Some potential LHC physics without detailed models

(but not without concreteness)

Riccardo Barbieri

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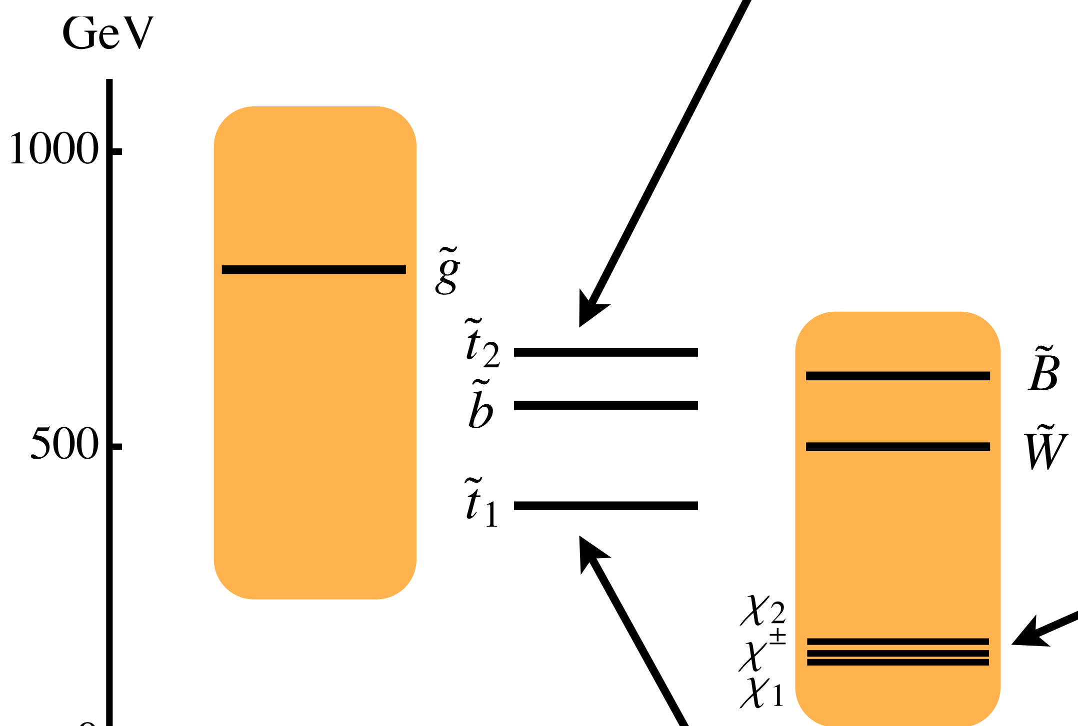
ElectroWeak Symmetry Breaking → weak coupling (!?)
ElectroWeak Symmetry Breaking → strong coupling (??)

Two examples:

1. s-particles at their naturalness limits — Pappadopulo
2. Light composite vectors — Carcamo, Corcella, Torre, Trincherini

"s-particles" at their naturalness limit

$\tilde{t}_1, \tilde{t}_2, \tilde{b}_L \Leftrightarrow$ strongest coupling to the Higgs system



(μ $\Leftrightarrow M_Z$ at tree level)

$\tilde{q}_1, \tilde{q}_2, \tilde{b}_R$ heavy enough ($\gtrsim \tilde{g}$) to be ~ irrelevant

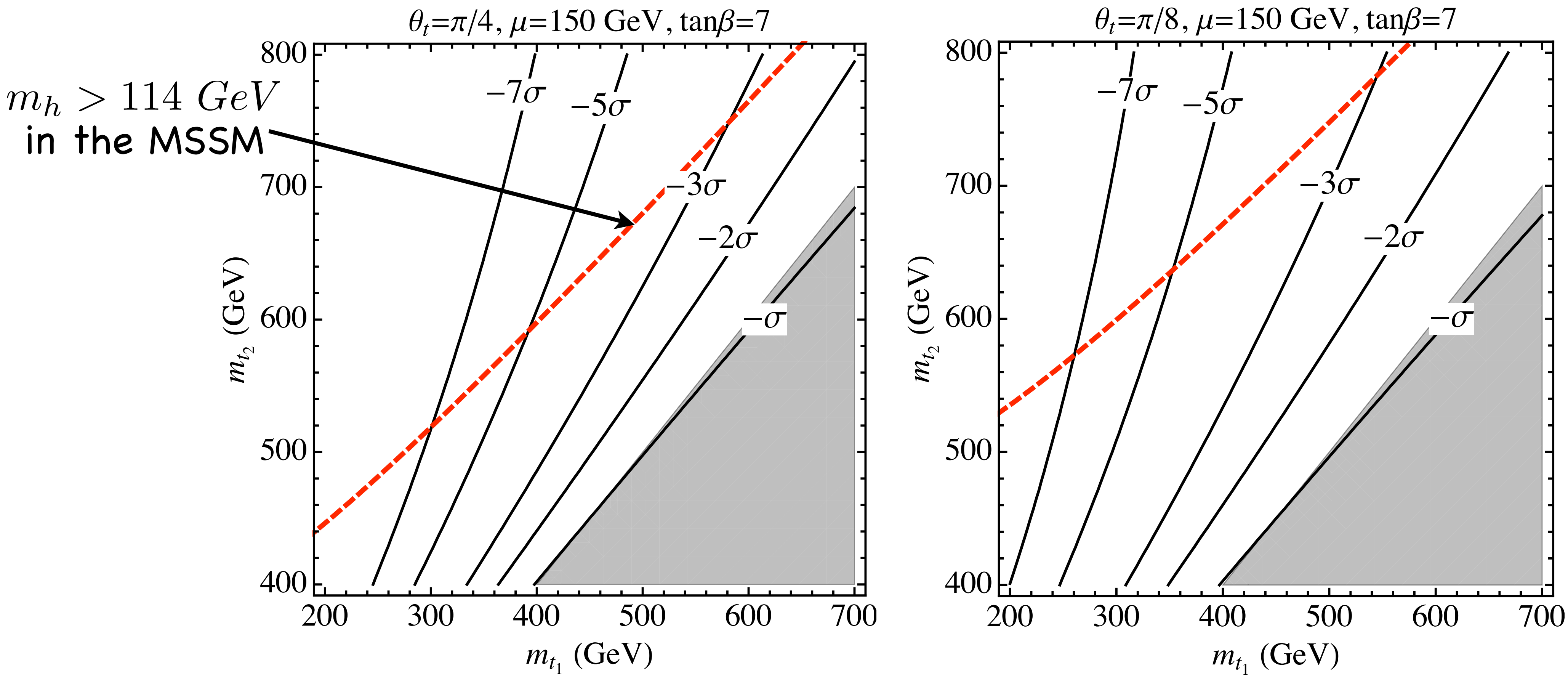
(where the s-leptons are almost doesn't matter)

Relevant physical parameters:

$$\boxed{m_{\tilde{g}} \qquad m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_t} \qquad (\mu,\ M_1,\ M_2) \qquad (\tan\beta)$$

[only the case μ< (<<) M_1, M_2 examined so far]

An example (and a generic concern, at least in the MSSM case)



(from stop-higgsino only and exactly CKM angles)

A synthetic description of the LHC phenomenology

3 semi-inclusive decays (up to < few % in any case)

$$\tilde{g} \to t\bar{t}\chi$$
$$\tilde{g} \to t\bar{b}\chi^- \, (\bar{t}b\chi^+)$$
$$\tilde{g} \to b\bar{b}\chi$$

direct or by cascade

forget cascades inside χ's

$b\bar{b}$ irrelevant whenever $\mu < M_1, M_2$

⇒ 4 semi-inclusive final states

$$pp \to \tilde{g}\tilde{g} \to tt\bar{t}\bar{t} + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to tt\bar{t}\bar{b}(\bar{t}\bar{t}tb) + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to tt\bar{b}\bar{b}(\bar{t}\bar{t}bb) + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to t\bar{t}b\bar{b} + \chi\chi$$

$$\chi = \chi^{\pm}, \chi_1, \chi_2$$

with rates determined by a single BR

$$B_{tb} \equiv BR(\tilde{g} \to t\bar{b}\chi^-) = BR(\tilde{g} \to \bar{t}b\chi^+) \approx \frac{1}{2}(1 - BR(\tilde{g} \to t\bar{t}\chi))$$

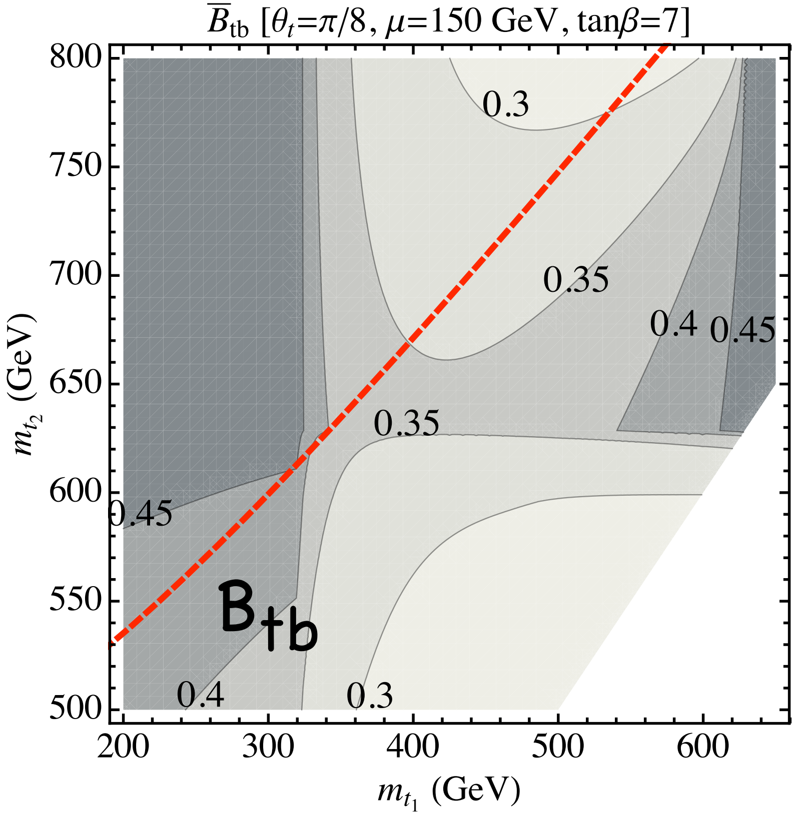
Multi-lepton events from semileptonic top decays

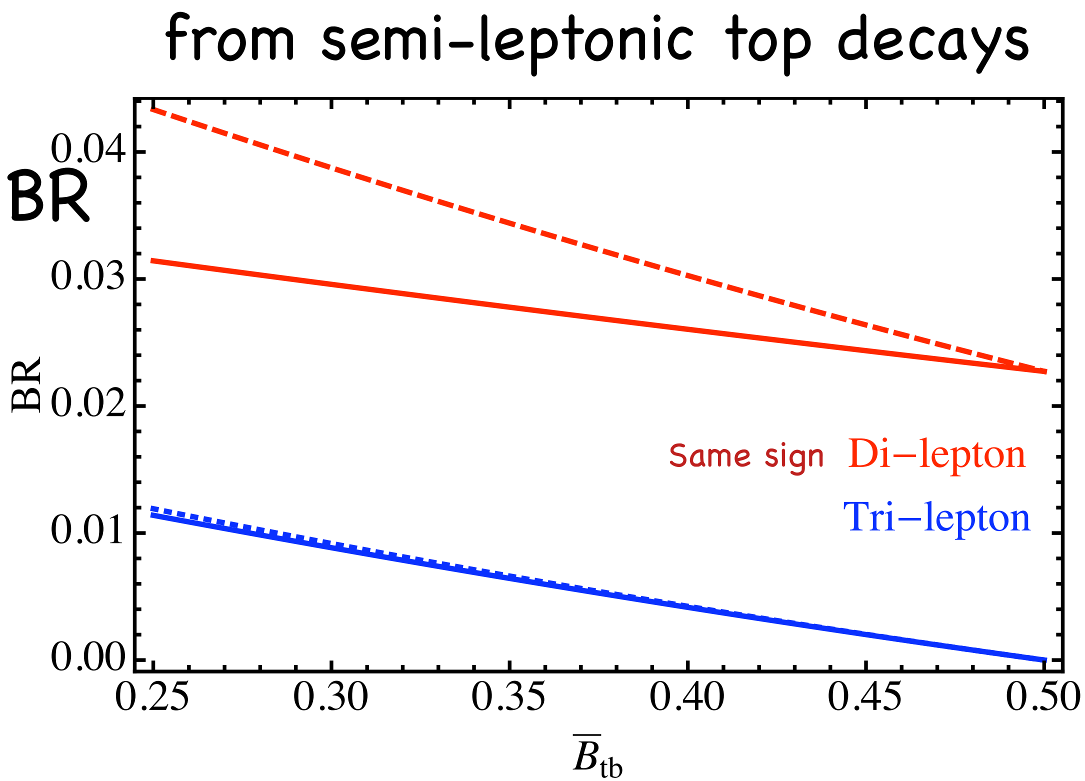
$$\sigma(l^\pm l^\pm, l^\pm l^+ l^-) = \sigma(\tilde{g}\tilde{g}) R(l^\pm l^\pm, l^\pm l^+ l^-)$$

$$R(l^\pm l^\pm + jets + E_{T miss}) = 2B_l^2 (B_{tb} + (1 - 2B_{tb})B_h)^2$$

$$R(l^\pm l^+ l^- + jets + E_{T miss}) = 4B_l^3 (1 - 2B_{tb})(B_{tb} + (1 - 2B_{tb})B_h)$$

$$B_l = 21\% \quad B_h = 68\%$$



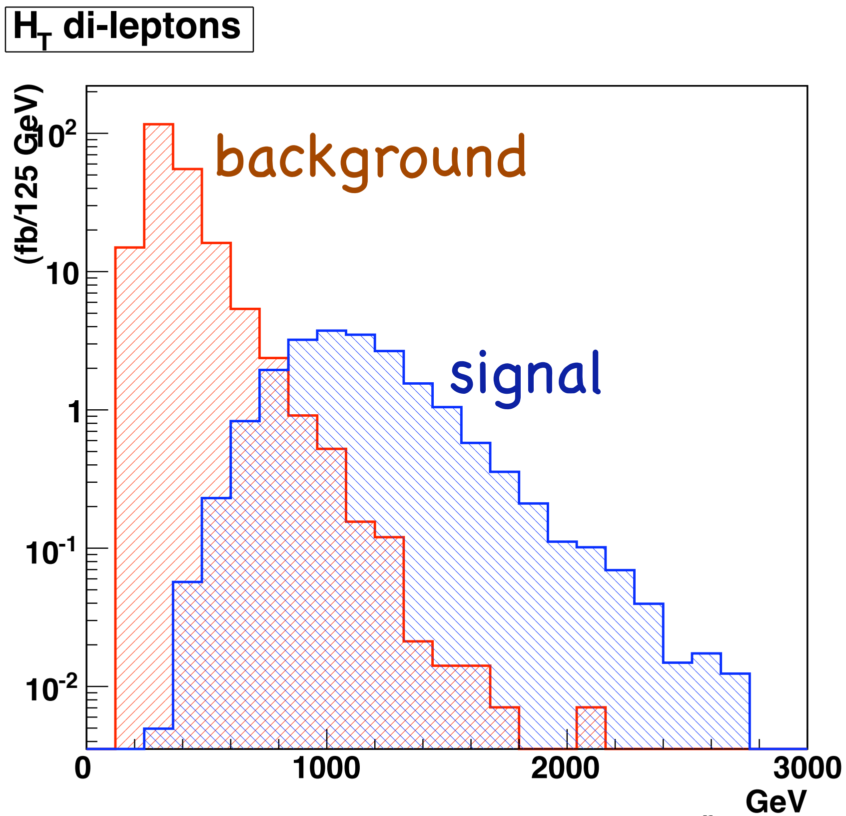


$$B_{tb} = 0.25 \div 0.5$$

Which sensitivity?

E.g.: at $\sqrt{s} = 14\ TeV$ and $m_{\tilde{g}} = 800\ GeV,\ B_{tb} = 0.35$

$$\sigma(l^{\pm}l^{\pm}) \approx 23\ fb$$
$$\sigma(l^{\pm}l^{+}l^{-}) \approx 7.5\ fb$$



Next:

Which sensitivity limit on $m_{\tilde{g}}$ for a given $\int Ldt$?

$M_1,\ M_2$ into play

Dark Matter?

Further leptons from inter-χ cascades

Light "composite" vectors

Generically: (not new(!), but useful(?) to be pushed further)

1. Keep SU(2)xU(1) gauge invariance but leave out the Higgs boson, while insisting on $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$ as relevant symmetry (except for g′≠0 and $m_t - m_b \neq 0$)

$$\mathcal{L} = \mathcal{L}^{SM}_{gauge} + \frac{v^2}{4} < (D_\mu U)^+ (D_\mu U) > + \frac{v}{\sqrt{2}} \bar{Q}_{Li} U Q_{Ri}$$

$$U(x) = e^{i\hat{\pi}(x)/v}\,, \qquad \hat{\pi}(x) = \tau^a \pi^a \qquad Q_{Ri} = \left(\begin{array}{c} \lambda^u_{ij} u_{Rj} \\ \lambda^d_{ij} d_{Rj} \end{array} \right)$$

$\Lambda \approx 4\pi v \approx 3$ TeV

2. Introduce new "composite" particles of mass <(<<)Λ consistently with 1 and see what happens:

scalars, fermions, vectors

Bagger et al

Vectors: a "composite" ρ-like state

V^{μ}_{a} = a $SU(2)_{L+R}$ - triplet   Why light? (unitarity, EWPT?)

The formalism is there since always (CCWZ):

$$u \equiv \sqrt{U} \rightarrow g_R u h^\dagger = h u g_L^\dagger$$ under $SU(2)_L \times SU(2)_R$

$$V_\mu = \frac{1}{\sqrt{2}} \tau^a V_\mu^a, \;\; V^\mu \rightarrow h V^\mu h^\dagger$$

unlike a standard gauge boson!

two more covariant vectors made of π, W, B

$$\Gamma_\mu = \frac{1}{2}\left[u^\dagger \left(\partial_\mu - i B_\mu\right) u + u \left(\partial_\mu - i W_\mu\right) u^\dagger\right]$$

$$u_\mu = u_\mu^\dagger = i u^\dagger D_\mu U u^\dagger$$

E.g.:

$$\mathcal{L}_{\rm kin}^V = -\frac{1}{4}\left\langle \hat{V}^{\mu\nu} \hat{V}_{\mu\nu} \right\rangle + \frac{M_V^2}{2} \left\langle V^\mu V_\mu \right\rangle \,,$$

$$\hat{V}_{\mu\nu} = \nabla_\mu V_\nu - \nabla_\mu V = \partial_\mu V + [\Gamma_\mu, V]$$

The generic Lagrangian

$$\mathcal{L}^V = \mathcal{L}_{SB} + \mathcal{L}^V_{kin} + \mathcal{L}^V_{int} + \ldots \qquad \mathcal{L}^V_{int} = \mathcal{L}_{1\mathrm{V}} + \mathcal{L}_{2\mathrm{V}} + \mathcal{L}_{3\mathrm{V}}$$

parity assumed

$$\mathcal{L}_{1\mathrm{V}} = -\frac{ig_V}{2\sqrt{2}}\left\langle \hat{V}^{\mu\nu}[u_\mu, u_\nu]\right\rangle - \frac{f_V}{2\sqrt{2}}\left\langle \hat{V}^{\mu\nu}(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u)\right\rangle$$

$$\mathcal{L}_{2\mathrm{V}} = g_1\langle V_\mu V^\mu u^\alpha u_\alpha\rangle + g_2\langle V_\mu u^\alpha V^\mu u_\alpha\rangle + g_3\langle V_\mu V_\nu[u^\mu, u^\nu]\rangle + g_4\langle V_\mu V_\nu\{u^\mu, u^\nu\}\rangle$$
$$+ g_5\langle V_\mu\left(u^\mu V_\nu u^\nu + u^\nu V_\nu u^\mu\right)\rangle + ig_6\langle V_\mu V_\nu(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u)\rangle$$

$$\mathcal{L}_{3\mathrm{V}} = \frac{ig_K}{2\sqrt{2}}\left\langle \hat{V}_{\mu\nu}V^\mu V^\nu\right\rangle$$

9 parameters (an embarrassment)

but many processes as well: study

$$W_L W_L \to VV$$
$$\bar{q}q \to VV$$

in various charge configurations

NDA guess

$$g_V\,,\ f_V \approx \frac{1}{4\pi}$$

$$g_{i=1,\ldots,6} \approx 1$$

$$g_K \approx 4\pi$$

but $M_V < \Lambda$!

leave out direct coupling of V to SM fermions (top?)

Large-s behaviour

In short, out of the many amplitudes:

$$A(W_L W_L \to V_L V_L) \propto \frac{s^2}{v^2 M_V^2} \qquad A(W_L W_L \to V_L V_T) \propto \frac{s^{3/2}}{v^2 M_V}$$

$$A(\bar{q}q \to VV) \propto \frac{s}{M_V^2}$$ (and a small coefficient)

Not surprising: taken at face value $\Lambda \approx 4\pi v \to (4\pi v M_V)^{1/2}$

Reduce A(WW) ≈ s/v^2 and A(qq) ≈ const by unique choice:

$$g_V = \frac{1}{g_K} \quad f_V = 2g_V \quad g_3 = -\frac{1}{4} \quad g_6 = \frac{1}{2} \quad g_1 = g_2 = g_4 = g_5 = 0$$

as in a gauge theory (see below). Exact or approximate?

"Composite" versus gauge vectors

Can study the correspondence of V_a^μ with one of the many vectors in $SU(2)_L \times SU(2)^N \times SU(2)_R$ broken to $SU(2)_{diag}$ by a generic sigma model

(BESS, 3-site, ... , deconstructed $SU(2)_L \times SU(2)_R$ in 5D)

Indeed, by appropriate field redefinitions:

$$\mathcal{L}^{gauge} = \Sigma_i \mathcal{L}_i^V + \frac{i\hat{g}_K^{lmn}}{2\sqrt{2}} \left\langle \hat{V}_{\mu\nu}^l V_m^\mu V_n^\nu \right\rangle$$

with

$$g_3 = -1/4, \;\; g_6 = 1/6 \qquad f_V^i = 2g_V^i \qquad \Sigma_j g_V^j g_K^{jii} = 1$$

and $\quad g_K \approx M_V/v$

and improved asymptotic behaviour of

$$W_L W_L \to VV \qquad f\bar{f}' \to VV$$

above any M_i^V threshold

V production and decays

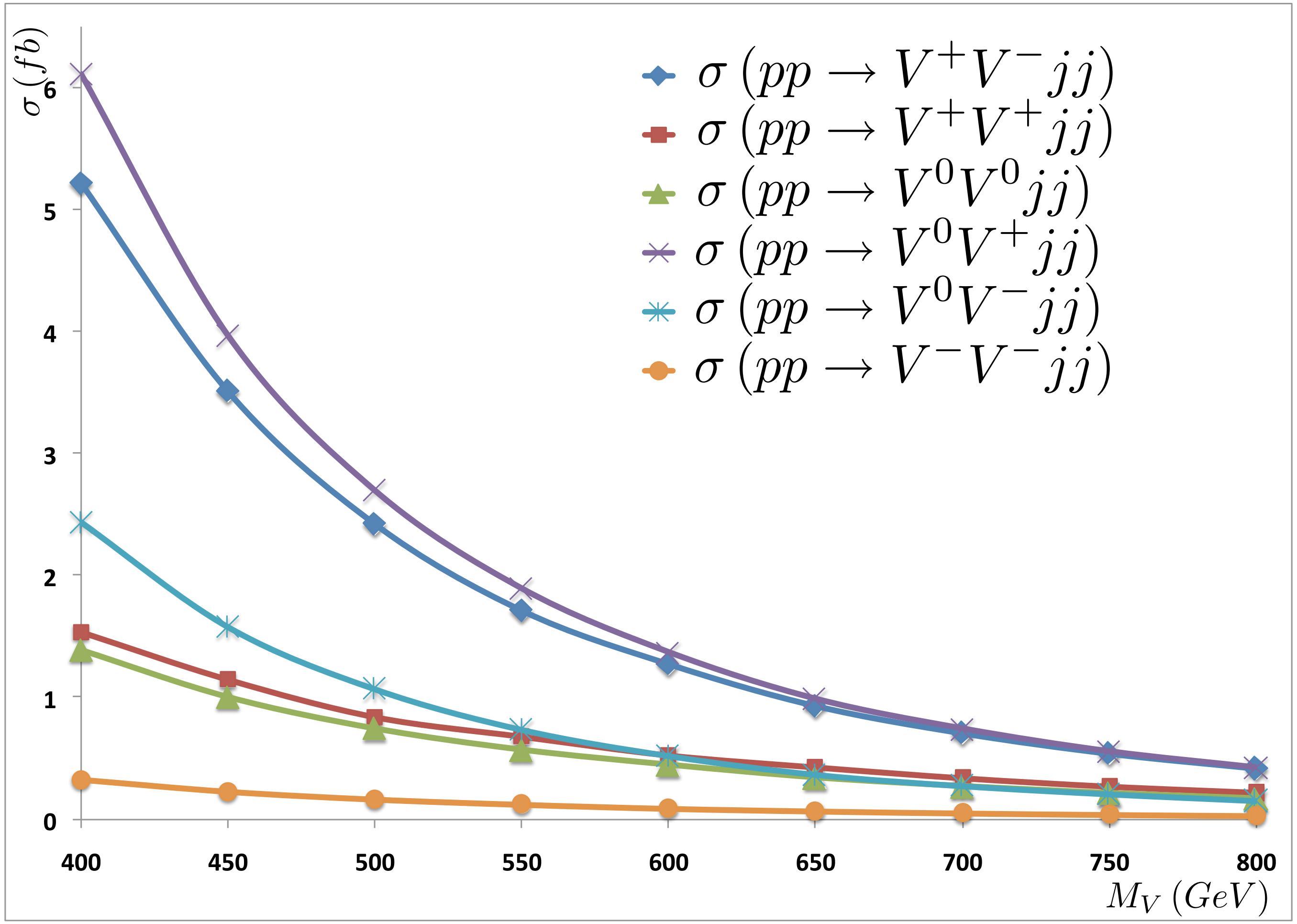
Narrow ($\Gamma \approx M_V^3 < 40$ GeV at $M < 1$ TeV) and dominated by $V \to WW/Z$ ($l\bar{l}$ small but$\neq 0$ because of VZ kin. mixing)
($V \to t\bar{t}$?)

Single V-production by WW-fusion (g_V)
Single V or associated VW/Z production by DY (f_V)

pair-V production by WW-fusion (g_V ,g_K ,g_i)
pair-V production by DY (f_V ,g_K ,g_6)

leading to 2W/Z, 3W/Z, 4W/Z final states (+jj)
$\to$ multi-leptons to be disantangled from the background

Vector Boson Fusion



$$g_V M_V = 200\ GeV$$

$$g_V g_K = 1/\sqrt{2}$$

and all other couplings as in a gauge model

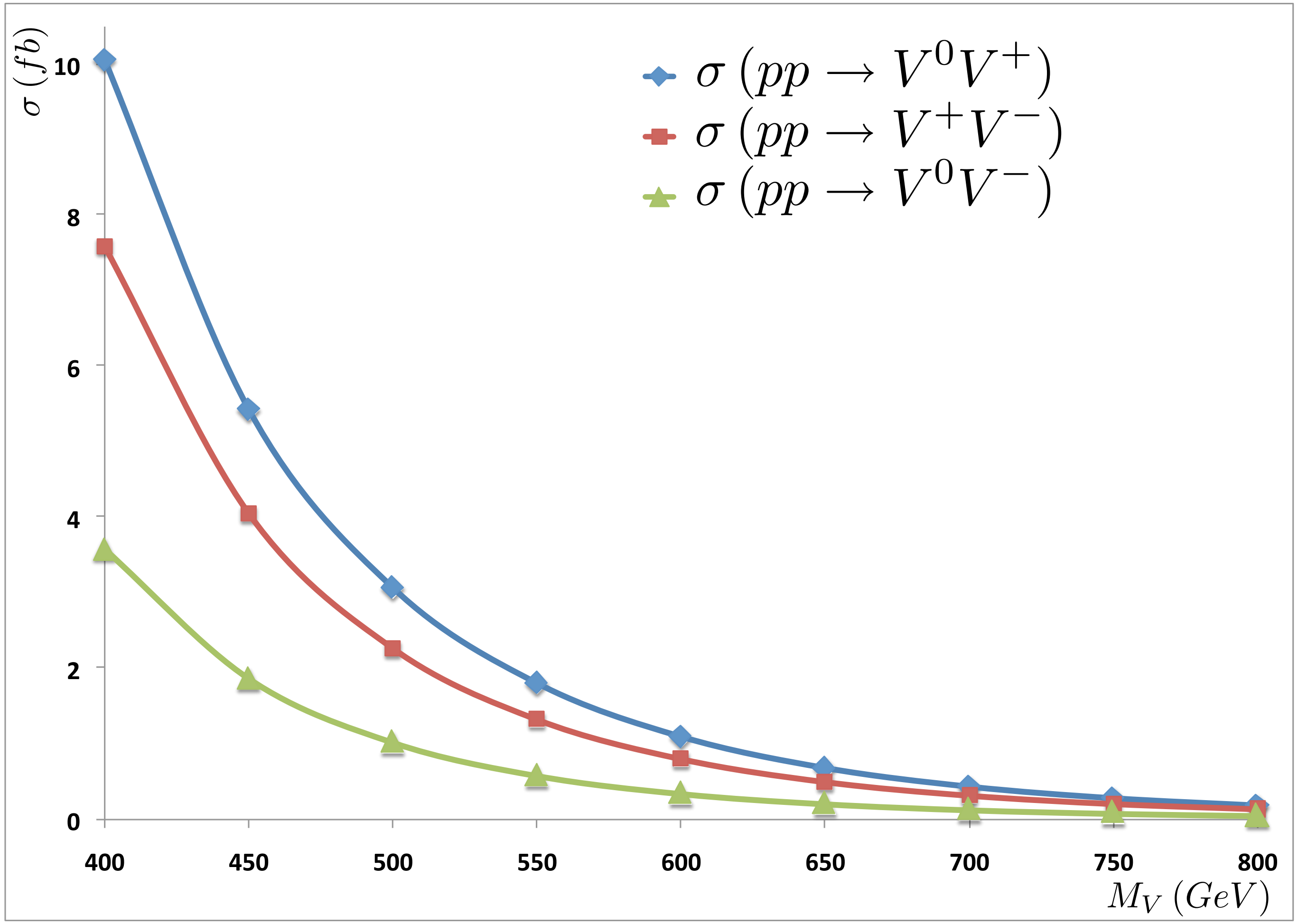
$$p_T(j) > 30\ GeV$$

$$|\eta(\ )|\quad 5$$

At M_V = 500 GeV

$\sigma(l^{\pm}l^{\pm}) \approx 0.3$ fb

Drell-Yan

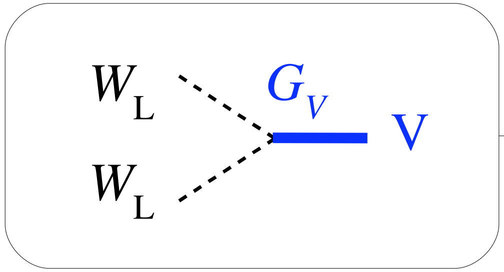


$f_V = 2g_V$

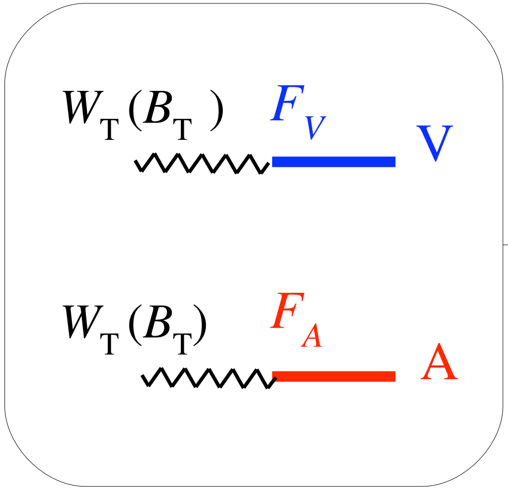
At M_V = 500 GeV $\sigma(l^\pm l^\pm) \approx 0.2$ fb

visible above background??

ElectroWeak Precision Test

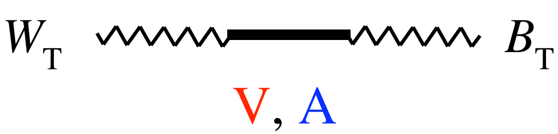


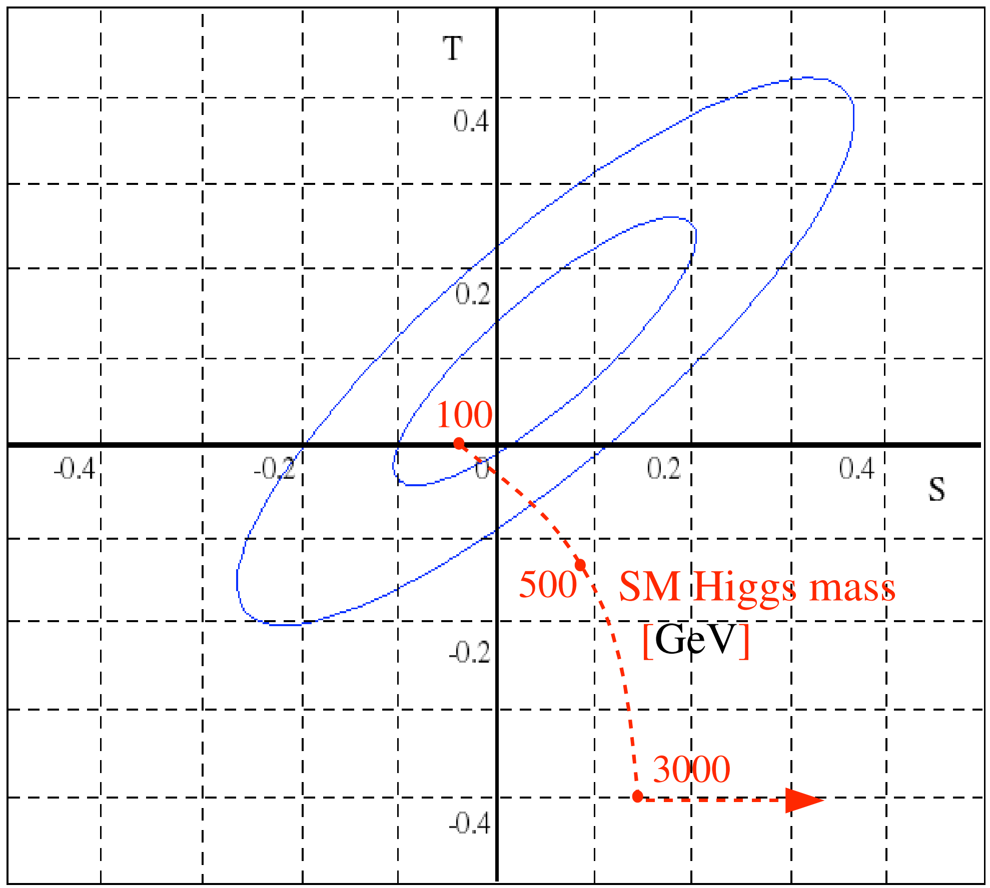
Control unitarity



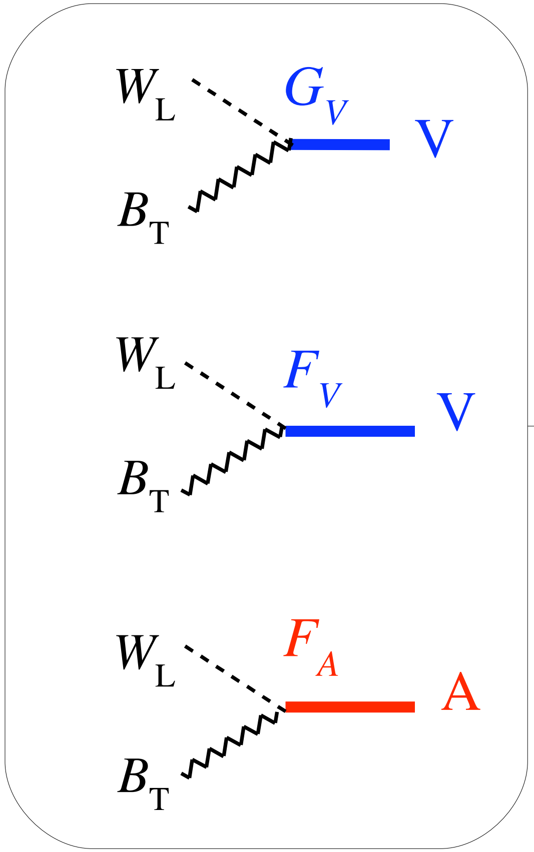
Tree-level positive contribution to S:

(which worsen the agreement with EWPO)

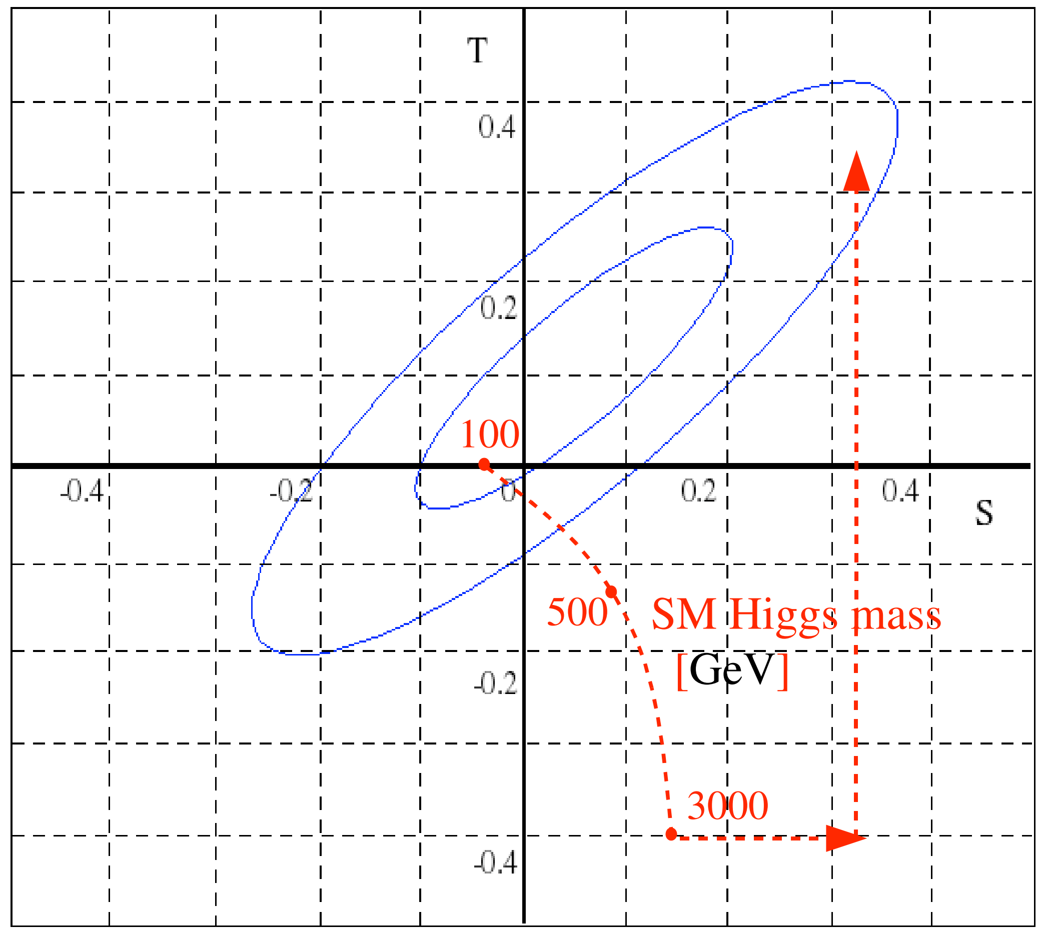


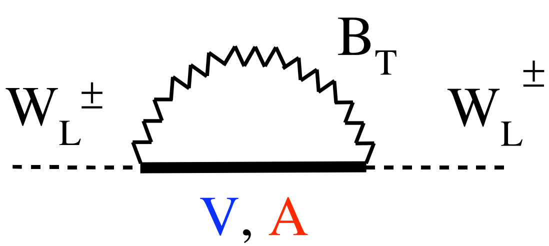


At the one-loop level the situation can become qualitatively very different



Potentially large (quadratically divergent) positive one-loop contribution to T





One-loop breaking of the costodial symmetry due to $g' \neq 0$

The leading contributions to S & T generated by the exchange of single heavy fields are:

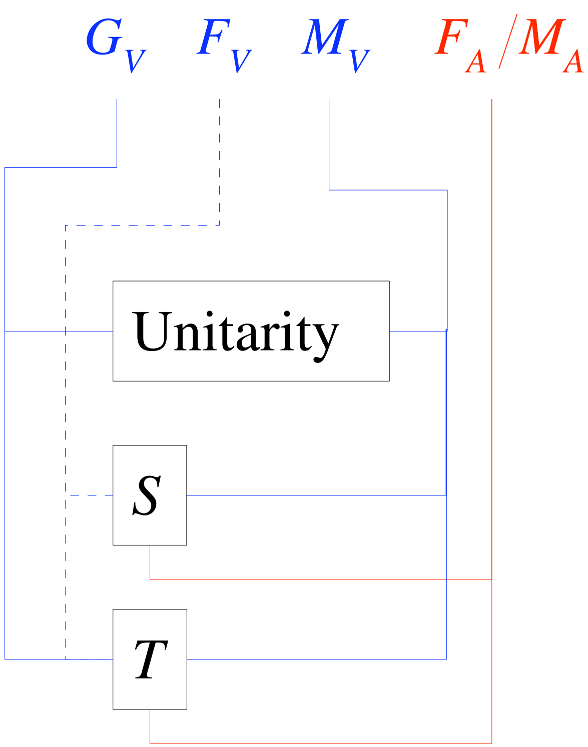
$$\Delta\hat{S}\,\begin{matrix}\text{vectors}\\ \text{(tree)}\end{matrix} = g^2\left(\frac{F_V^2}{4M_V^2}-\frac{F_A^2}{4M_A^2}\right)$$

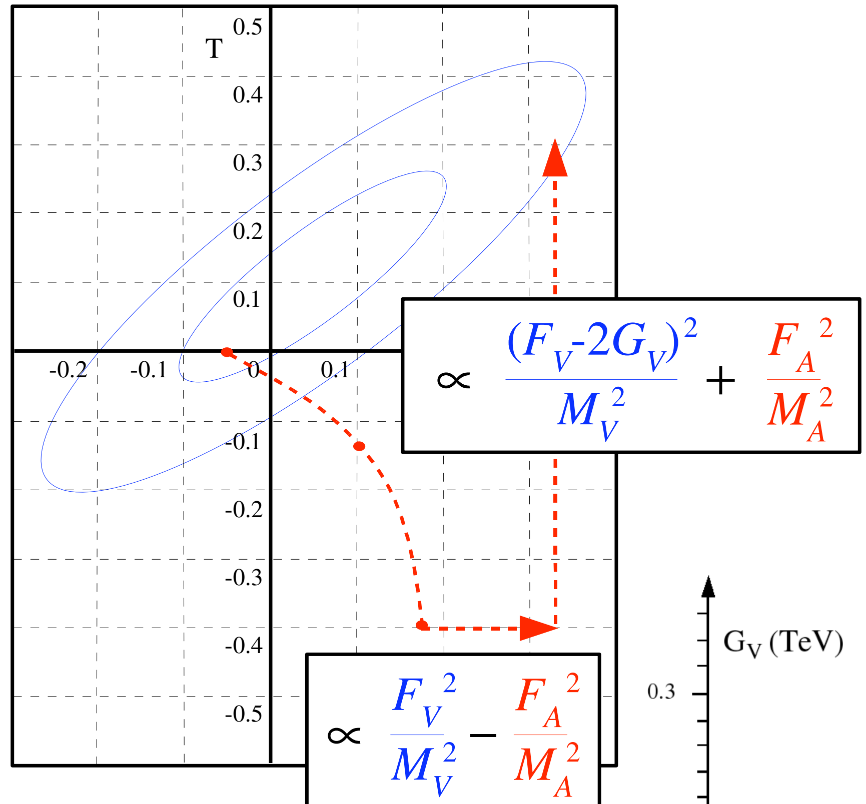
$$\Delta\hat{T}\,\begin{matrix}\text{vectors}\\ \text{(1-loop)}\end{matrix} = \frac{3\pi\alpha}{c_W^2}\left[\frac{F_A^2}{4M_A^2}+\left(\frac{F_V-2G_V}{2M_V}\right)^2\right]\frac{\Lambda^2}{16\pi^2v^2}+\ldots$$

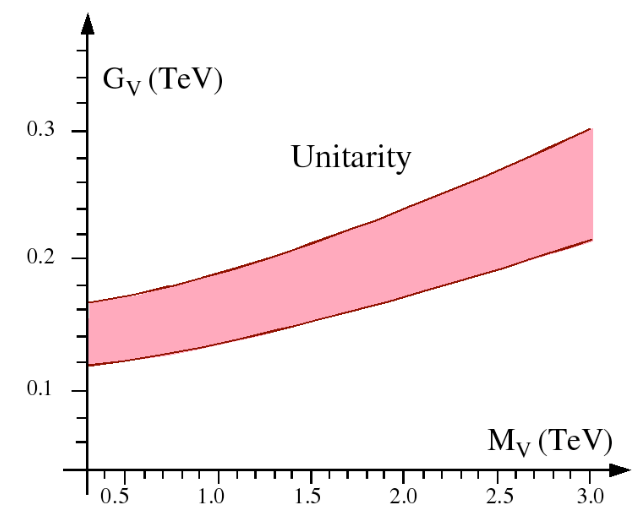
Unitarity and EWPO with heavy vectors

Assuming a QCD-type model, with a single light (A,V) set not saturating all the sum rules...

Free parameters:







EWSB: "weak" or "strong"?

"weak"

a relatively light Higgs boson exists

perturbativity extended →high E (M_{GUT}, M_{Pl})

perhaps (probably) embedded in susy

gauge couplings unify

"strong"

EWSB related to new forces, new degrees of freedom
or even new dimensions opening up in the TeVs

perturbativity lost in the multi-TeV range

high E extrapolation highly uncertain

KK-vector signals $\hat{V}$

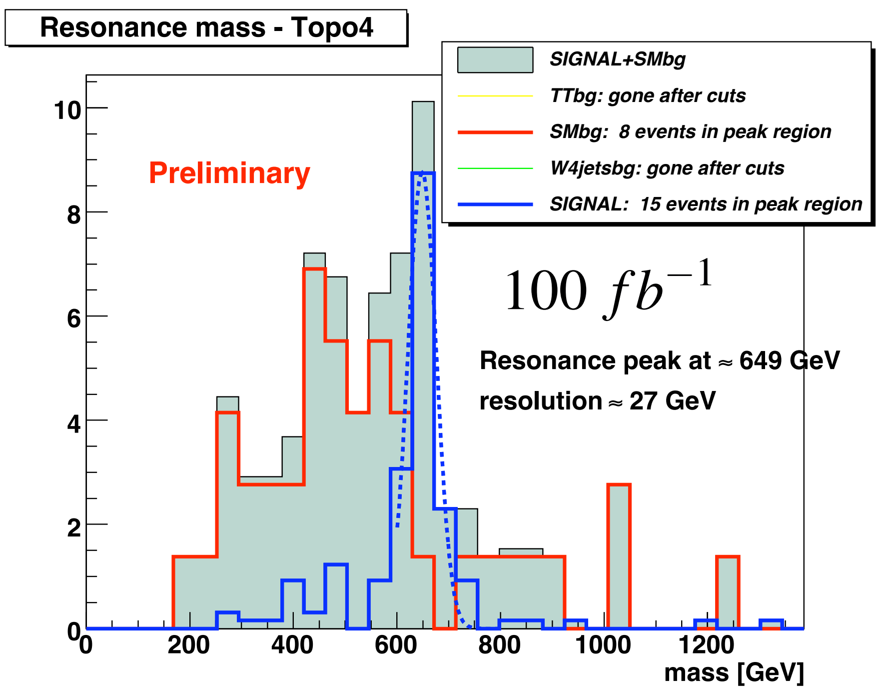
$$qq \to qq\,\hat{V} \qquad qq \to \hat{V} \qquad \hat{V} \to VV,\ t\bar{t},\ (hV)$$

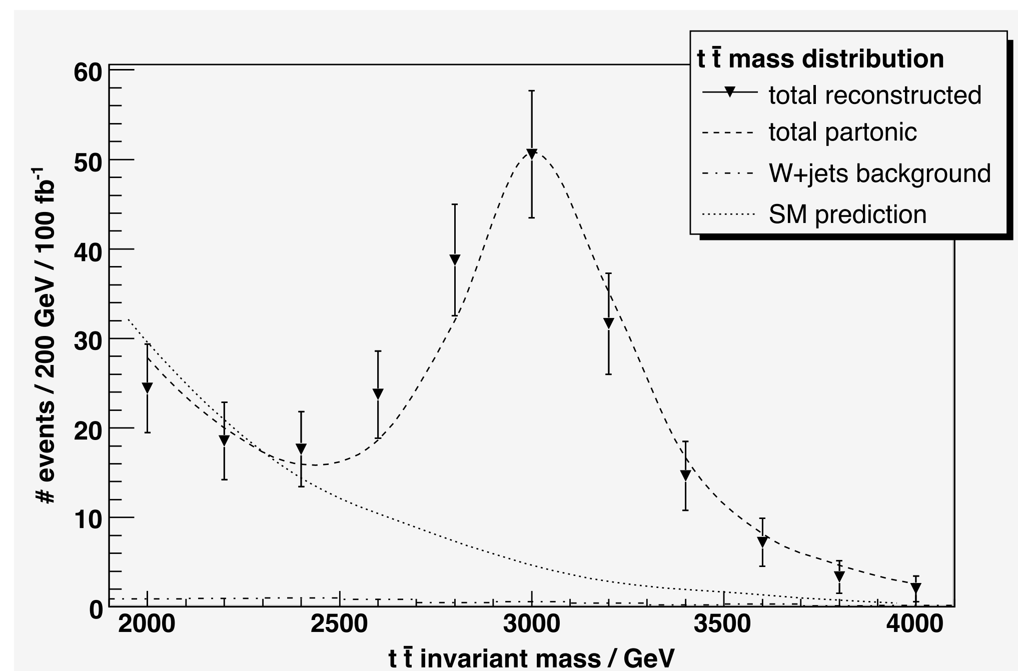
(t or b, depending on the charge)

$\hat{V} \to f\bar{f}$ probably not useful, because of small BR

$\hat{V}$ can also be a KK-gluon

$$pp \to qq\hat{W} \to qqWZ \to qq\,jet\,jet\,ll \qquad pp \to \hat{g} \to t\bar{t}$$





Azuelos, Delsart, Idarraga *Agashe et al*

KK-quark signals

$$Q \equiv (T^{2/3}, B^{-1/3}, X^{5/3})$$

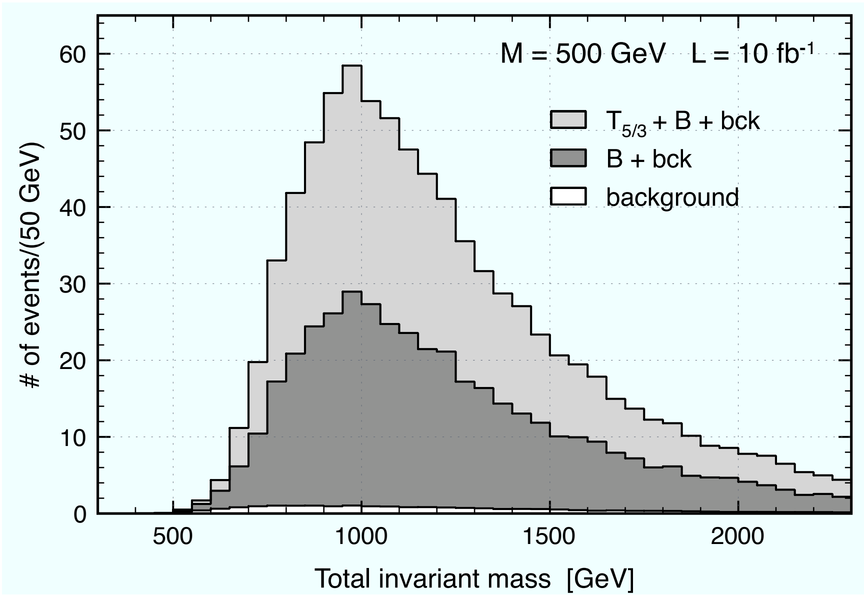
$$qq \to Q\bar{Q} \qquad\qquad Q \to tV,\ th$$

(t or b, depending on the charge)

If they exist, easier to catch than KK-vectors
(like squarks, but without $\not{E}_T$)

Single production also possible

$$pp \to X\bar{X} + B\bar{B} \to l^{\pm}l^{\pm} + jets + \not{E}_T \qquad T(1\ TeV) \to Z\,t \to l^+l^-l^{\pm}\nu b$$



Contino, Servant