The Post-Higgs World

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What will we do?

- That’s what the LHC is supposed to tell us!
- But will it?
- That depends what is out there
- Leaves us with big questions
  - What do we think is there and what should our long-term plan be?
- And “small” questions
  - How to make the most of what we have

Important often overlooked point

- Not finding anything beyond Higgs so far at the LHC is disappointing
- But it is not YET so surprising
- We already knew quite a lot
- Precision measurements already told us that particles heavy
  - Eg wino heavier than few hundred GeV generically implies gluino heavier than 900 GeV
- Would have been very surprising to have seen a strongly interacting state

Now

- We are only just beginning to probe genuinely new region of parameter space
- Not just true for supersymmetry
- True for extra-dimensional models as well
- Probably true for any new physics
  - Precision electroweak
  - Flavor changing
  - Not having seen anything yet and mass relations
- We are really only entering uncharted territory

Possible exceptions

- Eg 2 γ rate could have been/could be large
- New charged uncolored state of a few hundred GeV would not yet have been seen
- But not necessarily direct searches for "conventional" susy particles

My talk

- What should we be thinking about now?
- I’ll focus on “small questions
  - New ideas for how best to do searches
  - What models can do
- Summarize some of my contributions
  - Search methods
  - New models that accommodate data
  - Dramatically new models
- But also use it to express ideas about moving forward
- Good to think about general lessons of what to do now

What Should We Be Doing Now (next couple of years)?

- Thinking about
  - Tools
  - Models that are harder to find
  - Pure Theory
- Also thinking about bigger questions on what experiments will truly help us advance and how to achieve them
- My talk mostly focuses on former

I:Tools

- Despite years of effort, sometimes new or at least complementary experimental methods available
- Don't assume all search strategies have been explored
- Past example: LR w/ David Tucker-Smith
- $\alpha = p_{T2}/m_{jj}$
- Improved by CMS to α_T
- Other strategies followed eg razor method (Rogan et al)

General Idea of α

- Kinematical relationships different
- Among visible (observable) particles
- In presence of missing energy
- Kinematic regimes can be achieved that tell you missing energy was present
- Improved α_T was used for first CMS SUSY search
- Advanced razor method now used as well

Lesson?

- Really good thing. We have time—
  - You can focus on best bound most quickly
  - Or you can think about optimizing methods
  - Best do do both
- What other lessons?
  - Mostly Tucker-Smith and I arXiv:0806.1049 not credited
  - I’ll survive
- But theorists and experimenters are doing sometimes inspired work extending searches
- Very important since we now know LHC might not have enough energy and luminosity
- But you are doing a disservice to the community when you neglect to credit these people; need to keep this happening
- It’s a tricky business for them working on these methods and when there are major improvements
- One of the most important things today is extending searches beyond what was originally intended

General Lesson

- The existence of a new efficient way to look for supersymmetry in 2008 was a surprise to us
- After so many years of study
- But LHC was a new environment
- So worth thinking about new methods and new challenges that were faced
- Amazingly found a simple way to look based on kinematics
  - Not explicitly missing energy
- That worked—and was greatly improved on

One such improvement

- Boosted bs
- Good methods to search now
- Also led to improvements in Higgs associated production searches
  - Congratulations on that
  - I was very impressed
- Most important is to get this physics done
- But maybe occasionally recognize the interaction that is making it possible

Another method specific to LHC

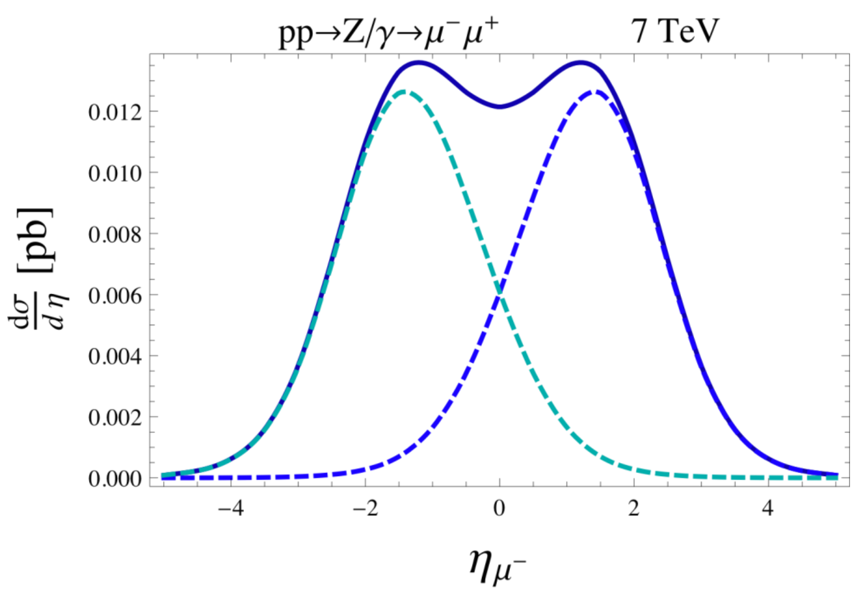
- Resonance searches (LR w/Kelley, Shuve arXiv:1011.0728)
- We showed statistical methods for searching for broad (or narrow) resonances
  - Allow one to distinguish resonance from SM (and compositeness)
- And to determine chiral properties
- Muon pseudorapidity distribution carries information about underlying physics
- Muon angle in CM frame (θ^*) useful for spin determination
- But we found **new variable** (ellipticity) good for determing chiral (parity) structures

Ellipticity

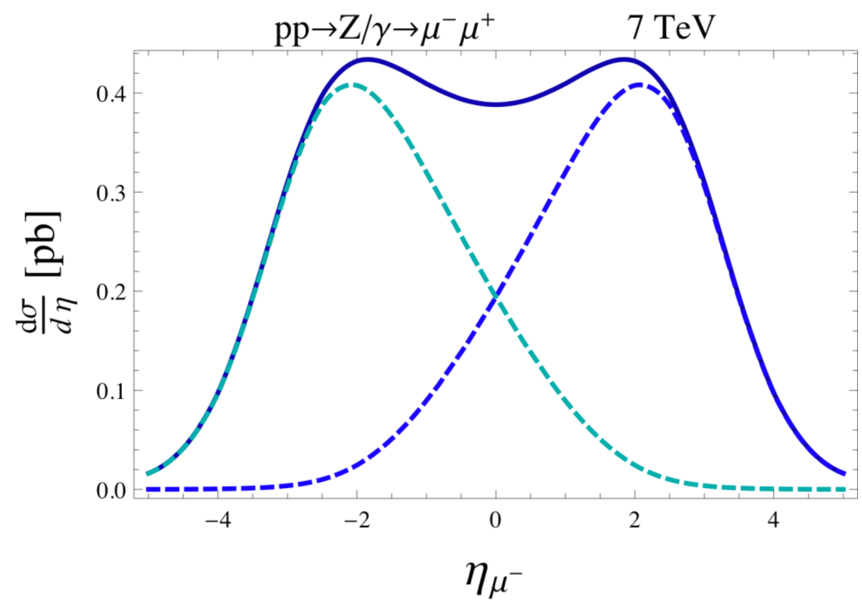
- Usual (forward-backward) asymmetry relies on finding which is quark and which is antiquark
- Ellipticity uses fact that muon preferentially forward in quark direction
  - Which has higher momentum
  - Antiquark can be backward and hence have less longitudinal momentum

μ^- pseudorapidity

$M_{\mu\mu} > 400$ GeV



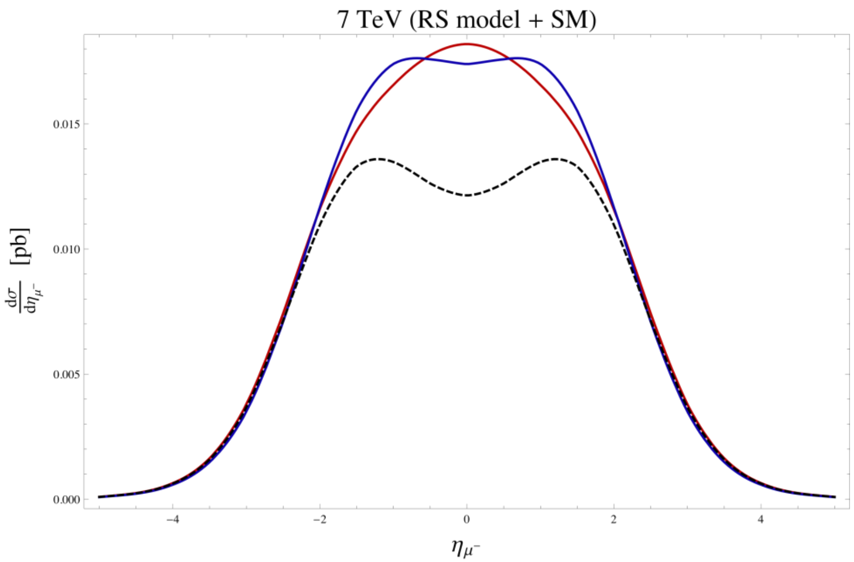
$M_{\mu\mu} > 150$ GeV



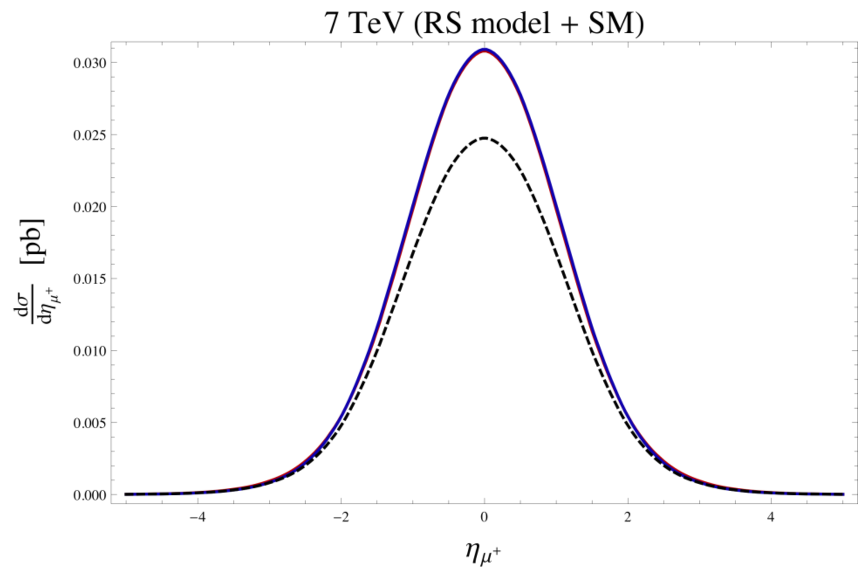
Pseudorapidity distributions

$E_{cm} = 7$ TeV
$k/M_{\rm pl} = 0.1$
$M_{\rm g} = 1300$ GeV
$\Lambda = 6590$ GeV

μ^-



μ^+



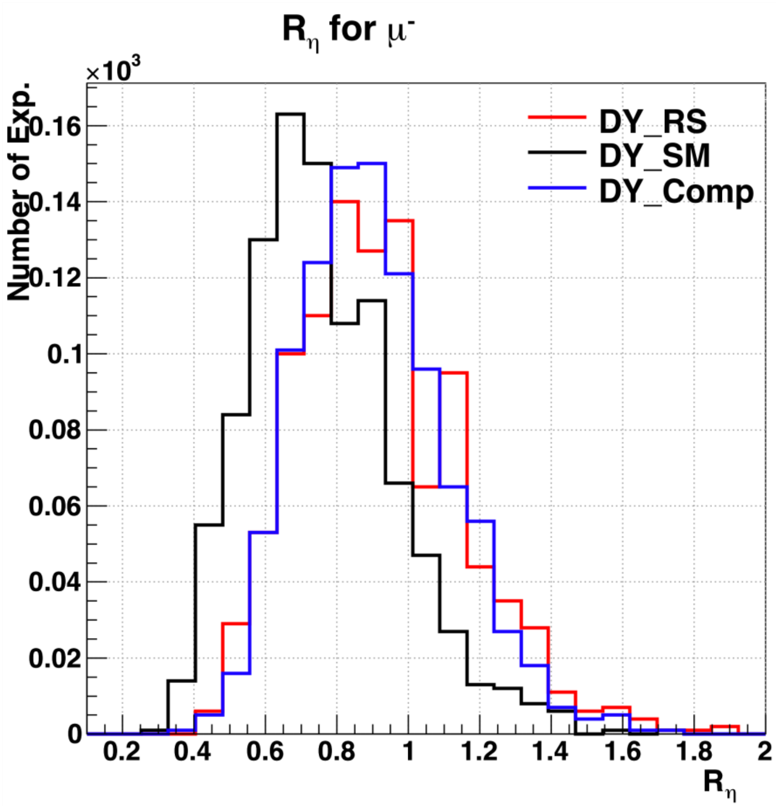
dashed black: SM
solid blue: composite (LL) model
solid red: RS model

Define observable

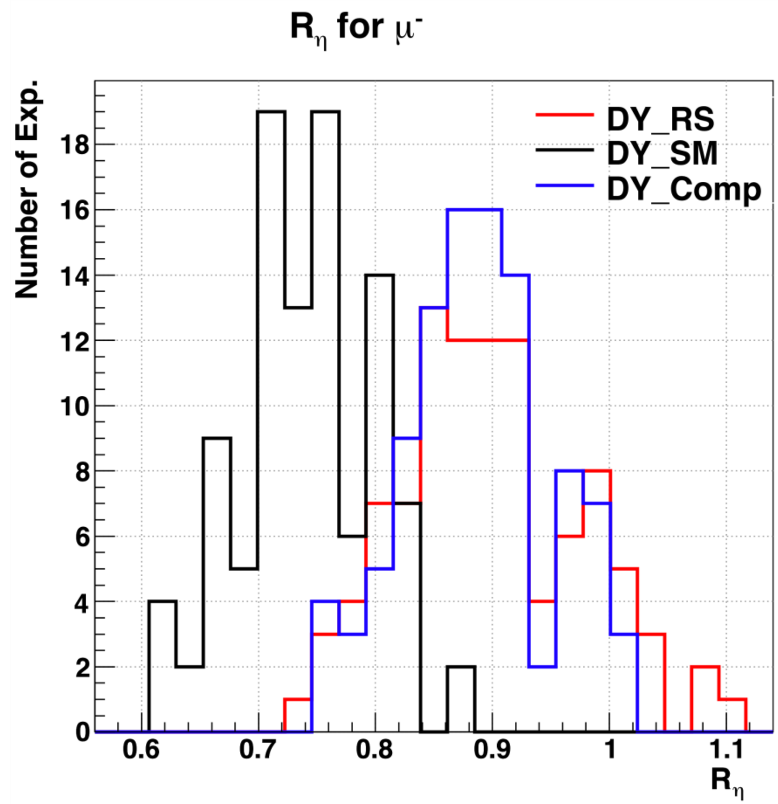
$$R_\eta = \frac{\displaystyle\int_{-1}^{1} d\eta \; \frac{d\sigma}{d\eta}}{\displaystyle\int_{-\eta_{\max}}^{\eta_{\max}} d\eta \; \frac{d\sigma}{d\eta}}$$

Separation of Distributions Helps Determine Parity of Underlying Resonance Physics

$1\ \text{fb}^{-1}$



$10\ \text{fb}^{-1}$



So tool-

- Measure angular distributions in novel ways
- People recognizing this for Higgs, BSM, etc
- Good for both
- Angular distributions can be a high statistics game
- Good to think about best methods
  - Not needing to find CM frame helpful in this case

Another “tools” challenge

- Stopped tracks
- Essential for identifying light winos (eg from anomaly mediation (w/Sundrum, also Guidice, Luty, Murayama, Rattazzi)
  - Charged state has small splitting from neutral state
  - Visible track but short (order few cms) (w/Feng, Moroi, Strassler, Su)
  - Pion from decay too low energy to see
  - Standard trackers would miss charged tracks (that don’t make it through all trackers) and final states
  - But they are leaving signals in the detector!
  - Need to trigger (additional jet) and measure stubs
  - Challenging but let’s find out if possible

And: Not only light winos

- Any SU(2) representation where mass splitting comes from radiative effects (w/Buckley, Shuve arXiv:0909.4549)
- Not serving essential model-building role
- But weak scale SU(2) reps not such a crazy possibility
- Would like to be able to see them
- And other reps might be more accessible

Simple Model; Small Splitting

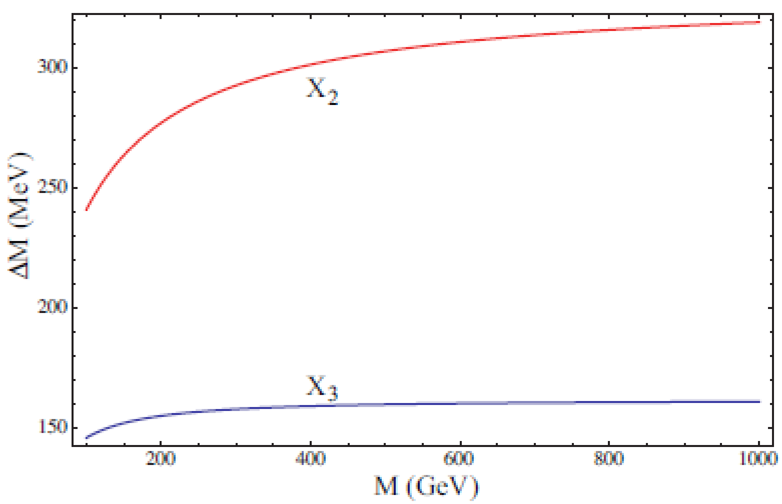
$$\mathcal{L} = i\bar{X}\not{D}X - M\bar{X}X.$$

$$X_2 = \begin{pmatrix} X_2^+ \\ X_2^0 \end{pmatrix} , \; \bar{X}_2 = \begin{pmatrix} \bar{X}_2^0 \\ X_2^- \end{pmatrix}$$

$$X_3 = \begin{pmatrix} X_3^+ \\ X_3^0 \\ X_3^- \end{pmatrix}$$

$$\Delta M = \frac{\alpha M}{4\pi}\left\{Q^2 f\left(\frac{M_Z}{M}\right) + \frac{Q(Q-2Y)}{\sin^2\theta_W}\left[f\left(\frac{M_W}{M}\right) - f\left(\frac{M_Z}{M}\right)\right]\right\}$$

$$f(x) = \frac{x}{2}\left[2x^3\ln x - 2x + \sqrt{x^2-4}(x^2+2)\ln(x^2-2-x\sqrt{x^2-4})/2\right]$$



Decay Length

$$\Gamma(X^\pm \to X^0\pi^\pm) = \frac{AG_F^2}{4\pi}\cos^2\theta_c f_\pi^2 \Delta M^3 \sqrt{1-\frac{m_\pi^2}{\Delta M^2}}$$

$$\Gamma(X^\pm \to X^0\ell^\pm\nu_\ell) = \frac{AG_F^2}{60\pi^3}\Delta M^5 \sqrt{1-\frac{m_\ell^2}{\Delta M^2}} P\left(\frac{m_\ell}{\Delta M}\right)$$

$$P(x) = 1 - \frac{9}{2}x^2 - 4x^4 + \frac{15x^4}{2\sqrt{1-x^2}}\tanh^{-1}\sqrt{1-x^2}.$$

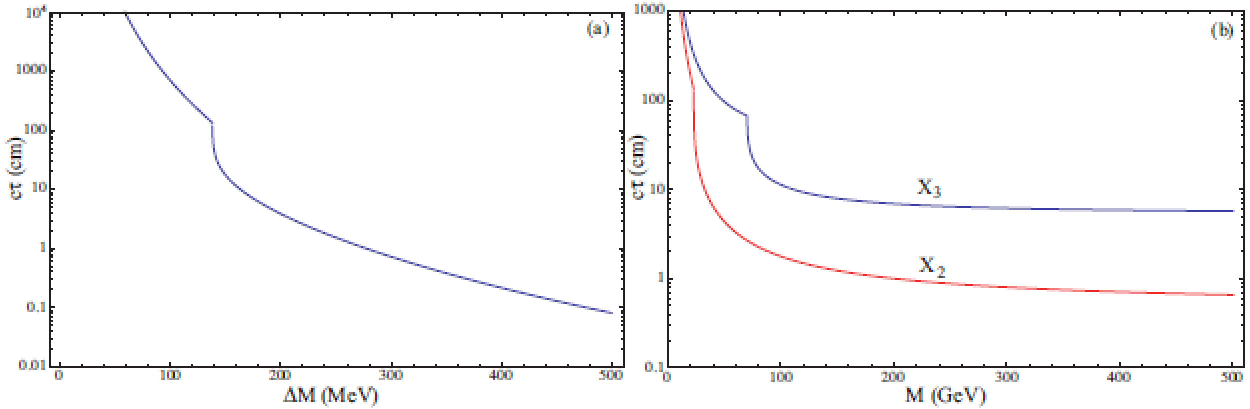


FIG. 2: Left: Lifetime of generic $X^\pm$ decaying to the final states $X^0 + \pi^\pm$ or $X^0 + \ell^\pm + \nu_\ell$ as a function of $X^\pm - X^0$ mass splitting ΔM. Here $\ell = e/\mu$. We have assumed that the X couples to $W^\pm$ with the same strength as a triplet (*i.e.* $A = 8$ in Eqs. (6) and (7) The 'kink' structure at $\Delta M = m_\pi$ is caused by the pion channel opening. Right: Lifetime of doublets $X_2^\pm$ and triplets $X_3^\pm$ decaying to the neutral states X_2^0/X_3^0 as a function of the neutral state mass M, assuming the mass splittings of Eq. (4).

Rates acceptable

$\sqrt{s}$ (TeV)	MET> 65 GeV	MET> 80 GeV	Jet $p_T > 110$ GeV	jet $p_T > 150$ GeV
13	50.2 fb	44.1 fb	34.2 fb	23.9 fb
10	26.5 fb	23.1 fb	17.1 fb	11.5 fb

TABLE I: The production cross section of $X_3\bar{X}_3$ pairs at $\sqrt{s} = 13$ TeV and 10 TeV with $M = 300$ GeV using four different trigger menus. These are triggers on MET> 65 GeV, MET> 80 GeV, highest jet $p_T > 110$ GeV, and a highest jet $p_T > 150$ GeV. All cross sections were calculated using MadGraph [28] and Pythia [29]. See text for further details.

X_3^0 Mass (GeV)	σ_{12} (fb)	σ_{30} (fb)	$\sigma_{12/30}$ (fb)
200	8.8	0.69	4.0
300	1.4	0.062	0.45
400	0.32	0.013	0.10
500	0.11	0.0037	0.029
600	0.036	0.0005	0.0062
700	0.013	0.0001	0.0025
800	0.0059	0.0000	0.0010
900	0.0025	0.0000	0.0005
1000	0.0012	0.0000	0.0002

TABLE II: The integrated cross sections for $X_3^+X_3^-$ +jets events in which $\min[Tc\tau] > 12$ cm (σ_{12}), as well as $\min[Tc\tau] > 30$ cm (σ_{30}); and $\min[Tc\tau] > 12$ cm, $\max[Tc\tau] > 30$ cm ($\sigma_{12/30}$), as a function of mass. Events were simulated at $\sqrt{s} = 13$ TeV with a MET trigger of 65 GeV. In addition to the $Tc\tau$ requirement, events passed an $|\eta| < 2.5$ cut on $X_3^\pm$ and an isolation cut of $\Delta R > 0.4$. The corresponding differential cross sections are shown in Fig. 4.

Major experimental challenge

- Background from random hits
- No real physics background
- How to deal with it?
  - Back to back
  - Relative rates
- With detector upgrade and inner tracker more inner this is worth thinking about
- More hits, more events recorded

Challenging

- But worth doing
- A couple of years to see if possible
- Especially when improved inner tracker
- Light winos tough at the moment, triplets possible
- Worth seeing if search can be done

One More Tool

- Surprising one: ISR Tagging (w/Krohn, Wang arXiv:1101.0810)
- Take advantage of difference new physics and SM
  - Eg pair production of new particle (squark, gluino)
- ISR gluon jet will have different properties

ISR Tagging

1. The jet's p_T is distinct (i.e. it is harder or softer than the others):

$$\frac{\max(p_{Ti}, p_{Tj})}{\min(p_{Ti}, p_{Tj})} > 2 \; \forall \; j \neq i \tag{1}$$

2. The jet is separated from the others in rapidity:

$$|y_i - y_j| > 1.5 \; \forall \; j \neq i \tag{2}$$

3. The jet is distinguished by its $m_i/p_{Ti} \equiv \Delta_i$ ratio [10]:

$$\frac{\max(\Delta_i, \Delta_j)}{\min(\Delta_i, \Delta_j)} > 1.5 \; \forall \; j \neq i \tag{3}$$

f a jet (again labeled i) is selected by any of the above riteria it should then satisfy *all* of the following:

- The selected jet must not be central: $|y_i| > 1$.
- It must not be too close to the other jets, which are all implicitly FSR jets:

$$|y_i - y_j| > 0.5 \; \forall \; j \neq i \tag{4}$$

- These other jets must be reasonably close to each other in p_T:

$$\frac{p_{Tj}}{p_{Tk}} < \rho + \frac{1/2}{1-\alpha} \tag{5}$$

for $p_{Tj(k)} = \max(\min)\{p_{Tl} | \forall \; l \neq i\}$, with $\rho = 2(3)$ for $N_f = 2(4)$, and where we have introduced the variable

$$\alpha = \frac{\min(p_{Ti}, \not{E}_T)}{\max(p_{Ti}, \not{E}_T)} \tag{6}$$

to relax this condition when the ISR is very hard.

- Finally, the implicit FSR jets must be somewhat central: $|y_j| < 2 \; \forall \; j \neq i$

Measuring Masses w IR Tagging

- Use fact that heavy particles produced near threshold
- Invariant mass of two heaviest BSM particles
- You measure ISR properties
- By finding boost using ISR (depends on invariant mass) where transverse momentum minimized
- You identify invariant mass squared

Sample Result

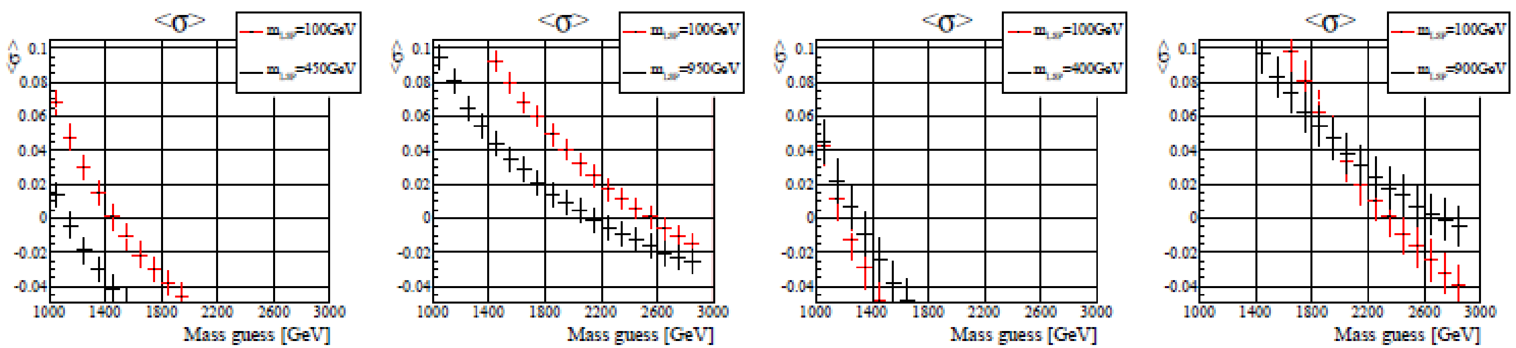


FIG. 1. The average sign of the FSR projection along the transverse ISR direction for, proceeding left to right, di-squark production using $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{q}} = 1$ TeV, and then di-gluino production with $m_{\tilde{g}} = 500$ GeV, $m_{\tilde{g}} = 1$ TeV, with the LSP mass indicated in the legends. The position at which the points intersect $\langle\sigma\rangle = 0$ is what we would identify as $m_{\rm BSM}$, i.e. it where the FSR momenta are balanced because the boost is 'correct'. We see that it is in general close to $2m_{\tilde{q}/\tilde{g}}$. Note that the errors indicated are just the statistical errors associated with our Monte Carlo sample sizes.

What are methods challenges for future

- Lots have to do with jets
  - They are messy
  - But carry a lot of information we are wasting
- Jet trimming, q-jets, etc
- Pushing searches to high energies

    Better efficiency means data better used
- But other searches should be pushed to higher energy too
  - Even early on, I was surprised muon searches for example being optimized at around a TeV
  - But not yet much thought to how far we can go in energy reach
- Becoming more and more clear how important this is

Other generalities on tools

- Dealing with pileup—I don’t know answers but clearly a critical challenge
- Finishing analyses—mostly unlikely to tell us anything earth-changing
- So think about novel methods—time to experiment with methods!
- Test on existing data while finishing analyses

And also still chance for conventional SUSY but only non-Strongly Interacting Particles Present at LHC energies (at least so far)

- In fact best hope (kinematically) was always in leptonic sector
- SUSY: charginos, sleptons
- Still not very strong bounds
- So possible susy there in current data still…

II: Models

- What should we be addressing?
- Phenomenological Fact
- Higgs lighter than other particles
- How heavy are they?

Models

- Data and naturalness calling for rethinking SUSY models
  - RS always had challenge of low and high scale
- Naturalness (Giudice and Dimopoulos) AND

  More Minimal Supersymmetric Theories (Cohen, Kaplan, Nelson)
- Also specific models (Csaki, LR, Terning), Stealth SUSY models (Reece) and many others)
- Important because specific signatures depends on models
- For example, light sbottom important for searches in our models

Give up naturalness?

- I'd say way too soon
- We just haven't explored enough energy scale
- And we've looked for simplest options
- Likely nature didn't cooperate
- Also not clear LHC upgrade will get us to necessary energy
  - We might have to be lucky with tail end particles lighter
  - Almost certainly not entire spectrum
- We should push as hard as we can
  - Both with theory and experiment

What is this telling us?

- Naturalness and experiments argue for two scales
  - Naturalness: want some particles light
    - Those that give large radiative corrections
  - Experiments: some particles should be heavy: few-10 TeV
- Several models of this sort
  - Little Higgs
  - New models of supersymmetry
  - RS with SUSY

Example in Supersymmetry

- w/Csaki, Terning 1201.1293
- Keep in mind naturalness only requires light stops, electroweakinos, Higgs
- Other particles (the ones we have looked for) could be heavier

Model

- Model based on Seiberg duality
  - Strongly interacting system formulated in UV
  - Seemingly different IR description
  - Essentially composite states
- We looked at (partially) composite Standard Model
  - Heavy top composite, light states fundamental
- Turns out tree level supersymmetry breaking communicated only to fundamental fields
  - Heavier and avoid observation
- Composite particles (eg top) light
  - Exactly what is required for naturalness!

Phenomenological Consequences

- Light stops
- Stop could even be (N)LSP
- Light sbottoms as well

- Interestingly, phenomenology of RS/SUSY model similar—light states the same

Sample Spectrum

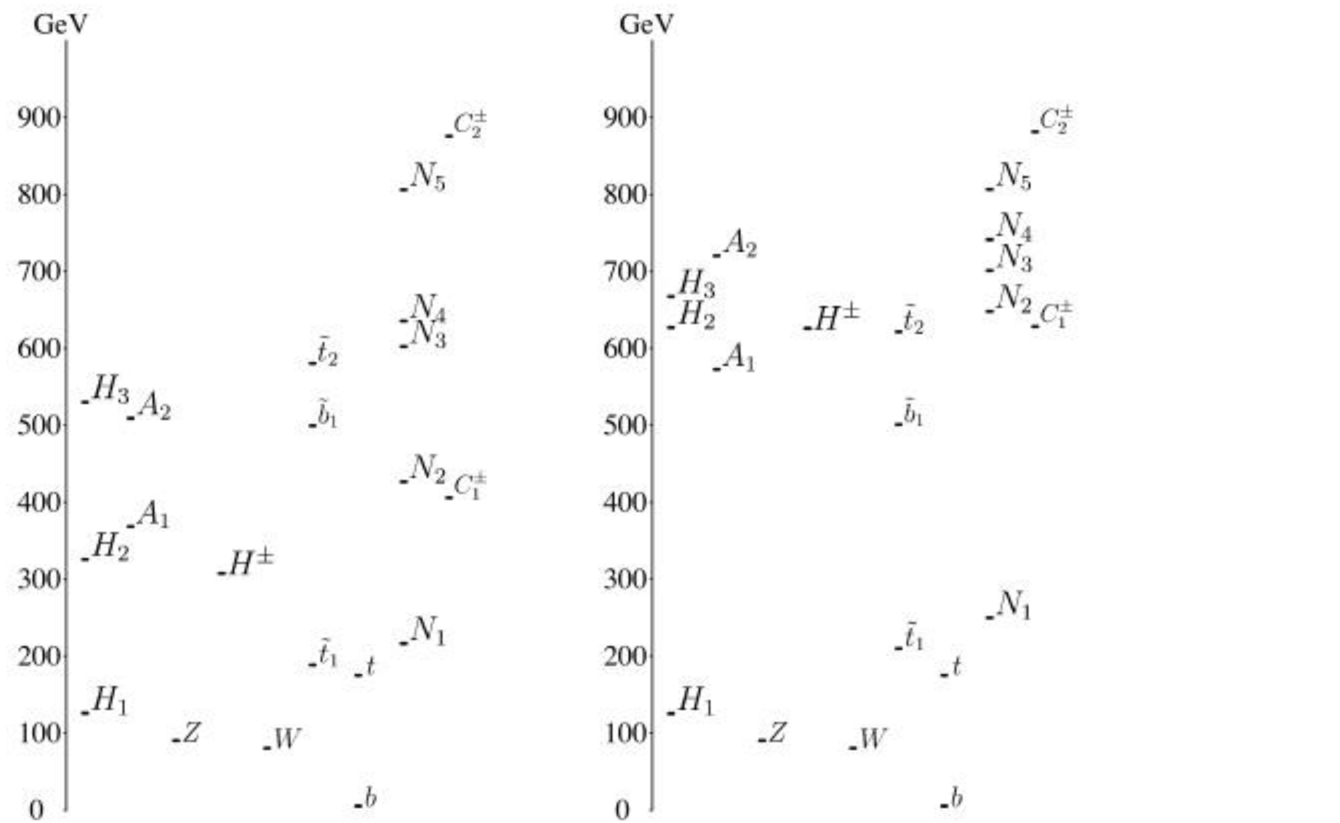


Figure 1: Light superpartners and Higgs particles for benchmark spectra 1 and 2 with a $\tilde{t}$ NLSP.

Search Strategies

- Depends on spectrum
- 4 Categories
  - Stop LSP—nearly degenerate to top
  - Stop LSP-more splitting
  - Neutralino LSP Gauge mediated spectrum
  - Neutralino with soft masses from radiative corrections

Search Strategies

- Stop NLSP can decay to top plus gravitino
- If (N)LSP is neutralino, stop can decay to top plus neutralino
- Or bottom plus chargino
- Neutralino will decay to photon plus gravitino
- Or Higgs/Z + gravition
- If Neutralino LSP, standard missing energy signals
- But spectrum very different
- Squarks heavier
- Gluino heavier (but can be close to stop mass)
- Relevant for search b

Example in RS

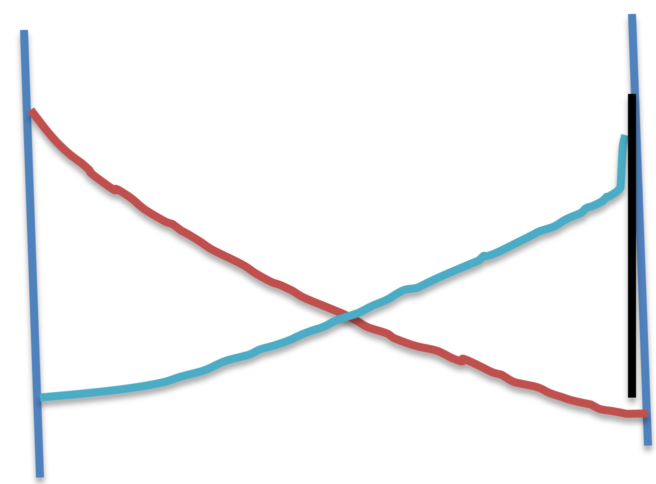
- Sundrum: SUSY splits and then returns
- SUSY broken at high scale
- Warped (RS) geometry protects mass scales
- But only down to 10 TeVish
- Low energy spectrum essentially supersymmetric
- Protects light Higgs
- True target mass is high
- What we can hope for is lower particles might emerge

Also: Keep in Mind Different Versions of RS

- If all particles but gravity on brane
  - Graviton KK mode
  - Clean signal: resonance decays to photons, electrons, muons in fixed ratio
  - Spin-2
  - Gap in spectrum
- If gauge bosons, fermions in bulk
  - Allows unification, flavor physics
  - Dominant signal: decay to tops
  - Best chance gluon KK mode
  - But bounded at 5 TeV level!
  - Want new methods to look for gluonic resonance
    - Decays predominantly to tops

What about flavor?
RS Nice Model of Flavor

- Hierarchies come from wavefunctions in bulk
- Higgs on IR brane—wf of fermion determines overlap
  - Exponentials automatic
- Automatic correlation between mixing angles and hierarchies
- Natural parameters
- ANARCHIC YUKAWAS



Neutrino Masses

- w/Perez
- Explained lepton masses and mixing angles too
  - (how many compelling models of flavor do that?)
  - Follows naturally by increased degeneracy among bulk lepton masses
    - Exponential only when mass splitting greater than inverse size~.03
- Predict θ_{13} to be large
- Measurement argues strongly for anarchy

Flavor Physics Taught Us Something

- Neutrinos have taught us very important qualitative characteristics essential to flavor models
- Large mixing ruled out many models
- Correlations masses and mixing suggestive
- θ_{13} remarkable

- BUT Even with all this hard to make sufficiently testable predictions
- Rule out models
- But hard to test
- Flavor measurements critical
- Not enough

III:What else to do?

- There is a role for pure theory
- Many models (supersymmetry, RS, etc) grew out of pure theory developments
- Long shots but some connections may exist that will be missed otherwise

Ambulance Chasing?

- I actually think it’s not always a waste of time
  - When genuinely new ideas emerge
- Squeezing parameter space of existing models probably not that interesting
  - Especially if data goes away

- Dark matter provides a nice lab for this
- Results released that people are quite skeptical about
  - DAMA: AdM
  - Fermi line: current work

New Ideas

- Sometimes new ideas emerge though
- Asymmetric Dark Matter (Finkbeiner, Weiner, etc.) important idea to incorporate and test
  - Often tests are different
  - Means existing searches need new interpretations
  - And sometimes new searches possible

Another idea: Fermi

- Double Disk Dark Matter (Fan, Katz, LR, Reece 1303.1521)
- Big new (recent) idea (though in some sense quite simple)
- Dark matter can have a small interacting component
  - Perhaps comparable to baryons
- But with dramatic consequences

Double Disk Dark Matter

- Dissipative interactions make component collapse into disk
- Also requires heavier dark matter and lighter electron-like matter plus dark photon
- New consequences for
  - Indirect detection: automatic boost factor!
    - Can be huge
  - CMB—acoustic peak, new non freestreaming degrees of freedom
  - Gaia survey—star velocity measurements about to be improved by 10,000
    - Can detect structure in our galaxy
    - We provide a nice target

Are these models right?

- We don’t know
- But very testable
- And not too crazy assumptions—very much like our known matter
- But only with models can we test these ideas
- New big unexplored ideas
- I don’t know what those ideas are in particle physics
- But combination of pushing existing ideas and paying attention to clues could propel us forward

Where are we? Good and Bad

- Not so disappointing
- Haven’t seen anything beyond SM
  - But I didn’t really expect we would
- But we have only less than a factor of two in energy
- Something might be there
- Or it might be beyond…
- Perhaps both!

Experimental Strategies to Improve

- Tools: I've mentioned some
  - New SUSY Search Methods
  - New Methods for Angle Measurements
  - Stopped tracks/stubs
  - ISR Radiation
- Tools to think about
  - Jets
  - Pileup

Models to Improve

- Naturalness vs Experimental Constraints
- Most natural and simple models should have been seen
- How unsimple do models need to be?
- My work: Light stops could have natural origin
- Other work: Light states can be natural in context of RS
  - Not clear these models are right
  - Also not clear they are ruled out

Or Moon Shots?

- Analog to DDDM
- Maybe we are still missing something big
- Often direction shown by small discrepancies
  - Sometimes even discrepancies that go away
- Remain open-minded
- But not epicycles
- Big Ideas

What else should we be doing?

- Future
- Experiment critical to future of physics
  - High energy, cosmology no exceptions
- We need to think about strategy
- I personally think we should be pushing toward higher energy – whatever role we can play
- Others might think this is wrong strategy even if right from physics point of view
- Where is America’s experimental program heading?
  - We’re not all Americans
  - But America’s future will be a big part of the future of high energy physics
  - What would we like to achieve
  - And how to go about achieving it?

Summary

- Edge.org What are you worried about?
- Not worried new physics not there
- Worried it’s not in limited regime we can currently probe
- Only one way to find out…
- Let’s see if methods I mentioned work
- Or others
- Try to push as hard as we can