LHC signals

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

Gordy Kane

LHC Conference, KITP, June 08

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) – see Lykken talk also
  -- 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

Philosophy

All 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, 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

OUTLINE

- Run up data, or low scale effective theory, to high scale?

- Is it Supersymmetry?

  -- Measure gluino spin early? At a hadron collider?

  [see Lykken talk also]

- Gaugino mass unification? At a hadron collider?

- Learn underlying high scale theory?

Top-down approach, based on "footprints" in "signature space"

GK, Piyush Kumar, Jing Shao, ph/0709.4259, and hep-ph/0610038

Binetruy, GK, Nelson, Liantao Wang, Ting Wang, ph/0312248

Some study of EW scale LHC inverse problem

-- LHCO, effective theories, degeneracies, marmoset …

But little study of obstacles to extrapolating up correctly

-- Kumar, GK, Morrissey, Toharia (ph/0612287)

-- Cohen, Roy, Schmaltz hidden sector effects

-- much more work needed here

OBSTACLES

Some obstacles to running up → opportunities to deduce new physics that cannot directly see [GK, Kumar, Morrissey, Toharia ph/0612287]

- Intermediate scale matter – gaugino masses affected but not ratios of gaugino masses (assuming GCU) – Ramond and Martin ~ 1993

- "S-term", hypercharge D term, $S=Tr(Ym^2)$, depends on all scalar masses
  -- effect of $S \neq 0$ can shift scalar masses a lot – if assume S=0 wrongly, make big mistake on scalars →
  -- if run $Y_k m_j^2 - Y_j m_k^2$ no problem, get right answer whether S=0 or not
  -- any other gauged U(1) symmetries will have S-terms too

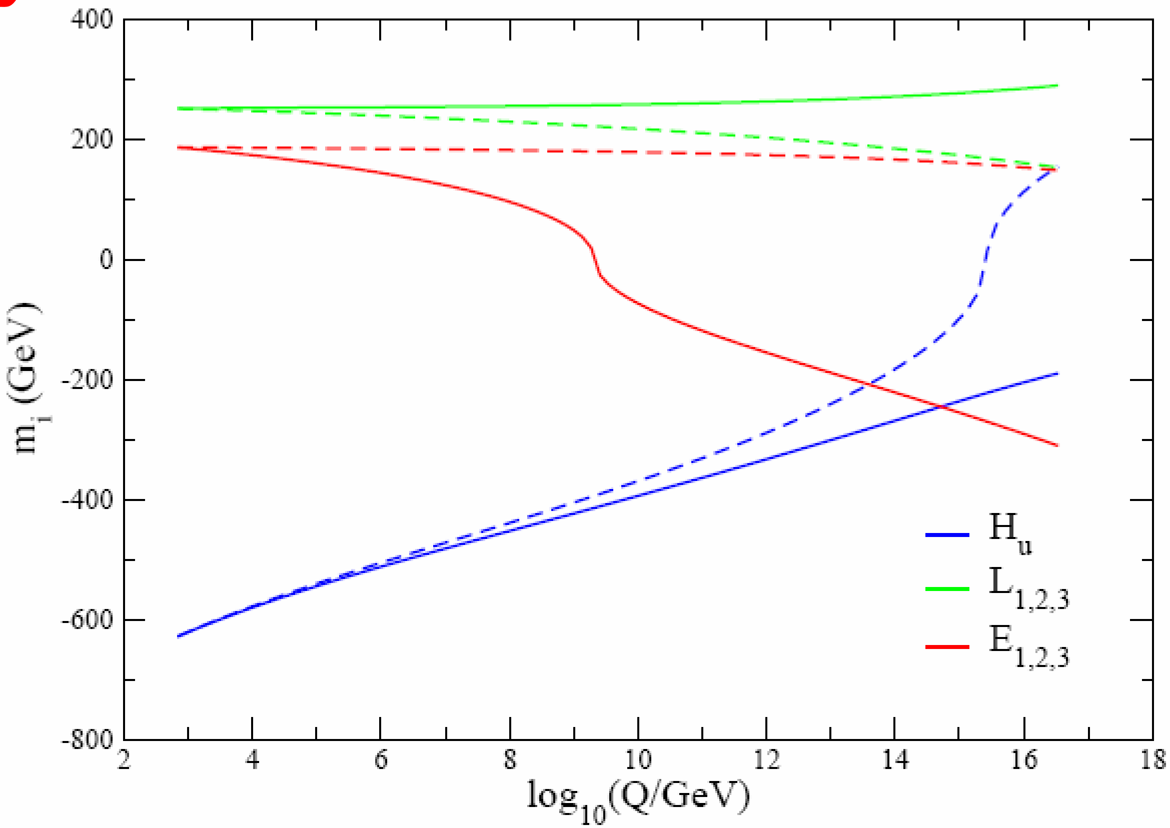
- Yukawa effects from heavy Majorana neutrinos that give see-saw neutrino masses

Can sometimes find combinations of soft parameters stable under running, unaffected by the new physics – then compare without such combinations and get clue that new physics is there!

m^2_{Hd} wrong at low scale, or big error so S≠0 effectively

$dm_i^2/dt \sim S x \cdots$

$dS/dt \sim S$



High scale masses no longer look unified

Figure 1: Deviations in the running of some of the SPS-5 soft masses due to setting $m^2_{H_d} = (1000\ \text{GeV})^2$ at the low scale. The solid lines show the running of $m^2_{H_u}$, m^2_E, and m^2_L with this perturbation, while the dashed lines show the unperturbed running of these soft masses. The unperturbed low-scale value of the down-Higgs soft mass is $m^2_{H_d} \simeq (235\,\text{GeV})^2$.

IS IT SUSY? GLUINO SPIN

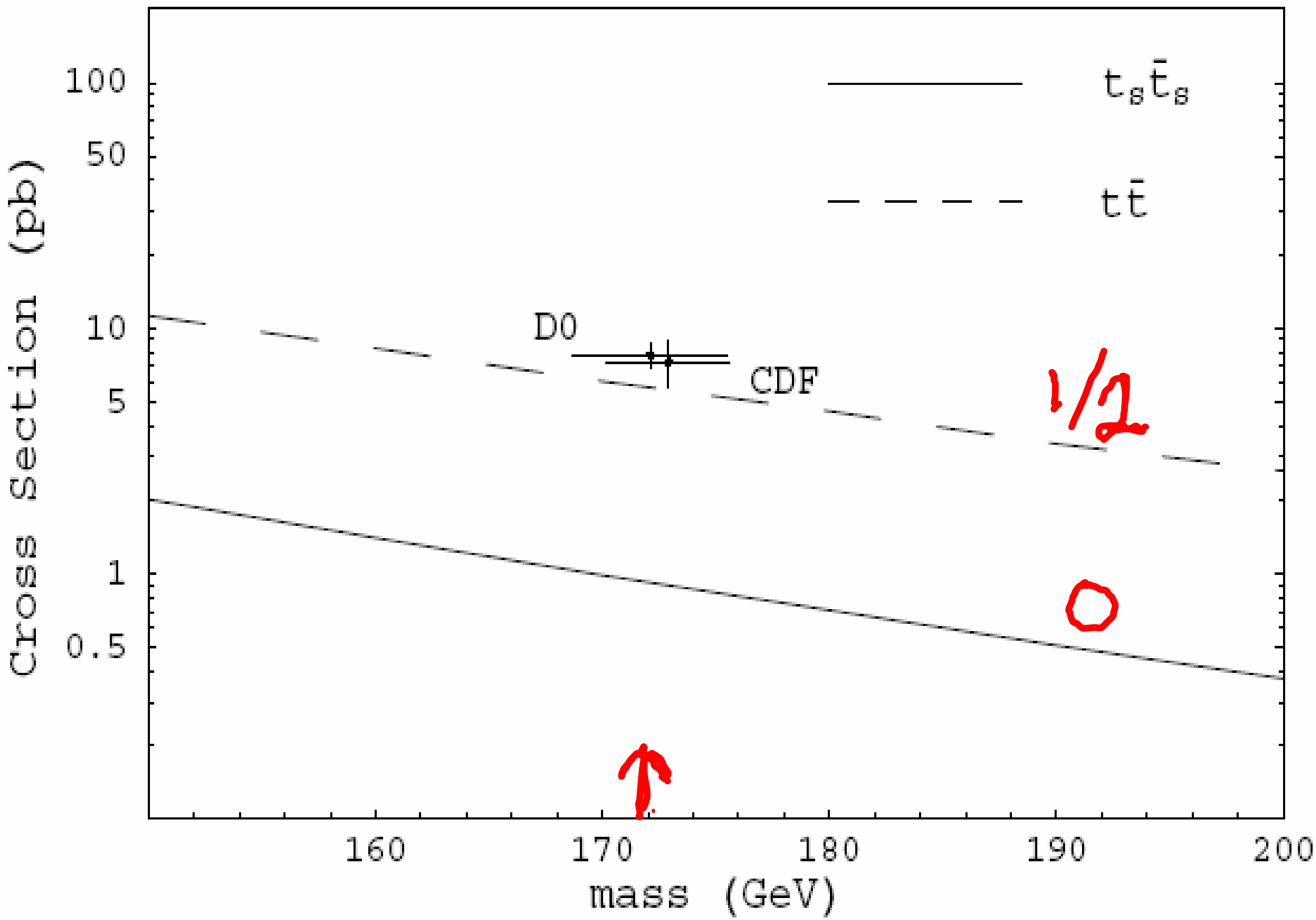
GK, Petrov, Shao, Wang 0805.1387

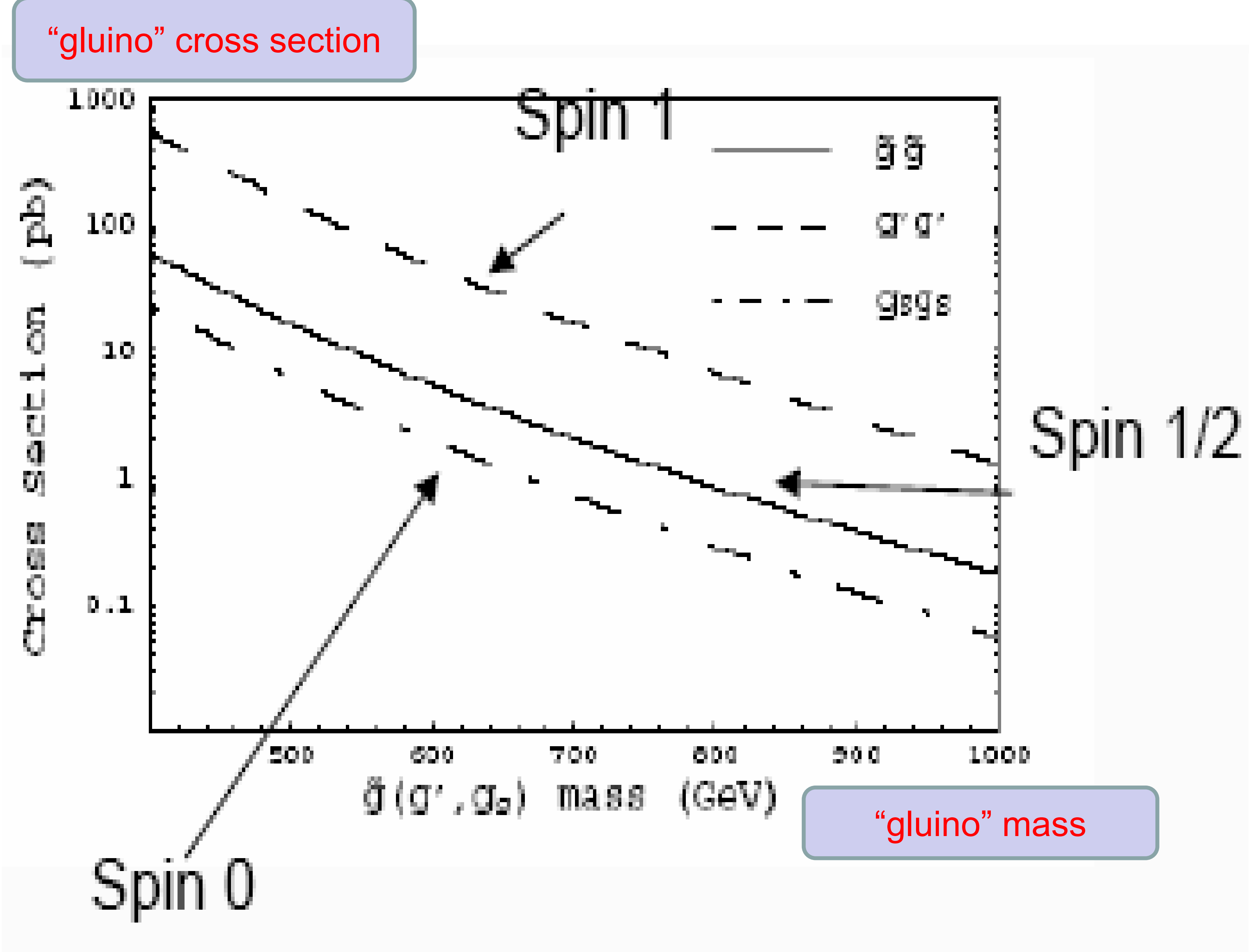
Depends on quantum theory and SM

- ***Suppose a good signal is found at LHC***
- Gluino? Or little running large KK extra …?
- 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
- 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
gg
g'g'
gsgs
1000
100
10
1
0.1
500
600
700
800
900
1000
Cross section (pb)
"gluino" mass

GAUGINO MASS UNIFICATION

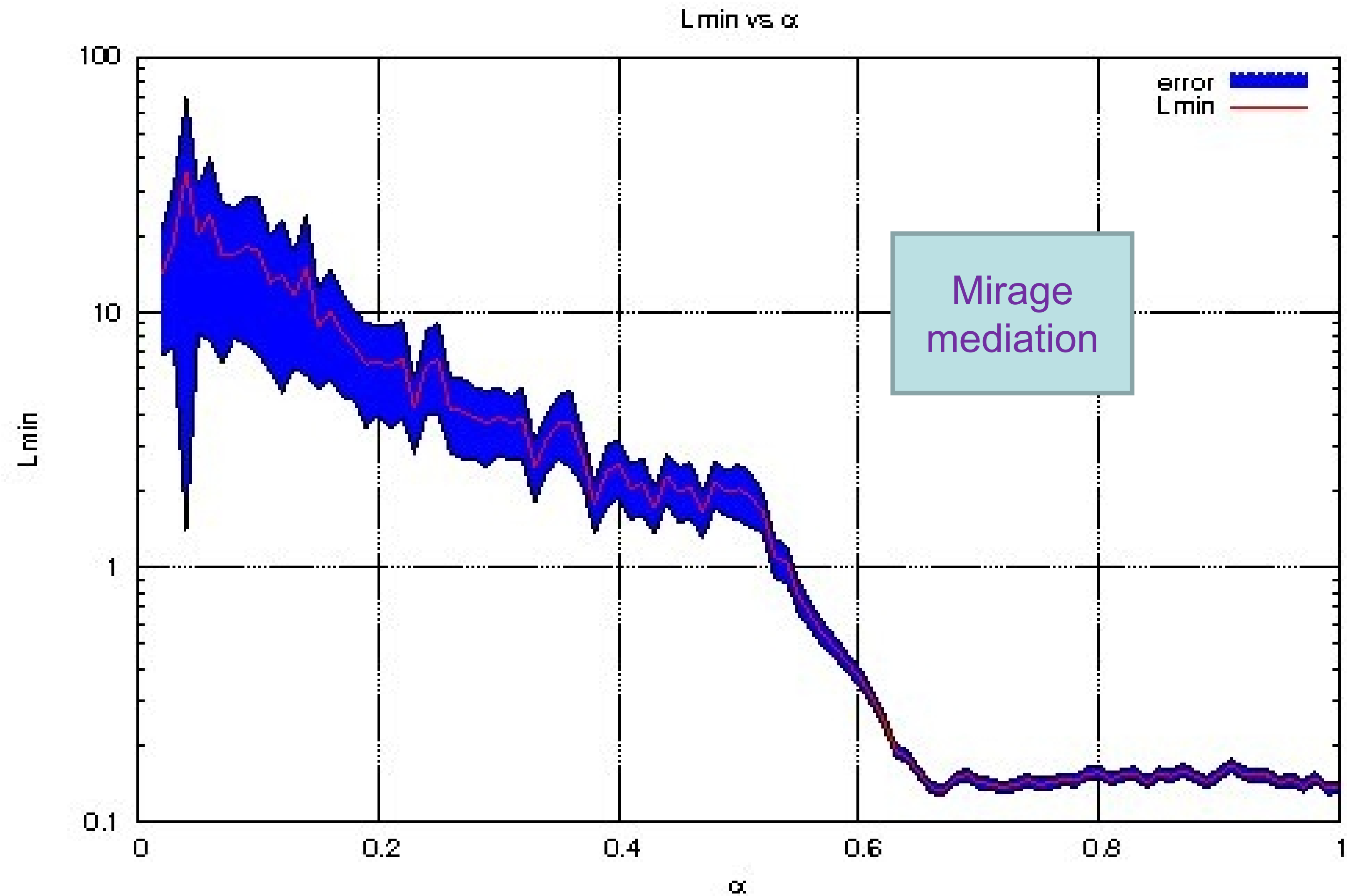
Would like to learn if gaugino masses unified at high scale
-- could be an important way to favor certain theories

Unlikely to measure all gaugino masses, or to run them up and get precision result

But 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

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



Mirage mediation

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

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

Today – 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!

Note degeneracy issue from point of view of underlying theory

– underlying (e.g. string) theory will have some not-yet-determined parameters (that affect collider results) at its natural scale □ M_{pl}

– the low scale effective theory has many parameters, e.g 105 – but all calculable from the underlying theory

– if express the (7--20) collider parameters in terms of the high scale theory parameters, many degeneracies eliminated

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

Could (and should) pursue this approach in any “theory”

– prefer to use string theory here since well motivated

-- string theories address all issues (but maybe Λ)

– have string-based models that essentially have SM, GCU, softly broken supersymmetry, DM, EW symmetry breaking, etc

-- can do reliable calculations in some cases with moduli stabilized, in valid supergravity approximation

– currently several semirealistic examples known, so can compare

So two themes here:

- ❑ General approach to relating LHC data and underlying theory
- ❑ Focus on relating string-motivated theories to low scale data, LHC

Not trying to make stronger claims about what is known about string theories than what is justified – no full constructions yet – making models that appear to be reasonable from point of view of what is known – assumptions are plausible

Do NOT want to find or argue for generic predictions of string theory – on the contrary, want and expect if change string theory or compactification or supersymmetry breaking or most assumptions it will change the predictions – then we can learn about the high scale theory from data

Nevertheless, find for any particular string-based model some definite unavoidable predictions, sometimes surprising

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, $\tan\beta$, etc

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

Criteria for semi-realistic string motivated vacua:

- N=1 supersymmetric 4D world, supersymmetry softly broken
- Moduli stabilized in (perhaps metastable) dS vacuum
- Stable hierarchy between EW and “string” scale, can connect perturbatively
- Visible sector accommodates MSSM particle content and gauge group, perhaps extended
- Mechanism for breaking EW symmetry
- Consistent with all experimental constraints
- Gauge coupling unification, at least accomodated

Present models not quite, but probably close enough – “frameworks” – well motivated, internally consistent – so far MSSM matter spectra

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 – Chameleon, Bridge etc

Can access most software at LHCO website

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"

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

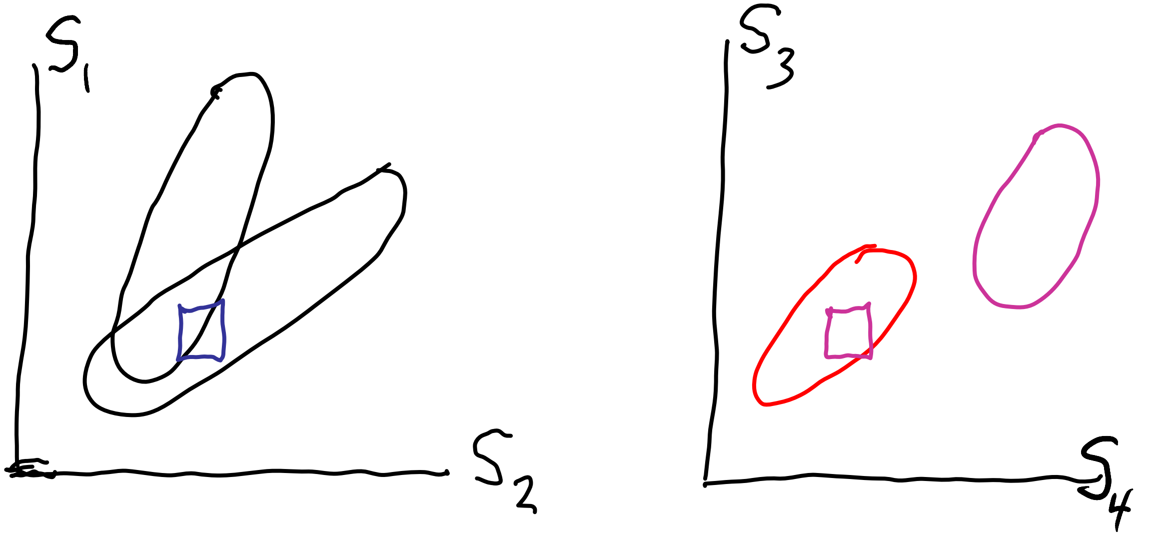
- $\not{E}_T$ > 100 GeV
- 2 or more jets, 1 or no jets, etc
- No charged leptons; one lepton; two leptons with SSSF, SSDF, OSSF, OSDF; trileptons
- Use b's, τ's too – even if not so easy initially, probably useful early for comparisons – then lots more signatures

Etc – so hundreds of possible signature plots

Imagine a signature space, S1, S2, … Sn

In general any two different string-models have different footprints, maybe overlapping in any given signature space plot

The parameters for which they overlap in one signature space plot are in general different from those for a different plot



EXAMPLES

Focus here on two Type IIB N=1 compactifications, plus M theory compactified on a manifold with G_2 holonomy – main examples for which moduli stabilized

KKLT1, KKLT2 – two ways to break supersymmetry

KKLT, Choi et al

LARGE volume

Balasubrumanian, Conlon, Quevedo et al

M theory compactified on manifold with G_2 holonomy

Acharya, Bobkov, GK, Kumar, Shao, Vaman, Watson

Discuss constructions with moduli stabilized so don't worry results could change – would like lots more – for each, would like to vary compactification and ~~SUSY~~, etc, too

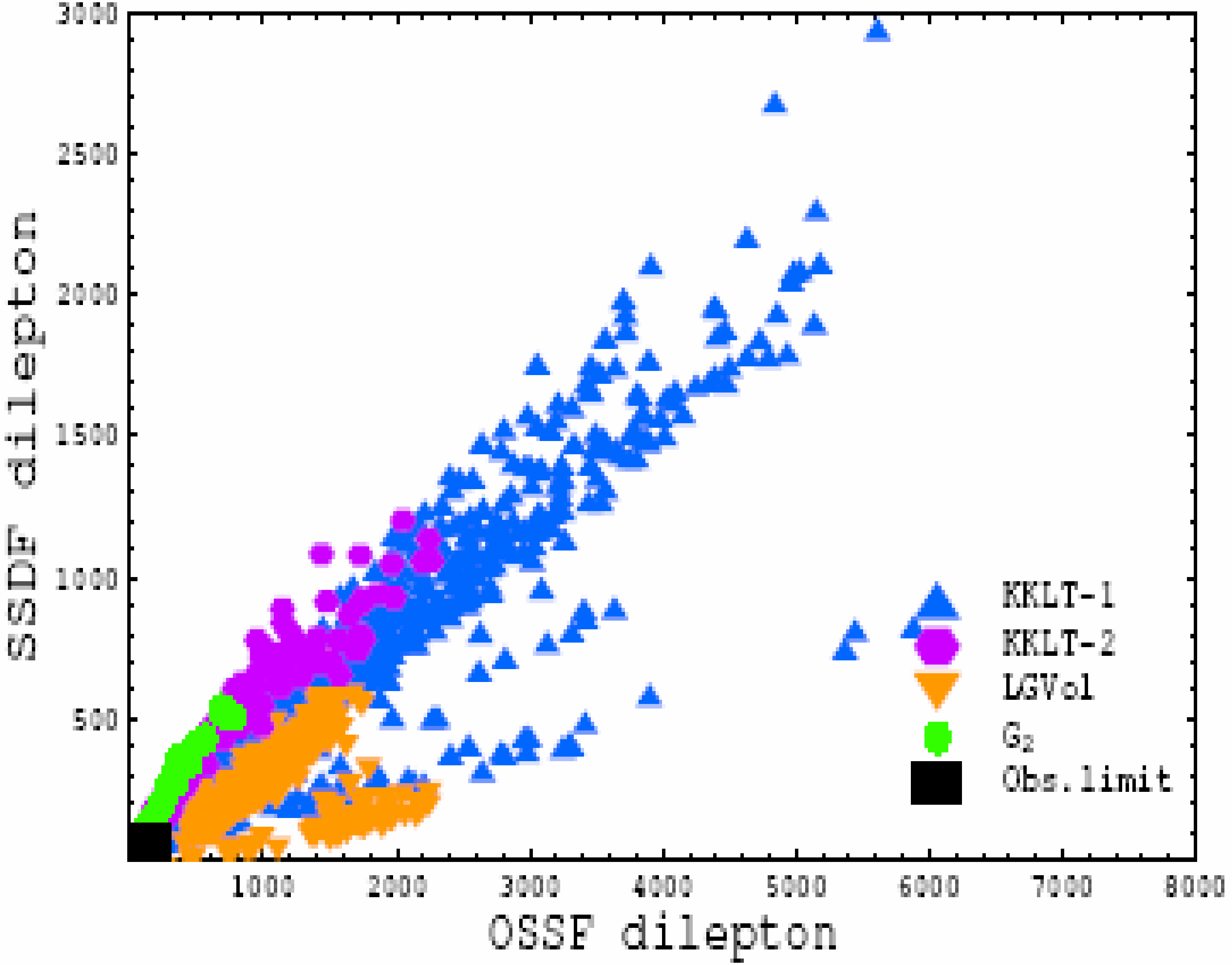
SM backgrounds?

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

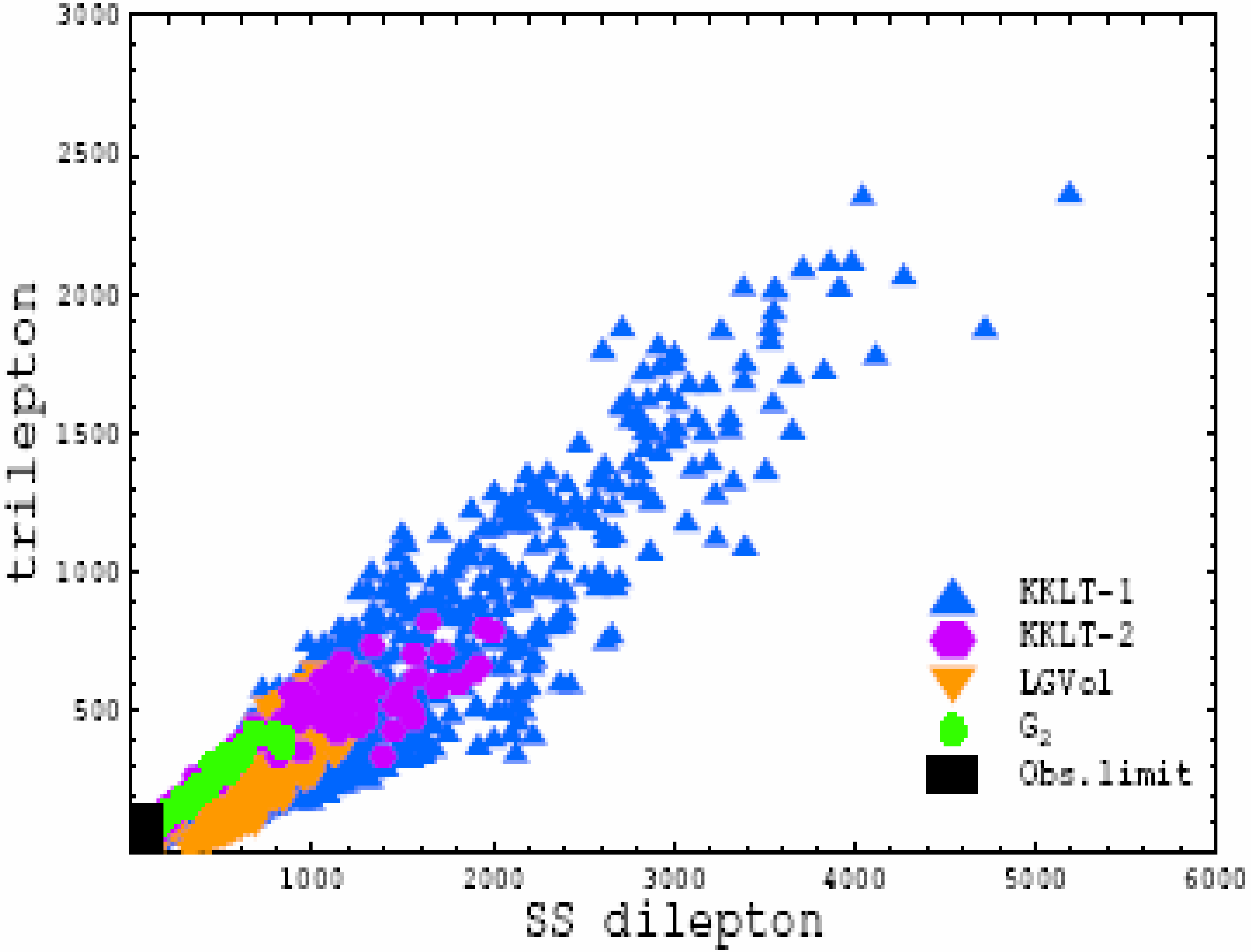
-- we have found that a good way to study issues at this stage is to estimate the level at which SM processes will enter and just indicate that on the plots

All event rates for 5 fb^{-1}

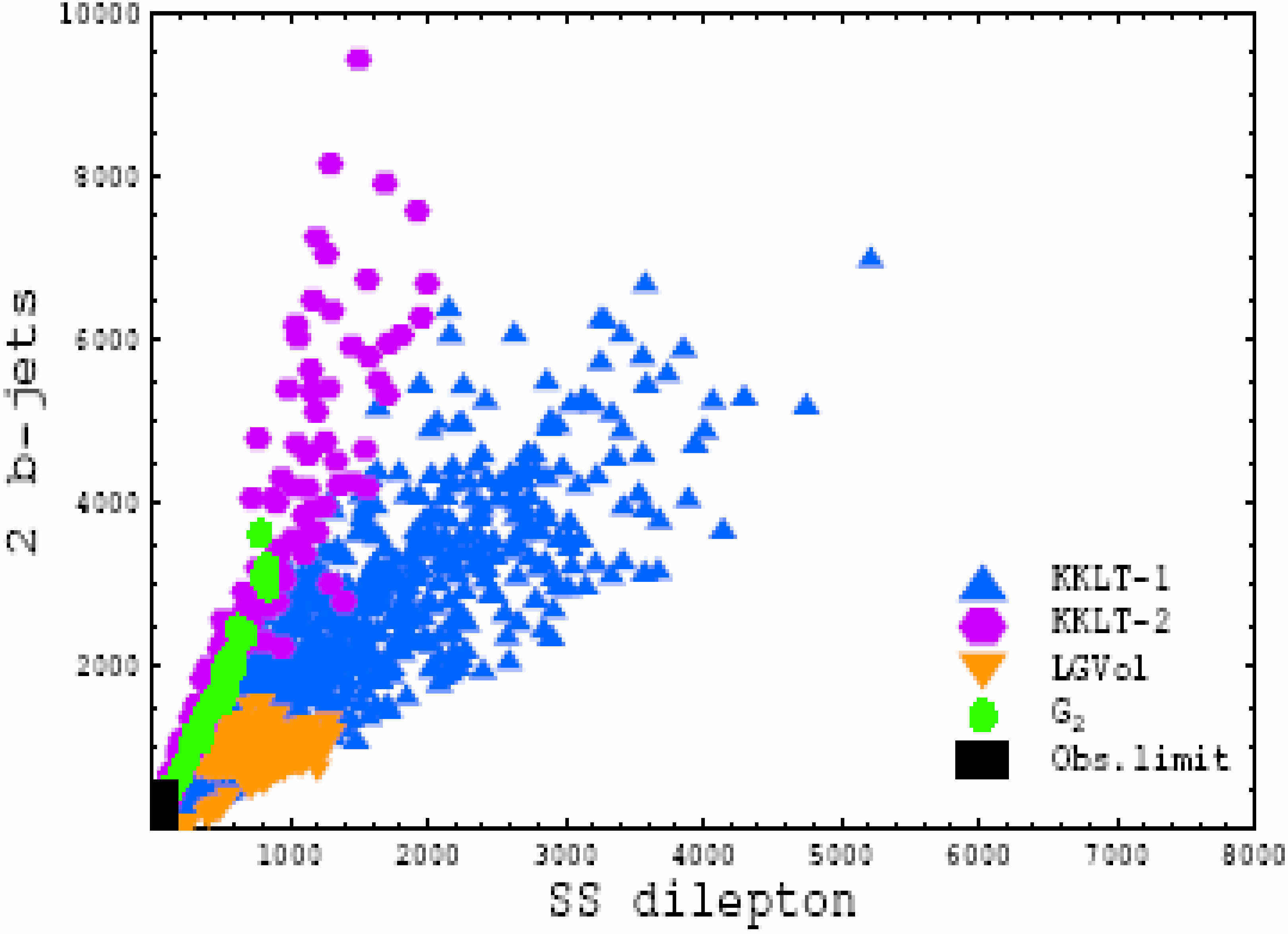
P_T (jet) > 200 GeV, P_T(lepton) > 10 GeV, missing E_T > 100 GeV



3000
2500
2000
1500
1000
500
1000
2000
3000
4000
5000
6000
7000
8000
SSDF dilepton
OSSF dilepton
KKLT-1
KKLT-2
LGVol
G2
Obs.limit

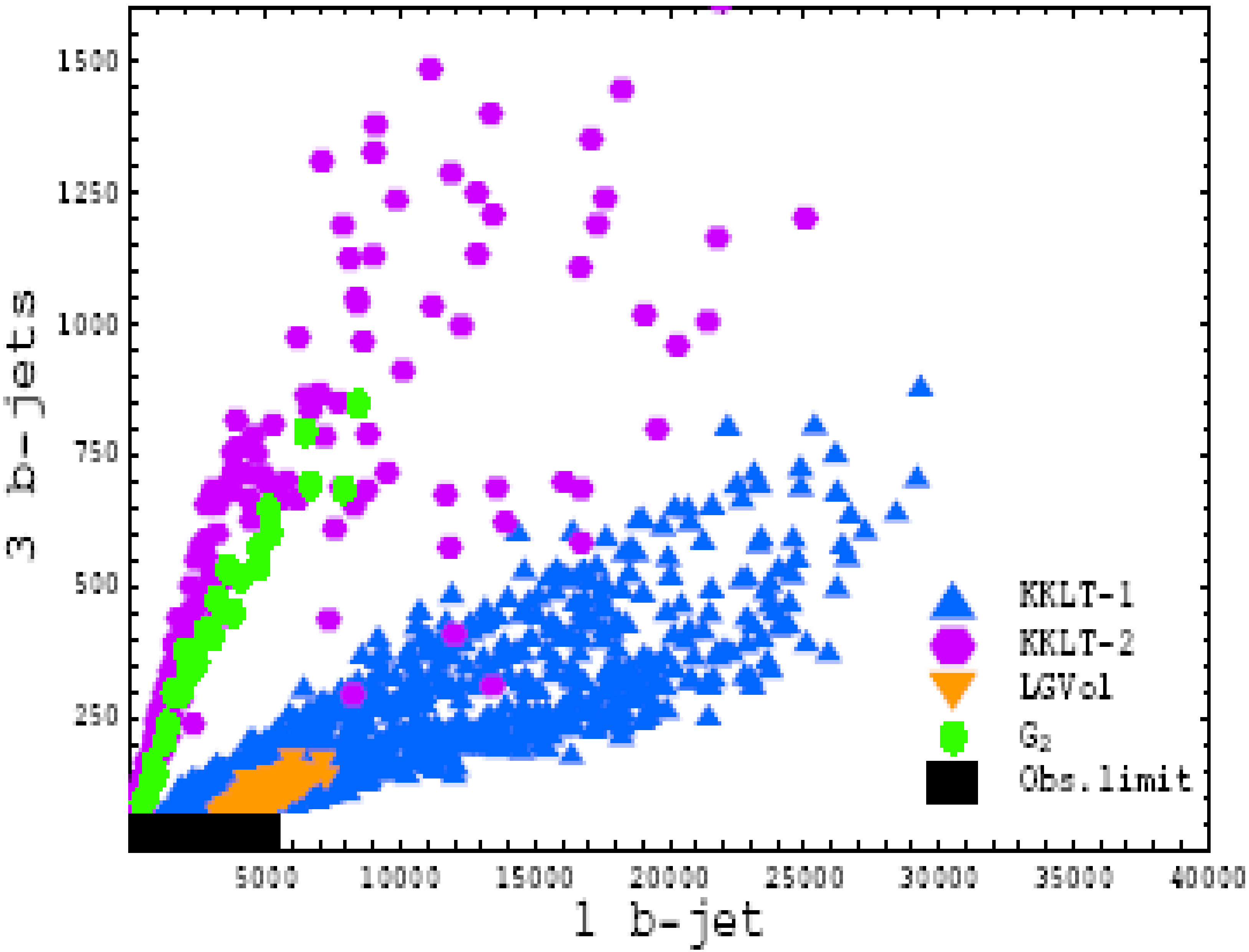


3000
2500
2000
1500
1000
500
trilepton
1000
2000
3000
4000
5000
6000
SS dilepton
KKLT-1
KKLT-2
LGVol
G_2
Obs.limit



10000
8000
6000
4000
2000
1000
2000
3000
4000
5000
6000
7000
8000
2 b-jets
SS dilepton
KKLT-1
KKLT-2
LGVol
G_2
Obs.limit

2D slices of footprints, all microscopic parameters varied



- Can always understand how underlying theories differ in qualitative terms
    - -- don't need to do this to use method, but important to gain confidence

e.g.

-- universality of tree level gaugino masses?

-- relative size of tree level and anomaly mediation gaugino masses?

-- origin, size of μ, Bμ?

-- hierarchy of scalar vs gaugino masses?

-- nature and content of LSP

-- hierarchy among scalars, e.g. 3rd family vs 1st, 2nd families

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 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

This approach will be much more powerful if a number of people study it, calculate for different string-models, look for weaknesses

– make catalog of footprints of string-susy-models, e.g. several ways of compactifying – study very different “corners” of M-theory – try to extend boundaries of regions

-- study other underlying theories

New method for learning about underlying theory from data, and for studying underlying theories – arguably best we can do

- Maybe no example will be consistent with the signature plots of data
- Maybe several examples will be consistent with the signature plots of data – welcome challenge!
- Maybe one class of theories…

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!