CalcHEP2.5:
new facilities and future prospects

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CalcHEP: old good features

- *user friendly interface*
- *easy to introduce new model, already has*

  SM,MSSM,NMSSM,LHT,LZP,LeptoQuarks and now 3-site model !

- *automatic implementation of user model using LanHEP*

  A. Semenov, http://theory.sinp.msu.ru/~semenov/lanhep.html.

  - *automatic feynman rules generaton for CalcHEP*
  - *allows to deal with different gauges*

    – important for the cross check

  - *has checks for*
    - the hermiticity
    - BRST invariance
    - em charge conservation
    - particle mixings, mass terms, mass matrices

- *CalcHEP is the generator of generators, so (recalling Konstantin's MC4BSM talk)*

N model builders + LanHEP + CalcHEP = N MC4BSM writers

Three Site Model Implementation with LanHEP

LanHEP

$$\mathcal{L}_{F^2} = -\frac{1}{2}\mathrm{Tr}\left(F_0^2 + F_1^2 + F_2^2\right)$$ **where** $$F_j^{\mu\nu} = \partial^\mu W_j^\mu - \partial^\nu W_j^\mu + i g_j \left[W_j^\mu, W_j^\nu\right]$$

```
%%%%%%%%%%  Kinetic and self interaction Lagrangian terms.
lterm  -F**2/4  where  F=deriv^mu*W23^nu-deriv^nu*W23^mu.
lterm  -F**2/4  where  F=deriv^mu*W0^nu^a-deriv^nu*W0^mu^a-g*eps^a^b^c*W0^mu^b*W0^nu^c.
lterm  -F**2/4  where  F=deriv^mu*W1^nu^a-deriv^nu*W1^mu^a-g/x*eps^a^b^c*W1^mu^b*W1^nu^c.
```

(gauge kinetic term as an example)

lhep 3-site.mdl

CalcHEP

P1	P2	P3	P4	> Factor
A	W+	W-		-g*v0g
A	~W+	~W-		-g*v0g
W+	W-	Z		-g/x
W+	W-	~Z		-g/x
W+	Z	~W-		-g/x
W+	~W-	~Z		-g/x
W-	Z	~W+		-g/x
W-	~W+	~Z		-g/x
Z	~W+	~W-		-g/x
~W+	~W-	~Z		-g/x
A	A	W+	W-	-g**2*v0g**2
A	A	~W+	~W-	-g**2*v0g**2
A	W+	W-	Z	-g**2*v0g/x
A	W+	W-	~Z	-g**2*v0g/x
A	W+	Z	~W-	-g**2*v0g/x
A	W+	~W-	~Z	-g**2*v0g/x
A	W-	Z	~W+	-g**2*v0g/x
A	W-	~W+	~Z	-g**2*v0g/x
A	Z	~W+	~W-	-g**2*v0g/x
A	~W+	~W-	~Z	-g**2*v0g/x

W+	W+	W-	W-	g**2/x**2
W+	W+	W-	~W-	g**2/x**2
W+	W+	~W-	~W-	g**2/x**2
W+	W-	W-	~W+	g**2/x**2
W+	W-	Z	Z	-g**2/x**2
W+	W-	Z	~Z	-g**2/x**2
W+	W-	~W+	~W-	g**2/x**2
W+	W-	~Z	~Z	-g**2/x**2
W+	Z	Z	~W-	-g**2/x**2
W+	Z	~W-	~Z	-g**2/x**2
W+	~W+	~W-	~W-	g**2/x**2
W+	~W-	~Z	~Z	-g**2/x**2
W-	W-	~W+	~W+	g**2/x**2
W-	Z	Z	~W+	-g**2/x**2
W-	Z	~W+	~Z	-g**2/x**2
W-	~W+	~W+	~W-	g**2/x**2
W-	~W+	~Z	~Z	-g**2/x**2
Z	Z	~W+	~W-	-g**2/x**2
Z	~W+	~W-	~Z	-g**2/x**2
~W+	~W+	~W-	~W-	g**2/x**2
~W+	~W-	~Z	~Z	-g**2/x**2

Three Site Model Implementation with LanHEP

LanHEP

$$\mathcal{L}_{F^2} = -\frac{1}{2}\mathrm{Tr}\left(F_0^2 + F_1^2 + F_2^2\right) \quad \textbf{where} \quad F_j^{\mu\nu} = \partial^\mu W_j^\mu - \partial^\nu W_j^\mu + i g_j \left[W_j^\mu, W_j^\nu\right]$$

```
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```
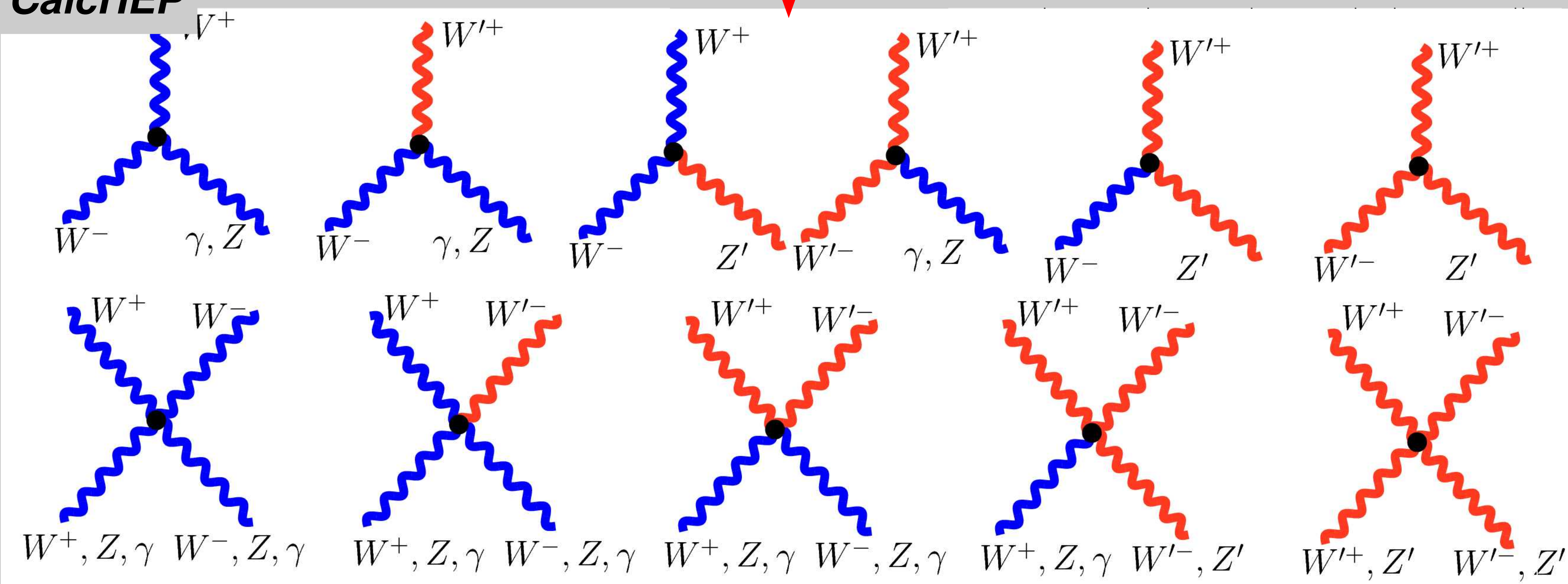

(gauge kinetic term as an example)

lhep 3-site.mdl

CalcHEP



CalcHEP 2.5: new features of event generation and interface with MC generators

- ***generates of events in cycle***

  $CALCHEP/bin/subproc_cycle [Luminosity/nEvens] [nMax]

- ***links together production and decay events into one chain***

  NSUB=SCANDIR(dir_name)

- ***has an interface with event generators***
  - **creates mixed events in Les Houches Accord format**

    COMMON/HEPRUP/ , /HEPEUP/

    event2pyth.c , event_mixer.f

    f77 -o event_mixer.x event_mixer.f event2pyth.c -lm
  - **reads mixed events from file into PYTHIA**

    call_pyth_mix.f

    f77   -o call_pyth_mix.x call_pyth_mix.f pythia6406.o

http://hep.pa.msu.edu/belyaev/public/calchep/

CalcHEP 2.5: new features

- ***Automatic witdh calculation ("on the fly")***

```
 Z prime boson|~Z |~Z |          0|2        |MZP    |!wZP  |1        |G   |Z'
 W prime boson|~W+|~W-|          0|2        |MWP    |!wWP  |1        |G   |W'+
```

- ***Polarized beams:*** $E\%, e\% \longrightarrow 2 * x \quad or \quad A\%, A\% \longrightarrow 2 * x$

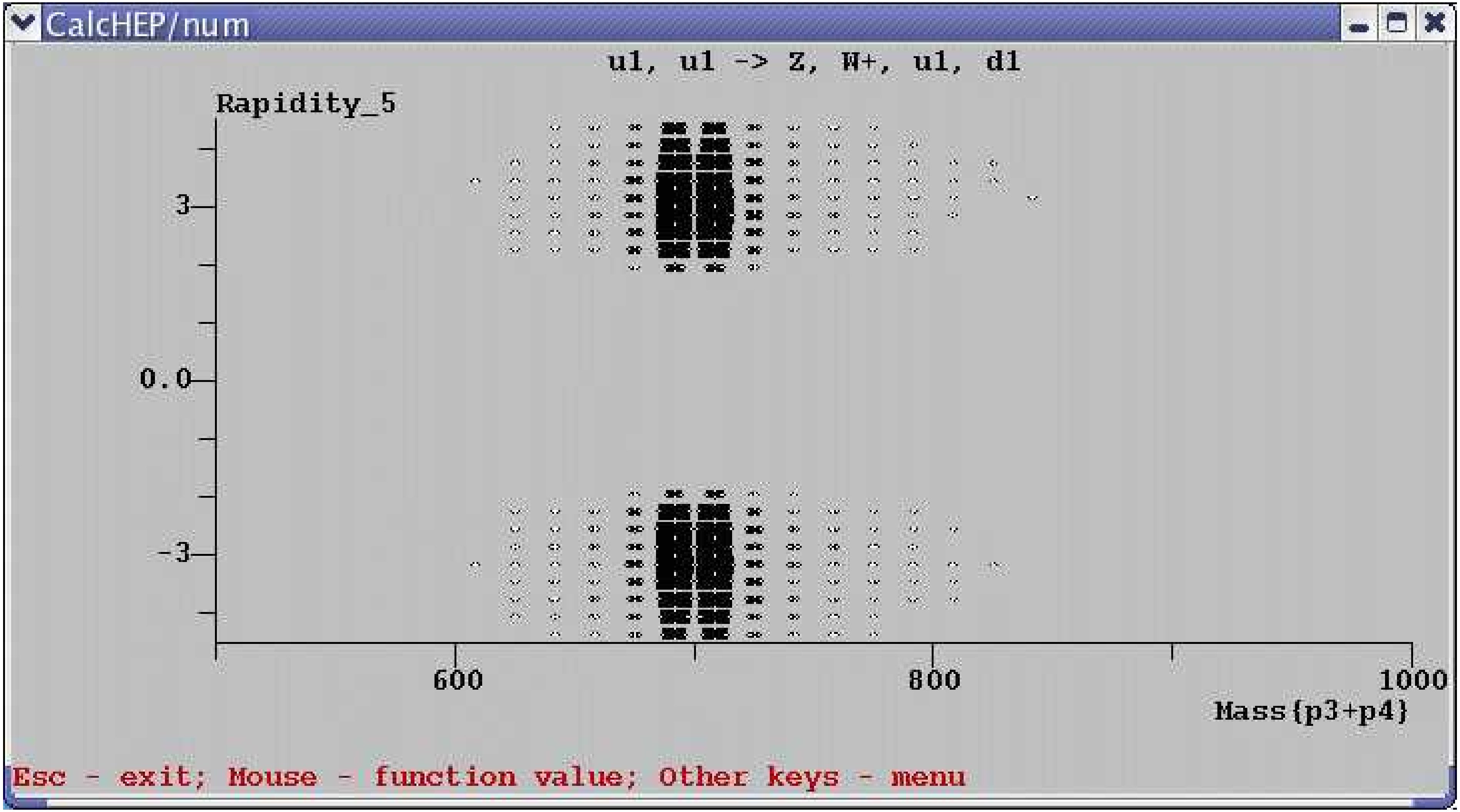
- ***Spin 3/2 and spin 2 massive particles are available in CalcHEP now***

- ***2 d distributions outputs in PAW and Gnuplot format***

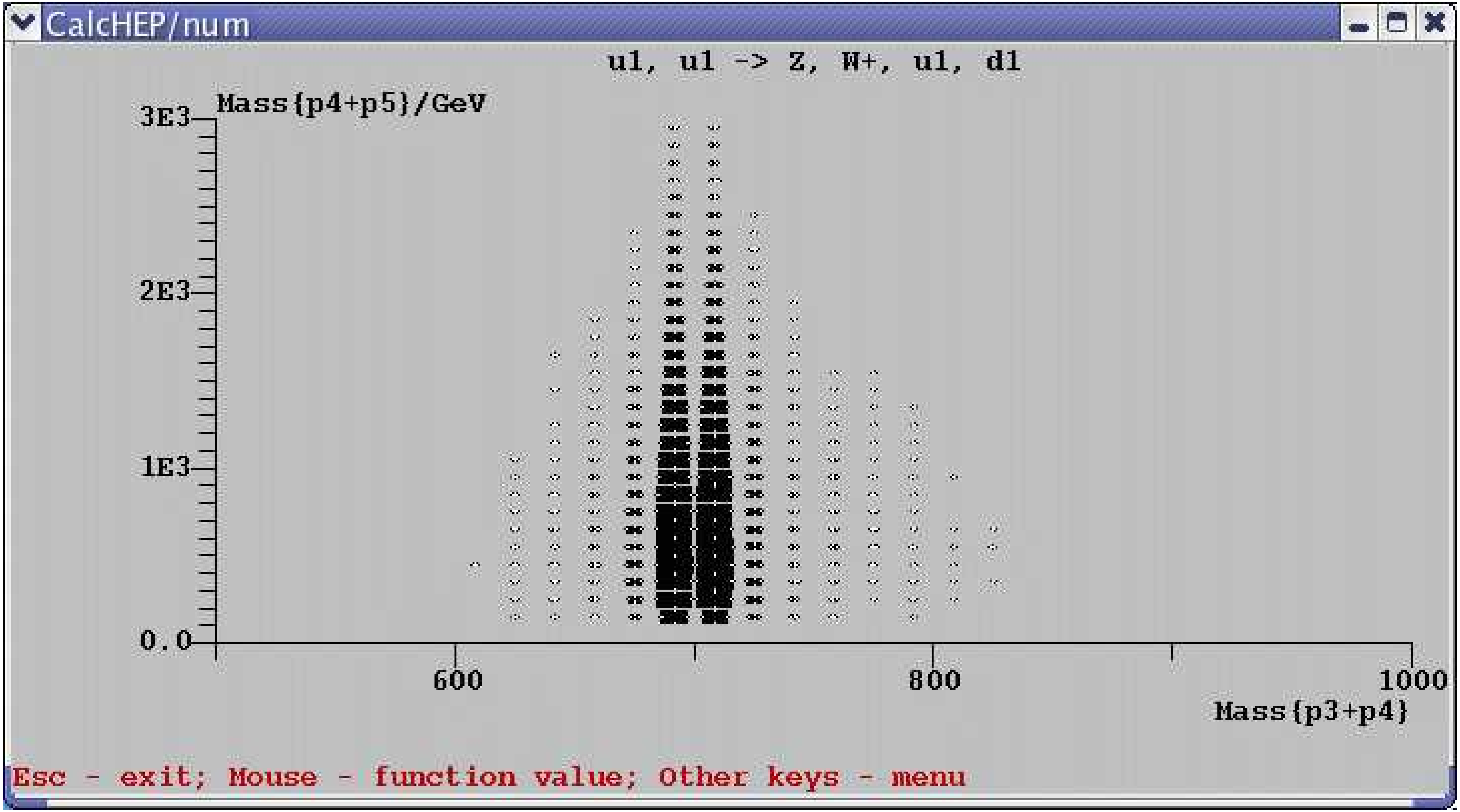
```
#--- GNUPLOT section ---
#GNUPLOT set title  'E,e ->m,M'
#GNUPLOT set xlabel 'cos(p1,p3)'
#GNUPLOT set ylabel 'Diff. cross section [pb]'
#GNUPLOT plot[-1:1] 'plot_1.txt' using (-1 +$0*0.02):1 w l
```

```
#--- PAW section ---
#PAW  TITLE 'E,e ->m,M'
#PAW  vector/Create X1(101)
#PAW  sigma X1=ARRAY(101,-1#1)
#PAW  vector/Create Y1(101)
#PAW  vector/Read Y1 'plot_1.txt' ' ' 'OC
#PAW  GRAPH 101 X1 Y1
```

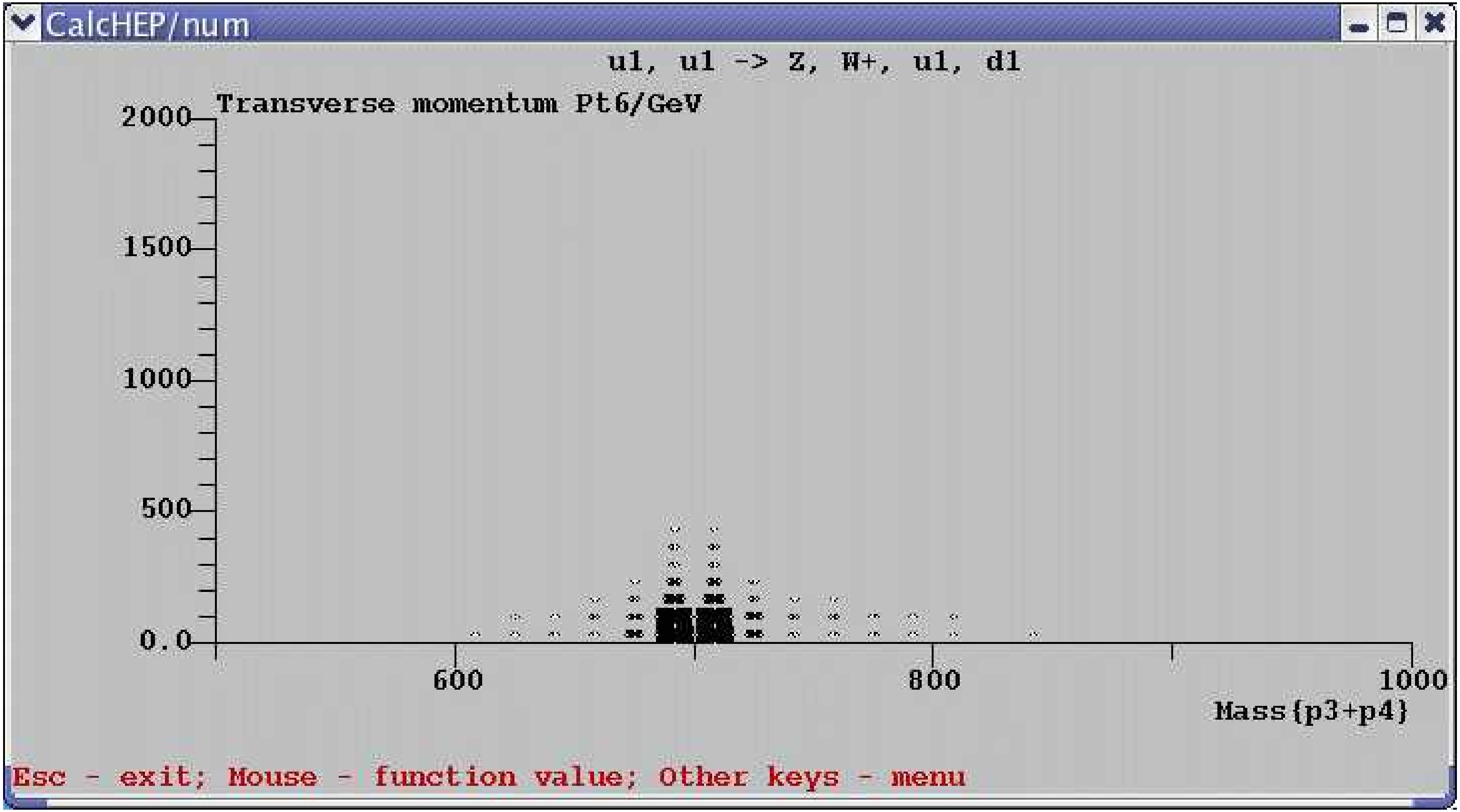
CalcHEP 2.5: examples of 2d plots



CalcHEP 2.5: examples of 2d plots



CalcHEP 2.5: examples of 2d plots



CalcHEP 2.5: new features

- ***dynamical linking, like in micrOMEGAs package:***
  - **the size of the executable is not limited by the number of diagrams, can calculate any number of diagrams now**
- ***allows now compilation on parallel processors:***
  - **~1-2 hours for 100K 2->4 squared diagrams / 10 processors**

Future prospects

- ***cuts generalization***
- ***QCD scale definition (leading diagram)***
- ***laser photon distribution sensitive to polarizations of incoming electron beam and photon***
- ***polarization for massive particles***
- ***implementation of symbolic calculations on parallel processors***

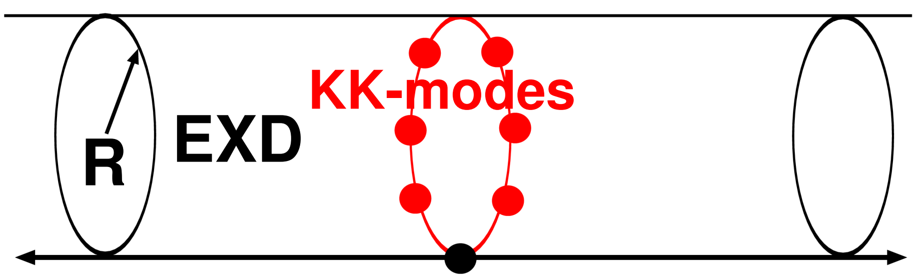
CalHEP 2.5 in action: study of Higgsless Models

collaboration with S. Chivukula, N. Christensen, E. Simmons, A. Pukhov, H.-J. He, Y.-P. Kuang B. Zhang

Low-energy effective theories with natural EW symmetry breaking alternative to Supersymmetry and Strong dynamics

- ***massive 4-d gauge bosons originate from 5-d gauge theory (moose representation) with appropriate boundary conditions***
- ***massive vector boson scattering amplitude is unitarised***

via KK modes exchange – not the Higgs boson exchange!



$$\hat{A}^a_\mu = \frac{1}{\sqrt{\pi R}}\left[A^{a0}_\mu(x_\nu) + \sqrt{2}\sum_{n=1}^{\infty} A^{an}_\mu(x_\nu)\cos\left(\frac{n x_5}{R}\right)\right]$$

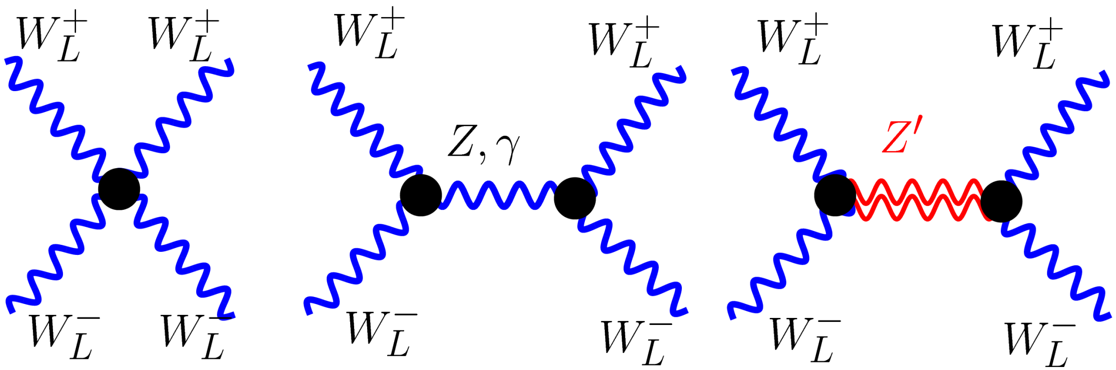
$$\hat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{n x_5}{R}\right)$$

5D gauge bosons expanded in eigenmodes on S^1/Z_2

- ***4-D gauge kinetic term contains*** $A^{an}_L \leftrightarrow A^{an}_5$:

$$\frac{1}{2}\sum_{n=1}^{\infty}\left[M_n^2(A^{an}_\mu)^2 - 2M_n A^{an}_\mu \partial^\mu A^{an}_5 + (\partial_\mu A^{an}_5)^2\right]$$

4D KK Mode Scattering

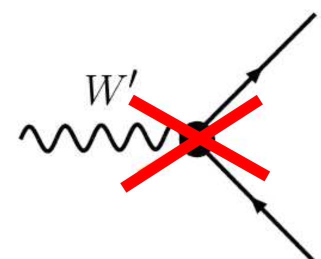


- ***Z' resonance unitarizes WW scattering, similar to what Higgs boson does in SM***
  (Chivukula,He,Dicus)

- ***Z' mass is bounded from above:*** $m_{Z_1} < \sqrt{8\pi}\, v$
- ***But it yields too much a value of S-parameter:*** $\alpha S \le \frac{4 s_Z^2 c_Z^2 M_Z^2}{8\pi v^2} = \frac{\alpha}{2}$
  (Chivukula, Simmons, He, Kurachi,Tanabashi)

- ***Solution – delocalization of the fermions: mixing of "brane" and "bulk" modes!***
(Cacciapaglia, Csaki, Grojean, Reece,Terning; Foadi Gopalakrishna, Schmidt)

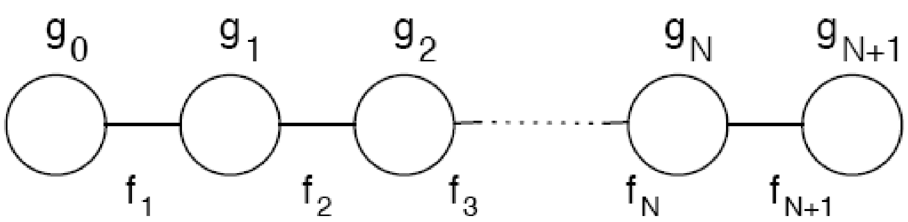
- ***Fermion delocalization profile can be chosen to match W-wave function along the 5th dimension:*** $g_i x_i \propto v_i^W$
leading to vanishing coupling of fermions to KK modes!
(Chivukula,Simmons,He, Kurachi, Tanabashi)



$\hat{S} = \hat{T} = W = 0$

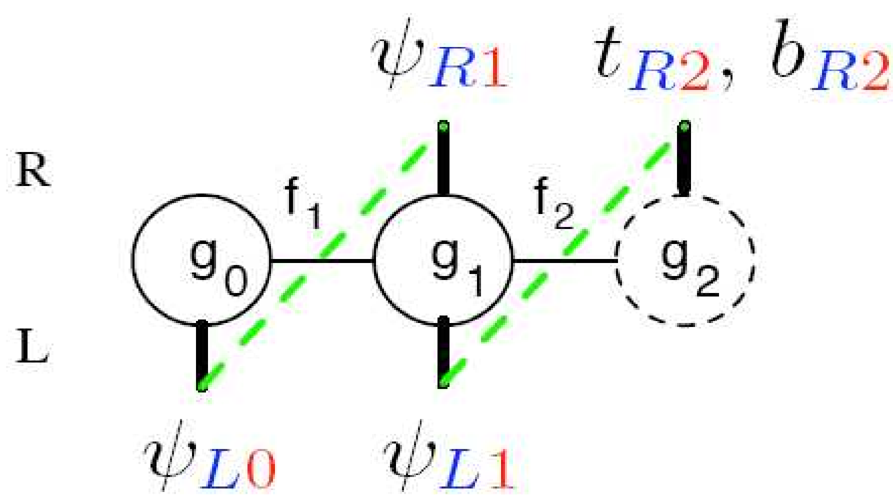
Three site model (TSM)

simplest, realistic, highly deconstructed,higgsless



Discretized 5th dimension written in the language of 'theory space'

(Arkani-Hammed, Georgi, Cohen; Hill, Pokorski, Wang)



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

gauge bosons: ***photon,Z,W, Z',W'***

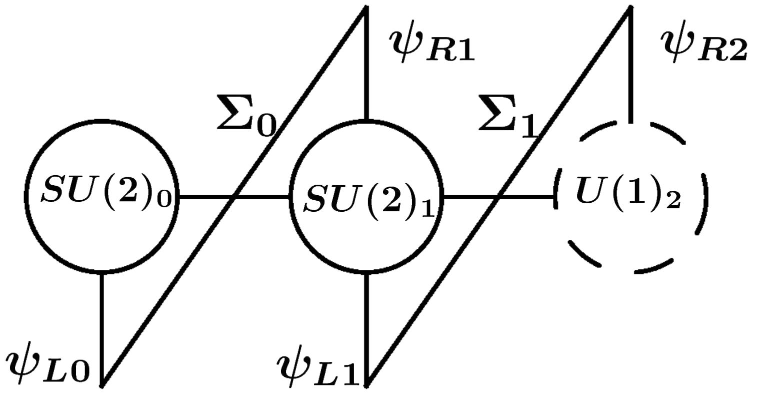
fermions: ***u, d, c, s, t, b***

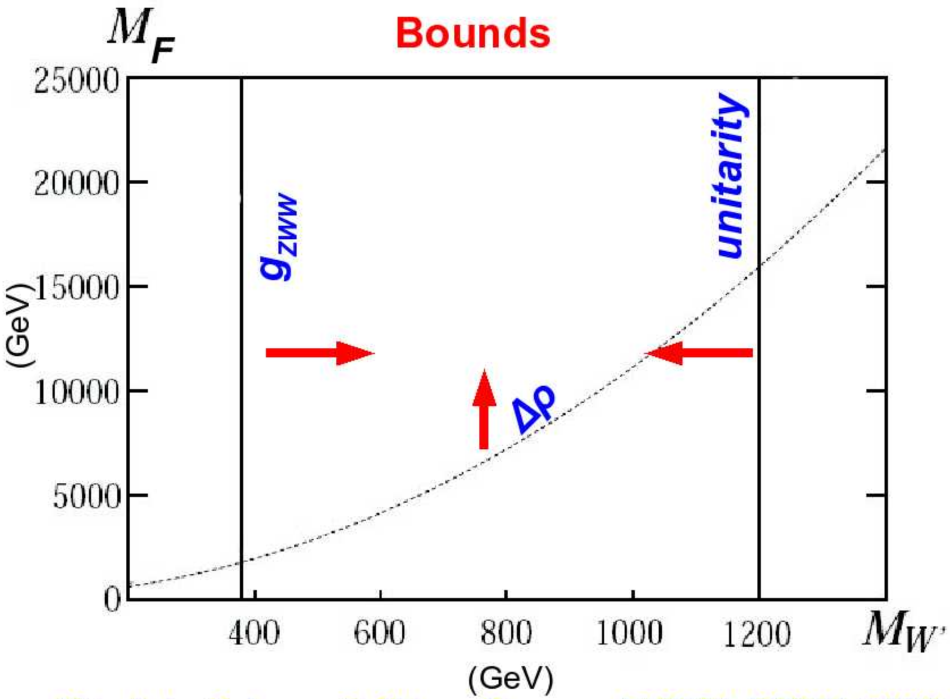
U, D, C, S, T, B

plus leptons

(Chivukula, Coleppa, Di Chiara,Simmons)

The Three Site Model parameter space is testable!





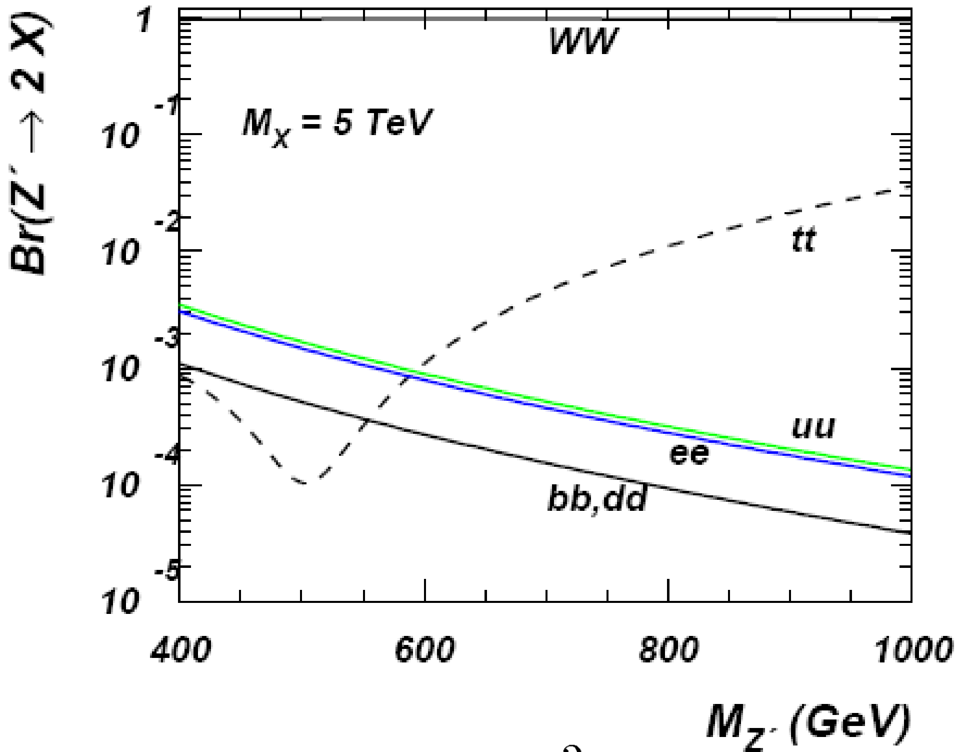
Chivukula, Coleppa, Di Chiara, Simmons: PRD **74**, 075011 (2006)

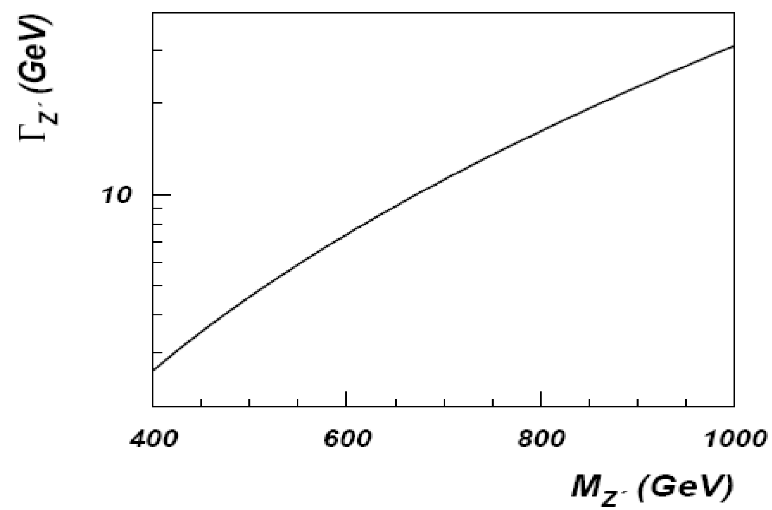
The parameter space is:

- Simple
- Bounded
  - from below by experiment
  - from above by unitarity
- **Can be tested at the LHC!**

Gauge boson widths and branchings

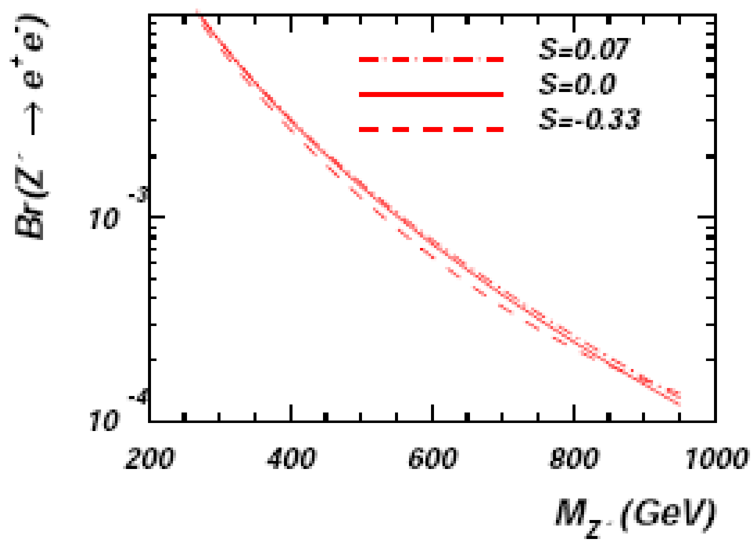
- **Fermiophobic nature of the gauge bosons**
- **Dominant decay into WW and WZ pairs**
- **Z' Br does not depend much on deviation from ideal delocalization**





$$\Gamma(Z' \to W^+W^-) = \frac{e^2 M_{W'}}{192\pi x^2 s_w^2}$$

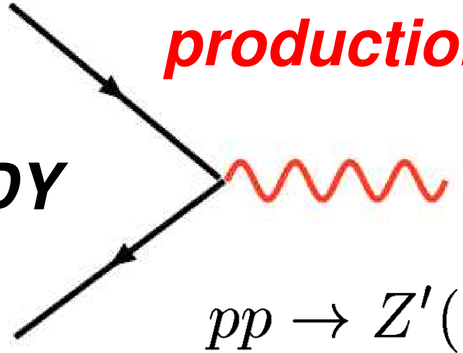
$$\Gamma(Z' \to e^+e^-) = \frac{5e^2 M_{W'} x^2 s_w^2}{384\pi c_w^4}$$



Three Site Model Signatures

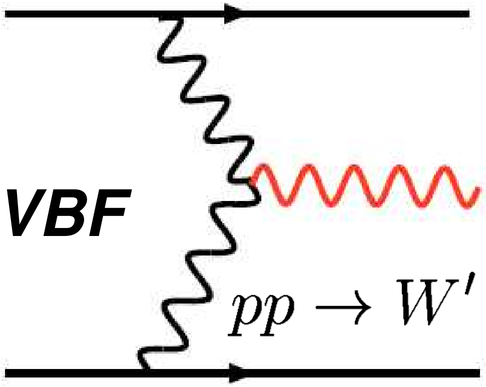
production

DY



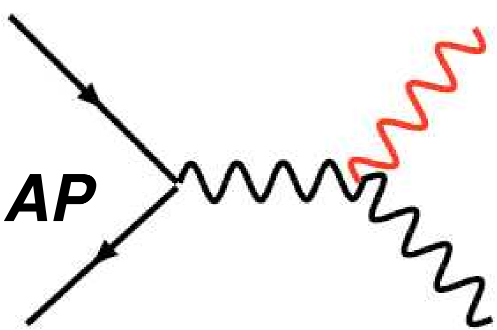
$pp \to Z'(W')$

VBF



$pp \to W'(Z')jj$

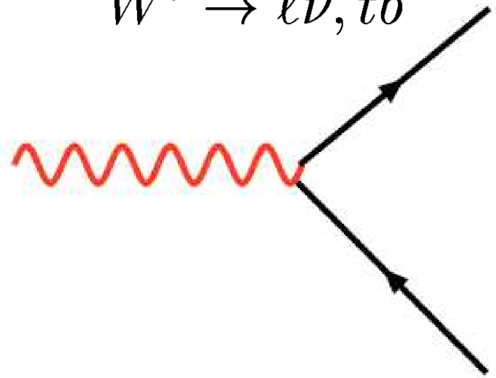
AP

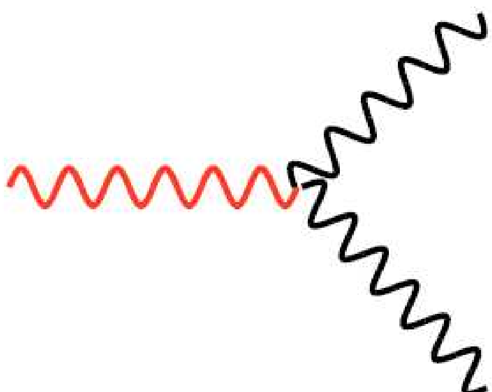


$pp \to WZ', WW', \ldots$

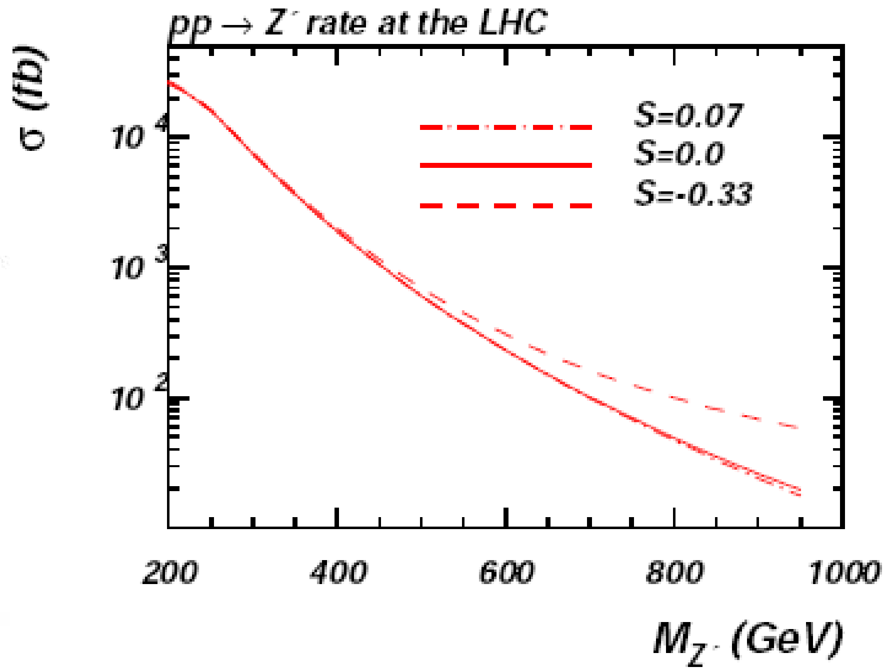
decay

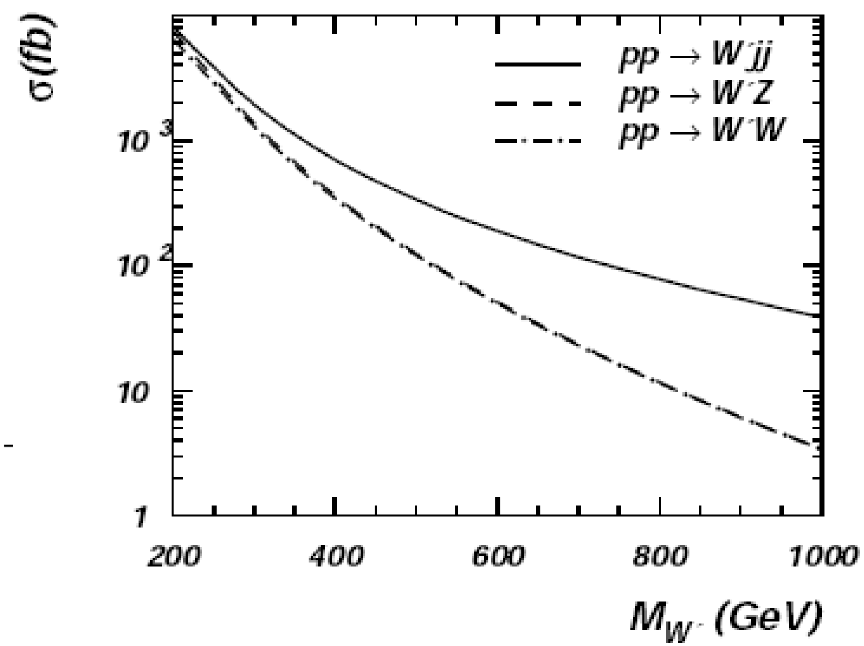
$Z' \to \ell^+\ell^-, t\bar{t}$
$W' \to \ell\nu, tb$



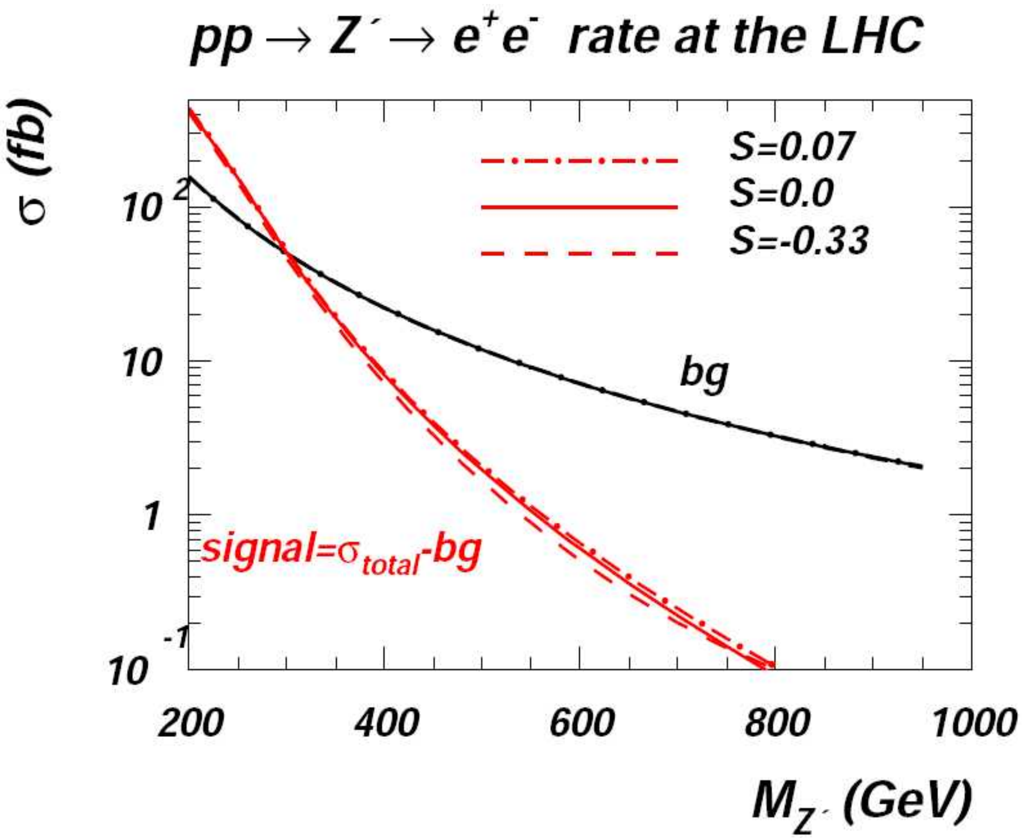


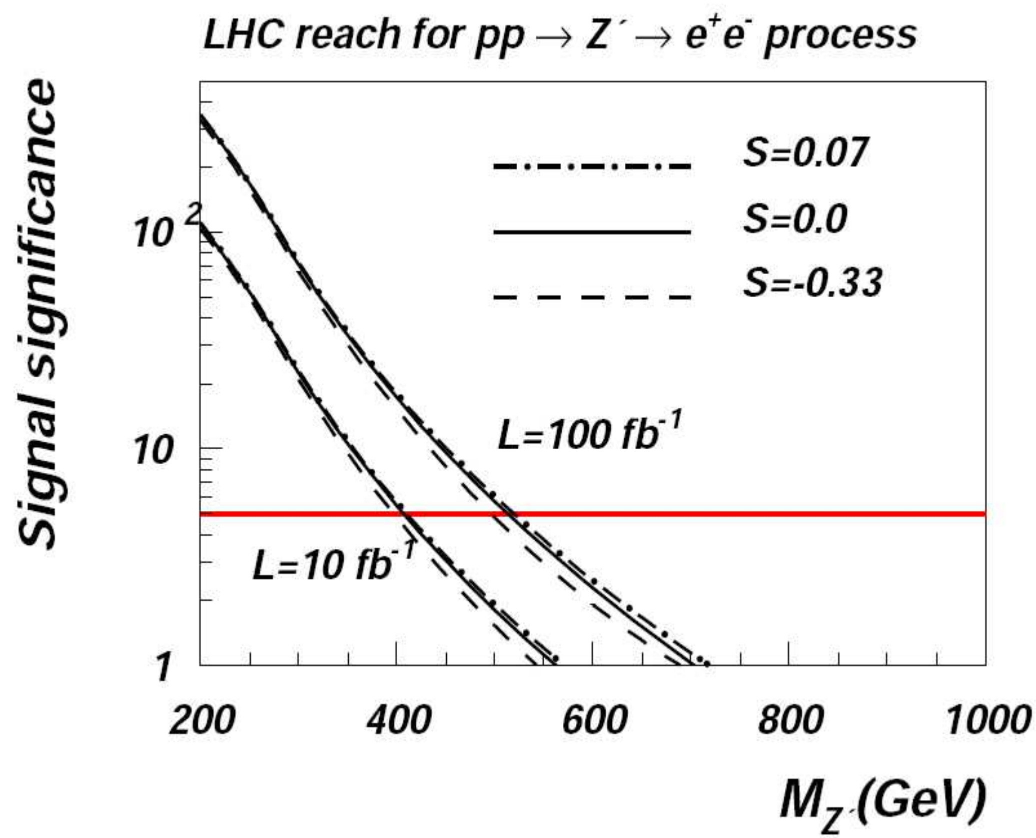
$Z' \to W^+W^- \to \ell^+\ell^-$
$W' \to WZ \to \ell\ell\ell\nu$





LHC reach for DY di-lepton signature





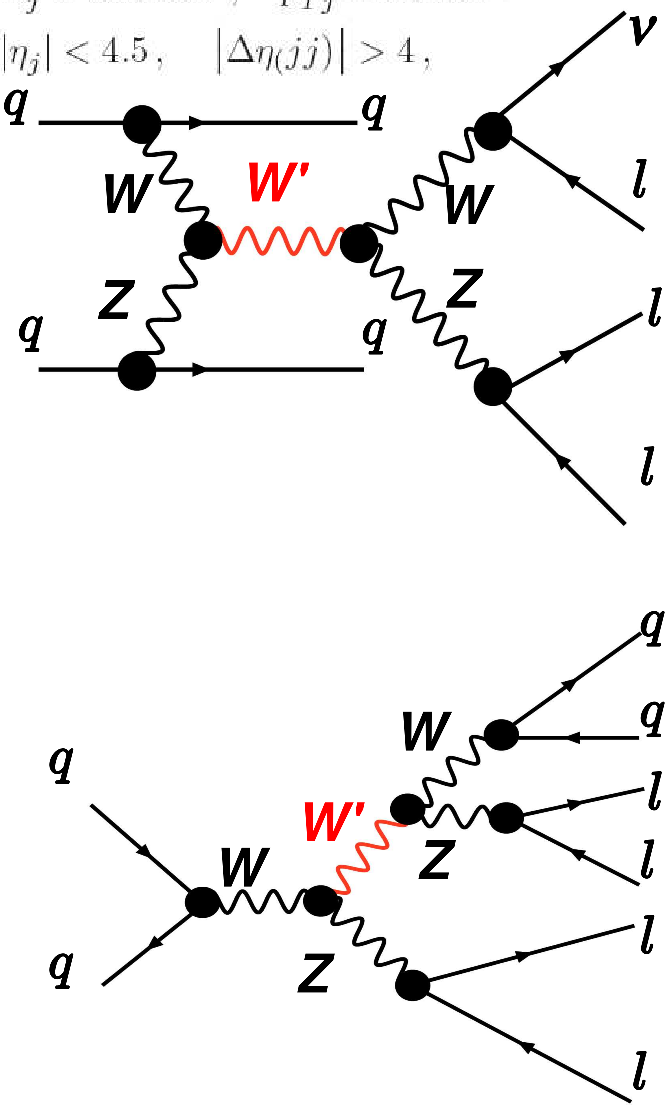
- Decay and production are suppressed by x^4 compared to 'usual' PYTHIA Z' model
- One should be prepared to face with this scenario with very different Z'/W' features
  - Discovery reach for DY process is about 0.5-0.6 TeV (vs 3-5 TeV)
  - fermiophobic Z' required by EW data (vs SM-like Z'-fermions couplings)
  - Z'WW coupling is non-vanishing to provide unitarity (vs vanishing Z'WW vertex)

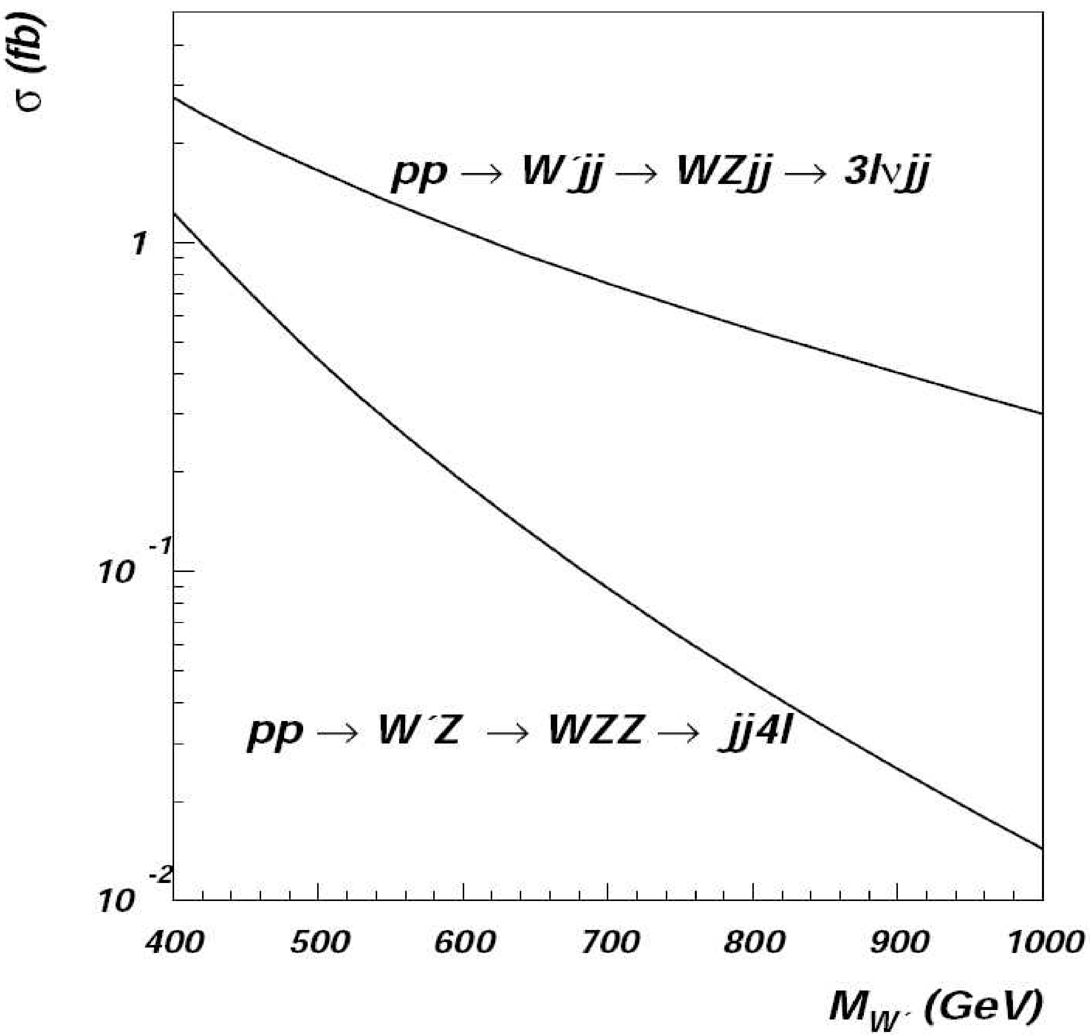
Vector-boson fusion WZ → W' and associate W'Z production are much more promising:

larger rates + clean signature

$E_j > 300\,\mathrm{GeV}, \quad p_{Tj} > 30\,\mathrm{GeV}$

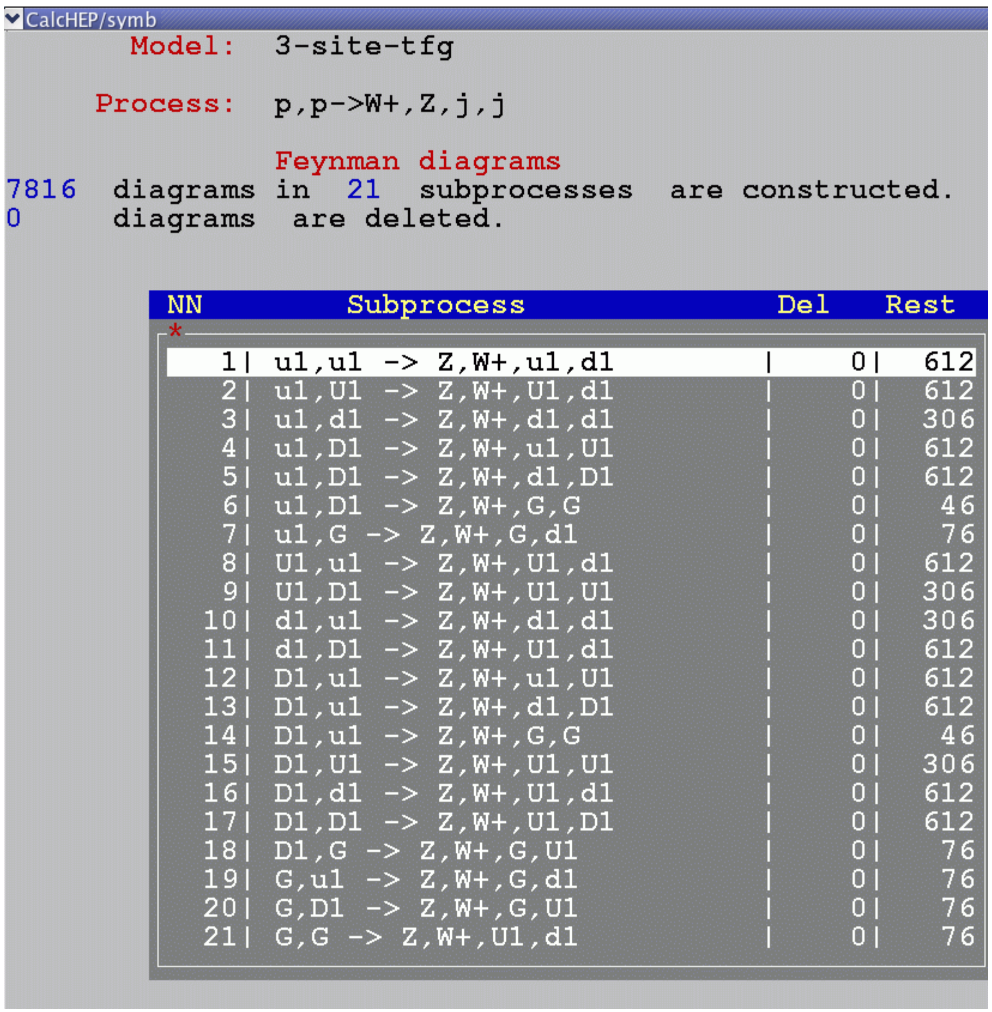
$|\eta_j| < 4.5, \quad |\Delta\eta(jj)| > 4,$





$pp \to W^+Zjj$: *Exact tree-level calculation with CalcHEP*

- ***No effective WZ approximation.***
- ***Complete set of signal and background diagrams including interference.***

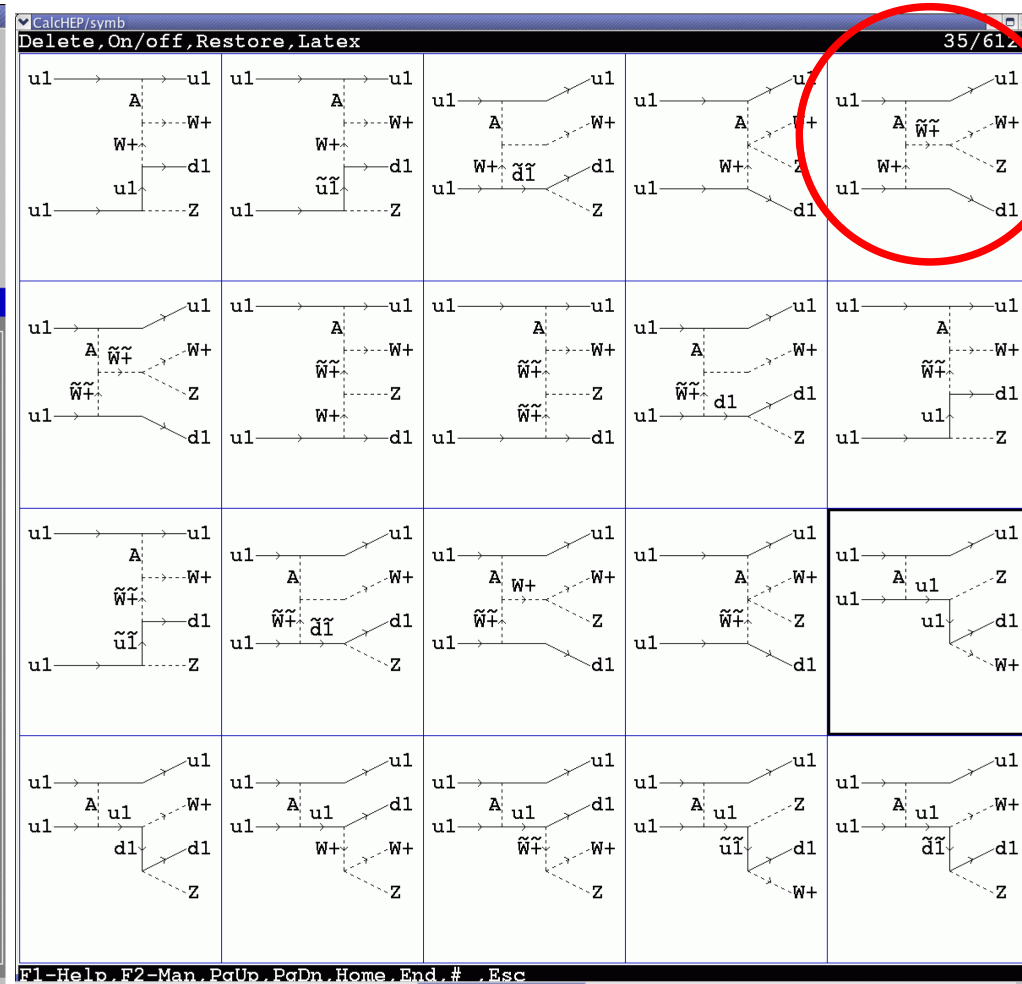

CalcHEP/symb

Model: 3-site-tfg

Process: p,p->W+,Z,j,j

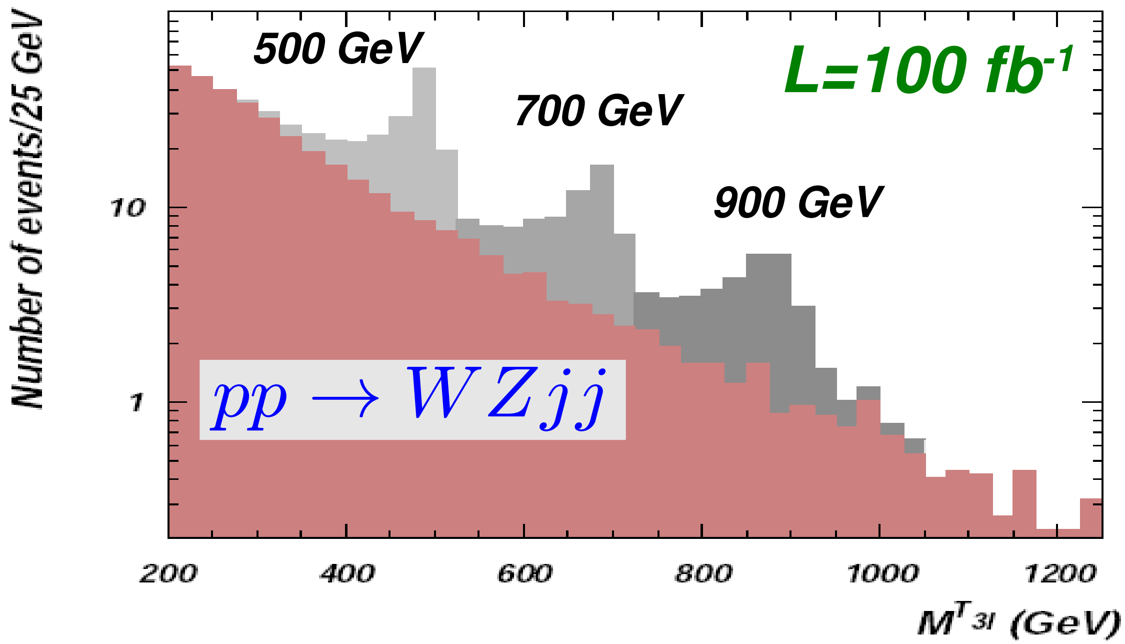
Feynman diagrams
7816 diagrams in 21 subprocesses are constructed.
0 diagrams are deleted.

NN	Subprocess	Del	Rest
1	u1,u1 -> Z,W+,u1,d1	0	612
2	u1,U1 -> Z,W+,U1,d1	0	612
3	u1,d1 -> Z,W+,d1,d1	0	306
4	u1,D1 -> Z,W+,u1,U1	0	612
5	u1,D1 -> Z,W+,d1,D1	0	612
6	u1,D1 -> Z,W+,G,G	0	46
7	u1,G -> Z,W+,G,d1	0	76
8	U1,u1 -> Z,W+,U1,d1	0	612
9	U1,D1 -> Z,W+,U1,U1	0	306
10	d1,u1 -> Z,W+,d1,d1	0	306
11	d1,D1 -> Z,W+,U1,d1	0	612
12	D1,u1 -> Z,W+,u1,U1	0	612
13	D1,u1 -> Z,W+,d1,D1	0	612
14	D1,u1 -> Z,W+,G,G	0	46
15	D1,U1 -> Z,W+,U1,U1	0	306
16	D1,d1 -> Z,W+,U1,d1	0	612
17	D1,D1 -> Z,W+,U1,D1	0	612
18	D1,G -> Z,W+,G,U1	0	76
19	G,u1 -> Z,W+,G,d1	0	76
20	G,D1 -> Z,W+,G,U1	0	76
21	G,G -> Z,W+,U1,d1	0	76



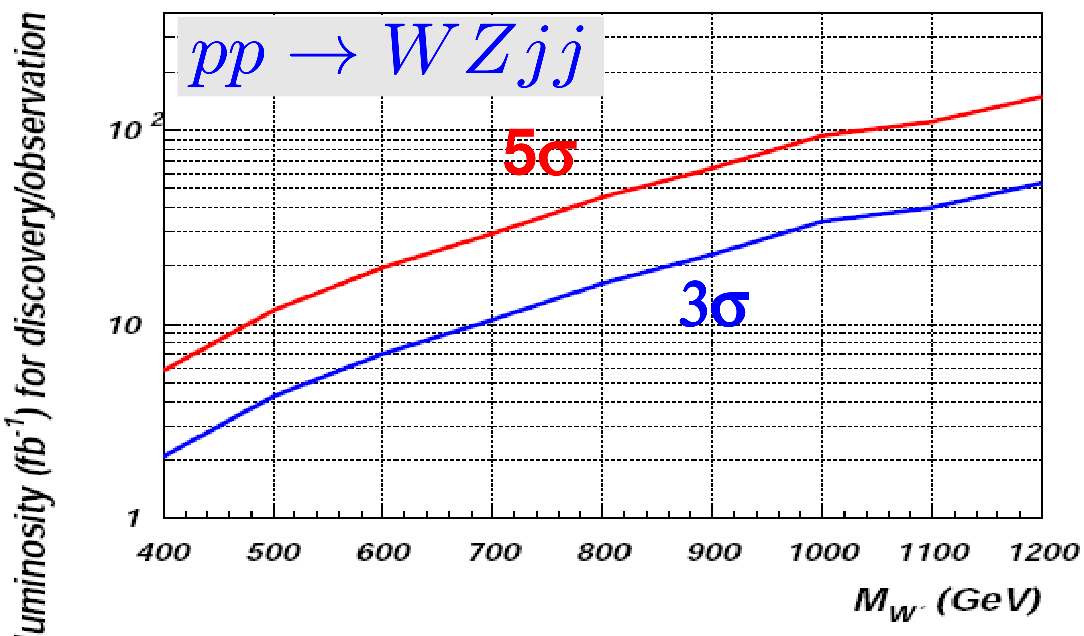
LHC reach for WZ->W' process (preliminary)

$E_j > 300$ GeV
$p_{Tj} > 30$ GeV
$|\eta_j| < 4.5$
$|\Delta\eta(jj)| > 4$
$p_{T\ell} > 15$ GeV
$|\eta_\ell| < 2.5$
$0.85 M_{W'} < M_T < 1.05 M_{W'}$

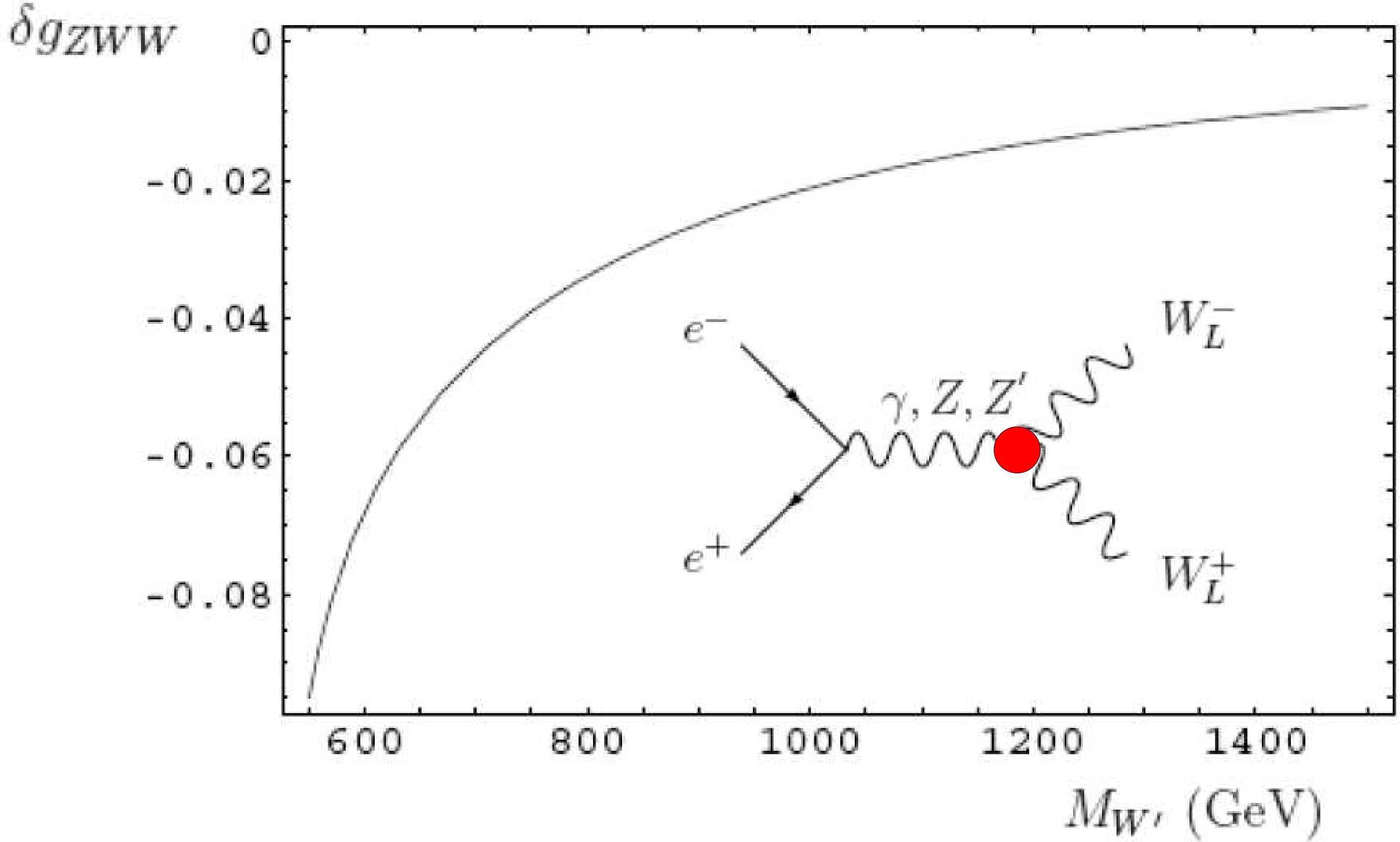


the complete WZjj BG is factor 4 bigger then PYTHIA effective V-boson approximation!

To be compared with Birkedal, Matchev, Perelstein(2005)



Prospects for ILC@ 0.5 TeV: g_{WWZ}



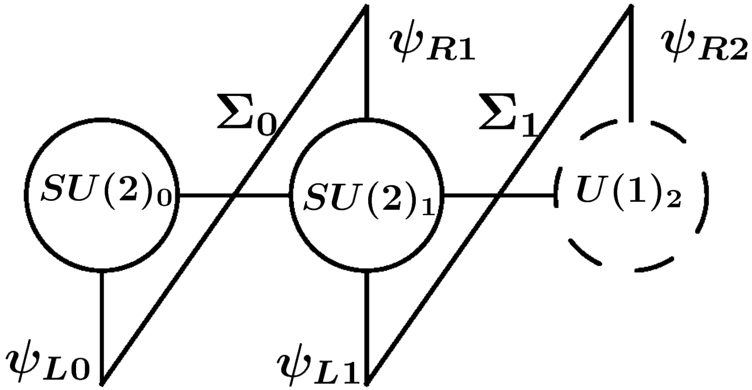
$$\delta g_{ZWW} = \frac{g_{\chi Zee} g_{ZWW}}{g_{\chi Zee_{SM}} g_{ZWW_{SM}}} + \frac{g_{\chi Z'ee} g_{Z'WW}}{g_{\chi Zee_{SM}} g_{ZWW_{SM}}} \frac{s - M_Z^2}{s - M_{Z'}^2} - 1$$

ILC sensitivity is ~ 4 x 10^{-4} with 500 fb^{-1}

hep-ex/0106057 American LC Working Group

Conclusions and outlook

- Three site model is compelling
  - Is simple, yet consistently implements the 1st KK mode of a Higgsless ED
  - Is representative of Higgsless models and their duals
  – dynamical symmetry breaking models
  - Is consistent with precision electroweak observables (IDEL)
  - Has a simple parameter space (M_F , $M_{W'}$)
- Implemented into ClacHEP – powerful tool for pheno/exp studies
  - model is complete and tested in both gauges
  - **public:** hep.pa.msu.edu/people/belyaev/public/3-site/
- Distinctive phenomenology of Z',W': one should be ready for this!
  - fermiophobic Z',W': di-lepton DY discovery range is up to $M_{W'}$ ~0.5-0.6 TeV
    – very different features as compared to Z' of SUSY U(1)' models
  - tri-lepton signature from WZ->W' signal can completely cover $M_{W'}$ space
  - 0.5 TeV ILC can test $M_{W'}$ beyond 1 TeV with g_{WWZ} coupling measurement



Gauge Sector

$$\mathcal{L}_{F^2} = -\frac{1}{2}\mathrm{Tr}\left[F_0^2 + F_1^2 + F_2^2\right]$$

Casalbuoni, De Curtis, Dominici, Gatto (BESS) PLB 155 (1985) 95

Gauge - Goldstone Sector

$$\mathcal{L}_{D\Sigma} = \frac{f^2}{2}\mathrm{Tr}\left[(D_\mu\Sigma_0)^\dagger D^\mu\Sigma_0 + (D_\mu\Sigma_1)^\dagger D^\mu\Sigma_1\right]$$

$$x = \frac{2M_W}{M_{W'}} \qquad M_W = g_1 f\frac{\sqrt{2+x^2-\sqrt{4+x^4}}}{2\sqrt{2}}$$

$$\frac{g_0}{g_1} = x \ll 1$$

$$\frac{g_2}{g_0} = s/c = t$$

$$\frac{1}{e^2} = \frac{1}{g_0^2} + \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

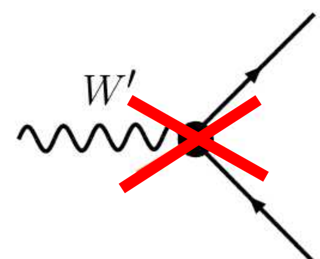
$$\Sigma_j = e^{i\frac{2\pi_j}{f}}$$

Fermion - Goldstone Sector

$$\mathcal{L}_{\Sigma\psi} = -M_F\left(\epsilon_L\bar{\psi}_{L0}\Sigma_0\psi_{R1} + \bar{\psi}_{L1}\psi_{R1} + \bar{\psi}_{L1}\Sigma_1\epsilon_R\psi_{R2}\right)$$

ideal delocalization (IDL): W' , Z' are fermiophobic!

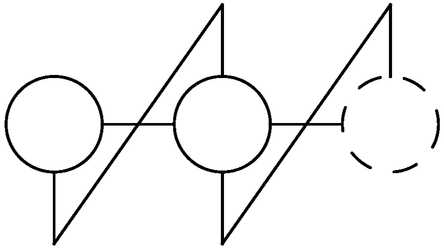
$$\frac{g_0(\psi^f_{L0})^2}{g_1(\psi^f_{L1})^2} = \frac{v_W^0}{v_W^1} \rightarrow \epsilon_L^2 = \frac{2x^2}{2 - x^2 + \sqrt{4+x^4}}$$



$$g_W^{TSM} = g_W^{SM} + O(x^4)$$

Independent parameters: M_W , s_W , $M_{W'}$, M_F

Allowed deviation from IDL



$$-0.33 < S < 0.07 \text{ at } 95\%\text{C.L.}$$

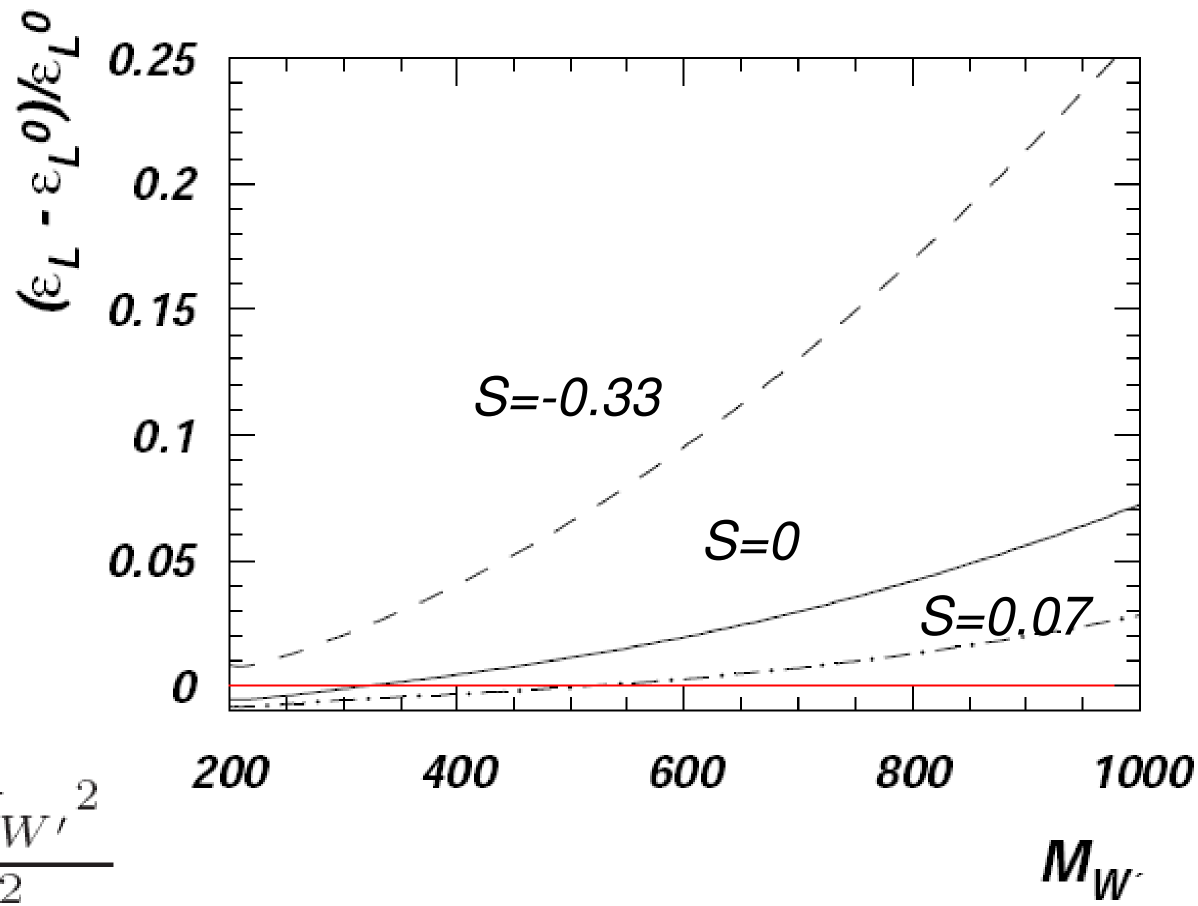
$$M_H^{ref} = 117\text{GeV}$$

$$g_{We\nu} = \frac{e}{s_M}\left(1 + \frac{\alpha_{em}}{4s_M^2}S^0\right)$$

$$g_{We\nu} = \frac{e}{s_M}\left(1 + \frac{x^2}{4} - \frac{\epsilon_L^2}{2}\right)$$

$$\epsilon_L^2 = \frac{1}{2}\left[x^2 - \frac{\alpha_{em}(1+x^2)}{s_M^2}S^0\right]$$

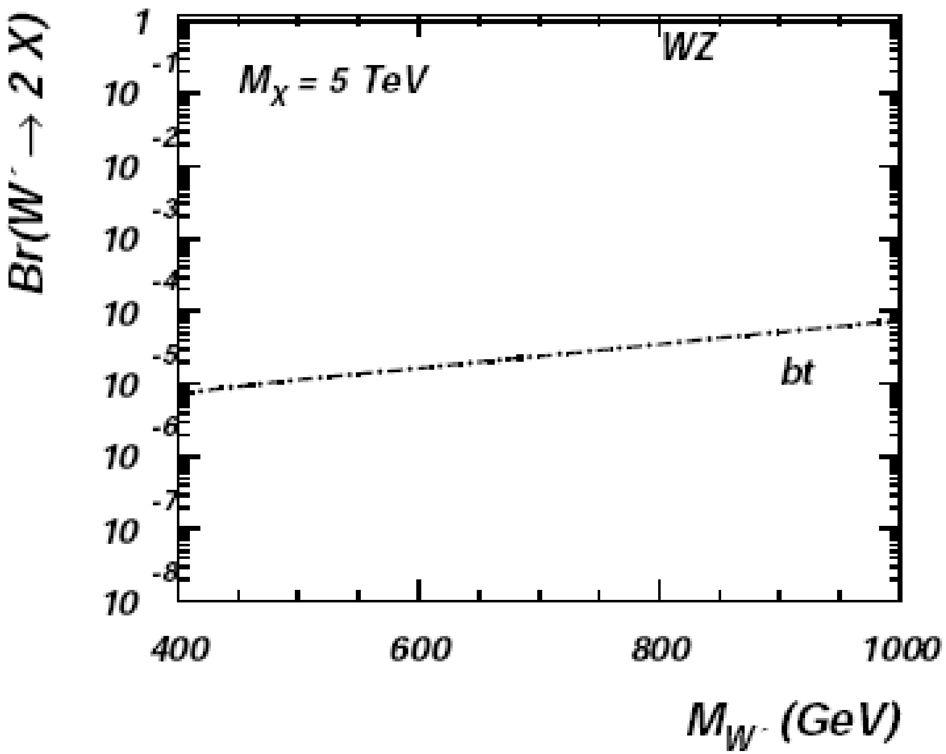
$$S = S^0 + \delta S = S^0 + \frac{1}{12\pi}\log\frac{M_{W'}{}^2}{M_{Href}^2}$$

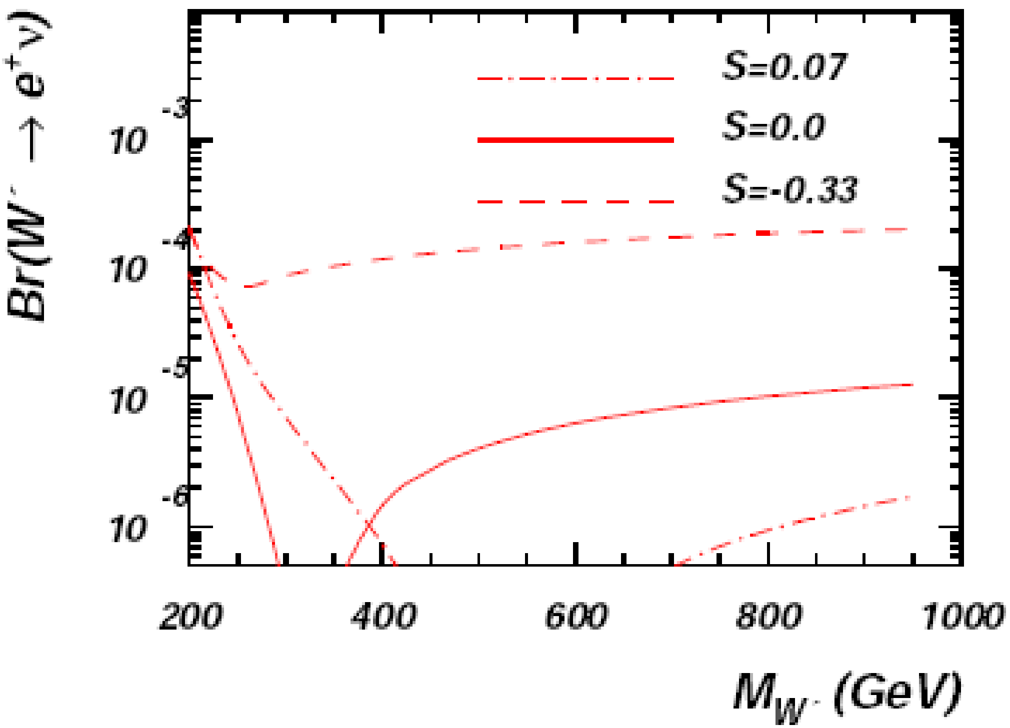


(Matsuzaki,Chivukula,Simmons,Tanabashi; Dawson,Jackson)

W' decays

- **decay into fermions more strongly depends on fermion delocalization**





$$\Gamma(W' \to e^+e^-) = \frac{e^2 M_{W'} x^2 \left(1 - \frac{2\epsilon_L^2}{x^2}\right)^2}{192\pi s_w^2}$$