Conformal Dynamics from LHC to Cosmology III

Francesco Sannino

Zakopane 2009

CP^3-Origins

Particle Physics & Origins of Mass

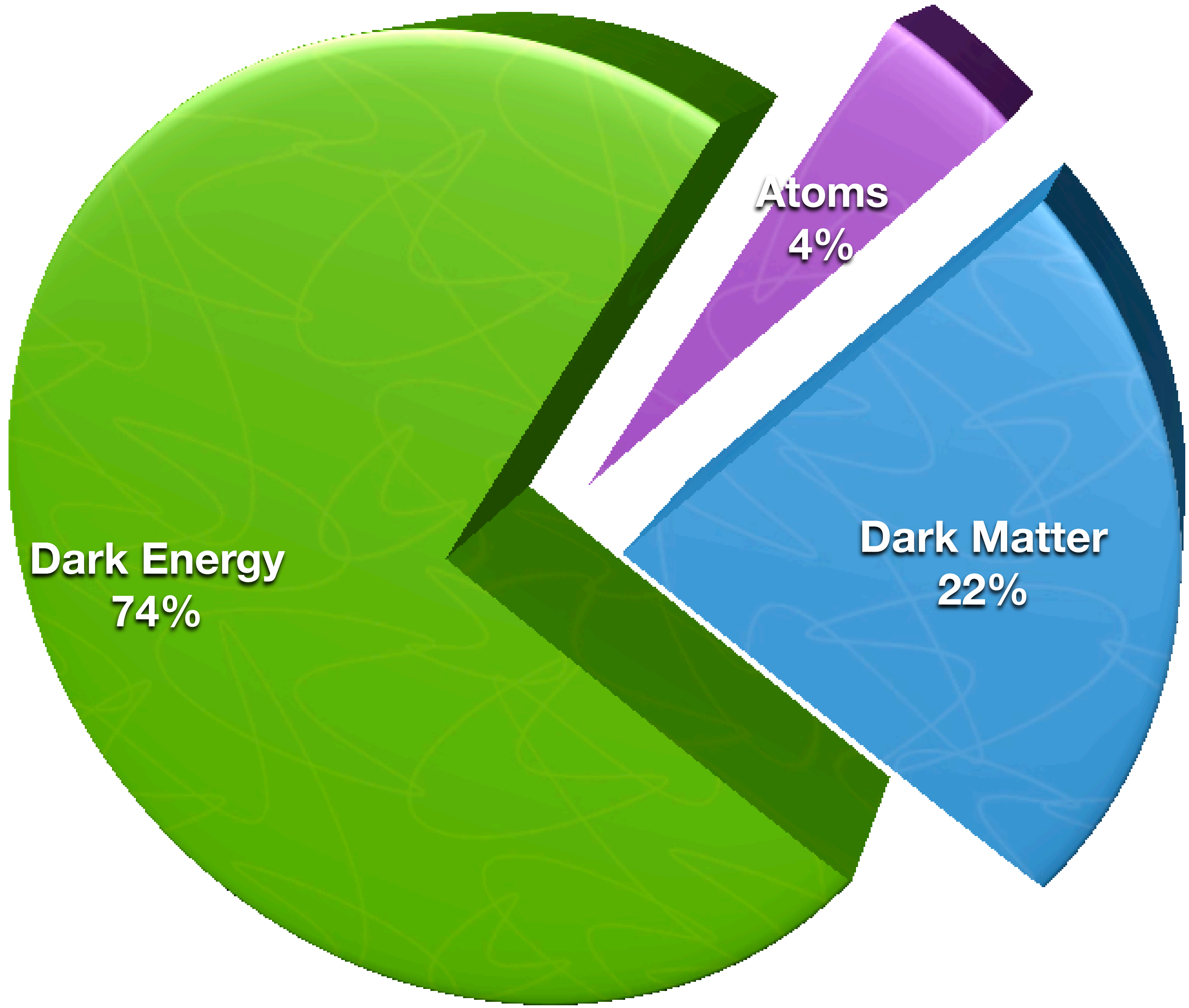

Technicolor
TOM HANKS
ANGELS & DEMONS

Lecture 1

SM is Unnatural

DEWSB

Need for Conformal Dynamics



Atoms
4%
Dark Matter
22%
Dark Energy
74%

Dark Matter

$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

Ω_B

U(1) baryon number approx. conserved.

We observe a B - Anti B asymmetry.

EW unbroken B - L allows B to survive the EW transition.

B - L need not to be conserved at GUT scales

What if DM is due to an asymmetry?

A particle similar to the nucleon

But electrically neutral

At most EW-type cross sections

Great if connected to the ESWB

Technicolor is a natural example (**TIMP**)

Technibarion is similar to the nucleon

TB number like the B number

At most EW-type cross sections

EW scale and interactions built in

Ultra Minimal Technicolor is the first physical realization
Ryttov - F.S. 08

PAMELA/ATIC Decaying Dark Matter + Unification,
Nardi, F.S., Strumia, 08.

Nussinov, 86
Barr - Chivukula - Farhi 90
Sarkar 96
Gudnason - Kouvaris - F.S. 06

Within Technicolor

TIMP can be a Boson or a Fermion

Can be (or not) neutral w.r.t. Weak Interactions

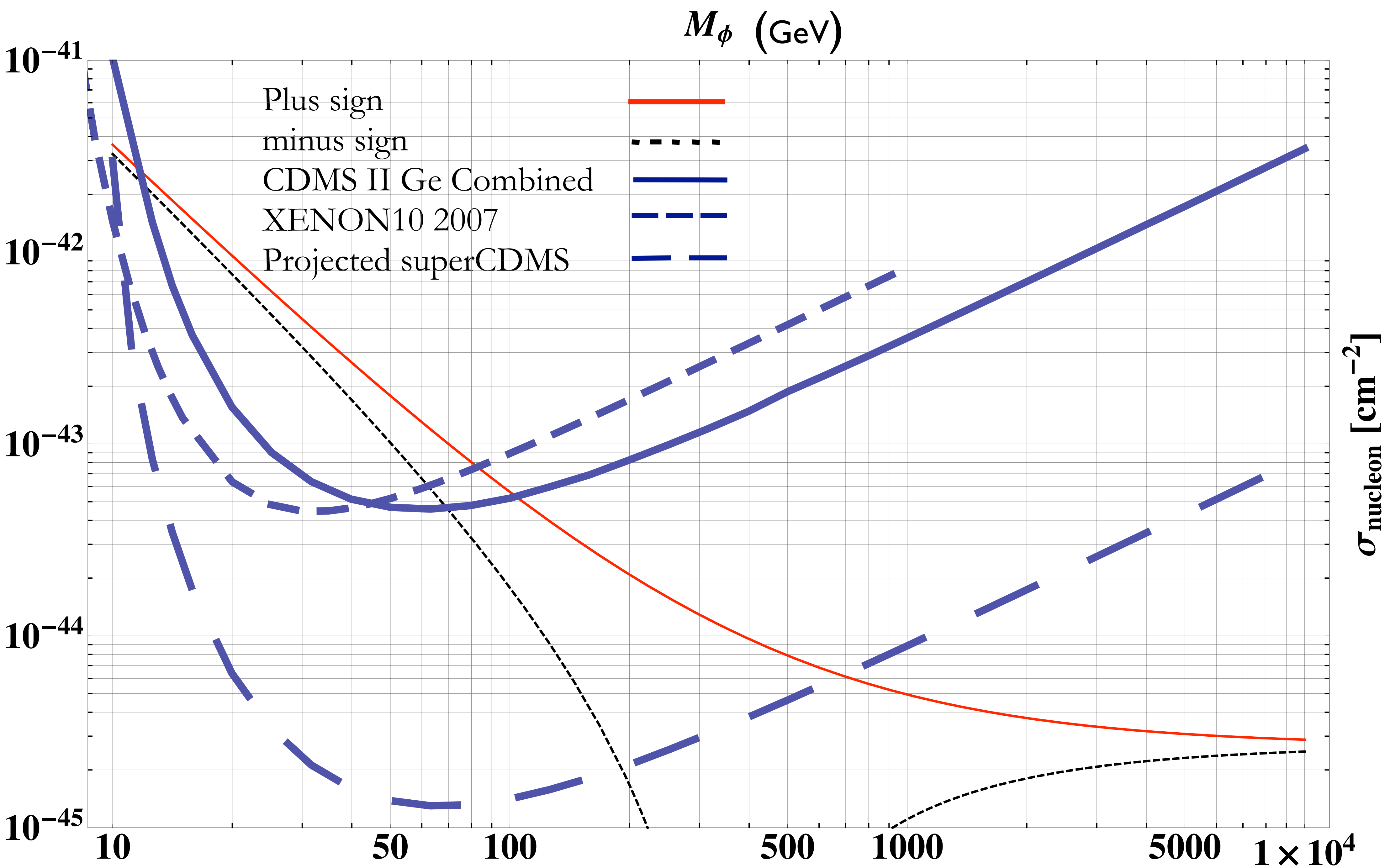
Ultra Minimal Technicolor

TIMP is a pseudo Goldstone-boson — Ryttov - F.S. 08

Composite Unparticle + TC — F.S. - Zwicky 08

Unbaryon (To investigate)

Earth Based Constraints



$d_M = 1$

$d_B = \pm 1$

$\Lambda = 3\ TeV$

$M_H = 300$ GeV

Foadi, Frandsen, F.S. 08

$$\sigma_{\text{nucleon}} = \frac{\mu^2}{4\pi}\left[\frac{Z}{A}\frac{8\pi\,\alpha\,d_B}{\Lambda^2} + \frac{d_M\, f m_N}{M_H^2 M_\phi}\right]^2$$

$$\mu = M_\phi m_N/(M_\phi + m_N)$$

Asymmetric DM Relic Density

$$\frac{m_{TB}}{m_p} \approx \frac{1 \text{ TeV}}{1 \text{ GeV}} = 10^3$$

$$\frac{TB}{B} \propto \exp\left[-\frac{m_{TB}(T^*)}{T^*}\right] \sim 10^{-3} \qquad T^* \sim 200 \text{ GeV}$$

$$\frac{\Omega_{TB}}{\Omega_B} = \frac{TB}{B}\frac{m_{TB}}{m_p} \sim \mathcal{O}(1)$$

Conditions

Universe Electric Neutrality

Chemical Equilibrium

EW Sphaleron Processes, Kuzmin-Rubakov-Shaposhnikov

TB - B violated at High Energies & approx. conserved at EW

(Extra) EW Phase Transitions

Baryogenesis

Cline, Jarvinen, F.S. 08

Jarvinen, Ryttov, F.S. 09

Lecture 2

Phases of Gauge Theories

Gauge Theories Knobs:

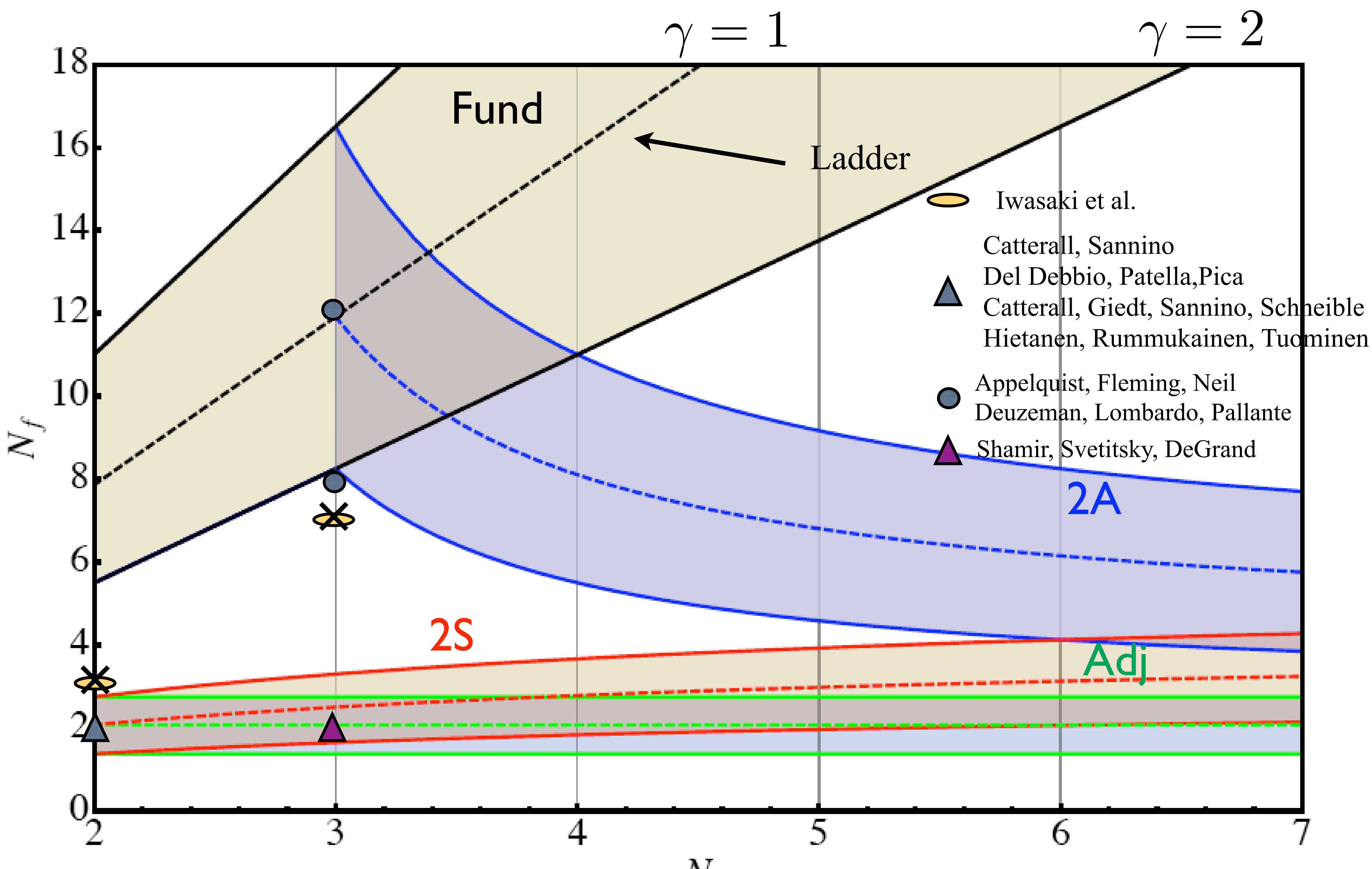
Nf, Nc, Representations, Temperature, ...

Discoveries:

IR CD for low number of flavors!

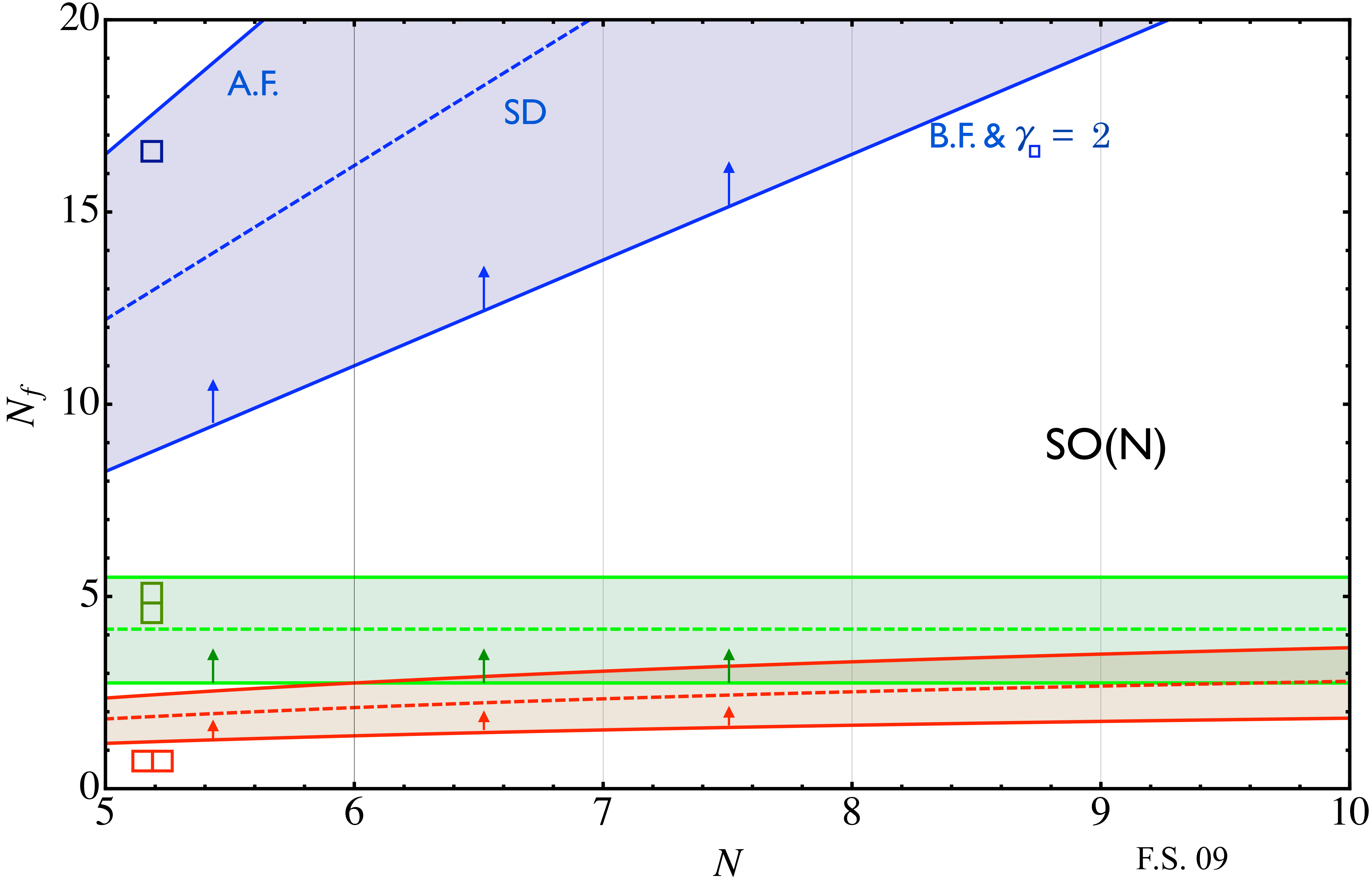
Universal Structure

Non-SUSY Phase Diagram Bound



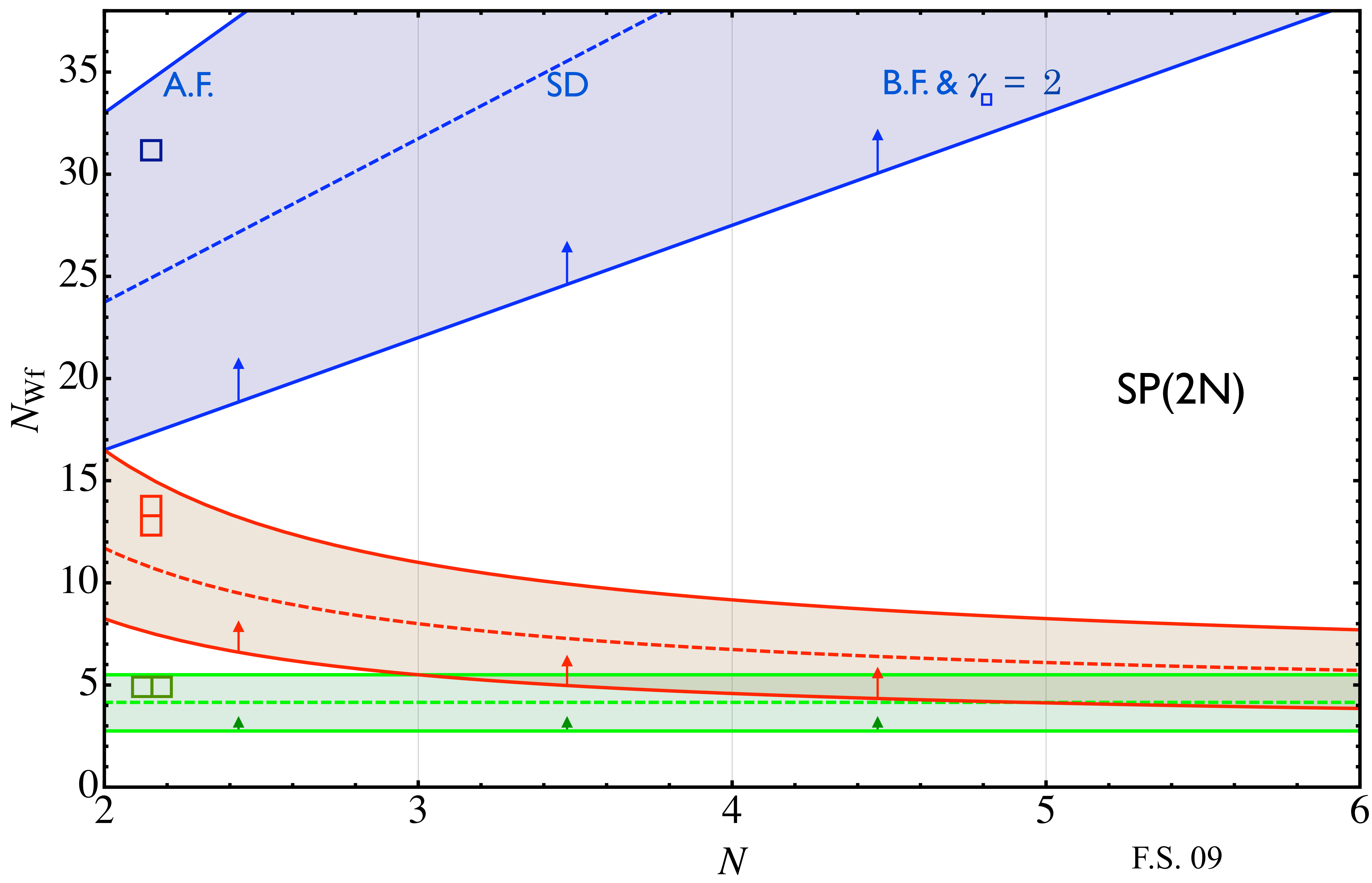
Ryttov and F.S. 07

SO(N) Phase Diagram



F.S. 09

Sp(2N) Phase Diagram

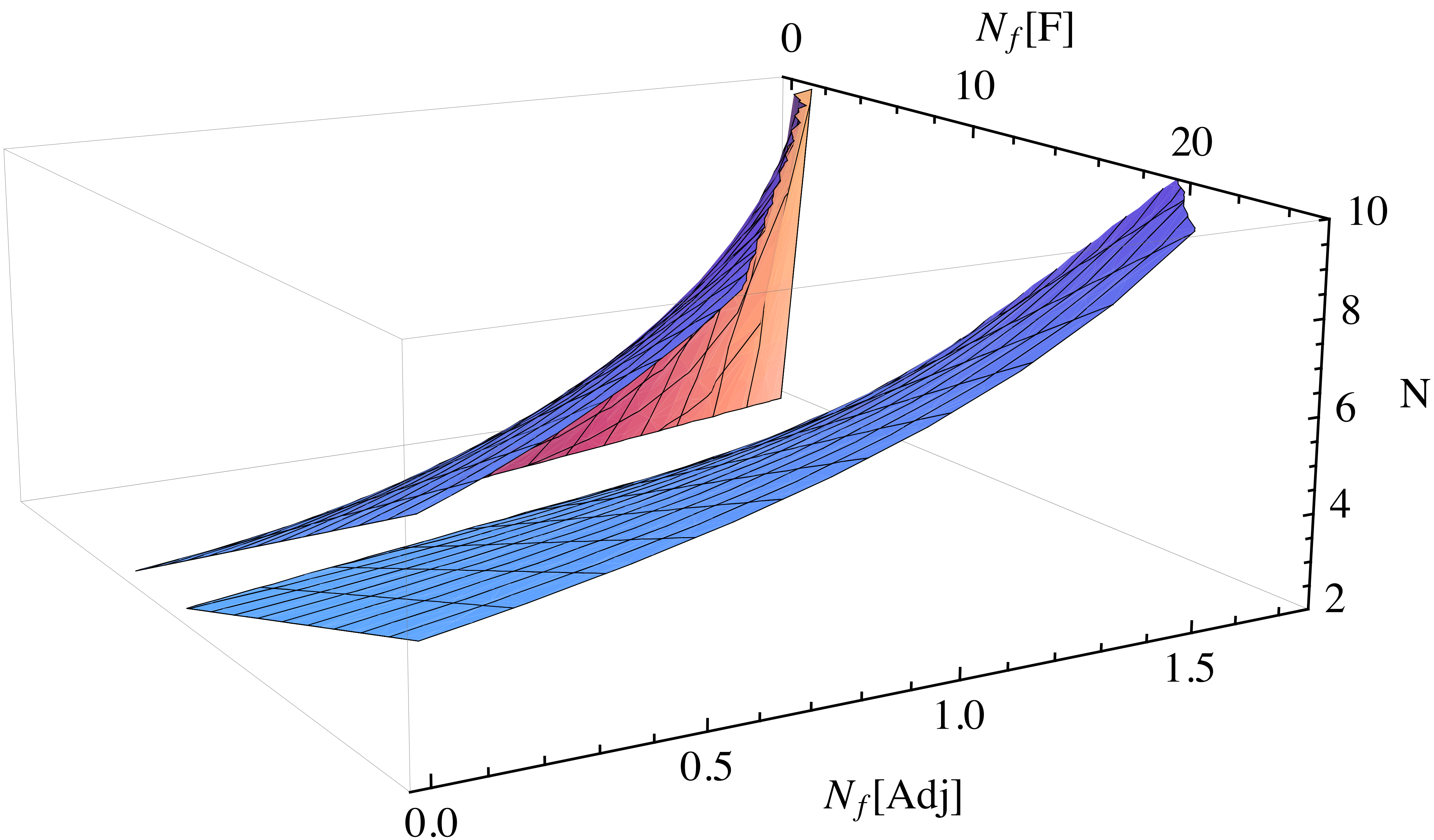


Conformal House

Ryttov and F.S. 09

2 Rep. Example

SU(N) Adjoint & Fundamental Dirac Matter



Lecture 3

Minimal Walking Models

Predictions for LHC

Unification

Minimal Walking Technicolor

F.S. and Tuominen 04

Dietrich, F.S. Tuominen 06

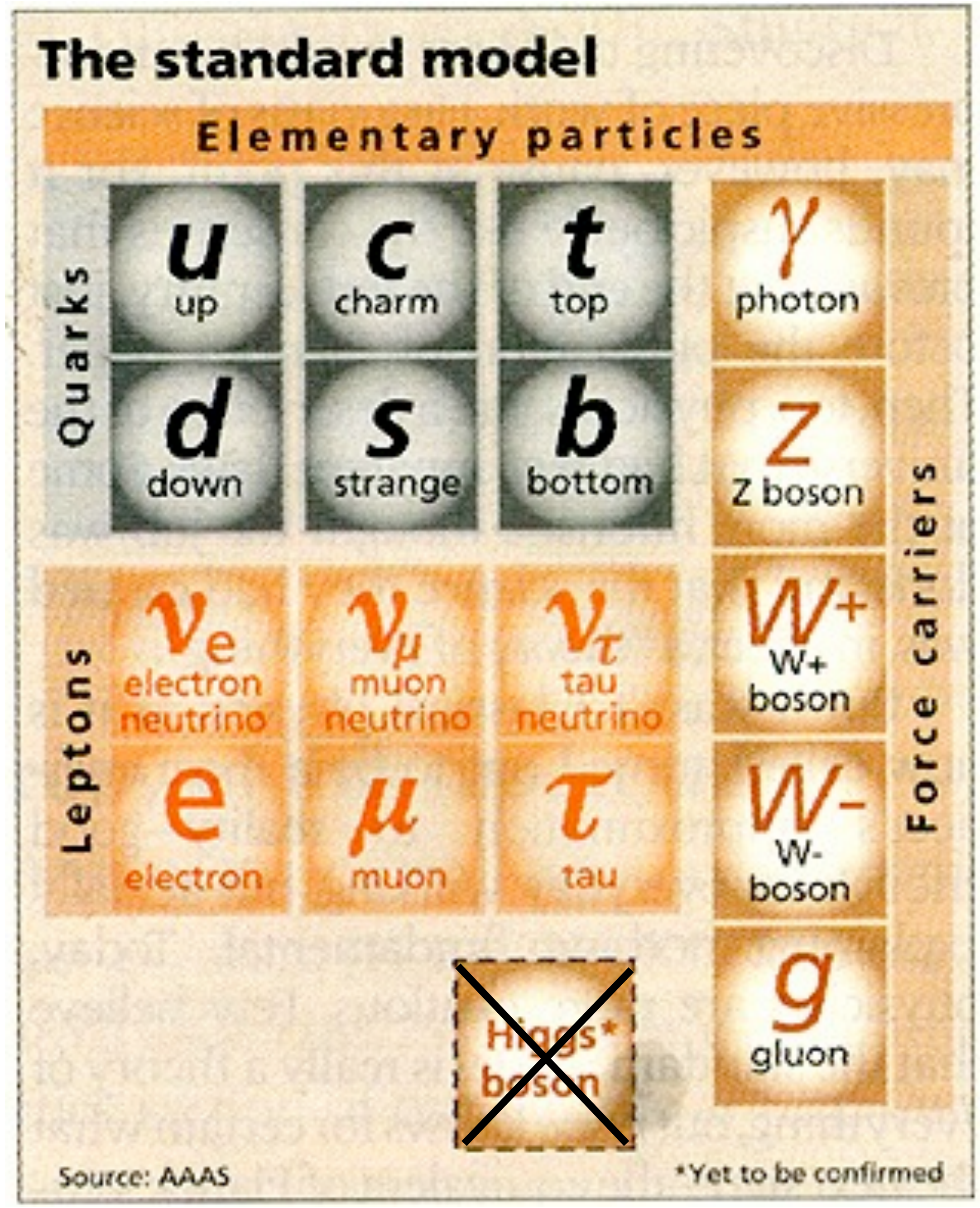
Gudnason, Kouvaris, F.S. 06

Gudnason, Ryttov, F.S. 06

Foadi, Frandsen, Ryttov, F.S. 07

Cline, Jarvinen, F.S. 08

Belyaev, Foadi, Frandsen, Jarvinen, Pukhov, F.S. 08



U(1)

SU(2)

SU(3)

N
Extra Neutrino

E
Extra Electron

U
t-up

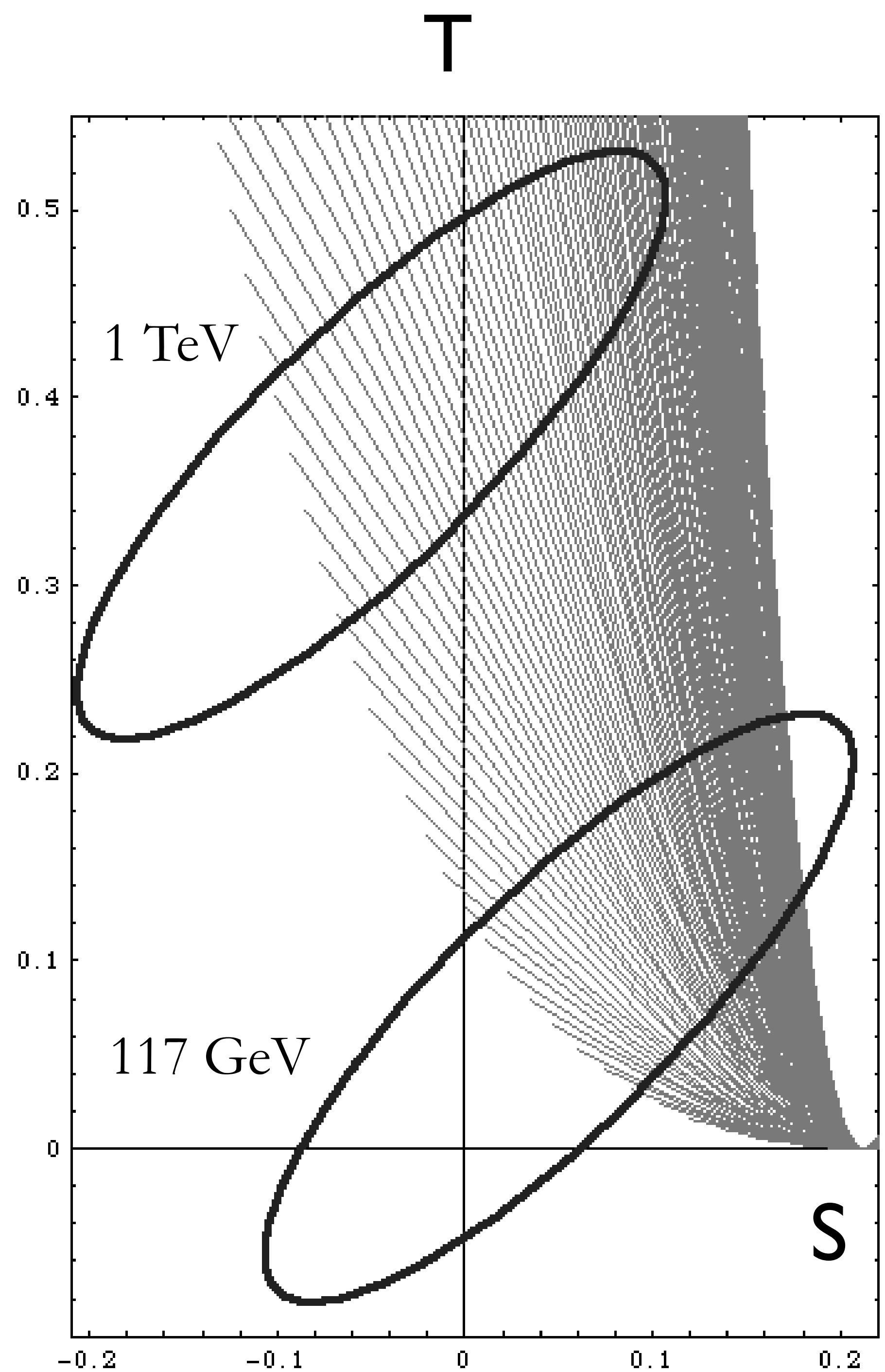
G
t-glue

SU(2)

D
t-down

U and D: Adj of SU(2)

MWT versus EWPD



LEP EWG Summer 2006

$100 \text{ Gev} < M_1 < 800 \text{ Gev}$

Y=-3/2 for Leptons

$100 \text{ Gev} < M_2 < 1000 \text{ Gev}$

$$S_{\text{Leptons}} = \frac{1}{6\pi}\left[1 - 2Y\ln\left(\frac{M_1}{M_2}\right)^2 + \frac{1+8Y}{20}\left(\frac{m_Z}{M_1}\right)^2 + \frac{1-8Y}{20}\left(\frac{m_Z}{M_2}\right)^2 + O\left(\frac{m_Z^4}{M_i^4}\right)\right]$$

MWT Features

The most economical WT theory

Compatible with precision measurements

Possible DM candidates and Unification investigated

Can support 1st order Electroweak Phase Transition

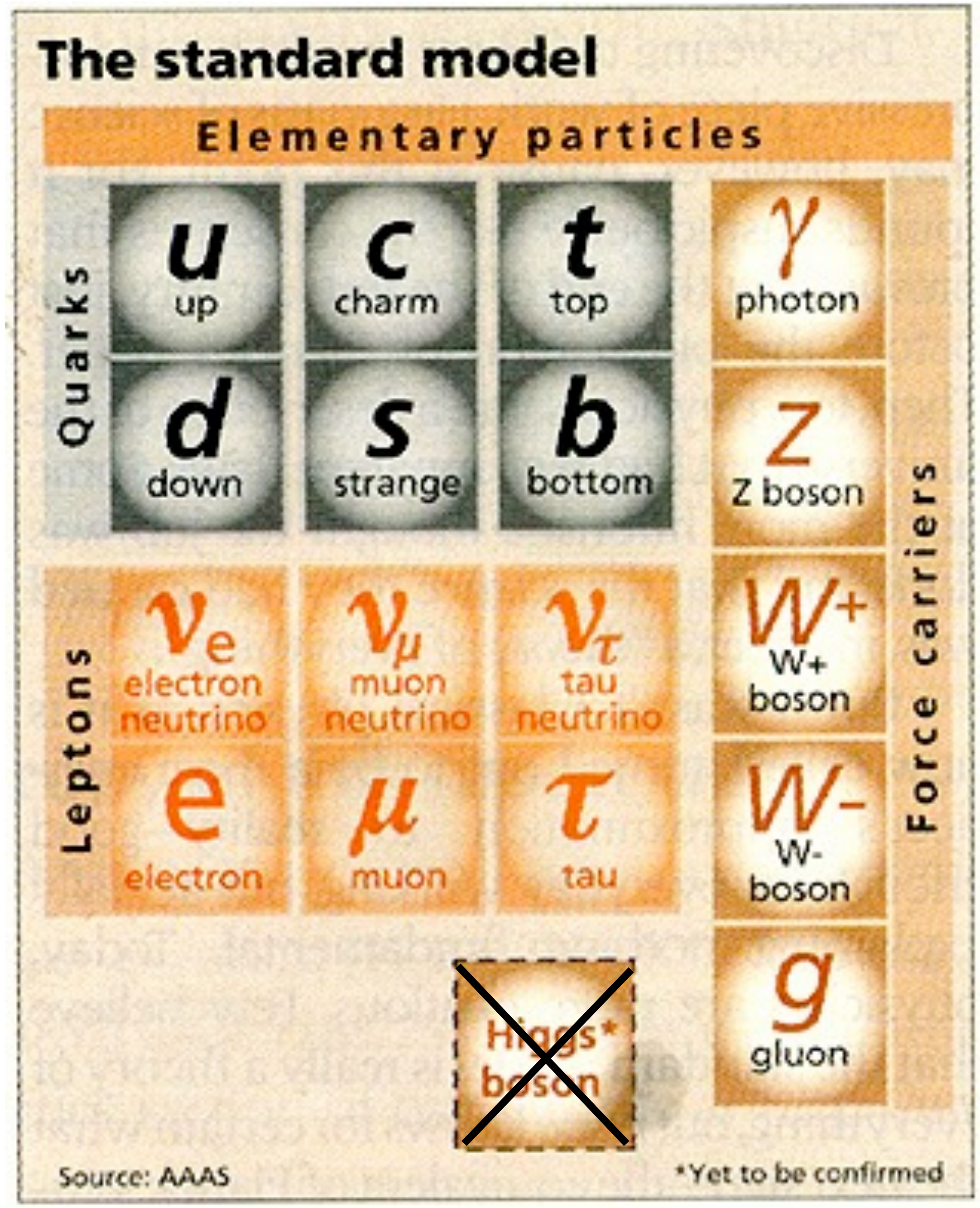
Can support exotic electric charges

Lattice studies have begun

Ultra Minimal Walking Technicolor

Ryttov and F.S. 08

Eichten and Lane



U(1)

SU(2)

SU(3)

U t-up

G t-glue

D t-down

$\lambda^1 \quad \lambda^2$ t-lambda

SU(2)

U and D: Fund of SU(2)

t-lambdas: Adj of SU(2)
Singlet of SM
Weyl Fermions

UMT Features

The most economical "2 rep" WT theory

Smallest naive S-parameter & # of fermions

Natural DM candidate visible at LHC

Order of the Electroweak PT under investigation

Rich unexplored Collider Phenomenology

Back to

Minimal Walking Technicolor

The Minimal Walking Theory

2 Adj. Dirac Flavors of SU(2)

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L, \qquad U_R^a, \qquad D_R^a \qquad a = 1, 2, 3$$

$$Y(Q_L) = \frac{y}{2} \qquad Y(U_R, D_R) = \left(\frac{y+1}{2}, \frac{y-1}{2}\right)$$

$$\mathcal{L}_L = \begin{pmatrix} N \\ E \end{pmatrix}_L \qquad N_R \qquad E_R$$

$$Y(\mathcal{L}_L) = -3\frac{y}{2} \qquad Y(N_R, E_R) = \left(\frac{-3y+1}{2}, \frac{-3y-1}{2}\right)$$

$\mathcal{N} = 4$ super Yang-Mills

The MWT Lagrangian

$$\mathcal{L}_H \rightarrow -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R$$

$$+i\bar{L}_L\gamma^\mu D_\mu L_L + i\bar{N}_R\gamma^\mu D_\mu N_R + i\bar{E}_R\gamma^\mu D_\mu E_R$$

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu\mathcal{A}^a_\nu - \partial_\nu\mathcal{A}^a_\mu + g_{TC}\epsilon^{abc}\mathcal{A}^b_\mu\mathcal{A}^c_\nu \qquad a,b,c = 1,\ldots,3$$

$$D_\mu Q^a_L = \left(\delta^{ac}\partial_\mu + g_{TC}\mathcal{A}^b_\mu\epsilon^{abc} - i\frac{g}{2}\vec{W}_\mu\cdot\vec{\tau}\delta^{ac} - ig'\frac{y}{2}B_\mu\delta^{ac}\right)Q^c_L$$

What you see is "not" what LHC will see

MWT effective lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Initial investigation we include:

Composite Higgs	H
Composite Axial - Vector States	$R_{1,2}$
Heavy V/V coupling	$\tilde{g}$
Bare mass of the Axial	M_A

LHC Phenomenology

In collaboration with

A. Belyaev
R. Foadi
M. T. Frandsen
M. O. Jarvinen
A. Pukhov

BFFJPS arXiv:0809.0793

CalcHep

Angels and Demons of LHC

Comprehensive Effective Technicolor Lagrangian

Vector Mesons

Yukawas

** Link to MWT via Modified Weinberg Sum Rules **

Written in a renormalizable form

With imposed constraints from Precision Data

A working technicolor benchmark

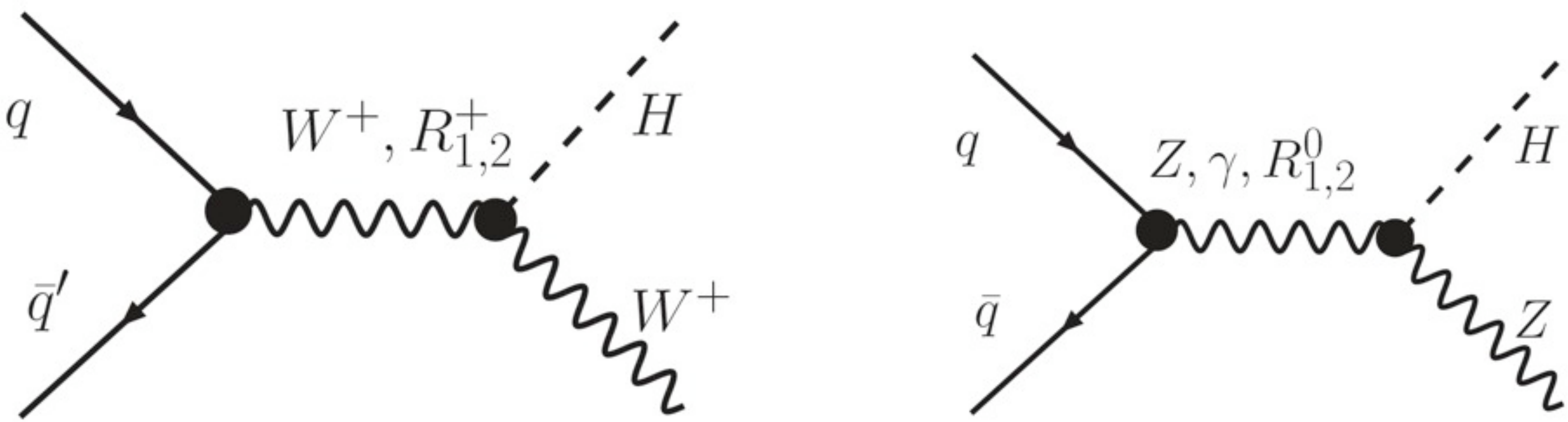
Foadi, Frandsen, Ryttov & F.S. 07

Composite Higgs Signals

Associate Higgs Production BFFJPS 08, Zerwekh 05

Higgs $\rightarrow \gamma\gamma$ To be done!

$$pp \to HV$$



$$HV \to VVV \to \text{leptons+jets}$$

$$pp \to HV$$

Walking/Higher dim. rep. can allow for:

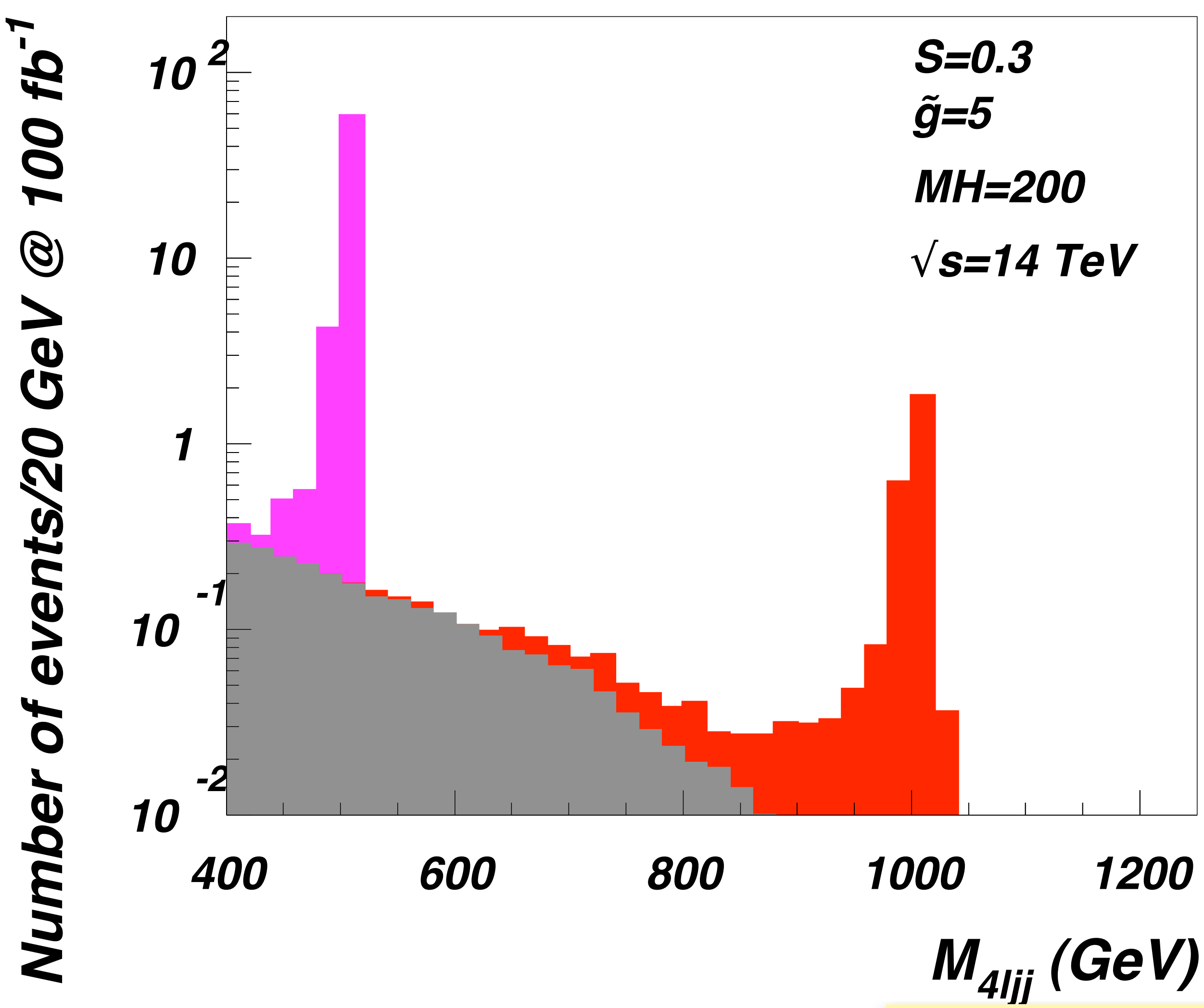
Light Composite Higgs

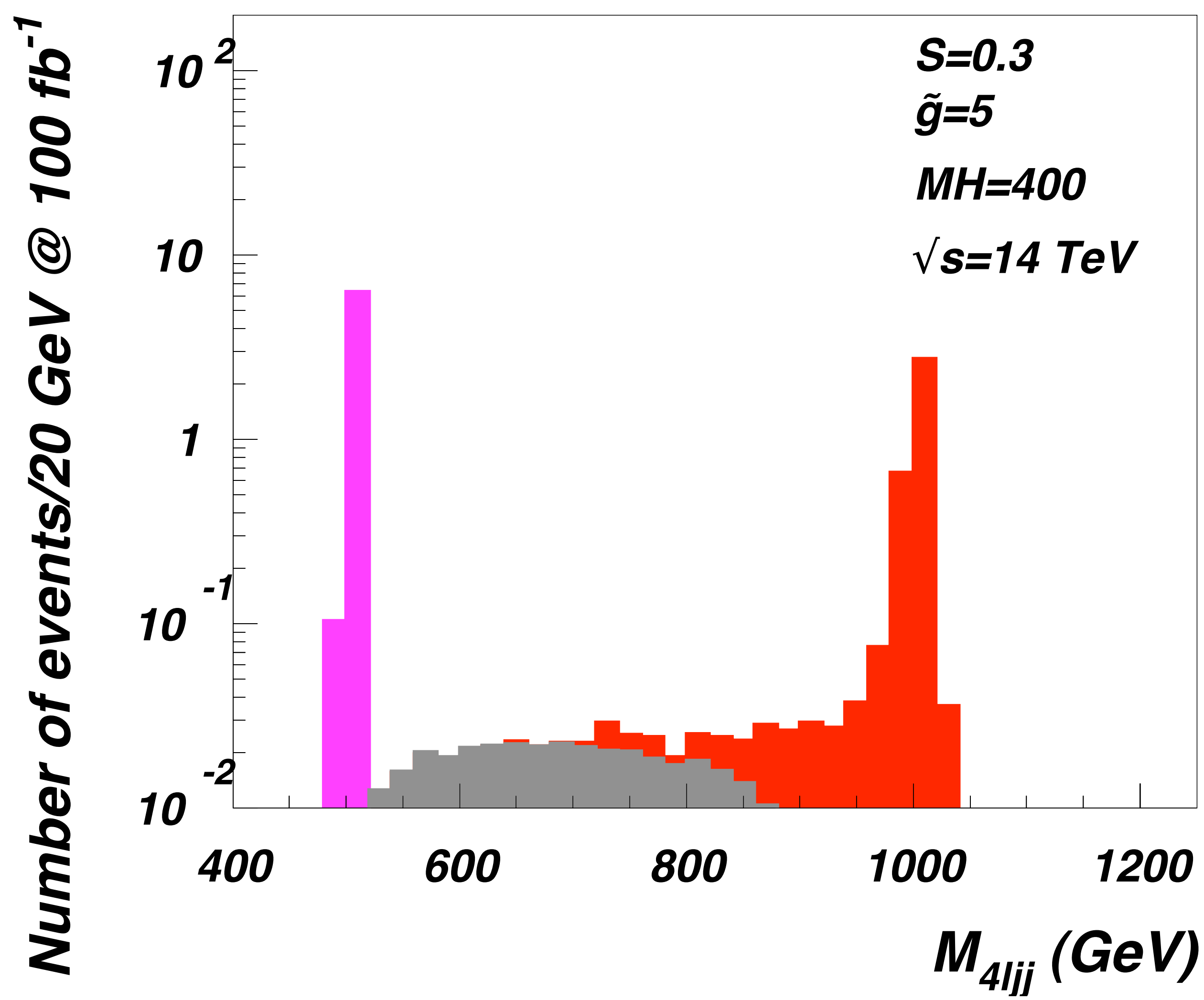
F.S. 08
Hong, Hsu, F.S. 04
Dietrich, F.S., Tuominen 05
Doff, Natale, Rodrigues da Silva 08
Doff, Natale, 09.

Light Composite Axial

Foadi, Frandsen, Ryttov F.S., 07
Eichten, Lane 07

$$pp \to HW^{\pm} \to W^{\pm}ZZ \to 4l + 2j$$





$$|\eta^J| < 4.5, \quad p_T^j > 30 \text{ GeV},$$

The way this event plot is done in a simple way.

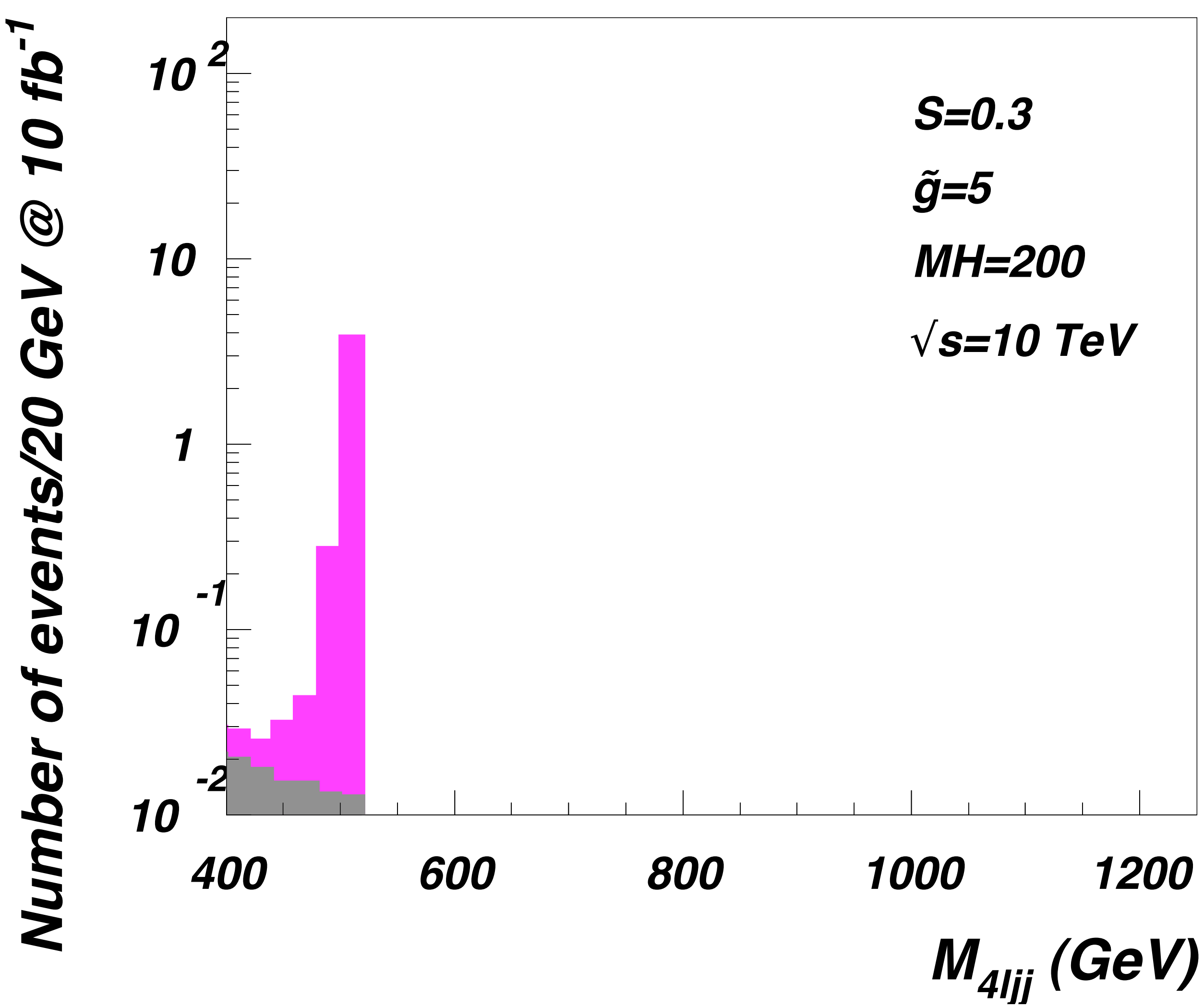
1]
Cross section is computed only for pp -> HW

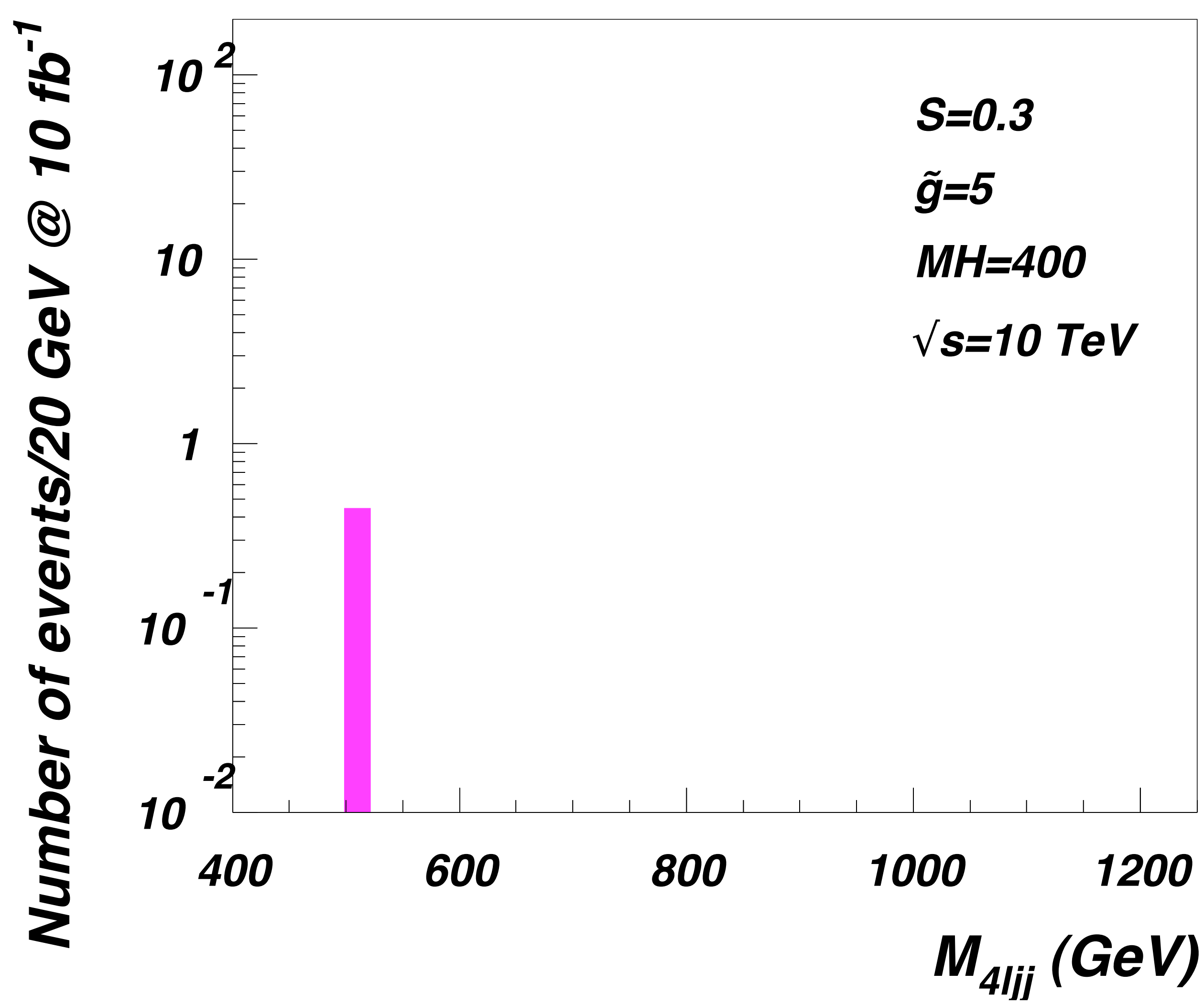
2]
Then CalcHEP adds decays of H to ZZ and on top of that it adds decay of W and ZZ to 4l and 2j.

A better way (we have not done)

pp -> WZZ. This means CalcHEP will need to compute many more diagrams. However, if we had done this fully. Once we added the cuts the results should be the same.

$$pp \to HW^{\pm} \to W^{\pm}ZZ \to 4l + 2j$$





$$|\eta^J| < 4.5, \quad p_T^j > 30 \text{ GeV}, \qquad |\eta^l| < 2.5, \quad p_T^l > 15 \text{ GeV}, \quad \Delta R(jj/jl) > .5$$

$$65 \text{ GeV} < M_{jj} < 95 \text{ GeV}$$

Further Signatures

New SM Fermions

Dietrich, F.S., Tuominen 05
Gudnason, Ryttov & F.S. 08

DM candidates

Foadi, Frandsen, FS. 08
Ryttov & F.S. 08
Gudnason, Kouvaris & F.S. 05
Kainulainen, Tuominen, Virkajarvi 06
Kouvaris 07; Kouvaris, Khlopov 08

Unification

Farhi-Susskind, 79

Gudnason-Ryttov-F.S. 06

1 - loop running for SU(n)

$$\alpha_n^{-1}(\mu) = \alpha_n^{-1}(M_Z) - \frac{b_n}{2\pi} \ln\left(\frac{\mu}{M_Z}\right)$$

Degree of SU(3)xSU(2)xU(1) Unification

$$B_{Th} \leftarrow \frac{b_3 - b_2}{b_2 - b_1} \quad = \quad \frac{\alpha_3^{-1} - \alpha^{-1}\sin^2\theta_w}{(1+c^2)\alpha^{-1}\sin^2\theta_w - c^2\alpha^{-1}} \rightarrow B_{Exp}$$

Unification Scale

$$M_{GUT} = M_Z \exp\left[2\pi \frac{\alpha_2^{-1}(M_Z) - \alpha_1^{-1}(M_Z)}{b_2 - b_1}\right]$$

Standard Model

$$b_3 = \frac{4}{3}N_g - 11$$

$$b_2 = \frac{4}{3}N_g - \frac{22}{3} + \underbrace{\frac{1}{6}}_{\text{Higgs}} \qquad B_{\text{Th}} \sim 0.53 \qquad B_{\text{Exp}} \sim 0.72$$

$$b_1 = \frac{3}{5}\left(\frac{20}{9}N_g + \frac{1}{6}\right) = \frac{4}{3}N_g + \underbrace{\frac{1}{10}}_{\text{Higgs}}$$

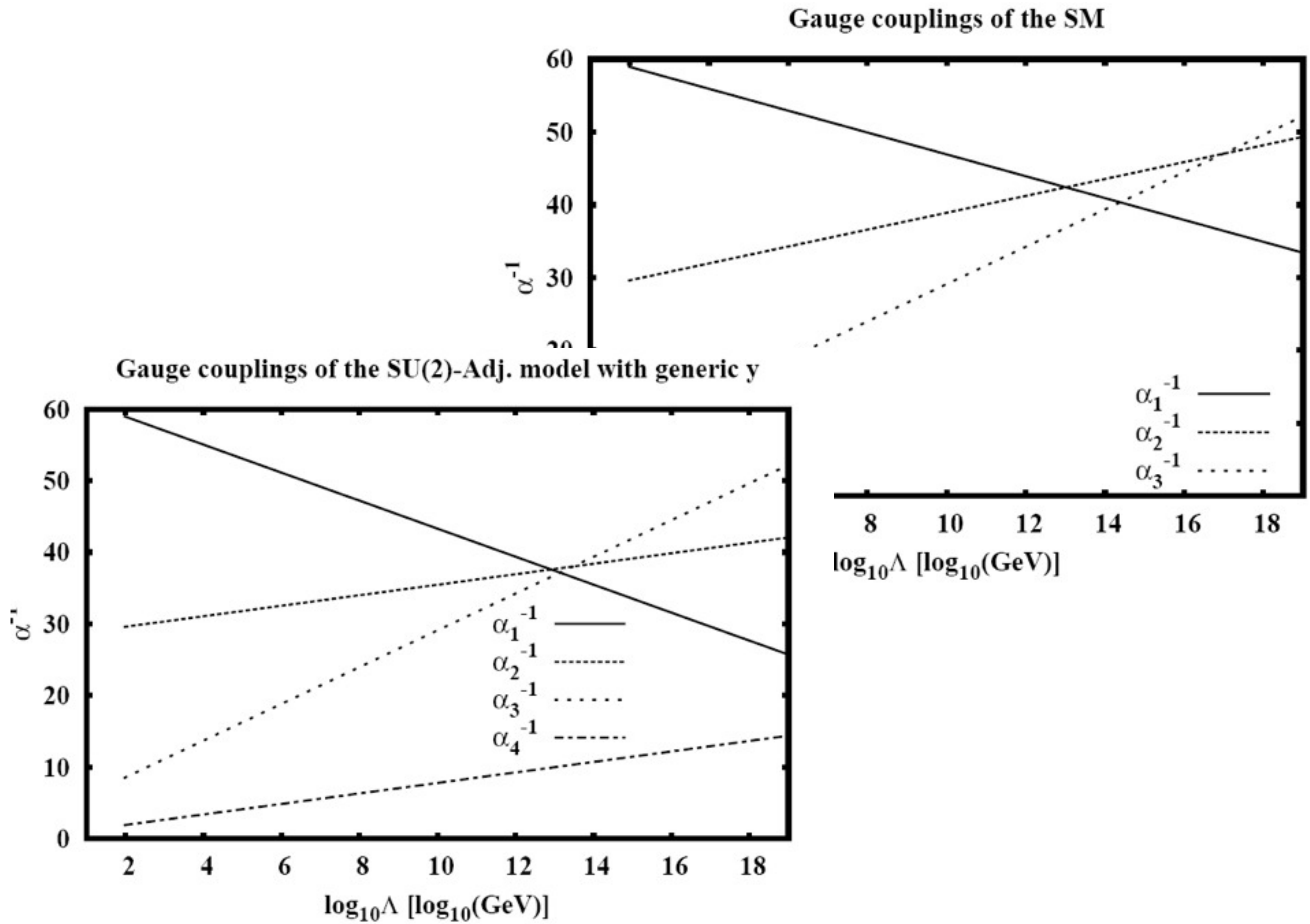
Minimal Walking Technicolor

$$b_3 = \frac{4}{3}N_g - 11$$

$$b_2 = \frac{4}{3}N_g - \frac{22}{3} + \frac{2}{3}\frac{1}{2}\left(\frac{2(2+1)}{2} + 1\right) = \frac{4}{3}\left(N_g + 1\right) - \frac{22}{3}$$

$$b_1 = \frac{3}{5}\left(\frac{20}{9}N_g + \frac{20}{9}\right) = \frac{4}{3}\left(N_g + 1\right)$$

$$B_{\text{Th}} \sim 0.68 \qquad B_{\text{Exp}} \sim 0.72$$


Gauge couplings of the SM
60
50
40
30
20
α⁻¹
8
10
12
14
16
18
log10Λ [log10(GeV)]
α1⁻¹
α2⁻¹
α3⁻¹
Gauge couplings of the SU(2)-Adj. model with generic y
60
50
40
30
20
10
0
α⁻¹
2
4
6
8
10
12
14
16
18
log10Λ [log10(GeV)]
α1⁻¹
α2⁻¹
α3⁻¹
α4⁻¹

Adding Adjoint SM Matter

Minimal Walking Technicolor + SM Adjoint Matter

Colored Octet of Majorana Particles

Weak Triplet of Majorana Fermions

Extra SM Weyl Singlet

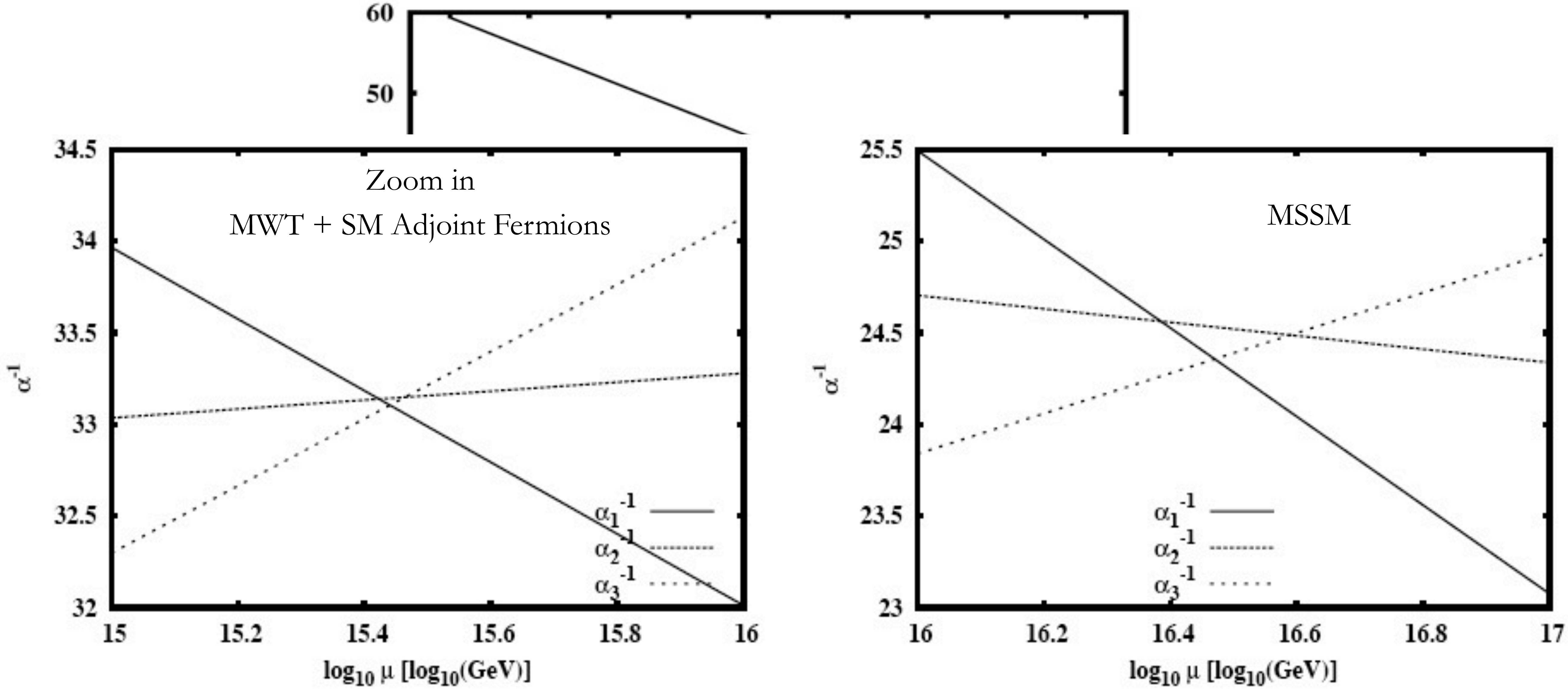
$$
\begin{aligned}
b_3 &= \frac{4}{3}N_g - 11 + 2 \\
b_2 &= \frac{4}{3}\left(N_g + 1\right) - \frac{22}{3} + \frac{4}{3} \\
b_1 &= \frac{4}{3}\left(N_g + 1\right)
\end{aligned}
$$

Gudnason-Ryttov-F.S. ph/0612230

Bajc-Senjanovic ph/0612029

$$B_{\mathrm{Th}} = 13/18 = 0.72(2) \quad \text{versus} \quad B_{\mathrm{Exp}} \simeq 0.72$$

MWT + SM Adjoint Fermions



What LHC can see and how may it deceive you

- Composite States: Technirho, composite (light) Higgs
- Detect Light Higgs: “Elementary or Composite ?”
- Study: $pp \longrightarrow HV$
- 4th Family of Leptons no Quarks

What LHC can see and how may it deceive you

- wino/bino/gluino-like produced. Have you seen SUSY, WTC or ... ?

- Study their couplings to SM fermions

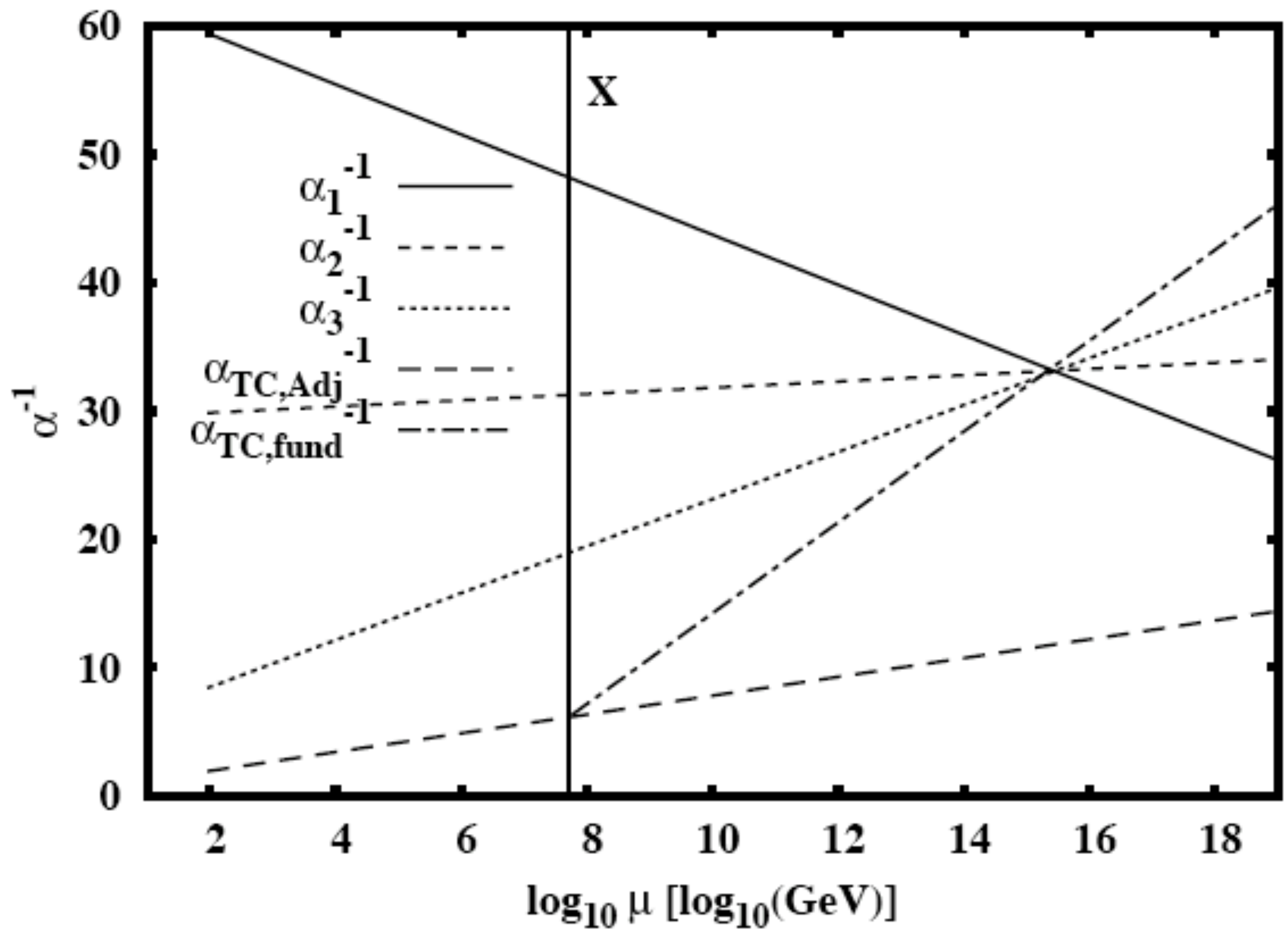
Unpleasant scenario:

- WW scatttering is unitarized at the tree level up to 4 TeV with new vectors states of about 1.5 TeV. LHC and ILC will not discover! (Foadi and FS 08)

Summary

- Introduced different types of viable technicolor theories
- Phase Diagram for Gauge Theories
- Presented Minimal Walking Technicolor
- Dark Matter as a technibaryon
- Unification

Unifying also TC
Cartoon!



Summary

- (Ultra) Minimal Walking Technicolor
- Associate Production of the Composite Higgs
- Heavy Vectors are best produced and detected via Drell-Yan

Beyond S-T-U

$$\hat{S} \equiv g^2\,\Pi'_{W^3B}(0)\ ,$$

$$\hat{T} \equiv \frac{g^2}{M_W^2}\left[\Pi_{W^3W^3}(0)-\Pi_{W^+W^-}(0)\right]\ ,$$

$$W \equiv \frac{g^2M_W^2}{2}\left[\Pi''_{W^3W^3}(0)\right]\ ,$$

$$\frac{1}{g^2} \equiv \Pi'_{W^+W^-}(0) \qquad \frac{1}{g'^2} \equiv \Pi'_{BB}(0)$$

$$\frac{1}{\sqrt{2}G_F} = -4\Pi_{W^+W^-}(0)$$

Burgess et al.
Barbieri et al.

Beyond S-T-U

$$
\begin{aligned}
Y &\equiv \frac{g'^2 M_W^2}{2} \left[\Pi''_{BB}(0)\right] \;, \\
\hat{U} &\equiv -g^2 \left[\Pi'_{W^3W^3}(0) - \Pi'_{W^+W^-}(0)\right] \;, \\
V &\equiv \frac{g^2\, M_W^2}{2} \left[\Pi''_{W^3W^3}(0) - \Pi''_{W^+W^-}(0)\right] \;, \\
X &\equiv \frac{g g'\, M_W^2}{2}\, \Pi''_{W^3B}(0) \;.
\end{aligned}
$$

Recovering S and T

$$\frac{\alpha S}{4s_W^2} = \hat{S} - Y - W$$

$$\alpha T = \hat{T} - \frac{s_W^2}{1 - s_W^2} Y$$

Computing the Parameters for (Minimal) Walking Technicolor

$$\hat{S} = \frac{(2-\chi)\chi g^2}{2\tilde{g}^2} ,$$

$$W = \frac{g^2}{2\tilde{g}^2}\frac{M_W^2}{M_A^2 M_V^2}(M_A^2 + (\chi-1)^2 M_V^2) ,$$

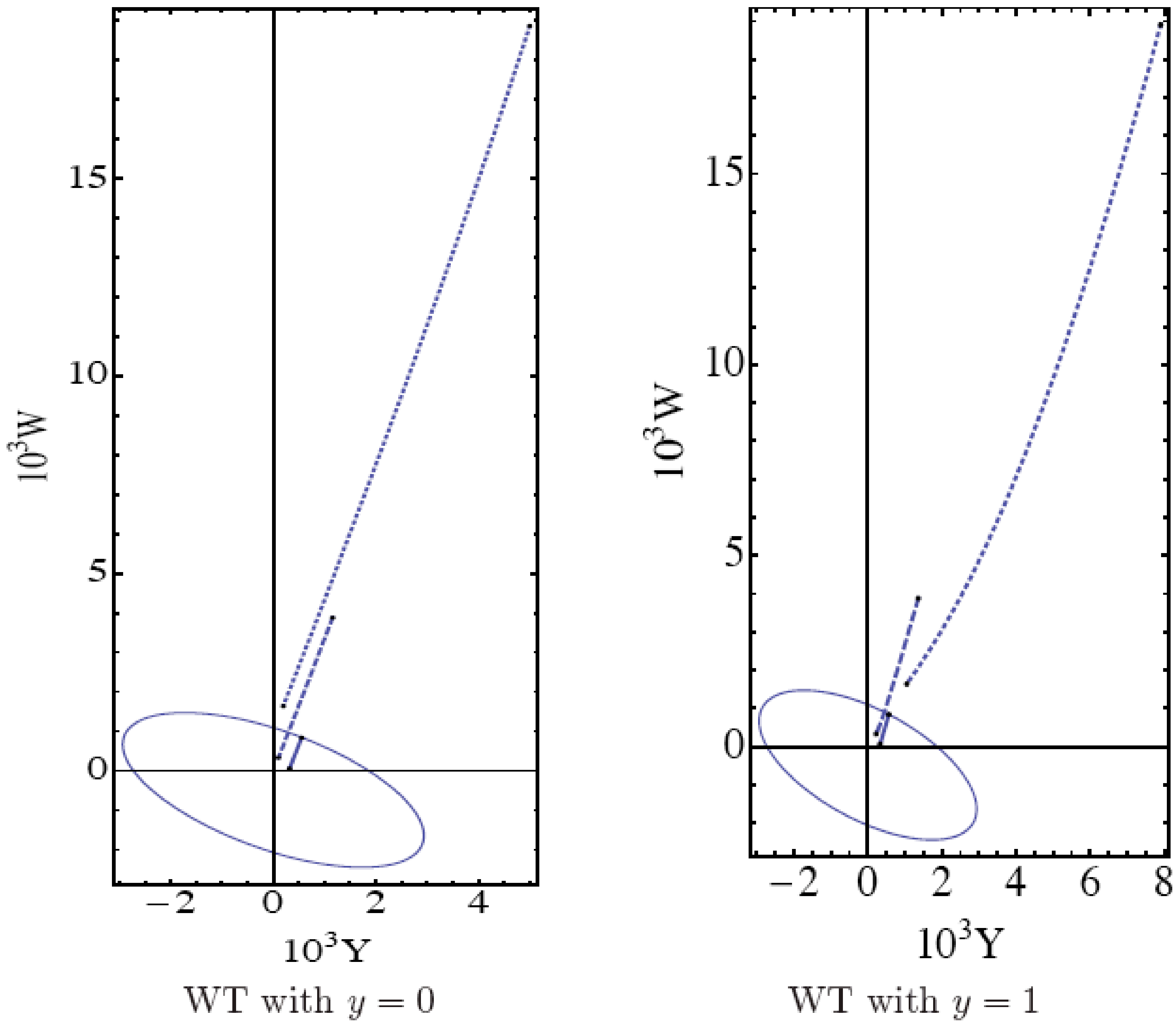
$$Y = \frac{g'^2}{2\tilde{g}^2}\frac{M_W^2}{M_A^2 M_V^2}((1+4y^2)M_A^2 + (\chi-1)^2 M_V^2)$$

$$X = \frac{g\,g'}{2\tilde{g}^2}\frac{M_W^2}{M_A^2 M_V^2}(M_A^2 - (\chi-1)^2 M_V^2) .$$

$$\hat{T} = \hat{U} = V = 0$$

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

Foadi, Frandsen, Ryttov, F.S.
Foadi, Frandsen, F.S.



95% confidence level error ellipses

Solid line $\tilde{g} = 8$, dashed-line $\tilde{g} = 4$, dotted one $\tilde{g} = 2$ $\hat{S} = 0.0004$

Closest point M_A=600 GeV, Further away M_A=150 GeV. Foadi, Frandsen, F.S.

Custodial Technicolor

$$M_A = M_V = M \text{ and } \chi = 0$$

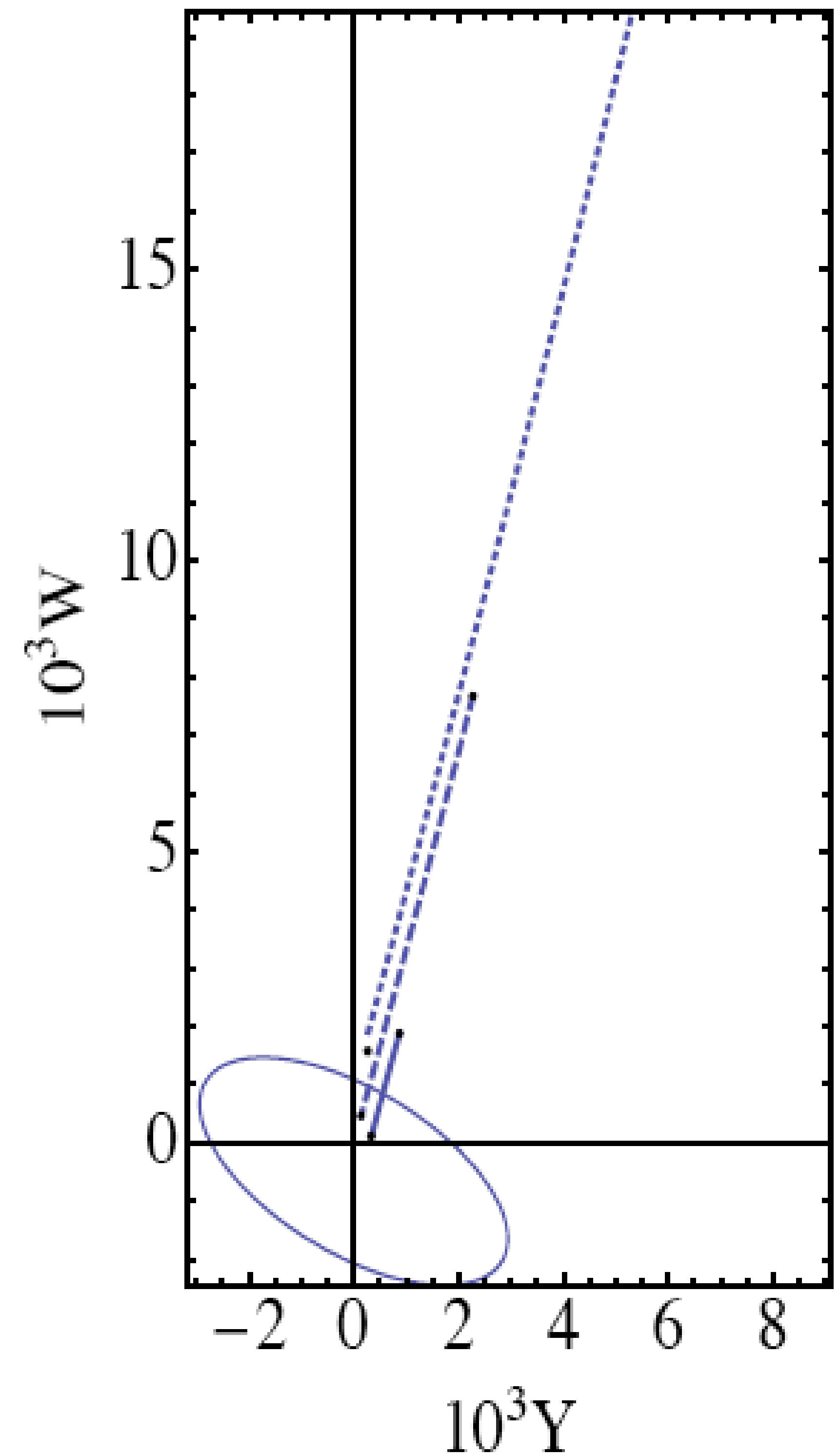
S=0 Appelquist, F.S.

Novel Symmetry

Still Constrained

$$W = \frac{g^2}{\tilde{g}^2}\frac{M_W^2}{M^2},$$

$$Y = \frac{g'^2}{2\tilde{g}^2}\frac{M_W^2}{M^2}(2+4y^2)$$



CT with $y = 0$

Low Energy Scalar Sector

$$M_{ij} \sim Q_i^\alpha Q_j^\beta \varepsilon_{\alpha\beta}$$

$$M = \begin{pmatrix} i\Pi_{UU} + \tilde{\Pi}_{UU} & \frac{i\Pi_{UD} + \tilde{\Pi}_{UD}}{\sqrt{2}} & \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^+ + A^+}{\sqrt{2}} \\ \frac{i\Pi_{UD} + \tilde{\Pi}_{UD}}{\sqrt{2}} & i\Pi_{DD} + \tilde{\Pi}_{DD} & \frac{i\Pi^- + A^-}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{2} \\ \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^- + A^-}{\sqrt{2}} & i\Pi_{\overline{UU}} + \tilde{\Pi}_{\overline{UU}} & \frac{i\Pi_{\overline{UD}} + \tilde{\Pi}_{\overline{UD}}}{\sqrt{2}} \\ \frac{i\Pi^+ + A^+}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{2} & \frac{i\Pi_{\overline{UD}} + \tilde{\Pi}_{\overline{UD}}}{\sqrt{2}} & i\Pi_{\overline{DD}} + \tilde{\Pi}_{\overline{DD}} \end{pmatrix}$$

Low Energy Vector Sector

$$A_i^{\mu,j} \sim \; Q_i^{\alpha}\sigma^{\mu}_{\alpha\dot\beta}\bar Q^{\dot\beta,j} - \frac{1}{4}\delta_i^j Q_k^{\alpha}\sigma^{\mu}_{\alpha\dot\beta}\bar Q^{\dot\beta,k}$$

$$A^{\mu} = \begin{pmatrix} \frac{a^{0\mu}+v^{0\mu}+v^{4\mu}}{2\sqrt{2}} & \frac{a^{+\mu}+v^{+\mu}}{2} & \frac{x^{\mu}_{UU}}{\sqrt{2}} & \frac{x^{\mu}_{UD}+s^{\mu}_{UD}}{2} \\ \frac{a^{-\mu}+v^{-\mu}}{2} & \frac{-a^{0\mu}-v^{0\mu}+v^{4\mu}}{2\sqrt{2}} & \frac{x^{\mu}_{UD}-s^{\mu}_{UD}}{2} & \frac{x^{\mu}_{DD}}{\sqrt{2}} \\ \frac{x^{\mu}_{\overline{UU}}}{\sqrt{2}} & \frac{x^{\mu}_{\overline{UD}}-s^{\mu}_{\overline{UD}}}{2} & \frac{a^{0\mu}-v^{0\mu}-v^{4\mu}}{2\sqrt{2}} & \frac{a^{-\mu}-v^{-\mu}}{2} \\ \frac{x^{\mu}_{\overline{UD}}+s^{\mu}_{\overline{UD}}}{2} & \frac{x^{\mu}_{\overline{DD}}}{\sqrt{2}} & \frac{a^{+\mu}-v^{+\mu}}{2} & \frac{-a^{0\mu}+v^{0\mu}-v^{4\mu}}{2\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}_{\rm Higgs} \ = \ \frac{1}{2}{\rm Tr}\left[D_{\mu}M D^{\mu}M^{\dagger}\right] - \mathcal{V}(M) + \mathcal{L}_{\rm ETC}$$

$$\begin{aligned}\mathcal{V}(M) \ &= \ -\frac{m^2}{2}{\rm Tr}[MM^{\dagger}] + \frac{\lambda}{4}{\rm Tr}\left[MM^{\dagger}\right]^2 + \lambda'{\rm Tr}\left[MM^{\dagger}MM^{\dagger}\right] \\ &- \ 2\lambda''\left[{\rm Det}(M) + {\rm Det}(M^{\dagger})\right] \ ,\end{aligned}$$

$$\mathcal{L}_{\rm ETC} = \frac{m_{\rm ETC}^2}{4}\ {\rm Tr}\left[MBM^{\dagger}B + MM^{\dagger}\right] + \cdots$$

$$M_H^2 = 2\ m^2 \qquad\qquad v^2 = \langle\sigma\rangle^2 = \frac{m^2}{\lambda + \lambda' - \lambda''}$$

$$\mathcal{L}_{\text{kinetic}} = -\frac{1}{2}\text{Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\text{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + m_A^2\ \text{Tr}\left[C_\mu C^\mu\right]$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i\tilde{g}\left[A_\mu, A_\nu\right]$$

$$C_\mu \equiv A_\mu - \frac{g}{\tilde{g}}\, G_\mu(y)$$

$$G_\mu = \begin{pmatrix} W_\mu & 0 \\ 0 & -\frac{g'}{g}B_\mu^T \end{pmatrix} + \frac{y}{2}\frac{g'}{g}B_\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathcal{L}_{\text{M}-\text{C}} = \tilde{g}^2\ r_1\ \text{Tr}\left[C_\mu C^\mu M M^\dagger\right] + \tilde{g}^2\ r_2\ \text{Tr}\left[C_\mu M C^{\mu T} M^\dagger\right]$$
$$+\ i\ \tilde{g}\, r_3\, \text{Tr}\left[C_\mu\left(M(D^\mu M)^\dagger - (D^\mu M)M^\dagger\right)\right] + \tilde{g}^2\ s\ \text{Tr}\left[C_\mu C^\mu\right]\text{Tr}\left[M M^\dagger\right]$$

$$\mathcal{L}_{\text{fermion}} = i\, \overline{q}^i_{\dot\alpha} \overline{\sigma}^{\mu,\dot\alpha\beta} D_\mu q^i_\beta + i\, \overline{l}^i_{\dot\alpha} \overline{\sigma}^{\mu,\dot\alpha\beta} D_\mu l^i_\beta + i\, \overline{L}_{\dot\alpha} \overline{\sigma}^{\mu,\dot\alpha\beta} D_\mu L_\beta + i\, \overline{\widetilde{Q}}_{\dot\alpha} \overline{\sigma}^{\mu,\dot\alpha\beta} D_\mu \widetilde{Q}_\beta$$
$$+ x\, \overline{\widetilde{Q}}_{\dot\alpha} \overline{\sigma}^{\mu,\dot\alpha\beta} C_\mu \widetilde{Q}_\beta$$

$$q^i = \begin{pmatrix} u^i_L \\ d^i_L \\ -i\sigma^2 {u^i_R}^* \\ -i\sigma^2 {d^i_R}^* \end{pmatrix}, \quad l^i = \begin{pmatrix} \nu^i_L \\ e^i_L \\ -i\sigma^2 {\nu^i_R}^* \\ -i\sigma^2 {e^i_R}^* \end{pmatrix}$$

$$\widetilde{Q} = \begin{pmatrix} \widetilde{U}_L \\ \widetilde{D}_L \\ -i\sigma^2 \widetilde{U}^*_R \\ -i\sigma^2 \widetilde{D}^*_R \end{pmatrix}$$ techniquark-technigluon $$L = \begin{pmatrix} N_L \\ E_L \\ -i\sigma^2 {N_R}^* \\ -i\sigma^2 {E_R}^* \end{pmatrix}$$

$$
\begin{aligned}
\mathcal{L}_{\text{Yukawa}} \;=\; & - y_u^{ij}\; q^{iT}\left(P_U M^*_{\text{off}} P_U\right) q^j - y_d^{ij}\; q^{iT}\left(P_D M^*_{\text{off}} P_D\right) q^j \\
& - y_\nu^{ij}\; l^{iT}\left(P_U M^* P_U\right) l^j - y_e^{ij}\; l^{iT}\left(P_D M^* P_D\right) l^j \\
& - y_N\; L^T\left(P_U M^*_{\text{off}} P_U\right) L - \; y_E\; L^T\left(P_D M^*_{\text{off}} P_D\right) L \\
& - \; y_{\widetilde{U}} \widetilde{Q}^T\left(P_U M^* P_U\right) \widetilde{Q} - \; y_{\widetilde{D}} \widetilde{Q}^T\left(P_D M^* P_D\right) \widetilde{Q} \; + \text{h.c.}
\end{aligned}
$$

$$
P_D = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1-\tau^3}{2} \end{pmatrix} \qquad\qquad P_U = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1+\tau^3}{2} \end{pmatrix}
$$

Higgsless versus Higgsful

Higgsless:

$$\frac{M_H}{M_V} > 1$$

Higgsful:

$$\frac{M_H}{M_V} \leq 1$$

Spectrum of Hadronic/Technihadronic States

Using 't Hooft Large N and Unitarity in Pion-Pion Scattering in QCD

Vector Meson is a quark-antiquark state: $\rho(770)$

Broad Sigma of multiquark nature $f_0(600)$

QCD is NOT higgsless!

F.S. & Schechter, 95
Harada, F.S. and Schechter, 03
Caprini, Colangelo,Leutwyler 05
Maiani,Piccinini, Polosa, Riquer 04
F.S. and Schechter, 07

Higgsless: ‘t Hooft Limit

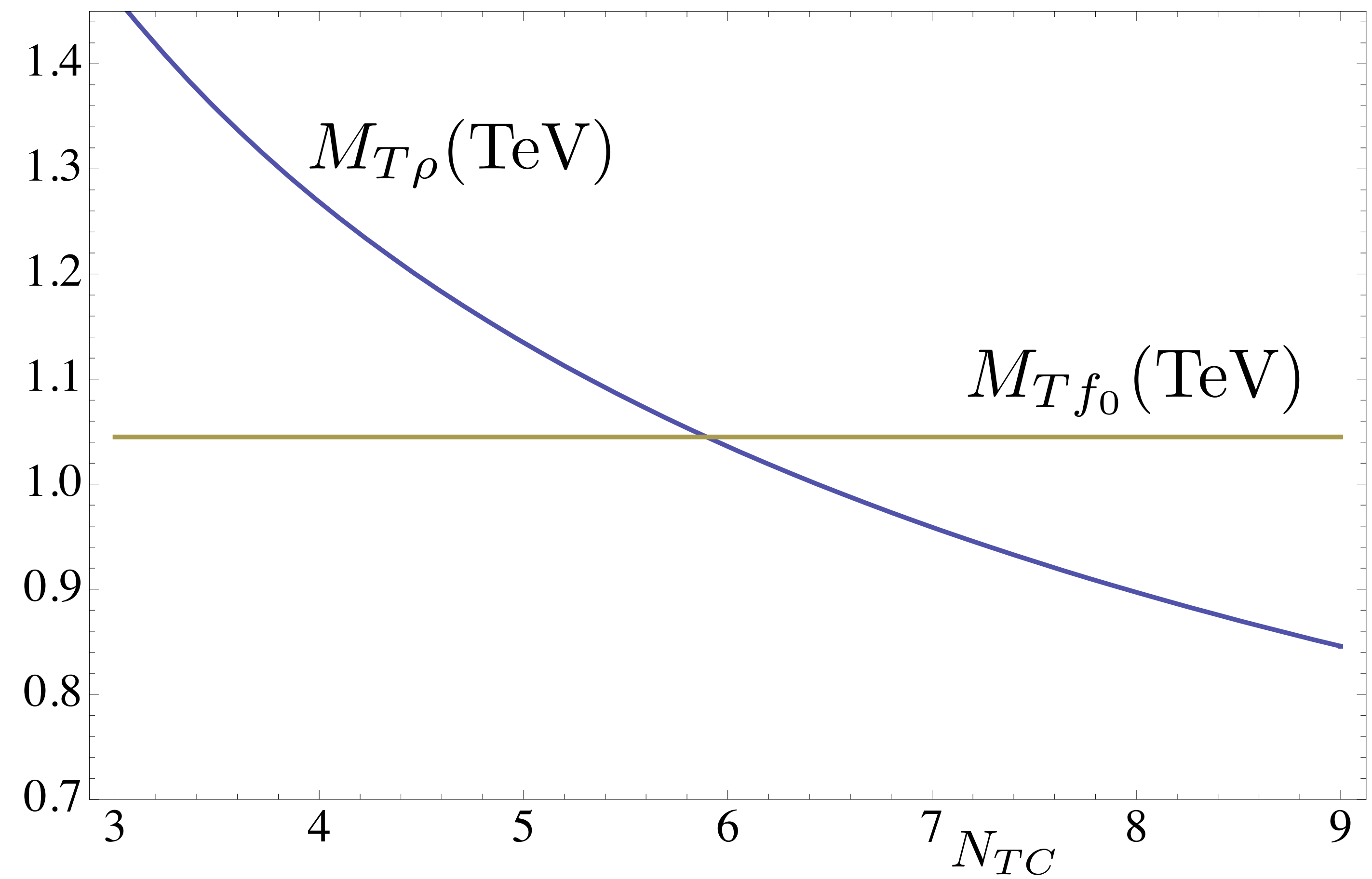
$$M_{T\rho} = \frac{\sqrt{2}v_0}{F_\pi} \frac{\sqrt{3}}{\sqrt{N_D\, N_{TC}}} m_\rho \qquad v_0 \sim 250\text{GeV}$$

$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi \sqrt{N_D}} \left(\frac{N_{TC}}{\sqrt{3}}\right)^{\frac{p-1}{2}} m_{f_0} \qquad p \geq 1$$

F.S. 07

$$N_D = \frac{N_{TF}}{2}$$

$$N_D = 2$$

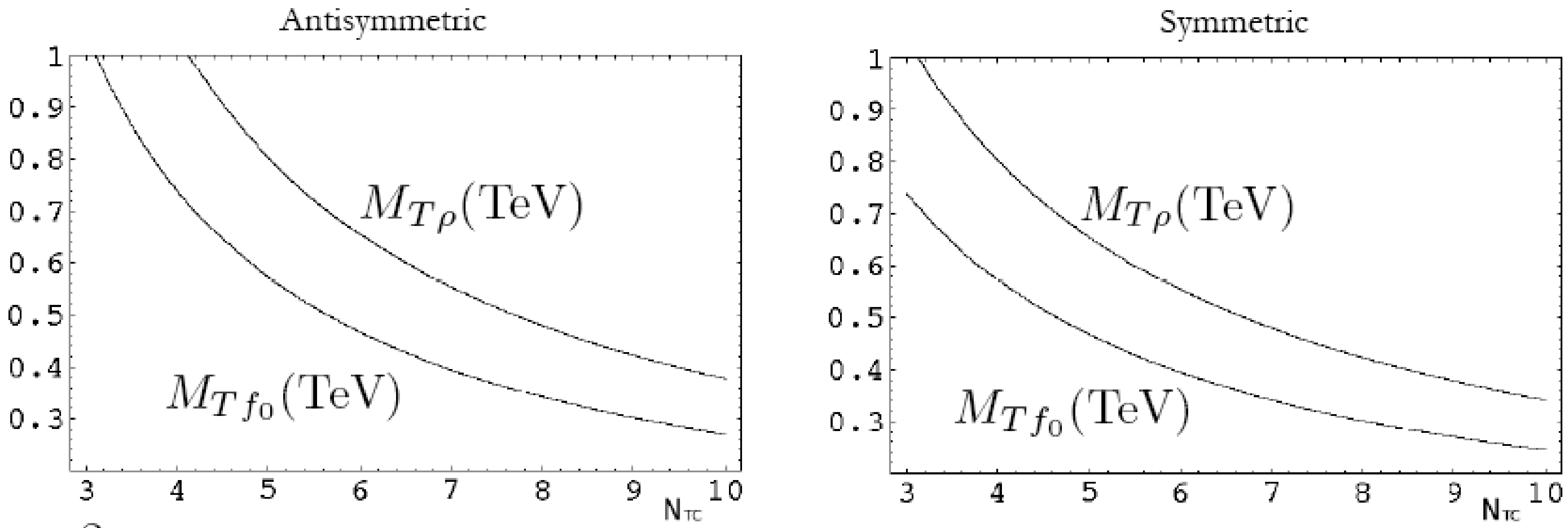


M_H/M_V < 1 in 2-index theories (Corrigan - Ramond Limit)

$$M_{T\rho} = \frac{\sqrt{2}v_0}{F_\pi} \frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D\, N_{TC}(N_{TC} \mp 1)}} m_\rho$$

$$M_{Tf_0} = \frac{\sqrt{2}v_0}{F_\pi} \frac{\sqrt{3}\sqrt{2}}{\sqrt{N_D\, N_{TC}(N_{TC} \mp 1)}} m_{f_0}$$

F.S. 07



$N_D = 2$

Signals Independent

of the

Composite Higgs

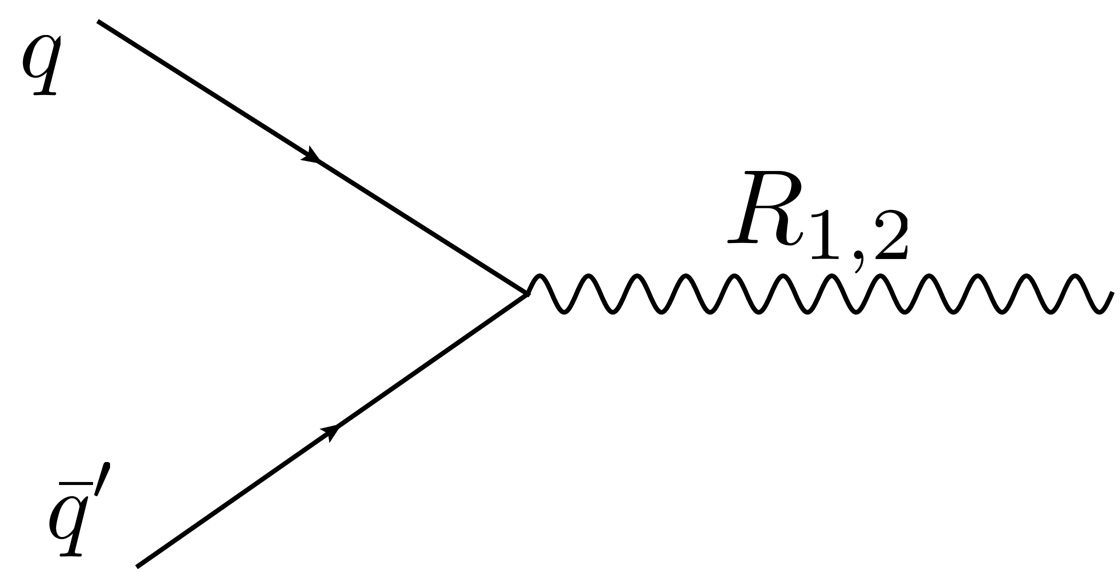
Heavy Vectors Signals

Drell-Yan production of heavy vectors

Vector Boson Fusion production of heavy vectors

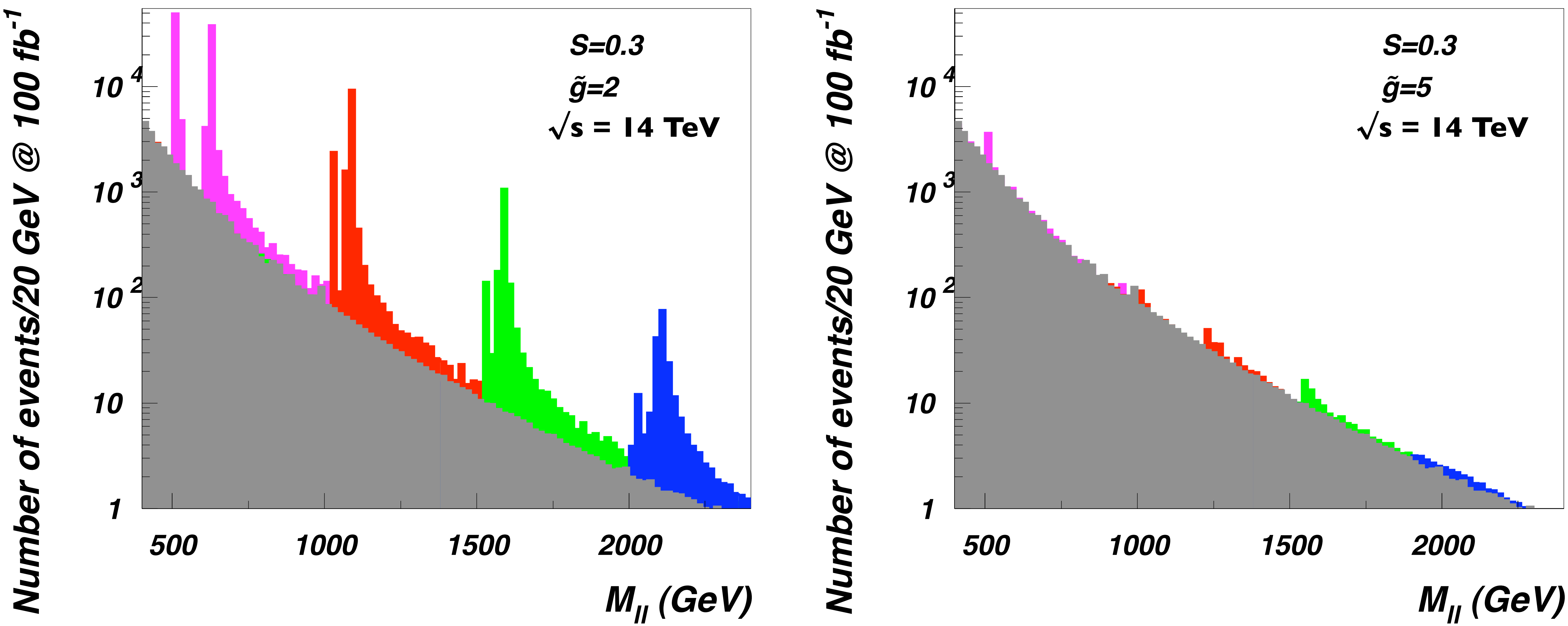
$$R_{1,2}$$

Drell Yan Production



Drell-Yan

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

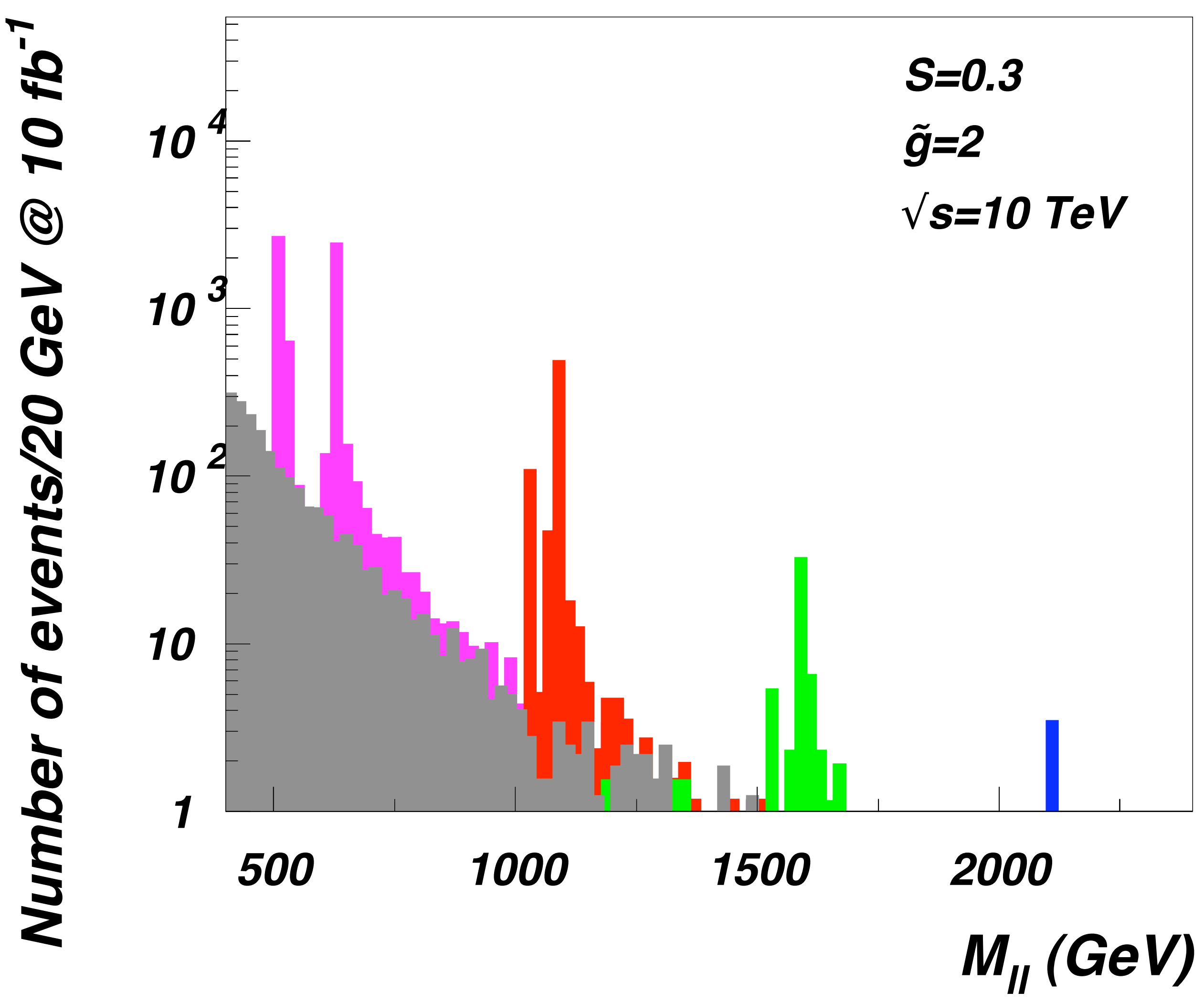


Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$ signal and background processes.

We consider $\tilde{g} = 2, 5$ respectively and masses $M_A = 0.5$ Tev (purple), $M_A = 1$ Tev (red), $M_A = 1.5$ Tev (green) and $M_A = 2$ Tev (blue)

Drell-Yan

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



Undetectable

$$\tilde{g} = 5$$

Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R^0_{1.2} \to \ell^+\ell^-$ signal and background processes.

We consider $\tilde{g} = 2, 5$ respectively and masses $M_A = 0.5$ Tev (purple), $M_A = 1$ Tev (red), $M_A = 1.5$ Tev (green) and $M_A = 2$ Tev (blue)

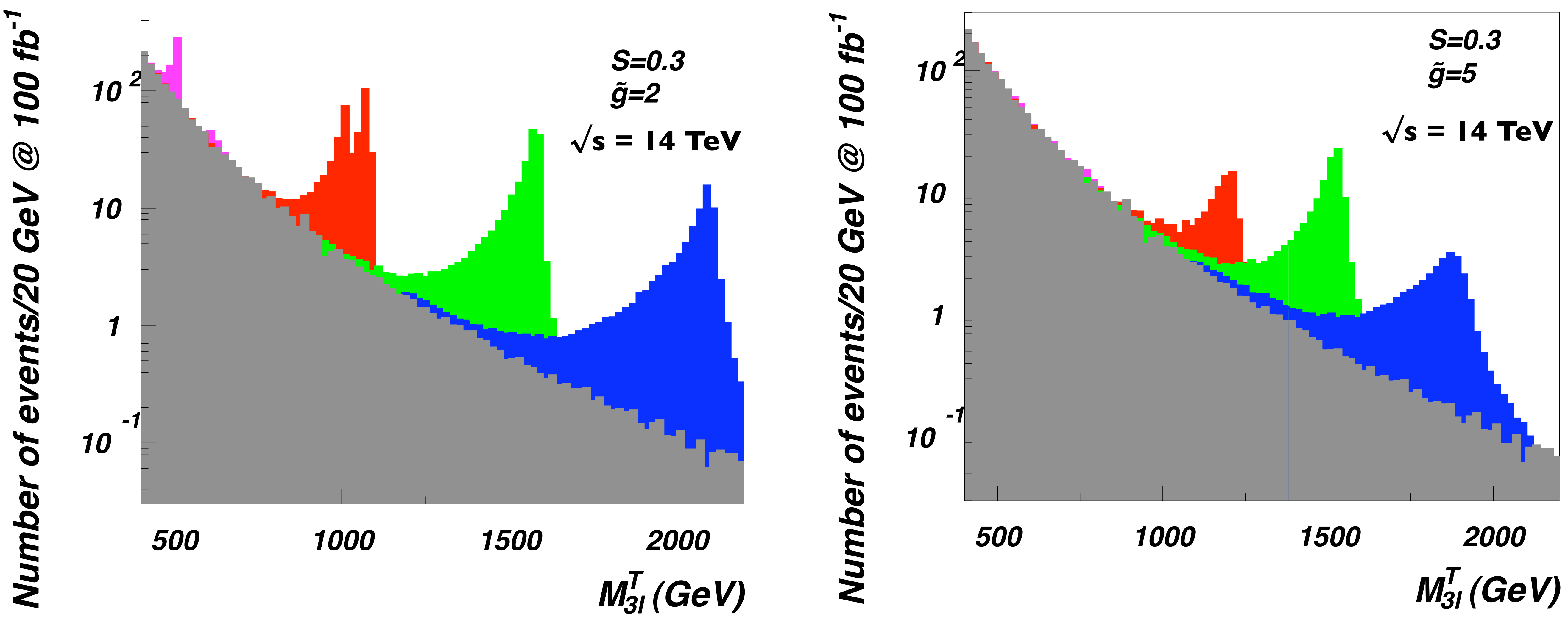
DY visible at small $\tilde{g}$ due to large mixing with W/Z

At small $\tilde{g}$ we observe near Vector-Axial degeneracy

Stronger coupling of the technirho to fermions.

Drell-Yan

$$pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$$

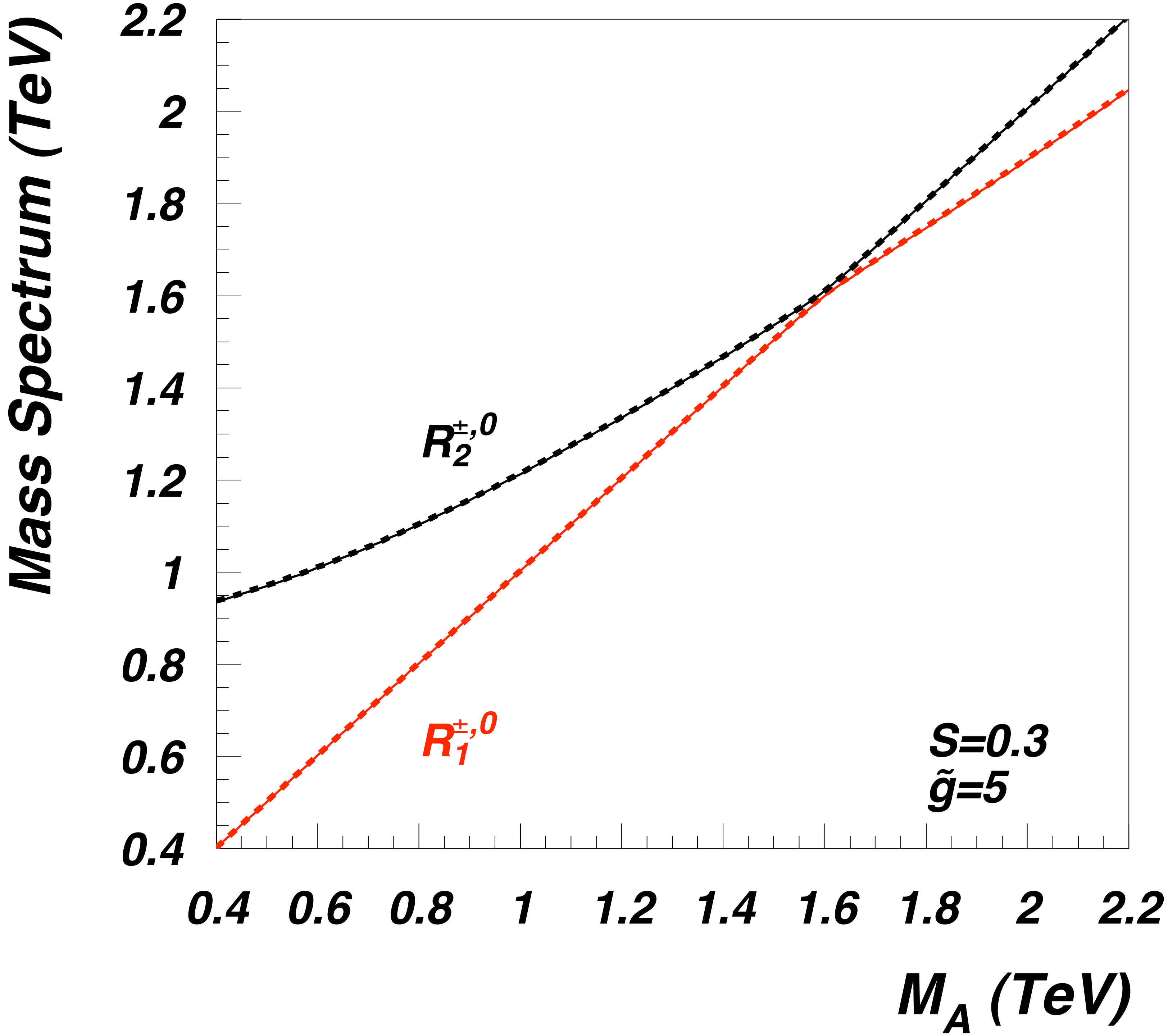


$M^T_{3\ell}$ mass distribution for $pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$ signal and background processes. We consider $\tilde{g} = 2, 5$ respectively and masses $M_A = 0.5$ Tev (purple), $M_A = 1$ Tev (red), $M_A = 1.5$ Tev (green) and $M_A = 2$ Tev (blue).

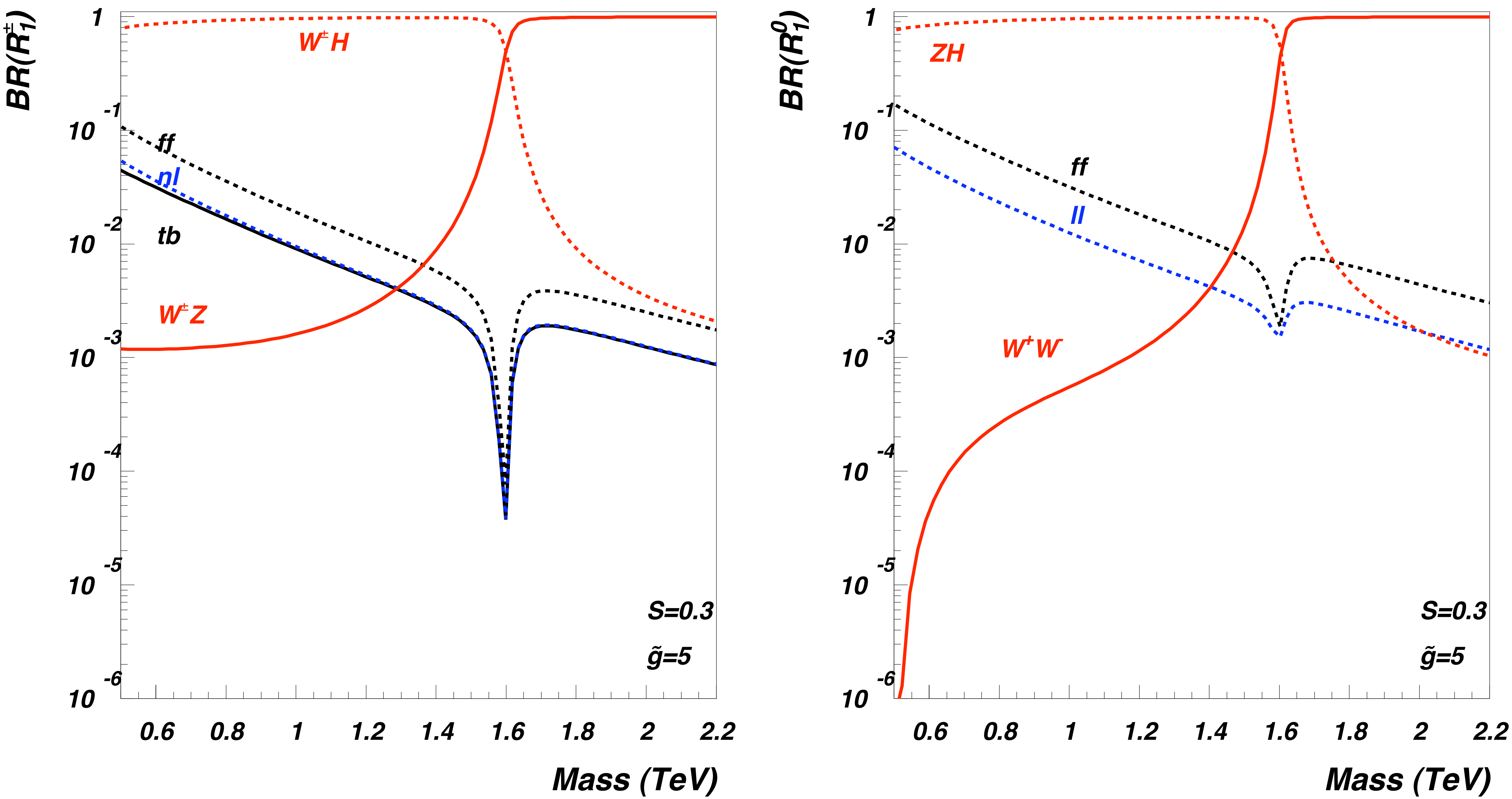
Peaks merge at large $\tilde{g}$ Mass because of the inversion point.

We still see a signal at large $\tilde{g}$ since now R decays via WZ which grows with $\tilde{g}$

Vector-Axial Spectrum

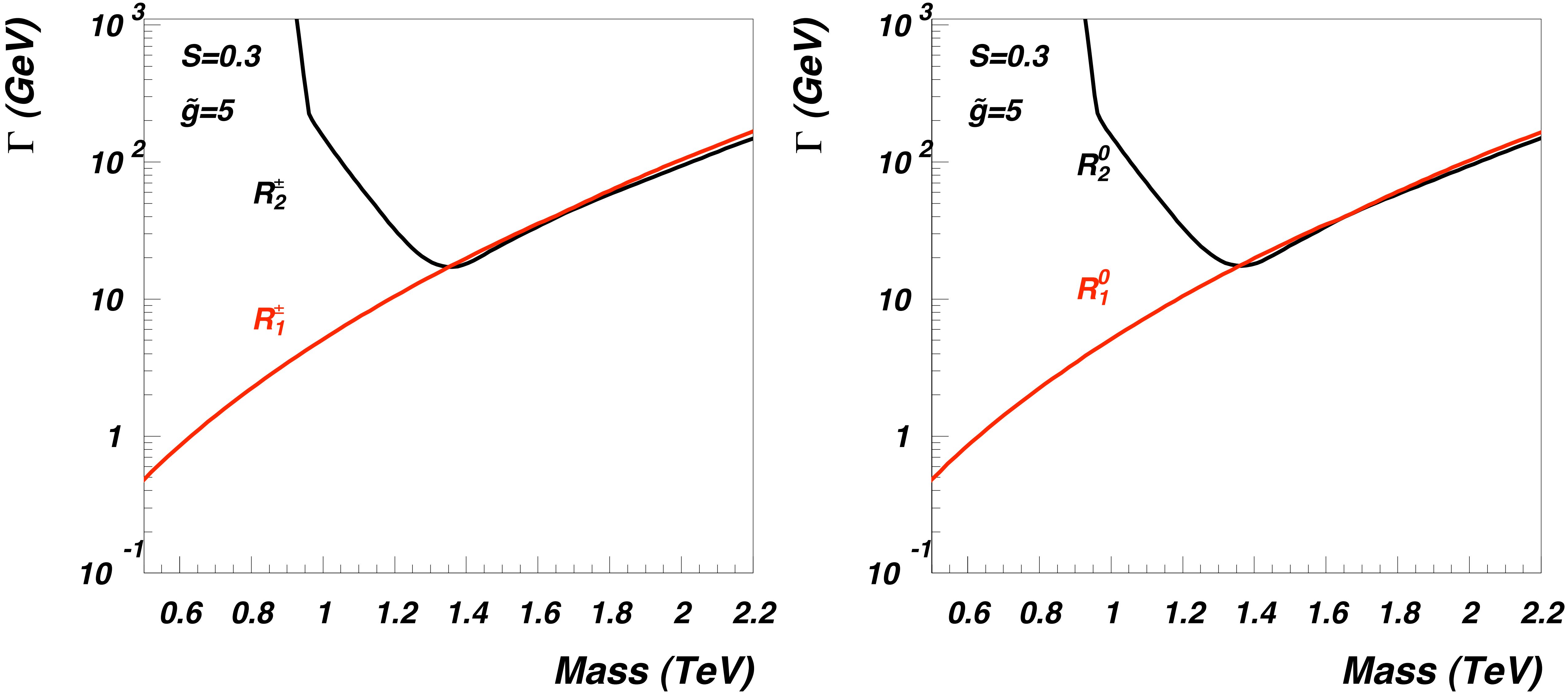


Vector Resonances Branching Ratios



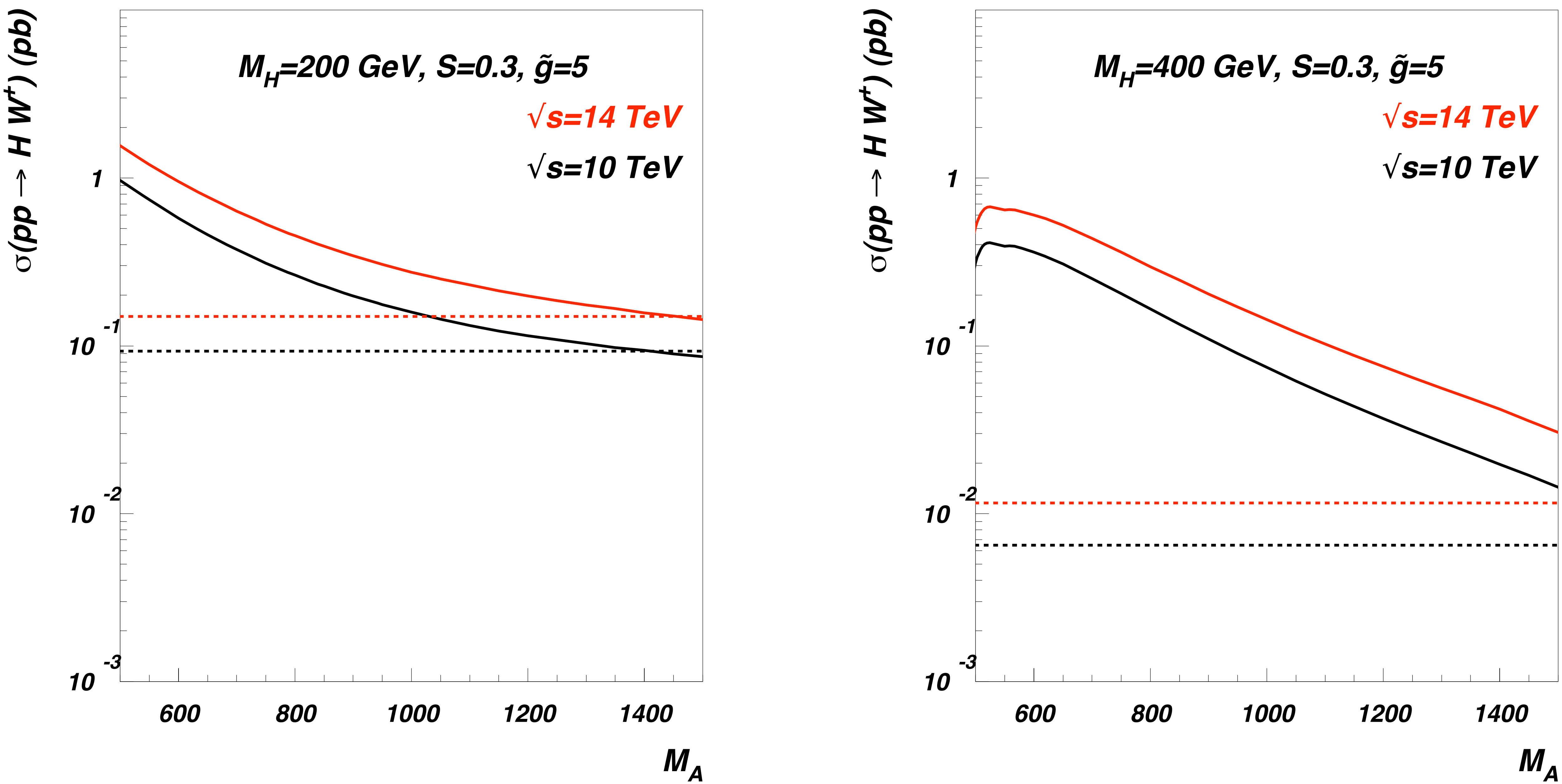
For light masses (Below vector/axial inversion) and large $\tilde{g}$: R1 -> HV is dominant.
M_H = 200 GeV.

Vector Resonances Decays



M_H = 200 GeV.

$$pp \to HV$$



$$HV \to VVV \to \text{leptons+jets}$$