Compactified M/string theory prediction (August 2011) of the Higgs boson mass and properties

→ $M_h \approx$ 126 GeV, SM-like

Ultimately we would like an underlying predictive theory – M/string theory seems to provide a good framework – some predictions not flexible

Gordy Kane, University of Michigan

KITP, Dec 2012

- Introduction – making string theory predictions for data
  - -- assumptions
  - -- stabilizing moduli
  - -- μ in string theory
- Higgs mass derivation
- Results
- Implications – little hierarchy problem reduced
- Associated LHC predictions for gluinos, charginos
- Naturalness?
- Final remarks

Philosophy to compute Higgs mass, properties:

Divide all compactified string/M theories into two classes

- **Some generically have TeV scale physics, REWSB, etc – study these -- if our world is described by a compactified string/M theory it will look like these – turns out it's easy to find them**
- **The rest**

Find many – "compactified constrained string/M theories, CCST"

Calculate M_h /M_Z for those solutions

PAPERS ABOUT M-THEORY COMPACTIFICATIONS ON G_2 MANIFOLDS

(11 D – 7 small D = our 4D)

Earlier work (stringy, mathematical) **:**

- Review of supergravity work, Duff hep-th/0201062
- Papadopoulos, Townsend th/9506150, 7D manifold with G_2 holonomy preserves **N=1 supersymmetry**
- Acharya, hep-th/9812205, **non-abelian gauge fields localized on singular 3 cycles**
- Acharya, hep-th/0011289
- Atiyah and Witten, hep-th/0107177
- Atiyah, Maldacena, Vafa, hep-th/0011256
- Acharya and Witten, hep-th/0109152, **chiral fermions supported at points with conical singularities**
- Witten, hep-ph/0201018 – shows **embedding MSSM probably ok**
- Beasley and Witten, hep-th/0203061, **Kahler form**
- Friedmann and Witten, th/0211269
- Lukas, Morris hep-th/0305078, **gauge kinetic function**
- **Acharya and Gukov, hep-th/0409101 – review – good summary of known results about singularities, holonomy and supersymmetry, etc – all G_2 moduli geometric *– gravity mediated because two 3-cycles won't interact directly in 7D manifold***

We started M/string compactification fall of 2005, interested in moduli stabilization, susy breaking, Higgs, since LHC coming

Do the derivation in M-theory case since those calculations effectively complete – results may hold in some or all other corners of string theory since they depend on only a few generic features

Our M-theory papers

--*Review arXiv:1204.2795 , Acharya, Kane, Kumar*

[***Acharya***, Kane, **Piyush Kumar**, Bobkov, Kuflik, Shao, **Ran Lu**, Watson, Bob Zheng]

- M-Theory Solution to Hierarchy Problem th/0606262
- **Stabilized Moduli, TeV scale,** ***squark masses = gravitino mass, gaugino masses suppressed*** 0701034
- **Spectrum, scalars heavy, wino-like LSP, large trilinears (no R-symmetry) 0801.0478**
- Study moduli, **Nonthermal** cosmological history**– generically moduli $\gtrsim$ 30 TeV so gravitino $\gtrsim$ 30 TeV,** squarks $\approx$ gravitino so squarks $\geq$ 30 TeV 0804.0863
- CP Phases in M-theory (weak CPV OK) and EDMs 0905.2986
- Lightest moduli masses < gravitino mass 1006.3272 (Douglas Denef 2004; Gomez-Reino, Scrucca 2006)
- **Axions** stabilized, strong CP OK, string axions OK 1004.5138
- Gluino, Multi-top searches at **LHC** (also Suruliz, Wang) 0901.336
- No flavor problems, (also Velasco-Sevilla Kersten, Kadota)
- Theory, phenomenology of μ in M-theory 1102.0566 via Witten
- Baryogenesis, ratio of DM to baryons (also Watson, Yu) 1108.5178
- String-motivated approach to little hierarchy problem, (also Feldman) 1105.3765
- **Higgs Mass Prediction** 1112.1059

Will explain details as relevant during talk – to take Higgs results fully seriously good to know other problems OK in same theory

”**GENERIC**” $\approx$ perhaps not theorem, but holds very generally – just calculate naturally without special assumptions – have to work hard to find or construct (non-generic) exceptions (if possible), and to show possible exceptions don’t have problems that exclude them

Nima, “Generic = not clever”

Our approach top-down, all results derived – could view it as the successful ultraviolet completion (in place 2007) of bottom-up approach a la Jared Kaplan, Nima and Savas, etc

Make assumptions, *not closely related to Higgs sector*

- **CC problem orthogonal – won't know for sure until solved**
- **Our world is described by compactified M-theory on G_2 manifold – can try to repeat for other corners of string theory**
- **Compactify M-theory on G_2 manifold in fluxless sector – can stabilize moduli**
- **Assume Hubble parameter H at end of inflation larger than $M_{3/2}$**
- **Assume top quark with yukawa coupling $\sim$ 1**

❑ **Include μ following Witten 2002 , via discrete symmetry**

- **Use generic Kahler potential (Beasley,Witten, 2002)** – include volume dependence on Kahler
- **Use generic gauge kinetic function from Lukas, Morris, 2003**

❑ **Assume gauge group and matter content at compactification is MSSM – can repeat for any other gauge group and matter content**

❑ Moduli, gravitino constraint from Big Bang nucleosynthesis

In early universe, when Hubble scale H decreases, moduli begin to oscillate in their potential, and quickly dominate energy density of universe – Early universe matter dominated, a "non-thermal" history

When H $\sim$ moduli decay width, $\Gamma_{mod} \sim M^3_{mod}/m^2_{pl}$ then the moduli decay → need $\mathbf{M_{mod}} \gtrsim$ **30 TeV** so decay occurs before nucleosynthesis – moduli decay dilutes DM, decay regenerates DM → **wino-like LSP**

Then theorem relating lightest moduli and gravitino → $M_{3/2} \gtrsim$ ***30 TeV –***

Then supergravity → **scalar masses (squarks, higgs scalars)** $\gtrsim$ **30 TeV**

Avoid BBN problem by late inflation? – Randall, Thomas 9407208-- extremely difficult – many attempts – de Gouvea, Moroi, Murayama ph/9701244 – Fan, Reece, Wang 1106.6044 – Choi et al recent

- **Generic relation between lightest moduli mass and gravitino mass** – basically that the gravitino is not lighter than lightest modulus – assumes supersymmetry breaking is involved in stabilizing at least one moduli

[Denef and Douglas hep-th/0411183, Gomez-Reino and Scrucca hep-th/0602246, Acharya Kane Kuflik 1006.3272]

Moduli mix with scalar goldstino, which generically has gravitino mass

Consider moduli mass matrix (but don't need to calculate it) -- Sgoldstino 2x2 piece of moduli mass matrix has mass scale $M_{3/2}$

For pos def mass matrix smallest eigenvalue of full matrix is smaller than any eigenvalue of (diagonal) submatrices

$$M^2_{\min} < m^2_{3/2}\left(2 + \frac{|r|}{m^2_{pl}}\right)$$

$M_{3/2} \gtrsim M_{mod} \gtrsim$ 30 TeV (BBN)

MODULI STABILIZATION

- All G_2 moduli fields have axionic partners which have a shift symmetry in the absence of fluxes (different from heterotic or IIB) – such symmetries can only be broken by non-perturbative effects

- So in zero-flux sector only contributions to superpotential are non-perturbative, from strong dynamics (e.g. gaugino condensation or instantons) – focus on former

- In M theory the superpotential, and gauge kinetic function, in general depend on all the moduli – all moduli geometric, on equal footing

- The hidden sector gaugino condensation produces an effective potential that stabilizes all moduli

A set of Kahler potentials, consistent with G_2 holonomy and known to describe some explicit examples, was given by Beasley-Witten th/0203061; Acharya, Denef, Valandro th/0502060, with

$$K = -3\ln(4\pi^{1/3}V_X)$$

$$V_X = \prod_{i=1}^{N} s_i^{a_i}, \quad \text{with} \quad \sum_{i=1}^{N} a_i = 7/3$$

$[V_X = V_7]$

We assume we can use this. More generally the volume will be multiplied by a function with certain invariances.

Assume hidden sector gaugino condensation

gauge kinetic function

$$W = \sum_{k=1}^{M} A_k e^{ib_k f_k}$$

Sometimes keep two terms – enough to find solutions with good properties such as being in supergravity regime, simple enough to do most calculations semi-analytically (as well as numerically)

$b_k = 2\pi / c_k$ where c_k are dual coxeter numbers of hidden sector gauge groups --- A_k are constants of order unity, and depend on threshold corrections to gauge couplings, some computed by Friedmann and Witten

$b_1 = 2\pi/P$, $b_2 = 2\pi/Q$

(Not “racetrack” – once moduli have any interaction they are stabilized)

The gauge kinetic functions here are integer linear combinations of all the moduli (Lukas, Morris th/0305078),

$$f_k = \sum_{i=1}^{N} \underline{N_i^k}\, z_i \,.$$

The microscopic constants a_i, b_k, A_k, N_i^k are determined for a given G_2 manifold (but not yet fully known) --they completely characterize the vacua – not dependent on moduli

For semi-analytic examples focus on the (well-motivated) case where two hidden sector gauge kinetic functions are equal (the corresponding three-cycles are in the same homology class)]

Include generic massless hidden sector chiral fermion states Q with N_c colors, N_f flavors, $N_f<N_c$ -- then (Affleck, Dine, Seiberg PRL 51(1983)1026, Seiberg hep-th/9402044, hep-th/9309335, Lebedev,Nilles, Ratz th/0603047)

$$W = A_1\, e^{i\frac{2\pi}{N_c-N_f}\sum_{i=1}^{N} N_i^{(1)} z_i}\, \det(Q\tilde{Q})^{-\frac{1}{N_c-N_f}} = A_1 \phi^a\, e^{ib_1\, f_1}$$

and define an effective meson field

$$\phi \equiv \left(\det(Q\tilde{Q})\right)^{1/2} = \phi_0 e^{i\theta}$$

Chiral fermions localized at pointlike conical singularities, so bulk moduli should have little effect on local physics, so assume matter Kahler potential slowly varying

$$W = A_1 \phi^a \, e^{ib_1 f} + A_2 e^{ib_2 f}$$

$$K = -3 \ln(4\pi^{1/3} V_X) + \phi\bar{\phi}$$

Calculate F terms → $F_{matter} \sim M_{3/2} \, M_{pl}$, $F_{mod} \sim \alpha_{gut} \, M_{3/2} \, M_{pl}$

The N=1 SUGRA scalar potential is then given by:

$$
\begin{aligned}
V \;=\; & \frac{e^{\phi_0^2}}{48\pi V_X^3}\Big[(b_1^2 A_1^2\phi_0^{2a}e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2^2A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2b_1b_2A_1A_2\phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}}\cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)) \\
& \times\sum_{i=1}^N a_i(\nu_i)^2 + 3(\vec{\nu}\cdot\vec{a})(b_1A_1^2\phi_0^{2\alpha}e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} + (b_1+b_2)A_1A_2\phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \\
& \times\cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)) + 3(A_1^2\phi_0^{2a}e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2A_1A_2\phi_0^a e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \\
& \times\cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)) + \frac{3}{4}\phi_0^2\,(A_1^2\phi_0^{2\alpha}\left(\frac{a}{\phi_0^2}+1\right)^2 e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2e^{-2b_2\vec{\nu}\cdot\vec{a}} \\
& +2A_1A_2\phi_0^a\left(\frac{a}{\phi_0^2}+1\right)e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}}\cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta))\Big].
\end{aligned}
\tag{101}
$$

$$m_{3/2} \equiv m_p^{-2} e^{\frac{K}{2m_p^2}} |W|$$

Semi-analytic example

$$m_{3/2} = m_{pl} \frac{\alpha_{GUT}^{7/2}}{\sqrt{\pi}} \frac{|Q-P|}{Q} e^{-\frac{P_{eff}}{Q-P}}$$

Q,P ranks of typical gauge groups from 3-cycle singularities

$$P_{eff} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2\sqrt{6(Q-P)})} \sim 60 \text{ when } Q-P=3$$

→ $m_{3/2} \approx 50$ TeV

($e^{-20} \approx 10^{-9}$, $\alpha_{GUT}^{7/2} \approx 10^{-5}$)

DE SITTER VACUUM, GAUGINO MASSES SUPRESSED

-- With only compactifiation moduli one gets AdS extrema – minima, maxima, saddle points (no go theorems, Maldacena and Nunez…) – some break susy, some preserve it

-- For M theory, positive F terms from chiral fermion condensates automatically present, cancel the $3W^2$ and give deS minima – “uplift”

-- also, in M theory case the deS minima come from susy preserving extremum if ignore meson F terms, so the minima is near a susy preserving point in field space where gaugino masses would vanish

-- so SM gaugino masses are doubly suppressed – vanish at susy preserving point, and get no contribution from large F terms of mesons

$$M_{1/2} \sim K_{mn} F_m \partial_n f_{SM}$$

-- can’t calculate suppression precisely, estimate $\sim$ 1/50

-- general situation not known – gauginos suppressed in heterotic?

Including the μ parameter in string theory

arXiv:1102.0556, Acharya, Kane, Kuflik, Lu

- Normally μ and tanβ treated as parameters, constrained to get EWSB
- Ultimately want to derive them from first principles
- If μ in W then it should be of order string scale
- Need symmetry to set μ=0
- Witten, hep-ph/0201018 – found discrete symmetry for G_2 compactification, closely connected to doublet-triplet splitting problem, proton lifetime, R-parity
- Witten did not break discrete symmetry so μ≡0 – when moduli are stabilized the effects generally not invariant so in M-theory with moduli stabilized the symmetry is broken
- **μ proportional to $M_{3/2}$** since μ → 0 if susy unbroken
- **Also μ proportional to moduli vev** since μ→0 if moduli not stabilized
- Stabilization led to moduli vev/M_{pl} < 0.1
- **So finally expect μ < 0.1 $M_{3/2}$**
- Witten discrete symmetry anomalous, Z_{18} ok

❑ WHY IS M_H LIGHT? -- QUICK SUMMARY

-- Recall no EWSB at high scale, generated by RGE running

High scale, compactified M theory, orbifold and conical singularities → gauge and chiral matter → gaugino and meson condensates, F-terms, supersymmetry-breaking, moduli stabilization, deS vacuum

Typical gauge groups → gaugino condensation $\sim 10^{-4-5}$ M_{planck}, cubed in superpotential, so $M_{3/2} \sim$ 50 TeV (top down)

$M_{3/2}$ > smallest eigenvalue of moduli mass matrix $\gtrsim$ 30 TeV, from BBN

Calculate soft-breaking Lagrangian: **scalars, trilinears, b -- ALL $\sim M_{3/2}$**

μ superpotential term zero from Witten discrete symmetry – broken by moduli stabilization, so $\mu_{eff} \sim$ (moduli vev/M_{pl})$M_{3/2}$ < few TeV

At high scale Higgs sector soft terms $\sim M_{3/2}$, no EWSB

Then M^2_{Hu} runs down, satisfies EWSB conditions (REWSB)

Now go through details

Higgs sector

In supersymmetric theory two higgs doublets present for anomaly cancellation – by "Higgs mass" mean mass of lightest CP-even neutral scalar in Higgs sector

Precise value depends on all the soft-breaking parameters including B, μ

Why 125 GeV? – not simple, must do RGE running, relate terms, smallest eigenvalue of matrix

Higgs potential at any scale – calculated at compactification scale, no parameters, then do RGE running to other scales

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \quad + \text{D terms}$$

→ Higgs mass matrix $\begin{pmatrix} m_{H_u}^2 + \mu^2 & -b \\ -b & m_{H_d}^2 + \mu^2 \end{pmatrix}$

Need negative eigenvalue for EWSB

$\tan\beta = v_u/v_d$ only meaningful after EWSB, doesn’t exist at high scales

Renormalization Group Equations

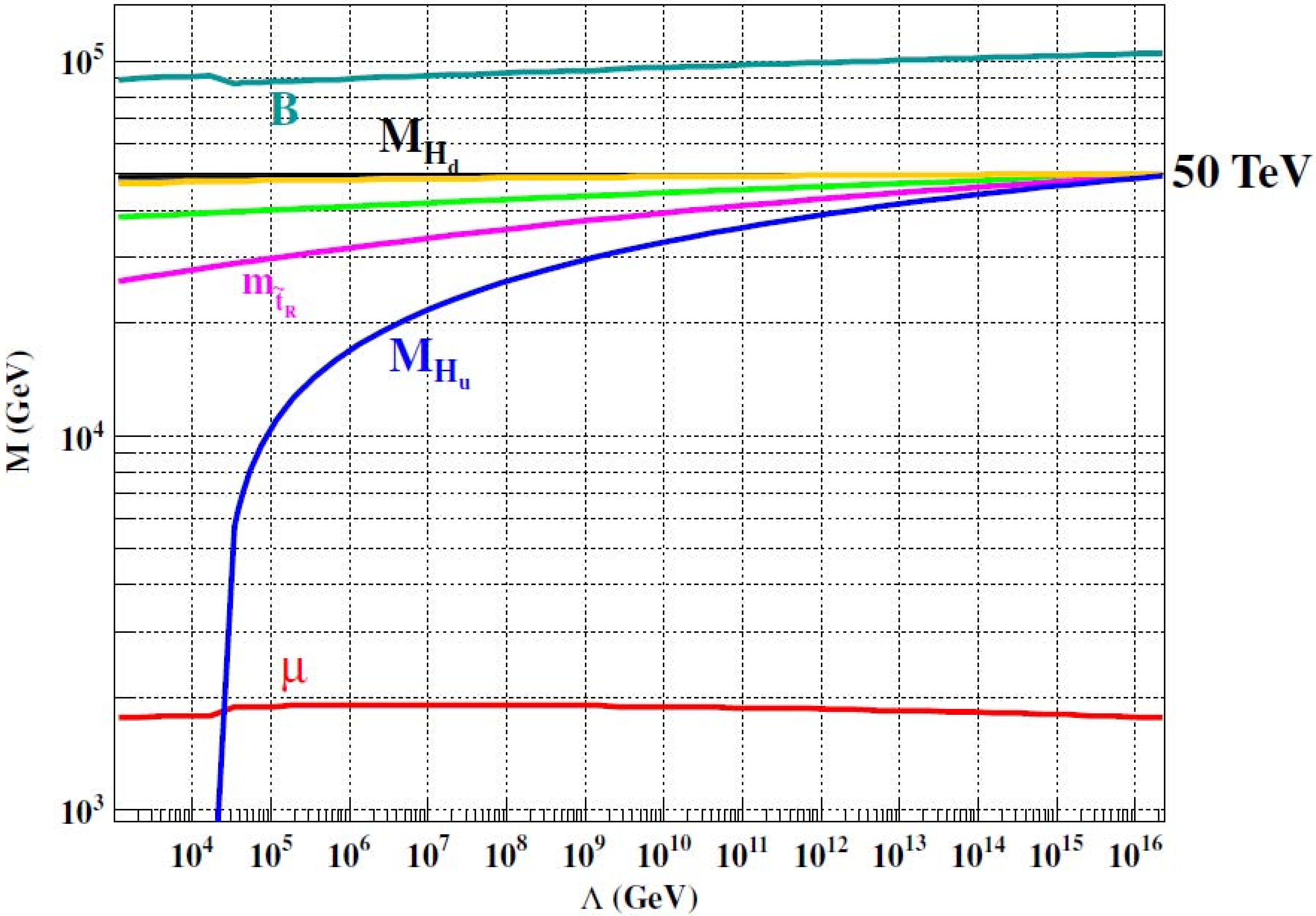
$$8\pi^2 \frac{dm_{H_u}^2}{dt} = 3|\lambda_t|^2\left(m_{H_u}^2 + m_Q^2 + m_T^2 + |A_{top}|^2\right)$$

$$8\pi^2 \frac{dm_T^2}{dt} = 2|\lambda_t|^2\left(m_{H_u}^2 + m_Q^2 + m_T^2 + |A_{top}|^2\right)$$

$$8\pi^2 \frac{dm_Q^2}{dt} = |\lambda_t|^2\left(m_{H_u}^2 + m_Q^2 + m_T^2 + |A_{top}|^2\right)$$

$$8\pi^2 \frac{d\,A_{top}}{dt} = 6\lambda_t^2 A_{top}$$

$$8\pi^2 \frac{d\,B}{dt} = 3\lambda_t^2 A_{top}$$



B
M_{H_d}
50 TeV
$m_{\tilde{t}_R}$
M_{H_u}
μ
M (GeV)
10^5
10^4
10^3
10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}
Λ (GeV)

THEORY AT HIGH SCALE, TECHNICAL DETAILS OF COMPUTING M_H

- Write theory at scale $\sim 10^{16}$ GeV, fix soft-breaking Lagrangian parameters by theory – no free parameters
- Run down, maintain REWSB
- Use "match-and-run" and also SOFTSUSY and Spheno, compare – match at $(M_{stop1}M_{stop2})^{1/2}$ – two-loop RGEs – expect public software to work since scalars not too large
- Main sources of imprecision for given $M_{3/2}$ are M_{top} (1 GeV uncertainly in M_{top} gives 0.8 GeV in M_h) , α_{strong} , theoretical gluino mass (allow 600 GeV to 1.2 TeV), trilinear couplings (allow 0.8-1.5M_0)

EWSB, μ, tanβ, naturalness

Usual EWSB conditions [so higgs potential minimum away from origin]:

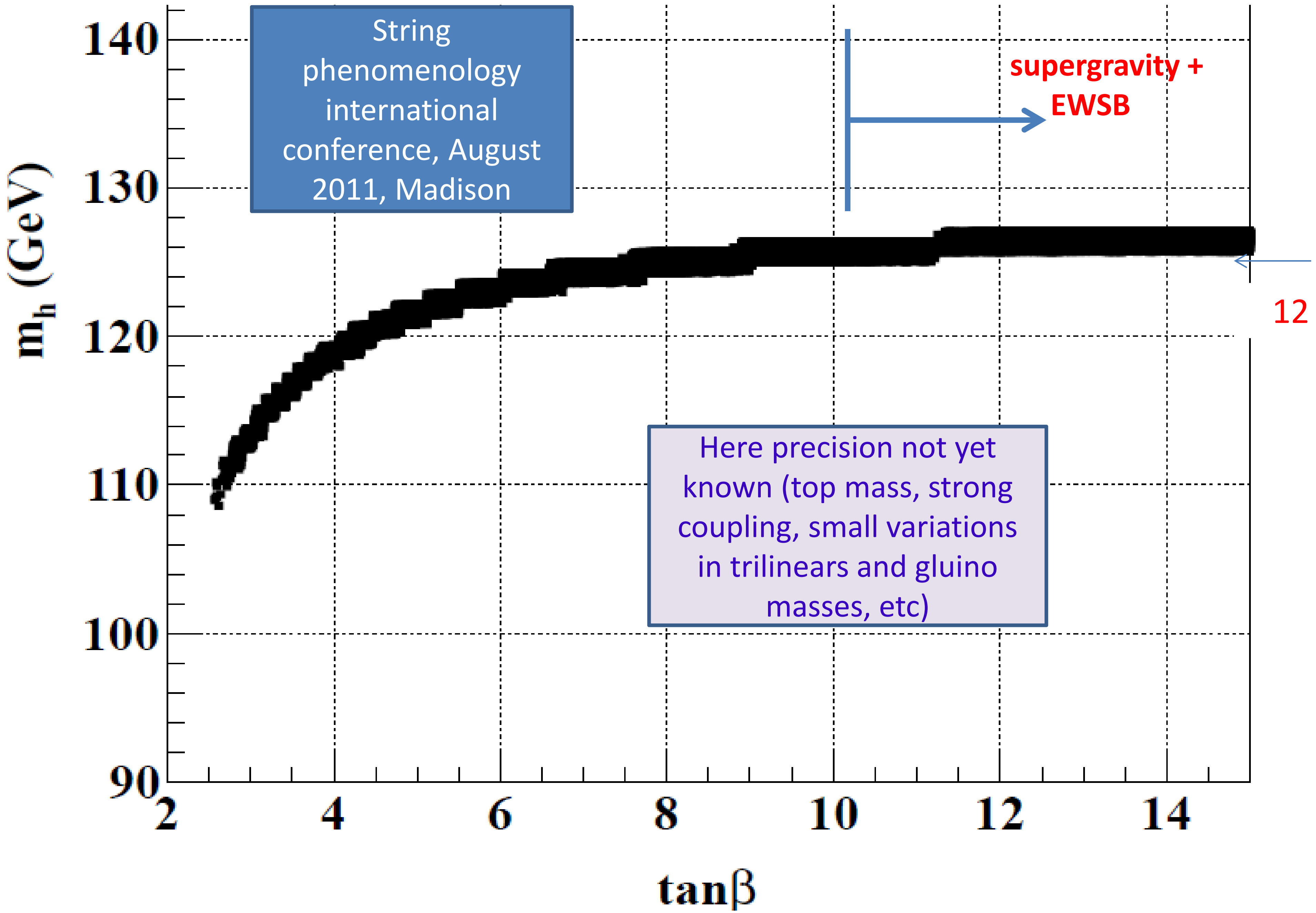
$M_Z^2 = -2\mu^2 + 2(M^2_{Hd} - M^2_{Hu} \tan^2\beta)/\tan^2\beta = \mathbf{-2\mu^2 + 2M^2_{Hd}/\tan^2\beta - 2M^2_{Hu}}$

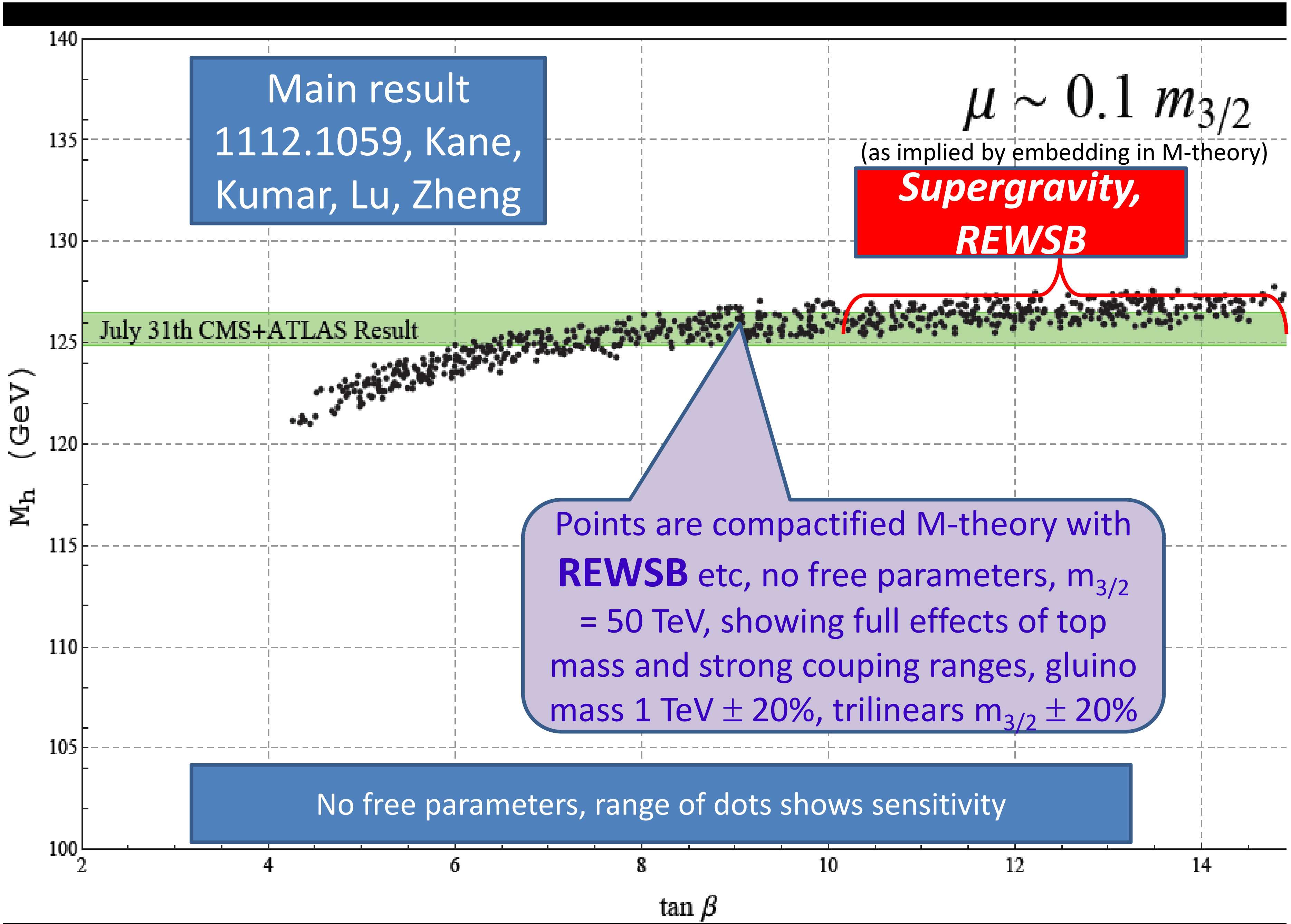
$2B\mu = \sin 2\beta\,(M^2_{Hu} + M^2_{Hd} + 2\mu^2)$

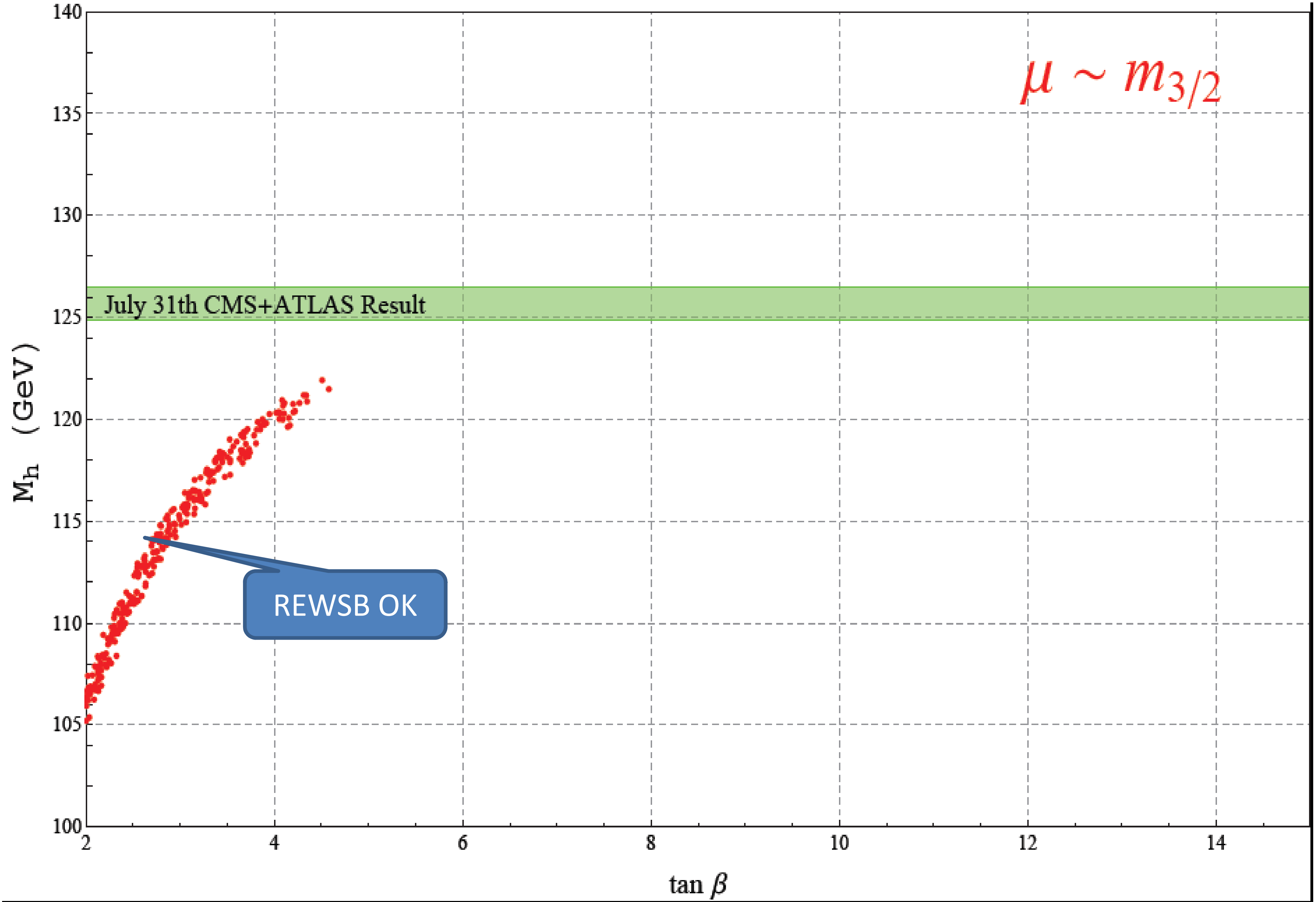
M^2_{Hu} runs to be small, M^2_{Hd} and B don't run much, μ suppressed, $\sin 2\beta \approx 2/\tan\beta$

If no μ from superpotential, and visible sector Kahler metric and Higgs bilinear coefficient independent of meson field, and if $F_{mod} << F_\phi$ then B (high scale)$\approx 2M_{3/2}$ – recall $\mu < 0.1 M_{3/2}$

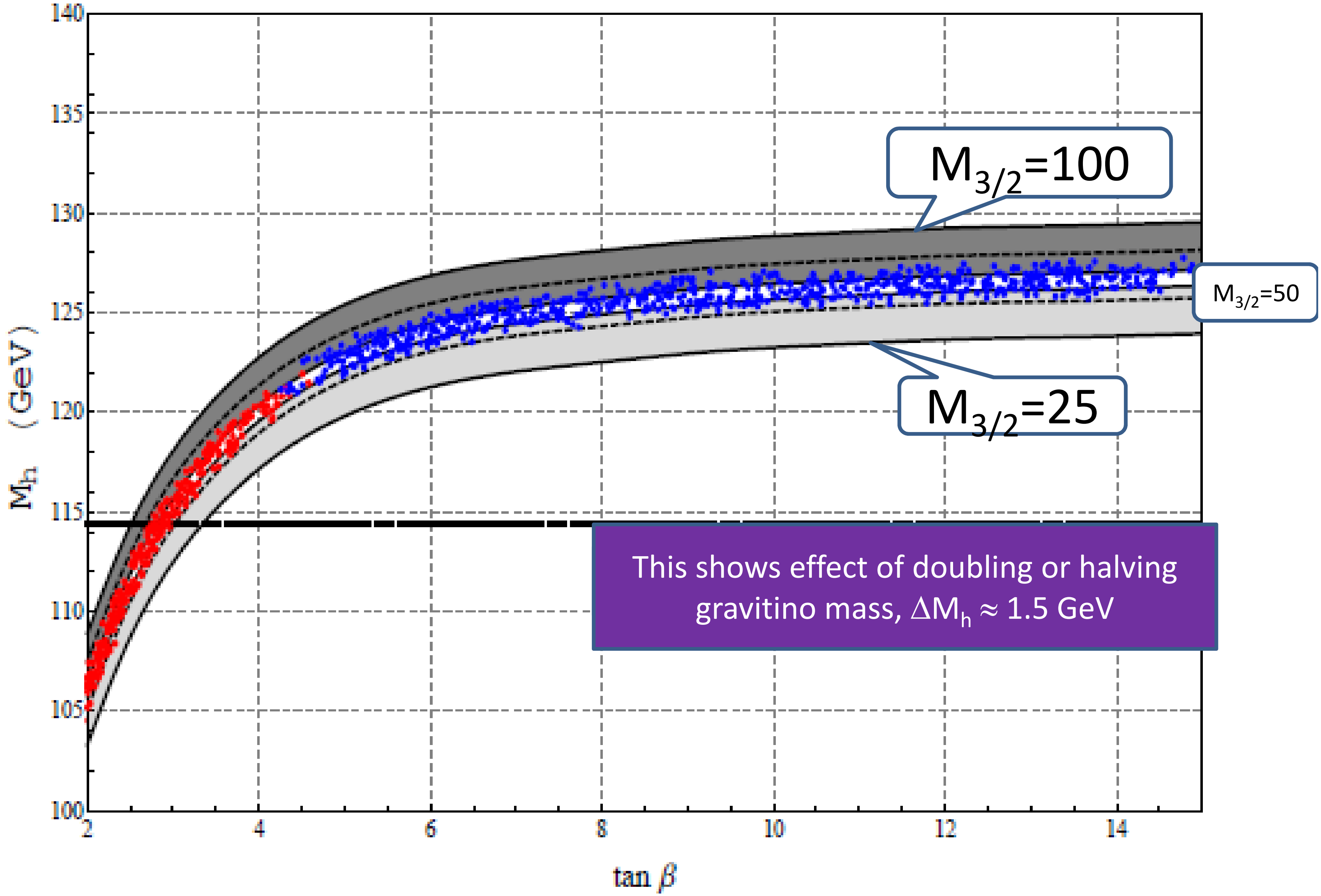
→ $\tan\beta \approx M^2_{Hd}/B\mu \approx M^2_{3/2}/B\mu$ → $\mathbf{\tan\beta \approx M_{3/2}/2\mu}$ (~ 15)


String phenomenology international conference, August 2011, Madison
supergravity + EWSB
12
Here precision not yet known (top mass, strong coupling, small variations in trilinears and gluino masses, etc)
m_h (GeV)
140
130
120
110
100
90
2
4
6
8
10
12
14
tanβ


Main result
1112.1059, Kane, Kumar, Lu, Zheng
$\mu \sim 0.1\ m_{3/2}$
(as implied by embedding in M-theory)
Supergravity, REWSB
July 31th CMS+ATLAS Result
Points are compactified M-theory with **REWSB** etc, no free parameters, $m_{3/2}$ = 50 TeV, showing full effects of top mass and strong couping ranges, gluino mass 1 TeV ± 20%, trilinears $m_{3/2}$ ± 20%
No free parameters, range of dots shows sensitivity
M_h (GeV)
tan β
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14



$\mu \sim m_{3/2}$
July 31th CMS+ATLAS Result
REWSB OK
M_h (GeV)
tan β
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14



This shows effect of doubling or halving gravitino mass, $\Delta M_h \approx 1.5$ GeV

Is h SM-like?

Theory -- all scalar terms in the soft-breaking Lagrangian predicted to be of order gravitino mass, $\gtrsim$ 30 TeV so “decoupling”limit

Still supersymmetric Higgs sector of course, but H, A, $H^{\pm}$ also about equal to the gravitino mass $\gtrsim$ 30 TeV, h light and SM-like

h is the lightest eigenvalue of the supersymmetric higgs mass matrix, in the decoupling limit –> BR are SM-like

Typically chargino and neutralino loops give few per cent deviations

$(\sigma$ x BR summed$)_{data}$ /(σ x BR summed$)_{SM}$ = 1.11±0.16

[but watch $\gamma\gamma$, etc, channels]

We assumed MSSM is gauge group and matter content at compactification – must calculate one gauge group and matter content at a time because of RGE running etc

- Can find models extending MSSM that give M_h same value as MSSM – Some U(1) extensions with no extra matter do not change mass value or BR

  -- SO(10) with RHν, no other extra matter gives 126

  -- MSSM plus U(1) plus singlet charged under U(1) does not generically give 126

  -- **We have no examples with M_h =126 and increased $\gamma\gamma$ width larger than $\sim$ 10 %**

Little hierarchy problem

Running of M^2_{Hu} in string/M theory [arXiv:1105.3765 Feldman, GK, Kuflik, Lu]

Compactified M theory → $A_0 \gtrsim M_0$

$$M^2_{Hu}(t) \approx f_M(t)\, M^2_0 - f_A(t)\, A^2_0$$

$$M_0 \approx A_0 \approx M_{3/2} \approx 50 \text{ TeV}$$

Kane,King Hep-th/9810374

f_M , f_A calculated from SM inputs, both about 0.12-0.13

So stringy prediction is a decrease $\sim$ 50 in M^2_{Hu} – if trilinears not large get order of magnitude less decrease in M^2_{Hu}

Greatly reduces "little hierarchy problem" – covers gap from $M_{3/2}$ to TeV

[If calculated M_h directly instead of ratio to Z, would get larger number, e.g. $M_Z \sim$ 1-2 TeV

Interesting to think about how precisely Higgs vev is constrained in order to give our world

– Donoghue, Dutta, Ross, Tegmark 0903.1024 argued that the higgs vev can vary a factor of a few without any change in SM physics]

➢ String/M theory crucial for *deriving* results!

-- Must have theory with **stabilized** ***moduli and spontaneous supersymmetry breaking –*** compactified string theories

-- Must have gravitino-moduli connection to get lower limit on gravitino mass

-- Must derive soft terms, otherwise could choose anything – e.g. large trilinears important, but people in past guessed they were small – string theory gave prediction of large trilinears

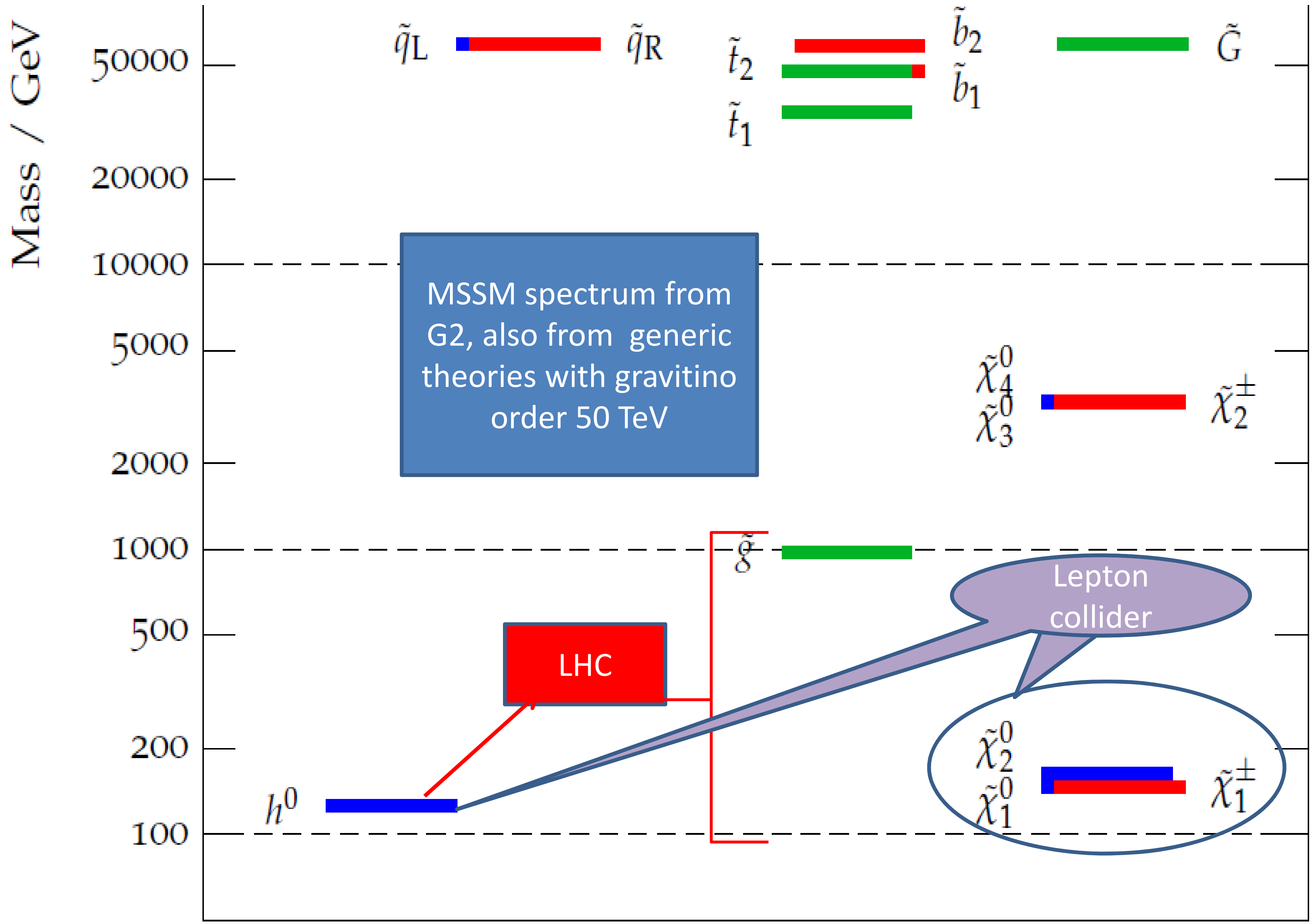
-- Must have μ embedded in string theory

-- Must exhibit string solutions with REWSB

-- Must have effectively no parameters

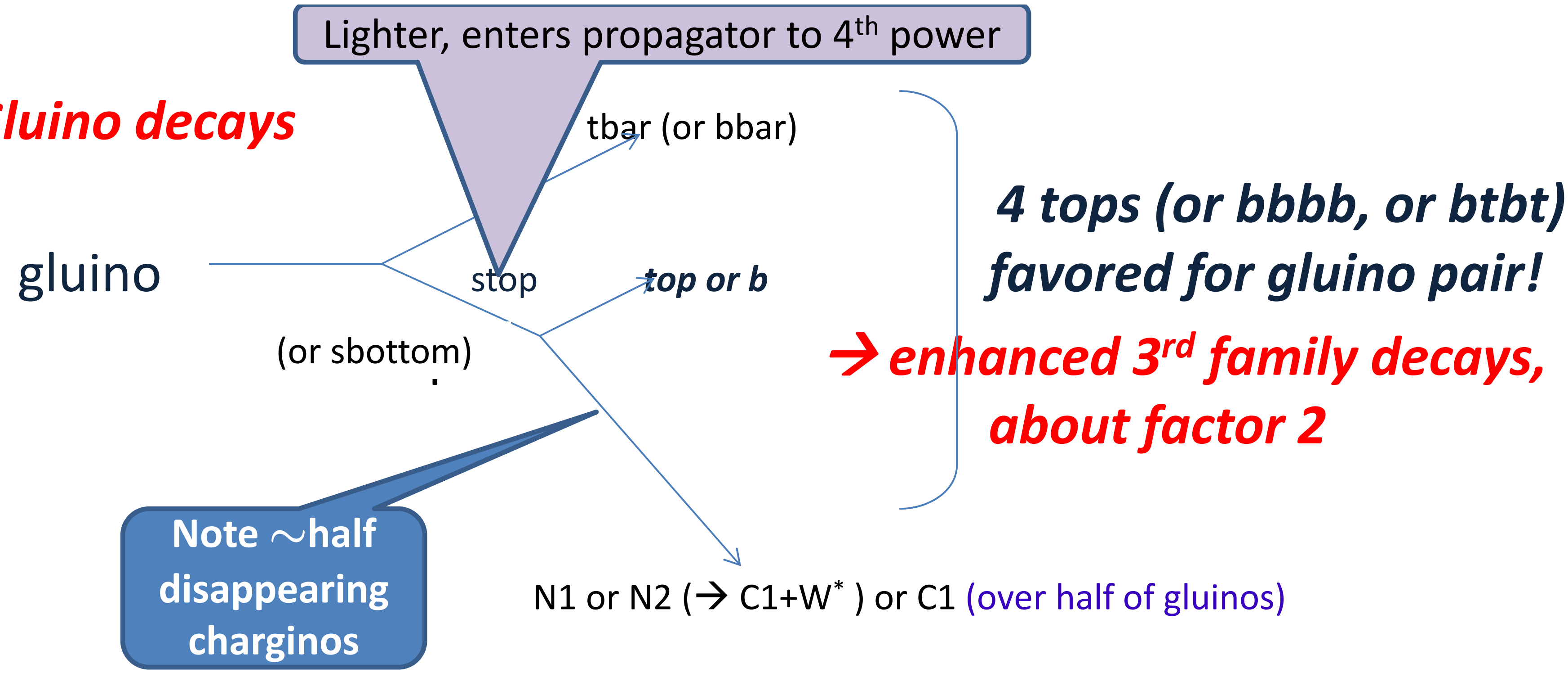
-- No R symmetry , since trilinears heavy and gauginos light

Some LHC predictions



Mass / GeV
50000
20000
10000
5000
2000
1000
500
200
100
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{t}_2$
$\tilde{t}_1$
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{G}$
MSSM spectrum from G2, also from generic theories with gravitino order 50 TeV
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{g}$
Lepton collider
LHC
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
h^0

Gluino decays



Gluino lifetime ~ 10^{-19} sec, decays in beam pipe

Gluino decays flavor-violating

Current limit for gluinos with enhanced 3rd family decays, very heavy scalars, ~ 900 GeV

Papers LHC14,0901.3367; LHC7, 1106.1963

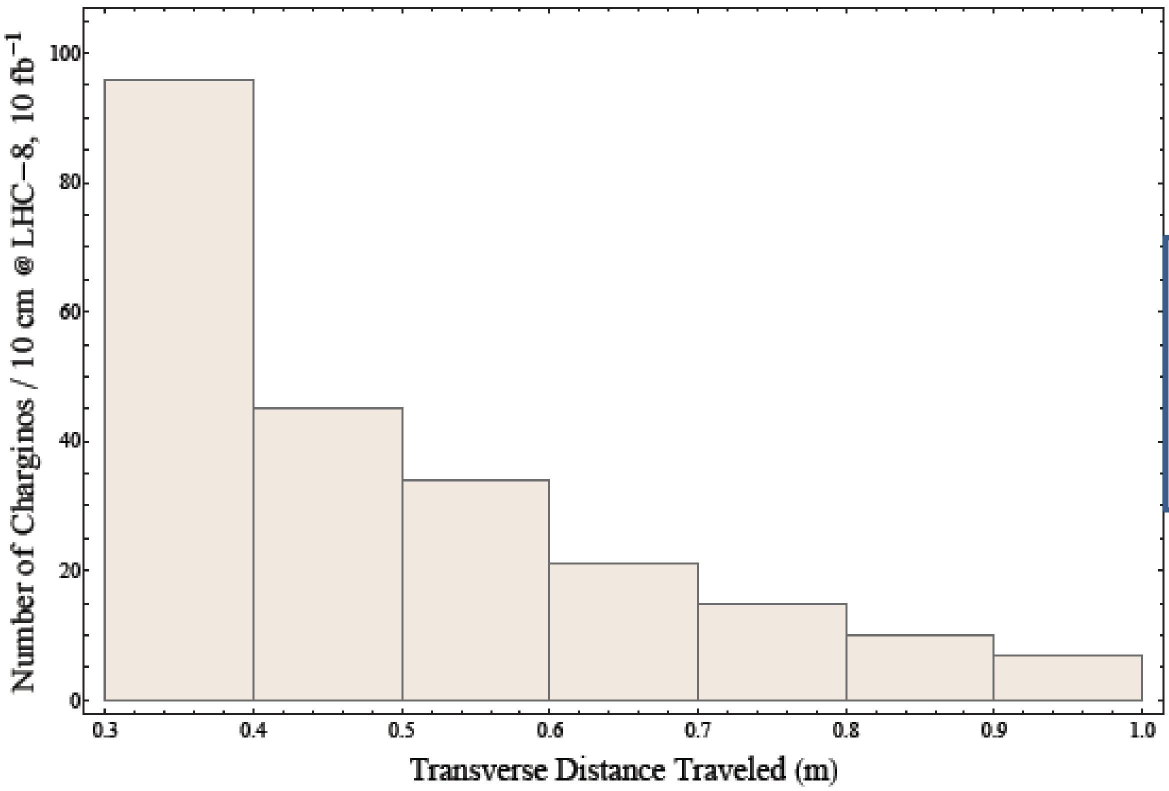
Realistic Branching Fraction

$$m_{3/2} = 50\,\mathrm{TeV}$$
$$M_{\mathrm{gluino}} = 900\,\mathrm{GeV}$$
$$M_{\mathrm{LSP}} = 145\,\mathrm{GeV}$$

$$BR(\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0) \approx 0.15$$
$$BR(\tilde{g} \rightarrow t\,\bar{b}\,\tilde{\chi}^- + h.c.) \approx 0.28$$
$$BR(\tilde{g} \rightarrow b\,\bar{b}\,\tilde{\chi}^0) \approx 0.08$$

So **BR (third family) ≈ ½**, BR (1st + 2nd families ≈ ½) per gluino

If wino-like LSP, chargino and LSP are nearly degenerate, so chargino → LSP plus very soft π^+ → **disappearing charginos in gluino decays** -- $\gamma c\tau \approx 10$ cm



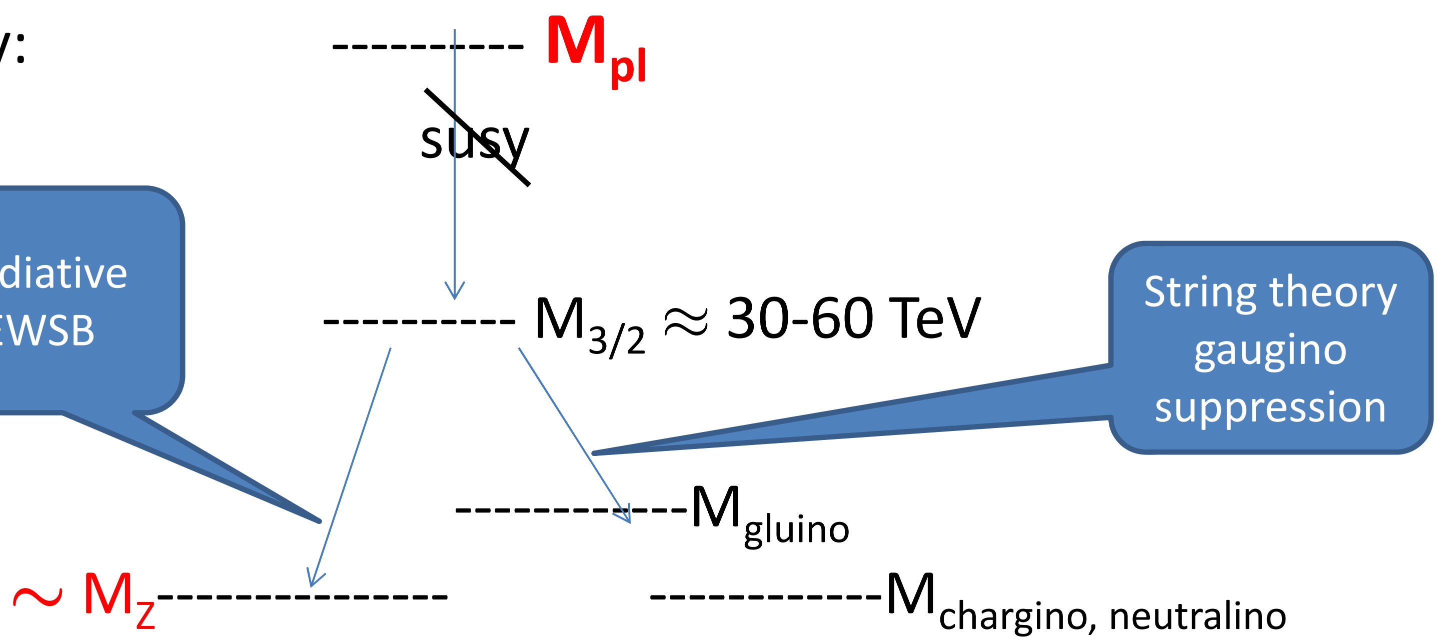
GK, Lu, Zheng 1202.4448

See Moroi et al for pair production of disappearing charginos

FIG. 1: Charged Winos resulting from gluino pair production, binned as a function of transverse distance traveled from the beam line. These results correspond to 10 fb^{-1} of LHC-8 data ($\sigma_{\tilde{g}\tilde{g}} \sim 235$ fb), with $m_{\tilde{g}} = 750$ GeV, $m_{\widetilde{W}} = 150$ GeV. For graphical purposes, charginos traveling a transverse distance < 30 cm are not shown.

Naturalness? Fine-tuning? Little hierarchy?

String theory:



Suppose string theory gives a successful description of our string vacuum – *Can string theory be unnatural?*

GENERIC PREDICTIONS

- Squarks, sleptons 30-60 TeV
- $B_s \rightarrow \mu\mu$ within 1-2% of SM
- $(g-s)_\mu$ within 5-10% of SM
- $\tan\beta \sim 15$
- M_h =126±2, susy higgs sector decoupling so H, A,$H^\pm$ > 30 TeV
- No invisible h decays
- Gluino $\sim$ 1 TeV, gluino decays flavor violating, 3rd family larger
- EDMe $\approx 10^{-30}$
- LSP wino-like but μ small
- Relic density of LSPs, axions both order 1
- $\sigma_{SI} \sim 10^{-46}$

Final remarks

- *Higgs data looks like data from compactified constrained string theory with stabilized moduli should look! – 126 GeV not unnatural! – SM-like Higgs not surprising!*
- Higgs looks like a fundamental particle – normal susy h in decoupling region – not weird

- *String theory finally maturing into a useful predictive framework that relates many explanations, tests*

- M theory compactified on G_2 manifold looks like good candidate for describing our string vacuum – explains many phenomena, predicts some -- Many features generic for other corners of string theory too
- Compactified M/string theory, squarks, sleptons 30-60 TeV
- μ, $\tan\beta$ included in theory, not free parameters