S. Godfrey
Pheno 2000
Madison
April 18 2000

Discovery and Identification of W' and Z' Bosons at e^+e^- Colliders

S.Godfrey, P. Kalyniak, B. Kamal
Carleton University, Ottawa
A. Leike
LMU München
M. Doncheski
Pennsylvania State - Mont Alto

1. Introduction
2. Models of Extra Gauge Bosons
3. Processes, Calculations, and Results
   (a) $e^+e^- \to \nu\bar{\nu}\gamma$
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4. Summary and Outlook

- Discovery and ID of Extra Gauge Bosons in $e^+e^- \to \nu\bar{\nu}\gamma$: [hep-ph/0002052]
- Constraints on Extra Gauge Bosons in $e\gamma$ Collisions: [hep-ph/0001074]
- Extra Gauge Bosons: M. Cvetic & S. Godfrey [hep-ph/9504216]

1 Introduction

- 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 : $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\psi$
      - Left-Right Symmetric Model $E_6/SO(10) \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$
    - non-GUT
      - Sequential Standard Model
      - Un-unified model (Georgi et al) $SU(2)_q \times SU(2)_l \times U(1)_Y$
      - Horizontal gauge models (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
  - 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

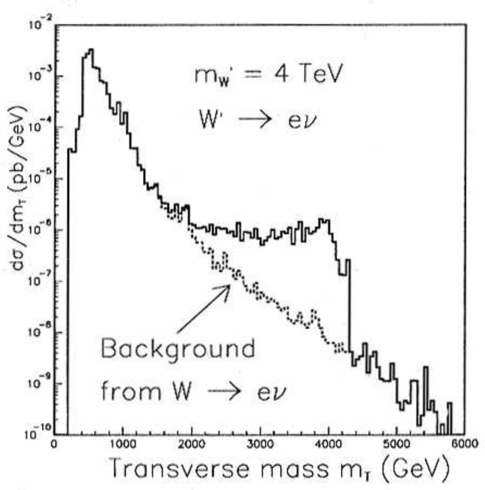
1. Discovery
   - Identify Signal
   - Distinguish it from background
2. Identification
   - Cross sections
   - Angular distributions
   - Decay signatures (Width, BR, etc)
   - Polarization

2 Models of Extra Gauge Bosons

- Sequential Standard Model (SSM)
  - Includes Z' and/or W' of higher mass with SM couplings
  - Rather arbitrary but commonly used as benchmark
- L-R Model $(SU(2)_L \times SU(2)_R \times U(1))$
  - Left handed fermions transform as $SU(2)_L$ doublets and $SU(2)_R$ singlets with revers true for Right handed fermions
  - Model parametrized by $\kappa = g_R/g_L$ with $0.55 \leq \kappa \leq 2.0$
- "Un-Unified Model" $(SU(2)_q \times SU(2)_l \times U(1)_Y)$
  - Quarks and Leptons transform as doublets under separate $SU(2)$ groups
  - Parametrize by ϕ - the mixing angle of charged gauge bosons with $0.24 \leq \sin\phi \leq 0.99$
  - The fermion couplings are all left-handed
- KK excitations- Large Extra Dimensions
  - Extend SM to 5-dimensions
  - We include exchange of W' and Z' corresponding to first KK excitation with $M_{Z'} \simeq M_{W'} = M_c = 1/R$
  - The Fermion couplings of 1st KK excitation are SM couplings enhanced by a factor of $\sqrt{2}$

3 W' Search and Identification

- $pp \to W_R + X$



  - W' up to 6 TeV

- $e^+e^- \to W_R^+ W_R^-$
  - Up to kinematic limit
  - Depends on κ, M_N, $M_{Z'}/M_{W_R}$

- $e^\pm \gamma \to W_R^\pm N$
  - Large rate up to kinematic limit

3.1 Present and Future Limits

Present Limits (PDB' 99):

- $M(W'_R) > 549$ GeV (ν_R is light)
- $M(W') > 720$ GeV (W' couples like W)
- $M(Z') > 600$ GeV (Z' in typical GUTs)
- $M(Z') > 779$ GeV (Z' couples like Z)

Future Limits from LHC:

- $M(W) > 4$ to 5 TeV (GUTs)
- $M(W'_R) > 6.4$ TeV (J. Collet, A. Ferrari; ATLAS)
- $M(Z') > 4.5$ TeV (Z' in typical GUTs)

LHC limits depend on g_L/g_R and on the right-handed CKM Matrix and can degrade by a factor of 2 or more

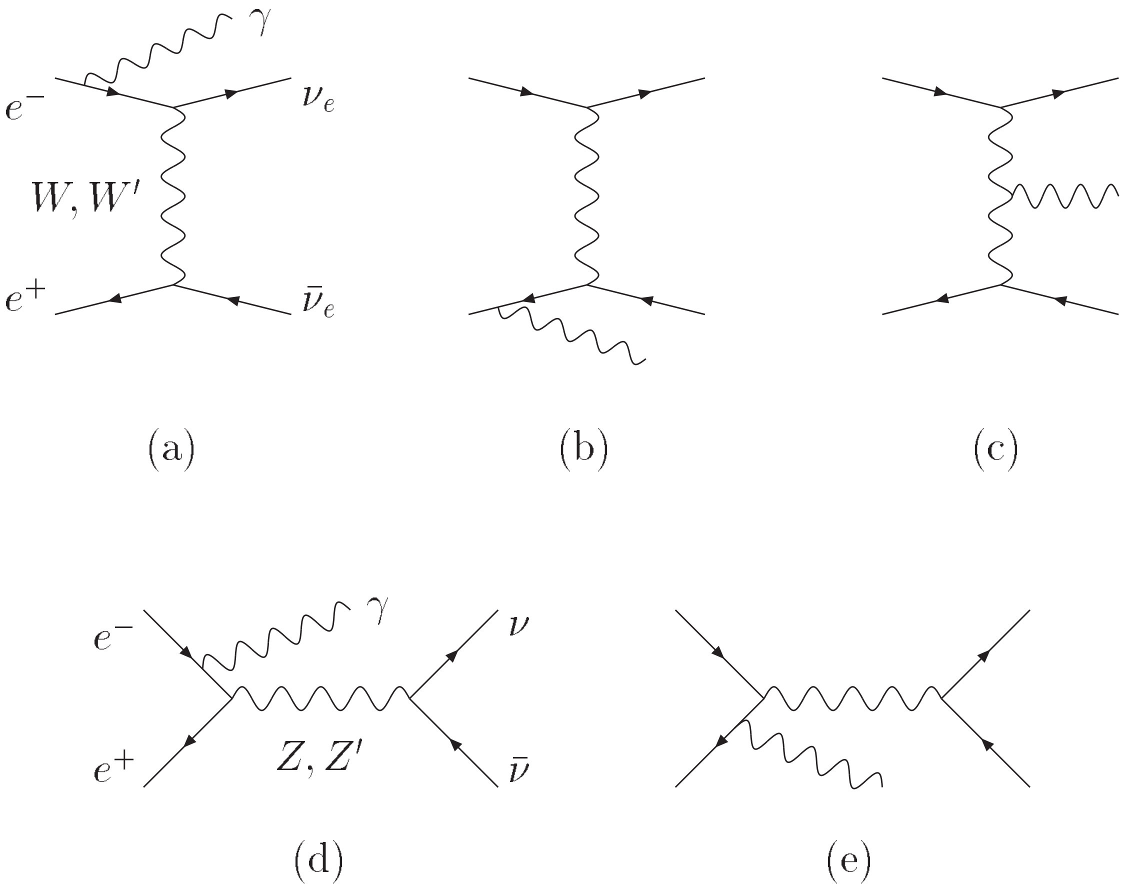
T.G. Rizzo, Phys. Rev. D**50**, 325(1994).

Future Limits from NLC:

- $M(Z') > 1$ to 6 TeV ($\sqrt{s} = 0.5$ TeV, $L_{int} = 50$ fb^{-1})
- $M(Z') > 2$ to 12 TeV ($\sqrt{s} = 1.0$ TeV, $L_{int} = 200$ fb^{-1})

4 Processes, Calculations, and Results

4.1 The Process $e^+e^- \to \nu\bar{\nu}\gamma$

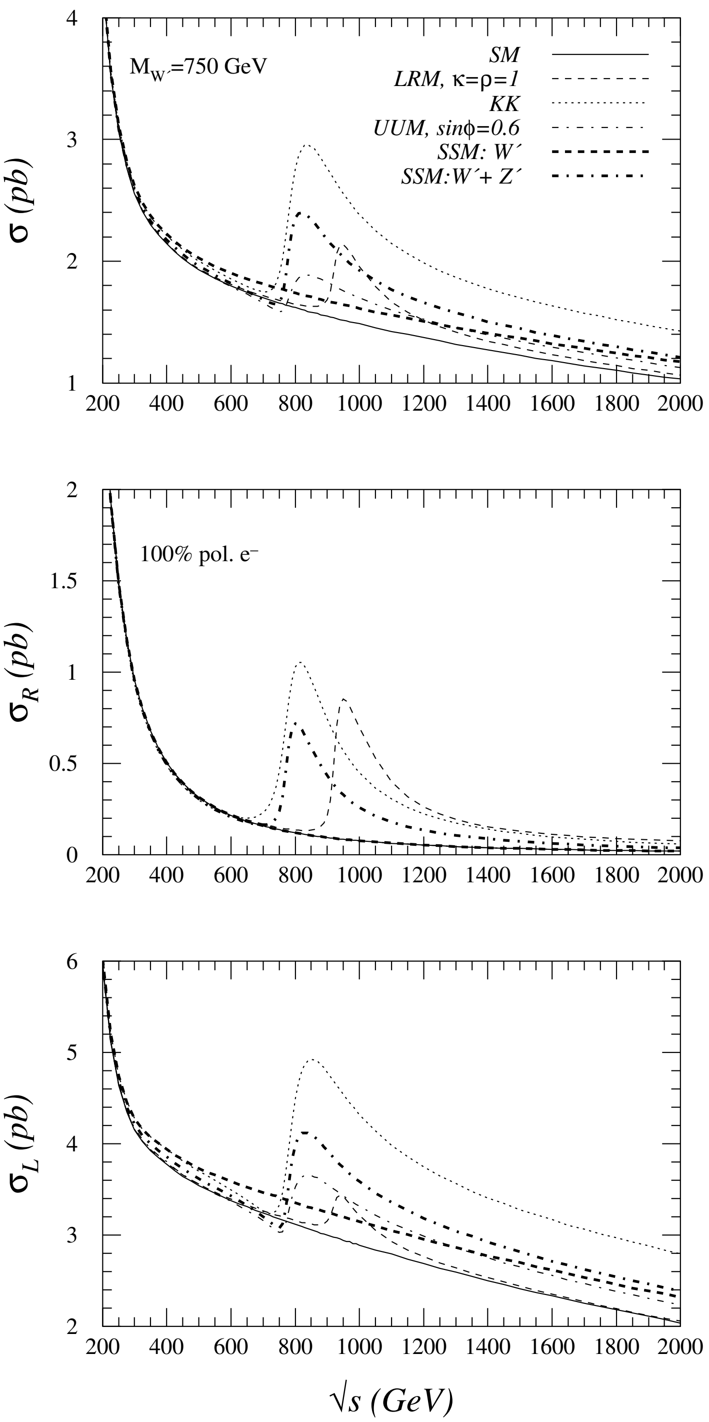


Preliminary study by J.L. Hewett, Snowmass'96, hep-ph/9704292.

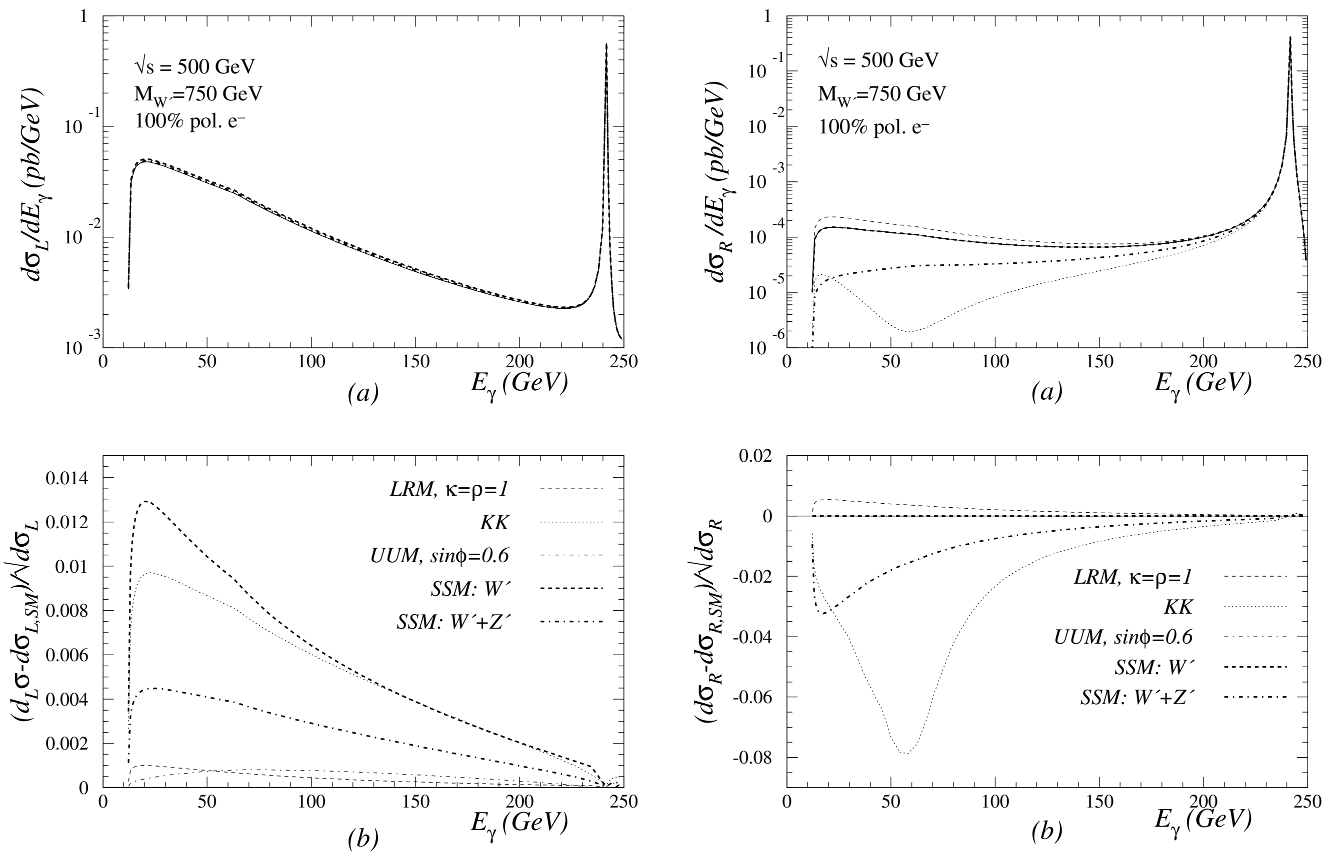
Independent calculations:

- CALKUL helicity amplitudes + Monte Carlo integration
- $|Matrix\ \ Elements|^2$ + Monte Carlo integration
- Partial analytic integration of $|Matrix\ \ Elements|^2$ + numerical integration

- Kinematic cuts to reflect finite detector acceptance:
  - $10^o \leq \theta_\gamma \leq 170^o$
  - $E_\gamma > 10$ GeV
- Backgrounds:
  - Radiative Bhabba-scatter with e^+ and e^- lost down beam pipe
    $$p_T^\gamma > \frac{\sqrt{s}\sin\theta_\gamma \sin\theta_v}{\sin\theta_\gamma + \sin\theta_v}$$
    where $\theta_v = 25$ mrad is minimum angle for veto detector
  - $e^+e^- \to \nu\bar{\nu}\nu'\bar{\nu}'\gamma$ must be taken into account but can be calculated in SM



The total cross sections σ, σ_L and σ_R versus $\sqrt{s}$ for $M_{W'} = 750$ GeV. For σ_L and σ_R, 100% e^- polarization is used. Results are given for the SM (solid line), LRM (dashed line), KK model (dotted line), UUM (dash-dotted line), SSM(W') (thick dashed line) and SSM($W' + Z'$) (thick dash-dotted line).



- $E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M^2_{\nu\bar{\nu}}}{s}\right)$
- Bulk of cross section from radiative return of Z^0
- For e^-_R large deviations but small cross section
- Pollution from e^-_L could overwhelm $\sigma(e^-_R)$
- Low E_γ region most sensitive to Z'
- Can increase statistical significance by binning

Discovery Limits for W''s

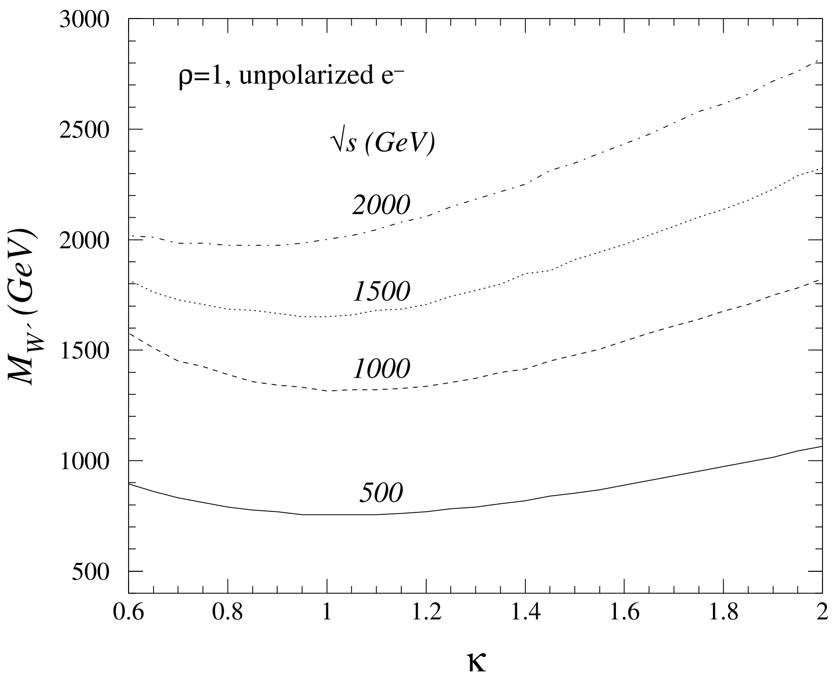
- Best limits using $d\sigma/dE_\gamma$ combined with polarization
- Similar limits using σ with Z^0 radiative return removed:

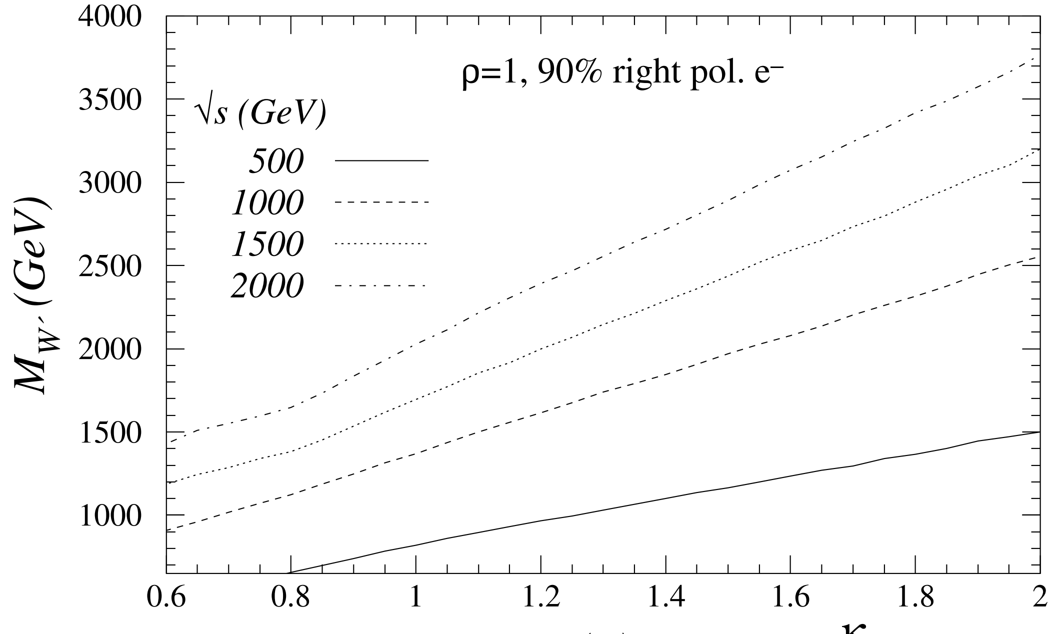
$$E_\gamma^{max} = \frac{\sqrt{s}}{2}(1 - M_Z^2/s) - 6\Gamma_Z$$

- But $d\sigma/dE_\gamma$ degraded less than σ when systematic errors included.
- Used 10 equal sized bins with:

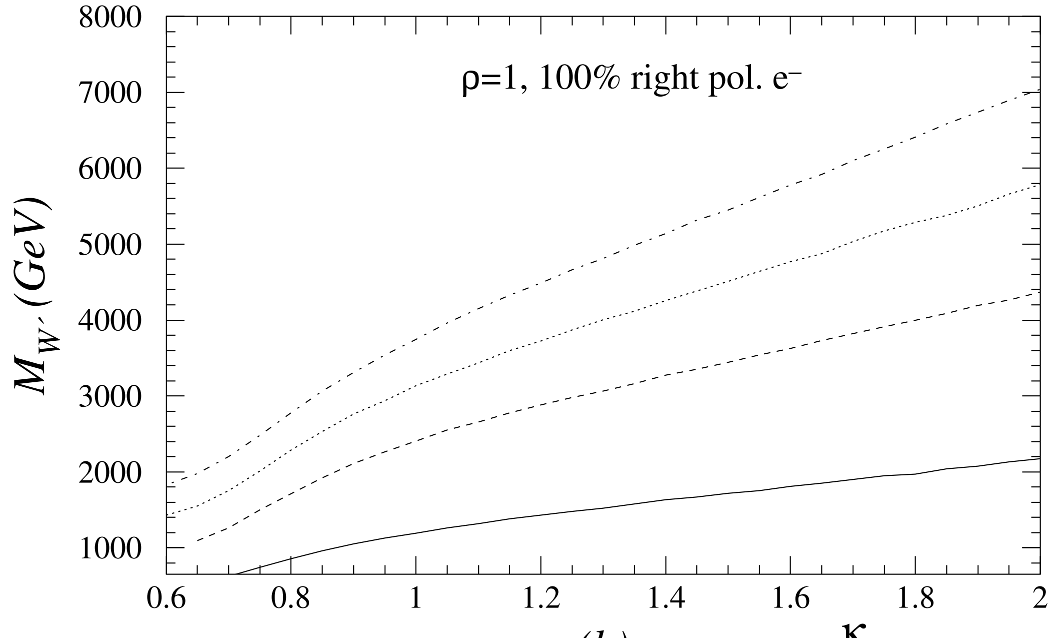
$$E_\gamma^{min} < E_\gamma < E_\gamma^{max} \quad \text{where} \quad E_\gamma^{min} = \frac{\sqrt{s}\sin\theta_v}{1+\sin\theta_v}$$

- Included 2% systematic error in quadrature with statistical error
- Used e_L^- except for LRM where used e_R^-
- Weaker limits obtained using: $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$

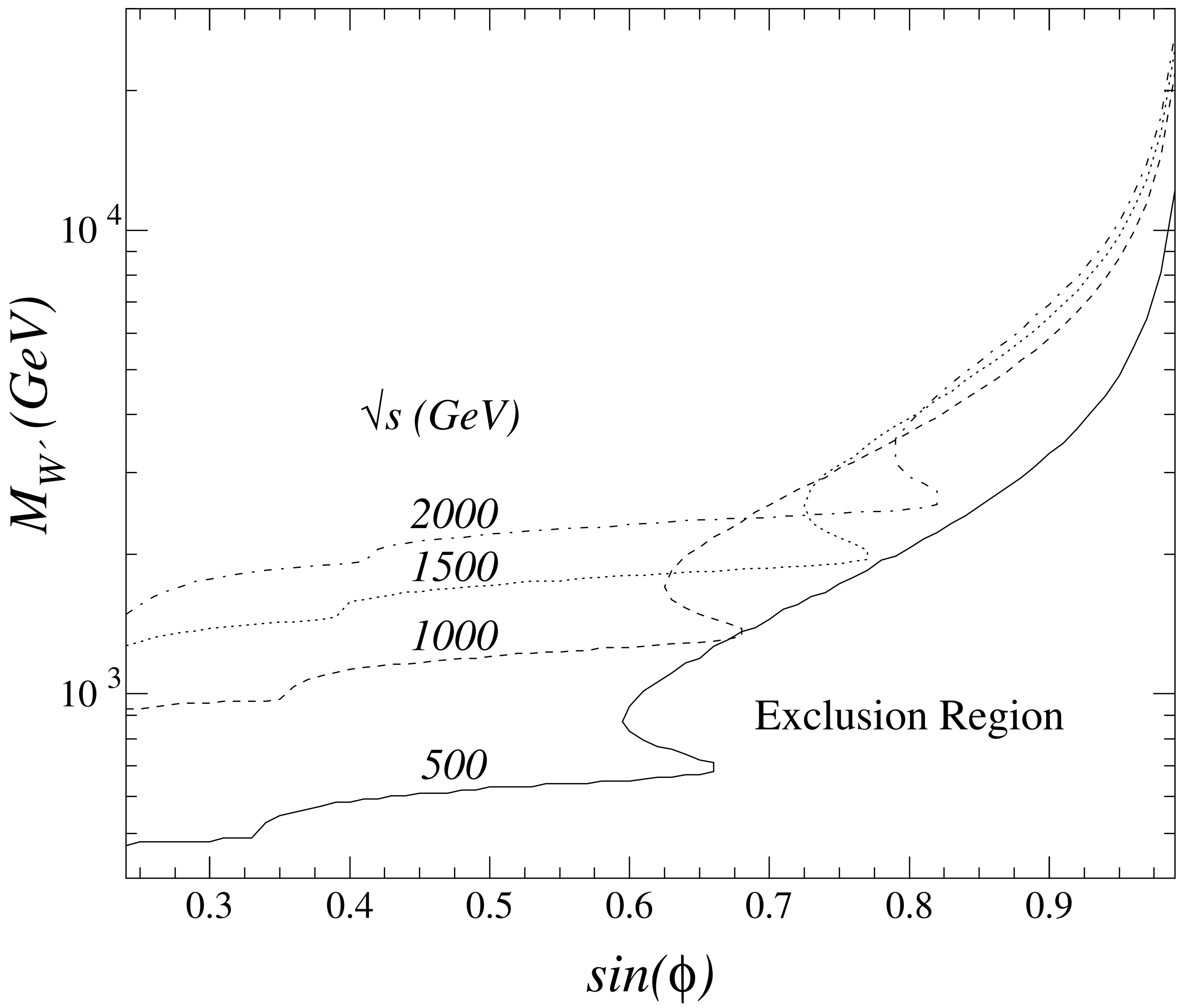



ρ=1, 90% right pol. e⁻
√s (GeV)
500
1000
1500
2000
$M_{W'}$ (GeV)
κ
4000
3500
3000
2500
2000
1500
1000
0.6
0.8
1
1.2
1.4
1.6
1.8
2

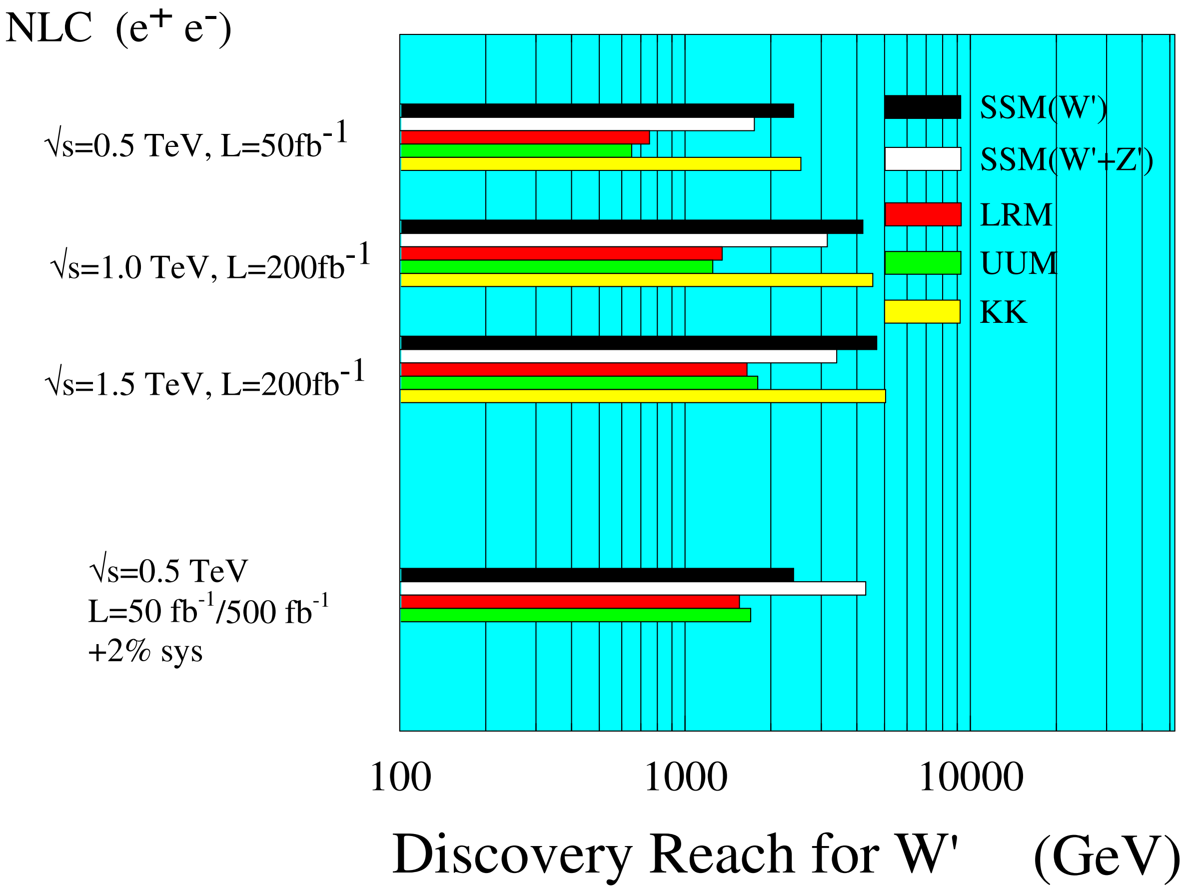
(a)


ρ=1, 100% right pol. e⁻
$M_{W'}$ (GeV)
κ
8000
7000
6000
5000
4000
3000
2000
1000
0.6
0.8
1
1.2
1.4
1.6
1.8
2

(b)

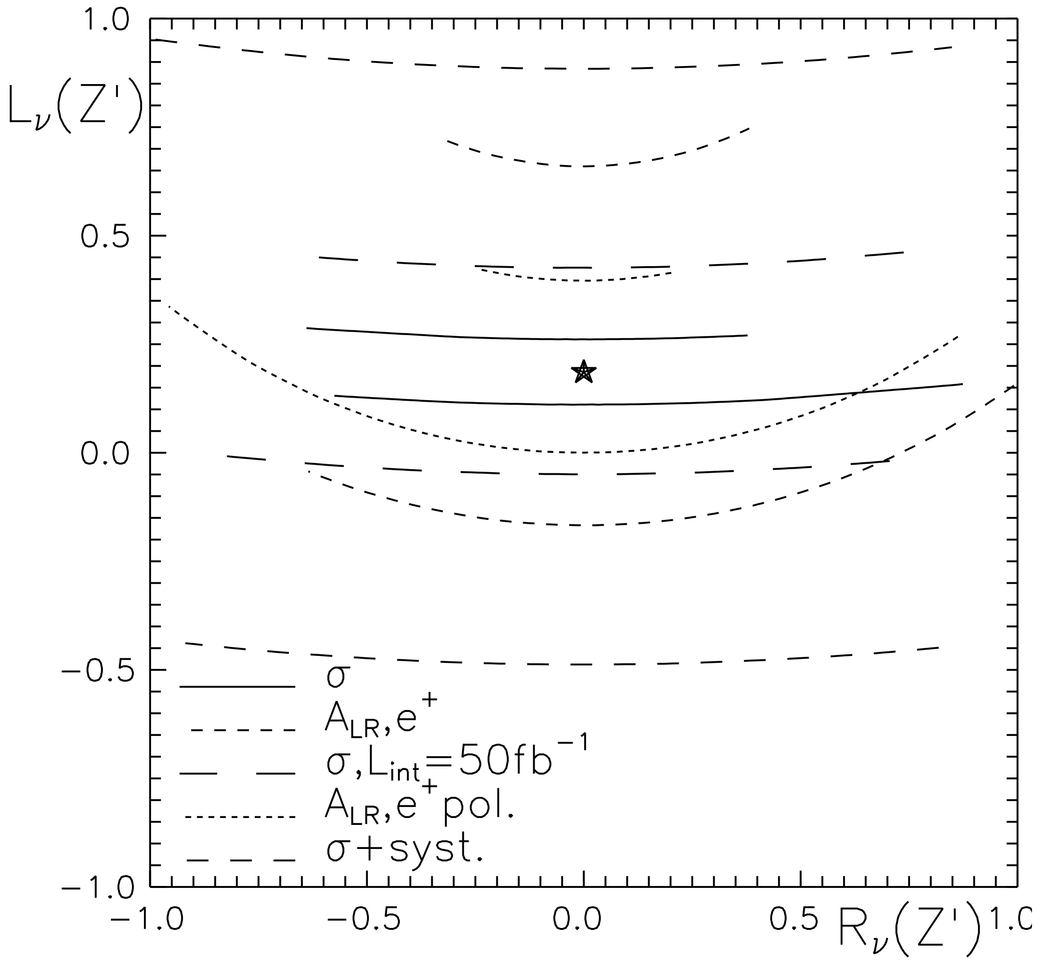


UUM unpolarized 95% C.L. W' mass limits versus $\sin\phi$, obtained for $\sqrt{s} = 500$, 1000, 1500 and 2000 GeV using $d\sigma/dE_\gamma$ as the observable and an integrated luminosity of 50 fb^{-1} for $\sqrt{s} = 500$ GeV and 200 fb^{-1} for the higher energies. Only statistical errors are used.

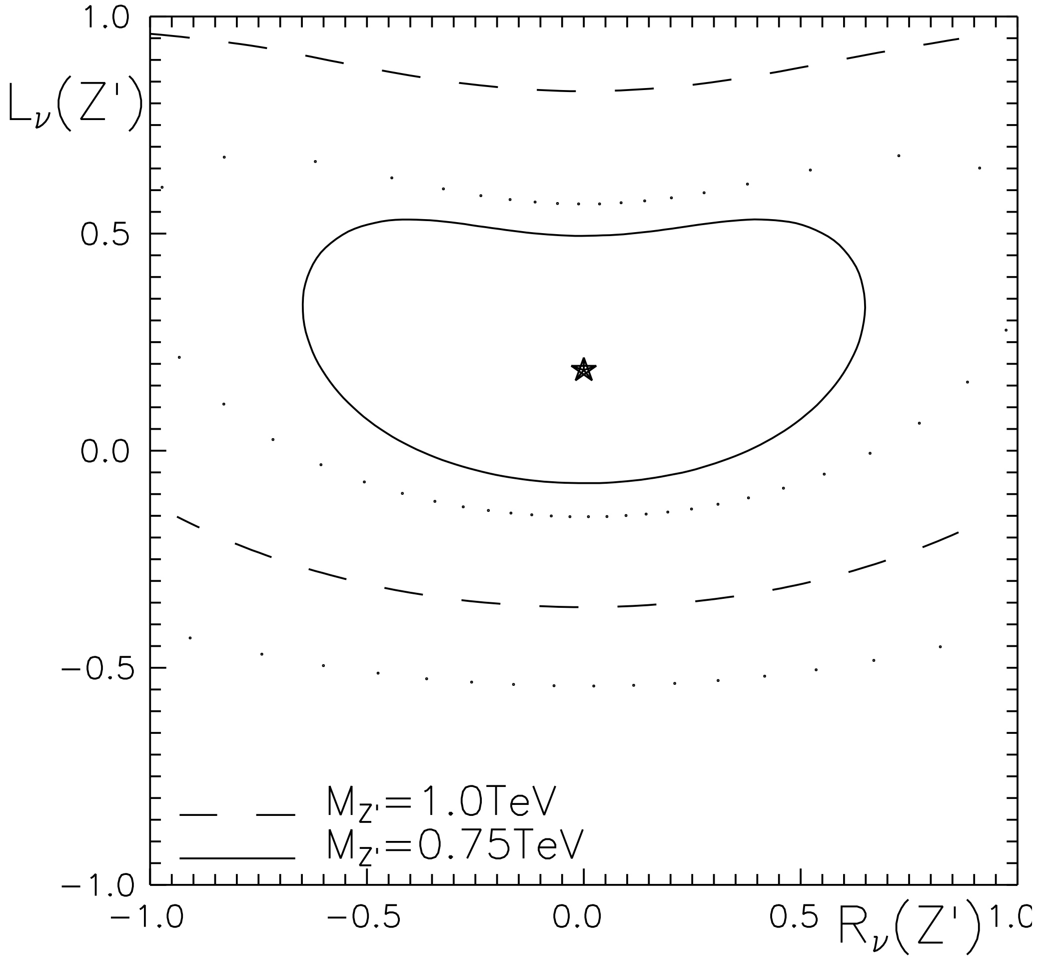

NLC (e+ e-)
√s=0.5 TeV, L=50fb-1
√s=1.0 TeV, L=200fb-1
√s=1.5 TeV, L=200fb-1
√s=0.5 TeV
L=50 fb-1/500 fb-1
+2% sys
SSM(W')
SSM(W'+Z')
LRM
UUM
KK
100
1000
10000
Discovery Reach for W' (GeV)

Constraints on Couplings

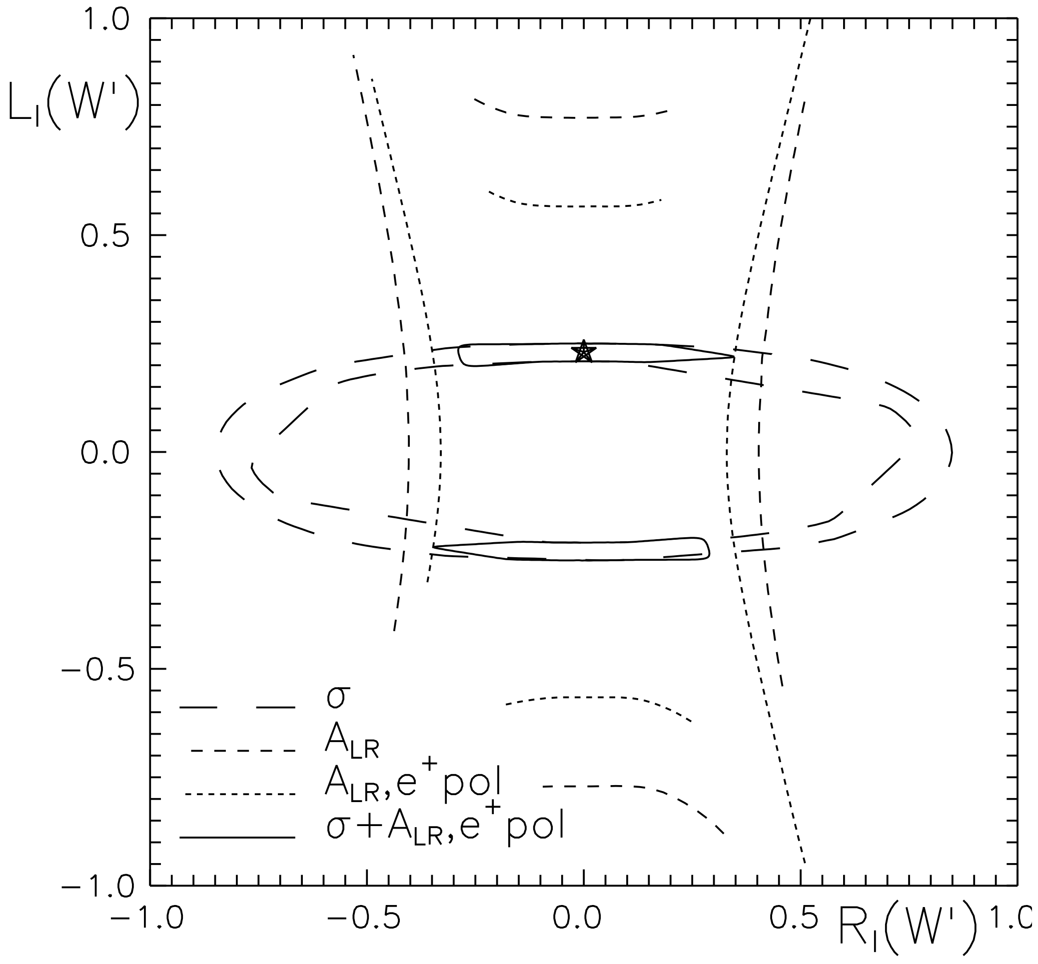
- If Z' exists much lower than search limit expect to be discovered at LHC or in $e^+e^- \to f\bar{f}$
- Want to learn its couplings
- Define: $L_f(Z) = \frac{g}{4c_W} a^f_{Z_i}$, $L_f(W) = \frac{g}{2\sqrt{2}} a_{W_i}$



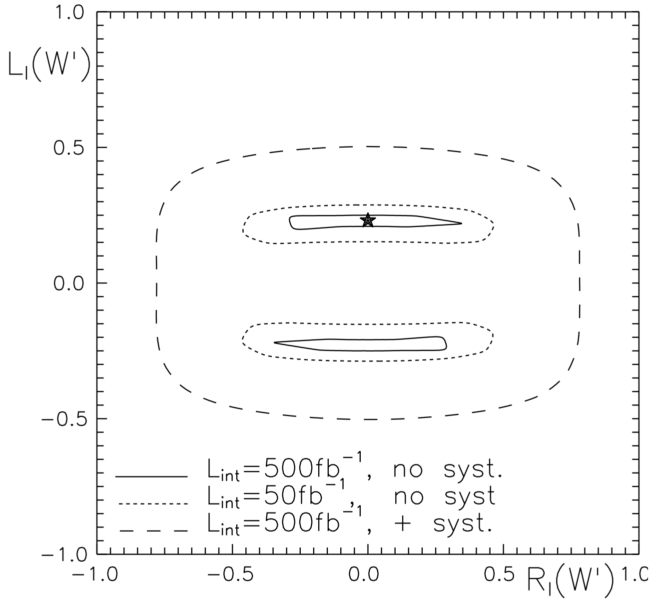
$\sqrt{s} = 0.5$ TeV, $M_{Z'} = 1.5$ TeV and $L_{\text{int}} = 500$ fb^{-1}, except in the indicated case where it is 50 fb^{-1}. The polarization of the electron beam is 90% and the positron beam is unpolarized, except in the indicated case where it is 60% polarized. Only statistical errors are included in this figure, except in the indicated case where a systematic error of 1% is included for σ. The assumed model is a Z' in the Sequential Standard Model [SSM (Z')], indicated by a star.



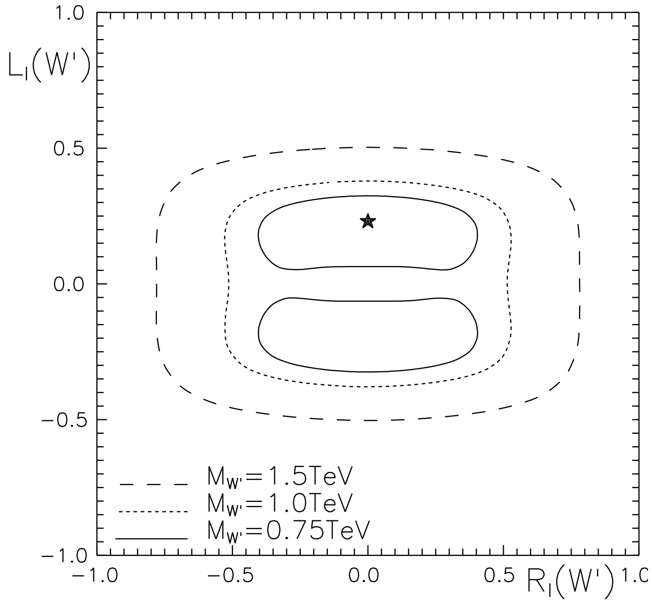
Using σ and A_{LR} combined as observables. The lines show the results for two different Z' masses. The dots indicate how the constraints relax if the error on the $Z'e^+e^-$ coupling measurement is included as described in the text. We take $\sqrt{s} = 0.5$ TeV, $L_{\rm int} = 500$ fb^{-1} and a systematic error of 2% (1%) for σ (A_{LR}). The assumed model [SSM (Z')] is indicated by a star.



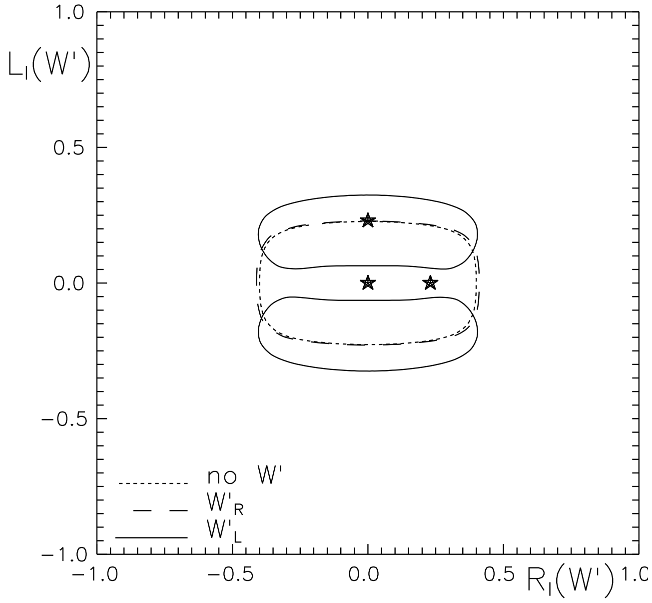
Constraints on the W' couplings using σ, A_{LR} and using σ and A_{LR} combined as observables. We take $\sqrt{s} = 0.5$ TeV, $L_{\rm int} = 500$ fb^{-1} and $M_{W'} = 1.5$ TeV. Only statistical errors are included in this figure. 90% electron and, where indicated, 60% positron polarization are used. The assumed model [SSM (W')] is indicated by a star.



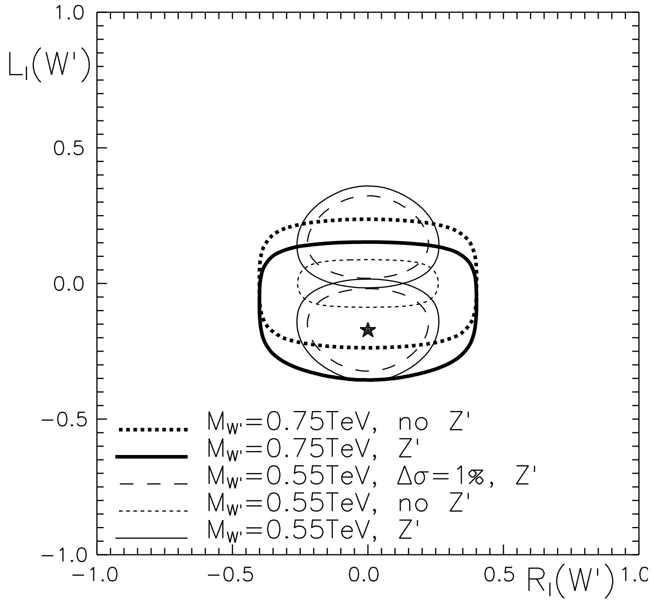
Constraints on the W' couplings using σ and A_{LR} combined. 90% electron and 60% positron polarization are used. We take $\sqrt{s} = 0.5$ TeV, $M_{W'} = 1.5$ TeV and $L_{\rm int} = 500$ fb^{-1}, except in the indicated case where it is 50 fb^{-1}. Only statistical errors are used, except in the indicated case where a systematic error of 2% (1%) is included for σ (A_{LR}). The assumed model [SSM (W')] is indicated by a star.



Constraints on the W' couplings using σ and A_{LR} combined for different W' masses. We take 90% electron and 60% positron polarization, $\sqrt{s} = 0.5$ TeV and $L_{\rm int} = 500$ fb^{-1}. A systematic error of 2% (1%) is included for σ (A_{LR}). The assumed model [SSM (W')] is indicated by a star.



Constraints on the W' couplings using σ and A_{LR} combined for different W' scenarios. We take 90% electron and 60% positron polarization, $\sqrt{s} = 0.5$ TeV, $L_{\rm int} = 500$ fb^{-1} and $M_{W'} = 0.75$ TeV. A systematic error of 2% (1%) is included for σ (A_{LR}). The assumed models are indicated by stars.

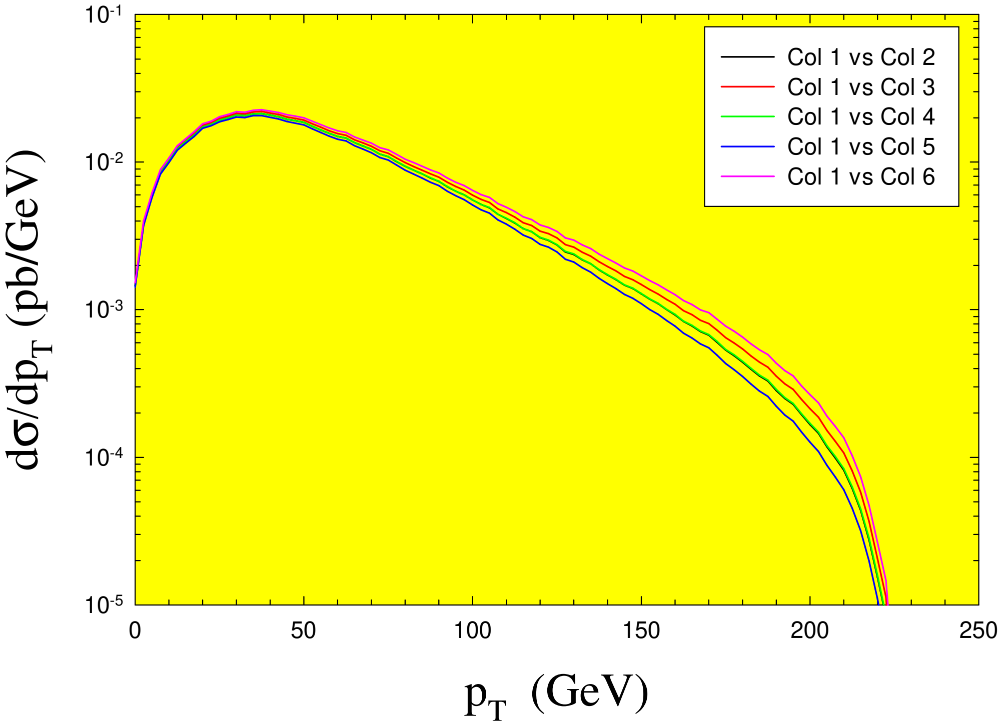


Constraints on the W' couplings using σ and A_{LR} combined in the UUM with $\sin\phi = 0.6$ for different W' masses and different fitting strategies; see text. We take 90% electron and 60% positron polarization, $\sqrt{s} = 0.5$ TeV and $L_{\rm int} = 500$ fb^{-1}. Unless otherwise indicated, a systematic error of 2% (1%) is included for σ (A_{LR}). The coupling of the assumed model (UUM) is indicated by a star.

4.2 The Process $e\gamma \to \nu_e \bar{q} q$

- Includes photon spectrum from backscattered laser
- Kinematic cuts to reflect finite detector acceptance:
  - $10^o \leq \theta_\gamma \leq 170^o$
  - Assume 2% systematic error
- Observables:
  - σ
  - σ_L
  - σ_R
  - A_{LR}
  - $d\sigma/dp_{T_q}$
  - $d\sigma/dE_q$
  - $d\sigma/d\cos\theta_q$

- Looked at many observables
- $d\sigma/dp_{T_q}$ most sensitive to W'
- Only σ_R sensitive to LR model but even very small pollution of e_L would totally swamp σ_R



$\sqrt{s} = 500$ GeV, $M_{W'} = 750$ GeV. Results are given for the SM, SSM, LRM, UUM and the KK model.

- Divide p_{T_q} into 10 bins and include 2% systematic error
- Limits in GeV (Preliminary)

$\sqrt{s} = 500$ GeV	SSM	LRM	UUM	KK
$L = 50$ fb^{-1}	1900	—	1900	2700
$L = 500$ fb^{-1}	2500	—	2500	>3000

5 Summary and Outlook

- Discovery Limits of W' in same ball park as LHC for some models although LHC generally higher
- If LHC discovers W' NLC important tool for identification
- Process can measure $Z'\nu\bar{\nu}$ couplings
- Limits severely degraded by systematic errors
- Need high luminosity and must minimize systematic errors
- $e\gamma \to q\nu$ analysis in progress