Walking Technicolor at Colliders

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Outline

- ❑ Vanilla technicolor Lagrangian
- ❑ Constraining parameter space
- ❑ Implementation on Monte Carlo tools
- ❑ LHC phenomenology

[Belyaev, Foadi, Frandsen, MJ, Pukhov, Sannino, arXiv:0809.0793]

[“Discovering technicolor” report, arXiv:1104.1255]

- ❑ Linear collider phenomenology

[Frandsen, MJ, Sannino, arXiv:1103.3271]

Vanilla technicolor

Effective theory:

[Foadi, Frandsen, Ryttov, Sannino 07]

- Lightest scalar state, composite Higgs H
- Lightest composite vector and axial spin-one states $R_1^{\pm,0}$, $R_2^{\pm,0}$

Vanilla technicolor

Chiral symmetry breaking structure:

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

- Simplest choice — included in more complicated patterns — template for walking technicolor
- Candidate theory: NMWT, $N_f = 2$ in $\square\square$ of $SU(3)_{TC}$
- Extending to, e.g., $SU(4) \to SO(4)$ (MWT) brings in extra composite states
  - Extra pseudo Goldstone bosons

    [Hapola, Mescia, Nardecchia, Sannino 12]
  - MWT also includes a fourth family of leptons

Vanilla technicolor

$\Rightarrow$ Lagrangian (strong technicolor sector only)

$M \leftrightarrow$ Higgs, $C_{\mathrm{L/R}} \leftrightarrow$ Spin-one states

$$
\begin{aligned}
\mathcal{L}_s &= +\frac{1}{2}\mathrm{Tr}\left[\partial_\mu M \partial^\mu M^\dagger\right] - \frac{1}{2}\mathrm{Tr}\left[F_{\mathrm{L}\mu\nu}F_{\mathrm{L}}^{\mu\nu} + F_{\mathrm{R}\mu\nu}F_{\mathrm{R}}^{\mu\nu}\right] \\
&+ +\frac{\mu^2}{2}\mathrm{Tr}\left[MM^\dagger\right] - \frac{\lambda}{4}\mathrm{Tr}\left[MM^\dagger\right]^2 + m^2\,\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right] \\
&+ \frac{\tilde{g}^2 s}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right]\mathrm{Tr}\left[MM^\dagger\right] - \tilde{g}^2\, r_2\,\mathrm{Tr}\left[C_{\mathrm{L}\mu} M C_{\mathrm{R}}^{\mu} M^\dagger\right] \\
&- \frac{i\,\tilde{g}\, r_3}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}\left(M\partial^\mu M^\dagger - \partial^\mu M M^\dagger\right) + C_{\mathrm{R}\mu}\left(M^\dagger\partial^\mu M - \partial^\mu M^\dagger M\right)\right]
\end{aligned}
$$

Vanilla technicolor

After adding SM fermions, including Yukawa and gauging under EW

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

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 $\mathcal{O}\left(g/\tilde{g}\right)$

Model implementation

- Implementation of walking technicolor with the FeynRules mathematica package

  [Christensen, Duhr]

  - Rewrite of the earlier LanHEP model
  - Interfaces to CalcHEP (tested), CompHEP, FeynArts, MadGraph (tested), Sherpa, . . .
  - Model published at the FeynRules wiki pages

    https://feynrules.phys.ucl.ac.be/wiki/TechniColor

    and at the CP^3-Origins webpage

    http://cp3-origins.dk/research/tc-tools

Model implementation

FeynRules model + little tweaks $\Rightarrow$

- ❑ CalcHEP model files for technicolor
- ❑ MadGraph model files for technicolor
- ❍ Tested by comparing to the LanHEP implementation and to SM implementations
- ❍ These files available at

  https://feynrules.phys.ucl.ac.be/wiki/TechniColor

  http://cp3-origins.dk/research/tc-tools

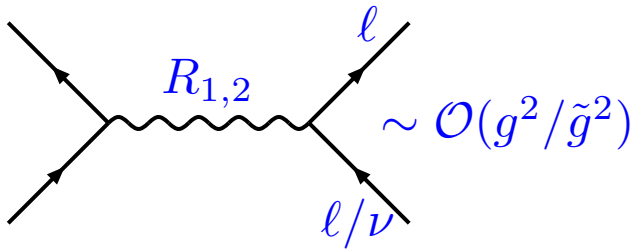
  no need to run FeynRules

Technicolor at the LHC

- Look for heavy spin-one states $R^0_{1,2}$, $R^\pm_{1,2}$
- Phenomenology controlled by $g/\tilde{g}$ (with $g \simeq 0.65$)
- Basic rough idea
  - Low $\tilde{g} \simeq 2-3$: dilepton final states

    DY $pp \to R_{1,2} \to \ell\ell/\ell\nu$

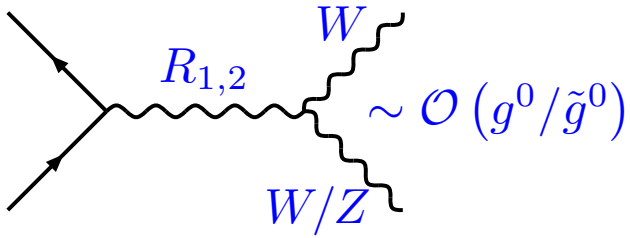
    or $e^+e^- \to R_{1,2} \to \mu^+\mu^-$



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

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

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



Technicolor at the LHC

Dilepton mass distributions at

10 fb^{-1}; $\sqrt{s} = 7$ TeV

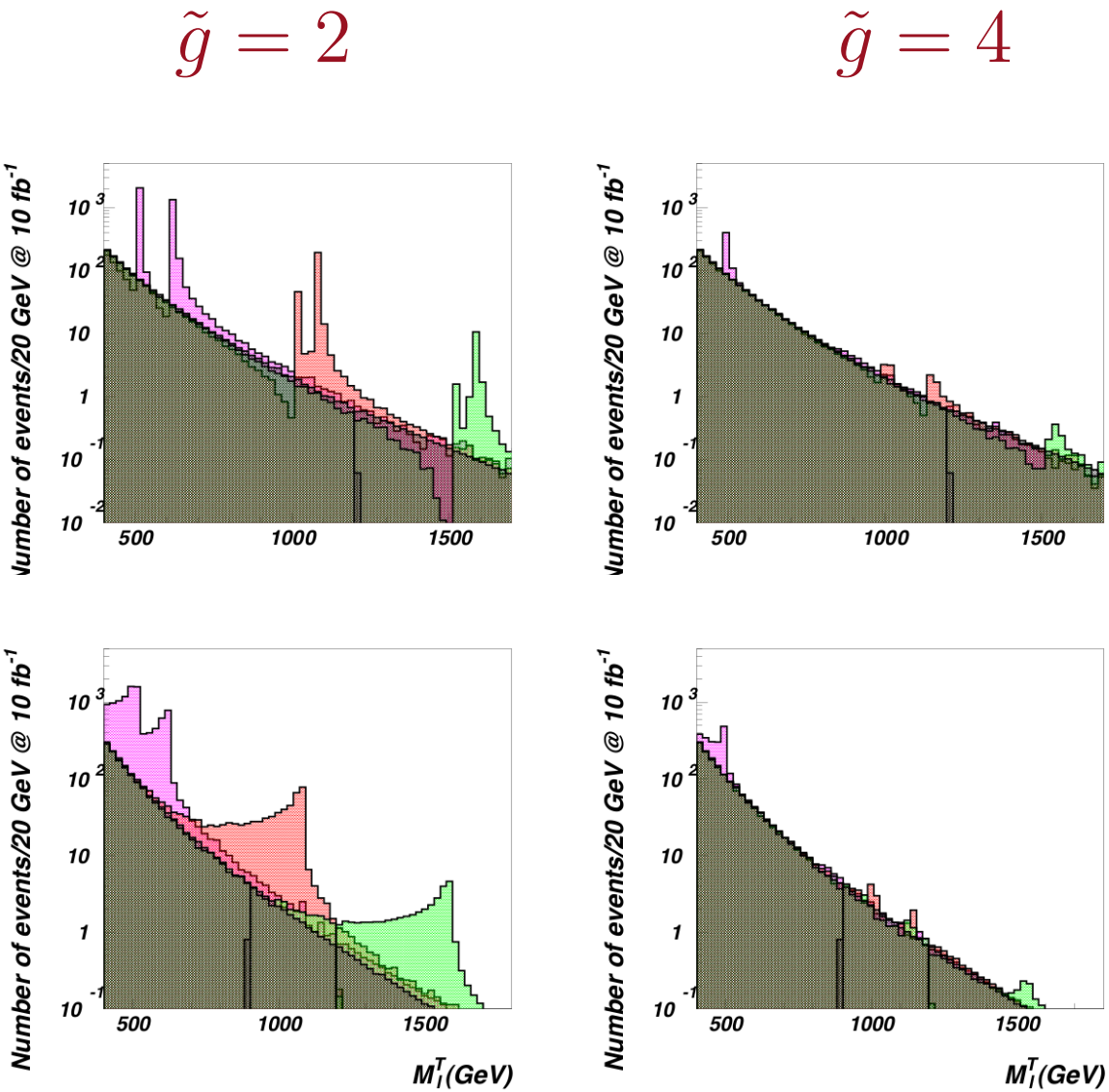
Top: Drell-Yan: Neutral

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

Bottom: Charged

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

$M_A =$ 0.5, 1, 1.5 TeV



Technicolor at the LHC

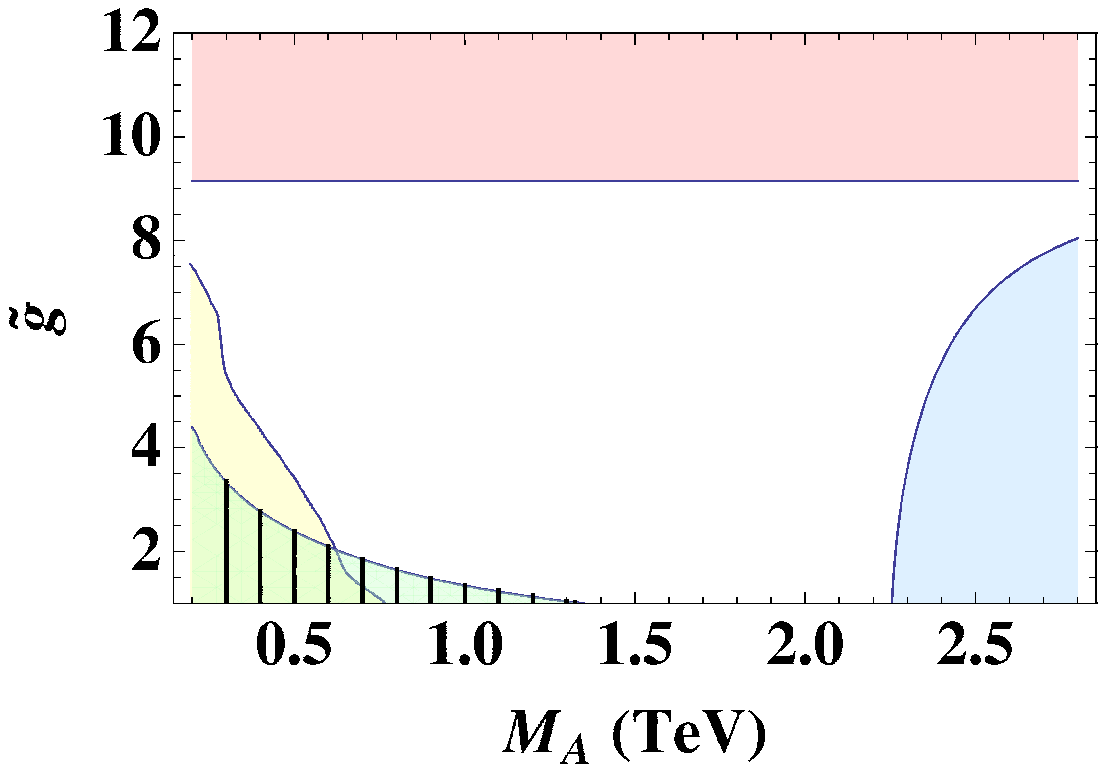
(Pre-LHC) constraints for M_A and $\tilde{g}$ from

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

  WSR with real couplings,

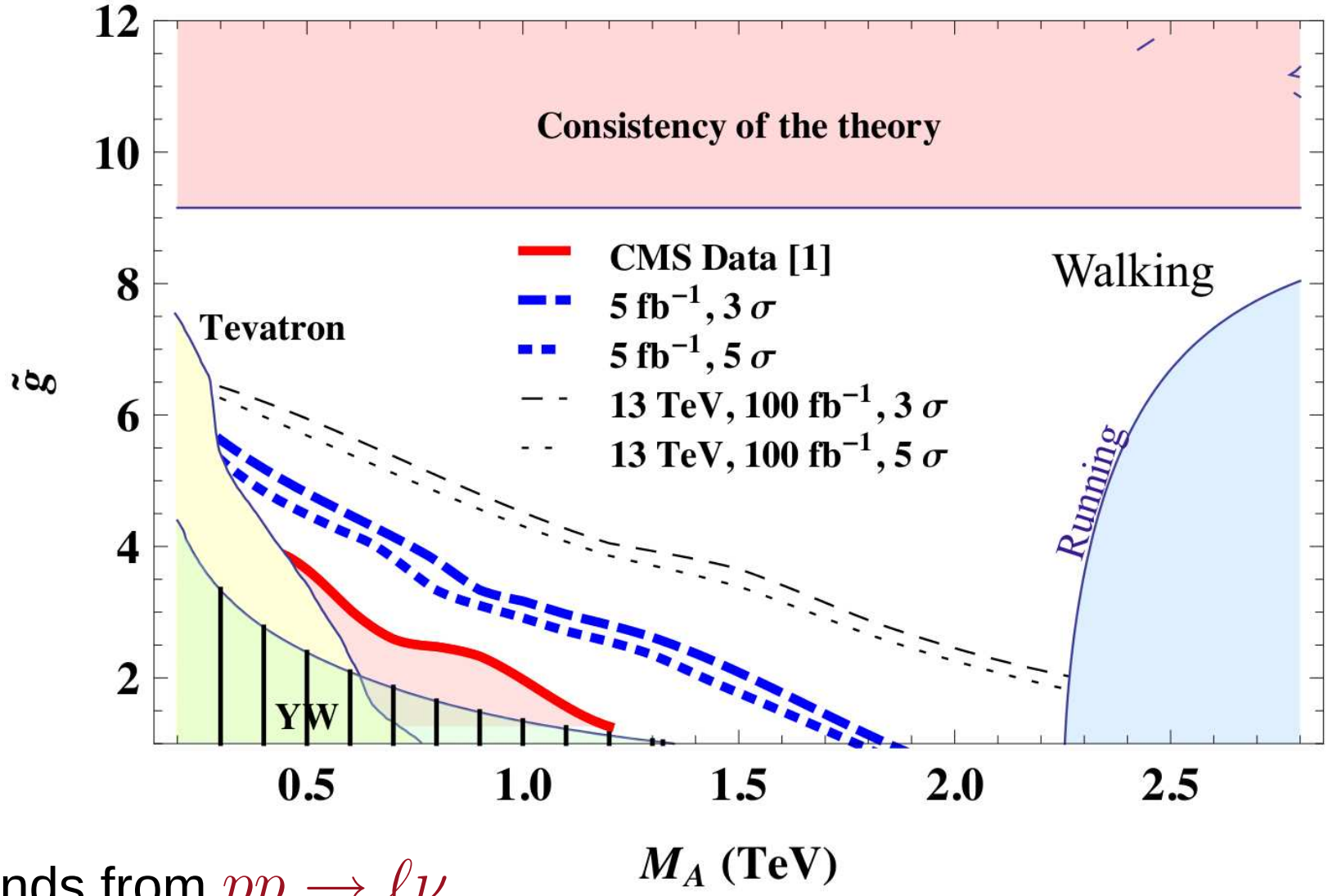
  2nd WSR $a > 0$

- ❑ Unitarity bounds (not included)



[Foadi,MJ,Sannino 08]

Technicolor at the LHC



Bounds from $pp \to \ell\nu$

[Andersen, Hapola, Sannino 11]

Region of low $\tilde{g}$ and M_A covered by LHC

Technicolor at the LHC

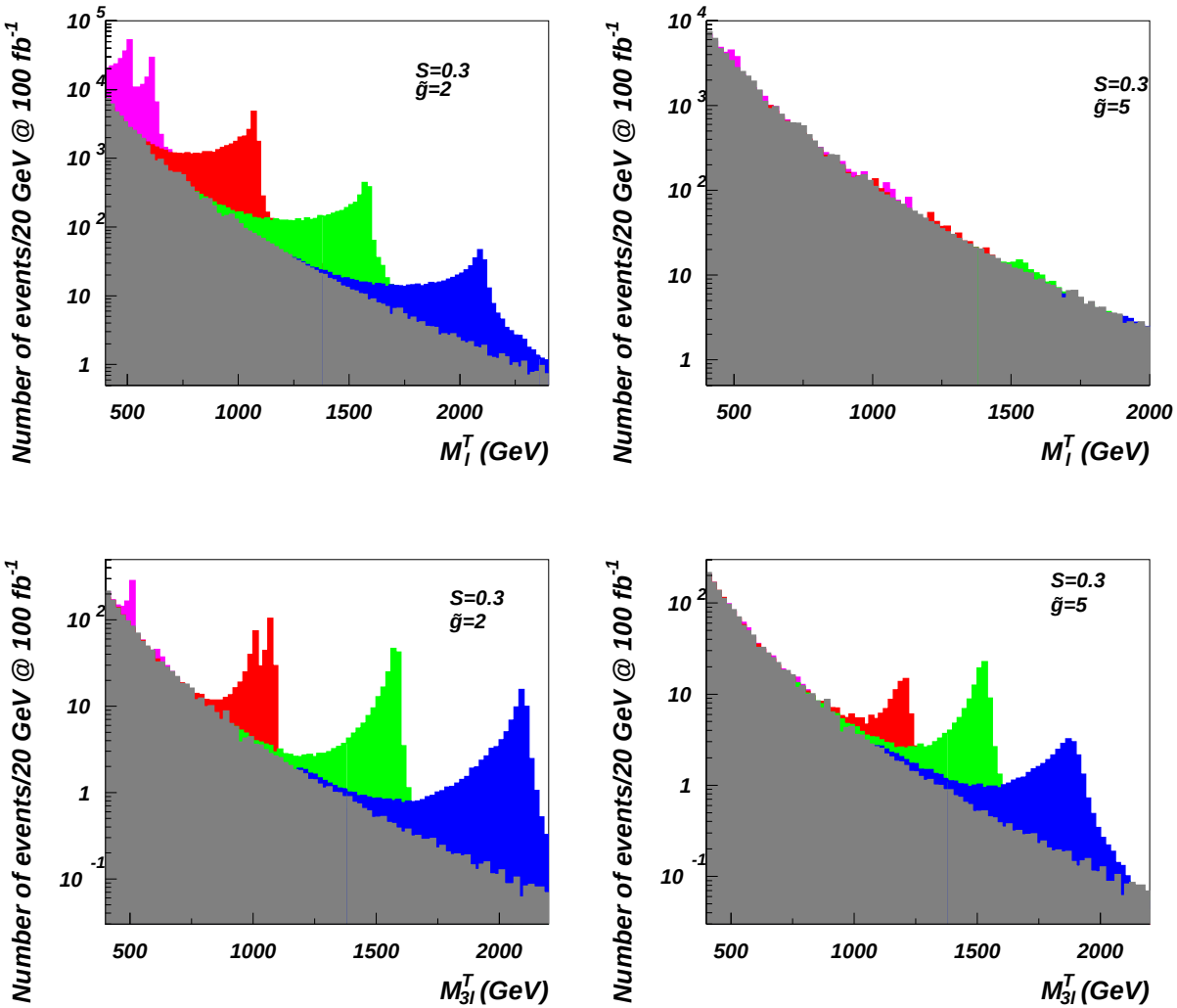
Dileptons vs. dibosons at 14 TeV

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

Bottom:

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

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



Technicolor at the LHC

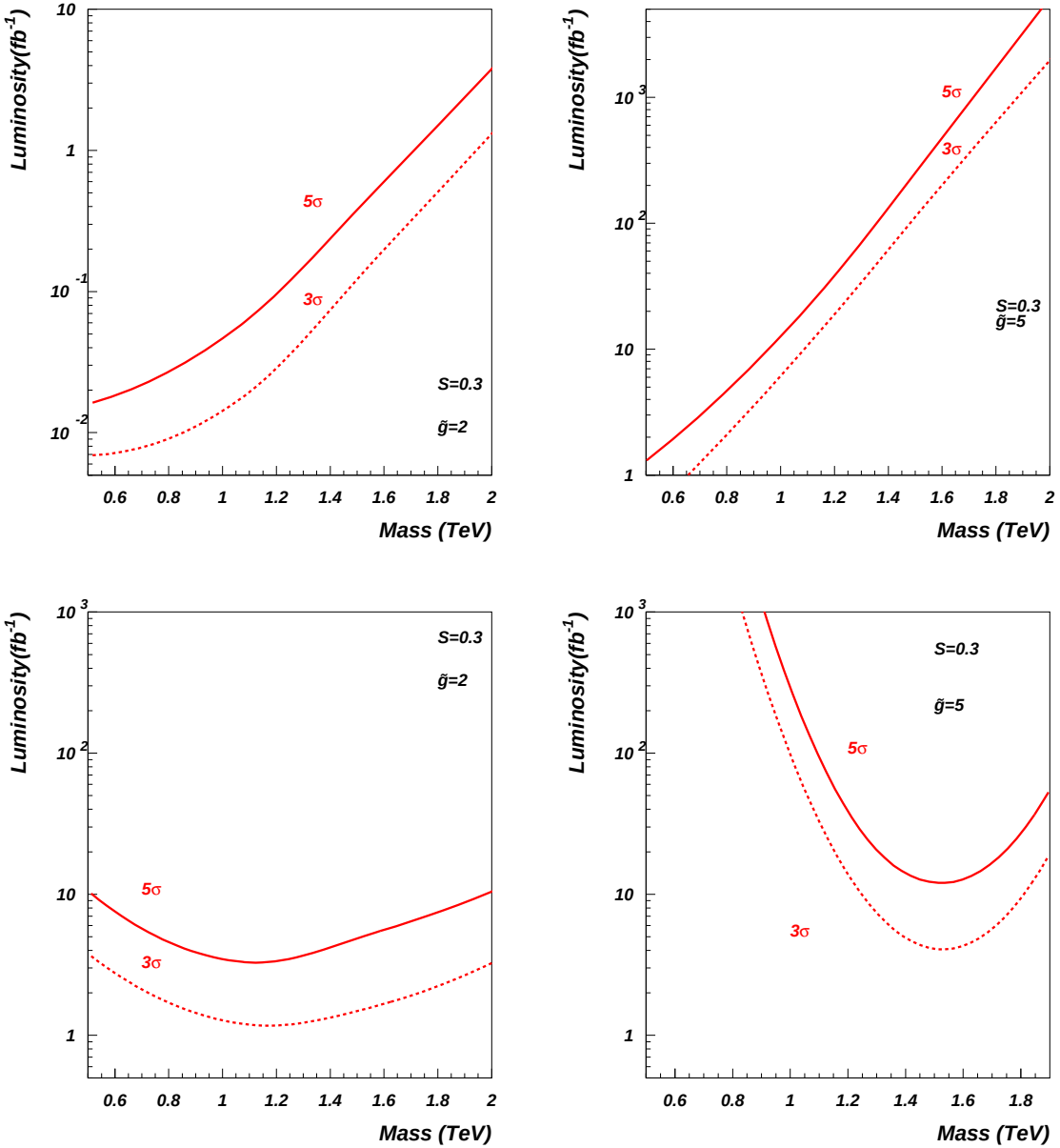
Reach estimates for

$\sqrt{s} = 14$ TeV

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

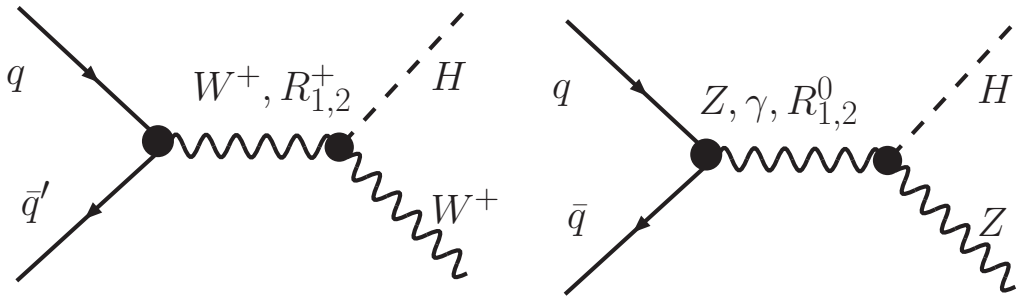
Bottom: $R_{1,2} \to WZ \to 3\ell + \nu$

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



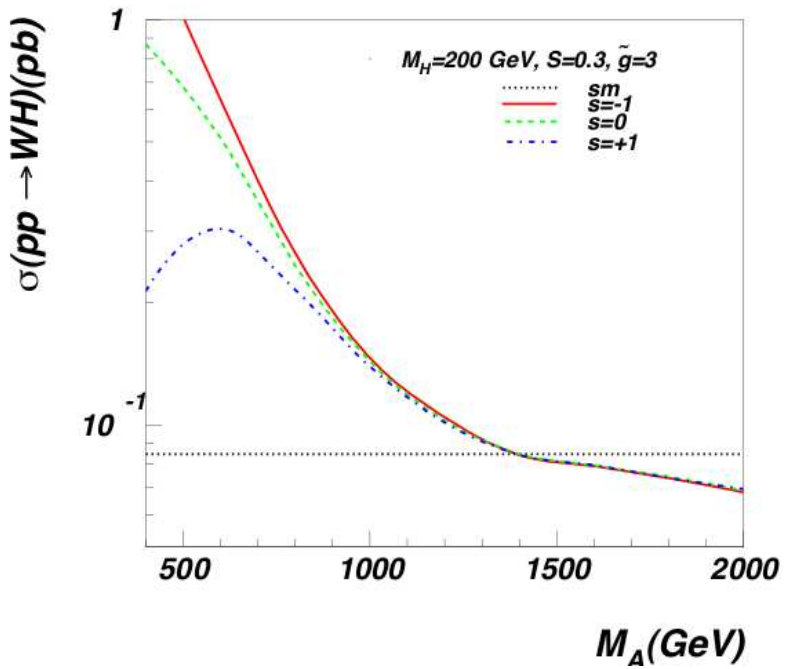
Technicolor at the LHC

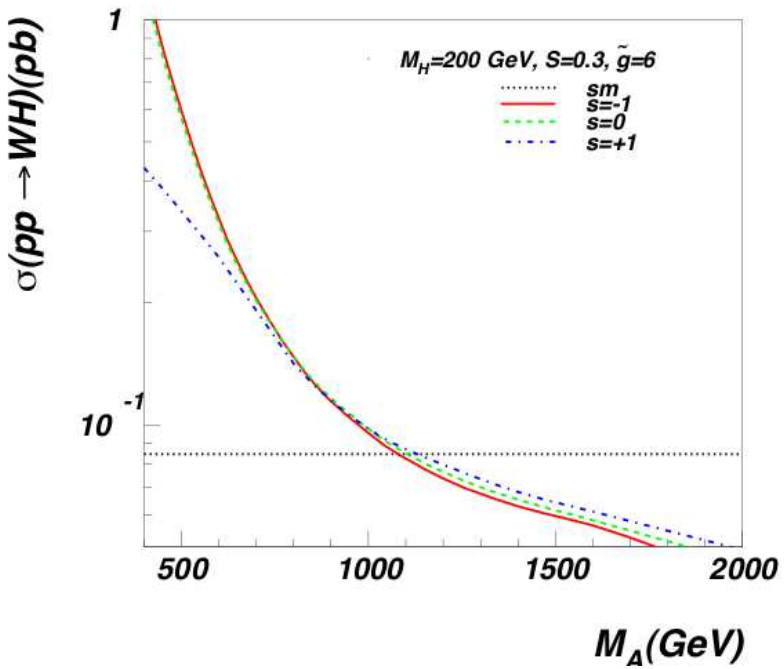
Higgs production in association with Z/W modified by composite spin-one states



[Zerwekh 05]

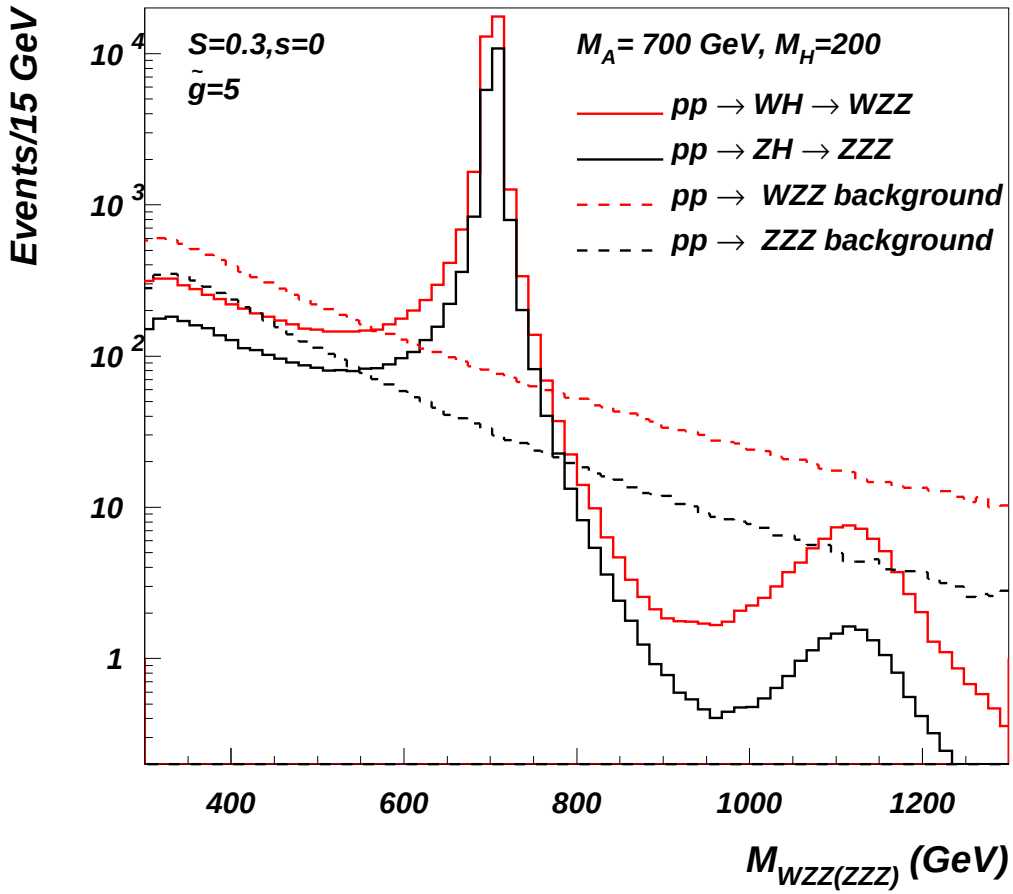
$\sigma(pp \to WH)$ compared to SM (dashed line): mostly enhanced





Technicolor at the LHC

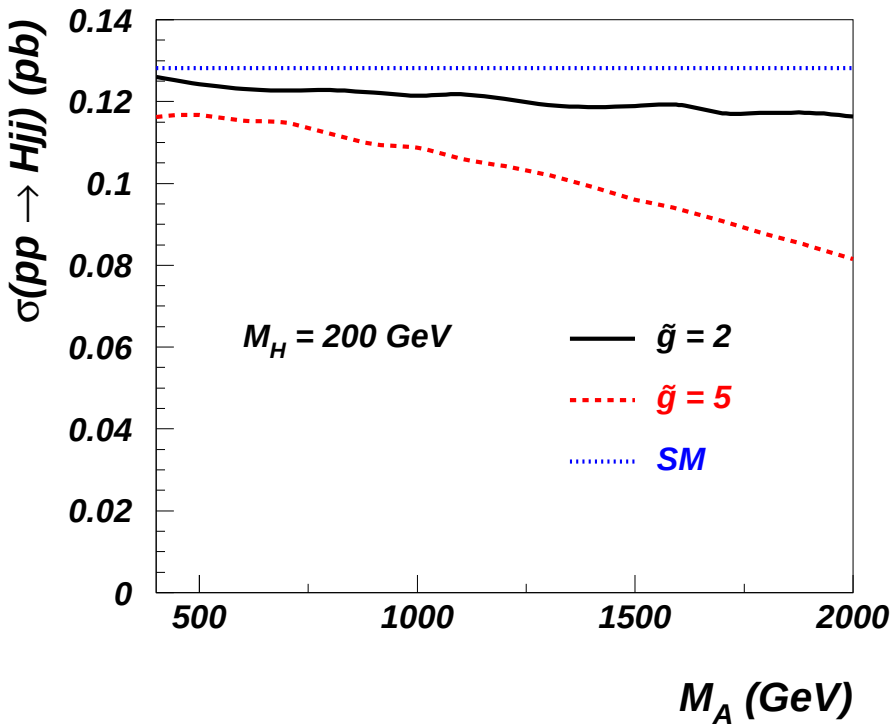
Axial (and vector) peaks in ZZZ and ZZW distributions at 100 fb^{-1}

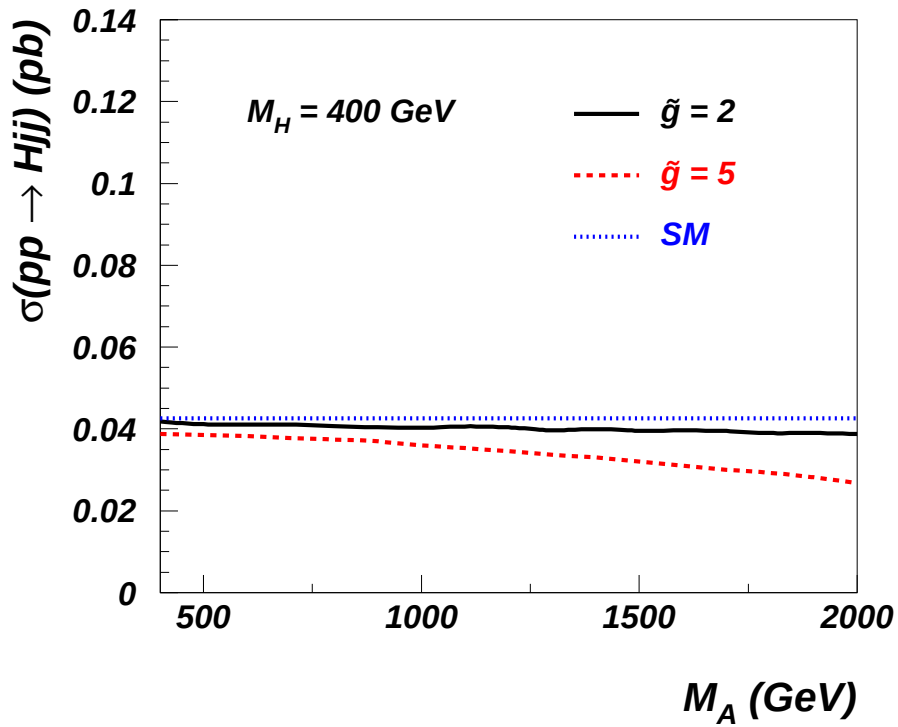


Axial signal (at around 0.7 TeV) will remain visible after adding branching to lepton final states (The simplest Higgs-vector coupling assumed here)

Technicolor at the LHC

Higgs production cross section in WW to Higgs fusion ($pp \to jjH$)

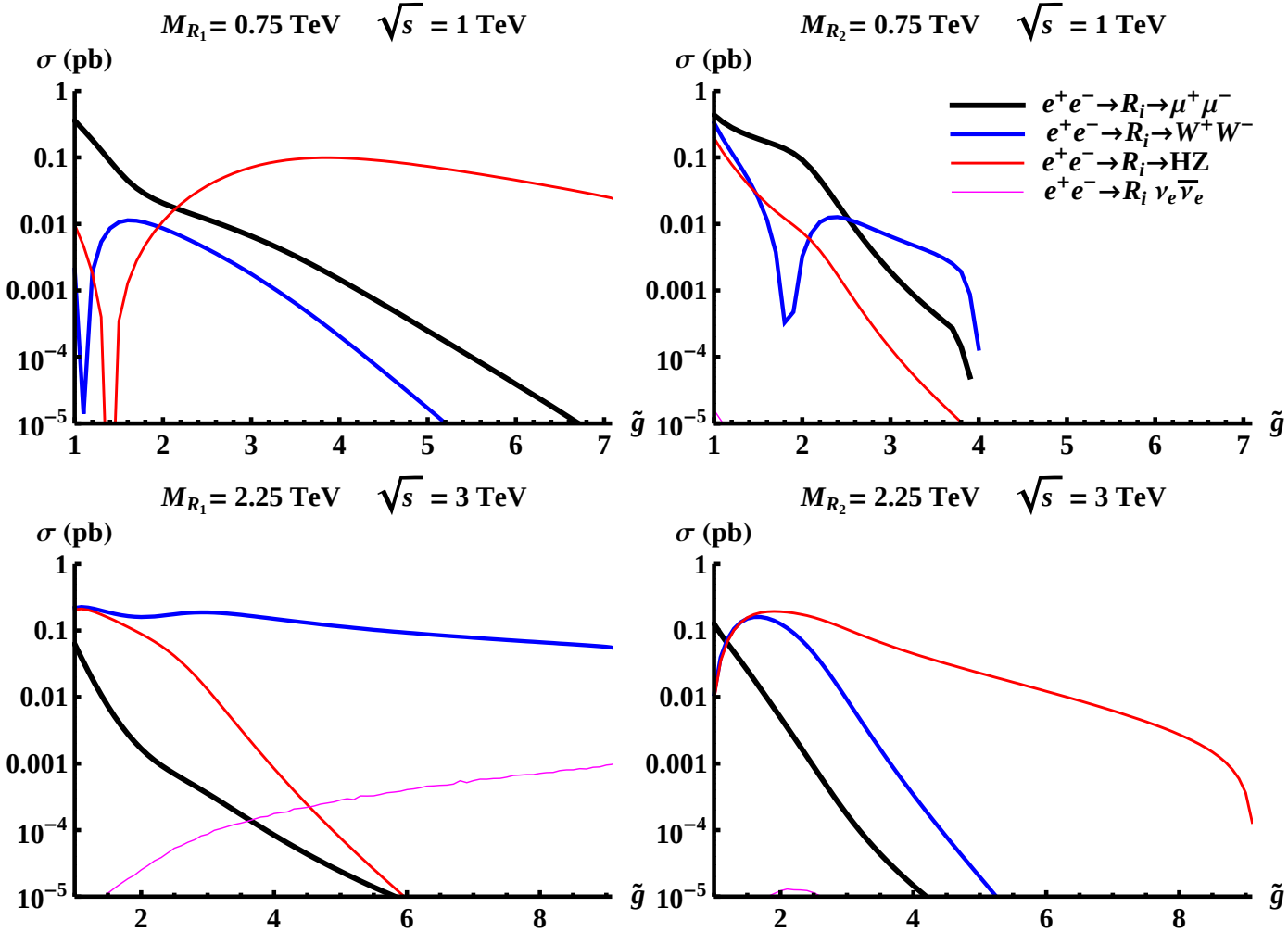




Technicolor at linear colliders

We study 1 TeV and 3 TeV scenarios

First study: $R_{1,2}$ detection via dilepton and diboson channels



Technicolor at linear colliders

Differential cross sections

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

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

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

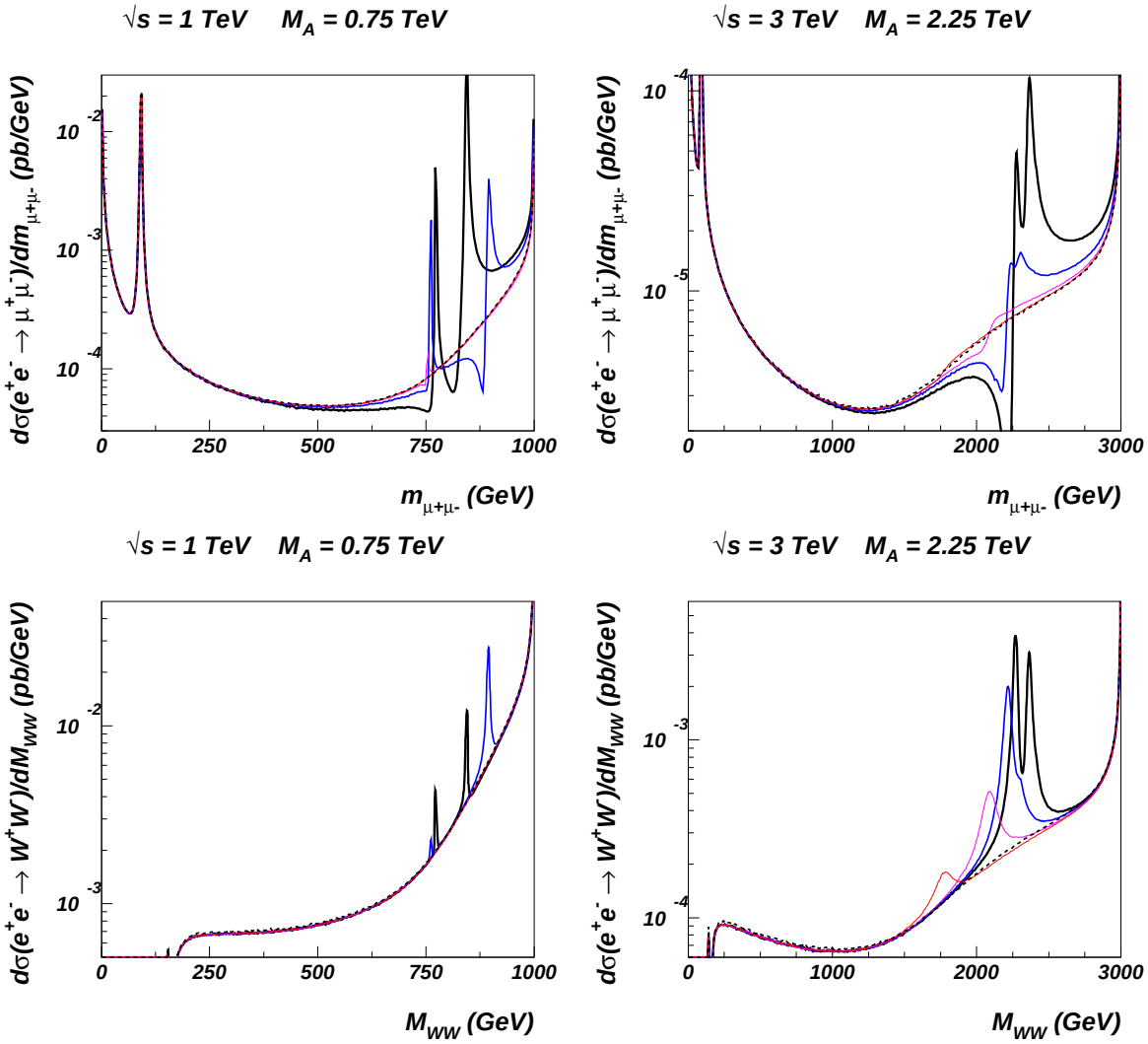
Top: dimuons

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

Bottom:

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

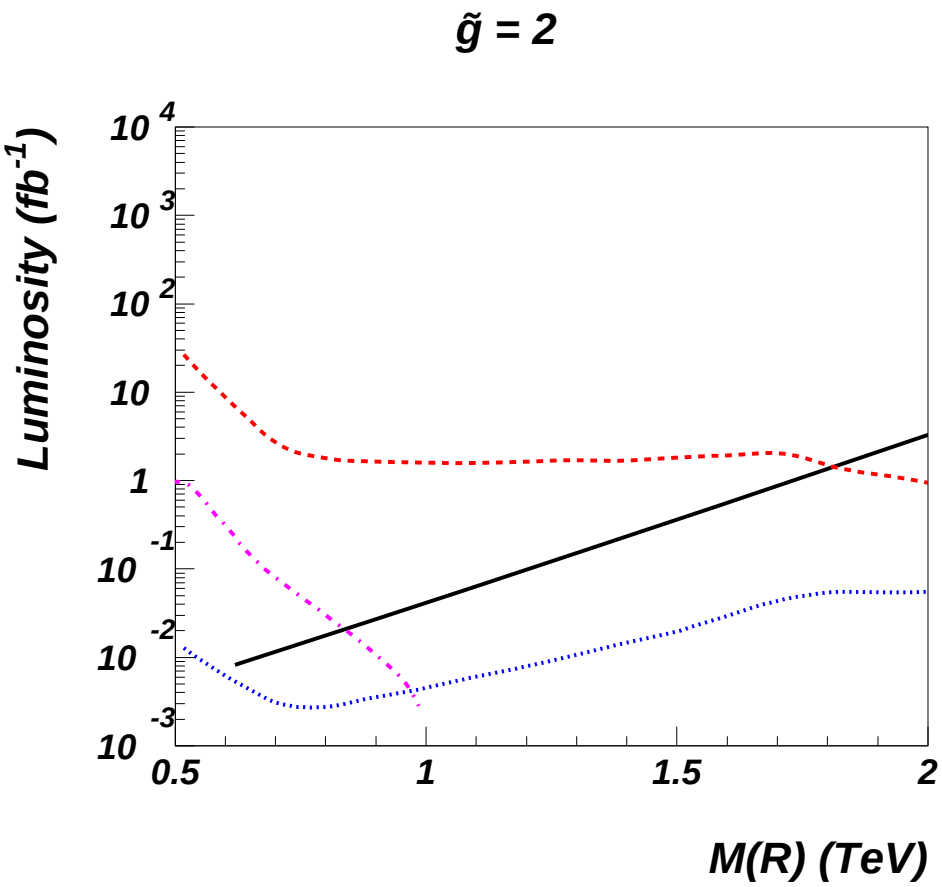
$\tilde{g} =$ 2, 3, 5, 8

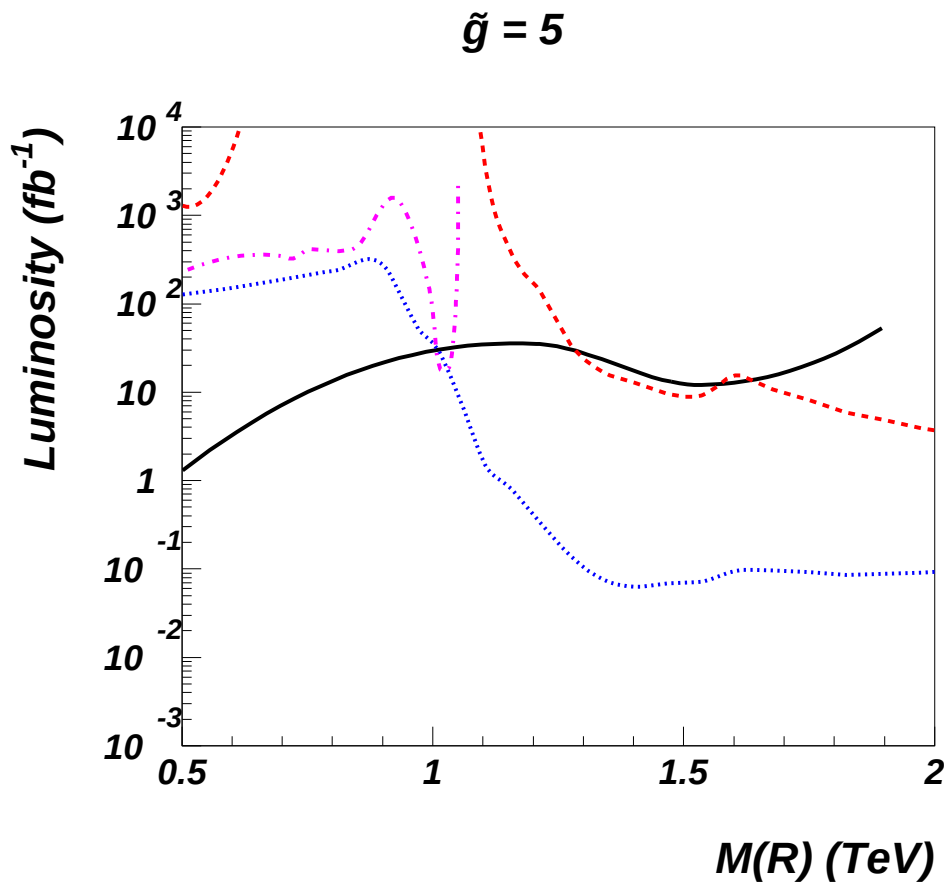


Technicolor at linear colliders

Combined $R_{1,2}$ reach from dilepton and WW/WZ production

LHC at 14 TeV/ LC scanning / 3 TeV LC / 1 TeV LC





Technicolor at linear colliders

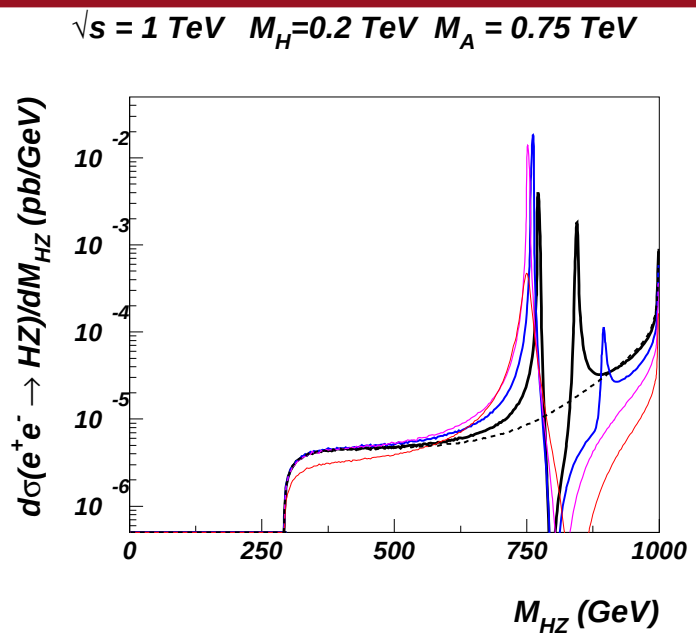
Differential cross section for

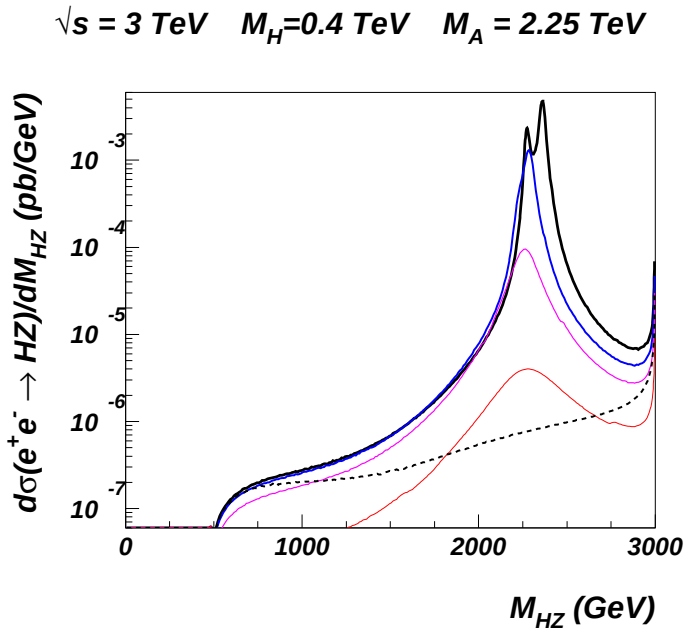
Associated Higgs production

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

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

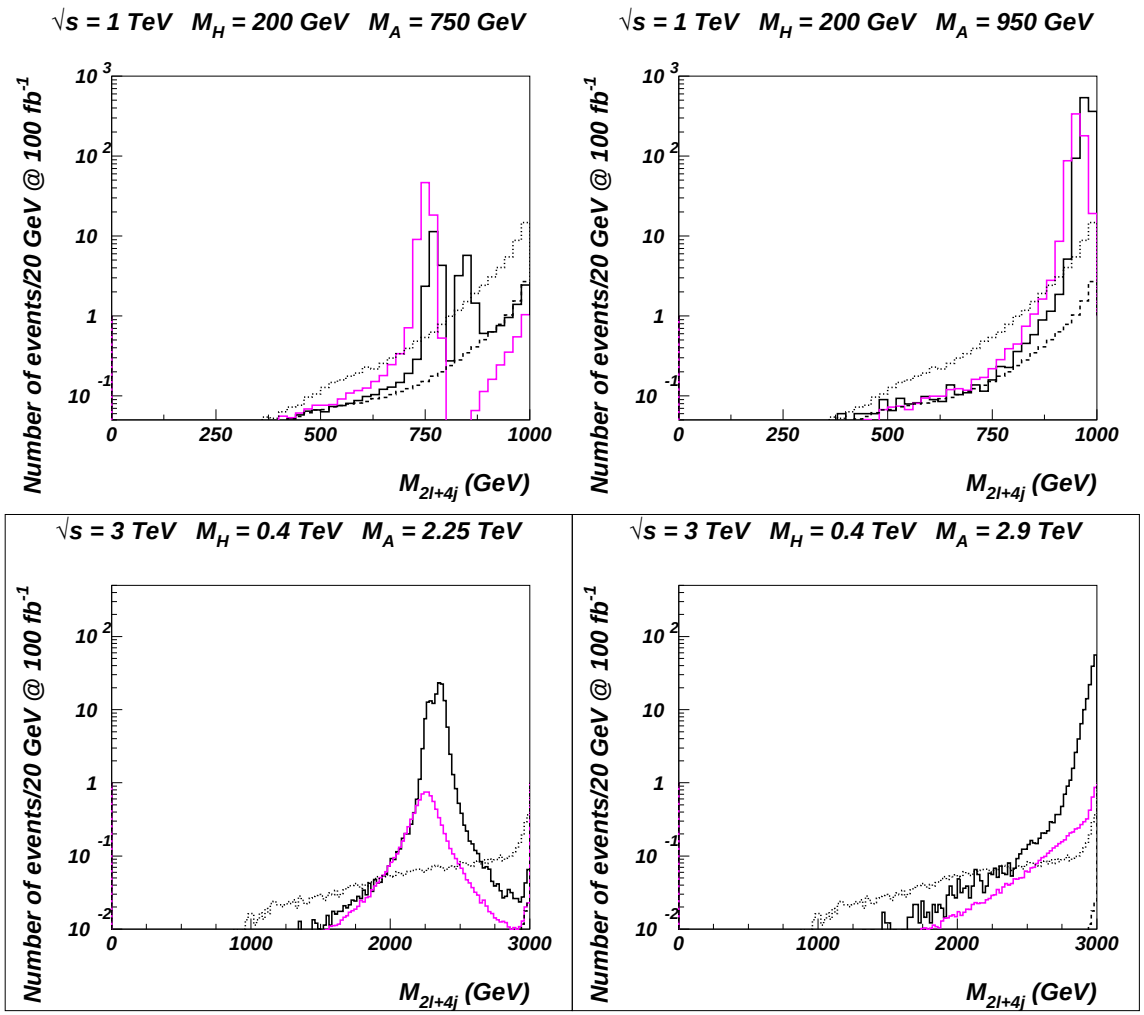
Bottom: $\sqrt{s} = 3$ TeV

$\tilde{g} =$ 2, 5

Dotted line: SM background

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

before cuts



Conclusion

- Implementation of (vanilla) technicolor on CalcHEP and MadGraph available
- LHC has the potential to discover TC spin-one meson(s) in the whole parameter space
- A linear collider can efficiently test technicolor up to its maximal $\sqrt{s}$

Backup slides

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]

Backup slides

Reach estimates

in the scanning mode

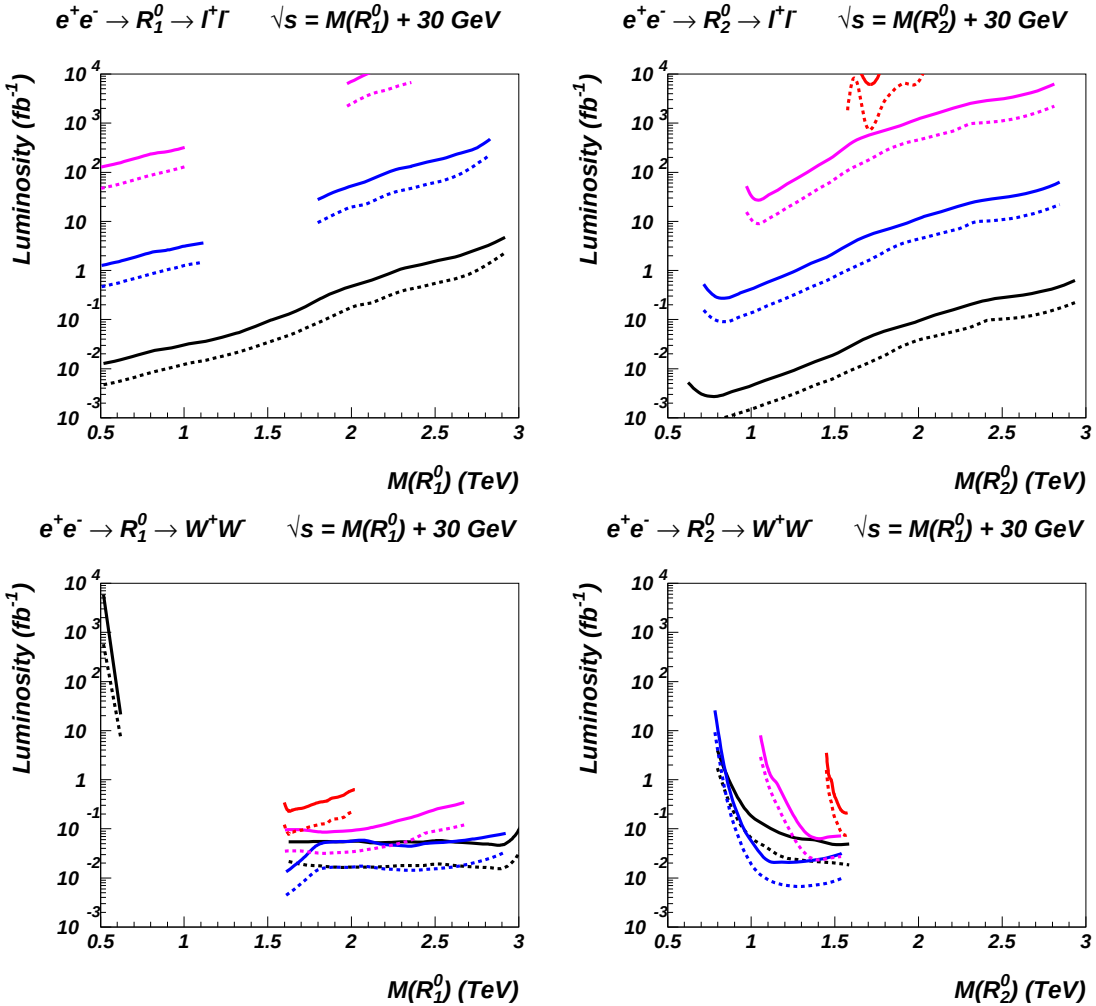
Left: R_1^0 Right: R_2^0

Top: dimuons

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

Bottom:

$$e^+e^- \longrightarrow R_{1,2} \longrightarrow W^+W^- \longrightarrow 2j + \ell + \nu$$



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