# Walking Technicolor in the light of the LHC data

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# Collaborators & Projects

- “Walking Technicolor in the light of Z' searches at the LHC
  A.Coupe, M.Frandsen, E. Olaiya, C. Shepherd-Themistocleous, AB
  **arXiv:1805.10867**

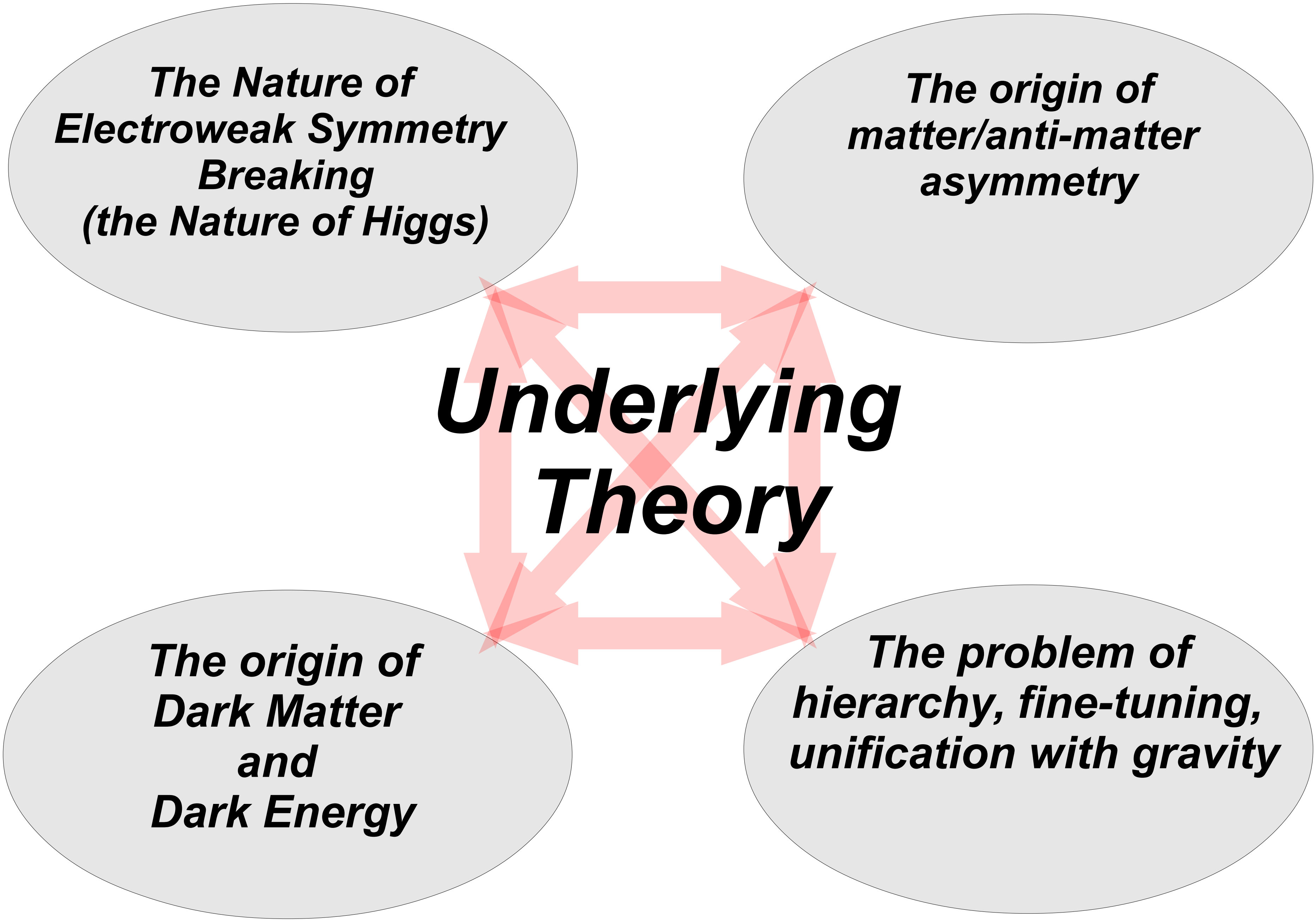
- “Excluding technicolor” A.Coupe, N.Evans, AB **to appear**

- “The Technicolor Higgs in the Light of LHC Data”
  M.Brown, R.Foadi, M.Frandsen, AB **arXiv:1309.2097**

- “Mixed dark matter from Technicolor “
  M.Frandsen, S. Sarkar, F.Sannino, AB **arXiv:1007.4839**

- “Technicolor Walks at the LHC”
  R. Foadi, M. Frandsen, M. Jarvinen, F. Sannino, AB **arXiv:0809.0793**

# Problems to be addressed by underlying theory



# SM Higgs vs Technicolor

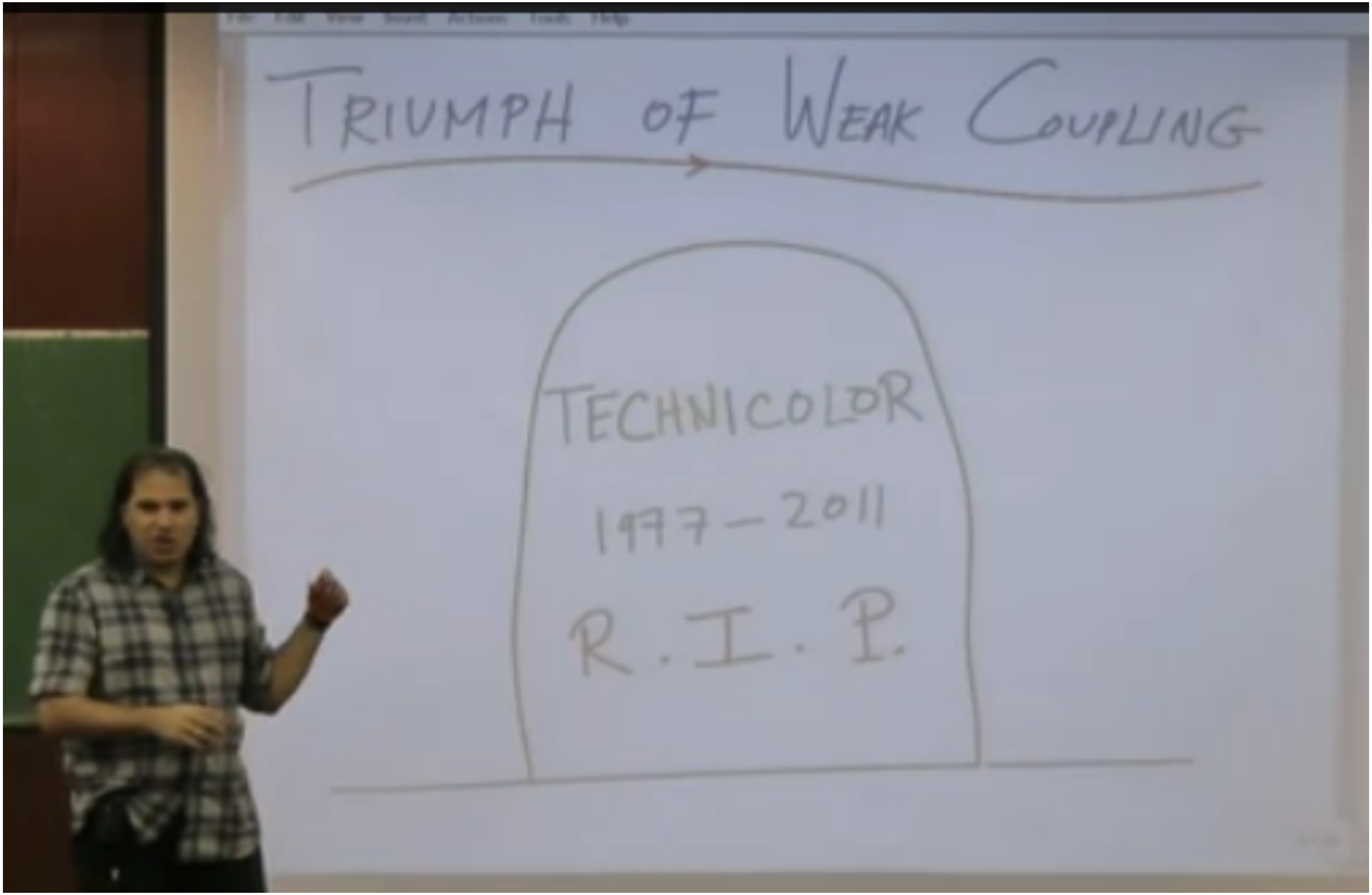
- *simple and economical*
- *GIM mechanism, no FCNC problems, EW precision data are OK for preferably light Higgs boson*
- *SM is established, perfectly describes data*
- *fine-tuning and naturalness problem; triviality problem*

$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \qquad \lambda(\mu) < \frac{3}{2\pi^2 \log\frac{\Lambda}{\mu}}$$

- *there is no example of fundamental scalar*
- *Scalar potential parameters and yukawa couplings are inputs*

- *complicated at the eff theory level*
- *FCNC constraints requires* ***walking****, potential tension with EW precision data*
- *no viable ETC model suggested yet, work in progress*
- *no fine-tuning, the scale is dynamically generated*
- *Superconductivity and QCD are examples of dynamical symmetry breaking*
- *parameters of low-energy effective theory are derived once underlying ETC is constructed*

# Is Technicolor really dead?



# Is Technicolor really dead?

## If title contains question, then the answer is ...

# NO!

# Is Technicolor really dead?

**If title contains question, then the answer is ...**

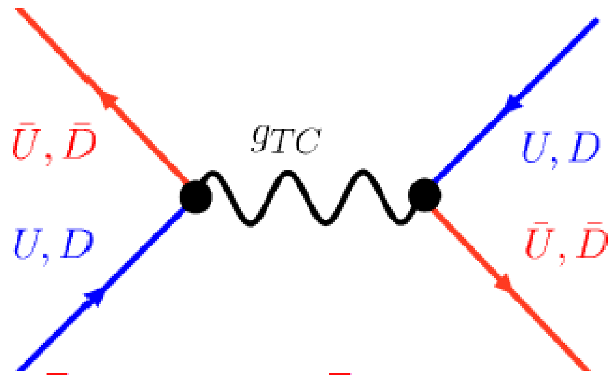
# NO!

# Not yet, let us see

# Technicolor

*Weinberg 76, Susskind 78*
*Farhi and Susskind 79*

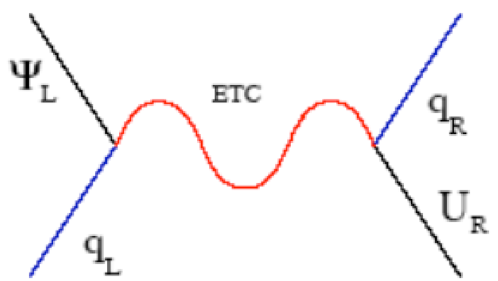
- *$SU(N_{TC})$ break the chiral symmetry of techniquarks*
- *their condensate breaks EW Symmetry*




$$\langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0$$

*Lane and Eichten 80*

- *Important componet of the theory:*
  *Extended Technicolor Sector – describes how SM fermions interact with the technifermioncondensate to acquire mass*




$$\Rightarrow \frac{g^2_{ETC}}{M^2_{ETC}} (\overline{\Psi}_L U_R)(\overline{q}_R q_L)$$

$$m_q \approx \frac{g^2_{ETC}}{M^2_{ETC}} \langle \overline{U} U \rangle_{ETC}$$

# Walking Technicolor

$$\langle \overline{U}U \rangle_{ETC} = \langle \overline{U}U \rangle_{TC} \exp\left( \int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

- ***For QCD – like running TC***
  ***$\gamma_m$ is small over this range, so:***

$$< \bar{Q}Q >_{ETC} \sim \ln\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma} < \bar{Q}Q >_{TC}$$

$$\langle \overline{U}U \rangle_{ETC} \approx \langle \overline{U}U \rangle_{TC} \approx 4\pi F_{TC}^3$$

$$\frac{M_{ETC}}{g_{ETC}} \approx 40\,\mathrm{TeV} \left( \frac{F_{TC}}{250\,\mathrm{GeV}} \right)^{\frac{3}{2}} \left( \frac{100\,\mathrm{MeV}}{m_q} \right)^{\frac{1}{2}}$$

- ***To avoid FCNC, one should have:***

$$\frac{M_{ETC}}{g_{ETC}\sqrt{\mathrm{Re}(\theta_{sd}^2)}} > 600\ \mathrm{TeV}$$

***which implies***

$$m_{q,\ell} \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle \overline{T}T \rangle_{ETC} < \frac{0.5\ \mathrm{MeV}}{N_D^{3/2}\,\theta_{sd}^2}$$

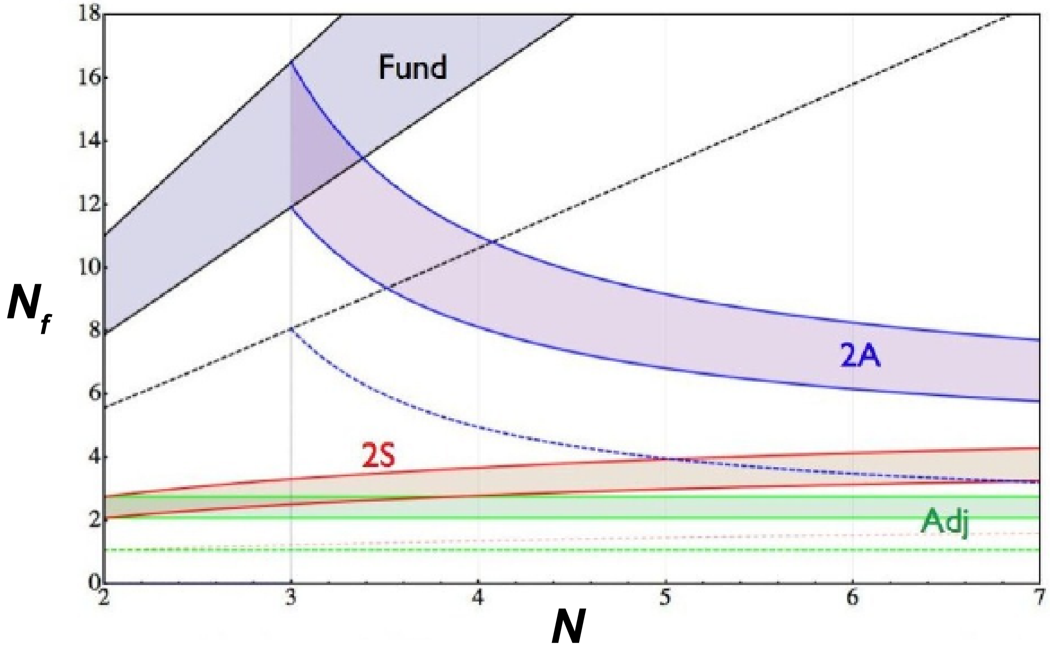
- ***Difficult to get masses even for s- and c-quarks: TC dynamics should be NOT like QCD, in a "walking theory" we have***

$$< \bar{Q}Q >_{ETC} \sim \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma(\alpha^*)} < \bar{Q}Q >_{TC}$$

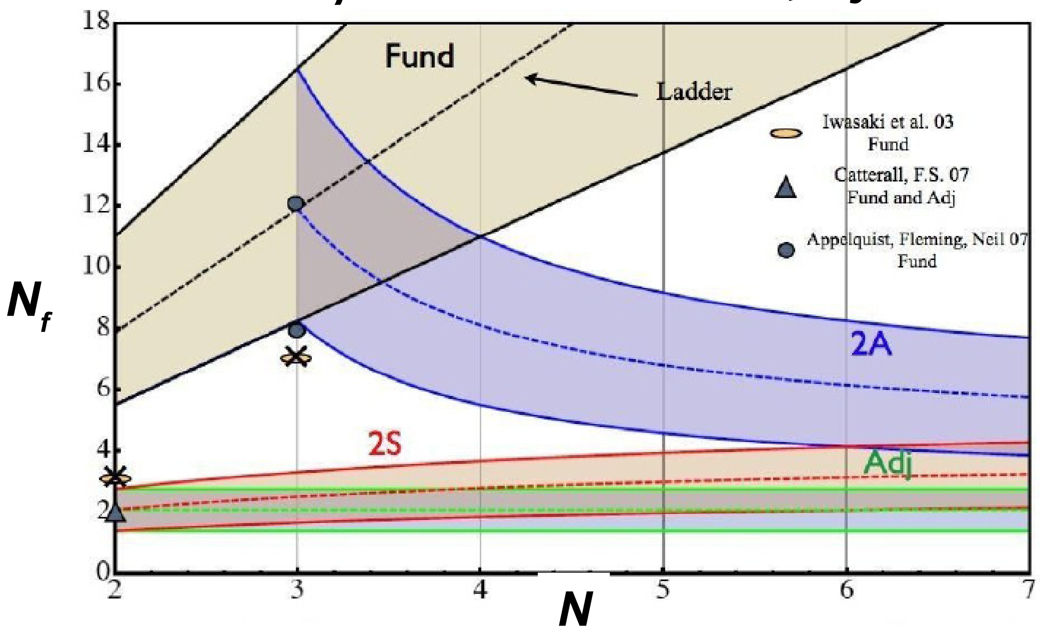
***Holdom 81; Appelquist, Wijewardhana 86***
***Enhanced SM fermion masses and suppressed FCNC***

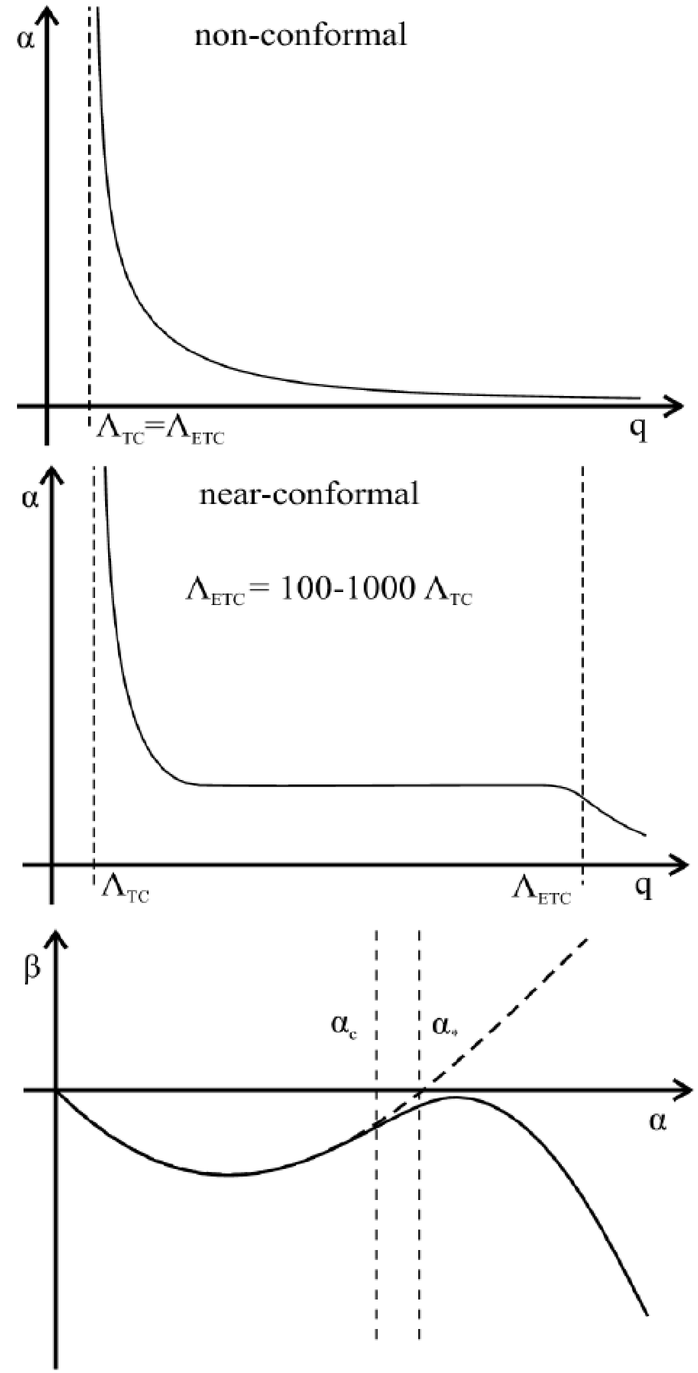
# Conformal Windows Studies

## Ladder approximation: Sannino, Dietrich 06




## All-orders β-function: Sannino, Ryttov 07



# Low Energy Effective NMWT Theory

- *$N_c = 3$, $N_f = 2$, in the two-index symmetric*
  *$SU(2)_L \times SU(2)_R \to SU(2)_V$*
- *spin-0 and spin-1 objects fill out representations of the chiral symmetry group*
- *higgs sector with a broken phase*
- *spin-1 resonances introduced as gauge fields*
  *(Bando, Kugo, Uehara,Yamawaki, and Yanagida 85)*
  **similar description used for the BESS model**
  *(Casalbuoni, Deandrea, De Curtis, Dominici, Gatto, Grazzini 95)*
- *See Applequist, Da Silva, Sannino 99 for description of vector mesons In EW symmetry breaking*
- *Effective Lagrangian*

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{higgs} + \mathcal{L}_{Higgs-vector} + \mathcal{L}_{fermion}$$

# Effective Lagrangian for SU(2)$_L$ X SU(2)$_R$

$$\mathcal{L}_{\rm boson} = -\frac{1}{2}{\rm Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}\widetilde{B}_{\mu\nu}\widetilde{B}^{\mu\nu} - \frac{1}{2}{\rm Tr}\left[F_{{\rm L}\mu\nu}F_{\rm L}^{\mu\nu} + F_{{\rm R}\mu\nu}F_{\rm R}^{\mu\nu}\right]$$

$$\mathcal{L}_{\rm Higgs} = \frac{\mu^2}{2}{\rm Tr}\left[MM^\dagger\right] - \frac{\lambda}{4}{\rm Tr}\left[MM^\dagger\right]^2$$

$\widetilde{W}_{\mu\nu}$ and $\widetilde{B}_{\mu\nu}$ are EW filed strength tensors

$F_{{\rm L/R}\mu\nu}$ are the field strength tensors associated to the vector meson fields $A_{{\rm L/R}\mu}$

**2x2 Matrix** $M = \frac{1}{\sqrt{2}}\left[v + H + 2\, i\, \pi^a\, T^a\right]\ ,\qquad a = 1,2,3$

**Covariant derivative** $D_\mu M = \partial_\mu M - i\, g\, \widetilde{W}_\mu^a\, T^a M + i\, g'\, M\, \widetilde{B}_\mu\, T^3$

# Effective Lagrangian for $SU(2)_L$ X $SU(2)_R$

$$
\begin{aligned}
& \mathcal{L}_{\text{Higgs-Vector}} = m^2 \ \mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right] \\
+ \quad & \frac{1}{2}\mathrm{Tr}\left[D_\mu M D^\mu M^\dagger\right] - \tilde{g}^2 \ r_2 \ \mathrm{Tr}\left[C_{\mathrm{L}\mu} M C_{\mathrm{R}}^\mu M^\dagger\right] \\
- \quad & \frac{i \ \tilde{g} \ r_3}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}\left(M D^\mu M^\dagger - D^\mu M M^\dagger\right) + C_{\mathrm{R}\mu}\left(M^\dagger D^\mu M - D^\mu M^\dagger M\right)\right] \\
+ \quad & \frac{\tilde{g}^2 s}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right] \mathrm{Tr}\left[M M^\dagger\right]
\end{aligned}
$$

$$
C_{\mathrm{L}\mu} \equiv A_{\mathrm{L}\mu} - \frac{g}{\tilde{g}}\widetilde{W}_\mu \ , \quad C_{\mathrm{R}\mu} \equiv A_{\mathrm{R}\mu} - \frac{g'}{\tilde{g}}\widetilde{B}_\mu \ .
$$

# Weinberg Sum Rules (WSR)

- spin 1 vector and axial resonances

$$V^a = \frac{A^a_L + A^a_R}{\sqrt{2}}, \quad A^a = \frac{A^a_L - A^a_R}{\sqrt{2}}$$

- masses and decay constants

$$M_V^2 = \frac{\tilde{g}^2}{4}\left[f^2 + (s - r_2)v^2\right] \qquad F_V = \frac{\sqrt{2}M_V}{\tilde{g}},$$

$$M_A^2 = \frac{\tilde{g}^2}{4}\left[f^2 + (s + r_2)v^2\right] \qquad F_A = \frac{\sqrt{2}M_A}{\tilde{g}}\chi$$

$$\chi \equiv 1 - \frac{v^2\,\tilde{g}^2\,r_3}{4M_A^2}$$

- Weinberg Sum Rules

$$S = 4\pi\left[\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2}\right] \qquad F_V^2 - F_A^2 = F_\pi^2 \qquad F_V^2 M_V^2 - F_A^2 M_A^2 = a\frac{8\pi^2}{d(R)}F_\pi^4$$

zeroth — first — second

*a>0, a ~ O(1) is consistent with the conformal window*

***Details: Appelquist, Sannino 98***

# Weinberg Sum Rules (WSR)

- **spin 1 vector and axial resonances**

$$V^a = \frac{A_L^a + A_R^a}{\sqrt{2}}, \qquad A^a = \frac{A_L^a - A_R^a}{\sqrt{2}}$$

- **masses and decay constants**

$$M_V^2 = \frac{\tilde{g}^2}{4}\left[f^2 + (s - r_2)v^2\right] \qquad F_V = \frac{\sqrt{2}M_V}{\tilde{g}},$$

$$M_A^2 = \frac{\tilde{g}^2}{4}\left[f^2 + (s + r_2)v^2\right] \qquad F_A = \frac{\sqrt{2}M_A}{\tilde{g}}\chi$$

$$\chi \equiv 1 - \frac{v^2\,\tilde{g}^2\,r_3}{4M_A^2}$$

- **Weinberg Sum Rules**

**$S$ parameter, or "zeroth WSR": important contributions from the near conformal region.**

$$S = 4\pi F_\pi^2\left[\frac{1}{M_V^2} + \frac{1}{M_A^2} - a\frac{8\pi^2 F_\pi^2}{d(R) M_V^2 M_A^2}\right]$$

# NMWT parameter space and particle content

- ***fixing S and using WSR parameter space is reduced to*** $\mathrm{M}_A,\ \tilde{g},\ s$

$$S = \frac{8\pi}{\tilde{g}^2}\left(1-\chi^2\right) \ ,$$

$$r_2 = r_3 - 1 \ .$$

$$\chi \equiv 1 - \frac{v^2\ \tilde{g}^2\ r_3}{4M_A^2}$$

- $s,\ M_H$ ***have sizable effect in the process involving composite Higgs***

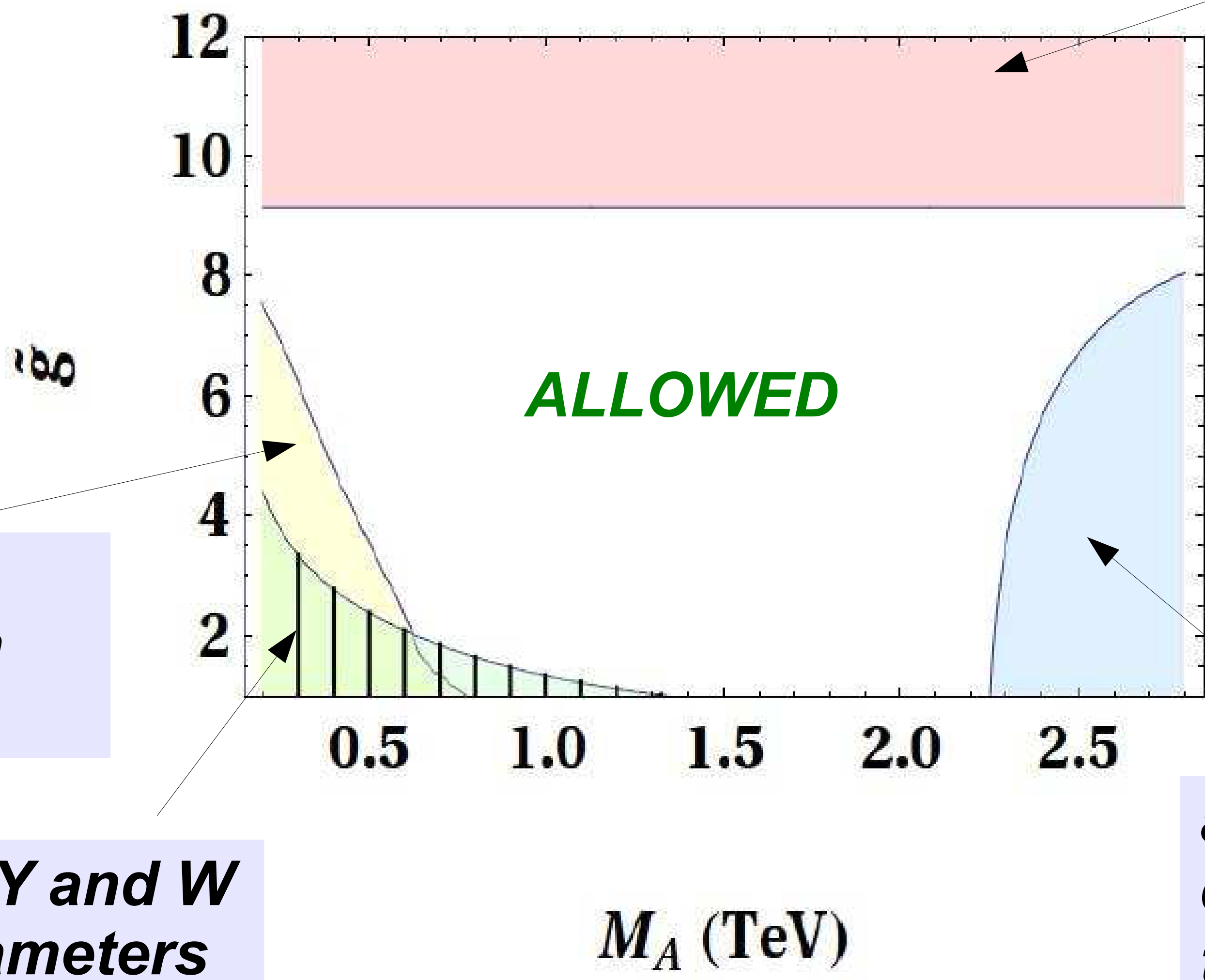
- ***new particles – two triplets of heavy mesons:***

$Z', W'^{\pm}$ ***and*** $Z'' W''^{\pm}$

# NMWT parameter space from 2007

imaginary $F_V$ and $F_A$

$$\tilde{g} > \sqrt{\frac{8\pi}{S}}$$




Collider limit from $pp \to e^+e^-$

EW Y and W parameters @95% CL

a<0, defined by the 2nd WSR

# Model Implementation into LanHEP and CalcHEP

## LanHEP (Andrei Semenov)

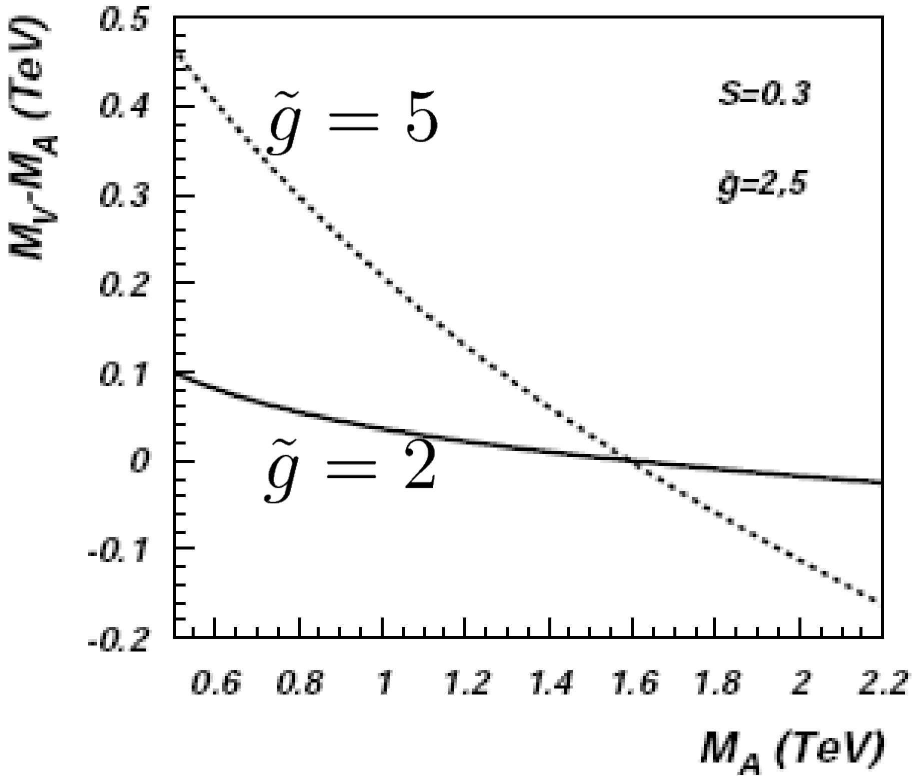
- ***Automatic generation of Feynman rules from the Lagrangian***
- ***Has checks for***
  - ***Hermiticity***
  - ***BRST invariance***
  - ***EM charge conservation***
  - ***Particle mixings, mass terms, and mass matrices***

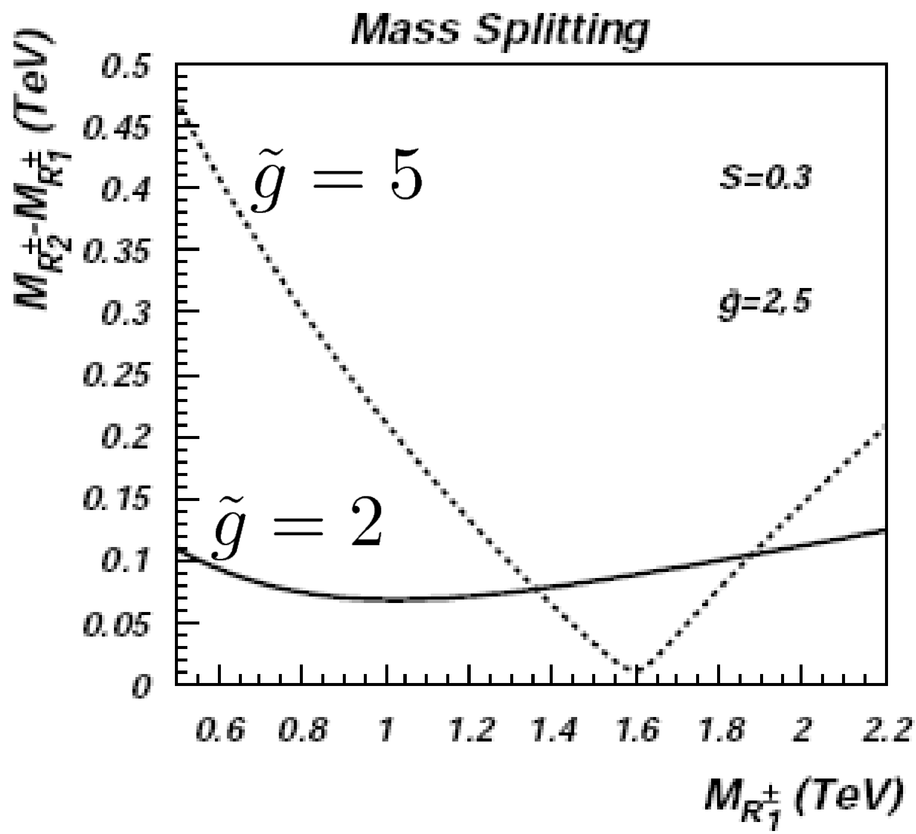
↔

## CalcHEP (AP, AB,NC)

- **Automatic calculations of tree-level processes within user-defined model**
- **User friendly graphical interface**
- **Easy implementation of new models**
  - **Especially using LanHEP**
- **Feynman gauge and unitary gauge**
  - **Important cross check.**

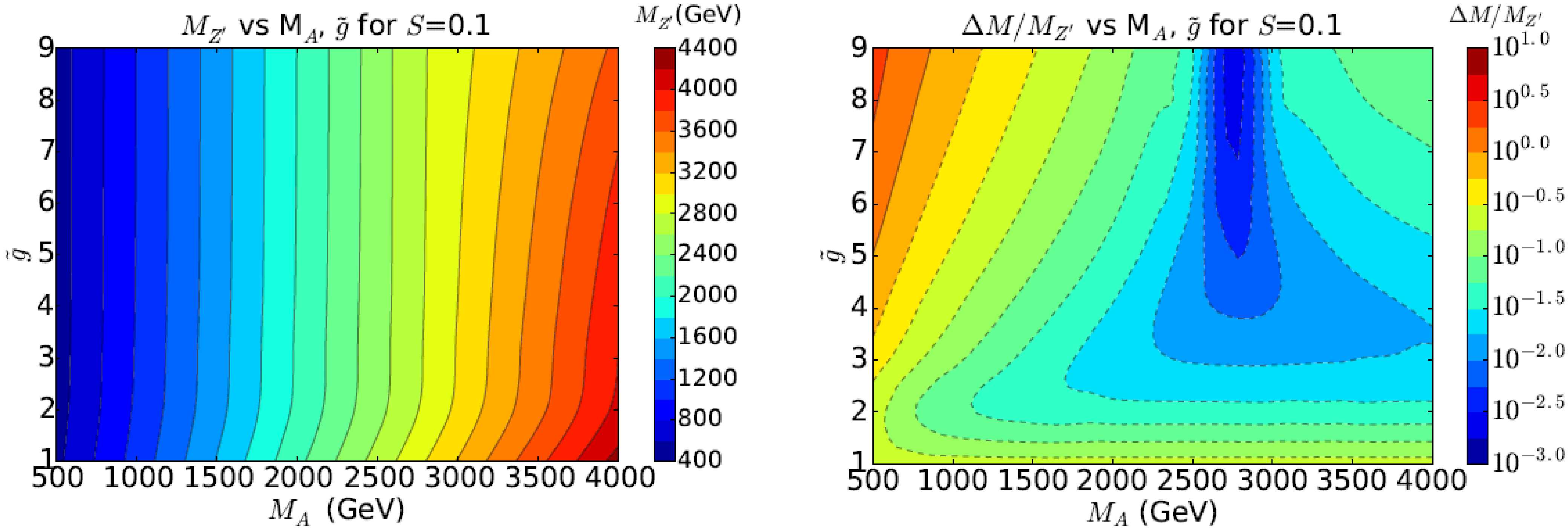
# Mass Spectrum



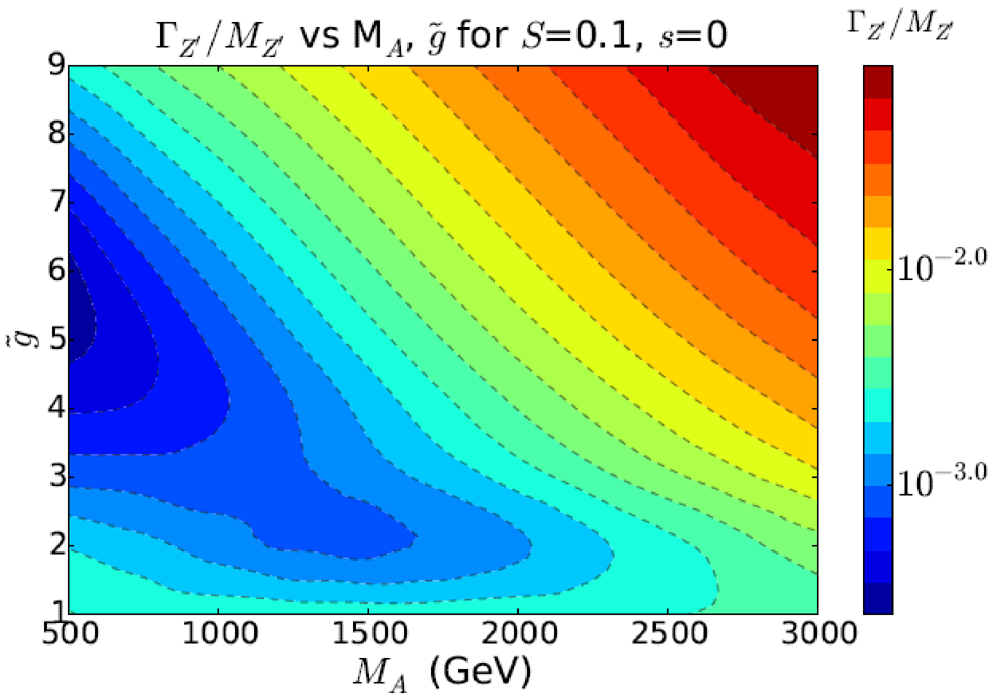

$$M^{\rm inv} = \sqrt{\frac{4\pi}{S}} F_\pi \ .$$

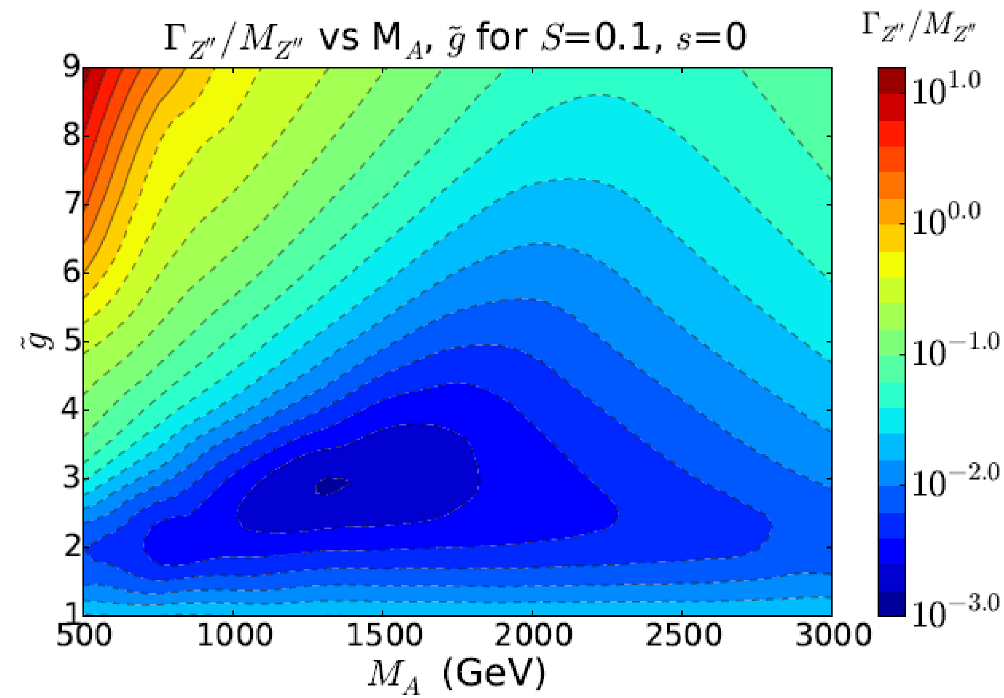
# Mass Spectrum




$$M_{inv}^2 = \left(1 + \frac{g_1^2 + g_2^2}{\tilde{g}^2}\right) \frac{4\pi}{S} F_\pi^2$$

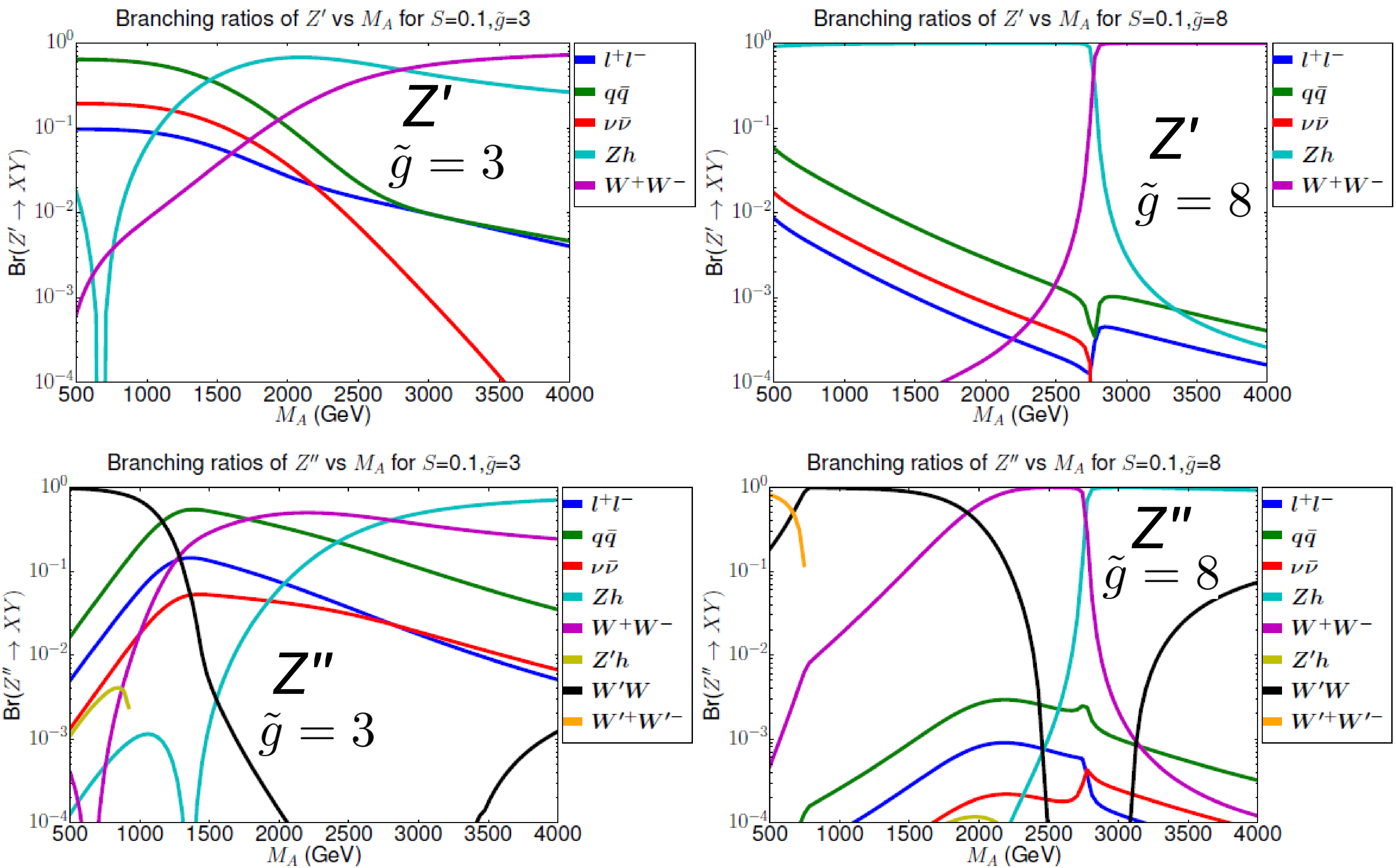
# Width/Mass ratio



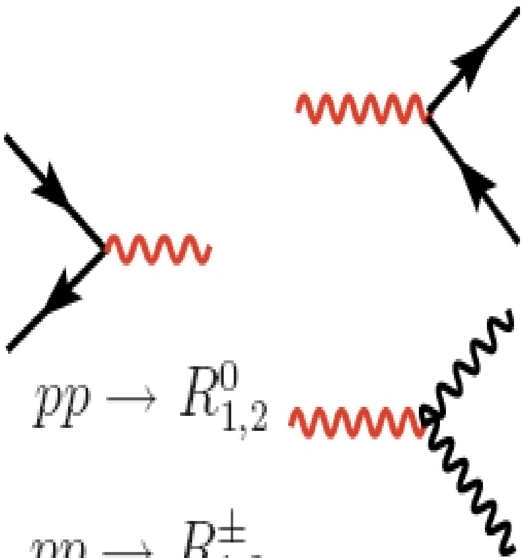




***Z' is narrow  essentially due to the small value of the S-parameter***

# Decay Branching Ratios



# LHC Signatures $R^0_{1,2} \equiv Z', Z'' \quad R^\pm_{1,2} \equiv W'^\pm, W''^\pm$



$pp \to R^0_{1,2}$

$pp \to R^\pm_{1,2}$

(1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$

(2) $\ell + \not{E}_T$ signature from the process $pp \to R^\pm_{1,2} \to \ell^\pm\nu$

(3) $3\ell + \not{E}_T$ signature from the process $pp \to R^\pm_{1,2} \to ZW^\pm \to 3\ell\nu$

***detector acceptance cuts***

$$|\eta^\ell| < 2.5 \qquad p_T^\ell > 15 \text{ GeV}$$

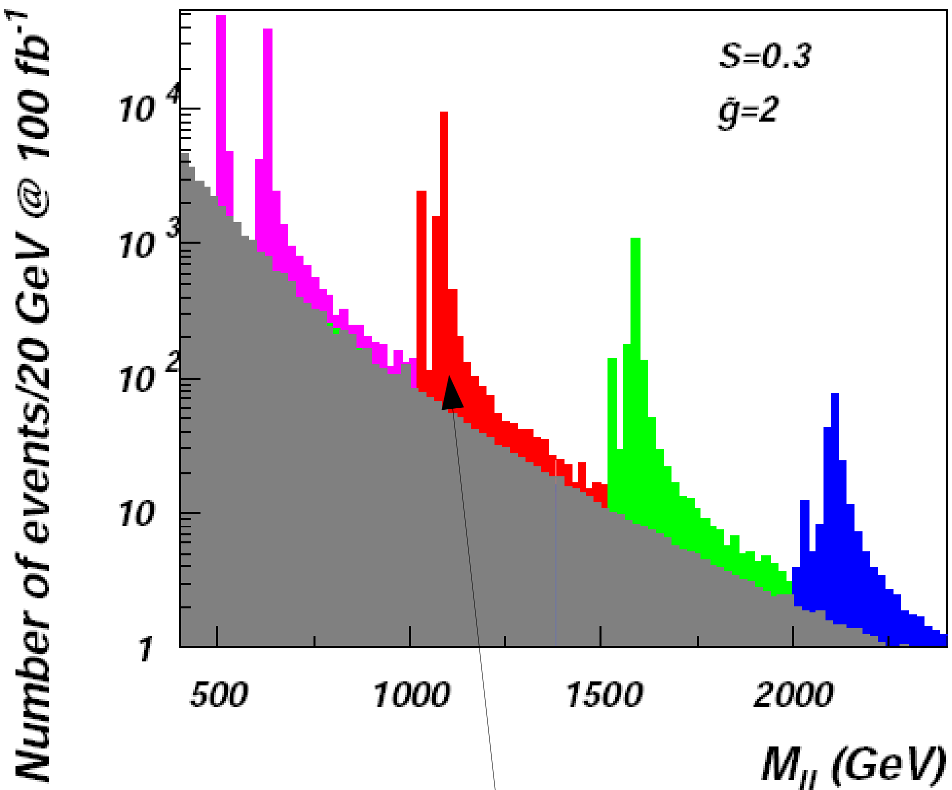
***transverse mass variable***

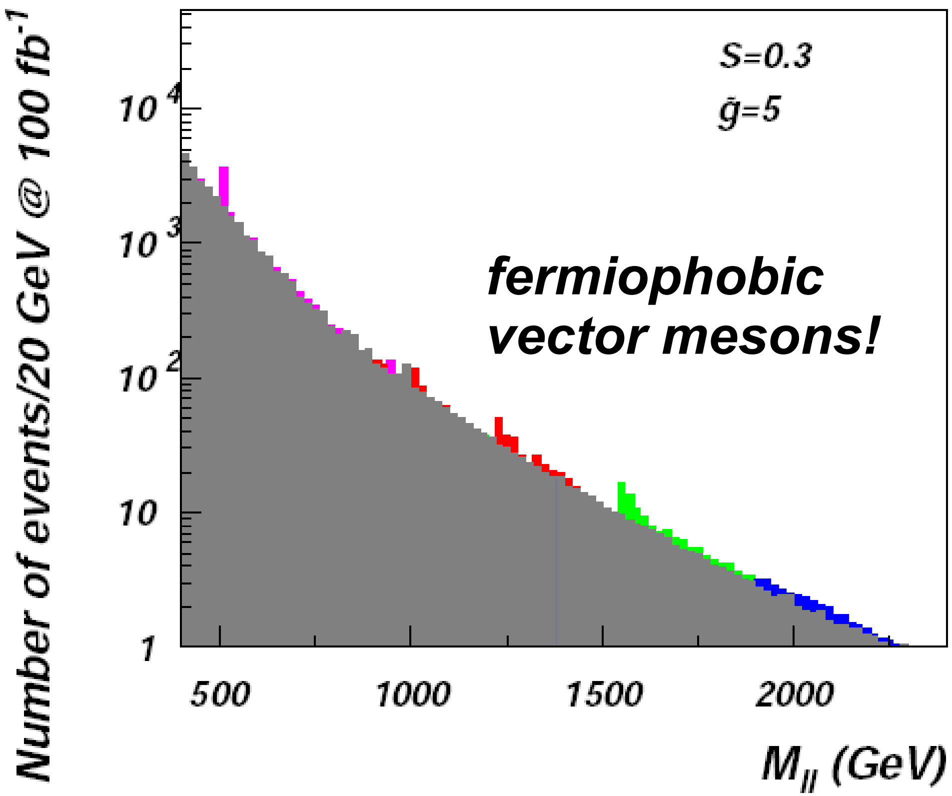
$$(M_\ell^T)^2 = [\sqrt{M^2(\ell) + p_T^2(\ell)} + |\not{p}_T|]^2 - |\vec{p}_T(\ell) + \vec{\not{p}}_T|^2$$

$$(M_{3\ell}^T)^2 = [\sqrt{M^2(\ell\ell\ell) + p_T^2(\ell\ell\ell)} + |\not{p}_T|]^2 - |\vec{p}_T(\ell\ell\ell) + \vec{\not{p}}_T|^2$$

# Signature (1)

(1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$




***double resonance signal pattern can be resolved***

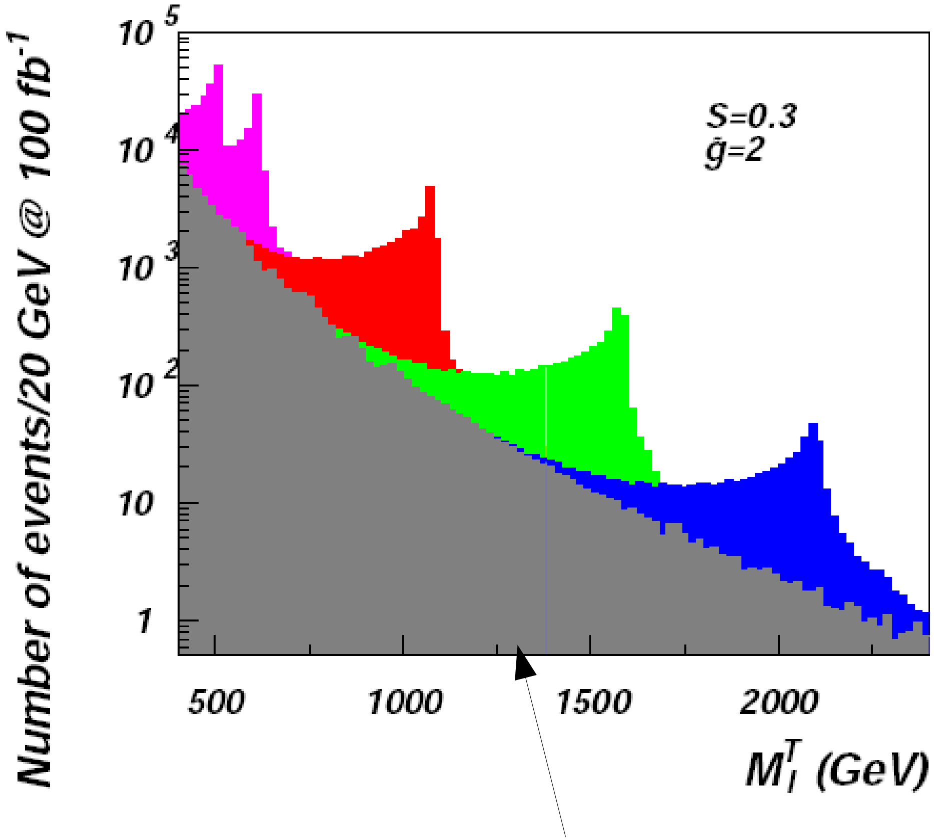
***couplings a suppressed by 1/gt***

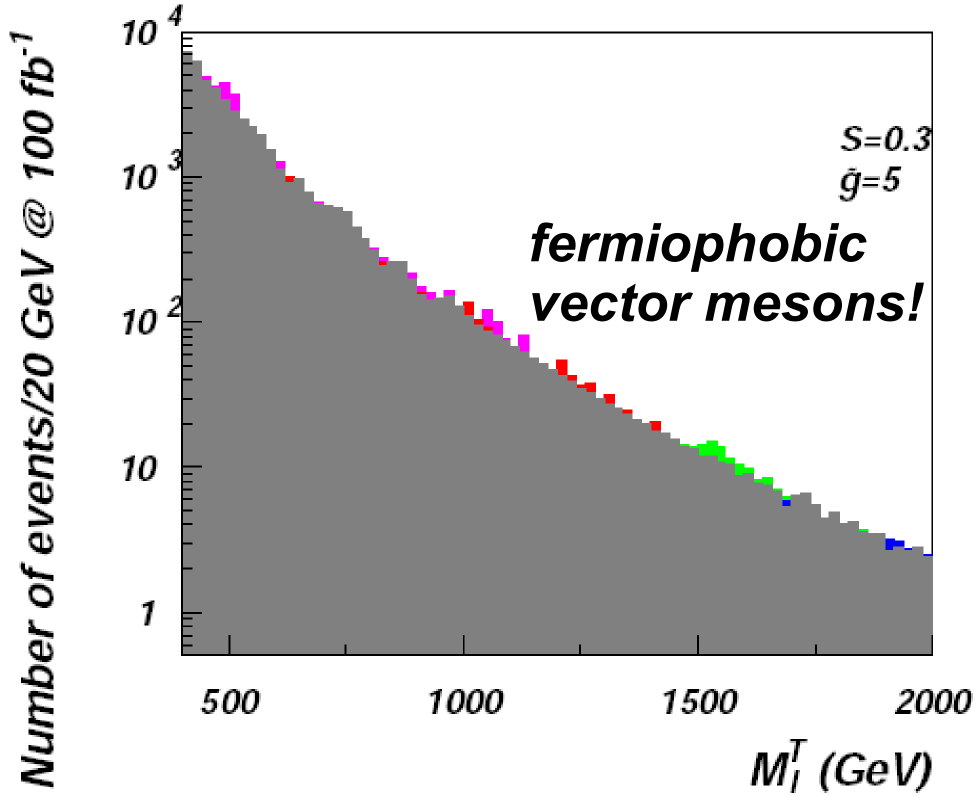
$$g^L_{Z'f\bar{f}} = \frac{\chi}{2\sqrt{2}\tilde{g}}\left(-I_3 g_2^2 + Y g_1^2\right), \qquad g^R_{Z'f\bar{f}} = \frac{\chi}{2\sqrt{2}\tilde{g}} q_f g_1^2,$$

$$g^L_{Z''f\bar{f}} = \frac{1}{2\sqrt{2}\tilde{g}}\left(I_3 g_2^2 + Y g_1^2\right), \qquad g^R_{Z''f\bar{f}} = \frac{1}{2\sqrt{2}\tilde{g}} q_f g_1^2,$$

# Signature (2)

(2) $\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to \ell^{\pm}\nu$

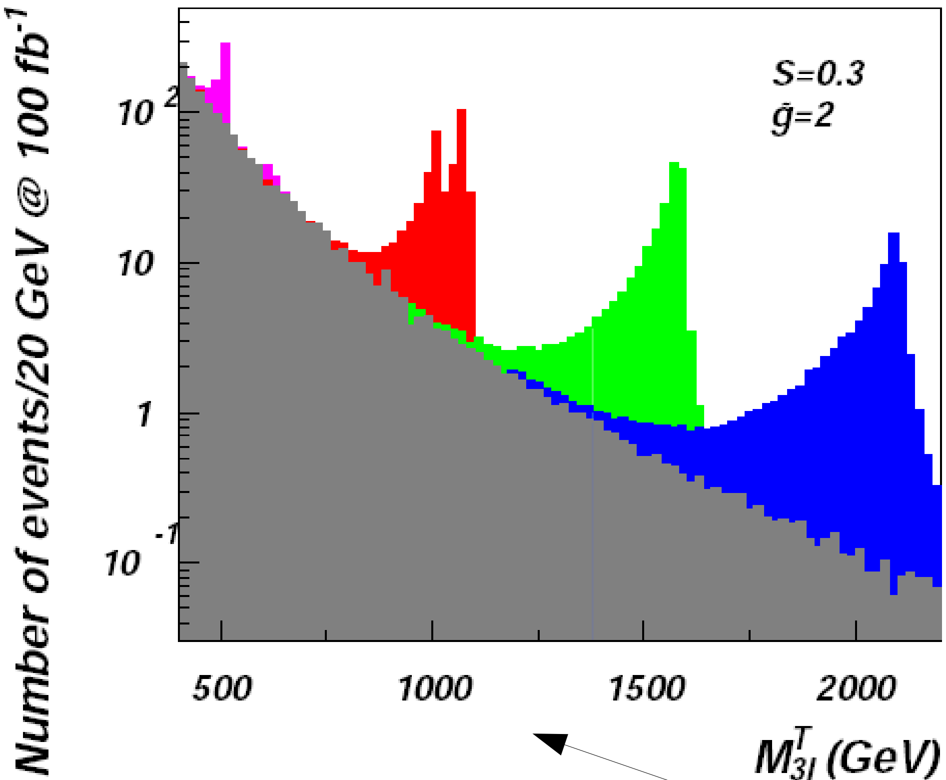


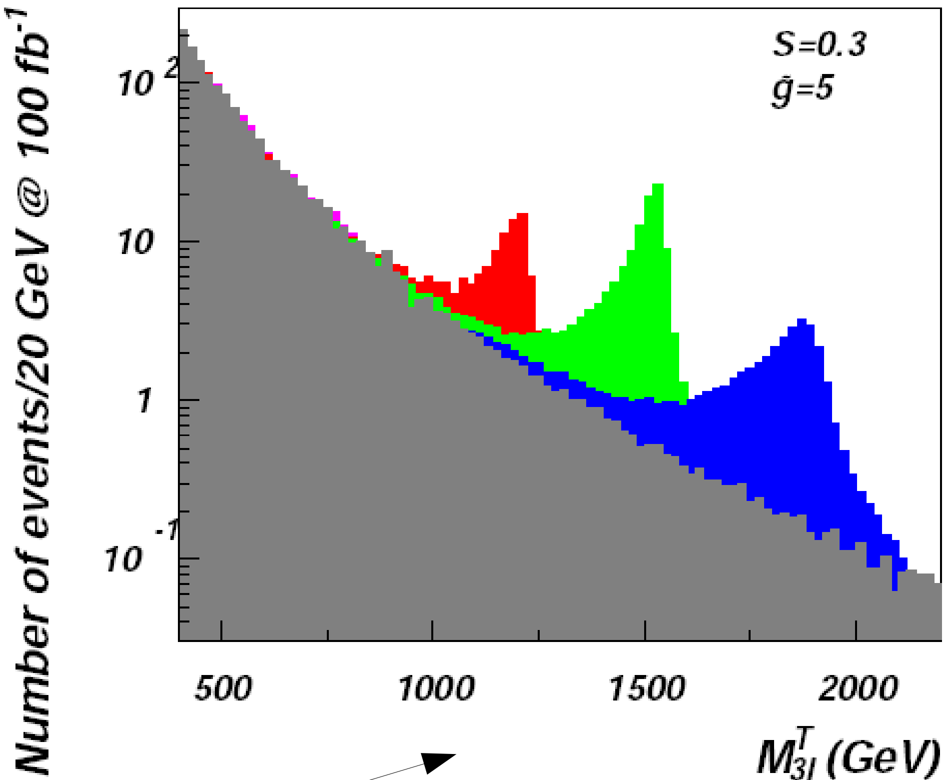




***for higher masses only one resonance is observed***

# Signature (3)

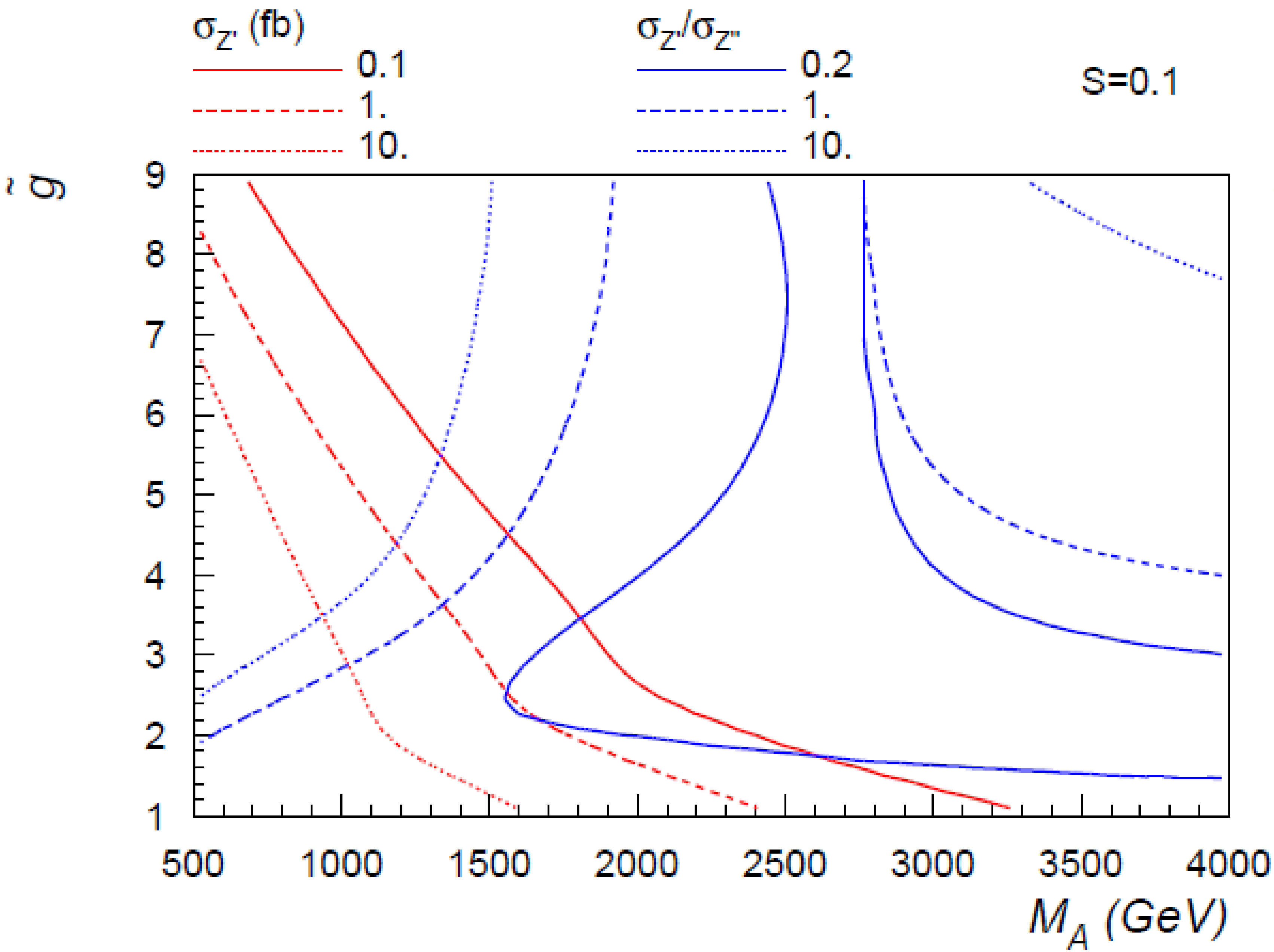
(3) $3\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$



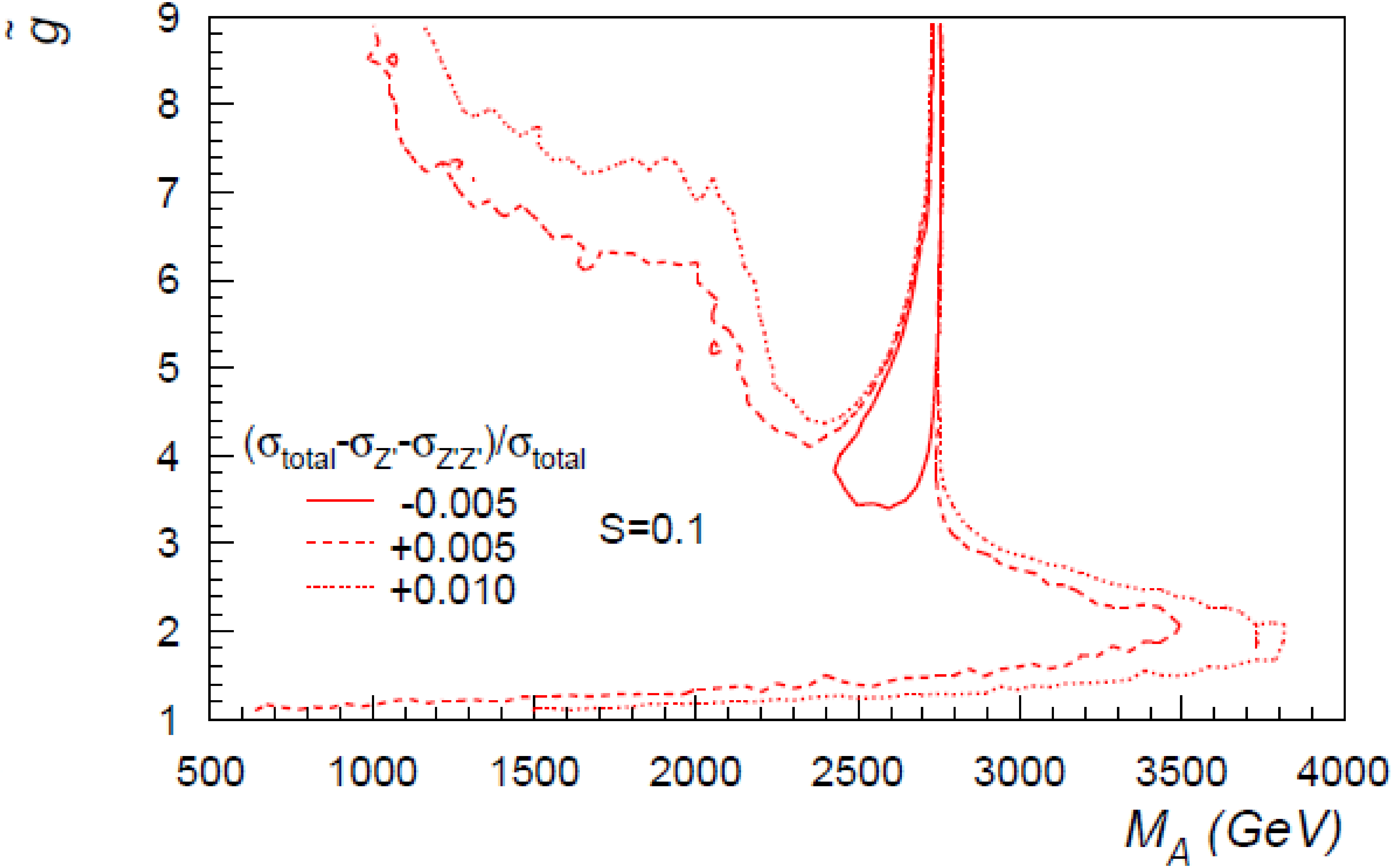




***highly complementary channel to fermiophobic ones: not very high rates, but clean signal***

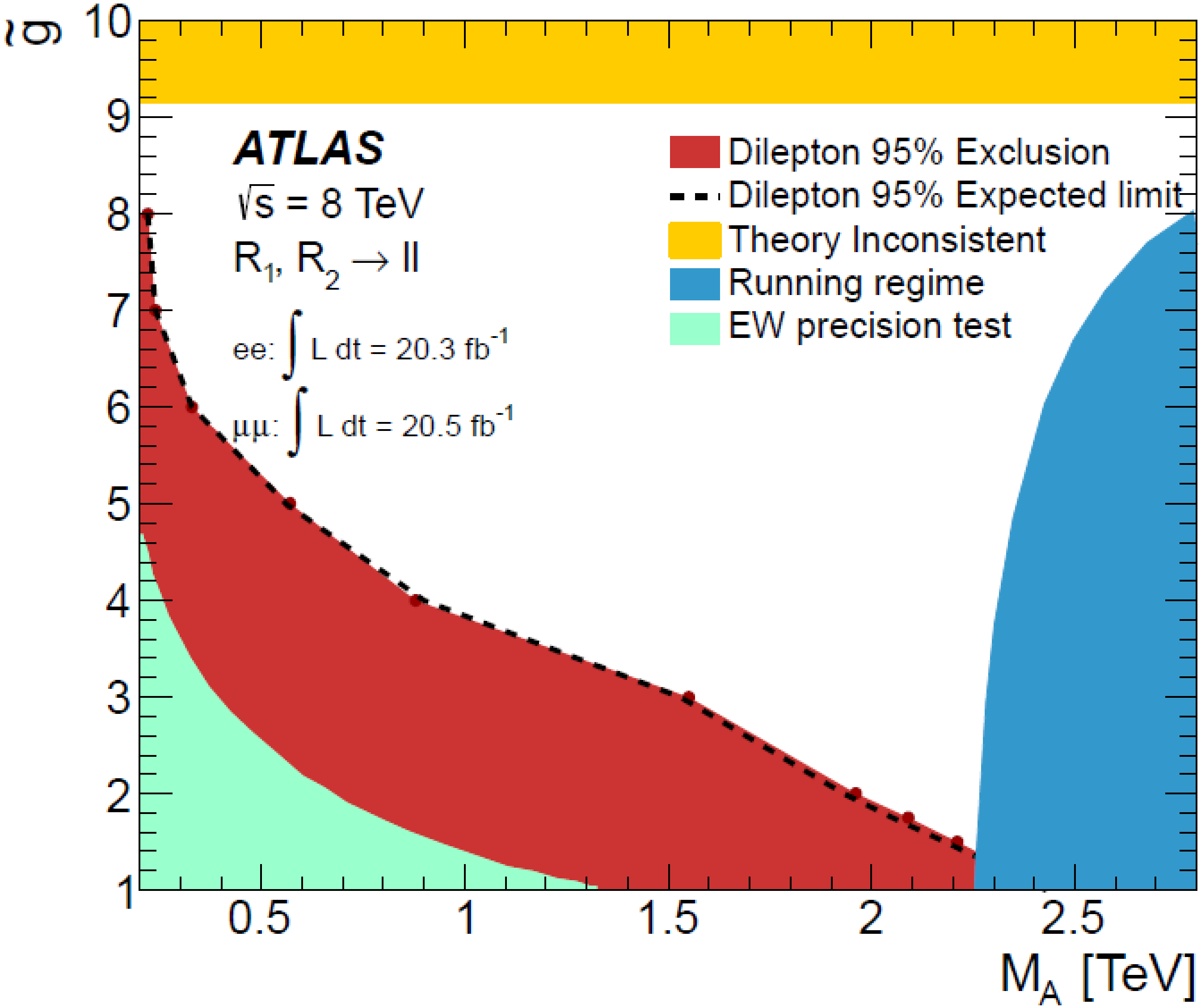
# Interplay of Z' and Z": relative production rates



# Interplay of Z' and Z": interference

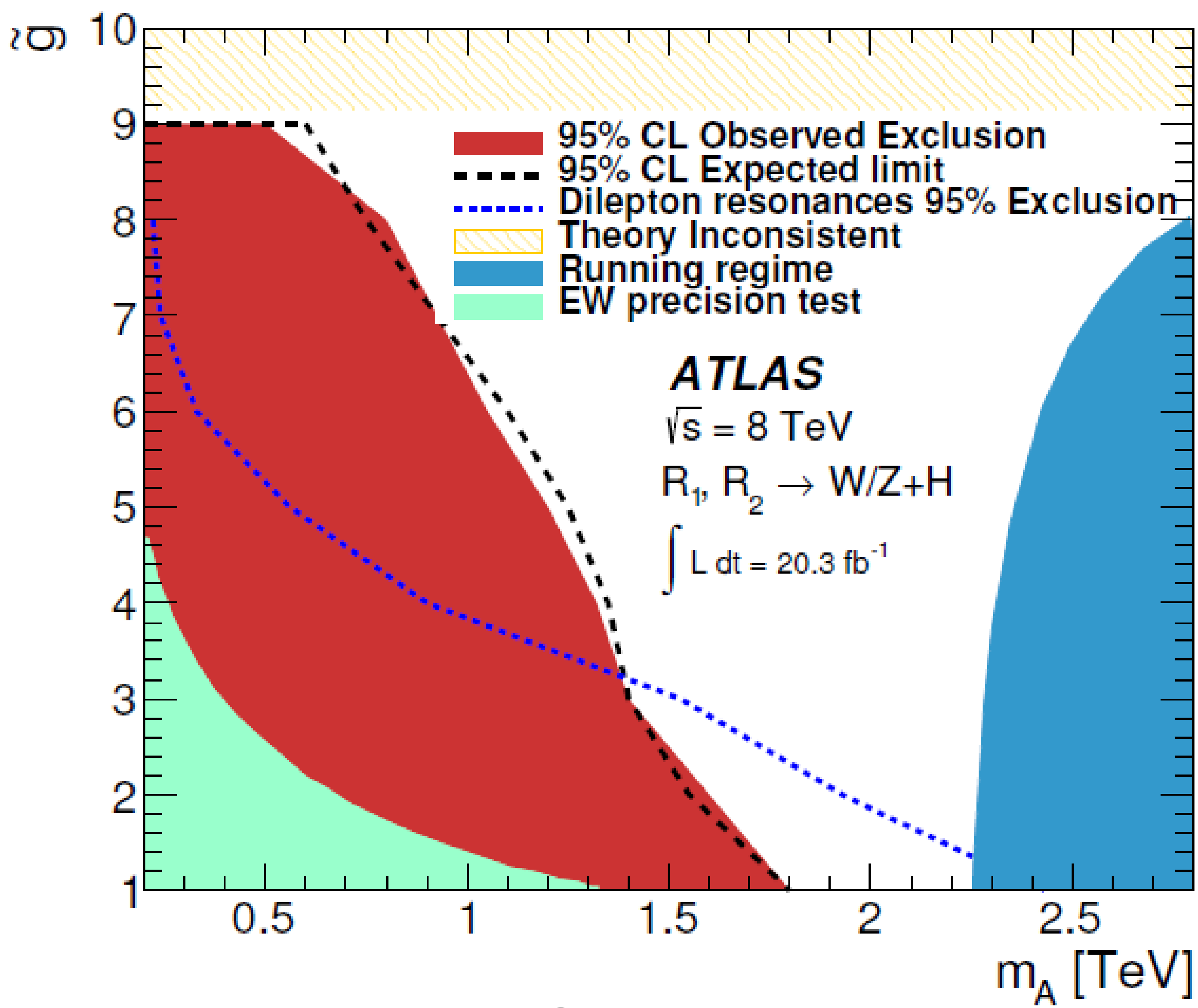


# Previous results from ATLAS – just one benchmark



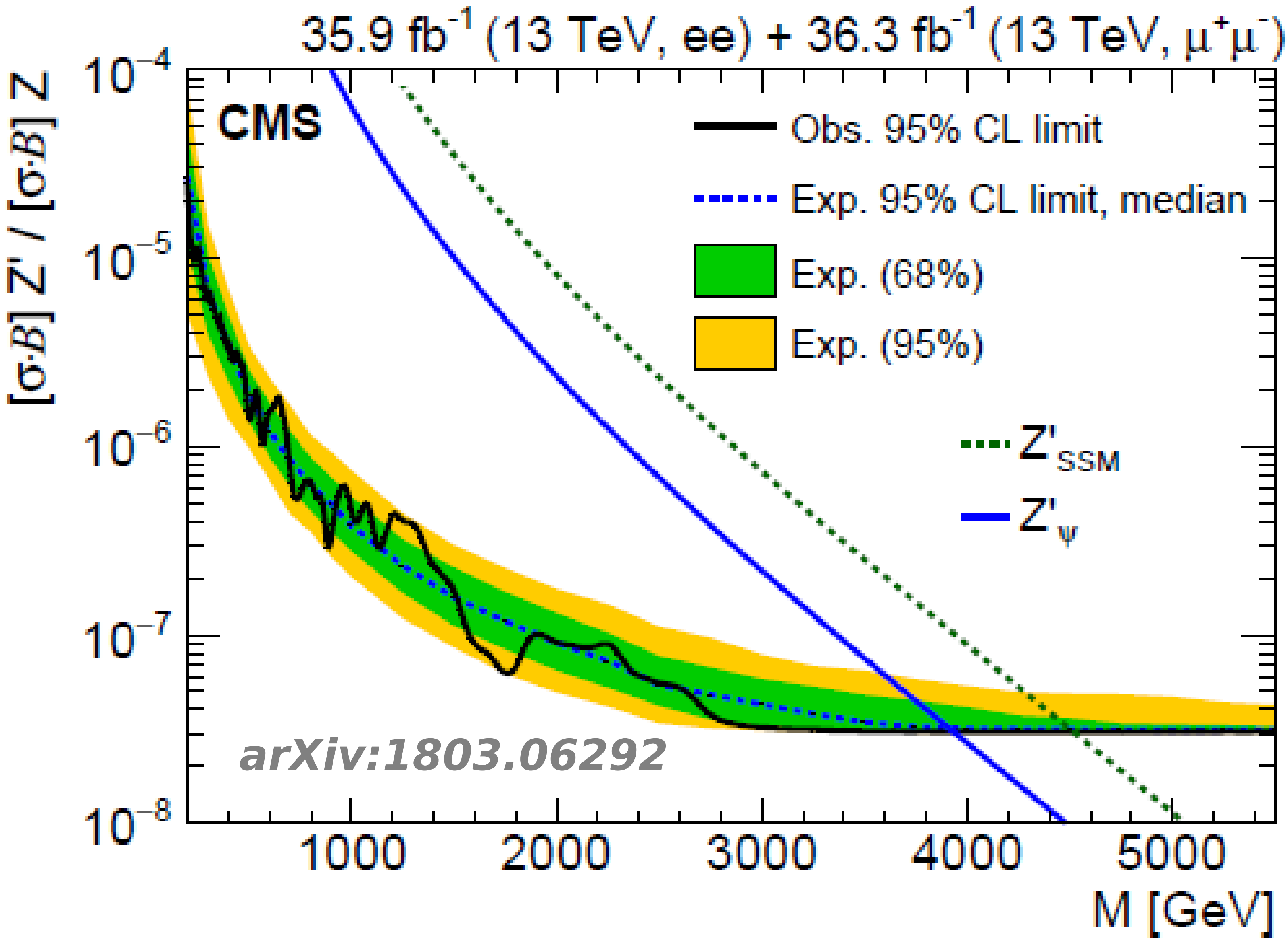

***ATLAS-1405.4123***

# Previous results from ATLAS – just one benchmark

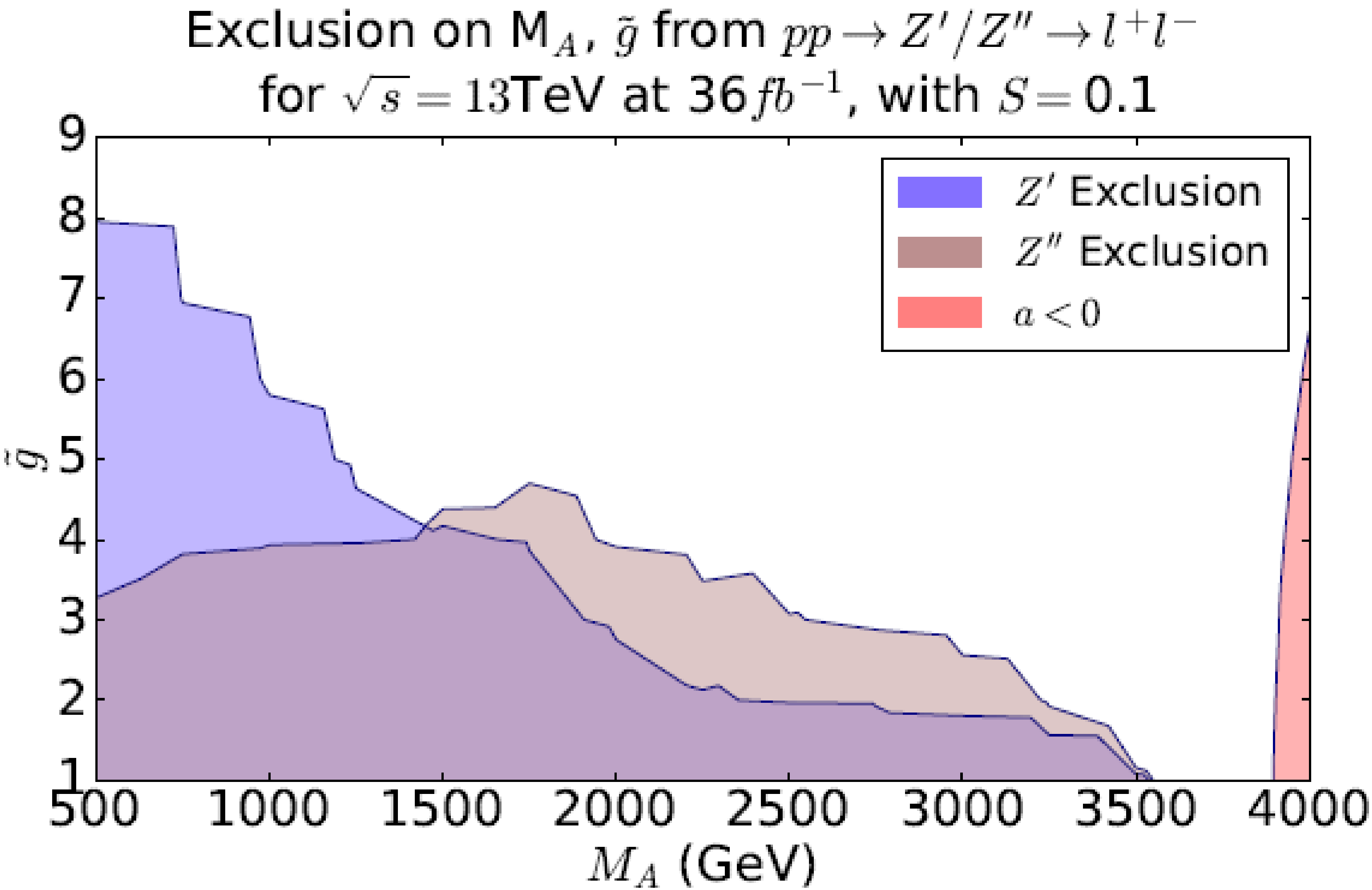


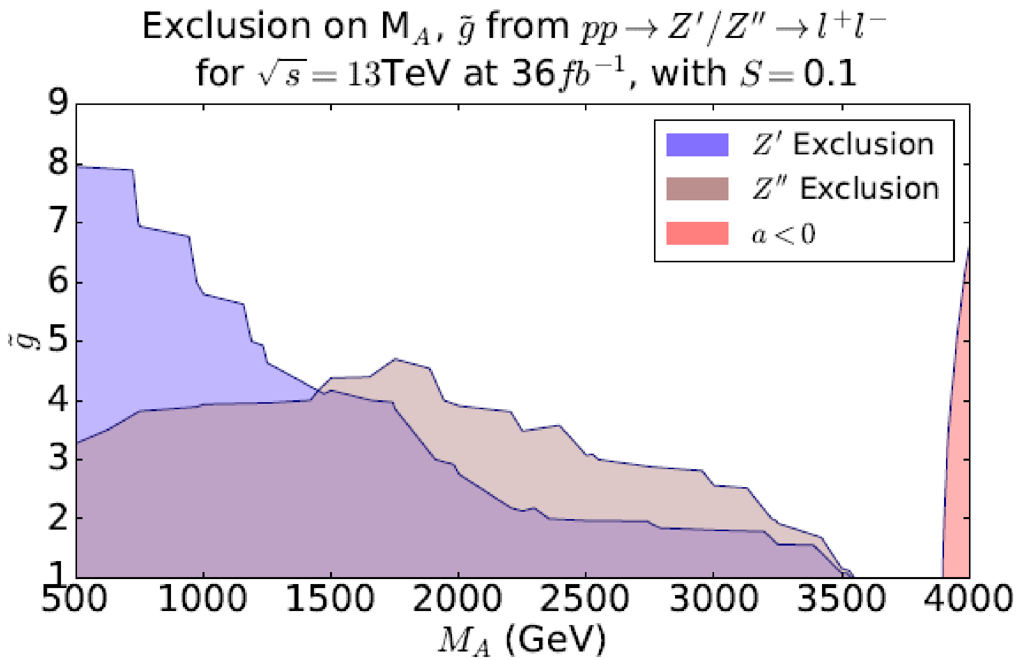

***ATLAS-1503.08089***

# Recent LHC results

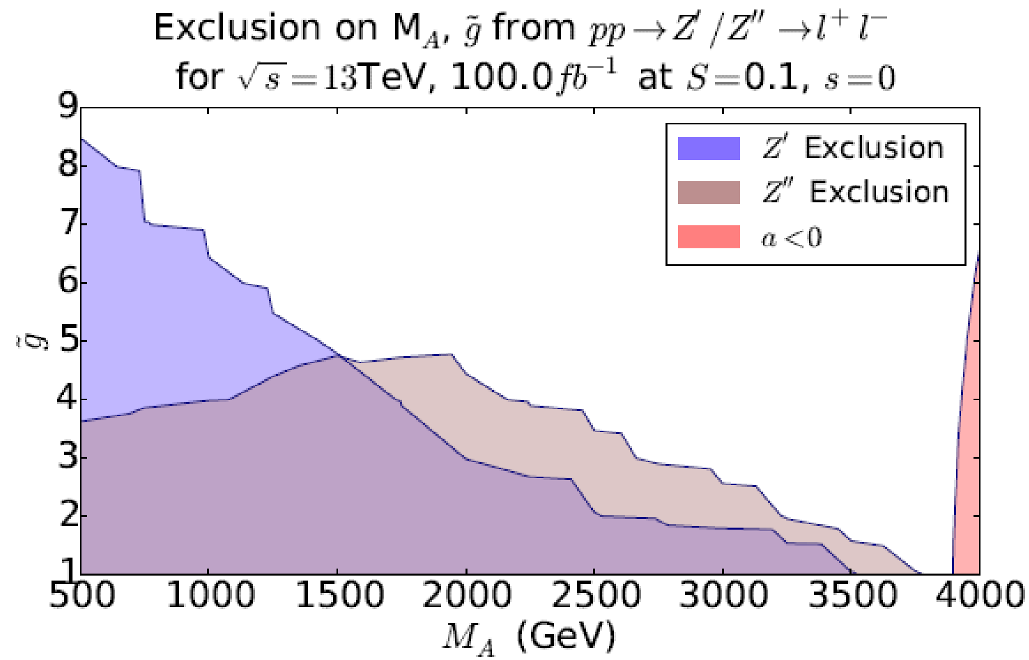


# WTC space exclusion using LHC searches

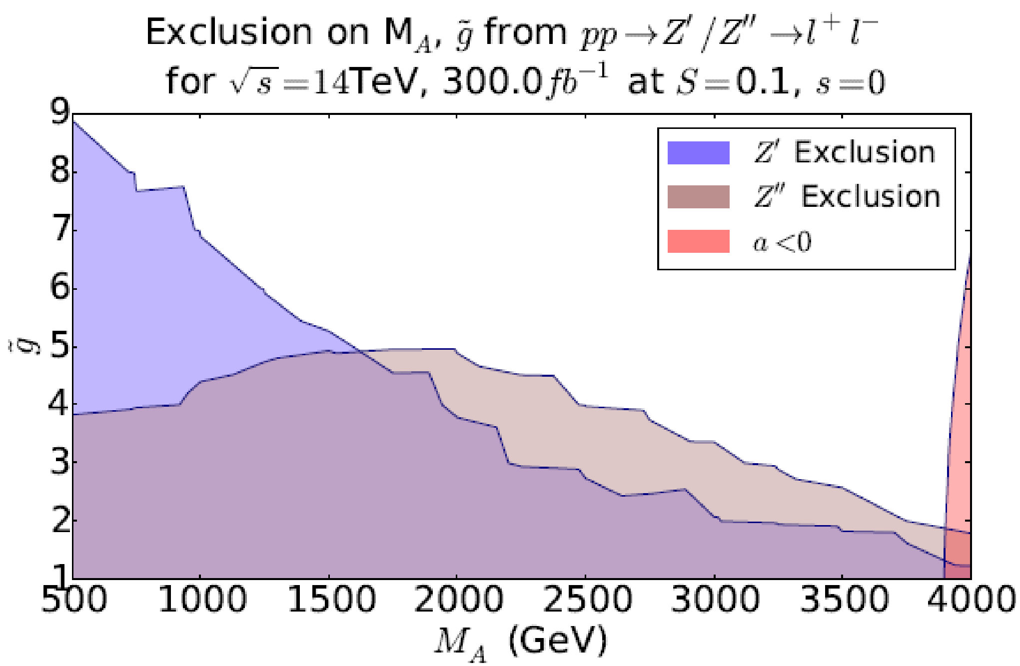


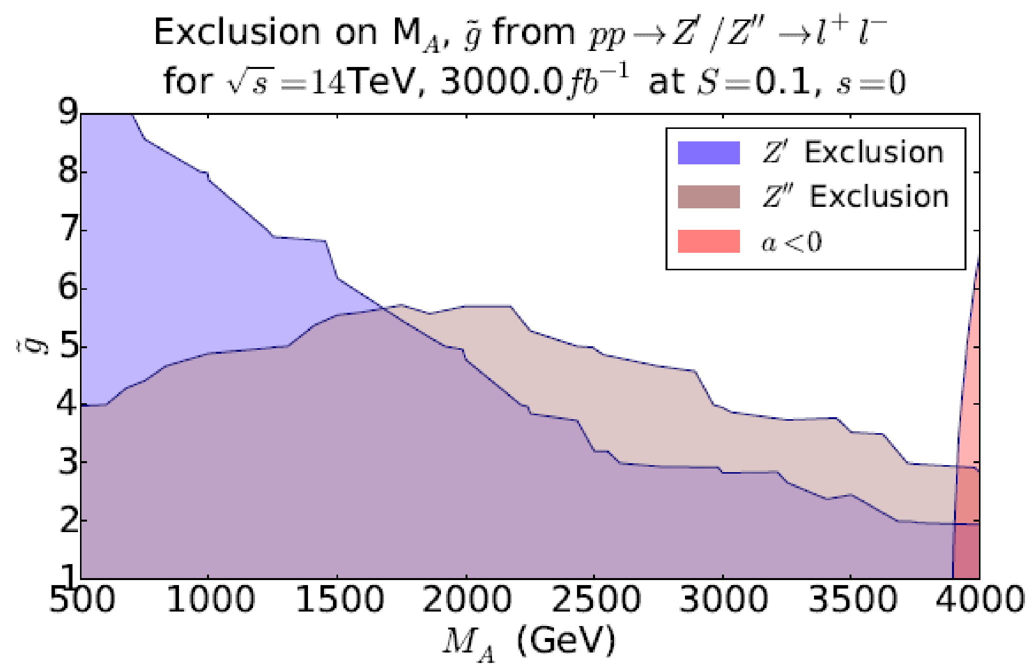

Exclusion on $M_A$, $\tilde{g}$ from $pp \to Z'/Z'' \to l^+l^-$
for $\sqrt{s} = 13$TeV at $36\,fb^{-1}$, with $S = 0.1$
$Z'$ Exclusion
$Z''$ Exclusion
$a < 0$
$\tilde{g}$
$M_A$ (GeV)

(a)


Exclusion on $M_A$, $\tilde{g}$ from $pp \to Z'/Z'' \to l^+l^-$
for $\sqrt{s} = 13$TeV, $100.0\,fb^{-1}$ at $S = 0.1$, $s = 0$
$Z'$ Exclusion
$Z''$ Exclusion
$a < 0$
$\tilde{g}$
$M_A$ (GeV)

(b)


Exclusion on $M_A$, $\tilde{g}$ from $pp \to Z'/Z'' \to l^+l^-$
for $\sqrt{s} = 14$TeV, $300.0\,fb^{-1}$ at $S = 0.1$, $s = 0$
$Z'$ Exclusion
$Z''$ Exclusion
$a < 0$
$\tilde{g}$
$M_A$ (GeV)


Exclusion on $M_A$, $\tilde{g}$ from $pp \to Z'/Z'' \to l^+l^-$
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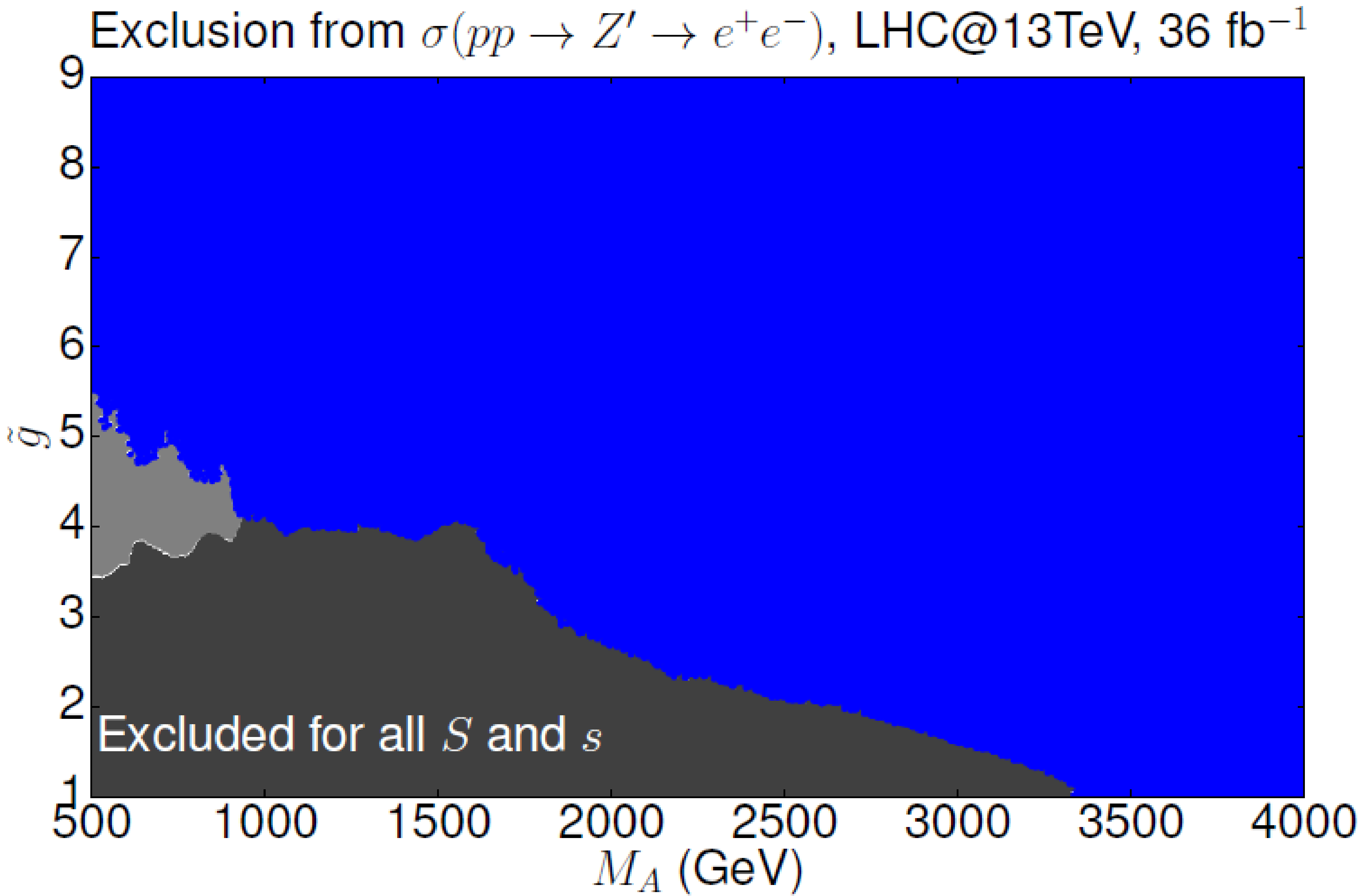
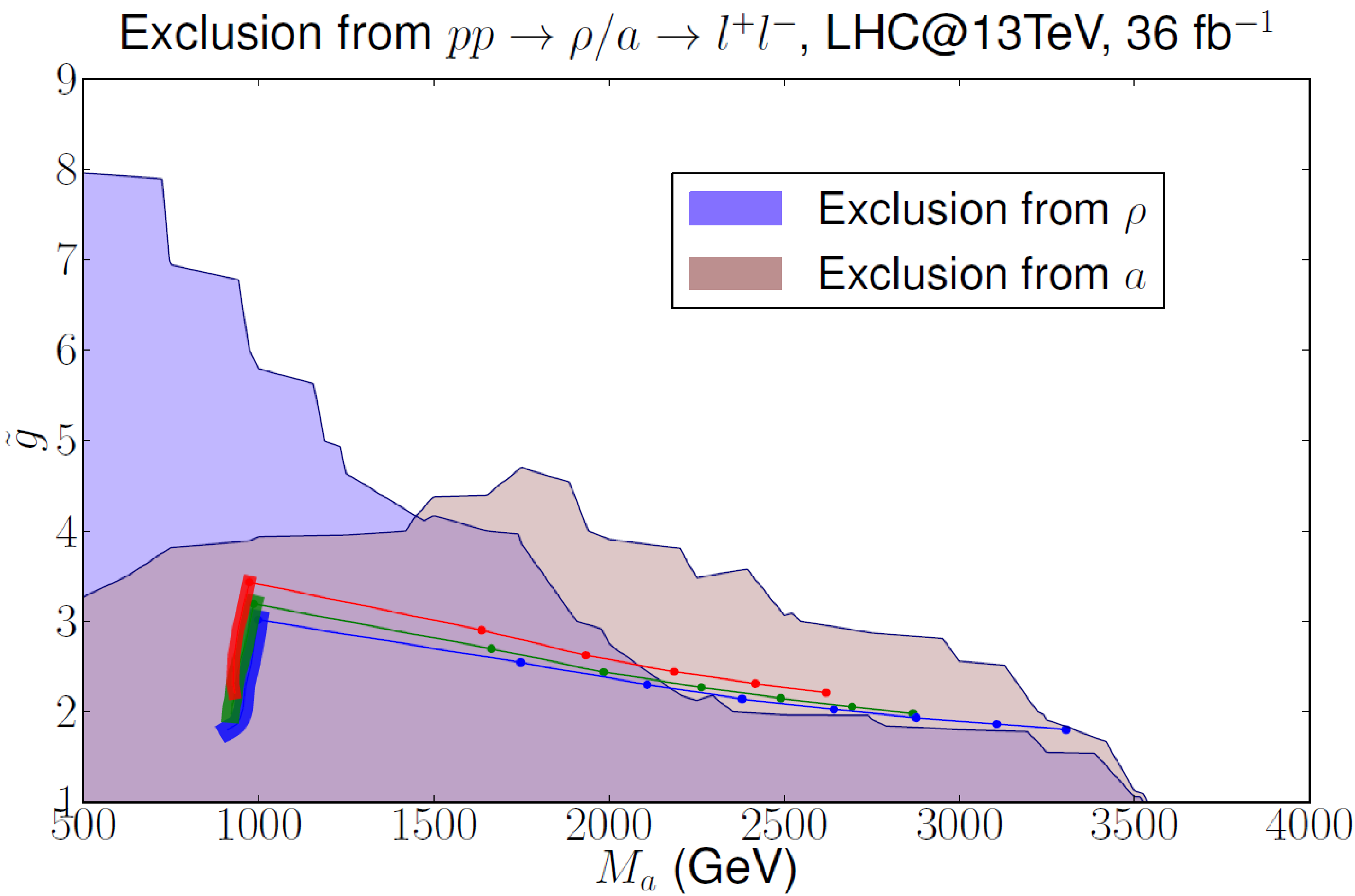
$Z'$ Exclusion
$Z''$ Exclusion
$a < 0$
$\tilde{g}$
$M_A$ (GeV)

# WTC space exclusion using from 4D scan

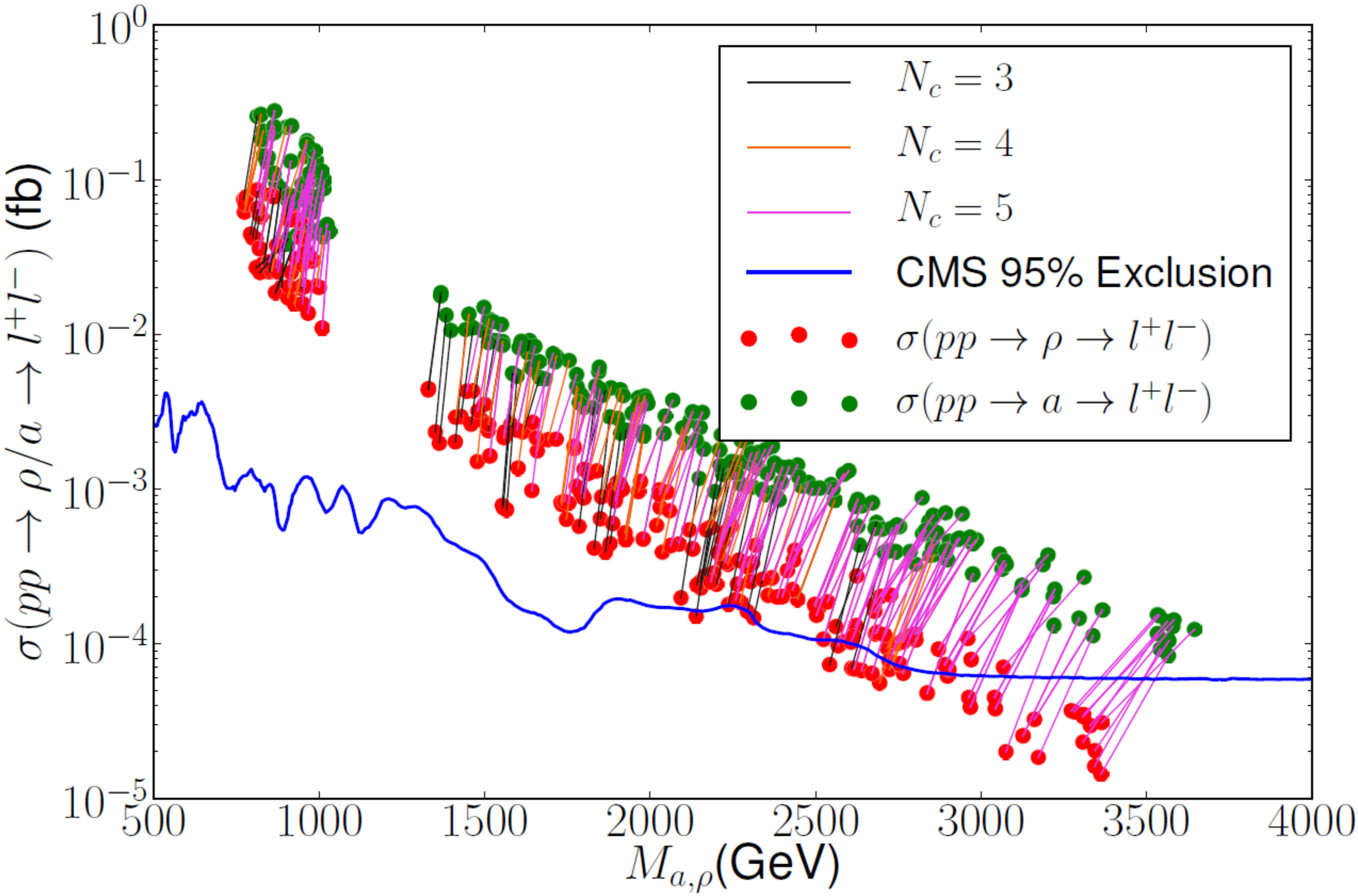


# WTC space exclusion within Holographic approach ( see Nick's talk)




**The role of pseudo-vector (Z") is crucial!**

# WTC space exclusion within Holographic approach




**The whole predicted 4D WTC parameter space is excluded!**