Technicolor Phenomenology in the LHC Era

Adam Martin (Yale)

Based on: J. Hirn (Yale), V. Sanz (BU), 0712. 3783
+ work in progress
G. Azuelos et al., 0802.3715

Lattice Gauge Theory for LHC Physics, LLNL, 2008

Motivation:

Strong EW-scale interactions are a possibility at the LHC; to be as prepared as possible we could:

- Hope there are no new strong interactions
- Solve strong interactions completely
- Use the lattice
- Develop generic, flexible scenarios useful for detailed phenomenology

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What we can do **NOW**

Outline:

- Strong interactions at the LHC:
  what's been done and why it's insufficient
- A bottom-up approach:
  Parameterizing Technivector scenarios
  - Higgsless basics
  - Extending higgsless techniques
  - Parameter constraints
  - Including lattice inputs
- Implementation + Phenomenology:
  low + high luminosity examples

What we know:

- Strong interactions are difficult!
- Rescaled QCD models are ruled out:

$$
\begin{aligned}
f_\pi &\rightarrow v \\
\pi_a &\rightarrow W_L, Z_L \\
\rho, a_1 &\rightarrow \rho_T, a_T
\end{aligned}
$$

S parameter:

$$S > 0, \mathcal{O}(1)$$

but, not generic

- EW scale strong interactions must be very different from QCD -- But then how do we calculate?
- Many attempts have been made:

Whats been done:

Very few collider studies!

- 4D:

  Walking Technicolor (Lane et al)
  Topcolor (Hill)
  Low-Scale TC (LSTC) (Lane et al)
  (D)BESS (Casalbuoni et al)
  Low-N TC (Sannino)
  Deconstructed Higgsless (Chivukula)
  ...

- 5D:

  Higgsless (Csaki et al)
  Composite Higgs (Pomarol et al)
  ...

Full Collider Study

(Georges's talk)

Parton Level

Moving beyond Models: Proposal

- Models carry baggage... let's be more general

Common feature: TeV scale spin-1 resonances (ρ_T, W_{KK})

- We would like a more flexible structure than rescaled QCD
    - new spectrum
    - new interactions?
    - better agreement with precision measurements?
    - easy interface with lattice studies

BUT:

- Most general $\mathcal{L}(\mathrm{SM}\ +\ \mathrm{spin}-1)$ has $\mathcal{O}(100)$ parameters

way too many for practical pheno!

Moving beyond Models: Proposal

We need an organizing principle

$\mathcal{L}_{\text{SM+spin-1}}\Big($ particles, masses, couplings $\Big)$

- NOT a new model, RATHER an organizing scheme

- Start by extending Higgsless techniques (5D)

Moving beyond Models: Proposal

We need an organizing principle

$\mathcal{L}_{\text{SM+spin-1}}\Big($

particles, masses, couplings

$\Big)$

a DEWSB equivalent of what mSUGRA is for MSSM

- NOT a new model, RATHER an organizing scheme

- Start by extending Higgsless techniques (5D)

Why Higglsess (5D) ?

As we'll see, in 5D:

- Flexible spectrum/interactions with only 4 free parameters + no new fields
- Easy to go to unitary gauge and mass eigenstates

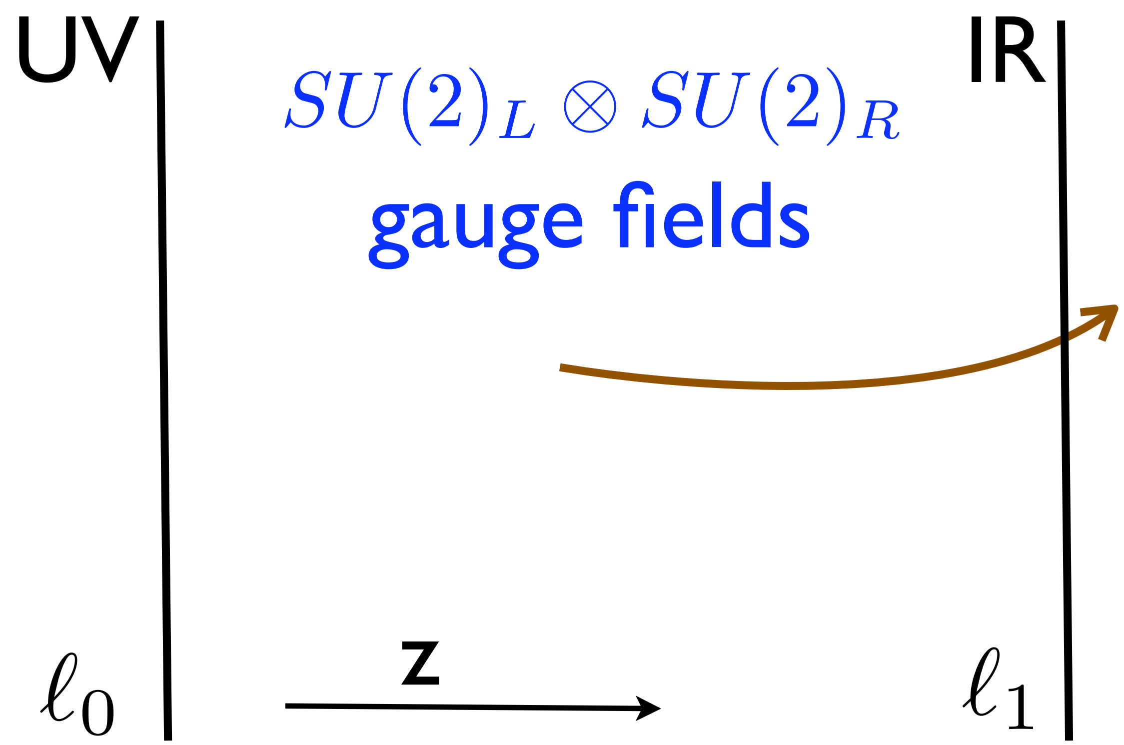
Simplifies implementation into MC programs

- Easy to add more resonances later on;

isosinglet resonances, scalars, pseudoscalars, fermions

Higgsless Basics:

- AdS/CFT inspired 5D version of strong DEWSB
- 5D interval $z \in (\ell_0, \ell_1)$;



- Bulk geometry; usually
$$\frac{\ell_0^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$$

- BC break EWS $\longrightarrow$ KK tower of states; zero modes are $\gamma, W^\pm, Z^0$
  +Vector, Axial resonances (not quite!): $W_n^\pm, Z_n$
- Resonancs couplings: $g_{ABC} \propto \int_{\ell_0}^{\ell_1} dz \frac{\ell_0}{z} \phi_A(z)\phi_B(z)\phi_C(z)$

Higgsless continued

- small $g_5 \longleftrightarrow$ large N_{TC}
- Spectrum: tower of narrow, weakly interacting resonances (large N_{TC})

  large coupling to W_L, Z_L comes from plugging in polarizations

  exchange of many resonances delays unitarity violation

- BUT, pure AdS leads to QCD-like spectrum

$$S > 0, \mathcal{O}(1)$$

(Agashe et al '07)

small perturbations don't help

Modifying Higgsless

- How can we extend the Higgsless framework to incorporate new features?
- Effective warp factors:

$$\mathcal{L} = -\frac{1}{2g_5^2} \int dx \; \omega_V(z) F_{V,NM} F_V^{NM} + \omega_A(z) F_{A,MN} F_A^{MN}$$

$$\omega_{V,A}(z) = \frac{\ell_0}{z} \exp\left(o_{V,A} \left(\frac{z^4}{\ell_1^4} \right) \right) \qquad o_{V,A} \leq 0$$

(Hirn, Sanz '06,'07)

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(Hirn, Sanz '06,'07)

Positive definite

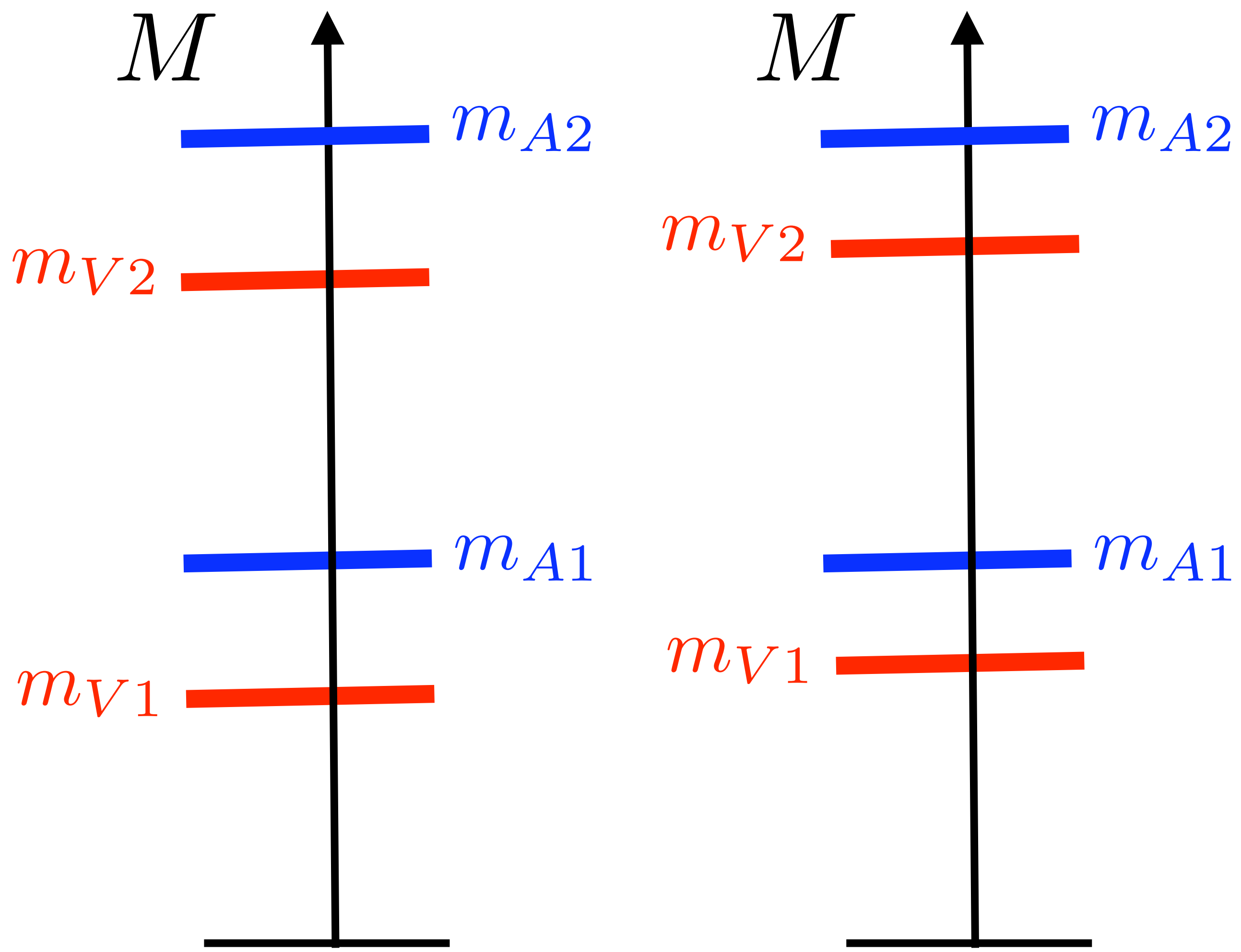
Deformed in IR - power of z unimportant

Acts like condensate

$$\Pi_{V,A} \sim \frac{o_{V,A}}{(Q\ell_1)^4}$$

Why this deformation? $\omega_{V,A} = \frac{\ell_0}{z} e^{o_{V,A} z^4/\ell_1^4}$

- Allows us to vary the length of the dimension the vector feels relative to the axial



$o_V = 0, o_A = 0$

Dialing o_V for fixed o_A :

Remember:

Eigenstates $W^{\pm}_{1,2}, Z^0_{1,2}$ are a mixture of V, A

$$|\psi_X(z)\rangle = |V_X(z), A_X(z)\rangle$$

- Added only 2 new parameters, no new fields
- Couplings $g_{W_1 W Z}$, etc. will also vary with ℓ_1, o_V, o_A

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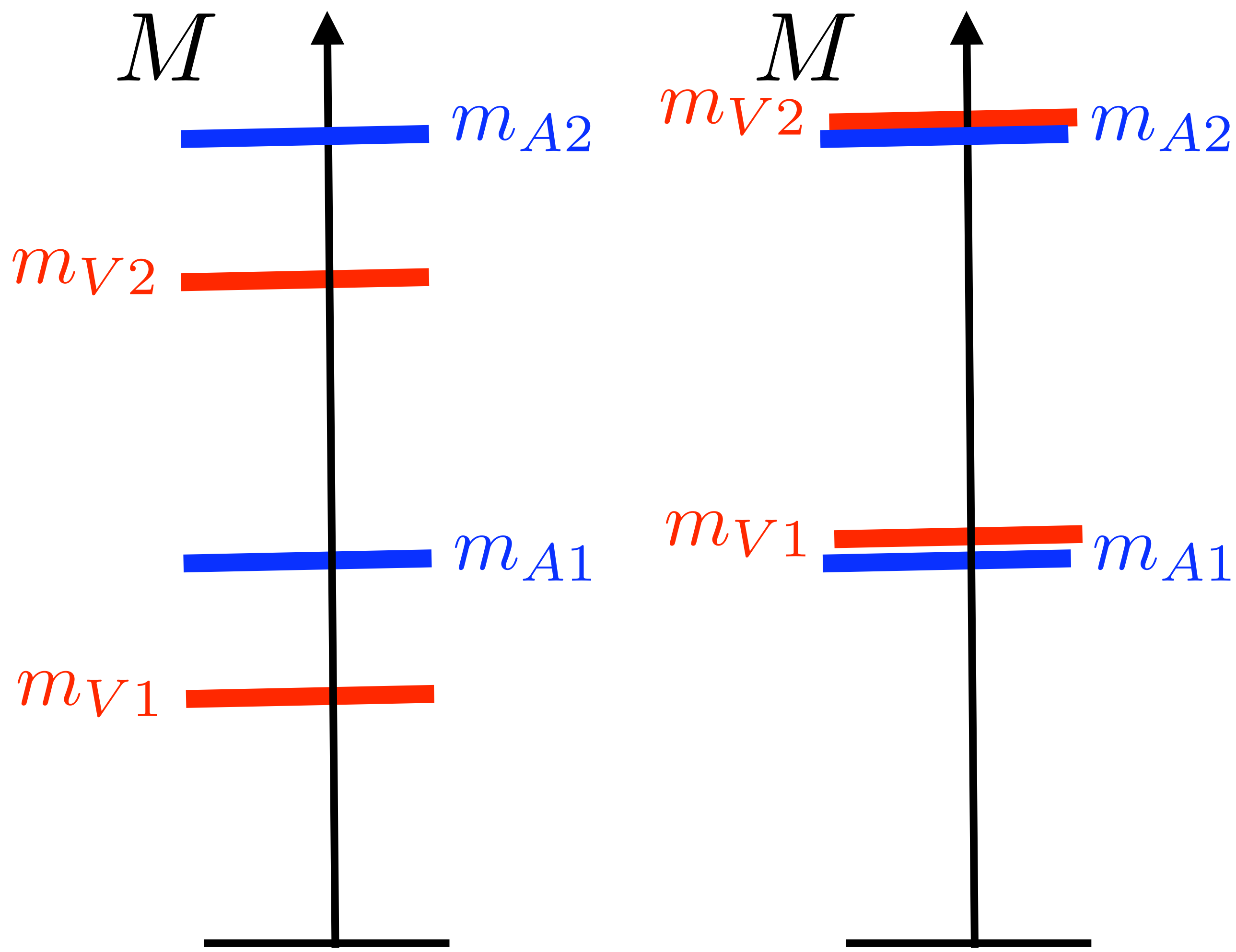

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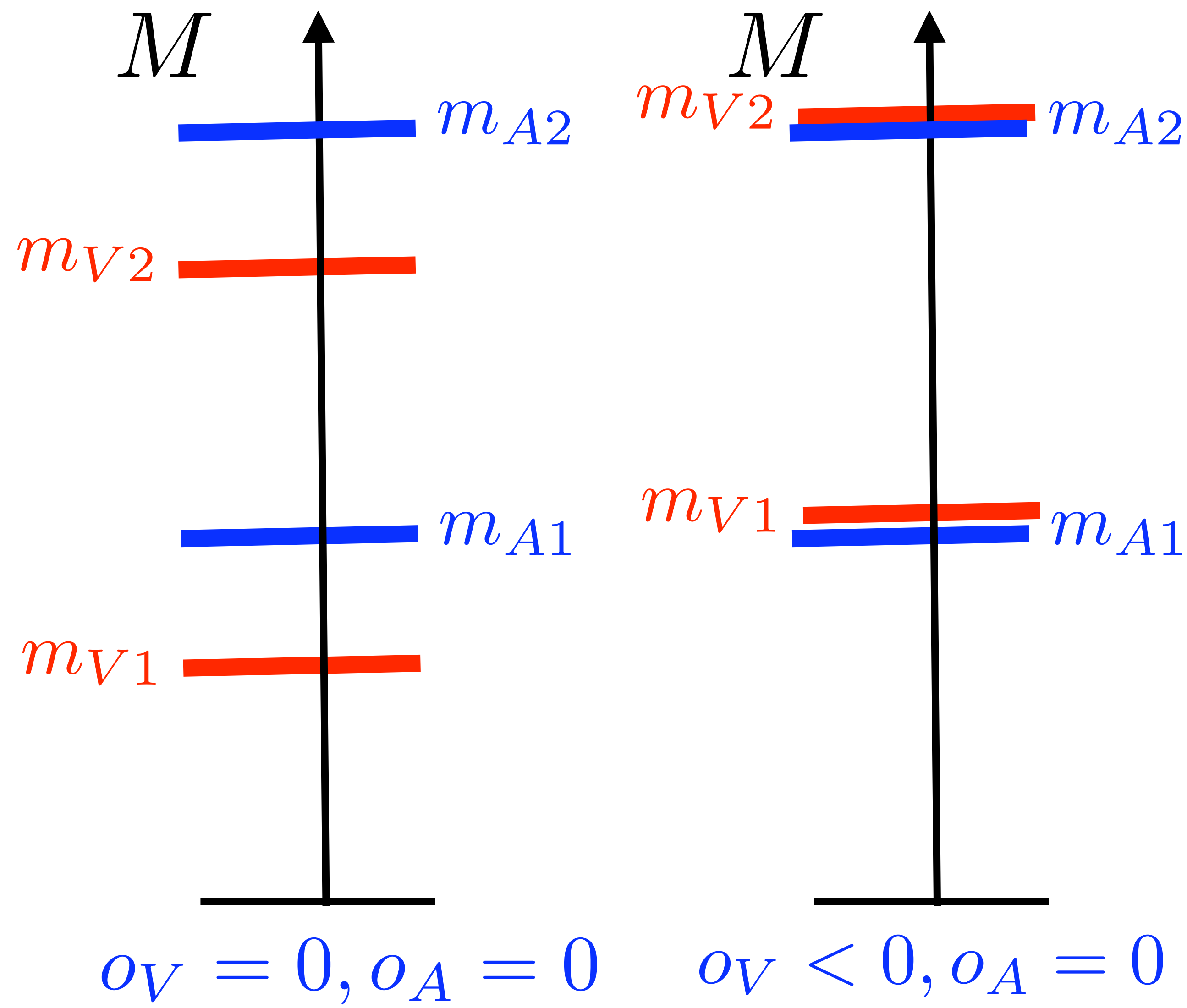

Dialing o_V for fixed o_A :

Degenerate spectrum

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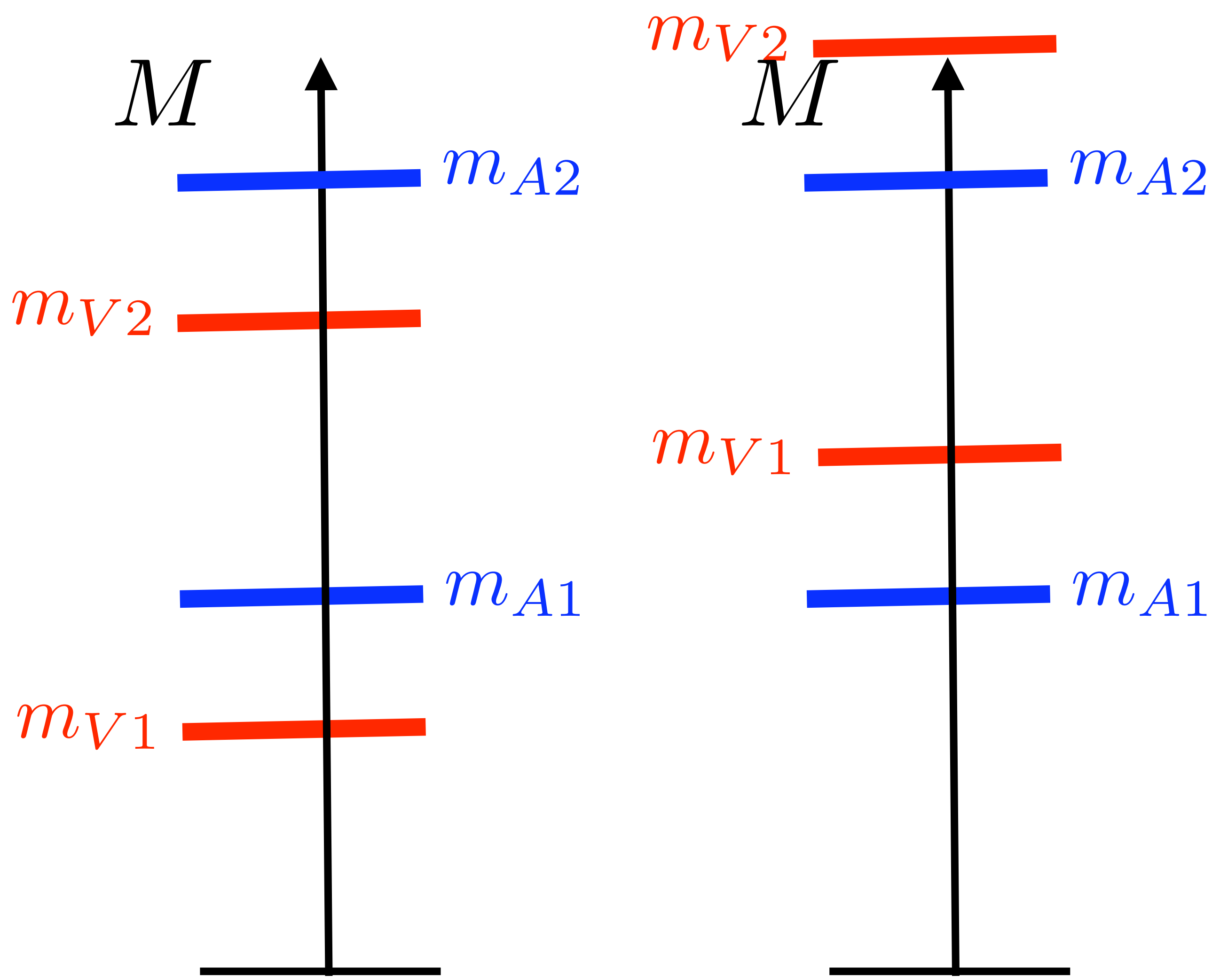

$o_V = 0, o_A = 0$ $\quad$ $o_V < 0, o_A = 0$

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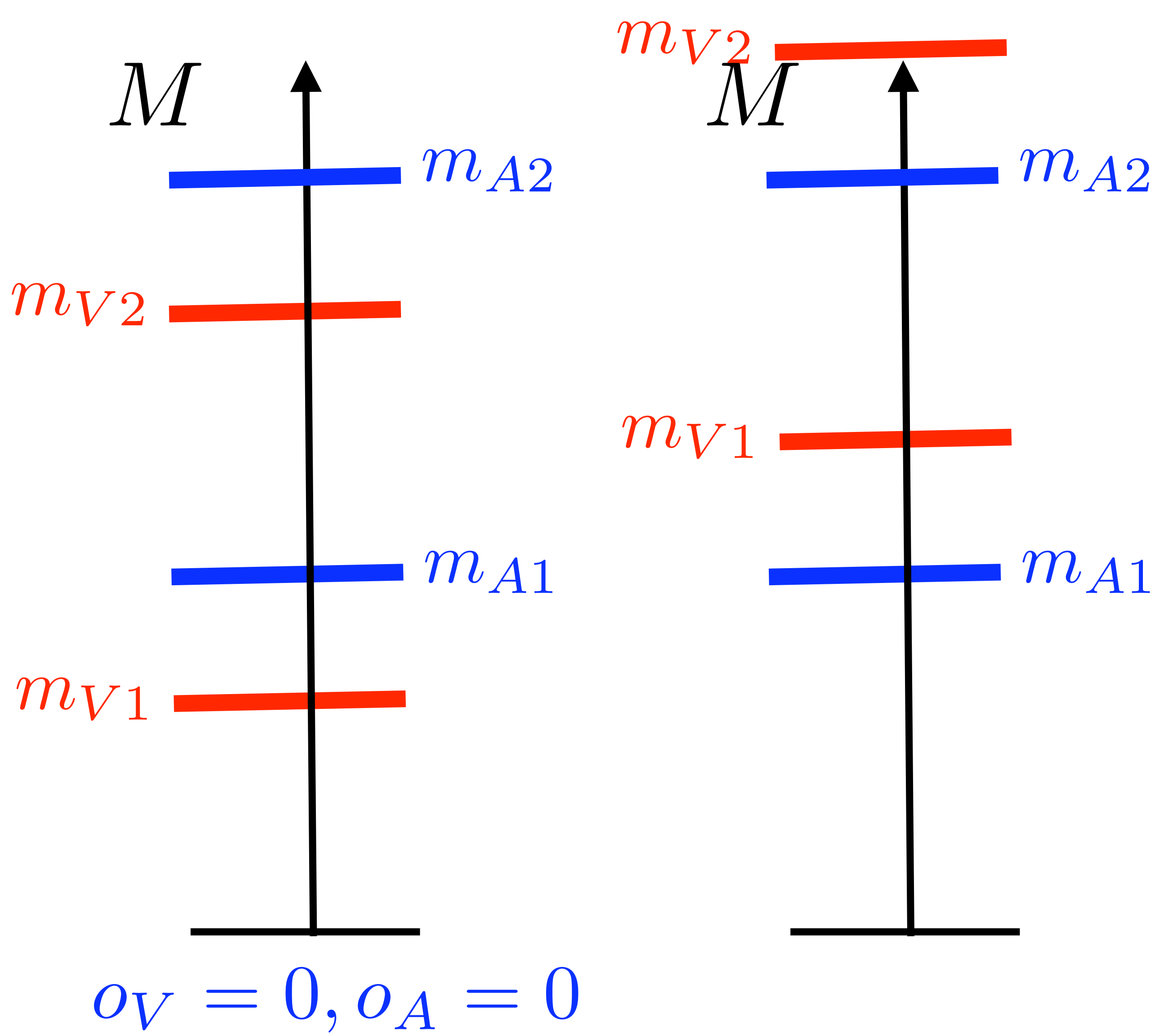

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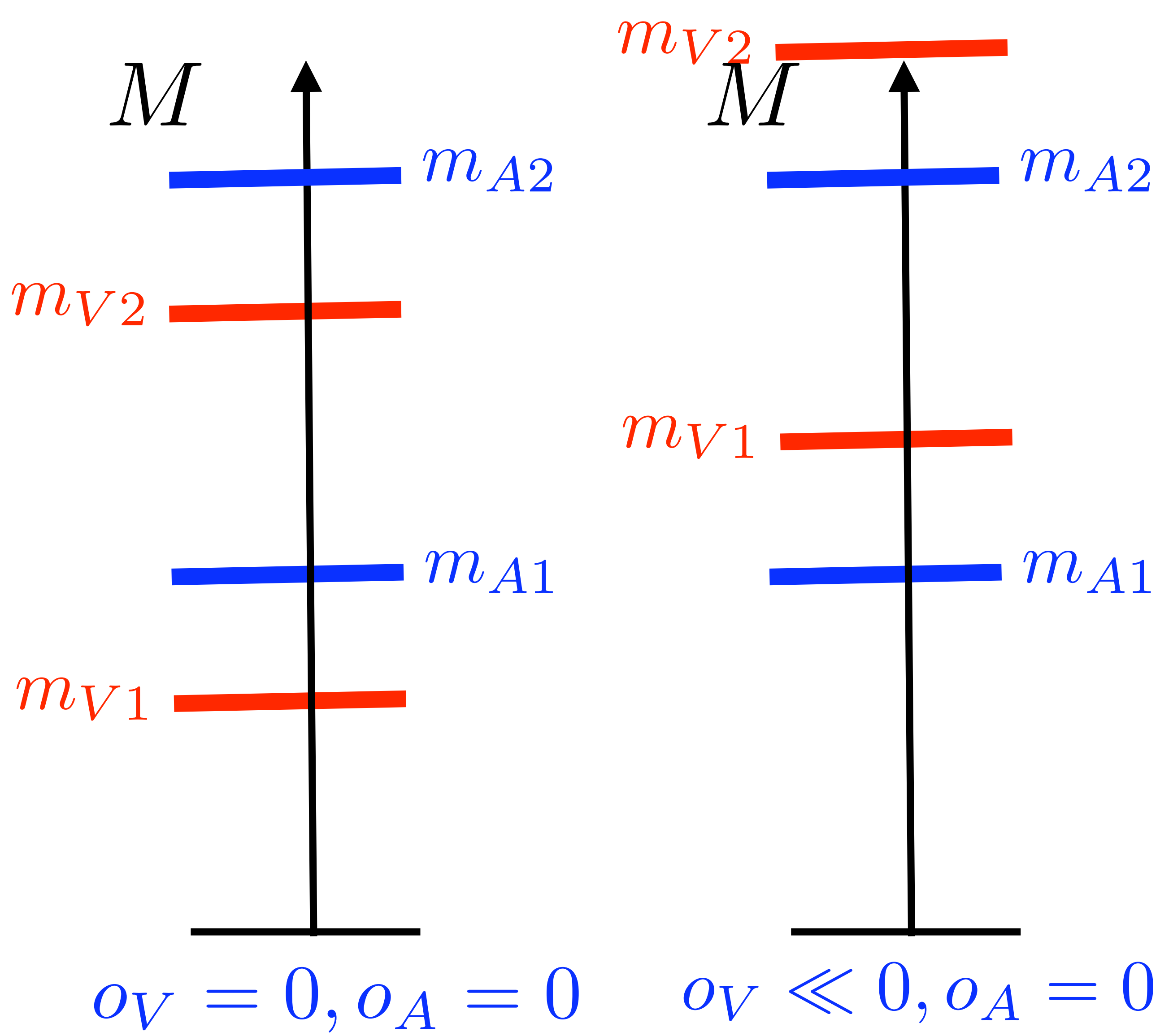

Dialing o_V for fixed o_A:

or Inverted spectrum

Remember:

Eigenstates $W^{\pm}_{1,2}, Z^0_{1,2}$ are a mixture of V, A

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- Added only 2 new parameters, no new fields
- Couplings $g_{W_1 WZ}$, etc. will also vary with ℓ_1, o_V, o_A

What do we gain?

- Parameter space contains non QCD-like spectrum

Using sum rules and simple resonance models, S ameliorated when $M_{W1} \cong M_{W2}$

(de Rafael-Knecht '97
Appelquist `98
Shrock, Kurachi `07)

$$S = 16\pi(\Pi'_{VV} - \Pi'_{AA})|_{Q^2=0}, \quad S = 4\pi\left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2}\right)$$

- Whenever $\omega_V \neq \omega_A$; unconventional triboson, 4-boson couplings

$$g_{W_1^- WZ} = g_1 \partial_{[\mu} W^-_{1\nu]} (W^+_{[\mu} Z^0_{\nu]}) + g_2 \partial_{[\mu} W^-_{\nu]} (Z^0_{[\mu} W^-_{1\nu]}) + g_3 \partial_{[\nu} Z^0_{\nu]} (W^-_{[1\nu} W^+_{\nu]})$$

$$g_1 \supset \int_{\ell_0}^{\ell_1} dz\ \omega_V (V_1 A_{W^+} A_Z) \cdots \neq g_3 \supset \int_{\ell_0}^{\ell_1} dz\ \omega_A (V_1 A_{W^+} A_Z) \cdots \neq g_2$$

Mixed photon coupling $g_{W_1^- W^+ \gamma}$ can be nonzero!

What do we gain?

New pheno. and a new twist on old pheno.

- Parameter space contains ne

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What about SM fermions?

- Coupling of fermions to the new resonances will determine the best production methods at the LHC
- Full 5D treatment of fermions would re-introduce many parameters...

For starters: one more parameter g_{ffV}

$$g_{ffW} = g_{SM}$$

- We can study several models of fermion interactions

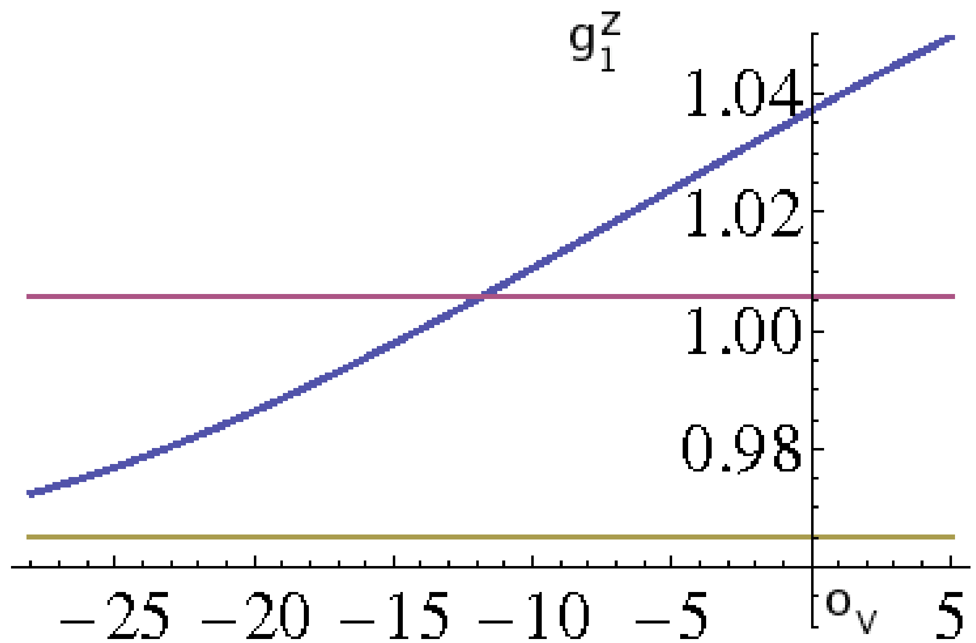
$$g_{ffV} = \kappa\, g_{ffW}$$

$$g_{ffV} \cong 0 \qquad \text{ideally delocalized}$$

$$g_{t_R t_R V} \gg g_{ffV} \qquad \text{mostly composite } t_R$$

Constraints:

- Parameter count: $\ell_1, \ell_0, g_5, \tilde{g}_5, o_V, o_A, g_{ffV}$
- For a given ℓ_1: o_V, o_A constrained by anomalous $g_{WW\gamma}$, g_{WWZ} couplings (LEP).



- LEP, Tevatron constrain fermion-resonance coupling

contact interactions: $\frac{(\bar{f}f)(\bar{f}'f')}{\Lambda^2}$

direct bounds: $\sigma(p\bar{p} \to Z'(W') \to \ell^+\ell^-(\ell\nu))$

indirect bounds: # high p_T objects (Z^0, γ)

Constraints:

overall scale: $M_{res} \sim \frac{1}{\ell_1}$

- Parameter count: $\ell_1, M_Z, M_W, \alpha_{em}, o_V, o_A, g_{ffV}$

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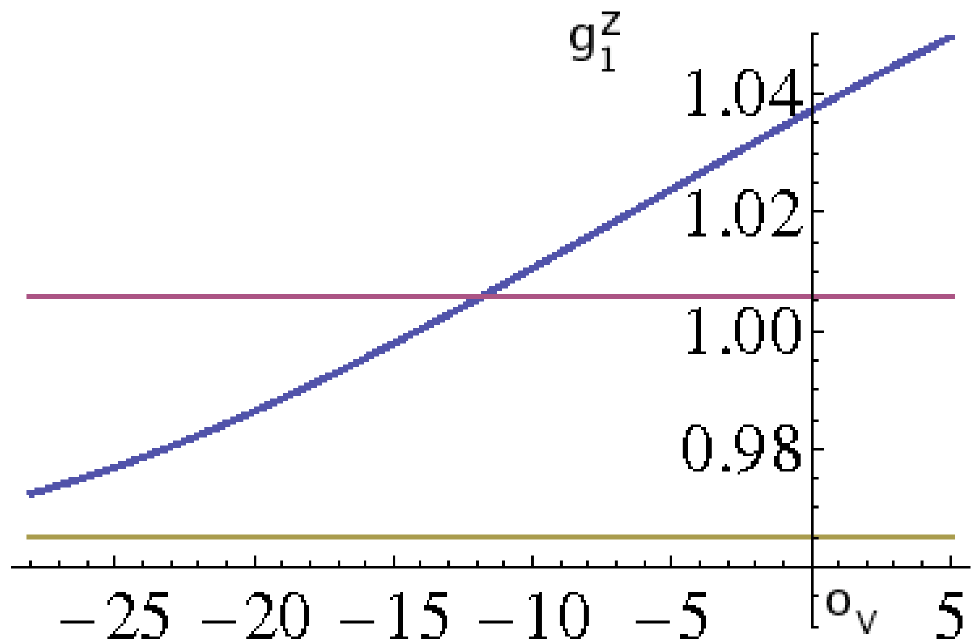

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What we need from Lattice:

Spectrum

- M_{V1} vs. M_{A1} :

Related to S: degenerate?
How do they vary with N_{TC}, N_{TF}

Simplest models has only spin-1 , W_L, Z_L

- What other states are present?

  Pseudoscalars: π_T
  Scalars: σ
  Isosinglets: ω_T, h_T
  Baryons
  ...

- How do masses vary with $m_{TF}, \langle\bar{\psi}\psi\rangle, N_{TF}, N_{TC}$?

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Scalars: σ
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Large $N_{TF} \to$ many π_T

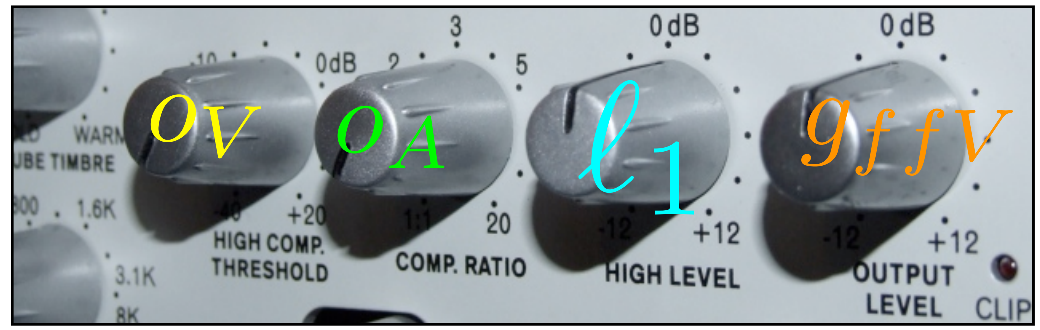
How heavy are these in near conformal theories?

- How do masses vary with $m_{TF}, \langle\bar{\psi}\psi\rangle, N_{TF}, N_{TC}$?

Combining Lattice and Pheno Simulation:

Up to now:

S, anomalous triboson couplings

$\mathcal{L}\Big($ 

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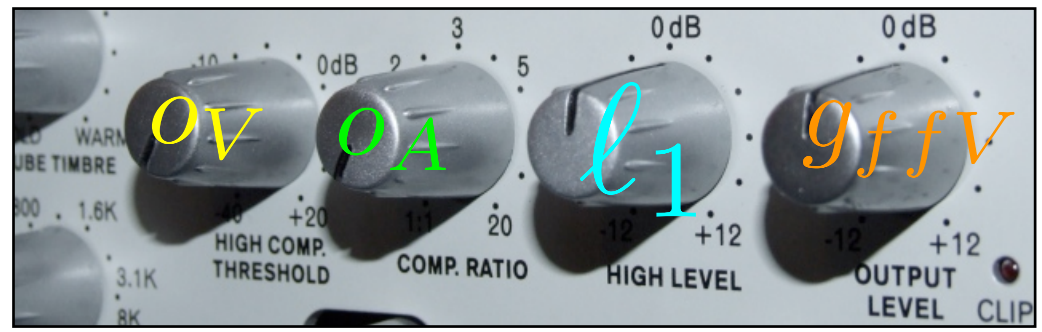

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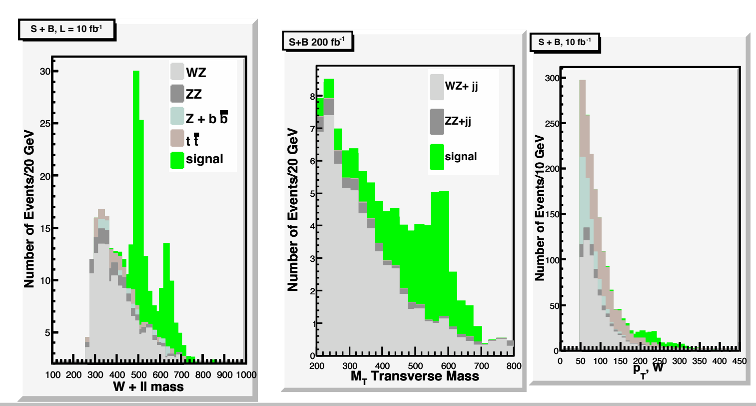
Collider Phenomenology



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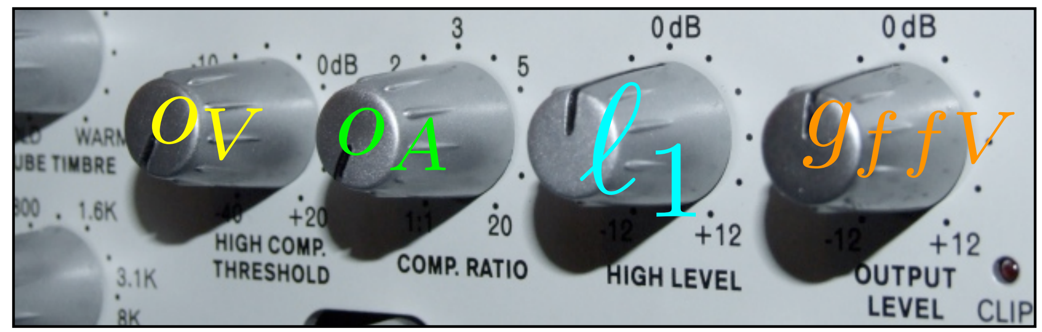
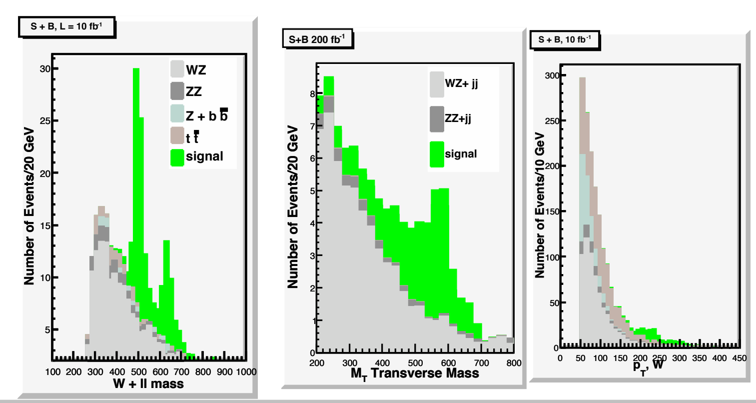


$$\Big)$$

With Lattice input:

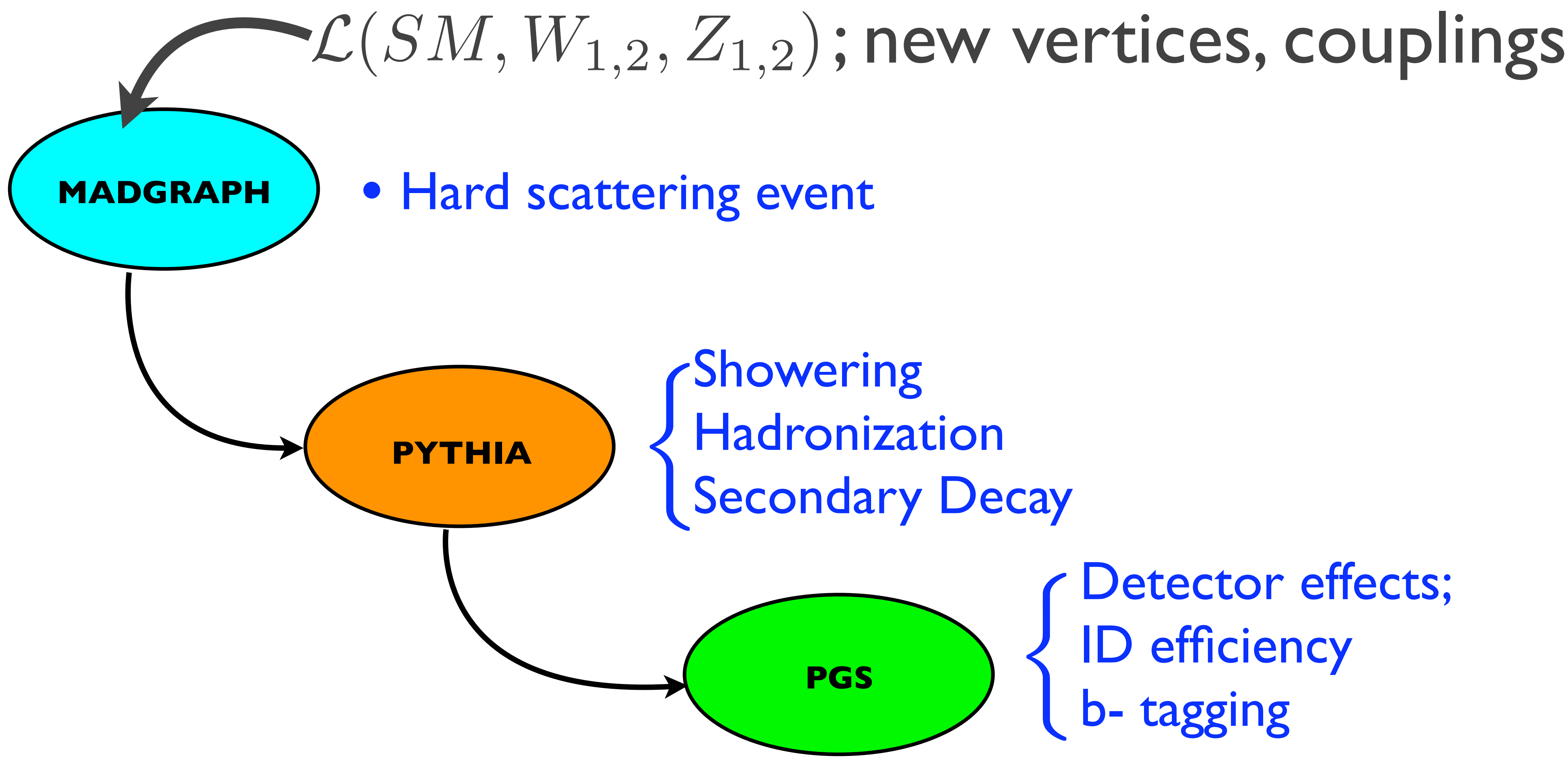
spectrum, particle content

Collider Phenomenology



Implementation

- Put first two resonance multiplets + interactions into matrix element generator MadGraph



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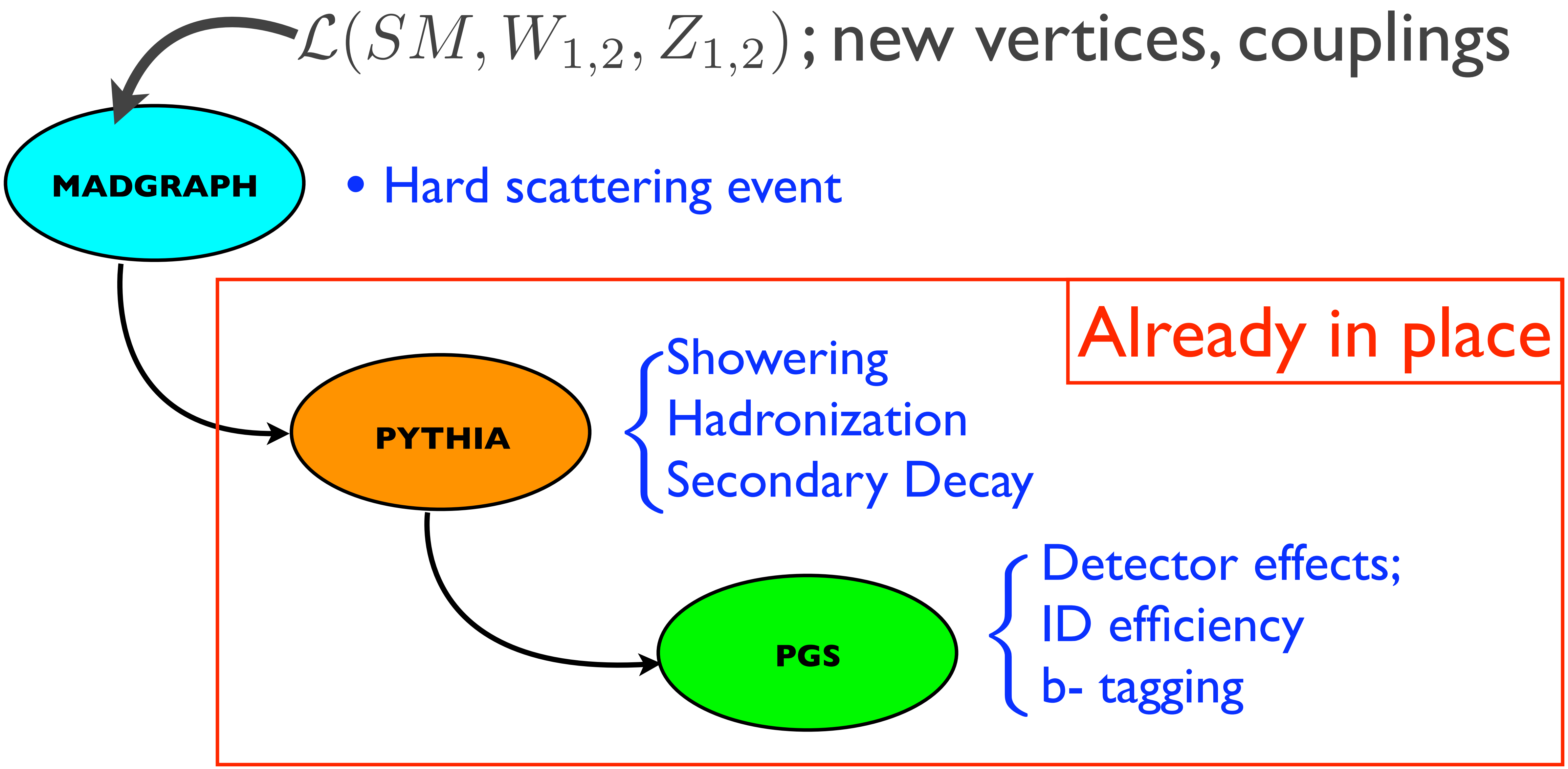
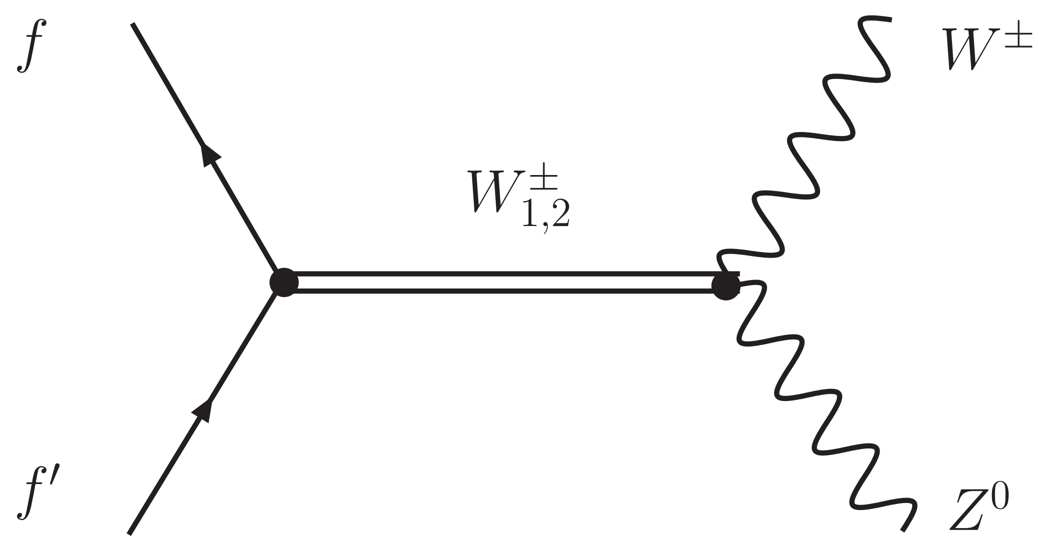


Low Luminosity Signals: s-channel

- Nonzero fermion-resonance coupling:

  → s-channel production is dominant



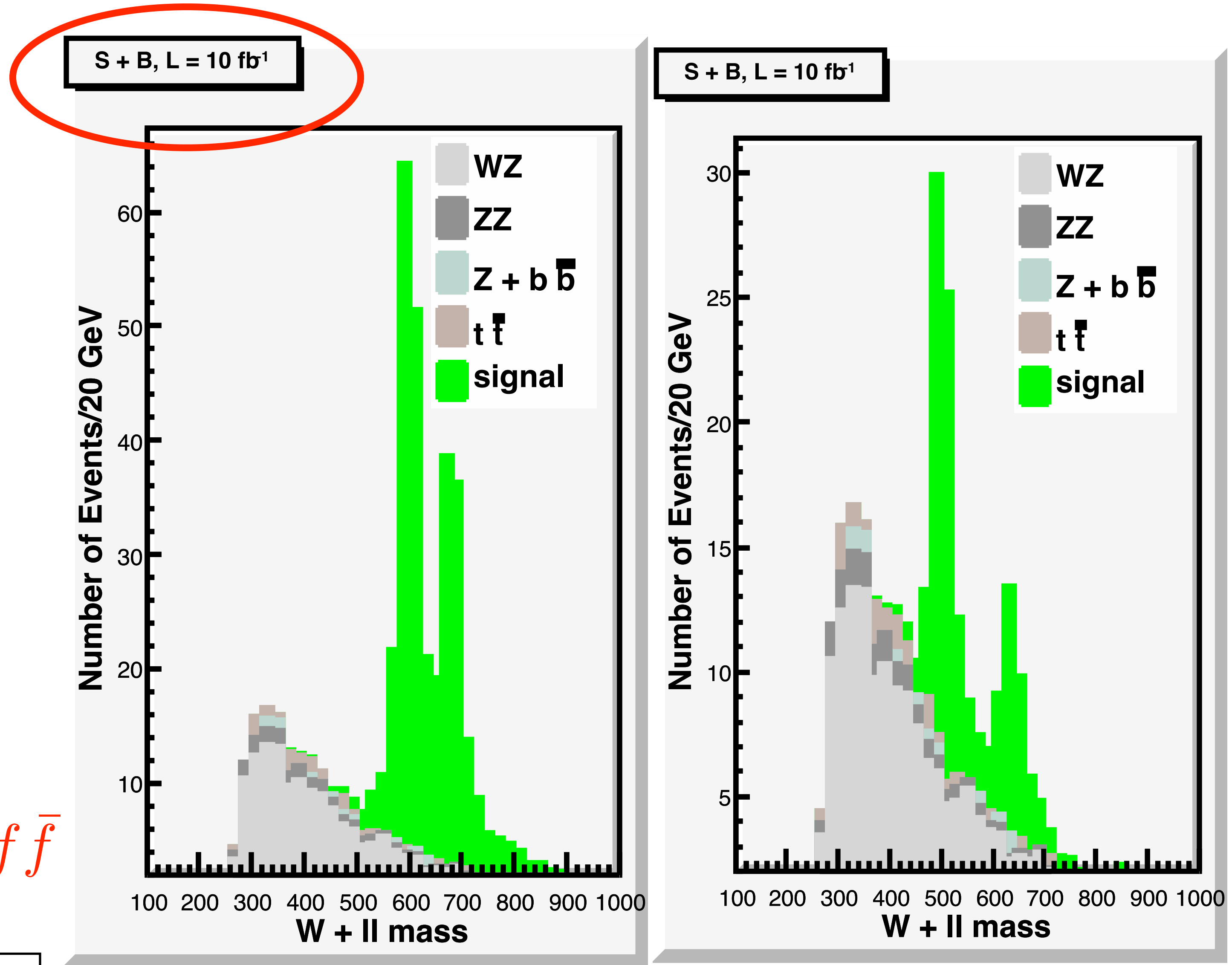
- Choosing couplings to satisfy all LEP + Tevatron constraints, we can still get a spectacular signal.

$$\sigma(pp \to W_{1,2} \to WZ) \propto \frac{M^4_{W_{1,2}}}{M_Z^2 M_W^2}$$

Enhancement from decays to longitudinal polarizations

Example: $pp \to W^{\pm}Z \to 3\ell + \nu$

- Two resonances - both couple to $W^{\pm}, Z^0$
- Seen within the first few fb^{-1} at LHC
- Neutral $Z^0_{1,2}$ can be seen in $Z^0_{1,2} \to W^+W^-, f\bar{f}$

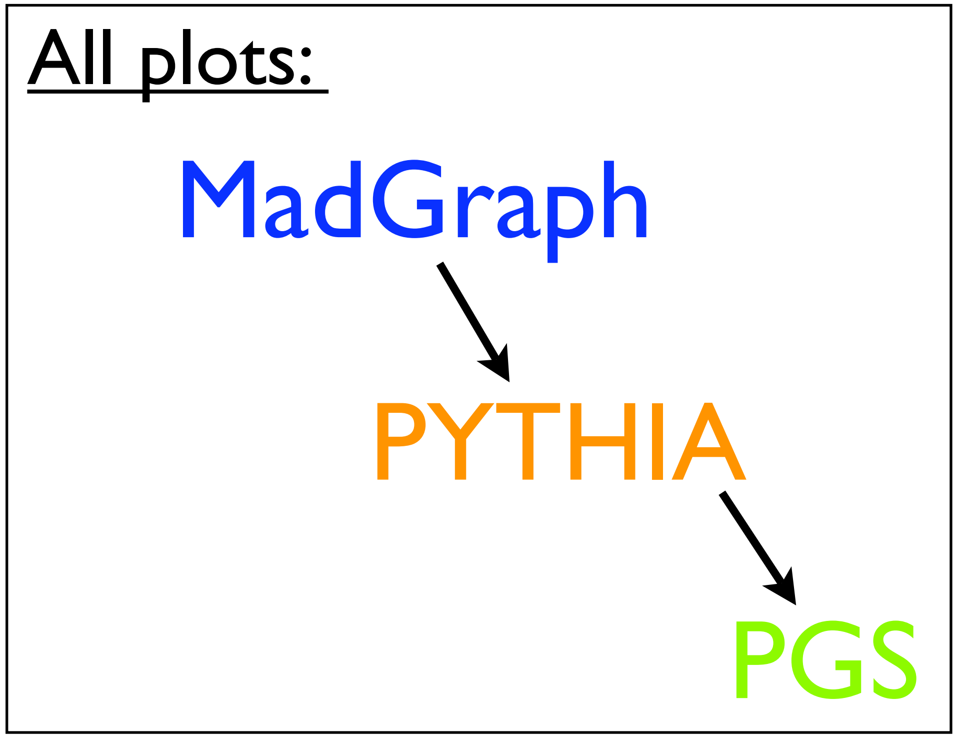


1.) $n_{lep} = 3, p_T > 10$ GeV, $|\eta| < 2.5$
$p_T > 30$ GeV for at least one

2.) $|M_{\ell^+\ell^-} - M_Z| < 3.0\Gamma_Z$

3.) $H_{T,jets} < 125$ GeV

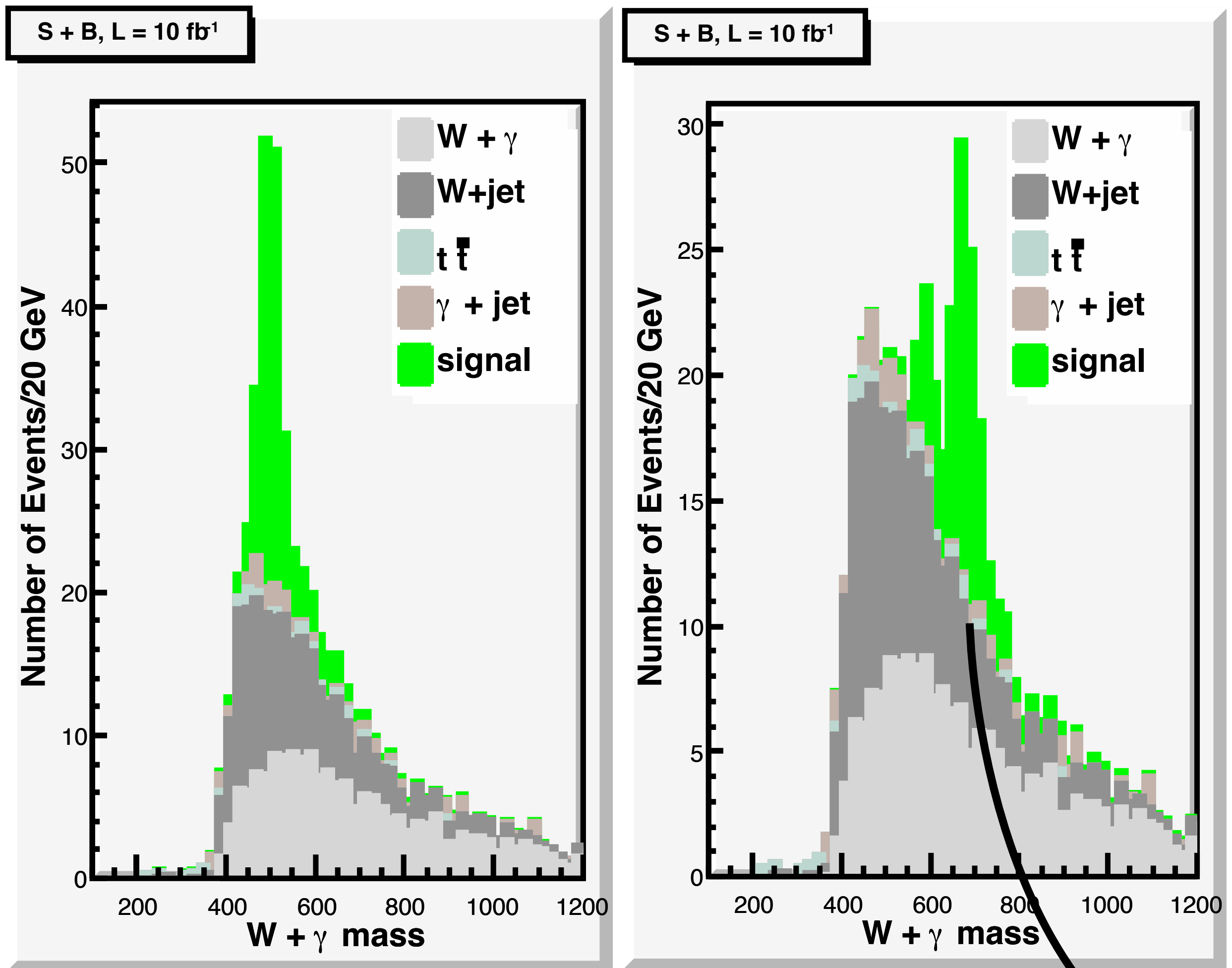
4.) $p_{T,W},\ p_{T,Z} > 100$ GeV



Example: $pp \to W^\pm\gamma \to \ell + \nu + \gamma$

When $\omega_V \neq \omega_A$: $g_{\gamma W^+ W_1^-} \partial_{[\mu}\gamma_{\nu]}(W^+_{[\mu}W^-_{1\nu]}) \neq 0$

is allowed, NOT permutations



$g_{W_1 W\gamma}$

- Does not exist in AdS Higgsless

$g_{H^\pm W\gamma}$

- Only at loop level in MSSM/ 2HDM

1.) $n_{lep} = 1, p_T > 10$ GeV, $|\eta| < 2.5$

2.) $n_\gamma = 1, p_T > 180$ GeV, $|\eta| < 2.0$

3.) $p_{T,W} > 180$ GeV

4.) $E_{T,miss} > 20.0$ GeV

Two peaks when:

$M_{W_2} - M_{W_1} \lesssim 90$ GeV

Example: $pp \to W^{\pm}\gamma \to \ell + \nu + \gamma$

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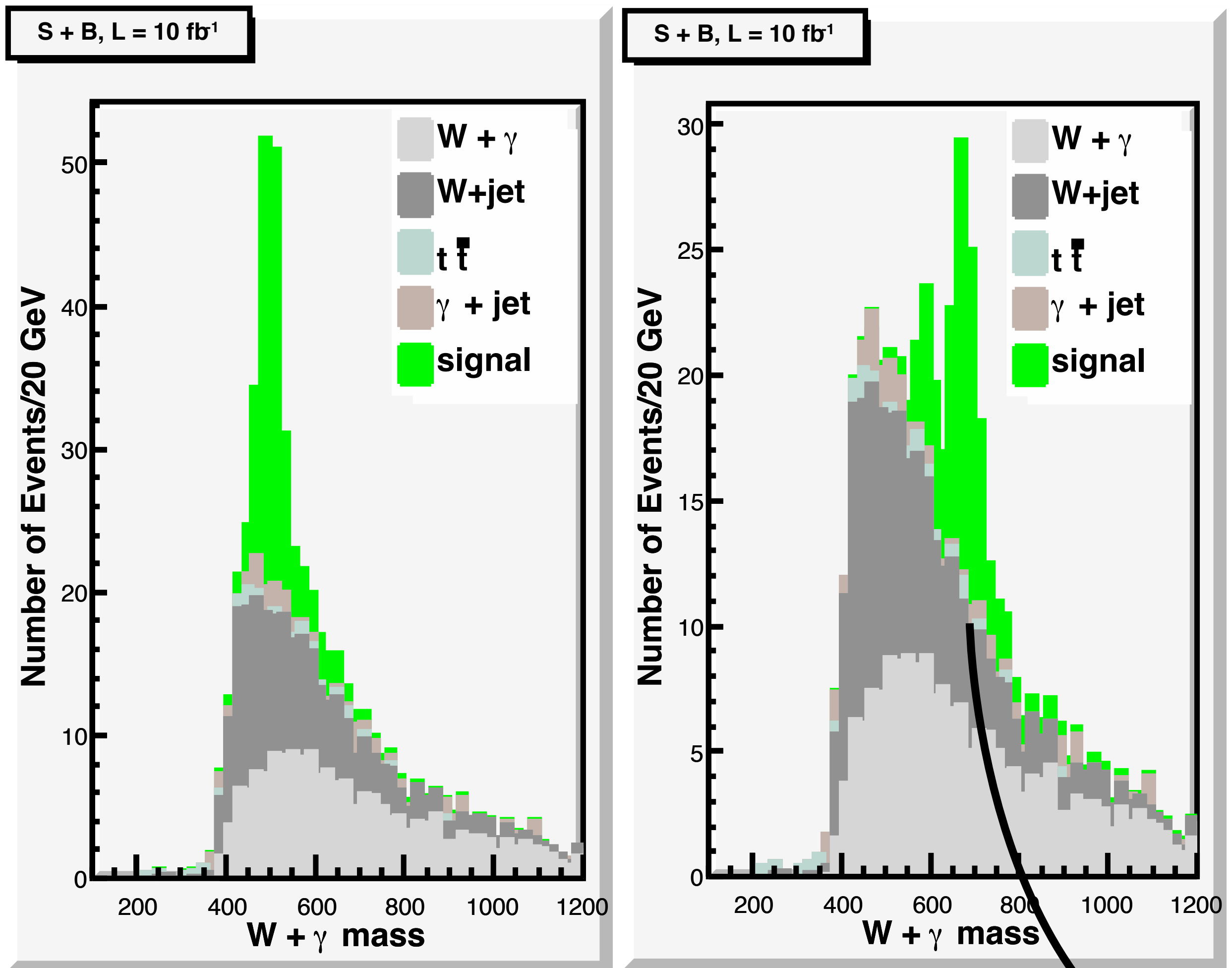

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- Does not exist in AdS Higgsless

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- Only at loop level in MSSM/ 2HDM

New Signal!

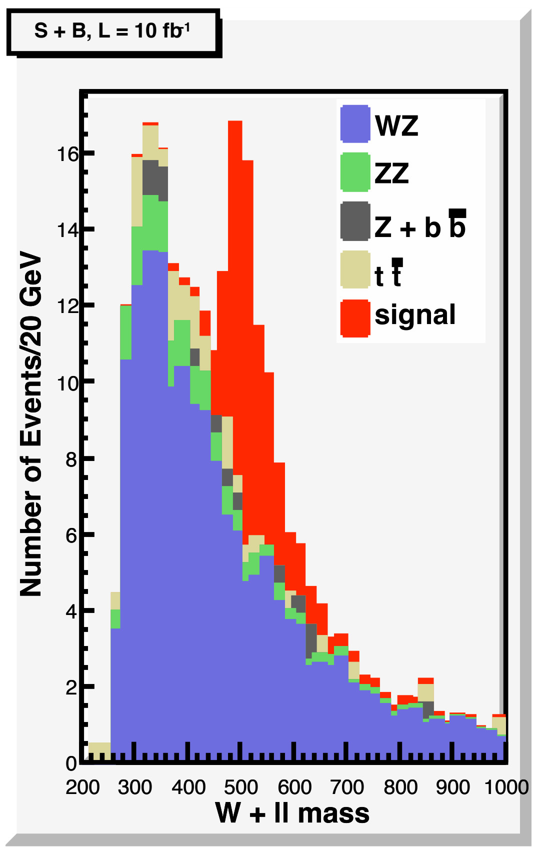
Two peaks when:

$M_{W_2} - M_{W_1} \lesssim 90 \text{ GeV}$

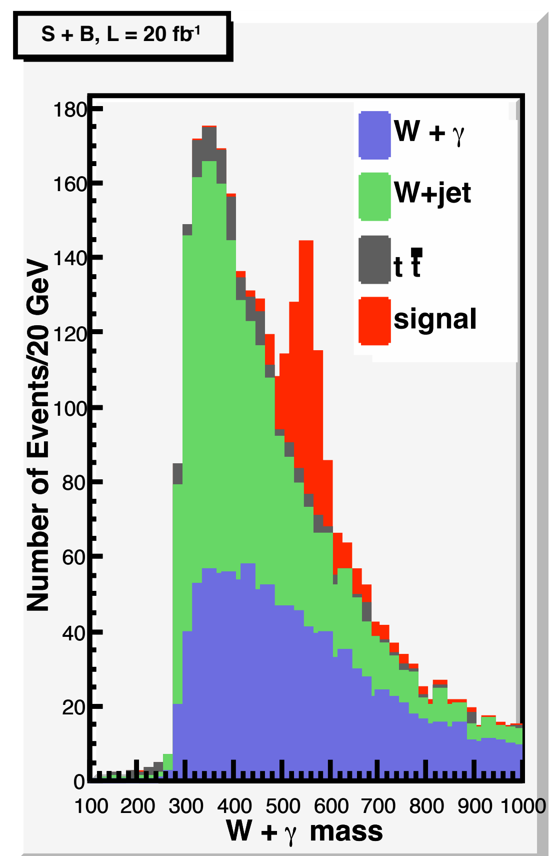
Comparison: s-channel production

Low-Scale TC

(Azuelos et al, Les Houches '07)



$W^{\pm}_{1,2} \to W^{\pm} Z^0$



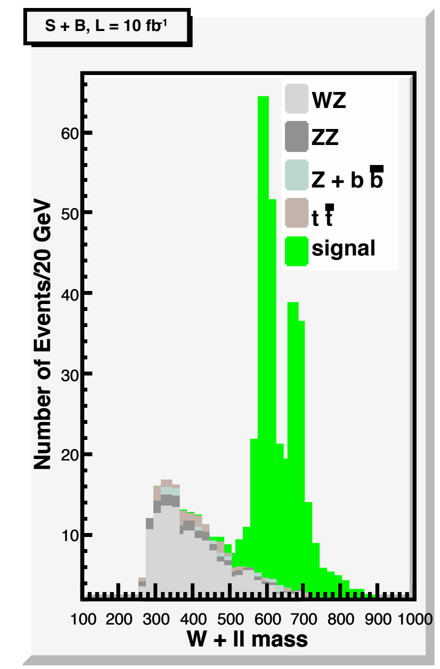
$W^{\pm}_{1,2} \to W^{\pm} \gamma$

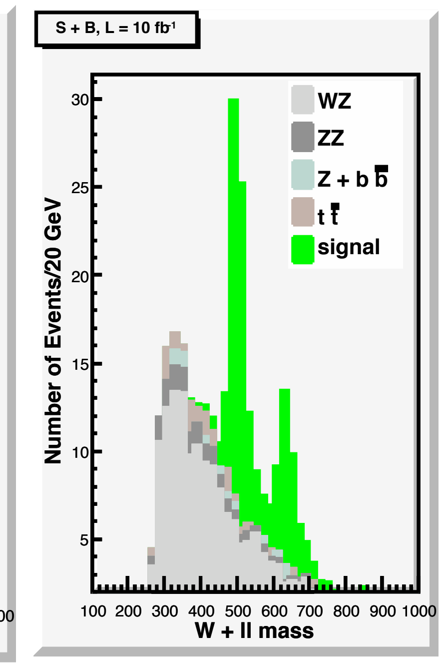
Only one peak

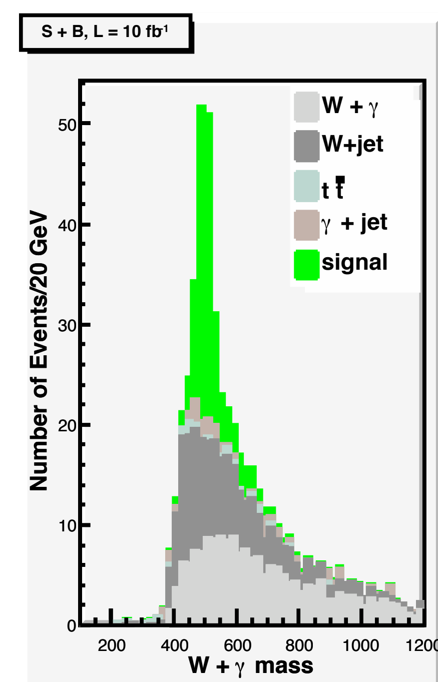
no $g_{W_2 W Z}$

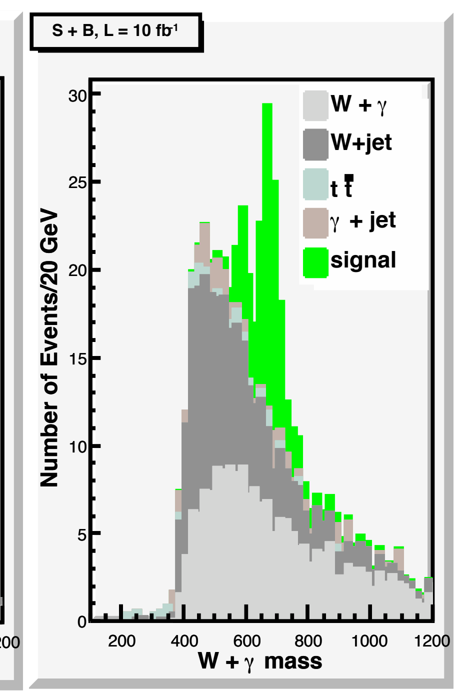
Effective Warp Factors

$W^{\pm}_{1,2} \to W^{\pm} Z^0$









$W^{\pm}_{1,2} \to W^{\pm} \gamma$

Two peaks

$M_{W_2} \cong M_{W_1}$, $g_{W_2 W Z} \neq 0$

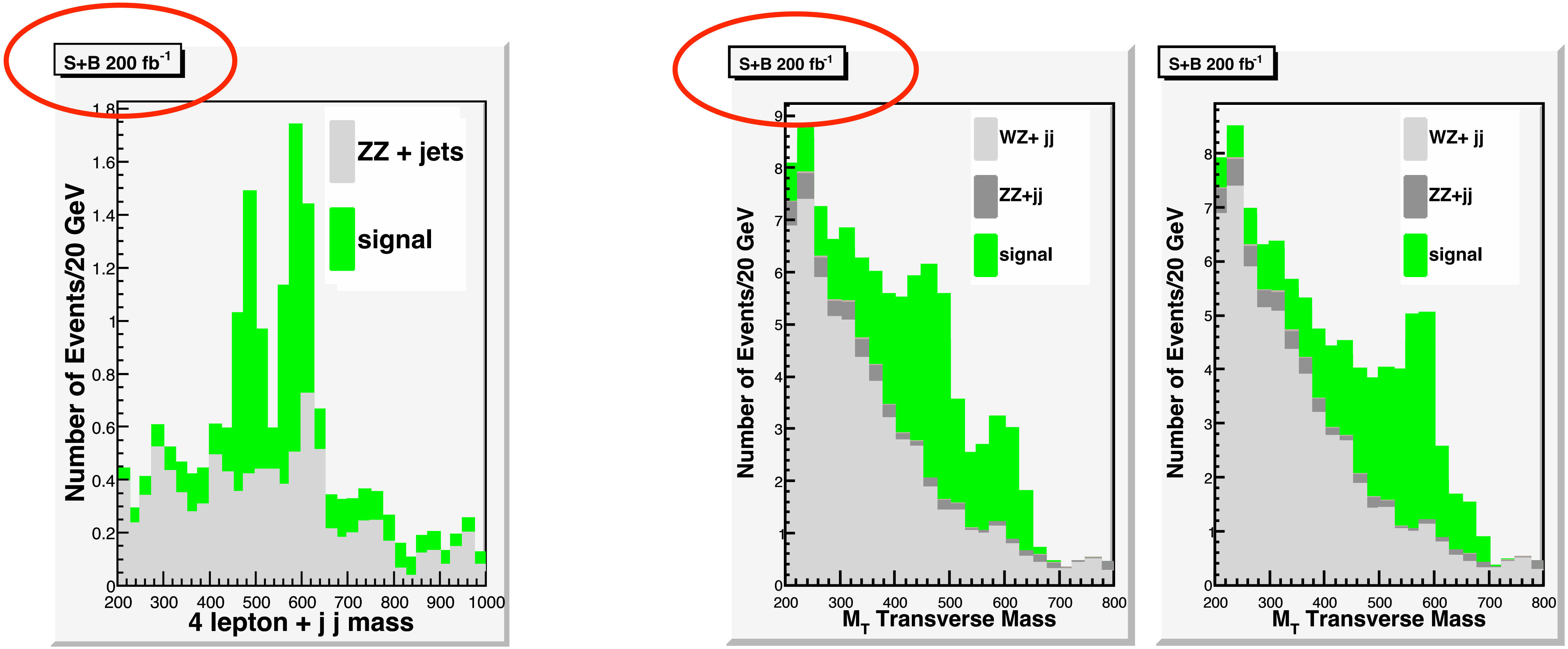
High Luminosity Signals: Fermiophobic

Associated Production:

$$pp \to Z^0 + W^{\pm}_{1,2} \to Z^0 Z^0 W^{\pm}$$

Vector Boson Fusion:

$$pp \to W^{\pm}_{1,2}\, jj \to W^{\pm} Z^0 jj$$



- Late discovery at LHC
- Parton level too optimistic
- Other channels: $W\gamma Z^0, W\gamma\gamma, W\gamma jj$

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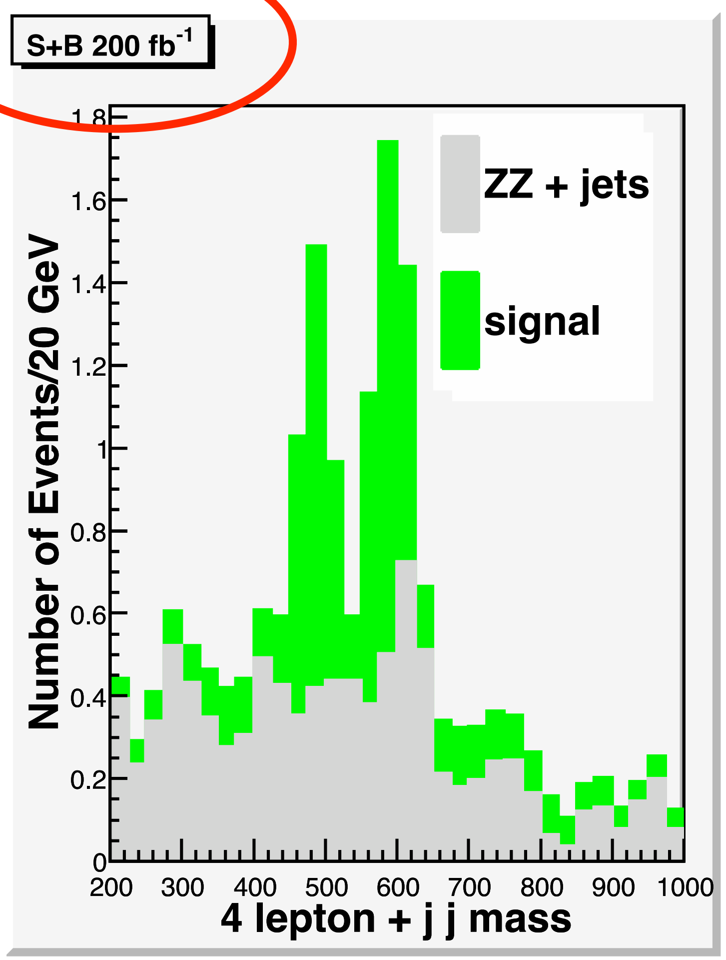

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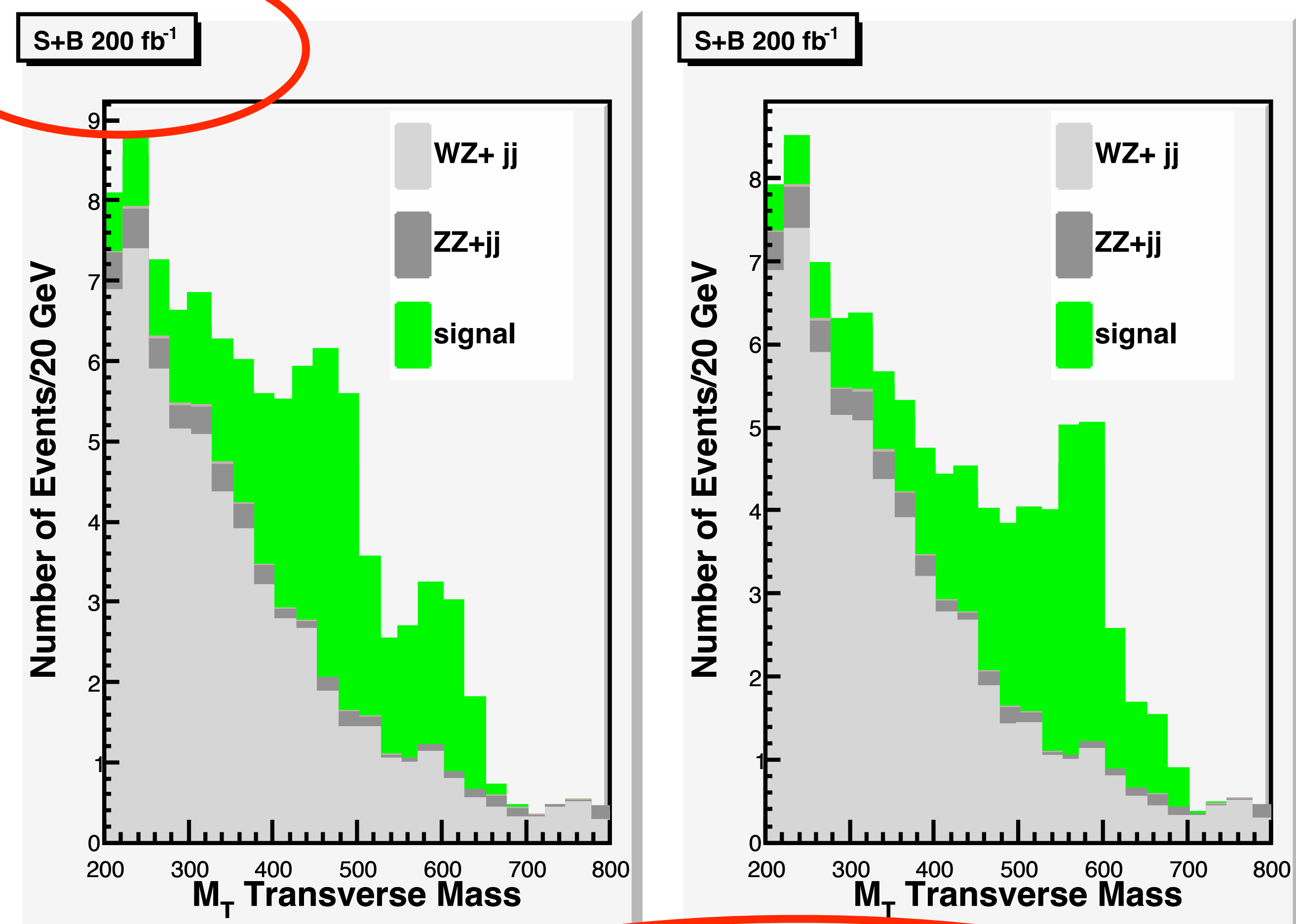

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Distinct features even if no fermion-resonance coupling

Conclusions:

- LHC is in the near future, yet detailed phenomenological studies of strong EW physics are lacking:

WHY?

  - simplest models ruled out
  - little info on non-QCD strong interactions
  - few models available for detailed study

  implementation in parton-level generators just starting (Hirn+AM+Sanz, Christensen at al, Sannino et al)

- 5D Effective warp factor scheme: Generates $\mathcal{L}(\mathrm{SM}\ +\ \mathrm{spin{-}1})$ with only a few free parameters: $\ell_0, \ell_1, o_V, o_A, g_{ffV}$. We can use it to interpolate between many viable models

- New features in phenomenology:

  2 nearby peaks, Resonance$-\gamma - W$ couplings

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LOTS OF WORK TO BE DONE!