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e^+e^- Workshop
FermiLab
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New Particles and Interactions at High Energy e^+e^- Colliders

NLC Exotics Study Group:

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DPF Study: Electroweak Symmetry Breaking & Beyond the Standard Model

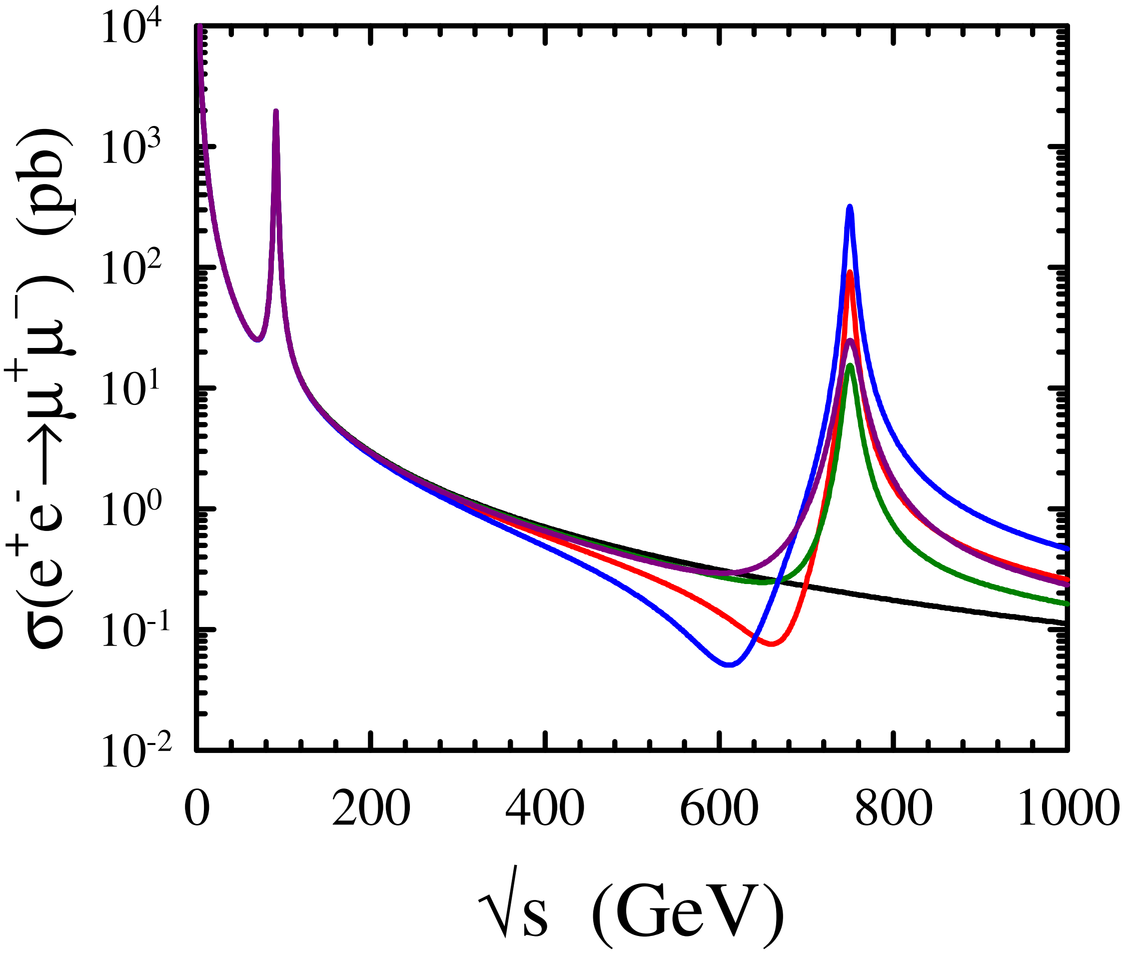
- Extra Gauge Bosons: M. Cvetic & S. Godfrey (`hep-ph/9504216`)
- New Particles and Interactions: A. Djouadi J. Ng & T. Rizzo (`hep-ph/9504210`)

- Many models approximate SM at present energies but have much richer particle spectrum above 100 GeV
  - Extensions of Standard Model Gauge Group
    * (SUSY) GUT
      · Extra U(1) Factors : $E_6 \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
      · Left-Right Symmetric Model
        $E_6/SO(10) \rightarrow SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$
    * non-GUT
      · Un-unified model (Georgi et al)
      · Horizontal model (Bagneid et al, Li & Ma)
      · Axigluon (Frampton et al)
      · Topcolour (Hill and Parke)
      · and on and on and on . . .
  - Composite Models
  - Technicolour Models
- Many Many Models

- To extrapolate to Planck scale need complete low energy particle content
- Need to elucidate and complete the TeV particle spectrum
- Many types of new particles:
  - Extra Gauge Bosons
  - New Fermions
    * 4th generations: $\begin{pmatrix} t' \\ b' \end{pmatrix}_L$, t'_R, b'_R
    * Mirror Fermions: t'_L, b'_L, $\begin{pmatrix} t' \\ b' \end{pmatrix}_R$
    * Vector fermions: $\begin{pmatrix} t' \\ b' \end{pmatrix}_L$, $\begin{pmatrix} t' \\ b' \end{pmatrix}_R$
    * Singlets (like massive neutrinos)
  - Extended Higgs Sector
  - Pseudo Goldstone Bosons
  - Leptoquarks
  - Vector Resonances
  - Dileptons: $B = 0$ and $L = \pm 2$
  - Diquarks: $B = \pm 2/3$ and $L = 0$
  - Excited Fermions; Substructure so $f \to f^{(1)}(\gamma, W, Z, g)$
  - TRULY WEIRD

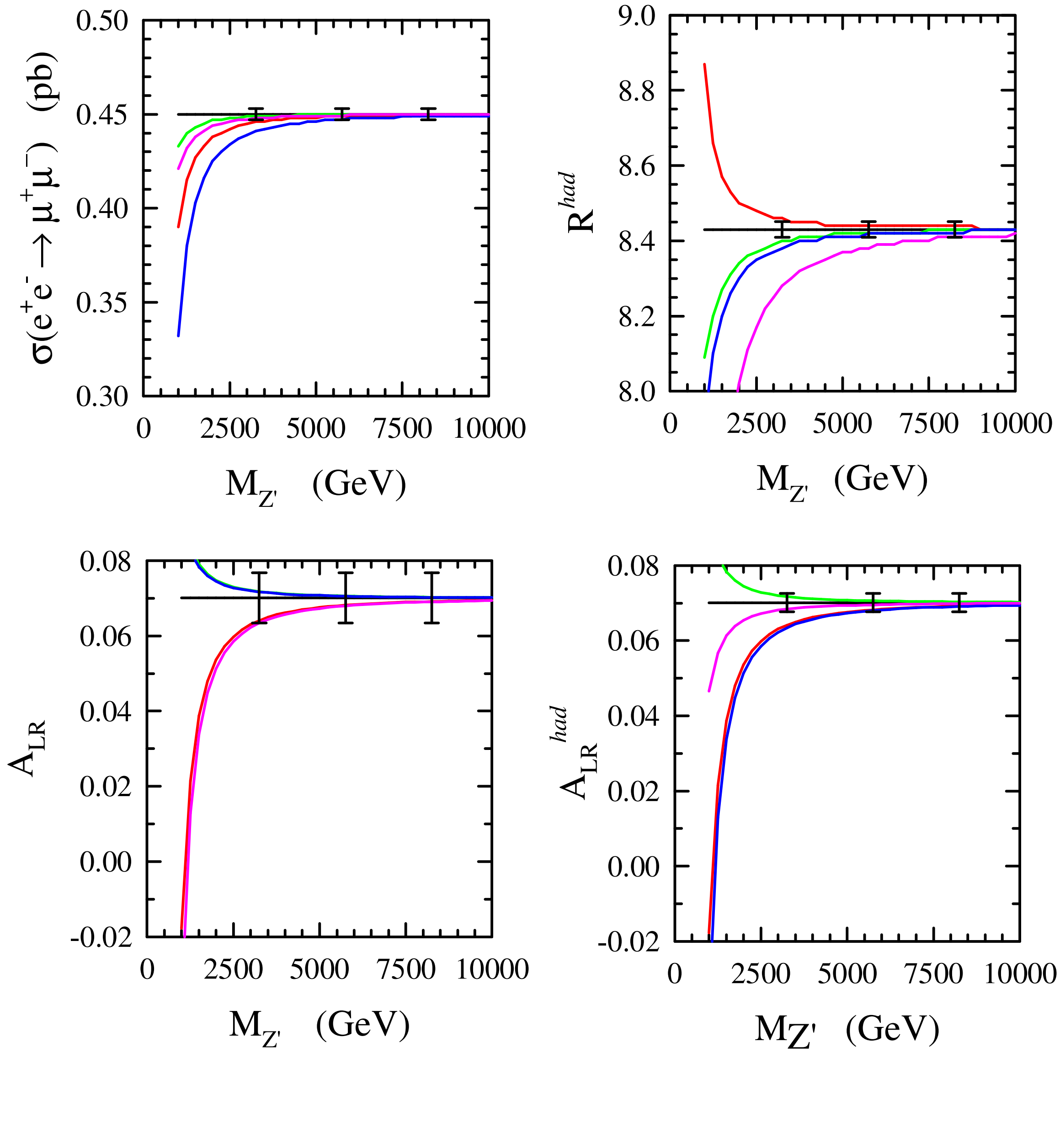
1. Discovery
   - Identify Signal
   - Distinguish it from background
2. Identification
   - Cross sections
   - Angular distributions
   - Decay signatures (Width, BR, etc)
   - Polarization

1 Z' Search and Identification

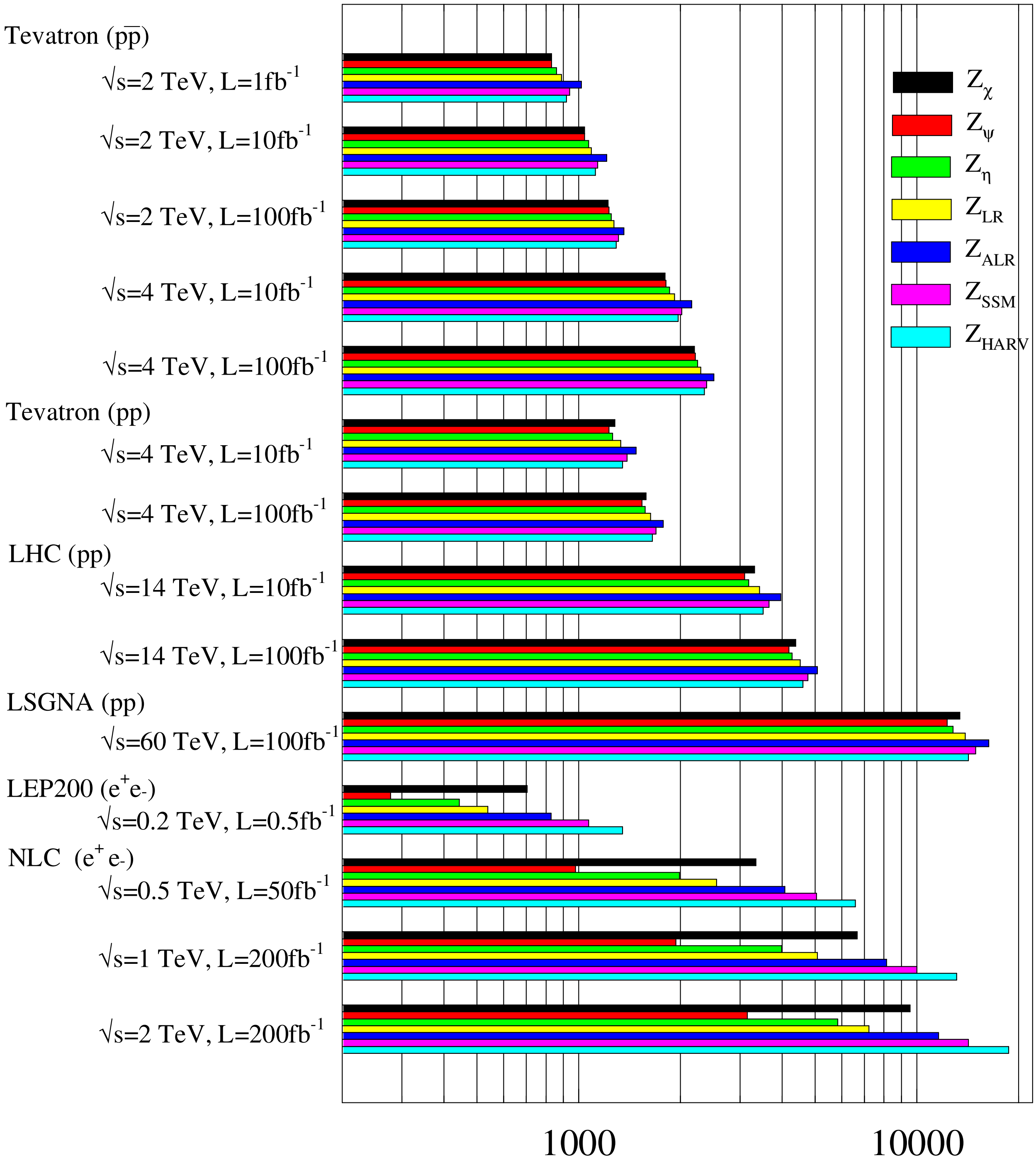


SM, $M_{Z'} = 750$ GeV: Z_χ, Z_{LR}, Z_{ALR}, Z_{SSM}

$\sigma_f \qquad A^f_{FB} \qquad A^f_{LR} \qquad A^f_{FB}(pol)$



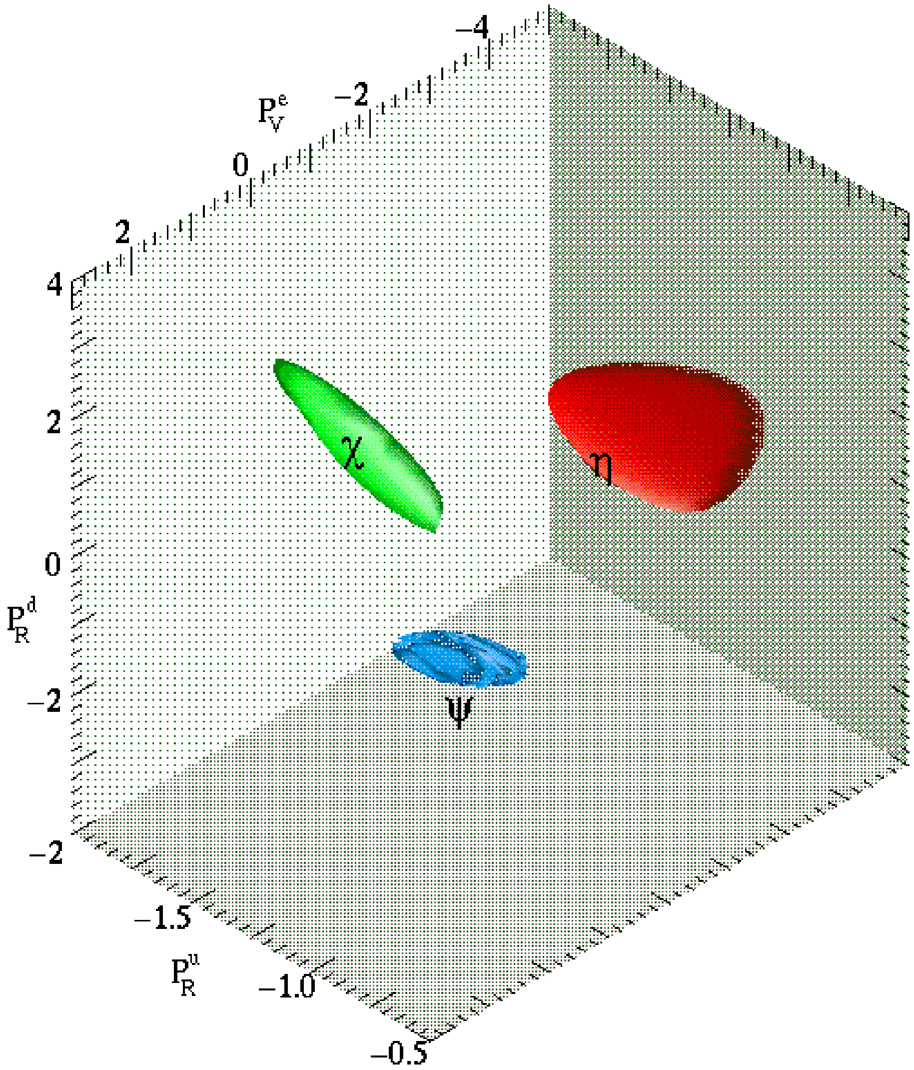
SM, Z_χ, Z_{LR}, Z_{ALR}, Z_{SSM}



Tevatron ($p\bar{p}$)
$\sqrt{s}$=2 TeV, L=1fb^{-1}
$\sqrt{s}$=2 TeV, L=10fb^{-1}
$\sqrt{s}$=2 TeV, L=100fb^{-1}
$\sqrt{s}$=4 TeV, L=10fb^{-1}
$\sqrt{s}$=4 TeV, L=100fb^{-1}
Tevatron (pp)
$\sqrt{s}$=4 TeV, L=10fb^{-1}
$\sqrt{s}$=4 TeV, L=100fb^{-1}
LHC (pp)
$\sqrt{s}$=14 TeV, L=10fb^{-1}
$\sqrt{s}$=14 TeV, L=100fb^{-1}
LSGNA (pp)
$\sqrt{s}$=60 TeV, L=100fb^{-1}
LEP200 (e^+e^-)
$\sqrt{s}$=0.2 TeV, L=0.5fb^{-1}
NLC (e^+e^-)
$\sqrt{s}$=0.5 TeV, L=50fb^{-1}
$\sqrt{s}$=1 TeV, L=200fb^{-1}
$\sqrt{s}$=2 TeV, L=200fb^{-1}
Z_χ
Z_ψ
Z_η
Z_{LR}
Z_{ALR}
Z_{SSM}
Z_{HARV}
1000
10000

Define

$$P_V^\ell \equiv \frac{g_L^\ell + g_R^\ell}{g_L^\ell - f_R^\ell} \qquad P_L^q \equiv \frac{g_L^q}{g_L^\ell - g_R^\ell} \qquad P_R^{u,d} \equiv \frac{f_R^{u,d}}{f_L^q}$$

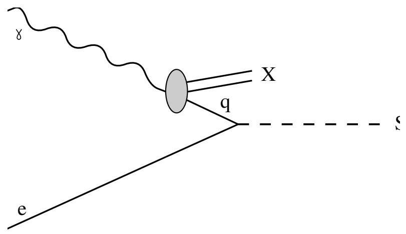


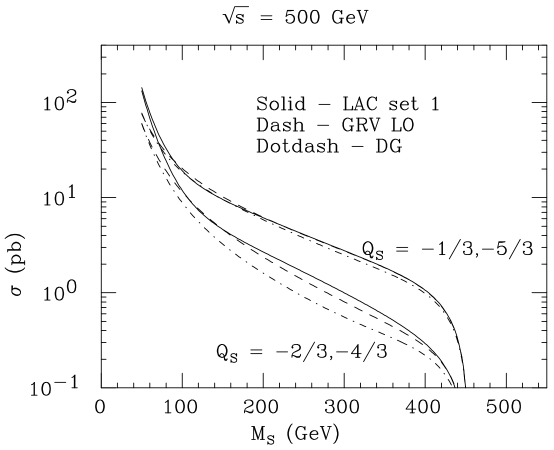
$M_{Z'} = 1$ TeV, $\sqrt{s} = 500$ GeV, L=50 fb^{-1}

- Good for $M_{Z'} \sim 1 - 2$ TeV
- Comparable to LHC
- No sign ambiguities (as in LHC)

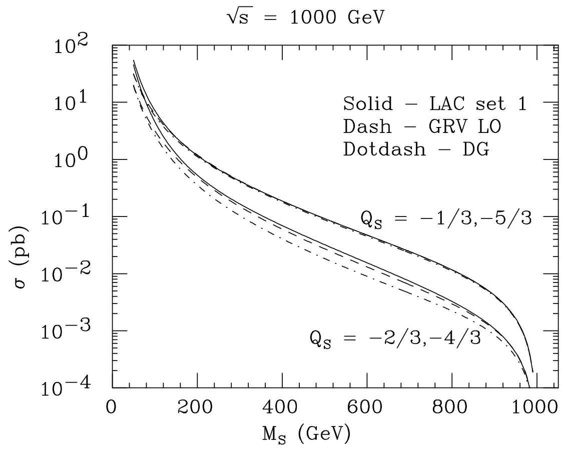
2 Leptoquark Production and Identification

- Colour (anti-) triplets
- Spin 0 or 1
- Carry baryon and lepton quantum numbers
- Appear in Guts, technicolour, composite models
- Signal is high p_T lepton balanced by a jet
- 10 types according to B-R-W classification





Backscattered Laser, $\sqrt{s} = 500$ GeV



e^+e^-, $\sqrt{s} = 1$ TeV

Leptoquark Identification

- Scalar or Vector by decay distributions
- Electron Polarization for coupling chirality

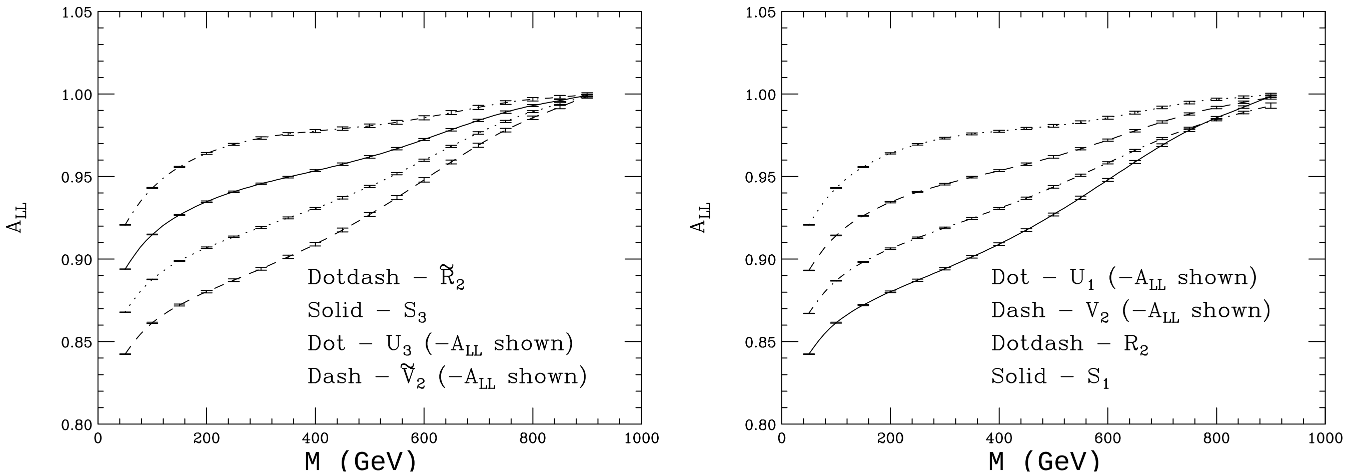
$$A^{+-} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{C_L^2 - C_R^2}{C_L^2 + C_R^2}$$

- Further divide using double asymmetry;
  - Scalars have σ^{++} σ^{--}
  - Vectors have σ^{+-} σ^{-+}

$$A_{LL} = \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})}$$

Scalars have +ve A_{LL} and Vectors have -ve A_{LL}

- Can uniquely determine leptoquark types
- Important to unravel underlying theory

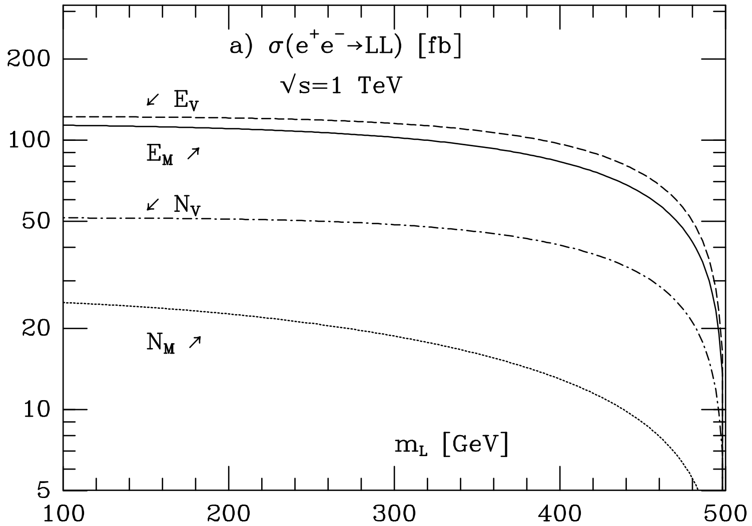


Backscattered Laser, $\sqrt{s} = 1$ TeV

3 New Elementary Fermions

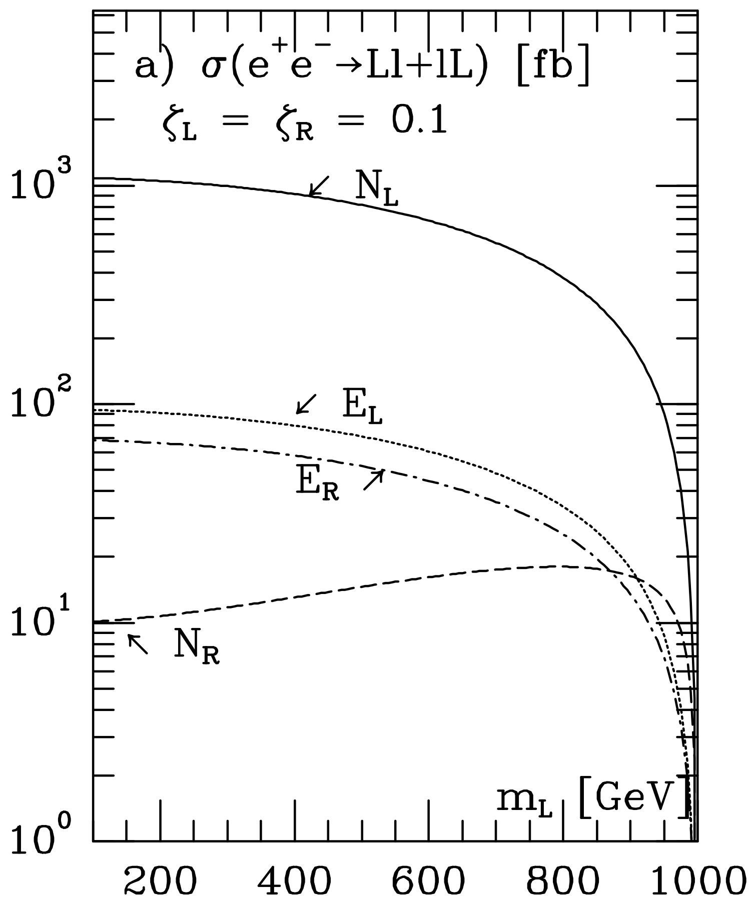
- 4th generation fermions
- vector-like fermions
- mirror fermions

Except for singlet neutrinos new fermions couple to the photon and/or weak bosons with full strength allowing for pair production with unambiguous cross section



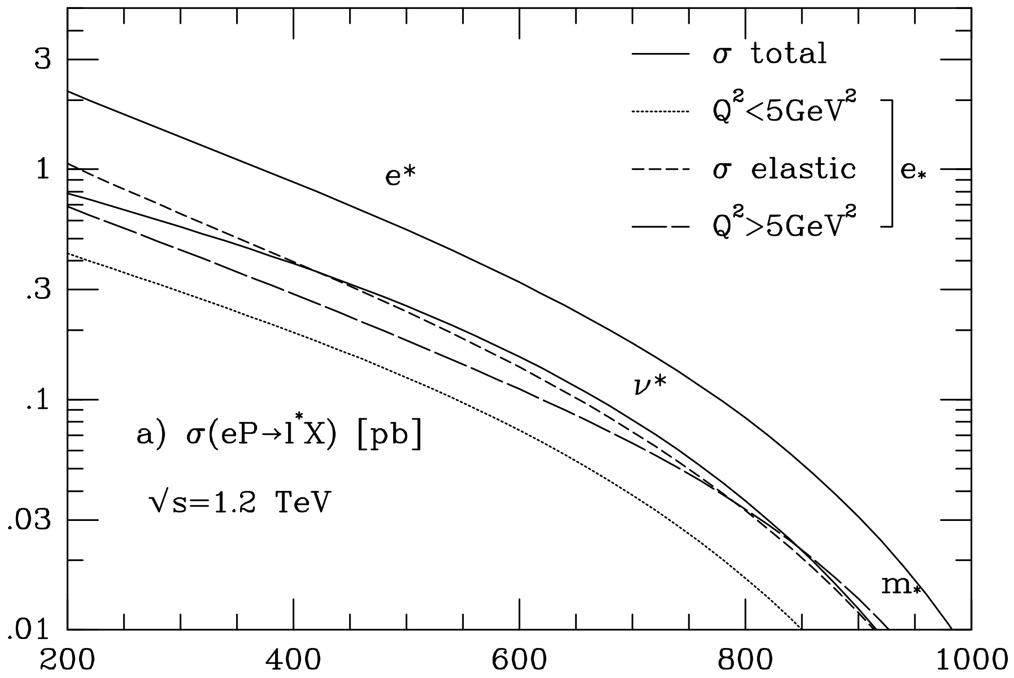
- Produced via $e^+e^- \to F\bar{F}$ through s-channel so $\sigma \sim \sigma_0$
- Masses close to kinematic limit can be probed
- Detection straightforward in clean environment of e^+e^- collider

- For conventional QN's new fermions can mix with their SM partners
- Mixing constrained by non-observation of FCNC
- If mixing not too small can produce singly in association with light partners
- If possible the mass search is much higher for a given collider
- Dominant decay via charged current
  - for $\theta < 0.1$ $\Gamma < 10$ MeV for $M_F = 0.1$ TeV
  - for $\theta < 0.1$ $\Gamma < 10$ GeV for $M_F = 1$ TeV



4 Excited Fermions

- Characteristic signal of substructure
- Rich spectrum of excited states
- No satisfactory model
- Pair produced in e^+e^- via s-channel
- Decay into gauge boson and ordinary partner: $f^* \to fV$
- Detection of f^* masses up to kinematic limit may be possible
- Can be singly produced with light partners but rates are suppressed by a factor of $1/\Lambda^2$



5 Summary

Particle	Present	LEP 2	Tev*	LHC	NLC
W_R	652		1180	5310	$\sqrt{s}/2^*$
Z_{SSM}	650	1070	2020	4760	5050
Leptoquark	180		250-400	1-2 TeV	450
axigluon	1000				
Leptons	$M_Z/2$				$\sqrt{s}/2^*$
Quarks	$M_Z/2$			$\sim$ 1 TeV	
q^*	600			5-6 TeV	
e^*				$\sim$ 4 TeV	$\sqrt{s}/2^*$
diquark	450				

- Lots more to do
- Complementarity of LHC and NLC
- Detailed Simulation Studies
- Look for Genuine Surprises!