Studies of Strong Symmetry Breaking

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LHC Workshop meeting
14 April, 1999

Strong Vector Boson Scattering

For a heavy Higgs $H \rightarrow W^+W^-, ZZ$, up to $M_H = 1$ TeV
$V_L V_L$ fusion is detectable

At TeV scale $V_L V_L \rightarrow V_L V_L$ could serve as a probe of a dynamical symmetry breaking by TeV scale interactions.

strongly interacting bosons:

$$\mathcal{L} = \mathcal{L}_{YM} + \mathcal{L}_G \leftarrow \text{Goldstone fields}$$

$$\mathcal{L}_G = \mathcal{L}_0 + \underbrace{\sum_{dim=4} \mathcal{L}_i + \cdots}$$

($\mathcal{L}_0$) generates M_W, M_Z — (the sum:) expansions in powers of the energy for scattering amplitude

Chiral Lagrangian Model
$SU(2)_{L+R}$ symmetry unbroken

$\rightarrow \sum_{dim=4} \mathcal{L}_i$ (10 terms) $\rightarrow$ 2 terms

$$\mathcal{L}^{(4)} = L_1 \left[Tr\, D_\mu U D^\mu U^+ \right]^2 + L_2 \left[Tr\, D_\mu U D^\nu U^+ \right]^2$$

where U : SU(2) matrix field of the G. fields
D_μ : SM covariant derivative.

L_1 and L_2 free parameters of the model.

Quasi-elastic 2-2 Amplitudes at high energies

$\longrightarrow$ $A(s,t,u)$. s, t, u Mandelstam Variabl

$$A(s,t,u) = \frac{s}{v^2} + \frac{1}{4\pi v^4}\left(2L_1 s^2 + L_2(t^2+u^2)\right) + \dots$$

If $\mathcal{L} \to \mathcal{L}_{YM} + \mathcal{L}_0 \Rightarrow A(s,t,u) \to \frac{s}{v^2}$

a_{IJ} scattering length with isospin I and angular Momentum J.

The only non-zero channels predicted by the Leading order ($\mathcal{L}_{YM}+\mathcal{L}_0$) are:

$$a_{00} = \frac{s}{16\pi v^2} \quad \text{higgs-type resonance}$$

$$a_{11} = \frac{s}{96\pi v^2} \quad \rho\text{-type resonance}$$

if $\mathcal{L} = \mathcal{L}_{YM} + \mathcal{L}_0 + \mathcal{L}^{(4)}$

$$M_V^2 = \frac{v^2}{4(L_2 - 2L_1) - \frac{1}{18(4\pi)^2}} \quad \text{and} \quad \Gamma_V = \frac{M_V^3}{96\pi v^2}$$

V = Vector resonance (ρ-like)

Energy limit at $\sqrt{s} = \mathcal{O}(1\,\mathrm{TeV})$

K-Matrix unitarization M.S. Chanowitz (hep-ph/9812215)

$a_{IJ} \nearrow$ when $s \nearrow$

$\rightarrow$ conflict with Unitarity

Partial wave unitarity : $\mathrm{Im}(a_{IJ}^{-1}) = -1$

" Unitary a_{IJ} is completely specified by specifying it's real part "

At leading term ($\mathcal{L}_{YM} + \mathcal{L}^0$)

$$\mathrm{Re}(a_{00}^{-1}) = \frac{16\pi v^2}{s}$$

$$a_{00} = \frac{s}{16\pi v^2}\left(1 - i\,\frac{s}{16\pi v^2}\right)^{-1}$$

K-Matrix Model $\rightarrow$ PYTHIA 6.

$W_L Z_L \longrightarrow W_L Z_L \longrightarrow l^+ l^- jj$

(A. Miagkov)

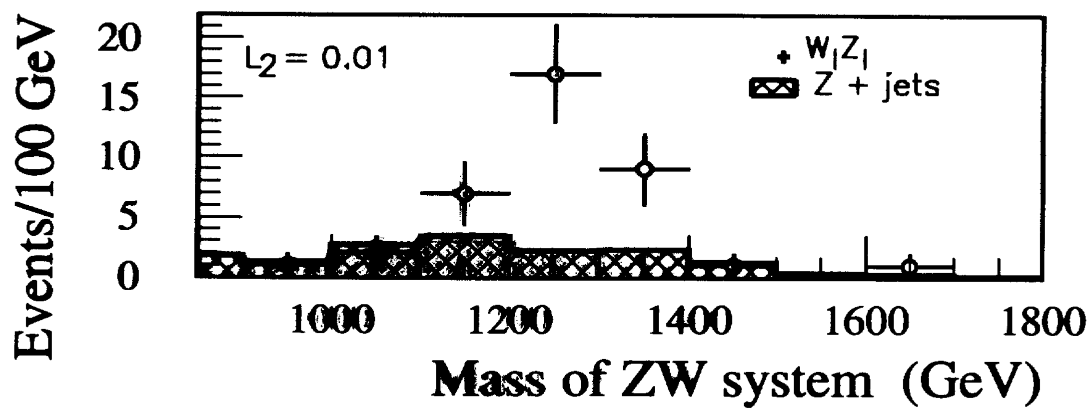
PYTHIA 5.7 + $V_L V_L$ scattering

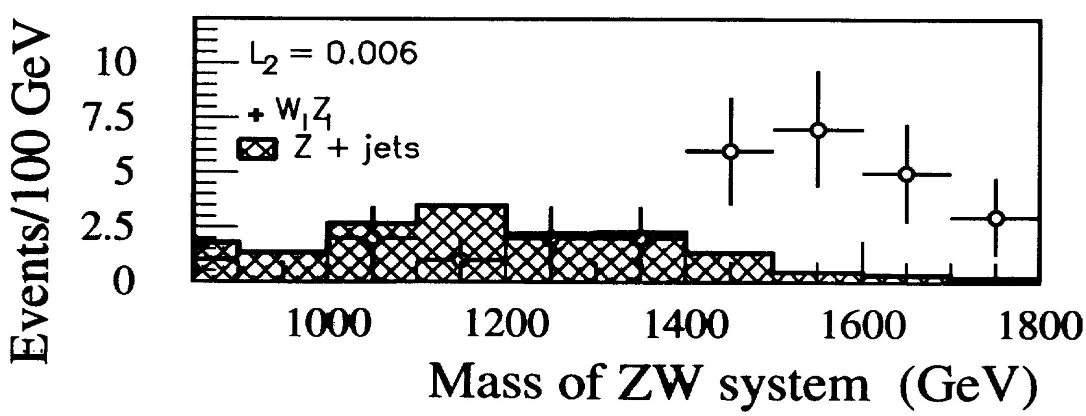
$L_1 = 0$, $L_2 = 0.01$, $\sigma \times BR = 2.8$ fb, $M_\rho = 1.2$ TeV/c^2

$L_1 = 0$, $L_2 = 0.006$, $\sigma \times BR = 1.5$ fb, $M_\rho = 1.5$ TeV/c^2

Background { - Continuum WZ production
- QCD from Z + jets

	$M_\rho = 1.2$ TeV		$M_\rho = 1.5$ TeV	
	$W_L Z_L$	Z + jets	$W_L Z_L$	Z + jets
Central jets cut	284	2187	145	1781
$M_{jj} = M_W \pm 15$ GeV/c^2	101	154	46	82
Leptonic cuts	70	84	36	47
Forward jet tagging	14	3	8	1.3





$$W_L^+ W_L^+ \longrightarrow W_L^+ W_L^+ \longrightarrow l^+ \nu l^+ \nu$$

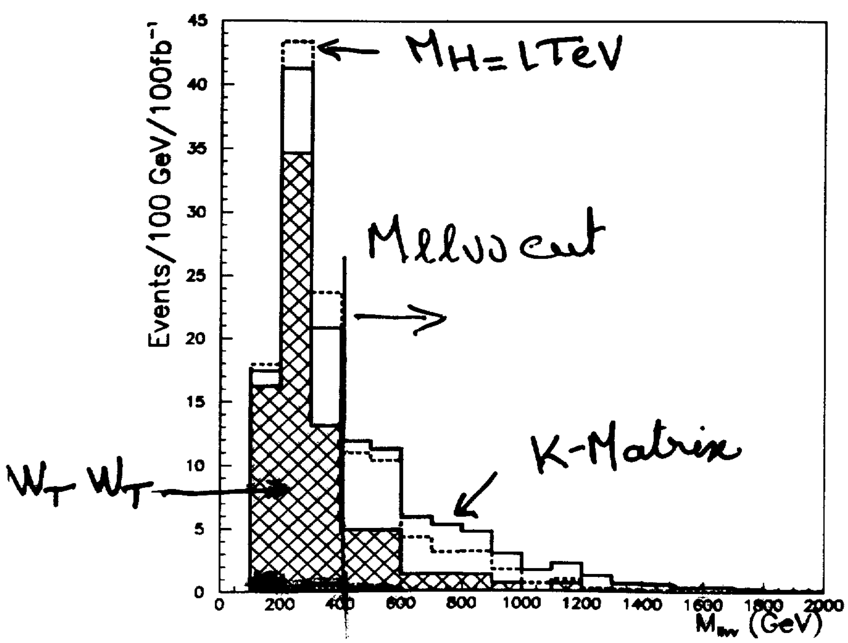
Non resonant channel but complementary with resonant WZ

$W_L^+ W_L^+$
- t-channel of $M_H = 1$ TeV $\sigma \times BR = 1.33$ fb
- K-Matrix Model $\sigma \times BR = 1.12$ fb
- chiral Lagrangian Model $L_1 = 0$, $L_2 = 0.006$, $\sigma \times BR = 0.484$; $L_1 = 0$, $L_2 = 0.01$, $\sigma \times BR = 0.379$

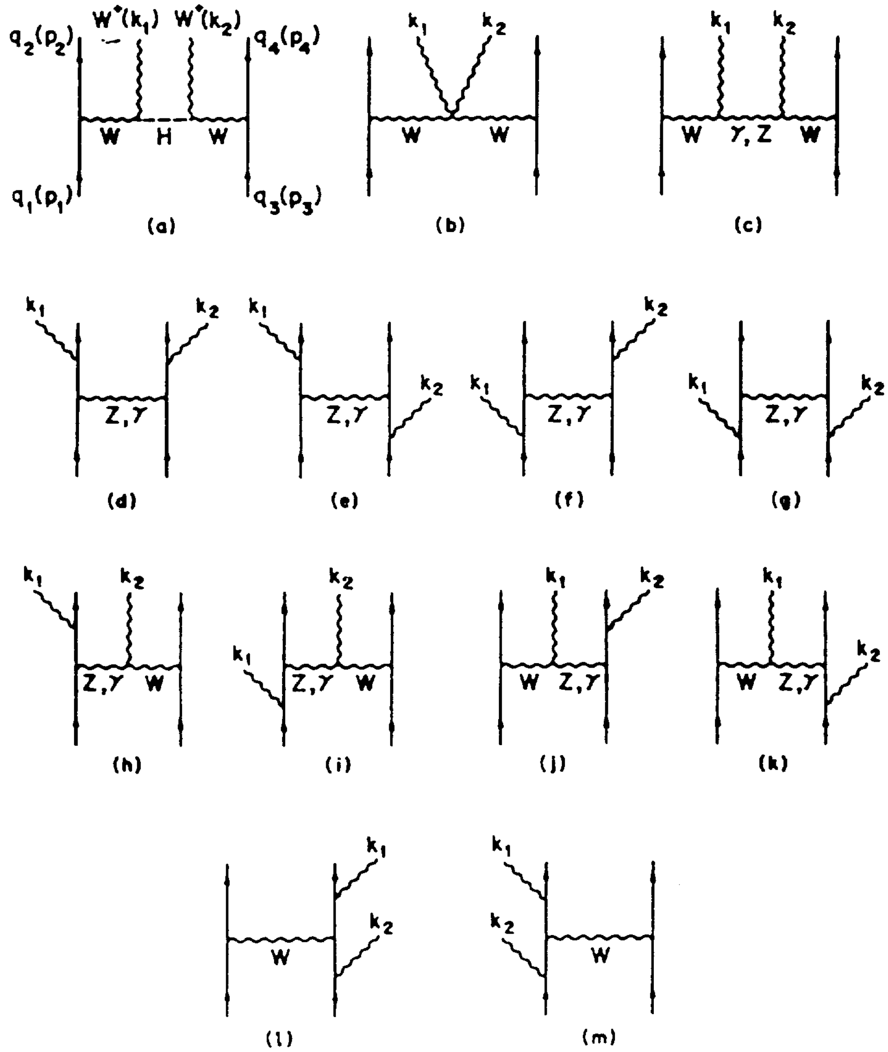
Backgrounds
- $W_T W_T$ from WW bremsstrahlung $O(\alpha^2)$
- gluons exchange and W bremsstrahlung $O(\alpha \cdot \alpha_s)$
- $Wt\bar{t}$, continuum WZ

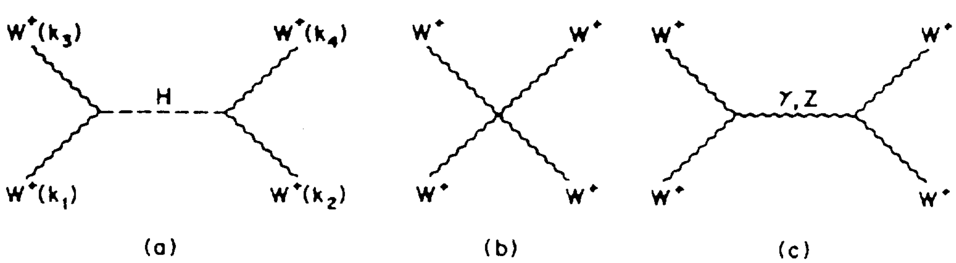
Cuts
- $2l^+$ $p_T > 40$ GeV and $|\eta| < 1.75$
- $\cos(\phi_{l_1} - \phi_{l_2}) < 0.5$, $M_{ll} > 100$ GeV
- 3 jets with 1 forward and 1 backward
- p_T(j-forw.) < 150 GeV and p_T(j-backw.) < 90 GeV

	$M_H = 1$ TeV	K-Matrix	$L_2 = 0.006$	$L_2 = 0.01$	W_{TT}
all cuts	42.6	50.3	17.1	11.8	76
$M_{ll\nu\nu} > 400$ GeV	21.0	34.8	8.2	5.1	14.5



Barger and al.
P.R D42 (1990) 3052





Technicolor

* Minimal classical technicolor
  New QCD with new quantum number Technicolor
  → technifermions
  chiral symetry $SU(2n)_L \times SU(2n)_R$ broken
  by $q\bar{q}$ condensate → Goldstone bosons π_T (SU(2
  → Longitudinal d.o.f of W and Z
  ⇒ massive W, Z
  → Broken $SU(2) \times U(1)$
  $M_W \Rightarrow f_{\pi_{QCD}} \rightarrow F_{\pi_T} = v = 246$ GeV
* Extended Technicolor (ETC)
  To generate correct fermion masses!
  - Global symmetry gauge group G_{ETC} embeds
    TC, color, U(1)
  - Breaking G_{ETC} ⇒ heavy ETC bosons
    wich couple to ℓ, q and technifermions ⇒ masse
* Walking TC

  Abscence of FCNC !

  α_{TC} is required to run slowly (walk)
* Top color assisted Technicolor (TC2)
  Large top quark mass !

  top mass arises mostly from new
  top-color interaction

Walking TC requires several representations of TC family → Multiscale TC. (K. Lane and Eichten)

⟹ technihadron resonances accessible at LHC energies (ω_T $(I=0, J=1)$, ρ_T $(1,1)$ ...

ie $q\bar{q}' \to \rho_T^{\pm} \to \pi_T^{\pm} \pi_T^{0}$

where $|\pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle$

Eichten, Lane and Wormesley

$$\to \quad \Gamma(\rho_T \to f\bar{f}) \propto m_\rho^4$$

$$\Gamma(\pi_T \to q q') \propto (m_q + m_{q'})^2$$

$$\frac{d\sigma}{d\hat{t}}(q q' \to \rho \to \pi\pi) \propto m_\rho^4$$

etc

⋮

Implemented in PYTHIA 6. with default Values:

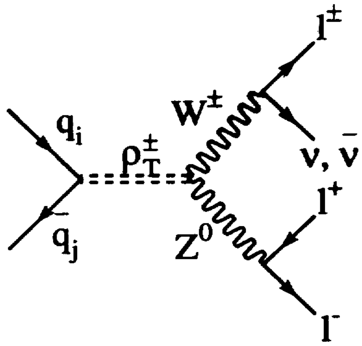
$N_{TC} = 4$

$\sin\chi = 1/3$

$F_T = F_\pi \cdot \sin\chi = 82$ GeV

$Q_U = e, \quad Q_D = 0$

$$\rho_T^{\pm} \longrightarrow W^{\pm} Z^{o} \longrightarrow l^{\pm} \nu l^{+} l^{-}$$



Background

WZ continuum production $\sigma = 0.3$ pb

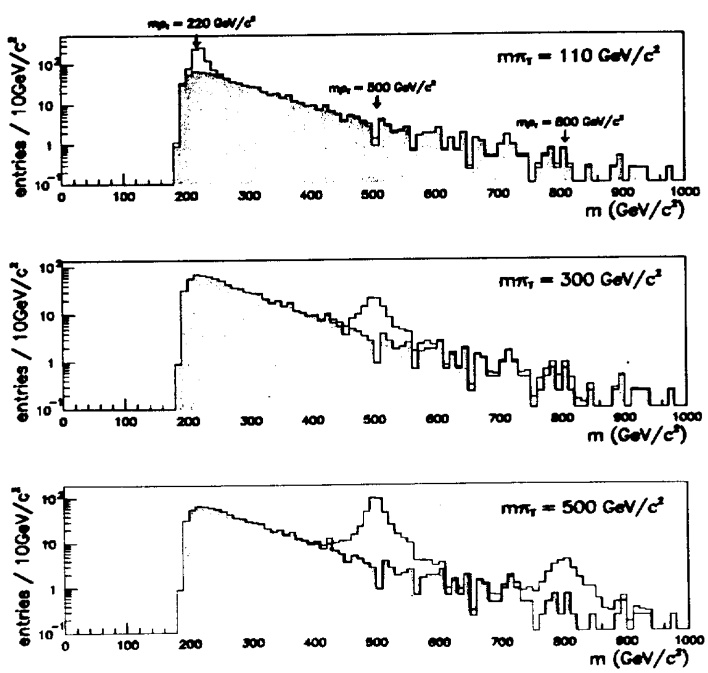
Cuts

3 leptons ($E_T > 5$(e), 6(μ))

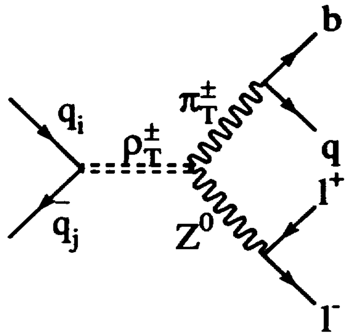
P_T (W, Z) > 40 GeV

$|\cos \hat{\theta}_{(\rho_T, WZ)}| < 0.8$

M_{ρ_T}	M_{π_T}	Γ_{ρ_T}	BR($\rho_T^{\pm} \to WZ$)	$\sigma \times$ BR (pb)	$S/\sqrt{B}$	$\sigma \times$ BR (pb) for 5σ
220	110	0.93	0.13	0.16	31.6	0.025
500	110	67.1	0.014	$1.04 \; 10^{-3}$	0.7	$7.4 \; 10^{-3}$
500	300	4.47	0.21	$1.3 \; 10^{-2}$	14.7	$0.4 \; 10^{-2}$
500	500	1.03	0.87	$5.4 \; 10^{-2}$	64.2	$0.42 \; 10^{-2}$
800	110	130.2	0.013	$1.5 \; 10^{-4}$	0.3	$2.5 \; 10^{-3}$
800	300	52.4	0.032	$3.6 \; 10^{-4}$	1.2	$1.5 \; 10^{-3}$
800	500	7.6	0.22	$2.5 \; 10^{-3}$	10.9	$1.2 \; 10^{-3}$



$$\rho_T^{\pm} \longrightarrow \pi_T^{\pm} Z^o \longrightarrow bql^+l^-$$



Backgrounds

- $t\bar{t}$
- Z + jets ($q\bar{q} \to gZ$, ZZ, $qg \to WZ$)
- WZ

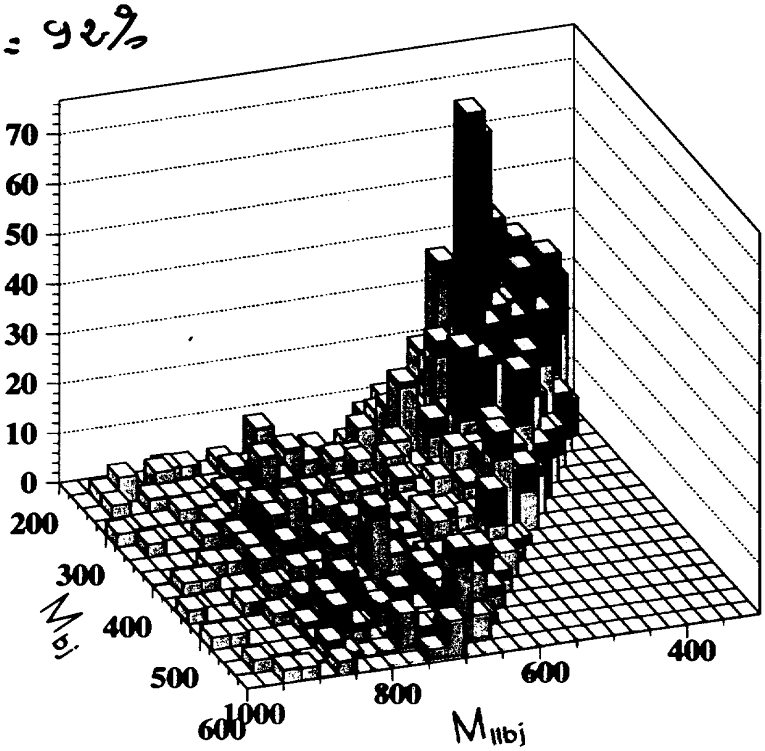
Cuts

2 leptons, $P_T(l_1) > 60$ GeV, $P_T(l_2) > 20$ GeV
1 b-jet $|\eta_b| < 2$ and $P_T^b > 75$ GeV
1 non b-jet $|\eta_j| < 2$ and $P_T^j > 75$ GeV
} $|\cos\hat{\theta}_{bj}| < \epsilon$

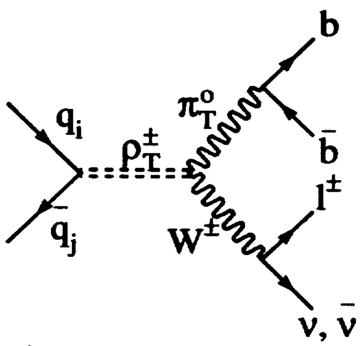
M_{ρ_T}	M_{π_T}	$BR(\rho_T^{\pm} \to Z^0 \pi_T^{\pm})$	$\sigma \times BR$ (pb)	$S/\sqrt{B}$	$\sigma \times BR$ (pb) for 5σ
500	300	39.8	0.104	11.5	0.045
800	500	38.2	0.018	6.1	0.015
800	250	13.0	0.006	1.67	0.018

$BR(\pi^{\pm} \to b\bar{c}, \bar{b}c) = 92\%$

— ρ_T
— $t\bar{t}$



$$\rho_T^{\pm} \longrightarrow W^{\pm}\pi_T^{0} \longrightarrow l\nu b\bar{b}$$



Backgrounds

$t\bar{t}$

Z + jets

WZ

W + jets ($q\bar{q} \to W$, gW, WW, $qg \to qW$)

Cuts

1 lepton $P_T^{\,l} > 30$ GeV

2 b-jets $P_T^{\,b_1} > 100$ GeV and $P_T^{\,b_2} > 50$ GeV

Central jet veto, No extra jet with $P_T > 40$ GeV, $|\eta_j| < 2$

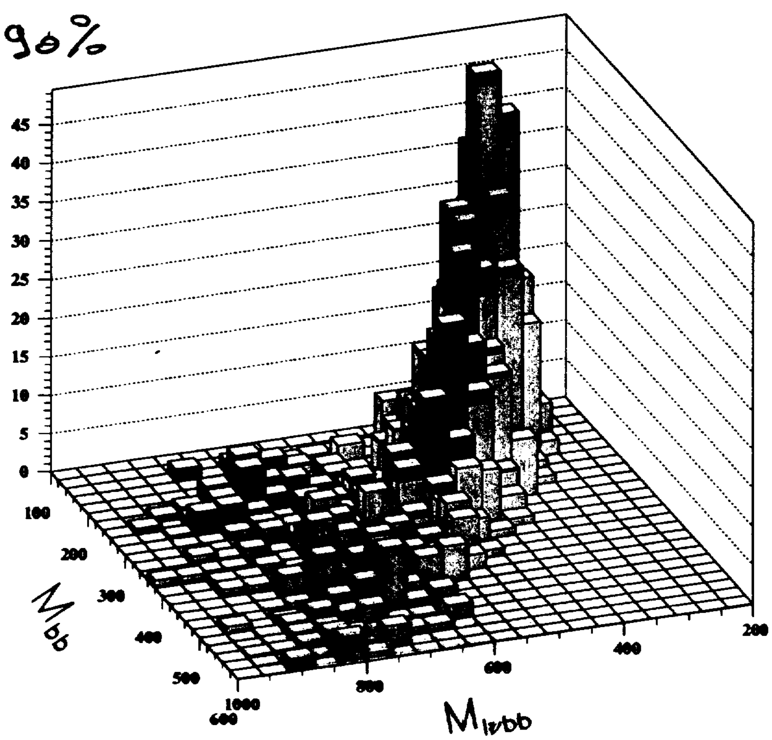
$|\cos\hat{\theta}_{l\nu bb}| < 0.6$

M_ρ	M_{π_T}	$BR(\rho_T \to W\pi_T^0)$	$\sigma \times BR$ (pb)	$S/\sqrt{B}$	$\sigma \times BR$ (pb) for 5σ
500	300	36.3	0.336	6.6	0.255
800	500	38.2	0.064	2.1	0.15
800	250	13.2	0.021	5.3	0.02

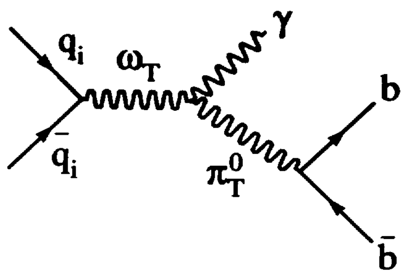
$BR(\pi^0 \to bb) = 90\%$

— $t\bar{t}$

— ρ_T



$$\omega_T \longrightarrow \gamma \pi_T^0 \longrightarrow \gamma b\bar{b}$$



Backgrounds

$q q \to g \gamma$

$q g \to q \gamma$ + QCD

$g g \to g \gamma$

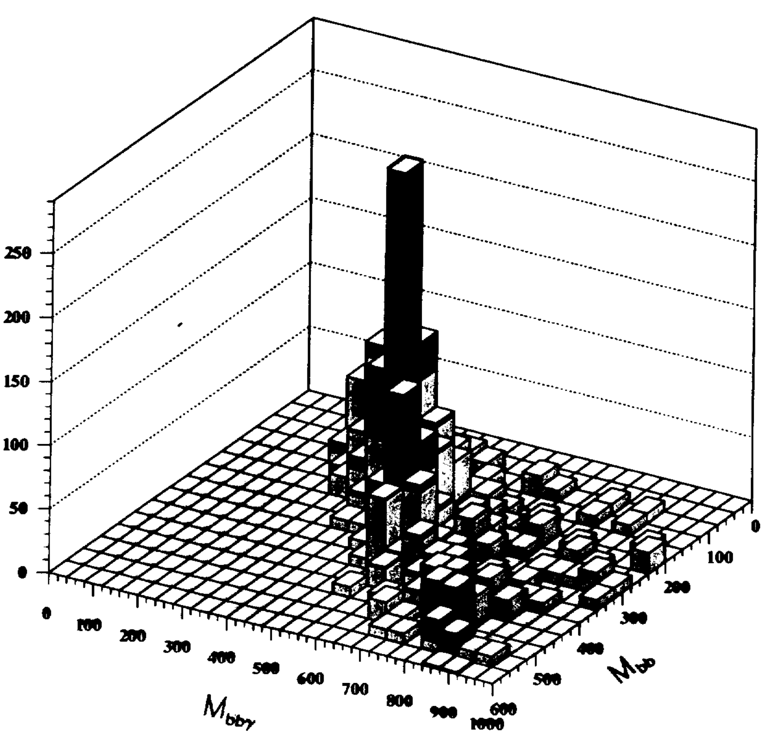
Cuts

1γ, $p_T^{\gamma} > 50$ GeV and $|\eta_\gamma| < 2$

2 b jets $p_T > 40$ GeV, $|\eta_b| < 2$

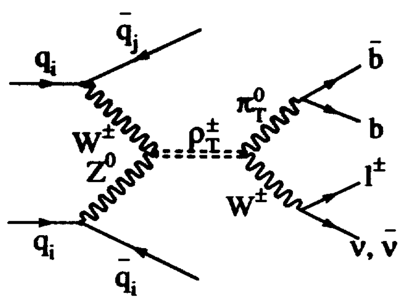
$|\theta_{b_1} - \theta_{b_2}| > 2$ radians

M_{ω_T}	σ (pb)	$\sigma \times BR$ (pb)	$S/\sqrt{B}$	$\sigma \times BR$ for 5σ (pb)
500	0.51	0.161	60	0.013
800	0.093	0.033	35	0.0046



$$\rho_T^{\pm} \longrightarrow W^{\pm}\pi_T^0 \longrightarrow l\nu b\bar{b}$$

from Vector Bosons fusion



$m_{\rho_T} = 800$ GeV

$m_{\pi_T} = 500$ GeV

PYTHIA + $WZ\pi_T$ and $\rho_T W \pi_T$ vertices

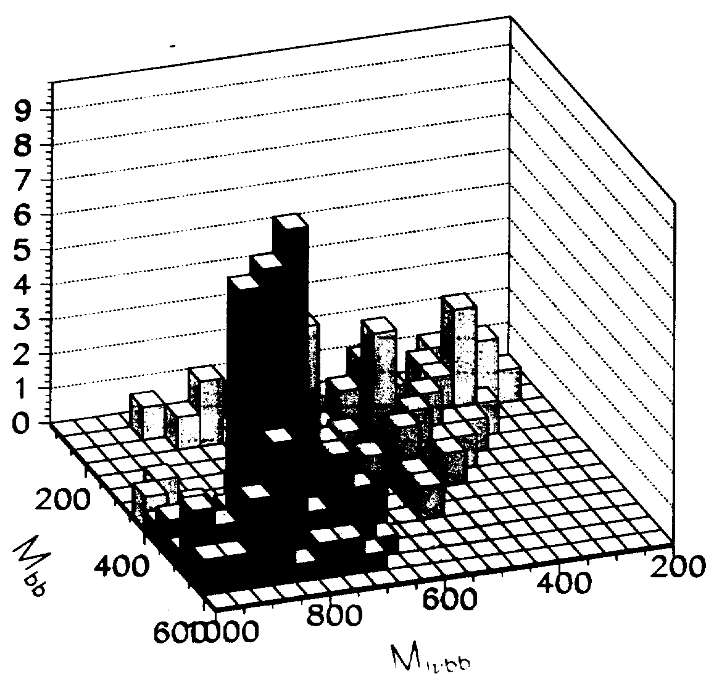
$\sigma_{\rho_T} = f(\sin\chi)$

Same background ass qq fusion

	ρ_T	$t\bar{t}$	W+jets	WZ	Z+jets
Presel. and other cuts	980	15000	635	20	85
Central jet veto	979	2078	175	10	36
Double jet tagging	81	42	3	0	0
E(Forw. jet) > 500 GeV	77	16	1.5	0	0

qq fusion $\sigma \times BR(5\sigma) = 150$ fb

WZ fusion $\sigma \times BR(5\sigma) = 71$ fb



Conclusion

- $V_L V_L$ scattering at TeV scale will provide clues about the nature of the Symmetry Breaking Sector
- ATLAS could be able to make good measurments of $V_L V_L$ scattering Amplitudes
- Even if there were a light Higgs boson and even if it were discovered, it would still be important to measure the VV scattering in the TeV region to probe the central prediction of the Higgs mecanism (No strong VV scattering!!)

- TC provides a dynamical means of breaking electroweak symmetry
- Many resonances predicted by multiscale TC
- They are generic resonances with many unknown parameters but ATLAS has the potential to detect them, in some cases very easily.