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Detection and Identification of W′ Bosons at High Energy e^+e^- Colliders

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1. Introduction

2. Models

3. Processes at e^+e^- Colliders

   i) $e^+ e^- \longrightarrow \nu \bar{\nu} \gamma$

   ii) $e \gamma \longrightarrow \nu q X$

4. Summary

Discovery and ID of extra gauge bosons in $e^+e^- \to \nu\bar{\nu}\gamma$, PRD61, 113009 [hep-ph/0001074]

Discovery and ID of W′ bosons in $e\gamma \to \nu q X$ [hep-ph/0008157]

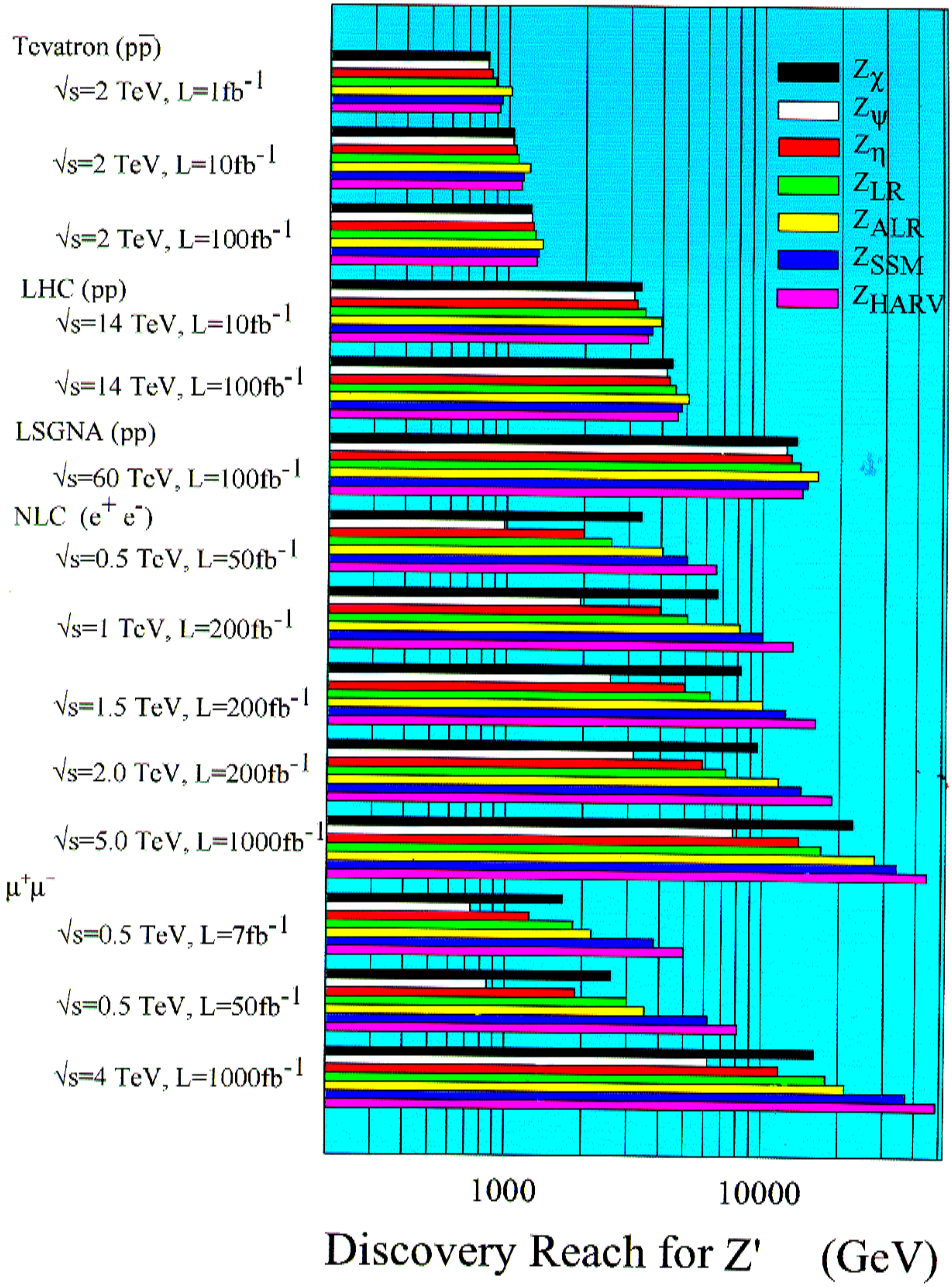
1. Introduction

- Many models are based on extensions of the SM gauge group, including in the context of GUTS
- Hence they include extra gauge bosons
- Extra Z''s have been well studied in the literature →
- W''s have been less studied
- Here, we look at indirect evidence for W''s at high energy Linear Colliders
- Indirect limits from low energy precision electroweak data
  - highly model dependent

eg. $m_{W_R} \gtrsim 1.6$ TeV $K_L - K_S$ mass difference in LR model with $g_L = g_R$
(Beall, Bender, Soni, PRL 48, 848 (1982))

$m_{W_R} > 715$ GeV   Simultaneous fit to charged neutral sectors
(Czakon et al PL B458, 355 (1999))

S. Godfrey


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}
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}
NLC ($e^+ e^-$)
$\sqrt{s}$=0.5 TeV, L=50fb^{-1}
$\sqrt{s}$=1 TeV, L=200fb^{-1}
$\sqrt{s}$=1.5 TeV, L=200fb^{-1}
$\sqrt{s}$=2.0 TeV, L=200fb^{-1}
$\sqrt{s}$=5.0 TeV, L=1000fb^{-1}
$\mu^+\mu^-$
$\sqrt{s}$=0.5 TeV, L=7fb^{-1}
$\sqrt{s}$=0.5 TeV, L=50fb^{-1}
$\sqrt{s}$=4 TeV, L=1000fb^{-1}
Z_χ
Z_ψ
Z_η
Z_{LR}
Z_{ALR}
Z_{SSM}
Z_{HARV}
1000
10000
Discovery Reach for Z' (GeV)

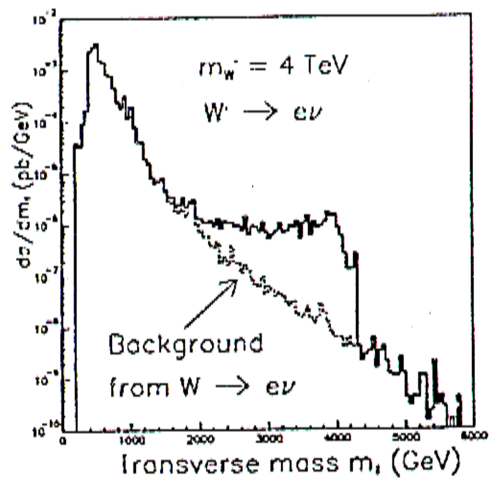
Direct Searches in Hadron Colliders

$pp \rightarrow W + X$

Present Limits (PDB '2000)

$m_{W_R'} > 720$ GeV

- W' with SM couplings decaying to $e\nu$, $\mu\nu$



Future Limits from LHC

$m_{W'} \gtrsim 6$ TeV

- model dependent (g_R/g_L, right-handed CKM, GUT)

(T. Rizzo, PR D50, 325 (1994); J. Collet, A. Ferrari – ATLAS)

Future Direct Limits from Linear Collider

$$\left.\begin{array}{l} e^+e^- \rightarrow W'^+ \, W'^- \\ e^\pm\gamma \rightarrow W'^\pm \, N \end{array}\right\} m_{W'} \text{ up to Kinematic limit}$$

2. Models with Extra Gauge Bosons

2.1 Sequential Standard Model (SSM)

- Benchmark rather than a model
- Extra gauge bosons with SM couplings
- SSM (W') $\leftarrow$ W' only, totally artificial
- SSM ($W'+Z'$) $\leftarrow$ Assume $M_{W'} = M_{Z'}$

2.2 General Left-Right Model (LRM)

- Extended gauge group is

$$\underbrace{SU(2)_L}_{g_L} \times \underbrace{SU(2)_R}_{g_R} \times U(1)_{B-L}$$

- f_L transform as doublets under $SU(2)_L$ and singlets under $SU(2)_R$
- $f_R \longrightarrow$ vice versa
- ν_R is included in the fermion content

- parametrize with κ and ρ:

$\rho = 1$ for Higgs doublets ← We use this.

$\rho = 2$ triplets

$$\frac{M_{Z'}^2}{M_{W'}^2} = \frac{\rho \kappa^2}{\kappa^2 - \tan^2\theta_W}$$

$\kappa = g_R / g_L$ $\qquad 0.55 \lesssim \kappa \lesssim 1-2$

from $\sin^2\theta_W \geq \dfrac{\kappa^2}{(1+\kappa^2)}$

- Neglect Z-Z' and W-W' mixing (constraints are stringent)

→ SM couplings for Z, W.

$$\mathcal{L}_{LR} = \frac{e\kappa}{\sqrt{2}\, s_W} W'^{+}_{\mu}\, \bar{\nu}_R \gamma^\mu e_R$$

$$+ \frac{e}{2 s_W c_W^2 \sqrt{\kappa^2 - t_W^2}} Z'_\mu \Big[\bar{\ell} \gamma^\mu (1-\gamma_5) s_W^2 (T_{3L} - Q_{em}) \ell$$

$$+ \bar{\ell} \gamma^\mu (1+\gamma_5)(\kappa^2 c_W^2 T_{3R} - s_W^2 Q_{em}) \ell \Big]$$

$$+ \text{h.c.}$$

(See eg. Mohapatra, "Unification + Supersymmetry")

2.3 "Un-unified" Model (UUM)

- Extended electroweak group is

$$SU(2)_q \times SU(2)_\ell \times U(1)_Y$$

  - Left-handed quarks and leptons each transform under their respective $SU(2)$
  - q_R, ℓ_R singlets under both $SU(2)_q$, $SU(2)_\ell$

- Parameter φ - angle which represents the mixing of the charged gauge bosons of the $SU(2)$'s.

$$0.24 \lesssim \varphi \lesssim 0.99$$

$$M_{W'} \sim M_{Z'}$$

$$\mathcal{L}_{uu} = -\frac{e}{2s_W}\frac{s_\varphi}{c_\varphi}\left[\sqrt{2}\, W'^{+}_\mu\, \bar{\nu}\gamma^\mu \ell_L + Z'_\mu\left(\bar{\nu}\gamma^\mu \nu_L - \bar{\ell}\gamma^\mu \ell_L\right)\right] + h.c.$$

- left-handed couplings

(Georgi, Jenkins, Simmons, PRL 62, 27 (1989), N.P. B 331, 541 (1990)
Barger + Rizzo, PR D41, 946 (1990).)

2.4 Kaluza-Klein excitations in models with large extra dimensions (KK)

- As minimal example consider 5DSM *

- Extra dimension of size $R \sim \mathrm{TeV}^{-1}$ may imply infinite tower of KK excitations of standard model gauge bosons

- Mass associated with compactification scale $\sim n\, M_c$

  $n = 1, \ldots, \infty$ $\qquad M_c \sim R^{-1}$

- Consider W', Z' corresponding to first KK excitation $\qquad M_{W'} = M_{Z'}$

- Global analyses constrain W, Z masses and couplings to be $\sim$ SM

- W', Z' couplings to fermions enhanced over SM by factor $\sqrt{2}$.

* (Masip + Pomeral, PR D60, 096005 (1999); Rizzo + Wells, ibid. 61, 016007 (2000); Giudice, Rattazzi, Wells, N. P. B544, 3 (1999); Han, Lykken, Zhang, P. R. D59, 105006 (1999).)

2.5 "3rd Family" Model (3FM)

• Third — heavy — family transforms according to its own SU(2)

$$\underset{\downarrow \text{ heavy}}{SU(2)_h}^{\nearrow g_h} \times \underset{\downarrow \text{ light}}{SU(2)_\ell}^{\nearrow g_\ell} \times U(1)_Y$$

via $\langle\sigma\rangle \sim (2,2,0)$ (h ℓ)

$$\downarrow$$

$$SU(2)_L \times U(1)_Y$$

via $\boxed{\langle\varphi\rangle \sim (1,2,1/2)}$ or $(2,1,1/2)$

$$\downarrow$$

$$U(1)_{em}$$

"Light breaking" scheme allows Z', W' as light as ~400 GeV

Parametrize via a mixing angle arising from the two SU(2)'s, φ.

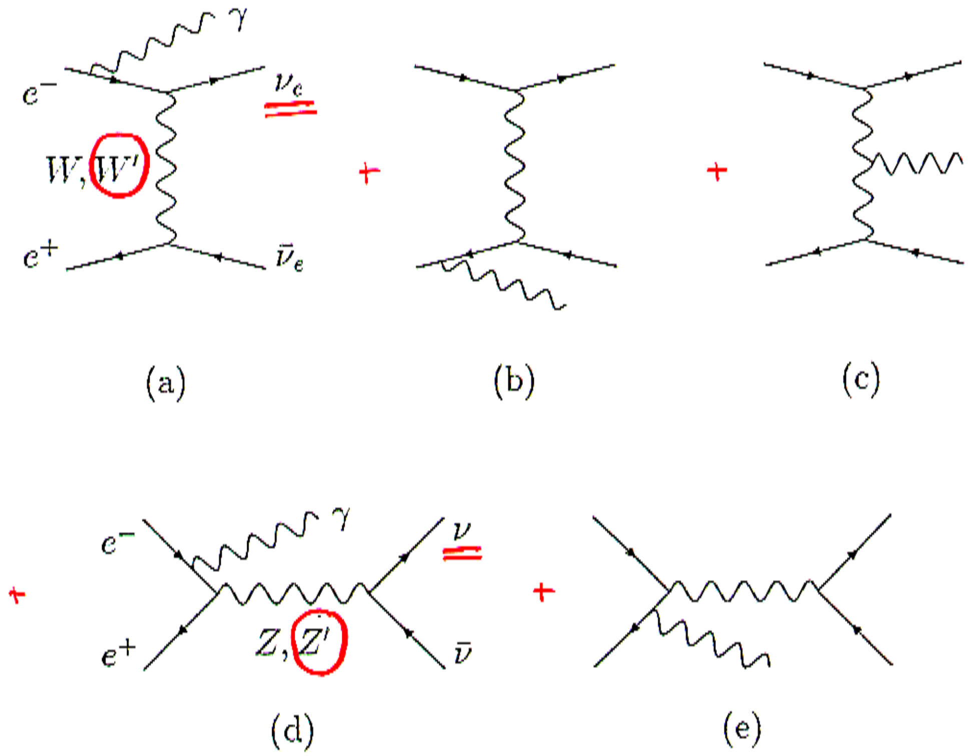
$$\mathcal{L} \sim \frac{1}{\sqrt{2}}\left[g\,\frac{c_\varphi}{s_\varphi}\,\bar{u}\,\gamma_\mu L\,d\,W'^{+} - g\,\frac{s_\varphi}{c_\varphi}\,\bar{t}\,\gamma_\mu L\,b\,W'^{+}\right] + h.c.$$

+ neutral sector

(Chivukula, Simmons, + Terning, PL B331, 383 (1994), PRD53, 5258 (1996)
Lynch, Mrenna, Narain, Simmons, hep-ph/0007286

3. i) The Process $e^+e^- \to \nu\bar{\nu}\gamma$

$\mathcal{M} =$



- Contributions from W′ and Z′ in models with both
- Preliminary work J. Hewett, Snowmass '96 p.887
  hep-ph/9704292

Independent methods as check

$\mathcal{M}$ via CALKUL helicity amplitude technique

<u>or</u>

$|\mathcal{M}|^2$ via trace calculation

M.C. integration

<u>or</u>

Partial analytic followed by numerical integration

- $\Gamma_{Z'} \to f\bar{f}$ calculated for each model

- Kinematics cuts imposed for detector acceptance were

$$E_\gamma \geq 10\,\mathrm{GeV} \qquad 10^\circ \leq \theta_\gamma \leq 170^\circ$$

- Background issues

  - Radiative Bhabha scattering with both e^+ and e^- lost down beam pipe

$$p_T^\gamma > \frac{\sqrt{s}\,\sin\theta_v \sin\theta_\gamma}{\sin\theta_\gamma + \sin\theta_v}$$

θ_v - minimum angle to veto e^+, e^- — take 25mrad

  - $e^+e^- \to \nu\bar{\nu}\,\nu'\bar{\nu}'\,\gamma$ (Denner et al. N.P. B560, 33(1999))

- Considered various observables

$$\sigma,\ \sigma_L,\ \sigma_R,\ \frac{d\sigma}{dE_\gamma},\ \frac{d\sigma}{d\cos\theta_\gamma},\ A_{LR},\ A_{FB}$$

$M_W = 80.33\,\mathrm{GeV}$ $\qquad \sin^2\theta_W = 0.23124$

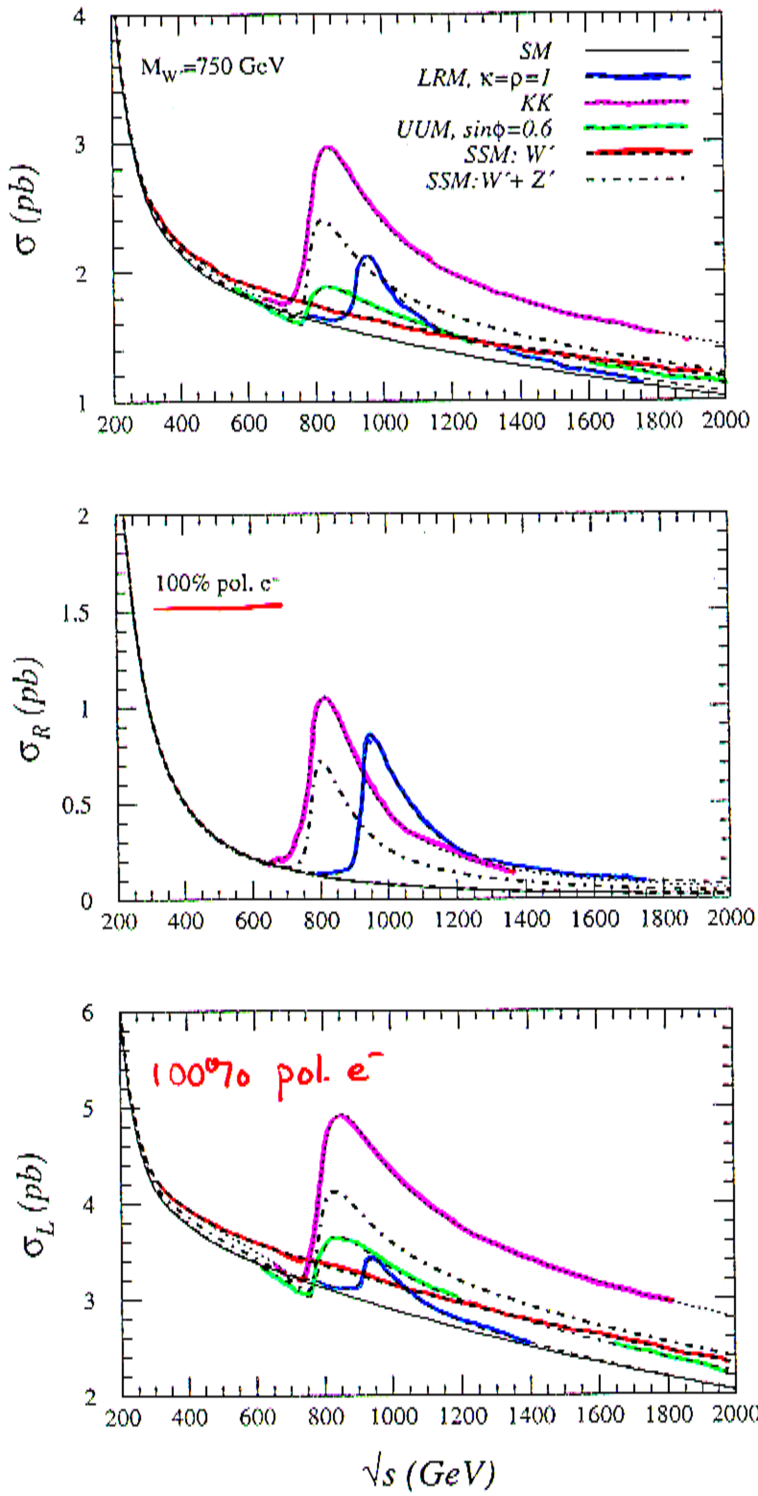
$M_Z = 91.187\,\mathrm{GeV}$ $\qquad \alpha = 1/128$

$\Gamma_Z = 2.49\,\mathrm{GeV}$

σ

σ_R

σ_L



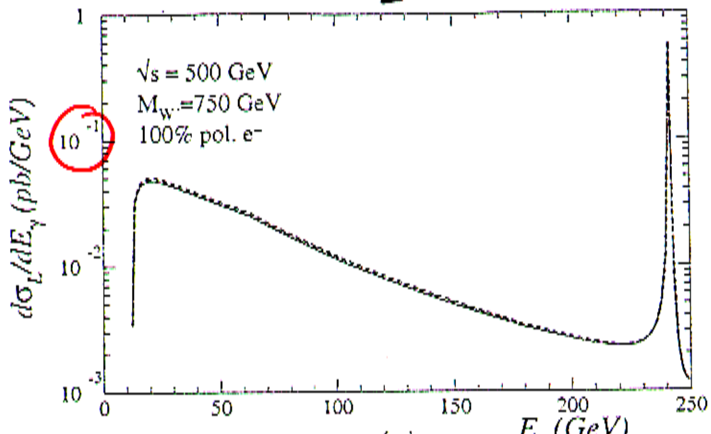
LRM $(\kappa=\rho=1)$
KK
UUM $(\sin\phi=.6)$
SSM (W′)
SSM (W′+Z′)

$M_{W'} = 750$ GeV

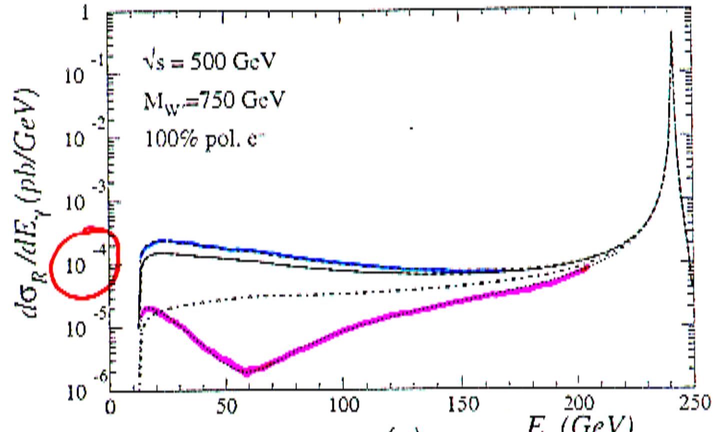
Z′ peaks

$\sqrt{s} = 500$ GeV $\quad M_{W'} = 750$ GeV

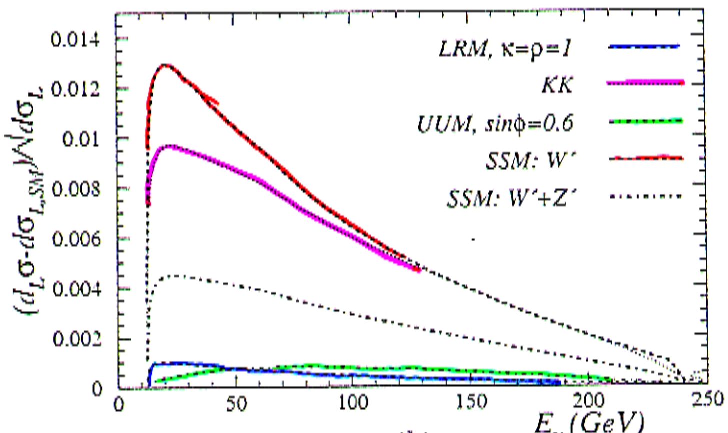
e_L^- $\quad\quad$ e_R^-



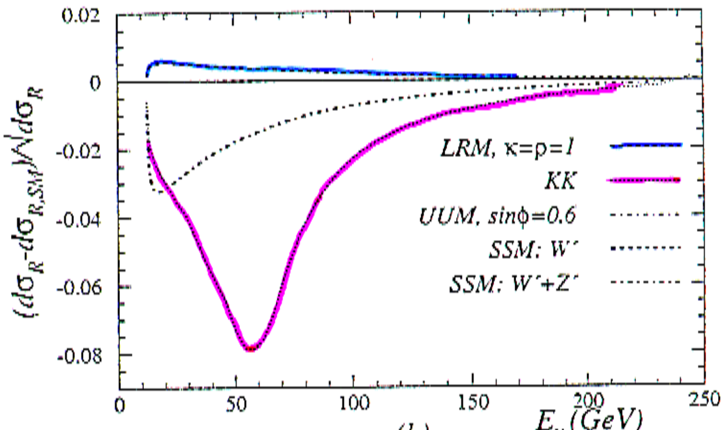
(a)



(a)



(b)



(b)

$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - M^2_{\nu\bar{\nu}}/s\right)$$

- Radiative return to Z-pole is dominant feature <u>but</u> not most sensitive region to W', Z'.
- Low E_γ region most sensitive to new physics
- σ_R significantly lower than σ_L

$\Downarrow$

- For realistic polarization, e_L^- pollution can swamp $\sigma(e_R^-)$

Mass Discovery Limits for W′'s

- Limits are highly model and machine dependent

Range: 0.65 TeV ⟶ 6.45 TeV

$\sqrt{s} = 500$ GeV, $\int \mathcal{L}dt = 50\, fb^{-1}$, UUM

$\sqrt{s} = 1.5$ TeV, $\int \mathcal{L}dt = 500\, fb^{-1}$, KK

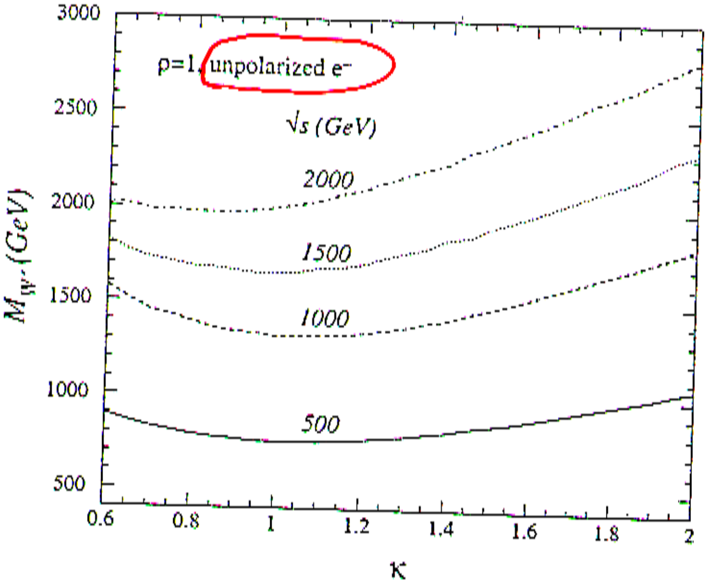
Imposing 2% systematic error (in quadrature with statistical):

0.6 TeV ⟶ 2.55 TeV

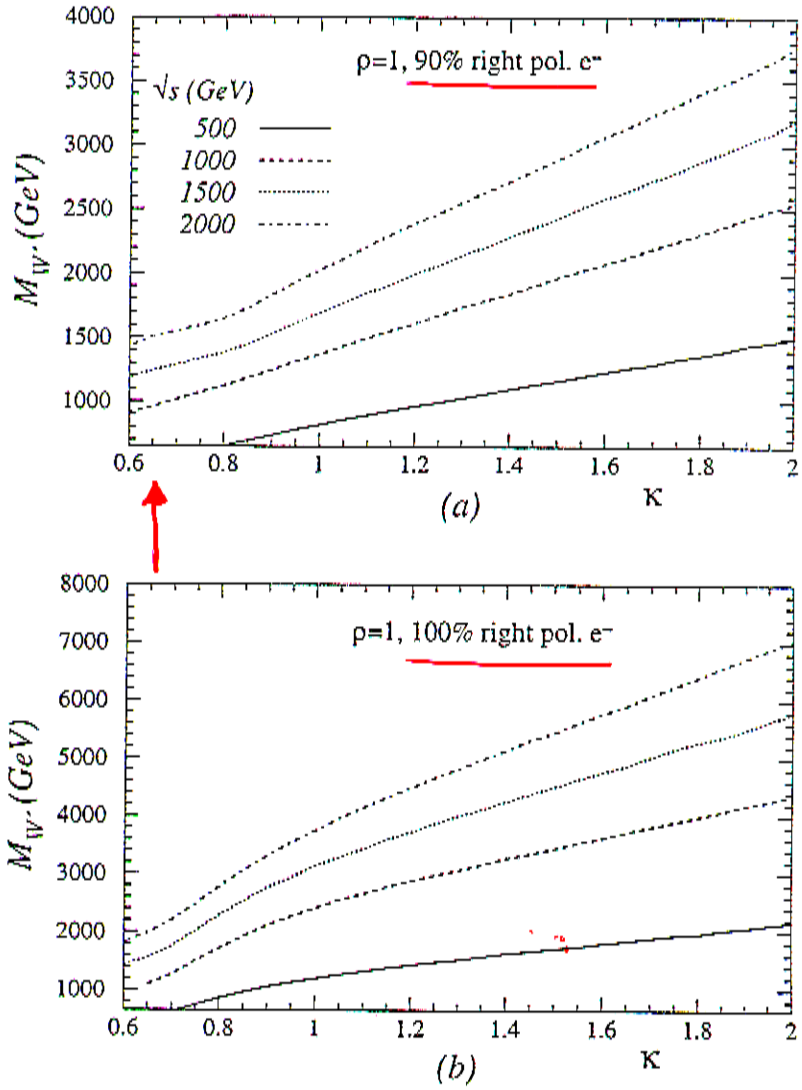
- Important to minimize systematics
- Best limits obtained using $d\sigma/dE_\gamma$ along with beam polarization (e_L^- for all except LRM)
- Similar results using σ provided we cut out Z-pole using $E_{\gamma\,max} = \frac{\sqrt{s}}{2}\left(1 - \frac{M_Z^2}{s}\right) - 6\Gamma_Z$
- <u>But</u> limits from $d\sigma/dE_\gamma$ were degraded less by systematic error than those from σ.
- Used 10 equal size energy bins in range $E_\gamma^{min} < E_\gamma < E_\gamma^{max}$

$$E_\gamma^{min} = \frac{\sqrt{s}\sin\theta_v}{1+\sin\theta_v}$$ from p_T cut (supercedes $E_\gamma > 10$ GeV)

Mass Discovery Limits for LRM



$\kappa = g_R / g_L$



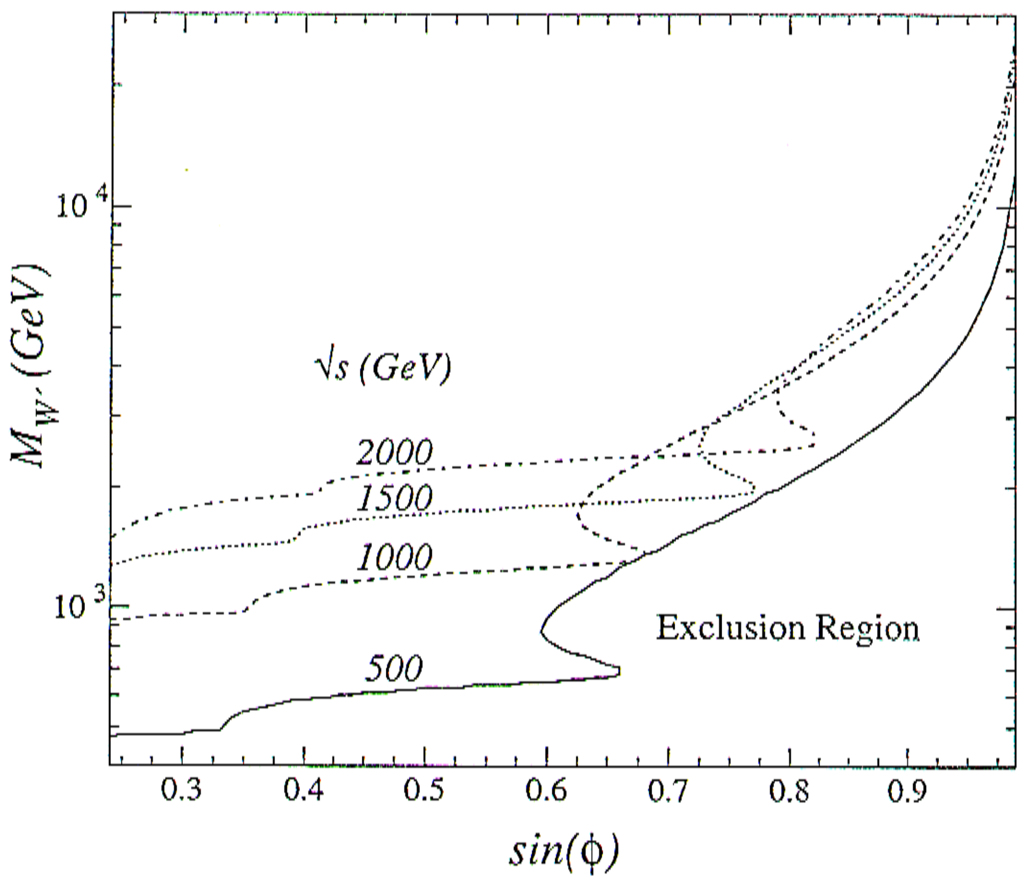
For $\sqrt{s} = 500$ GeV $\rightarrow$ used $50\,fb^{-1}$

higher energies $\rightarrow$ used $200\,fb^{-1}$

These plots do not include systematic error.

Limits from $d\sigma / dE_\gamma$

Mass Discovery Limits for UUM



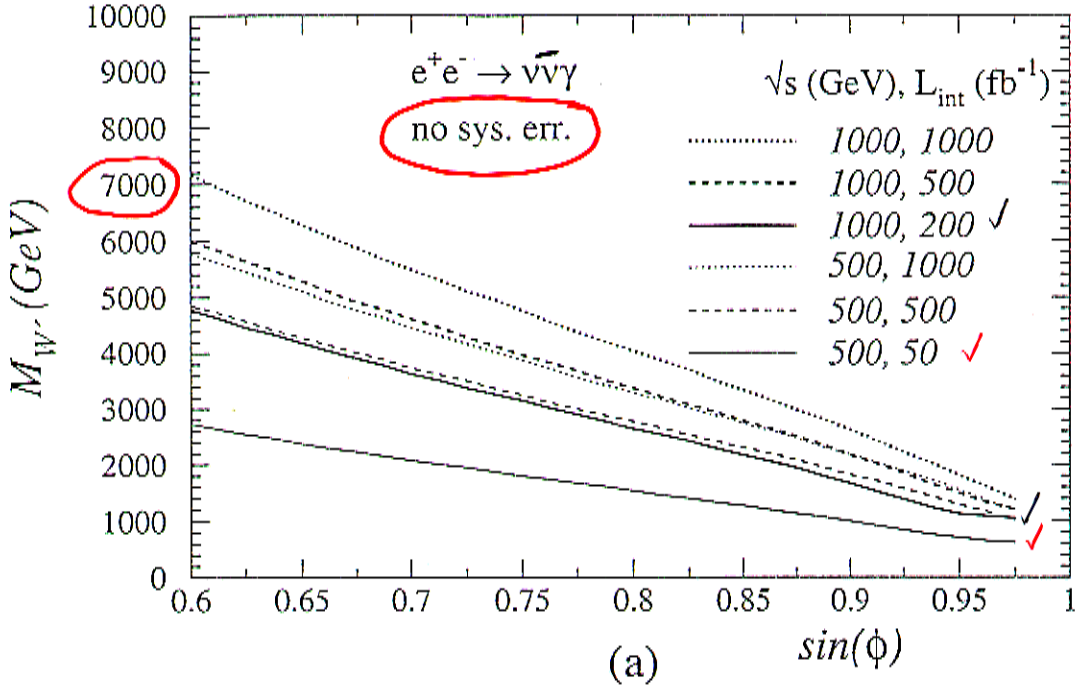
unpolarized

$\sqrt{s} = 500 \longrightarrow 50\, fb^{-1}$
higher $\longrightarrow 200\, fb^{-1}$

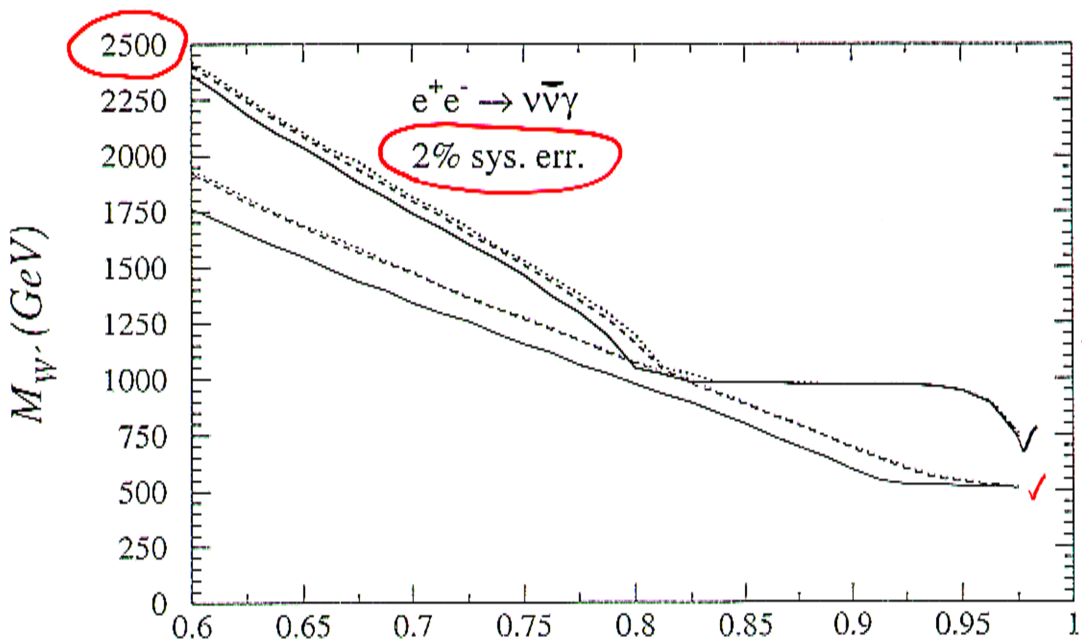
Statistical errors only

Limits from $d\sigma/dE_\gamma$

Mass Discovery Limits for 3FM



(a)



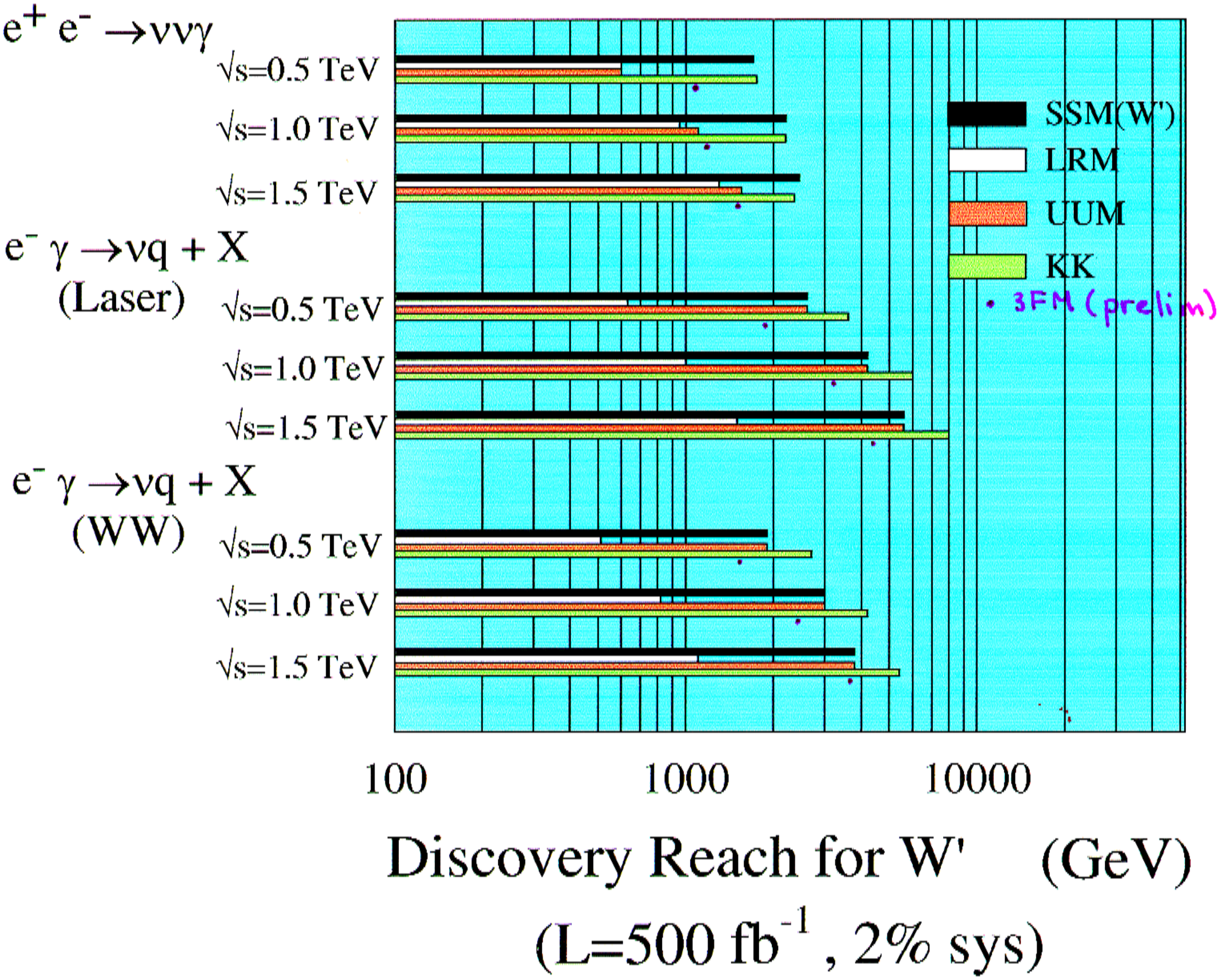
(b)

Different energy / luminosity scenarios.

Shows effect of systematics

Limits from $d\sigma / dE_\gamma$

Preliminary

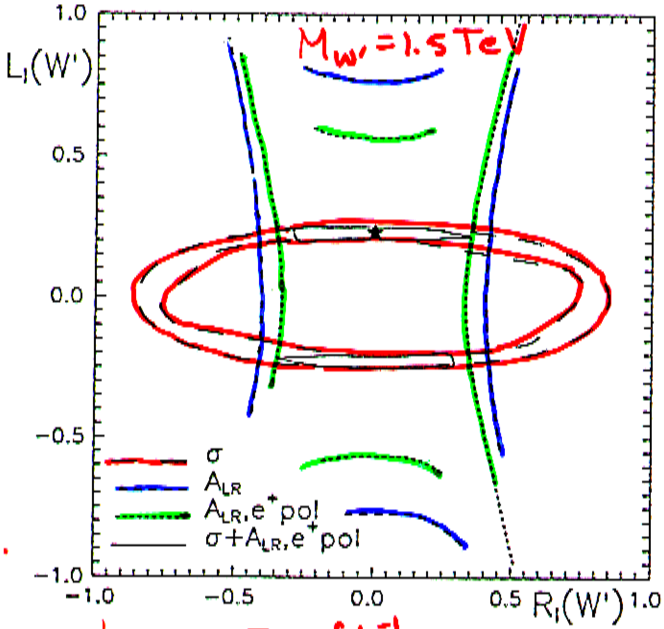


$e^+ e^- \rightarrow \nu\nu\gamma$
√s=0.5 TeV
√s=1.0 TeV
√s=1.5 TeV
$e^- \gamma \rightarrow \nu q + X$
(Laser)
√s=0.5 TeV
√s=1.0 TeV
√s=1.5 TeV
$e^- \gamma \rightarrow \nu q + X$
(WW)
√s=0.5 TeV
√s=1.0 TeV
√s=1.5 TeV
SSM(W')
LRM
UUM
KK
• 3FM (prelim)
100
1000
10000
Discovery Reach for W' (GeV)
($L=500\ fb^{-1}$, 2% sys)

Constraints on W′ couplings

★ SSM (W′)

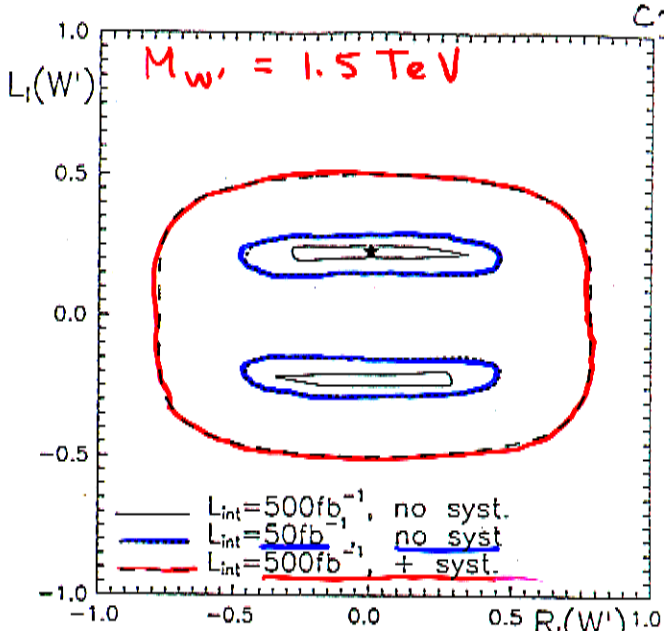
1.



$L_{int} = 500\, fb^{-1}$
Stat. only

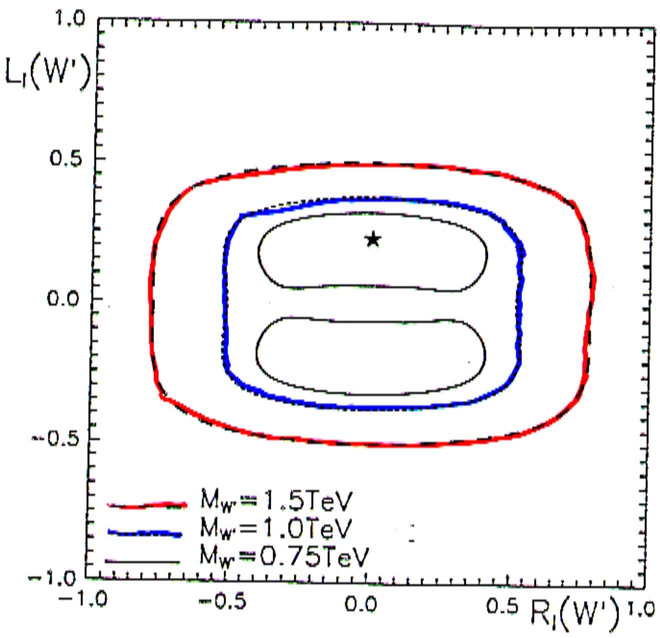
c~4

2.



$\sigma + A_{LR}$
P_{e^-}, P_{e^+}

$W' \ell \nu \sim i \gamma_\mu [(1-\gamma_5) L_\ell(W') + (1+\gamma_5) R_\ell(W')]$



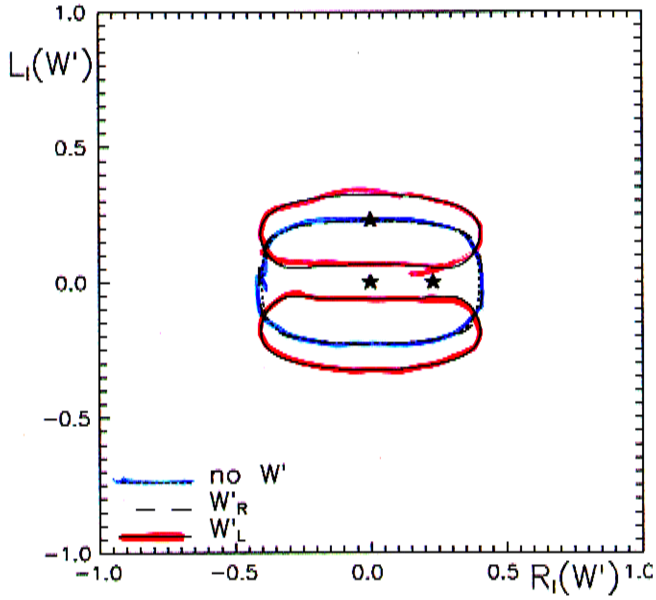
$L_{int} = 500 fb^{-1}$
+ syst.
$\sigma + A_{LR}$
P_{e^-}, P_{e^+}

1. Various observables
2. Vary luminosity, systematics
3. Vary mass

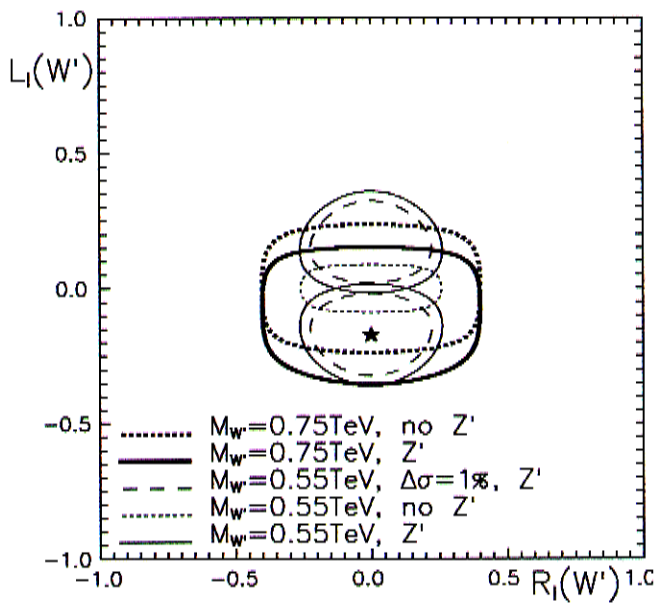
$\sqrt{s} = 500$ GeV

When relevant, $P_{e^-} = 90\%$ $P_{e^+} = 60\%$

(c_L, c_R: ~ −4 → +4)



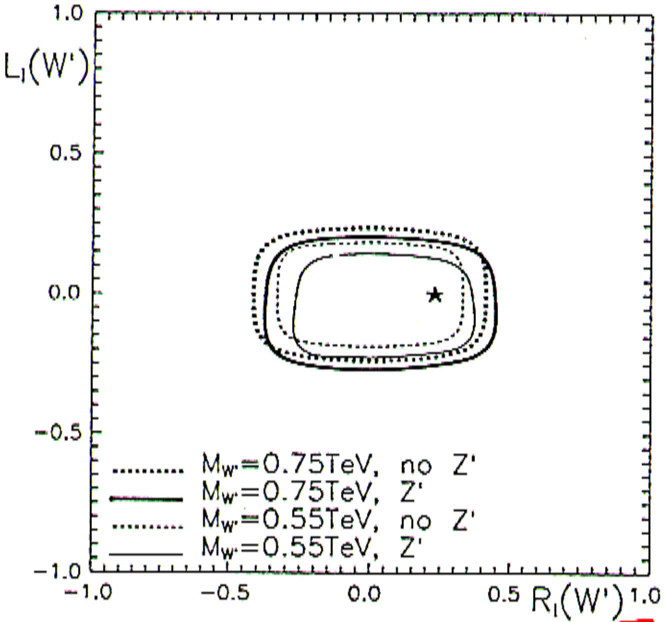
Constraints on the W' couplings using σ and A_{LR} combined for different W' scenarios. We take 90% electron and 60% positron polarization, $\sqrt{s} = 0.5$ TeV, $L_{\rm int} = 500$ fb^{-1} and $M_{W'} = 0.75$ TeV. A systematic error of 2% (1%) is included for σ (A_{LR}). The assumed models are indicated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



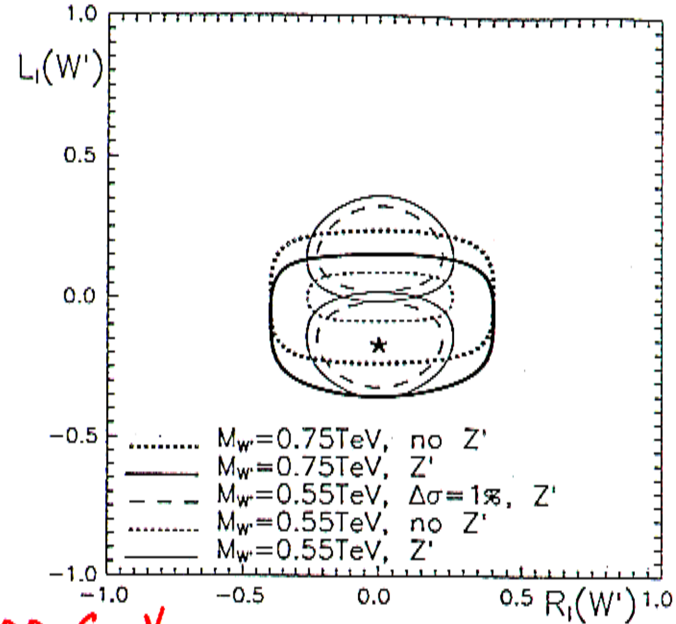
Constraints on the W' couplings using σ and A_{LR} combined in the UUM with $\sin\phi = 0.6$ for different W' masses and different fitting strategies; see text. We take 90% electron and 60% positron polarization, $\sqrt{s} = 0.5$ TeV and $L_{\rm int} = 500$ fb^{-1}. Unless otherwise indicated, a systematic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

Constraints on W′ Couplings

* "LRM"



* UUM $\sin\varphi = 0.6$



$\sqrt{s} = 500$ GeV

$L_{int} = 500\ fb^{-1}$

$\sigma + A_{LR}$, syst.

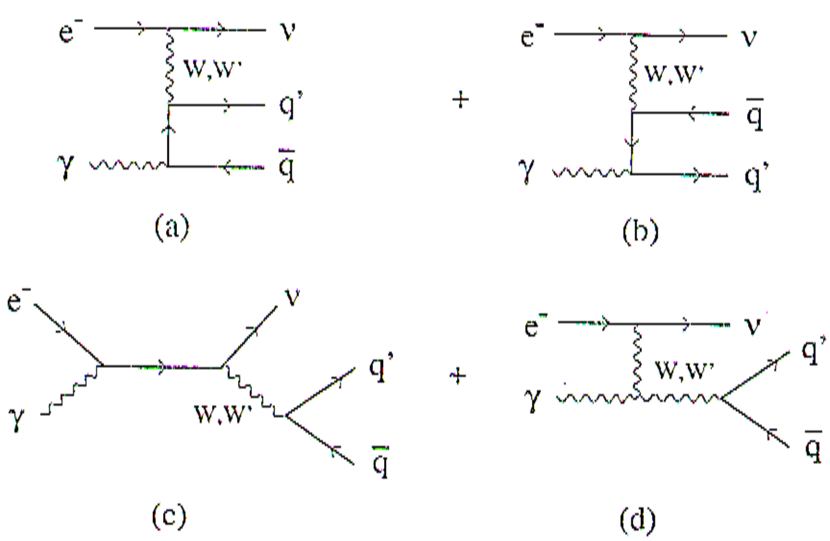
P_{e^-}, P_{e^+}

$\rho = K = 1$

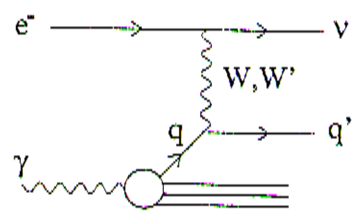
$\sigma + A_{LR}$

3. ii) The Process $e\gamma \to \nu q X$

$e\gamma \to \nu q q'$



$\sim$



$eq \to \nu q'$

$$\sigma = \int dx \int dy\; f_{\gamma/e}(x, \sqrt{s}/2)\, f_{q/\gamma}(y, Q^2)\, \hat{\sigma}(eq \to \nu q')$$

photon distribution
- backscattered laser photon spectrum

  or
- WW spectrum

quark content of the photon:
- included u, d, s, c
- leading order GRV

Gluck, Reya, Vogt PR D46, 1973 (1992).

Resolved photon

$$\hat{\sigma}(e^- q \to \nu q') = \frac{\pi \alpha^2}{4 \sin^4\theta_W} \int d\hat{t} \;\; f(\hat{s}, \hat{u})$$

$$f(\hat{s},\hat{u}) = \frac{1}{(\hat{t}-M_W^2)^2} \Bigg\{ 1 + 2\, C_L^q C_L^\ell \left(\frac{\hat{t}-M_W^2}{\hat{t}-M_{W'}^2} \right)$$

$$+ \frac{1}{2} \left(\frac{\hat{t}-M_W^2}{\hat{t}-M_{W'}^2} \right)^2 \Big[(C_L^{q\,2} + C_R^{q\,2})(C_L^{\ell\,2} + C_R^{\ell\,2})(1 + \hat{u}^2/\hat{s}^2)$$

$$+ (C_L^{q\,2} - C_R^{q\,2})(C_L^{\ell\,2} - C_R^{\ell\,2})(1 - \hat{u}^2/\hat{s}^2) \Big] \Bigg\}$$

$e^- \bar{q} \to \nu \bar{q}'$ $\qquad$ $f(\hat{s},\hat{u}) \Leftrightarrow f(\hat{u},\hat{s})$ $\qquad$ back scattered laser

$e^+ \bar{q} \to \bar{\nu} \bar{q}'$ $\qquad$ $f(\hat{s},\hat{u})$

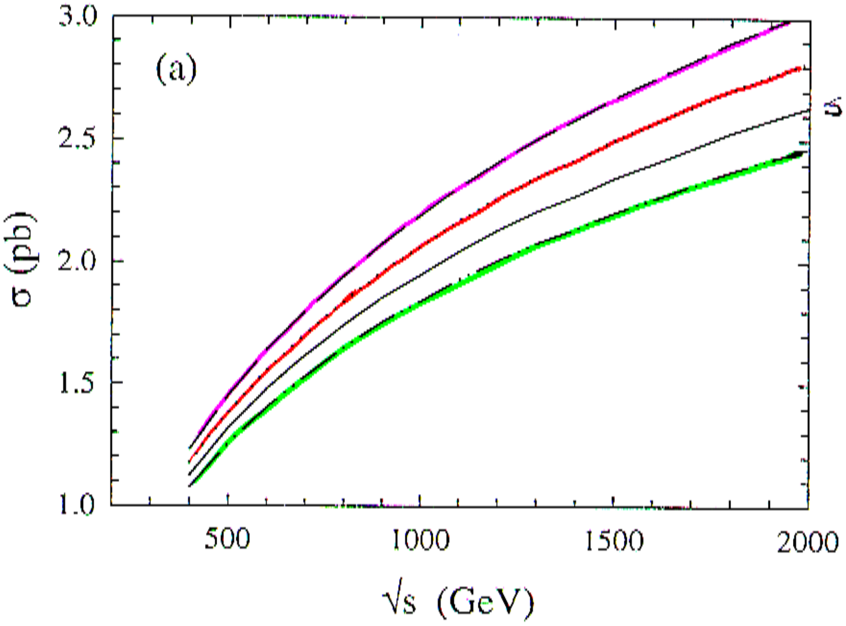
$e^+ q \to \bar{\nu} q'$ $\qquad$ $f(\hat{u},\hat{s})$ $\qquad$ WW includes all

$$W_i f \bar{f}' = \frac{ig}{\sqrt{2}} \gamma_\mu \left(\frac{1-\gamma_5}{2} C_L^{W_i} + \frac{1+\gamma_5}{2} C_R^{W_i} \right)$$

For detector acceptance, use

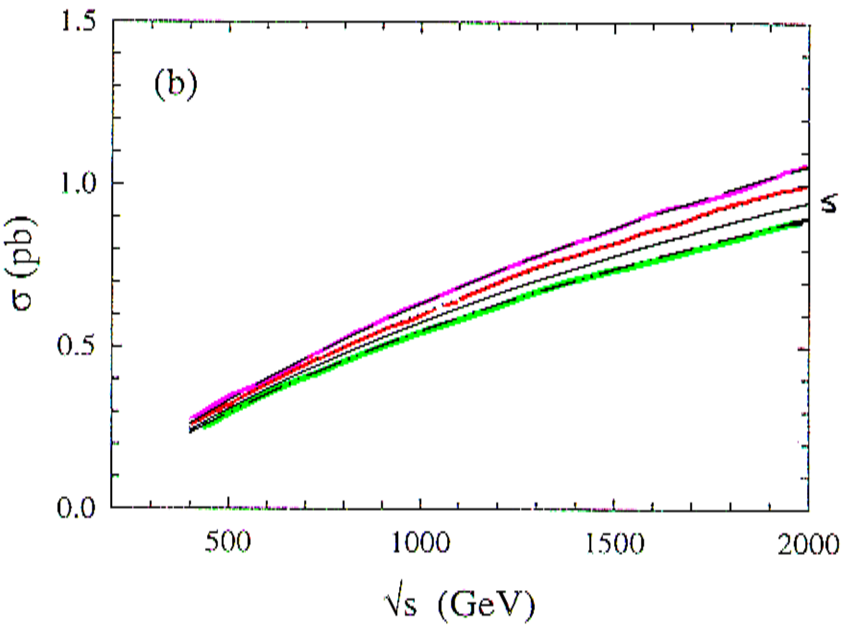
$$10^\circ \le \theta_{q(\bar{q})} \le 170^\circ$$

$\sigma(e\gamma \to \nu q X)$



SM~LRM

Backscattered laser



SM~LRM

Weizsäcker-Williams

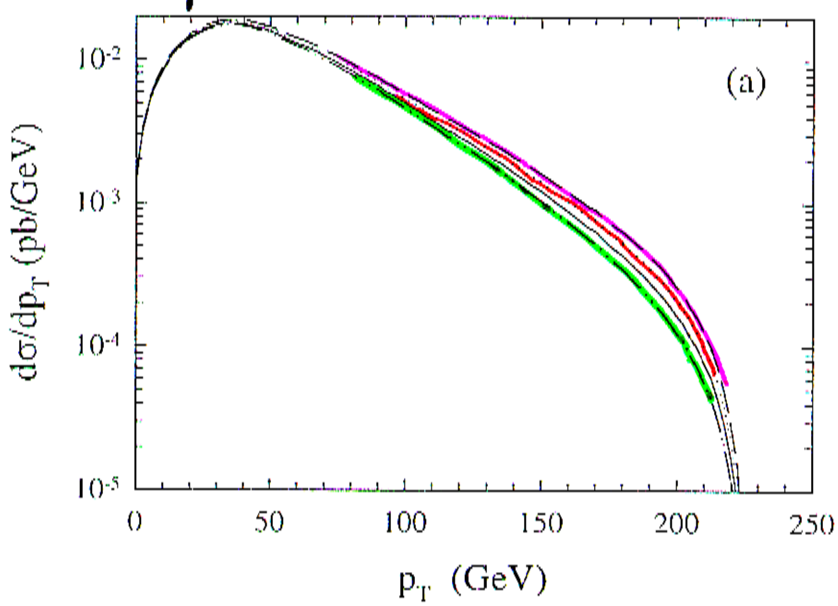
$M_{W'} = 750\ \mathrm{GeV}$

$$W_i f\bar{f} = \frac{ig}{\sqrt{2}} \gamma^\mu \left(\frac{(1-\gamma_5)}{2} C_L^{W_i} + \frac{(1+\gamma_5)}{2} C_R^{W_i} \right)$$

SSM
UUM
KK

UUM $\quad C_L^{\text{lepton}} = -\dfrac{\sin\varphi}{\cos\varphi} \qquad C_L^{\text{quark}} = \dfrac{\cos\varphi}{\sin\varphi} \qquad C_R^{l} = C_R^{q} = 0$

$\frac{d\sigma}{dp_{T_q}}\ (e\gamma \to \nu q X)$



SM
SSM
UUM
KK

$\sqrt{s} = 500$ GeV $\qquad M_{W'} = 750$ GeV

- backscattered laser

- Considered various observables

$\sigma,\ \sigma_L,\ \sigma_R,\ d\sigma/dp_{T_q},\ d\sigma/dE_q,\ d\sigma/d\cos\theta_q \to$ BKgd

- Range of Mass limits

0.53 TeV $\longrightarrow$ 10 TeV $\qquad$ backscattered laser

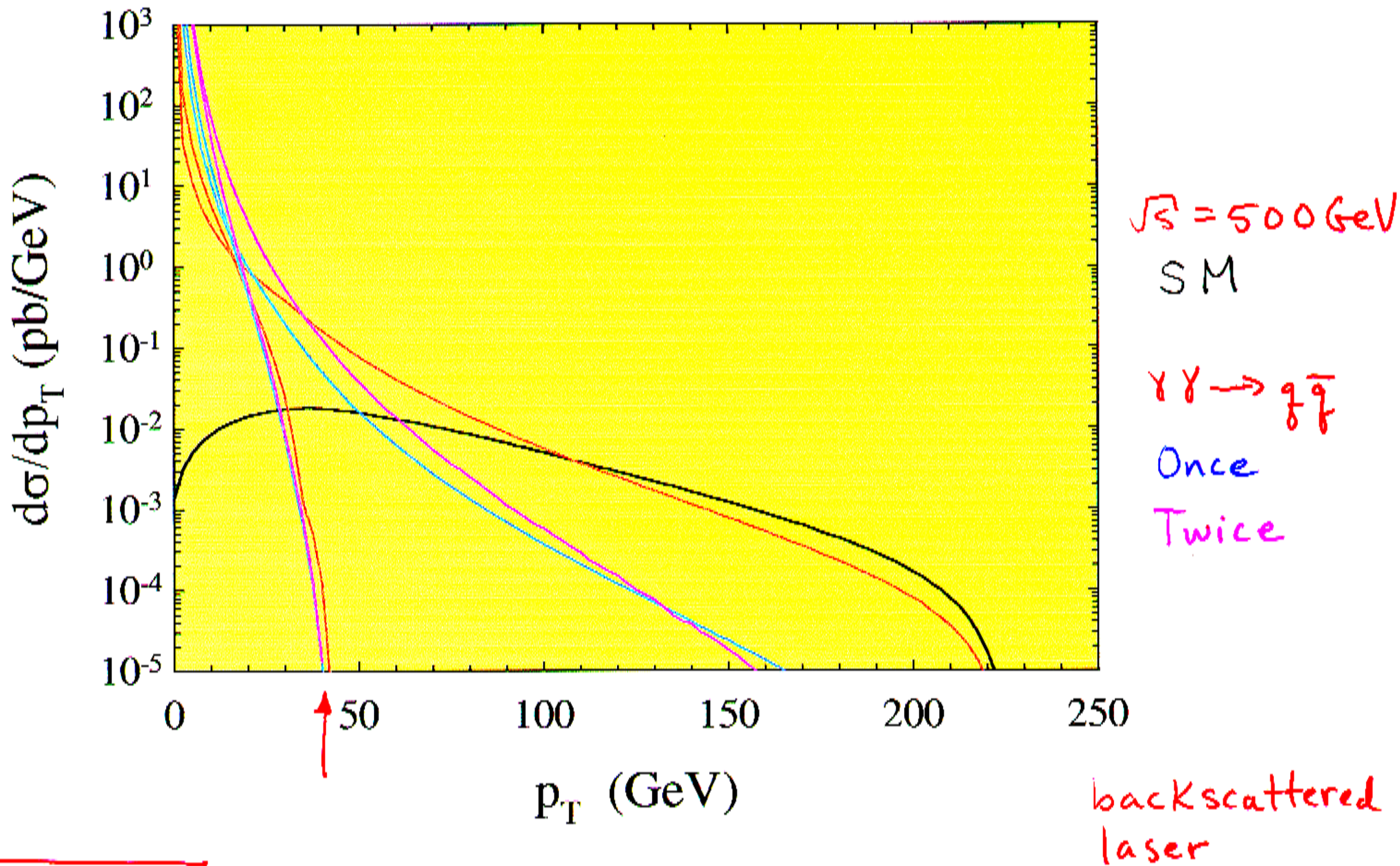
0.38 $\longrightarrow$ 6.4 $\qquad$ WW

$\sqrt{s} = 500$ GeV, $\int \mathcal{L}dt = 50\,fb^{-1}$, LRM $\qquad$ $\sqrt{s} = 1.5$ TeV, $\int \mathcal{L}dt = 500\,fb^{-1}$, KK

Imposing 2% systematic error:

0.51 $\longrightarrow$ 8 $\qquad$ b.l.

0.37 $\longrightarrow$ 5.4 $\qquad$ WW



- $\boxed{d\sigma/dp_{Tq}}$ yields best mass discovery limits
- $d\sigma/dE_q$ a close second
- polarization only of interest at all for LRM but degraded by realistic degree of poln. and by syst.

Backgrounds

- Two jet final states with one jet lost

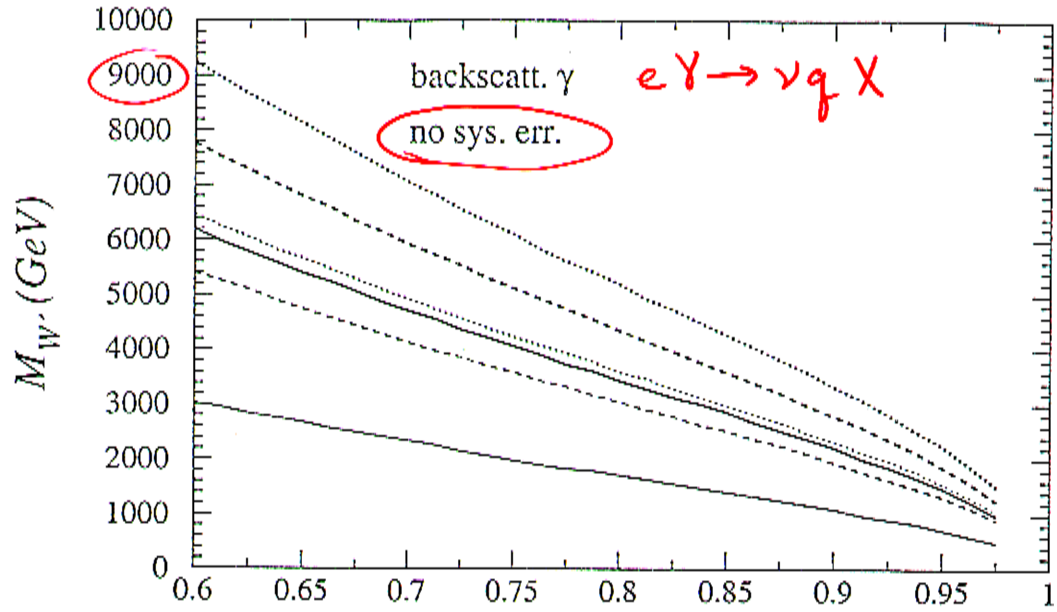
$\gamma\gamma \to q\bar{q}$

Once resolved processes: $\gamma g \to q\bar{q}$ $\gamma q \to g q$

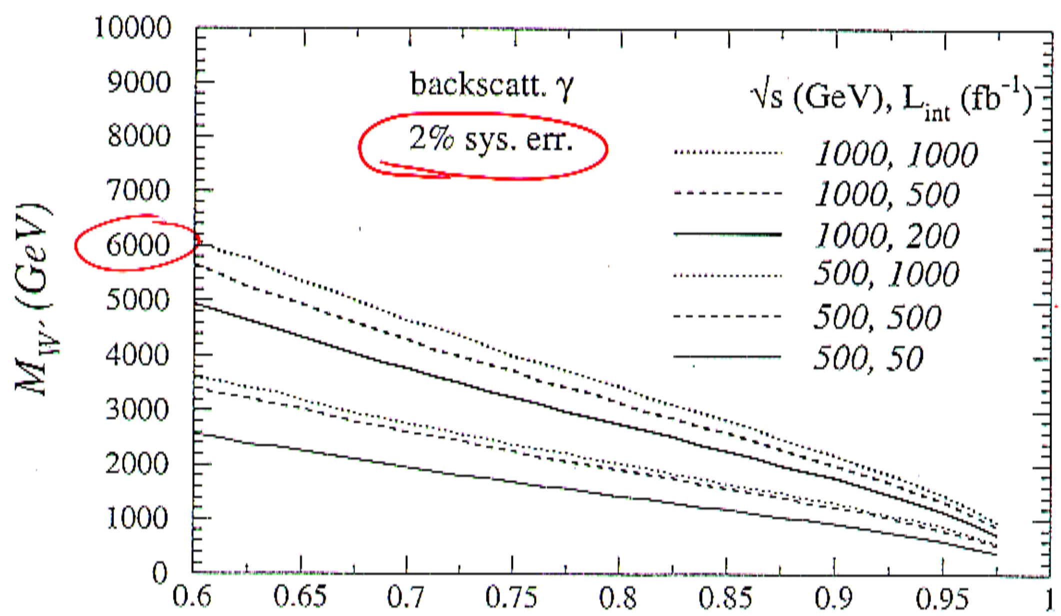
Twice resolved: $gg \to q\bar{q}$ $q\bar{q} \to q\bar{q}$ $qq \to qq$ $gg \to gg$ $qg \to qg$

$\sqrt{s} = 500$ GeV $p_{Tq} > 40$ GeV
$\sqrt{s} = 1000$ GeV $p_{Tq} > 75$ GeV
$\sqrt{s} = 1500$ GeV $p_{Tq} > 100$ GeV

Mass discovery limits for 3FM



(a)



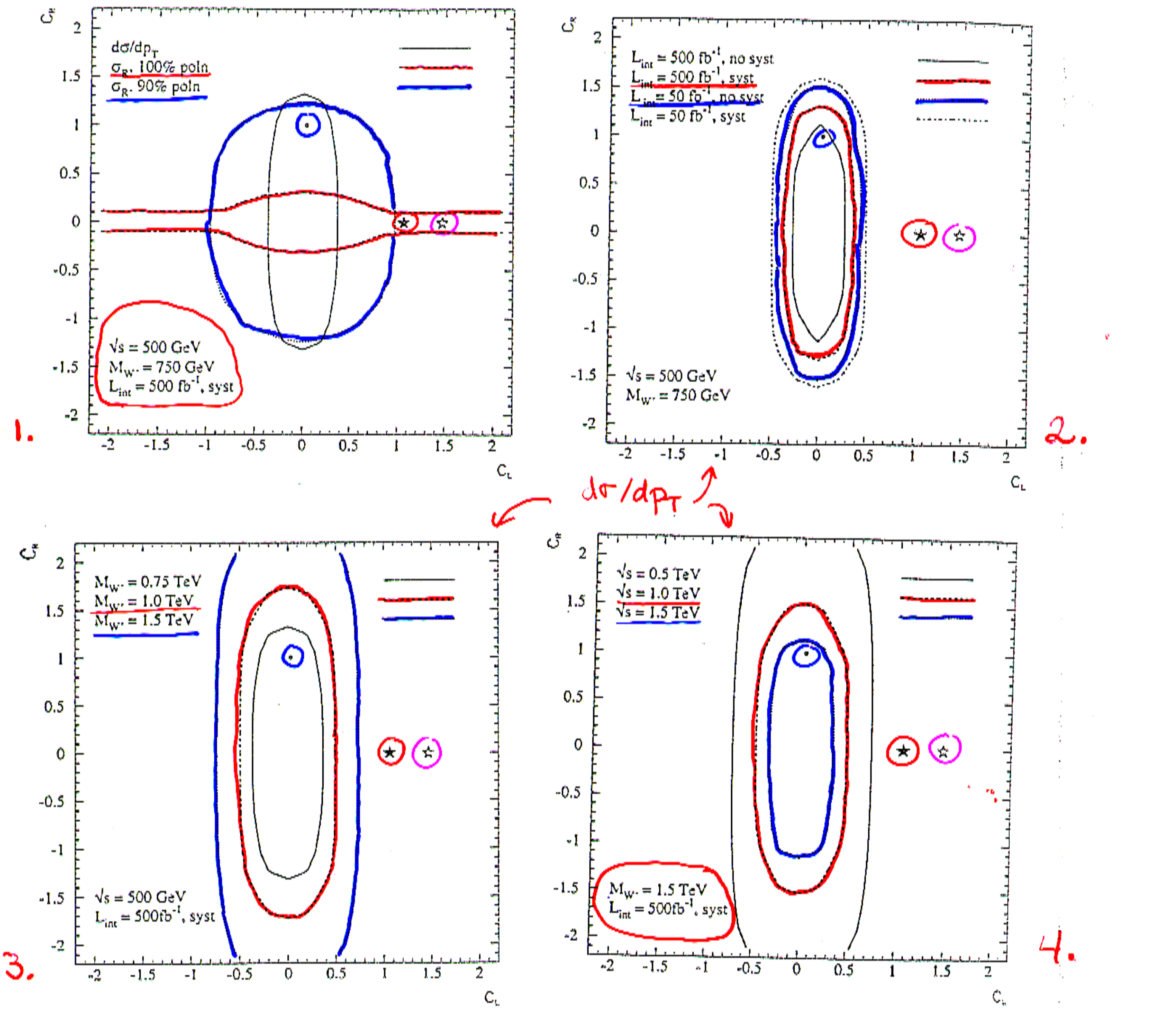
(b)

Limits from $d\sigma / d p_{Tq}$

Constraints on Couplings

SSM LRM KK

$(c_L^e = c_L^q ;\ c_R^e = c_R^q)$



1. Various observables
2. Vary luminosity, systematic errors
3. Vary $M_{W'}$
4. Vary $\sqrt{s}$ $\quad M_{W'} = 1.5\,\text{TeV}$

$\left.\begin{matrix}1.\\2.\\3.\end{matrix}\right\}\ \sqrt{s} = 500\,\text{GeV}$

(L, R: $\sim -.5 \to +.5$)

4. Summary

- Processes $e^+e^- \to \nu\bar{\nu}\gamma$

  $e\gamma \to \nu q X$ provide useful information in search and identification of W''s.

- Mass discovery limits competitive with LHC for some scenarios (models, machines)

- Upon discovery of W', Z' at LHC $\to$ could use LC as a tool to identify origins

- Combine info from $e^+e^- \to \nu\bar{\nu}\gamma$ and $e\gamma \to \nu q X$ for W' couplings to both leptons and quarks $(Z'\nu\bar{\nu})$

- These processes become systematics limited $\to$ important to minimize the syst. error and obtain high luminosity