Heavy vectors in Higgsless models

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Introduction

- Experiments provide unambiguous indications that the SM gauge group is spontaneously broken [$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$]
- One elementary $SU(2)_L$ scalar doublet with φ^4 potential is the most economical & simple choice
- $L_{Higgs}(\varphi, A^i, \psi^i) = D_\mu\varphi^+ D_\mu\varphi + \mu^2 \varphi^+\varphi - \lambda (\varphi^+\varphi)^2 + Y^{ij} \psi_L^i \psi_R^j$
  - not the only allowed possibility
- So far only the ground state of this Lagrangian has been tested with good accuracy
  - $<\varphi>=246$GeV <-> m_W, m_Z
- Some dynamical sensitivity to the Higgs mechanims is obtained from EWPO
  - Indirect indication of a light m_H

Peskin & Takeuchi [PRL65:964,1990]
Altarelli & Barbieri [PLB253:161,1991]
...
Barbieri et al. [hep-ph/0405040]

Do we need a fundamental Higgs field?

- EWPO indicate:
  - a spontaneous breaking of $SU(2)_L \times U(1)_Y$
  - the breaking mechanism must respect, to a good accuracy, the custodial symmetry [$m_Z^2/m_W^2 \approx 1 + (g'/g)^2$]
- General formulation of the symmetry breaking mechanism in absence of a fundamental Higgs (or for large Higgs masses) in terms of a Chiral Lagrangian:

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

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

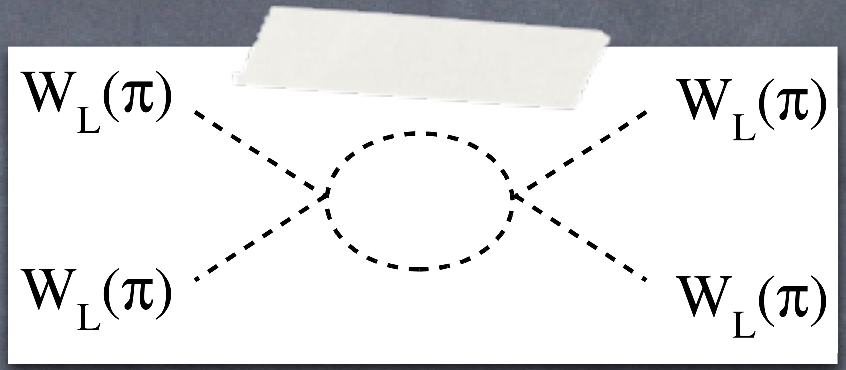
3 Goldstones of the SM

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

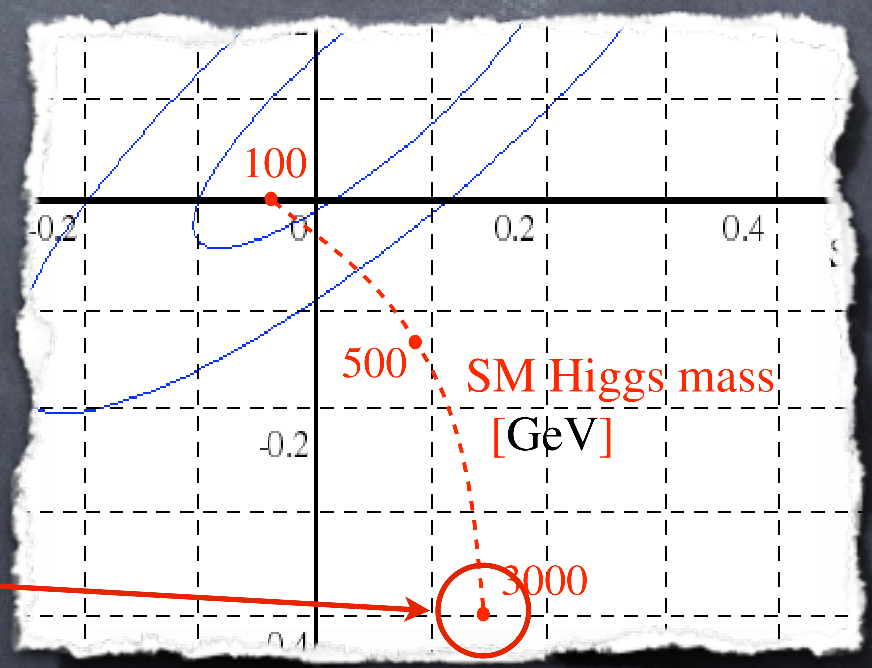
$D_\mu U = -ig' B_\mu U + ig\, U W_\mu$

EW Chiral Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{gauge}(A^i, \psi^i) + \mathcal{L}_{Yukawa}(U, \psi^i) + \frac{v^2}{4}\mathrm{Tr}(D_\mu U^\dagger D^\mu U)$$



- contains all the degrees of freedom we have directly probed in experiments
- naive cut-off dictated by the convergence of EW loops: $\Lambda_{NDA} = 4\pi v \approx 3$ TeV
- perfectly describes particle physics up 3 TeV, beyond the tree level, with only two drawbacks
  - (point toward the existence of new degrees of freedom below the naive cut-off):
  - Violation of unitarity in $W_L W_L \to W_L W_L$ scattering (tree-level amplitude violates unitarity for $s \approx 1$ TeV)
  - Bad fit to S and T



Introducing heavy vectors

- A natural alternative to Higgs-type mechanisms in curing the problem of unitarity in WW → WW scattering is represented by heavy vector fields
- Expected in many non-SUSY scenarios:
  - techni-rho in technicolor,
  - massive gauge bosons in 5-dimensional theories, hidden gauge-models
- Difficult task is to cure at the same time unitarity and EWPO
  - can be analysed in general terms constructing an appropriate effective chiral Lagrangian with the heavy vectors as new explicit d.o.f.

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

Heavy vectors in the EW Chiral Lagrangian

Barbieri et al. [0806.1624]

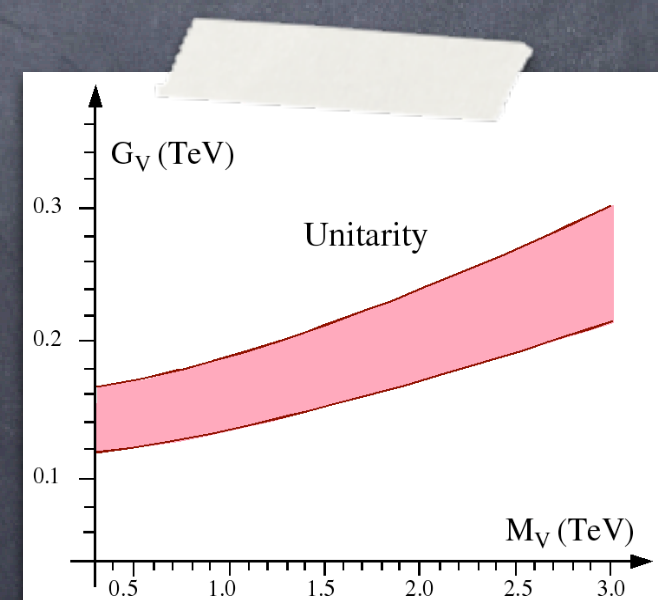
- Consider an effective theory based on the following two main assumptions:
  - The (new) dynamics that breaks the SM EW symmetry is invariant under the global symmetry $SU(2)_L \times SU(2)_R$ and under the discrete parity P: $SU(2)_L \leftrightarrow SU(2)_R$
  - One vector (V), or one vector + one 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 Λ = 2-3 TeV
- Effective Lagrangian expansion based on ordering of operators according to the standard derivative (momentum) expansion

Unitarizing W_LW_L scattering

Barbieri et al. [0806.1624]

- No tree-level violation of unitarity for
  - $G_V^2 = v^2/3$
- The unitarity constraint is almost insensitive to the value m_V

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



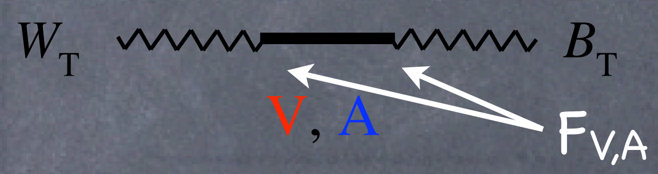
EWPO

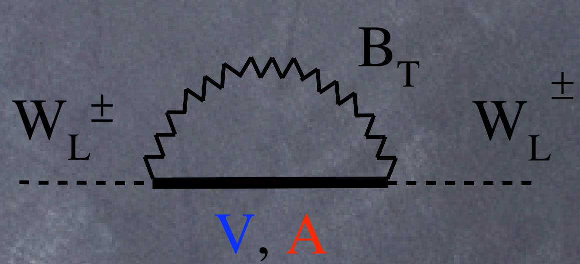
Barbieri et al. [0806.1624]

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

$$\Delta\hat{S} = g^2\left(\frac{F_V^2}{4m_V^2} - \frac{F_A^2}{4m_A^2}\right)$$

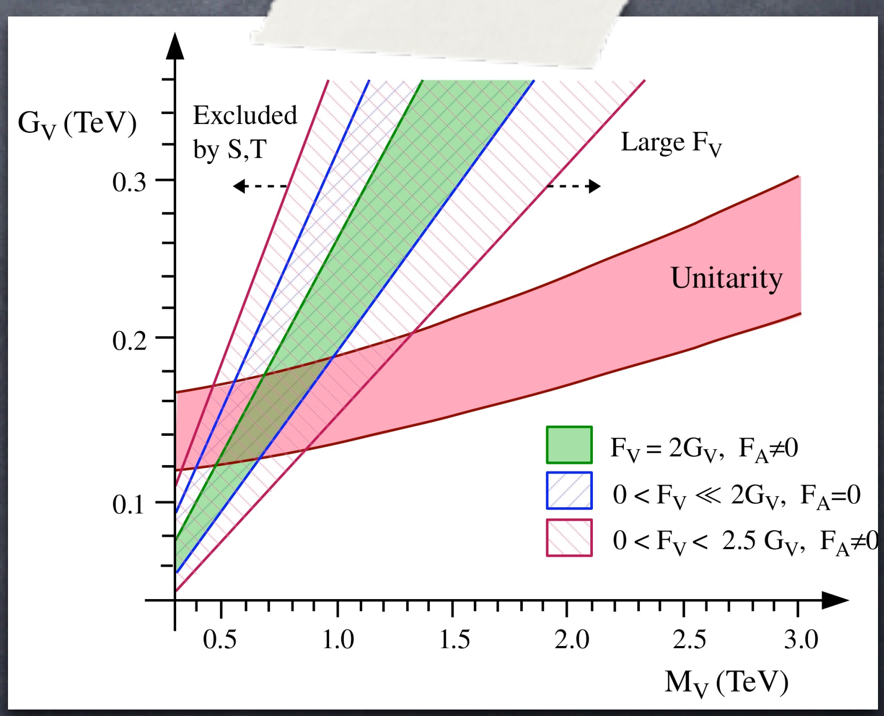
$$\Delta\hat{T} = \frac{3\pi\alpha}{c_W^2}\left[\frac{F_A^2}{4m_A^2} + \left(\frac{F_V - 2G_V}{2m_V}\right)^2\right]\frac{\Lambda^2}{16\pi^2 v^2} + \dots$$





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

- Two natural ways to accommodate the bounds:
  - Both V and A light, almost degenerate
  - Only V light, with small F_V
- EWPO& unitarity can be accommodated for specific choices of the free parameters



Main conclusion:
We need at least one relatively light vector field

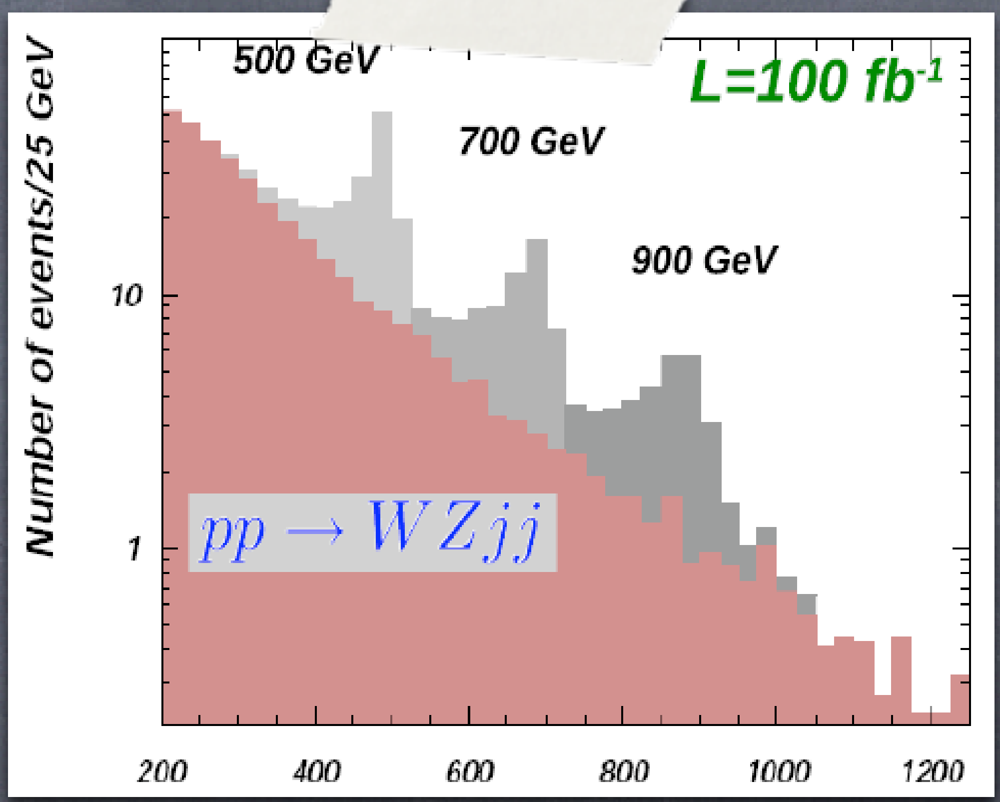
Producing the heavy vectors at the LHC

- Main properties of vector fields
  - Leading decay mode: 2 longitudinal SM gauge bosons
    - $\Gamma_{V^+} \approx \Gamma^V_{WZ} = \frac{G_V^2 m_V^3}{48\pi v^4}\left[1+\mathcal{O}(g^2\epsilon^2)\right]$, 5 GeV [m_V = 0.5 TeV] 40 GeV [m_V = 1.0 TeV]
    - $\Gamma_{V^0} \approx \Gamma^V_{WW} = \Gamma^V_{WZ}\left[1+\mathcal{O}(g^2\epsilon^2)\right]$
    - Narrow widths!
    - ZZ channel forbidden
  - Coupling to SM fermions highly suppressed
    - $Br(V^0 \to q\bar{q}) \approx 3Br(V^0 \to \ell^+\ell^-) \approx \frac{6F_V^2 m_W^4}{G_V^2 m_V^4}$ 1.6% [m_V = 0.5 TeV, F_V = $2G_V$] 0.1% [m_V = 1.0 TeV, F_V = $2G_V$]
- Leading decay modes of axial fields can be to a vector and SM g. b.

Producing the heavy vectors at the LHC

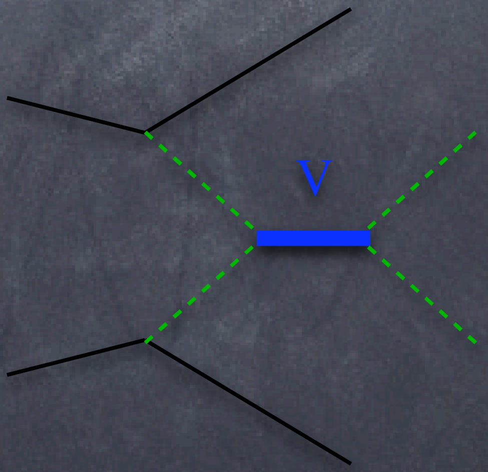
- The most general signature of Higgsless models is the appearance of the vector state in WW scattering [pp → V + jj (WW fusion) → WW(WZ) + jj]

- Model-independent link with the unitarity problem



m_V [GeV]

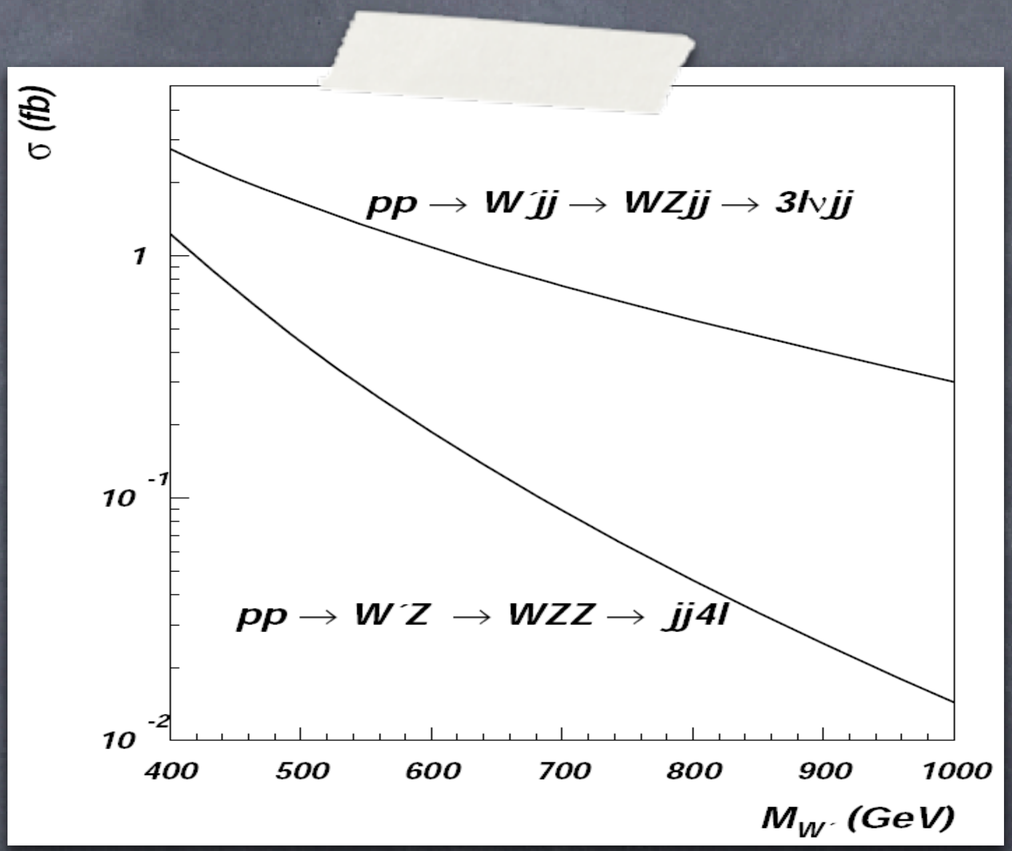
Belyaev [0711.1919]



Producing the heavy vectors at the LHC

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

- A difficult analysis, which requires high statistics.

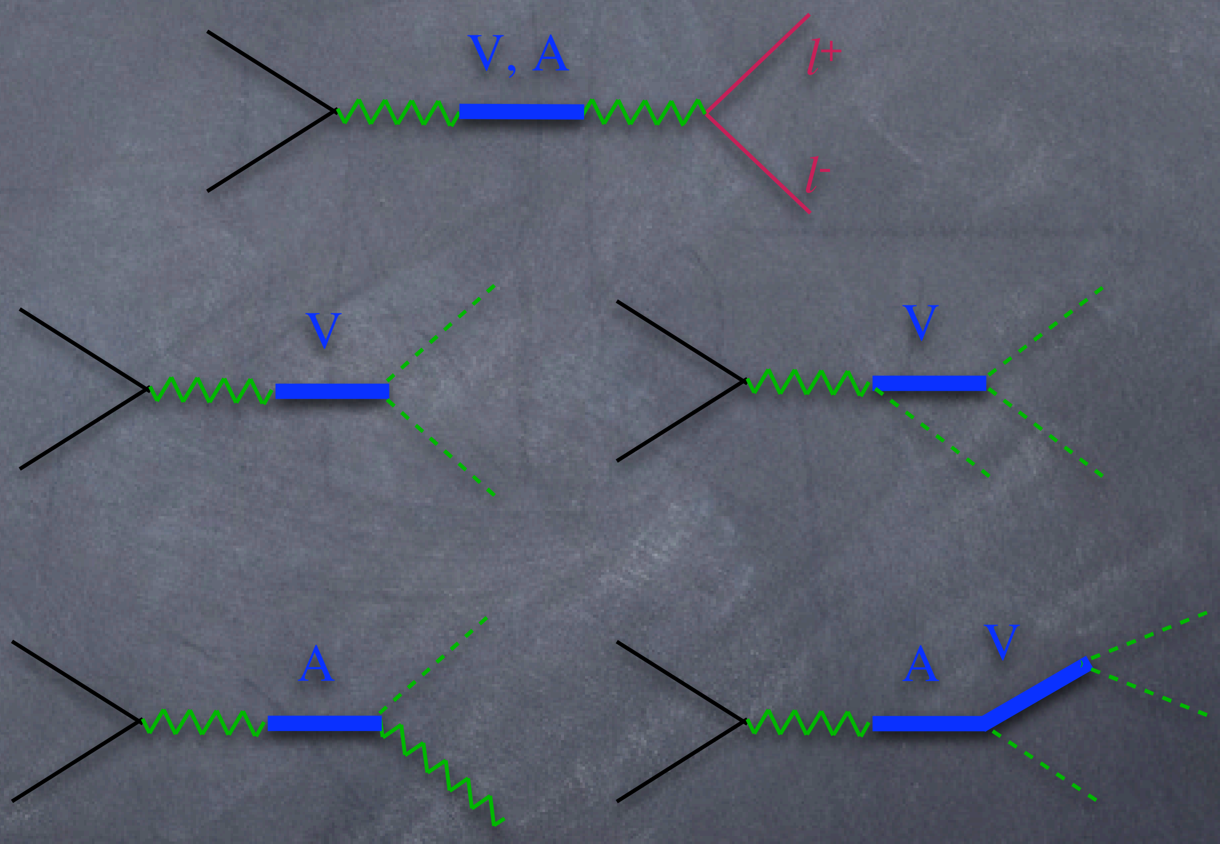


Belyaev [0711.1919]

Resonant cross section including
- leptonic BR's (l=e,μ) [ε_{lept} = 21% x 6.7% = 1.5%]
- p_T(jets) > 30 GeV
- standard VBF jet cuts [$\Delta\eta$ > 4, M_{jj} > 1TeV ε_{VBF} < 30%]

Producing the heavy vectors at the LHC

- A potentially cleaner signal (if the resonances are not too heavy) 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



Producing the heavy vectors at the LHC

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

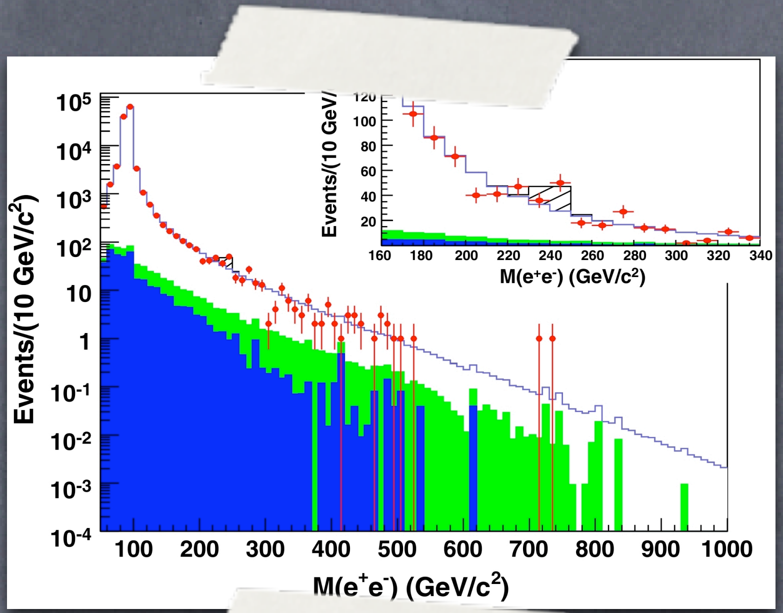
Cata, Isidori & J.F.K [0905.0490]

	$M = 500$ 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

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

Signal of heavy vectors at the Tevatron?

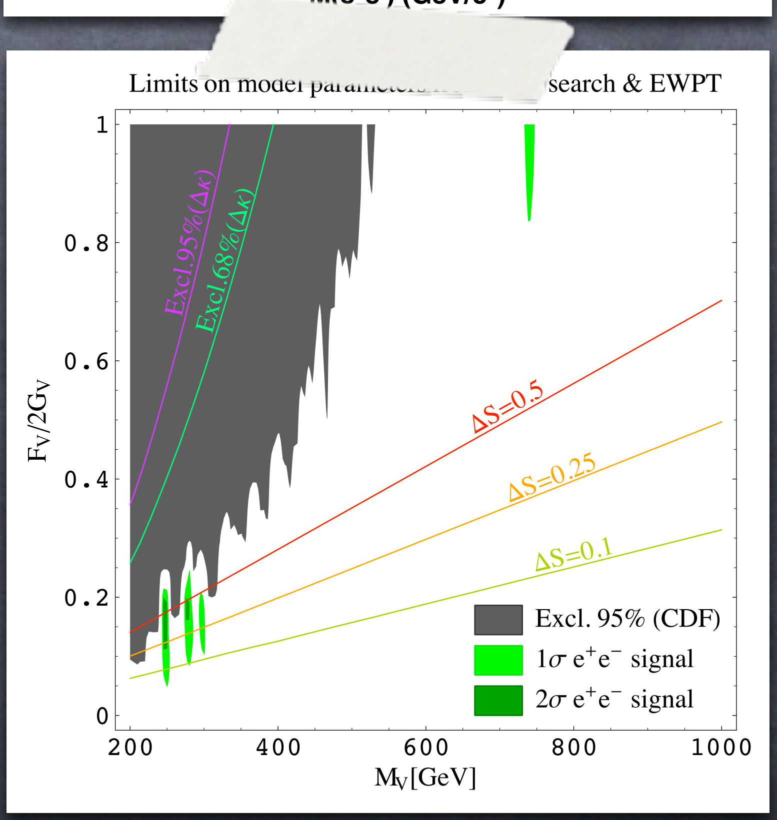
- The l^+l^- state of the art is the analysis of the e^+e^- final state in p-pbar collisions published by CDF



CDF [0810.2059]

- Using their data as normalization for the SM events (takes into account all the relevant exp. efficiencies!), we have produced an exclusion plot in the F_V-m_V plane

- Two main assumptions:
  - G_V fixed by unitarity
  - $m_A >> m_V$



Cata, Isidori & J.F.K [0905.0490]

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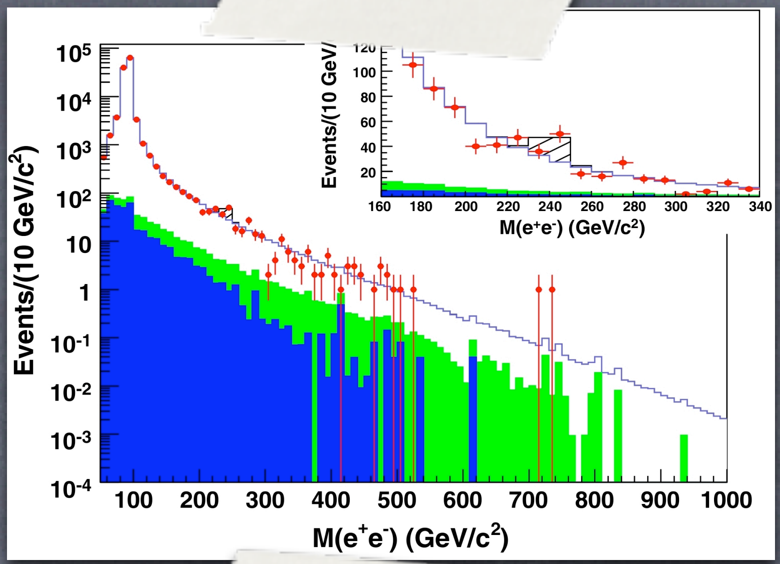
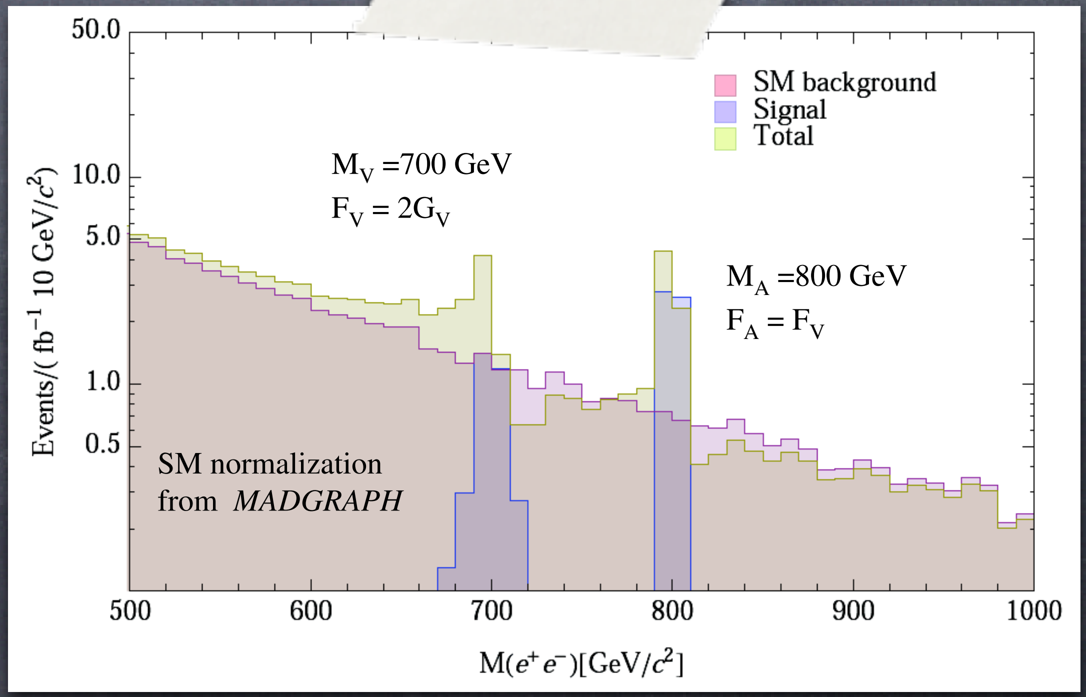


CDF [0810.2059]
[0811.0053]

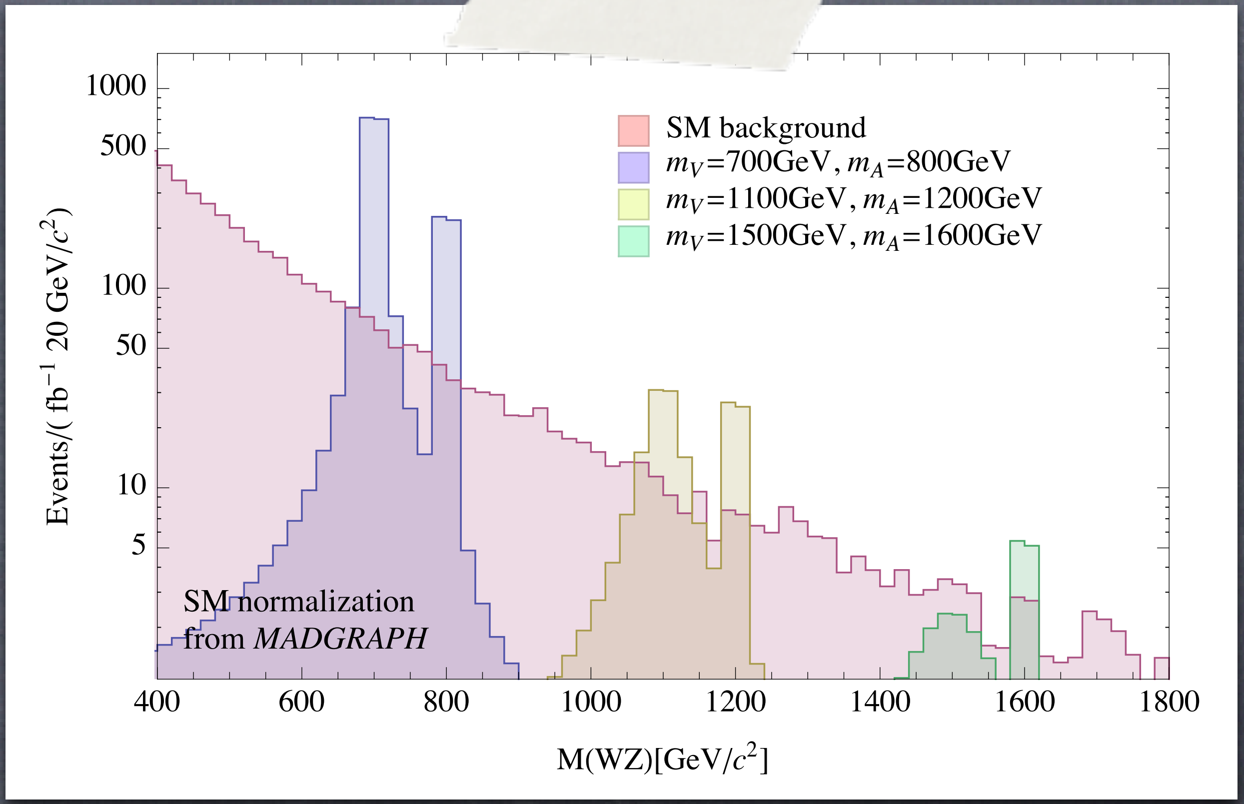
- If, on the other hand, the excess at higher mass will become significant, we can hope to see a clear signal at the LHC (even with 1-2 fb^{-1})
  - Not huge peaks as with a sequential Z', but they should be clearly visible.



Cata, Isidori & J.F.K
[0905.0490]

Signals for heavy vectors at the LHC

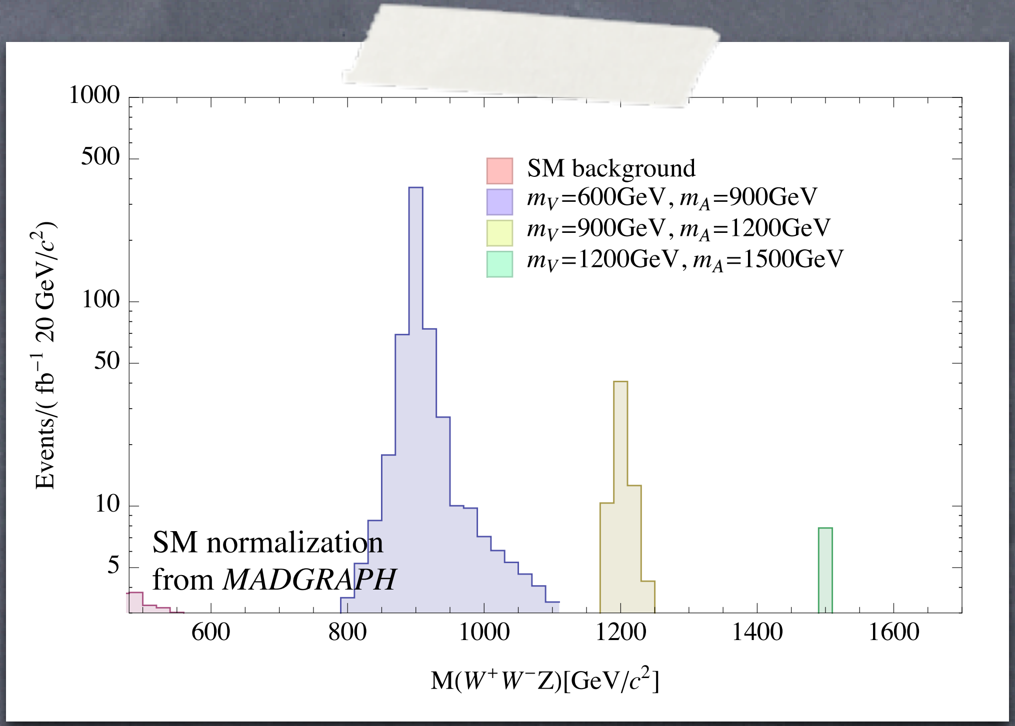
- Two SM gauge boson final states
- Some illustrative examples
  - [WZ] $BrZ_{lept} \times BrW_{lept} = 1.5$ %
  - $F_V = 2G_V$
  - $F_A = F_V$
  - G_V fixed by unitarity

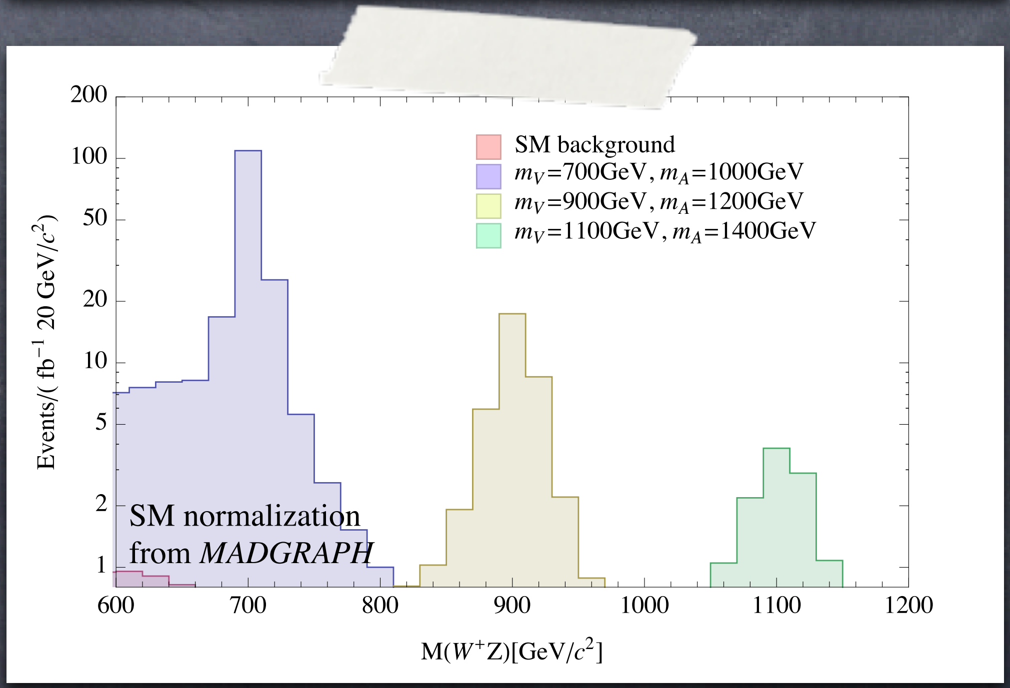


- [Warning: the configurations of free params. are realistic, but maximize the signal...]

Signals for heavy vectors at the LHC

- Three SM gauge boson final states
- Some illustrative examples
  - [WWZ] $BrZ_{lept} \times BrW_{lept} \times BrW_{had}$ = 0.9 %
  - $F_V = 2G_V$
  - $F_A = F_V$
  - G_V fixed by unitarity
  - $g_A = 1/2$
- In the WWZ final state it is also worth to look at the WZ invariant-mass distribution





Conclusions

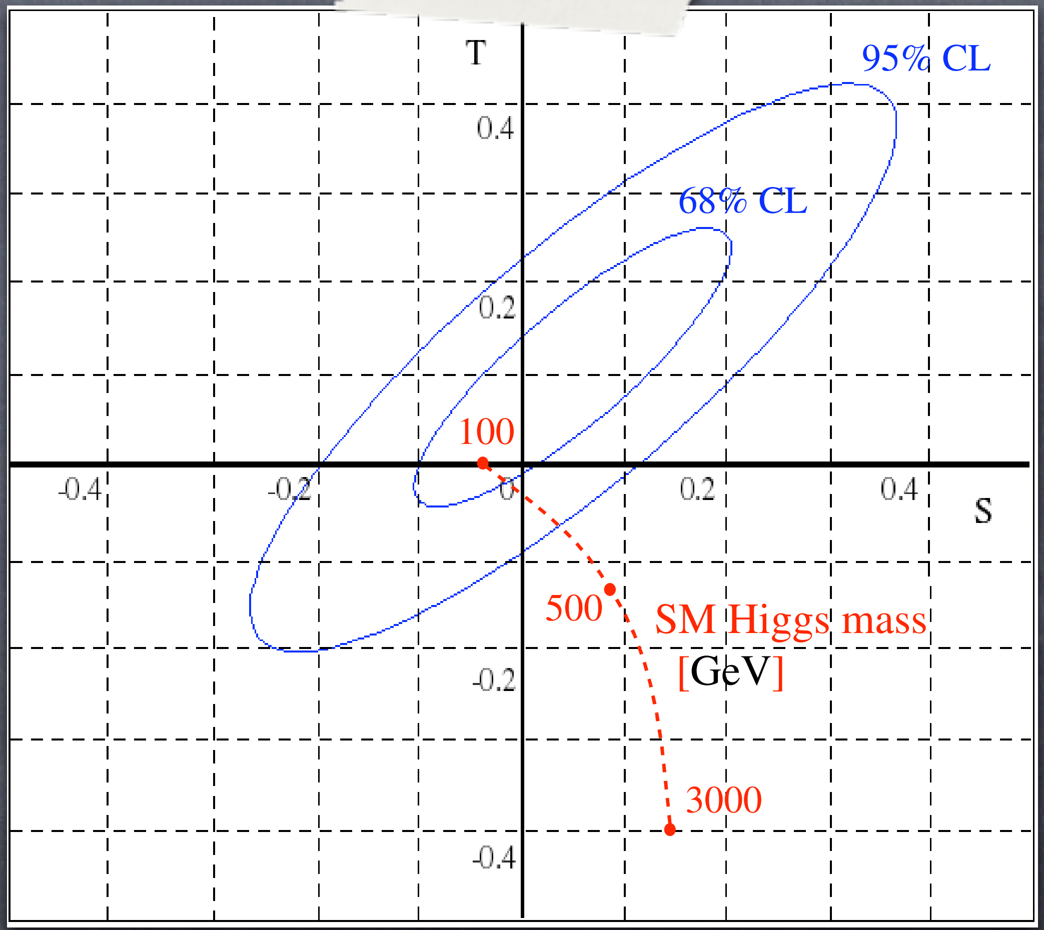
- Heavy vector fields, which replace the Higgs boson in maintaining perturbative unitarity up to LHC energies, are naturally expected in a wide class of Higgsless models.
- The most general signature of these models is the appearance of the lightest vector state in WW scattering (model-independent link with the unitarity problem).
- The Drell-Yan production of the new states is subject to larger uncertainties.
- 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.
- The results in the e^+e^- channel from Tevatron are already providing a significant information.
- The 2 and 3 SM gauge boson final states seems to be quite promising and would deserve a more realistic study.

Backup Slides

EWPO in the SM

Peskin & Takeuchi [PRL65:964,1990]
Altarelli & Barbieri [PLB253:161,1991]
...
Barbieri et al. [hep-ph/0405040]

- Some dynamical sensitivity to the Higgs mechanims is obtained from EWPO
- Indirect indication of a light m_H under the hypothesis of a heavy cut-off for the SM as effective theory
    - (<-> fine tuning in the Higgs mass term)



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

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

Heavy vectors in the EW Chiral Lagrangian

- With 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]
    - $V_\mu \to V_\mu + \beta\, [\,\pi, \partial_\mu \pi]$, $A_\mu \to A_\mu + \alpha\, \partial_\mu \pi$
    - This problem can be avoided describing the heavy spin-1 states by means of antisymmetric tensors ($R_{\mu\nu} = V_{\mu\nu}, A_{\mu\nu}$):

Gasser & Leutwyler [Annals Phys.158:142,1984]
Ecker et al. [Phys.Lett.B223:425,1989]

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

$$\langle 0|R^{\mu\nu}|R(p,\epsilon)\rangle = \frac{i}{m_R}[p_\mu\epsilon_\nu - p_\nu\epsilon_\mu]$$

$$\nabla_\mu R = \partial_\mu R + [\Gamma_\mu, R] \qquad \Gamma_\mu = \frac{1}{2}[u^\dagger D_\mu u + u D_\mu u^\dagger]\,, \quad u^2 = U$$

Heavy vectors in the EW Chiral Lagrangian

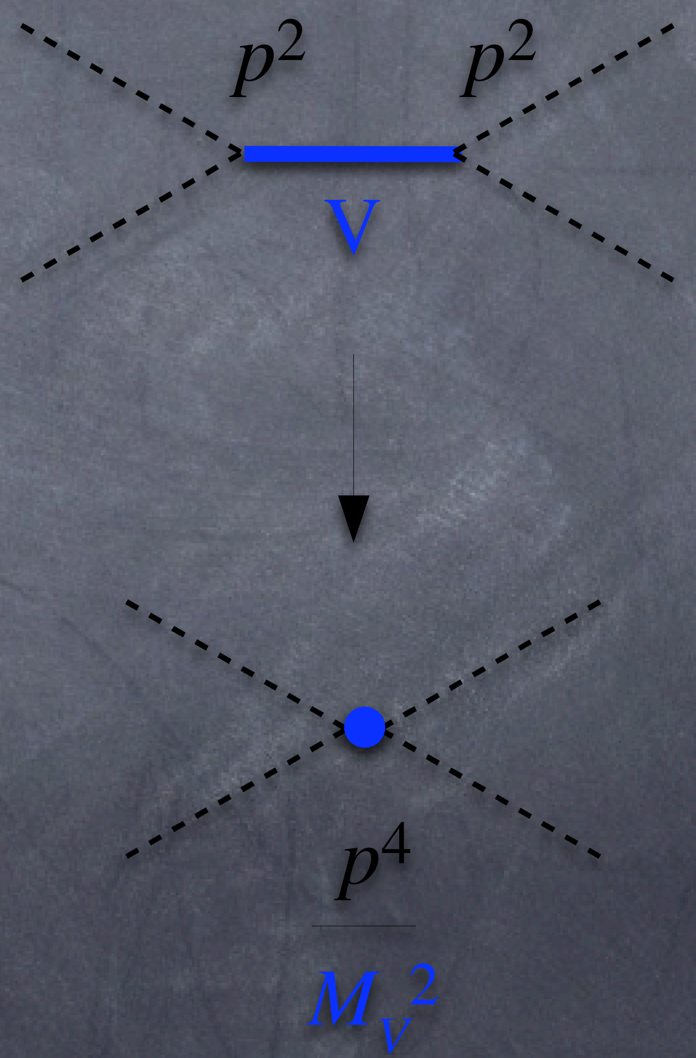
- In the antisymmetric formulation the couplings between heavy fields and Goldstone bosons start at $O(p^2)$ $\Rightarrow$ integrating out the heavy fields

  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

- 1$\Leftrightarrow$1 correspondence between

  lowest-order vector couplings [$O(p^2)$] and next-to-leading order Goldstone-boson couplings [$O(p^4)$]



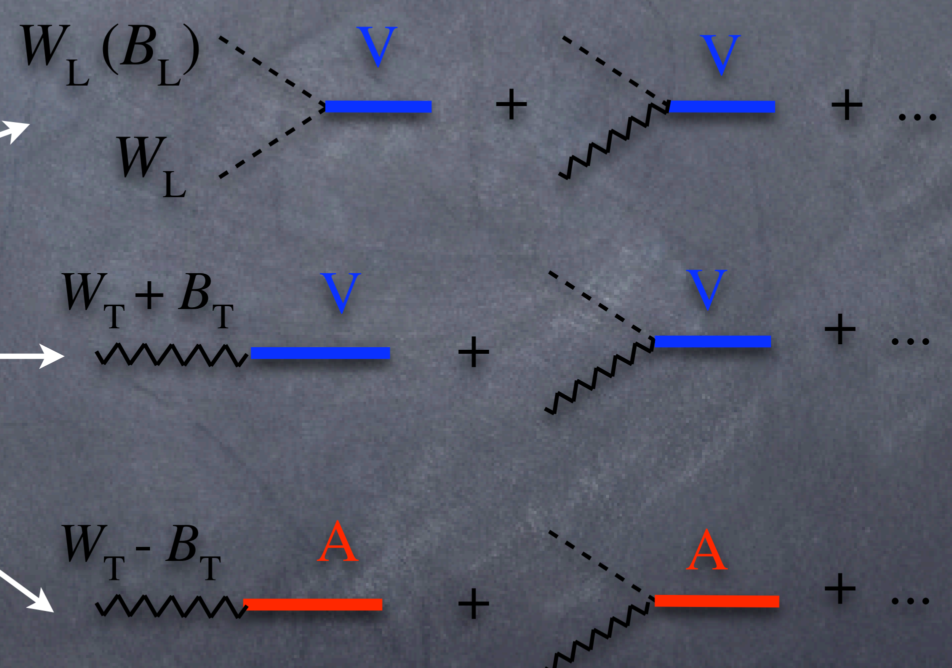
Heavy vectors in the EW Chiral Lagrangian

- 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 = $O(v)$

$$[u_\mu = i u^\dagger D_\mu U u^\dagger] \qquad \mathcal{L}_{int} = \frac{i}{2\sqrt{2}} G_V \mathrm{Tr}(V^{\mu\nu}[u_\mu, u_\nu])$$

$$+ \quad \frac{1}{2\sqrt{2}} F_V \mathrm{Tr}(V^{\mu\nu}(u\hat{W}^{\mu\nu}u^\dagger + u^\dagger \hat{B}^{\mu\nu} u))$$

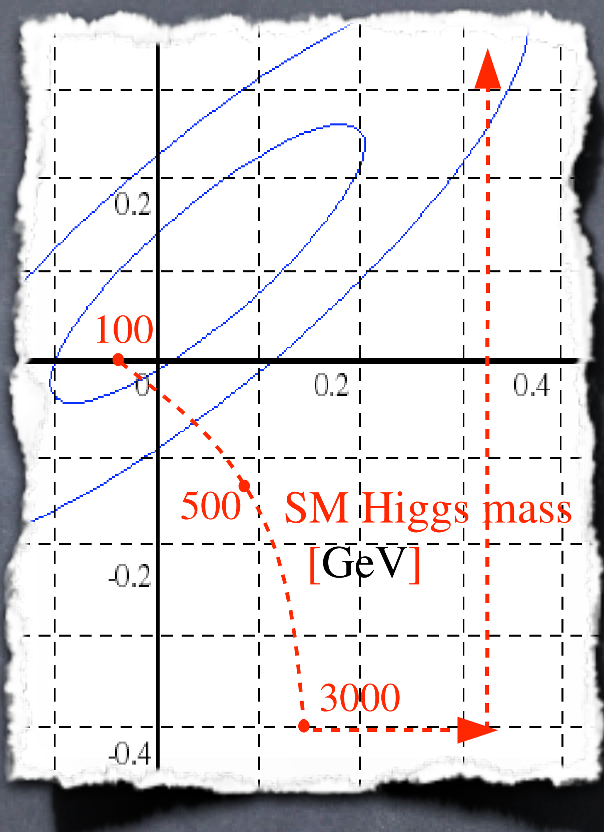
$$+ \quad \frac{1}{2\sqrt{2}} F_A \mathrm{Tr}(A^{\mu\nu}(u\hat{W}^{\mu\nu}u^\dagger - u^\dagger \hat{B}^{\mu\nu} u))$$

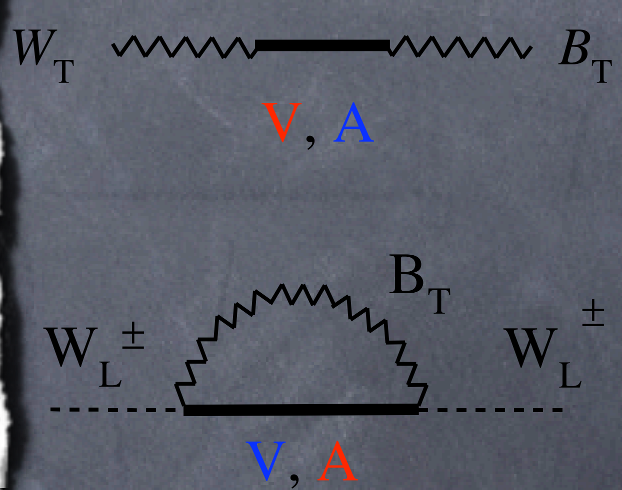


  - Specific UV completions of this effective theory correspond to specific choices of the free parameters.

EWPO with Resonances

- Tree-level positive contribution to S:
  - (worsens the agreement with EWPO)
- At 1-loop level potentially large (quadratically divergent) positive contribution to T
  - One-loop breaking of the custodial symmetry due to g' ≠ 0





$$\Delta\hat{S} = g^2\left(\frac{F_V^2}{4m_V^2} - \frac{F_A^2}{4m_A^2}\right)$$

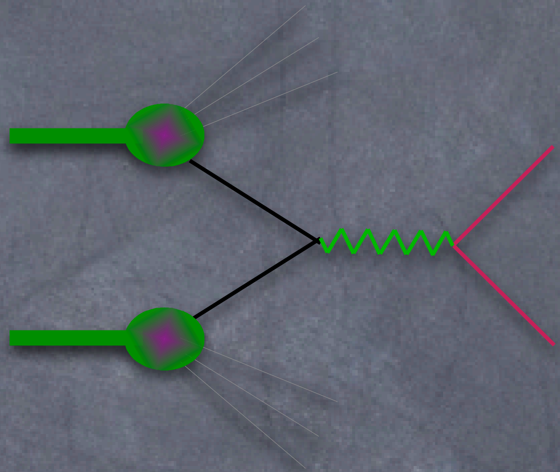
$$\Delta\hat{T} = \frac{3\pi\alpha}{c_W^2}\left[\frac{F_A^2}{4m_A^2} + \left(\frac{F_V - 2G_V}{2m_V}\right)^2\right]\frac{\Lambda^2}{16\pi^2 v^2} + \ldots$$

Producing the heavy vectors at the LHC

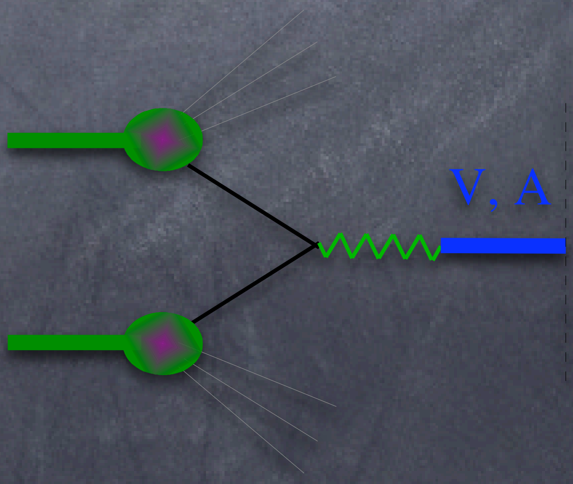
- Main properties of axial fields
  - $O(m_A^3)$ widths only from A→VW
    - [mediated by effective ops. with two heavy fields A[∂V,∂U], not included in L_{int}]
    - potentially suppressed if $m_A \approx m_V$
    - $\Gamma^A_{V^+W^-} = \Gamma^A_{V^-W^+} = \Gamma^A_{V^0W^+} = \Gamma^A_{V^+Z} \doteq \Gamma^A_{VW}\,,$
    - $\Gamma^A_{VW} = \frac{m_A^3}{48\pi v^2}(1-r^2)^3\left[g_A^2(1+2r^2)+g_V^2\left(1+\frac{2}{r^2}\right)+6g_Ag_V\right]$
  - $O(m_A)$ widhts of the type A → longitudinal + transverse SM gauge bosons,
    - $\Gamma^A_{WW} = \frac{g^2F_A^2m_A}{192\pi v^2}\,,\quad \Gamma^A_{WZ} = \frac{1}{2}\Gamma^A_{WW}\left[1+\frac{(1-2s_W^2)^2}{c_W^2}\right]\,,\quad \Gamma^A_{W\gamma} = 2s_W^2\;\Gamma^A_{WW}$
    - leading decay modes if $m_A \approx m_V$
- Decay widhts to SM fermions identical to the vector case, with corresponding BR enhanced by the suppression of the total rate

Producing the heavy vectors at the LHC

- A potentially clean signal (if the resonances are not too heavy) is the Drell-Yan production of the resonances and subsequent decay into l^+l^-, 2 and 3 SM heavy gauge bosons
  - easy to estimate (and simulate) normalizing the non- standard rate to SM Drell-Yan processes at the partonic level



SM



resonance to EW f.s.

Producing the heavy vectors at the LHC

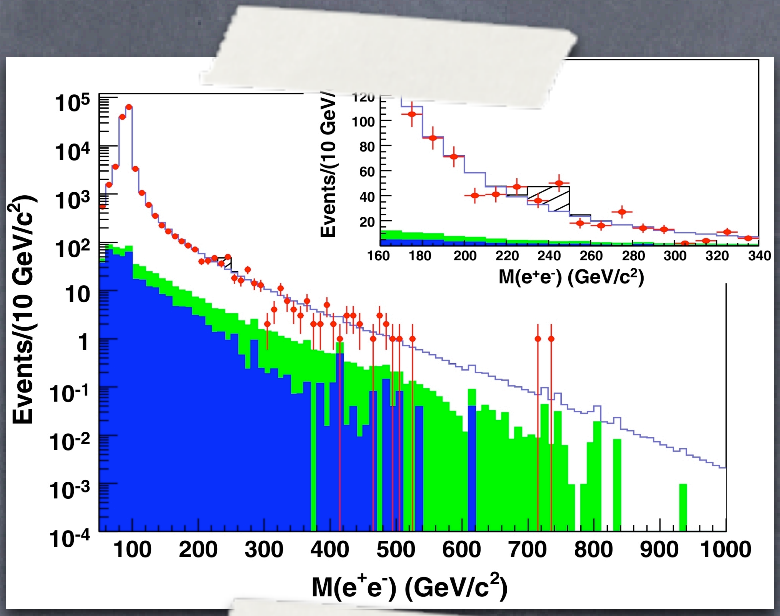
Cata, Isidori & J.F.K [0905.0490]

- E.g. for charged final states we define the form factor
  - $F_f^{R^+}(q^2) = \dfrac{\sigma(u\bar{d} \to R^+ \to f)}{\sigma(u\bar{d} \to \mu^+\nu)_{\rm SM}}$
  - $\dfrac{d}{dq^2}\sigma(pp \to R^+ \to f) = F_f^{R^+}(q^2)\dfrac{d}{dq^2}\sigma(pp \to \mu^+\nu)_{\rm SM}$
- As long as we can neglect interference effects (with SM or among different resonant contributions), the partonic resonant width is simply given by
  - $\sigma(q_i\bar{q}_j \to R \to f) = \dfrac{12\pi\Gamma_R^2 Br_{\rm in}^R Br_f^R}{(q^2-m_R^2)^2 + m_R^2\Gamma_R^2}\left[1 + \mathcal{O}\left(\dfrac{q^2-m_R^2}{m_R^2}\right)\right]$

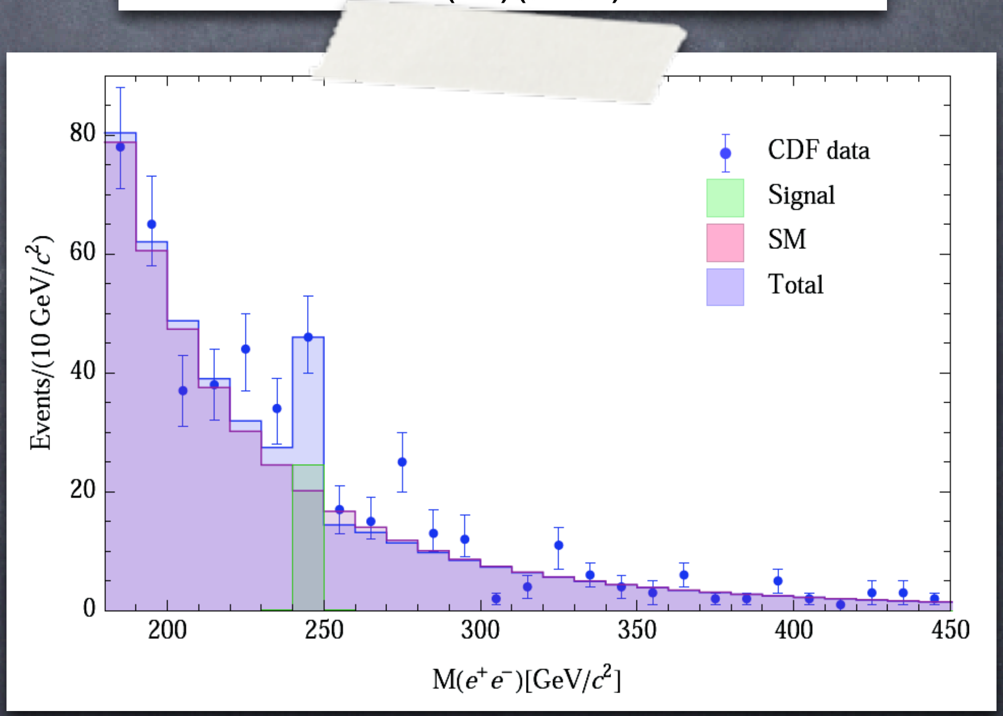
Signal of heavy vectors at the Tevatron?

- The l^+l^- state of the art is the analysis of the e^+e^- final state in p-pbar collisions published by CDF
- 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 $m_A \approx 1.3$ TeV to obtain a good EWPO fit

excluded by CDF [0811.0053]



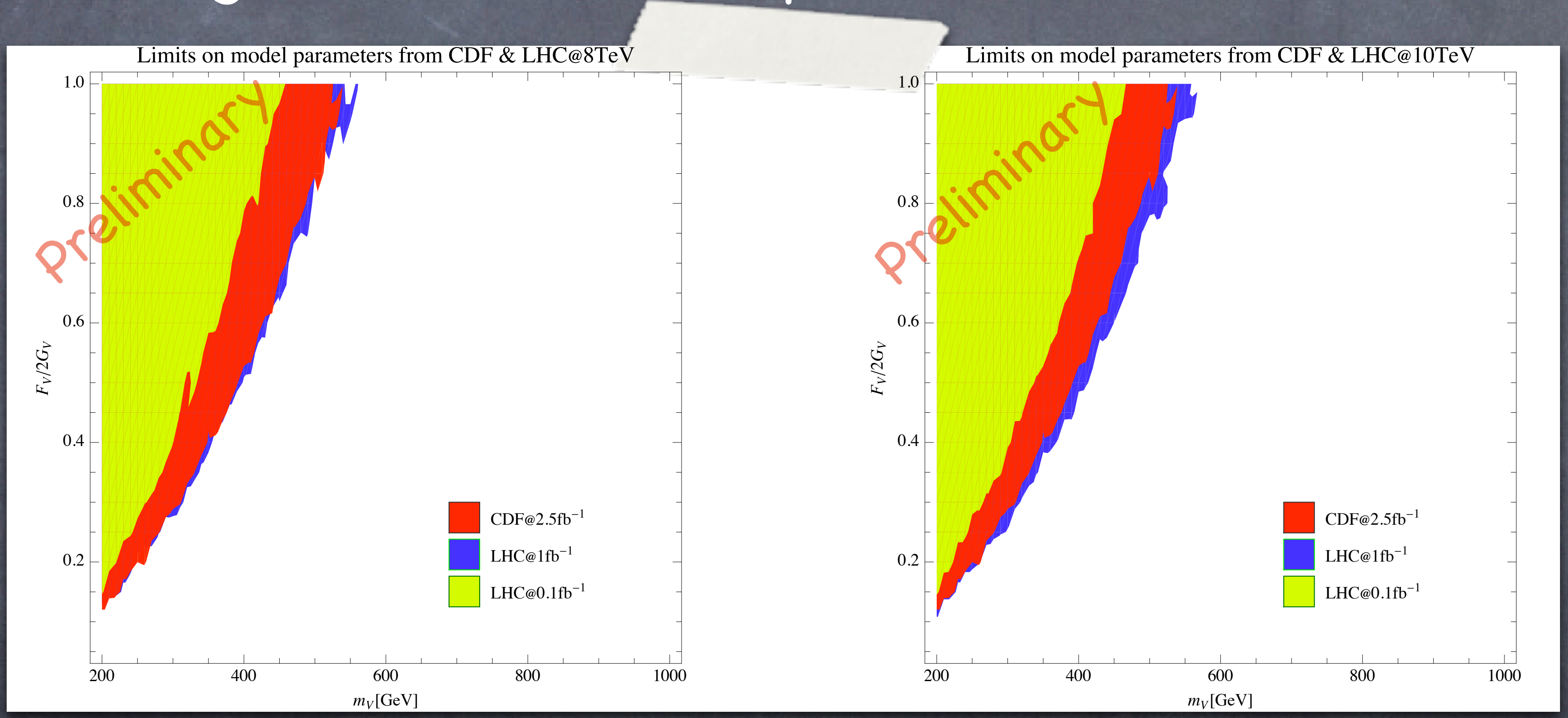
CDF [0810.2059]



Cata, Isidori & J.F.K [0905.0490]

Early LHC Reach

- At energies of 4TeV, 5TeV per beam



- Reach in di-lepton channels statistics dominated!
- Need $O(1fb^{-1})$ of data to surpass current Tevatron limits

Signals for heavy vectors at the LHC

- Two & three SM gauge boson final states
- A detailed estimate of the realistic efficiency for the detection of the heavy vectors in these final states [WZ, WW] + [WWW, WWZ, WZZ] has not been performed yet. So far we have analysed only the signal against the irreducible SM background = same e.w. final state
- Selecting leptonic decay is a high price to pay (in terms of efficiencies), but it should ensure a good rejection against non-irreducible backgrounds.
  - Some reference theoretical efficiencies:
    - [WZ] $BrZ_{lept} \times BrW_{lept}$ = 1.5 %
    - [WWZ] $BrZ_{lept} \times BrW_{lept} \times BrW_{had}$ = 0.9 %
    - [WZZ] $BrZ_{lept} \times BrW_{lept} \times BrZ_{had}$ = 1 %
    - [WZZ] $(BrZ_{lept})^3 \times BrZ_{had}$ = 0.4 %
    - [WWW] $(BrW_{lept})^3$ = 1%

Signals for heavy vectors at the LHC

- In the WWZ final state it is also worth to look at the WZ invariant-mass distribution
  - With high statistics (100 fb^{-1}), here we can hope to see a signal even without a light axial vector