Deciphering New Physics at LHC

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Plan

- Introduction
- Intra-framework issues
- Inter-framework Issues
- Robustness of Smoking Gun signatures
- Conclusions

Introduction

- Naturalness of the Weak scale $\Longrightarrow$ Physics beyond the SM
- LHC : The First Genuine opportunity to uncover the TeV scale

Assume: We see an excess of events in inclusive analyses

How readily can we know the nature of the New Physics from Data?

- Is it Supersymmetry?
- Is it an Extra Dimensional scenario?
- Or Something Else?!

Understanding It

Experimentally measure the Properties

What does that mean?

Know the Lagrangian parameters:

- Masses
- Gauge quantum numbers
- Other couplings and parameters

From the Data to Theory

The so-called LHC Inverse Problem

(For the Theorists :)

** Talk by Sreerup Raychaudhuri*

Usual path for the experimentalists

The Observables

Number of events in particular channels ($\sigma \times Br$)

Kinematic Distributions (M_{inv}, p_T etc.)

Asymmetries (like charge and angular ones)

LHC Data & SUSY

- Let's go back 10-15 years back

  SUSY was the only popular BSM scenario

- **The MSSM** : The Minimal Supersymmetric Standard Model

SM + Higgs-Doublets + Super-Partners + Conserved R-Parity + Conserved CP

Infested with a 'Little' Too Many Parameters

- **Even with Some Reasonable Simplifying Assumptions**

# of Non-Trivial Parameters $>$ Useful Observables

Unambiguous Understanding is Difficult

But, for Over a Decade, LHC would not have a peer (:-(

R-Parity: Collider Implications

- **Lightest Stable Neutral Particle $\longrightarrow$ Cold DM (WIMP)**

The LSP : χ_1^0

- **Partners appear in pair at any vertex $\longrightarrow$ Precision Data**
- **LSP as Dark Matter / Missing Energy at Colliders**
- **Large Missing Energy: Broadly signals such scenarios**

Flipside: Makes Precise Event-Reconstruction Impossible

What To Look For In The Data?

- **The Generic Final State (SM & BSM)**

multi-jet + multi-lepton + multi-photon + missing energy

(arising from stable particles)

- **Establish Definitive Excess in signal(s)**

i.e. Be Convinced that the SM Can Never explain the excess

The "so-called" BackGround (BG)

Extremely Hostile LHC Atmosphere!

- *Understand the BG Better* ● *Understand the Systematics Better*

LHC Data & a Constrained MSSM

- **The Minimal Supergravity inspired scenarios**
  - The Advantage : 4-5 Free Parameters (< # of Observables)
    Naturally More Predictive $\longrightarrow$ Benchmarking
    Simpler Analysis at Simulation Level
  - The Danger : Could Inflict Bias the Interpretation of
    Experimental Observations

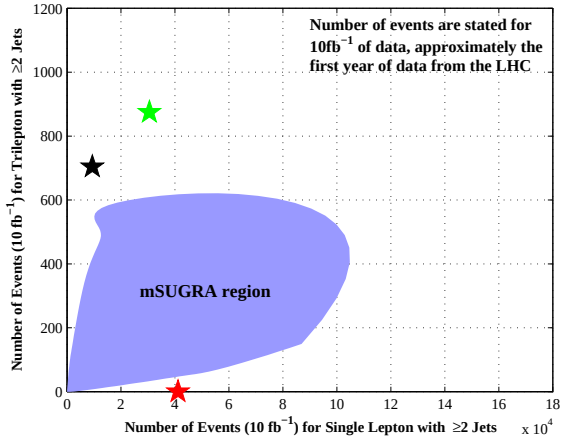
- **The Best Bet when Data is Available**
  - **Analyze Data for as many Observables as possible (Multi-channel)**
  - **Could turn out to be an Over-Defined System**
  - **Solve the Parameters using Some**
  - **Check Consistency with the Rest**

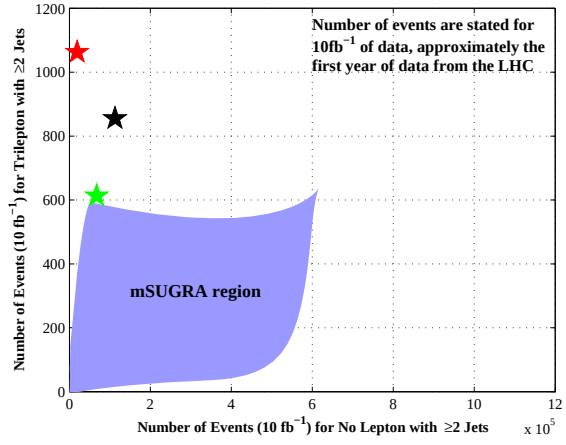
LHC Data & SUSY

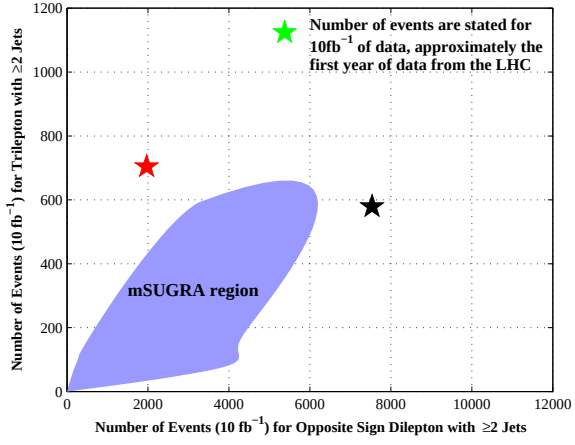
The Intra-Framework Issues

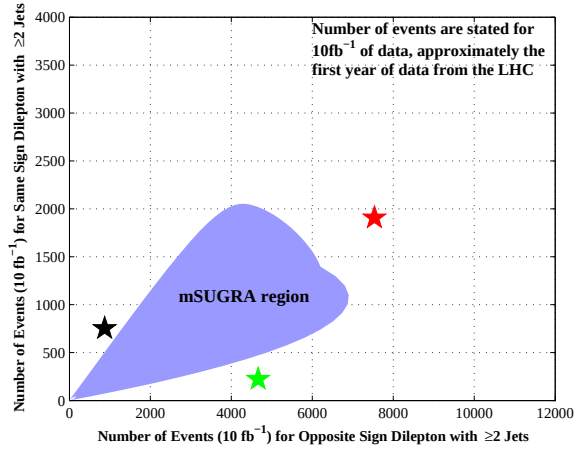
Signature Space: An Emerging Concept

Bourjaily, Kane, Kumar, Wang









- ***Ratios might help minimize irregularities/errors in individual patterns***

Universal Gaugino Mass

- **A Universal Gaugino Mass at a High Scale (Grand Unification)**
  - Obtained in the Simplest SUSY-GUT scenario
  - Renormalization Group Running to EW scale gives

$$M_1 : M_2 : M_3 = 1 : 2 : 6$$

  - SUSY cascades lead to characteristic Signal Rates

Departure from Universality can drastically alter the relative signal strengths

Non-universal Gaugino Masses

- **In general, high-scale Non-universality is a possibility**
  - **Generate non-universal mass terms via Higher GUT reps.**
  - **Gaugino Masses have Characteristic Ratios at the GUT scale**
  - **Considered SU(5) and SO(10) cases**

SU(5)

Representations	$M_3 : M_2 : M_1$ at M_{GUT}	$M_3 : M_2 : M_1$ at M_{EWSB}
1	1:1:1	6:2:1
24	2:(-3):(-1)	12:(-6):(-1)
75	1:3:(-5)	6:6:(-5)
200	1:2:10	6:4:10

Non-universal Gaugino Masses

- **An Event-generator level Signal-based Analysis**

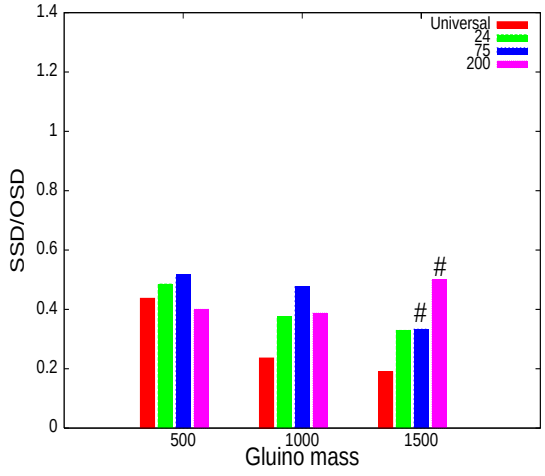
  + toy calorimeter simulation

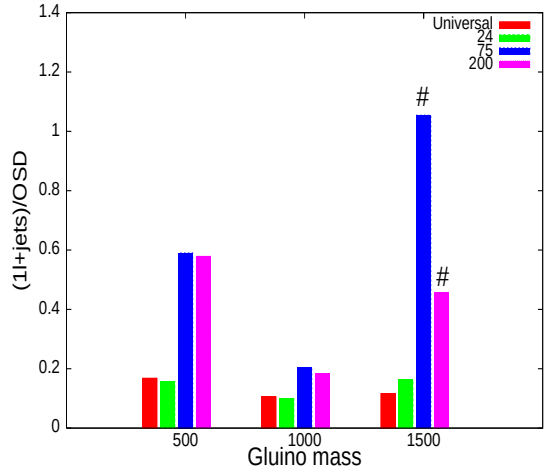
  - **Multichannel Analysis $\longrightarrow$ Signature Space**
  - **Ratios of events in different final states were considered**
  - **Scanning of representative region of paramater space**

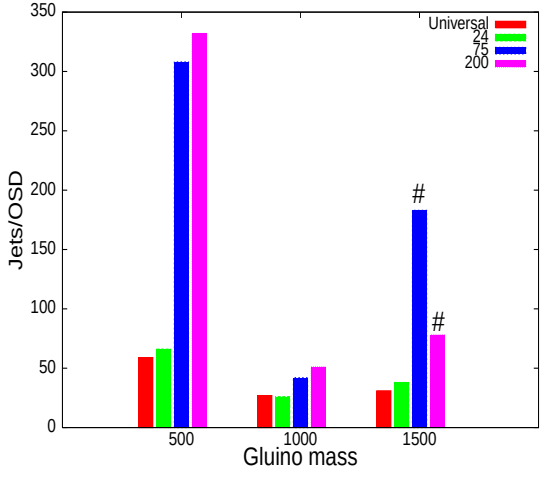
Bhattacharya, AD, Mukhopadhyaya

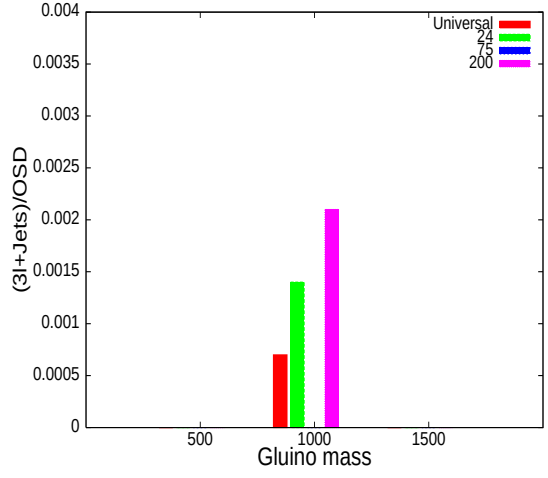
arXiv:0708.2427 [hep-ph] **JHEP 0710:080,2007**

Non-universal Gaugino Masses









Event ratios in SU(5): $m_{\tilde{f}}$ =1000 GeV, μ =300 GeV, $\tan\beta = 5$

Non-universal Gaugino Masses

- **Imprints of Non-universality may become Clearly Distinguishable**
- **Absolute Event Rates would provide Additional Handle**
- **Multilepton channels, especially Trileptons, can be rather useful**

Good news for our experimentalists friends!

Non-universal Scalar Masses

- **Squark-slepton non-universality**
- **Non-universality in the Sfermion masses of the 3rd family**
- **The effect of $SO(10)$ D-terms in SUSY GUTs**

Again, Multi-channel Analysis! ***Differentiating from the mSUGRA spectrum!***

Introduced earlier in a work by Amitava Datta, AD, M. Drees & D.P. Roy in the Tevatron context ***Phys. Rev. D61 (2000) 055003***

Trilepton channels could be particularly useful

Bhattacharya, AD, Mukhopadhyaya, *Phys.Rev.D78:035011,2008*

Hadronically Quiet Trileptons

Long known to be a very clean signal for SUSY arising out of Direct Productions of Chargino & Neutralino at the hadron colliders

- **A scenario with** $\mathrm{m}_{\tilde{\mathrm{q}}}, \mathrm{m}_{\tilde{\mathrm{g}}} >> 1$ **TeV while the charginos and neutralinos are light**
- **So that productions of only *electroweak inos* would matter facilitating HQT final state**
- **Almost necessarily a non-universal scenario**
- **Can Serve as a Benchmark**

Possible to explore a substantial region of the parameter space (masses $<$ 500 GeV) via HQT mode

Bhattacharya, AD, Mukhopadhyaya (PRD, 2008)

Gaugino Masses and Higgs Physics

- **Gaugino masses get highly involved in the production of Higgs bosons under SUSY cascade decays**

  AD, Djouadi, Guchait, Mambrini

  AD, Djouadi, Guchait, Moortgat

- **Non-universal gaugino masses would affect Higgs boson productions under SUSY cascades**

  Bandyopadhyay, AD, Mukhopadhyaya (PLB)

  Bandyopadhyay (JHEP)

- **Non-universality in Gaugino masses is reflected in the relative production rates $H^{\pm}$ and h: Relative rates complementary to that in the Universal case**

A Dilemma

If It Quacks Like SUSY

If It Walks Like SUSY

If It Looks Like SUSY

Then It Has To Be SUSY.

A Dilemma

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Or Is It ?!

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The Inter-Framework Issues

Competing Frameworks

There are more than one frameworks to stake claim!

Supersymmetry (SUSY)

Universal Extra Dimensions (UED)

Little Higgs Framework

The Common Features:

- *Duplication of SM states* (*new physics partners*)
- *Massive Partners with Similar Spectrum*
- *Similar Gauge Interactions*

May appear Very Similar otherwise

Z_2 Symmetry: Collider Implications

Discrete Z_2 Symmetry

R-parity	KK-parity	T-parity
SUSY	*UED*	*Little Higgs*
LSP	*LKP*	*LTP*

Dark Matter Candidates

Carriers of Missing Energy

Not at all Discrminatory

Masses and the Couplings

- **The Candidate Scenarios predict New Heavy particles**
  - **– Not enough fundamental to identify the new physics**
  - **– Probes only possible variants of a broad scenario**

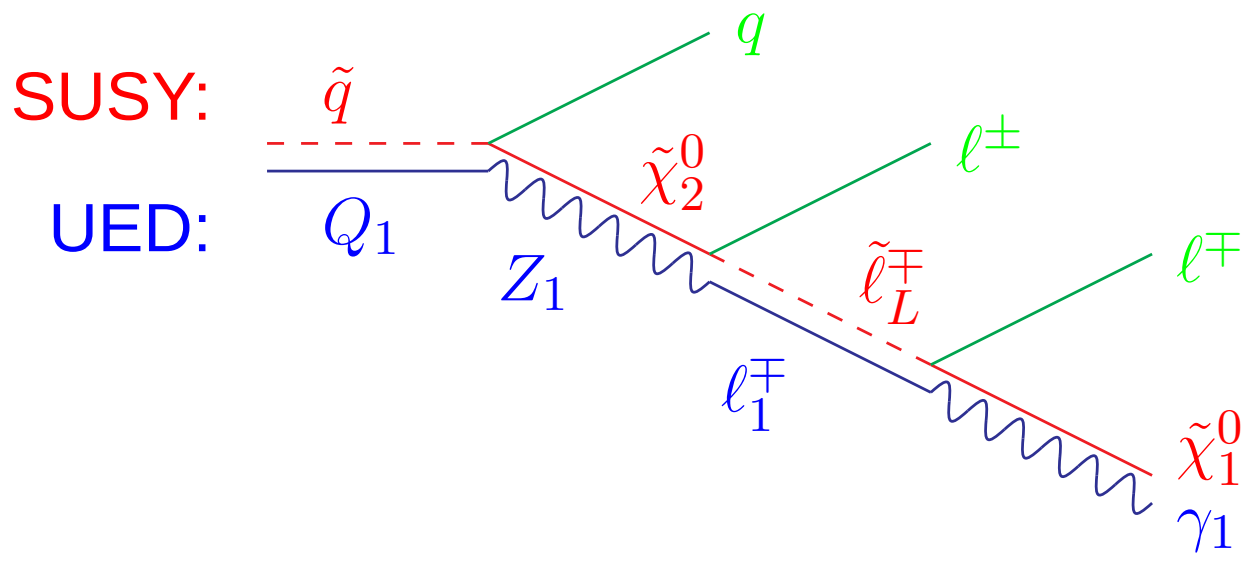
Precise Determination of Spectra/Coupling is Difficult, anyway

The Twin Diagram *SUSY vis-a-vis UED*

Cheng, Matchev, Schmaltz

Battaglia, AD, De Roeck, Kong, Matchev

AD, Kong, Matchev



The Spin of the Partners

Broadly Two Classes of Scenarios:

– *SM partners with same spin (like UED, LH)*

– *SM partners differing by spin $\frac{1}{2}$ (like SUSY)*

Measuring the Spins may become crucial

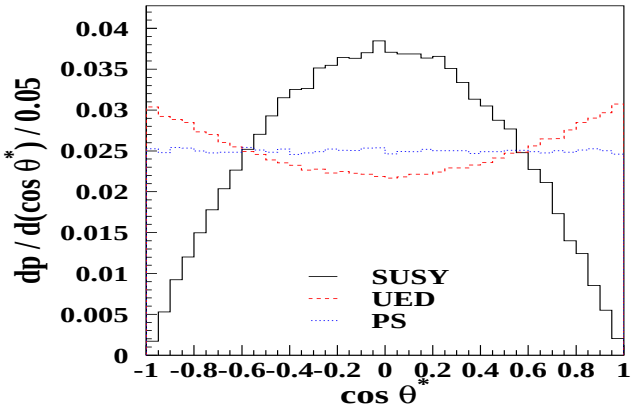
And, sometimes the Single Way to Distinguish

One Very Specific LHC Inverse Problem

So Knowing the Spin is Crucial

- **Angular Distribution for a $2 \to 2$ Scattering Cross Section is a Powerful Discriminator (in the CM frame)**

Datta, Kong, Matchev



$$\left(\frac{d\sigma}{d\cos\theta^*}\right)_{\text{SUSY, scalar}} \propto 1 - \cos^2\theta^*$$

$$\left(\frac{d\sigma}{d\cos\theta^*}\right)_{\text{UED, fermion}} \propto 1 + \cos^2\theta^*$$

So Knowing the Spin Is Crucial

- **At the LHC**

  — **The Laboratory Frame is not the CM frame, in general**

  — **Spin analysis needs Boost-Back to the CM frame**

  — **At the LHC, Boost is along the Beam Pipe**

  — **No Control over the Parton Momenta in the beam**

  — **So, Boost in each event is Undetermined**

Knowing Spin at the LHC : A Difficult Proposition

Find *Boost-Independent Variables Sensitive to Spins*

Shows Moderate Promise: Thrust Area of Research

Indirect Hint of Spin

Total Cross Section may give an initial hint

$*$ *However, only possible if Masses are apriori measured*

(at least, crudely)

Caveat: **Mass measurement may employ Transverse Observables**

(like the so-called Effective Mass: $E_T^{miss} + \sum_{jet} p_{T\,jet}$)

Not much sensitive to absolute mass

Rather depends on $\Delta m = m_{decaying} - m_{LSP}$

Mass Measurements

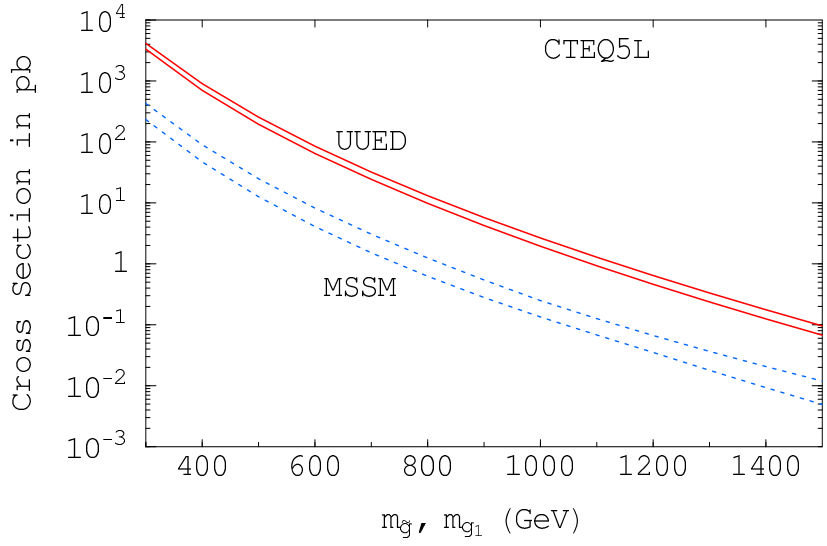
Another Extremely Active Area in LHC Studies

An issue since most New Physics scnearios predict large Missing Energy in events (carried by the DM candidate produced in a pair)

Full Reconstruction of Momenta (and hence masses) is a Nontrivial job

No Consensus over a Generic Technique at this point of time

Spin info. from cross section



$$pp \to \tilde{g}\tilde{g}/g_1 g_1$$

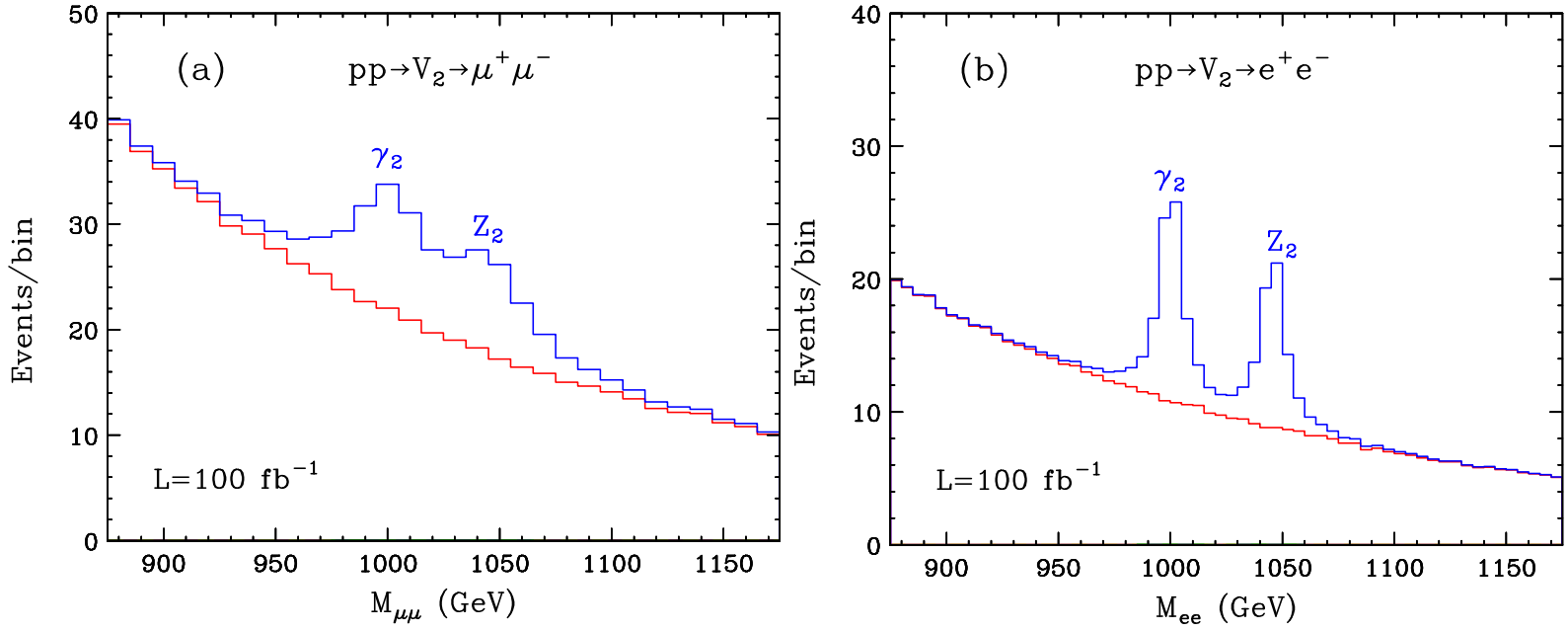
Mass Scale of New Physics: $M_{eff} = E_T^{miss} + \sum_{jet} p_{T\,jet}$

Peaks at $2M_{new}$ $(M_{new} \approx min(m_g^*, m_q^*))$

UED has a larger cross section for a given mass

Level-2 DiResonances in UED

AD, Kong, Matchev



$$R^{-1} = 500 \text{ GeV}$$

Higgs Sectors of the MSSM & UED

Even the Higgs Sectors Look Very Similar!!

2 CP-even Neutral, 1 CP-odd Neutral and 2 Charged States

- **A Subtle Difference:**

MSSM Higgs Bosons: **Origin in Two Higgs Doublets**: **R-parity Even**

UED Higgs Bosons: **Origin in Orbifold Compactification**

Level '0' Higgs boson (the SM Higgs boson) is KK-parity Even

Excited Higgs bosons (from the first KK-level) are KK-odd

Higgs Sectors of the MSSM & UED

- **An Excited UED Higgs boson is to be produced with another KK-odd UED excitation**: **Resonant Higgs Production Disallowed**
- $M_{n=1} \sim R^{-1} \gtrsim 500$ **GeV**: **Phase space suppression is an issue**
- **Direct Production of Excited Higgs is Electroweak in nature**

  Very Low Rates
- **UED-Cascades seem to be one (if not only) viable source**

  Bhattacherjee, Bandyopadhyay and AD
  arxiv:0909.3108 (hep-ph)
- **Lone Higgs Scenario**: **One sees MSSM-like excitations**

  + ONLY the lightest Higgs boson

SUSY Vs Little Higgs (LH) Scenario

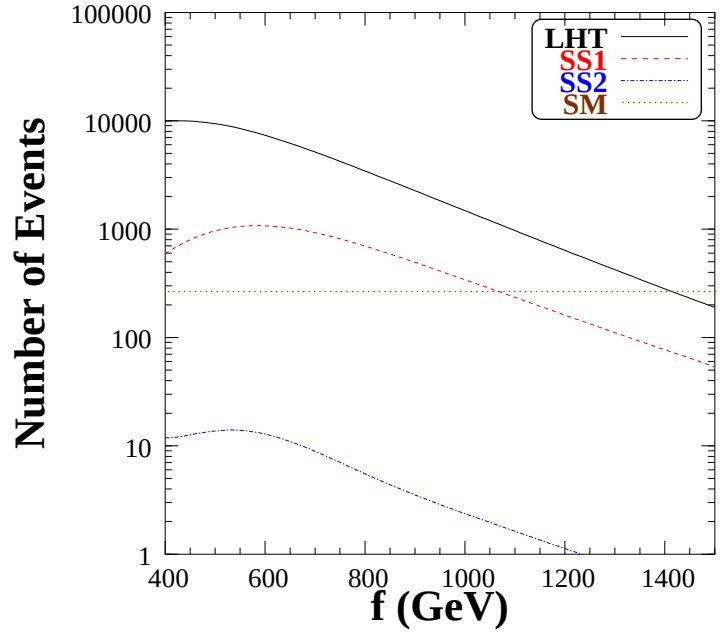
- **Global $SU(5) \to SO(5)$ via SSB at scale $f \sim 1$ TeV $\to$ Masses**
  - **Discrete T-parity invoked**
  - **T-odd Heavy Gauge Bosons $W_H^{\pm}, Z_H, A_H$ acquire masses $\sim f$**
  - **T-odd Heavy Leptons/Quarks q_H, l_H acquire masses $\sim \kappa_f f$**

- **Two major differences**
  - **New excitations in SUSY and LHT have different Spins**
  - **No counterpart of Gluino of SUSY in LH**

- **Rather Heavy Gluino $\longrightarrow$ "SUSY-LH" confusion Near-complete**

SUSY Vs LHT

- **Hadronically Quiet Trileptons as Discriminators**
  - $\mathbf{pp \to Z_H W_H^{\pm}/\chi_2^0 \chi_1^{\pm}} \quad : \quad \mathbf{Z_H/\chi_2^0 \to \ell^* \ell A_H/\chi_1^0}$
  - **Discrimination possible with some knowledge about the mass spectrum** **Best usable when** $\ell^* < \mathbf{W_H, Z_H/\chi_2^0 \chi_1^{\pm}}$



Dilemma - II

If It Doesn't Quack Like SUSY

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Then It Is Probably Not SUSY.

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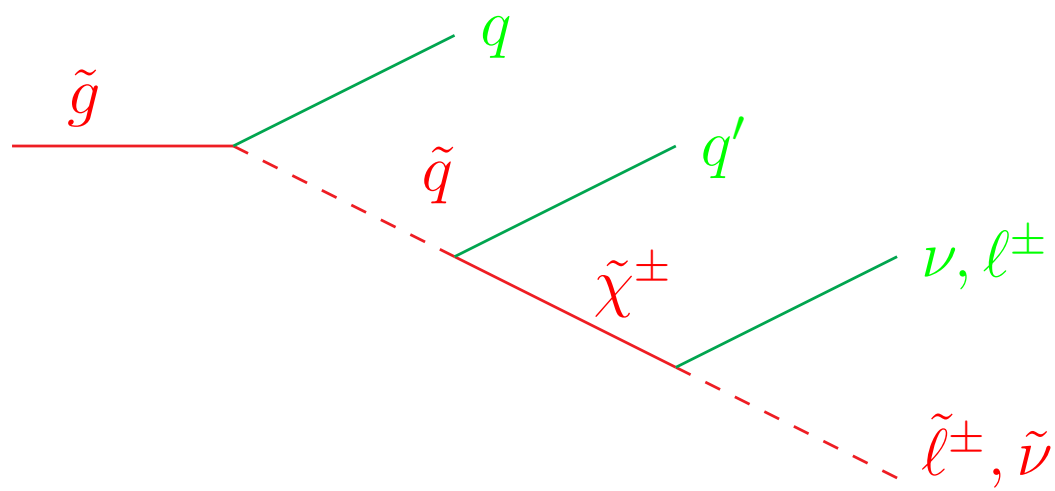
Or Is It ?!

SUSY and Same-Sign Dilepton (SSD

- **Known to be a characteristic final state**



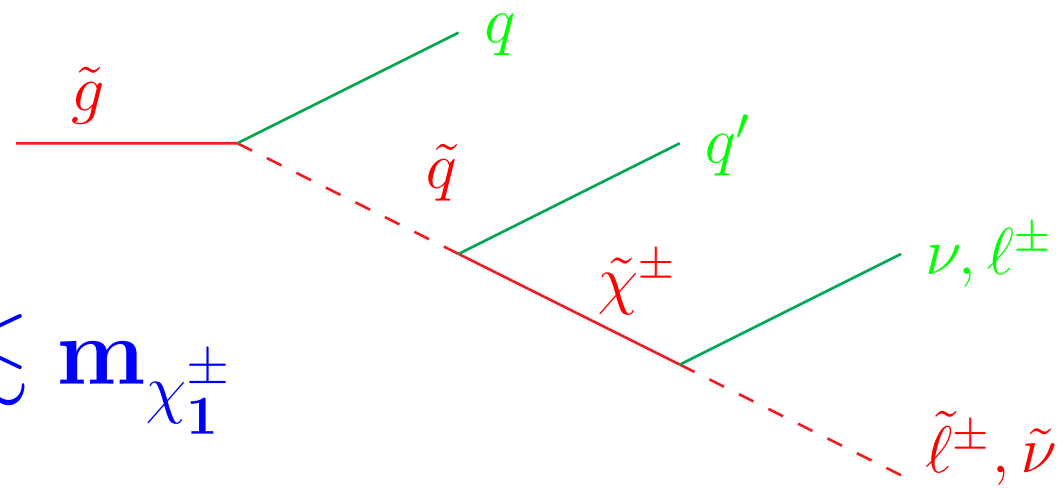
- **Equal counts for (++) and ($-$ $-$) pairs**
- **Tiny Background, Quick Analysis**

But How Robust ?

SUSY and Depleted SSD

Spectrum-induced

AD, Kane, Toharia

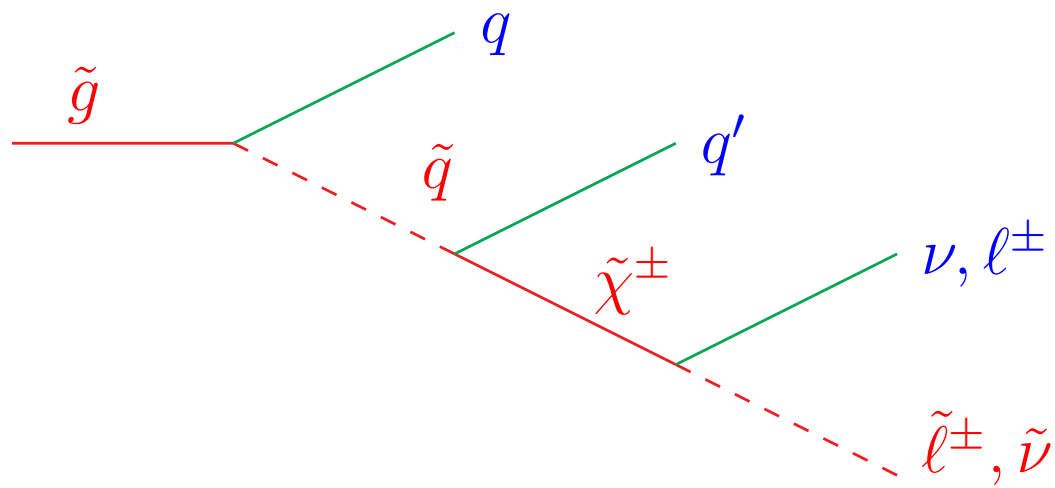


- $\mathbf{m_{\tilde{q}/\tilde{g}} \lesssim m_{\chi_1^{\pm}}}$
- $\mathbf{m_{\tilde{q}_R} < m_{\tilde{g}} < m_{\tilde{q}_L}}$
- $\mathbf{m_{\tilde{t}_1} < m_{\tilde{g}} < m_{\tilde{q}_{L,R}}}$

- **Split SUSY type (Large $\mathbf{m_{\tilde{q}}}$):** $\tilde{\mathrm{g}} \rightarrow \mathrm{g}\chi_1^0$

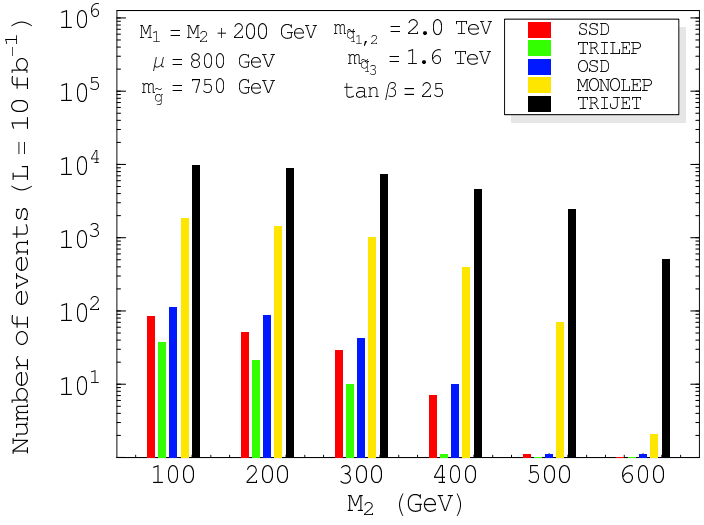
SUSY and Depleted SSD

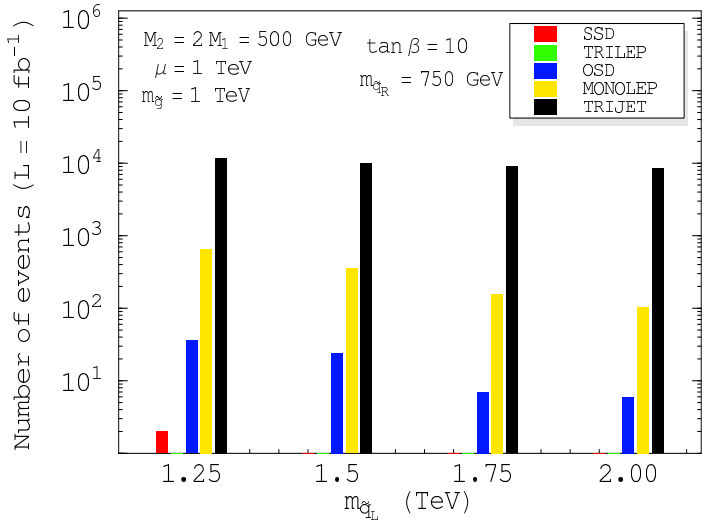
Spectrum + Detector- induced

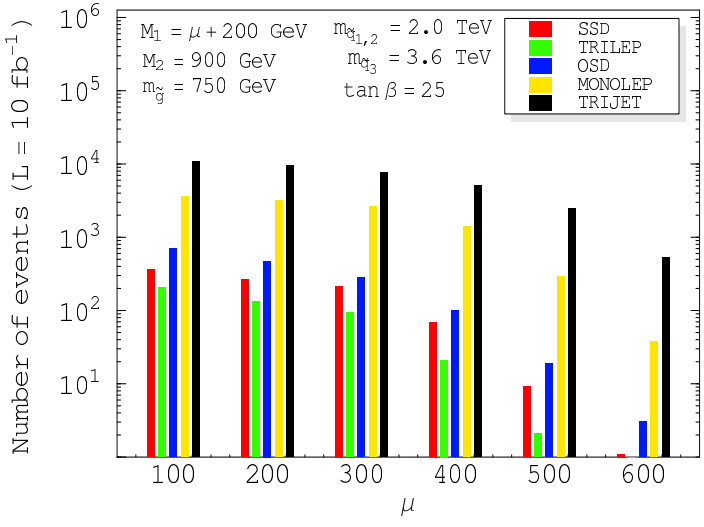


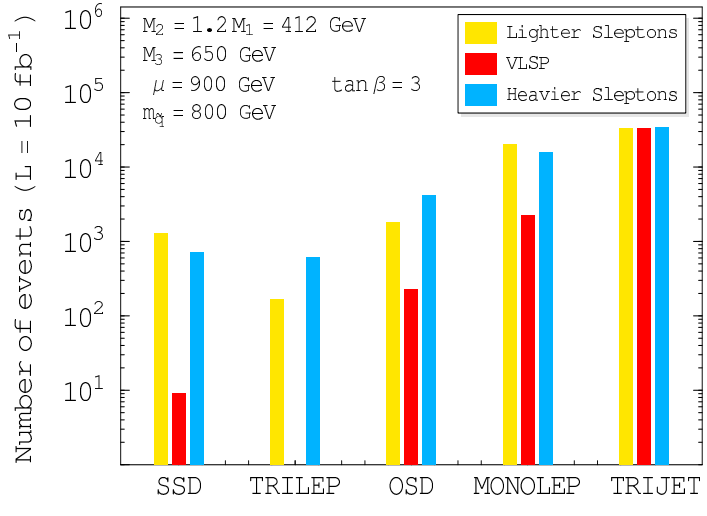
- **AMSB type :** $\mathbf{m}_{\chi_1^\pm} \approx \mathbf{m}_{\chi_1^0} \Rightarrow \chi_1^\pm \rightarrow \chi_1^0\, \nu\, \ell^\pm$ **(soft)**
  $\rightarrow \chi_1^0\, \pi^\pm$ **(soft)**
- **VLSP type :** $\mathbf{m}_{\chi_1^0} < \mathbf{m}_{\tilde{\nu}} \lesssim \mathbf{m}_{\chi_1^\pm} \Rightarrow \chi_1^\pm \rightarrow \tilde{\nu}\, \ell^\pm$ **(soft)**

SUSY and Depleted SSD









Conclusions

- Early Data: New Physics Signatures can be confusing
- Multichannel-information would be crucially important
- Measuring masses with better accuracy could hold the key
- Mass/Spin-measurements: Big strides; need for improved strategies
- Real Data: the Ultimate Guide in chalking out final strategies
- Nevertheless, exploring plausibilities and warming up to face them would go a long way when the time comes