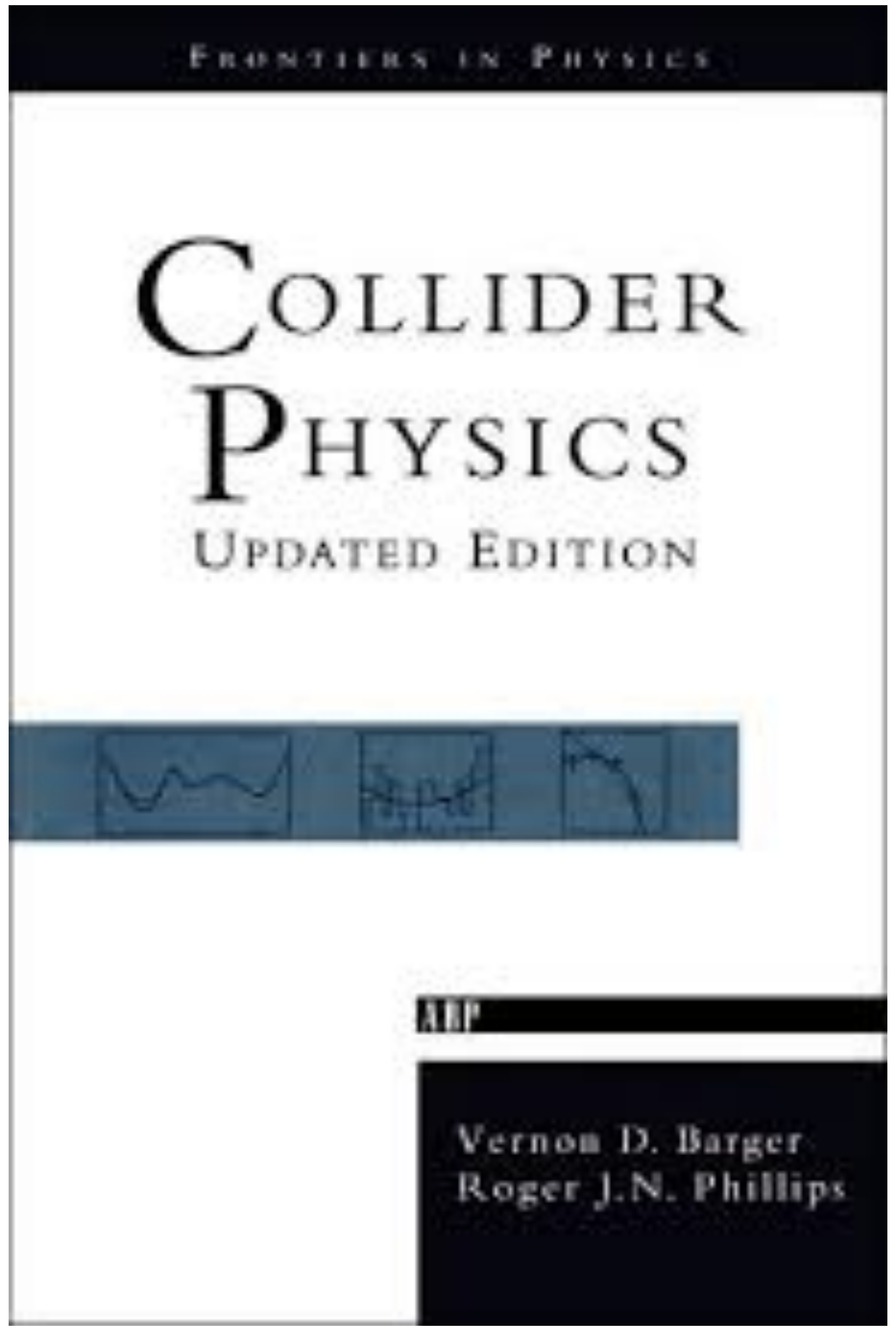
Research fun with Vernon throughout the years

Howie Baer, University of Oklahoma
June 5, 2025



FRONTIERS IN PHYSICS

COLLIDER PHYSICS
UPDATED EDITION

ABP

Vernon D. Barger
Roger J.N. Phillips

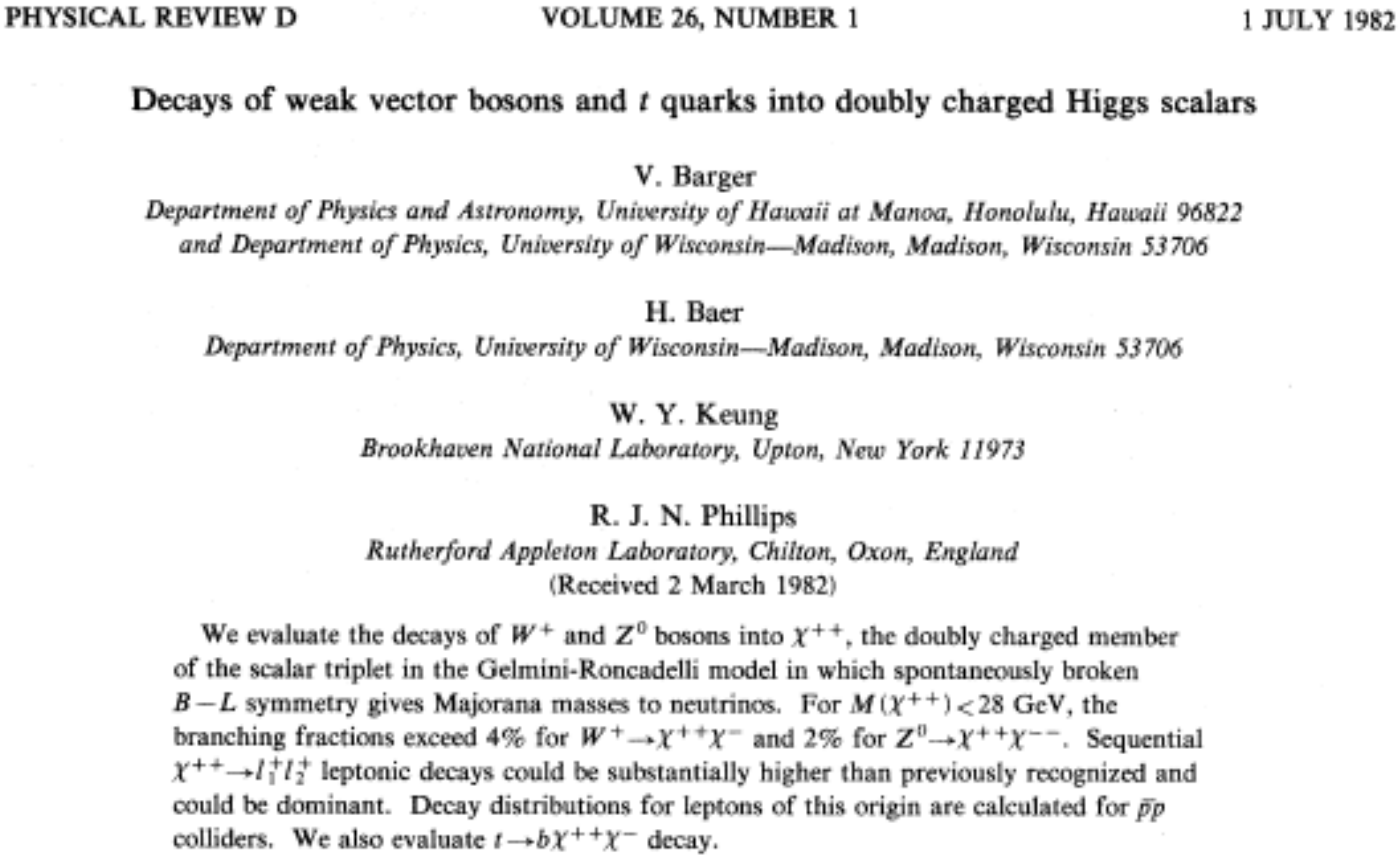
Beginnings

- Vernon graduated Ph. D. 1964 (Penn State) and quickly gained expertise in phenomenological theories of high energy scattering: Regge pole theory (early work with Marty Olsson, Dave Cline (1969 book) Roger Phillips)
- moved to parton model/gauge theories 1974
- I enrolled as Freshman at UW in Fall, 1975
- First met VB by taking UG Classical Mechanics, Fall, 1976
- Vernon fresh back frm Hawaii, always smiling and wearing Hawaiian shirts
- Gave easy exams which I nonetheless flubbed

Then

- Summer 1977: worked as UG hourly for Vernon, updating preprints to published versions and learning plotting for upcoming E&M book
- But I moved heavily into wilderness/whitewater paddling and got over my head taking too many grad courses
- Went to grad school at U Maryland to try GR with Misner; dabbled in QFT but quickly transferred back to UW for Fall 1980 semester
- Paddled 550 miles on South Seal/North Knife trip summer 1980, but when back to UW, boasted to VB that I could do Feynman diagrams

- Vernon recommend me to take Quals in Fall 1980 and Prelim exam Spring 1981
- I expected to fail, so helped organize 900 mile, 52 day canoe trip to Canadian Barren grounds
- When I accidentally passed prelims, Vernon offered me an RA for summer. But had to turn it down due to canoe trip.
- ``I thought you wanted to do research"
- But started as RA in Fall 1981
- First paper: 1982 with VB, RJNP and Wai-Yee Keung



PHYSICAL REVIEW D VOLUME 26, NUMBER 1 1 JULY 1982

Decays of weak vector bosons and t quarks into doubly charged Higgs scalars

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(Received 2 March 1982)

We evaluate the decays of W^+ and Z^0 bosons into χ^{++}, the doubly charged member of the scalar triplet in the Gelmini-Roncadelli model in which spontaneously broken $B-L$ symmetry gives Majorana masses to neutrinos. For $M(\chi^{++})<28$ GeV, the branching fractions exceed 4% for $W^+\to\chi^{++}\chi^-$ and 2% for $Z^0\to\chi^{++}\chi^{--}$. Sequential $\chi^{++}\to l_1^+ l_2^+$ leptonic decays could be substantially higher than previously recognized and could be dominant. Decay distributions for leptons of this origin are calculated for $\bar{p}p$ colliders. We also evaluate $t\to b\chi^{++}\chi^-$ decay.

Yee taught me how to do MC integration!

grad school work

- 1983: lots of excitement over W, Z discovery by UA1/UA2 at CERN
- QCD was relatively new; backgrounds were not well-known
- Vernon and Roger and Alan Martin: discoverying 40 GeV top-quark in Rubbia's data?
- Anyway, searching for top-quark and 4th generation quarks and leptons a good idea:

$$(\nu_L, L) \text{ and } (a, v)$$

POSSIBLE HEAVY LEPTON SIGNALS AT $\bar{p}p$ COLLIDERS

V. BARGER, H. BAER
Physics Department, University of Wisconsin, Madison, WI 53706, USA

A.D. MARTIN, E.W.N. GLOVER
Physics Department, University of Durham, Durham, England

and

R.J.N. PHILLIPS
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

Received 27 August 1983

If a new sequential heavy lepton L exists with mass below that of the W boson, it will give rise to the following decay chains: $W \rightarrow L\nu_L$ with $L \rightarrow e\nu_e\bar{\nu}_L$ or $L \rightarrow Q\overline{q}\overline{\nu}_L$. We critically study, and quantify, the possibility of identifying this heavy lepton signal against the various backgrounds in high energy $\bar{p}p$ collisions. We find that the leptonic decay signal is plagued by serious $\bar{b}b$, $W \rightarrow e\nu$, and $W \rightarrow \tau\nu$ backgrounds, whereas the hadronic decay mode leads to a distinctive signature, after selected cuts are applied. We discuss how the mass of such a lepton may be determined.

Systematic procedures for identifying t quarks in $\bar{p}p$ collider events with a muon and jets

V. Barger and H. Baer
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A. D. Martin
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R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England
(Received 31 October 1983)

Substantial rates are predicted for events containing a muon and jets resulting from $W \rightarrow t\bar{b}$, $Z \rightarrow t\bar{t}$, and $t\bar{t}$ hadroproduction, with $t \rightarrow \mu\nu b$ decay. We investigate selective cuts to reject backgrounds from $b\bar{b}$, $c\bar{c}$, and $c\bar{s}$ production and to identify the t-quark events. For example, from a data sample containing 50 $W^{\pm} \rightarrow e^{\pm}\nu$ events, we expect that clean samples of approximately 4 $t\bar{b}$- (or $\bar{t}b$-) and conservatively 4 $t\bar{t}$-initiated $\mu^{\pm}$+jets events can be selected for a t-quark mass below 45 GeV. We suggest methods for distinguishing the contributions and for determining m_t.

---

p

Heavy leptons from W decay

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A. D. Martin and E. W. N. Glover
Physics Department, University of Durham, Durham, England

R. J. N. Phillips
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(Received 18 November 1983)

We investigate the possibility of detecting a new heavy lepton at the $\bar{p}p$ collider through the decay mode $W \rightarrow L\nu_L$. We consider both the leptonic ($L \rightarrow e\nu_e\bar{\nu}_L$) and hadronic ($L \rightarrow \bar{q}Q\bar{\nu}_L$) sequential decays of the L. We present detailed calculations to show that the leptonic decay rate is exceeded, for all kinematic ranges, by background contributions from $W \rightarrow e\nu_e$ and $W \rightarrow \tau\nu_\tau \rightarrow e\nu_e\bar{\nu}_\tau\nu_\tau$ decays. On the other hand, the hadronic decay leads to a promising, distinctive signature: a large missing transverse momentum balanced by two recognizable jets. Selective cuts can be imposed to remove background contributions, and the remaining event rate is about 10% of the $W \rightarrow e\nu$ rate if the mass of the lepton is below 50 GeV.

The background to t-quark signals from higher-order QCD contributions

V. Barger, H. Baer, and K. Hagiwara
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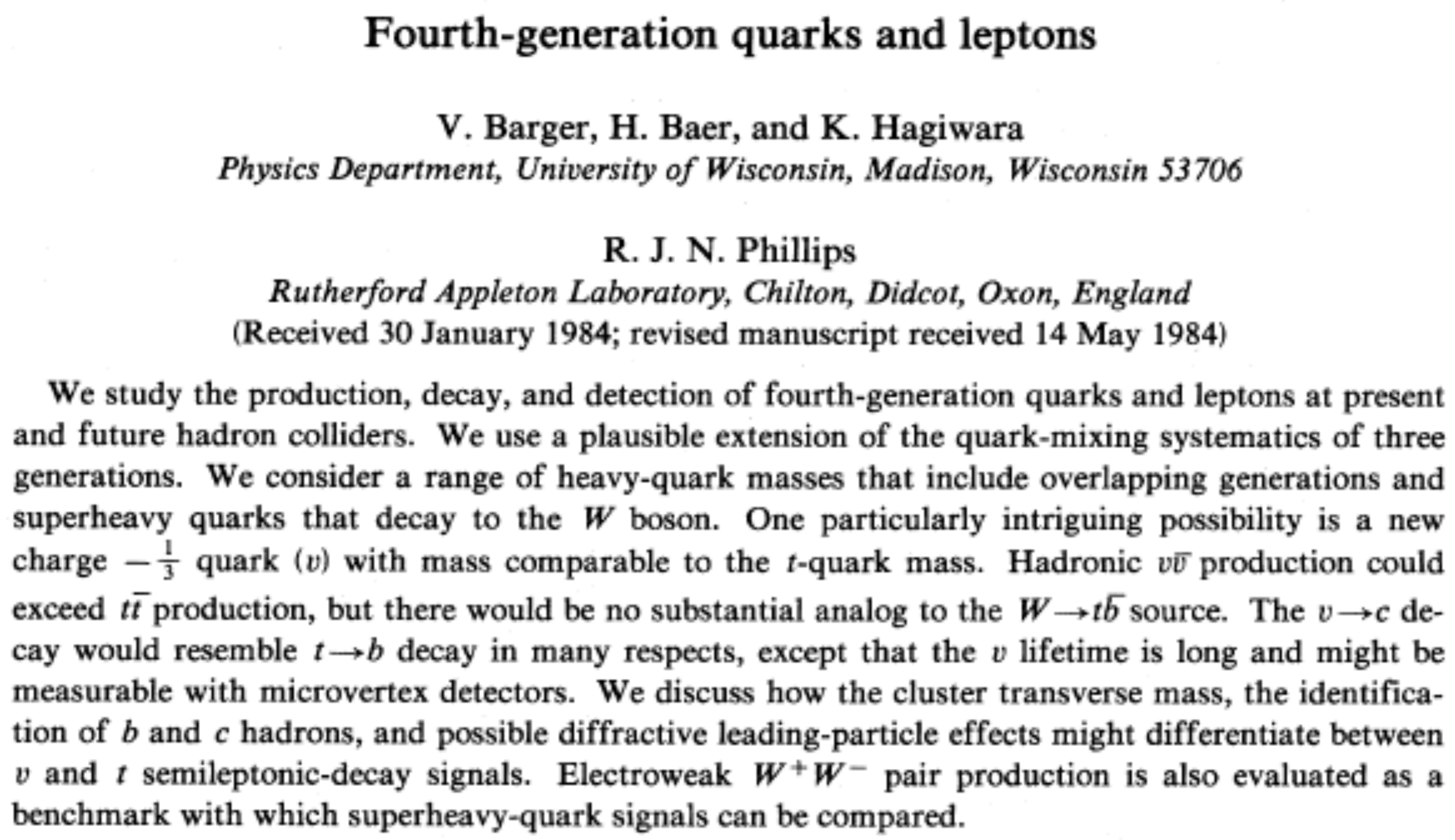
R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England
(Received 27 December 1983)

In $p\bar{p}$ collider experiments, the higher-order QCD subprocesses $q\bar{q} \rightarrow gQ\bar{Q}$, $qg \rightarrow qQ\bar{Q}$, $gg \rightarrow gQ\bar{Q}$ (with $Q = c,b$) can lead to events with high-p_T leptons and apparently broad jets that may fake the usual signals of t-quark production and decay. We evaluate these contributions quantitatively, with plausible approximations, and conclude that the background they provide can be largely eliminated by suitable experimental selection criteria.

this turned into a thesis (Linda typed thesis and I proof-read on 550 mile Kazan river trip during summer 1984



Fourth-generation quarks and leptons

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R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

(Received 30 January 1984; revised manuscript received 14 May 1984)

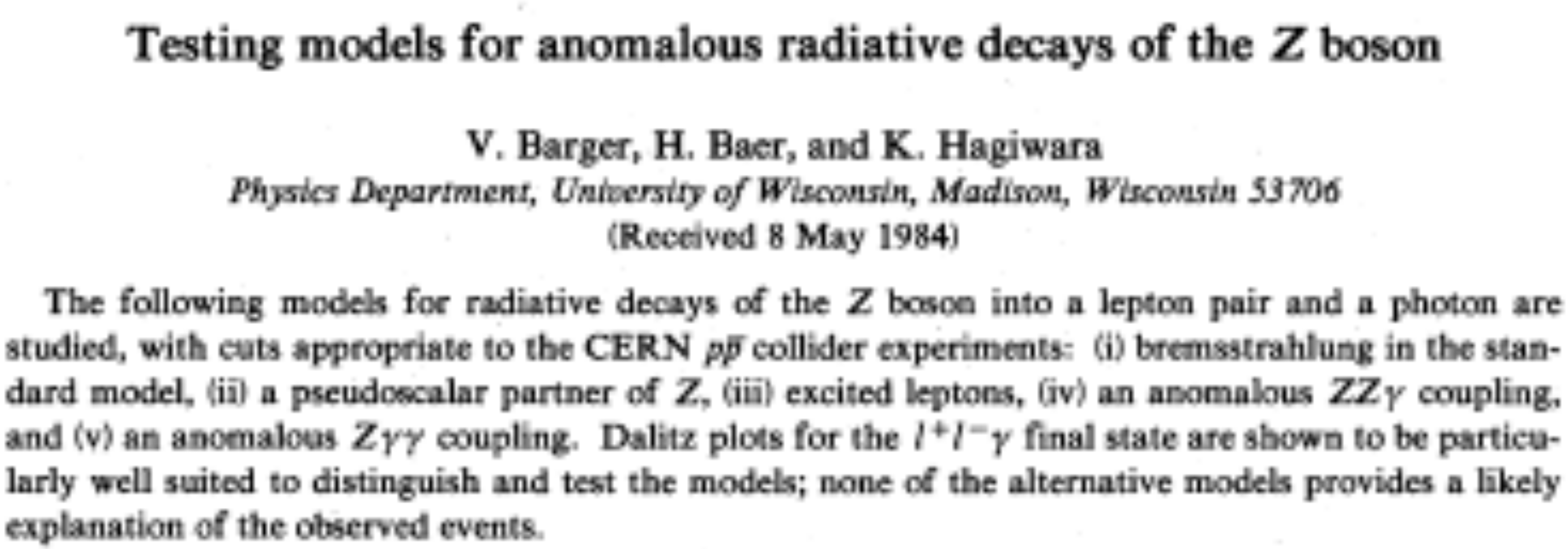
We study the production, decay, and detection of fourth-generation quarks and leptons at present and future hadron colliders. We use a plausible extension of the quark-mixing systematics of three generations. We consider a range of heavy-quark masses that include overlapping generations and superheavy quarks that decay to the W boson. One particularly intriguing possibility is a new charge $-\frac{1}{3}$ quark (v) with mass comparable to the t-quark mass. Hadronic $v\bar{v}$ production could exceed $t\bar{t}$ production, but there would be no substantial analog to the $W \to t\bar{b}$ source. The $v \to c$ decay would resemble $t \to b$ decay in many respects, except that the v lifetime is long and might be measurable with microvertex detectors. We discuss how the cluster transverse mass, the identification of b and c hadrons, and possible diffractive leading-particle effects might differentiate between v and t semileptonic-decay signals. Electroweak W^+W^- pair production is also evaluated as a benchmark with which superheavy-quark signals can be compared.

PRODUCTION OF NEW QUARKS AND LEPTONS AT PROTON - ANTI-PROTON COLLIDERS

#1

- Howard Arthur Baer(Wisconsin U., Madison) (Dec, 1984)

anomalous UA1/UA2 llgamma events



Testing models for anomalous radiative decays of the Z boson

V. Barger, H. Baer, and K. Hagiwara
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(Received 8 May 1984)

The following models for radiative decays of the Z boson into a lepton pair and a photon are studied, with cuts appropriate to the CERN $p\bar{p}$ collider experiments: (i) bremsstrahlung in the standard model, (ii) a pseudoscalar partner of Z, (iii) excited leptons, (iv) an anomalous $ZZ\gamma$ coupling, and (v) an anomalous $Z\gamma\gamma$ coupling. Dalitz plots for the $l^+l^-\gamma$ final state are shown to be particularly well suited to distinguish and test the models; none of the alternative models provides a likely explanation of the observed events.

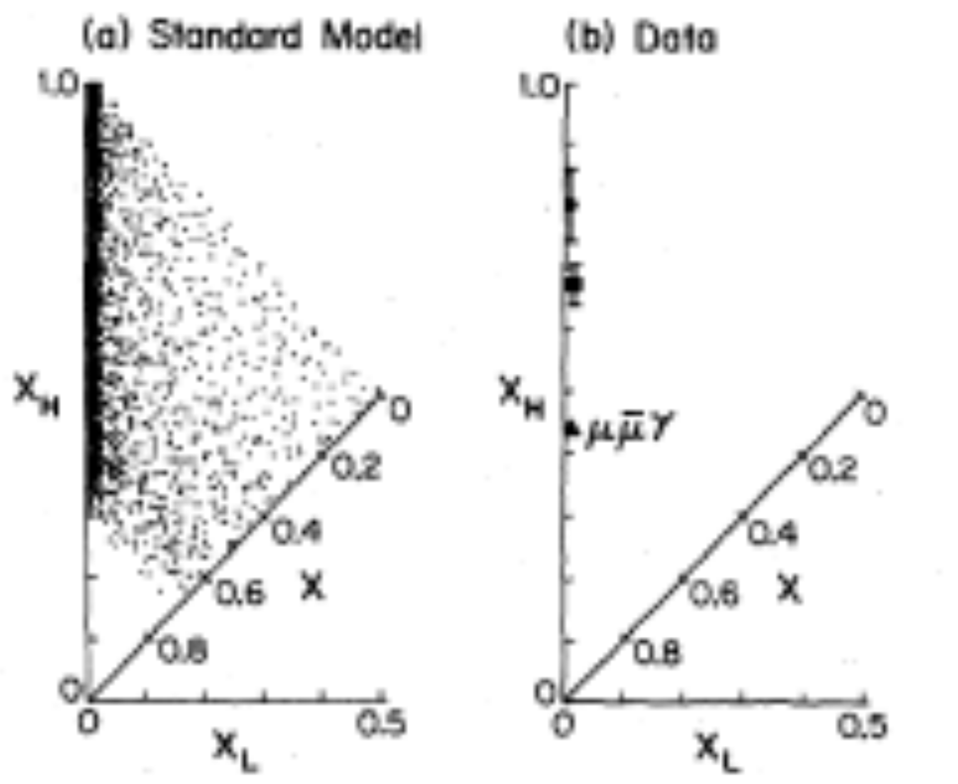


FIG. 1. (a) Dalitz plot for the process $p\bar{p}\rightarrow l^+l^-\gamma$ + anything, in the standard model with cuts as described in the text. (b) Dalitz-plot locations of data points from Refs. 2 ($e^+e^-\gamma$) and 4 ($\mu^+\mu^-\gamma$).

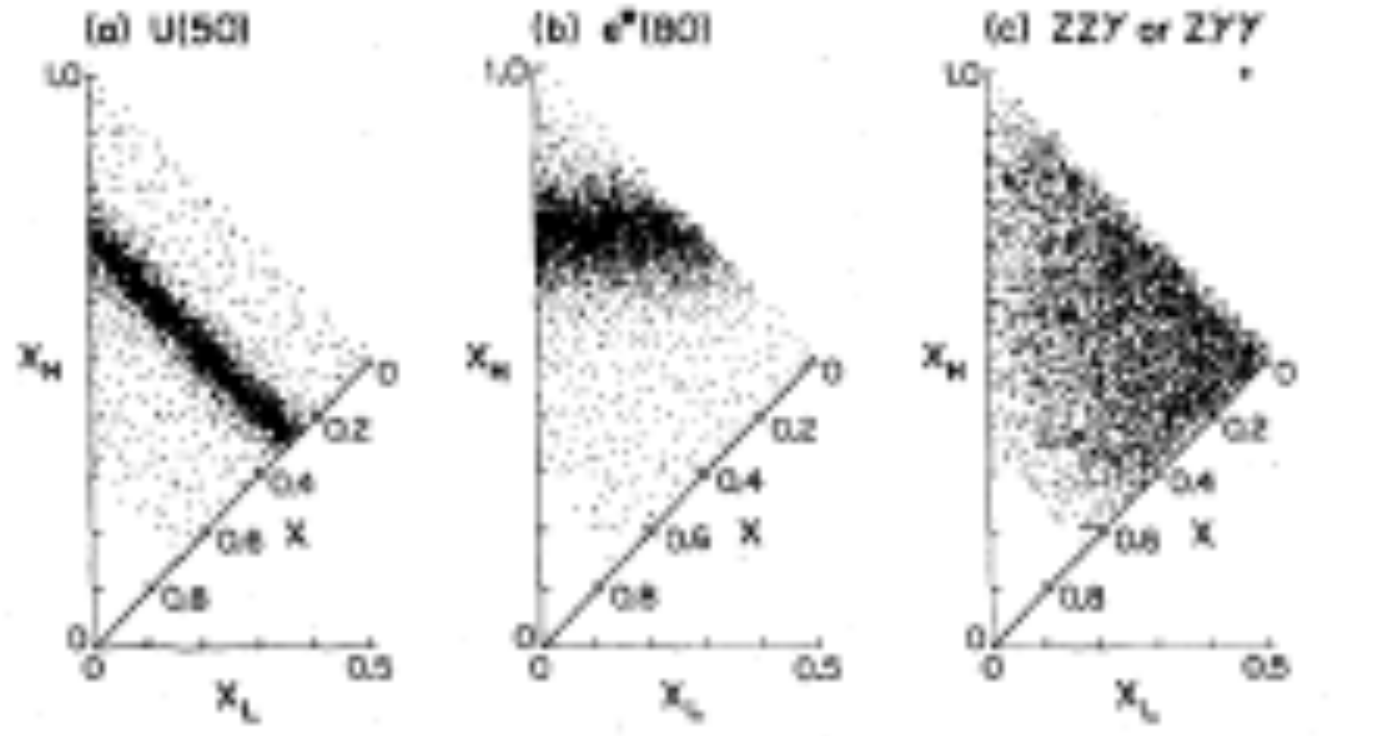
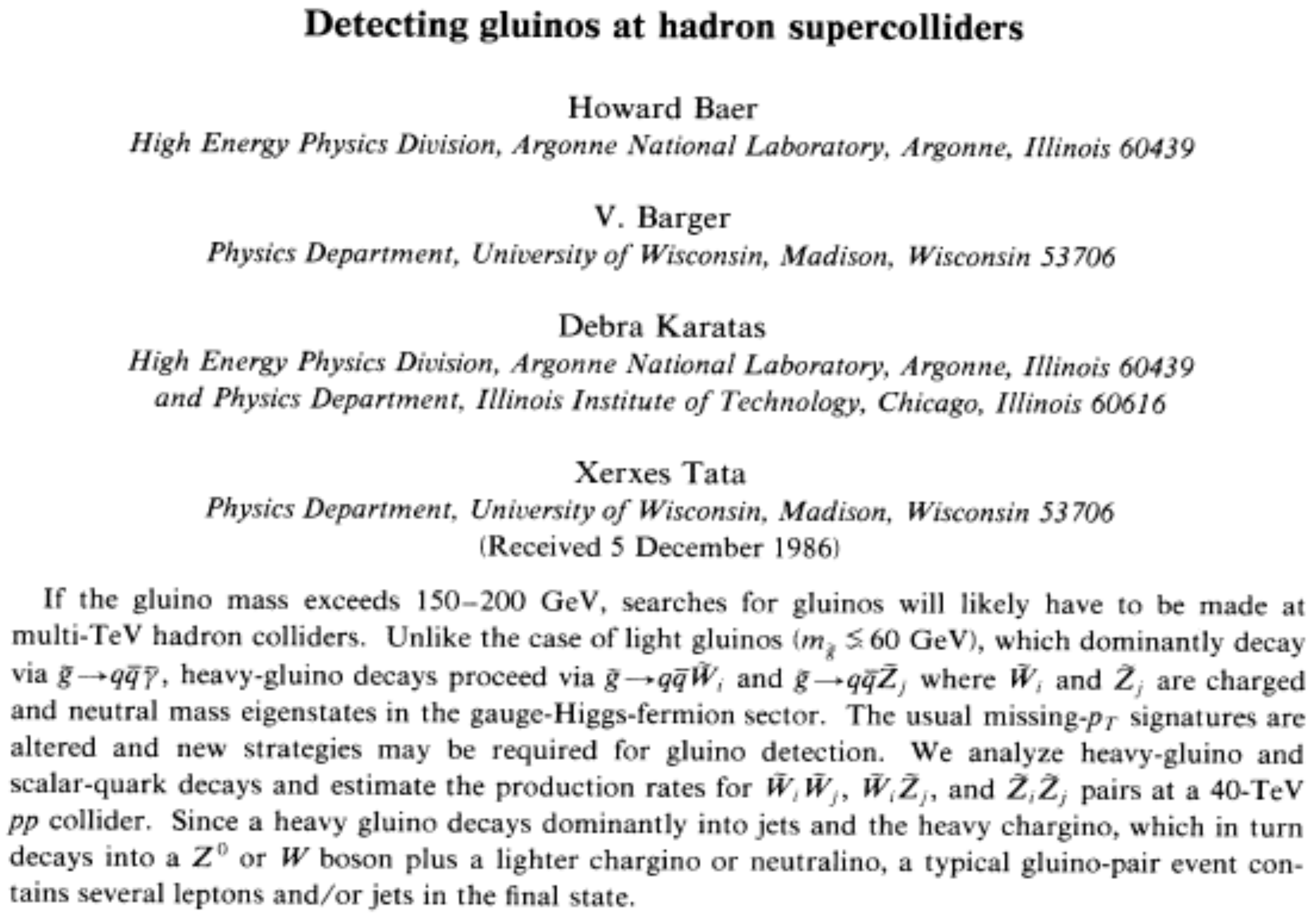


FIG. 2. Dalitz plots for the process $p\bar{p}\rightarrow l^+l^-\gamma$ + anything, for alternative models of radiative Z decay with cuts. The models illustrated are (a) $Z\rightarrow U\gamma$ with $m_U=50$ GeV, (b) $Z\rightarrow e^*\bar{e}+e\bar{e}^*$ with $m_{e^*}=80$ GeV, and (c) $Z\rightarrow Z^*\gamma$ or $\gamma^*\gamma$.

looked like bremsstrahlung

1984-1985-1986

- John Ellis thought monjet+MET signal at CERN SppbarS was SUSY
- Had help simulating signal from Henrik Kowalski, but Henrik had experimental duties, so CERN theory group hired a MC jock (me) to help explore exotic events that were appearing at UA1/UA2
- Went to CERN Fall 1984, met Xerxes Tata and collaborated with John& Dimitri
- Returned to USA in Fall 1985 (Argonne NL) where we developed SUSY cascade decays 1986 (after 900 mile Back river expedition)



Detecting gluinos at hadron supercolliders

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V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

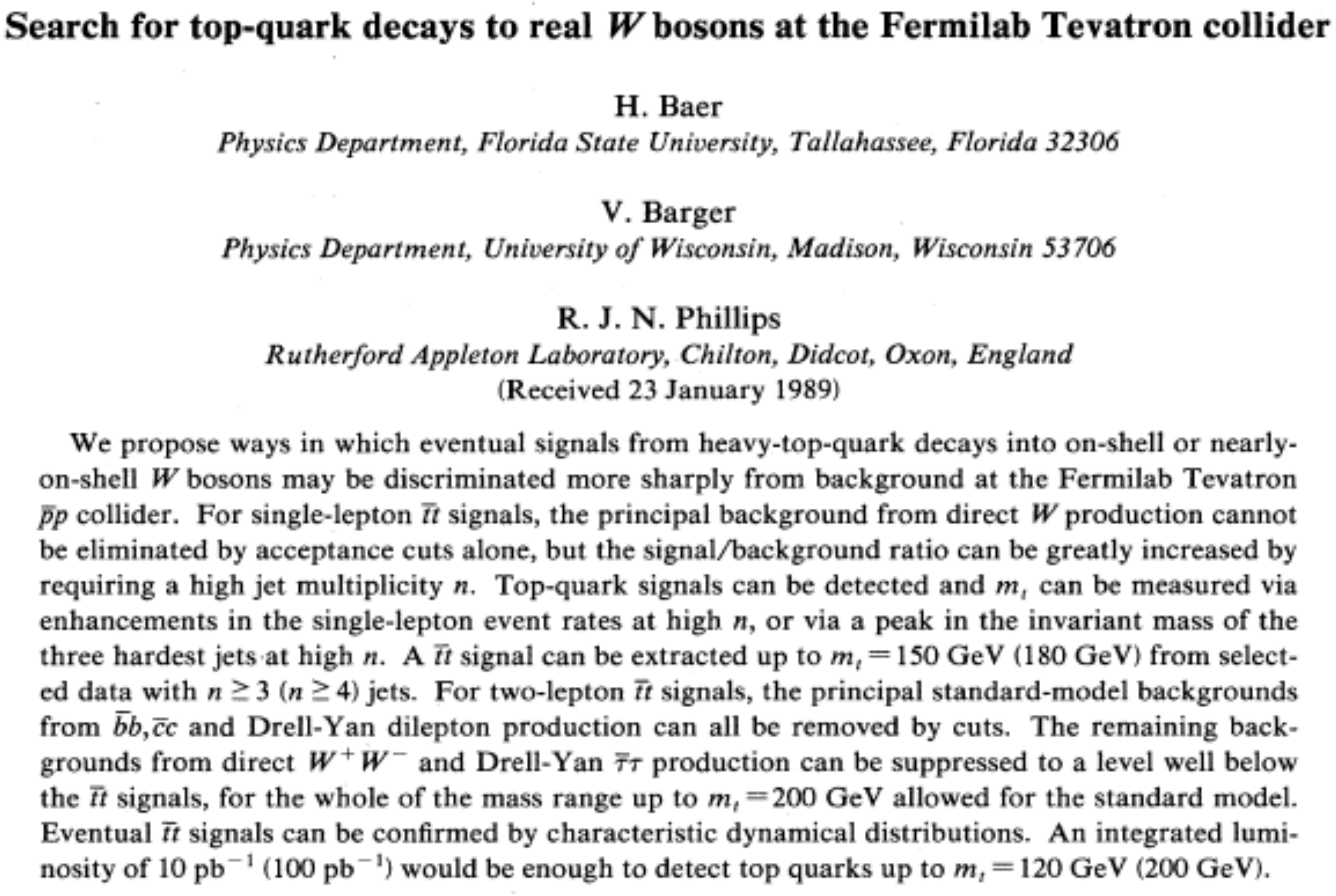
Debra Karatas
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
and Physics Department, Illinois Institute of Technology, Chicago, Illinois 60616

Xerxes Tata
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

(Received 5 December 1986)

If the gluino mass exceeds 150–200 GeV, searches for gluinos will likely have to be made at multi-TeV hadron colliders. Unlike the case of light gluinos ($m_{\tilde{g}} \lesssim 60$ GeV), which dominantly decay via $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$, heavy-gluino decays proceed via $\tilde{g} \rightarrow q\bar{q}\tilde{W}_i$ and $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_j$ where $\tilde{W}_i$ and $\tilde{Z}_j$ are charged and neutral mass eigenstates in the gauge-Higgs-fermion sector. The usual missing-p_T signatures are altered and new strategies may be required for gluino detection. We analyze heavy-gluino and scalar-quark decays and estimate the production rates for $\tilde{W}_i\tilde{W}_j$, $\tilde{W}_i\tilde{Z}_j$, and $\tilde{Z}_i\tilde{Z}_j$ pairs at a 40-TeV *pp* collider. Since a heavy gluino decays dominantly into jets and the heavy chargino, which in turn decays into a Z^0 or W boson plus a lighter chargino or neutralino, a typical gluino-pair event contains several leptons and/or jets in the final state.

culmination of top-quark papers



Search for top-quark decays to real W bosons at the Fermilab Tevatron collider

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V. Barger
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R. J. N. Phillips
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(Received 23 January 1989)

We propose ways in which eventual signals from heavy-top-quark decays into on-shell or nearly-on-shell W bosons may be discriminated more sharply from background at the Fermilab Tevatron $\bar{p}p$ collider. For single-lepton $\bar{t}t$ signals, the principal background from direct W production cannot be eliminated by acceptance cuts alone, but the signal/background ratio can be greatly increased by requiring a high jet multiplicity n. Top-quark signals can be detected and m_t can be measured via enhancements in the single-lepton event rates at high n, or via a peak in the invariant mass of the three hardest jets at high n. A $\bar{t}t$ signal can be extracted up to $m_t = 150$ GeV (180 GeV) from selected data with $n \geq 3$ ($n \geq 4$) jets. For two-lepton $\bar{t}t$ signals, the principal standard-model backgrounds from $\bar{b}b, \bar{c}c$ and Drell-Yan dilepton production can all be removed by cuts. The remaining backgrounds from direct W^+W^- and Drell-Yan $\bar{\tau}\tau$ production can be suppressed to a level well below the $\bar{t}t$ signals, for the whole of the mass range up to $m_t = 200$ GeV allowed for the standard model. Eventual $\bar{t}t$ signals can be confirmed by characteristic dynamical distributions. An integrated luminosity of 10 pb^{-1} (100 pb^{-1}) would be enough to detect top quarks up to $m_t = 120$ GeV (200 GeV).

*introduced H_T variable

since didn't know of CDF

b-tagging at the time

*top-quark discovered

1995 by CDF with ~100 pb-1

VB and I had a hiatus for next 17 years until my sabbatical at UW in Fall, 2006

Then began ramping up for initial LHC runs and potential

for discovery of standard SUSY (CMSSM)

Alas, the expected SUSY signals failed

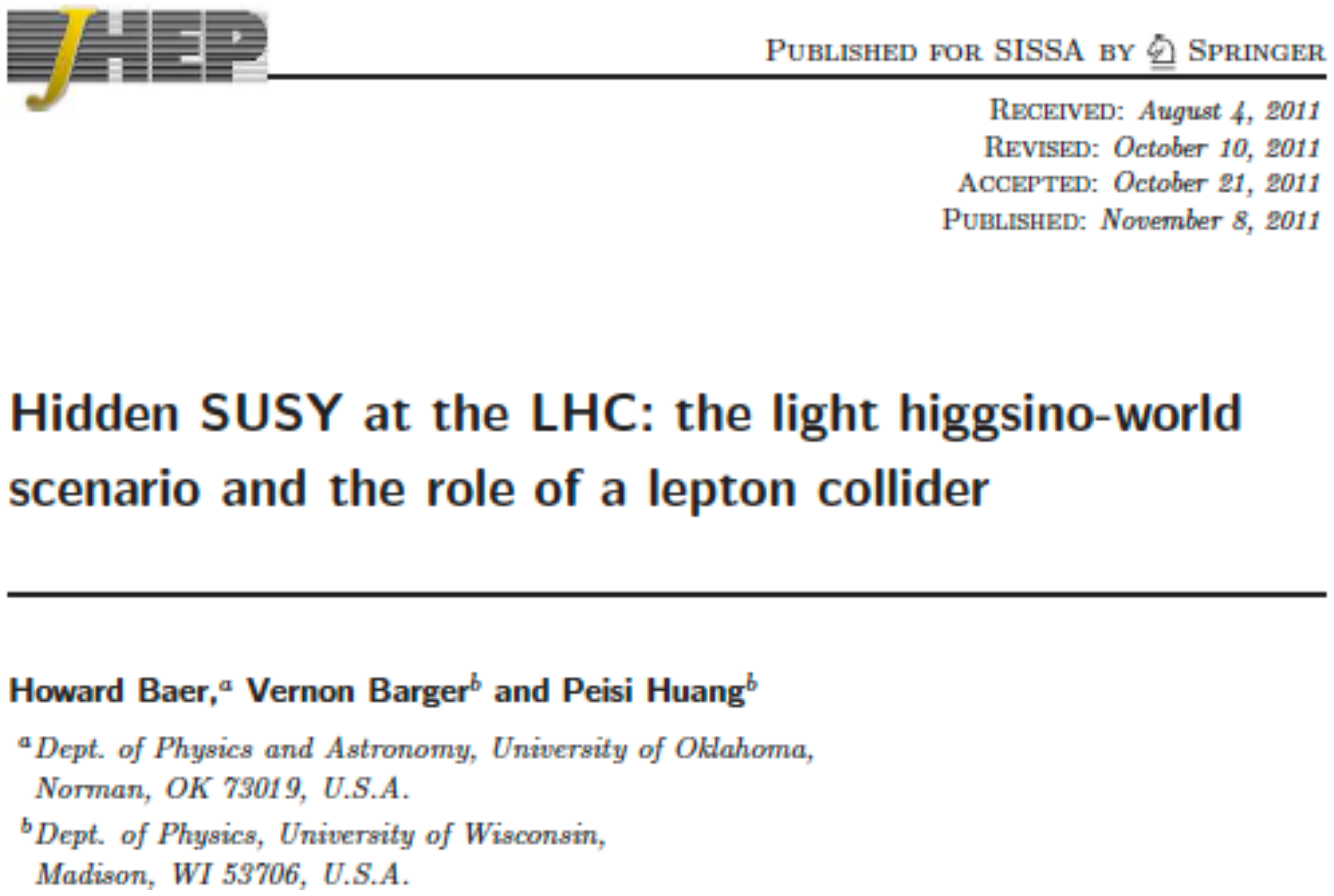
to materialize although mh(125) did-

this raised the naturalness question

to prominence!

toward the little hierarchy problem

- low mu scenario, light higgsinos in NUHM2,3,4
- implications of h(125) for SUSY searches: NUHM with large A0



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Accepted: *October 21, 2011*
Published: *November 8, 2011*

Hidden SUSY at the LHC: the light higgsino-world scenario and the role of a lepton collider

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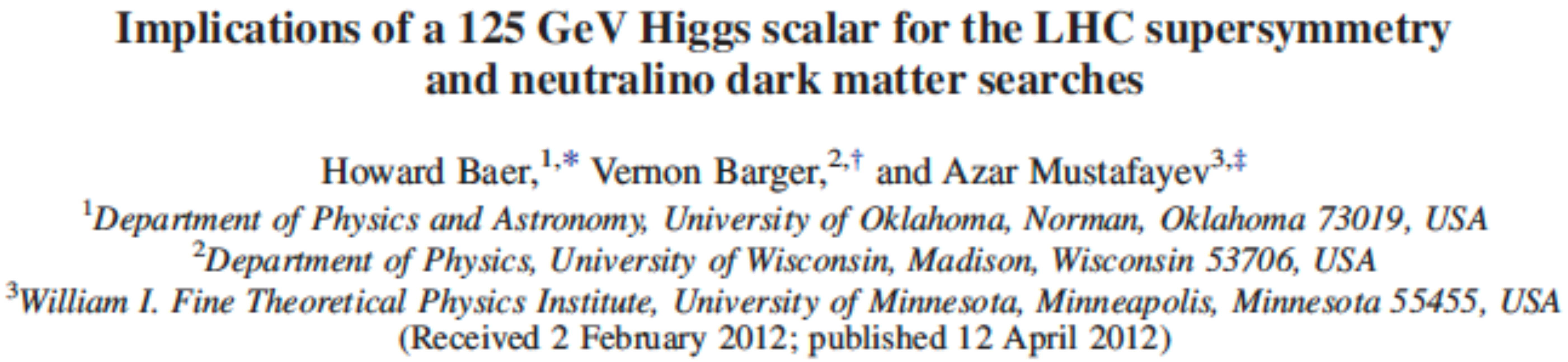
Norman, OK 73019, U.S.A.
[b] *Dept. of Physics, University of Wisconsin,*
Madison, WI 53706, U.S.A.



Implications of a 125 GeV Higgs scalar for the LHC supersymmetry and neutralino dark matter searches

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[2] *Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*
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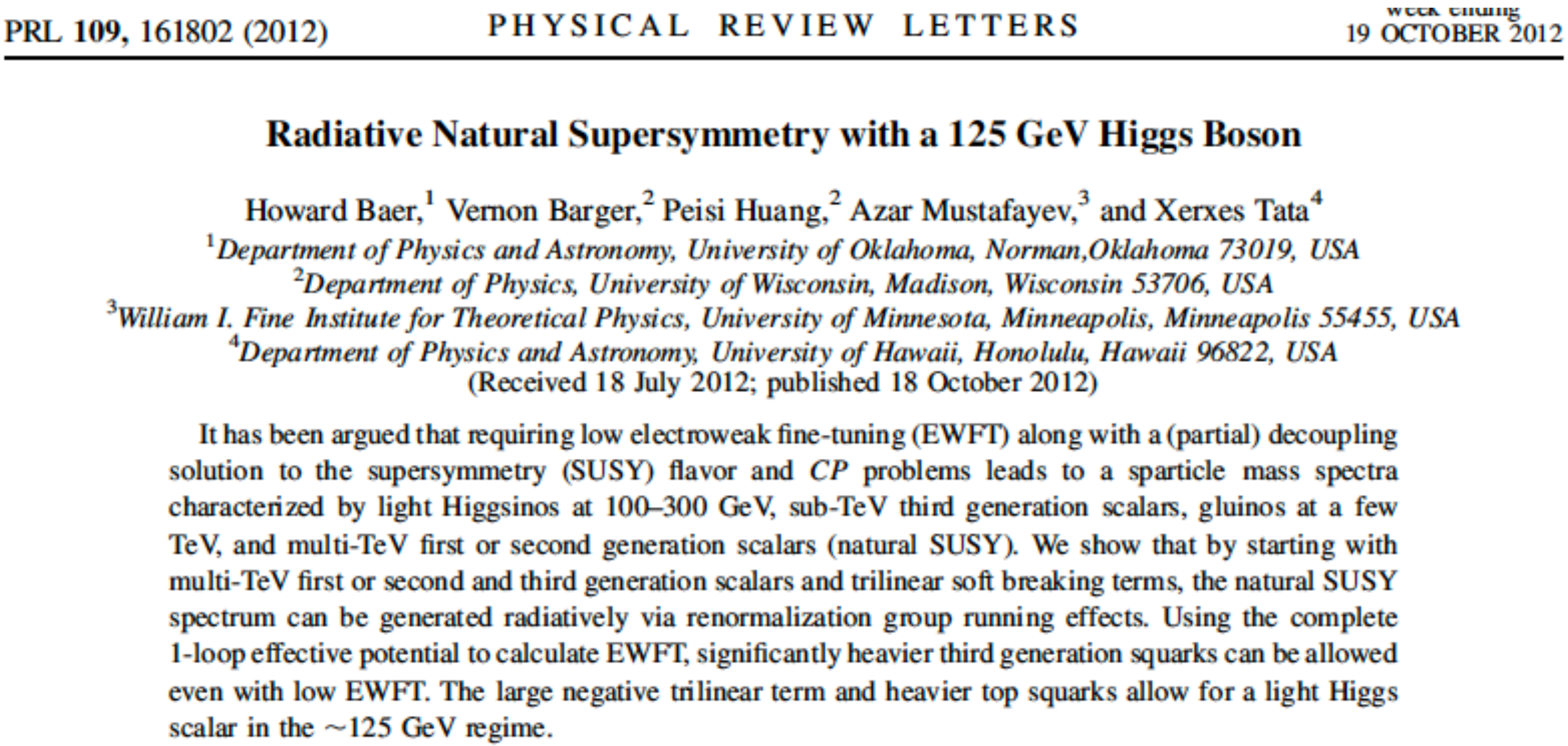
(Received 2 February 2012; published 12 April 2012)

In this paper, we found the correct naturalness measure DEW and showed how natural SUSY could be generated radiatively



PRL **109,** 161802 (2012) PHYSICAL REVIEW LETTERS week ending
19 OCTOBER 2012

Radiative Natural Supersymmetry with a 125 GeV Higgs Boson

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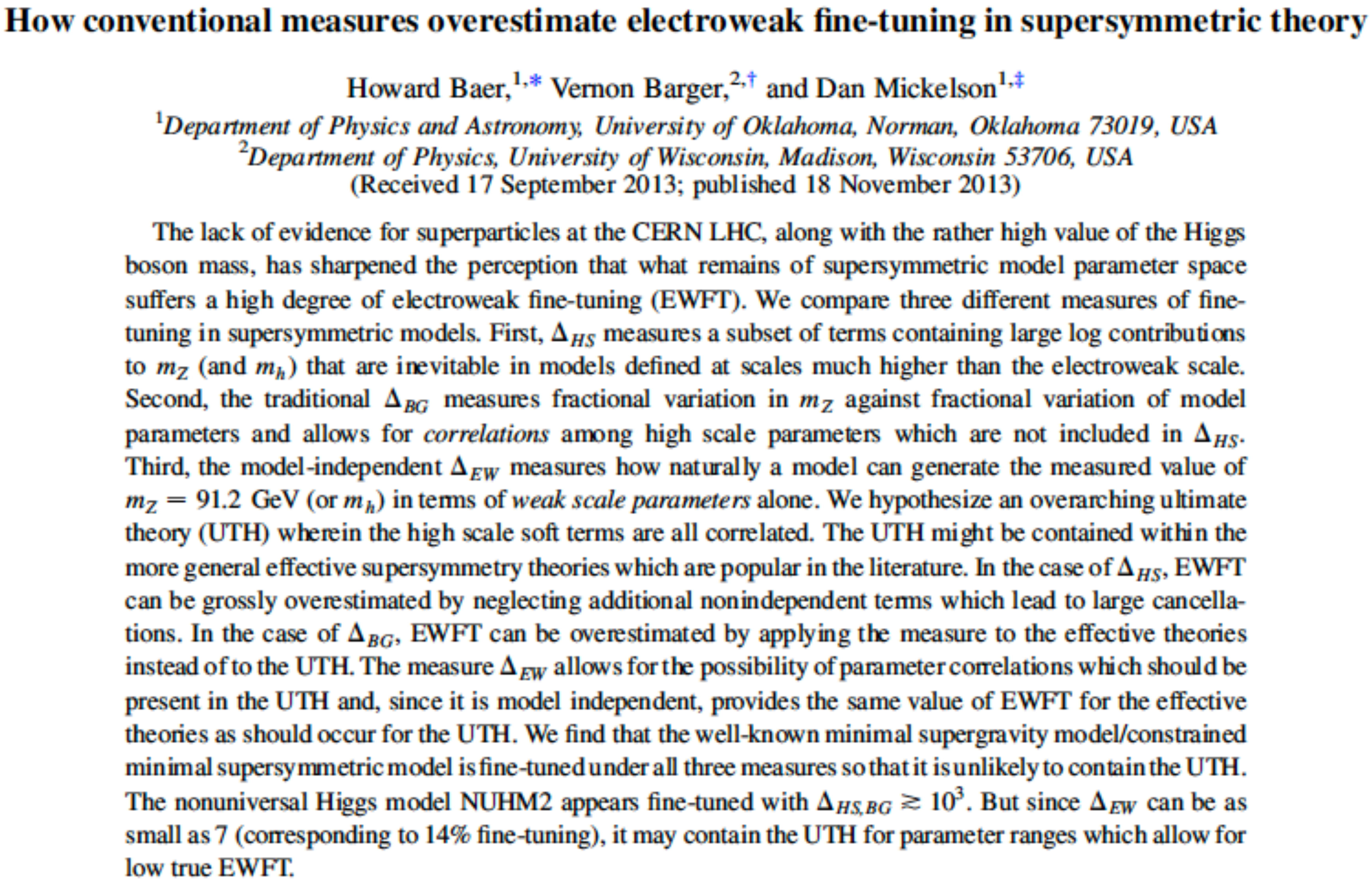
(Received 18 July 2012; published 18 October 2012)

It has been argued that requiring low electroweak fine-tuning (EWFT) along with a (partial) decoupling solution to the supersymmetry (SUSY) flavor and *CP* problems leads to a sparticle mass spectra characterized by light Higgsinos at 100–300 GeV, sub-TeV third generation scalars, gluinos at a few TeV, and multi-TeV first or second generation scalars (natural SUSY). We show that by starting with multi-TeV first or second and third generation scalars and trilinear soft breaking terms, the natural SUSY spectrum can be generated radiatively via renormalization group running effects. Using the complete 1-loop effective potential to calculate EWFT, significantly heavier third generation squarks can be allowed even with low EWFT. The large negative trilinear term and heavier top squarks allow for a light Higgs scalar in the ~125 GeV regime.

and then we showed how previous naturalness measures went wrong



How conventional measures overestimate electroweak fine-tuning in supersymmetric theory

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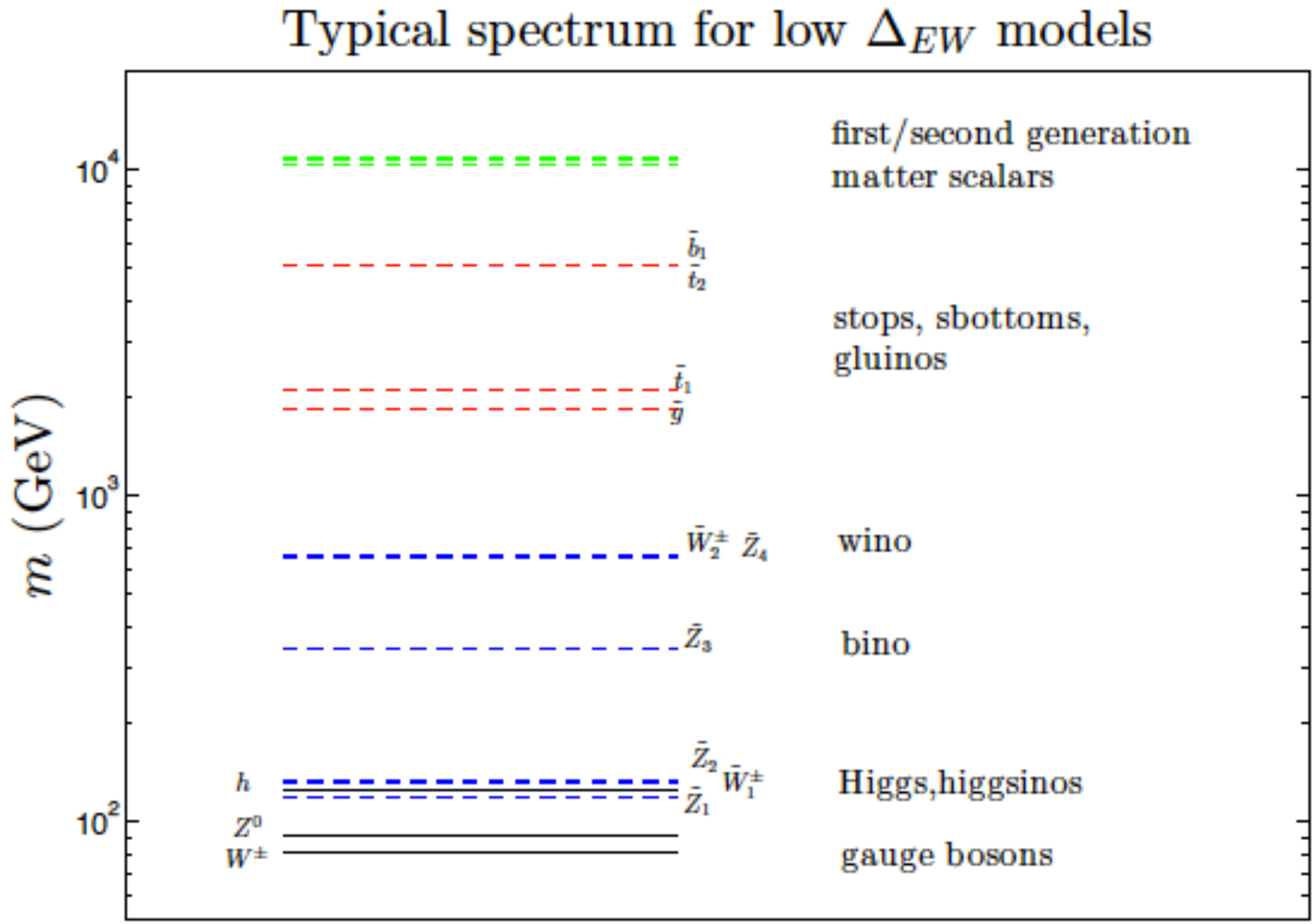
(Received 17 September 2013; published 18 November 2013)

The lack of evidence for superparticles at the CERN LHC, along with the rather high value of the Higgs boson mass, has sharpened the perception that what remains of supersymmetric model parameter space suffers a high degree of electroweak fine-tuning (EWFT). We compare three different measures of fine-tuning in supersymmetric models. First, Δ_{HS} measures a subset of terms containing large log contributions to m_Z (and m_h) that are inevitable in models defined at scales much higher than the electroweak scale. Second, the traditional Δ_{BG} measures fractional variation in m_Z against fractional variation of model parameters and allows for *correlations* among high scale parameters which are not included in Δ_{HS}. Third, the model-independent Δ_{EW} measures how naturally a model can generate the measured value of $m_Z = 91.2$ GeV (or m_h) in terms of *weak scale parameters* alone. We hypothesize an overarching ultimate theory (UTH) wherein the high scale soft terms are all correlated. The UTH might be contained within the more general effective supersymmetry theories which are popular in the literature. In the case of Δ_{HS}, EWFT can be grossly overestimated by neglecting additional nonindependent terms which lead to large cancellations. In the case of Δ_{BG}, EWFT can be overestimated by applying the measure to the effective theories instead of to the UTH. The measure Δ_{EW} allows for the possibility of parameter correlations which should be present in the UTH and, since it is model independent, provides the same value of EWFT for the effective theories as should occur for the UTH. We find that the well-known minimal supergravity model/constrained minimal supersymmetric model is fine-tuned under all three measures so that it is unlikely to contain the UTH. The nonuniversal Higgs model NUHM2 appears fine-tuned with $\Delta_{HS,BG} \gtrsim 10^3$. But since Δ_{EW} can be as small as 7 (corresponding to 14% fine-tuning), it may contain the UTH for parameter ranges which allow for low true EWFT.



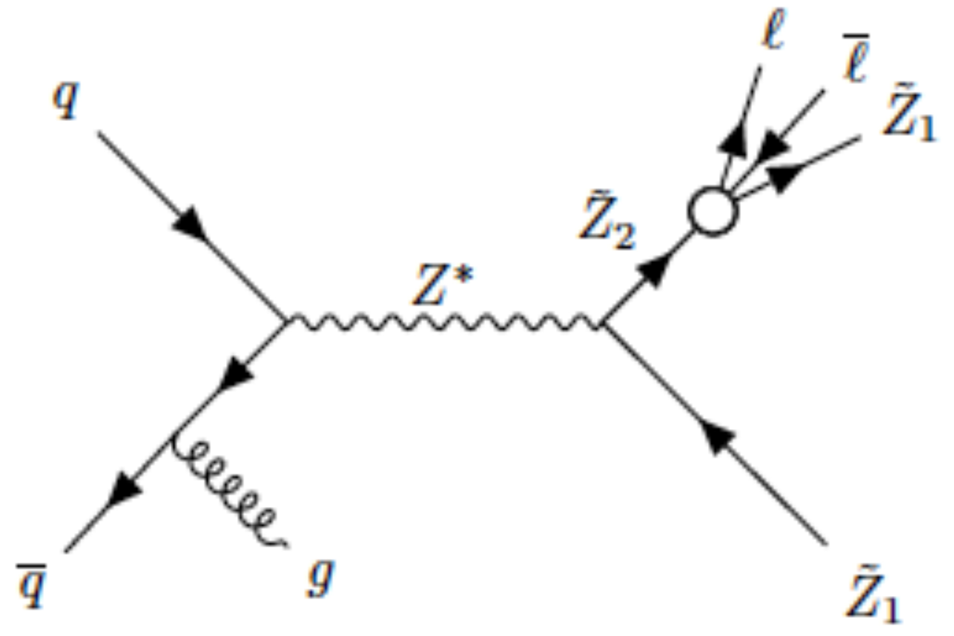
Typical spectrum for low Δ_{EW} models

There is a Little Hierarchy, but it is no problem

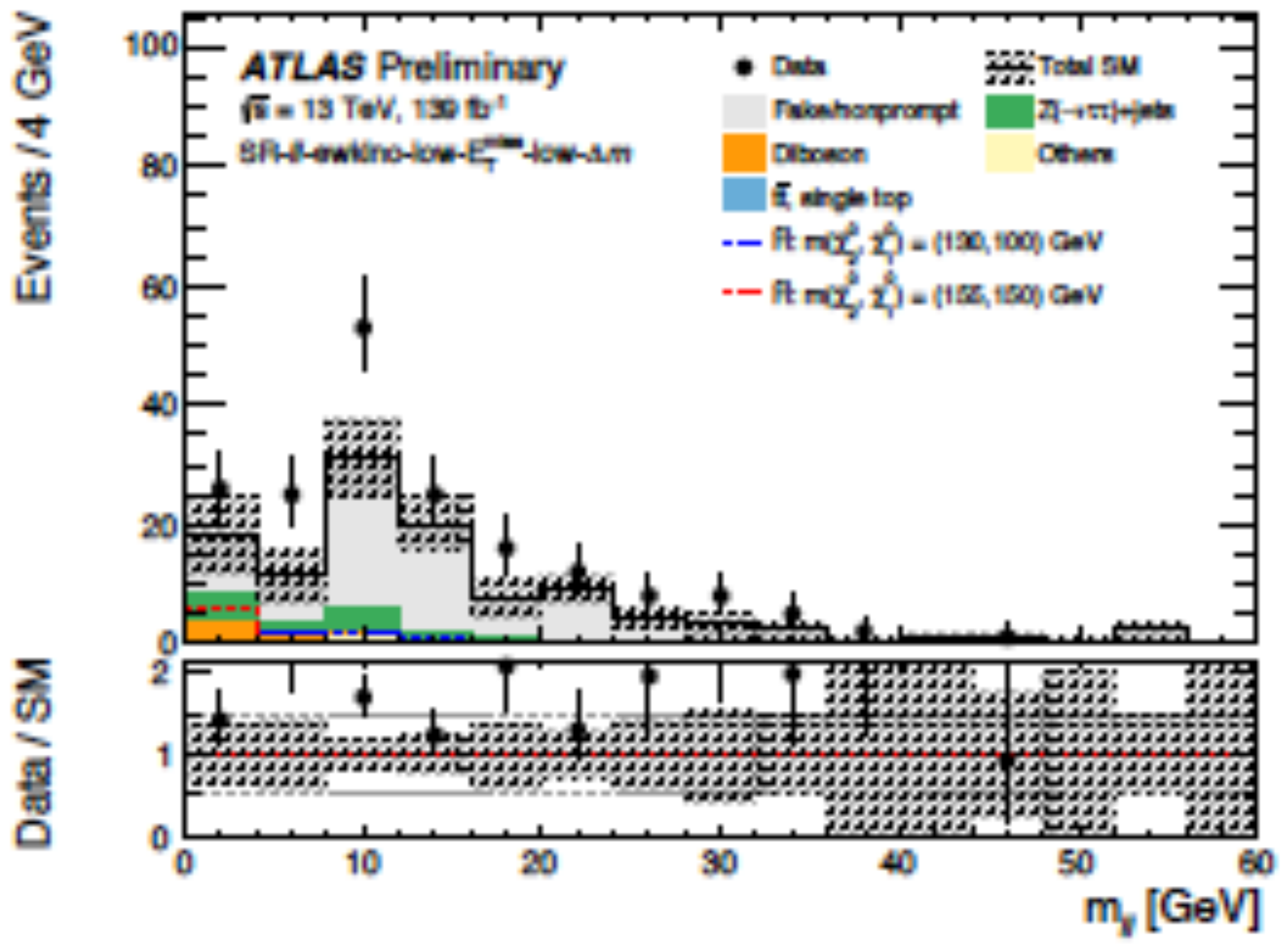
$\mu \ll m_{3/2}$ higgsinos likely the lightest superparticles!

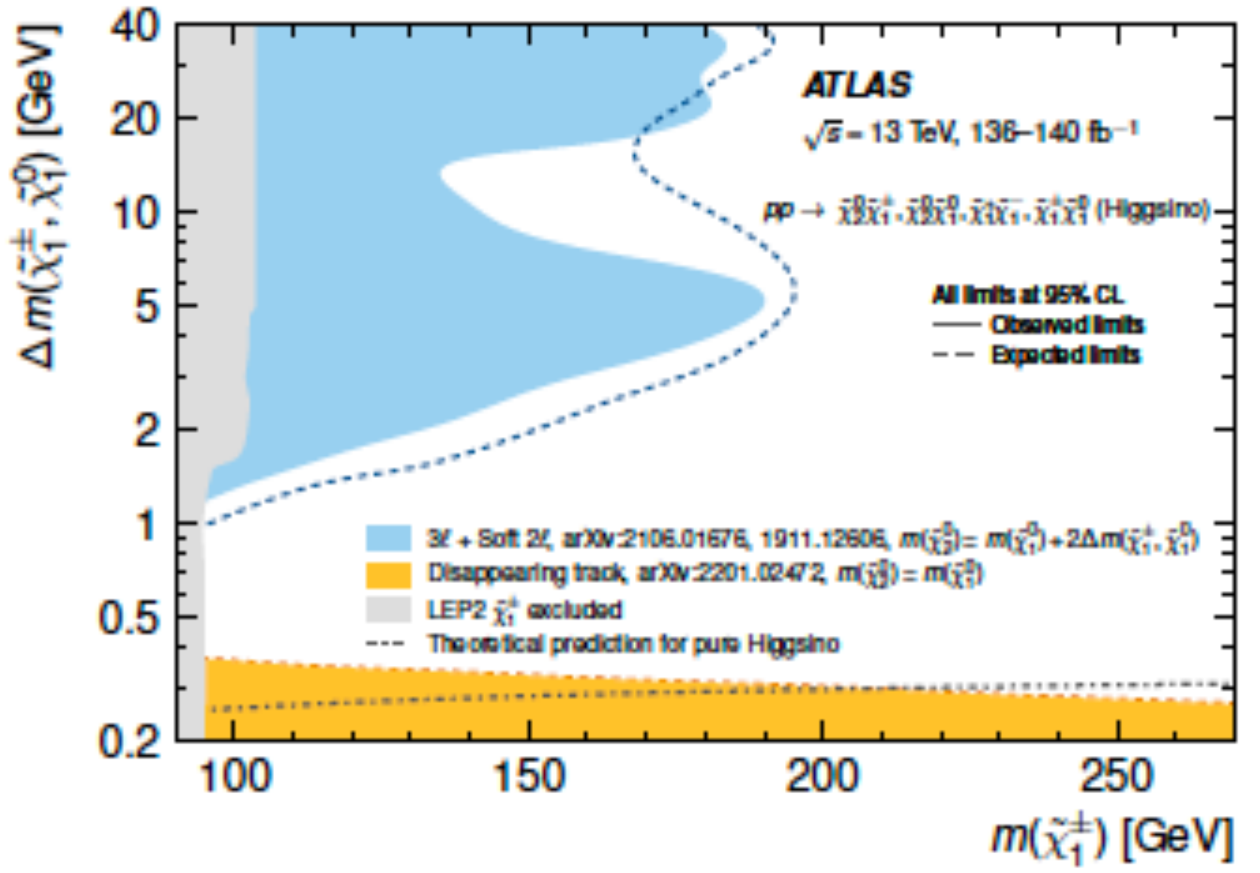
Natural SUSY: only higgsinos need lie close to weak scale

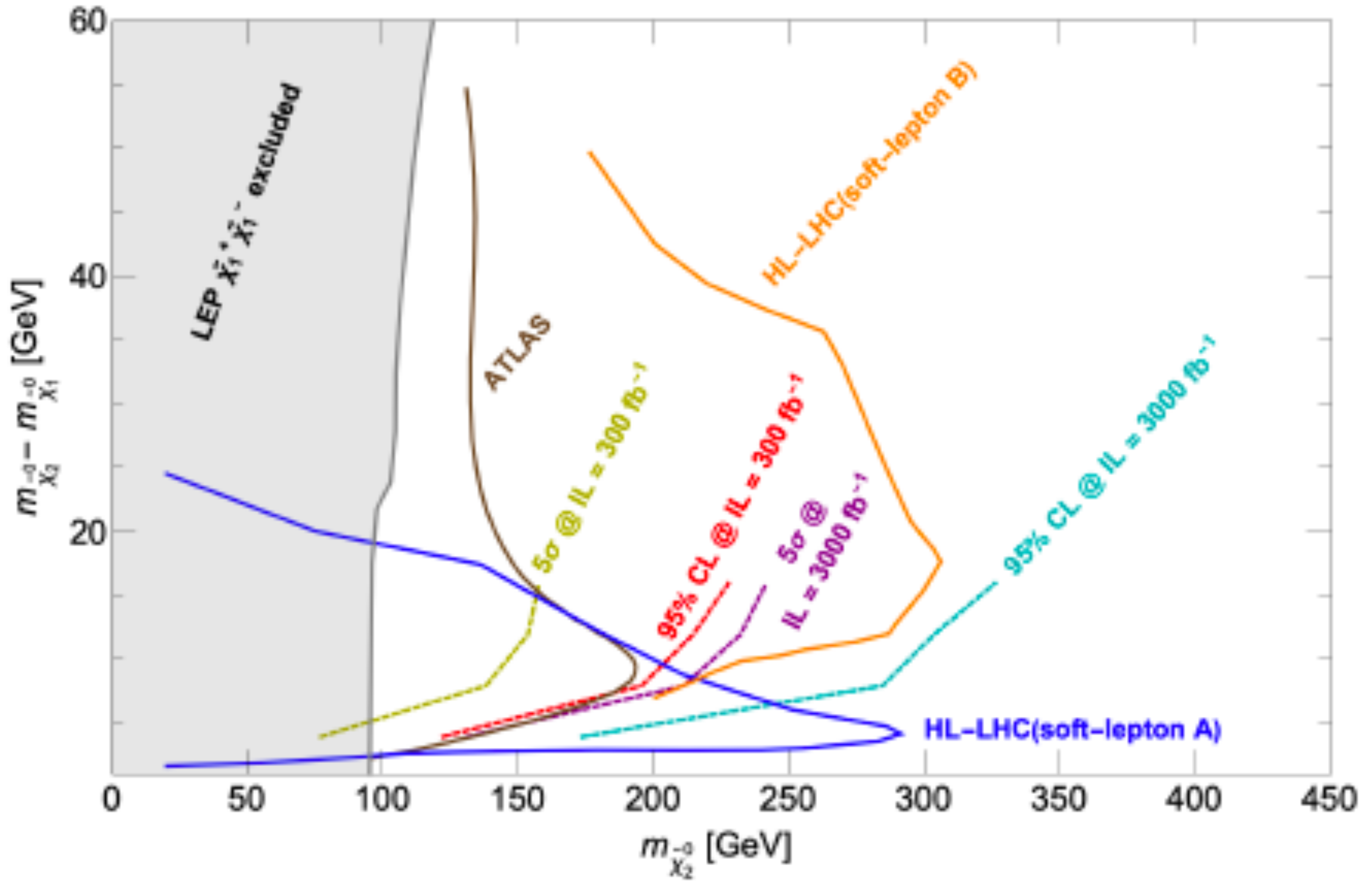
Soft dilepton+jet+MET signature from higgsino pair production



HB, Barger, Huang, 1107.5581;
Z. Han, Kribs, Martin, Menon, 1401.1235;
HB, Mustafayev, Tata; 1409.7058;
C. Han, Kim, Munir, Park, 1502.03734;
HB, Barger, Savoy, Tata, 1604.07438;
HB, Barger, Salam, Sengupta, Tata,2007.09252;
HB, Barger, Sengupta, Tata, 2109.14030



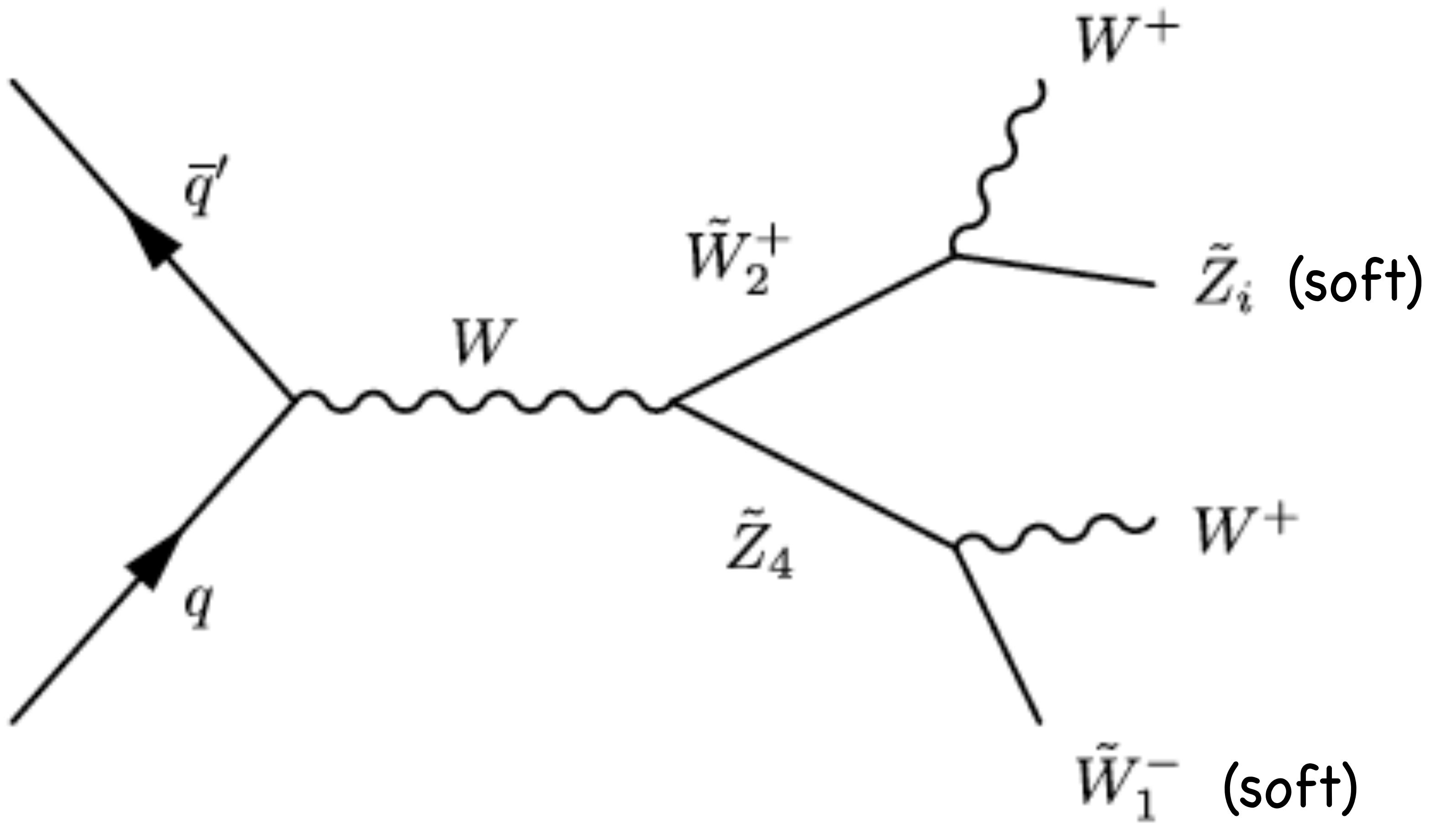




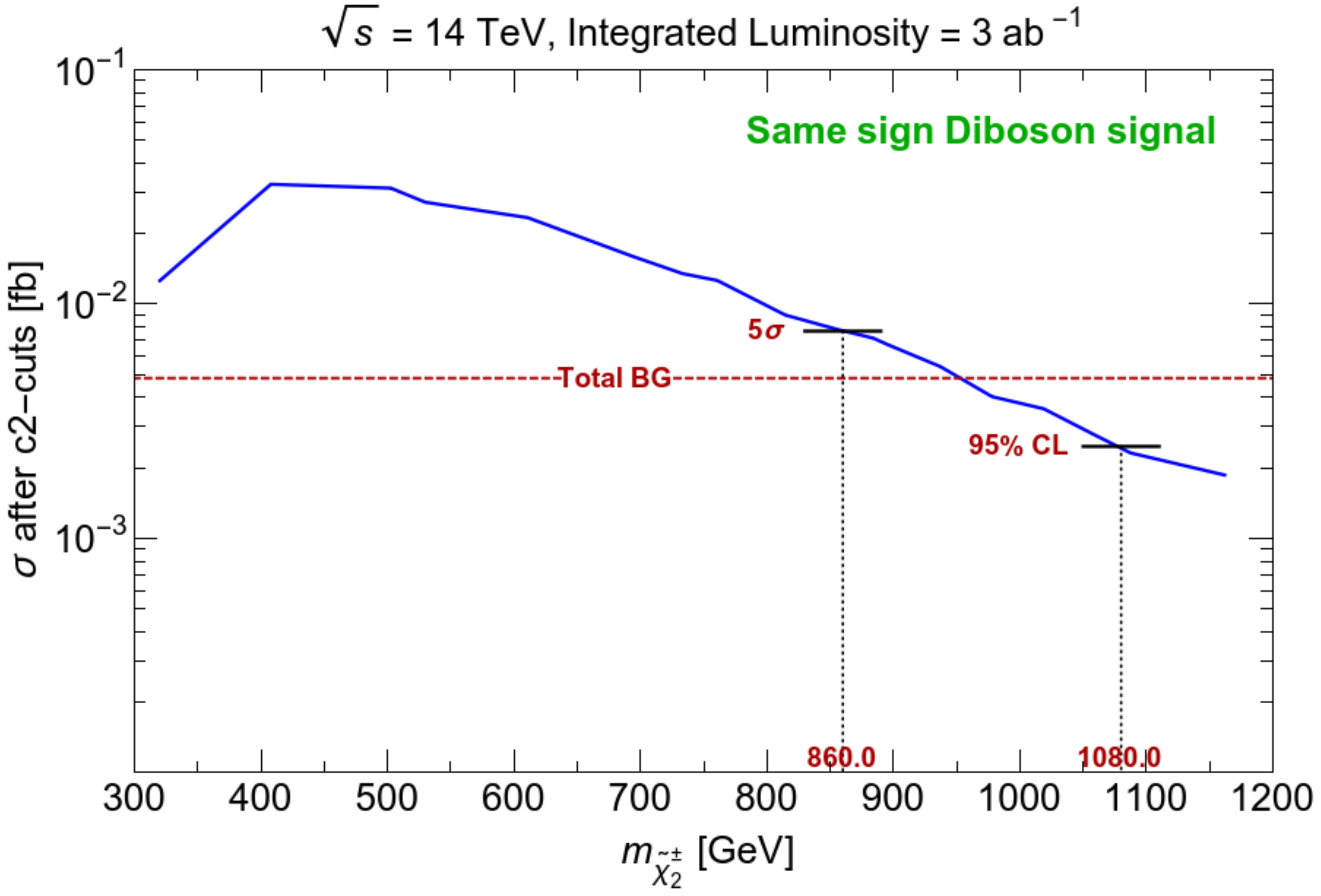
It appears that HL-LHC can see much (but not all) of natural SUSY p-space;
signal in this channel should emerge slowly as more integrated luminosity accrues

ATLAS/CMS: 2-sigma excess from Run 2!

Distinctive new same-sign diboson (SSdB) signature from SUSY models with light higgsinos!



wino pair production



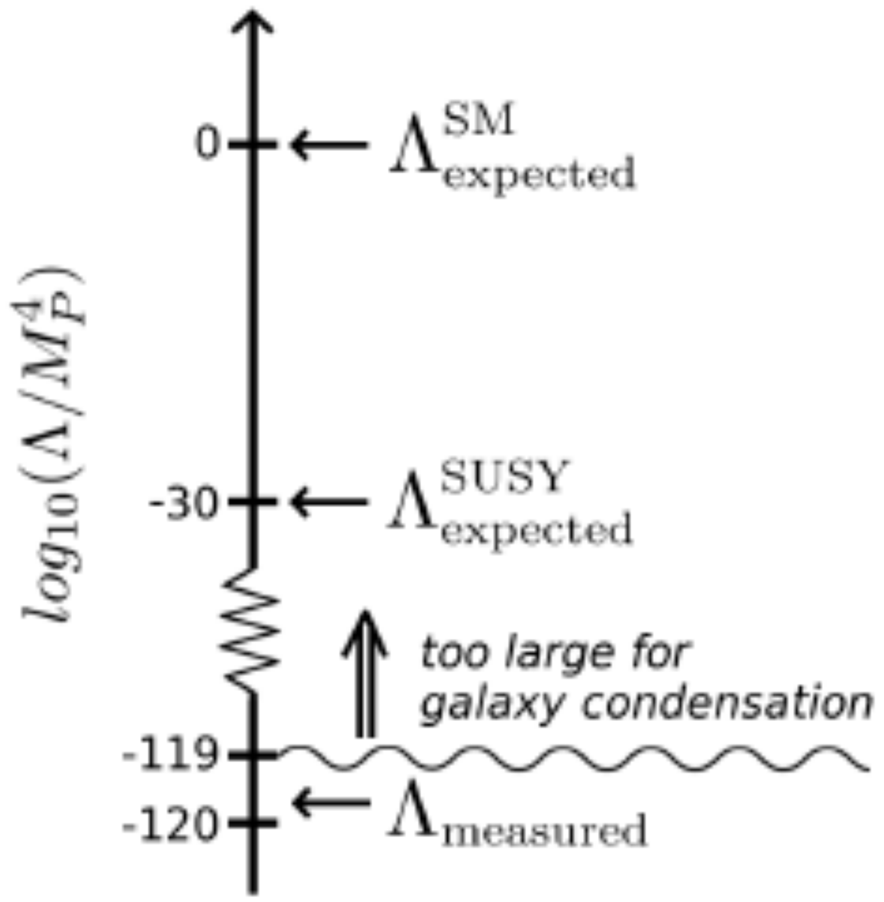
This channel offers added reach of LHC14 for natSUSY; it is also indicative of wino-pair prod'n followed by decay to higgsinos

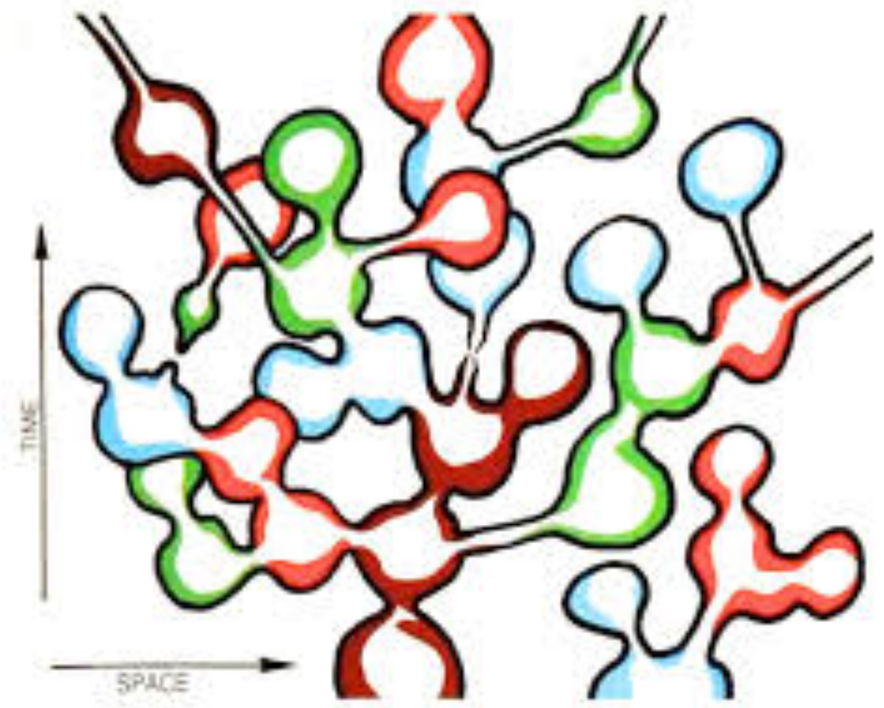
So far: no distinct ATLAS/CMS analysis

H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, W. Sreethawong and X. Tata, *Phys. Rev. Lett.* **110** (2013) 151801.

How does this all relate to string landscape?

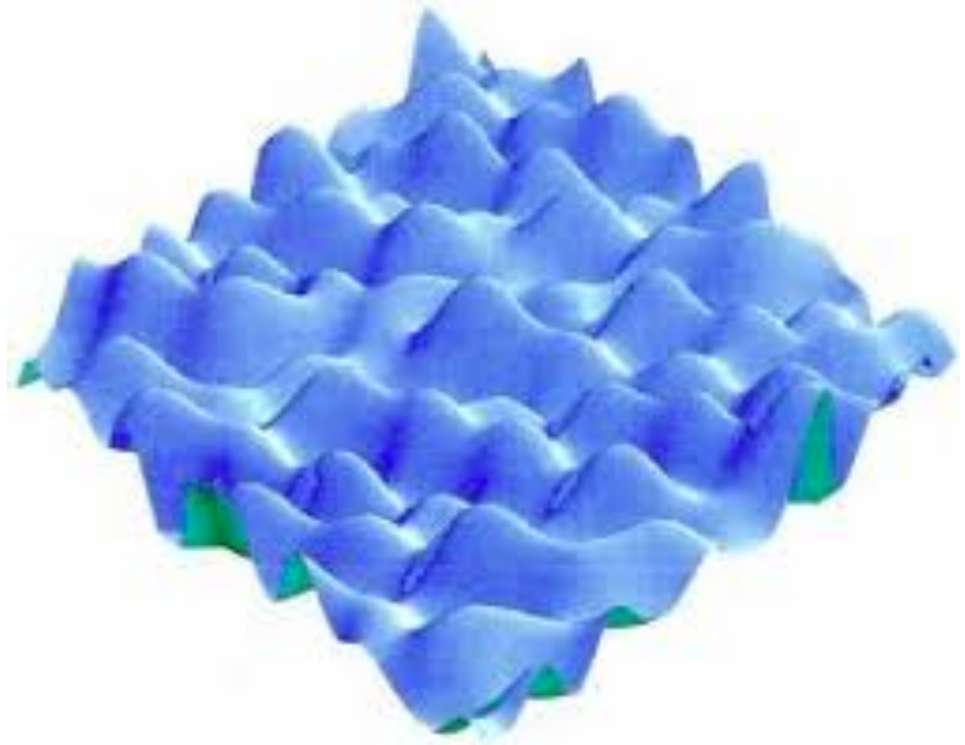
It is sometimes invoked that maybe we should abandon naturalness:
after all, isn't the cosmological constant (CC) fine-tuned?





eternally inflating
multiverse

In the landscape with 10^500 vacua with different CCs,
then the tiny value of the CC may not be surprising since
larger values would lead to runaway pocket universes
where galaxies wouldn't condense-
anthropics: no observers in such universes (Weinberg)



Bousso &
Polchinski

The CC is as natural as possible subject to the condition
that it leads to galaxy condensation

For some recent review material, see M. Douglas,
The String Theory Landscape, 2018, Universe 5 (2019) 7, 176

In fertile patch of vacua with MSSM as weak scale effective theory
but with no preferred SUSY breaking scale...

$$dP/d\mathcal{O} \sim f_{prior} \cdot f_{selection}$$

What is f(prior) for SUSY breaking scale?

In string theory, usually multiple (~10) hidden sectors
containing a variety of F- and D- breaking fields

For comparable <Fi> and <Dj> values, then expect

$$f_{prior} \sim m_{soft}^{2n_F+n_D-1}$$

Douglas ansatz

arXiv:0405279

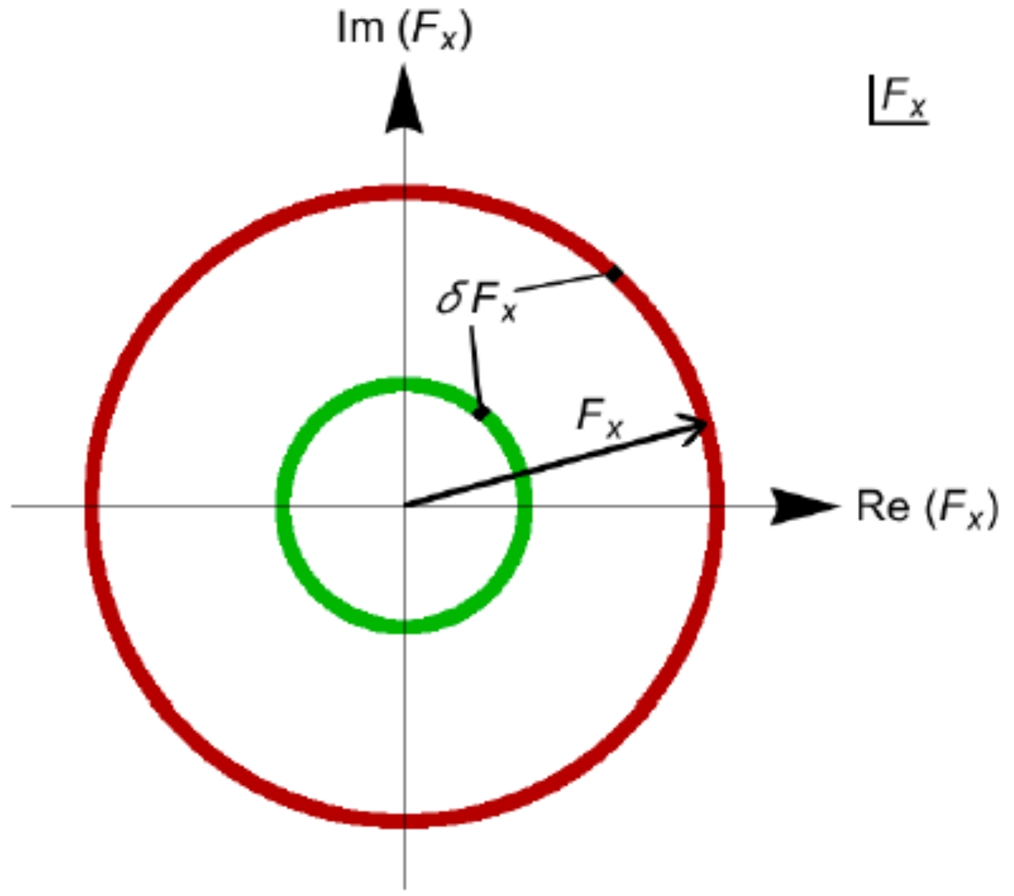


Figure 1: Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

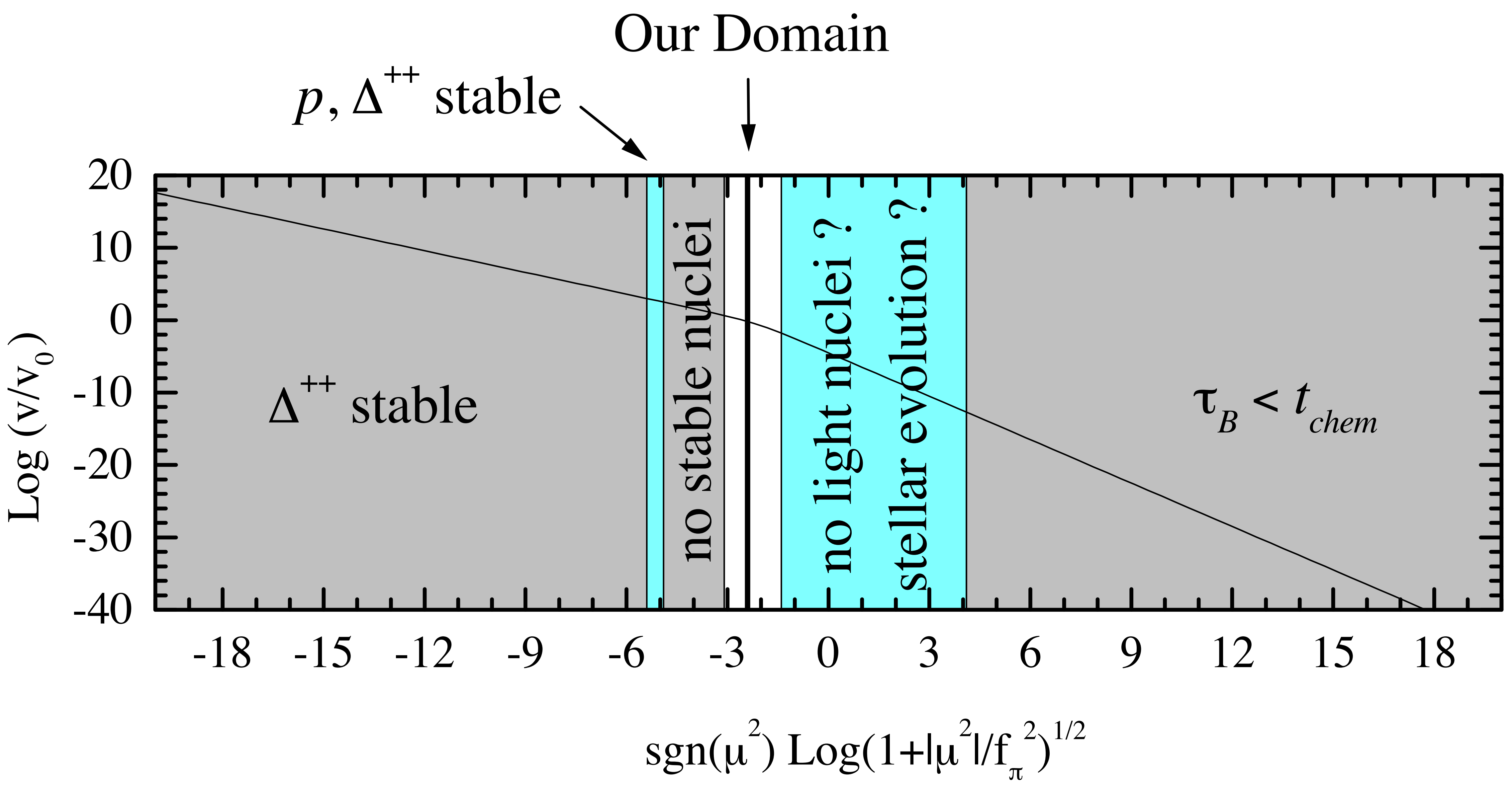
Under single F-term
SUSY breaking,
expect linearly increasing
statistical selection
of soft terms

For uniform values of SUSY breaking fields,
expect landscape to prefer
high scale of SUSY breaking!

$$m_{hidden}^4 = \sum_i F_i F_i^\dagger + D_\alpha D_\alpha$$

What about f_selection ?

Agrawal, Barr, Donoghue, Seckel result (1998):
pocket-universe value of weak scale
cannot deviate by more than
factor 2-5 from its measured value
lest disasters occur in nuclear physics: no nuclei, no atoms
(violates atomic principle)

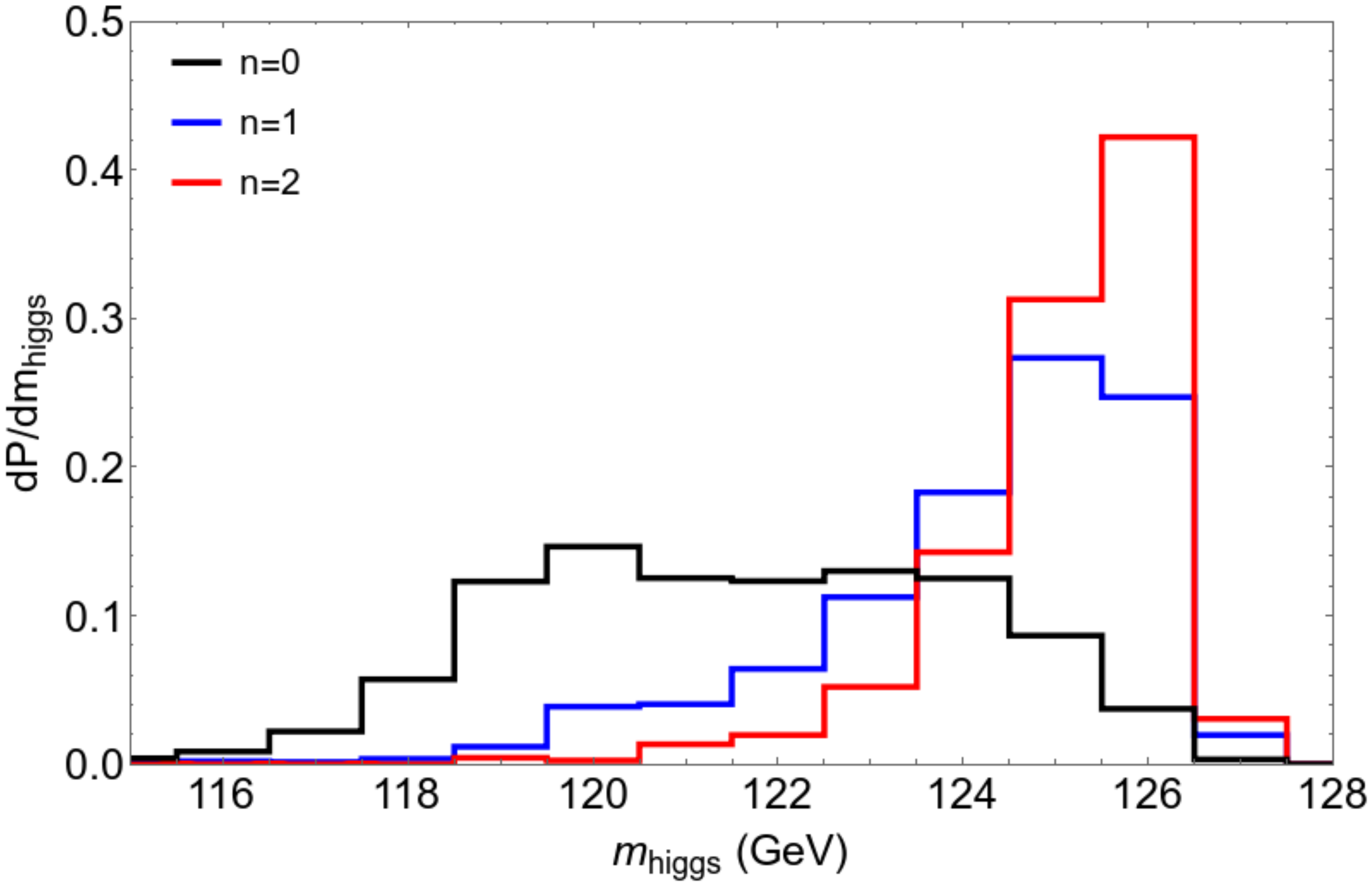


m(weak) must lie within ABDS window to have atoms/chemistry:
~50 GeV < m(weak) < ~350 GeV

ABDS window <=> DEW<~30

Making the picture more quantitative:

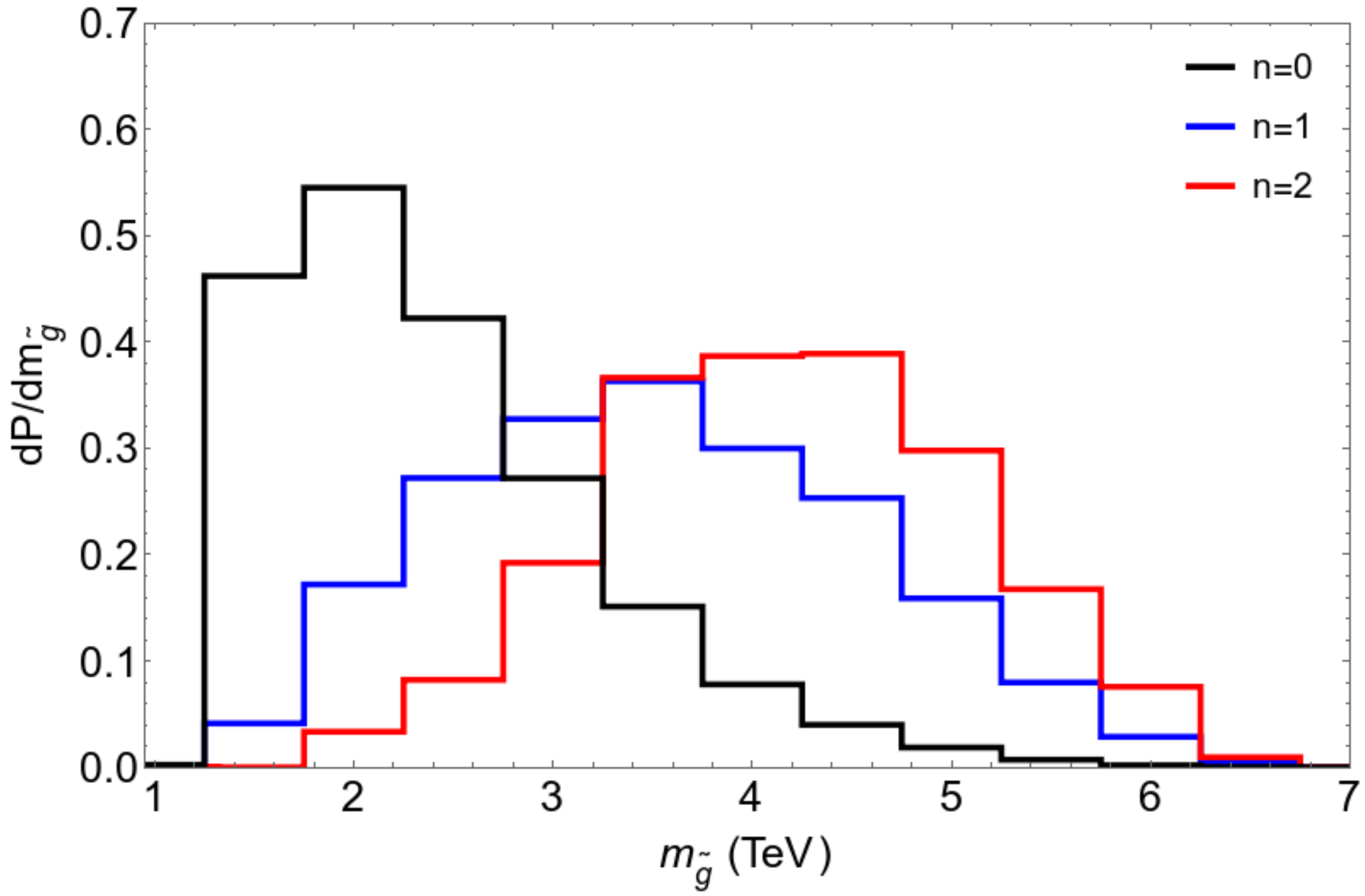
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} dm^2_{hidden}$$



m(h)~125 most favored for n=1,2

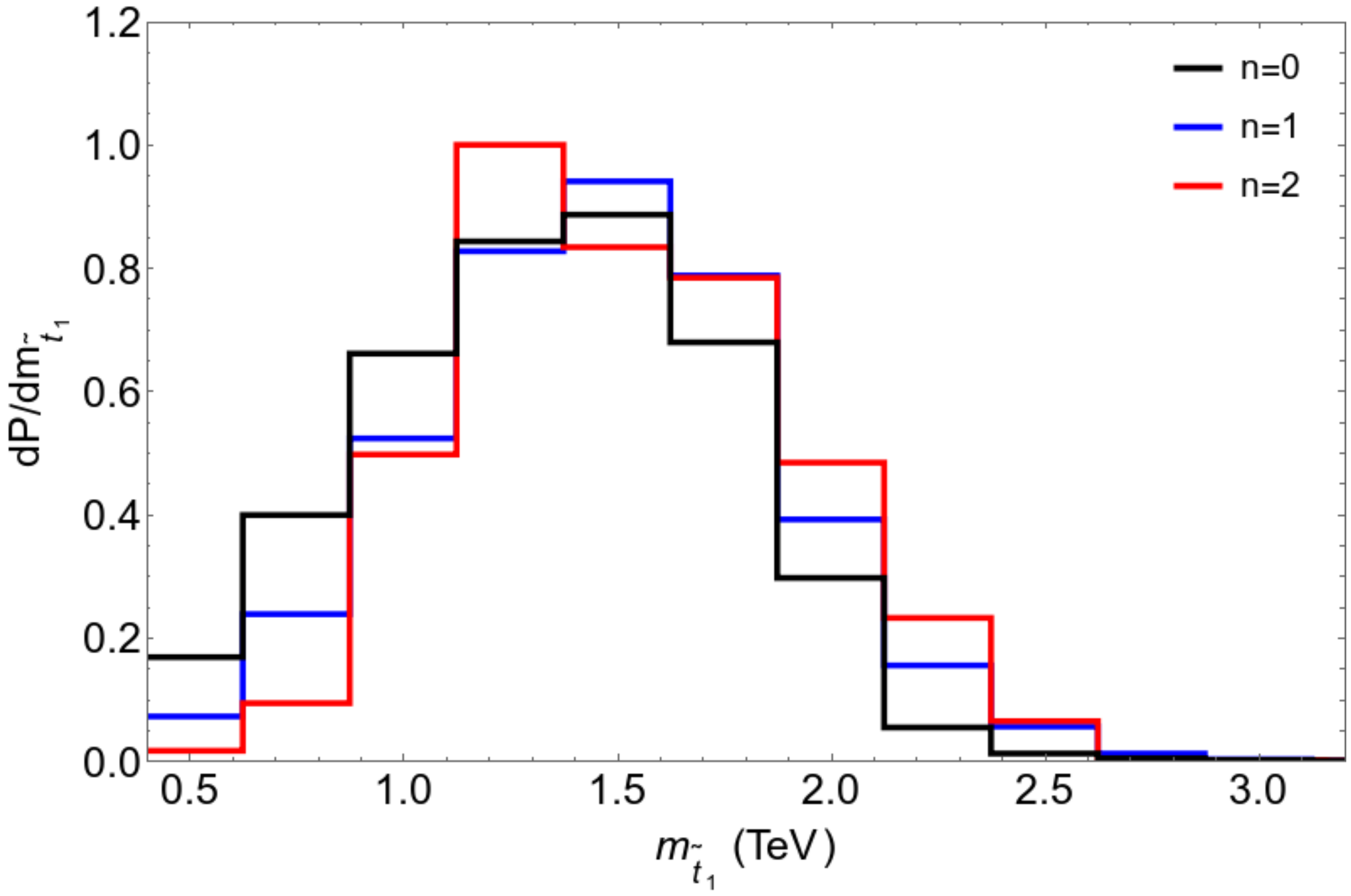
HB,Barger, Serce, Sinha

What is corresponding distribution for gluino mass?



gluino typically beyond LHC 14 reach
(need higher energy hadron collider)

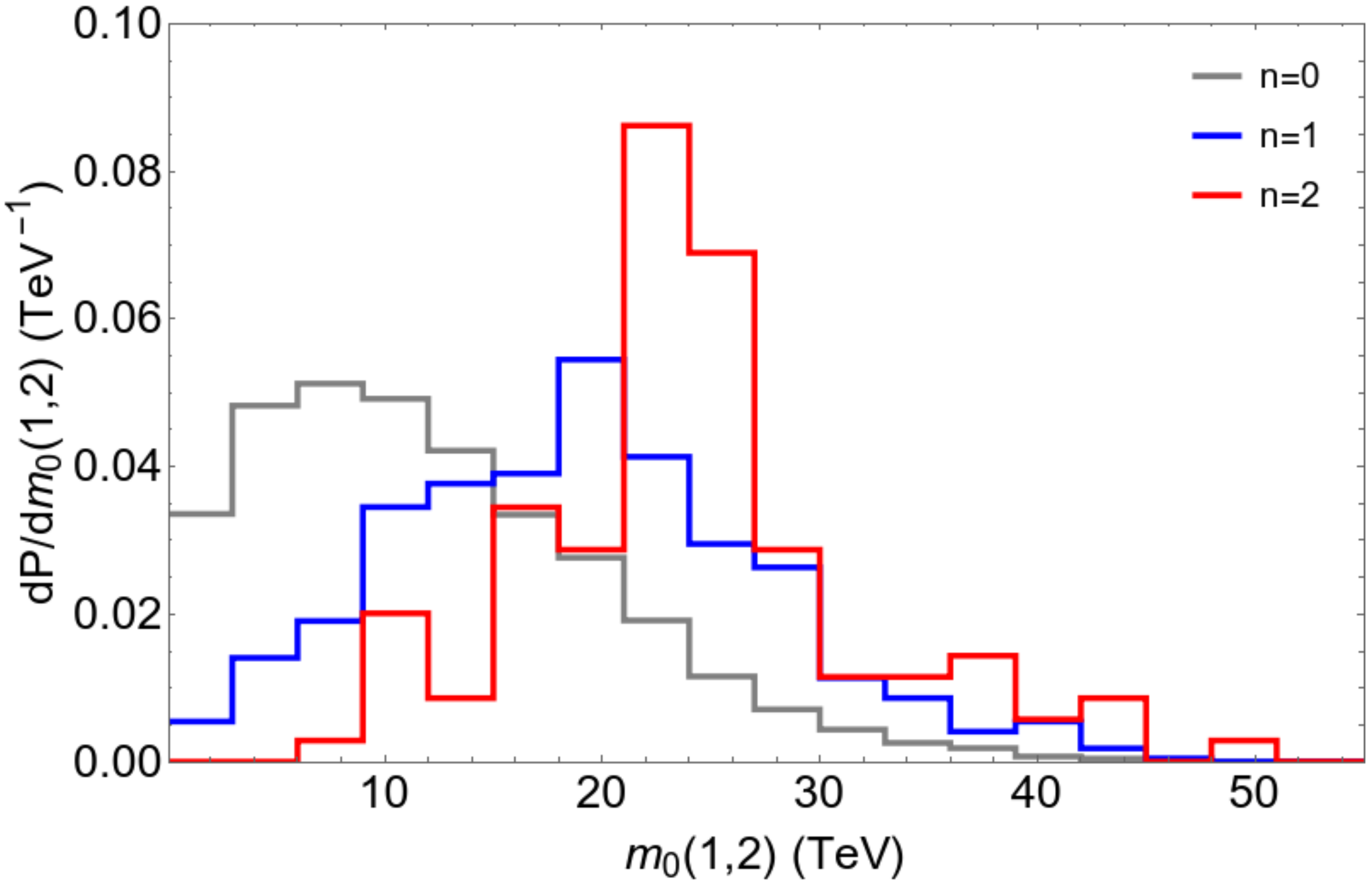
and top-squark mass m(t1)?



m(t1) typically beyond present LHC reach

first/second generation sfermions pulled to 10-40 TeV:
landscape mixed decoupling/quasi-degeneracy sol'n to SUSY flavor/CP problems

HB, Barger, Sengupta, arXiv:1910.00090



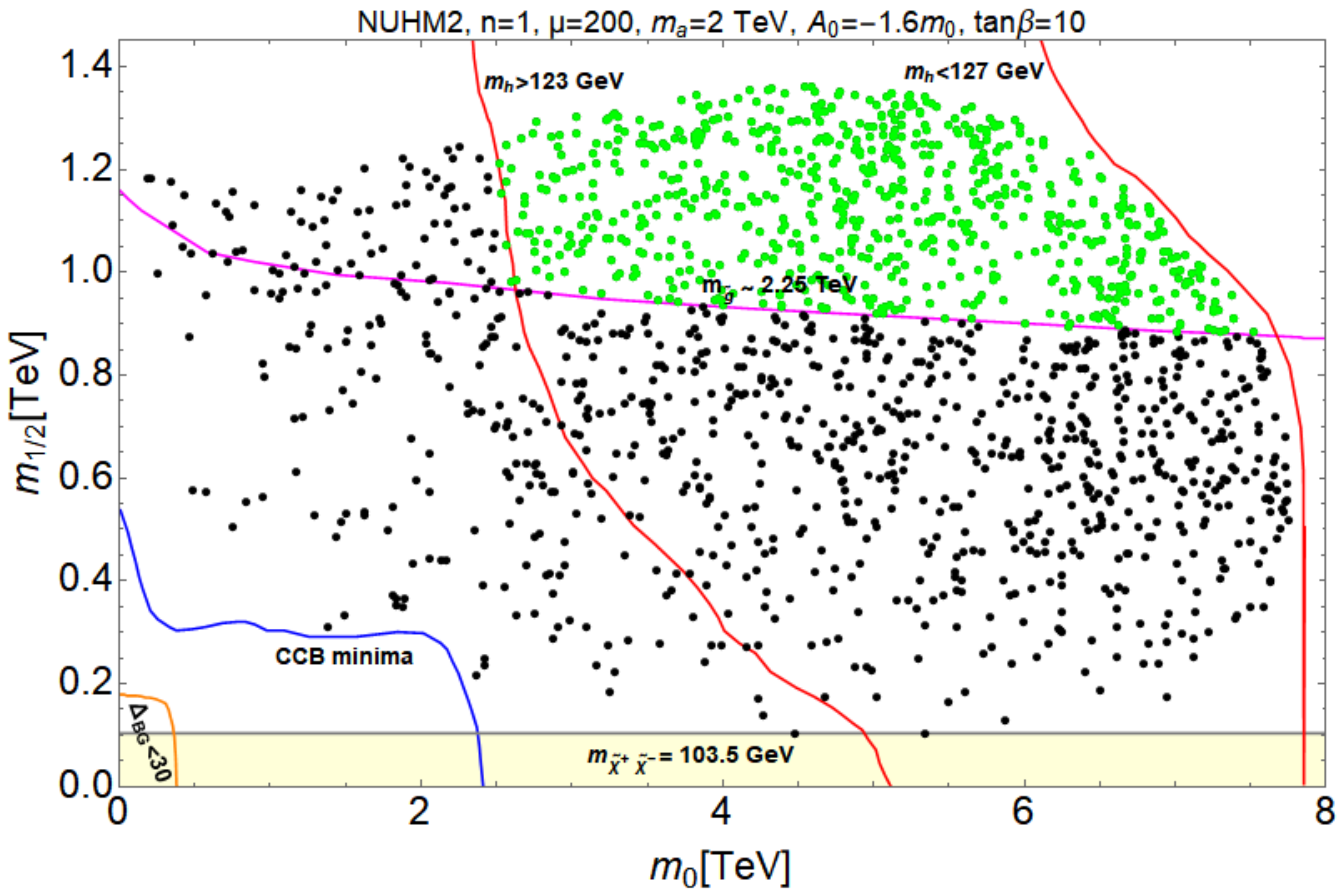
Stringy naturalness: higher density of points are more stringy natural!

conventional natural: favor low m0, mhf

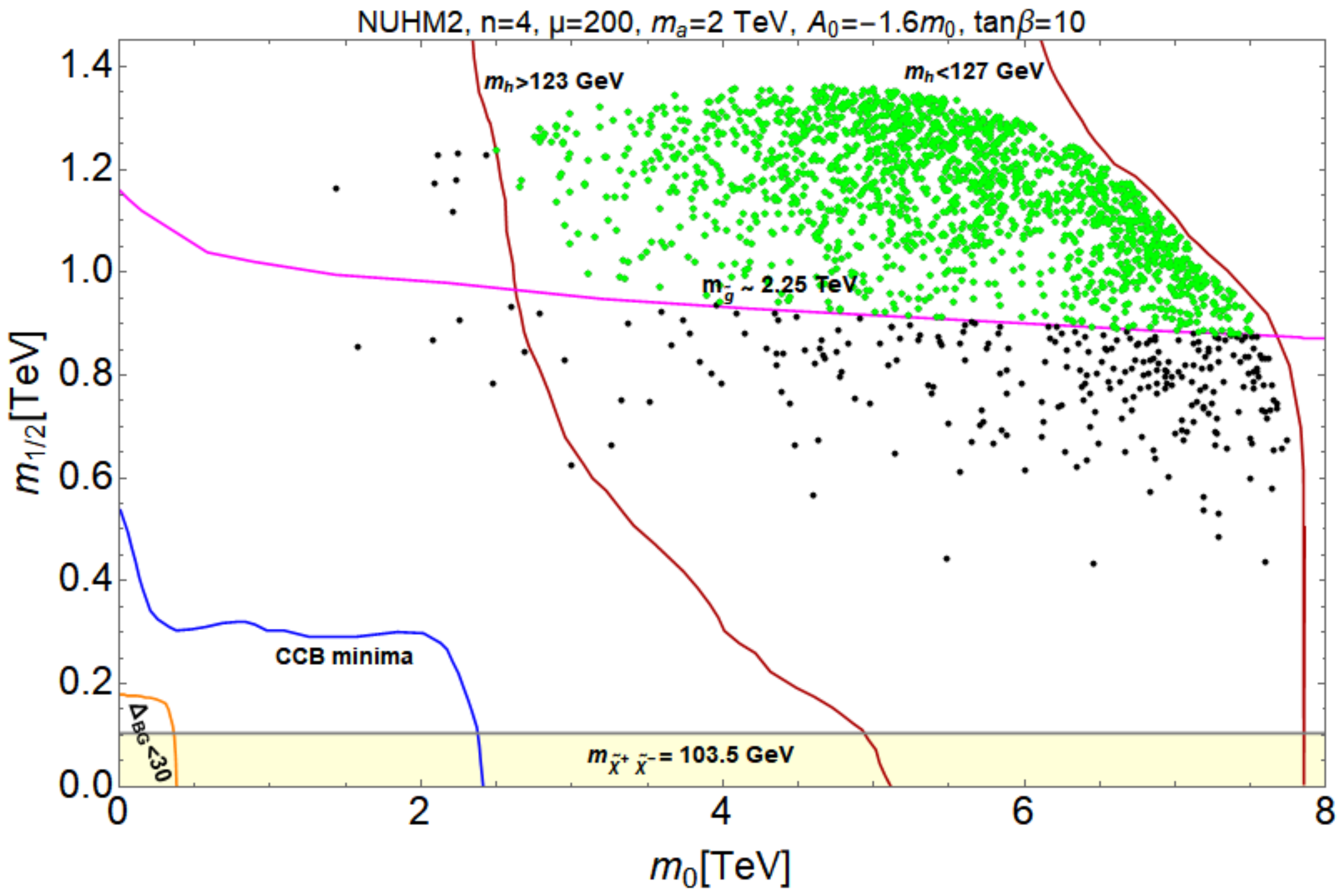
stringy naturalness: favor high m0, mhf so long as m(weak)~100 GeV

HB, Barger, Salam, arXiv:1906.07741

Living dangerously: Arkani-Hamed, Dimopoulos, Kachru, hep-ph/0501082



$m(soft)^1$



$m(soft)^4$

Under stringy naturalness, a 3 TeV gluino is more natural than a 300 GeV gluino!

recent work on dark matter

- discrete R-symmetries (Z(24)^R) solution to axion quality (arXiv:1810.03713)

- re-evaluation of cosmological moduli problem: finally, all modulus decays to (PQ)MSSM particles exactly calculated at tree-level (w/ R. Wiley-Deal, arXiv:2201.06633, 2301.12546)

- all axion DM from SUSY: using discrete R-symmetry to solve SUSY mu problem, then both U(1)_PQ and RPC emerge as accidental, approximate symmetries with RPV terms suppressed by (fa/mP)^n . For n=1, all wimps decay away in early universe leaving all SUSY DFSZ axion as DM: SUSY => a DM candidate still true, but paradigm shift: the DM candidate is the axion! (Consistent with lack of wimp signal at LZ) arXiv:2502.06955 and arXiv:2505.09785

Conclusions

- It's been a wild ride working with Vernon- lots of fun!
- Got anomalous events right
- Got top quark right
- Confident in natural SUSY
- Confident in string landscape
- Confident in LHC chances for SUSY discovery (even though community thinking proceeds on a different path)
- Best theory out there on SUSY dark matter
- But Vernon's top collaborator still RJN Phillips: would need to publish 5 papers/year over next 16 years to catch up! By then Vernon will be 102 !