Expectations for beyond-SM physics @ LHC

Slava Rychkov (SNS Pisa)

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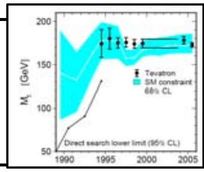
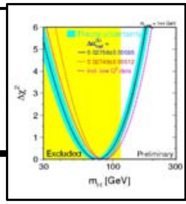
LHC versus SppS, TeVatron

Similarities:

	prior indirect information	*discovery*
SppS	$G_F, \sin^2\theta \Rightarrow M_W \approx 80\,\text{GeV} \pm 10\%$	W(1983)
TeVatron	LEP: m_{top}=150±50 GeV(1990) 170±20 GeV (1995) 	top (1995)
LHC	m_H>114 GeV m_H<144 GeV (95% CL) 	Higgs 2010?

Differences

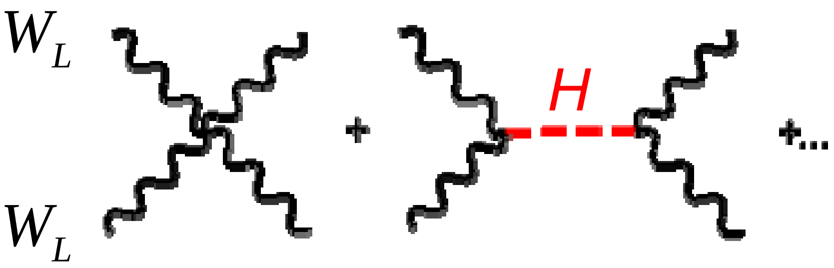
1. *How many Higgs bosons and where is uncertain:*
   a) there are infinitely many theoretically allowed Higgs sectors
   b) indirect limits do not apply to extended models

2. *It's not only about Higgs:*
   a) All known scalar particles are composites.
   Naturally light fundamental scalars require supersymmetry.
   b) We are going beyond a new physical ***scale***. Surprises?

=> LHC potentially much more exciting!

Indirect Higgs boson limits *caveat emptor*

1. *Tree level unitarity in longitudinal WW scattering*



$$A \sim G_F s - G_F s \sim G_F M_H^2$$

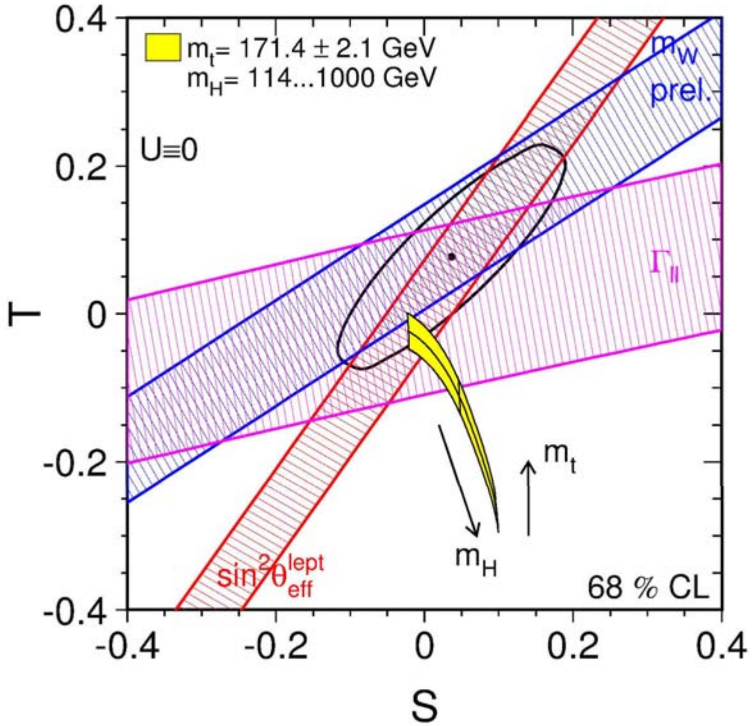
contact+γ,Z

Higgs exchange

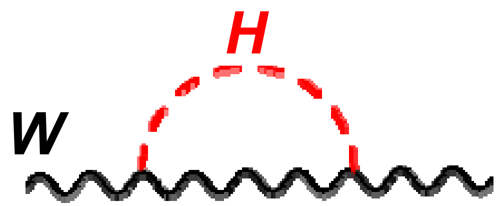
From finite term: $\boxed{M_H < 1\,\mathrm{TeV}}$

N.B.: $\Gamma_H \approx 0.5 M_H \left(M_H/1\,\mathrm{TeV}\right)^2$

2. *Loop effects in Electroweak observables*



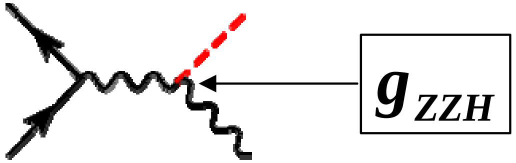
$$\boxed{m_H < 144 \text{ GeV } (95\% \text{ C.L.})}$$



Logarithmic Higgs mass dependence

Direct Higgs boson limits

LEP2: $e^+e^- \to ZH$

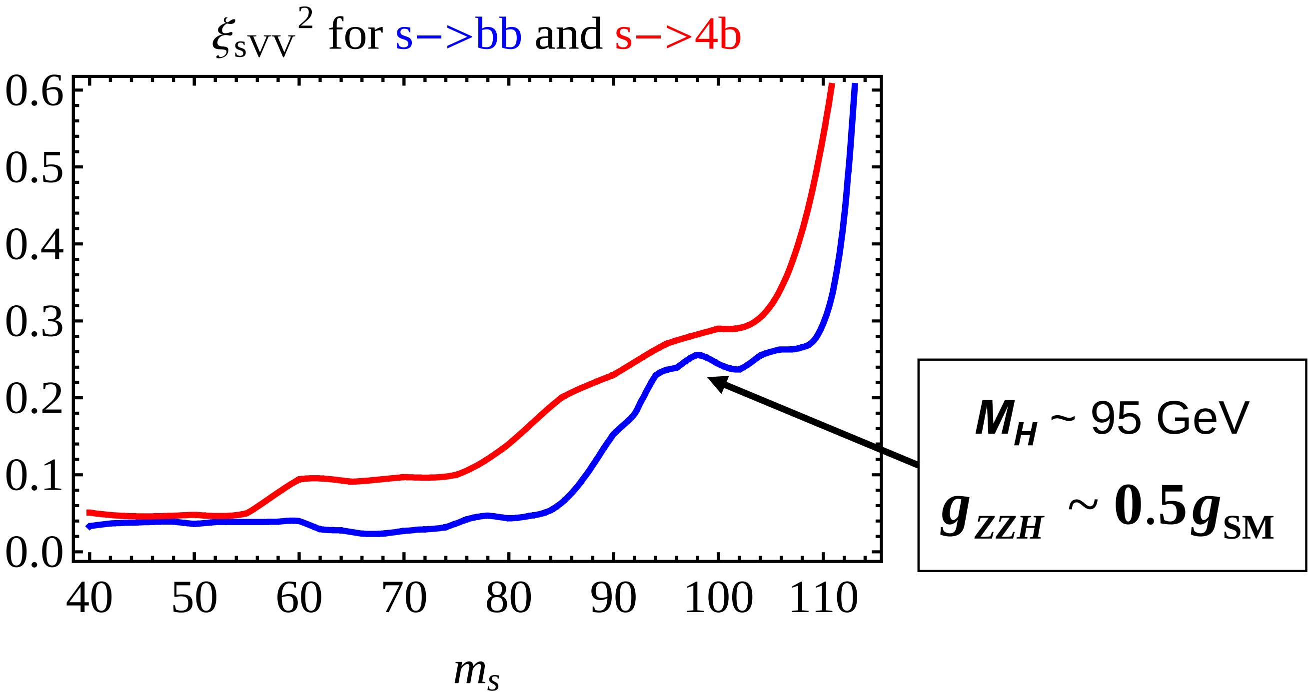


For $g_{ZZH} = g_{SM}$:

$H \to b\bar{b}$	M_H >114.4 GeV (95%CL)
$H \to$ invisible	>114 GeV
$H \to \varphi\varphi \to 4b$	>110 GeV
$H \to \varphi\varphi \to 4\tau$	>86 GeV
$H \to$ anything	>82 GeV

SM

For $\xi = \left(\frac{g_{ZZH}}{g_{SM}}\right)^2 < 1$



Q&A about Higgs boson

Question	*Answer*	*Explanation*
Can it be significantly heavier than expected?	Yes	**New** particles contributing to T,S
Could it have escaped detection?	Yes	**New** particles dominating Higgs decays
Can one make it without Higgs particle?	Yes	Unitarity can instead be restored by **new** heavy vectors (see below)

Where is new physics?

New physics (NP) at short distances: $\Lambda_{NP} = ..., M_{SUSY}, M_{DM}, M_{seesaw}, M_{GUT}, M_{Planck}$

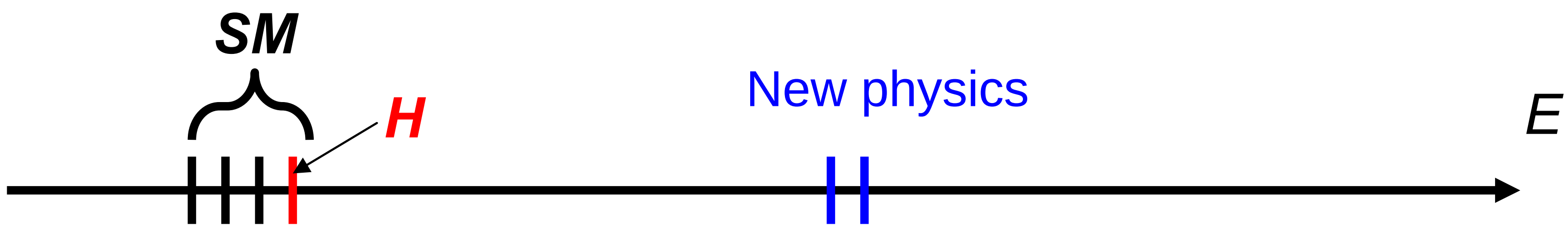
How to keep beautiful consistency of SM with experimental tests?

No problem at all, even without knowing what this NP is, provided:

1. SU(3)xSU(2)xU(1) is kept intact

2. Low energy spectrum is that of the SM,
   with the inclusion of the Higgs boson

3. $\Lambda_{NP} >> G_F^{-1/2}$



$\longleftarrow \Lambda_{NP} \longrightarrow$

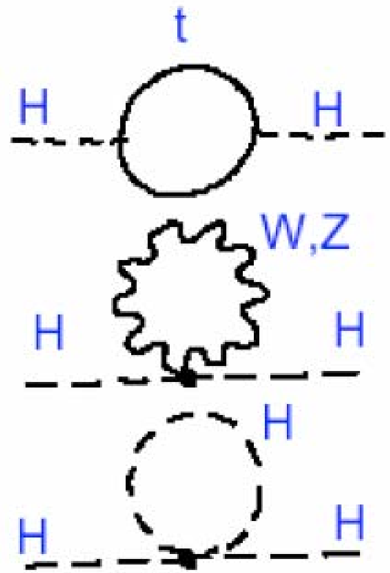
To resolve naturalness "**problem**"

To suppress contributions to Electroweak observables

Why "a problem"?

1. To address it at all, need a "calculable" Higgs mass

2. In the SM



$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2 \quad (*)$$

with known coeff.s for a given cut-off

3. Even though $\Lambda \to \infty$,
whatever will cutoff these div.s is likely to leave a significant contribution to m_h^2 (see below) Too big?

4. Using the naive estimate of $(*)$
and <u>barring accidental cancellations</u> $\Rightarrow$

$$\boxed{\begin{array}{l} \Lambda_t \approx 3.5\, m_h \\ \Lambda_g \approx 9\, m_h > \Lambda_t \\ \Lambda_h \approx 1.3 \text{ TeV} \end{array}}$$

5. Especially Λ_t low enough that one might have already seen its (indirect)signs

Solutions to naturalness problem

(Conservative)
There is no Higgs boson (!?)

1

An Approximate Symmetry keeps Higgs boson light

Global Symmetry
(pseudo-Goldstone Higgs)
$$h \rightarrow h + \alpha$$

2

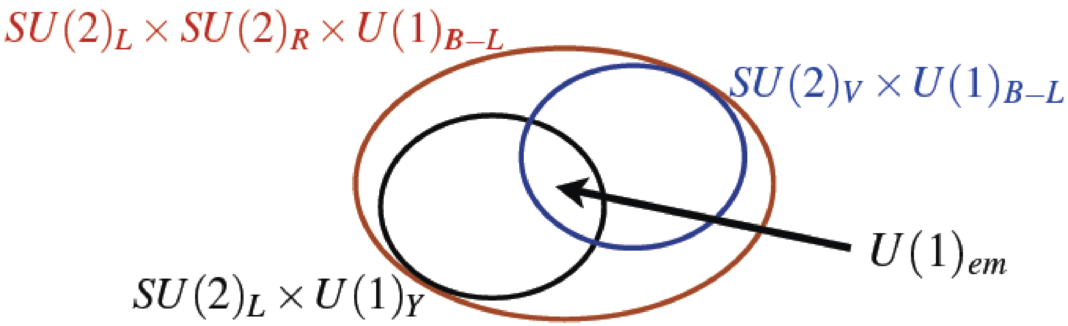
Supersymmetry
$$h \leftrightarrow \chi$$

3

1 Higgsless models

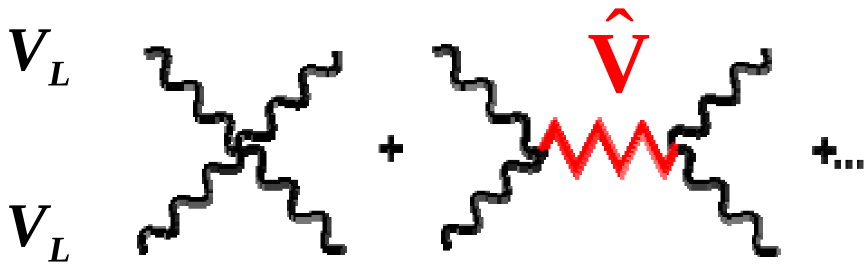
Strong coupling @ TeV, Electroweak Chiral Lagrangian, Technicolor, etc

Electroweak breaking via $SU(2)_L x SU(2)_R \rightarrow SU(2)_V$ breaking:



Unitarization by new massive vector bosons with mass < 2 TeV:

(V=W,Z)



Like ρ-meson does for pion scattering in QCD

Narrow resonances, even when heavy: $\Gamma_{\hat{V}} \approx 4\% M_{\hat{V}} \left(M_{\hat{V}} / 1\,\mathrm{TeV} \right)^2$

50% for Higgs boson

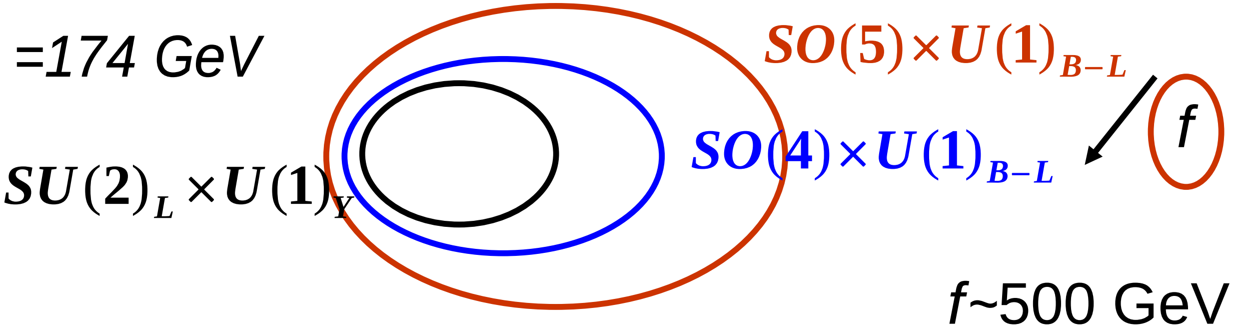
Unobserved effects expected from $\hat{\mathbf{V}}$ - $\mathbf{V}$ *mixing unless* $\hat{\mathbf{V}}$ *is heavy*

WWZ vertex => $M_{\hat{V}} > 400\,\mathrm{GeV}$

S,T fit => $M_{\hat{V}} = 1-2\,\mathrm{TeV}$ (see below)

2 Pseudo-Goldstone Higgs boson

- *A two-scale picture: f > v =174 GeV*



- *SO(5) sector strongly interacting => Higgs boson is "composite"*

- *Top loop corrections to m_h^2 cut off by states with the same spin and gauge quantum numbers (new heavy quarks)*

- *hVV coupling suppressed, relative to the SM, by a factor* $(1-v^2/f^2)^{1/2}$

- *Still need heavy vectors to restore unitarity (may be factor 2-3 heavier than in Higgsless case)*

Electroweak Precision Tests

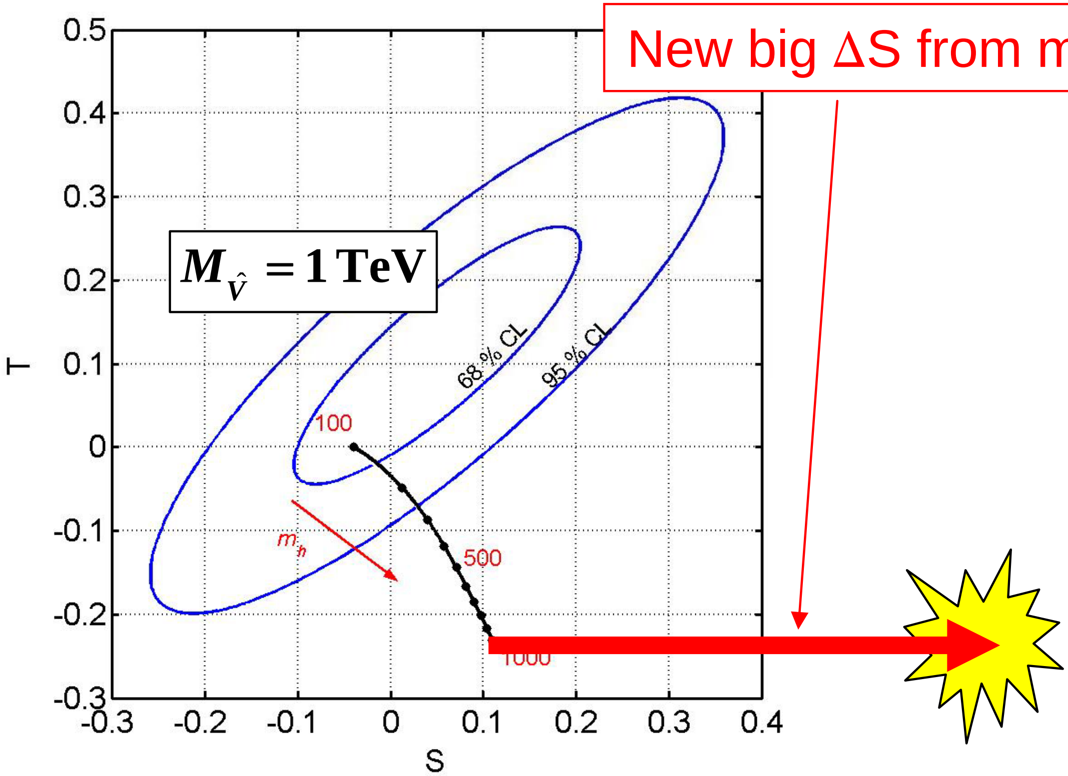
Higgsless

Same as for heavy SM Higgs boson

$$\Delta T \approx -0.1 \ln \frac{M_{\hat{V}}}{100\ \mathrm{GeV}}$$

$$\Delta S \approx 0.05 \ln \frac{M_{\hat{V}}}{100\ \mathrm{GeV}} + 0.6 \left(\frac{1\ \mathrm{TeV}}{M_{\hat{V}}} \right)^2$$

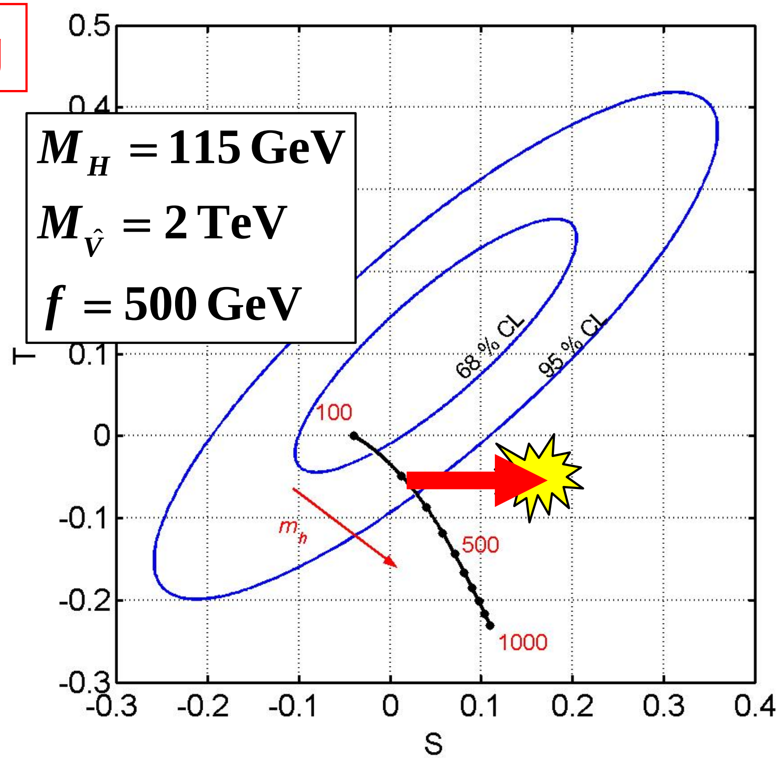
New big ΔS from mixing



pseudo-GB Higgs

$$\Delta T \approx -0.1 \ln \frac{M_{H,eff}}{100\ \mathrm{GeV}}$$

$$\Delta S \approx 0.05 \ln \frac{M_{H,eff}}{100\ \mathrm{GeV}} + 0.6 \left(\frac{1\ \mathrm{TeV}}{M_{\hat{V}}} \right)^2$$



A problem unless something missing…

Main phenomenology

V - W,Z $\qquad \hat{\mathrm{V}}$ - *new heavy vectors*

	Higgs-less	*pGB Higgs*
$A(V_L V_L \to V_L V_L)$ below $\hat{\mathrm{V}}$	s/v^2	s/f^2
$M_{\hat{V}}$	$g_s v < 2\,\mathrm{TeV}$	$g_s f < 2\,\mathrm{TeV}(f/v)$
$\hat{\mathrm{V}}\mathrm{VV}$ coupling	g_s strong	
$\hat{\mathrm{V}} f\bar{f}$	$g(g/g_s)$	
$\hat{\mathrm{V}} t\bar{t}$	?	strongish
new heavy quarks $T^{2/3}, B^{-1/3}, X^{5/3}$	✗	✓ m~TeV

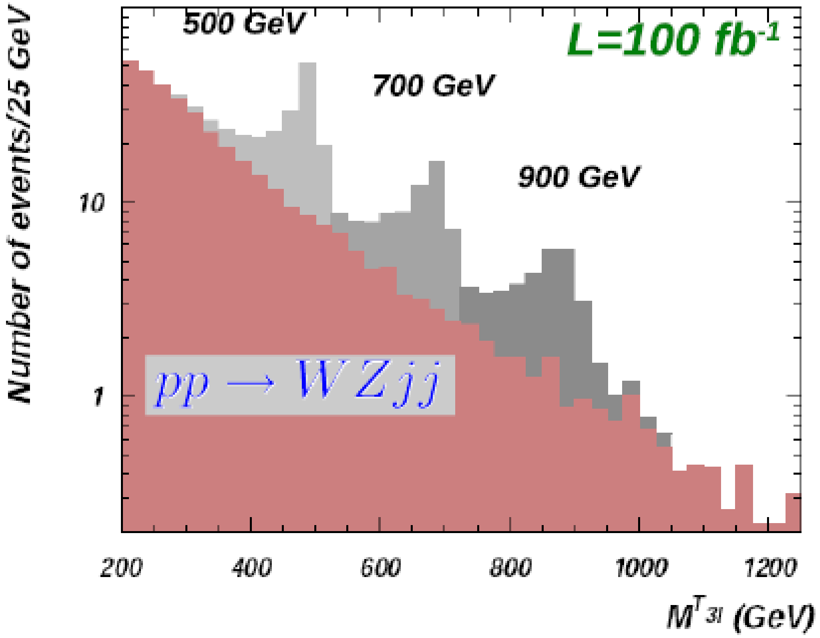
Signals of heavy vectors $\hat{\mathbf{V}}$

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

(t or b, depending on the charge)

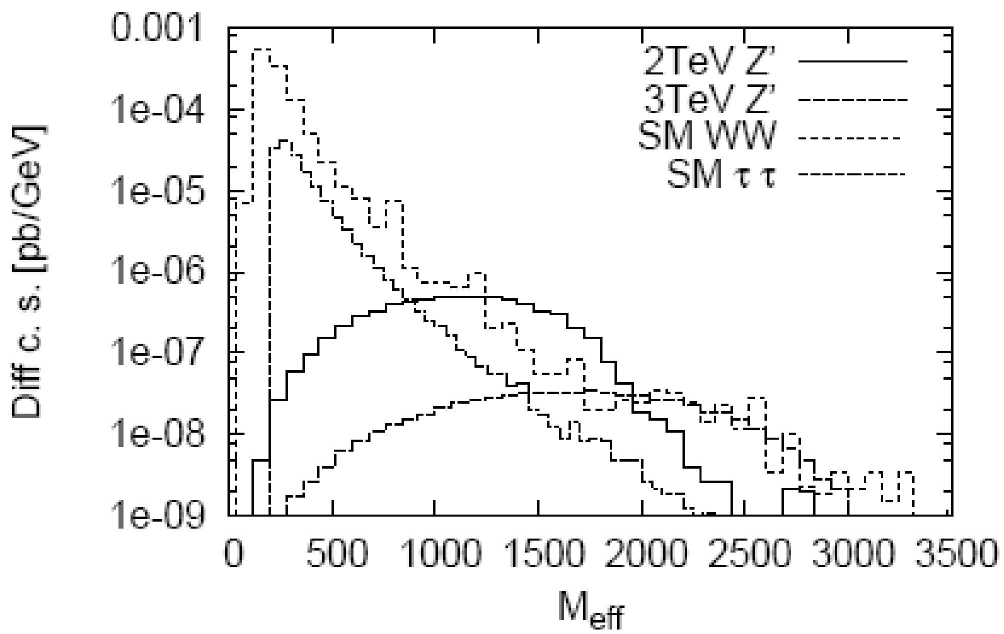
$\hat{V} \to f\bar{f}$ probably not useful, because of small BR

$$pp \to \hat{W}qq \to WZqq \to qq3l\nu$$



Belyaev et al

$$pp \to \hat{Z} \to W^+W^- \to 2l2\nu$$



Agashe et al

Signals of heavy quarks

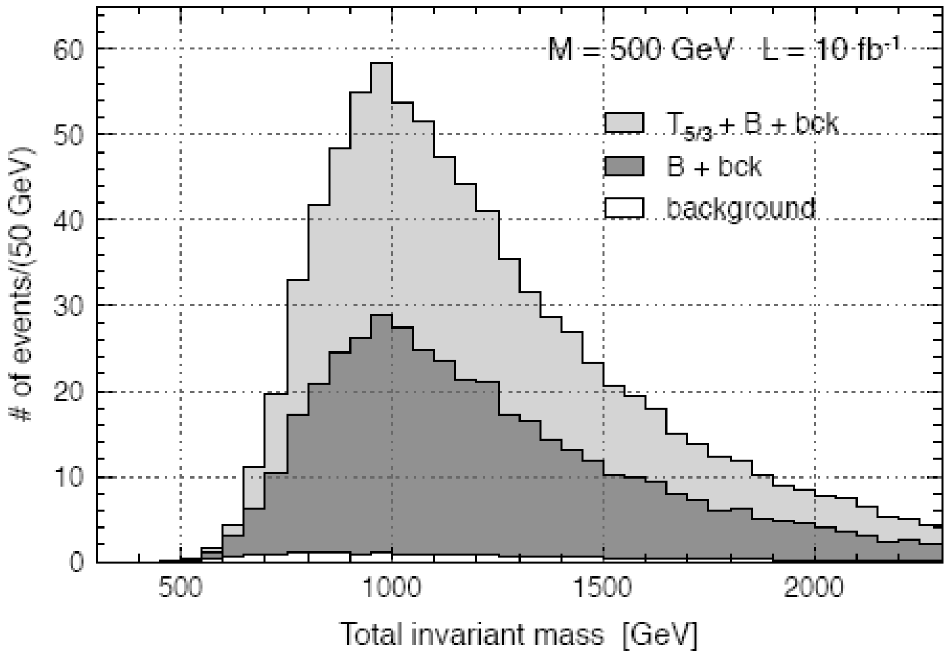
$$Q \equiv (T^{2/3}, B^{-1/3}, X^{5/3})$$

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

(t or b, depending on the charge)

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

$$pp \to X\bar{X} + B\bar{B} \to l^{\pm}l^{\pm} + jets + \not{E}_T$$



Contino, Servant

3 *Supersymmetry at the LHC*

(if you care of the prediction!)

Pros

$\Rightarrow$ Neatly solves the naturalness problem of the Fermi scale

$\Rightarrow$ Gauge coupling unification

$\Rightarrow$ Alternatives in worse shape (EWPT)

Contras (none decisive)

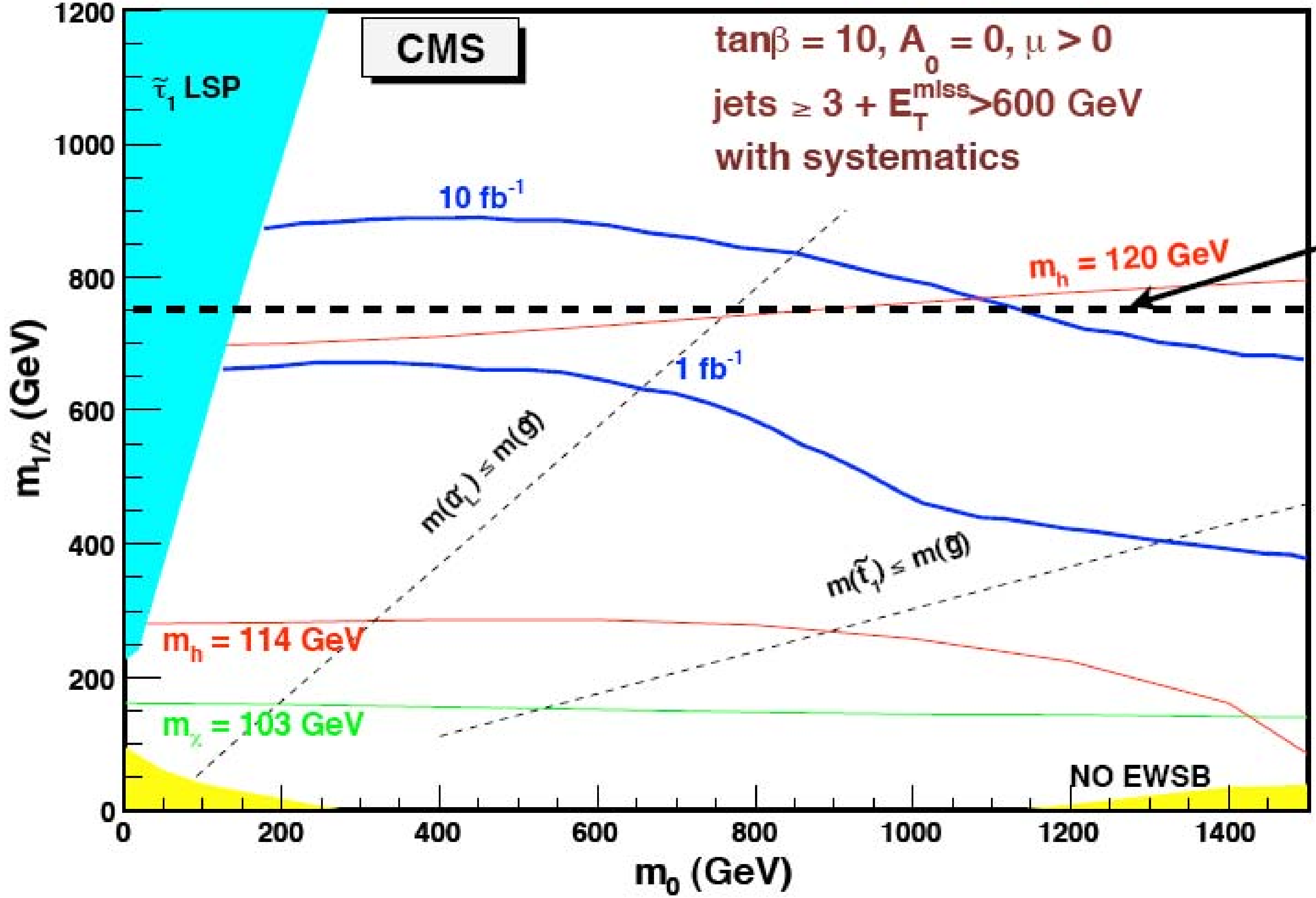
✓ $\Rightarrow$ No Higgs boson ✓

$\Rightarrow$ No flavour effects (but follow $\mu \rightarrow e + \gamma$ at PSI)

$\Rightarrow$ No superpartners

mSUGRA discovery potential: Easy (?)

cascade decays of gluinos/squarks into lighter neutralinos/charginos/sleptons



$m(\tilde{g}) \approx 2.5\ TeV$

$m^2(\tilde{q}) \approx m_0^2 + 5m_{1/2}^2$

$m(\tilde{g}) \approx 2.7m_{1/2}$

$m(\tilde{w}) \approx 0.8m_{1/2}$

$m(\tilde{b}) \approx 0.4m_{1/2}$

$$pp \to \tilde{g}\tilde{g} \to /E_T + jets\ (+\mu^{\pm}/l^+l^-/Z/t)$$

Where is the supersymmetric Higgs boson?

View n^0 1

MSSM 2x4 - (2+1) = 5 = 2 + 1 + 1 + 1

$H^\pm \quad h \quad H \quad A$

$$m_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2})]$$

⇒ *Take large tanβ (muon anomaly?) and large stop mass*

for $A_t/m_{\tilde{t}} \lesssim 1$ $\boxed{m_{\tilde{t}} \gtrsim 900 \text{ GeV}}$

to comply with the LEP bound

⇒ *Swallow, e.g. in SUGRA,* $\Delta M_Z^2 \approx (2 \div 3) m_{\tilde{t}}^2 \geq 100\ M_Z^2$

⇒ *h just around the corner and quasi-standard*

Where is the supersymmetric Higgs boson?

View n^0 2

1. *Even assuming, for good reasons, that supersymmetry is relevant to nature, NO theorem that requires it to be visible at the LHC*

2. *For supersymmetry to be visible at the LHC, need a maximally natural solution of the hierarchy problem*

3. *Since the top, and so the stop, are the particles with the strongest coupling to the Higgs boson, insist on a moderate stop mass*

$\Rightarrow$ *Motivates search of (reasonably simple) alternatives*

$\Rightarrow$ *h not standard and not even light?*

Two examples, based on the NMSSM

(others have been considered)

$$\Delta V = \lambda^2 |H_1 H_2|^2$$

$CP^+ : \quad h_1 < h_2 < h_3 \qquad CP^- : \quad A_1 < A_2 \qquad H^\pm$

1 $\lambda(G_F^{-1/2}) \approx 2$ (not obviously consistent with unification)

$m(h_1) = 150 \div 300\ GeV$ and $\approx$ standard

(but very much NON-susy-like)

$h_2 \to h_1 h_1 \to 4V \to l^+ l^-\ 6j$

$A_1 \to h_1 Z \to VV\ Z \to l^+ l^-\ 4j$

2 $\lambda(G_F^{-1/2}) \lesssim 0.7$ (consistent with unification)

$m(h_2) = 115 \div 125\ GeV$

$h_2 \to A_1 A_1 \to 4b$

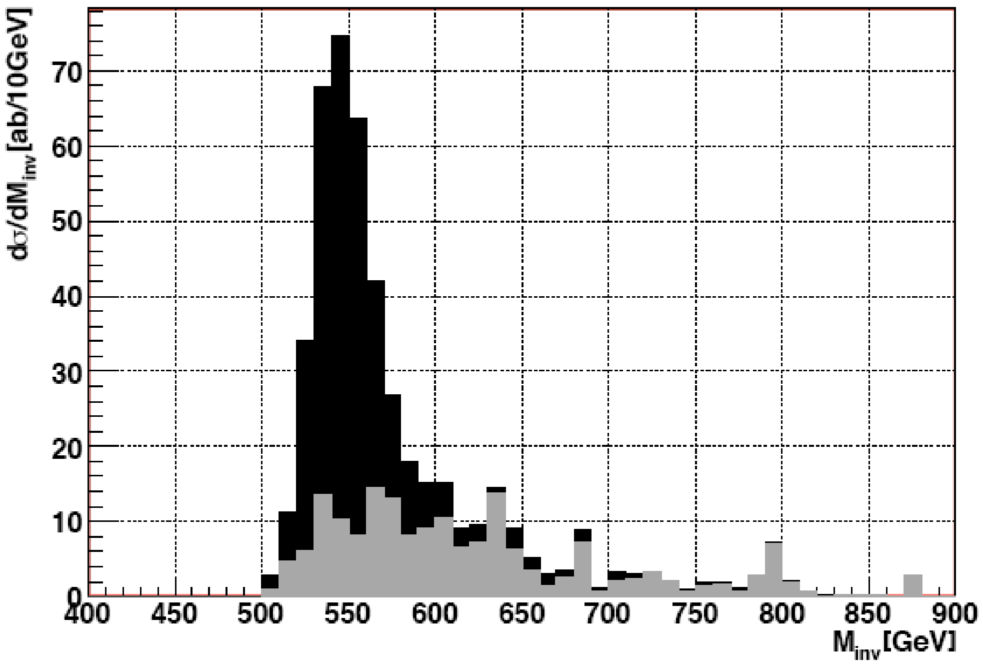
or

$m(h_2) = 95 - 100\ \mathrm{GeV}$

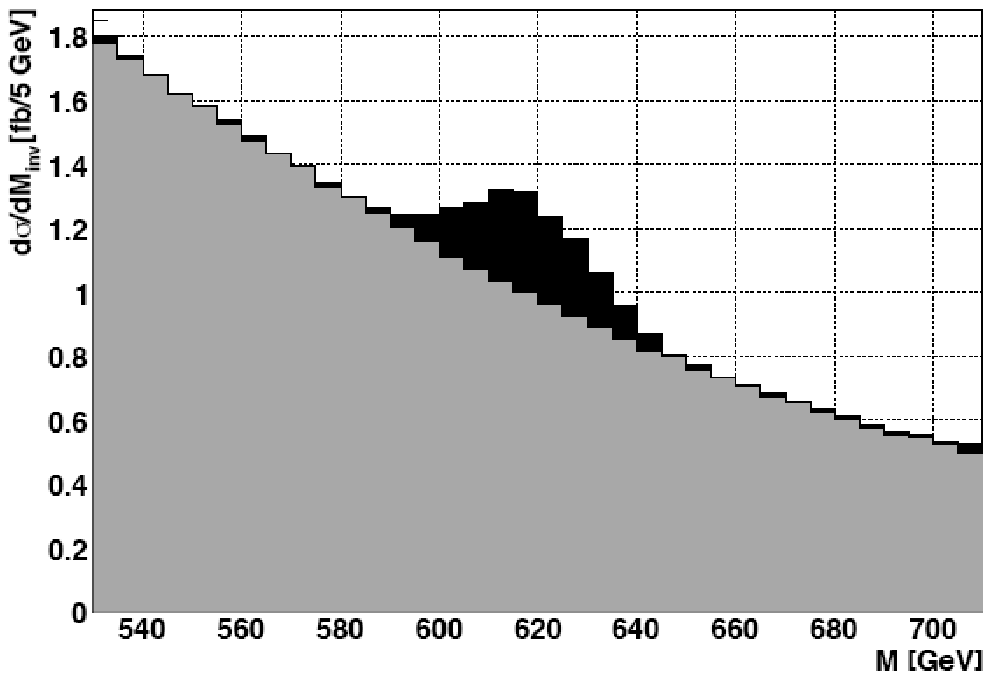
$h_2 \to A_1 A_1 \to 4\tau$

1

$\lambda_{low\ energy} \leq 2$



$$H \to hh \to 4V \to 2l\ 6\,jets$$

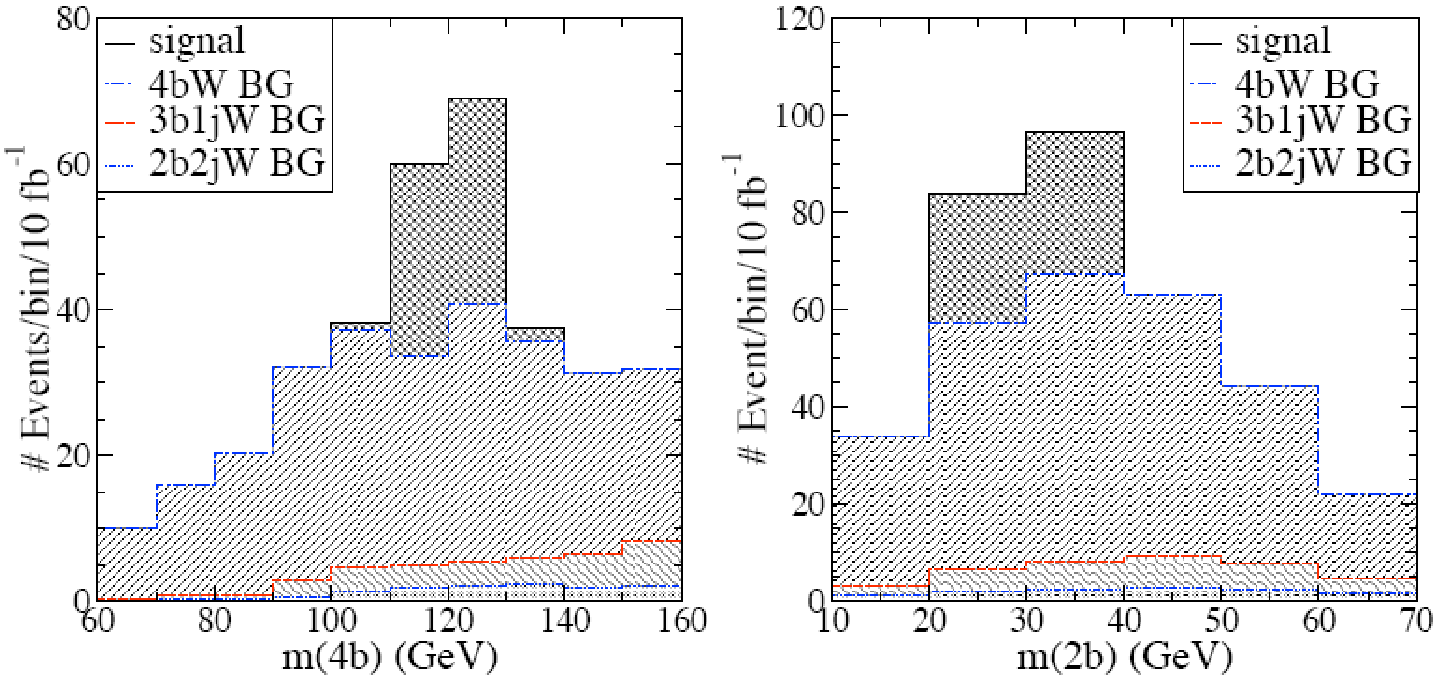


$$A \to Zh \to Z\ 2V \to 2l\ 4\,jets$$

Cavicchia, Franceschini, R.

2

$pp \to V\,h \to l\nu\, A_1 A_1 \to l\nu\, 4b$



$m_h = 120\ GeV$ $\qquad$ $m_{A_1} = 30\ GeV$

Carena, Han, Huang, Wagner

Summary of signals

Some mutually excluding

$$\boxed{\int Ldt \leq 1fb^{-1}}$$

1. Gluino/squark cascade decays, stable R-hadrons, light gravitino…)

$$\boxed{\int Ldt = 1 \div 30fb^{-1}}$$

2. SM-like Higgs boson

3. Heavy quarks

$$\boxed{\int Ldt \geq 30fb^{-1}}$$

4. Heavy vectors

5. Non-standard SUSY Higgs bosons

6. EW gauge/higgsino decays

Conclusions

	Higgs boson	*BSM @ TeV*	*My likelihood estimate*
1.	✗ experimentalist's nothing	✗	– (theoretically inconsistent)
2.	✓ theoriist's nothing	✗	10% ☹
3.	✗	✓	10% (Higgsless)
4.	✓	✓	40% pseudo-Goldstone Higgs 40% SUSY
			Σ=100%

Expectations are high. Experiment will decide.
Physics in its normal way of operation.