String theory and generic predictions for our world – superpartner masses, LHC signatures, dark matter, EWSB, cosmological history of universe, etc

Gordy Kane

String phenomenology, Madison, August 2011

String theory is hard – try to find ways to make contact with experiment by using general arguments and properties, and work around some difficult issues

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- Have good collaborators [***Acharya***, Bobkov, Kuflik,Kumar, Lu,Shao, Watson, Wang…..]

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- Stabilize moduli – stabilization should involve susy-breaking, have sugra limit
- Include theoretical and phenomenological and cosmological constraints

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→ detailed predictions for LHC and DM signatures

→ ***explain*** **Little Hierarchy problem – new –** see talk of Ran Lu

All explicitly done for G_2

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Specialize to G_2 – then include μ in theory by Witten mechanism

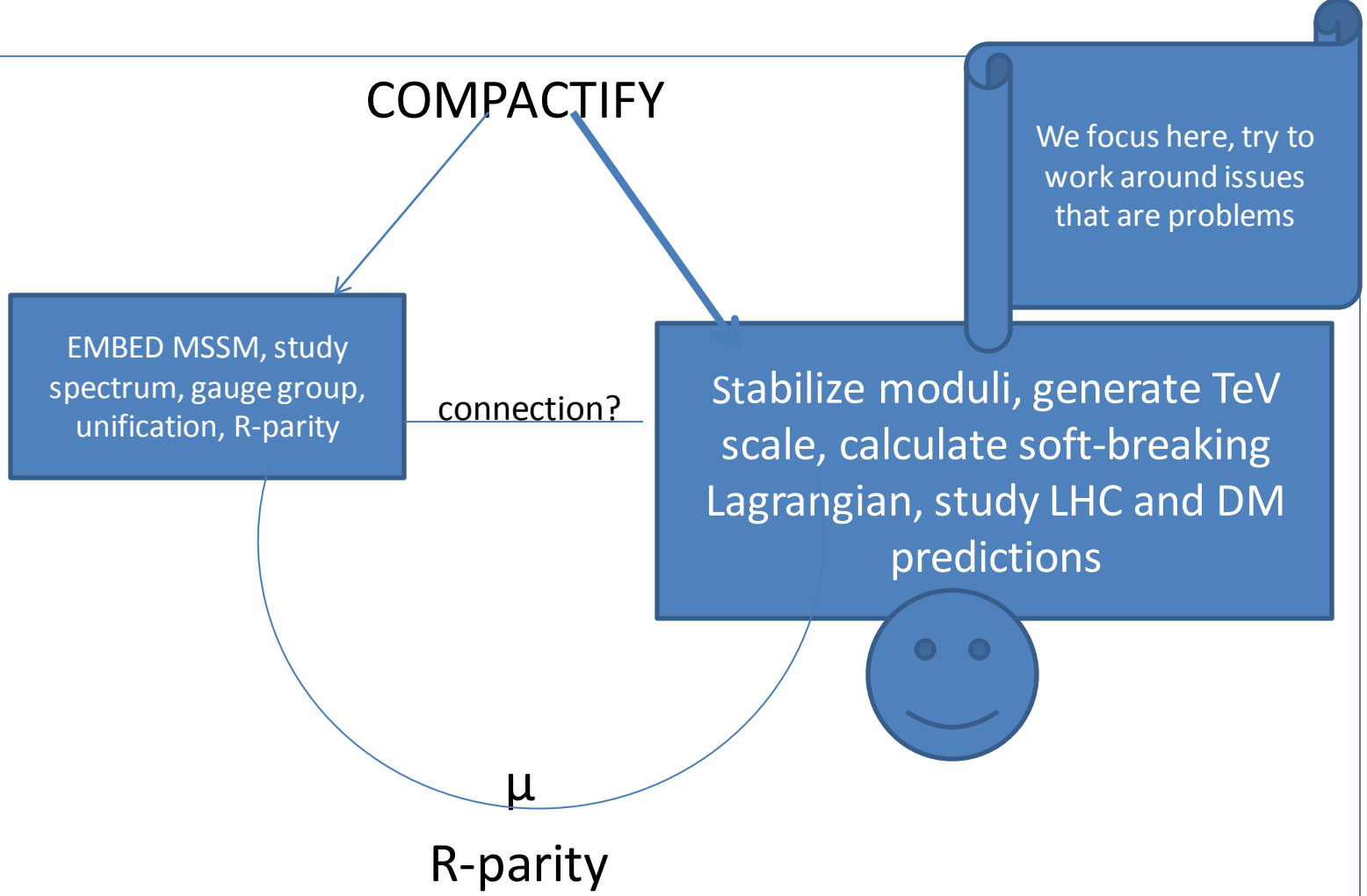
→ gauginos, μ ***are*** suppressed, → more LHC predictions

→ detailed DM predictions – LSP content, calculate relic density, DM direct detection

→ soft breaking Lagrangian real so CPV predictions – no flavor problems

All explicitly done for G_2

”generic” $\approx$ perhaps not theorem, but holds very generally – have to work hard to find or construct exception, and to show possible exceptions don’t have problems



Stabilization, generating TeV scale easier in M-theory – lack of knowledge of metric not big obstacle

Now turn to ***moduli mass matrix in generic string theory*** with some supersymmetry breaking, and examine relation between moduli mass and gravitino mass!

Write scalar potential and mass matrix in terms of usual real function

$$G = K + m_{pl}^2 ln(W\bar{W}/m_{pl}^6)$$

$$V = m_{pl}^2 e^{G/m_{pl}^2} \left(G^i G_i - 3m_{pl}^2\right)$$

$$\begin{pmatrix} M_{i\bar{j}}^2 & M_{ij}^2 \\ M_{\bar{i}\bar{j}}^2 & M_{\bar{i}j}^2 \end{pmatrix}$$

Acharya, Kane, Kuflik
arxiv:1006.3272

$$\begin{aligned} M_{i\bar{j}}^2 &= e^{G/m_{pl}^2} \left(\nabla_i G_k \nabla_{\bar{j}} G^k - R_{i\bar{j}k\bar{l}} G^k G^{\bar{l}} + G_{i\bar{j}}\right) \\ M_{ij}^2 &= e^{G/m_{pl}^2} \left(2\nabla_i G_j + G^k \nabla_i \nabla_j G_k\right) \end{aligned}$$

where subscripts on G denote derivatives

Scrucca, Louis 2005
Douglas, Denef 2006

This is the extended moduli mass matrix, including whatever mixes with moduli, such as scalar goldstinos

Assume moduli stabilization gets some contribution from susy breaking – to avoid, would have to stabilize all moduli some other way, *AND* guarantee no contribution from any form of susy breaking

Since we are only interested in minima of the potential, the mass matrix is positive definite by assumption. Hence, we use the theorem (see Appendix C) that its smallest eigenvalue, $m^2_{\min}$, is less than $\xi^\dagger M \xi$ for any unit vector ξ. Extending the work of [12], we take $\xi = (G^{\bar{j}} \quad c\,G^j)/\sqrt{3(1+|c|^2)}$ for $c \in \mathbb{C}$, which is aligned in the (moduli components of the) two sGoldstino directions $\eta = G^i\phi_i$ and $\bar{\eta} = G_i\phi^i$. This gives a one (complex) parameter class of constraints on the upper bound of the lowest mass eigenvalue

$$
\begin{aligned}
m^2_{\min} &\leq \tfrac{1}{3(1+|c|^2)} \begin{pmatrix} G^i & c^\dagger G^{\bar{i}} \end{pmatrix} \begin{pmatrix} M^2_{i\bar{j}} & M^2_{ij} \\ M^2_{\bar{i}\bar{j}} & M^2_{\bar{i}j} \end{pmatrix} \begin{pmatrix} G^{\bar{j}} \\ cG^j \end{pmatrix} \\
&\leq m^2_{3/2} \left(2\frac{|1-c|^2}{1+|c|^2} + \mathrm{Re}\{\frac{2c}{1+|c|^2}\frac{u}{m^2_{pl}}\} - \tfrac{r}{m^2_{pl}} \right)
\end{aligned}
\tag{4}
$$

where $u \equiv \frac{1}{3}G^iG^jG^k\nabla_i\nabla_jG_k$, $r \equiv \frac{1}{3}R_{i\bar{j}k\bar{l}}G^iG^{\bar{j}}G^kG^{\bar{l}}$ and $m^2_{3/2} = m^2_{pl}e^{G/m^2_{pl}}$. r is the holomorphic sectional curvature of the scalar field space, evaluated in the sGoldstino directions

m_{min} is the smallest eigenvalue of the extended moduli mass matrix, and

$$r \equiv \frac{1}{3} R_{i\bar{j}k\bar{l}} G^i G^{\bar{j}} G^k G^{\bar{l}}$$

is the holomorphic sectional curvature of the scalar space. Can get several bounds, in particular,

$$m_{\rm min}^2 < m_{3/2}^2 \left(2 - \frac{r}{m_{pl}^2} \right)$$

Generically r is order unity or smaller in planck units, so there will be at least one modulus with mass about the gravitino mass!

Moduli, gravitino masses not independent!

Cosmological constraints:

Moduli couple universally to all matter, particles and superpartners, via Planck suppressed gauge invariant operators, so can calculate their lifetimes – if they decay during nucleosynthesis they dilute it – if later, overclose universe

→ moduli mass $\gtrsim$ 30 TeV

→ gravitino mass $\gtrsim$ 30 TeV !!

Moroi, Randall NucPhysB (2000)570
Acharya, Kumar, Bobkov, Kane, Shao, Watson, arxiv:0804.0863

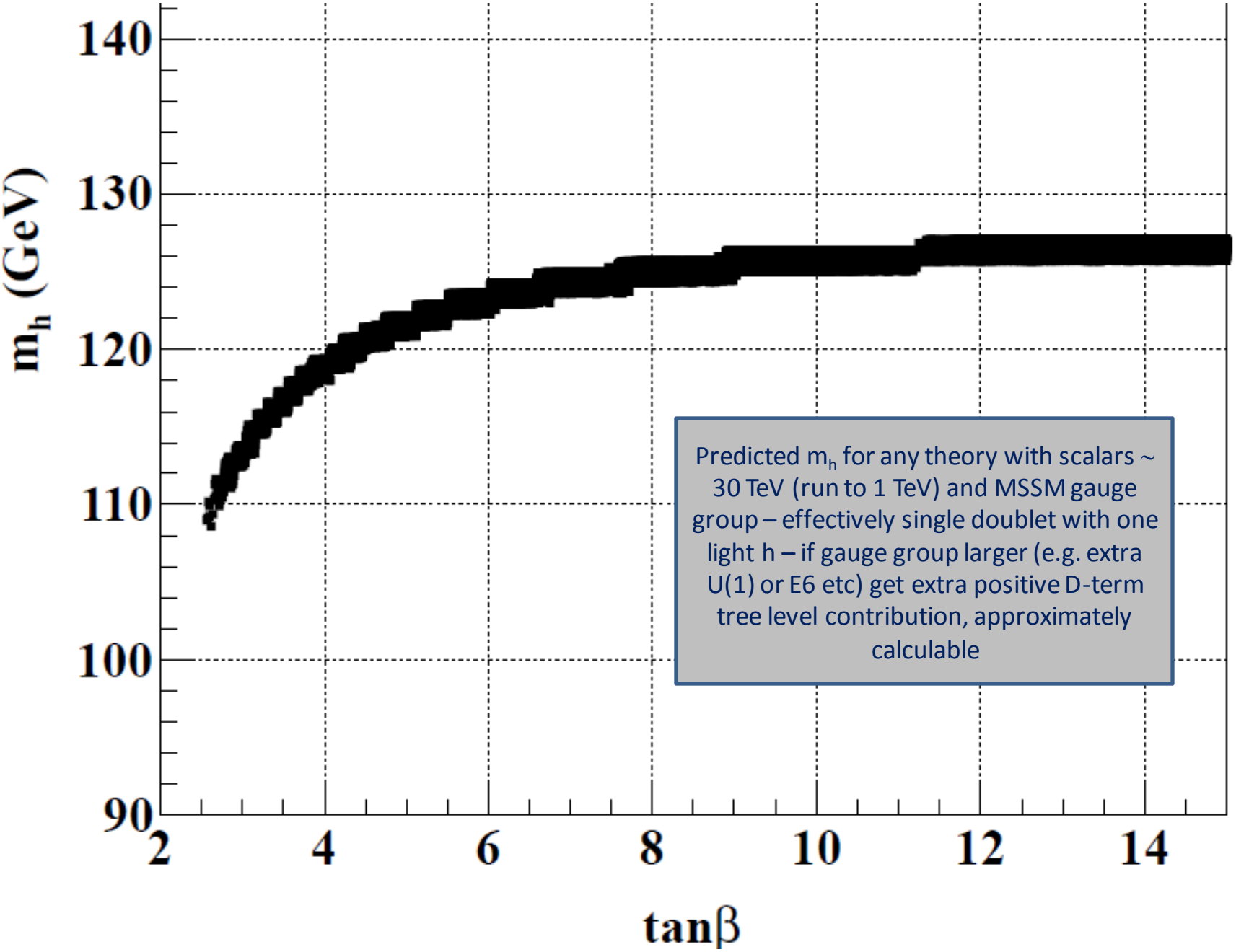
Given these results, supergravity implies that scalar masses (and trilinears) $\sim$ gravitino mass → scalars $\gtrsim$ 30 TeV !!

→Generic predictions for LHC – scalars too heavy to see at LHC

– ***<u>also, as if one higgs doublet</u>***

Surprising? Problem?

NO!



Predicted m_h for any theory with scalars ~ 30 TeV (run to 1 TeV) and MSSM gauge group – effectively single doublet with one light h – if gauge group larger (e.g. extra U(1) or E6 etc) get extra positive D-term tree level contribution, approximately calculable

Also

- Temperature when typical moduli decay $\sim$ 10 MeV
- Entropy released $\sim$ temp^3
- Thermal freezeout temp $\sim$ 10 GeV → dilution $\sim 10^9$
- So all features before moduli decay diluted, including thermal DM
- Moduli decay into LSP via all superpartners, so repopulate, recalculate relic density – can be about right!

→Thus the universe has a non-thermal cosmological history!

Thus two major generic predictions for any compactified string/M-theory that could describe our world, even if don't know W, f, K, spectrum!

LHC predictions very testable

Also -- Low scale gauge mediation has light gravitino, so unlikely to be significant source of supersymmetry breaking or mediation

Caveats?

Fan, Reece,Wang– hard to evade with late inflation – maybe not impossible

If want to decouple from supersymmetry breaking, must not only show can stabilize moduli without susy breaking, must also show there is NO contribution from susy breaking

Non-generic – perhaps non-generic vacua can be constructed that are viable -- challenging

“COULD DESCRIBE OUR WORLD”:

- 4D
- TeV scale emerges
- deS
- CC small
- BBN
- N=1 susy
- Susy breaking
- Supergravity framework

Expect many solutions, vacua, that *can* describe our world, many that cannot – don’t care about latter

GAUGINO MASS and μ -- SUPPRESSION?

- Gaugino masses arise from derivatives of gauge kinetic function
- Theorem of Maldecena and Nunez; Douglas → if only have usual moduli, get AdS minima – **must have a second source of susy-breaking** that gives large F-terms
- In G_2 case gauge matter arises from orbifold singularities – generically get chiral matter from conical singularities, get "mesons", large F-terms, uplift to deS minimum –spontaneous susy breaking
- KKLT adds anti-D3-brane – explicit susy-breaking
- In both, 2nd source of susy-breaking does not contribute to gauge kinetic function, so contributes to $M_{3/2}$ but not to gaugino masses
- LARGE volume assumes no-scale structure, has gaugino mass suppression
- ***But general conditions for gaugino suppression not known yet***

  -- R-symmetry?

  -- probably not – trilinears large, crucial for EWSB – not how it works in G2 – could be different in different corners

- μ set to zero in superpotential by symmetry, then non-zero by symmetry breaking – μ should vanish with $M_{3/2}$ ***and*** with extra symmetry, so doubly suppressed (works in G_2 case) – general case not understood yet

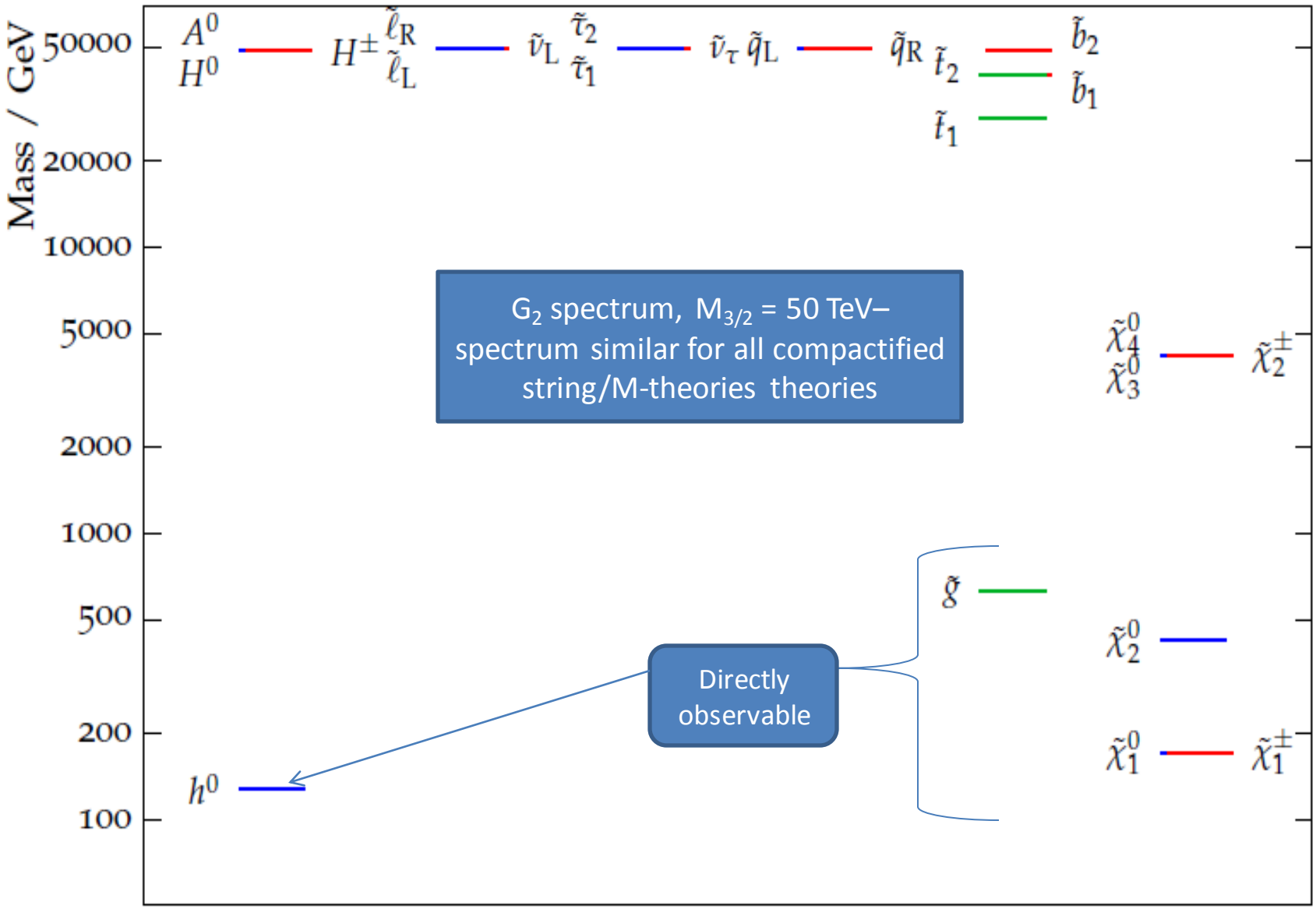
PROCEED BY ASSUMING GAUGINO MASSES SUPPRESSED, $\mu \sim M_{3/2}/10\text{-}20$

[What if gaugino masses not suppressed? Only see light Higgs boson]

SUPERPARTNER SPECTRUM

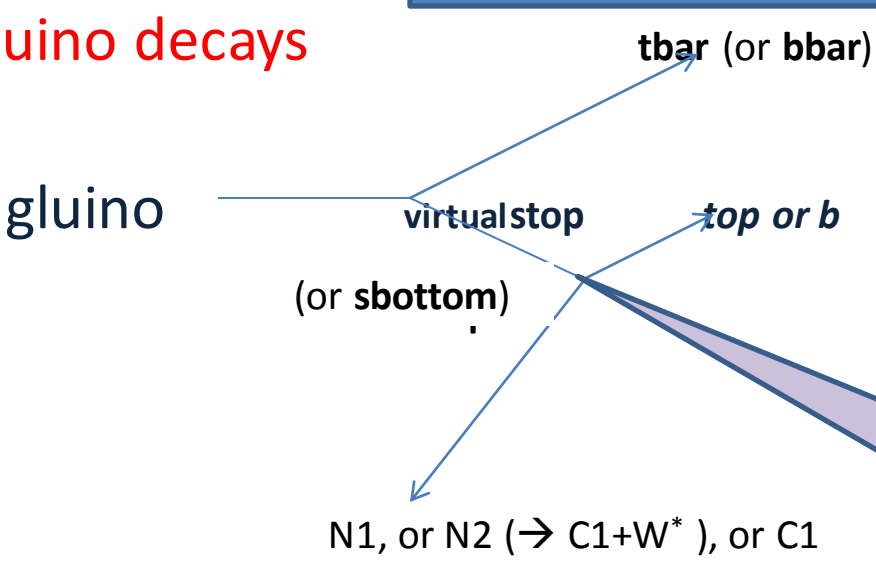
- Run scalars from $\sim$ 30 TeV down to gluino scale to study decay BR

- RGE running – usual MSSM running, same as for REWSB -- M_{Hu}^2 runs fastest, running fastest when large Yukawas and large trilinears enter -- RH stop next, LH stop, sbottom, etc


Mass / GeV
50000
20000
10000
5000
2000
1000
500
200
100
A^0
H^0
$H^\pm$
$\tilde{\ell}_R$
$\tilde{\ell}_L$
$\tilde{\nu}_L$
$\tilde{\tau}_2$
$\tilde{\tau}_1$
$\tilde{\nu}_\tau$
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{t}_2$
$\tilde{t}_1$
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{g}$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
h^0
G$_2$ spectrum, M$_{3/2}$ = 50 TeV–
spectrum similar for all compactified
string/M-theories theories
Directly
observable

gluinos light in models, $\lesssim$TeV

Gluino decays



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

Very good signature, small background!

[for lighter gluinos phase space suppresses tops in favor of b's]

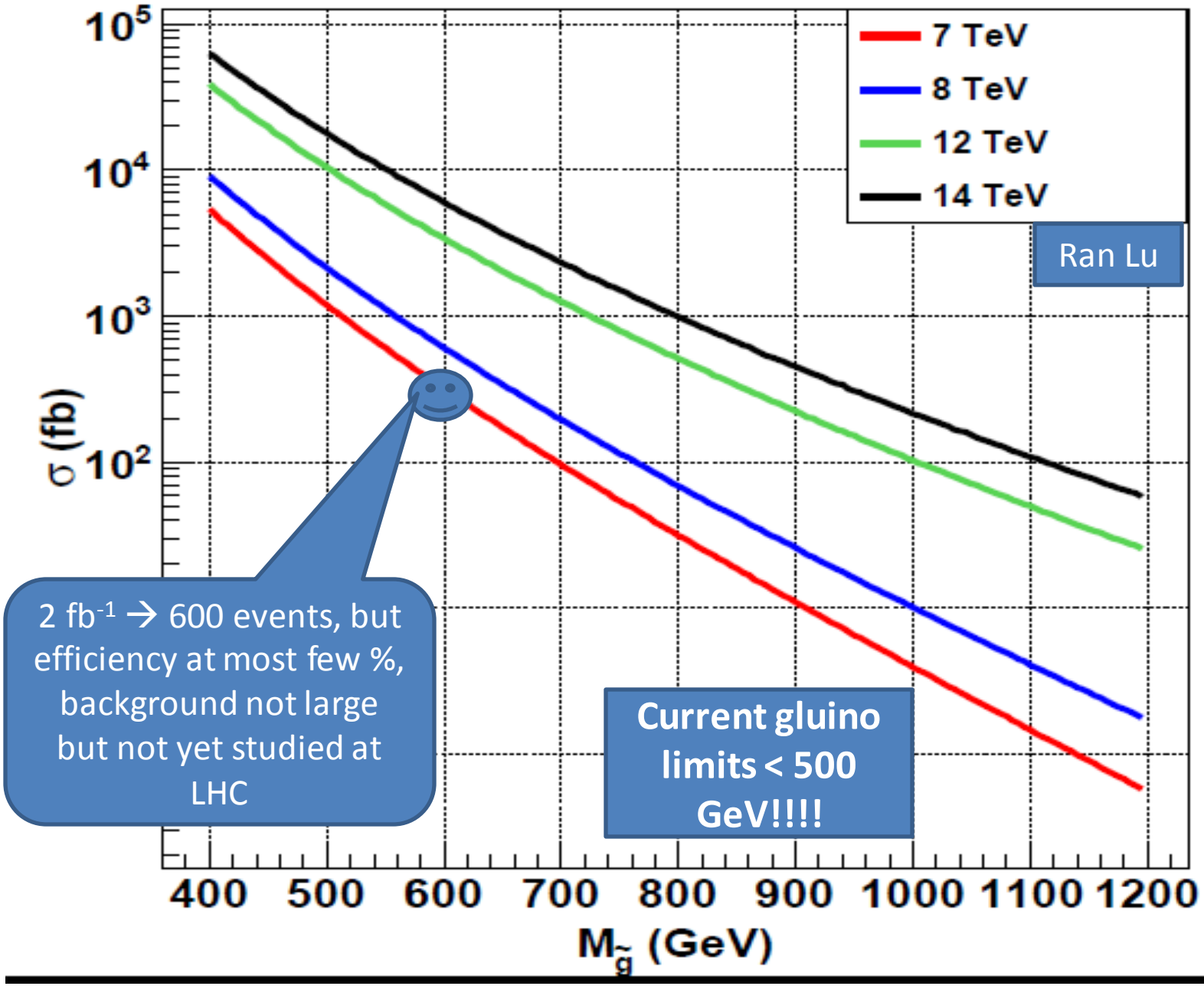
If get sample of gluino events can look for chargino decays in first layers of tracking and distinguish if this decay is N1, N2, C1

e.g. MODES	BR
G→t tbar N2	~ ½
→t bbar C1	~ ¼
→b bbar N1	~ ¼
→g N1+N2	~ 1%
→ light squarks + N1, N2	

lifetime ~ 10^{-19} sec

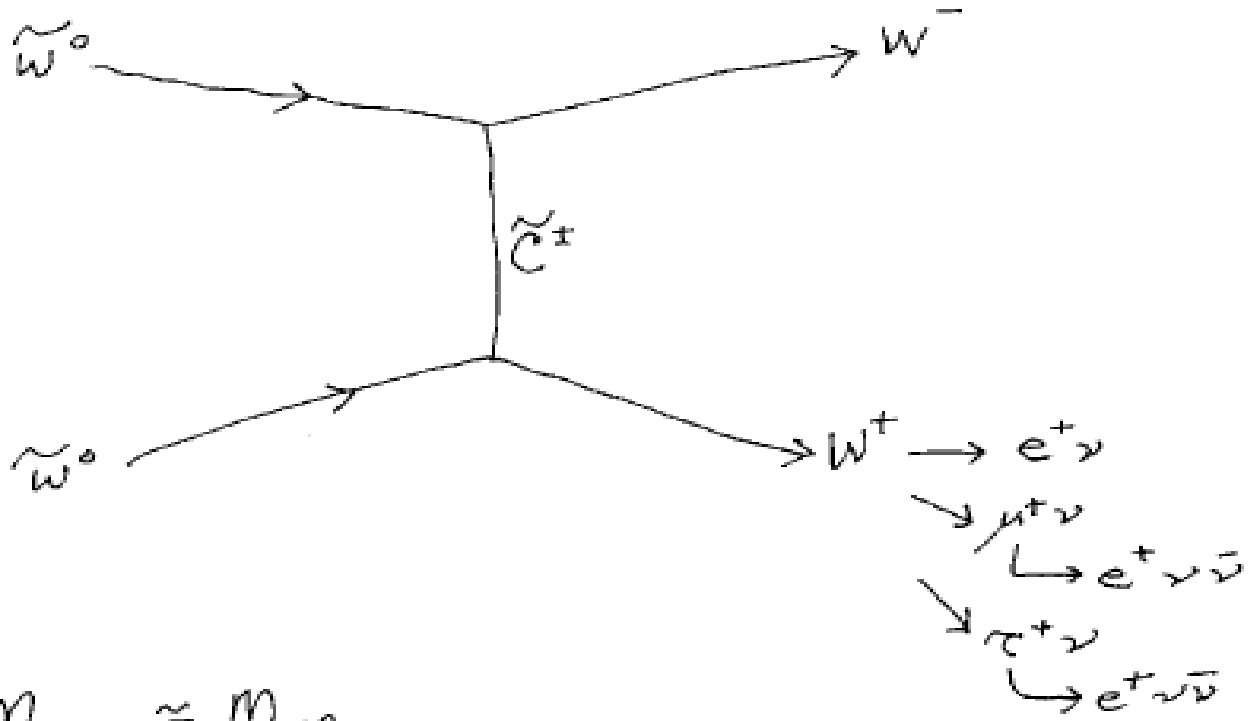
Can learn much from LHC data – BR depend on $M_0 = M_{3/2}$, etc from running, and on whether LSP is wino-like and its higgsino bino, mixture

Acharya, Grajek, Kane, Kuflik, Suruliz, Wang, arxiv:0901.3367
Kane, Kuflik, Lu, Wang arxiv: 1101.1963


7 TeV
8 TeV
12 TeV
14 TeV
Ran Lu
10^5
10^4
10^3
10^2
σ (fb)
400 500 600 700 800 900 1000 1100 1200
$M_{\tilde{g}}$ (GeV)
2 fb^{-1} → 600 events, but efficiency at most few %, background not large but not yet studied at LHC
Current gluino limits < 500 GeV!!!!

What is the LSP? Can say a lot, but not yet totally settled by the theory

- *If LSP is most of dark matter*, then in non-thermal cosmological history need large annihilation cross section to not overclose universe → wino-like
- Wino-like gives good description of PAMELA data if mass in 140-200 GeV range
- ***In G_2 universal gaugino masses are suppressed to same mass scale as anomaly contribution (when CC set to zero) → wino-LSP***
- ***Then when μ problem solved get some higgsino mixture so wino-like, not pure wino***
- If only μ suppressed but not gluino then observable spectrum is N2, N1, C1 – still detectable!

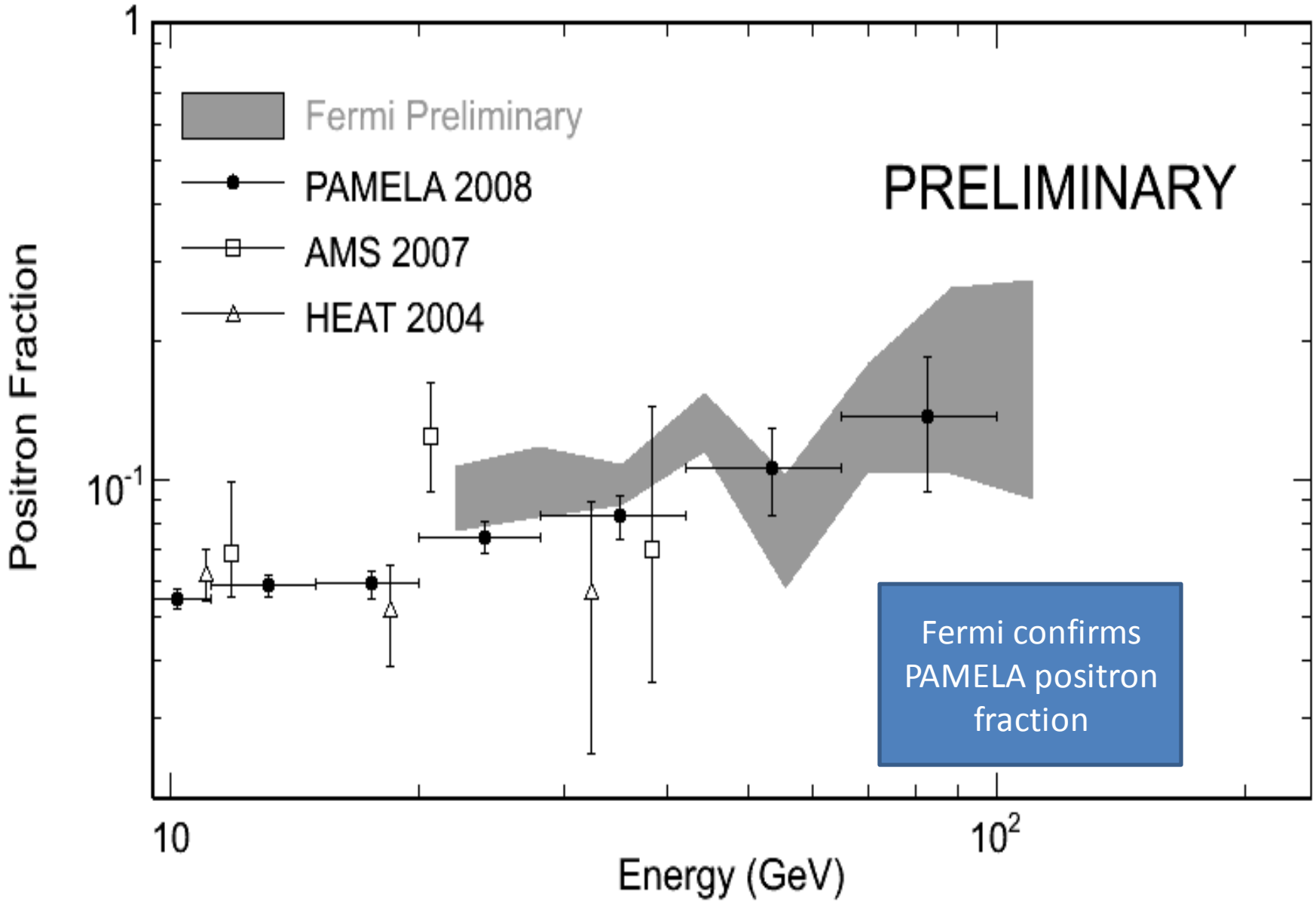


$M_{\tilde{C}^\pm} \simeq M_{\tilde{W}^0}$

Couplings full strength EW

No parameters except mass of $\tilde{W}^0$

For wino mass in PAMELA range ,
$\langle\sigma v\rangle \approx 2\times10^{24}\,cm^3/sec$



Fermi confirms PAMELA positron fraction

LITTLE HIERARCHY, FT, PROBLEM

Feldman, Kane, Kuflik, Lu

Need to explain the higgs vacuum expectation value, <h>, or equivalently the Z and W masses, e.g.

$$M_Z = g_{EW} \langle h \rangle.$$

Cannot do that within Standard Model, new physics must do it, so answer will have form

$$M_Z{}^2 = M^2_{gluino} \pm \mu^2 \pm \text{more terms}$$

or numerically in TeV^2 units

$$0.01 \approx 3 \pm 1 \pm \text{etc}$$

so typically fine-tuning of order 1% -- normally such fine-tuning not present in physics –much concern and effort for two decades

Of course, should not have FT in a good theory – string theory?

EWSB, LITTLE HIERARCHY PROBLEM –NEW APPROACH, SOLUTION

[detailed explanation in talk of Ran Lu]

Feldman, Kane, Kuflik, Lu arxiv:1105.3765

Any theory with $M_0 \simeq A_0 \simeq M_{3/2} \sim$ 30 TeV, and $B_0 \approx 2M_{3/2}$, and

$$M_0^2, A_0^2, B_0^2 \gg \mu^2, M_a^2$$

will have a large region of parameters with EWSB, and with

$$M_Z^2/2 + \mu^2 \lesssim (\text{TeV})^2$$

These are the natural ranges expected in compactified string/M-theory!

The usual EWSB conditions can be seen to imply

$$M_Z^2/2 + \mu^2 \approx \frac{\bar{m}_{H_d}^2}{B^2 - \bar{m}_{H_d}^2} \bar{m}_{H_u}^2$$

[$B=2M_{3/2}$ if guarantee no μ from superpotential]

Run from $M_{3/2}$ down to TeV scale -- $m_{H_d}^2(t)$ essentially does not run, B runs down to about 1.7 $M_{3/2}$, and $m_{H_u}^2(t)$ runs as

$$m_{H_u}^2(t) \simeq f_{M_0}(t) M_0^2 - f_{A_0}(t) A_0^2$$

where f_{M_0}, f_{A_0} depend only on SM quantities, essentially the top yukawa and the gauge couplings, they run to

$$f_{M_0} \simeq f_{A_0} \simeq 0.1$$

Thus there is a double suppression, with each term suppressed by nearly an order of magnitude, and a large cancellation of the two terms, but no fine tuning.

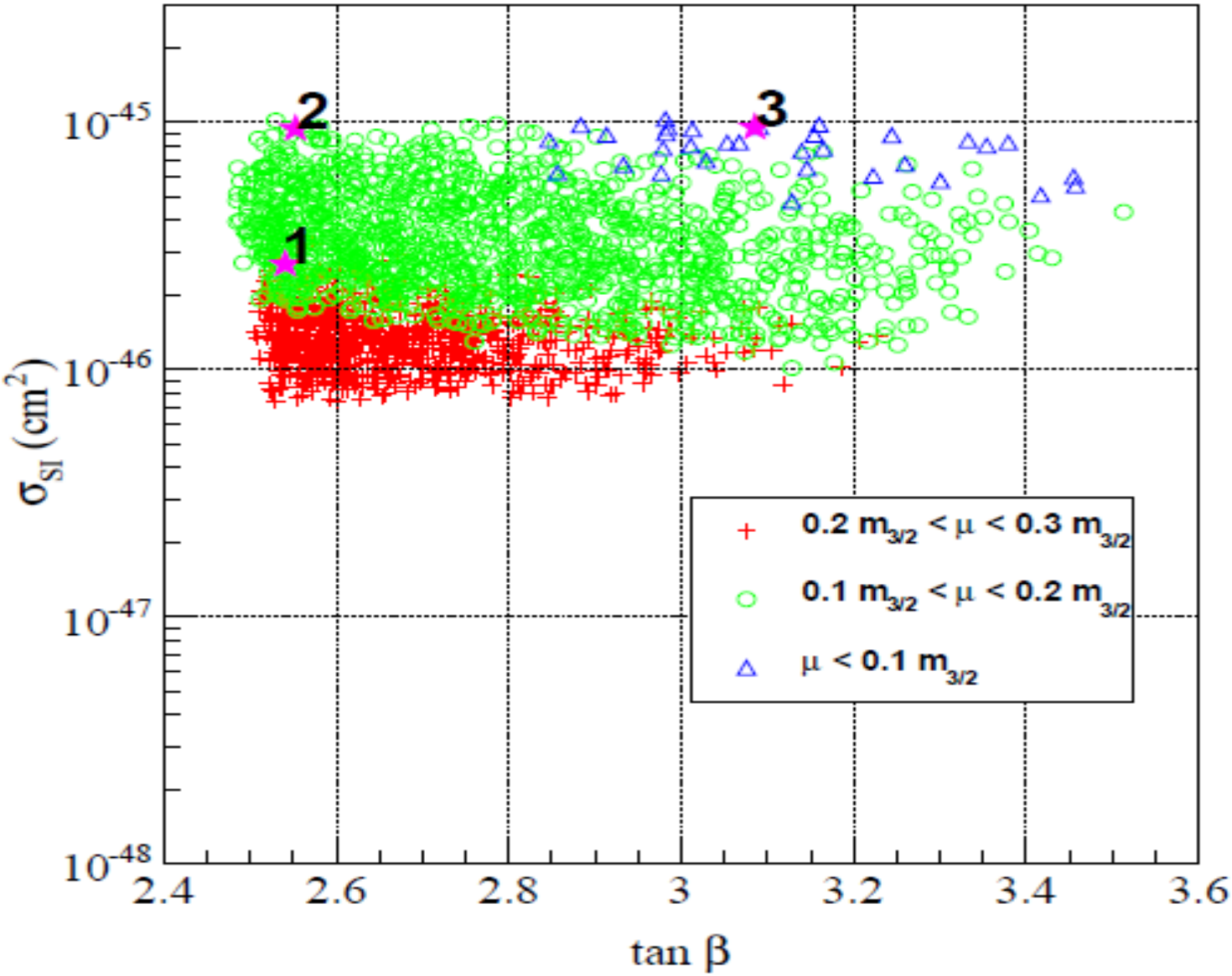
Interesting to think about how precisely $M_Z^2/2 + \mu^2$ Is determined – Donoghue, K. Dutta, A. Ross, M. Tegmark pointed out that the higgs vev can vary a factor of a few without any change in SM physics

Little hierarchy problem gone, robust EWSB, if scalars and trilinears $\geq$ 30 TeV and about same size

THEORY AND PHENOMENOLOGY OF μ IN M-THEORY

[Acharya, Kane, Kuflik, Lu arxiv:1102.0556]

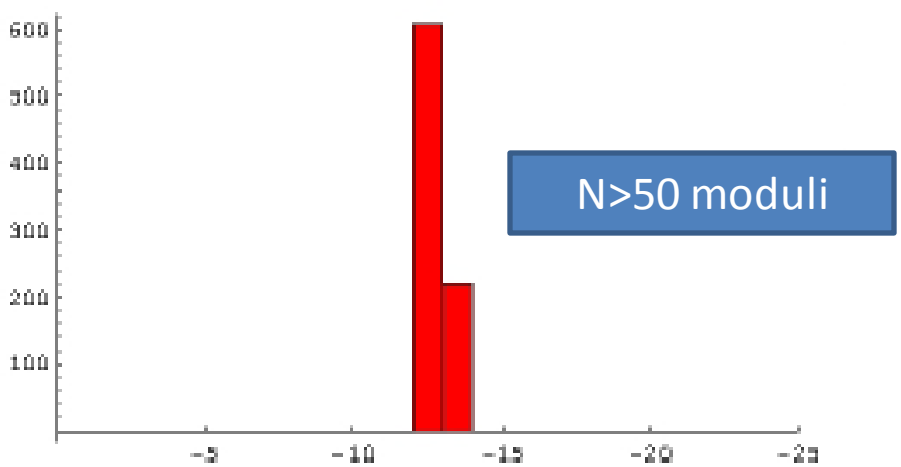
- The following works in M-theory – don't yet know if there is equivalent approach in all corners, but seems likely
- Need to have symmetry so μ=0 in superpotential – but phenomenologically μ≠ 0
- Witten (hep-ph/0201018) introduced a discrete symmetry that was satisfactory, but left it unbroken
- It is broken by the moduli stabilization
- Then μ is suppressed compared to $M_{3/2}$ by amount of order <moduli>/M_{pl} $\lesssim$ 0.1, so $\boldsymbol{\mu \lesssim 0.1 M_{3/2}}$
- Then have estimates for full neutralino and chargino mass matrices, LSP indeed wino-like, can predict cross sections on protons, neutrons – consistent with EWSB
- Note pure wino does not scatter on proton, neutron – does scatter with higgsino mixture, so upper limit meaningful


2
3
1
10^{-45}
10^{-46}
10^{-47}
10^{-48}
σ_{SI} (cm^2)
2.4
2.6
2.8
3
3.2
3.4
3.6
tan β
0.2 $m_{3/2}$ < μ < 0.3 $m_{3/2}$
0.1 $m_{3/2}$ < μ < 0.2 $m_{3/2}$
μ < 0.1 $m_{3/2}$

$M_{3/2}$ upper limit?

(a) $M_{3/2} < 500 \text{ TeV} \times C/(V_7)^{3/2}$

(b)



(c) $\Omega_{DM} \sim 0.1\ (M_{3/2}\ /50 \text{ TeV})^{3/2}$ so $M_{3/2} < 250$ GeV

Cosmological constant problems?

-- ***naively*** too large – explain actual value? – why now?

- Does present inability to solve this cause a problem for understanding our string vacuum?
- Probably not – basically an orthogonal issue in most ways of thinking about it, particularly if true CC (rather than a scalar field)
- In M-theory case (and other approaches) we calculate all observables before and after tuning CC to zero, and find no large effects – standard method
- Note analogous issue with strong CP problem – many predictions for QCD would be different if strong CP effects ~ 1, but we successfully ignore it

→CC problem(s) – interesting – but probably not most important problem(s) in physics – solving them not likely to help with all the rest we want to understand – not solving them not likely to hinder us

String theory framework has many solutions ("landscape")

- If many of them can have compactified solutions with stabilized moduli need to understand how, and implications
- Suppose there are many
- Some have argued that if there are many, then it is unlikely we can find one (or more) describing *our* vacuum
- But it is not like throwing darts and choosing vacua and testing them – we already know so much about what to look for and are addressing so many questions whose answers are related that it is reasonable to be optimistic about finding very good candidates for our string vacuum, and soon – examples like the G_2 one show major progress possible
- Of course, unlikely to find our vacuum from top-down string theory

Concluding remarks

- Moduli, $M_{3/2}$, scalars, trilinears $\geq$ 30 TeV → consistent picture, well motivated

- *Gluinos are light (probably very light) in some compactifications – if not in all, then can distinguish different compactifications!*

- ***Watch for gluinos at LHC, decaying mainly into 3rd family (b's, tops) – current limit $\lesssim$ 500 GeV***

- Single light Higgs boson, mass about 127 GeV unless gauge group extended

- ***Meaningful predictions possible from compactified string theories even if much is not understood !***

The ***baryon-dark matter ratio*** via moduli decay in AD baryogenesis, KSWY, in preparation flat direction baryogenesis gives order 1 asymmetry, diluted by moduli decay – moduli decay also provides DM

Flavour issues for string-motivated heavy scalar spectra: the G2-MSSM case.KKKV [arxiv:1107.3105] check no flavor problems -- UVMFV

A new (string motivated) approach to the ***little hierarchy problem*** FKKL [1105.3765] explain little hierarchy, fine-tuning

Signal and background for generic string theory ***LHC predictions for 7 TeV***, KKLW, [1101.1963] 4-top, tbtb events main signal from gluino production

Theory and phenomenology of μ in M-theory, AKKL arXiv: [1102.0566] *include μ in string theory, DM wino-like,* **Xenon** *etc predictiions*

String Theories and Moduli Stabilization Imply ***Non-Thermal Cosmological History*** AKK [arXiv:1006.3272] *General compactified string theory with moduli stabilized (not just M-theory)* → ***scalars*** $\sim M_{3/2}$

M Theory Solution to the ***Strong CP Problem*** and Constraints on the Axiverse ABK, [1004.5138]

Dark Matter as a Guide Toward a Light Gluino at the ***LHC***. FKLN [arXiv:1002.2430] *LHC predictions normalizing mass scale to PAMELA data*

PAMELA Data as a Signal of Non-Thermal Wino Dark Matter. KLW[arXiv:0906.4765]*Wino LSP gives good description of PAMELA positron and antiproton data*

Identifying Multi-Top Events from Gluino Decay at the ***LHC***, AGKKSW [arXiv:0901.3367] *Generic signature of G2-MSSM at LHC – 4 top events*

CP-violating Phases in M-theory and EDMs. KKS [arXiv:0905.2986] *All terms in soft breaking Lagrangian have same phase – solves weak CP problem*

Non-thermal DM and the Moduli Problem in String Frameworks. AKBKSW[arXiv:0804.0863] ***G2 Moduli physics****, decay, relic density, non-thermal history*

The G2-MSSM: An M Theory motivated model of Particle Physics. ABKSK [arXiv:0801.0478] ***Calculate spectrum****, study wino LSP, GCU*

Explaining the Electroweak Scale and Stabilizing Moduli in M Theory. Acharya,Bobkov, Kane, Kumar, Shao.[hep-th/0701034]
M-theory on G2 manifold – Supersymmetry breaking and moduli stabilization*, calculate scalar potential, deS minimum, wino LSP*

X