Walking Technicolor
at Colliders

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CP^3 - Origins

Particle Physics & Origin of Mass

Odense

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Lagrangian for walking technicolor

- Standard model fermions — Lagrangian in terms of elementary fields

$\Updownarrow$ EW   ($\Updownarrow$ ETC)

- Technicolor sector — Composite states — Effective Lagrangian $\Leftarrow$ Chiral symmetry (breaking)

Lagrangian for walking technicolor

Lagrangian: NMWT/MWT, $SU(2)_L \times SU(2)_R \to SU(2)_V$

$$
\begin{aligned}
\mathcal{L} \;=\;& -\frac{1}{2}\mathrm{Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}\widetilde{B}_{\mu\nu}\widetilde{B}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\left[\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}\right] - \frac{1}{2}\mathrm{Tr}\left[F_{\mathrm{L}\mu\nu}F_{\mathrm{L}}^{\mu\nu} + F_{\mathrm{R}\mu\nu}F_{\mathrm{R}}^{\mu\nu}\right] \\
&+ m^2\,\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right] + \frac{1}{2}\mathrm{Tr}\left[D_\mu M D^\mu M^\dagger\right] - \tilde{g}^2\, r_2\,\mathrm{Tr}\left[C_{\mathrm{L}\mu} M C_{\mathrm{R}}^{\mu} M^\dagger\right] \\
&- \frac{i\,\tilde{g}\,r_3}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}\left(M D^\mu M^\dagger - D^\mu M M^\dagger\right) + C_{\mathrm{R}\mu}\left(M^\dagger D^\mu M - D^\mu M^\dagger M\right)\right] \\
&+ \frac{\tilde{g}^2 s}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right]\mathrm{Tr}\left[M M^\dagger\right] + \frac{\mu^2}{2}\mathrm{Tr}\left[M M^\dagger\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M M^\dagger\right]^2 \\
&+ i\,\overline{q}^{i}_{\dot\alpha}\overline{\sigma}^{\mu,\dot\alpha\beta}D_\mu q^i_\beta + i\,\overline{l}^{i}_{\dot\alpha}\overline{\sigma}^{\mu,\dot\alpha\beta}D_\mu l^i_\beta + i\,\overline{L}_{\dot\alpha}\overline{\sigma}^{\mu,\dot\alpha\beta}D_\mu L_\beta \\
&- \left[\bar{q}^i_L\,(Y_u)^j_i\,M\,\frac{1+\tau^3}{2}\,q_{jR} + \bar{q}^i_L\,(Y_d)^j_i\,M\,\frac{1-\tau^3}{2}\,q_{jR} + \mathrm{h.c.}\right]
\end{aligned}
$$

Constraining parameter space

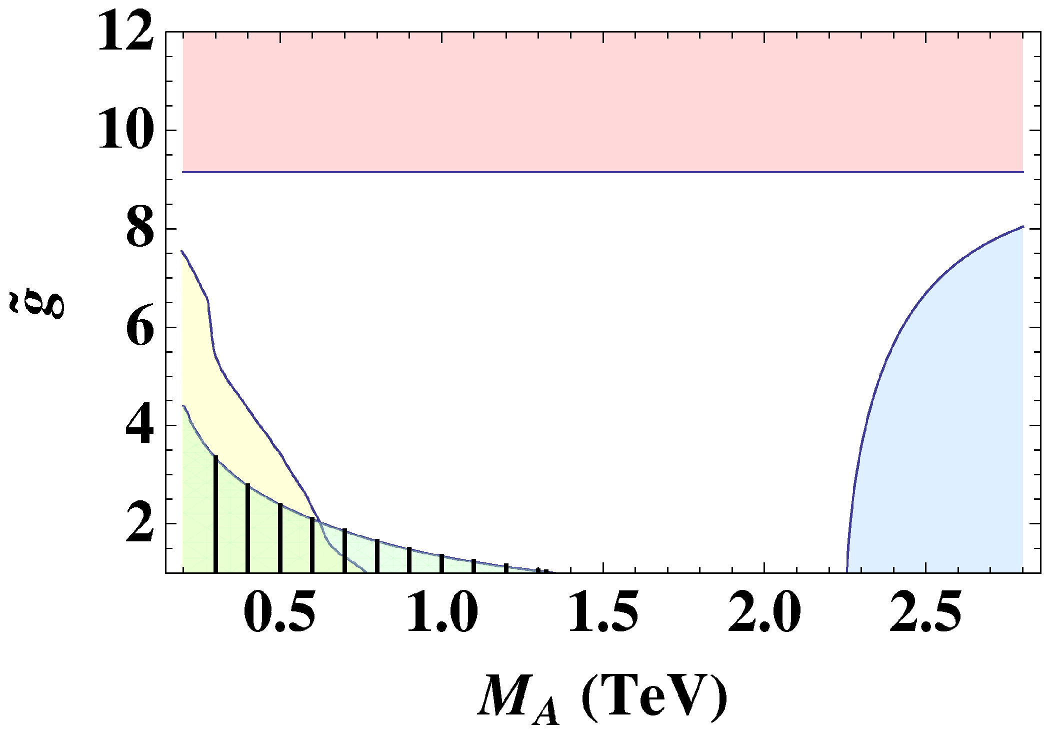
Use Weinberg sum rules and the S parameter to link to underlying theory $\Rightarrow$ remaining parameters M_A, $\tilde{g}$ (and the Higgs mass)

Constraints for M_A and $\tilde{g}$ from

- Tevatron searches
- EW precision (W and Y)
- Consistency:

  WSR with real couplings,

  2nd WSR $a > 0$



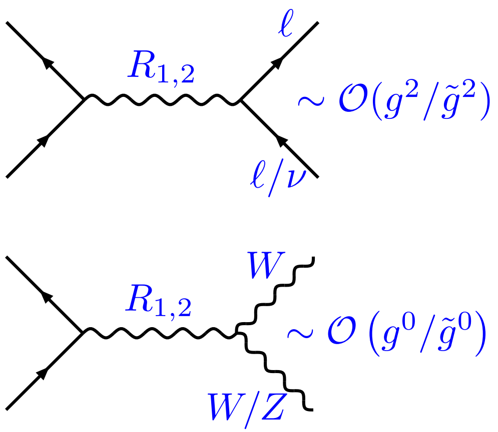
Model implementation

- Complete, tested implementation (used in this study)
  - LanHEP — Automatic generation of Feynman rules $\longrightarrow$
  - CalcHEP — Parton level cross sections and event generation
- Implementation with FeynRules mathematica package
  - Under testing
  - Interfaces to CalcHEP/CompHEP, FeynArts, MadGraph, Sherpa, . . .

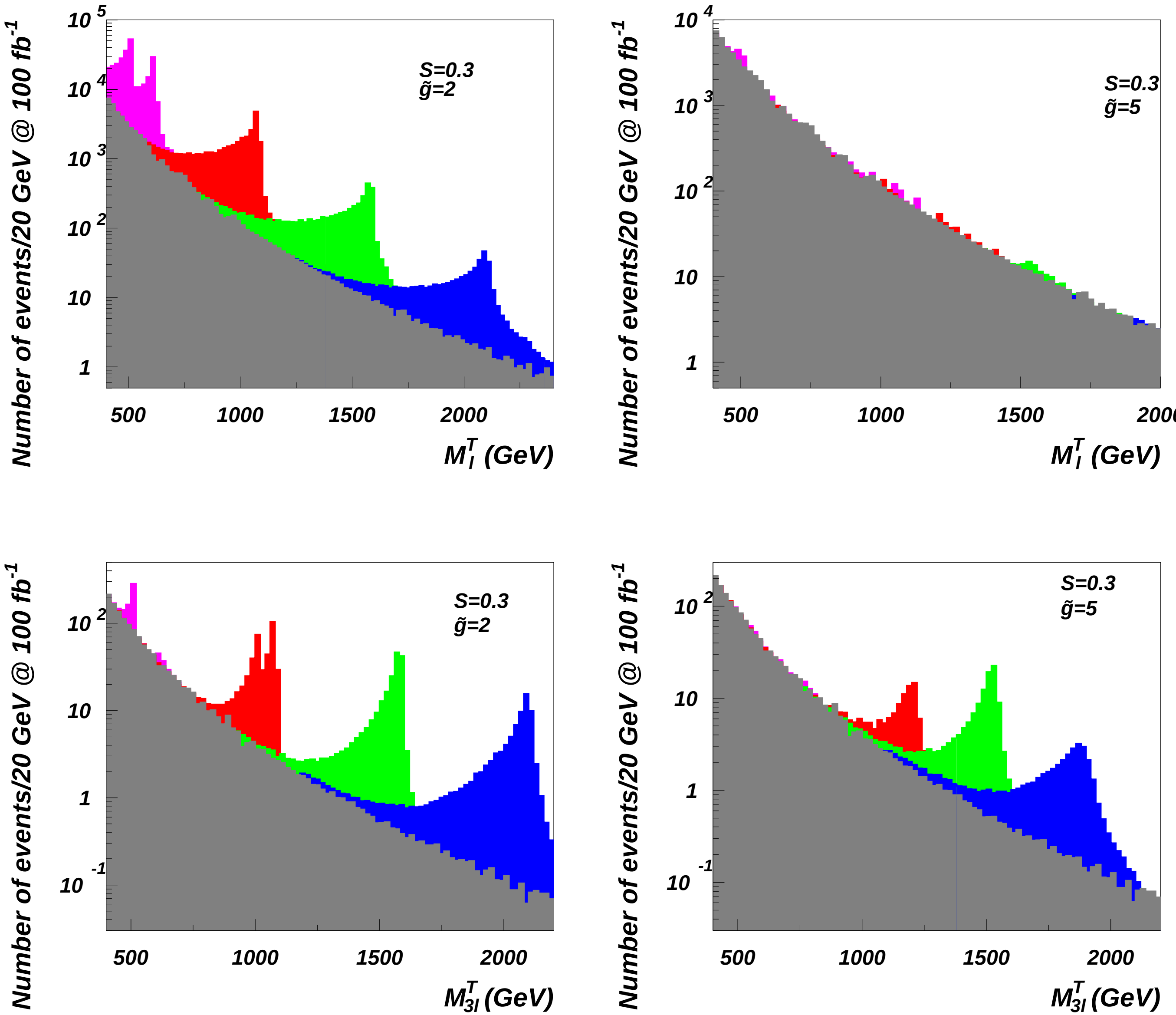
Technicolor at the LHC

100 fb^{-1}; 14 TeV

$pp \to R_{1,2}$; Dilepton vs. diboson decay



M_A= 0.5, 1, 1.5, 2 TeV

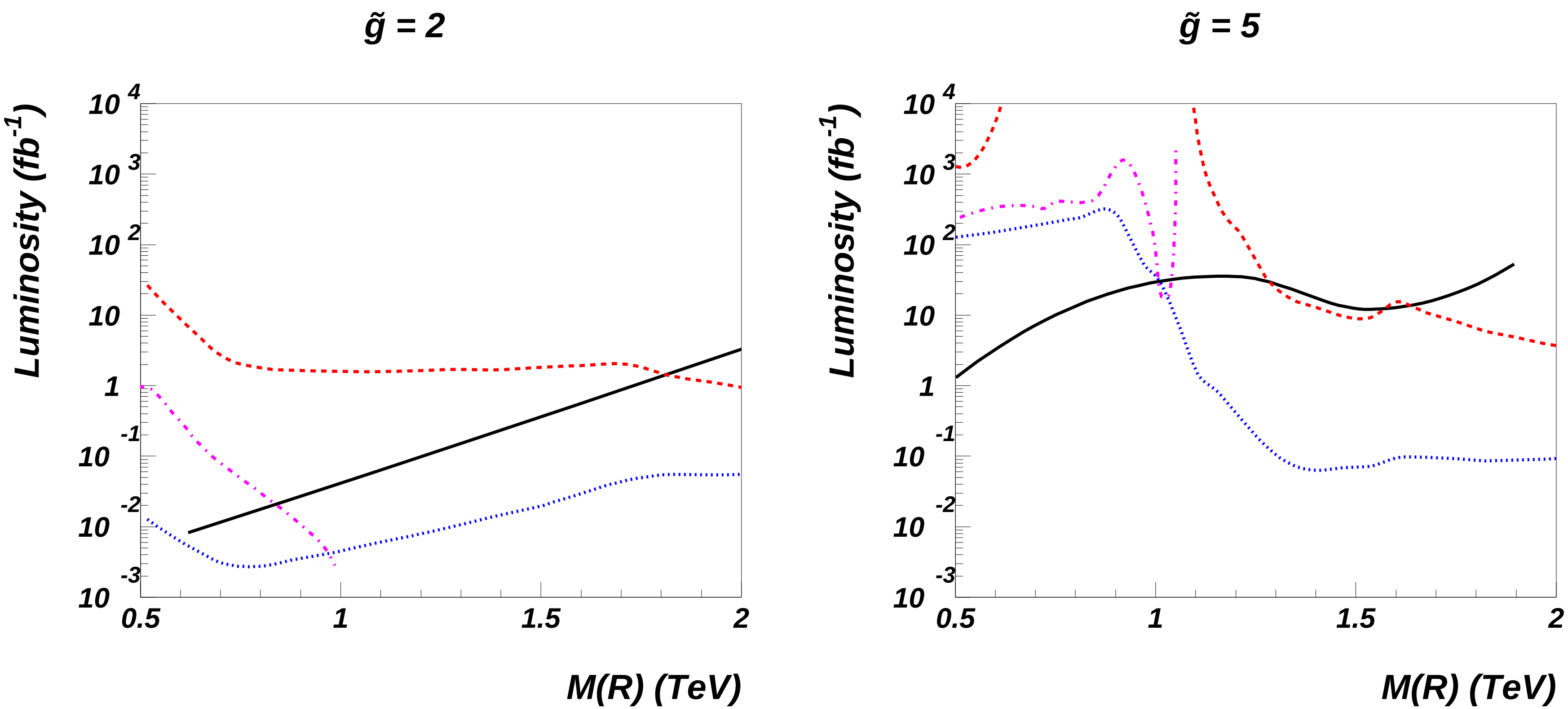


[arXiv:0809.0793 A. Belyaev, R. Foadi, M. T. Frandsen, MJ, A. Pukhov, F. Sannino]

Technicolor at LHC and at linear colliders

Reach estimates for $pp \rightarrow R_{1,2}$ and $e^+e^- \rightarrow R_{1,2}$

- LHC (black)
- 1 TeV LC
- 3 TeV LC
- LC scanning

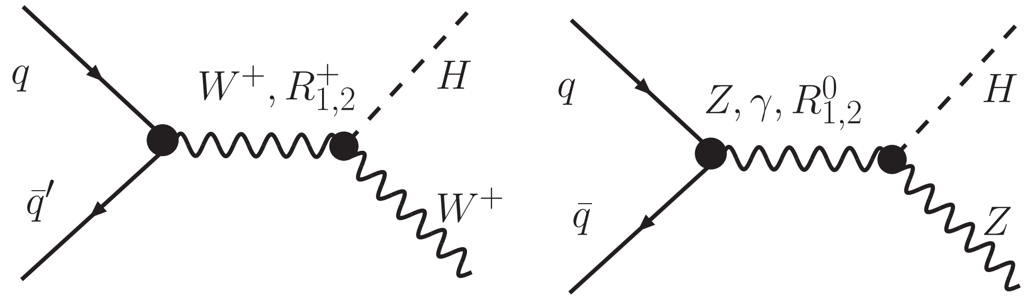


Conclusion

- Effective field theory was used to study walking technicolor at colliders
- LHC has the potential to discover TC spin-one meson(s) in the whole parameter space
- Linear collider study and an update for LHC in progress

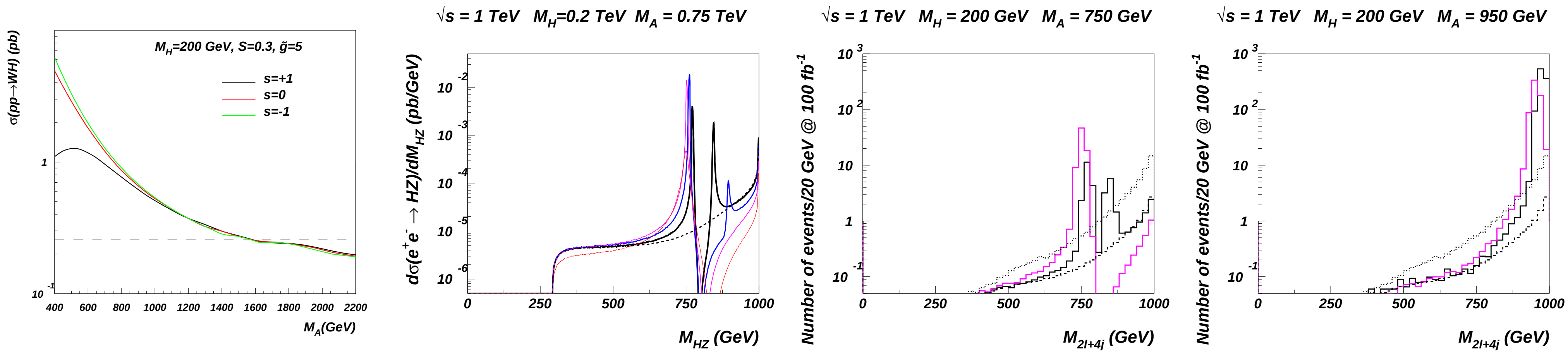
Associated Higgs production

Higgs production in association with Z/W modified by composite spin-one states



[Zerwekh 05]

Strong enhancement of $\sigma(pp \to WH)$ and $\sigma(e^+e^- \to ZH)$



Constraining parameter space

Weinberg sum rules (WSRs) and the S parameter — assuming saturation by first pair of resonances

- First WSR

$$F_V^2 - F_A^2 = F_\Pi^2$$

$\Rightarrow$ eliminates one parameter

- Second WSR for walking dynamics

$$F_V^2 M_V^2 - F_A^2 M_A^2 = a \frac{8\pi^2}{d(R)} F_\pi^4 \quad \text{with} \quad a = \mathcal{O}(1)$$

- The S parameter ("0th WSR")

$$S = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right)$$

fixed to its small naive value 0.3

Constraining parameter space

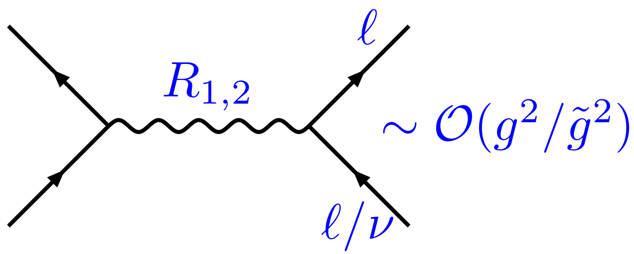
After WSR $\longrightarrow$ most important parameters M_A, $\tilde{g}$ (and the Higgs mass)

- M_A: (Axial) spin-one mass scale
  - Low mass window $M_A \lesssim 1$ TeV: $M_A < M_V$ by WSR
  - High mass window $M_A \approx 2$ TeV: $M_A > M_V$
- $\tilde{g}$: TC interaction strength
  - Mixing of the heavy composite vectors ($R_{1,2}$) with Z, W bosons $\mathcal{O}\left(g/\tilde{g}\right)$

Phenomenology

- Look for heavy spin-one states $R_{1,2}$
- Phenomenology controlled by $g/\tilde{g}$ (with $g \simeq 0.65$)
- Basic rough idea
  - Low $\tilde{g} \simeq 2-3$: dilepton final states

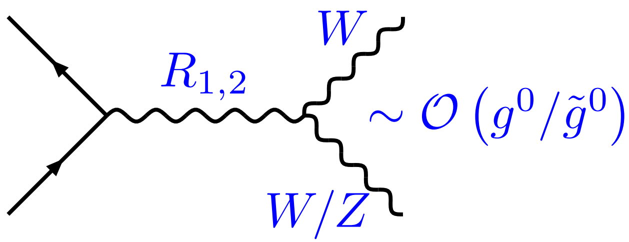
    DY $pp \to R_{1,2} + X \to 2\ell + X$ or $e^+e^- \to R_{1,2} \to \mu^+\mu^-$

  - High $\tilde{g} \gtrsim 5$: decay to ZZ, ZW, WW

    e.g. $pp \to R_{1,2} + X \to ZW + X$

    or $e^+e^- \to R_{1,2} \to W^+W^-$

Technicolor at the LHC

Dilepton mass distributions at

$100\ \text{fb}^{-1};\ \sqrt{s} = 14$ TeV

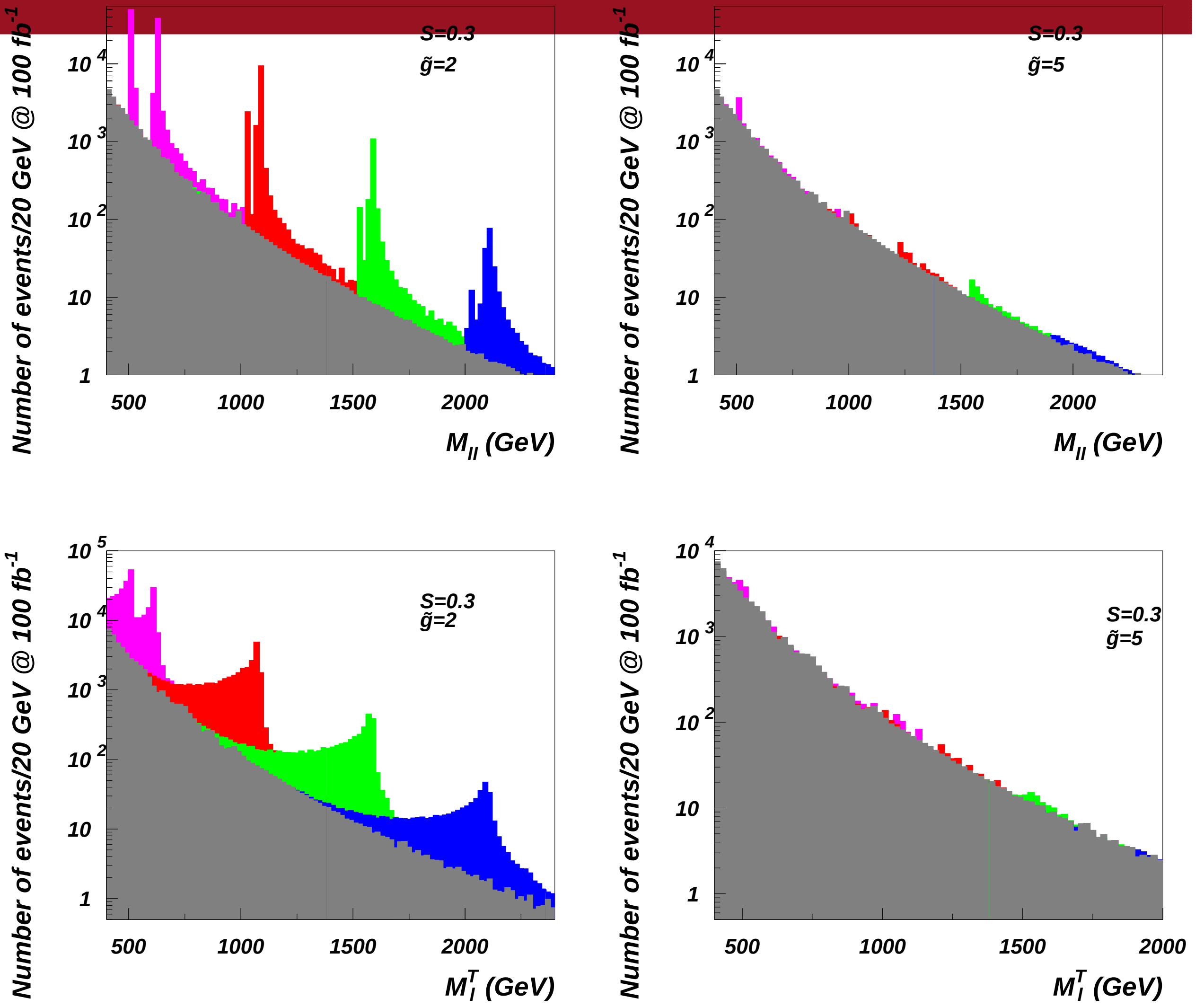
Top: Drell-Yan: Neutral

$R^0_{1,2} \to \ell^+\ell^-$

Bottom: Charged

$R^{\pm}_{1,2} \to \ell^{\pm}\nu$

$M_A = 0.5, 1, 1.5, 2$ TeV



[arXiv:0809.0793 A. Belyaev, R. Foadi, M. T. Frandsen, MJ, A. Pukhov, F. Sannino]

Technicolor at the LHC

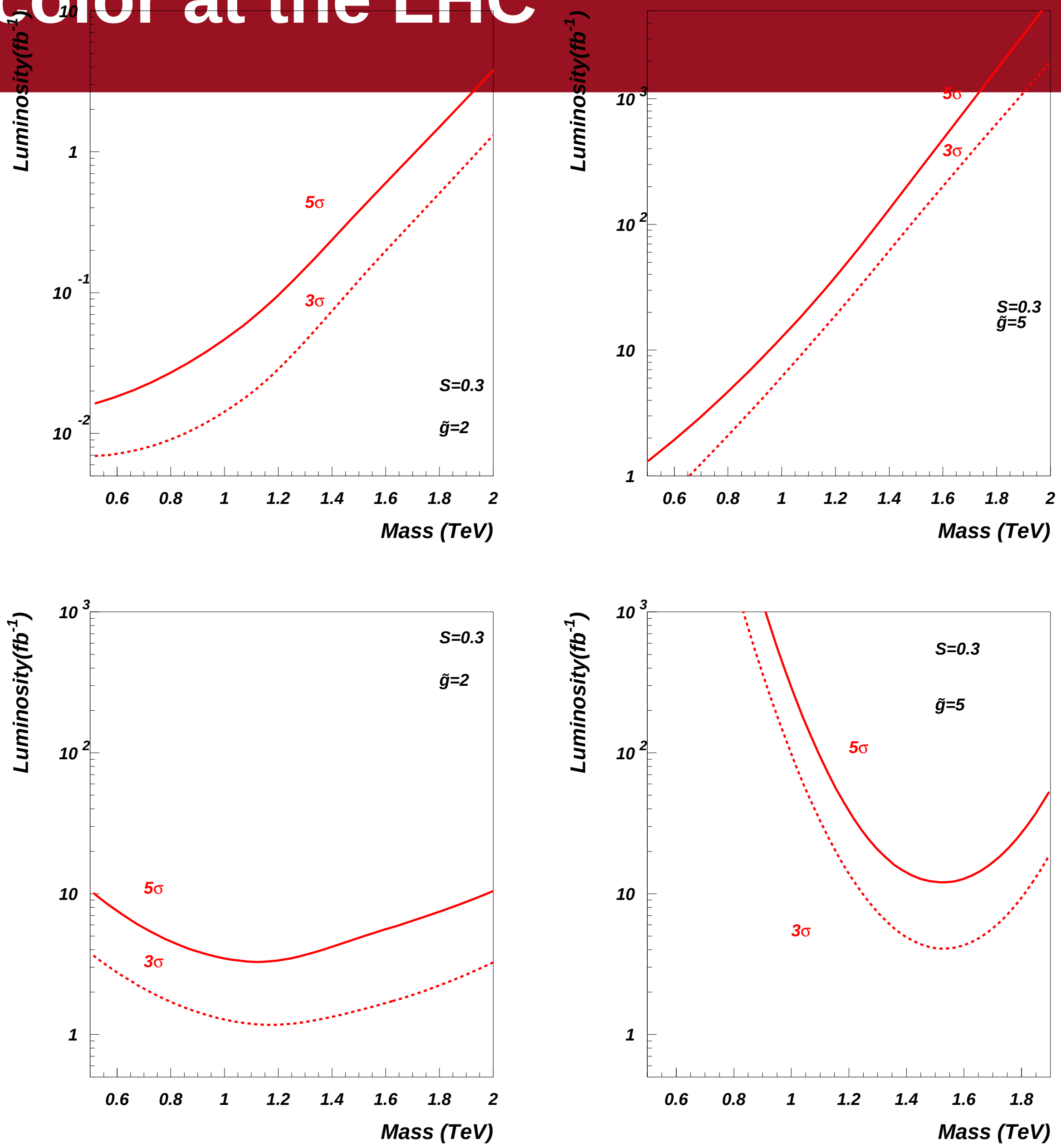
Reach estimates for

$\sqrt{s} = 14$ TeV

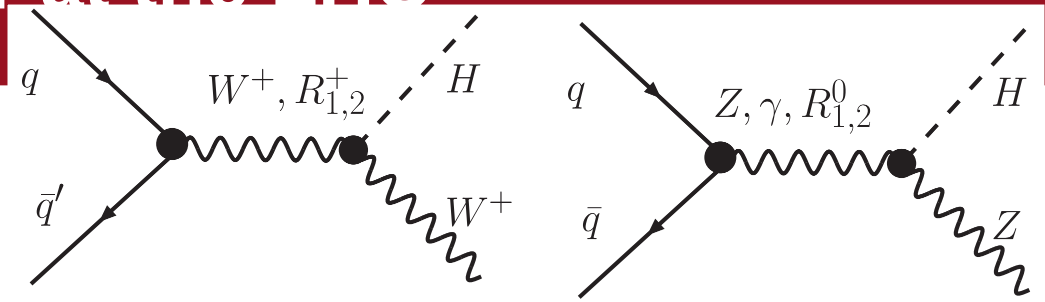
Top: Drell-Yan $R_{1,2} \to \ell\ell$

Bottom: $R_{1,2} \to WZ \to 3\ell + \nu$

With 10-100 fb^{-1} parameter space covered



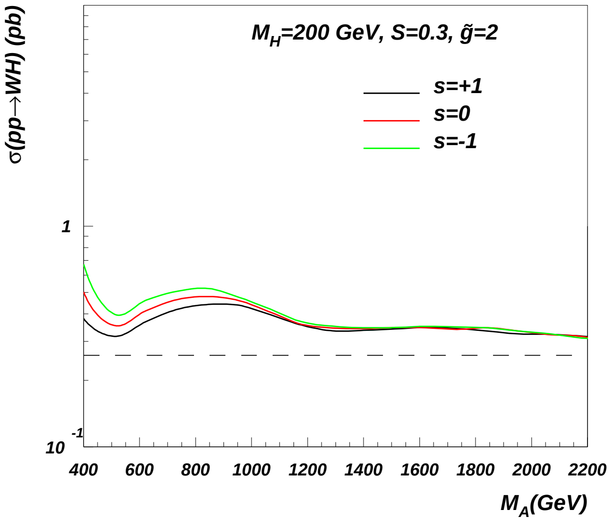
Technicolor at the LHC

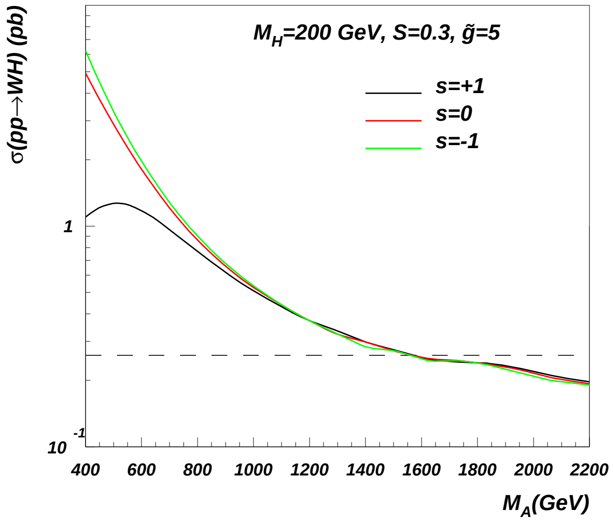


Higgs production in association with Z/W modified by composite spin-one states

[Zerwekh 05]

Higgs production cross section in $pp \to WH$ compared to SM (dashed line): mostly enhanced





Technicolor at linear colliders

Differential cross sections

$d\sigma/dM_{\mathrm{tot}}$

$\sqrt{s} = 1$ TeV (right) and

$\sqrt{s} = 3$ TeV (left)

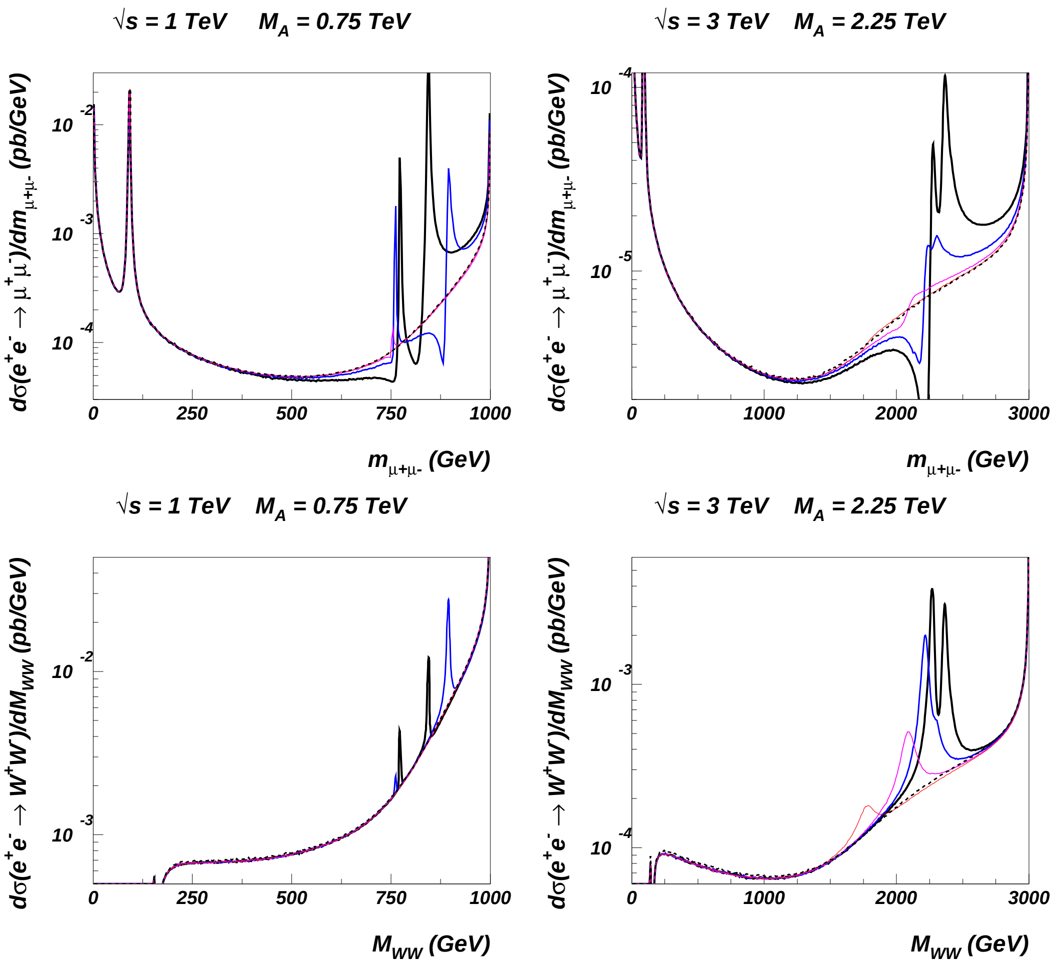
Top: dimuons

$e^+e^- \to R_{1,2} \to \mu^+\mu^-$

Bottom:

$e^+e^- \to R_{1,2} \to W^+W^-$

$\tilde{g} =$ 2, 3, 5, 8



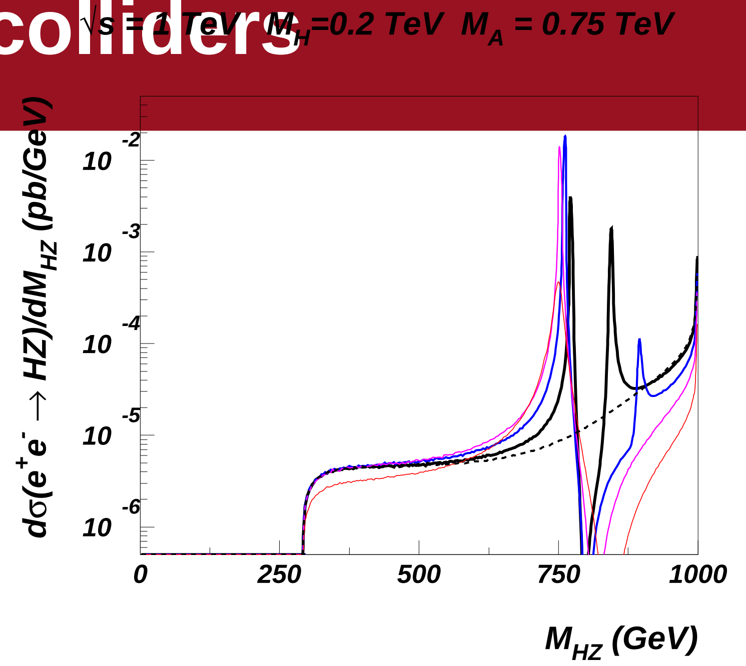
Technicolor at linear colliders

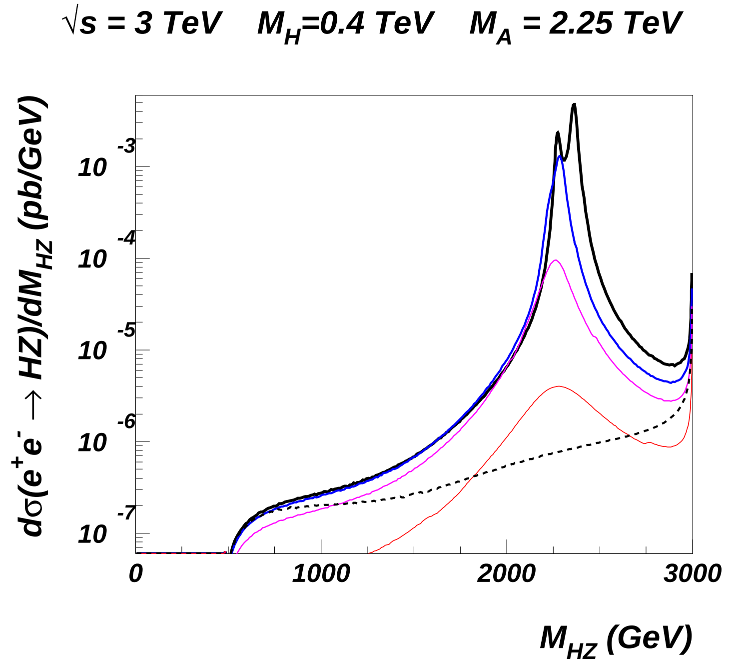
Differential cross section for

Associated Higgs production

$$e^+e^- \to R^0_{1,2} \to HZ$$

Large enhancement with respect to SM





Technicolor at linear colliders

Full event analysis for

$HZ \to 4j + 2\ell$

final state

Top: $\sqrt{s} = 1$ TeV

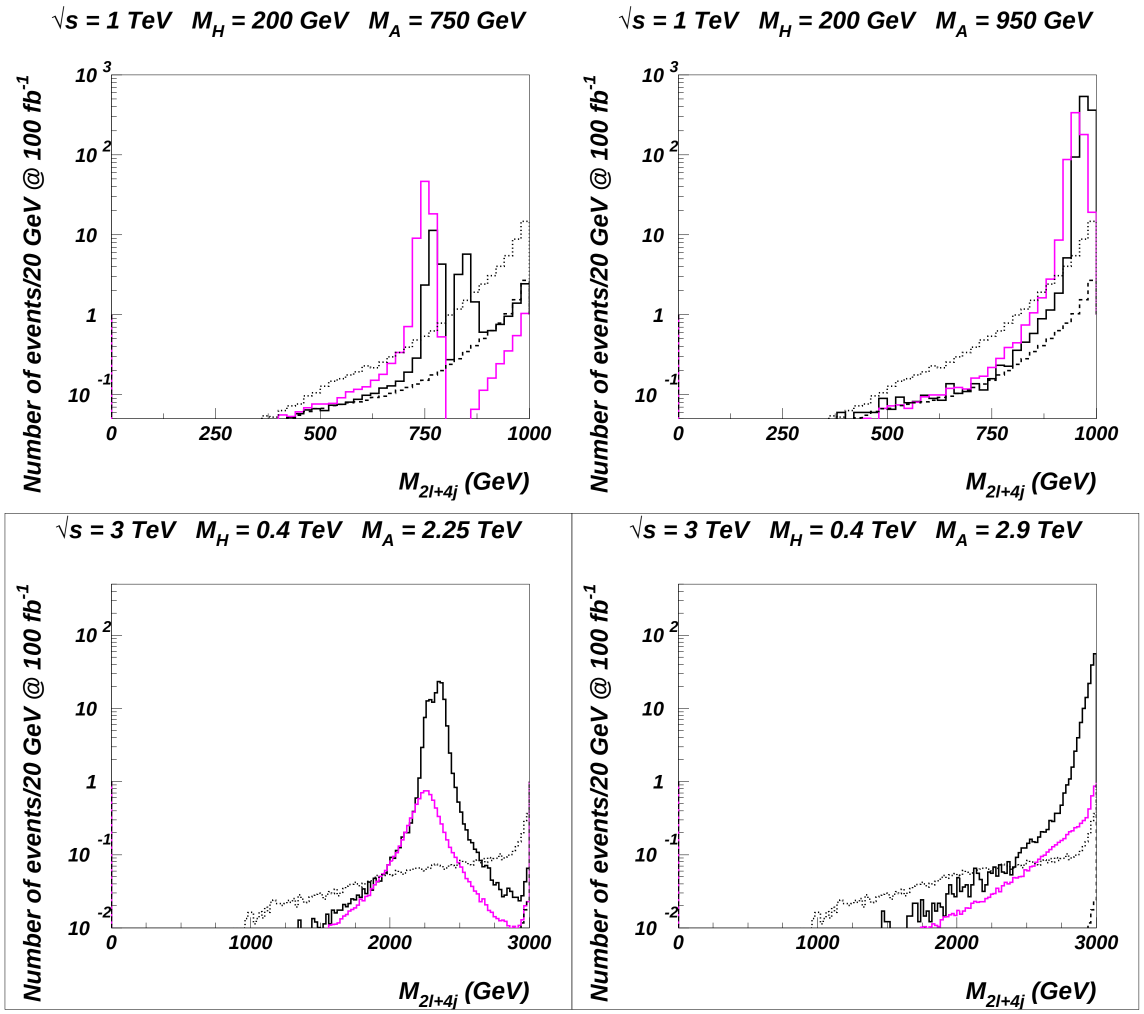
Bottom: $\sqrt{s} = 3$ TeV

$\tilde{g} =$ 2, 5

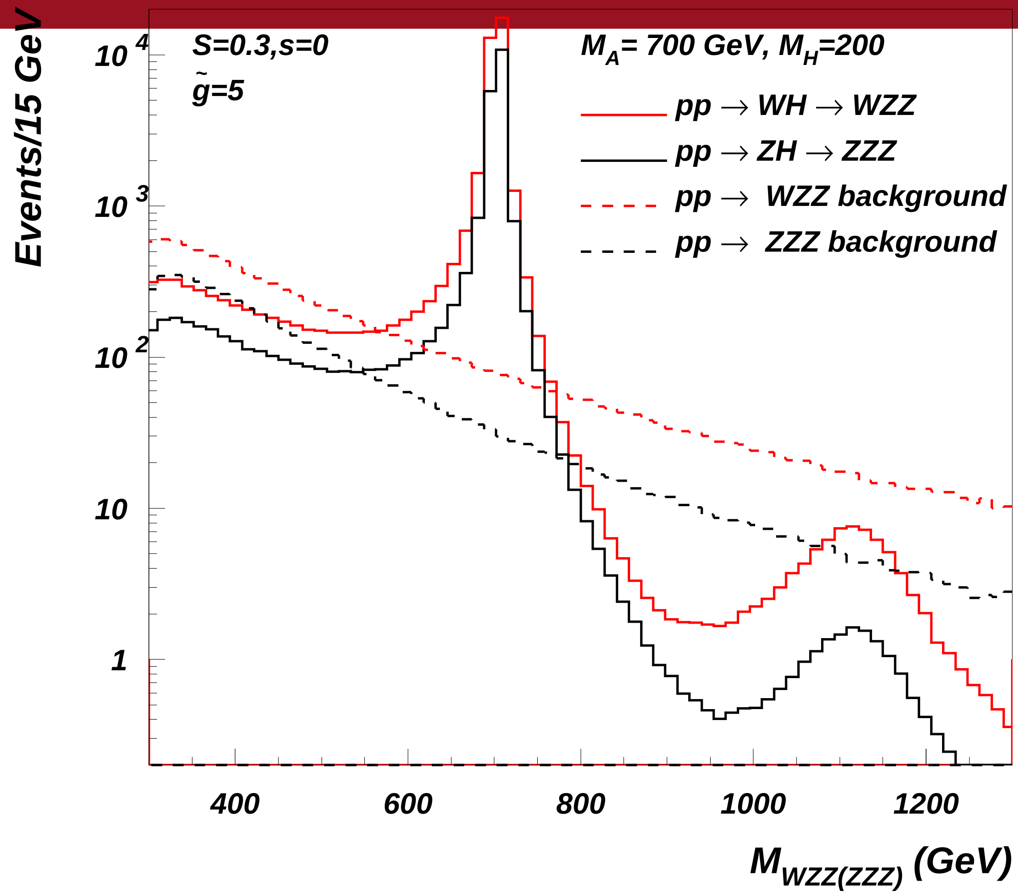
Dotted line: SM background

$e^+e^- \to ZWW \to 4j+2\ell$

before cuts



Technicolor at linear colliders



Axial (and vector) peaks in ZZZ and ZZW distributions at 100 fb^{-1}

Axial signal (at around 0.7 TeV) will remain visible after adding branching to lepton final states (The simplest Higgs-vector coupling assumed here)

Technicolor at linear colliders

Walking technicolor (WT) models can allow for a light composite Higgs (a few hundred GeV)

- Scalar $f_0(660)$ in QCD lighter than vector states
- Large N_c scaling argument
- Higgs mass further reduced by walking dynamics?

[Hong, Hsu, Sannino 04]
[Dietrich, Sannino, Tuominen 05]
[Sannino 08]

- Solving truncated Schwinger-Dyson and Bethe-Salpeter equations

[Doff, Natale 08,09]

- Light Higgs can help to unitarize WW scattering

[Foadi, MJ, Sannino 08]