Collider Phenomenology of the 'Higgsless' Models

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hep-ph/0412278

- Introduction to "Higgsless" Models
- Massive Gauge Boson Scattering and Unitarity
  - Standard Model
  - "Higgsless"
- Testing the Mechanism of EWSB and Unitarity Preservation
- Conclusion and Outlook

Introduction

The Standard Model is <u>INCOMPLETE</u>.

- Higgs boson remains undiscovered

Leaves interesting unanswered questions:

How is electroweak symmetry broken?

How do fermions get their masses?

How do the $W^{\pm}$ and Z^{0} get their masses?

How is unitarity preserved in $WW \to WW$ and $WZ \to WZ$ scattering?

Leads to interesting models:

Higgs-containing models

Higgs (1964) → SUSY Higgs (1975)
- → Fat Higgs hep-ph/0311349 Harnik et. al.
- → Little Higgs hep-ph/0206021 Arkani-Hamed et. al.
- → Little SUSY Higgs hep-ph/0408192 A.B., Z. Chacko, M.K. Gaillard
- → Phat Higgs hep-ph/0408329 A.D., [illegible]
- → <u>Many</u> others

Technicolor models (strongly-coupled Higgsless)

Gildener + Weinberg (1976)

Dimopoulos + Susskind, Weinberg (1979) + many others

Still current, see Luty + Okui hep-ph/0409274 and more!

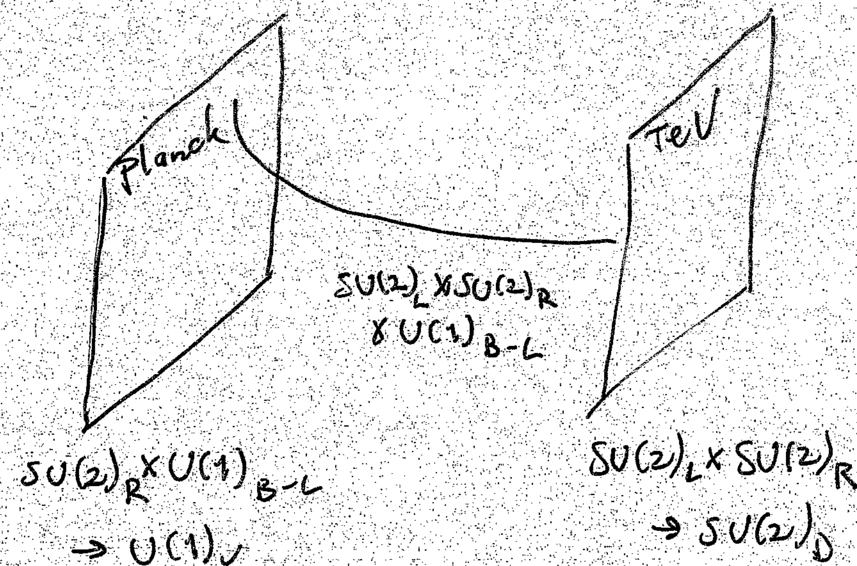
'Higgsless' models (weakly coupled Higgsless)

Csaki et. al. hep-ph/0305237

hep-ph/0308038

Introduction to Higgsless

- Electroweak symmetry is broken by higher-dimensional boundary conditions, not a Higgs mechanism



- Usual SM value of $\frac{M_W}{M_Z}$ guaranteed by $SU(2)_R$ bulk symmetry (like custodial $SU(2)$ in SM (Sikivie et.al 1979), Agashe, et.al. 2003)

- Fermion mass generation and placement is very model-dependent, we won't deal with it here.

- No Higgs, so unitarity is restored by KK gauge bosons.

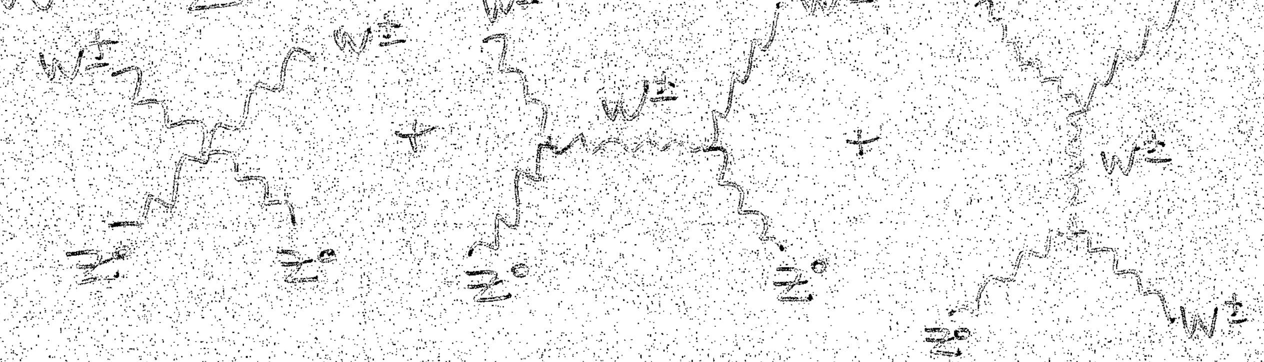
Massive Gauge Boson Scattering and Unitarity

- EWSB $\Rightarrow$ massive $W^\pm$ and Z^0
  - $\Rightarrow$ extra polarizations for $W^\pm$ and Z^0
  - $\Rightarrow$ interesting behavior for gauge boson scattering

(we'll focus on $WZ \to WZ$)

In the Standard Model without a Higgs,

$W^\pm Z^0 \to W^\pm Z^0$



$$\frac{\mathcal{M}^{W^\pm Z W^\pm Z}_{SM-H}}{1/(M_W^2 M_Z^2)} = \left(g_{WWZZ} - g^2_{WWZ}\right)\left[(c^2-6c-3)E^4 + (c^2-3c-2)M_Z^2 E^2 - (c^2-9c-4)M_W^2 E^2\right] + g^2_{WWZ}\frac{M_Z^4(1-c)}{2M_W^2}E^2 + \mathcal{O}(E^0)$$

c: cosine of scattering angle

E: energy of incoming W in c.m. frame

At high energy, this leads to violations of unitarity (probability > 1)!

That doesn't make any sense, so something HAS to fix it:

- underlying gauge theory forces

$$g_{WWZZ} = g_{WWZ}^2 \quad \text{(in S.M.)}$$

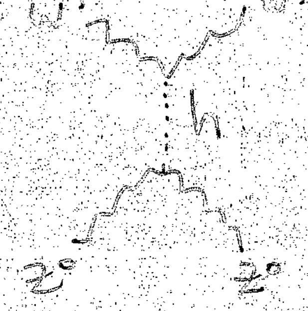
That helps!

$$\frac{\mathcal{M}^{W^\pm Z W^\pm Z}_{SM-H}}{i/(M_W^2 M_Z^2)} = g_{WWZ}^2 \frac{M_Z^4(1-c)}{2M_W^2} E^2 + \mathcal{O}(E^0)$$

Still NOT unitary (unitary: $\mathcal{M} \sim$ const.)

New particles? (like the Higgs)

In the Standard Model, there is the Higgs:



This restores unitarity so that

$$\frac{\mathcal{M}_{SM}^{W^\pm Z W^\pm Z}}{i/(M_W^2 M_Z^2)} = \mathcal{O}(E^0)$$

If the Higgs is absent, unitarity appears to be violated at a scale:

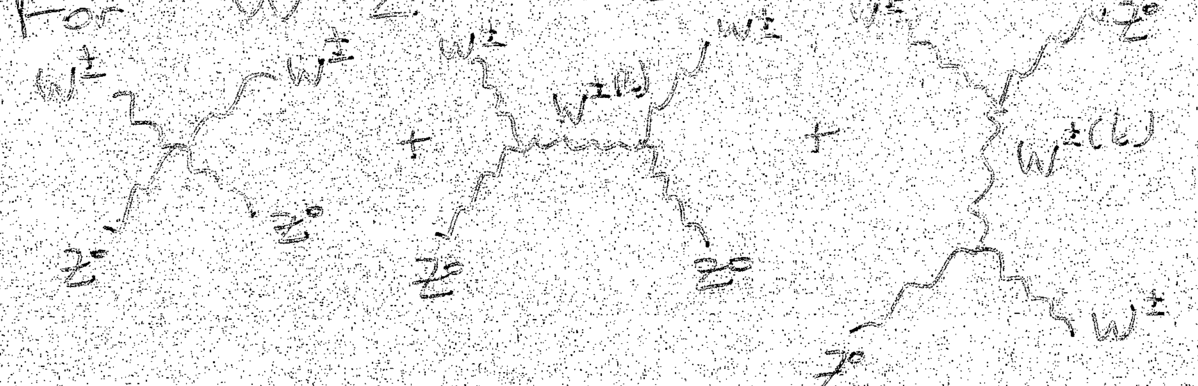
$$\Lambda \sim 4\pi \frac{M_W}{g} \sim 1.8 \text{ TeV}$$

If new particles (or something else?) don't appear before this scale, $W^\pm$, Z become strongly coupled.

What happens in these new "Higgsless" models of EWSB?

- no Higgs, but we've got KK excitations of the $W^\pm$ and Z and γ

For $W^\pm Z^0 \to W^\pm Z^0$ we now have



For each $W^{\pm(k\neq 0)}$ we get the additional contribution

$$\frac{\Delta \mathcal{M}_k^{W^\pm Z W^\pm Z}}{1/(M_W^2 M_Z^2)} = -\left(g^{(k)}_{WZW^{(k)}}\right)^2 \Big[(c^2-6c-3)E^4 + (c^2-2c-3)M_Z^2 E^2 - (c^2-10c-3)M_W^2 E^2 + (1-c)\frac{3(M_{W^{(k)}})^4 - (M_W^2-M_Z^2)^2}{2(M_{W^{(k)}})^2} E^2 \Big] + \mathcal{O}(E^0)$$

So in order for the $W^{\pm(k\neq 0)}$'s to restore unitarity in $W^\pm Z^0 \to W^\pm Z^0$, the following sum rules must be obeyed:

$$g_{WWZZ} = g_{WWZ}^2 + \sum_{i=1,\dots}^{\infty} \left(g^{(i)}_{WZW^{(i)}}\right)^2$$

$$2\left(g_{WWZZ} - g_{WWZ}^2\right)\left(M_W^2 + M_Z^2\right) + g_{WWZ}^2 \frac{M_Z^4}{M_W^2} = \sum_{i=1,\dots}^{\infty} \left(g^{(i)}_{WZW^{(i)}}\right)^2 \left[3\left(M_{W^{(i)}}\right)^2 - \frac{\left(M_Z^2 - M_W^2\right)^2}{\left(M_{W^{(i)}}\right)^2}\right]$$

These are satisfied exactly in 5D theories if the whole K.K. tower is taken into account

(required by gauge invariance and locality of the underlying theory)

Eventually the increasing number of inelastic channels do spoil unitarity but this is delayed until

$$\Lambda_{NDA} \sim \frac{3\pi^4}{g^2} \frac{M_W^2}{M_{W^{(1)}}} \quad \left(\mathcal{O}(5\text{-}10\,\text{TeV})\right)$$

Testing the Mechanism of EWSB and Unitarity Restoration (@ the LHC)

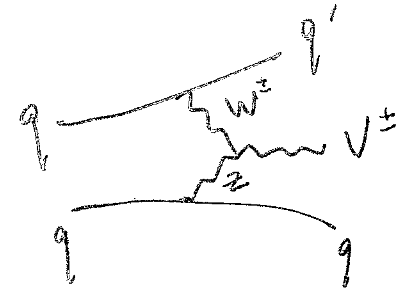
How can we discover (or rule out) the 'Higgsless' models at the LHC?

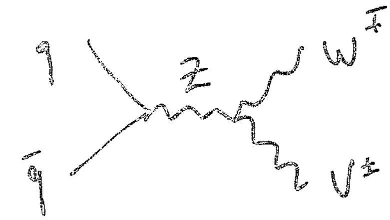
We can try to produce the new gauge bosons singly

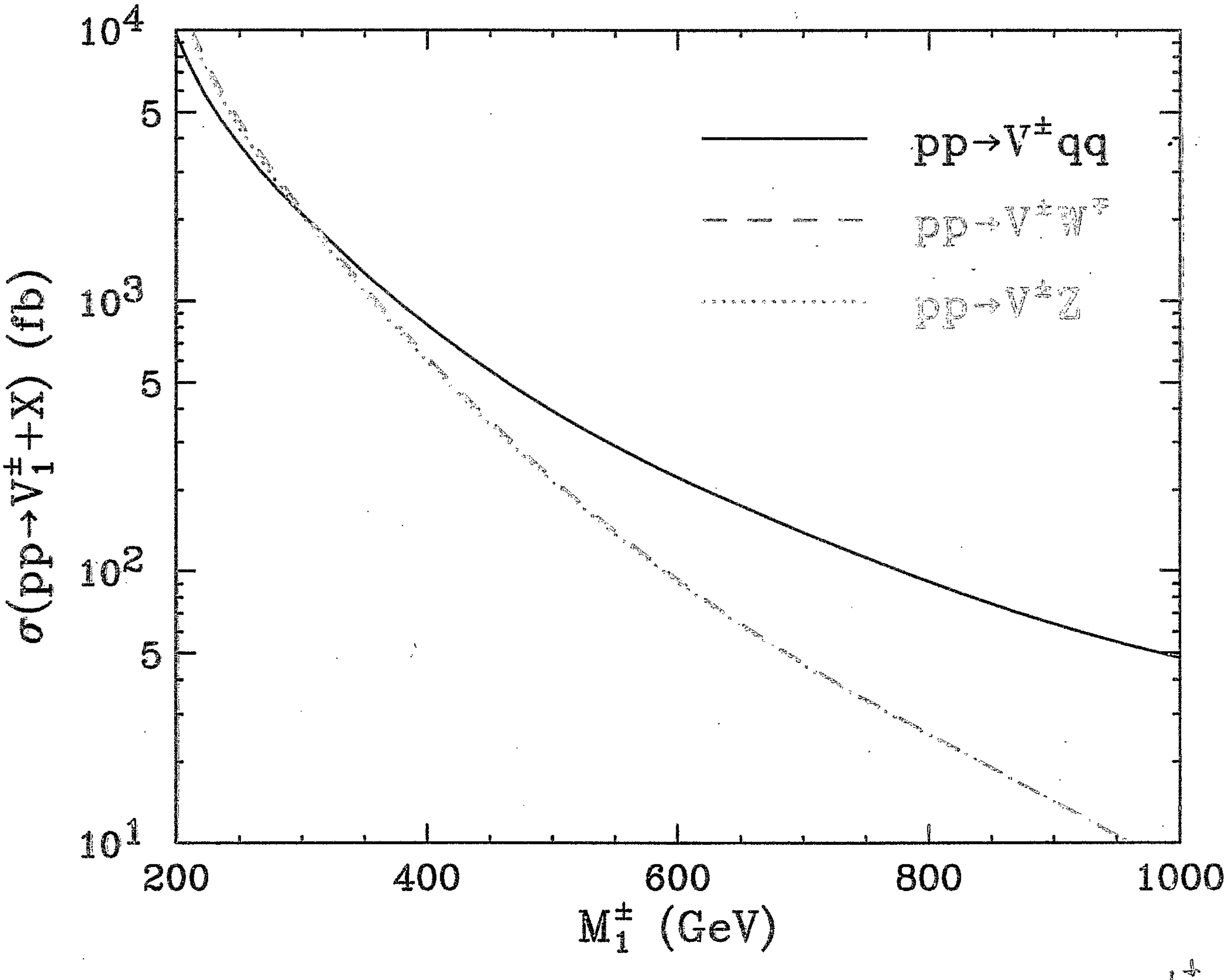
H. Davoudiasl et al. hep-ph/0312192

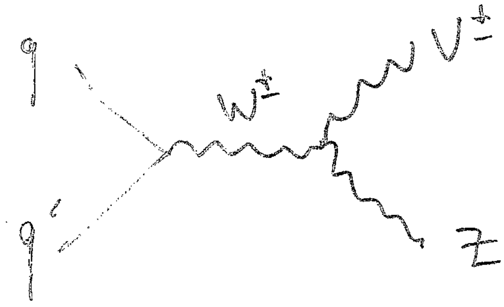
- Doesn't test the 'Higgsless' unitarity restoration mechanism
- $q q' W^{(k)}$ couplings are very model-dependant (could be suppressed)

Too bad the LHC isn't a 'Massive Gauge Boson Collider'!

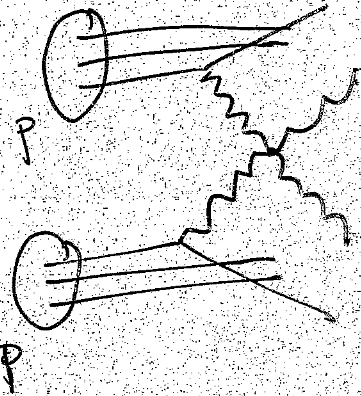

q
q'
W±
V±
Z
q
q


q
Z
W∓
q̄
V±


pp→V±qq
pp→V±W∓
pp→V±Z
σ(pp→V±1+X) (fb)
M±1 (GeV)
10^4
5
10^3
5
10^2
5
10^1
200
400
600
800
1000


q
W±
V±
q'
Z

But it IS!



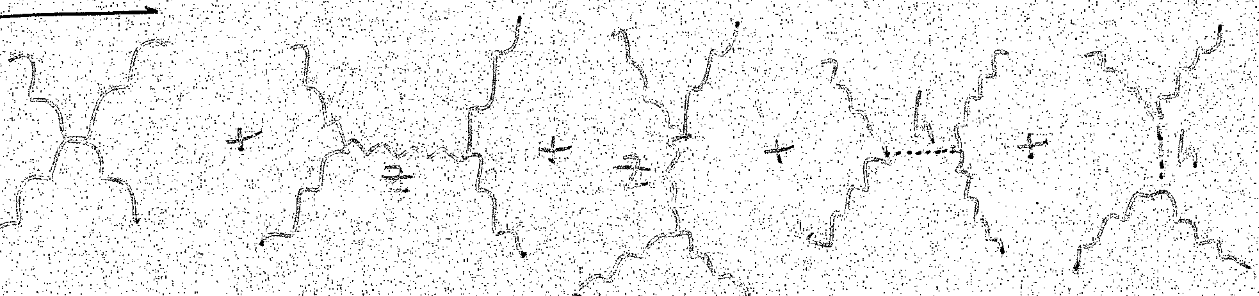
IF YOU COUNT BREMSSTRAHLUNG...

So we can actually test unitarity restoration of massive gauge boson scattering!

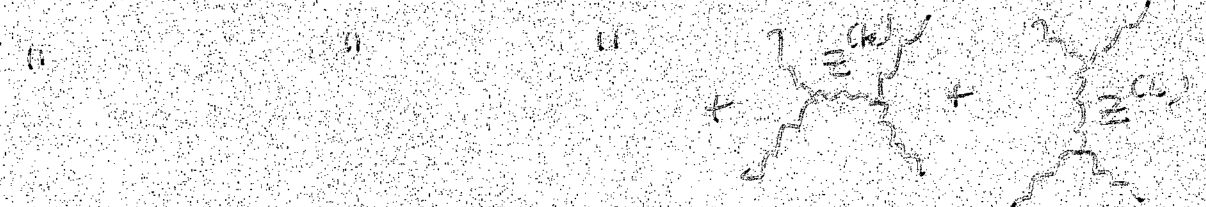
But what can we use to distinguish SM (with a Higgs) from Higgsless (or technicolor)?

$WW \to WW$?

SM:



Higgsless:



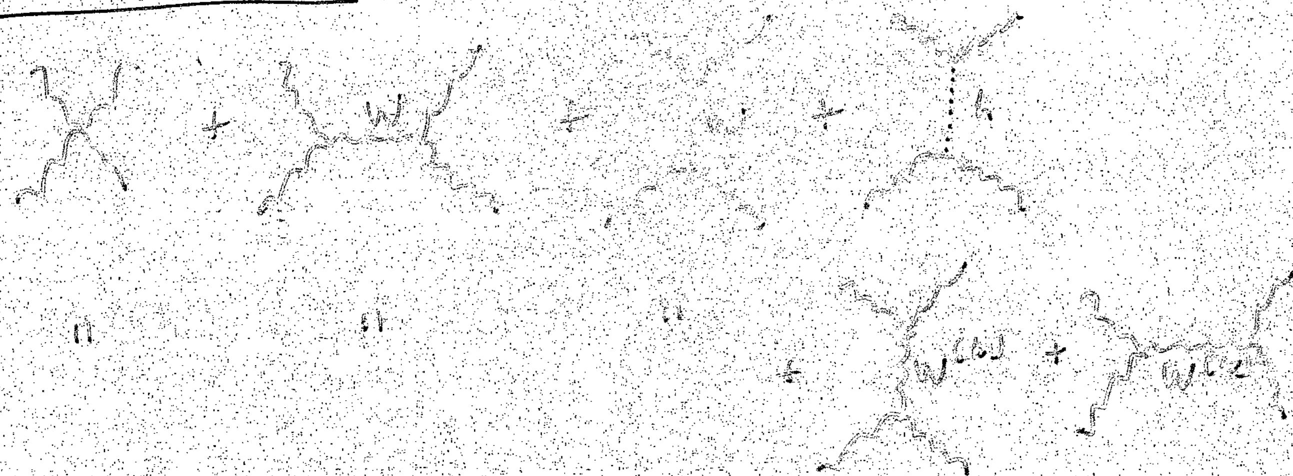
Hmm. Same resonance structure.

Might get fooled ($m_h = m_{Z^{(k)}}$?)

WZ → WZ?

SM:

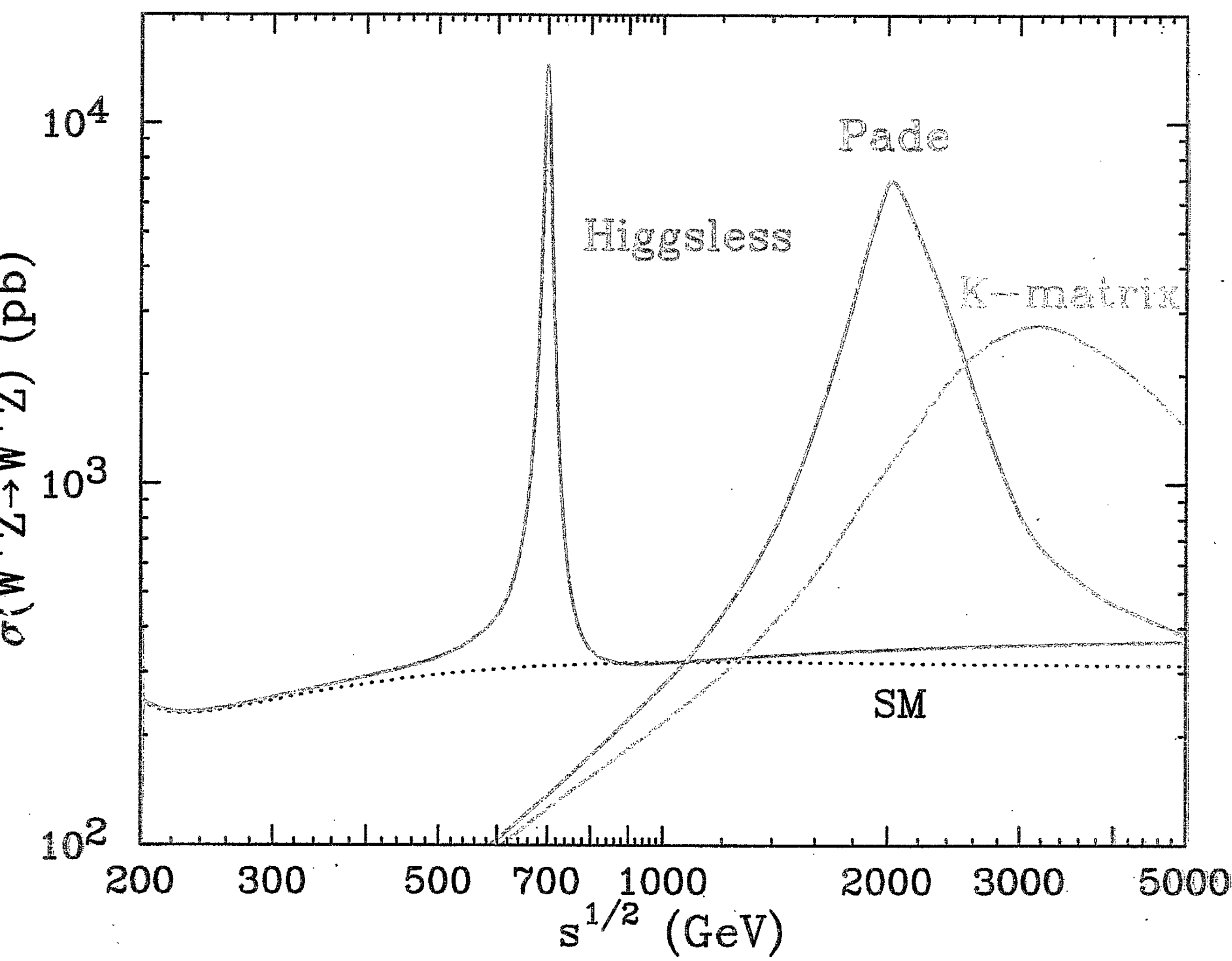
Higgsless:



A different resonance structure!

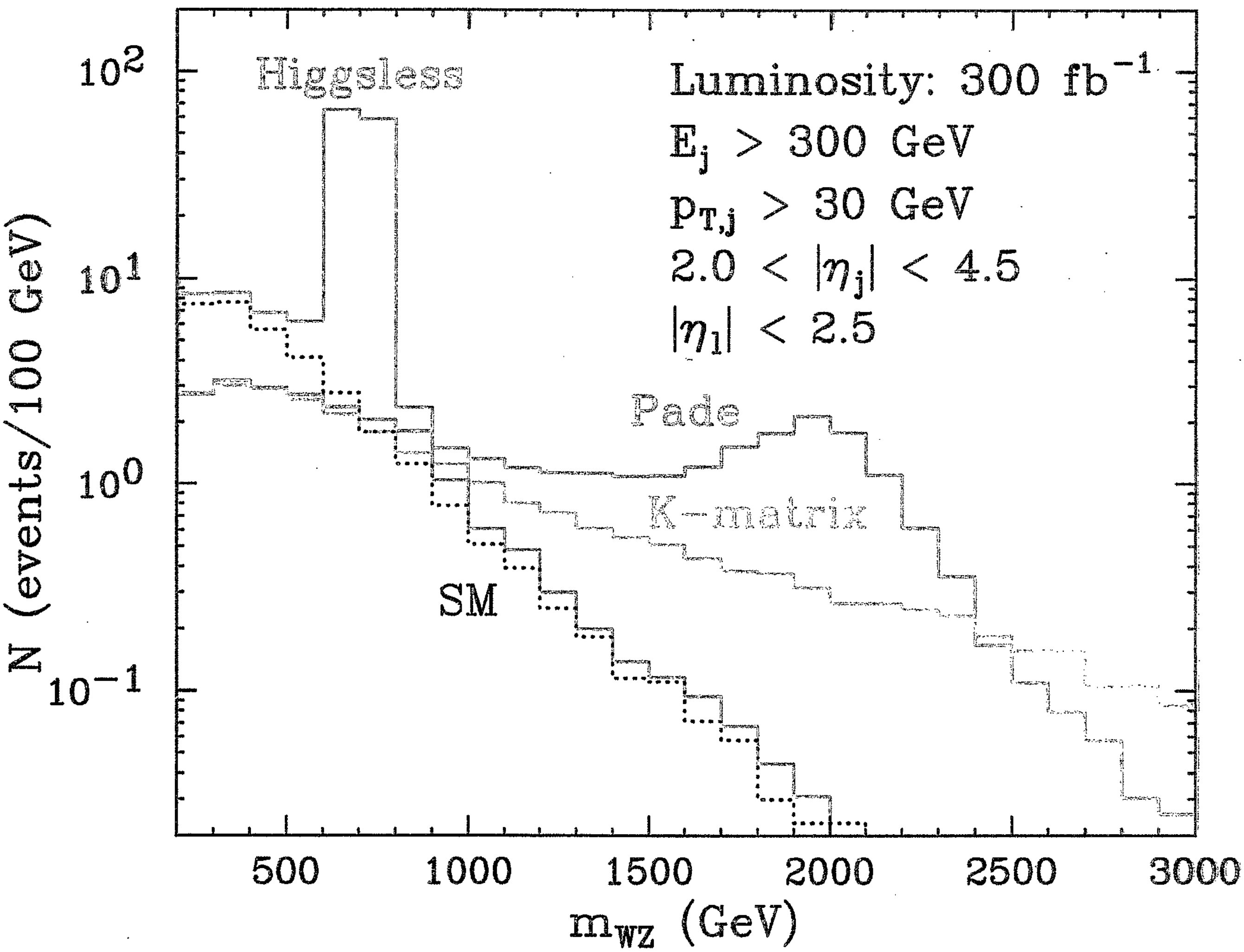
Distinguishable s-channel resonance?	WW→WW	WZ→WZ
SM	No	No
Higgsless	No	Yes!

If we see an s-channel resonance in WZ → WZ, we know it isn't the Higgs!



Pade
Higgsless
K-matrix
SM
10^4
10^3
10^2
$\sigma(W^+Z \to W^+Z)$ (pb)
200
300
500
700
1000
2000
3000
5000
$s^{1/2}$ (GeV)

$2j + 3\ell + \not{E}_T$



Results of LHC Analysis

- 1 year of running at low luminosity :
  (10 fb^{-1} of data)

  LHC can probe Higgsless models up to
  $$M_{k=1}^{\pm} \lesssim 550 \text{ GeV}$$

- To cover <u>entire</u> preferred range ($M_{k=1}^{\pm} \lesssim 1$ TeV)

  requires 60 fb^{-1} of data

  LHC: total luminosity (expected) 100 fb^{-1} ~ 300 fb^{-1}

Measuring $W W_{k=1} Z$ coupling

- To measure $g^{(1)}_{W^{\pm}ZW_{k=1}}$, we need to determine

$$\sigma(pp \to 2j + W_{k=1}) \equiv \sigma_{tot}$$

We've only actually determined

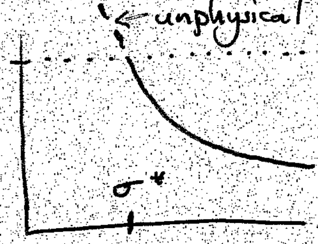
$$\sigma(pp \to 2j + 3\ell + \not{E}_T) \longrightarrow \sigma(pp \to 2j + W^{\pm} Z)$$

In the resonance region, what we observe is:

$$\text{Obs.} = \sigma_{tot}\, BR(W^{\pm}_{k=1} \to W^{\pm} Z) = \sigma_{tot} \frac{\Gamma(W^{\pm}_{k=1} \to W^{\pm} Z)}{\Gamma_{tot}(W^{\pm}_{k=1})}$$

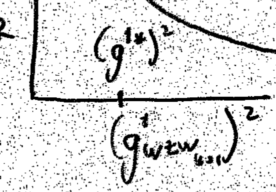
Since $\Gamma_{tot}(W^{\pm}_{k=1}) = \sum_i \Gamma(W^{\pm}_{k=1} \to \text{Final State "}i\text{"})$, $\boxed{BR < 1}$

We measure one number for Obs., so Obs. = const.



So we know $\sigma_{tot} > \sigma^*$

Since $\sigma_{tot} \propto (g^1_{WZW_{k=1}})^2$



we know $\boxed{g^1_{WZW_{k=1}} > g^{1*}}$

From the sum rules, we have $g^1_{WZW_{k=1}} \lesssim \frac{g_{WWZ} M_Z^2}{\sqrt{3}\, M^{\pm}_{W^1} M_W}$

So Higgsless can be ruled out if we measure $\boxed{g^{1*} > \frac{g_{WWZ} M_Z^2}{\sqrt{3}\, M^{\pm}_{W^1} M_W}}$

Conclusions and Outlook

1. Higgsless Models provide a new, interesting alternative to Higgsed theories of EWSB.
2. Electroweak symmetry is broken by boundary conditions in extra dimensions. (4D realizations exist)
3. Unitarization of gauge boson scattering is achieved by KK gauge boson contributions. (Constrained by sum rules!)
4. The resonance structure in $W^\pm Z$ scattering in Higgsless models differs from that of SM, so the unitarization mechanism can be probed experimentally! (s-channel resonance in $W^\pm Z$ scattering is absent in S.M.)

   Excellent prospects @ LHC can probe all of preferred parameter space with 60 fb^{-1} of data
5. Testing sum rules is more difficult, but some exclusion is possible.
6. Will probably help with a Linear Collider?