Working Technicolor at the LHC

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CP3 - Origins

Particle Physics & Origin of Mass

4 March 2011, La Thuille

Outline

- Technicolor
- Walking Dynamics and Minimal Models
- Phenomenology at the LHC

Technicolor

QCD lesson:

Chiral Symmetry: $SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{u}_L u_R + \bar{d}_L u_R \rangle = \Lambda^3_{\text{QCD}}} SU(2)_V$

Gauge Symmetry: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

$$M_W = \frac{gF_\pi}{2} \sim 29\,\text{MeV}$$

New Strong Interactions at higher scale [Weinberg, Susskind]

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

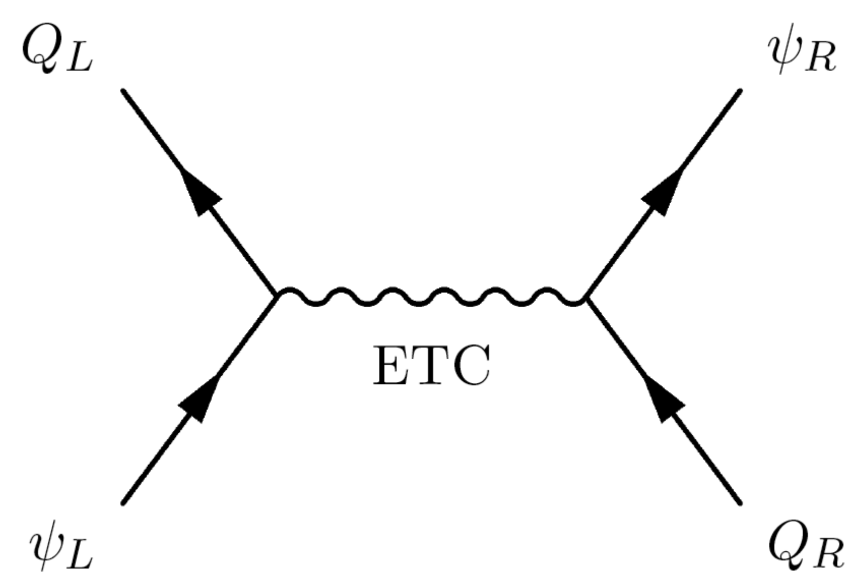
Q_L, Q_R Techniquarks

Global Symmetry: $SU(N)_L \times SU(N)_R \longrightarrow SU(N)_V$

$$\langle \bar{Q}Q \rangle = \Lambda^3_{\text{TC}} = (246\,\text{GeV})^3 \qquad M_W = \frac{gF_\pi^{TC}}{2} \sim 80\,\text{GeV}$$

Extended Technicolor

Fermion Masses: $\bar{L} \cdot H e_R \quad \rightarrow \quad \bar{L} \frac{\bar{Q}Q}{\Lambda_{ETC}^2} e_R$



$$\alpha_{ab} \frac{\bar{Q}T^a Q \bar{Q} T^b Q}{\Lambda_{ETC}^2} + \beta_{ab} \frac{\bar{Q}_L T^a Q_R \bar{\psi}_R T^b \psi_L}{\Lambda_{ETC}^2} + \gamma_{ab} \frac{\bar{\psi}_L T^a \psi_R \bar{\psi}_R T^b \psi_L}{\Lambda_{ETC}^2} + \ldots$$

PNG Masses

SM-Fermion Masses

FCNC Operators

Gamma - Terms

$$\frac{1}{\Lambda_{ETC}^2}(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d) + \frac{1}{\Lambda_{ETC}^2}(\bar{\mu}\gamma^5 e)(\bar{e}\gamma^5 e) + \ldots$$

$$\downarrow$$

$$\Lambda_{ETC} \geq 10^3 \Lambda_{TC}$$

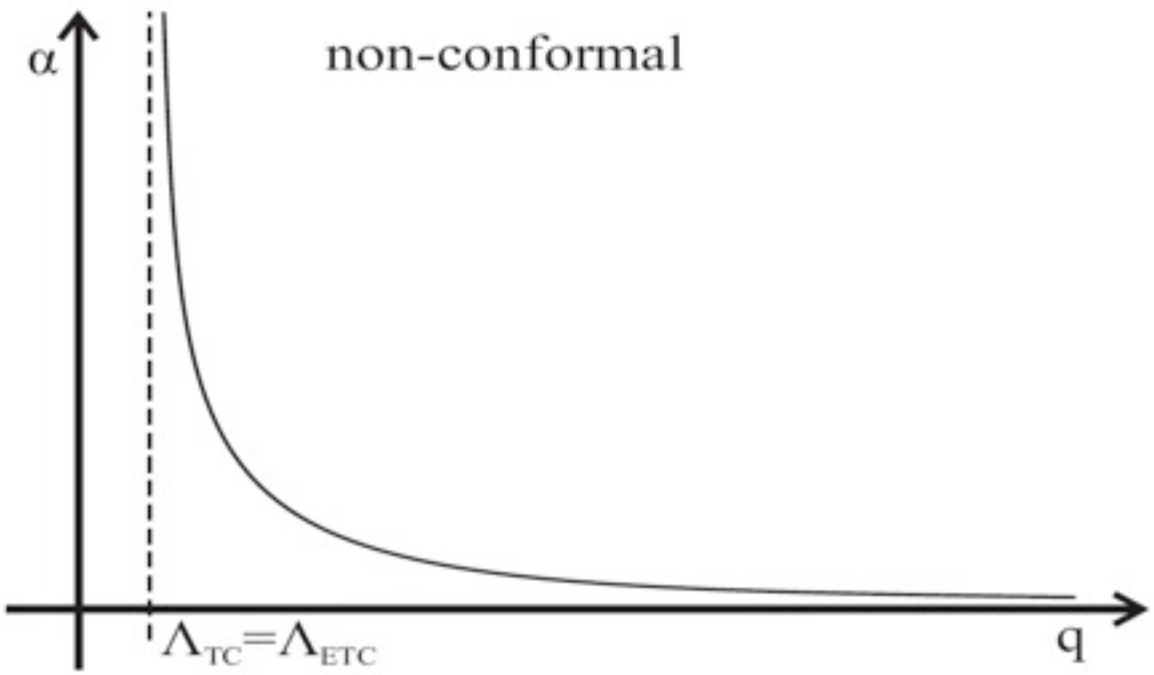
QCD like dynamics: $< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda_{TC}^3$

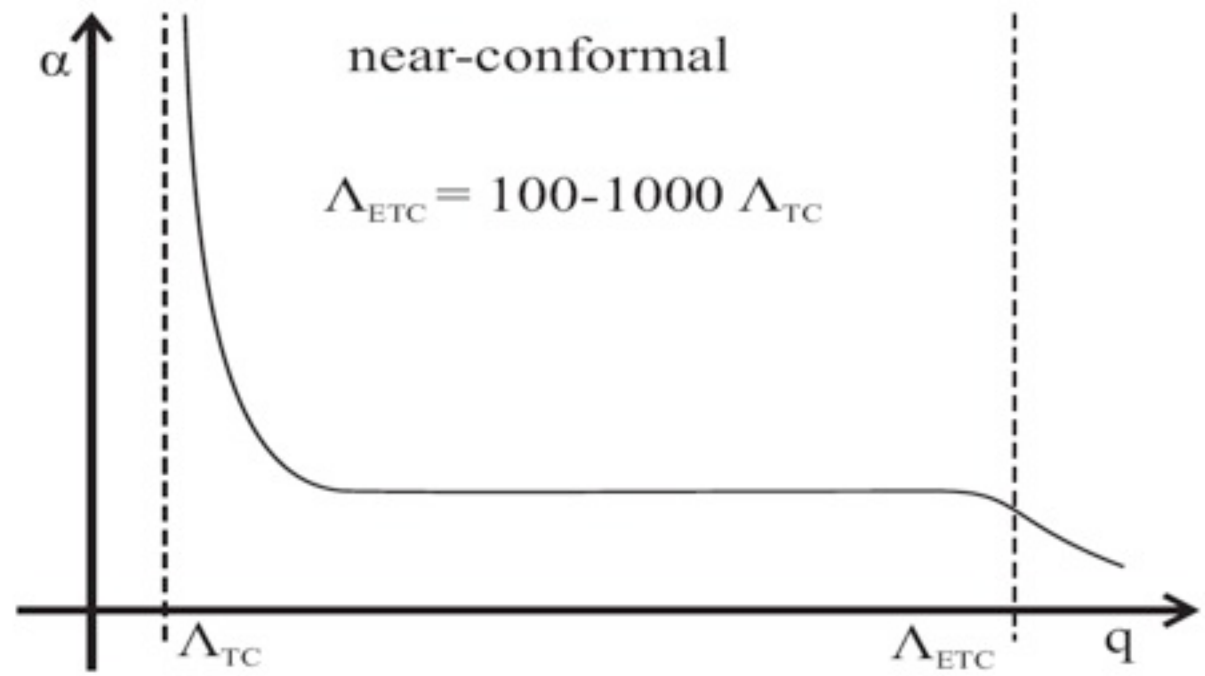
$$m_{\mathrm{f}} \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\mathrm{Top}}$$

Is it possible to enhance $< \bar{Q}Q >_{ETC}$ *?*

New type of dynamics

[Holdom]





$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} = \frac{g^2_{ETC}}{\Lambda^2_{ETC}} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma_m(\alpha^*)} < \bar{Q}Q >_{TC}$$

Need large anomalous dimension

Minimal models of WT

Guidelines for model building:

- Walking dynamics
- Minimising the contribution to S

$$S_{\text{naive}} = \frac{d(r)N_f}{12\pi}$$

Gauge Group, i.e. SU, SO, SP

Matter Representation

# of Flavors

- Minimal WT Dietrich, Sannino, Tuominen

$SU(2)_{TC}$ $\Box\Box$ **U** **D** **N** **E**

Global Symmetry:

$$SU(4) \longrightarrow SO(4)$$

3+6 NGB

- Next to MWT Dietrich, Sannino, Tuominen

$SU(3)_{TC}$ $\Box\Box$ **U** **D**

Global Symmetry:

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

3 NGB

WT Effective Lagrangian

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

In the initial investigation we include:

Composite Higgs

Composite Axial - Vector States

Walking/Higher dim. rep. can allow for:

Light Composite Higgs

Sannino 08

Hong, Hsu, Sannino, 04

Dietrich, F.S., Tuominen 05

Doff, Natale, Rodrigues da Silva 08

Doff, Natale, 09.

Light Composite Axial

Foadi, Frandsen, Ryttov, Sannino 07

Eichten, Lane 07

NMWT Effective Lagrangian

- Next to MWT $SU(3)_{TC}$ ☐☐ **U** **D** $SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V$

$$
\begin{aligned}
\mathcal{L}_{\rm boson} \; = \; & -\frac{1}{2}{\rm Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}\widetilde{B}_{\mu\nu}\widetilde{B}^{\mu\nu} - \frac{1}{2}{\rm Tr}\left[F_{{\rm L}\mu\nu}F_{\rm L}^{\mu\nu} + F_{{\rm R}\mu\nu}F_{\rm R}^{\mu\nu}\right] \\
& + \; m^2\;{\rm Tr}\left[C_{{\rm L}\mu}^2 + C_{{\rm R}\mu}^2\right] + \frac{1}{2}{\rm Tr}\left[D_\mu M D^\mu M^\dagger\right] - \tilde{g}^2\; r_2\;{\rm Tr}\left[C_{{\rm L}\mu} M C_{\rm R}^\mu M^\dagger\right] \\
& - \; \frac{i\;\tilde{g}\;r_3}{4}{\rm Tr}\left[C_{{\rm L}\mu}\left(M D^\mu M^\dagger - D^\mu M M^\dagger\right) + C_{{\rm R}\mu}\left(M^\dagger D^\mu M - D^\mu M^\dagger M\right)\right] \\
& + \; \frac{\tilde{g}^2 s}{4}{\rm Tr}\left[C_{{\rm L}\mu}^2 + C_{{\rm R}\mu}^2\right]{\rm Tr}\left[M M^\dagger\right] + \frac{\mu^2}{2}{\rm Tr}\left[M M^\dagger\right] - \frac{\lambda}{4}{\rm Tr}\left[M M^\dagger\right]^2 \qquad (3.47)
\end{aligned}
$$

- Different underlying theories can have the same chiral symmetry breaking
- New particles - two triplets of heavy vectors: $R_1^\pm, R_1^0$ and $R_2^\pm, R_2^0$
- Link to the underlying TC theory via Modified Weinberg Sum Rules
- Relevant parameters: $\tilde{g},\; M_A,\; M_H$

Model Implementation

Energy

BSM

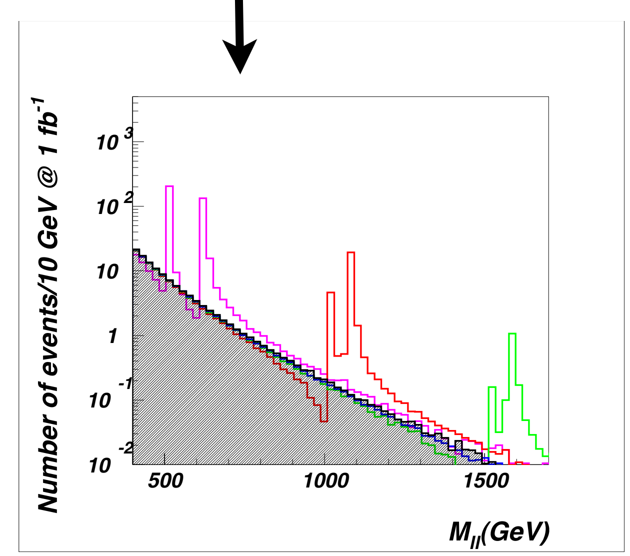
Λ

Underlying Theory:
(N)MWT
arXiv: hep-ph/0405209

Effective Lagrangian
arXiv:0706.1696 [hep-ph]

FeynRules
arXiv:0806.4194 [hep-ph]

MadGraph,
CalcHep, ...

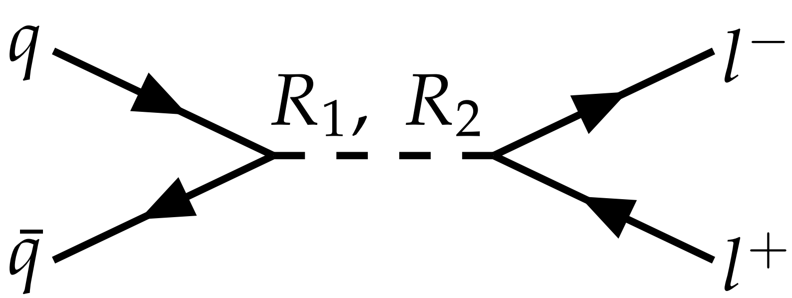


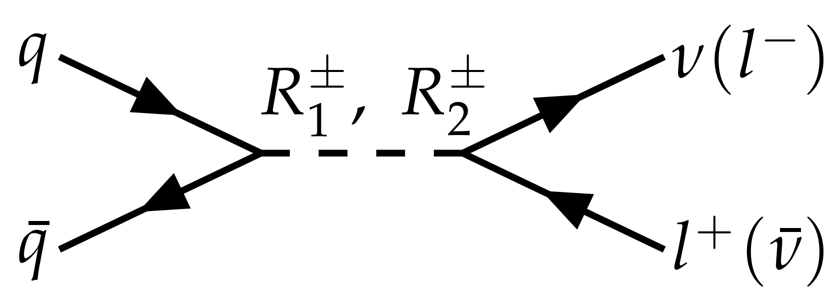
http://cp3-origins.dk/research/tc-tools
http://feynrules.phys.ucl.ac.be/wiki/TechniColor

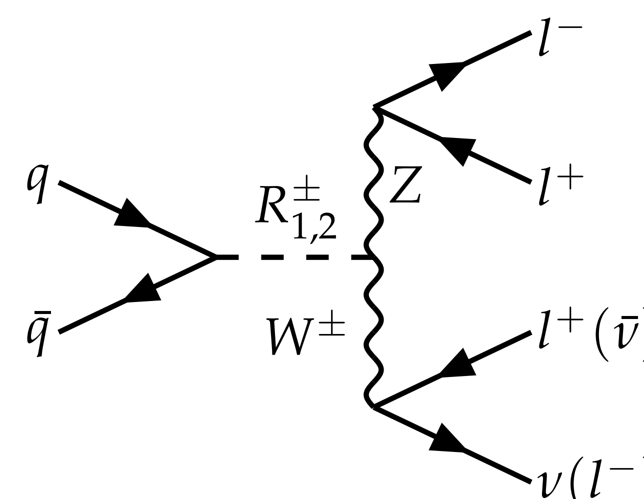
Spin one at LHC

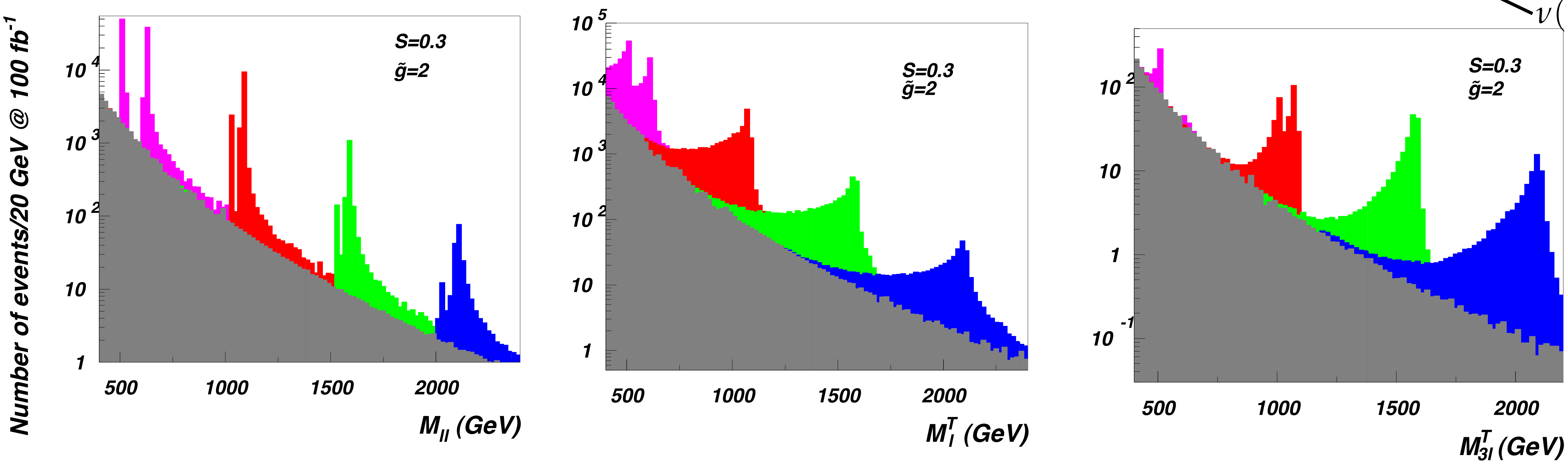
- Drell-Yan Production

$$pp \to R^0_{1,2} \to l^+ l^- \qquad pp \to R^\pm_{1,2} \to l^\pm \nu \qquad pp \to R^\pm_{1,2} \to ZW^\pm \to 3l\nu$$







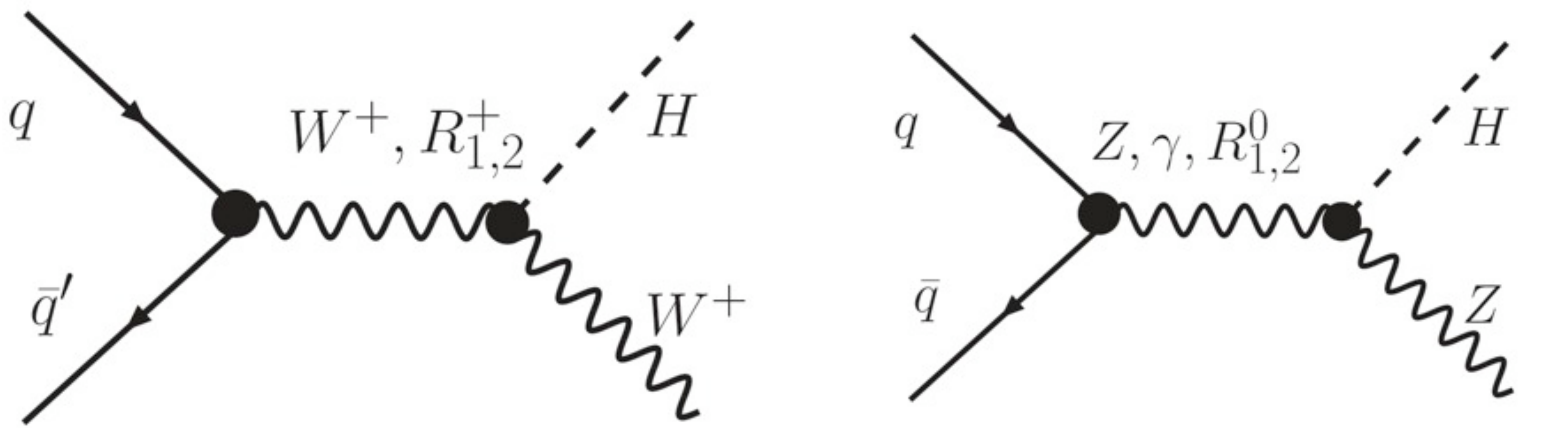


[0809.0793, Belyaev, etal.]
[CP3 Report, Antola etal, to appear soon]

100 fb^{-1}; 14 TeV

M_A=0.5,1,1.5, 2 TeV

Higgs Phenomenology



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

Conclusions

- Dynamical EWSB can naturally occur at the LHC
- Simplest models of Walking Technicolor
- A lot of work to be done: lattice simulations, discrimination among different strongly interacting scenarios, more phenomenological analysis,...

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**

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

zeroth **first** **second**

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

Details: Appelquist, Sannino 98

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]

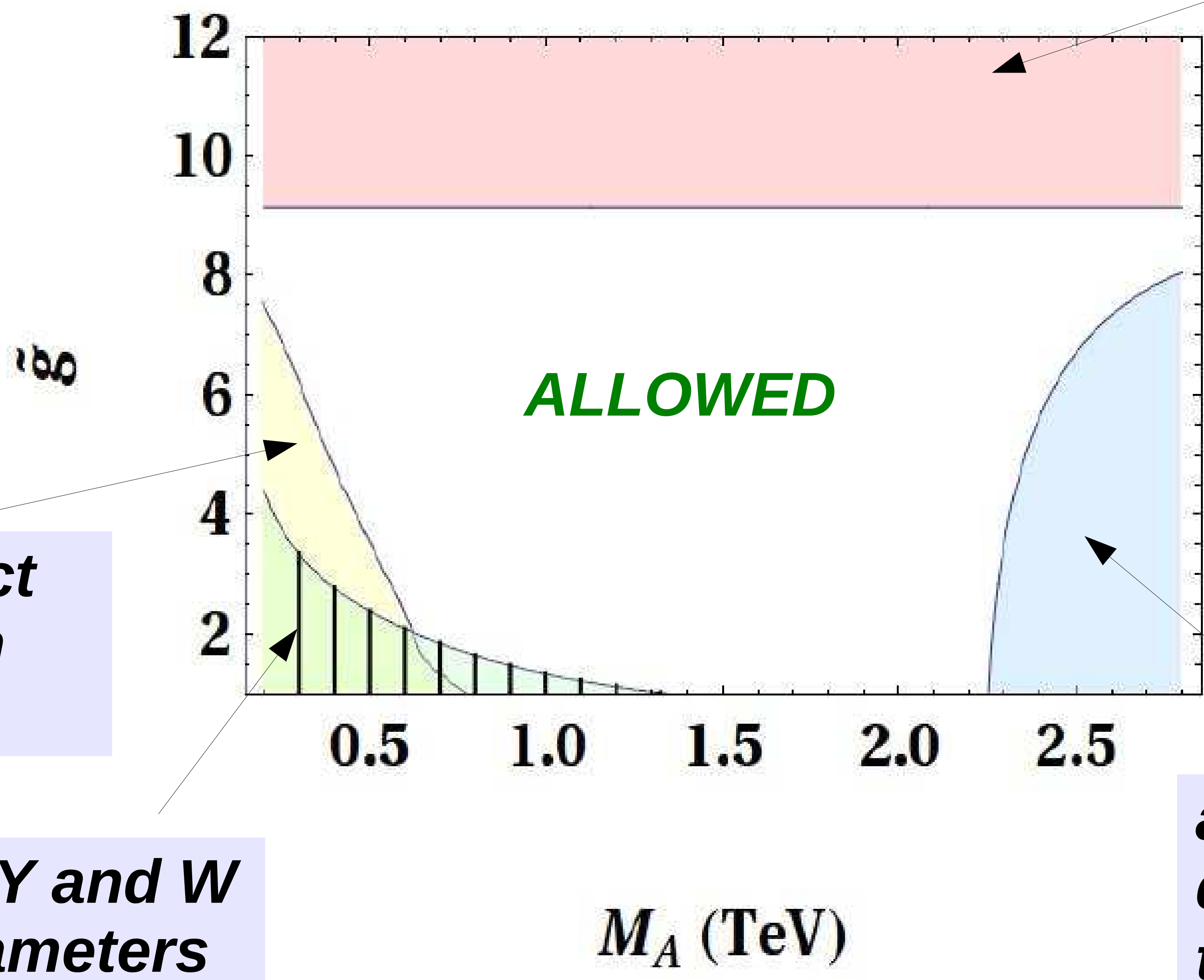
- Solving truncated Schwinger-Dyson and Bethe-Salpeter equations

[Doff, Natale 08,09]

- Light Higgs can help to unitarize WW scattering

[Foadi, MJ, Sannino 08]

Viable NMWT parameter space



imaginary F_V and F_A

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

CDF direct limit from pp -> e^+e^-

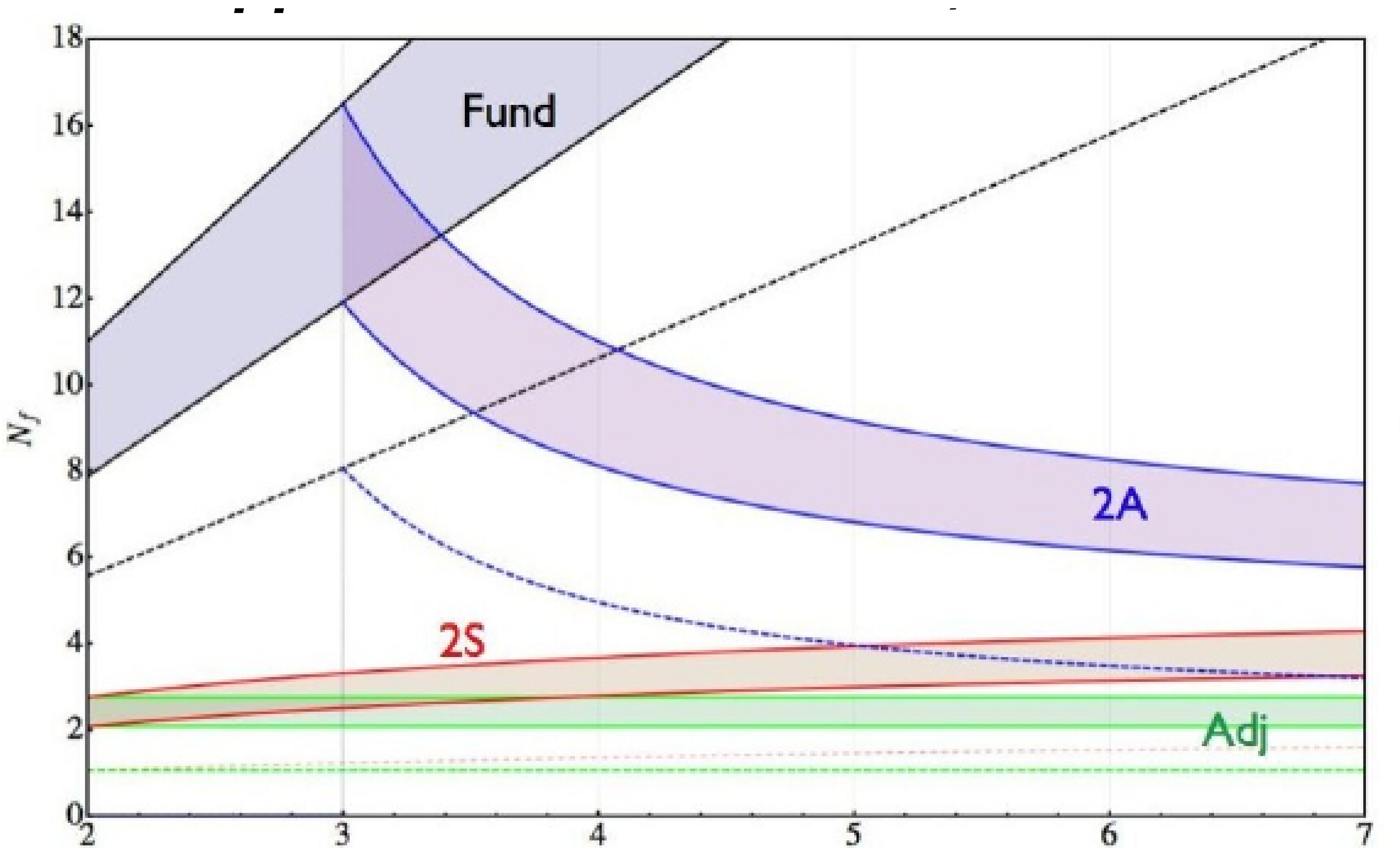
EW Y and W parameters @95% CL

a<0, defined by the 2nd WSR

Barbieri, Pomarol, Rattazzi,Strumia 04

SM Higgs vs Technicolor

SM Higgs	Technicolor
simple and economical	*complicated at the effective theory level*
GIM mechanism, no FCNC problems, EW precision data are OK for preferably light Higgs boson	*FCNC constraints requires* ***walking****, potential tension with EW precision data*
SM is established, perfectly describes data	*no viable ETC model suggested yet, work in progress*
fine-tuning and naturalness problem	*no fine-tuning, the scale is dynamically generated*
there is no example of fundamental scalar	*Superconductivity and QCD are examples of dynamical symmetry breaking*
Scalar potential parameters and yukawa couplings are inputs	*parameters of low-energy effective theory are derived once underlying ETC is constructed*



Fund
2A
2S
Adj
N_f
18
16
14
12
10
8
6
4
2
0
2
3
4
5
6
7