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

→ M_h = 126 ± 2 GeV, SM-like

GK, Ran Lu, Bob Zheng, Piyush Kumar + Bobby Acharya, Konstantin Bobkov, Jing Shao, …

AND "NEW" COMPACTIFIED M-THEORY STUDY OF GENERIC PREDICTION OF THE GLUINO MASS (AND SIGNATURES) – THEORETICALLY HARDER THAN H -- PROBABLY

$$800 \text{ GeV} \lesssim M_{\tilde{g}} \lesssim 1500 \text{ GeV}$$

Gordy Kane, University of Michigan

KITP, JULY 2013

- Introduction – making string theory predictions for data
  - -- *assumptions* – not directly related to Higgs sector
  - -- stabilizing moduli – crucial for derivation
  - -- μ, $\tan\beta$ not parameters in string theory
- Higgs mass derivation
- Results
- Implications
  - Gluino mass prediction
  - Associated LHC predictions for gluino BR, charginos, LSP
- Naturalness? – what you talk about if no theory
- Little hierarchy problem reduced – gone?
- Final remarks

Goal: Understand the ground state of our M/string theory – we live there – M/string theory provides powerful framework Beyond SM

Higgs discovery great – closes one era whose goal was to describe our world (400 years) – opens new era with Higgs physics pointing toward deeper underlying theory, why the SM is what it is – Expect Supersymmetric Standard Model (SSM)

Data seems consistent with that – observed higgs behaves just like the decoupling limit of Supersymmetric Standard Model, long well known

Is M_h too large for that to make sense? Need a theory to define "large"!

→M/string theory →**M_h just right, explains "why 126"**

Often people use "naturalness" as criterion – but that is only what you would use in the absence of a theory!

M\string theories have matured to the stage where can use them to get, test predictions -- obviously must compactify to 4D – So have candidate theory framework to ask if M_h "natural" – moduli describe small extra D, must be given vacuum values (stabilized)

We did that for the Higgs mass and properties – work in compactified fluxless M-theory since stabilizing moduli works well there – results may hold in other corners of string theory too (depends on μ too)

We found (summer 2011) the theory ***generically*** and ***naturally*** has solutions with EWSB, with the decoupling limit of Supersymmetric Standard Model, with $M_h = 126 \pm$ about 1%, for gravitino mass of 50 TeV – M_h increases (decreases) 1.5 GeV for doubling (halving)

Gravitino mass gives splitting with graviton, measures amount of susy breaking – calculate gravitino mass from Planck mass -- Gravitino mass ($M_{3/2}$) approximately calculable in the theory, and also phenomenologically constrained, to region about 30-100 TeV --

There has not been enough thought about what it means to make predictions, explanations from string theory for data – predictions, explanations should be based on <u>generic</u> projection of extra dimensional theories into 4D large spacetime, plus small dimensions

Require boundary conditions (e.g. solutions with EWSB) but calculate masses as output

”**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

String theory only fully predictive if results generic – not generic *means* tuning *<u>something</u>* – risky

– could have nature’s theory being constrained by M/string theory framework but needing limited tuning – but hopefully not

Take compactifications seriously

❑ Philosophy to compute Higgs mass, gluino mass, properties:

Divide all compactified string/M theories into two classes

- **Some generically have softly-broken supersymmetry, TeV scale physics, EWSB, μ and tanβ not parameters, no contradictions with nucleosynthesis, cosmology, etc – study all these theories -- 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"

Calculate M_h /M_Z, gluino mass, etc for those solutions → 126 and more

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
- **Witten, 1995 → M-theory**
- Papadopoulos, Townsend th/9506150, 7D manifold with G_2 holonomy preserves **N=1 supersymmetry → vacuum stability after EWSB**
- 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, superpartners, since LHC coming

Do the derivations here in M-theory case since those calculations more complete – results may hold in some or all other corners of string theory since they depend on only a few generic features of resulting soft-breaking Lagrangian (μ, tanβ?)

So far, only compactified M-theory has stabilized moduli, de Sitter vacuum, no cosmological moduli problem – no other string theory limit

Our M-theory papers --*Review arXiv:1204.2795 , Acharya, Kane, Kumar*

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

- M-Theory Solution to Hierarchy Problem th/0606262
- **Stabilized Moduli, TeV scale,** ***squark masses*** *= gravitino mass, few* ***tens of TeV****; gaugino masses suppressed* ***0701034***
- Spectrum, scalars $\gtrsim$ **30 TeV, 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** $\lesssim$ **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** (new paper coming)
- **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 (GK, Kumar, Lu, Zheng)
- **Gluino mass prediction,** paper in preparation

To take Higgs and gluino results fully seriously good to know other major physics questions addressed OK in same theory

Next briefly compare M-**theory** derivation with **models** assuming heavy scalars – early paper speculating scalars heavy James Wells hep-th/0302127

- See many features are different – alert you to watch for them during derivations
- History very distorted, even recently

COMPACTIFIED(STRING)**M THEORY**

- **Derive** solution to large hierarchy problem
- Generic solutions with **EWSB derived**
- main F term drops out of **gaugino masses** so **dynamically suppressed**
- **Trilinears > $M_{3/2}$** necessarily
- **μ incorporated in theory (M-theory)**
- Little hierarchy significantly reduced
- **Scalars = $M_{3/2}$ ~ 50 TeV necessarily** , scalars only ~ 50 TeV, not superheavy
- Gluino lifetime $\lesssim 10^{-19}$ sec, always decays in beam pipe
- **$M_h \approx$126 GeV unavoidable**, predicted

SPLIT SUSY (ETC) MODELS

- Assumes **no solution possible for large hierarchy problem**
- **EWSB assumed**, not derived
- **Gauginos suppressed by assumed** R-symmetry, suppression arbitrary
- Trilinears small, suppressed compared to scalars
- **μ not in theory** at all; guessed to be $\mu \sim M_{3/2}$
- No solution to little hierarchy
- Scalars **assumed** very heavy, whatever you want, e.g. 10^{10} GeV
- Long lived gluino, perhaps meters or more
- **Any MSSM M_h allowed**

Now Main Derivation – first make assumptions, *not closely related to Higgs sector*

- ○ **CC problem orthogonal – won't know for sure until solved**
- ○ **Our world described by compactified M-theory G_2 manifold, fluxless** (can try to repeat for other corners of string theory)
- ○ **Assume Hubble parameter H at end of inflation larger than $M_{3/2}$**
- ○ **Assume top quark with yukawa coupling $\sim$ 1 (work underway)**
- ○ **Assume compact singular G2 manifold exists with assumed properties**
- ❑ **Include μ via discrete symmetry** (Witten 2002) – paper 2 coming
- ○ **Use generic Kahler potential (Beasley,Witten, 2002) and generic gauge kinetic function (Lucas, Morris, 2003)**
- ❑ **Assume gauge group and matter content at compactification is MSSM – can repeat for any other gauge group and matter content (others under study)**

GENERICALLY THESE **EXPLAIN "WHY 126"** -- overview

- Compactification → moduli → $M_{\text{lightest modulus}} \geq$ 30 TeV for BBN
- Susy ~~by~~ gaugino condensation → $M_{3/2} > M_{\text{lightest modulus}}$
- CC$\approx$0, Supergravity → $M_{\text{soft scalars}} = M_{3/2}$
- μ doubly suppressed – symmetry to remove μ from superpotential broken by moduli stabilization, so additional moduli vev/M_{pl}
- REWSB conditions easy to satisfy
- Supergravity, solutions with EWSB → 1.5 μ tan$\beta \approx M_{3/2}$ → tanβ$\gtrsim$10
- Trilinears $A \approx e^{K/2} F^{\varphi} K_{\varphi} > M_{0}$, large – important for little hierarchy

The prediction of 126 is not an accident or a planned result

It is here to stay in generic theory

Upper limit on gluino mass also – basically, gluino mass proportional to gravitino mass – proportionality constant calculable – gravitino mass bounded by phenomenology and theory

❑ Moduli, gravitino constraint from BBN

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, $\Gamma_{\rm mod} \sim \mathbf{M^3_{mod}}/m^2_{pl}$ then the moduli decay → need $\mathbf{M_{mod}} \gtrsim$ **30 TeV** so decay occurs before nucleosynthesis – moduli decay dilutes any DM that arose before

Moduli decay regenerates DM → **wino-like LSP to not overclose univ**

Then theorem relating lightest moduli and gravitino → ***$M_{3/2} \gtrsim$ 30 TeV –***
Then supergravity → **scalar masses (squarks, higgs scalars) $\gtrsim$ 30 TeV**

Stronger than generic

❑ Generic relation of lightest moduli and gravitino masses

– 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 →

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

→ **$M_{3/2} \gtrsim M_{\text{lightest modulus}} \gtrsim$ 30 TeV** (BBN)

❑ From Planck scale to 50 TeV "dimensional transmutation"

Scale of gaugino condensation $\Lambda \approx M_{pl}\ \exp(-8\pi^2/3Qg^2) \approx \exp(2\pi \mathrm{Imf}/3Q)$

where $\mathrm{Imf} = \sum N_i\, s_i$

Q is rank of condensing gauge group

Q,P ranks of typical condensing gauge groups – physical solutions need $Q-P=3$, $\mathrm{Imf}=14Q/\pi \rightarrow \Lambda \approx M_{pl}\, e^{-28/3} \approx 2\times10^{14}$ GeV, so

$\Lambda \approx 10^{-4}\ M_{pl} \approx$ *scale at which supersymmetry broken*

Then $W \sim \Lambda^3 \sim 10^{-12}\ M_{pl} \sim 2\times10^6$ GeV = 2×10^3 TeV. Also expect inverse volume factor $1/V_7$ from $e^{K/2}$ so

$M_{3/2} \approx e^{K/2}\ W \sim 50$ TeV

Note Imf/Q not explicitly dependent on Q – still dependent because of V_7 and P_{eff}, but weakly – so Λ rather well determined

❑More details on gravitino mass – semi-analytic example

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

Q,P ranks of typical gauge groups from 3-cycle singularities, Q=6,7,8,9 – moduli vevs $\sim$ 3Q $\sim$ 1/α_{GUT} -- put CC=0 to solve for Pln( )=P_{eff}

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

→ $m_{3/2} \approx$ 50 TeV

($e^{-20} \approx 10^{-9}$, $P_{eff} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2\sqrt{6(Q-P)})} \sim 60$ when $Q-P=3$

$M_{GUT} = M_{11}\, \alpha_{Gut}^{\;1/3}$)

- **Including μ parameter in string theory**($W=\mu H_u\, H_d + \ldots$ so $\mu \sim 10^{16}$ GeV)
- Normally μ and $\tan\beta$ 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 $\mu=0$

arXiv:1102.0556, Acharya, Kane, Kuflik, Lu

- Witten, hep-ph/0201018 – found discrete symmetry for G_2 compactification, closely connected to doublet-triplet splitting problem, proton lifetime, R-parity
- Unbroken discrete symmetry so $\mu\equiv 0$ – 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 $\mu \rightarrow 0$ if susy unbroken
- **Also μ proportional to moduli vev** since $\mu \rightarrow 0$ if moduli not stabilized
- Stabilization led to moduli vev/$M_{pl} \lesssim 0.1$
- So predict **$\mu < 0.1\, M_{3/2}$** , not parameter, not yet precisely calculated
- Paper II in preparation (Acharya, Kane, Kumar, Lu, Zheng)

❑ WHY 126? -- 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 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) – calculate M_h for all solutions, **get 126 ±1GeV for $M_{3/2}$ = 50 GeV**

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 126 GeV? – conceptually simple, but not numerically – no simple formula, 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

tanβ = v_u/v_d only meaningful after EWSB, doesn't exist at high scales – parameter before, now calculate it approximately

❑ EWSB, μ, calculate tanβ, naturalness

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

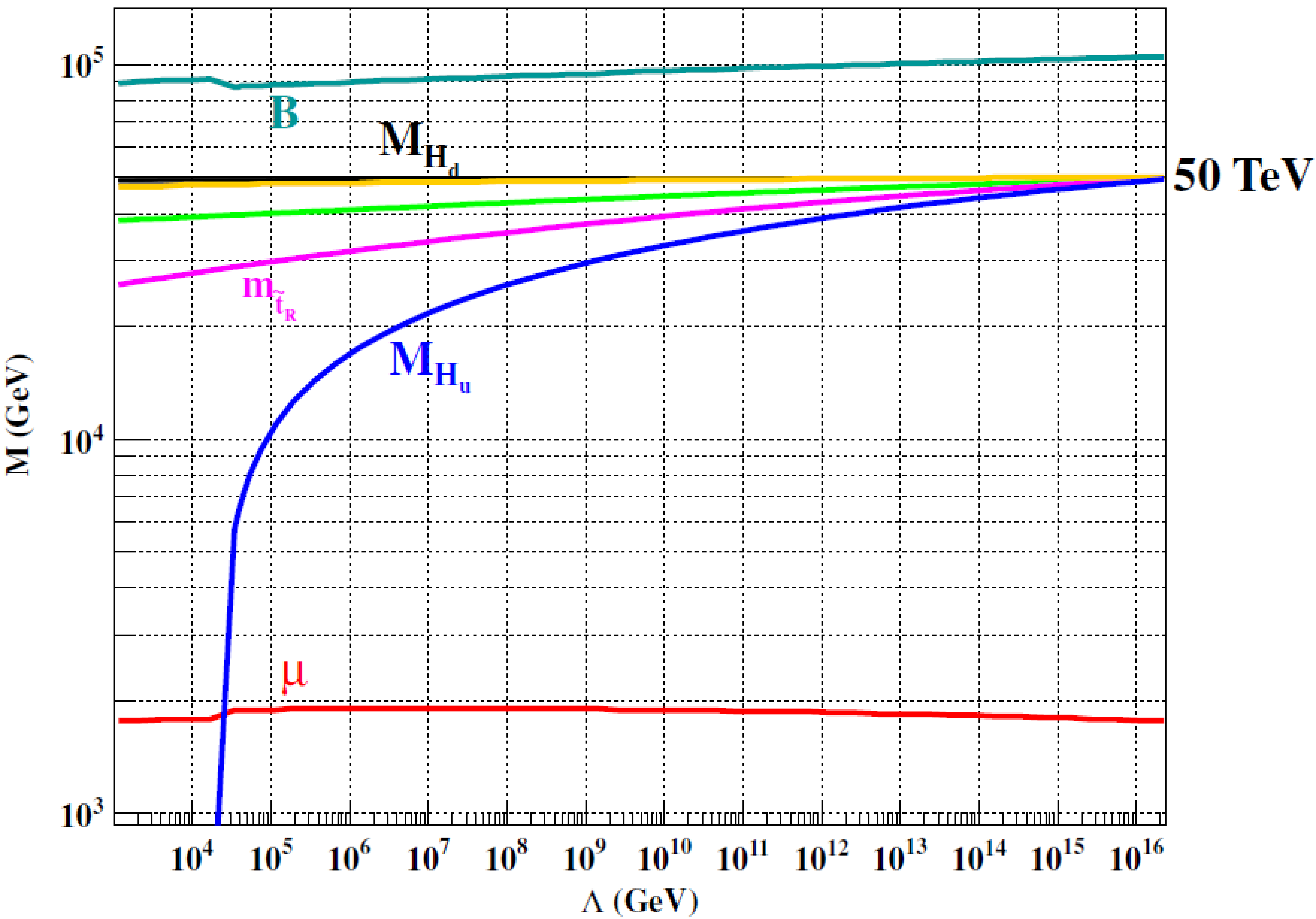
$M_Z^2 = -2\mu^2 + 2(M^2_{Hd} - M^2_{Hu}\tan^2\beta)/\tan^2\beta = \mathbf{-2\mu^2 + 2M^2_{Hd}/\tan^2\beta - 2M^2_{Hu}}$

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

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

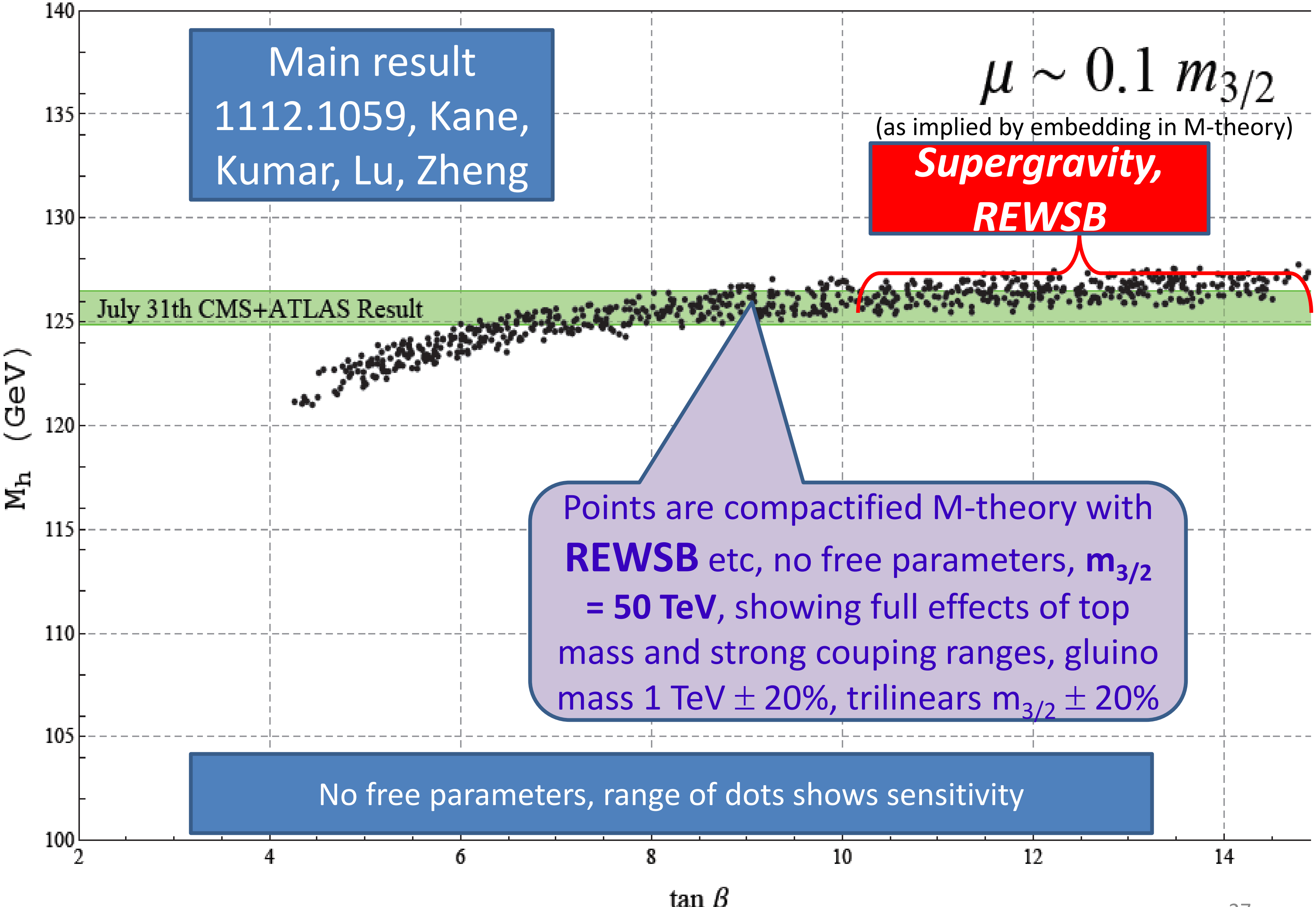
If no μ from superpotential, and visible sector Kahler metric and Higgs bilinear coefficient independent of meson field, and if $F_{mod} << F_\phi$ then B (high scale)$\approx 2M_{3/2}$ – recall $\mu < 0.1 M_{3/2}$

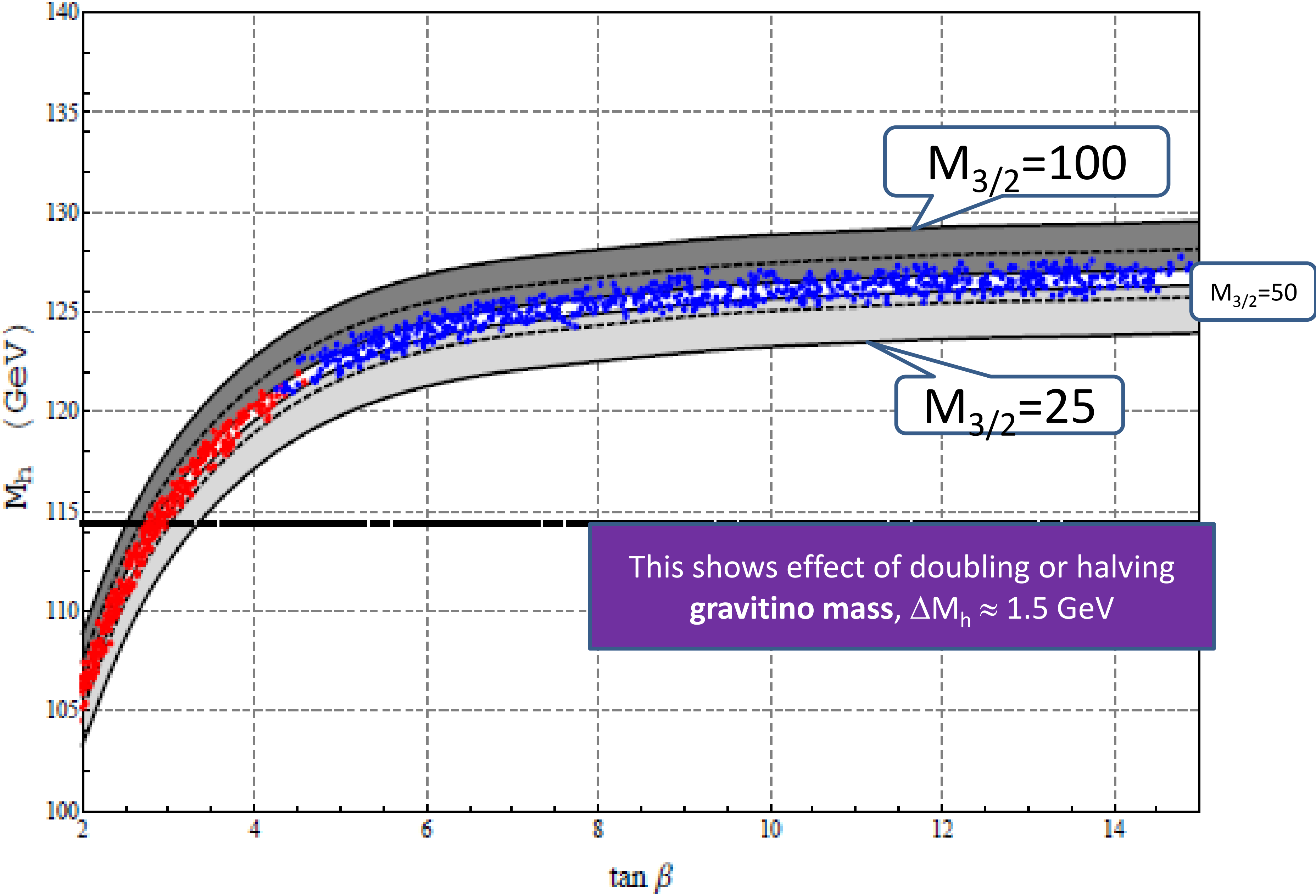
→ $\tan\beta \approx M^2_{Hd}/B\mu \approx M^2_{3/2}/B\mu$ → $\mathbf{\tan\beta \approx M_{3/2}/2\mu}$ ($\sim$ 15)


B
M_{H_d}
50 TeV
$m_{\tilde{t}_R}$
M_{H_u}
μ
10^5
10^4
10^3
M (GeV)
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)**


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, $\mathbf{m_{3/2}}$ **= 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)
$\tan\beta$
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14



M3/2=100
M3/2=50
M3/2=25
This shows effect of doubling or halving gravitino mass, ΔMh ≈ 1.5 GeV
Mh (GeV)
tan β
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14

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$)_{data}$ /$(\sigma$ x BR summed$)_{SM}$ = 1.02±0.11 (Ellis and Sun)

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

TURN TO GAUGINO MASSES

❑ 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 for CC 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 minimum 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

$$M_{1/2} \sim K_{mn}\, F_m\, \partial_n\, \mathbf{f}_{\mathbf{SM}}$$

-- Size of suppression calculated by setting CC=0 at potential minimum

-- probably gauginos suppressed in heterotic, IIB but differently?

-- nightmare scenario not present in M-theory

The theory implies that the tree level suppression was by a factor

P_{eff} $=P \ln(Q A_1 \phi_0^2/P A_2)$, where Q, P, A_1, A_2 are from the superpotential, and ϕ_0^2 is the meson condensate vacuum value – then **the value of P_{eff} is fixed by setting the potential at its minimum to be zero**

Numerically $P_{eff} \approx 62$ gives vanishing CC, and that suppresses the tree level gaugino masses – end up similar in size to the anomaly mediation one-loop contribution

Then the **high scale** gaugino masses are

$M_1 \approx (-.03(1+\varepsilon) + 0.30\alpha_{GUT})M_{3/2}$, $\alpha_{GUT} \approx 1/25$ from V_3

$M_2 \approx (-.03(1+\varepsilon) + 0.52\alpha_{GUT})M_{3/2}$,

$M_3 \approx (-.03(1+\varepsilon) + 0.58\alpha_{GUT})M_{3/2}$,

ε due to KK threshold corrections, Kahler corrections, etc – hard to calculate – combine into an effective parameter

- Recall non-thermal cosmological history, LSP's washed out by large entropy, but regenerated by moduli decay

- Need wino-like LSP to have large enough annihilation rate to not overclose the universe (apparently no RPV LSP decay in M-theory)

- For ε in wino-LSP region ($M_2 < M_1$) have **upper limit on gluino mass!**

- Higgs mass ok for $M_{3/2} \lesssim 90$ TeV → 800GeV $\lesssim M_{\tilde{g}} \lesssim 1.5$ TeV

○ Best value of M_h gives $M_{\tilde{g}} \lesssim 1$ TeV

Have usual $W_{RPV} = \lambda LLE^c + \lambda' U^c D^c D^c + \lambda'' QLD^c + \kappa LH_u$

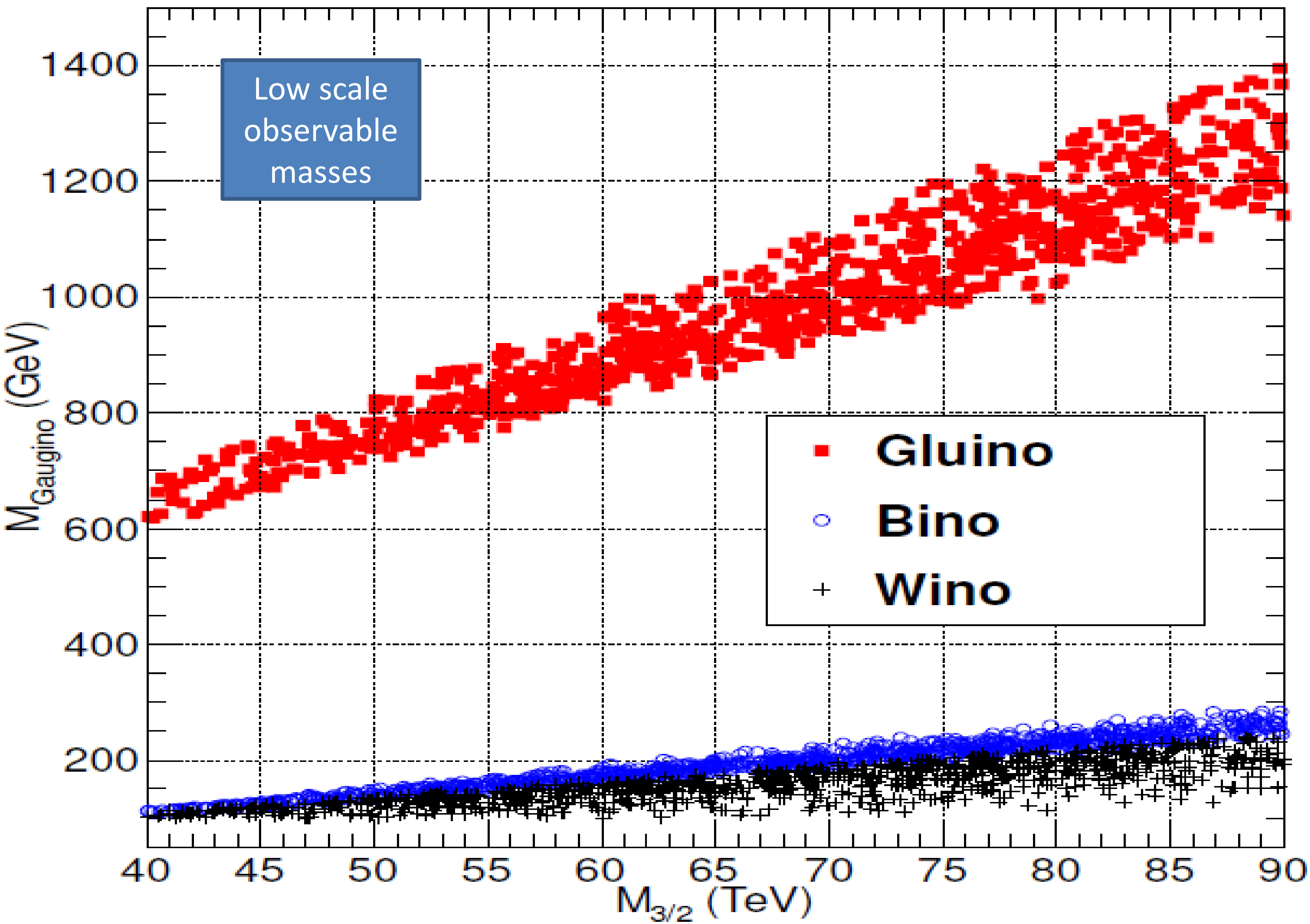
- μ, doublet-triplet splitting in M-theory solved via Witten discrete matter and moduli symmetry plus Wilson line SU(5) breaking
- Moduli stabilization breaks discrete symmetry, generates $\mu \neq 0$, $\mu \lesssim M_{3/2}$ <moduli>/M_{pl} , does not destabilize D-T splitting

No leftover Z_M -- then generates bilinear term with coefficient ~ $\mu \rightarrow \nu$ masses too large by $\gtrsim 10^4$, or worse, effects – cannot rotate away

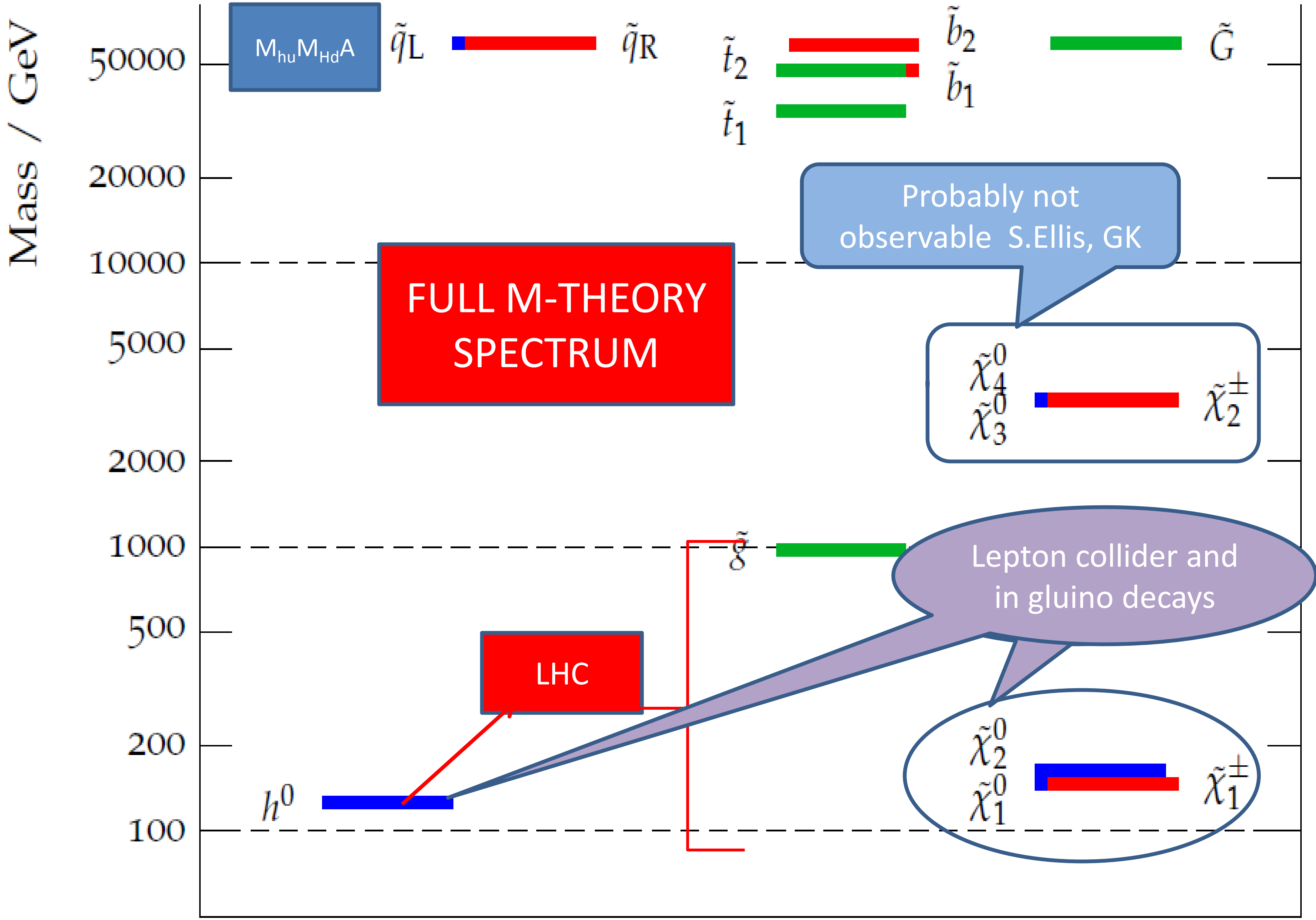
Leftover $Z_M \rightarrow$ "R-Parity", stable LSP

- Consistency with Wilson line action gives conditions on Z_N , Z_M charges
- Solutions with REWSB, Z_N ,Z_M etc exist

[Acharya, Kane, Kumar, Lu, Zheng, in preparation]

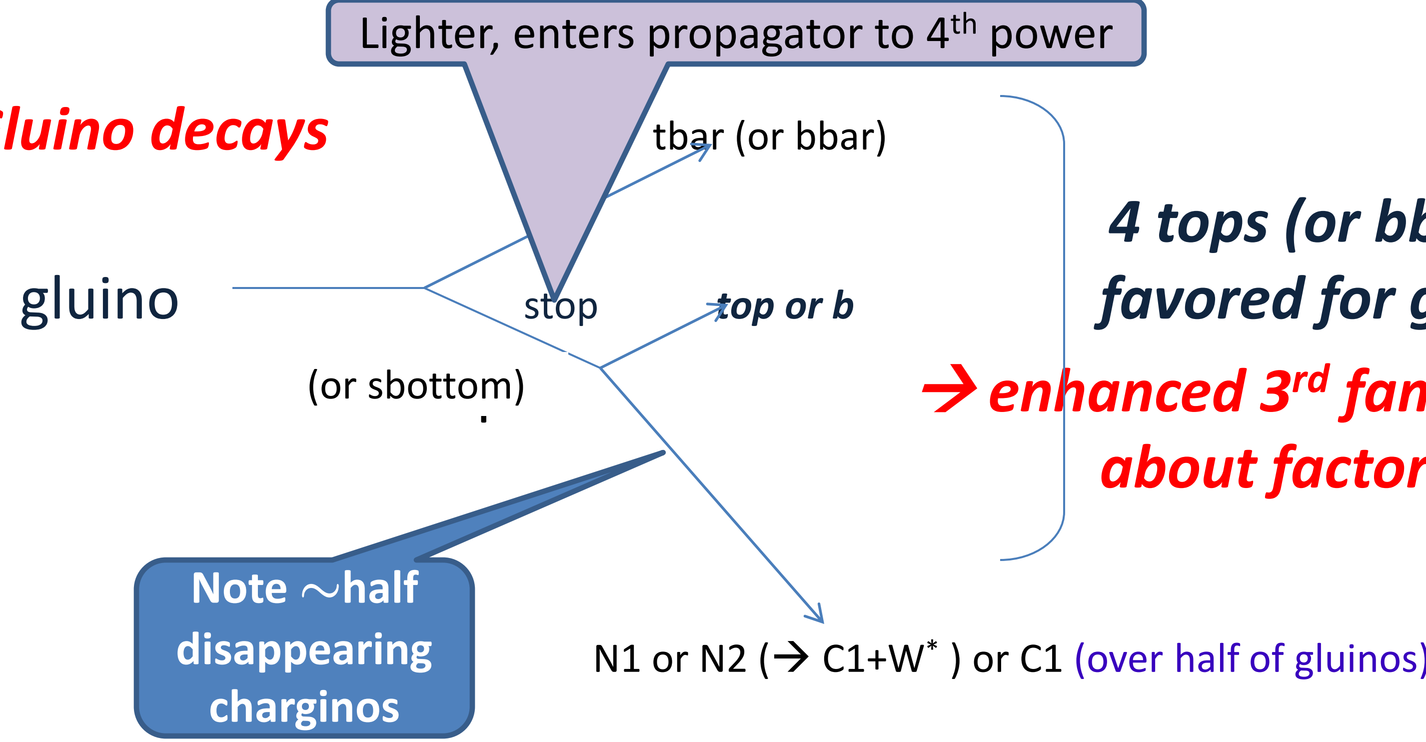


Low scale observable masses
Gluino
Bino
Wino
$M_{Gaugino}$ (GeV)
$M_{3/2}$ (TeV)
1400
1200
1000
800
600
400
200
40
45
50
55
60
65
70
75
80
85
90



Mass / GeV
50000
20000
10000
5000
2000
1000
500
200
100
$M_{hu}M_{Hd}A$
$\tilde{q}L$
$\tilde{q}R$
$\tilde{t}_2$
$\tilde{t}_1$
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{G}$
Probably not observable S.Ellis, GK
FULL M-THEORY SPECTRUM
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{g}$
Lepton collider and in gluino decays
LHC
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
h^0

Gluino decays



4 tops (or bbbb, or btbt) favored for gluino pair!

→ enhanced 3rd family decays, about factor 2

M theory 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 of order one TeV

Papers LHC14,0901.3367; LHC7, 1106.1963

Realistic Branching Fraction

$$\left.\begin{array}{r} m_{3/2} = 50\,\mathrm{TeV} \\ M_{\mathrm{gluino}} = 900\,\mathrm{GeV} \\ M_{\mathrm{LSP}} = 145\,\mathrm{GeV} \end{array}\right\}$$

$$BR(\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0) \approx 0.15$$

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

$$BR(\tilde{g} \rightarrow b\,\bar{b}\,\tilde{\chi}^0_1) \approx 0.08$$

$$\tilde{\chi}^0_2 \approx 0.1 \qquad \tilde{\chi}^0_1 \approx 0.05$$

So **BR for each gluino to third family ≈ ½,**

BR (1^{st} + 2^{nd} families ≈ ½) per gluino

$$\tilde{\chi}^0_2 \rightarrow W^{\pm}\,\tilde{\chi}^{\mp}_1$$

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

→ 3 layers

GK, Lu, Zheng 1202.4448

See Moroi et al for pair production of disappearing charginos

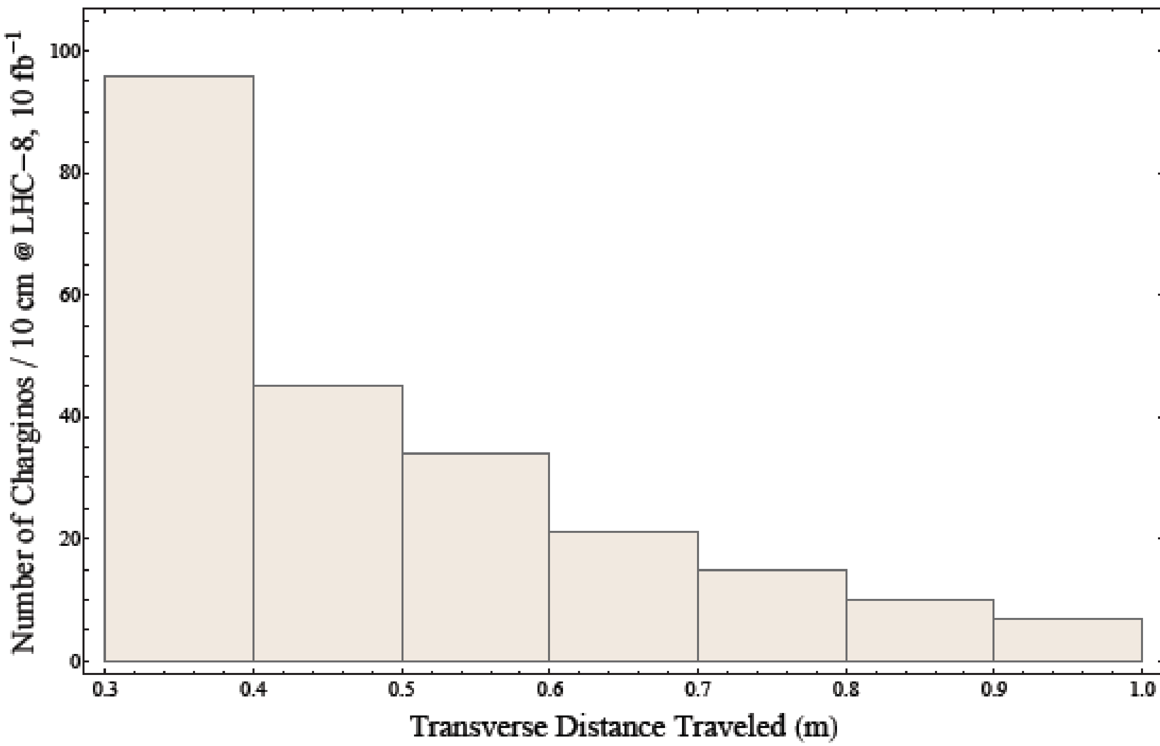


FIG. 1: Charged Winos resulting from gluino pair production, binned as a function of transverse distance traveled from the beam line. These results correspond to 10 fb^{-1} of LHC-8 data ($\sigma_{\tilde{g}\tilde{g}} \sim 235$ fb), with $m_{\tilde{g}} = 750$ GeV, $m_{\widetilde{W}} = 150$ GeV. For graphical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

LITTLE HIERARCHY PROBLEM – solved in compactified theory?

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

Compactified M theory → $A_0 > M_0$

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

A_0 **>** $M_0 = M_{3/2} \approx 50$ TeV

(leading order $A_0 = 1.49 M_0$)

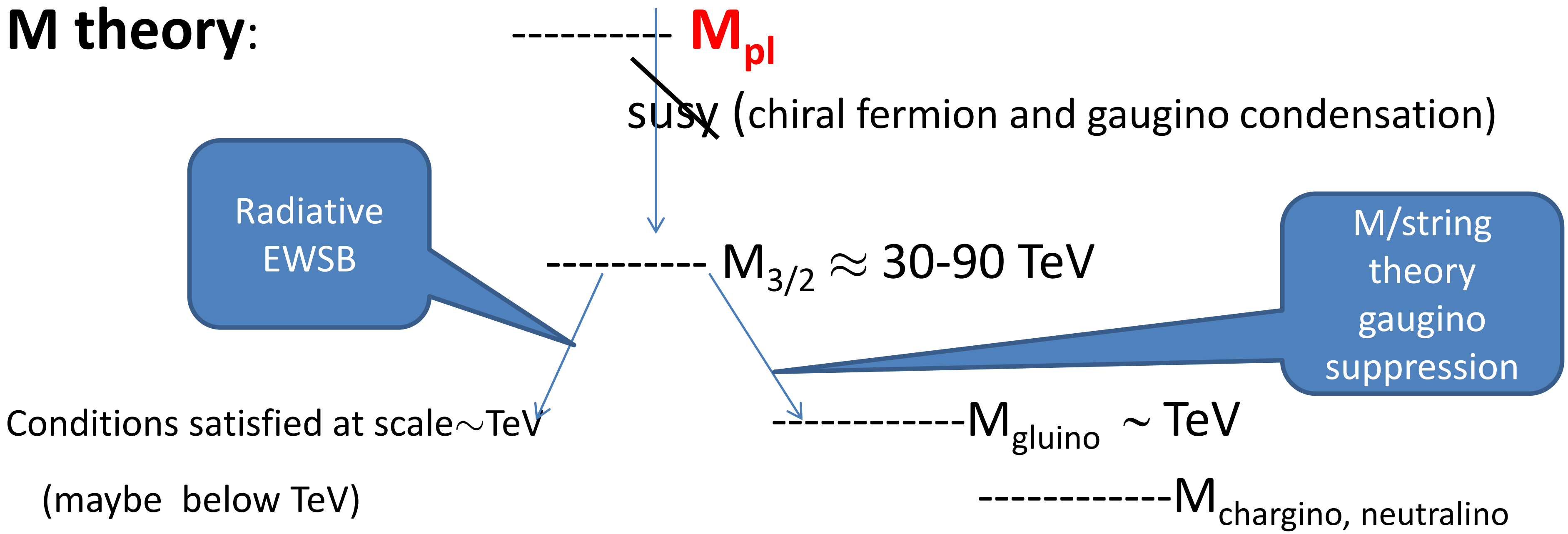
f_M , f_A calculated from SM inputs, both about 0.12-0.13

So stringy prediction is a decrease ~ 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

Naturalness? Fine-tuning? Little hierarchy?

M theory:



Work in progress – FT, little hierarchy may be solved dynamically in the theory – theories need not be naively natural

➢ String/M theory crucial for *deriving Higgs* 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

Final remarks: Phenomenological

- ***Higgs data looks like data from compactified constrained string theory with stabilized moduli should look! – 126 GeV not unnatural or FT! – SM-like Higgs not surprising!***

- **Higgs looks like a fundamental particle – normal susy h in decoupling region – not weird or fine-tuned**

- ***Higgs BRs near SM ones seems unavoidable prediction***

- **Compactified M/string theory, squarks, sleptons ~50 (30-90) TeV**

- **Gluinos ~ 1 TeV (< 1.5 TeV) – 3rd family about half of gluino decays, sum of 1st + 2nd about half**

Final remarks: Theoretical

- ***Compactified M/string theory maturing into a useful predictive framework that relates many explanations, tests***

- **M theory compactified on G_2 manifold looks like a good candidate to continue to explore for describing our string vacuum – explains many phenomena, predicts some -- some features generic for other corners of string theory too**

- **μ, $\tan\beta$ in theory, not free parameters – no free parameters!**

“if people don’t want to come to the ballpark nobody’s going to stop them”

Yogi Berra

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

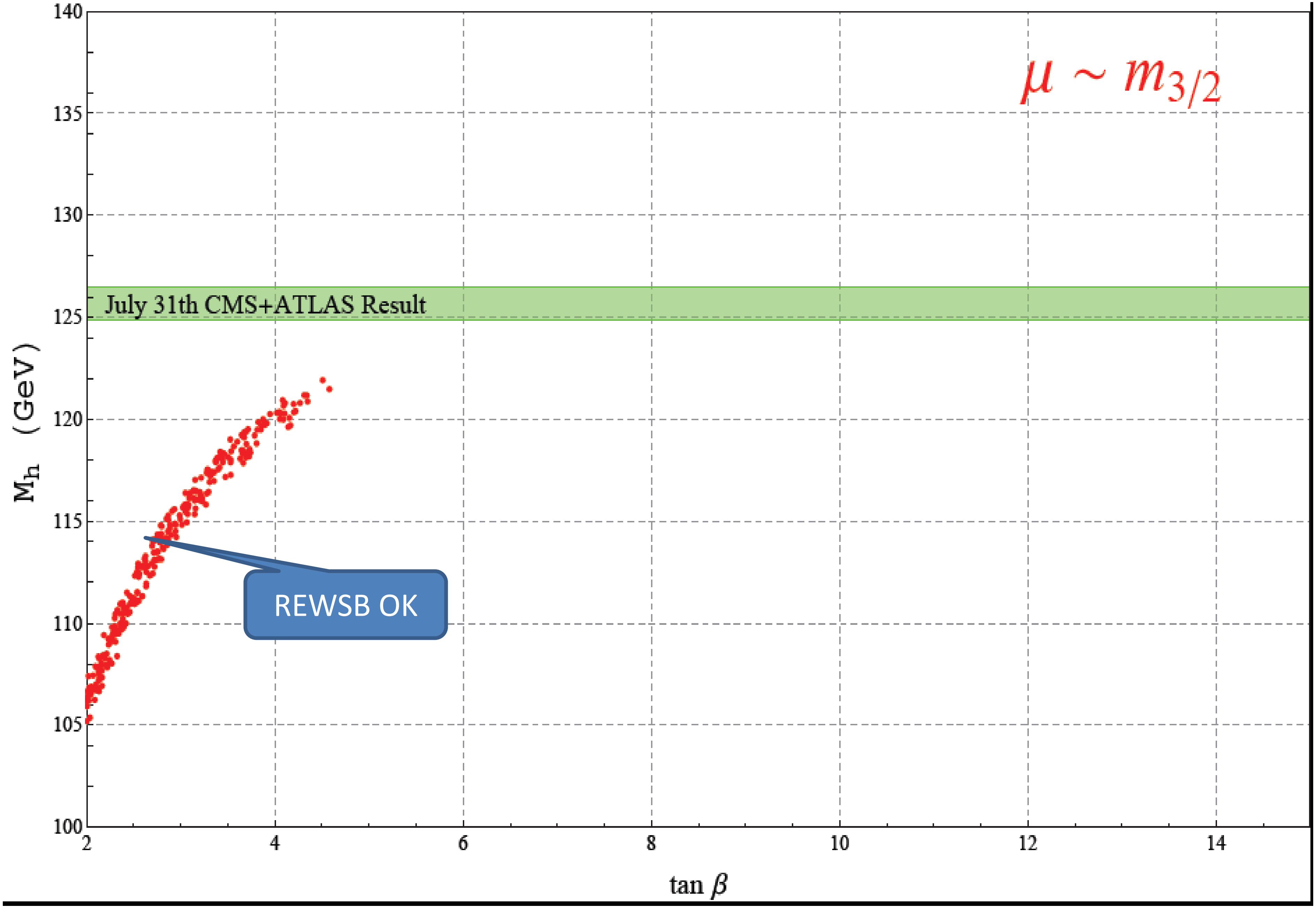
- Can find models extending MSSM that give M_h same value as MSSM – Some U(1) extensions with no extra matter do not change mass value or BR

-- SO(10) with RHν, no other extra matter gives 126, E6 under study

-- 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 $\sim$ few %**

→ probably strong prediction that BR($\gamma\gamma$), ZZ,WW,bb,$\tau\tau$ have SM value,



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

For one-loop RGE running get the **EW scale gaugino masses**:

$$m_1 \approx (-0.009 + 0.014\,\varepsilon\,)M_{3/2},$$
$$m_2 \approx (-0.010 + 0.027\,\varepsilon\,)M_{3/2},$$
$$m_3 \approx (-0.028 + 0.097\,\varepsilon\,)M_{3/2},$$

(numbers to illustrate – for the graphs we use full 2-3 loop running and corrections, from SoftSusy and Spheno)

GENERIC PREDICTIONS from compactified M theories

- ***Squarks, sleptons 30-60 TeV***, trilinears > scalars, no R symmetry
- Non thermal cosmological history
- Low scale gauge mediation not significant source of supersymmetry breaking since gravitino mass of order 50 TeV
- $B_s \rightarrow \mu\mu$ within 1-2% of SM
- $(g\text{-}s)_\mu$ within 5-10% of SM
- $\tan\beta \gtrsim 10$
- ***M_h =126±2***, susy higgs sector decoupling so H, $A, H^\pm > 30$ TeV
- No invisible h decays
- ***Gluino $\lesssim$ 1 TeV, gluino decays flavor violating, 3rd family larger***
- EDMe $\approx 10^{-30}$
- LSP wino-like but μ small so mixing
- Relic density of LSPs, axions both order 1
- $\sigma_{SI} \sim 10^{-46}$