Review of Minimal Walking Theories

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Confinement XI

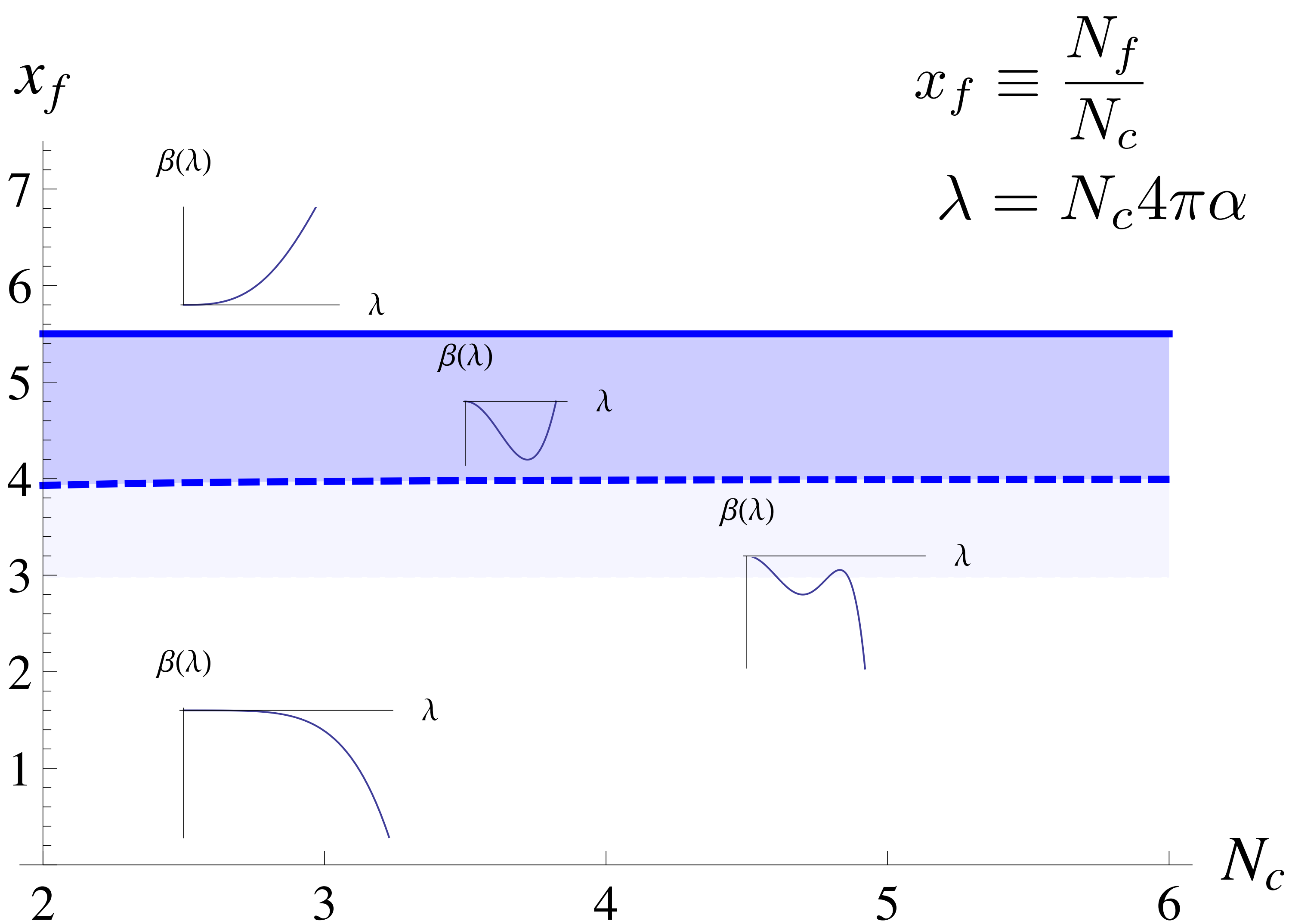
11. 9. 2014 St. Petersburg

Outline

1. Strong dynamics in isolation: Vacuum phases
2. Coupling with the Standard Model: A light scalar
3. Other directions: Dark matter

1. Strong dynamics in isolation: Vacuum phases

Theory motivation: phases of gauge theories



Given a gauge theory and its matter content,

- Where are the borderlines between different behaviors?
- Is there a quasi-conformal region (walking)?
- What are the relevant scales, excitation spectrum etc.?

(Also talks by T. Ryttov and E. Mølgaard)

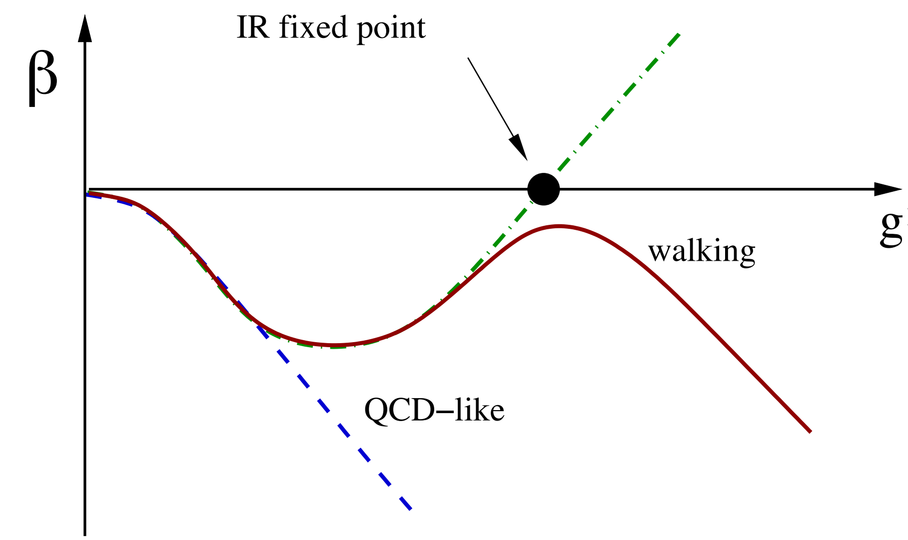
The traditional approach: ladder approximation

Miransky, Yamawaki, 1997; Appelquist, Terning, Wijewardhana 1996

Fixed point from 2-loop betaf. $\alpha^* = -\frac{\beta_0}{\beta_1}(4\pi)$

Critical coupling for chiral breaking from SD-equ. $\alpha_c = \frac{\pi}{3C_2(R)}$

Conformal window: $\alpha^* \leq \alpha_c$



Depends on N_c , N_f and fermion representation R

Alternatives:

Holography, e.g. Kiritsis, Järvinen 2012; Alho, Evans, Tuominen 2014; (see Järvinen's talk)

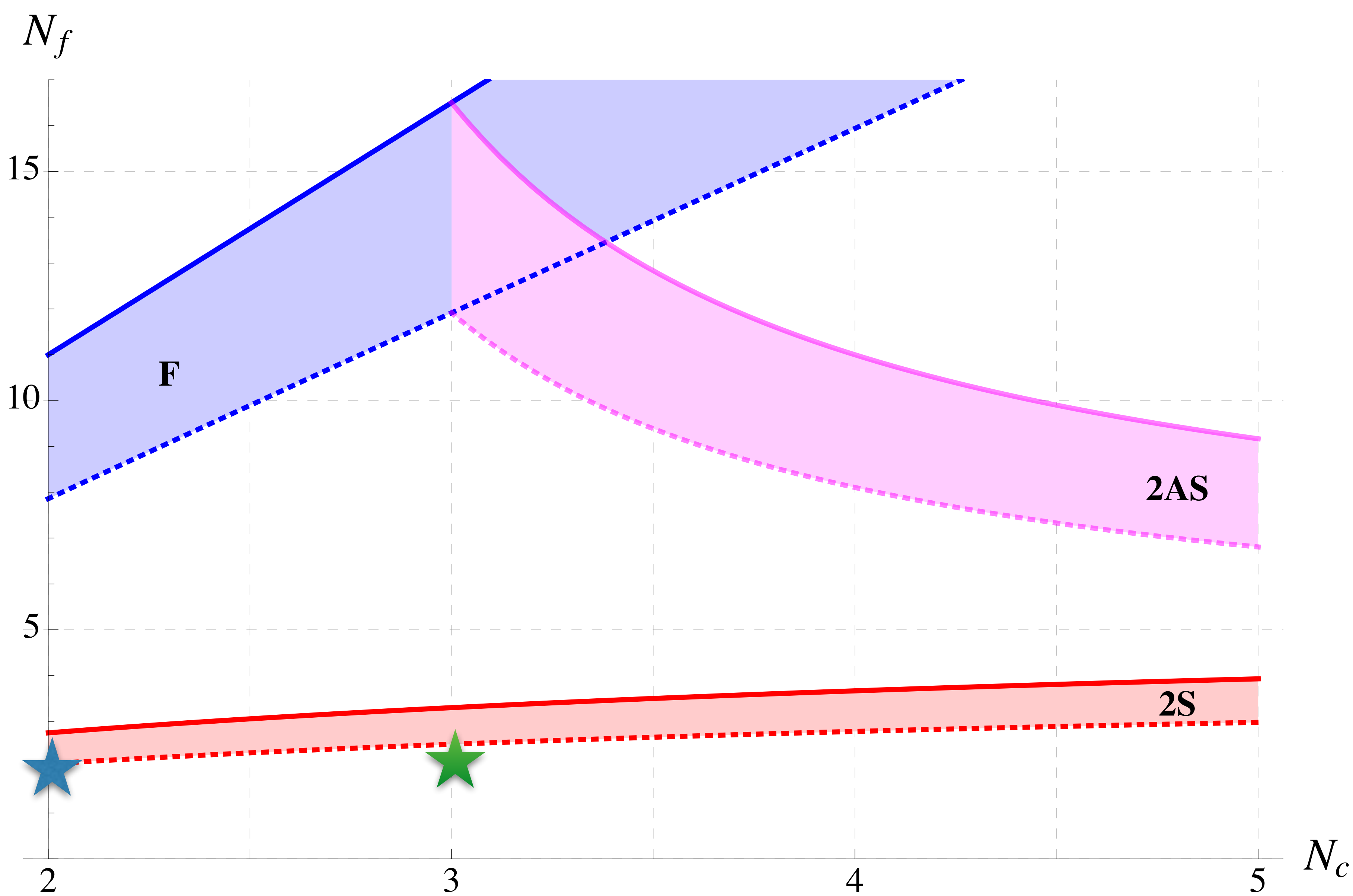
Beta function ansätze, e.g. Ryttov, Sannino 2009; Antipin, Tuominen 2009

Thermal dof count, Appelquist, Cohen, Schmaltz 1999

...

All in quantitative agreement with the ladder appro.

Ladder results (Sannino, Tuominen PRD 71 (2004) hep-ph/0405209)



Two minimal models:


SU(2) + 2 adjoint flavors:
SU(2)-Minimal Walking Theory (SU(2)MWT)


SU(3)+2 sextet flavors:
SU(3)MWT

A perfect program for lattice studies:

Lots of efforts during last 5 years.

SU(2) adjoint: (Catteral et al., Hietanen et al., Del Debbio et al.,...)

SU(2) fundamental: (Del Debbio et al., Karavirta et al.,...)

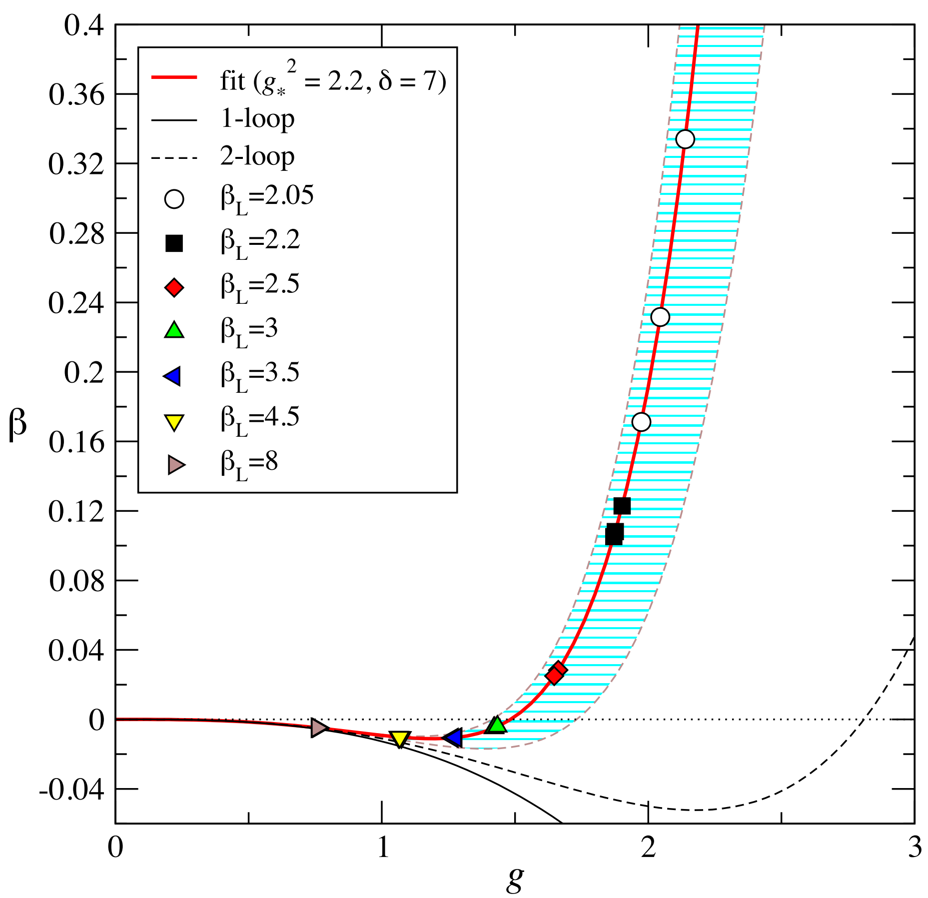
SU(3) fundamental: (Appelquist et al., Kuti et al.,...)

SU(3) sextet: (De Grand et al.,...)

First large-scale simulations:

A. Hietanen et al. JHEP (2009) , 0812.1467

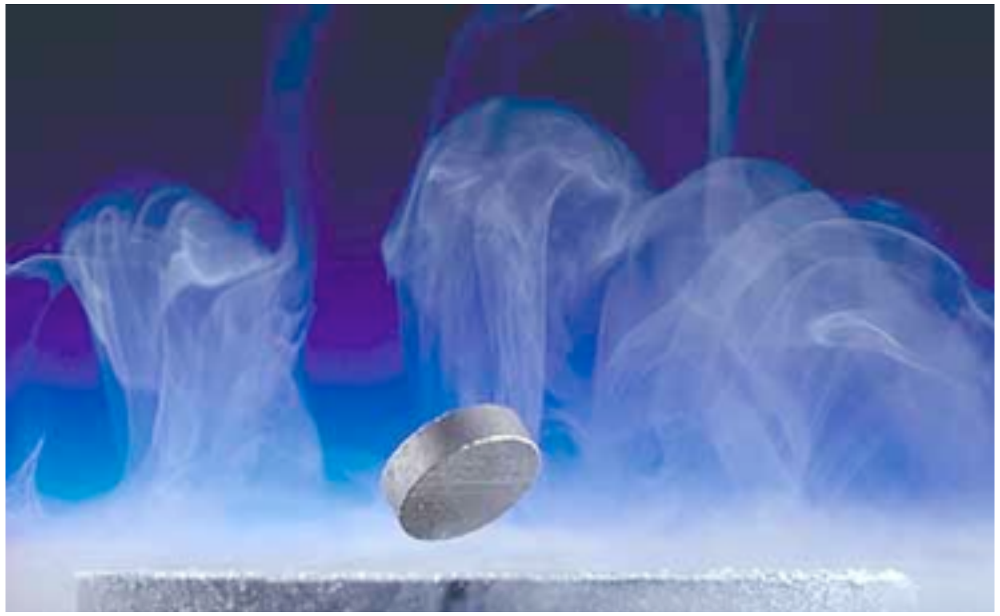
A. Hietanen et al. PRD 80 (2009), 0904.0864



SU(2), 2 adjoint flavors

- IR Conformal
- Confirmed by other groups.

Phenomenology motivation: dynamical EWSB



Vintage compositeness: replicate QCD

Weinberg '79,
Susskind '79

Higgs mechanism as usual from SSB+gauge symm.

$\langle \bar{Q}_L Q_R \rangle = \Lambda_{\rm TC}^3, \quad \Lambda_{\rm TC} \simeq 1 \text{ TeV}$

The Higgs is composite.

$\pi^{\pm}, \pi^0 \to W_L^{\pm}, Z_L \qquad M_W = \frac{g F_{\rm TC}}{2}, \qquad F_{\rm TC} \simeq 250\,\text{GeV}$

Phenomenological tensions, S-parameter, ETC, etc. suggest non QCD-like dynamics instead (i.e. walking?)

Plenty of pheno studies based on SU(2)MWT and SU(3)MWT.
- Oblique corrections, vector mesons, coupling to SM fermions,...

Dietrich, Sannino, Tuominen 2005, Foadi et al. 2007, Belyaev et al. 2009, ...

Coupling with SM fields changes properties from those observed in isolation.

2. Coupling with the Standard Model: A light scalar

Recall Pagels-Stokar:

$$F_\Pi^2 \simeq 4NM^2 \ln\left(\frac{\Lambda_{\rm TC}^2}{M^2}\right)$$

Setting $F_\pi = 246\,\mathrm{GeV}$ and $\Lambda_{\rm TC} \simeq 2 \ldots 10\,\mathrm{TeV}$, this implies that the dynamical mass is constrained: $M \simeq 0.5 \ldots 1\,\mathrm{TeV}$

So how to get 125 GeV?

Example: the mass difference of neutral and charged pions in QCD:

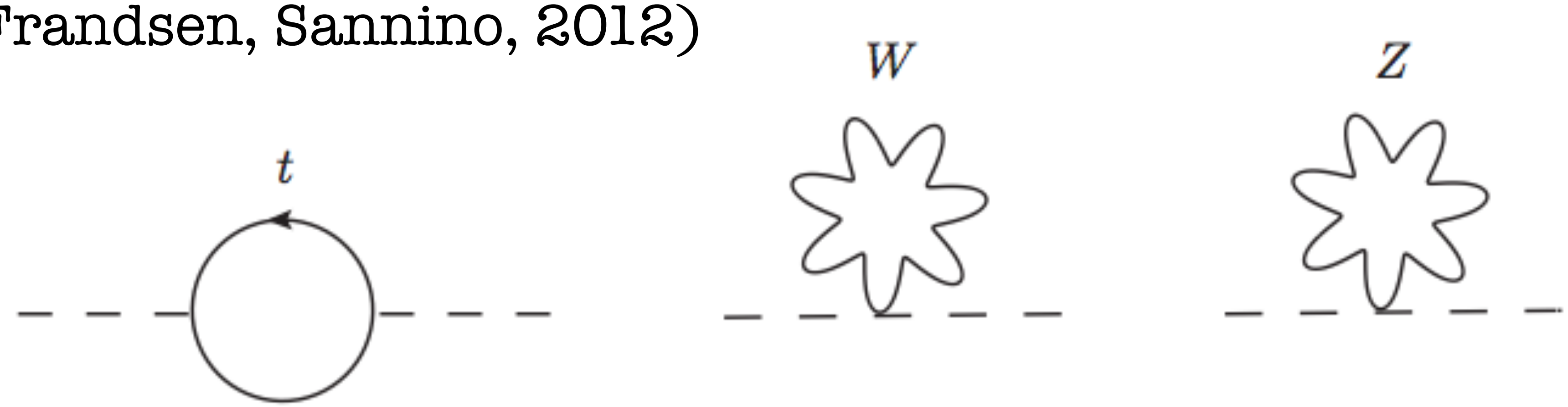
$$m_{\pi^+}^2 - m_{\pi^0}^2 \simeq (35\,\mathrm{MeV})^2 \propto \alpha_{\mathrm{EM}}$$

This is small, $\mathcal{O}(0.1 f_\pi)$, because α_{EM} is small.

Take $\alpha_{\mathrm{EM}} \sim 1/(4\pi)$ and the effect is $\mathcal{O}(f_\pi)$.

In SM couplings are not small, e.g. top Yukawa

(Foadi, Frandsen, Sannino, 2012)



We will now consider this in a setting where all (nonzero) masses are generated dynamically

Consider a model (Di Chiara, Foadi, Tuominen (2014))

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm TC} + \mathcal{L}_{\rm ETC}$$

A very simple extended dynamics to generate top mass:

$M_{\rm ETC}$

$$\mathcal{L}_{\rm ETC} = 2G\left(\bar{q}_L t_R \overline{U}_R Q_L + \text{h.c.}\right) \qquad G \sim \frac{1}{M_{\rm ETC}^2}$$

$$\Sigma = \exp(i\Pi^a \tau^a / v)$$

$\Lambda_{\rm TC} \simeq 4\pi F_\Pi$

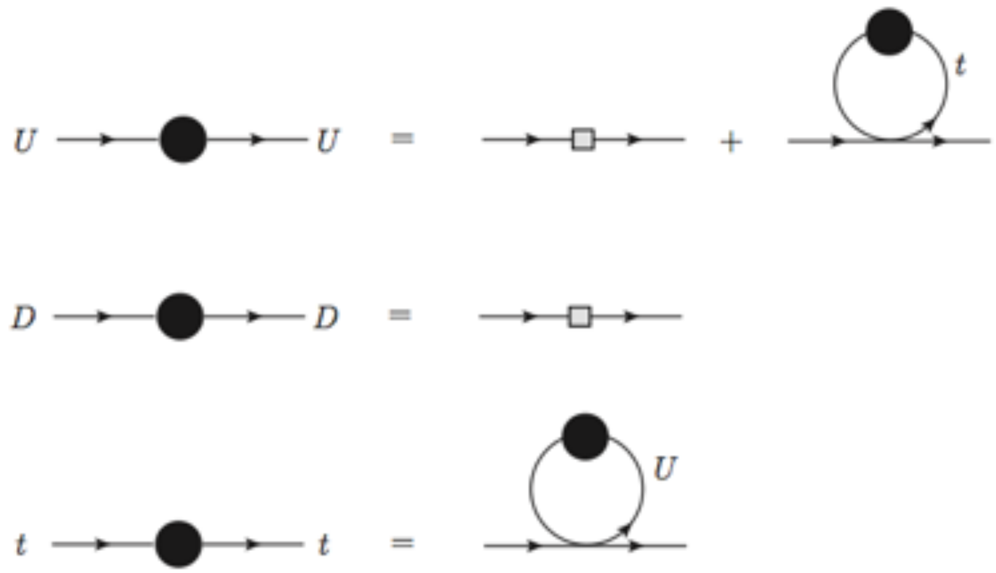
$$\mathcal{L}_{\rm TC} = \overline{Q}_L\ i\not{D} Q_L + \overline{U}_R\ i\not{D} U_R + \overline{D}_R\ i\not{D} D_R$$
$$-M\left(1 + \frac{y}{v}H + \cdots\right)\left(\overline{Q}_L \Sigma Q_R + \overline{Q}_R \Sigma^\dagger Q_L\right) - \frac{m^2}{2}H^2 + \cdots$$

U,D in N dimensional rep. of a new strong gauge group.

$F_\Pi \simeq 246\,\text{GeV}$

Question: what is the mass of the composite scalar H ?

The masses determined by gap eqs:



$$M_U = \frac{N_c G M_t}{4\pi^2}\left(M_{\rm ETC}^2 - M_t^2 \ln\frac{M_{\rm ETC}^2 + M_t^2}{M_t^2}\right)$$

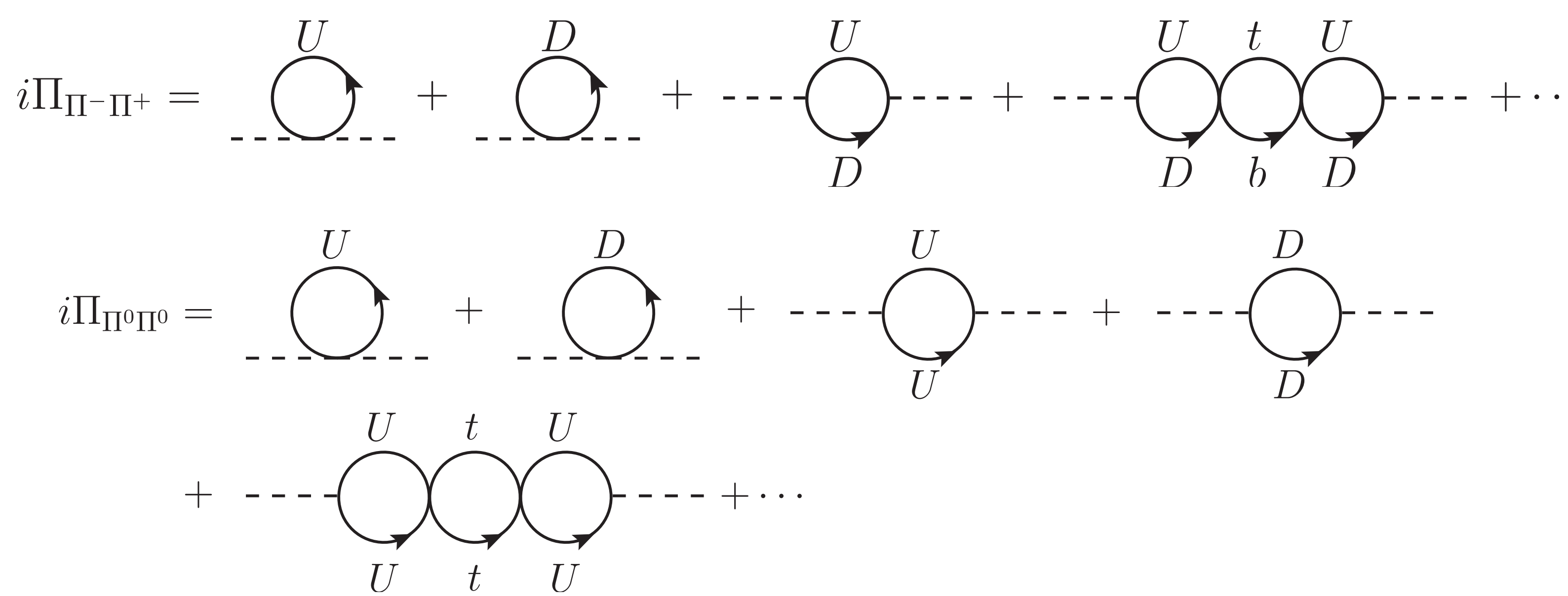
$$M_D = M$$

$$M_t = \frac{N G M_U}{4\pi^2}\left(\Lambda_{\rm TC}^2 - M_U^2 \ln\frac{\Lambda_{\rm TC}^2 + M_U^2}{M_U^2}\right)$$

Work to leading order in N and N_c assuming both large and N/N_c finite.

Consistency checks:

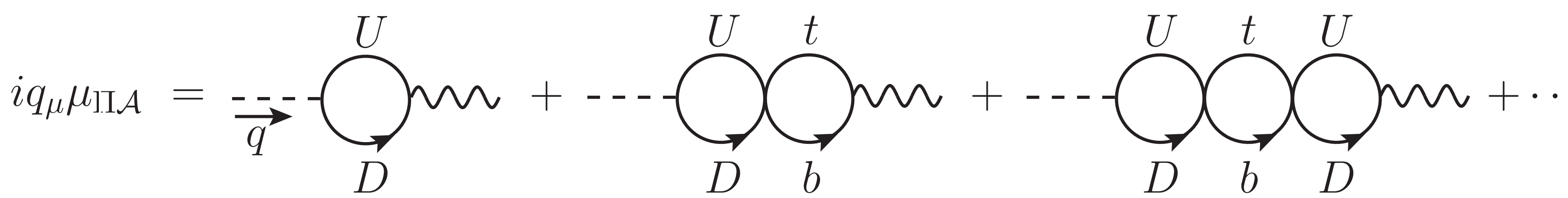
Evaluate



Using the gap equations, one proves $M_{\Pi^0} = M_{\Pi^\pm} = 0$

Also: transversality of W and Z vacuum polarisations can be shown.

To match with EW, need pion decay constant



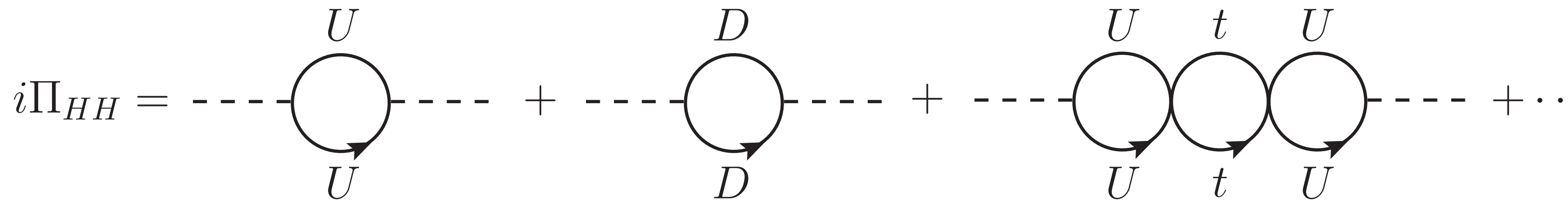
$$F_\Pi = \lim_{q^2 \to 0} \frac{\mu_{\Pi\mathcal{A}}(q^2)}{\sqrt{\Sigma'_{\Pi^-\Pi^+}(q^2)}}$$

In the limit $G \to 0$ this is just Pagels-Stokar: $F_\Pi^2 \simeq 4NM^2 \ln\left(\frac{\Lambda_{\rm TC}^2}{M^2}\right)$

Using known values of M_t and F_Π, everything expressed in terms of $\Lambda_{\rm TC}$ and $M_{\rm ETC}$

Expect: $\Lambda_{\rm TC} \simeq 3\,{\rm TeV}$ $\quad M_{\rm ETC} \simeq 5\,{\rm TeV}$

The scalar mass: $\Sigma_{HH}(q^2) = q^2 - m^2 - \Pi_{HH}(q^2)$



First, set $G = 0$ and trade m with the dynamical mass M_{H0} via

$$\Sigma_{HH}(q^2 = M_{H0}^2) = 0$$

Then, at $G \neq 0$ solve for M_{H0} by setting

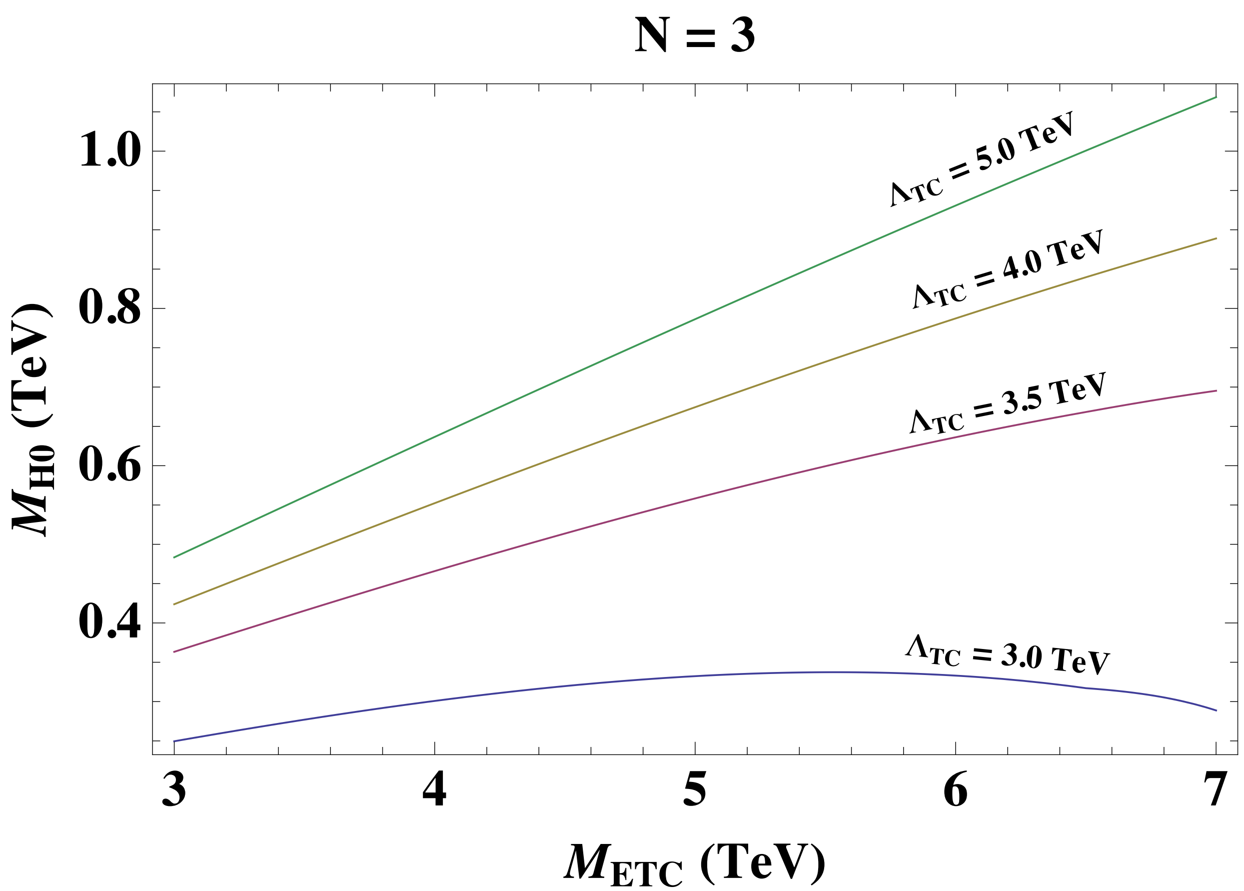
$$\Sigma_{HH}(q^2 = M_H^2) = 0 \quad @ \quad M_H^2 = (125)^2 \,\mathrm{GeV}^2$$

In the limit $M_{H0} \ll \Lambda_{\mathrm{TC}} \ll M_{\mathrm{ETC}}$ the dynamical mass is given by

$$M_{H0}^2 \simeq \frac{1}{\ln(\Lambda_{\mathrm{TC}}^2/M^2)} \frac{\frac{N_c}{N}\frac{M_t^2}{M_U^2}}{1 - \frac{N_c}{N}\frac{M_t^2}{M_U^2}\frac{M_{\mathrm{ETC}}^2}{\Lambda_{\mathrm{TC}}}} M_{\mathrm{ETC}}^2$$

So M_{H0} can be large even if the physical Higgs is light.

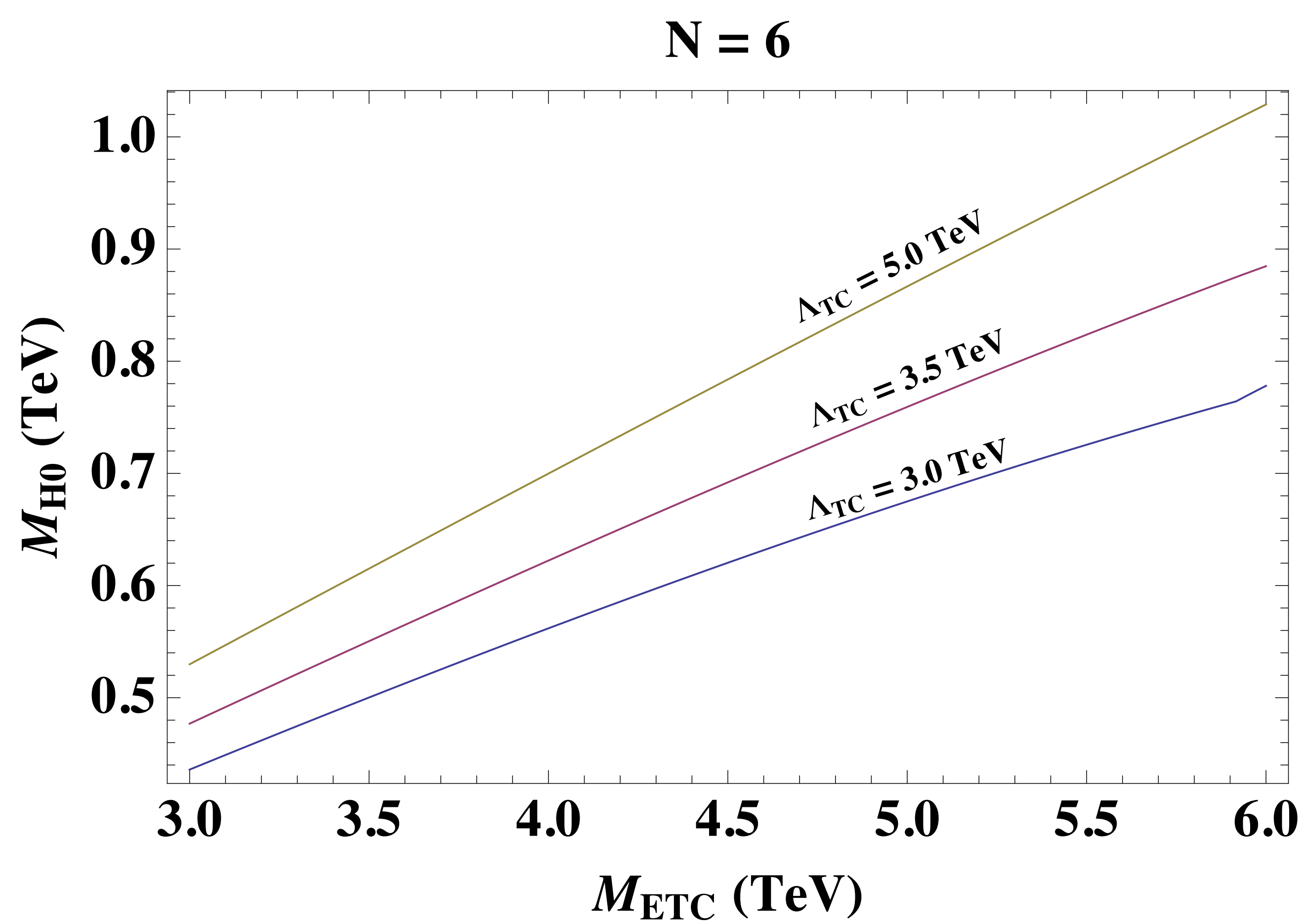
Numerical evaluation:

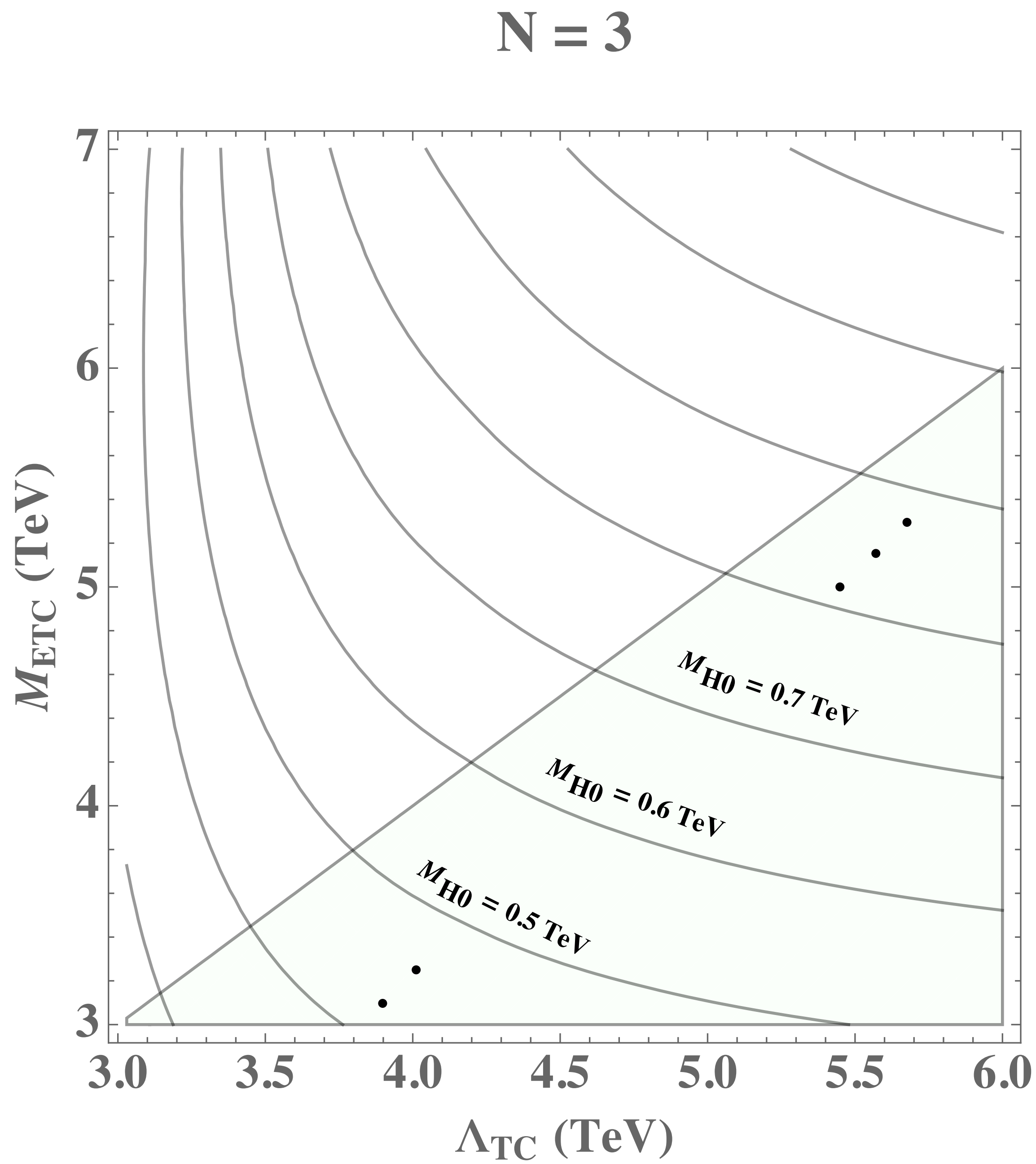


e.g. SU(3) gauge theory and
U, D fermions in 3-dim. rep.
(Scaled-up QCD)

SU(3) gauge theory and
U, D fermions in 6-dim. rep.

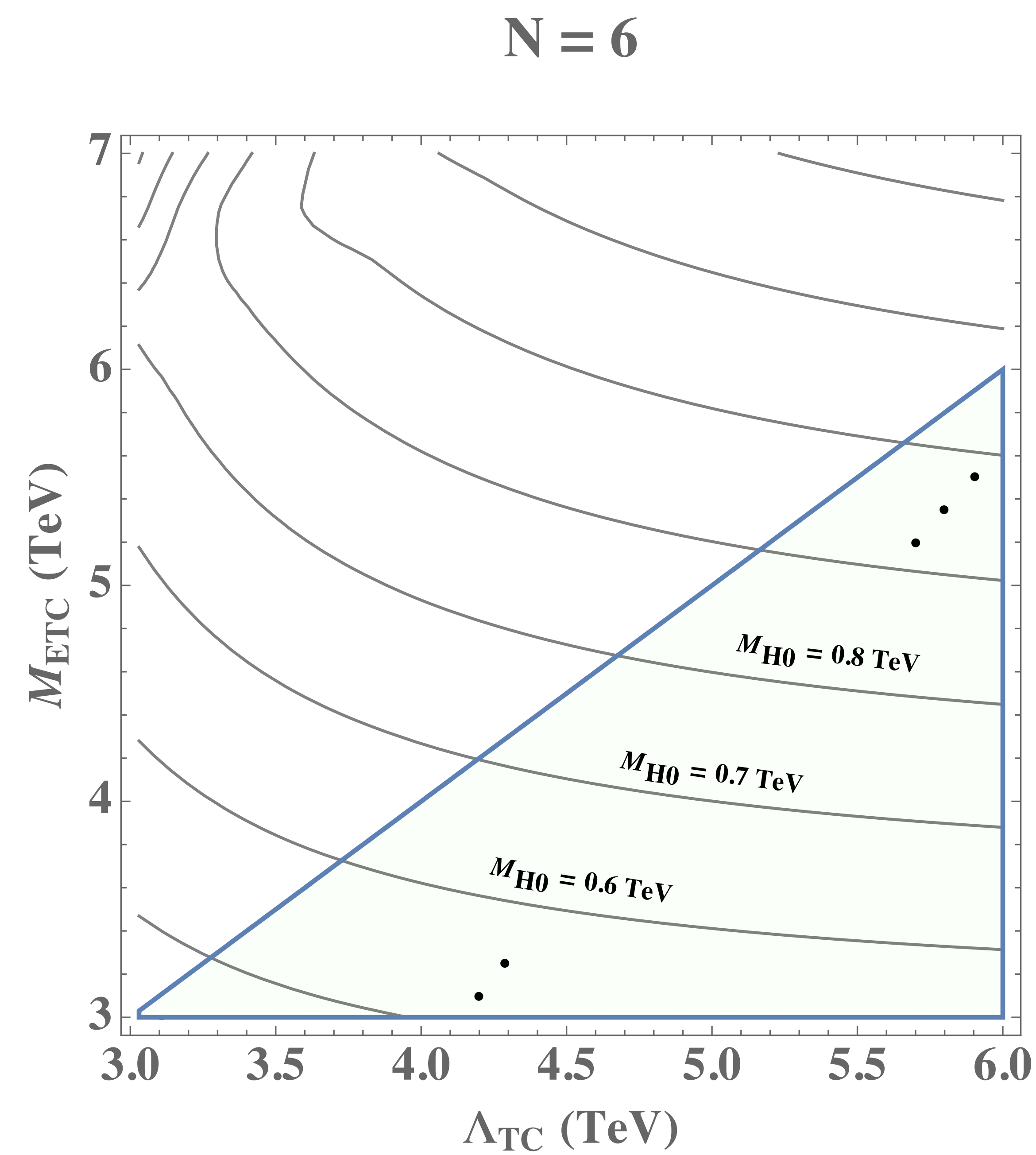
e.g. SU(3)MWT



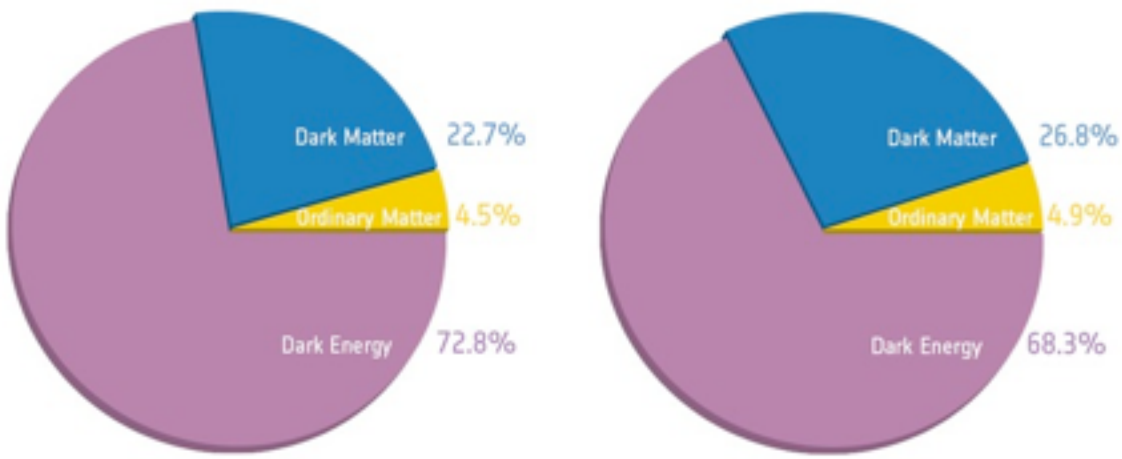


Inside the shaded region

$$M_{\rm ETC} < \Lambda_{\rm TC}$$



3. Other directions:
Dark matter



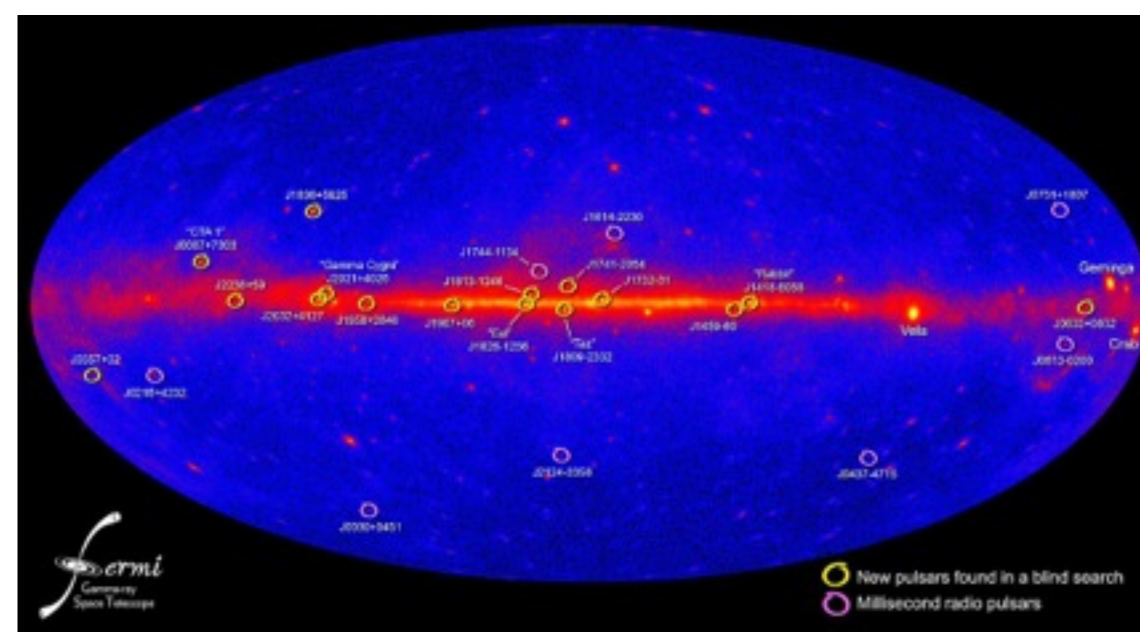
Before Planck

After Planck

$$SU(3) \times SU(2) \times U(1)$$

SM to explain just 5%

What new gauge structures provide the 95% ?



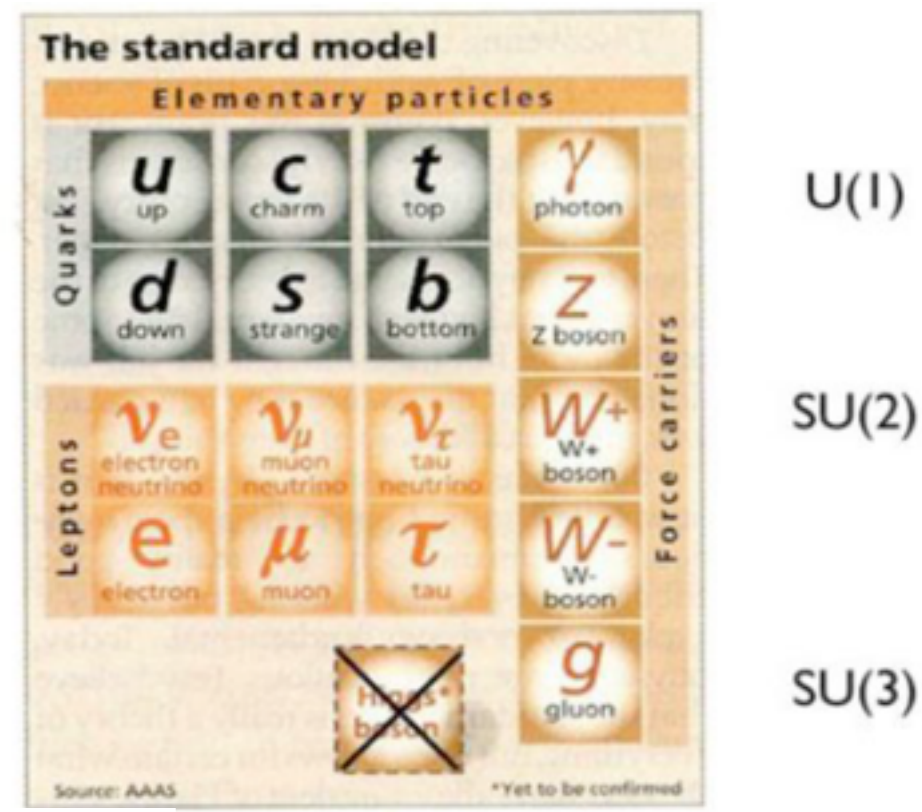
SU(2)MWT

One weak doublet in 3 of SU(2): Witten anomaly.

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

Cure by introducing one doublet of TC/QCD singlet fermions

$$L_L = \begin{pmatrix} N \\ E \end{pmatrix}_L , \qquad N_R \, , \; E_R$$



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

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

Two immediate DM candidates:

$y = 1/3$ 4th neutrino: Kainulainen, Tuominen, Virkajärvi JCAP 1002 (2010)

$y = 1$

A lightest neutral technibaryon. It is also a PGB.

Scattering of DM on nuclei via scalar and/ or photon exchange

$$\frac{d\sigma}{dE} \sim A \frac{\langle R_E^2 \rangle^2}{M_{\rm DM}^2} + B \frac{\kappa^2}{M_{\rm DM}^2}$$

From lattice: form factors of composite states.
(talk by R. Lewis)

Summary:

Minimal walking theories in isolation

- vacuum phase diagrams
- spectra of composite states

Minimal walking theories coupled with SM

- dynamical EWSB
- a light Higgs
- dark matter candidates

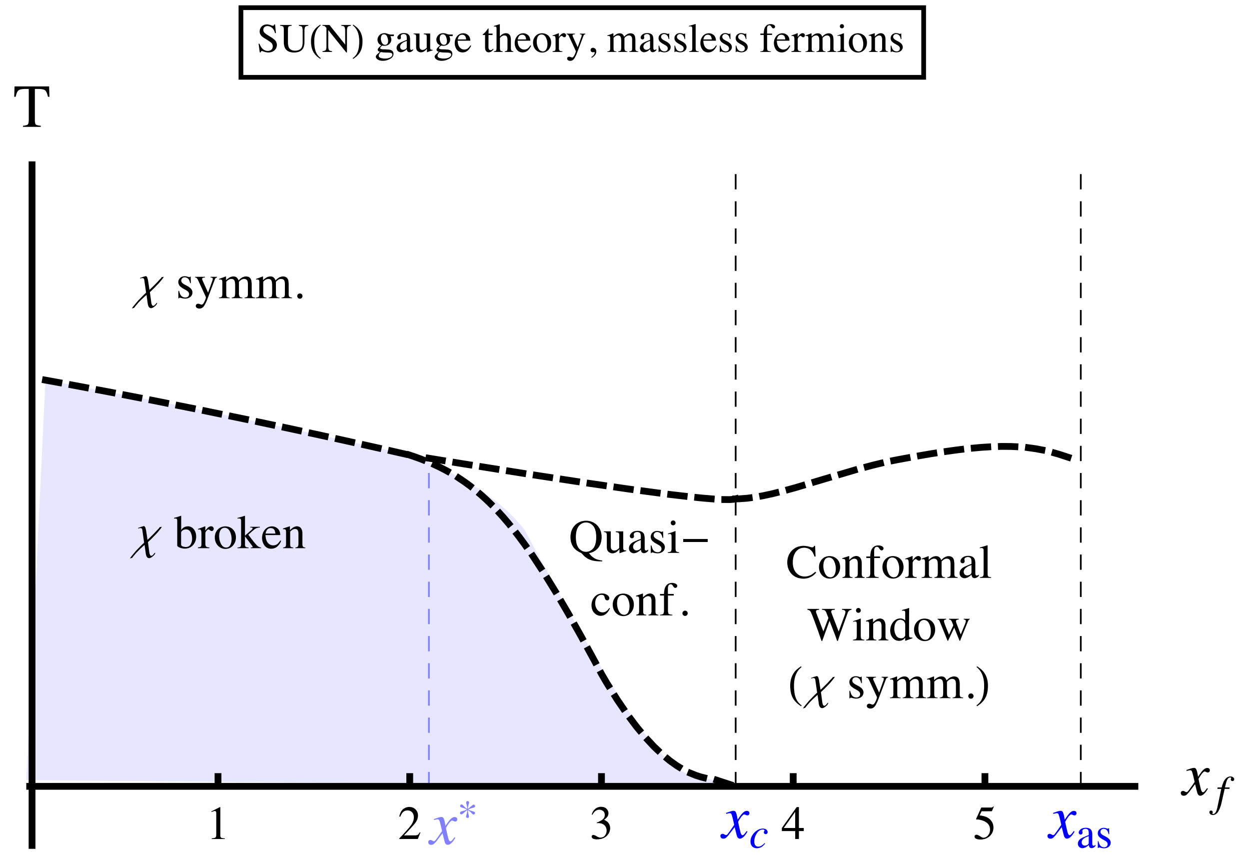
Outlook:

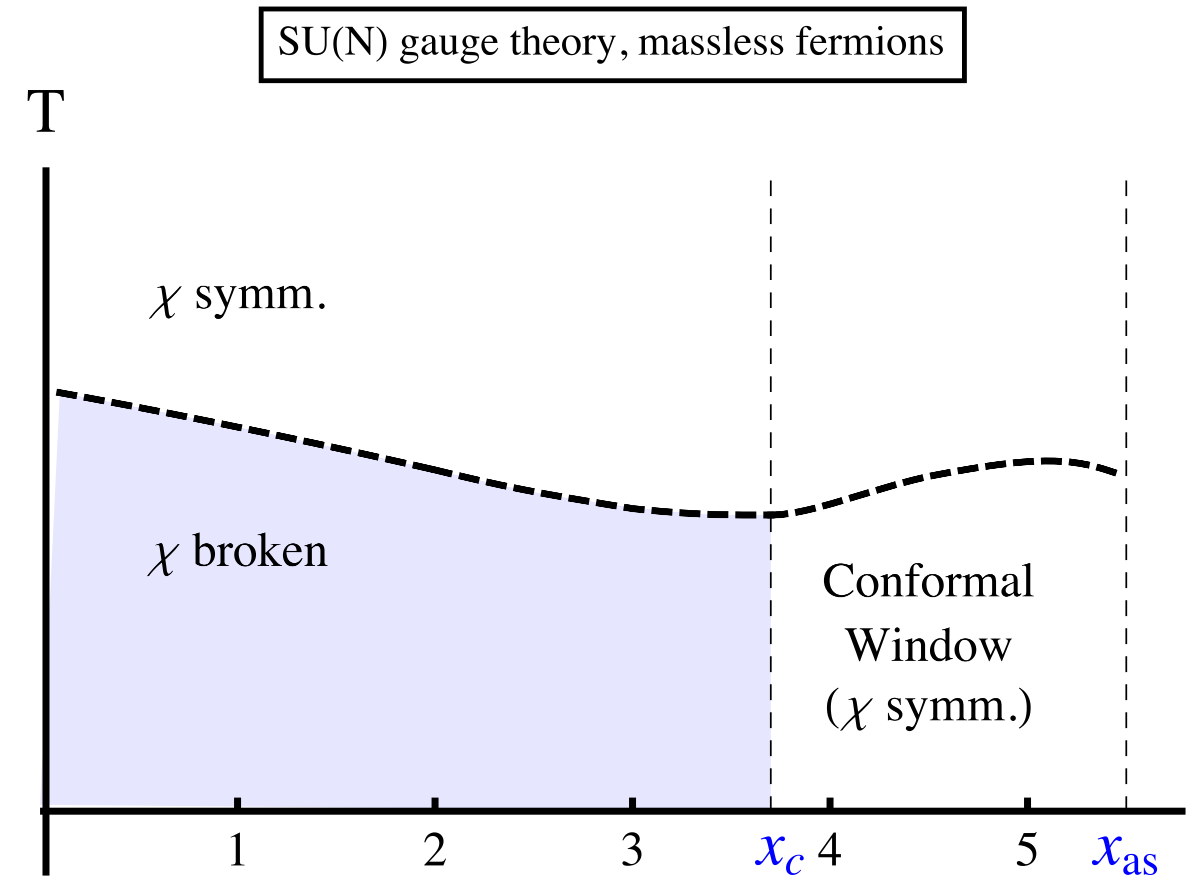
Combination of model building,
phenomenology
and lattice results.

Extra slides

There may not exist walking at all....

(finite T phase diagrams: K. Tuominen, Phys. Rev. D87 (2013), 1206.5772)





A light scalar from strong dynamics:

(Dietrich, Sannino, Tuominen (2005))

$$\theta^{\mu}_{\mu} = -M^2_{\sigma}(N_f)\sigma^2 \simeq -M^2_{\sigma}(N_f)\Lambda^2 = -\frac{\beta}{2g}\Lambda^4$$

$$\beta \simeq -c(\alpha_c - \alpha^*) \to 0$$

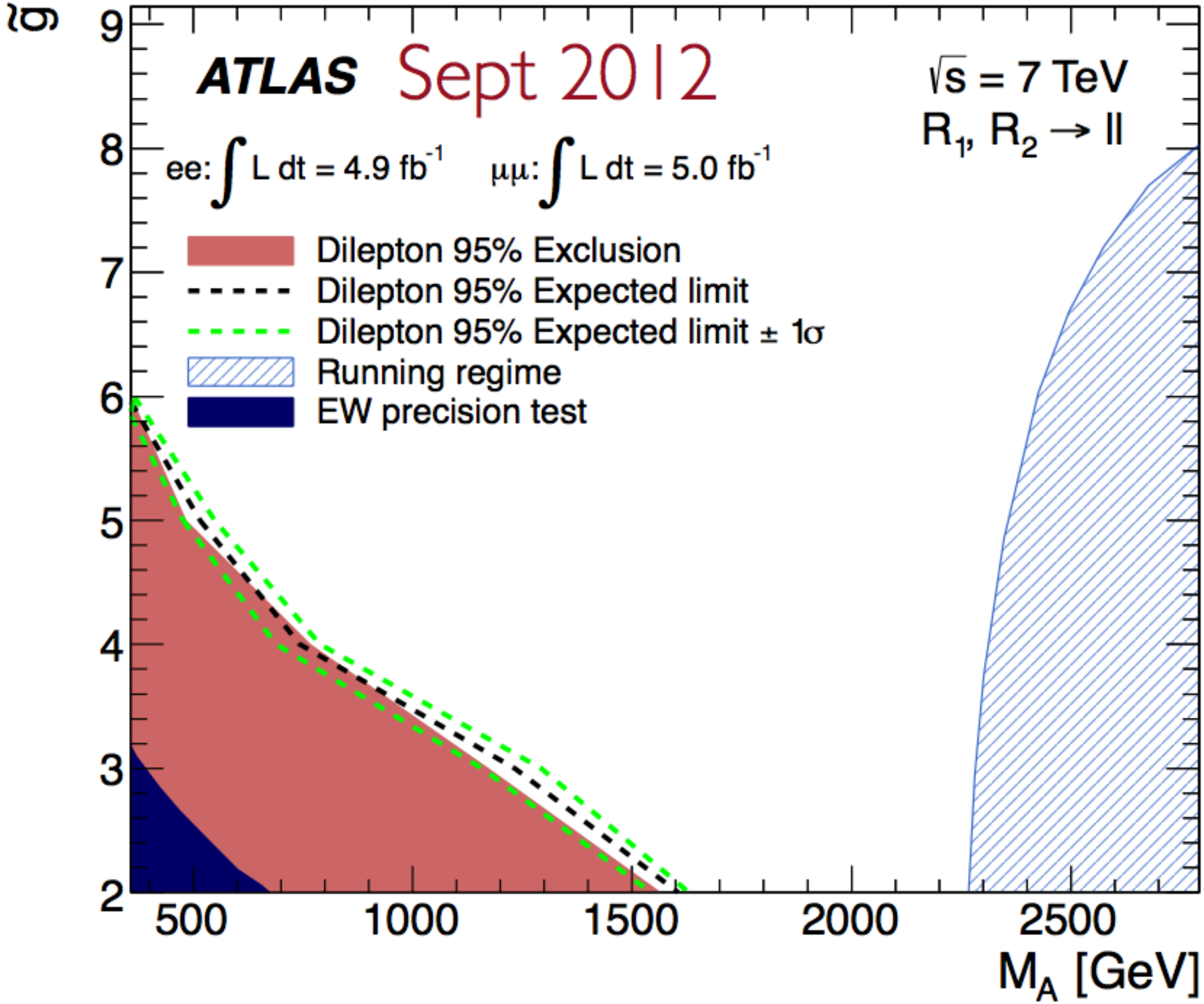
$$M^2_{\sigma}(N_f) \simeq (N_{fc} - N_f)\Lambda^2$$

Parametrically light scalar

(Finely tuned, near conformal)

In principle this is seen at LHC:

- A light scalar (observed),
- Parametrically heavy meson spectrum (not seen yet).



g̃
ATLAS Sept 2012
√s = 7 TeV
R1, R2 → ll
ee: ∫ L dt = 4.9 fb-1
μμ: ∫ L dt = 5.0 fb-1
Dilepton 95% Exclusion
Dilepton 95% Expected limit
Dilepton 95% Expected limit ± 1σ
Running regime
EW precision test
2
3
4
5
6
7
8
9
500
1000
1500
2000
2500
MA [GeV]