Collider Phenomenology of models with Dynamical EW Symmetry breaking

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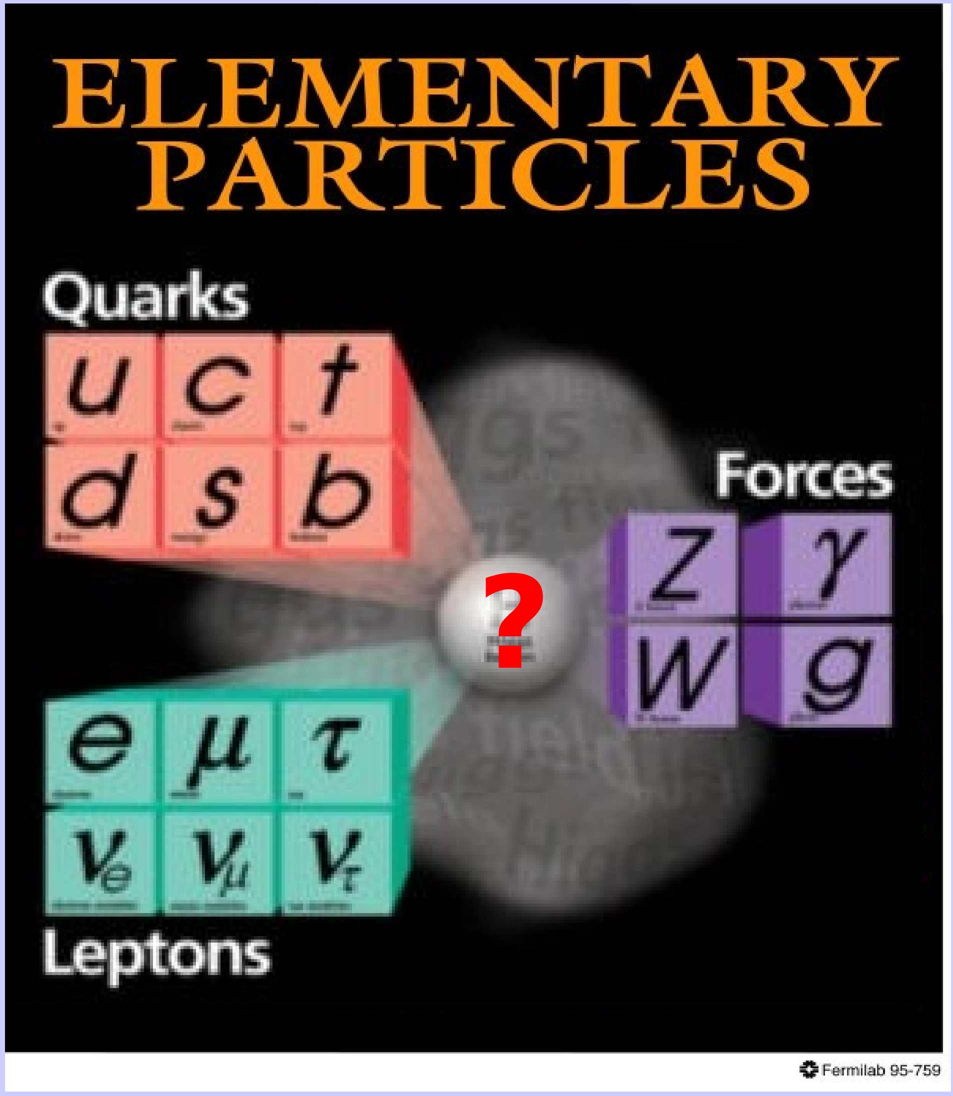
OUTLINE

- ***Motivation for models with Dynamical Symmetry Breaking***
- ***LHC & ILC phenomenology and tools***
- ***Beyond the Minimal Higgsless model***
- ***Conclusions***

Collaborators:
Chivukula, Christensen, Foadi, Frandsen, Järvinen, He, Kuang, Pukhov, Qi, Sannino, Simmons, Zhang

The present status of the SM

- Based on $SU(3)xSU(2)_L xU(1)_Y$ gauge symmetry spontaneously broken down to $SU(3)xU(1)_e$:
- Matter: 3 generations of quarks and leptons
- One of the central role is played by Higgs field
  - *one higgs doublet, interacts with all fields*
  - *develops condensate*
  - *W,Z bosons, lepton and quarks and Higgs field itself acquires mass*



Higgs boson is not found yet and is the most wanted particle!
The present Higgs mass limit is M_H>114.4 GeV from LEP2
The mechanism responsible for EWSB symmetry remains unknown!

What do we know about Electroweak Symmetry Breaking?

It takes Place!

- *status of theory of electro-weak interactions: per mil precision measurements confirm its SU(2)L × U(1)Y gauge structure*

- *the symmetry is broken – W and Z bosons are massive: there are serious problems in any Lorentz-invariant theory of massive vector bosons, unless those particles are Yang-Mills bosons and the gauge symmetry is spontaneously broken*

  [Nambu,Anderson; Higgs; Englert,Brout; Guralnik, Hagen,Kibble;...]

- *How $SU(2)_L \times U(1)_Y$ is broken?*

  $SU(2)_L \times U(1)_Y$ does not break its own symmetry – couplings are weak
  - *Higgs mechanism?*
  - *Dynamical symmetry breaking (Technicolor)?*
  - *Extra dimensions?*
  - *...?*

Non-linear sigma model

One can eliminate h(x) and still have EWSB via Sigma term in the Higgsless model

$$\mathcal{L}_H \to \mathcal{L}_\Sigma = \frac{v^2}{4}\,\mathrm{tr}\Big([\mathcal{D}^\mu\Sigma]^\dagger\,\mathcal{D}_\mu\Sigma\Big)$$

$$|D_\mu\varphi|^2$$

$$= \begin{pmatrix}0 & v/\sqrt{2}\end{pmatrix}\left|\frac{g}{\sqrt{2}}W^+\sigma^+ + \frac{g}{\sqrt{2}}W^-\sigma^- + \frac{g}{2}W^0\sigma^3 + \frac{g'}{2}B\right|^2\begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix}$$

$$= \frac{v^2}{4}[g^2W^+W^- + \frac{1}{2}(-gW^0 + g'B)^2]$$

Non-linear sigma model

There are many 4D CP-conserving operators that can be written down

$\mathcal{L}_1=\frac{1}{2}g^2\alpha_1 B_{\mu\nu}\mathrm{Tr}(TF^{\mu\nu})$

$\mathcal{L}_2=\frac{1}{2}ig\alpha_2 B_{\mu\nu}\mathrm{Tr}(T[V^\mu,V^\nu])$

$\mathcal{L}_3=ig\alpha_3\mathrm{Tr}(F_{\mu\nu}[V^\mu,V^\nu])$

$\mathcal{L}_4=\alpha_4[\mathrm{Tr}(V_\mu V_\nu)]^2$

$\mathcal{L}_5=\alpha_5[\mathrm{Tr}(V_\mu V^\mu)]^2$

$\mathcal{L}_6=\alpha_6\mathrm{Tr}(V_\mu V_\nu)\mathrm{Tr}(TV^\mu)\mathrm{Tr}(TV^\nu)$

$\mathcal{L}_7=\alpha_7\mathrm{Tr}(V_\mu V^\mu)[\mathrm{Tr}(TV_\nu)]^2$

$\mathcal{L}_8=\frac{1}{4}g^2\alpha_8[\mathrm{Tr}(TF_{\mu\nu})]^2$

$\mathcal{L}_9=\frac{1}{2}ig\alpha_9\mathrm{Tr}(TF_{\mu\nu})\mathrm{Tr}(T[V^\mu,V^\nu])$

$\mathcal{L}_{10}=\frac{1}{2}\alpha_{10}[\mathrm{Tr}(TV_\mu)\mathrm{Tr}(TV_\nu)]^2$

$\mathcal{L}_{11}=\alpha_{11}\mathrm{Tr}[(\mathcal{D}_\mu V^\mu)^2]$

$\mathcal{L}_{12}=\frac{1}{2}\alpha_{12}\mathrm{Tr}(T\mathcal{D}_\mu\mathcal{D}_\nu V^\nu)\mathrm{Tr}(TV^\mu)$

$\mathcal{L}_{13}=\frac{1}{2}\alpha_{13}[\mathrm{Tr}(T\mathcal{D}_\mu V_\nu)]^2$

$\mathcal{L}_{14}=\alpha_{14}[\mathrm{Tr}(F_{\mu\nu}V^\nu)\mathrm{Tr}(TV^\mu) - \mathrm{Tr}(F_{\mu\nu}V^\mu)\mathrm{Tr}(TV^\nu)]$

$\mathcal{L}_{15}=2i\alpha_{15}\mathrm{Tr}(V_\mu\mathcal{D}_\nu V^\nu)\mathrm{Tr}(TV^\mu)$

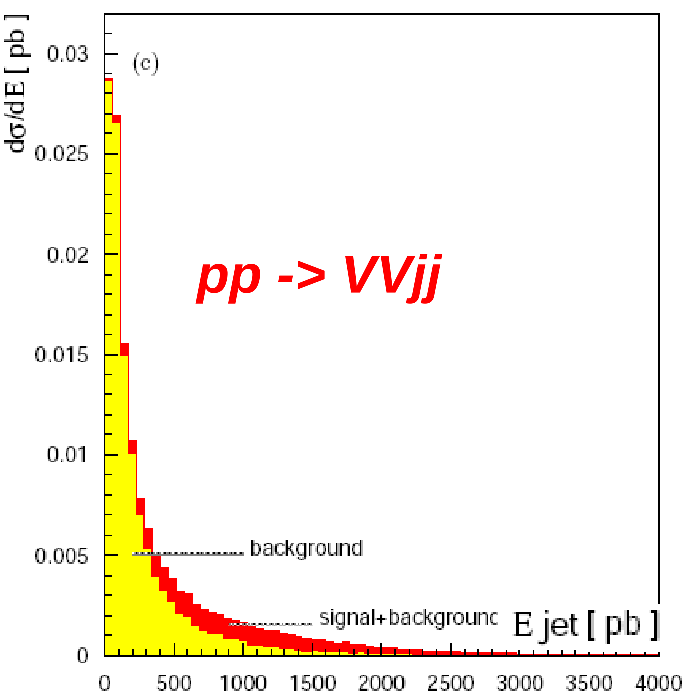
$\mathcal{L}_{16}=i\alpha_{16}\mathrm{Tr}[T(\mathcal{D}_\mu V_\nu+\mathcal{D}_\nu V_\mu)] \times\mathrm{Tr}(V^\mu V^\nu)$

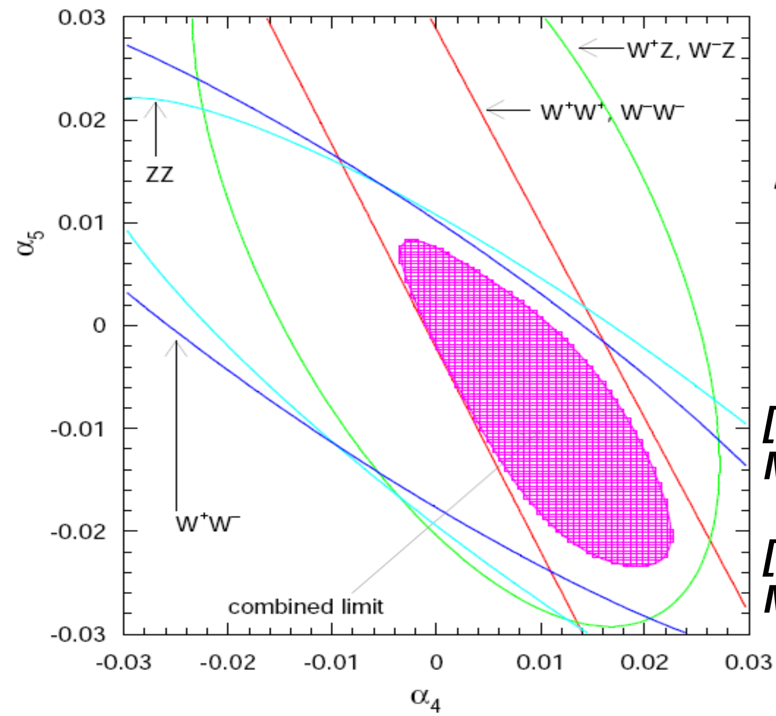
$\mathcal{L}_{17}=\frac{1}{2}i\alpha_{17}\mathrm{Tr}[T(\mathcal{D}_\mu V_\nu+\mathcal{D}_\nu V_\mu)] \times\mathrm{Tr}(TV^\mu)\mathrm{Tr}(TV^\nu)$

$\mathcal{L}_{18}=\frac{1}{2}i\alpha_{18}\mathrm{Tr}([V_\mu,T]\mathcal{D}^\mu\mathcal{D}^\nu V_\nu)$

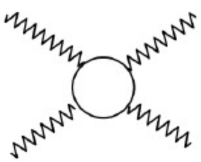
[Appelquist, Bernard '80 ; Longitano '80]

which can be tested at the LHC





the only quartic interactions under custodial symmetry



$$\mathcal{L}_4=\alpha_4(\mathrm{tr}\,[V_\mu V_\nu])^2$$
$$\mathcal{L}_5=\alpha_5(\mathrm{tr}\,[V_\mu V^\mu])^2$$

[AB, Eboli, Gonzalez–Garcia, Mizukoshi, Novaes, Zacharov '98]

[Eboli, Gonzalez–Garcia, Mizukoshi '06]

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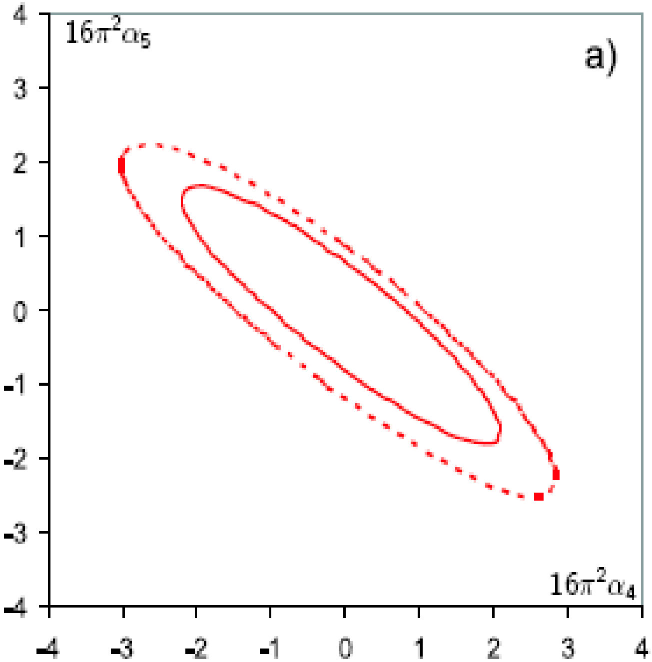
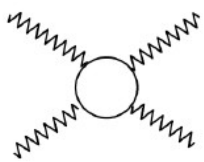
$$\mathfrak{L}_{18} = \tfrac{1}{2} i \alpha_{18} \mathrm{Tr}([V_\mu, T] \mathfrak{D}^\mu \mathfrak{D}^\nu V_\nu)$$

[Appelquist, Bernard '80 ; Longitano '80]

ILC will slightly improve quartic coupling measurement



the only quartic interactions under custodial symmetry



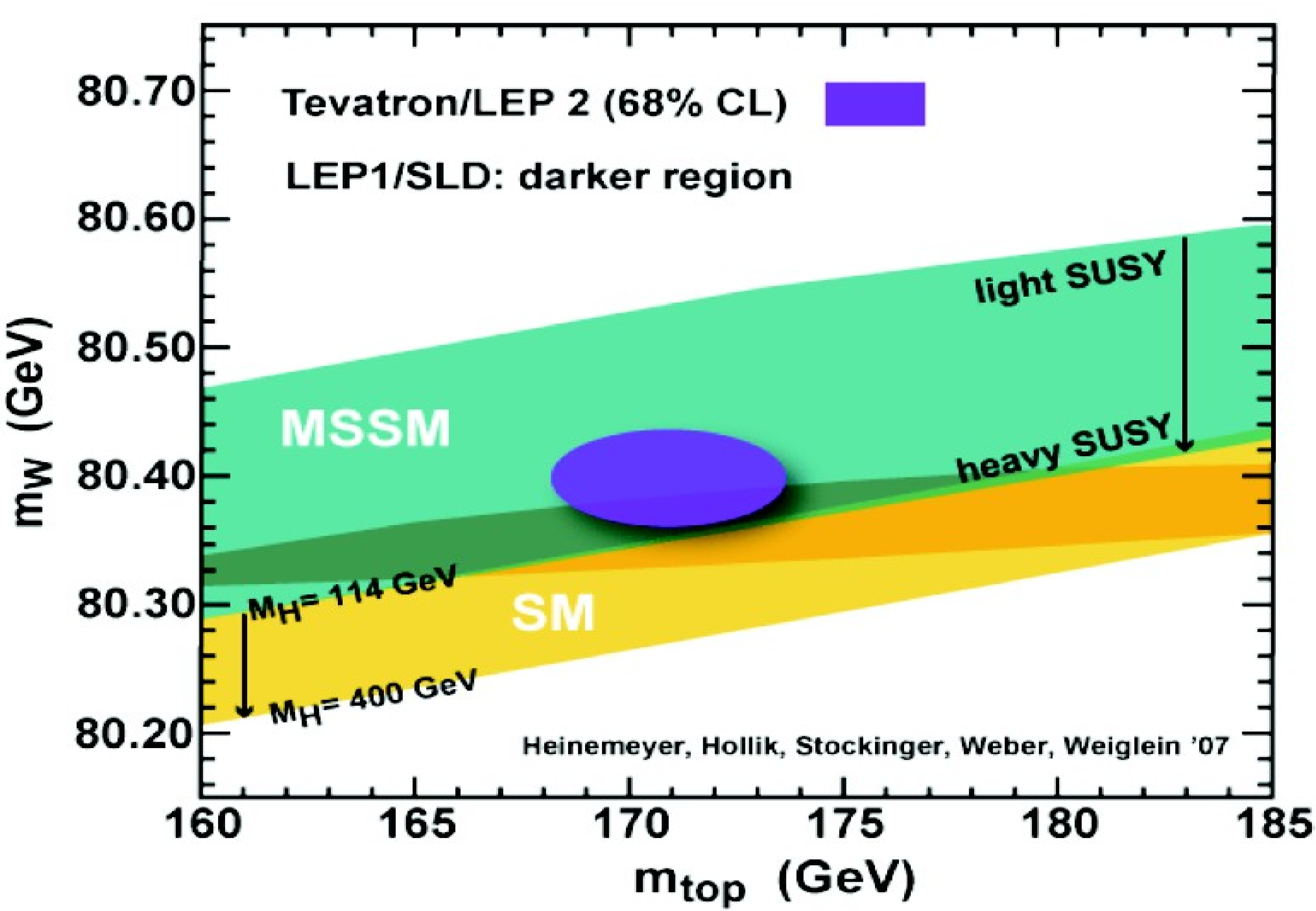
$$\mathcal{L}_4 = \alpha_4 (\mathrm{tr}\, [V_\mu V_\nu])^2$$

$$\mathcal{L}_5 = \alpha_5 (\mathrm{tr}\, [V_\mu V^\mu])^2$$

[Eboli, Gonzalez-Garcia, Lietti, Novaes '00]

[Beyer, Kilian, Krstonosic, Monig, Reuter, Schmidt, Schroder '06]

Higgs (if there is) prefers to be non-SM like!



Why do/should we think about alternative way of Electroweak Symmetry Breaking?

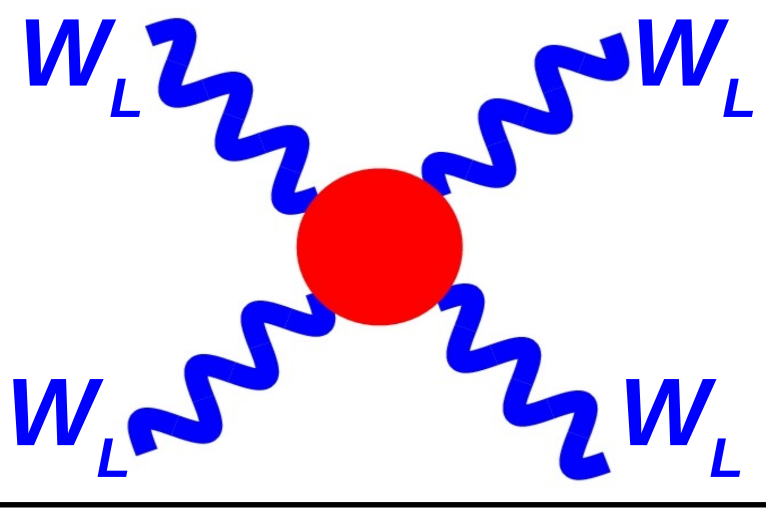
Example of Comparison
SM Higgs vs Technicolor

SM Higgs	Technicolor
simple and economical	*complicated at the effective theory level*
GIM mechanism, no FCNC problems, EW precision data are OK for preferably light Higgs boson	*FCNC constraints require* ***walking,*** *potential tension with EW precision data*
SM is established, perfectly describes data	*no viable ETC model suggested yet, work in progress*
fine-tuning and naturalness problem; triviality problem	*no fine-tuning, the scale is dynamically generated*
there is no example of fundamental scalar	*Superconductivity and QCD are examples of dynamical symmetry breaking*
Scalar potential parameters and yukawa couplings are inputs	*parameters of low-energy effective theory are derived once underlying ETC is constructed*

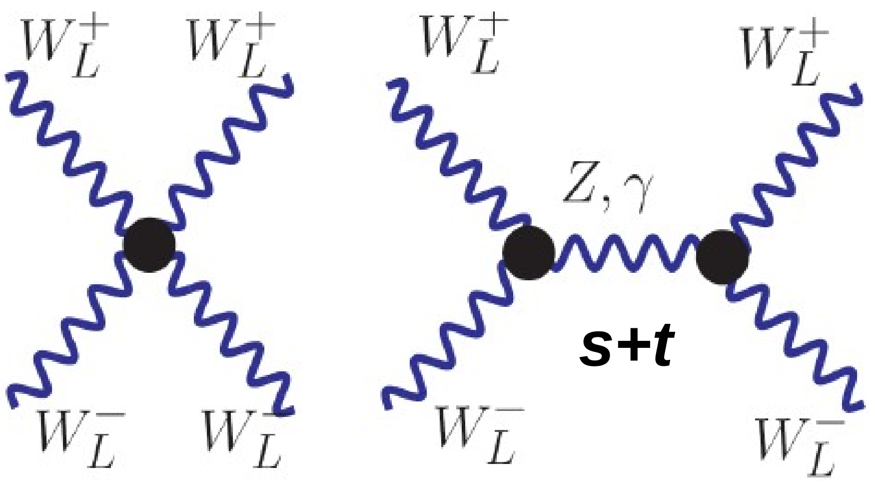
Electroweak Symmetry Breaking without Higgs boson but within the Electroweak theory

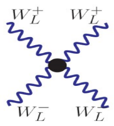
Electroweak Symmetry Breaking without Higgs boson but within the Electroweak theory

The Loss of Unitarity and EW precision data is the main worry!

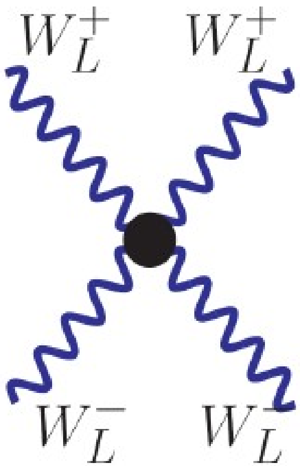


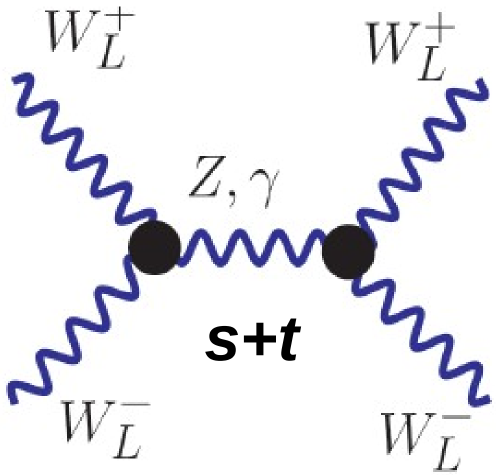
Unitarity with and without Higgs boson

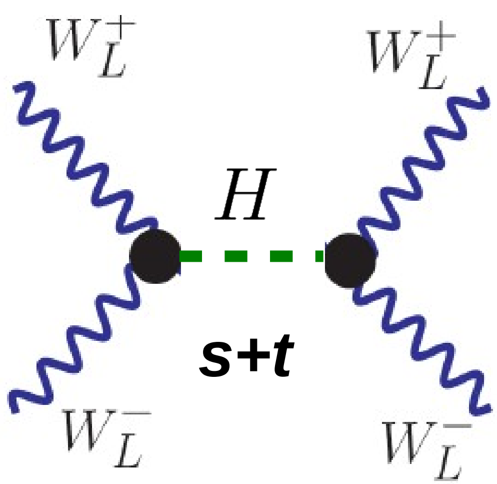


Graphs	$g^2 \frac{E^4}{m_w^4}$	$g^2 \frac{E^2}{m_w^2}$
	$-3 + 6\cos\theta + \cos^2\theta$	$+2 - 6\cos\theta$
s	$-4\cos\theta$	$-\cos\theta$
t	$+3 - 2\cos\theta - \cos^2\theta$	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
Sum	0	$+\frac{1}{2} + \frac{1}{2}\cos\theta$

Unitarity with and without Higgs boson







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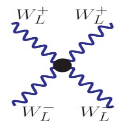	$-3 + 6\cos\theta + \cos^2\theta$	$+2 - 6\cos\theta$
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Sum	0	$+\frac{1}{2} + \frac{1}{2}\cos\theta$
		$-\frac{1}{2} - \frac{1}{2}\cos\theta$
		0

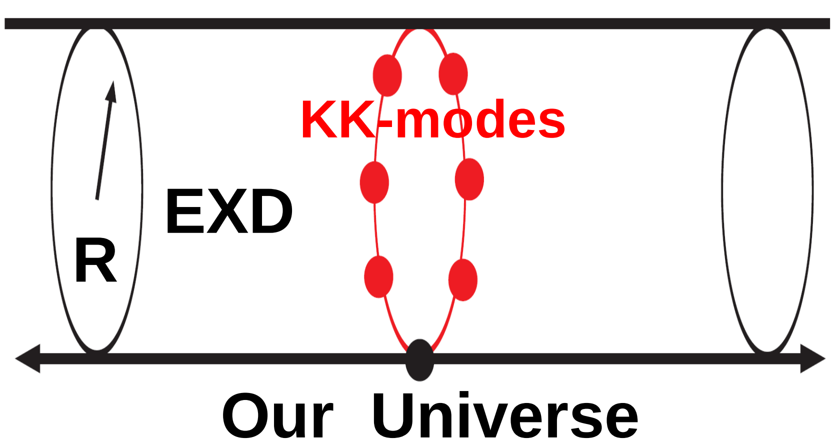
If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi}v \simeq 1.2\,\mathrm{TeV}$

How one can preserve unitarity without Higgs ?

Higgsless Models

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

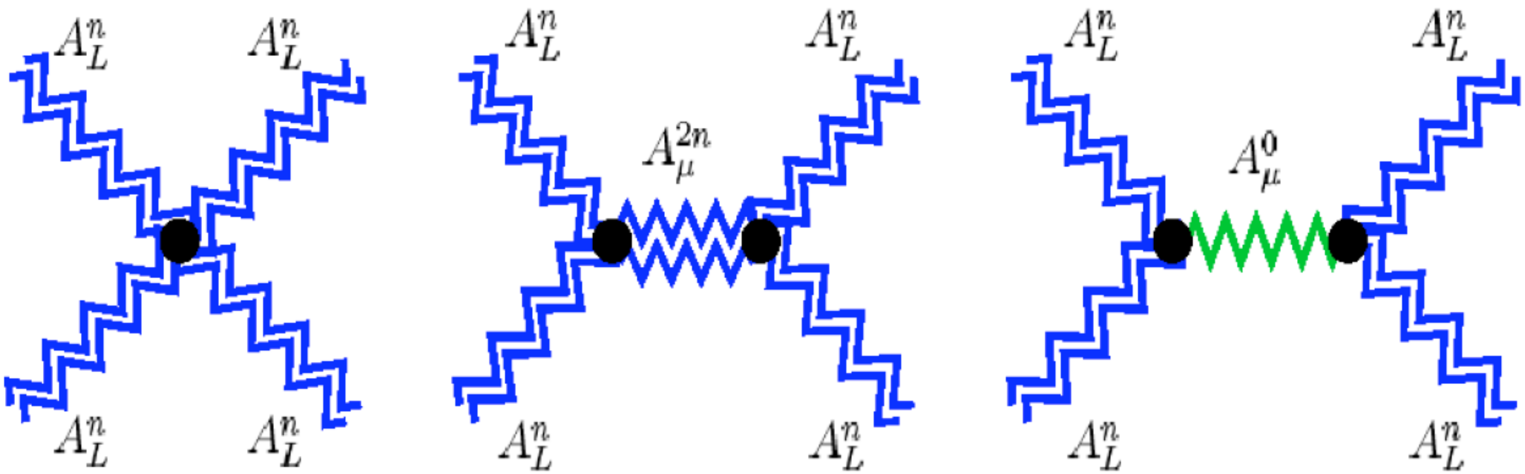
➧ *4-D gauge kinetic term*

$$A^{an}_L \leftrightarrow A^{an}_5 \quad :$$

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

BC: $\partial_5 A^{\mu a} = 0$ and $A^a_5 = 0$

4D KK Mode Scattering



+ Crossing Channels

$$\mathcal{A} = \mathcal{A}^{(4)} \frac{E^4}{M_n^4} + \mathcal{A}^{(2)} \frac{E^2}{M_n^2} + \mathcal{A}^{(0)} + \mathcal{O}\left(\frac{M_n^2}{E^2}\right)$$

$$\mathcal{A}^{(4)} = i\left(g_{nnnn}^2 - \sum g_{nnk}^2\right) a^{(4)}(\theta)$$

$$a^{(4)}(\theta) = \left(f^{abe} f^{cde}(3 + 6\cos\theta - \cos^2\theta) + 2(3 - \cos^2\theta) f^{ace} f^{bde}\right)$$

E^4 sum rule: $\quad g_{nnnn}^2 = \sum_k g_{nnk}^2$

$$\mathcal{A}^{(2)} = \frac{i}{M_n^2}\left(4 g_{nnnn} M_n^2 - 3\sum_k g_{nnk}^2 M_k^2\right) a^{(2)}(\theta)$$

$$a^{(2)}(\theta) = \left(f^{ace} f^{bde} - \sin^2\tfrac{\theta}{2}\ f^{abe} f^{cde}\right)$$

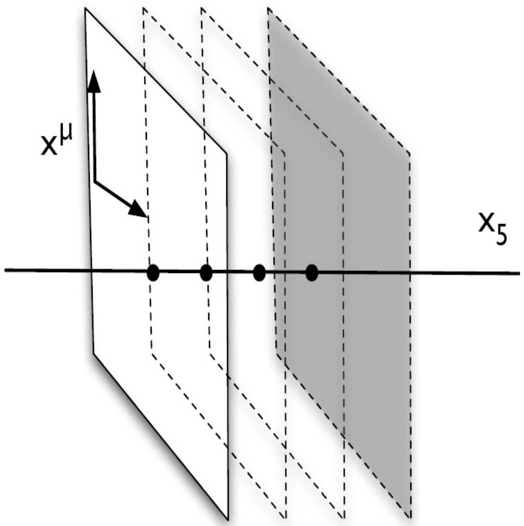
E^2 sum rule: $\quad g_{nnnn} M_n^2 = \frac{3}{4}\sum_k g_{nnk}^2 M_k^2$

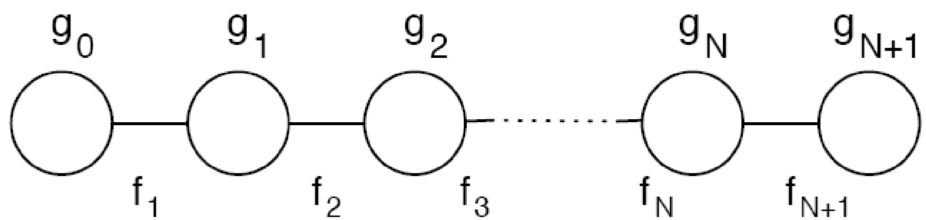
- ***Cancellation of bad high energy behavior provided through***
- ***exchange of massive vector particles***

Chivukula, He, Dicus; Csaci, Grojean, Pilo, Murayama, Pilo, Terning

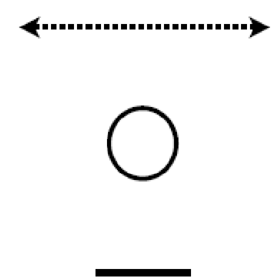
DECONSTRUCTION

moose diagram can be interpreted as the discretization of a continuum gauge theory in 5D along a fifth dimension





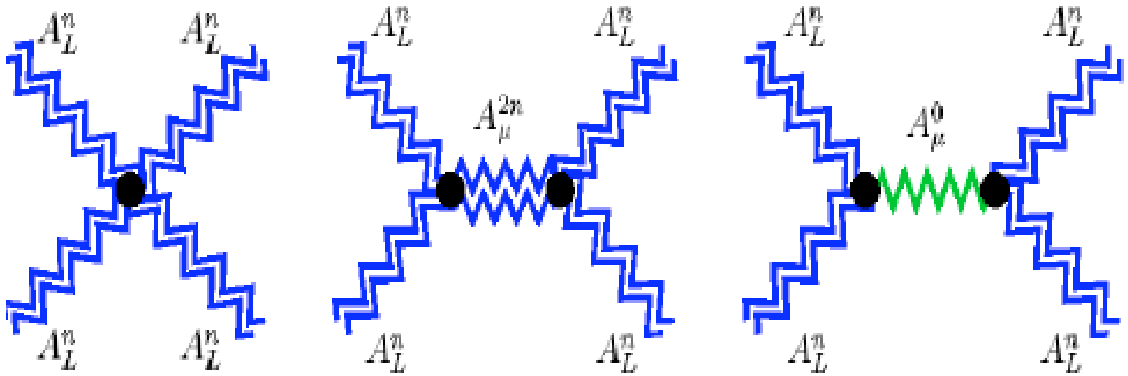
- Discretize fifth dimension
- 4D gauge group at each site
- Nonlinear sigma model link fields



- To include warping: vary f_j
- For spatially dependent coupling: vary g_k
- Continuum Limit: take $N \rightarrow$ infinity
- Finite N, a 4D theory w/o 5D constraints

Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang

Conflict S and Unitarity



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

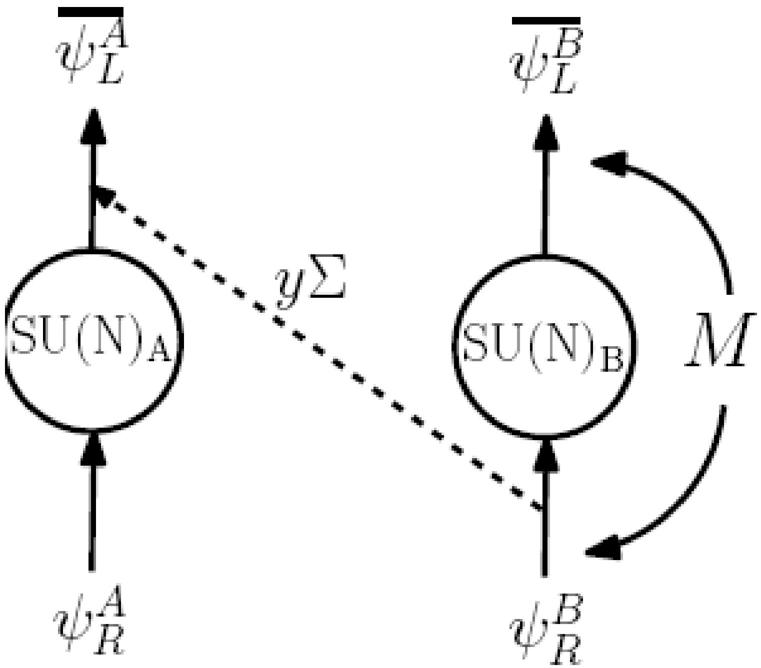
- ***Z' mass is bounded from above:*** $m_{Z_1} < \sqrt{8\pi}\, v$

- ***... and yields too much a value of S-parameter:*** $\alpha\, S \geq \frac{4 s_Z^2 c_Z^2 M_Z^2}{8\pi v^2} = \frac{\alpha}{2}$
  [Chivukula, Simmons, He, Kurachi,Tanabashi]

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

- ***Alternatively there could be a large contribution to T parameter***

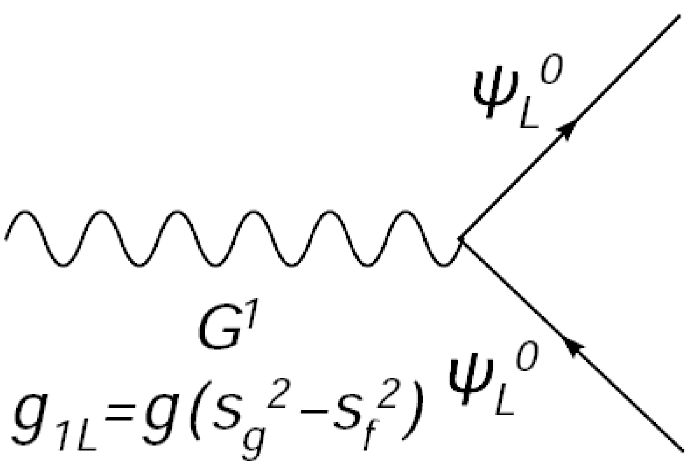
Fermion delocalization

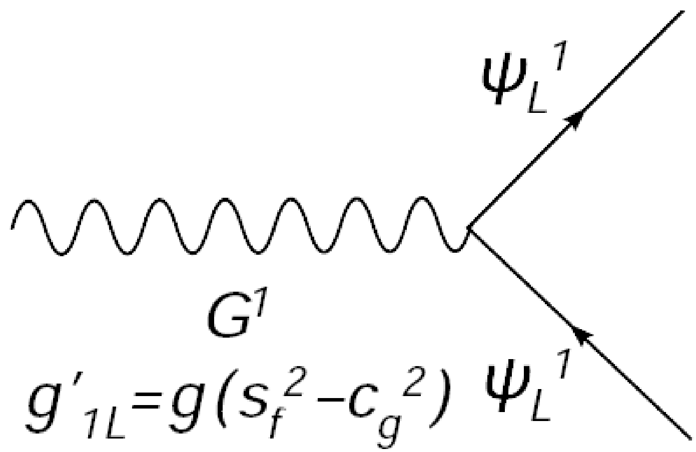


$$\begin{pmatrix} G^0_\mu \\ G^1_\mu \end{pmatrix} = \begin{pmatrix} c_g & s_g \\ s_g & -c_g \end{pmatrix} \begin{pmatrix} A_\mu \\ B_\mu \end{pmatrix}$$

$$\begin{pmatrix} \psi^0_L \\ \psi^1_L \end{pmatrix} = \begin{pmatrix} -c_f & s_f \\ s_f & c_f \end{pmatrix} \begin{pmatrix} \psi^A_L \\ \psi^B_L \end{pmatrix}$$

Mixing of light and heavy fermions helps to suppress contribution from heavy bosons to the EW observables!



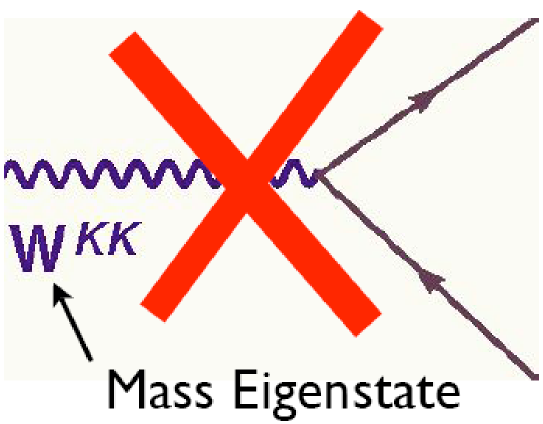


Ideal Fermion Delocalization

- Recall that the light W's wavefunction is orthogonal to wavefunctions of KK modes
- Choose fermion delocalization profile to match W wavefunction profile along the 5th dimension:

$$g_i x_i \propto v_i^W$$

- No (tree-level) fermion couplings to KK modes!



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

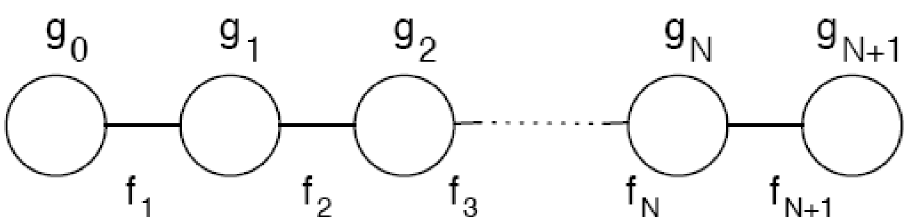
$$Y = M_W^2(\Sigma_W - \Sigma_Z)$$

Fermion delocalization profile can be chosen to match W-wave function along the 5th dimension:

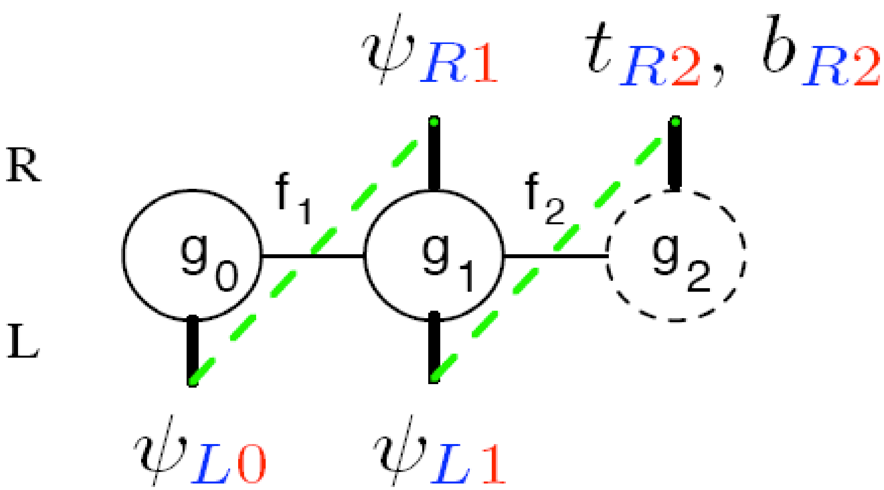
leading to vanishing coupling of fermions to KK modes!

[Chivukula,Simmons,He, Kurachi, Tanabashi; Casalbuoni, De Curtis, Dolce, Dominici]

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]



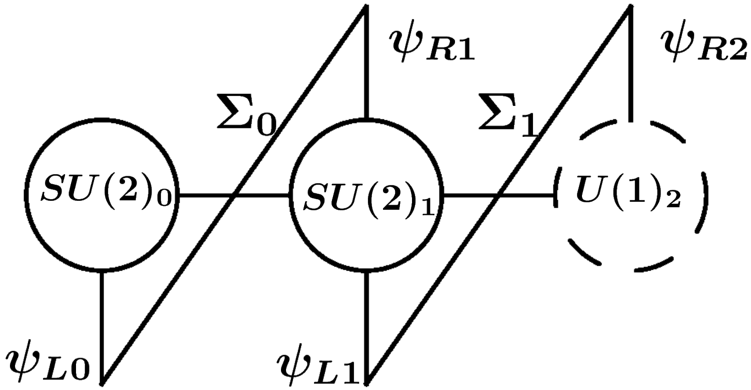
$$SU(2) \times SU(2) \times U(1)$$

[Chivukula, Coleppa, Di Chiara,Simmons '06]

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

gauge sector is the BESS model
[Casalbuoni, De Curtis, Dominici,Gatto '85]

fermions: u, d, c, s, t, b
U, D, C, S, T, B
plus leptons



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

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

$$D_\mu\Sigma_j = \partial_\mu\Sigma_j + ig_jW_j\Sigma_j - ig_{j+1}\Sigma_jW_{j+1}$$

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

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

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

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

$$x = \frac{2M_W}{M_{W'}}$$

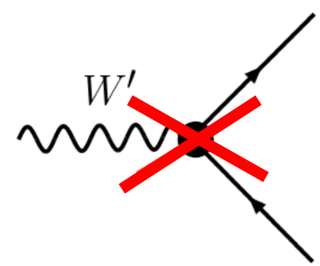
$$M_W = g_1 f\frac{\sqrt{2+x^2-\sqrt{4+x^4}}}{2\sqrt{2}}$$

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!

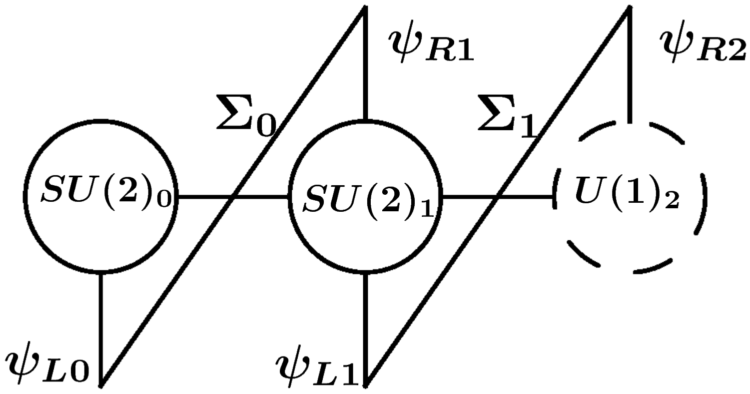
$$\frac{g_0(\psi^f_{L0})^2}{g_1(\psi^f_{L1})^2} = \frac{v_W^0}{v_W^1} \rightarrow \epsilon_L^2 = \frac{2x^2}{2-x^2+\sqrt{4+x^4}}$$



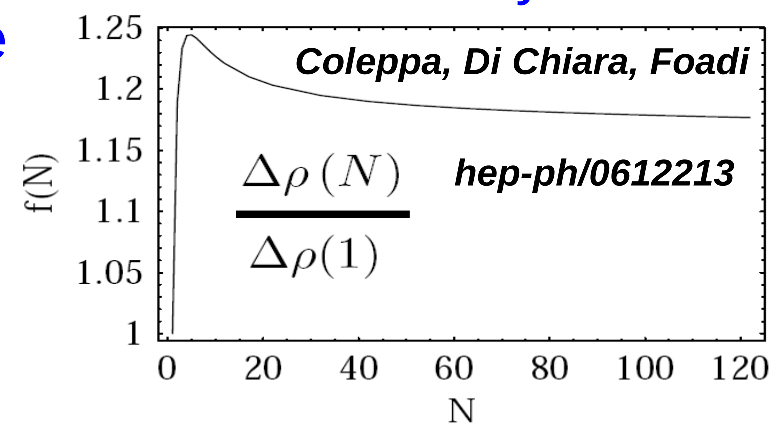
$$g_W^{TSM} = g_W^{SM} + O(x^4)$$

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

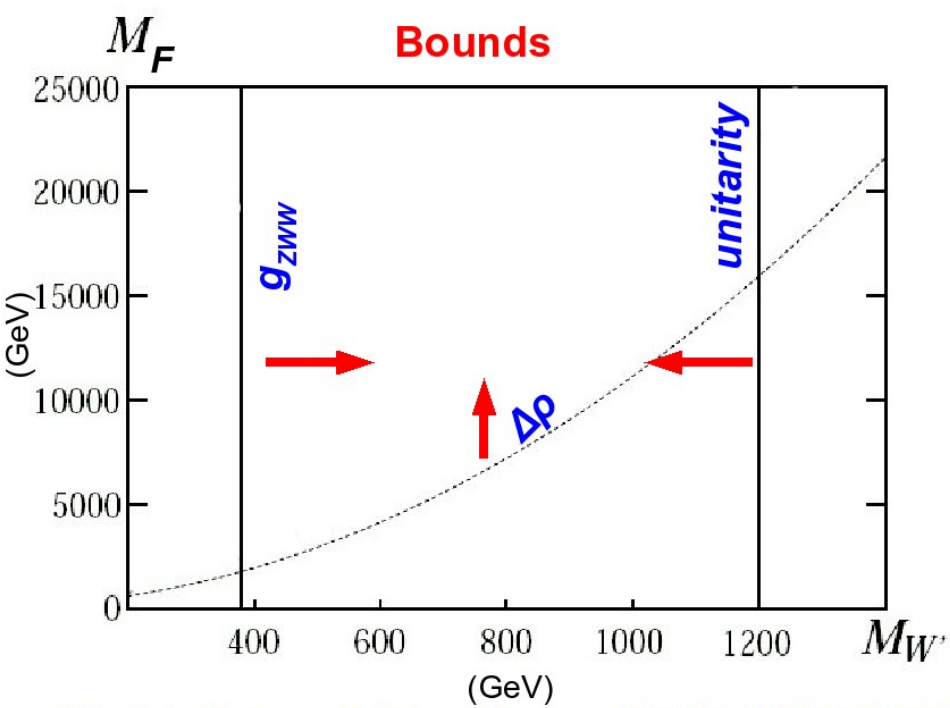
The Three Site Model representative and testable!



- The parameter space is: simple and bounded
  - from below by experiment
  - from above by unitarity
- Low energy phenomenology of a Higgsless ED is dominated by the 1st KK mode

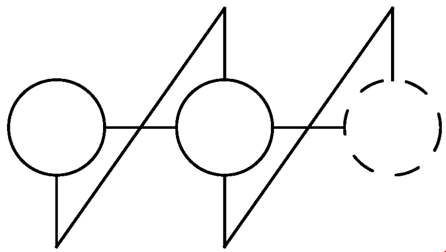


- The Three Site Model consistently implements the 1st KK mode in a gauge invariant way
- **Can be tested at the LHC**



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

Tools



CalcHEP

[Alexander Pukhov, AB, Neil Christensen]

- **Automatic calculations of tree-level processes within user-defined model**
- **User friendly graphical interface**
- **Easy implementation of new models**
  - **Especially using LanHEP**
- **Feynman gauge and unitary gauge**
  - **Important cross check.**

- ***New features of CalcHEP***
  - ***batch interface*** *[Neil Christensen]*
  - ***Improved CalcHEP-MC interface*** *[AB, Pukhov]*

LanHEP [Andrei Semenov]

- ***Automatic generation of Feynman rules from the Lagrangian***
- ***Has checks for***
  - ***Hermiticity***
  - ***BRST invariance***
  - ***EM charge conservation***
  - ***Particle mixings, mass terms, and mass matrices***

Example of model Implementation using LanHEP

LanHEP

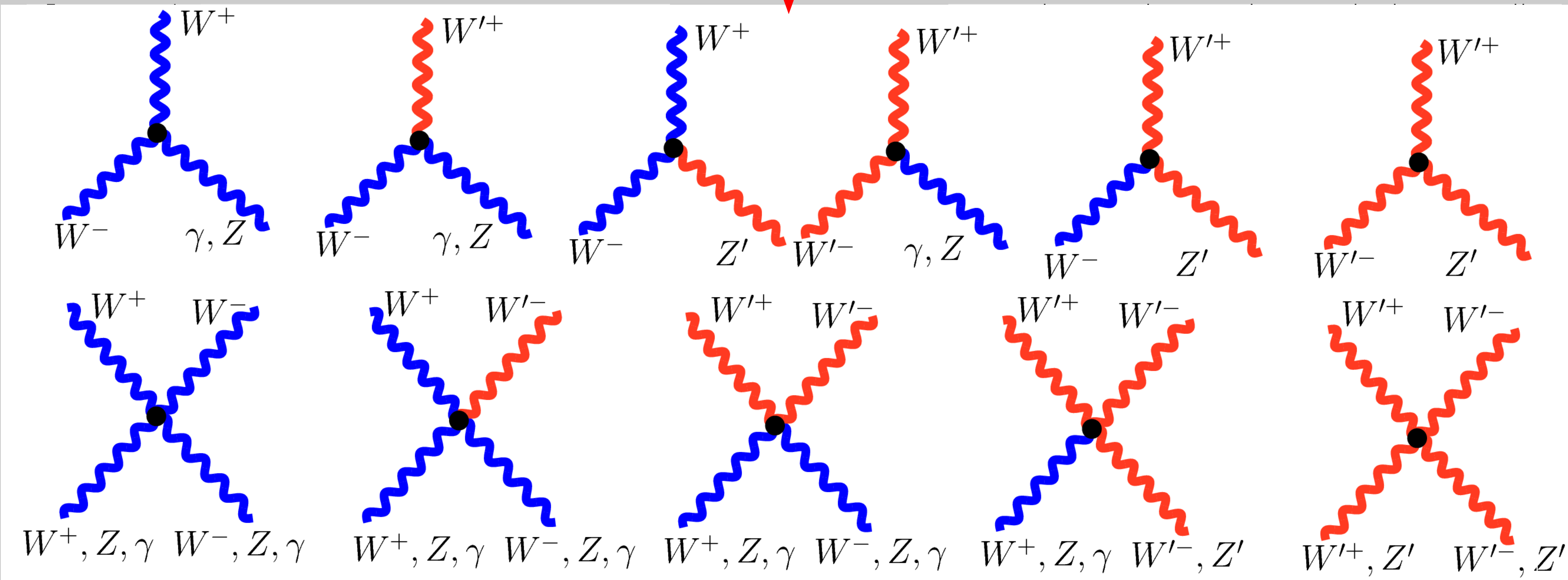
$$\mathcal{L}_{F^2} = -\frac{1}{2}\mathrm{Tr}\left(F_0^2 + F_1^2 + F_2^2\right)$$ **where** $$F_j^{\mu\nu} = \partial^\mu W_j^\mu - \partial^\nu W_j^\mu + i g_j \left[W_j^\mu, W_j^\nu\right]$$

```
%%%%%%%%%%  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



Example of model Implementation using LanHEP

LanHEP

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

```
%%%%%%%%%%  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

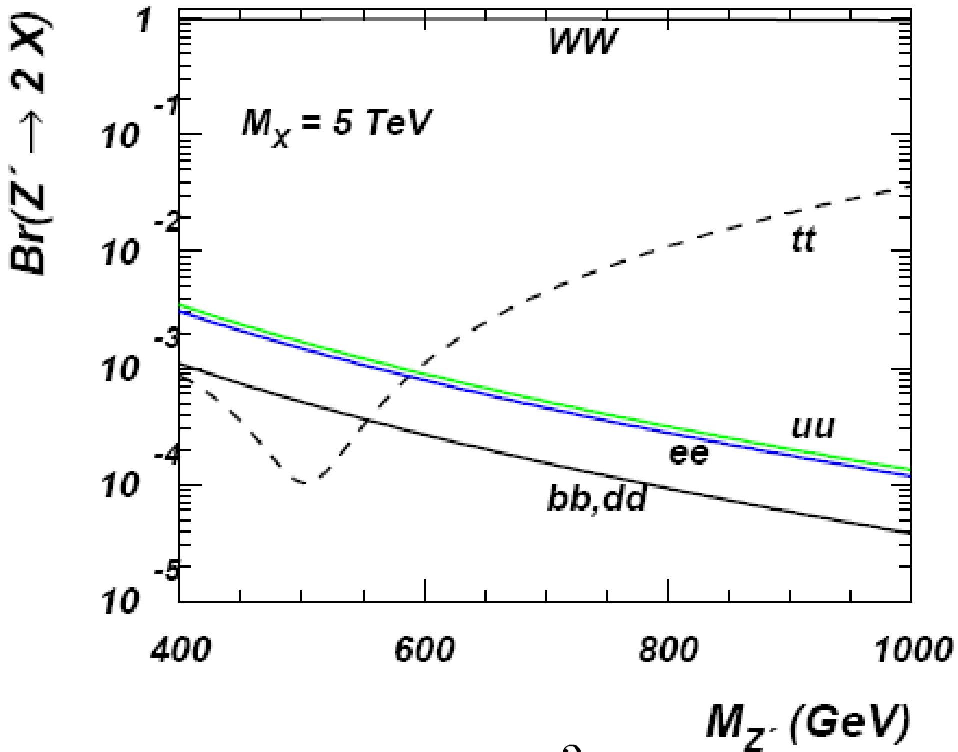
Lagrangian

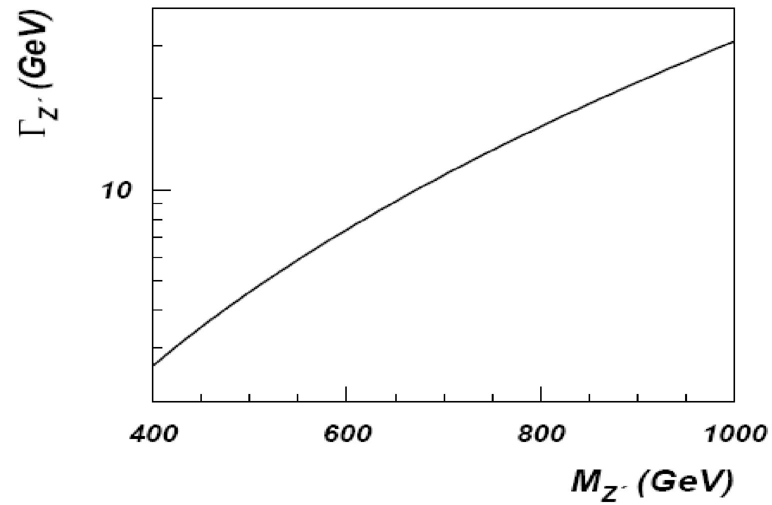
P1	P2	P3	P4	> Factor
A	W+	W-		-g*v0g
A	~W+	~W-		-g*v0g
W+	W-	Z		-g/x
W+	W-	~Z		-g/x
W+	Z	~W-		-g/x
W+	~W-	~Z		-g/x
W-	Z	~W+		-g/x
W-	~W+	~Z		-g/x
Z	~W+	~W-		-g/x
~W+	~W-	~Z		-g/x
A	A	W+	W-	-g**2*v0g**2
A	A	~W+	~W-	-g**2*v0g**2
A	W+	W-	Z	-g**2*v0g/x
A	W+	W-	~Z	-g**2*v0g/x
A	W+	Z	~W-	-g**2*v0g/x
A	W+	~W-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

Gauge boson widths and branchings

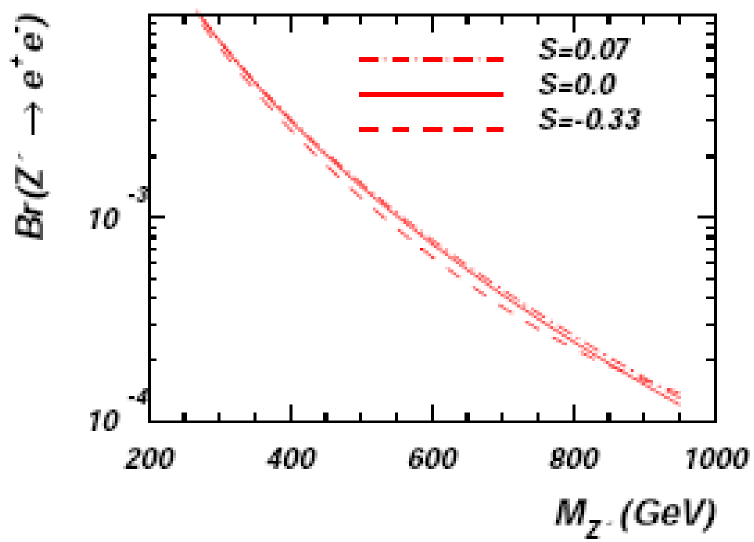
- **Fermiophobic nature of the gauge bosons**
- **Dominant decay into WW and WZ pairs**
- **Z' Br does not depend much on deviation from ideal delocalization**





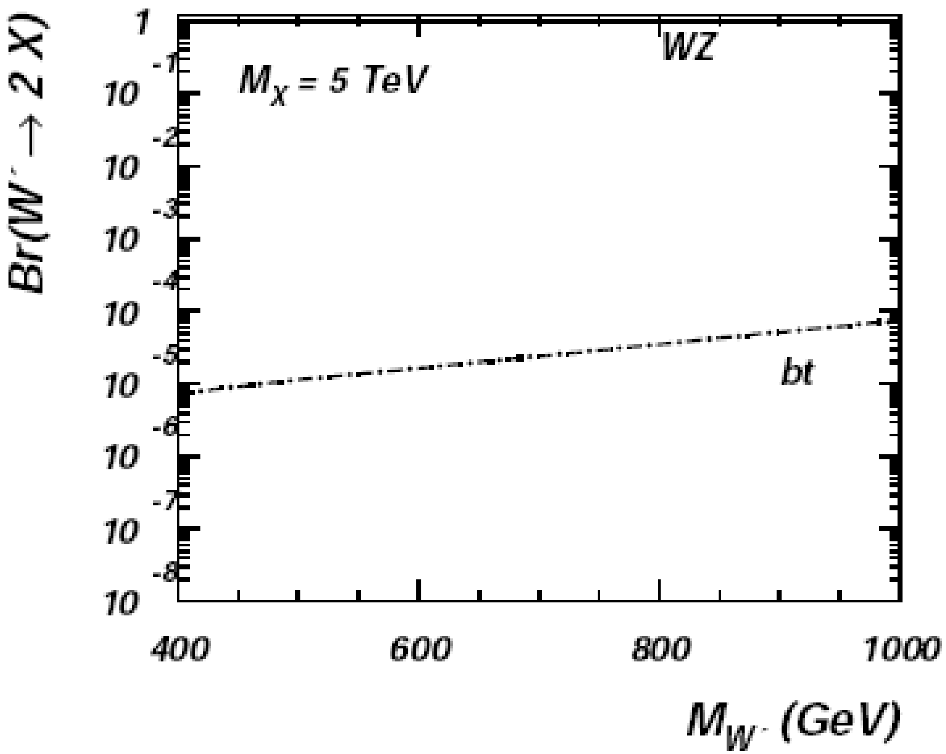
$$\Gamma(Z' \to W^+W^-) = \frac{e^2 M_{W'}}{192\pi x^2 s_w^2}$$

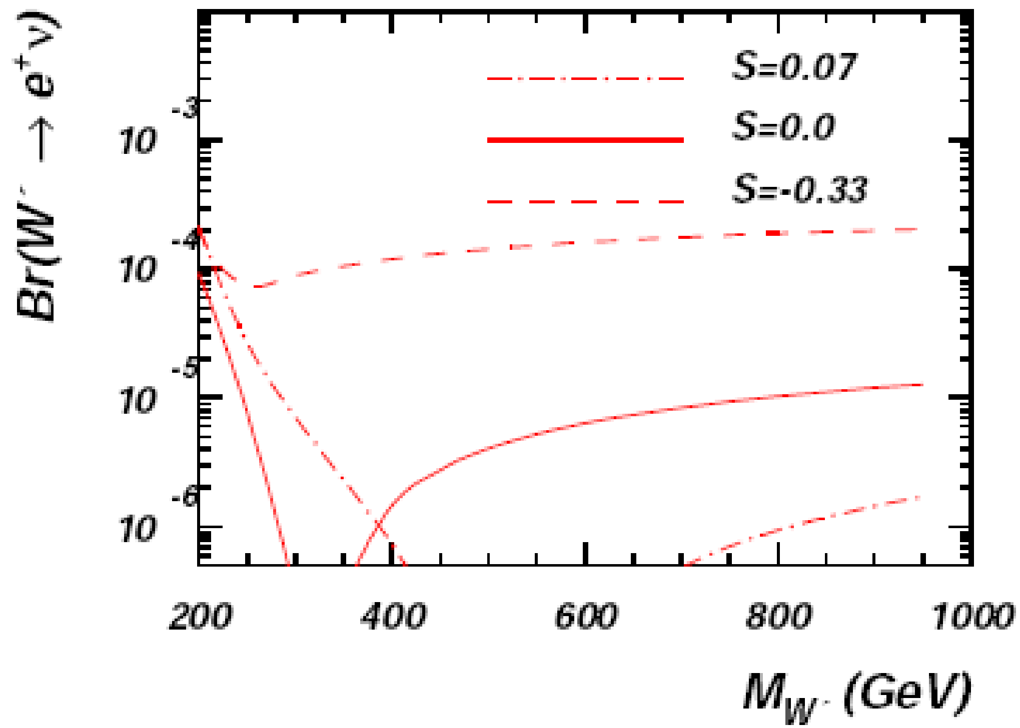
$$\Gamma(Z' \to e^+e^-) = \frac{5e^2 M_{W'} x^2 s_w^2}{384\pi c_w^4}$$



W' decays

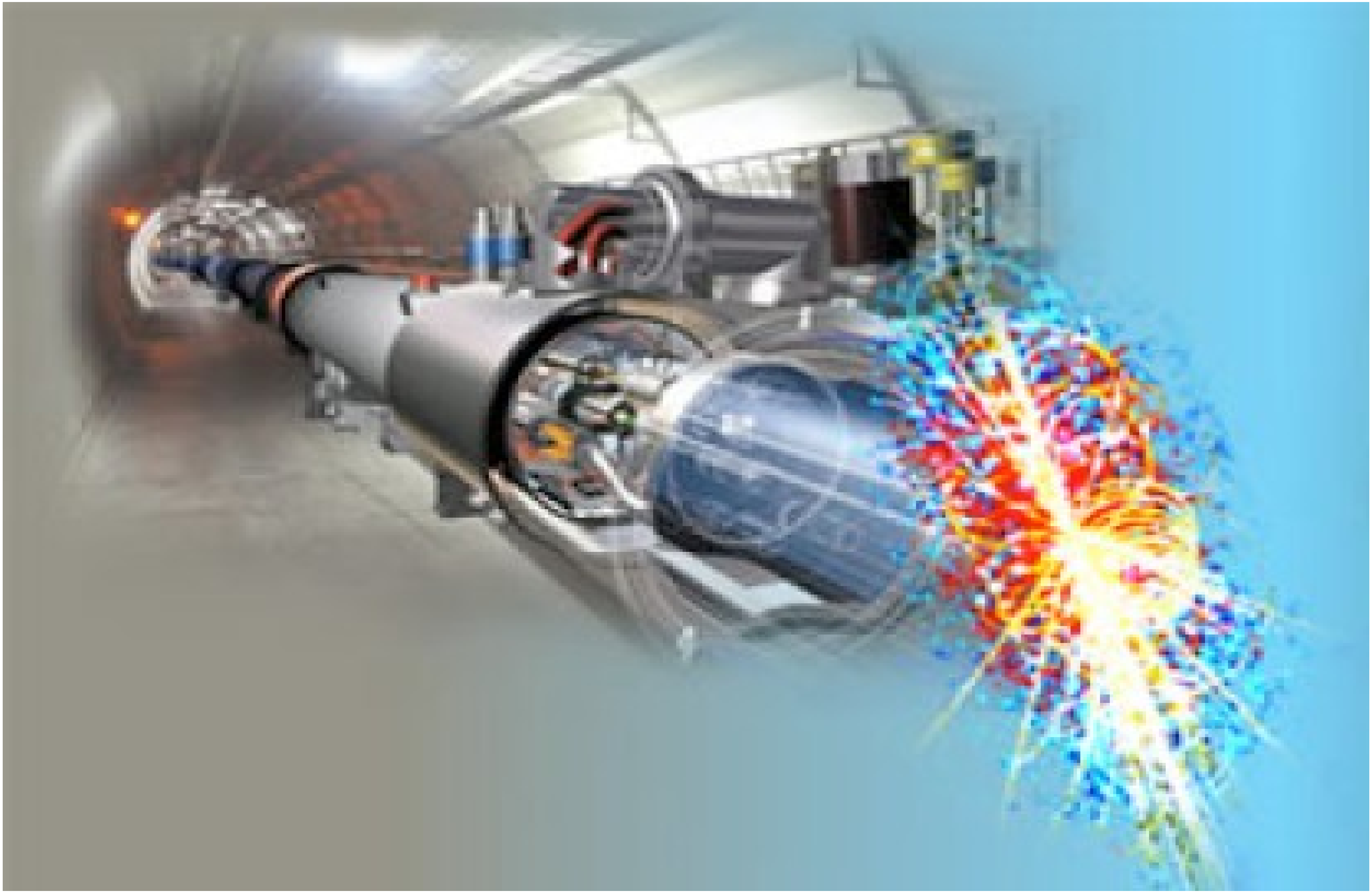
- **decay into fermions more strongly depends on fermion delocalization**





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

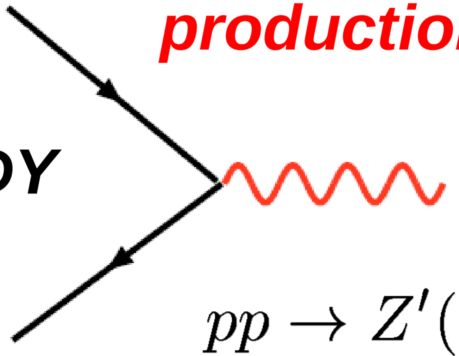
LHC SIGNATURES



Three Site Model Signatures

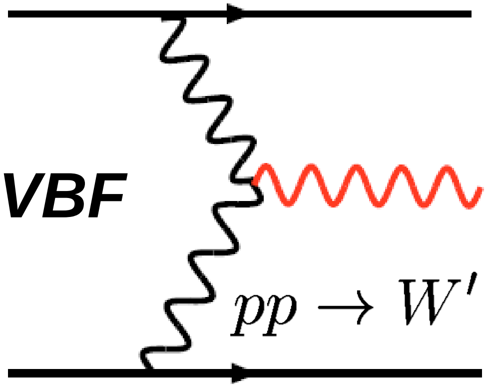
production

DY



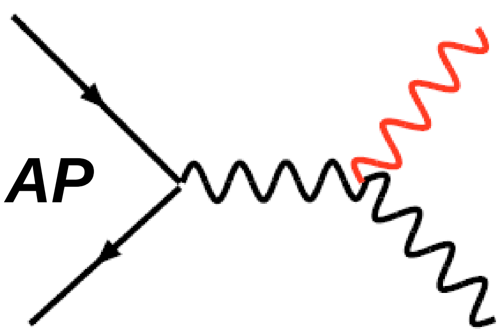
$pp \to Z'(W')$

VBF



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

AP

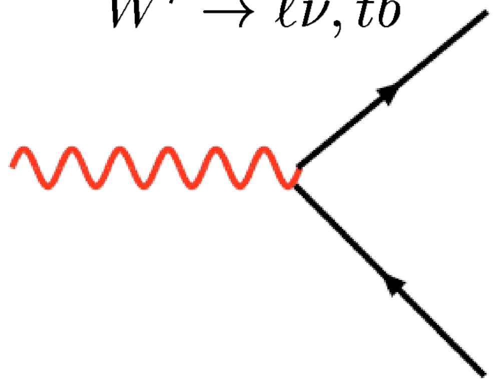


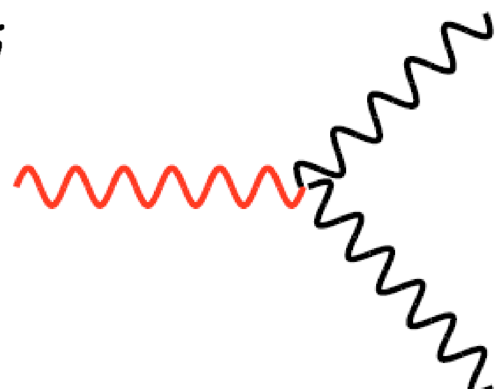
$pp \to WZ', WW', \ldots$

decay

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

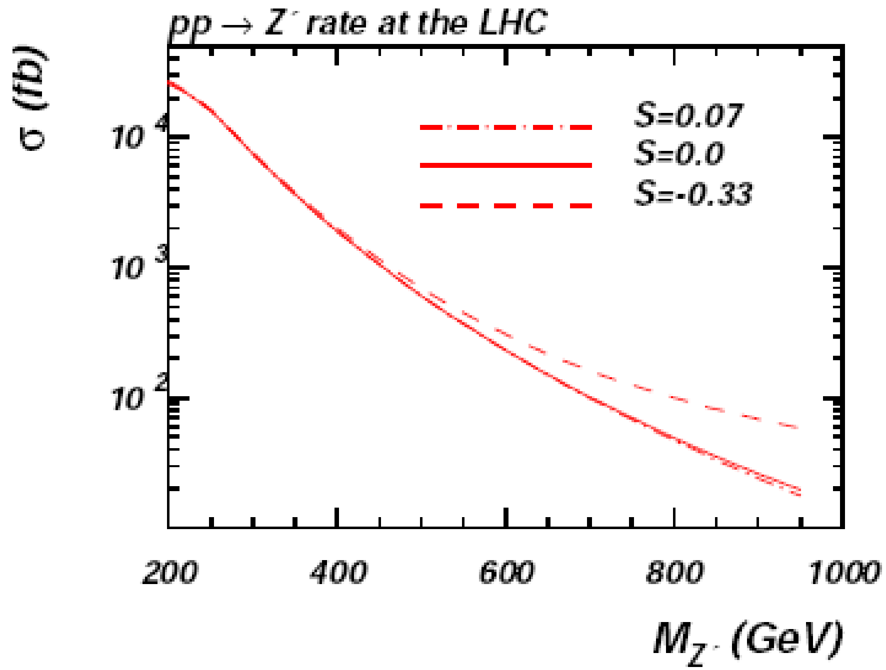
$W' \to \ell\nu, tb$

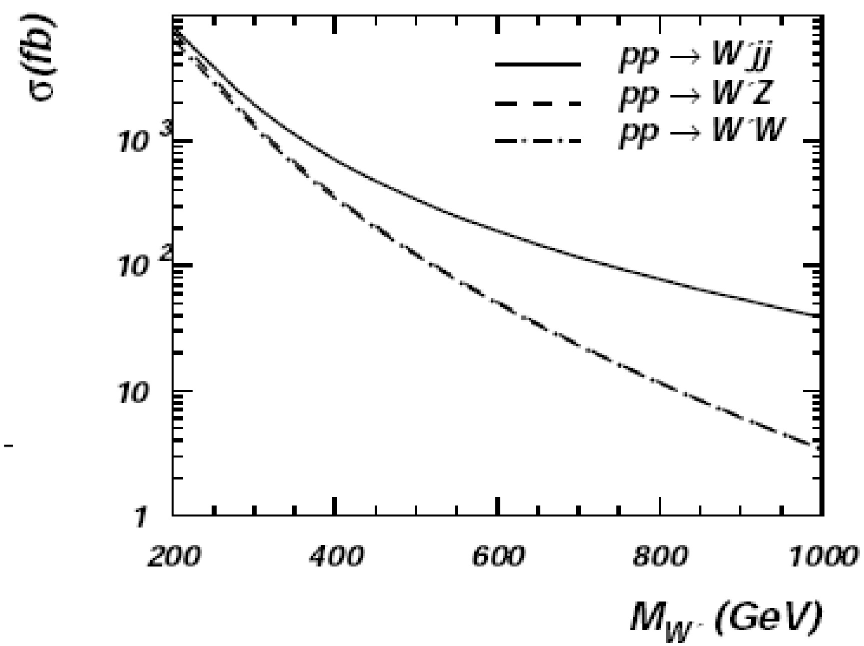




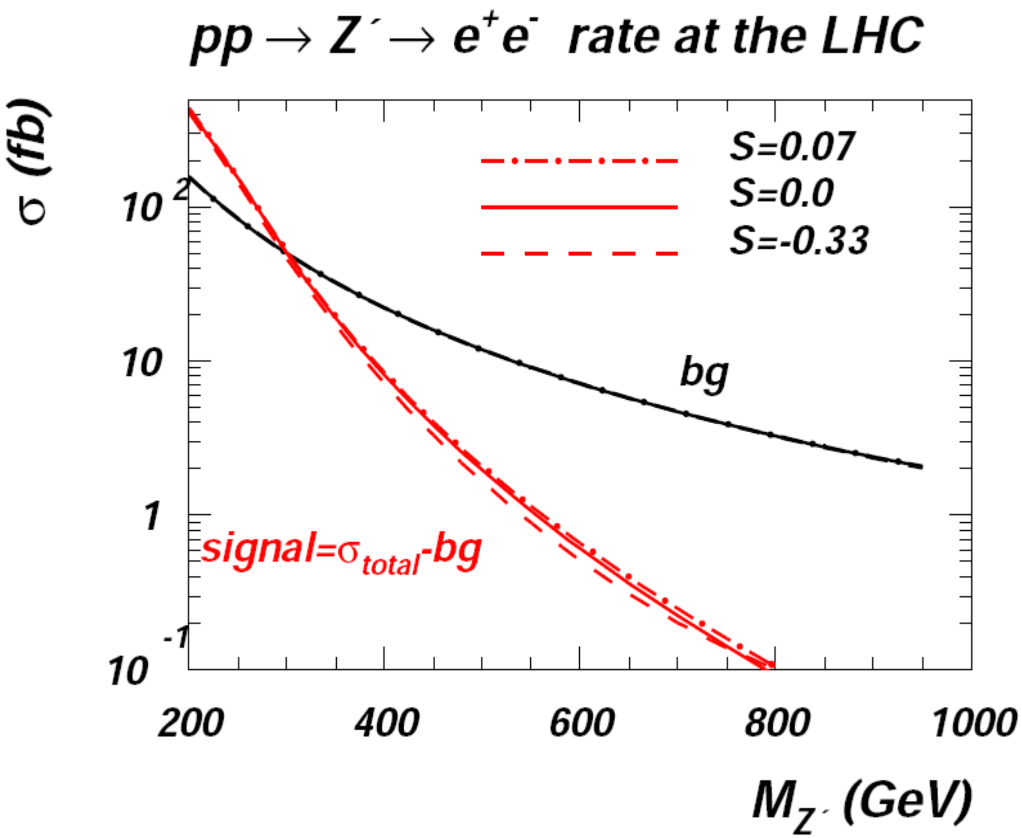
$Z' \to W^+W^- \to \ell^+\ell^-$

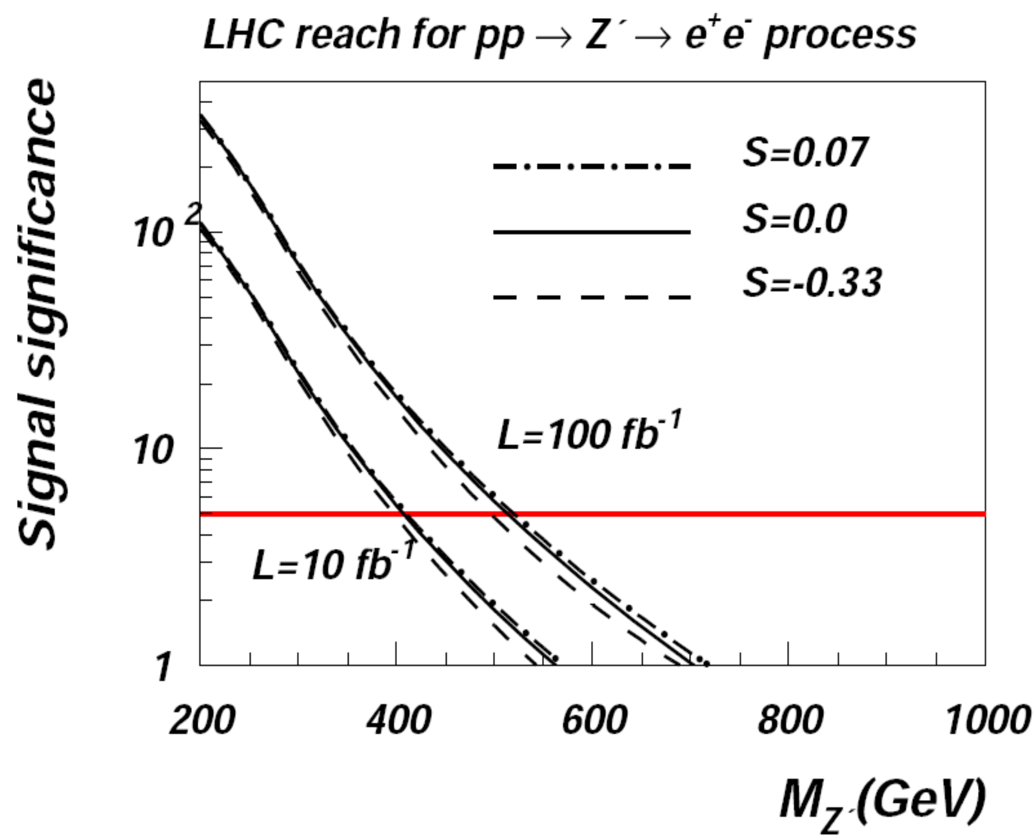
$W' \to WZ \to \ell\ell\ell\nu$





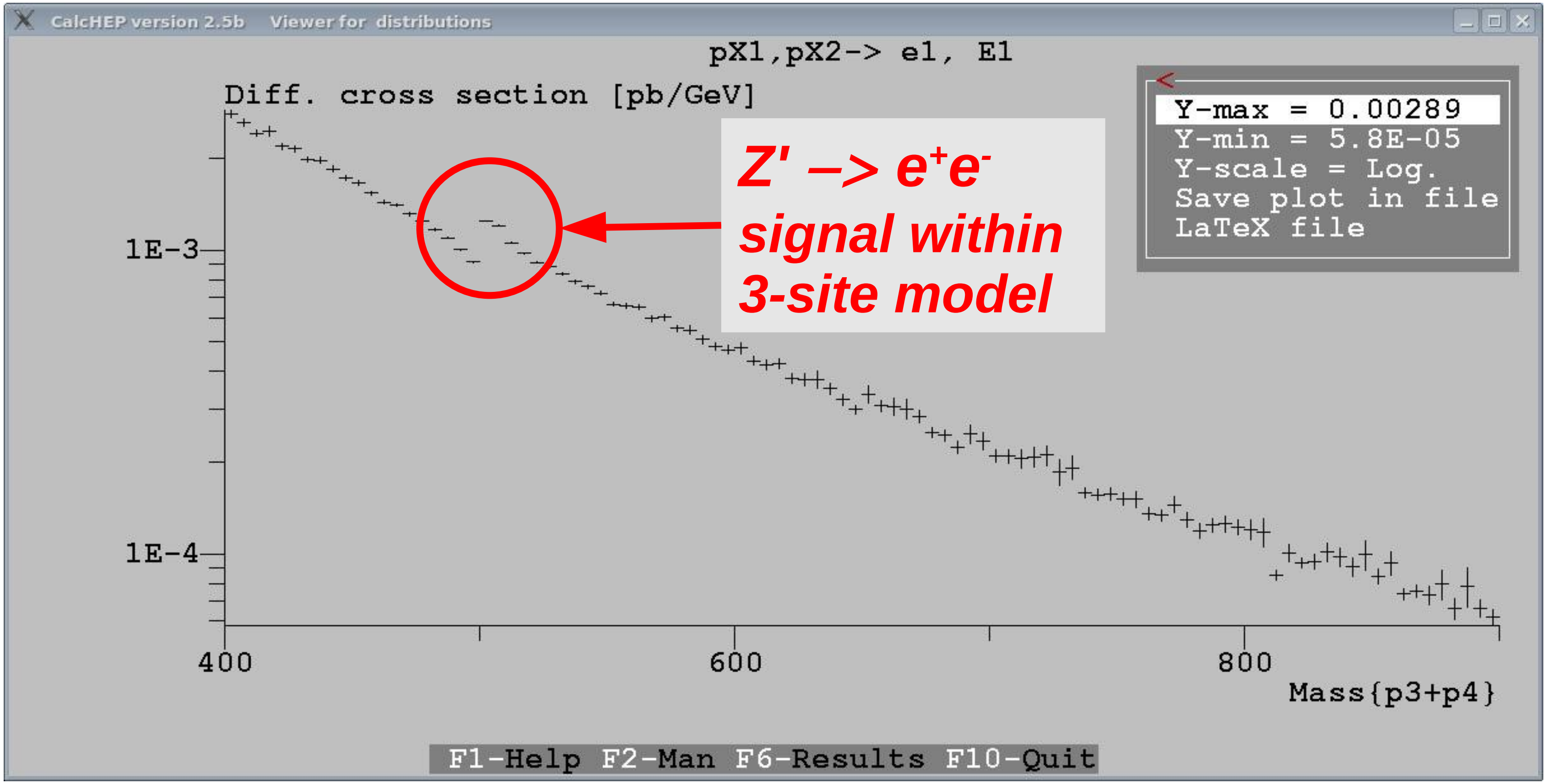
LHC reach for DY di-lepton signature





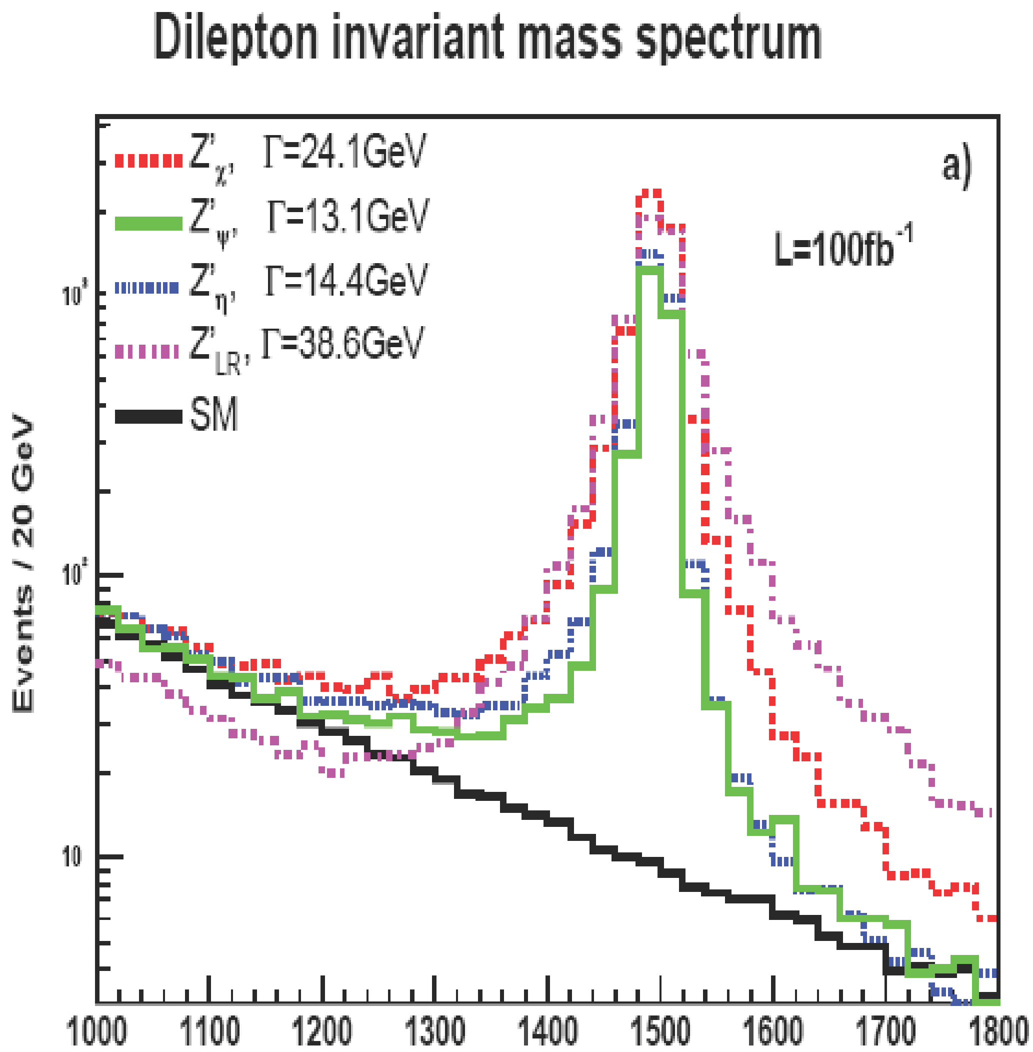
- Decay and production are suppressed by x^4 compared to 'usual' PYTHIA Z' model
- One should be prepared to face with this scenario with **very different Z'/W' features**

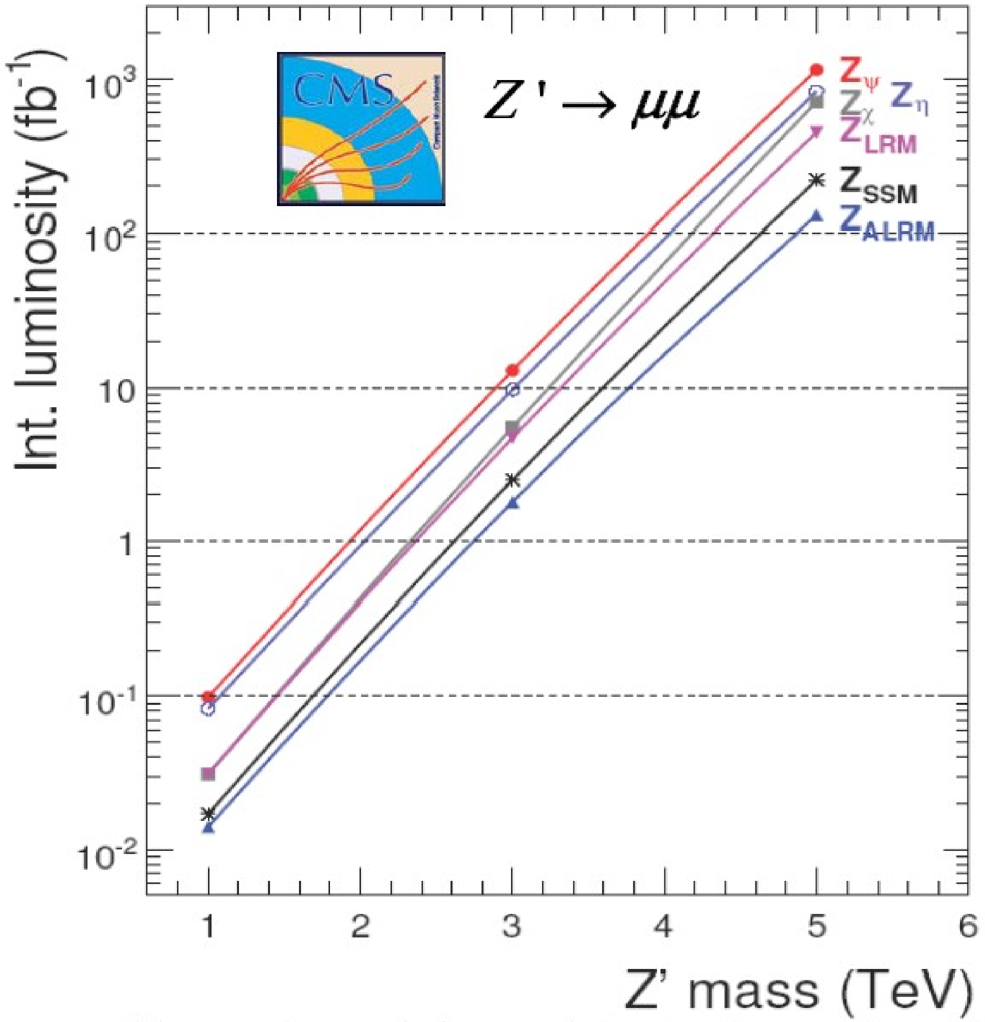
LHC reach for DY di-lepton signature



- Decay and production are suppressed by x^4 compared to SM-like Z' models
- 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**

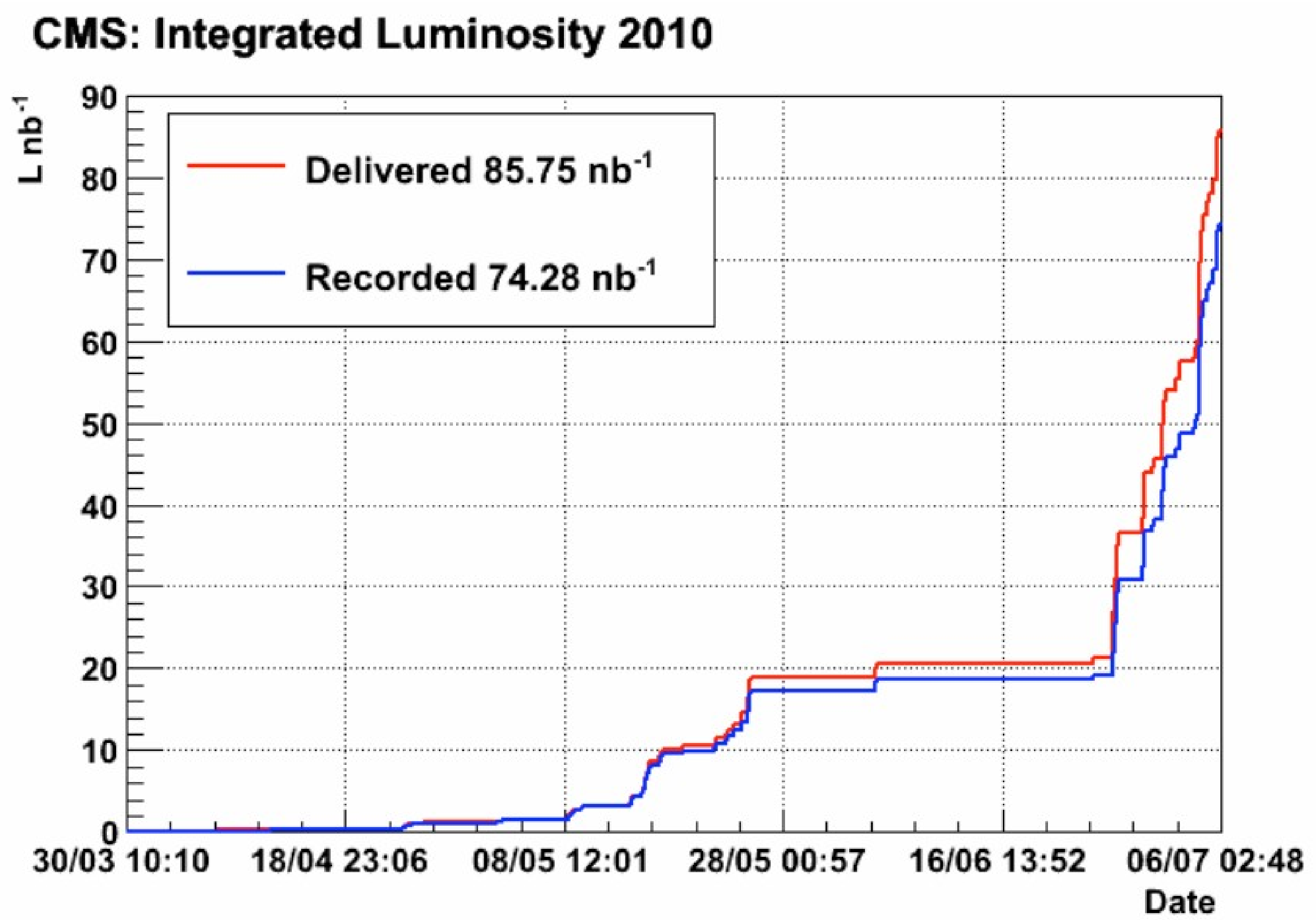
Could be a big surprise for experimentalists expecting charming DY dilepton signatures from Z' upto 5 TeV!



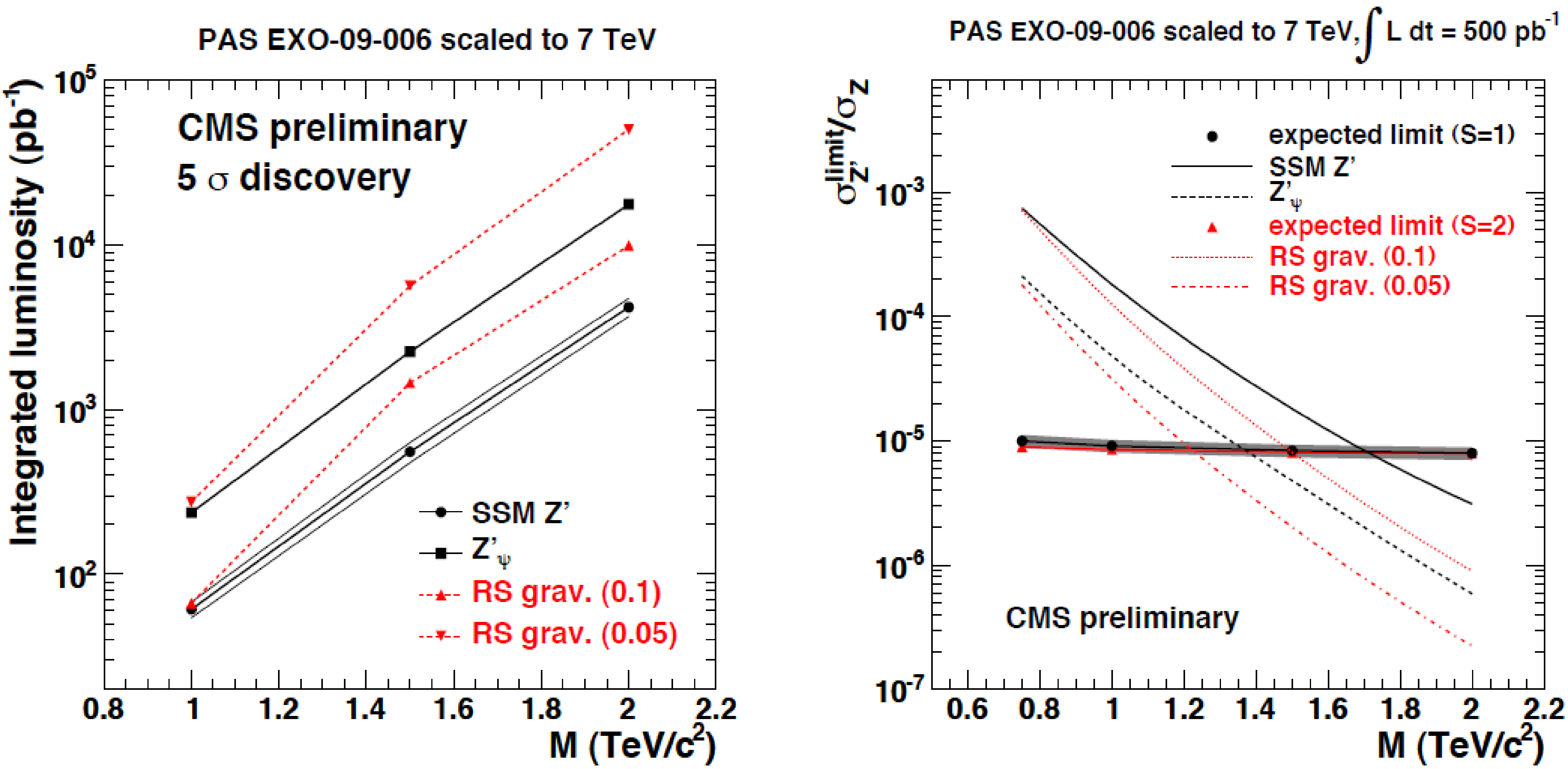


LHC status at @7TeV

- LHC has really started to deliver luminosity
  - Bunches ~1e11
  - Had L_{inst} of ~1e30 (only for 0.8h)
  - Currently running 10b4-2-4 (10 bunches, 4 colliding only in CMS)
  - Soon 12 bunches (8 colliding in CMS)
- Technical stop on July 17th to allow 24+ bunches



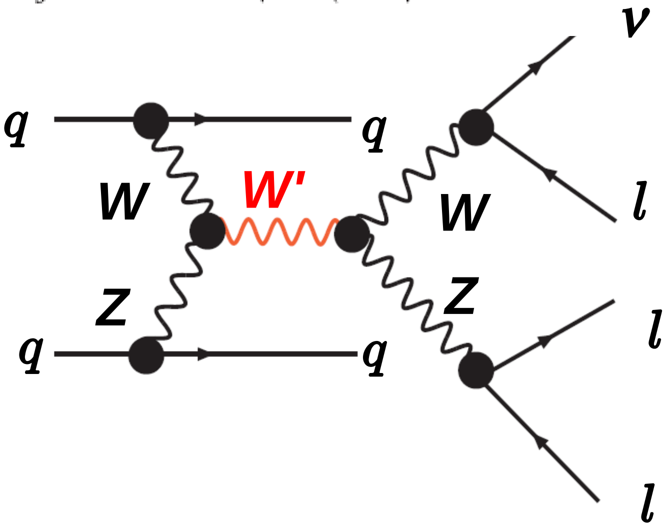
LHC projected potential @7TeV

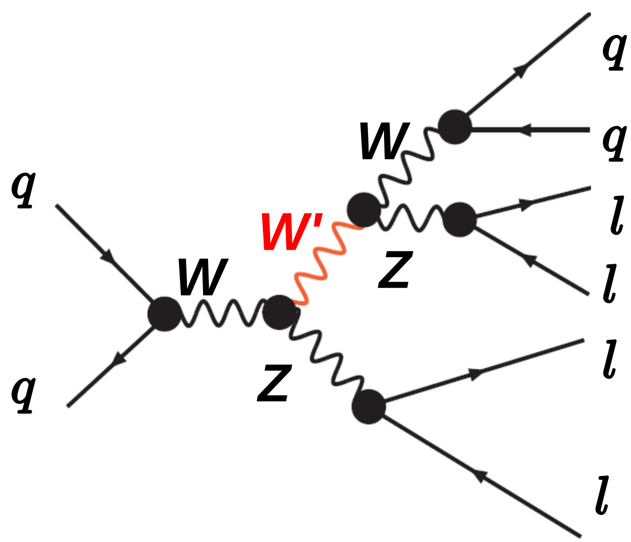


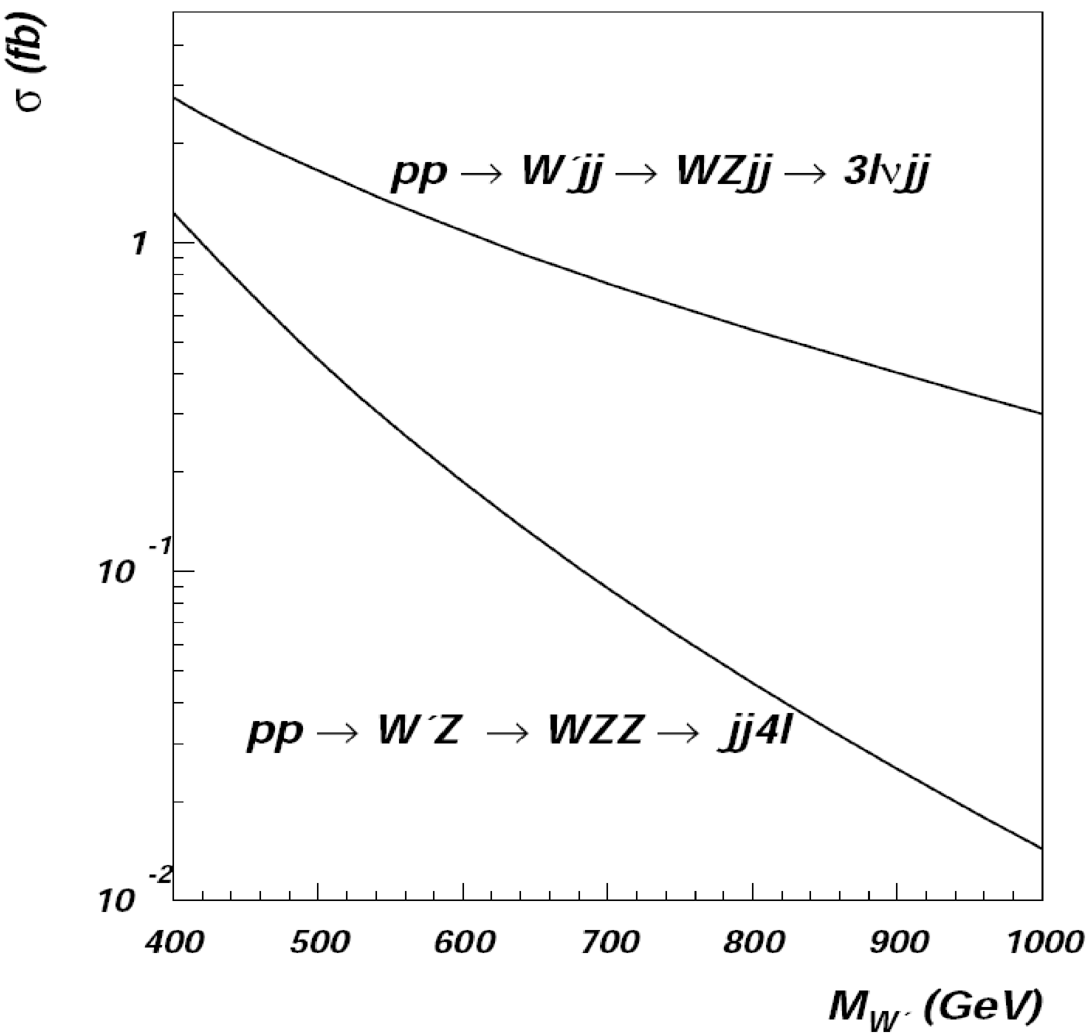
Vector-boson fusion WZ → W' and associate W'Z production are much more promising:
larger rates + clean signature

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

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







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

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

CalcHEP/symb

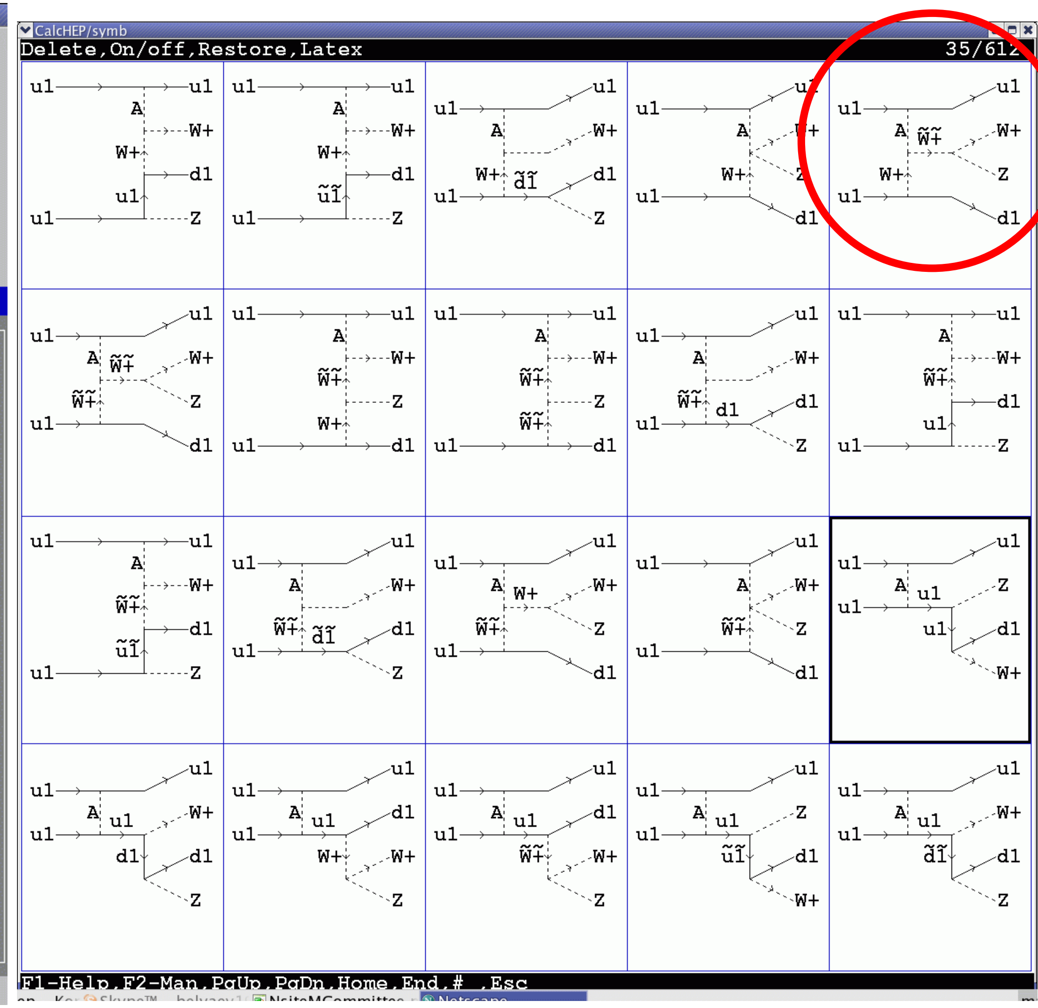
Model: 3-site-tfg

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

Feynman diagrams

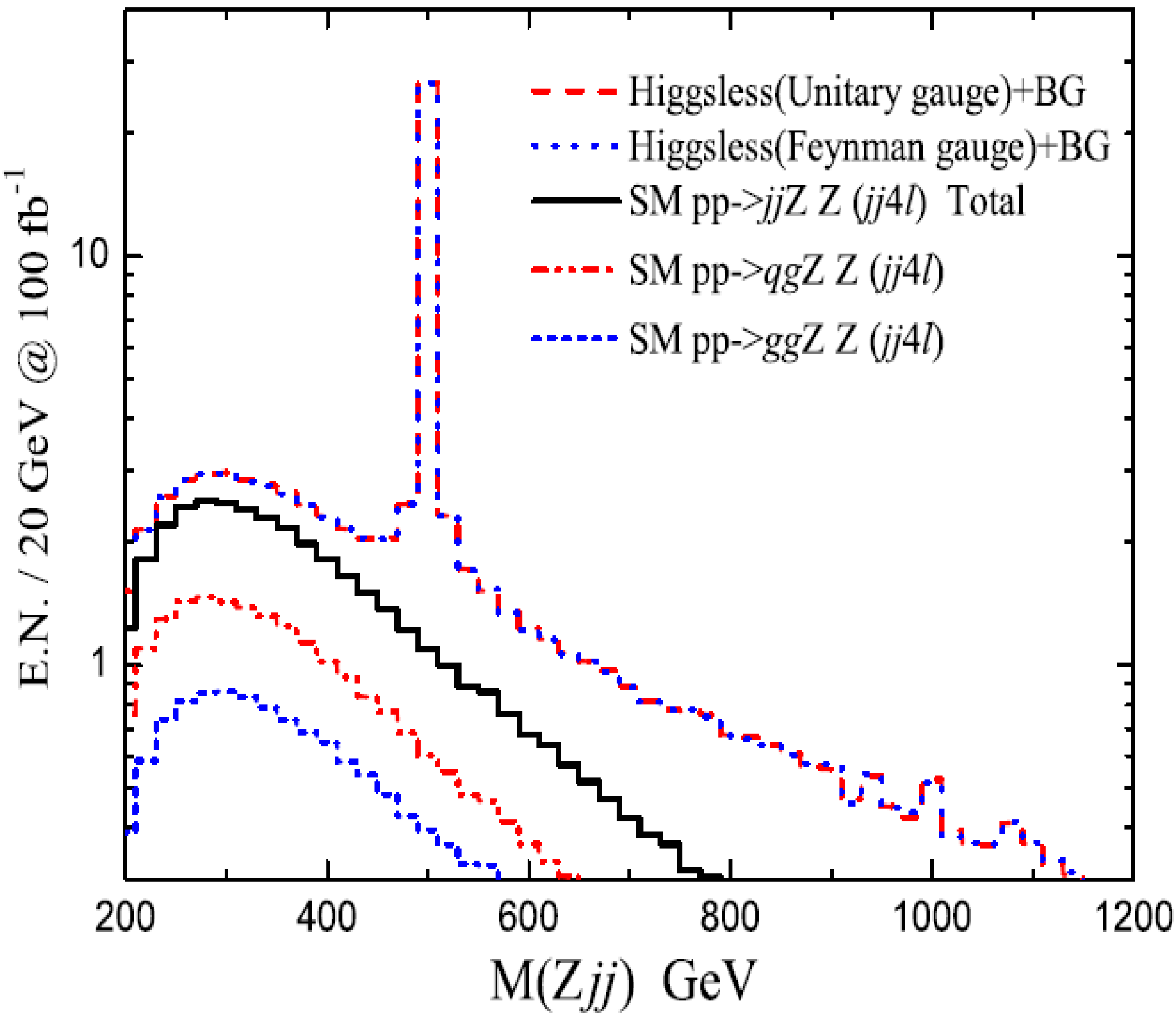
7816 diagrams in 21 subprocesses are constructed.
0 diagrams are deleted.

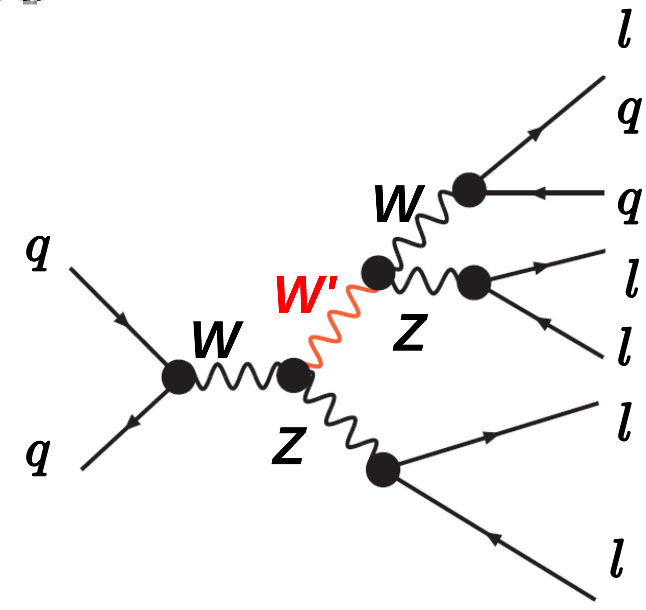
NN	Subprocess	Del	Rest
1	u1,u1 -> Z,W+,u1,d1	0	612
2	u1,U1 -> Z,W+,U1,d1	0	612
3	u1,d1 -> Z,W+,d1,d1	0	306
4	u1,D1 -> Z,W+,u1,U1	0	612
5	u1,D1 -> Z,W+,d1,D1	0	612
6	u1,D1 -> Z,W+,G,G	0	46
7	u1,G -> Z,W+,G,d1	0	76
8	U1,u1 -> Z,W+,U1,d1	0	612
9	U1,D1 -> Z,W+,U1,U1	0	306
10	d1,u1 -> Z,W+,d1,d1	0	306
11	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



$$pp \to W'^{(*)} Z \to WZZ \to jj\,\ell^+\ell^-\ell^+\ell^-$$

[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]



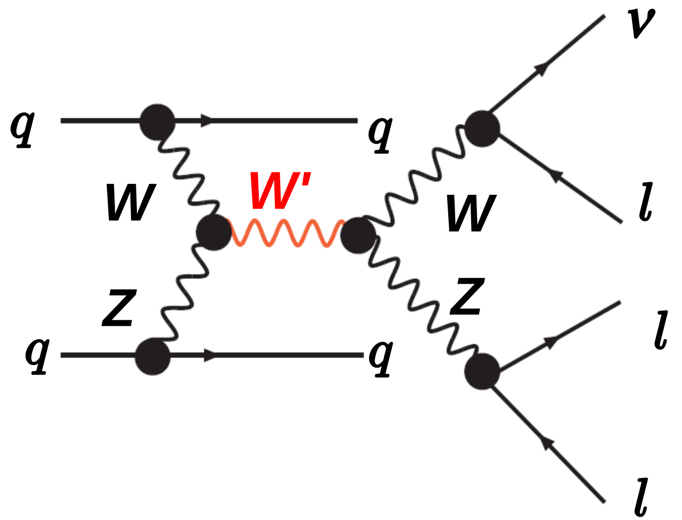


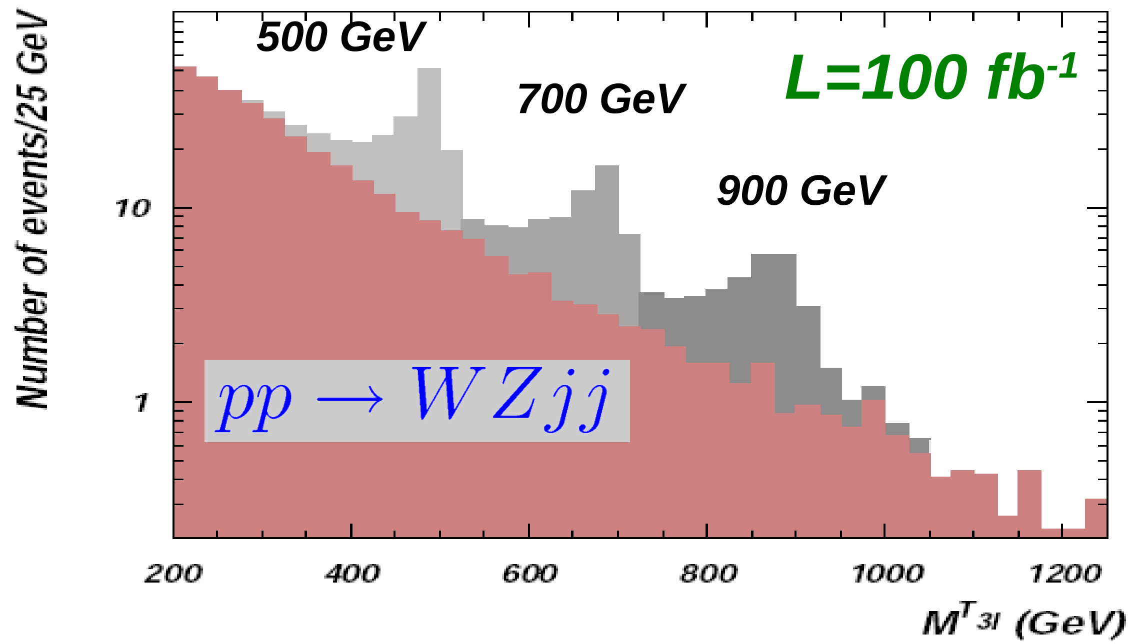
$$p_{T\ell} > 10\,\text{GeV}, \qquad |\eta_\ell| < 2.5$$
$$p_{Tj} > 15\,\text{GeV}, \qquad |\eta_j| < 4.5$$

$$M_{jj} = 80 \pm 15\,\text{GeV}, \qquad \Delta R(jj) < 1.5$$
$$\sum_Z p_T(Z) + \sum_j p_T(j) = \pm 15\,\text{GeV}.$$

LHC reach for WZ->W' process

[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]





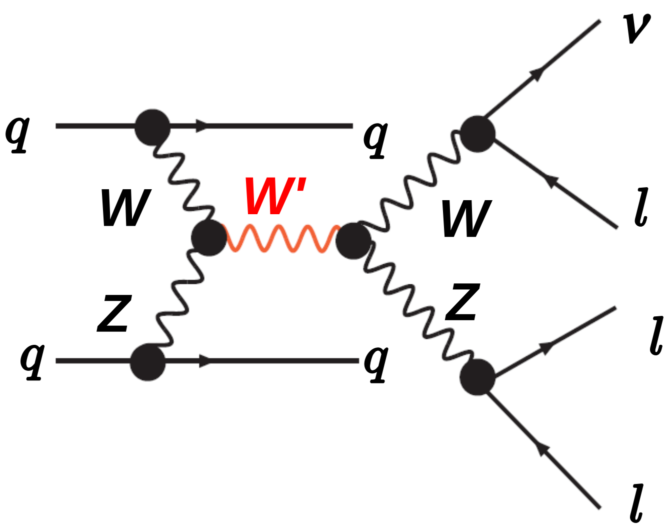
the complete WZjj BG is factor 4 bigger then PYTHIA effective V-boson approximation!

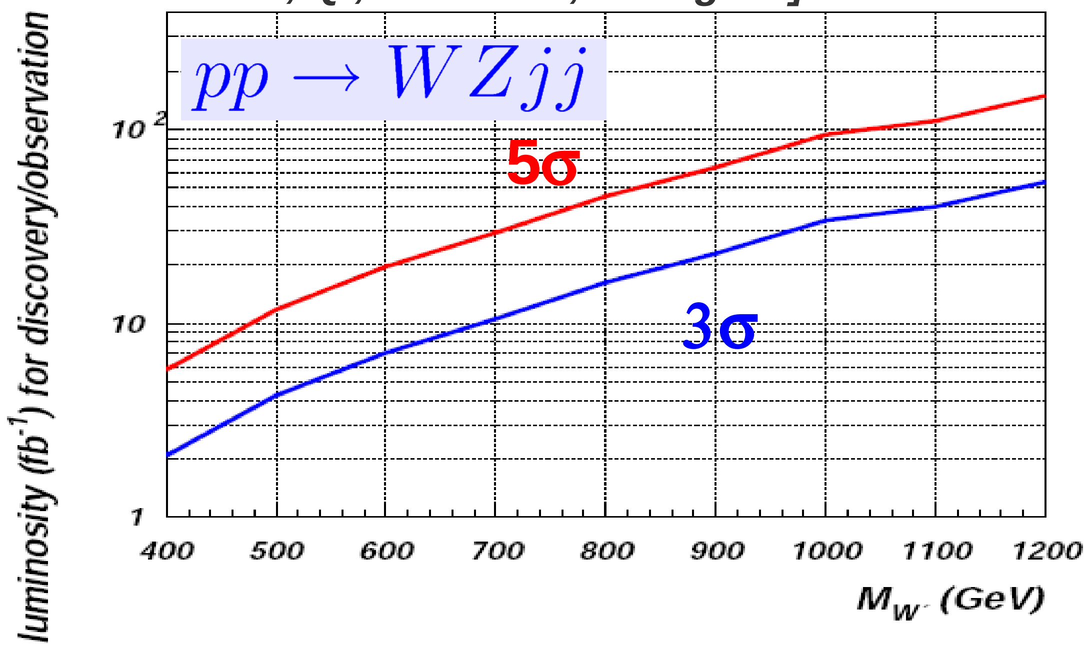
$$E_j > 300 \text{ GeV}$$
$$p_{Tj} > 30 \text{ GeV}$$
$$|\eta_j| < 4.5$$
$$|\Delta\eta(jj)| > 4$$
$$p_{T\ell} > 15 \text{ GeV}$$
$$|\eta_\ell| < 2.5$$
$$0.85 M_{W'} < M_T < 1.05 M_{W'}$$

To be compared with Birkedal, Matchev, Perelstein '05

LHC reach for WZ->W' process

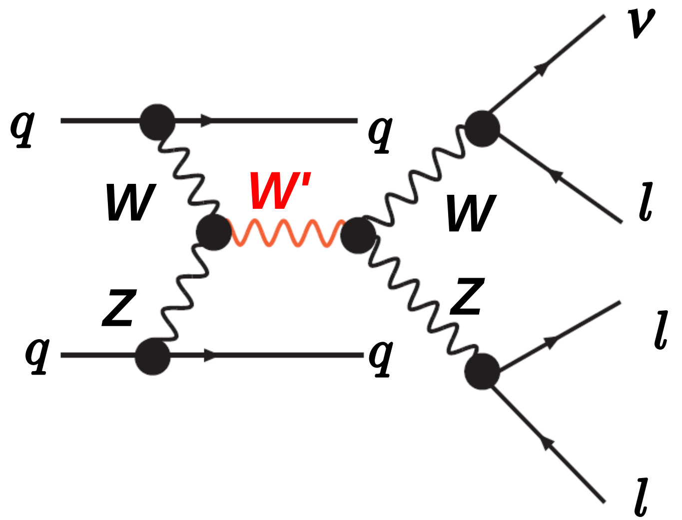
[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]

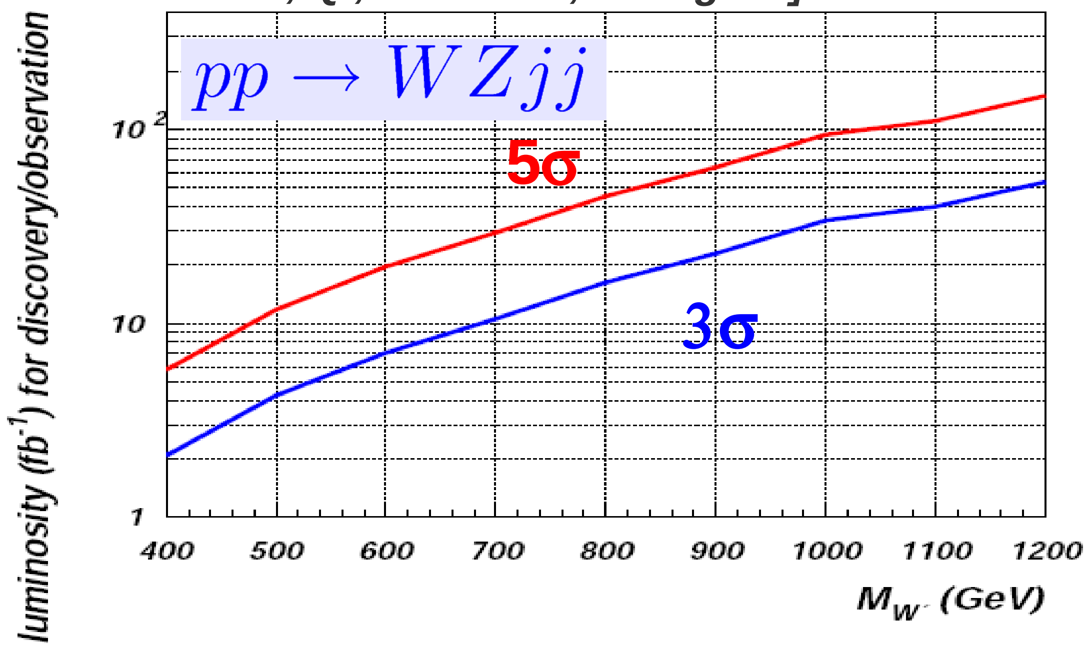




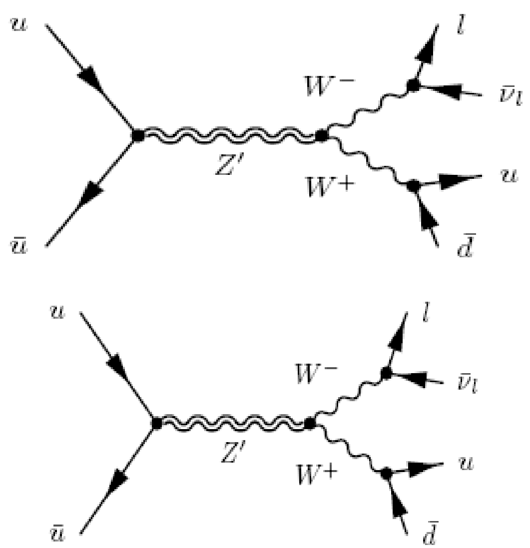
LHC reach for WZ->W' process

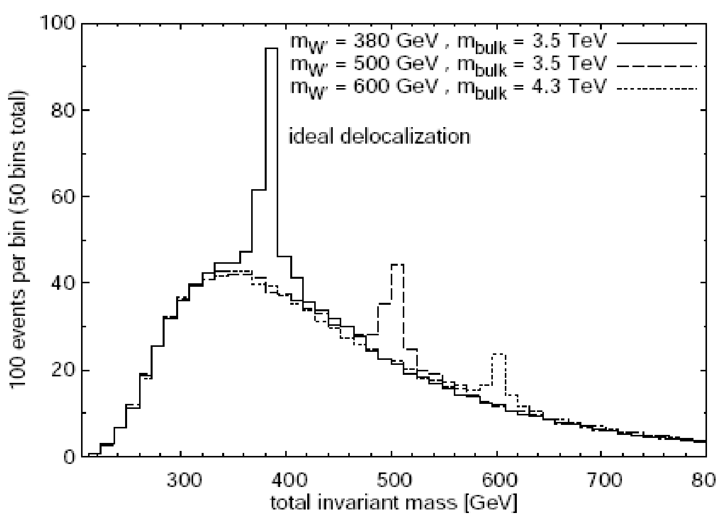
[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]

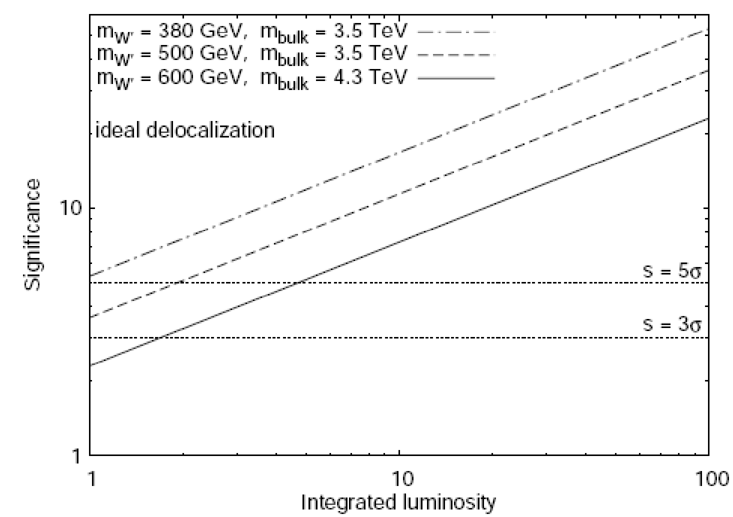




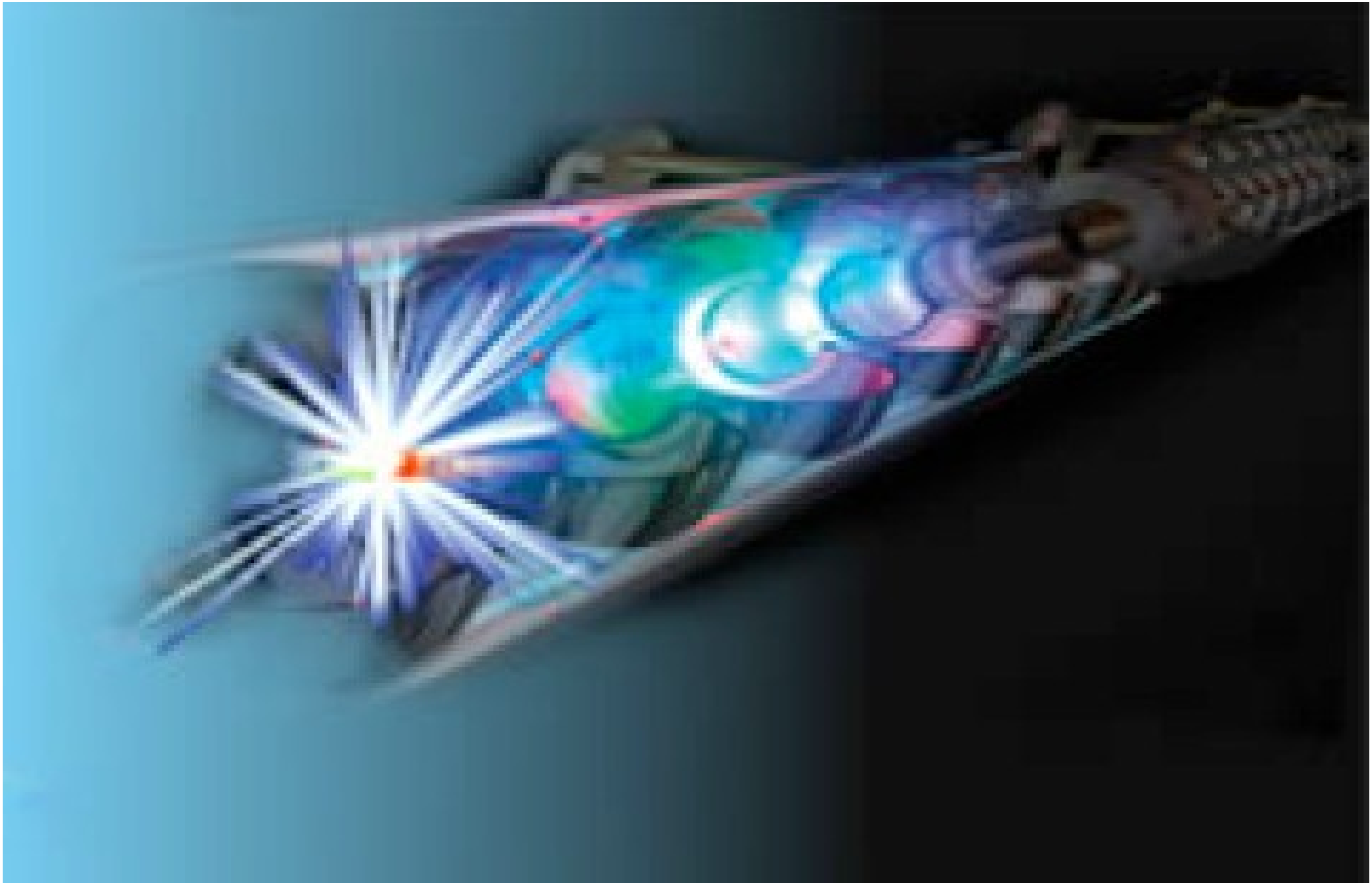
LHC reach for s-channel Z' and W' [Ohl,Speckner '08]







ILC PHENOMENOLOGY



ILC potential

clean environment and precision measurements
[e.g. see Ohl, Djouadi, ... talks]

- ***precision gauge boson couplings measurement** will allow to establish sum rules*

$$g_{\rm WWWW} = g^2_{\rm WWZ} + g^2_{\rm WW\gamma} + \sum_i (g^{(i)}_{\rm WWV})^2,$$

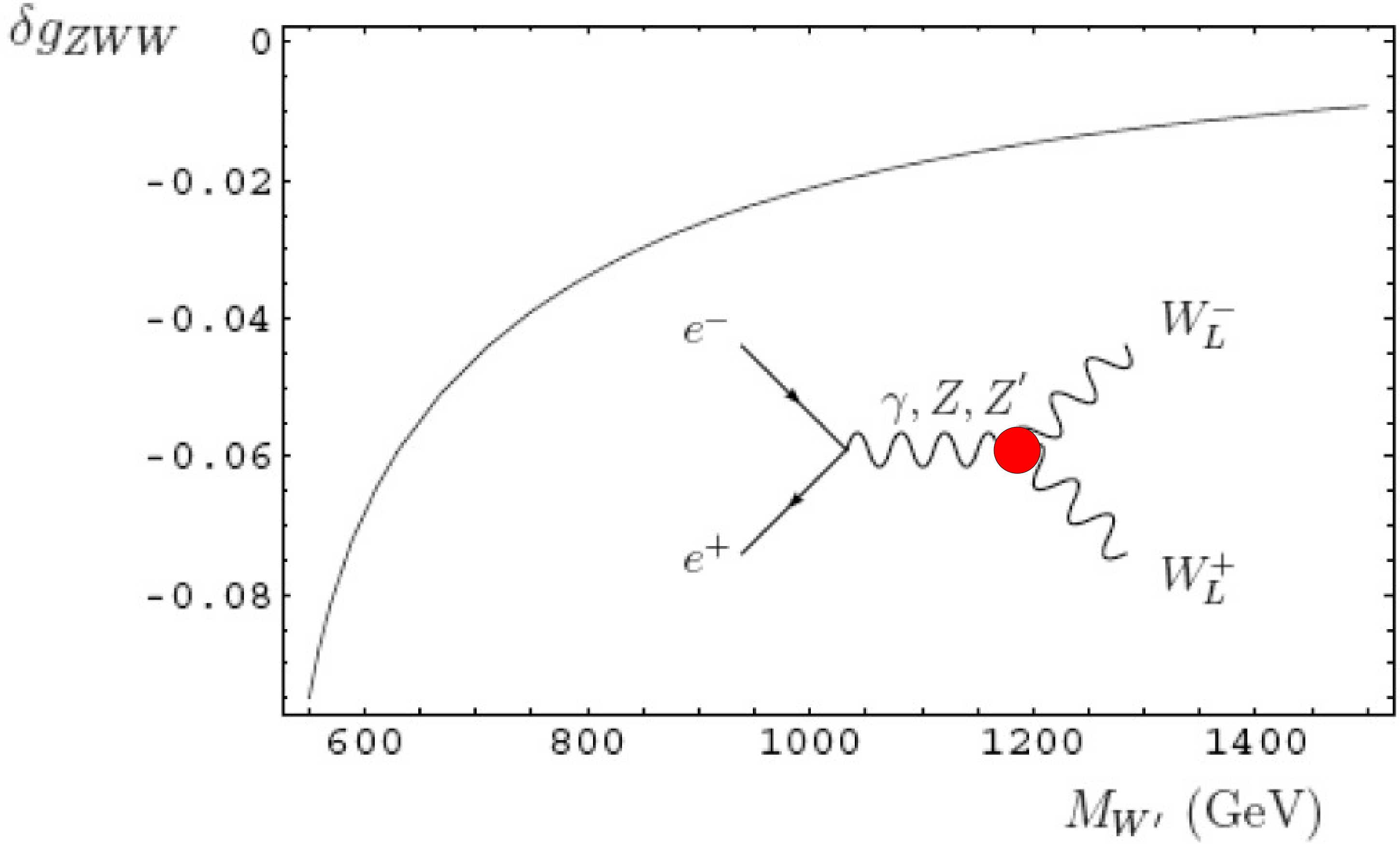
$$4 g_{\rm WWWW} M^2_{\rm W} = 3 \left[g^2_{\rm WWZ} M^2_{\rm Z} + \sum_i (g^{(i)}_{\rm WWV})^2 \, (M^0_i)^2 \right]$$

- ***high mass resolution** will allow to perform spectroscopy of new accessible resonances expected to be below 1 TeV*

- ***has indirect sensitivity to larger mass scale than LHC***

- ***dominant hadronic decay modes** can be used now – W' mass can be fully reconstructed*

Prospects for ILC@ 0.5 TeV: g_{WWZ}

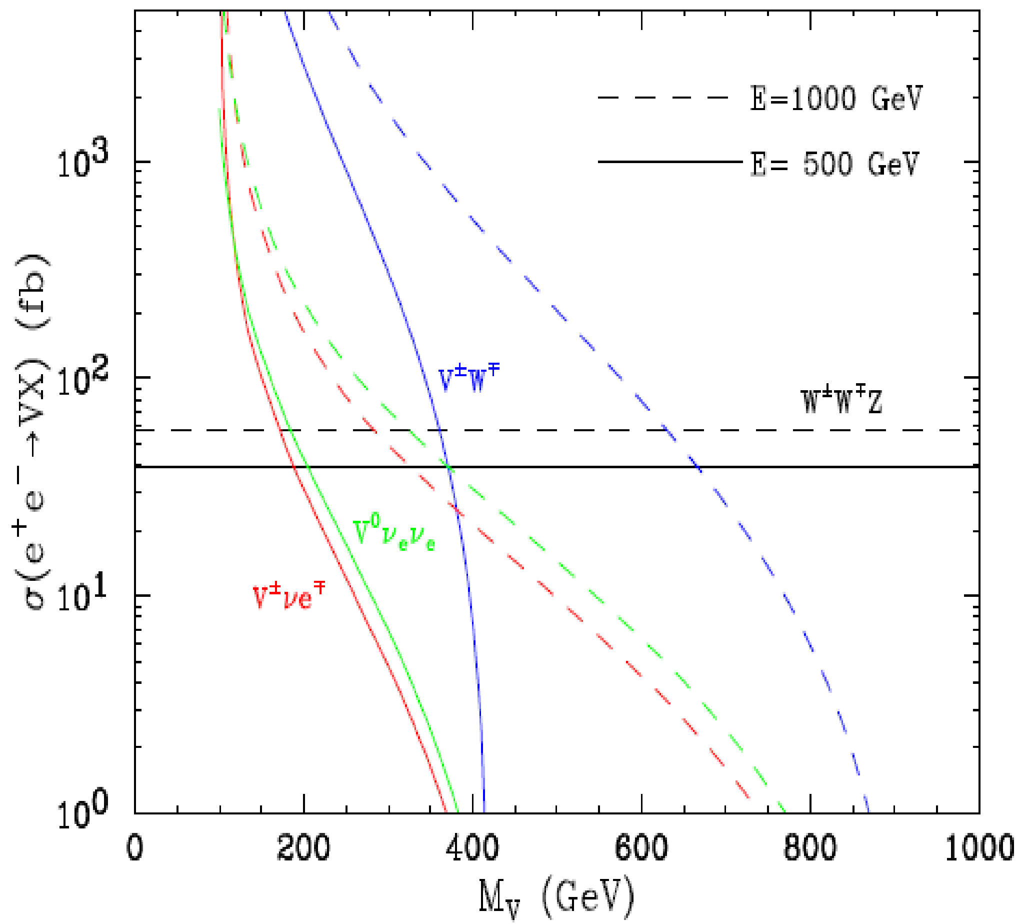


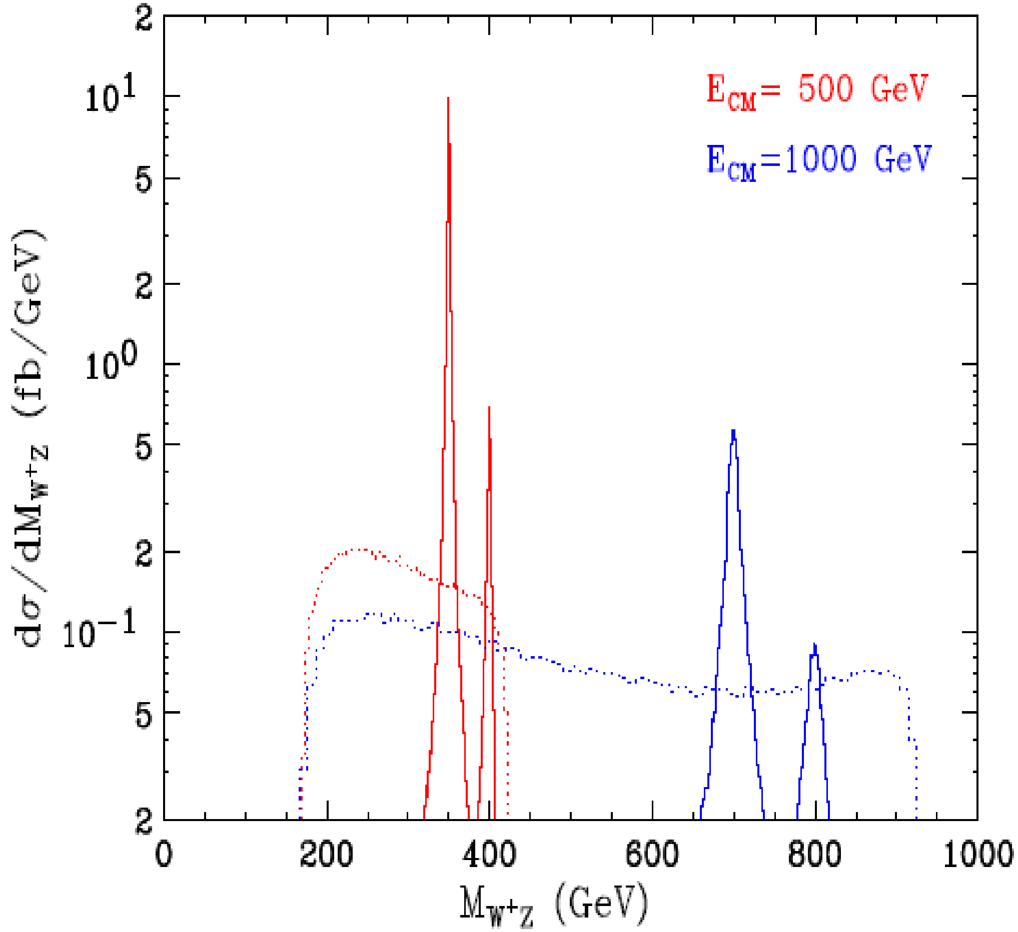
$$\delta g_{ZWW} = \frac{g_{\chi Zee}\, g_{ZWW}}{g_{\chi Zee_{SM}}\, g_{ZWW_{SM}}} + \frac{g_{\chi Z'ee}\, g_{Z'WW}}{g_{\chi Zee_{SM}}\, g_{ZWW_{SM}}} \frac{s - M_Z^2}{s - M_{Z'}^2} - 1$$

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

hep-ex/0106057 American LC Working Group

W' production at the ILC via VBF





Birkedal, Matchev, Perelstein '05

Beyond the 3-site model

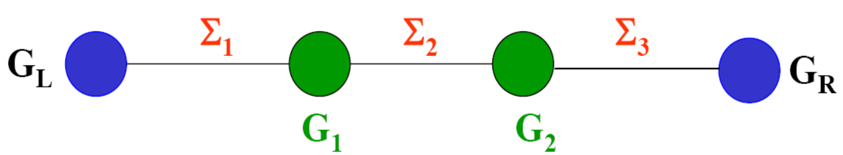
there is an increasing progress in Higgsless models and Technicolor models

see e.g. recent talks at "Dynamical Electroweak Symmetry Breaking", Sep '08, Denmark

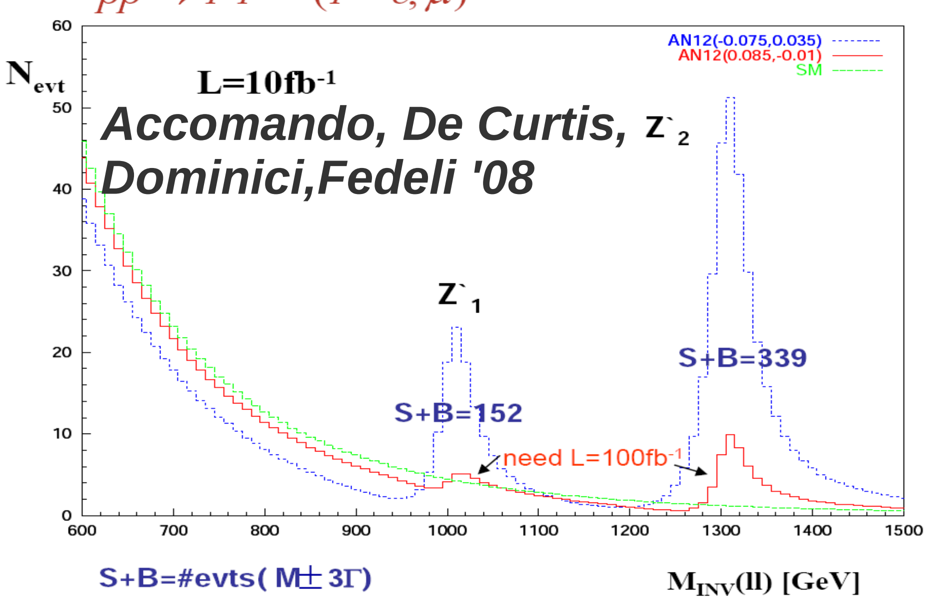
equivalent description on the languages of Deconstructon and Technicolor
[Barbieri, Isidori, Rychkov,Trincherini '08]

The Higgsless 4-site Linear Moose model

[see talk by Dominici]



$pp \to l^+ l^- \quad (l = e, \mu)$



equivalent to

Next to Minimal Walking Technicolor (NMWT)

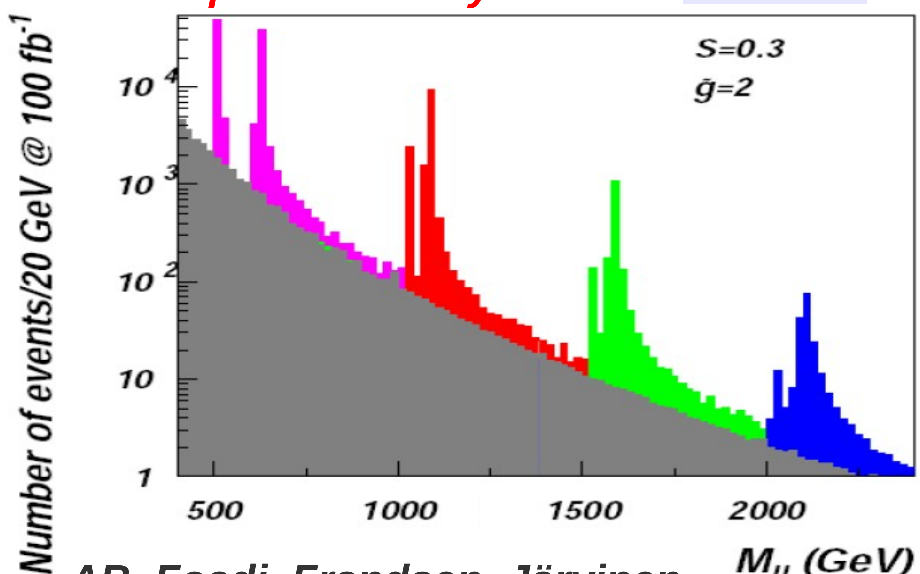
$N_c = 3$, $N_f = 2$

in the two-index symmetric

$SU(2)_L$ X $SU(2)_R$ –> $SU(2)_V$

two triplets of heavy mesons

$R_1^{\pm}(R_2^{\pm})$ **and** $R_1^0(R_2^0)$



AB, Foadi, Frandsen, Järvinen, Pukhov, Sannino '08

Z' is not necessarily fermiophobic! *Complementarity of DY di-lepton and di-boson channels*

Effective Lagrangian for SU(2)$_L$ X SU(2)$_R$ to order O(p^2)

$$\mathcal{L}_{\rm boson} = -\frac{1}{2}{\rm Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}\widetilde{B}_{\mu\nu}\widetilde{B}^{\mu\nu} - \frac{1}{2}{\rm Tr}\left[F_{{\rm L}\mu\nu}F_{\rm L}^{\mu\nu} + F_{{\rm R}\mu\nu}F_{\rm R}^{\mu\nu}\right]$$

$$\mathcal{L}_{\rm Higgs} = \frac{\mu^2}{2}{\rm Tr}\left[MM^\dagger\right] - \frac{\lambda}{4}{\rm Tr}\left[MM^\dagger\right]^2$$

$\widetilde{W}_{\mu\nu}$ and $\widetilde{B}_{\mu\nu}$ are EW filed strength tensors

$F_{{\rm L/R}\mu\nu}$ are the field strength tensors associated to the vector meson fields $A_{{\rm L/R}\mu}$

2x2 Matrix $M = \frac{1}{\sqrt{2}}\left[v + H + 2\ i\ \pi^a\ T^a\right]\ , \qquad a = 1,2,3$

Covariant derivative $D_\mu M = \partial_\mu M - i\ g\ \widetilde{W}^a_\mu\ T^a M + i\ g'\ M\ \widetilde{B}_\mu\ T^3$

Effective Lagrangian for SU(2)$_L$ X SU(2)$_R$ to order O(p^2)

$$
\begin{aligned}
& \mathcal{L}_{\text{Higgs}-\text{Vector}} = m^2 \ \text{Tr}\left[C_{\text{L}\mu}^2 + C_{\text{R}\mu}^2\right] \\
+ \quad & \frac{1}{2}\text{Tr}\left[D_\mu M D^\mu M^\dagger\right] - \tilde{g}^2 \ r_2 \ \text{Tr}\left[C_{\text{L}\mu} M C_{\text{R}}^\mu M^\dagger\right] \\
- \quad & \frac{i \ \tilde{g} \ r_3}{4}\text{Tr}\left[C_{\text{L}\mu}\left(M D^\mu M^\dagger - D^\mu M M^\dagger\right) + C_{\text{R}\mu}\left(M^\dagger D^\mu M - D^\mu M^\dagger M\right)\right] \\
+ \quad & \frac{\tilde{g}^2 s}{4}\text{Tr}\left[C_{\text{L}\mu}^2 + C_{\text{R}\mu}^2\right] \text{Tr}\left[M M^\dagger\right]
\end{aligned}
$$

$$
C_{\text{L}\mu} \equiv A_{\text{L}\mu} - \frac{g}{\tilde{g}}\widetilde{W_\mu} \ , \quad C_{\text{R}\mu} \equiv A_{\text{R}\mu} - \frac{g'}{\tilde{g}}\widetilde{B_\mu} \ .
$$

NMWT parameter space and particle content

- ***fixing S=0.3 ~ S_{pert} and using WSR parameter space is reduced to*** $M_A,\ \tilde{g},\ s,\ M_H$

$$S = \frac{8\pi}{\tilde{g}^2}\left(1-\chi^2\right)\ ,$$

$$r_2 = r_3 - 1\ .$$

$$\chi \equiv 1 - \frac{v^2\ \tilde{g}^2\ r_3}{4M_A^2}$$

- $s,\ M_H$ ***have sizable effect in the process involving composite Higgs***

- ***new particles – two triplets of heavy mesons:***

  $R_1^{\pm}(R_2^{\pm})$ ***and*** $R_1^0(R_2^0)$

Walking Technicolor and S-parameter

Perturbative S reads as: $$S_{\rm pert} = \frac{N_D}{6\pi}$$

N_c=2 case

*Conformal window condition for the **fundamental** representation* $$N_f \simeq 8 \Longrightarrow S_{\rm pert} \simeq 0.42$$

*Conformal window condition for the **adjoint** representation* $$N_f \simeq 2 \Longrightarrow S_{\rm pert} \simeq 0.16$$

Small N_f is preferred

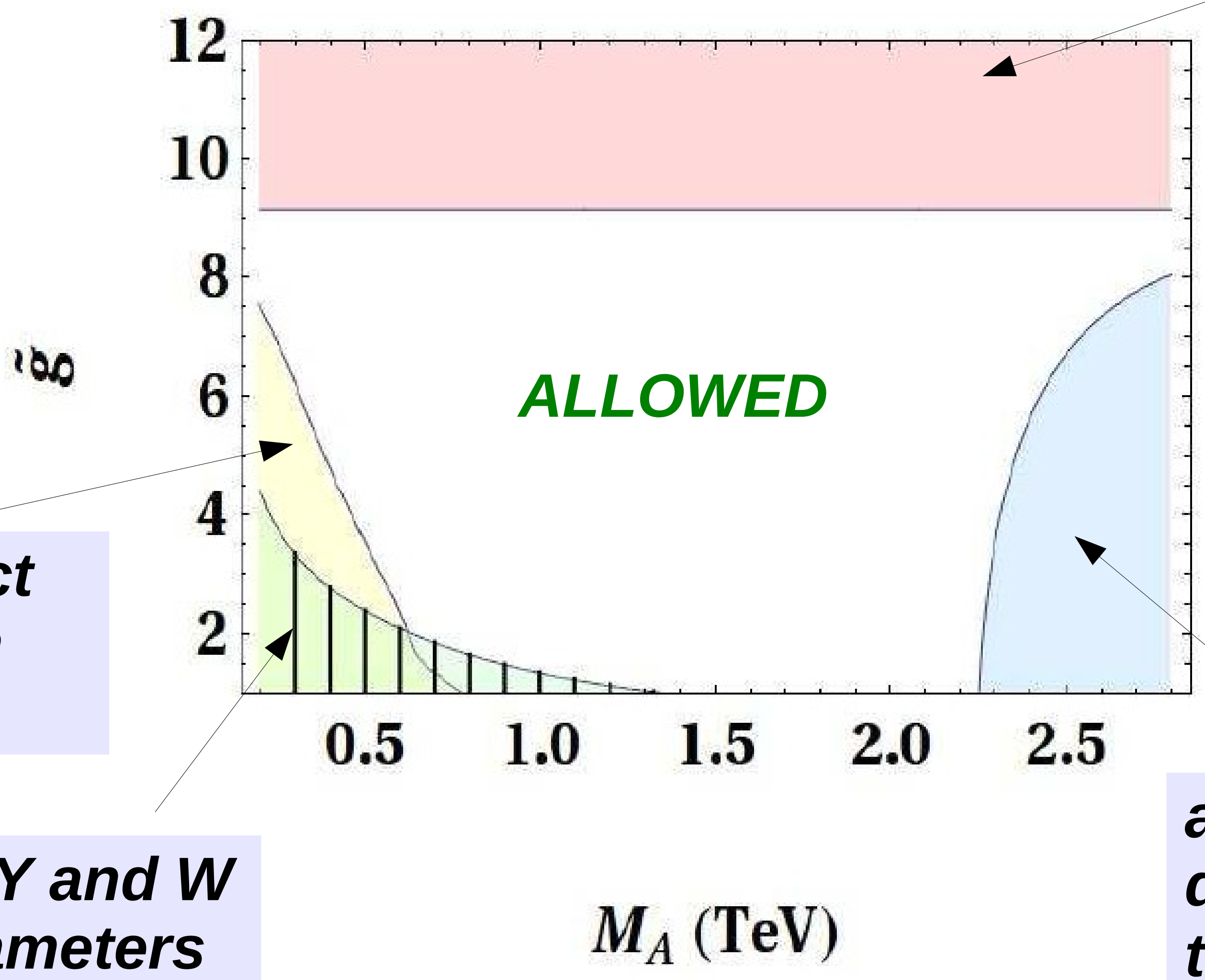
N_f=2 in the higher dimensional representation of N_c=2 case is promising to be studied:

***Minimal Walking Technicolor** (Sannino, Tuominen 05)*

Viable NMWT parameter space

imaginary F_V and F_A

$$\tilde{g} > \sqrt{\frac{8\pi}{S}}$$



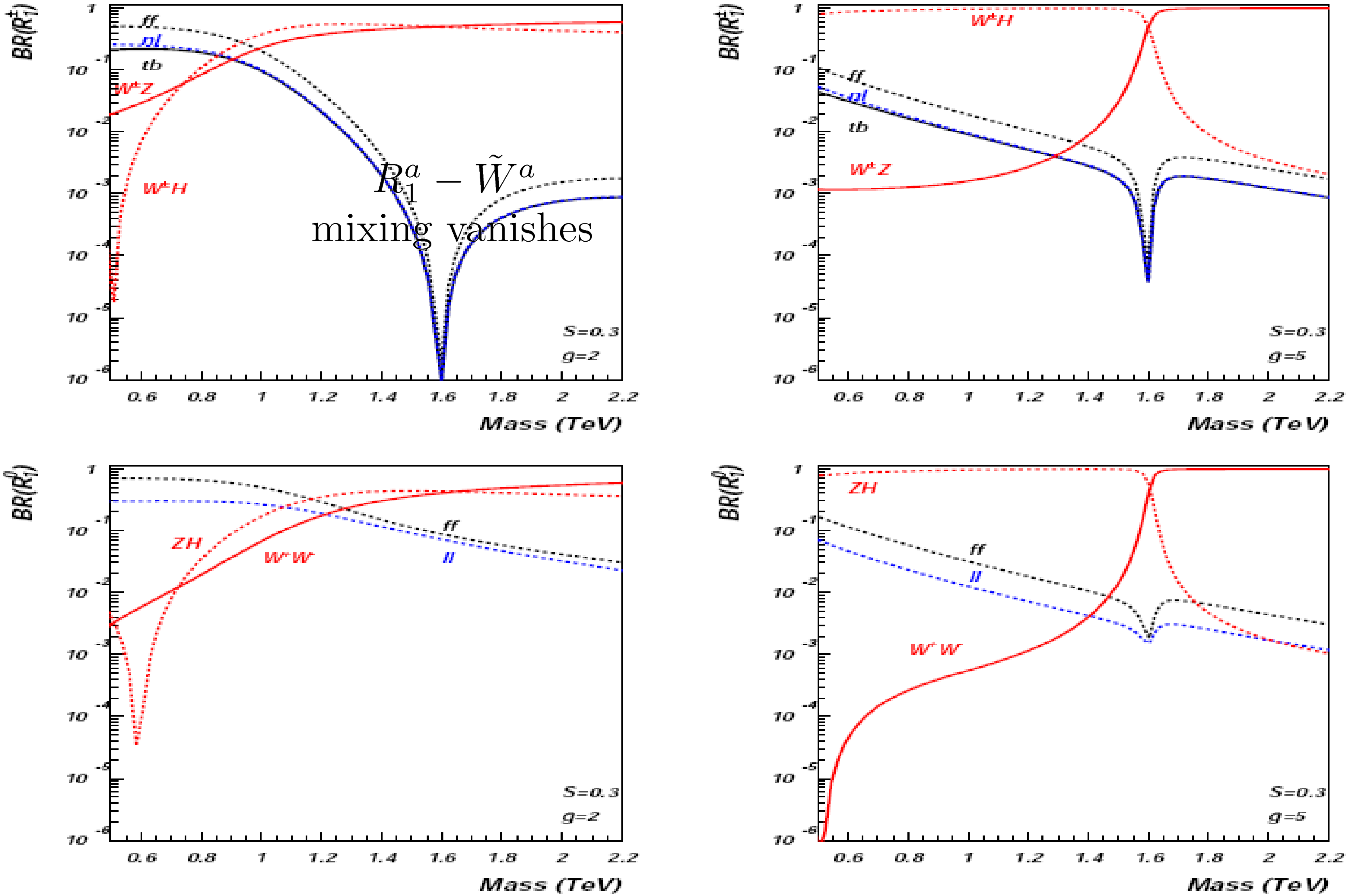
CDF direct limit from pp -> e^+e^-

EW Y and W parameters @95% CL

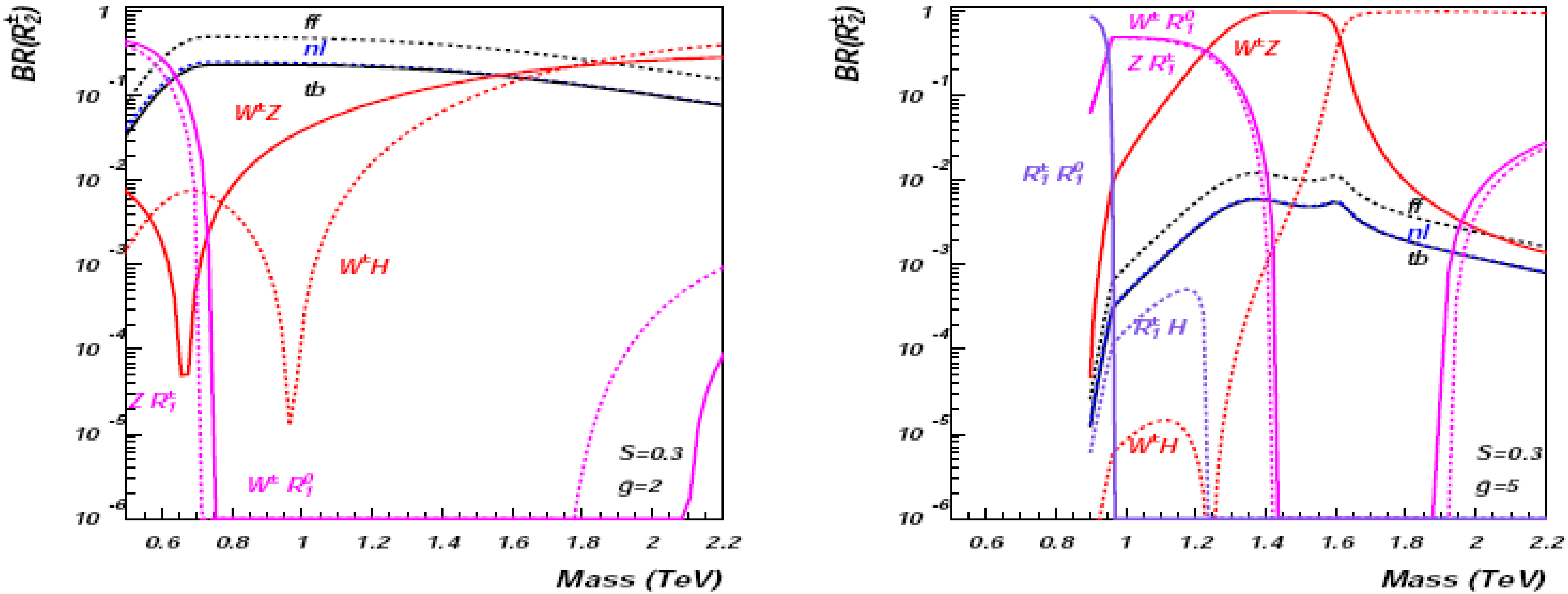
a<0, defined by the 2[nd] WSR

Barbieri, Pomarol, Rattazzi,Strumia 04

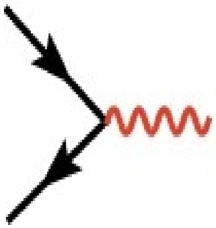
Decay Branching Ratios (R_1)

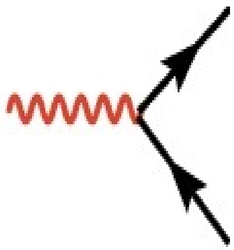


Decay Branching Ratios (R_2)



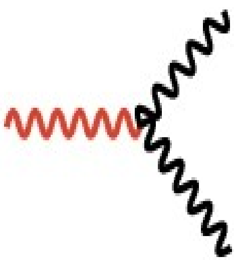
LHC Signatures





(1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$

(2) $\ell + \not{E}_T$ signature from the process $pp \to R^\pm_{1,2} \to \ell^\pm \nu$



(3) $3\ell + \not{E}_T$ signature from the process $pp \to R^\pm_{1,2} \to ZW^\pm \to 3\ell\nu$

$pp \to R^0_{1,2}$

$pp \to R^\pm_{1,2}$

detector acceptance cuts

$$|\eta^\ell| < 2.5 \qquad p_T^\ell > 15 \text{ GeV}$$

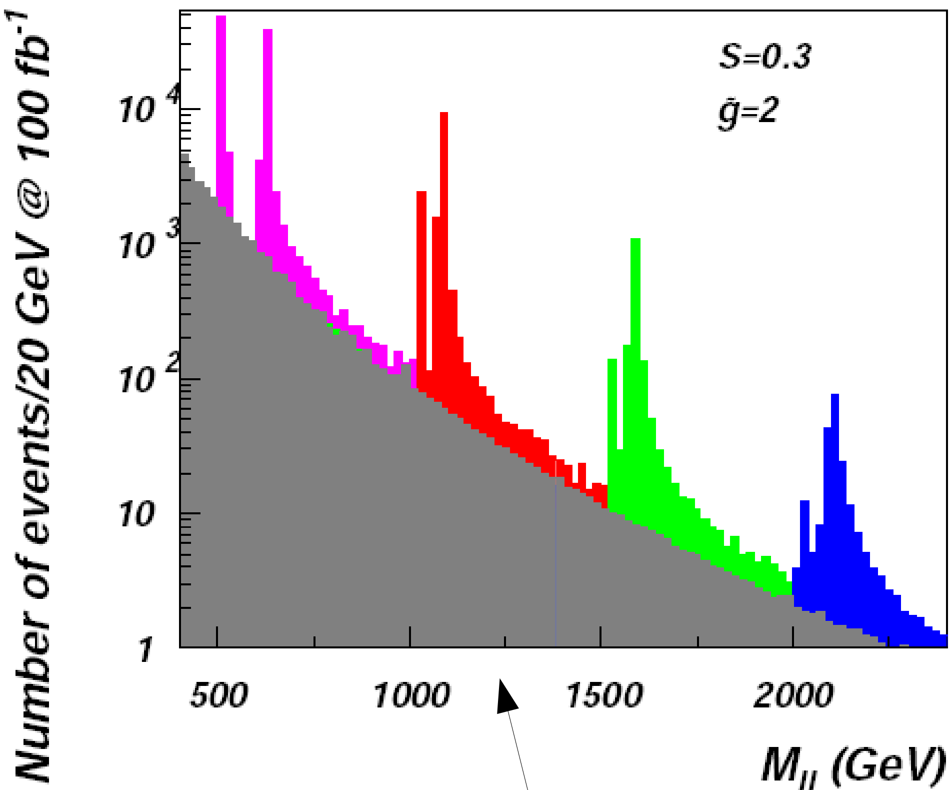
transverse mass variable

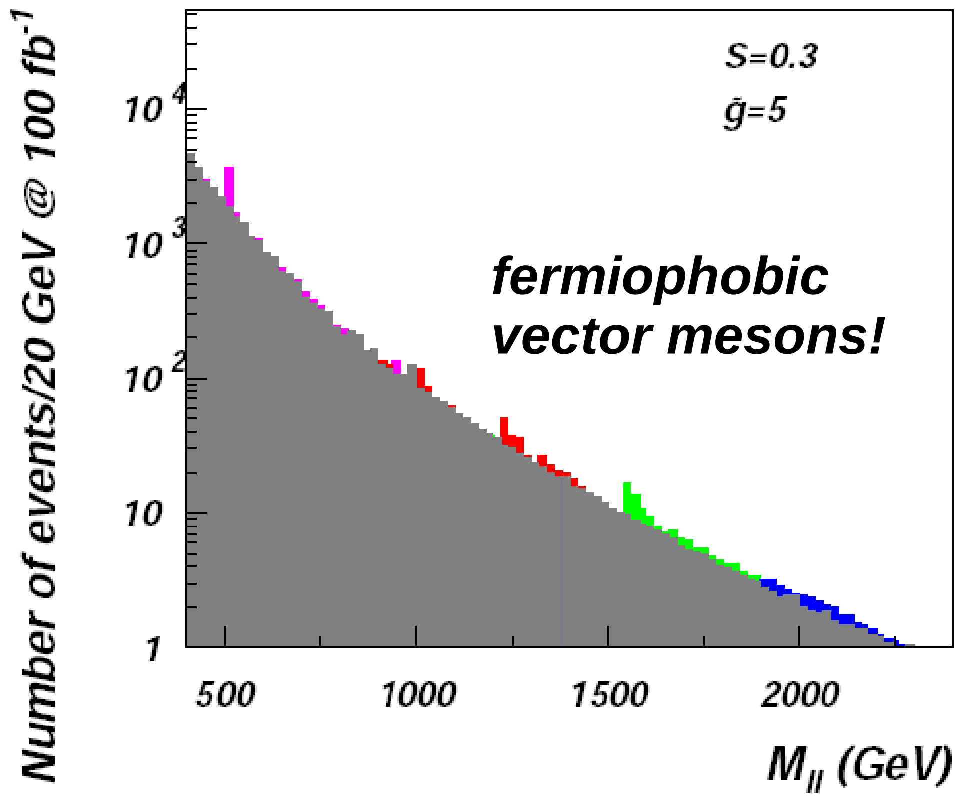
$$(M_\ell^T)^2 = [\sqrt{M^2(\ell) + p_T^2(\ell)} + |\not{p}_T|]^2 - |\vec{p}_T(\ell) + \vec{\not{p}}_T|^2$$

$$(M_{3\ell}^T)^2 = [\sqrt{M^2(\ell\ell\ell) + p_T^2(\ell\ell\ell)} + |\not{p}_T|]^2 - |\vec{p}_T(\ell\ell\ell) + \vec{\not{p}}_T|^2$$

Signature (1)

(1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$

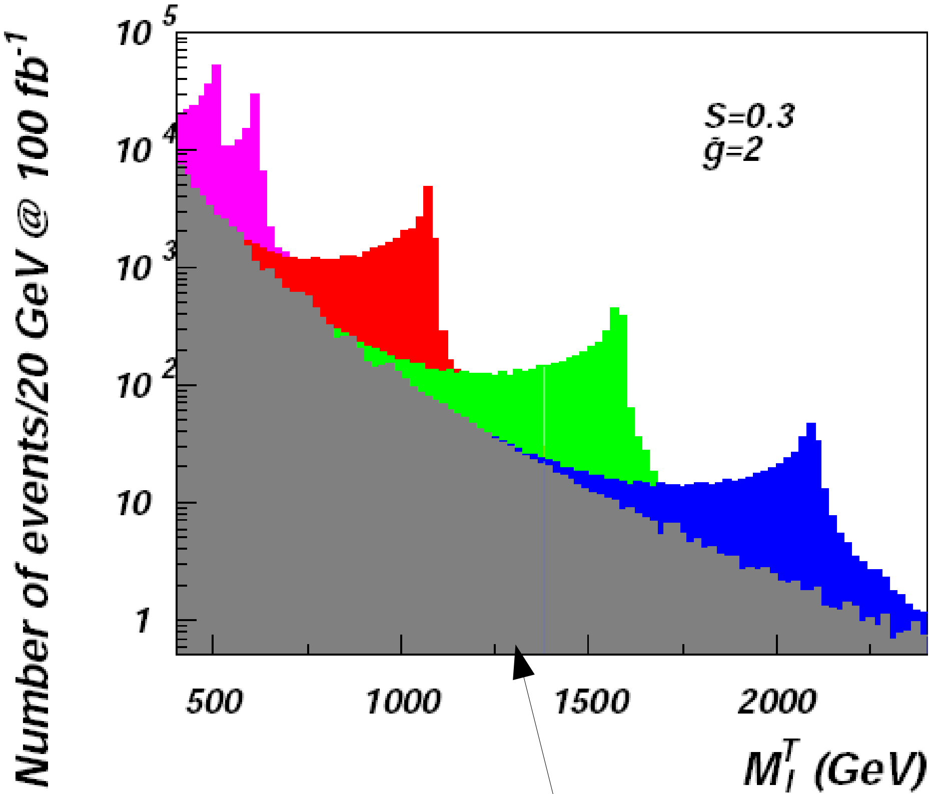


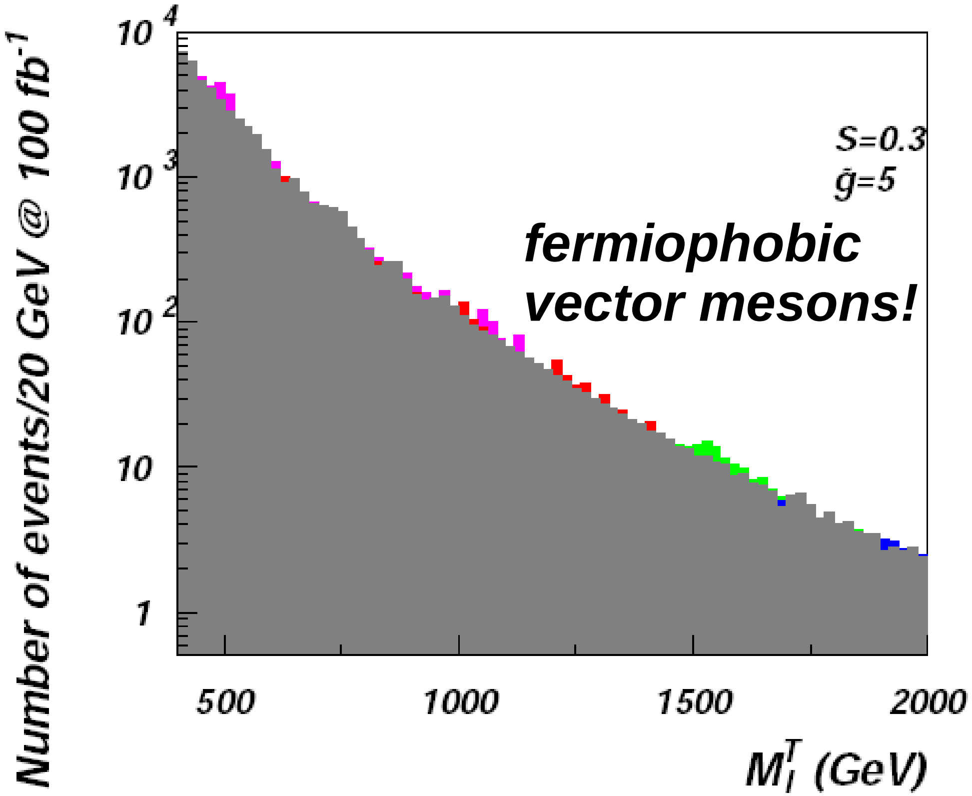


double resonance signal pattern can be resolved ---
distinct footprint, different from 3-site model
(Chivukula,Coleppa, Di Chiara, Simmons, He, Kurachi,Tanabashi 06)
or generic Z' models

Signature (2)

(2) $\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to \ell^{\pm}\nu$

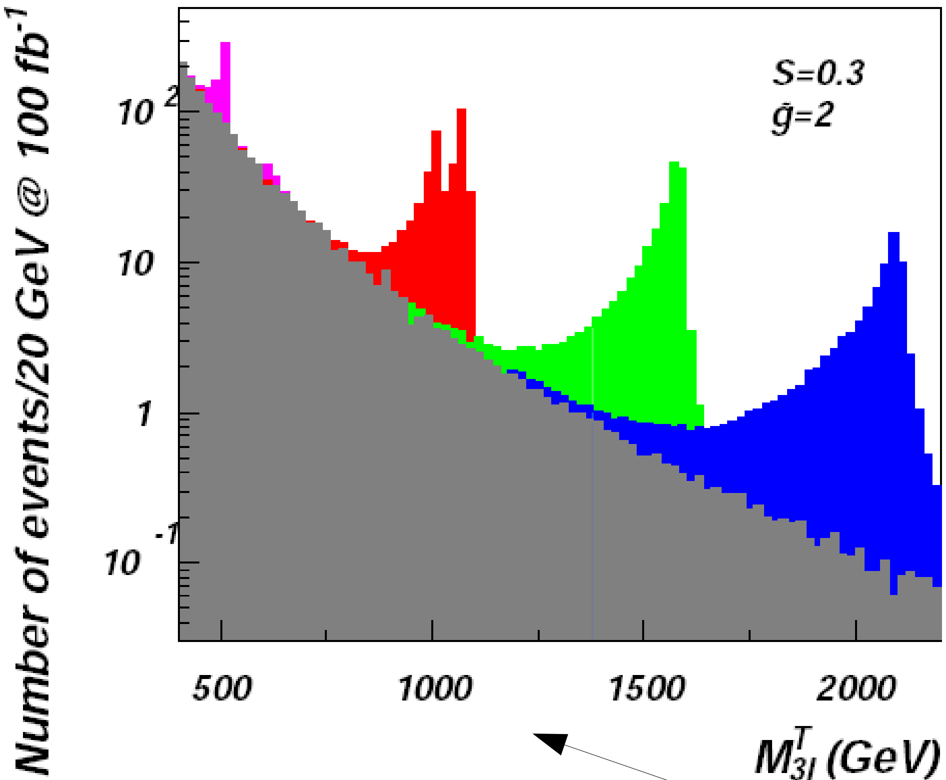


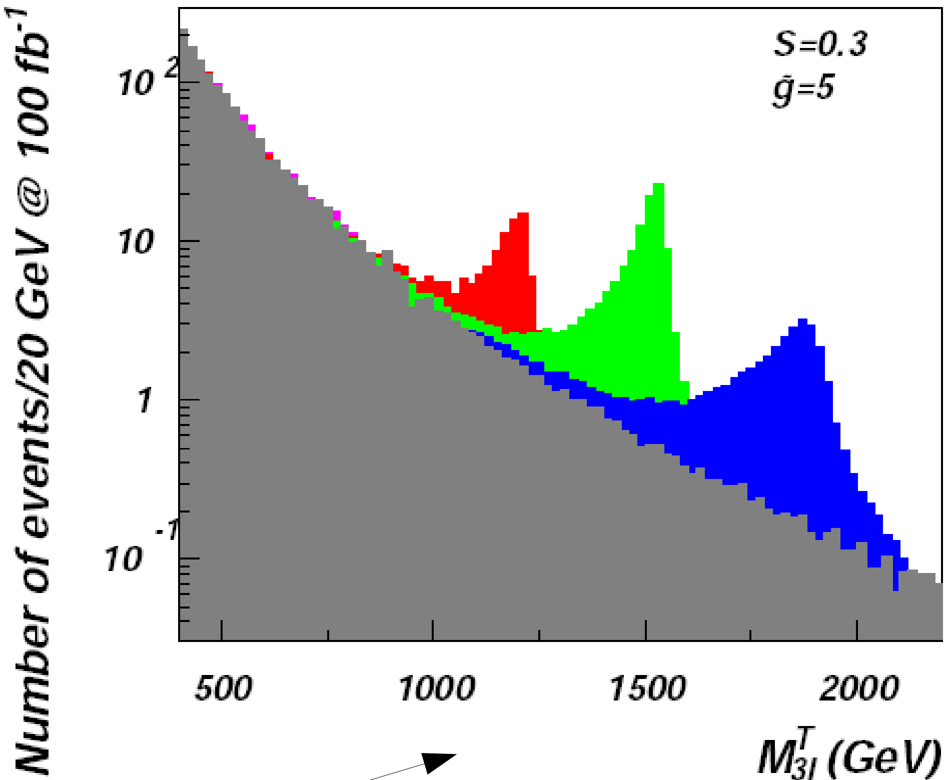


for higher masses only one resonance is observed

Signature (3)

(3) $3\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$

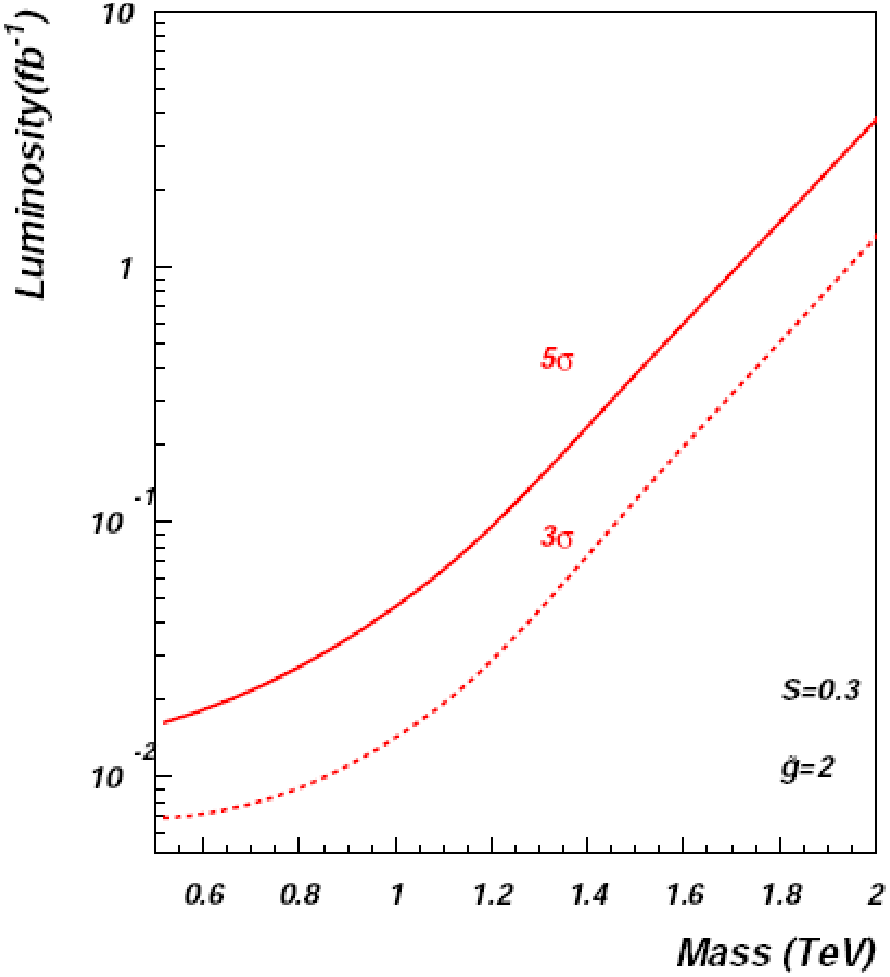


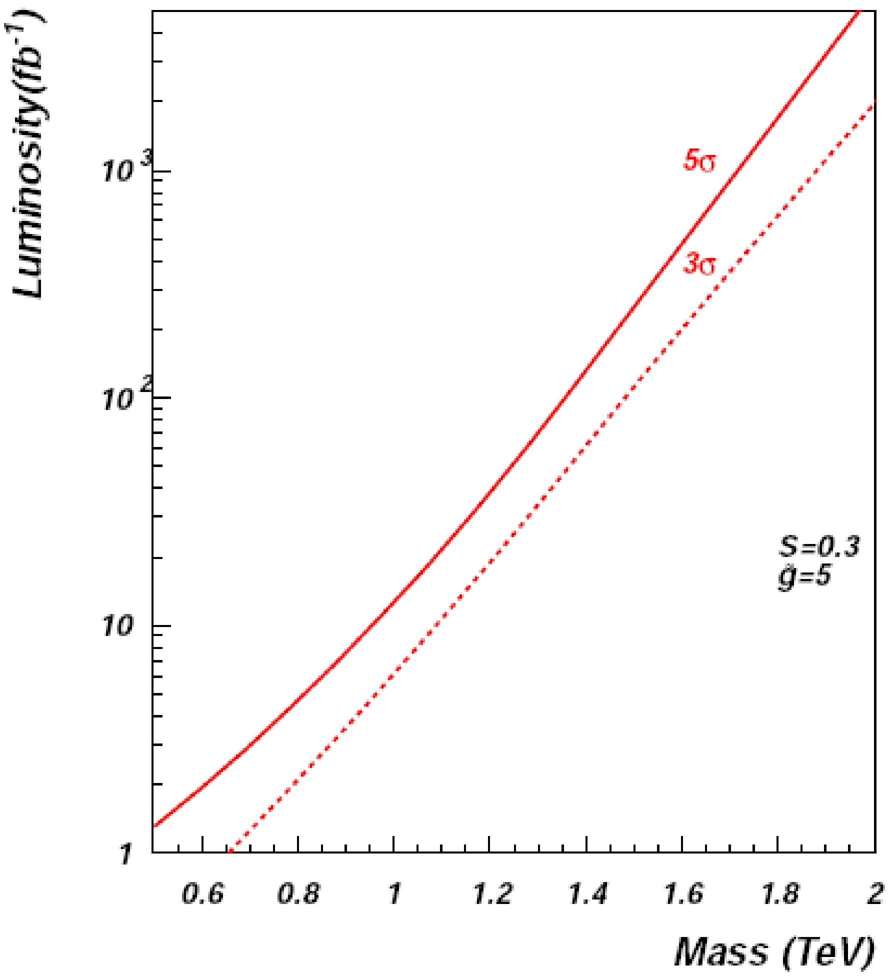


highly complementary channel to fermiophobic ones:
not very high rates, but clean signal

LHC discovery potential for NMWT

(1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$





LHC discovery potential for NMWT

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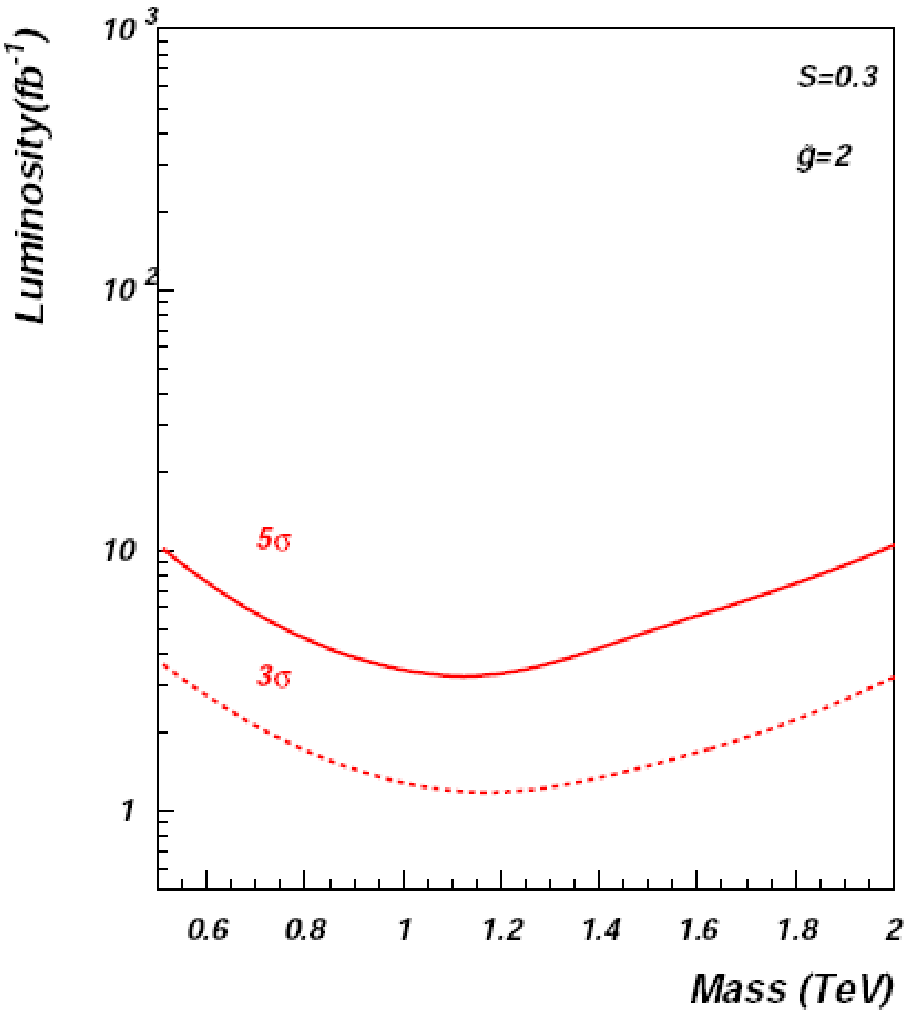
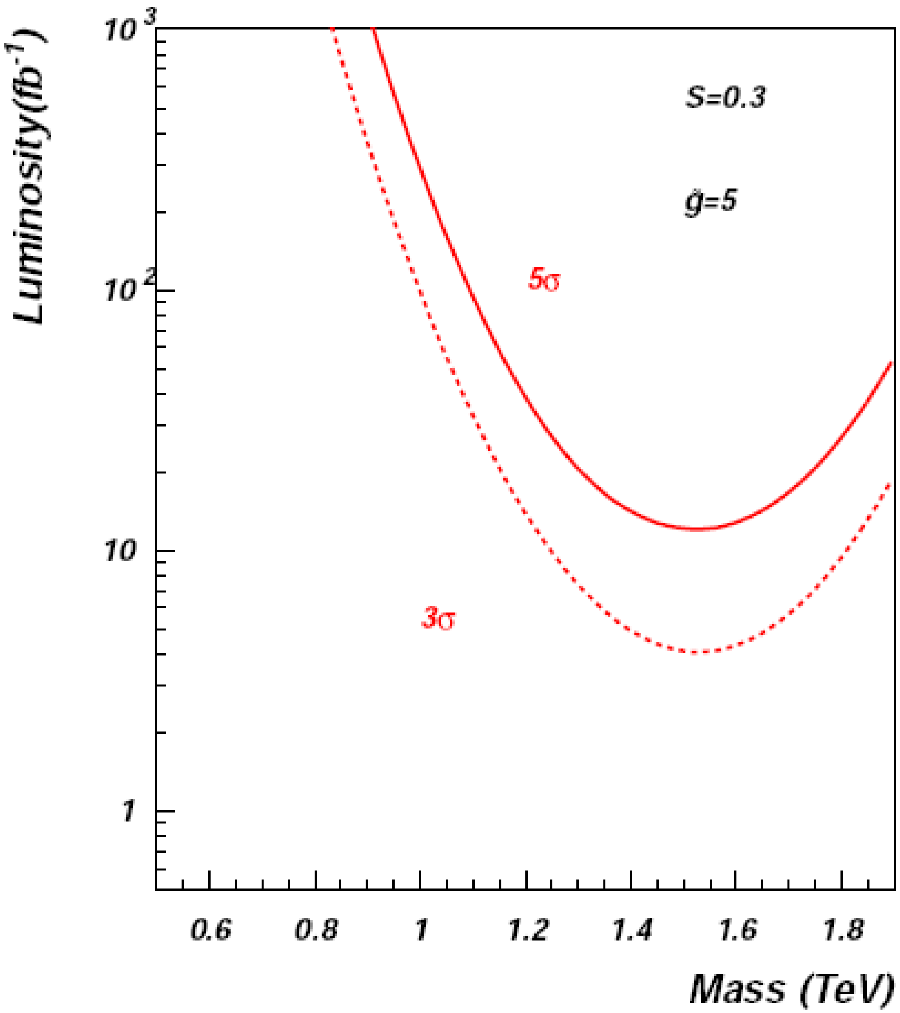
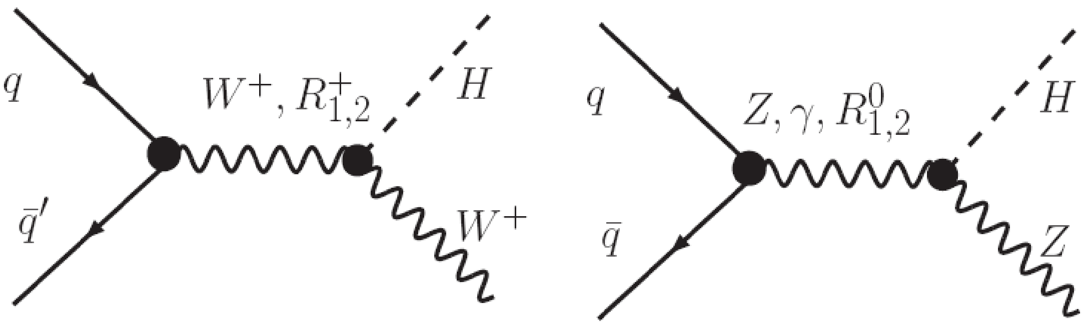
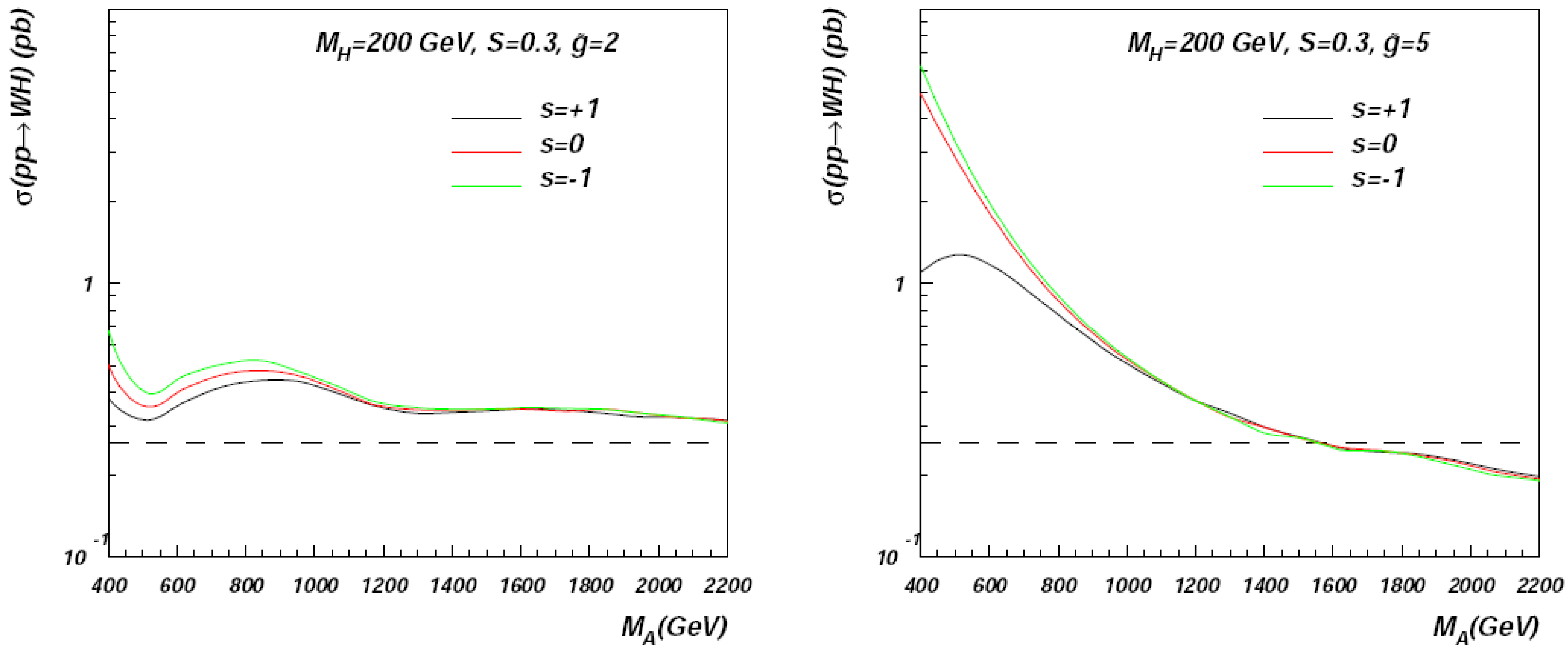




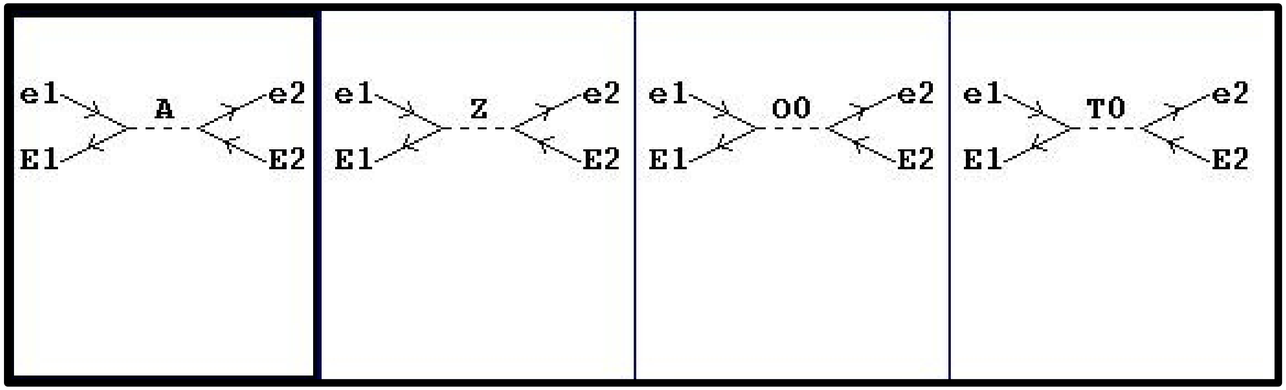
Composite Higgs Phenomenology

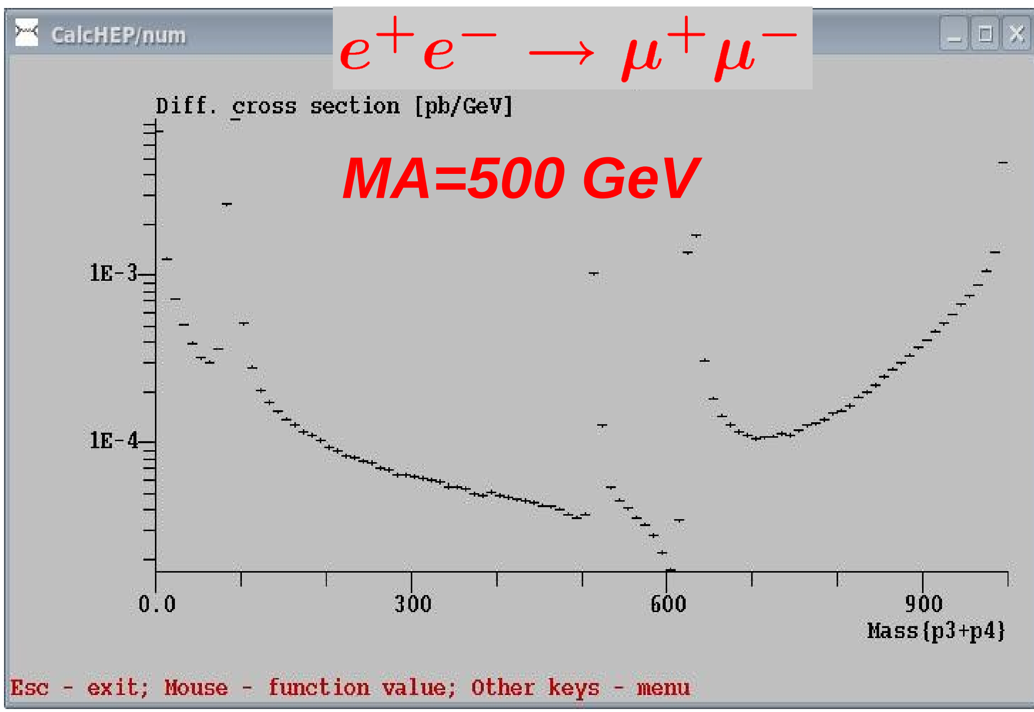


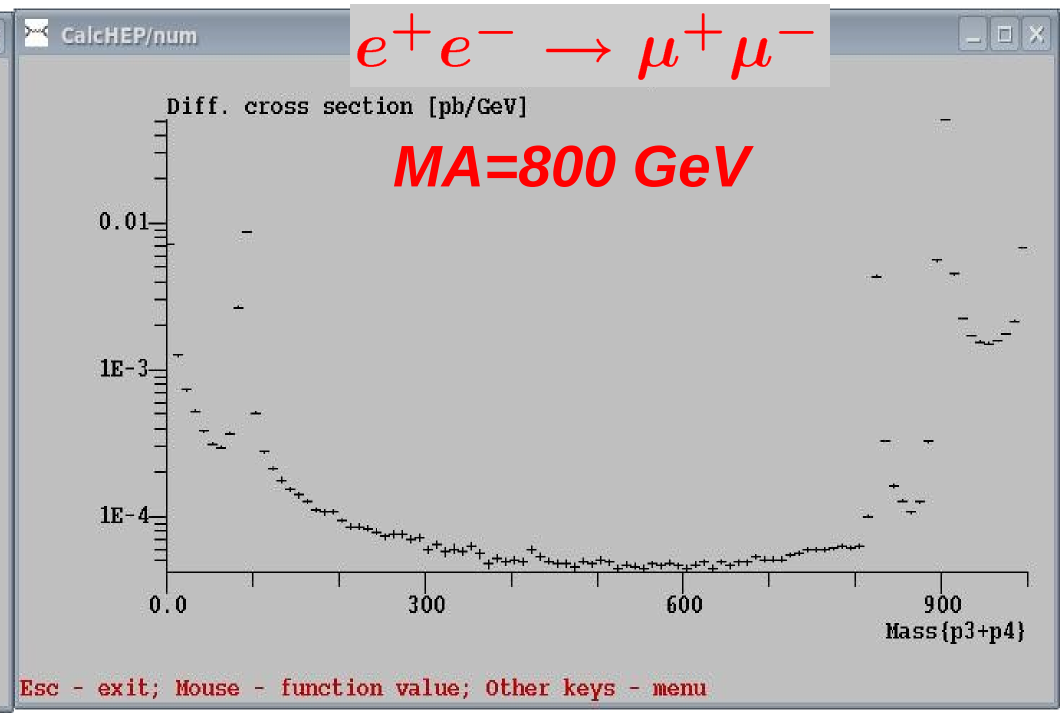


Higgs-vector boson associate production can be significantly enhanced
noted by   Zerwekh 06

NMWT model studies at ILC@1TeV
(work in progress)

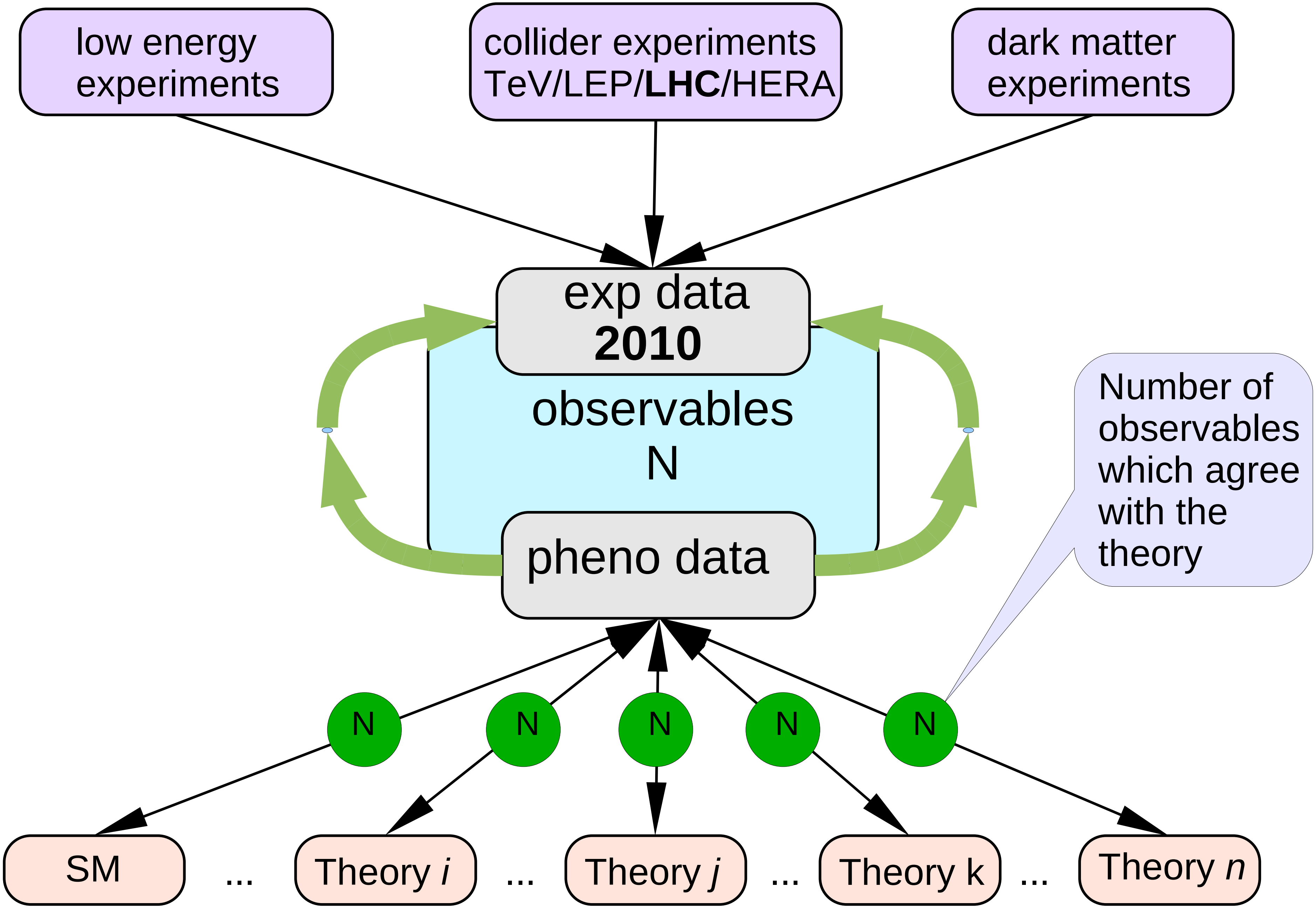




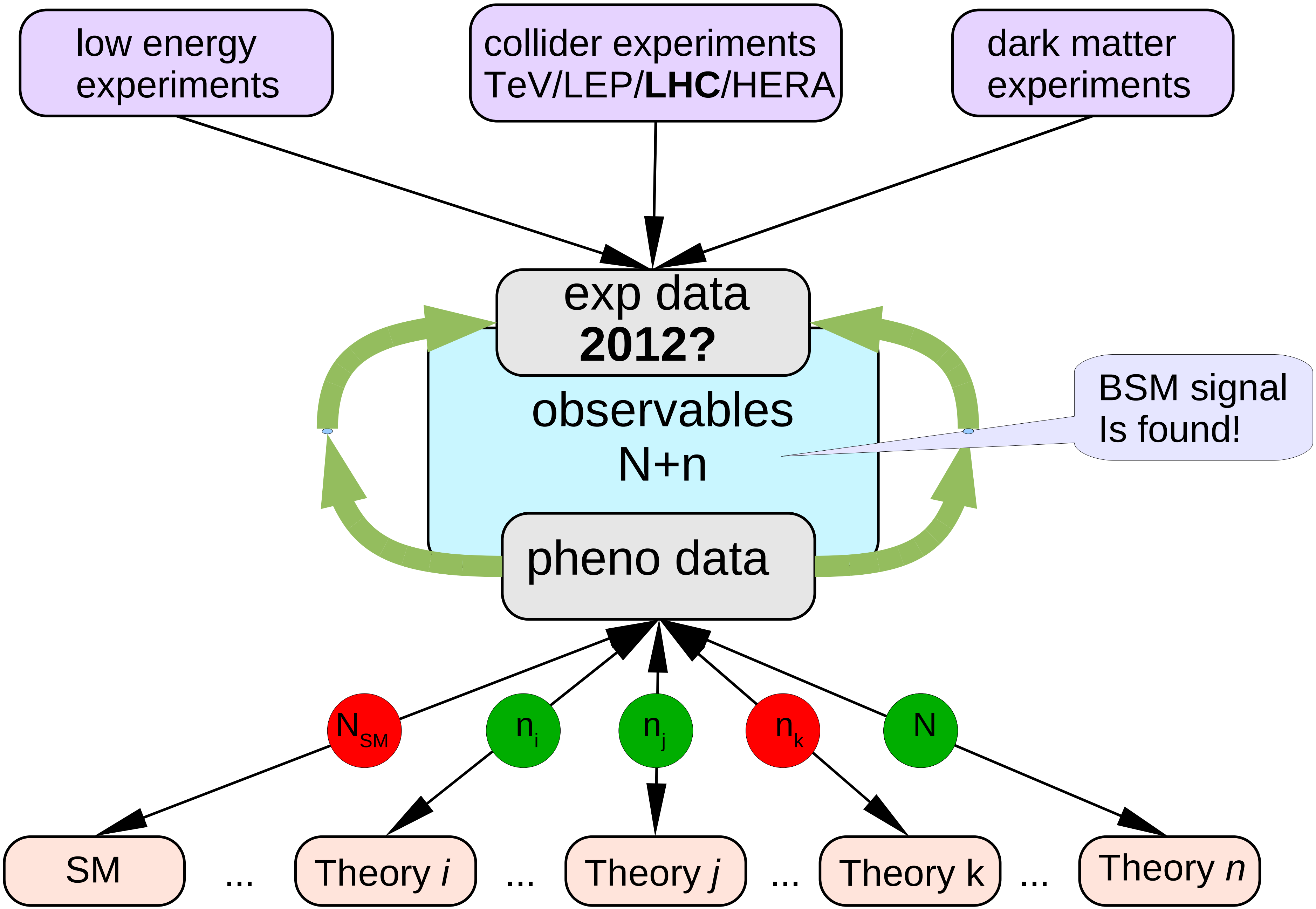


Our Expectations from LHC

Possible scenario in the near future



Possible scenario in the near future



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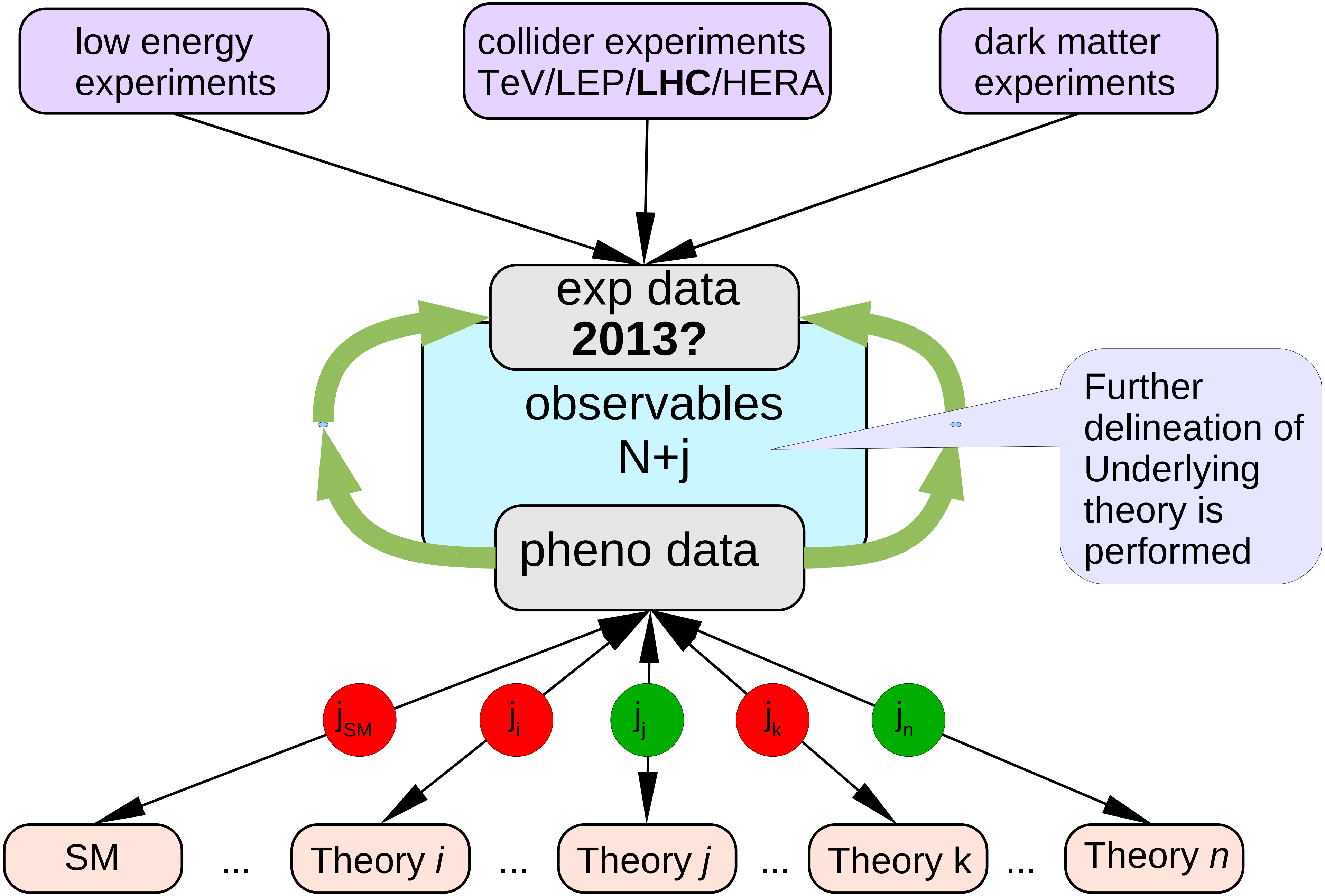
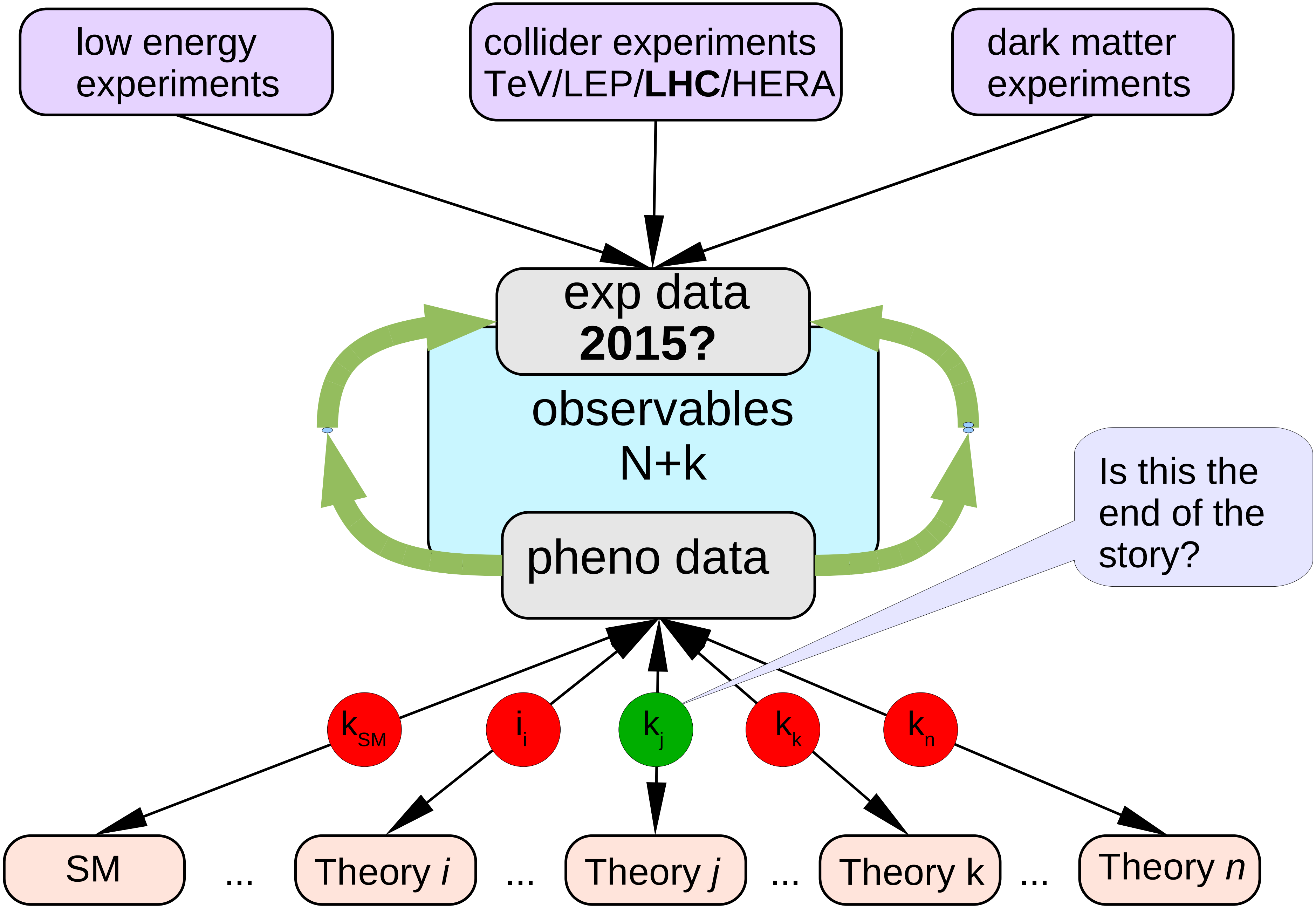
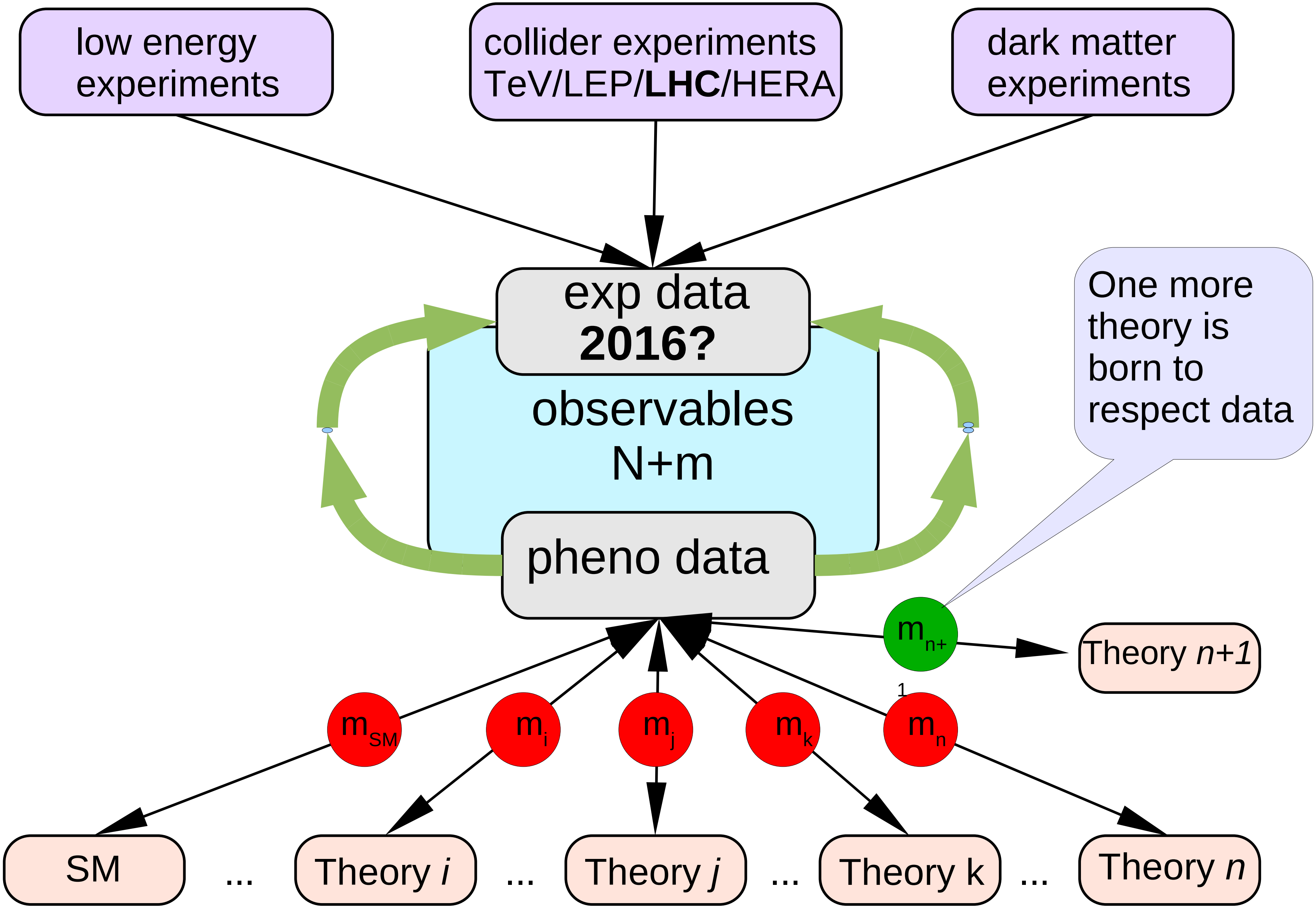


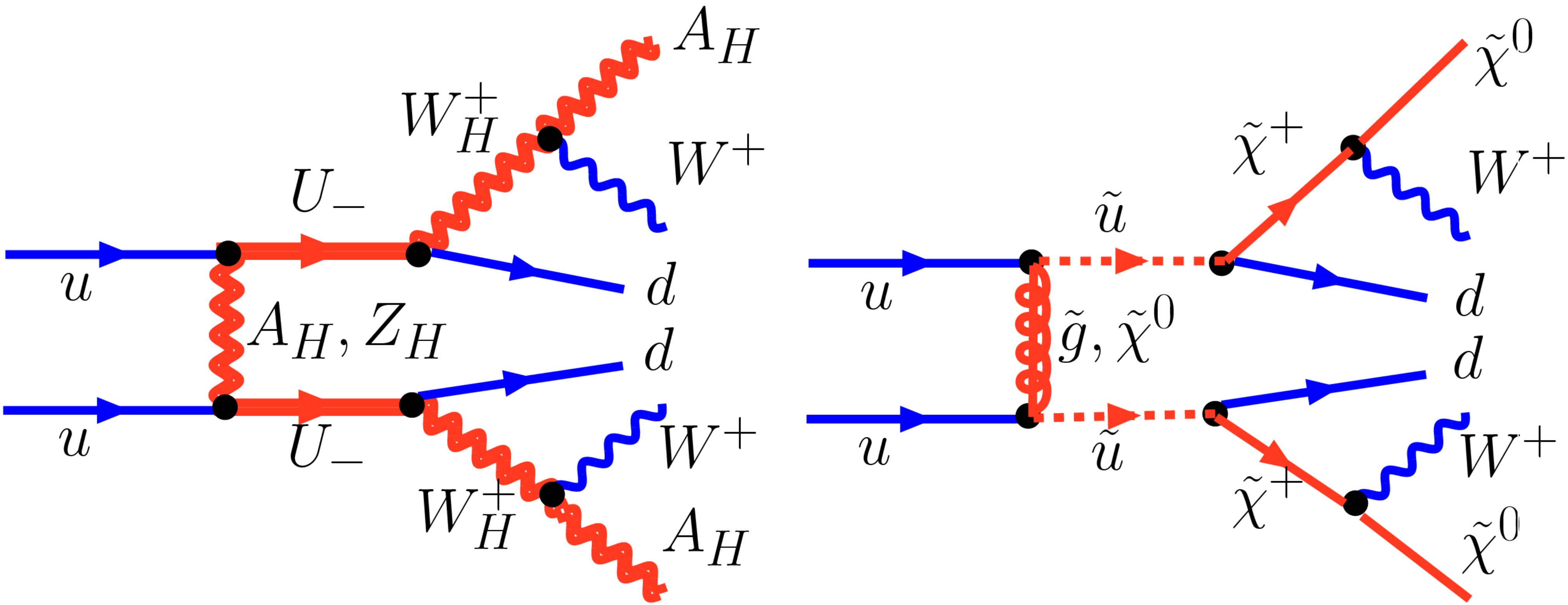
Possible scenario in the near future



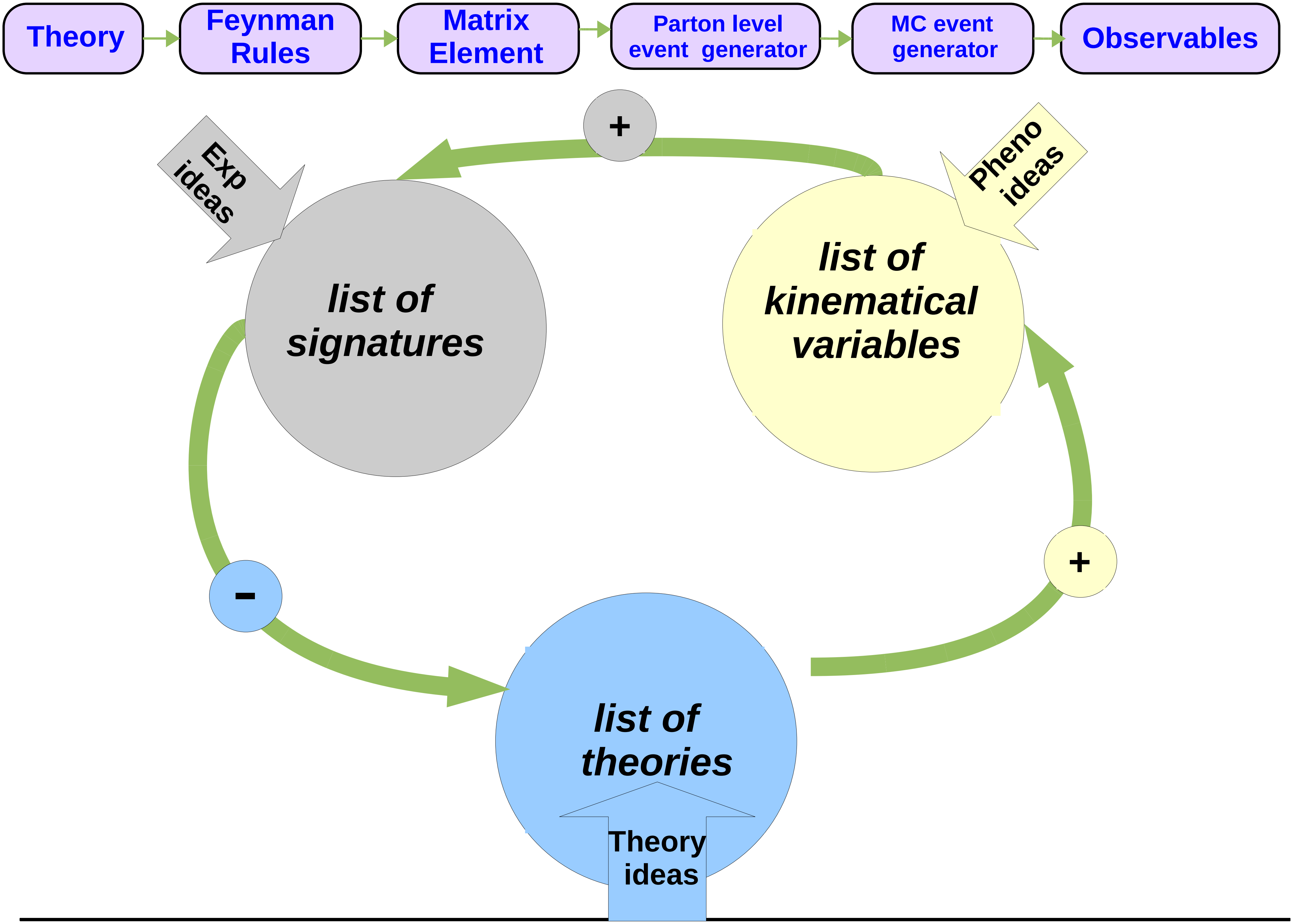
Possible scenario in the near future



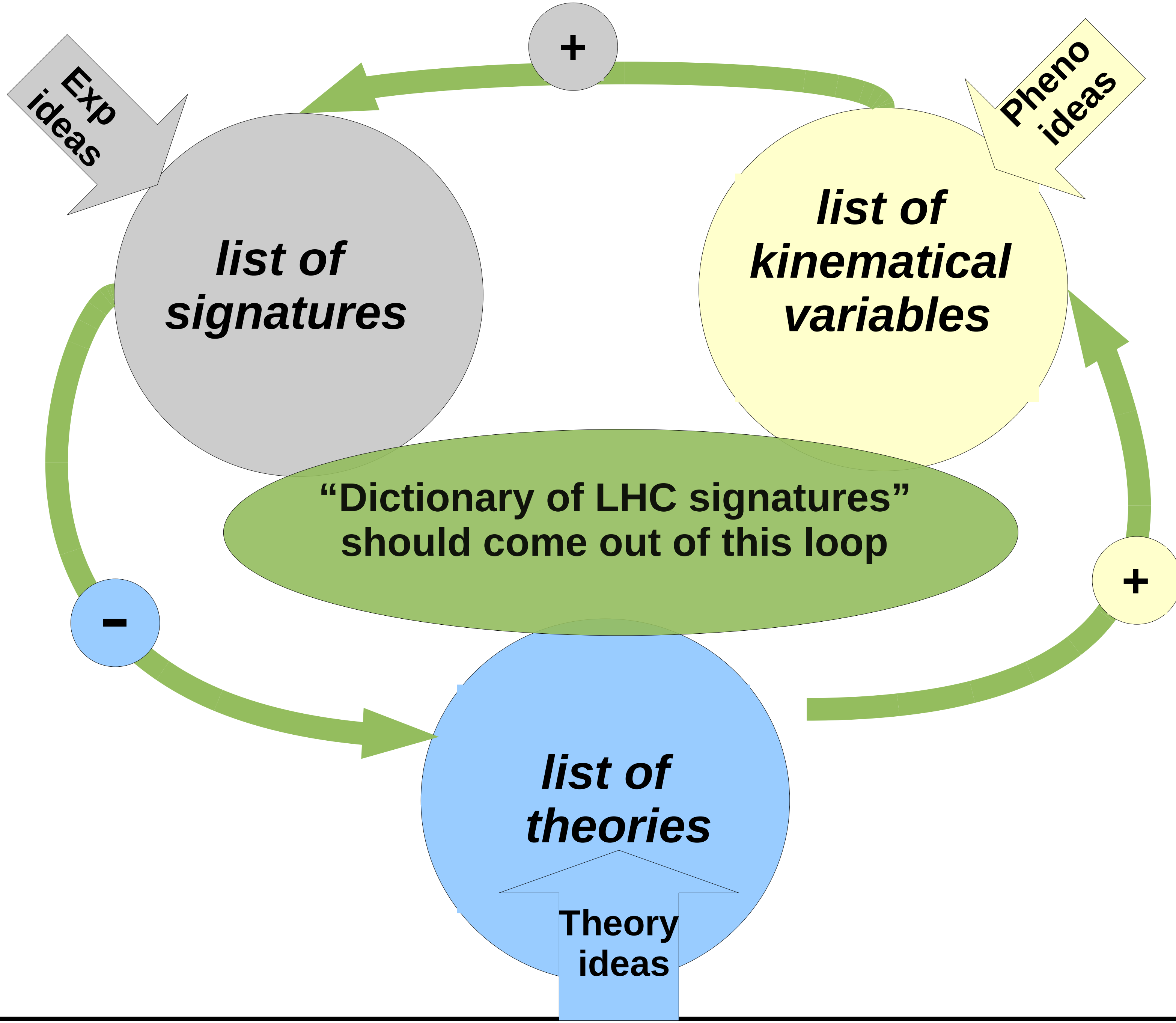
Signatures could look alike



LHT **SUSY**


Theory
Feynman Rules
Matrix Element
Parton level event generator
MC event generator
Observables
+
Exp ideas
Pheno ideas
list of signatures
list of kinematical variables
+
–
list of theories
Theory ideas

The strategy for delineating of underlying theory

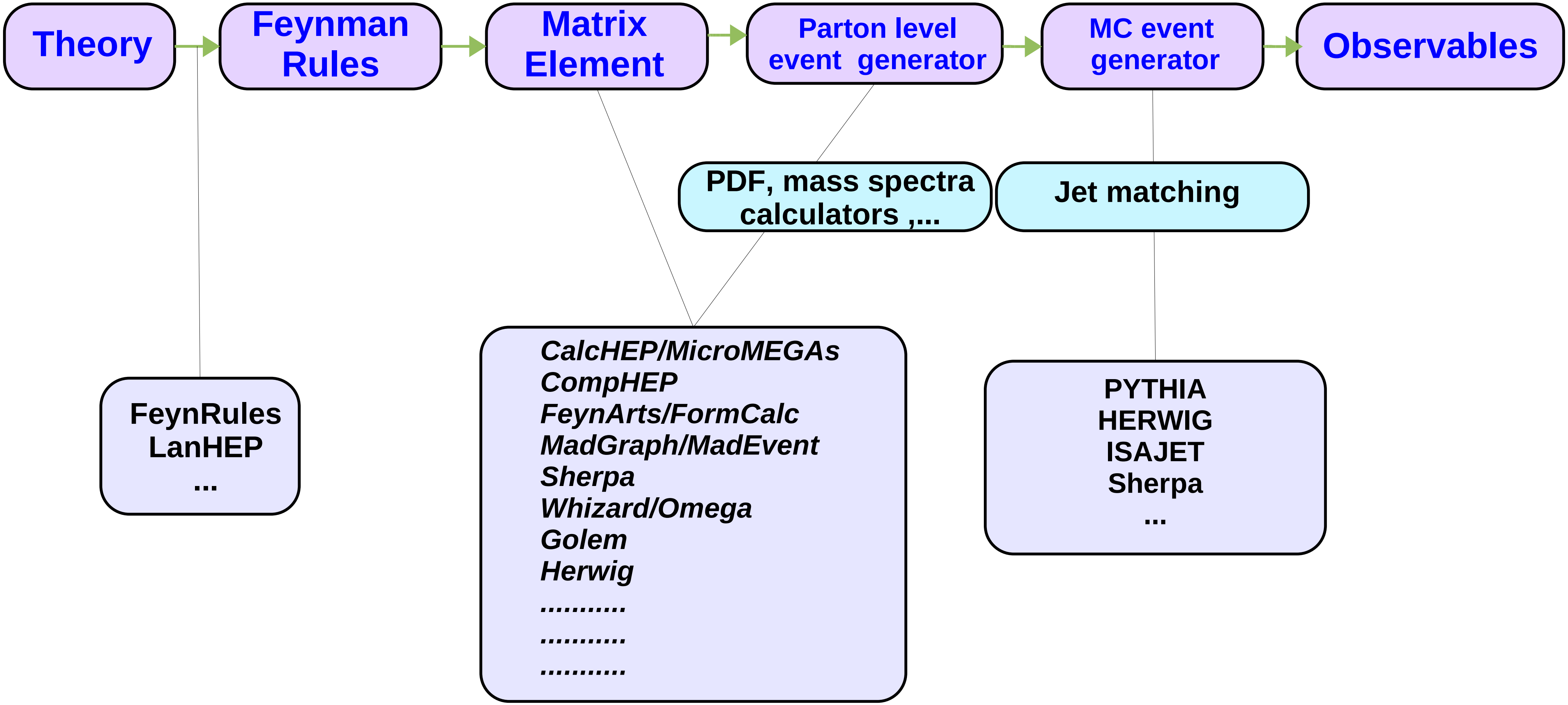


First Steps towards "Dictionary"

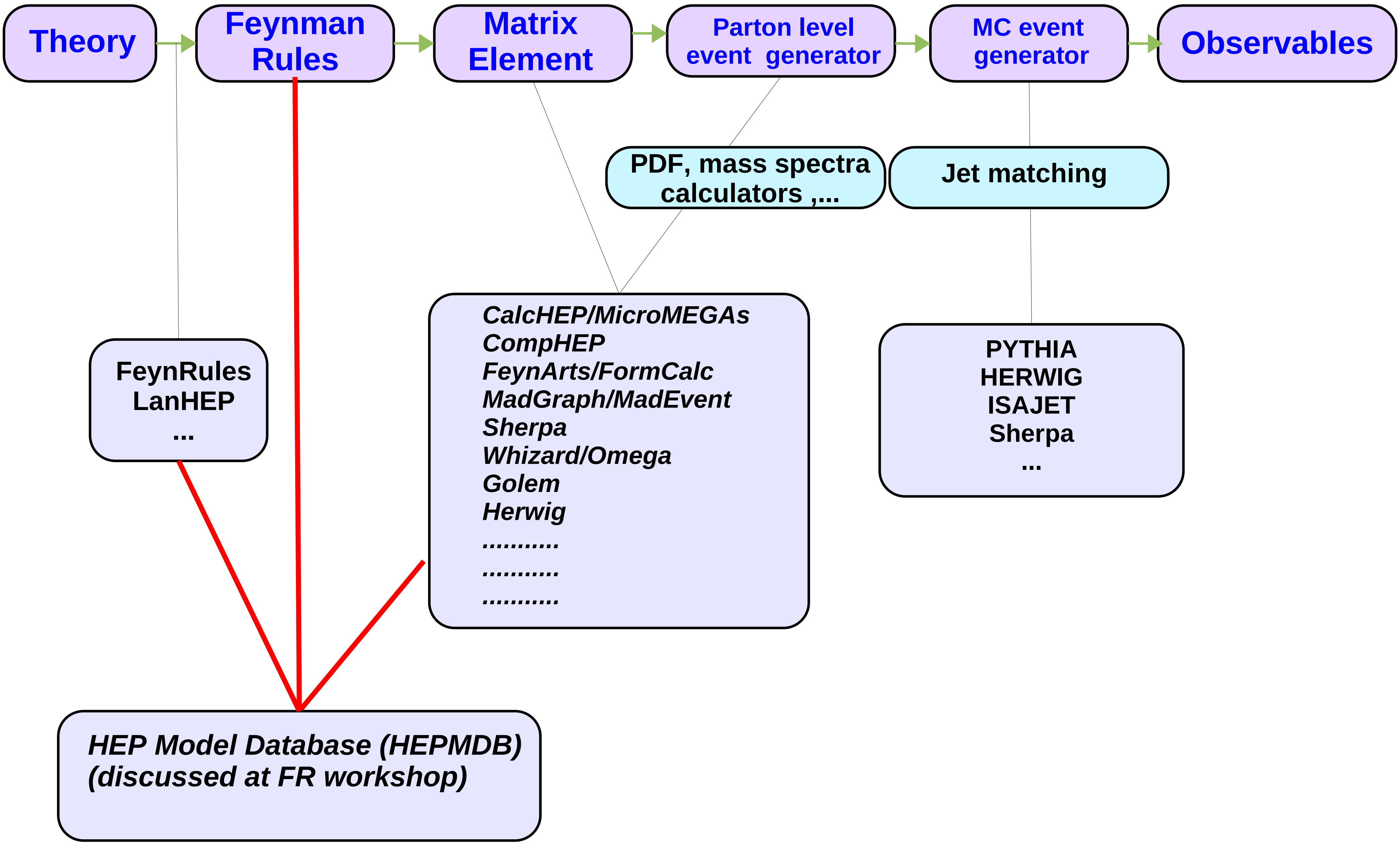
A.B., Asesh Datta, Albert De Roeck, Rohini Godbole, Bruce Mellado, Andreas Nyffeler, Chara Petridou, D.P. Roy, Pramana 72:229-238,2009. e-Print: arXiv:0806.2838 [hep-ph]

Variables		SUSY (MSSM)	LHT	UED
Spin		heavy partners differ in spin by 1/2	heavy partners have the same spin, no heavy gluon	heavy partners have the same spin
Higher level modes		NO heavy partners	NO heavy partners	YES heavy partners
$N_{l^+l^+}/N_{l^-l^-}$		$R_{SUSY} < R_{LHT}$	R_{LHT}	$R_{UED} \simeq R_{LHT}$
SS leptons rates		from several channels: SS heavy fermions, Majorana fermions	only from SS heavy fermions	only from SS heavy fermions
$R = \frac{N(\not{E}_T + jets)}{N(l's + \not{E}_T + \text{jets})}$		R_{SUSY}	$R_{\text{LHT}} < R_{\text{SUSY}}$	R_{UED} to be studied
b-jet multiplicity		enhanced (FP)	not enhanced	not enhanced
Single heavy top		NO	YES	YES via KK2 decay
polarization effects	$tt + \not{E}_T$	to be studied	to be studied	to be studied
	$\tau\tau + \not{E}_T$	to be studied	to be studied	to be studied
Direct DM detection rate		high (FP) low (coann)	low (Bino-like LTP)	typically low for γ_1(5D) DM [22] typically high for γ_H(6D) DM [22]

Tools for delineating underlying theory



Tools for delineating underlying theory



Conclusions and outlook

- **Dynamical EWSB models are compelling:**
  - ***no hierarchy problem, analog is realized in nature (QCD), effective theory parameters are potentially derivable from underlying theory***
  - ***holography principles, applications to hadronization***
  - ***new phenomenology including new DM developments***
- **Models implemented:**
  - **3-site model, 3-site HLS model**
  - **4-site model**
  - **MWTC, NMWTC + DM sector**
  - **New requests?**

Conclusions and outlook

- **Distinctive phenomenology:**
  - **One or several Z'/W'**
  - **Boosted Z,W,H bosons and boosted heavy quarks**
  - **Combining different signatures: the way to establish no-loose theorem?**
  - **3-site model: di-lepton DY discovery range is up to $M_{W'}$ ~0.5-0.6 TeV, tri-lepton signature from WZ->W' signal can completely cover $M_{W'}$ space**
  - **one step beyond the minimal Higgsless model**
  - **Z' is not necessarily fermiophobic**
  - **equivalence between 4-site and NMWT models**
  - **DM within TC models: more exciting signatures – collider ones as well as signals at Direct and Indirect DM search experiments**
- **What we expect from this workshop**
  - **discuss current progress and new ideas**
  - **discuss new possible projects**
  - **requests for tools? (FR generators, ME generators, MC generators)**
  - **Anything not mentioned above?**

Conclusions and outlook

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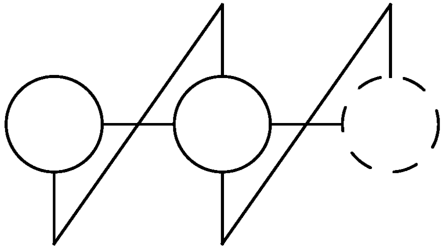
  - **Anything not mentioned above?**

THANKS TO ALL OF YOU!

Allowed deviation from IDL



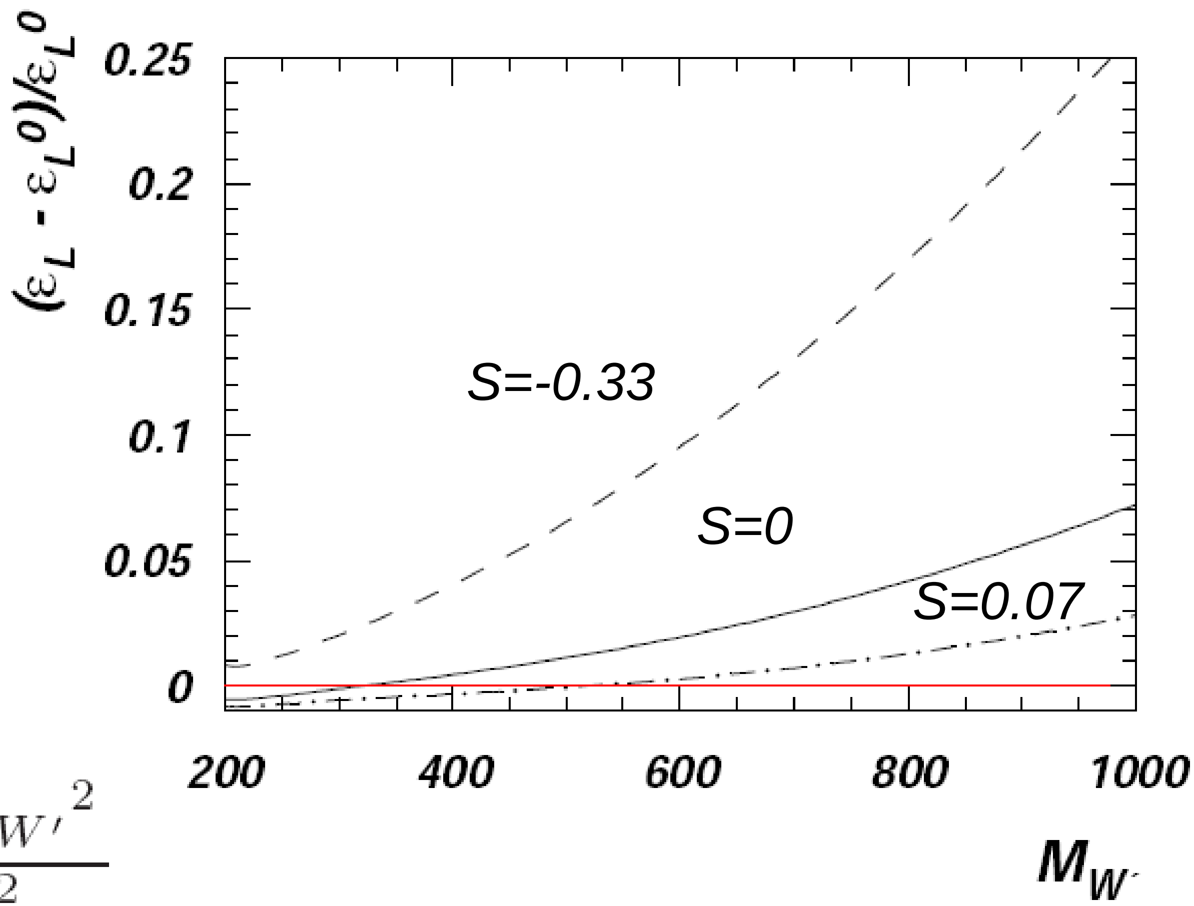
$$-0.33 < S < 0.07 \text{ at } 95\%\text{C.L.}$$
$$M_H^{ref} = 117\text{GeV}$$

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

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

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

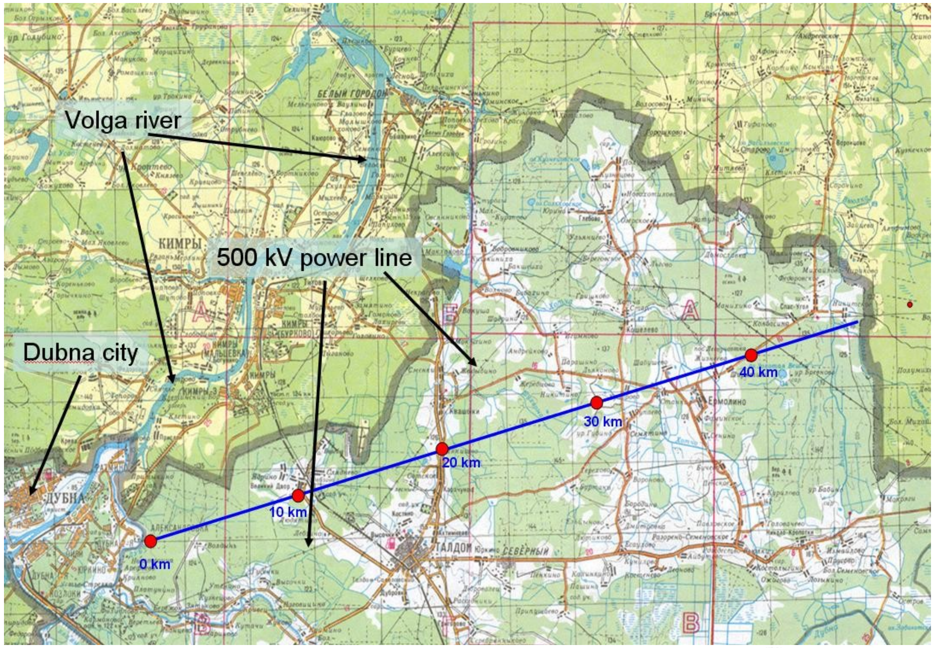
$$S = S^0 + \delta S = S^0 + \frac{1}{12\pi}\log\frac{{M_{W'}}^2}{M^2_{Href}}$$

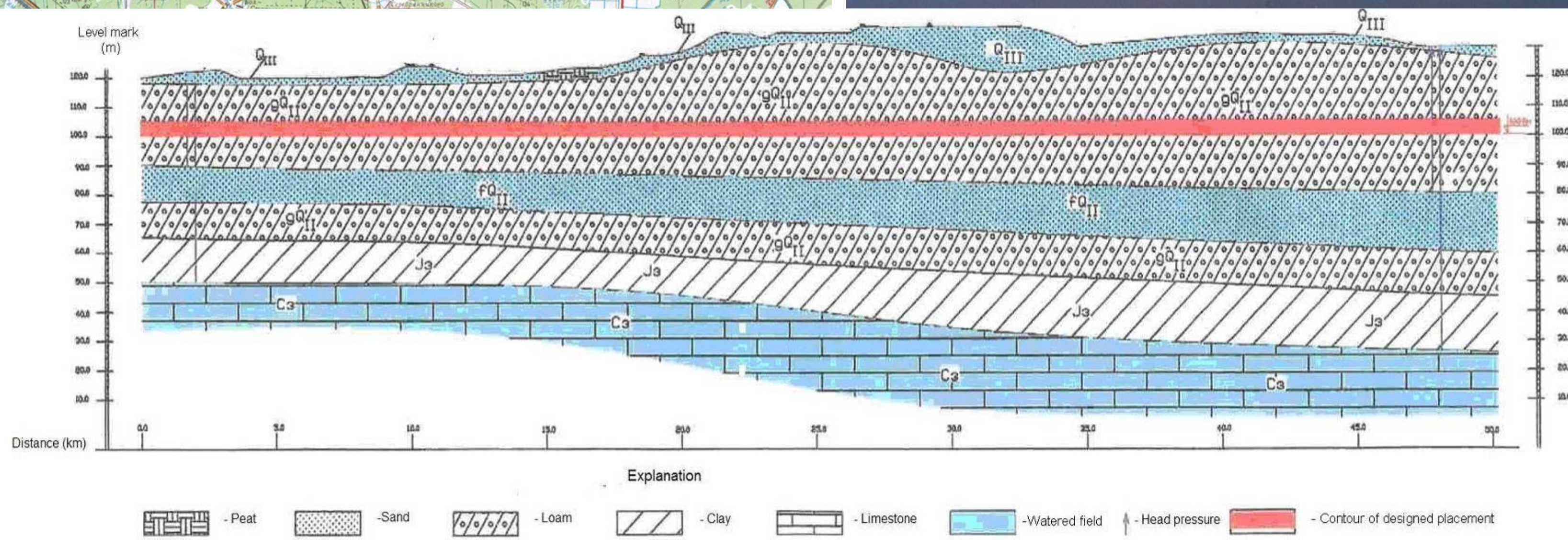


[Matsuzaki,Chivukula,Simmons,Tanabashi; Dawson,Jackson]

One more hope for the ILC? (Dubna, Russia)

Sissakian, Shirkov, Trubnikov, Budagov, Denisov, Kozlov, Tokareva, Vorozhtsov, Ivanov '08

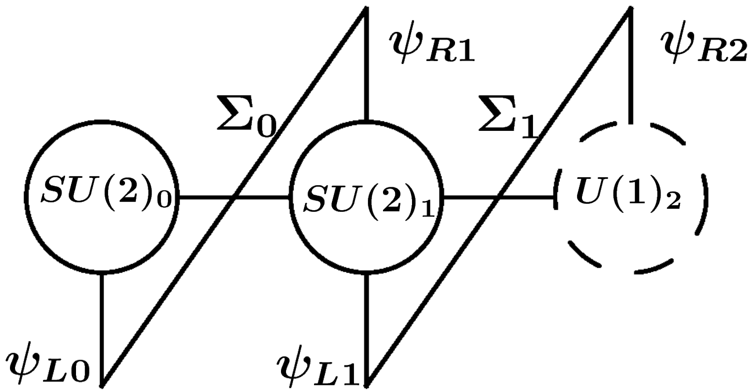


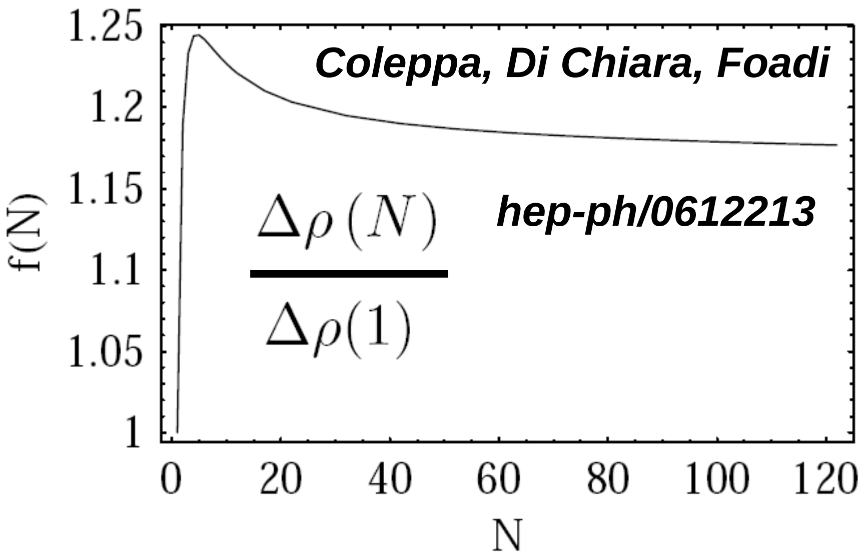


Appendix

TSM: Representative of a Higgsless Extra Dimension

- Low energy phenomenology of a Higgsless ED is dominated by the 1st KK mode.

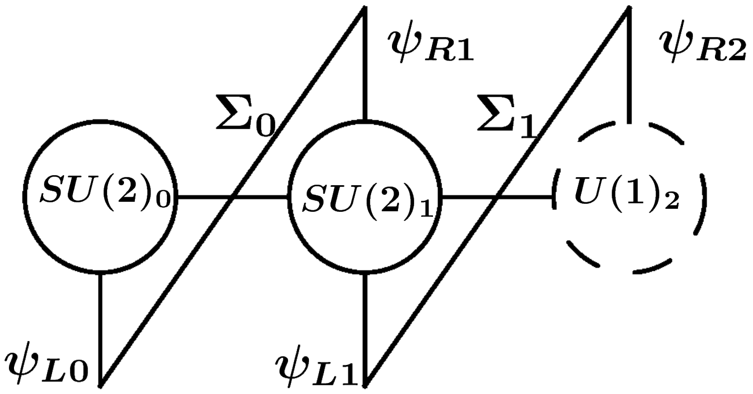




-

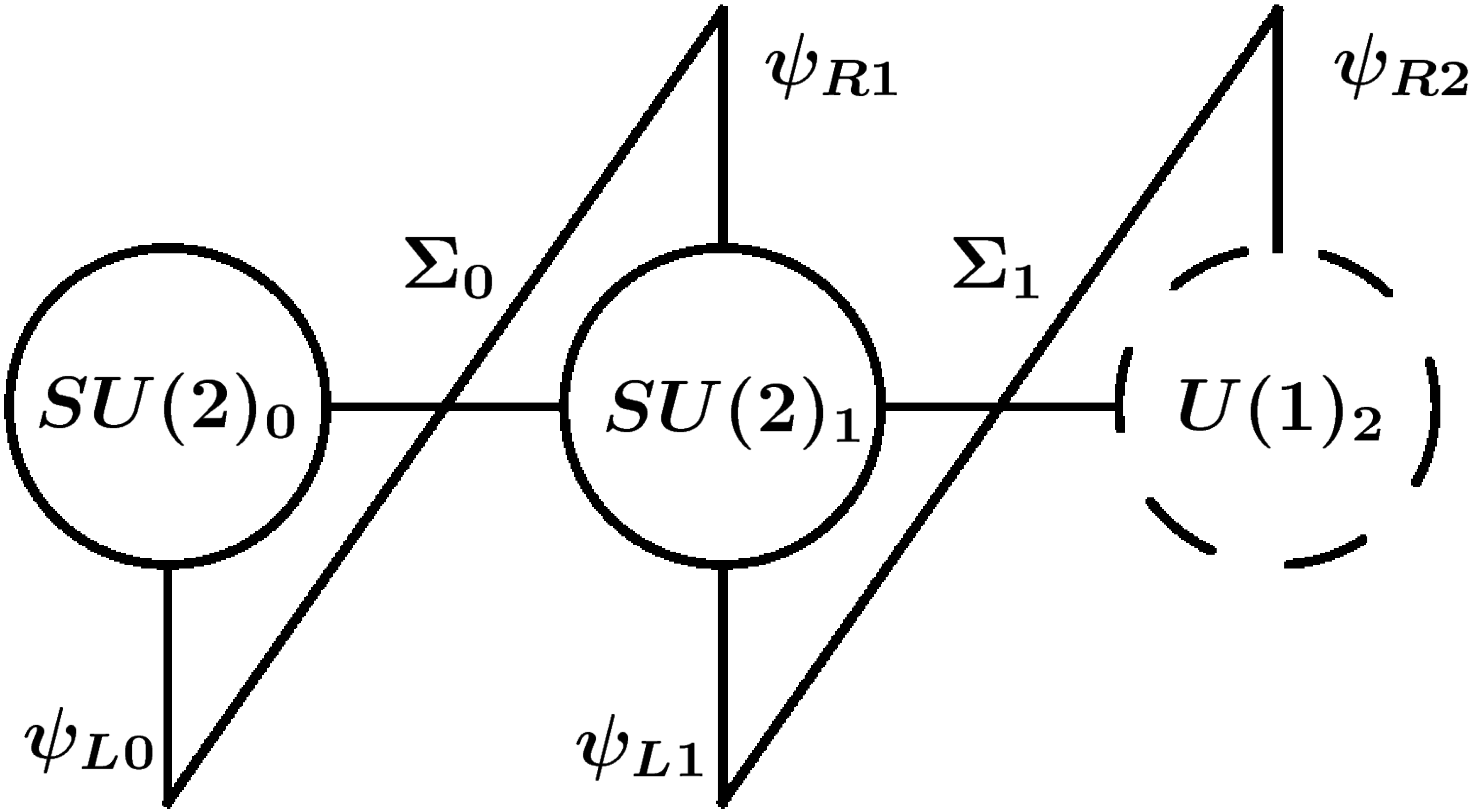
- The Three Site Model consistently implements the 1st KK mode in a gauge invariant way.

TSM: Representative of Dynamical EWSB

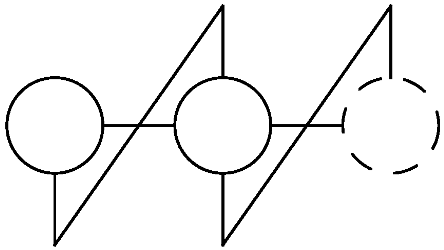


- Warped Higgsless ED is conjectured to be dual to a walking technicolor theory.
- The Three Site Model consistently implements the vector resonances (TC) in a gauge invariant way.
- Satisfies precision electroweak measurements (S=0).

The Three Site Model



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

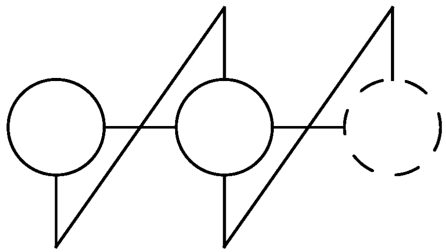


Particle Content

$$\gamma, G \qquad Z, W^{\pm} \qquad Z', W'^{\pm}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} u' \\ d' \end{pmatrix} \begin{pmatrix} c' \\ s' \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad \begin{pmatrix} \nu'_e \\ e' \end{pmatrix} \begin{pmatrix} \nu'_\mu \\ \mu' \end{pmatrix} \begin{pmatrix} \nu'_\tau \\ \tau' \end{pmatrix}$$



$SU(2)_0 \times SU(2)_1 \times U(1)_2$

Gauge Sector

$$g_0 = g, \quad g_1 = \tilde{g}, \quad g_2 = g'$$
$$\tilde{g} \gg g, g'$$
$$\Rightarrow g/\tilde{g} = x \ll 1, g'/g = s/c = t$$

$$\frac{1}{e^2} = \frac{1}{g^2} + \frac{1}{\tilde{g}^2} + \frac{1}{g'^2}$$

$$W_j = \begin{pmatrix} \frac{1}{2}W_j^0 & \frac{1}{\sqrt{2}}W_j^+ \\ \frac{1}{\sqrt{2}}W_j^- & -\frac{1}{2}W_j^0 \end{pmatrix}$$

where j=0,1

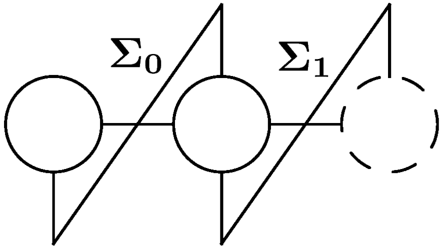
$$\mathcal{L}_{F^2} = -\frac{1}{2}\mathrm{Tr}\left[F_0^2 + F_1^2 + F_2^2\right]$$

$$W_2 = \begin{pmatrix} \frac{1}{2}W_2^0 & 0 \\ 0 & -\frac{1}{2}W_2^0 \end{pmatrix}$$

where

$$F_j^{\mu\nu} = \partial^\mu W_j^\mu - \partial^\nu W_j^\mu + i g_j \left[W_j^\mu, W_j^\nu\right]$$

Casalbuoni, De Curtis, Dominici, Gatto (BESS) Phys. Lett. B155 (1985) 95



$SU(2)_0 \times SU(2)_1 \times U(1)_2$

Gauge - Goldstone Sector

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

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

where

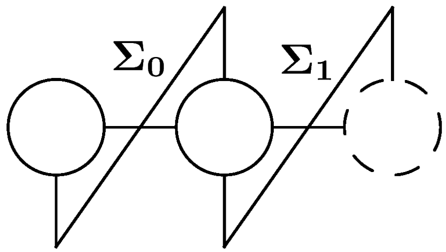
$$D_\mu \Sigma_j = \partial_\mu \Sigma_j + i g_j W_j \Sigma_j - i g_{j+1} \Sigma_j W_{j+1}$$

$$\pi_j = \begin{pmatrix} \frac{1}{2}\pi_j^0 & \frac{1}{\sqrt{2}}\pi_j^+ \\ \frac{1}{\sqrt{2}}\pi_j^- & -\frac{1}{2}\pi_j^0 \end{pmatrix}$$

This gives the gauge boson mass matrices:

$$M_\pm^2 = \frac{f^2}{4} \begin{pmatrix} g_0^2 & -g_0 g_1 \\ -g_0 g_1 & 2g_1^2 \end{pmatrix}$$

$$M_N^2 = \frac{f^2}{4} \begin{pmatrix} g_0^2 & -g_0 g_1 & 0 \\ -g_0 g_1 & 2g_1^2 & -g_1 g_2 \\ 0 & -g_1 g_2 & g_2^2 \end{pmatrix}$$



$SU(2)_0 \times SU(2)_1 \times U(1)_2$

Independent parameters: M_W , M_Z , e , $M_{W'}$

Dependent parameters: g_0 , g_1 , g_2 , f

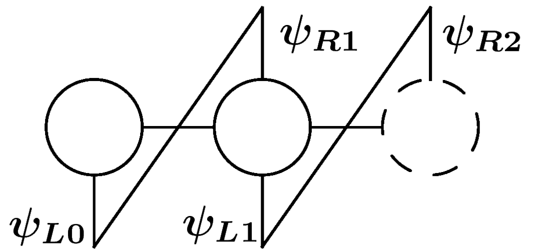
$$x = \frac{g_0}{g_1} \qquad t = \frac{g_2}{g_0}$$

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

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

$$\frac{M_W^2}{M_Z^2} = \frac{2+x^2-\sqrt{4+x^4}}{2+x^2(1+t^2)-\sqrt{4+x^4(1-t^2)^2}}$$

$$M_W = g_1 f\,\frac{\sqrt{2+x^2-\sqrt{4+x^4}}}{2\sqrt{2}}$$



$SU(2)_0 \times SU(2)_1 \times U(1)_2$

Fermion - Gauge Sector

$$\mathcal{L}_{D\psi} = \bar{\psi}_{L0} \not{D}\, \psi_{L0} + \bar{\psi}_1 \not{D}\, \psi_1 + \bar{\psi}_{R2} \not{D}\, \psi_{R2}$$

$Y_{0,1Q} = 1/6 \quad Y_{0,1L} = -1/2$

$Y_{2u} = 2/3$

$Y_{2d} = -1/3 \quad Y_{2e} = -1$

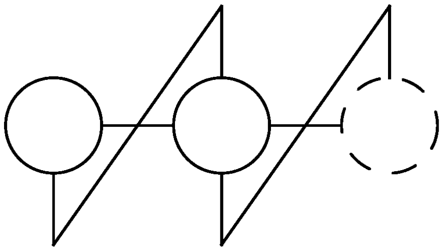
where

$$D_\mu \psi_j = \partial_\mu \psi_j + i g_j W_j \psi_j + i g_2 Y_{jf} W_2 \psi_j$$

for *j=1,2*
and

$$D_\mu \psi_2 = \partial_\mu \psi_2 + i g_2 Y_{2f} W_2 \psi_2$$

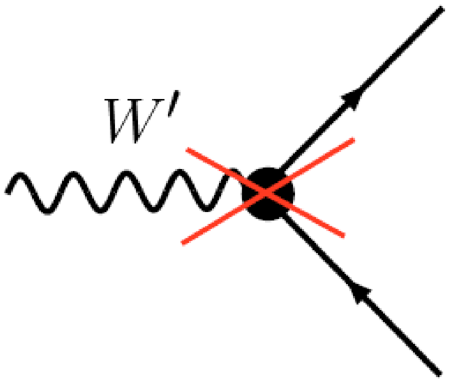
Ideal Delocalization (IDEL)



$$g_i v^i_{Le} v^i_{L\nu} = [g_{W_{SM}} + O(x^4)] v^i_W$$

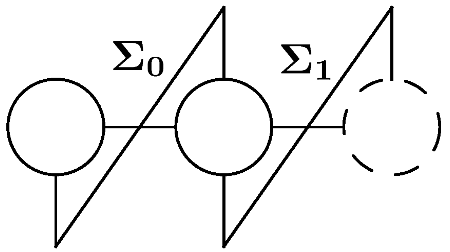
$$\epsilon_L^2 = \frac{2x^2}{2 - x^2 + \sqrt{4 + x^4}}$$

$$\begin{aligned} g_{W_{TSM}} &= g_0 v^0_{Le} v^0_{L\nu} v^0_W + g_1 v^1_{Le} v^1_{L\nu} v^1_W \\ &= [g_{W_{SM}} + O(x^4)] \left(v^0_W v^0_W + v^1_W v^1_W \right) \\ &= g_{W_{SM}} + O(x^4) \end{aligned}$$



$$\begin{aligned} g_{W'_{TSM}} &= g_0 v^0_{Le} v^0_{L\nu} v^0_{W'} + g_1 v^1_{Le} v^1_{L\nu} v^1_{W'} \\ &= g_{W_{SM}} \left(v^0_W v^0_{W'} + v^1_W v^1_{W'} \right) \\ &= 0 \end{aligned}$$

Chivukula, Simmons, He, Kurachi, Tanabashi: PRD 72, 015008 (2005)
Casalbuoni, Deandrea, De Curtis, Dominici, Gatto, Grazzini, : PRD 53, 5201 (1996)



Gauge Fixing Sector

$$\mathcal{L}_{GF} = -\mathrm{Tr}\left[G_0^2 + G_1^2 + G_2^2\right]$$

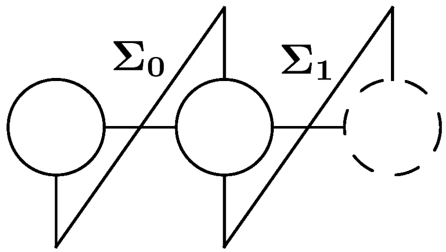
where

$$G_0 = \partial \cdot W_0 - \tfrac{1}{2} g_0 f(\pi_0 \quad)$$

$$G_1 = \partial \cdot W_1 - \tfrac{1}{2} g_1 f(\pi_1 - \pi_0)$$

$$G_2 = \partial \cdot W_2 - \tfrac{1}{2} g_2 f(\quad - \pi_1^{ns})$$

$$\pi_1^{ns} = \begin{pmatrix} \frac{1}{2}\pi_j^0 & 0 \\ 0 & -\frac{1}{2}\pi_j^0 \end{pmatrix}$$



$SU(2)_0 \times SU(2)_1 \times U(1)_2$

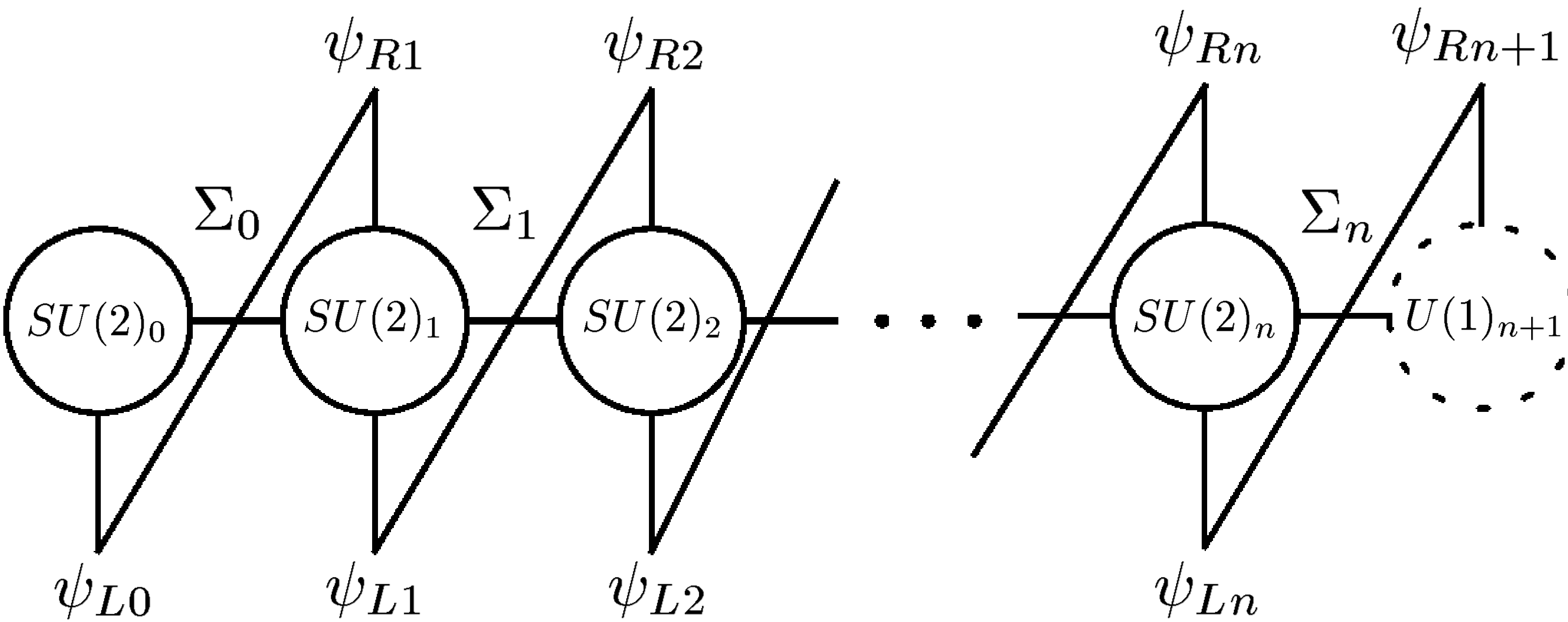
Ghost Sector

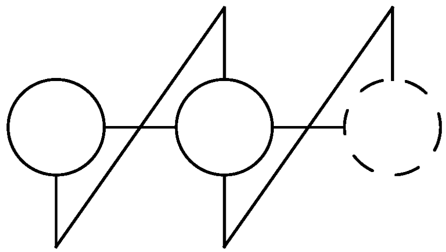
$$\mathcal{L}_{\bar{c}c} = -\mathrm{Tr}\Big[\bar{c}_0\delta_{_{BRST}}G_0 + \bar{c}_1\delta_{_{BRST}}G_1 + \bar{c}_2\delta_{_{BRST}}G_2\Big]$$

where

$$\delta_{_{BRST}}W_{\mu j} = -\Big(\partial_\mu c_j + ig_j\,[\,W_{\mu j}\,,\,c_j\,]\Big)$$

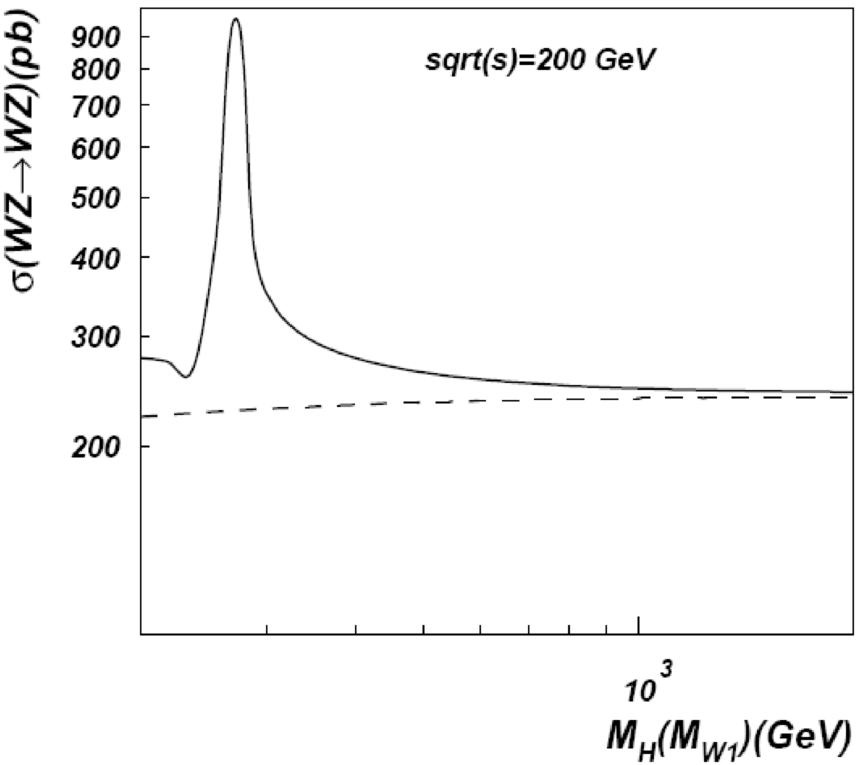
$$\delta_{_{BRST}}\pi_j = \tfrac{1}{2}f\big(g_jc_j - g_{j+1}c_{j+1}\big) + \tfrac{i}{2}\,[\,g_jc_j + g_{j+1}c_{j+1}\,,\,\pi_j\,]$$
$$-\tfrac{1}{6f}\big[\,\pi_j\,,\,[\,\pi_j\,,\,g_jc_j - g_{j+1}c_{j+1}\,]\,\big] + \cdots$$


ψ_{R1}
ψ_{R2}
ψ_{Rn}
ψ_{Rn+1}
Σ_0
Σ_1
Σ_n
$SU(2)_0$
$SU(2)_1$
$SU(2)_2$
$SU(2)_n$
$U(1)_{n+1}$
ψ_{L0}
ψ_{L1}
ψ_{L2}
ψ_{Ln}

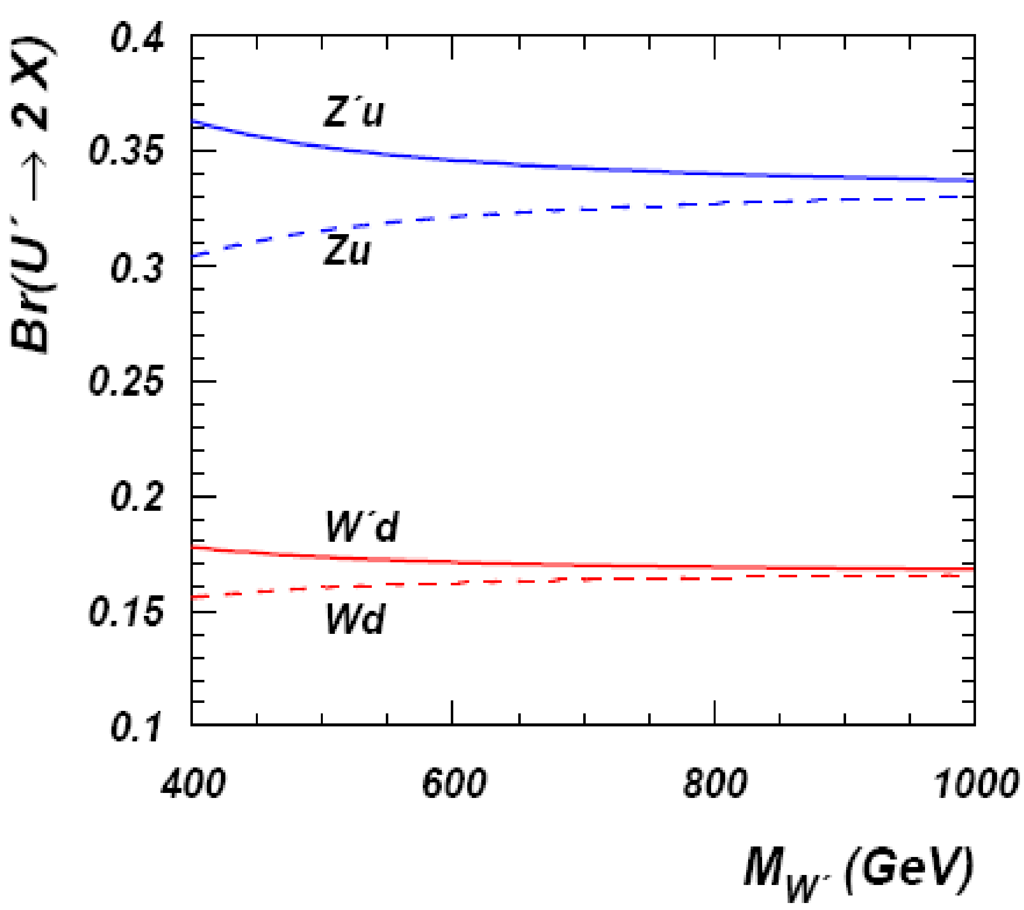


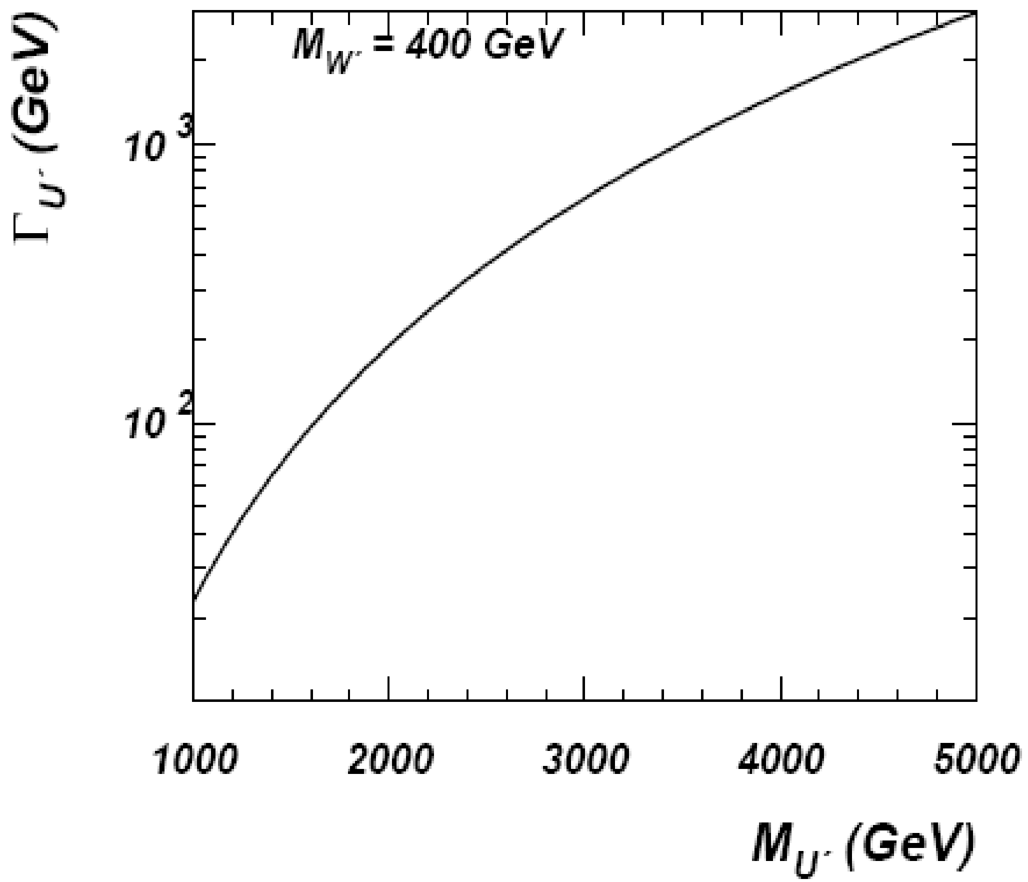
Checks:

- **Feynman vs. Unitary gauge.**
- **Decoupling of heavy fields.**
- **Masses and mixings (LanHEP).**
- **Hermiticity (LanHEP).**



Heavy fermions





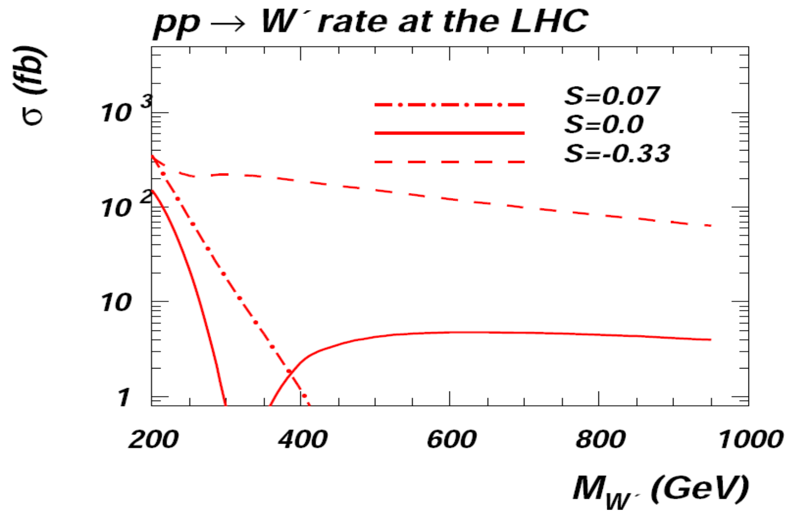
- ***crucial ingredient of the model, in particular, provide unitarity***
- ***but are too heavy to be observed even in strong pair production processes***

LHC reach for DY tri-lepton signature

In case of maximal deviation from idea delocalization

$$pp \to W' \to WZ \to 3\ell + \nu$$

process can become important

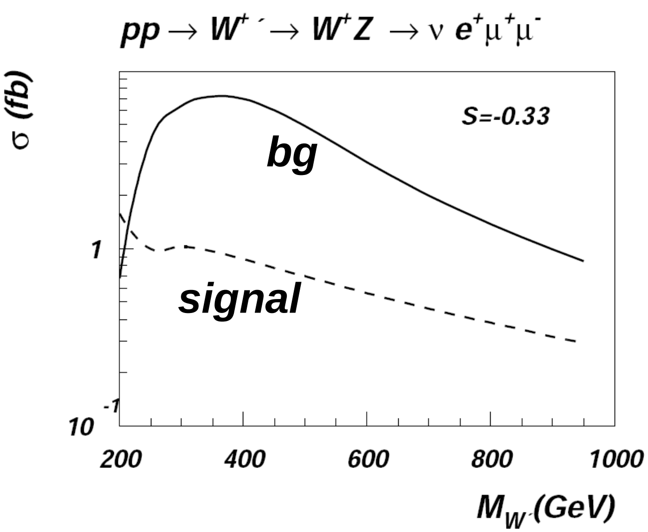


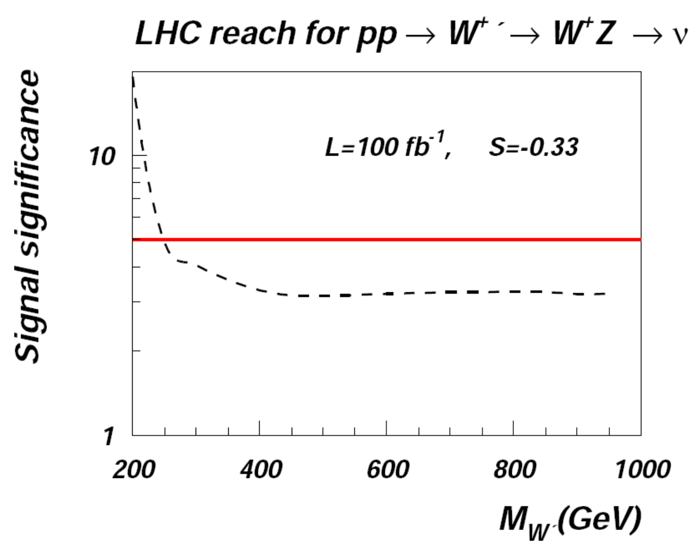
cuts:

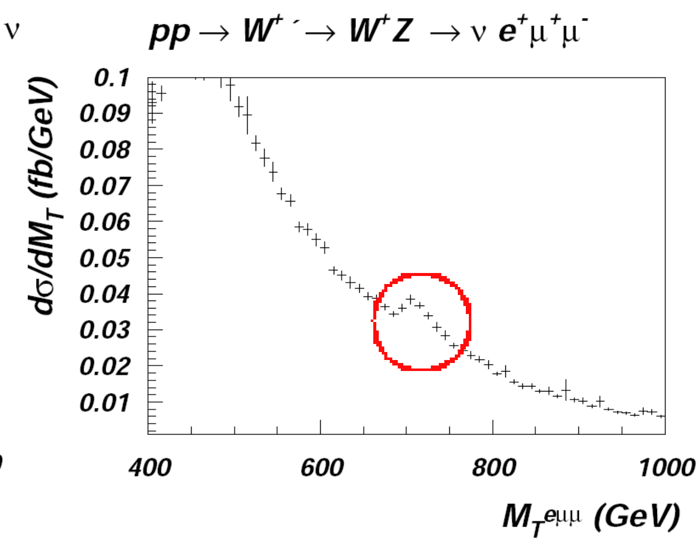
$$|M_{\mu^+\mu^-} - M_Z| < 10 \text{ GeV}$$
$$P_T^\ell > 20 \text{ GeV}$$
$$M_{W'} + 5\Gamma_{W'} > M_T^{e\mu\mu} > M_{W'} - \Gamma_{W'}$$

~ 1 fb for $M_{W'}$=700 GeV but

further BG reduction is necessary: work in progress

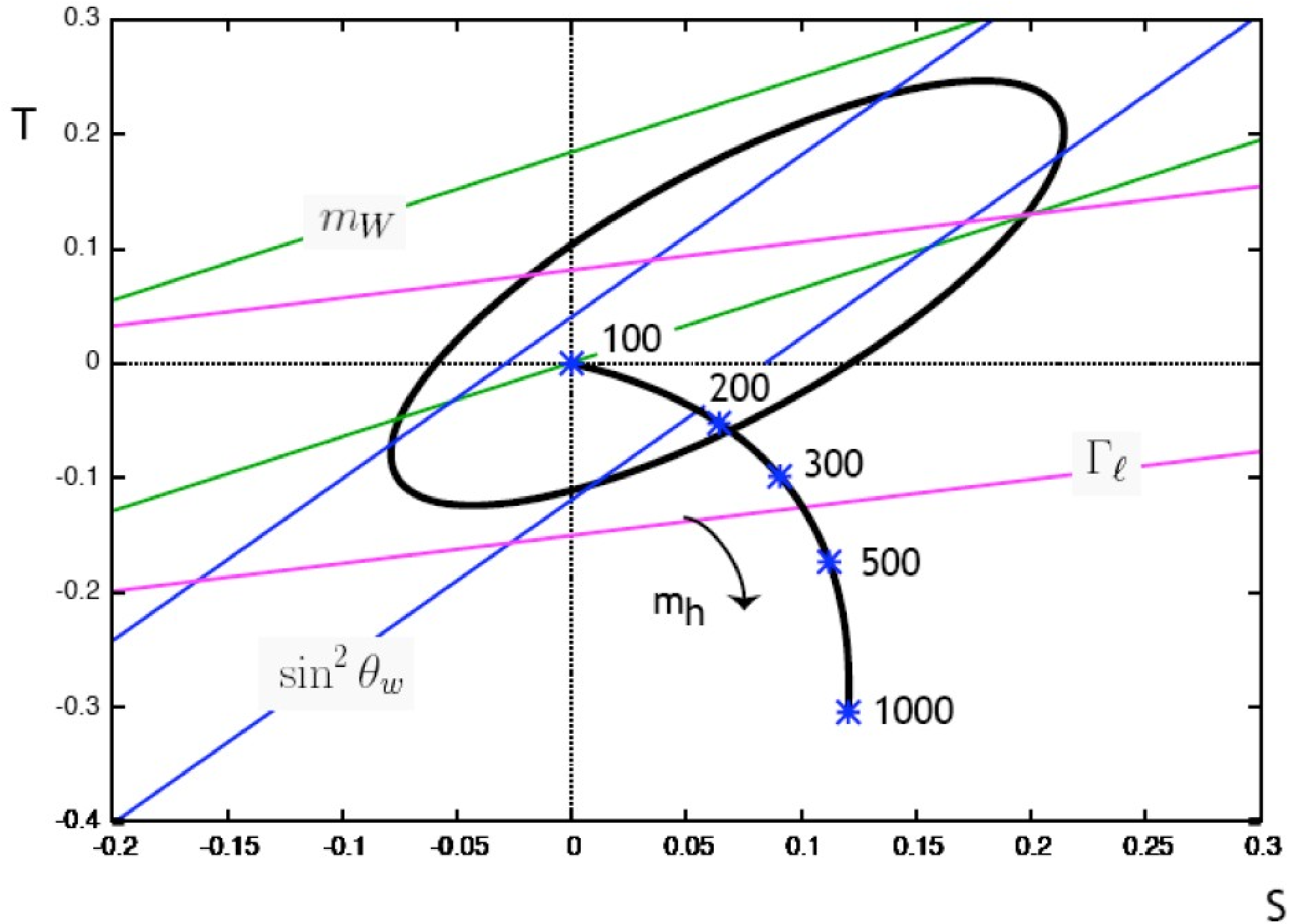






EW precision data

Fits to precision electroweak data also constrain the Higgs boson mass in the SM.



LEP EWWG: $m_h < 240$ GeV (95% conf.)