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

⇒ 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

⇒ 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

See Talk by Steve King, Monday, January 7 at 10AM

Field Content of the Fundamental Representation

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

⇒ 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

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

- Couplings of exotics to Standard Model fields

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

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

Superpotential Interactions

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

$\Rightarrow$ If both W_{LQ} *and* W_{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

$$m^2_{\widetilde{D}} = \left(\begin{array}{cc} m^2_{aa} & m^2_{ab} \\ m^2_{ab} & m^2_{bb} \end{array} \right)$$

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

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

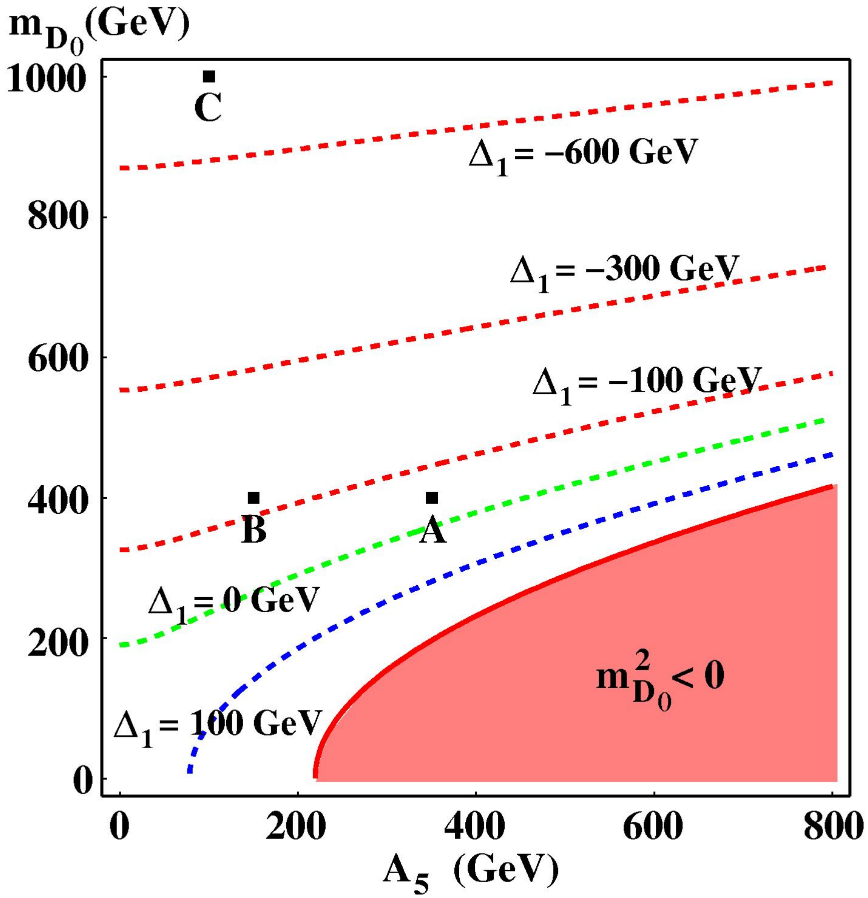
$$\Delta_1 \equiv m_{D_{1/2}} - m_{D_0^1} \; ; \quad \Delta_2 \equiv m_{D_{1/2}} - m_{D_0^2}$$

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

Some Sample Patterns for Splitting Δ_1

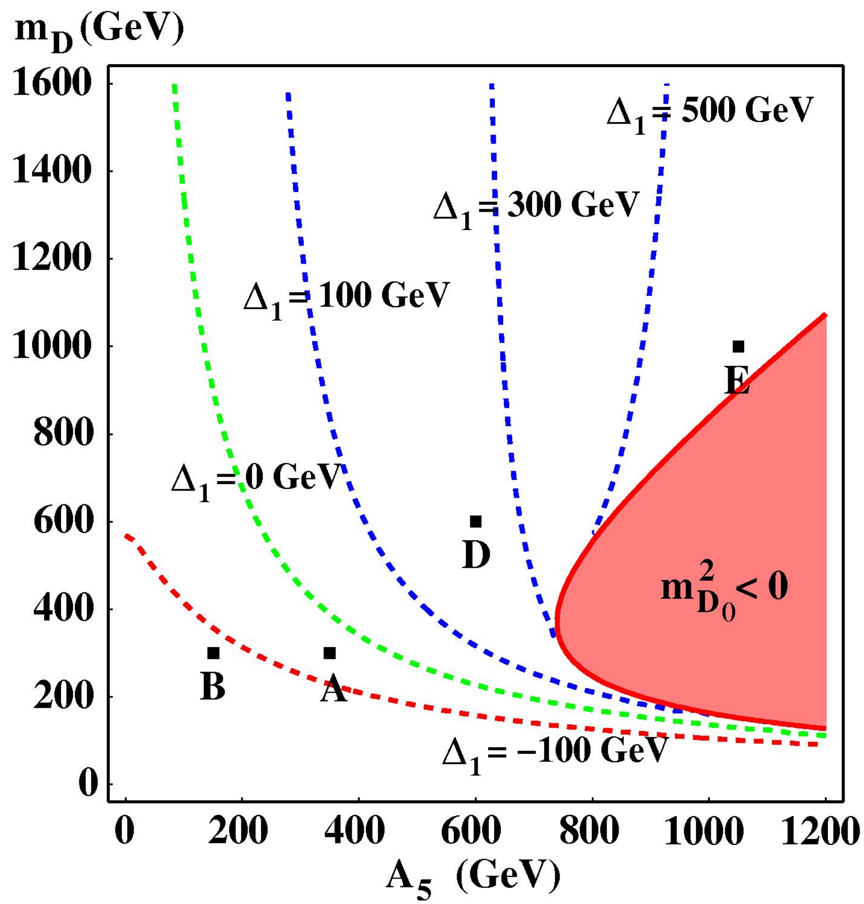
Fixed fermion mass

$M_D = 300$ GeV



Fixed (common) scalar mass

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



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

Future Reference: SPS1A

⇒ 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

⇒ Signatures at the LHC depend on how Δ_i compare to SUSY mass values

Modifying PYTHIA

⇒ The entire exotic sector was added to `PYTHIA`

- Six new states: $D^{\mathrm{LQ}}_{1/2}$, $(D^{\mathrm{LQ}}_{0})_{1,2}$, $D^{\mathrm{DQ}}_{1/2}$, $(D^{\mathrm{DQ}}_{0})_{1,2}$
- SUSY and non-SUSY decay modes for each state (more later)
- New production processes:
  - ⋆ $q+\bar{q}\rightarrow D^{\mathrm{LQ}}_{1/2}+\overline{D^{\mathrm{LQ}}_{1/2}}$, $D^{\mathrm{DQ}}_{1/2}+\overline{D^{\mathrm{DQ}}_{1/2}}$
  - ⋆ $g+g\rightarrow D^{\mathrm{LQ}}_{1/2}+\overline{D^{\mathrm{LQ}}_{1/2}}$, $D^{\mathrm{DQ}}_{1/2}+\overline{D^{\mathrm{DQ}}_{1/2}}$
  - ⋆ $q+\bar{q}\rightarrow (D^{\mathrm{LQ}}_{0})_i+(\overline{D^{\mathrm{LQ}}_{0}})_j$, $(D^{\mathrm{DQ}}_{0})_i+(\overline{D^{\mathrm{DQ}}_{0}})_j$
  - ⋆ $g+g\rightarrow (D^{\mathrm{LQ}}_{0})_i+(\overline{D^{\mathrm{LQ}}_{0}})_j$, $(D^{\mathrm{DQ}}_{0})_i+(\overline{D^{\mathrm{DQ}}_{0}})_j$
  - ⋆ $q+g\rightarrow (D^{\mathrm{LQ}}_{0})_i+e^-\ \mathrm{or}\ \ \nu_e$
  - ⋆ $\bar{q}+g\rightarrow (D^{\mathrm{DQ}}_{0})_i+\bar{q}$
  - ⋆ $\bar{u}+\bar{d}\rightarrow (D^{\mathrm{DQ}}_{0})_i$ (resonant production)

⇒ New color flow algorithms for diquark interactions....

Modifying PYTHIA

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- SUSY and non-SUSY decay modes for each state (more later)
- New production processes:

  ⋆ $q + \bar{q} \to D^{\rm LQ}_{1/2} + \overline{D^{\rm LQ}_{1/2}}$, $D^{\rm DQ}_{1/2} + \overline{D^{\rm DQ}_{1/2}}$

  ⋆ $g + g \to D^{\rm LQ}_{1/2} + \overline{D^{\rm LQ}_{1/2}}$, $D^{\rm DQ}_{1/2} + \overline{D^{\rm DQ}_{1/2}}$

  ⋆ $q + \bar{q} \to (D^{\rm LQ}_0)_i + (\overline{D^{\rm LQ}_0})_j$, $(D^{\rm DQ}_0)_i + (\overline{D^{\rm DQ}_0})_j$

  ⋆ $g + g \to (D^{\rm LQ}_0)_i + (\overline{D^{\rm LQ}_0})_j$, $(D^{\rm DQ}_0)_i + (\overline{D^{\rm DQ}_0})_j$

  ⋆ $q + g \to (D^{\rm LQ}_0)_i + e^- \ \text{or} \ \nu_e$

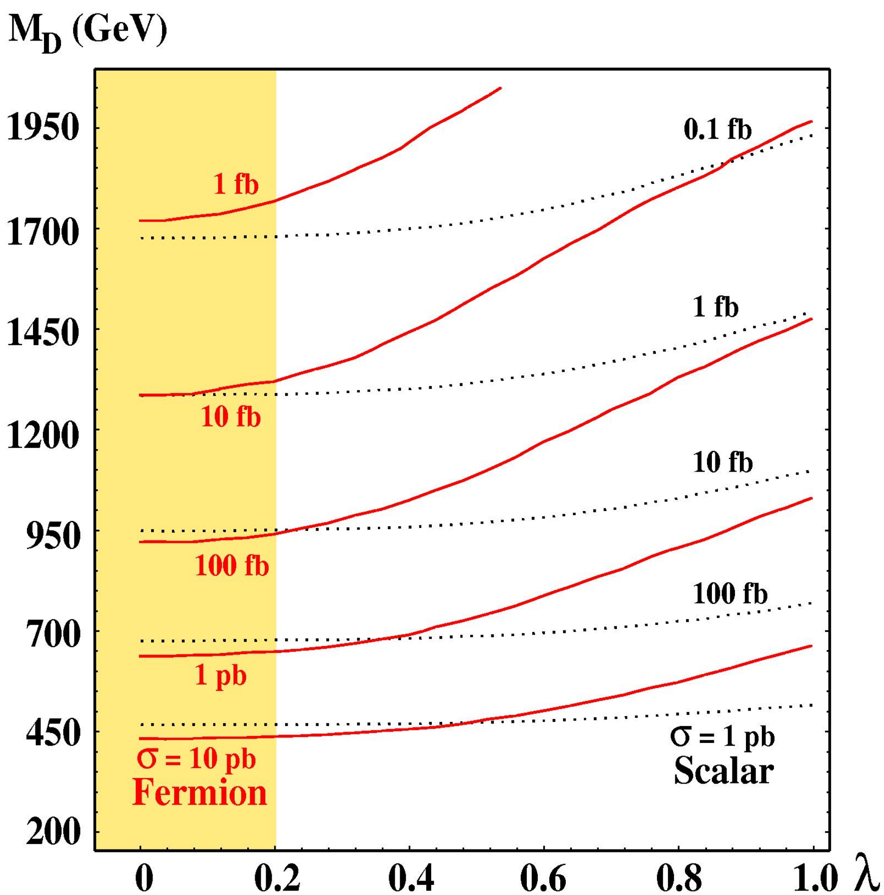
  ⋆ $\bar{q} + g \to (D^{\rm DQ}_0)_i + \bar{q}$

  ⋆ $\bar{u} + \bar{d} \to (D^{\rm DQ}_0)_i$ (resonant production)

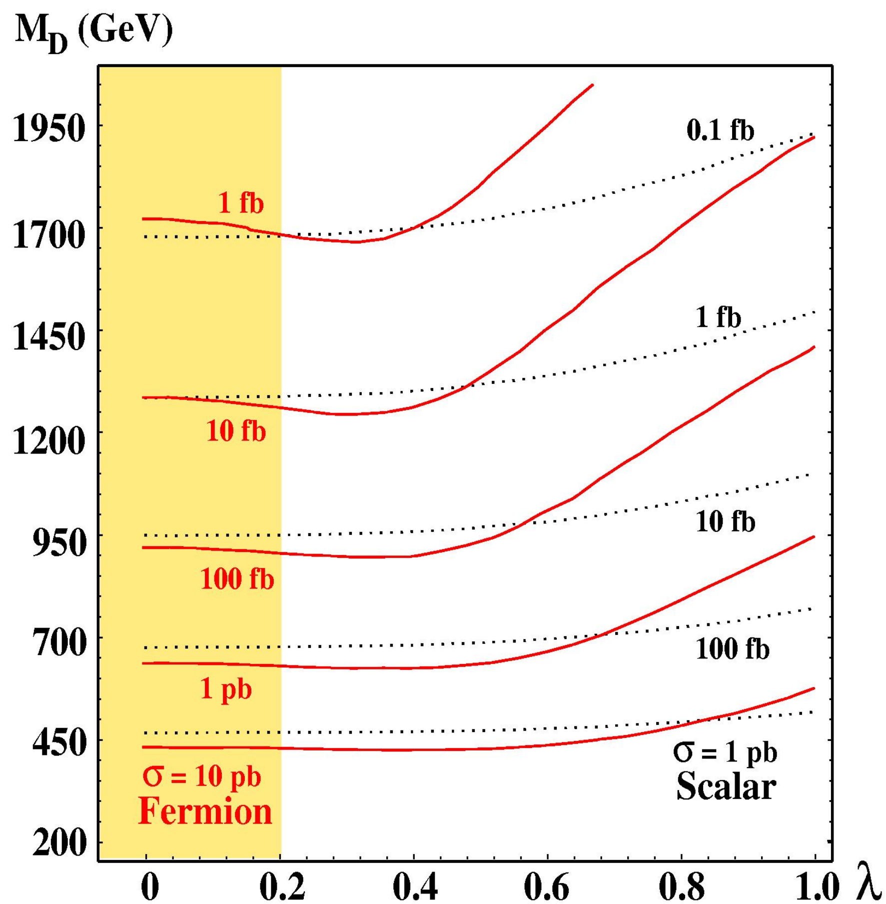
⇒ New color flow algorithms for diquark interactions....ACK!!

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

Pair Production at the LHC

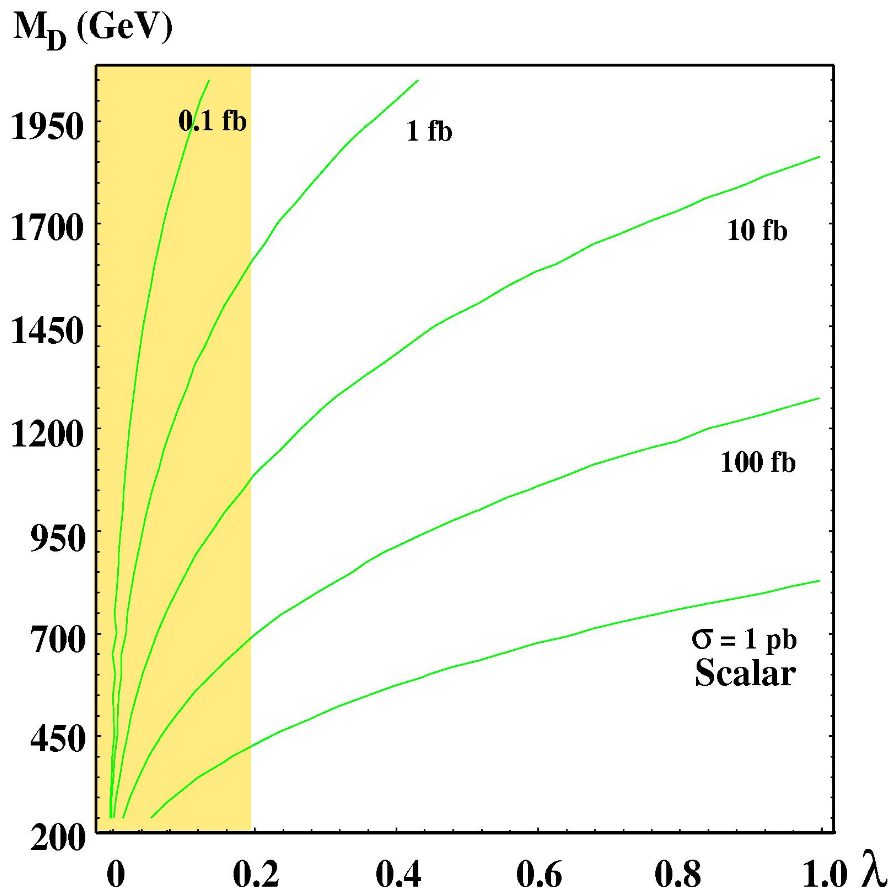


Leptoquark pair production

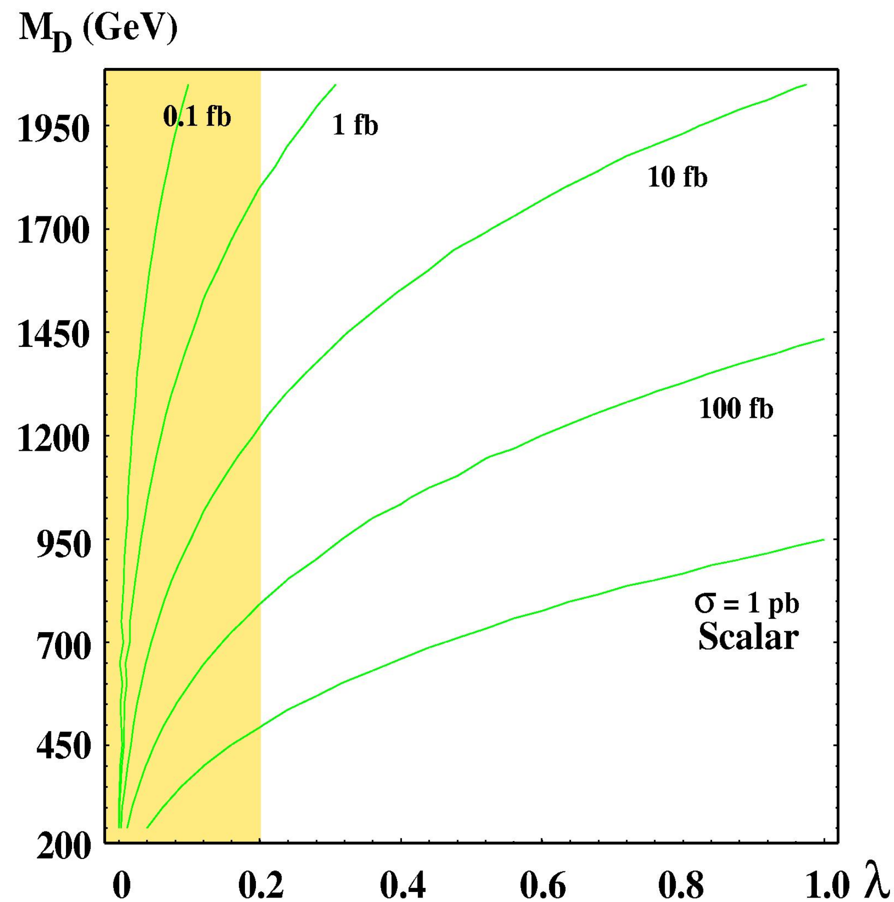


Diquark pair production

Associated Production at the LHC



Leptoquark associated production
$(q + g \to D_0^{\mathrm{LQ}} + \ell, \nu)$



Diquark associated production
$(\bar{q} + g \to D_0^{\mathrm{DQ}} + \bar{q})$

$\Rightarrow$ Large production cross-sections...should we have seen them by now?

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.:

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

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

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

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

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

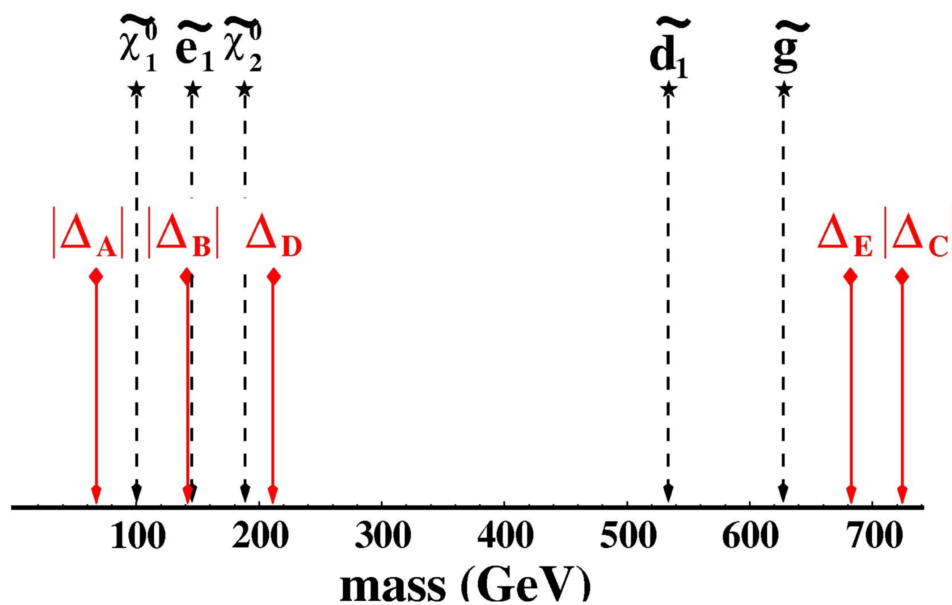
Prompt Decay Final States

	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 + $\widetilde{g}$						✓			✓	
$\widetilde{f} + f'$	✓ LQ	NA	✓ LQ	NA	✓ LQ	NA	✓	NA	✓	NA
$f + f'$	NA	✓	NA	✓	NA	✓	NA	✓	NA	✓
$\widetilde{\chi}_1^0 + f + f'$	✓ DQ		✓ DQ		✓ DQ					

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

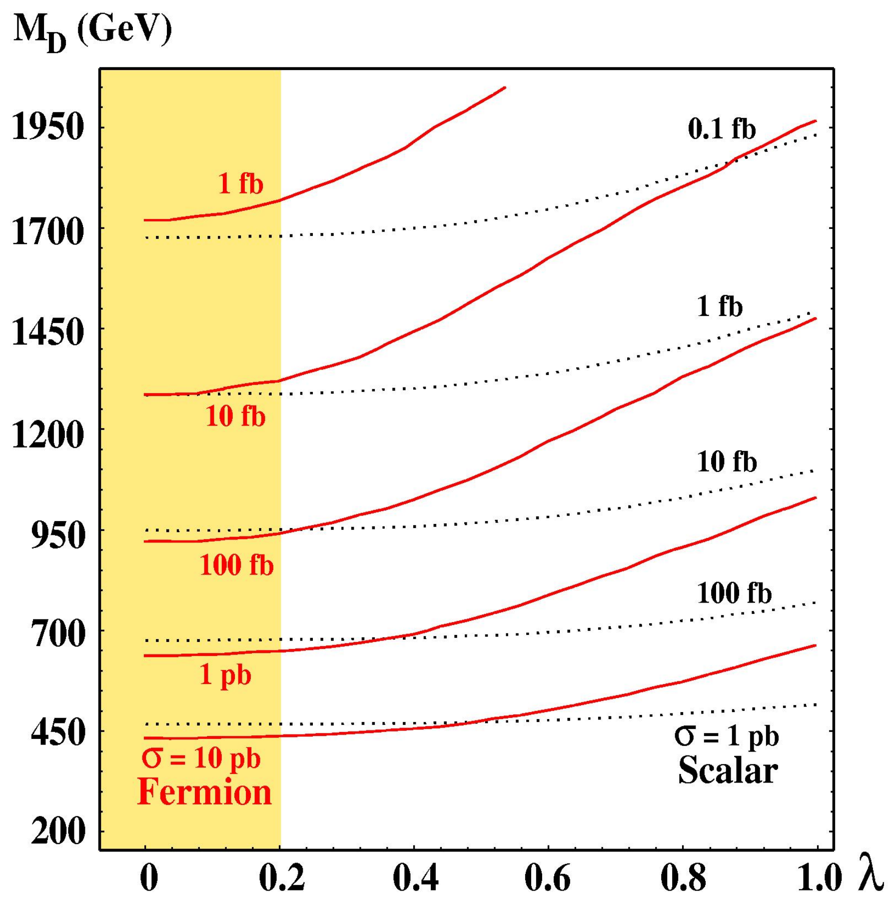
	$m_{D_{1/2}}$	$m_{D_0^1}$
Case A	300	367
Case B	300	441
Case C	300	1024
Case D	600	388
Case E	1000	318

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

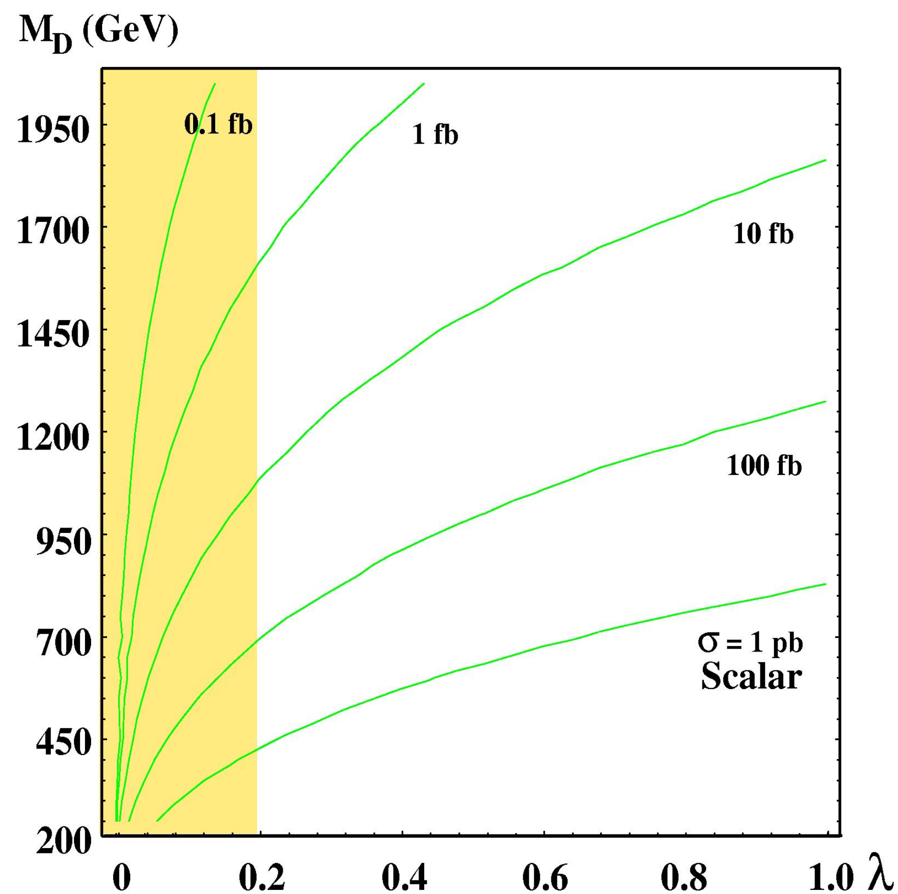


Leptoquark Production at the LHC

Pair production



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



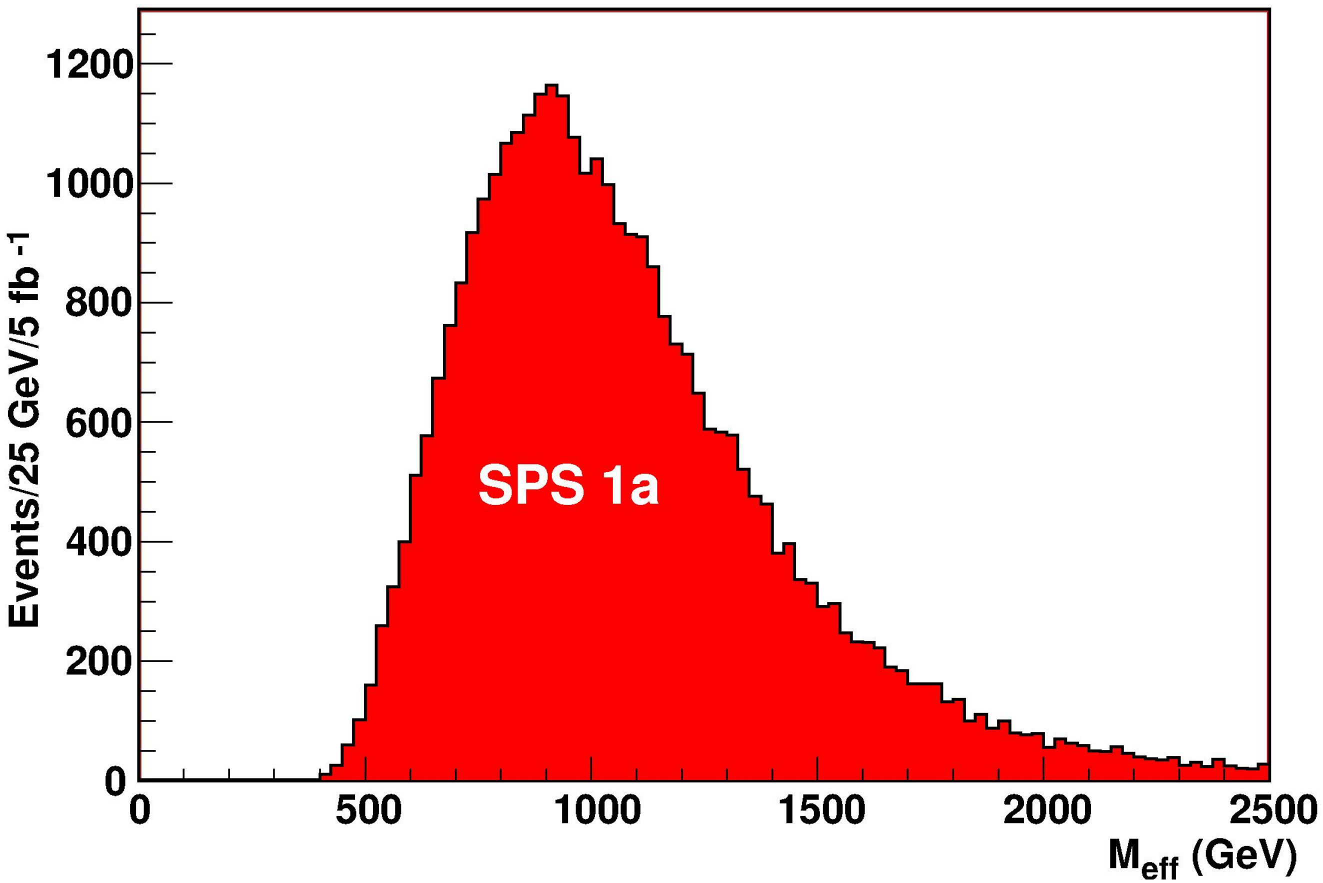
Events at LHC with $5\,\mathrm{fb}^{-1}$ integrated luminosity

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

Discovery of New Physics

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

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



- Event selection criteria:
  - ⋆ $N_{\text{jets}} \geq 4$, with $p_{T,1}^{\text{jet}} \geq 100$ GeV and $p_{T,i}^{\text{jet}} \geq 50$ 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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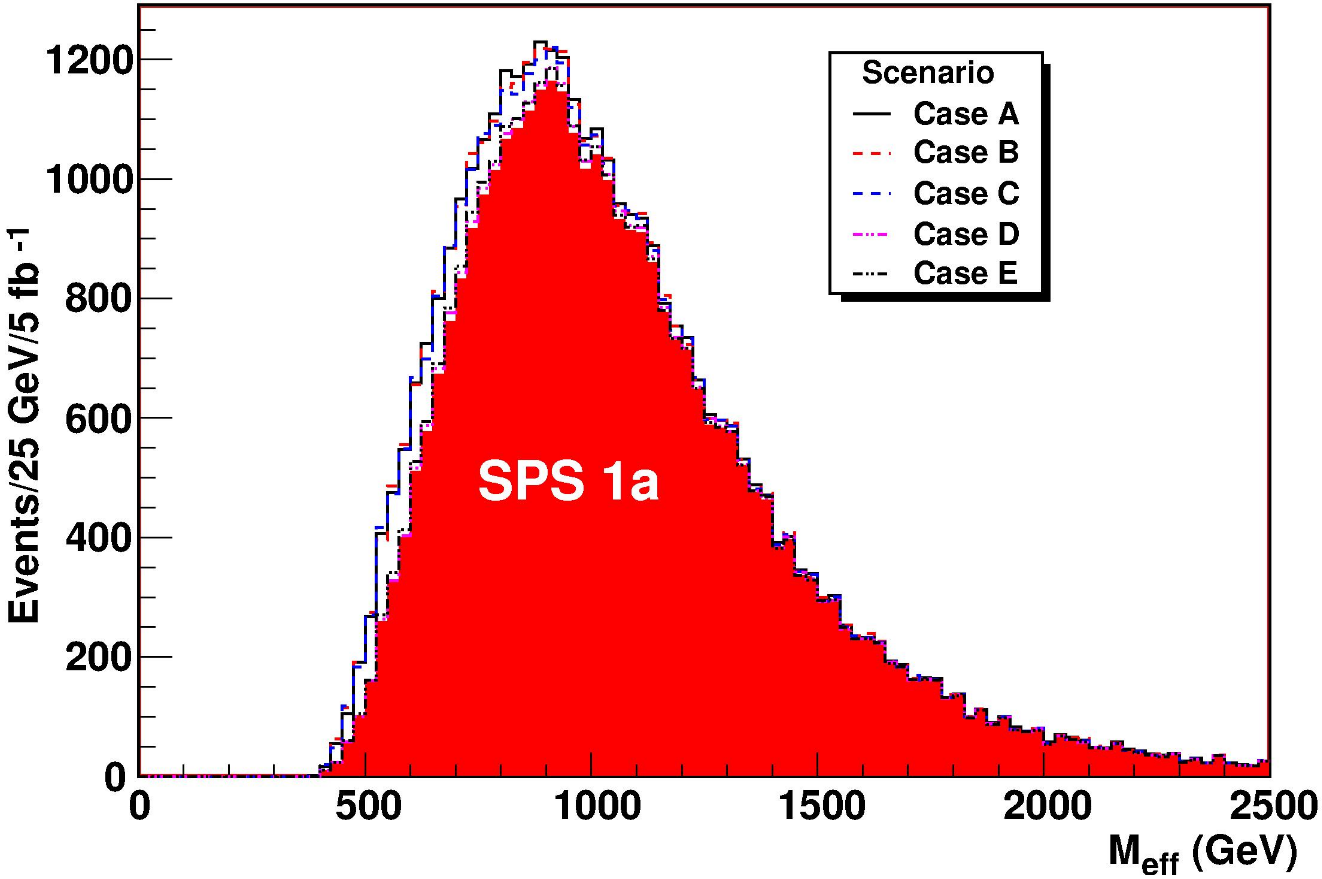

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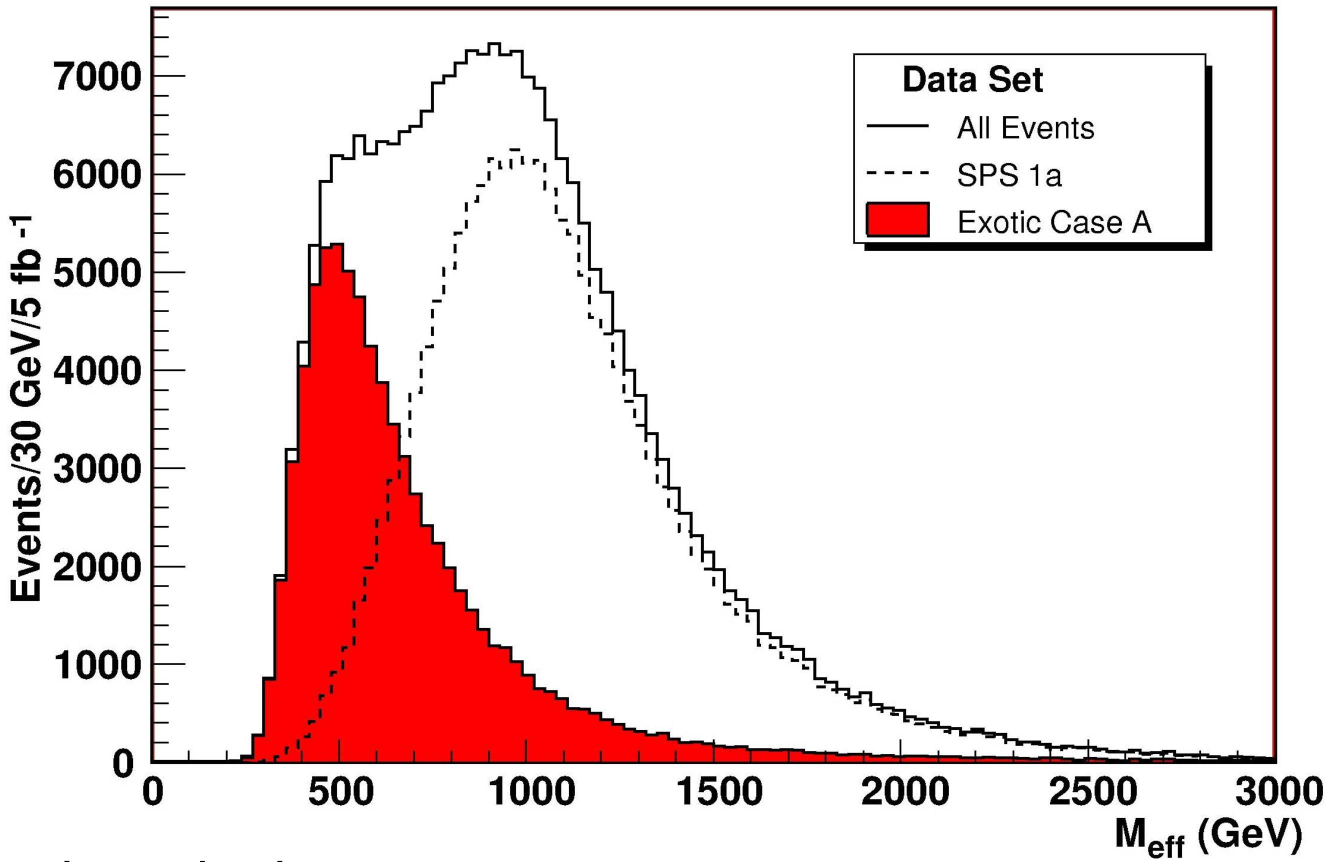
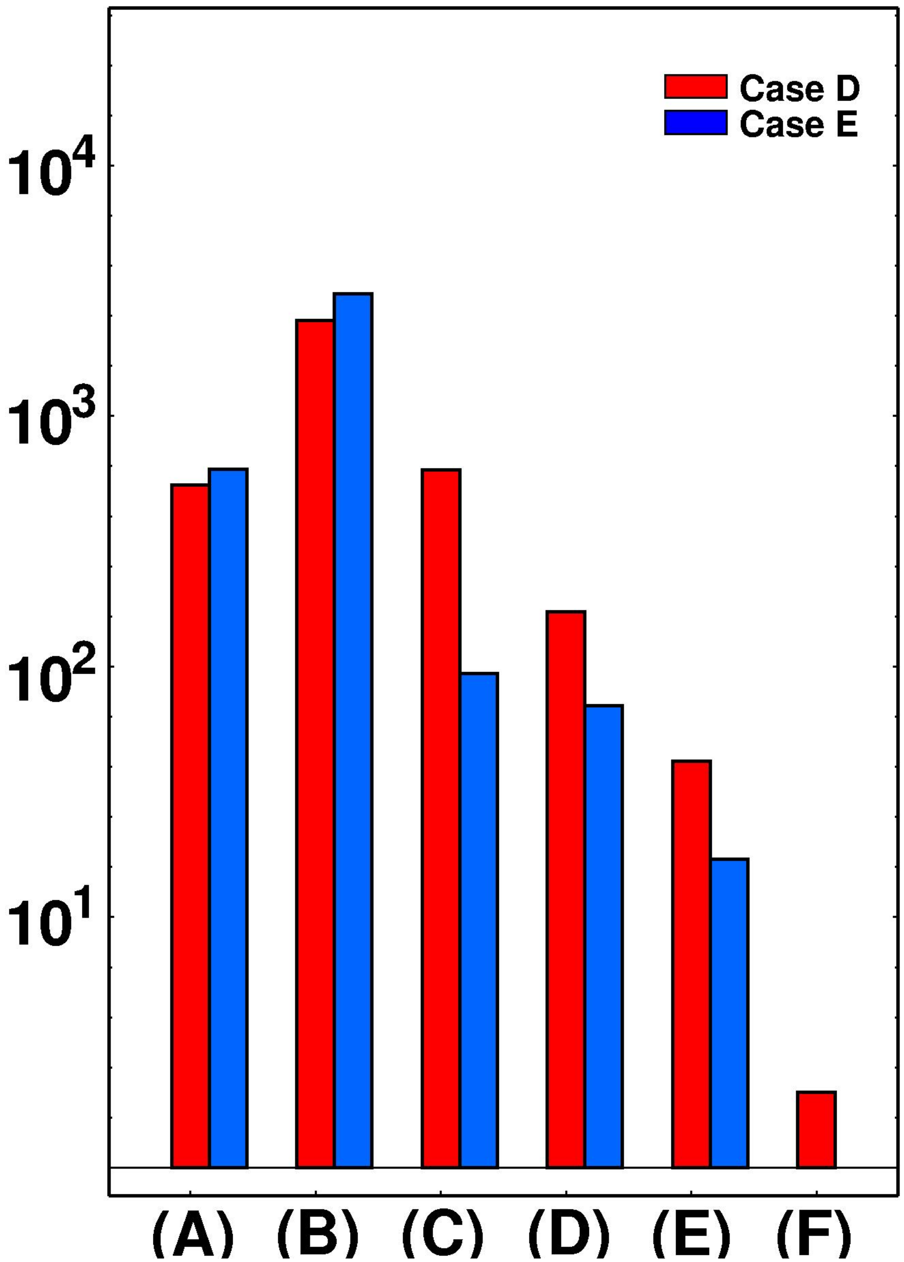
Where are the exotic events?

- Try something *more* inclusive: $M_{\rm eff} = \sum_i^{\rm all} p_{T,i} + \not\!\!E_T$



- Event selection criteria:
  - ⋆ $N_{\rm jets} \geq 2$, with $p_{T,i}^{\rm jet} \geq 50$ 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



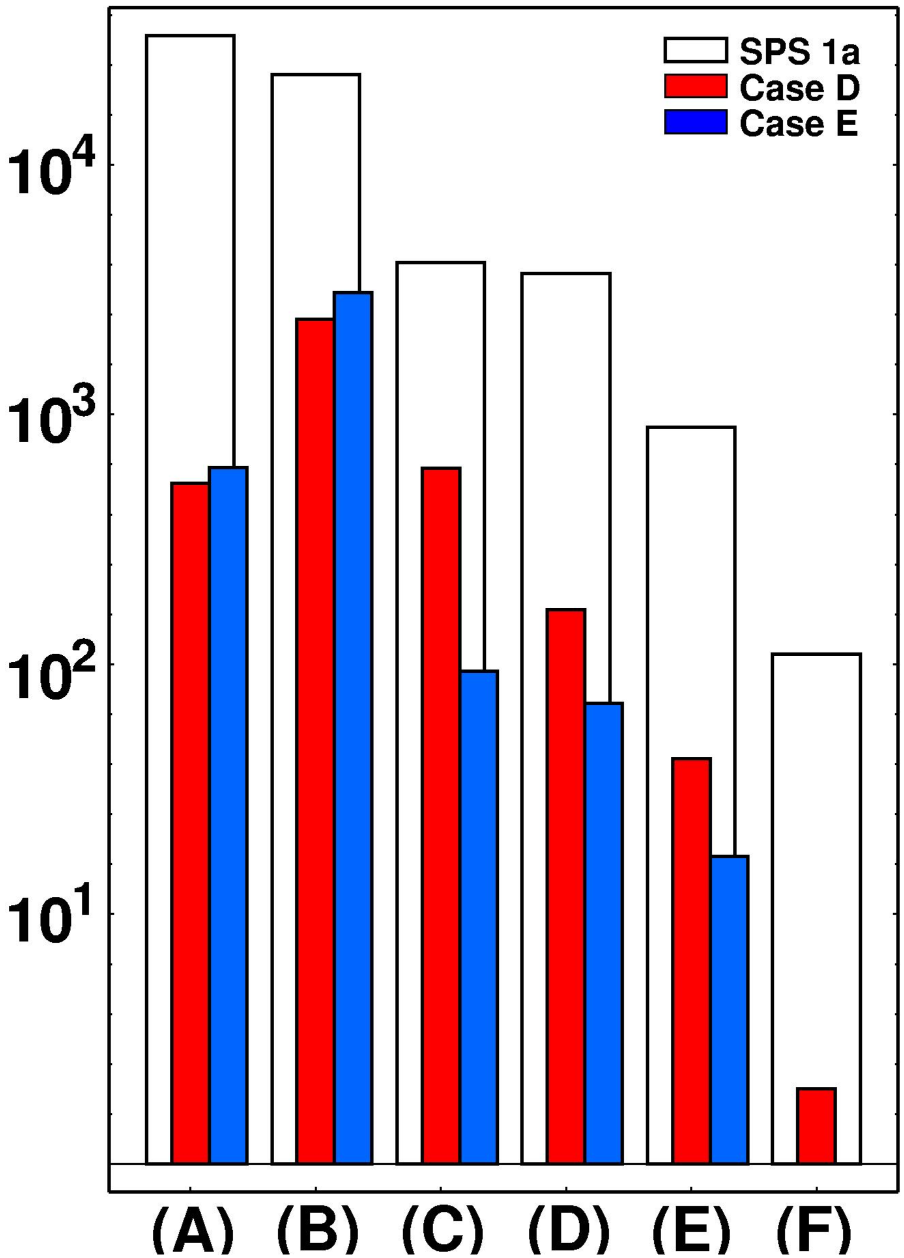
Inclusive signatures
(all have $\not\!\!E_T \geq 100$ GeV, $S \geq 0.2$)

- (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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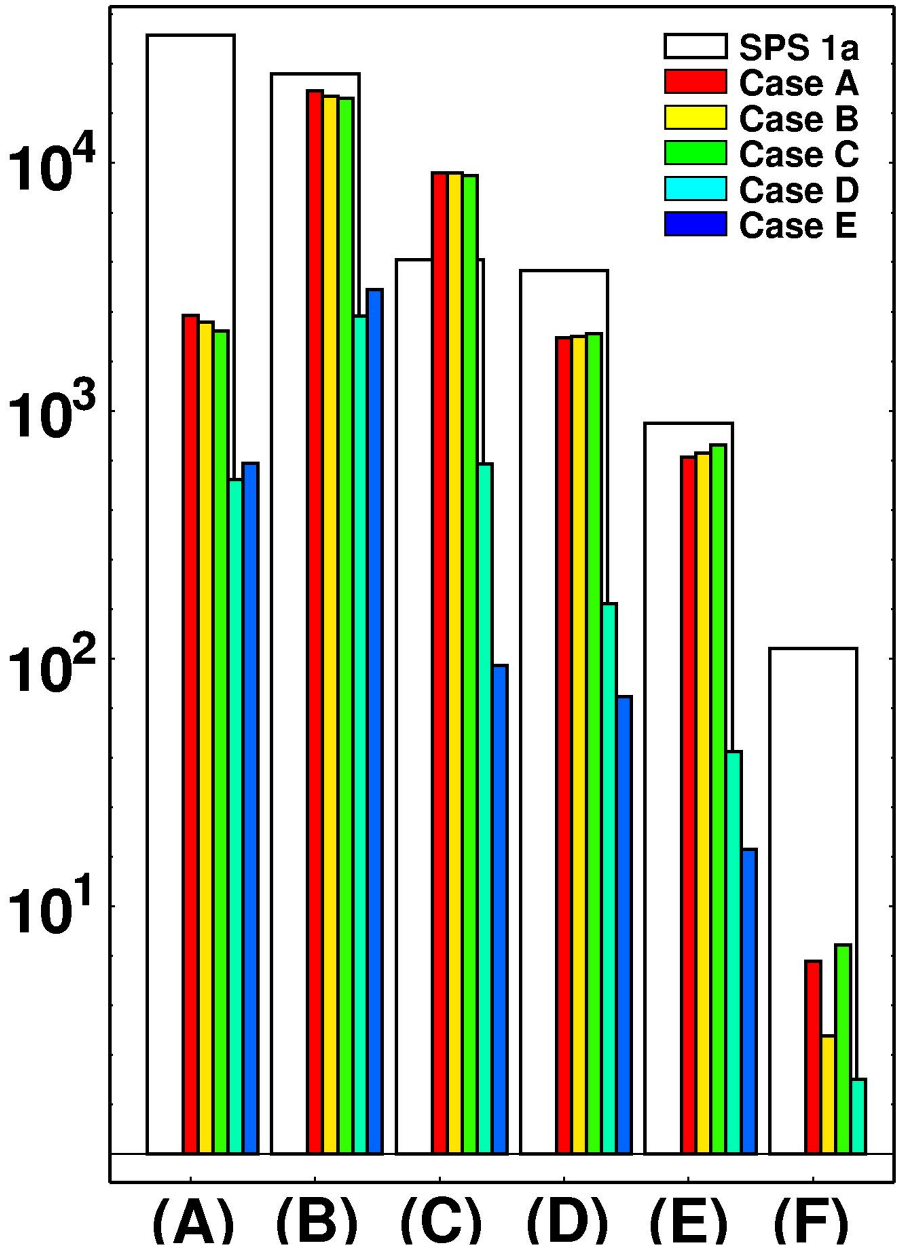
Add Fermionic LEP Cases



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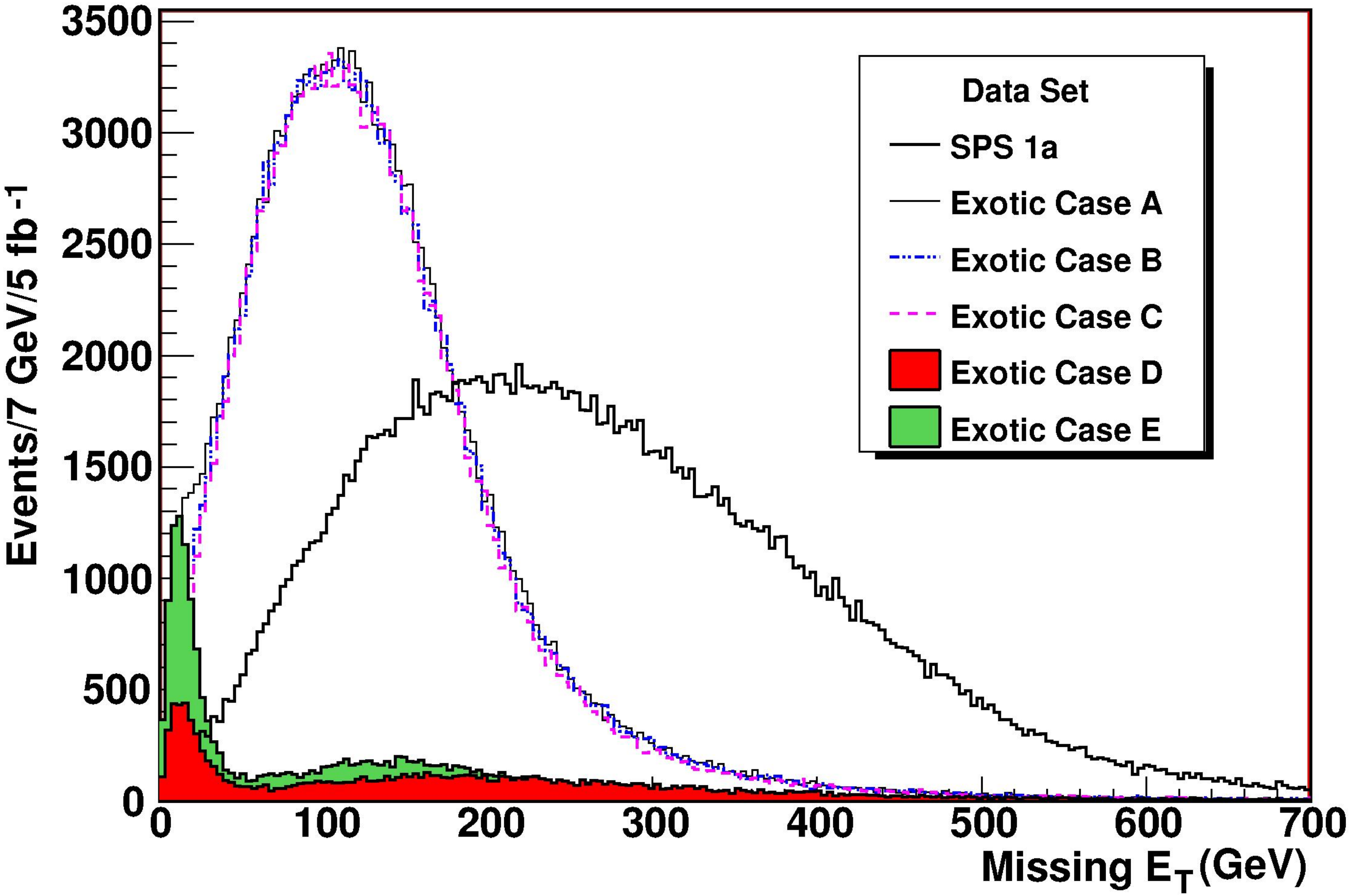
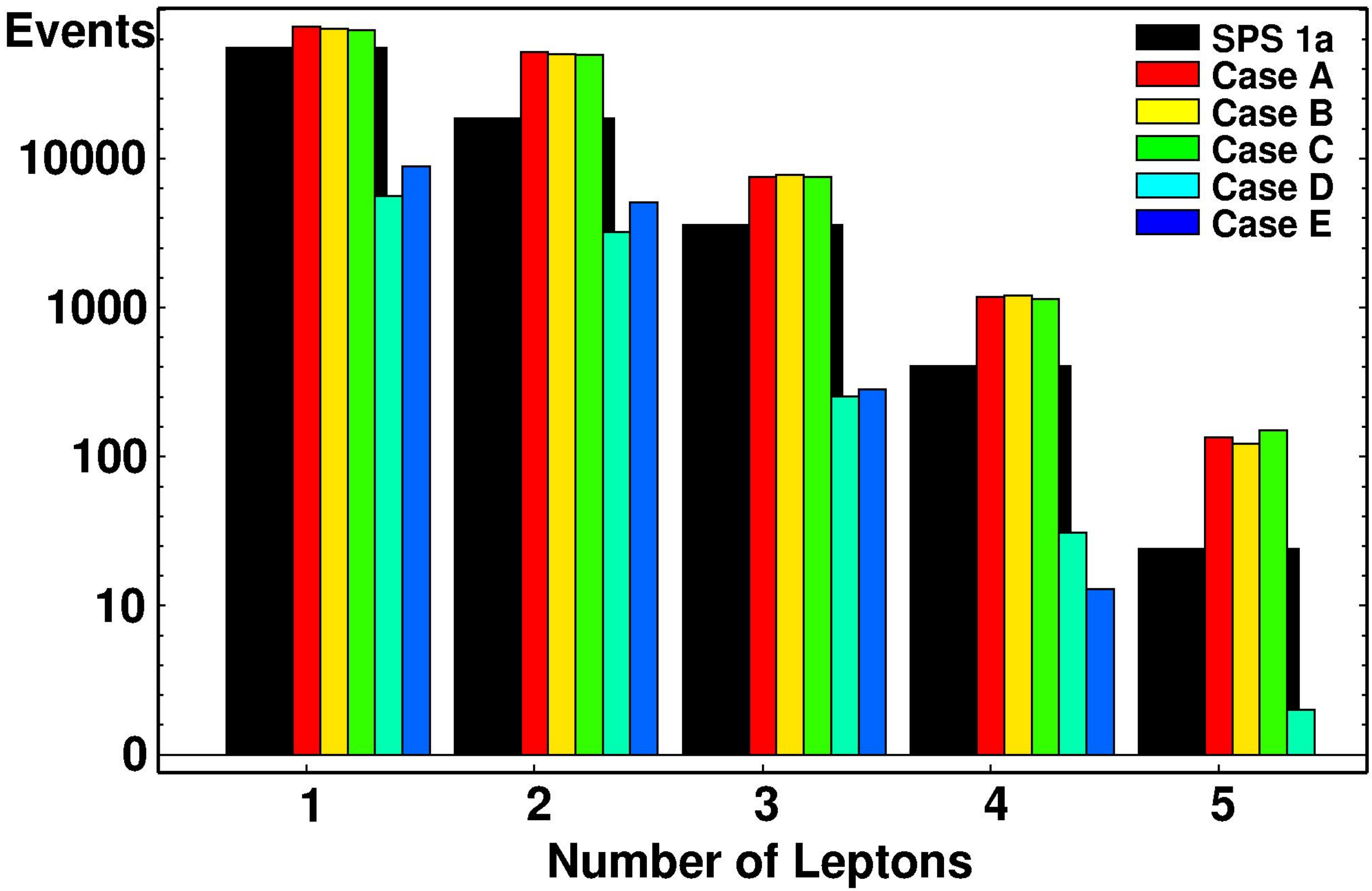
For (B)-(F) we require $N_{\rm jets} \geq 2$, $p_{T,1}^{\rm jet} \geq 100$ GeV, $p_{T,2+}^{\rm jet} \geq 50$ GeV

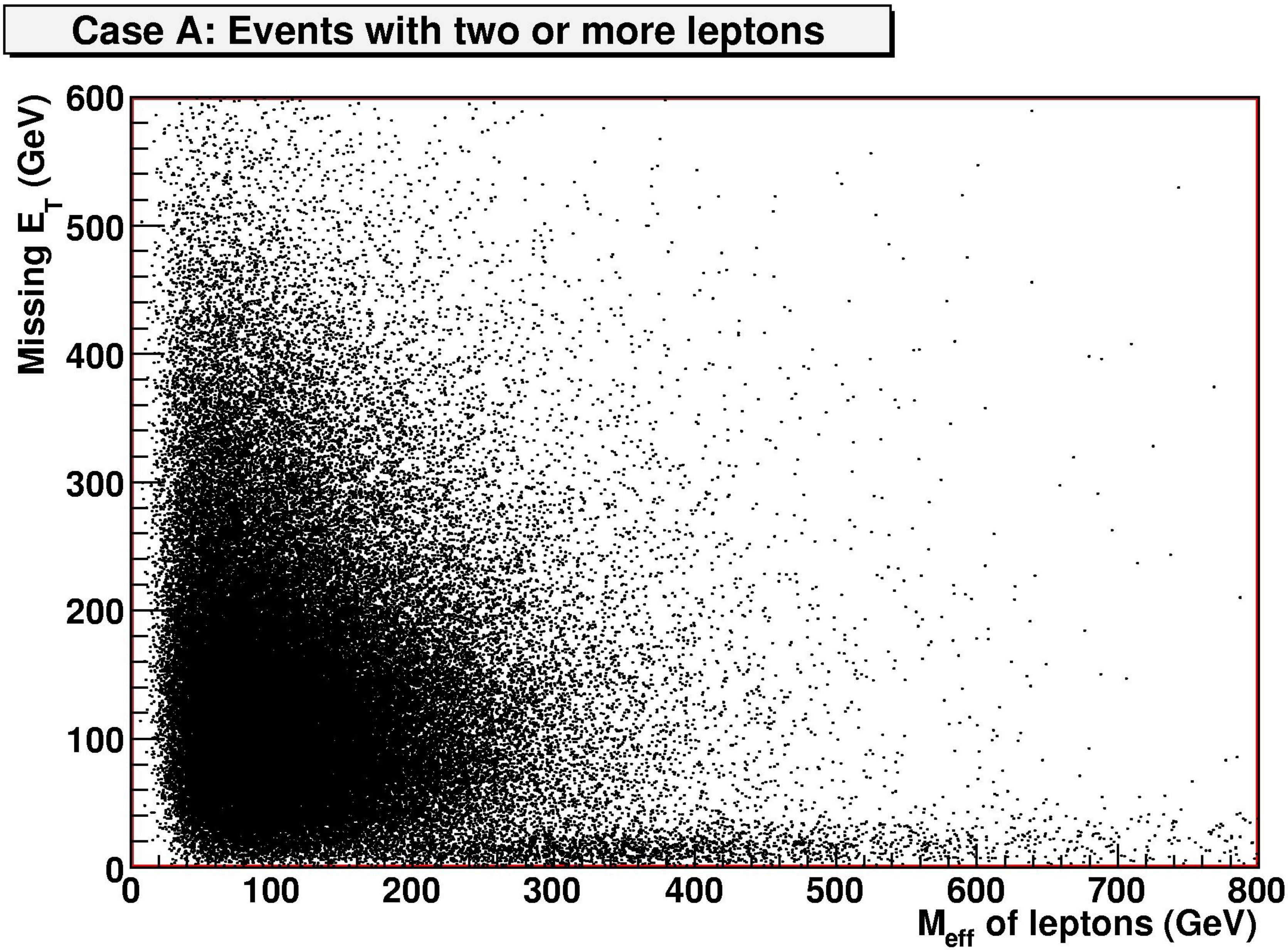
Missing Transverse Energy Distribution



Lepton Multiplicity



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



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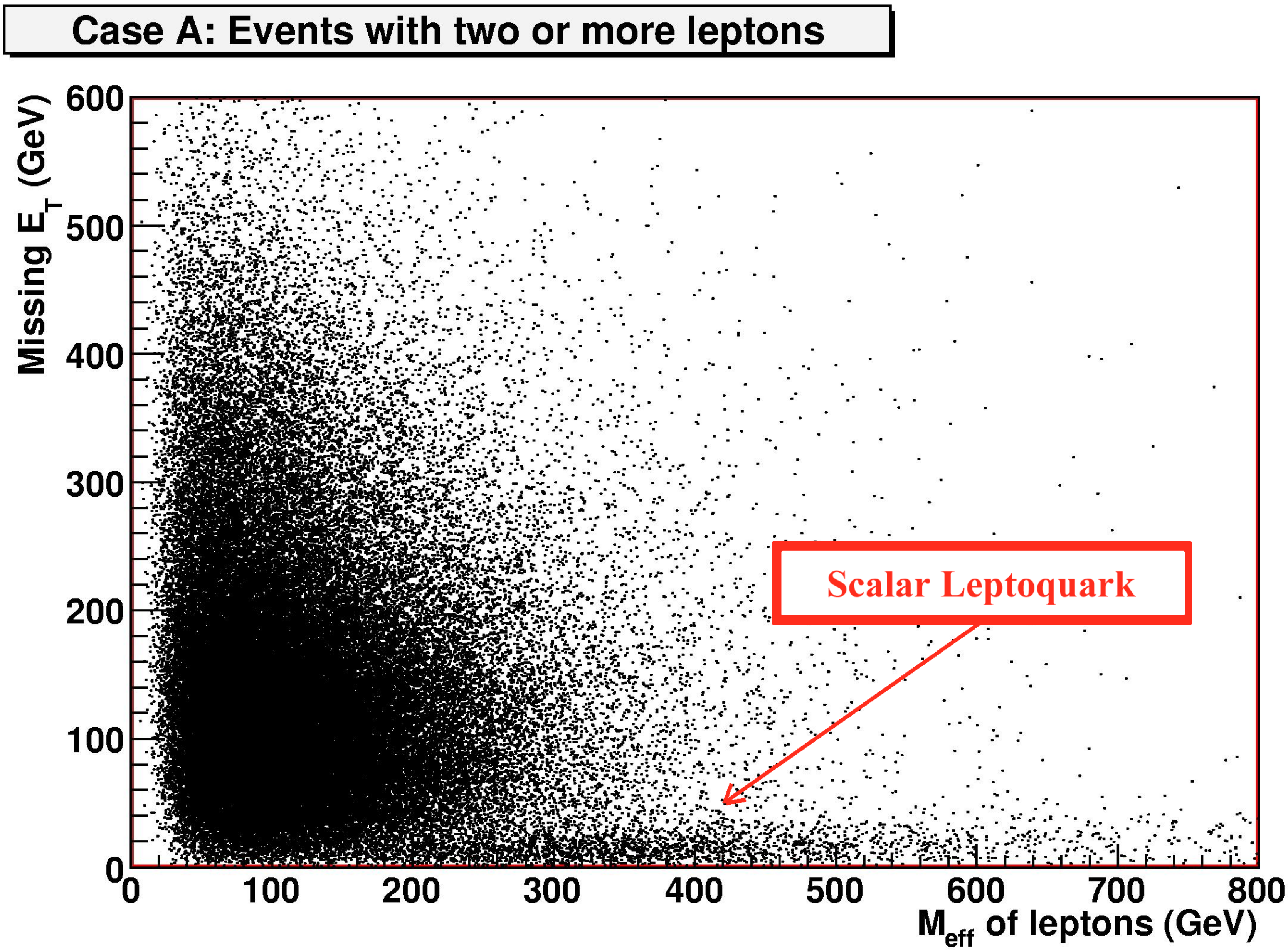
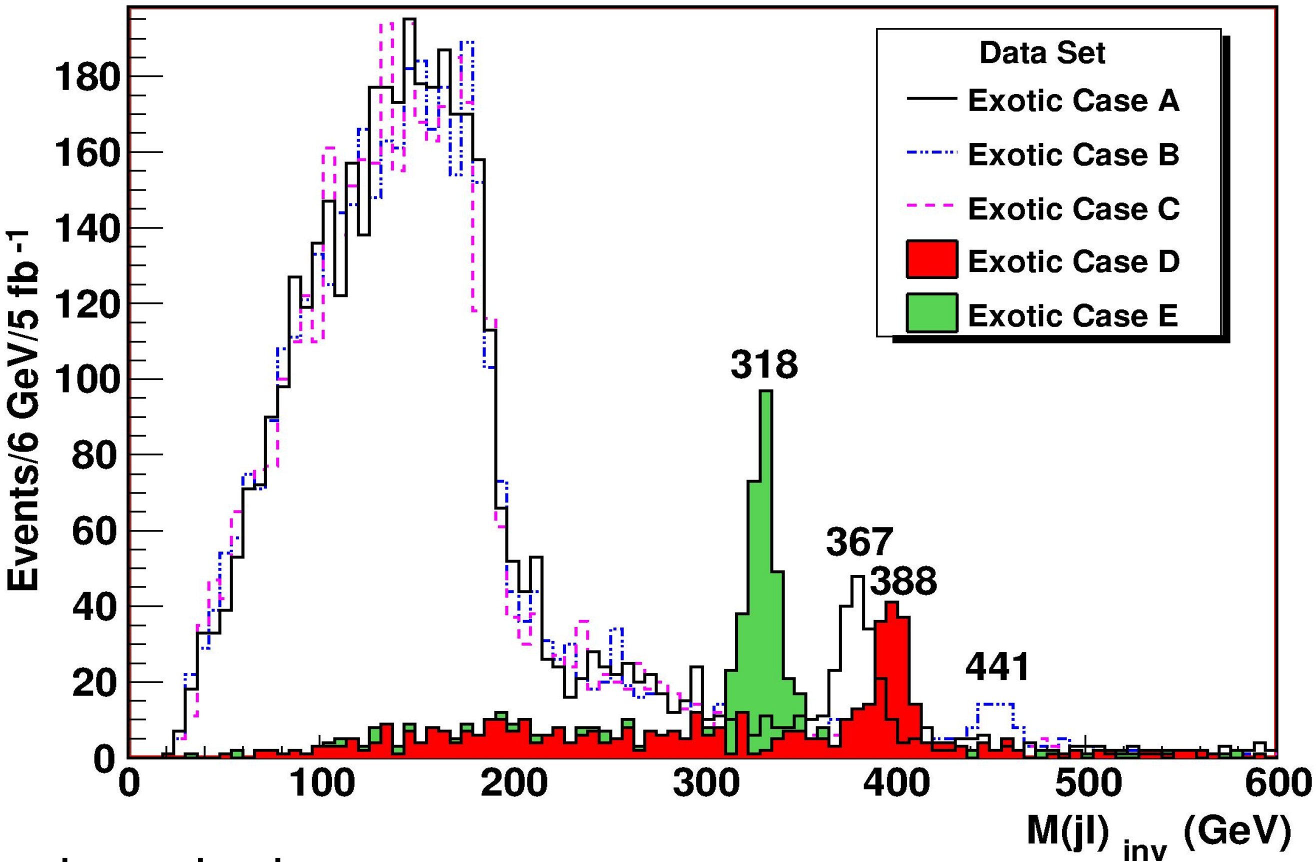


Isolating the Exotic Component

- 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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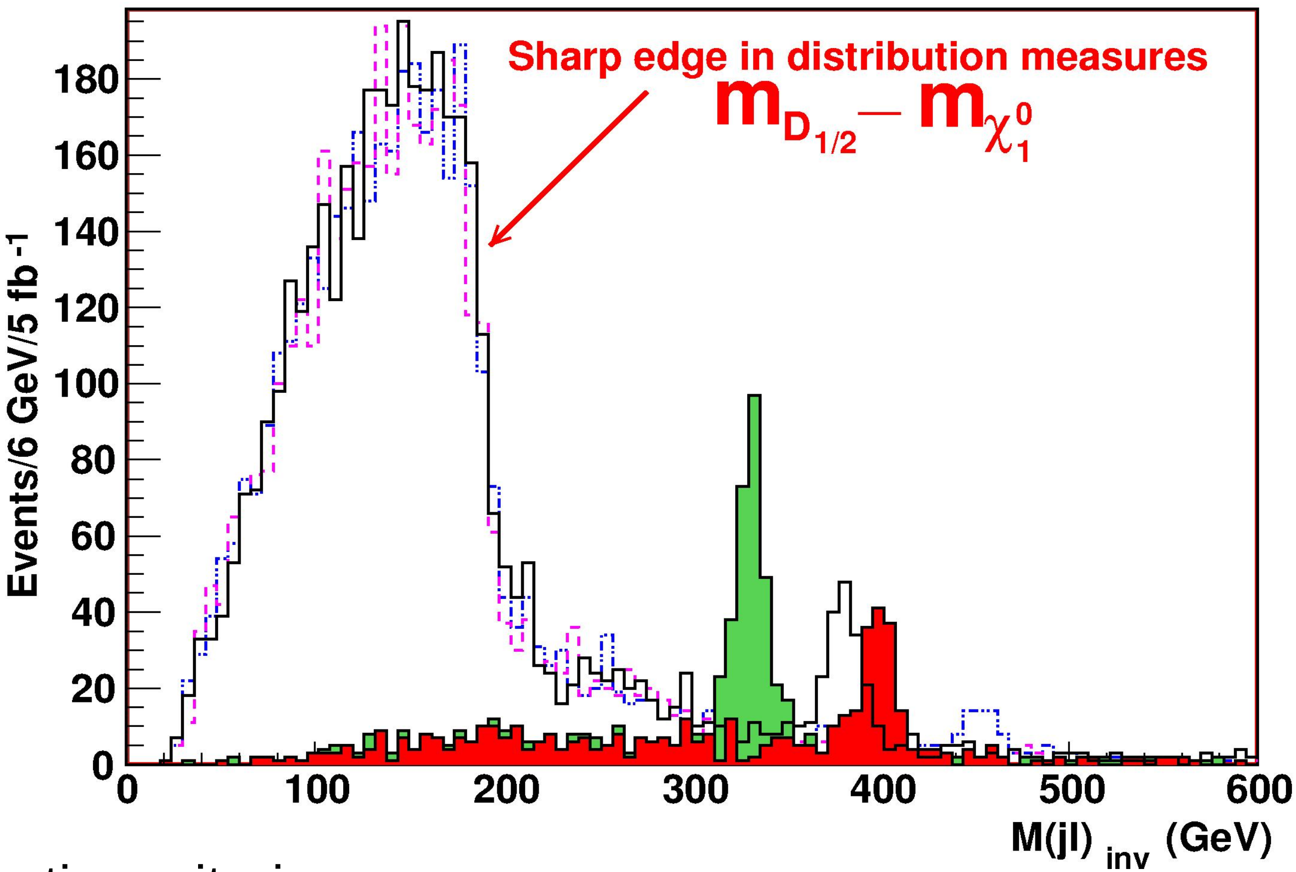

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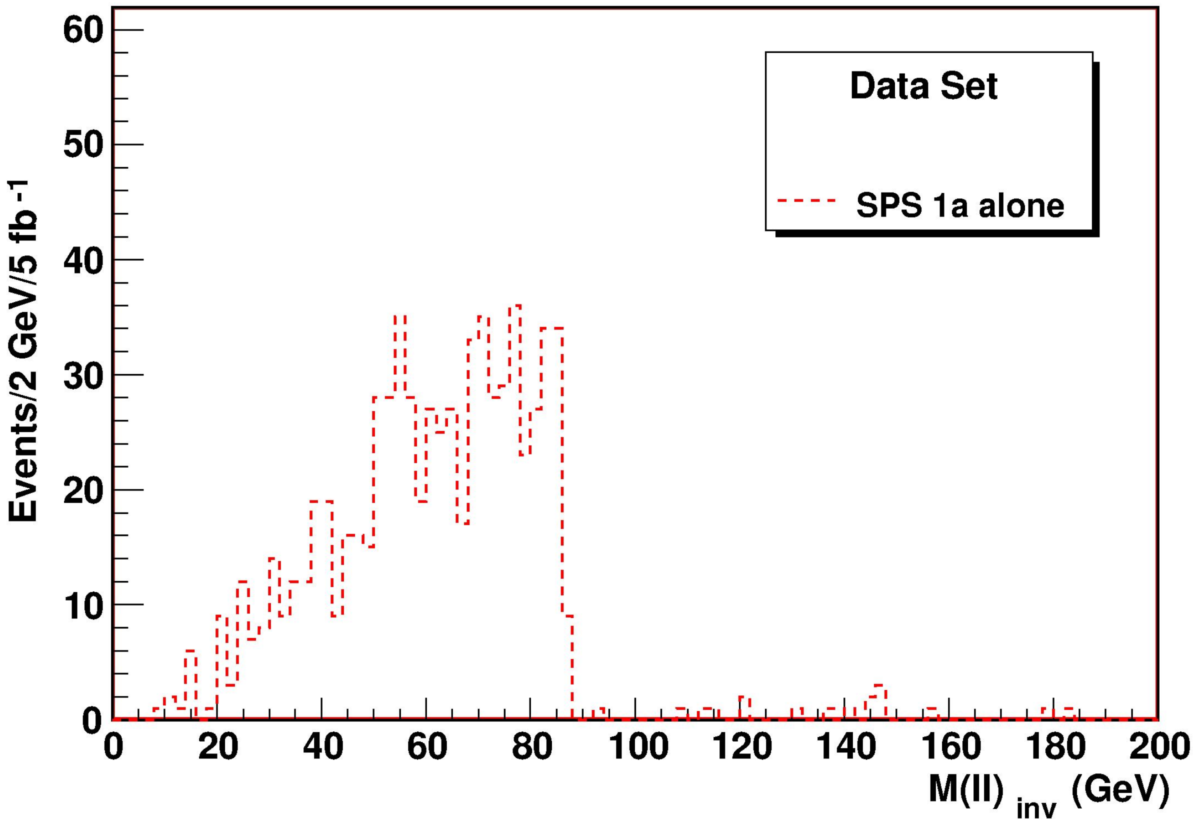
Dilepton Invariant Mass Distribution

- Flavor-subtracted invariant mass of dilepton pairs

$M_{\rm inv}(e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-)$

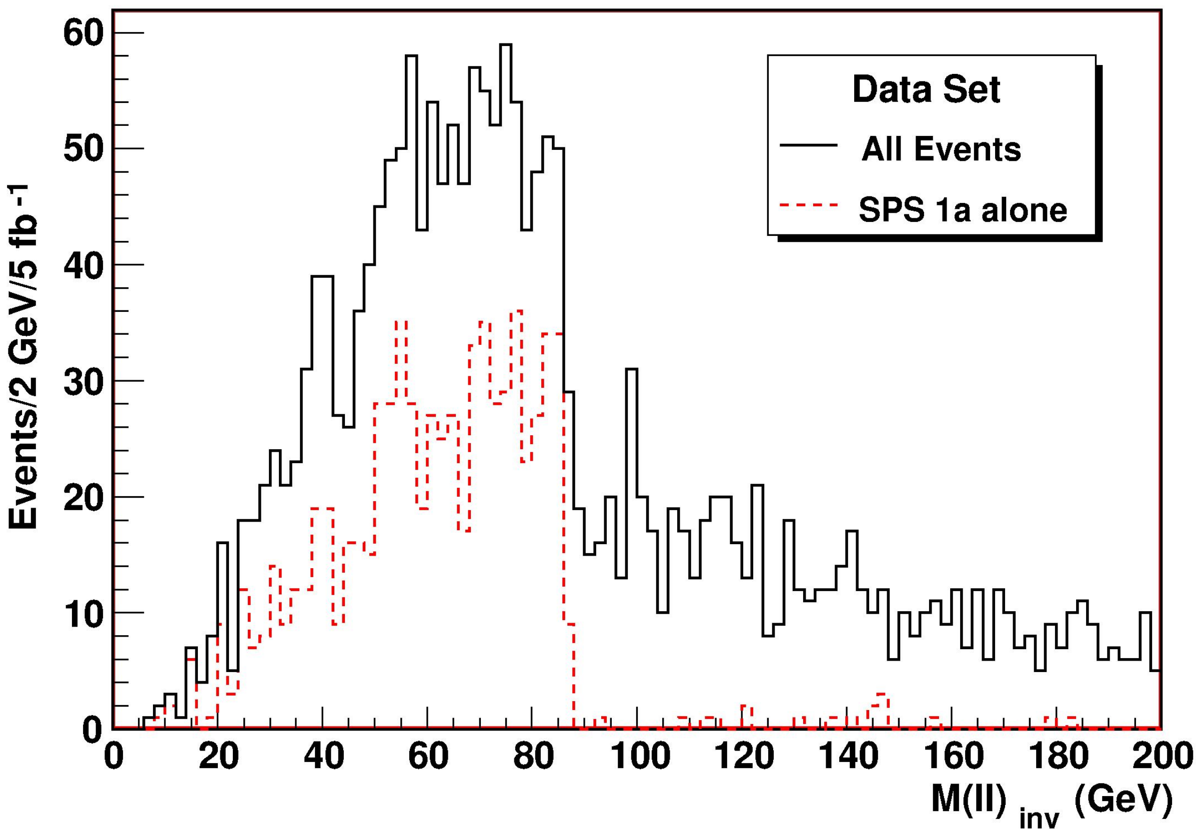
Hinchliffe et al., **PRD55** (1997) 5520
Denegri, Majerotto, Rurua, **PRD58** (1998) 095010
Nojiri & Yamada, **PRD60** (1999) 015006



- 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
  $M_{\mathrm{inv}}(e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-)$



- "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

Bounds: Indirect Limits

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

⇒ For our leptoquarks, strongest constraint is μ - e conversion

- Exchange of D_0, D_0^c in the s-channel (fewer diagrams than $R\!\!\!/_p$ MSSM)
- Limit from SINDRUM II: $\frac{\sigma(\mu^- T_i \to e^- T_i)}{\sigma(\mu^- T_i \to \text{ capture})} < 4.3 \times 10^{-13}$

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

⇒ 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

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

Quasi-Stable: Hadronization

$\Rightarrow$ Exotics stable on timescale of detector will hadronize $\Rightarrow$ *R-hadrons*

- Exotic component can be scalar or fermion
- Can produce LEP in pairs or NLEP with cascade decays to LEP
- R-hadrons contain one less active quark than split-SUSY analogs (total cross section for interaction with nucleons reduced)

$\Rightarrow$ Lowest-lying R-hadrons: $D\bar{d}$, $D\bar{u}$, Ddd, Duu and two combinations of Ddu (plus anti-states).

- Bulk of R-hadron mass accounted for by exotic
- Exotic component largely sterile in interactions
- R-mesons lightest, approximately degenerate in mass
- Of R-baryons, neutral Dud in s-wave configuration lighter than p-wave or charged Ddd, Duu states

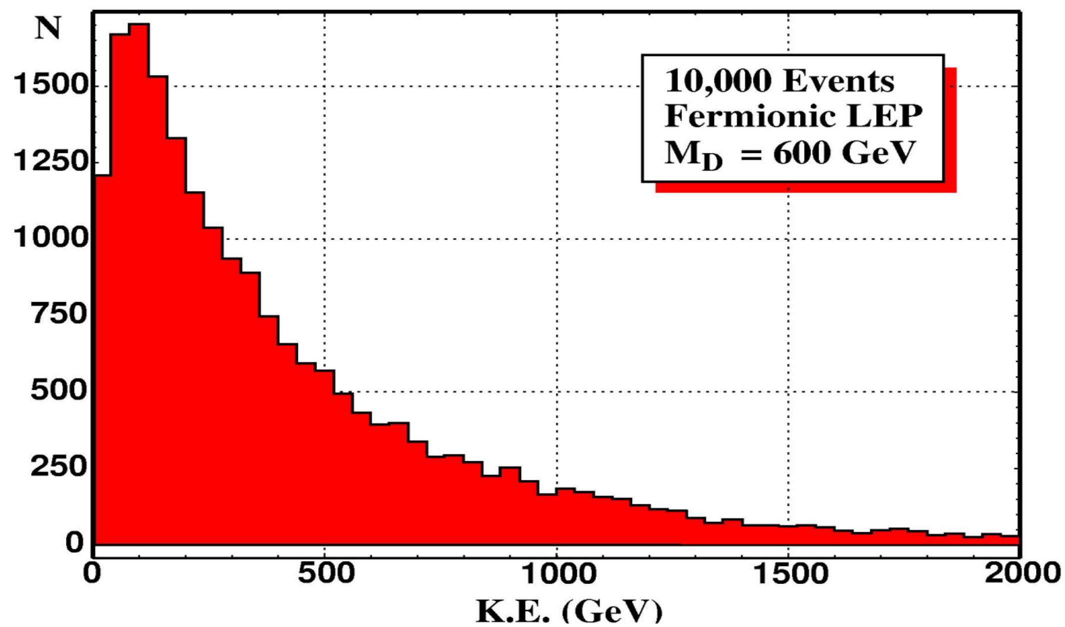
R-hadrons in the Calorimeter System

⇒ Interactions: elastic scattering off nucleons, charge-exchange interactions, meson-to-baryon/baryon-to-meson interactions

- R-mesons $D\bar{q}$ transition to baryons by producing a light pion ⇒ resulting Dqq R-baryon remains a baryon (absence of anti-quarks in detector material)
- R-baryon $D^c\bar{q}\bar{q}$ rapidly transitions to R-meson $D^c q$ through quark/anti-quark annihilation ⇒ R-meson $D^c q$ remains an R-meson throughout calorimeter

- Typical interaction cross-section ~ 12 mb (mesons), ~ 24 mb (baryons)
- Implies 6-10 interactions through calorimeter
- Typical energy loss per interaction is 0.2 - 2.2 GeV for $E_{\rm kin} \sim 400$ GeV

A. Kraan, *Eur. Phys. Jour.*, **C37** (2004)



R-hadrons in the Muon System

⇒ Most (but not all) R-hadrons punch-through to muon system

- D's arrive as neutral R-baryons, D^c's as neutral or charged R-mesons
- Charged R-mesons leave track in muon system
- Particle ID: β typically much lower than that for muons

⇒ Key observable is time-of-flight (TOF) across some fiducial length

- Temporal resolution in muon system at ATLAS/CMS is $\sigma_t \sim 1.5\,\mathrm{ns}$
- Restive plate chambers spaced apx. 1 meter apart; separation between first and last plate $\sim$ 3 meters
- Require ΔTOF across 3 m for exotic relative to $\beta \simeq 1$ muon to be greater than 3 ns
- Also require arrival at muon chamber within 18 ns ($\beta_D \geq 0.5$)

Nisati, Petrarca, Salvini, *Mod. Phys. Lett.*, **A12** (1997)

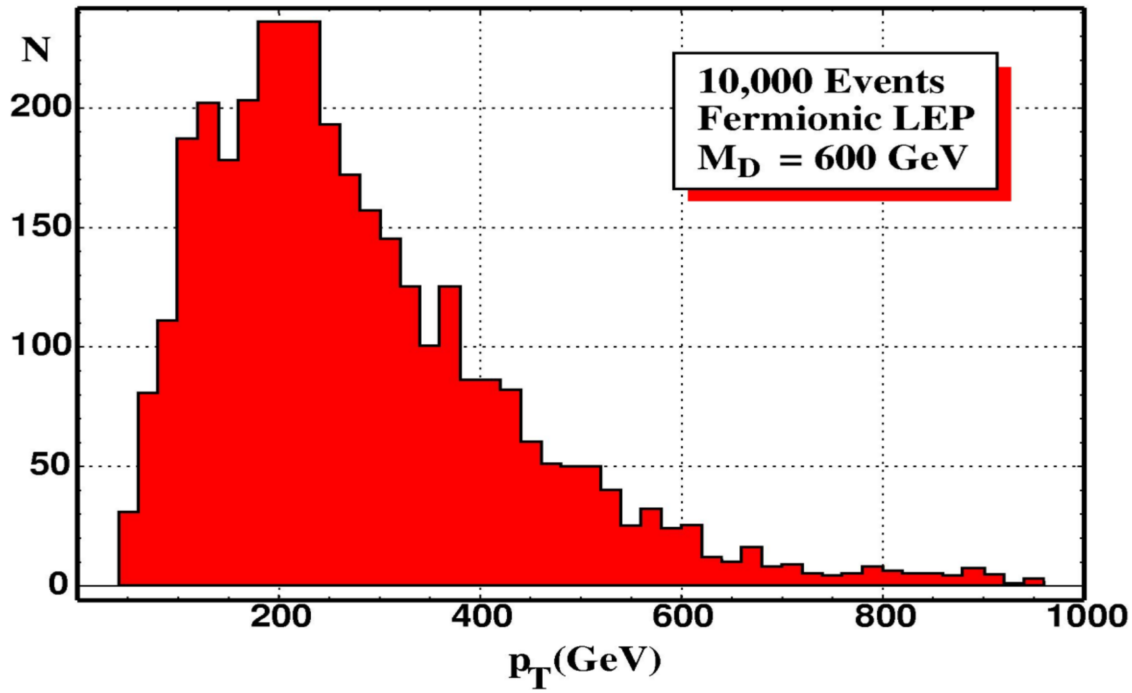
⇒ Using TOF in the muon system provides highly significant $S/\sqrt{B}$

Kraan, Hansen, Nevski, hep-ex/0511014 (2005)

Triggering

⇒ Low-level triggers look at calorimetery and muon system *individually*

- Direct production of LEP pairs ⇒ little $E_T^{\rm sum}$ in calorimeter (typically 10-50 GeV)
- Produced back-to-back in c.m. frame ⇒ little $E_T^{\rm miss}$ as well
- Remains true if NLEP pair produced with, e.g., $D_0 \to D_{1/2}\widetilde{\chi}_1^0$ (typically $E_T^{\rm miss} \lesssim 35$ GeV)
- Can trigger on the (single) muon track if minimum threshold for p_T is met (we take $p_T^{\rm min} = 15$ GeV).



Quasi-Stable: Overall Acceptance

	Benchmark Point				
	A	B	C	D	E
Geom. Accept.	75.5%	79.9%	82.3%	86.8%	82.5%
Charged Frac.	25.2%	25.0%	25.1%	25.2%	25.4%
Temp. Accept.	82.7%	82.8%	81.9%	79.1%	76.9%
TOF	97.3%	96.5%	97.2%	97.3%	97.0%
Total Accept.	15.3%	16.0%	16.5%	16.9%	15.6%
N_{signal} $(\times 10^3)$	120	119	119	11.2	26.6
N_{stop} $(\times 10^3)$	11.1	10.8	11.3	1.36	4.56

- Geometrical acceptance represents the fraction of R-hadrons that are produced with $|\eta| \leq 2.4$
- Temporal acceptance represents the fraction of charged non-stopping R-hadrons that arrive within 18 ns of the primary interaction for the event
- The percentage that traverse a 3 meter fiducial distance at least 3 ns slower than a $\beta = 1$ muon would is given by TOF
- The product of these fractions is the total acceptance
- The number of signal events (as well as the number of stopping R-hadrons) is given for 10fb^{-1} of integrated luminosity

Quasi-Stable: Reach at LHC