Theory and Phenomenology of

Heavy Vectors in Higgsless Models

Gino Isidori

[*INFN - Frascati*]

- Introduction
- Heavy vectors in the EW Chiral Lagrangian and EWPO
- Phenomenology of the heavy vectors at the LHC
- The l^+l^- final state & present constraints from Tevatron
- Conclusions

Introduction

Experiments provide unambiguous indications that the SM gauge group is spontaneously broken [$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$]

However, so far only the ground state of the SM Higgs Lagrangian

$$\mathscr{L}_{\text{Higgs}}(\phi, A_i, \psi_i) = D_\mu \phi^+ D^\mu \phi + \mu^2 \phi^+ \phi - \lambda (\phi^+ \phi)^2 + Y^{ij} \psi_L^{\ i} \psi_R^{\ j} \phi$$

with the corresponding Goldstone-boson structure & the custodial symmetry, has been tested with good accuracy [$\langle \phi \rangle = 246$ GeV $\Leftrightarrow m_{W,Z}$]

The only (weak) evidence in favour of a "fundamental" Higgs is obtained from EWPO: indirect indication of a light m_H

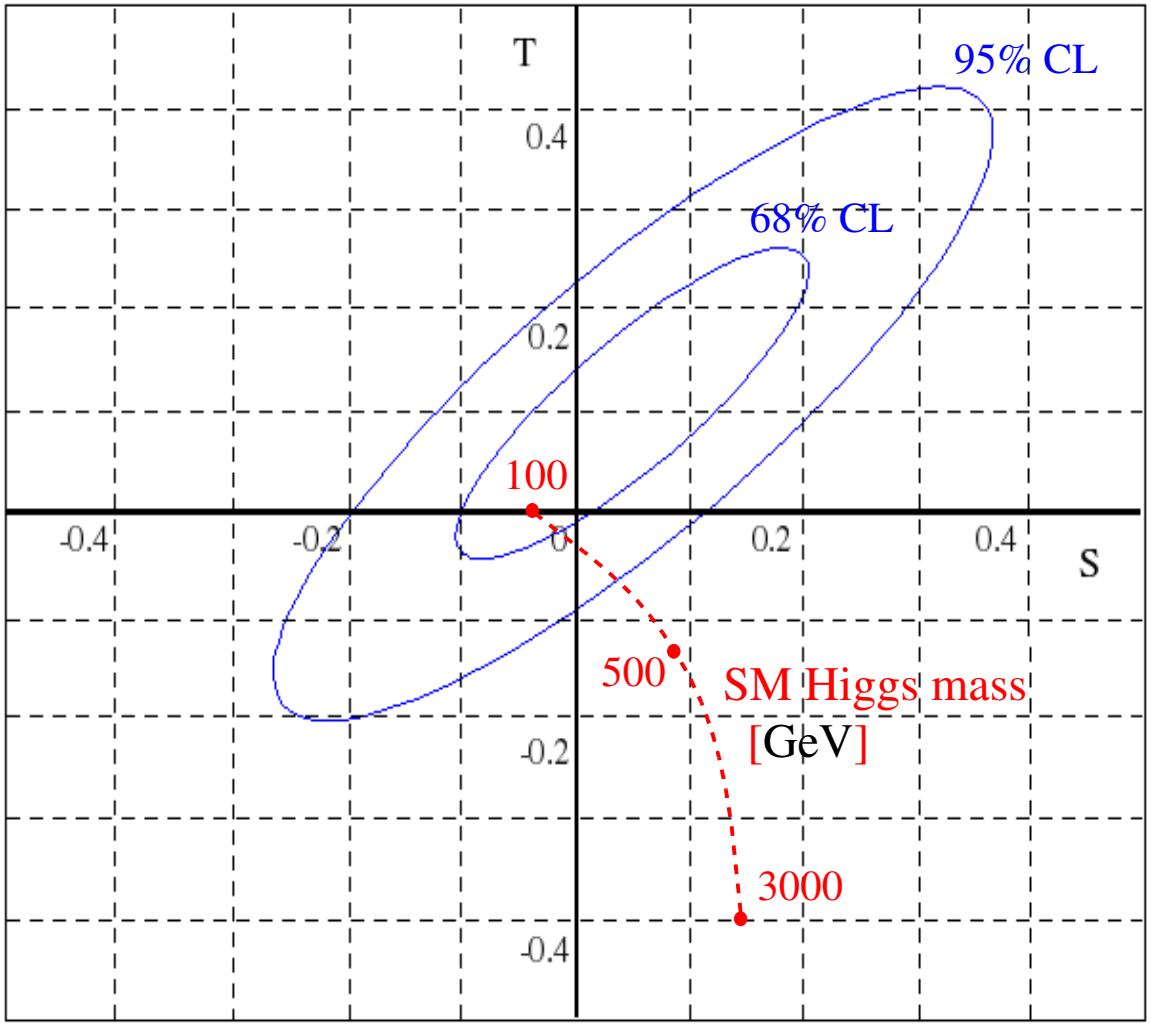
This indication holds under the hypothesis of an heavy cut-off for the SM viewed as an effective theory

naturalness problem
for the Higgs mass term

$$T = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$

$$S = \frac{g}{g'} \frac{d\Pi_{30}(q^2)}{dq^2}\bigg|_{q^2=0}$$

Peskin, Takeuchi, '90
Altarelli, Barbieri, '91
⋮
Barbieri, Pomarol, Rattazzi, Strumia, '04



Do we really need a fundamental Higgs field ?

Not really: The only clear indication of EWPO is that we need the spontaneous breaking of the SM gauge group, and that the breaking mechanism must respect, to a good accuracy, the $SO(4) \sim SU(2)_L \times SU(2)_R$ global symmetry of the SM Higgs potential

General formulation of the symmetry breaking in absence of a fundamental Higgs (or for large Higgs masses) in terms of the e.w. chiral Lagrangian:

Weinberg, '79
Longhitano, '80-'81
Appelquist & Bernard, '80-81

$$\mathscr{L}_\chi^{(2)} = \frac{v^2}{4}\,\mathrm{Tr}(D_\mu U^+ D^\mu U)$$

$$U \to g_R\, U\, g_L^{\,+} = e^{i\pi/v}$$

3 Goldstone bosons of the SM

$v = 246$ GeV

global:

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

local:

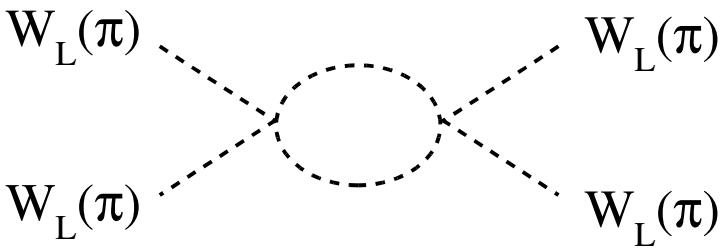
$$SU(2)_L \times \quad U(1)_Y \quad \to U(1)_Q$$

$$D_\mu U = -ig' B_\mu U + igUW_\mu$$

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_i, \psi_i) + \mathscr{L}_{\text{Yukawa}}(U, \psi_i) + \frac{v^2}{4}\text{Tr}(D_\mu U^+ D^\mu U)$$

This Lagrangian contains all the degrees of freedom we have directly probed in experiments

Naive cut-off dictated by the convergence of EW loops: $\Lambda^{\text{NDA}} = 4\pi v \sim 3$ TeV



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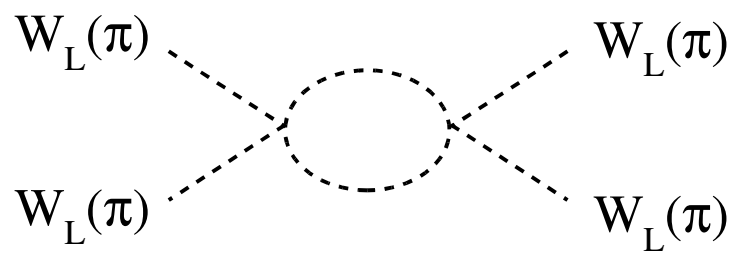
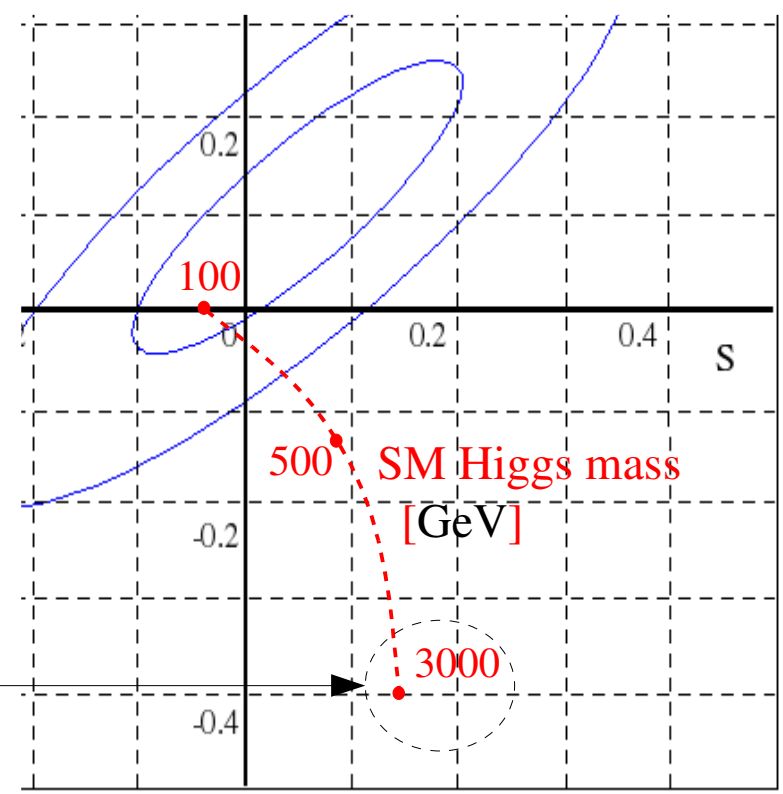


Naive cut-off dictated by the convergence of EW loops: $\Lambda^{\text{NDA}} = 4\pi v \sim 3$ TeV

$\mathscr{L}_{\text{eff}}$ perfectly describe particle physics up to ~ 3 TeV, beyond the tree level, with only two drawbacks (which point toward the existence of <u>new degrees of freedom below the naive cut-off</u>):

- Violation of unitarity in $W_L W_L \to W_L W_L$ (tree-level ampli.violates unitarity for $s \sim 1$ TeV)
- Bad fit to S and T



A natural alternative to fundamental scalars in curing the problem of unitarity in $W_L W_L \to W_L W_L$ scattering is represented by heavy vector fields

Heavy vectors are indeed expected in many non-SUSY scenarios [e.g.: the techni-rho in *technicolor*, the massive gauge bosons in *5-dimensional theories* or their 4-dim. deconstructed versions (3 sites, 4 sites, ...)...]

As is well known from the early days of technicolor, the difficult task is to cure at the same time unitarity and EWPO

↓

The indirect constraint on this class of models, as well as the LHC phenomenology, can be analysed in general terms constructing an appropriate effective chiral Lagrangian with the heavy vectors as new explicit d.o.f.

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Yukawa}(U, \psi_i) + \mathscr{L}_{\chi}$$

$$\mathscr{L}_{\chi} = \frac{v^2}{4}\,{\rm Tr}(D_\mu U^+ D^\mu U) + \mathscr{L}_{\rm kin}(R, U, A_i; M_R) + \mathscr{L}_{\rm int}(R, U, A_i; G_R)$$

Heavy vector in the EW Chiral Lagrangian and EWPO

We consider an effective theory based on the following 3 simple and rather general assumptions:

- The (new) dynamics that breaks the SM e.w. symmetry is invariant under the global symmetry $SU(2)_L \times SU(2)_R$ and under the discrete parity $L \leftrightarrow R$
- One vector (V), or one vector + one axial-vector (V+A), both belonging to the adjoint representation of $SU(2)_{L+R}$ (triplets), are the only light fields below a cut-off $\Lambda = 2\text{-}3$ TeV
- The SM fermions interact with the new states only via the SM gauge fields

Barbieri, GI, Richcov, Trincherini '08

Having defined the spectrum and the symmetry, it is (almost) straightforward to write the Lagrangian, ordering the operators according to the standard derivative (momentum) expansion

In the case of heavy spin-1 fields, there is a peculiar problem related to the possible mixing of the heavy states and the Goldstone bosons.

Describing the heavy states in terms of Lorentz vectors (V_μ & A_μ), we have a possible mass-mixing of $O(p)$ [→ *tedious redefinition of the fields and miss-match in the power counting at low energies*]

$$V_\mu \to V_\mu + \beta\,[\pi, \partial_\mu \pi] + \ldots \qquad\qquad A_\mu \to A_\mu + \alpha\,\partial_\mu \pi + \ldots$$

This problem can be avoided describing the heavy spin-1 states by means of <u>antisymmetric tensors</u> ($R^{\mu\nu} = V^{\mu\nu}$, $A^{\mu\nu}$):

Gasser & Leutwyler, '84
Ecker *et al.* '89

$$\mathcal{L}_{\rm kin}(R^{\mu\nu}) = -\frac{1}{2}{\rm Tr}\left(\nabla_\mu R^{\mu\nu}\nabla^\sigma R_{\sigma\nu}\right) + \frac{1}{4}M_R^2{\rm Tr}\left(R^{\mu\nu}R_{\mu\nu}\right)$$

$$\langle\, 0 \mid R^{\mu\nu} \mid R(p,\epsilon)\,\rangle \;=\; \frac{i}{M_R}\left[\, p_\mu\epsilon_\nu - p_\nu\epsilon_\mu \,\right]$$

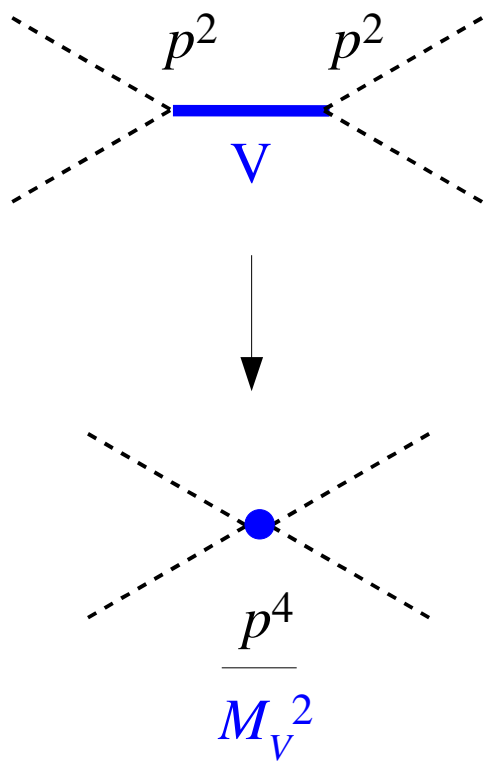
$$\nabla_\mu R = \partial_\mu R + [\Gamma_\mu, R] \qquad\qquad \Gamma_\mu = ½\,[u^+ D_\mu u + u\, D_\mu u^+] \qquad u^2 = U$$

In the antisymmetric formulation the couplings between heavy fields and Goldstone bosons start at $O(p^2)$ $\Rightarrow$ integrating out the heavy fields we are automatically projected into the basis of the $O(p^4)$ chiral operators with light fields only.

In QCD case this procedure leads to a successful description of all the leading $O(p^4)$ light-field couplings

Ecker *et al.* '89

One-to-one relation between the $O(p^2)$ (lowest-order) couplings of the heavy vectors and the $O(p^4)$ Goldstone-boson operators.

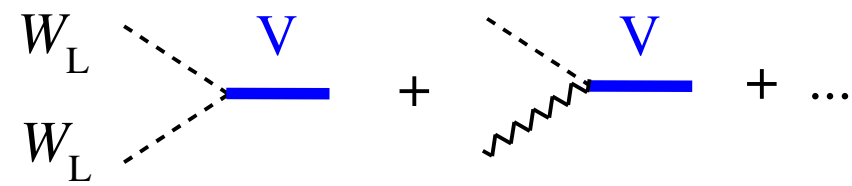


N.B.: starting from a fundamental theory with massive gauge bosons, the transformation to the antisymmetric-tensor formalism can be by obtained by an appropriate matching procedure.

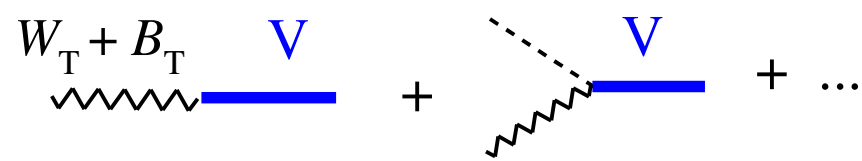
The dynamics of the system below the cut-off is described by 3 + 2 parameters: $(M_V, G_V, F_V) + (M_A, F_A)$.

Naive dimensional analysis implies $F_{V(A)}, G_V = O(v)$

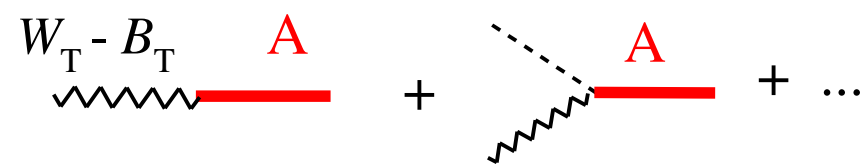
$$\mathcal{L}_{\rm int} = \frac{i}{2\sqrt{2}} G_V \, {\rm Tr}\left(V^{\mu\nu}[u_\mu, u_\nu]\right) \longrightarrow$$



$$+ \frac{1}{2\sqrt{2}} F_V \, {\rm Tr}\left(V^{\mu\nu}(u\hat{W}^{\mu\nu}u^\dagger + u^\dagger \hat{B}^{\mu\nu}u)\right) \longrightarrow$$

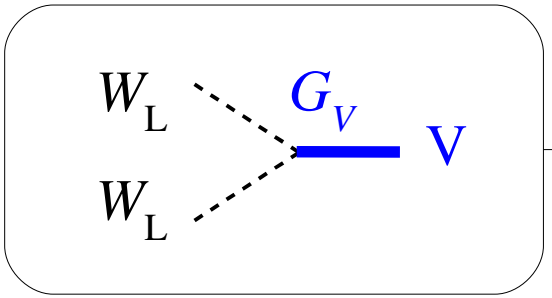


$$+ \frac{1}{2\sqrt{2}} F_A \, {\rm Tr}\left(A^{\mu\nu}(u\hat{W}^{\mu\nu}u^\dagger - u^\dagger \hat{B}^{\mu\nu}u)\right) \longrightarrow$$

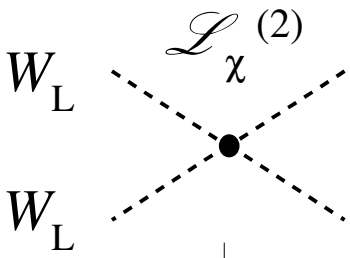


N.B.: Specific UV completions of this effective theory correspond to specific choices of the free parameters. $[\, u_\mu = i\, u^+ D_\mu U u^+ \quad u^2 = U \,]$

For instance, in *hidden gauge models* (or 4-dim. deconstructions), such as $SU(2)_L \times SU(2)^N \times SU(2)_R$, we always have $F_V = 2\, G_V$



Control unitarity:



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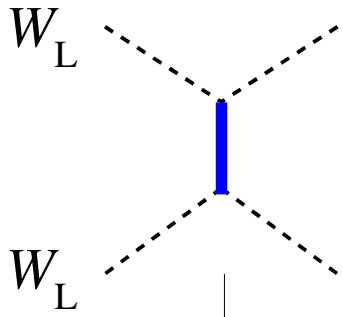

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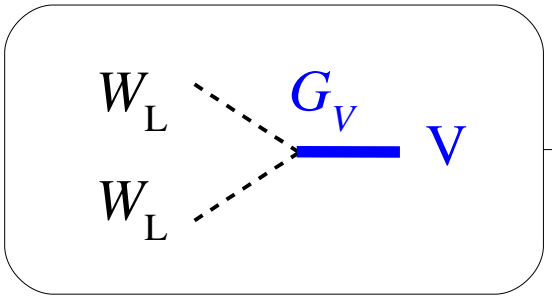
no tree-level violation of unitarity for

$$G_V^2 \approx \frac{v^2}{3}$$

$$A = \frac{s}{v^2} - \frac{G_V^2}{v^4}\left[3s + M_V^2\left(\frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2}\right)\right]$$



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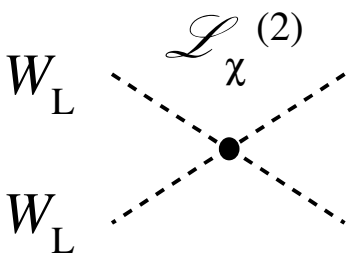

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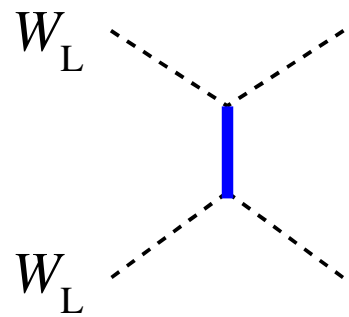

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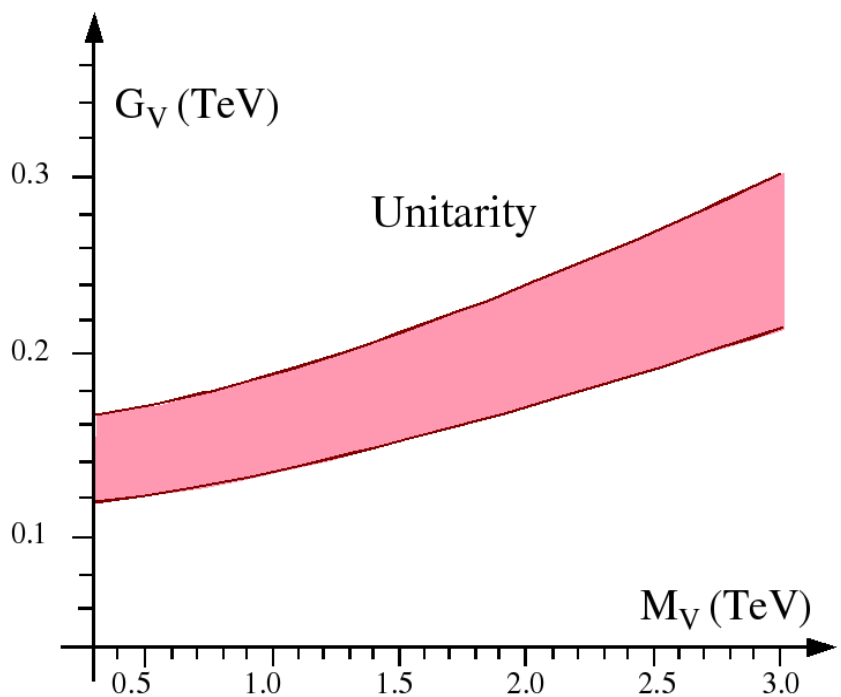
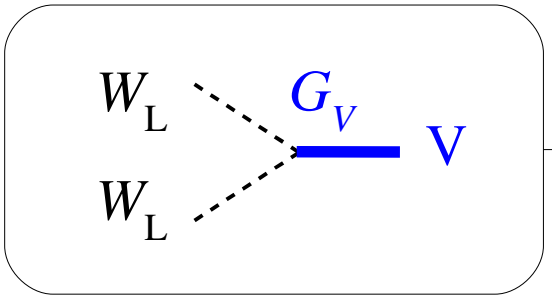
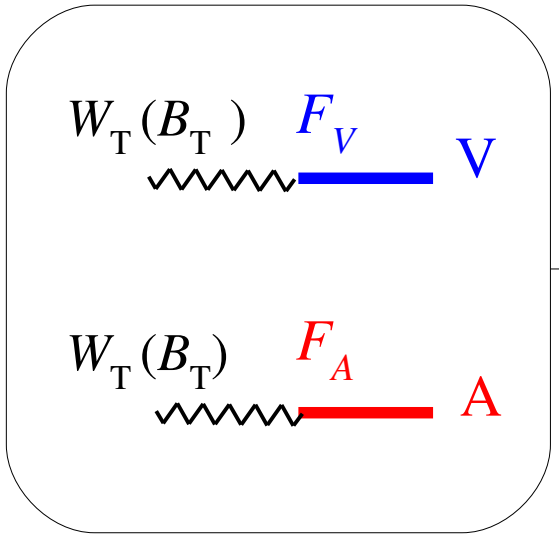
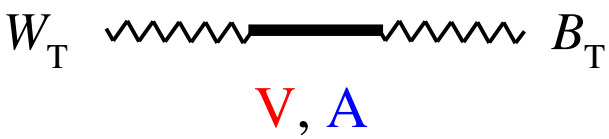


N.B.: The unitarity constraint is almost insensitive to the value M_V

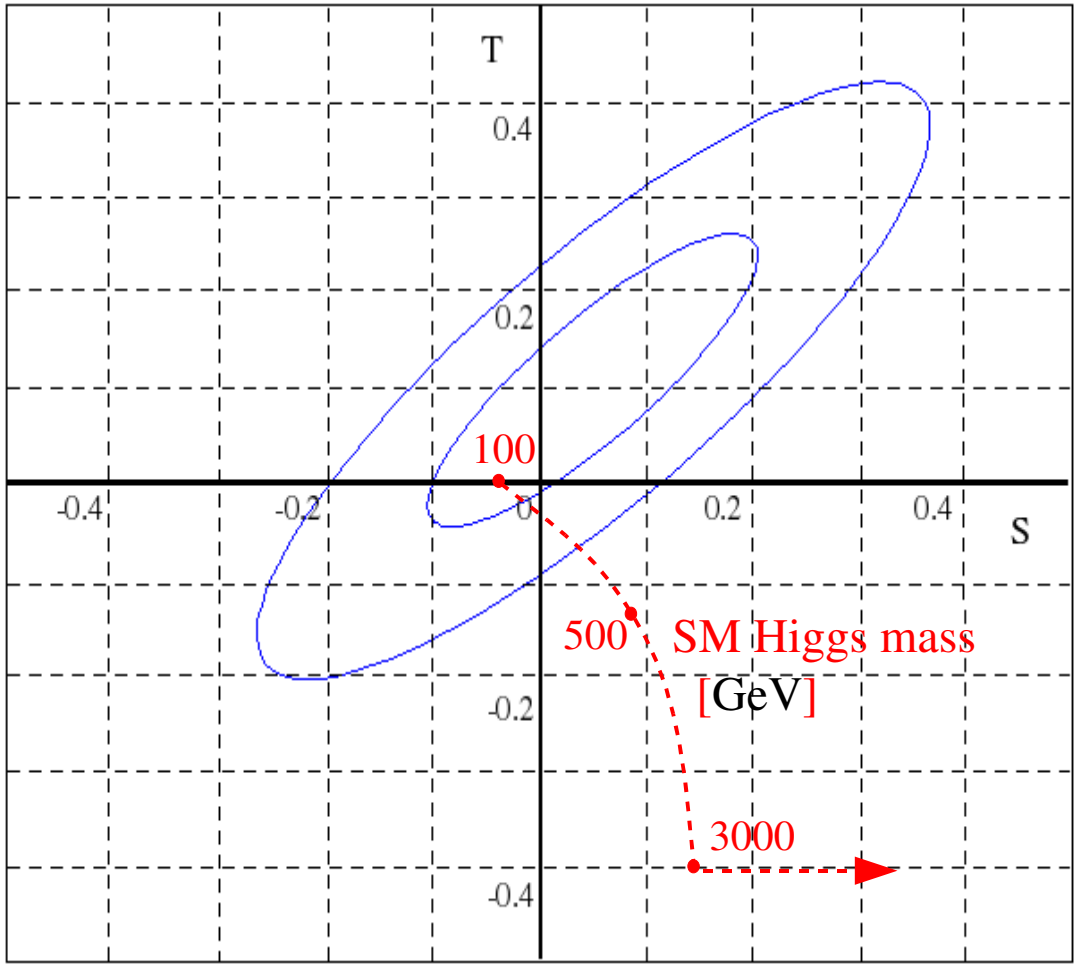


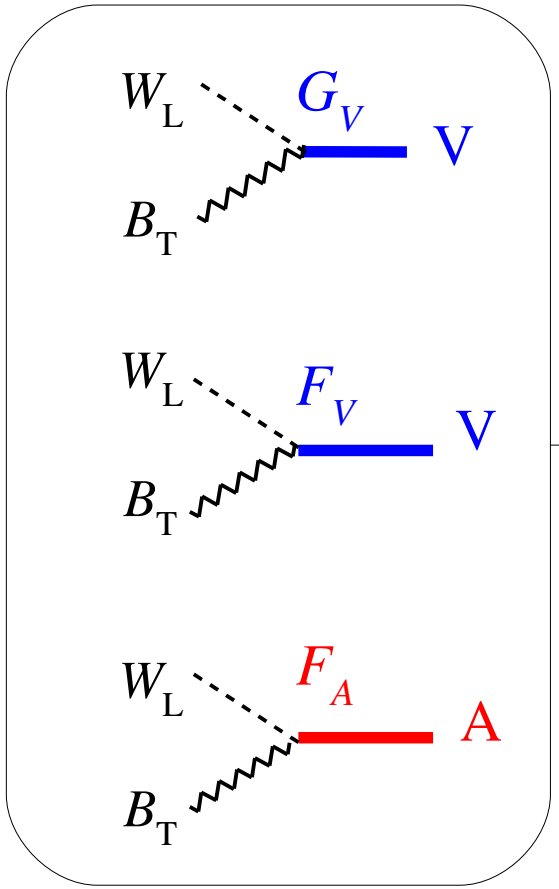




Control unitarity

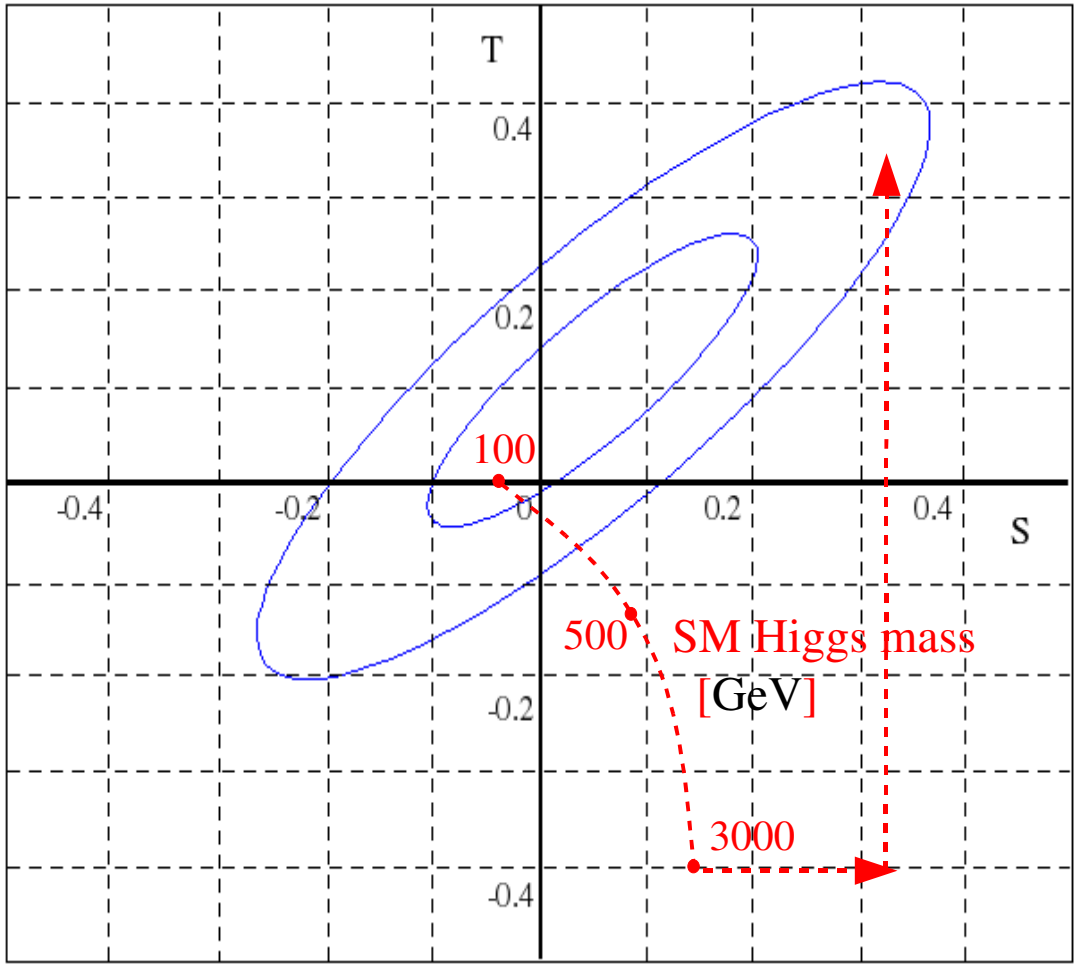
Tree-level positive contribution to S:
(which worsen the agreement with EWPO)

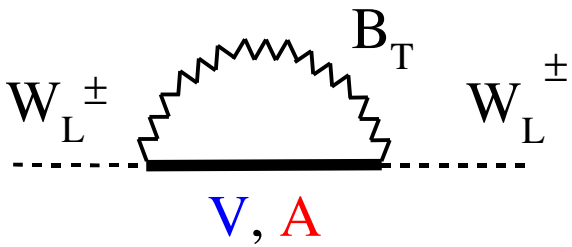




At the one-loop level the situation can become qualitatively very different

Potentially large (quadratically divergent) <u>positive one-loop contribution to T</u>





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

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

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

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

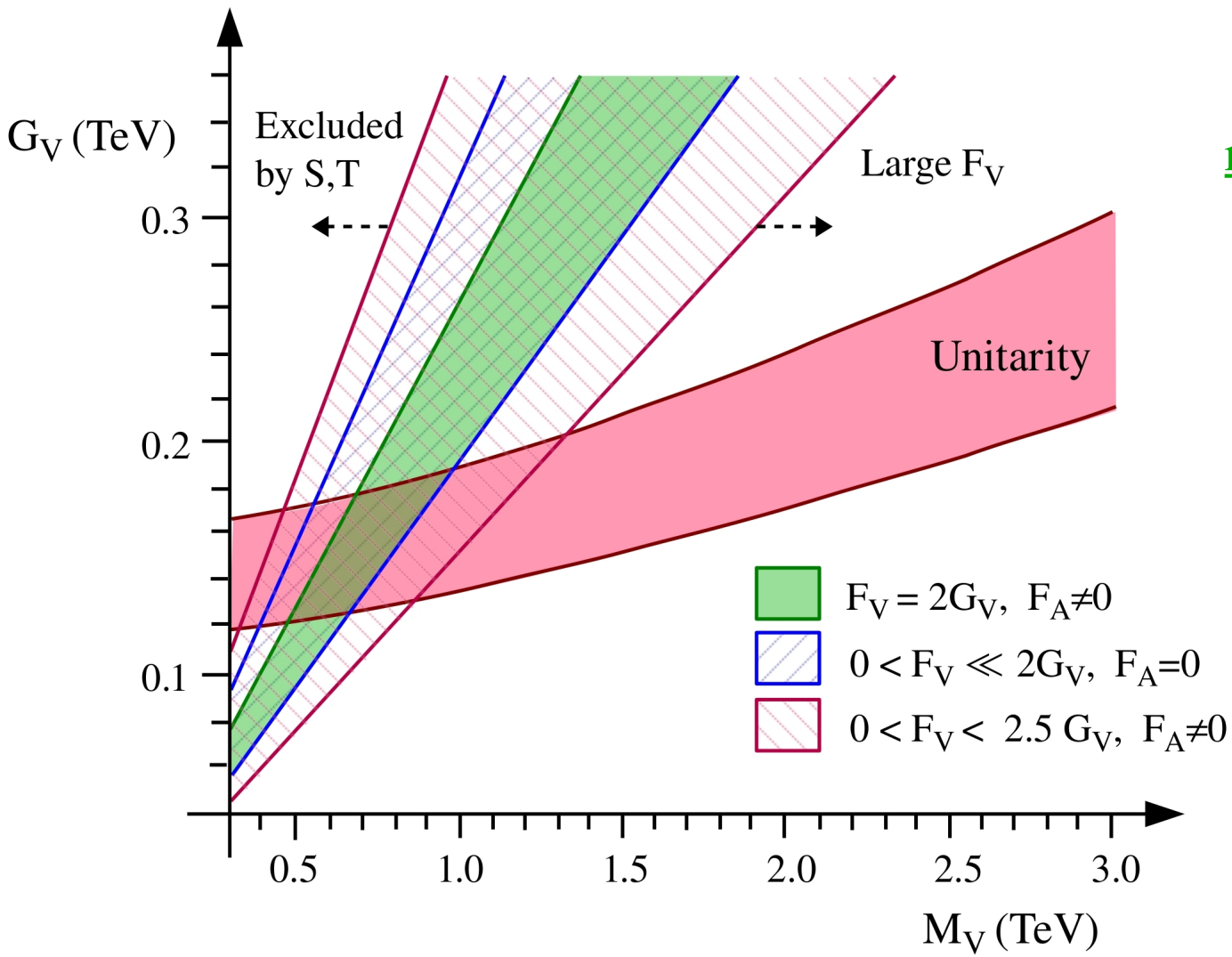
O(1) factor
[Λ replaced by some heavy mass]

Two natural ways to accomodate the EWPO bounds:

Barbieri, GI, Richcov, Trincherini '08

- Both V and A light, almost degenerate (good fit with $F_V \approx 2G_V$)
- Only V light, with small F_V ($F_V \ll 2G_V$)

Putting all the ingredients together, EWPO& unitarity can be accomodated for specific choices of the free parameters:



Main conclusion:

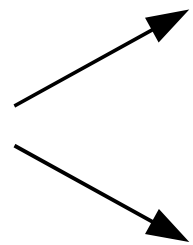
We need at least one relatively light vector field

Barbieri, GI, Richcov, Trincherini '08

This conclusion is based on a pure phenomenological approach (with the effective couplings in the NDA range).

Natural questions to address, if we aim to determine the UV completion of this model:

- Is the large contribution to T (~ *quadratic divergence*) compatible with existing models?



No if the heavy vectors are the gauge bosons of a broken hidden gauge symm. (with ren. Lagrangian)

Yes in generic QCD-like frameworks (heavy vectors = composite fields)

- How light can $M_{V,A}$ be ?
  Which is the cut-off of chiral Lagrangian with the heavy vectors ?

  For light masses the NDA cut-off drops to $\Lambda^{\rm NDA} = M_R \times (v/G_R)$
  (light masses $\leftrightarrow$ small couplings)

  However, the theory could have a higher cut-off if the G_R satisfy appropriate sum-rules

Producing the heavy vectors at the LHC

Main properties of the *vector fields*:

1) Leading decay mode: 2 longitudinal SM gauge bosons

$$\Gamma(V^0 \to W^+W^-) \approx \frac{G_V^2 M_V^3}{48\pi v^4}$$

5 GeV [$M_V = 0.5$ TeV]

40 GeV [$M_V = 1.0$ TeV]

$$\Gamma(V^+ \to W^+Z) \approx \Gamma(V^0 \to W^+W^-)$$

- Quite narrow widhts !
- ZZ channel forbidden

2) Coupling to SM fermions highly suppressed,
but not negligible for light masses:

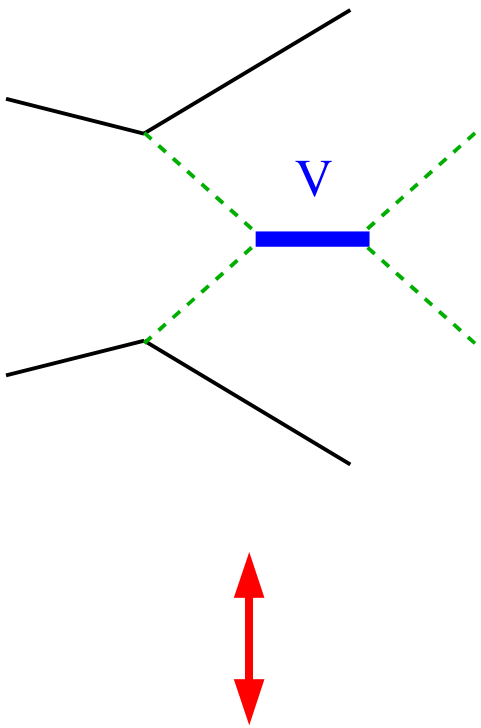
$$B(V^0 \to q\bar{q}) \approx 3\, B(V^0 \to l^+l^-) \approx \frac{6\, F_V^2\, m_W^4}{G_V^2\, M_V^4}$$

1.6% [$M_V = 0.5$ TeV, $F_V = 2G_V$]

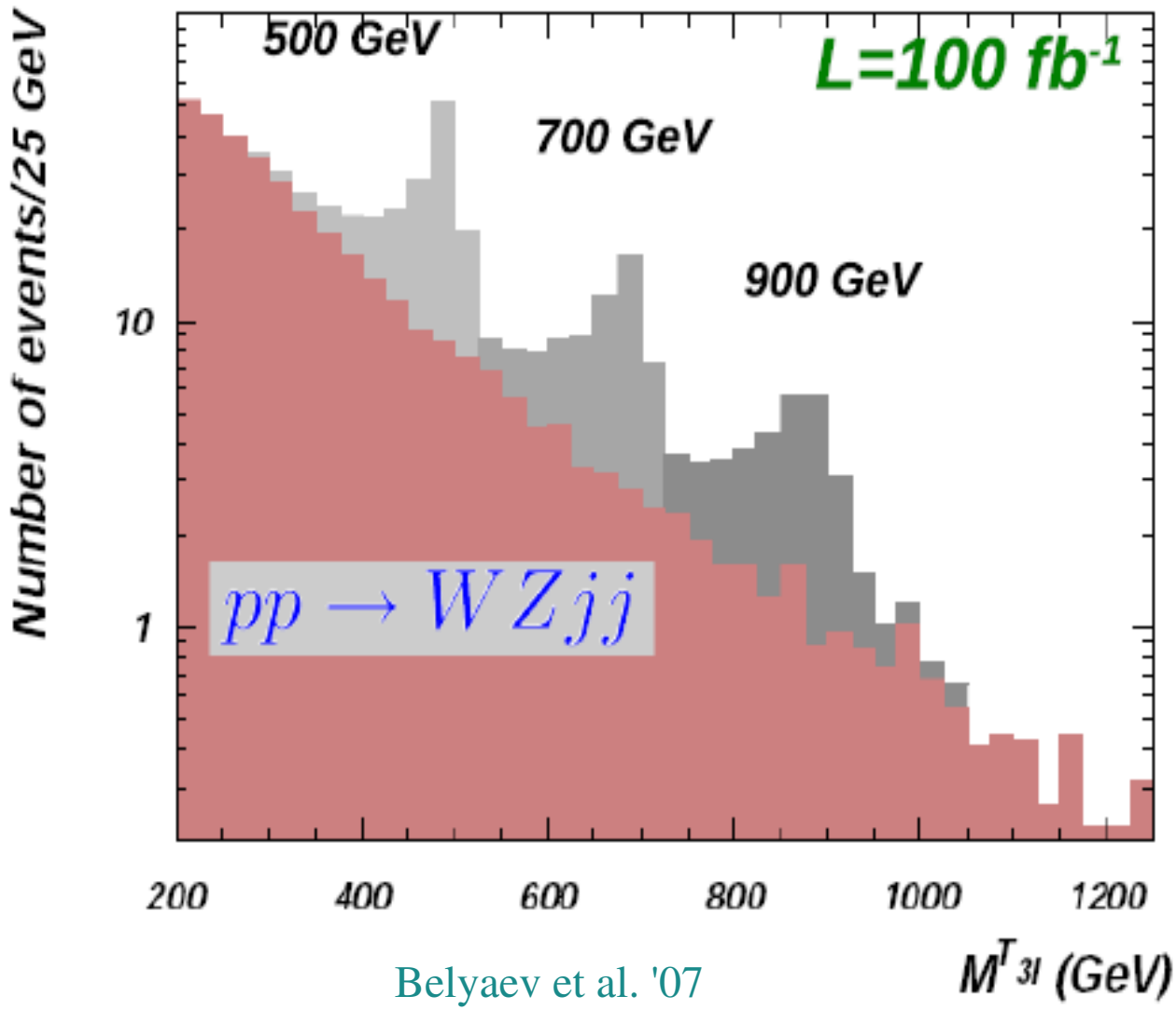
0.1% [$M_V = 1.0$ TeV, $F_V = 2G_V$]

The most general signature of Higgless models is the appearence of the vector state in WW scattering [pp → V + jj (WW fusion) → WW(WZ) + jj]

However, this is certainly a difficult analysis, which requires high statistics.

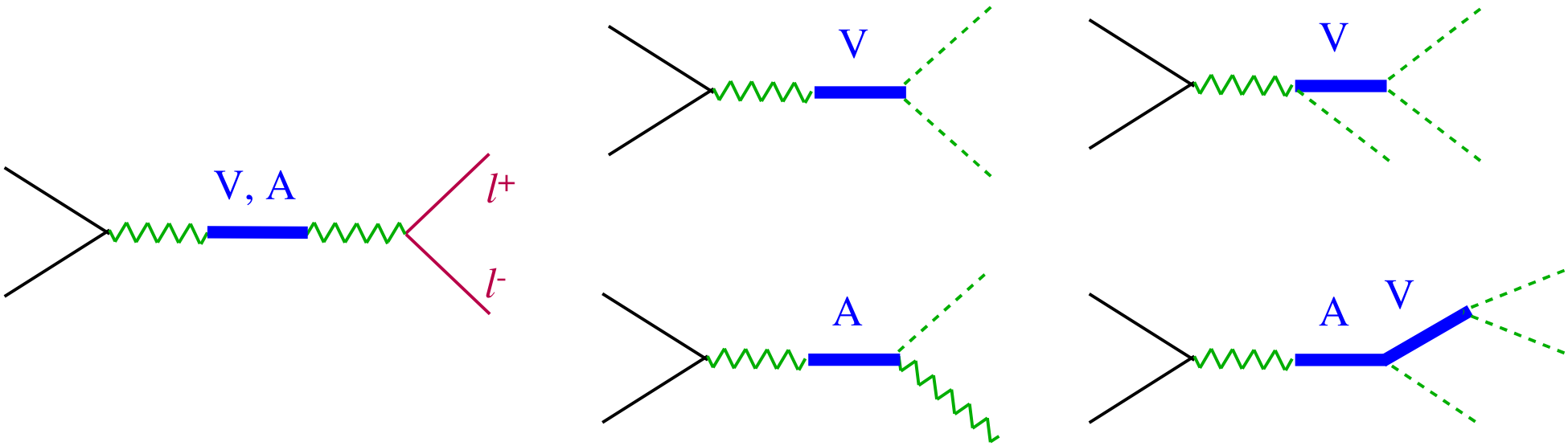


Model-independent link with the unitarity problem



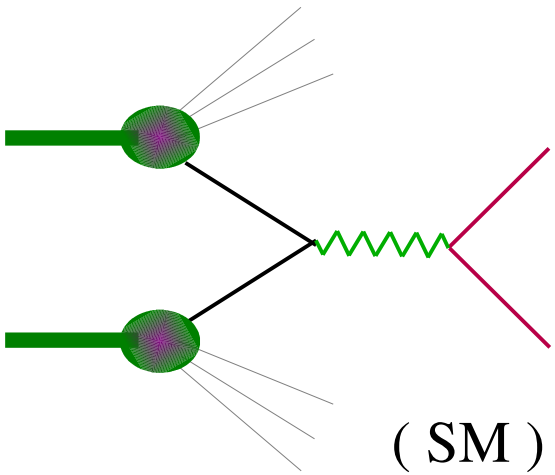
Belyaev et al. '07

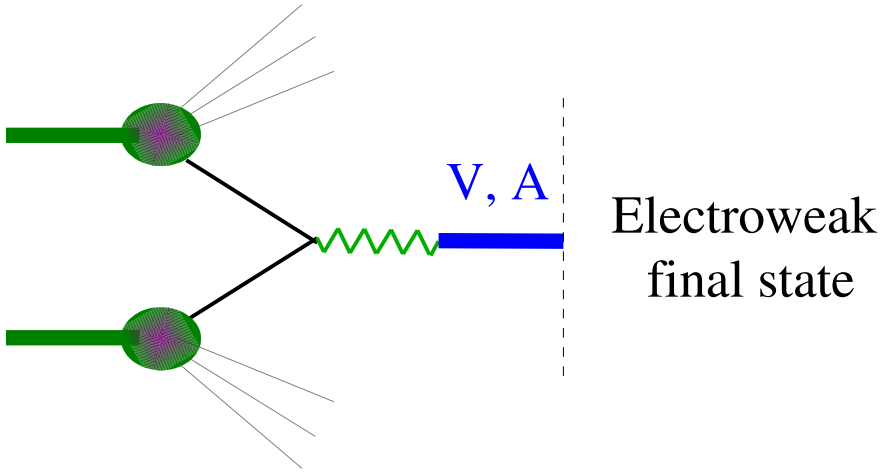
A potentially more clean signal -<u>if the resonances are not too heavy</u>- is the Drell-Yan production of the resonances and subsequent decay into l^+l^-, 2 and 3 SM heavy gauge bosons:



Link to the contribution
of the heavy vectors to EPWO

This signature is also particularly simple to estimate (and simulate) normalizing the non-standard rate to SM Drell-Yan processes at the partonic level:





E.g.: for charged final states we can define the form factor:

$$\mathcal{F}_f^{R^+}(q^2) = \frac{\sigma(u\bar{d} \to R^+ \to f)}{\sigma(u\bar{d} \to \mu^+\nu)_{\rm SM}}$$

$$\frac{d}{dq^2}\sigma(pp \to R^+ \to f) = \mathcal{F}_f^{R^+}(q^2)\frac{d}{dq^2}\sigma(pp \to \mu^+\nu)_{\rm SM}$$

Given the narrow widths, for low masses the signals are quite large.

E.g.:

$$\mathcal{F}_{WZ}^{V^+}(q^2) \approx 80 \times \left(\frac{1\ \text{TeV}}{M_V}\right)^4 \left(\frac{F_V}{2G_V}\right)^2 \frac{q^2\Gamma_V^2}{(q^2 - M_V)^2 + M_V^2\Gamma_V^2}$$

	$M = 500$ GeV	$M = 750$ GeV	$M = 1000$ GeV
$\sigma(pp \to V^+ \to X)_{\sqrt{s}=14\ \text{TeV}}$	11 pb	1.2 pb	0.23 pb
$\sigma(pp \to V^+ \to X)_{\sqrt{s}=10\ \text{TeV}}$	6.7 pb	0.7 pb	0.13 pb

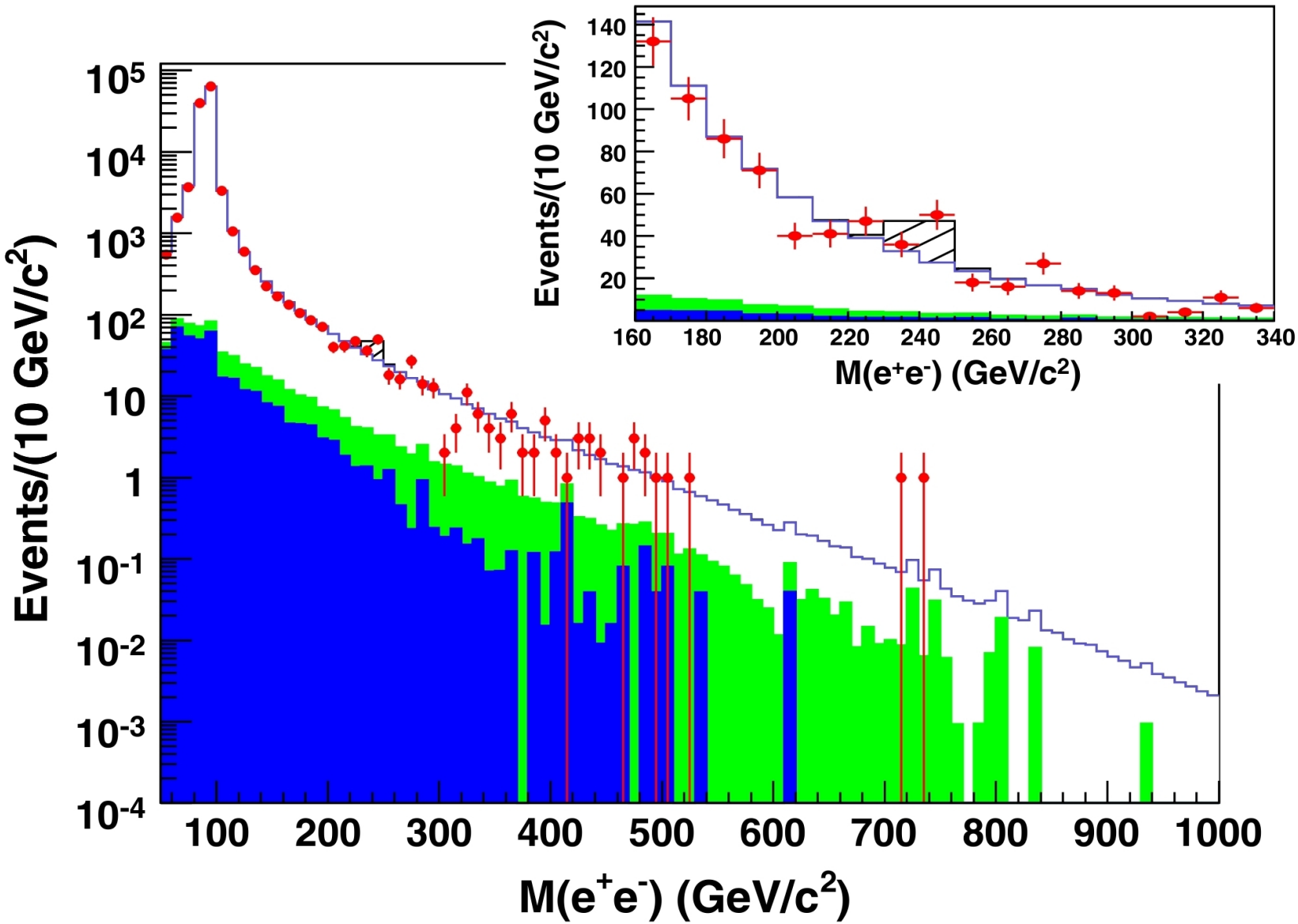
Cata, GI, Kamenik, '09

However....

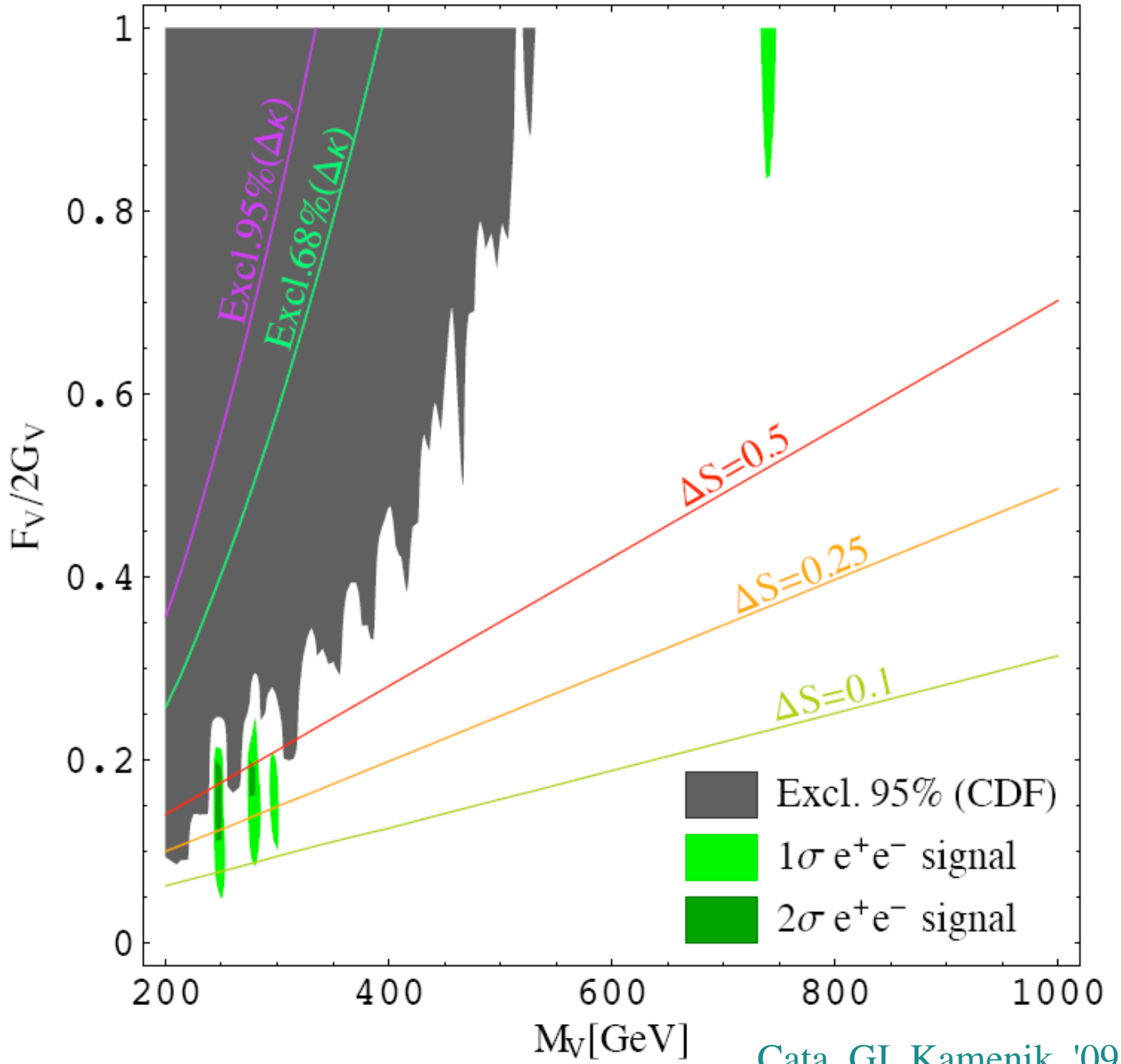
- The leading decay modes (2W, 3W) have low efficiencies
- The l^+l^- case is suppressed by the small B($R \to l^+l^-$)

The l^+l^- final state & present constraints from Tevatron

Here the state of the art is the analysis of the e+e- final state in $p\bar{p}$ collision published by CDF [PRL 102 (2009) 031801]:



Using the CDF data as normalization for the SM events, we have produced an exlusion plot in the F_V-M_V plane (which takes into account all the relevant exp. efficiencies!) →



Two main assumptions:

- G_V fixed by unitarity
- $M_A >> M_V$

Cata, GI, Kamenik, '09

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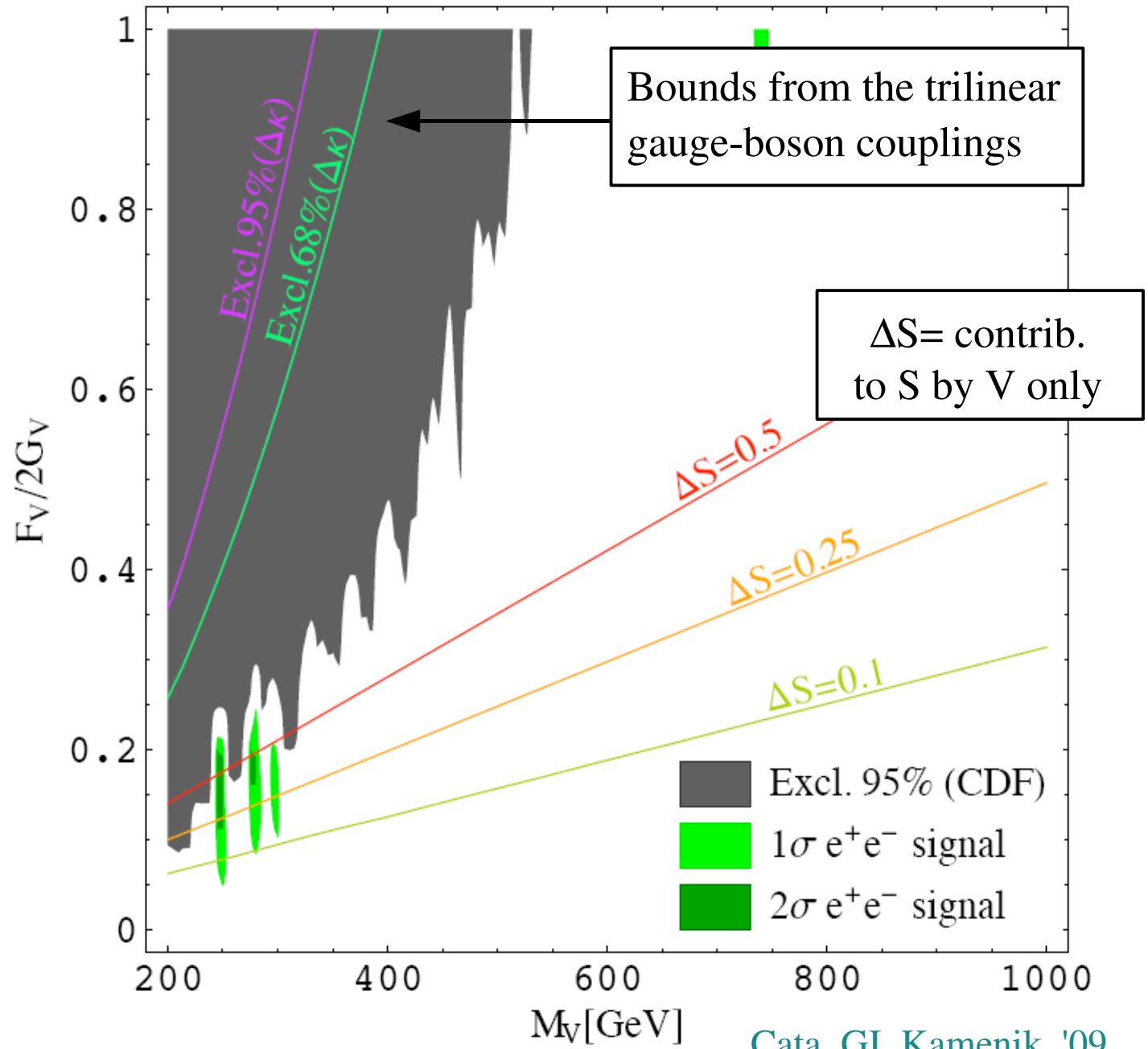

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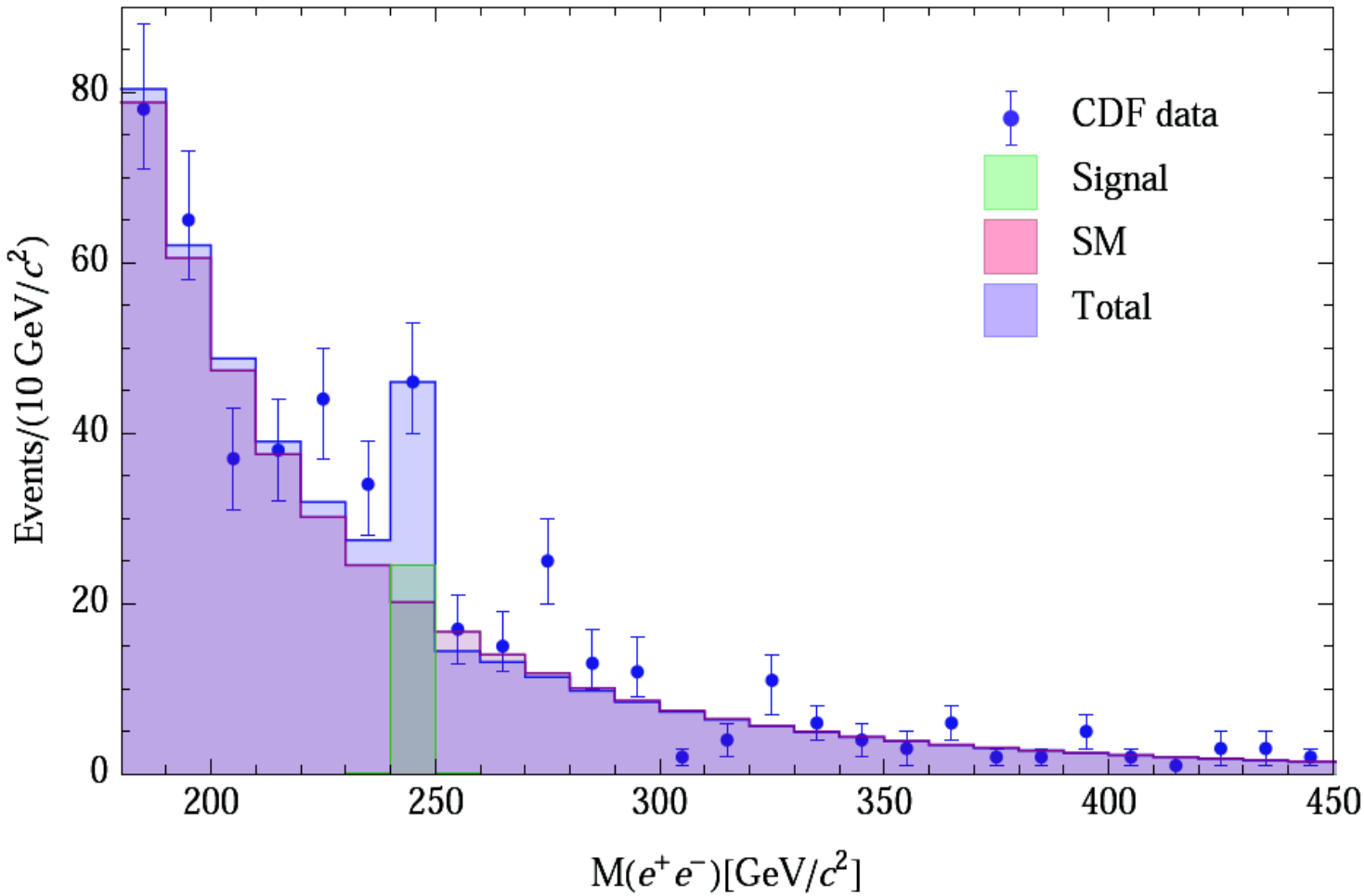
The "2σ *excess*" can be fitted nicely by a light vector resonance:

$M_V \approx 246$ GeV

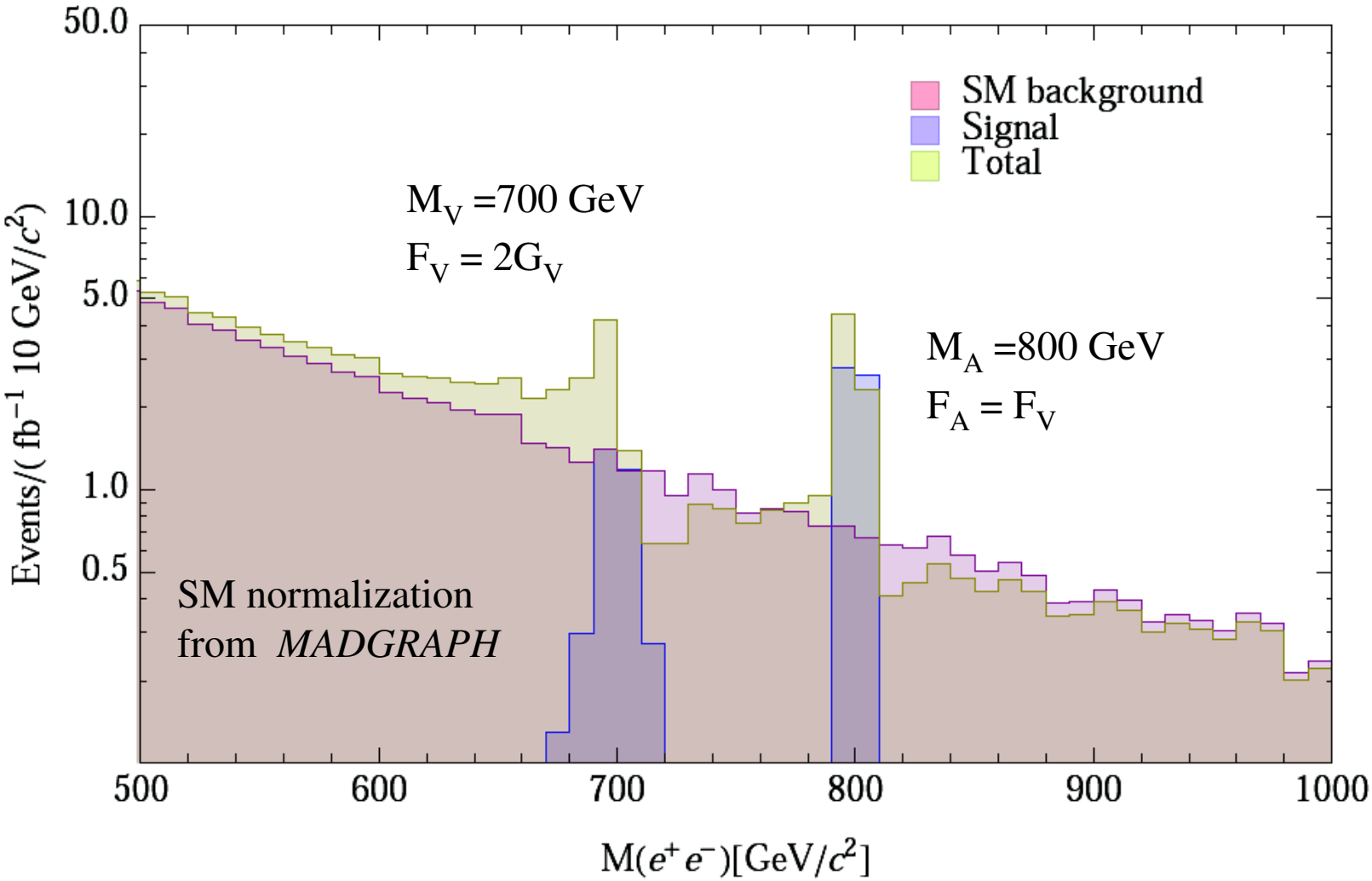
$F_V \approx 50$ GeV



Predictions derived within the effective theory:

- similar peak also in the $\mu^+\mu^-$ final state
- axial state with $M_A \sim 1.3$ GeV to obtain a good EWPO fit (T parameter)

If, on the other hand, the excess at higher mass will become significant, we can hope to see a clear signal at the LHC (even with 1-2 fb^{-1}):



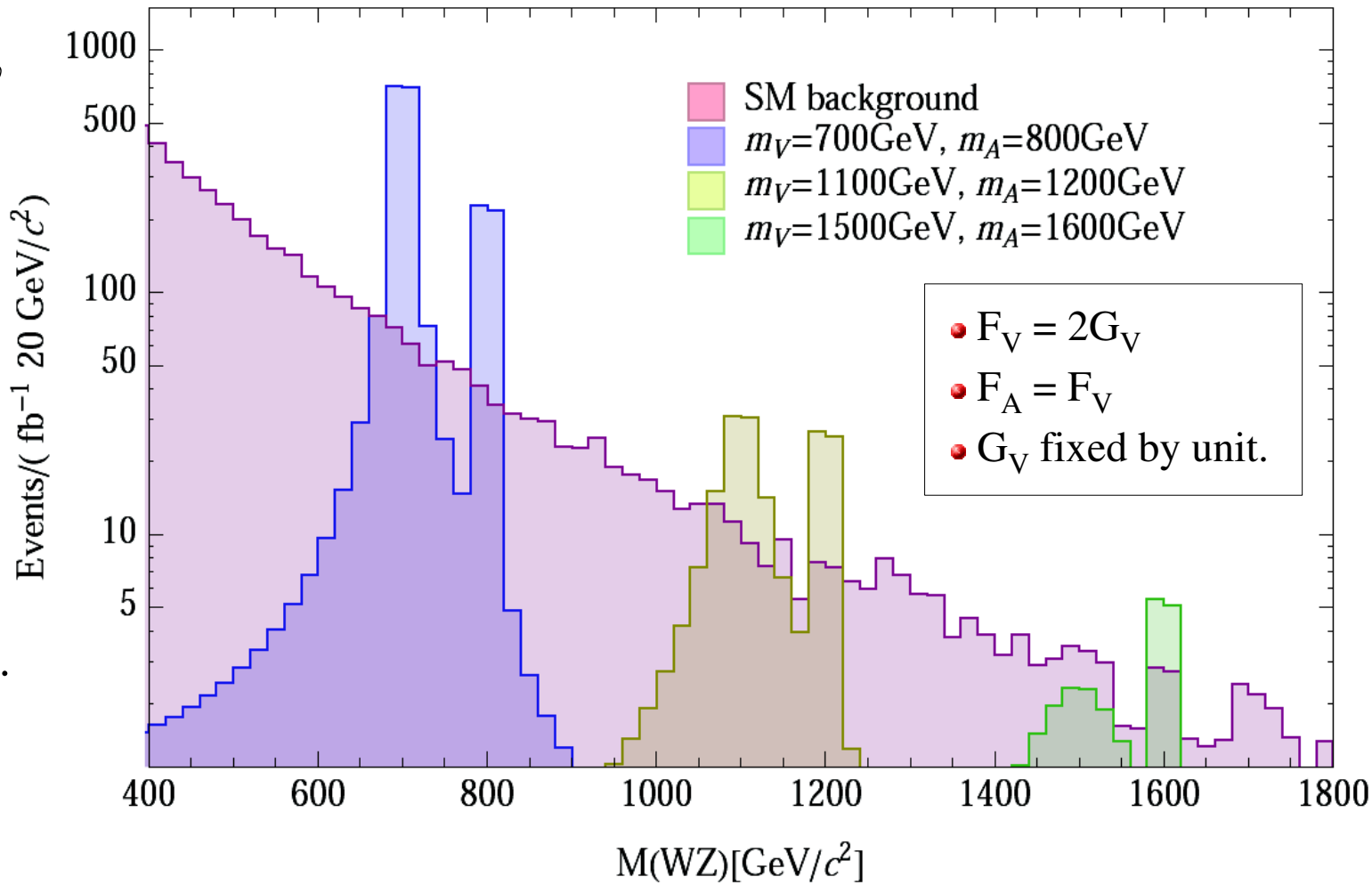
These are not huge peaks, as with a *sequential Z'*, but they should be clearly visible.

For vector masses above ~ 800 GeV the signal/background ratio is too small in the l^+l^- case; however, a signal could still be seen up to ~ 1500 GeV (with high statistics) in the leading decay modes with 2 or 3 SM gauge bosons [WZ, WW] + [WWW, WWZ, WZZ].

E.g.: The WZ final state

Leptonic efficiency:

$B_Z^{lept} \times B_W^{lept} = 1.5\ \%$



N.B.: here the SM bkg. is only the irreducible e.w. bkg. (WZ within the SM)

Conclusions

Heavy vector fields could replace the Higgs boson in maintaining perturbative unitarity up to LHC energies. Introducing the heavy vectors in the e.w. chiral Lagrangian is an efficient and general tool to address their role in EWPO and to investigate their signatures at the LHC.

- Heavy vectors alone could satisfy EWPO, if there is at least one light vector state (mass < 1 TeV), and the trilinear couplings of the heavy fields are not those of massive gauge bosons.
- The most general signature of the heavy vectors is the appearance of the lightest vector state in WW scattering (model-independent link with the unitarity problem).
- The Drell-Yan production of the new states is subject to larger uncertainties. However, for light $M_{V(A)}$ we could expect visible signals (even with low statistics), and the information could help to clarify the role of the heavy vectors in EWPO.

Extra Slides

⋆ QCD-like theories

On general dimensional grounds we expect $G_V, F_V, F_A = O(\mathrm{v})$

In QCD this expectation is respected [$F_V/\mathrm{v} \approx 1.6$, $G_V/\mathrm{v} \approx 0.6$–$0.8$, $F_A/\mathrm{v} \approx 1.0$–$1.6$] and we have a clear evidence that the coefficient of the quadratic divergence in T is non vanishing :

- $\Gamma(a_1 \to \pi\,\gamma) \neq 0 \;\Leftrightarrow\; F_A \neq 0$
- $d\Gamma(\pi \to l\nu\,\gamma) \;\Leftrightarrow\; \langle\, \gamma \,|\, a_\mu \,|\, \pi \,\rangle \neq \begin{matrix} \textit{pure } \pi \\ \textit{pole term} \end{matrix} \;\Leftrightarrow\; F_A \neq 0$ or $(F_V - 2G_V) \neq 0$

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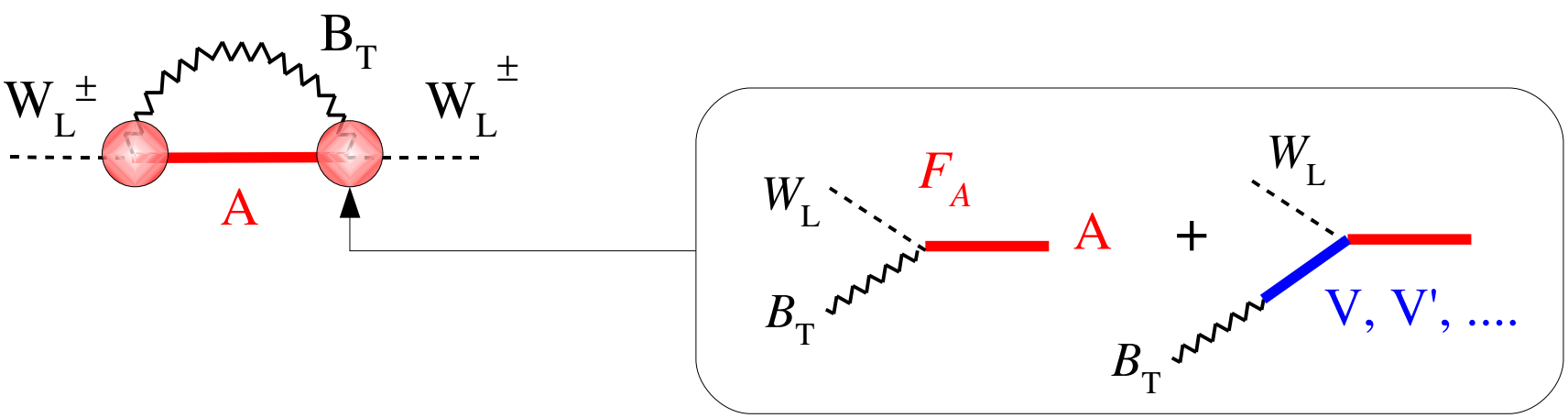
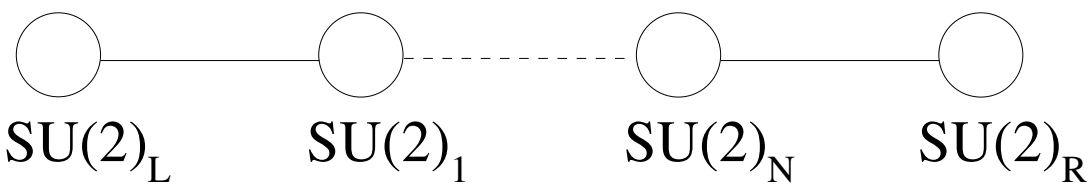
The divergence is cut off by diagrams with more than one heavy field, which lead to a smooth q^2 behavior of $\langle A | \mathrm{v}_\mu(q^2) | \pi \rangle$ and $\langle V | a_\mu(q^2) | \pi \rangle$ amplitudes



⇒ sizable contribution to T if the smooth q^2 behavior is reached only after including heavy states near or above the 3 TeV cut-off

⋆ Explicit gauge models

The structure of gauge models, with "soft" (linear-sigma-model type) breaking is much more constrained: the couplings of the heavy fields to the SM fields are controlled only by the SB Lagrangian.



$$\mathscr{L} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{SB}}$$

- Trilinear couplings completely specified
- No mixing between SM and other gauge bosons

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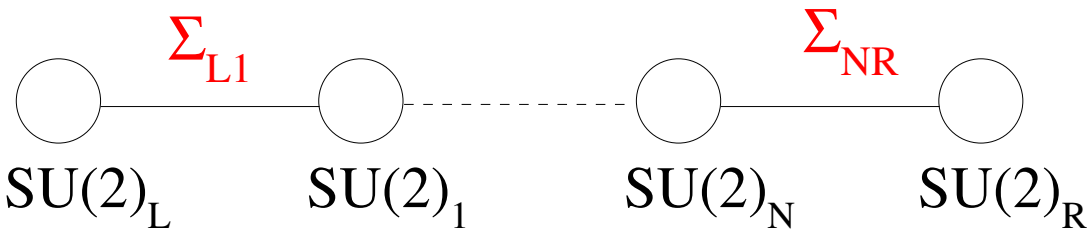

$$\mathscr{L} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{SB}}$$

$$\mathscr{L}_{\text{SB}} = \Sigma_{\{IJ\}} \, \text{Tr}(D_\mu \Sigma_{IJ}{}^{+} D^\mu \Sigma_{IJ})$$

After field redefinitions the SB Lagrangian assumes the form:

$$\mathscr{L}_{\text{SB}} = \sum_{i=1}^{N_V} v_{V_i}^2 \langle (\bar{V}_i^\mu - i\alpha_i \Gamma^\mu)^2 \rangle + \sum_{i=1}^{N_A} v_{A_i}^2 \langle (\bar{A}_i^\mu - \beta_i \frac{u^\mu}{2})^2 \rangle + \frac{v^2}{4} \langle (u^\mu)^2 \rangle$$

$F_V = 2G_V$

"$F_A = 0$"

[no $A\pi v$ trilinear coupl. after eliminating the $A\pi$ mixing]

$\Gamma_\mu \sim v_\mu + [\pi, \partial_\mu \pi] + \ldots$

$u_\mu \sim \partial_\mu \pi + a_\mu + [\pi, v_\mu] + \ldots$

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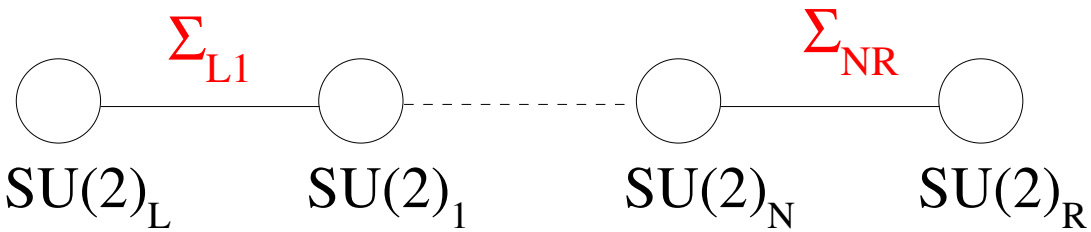


$$\mathscr{L} = \mathscr{L}_{gauge} + \mathscr{L}_{SB}$$

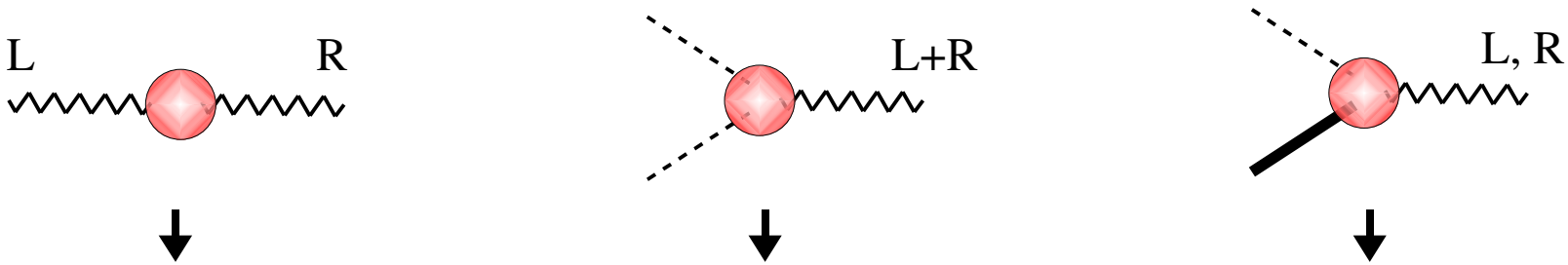
$$\mathscr{L}_{SB} = \Sigma_{\{IJ\}} \mathrm{Tr}(D_\mu \Sigma_{IJ}{}^+ D^\mu \Sigma_{IJ})$$

In such scenario we never generate a large contribution to T [vanishing coeff. for the quadratic divergence].

However, such scheme is not the most general possibility and indeed it <u>does not provide a good description of QCD.</u>

⋆ Sum rules

Imposing a good UV behavior on all the relevant 2- and 3-point functions involving $SU(2)_L \times SU(2)_R$ external fields (or SM transverse gauge fields) leads to a series of constraints (sum rules) on the parameters of the model



$$\sum_{i=1}^{N_V} F_{V_i}^2 - \sum_{i=1}^{N_A} F_{A_i}^2 = v^2$$

$$\sum_{i=1}^{N_V} F_{V_i}^2 M_{V_i}^2 - \sum_{i=1}^{N_A} F_{A_i}^2 M_{A_i}^2 = 0$$

$$\sum_i F_{V_i} G_{V_i} = v^2$$

$$2\sum_{j=1}^{N_V} g_j^{A_i} F_{V_j} = F_{A_i}$$

$$2\sum_{j=1}^{N_A} g_j^{V_i} F_{A_j} = F_{V_i} - 2G_{V_i}$$

Tightly constrained system if we try to satisfy all the sum rules with a single "light" (A,V) pair ⇒ too large ΔS, too small ΔT.

If the sum rules are not saturated by single "light" (A,V) pair, we can satisfy them with arbitrary G_V, $F_{V,A} = O(v)$ for the light pair and heavy states of mass O(3 TeV)