The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1970-14

Signaling the Arrival of the LHC Era

8 - 13 December 2008

The LHC – a "why" machine

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Trieste, December 2008

OUTLINE

- o Long introduction – explain title
- o Supersymmetry – why
- o PAMELA positron excess – wino LSP dark matter?
- o LHC – dark matter and LHC
    - -- is it supersymmetry – find one superpartner, measure its spin
    - -- test gaugino mass unification even though cannot measure gaugino masses
    - -- gluinos – very light? -- 4 top signature, early discovery
    - -- from LHC directly to string theory
- o Remarks

The Standard Model(s) of particle physics and cosmology are wonderful, exciting descriptions of the world we see.

They successfully *describe* the world we see, and how it works.

BUT….

We know that about a quarter of the universe is dark matter, and we know that about a percent of that is neutrinos, and about a sixth is neutrons and protons.

But we don't know what the rest is – we do know the rest is *not* made of quarks and leptons.

Similarly, we know that the part that is neutrons and protons is matter, and not antimatter. But at the big bang there should have been an equal mixture, and we do not know how it got to be just matter.

We have a Higgs mechanism that works well technically, but we don’t know its physical origin

-- we just assume there is a Higgs field, and the energy of the universe is lower if the Higgs field has a non-zero value in the vacuum (ground state)

-- it doesn’t seem to matter that the mass of the quanta of the Higgs field (Higgs bosons) gets quantum corrections that should make that mass (and therefore all quark and lepton and W masses) of order 10^16 GeV – we don’t know why that doesn’t matter [the hierarchy problem]

THERE IS MUCH THE STANDARD MODEL(S) ***CAN*** ***accommodate*** ***but NOT*** EXPLAIN

- Neither cosmology nor the SMs can tell us what the ***dark matter*** is
- Neither cosmology nor the SMs can explain the ***matter asymmetry***
- Neither cosmology nor the SMs can tell us the physical nature of the ***inflaton*** field
- The SMs *cannot* tell us why there are ***3 families*** of leptons and quarks or even why there are more than one
- The SMs *cannot* give us insight into how to ***unify gravity and the other forces***
- The SMs *cannot* explain the origin of the ***Higgs physics***
- The SMs *cannot* allow calculation of the electron or muon or quark ***masses***
- The SMs *cannot* describe ***neutrino masses*** without adding a new mass scale
- *The SM has a* **quantum hierarchy problem**, *very serious*
- The SM cannot explain ***parity violation***

"cannot " means cannot

These are “why” questions

There is no reason to be confident we will be able to answer them – just wanting to is no guarantee

No amount of cosmology can fully answer these questions

The answers will have to come from data that points to an underlying theory, and we have to guess that theory – as physics has always proceeded historically

Today is a very exciting time to be in particle physics – on the data side, we have LHC coming, and dark matter experiments

On the theory side there is a framework, string theory, that addresses all these questions

SOME QUESTIONS

√ **_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 theory addresses what we want to understand

Many tests of string theory

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

Philosophy

The clues we have are consistent with and suggestive of an underlying theory that unifies all forces at a short distance scale not far from the Planck scale, and is perturbative to the unification scale

In that theory most questions can be addressed – matter spectrum, dark matter, matter asymmetry, EWSB, hierarchy problem, unification of forces, CPV, supersymmetry breaking, etc

Assume that is so until forced to give it up – an attractive world, in which we can understand much – don't give up addressing important questions

*What **could** answer these questions?*

*Remarkably, in past 2-3 decades, have learned that if we hope to **explain** these things the direction we need to go is to embed our 4D world in additional space-time dimensions*

Two approaches show great promise for explaining what cosmology and the Standard Model(s) cannot:

- ❑ Supersymmetry – for every space-time dimension add a quantum dimension

- ❑ String theory – add 6(7) space dimensions like ours, except that ours inflated, others didn't – all 10 D have a quantum dimension too – extra dimensions naturally Planck scale size

LHC is a “why” machine

- The Standard Model(s) describe the world we see, but do not explain it

- LHC data will not qualitatively improve our description – rather, it may provide the clues that allow us to learn about the dark matter, the Higgs physics, the matter asymmetry, etc, and test underlying theories such as string theory

- Supersymmetry opens a window to the Planck scale, and studying how supersymmetry is broken gives clues toward understanding our string vacuum

The idea of supersymmetry (~1973):

THE LAWS OF NATURE DON'T CHANGE IF BOSONS $\leftrightarrow$ FERMIONS IN THE EQUATIONS DESCRIBING THE LAWS

Originally very surprising – matter particles (e,u,d…) were fermions, force particles (γ,g,W,Z) were bosons – in quantum theory they were treated very differently – the idea was studied just to see if it could work

Full mathematical relativistic quantum field theory – no new parameters if symmetry unbroken

Only idea in history of science that emerged purely from theoretical study rather than from trying to understand data, puzzles – studied because it was a beautiful idea

TURNED OUT IT COULD EXPLAIN MAJOR PROBLEMS

We learned from LEP (electron-positron CERN collider) – 1990-2001 – several powerful results

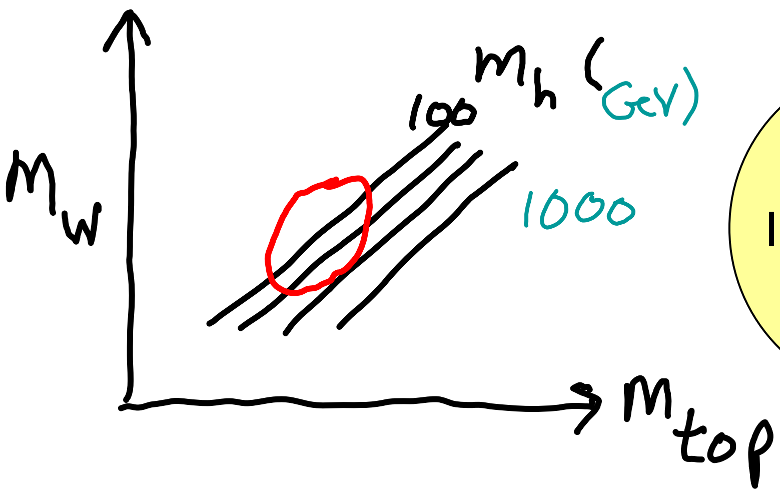
- Upper limit on m_{higgs} ~ 160 GeV
- No deviations from SM predictions at 0.1% level
  → any new physics is likely to be perturbative, weakly coupled
- Unification of force strengths – in quantum theory can extrapolate forces to high energies, short distances

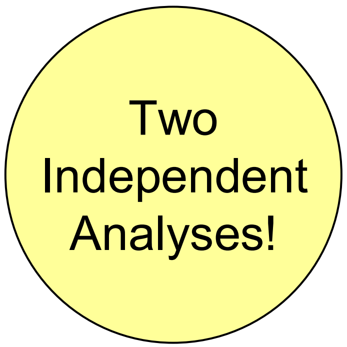
These are predicted by supersymmetry

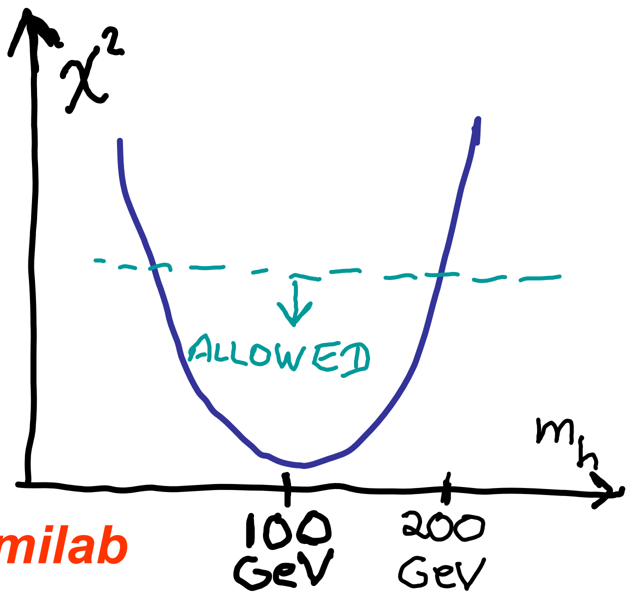
In addition, supersymmetry stabilizes the hierarchy, provides a dark matter candidate, and provides a stable high scale that allows small neutrino masses by a see-saw mechanism

- Technically the Higgs physics add-on to the SM works fine
- If Higgs field exists, then quanta of field must exist, Higgs bosons

- Good indirect evidence they do exist! – from LEP electron-positron collider at CERN, 1991-2001 – measured accurately about 20 quantities that should be described by the SM – all SM parameters known except Higgs boson mass – so fit all data with one parameter – get good fit if m_h below about 160 GeV
- Also W mass vs top quark mass



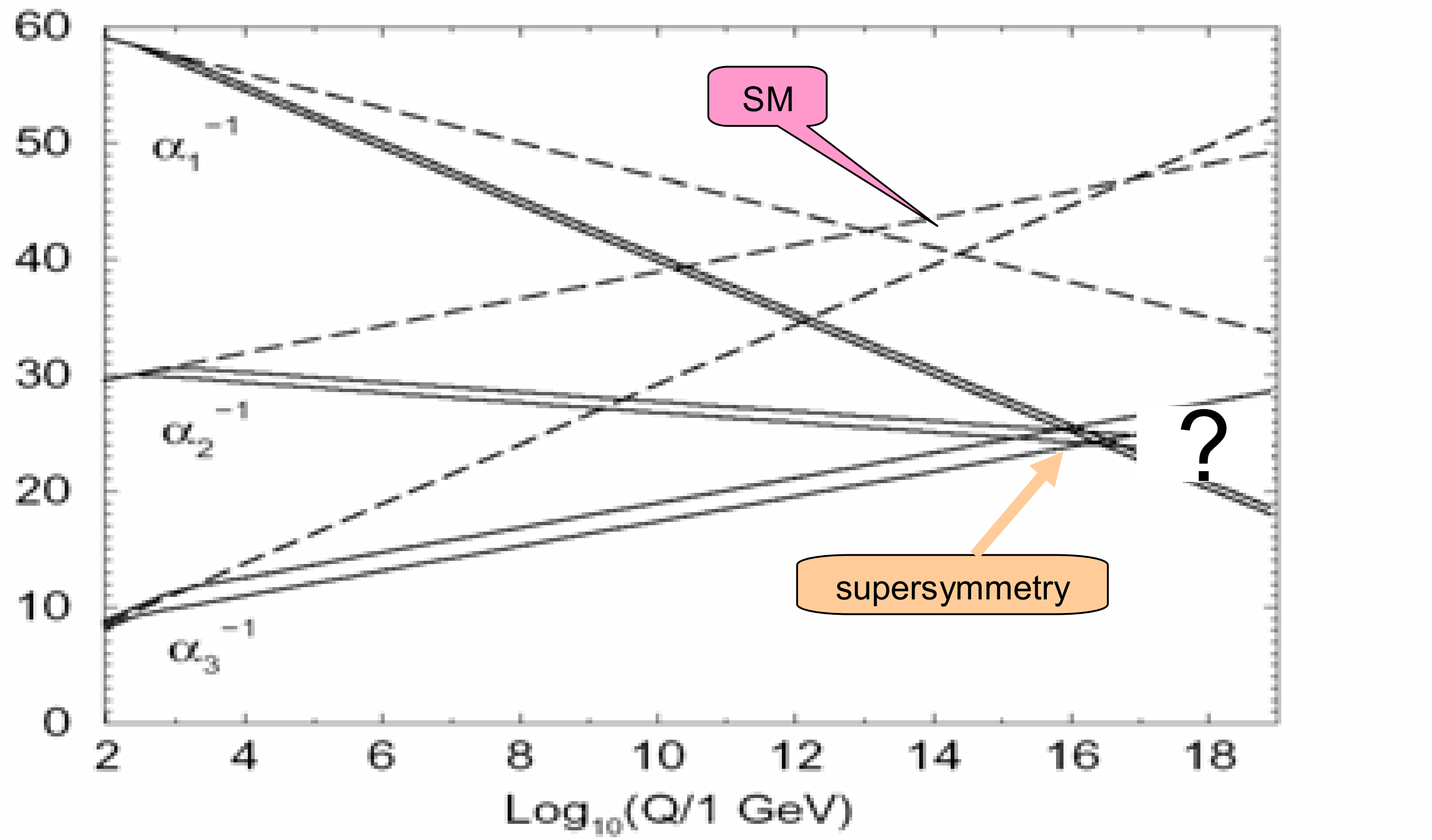




Should be observed at LHC, or before at Fermilab

$\alpha = e^2/4\pi$
$\hbar = c = 1$

Suggests (1) Theory simpler at ~ 10^{16} GeV
(2) High and low scales connected perturbatively



Also suggests that a supersymmetric theory opens a window, from the weak-TeV scale to the unification and almost-Planck scales, where string theory is formulated!

HIERARCHY PROBLEM!

- In quantum theory, every particle spends some time as virtual combinations of all other particles

- For technical reasons, scalar (spin zero) particle (Higgs bosons) masses are quite sensitive to masses of the virtual particles

- So Higgs boson masses driven up to the highest scale of particles and interactions – presumably Planck scale or unification scale

- Masses of e, W, Z, etc proportional to Higgs mass, so all masses should be that heavy

- 1979 – realized that supersymmetry can stabilize the quantum hierarchy

  -- particle and superpartner have same mass for unbroken supersymmetry, and fermion mass not sensitive, so scalar mass stabilized

  -- quantum contributions of fermions, bosons have opposite sign, so cancel if superpartner masses not very different from partner masses

→ Superpartner masses can be $\lesssim$ few hundred GeV or so and no hierarchy problem

SO ASSUME SUPERPARTNERS ~ 1 TeV -- THEN CAN DERIVE MUCH:

- 1982 Can explain Higgs physics
- 1983 Can explain why the forces look different to us in strength and properties, but become the same at high energies, so we can make sense of the idea of unifying their description
- 1983 Provide a dark matter candidate (the lightest superpartner)
- 1991 Allow an explanation of the matter asymmetry of the universe
- 1992 Explain why all current data is consistent with the Standard Model(s) even though we expect new physics at the weak scale

ALL SIMULTANEOUSLY

ALL WELL AFTER INTRODUCTION OF SUPERSYMMETRY

In addition there are theoretical motivations:

- If supersymmetry is a local symmetry it implies General Relativity – if Einstein had not invented General Relativity it would have been (i.e. it was) written in 1975 by studying supersymmetry

  -- supersymmetry transformation affects spin – spin part of angular momentum – generators of angular momentum transformations part of Poincare group – connects to gravity equations

- String theory probably requires supersymmetry if string theory is relevant to understanding our world

Supersymmetry must be a broken symmetry, or would have seen some superpartners

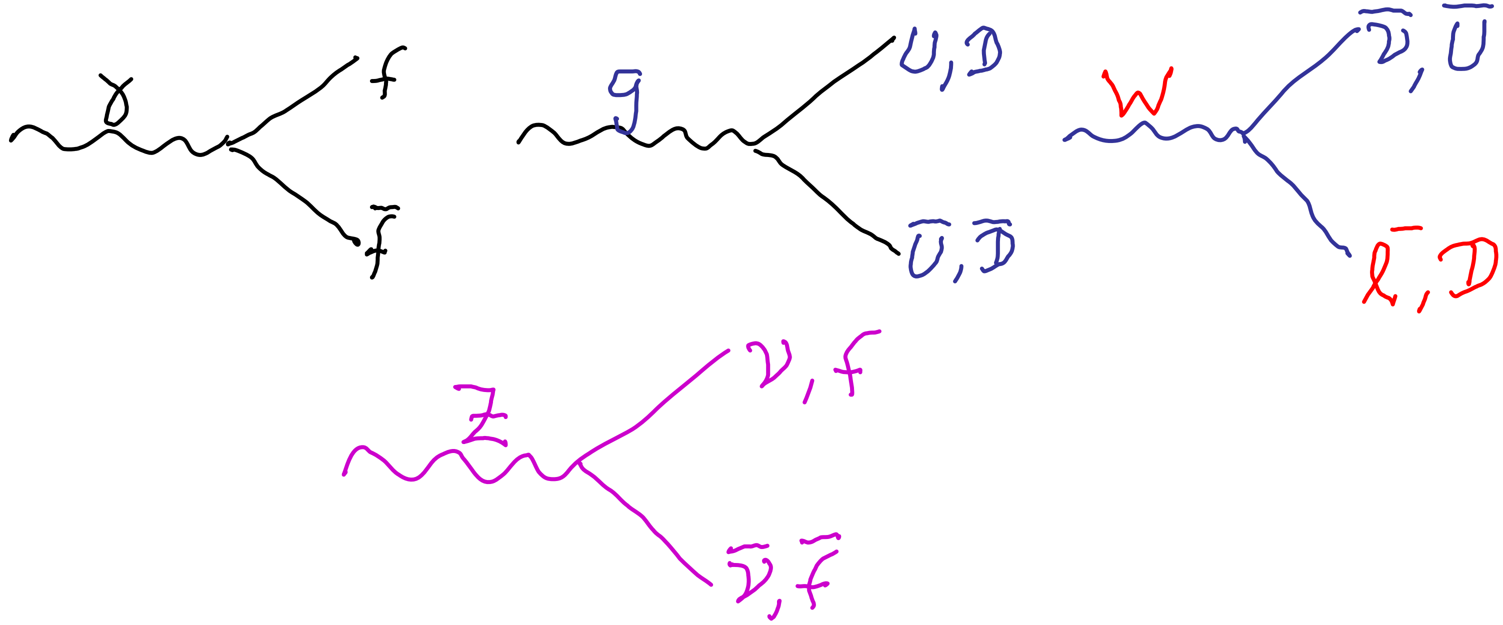
Superpartners can have (complex, flavor dependent) masses different from Standard Model particles – introduces parameters if we do not have a theory of mass

Supersymmetry is a full mathematical theory

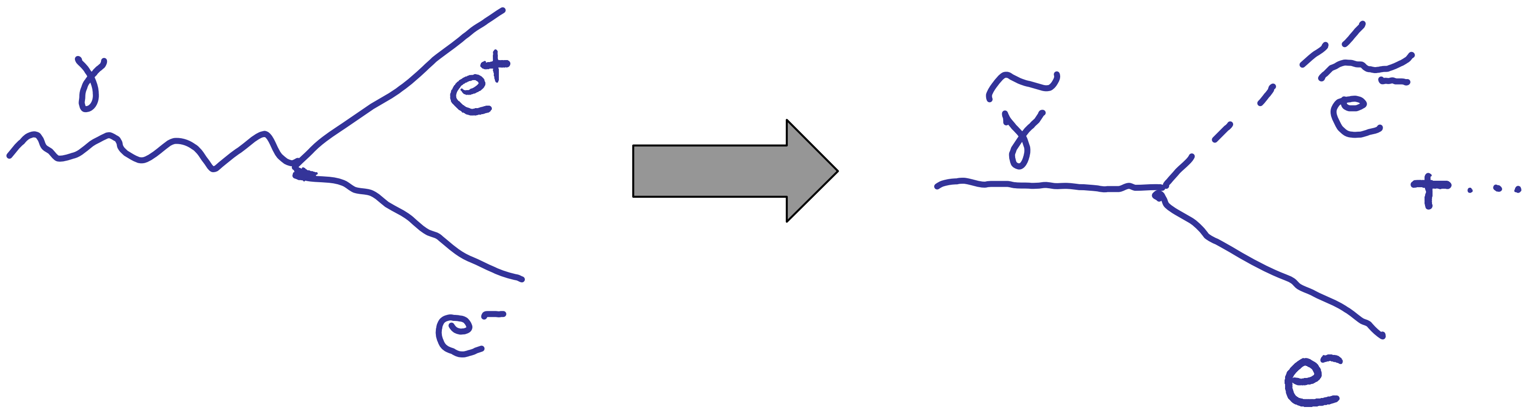
Can summarize the perturbative SM by a set of vertices for Feynman diagrams: let

$f = e, \mu, \tau, d, s, b, u, c, t \quad l^{\pm} = e^{\pm}, \mu^{\pm}, \tau^{\pm} \quad U = u, c, t \quad D = d, s, b \quad \nu = \nu_e, \nu_\mu, \nu_\tau$

Then all the phenomena in nature that we see involving fermions are described by gravity plus the four vertices:



To make the theory supersymmetric, add the vertices with particles turned into superpartners in pairs, all ways



Everything is known about the supersymmetric SM except the masses of the particles – no theory (except hopefully string theory) can predict masses from first principles

No parameters for unbroken theory

Any problems with supersymmetry?

One, but common to all theories – “little hierarchy” problem.
-- Often misunderstood – not about higgs mass being too light – that is special to MSSM and goes away in most extensions, for example

But M_Z is too light – basically, in supersymmetry, or in any other model/theory, M_Z is expressed in terms of new physics (superpartner masses for supersymmetry) -- always a small number in terms of larger ones, and a basic issue

This is a problem in all approaches – most serious problem in particle physics today

The lightest superpartner (LSP) is very important phenomenologically

- Superpartners produced in pairs at colliders
- LSPs at end of superpartner decay chains
- LSP can be partner of photon, Z boson, Higgs boson, neutrino, gravitino or linear combination (could calculate this if superpartner masses known)
- LSP interacts at most weakly
- LSP normally stable

  -- every event has 2 LSPs, both escape detector
- Missing energy a basic signature of superpartners

LSP may also be the dark matter of the universe!

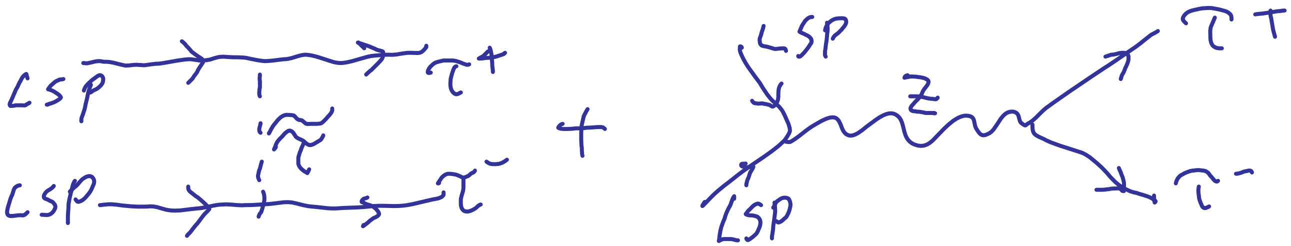
- Big Bang, universe cools – after a while only

  γ, e, u, d, ν, LSP remain

  nuclei

  atoms

- Calculate relic density of LSPs – some annihilate, e.g.

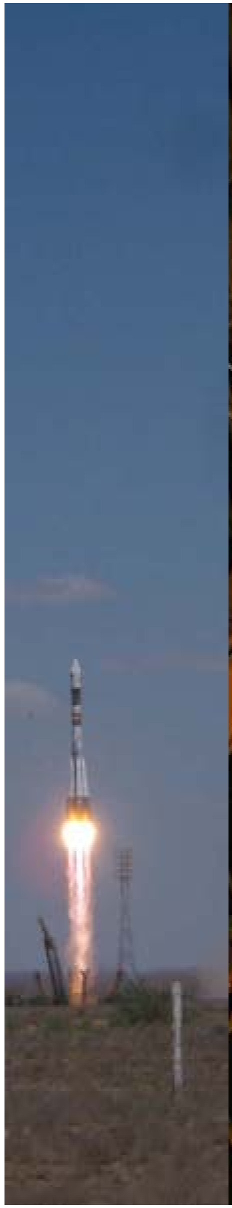


- Need to know superpartner properties to work out numbers – for reasonable values, answer about right for weakly interacting particle with mass ~ 100 GeV

There are several astrophysical “anomalies” that could tell us about dark matter

Various interpretations initially possible

- Pulsars, normal complicated stuff
- Dark matter annihilating in the galaxy



First Results from the PAMELA Space Mission

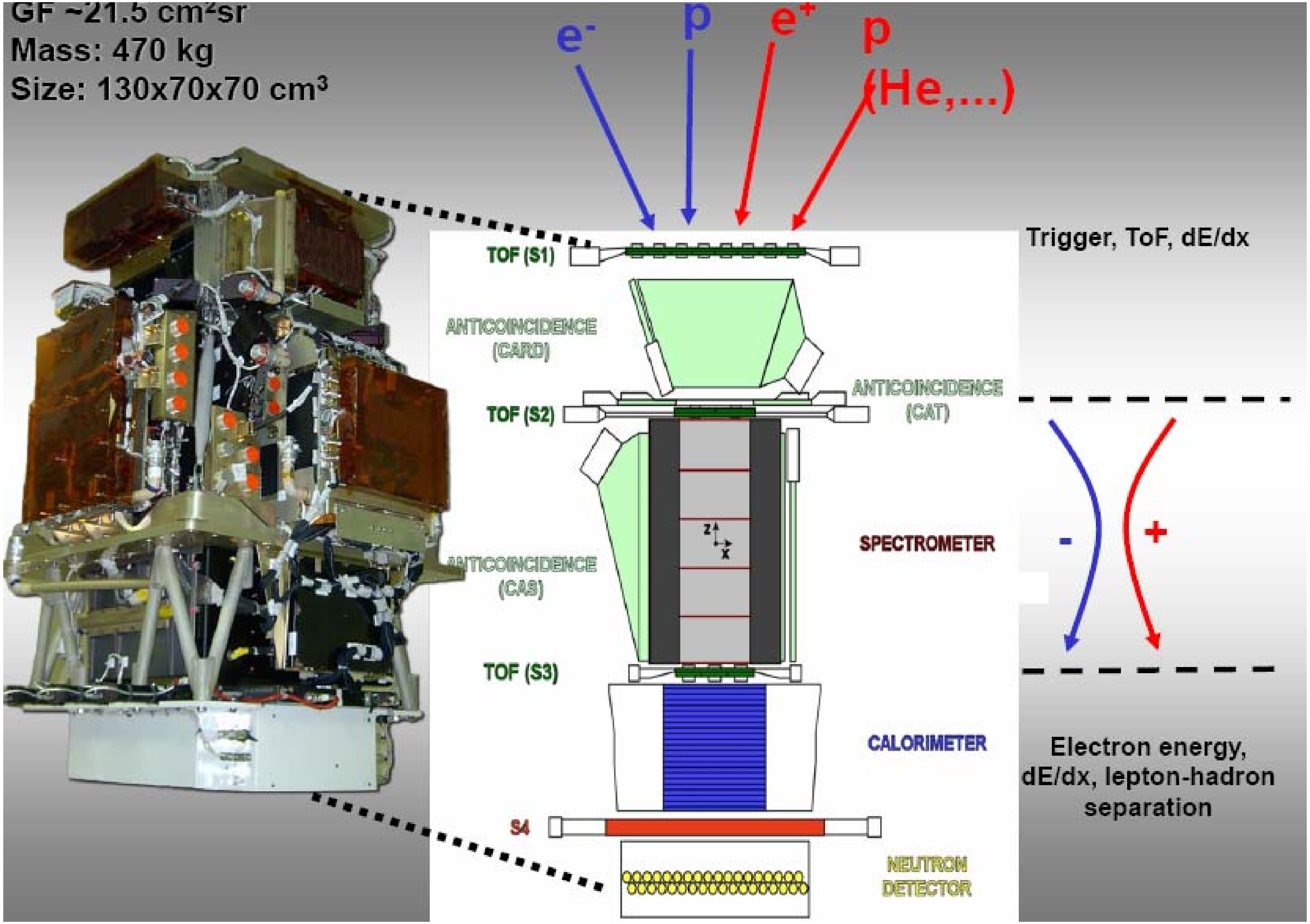
Mirko Boezio

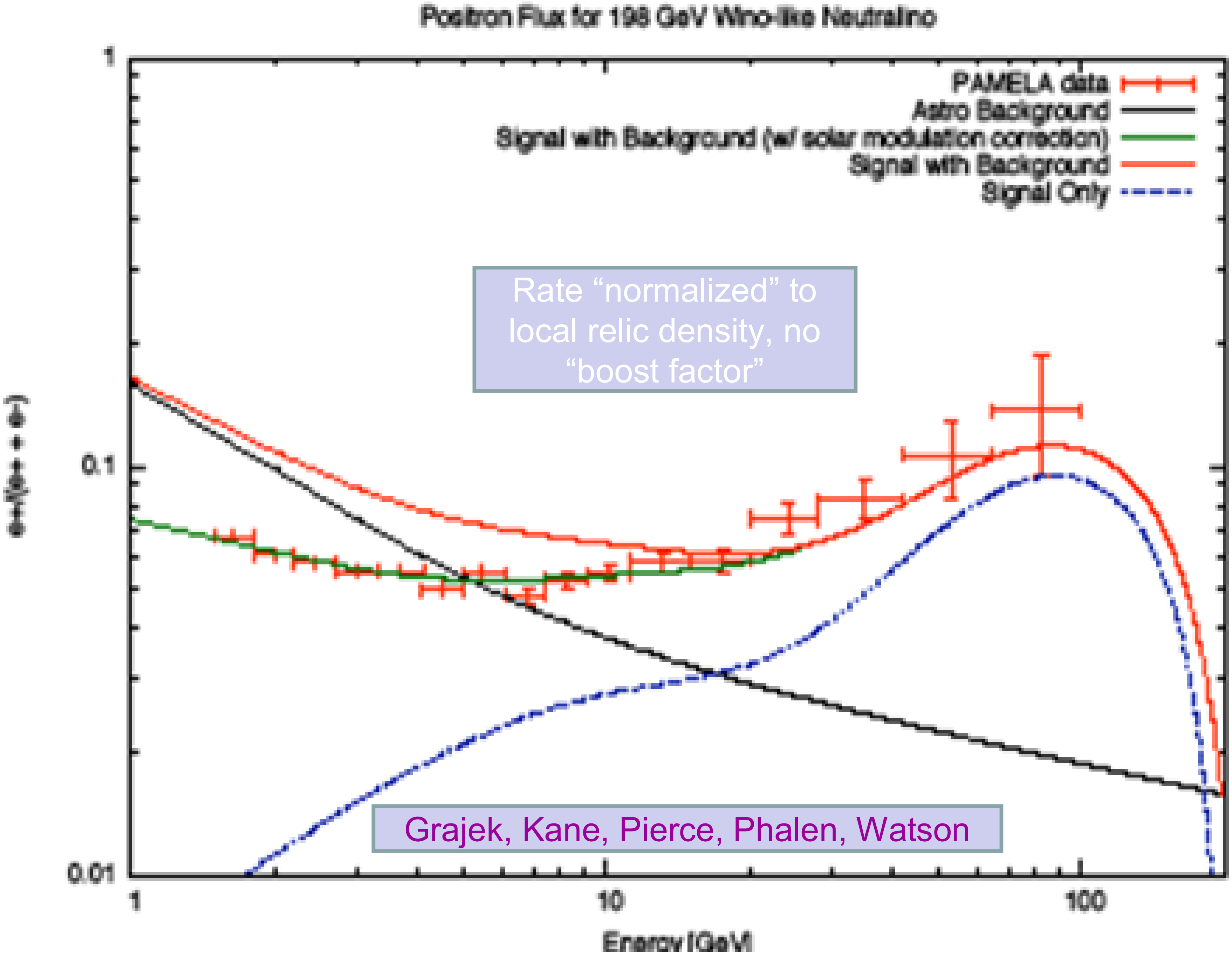
INFN Trieste, Italy

ICHEP2008

August 1st 2008

Philadelphia


GF ~21.5 cm²sr
Mass: 470 kg
Size: 130x70x70 cm³
e-
p
e+
p
(He,...)
Trigger, ToF, dE/dx
TOF (S1)
ANTICOINCIDENCE (CARD)
ANTICOINCIDENCE (CAT)
TOF (S2)
SPECTROMETER
-
+
ANTICOINCIDENCE (CAS)
TOF (S3)
CALORIMETER
Electron energy, dE/dx, lepton-hadron separation
S4
NEUTRON DETECTOR


Positron Flux for 198 GeV Wino-like Neutralino
PAMELA data
Astro Background
Signal with Background (w/ solar modulation correction)
Signal with Background
Signal Only
Rate "normalized" to local relic density, no "boost factor"
Grajek, Kane, Pierce, Phalen, Watson
e+/(e+ + e-)
Energy [GeV]
1
0.1
0.01
1
10
100

Wino LSP – very well motivated

-- anomaly mediated supersymmetry breaking

-- M theory compactified on G2

-- MSSM-Hewett, Rizzo et al

Does a wino LSP describe the PAMELA data?

[Grajek, Kane, Pierce, Phalen, Watson]

- Rate – wino annihilates well, too little relic density -- non-thermal – normalize to local relic density – no boost factor
- Profile of galaxy DM? – small energy dependent boost factors?
- Antiprotons – factor two large? OK simultaneously with rate?
- Gammas? Egret? GLAST?
- ATIC? – cannot describe ATIC data

Note positrons and antiprotons come from different parts of galaxy, have different energy loss mechanisms

Probably need wino mass about 200 GeV – constraints worse for lower mass, rate smaller for larger mass

Can get good agreement with all data separately

Showing can get good *simultaneous* agreement with all data and constraints is major computing problem – work underway

CONCLUDE: *premature to exclude wino LSP DM*

EXPERIMENTAL TESTS SOON:

- PAMELA larger energy positrons 100-200 GeV – must see “turnover”
- PAMELA electrons
- GLAST
- LHC

THEORY “TESTS”:

- Non-thermal cosmology
- Energy dependent boost factors
- Galactic propagation for signals, backgrounds

- Must *calculate* relic density of given candidate!!!!!

- Non-thermal origin of DM – always non-thermal in string theories?

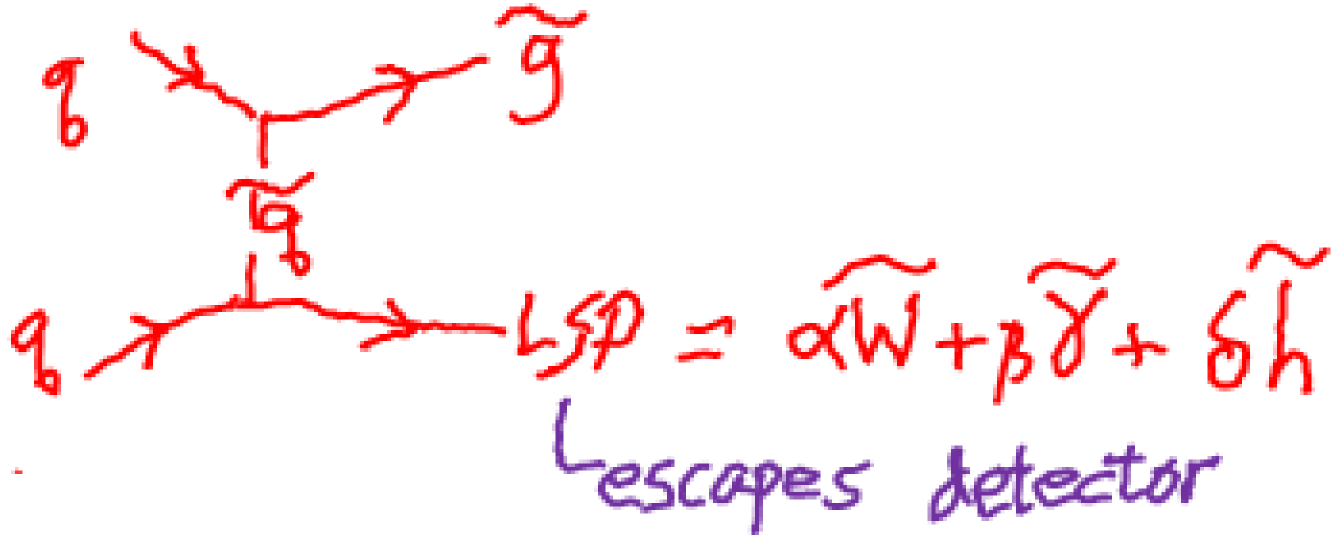
Dark matter at LHC

Ultimately must compute relic density for any candidate, cannot measure it

LHC will tell us much about DM in addition to missing energy events!

Can study composition of LSP by studying different processes at LHC – each LSP type couples differently to other stuff

e.g. higgsinos couple to quark-squark proportional to quark mass, so suppressed, while wino couples to left handed quarks but not right handed



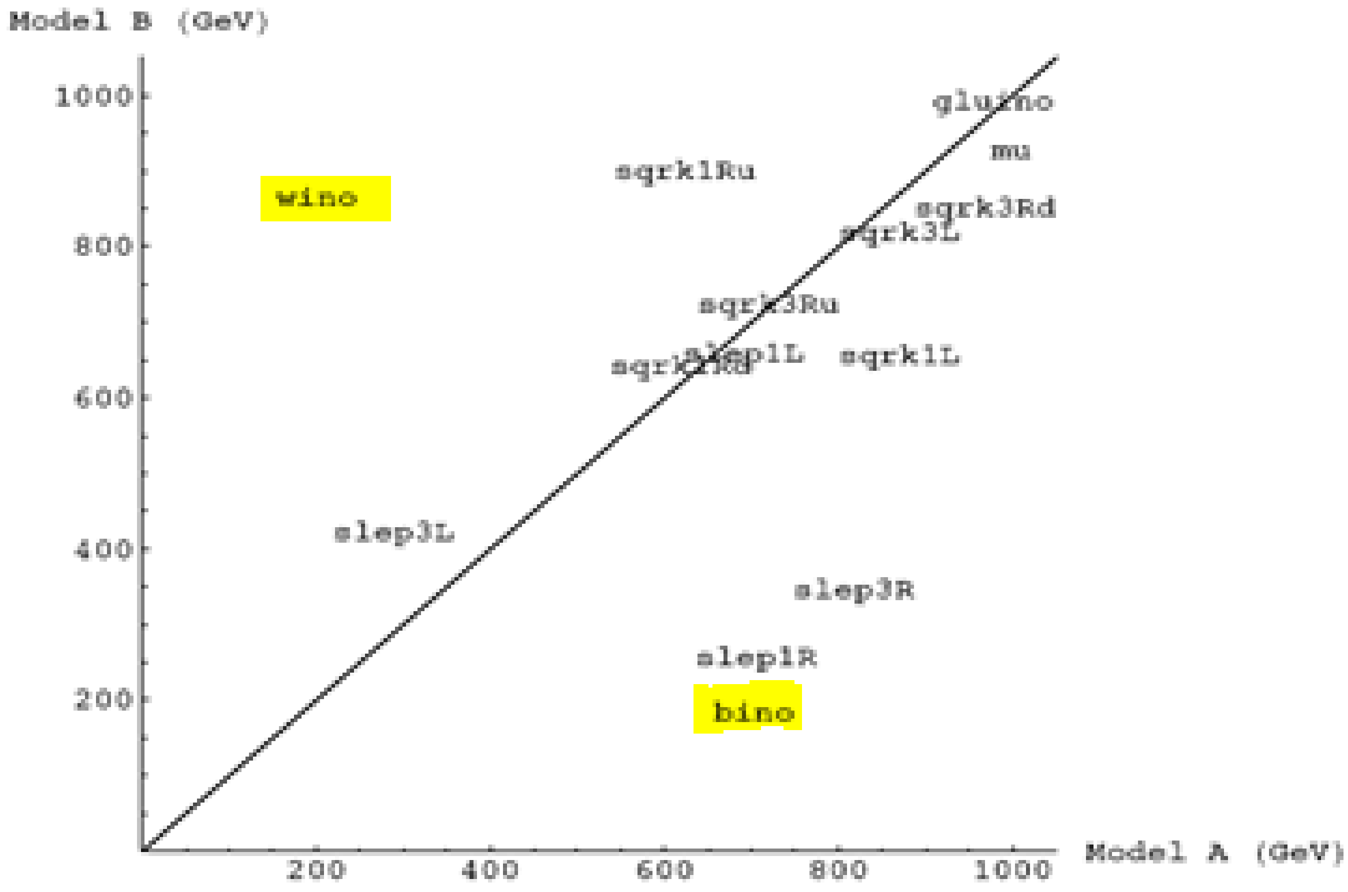
Not discovery channels – but after gluino and squark masses and BR known, probably observable

Two models with same signatures but different parameters and very different physics

Arkani-Hamed, Kane, Thaler, Wang ph/0512190

Recent work on removing degeneracies by using DM, B. Nelson et al, 0804.2899

Flippers: 17653 vs. 20026



LHC signals

- ❑ Can we interpret the new physics when it is discovered?
- ❑ Can we relate it to the underlying theory?

Suppose LHC reports a signal beyond the SM

- Experimenters and SM theorists will get that right

WANT TO INTERPRET IT! WHAT *IS* THE NEW TeV SCALE PHYSICS?

- Is it really supersymmetry? (easy)

  -- What superpartners are produced? (harder)

  -- Soft-breaking parameters? (very hard)
- L_{soft} (EW)?
- L_{soft} (Unif)?
- Underlying theory?

"LHC inverse problems"

Can we figure out how to go beyond learning the masses of some superpartners? If indeed supersymmetry, the new information will be mainly about supersymmetry breaking

Of course, do all in parallel

IS IT SUSY? GLUINO SPIN

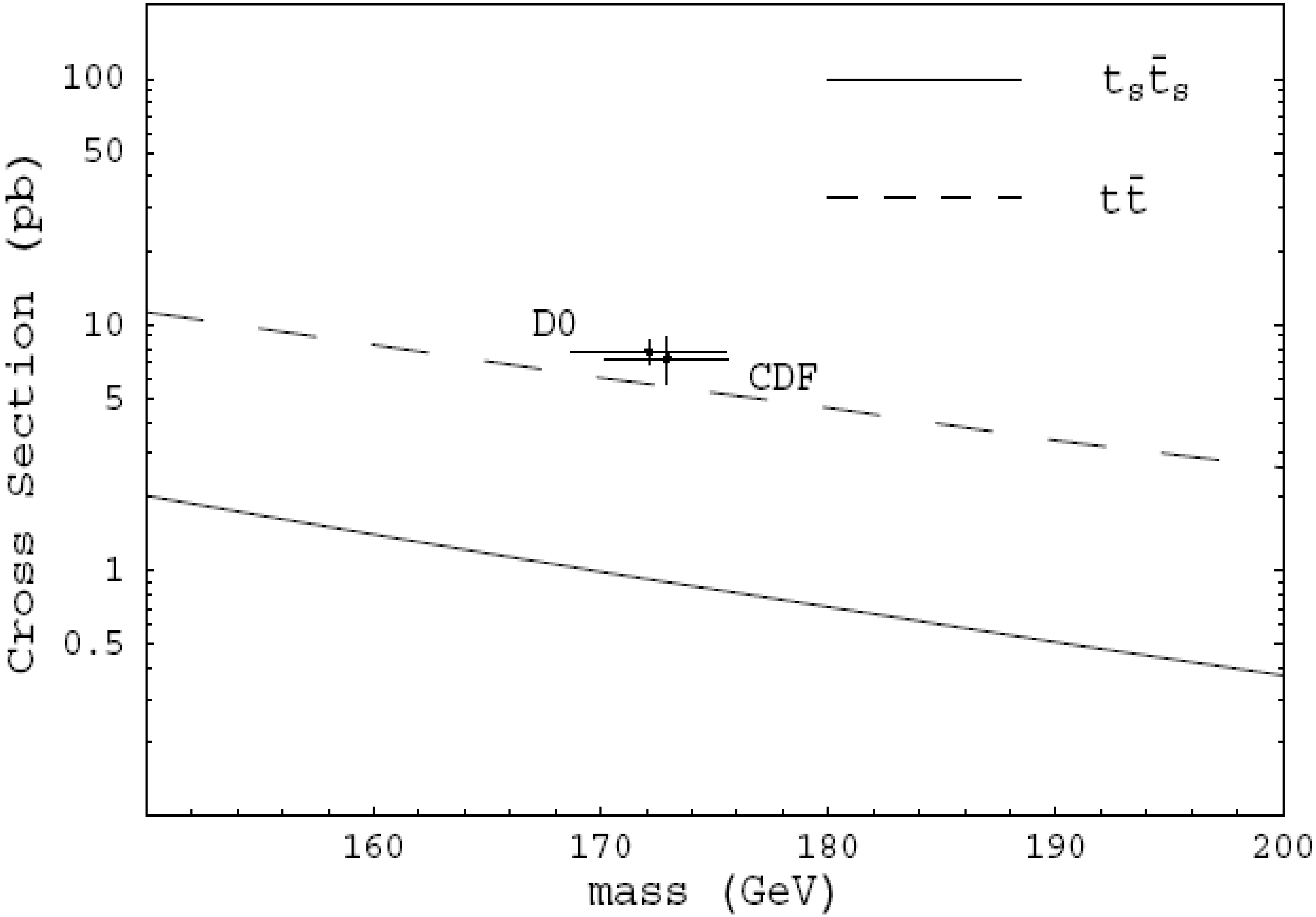
GK, Petrov, Shao, Wang 0805.1387

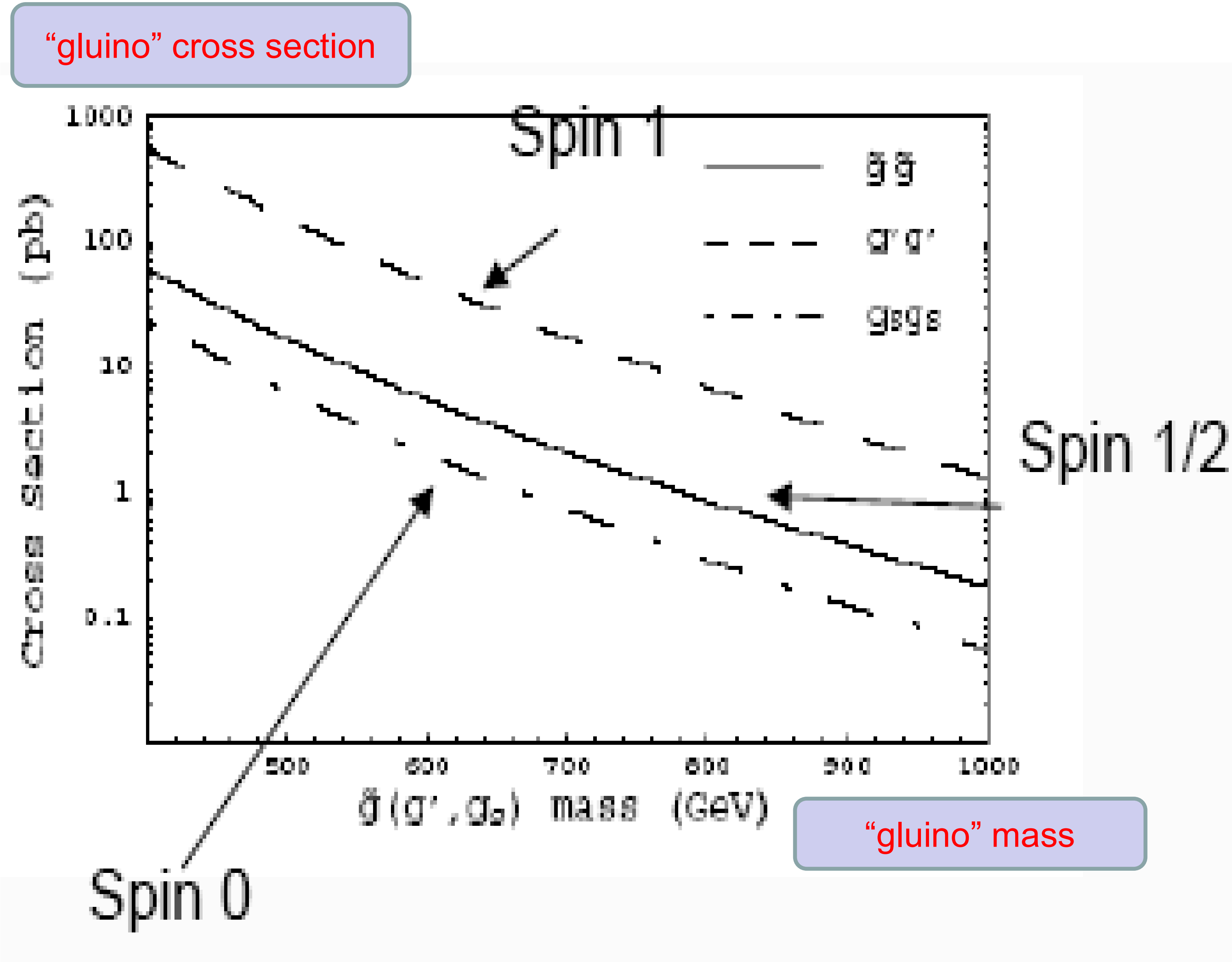
Depends on quantum theory and SM

- ***Suppose a good signal is found at LHC***
- Gluino? Or other "partners"
- Want to determine spin – gluino spin ½, others integer
- Suppose measure mass – then production cross section uniquely predicted
- Spin quantized, usually quite different rates for different spins →
- For larger signals production usually QCD, in general SM, so rate known →
- Only use total rate(s), not bins, so should work early, with low luminosity
- But could be seeing mass difference rather than mass – then heavier alternative could fake gluino – can break degeneracy with any observables sensitive to relative strengths of say gluino pair, squark-gluino, squark-squark – measure several rates instead of mass
- Not guaranteed to always work, but should work for most "worlds" – initially assume standard color and other quantum numbers, later check
- Currently analyzing in benchmark models – will also get more accurate estimates of needed luminosity

See also Hubisz, Lykken, Pierini, Spiropulu 0805.2398

Top quark spin determined by mass and cross section




"gluino" cross section
Spin 1
Spin 1/2
Spin 0
Cross section (pb)
1000
100
10
1
0.1
500
600
700
800
900
1000
"gluino" mass
mass (GeV)

GAUGINO MASS UNIFICATION

Would like to learn if gaugino masses unified at high scale

-- could be an important way to favor certain theories

Altunkravek, Grajek, Holmes, Kane, Kumar, Nelson,

Unlikely to measure all gaugino masses, or to run them up and get precision result – even if could measure chargino and neutralino masses, have to invert mass matrices to get gaugino masses – also don't know phases

But experimental signatures ***are*** sensitive to the high scale gaugino masses – so can find several signatures that allow testing GMU -- paper gives signatures, why sensitive

Initial study for one parameter mirage mediation – more complicated analyses underway

Consider issue of gaugino mass unification at the string scale

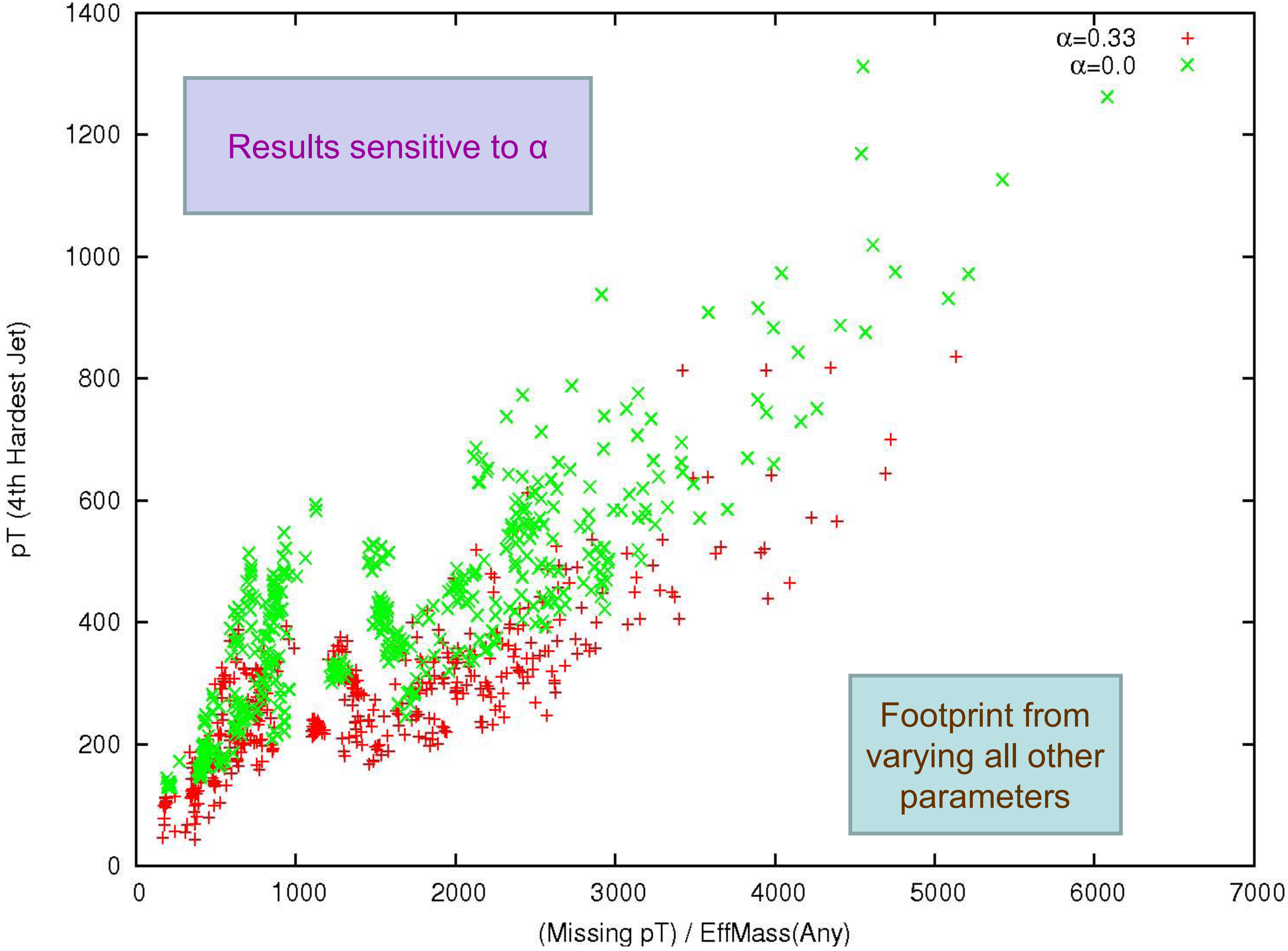
Test by measuring M_1, M_2, M_3

-- but if one could measure them it would be at the collider scale – would have to extrapolate up – but the running could depend on other matter, etc

-- but cannot measure them – the neutralino and chargino *mass* eigenstates are what is observable, at best, and to invert them to get M_1, M_2 is probably impossible – even M_3 is related to the gluino mass by QCD and susy-QCD corrections

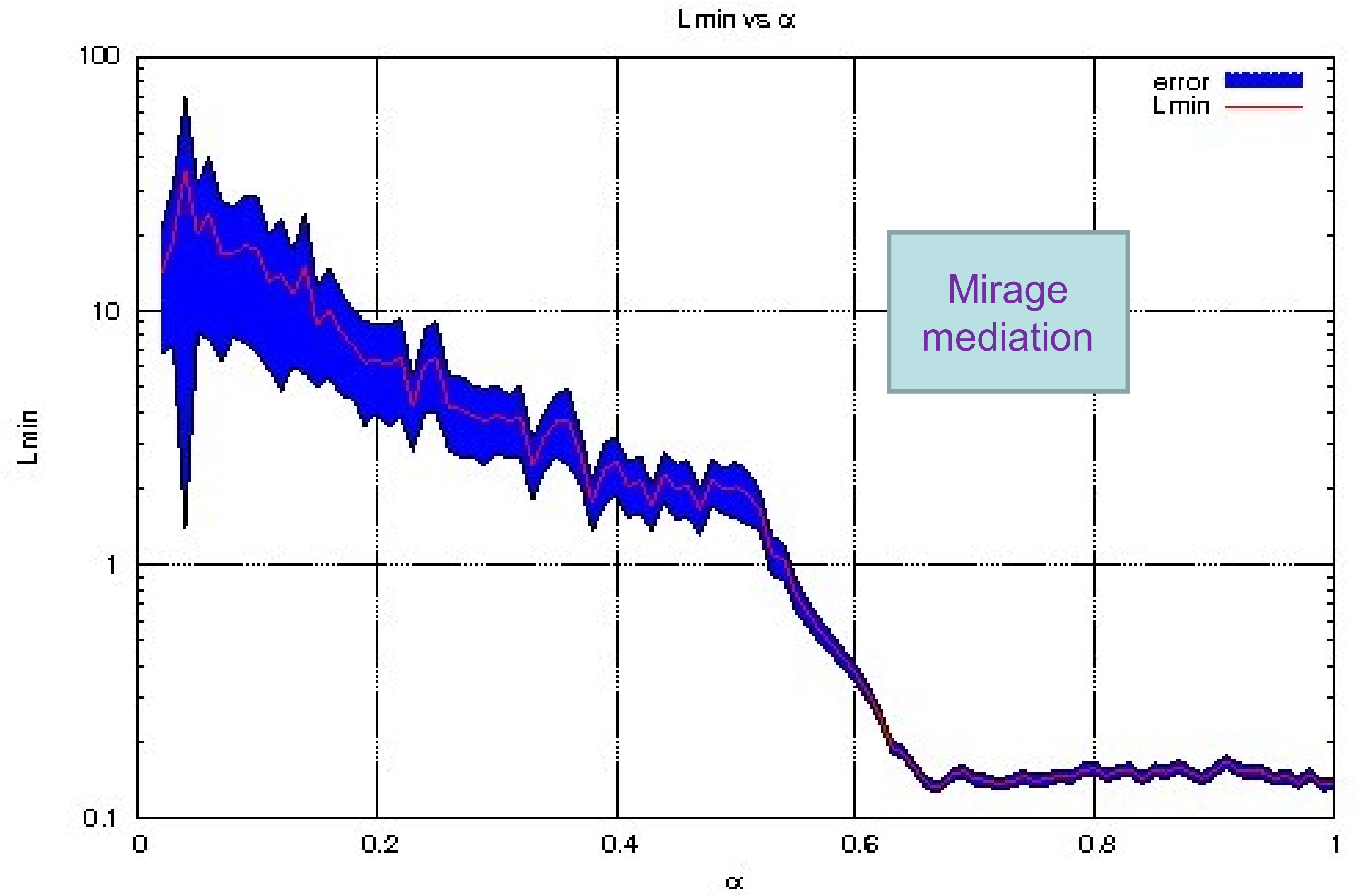
[Altunkavnak, Grajek, Holmes, Kane, Kumer, Nelson; See also Bhattacharya, Datta, Mukhopadhyaya]

Nevertheless, the footprints in signature space DO depend on the gaugino masses in observable ways – more or fewer leptons, more or fewer jets of given energy because of spacing between states, etc



Results sensitive to α
Footprint from varying all other parameters
α=0.33
α=0.0
pT (4th Hardest Jet)
(Missing pT) / EffMass(Any)
0
200
400
600
800
1000
1200
1400
0
1000
2000
3000
4000
5000
6000
7000

Luminosity required to measure given α, fb^{-1}

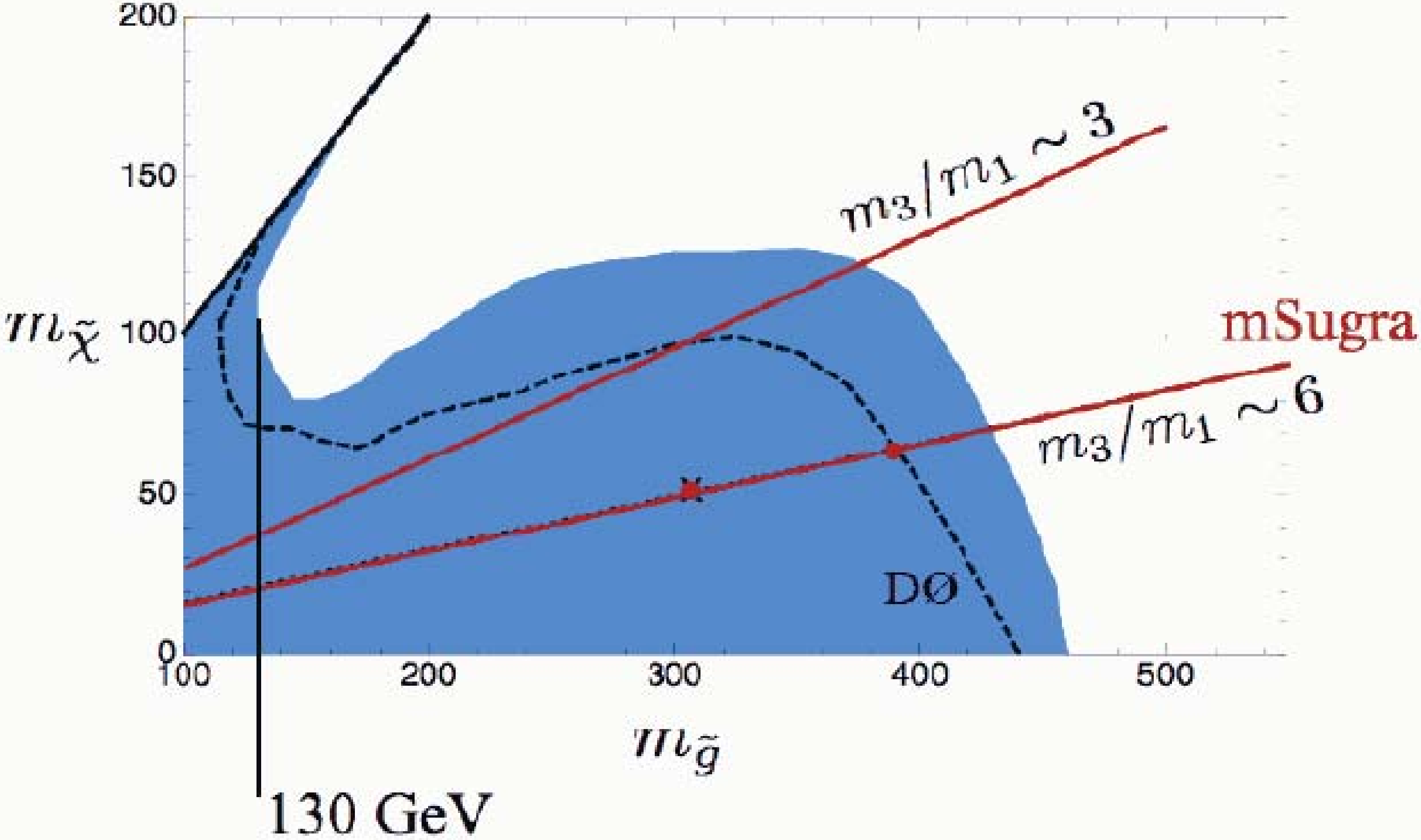


Altunkaynak, Grajek, Holmes, GK, Kumar, Nelson, in preparation

Gluinos have large cross sections – what do we know about them?

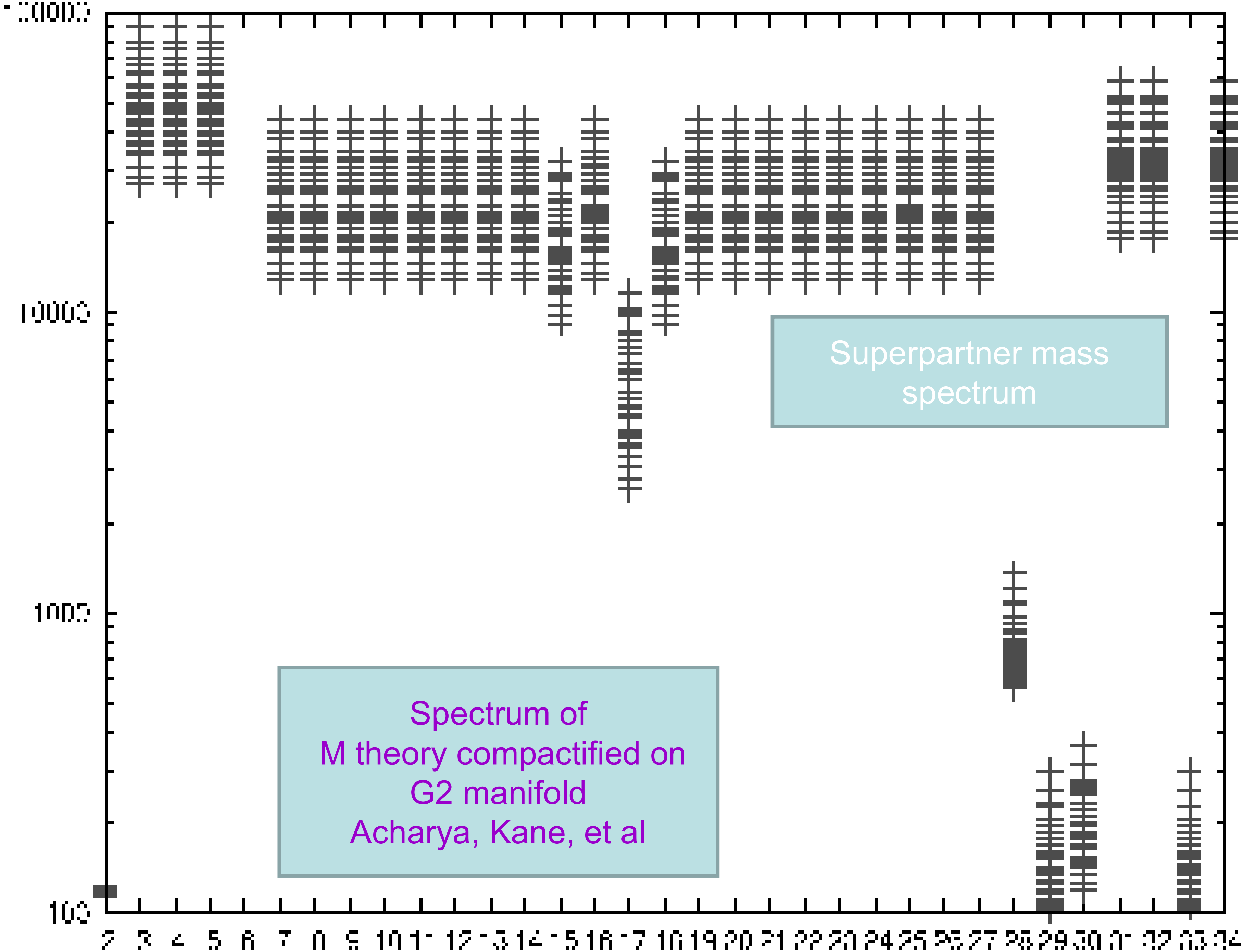
Tevatron Exclusion Limits

$S/B > 1$



Combines 1j, 2j, 3j, & 4j results

Alwell, Wacker et al

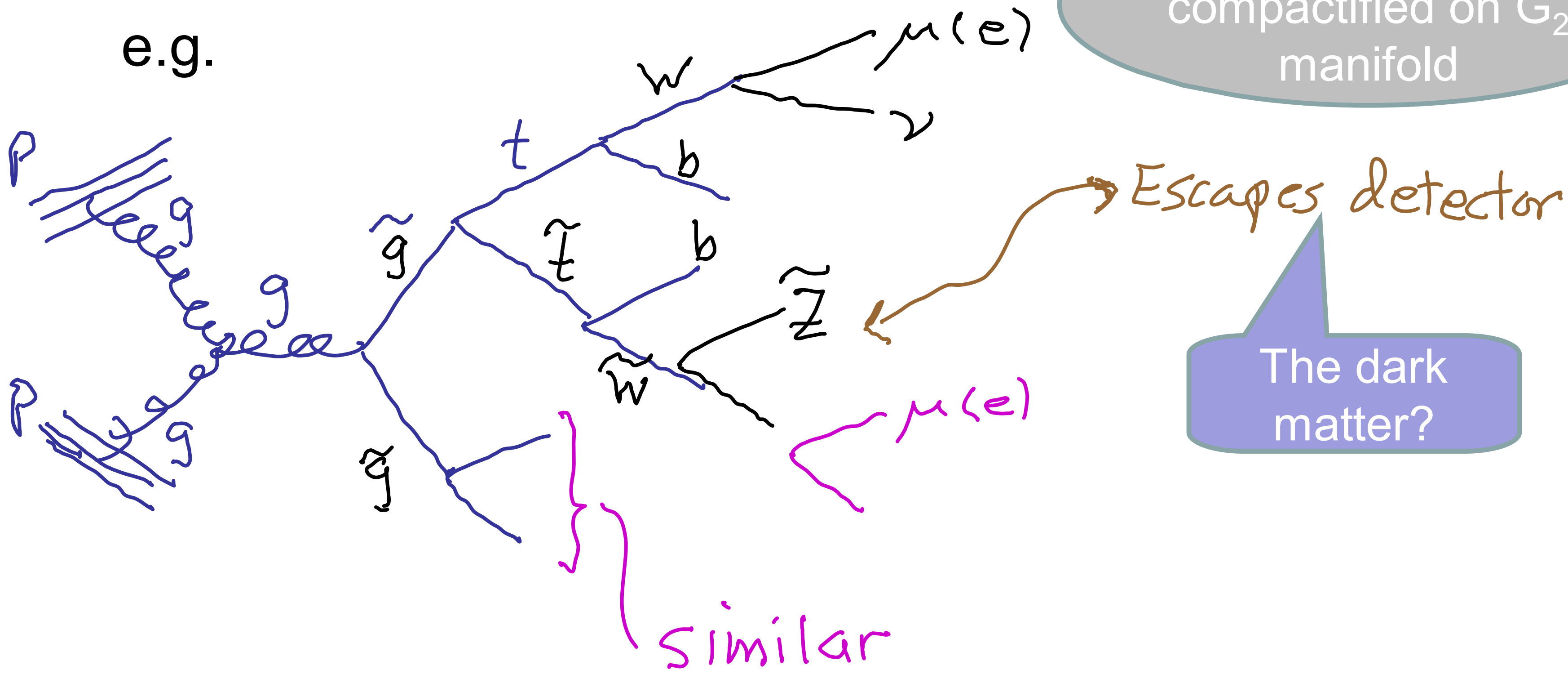

Superpartner mass spectrum
Spectrum of
M theory compactified on
G2 manifold
Acharya, Kane, et al

- gluinos produced, $\sigma \sim$ few pb
- RGE running from $M_{3/2}$ and scalar scale gives lightest stop significantly lighter than other scalars (few TeV), so it dominates gluino decay

Collider signatures of superpartners:

From M theory compactified on G_2 manifold

e.g.



$\longrightarrow$ 4 b's, $\ell^{\pm}$, large missing p_{Trans}

Very hard for Standard Model events to fake this

For 1 TeV gluinos at LHC, about 1 event per pb^{-1}, ~ 100 first “month”

UNDERLYING THEORY?

Most work relating to underlying theory so far:

Calculate top-down example, with specific guessed parameters
-- hope what is found can be recognized as what was calculated

Instead argue that phenomenologically it makes sense to analyze semi-realistic classes of underlying (e.g.string) theory motivated vacua – makes sense to try to map LHC signatures onto these, connect patters of signatures to classes of such vacua -- systematic procedure

Supersymmetric weak scale effective theories have “105 parameters” – supersymmetric low scale theories from an underlying high scale theory may have a few parameters!

Of course, don’t know the correct underlying theory (yet)

But the signatures do depend on the parameters, and so the patterns of signatures reflect the parameters – so try to approach data in the context of underlying theory to improve situation

SIGNATURES

Think about what experimenters actually report -- "signatures", e.g.

-- number of events with $\not{E}_T$ > 100 GeV, 2 or more jets (E>50 GeV), etc, and distribution of such events vs. P_T of most energetic jet, etc

– number of events with lepton pairs with same sign charge and opposite flavor and $\not{E}_T$>100GeV, etc

From these, can we figure out what new physics is produced, and how to interpret it?

Very difficult to measure most superpartner masses, tanβ, etc

But possible to study gaugino mass unification (as above) using such signatures

SO – PROCEED TO CALCULATE PREDICTIONS FROM STRING THEORIES FOR LHC DATA

-- pick some corner of "string theory", e.g. heterotic, or IIA, or M theory, etc

-- compactify to 4D – on Z_3 orbifold, or appropriate D-branes, or C-Y 6D space, or 7D manifold with G_2 holonomy, etc

-- stabilize moduli, break supersymmetry and establish mediation mechanism – hidden sector gaugino condensation, or anti-D-brane, etc

-- generate or accommodate Planck-EW hierarchy

-- take 4D field theory limit, e.g. supergravity

There already exist constructions that allow most of above – may also have matter spectrum calculated -- make reasonable assumptions about visible matter spectrum, MSSM

Later look for additional constructions and variations on these

- Write high (~compactification) scale string theory effective 4D Lagrangian – e.g. determine f, W, K from underlying microscopic theory – use supergravity techniques to calculate L_{soft} – gives initial conditions for calculating collider scale values

- Use RGEs to run down to EW scale – programs already exist for MSSM and some extensions, softsusy, spheno, suspect… -- have a "complete" theory so include intermediate scale matter, hidden sector effects, etc

- Impose constraints – consistent EW symmetry breaking – experimental bounds on higgs, superpartner masses – upper bound on LSP relic density – CPV and flavor constraints, etc – in a complete model more can be calculated

- Generate events for short distance processes such as superpartner production, with Pythia, madgraph, alpgen, comphep (calchep), herwig

- Hadronize to long distances, quarks and gluons into jets, decay taus – pythia, isajet, herwig

- Cuts, triggering, combine overlapping jets – PGS

- Test framework

Sounds complicated

But software exists for every part – as a result of LHC Olympics, software user friendly, and mostly linked – useable for some new physics models or MSSM plus some exotics – software being improved

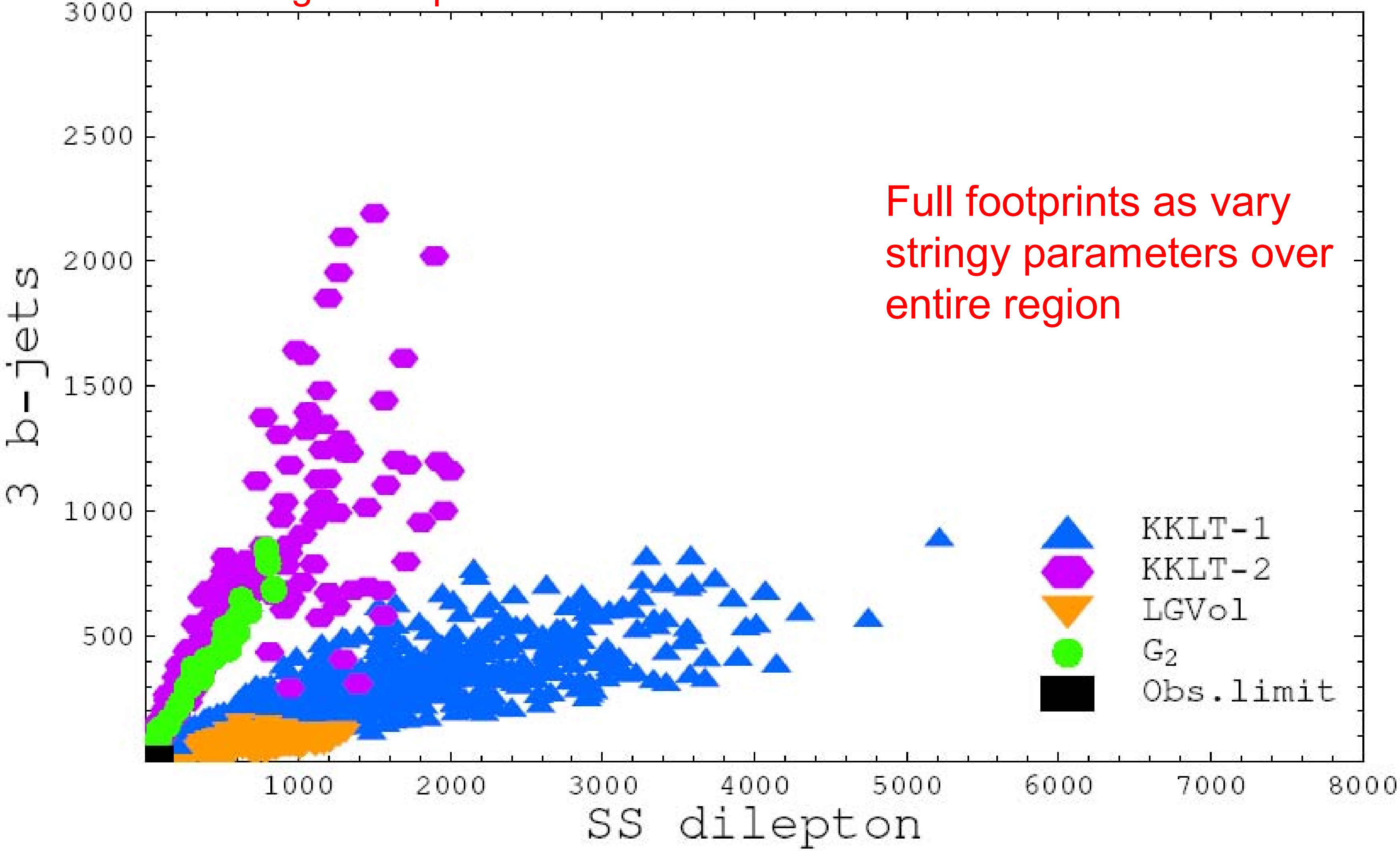
Vary all the as-yet-undetermined microscopic parameters that may affect LHC predictions – e.g. modular weights, rank of gaugino condensation groups, integer coefficients of moduli in G_2 gauge kinetic function, etc

→ “footprint” of that string-susy-model in “signature space”

LHC – systematic way to study string theories (any underlying theories)

Kane, Kumar, Shao ArXiv 0709.4259

Signature plots



Full footprints as vary stringy parameters over entire region

Change how compactify, repeat – change how break supersymmetry, repeat – systematically

For each case, graph entire footprint, not result of a few parameters that may or may not be representative

→ Footprints ***do not*** fill entire signature space

Even early at LHC will have many signatures and distributions

- $\not{E}_T$ > 100 GeV
- 2 or more jets, 1 or no jets, etc
- No charged leptons; one lepton; two leptons with SSSF, SSDF, OSSF, OSDF; trileptons
- Use b's, τ's too – even if not so easy initially, probably useful early for comparisons – then lots more signatures

Etc – so hundreds of possible signature plots

SM backgrounds?

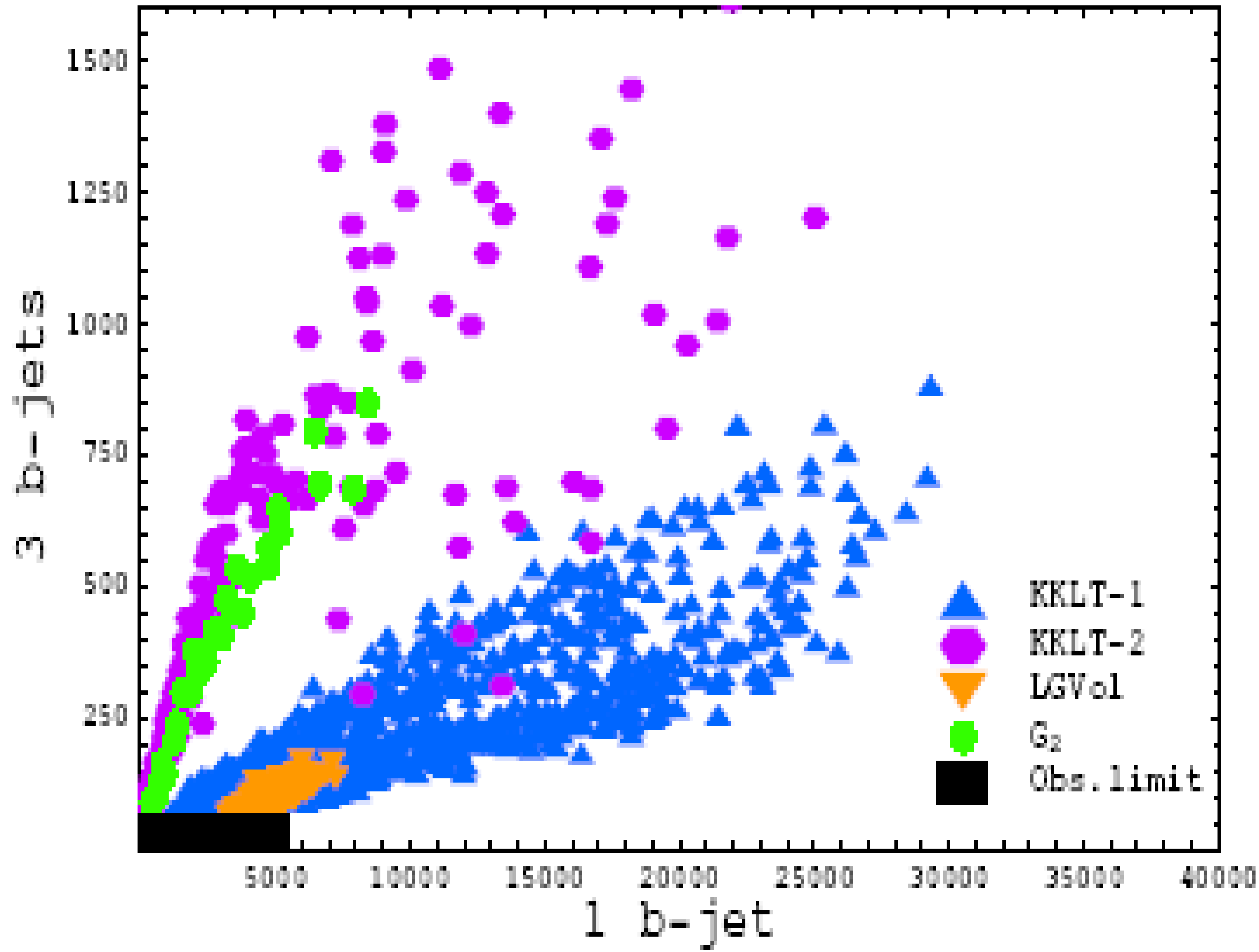
-- when there is a real signal experimenters will report the excesses – some signatures yes, some not – both contain useful information

-- we have found that a good way to study issues at this stage is to estimate the level at which SM processes will enter and just indicate that on the plots

All event rates for 5 fb^{-1}

P_T (jet) > 200 GeV, P_T(lepton) > 10 GeV, missing E_T > 100 GeV

2D slices of footprints, all microscopic parameters varied



Overlaps on one signature plot correspond to different parameters from overlaps on different signature plot – can separate!

Can use any type of distribution, histogram, etc

Possible advantages over low scale effective theory approach:

- No swampland
- Reduce degeneracy problem
- Have theory so have cosmology, can include inflation parameters, can calculate Dark Matter relic density, scattering, annihilation data as signatures
- Have theory so can include complex phases, study CP violation, matter asymmetry
- May relate g_μ-2, some flavor physics, EDMs, to LHC

Of course, always include all possible information

Also, will learn a lot about string theory (underlying theories) by challenging them to connect to phenomenology

CONCLUDING REMARKS

If didn’t know about dark matter, supersymmetry would have predicted it, made us look for it – that’s what actually happened for dark matter not made of protons and neutrons

If didn’t know about gravity, families, gauge theories of forces, quarks and leptons, string theory would have suggested them – examples exist for all of these

LHC data ***will*** depend on hidden sector, on the compactification manifold, etc (or equivalent for other theories)

LHC data *will* be sensitive to gaugino mass unification, type of LSP – analyses underway

Not sensitive to *only* hidden sector or *only* LSP, but overcome that by using a number of signature plots

Different classes of realistic string frameworks give limited and generally different footprints – can be distinguished

Remarkable if any string constructions (or any underlying theory) can be consistent with data on lots of signature plots!

SOME QUESTIONS

	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?			√

√ ***addressed***
√√ ***explained***
~ ***accommodate***

LHC directly

String theory addresses what we want to understand

Many stringy tests

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

LHC is a "why" machine (and PAMELA, GLAST)

- The Standard Model(s) describe the world we see, but do not explain it

- LHC data will not improve our qualitative description – rather, it may provide the clues that allow us to learn about the dark matter, the Higgs physics, the matter asymmetry, and test underlying theories such as string theory

- In addition to its phenomenological motivations, supersymmetry opens a window to the Planck scale, and studying how supersymmetry is broken gives clues toward understanding our string vacuum