Walking Technicolor in light of Z' searches at the LHC

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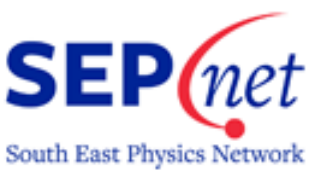


Outline

1. Motivation
2. NMWT Setup
3. Phenomenology and LHC Sensitivity
4. Outlook

Motivation for Technicolor

- Standard Model has many issues; hierarchy problem, no Dark Matter candidate, etc.
- Higgs discovery at LHC leaves many open questions - Which Higgs? Fundamental or Composite? Higgs mechanism realised?
- **Walking Technicolor** (WTC) offers dynamical alternative to spontaneous EWSB
- WTC also addresses hierarchy problem and has a consistent Higgs boson-like *composite* particle

Standard Model vs Technicolor

SM

- Simple, concise lagrangian
- No FCNC issues or tension with EW precision data
- Established and well tested model, agrees with current observation
- Fine-tuning and naturalness problem in 1-loop Higgs mass corrections
- No example of fundamental scalar

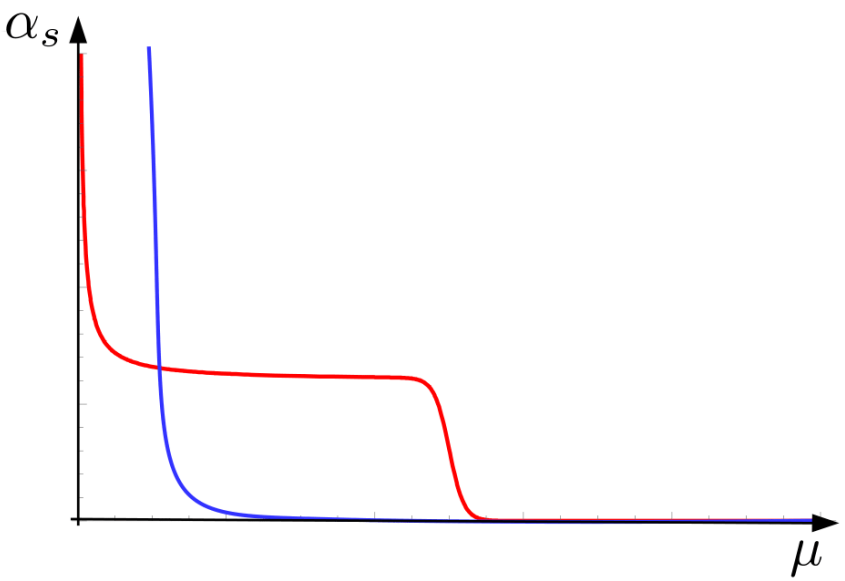
TC

- Complicated eff. lagrangian
- Constraints from FCNC require *walking*, possible EW precision data tension
- TC/Higgs interactions mediated by unknown ETC sector, no viable ETC model
- No fine-tuning, $\Lambda_{TC} \sim 1\text{TeV}$ dynamically generated
- DSB seen in nature e.g. QCD, superconductivity

'Walking' dynamics

New gauge bosons formed at Extended Technicolor (ETC) scale, but evaluated at TC scale.

How does α_{TC} run between Λ_{TC} and Λ_{ETC}?



Running α_{TC} (QCD-like)
Walking α_{TC}

Setup of NMWT

NMWT is encoded into the chiral Lagrangian

$$\begin{aligned}\mathcal{L}_{boson} = &-\frac{1}{2}\mathrm{Tr}\left[\tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right] - \frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}[F_{L\mu\nu}F_L^{\mu\nu} + F_{R\mu\nu}F_R^{\mu\nu}] \\ &+ m^2\mathrm{Tr}[C_{L\mu}^2 + C_{R\mu}^2] + \frac{1}{2}\mathrm{Tr}[D_\mu M D^\mu M^\dagger] - \tilde{g}^2 r_2 \mathrm{Tr}[C_{L\mu} M C_R^\mu M^\dagger] \\ &- \frac{i\tilde{g}r_3}{4}\mathrm{Tr}[C_{L\mu}(MD^\mu M^\dagger - D^\mu M M^\dagger) + C_{R\mu}(M^\dagger D^\mu M - D^\mu M^\dagger M)] \\ &+ \frac{\tilde{g}^2 s}{4}\mathrm{Tr}[C_{L\mu}^2 + C_{R\mu}^2]\mathrm{Tr}[MM^\dagger] + \frac{\mu^2}{2}\mathrm{Tr}[MM^\dagger] - \frac{\lambda}{4}\mathrm{Tr}[MM^\dagger]^2\end{aligned} \tag{1}$$

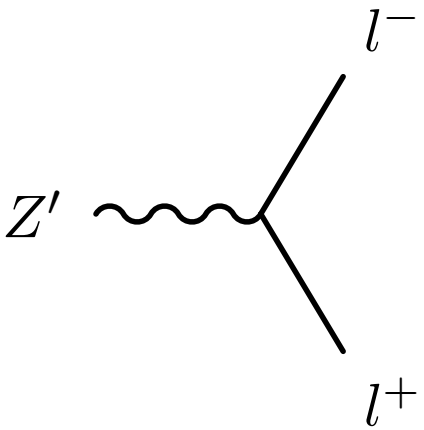
Key constructs in equation 1:

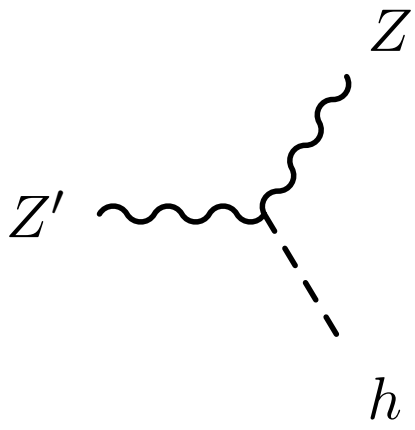
$$C_{L\mu} \equiv A_{L\mu} - \frac{g}{\tilde{g}}\tilde{W}_\mu, \qquad C_{R\mu} \equiv A_{R\mu} - \frac{g'}{\tilde{g}}\tilde{B}_\mu, \tag{2}$$

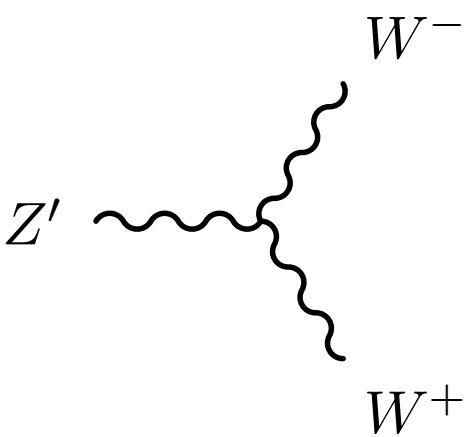
Belyaev *et al* 0809.0793v1

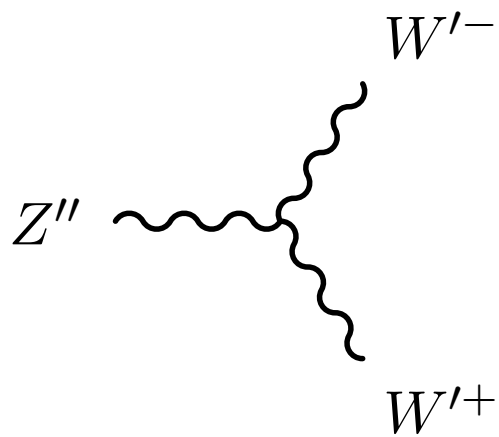
Particle Spectrum

Two heavy gauge triplets: (Z', W'^{+}, W'^{-}), (Z'', W''^{+}, W''^{-})









NMWT Parameter Space

Connect effective $\mathcal{L}$ to underlying theory using vector/axial-vector masses and decay constants

$$M_V^2 = m^2 + \frac{\tilde{g}^2(s - r_2)v^2}{4}, \qquad M_A^2 = m^2 + \frac{\tilde{g}^2(s + r_2)v^2}{4}, \tag{3}$$

and Weinberg Sum Rules (WSR)

$$S = 4\pi \left[\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right]. \tag{4}$$

NMWT defined by 4-D parameter space

$$\boxed{M_A, \qquad \tilde{g}, \qquad S, \qquad s.} \tag{5}$$

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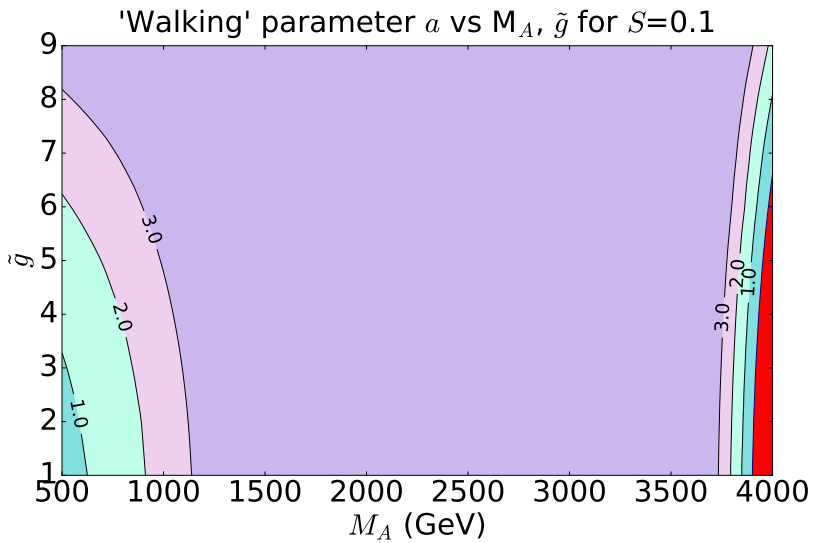
Theoretical constraints

We can constrain the parameter space by considering deviations from 2nd WSR

$$a\frac{8\pi^2}{d(R)}F_\pi^4 = F_V^2 M_V^2 - F_A^2 M_A^2, \tag{6}$$

Require $a > 0$ for walking dynamics



Model Implementation

LanHEP

$$\mathcal{L}_{kin} = -\frac{1}{2}\mathrm{Tr}\left[\tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right] - \frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\left[F_{L\mu\nu}F_L^{\mu\nu} + F_{R\mu\nu}F_R^{\mu\nu}\right]$$

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Gauge and Vector Kinetic plus Self Interaction Terms %%%%%%%%%%%%%%%

lterm -F**2/4  where  F = deriv^mu*B1^nu-deriv^nu*B1^mu.

lterm -F**2/4  where  F = deriv^mu*WW1^nu^a-deriv^nu*WW1^mu^a -g2*eps^a^b^c*WW1^mu^b*WW1^nu^c.

lterm -F**2/4  where  F = deriv^mu*AL1^nu^a-deriv^nu*AL1^mu^a -g0*eps^a^b^c*AL1^mu^b*AL1^nu^c.

lterm -F**2/4  where  F = deriv^mu*AR1^nu^a-deriv^nu*AR1^mu^a -g0*eps^a^b^c*AR1^mu^b*AR1^nu^c.
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```
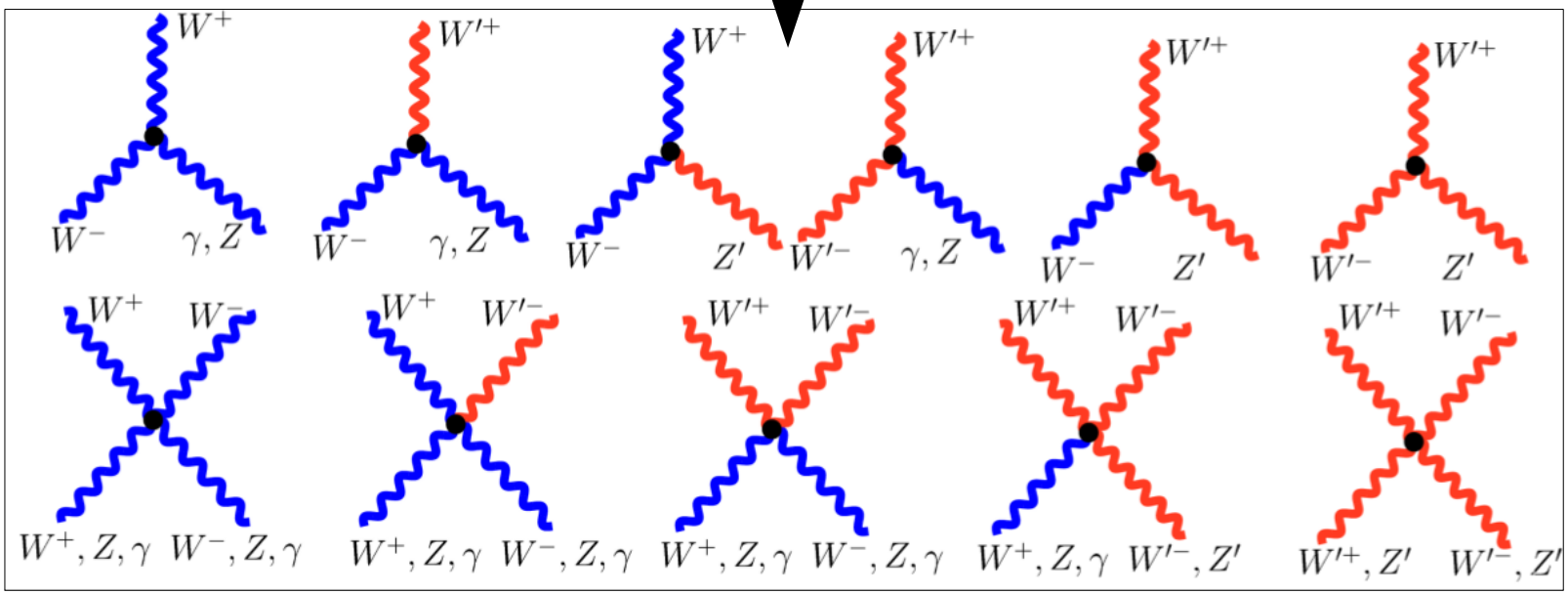
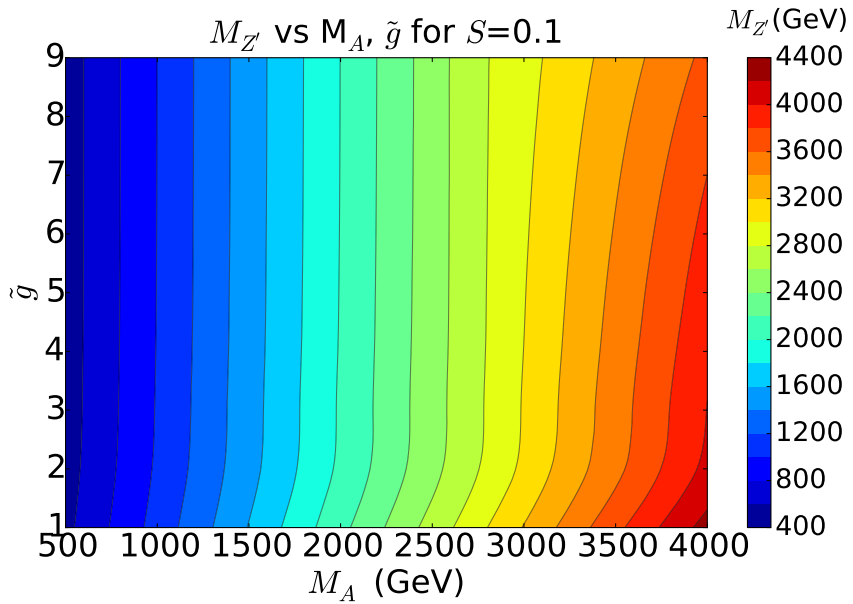
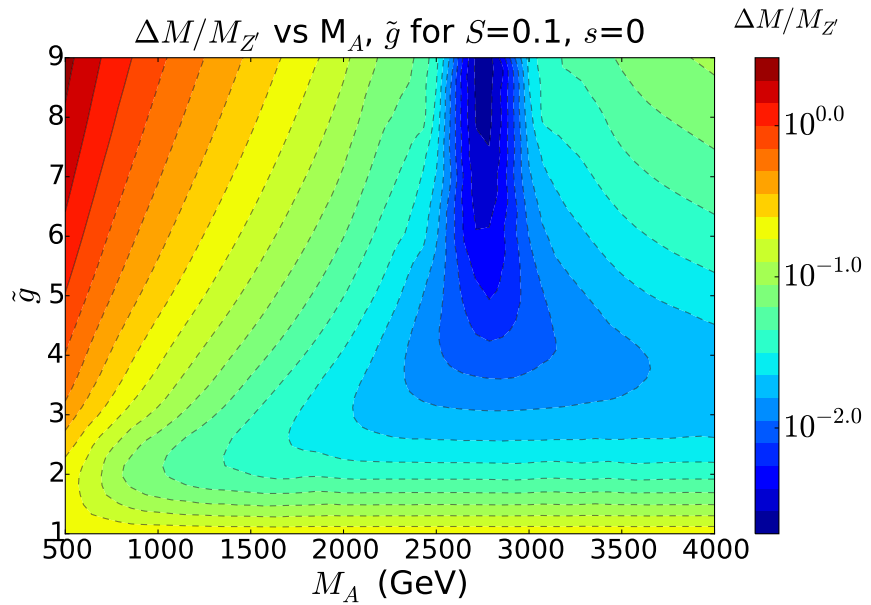

CalcHEP

lhep nmwt_feyn_excluderg.mdl



Mass Spectrum



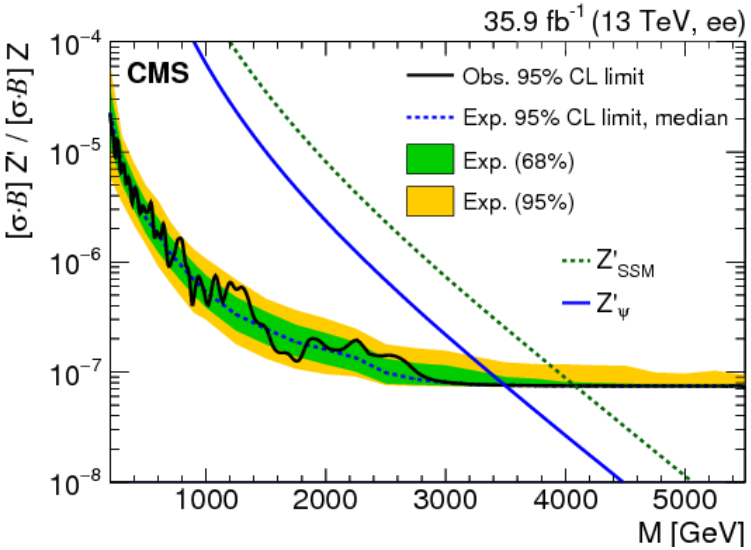


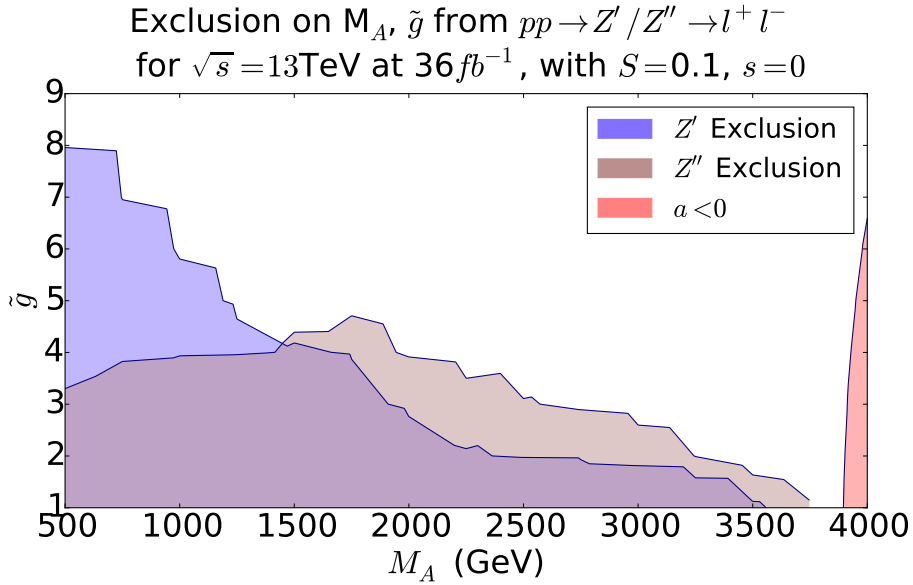
$M_{Z'} \simeq M_A$ (scale of NMWT) up to mass inversion M_{inv}.

At M_{inv}, $Z'(Z'')$ switches to mostly vector(axial-vector) resonance

Experimental limit

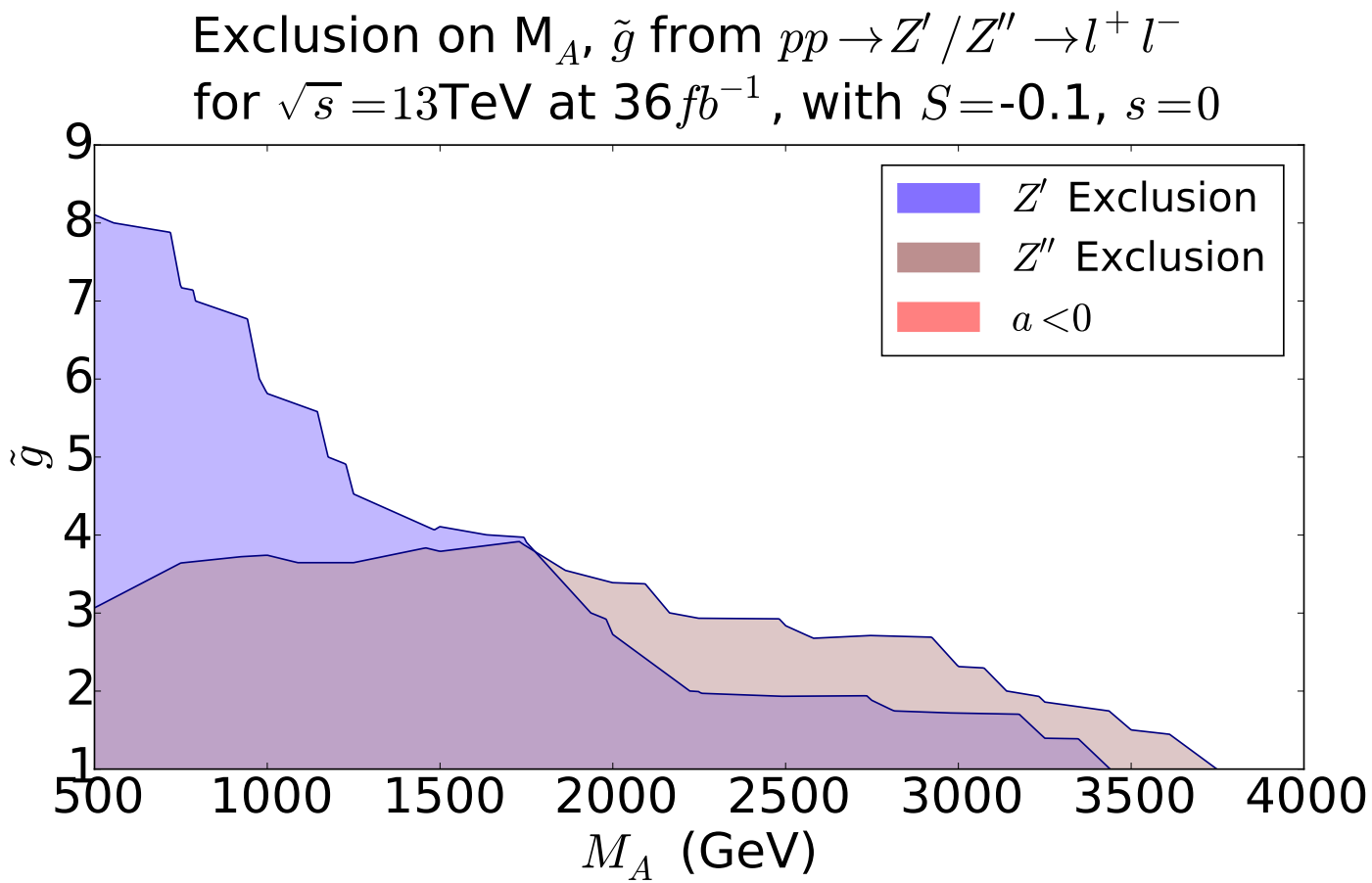
We calculate $\sigma^{NNLO}(pp \to Z'/Z'' \to l^+l^+)$ by applying NNLO K-factors to LO σ_{theory} from CalcHEP.



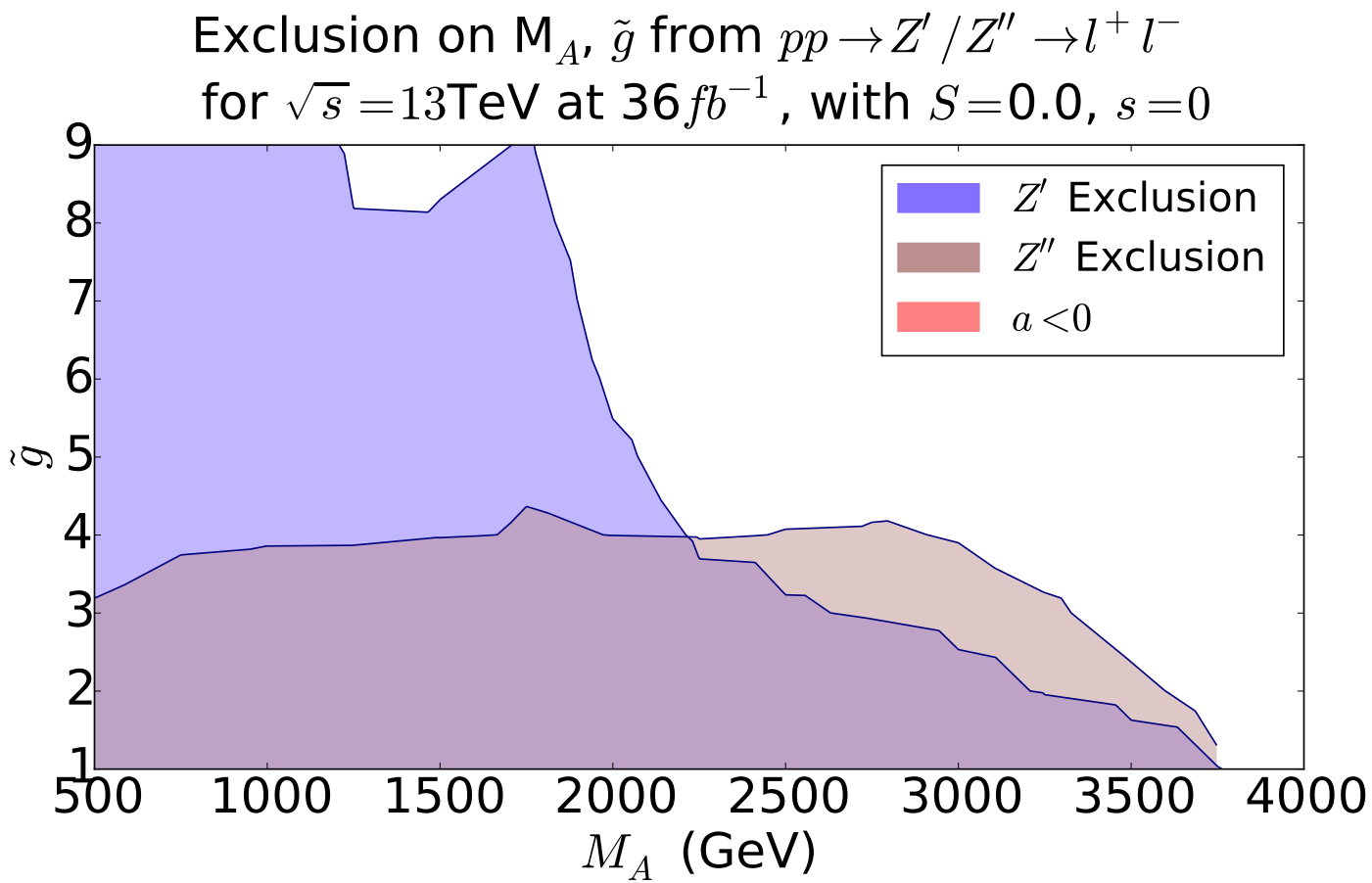


Exclusion region defined by region where $\sigma^{NNLO}_{theory} > \sigma^{exp}$, Z' and Z'' exclude complementary regions of the NMWT parameter space.

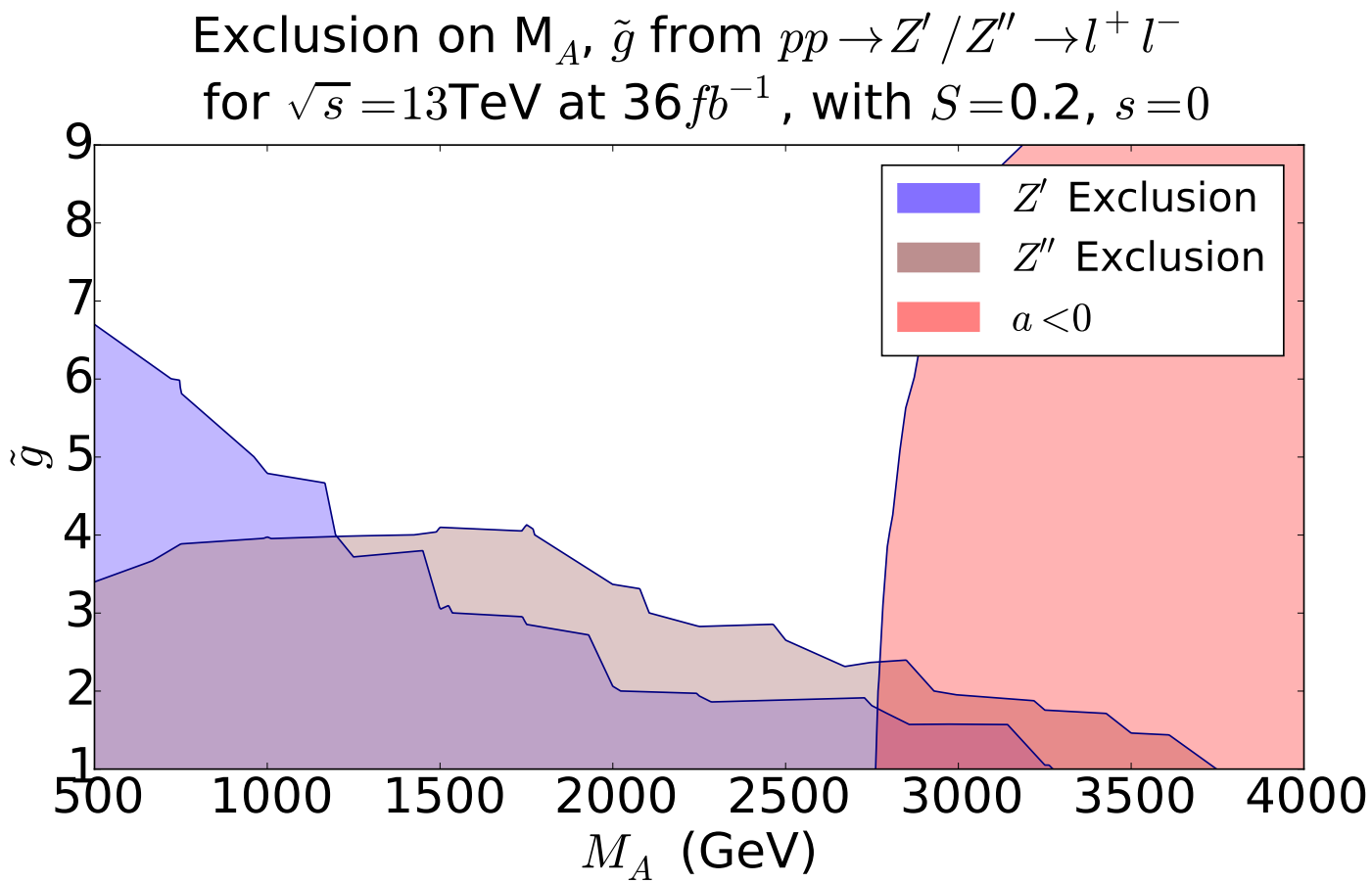
S dependence of excluded region: $S = -0.1$



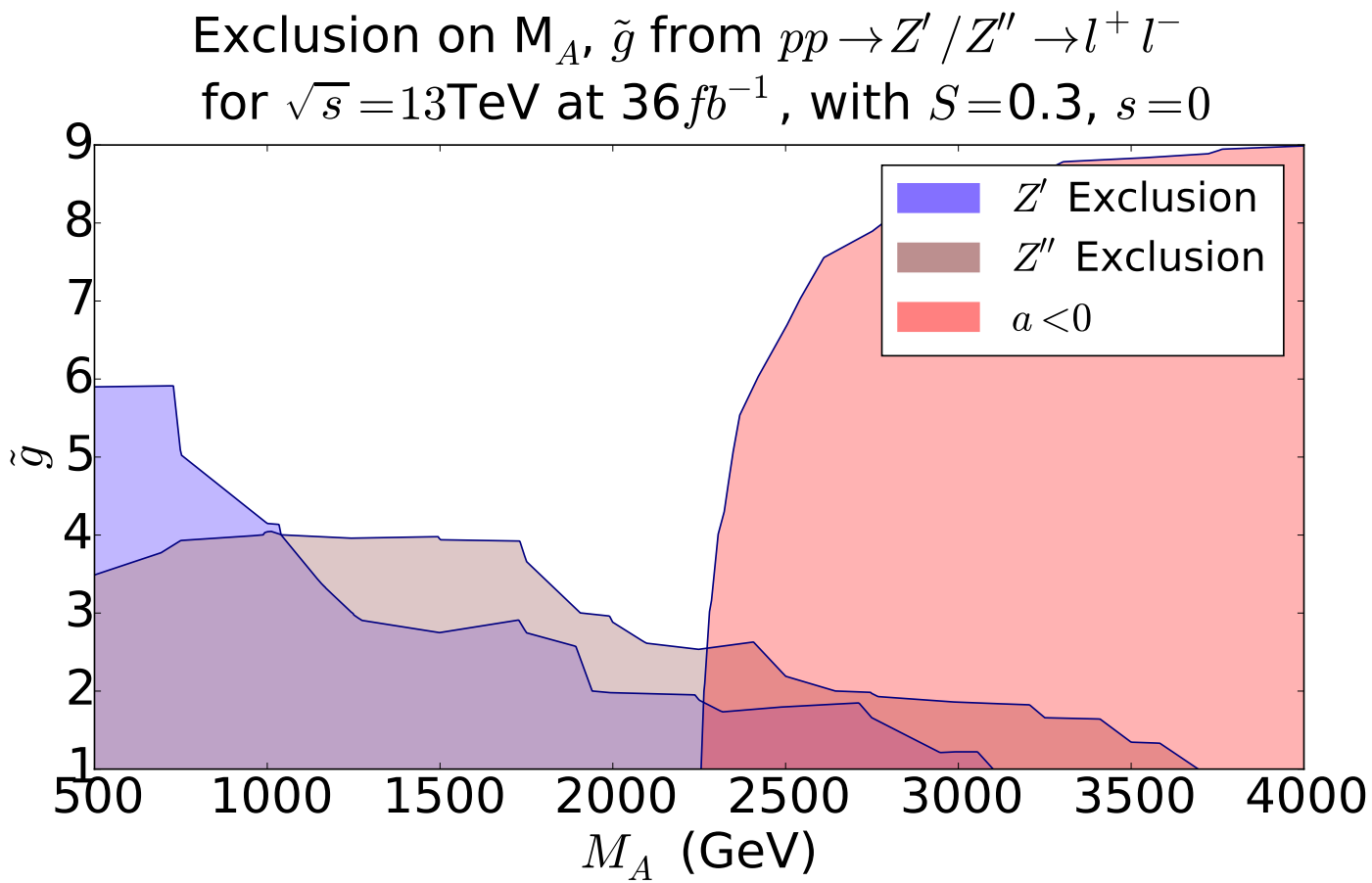
S dependence of excluded region: $S = 0.0$



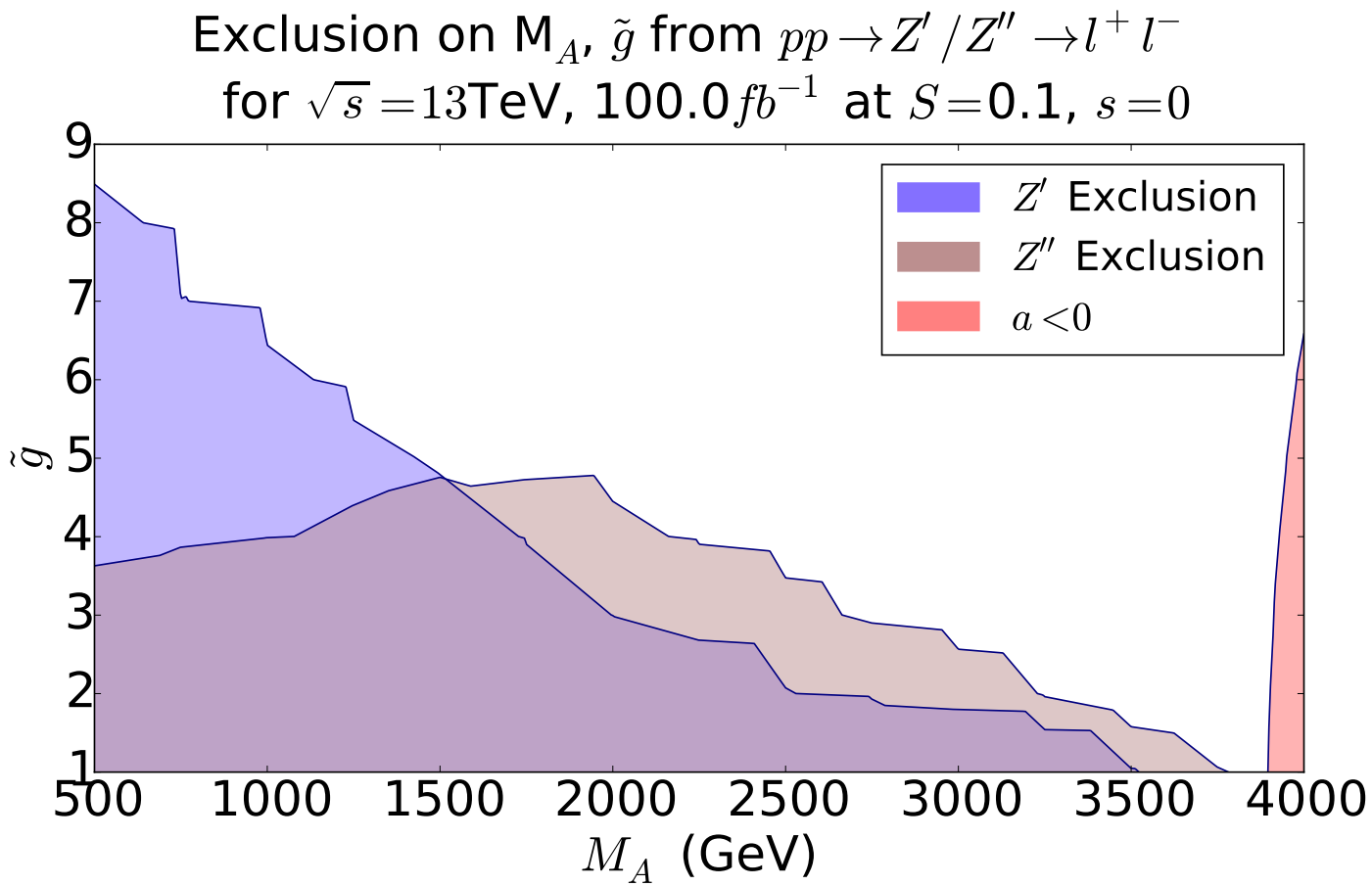
S dependence of excluded region: $S = 0.2$



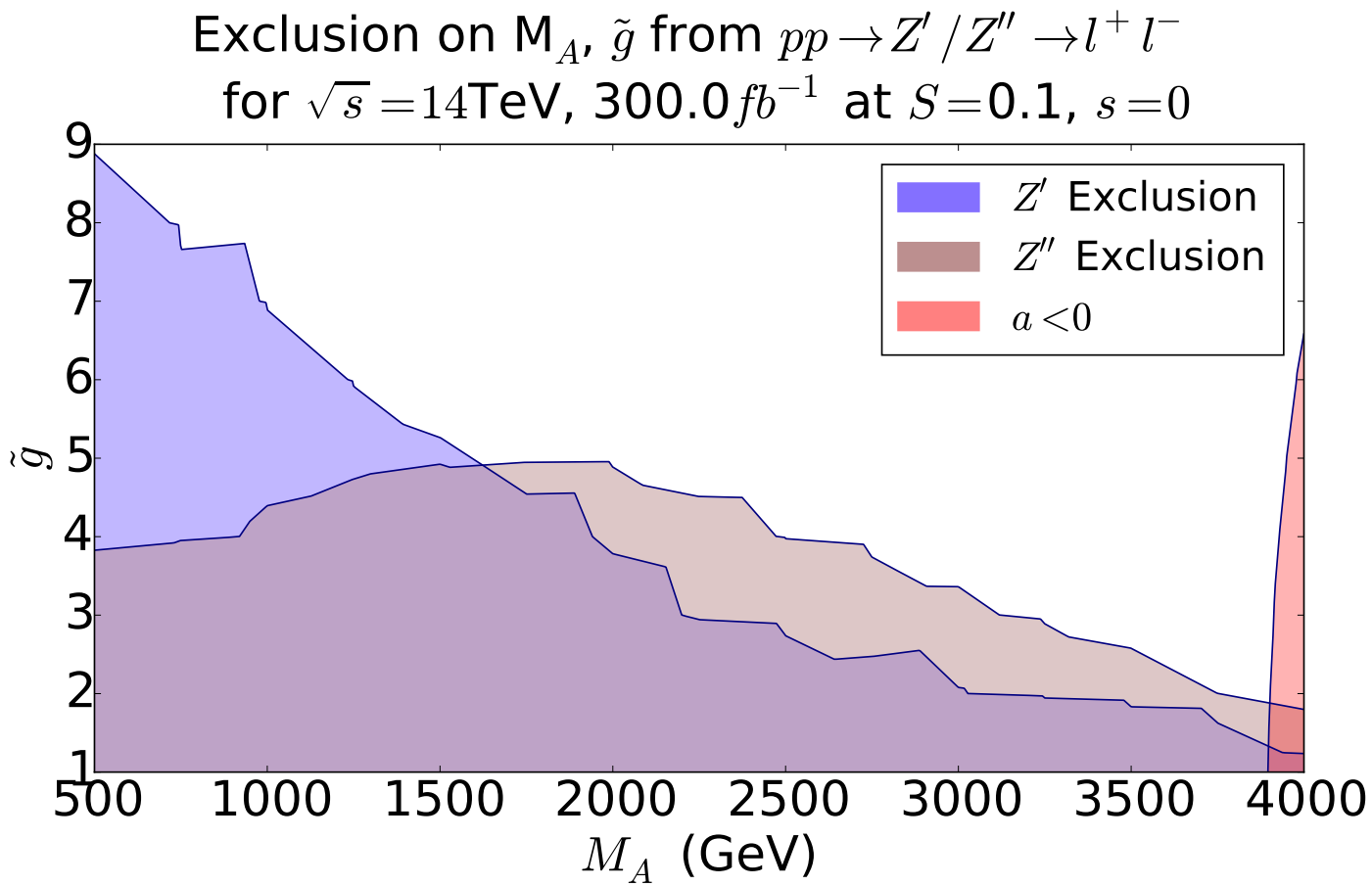
S dependence of excluded region: $S = 0.3$



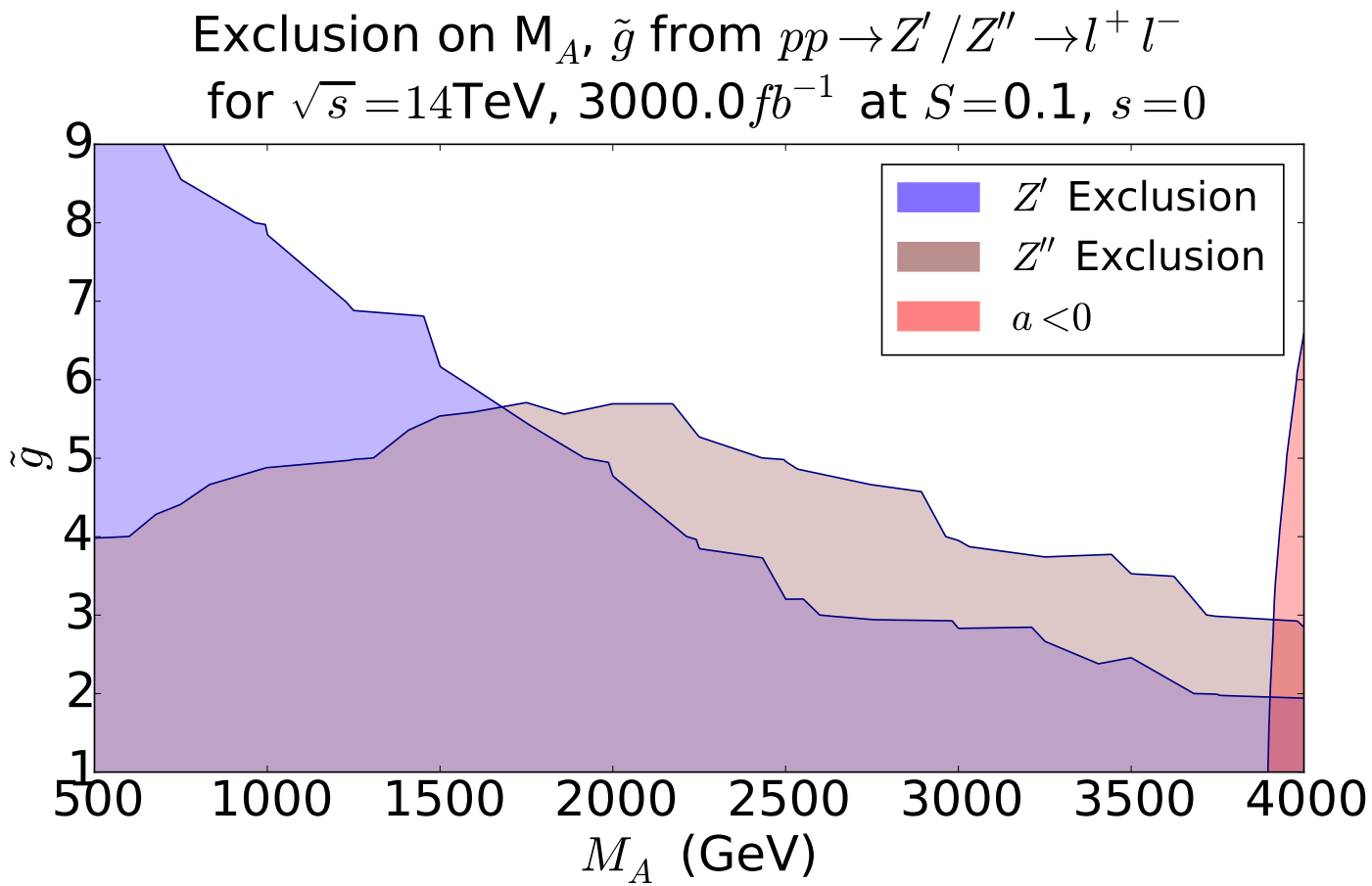
Predicted Exclusions from HLLHC: $\sqrt{s} = 13\text{TeV}$, 100fb^{-1}



Predicted Exclusions from HLLHC: $\sqrt{s} = 14$TeV, 300fb^{-1}



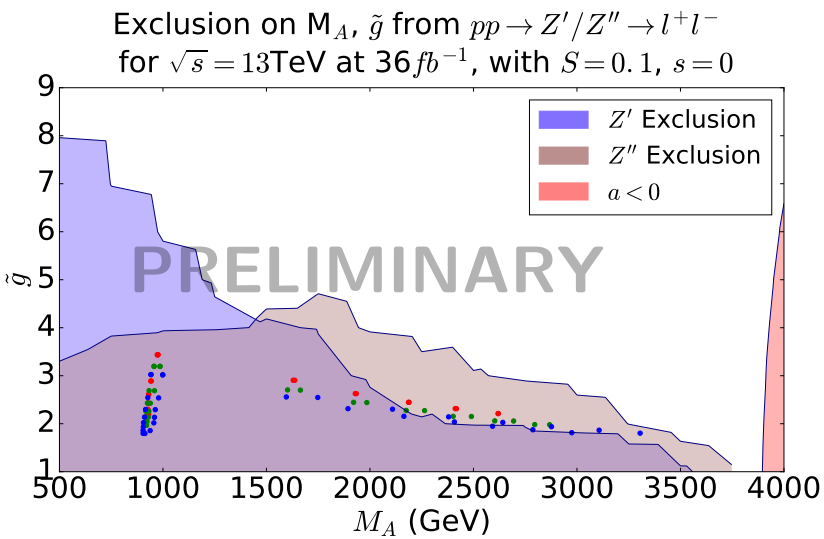
Predicted Exclusions from HLLHC: $\sqrt{s} = 14$TeV, 3000fb^{-1}



Outlook for WTC

NMWT model being tested from a Holography perspective in collaboration with Nick Evans and Marc Scott.

Calculate entire spectrum of possible NMWT models using Holography to predict NMWT parameters.



Project onto our parameter space, can state which possible NMWT theories are excluded. Results to come soon!

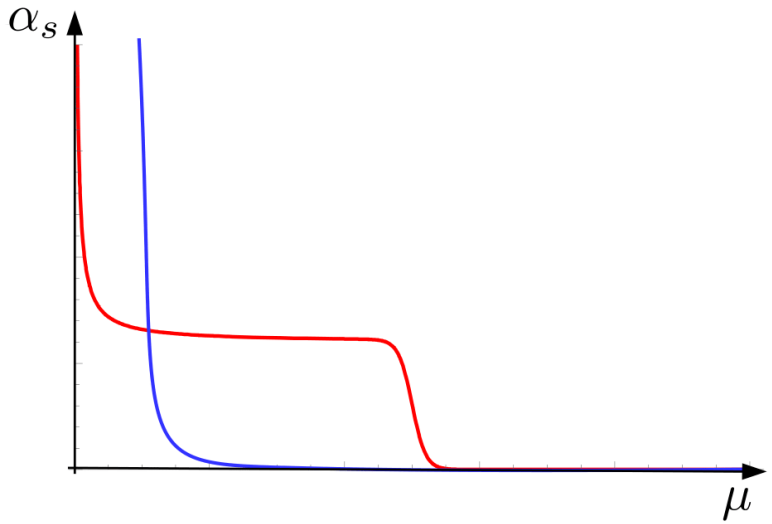
Thank you!

Why 'Walking' Technicolor?

To give mass to SM fermions, need new gauge bosons at *Extended Technicolor* scale Λ_{ETC}.

$\langle\psi\bar{\psi}\rangle$ evaluated at TC scale, but runs to ETC scale

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \exp \int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu}\gamma(\mu), \tag{7}$$



If $\alpha(\mu)$ running

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \ln\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma}$$

If $\alpha(\mu)$ *walking*

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma}$$

Weinberg Sum Rules

- Zeroth WSR

$$S = 4\pi \left[\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right] \tag{8}$$

- First WSR

$$F_V^2 - F_A^2 = F_\pi^2 \tag{9}$$

- Second WSR

$$F_V^2 M_V^2 - F_A^2 M_A^2 = a \frac{8\pi^2}{d(R)} F_\pi^4 \tag{10}$$

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Particle Spectrum

Theory with simplest global symmetry is NMWT, which adds $SU(2)_R$ group to SM. Global (chiral) symmetry is

$$SU(2)_L \times SU(2)_R \times U(1)_Y . \tag{11}$$

Chiral symmetry breaking pattern:

$$2_L \otimes 2_R \otimes 1_Y \to 3_{V/A} + 1_V , \tag{12}$$

We have **two gauge triplets** in TC sector under *hidden local symmetry* in the EFT. Physical particles are $Z', W'^{\pm}$ and $Z'', W''^{\pm}$.

Gauge Mixing Matrix

Matrix of gauge field mixing can be set up directly from $\mathcal{L}_{boson}$

$$\mathcal{M}_N^2 = \begin{pmatrix} \frac{g_1^2}{\tilde{g}^2} M_V^2 & 0 & \frac{g_1}{\sqrt{2}\tilde{g}} M_A^2 \chi & -\frac{g_1}{\sqrt{2}\tilde{g}} M_V^2 \\ 0 & \frac{g_2^2}{\tilde{g}^2} M_V^2 & -\frac{g_2}{\sqrt{2}\tilde{g}} M_A^2 \chi & -\frac{g_2}{\sqrt{2}\tilde{g}} M_V^2 \\ \frac{g_1}{\sqrt{2}\tilde{g}} M_A^2 \chi & -\frac{g_2}{\sqrt{2}\tilde{g}} M_A^2 \chi & M_A^2 & 0 \\ -\frac{g_1}{\sqrt{2}\tilde{g}} M_V^2 & -\frac{g_2}{\sqrt{2}\tilde{g}} M_V^2 & 0 & M_V^2 \end{pmatrix}. \tag{13}$$

Analytic masses

We diagonalise $\mathcal{M}_N^2$ perturbatively order by order in $\tilde{g}^{-1}$,

$$\mathcal{N}^\dagger \mathcal{M}_N^2 \mathcal{N} = \mathcal{D}, \tag{14}$$

where diagonal elements of $\mathcal{D}$ are square masses.

To 2nd order,

$$M_{Z'}^2 = M_A^2 \left(1 + \frac{g_1^2 + g_2^2}{\tilde{g}^2}\chi^2\right) \tag{15}$$

$$M_{Z''}^2 = M_A^2 \left(1 + \frac{g_1^2 + g_2^2}{2\tilde{g}^2}\right)\left(\chi^2 + \frac{\tilde{g}^2 F_\pi^2}{2M_A^2}\right), \tag{16}$$