A NEW YUKAWA UNIFIED SUSY SCENARIO

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YUKAWA UNIFICATION

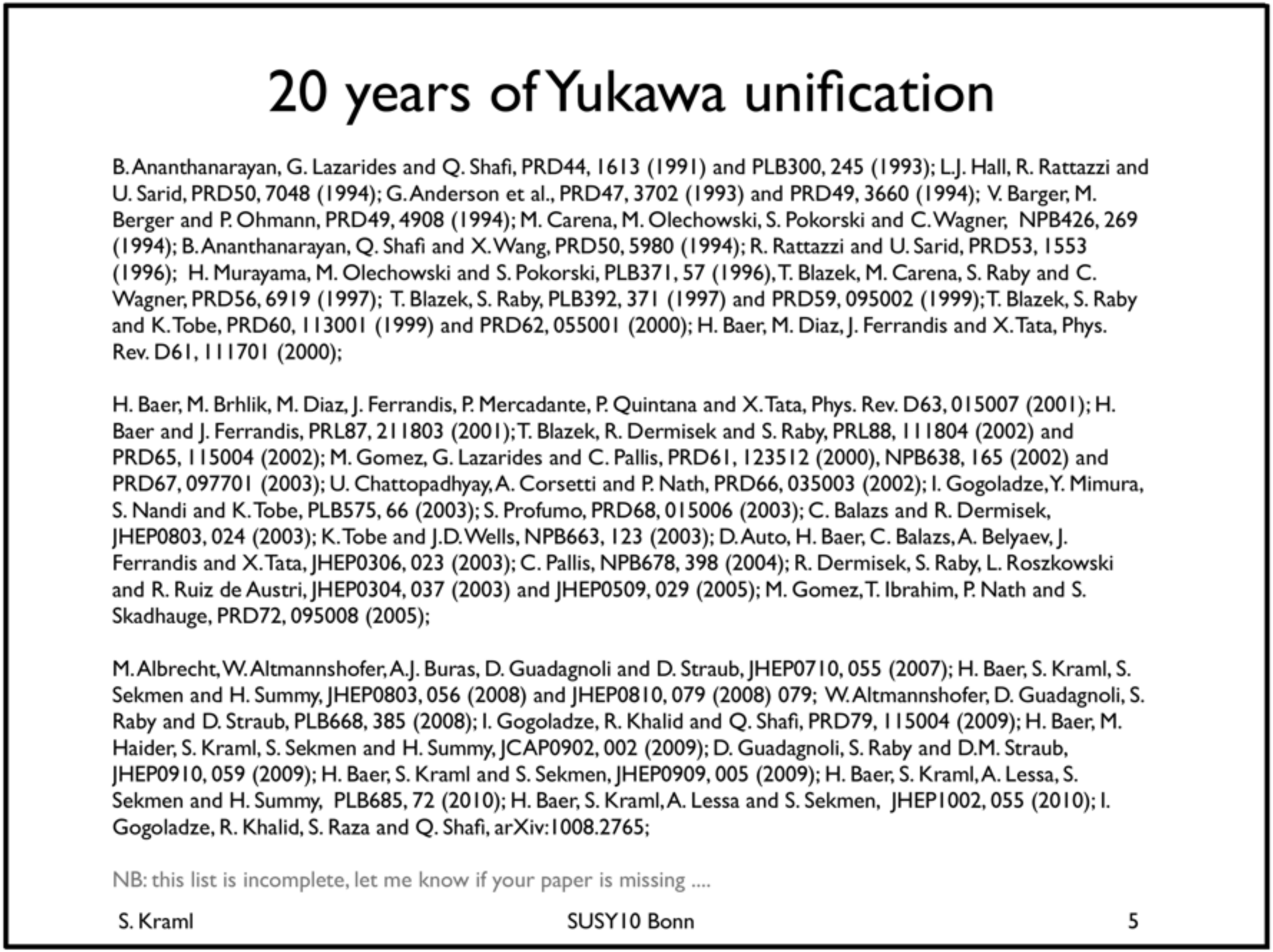
- In physics, **unification is good**
- SO(10) SUSY GUTs have a great deal of unification
  - Fermions and bosons (SUSY)
  - All matter particles (and RH neutrino) in one rep.
  - Gauge groups/ coupling/ -inos unified
- The simplest SO(10) SUSY GUT models have

$$y_t = y_b = y_\tau = y_\nu$$

YUKAWA UNIFICATION

- More general possibilities exist in SO(10)

- But 3rd generation Yukawa Unification is an appealing idea, even if not a necessary consequence of SO(10) SUSY GUTs



20 years of Yukawa unification

B. Ananthanarayan, G. Lazarides and Q. Shafi, PRD44, 1613 (1991) and PLB300, 245 (1993); L.J. Hall, R. Rattazzi and U. Sarid, PRD50, 7048 (1994); G. Anderson et al., PRD47, 3702 (1993) and PRD49, 3660 (1994); V. Barger, M. Berger and P. Ohmann, PRD49, 4908 (1994); M. Carena, M. Olechowski, S. Pokorski and C. Wagner, NPB426, 269 (1994); B. Ananthanarayan, Q. Shafi and X. Wang, PRD50, 5980 (1994); R. Rattazzi and U. Sarid, PRD53, 1553 (1996); H. Murayama, M. Olechowski and S. Pokorski, PLB371, 57 (1996), T. Blazek, M. Carena, S. Raby and C. Wagner, PRD56, 6919 (1997); T. Blazek, S. Raby, PLB392, 371 (1997) and PRD59, 095002 (1999); T. Blazek, S. Raby and K. Tobe, PRD60, 113001 (1999) and PRD62, 055001 (2000); H. Baer, M. Diaz, J. Ferrandis and X. Tata, Phys. Rev. D61, 111701 (2000);

H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D63, 015007 (2001); H. Baer and J. Ferrandis, PRL87, 211803 (2001); T. Blazek, R. Dermisek and S. Raby, PRL88, 111804 (2002) and PRD65, 115004 (2002); M. Gomez, G. Lazarides and C. Pallis, PRD61, 123512 (2000), NPB638, 165 (2002) and PRD67, 097701 (2003); U. Chattopadhyay, A. Corsetti and P. Nath, PRD66, 035003 (2002); I. Gogoladze, Y. Mimura, S. Nandi and K. Tobe, PLB575, 66 (2003); S. Profumo, PRD68, 015006 (2003); C. Balazs and R. Dermisek, JHEP0803, 024 (2003); K. Tobe and J.D. Wells, NPB663, 123 (2003); D. Auto, H. Baer, C. Balazs, A. Belyaev, J. Ferrandis and X. Tata, JHEP0306, 023 (2003); C. Pallis, NPB678, 398 (2004); R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz de Austri, JHEP0304, 037 (2003) and JHEP0509, 029 (2005); M. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, PRD72, 095008 (2005);

M. Albrecht, W. Altmannshofer, A.J. Buras, D. Guadagnoli and D. Straub, JHEP0710, 055 (2007); H. Baer, S. Kraml, S. Sekmen and H. Summy, JHEP0803, 056 (2008) and JHEP0810, 079 (2008) 079; W. Altmannshofer, D. Guadagnoli, S. Raby and D. Straub, PLB668, 385 (2008); I. Gogoladze, R. Khalid and Q. Shafi, PRD79, 115004 (2009); H. Baer, M. Haider, S. Kraml, S. Sekmen and H. Summy, JCAP0902, 002 (2009); D. Guadagnoli, S. Raby and D.M. Straub, JHEP0910, 059 (2009); H. Baer, S. Kraml and S. Sekmen, JHEP0909, 005 (2009); H. Baer, S. Kraml, A. Lessa, S. Sekmen and H. Summy, PLB685, 72 (2010); H. Baer, S. Kraml, A. Lessa and S. Sekmen, JHEP1002, 055 (2010); I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, arXiv:1008.2765;

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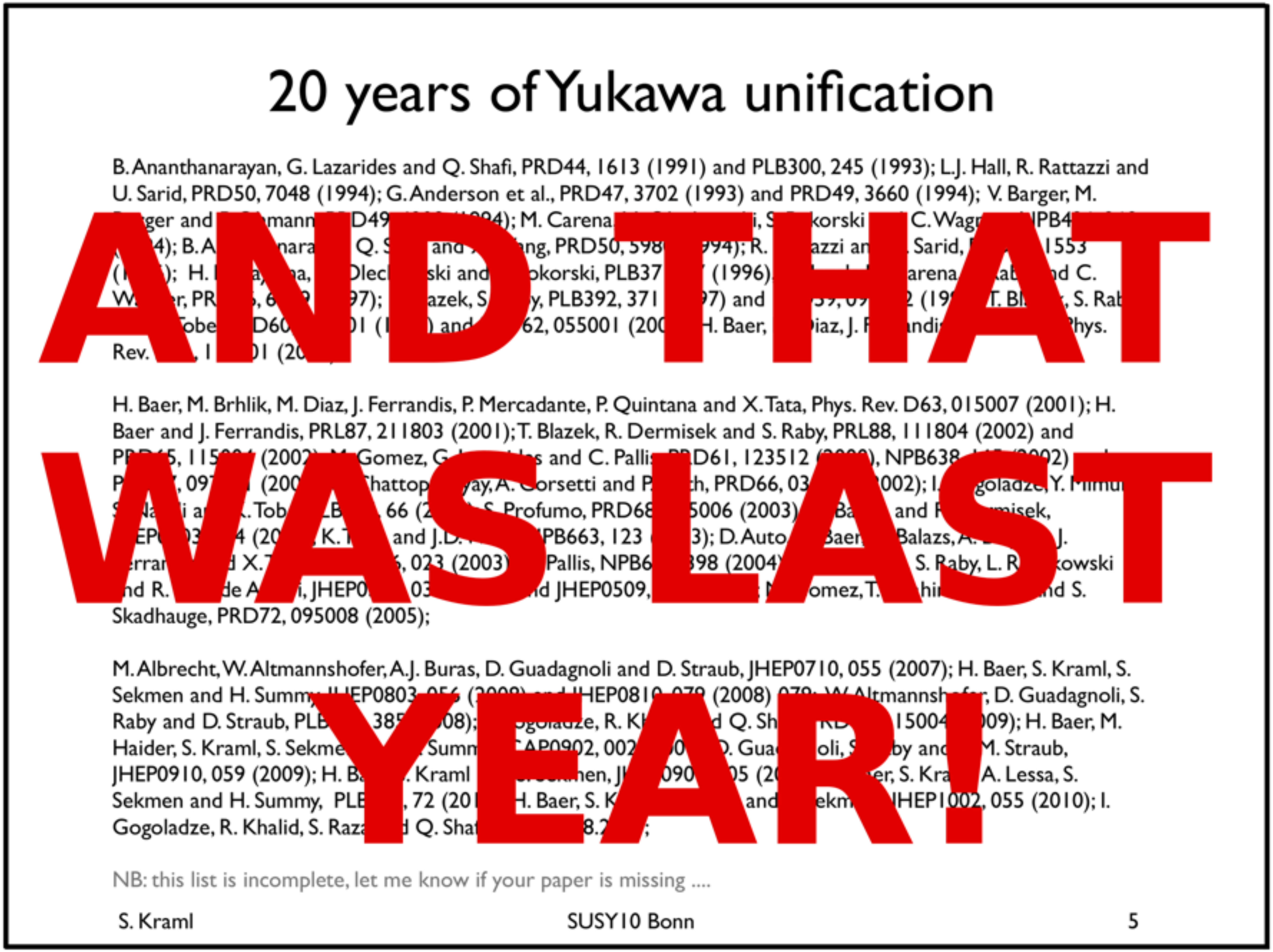
FROM SABINE KRAML'S PLENARY TALK AT SUSY 2010



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H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D63, 015007 (2001); H. Baer and J. Ferrandis, PRL87, 211803 (2001); T. Blazek, R. Dermisek and S. Raby, PRL88, 111804 (2002) and PR[illegible]5, 115[illegible] (2002[illegible] Gomez, G[illegible]s and C. Pallis, [illegible]D61, 123512 ([illegible]), NPB638 [illegible]2) [illegible] P[illegible], 09[illegible] (200[illegible]hattop[illegible]yay, A. Corsetti and P[illegible]h, PRD66, 03[illegible]002); I. [illegible]goladze, Y. Mimu[illegible] S[illegible]i a[illegible]. Tob[illegible], 66 (2[illegible] S. Profumo, PRD68[illegible]5006 (2003)[illegible]Ba[illegible] and [illegible]misek, [illegible]EP[illegible]4 (20[illegible] K. T[illegible] and J.D. [illegible]PB663, 123 ([illegible]3); D. Auto[illegible]Baer[illegible]Balazs, A. [illegible] J. [illegible]rrar[illegible] X. T[illegible], 023 (2003)[illegible]Pallis, NPB6[illegible]398 (2004)[illegible] S. Raby, L. R[illegible]kowski [illegible]d R. [illegible]de A[illegible]i, JHEP0[illegible] 03[illegible]d JHEP0509, [illegible] M. [illegible]omez, T. [illegible]hi[illegible]nd S. Skadhauge, PRD72, 095008 (2005);

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NB: this list is incomplete, let me know if your paper is missing ....

S. Kraml SUSY10 Bonn 5

AND THAT WAS LAST YEAR!

WHICH IS A GOOD INTRO. TO YUKAWA UNIFICATION

DIFFICULTIES

(from *The Simpsons*)

DIFFICULTIES

- Large SUSY threshold corrections to the bottom mass generally spoil bottom - tau unification

$$\left(\frac{\delta m_b}{m_b}\right) \approx \frac{g_3^2}{12\pi^2}\frac{\mu M_3}{m_{\tilde{b}}^2} + \frac{f_t^2}{32\pi^2}\frac{\mu A_t}{m_{\tilde{t}}^2}\tan\beta + \ldots$$

Hall, Rattazzi, Sarid, 1994;
Carena, Olechowski, Pokorski, Wagner, 1994.

- Yukawa Unification will only work for particular SUSY spectra

DIFFICULTIES

- Higgs mass parameters need to be split at the GUT scale by D-terms for REWSB to work

$$m_{H_u}^2 < m_{H_d}^2 \quad \Rightarrow \quad m_{H_{u,d}}^2 = m_{10} \mp 2M_D^2$$

Murayama, Olechowski and Pokorski, 1996

- Need to add M_D^2 as a parameter. Not a real problem, but aesthetically makes scenario more complicated/ less unified.

CONSEQUENCES

- Consider the SO(10) inspired parameter space

$$m_{1/2},\ m_{16},\ m_{10},\ M_D^2,\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

- Demanding approximate Yukawa unification with $\mathrm{sign}(\mu) > 0$ (for g-2) leads to
  - Heavy sfermions
  - Light gluinos
  - Bino LSP with low annihilation cross section (neutralino decays to e.g. axino)

See, for example papers by H. Baer, S. Kraml, A. Lessa, S. Sekmen, H. Summy
0801.1831, 0809.0710, 0812.2693, 0908.0134, 0910.2988, 0911.4739

WHAT WE WANT

- Lighter scalars (but not too light!): to allow complementarity with flavor physics
- Heavier gluinos
  (problem of missing missing energy events at LHC)
- Neutralino relic density in allowed range
- To say something about neutrino mixings
  (if possible)

$y_T > y_b$

- For $\mu > 0$, $$\frac{g_3^2}{12\pi^2}\frac{\mu M_3}{m_{\tilde{b}}^2},$$ the dominant contribution to $$\left(\frac{\delta m_b}{m_b}\right),$$ is positive
- So y_b is suppressed relative to y_T
- If we choose tan β such that $y_b = y_t$, then $y_T > y_{t/b}$

NON-DIGAONAL YUKAWA MATRIX

- Instead of

$$Y_e(M_{\text{GUT, diagonal}}) = \begin{pmatrix} y_\mu & 0 \\ 0 & y_\tau \end{pmatrix}$$

consider

$$Y_e(M_{\text{GUT}}) = \begin{pmatrix} y_{22} & x \\ x & y_{t/b} \end{pmatrix}$$

NON-DIGAONAL YUKAWA MATRIX

- The tau is a mixture between

  the charged lepton state in the (otherwise)

  Yukawa Unified (3rd Generation) **16**

  and the charged lepton state in another **16** (2nd Generation)

THE MIXING ANGLE

- The Yukawa Matrix can be re-expressed

  $$\frac{y_\tau + y_\mu}{2}\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \frac{y_\tau - y_\mu}{2}\begin{pmatrix}-\cos 2\Theta & \sin 2\Theta\\ \sin 2\Theta & \cos 2\Theta\end{pmatrix}$$

  in terms of the mixing angle, Θ

- The transformation from the diagonal Yukawa matrix preserves the determinant, so

  $$\sin^2 2\Theta = \frac{4(y_{t/b}(y_\tau + y_\mu - y_{t/b}) - y_\tau y_\mu)}{(y_\tau - y_\mu)^2}$$

THE MIXING ANGLE

- If we ignore y_μ, we obtain

$$\sin^2 2\Theta \approx 4\frac{R-1}{R^2}$$

where $R = \frac{y_\tau}{y_{t/b}}$

(R measures the “non-unification” of Yukawa couplings in standard scenarios)

THE MIXING ANGLE

- If we ignore y_μ, we obtain

$$\sin^2 2\Theta \approx 4\frac{R-1}{R^2}$$

thus

$$\sin^2 2\Theta \approx 1 \text{ when } R \approx 2$$

NEUTRINO MIXING

- In the absence of other mixings, the 2 generation PMNS matrix is given by

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

So $\theta_{23} = -\Theta$

and $\sin^2 2\theta_{23} = \sin^2 2\Theta$

PUNCHLINE

- The mixing angle we invoke to explain the largeness of y_T is related to neutrino oscillations

- $R \approx 2$ would explain/ postdict one of the observed neutrino mixing angles

TECHNICALITIES/ CAVEATS

- A gap in the argument on the previous slide:
  We compare the mixing angle in the lepton sector to the mixing angle in the neutrino sector at low energies
- In the absence of neutrino Yukawas, mixing angle is RGE invariant
- Actually, the mixing angle will run due to neutrino Yukawa contributions to the charged lepton RGE
- Large values 3rd generation neutrino Yukawas generically lead to largish lepton flavor violation.
  May need to "dilute" Yukawa coupling e.g. by mixing "3rd generation" right handed neutrino with other states

QUESTION

- Can we find allowed points in the SO(10)

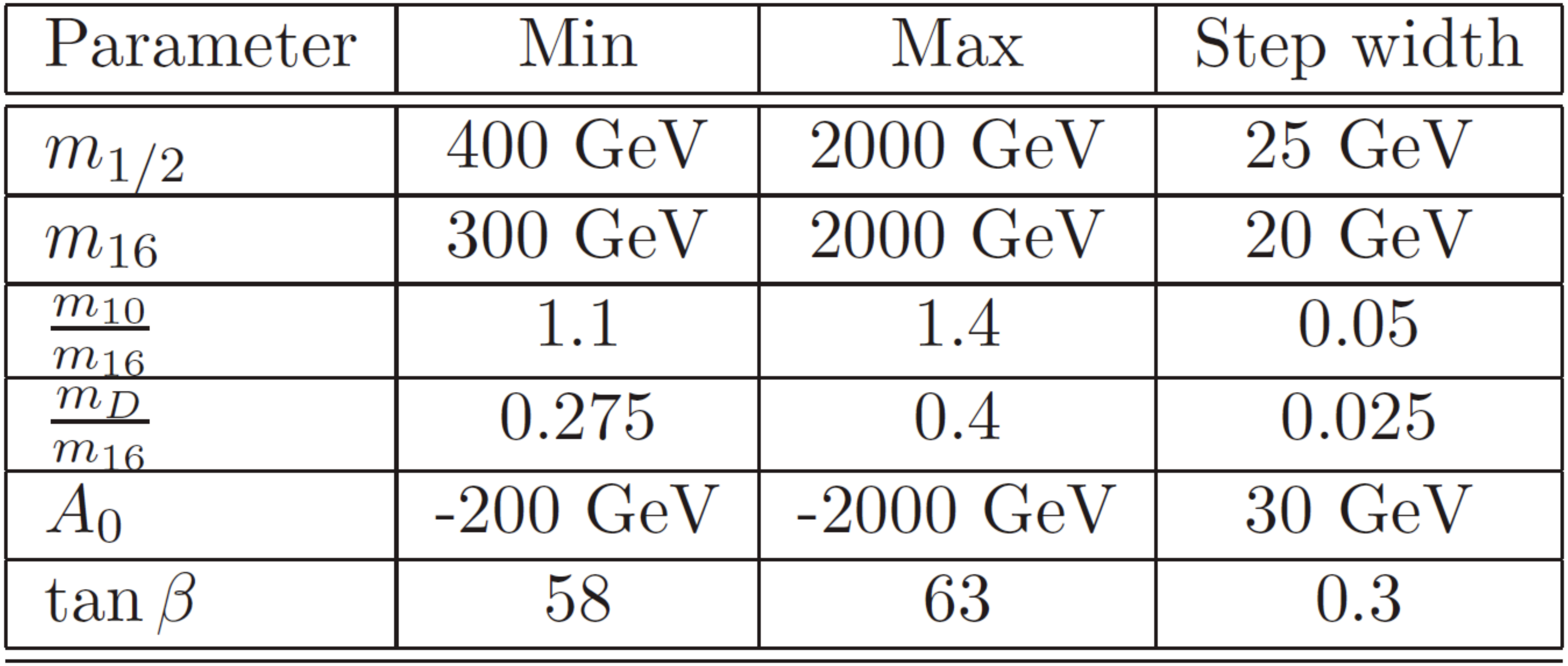
$$m_{1/2},\ m_{16},\ m_{10},\ M_D^2,\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

parameter space,

which satisfy $\sin^2 2\theta_{23} \approx 1$

SCAN: RANGES

- To answer this question, we performed a scan of the parameter space



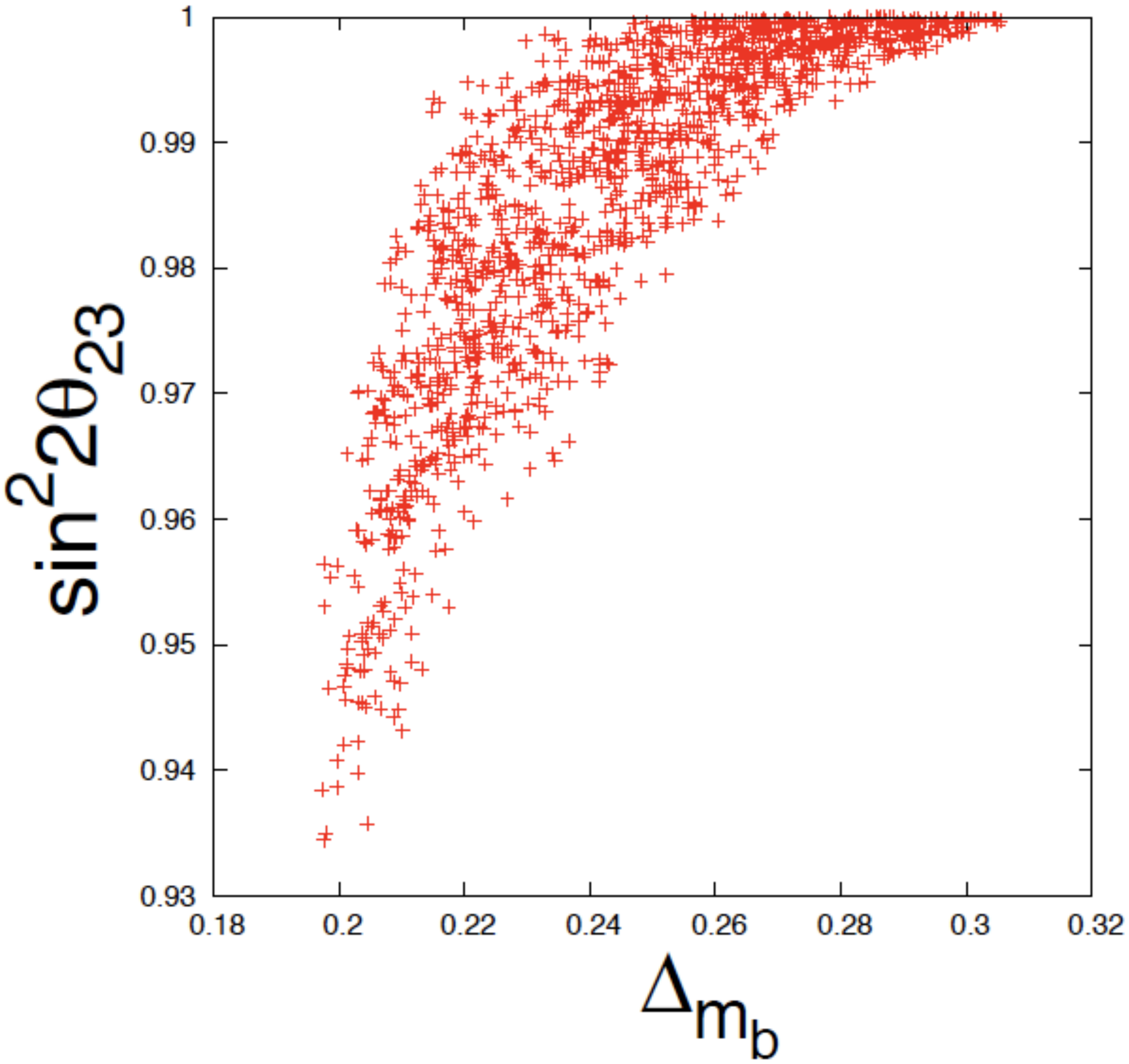
Parameter	Min	Max	Step width
$m_{1/2}$	400 GeV	2000 GeV	25 GeV
m_{16}	300 GeV	2000 GeV	20 GeV
$\frac{m_{10}}{m_{16}}$	1.1	1.4	0.05
$\frac{m_D}{m_{16}}$	0.275	0.4	0.025
A_0	-200 GeV	-2000 GeV	30 GeV
$\tan\beta$	58	63	0.3

SCAN: CONSTRAINTS

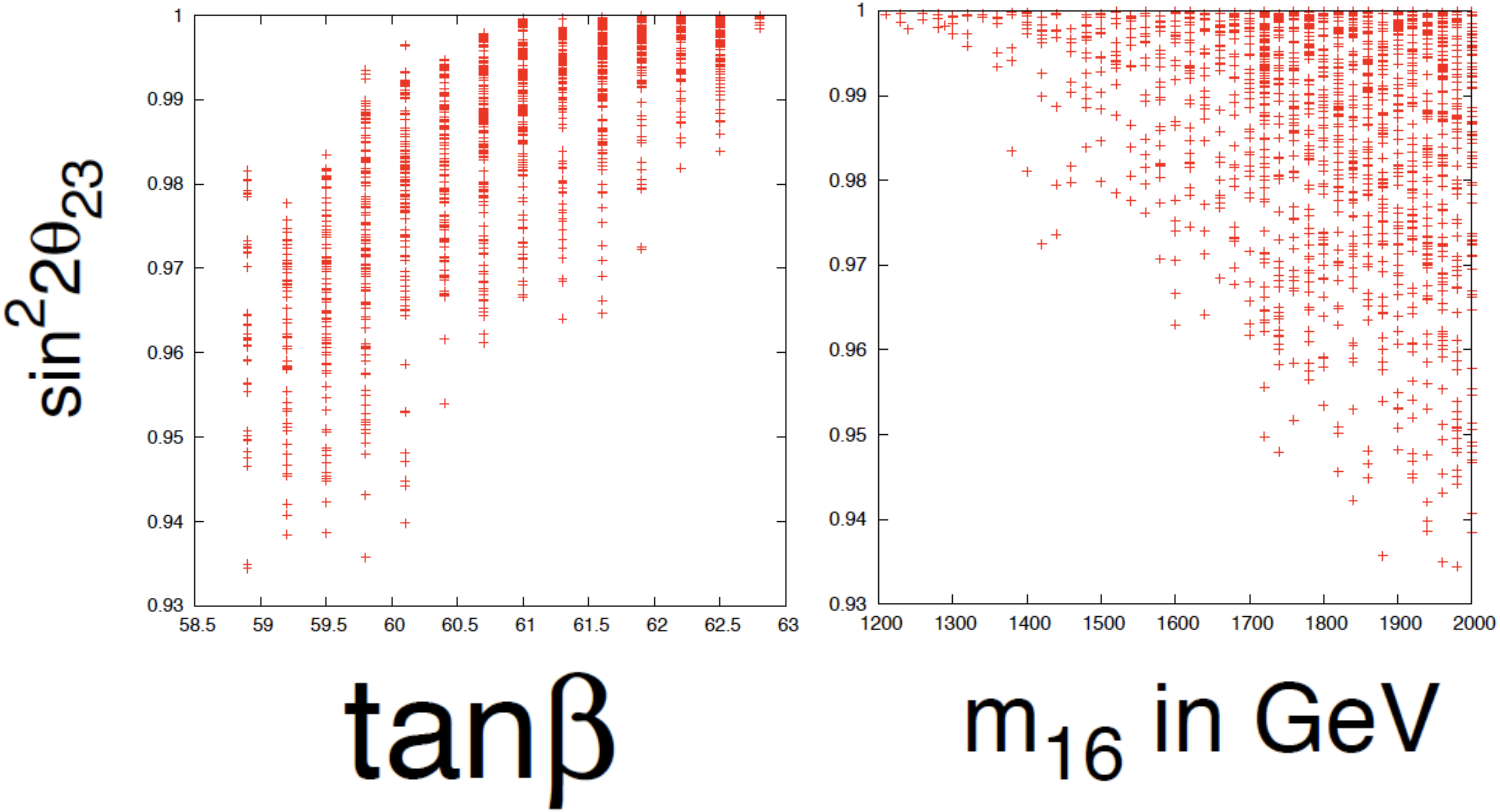
- Constraints imposed include
    - Approximate top-bottom unification demanded
    - R < 2
    - Collider constraints (esp. LEP) on sparticles, Higgses
    - Relic density in WMAP range
    - Constraints on spin-dependent and spin-independent WIMP direct detection cross sections

SCAN: RESULTS

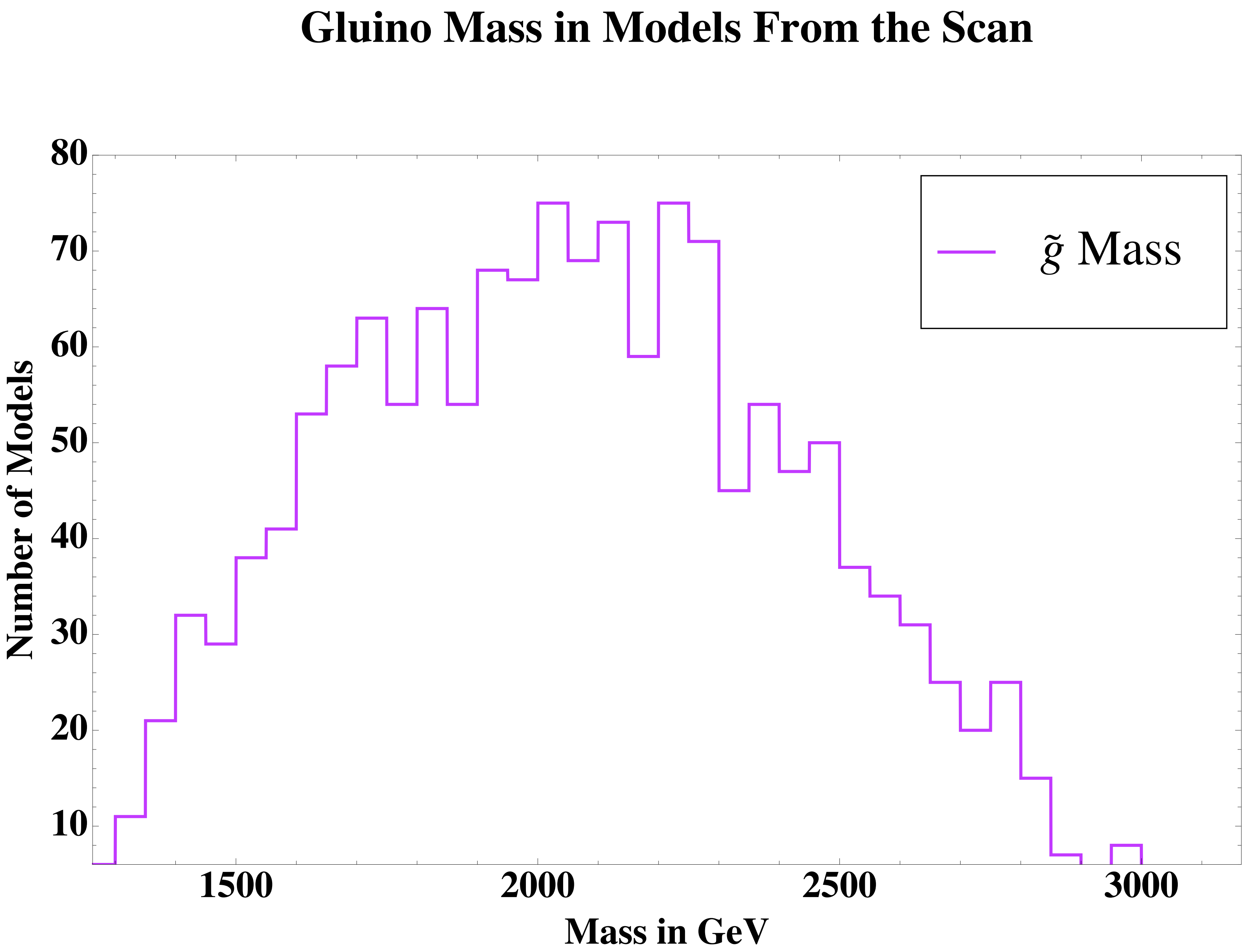
- Points in parameter space allowed by constraints generically have R ≈ 2



SCAN: RESULTS

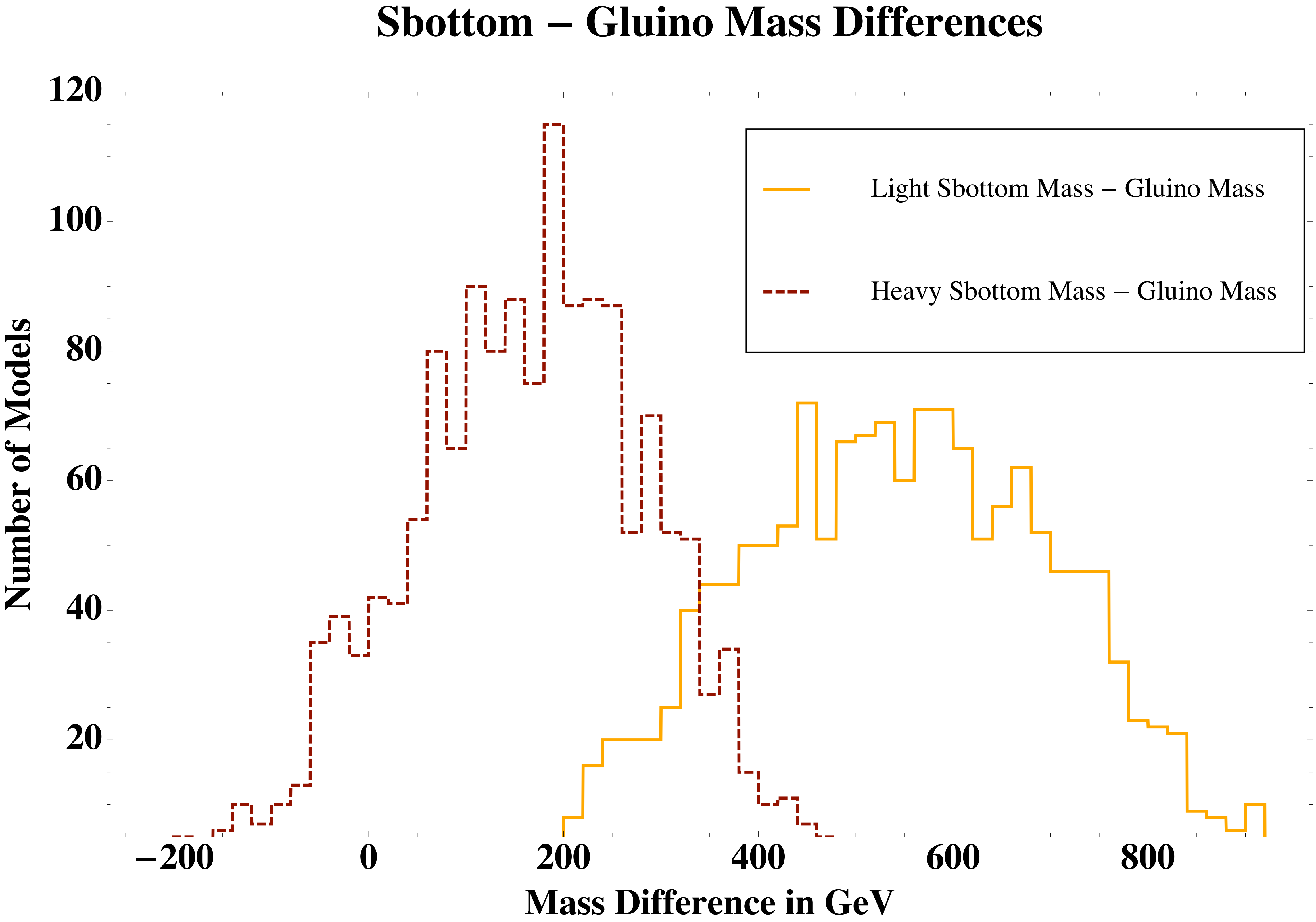


GLUINOS



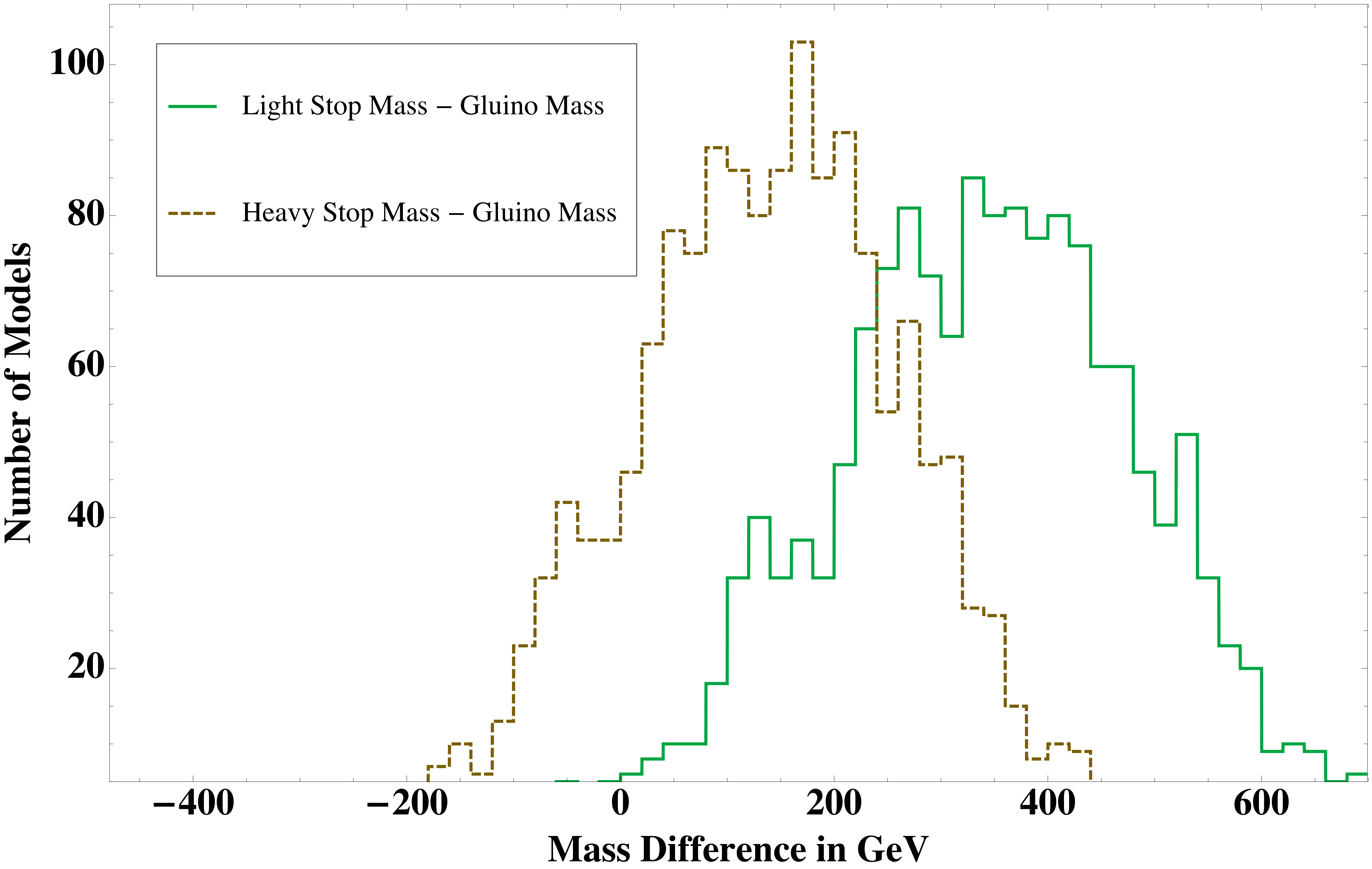
Scan parameters keep gluinos above current bounds

SBOTTOMS



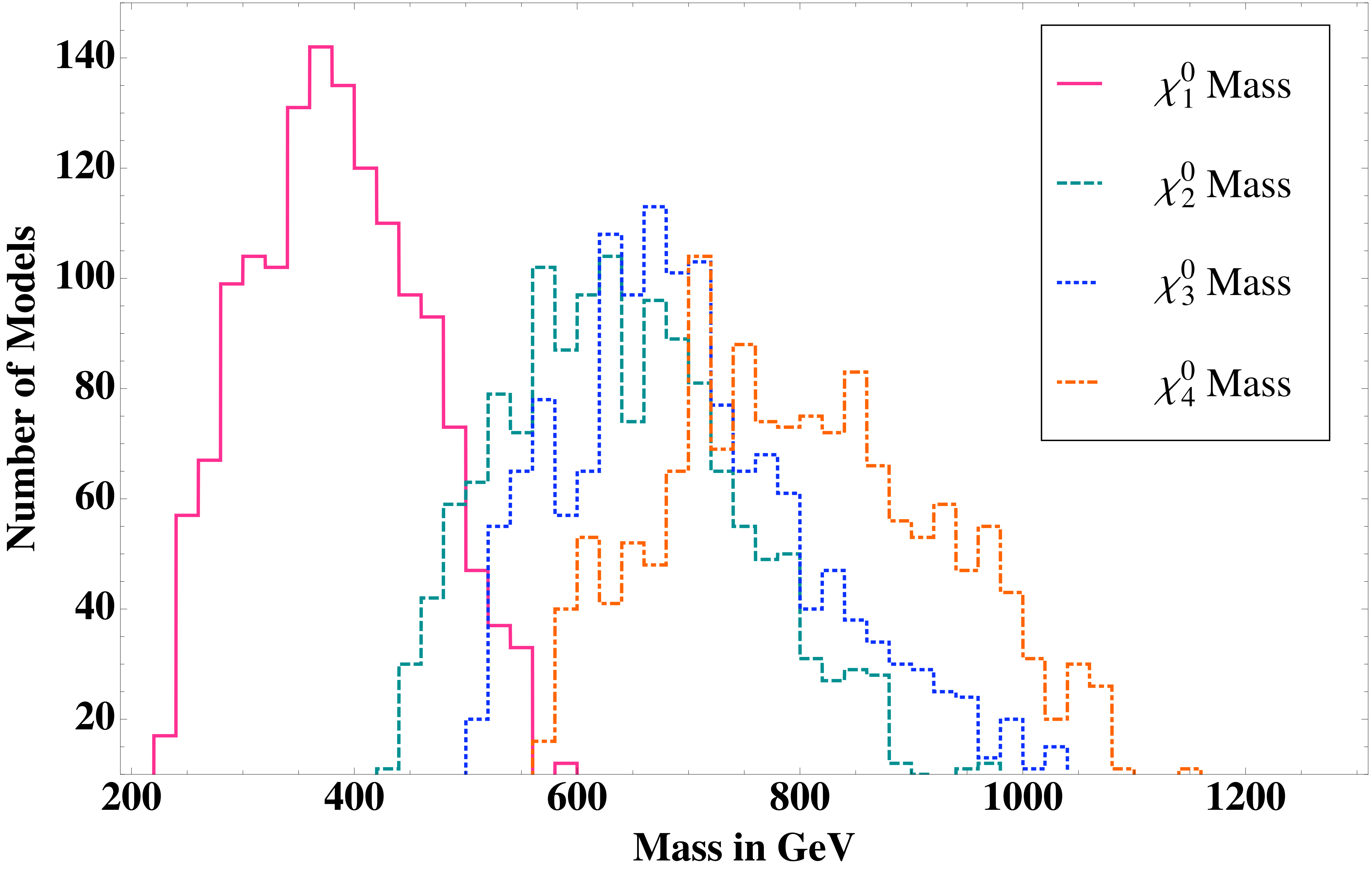
Sbottom – Gluino Mass Differences
120
100
80
60
40
20
Number of Models
−200
0
200
400
600
800
Mass Difference in GeV
Light Sbottom Mass – Gluino Mass
Heavy Sbottom Mass – Gluino Mass

STOPS



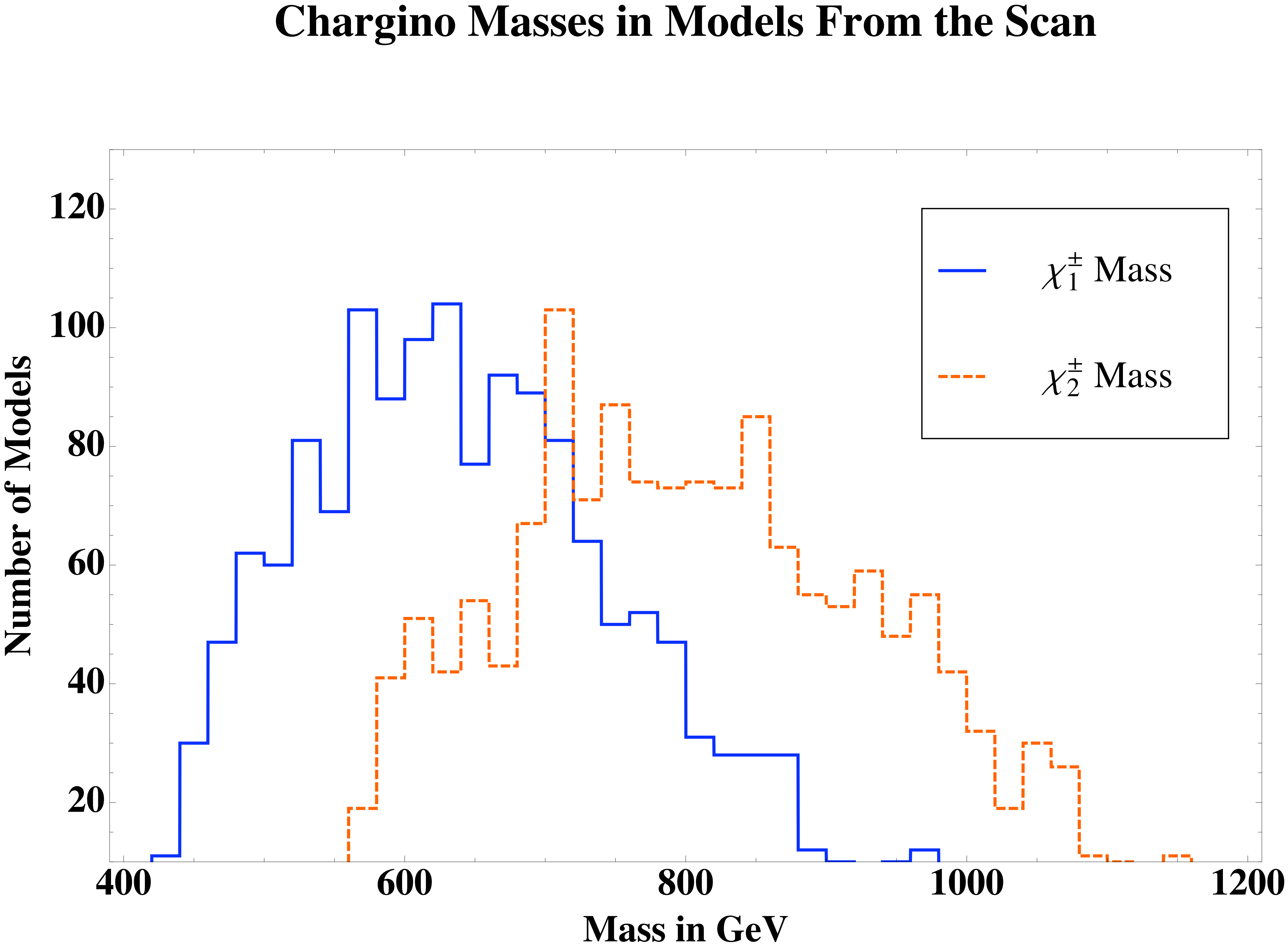
Stop – Gluino Mass Differences

NEUTRALINOS



Neutralino Masses in Models From the Scan

CHARGINOS

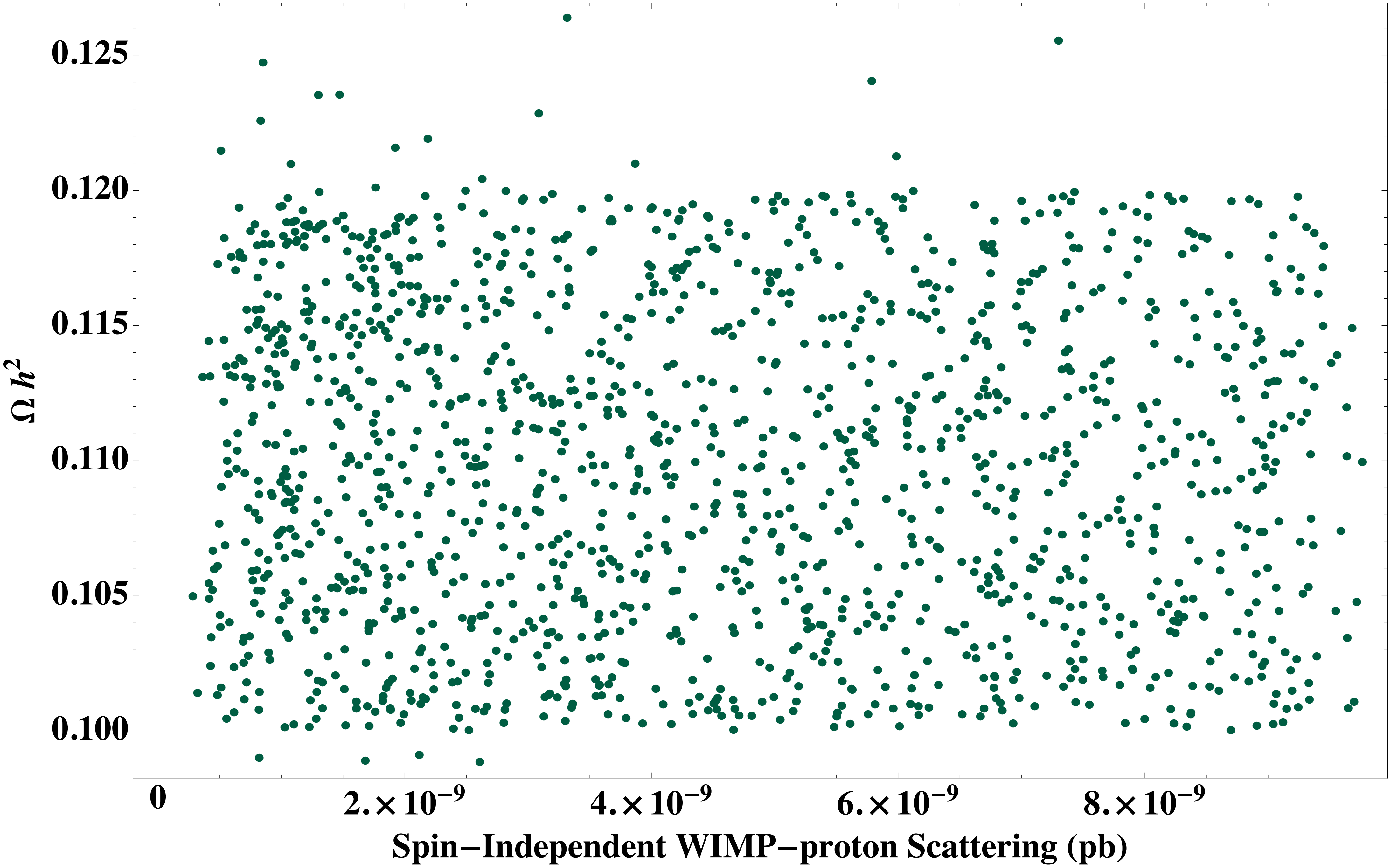

Chargino Masses in Models From the Scan
$\chi_1^\pm$ Mass
$\chi_2^\pm$ Mass
Number of Models
Mass in GeV
120
100
80
60
40
20
400
600
800
1000
1200

LHC PHENO

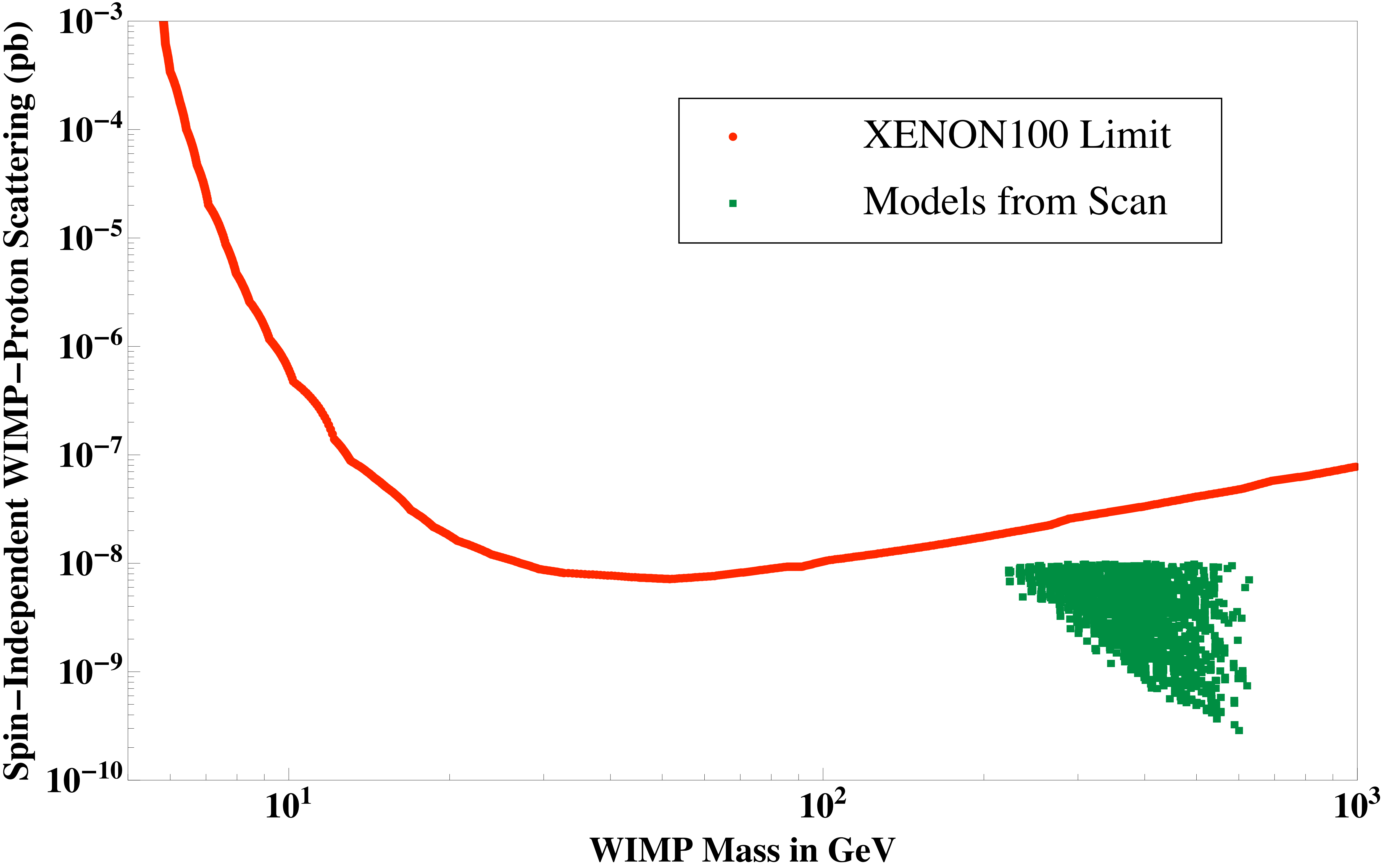
- Dominant signature (eventually) will be gluino production
- The gluino will mostly decay to bottom-sbottom and, to a lesser extent, top-stop
- The sbottom and stop will in turn decay to neutralinos, charginos + 3rd generation quarks
- Final states will generally involve tops and/or b-tagged jets

DARK MATTER

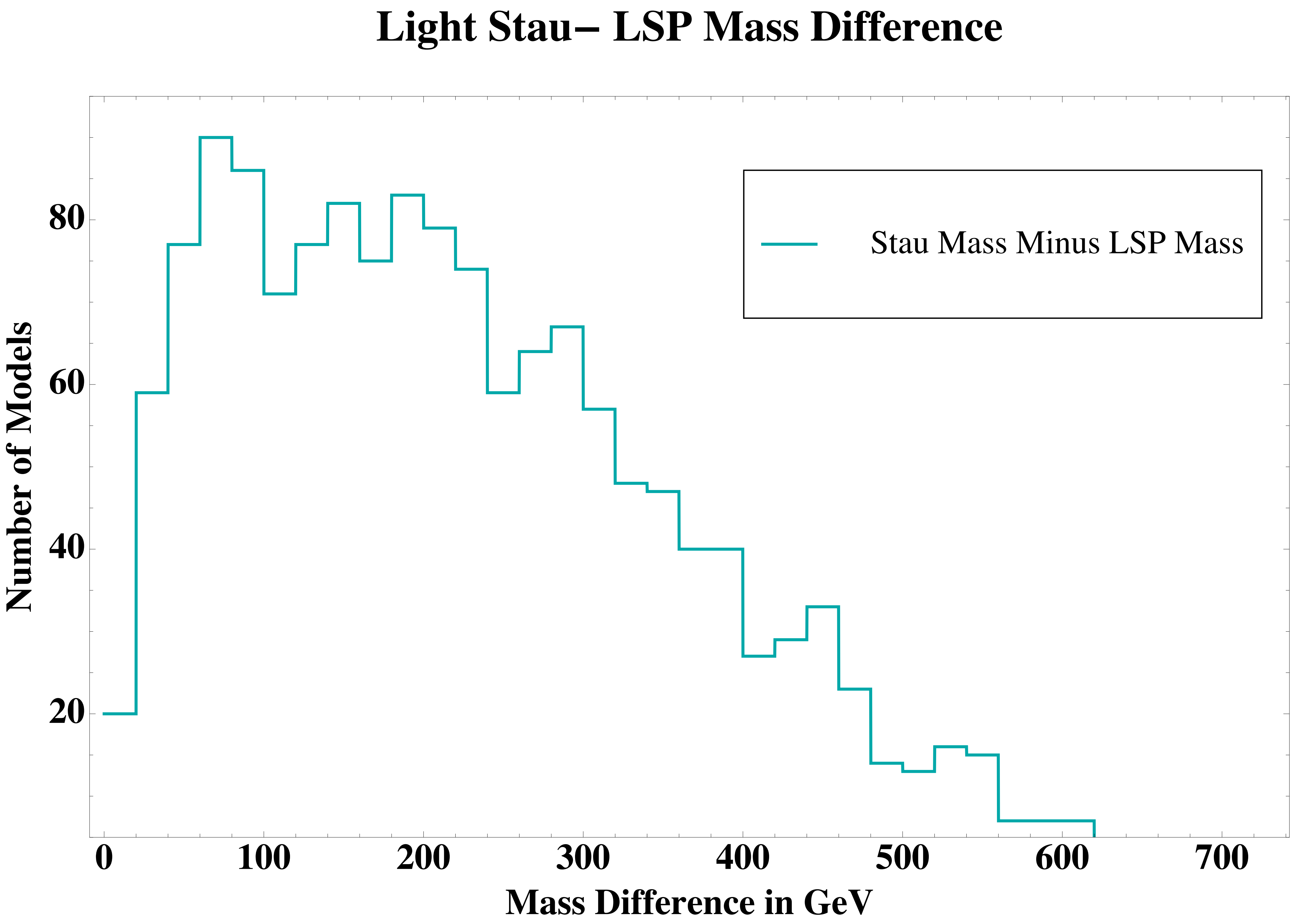
Relic Density and WIMP Direct Detection Cross Section



DARK MATTER


XENON100 Limit
Models from Scan
Spin-Independent WIMP-Proton Scattering (pb)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{1}
10^{2}
10^{3}
WIMP Mass in GeV

STAUS


Light Stau– LSP Mass Difference
Stau Mass Minus LSP Mass
Number of Models
80
60
40
20
0
100
200
300
400
500
600
700
Mass Difference in GeV

CONCLUSIONS

- A modification of the standard Yukawa Unification scenario, where we assume inter-generational mixing for charged leptons,
- explains $\sin^2 2\theta_{23} \approx 1$
- gives interesting, viable LHC, dark matter, and flavor phenomenologies- should see signals in the very near future!