

Higgsless Electroweak Phenomenology

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Higgs Role in the SM

- W/Z masses $w/p=1$
- generate fermion masses
- unitarize gauge boson scattering

Goal: Do all the above w/no Higgs
using 5^{th} components of gauge fields as
Goldstone bosons \therefore BC's induce symmetry
breaking \Rightarrow correct masses + couplings

* BC's distort wave functions inducing masses
 \rightarrow generalize typical orbifold conditions
that can't break gauge symmetries
 \rightarrow [Example]

Attempt at a realistic model (Csaki et al)

\Rightarrow LR model in RS bulk \oplus boundary kinetic terms

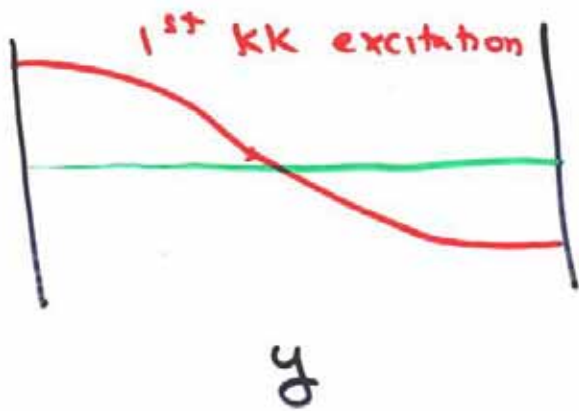
\rightarrow $\begin{cases} SU(2)_R \otimes U(1)_{B-L} \rightarrow U(1)_Y \text{ on Planck brane} \\ SU(2)_L \otimes SU(2)_L \rightarrow SU(2)_D \text{ on TeV brane} \end{cases}$

\downarrow
custodial
 $SU(2)$

\hookrightarrow GED only

TGR
Victoria
2004

Standard Case: $U(1)$ w/ S^1/\mathbb{Z}_2 orbifold



"0" mode

$$\begin{cases} \partial A_n | = 0 \\ A_5 | = 0 \end{cases}$$

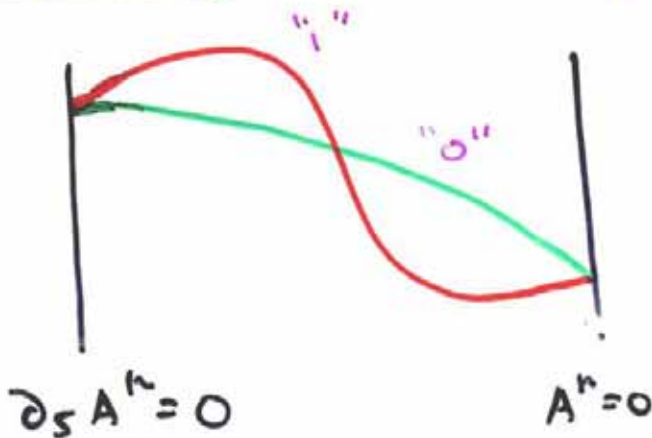
$$\begin{cases} A_n^{(n)} \sim \cos(ny/R) & \left\{ \begin{array}{l} n=0, \dots \\ n=1, \dots \end{array} \right. \\ A_5^{(n)} \sim \sin(ny/R) \end{cases}$$

• "flat" zero mode is massless + symmetry remains unbroken

• Orbifolding removes $A_5^{(0)}$ from spectrum \therefore cannot be "eaten" as a Goldstone

\Rightarrow Recall $A_n^{(n)}$ eat $A_5^{(n)}$ to get mass...

Toy Case: Generalized BC's...



"0" mode cannot be flat here due to BC's...

$$\begin{cases} A_n \sim a_n \cos m_n y + b_n \sin m_n y \\ A_n(y=0) = 0 \rightarrow a_n = 0 \\ \partial_y A_n(L) = 0 \rightarrow \cos(m_n L) = 0 \\ m_n = \frac{n+1/2}{R} \rightarrow \boxed{m_0 = \frac{1}{2R} \neq 0} \end{cases}$$

The "zero" mode is massive!

$U(1)$ gauge symmetry is broken by BC's

!!!

Lots of parameters

$\{g_{5L}, g_{5R}, g_{5B-L}\}$ $\rightarrow 20(1)$

$\hookrightarrow G_F, M_Z, \boxed{K \equiv g_{5R}/g_{5L}}$

brane kinetic term parameters

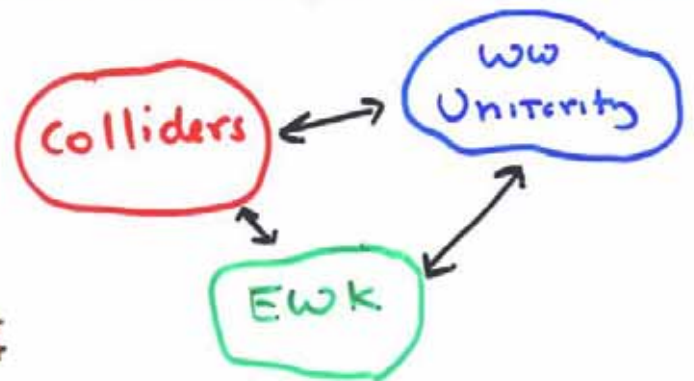
$\boxed{\delta_B, \delta_D, \delta_L, \delta_Y}$ for $U(1)_{B-L}, SU(2)_{D,L}$
+ $U(1)_Y$

- Too many parameters for grid study [5]

\Rightarrow Monte Carlo parameter space study

(keep SM fermions on Planck brane for simplicity)

- Model Tension:



\rightarrow KK's must play role of Higgs in $W_L W_L$ scattering

YET

\rightarrow not be so light to have yet been seen at the Tevatron (or indirectly in contact int's at LEP2)

While

\rightarrow Minimizing disruption of EWK SM good results {e.g., $g=1$ }

e.g.,

$$\sin^2 \theta_{0s} \equiv 1 - \frac{M_W^2}{M_Z^2}$$

$$\sin^2 \theta_{\text{eg}} \equiv e^2 / g_{\text{ffw}}^2$$

$$\sin^2 \theta_{\text{eff}} \text{ at } Z\text{-pole}$$

are All equal at the tree level in the SM...

but differ at loop level...

Here they differ at tree-level!

\therefore Pick $\{ \kappa, \delta_i \}$ and demand:

• no ghosts
(in any tower)

$$\frac{g_{B-L}^2}{g_L^2} = \lambda^2 > 0$$

$$|\delta g_{\text{tree}}| < 0.005$$

$$\frac{|s_i^2 - s_{0s}^2|}{s_{0s}^2} < 0.005$$

• KK's avoid Tevatron / LEP II constraints

• light enough KK ($< 1.5 \text{ TeV}$) + right coupling (to WW, i.e., isospin not B-L or Y)

• no dangerous tachyons { strongly coupled to $\bar{f}f$ or WW +/or light }

• Let's see what happens as we filter models through these cuts...

δ_i signs arbitrary

Cuts	κ	0.75	0.9	1.0	1.25	1.5	2.0	3.0	4.0
Initial Sample		308,710	141,950	1,307,463	251,970	271,570	145,570	181,274	136,920
$\lambda^2 > 0$		130,286	62,202	585,011	115,455	125,035	67,662	82,583	16,204
No γ, Z ghosts		130,286	62,202	585,011	115,455	125,035	67,662	82,583	16,204
$ \delta\rho < 0.005$		16,181	7,887	76,994	16,728	20,183	13,799	24,223	2,958
$ s_{\text{eff}}^2 - s_{\text{os}}^2 < 0.005s_{\text{os}}^2$		676	387	3,665	875	1,356	1,328	3,838	2,899
$ s_{\text{eg}}^2 - s_{\text{os}}^2 < 0.005s_{\text{os}}^2$		242	159	1,539	332	545	576	1,805	2,013
No Z' ghost		242	159	1,539	322	545	576	1,805	2,013
Z' Tevatron		150	102	1134	217	393	439	1,556	1,830
$m_{Z'} < 1.5$ TeV		74	50	644	90	180	202	828	1,581
LEP II indirect		70	45	550	72	80	175	796	1,178
Not $B-L$ coupling		24	13	112	12	8	12	65	0
No Tachyons		0	0	0	0	0	0	7	0
PUV		0	0	0	0	0	0	0	0

Table 1: Data samples and their responses to the various cuts as described in the text. The values represent the number of cases surviving each of the various cuts.

- **None** survive PU requirement, ie, PUV occur at $\sqrt{s} \gtrsim 2\text{TeV}$ { sm w/ no Higgs boson }

→ Figs tell all

Thousands of models pass collider + EWK tests !!

ALL $\delta_i \geq 0$ Sample

Cuts κ	1.0	1.5	2.0	2.5	2.75	3.0	4.0
Initial Sample	611,150	304,680	178,320	122,801	266,801	169,862	70,661
$\lambda^2 > 0$	611,150	304,680	178,320	122,801	266,801	169,862	70,661
No γ, Z ghosts	611,150	304,680	178,320	122,801	266,801	169,862	70,661
$ \delta\rho < 0.005$	168,732	159,537	107,709	89,124	211,944	146,087	69,867
$ s_{\text{eff}}^2 - s_{\text{os}}^2 < 0.005s_{\text{os}}^2$	0	502	1,506	2,734	8,600	7,456	8,724
$ s_{\text{eg}}^2 - s_{\text{os}}^2 < 0.005s_{\text{os}}^2$	0	244	760	1,505	4,887	4,308	5,317
No Z' ghost	0	244	760	1,505	4,887	4,308	5,317
Z' Tevatron	0	6	145	530	2,204	2,233	4,174
$m_{Z'} < 1.5$ TeV	0	6	143	530	2,086	2,112	3,919
LEP II indirect	0	6	143	509	2,086	2,112	3,919
Not $B - L$ coupling	0	0	0	0	0	0	0
No Tachyons	0	0	0	0	0	0	0
PUV	0	0	0	0	0	0	0

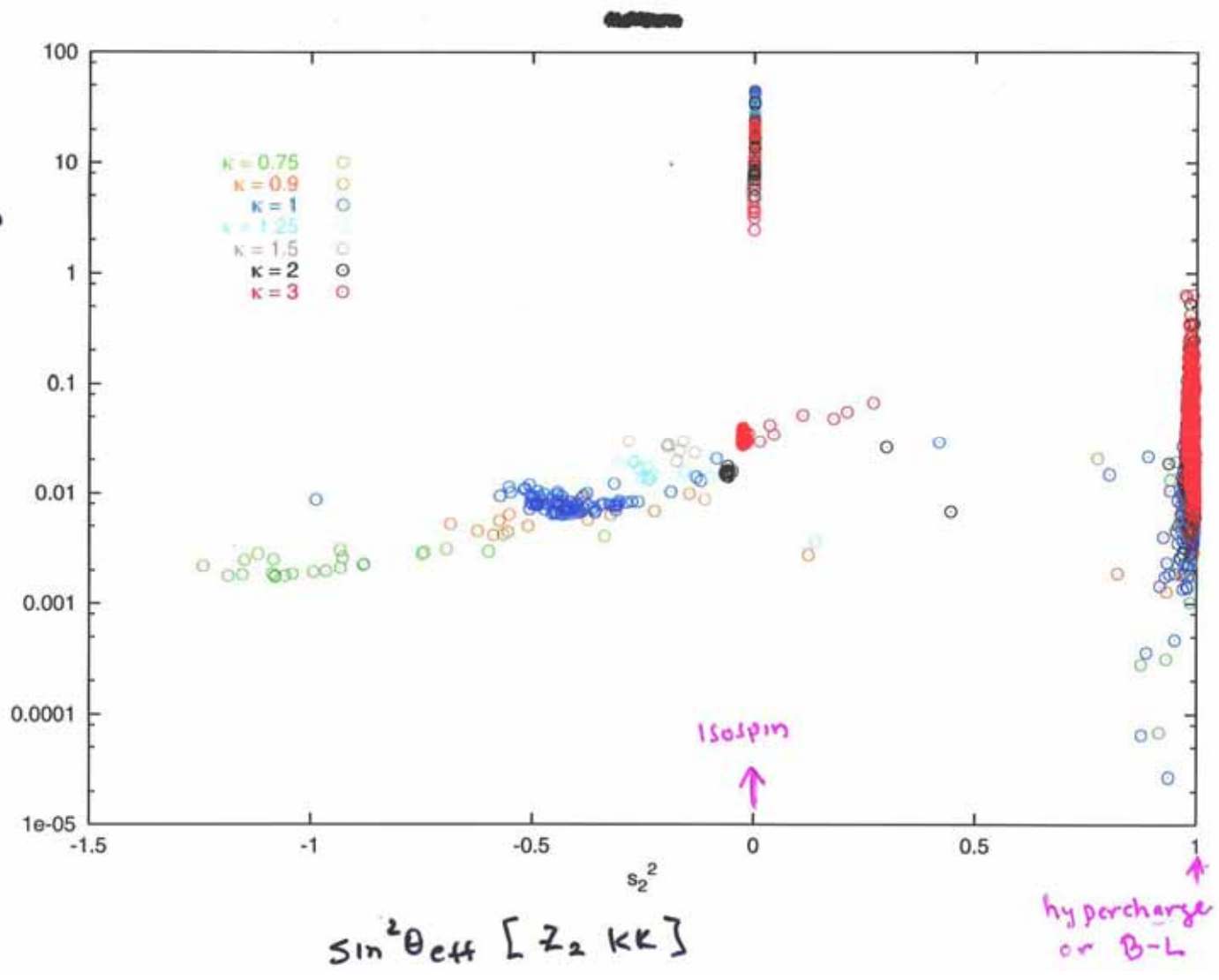
Table 2: Same as the previous table but now for a special set of runs assuming all the $\delta_i \geq 0$. Note that many cases survive until the $B - L$ or Y cut is employed.

None survive ~~B/L~~ coupling requirements

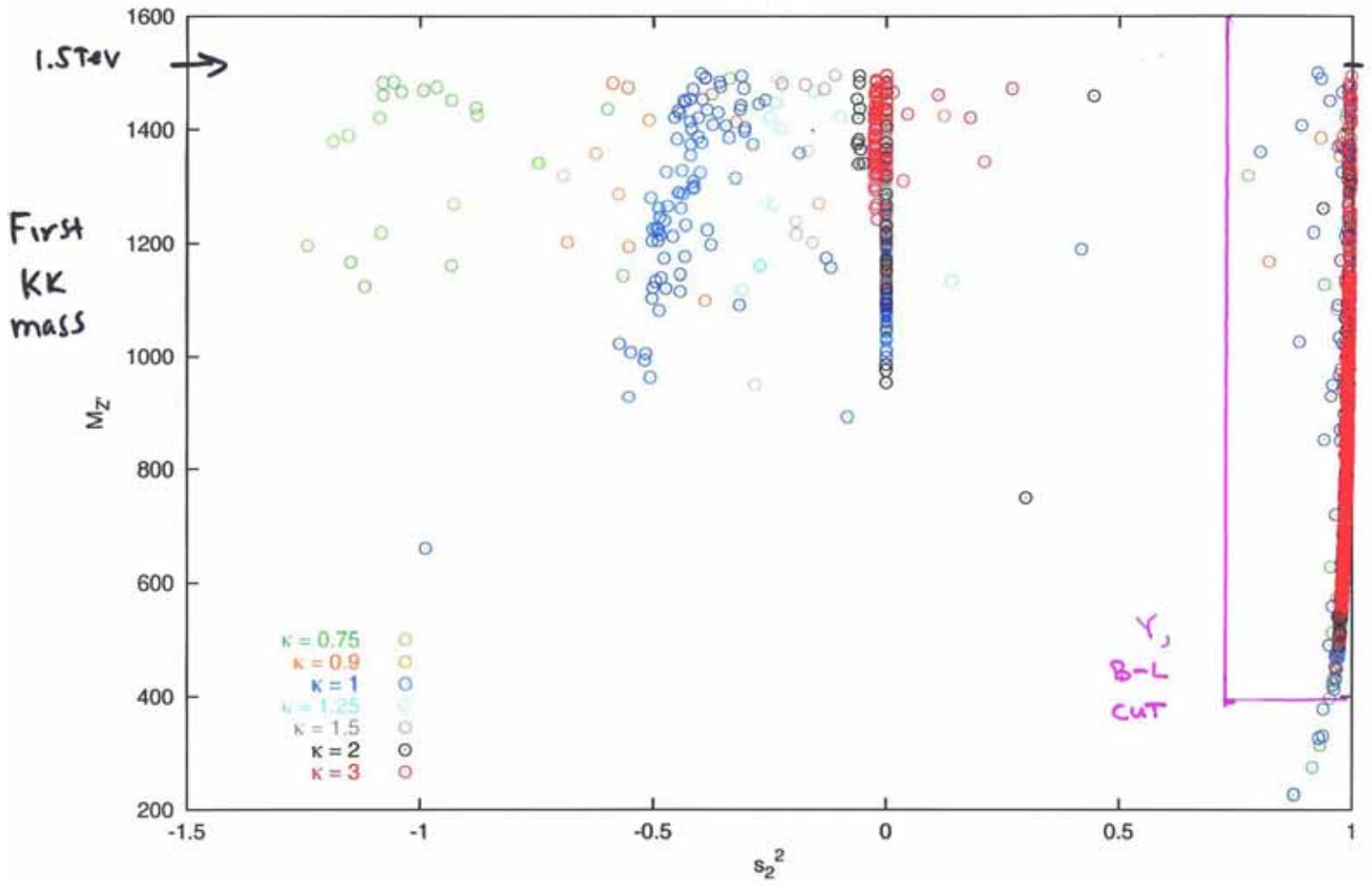
However, again Thousands survive EWK + Collider tests

All EWK + collider cuts (+ no ghosts etc)

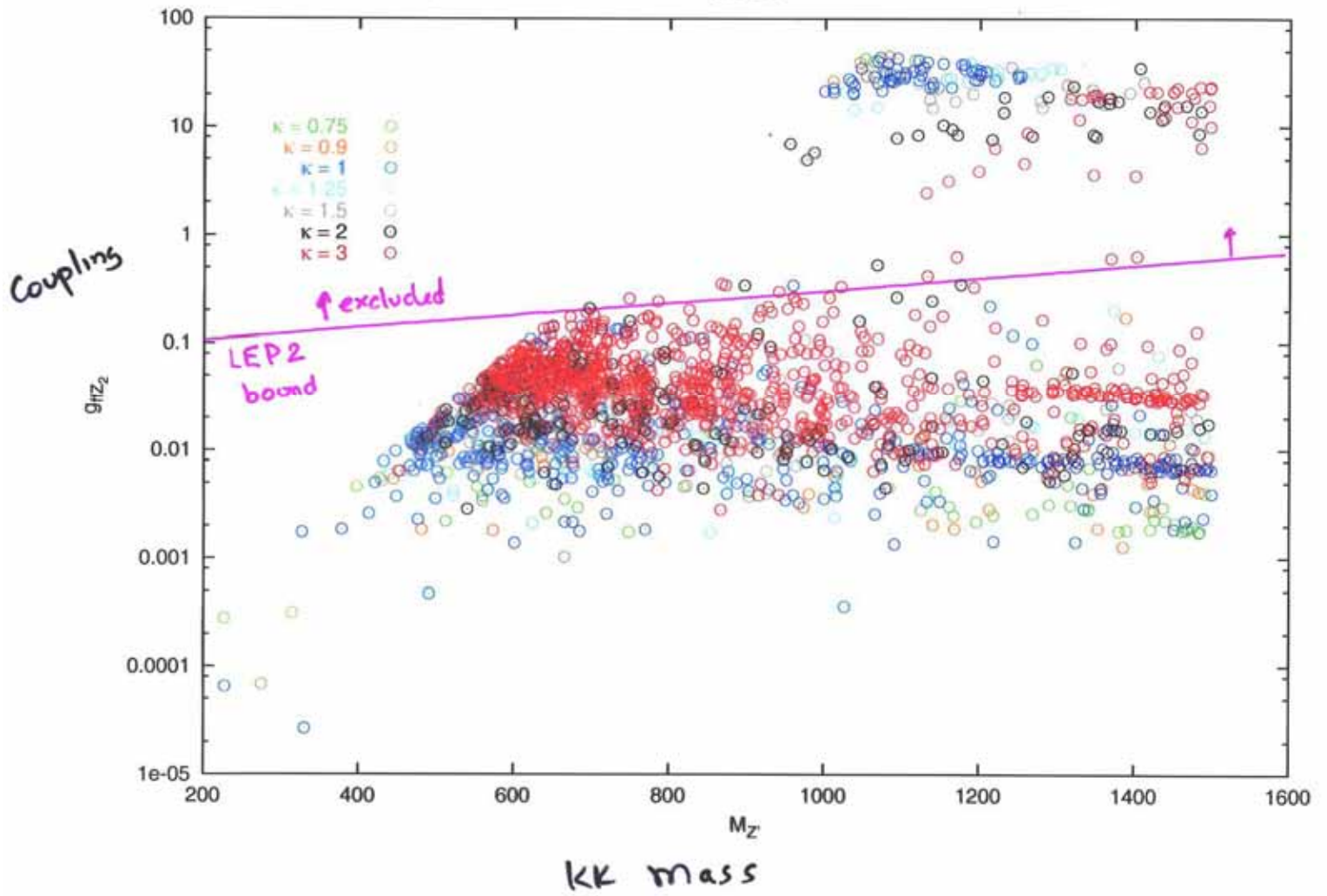
Couplings
in g_1
units



EWK + TeV cuts (+ no ghosts etc)

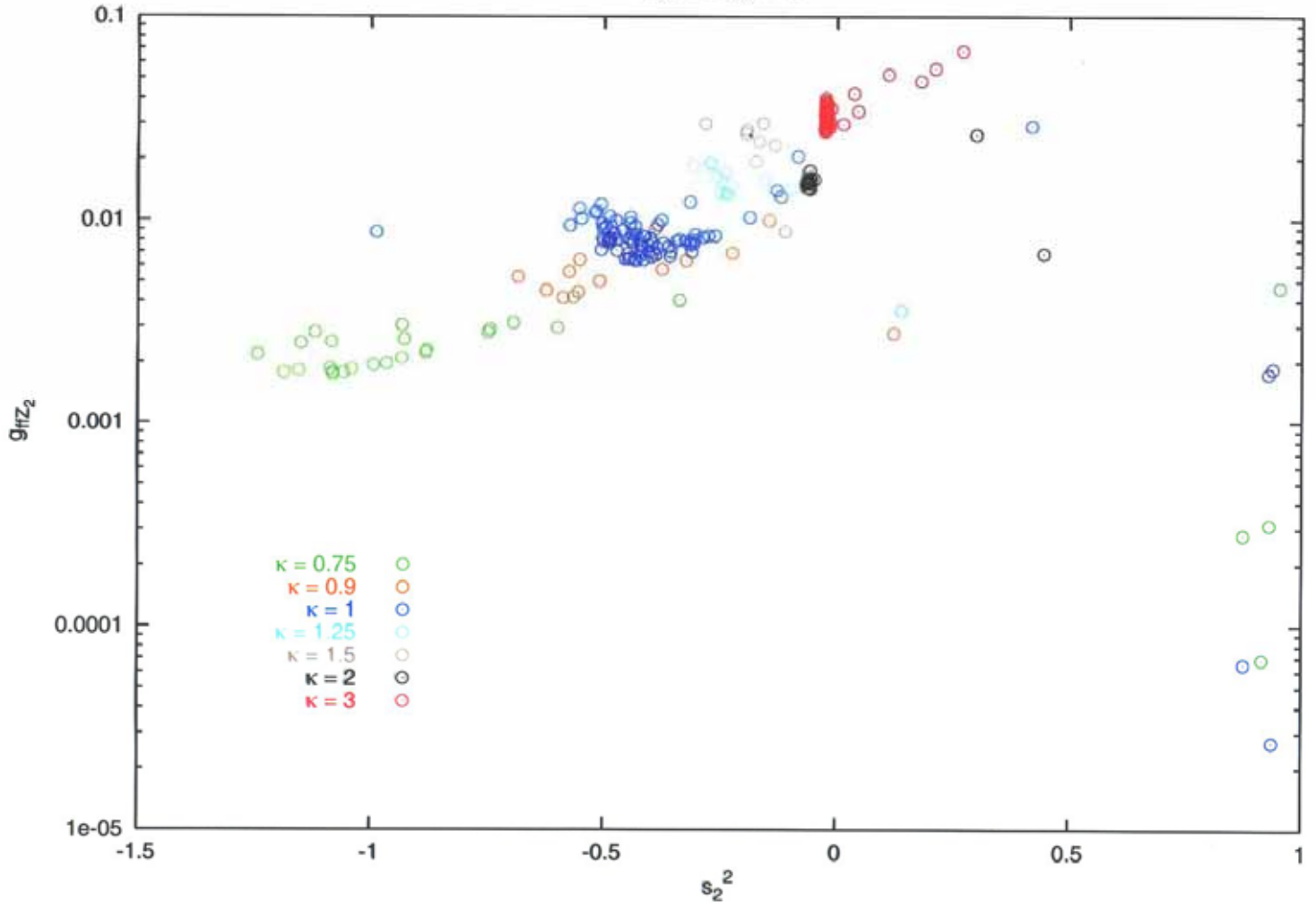


Effect of LEP 2 cuts



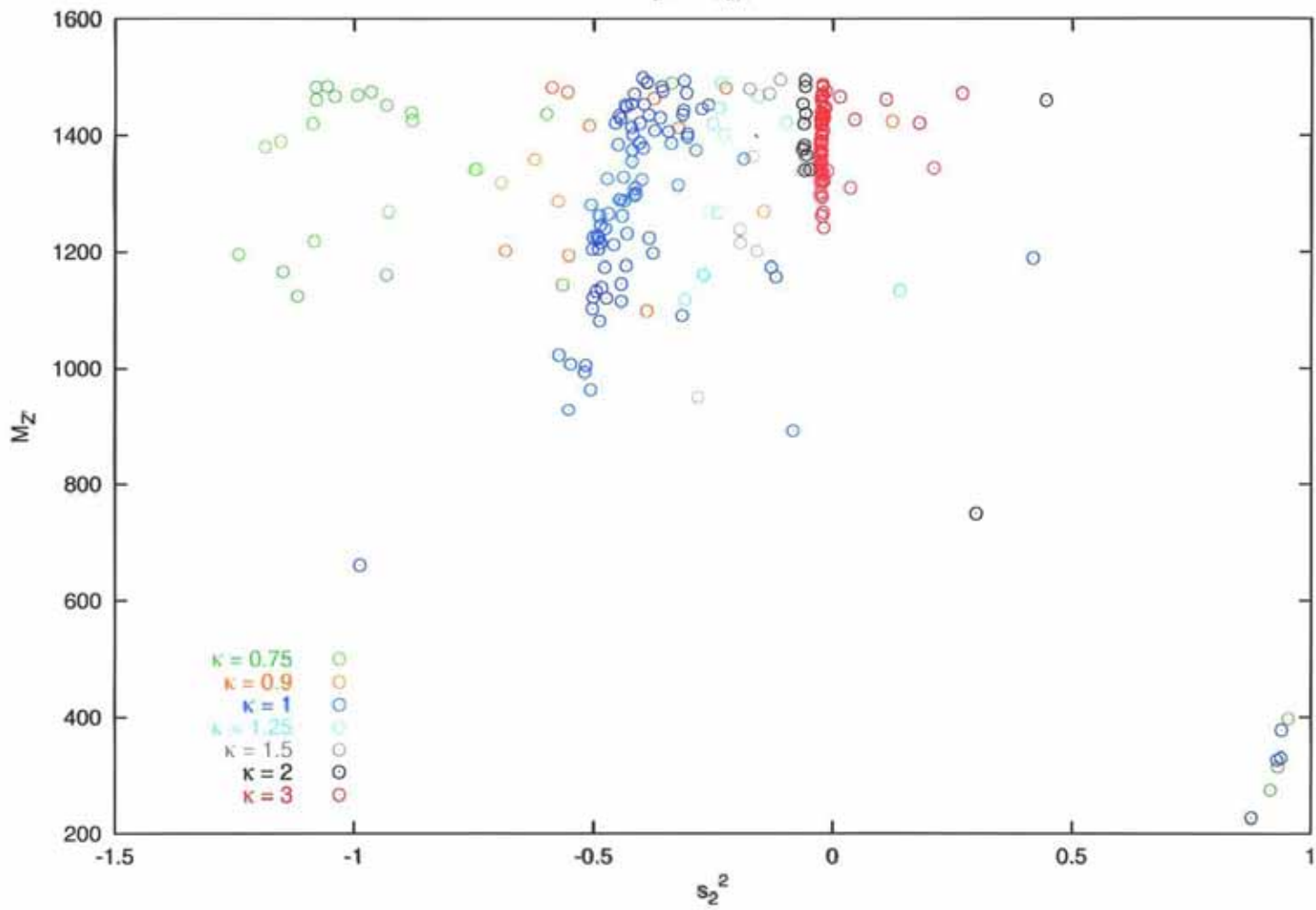
After LEP 2 + Υ cuts

s_2^2 and g_{ffZ} cuts



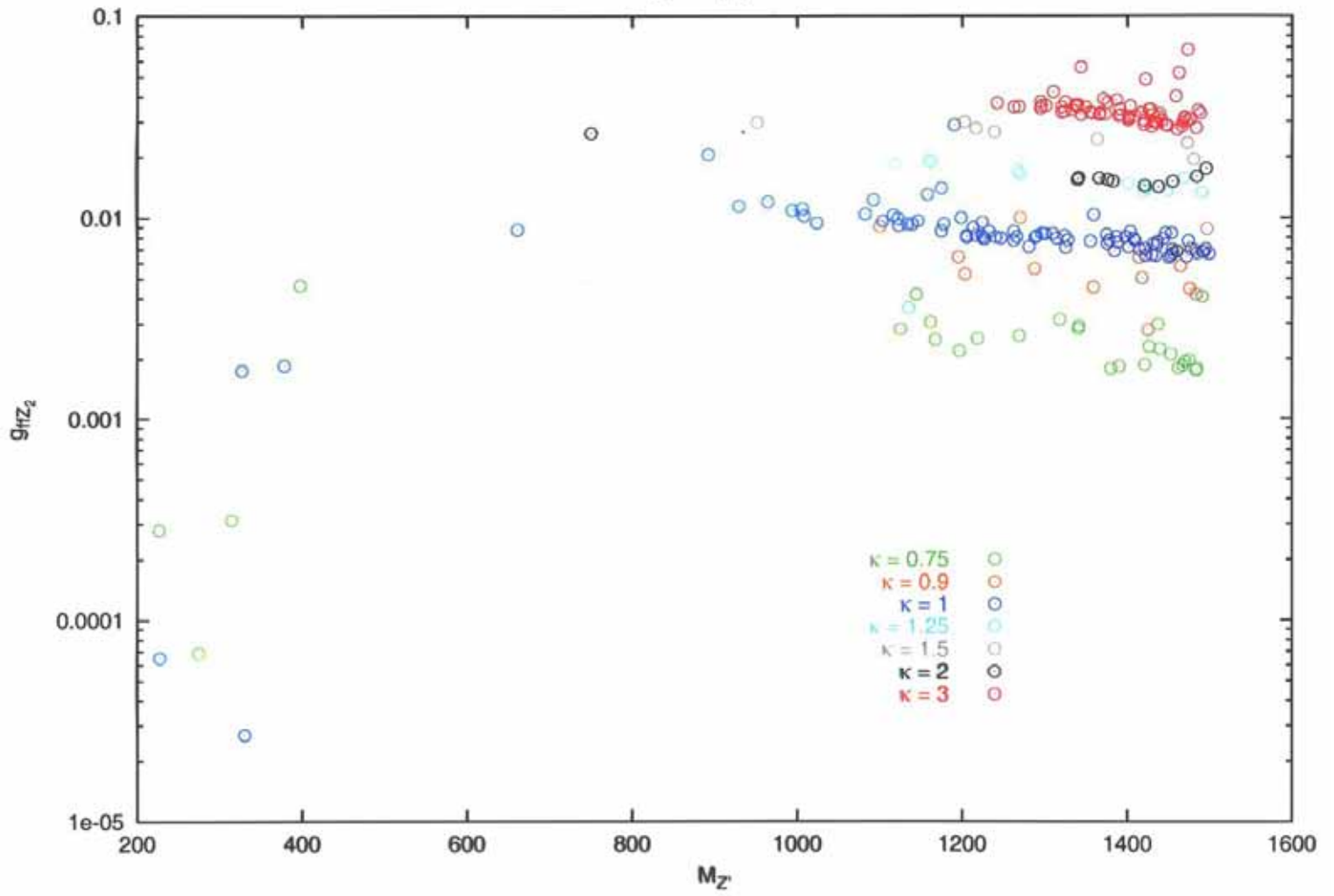
After LEP2 + γ cuts

s_2^2 and g_{HZ} cuts

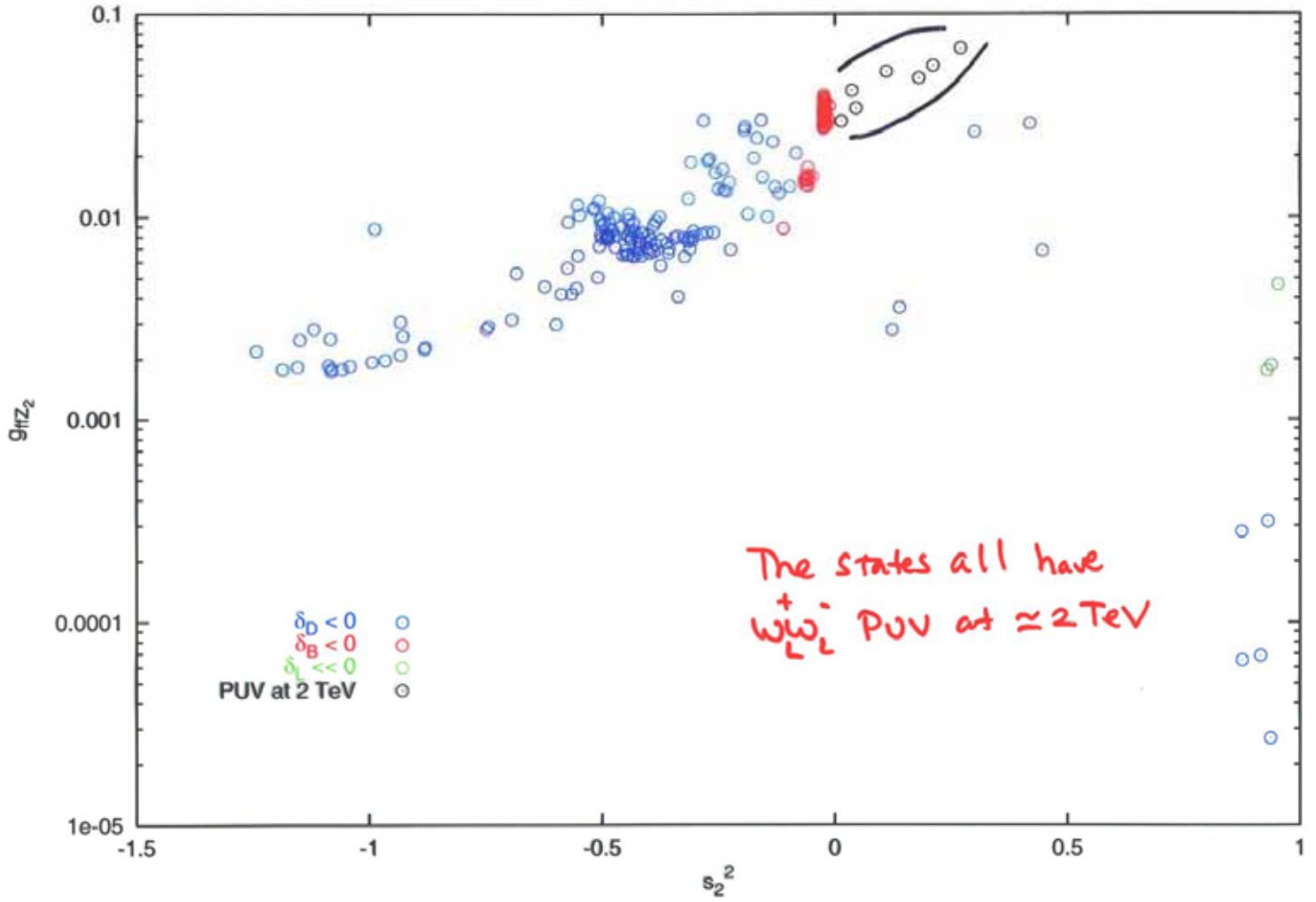


After LEP 2 + Υ -cuts

s^2_2 and g_{HZ} cuts



Tachym Cuts



⇒ After a sample of $\sim 5 \cdot 10^6$ models we find

None

which satisfy our constraints....

→ Back to model building!

What would a successful model look like at a collider??

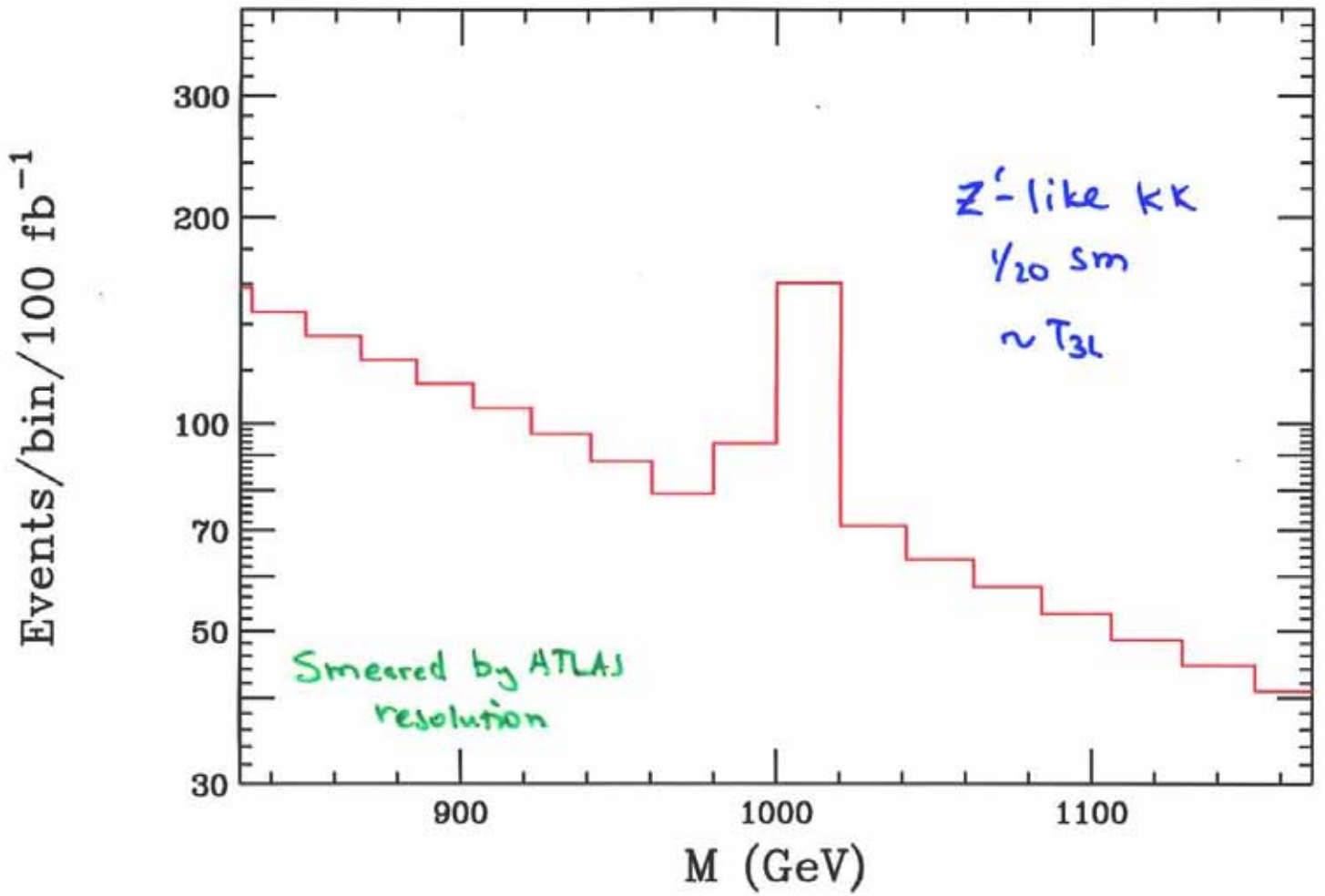
- A set of relatively light neutral $k k'$'s with small couplings to fermions (narrow!)
- Many coupled to weak isospin
- Significant coupling to $W W$

LHC should see SOME of these states
... but maybe not all.

LC will be necessary to fill in complete spectrum + measure couplings

→ lepton pair / jet pair / $W W$ pair channels
(all) important

Drell-Yan at LHC

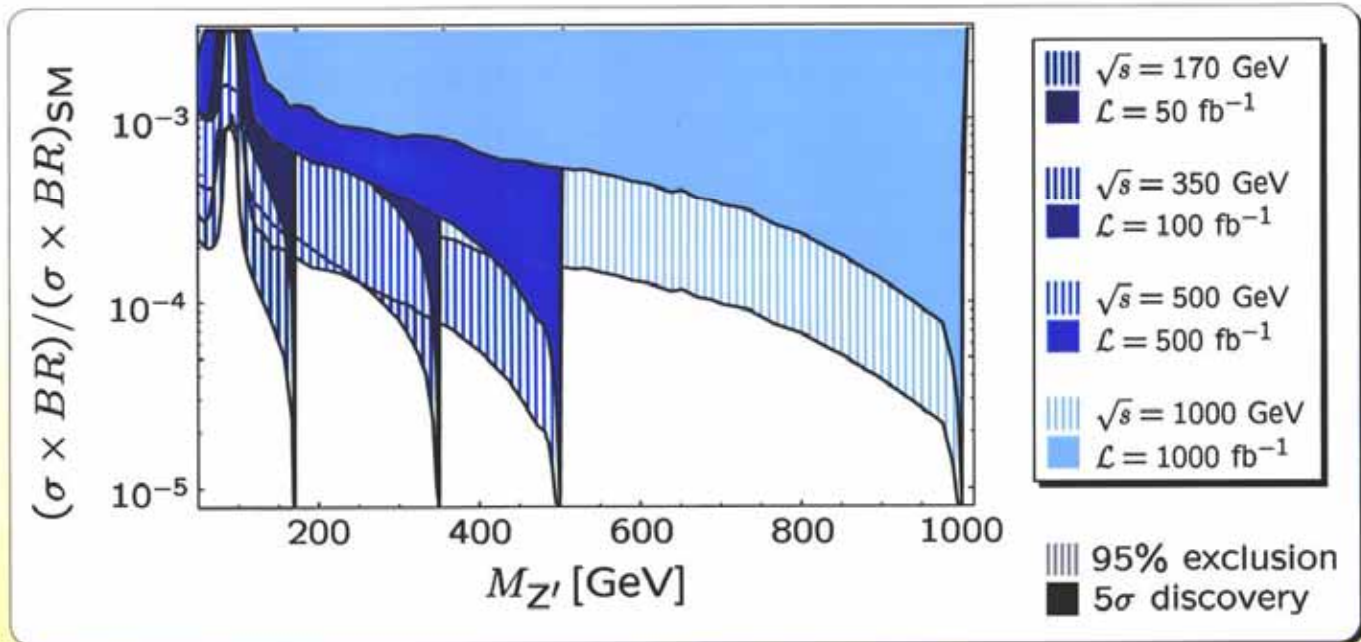


LC Z' search by radiative return

Freitas e Paris

Results for di-jet channel

Cuts: $\cos\theta_\mu \leq 0.94$ $\Delta E_{jj} = 2\sqrt{0.06125 \text{ GeV} \cdot \sqrt{s} + 0.000225 s}$



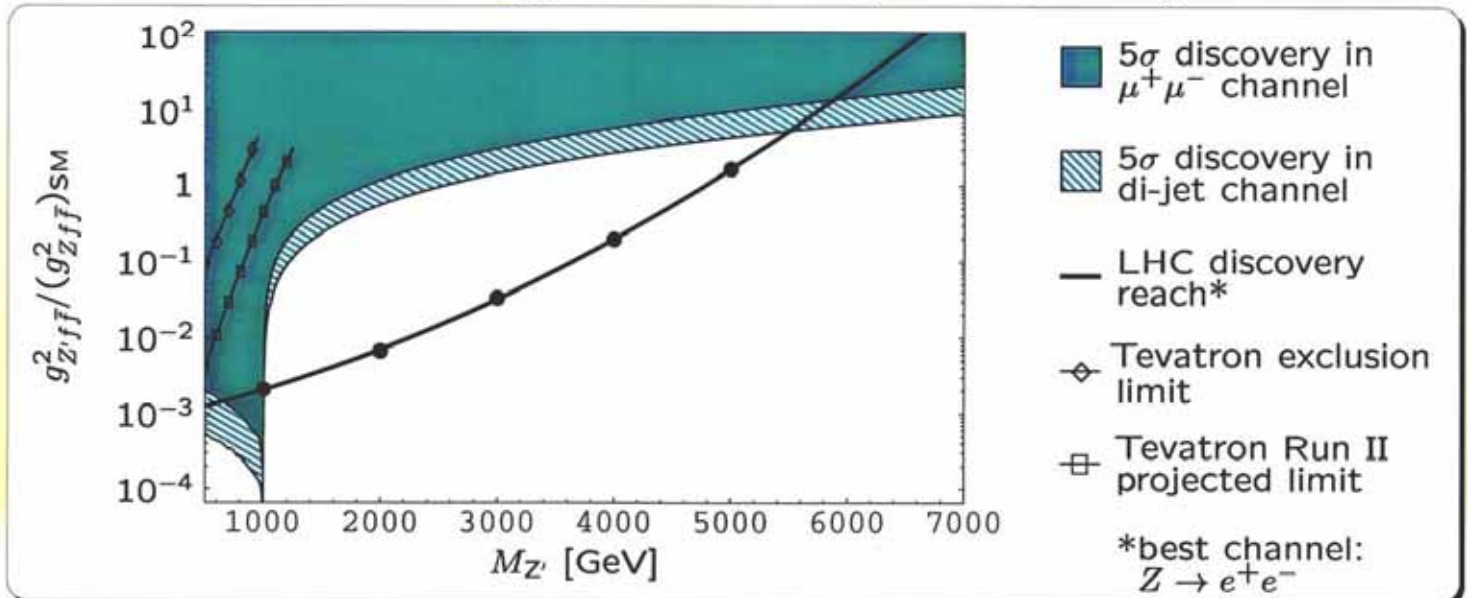
Comparison with hadron colliders

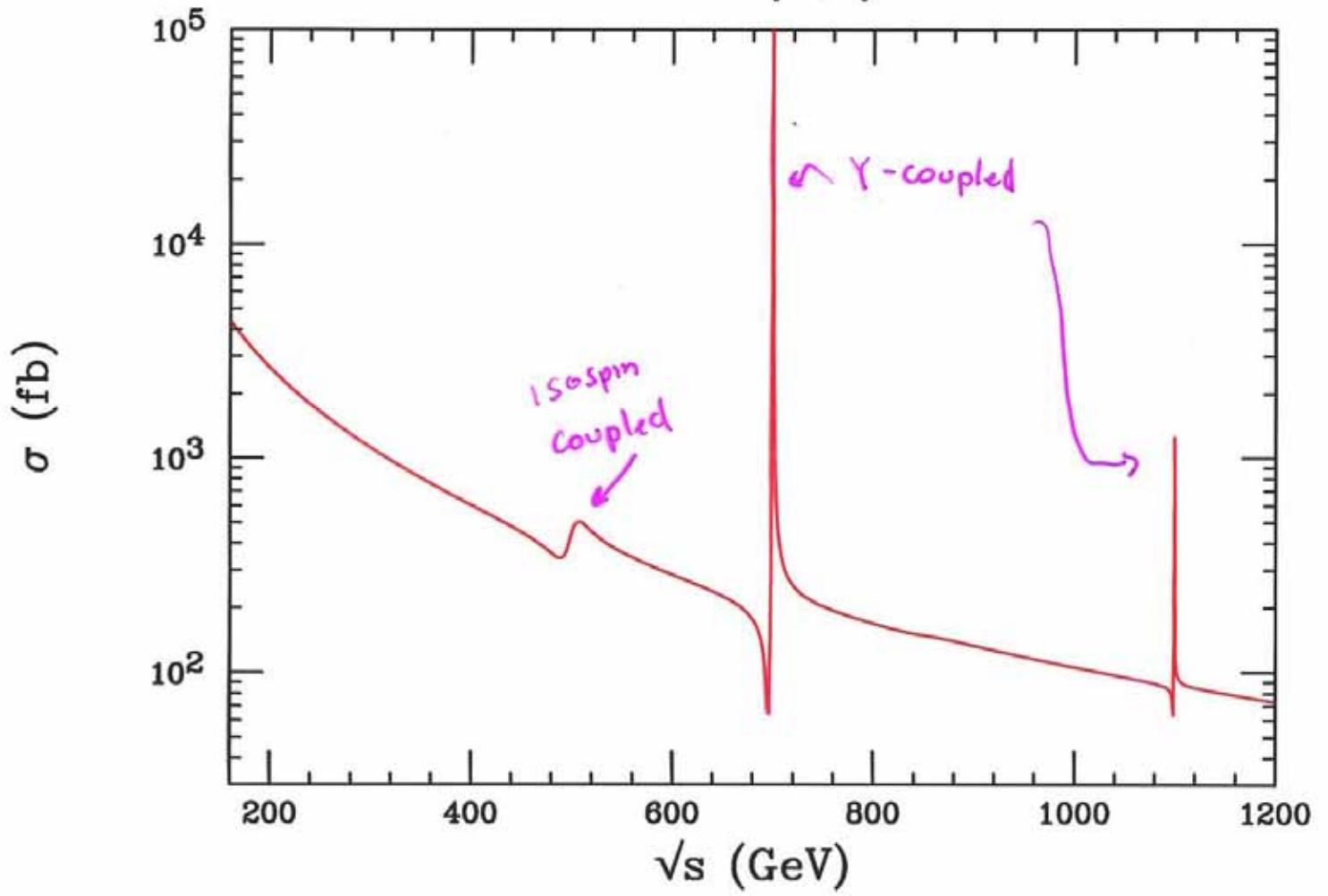
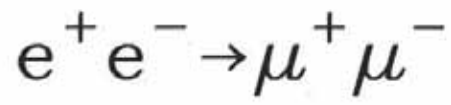
Combination of searches with radiative-return method for $M_{Z'} < \sqrt{s}$ and contact-interaction method for $M_{Z'} > \sqrt{s}$:

Sensitivity to high masses $M_{Z'}$, but only moderate coupling strength $g_{Z'f\bar{f}}^2 / (g_{Zf\bar{f}}^2)_{SM}$

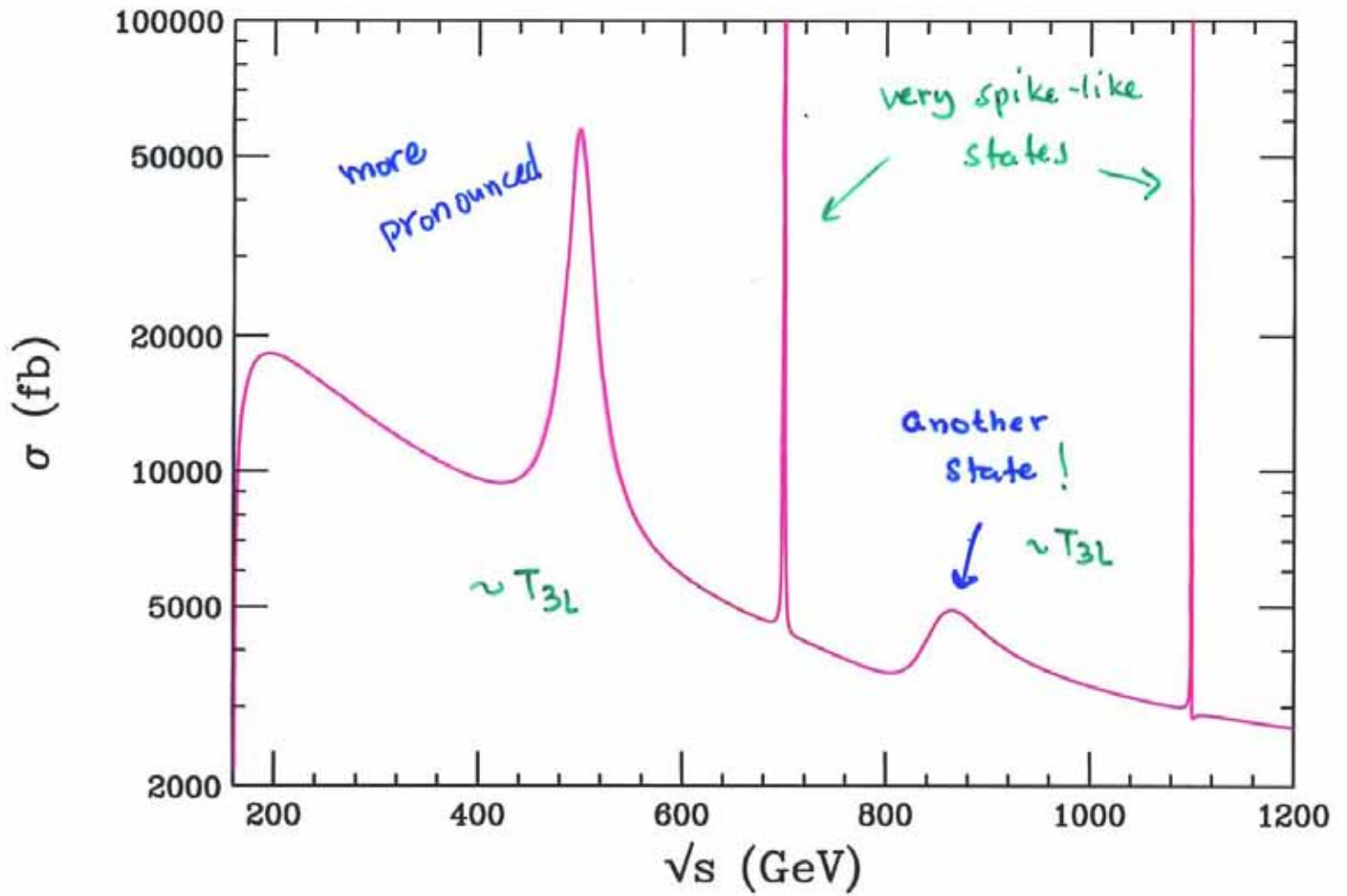
Example for $BR = BR_{SM}$:

$\sqrt{s} = 1000 \text{ GeV}$, $\int \mathcal{L} = 1000 \text{ fb}^{-1}$





importance of
 $e^+e^- \rightarrow W^+W^-$ channel



Benchekroun
Driouichi +
Hoummada

Atlas

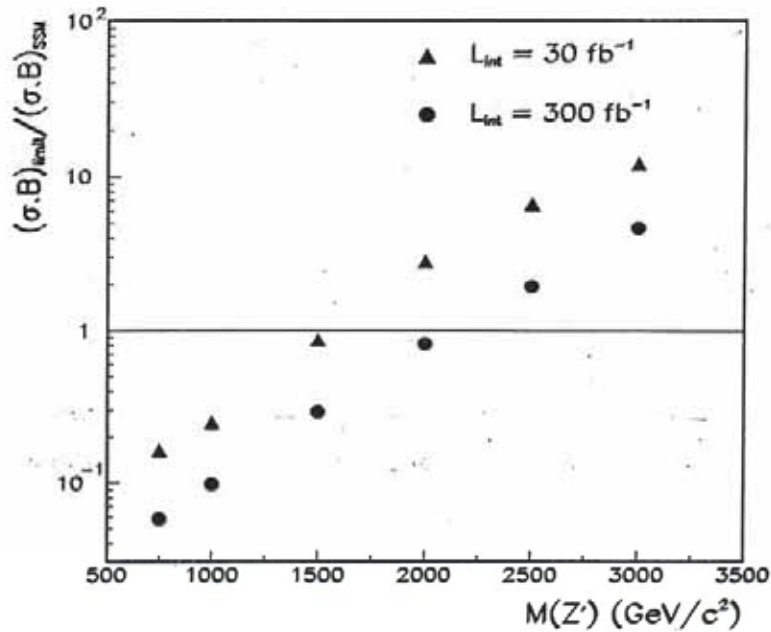


Figure 5: Discovery limit of a Z' boson in the $Z' \rightarrow WW \rightarrow \nu_{ij}jj$ channel for an integrated luminosity of 30 fb^{-1} and 300 fb^{-1}

LHC has reasonable sensitivity to
 Z' -like objects $\rightarrow W^+W^-$ provided
couplings are large enough

Conclusions

- A Monte Carlo scan of the LR Higgsless model

→ **No** fully successful model : **PUV**

But many satisfy EWK + Collider constraints

→ more model building required

- We have Some idea about what a realistic model will look like at a collider : both LHC + LC signatures → WW channels are important !