Compactified String/M-theory prediction of the Higgs boson mass and properties

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Program since 2006 with ***Bobby Acharya***, Piyush Kumar, Ran Lu, Eric Kuflik, Konstantin Bobkov, Bob Zheng, Scott Watson, Jing Shao…

Recent Review "**Constrained Compactified string/M-theories** – Higgs bosons, LHC, and more particle physics predictions", Acharya, Kane, Kumar arXiv:1204.2795

Here focus on Higgs boson prediction. See Acharya talk on compactification and overview, Kumar on DM, Lu on LHC

Philosophy

Look for generic solutions of **compactified** string/M theory with TeV scale physics emerging, no cosmological or phenomenological problems, Higgs mechanism (Radiative Electroweak Symmetry Breaking), etc – find many

Calculate M_h / M_Z for those solutions

(At end comment on calculation of M_h , not ratio)

Remarkably, compactified string/M-theory predicts (ahead of time – Aug 2011) the **Higgs boson mass** ($M_h/M_Z \rightarrow M_h \approx 125$ GeV) – focus on M-theory, but most results more generic -- theory, not model

- **Make some good** assumptions ***not closely related to Higgs sector***
  - Compactify M-theory on G_2 manifold in fluxless sector
  - Assume gauge group below compactification is MSSM -- can calculate for other gauge groups and find out if results change
  - Assume Hubble parameter H at end of inflation larger than $M_{3/2}$
  - Assume supergravity field theory after compactification
  - Assume top quark with yukawa coupling ~ 1 (true)
  - Include μ following Witten approach
  - Expected Kahler potential, gauge kinetic function, ok
- **No free parameters**, all calculated in compactified string/M theory
  - mild sensitivity to gravitino mass, $\delta M_{3/2} = 50$ TeV $\rightarrow \delta M_h \approx 1.5$ GeV
  - mild sensitivity to $\tan\beta$
  - $\tan\beta$ and μ related by EWSB, sensitive to size of μ

Why is M_h light?

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

Typical gauge groups → condensation $\sim 10^{-4-5}$ M_{planck} , cubed in superpotential, so $M_{3/2} \sim$ 50-100 TeV (top down)

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

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

Gaugino masses suppressed since meson F terms dominate but don't contribute to gaugino masses

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

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

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

Derive generic relation between lightest moduli mass and gravitino mass – basically that the gravitino is not lighter than lightest moduli – assumes supersymmetry breaking is involved in stabilizing at least one moduli (which generically happens, could not show it wasn't)

[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 $M_{3/2}$

Can show for pos def mass matrix that smallest eigenvalue of full matrix is smaller than any eigenvalue of (diagonal) submatrices

$M_{3/2} > M_{mod} \gtrsim 30$ TeV from BBN

Higgs sector

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

If Z boson gets mass from Higgs mechanism can show $M_h \lesssim 2M_Z$ if theory perturbative up to $\sim$ unification scale, $M_h \lesssim 140$ GeV for MSSM

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

$$V = (|\mu|^2 + m^2_{H_u})|H^0_u|^2 + (|\mu|^2 + m^2_{H_d})|H^0_d|^2 - (b\, H^0_u H^0_d + \mathrm{c.c.}) \quad + \mathrm{D\ terms}$$

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

Need negative eigenvalue for EWSB – **expect no EWSB at high scales** -- as M^2_{Hu} runs down, get EWSB, Higgs vevs

$\tan\beta = v_u/v_d$ only meaningful after EWSB, doesn't exist at high scales – $v^2_u + v^2_d \sim M^2_W$, input W mass value

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

Compactified string/M theory → $A^2_0 \gtrsim M^2_0$

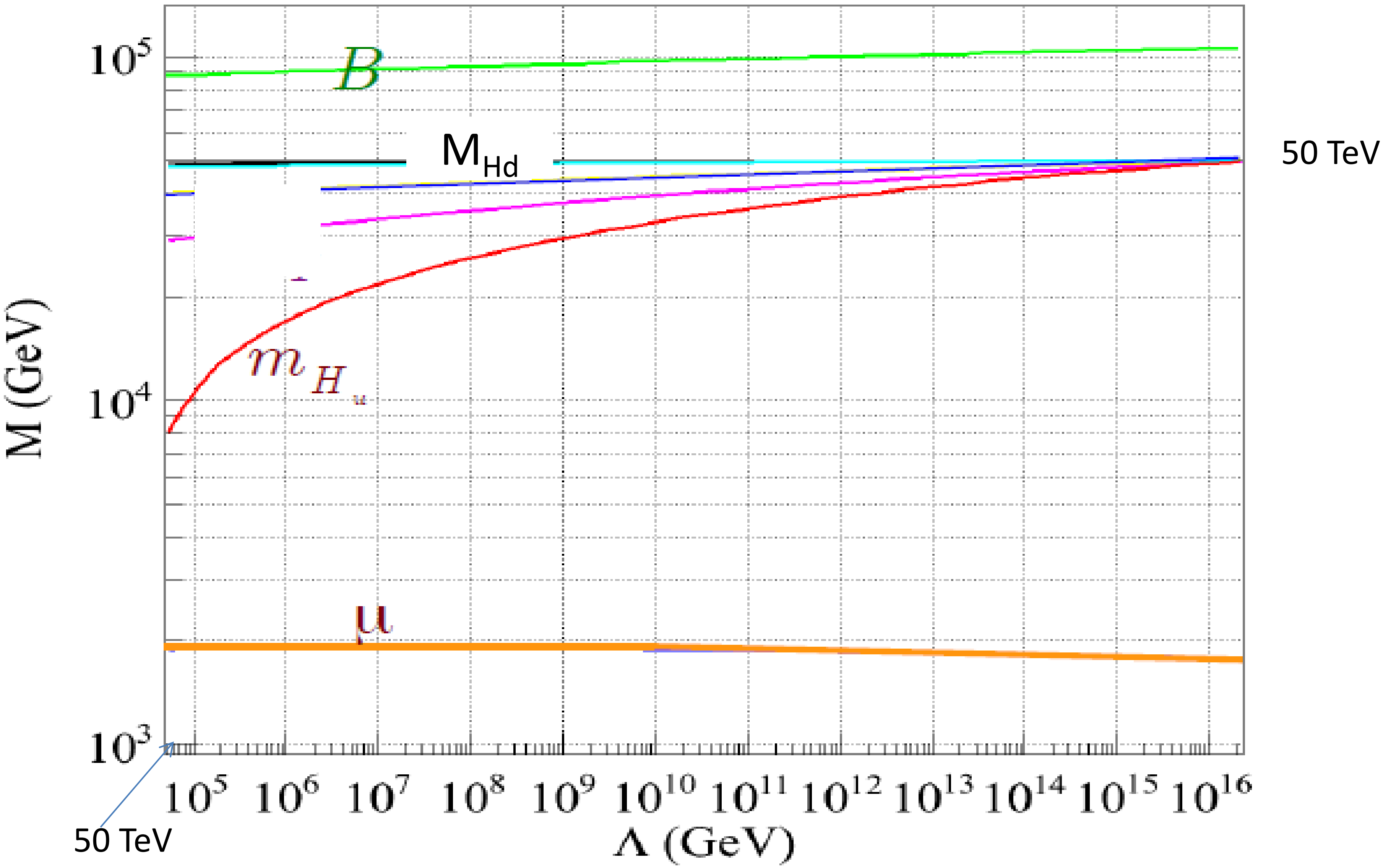
$$\mathbf{M^2_{Hu}\,(t) \approx f_M\,(t)\, M^2_0 - f_A\,(t)\, A^2_0}$$

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

f_M , f_A calculated from SM inputs, both about 0.1

So stringy prediction is a decrease $\sim 10^{-2}$ in M^2_{Hu} – if trilinears not large get order of magnitude less decrease in M^2_{Hu}

Greatly reduces “little hierarchy problem”



B
M_Hd
50 TeV
m_Hu
μ
M (GeV)
10^5
10^4
10^3
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)
50 TeV

THEORY AT HIGH SCALE, 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
- $\tan\beta$ calculable in principle but not yet accurately -- constrained since related to B, μ via supergravity and EWSB – maintain $B \approx 2M_{3/2}$ so μ not in superpotential
- 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)

Basic argument:

- **Assume** supergravity in field theory limit – then scalars from soft breaking supersymmetry Lagrangian all have $M_{scalars} \sim M_{3/2}$
- So squarks $\gtrsim$ 30 TeV, not observable at LHC!
- **Assume** MSSM below compactification scale for initial calculation – no free parameters, soft Lagrangian fully predicted
- Scalars include Higgs sector soft terms M^2_{Hu} , M^2_{Hd}
- **Ask for solutions that have a higgs mechanism (higgs vevs nonzero) after RGE running, radiative EWSB – find many -- don't care about others, not our world**
- $15 \gtrsim \tan\beta \gtrsim 5$ from supergravity consistency, $\tan\beta \approx 10$
- Then supersymmetric higgs sector a "decoupling" one, mass eigenstates H, A, $H^{\pm}$ also $\gtrsim$ 30 TeV , h light, and can calculate M_h / M_Z
- Predict M_h = 126 GeV for $\tan\beta \gtrsim 6$
- Calculations predict h should behave like SM higgs – deviations only from chargino loop for $h \to \gamma\gamma$, at most a few per cent

EWSB, μ, tanβ, naturalness

Usual EWSB conditions (tanβ>1) [ensure higgs potential minimum away from origin]:

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

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

M^2_{Hu} runs to be small, M^2_{Hd} and B don't run much, μ suppressed, $\sin 2\beta \approx 2/\tan\beta$, $B \approx 2M_{3/2}$

→ $\tan\beta \approx M^2_{Hd}/B\mu \approx M^2_{3/2}/B\mu$ → **$\mu\tan\beta \approx M_{3/2}/2$**

e.g. $M_{3/2}$ = 60 TeV, μ = 3 TeV, **tanβ = 10**, some uncertainty so examine $5 \lesssim \tan\beta \lesssim 15$

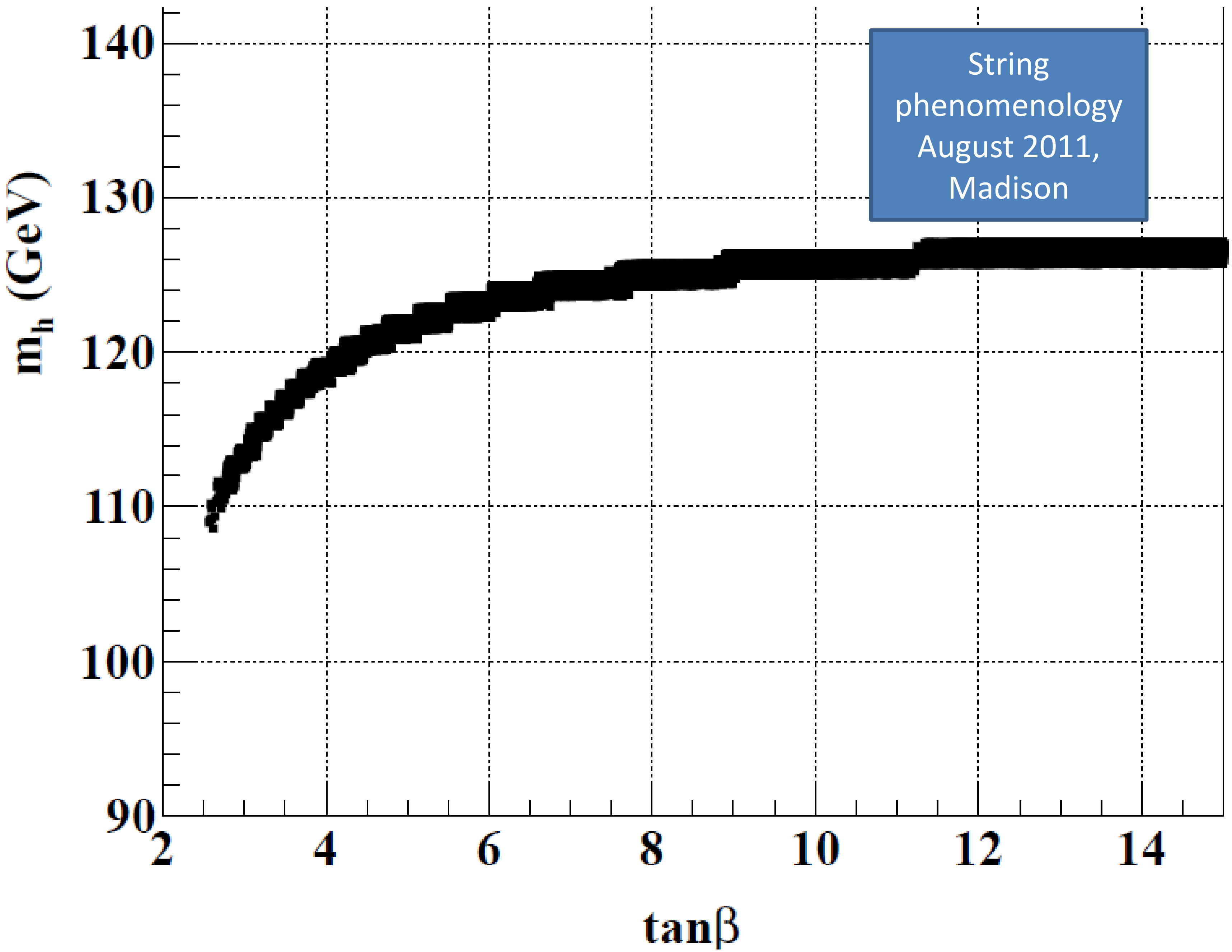
Including the μ parameter in string theory

arXiv:1102.0556, Acharya, Kane, Kuflik, Lu

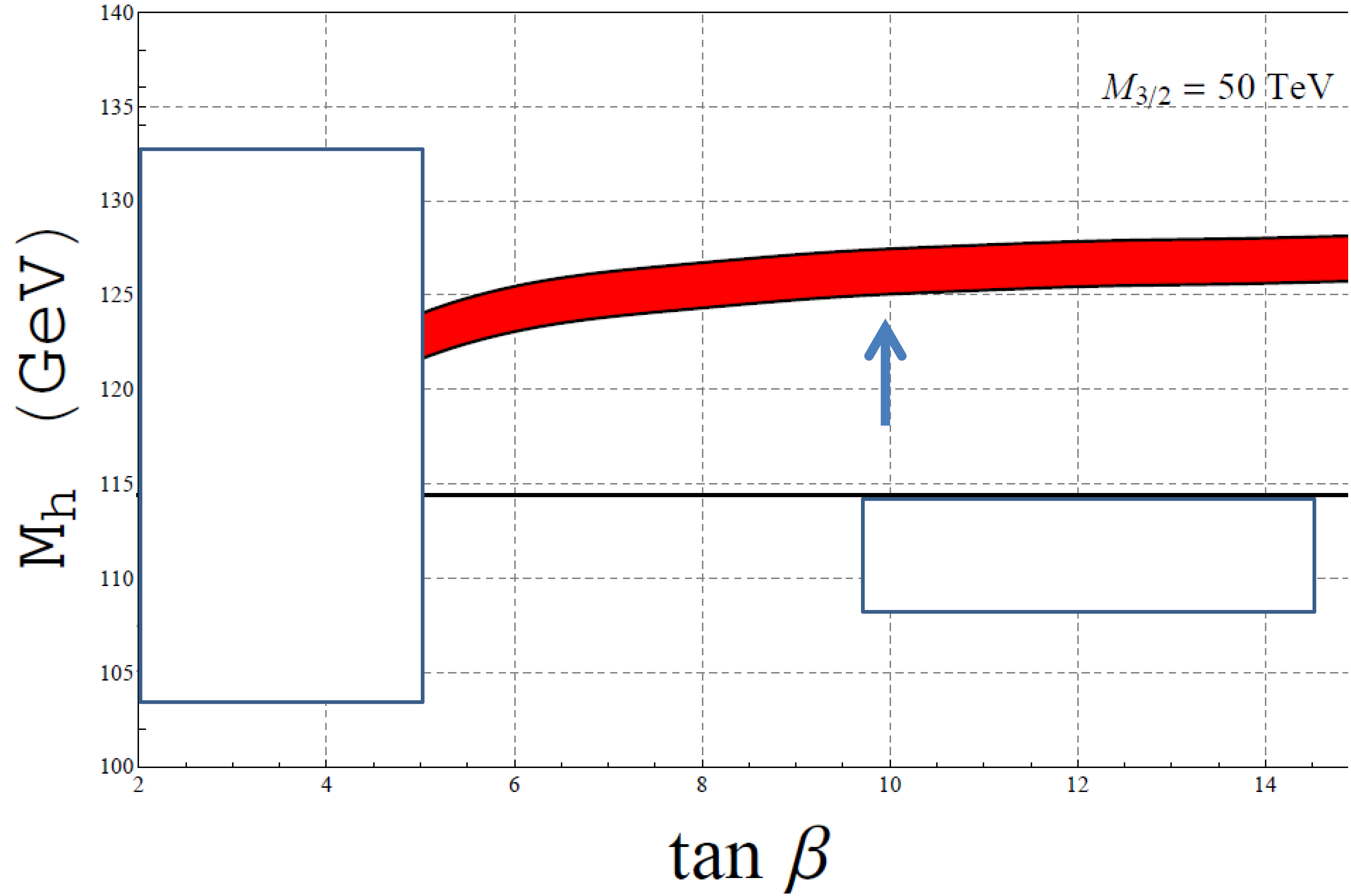
- Normally μ and tanβ treated as parameters, constrained to get EWSB
- Ultimately want to derive them from first principles
- If μ in W then it should be of order string scale
- Need symmetry to set μ=0
- Witten, hep-ph/0201018 – introduced discrete symmetry for G_2 compactification, closely connected to doublet-triplet splitting problem, proton lifetime, R-parity
- Witten did not break discrete symmetry so $\mu \equiv 0$ – when moduli are stabilized the effects generally not invariant so the symmetry is broken

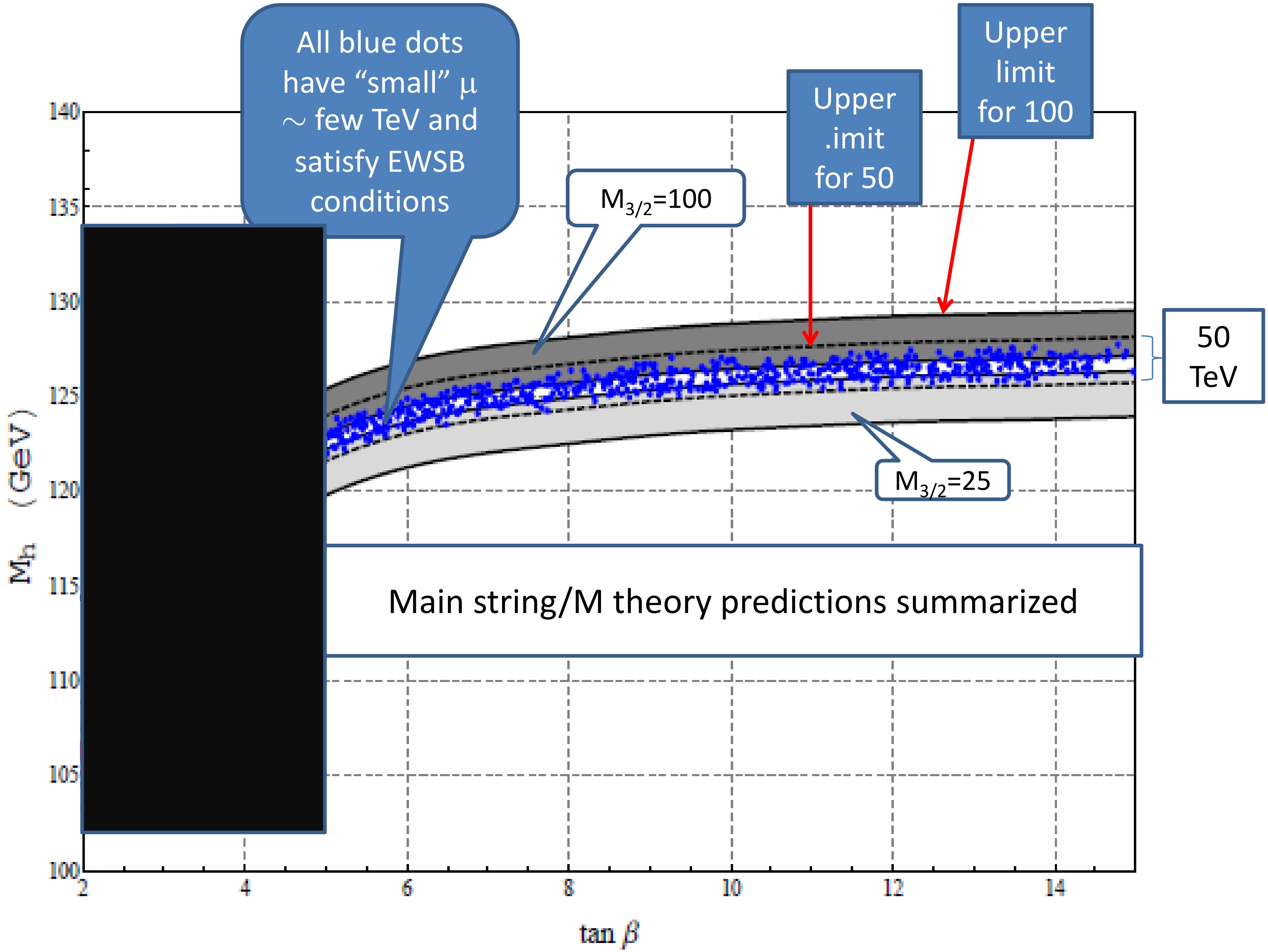
Size of μ

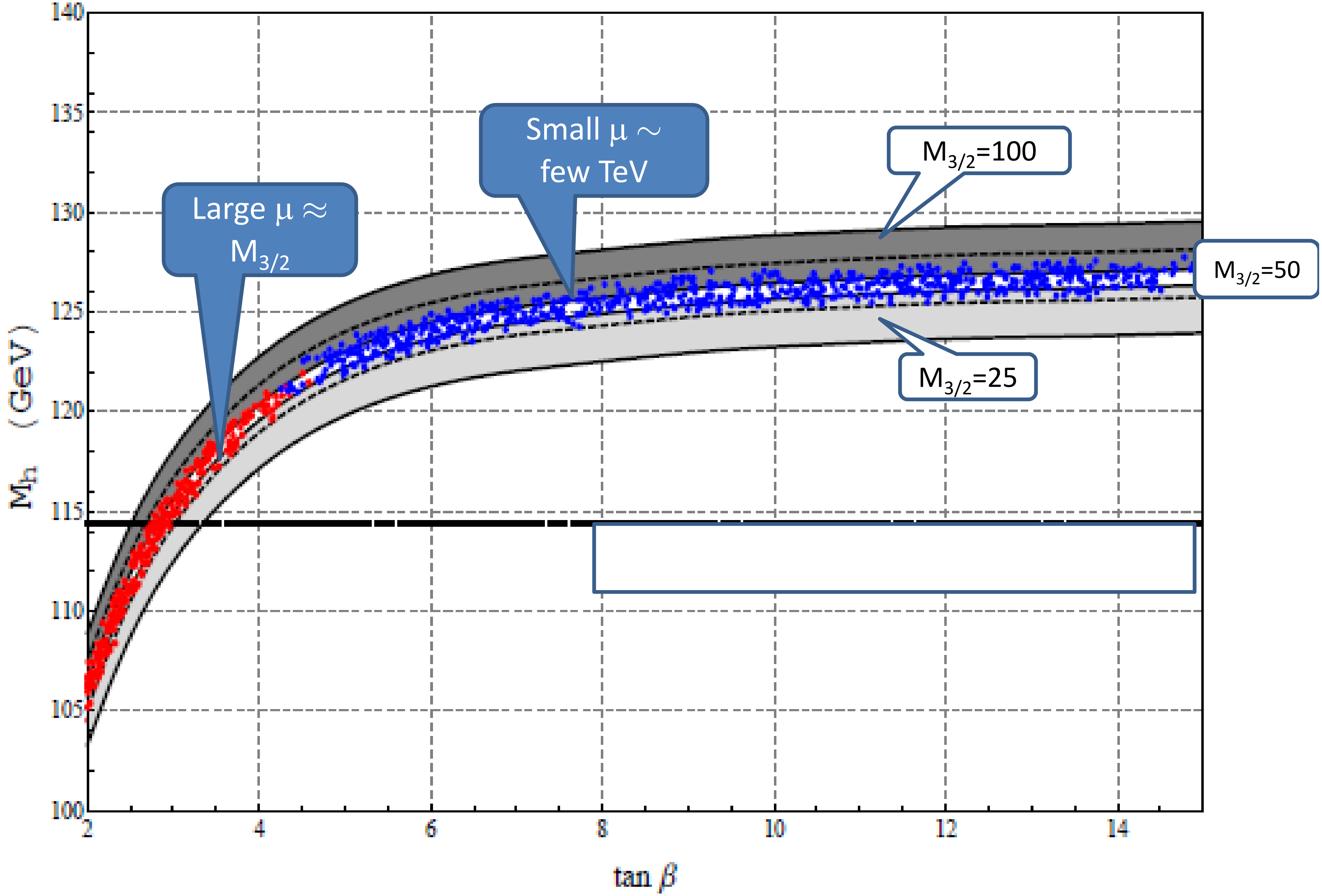
- μ proportional to $M_{3/2}$ since $\mu \to 0$ if susy unbroken
- Also μ proportional to moduli vev since $\mu \to 0$ if moduli not stabilized
- Stabilization led to moduli vev/$M_{pl} \lesssim 0.1$
- So finally expect $\mu \lesssim 0.1\, M_{3/2}$
- Significantly affects M_h , also direct detection



String phenomenology August 2011, Madison
m_h (GeV)
140
130
120
110
100
90
2
4
6
8
10
12
14
tanβ


$M_{3/2}$ = 50 TeV
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14
M_h (GeV)
tan β


All blue dots have "small" μ ~ few TeV and satisfy EWSB conditions
$M_{3/2}$=100
Upper .imit for 50
Upper limit for 100
50 TeV
$M_{3/2}$=25
Main string/M theory predictions summarized
M_h (GeV)
tan β
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14



Small μ ~ few TeV
Large μ ≈ M3/2
M3/2=100
M3/2=50
M3/2=25
Mh (GeV)
tan β
140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14

MSSM assumption

- Can find models extending MSSM that give M_h same value as MSSM

- Can find models generically in conflict with extending MSSM (may not conflict at specific points)

Implications

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

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

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

-- Must derive soft terms, otherwise could choose anything – e.g. large trilinears crucial, people in past guessed (wrong) – string theory gave prediction

-- Must have μ embedded in string theory

-- Must exhibit string solutions with EWSB

-- must have effectively no parameters

- Surprisingly, little interest from string theorists

Compactified string/M theory

- Derive solution to large hierarchy problem
- Generic solutions with EWSB
- Gauginos suppressed dynamically, dominant F term does not contribute
- Trilinears $\approx M_{3/2}$
- Little hierarchy mostly solved
- Scalars $\approx M_{3/2}$, not so heavy $\approx$ 50 TeV
- Gluino lifetime $\lesssim 10^{-19}$ sec, decay in beam pipe
- $M_h \approx 125$ GeV

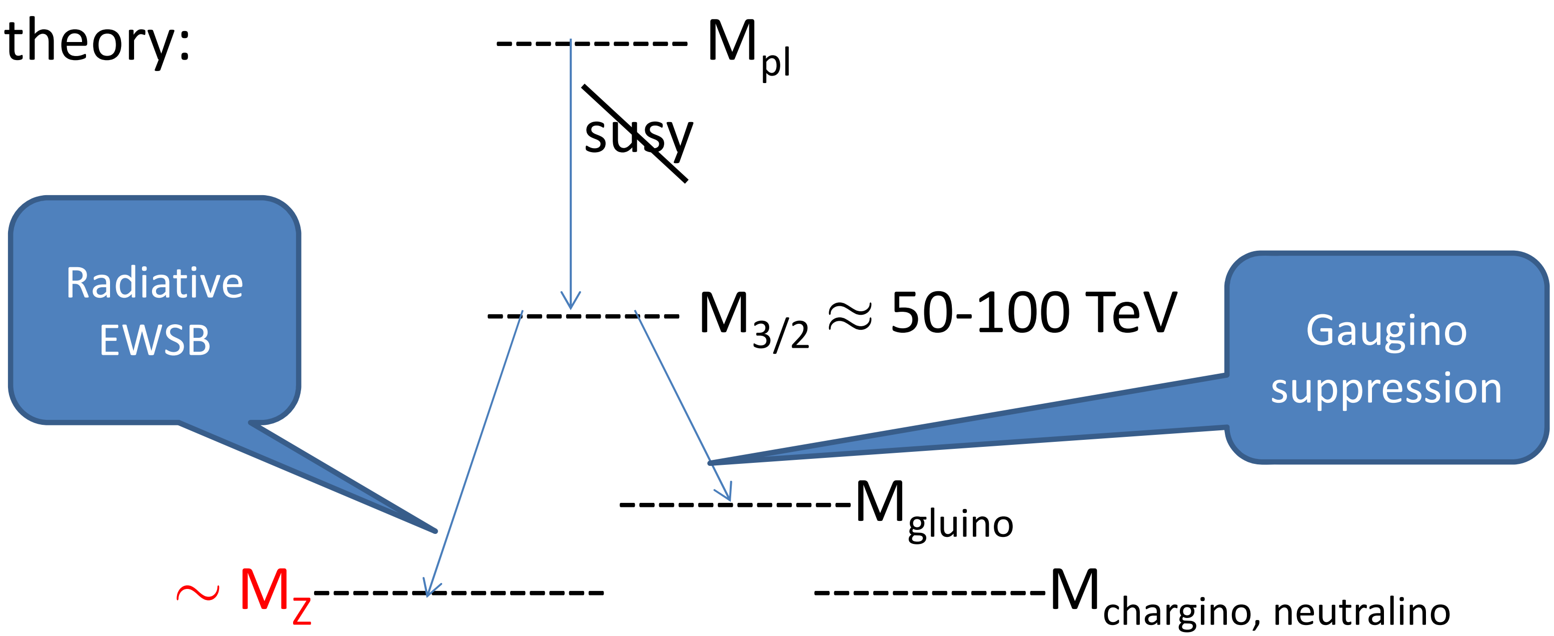
Split susy (etc) models

- Assume no solution to large hierarchy problem
- EWSB assumed, not derived
- Gauginos suppressed by assumed R-symmetry, suppression arbitrary
- Trilinears suppressed
- No solution to little hierarchy
- Scalars assumed very heavy, whatever you want, e.g. 10^{10} GeV
- Long lived gluino, meters or more
- $M_h \neq 125$ GeV

Naturalness? Fine-tuning? Little hierarchy?

$M_h \approx 125$ GeV needs $M_{stop} \sim 25$ GeV – unnatural?

String theory:



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

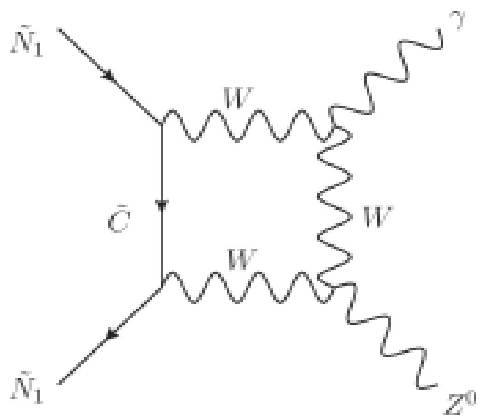
If calculated M_h directly instead of ratio to Z, would get larger number, e.g. $M_Z \approx$ a TeV

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

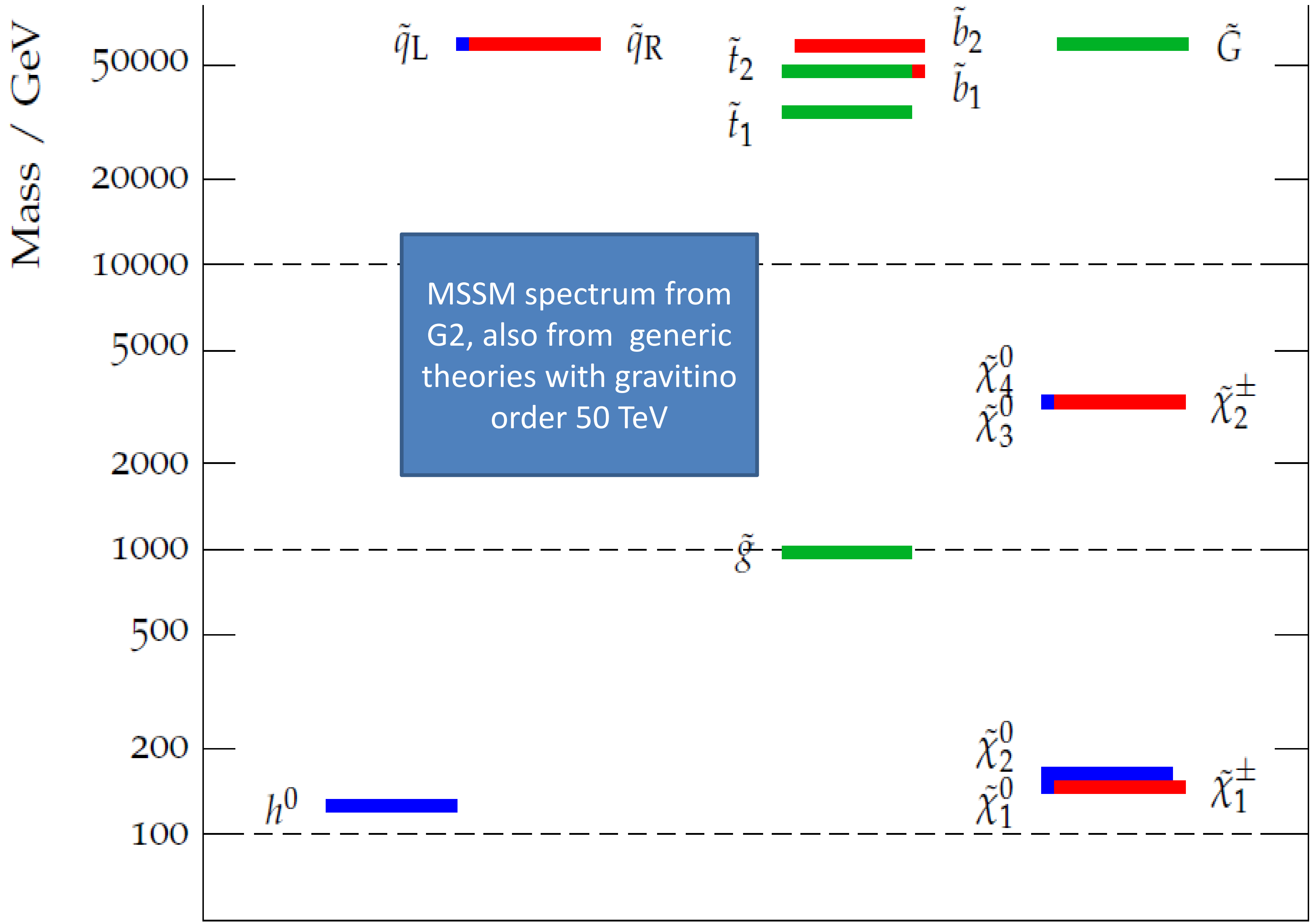
– they only vary one thing at a time, typically the allowed range is larger if several constraints are considered

Talk of Piyush Kumar – 130 GeV monoenergetic gamma from DM annihilation, non-thermal cosmological history → wino-like DM, LSP mass ≈ 144 GeV

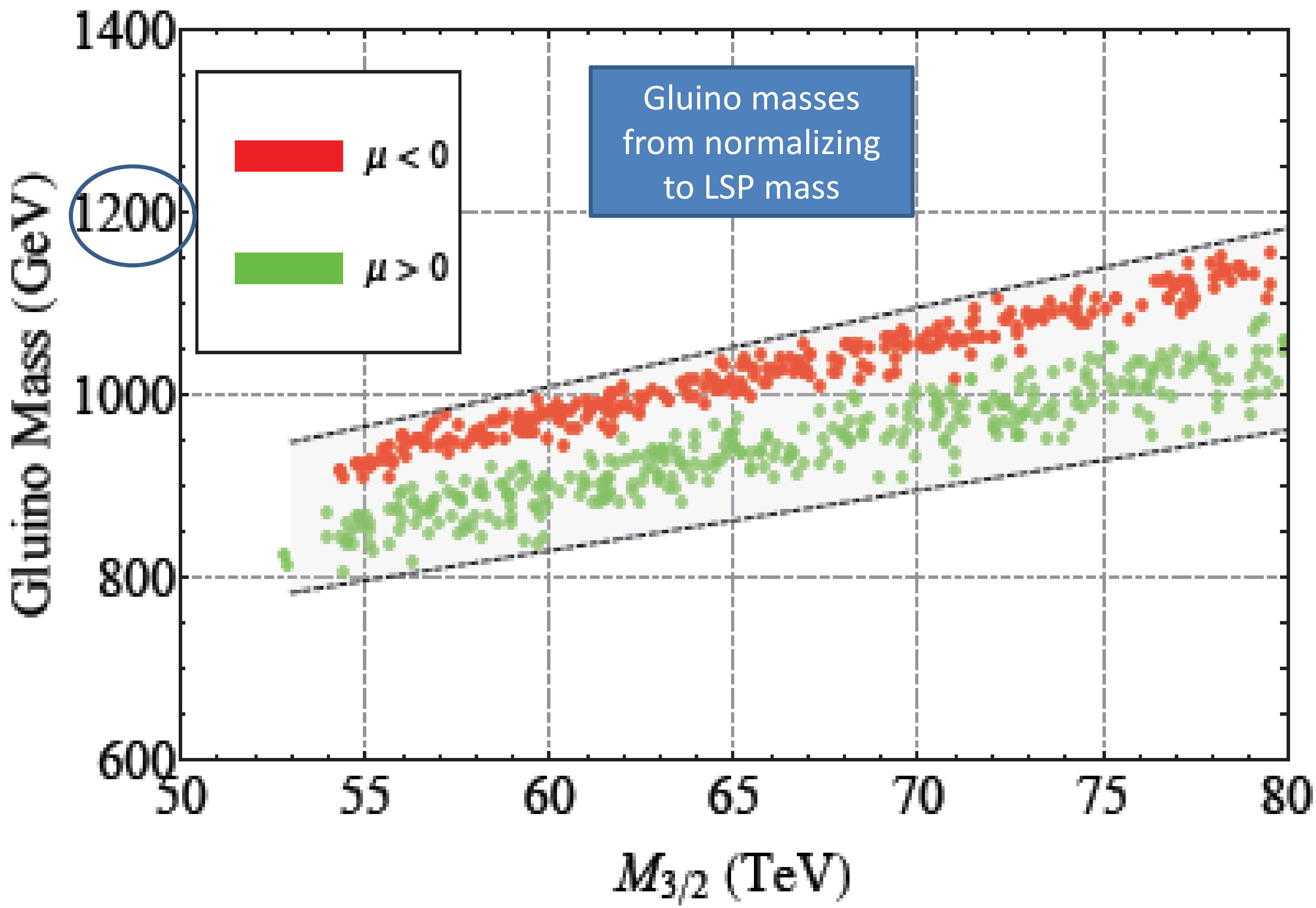


$$E_\gamma = m_{LSP}\left(1 - \frac{m_Z^2}{4 m_{LSP}^2}\right)$$

Talk of Ran Lu -- LHC

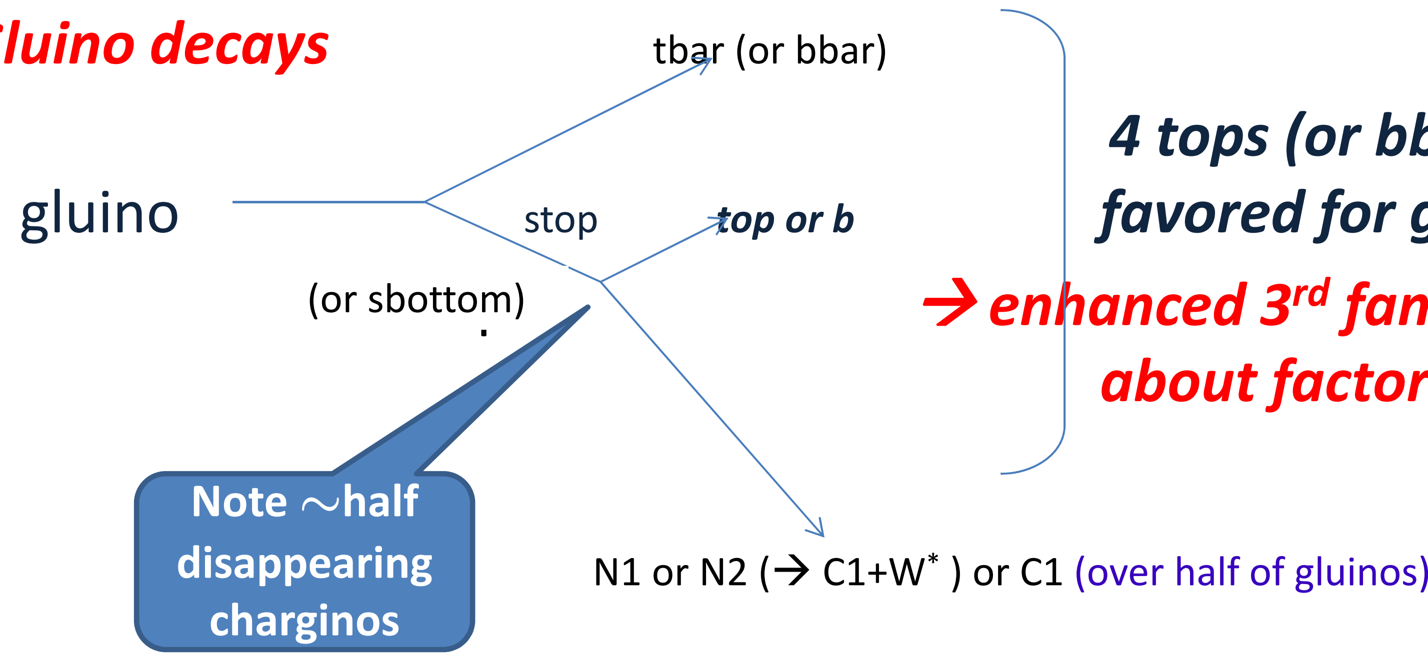


Mass / GeV
50000
20000
10000
5000
2000
1000
500
200
100
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{t}_2$
$\tilde{t}_1$
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{G}$
MSSM spectrum from G2, also from generic theories with gravitino order 50 TeV
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{g}$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



1400
1200
1000
800
600
Gluino Mass (GeV)
50
55
60
65
70
75
80
$M_{3/2}$ (TeV)
$\mu < 0$
$\mu > 0$
Gluino masses from normalizing to LSP mass

Gluino decays



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

→ enhanced 3rd family decays, about factor 2.5

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

Current limit for gluinos with enhanced 3rd family decays, heavy scalars, about 750 GeV from all published ATLAS, CMS data

LHC14,0901.3367; LHC7, 1106.1963

Realistic Branching Fraction

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

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

So **BR (third family) $\approx$ ½**, BR (1st + 2nd families $\approx$ ½), half of all gluino pairs have 4 b's

For wino-like LSP, chargino and LSP are nearly degenerate, so chargino → LSP plus very soft π^+ → **disappearing charginos** in $\sim$ half of events

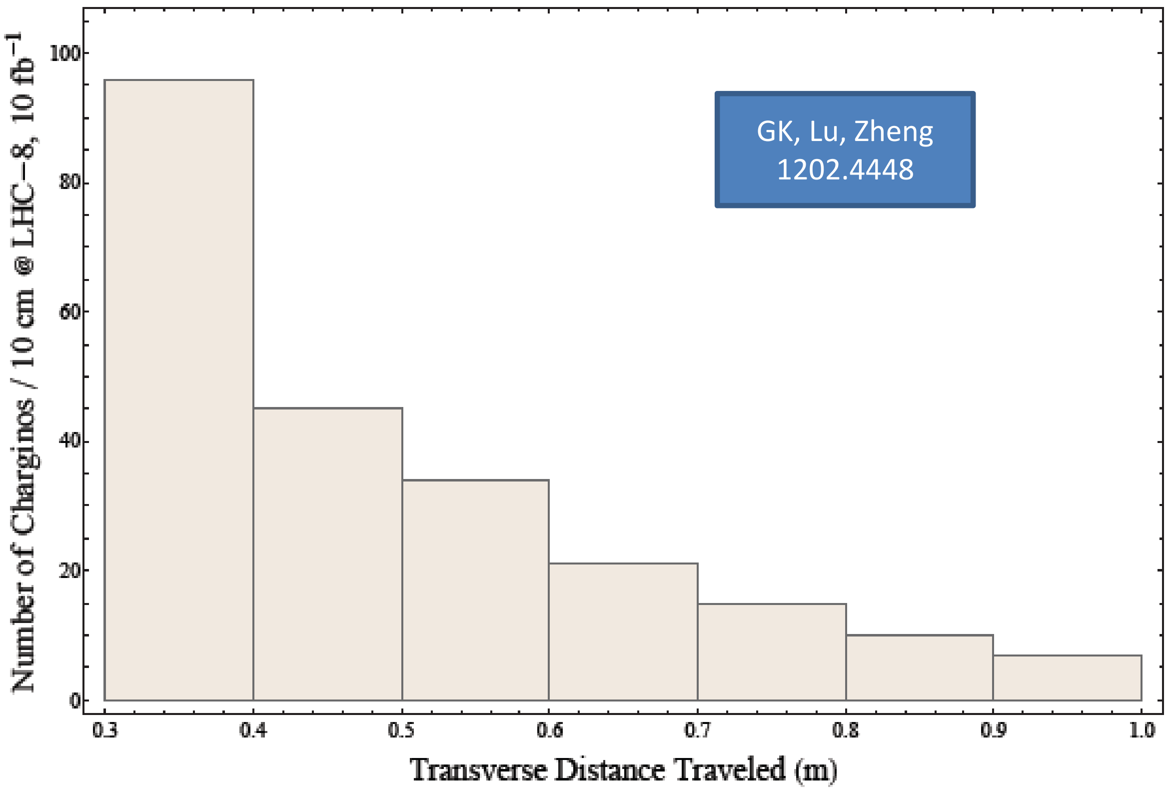


FIG. 1: Charged Winos resulting from gluino pair production, binned as a function of transverse distance traveled from the beam line. These results correspond to 10 fb^{-1} of LHC-8 data ($\sigma_{\tilde{g}\tilde{g}} \sim 235$ fb), with $m_{\tilde{g}} = 750$ GeV, $m_{\widetilde{W}} = 150$ GeV. For graphical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

Final remarks

- **Finally data – maybe now for both higgs, DM – gluinos in 2012**
- **Higgs, DM data looks like data from compactified constrained string theory with stabilized moduli should look!**
- **M theory compactified on G_2 manifold looks like a good candidate for describing our string vacuum – explains a number of phenomena and predicts some (assuming Higgs data, 130 GeV gamma real) – moduli stabilized, TeV scale, GCU, weak CPV, strong CPV, baryogenesis, ratio of B/DM, string axions, no flavor problem -- Many features generic.**