Desperately seeking SUSY: Evaluation of early aspirations for SUSY

Stuart Raby

SUSY after LHC 2016
Bethe Forum
Bonn, Germany
May 29, 2017

THE OHIO STATE UNIVERSITY
DEPARTMENT OF PHYSICS

Outline

- The early years
  - Pre- 1980
    - Salam & Strathdee
    - Wess & Zumino
    - Fayet & Ferrara **Phys.Rept. 32, 249 (1977)**
    - Fayet & Farrar **Phys.Lett. 76B, 575 (1978)**
      - R-hadrons – M_{gluino}~5 GeV
    - Freedman, van Nieuwenhuizen & Ferrara 1976
    - Cremmer, Julia, Scherk, van Nieuwenhuizen, Ferrara & Girardello SuperHiggs 1978

- Post- 1980

Witten; Dine, Fischler & Srednicki IAS

Dimopoulos & Raby Stanford

Gauge-Mediated SUSY Breaking

Fischler, Nilles, Polchinski, Raby & Susskind

U(1) D-term Exact at one loop

Dimopoulos, Raby & Wilczek SUSY GUTs

Ibanez & Ross Radiative EWSB

Nilles & Raby SUSY PQ symmetry

- Solving the gauge hierarchy problem
- Lenny returns from Princeton

Witten (SUSY unbroken at tree level: then unbroken to any finite order in perturbation theory)

Step one – learn supersymmetry

Fayet & Ferrara Physics Reports

1. There was NO MSSM in this report
a) U(1) FI breaking – anomalous U(1)
b) O'Raifeartaigh breaking – $\sum_J (-1)^{2J} m_J^2 = 0$
2. Dynamical symmetry breaking – LOOPs

Scalar & gaugino masses radiatively

Witten

If U(1) is embedded in a GUT, then D-term Vanishes to all finite orders

About the same time :

- Dimopoulos & Raby SuperColor

  $SU(4)_C \times SU(2)_L \times U(1)_{T3R} \times SU(N)_{SC}$

  Safe U(1)s

  Gaugino condensate breaks SUSY

- Dine, Fischler & Srednicki

  $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(N)_{SuperTechnicolor}$

  Quote Witten on U(1)s

  Gaugino condensate breaks SUSY

- Witten – index theorem SUSY unbroken in SU(N) !

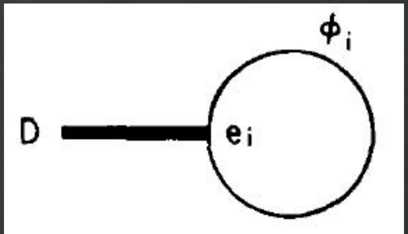
Witten

If U(1) is embedded in a GUT, then D-term Vanishes to all finite orders

Suggests high-low scale collusion

U(1) problem was a killer for SUSY naturalness

$$\langle D \rangle \propto g \sum_i e_i \, \Lambda^2 \quad \text{at one loop}$$



Fischler, Nilles, Polchinski, Raby & Susskind

U(1) D-term exact at one loop

Dimopoulos, Raby & Wilczek **SUSY GUTs**

Dimopoulos & Georgi Introduce soft SUSY breaking masses into low energy theory -MSSM (Girardello & Grisaru)

Ibanez & Ross

2 loops

Marciano & Senjanovic

Einhorn & Jones

$$b = \frac{11}{3}C_2(G) - \frac{2}{3}T(R_f)N_f(R_f) - \frac{1}{3}T(R_s)N_s(R_s)$$

Dimopoulos, Raby & Wilczek SUSY GUTs

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$$b = \frac{11}{3}C_2(G) - \frac{2}{3}T(R_f)N_f(R_f) - \frac{1}{3}T(R_s)N_s(R_s)$$

$$b_{SUSY} = 3C_2(G) - T(R_\chi)N_\chi(R_\chi)$$

Phys. Rev. D 1981

Supersymmetry and the scale of unification

S. Dimopoulos

Institute for Theoretical Physics, Stanford University, Stanford, California 94305,
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106,
and University of Michigan, Ann Arbor, Michigan 48109

S. Raby

Institute for Theoretical Physics, Stanford University, Stanford, California 94305
and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Frank Wilczek

Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

(Received 20 April 1981)

Unified theories which are supersymmetric down to energies $\sim 10^3$–10^5 GeV have been proposed as possible solutions to the gauge-hierarchy problem. The additional particles then required have significant effects on renormalization of coupling constants. The previous successful calculation of the weak mixing angle is only slightly changed, but the scale of unification is moved significantly higher, into the range of the Planck mass. This may be suggestive of an eventual unification including gravity, and markedly reduces the predicted rate of nucleon decay.

Radiative Electroweak Symmetry Breaking

$SU(2)_L \times U(1)$ SYMMETRY BREAKING AS A RADIATIVE EFFECT OF SUPERSYMMETRY BREAKING IN GUTs

Luis IBÁÑEZ [1] and Graham G. ROSS [2]
Department of Theoretical Physics, Oxford OX1 3NP, UK

Received 7 January 1982

Phys. Lett. B 1982

$N = 1$ SUPERGRAVITY, THE BREAKING OF $SU(2) \times U(1)$ AND THE TOP-QUARK MASS

L.E. IBÁÑEZ and C. LÓPEZ
Departamento de Fisica Teórica, C-XI, Universidad Autónoma de Madrid, Cantoblanco, Madrid-34, Spain

Received 28 February 1983

Phys. Lett. B 1983

Spontaneously broken $N = 1$ supergravity coupled to grand unified theories generates soft terms which break explicitly the residual global supersymmetry. These soft terms characterized by the gravitino mass scale induce radiatively the breaking of the $SU(2) \times U(1)$ symmetry. This is achieved for top-quark masses 50 GeV $\lesssim m_t \lesssim$ 190 GeV. For negligible (susy-breaking) gaugino masses we give an analytical lower bound on m_t as a function of the strength of the trilinear scalar couplings (A).

Geometric Hierarchy

Witten Inverted Hierarchy i.e. generate GUT scale from weak scale

Dimopoulos & Raby, Banks and Kaplunovsk

Inverted Hierarchy i.e. generate GUT scale and weak scale from intermediate scale

Polchinski & Susskind, Dimopoulos & Raby

SUSY breaking decoupling theorem

$$m_{soft} \approx \frac{\Lambda_{SUSY}^2}{M_{messenger}}$$

Supergravity era

Chammsedine, Arnowitt & Nath 1982

Barbieri, Ferrara & Savoy

Hall, Lykken & Weinberg 1983

Nilles, Srednicki & Wyler

$$m_{soft} \approx \frac{\Lambda^2_{SUSY}}{M_{Pl}} \qquad \sum_J (-1)^{2J} m_J^2 = 4 m_{3/2}^2$$

Ferrara, Girardello & Nilles 1983

gaugino condensates in SUGRA break SUSY

$$m_{soft} \sim \langle \lambda\lambda \rangle / (M_{messenger})^2$$

Dynamical SUSY Breaking

Via non-perturbative contributions to the superpotential

Affleck, Dine & Seiberg 1984

Dine, Nelson & Shirman 1994

Cosmology

Dark Matter

Pagels & Primack, Weinberg; Goldberg ~1983

Cosmological Moduli problem

Coughlan, Fischler, Kolb, Raby & Ross 1983

Gravitino problem

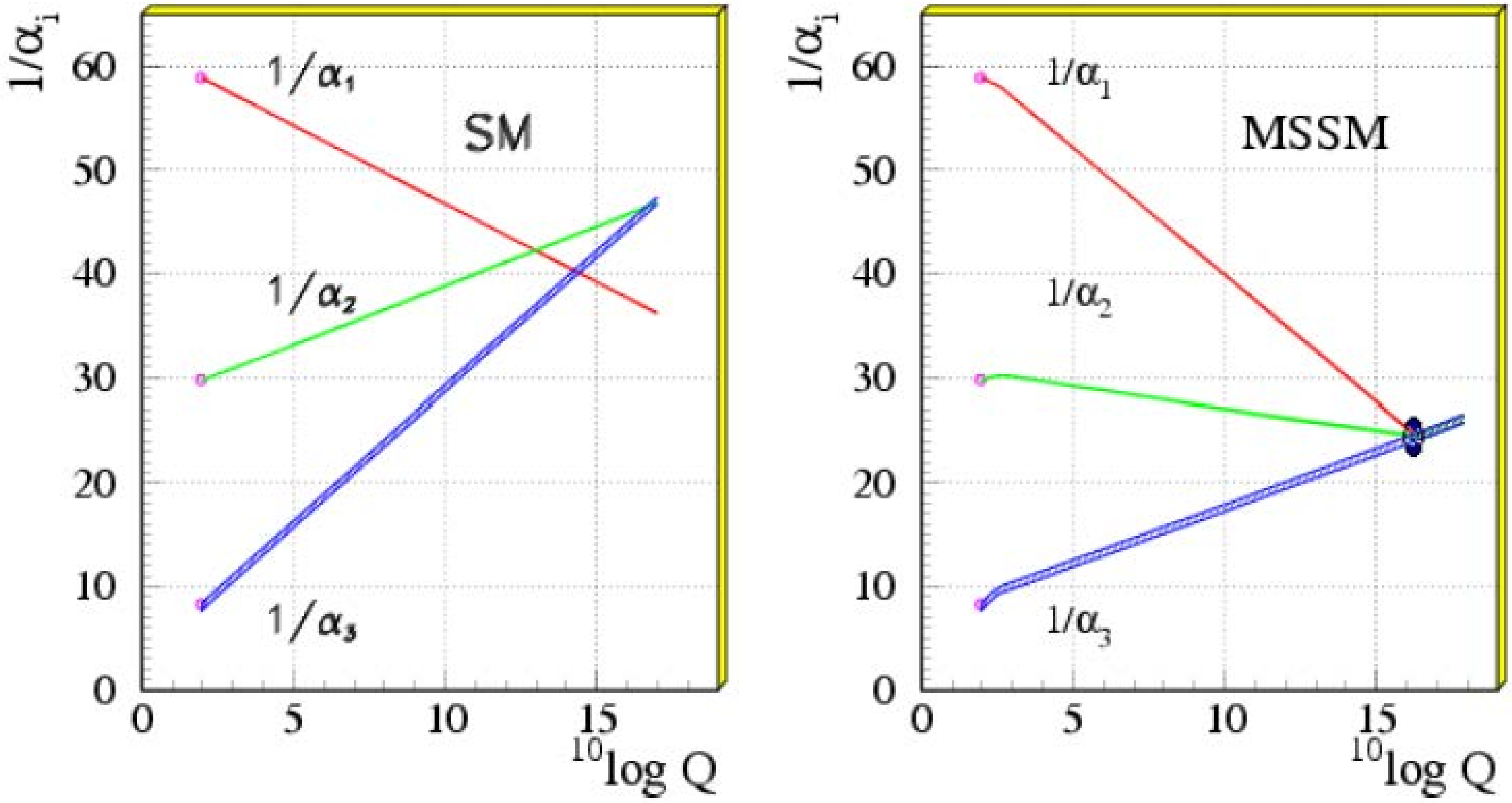
NMSSM

Nilles, Srednicki & Wyler, Frere, Jones & Raby
1983

Particle Physics : A Los Alamos Primer 1984

republished in 1988 by Cambridge Press

"An encouraging feature of the theory is that low energy supersymmetry can be verified in the next ten years, possibly as early as next year with experiments now in progress at the CERN proton-antiproton collider. .... Hopefully, it will not be too long before we learn whether or not the underlying structure of the universe possesses this elegant, highly unifying symmetry."



LEP CERN
1991

$N = 1$ SUPERGRAVITY, THE BREAKING OF SU(2) × U(1) AND THE TOP-QUARK MASS

L.E. IBÁÑEZ and C. LÓPEZ
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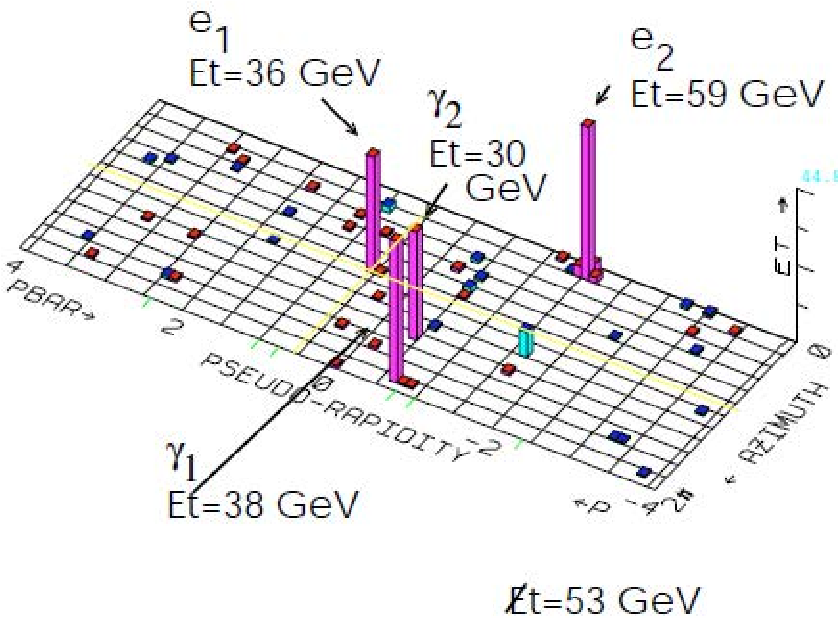
Top quark discovered 1995 Fermilab

SUSY on a ROLL



S. Park for CDF 1995

FIG. 10. A zoo event (run 68739 / event 257646) with 2 electrons, 2 photons and large $\not{E}_T$.

Low Energy GMSB

Dimopoulos, Dine, Raby, Thomas 1996

$$p\,\overline{p} \rightarrow \widetilde{e^+}\,\widetilde{e^-} \rightarrow e^+ e^- \gamma\,\gamma + E_T^{miss}$$

Higgs physics at LEP-2
Higgs working group
M. Carena and P.M. Zerwas, convenors 1996

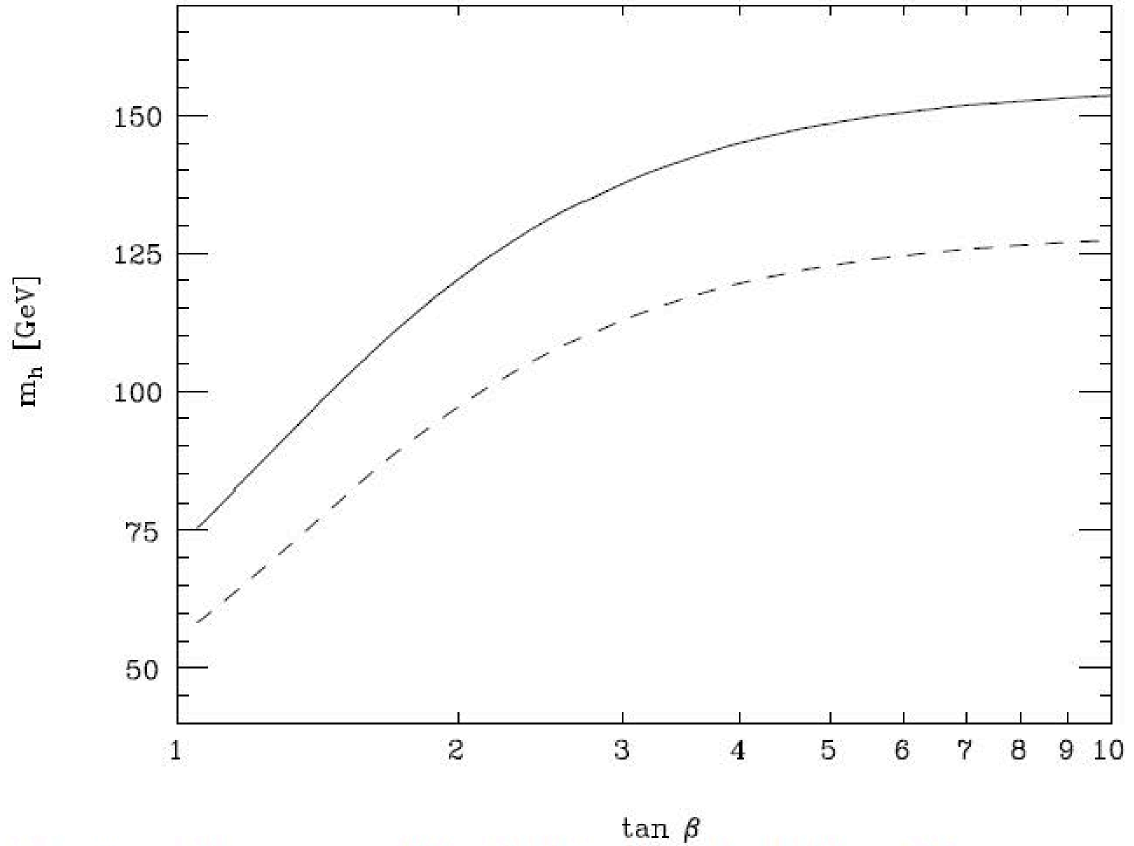


Figure 17: *Upper limit on the mass of the lightest neutral Higgs boson mass m_h as a function of $\tan\beta$ for zero mixing (dashed line) and for the maximal impact of mixing in the stop sector (solid line); $M_S = 1$ TeV.*

Naturalness of supersymmetric models

Moriond 1999

Alessandro Strumia

*Dipartimento di Fisica, Università di Pisa
ed INFN, sezione di Pisa, I-56126 Pisa, Italia*

After presenting a simple procedure for testing naturalness (similar to Bayesian inference and not more subjective than it) we show that LEP2 experiments pose a naturalness problem for 'conventional' supersymmetric models. About 95% of the parameter space of minimal supergravity MSSM is excluded by LEP2 experiments. Moreover in this model elec-

$$m_0,\ |A_0|,\ |M_{1/2}|,\ |\mu_0|,\ |B_0| = (\text{random \# 0 - 1})\ m_{SUSY}$$

Density of points proportional to 1/FT
and $\tan\beta < 10$

Haggling over the Fine-Tuning Price of LEP
Chankowski, Ellis, Olechowski & Pokorski 1999

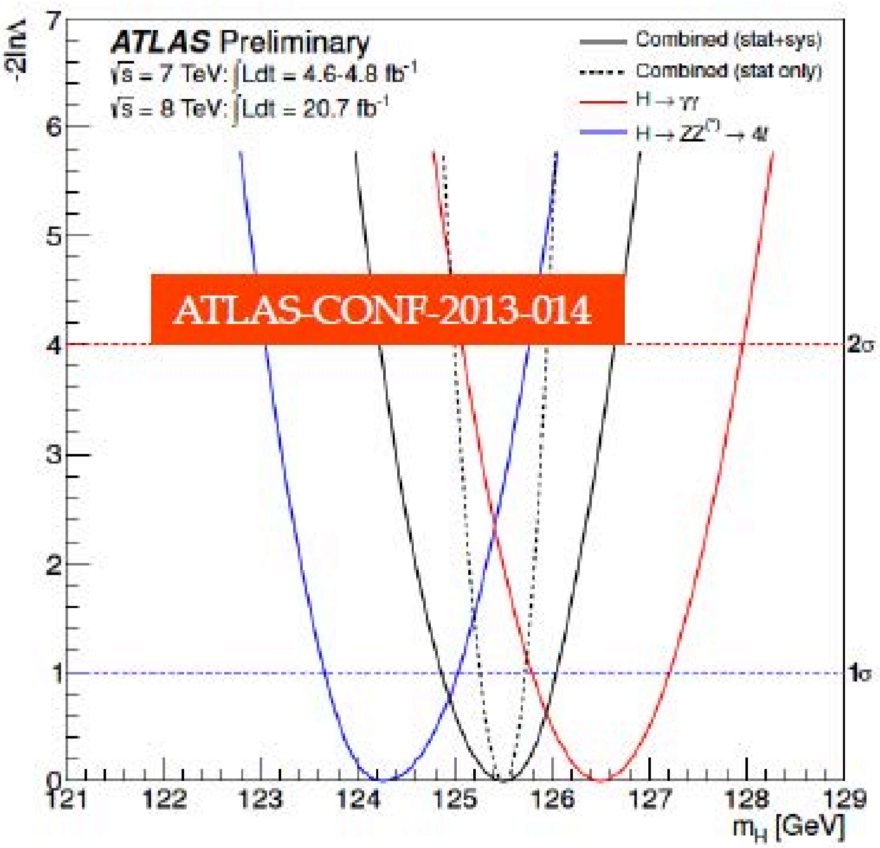
For now, however, let us summarize our discussion of naturalness constraints with the following quote from (Chankowski *et al* 1999), 'We re-emphasize that naturalness is [a] subjective criterion, based on physical intuition rather than mathematical rigour. Nevertheless, it may serve as an important guideline that offers some discrimination between different theoretical models and assumptions. As such, it may indicate which domains of parameter space are to be preferred. However, one should be very careful in using it to set any absolute upper bounds on the spectrum. We think it safer to use relative naturalness to compare different scenarios, as we have done in this paper.' As these authors discuss in their paper, in some cases the amount of fine-tuning can be decreased dramatically if one assumes some linear relations between GUT scale parameters. These relations may be due to some, yet unknown, theoretical relations coming from the fundamental physics of SUSY breaking, such as string theory.

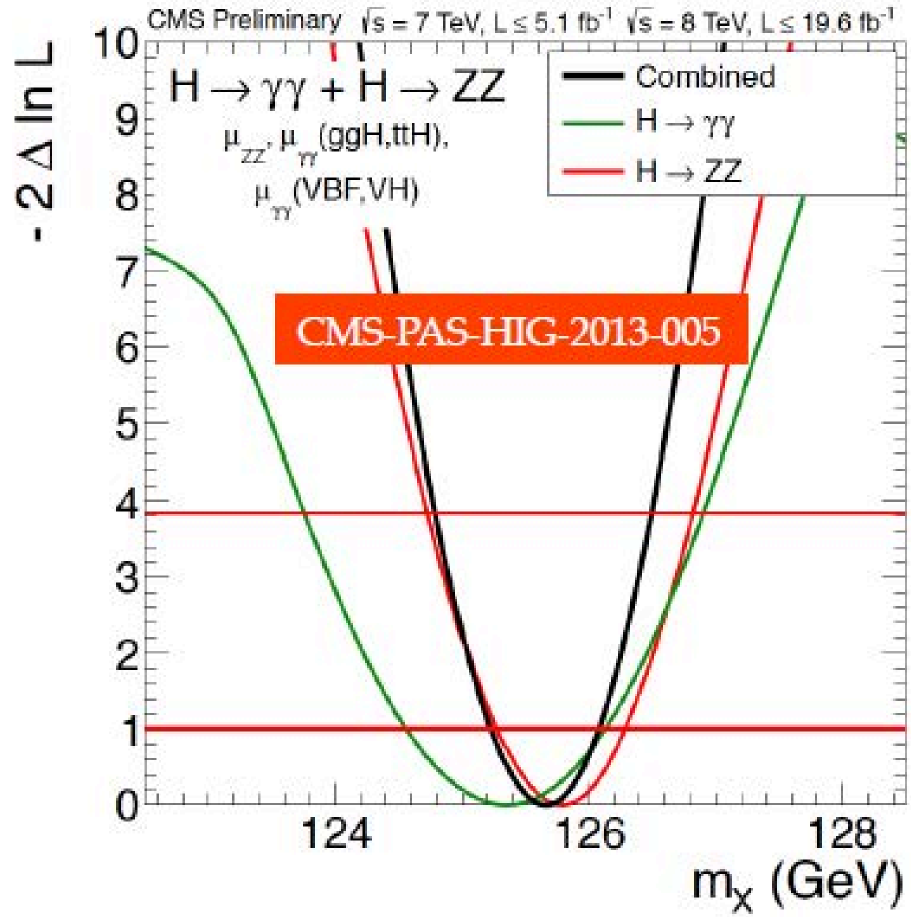
Desperately seeking SUSY   IOP 2004

"Assuming SUSY particles are observed at the LHC, then the fun has just begun. It will take many years to prove that it is really supersymmtry. Assuming SUSY is established, a SUSY desert from M_Z to M_G (or M_N) becomes highly likely. Thus precision measurements at the LHC or a Linear Collider will probe the boundary conditions at the very largest and fundamental scales of nature. With the additional observation of proton decay and/or precise GUT relations for sparticle masses, GUTs can be confirmed. Hence with experiments at TeV scale accelerators or in underground detectors for proton decay, neutrino oscillations or dark matter, the fundamental superstring physics can be probed. Perhaps then we may finally understand who ordered three families. It is thus no wonder why the elementary particle physics community is *desperately seeking SUSY.*"

Higgs at the LHC !!! Consistent with SUSY bounds

Measured from γγ and ZZ*(4l) mass spectra: needed to predict σxBR

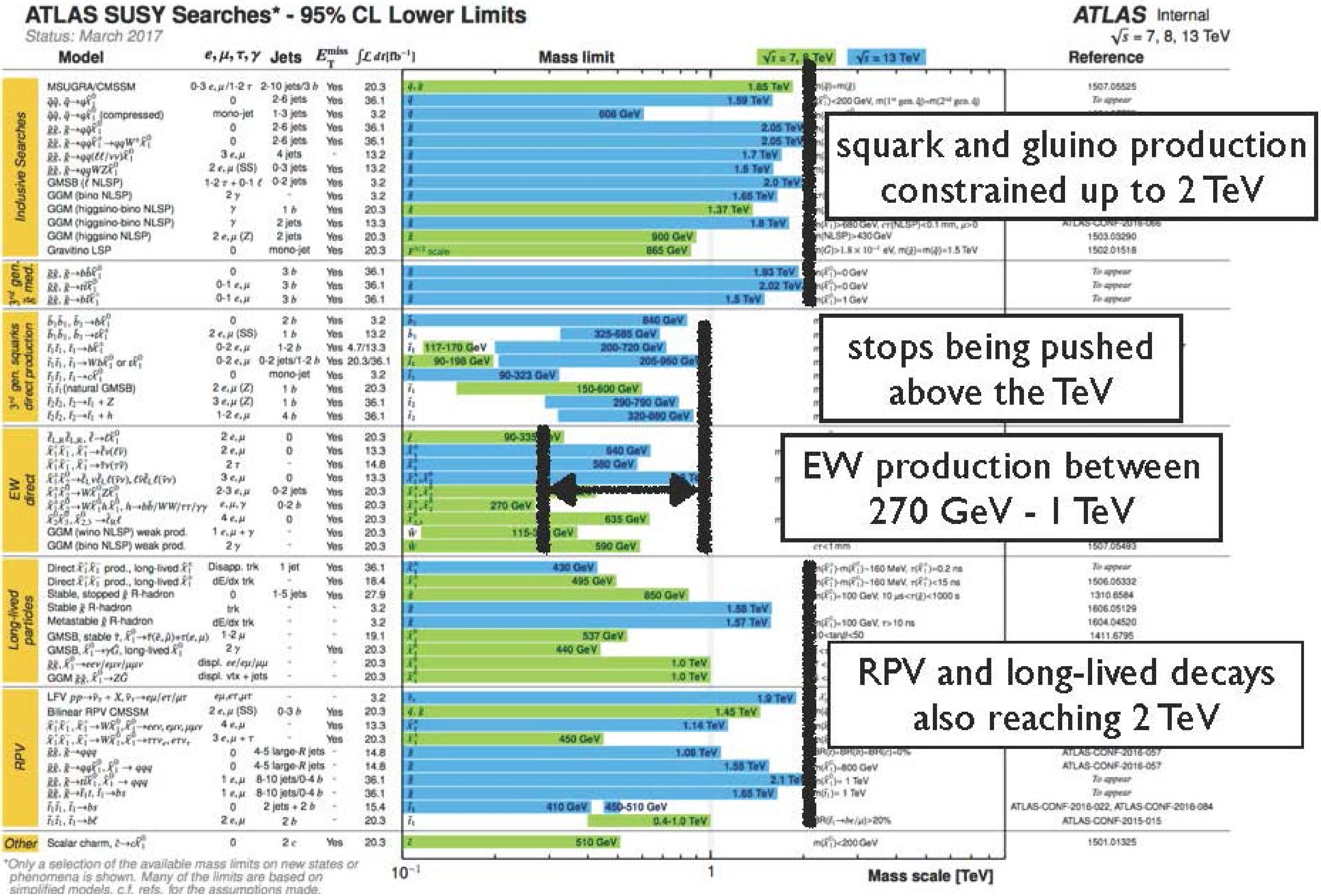




$$ATLAS : M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{syst}\, GeV$$

$$CMS : M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}\, GeV$$

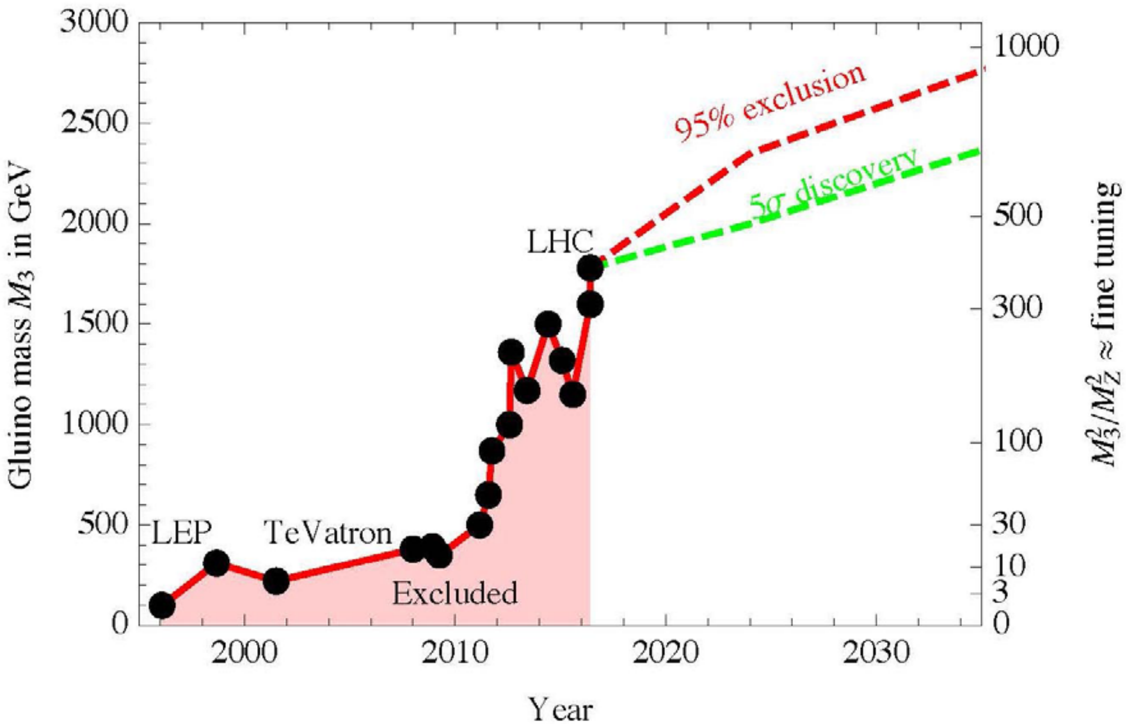
BUT still NO SUSY

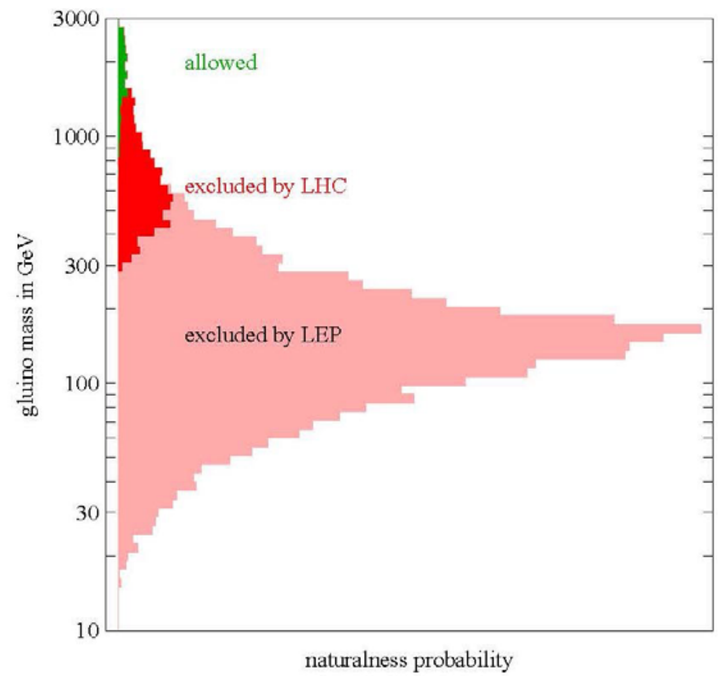


Amoroso ATLAS Moriond 2017

2010: LHC data speak

Strumia 2016

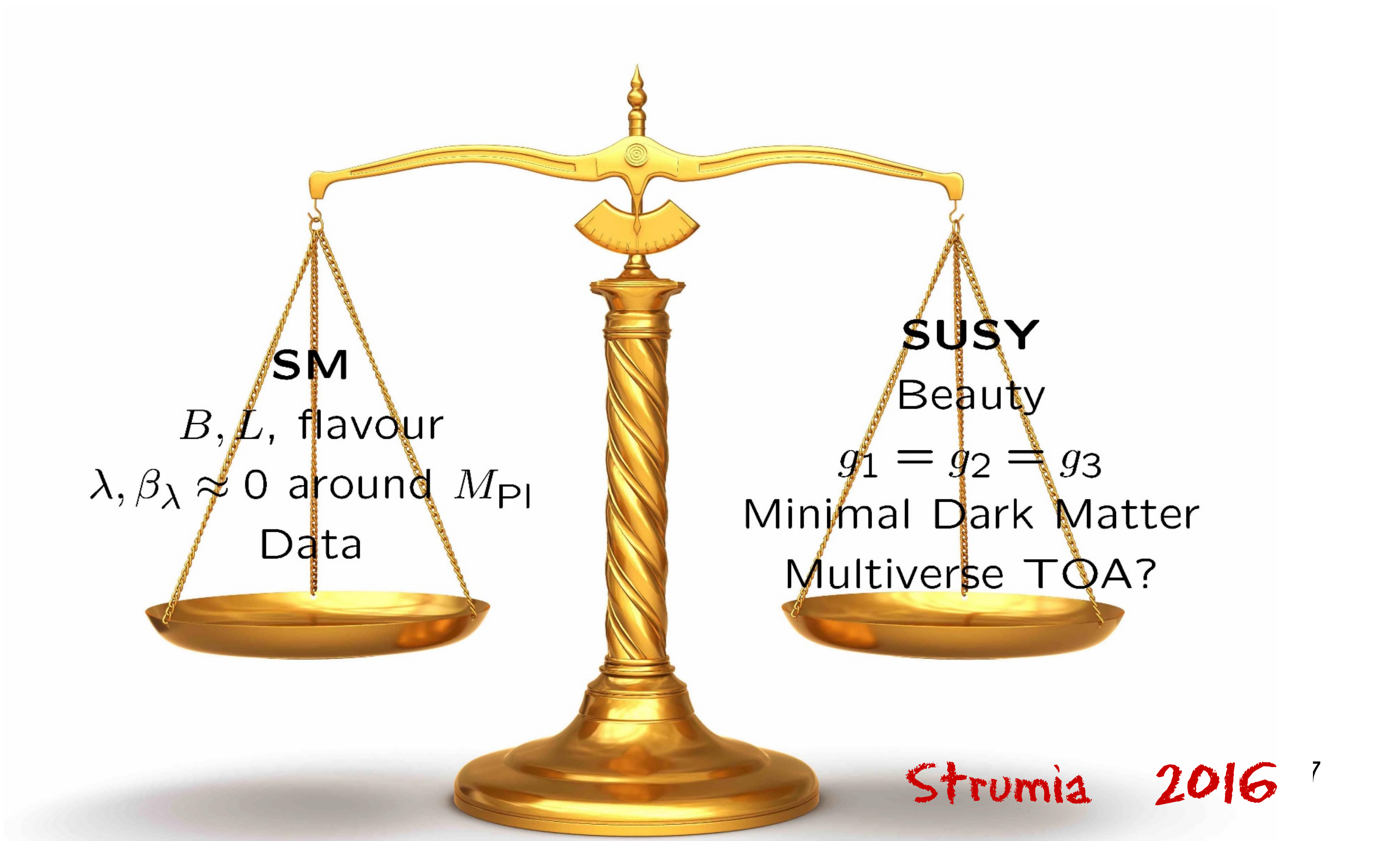




Is SUSY well?

No

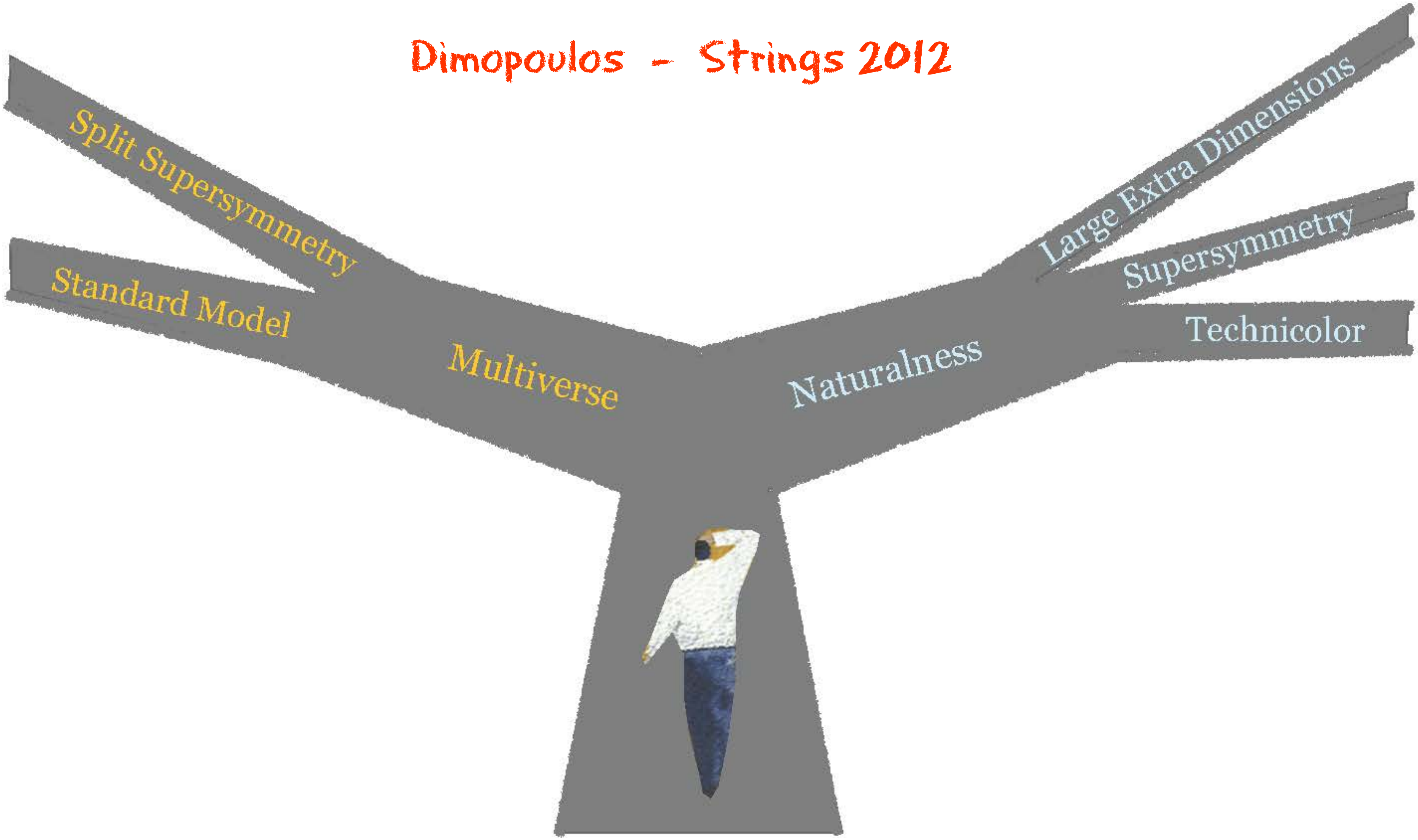
Giving up naturalness maybe better than giving up the rest



Strumia 2016

What can the Higgs tell us?

Dimopoulos - Strings 2012



Waiting since 1981 – Unification ??

1. MZ << MGUT "Natural"
2. Explains Charge Quantization and family structure
3. Predicts Gauge Coupling Unification
4. Predicts Yukawa Coupling Unification
5. + Family Symmetry ⇒ Hierarchy of Fermion Masses
6. Neutrino Masses via See – Saw scale ~ 10^{-3}–10^{-2} M_{GUT}
7. LSP – Dark Matter Candidate
8. Baryogenesis via Leptogenesis
9. SUSY Desert ⇒ LHC experiments probe physics M_{planck}
10. SUSY GUTs are natural extension of the SM
11. SUSY GUTs ⇒ MSSM in Strings

Simple Theory makes many predictions

- Pati-Salam 3 family model
  with D_4 family symmetry & $\mathbb{Z}_4^R$ symmetry
- Yukawa Unification – 3rd family only
- Global χ^2 fits & predictions

Yukawa Unification

$$\lambda \ 16_3\ 10\ 16_3$$

~ Universal Gaugino Masses

Fit t,b,tau requires

$$A_0 \approx -2m_{16} \quad m_{10} \approx \sqrt{2}m_{16}$$

$$m_{16} > \textit{few}\ \text{TeV} \qquad \mu, M_{1/2} << m_{16}$$

$$\tan\beta \approx 50$$

Summary
First order results
Third family only

- Universal scalar masses > 10 TeV
- Third family scalars much lighter
- Light Higgs is SM-like
- Gluinos want to be light

$$
\begin{aligned}
W_{\rm PS} =& \lambda \mathcal{Q}_3\, \mathcal{H}\, \mathcal{Q}_3^c + \mathcal{Q}_a\, \mathcal{H}\, F_a^c + F_a\, \mathcal{H}\, \mathcal{Q}_a^c \\
& + \bar{F}_a^c \left(M_F\, F_a^c + \mathbf{15}\, \frac{\phi_a}{\hat{M}}\, \mathcal{Q}_3^c + \mathbf{15}\, \frac{\tilde{\phi}_a}{\hat{M}}\, \mathcal{Q}_a^c + \mathbf{A}\, \mathcal{Q}_a^c + \Theta'\, \mathcal{Q}_a^c + \frac{\tilde{\Theta}_a}{\hat{M}}\, \mathcal{Q}_a^c \right) \\
& + \bar{F}_a \left(M_F\, F_a + \mathbf{15}\, \frac{\phi_a}{\hat{M}}\, \mathcal{Q}_3 + \mathbf{15}\, \frac{\tilde{\phi}_a}{\hat{M}}\, \mathcal{Q}_a + \mathbf{A}\, \mathcal{Q}_a + \Theta'\, \mathcal{Q}_a - \frac{\tilde{\Theta}_a}{\hat{M}}\, \mathcal{Q}_a \right)
\end{aligned}
$$

$$\{Q_3,\, Q_a,\, F_a\} = (4,2,1,1), \quad \{Q_3^c,\, Q_a^c,\, F_a^c\} = (\bar{4},\bar{2},1,1)$$

$$\phi_a,\ \theta_a,\ B_2,\ \left\{\tilde{\theta}_a,\, \theta'\right\} \text{ flavon fields}$$

$$a = 1,2 \quad D_4 \ \text{ family index}$$

$$M_F \propto 1 + \alpha\, X + \beta\, Y, \quad \langle 15 \rangle \propto B - L$$

$\tilde{\theta},\ \theta'$ terms added (real), $\alpha,\ \beta$ now complex

$$\begin{aligned} \mathcal{W}_{neutrino} &= \bar{S}^c\,(\lambda_2\,N_a\,Q_a^c \;+\; \lambda_3\,N_3\,Q_3^c) \\ &\quad -\frac{1}{2}\,(\lambda_2' Y\;N_a\;N_a \;+\; \frac{\tilde{\theta}_a\,\tilde{\theta}_b}{\hat{M}}\;N_a\,N_b \;+\; \lambda_3' Y\;N_3\;N_3) \\ &= \frac{\lambda_2^2}{2\,M_1}(\bar{S}^c\;Q_1^c)^2 \;+\; \frac{\lambda_2^2}{2\,M_2}(\bar{S}^c\;Q_2^c)^2 \;+\; \frac{\lambda_3^2}{2\,M_3}(\bar{S}^c\;Q_3^c)^2, \end{aligned}$$

$$M_1 = \lambda_2' Y,\; M_2 = \lambda_2' Y + \frac{\tilde{\theta}_2^2}{\hat{M}},\; M_3 = \lambda_3' Y$$

$$\Rightarrow \qquad \frac{1}{2} M_{R_1}\,\overline{\nu_1}\,\overline{\nu_1} + \frac{1}{2} M_{R_2}\,\overline{\nu_2}\,\overline{\nu_2} + \frac{1}{2} M_{R_3}\,\overline{\nu_3}\,\overline{\nu_3}$$

Global χ^2 analysis

Sector	Input Parameters	No.
Gauge	$\alpha_G,\ M_G,\ \epsilon_3$	3
SUSY (GUT scale)	$m_{16},\ M_{1/2},\ A_0,\ m_{H_u},\ m_{H_d}$	5
Yukawa Textures	$\lambda, \epsilon, \tilde{\epsilon}, \epsilon', \xi, \alpha, \beta, \theta', \tilde{\theta}, \phi_{\epsilon'}, \phi_\xi, \phi_\alpha, \phi_\beta$	13
Neutrino	$M_{R_1},\ M_{R_2},\ M_{R_3}$	3
SUSY (EW Scale)	$\tan\beta,\ \mu$	2
Total		26

26 parameters at GUT scale

51 Observables in χ^2 function

Poh, Raby and Wang arXiv:1703.09309

m_{16}/TeV	20	25
$M_{\tilde{g}}$/TeV	1.90	1.90
$g\tilde{\chi}_1^0$	0.000	0.000
$g\tilde{\chi}_2^0$	0.002	0.001
$g\tilde{\chi}_3^0$	0.005	0.007
$g\tilde{\chi}_4^0$	0.002	0.004
$tb\tilde{\chi}_1^+$	0.234	0.186
$tb\tilde{\chi}_2^+$	0.274	0.322
$t\bar{t}\tilde{\chi}_1^0$	0.019	0.023
$t\bar{t}\tilde{\chi}_2^0$	0.054	0.039
$t\bar{t}\tilde{\chi}_3^0$	0.113	0.105
$t\bar{t}\tilde{\chi}_4^0$	0.097	0.106
$b\bar{b}\tilde{\chi}_1^0$	0.010	0.011
$b\bar{b}\tilde{\chi}_2^0$	0.064	0.054
$b\bar{b}\tilde{\chi}_3^0$	0.082	0.082
$b\bar{b}\tilde{\chi}_4^0$	0.044	0.059

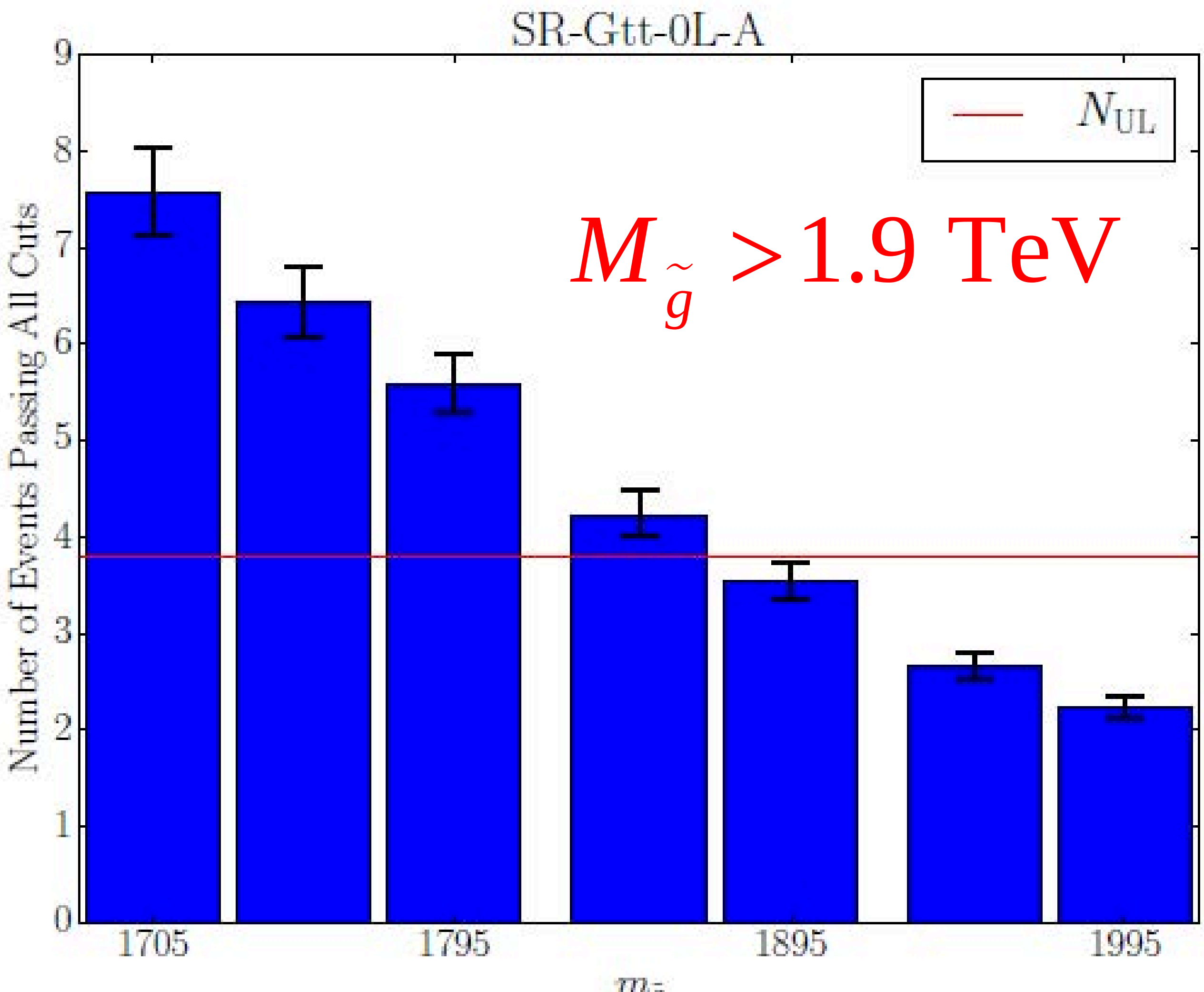
NOT simplified model

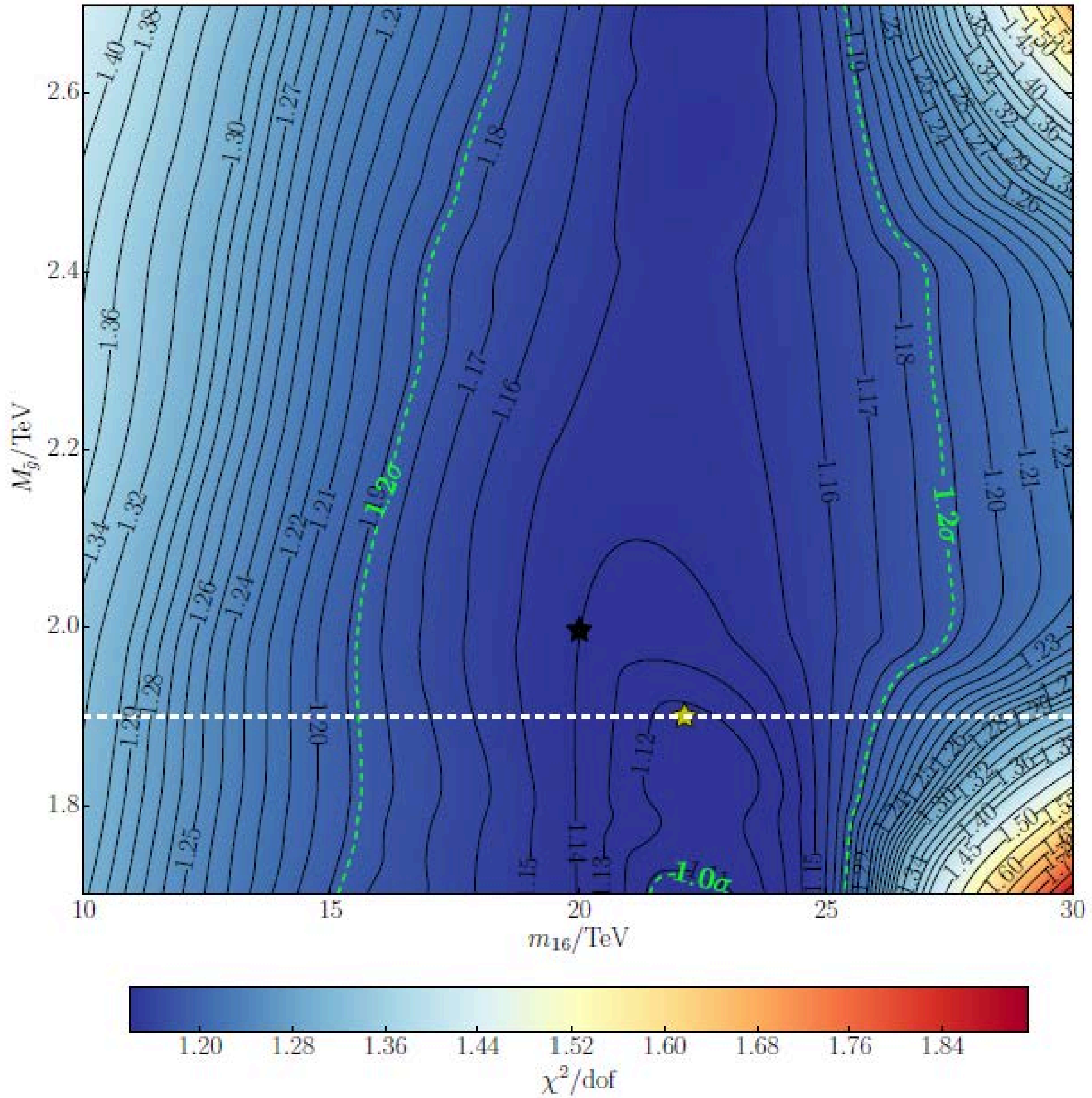
Compare to ATLAS &
CMS data

ATLAS - CONF - 2016 - 52

$\mathrm{N}^{Signal\ Leptons} = 0,\ N^{Jet} \geq 8,\ N_{b-jet} \geq 3,\ p_T^{jet} > 30\,\mathrm{GeV},\ E_T^{miss} > 400\,\mathrm{GeV},$

$\Delta\phi_{\min}^{4j} > 0.4\,rad,\ m_{T,\min}^{b-jets} > 80\,\mathrm{GeV},\ \mathrm{m}_{eff}^{incl} > 2000\ \mathrm{GeV},\ \mathrm{M}_J^{\Sigma} > 200\ \mathrm{GeV}$




$M_{\tilde{g}}$/TeV
m_{16}/TeV
χ^2/dof
1.2σ
1.0σ
1.20 1.28 1.36 1.44 1.52 1.60 1.68 1.76 1.84

Benchmark point with $m_{16} = 20.0\,\text{TeV}$, $M_{\tilde{g}} = 2.00\,\text{TeV}$

Sector	Input Param.	Best Fit
Gauge	$1/\alpha_G$	26.0
	$M_G/10^{16}$ GeV	2.25
	$\epsilon_3/\%$	-1.68
SUSY (GUT scale)	m_{16}/TeV	20.0
	$m_{1/2}/\text{GeV}$	660
	A_0/TeV	-40.6
	$(m_{H_d}/m_{16})^2$	1.98
	$(m_{H_u}/m_{16})^2$	1.61
Neutrino	$M_{R_1}/10^9$ GeV	4.62
	$M_{R_2}/10^{11}$ GeV	8.32
	$M_{R_3}/10^{13}$ GeV	4.71
SUSY (EW Scale)	$\tan\beta$	50.4
	μ/GeV	630

Sector	Input Param.	Best Fit
Yukawa Textures	λ	0.617
	$\lambda\epsilon$	0.0326
	$\lambda\tilde{\epsilon}$	0.0100
	$\lambda\epsilon'$	-0.00300
	$\lambda\xi$	0.00201
	α	0.138
	β	0.0277
	$\theta'/10^{-5}$	5.03
	$\tilde{\theta}/10^{-5}$	2.92
	$\phi_{\epsilon'}/\text{rad}$	-0.277
	ϕ_{ξ}/rad	3.41
	ϕ_{α}/rad	0.963
	ϕ_{β}/rad	-1.26

Benchmark point with $m_{16} = 20.0\,\text{TeV}$, $M_{\tilde{g}} = 2.00\,\text{TeV}$

Observable	Fit	Exp.	Pull	σ
M_Z/GeV	91.1876	91.1876	0.0000	0.4514
M_W/GeV	80.4734	80.3850	0.2238	0.3949
$1/\alpha_{\text{em}}$	137.3435	137.0360	0.4478	0.6867
$G_\mu/10^{-5}\,\text{GeV}^{-2}$	1.1761	1.1664	0.8264	0.0118
$\alpha_3(M_Z)$	0.1177	0.1181	0.4791	0.0008
M_t/GeV	174.0978	173.2100	0.4161	2.1338
$m_b(m_b)/\text{GeV}$	4.3264	4.1850	1.0388	0.1362
m_τ/Mev	1776.0100	1776.8600	0.0428	19.8568
$(M_b - M_c)/\text{GeV}$	3.3028	3.4500	0.4098	0.3592
$m_c(m_c)/\text{GeV}$	1.2685	1.2700	0.0442	0.0332
$m_s(2\,\text{GeV})/\text{Mev}$	97.7602	98.0000	0.0393	6.0987
$m_s/m_d(2\,\text{GeV})$	18.5692	19.5000	0.3843	2.0519
Q	21.5785	23.0000	0.6256	2.2725
$m_u(2\,\text{GeV})/\text{MeV}$	2.6880	2.3000	0.7758	0.5002
$m_d(2\,\text{GeV})/\text{MeV}$	5.2646	4.7500	1.1417	0.4508
M_μ/MeV	105.2131	105.6584	0.2053	2.1690
M_e/MeV	0.5108	0.5110	0.0278	0.0057
$\lvert V_{ud}\rvert$	0.9745	0.9742	0.0622	0.0049
$\lvert V_{us}\rvert$	0.2245	0.2248	0.2615	0.0013
$\lvert V_{ub}\rvert/10^{-3}$	3.9904	4.1300	0.2305	0.6056
$\lvert V_{cd}\rvert$	0.2244	0.2200	0.8509	0.0051
$\lvert V_{cs}\rvert$	0.9735	0.9950	1.2853	0.0167
$\lvert V_{cb}\rvert/10^{-3}$	44.1574	40.7500	1.4038	2.4272
$\lvert V_{td}\rvert/10^{-3}$	7.9898	8.2000	0.3378	0.6222
$\lvert V_{ts}\rvert/10^{-3}$	43.6115	40.0000	1.2691	2.8458
$\lvert V_{tb}\rvert$	0.9990	1.0090	0.3179	0.0314
$\sin 2\beta$	0.6922	0.6910	0.0672	0.0173
$\epsilon_K/10^{-3}$	2.0225	2.2330	1.0379	0.2028

$\Delta M_{B_s}/\Delta M_{B_d}$	43.7269	34.8479	1.0037	8.8463
$\Delta M_{B_d}/10^{-10}$ MeV	2.9005	3.3540	0.7802	0.5812
$m_{21}^2/10^{-5}$ eV^2	7.3484	7.3750	0.0658	0.4044
$m_{31}^2/10^{-3}$ eV^2	2.5096	2.5000	0.0726	0.1323
$\sin^2\theta_{12}$	0.2960	0.2975	0.0915	0.0166
$\sin^2\theta_{23}$	0.4419	0.4435	0.0599	0.0266
$\sin^2\theta_{13}$	0.0217	0.0215	0.1493	0.0010
M_h/GeV	122.7975	125.0900	0.4854	4.7225
$BR(b \to s\gamma)/10^{-6}$	299.9500	332.0000	0.2243	142.9017
$BR(B_s \to \mu^+\mu^-)/10^{-9}$	5.1836	2.9500	1.6808	1.3289
$BR(B_d \to \mu^+\mu^-)/10^{-9}$	0.1223	0.4000	1.8234	0.1523
$BR(B \to \tau\nu)/10^{-6}$	96.4950	106.0000	0.1822	52.1761
$BR(B \to K^*\mu^+\mu^-)_{1 \le q^2 \le 6\,\mathrm{GeV}^2}/10^{-7}$	0.5456	0.3400	0.3567	0.5765
$BR(B \to K^*\mu^+\mu^-)_{14.18 \le q^2 \le 16\,\mathrm{GeV}^2}/10^{-7}$	0.7904	0.5600	0.1531	1.5055
$q_0^2(A_{\mathrm{FB}}(B \to K^*\mu^+\mu^-))/\mathrm{GeV}^2$	3.8492	4.9000	0.7921	1.3265
$F_L(B \to K^*\mu^+\mu^-)_{1 \le q^2 \le 6\,\mathrm{GeV}^2}$	0.7522	0.6500	0.2917	0.3503
$F_L(B \to K^*\mu^+\mu^-)_{14.18 \le q^2 \le 16\,\mathrm{GeV}^2}$	0.3514	0.3300	0.0725	0.2952
$P_2(B \to K^*\mu^+\mu^-)_{1 \le q^2 \le 6\,\mathrm{GeV}^2}$	0.0679	0.3300	1.4536	0.1803
$P_2(B \to K^*\mu^+\mu^-)_{14.18 \le q^2 \le 16\,\mathrm{GeV}^2}$	-0.4333	-0.5000	0.3381	0.1973
$P_4'(B \to K^*\mu^+\mu^-)_{1 \le q^2 \le 6\,\mathrm{GeV}^2}$	0.5788	0.5800	0.0029	0.4007
$P_4'(B \to K^*\mu^+\mu^-)_{14.18 \le q^2 \le 16\,\mathrm{GeV}^2}$	1.2177	-0.1800	1.7055	0.8195
$P_5'(B \to K^*\mu^+\mu^-)_{1 \le q^2 \le 6\,\mathrm{GeV}^2}$	-0.3221	0.2100	2.0721	0.2568
$P_5'(B \to K^*\mu^+\mu^-)_{14.18 \le q^2 \le 16\,\mathrm{GeV}^2}$	-0.7119	-0.7900	0.1545	0.5053
Total χ^2			30.9061	

m_{16}/TeV	20	25	20	25
$M_{\tilde{g}}$/TeV	2.00	2.00	2.60	2.60
χ^2/dof	1.14	1.16	1.18	1.17
$m_{\tilde{t}_1}$/TeV	3.68	4.70	3.70	4.65
$m_{\tilde{t}_2}$/TeV	4.38	5.52	4.43	5.49
$m_{\tilde{b}_1}$/TeV	4.17	5.32	4.17	5.23
$m_{\tilde{b}_2}$/TeV	4.32	5.47	4.36	5.43
$m_{\tilde{\tau}_1}$/TeV	7.47	9.30	7.52	9.27
$m_{\tilde{\tau}_2}$/TeV	12.2	15.2	12.2	15.2
$m_{\tilde{\chi}_1^0}$/GeV	352	352	474	474
$m_{\tilde{\chi}_2^0}$/GeV	586	636	650	665
$m_{\tilde{\chi}_1^+}$/GeV	585	636	646	661
$m_{\tilde{\chi}_2^+}$/GeV	710	751	911	914
$(M_A \approx M_{H^0} \approx M_{H^\pm})$/TeV	5.18	6.39	5.39	6.67
edm$_e/10^{-32}$ e cm	-3.46	-1.77	-4.47	-2.28
BR$(\mu \to e\gamma)/10^{-17}$	2.08	0.922	1.84	0.869
$\sin\delta$	0.759	0.935	0.644	0.993

Searching for the standard model in the string landscape : SUSY GUTs   IOP 2011

Heterotic orbifold models

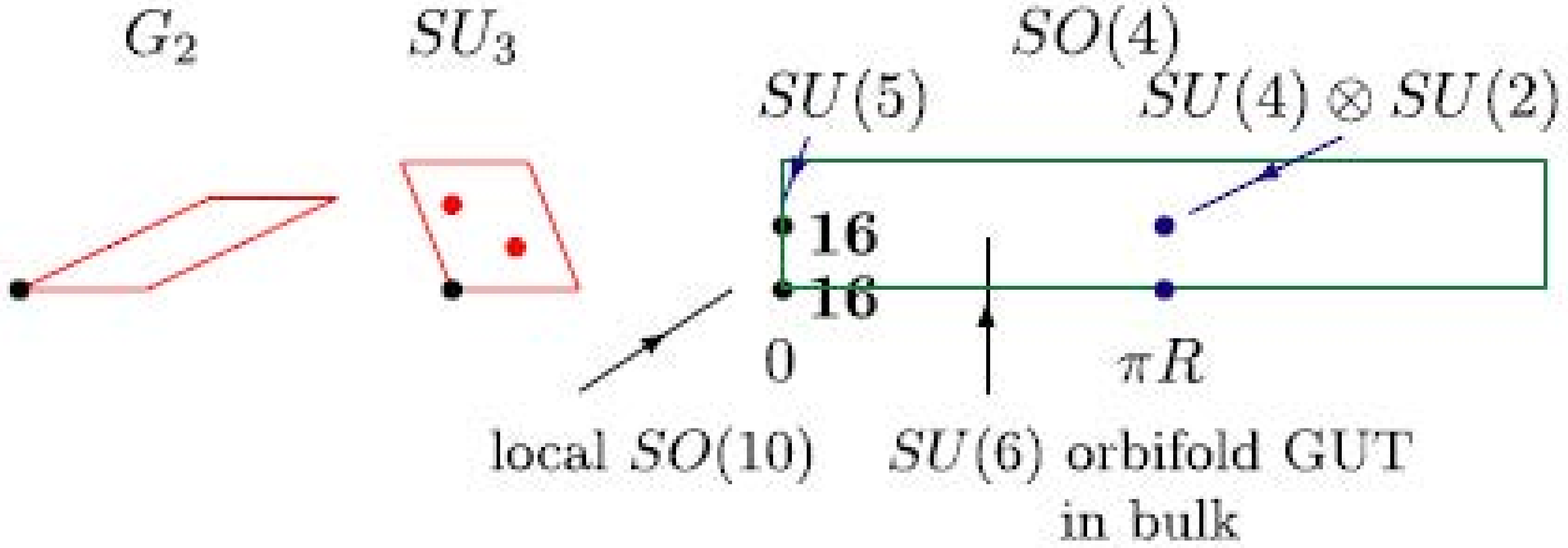
Kobayashi, Raby & Zhang; Buchmuller, Hamaguchi, Lebedev & Ratz; Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange & Wingerter ; Choi, Kim & Kyae; Farragi

Heterotic CY3 models

Anderson, Braun, Donagi, Gray, He, Lukas, Ovrut, Palti

F theory models

Beasley, Heckman & Vafa; Donagi & Wijnholt; Marsano, Schafer-Nameki & Saulina; Blumenhagen, Cvetic, Grimm, Weigand


G_2
SU_3
$SO(4)$
$SU(5)$
$SU(4) \otimes SU(2)$
16
16
0
πR
local $SO(10)$
$SU(6)$ orbifold GUT in bulk

It takes SUSY GUTs to find the
MSSM in the
String Landscape !!!

(i) They incorporate local GUTs with two complete families localized at orbifold fixed points;

(ii) They incorporate a 5D $SU(6)$ orbifold GUT with gauge–Higgs unification and the third family in the bulk;

(iii) As a consequence, they have gauge-Yukawa unification for the top quark (thus explaining why the top quark is heavy);

(iv) They incorporate doublet–triplet splitting with a μ term which is naturally small;

(v) They have an exact R parity. (Moreover, recently it was discovered that similar models can incorporate a $\mathbb{Z}_4^R$ symmetry which allows all Yukawa interactions and neutrino masses while forbidding the μ term and dimension 5 baryon and lepton number violating operators at the perturbative level [136]. The $\mathbb{Z}_4^R$ symmetry is possible due to the final $\mathbb{Z}_2$ orbifold.);

(vi) As a consequence of the $\mathbb{Z}_2$ orbifold, the model has a D_4 family symmetry which can ameliorate problems with flavor changing neutral currents while at the same time accommodating a hierarchy of quark and lepton masses;

(vii) Approximate R symmetries naturally generate a small constant contribution to the superpotential, setting the scale for the gravitino mass once supersymmetry breaking is generated.

Heterotic Orbifold Models

Summary

Still waiting after all these years

It took ~50 years to find the Higgs

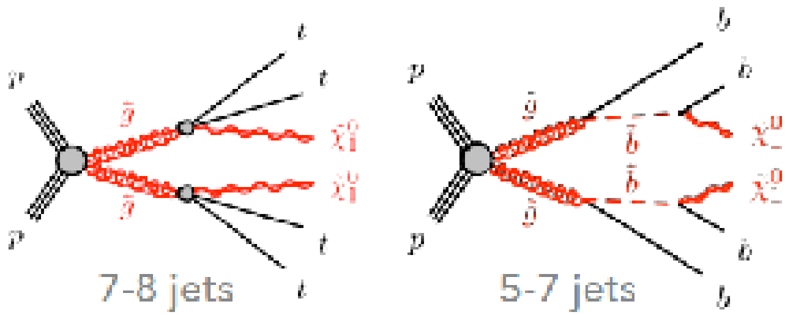
Beautiful extension of the SM and Poincare invariance

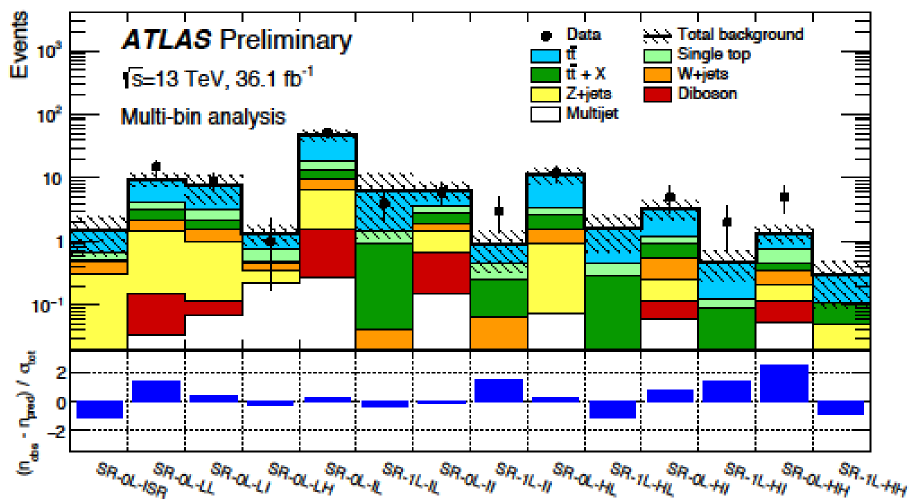
Anthropics may explain the cosmological constant
BUT expect SUSY GUTs to explain the rest !!

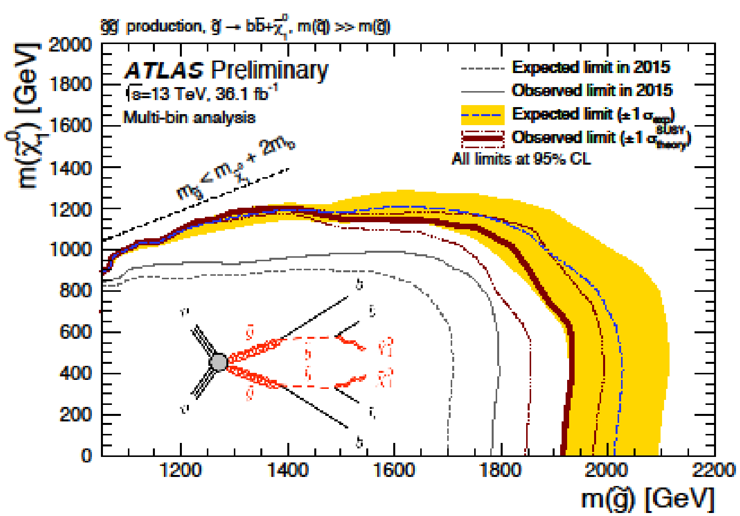
0/1L, ≥3 B-JETS [ATLAS]

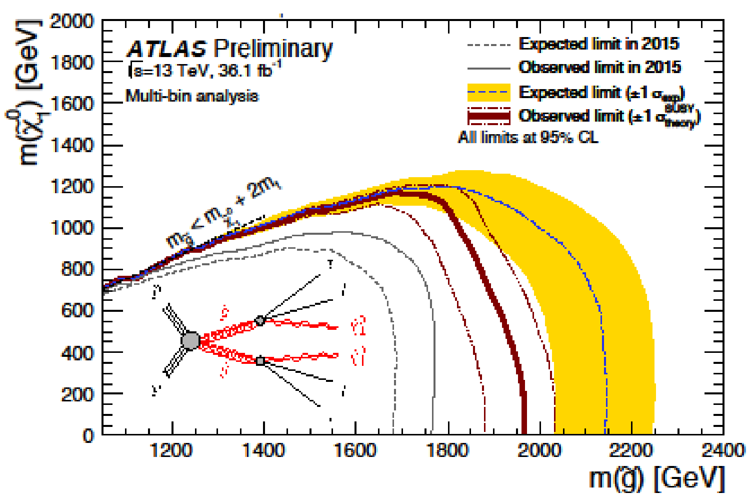
Amoroso ATLAS Moriond 2017

Results consistent with the SM expectation

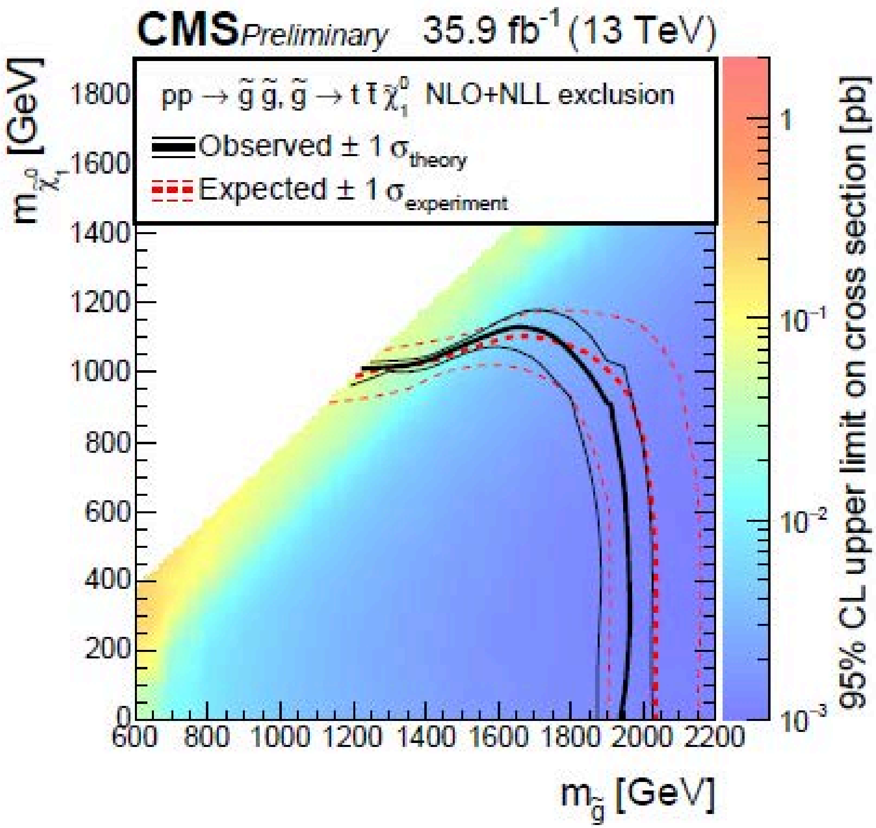


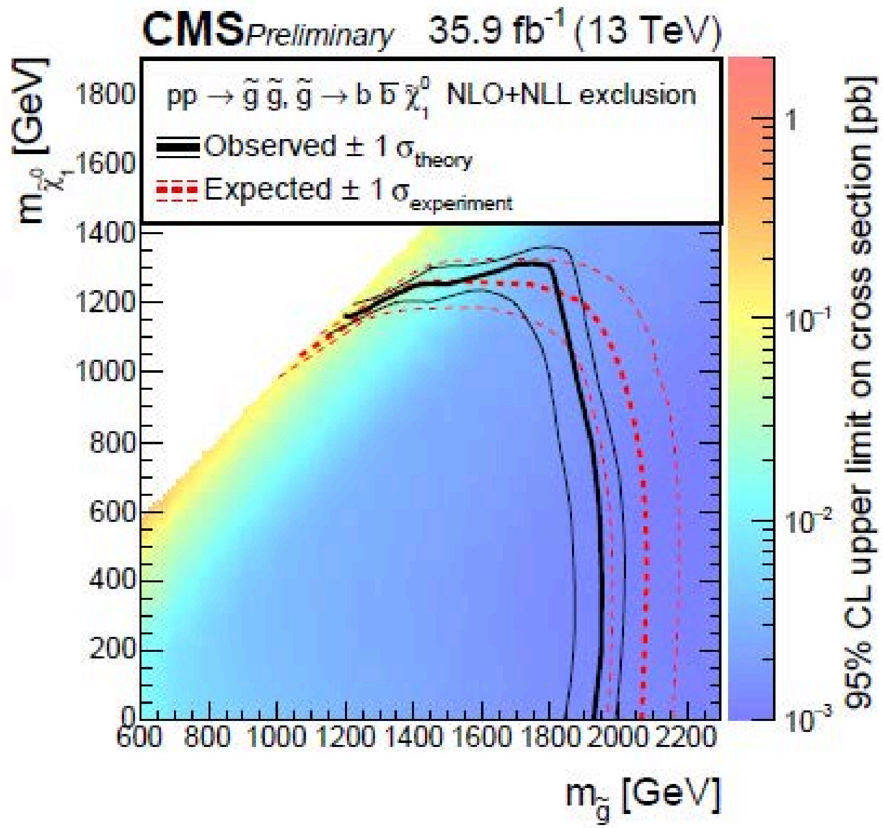




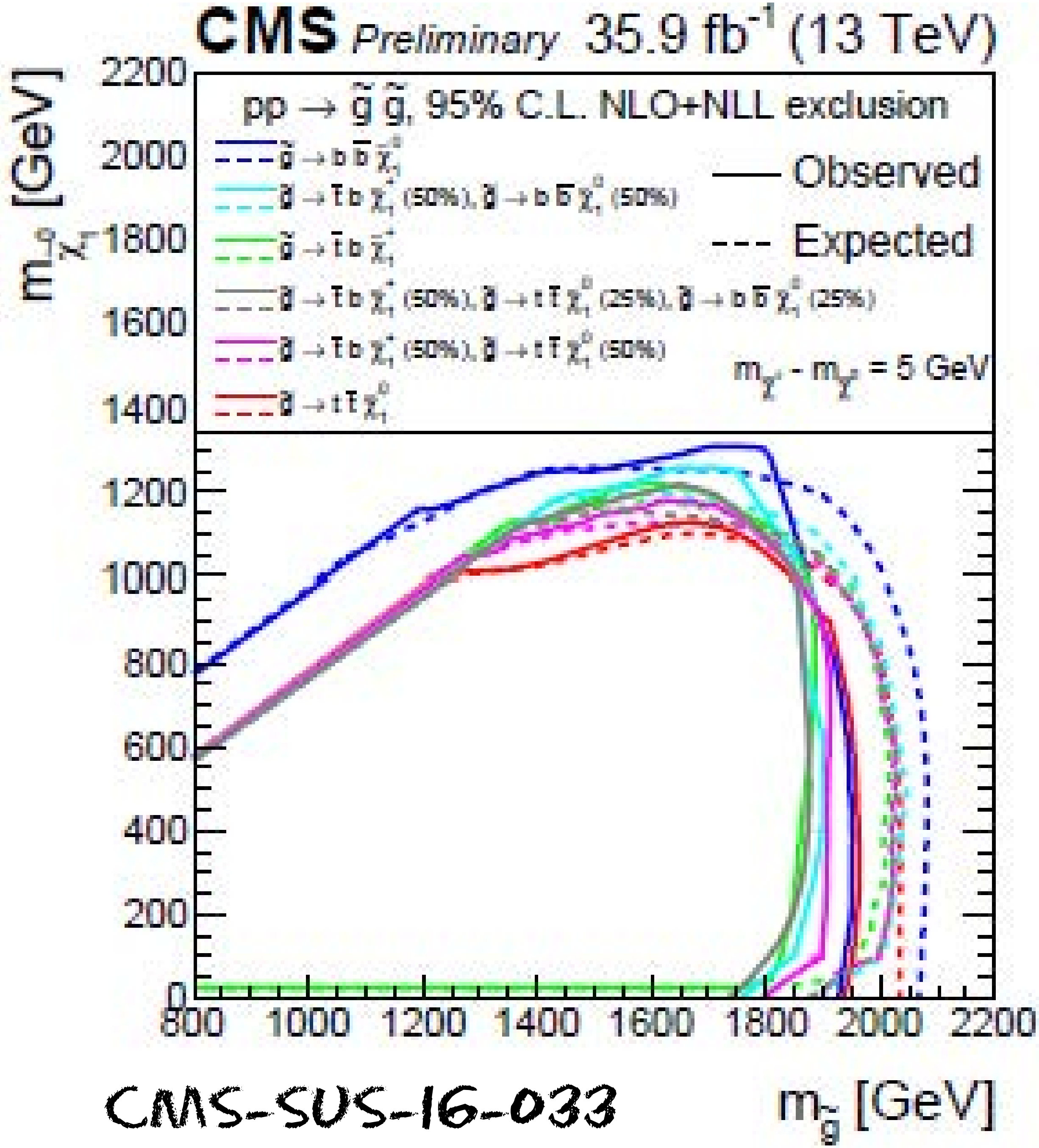


University of Victoria





CMS-SUS-16-033



CMS-SUS-16-033

NOT "Natural" SUSY

BUT SUSY does not completely decouple

NOT "Split" SUSY

BUT gravitino & moduli sufficiently heavy
so NO cosmological problems

Poh & Raby 2016

"SUSY on the Edge"

painting by Hans Werner Sahm