_1 \rightarrow \frac{3}{10}N_H + 2N_G = \frac{33}{5}\\
\frac{23}{218} = 0.1055 \leftarrow\ & x \rightarrow \frac{1}{7}.
\end{aligned}$$

- Data: $x = \frac{1}{6.92 \pm 0.07}$

JE, Kelley & Nanopoulos

1991

LEP Data Consistent with Supersymmetric Grand Unification

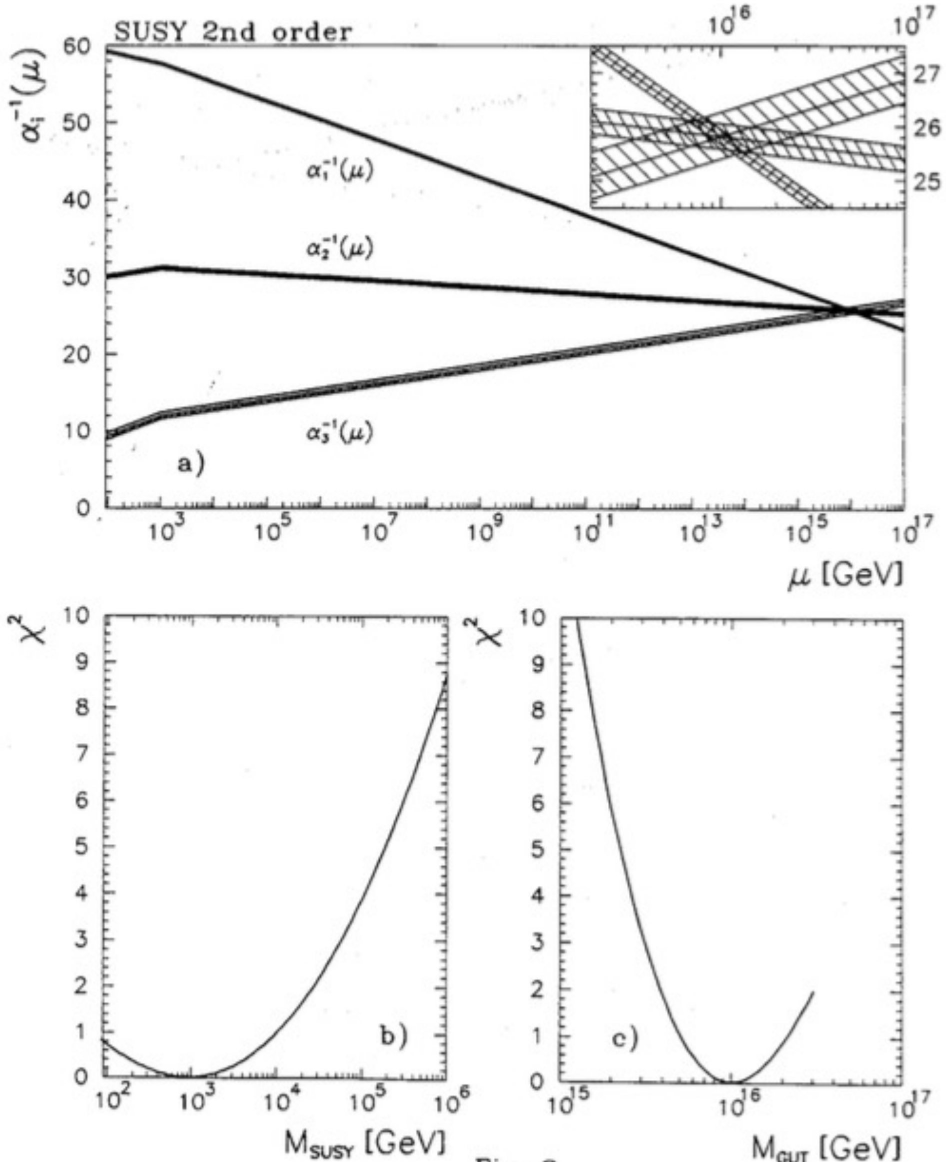
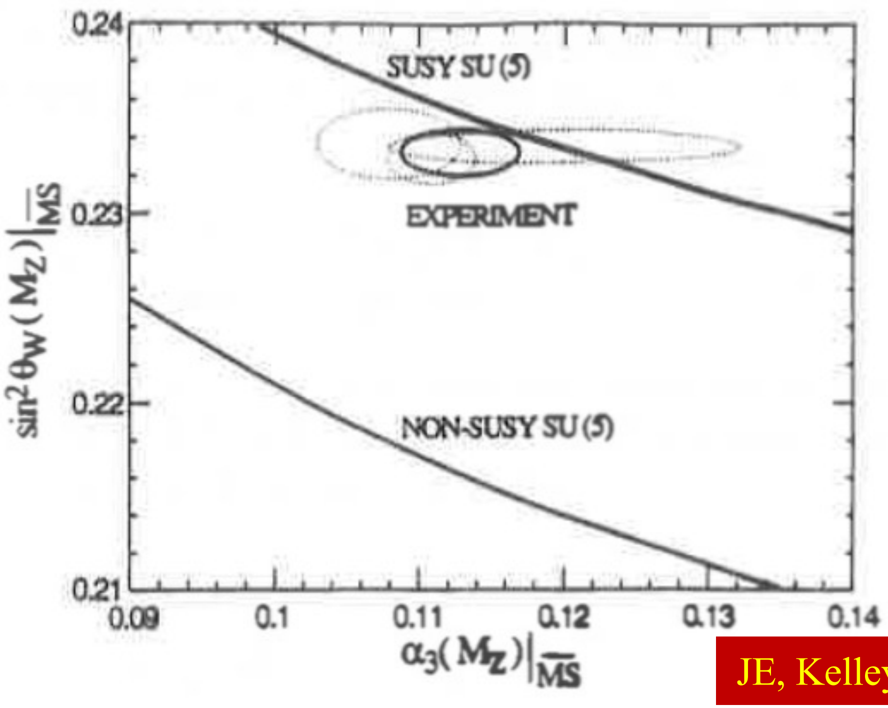


Fig. 2

Amaldi, de Boer & Furstenau



JE, Kelley & Nanopoulos

1979+

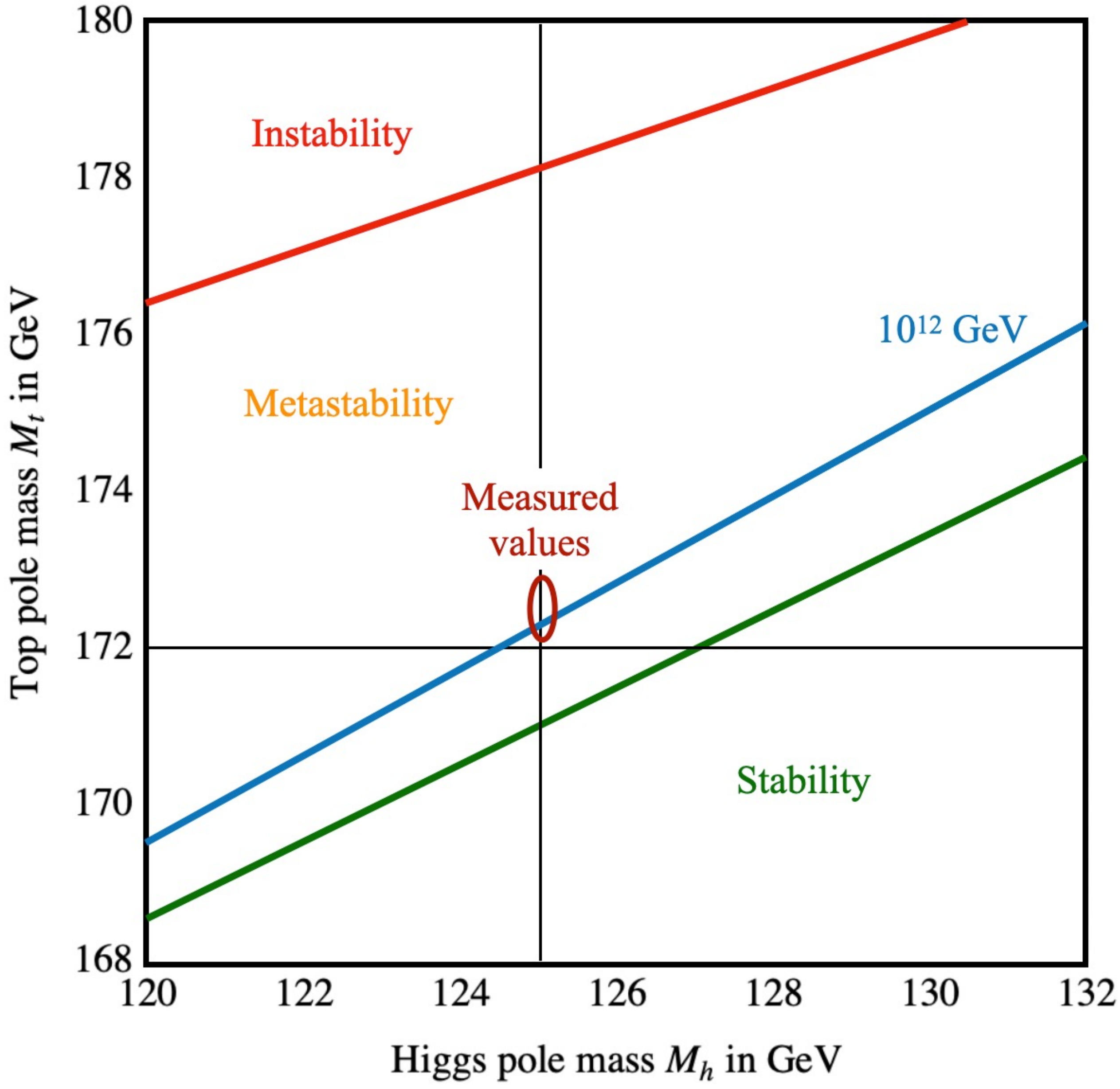
Is "Empty Space" Unstable?

Politzer & Wolfram,
Hung,
Cabibbo, Maiani, Parisi & Petronzio;

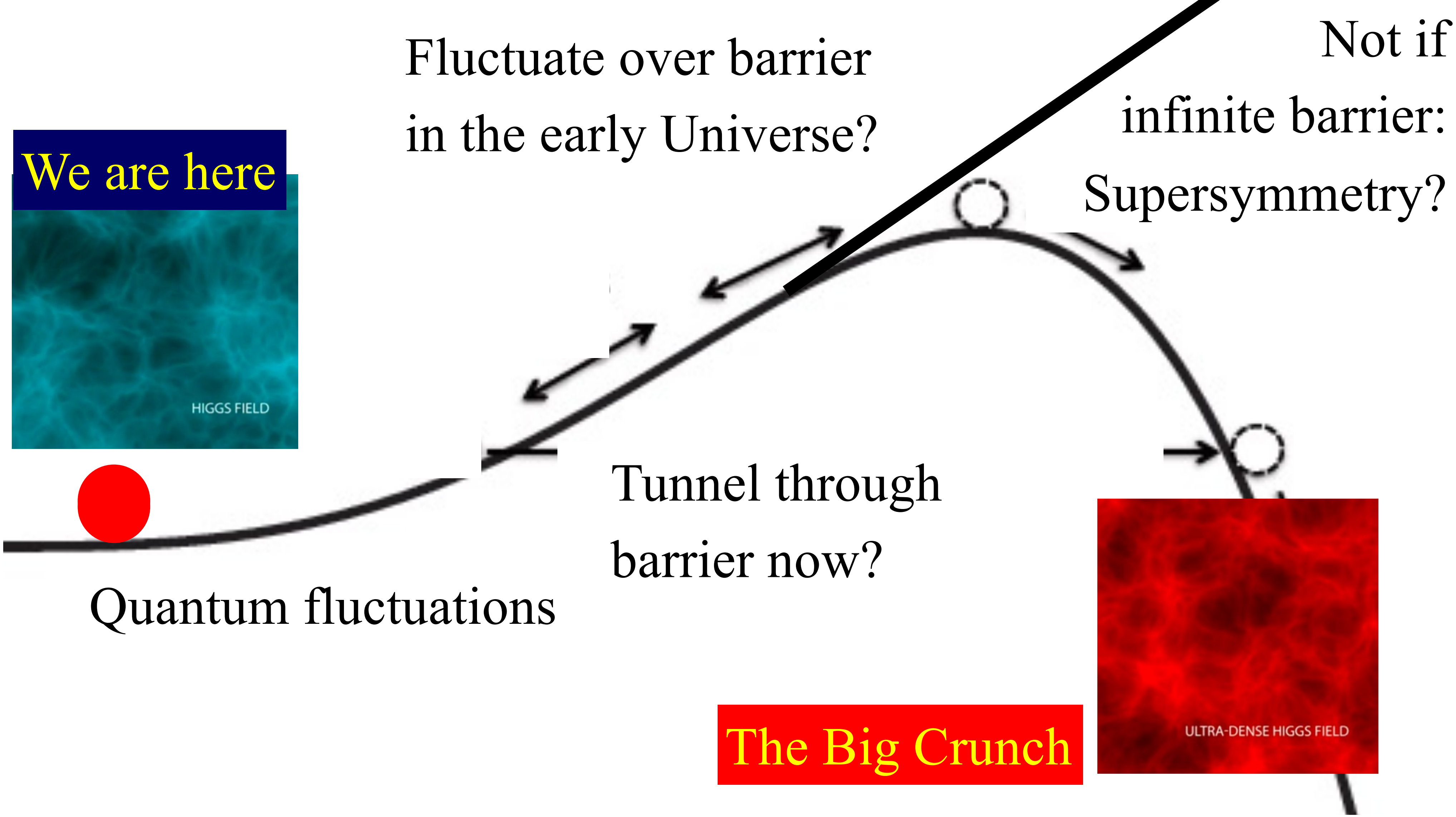
Depends on masses of Higgs boson and top quark, strong coupling

Instability scale
$\sim 10^{12}$ GeV

Buttazzo et al, arXiv:1307.3536;
Franceschini et al, 2203.17197



Will the Universe Collapse?
Should it have Collapsed already?

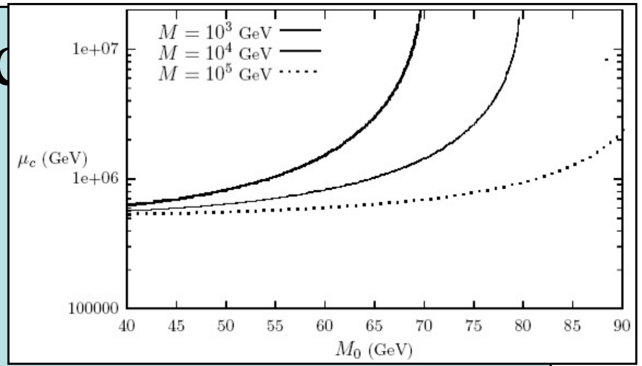


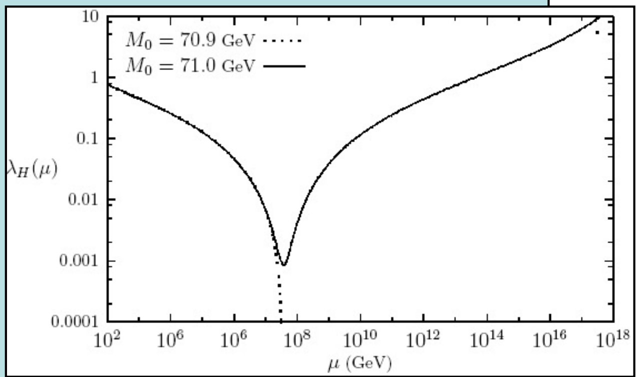
How to Stabilize a Light Higgs Boson?

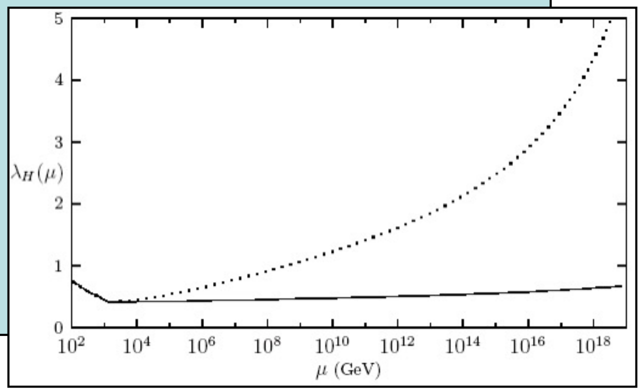
- Top quark destabilizes potential: introc
  stop-like scalar:

$$\mathcal{L} \supset \; M^2|\phi|^2 + \frac{M_0}{v^2}|H|^2\,|\phi|^2$$

- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  - just like Higgsinos
- Very like **Supersymmetry!**



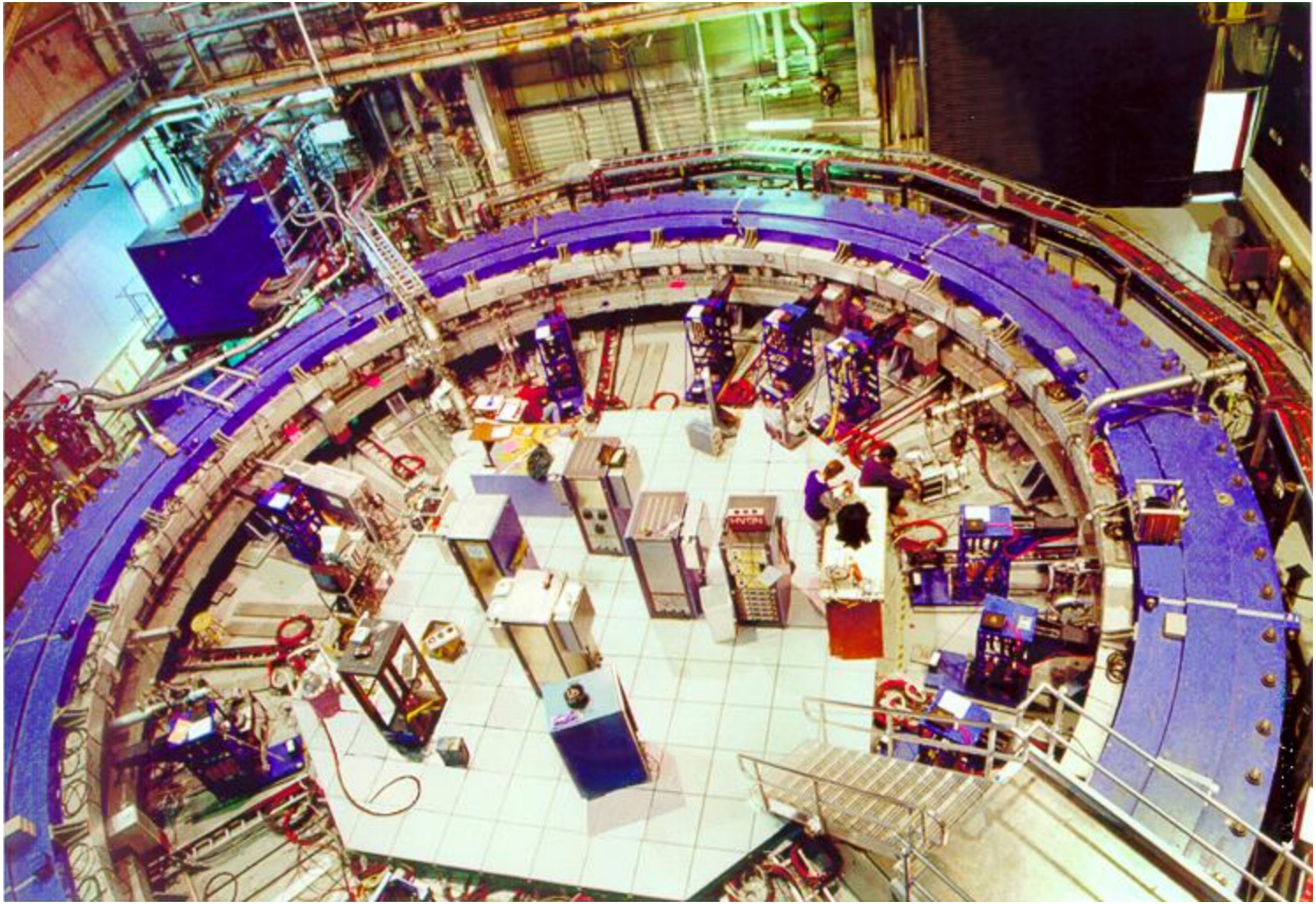




JE & D. Ross, 2000

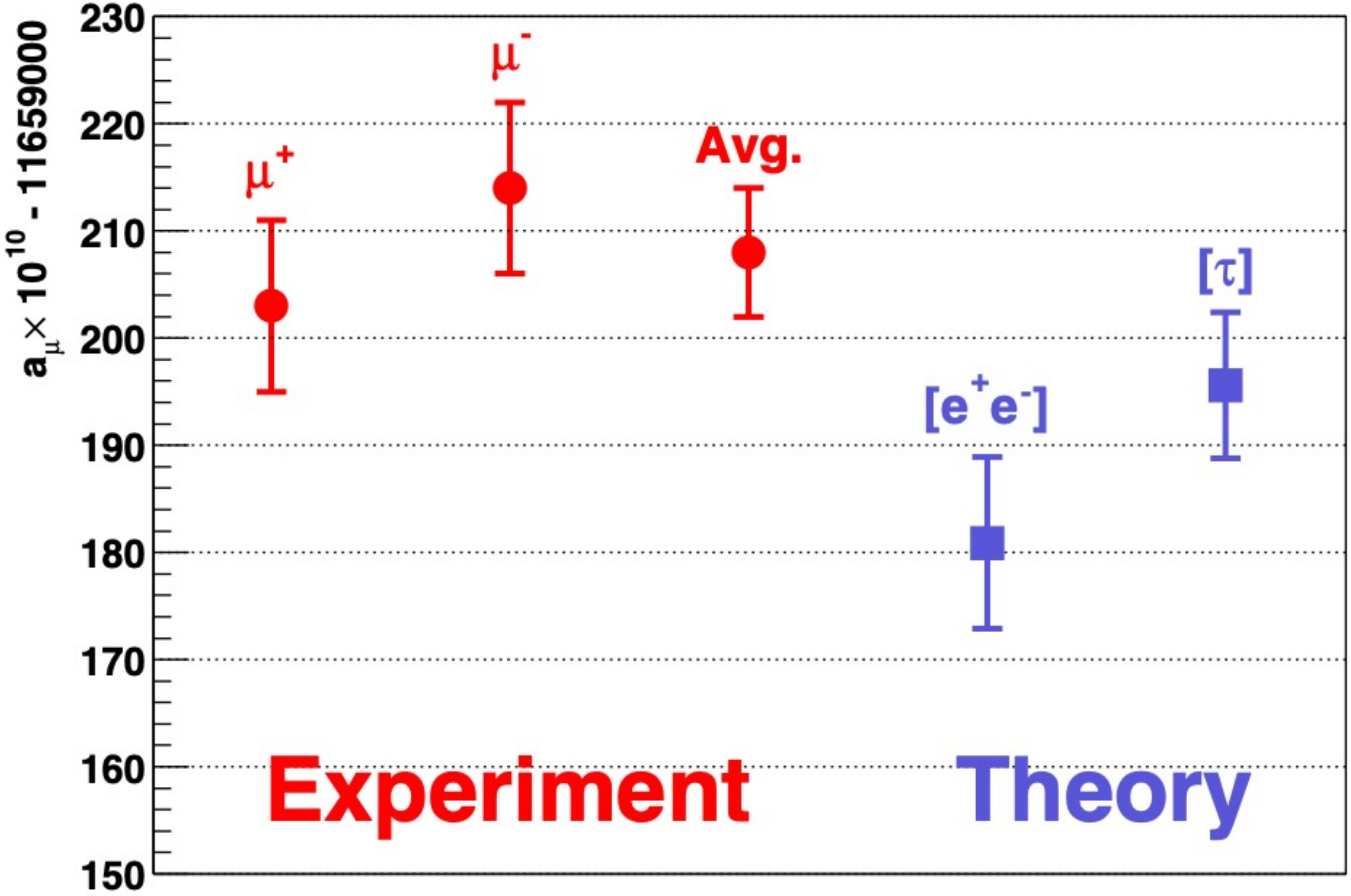
BNL $g_\mu - 2$ Experiment

E821 experiment, 2001 - 2006



2001/6

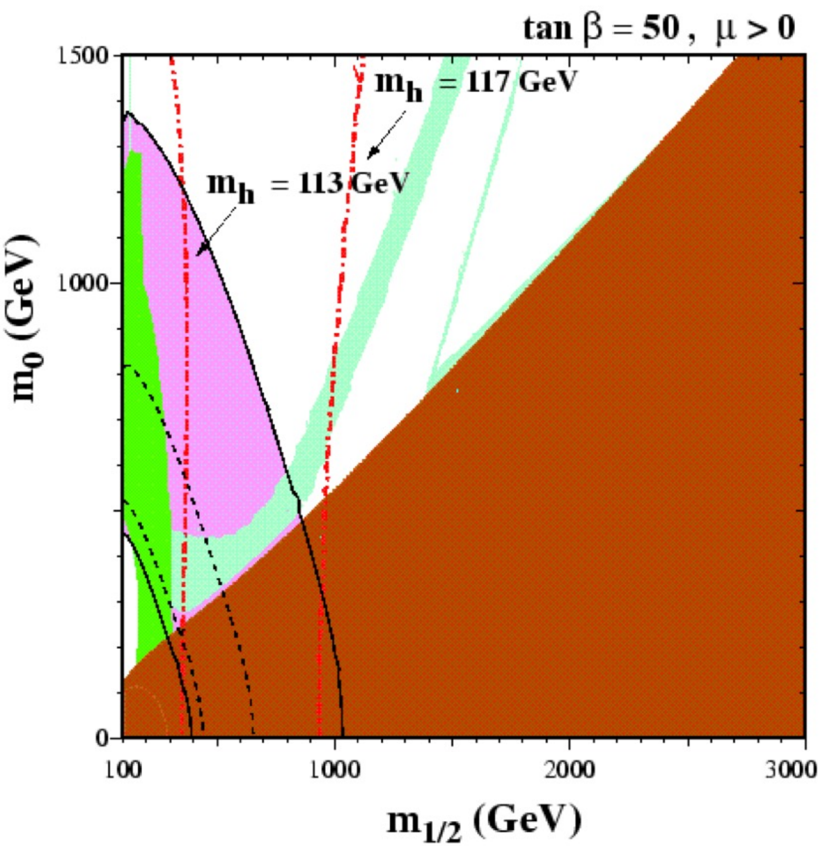
Possible Discrepancy with Theory?



$$\delta a = \pm 0.47\text{ppm}$$

BNL E821 experiment, 2001 - 2006

$g_\mu - 2$ in Supersymmetry v2: the CMSSM



N·H
ELSEVIER
24 May 2001
Physics Letters B 508 (2001) 65–73
PHYSICS LETTERS B
www.elsevier.nl/locate/npe

Combining the muon anomalous magnetic moment with other constraints on the CMSSM

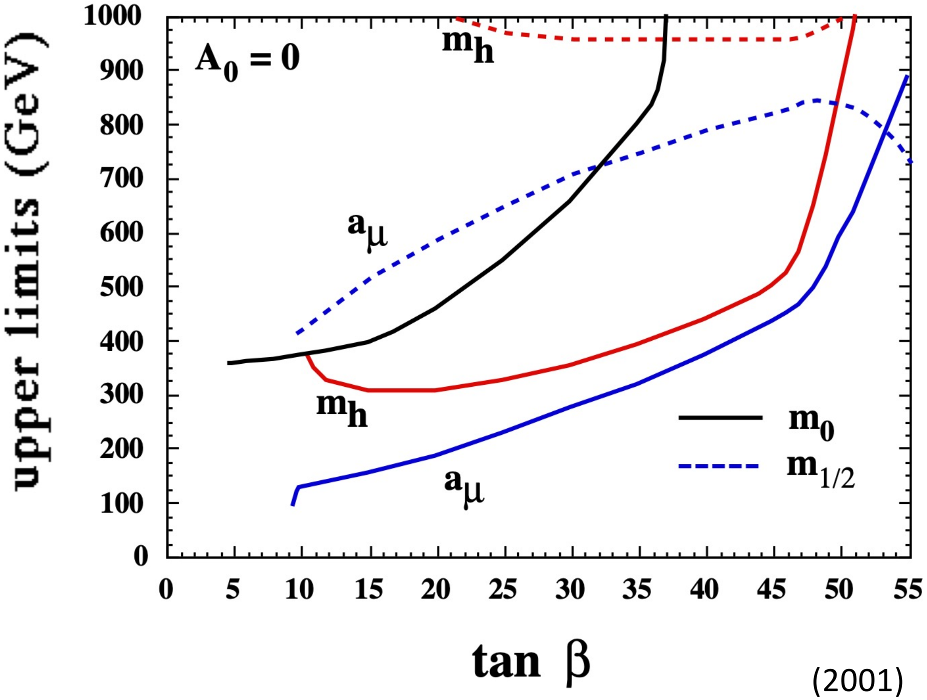
John Ellis [a], D.V. Nanopoulos [b,c,d], Keith A. Olive [a,e]

[a] *TH Division, CERN, Geneva, Switzerland*
[b] *Department of Physics, Texas A&M University, College Station, TX 77843, USA*
[c] *Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, TX 77381, USA*
[d] *Chair of Theoretical Physics, Academy of Athens, Division of Natural Sciences, 28 Panepistimiou Avenue, Athens 10679, Greece*
[e] *Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

Received 16 March 2001; accepted 10 April 2001
Editor: R. Gatto

Abstract

We combine the constraint suggested by the recent BNL E821 measurement of the anomalous magnetic moment of the muon on the parameter space of the constrained MSSM (CMSSM) with those provided previously by LEP, the measured rate of $b \to s\gamma$ decay and the cosmological relic density $\Omega_\chi h^2$. Our treatment of $\Omega_\chi h^2$ includes carefully the direct-channel Higgs poles in annihilation of pairs of neutralinos χ and a complete analysis of $\chi - \tilde{\ell}$ coannihilation. We find excellent consistency between all the constraints for $\tan\beta \gtrsim 10$ and $\mu > 0$, for restricted ranges of the CMSSM parameters m_0 and $m_{1/2}$. All the preferred CMSSM parameter space is within reach of the LHC, but may not be accessible to the Tevatron collider, or to a first-generation e^+e^- linear collider with centre-of-mass energy below 1.2 TeV. © 2001 Published by Elsevier Science B.V.



(2001)

2013

PRL **111,** 111301 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

No-Scale Supergravity Realization of the Starobinsky Model of Inflation

John Ellis,[1,*] Dimitri V. Nanopoulos,[2,†] and Keith A. Olive[3,‡]

[1]*Department of Physics, Theoretical Particle Physics and Cosmology Group, King's College London, London WC2R 2LS, United Kingdom and Theory Division, CERN, CH-1211 Geneva 23, Switzerland*

[2]*George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA, Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, Texas 77381, USA, and Division of Natural Sciences, Academy of Athens, 28 Panepistimiou Avenue, Athens 10679, Greece*

[3]*William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

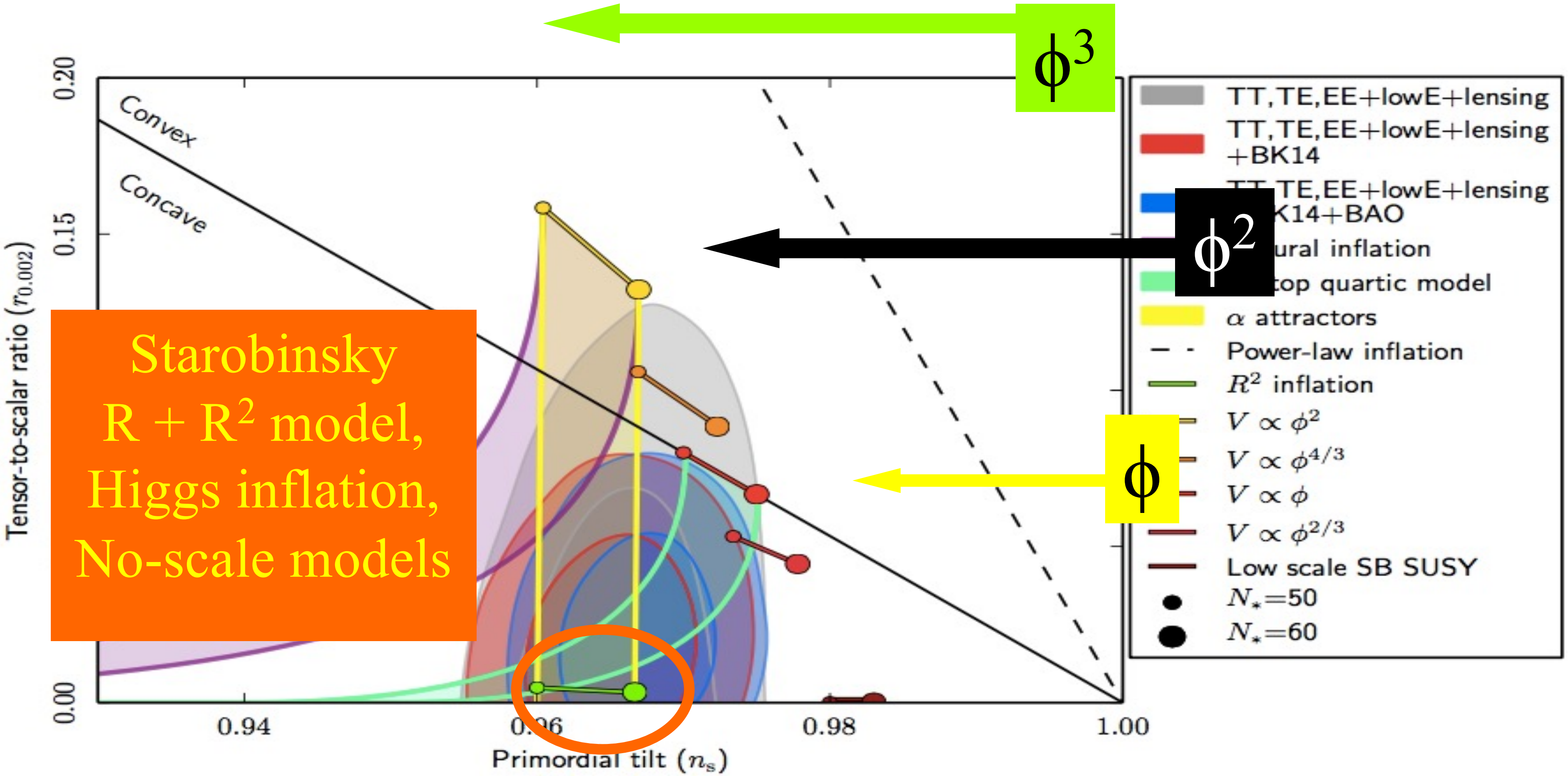
(Received 8 May 2013; published 9 September 2013; corrected 12 September 2013)

We present a model for cosmological inflation based on a no-scale supergravity sector with an $SU(2,1)/SU(2) \times U(1)$ Kähler potential, a single modulus T, and an inflaton superfield Φ described by a Wess-Zumino model with superpotential parameters (μ, λ). When T is fixed, this model yields a scalar spectral index n_s and a tensor-to-scalar ratio r that are compatible with the Planck measurements for values of $\lambda \simeq \mu/3M_P$. For the specific choice $\lambda = \mu/3M_P$, the model is a no-scale supergravity realization of the $R + R^2$ Starobinsky model.

DOI: 10.1103/PhysRevLett.111.111301 PACS numbers: 04.65.+e, 04.50.Kd, 12.60.Jv, 98.80.Cq

No-Scale supergravity + Wess-Zumino model ➔ Starobinsky-like inflation

Inflationary Landscape



2017 Flipped Almost

A Model of Everything

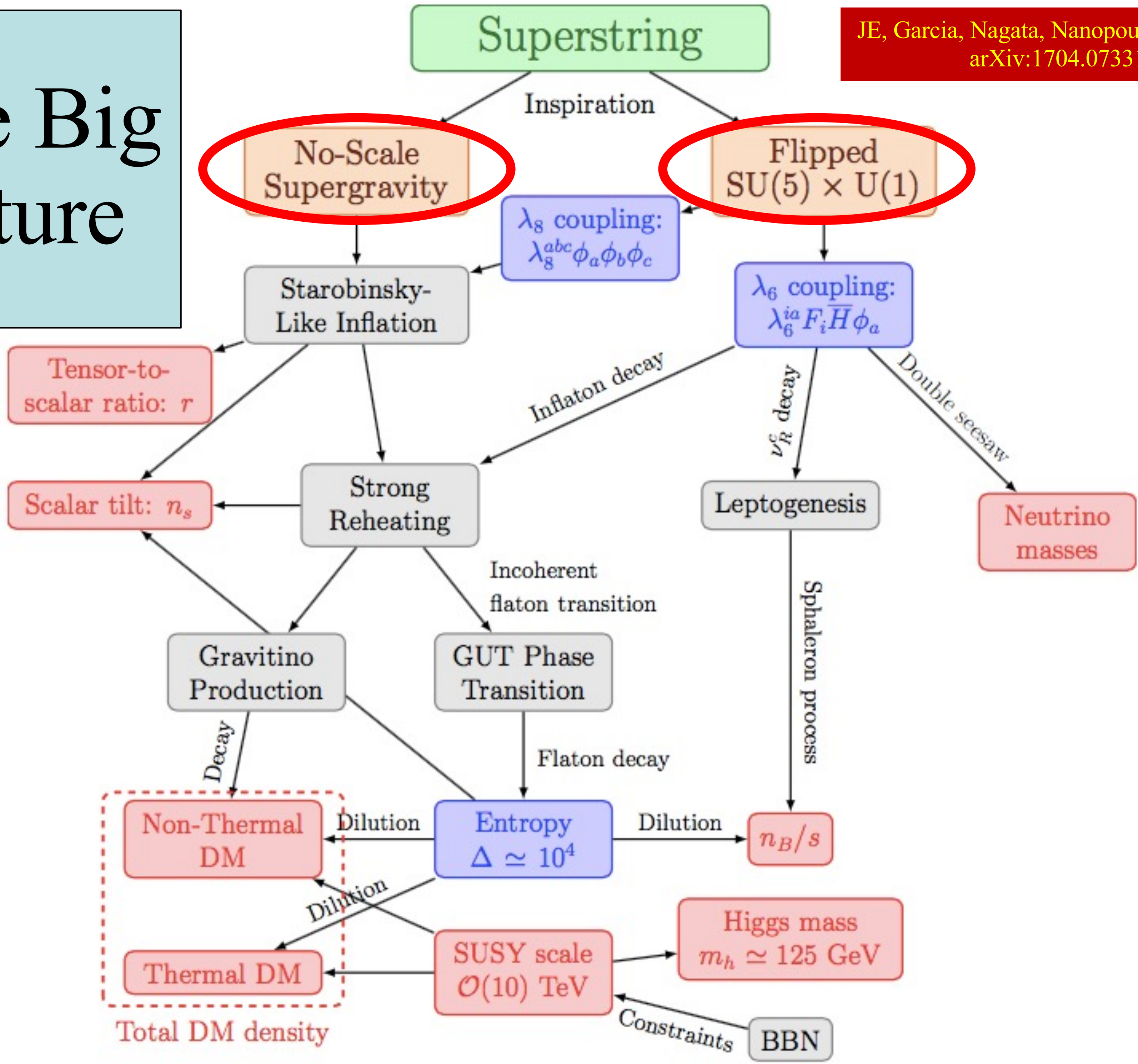
Below the Planck Scale

- Simple GUT models (SU(5), SO(10)) not obtained from weakly-coupled string
  - They need adjoint Higgs, …
- **Flipped SU(5)×U(1) derived**, has advantages
  - Small (5-, 10-dimensional) Higgs representations
  - Long-lived proton, neutrino masses, leptogenesis, …
- Construct model of Starobinsky-like inflation within flipped SU(5)×U(1) framework

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

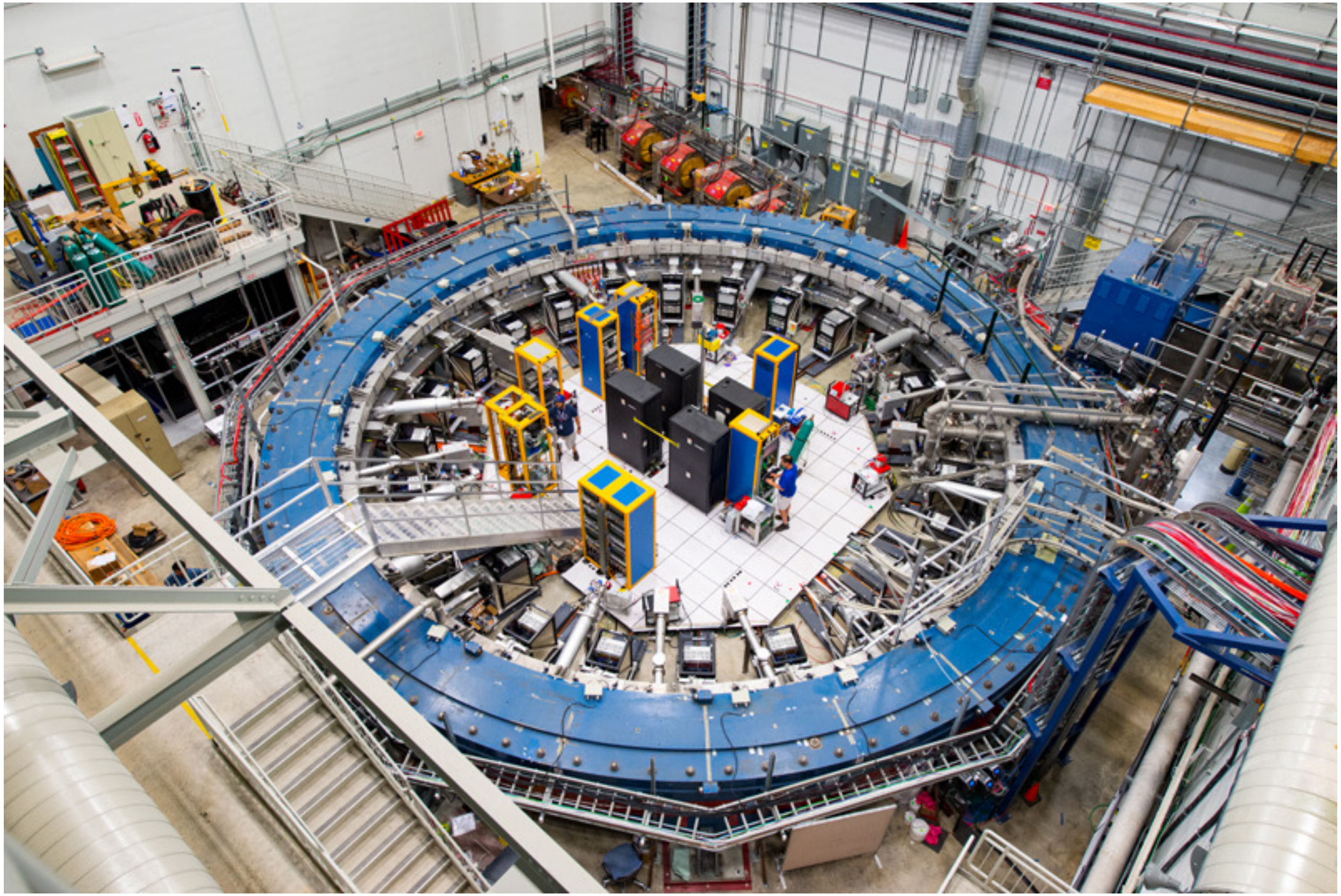
The Big Picture

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331



2021

Fermilab $g_\mu - 2$ Experiment

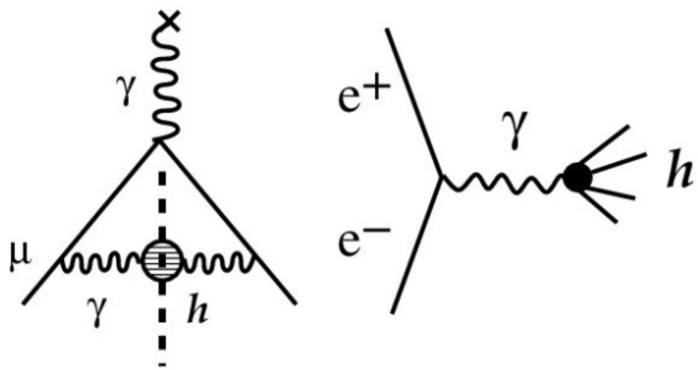


Does the magnet look familiar?

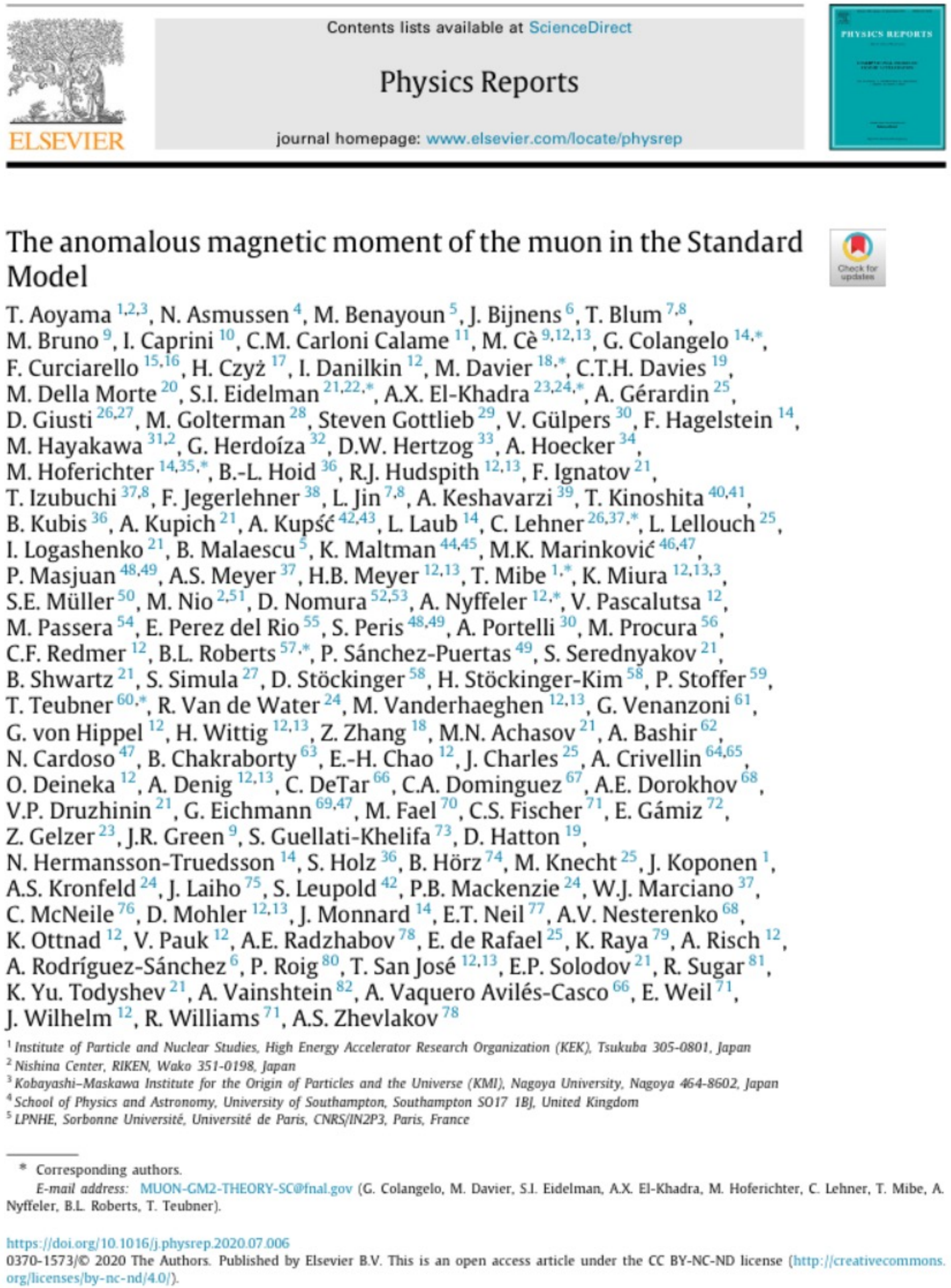
2020

$g_\mu - 2$ Theory Initiative

- Review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation



Aoyama et al, arXiv:2006.04822



Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

[1] Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
[2] Nishina Center, RIKEN, Wako 351-0198, Japan
[3] Kobayashi–Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya 464-8602, Japan
[4] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom
[5] LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France

* Corresponding authors.
E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).

https://doi.org/10.1016/j.physrep.2020.07.006

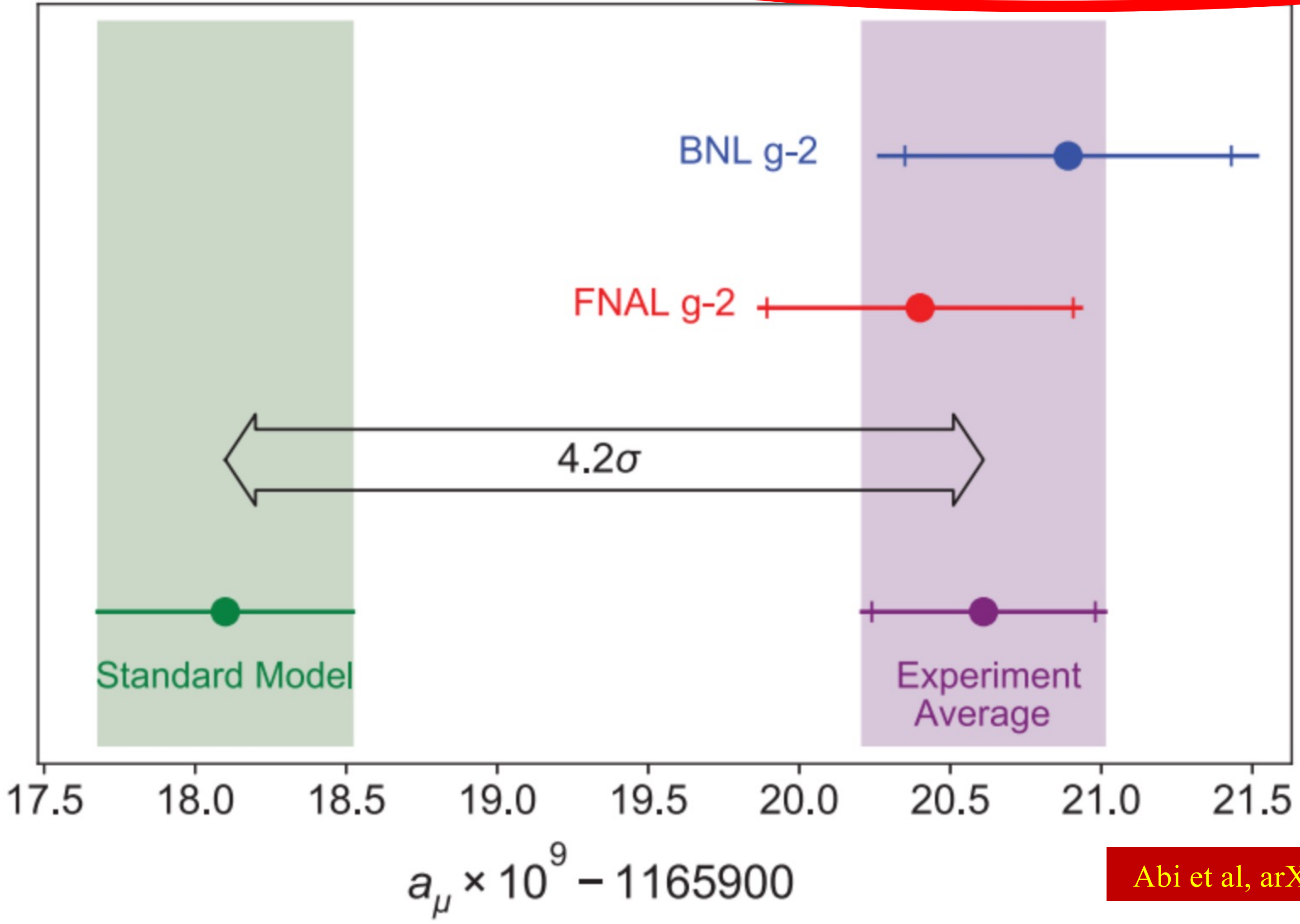
2021

Fermilab $g_\mu - 2$ Measurement

FNAL result: $a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\ \text{ppm})$

Combined result: $a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\ \text{ppm})$

Difference from Standard Model: $a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$

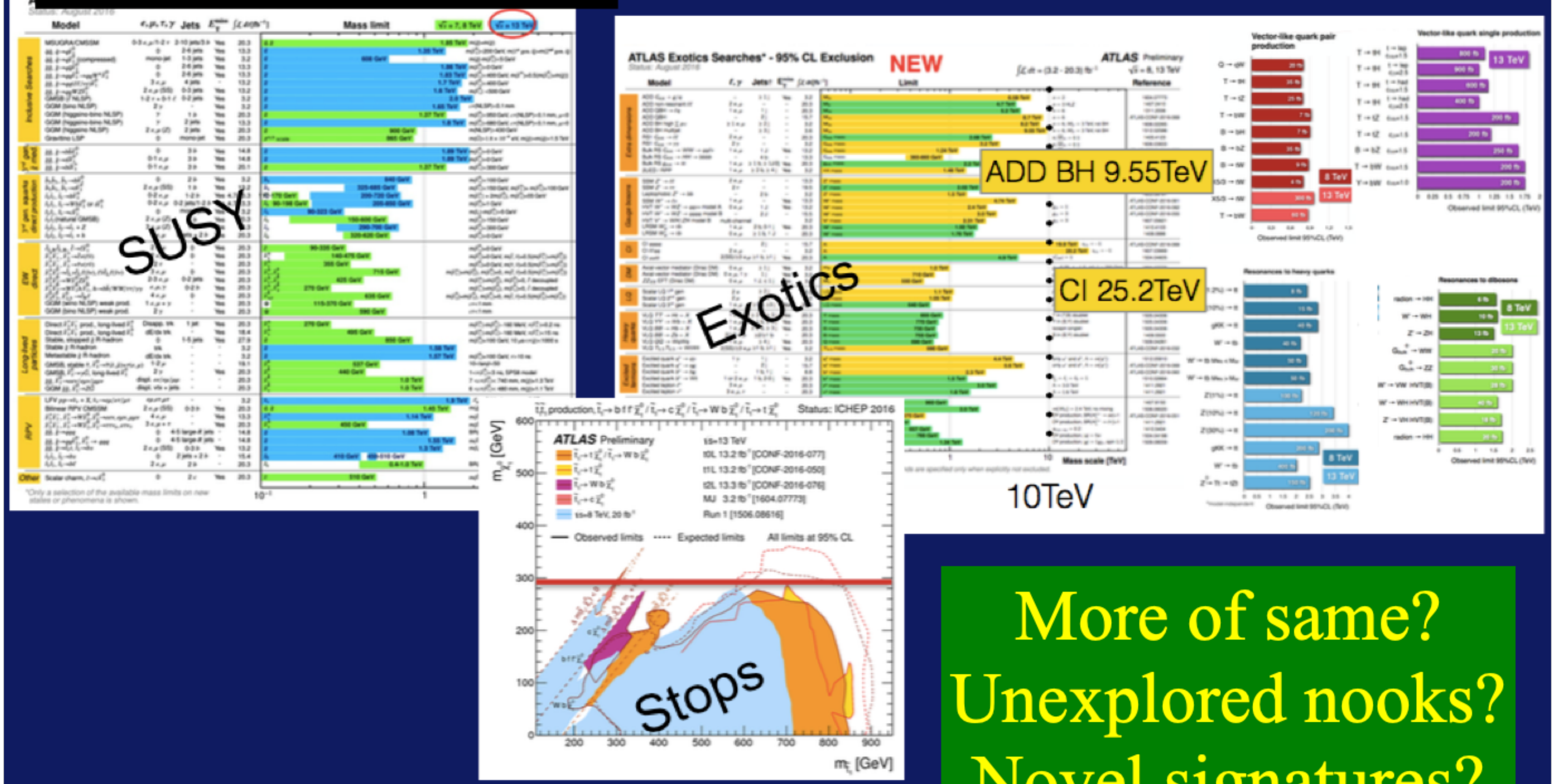


Abi et al, arXiv:2104.03281

Nothing (yet) at the LHC

No supersymmetry

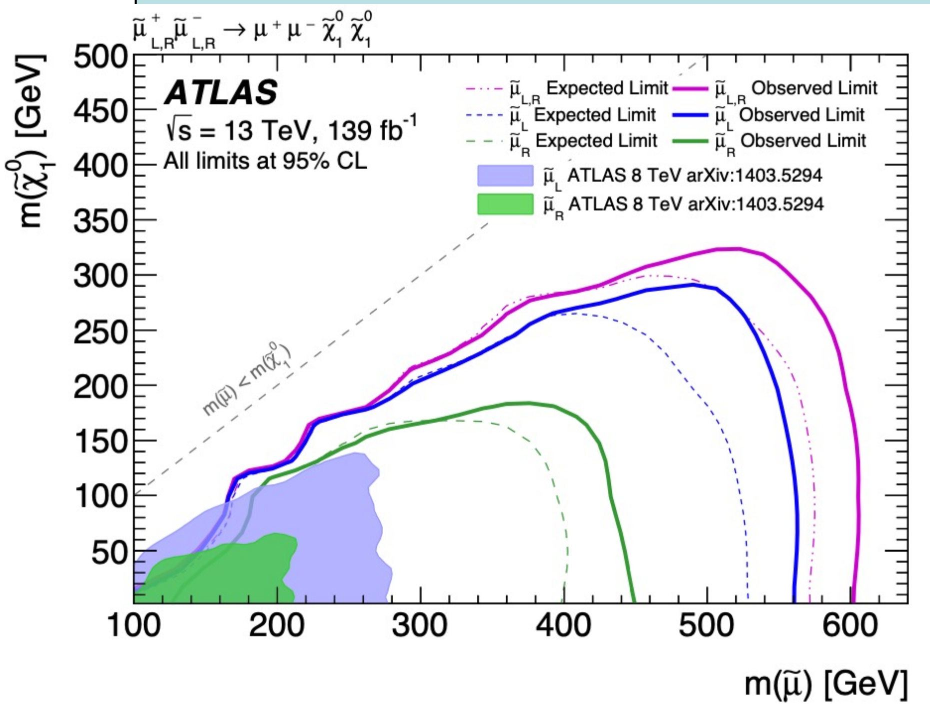
Nothing else, either

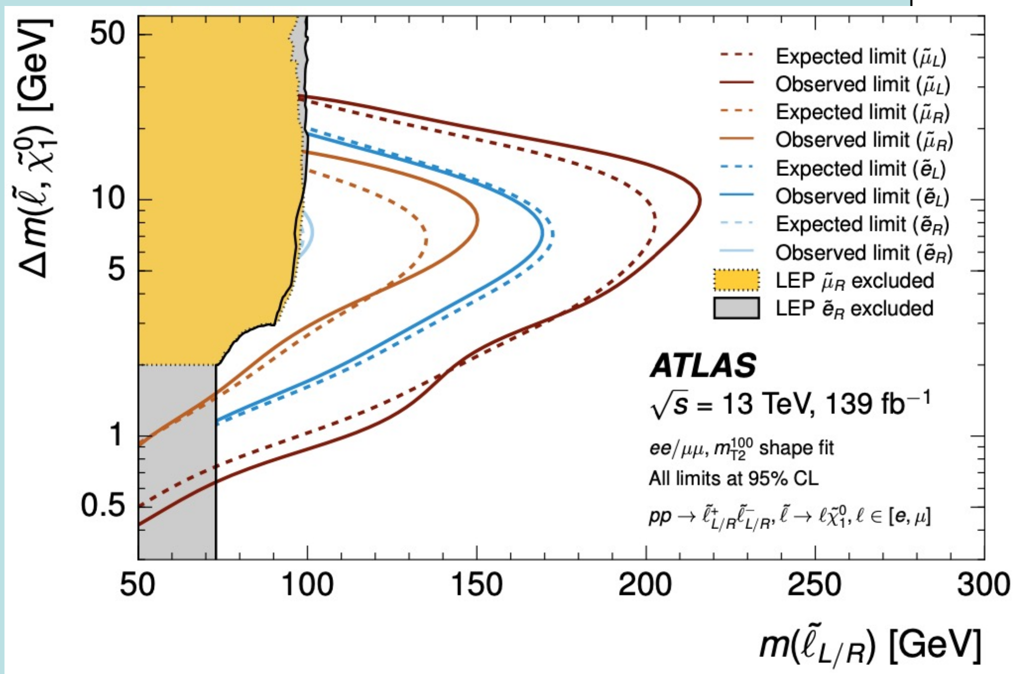


More of same?
Unexplored nooks?
Novel signatures?

LHC vs Supersymmetry

- LHC does not exclude (relatively) light electroweakly-interacting particles, e.g., sleptons

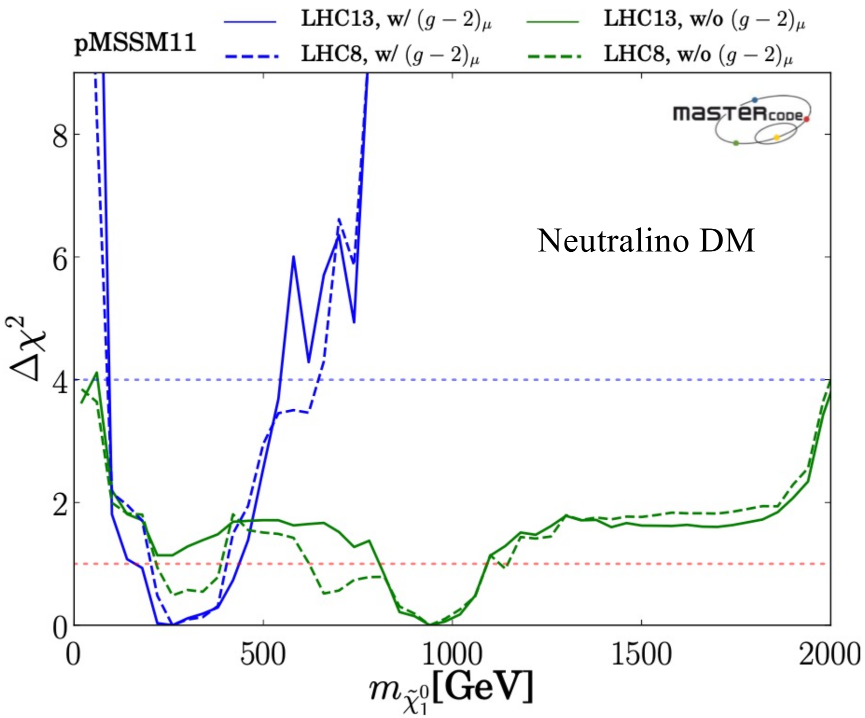


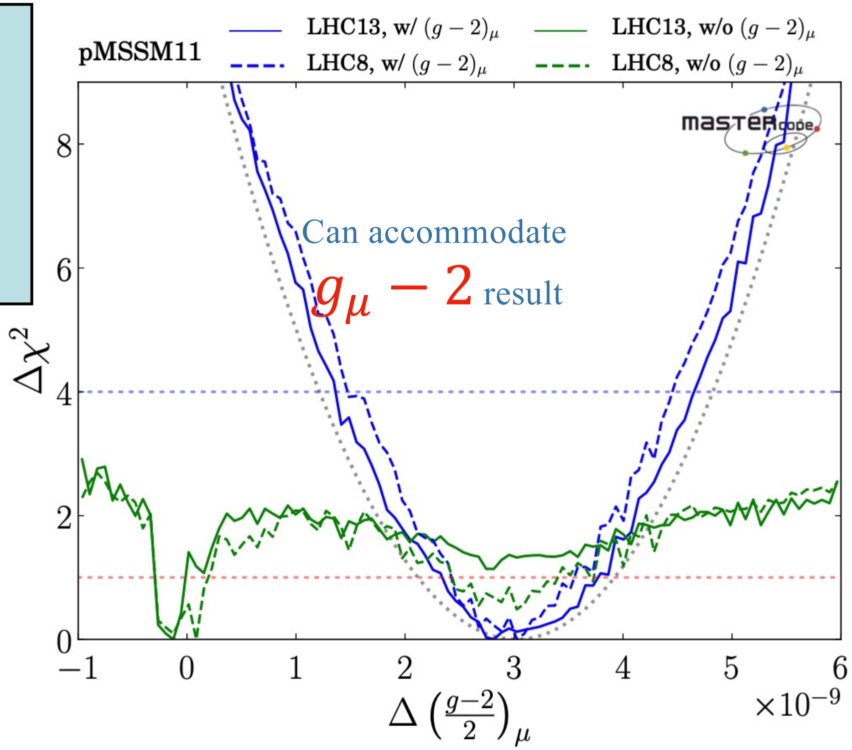


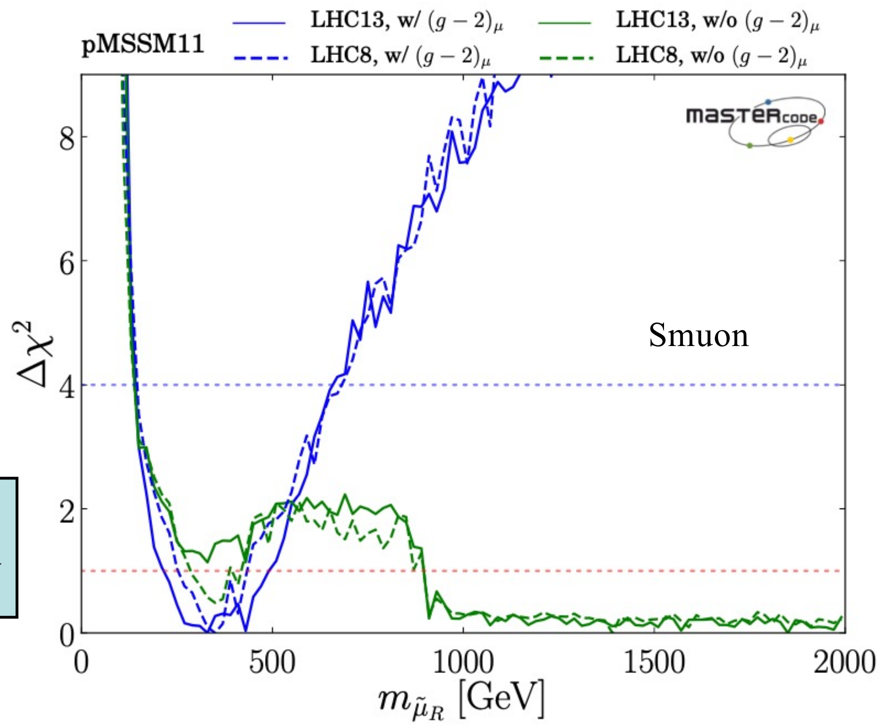
- LHC favours squarks & gluinos > 2 TeV (but loopholes)

$g_\mu - 2$ in Phenomenological Supersymmetry (pMSSM11)

No relation between squark/gluino masses and slepton/neutralino masses







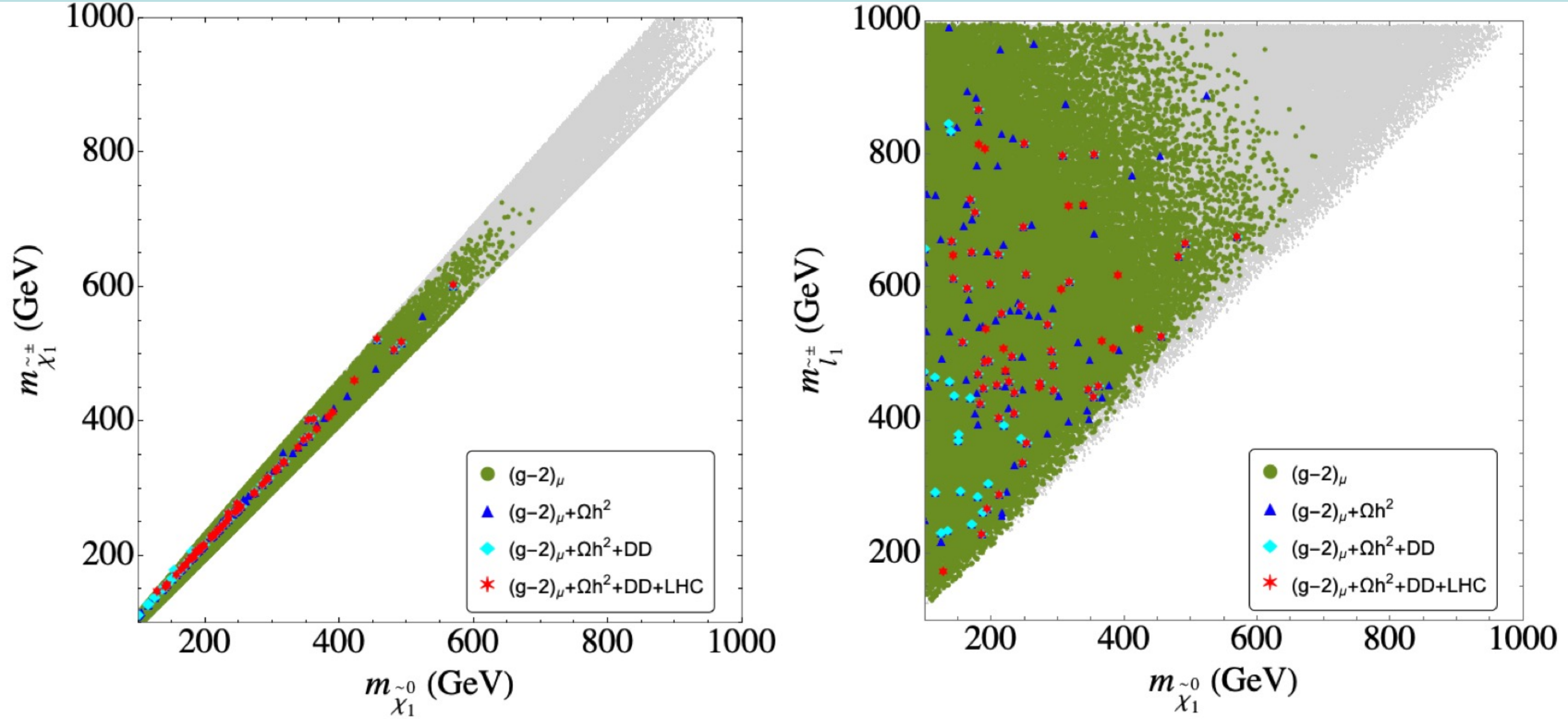
No problem accommodating BNL/FNAL result
Neutralino DM, smuon masses ~ 300/400 GeV

MasterCode, E. Bagnaschi, …, JE et al, arXiv:1710.11091

2021

Supersymmetry & $g_\mu - 2$

- $g_\mu - 2$-friendly scenario with light neutralino, chargino, slepton



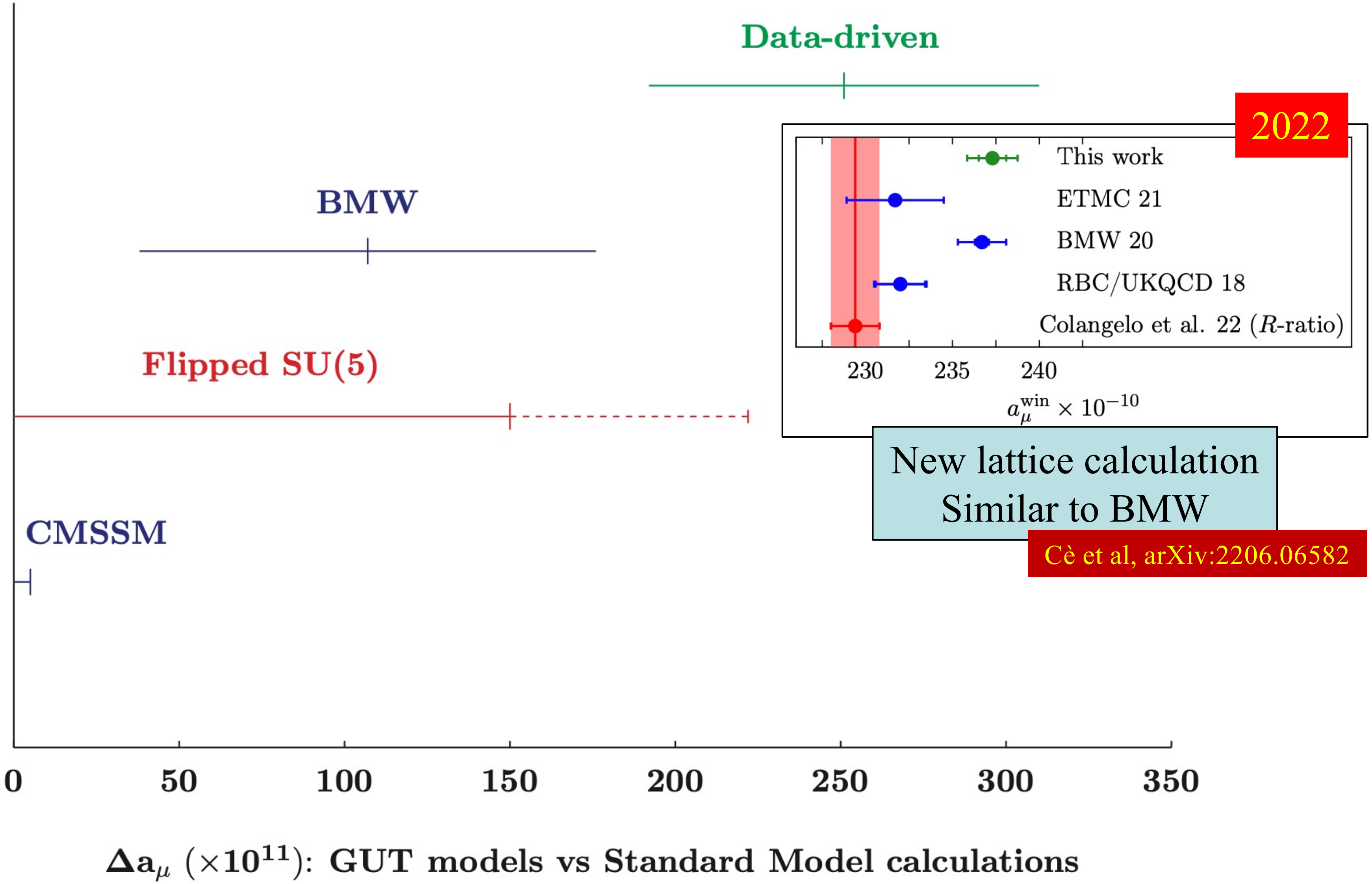
- **Red star** points include all relevant LHC and direct scattering constraints

Chakraborti, Heinemeyer & Saha, arXiv:2104.03287

2021

$g_\mu - 2$ in CMSSM & Flipped SU(5)

vs Lattice, Data-Driven Calculation



New lattice calculation
Similar to BMW

Cè et al, arXiv:2206.06582

JE, Evans, Nagata, Nanopoulos & Olive, arXiv:2107.03025

2022

CDF Collaboration, Science 376 (2022) p170

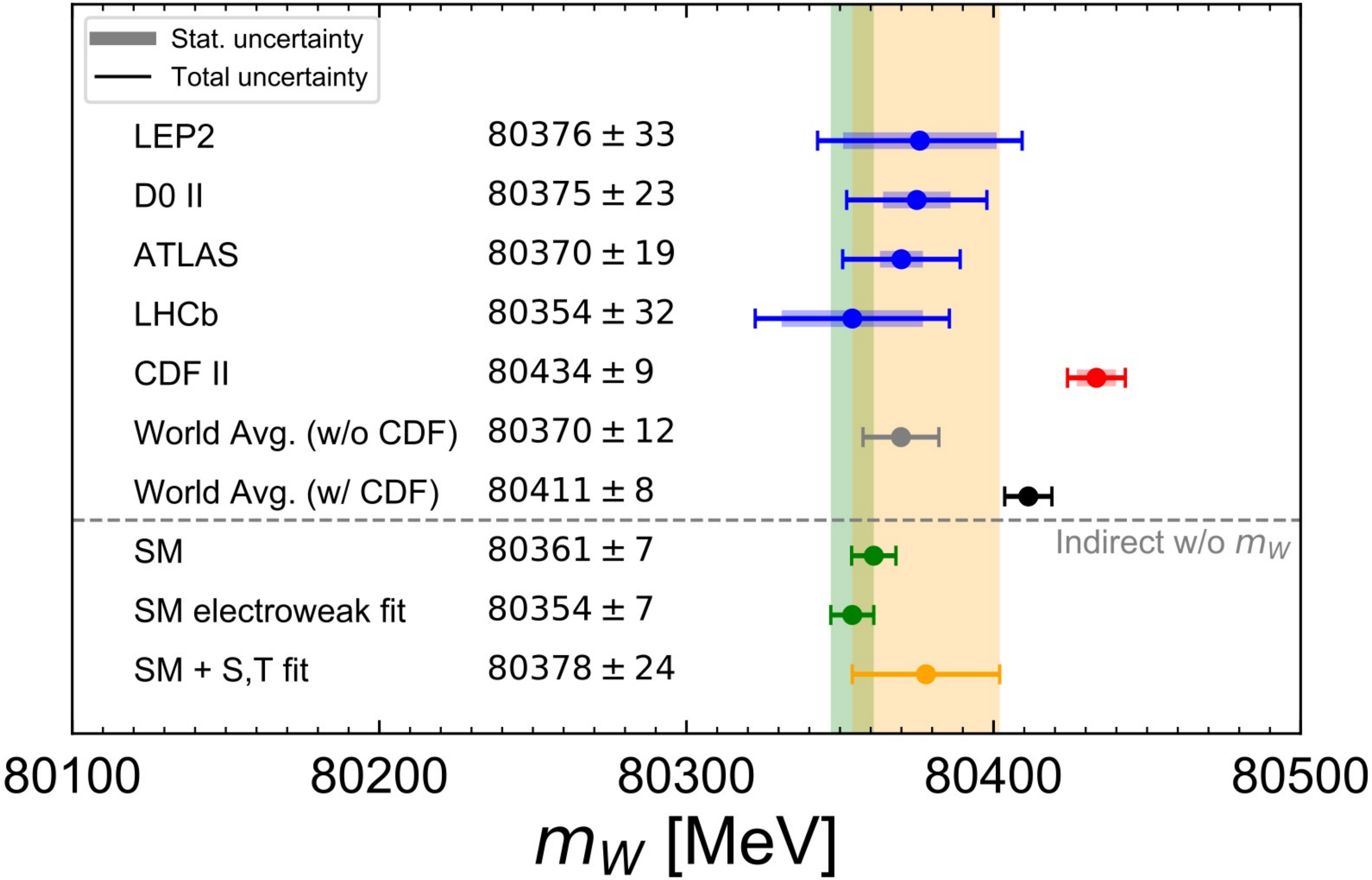
PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6], A. Annovi[7], J. Antos[8,9], G. Apollinari[6], J. A. Appel[6], T. Arisawa[10], A. Artikov[11], J. Asaadi[12], W. Ashmanskas[6], B. Auerbach[13], A. Aurisano[12], F. Azfar[14], W. Badgett[6], T. Bae[15,16,17,18,19,20,21], A. Barbaro-Galtieri[22], V. E. Barnes[23], B. A. Barnett[24], P. Barria[25,26], P. Bartos[8,9], M. Bauce[3,4], F. Bedeschi[25], S. Behari[6], G. Bellettini[25,27], J. Bellinger[28], D. Benjamin[29], A. Beretvas[6], A. Bhatti[30], K. R. Bland[31], B. Blumenfeld[24], A. Bocci[29], A. Bodek[32], D. Bortoletto[23], J. Boudreau[33], A. Boveia[34], L. Brigliadori[35,36], C. Bromberg[37], E. Brucken[1,2], J. Budagov[11]§, H. S. Budd[32], K. Burkett[6], G. Busetto[3,4], P. Bussey[38], P. Butti[25,27], A. Buzatu[38], A. Calamba[39], S. Camarda[40], M. Campanelli[41], B. Carls[42], D. Carlsmith[28], R. Carosi[25], S. Carrillo[43]§, B. Casal[44], M. Casarsa[45], A. Castro[35,36], P. Catastini[46], D. Cauz[45,47,48], V. Cavaliere[42], A. Cerri[22], L. Cerrito[41], Y. C. Chen[49], M. Chertok[50], G. Chiarelli[25], G. Chlachidze[6], K. Cho[15,16,17,18,19,20,21], D. Chokheli[11], A. Clark[51], C. Clarke[52], M. E. Convery[6], J. Conway[50], M. Corbo[6], M. Cordelli[7], C. A. Cox[50], D. J. Cox[50], M. Cremonesi[25], D. Cruz[12], J. Cuevas[44], R. Culbertson[6], N. d'Ascenzo[6], M. Datta[6], P. de Barbaro[32], L. Demortier[30], M. Deninno[35]§, M. D'Errico[3,4], F. Devoto[1,2], A. Di Canto[25,27], B. Di Ruzza[6], J. R. Dittmann[31], S. Donati[25,27], M. D'Onofrio[53], M. Dorigo[45,54], A. Driutti[45,47,48], K. Ebina[10], R. Edgar[5], A. Elagin[34], R. Erbacher[50], S. Errede[42], B. Esham[42], S. Farrington[14], J. P. Fernández Ramos[55], R. Field[43], G. Flanagan[6], R. Forrest[50], M. Franklin[46], J. C. Freeman[6], H. Frisch[34], Y. Funakoshi[10], C. Galloni[25,27], A. F. Garfinkel[23], P. Garosi[25,26], H. Gerberich[42], E. Gerchtein[6], S. Giagu[56], V. Giakoumopoulou[57], K. Gibson[33], C. M. Ginsburg[6], N. Giokaris[57]§, P. Giromini[7], V. Glagolev[11], D. Glenzinski[6], M. Gold[58], D. Goldin[12], A. Golossanov[6], G. Gomez[44], G. Gomez-Ceballos[59], M. Goncharov[59], O. González López[55], I. Gorelov[58], A. T. Goshaw[29], K. Goulianos[30], E. Gramellini[35], C. Grosso-Pilcher[34], J. Guimaraes da Costa[46], S. R. Hahn[6], J. Y. Han[32], F. Happacher[7], K. Hara[60], M. Hare[61], R. F. Harr[52], T. Harrington-Taber[6], K. Hatakeyama[31], C. Hays[14], J. Heinrich[62], M. Herndon[28], A. Hocker[6], Z. Hong[12], W. Hopkins[6], S. Hou[49], R. E. Hughes[63], U. Husemann[64], M. Hussein[37], J. Huston[37], G. Introzzi[25,65,66], M. Iori[56,67], A. Ivanov[50], E. James[6], D. Jang[39], B. Jayatilaka[6], E. J. Jeon[15,16,17,18,19,20,21], S. Jindariani[6], M. Jones[23], K. K. Joo[15,16,17,18,19,20,21], S. Y. Jun[39], T. R. Junk[6], M. Kambeitz[68], T. Kamon[15,16,17,18,19,20,21,12], P. E. Karchin[52], A. Kasmi[31], Y. Kato[69], W. Ketchum[34], J. Keung[62], B. Kilminster[6], D. H. Kim[15,16,17,18,19,20,21], H. S. Kim[6], J. E. Kim[15,16,17,18,19,20,21], M. J. Kim[7], S. H. Kim[60], S. B. Kim[15,16,17,18,19,20,21], Y. J. Kim[15,16,17,18,19,20,21], Y. K. Kim[34], N. Kimura[10], M. Kirby[6], K. Kondo[10]§, D. J. Kong[15,16,17,18,19,20,21], J. Konigsberg[43], A. V. Kotwal[29]*, M. Kreps[68], J. Kroll[62], M. Kruse[29], T. Kuhr[68], M. Kurata[60], A. T. Laasanen[23], S. Lammel[6], M. Lancaster[41], K. Lannon[63], G. Latino[25,26], H. S. Lee[15,16,17,18,19,20,21], J. S. Lee[15,16,17,18,19,20,21], S. Leo[42], S. Leone[25], J. D. Lewis[6], A. Limosani[29], E. Lipeles[62], A. Lister[51], Q. Liu[23], T. Liu[6], S. Lockwitz[64], A. Loginov[64]§, D. Lucchesi[3,4], A. Lucà[7,6], J. Lueck[68], P. Lujan[22], P. Lukens[6], G. Lungu[30], J. Lys[22]§, R. Lysak[8,9], R. Madrak[6], P. Maestro[25,26], S. Malik[30], G. Manca[53], A. Manousakis-Katsikakis[57], L. Marchese[35], F. Margaroli[56], P. Marino[25,70], K. Matera[42], M. E. Mattson[52], A. Mazzacane[6], P. Mazzanti[35], R. McNulty[53], A. Mehta[53], P. Mehtala[1,2], A. Menzione[25]§, C. Mesropian[30], T. Miao[6], E. Michielin[3,4]. D. Mietlicki[5], A. Mitra[49], H. Miyake[60], S. Moed[6], N. Moggi[35], C. S. Moon[15,16,17,18,19,20,21], R. Moore[6], M. J. Morello[25,70], A. Mukherjee[6], Th. Muller[68], P. Murat[6], M. Mussini[35,36], J. Nachtman[6], Y. Nagai[60], J. Naganoma[10], I. Nakano[71], A. Napier[61], J. Nett[12], T. Nigmanov[33], L. Nodulman[13], S. Y. Noh[15,16,17,18,19,20,21], O. Norniella[42], L. Oakes[14], S. H. Oh[29], Y. D. Oh[15,16,17,18,19,20,21], T. Okusawa[69], R. Orava[1,2], L. Ortolan[40], C. Pagliarone[45], E. Palencia[44], P. Palni[58], V. Papadimitriou[6], W. Parker[28], G. Pauletta[45,47,48], M. Paulini[39], C. Paus[59], T. J. Phillips[29], G. Piacentino[6], E. Pianori[62], J. Pilot[50], K. Pitts[42], C. Plager[72], L. Pondrom[28], S. Poprocki[6], K. Potamianos[22], A. Pranko[22], F. Prokoshin[11], F. Ptohos[7], G. Punzi[25,27], I. Redondo Fernández[55], P. Renton[14], M. Rescigno[56], F. Rimondi[35]§, L. Ristori[25,6], A. Robson[38], T. Rodriguez[62], S. Rolli[61], M. Ronzani[25,27], R. Roser[6], J. L. Rosner[34], F. Ruffini[25,26], A. Ruiz[44], J. Russ[39], V. Rusu[6], W. K. Sakumoto[32], Y. Sakurai[10], L. Santi[45,47,48], K. Sato[60], V. Saveliev[6], A. Savoy-Navarro[6], P. Schlabach[6], E. E. Schmidt[6], T. Schwarz[5], L. Scodellaro[44], F. Scuri[25], S. Seidel[58], Y. Seiya[69], A. Semenov[11], F. Sforza[25,27], S. Z. Shalhout[50], T. Shears[53], P. F. Shepard[33], M. Shimojima[60], M. Shochet[34], I. Shreyber-Tecker[73], A. Simonenko[11], K. Sliwa[61], J. R. Smith[50], F. D. Snider[6], H. Song[33], V. Sorin[40], R. St. Denis[38]§, M. Stancari[6], D. Stentz[6], J. Strologas[58], Y. Sudo[60], A. Sukhanov[6], I. Suslov[11], K. Takemasa[60], Y. Takeuchi[60], J. Tang[34], M. Tecchio[5], P. K. Teng[49], J. Thom[6], E. Thomson[62], V. Thukral[12], D. Toback[12], S. Tokar[8,9], K. Tollefson[37], T. Tomura[60], S. Torre[7], D. Torretta[6], P. Totaro[3], M. Trovato[25,70], F. Ukegawa[60], S. Uozumi[15,16,17,18,19,20,21], F. Vázquez[43], G. Velev[6], K. Vellidis[57], C. Vernieri[25,70], M. Vidal[23], R. Vilar[44], J. Vizán[44], M. Vogel[58], G. Volpi[7], P. Wagner[62], R. Wallny[6], S. M. Wang[49], D. Waters[41], W. C. Wester III[6], D. Whiteson[62], A. B. Wicklund[13], S. Wilbur[50], H. H. Williams[62], J. S. Wilson[5], P. Wilson[6], B. L. Winer[63], P. Wittich[6], S. Wolbers[6], H. Wolfmeister[63], T. Wright[5], X. Wu[51], Z. Wu[31], K. Yamamoto[69], D. Yamato[69], T. Yang[6], U. K. Yang[15,16,17,18,19,20,21], Y. C. Yang[15,16,17,18,19,20,21], W.-M. Yao[22], G. P. Yeh[6], K. Yi[6], J. Yoh[6], K. Yorita[10], T. Yoshida[69], G. B. Yu[15,16,17,18,19,20,21], I. Yu[15,16,17,18,19,20,21], A. M. Zanetti[45], Y. Zeng[29], C. Zhou[29], S. Zucchelli[35,36]

2022

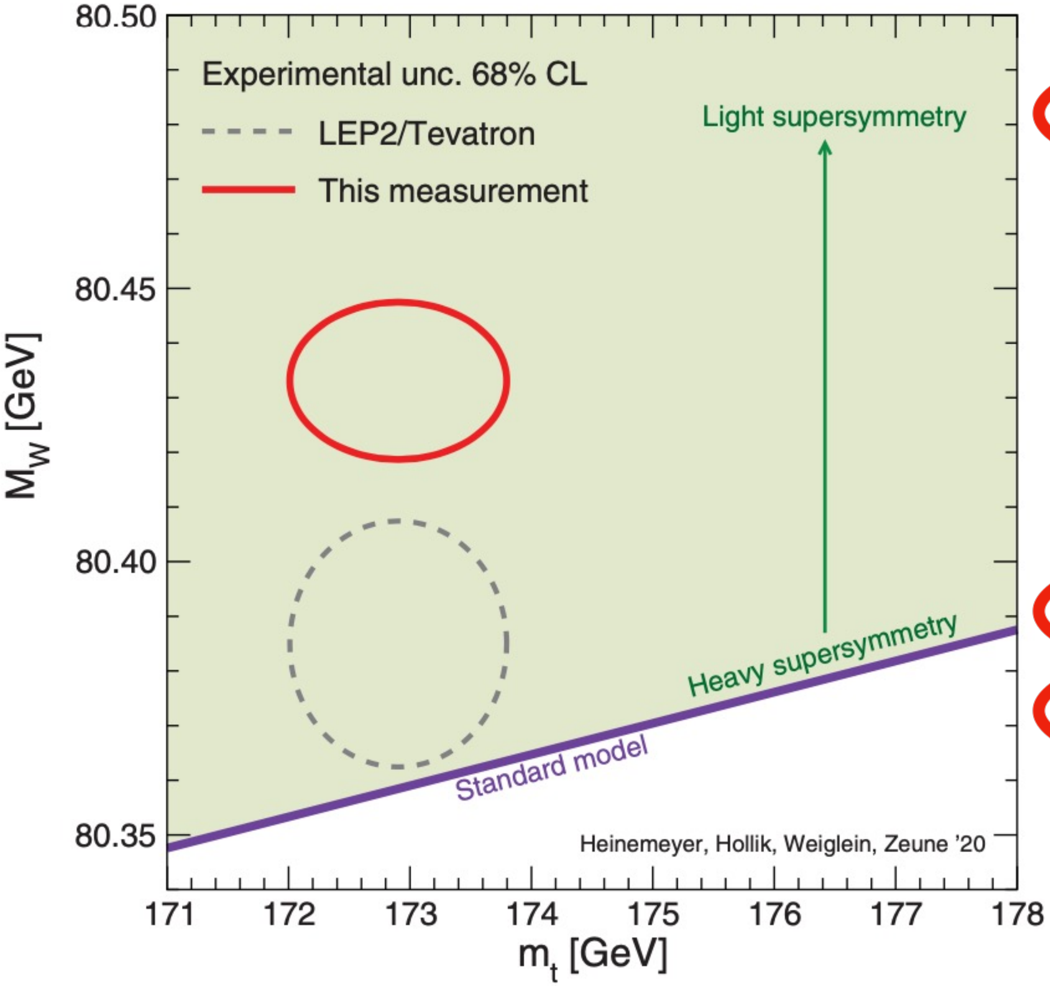
CDF Measurement of the W Mass
Compared with Previous Measurements



Tension: 7-σ discrepancy with Standard Model?

2022

CDF Measurement of the W Mass



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

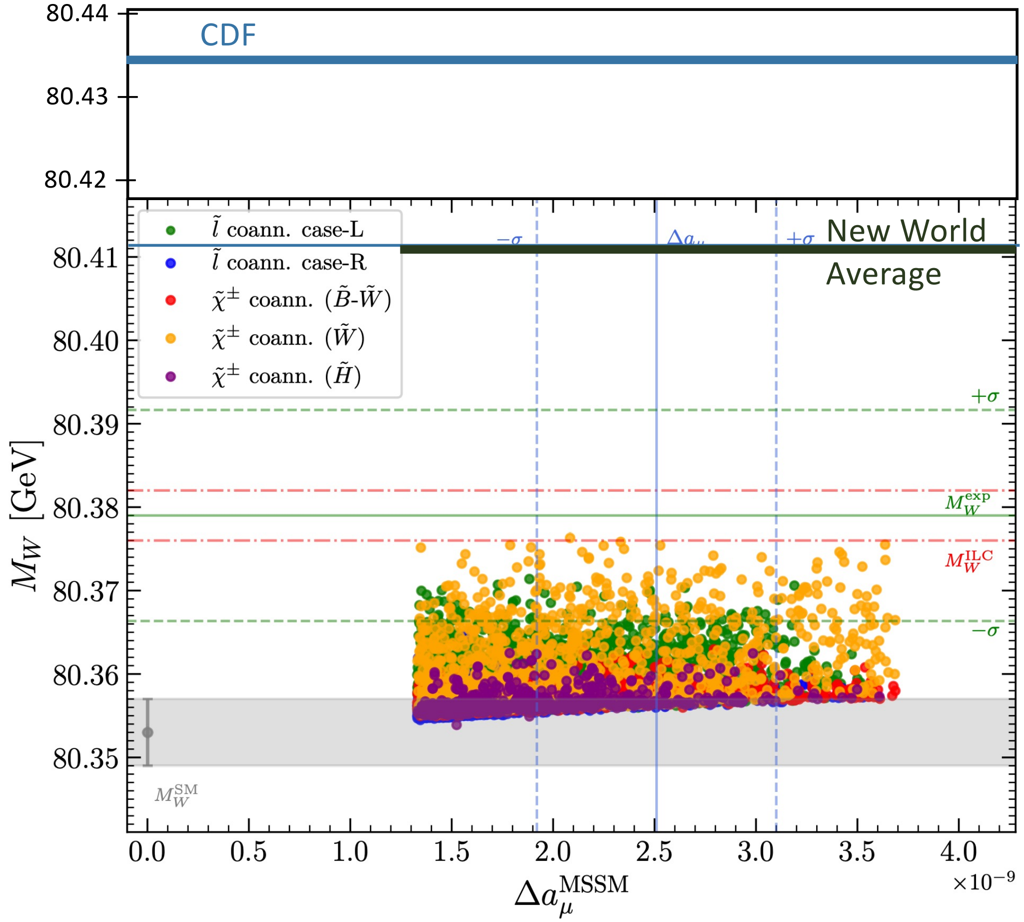
Biggest uncertainties: lepton energy, p_T model, parton distributions, backgrounds

CDF Collaboration, Science 376 (2022) p170

2022

W Mass in Supersymmetry?

- Survey of possible contributions from electroweak particles
- Can reach old world average, but not CDF or new world average
- Additional contribution from stops?



Bagnaschi, Chakraborti, Heinemeyer, Saha & Weiglein, arXiv:2203.15710

2022

What lies beyond the Standard Model?

Supersymmetry

New motivations From LHC Runs 1 & 2

- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, …, dark matter