ElectroWeak Symmetry Breaking

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(not the first time, while waiting for the LHC)

see, e.g., arXiv:0802.3988 and ref.s therein

The impact of the Large Hadron Collider on EWSB (and a word of caution)

1. The first thorough exploration of the energy scales well above $G_F^{-1/2}$

$$\Lambda_{QCD},\ G_F^{-1/2}$$

2. No comparable prior situation at the SppS or at the TEVATRON

1984: W, Z
1994: top
201?: the Higgs boson of the SM

EWSB: "weak" or "strong"?

"weak"

a relatively light Higgs boson exists

perturbativity extended $\rightarrow$ 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

The "weak coupling" way

Favoured by indirect-data

EWPT, unification (susy), flavour (?), ν-masses (?)

Which problems, if susy?

No Higgs boson so far (hidden in LEP data? E.g. $h \to aa \to 4\tau$)
(the MSSM not the end of the story?)

Flavour? (follow $\mu \to e\gamma$ at PSI)
(2008: $BR \leq 10^{-11}$ with 2 weeks of data)

Tuning? (It could be right and we might never know)

Which signals?

Much work already done

"Model independence"

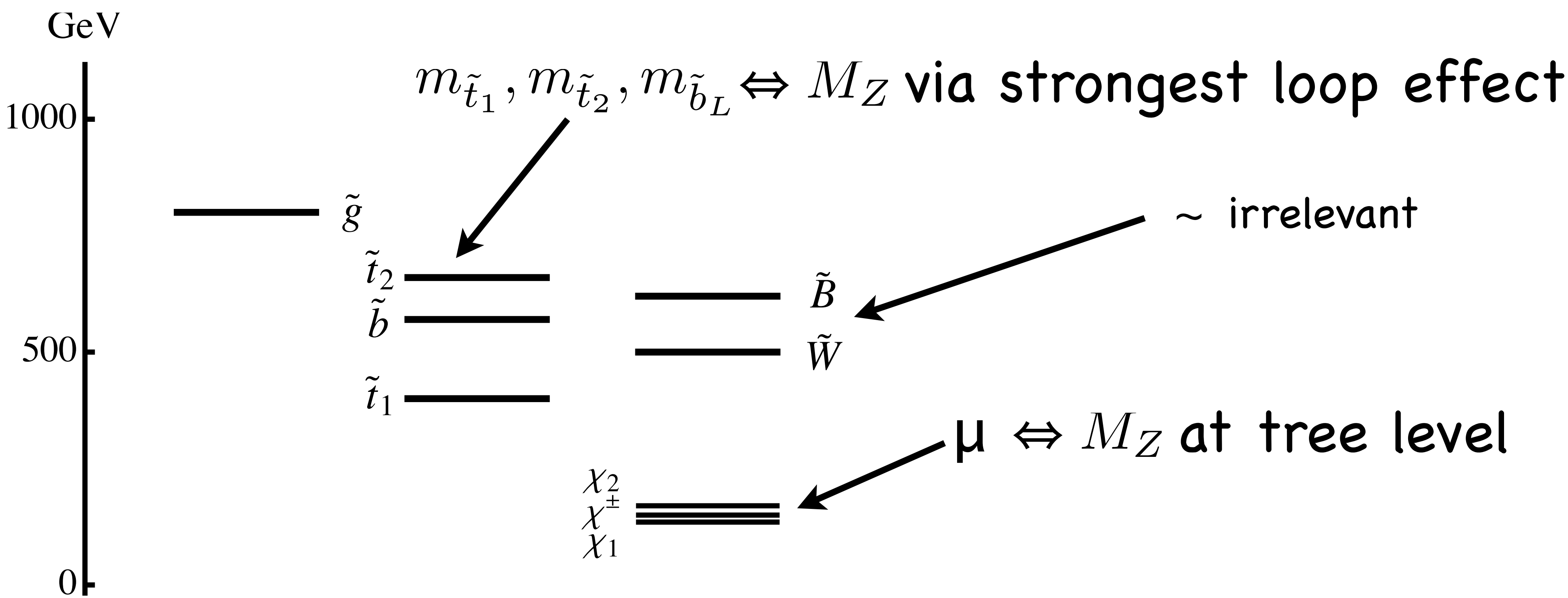
Surprises

Note the number of question marks!

“Model independence”: just an example

A motivated s-particle spectrum below 1 TeV

“s-particles” at their naturalness limit



Relevant physical parameters: $m_{\tilde{g}}, \mu, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_t$

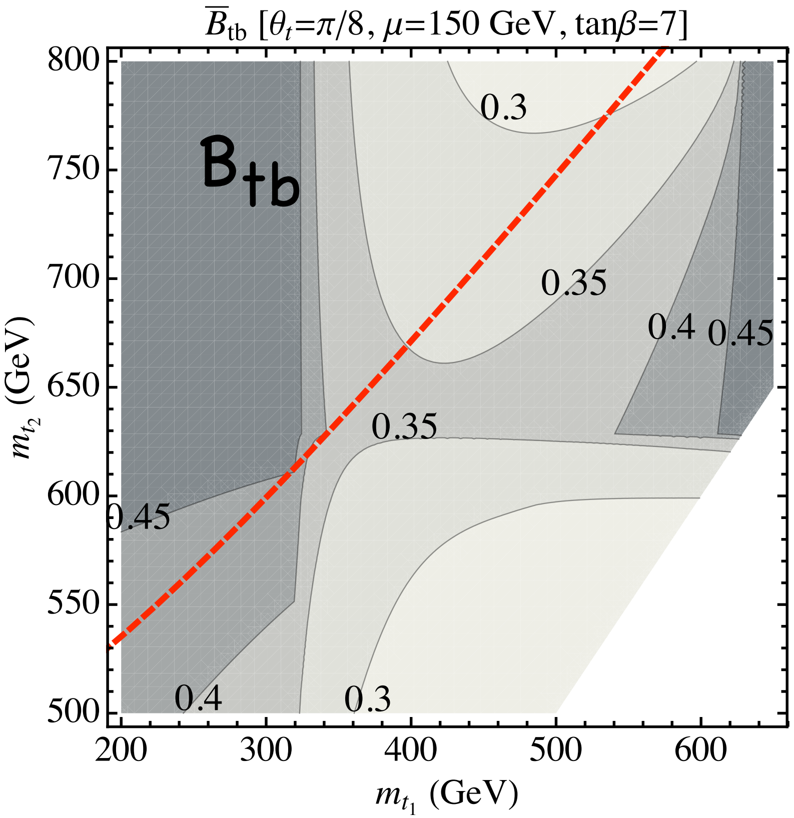
4 semi-inclusive final states (up to < few %)

$$pp \to \tilde{g}\tilde{g} \to tt\bar{t}\bar{t} + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to tt\bar{t}\bar{b}(\bar{t}\bar{t}tb) + \chi\chi$$
$$pp \to \tilde{g}\tilde{g} \to tt\bar{b}\bar{b}(\bar{t}\bar{t}bb) + \chi\chi \qquad \chi = \chi^{\pm}, \chi_1, \chi_2$$
$$pp \to \tilde{g}\tilde{g} \to t\bar{t}b\bar{b} + \chi\chi$$

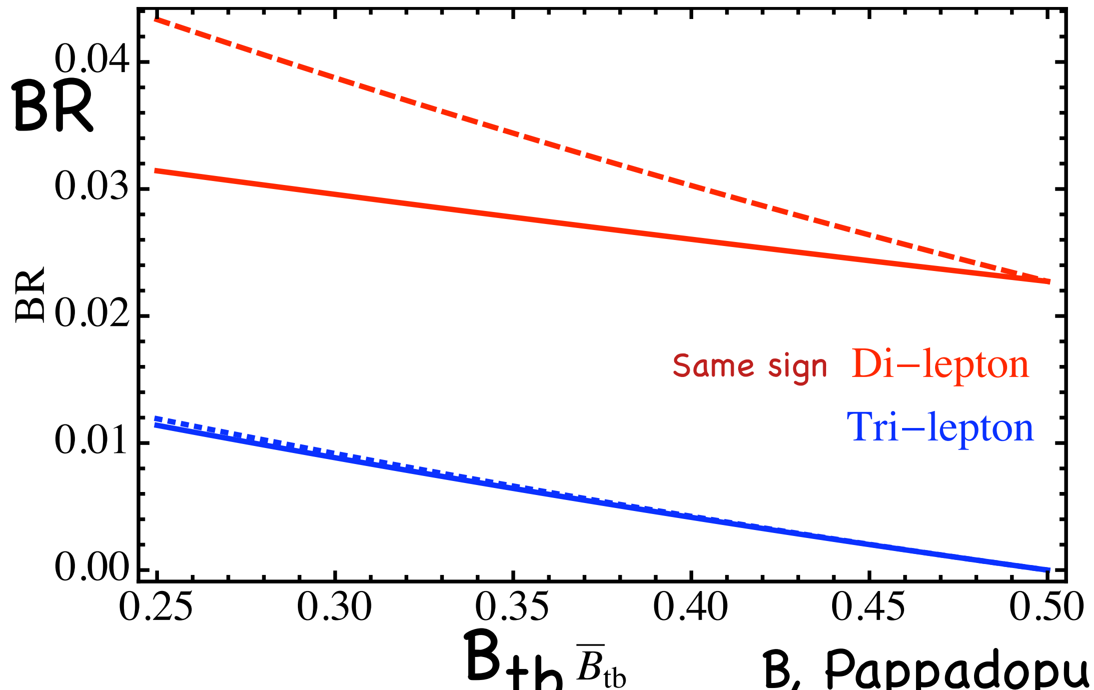
with rates determined by a single BR

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

σ (SS di-leptons, tri-leptons) = σ ($\tilde{g}\tilde{g}$) BR



from semi-leptonic top decays



B, Pappadopulo

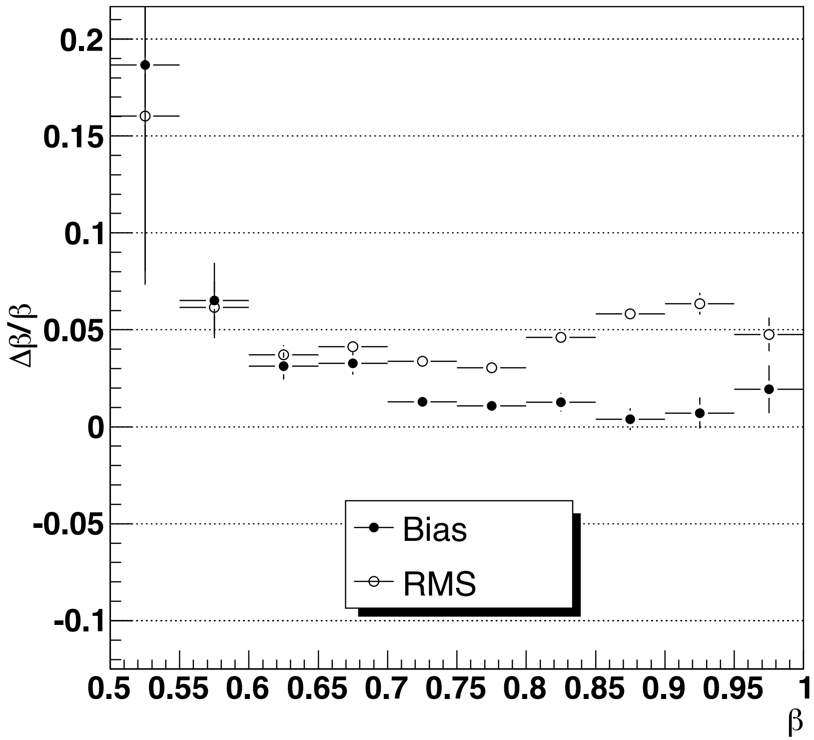
Surprises: another example

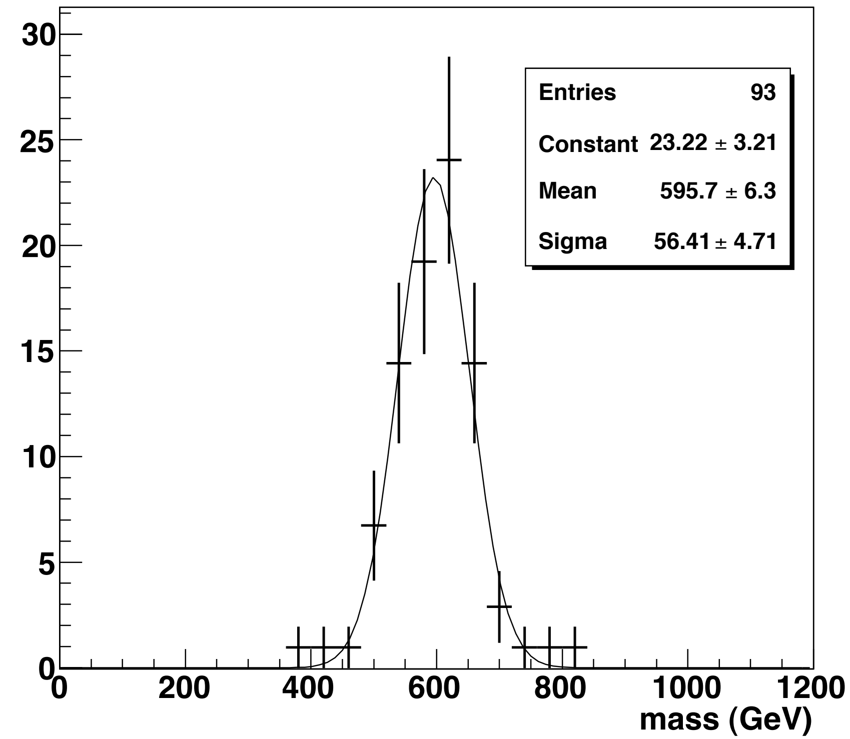
"Stable" R-hadrons (made of $\tilde{g}$ or of $\tilde{t}$)

because "LSP", up to gravitino decays, or because of superheavy squarks (in the gluino case)

by dE/dx and time-of-flight

600 GeV gluino (0.5 fb^{-1})



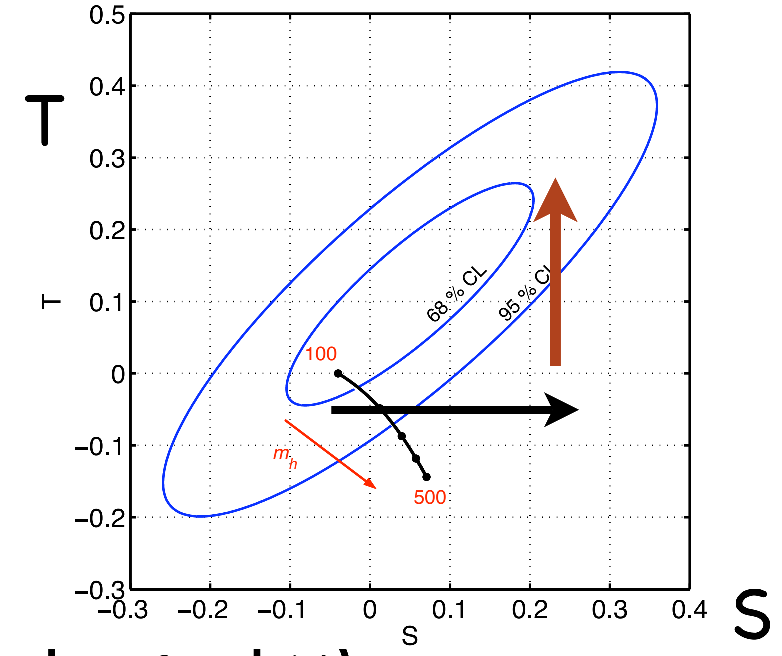


Rizzi

The "strong coupling" way

Disfavoured by indirect-data

EWPT: mostly ΔS>0, but don't forget the S↔T correlation



Models not fully convincing

(although enlarged by 5D↔4D holography)

Flavour problematic?

(yes, but what about the SM λ_{ij}^Y ?)

"Higgs" or "Higgs-less"?

(a real question, although with a most likely answer)

Any "model independent" way to see the LHC data?

An attempt: back to "minimality"

(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 $g' \neq 0$ and $m_t - m_b \neq 0$)

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

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

Consistent with all data so far, except the EWPT (although $\rho \approx 1$) and reliable only up to $\Lambda \approx 4\pi v$

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

scalars, fermions, vectors

Bagger et al

Scalars: a "composite" Higgs boson

Contino et al

h = $SU(2)_{L+R}$- singlet   Why light? (PGB, $h=A_5$,...)

$$\mathcal{L} = \mathcal{L}^{SM}_{gauge} + \frac{1}{2}(\partial_\mu h)^2 - V(h) + \mathcal{L}^h_{SB} \ + \ldots$$

MFV

$$\mathcal{L}^h_{SB} = \frac{v^2}{4} < (D_\mu U)^+(D_\mu U) > (1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}) + \frac{v}{\sqrt{2}}\bar{Q}_{Li}U(1 + c\frac{h}{v})Q_{Ri}$$

If (π_a, h) = linear SU(2)xU(1) multiplet: a=b=c=1

EWPT OK and consistency well above $4\pi v$ (if m_h small enough)

Too good not to be true!?!

Yet, if h found (by the usual means), hard to overestimate the importance of measuring a,b,c as well as possible

How?

h production and decays at the LHC

$WW \to WW$ not so useful

rather $WW \to hh$

but only for high luminosity

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)

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

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

$$\mathcal{L}_{2\mathrm{V}} = g_1 \langle V_\mu V^\mu u^\alpha u_\alpha \rangle + g_2 \langle V_\mu u^\alpha V^\mu u_\alpha \rangle + g_3 \langle V_\mu V_\nu [u^\mu, u^\nu] \rangle + g_4 \langle V_\mu V_\nu \{u^\mu, u^\nu\} \rangle$$
$$+ g_5 \langle V_\mu \left(u^\mu V_\nu u^\nu + u^\nu V_\nu u^\mu \right) \rangle + i g_6 \langle V_\mu V_\nu (u W^{\mu\nu} u^\dagger + u^\dagger B^{\mu\nu} u) \rangle$$

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

$$u = \sqrt{U}$$
$$u_\mu = i u^\dagger D_\mu U u^\dagger$$

9 parameters (an embarrassment)
but many processes as well

Carcamo et al

"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)

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

with partially improved asymptotic behaviour of

$$W_L W_L \to VV$$

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

V production and decays

Narrow (Γ<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)

→ multi-leptons to be disantangled from the background

Belyaev et al
Cata' et al
Carcamo et al

Last but not least
(especially for this workshop)

Perhaps the most exciting aspect of a fundamental theory of particles and space-time is that it can allow to calculate the content and the evolution of the universe.

We are not close! A clue from EWSB?

Numerically, if $\rho_{DM} \approx v n_{DM}$

$$\frac{n_{DM}}{n_\gamma} \approx O\left(\frac{v}{M_{Pl}}\right) \quad \text{with} \quad v = G_F^{-1/2}$$

We know very well one explanation for this (WIMP)

An accident? Other explanations?

Which consequences for the LHC?

Conclusions

⇒ The Fermi scale, one of the two fundamental scales in particle physics, thoroughly explored at the LHC for the first time.

⇒ Real questions: (in spite of our own preferences)
EWSB: weak or strong?
Higgs boson: elementary of composite, if existent at all?

⇒ (for theorists) Useful to prepare to see the data in "model independent" ways, as much as possible

⇒ $G_F^{-1/2} \Leftrightarrow$ DM !?!

⇒ With LHC on, physics (about EWSB) in its normal way of operation

KK-vector signals $\hat{V}$

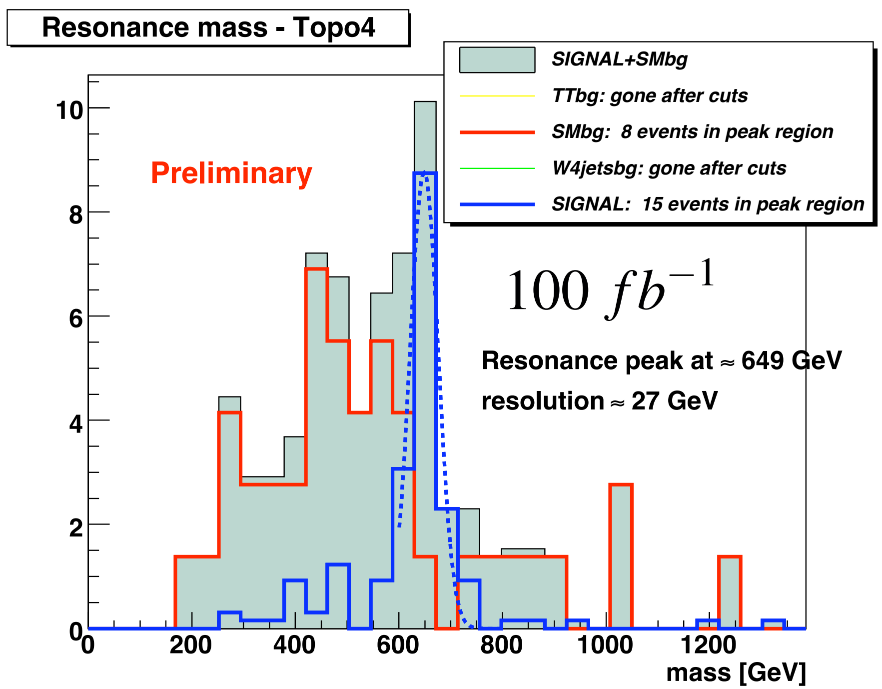
$$qq \to qq\,\hat{V} \qquad qq \to \hat{V} \qquad \hat{V} \to VV,\ t\bar{t},\ (hV)$$

(t or b, depending on the charge)

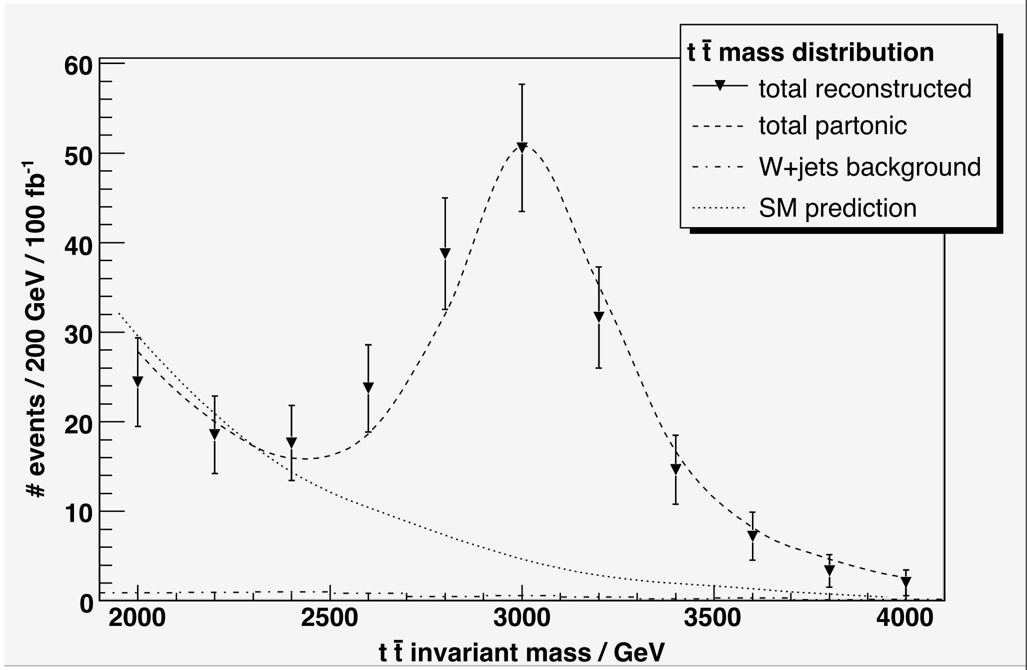
$\hat{V} \to f\bar{f}$ probably not useful, because of small BR

$\hat{V}$ 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

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

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

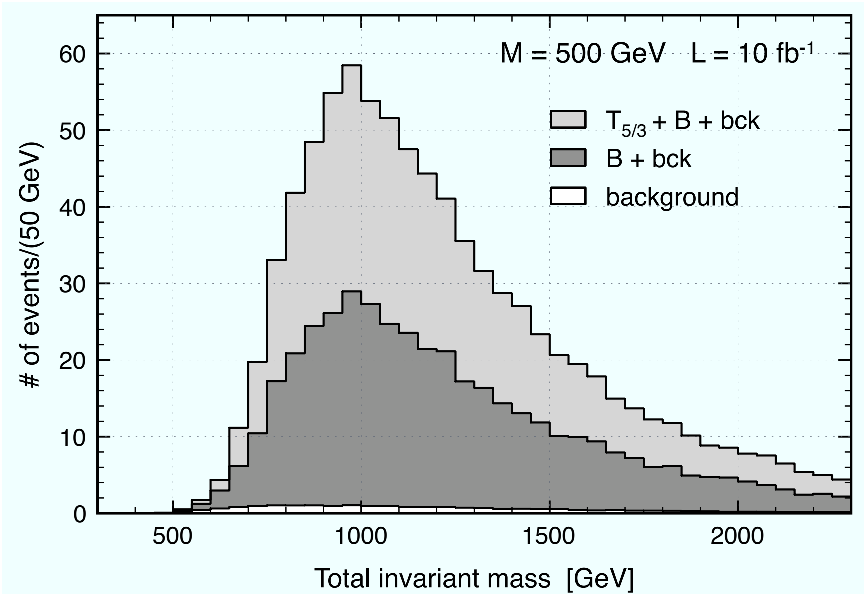
(t or b, depending on the charge)

If they exist, easier to catch than KK-vectors

(like squarks, but without $\not{E}_T$)

Single production also possible

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



Contino, Servant