TOP-BESS MODEL

AND

ITS PHENOMENOLOGY

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Outline

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Electroweak Symmetry

Gauge Principle

$$SU(2)_L \times U(1)_Y \quad \Rightarrow \quad \text{EW interactions}$$

theory = experiment ... to high precision

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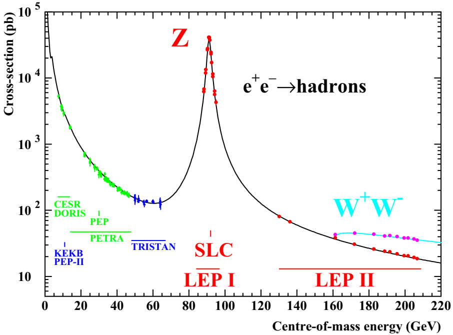

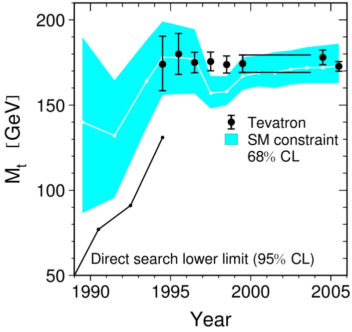

ESB PUZZLE

masses **break** EW symmetry

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How to reconcile EW symmetry with masses?

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the puzzle: $\mathcal{L}_{spont.ESB} = ?$

Benchmark hypothesis $\longrightarrow$ SM Higgs

- $SU(2)_L$ complex scalar doublet Φ
- $v = \langle 0|\Phi|0\rangle$

Higgs boson

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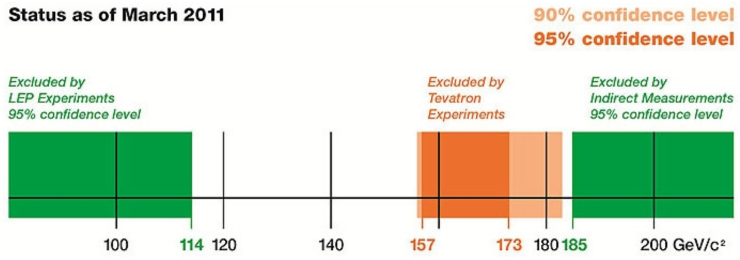

BENCHMARK HYPOTHESIS → SM HIGGS

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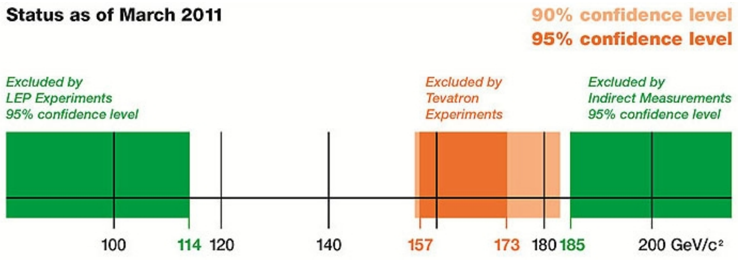

theoretical pathologies → just a good parameterization of ESB?

ESB alternatives

strongly interacting:

- new *non-perturbative* forces
- new particles $\rightarrow$ *bound states*
- TC and its extensions

weakly interacting:

- new *perturbative* forces
- new *elementary* fields
- more Higgses, SUSY

$\searrow$ $\swarrow$

extra-dimensions:

- 4D *strongly* interacting $\longleftrightarrow$ 5D *weakly* interacting
- Kaluza-Klein towers

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New particles WANTED!

Model InDependent

heavy/no Higgs violates unitarity $\approx$ 1 TeV

Model Dependent

- SUSY: ... superpartners, Higgs-like scalars
- TC: ... bound states
- extra-dim: ... KK towers

Effective description of Strong ESB

- $SU(2)_L \times U(1)_Y$ broken *dynamically*
- LHC $\rightarrow$ the *lightest* BSM resonances
- *not* solvable perturbatively
- *chiral effective* Lagrangian for Goldstone bosons

  nonlinear sigma model

- ... + resonances

  scalar, vector, ...

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Outstanding Top Quark

$m_t \approx v/\sqrt{2}$ → special role in ESB?

new physics behind m_t

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ESB related

$W^\pm, Z, t$ ... *couple significantly* to the same new resonances (Extended TC)

ESB *unrelated*

t vs. $W^\pm, Z$ ... *couple significantly* to different new resonances (Topcolor Assisted TC)

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Minimal ESB requirements

- $G \xrightarrow{SSB} H$

$$G = SU(2)_L \times SU(2)_R, \quad H = SU(2)_{L+R}$$

- massive $W^\pm$, Z ... Nambu-Goldstone bosons

$$M_{W,Z} \sim v = 1/\sqrt{2^{1/2} G_F} \approx 250 \text{ GeV}$$

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G/H non-linear sigma model ... no Higgs boson

ESB: $G = SU(2)_L \times S(U)_R$ $\rightarrow$ $H = SU(2)_{L+R}$ ... $G/H = SU(2)_{L-R}$

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}[(\partial_\mu U^\dagger)(\partial^\mu U)] \approx \frac{1}{2}(\partial_\mu \pi^a)(\partial^\mu \pi^a) + \mathcal{O}(1/v)$$

$U = \mathrm{e}^{2i\pi(x)/v} \approx \mathbb{I} + \frac{2i}{v}\pi^a(x)\tau^a$ ... $[\tau^a, \tau^b] = i\varepsilon^{abc}\tau^c, \quad a,b,c = 1,2,3$

$G: \quad U \rightarrow g_L \, U \, g_R^\dagger$ ... $g_{L,R} \in SU(2)_{L,R}$

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Higgsless ESB + Vector Resonances

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Any NLσM(G/H) is *gauge equivalent* to "linear" $G_{glob} \times H_{loc}$ model.

- vector resonances = *dynamical* H_{loc} gauge bosons
- spont. breaking of H_{loc} $\rightarrow$ mass for $V_\mu^a(x)$ multiplet

$$M_V = \frac{\sqrt{\alpha}\, g'' v}{2}$$

- EW gauge bosons $\rightarrow$ mixing
- QCD ρ-meson = dynamical GB of $[SU(2)_L \times SU(2)_R]^{glob} \times SU(2)_V^{loc}$

$\alpha = 2 \quad \Rightarrow \quad$ Sakurai's Lagrangian with ρ-γ mixing and ρ dominance

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    $g \quad g' \quad g'' \quad e$
- *SM fermions:*
  - direct cplng: universal chiral ... bg'', $b'g''$
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$$g \ll \sqrt{\alpha} g'' \quad \Leftrightarrow \quad M_{W^\pm}, M_Z \ll M_{V^0}$$

neutral

$$M_A = 0$$
$$M_Z = \frac{vG}{2}\left[1 - \frac{(g^2 - g'^2)^2}{2g''^2 G^2}\right]$$
$$M_{V^0} = \frac{\sqrt{\alpha} v g''}{2}\left(1 + \frac{G^2}{2g''^2}\right)$$

... $G = \sqrt{g^2 + g'^2}$

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BESS Model: LOW-ENERGY LIMITS

- $0.008 \leq b \leq 0.015$ @ 90%C.L. ... when $g'' = 10$
  - A^{ℓ}_{FB} at Z-peak
  - $\Gamma(Z \to \ell\bar{\ell})$
- $b' \to 0$
  - R-neutrinos absent
  - $K_L - K_S$ mass difference

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- *gauge sector* identical to BESS
- *fermion sector*:
  - *motivation:* extraordinary m_t
  - 3rd quark generation singled out ... b_L, b_R
  - *bottom*$_R$ disentangled from *top*$_R$ ... p
  - new fermion Lagrangian terms ... λ_L, λ_R
    - negligible at V-peak
    - significantly relax low-energy limits
  - *consequences:* weakened low-energy limits on b's (... and λ's)
- *parity:*
  - gauge sector parity invariant
  - new fermion physics parity invariant only if $p = 1$, $b_L = b_R$, $\lambda_L = -\lambda_R$

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    - significantly relax low-energy limits
  - *consequences:* weakened low-energy limits on b's (... and λ's)
- *parity:*
  - gauge sector parity invariant
  - new fermion physics parity invariant only if $p = 1$, $b_L = b_R$, $\lambda_L = -\lambda_R$

TOP-BESS MODEL

- *gauge sector* identical to BESS
- *fermion sector*:
  - *motivation:* extraordinary m_t
  - 3^{rd} quark generation singled out ... b_L, b_R
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Outline

TOP-BESS: NEW COUPLINGS

HLS VECTOR TRIPLET COUPLINGS:

- $SU(2)_{HLS}$ gauge coupling ... g''
- $V^0 \mathtt{t}_L \mathtt{t}_L$, $V^{\pm} \mathtt{t}_L \mathtt{b}_L$, $V^0 \mathtt{b}_L \mathtt{b}_L$ ... $b_L \cdot g''$
- $V^0 \mathtt{t}_R \mathtt{t}_R$ ... $b_R \cdot g''$
- $V^{\pm} \mathtt{t}_R \mathtt{b}_R$ ... $p \cdot b_R \cdot g''$, $0 \leq p \leq 1$
- $V^0 \mathtt{b}_R \mathtt{b}_R$ ... $p^2 \cdot b_R \cdot g''$

2 *lambda* TERMS ... λ_L, λ_R

- *negligible at V-peak*
- *modify interaction of fermions with EW gauge bosons*

Decay Widths

predominantly: $V \to (W, Z) + (t, b)$ ... *with an exception*

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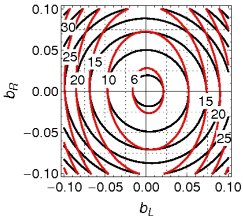
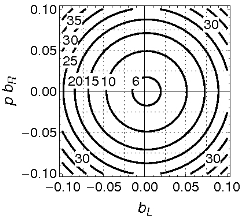


V^0 total width (GeV)

$M_{V^0} = 1$ TeV
$g'' = 20$
$p = 1$
$p = 0$



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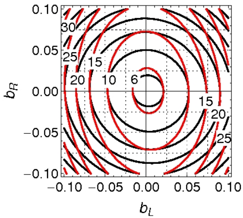

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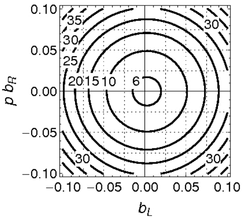

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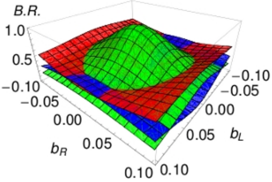
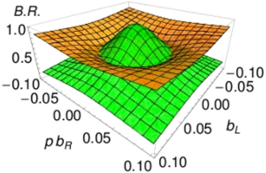


Branching Ratios



Unitarity constraints

- $SS^\dagger = \mathsf{I}$
- $W_L^+W_L^-$, Z_LZ_L, $W_L^\pm Z_L$, $W_L^\pm W_L^\pm$
- tree level
- $J = 0$ partial waves
- Equivalence Theorem ... $M_{W,Z} \ll \sqrt{s} \ll 4\pi v \approx 3$ TeV

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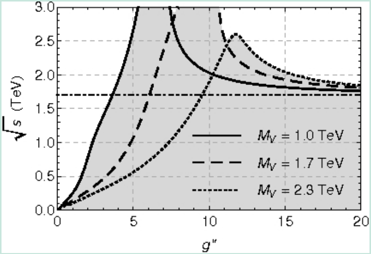
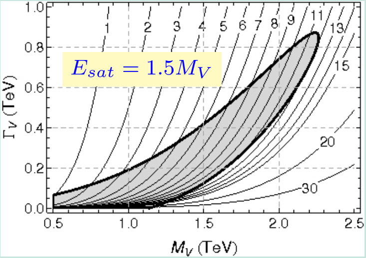


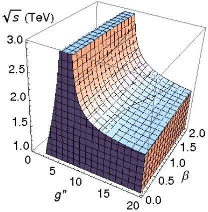


$b_{L,R} = \lambda_{L,R} = 0$

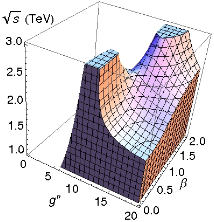
Unitarity & new fermion couplings

$$\beta = [b_L^2 + b_R^2(1+p^2)/2]^{1/2}$$

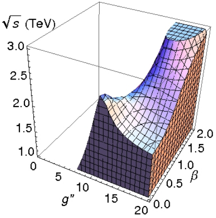
$M_V = 1$ TeV



$M_V = 2$ TeV



$M_V = 2.3$ TeV



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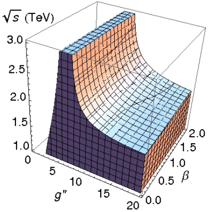

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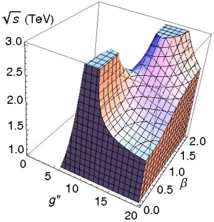

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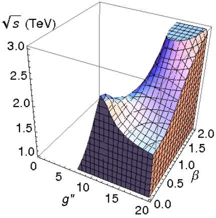
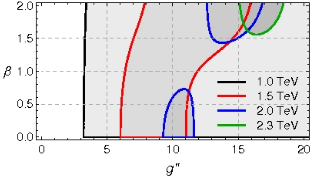


$E_{sat} = 1.5 M_V$ $\Rightarrow$



low-E tBESS: Matching the experiment

$\mathcal{L}_{tBESS} \longrightarrow \mathcal{L}_{tBESS}^{low-E}$ ... integrating out V

1. the non-decoupling limit $\alpha \to \infty$ (g'' fixed) ... $M_V \to \infty$
2. EofM $\to \mathcal{L}_{tBESS}$ ... $\boldsymbol{V}_\mu = (\boldsymbol{W}_\mu + \boldsymbol{B}_\mu)/2$
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Obtaining low-E limits … $\mathcal{L}_{tBESS}^{low-E}$

1. measured observables $= f$(tBESS params) … M, Γ, A_{FB}, etc.
2. find deviations from the SM relations

$$M_W^2/M_Z^2 = c_\theta^2 \left(1 - \frac{s_\theta^2}{c_{2\theta}} \Delta r_W\right), \qquad \text{etc.}$$

… the deviations are function of tBESS params

3. measurements $\to$ deviations $\to$ (limits on) tBESS params

LOW-ENERGY DATA

LEP + SLC + Tevatron $\Rightarrow$ measured observables

EWPD epsilon analysis

ϵ_1 ... $\Gamma(Z \to l\bar{l}) + A^l_{FB}$

ϵ_2 ... $+ M_W/M_Z$

ϵ_b ... $+ \Gamma(Z \to b\bar{b})$

independent of m_t and M_H

$B \to X_s \gamma$

- limits on $W^\pm t_L b_L$ and $W^\pm t_R b_R$ vertices

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- $\delta\epsilon^{SM}$ $\leftarrow$ *SM weak loops* … m_t and M_H enters
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LOW-E LIMITS ON g''

	tree	SM loops	NP loops		
			Wtb	Ztt	Zbb
ϵ_1	✓	✓	✓	✓	×
ϵ_3	✓	✓	×	×	×
ϵ_b	✓	✓	✓	✓	×

$\Downarrow$

tBESS excluded at 72% C.L., 90% C.L., 95% C.L.

TWO SOLUTIONS:

- remove *deficiencies*
  - missing NP loops
  - "SM+NP loops" approximation
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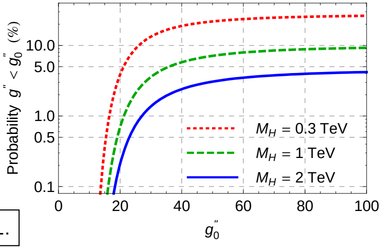

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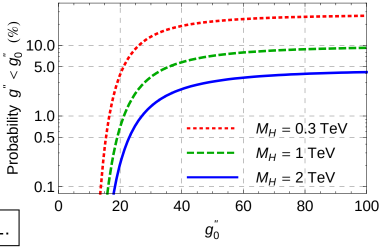

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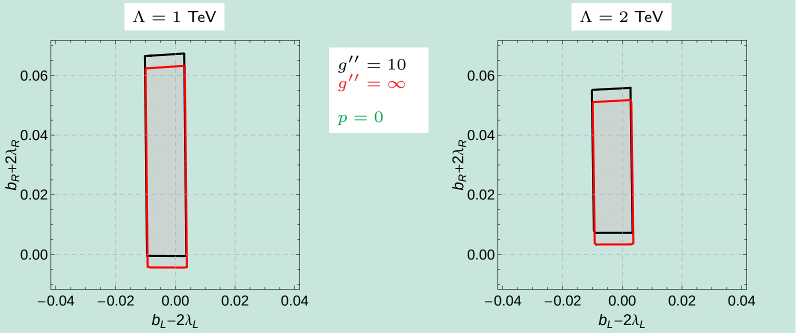

The intersections of the 90% *C.L. allowed regions:* ϵ_1, ϵ_b, $B \to X_s\gamma$

fine tuning $< 10\%$ $\Rightarrow$ $|b_L| \lesssim 0.13$

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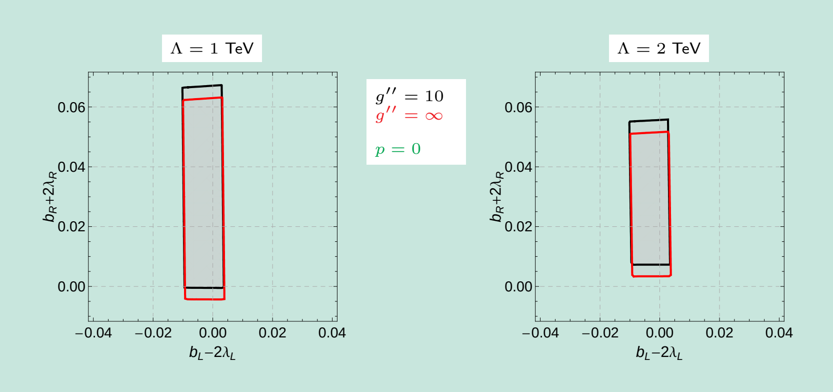

The intersections of the 90% C.L. allowed regions: ϵ_1, ϵ_b, $B \to X_s\gamma$

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The Death Valley

direct + indirect cplngs $\Rightarrow$ DV

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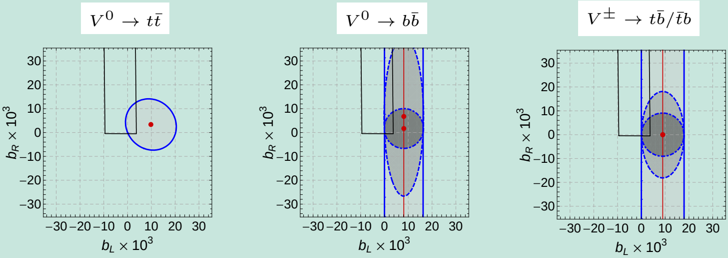
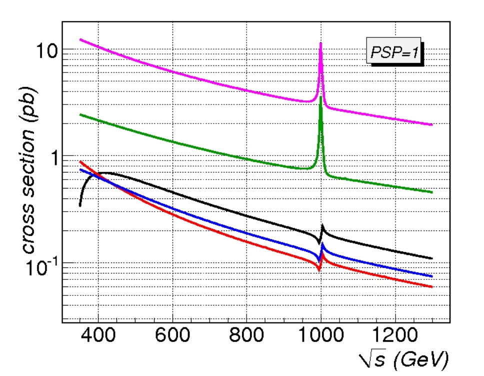


$g'' = 10,\ \lambda_L = \lambda_R = 0$

The Death Valley regions for the principal decay channels of the V resonances.

Hiding the peak

$M_V = 1$ TeV, $g'' = 20$, $p = 0$, $\lambda_R = 0$



$e^+e^- \to W^+W^-$

$u\bar{d} \to W^+Z$

$e^+e^- \to t\bar{t}$

$u\bar{d} \to t\bar{b}$

$e^+e^- \to b\bar{b}$

no direct cplng

$b_L = 0$

$b_R = 0$

$\lambda_L = 0$

The illustration of the peak hiding effect.

HIDING THE PEAK

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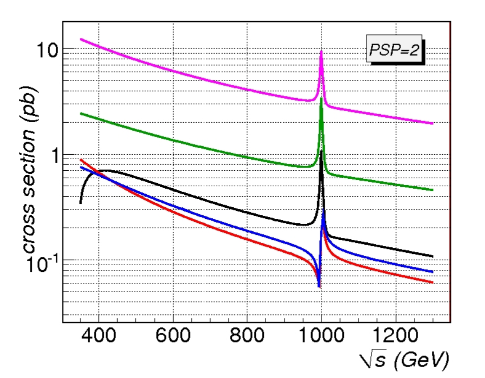

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outside the DV

$b_L = -0.010$

$b_R = +0.030$

$\lambda_L = 0$

The illustration of the peak hiding effect.

Hiding the peak

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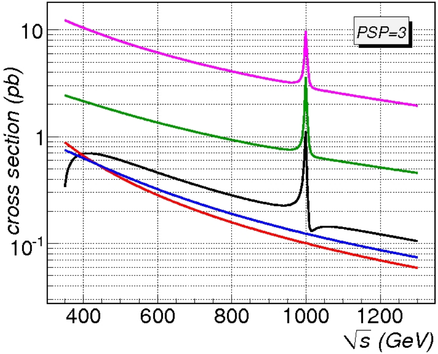

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$e^+e^- \to b\bar{b}$

$t\bar{b}$ & $b\bar{b}$ in the DV

$b_L = +0.009$

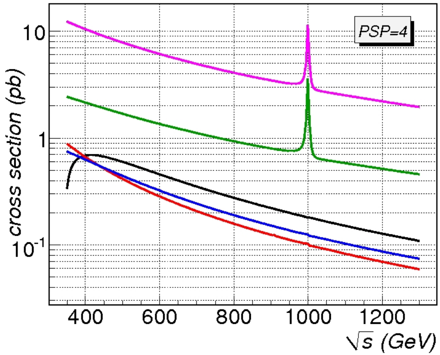
$b_R = +0.030$

$\lambda_L = +0.006$

The illustration of the peak hiding effect.

Hiding the peak

$M_V = 1$ TeV, $g'' = 20$, $p = 0$, $\lambda_R = 0$



$e^+e^- \to W^+W^-$
$u\bar{d} \to W^+Z$
$e^+e^- \to t\bar{t}$
$u\bar{d} \to t\bar{b}$
$e^+e^- \to b\bar{b}$

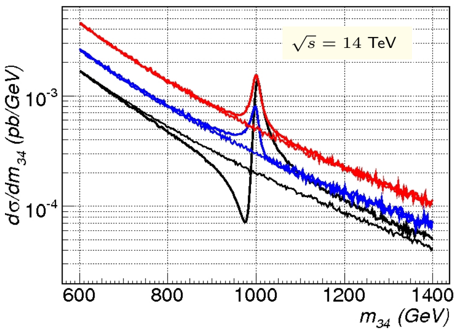
all in the DV

$b_L = +0.0098$
$b_R = +0.0034$
$\lambda_L = +0.006$

The illustration of the peak hiding effect.

LHC: Drell-Yan processes

$M_V = 1$ TeV, $g'' = 20$; $M_H = 115$ GeV



$pp \to W^+W^-X$
31.85 pb

$pp \to (W^+Z + \text{c.c.})X$
10.75 pb

$pp \to (t\bar{b} + \text{c.c.})X$
4.18 pb

fermion params

$p = 0.5$
$b_L = -0.072$
$b_R = +0.074$
$\lambda_L = -0.030$
$\lambda_R = -0.030$

Probing the tBESS resonances at the LHC.

Conclusions

- effective description of strong ESB new physics needed
- top-BESS — modification of BESS, special role of top quark
  - *new SU(2) resonance triplet*
  - *direct coupling to top and bottom*
  - *λ-terms*
- low-E limits on the fermion parameters relaxed
- the Death Valley effect
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Appendix