Theory and Phenomenology of Exotic Isosinglet Quarks and Squarks

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Motivations

$\Rightarrow$ Exotic $SU(2)$-singlet quarks appear in many contexts

- $SO(10)$, E_6, $U(1)$-prime models, NMSSM,...
- Extremely common in semi-realistic string constructions
- Can be perfectly consistent with gauge coupling unification

$\Rightarrow$ A rich laboratory for new physics to explore:

- Mixing
- Leptoquarks
- Diquarks
- Quasi-stable

$\Rightarrow$ Good case study for "what-if" scenarios at the LHC...
even within SUSY contexts!

A Framework: E_6-based Models

$\Rightarrow$ Why E_6?

- Logical coherence
- Smallest (non-anomalous) extension of the MSSM capable of producing all the above cases
- Long pedigree among model-builders
- Common in string constructions

$\Rightarrow$ Standard Model gauge group typically extended by additional $U(1)$'s

$$\begin{aligned} E_6 &\rightarrow SO(10) \times U(1)_\psi \\ &\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \\ &\rightarrow SU(3) \times SU(2) \times U(1)_Y \times U(1)_\chi \times U(1)_\psi, \end{aligned}$$

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We will not consider true E_6 GUTs!

- NO additional $SU(2)$ singlets and doublets
- NO Z'-bosons
- NO additional neutralinos
- NO GUT relations amongst Yukawa couplings

Field Content of the Fundamental Representation

$\Rightarrow$ Fundamental $\mathbf{27} \rightarrow \mathbf{16}$ of SO(10) + $\{D,\ D^c\}$, $\left\{H,\ \overline{H}\right\}$ and singlet S

Field	Q_Y	$2\sqrt{6}Q_\psi$	$2\sqrt{10}Q_\chi$	$2\sqrt{15}Q_\eta$
Q_i	1/6	1	-1	2
u_i^c	-2/3	1	-1	2
d_i^c	1/3	1	3	-1
L_i	-1/2	1	3	-1
e_i^c	1	1	-1	2
ν_i^c	0	1	-5	5
$(H_u)_i$	1/2	-2	2	-4
$(H_d)_i$	-1/2	-2	-2	-1
D_i	-1/3	-2	2	-4
D_i^c	1/3	-2	-2	-1
S_i	0	4	0	5

$\Rightarrow$ In principle, as many as two surviving $U(1)$-primes...
In practice, we only consider one combination:

$$Q' = Q_\chi \cos\theta_E + Q_\psi \sin\theta_E; \quad U(1)_\eta \rightarrow \theta_E = 2\pi - \tan^{-1}\sqrt{5/3}$$

Superpotential Interactions

$\Rightarrow$ Gauge invariant superpotential for E_6 is simply $W = \lambda_{ijk}\mathbf{27}_i\mathbf{27}_j\mathbf{27}_k$

- Allowed couplings when broken into SM gauge group

$$\begin{aligned} W &= W_0 + W_{\rm LQ} + W_{\rm DQ} \\ &= \lambda^1_{ij} Q_i u^c_j H_u + \lambda^2_{ij} Q_i d^c_j H_d + \lambda^3_{ij} L_i e^c_j H_d + \lambda^{11}_{ij} L_i \nu^c_j H_u \\ &\quad + \lambda^4 S H_d H_u + \lambda^5_{ij} S D_i D^c_j + W_{\rm LQ} + W_{\rm DQ} \end{aligned}$$

- Couplings of exotics to Standard Model fields

$$W_{\rm LQ} = \lambda^6_{ijk} D_i u^c_j e^c_k + \lambda^7_{ijk} D^c_i Q_j L_k + \lambda^8_{ijk} D_i d^c_j \nu^c_k$$

$$W_{\rm DQ} = \lambda^9_{ijk} Q_i Q_j D_k + \lambda^{10}_{ijk} D^c_i u^c_j d^c_k$$

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$$W_{\rm DQ} = \lambda^9_{ijk} Q_i Q_j D_k + \lambda^{10}_{ijk} D^c_i u^c_j d^c_k$$

$\Rightarrow$ Vacuum expectation value $\langle S \rangle \equiv s$ generates supersymmetric mass terms $\lambda_4 s \equiv \mu_{\rm eff}$ and $\lambda_5 s \equiv M_D$

$\Rightarrow$ If both $W_{\rm LQ}$ *and* $W_{\rm DQ}$ then fast proton decay

- No unambiguous B and L quantum number possible for D, D^c

Masses and Charge Assignments

$\Rightarrow$ Will thus *assume* a conserved B and L and choose $B(D)$ and $L(D)$ values

Leptoquark $B(D) = 1/3$ and $L(D) = 1$; only $W_{\rm LQ}$ allowed

Diquark $B(D) = -2/3$ and $L(D) = 0$; only $W_{\rm DQ}$ allowed

Standard $B(D) = 1/3$ and $L(D) = 0$; both $W_{\rm LQ}$ and $W_{\rm DQ}$ *forbidden*

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$\Rightarrow$ Scalar mass matrices depend on SUSY breaking and $U(1)$-prime charges

$$m^2_{\widetilde{D}} = \begin{pmatrix} m^2_{aa} & m^2_{ab} \\ m^2_{ab} & m^2_{bb} \end{pmatrix}$$

$$\begin{aligned}
m^2_{aa} &= m^2_{\widetilde{D}} + m^2_D + \frac{1}{3}\sin^2\theta_W \cos 2\beta M_Z^2 + g'^{\,2} Q'_D (Q'_S s^2 + Q'_{H_u} v_u^2 + Q'_{H_d} v_d^2) \\
m^2_{bb} &= m^2_{\widetilde{D}^c} + m^2_D - \frac{1}{3}\sin^2\theta_W \cos 2\beta M_Z^2 + g'^{\,2} Q'_{D^c} (Q'_S s^2 + Q'_{H_u} v_u^2 + Q'_{H_d} v_d^2) \\
m^2_{ab} &= m_D \left(A_5 + \mu_{\rm eff} \left(\frac{v_u v_d}{s^2} \right) \right),
\end{aligned}$$

Our Benchmark Cases

Sample spectra for the exotic SUSY sector

Parameter	A	B	C	D	E
$M_{D_{1/2}}$	300	300	300	600	1000
m_{D_0}	400	400	1000	400	400
$m_{D_0^c}$	400	400	1000	400	400
A_5	350	150	100	600	1050
			$U(1)_\eta$ Model		
$M_{D_0^1}$	367	441	1024	388	318
$M_{D_0^2}$	587	553	1053	932	1482

(All values are in GeV at the electroweak scale)

$\Rightarrow$ It is convenient to define the mass splitting measurs

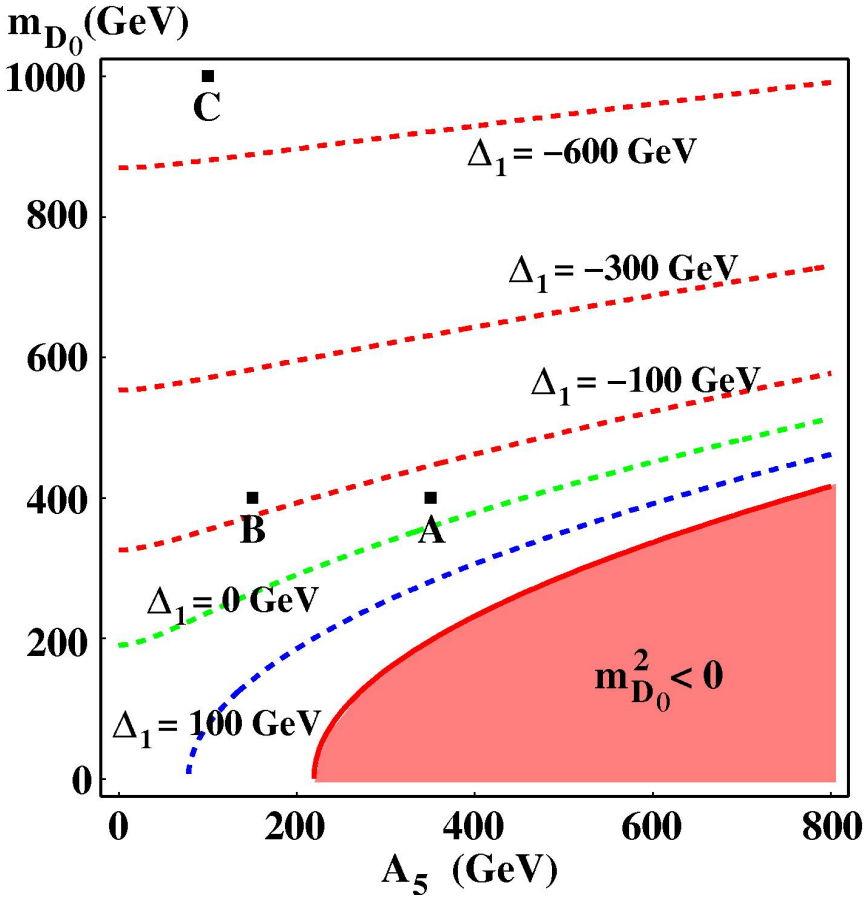
$$\Delta_1 \equiv m_{D_{1/2}} - m_{D_0^1} \; ; \quad \Delta_2 \equiv m_{D_{1/2}} - m_{D_0^2}$$

$\Delta_1 < 0 \rightarrow$ fermion lightest exotic particle (LEP)

Some Sample Patterns for Splitting Δ_1

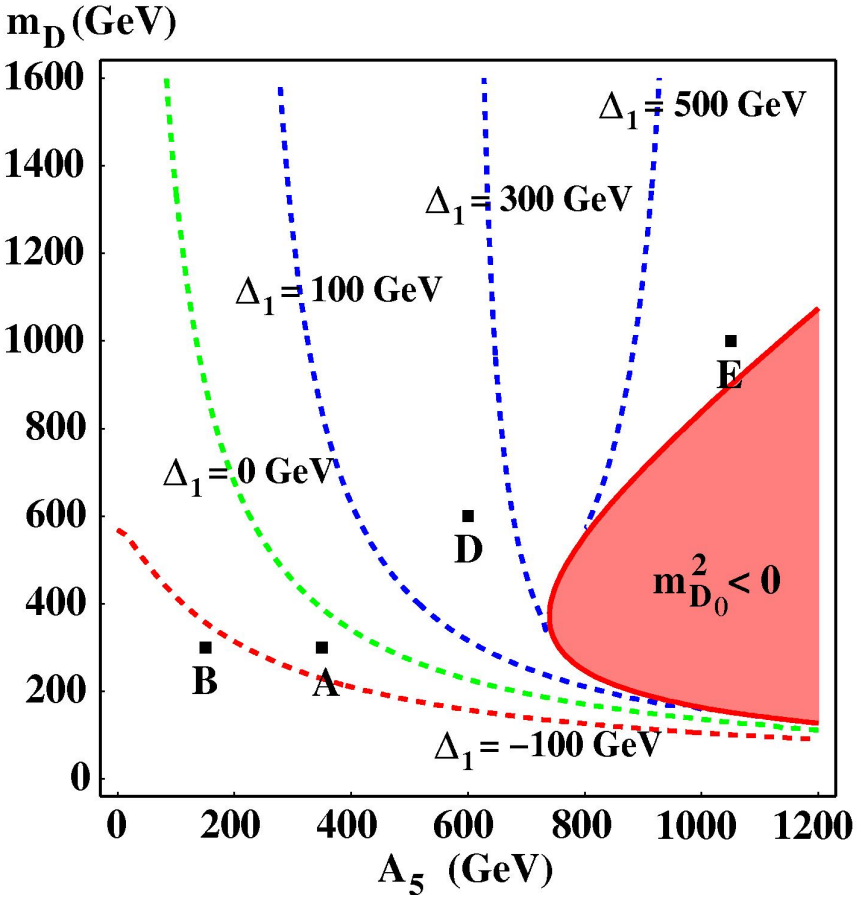
Fixed fermion mass

$M_D = 300$ GeV



Fixed (common) scalar mass

$M_{D_0} = m_{\widetilde{D}} = m_{\widetilde{D}^c} = 400$ GeV



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Future Reference: SPS1A

$\Rightarrow$ For comparison, consider the particle spectrum for Snowmass Point 1A

Parameter	SPS 1A	Parameter	SPS 1A
$m_{\widetilde{N}_1}$	99.9	$m_{\tilde{t}_1}$	381.4
$m_{\widetilde{N}_2}$	188.4	$m_{\tilde{t}_2}$	587.3
$m_{\widetilde{N}_3}$	375.5	$m_{\tilde{c}_1}$, $m_{\tilde{u}_1}$	535.3
$m_{\widetilde{N}_4}$	394.0	$m_{\tilde{c}_2}$, $m_{\tilde{u}_2}$	554.5
$m_{\widetilde{C}_1^\pm}$	187.7	$m_{\tilde{b}_1}$	504.5
$m_{\widetilde{C}_2^\pm}$	394.7	$m_{\tilde{b}_2}$	535.0
$m_{\tilde{g}}$	627.9	$m_{\tilde{s}_1}$, $m_{\tilde{d}_1}$	534.4
B-ino%	97.4%	$m_{\tilde{s}_2}$, $m_{\tilde{d}_2}$	559.3
m_h	111.7	$m_{\tilde{\tau}_1}$	145.5
m_A	412.7	$m_{\tilde{\tau}_2}$	220.6
$m_H^\pm$	420.3	$m_{\tilde{\mu}_1}$, $m_{\tilde{e}_1}$	145.8
μ	369.4	$m_{\tilde{\mu}_2}$, $m_{\tilde{e}_2}$	211.4

$\Rightarrow$ Signatures at the LHC depend on how Δ_i compare to SUSY mass values

Modifying PYTHIA

$\Rightarrow$ The entire exotic sector was added to PYTHIA

- Six new states: $D^{\rm LQ}_{1/2}$, $(D^{\rm LQ}_0)_{1,2}$, $D^{\rm DQ}_{1/2}$, $(D^{\rm DQ}_0)_{1,2}$
- SUSY and non-SUSY decay modes for each state (more later)
- New production processes:
  - $q + \bar{q} \to D^{\rm LQ}_{1/2} + \overline{D^{\rm LQ}_{1/2}}$, $D^{\rm DQ}_{1/2} + \overline{D^{\rm DQ}_{1/2}}$
  - $g + g \to D^{\rm LQ}_{1/2} + \overline{D^{\rm LQ}_{1/2}}$, $D^{\rm DQ}_{1/2} + \overline{D^{\rm DQ}_{1/2}}$
  - $q + \bar{q} \to (D^{\rm LQ}_0)_i + (\overline{D^{\rm LQ}_0})_j$, $(D^{\rm DQ}_0)_i + (\overline{D^{\rm DQ}_0})_j$
  - $g + g \to (D^{\rm LQ}_0)_i + (\overline{D^{\rm LQ}_0})_j$, $(D^{\rm DQ}_0)_i + (\overline{D^{\rm DQ}_0})_j$
  - $q + g \to (D^{\rm LQ}_0)_i + e^-$ or ν_e
  - $\bar{q} + g \to (D^{\rm DQ}_0)_i + \bar{q}$
  - $\bar{u} + \bar{d} \to (D^{\rm DQ}_0)_i$ (resonant production)

$\Rightarrow$ New color flow algorithms for diquark interactions....

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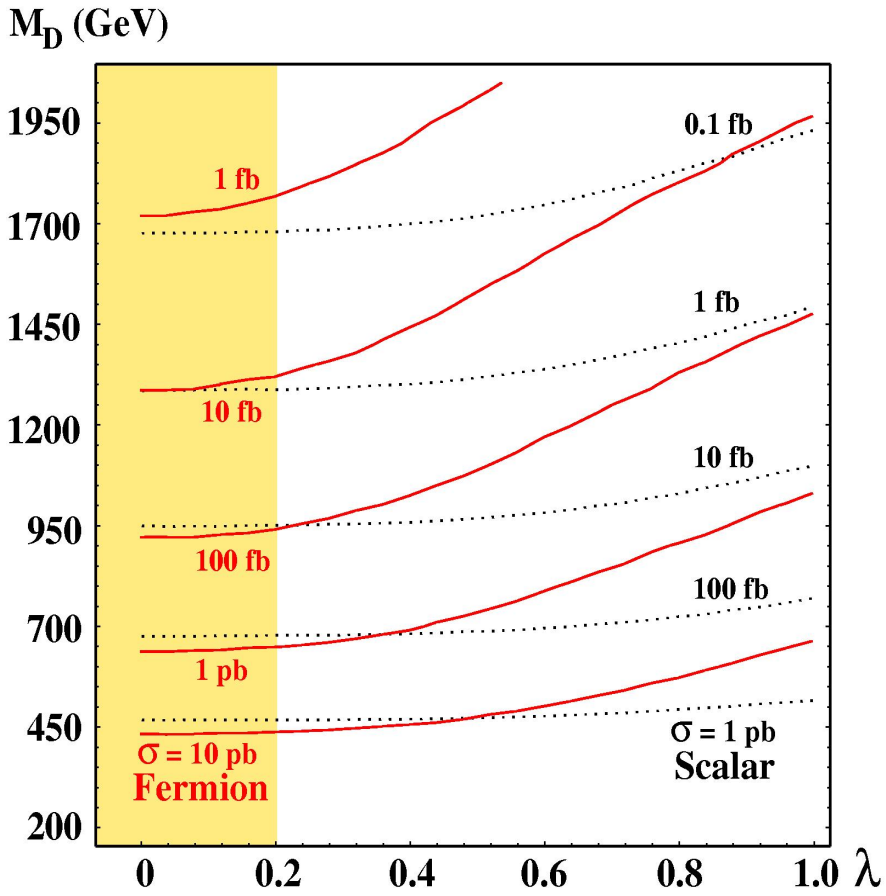
$\Rightarrow$ New color flow algorithms for diquark interactions....ACK!!

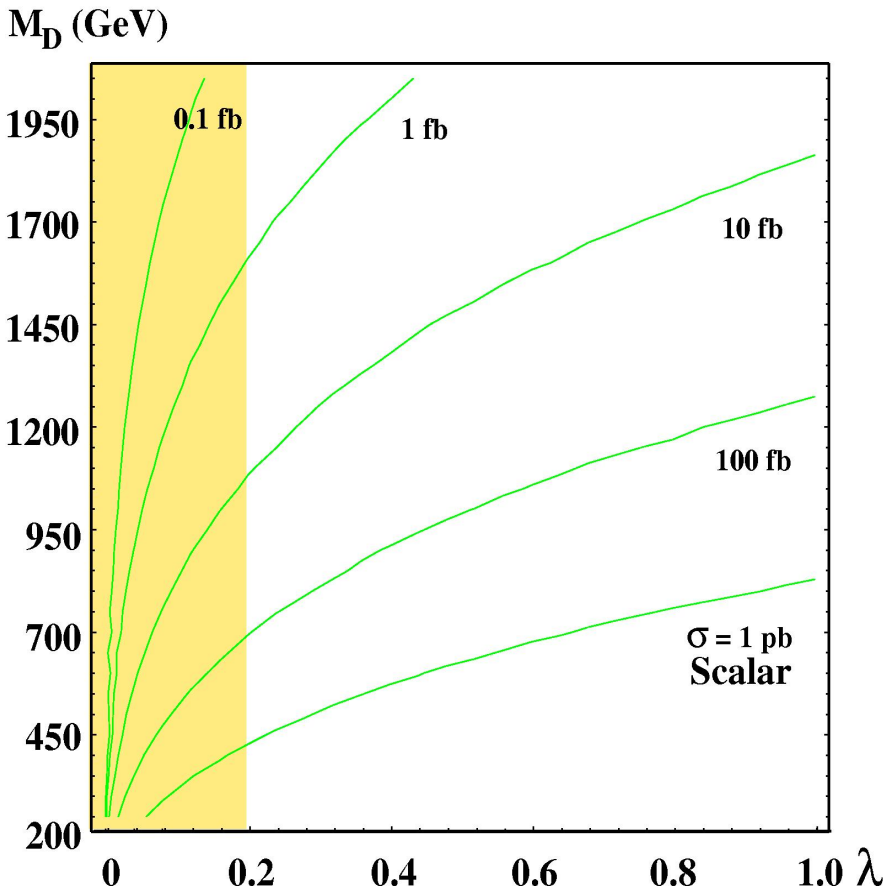
$$W_{\rm DQ} = \lambda^9_{ijk} Q_i Q_j D_k + \lambda^{10}_{ijk} D^c_i u^c_j d^c_k$$

Leptoquark Production at the LHC

Pair production

$$q + g \to D_0^{\mathrm{LQ}} + \ell, \nu$$





Events at LHC with $5\,\mathrm{fb}^{-1}$ integrated luminosity

SPS 1a	Case A	Case B	Case C	Case D	Case E
185,544	161,284	156,020	152,342	11,589	17,921

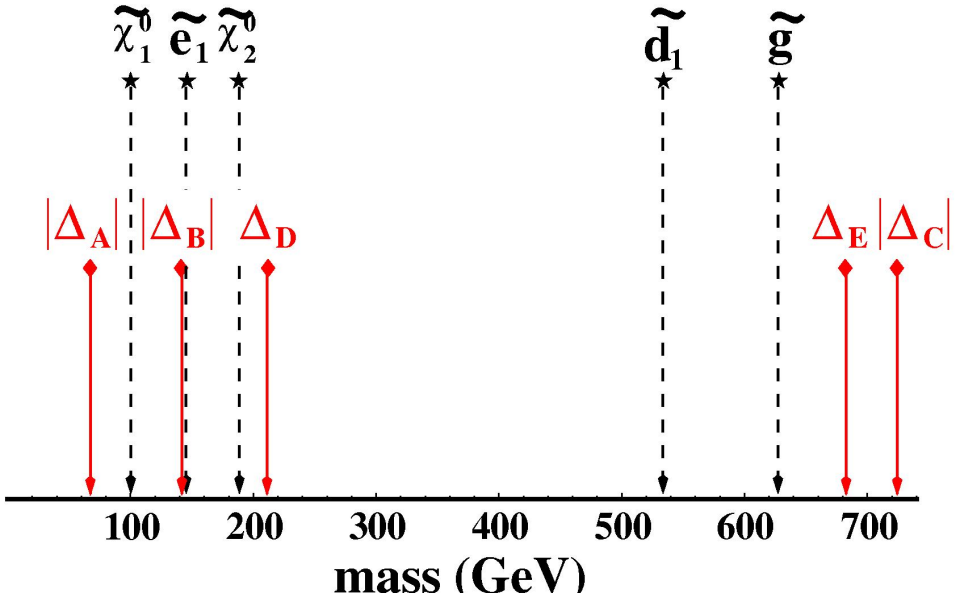
Prompt Decay Final States

	Fermionic LEP						Scalar LEP			
	Case A		Case B		Case C		Case D		Case E	
Decay	$D_{1/2}$	D_0^1	$D_{1/2}$	D_0^1	$D_{1/2}$	D_0^1	$D_{1/2}$	D_0^1	$D_{1/2}$	D_0^1
partner + $\widetilde{\chi}_1^0$				✓		✓	✓		✓	
partner + $\widetilde{\chi}_2^0$						✓	✓		✓	
partner + $\widetilde{\chi}_3^0$						✓			✓	
partner + $\widetilde{\chi}_4^0$						✓			✓	
partner + $\widetilde{g}$						✓			✓	
$\tilde{f} + f'$	$\checkmark_{\rm LQ}$	NA	$\checkmark_{\rm LQ}$	NA	$\checkmark_{\rm LQ}$	NA	✓	NA	✓	NA
$f + f'$	NA	✓	NA	✓	NA	✓	NA	✓	NA	✓
$\widetilde{\chi}_1^0 + f + f'$	$\checkmark_{\rm DQ}$		$\checkmark_{\rm DQ}$		$\checkmark_{\rm DQ}$					

Masses for $U(1)_\eta$ model (GeV)

	$m_{D_{1/2}}$	$m_{D_0^1}$
Case A	300	367
Case B	300	441
Case C	300	1024
Case D	600	388
Case E	1000	318

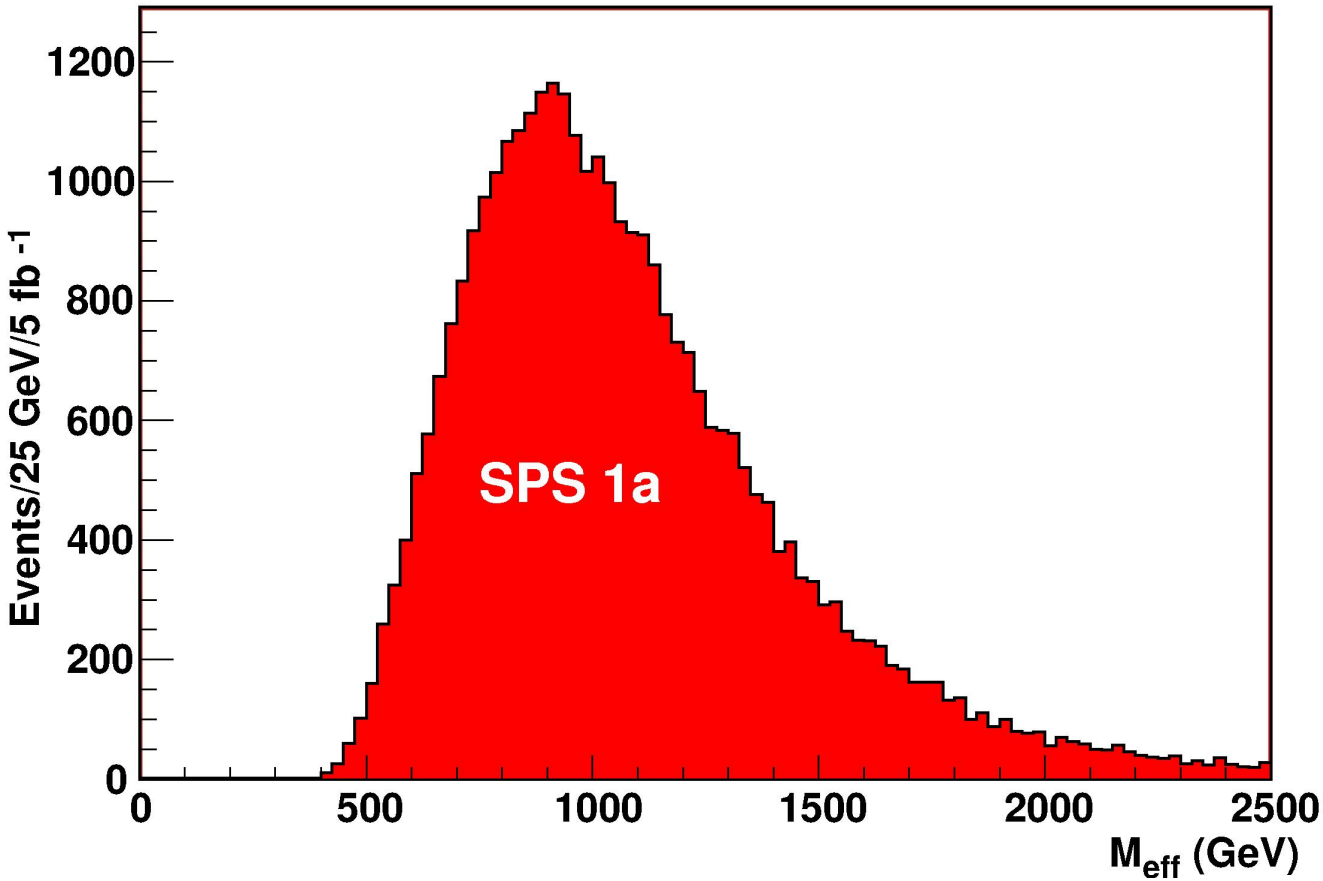
$$\Delta_1 \equiv m_{D_{1/2}} - m_{D_0^1}$$



Discovery of New Physics

- Most inclusive SUSY discovery tool: $M_{\rm eff} = p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + \not{E}_T$

Baer, Chen, Paige, Tata, PRD52 (1995) 2746



- Event selection criteria:
  - ⋆ $N_{\rm jets} \geq 4$, with $p_{T,1}^{\rm jet} \geq 100$ GeV and $p_{T,i}^{\rm jet} \geq 50$ GeV for $i = 2,\ 3,\ 4$
  - ⋆ No isolated leptons with $p_T \geq 20$ GeV
  - ⋆ Transverse sphericity $S \geq 0.2$
  - ⋆ Missing E_T of at least 100 GeV

Hinchliffe et al., PRD55 (1997) 5520

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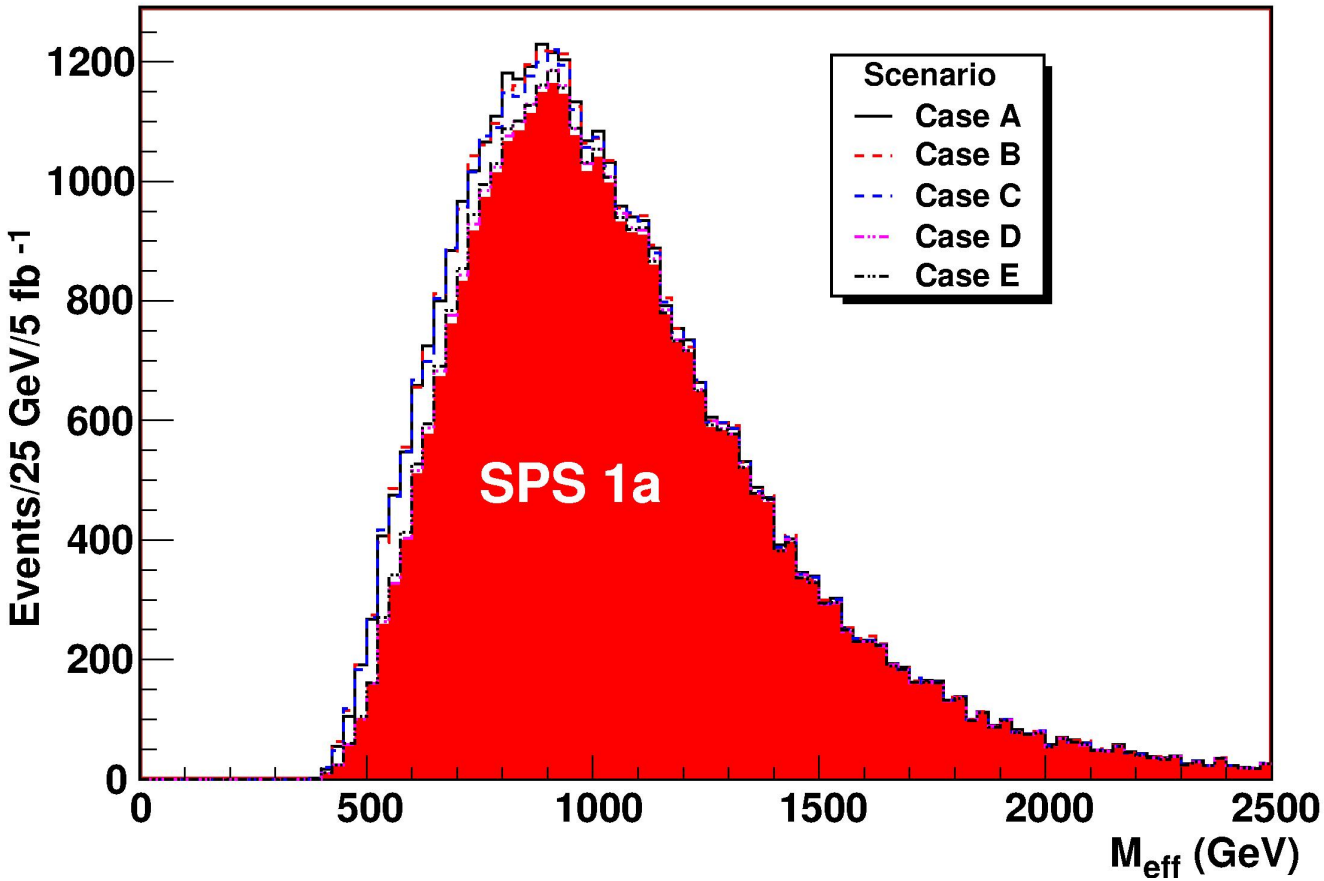

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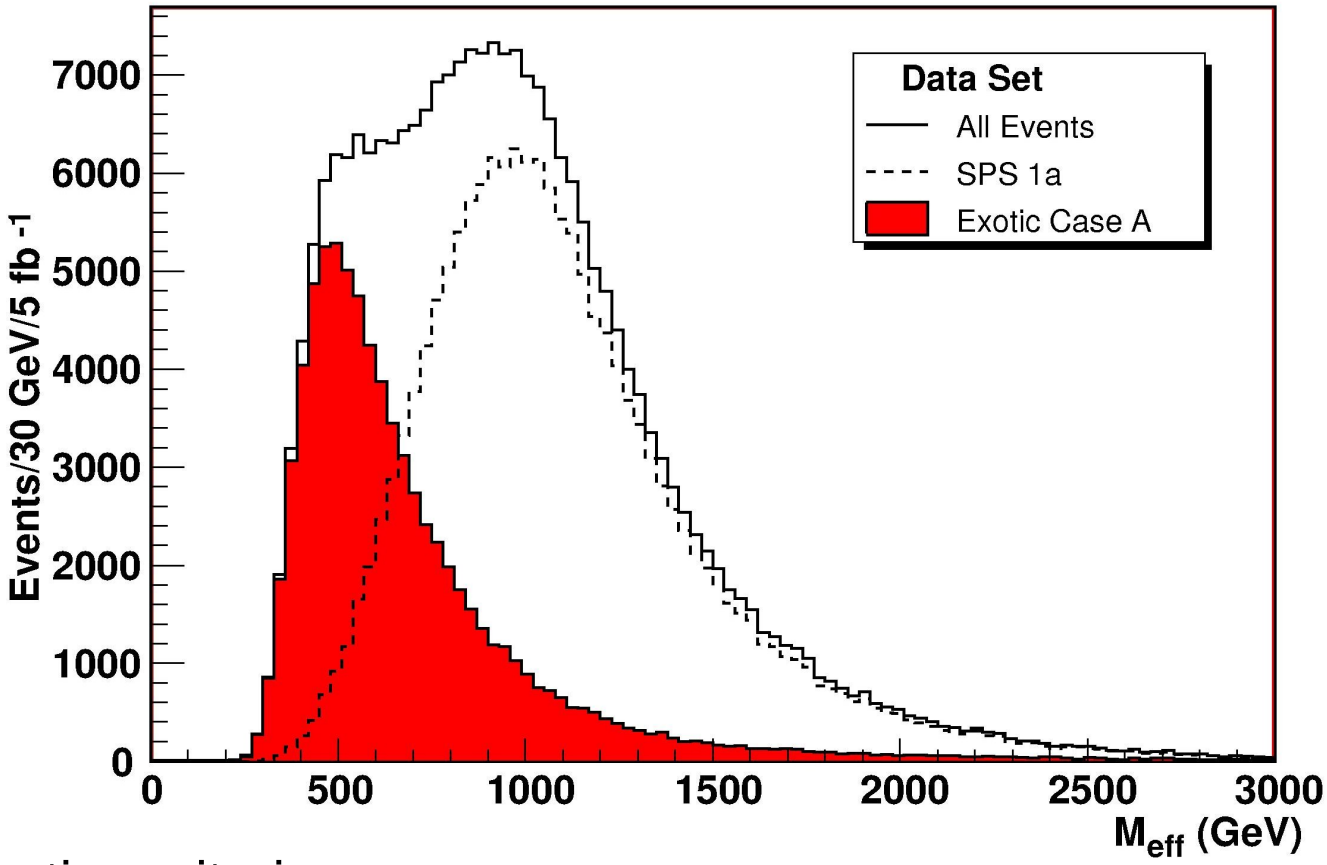
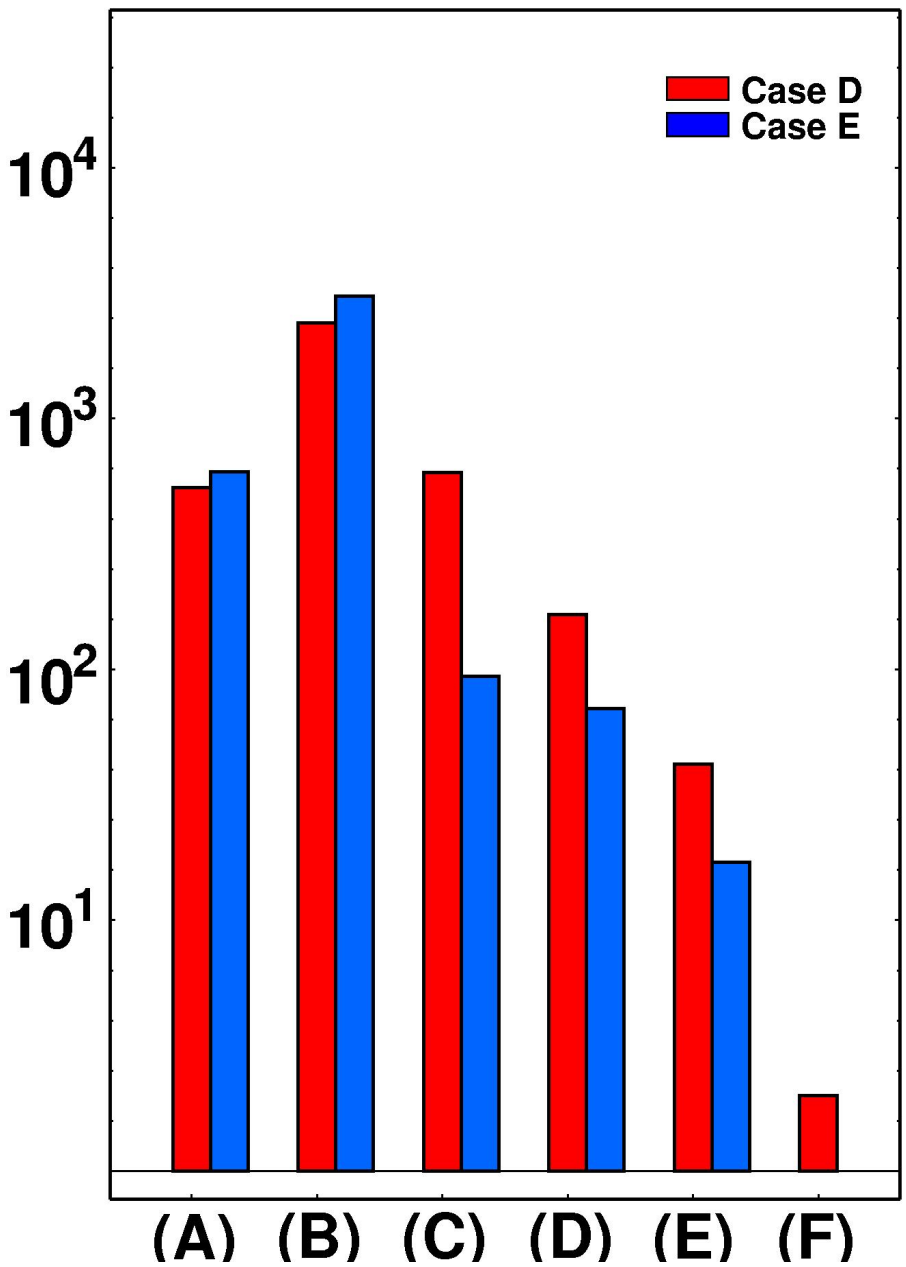
Where are the exotic events?

- Try something *more* inclusive: $M_{\text{eff}} = \sum_i^{\text{all}} p_{T,i} + \not{E}_T$



- Event selection criteria:
  - ⋆ $N_{\text{jets}} \geq 2$, with $p_{T,i}^{\text{jet}} \geq 50$ GeV
  - ⋆ Any number of isolated leptons with $p_T \geq 10$ GeV
  - ⋆ Transverse sphericity $S \geq 0.2$
  - ⋆ Missing E_T of at least 100 GeV

Inclusive Signature Counts: LQ Cases D and E



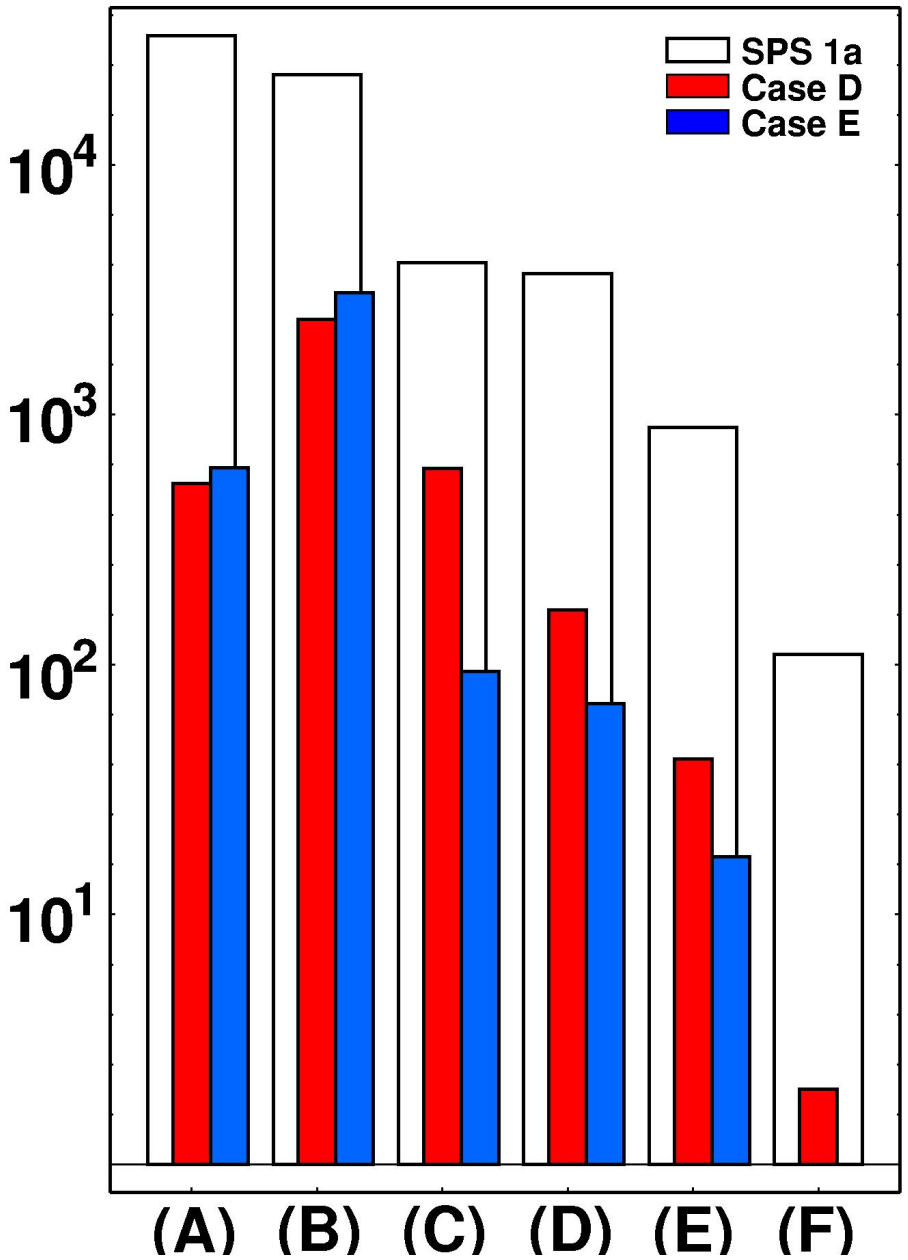
Inclusive signatures
(all have $\not{E}_T \geq 100$ GeV, $S \geq 0.2$)

- (A) Inclusive multijets with $N_{\rm jets} \geq 3$, no isolated leptons, $p_{T,i}^{\rm jet} \geq 100$ GeV for $i = 1, 2, 3$
- (B) One lepton plus jets
- (C) OS dileptons plus jets
- (D) SS dileptons plus jets
- (E) Trileptons plus jets
- (F) Three taus plus jets

Leptons/taus must be isolated with $p_T \geq 20$ GeV

For (B)-(F) we require $N_{\rm jets} \geq 2$, $p_{T,1}^{\rm jet} \geq 100$ GeV, $p_{T,2+}^{\rm jet} \geq 50$ GeV

“The Background to SUSY is More SUSY”



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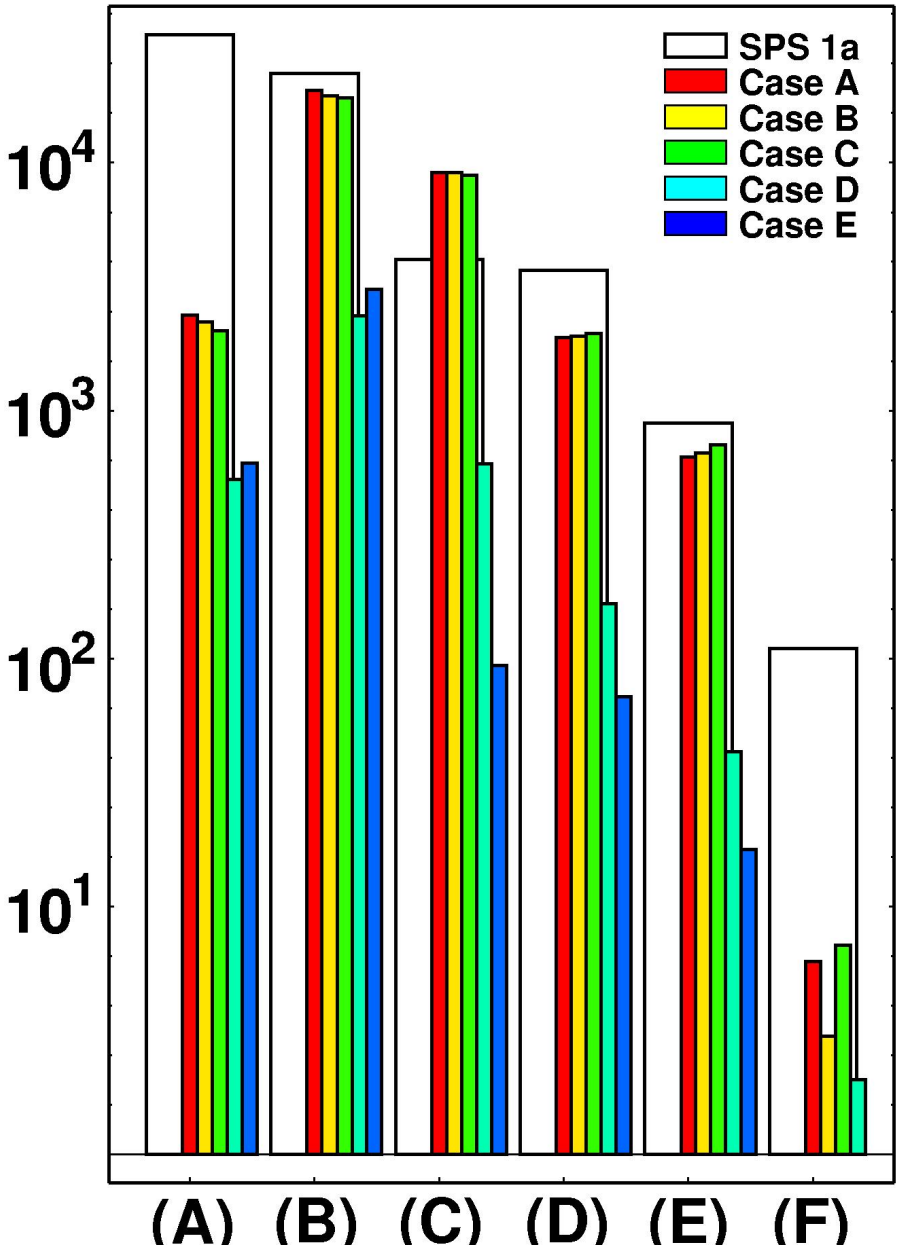
Add Fermionic LEP Cases



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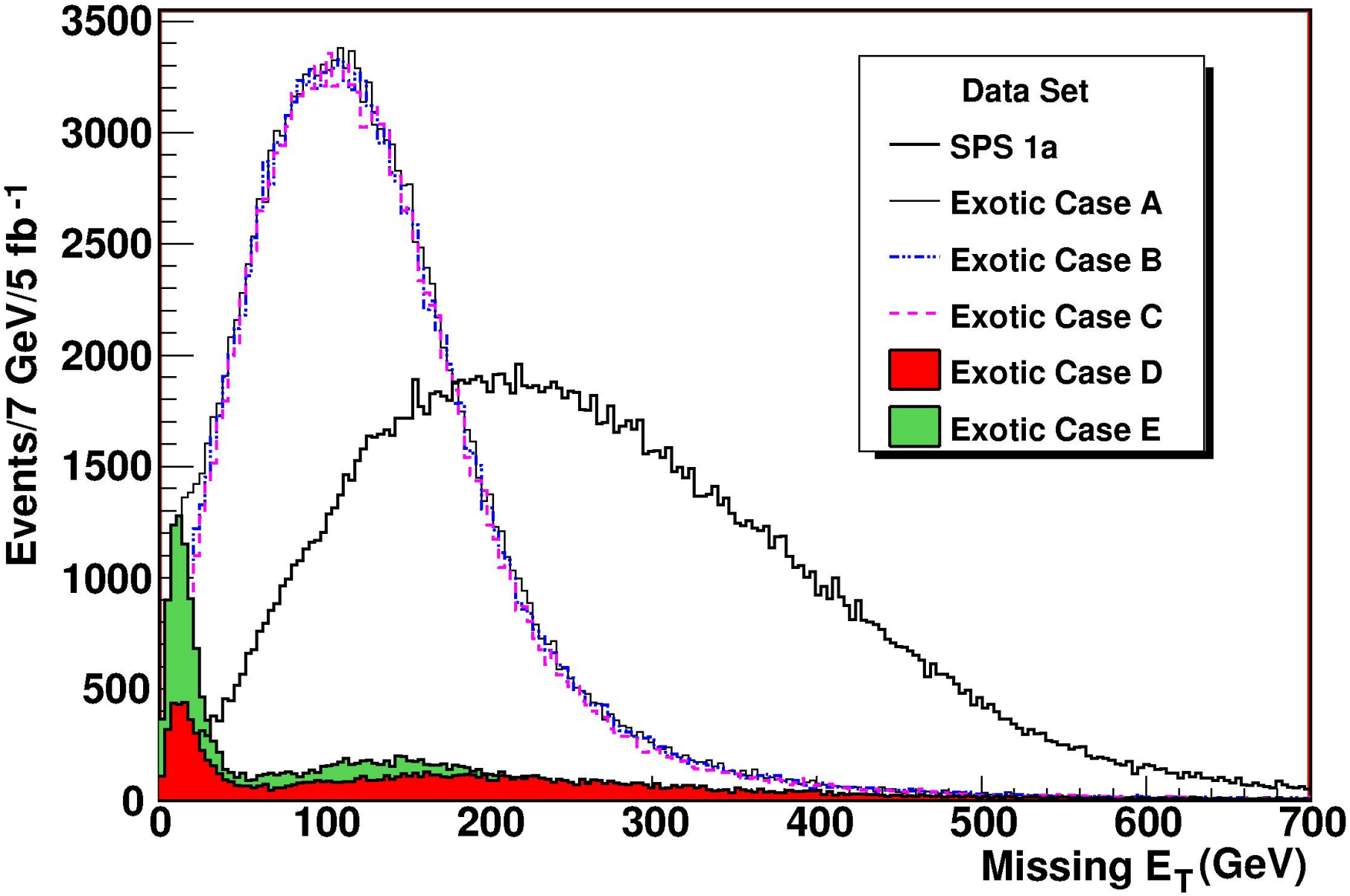
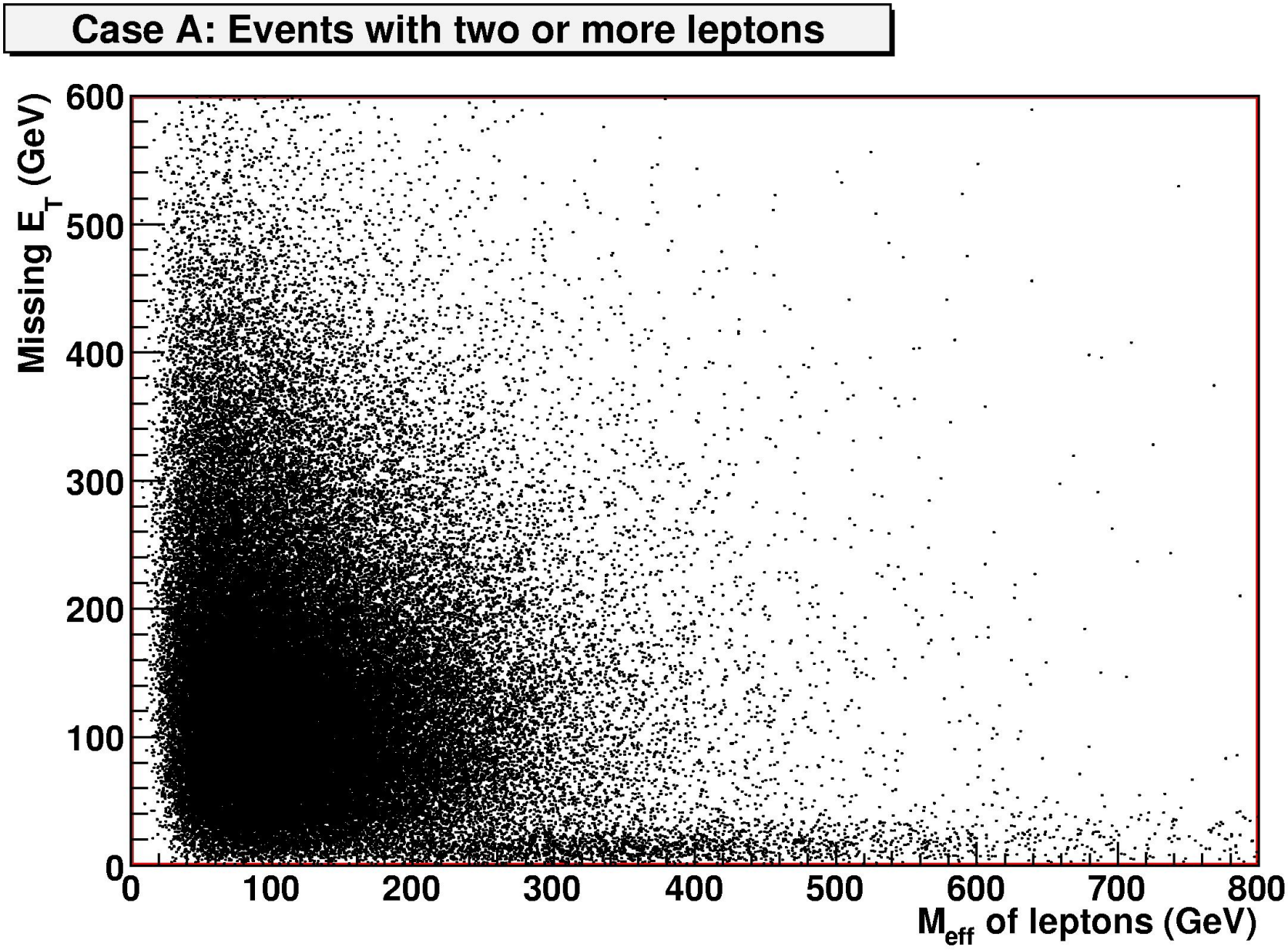
Missing Transverse Energy Distribution



Correlation: Leptonic Effective Mass with $\not{E}_T$



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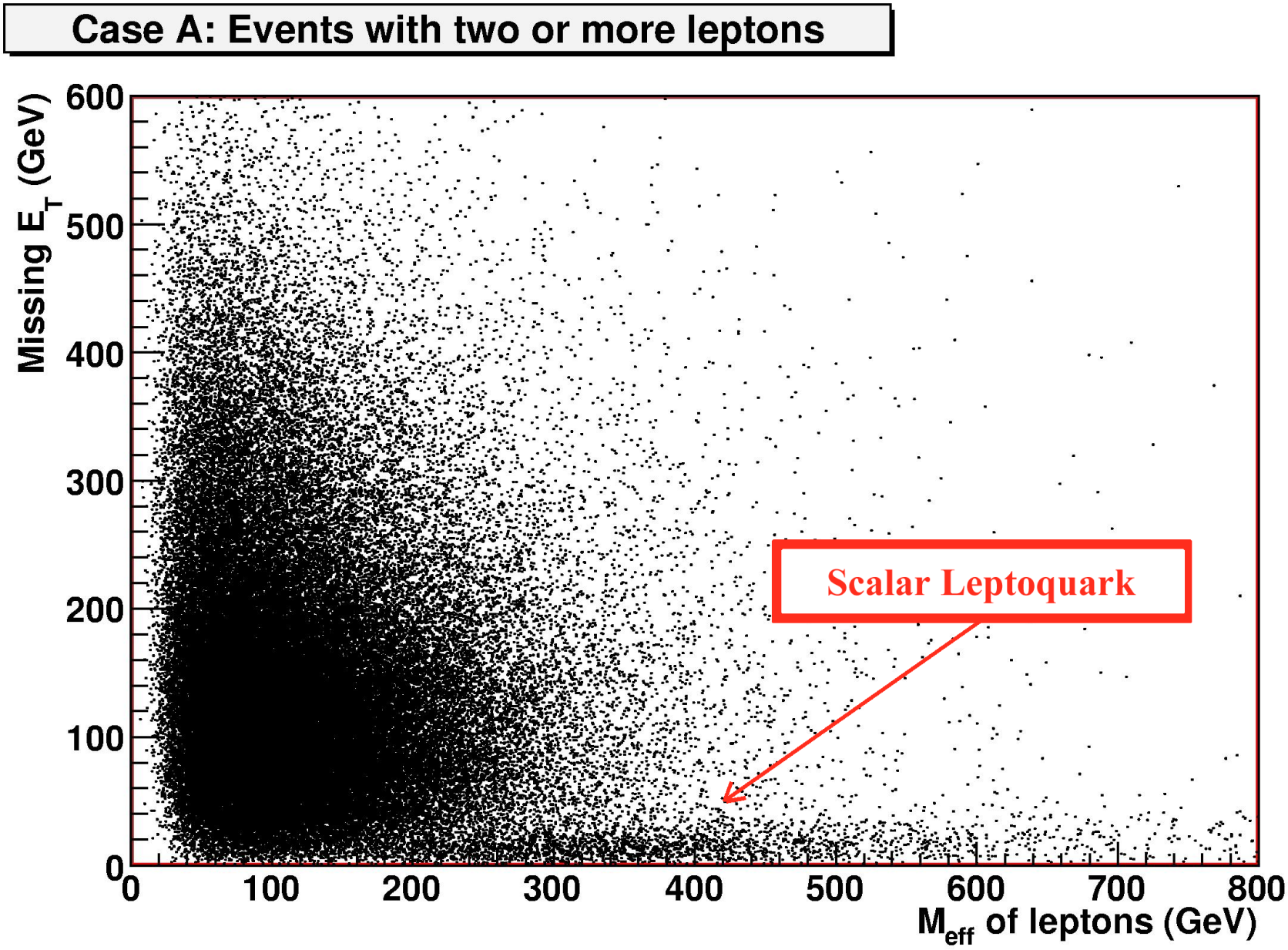
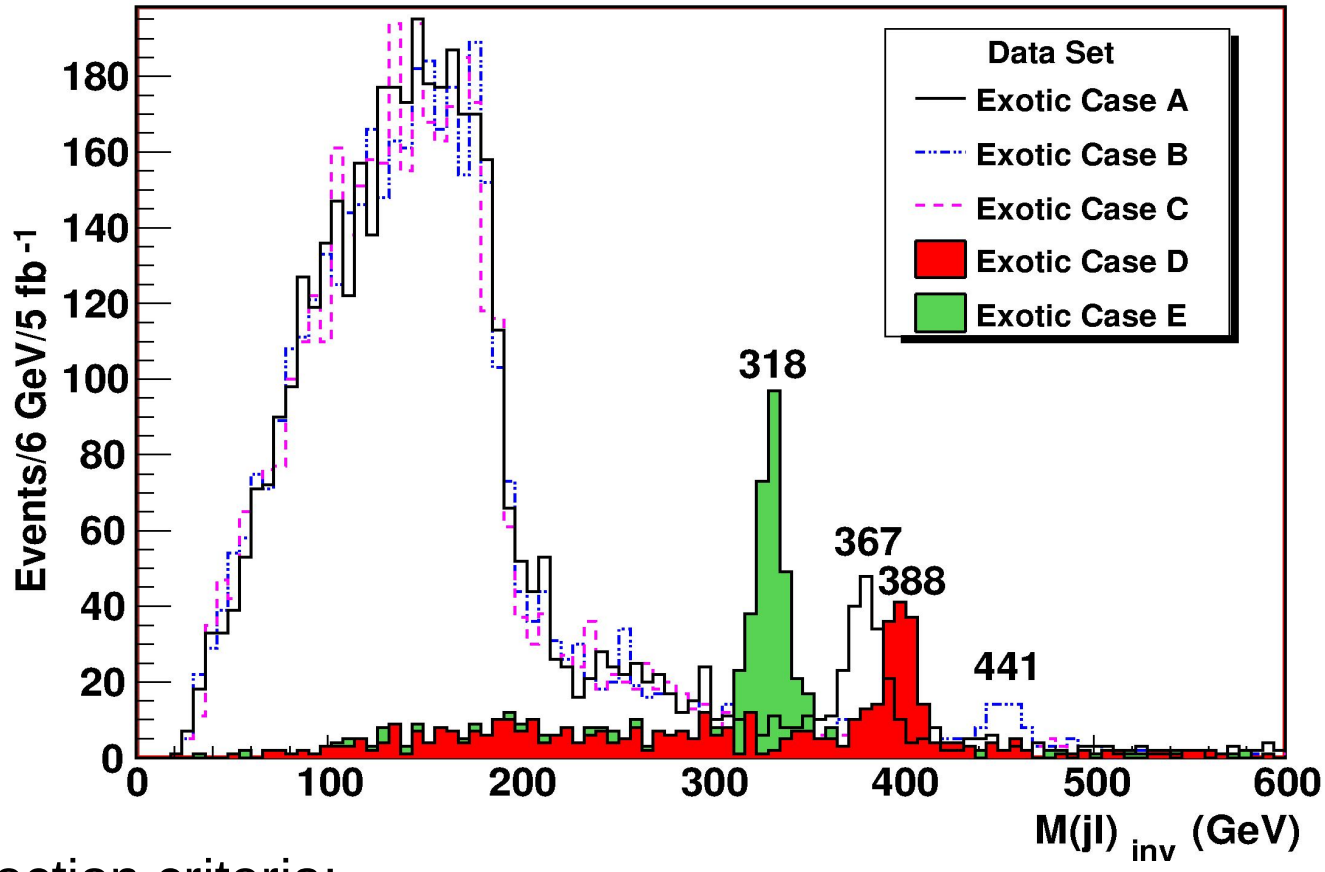


Isolating the Exotic Component

- Form invariant mass of hardest lepton and second hardest jet in the event



- Event selection criteria:
  - ⋆ Precisely two jets and two opposite-sign leptons, no $\not{E}_T$ cut
  - ⋆ Veto B-jets and demand both jets have $p_T \geq 50$ GeV
  - ⋆ Require transverse sphericity $S \leq 0.7$
  - ⋆ Hardest lepton must have $p_T \geq 50$ GeV, trailing lepton must have $p_T \geq 20$ GeV

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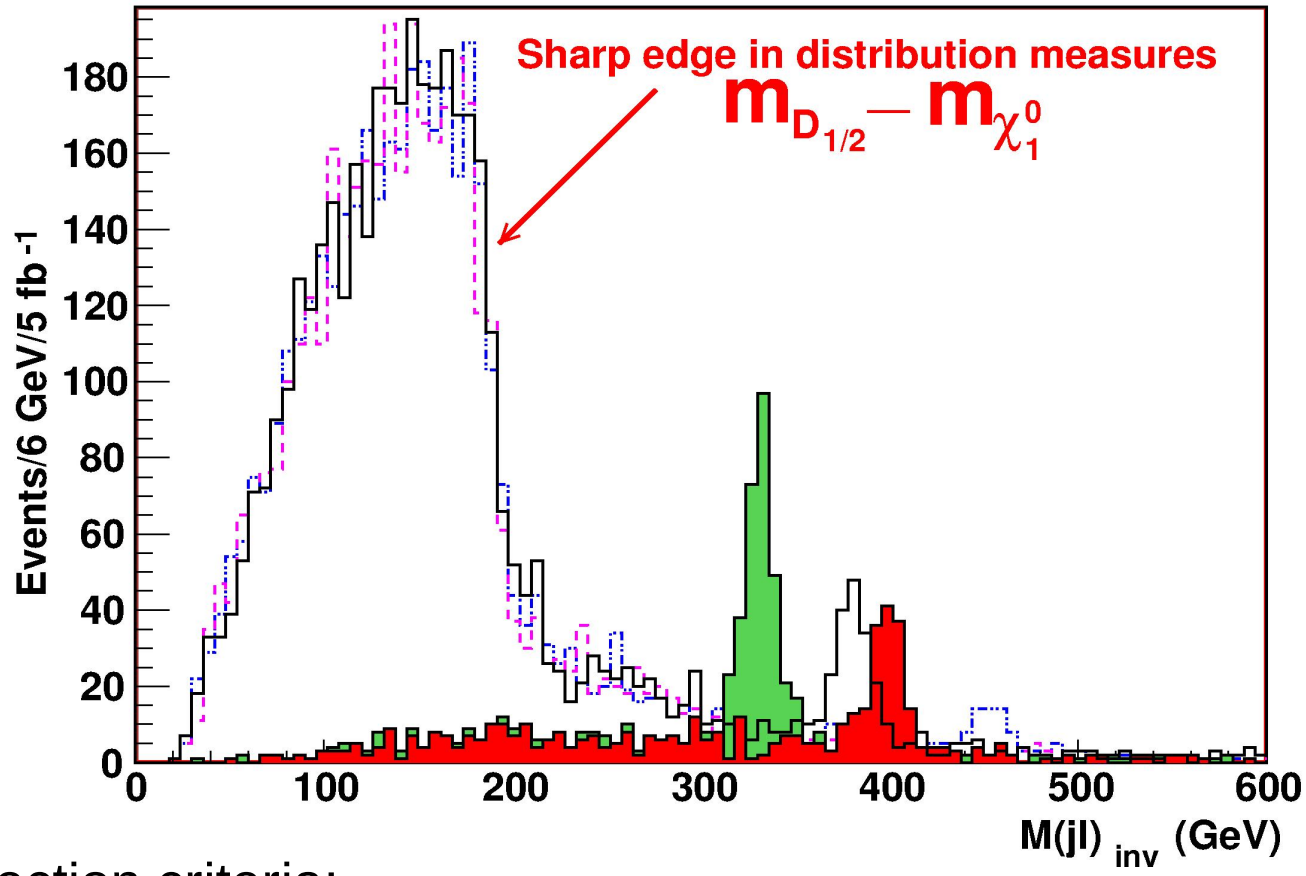
- Form invariant mass of hardest lepton and second hardest jet in the event

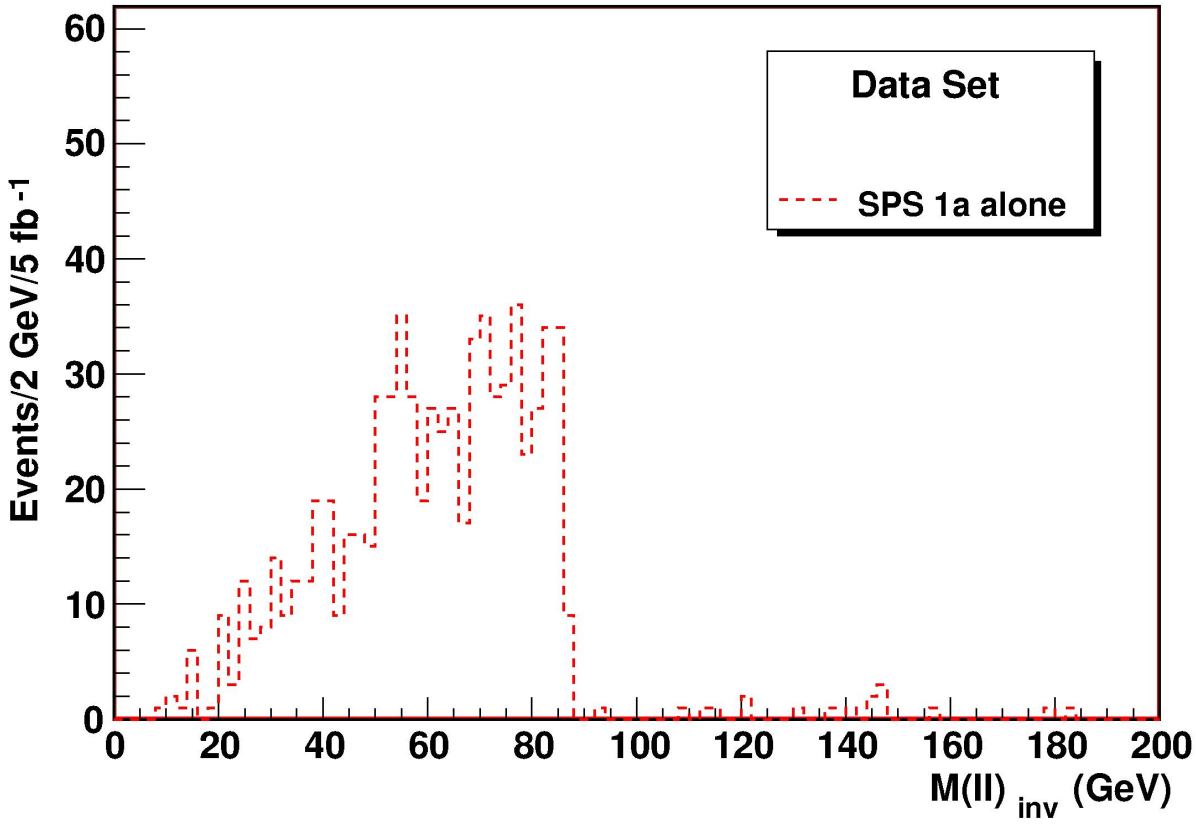


- Event selection criteria:
  - ⋆ Precisely two jets and two opposite-sign leptons, no $\not{E}_T$ cut
  - ⋆ Veto B-jets and demand both jets have $p_T \geq 50$ GeV
  - ⋆ Require transverse sphericity $S \leq 0.7$
  - ⋆ Hardest lepton must have $p_T \geq 50$ GeV, trailing lepton must have $p_T \geq 20$ GeV

Dilepton Invariant Mass Distribution

- Flavor-subtracted invariant mass of dilepton pairs
  $M_{\rm inv}(e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-)$

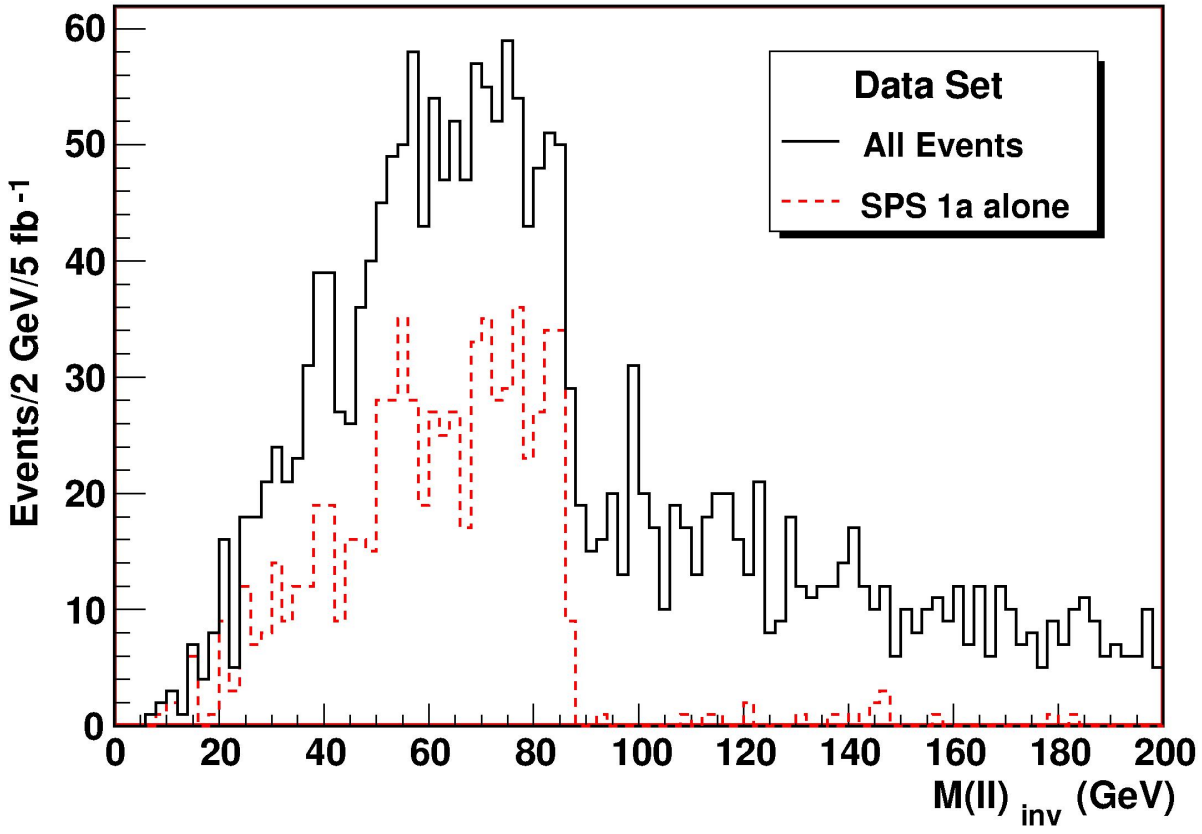
Hinchliffe et al., PRD55 (1997) 5520
Denegri, Majerotto, Rurua, PRD58 (1998) 095010
Nojiri & Yamada, PRD60 (1999) 015006



- Event selection criteria:
  - ⋆ $N_{\rm jets} \geq 4$ with $p_{T,1} \geq 150$ GeV, $p_{T,2} \geq 100$ GeV and $p_{T,3} \geq 50$ GeV
  - ⋆ Precisely two leptons, each having $p_T \geq 15$ GeV
  - ⋆ Missing E_T of at least 150 GeV

Dilepton Invariant Mass Distribution

- Flavor-subtracted invariant mass of dilepton pairs
  $M_{\rm inv}(e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-)$



- "Lowest rung" on SUSY mass reconstruction ladder
- Degradation in kinematic edge measurement $\Rightarrow$ uncertainty in reconstructing $m_{\chi_2^0} - m_{\chi_1^0}$
- All other exclusive measurements/reconstructions hang on this initial measurement!

Gjelsten, Miller, Osland, JHEP **12** (2004) 003

Conclusions and Outlook

⇒ SU(2)-singlet quarks the simplest, well-motivated extension of the MSSM – yet hardly studied at the LHC

⇒ Some “rethinking” of our SUSY-playbook is in order

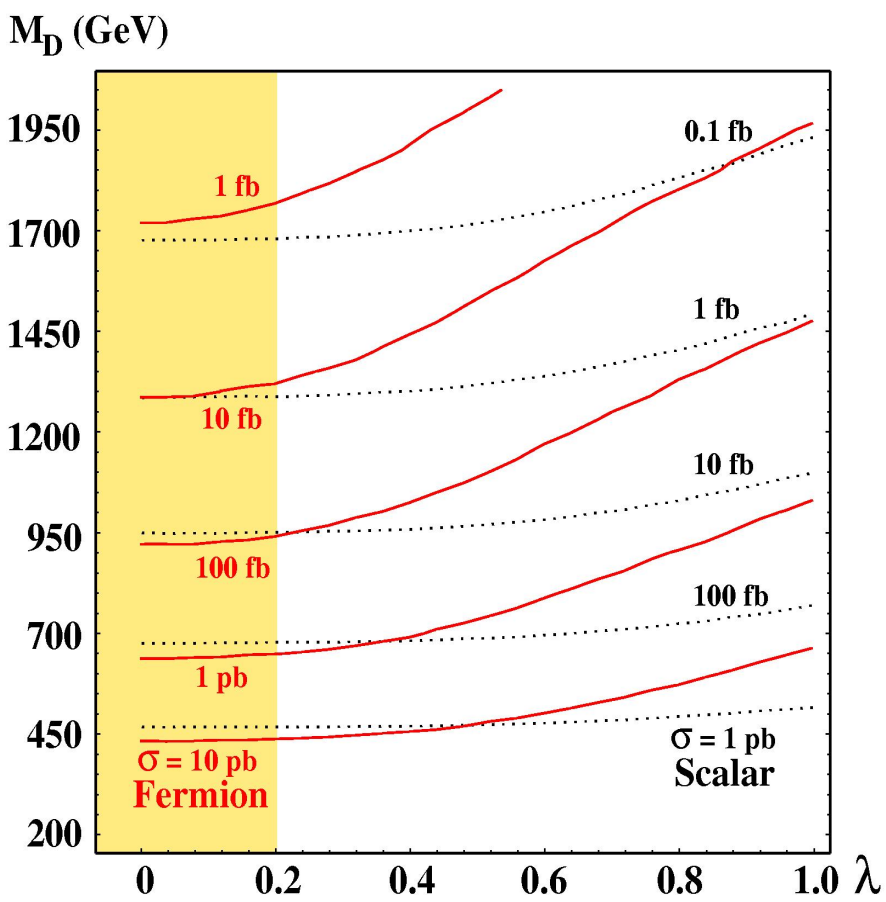
⇒ Future interesting directions:

- Try fitting plain-vanilla MSSM to these inclusive signatures – where (and when) do the fits break down?
- How robust are SUSY extraction & measurement algorithms?
- Need a more sophisticated treatment of diquark cases
- Can we reconstruct the exotic fermion in these cases? Can the associated production mode be observed?

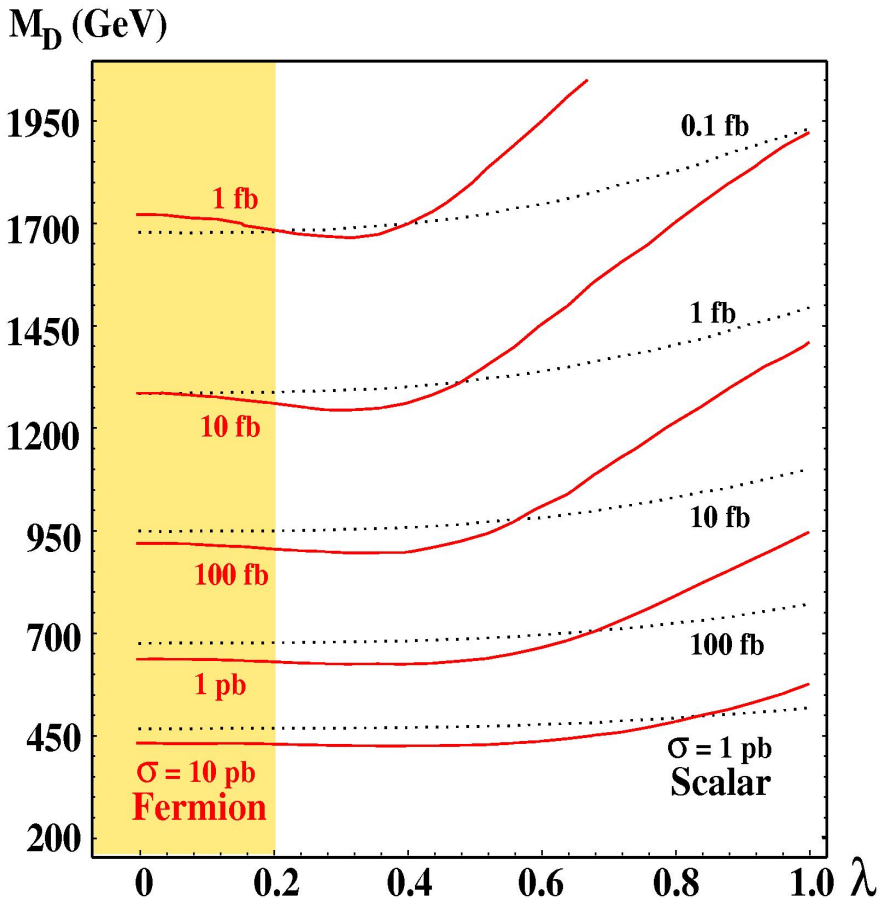
⇒ “What-if” cases like these are good practice for the LHC data era!

Supporting Slides

Pair Production at the LHC

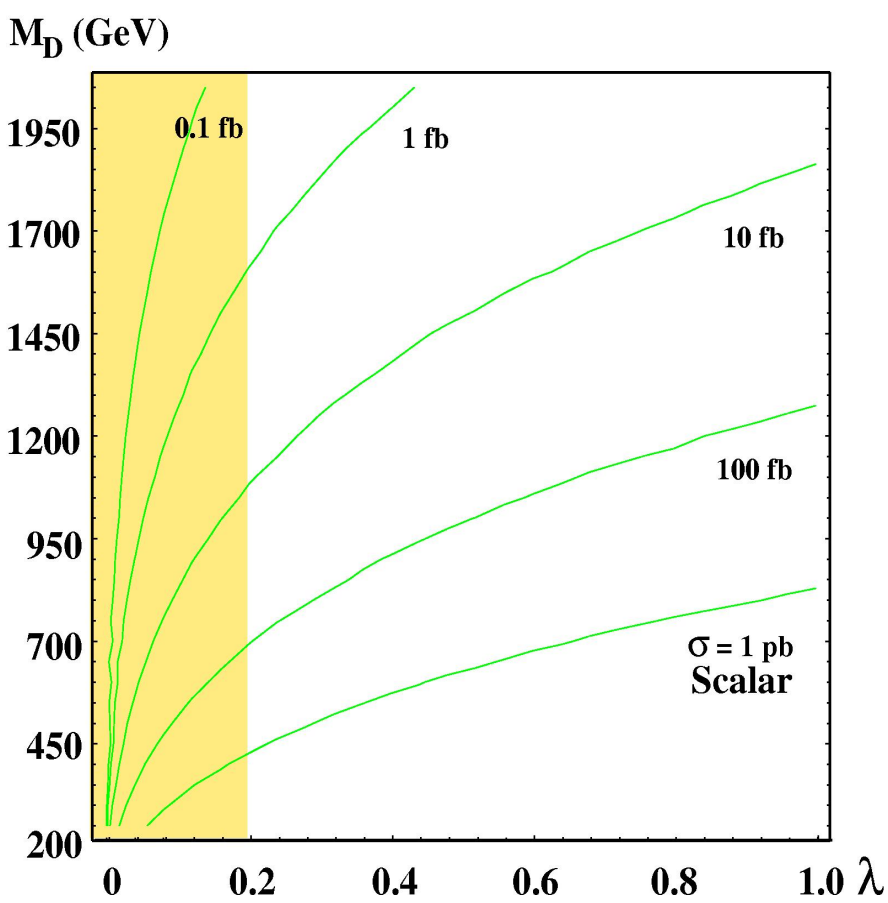


Leptoquark pair production



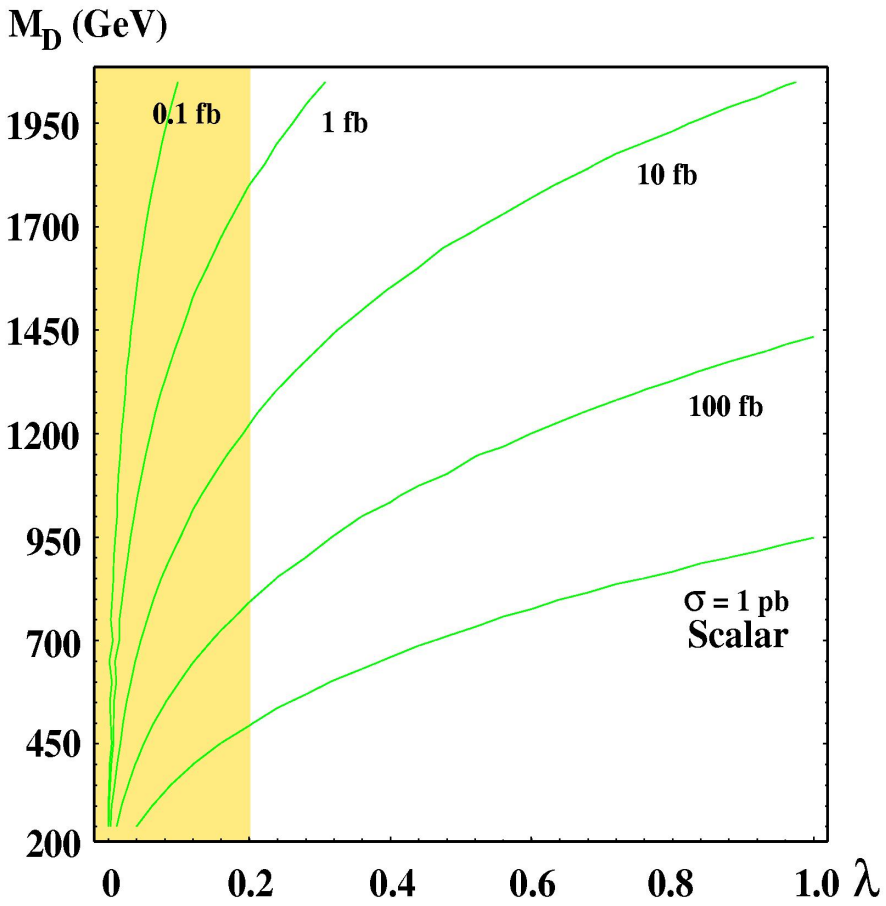
Diquark pair production

Associated Production at the LHC



Leptoquark associated production

$(q + g \rightarrow D_0^{\mathrm{LQ}} + \ell, \nu)$



Diquark associated production

$(\bar{q} + g \rightarrow D_0^{\mathrm{DQ}} + \bar{q})$

Bounds: Direct Searches

Diquarks

- Search for resonant scalar production and subsequent decays into two jets
- Assuming $\mathrm{Br}(D_0^{\mathrm{DQ}} \to \bar{q}\bar{q}) = 1$, CDF excludes $300\ \mathrm{GeV} \lesssim m_{D_0^1} \lesssim 450\ \mathrm{GeV}$ at 95% C.L.
- Limit essentially disappears for smaller $\mathrm{Br}(D_0^{\mathrm{DQ}} \to \bar{q}\bar{q})$

Leptoquarks

- Limits on scalar leptoquark pair production at Tevatron as a function of $\mathrm{Br}(D_0^{\mathrm{LQ}} \to \ell q)$ and $\mathrm{Br}(D_0^{\mathrm{LQ}} \to \nu q)$ at 95% C.L.:

$$m_{D_0^1} \geq 256,\ 234,\ 145\ \mathrm{GeV}\ \text{for}\ \mathrm{Br}(D_0^{\mathrm{LQ}} \to eq) = 1,\ 0.5,\ 0.1$$

$$m_{D_0^1} \geq 251,\ 208,\ 143\ \mathrm{GeV}\ \text{for}\ \mathrm{Br}(D_0^{\mathrm{LQ}} \to \mu q) = 1,\ 0.5,\ 0.1$$

- HERA (H1 and ZEUS) limits, assuming $\mathrm{Br}(D_0^{\mathrm{LQ}} \to \ell q) = \mathrm{Br}(D_0^{\mathrm{LQ}} \to \nu q)$:

$$m_{D_0^1} \gtrsim 290\ \text{for}\ \lambda^9 = \lambda^{10} \equiv \lambda = 0.3$$

$$m_{D_0^1} \gtrsim 270\ \text{for}\ \lambda^9 = \lambda^{10} \equiv \lambda = 0.1$$

Bounds: Indirect Limits

$\Rightarrow$ Indirect constraints more model dependent: family structure, $B(D)$ and $L(D)$ assignments, $U(1)$-prime charges, SUSY breaking etc.

$\Rightarrow$ For our leptoquarks, strongest constraint is μ - e conversion

- Exchange of D_0, D_0^c in the s-channel (fewer diagrams than $\not{R}_p$ MSSM)
- Limit from SINDRUM II: $\frac{\sigma(\mu^- T_i \to e^- T_i)}{\sigma(\mu^- T_i \to \text{ capture})} < 4.3 \times 10^{-13}$

$$\Rightarrow \boxed{\lambda^{6,7} < 3 \times 10^{-4} \left(\frac{m_{D_0}}{100 \text{ GeV}} \right)}$$

$\Rightarrow$ For our diquarks, strongest constraint is K_L - K_S mass difference

- Most important contribution is box diagram with two exotic supermultiplets with two u, c, t supermultiplets

- Assuming external d and s and internal u a typical bound is

$$\boxed{\lambda^{9,10} < 0.04 \left(\frac{\max(m_{\tilde{u}_i}, m_{D_0})}{100 \text{ GeV}} \right)^{1/2}}$$