FROM DATA TO THEORY
-- INVERSE PROBLEMS FOR LHC, DARK MATTER, INFLATION AND …

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May 2006

The goal of particle physics?

Find encompassing, underlying theory that describes and explains phenomena, origin and properties of matter and forces, origin and properties of the universe, origin and role of quantum theory and relativity…

How do we do that?

Just think about it?

Iterate data and theory!

We are at a unique and exciting stage – Standard Models of particle physics and cosmology provide full ***description*** of the world, but not "why"

To go further, need data, and need to interpret data – particle physics has been data poor – now LHC, maybe DM, EDM data coming!

OUTLINE

- Supersymmetry – the default
- Cosmology is a subfield of supersymmetry
- Higgs physics issues – fine tuning?
- Inclusive signatures are all there is at hadron colliders
- LHC Inverse Problem – from inclusive signatures to spectrum, underlying theory
- Is it SUSY?
- “LHC Olympics”
- Degeneracies – a new complication
- Dark Matter Inverse Problem
- From LHC to the 10D string theory?

Supersymmetry remains the default to extend the SM and strengthen its foundations – very good motivation

- Part of attractive top-down picture – deeper, simpler theory at very short distances ~ unification scale
- Can stabilize hierarchy – assume low scale superpartners (and μ) to get weak scale
- Then *derive* gauge coupling unification, electroweak symmetry breaking (Higgs mechanism)
- Can have dark matter candidate particle, can explain matter asymmetry, can calculate electroweak mixing angle
- Consistent with all data, predicts no physics beyond-the-SM at LEP, m_h<200 GeV
- Alternative approaches generally don't get GCU, need extra assumption for EWSB, don't automatically explain absence of LEP signal

"MSSM" means softly broken minimal supersymmetric Standard Model – same SU(3)xSU(2)xU(1) gauge symmetry as SM, 2 Higgs doublet fields, plus "R-parity"

So every SM particle has a superpartner – spin ½ unit different, mass can be different

Low scale theory can be extended, "EMSSM"

Why is cosmology now a subfield of supersymmetry?

o dark matter – but what is the dark matter?

-- three candidates suggested by data and good theories, neutrinos, axions and lightest superpartner (LSP)

– presumably all present, perhaps others -- how much of each

– must detect signal of each, then ***must calculate relic density of each*** -- (Ω_{DM}~0.2, Ω_{ν}<0.01, Ω_{axion} impossible?)

– LSP relic density calculations require knowledge of cosmology, superpartners masses and couplings , LSP combination of bino, wino, higgsinos

COSMOLOGY CONSTRAINS DARK MATTER PROPERTIES, BUT NEED PARTICLE PHYSICS TO SUPPLY THE DARK MATTER PARTICLE – KNOWLEDGE OF LSP CRUCIAL

Dark Matter Inverse Problem

[Brhlik, Chung, GK hep-ph/0005158; Bourjaily and GK, hep-ph/0501262]

- Origin of matter asymmetry?

  -- cosmology tells us universe began from neutral vacuum and initially was equally matter and antimatter – and that it is now mainly matter, not antimatter – need particle physics to generate the asymmetry

  -- main methods use supersymmetry, or need it to have a high scale consistently in the theory

  -- actually several good ways to get matter asymmetry – leptogenesis, EW baryogenesis, Afflect-Dine, fluxes (Ibanez) – all may contribute – ***calculate how much from each*** – role of data? – for EW baryogenesis need light stop, chargino, phase… etc

Matter asymmetry Inverse Problem

- inflation, followed by Big Bang -- but *what is the inflaton?*

-- RH sneutrino? -- A superpartner…

[Yanigida et al, Ellis et al, King et al]

-- flat directions in squark-slepton space, e.g. [Allahverdi, Garcia-Bellido, Enqvist, Muzumdar]

-- scalar fields from string theory (moduli), near string scale, so need to be able to connect high and low scale theories to learn about them – e.g. recent approaches have moduli potentials from "fluxes" (generalizations of electromagnetic fields)

[Gaillard, Binetruy; Kallosh, Kachru, Linde, Trevidi; Tye et al]

--also have supersymmetry broken by fluxes → superpartner masses and interactions, measured at colliders, can determine inflation parameters

COSMOLOGY CONSTRAINS INFLATON POTENTIAL BUT NEED PARTICLE PHYSICS TO SUPPLY THE INFLATON

IF SUPERSYMMETRY EXPLAINS HIGGS MECHANISM AND EWSB, EXPECT LIGHT HIGGS BOSON – ONLY QUANTITATIVE PREDICTION

- In MSSM "light" means < 130 GeV – but putting in constraints from non-discovery of superpartners or their effects, to get m_h>100 GeV takes some arranging of parameters – but LEP limit larger

- Is that a problem?

  -- $4\sin^2\theta-1 \ll 1$ for $\sin^2\theta=0.23$, i.e. an accident

  -- LEP limits not general, e.g. lighter h ok for CPV MSSM, for h→ two LSP,…

  -- not much fine-tuning if superpartners light, e.g. gluino at Tevatron, trilinears large, …

  -- -- EMSSM? – e.g. NMSSM – generally string theory gives low scale EMSSM and/or CPV MSSM – then usual limits on higgs bosons do not apply

- In general supersymmetric theory, EMSSM, assume only that theory stays perturbative up to unification scale, and Higgs mechanism gives mass to W,Z – then $m_h \leq 2M_Z$ approximately [1993 GK, Kolda, Wells; Espinosa and Quiros] – no dependence on how supersymmetry is broken, on other vevs, etc. -- upper limit, actual mass could be much smaller

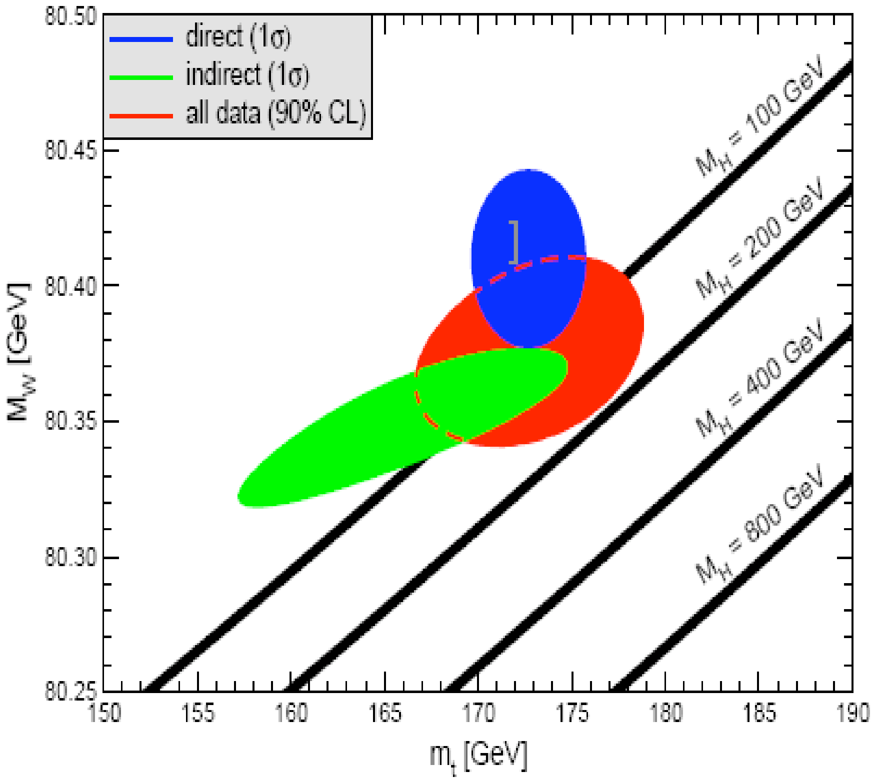


FIGURE 2. One-standard-deviation (39.35%) region in M_W as a function of m_t for the direct and indirect data, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. The SM prediction as a function of M_H is also indicated. The width of the M_H bands reflects the theoretical uncertainty in the prediction.

Two independent experimental analyses
Imply mh< about 200 GeV

- Whole region below about 200 GeV can be covered at Tevatron+LHC in almost all models

- If m_h < 115 GeV Tevatron probably easier!!

- What if Higgs boson not seen at LHC? Look harder at Tevatron!

  (and study longitudinal WW scattering at LHC)

- One possible implication of no h at LEP: gaugino masses not unified [since light gluino helpful, GK, King] – testable – and points toward string theories with non-universal gaugino masses, e.g. gaugino masses suppressed at tree level

- If extend MSSM -- NMSSM well motivated (get μ at low scale, common in string theories),

  --N=s+ia -- suggests [Gunion et al, Pierce et al, ?]

$$h \text{ ® } a + a, a \text{ ® } \tau^{+}\tau^{-}$$

  -- LEP limit on such an h < 85 GeV

  -- then can use gg→h inclusive production at Tevatron

  -- good signatures, a’s boosted, trileptons with different kinematics, etc

  -- difficult at LHC, better at Tevatron with 5-20 fb^{-1}

The form the Higgs physics takes points to how the SM gets extended – provides input to inverse problem

HOPEFULLY, SOON DATA FROM LHC (OR TEVATRON) WILL PROVIDE A SIGNAL OF PHYSICS BTSM

After the champagne…..

- First question -- is there really a BTSM signal? – compare carefully with the SM – experimenters will do that well, based on existing and coming theory calculations – more work needed, but under control

- *At hadron colliders experimenters will measure σxBR, and some kinematical quantities, distributions – "inclusive signatures" [GK, hep-ph/9709318, Frisch…] -- but nothing they measure is in the Lagrangian*

- How do we go from such information toward the spectrum of superpartners, and the underlying theory?

  (For at least a decade after have LHC data cannot have a linear collider)

LHC Inverse Problem

Usual approach has been “forward” calculations – really assuming that if one calculates signatures of many models one will recognize what is observed – but that assumes a unique relation between signatures and models – forward approach useful, but unlikely to be sufficient

LHC INVERSE PROBLEM:

1. Is it SUSY? Or …

2. What spectrum of superpartners gives the observed signal? *Degeneracies!*

3. Can one figure out the low scale Lagarangian?

(A major issue – the mass eigenstate masses and decay rates come from diagonalizing matrices formed from the Lagrangian parameters)

4. Can one deduce the mass and properties of the LSP in order to calculate its relic density?

5. Can one figure out the unification scale Lagrangian?

1. IS IT SUPERSYMMETRY? [Datta, GK, Toharia, hep-ph/0510204]

Several robust types of signatures – *GENERAL ANALYSIS (not msugra)*

- Events with missing transverse energy, from escaping LSP
- Same-sign leptons (or b's or tops) because gauginos are Majorana fermions
- b-rich events if stops or sbottoms are the lightest squarks, since gluino decays then dominated by decays through them
- Trileptons if charginos and neutralinos light and if LSP significantly lighter than others
- Can get prompt photons
- Etc.
- Note analyses within "msugra" can be quite misleading – many signatures not possible

If not these signatures, the events give excess jets and relative jet multiplicities, and one can find them.

Is it extra dimensions instead of susy?

Can we distinguish susy from UED? – yes

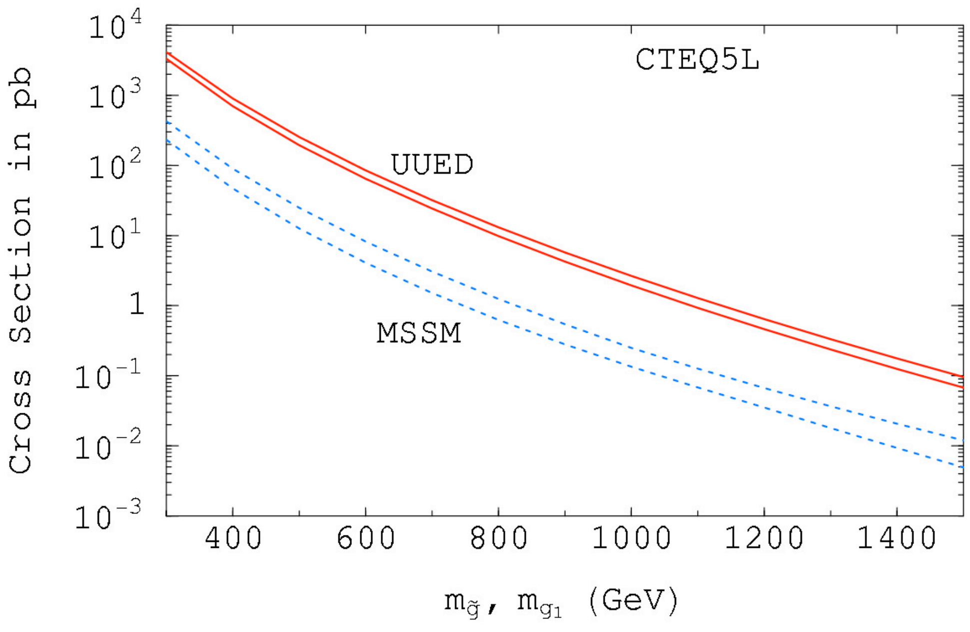
Traditional way people hoped to demonstrate what is discovered is indeed supersymmetry is to measure the superpartner spins, and gauge couplings (which are predicted by the symmetry) – difficult, but will *eventually* be done even at LHC (easier at linear collider but …)

In fact, probably can effectively measure some spins initially at hadron colliders by using relation between spin and cross section once know mass scale

The particle spins are different – e.g. in Kaluza-Klein theories it is the spin 1 gluon recurrence that fakes gluinos – but *at a fixed mass* the production cross sections differ by an order of magnitude so easy to distinguish [Datta, GK, Toharia hep-ph/0510204] – really sensitive to mass difference [Cheng, Low, Wang hep-ph/0510225, and Meade, Reece hep-ph/0601124], so may need two scales – once there is data to fix the mass scales, then one can distinguish – need data from Tevatron to get both scales (study in examples)

Also, in SUSY leptons from sleptons and various sources, but in UED from W', Z' so branching ratios different if sleptons not too heavy

I think "is it susy" will not be hard to settle at LHC



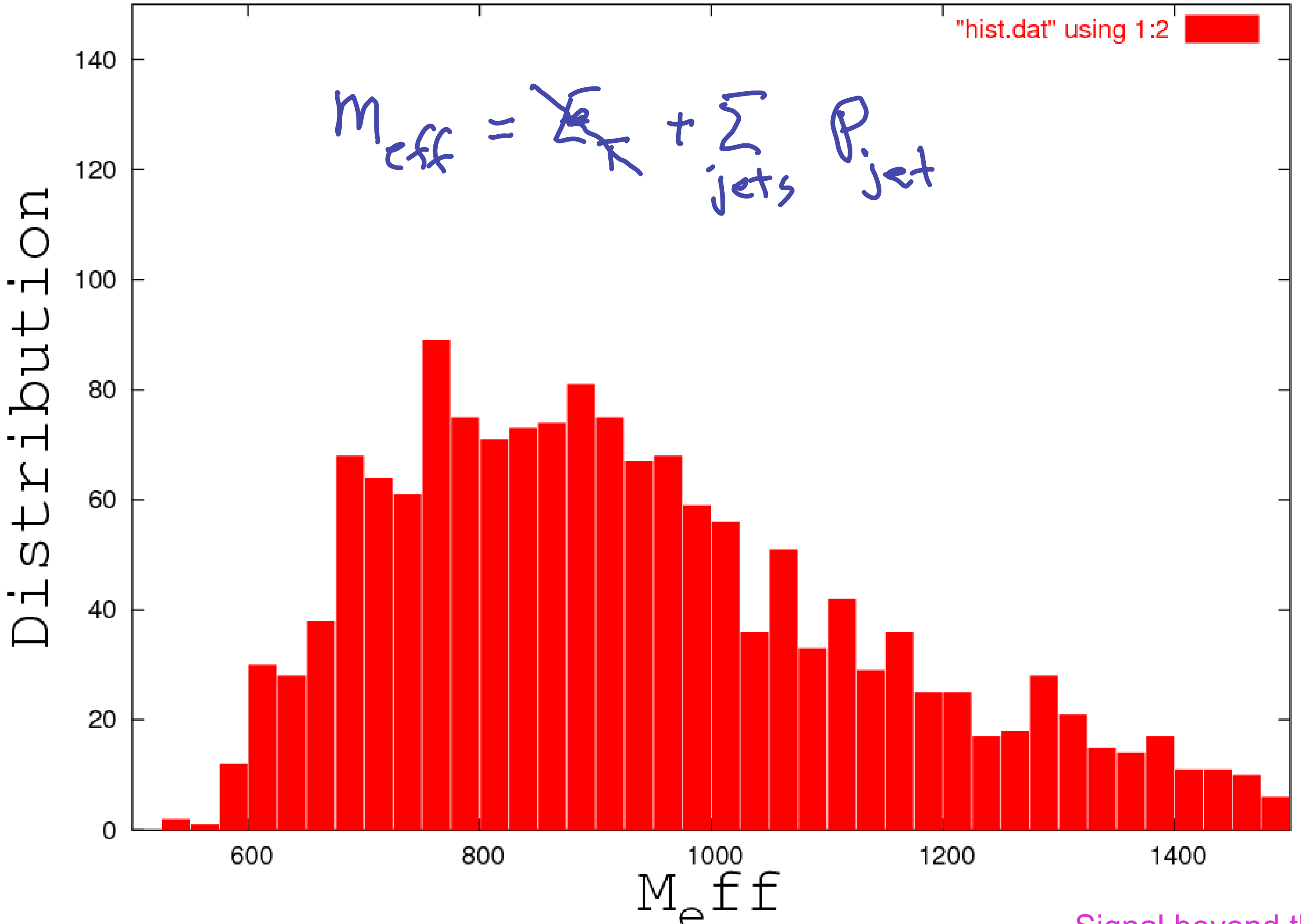
2. Can we learn what spectrum of superpartners gives the observed signal?

-- e.g. see “X” events with same sign, same flavor dileptons (plus ≥ 2 >100 GeV jets), “Y” events with opposite sign dileptons, etc, “inclusive signatures” – but can’t measure masses, BR of superpartners directly because 2 escaping LSP’s, each signature may be from several channels, etc

LHC Olympics!

- o Simulate results of first year LHC running – post on web site, “blackboxes” – as one would get data from talks by experimenters at first conference, inclusive signatures, numbers and distributions – [also as data would come from detectors so can calculate rates, distributions]
- o So far – Michigan blackbox, start with underlying 10D theory, assume compactification, susy breaking, get spectrum, calculate inclusive signatures – Harvard, Washington assume spectrum of superpartners, calculate signatures

$$M_{eff} = \cancel{E}_T + \sum_{jets} p_{jet}$$



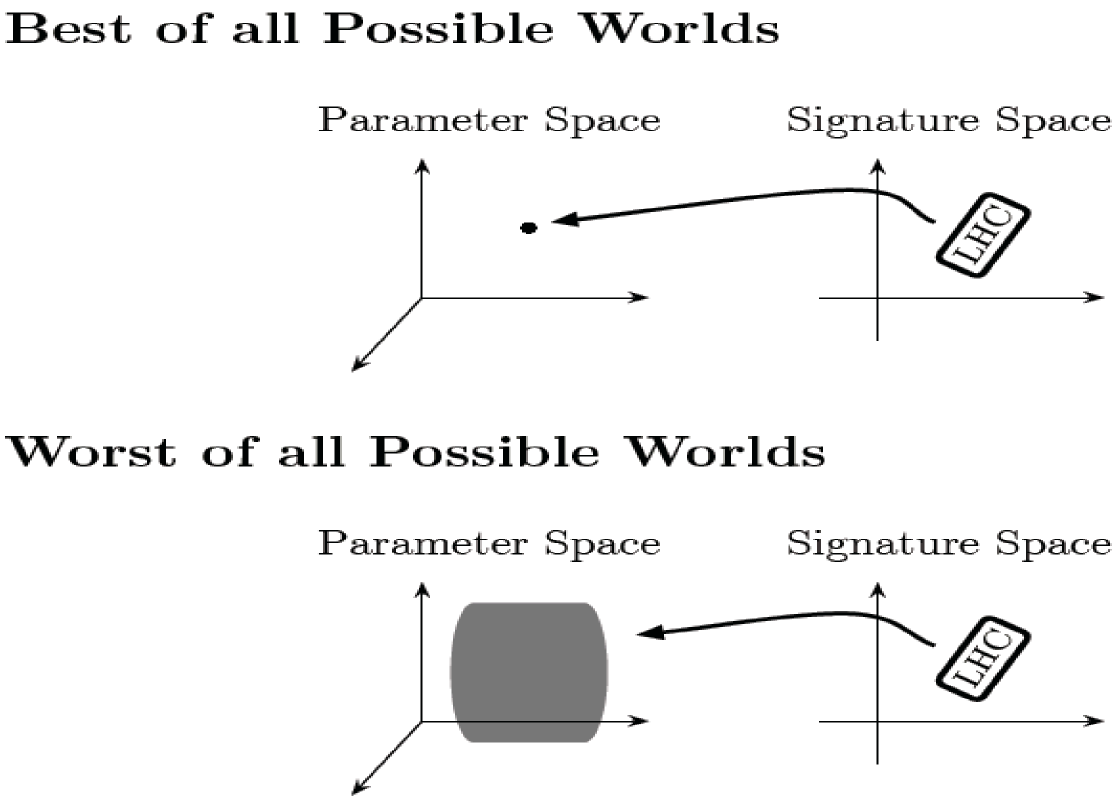
Signal beyond the SM

Leptons:	N jets: 0	1	2	3	>3
0	2919	10284	10694	6857	4734
1	607	1693	1458	760	411
SS	15	49	25	9	5
OS	27	35	25	7	6
trileptons	0	0	0	0	0

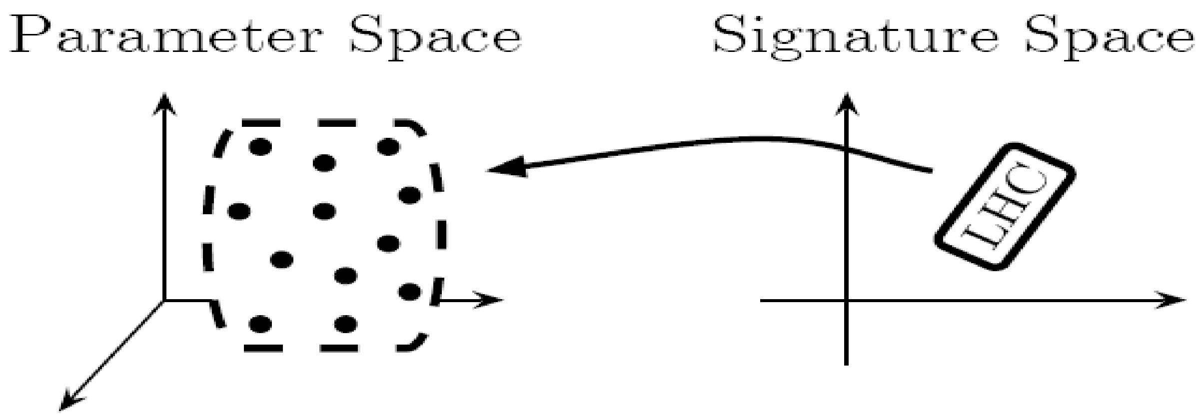
DEGENERACIES!

- Generally assumed in past that experimenters would find a set of signals, from which we would learn the superpartner masses
- But at a hadron collider turns out there are degeneracies

[Arkani-Hamed, GK, Thaler, Wang hep-ph/0512190]



Our Picture of the Inverse Map



Degeneracies!

Many small footprints in a large overall region.

"Forward" approach fails!

- *Islands are different in important ways – e.g. some LSPs give very different relic densities from others, some have gaugino mass unification*
- *"degenerate" means different ways of satisfying the constraints*

Parameters :

$$M_1, M_2, M_3, \mu$$

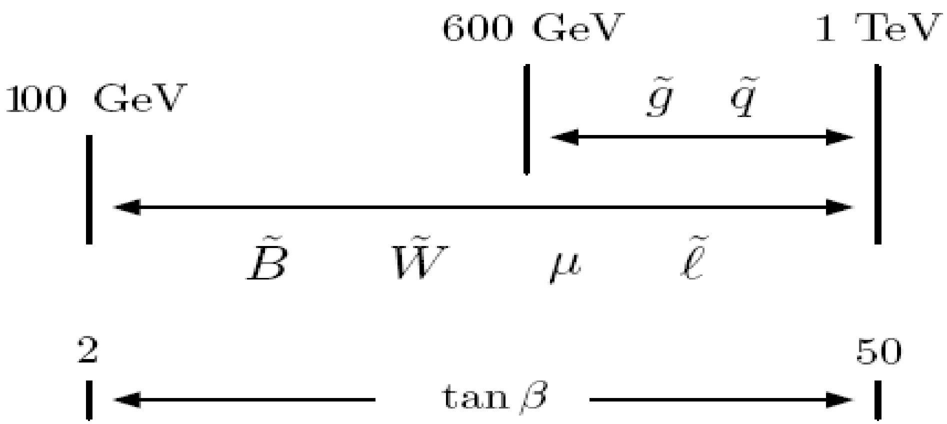
$$m_{\tilde{q}_L}^{1,2}, m_{\tilde{q}_R}^{1,2}, m_{\tilde{t}_{1,2}}, m_{\tilde{b}_{1,2}}, A_t, A_b$$

$$m_{\tilde{l}_L}^{1,2}, m_{\tilde{l}_R}^{1,2}, m_{\tilde{\tau}_{1,2}}$$

$$\tan\beta$$

$$m_{h,} m_A, m_H$$

Choosing 39,137 MSSMs



$$\tilde{q}\left\{\begin{array}{lll}\tilde{q}_L & \tilde{q}_{Ru} & \tilde{q}_{Rd}\\ \tilde{q}_L^3 & \tilde{q}_{Ru}^3 & \tilde{q}_{Rd}^3\end{array}\right.$$

$$\tilde{\ell}\left\{\begin{array}{ll}\tilde{\ell}_L & \tilde{\ell}_R\\ \tilde{\ell}_L^3 & \tilde{\ell}_R^3\end{array}\right.$$

Constraints: Nothing more than 50 GeV decoupled

Max Colored > Max Electroweakino > Max Slepton

No slepton LSP.

We simulated $m = 39137$ MSSMs (+ 3889 in total...)

Number of pairs with matching LHC signatures $= 364$

$$N_{\mathrm{sig\,bins}} \sim m^2/d \sim 4 \times 10^6$$

$$N_{\mathrm{models}} \sim 10^8 \text{ (From parameter ranges.)}$$

Probability of choosing correct model at LHC is 1 in 25.

Equivalently, for every model, there are 24 other (well motivated?) models with the same LHC signatures.

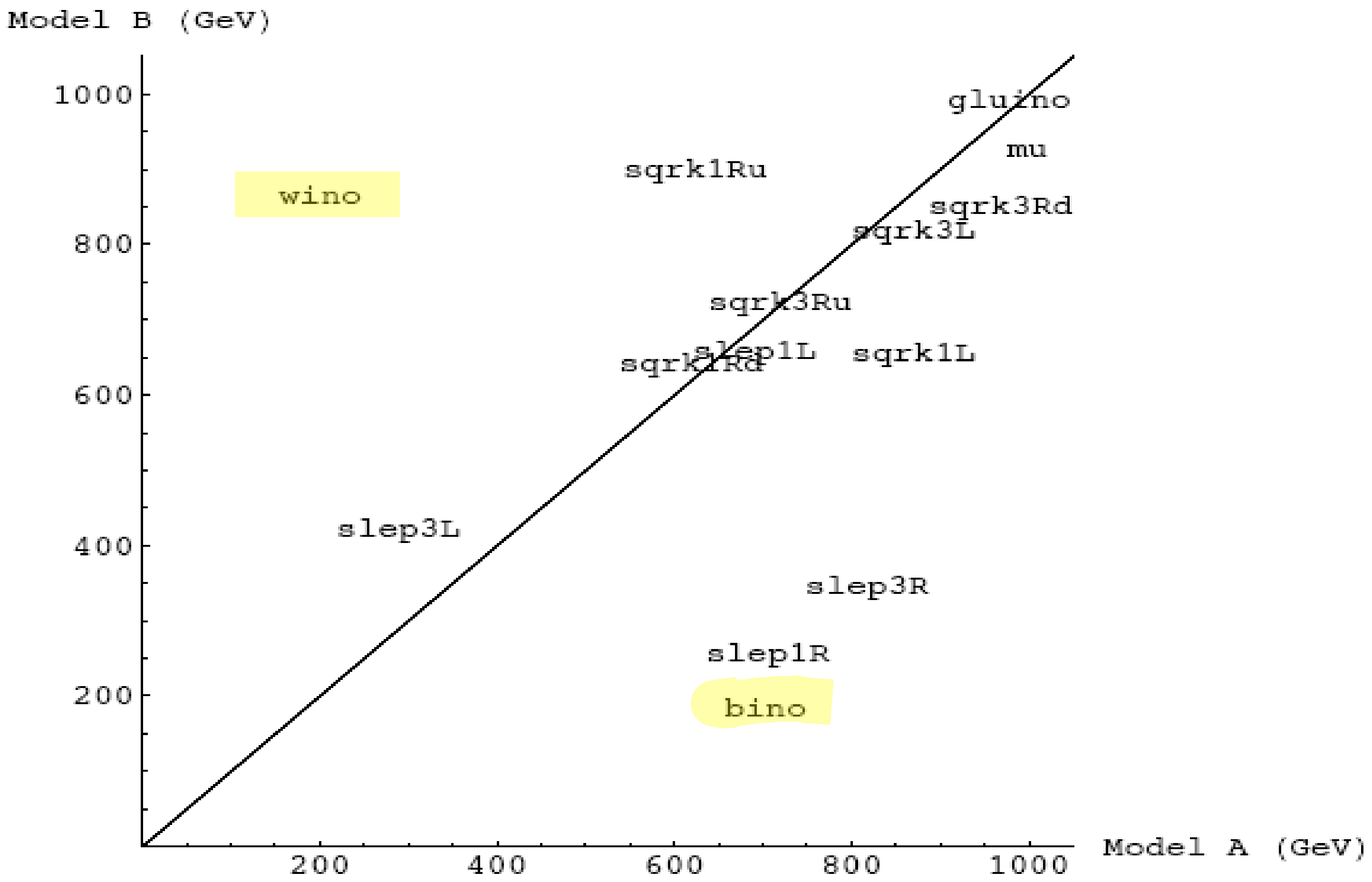
[statistical analysis, can estimate number but only find examples accidentally]

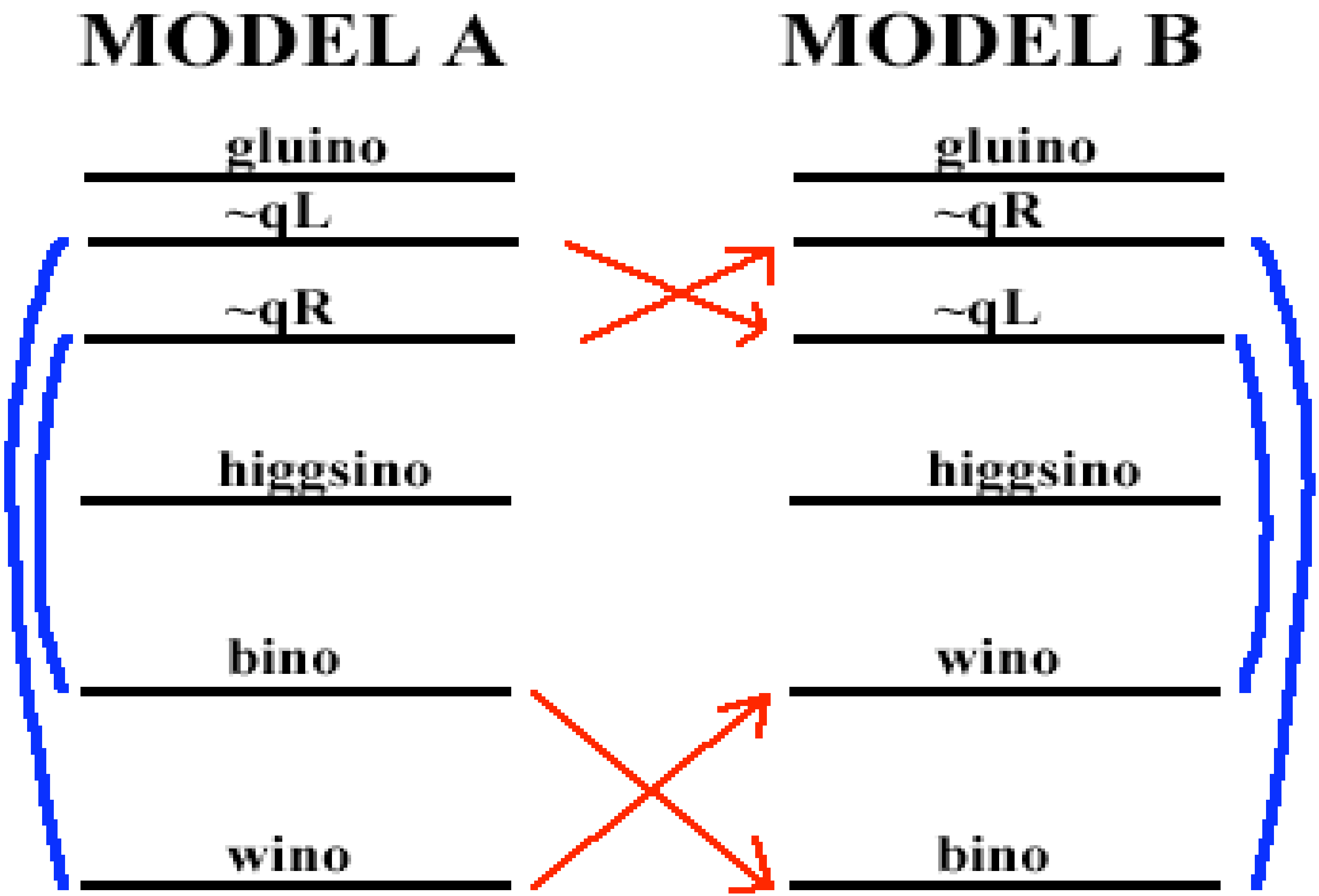
CATALOG DEGENERACIES:

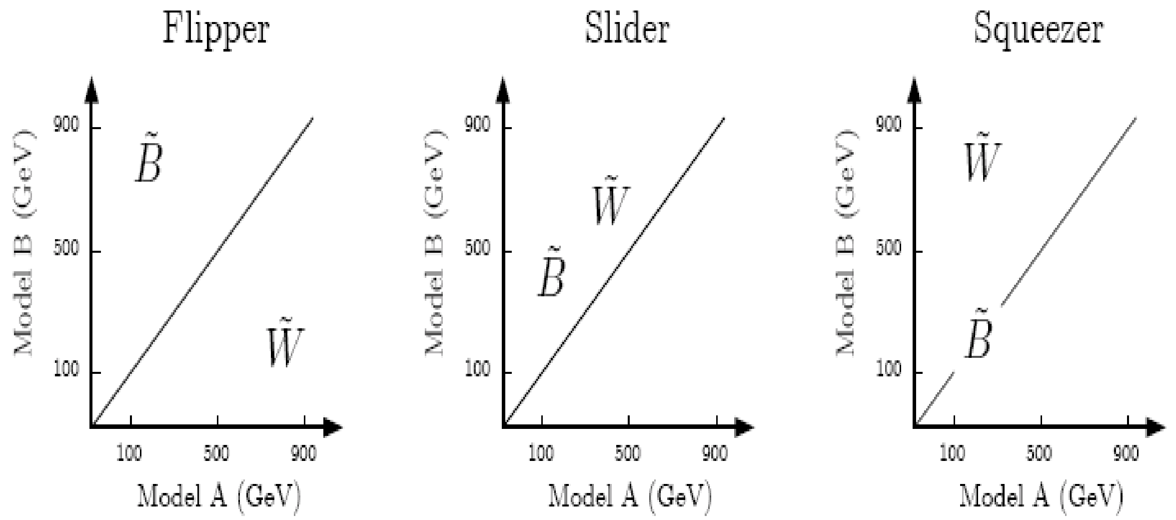
models different if anything not on diagonal

Flippers: 17653 vs. 20026

→ Same collider signatures




MODEL A
MODEL B
gluino
~qL
~qR
higgsino
bino
wino
gluino
~qR
~qL
higgsino
wino
bino



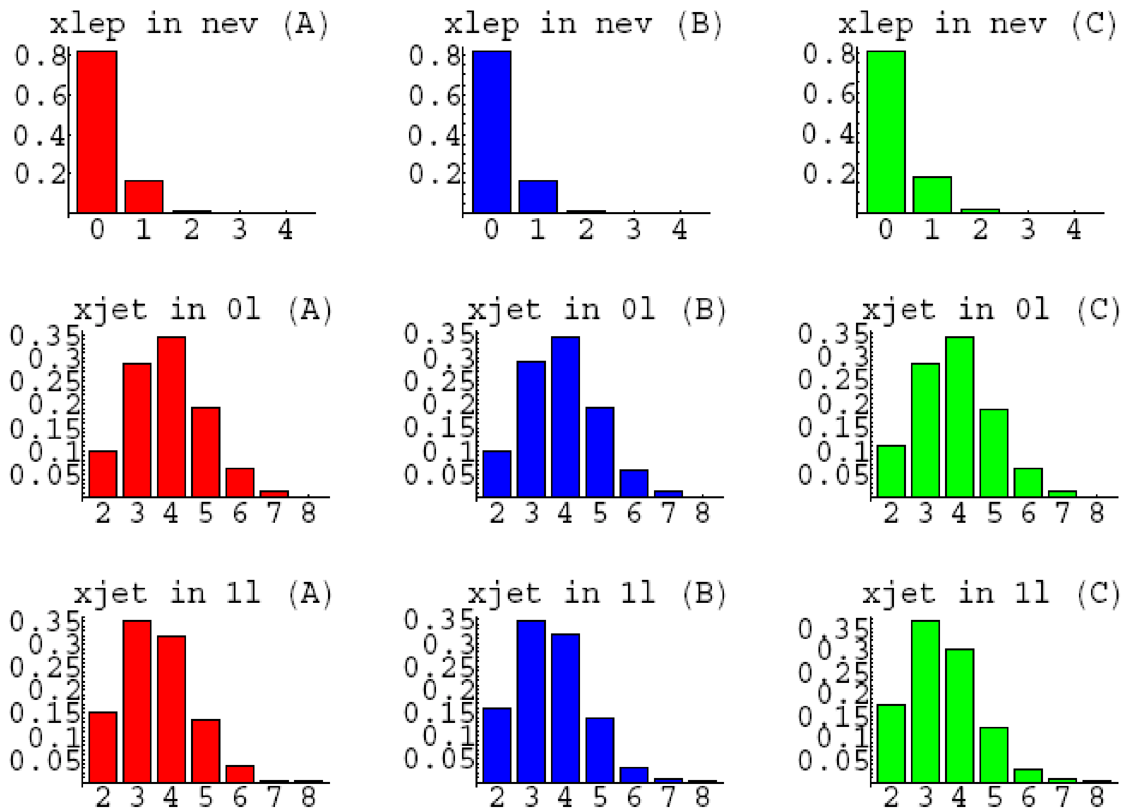
-- actually found a flipper in analyzing Seattle blackbox

After evidence for physics beyond the standard model, can we disentangle these (and other?) degeneracies?

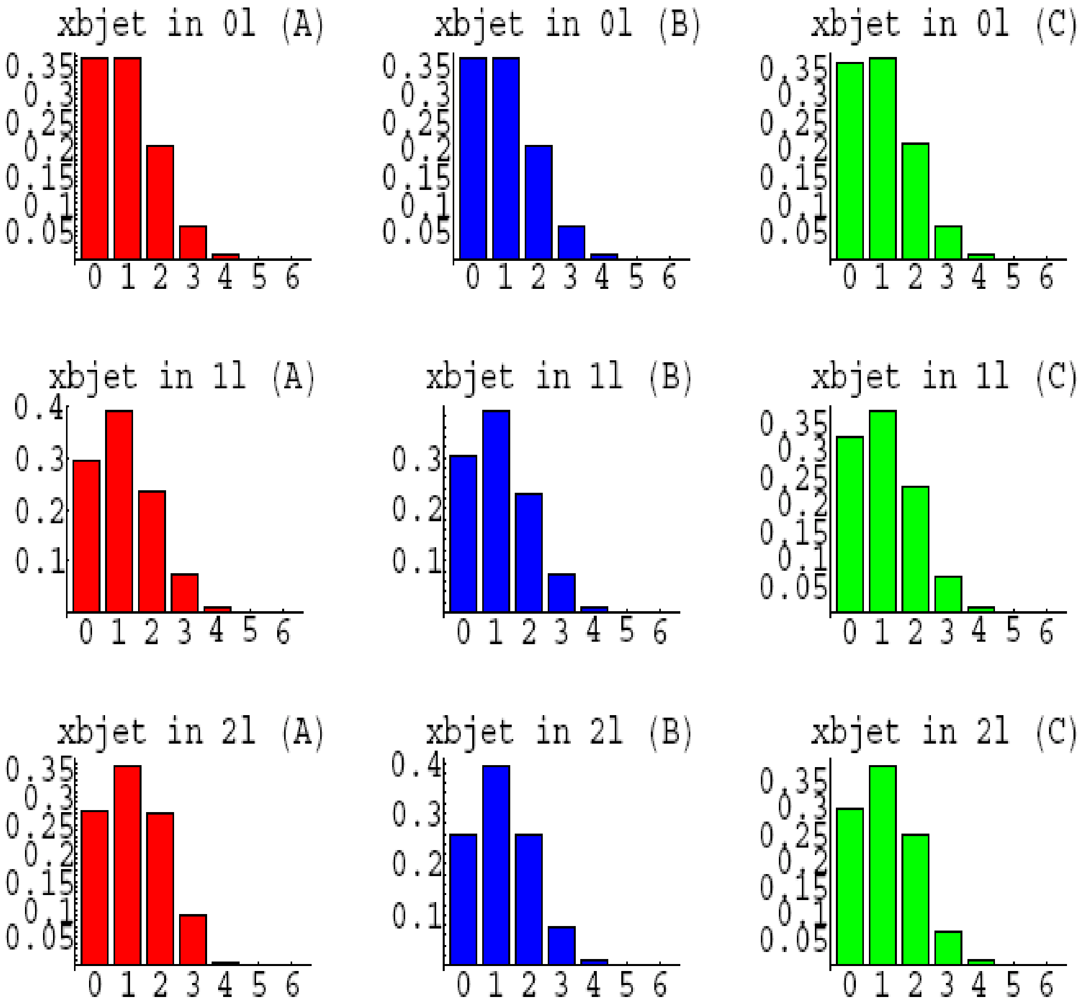
$$A = B \text{ or } B = C\ ?$$

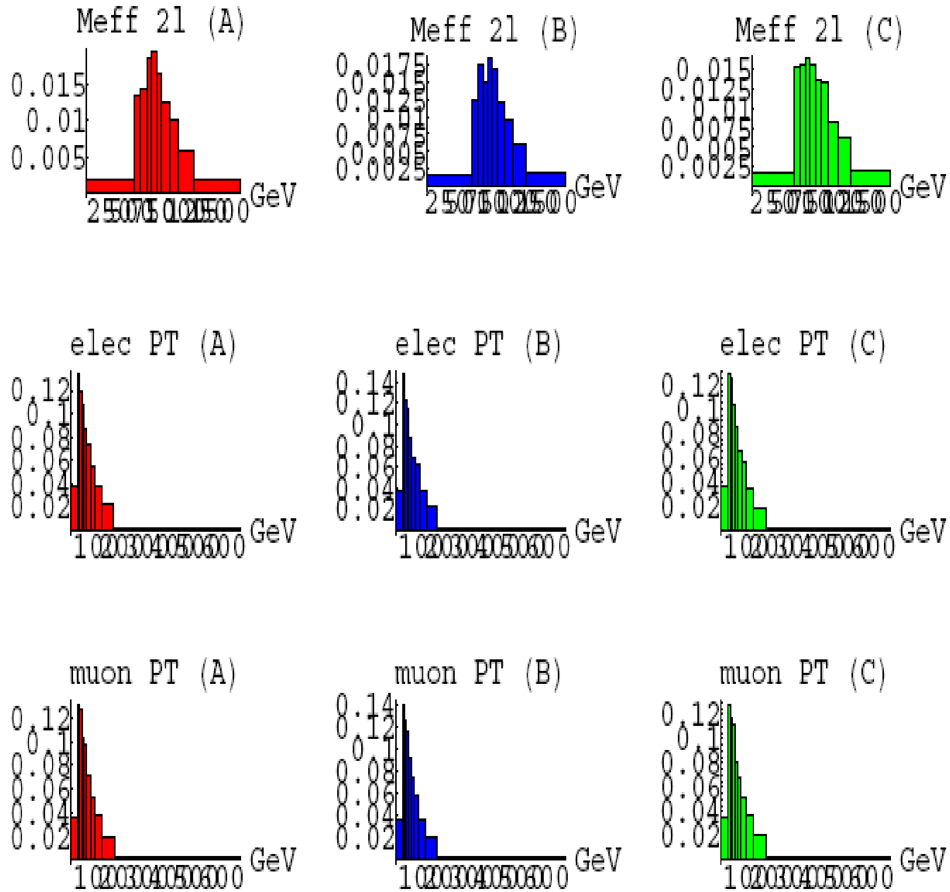
Degeneracies not just global, but for every signature!

Each row a signature

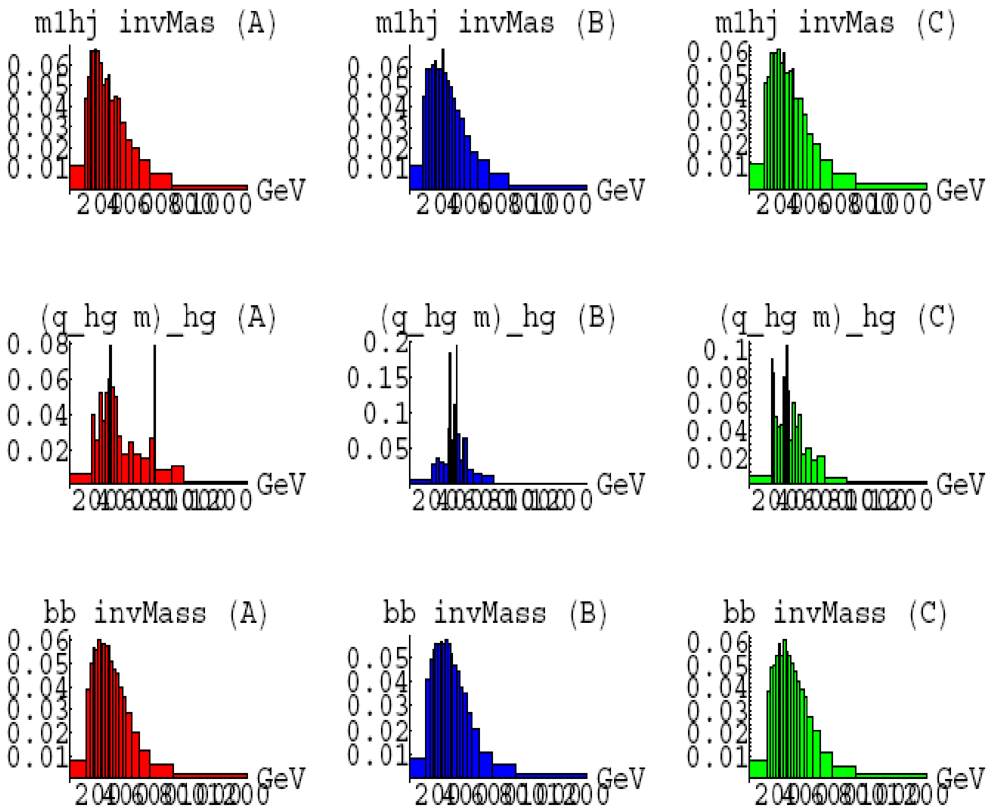


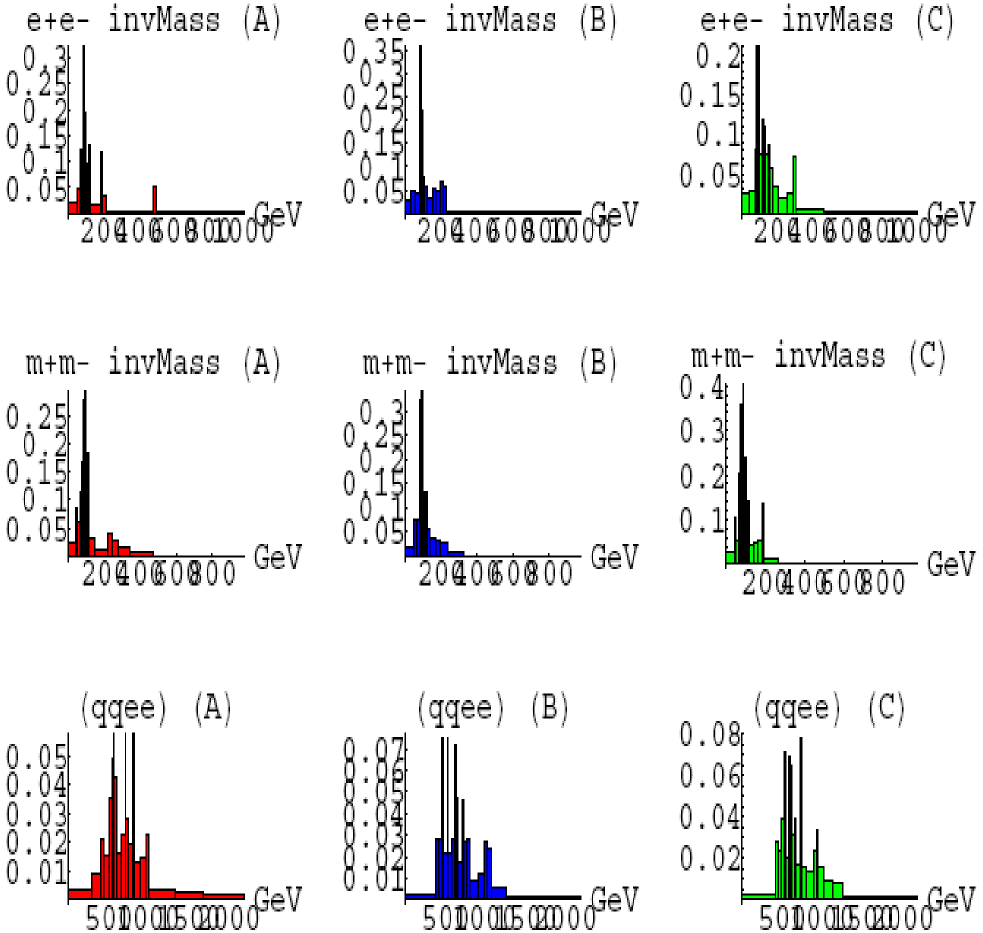
Two models – 3rd is one of them with different initial random number


xbjet in 0l (A)
xbjet in 0l (B)
xbjet in 0l (C)
xbjet in 1l (A)
xbjet in 1l (B)
xbjet in 1l (C)
xbjet in 2l (A)
xbjet in 2l (B)
xbjet in 2l (C)
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
0 1 2 3 4 5 6


Meff 2l (A)
Meff 2l (B)
Meff 2l (C)
elec PT (A)
elec PT (B)
elec PT (C)
muon PT (A)
muon PT (B)
muon PT (C)
GeV

A = B or B = C (or A = C) ?

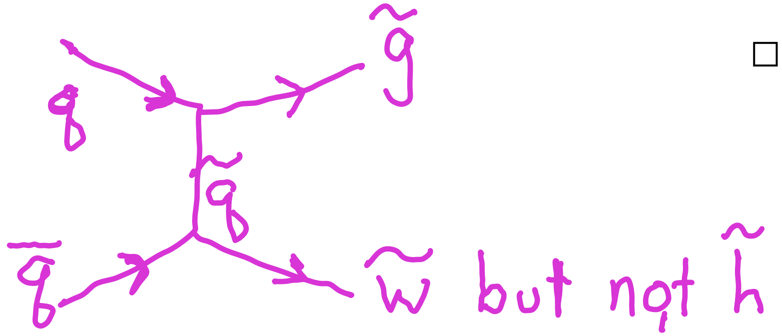

m1hj invMas (A)
m1hj invMas (B)
m1hj invMas (C)
(q_hg m)_hg (A)
(q_hg m)_hg (B)
(q_hg m)_hg (C)
bb invMass (A)
bb invMass (B)
bb invMass (C)
GeV


e+e- invMass (A)
e+e- invMass (B)
e+e- invMass (C)
m+m- invMass (A)
m+m- invMass (B)
m+m- invMass (C)
(qqee) (A)
(qqee) (B)
(qqee) (C)
GeV

Suppose LHC finds a signal – very difficult for LHC to deduce nature of LSP– leptons soft – flippers, etc

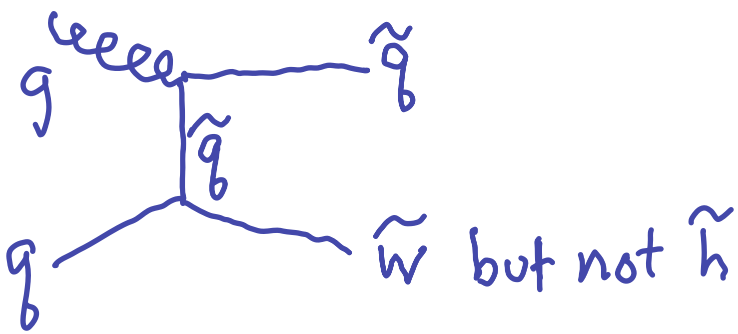
Several ways to remove higgsino/wino LSP degeneracy by observing other channels, e.g. using Tevatron data!

1.

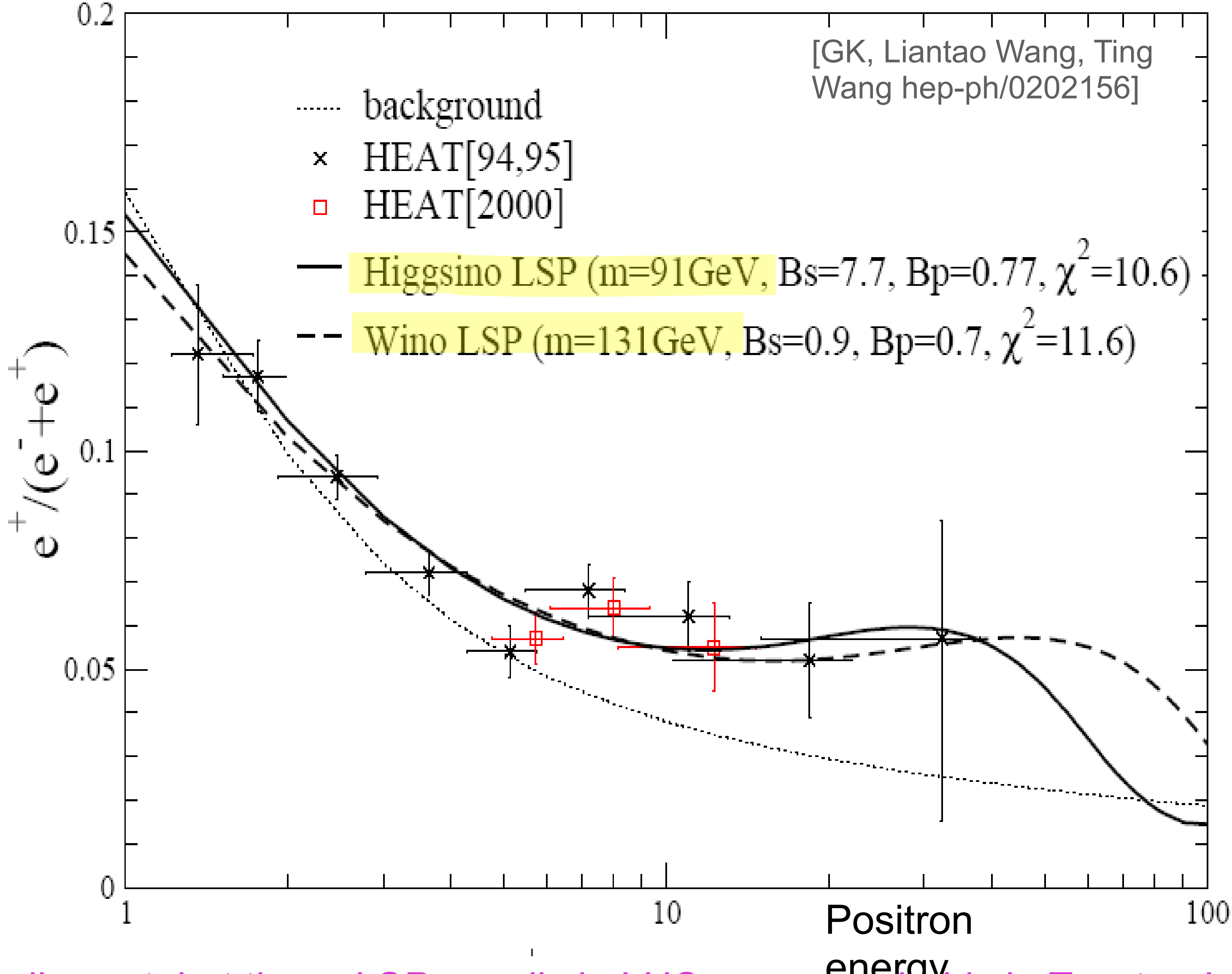


- Note quark partons, better at tevatron
- Signature jj+ $\not{E}_T$

Light gluino



Light squark



No studies yet, but these LSPs easily in LHC range, probably in Tevatron's – recently supported by AMS – Pamela next opportunity

3. From spectrum to Lagrangian?

e.g. consider charginos:

$$M_{\tilde{C}} = \begin{pmatrix} M_2 e^{i\phi_2} & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu e^{i\phi_\mu} \end{pmatrix}$$

$$M_{\tilde{C}_1}{}^2 + M_{\tilde{C}_2}{}^2 = M_2{}^2 + \mu^2 + 2 M_W{}^2$$

$$M_{\tilde{C}_1}{}^2 M_{\tilde{C}_2}{}^2 = M_2{}^2 \mu^2 + 2 M_W{}^4 \sin^2 2\beta - 2 M_W{}^2 M_2 \mu \sin 2\beta \cos(\phi_2 + \phi_\mu)$$

- Four unknowns, two observables, can't invert!
- Masses, cross sections depend on phases!
- In general, more parameters than useful observables at hadron collider!

ANOTHER KIND OF DEGENERACY PROBLEM

The MSSM has a lot of parameters – but all are fundamental physics parameters, all come from complex masses just as in the SM – most because of flavor

Two ways to reduce degeneracies

- More **independent** signatures – we already use ~ 1800 signatures, so need new kinds
  - use jet charges, so can have quark flavor information – done successfully at LEP---- can also use for studying CPV at LHC
  - Tevatron data provides independent signatures!

- Knowledge of the theory relating parameters – e.g. know origin of susy breaking, or know string theory – of course, we do not actually know that, but in a given theory one can remove the degeneracies, incorporate the LHC info, and make other predictions – if a given theory works pursue it, test it – in fact, we think signatures sensitive to string physics (GK, Piyush Kumar, Jing Shao, in progress)

Can we combine theory, data to eliminate degeneracies, favor some theory(s) and disfavor others?

String theory is attractive because it allows us to ***address*** all questions – families, fermion masses, dark matter, matter asymmetry, inflation, supersymmetry and supersymmetry breaking, EWSB, CPV, …even gravity, in a quantum theory

String theory not yet well enough understood to directly connect to low energy physics, collider physics – using effective field theory, effective potentials to connect to particle physics not guaranteed – but we think trying to learn from collider data may help learn how to relate string theory to the real world, and may favor some regions of the M-theory amoeba over others

Use semi-realistic string constructions – don't worry about not yet having a perfect theory, exotics, etc

Construction/ Signatures	A	B	C	D	E	F	G
HM–A	√	√	√	√	√	√	√
HM–B	√	√	√	√	√	√	√
HM–C	Both	Both	Both	√	√	√	√
PH–A	x	x	√	√	√	√	x
PH–B	x	x	x	N.O.	√	x	x
II–A	x	x	Both	√	x	x	Both
II–B	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.

Choose median signal--√ above, x below, both, N.O. not observable

Useful signatures

- **A** – Number of events with OS dileptons and ≥2 jets.
- **B** – Number of events with OSDF dilepton and ≥2 jets.
- **C** – Number of events clean dileptons.
- **D** – (X/Y), X= # of events with 2 leptons and 1 or 2 b jets and ≥ 2 jets.
  Y= # of events with 2 leptons and 0 b jets and ≥ 2 jets.
- **E** – (X/Y), X= # of events with 1 photon and ≥ 2 jets.
  Y= # of events with 0 photon and ≥ 2 jets.
- **F** – Number of events with 1 tau and ≥ 2 jets
- **G** – Endpoint of the OS dilepton invariant mass distribution.

- *HM-A* : Heterotic M-theory models with one kahler modulus.
- *HM-B* : Heterotic M-theory models with one kahler modulus and one five-brane.
- *HM-C* : Herterotic M-theory models with two kahler moduli.
- *PH-A* : Perturtabative Heterotic string theory models with kahler stabilization of dilaton.
- *PH-B* : Perturbative Heterotic string theory models with multiple gaugino condensates.
- *II-A* : Type II A string theory models with Intersecting D-branes.
- *II-B* : Type II B string theory models with KKLT-like moduli

Surprising how few stringy theories are in a form where high scale soft terms are known

For now, include μ, $\tan\beta$ by imposing REWSB – should have calculating μ as a goal

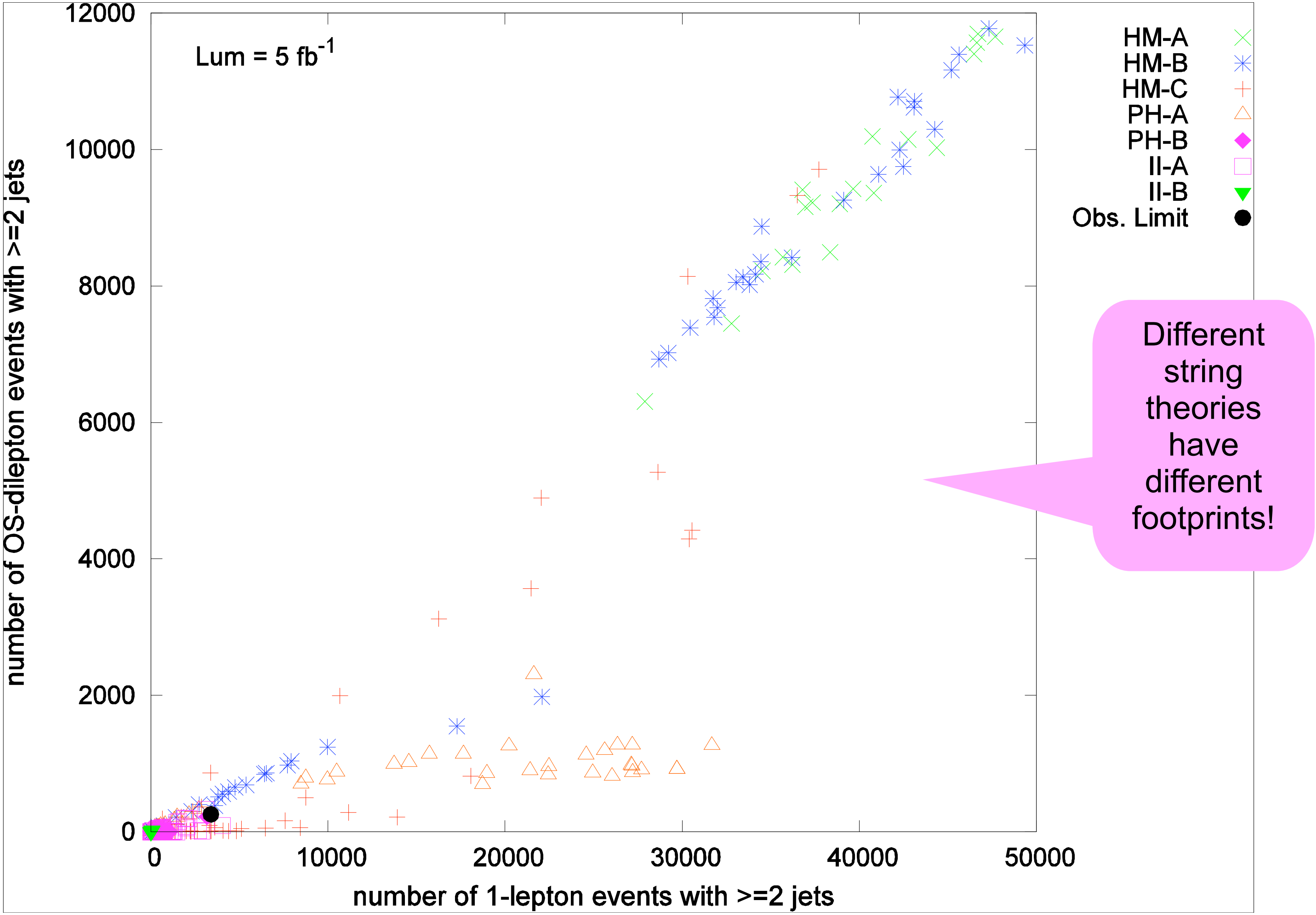
Technical details

- **RG Evolution from Unification Scale to Electroweak scale**
  -- Using SuSPECT, only a subset compatible with low energy constraints
  $M_{Chargino}$ > 105 GeV, M_{LSP} > 60 GeV, M_{higgs} >110 GeV ,
  relic density < 0.15, b→s+γ.

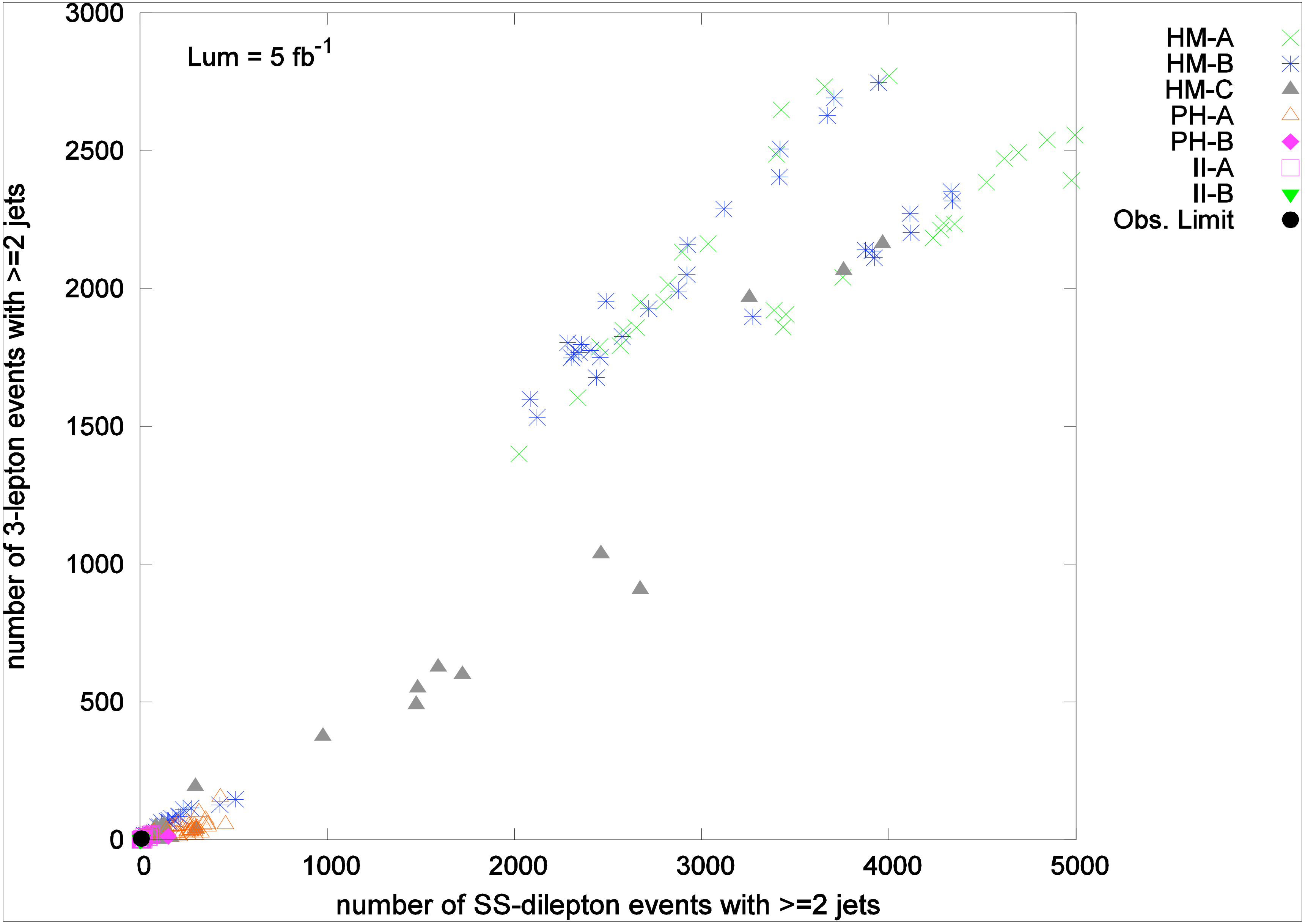
- **Simulating event generation in LHC**
  -- using PYTHIA 6.324

- **Detector Simulation**
  - Modified Version of PGS (pretty good simulation)
  - Definitions and Trigger-level cuts, as in the LHC Olympics.
  - Event selection cuts : Lepton, Photon PT > 20 GeV.
    Jet PT > 100 GeV.
    Missing ET > 100 GeV.

- **Standard Model Background**
  - tt background, diboson background. W+jets not included at this stage.
  - Technically, W+jets background not available now.


Lum = 5 fb^{-1}
number of OS-dilepton events with >=2 jets
number of 1-lepton events with >=2 jets
0
2000
4000
6000
8000
10000
12000
0
10000
20000
30000
40000
50000
HM-A
HM-B
HM-C
PH-A
PH-B
II-A
II-B
Obs. Limit
Different string theories have different footprints!

Tri-lepton vs. SS dilepton



HM-A construction --- Universal gaugino mass soft terms.

→ Hierarchy between gauginos fixed ($M_1<M_2<M_3$)

→ Flipper degeneracy *not* possible.

Since $M_2 \approx 2 M_1$ at low scale, squeezer degeneracy also *not* possible.

Turns out that slider degeneracy is also not allowed.

--- Do not want to vary the gluino mass a lot, or get total rate wrong.

--- The electroweak-ino spectrum also more or less fixed by the universality of gaugino masses.

--- Cannot get a “big-enough” slider.

There exists no degeneracy in the HM-A construction !

Construction/ Signatures	A	B	C	D	E	F	G
HM-A	√	√	√	√	√	√	√
HM-B	√	√	√	√	√	√	√
HM-C	Both	Both	Both	√	√	√	√
PH-A	x	x	√	√	√	√	x
PH-B	x	x	x	N.O.	√	x	x
II-A	x	x	Both	√	x	x	Both
II-B	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.

Choose median signal--√ above, x below, both, N.O. not observable

- Results very encouraging for the idea that data and string theory can be connected much more directly than naively expected!
- Worth major effort

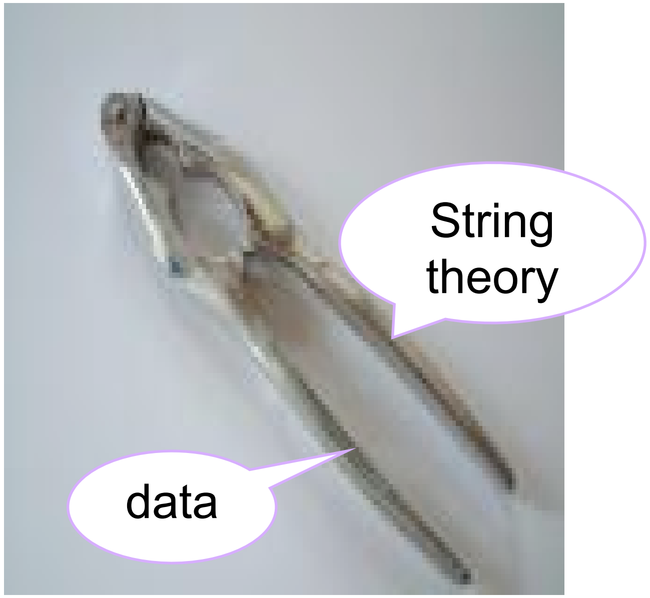
- Extend theoretically and phenomenologically
  - -- very good to work out more constructions – particularly some with all moduli lifted
  - -- add dark matter and other non-collider signatures

Soon should have LHC, maybe DM data

"Bottom-up string physics" may be very powerful in pointing toward the right class(es) of string theories -- focus attention → fast progress

But only if use data, theory together

Nutcracker approach



Lots of good thinking, work needed

Same for DM relic density, inflaton…

Dark Matter Inverse Problem

Now turn to dark matter – how can we deduce the relic density, learn if LSP (or …) is all the DM?

[Brhlik, Chung, GK hep-ph/0005158]

Much of literature is full of assumptions, mostly not checkable – hadron collider alone not enough

[Bourjaily, GK hep-ph/0501262]

Bino-like: bino part of LSP > 0.97

EMSSM's

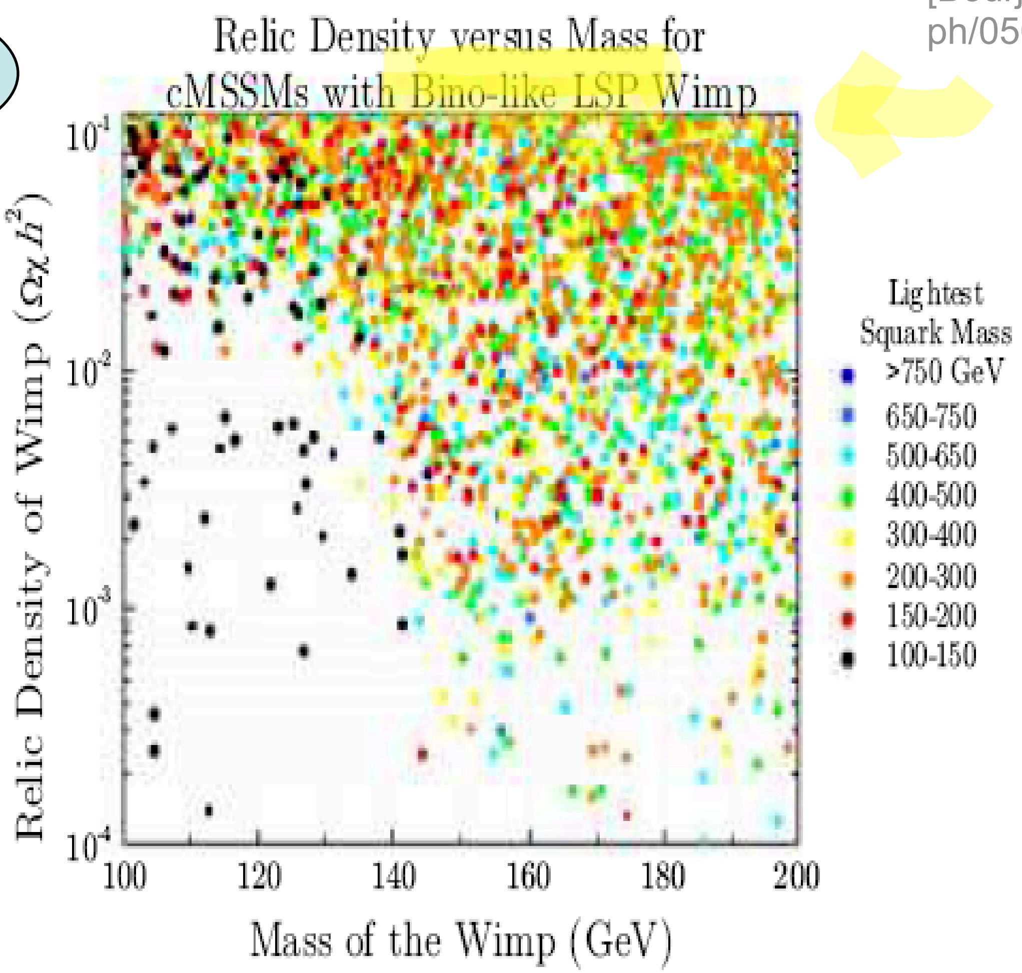


FIG. 1: The relic densities of more than 2500 constrained MSSMs with a Bino-like LSP as a function of m_χ. The mass of the lightest squark is indicated by color. Notice that there is almost no correlation whatsoever between mass and relic density. The lack of correlation is clear even when one knows the mass of the lightest squark.

So LHC data alone cannot allow calculation of relic density

CONSIDER TWO MODELS:

Show here Lagrangian parameters, spectrum, relic density, LSP detection

Gaugino fraction—note smaller gf has larger relic density!

	μ	m_0	$m_{1/2}$	m_A	$\tan\beta$	A_t	A_b	m_{LSP}	m_{stop}	m_{gluino}	m_h	$\Omega_{LSP}h^2$	gf	Ge	sol
A:	308	413	327	380	11	-.98	-.98	158	351	1138	112	0.10	.94	10^{-5}	0.8
B:	-442	406	326	338	15	0.8	0.02	163	360	1134	110	0.002	.99	3×10^{-8}	10^{-3}

SAME COLLIDER SIGNATURES

Counts/day/kg-keV
In 20 keV bin

Muons/yr-sq km

Don't just scale with relic density

[Bourjaily, GK hep-ph/0501262]