Twin Higgs, Little Twin Higgs

and signature ??

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Little Hierarchy Problem

EW symmetry breaking in standard model

$$V = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Higgs mass is UV sensitive

$$m^2 \sim m_B^2 + O\left(\frac{\Lambda^2}{16\pi^2}\right)$$

Precision EW ⟹ new physics at $\Lambda \gtrsim 5$ TeV

Global fits ⟹ Higgs mass $\lesssim 200$ GeV

m $\lesssim 130$ GeV

Cancellation between m_B^2 and Λ^2 is needed. Fine tuning $\sim$ 2%

With cut off 5 TeV

Twin Higgs mechanism was proposed, using the idea
that Higgs is a pseudo Goldstone boson, to solve the problem.

[Chacko,HSG and Harnik]

Now there are two classes of realistic models

- Mirror model -- SM^2
- Left-right model -- $SU(2)_{L,R}$

Few things to remind you about these classes of models are

- The leading role is played by the simplest symmetry you can imagine ----- Z_2
- Quadratic divergences are cancelled at all loops !!
- EWSB with only mild tuning can be achieved even if no tree level quartic is introduced (This is also one of the reason why they stay to be so simple).

Since there is no tree level potential for the Goldstone, both the quadratic and quartic terms come from the expansion of the one loop generated potential.

- Suppressing the one-loop contribution will NOT change the vev or tuning significantly. It only make the Higgs lighter. (Let me remind you that there is a lower bound on Higgs mass)
- If there is a operator that give a quartic but not mass to the SM Higgs, we can reduce fine tuning and raise the cut off.

- Question : Can we find a simple way to introduce a tree level quartic without generating m^2 for the SM Higgs ?
- Answer : Yes, for the mirror model.

[Chacko, Nomura, Papucci and Perez]

In this case, mirror photon is massive. It is good !

(don't have to worry about photon-mirror photon mixing, although mixing arise only at 4-loop)

Or bad

(difficult in cosmology)

- Next question : Can we do the same for the LR model ?
- First thought : No. there is no mirror photon in LR model and that is our photon picking up the mass. It is, as you know, very bad !

However, with a "little" twist, it is possible !

Outline

- Twin Mechanism
- Twin Higgs from Left-Right Symmetry
- Little Twin -- a way to get a tree level quartic in LR model
- Phenomenology
- Conclusion

Higgs : Like a Pion ?

- Idea : Higgs is pseudo-Goldstone boson (like π)
  → 'Naturally' lighter at tree level
- Original problem : large one-loop correction to mass (NOT tree level)
- Pseudo Goldstone : same large one-loop correction unless the breaking term is small or soft.
- Higgs is charged under SM → embedding is partial.
  → gauge couplings (hard) break the global symmetry.
- The problem remains (just like standard model).
- More structure is needed.

Twin Mechanism

- Basic idea : Goldstone boson $\oplus$ discrete symmetry
- Global SU(4) symmetry in Higgs potential
- H transform as a fundamental
- <H>=(0,0,0,f) break SU(4) to SU(3) ⇒ 7 Goldstone bosons
- $H=(H_A,H_B)$, both H_A and H_B are corresponding doublets under
- $SU(2)_A \times SU(2)_B \subset SU(4)$ are gauged
- SU(4) is explicitly broken ⇒ Goldstone bosons get a mass.

∞

$$\alpha\Lambda^2 H_L^\dagger H_L + \beta\Lambda^2 H_R^\dagger H_R = \alpha\Lambda^2 H^\dagger H$$

Z_2

For the GB, quadratically divergent m^2 vanishes to all order

Left-Right Models

[Chacko,HSG,Harnik. hep-ph/0512088]

- Twin parity can be realized by left-right symmetry.

$$\mathrm{L} \overset{\text{Twin}}{\longleftrightarrow} \mathrm{R}$$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \longleftrightarrow \begin{pmatrix} u_R \\ d_R \end{pmatrix} = Q_R$$

$$H_L^i \longleftrightarrow H_R^i \quad \Rightarrow \quad H^i = \begin{pmatrix} H_L^i \\ H_R^i \end{pmatrix}$$

Traditional LR model contains Higgs in triplet and bi-doublet.

Twin mechanism seems to work only for fundamental representation.

Higgs Sector

- Two set of scalar fields : H^1 and H^2
- Second set of scalar is needed to evade bound from Z' searches
- Focus on effective theory below the scale $\Lambda \sim 4\pi f$
- H^i is non-linearly realized
- Transforms under SU(4) as a fundamental

$$H^i = f_i e^{\pi_i} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \;;\; \pi_i = \begin{pmatrix} & 0 & & h_1^\dagger \\ & & & h_2^\dagger \\ & & & C^\dagger \\ h_1 & h_2 & C & \phi \end{pmatrix}_i$$

Gauge Sector

$$SU(2)_L \times \cancel{SU(2)_R \times U(1)_{B-L}}$$

$$\Big\downarrow \langle H \rangle = f$$

$$U(1)_Y$$

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left-right symmetry $\longrightarrow$ $g_L = g_R = g_2$

Massive gauge bosons : W_H and Z_H with masses

$$m_{ZH}^2 \sim m_{WH}^2 \sim \tfrac{1}{2} g^2 (f_1^2 + f_2^2)$$

Z' searches $\longrightarrow$ $f_2 \gtrsim 2$ TeV , $f_1 \sim 800$ GeV

Top Sector

In addition to Q_L and Q_R for each family,
There are one vector-like pair of quarks T_L and T_R in the top sector
With these extra particles, we can write

$$y(\overline{Q}_R H_R^\dagger)T_L + y(\overline{Q}_L H_L^\dagger)T_R + M\overline{T}_L T_R \qquad m_{TH}^2 \sim M^2 + y^2 f_1^2$$

Preserve L-R symmetry
M can be arbitrarily small

Higgs Potential and Fine Tuning

- Higgs m^2 get a negative contribution from top loop
- Positive contribution from gauge loop
- Tuning these two terms to get correct EW symmetry breaking fix $\hat{f}$ with f
- Fine tuning is ~ 12 % for f=800 GeV and 27% for f=500 GeV with the best case scenario $\Lambda=4\pi f$

Λ (TeV)	f (GeV)	$\hat{f}$ (TeV)	M (GeV)	$\sqrt{B}$ (GeV)	m_h (GeV)	Tuning
10	800	4.29	150	50	174	0.117
6	500	2.27	150	50	172	0.270
5	800	4.68	150	50	155	0.124

Tree Level Quartic

Mismatch operator : a quartic operator that does not generate a mass term.

[Kaplan and Schmaltz, in Little Higgs model]

[Chacko, Nomura, Papucci and Perez, Twin Higgs from Mirror symmetry]

Idea : in the mirror model, with the miss-aligned vev

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} \; ; \; \widehat{H} = \begin{pmatrix} 0 \\ 0 \\ \widehat{f} \\ 0 \end{pmatrix}$$

the operator

$$\left| H^\dagger \widehat{H} \right|^2$$

gives a quartic to standard model Higgs but only gives masses to mirror Higgs.

This is easy to see from the expansion

$$H = \begin{pmatrix} ih \\ C \\ f - \frac{h^\dagger h}{2f} \end{pmatrix} \quad ; \quad \widehat{H} = \begin{pmatrix} i\hat{h} \\ \widehat{f} - \frac{\hat{h}^\dagger \hat{h}}{2\widehat{f}} \\ \widehat{C} \end{pmatrix} \begin{matrix} \} \text{ SU(2)\_SM} \\ \} \text{ SU(2)'} \end{matrix}$$

$$\left| H^\dagger \widehat{H} \right|^2 = \left| h^\dagger \hat{h} \right|^2 + \left| \widehat{f} C + f \widehat{C} \right|^2 + \ldots$$

The operator only generate mass terms for the mirror Higgs C and others.

Note also that the mirror photon becomes massive since
the mirror SU(2) X U(1) is totally broken.

Quartic in LR model

[HSG and Krenke]

- There are already two Higgs in the LR model. We can use the trick without introducing any new particle. However, the above design seems to cause problem in the LR model.
- Recall that unlike the mirror model, there is only one U(1) in the LR model (No twin). the mis-alignment of vev breaks the symmetry

$$SU(2)_R \times U(1)_{B-L}$$

↓

Nothing ⇒ Photon become massive

.

There are two equivalent ways to achieve the task:

- Asymmetry U(1) change assignment for H and $\widehat{H}$
- Construct a different quartic operator

We propose the operator

$$\left| H_L^\dagger \widehat{H_L} \right|^2 + \left| H_R^T \tau_2 \widehat{H_R} \right|$$

together with the aligned vev

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} \; ; \; \widehat{H} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \widehat{f} \end{pmatrix}$$

No mass for the SM Higgs and the photon remains massless.

Is the left-right symmetry destroyed ?

This two terms will first seem asymmetry
but one can define an alternative twin symmetry

$$H_L \leftrightarrow H_R \longrightarrow \text{P}$$

$$\widehat{H}_L \leftrightarrow \tau_2 \widehat{H}_R^* \longrightarrow \text{CP}$$

- But this symmetry is not preserved by the $U(1)_{B-L}$ gauge couplings.
- Fortunately, what we are trying to solve is the little hierarchy problem.
- We need only to protect the quadratic terms up to one-loop
  (exact twin symmetry has over done in this sense).

- All gauge couplings preserve the usual twin symmetry

$$H_L \leftrightarrow H_R \qquad \widehat{H}_L \leftrightarrow \widehat{H}_R$$

or

$$H_L \leftrightarrow \tau_2 H_R^* \qquad \widehat{H}_L \leftrightarrow \tau_2 \widehat{H}_R^*$$

Either one of these discrete symmetry is enough to protect the pseudo Goldstone boson from getting quadratically divergent masses.
Quadratically divergent term arise only when the Twin symmetry is
collectively broken at at least 2 loops. (3 loop and $\propto g_{B-L}^2$)

Small m^2

- We also try to suppress m^2 as much as we can. The Largest contribution comes from top Yukawa. We need to make the top Yukawa SU(4) invariant. The original top Yukawa term

$$y(\bar{Q}_R H_R^\dagger)T_L + y(\bar{Q}_L H_L^\dagger)T_R + M\bar{T}_L T_R$$

introduce two sets of vector-like quarks $(\tilde{Q}_L, \tilde{Q}_L^c)$

$(\tilde{Q}_R, \tilde{Q}_R^c)$

each complete one of the two top Yukawa terms to SU(4) invariant.

$$y(\bar{Q}_R H_R^\dagger + \bar{\tilde{Q}}_L H_L^\dagger)T_L + y(\bar{Q}_L H_L^\dagger + \bar{\tilde{Q}}_R H_R^\dagger)T_R + M\bar{T}_L T_R + M_L \bar{\tilde{Q}}_L \tilde{Q}_L^c + M_R \bar{\tilde{Q}}_R \tilde{Q}_R^c$$

SU(4) invariant is broken softly by $M_L = M_R$ that decouple the vector-like quarks.

Summary

- We have found a way to introduce a tree level quartic
  (large λ)
- Quadratically divergent is still protected at one loop.
  (collective Z_2 breaking)
- Large log divergent from top Yukawa become finite
  (small m^2; SU(4) invariant top Yukawa)

The fine tuning is about 30 % for Λ = 10 TeV

Phenomenology- review

mirror

⇩

~ 5 % invisible Higgs decay

--Probably out of LHC reach

--An example of dark(colorless) solution.

Left-right

⇩

Many observable new particles:

- traditional left right model

  WH, ZH

- vector-like heavy top

  TH (colorful)

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The little twin Higgs

- New degree of freedom
  - Two vector-like quark (m ~ few TeV), probably too hard to be produced
- New coupling
  - Tree level quartic coupling. Change the dynamic of scalars
- New vev
  - The new quartic operator does not break the parity that make the dark matter $\hat{h}^0$ stable. But the parity is spontaneously broken. The new model does not have dark matter candidate.

Leading order collider signature is unchanged

Phenomenology -LR model

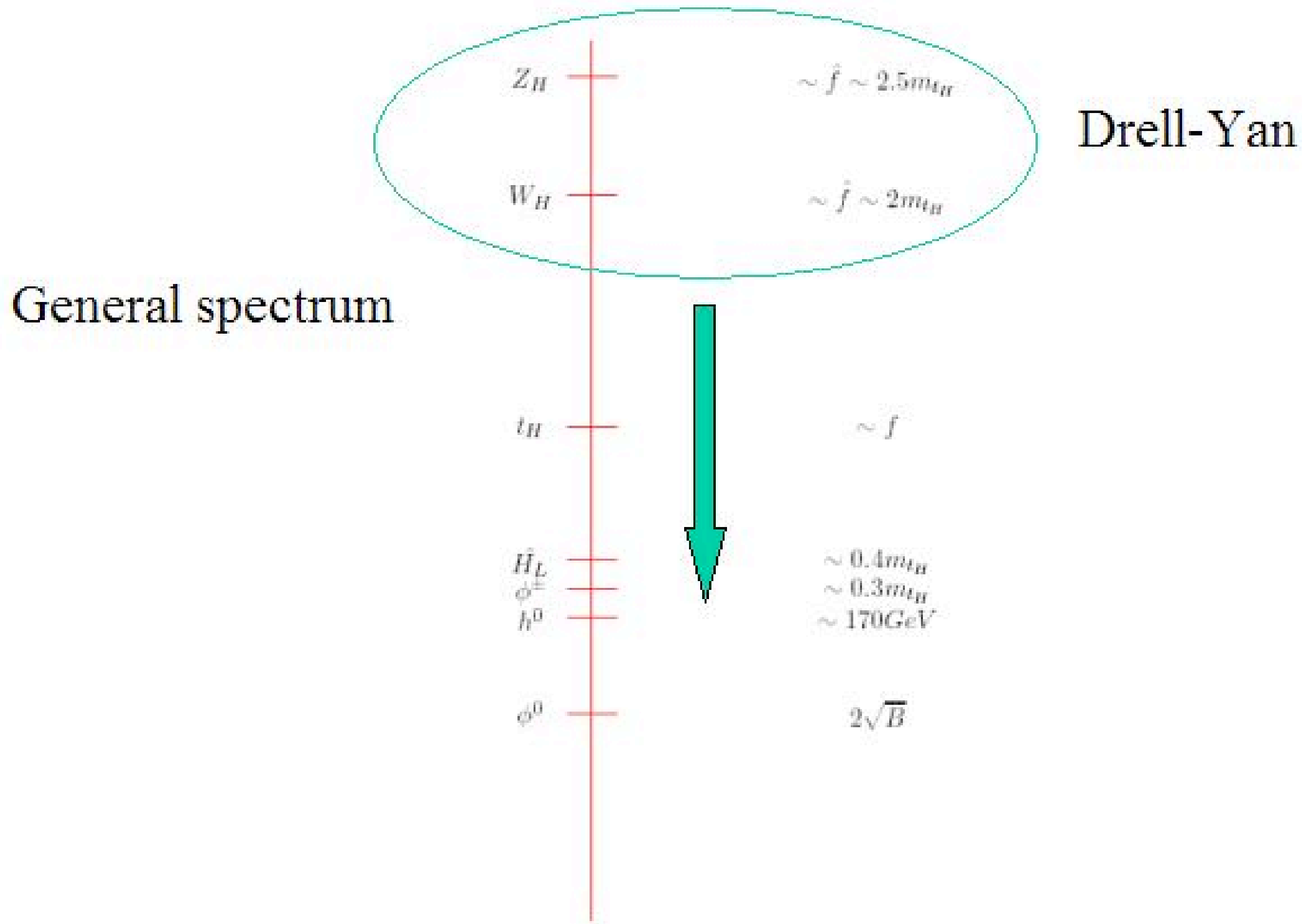
[HSG and Su]

New parameters : $f, \hat{f}, y, M$ (very few)

- $\hat{f}$ is fixed by f to get m_W
- y is fixed by m_t
- M is arbitrary. It can even be zero

New particles

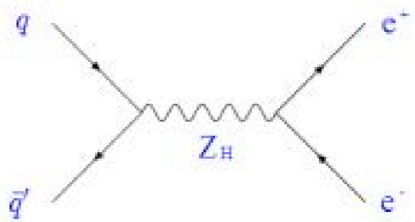
- W_H, Z_H
- T_H
- 14-6=8 : h°, $\widehat{H}_L$, $\phi^\pm$ and ϕ^0

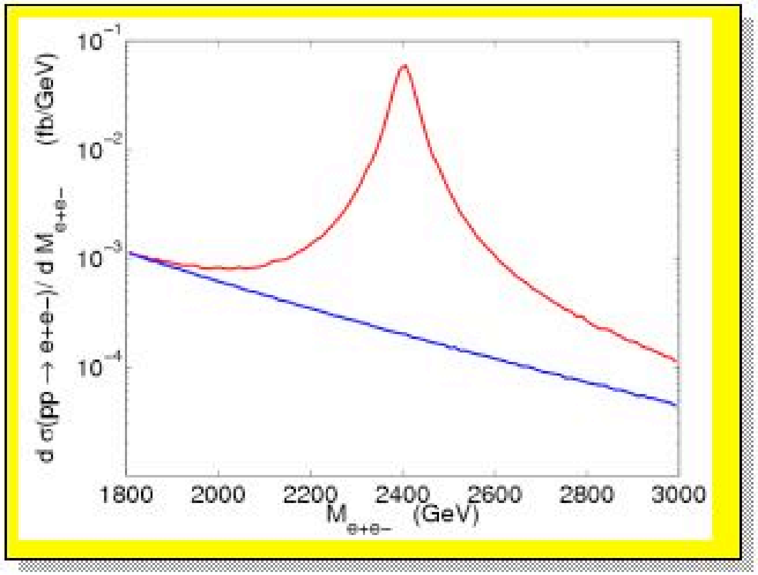

Drell-Yan
General spectrum
Z_H
$\sim \hat{f} \sim 2.5 m_{t_H}$
W_H
$\sim \hat{f} \sim 2 m_{t_H}$
t_H
$\sim f$
$\hat{H}_L$
$\sim 0.4 m_{t_H}$
$\phi^{\pm}$
$\sim 0.3 m_{t_H}$
h^0
$\sim 170 GeV$
ϕ^0
$2\sqrt{B}$

Z_H and W_H are produced by Drell-Yan process

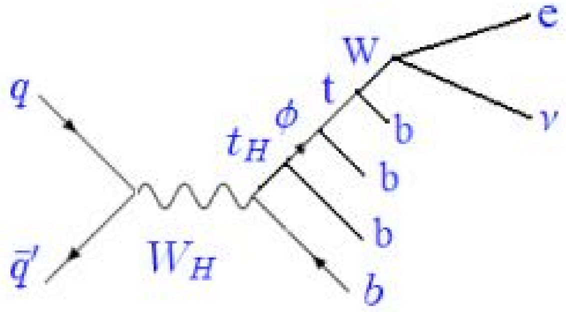
Z_H mass

Can be measure through

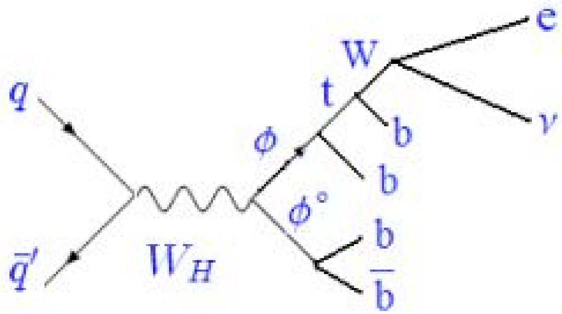




Two W_H decay chain (for M = 150 GeV)



- have nice leptonic final state
- particle in the chain are on shell
- reconstruct TH, WH, charged sclar
- with help from tagging b and cuts, BG can be largely reduced



We can definitely see these particles at the LHC

However,

The color heavy top can appear dark

In the special case $M = 0$

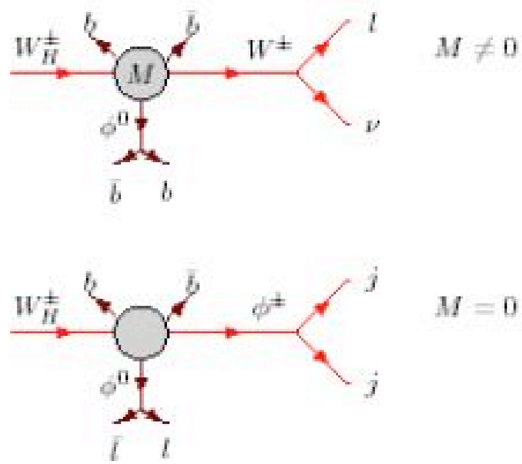
[Chacko, HSG and Krenke]

work in progress

$$(\bar{Q}_R H_R^\dagger)T_L + (\bar{Q}_L H_L^\dagger)T_R + \cancel{M\bar{T}_L T_R}$$

Heavy top — SM top

decouple



Either

- Final states are hadronic
- Suppress by small Yukawa

Only easy signal is $Z_H \rightarrow ee$

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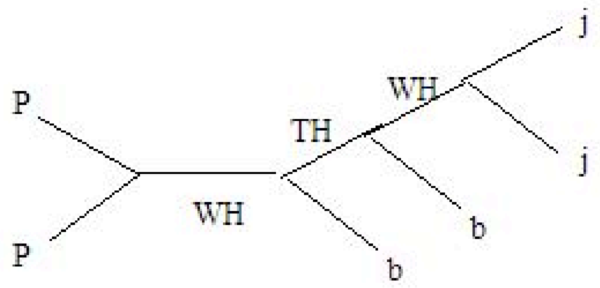
Why consider M=0 "special" case

- some TH contributions to precision electroweak depend on M

  kill these contributions by setting M $\rightarrow$ 0
- the model works exactly as effective as non zero M
- minimal set of parameter.
- It is technically natural, i.e. there is a chiral symmetry protecting the mass.
- It become another example of dark solution of little hierarchy problem.
- challenging but we don't want to miss finding our model at the LHC.

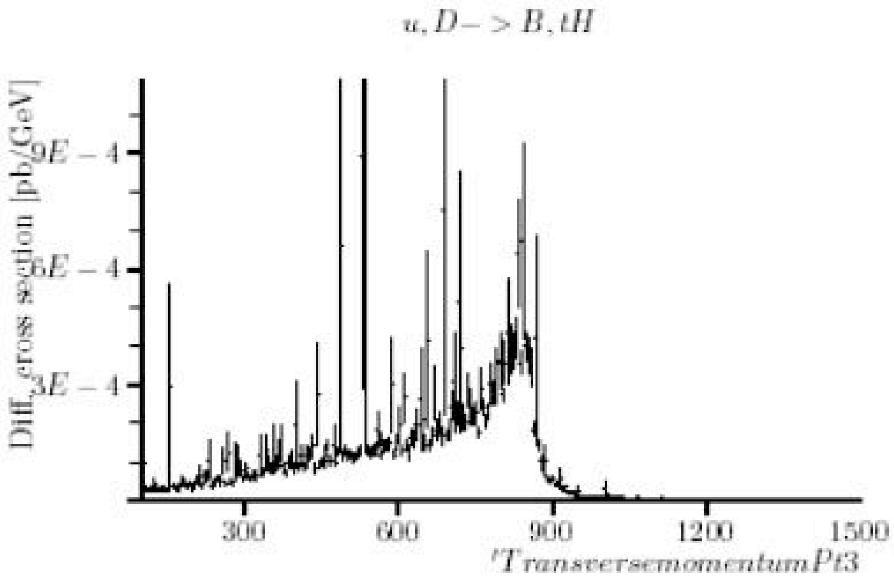
Simplest signal : 2b + 2jet (compete with μb 4-jet QCD background)



- Signal is of order ~ few 100 fb before any cut or b-tagging.
- For WH ~ 2 TeV, the first b jet has P_T peak at ~ 800 GeV
- Very likely the 2 jet and the second b all have P_T ~ 400 GeV

  To suppress the QCD background, we need to tag the 400 GeV b-jet, and require one 800 GeV high P_T jet
- Two resonances : m_{TH} and m_{WH}

  use the invariant mass of bjj and bbjj


$u, D- > B, tH$
Diff. cross section [pb/GeV]
$9E-4$
$6E-4$
$3E-4$
300
600
900
1200
1500
$'TransversemomentumPt3$

Tagging High P_T b-jet

- no study on b-tagging at P_T > few 100 GeV, and efficiency at Tev is expected to be small
- We assume for $P_T \sim 400$ GeV, the efficiency ~ 40% and the rejection ~2.5 %
- For higher P_T assume b-tagging is impossible
- our signal is actually 1b + 3 jet, however, keep all events with one or two b jet.
- cut : at least one b with $P_T > 300$ GeV, one other jet (b or light) has $P_T > 600$ GeV

L. March, E. Ros, M. Vos, talk presented at the Les Houches BSM working group, Twin Higgs discussion session, 23rd June, 2007.

Preliminary result ~

Signal(pb) (From CalcHEP) — Backgroud(pb) (From Madgraph)

	b+3 jet	4b	2b+2 jet	4 jet
No cut	0.2	4	>600	>1000
600 GeV jet +300 GeV b	~0.1	<0.1	4	30
B tag factor	0.4	0.7	0.4	0.1
Cross-section	0.04	<0.07	1.6	3
Inv mass				

$\frac{S}{B} \sim 0.01$

or

$\frac{S}{\sqrt{B}} \sim 3$

for luminosity of 30 fb^{-1}

??

Conclusion

- LEP paradox is solved by Twin Mechanism
- Original LR model is improve by collective symmetry breaking of twin parity: for cut off of 10 TeV
    - Original model fine tuning : 11 %
    - Improved model fine tuning : 30 %

Predict

- Extra gauge bosons W_H and Z_H with mass ~ few TeV
- Extra top quarks of mass ~ f ~ 800 GeV
- These particles are within LHC reach
- Even for the decoupling case, reconstructing the heavy top is possible.

More detailed analysis needs to be done (work in progress)