v1.011

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The No-Higgs Signal:
Strong WW Scattering at the LHC

Topics

- Introduction
- Higgs Mechanism - no Higgs boson
- No Higgs Mechanism - e.g., 5-d models
- Precision Electroweak Constraints
- Illustrative Signals @ LHC
  - W^+W^+ / WZ complementarity
- Bottom Line

Fifty years of HEP has led us to a fundamental question,

What breaks EW symmetery? (aka origin of mass)

that is special in one respect:

We know how to find the answer!

➡ **Build and run the LHC**

Ability to observe strong WW scattering is essential:

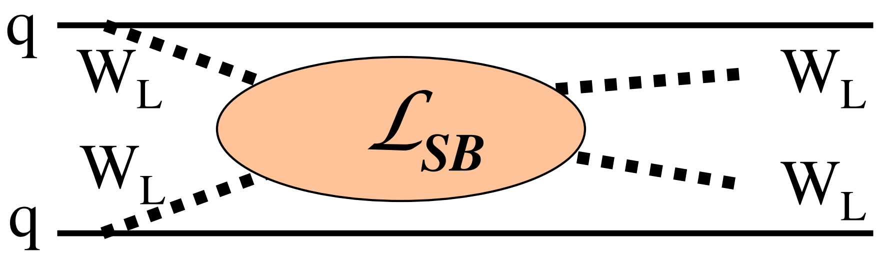
See it -	strongly coupled quanta	**>** 1 TeV
Don’t see -	weakly coupled quanta	**<** 1 TeV
	(Higgs boson(s) if Higgs mech. is valid)	

If light quanta are not seen, absence of strong WW scattering would be a signal to look harder below < 1 TeV, ***not*** *>> 1 TeV.*

$W_L \not\in \mathcal{L}_{gauge}$ **but** $W_L \in \mathcal{L}_{\boldsymbol{SB}}$

⇒ $W_L W_L$ scattering probes the unknown dynamics of $\mathcal{L}_{\boldsymbol{SB}}$

$W_L\, W_L$ Fusion:



Strong $W_L W_L$ scattering signal:
excess of $W_L W_L$ pairs (above SM/light Higgs prediction)

⇒ EWSB from strong dynamics

Higgs mechanism

$$\mathcal{L} = \mathcal{L}_{gauge} \qquad + \qquad \mathcal{L}_{SB}$$

Local SU(2) x U(1)
$m_W = m_Z = 0$
Transverse pol'ns

Global sym. G → H
Goldstone's w,z couple to J_{gauge}

$$w,z \longrightarrow W_L Z_L$$

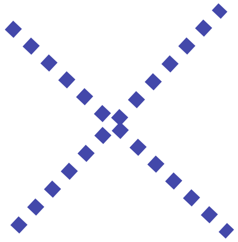
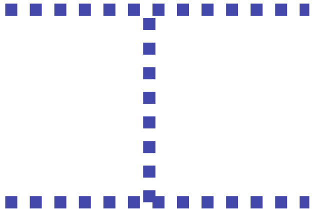
$$\boxed{\underline{\text{Equiv. Th'm}}\text{:}\quad \mathcal{M}(W_L(p_1)\ldots W_L(p_n)) = \mathcal{M}(w(p_1)\ldots w(p_n))_R \quad E_i >> m_W}$$

Don't know $\mathcal{L}_{SB}$, **G, H, but G** $SU(2)_L \square U(1)_Y$ **and H** $U(1)_Q$

Low Energy Theorem } $\mathcal{M}(w^+w^- \rightarrow zz) = s/\square v^2$ $\quad s << \square_{SB}^2$ { Like Weinberg □□ LET

$\Rightarrow$ $\boxed{\mathcal{M}(W_L^+ W_L^- \rightarrow ZZ) = s/\square v^2}$ $\quad m_w^2 << s << \square_{SB}^2$ MC-Gaillard-Golden -Georgi

U gauge: no Goldstone bosons

$\mathcal{M}(W_L^+ W_L^- \rightarrow ZZ)_{\text{gauge sector}} =$  $+$ 

$= g^2 s/4\square m_W{}^2 + O(g^2 s^0) \;\square\; s/\square v^2 \qquad s >> m_W{}^2$

$\Rightarrow \mathcal{M}(W_L^+ W_L^- \rightarrow ZZ) \;\square\; s/\square v^2, \quad \square_{SB}{}^2 >> s >> m_W{}^2 \left\{ \right.$ ***$\mathcal{L}_{SB}$ decouples to all orders***

$\Rightarrow$ Low Energy Theorem = "Bad" UV behavior

Moral of the story:

- $W_L W_L$ scattering is Goldstone boson dynamics of $\mathcal{L}_{SB}$
- U-gauge derivation shows that LET is valid even if there is no Higgs mechanism.

Unitarity

LET $a_{00}(W_L W_L) = s/16\square v^2$

$\mathrm{Re}\ a_{00} \leq 1/2$ $E \ \square\ 1.2$ TeV

$|\ a_{00}\ | \leq 1$ $E \ \square\ 1.8$ TeV

$\Longrightarrow \quad M_{SB} \lesssim O(2)$ TeV

$\mathcal{L}_{SB}$ Weak

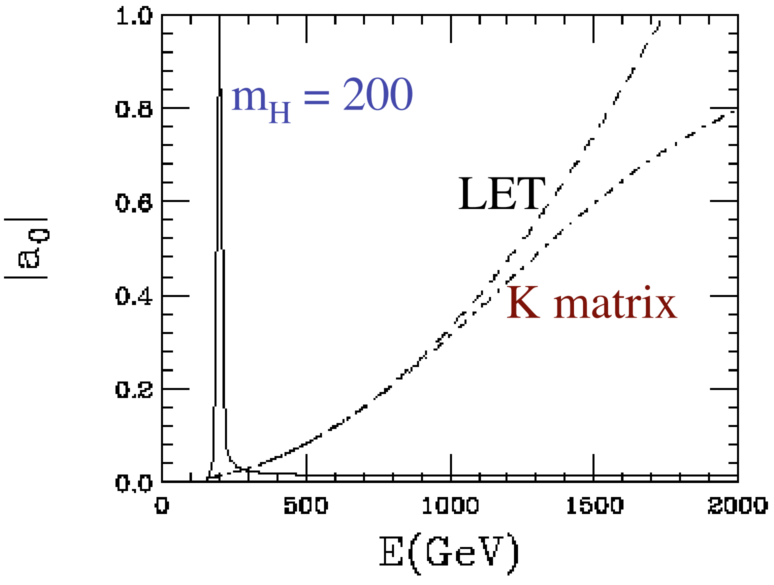
$\mathcal{M} \sim s/v^2\ (1 - s/s\text{-}m_H^2)$

$\xrightarrow[s \gg m_H^2]{} \quad m_H^2/v^2 \sim \square_H$

$a_{00} \sim (m_H/1.8\ \mathrm{TeV})^2$

$\mathcal{L}_{SB}$ Strong

$a_{00} \sim O(1)$ for $E > 1$ TeV



No Higgs Mechanism?

- Higgs mechanism an article of faith for 40 years
- Not tested - LHC will test it

Expt'l success implies $\mathcal{L}_{SU(2) \times U(1)}$ is a good effective theory below the scale of new physics, even if $\not\square$ Higgs mechanism.

➡ Low energy theorems still valid

Unitarity then requires SOMETHING to cut off $a_0(W_L W_L)$

Again,

IF $\square_{SOMETHING} \geq O(1)$ TeV

THEN $\square(W_L W_L)$ is strong

Example of “SOMETHING”: EWSB in 5 dimensions

- EWSB from boundary condition on compact 5’th dimension
- Bad UV cancelled by exchange of Kaluza-Klein gauge bosons,

  $W_n, Z_n, \square_n$ $\qquad$ $M_n \sim n/R$

Chivukula,
Dicus, He

- 5-d Yang Mills is nonrenormalizable

$$g_5^2 = \square R\, g_4^2$$

$$\dim [\, g_5^2 \,] = 1$$

Cutoff at $\square\ \mu\ 1/g_5^2$

Strong dynamics at $\square \sim O(\, 2 - 10\,)$ TeV (strings?)

At the LHC, $W_L W_L$ scattering is weak or strong, depending on mass of KK's

$M_1 << 1$ TeV	weak	As for Higgs mech.
$M_1 \sim O($ TeV $)$	strong	

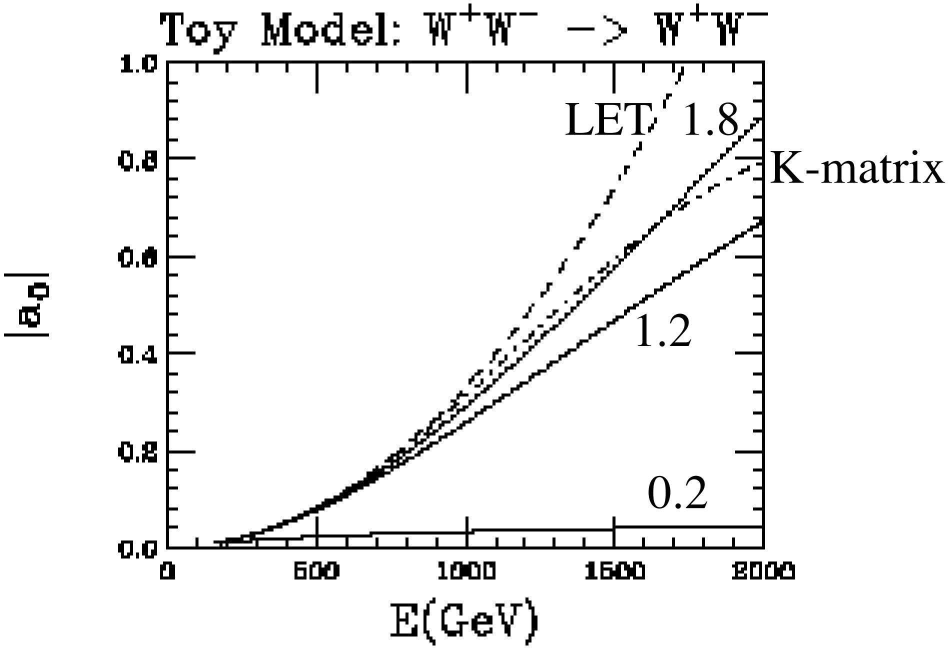
E.g., Toy Model SU(2) □ U(1) "Georgi-Glashow"

$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$

- Unitarity alla Csaki et al. sum rules
- Assume dominance of 1'st KK, $□_1$

Consider $M_1 = 0.2, 1.2, 1.8$

N.B., resonances visible in a_1



Strong coupling favored - smallest EW corrections
Best chance to agree with precision EW
(& optimized to evade direct KK searches)

Burdman-Nomura
Barbieri et al.

Strongly coupled version resembles technicolor, but with better prospects to include fermion masses without big FCNC.

Higgs revenge?

Leading candidate, AdS_5, has dual CFT_4 description
with EWSB from strong gauge force,
i.e., technicolor in CFT_4 setting.

Csaki et al.

Precision Electroweak Constraints

Data appear to favor light m_H,
currently $m_H < 230$ GeV 95% CL

< 250 with
NuTeV

But

1) New (oblique) physics can raise scale of m_H
arbitrarily, with CL 0.18 □ 0.11
2) 3□ discrepancy between A_{LR} & $A_{FB}{}^b$
raises questions about reliability of m_H fit.

0.02 □ 0.007
with NuTeV

LEP cannot definitively determine the scale of EWSB.
LHC can.

New Physics & m_H

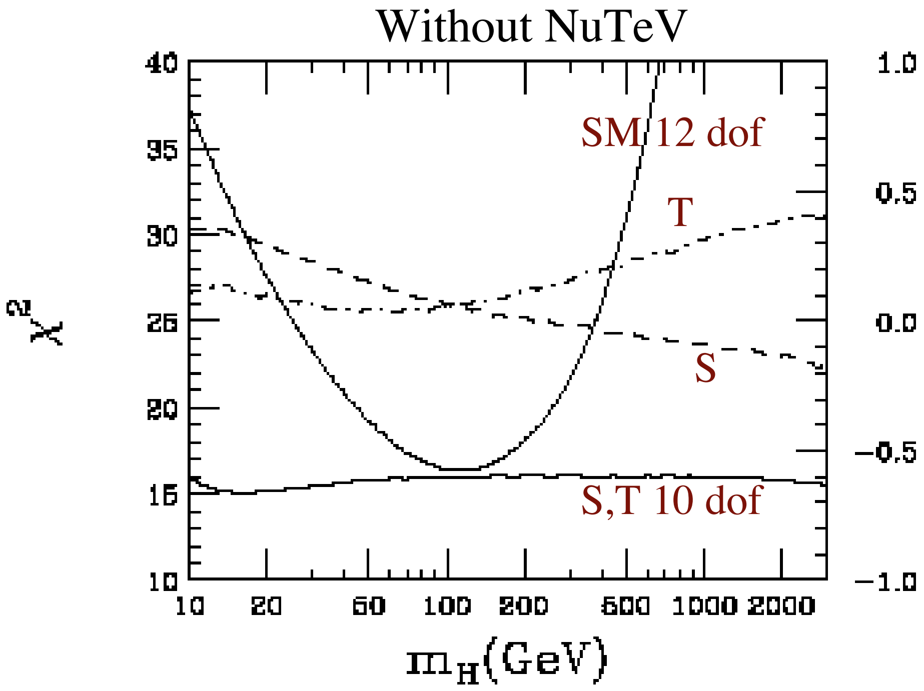
Varying S,T

$\Rightarrow$ ~ flat χ^2 dist.

Need S < 0,

difficult,

not impossible



Csaki et al. $\Rightarrow$ 5d models with S < 0.

However, in broad class of 5d models,

Chivukula et al.

$$S - 4\cos^2\theta_W T = 4\alpha^{-1}\sin^2\theta_W \cos^2\theta_W M_Z^2 \sum_n 1/M_n^2 \gtrsim 1/3$$

so that $S < 0 \longrightarrow T < 0$

<u>BUT</u> S,T [5d] ≠ S,T [exp't]

} Open problem

Reliability of m_H fit?

$\sin^2\theta_W^{\ell,\mathrm{eff}}$ dominates m_H fit, but the two most precise measurements of $\sin^2\theta_W^{\ell,\mathrm{eff}}$, A_{LR} & A_{FB}^b, have an enduring 3σ disagreement.

- Statistical fluctuation?

- New physics? → m_H unknown

-Underestimated systematic uncertainty?
Hadronic asyms, A_{FB}^b, A_{FB}^c, Q_{FB}, have challenging theor. & expt'l systematics,
But sys error would not solve the problem:
➡ $m_H = 55$ GeV, $CL(m_H > 114) = 11\%$
➡ New physics → m_H unknown
(or 11% statistical fluctuation)

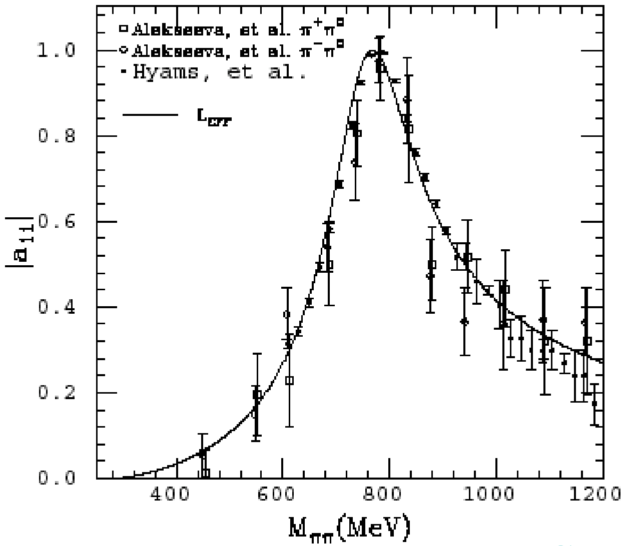
{CL = 5%
with prior
top mass

To accept SM fit of m_H, it is necessary to believe anomalies have statistical origin - not clear…

Signals @ LHC: a QCD'ish example

Weinberg
BESS

$\mathcal{L}_{eff}$ with chiral inv. □□□ inter'n
K-matrix unitarization
Parameters: $F_{□}$, $m_{□}$, $□_{□}$

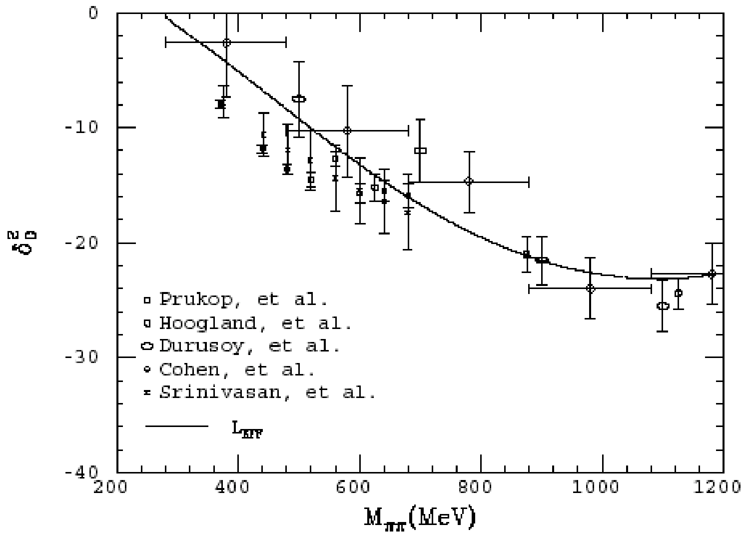


MC, Kilgore

Fits better than it should.

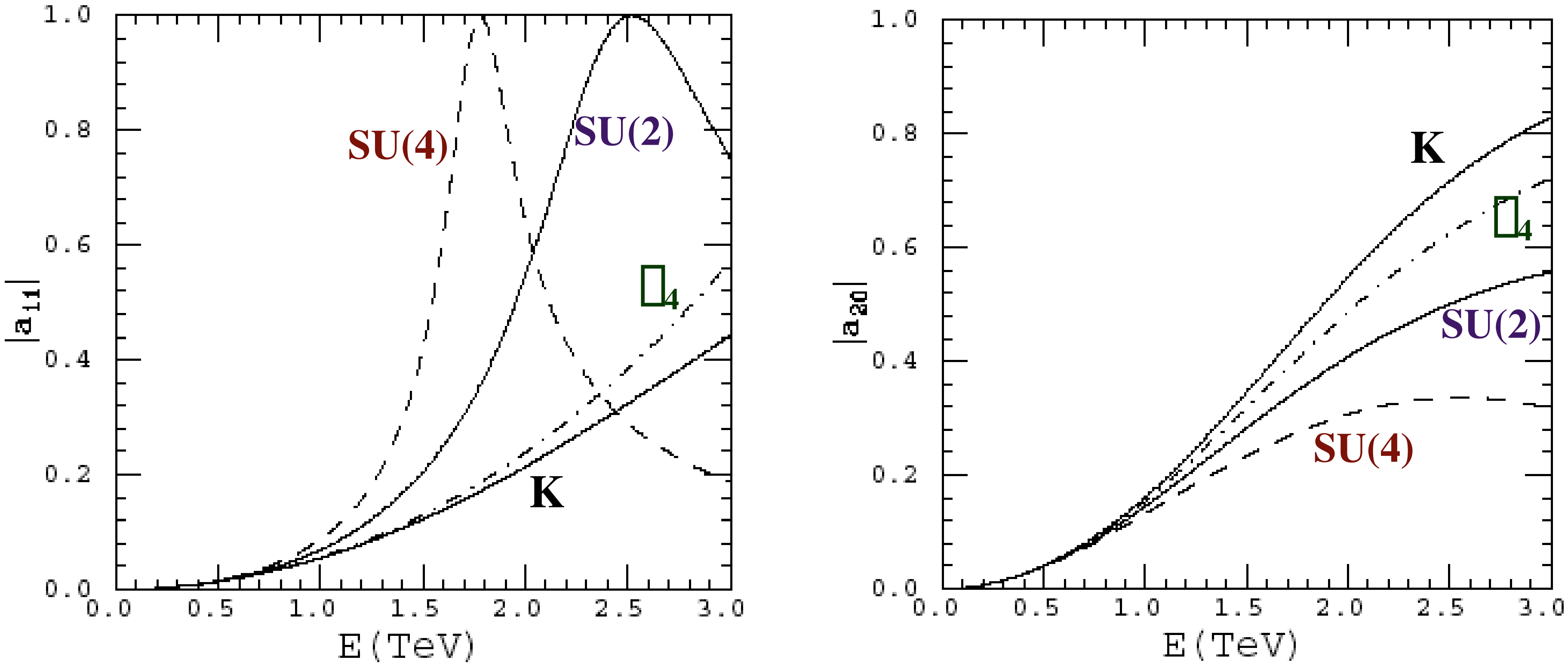
Qualitative success for I = 2:
$□^4$ interferes destructively with
□□□ exchange, causing a_{20}
to flatten.

Apply to $SU(2,4)_{TC}$ & $m_{□}$ = 4 TeV



Complementarity: as $m_{□}$ increases,
a_{11}(WZ) decreases (resonant)
$a_{20}(W^+ W^+)$ increases (nonres)

Complementarity: WZ & W^+W^+



MC, Kilgore

As WZ resonance signal decreases with increasing $m_{\square}$, nonresonant W^+W^+ signal increases.

'K' = K-matrix unitarization of LET
'$\square_4$' has $m_{\square}$= 4 TeV, $f_{\square\square\square}$ from □(770)

$W^+W^+ + W^-W^-$

Signal: 2 central, isolated, hi-p_T, like-sign leptons + 2 forward jets in an otherwise quiet event.

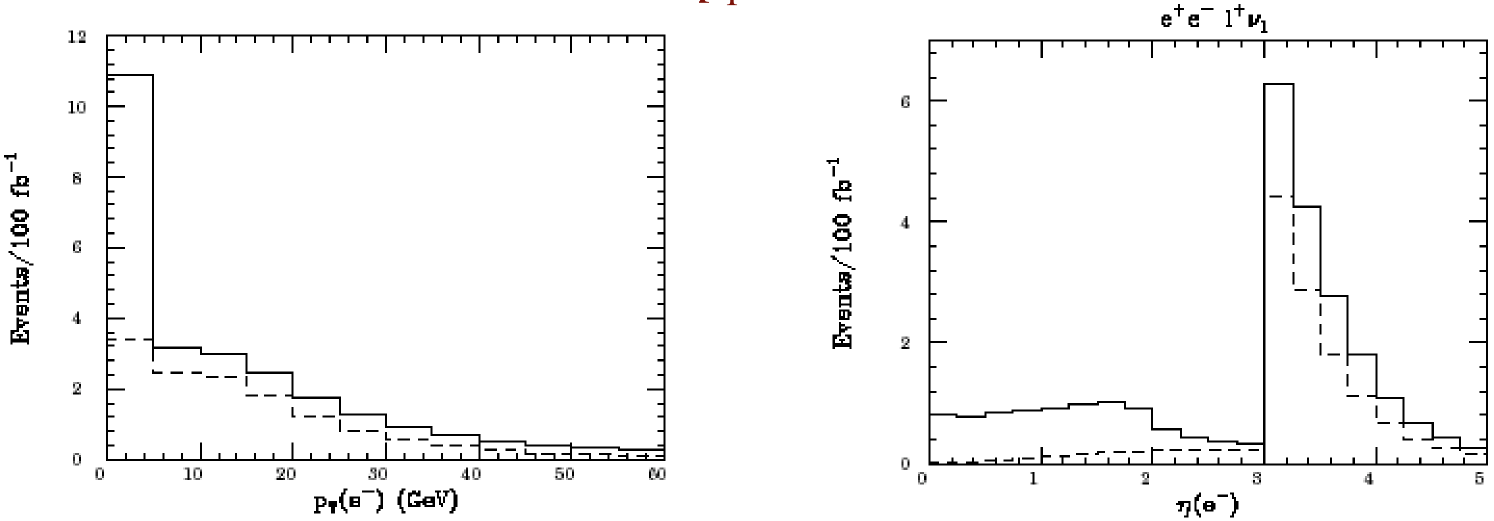
Bkgds: $qq \to qqW^+W^+$ α_W^2, $\alpha_W\alpha_S$
$\bar{t}t$, $\bar{t}tW^+$
W^+Z with unobserved e^- or μ^- !

Azuelos, Leroy, Tafirout

Assume e^-, μ^- invisible for $\eta > 3$

MC, Kilgore

For $\eta < 3$ assume e^-, μ^- invisible for $p_T < 5$ GeV, except e^- collinear with e^+ & $p_T > 1$



Figures: $q\bar{q} \to e^+e^-\ \ell^+\nu$ events that escape veto with $e^+\ell^+$ in signal region.

W^+Z and $W^+\gamma^*$ are included; dashes denote WZ.

Optimize cuts for each model

$\square_{\ell} < \square_{\ell}^{MAX}$

$p_{T\ell} > p_{T\ell}^{MIN}$ $\square_{SIG}$ μ $\square$ s, $\square_{BKGD}$ μ 1/$\square$s

$\cos \square_{\ell\ell} < \cos \square_{\ell\ell}^{MAX}$ leptons better aligned for W_L than W_T

CJV: No jets w $p_T > 60$, $\square < 2.5$ kills top bkgds

Efficiencies assumed:

0.85	isolated e or □	
0.95	$Z \square \ell^+ \ell^-$	
0.95	wrong sign veto efficiency within acceptance	Also studied 0.90, 0.98.

Compute $\mathcal{L}_{MIN}$, minimum luminosity such that

$$S/\ B > 5$$

$$S/\ \overline{S + B} > 3$$

$$S > B$$

Probably too conservative

Results

MC
Kilgore

m_ρ (TeV)	1.8	2.5	4.0
$\mathcal{L}_{MIN}$(WW) (fb^{-1})	200	150	110
$\mathcal{L}_{MIN}$(WZ) (fb^{-1})	44	320	NS

$\left\{\right.$ W^-W^- included

~ 150 fb^{-1} is "No-lose" luminosity.

- Forward jet tag (not used in this study) would probably improve result -- especially useful against $\bar{q}q \rightarrow W^+Z/W^+\gamma^* \rightarrow$ " W^+W^+ " bkgd.
- This study: $WZ \rightarrow \ell\nu + \ell^+\ell^-$, with $\ell = e$ or μ.
  If W → *hadrons* is viable, better results are possible.

Theorist estimates are clearly oversimplified and optimistic
(no attempt to simulate detector, model pileup, charge mis-identification …)
BUT it is nevertheless likely that experimenters working with real data
will be able to devise and test strategies that yield even better results,
e.g., CERN yellow book significantly underestimated LEP I Higgs reach.

Bottom Line(s)

Origin of EWSB is completely unknown -- many possibilities are open, probably some not yet even imagined.

With enough luminosity and expt'l ingenuity, the LHC is sure to lead us to the answer.

To cover all possibilities it is essential to develop the capability to observe strong WW scattering if it exists or to exclude it if it does not.