HOW WELL CAN WE *UNDERSTAND* OUR UNIVERSE?

OR,

THE BOTTOM OF THE ICEBERG

In which I argue that recent progress in theoretical frameworks, plus existing and forthcoming data, may soon allow us to achieve a testable understanding of the string vacuum we live in, and make progress on understanding its relation to ultimate questions

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SpaceX

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“EXPLAIN”, “UNDERSTAND”

-- More than a description or rewording

- In quantum theory of atoms, magnetism is really explained, in terms of alignment of spins and orbital angular momentum of electrons – magnetism not there initially, or put in, it is deduced, it emerges

- In Standard Model proton not present in Lagrangian or QCD theory of quarks, but it emerges as an *inevitable* prediction of the theory – calculate its spin, electric charge, magnetic moment, mass – the Standard Model *explains* the proton

    -- if we had not known about proton, Standard Model would have predicted it

Where are we today?

To achieve understanding, several requirements – at least:

- Learn the ***rules*** to calculate – relativistic quantum field theory rules, valid for any force, particles

  -- in place since $\sim$ 1930 – expect them not to change

- Learn ***particles*** from which everything is built up, including dark matter particles – quarks and leptons and lightest superpartners(?)
- Learn ***forces*** acting on the particles – electroweak, strong (+gravity)

These (rules, particles, forces) combine to form the Standard Model of particle physics

Strong indirect evidence that laws of nature are supersymmetric:

- Stabilizes ***hierarchy*** between weak scale and Planck scale!
- *Data* from LEP suggest

  -- high scale ***unification*** of gauge coupling strengths as expected in supersymmetry

  -- ***light Higgs*** boson ($\lesssim 2M_Z$) as required in supersymmetry

  -- ***no deviations*** from Standard Model predictions, expected in supersymmetry
- Supersymmetry provides a ***dark matter candidate*** (LSP)
- Supersymmetry allows a derivation of the ***Higgs mechanism***
- Supersymmetry allows an explanation of the ***matter asymmetry***

These arguments lose impact unless some superpartner masses $\lesssim$ TeV

And if indeed nature is supersymmetric, that allows us to calculate predictions perturbatively from high scale for collider scale, or extrapolate data implications to high scale – ***opens a window to the Planck scale***

So assume supersymmetry is part of our description of nature

SOME MORE ASSUMPTIONS

- There is an underlying theory
- We can comprehend it
- String theory exists even if we can't yet define it – think of string theory as the study of theories that *could* be the ultimate theory
- We live in the ***ground state*** of a string theory – call it a string vacuum
- Great progress in learning about string theory ground states, going to 4D, stabilizing moduli, embedding MSSM
- Can construct examples such as a heterotic string compactified on some Calabi-Yau manifold, or M-theory compactified on a manifold with G_2 holonomy, etc
- We need data to figure out the underlying theory – need string theory as a framework, but top down not enough – most string theorists study string theory mainly for its own sake – string phenomenologists focus on learning ground state

To say we understand our string vacuum, we must ***simultaneously*** explain many things, including

- parity violation
- how the electroweak symmetry is broken
- why quarks and leptons
- fermion mass hierarchy
- $m_{up} < m_{down}$ but $m_{top} > m_{bottom}$
- why our forces and their unification
- origin of weak CP violation
- suppression of strong CP violation
- small but non-zero neutrino masses
- what is dark matter
- origin of the matter asymmetry
- ratio of baryons to dark matter
- what is the inflaton
- what is the cosmological history

[probably don't have to explain dark energy, see below]

Such a list probably mostly satisfactory for many people

String "theory" gives a framework to do this – string "theory" ***addresses*** what we want to understand

Today some string constructions of our 4D world address most questions – all questions addressed in some constructions

SOME QUESTIONS
Beyond SM

√ ***addressed***

√√ ***explained***

~ ***accommodate***

	Standard Model(s)	*Supersymmetric SM(s)*	*String theories*
What form is matter?	√		
What *is* matter			√
What is light?	√√		
What interactions give our world?	√		√
Gravity			√√
Supersymmetry?			√
How is supersymmetry broken?			√
Stabilize quantum hierarchy?		√√	
Explain hierarchy?			√
Unify force strengths?		√√	
Higgs physics?		√	√
What is dark matter?	~	√	√
Baryon asymmetry?	~	√	√
More than one family? 3?	~	~	√
Values of quark, lepton masses?	~	~	√
Origin of CP violation?		√	√
Origin of P violation?	~	~	√
What is the inflaton?		√	√
Dark energy?			√
Cosmological Constant Problem?			√
What **is** an electron? Electric charge?			√
Space-time?			√
Why quantum theory?			√

"String phenomenology" is the subfield that studies the above questions

This approach based on simple, old-fashioned, conservative world-view

- Natural place to formulate laws of nature $\sim$ Planck scale (string scale)
- Laws of nature supersymmetric
- Supersymmetry broken dynamically, e.g. gaugino condensation
- Naturally get metastable deSitter ground state, vacuum
- TeV scale generated dynamically – some superpartner masses $\lesssim$ TeV
- String scale and TeV scale connected perturbatively
- Dark matter is (mainly) the lightest superpartner
- EW symmetry radiatively broken
- Gauge coupling unification important clue

Stick to such an attractive picture as long as possible – currently no contradictions with phenomenology, no problems with such a picture

Not necessary, but possible – generic? – inevitable?

Show a particular string-based construction as "existence proof" – use it here to illustrate how details of theory and phenomenology could fit together, and address many issues simultaneously – testable several ways soon – not selling it – other constructions too, also testable (KKLT+Choi, Quevedo et al, Vafa et al)

M-theory compactified on manifold of G_2 holonomy – moduli stabilized in fluxless sector, and supersymmetry broken at high scales simultaneously (gaugino condensation) – moduli geometrical, generically in gauge kinetic function, enter superpotential non-perturbatively – calculate metastable de Sitter minimum of potential

[several papers by Acharya, Bobkov, Kane, Kumar, Shao, Vaman, Watson]

The Standard Model, the arguments for supersymmetry are not new

They allow us to formulate questions to go beyond the Standard Model – supersymmetry allows connecting the our scale with the unification (string…) scale perturbatively, testing high scale ideas against our data, extrapolating data implications to high scales

THEY ALLOW THE BOUNDARIES OF PHYSICS TO CHANGE, ALLOW US TO ASK ULTIMATE QUESTIONS, “WHY?”

What is new recently, or coming soon, that lets us argue for progress soon?

Confirm Higgs in 1-2 years at Tevatron – 3-4 years at LHC

Data from PAMELA, Fermi, AMS2, Xenon100 and other direct detection

Data from LHC

→ ***Can confirm indirect evidence for supersymmetry, and tell us the form it takes***

Plus *simultaneous* descriptions of many issues in string-based models (such as the M-theory based model)

MY ARGUMENT IS NOT THAT THIS M-THEORY BASED MODEL *IS* CORRECT, BUT THAT IMPROVEMENTS IN UNDERSTANDING CONSTRUCTION OF STRING-BASED MODELS THAT ADDRESS ISSUES, PLUS DATA ON DARK MATTER AND FROM LHC, MAY SOON ALLOW RAPID PROGRESS – NOT POSSIBLE BEFORE "NOW"

More detail on the M-theory based model:

- generates TeV scale physics by the conventional gaugino condensation mechanism →$M_{3/2} \sim$ ten(s) of TeV
- scalar masses $\sim M_{3/2}$
- tree level gaugino masses (gluino, chargino, neutralinos) suppressed (by form of supersymmetry breaking) so same order as anomaly mediation contribution →wino LSP generic
- Moduli masses and lifetimes ($\sim 10^{-3}$ sec) and branching ratios calculable – non-thermal cosmological history – dark matter arises from moduli decays (relic density in model few times observed value) [effect first studied (motivated by anomaly mediation) by Moroi, Randall $\sim$ 1999]
- Can describe PAMELA positron excess (and antiprotons) – normalize wino mass to PAMELA → $M_{gluino} \lesssim 950$ GeV, gluino signatures good for detection at LHC
- Addresses other issues too

The properties of the LSP determine many features of what will be observed

– can be partner of photon, Z, neutral W, Higgs boson, or linear combination

– very different annihilation cross sections (factor over 200) in galaxy and different annihilation products

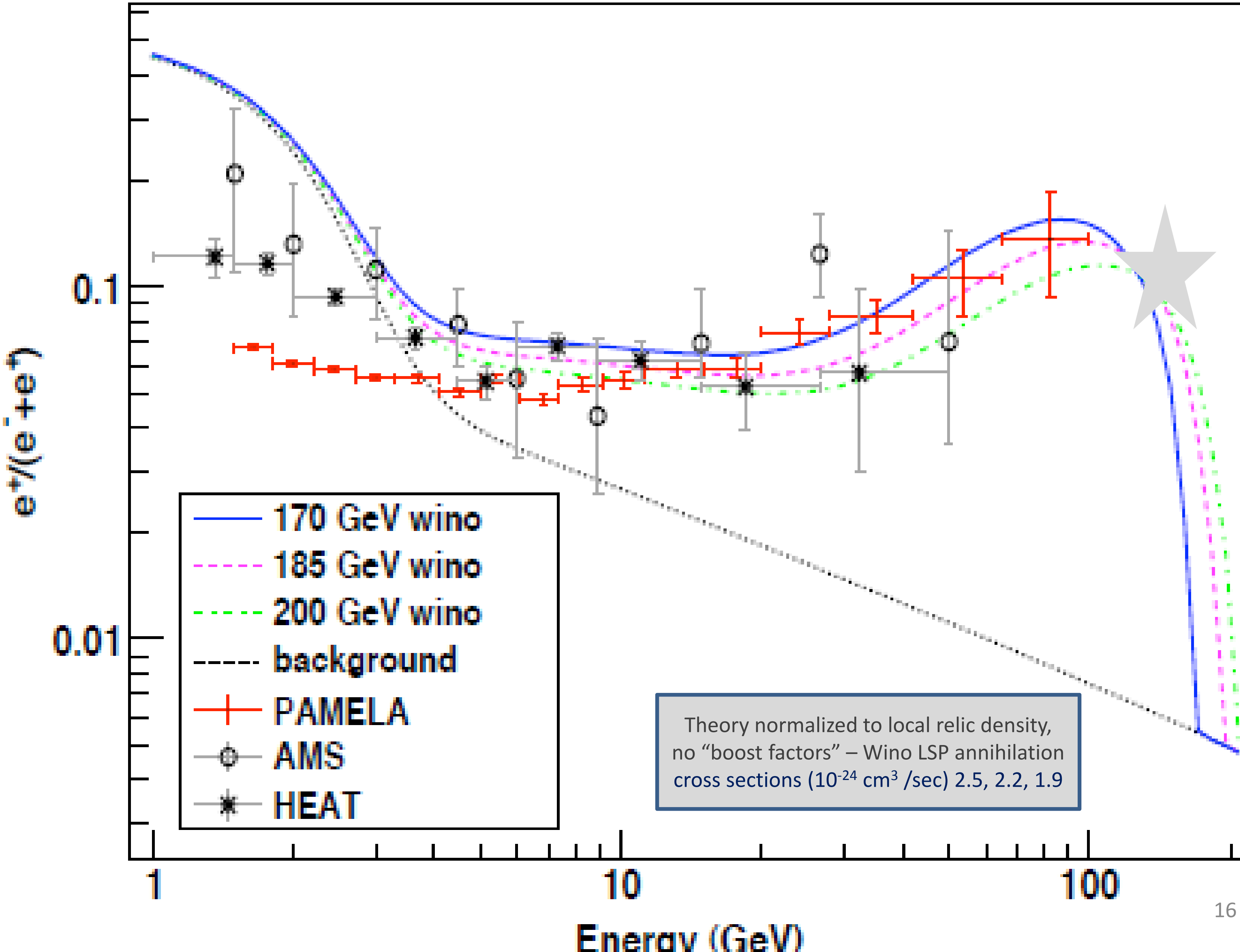
– very different direct scattering on nuclei (orders of magnitude)

– very different LHC signatures

– very different cosmological histories if all or most of relic density

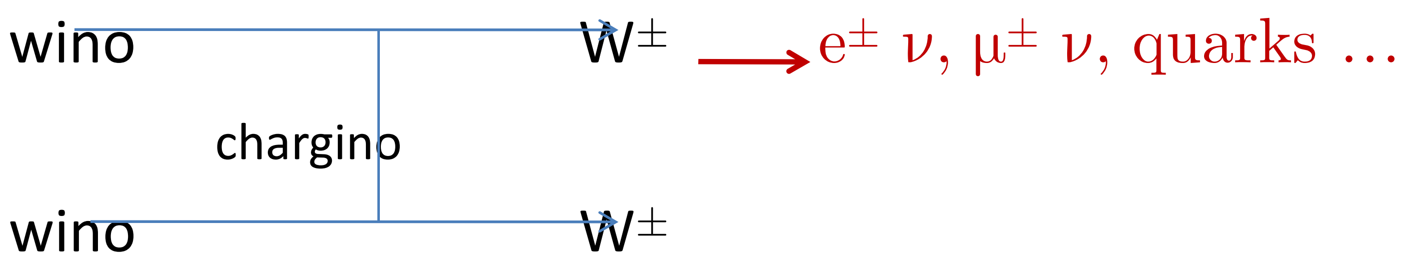
– stable or metastable on scale of lifetime of universe

→ ***So if we learn about it from PAMELA, Fermi, LHC we can tie together many areas***

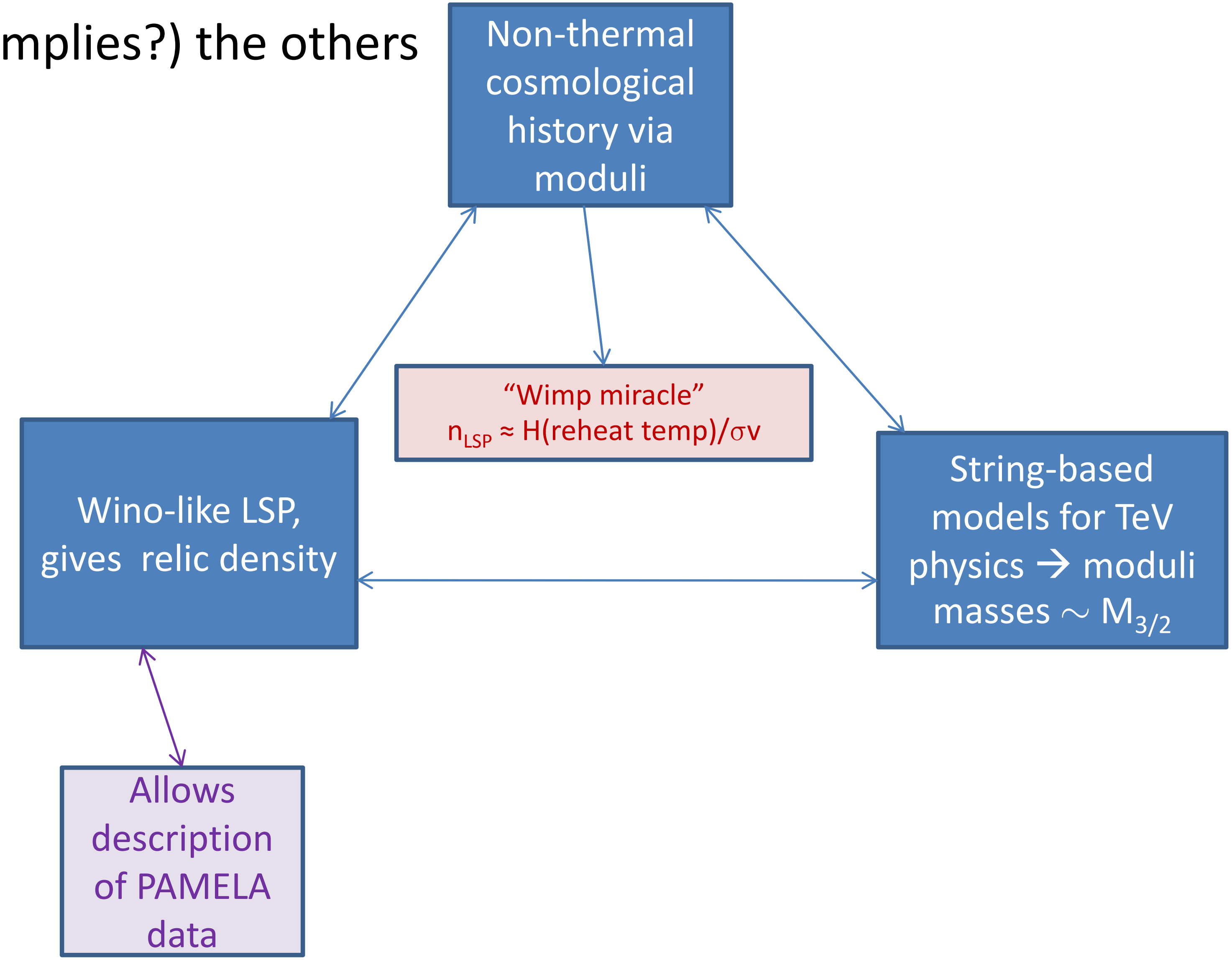

e+/(e-+e+)
0.1
0.01
1
10
100
Energy (GeV)
170 GeV wino
185 GeV wino
200 GeV wino
background
PAMELA
AMS
HEAT
Theory normalized to local relic density,
no “boost factors” – Wino LSP annihilation
cross sections (10-24 cm3 /sec) 2.5, 2.2, 1.9

Is non-thermal cosmological history a problem? NO, maybe success!

- Generically, string theories with TeV physics have "light moduli" with masses $\sim M_{3/2}$ – they decay later than thermal freezeout temperature, produce much entropy and many LSP's – arguably such a history implied by string theories with TeV physics [detailed stringy calculations for M-theory model]
- In such theories get about right relic density and "WIMP miracle" ***IF*** the wimp annihilation cross section is that of wino, which is large!– if thermal history and large wino LSP annihilation rate, relic density small [$(\sigma v)_{wino} \approx 2\text{x}10^{-24}$ cm^3 /sec]
- That large annihilation rate also allows possibility of describing PAMELA data without unreasonable "boost factors"



Can argue that any of these generically suggests (implies?) the others

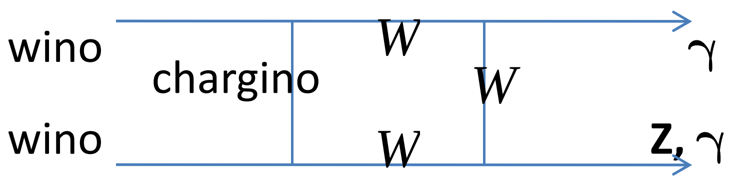


Thus we may have been lucky and seen the first “direct” evidence of dark matter ***and*** supersymmetry (the positron excess) – if so it tells us the LSP mass, character too

How can this be tested/confirmed?

Satellite data:

- AMS2 can confirm and extend PAMELA data itself, and test interpretation at higher energies – by fall 2010?
- Fermi could see gammas from wino annihilation, both continuous spectrum (diffuse, and dwarf galaxies) and particularly monoenergetic lines from γZ and $\gamma\gamma$ -- already “disfavors” signal at one wino mass, which I interpret as implying they should see a signal in the next analysis stage



at $E_\gamma = M_{wino}$, M_{wino}- 12 GeV (rate somewhat larger for γZ)

Direct detection of LSP:

- Pure wino has very small rate to scatter on nuclei – probably excluded if CSMSII, Xenon100 see signal
- But with $\sim$ 10% higgsino mixture can have direct scattering in CDMSII, Xenon100 region, and still good description of PAMELA data, so here the data is not qualitatively definitive
- → wino-like LSP works for both PAMELA and direct signal at next level

LHC:

- ***IS it supersymmetry***? – measure gluino spin – maybe early

- ***Supersymmetry breaking***

  -- If supersymmetry unbroken, no new parameters beyond Standard Model ones

  -- If supersymmetry unbroken the EW symmetry also unbroken, no Higgs mechanism – no quark and lepton and W,Z masses

  -- Understanding supersymmetry breaking essential for understanding how string ground state arises, how moduli (so force strengths, mass values) are determined

- With data from LHC, the patterns of masses and decays, these issues may fall into place

- For wino-like LSP, chargino and neutralino essentially degenerate – main LHC source of events with good signatures is gluino production, followed by gluino decay to chargino, neutralinos – in models $2 \lesssim M_{gluino}/M_{wino} \lesssim 9$ – in many string constructions spectrum compressed – in M-theory normalized to describe PAMELA, $M_{gluino} \lesssim 950$ GeV – squarks very heavy

Any issues or clues that are worrisome?

“Little hierarchy problem”

– Most difficult issue in particle physics today, no candidate solutions

- If we claim we understand our world deeply, we must be able to calculate M_Z , which is zero before EW symmetry breaking – EW symmetry breaking *requires* physics beyond Standard Model – so

$$M_Z^2 = F(M_{new}^2)$$

Data: LHS≈0.008 TeV^2, but absence of signals observed at LEP, Tevatron constrains masses on RHS to be larger than $\sim$ (1 TeV)^2

- e.g. radiative EW symmetry breaking in supersymmetry – gluino mass, μ, squarks etc on RHS – gluino coefficient $\sim$ 5
- Sometimes treated as tension between Higgs mass and Z mass and superpartner masses, but only that in minimal SSM, and easily fixed

Major problem in ***ALL*** approaches to go beyond Standard Model, so not special problem for any approach – Accidental fine tuning? Conceptual issue?

Cosmological constant problems?

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

- Does 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 quintessence)
- In typical model of string vacuum, value of scalar potential at minimum $\sim (M_{3/2}M_{Pl})^2$ so have to be able to tune this to $\sim$ zero
- In M-theory case we calculate all observables before and after tuning, and find no large effects
- Note analogous issue with strong CP problem – many predictions for QCD would be different if strong CP effects $\sim$ one, but we successfully ignore it

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

FINAL REMARKS

In recent years major theoretical progress – essentially all issues addressed in some ways – string based framework has seen major progress in relating to real world

Maybe finally can soon have one approach with coherent, consistent framework addressing all issues

Much more to derive, measure

- If we know the corner of string theory, how to go to 4D, how supersymmetry is broken → many will focus on those approaches (instead of 2N approaches for N theorists) – progress will be rapid
- Data will test ideas in multiple ways

Think in terms of "effective theories"

-- can study planets without having to understand quarks or clusters of galaxies

-- can study quarks without having to understand stars

Each effective theory of part of nature has inputs

-- e.g. in atomic physics input electrons, their charge and mass, nuclei and their charges and masses and spins etc, and electromagnetic force + rules → output many results

In physics can organize in terms of a hierarchy … molecules – atoms – nuclei and electrons – protons and neutrons – quarks

Definition: any theory with inputs is an effective theory

More precisely, effective theories have parameter inputs and conceptual inputs

I have argued here that it is reasonable to defend the point of view that we are poised to construct and test a model/theory of our world that addresses all the issues together coherently, and has no (or almost no) parameter inputs → *cautious excitement*

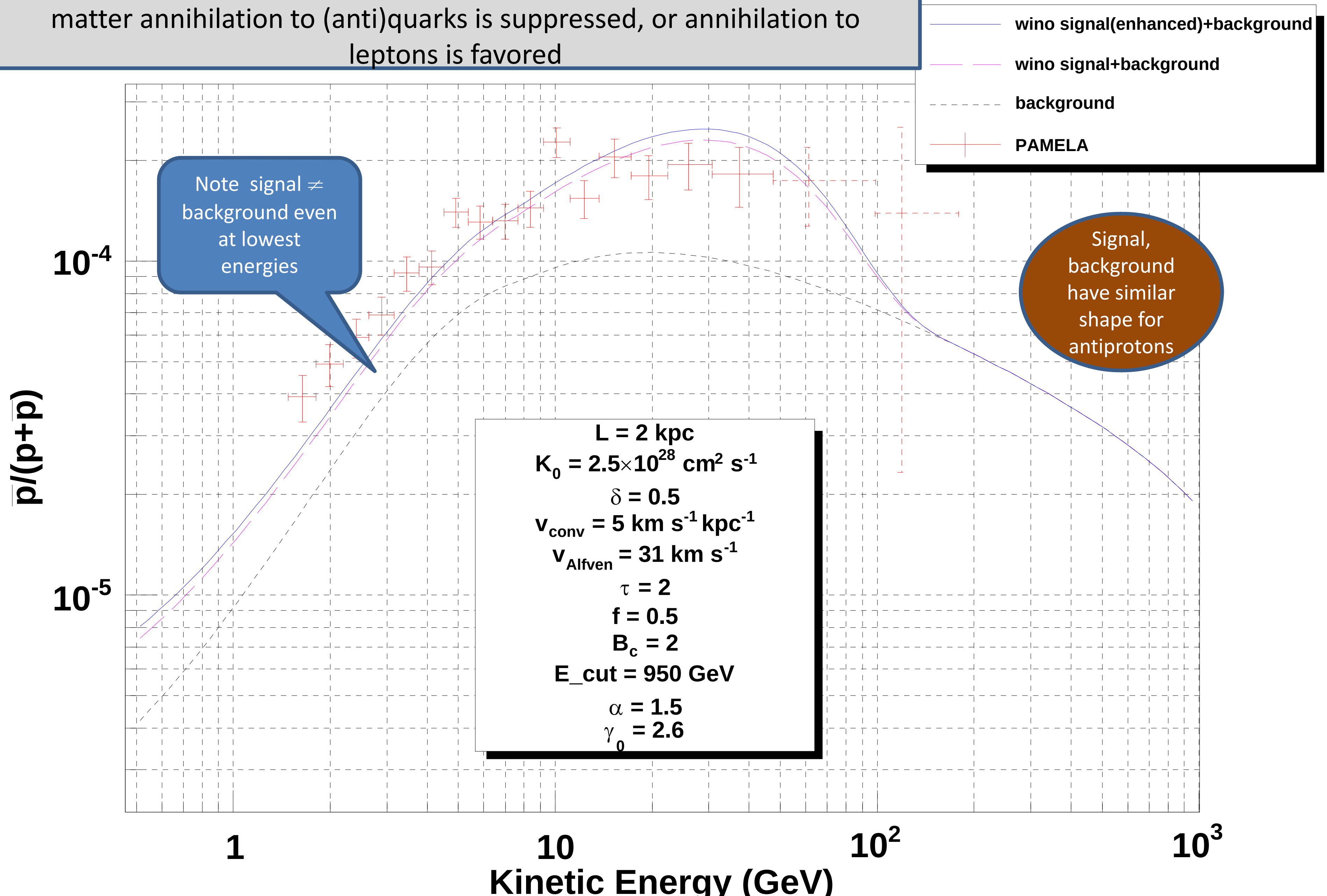
Then – work on extending it toward "no conceptual inputs" (e.g. space-time, quantum theory, uniqueness) – once we have an understanding of our stringy world it should be much easier (and fun) to figure out whether there are many, whether they can have different laws, etc “if people don’t want to come to the ballpark nobody’s going to stop them”

Yogi Berra

Antiprotons

- Galprop, DarkSusy contain a default analytic antiproton cosmic ray background determined by fitting older BESS, HEAT data – older results ***defined*** as background
- If you have a model for origin of antiprotons you could propagate them if you use galprop, or just use the default (used by almost everyone)
- If you study propagation, find that resulting antiproton flux can vary factor of 2-3 from the default
- When we propagate everything, we find good descriptions about half background, half signal – expected physically since annihilation antiprotons from soft antiquarks
- Galprop running time hours, so we are computer limited and have not been able to do scans or fits, just educated guesses for parameters – about 7 parameters can be important

It is incorrect to say PAMELA data implies or even suggests that dark matter annihilation to (anti)quarks is suppressed, or annihilation to leptons is favored



HIGGS BOSON – crucial to complete SM

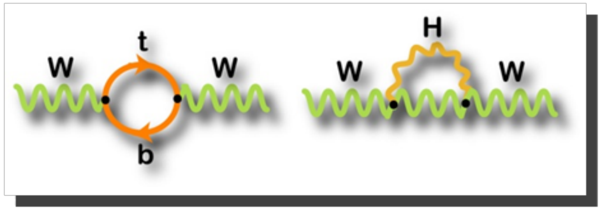
- Global fit to LEP data, plus effect of Higgs radiative corrections to M_W – M_{top} relation, imply $M_h \lesssim 160$ GeV
- So far signal/background has been improving much faster than $\sqrt{N}$ at Tevatron because systematics improved, more connected channels added – expected to continue
- Tevatron can cover that entire region with about 12 fb^{-1} per detector integrated luminosity, which it should get in 1-2 years if collider and detectors and experimenters keep working
- Now Tevatron is expected to run two more years, because of stimulus money – more manpower available for analysis since LHC slowdown

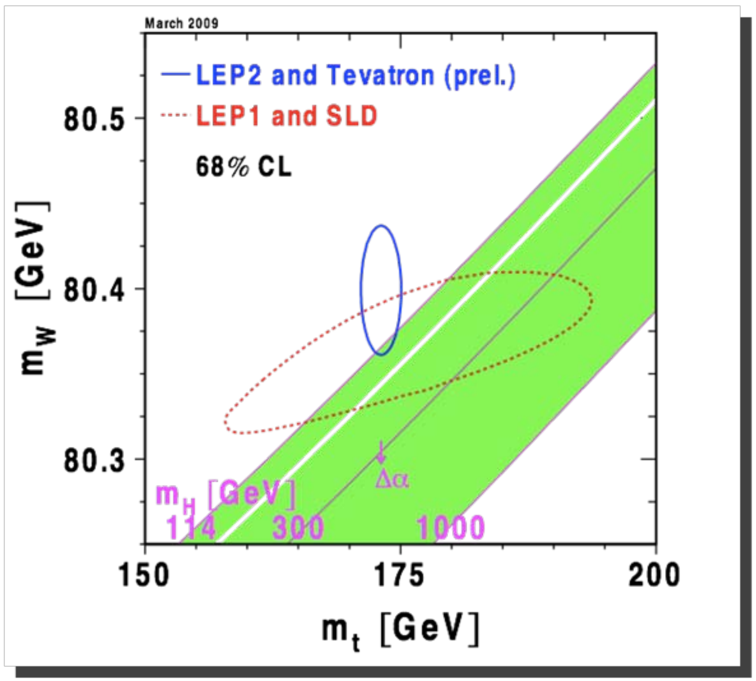
→ Very likely Higgs boson will be detected at Tevatron in $\sim$ 2 years

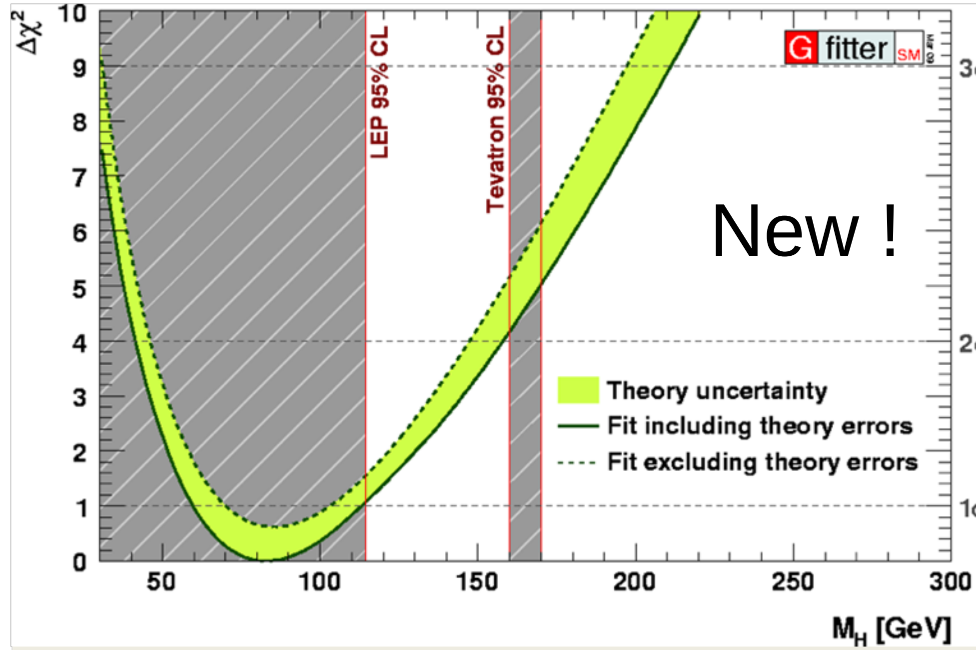
LHC Higgs analysis difficult – could see 2-3 σ effect in each of several channels after 2-3 years running at fairly high luminosity

But Tevatron will at best detect h – LHC essential for properties

Precision ==> Higgs constraints







Expected now with all constraints :

$M_H = 90^{+36}_{-27}$ GeV

$M_H < 163$ GeV @ 95 % CL

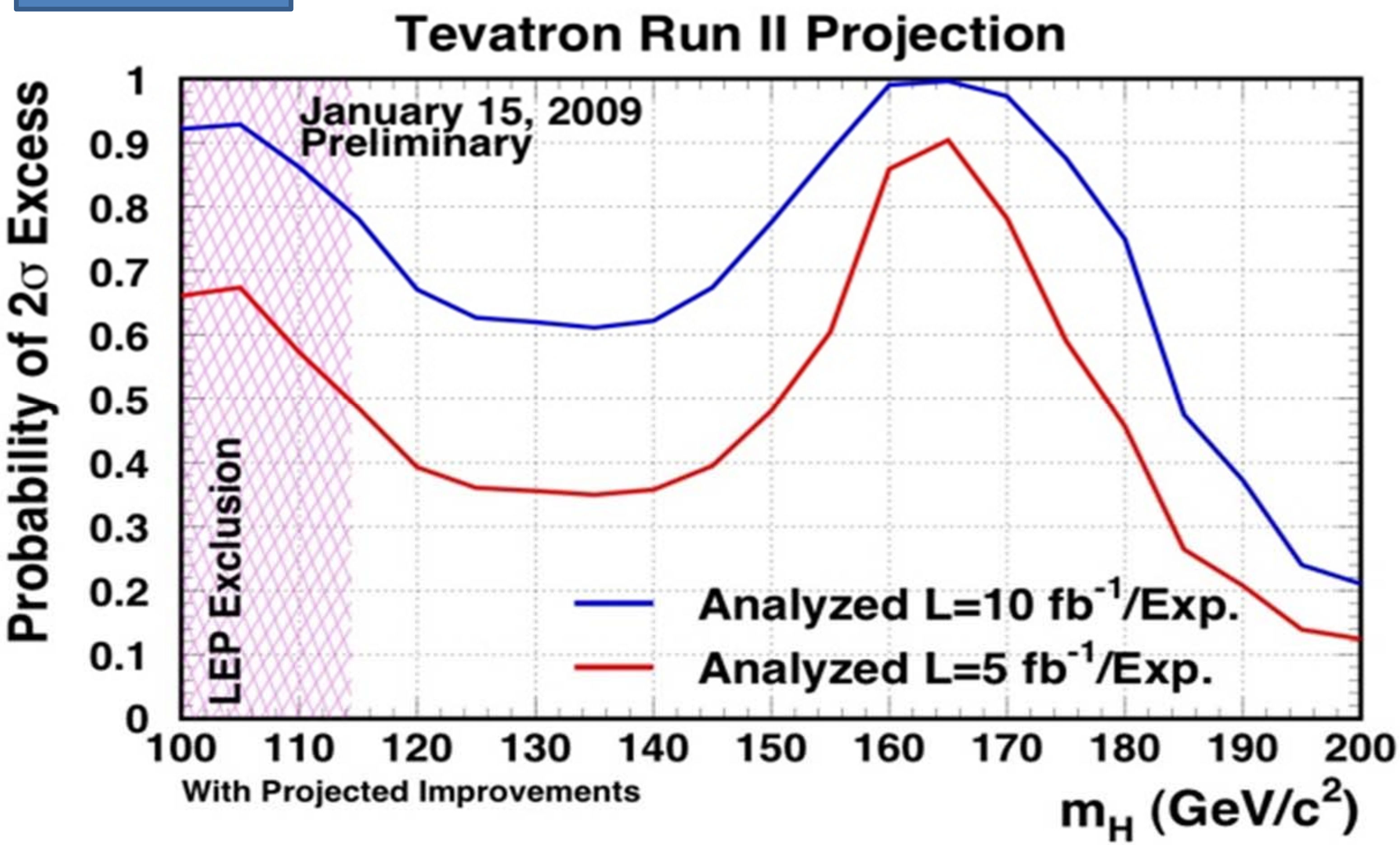
With 10 fb^{-1}

If dMw=15 MeV and dMtop=1 GeV [for Mw= 80.400] expect

$M_H = 71 + 24 - 19$ GeV

$M_H < 117$ GeV @ 95% CL !

For Standard Model Higgs boson



Recently, a number of different approaches have yielded examples of models with the exact MSSM spectrum. These include heterotic $\mathbb{Z}_6$ [4, 5], $\mathbb{Z}_{12}$ [6], $\mathbb{Z}_2 \times \mathbb{Z}_2$ [7] orbifolds as well as smooth Calabi–Yau compactifications [8–10] of the heterotic string.[1] In fact, it has been shown in Refs. [5, 18] that there is a "fertile patch" in the heterotic landscape, where more than 0.1% of all inequivalent models have the MSSM spectrum.

Lebedev and Ramos-Sanchez,
arXiv:0912.0477

μ Problem

- No special progress – several solutions possible
- Easy to have Giudice-Masiero mechanism, μ=0 before supersymmetry breaking, so $\mu\sim$ soft breaking terms -- then $\mu \sim B\mu$ so tan$\beta \sim 1$ in simplest cases, but larger tanβ possible
- NMSSM stringy models possible

Testing string theory? – lots of confusion

- Test F=ma?

  -- not in general

  -- have to put in a force, mass, calculate a
- Similar for Schrodinger equation
- Analogous for string theory

  -- go to 4D, break supersymmetry, etc – calculate predictions, test – lots of examples
- More general tests possible for quantum theory (e.g. superposition, entanglement) and for quantum field theory (e.g. all electrons identical, spin and statistics) – don’t know yet if such tests also exist for string theory
- Do not need to be at Planck scale to test theory -- e.g. at big bang, or dinosaur extinction, or at speed of light

X