DIAS
Danish Institute
for Advanced Study

University of Southern Denmark

New Composite Dynamics

Francesco Sannino

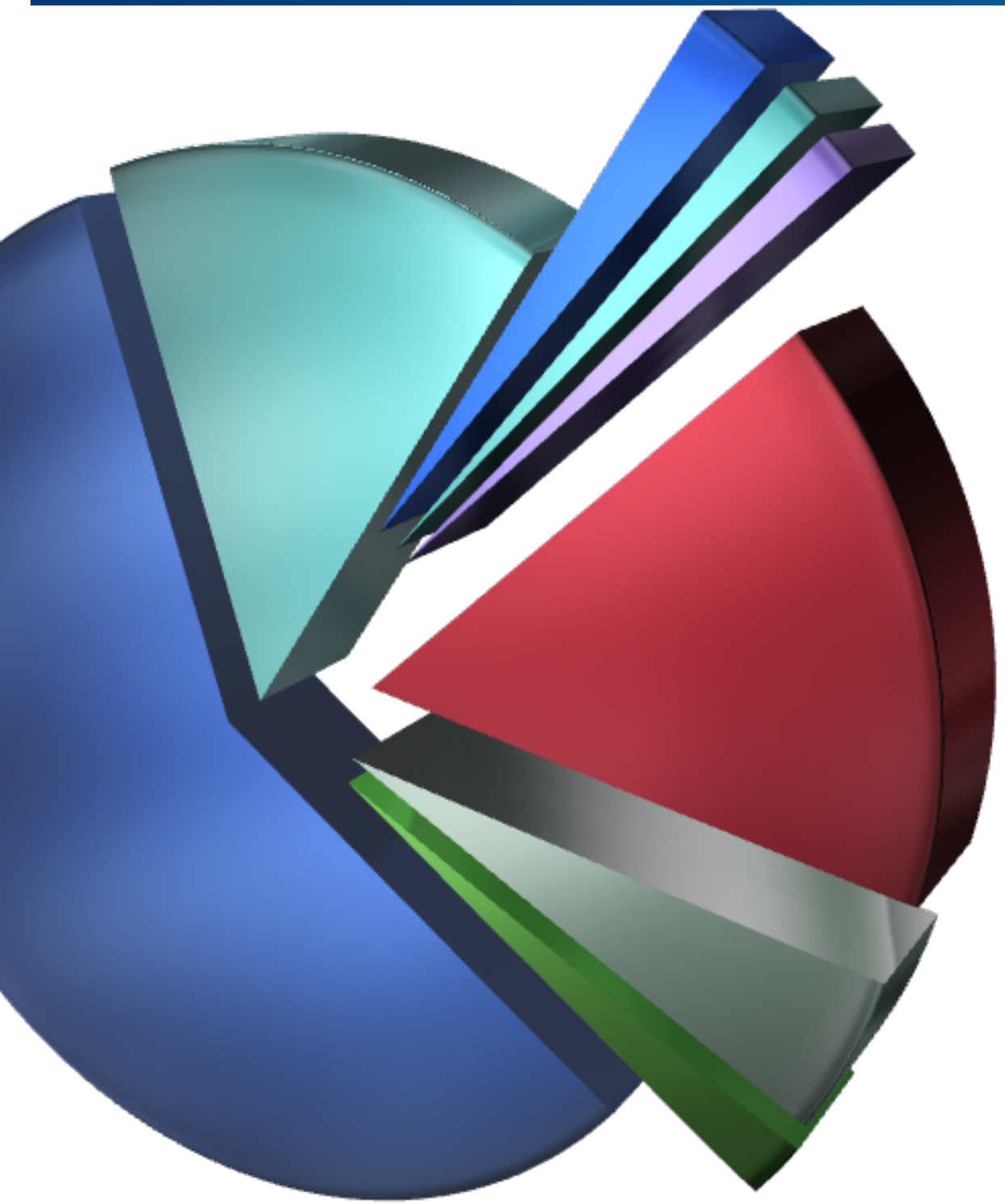
CP³ - Origins
Particle Physics & Cosmology

SEWM @ Swansea 2012

Now


Electro
Magnetic
Strong
Weak
Atoms
4%
Gravity
Dark Energy
74%
?
Dark Matter
22%
?

Future pie ?



- New weak & strong forces
- Composite Higgs/SM
- Composite dark matter
- Composite inflation
- ....

Fermi Scale

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246 \text{ GeV}$$

$$M_H^2 = 2\lambda\, v^2$$

Natural SM mass spectrum

$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246 \text{ GeV}$$

$$M_W = g\,\frac{v}{2} \approx g\ 123 \text{ GeV}$$

$$M_H = \lambda\,\sqrt{2}\,v \approx \lambda\ 345 \text{ GeV}$$

$$m_f = \lambda_f \frac{v}{\sqrt{2}} \approx \lambda_f\ 174 \text{ GeV}$$

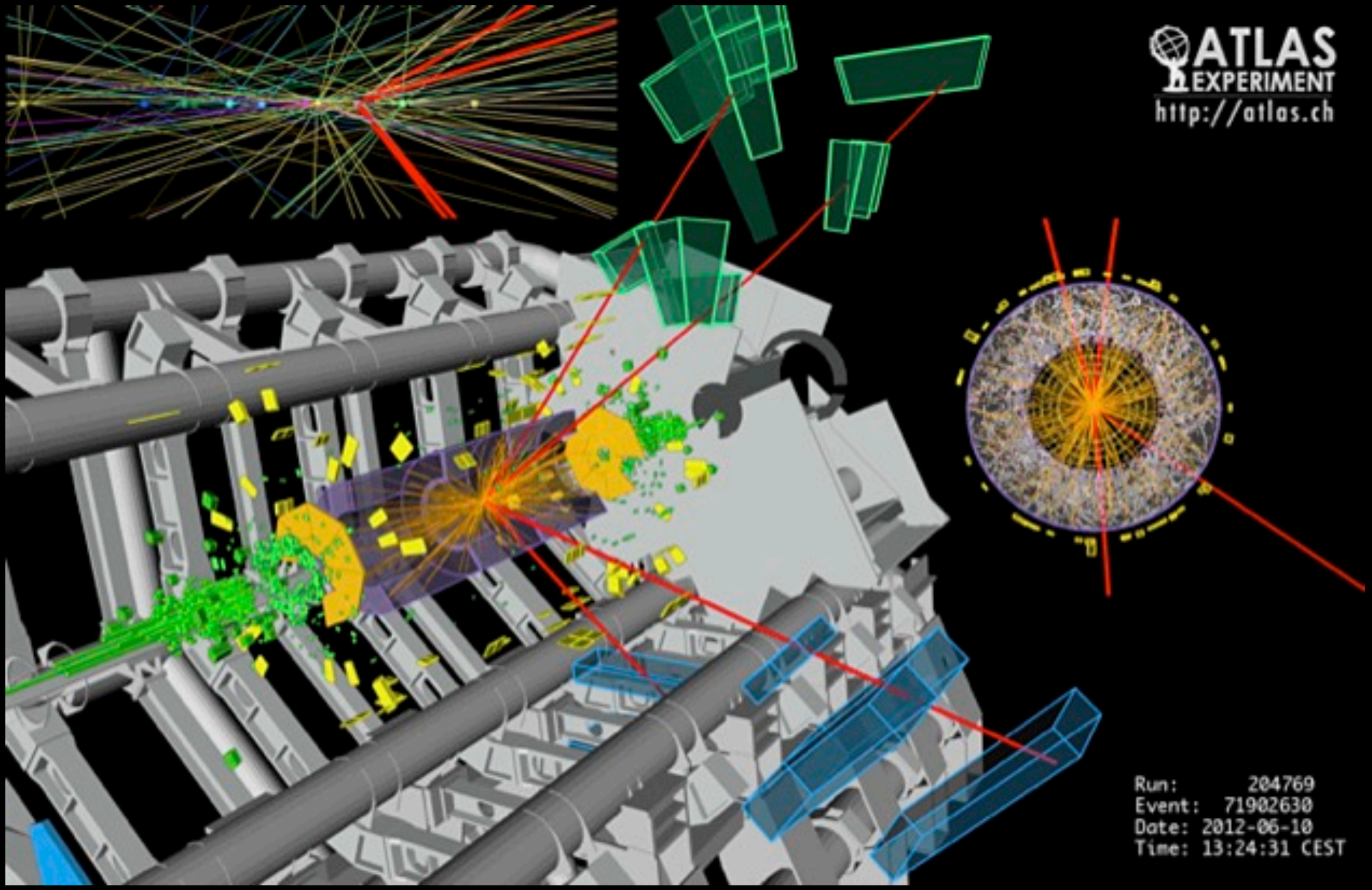
or zero

Top has the right energy scale!

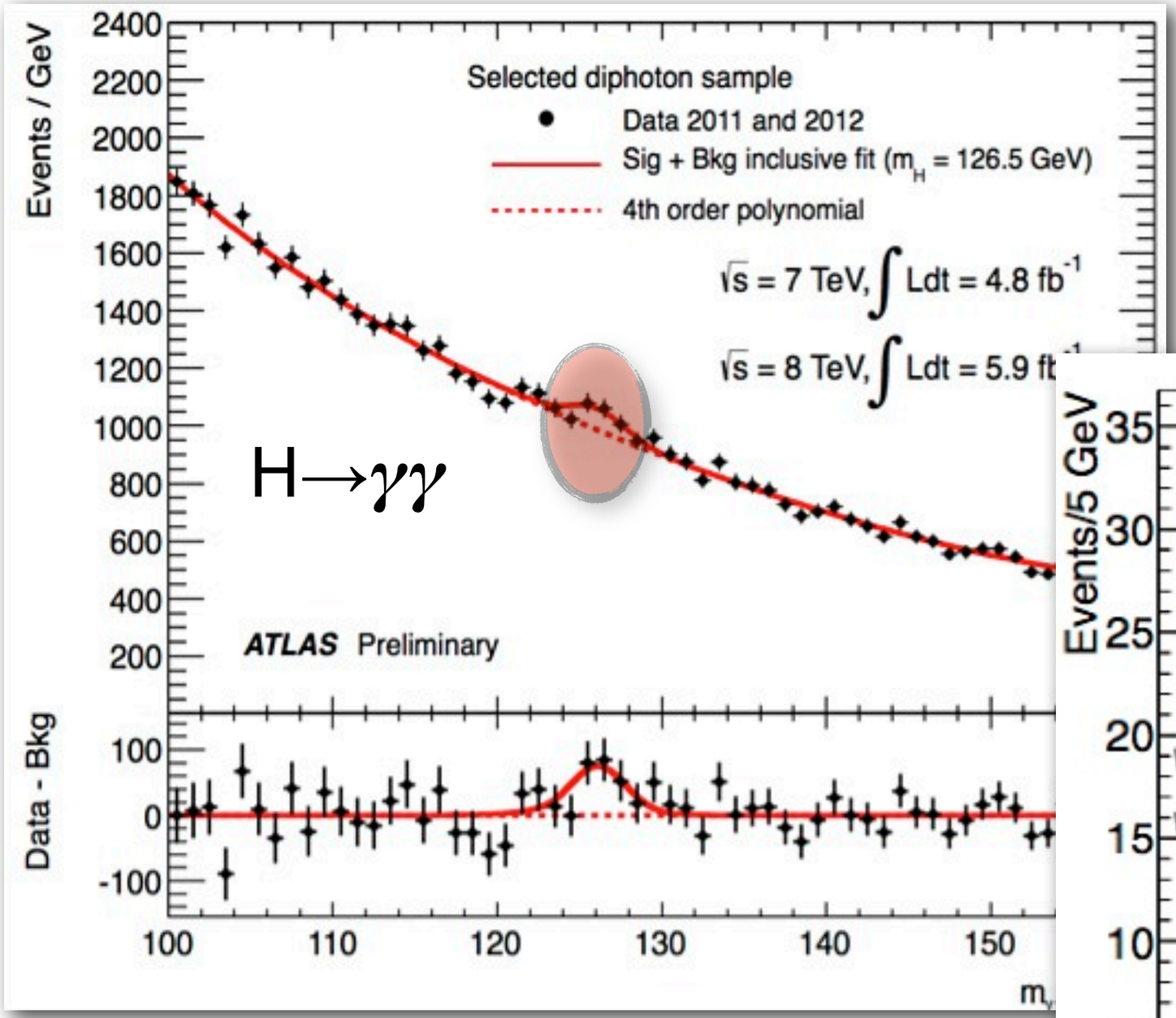
Light quarks and leptons are also natural!

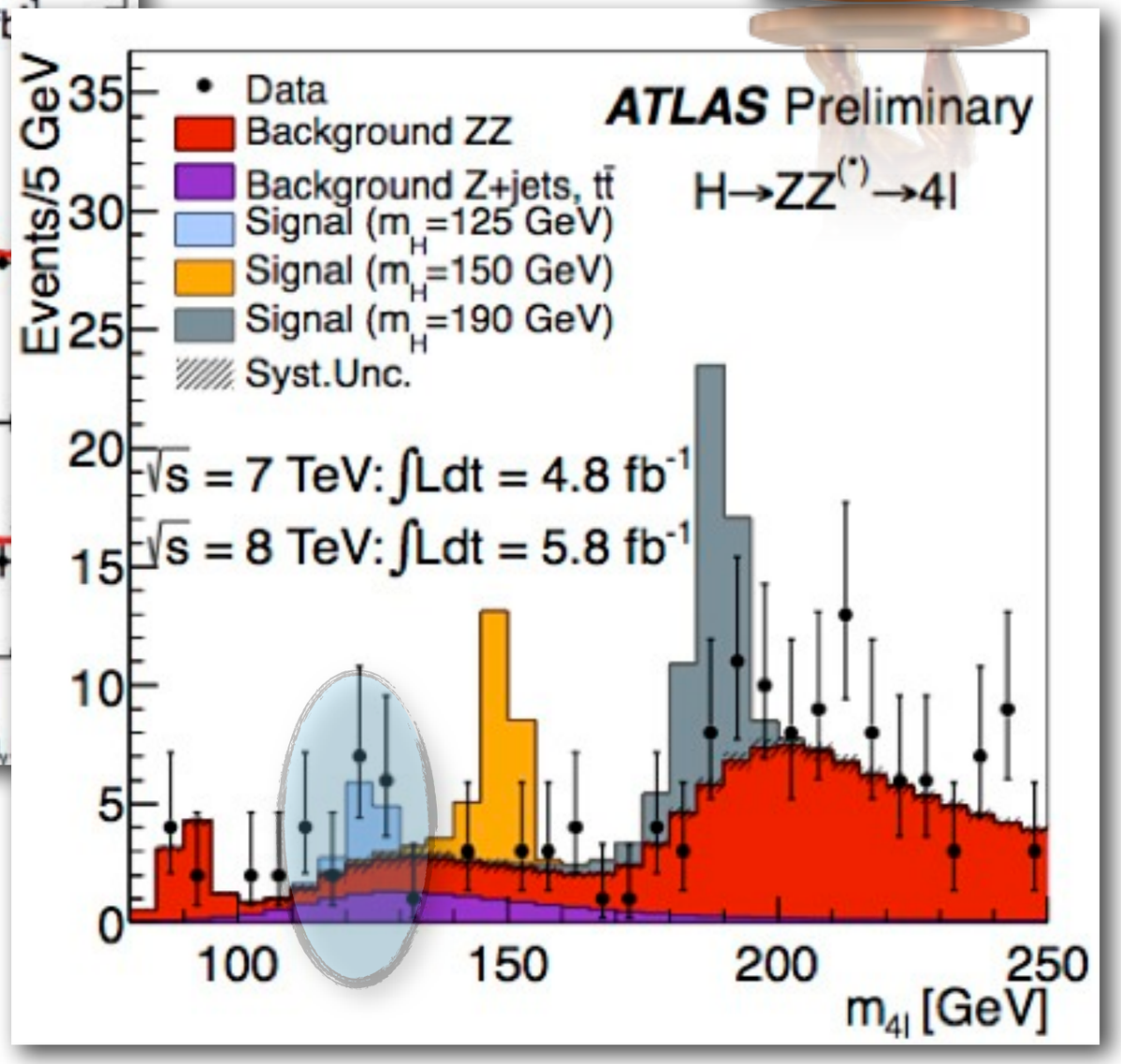
The scent of the Higgs

Higgs Decay to four muons 2012

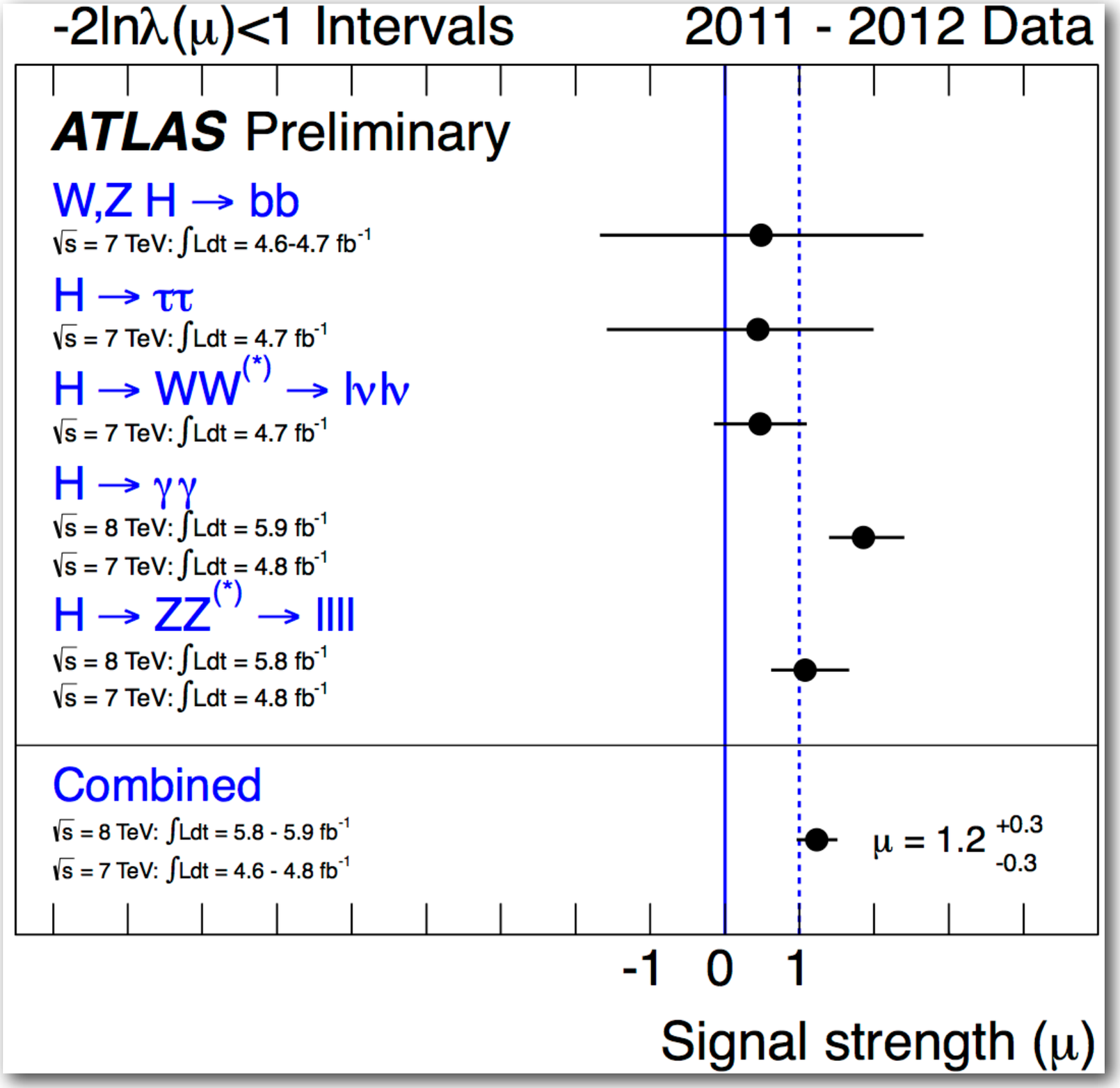


2 bumps


Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb-1
√s = 8 TeV, ∫ Ldt = 5.9 fb-1
H→γγ
ATLAS Preliminary
Events / GeV
Data - Bkg
m_γγ

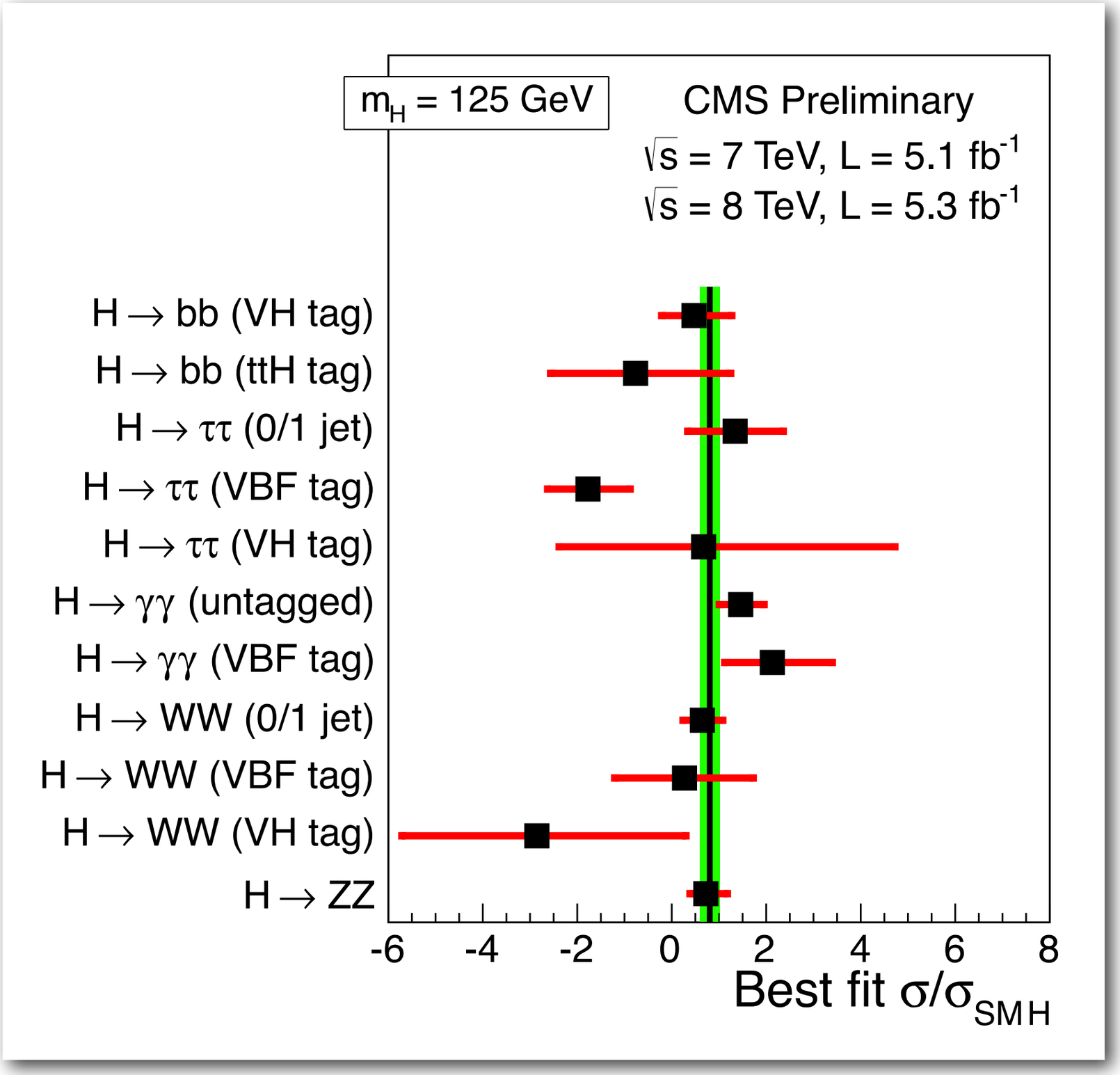

Data
Background ZZ
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m_4l [GeV]

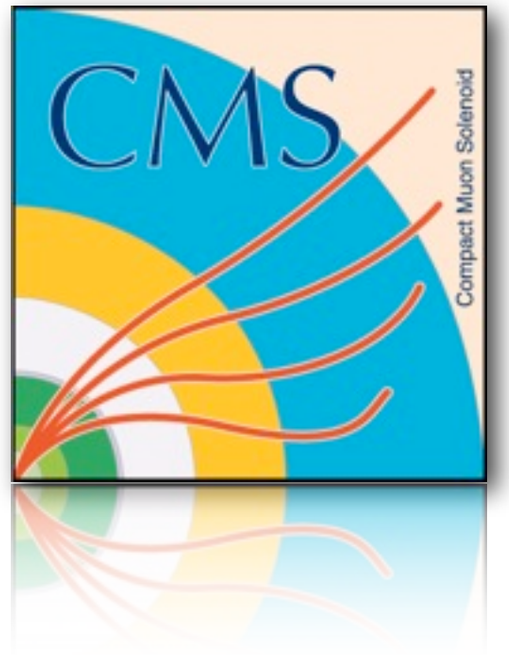
Does it look like the Higgs?



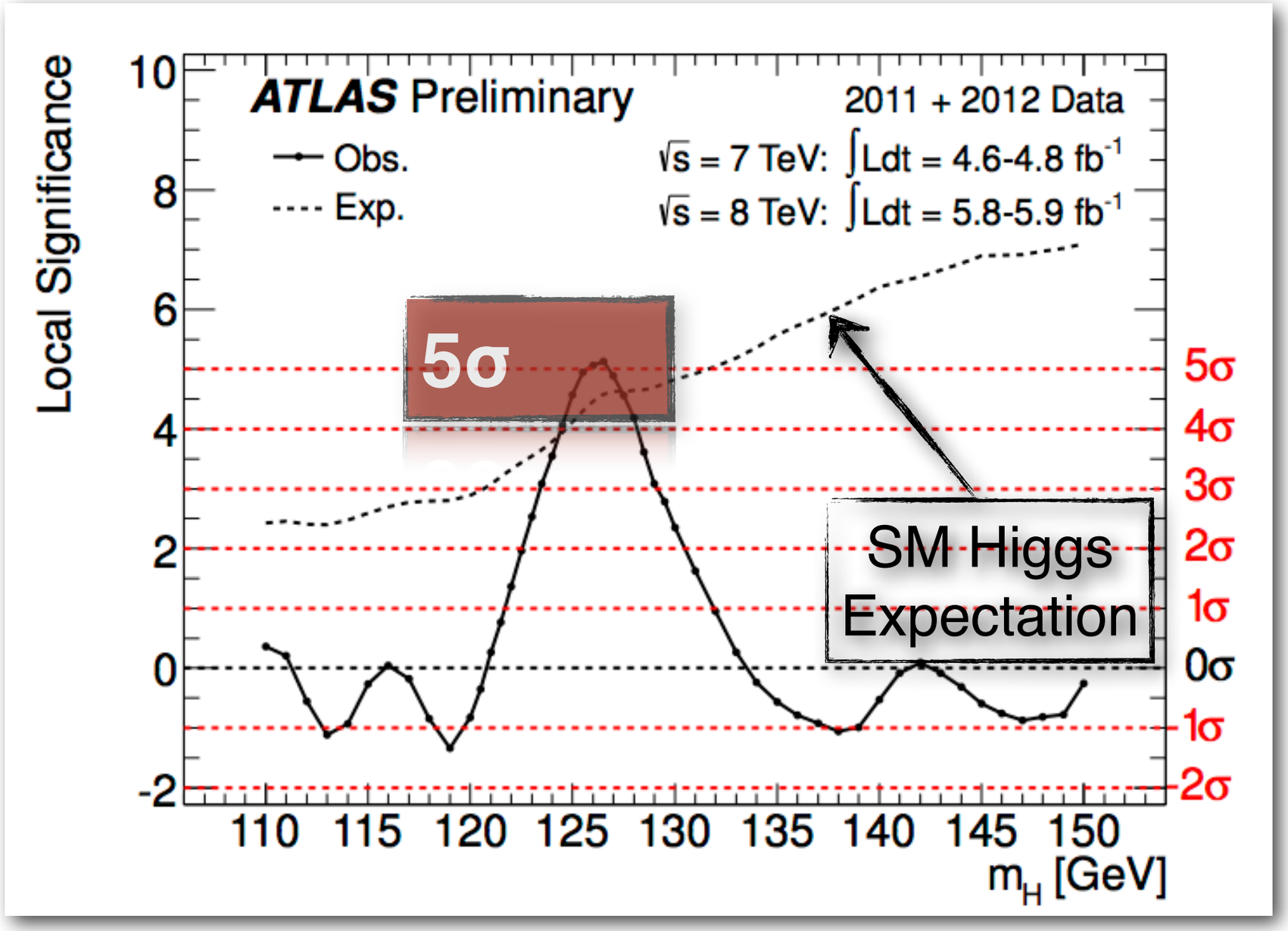


Does it look like the Higgs, 2?





New particle!


ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Local Significance
5σ
SM Higgs Expectation
m_H [GeV]
5σ
4σ
3σ
2σ
1σ
0σ
1σ
2σ



What next?

- SM Higgs ?
- Intermediate / Low scale SUSY ?
- Composite (conformal) dynamics ?
- X Compositeness ?
- ??

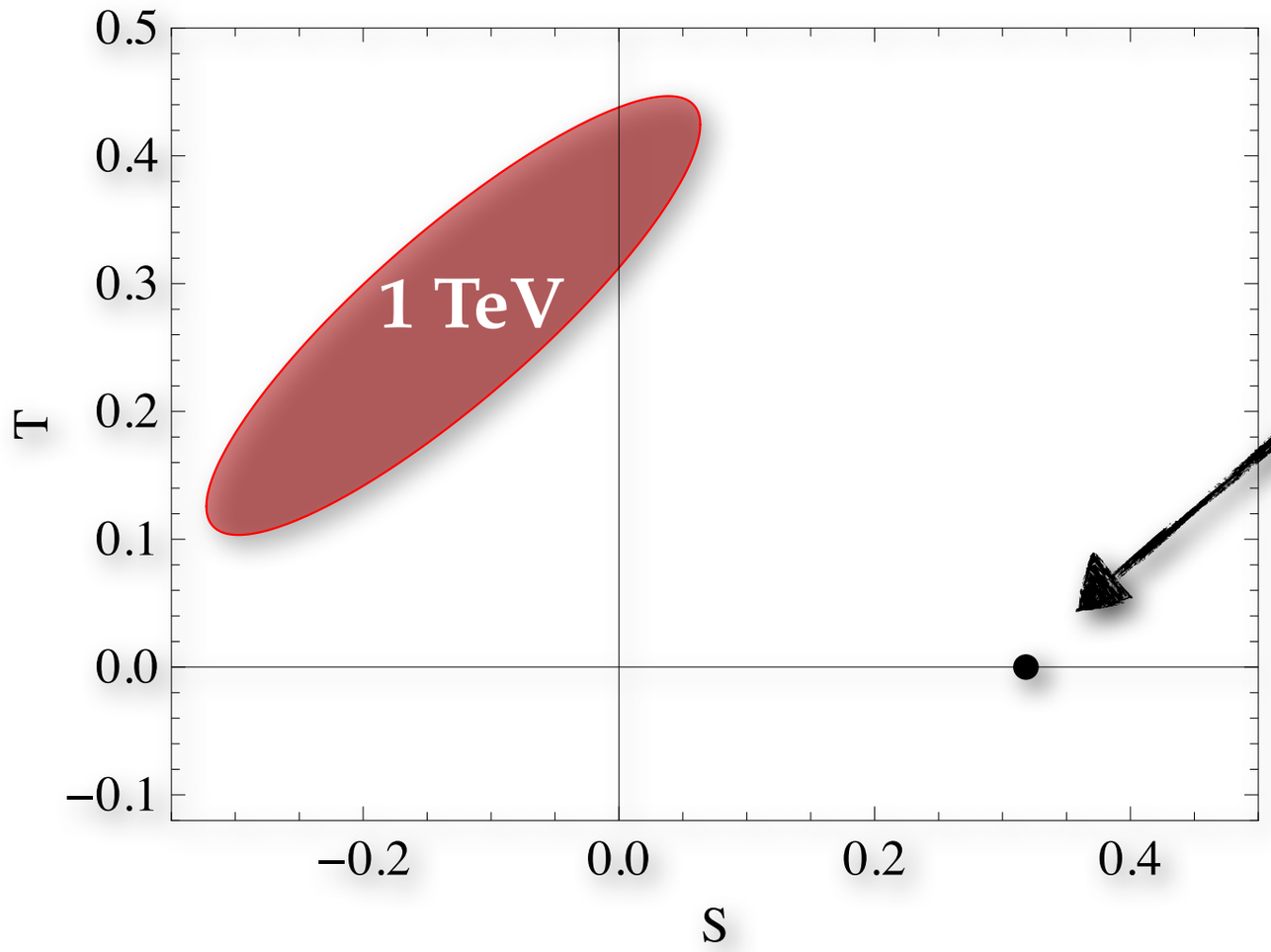
Compositeness

- Only Higgs sector is composite [Technicolor]
- Standard Model Fermions are composite [Preons]
- Partial compositeness: Bosonic/SUSY Technicolor ...
- X compositeness [Magnetic Standard Model] Sannino 11

Technicolor

Is "Old" Technicolor dead?

Was dead 2 decades ago !



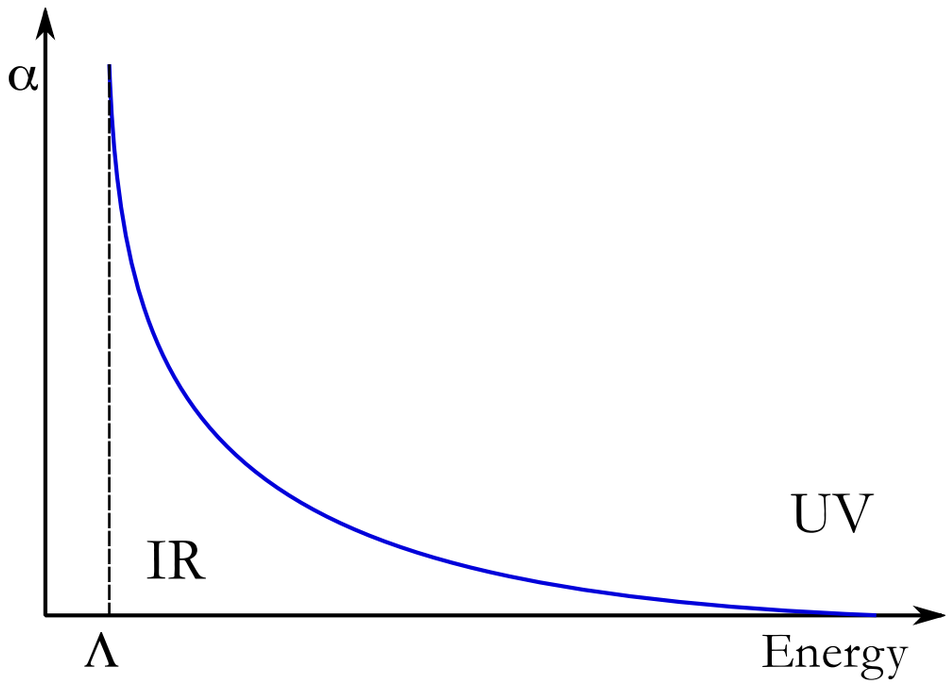
SU(3) + 1 Fund. Doublet

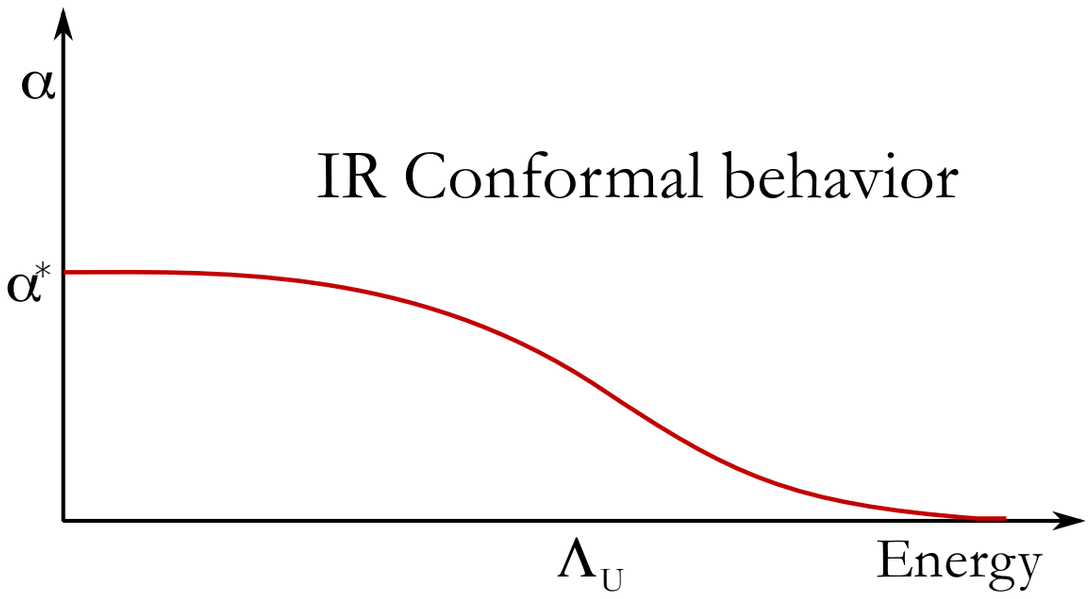
Weinberg, Susskind

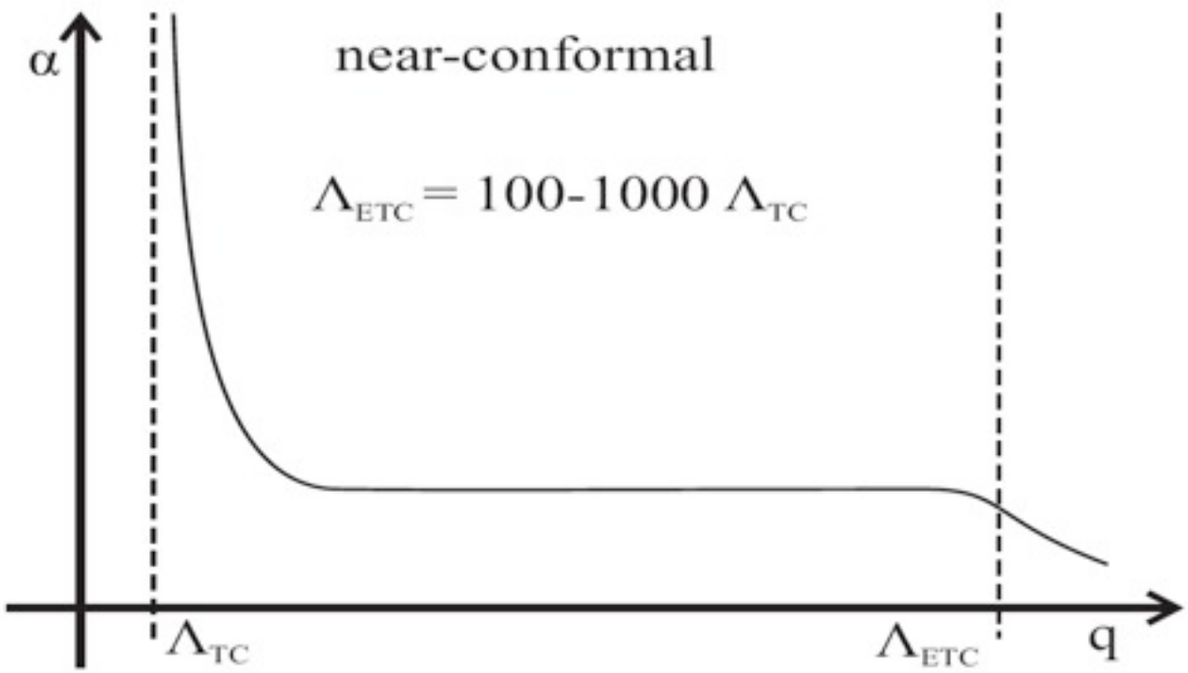
$$M_H = \frac{F_{TC}}{F_\pi} M_\sigma \simeq 1.5 \text{ TeV}$$

- Technicolor = massless SM.
- Extend TC works if fermion condensate is enhanced

Walking







Holdom,

Appelquist, Miranski, Yamawaki, Wijewardhana...

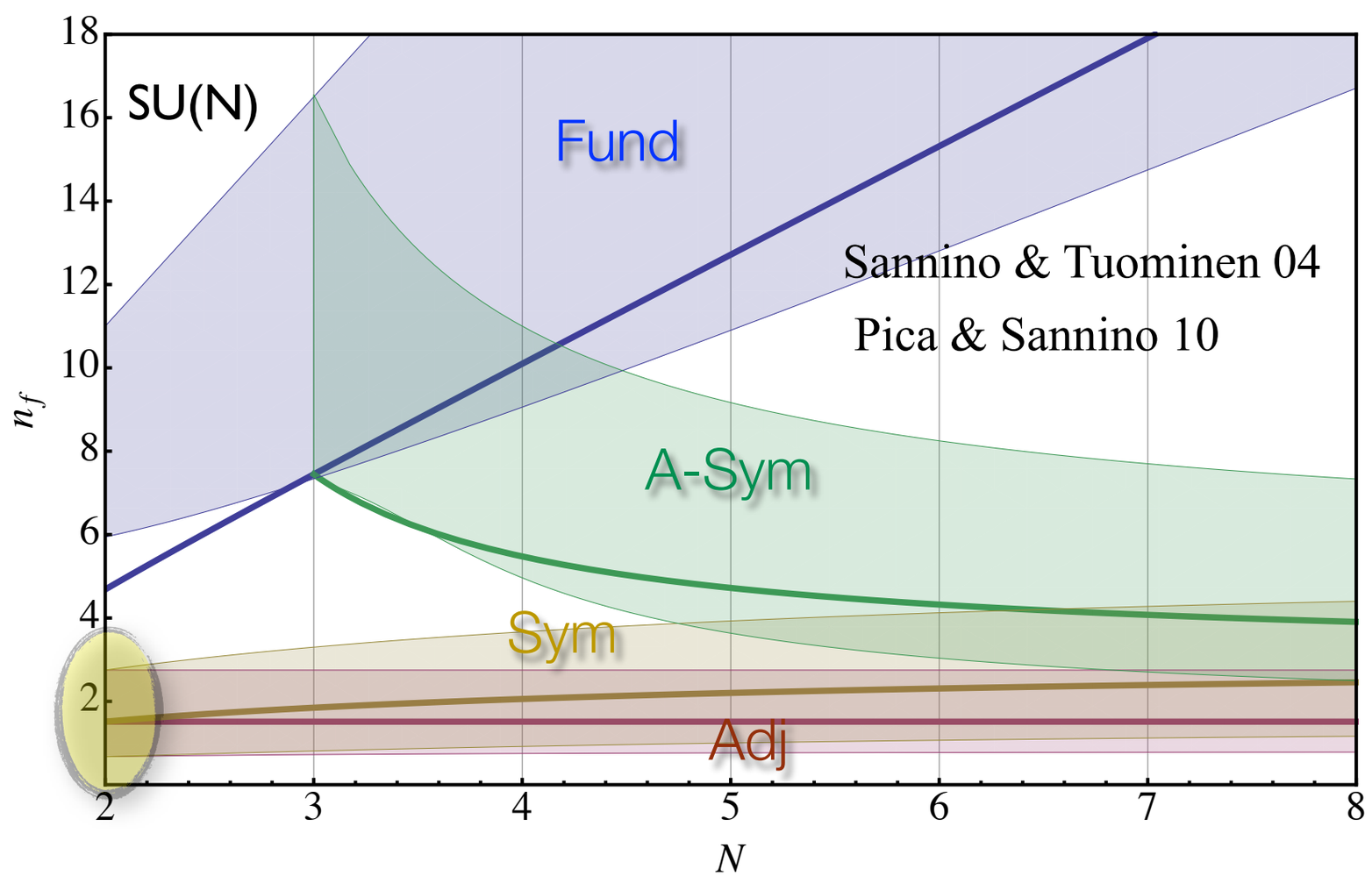
Since 2004 - Minimal TC
[Original Name: Light Composite Higgs]

- Can feature Light Composite/Conformal Higgs/...
- Wish small S-parameter & FCNC
- Dark matter candidates

Sannino, Tuominen 04

Hong, Hsu, Sannino 04

Dietrich, Sannino, Tuominen 05



The Devil is in the details



- Weak/Strong ETC
- Top assisted TC
- (Top) Technipion impostor
- SUSY & Technicolor

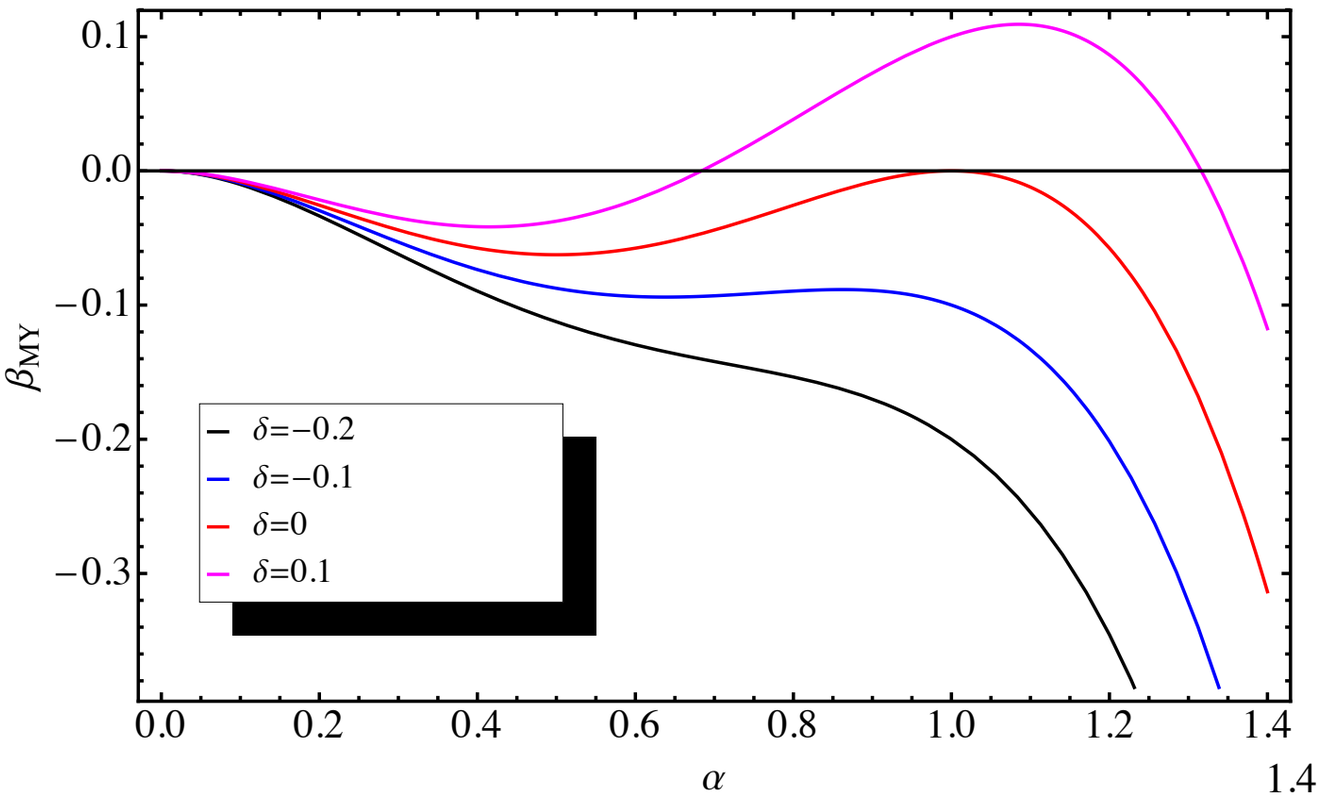
- To disentagle:
- Effective theory for SM + (Pseudo)Scalar
- Add higher order operators + matching

Foadi & Sannino 12

For a review see: Frandsen & Sannino 12

To walk or not to walk

Walking = Near conformal



$$\beta_{MY} = -\alpha^2 \left((\alpha - 1)^2 - \delta \right)$$

$$\delta = n_f - n_f^c$$

Sannino 2012

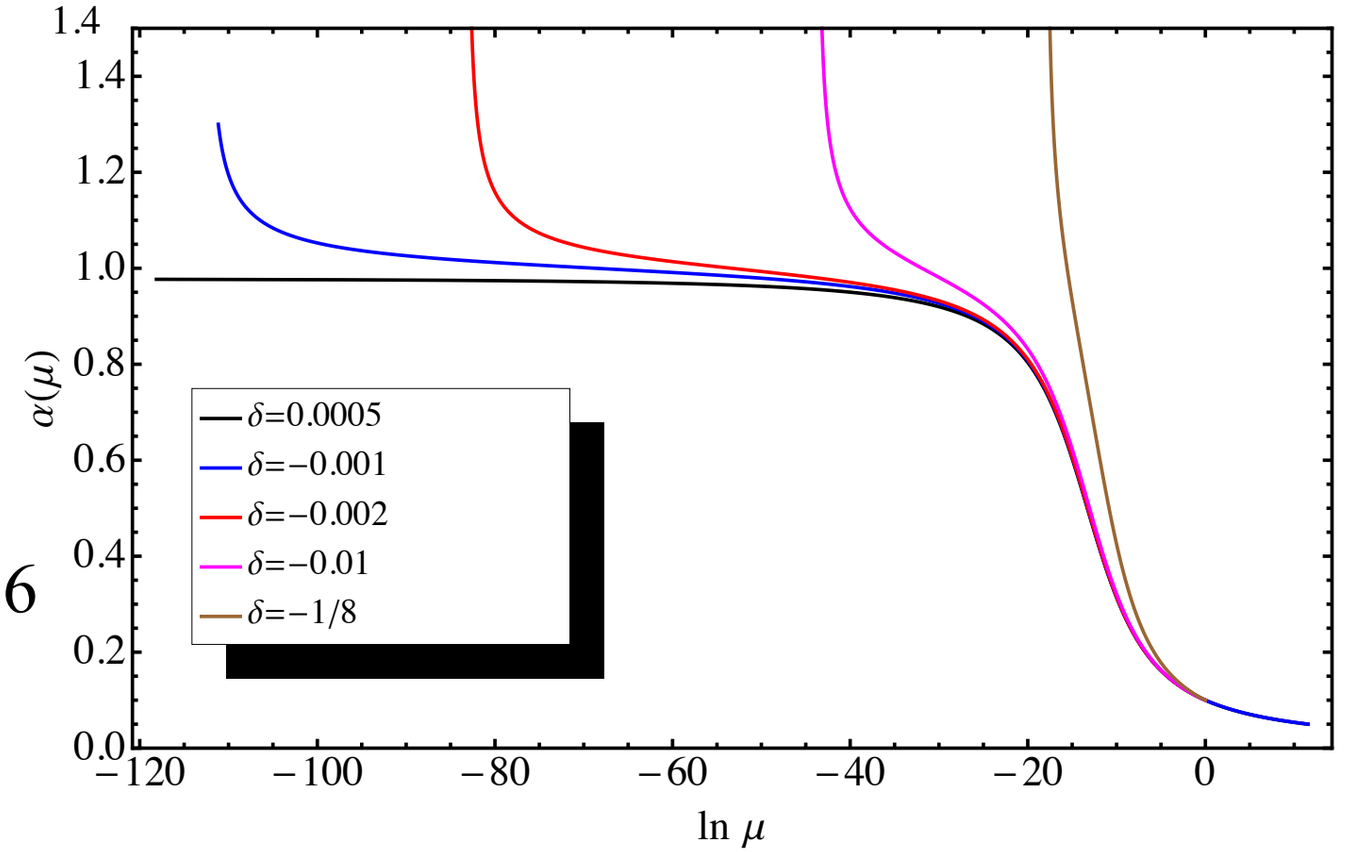
Miransky 85

Miransky & Yamawaki 89

Miransky & Yamawaki 97

Yamawaki, Bando, Matumoto 86

Appelquist, Karabali, Wijewardhana 86



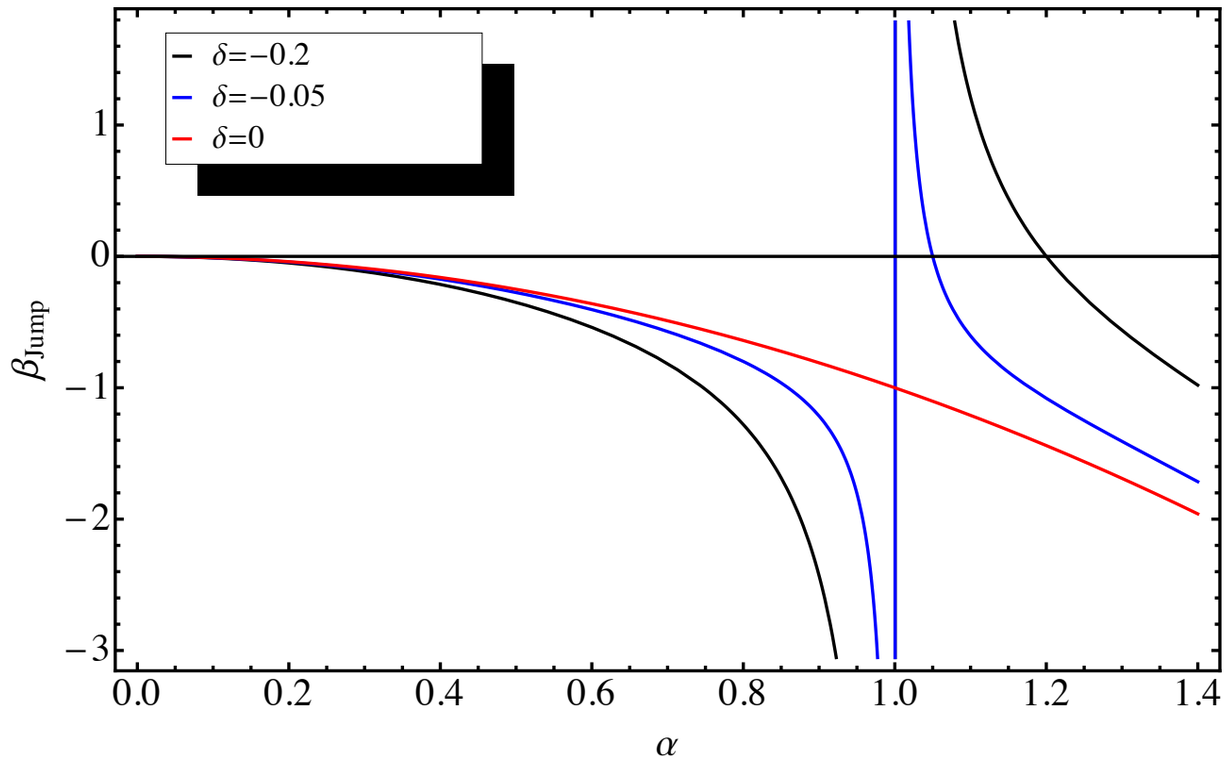
© Francesco Sannino

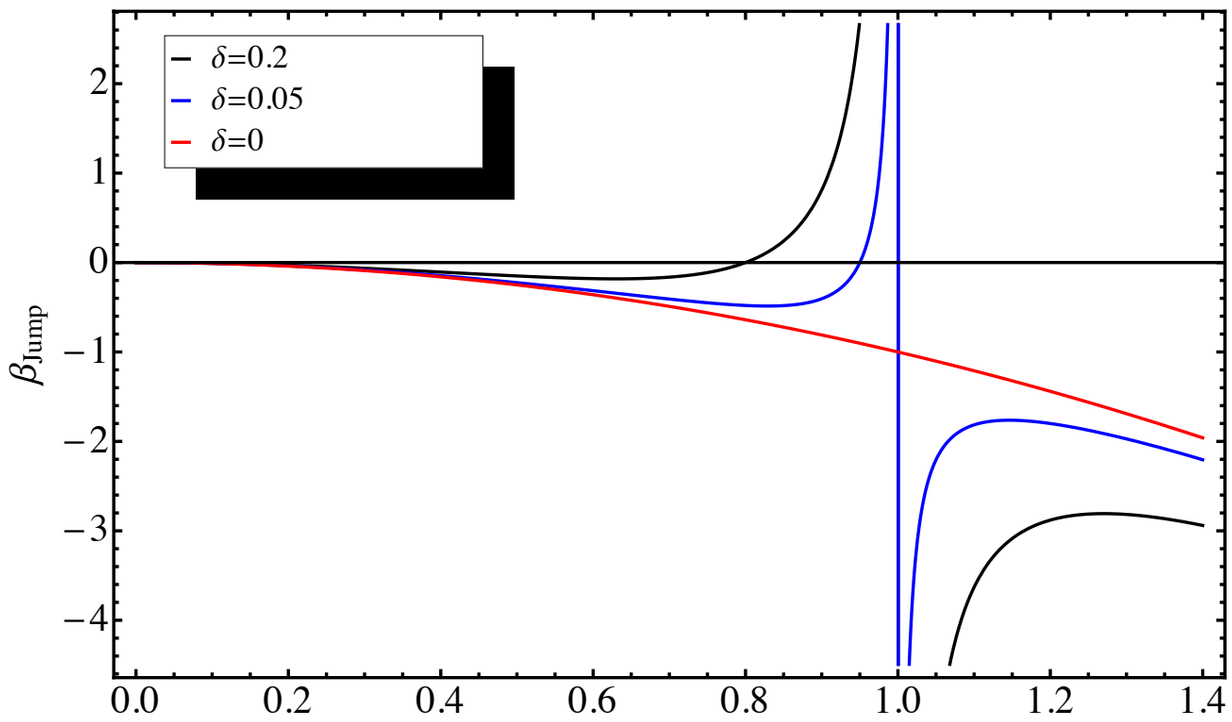
Condensate Enhancement

$$\langle \bar{Q}Q \rangle_\mu = \exp\left(\int_{\alpha(\Lambda)}^{\alpha(\mu)} \mathrm{d}\alpha \frac{\gamma(\alpha)}{-\alpha^2((\alpha-1)^2+|\delta|)} \right) \langle \bar{Q}Q \rangle_\Lambda$$

$$\simeq \exp\left(\gamma(1) \int_{\alpha(\Lambda)}^{\alpha(\mu)} \mathrm{d}\alpha \frac{1}{\beta_{MY}} \right) \langle \bar{Q}Q \rangle_\Lambda \; = \left(\frac{\mu}{\Lambda} \right)^{\gamma(1)} \langle \bar{Q}Q \rangle_\Lambda$$

Jumping

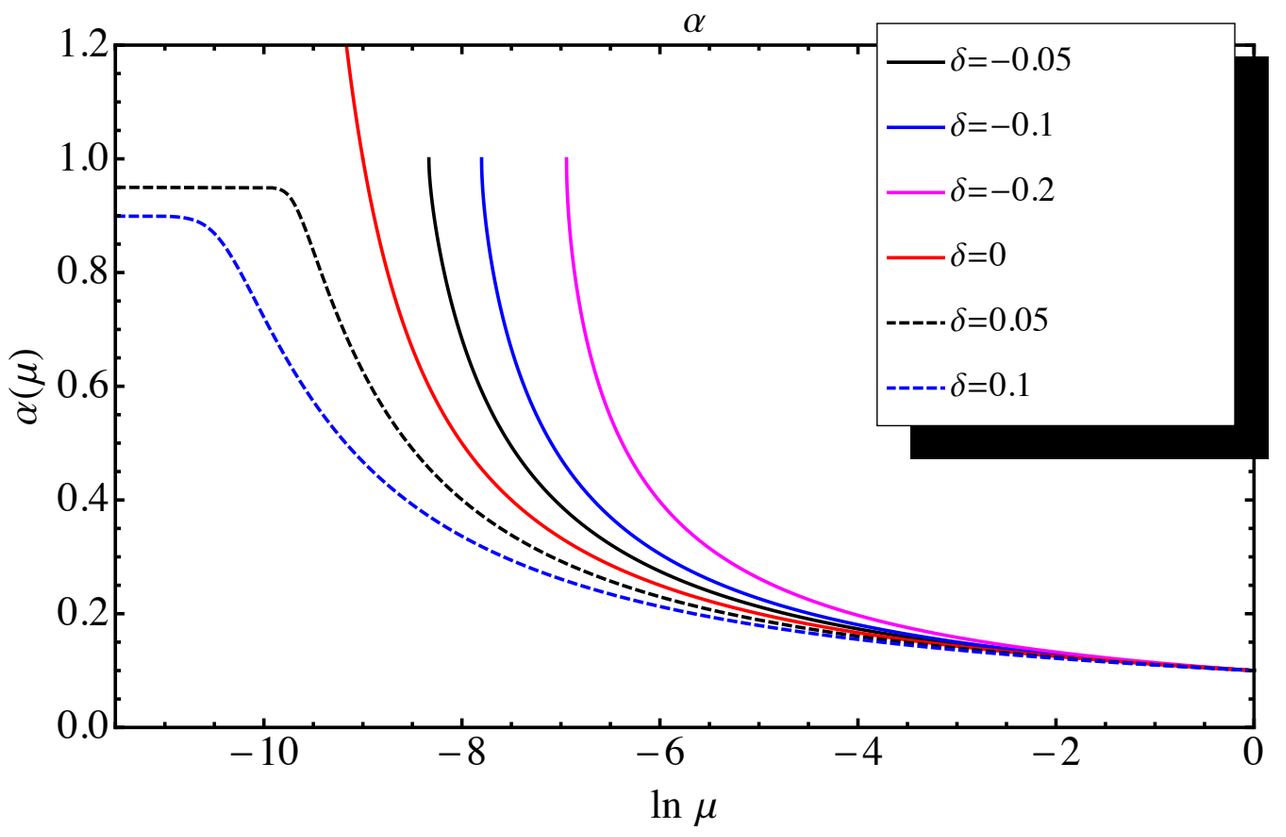




$$\beta_{Jump} = -\alpha^2 \frac{1-\delta-\alpha}{1-\alpha}$$

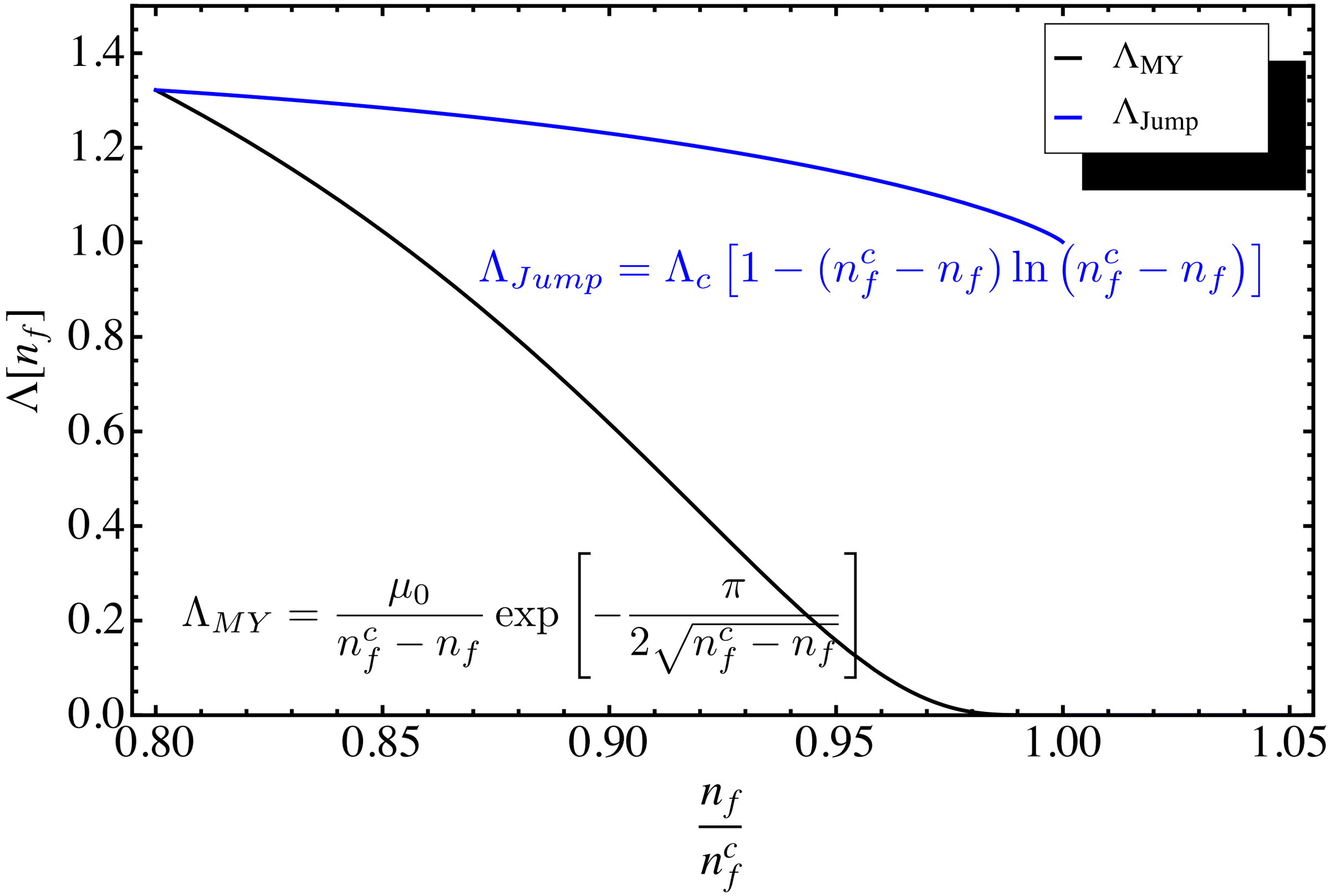
$$\delta = n_f - n_f^c$$

$$\langle \bar{Q}Q \rangle_\mu \simeq \gamma(1) \ \ln\left(\frac{\mu}{\Lambda}\right) \langle \ \bar{Q}Q \rangle_\Lambda$$

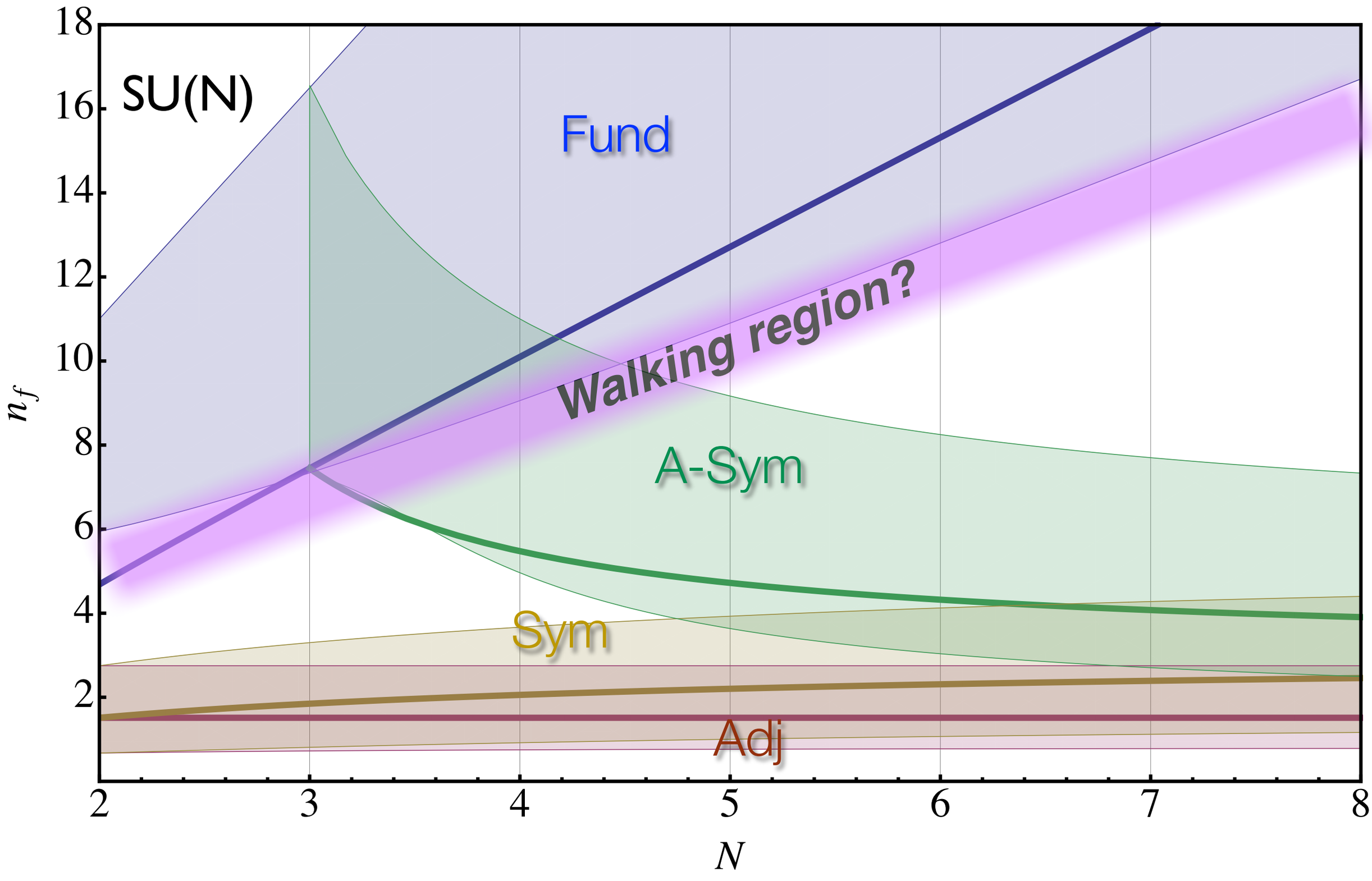


Sannino 2012

Walking or Jumping?



SU(N) Phase Diagram



Scent of Walking

QCD + Adj + Fund. Meson

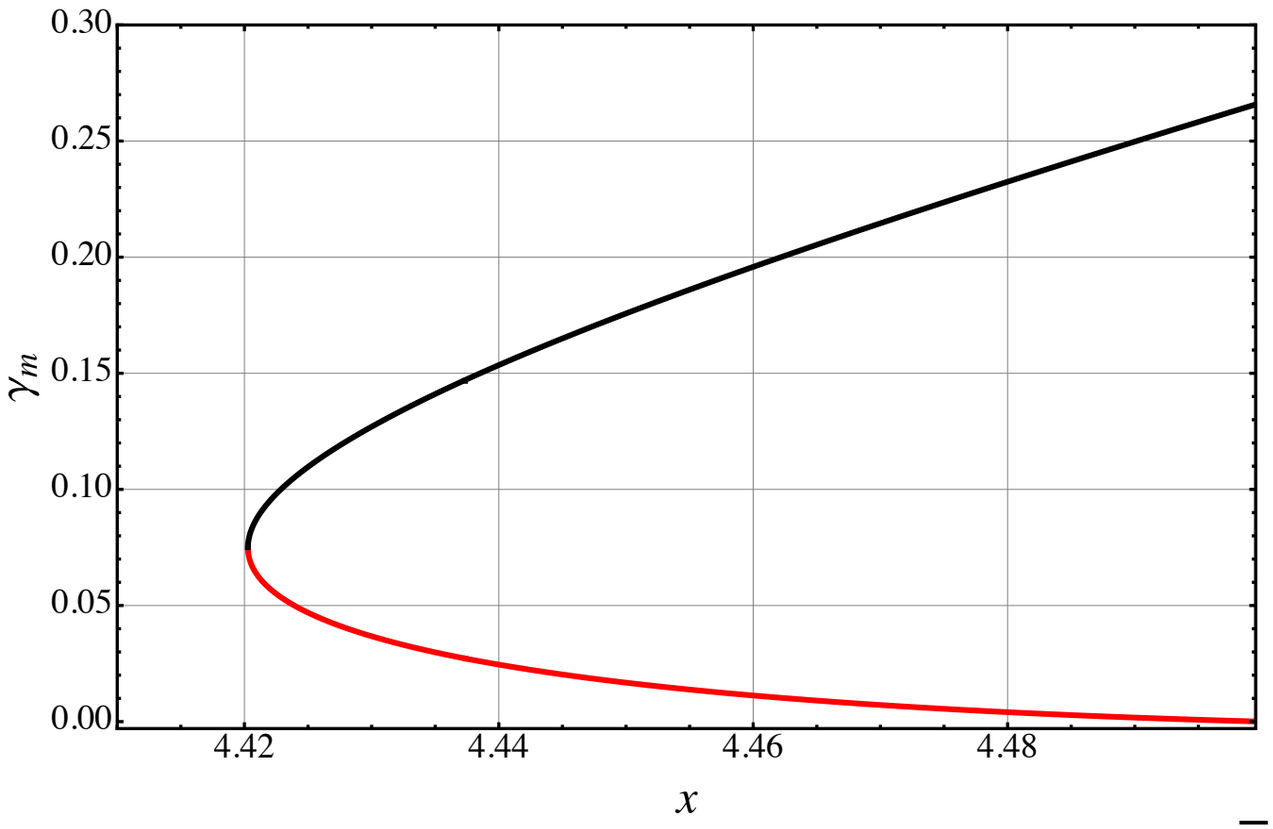
$$Tr\left[-\frac{1}{2}F^{\mu\nu}F_{\mu\nu} + i\bar{\lambda}\not{D}\lambda + \overline{Q}i\not{D}Q + \partial_\mu H^\dagger \partial^\mu H + y_H \overline{Q} H Q\right]$$

$$-u_1(Tr[H^\dagger H])^2 - u_2 Tr(H^\dagger H)^2 \,.$$

Fields	$[SU(N_c)]$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
q	$\square$	$\overline{\square}$	1	$\frac{N_f - N_c}{N_c}$	$-\frac{N_c}{N_f}$
$\widetilde{q}$	$\overline{\square}$	1	$\square$	$-\frac{N_f - N_c}{N_c}$	$-\frac{N_c}{N_f}$
H	1	$\square$	$\overline{\square}$	0	$\frac{2N_c}{N_f}$
G_μ	Adj	1	1	0	0

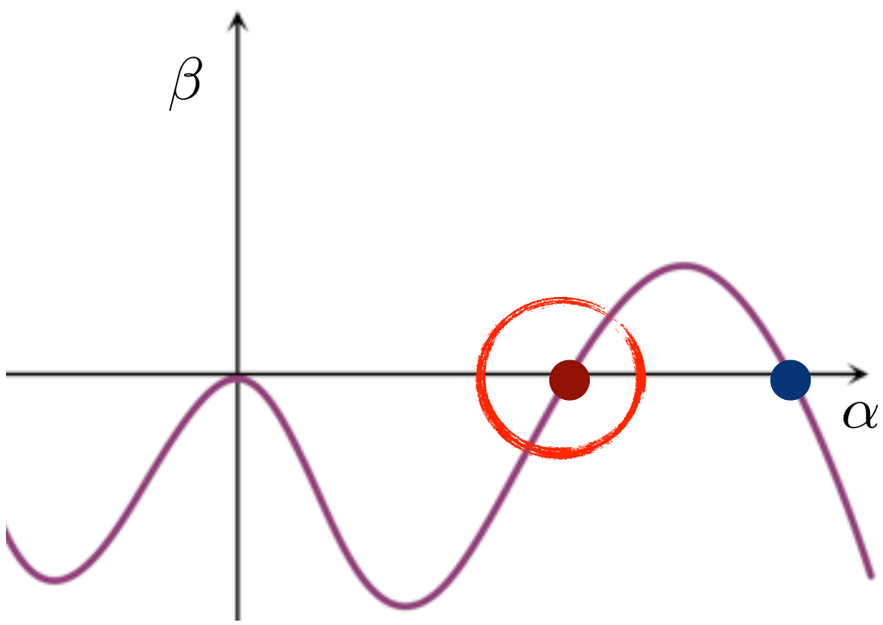
Antipin, Mojaza, Sannino 2011

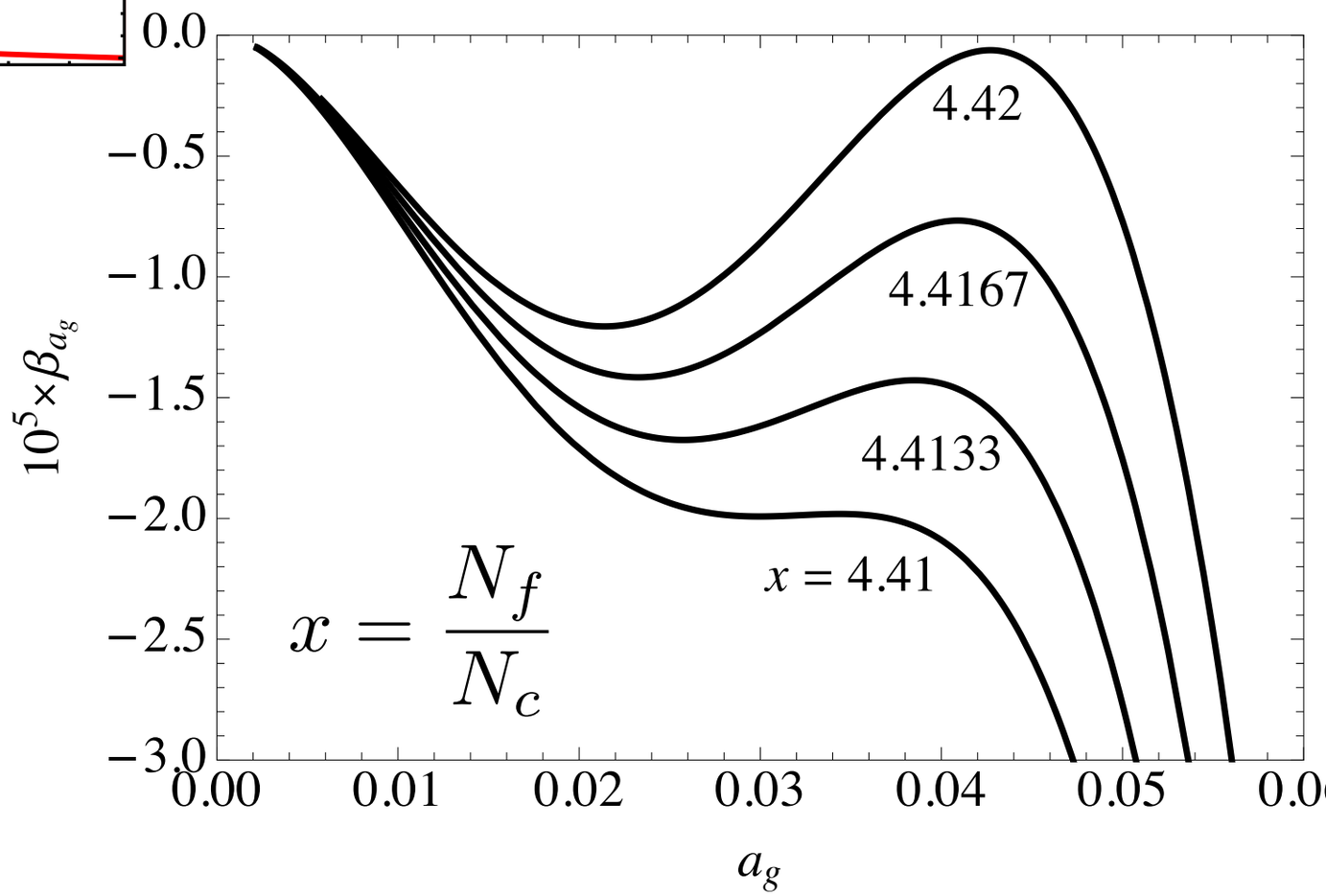
Conformal Window and Walking



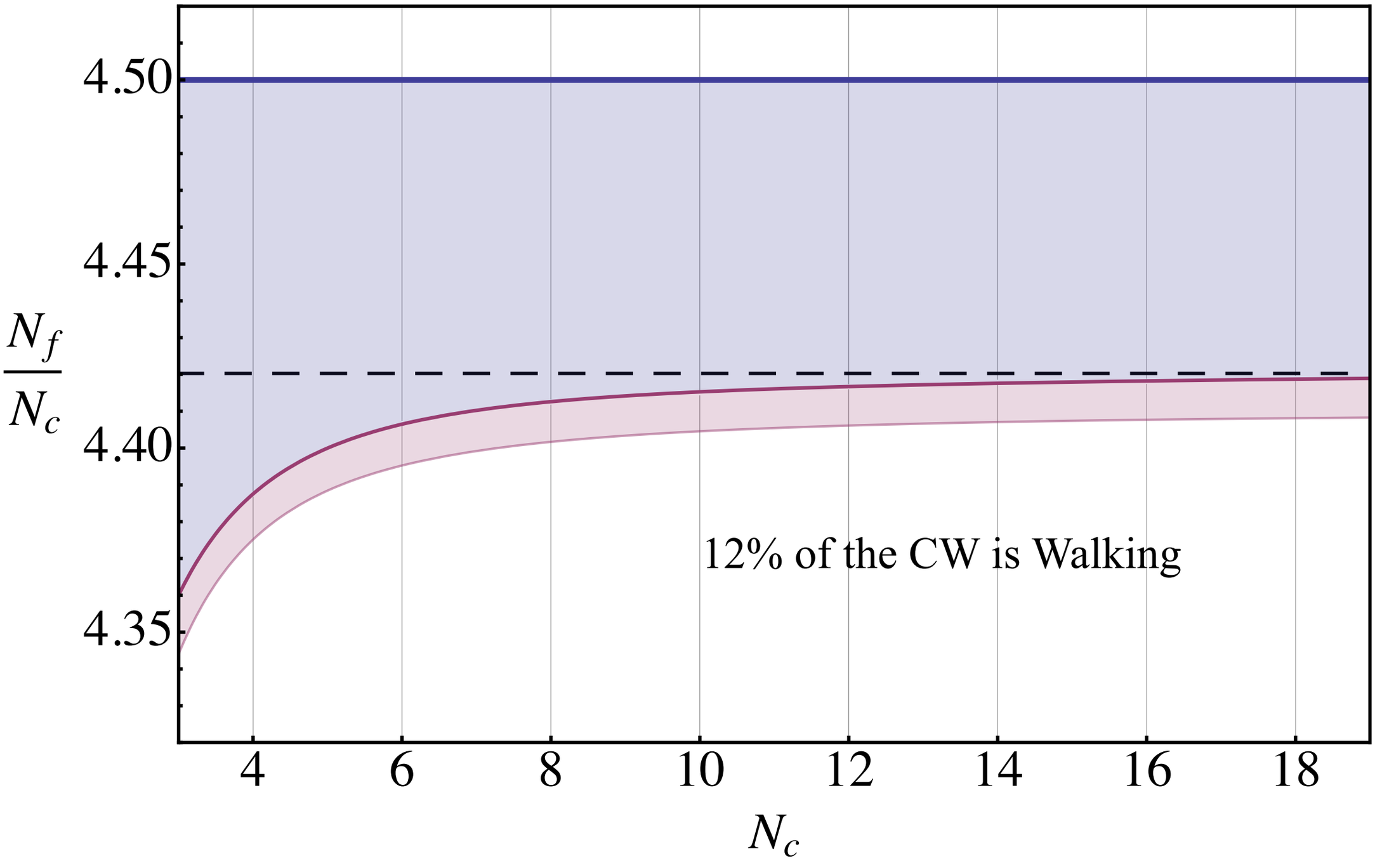
Needs 2nd order in PT

Checked Coleman-Weinberg





Conformal Window and Walking



Antipin, Di Chiara, Mojaza, Mølgaard, Sannino 2012

Higgs - again

A Walking Higgs?

"Higgs" @ 125 GeV vs unitarity scale:

$$\frac{M_H}{1.2\ \mathrm{TeV}} \simeq 0.1$$

- Mass of the "Higgs" versus EW ChPT convergence radius scale:

$$\frac{M_H}{4\pi v} \simeq 0.04 \quad \longleftrightarrow \quad \text{Conformal Goldstone}$$

- Compare with mass of the pion versus ChPT convergence radius:

$$\frac{M_\pi}{4\pi F_\pi} \simeq 0.1 \quad \longleftrightarrow \quad \text{Goldstone}$$

Conformal Quasi-Goldstone

◉ Breaking of scale (conformal) symmetry

$$\partial_\mu D^\mu = \Theta^\mu_\mu = \sum_i \beta(g_i) \frac{\partial \mathcal{L}}{\partial g_i}$$

◉ Dilaton mass and decay constant

$$\langle D | \partial_\mu D^\mu | 0 \rangle = -f_D m_D^2$$

◉ In near-conformal technicolor like models

$$f_D = v \qquad\qquad m_D = M_H$$

LHC Walking Higgs discovery?

$$f_D = v \quad m_D = M_H$$

- Implies

$$m_D \ll 4\pi f_D \ , \qquad m_D < f_D$$

- For comparison in QCD

$$M_\pi \ll 4\pi F_\pi \ , \qquad M_\pi \simeq F_\pi$$

- What kind of models can do this?

Walking Models

- Conformal technicolor models (Light Composite Higgs)

$$\frac{M_H}{v} \simeq (N_f^c - N_f)^\nu$$

Dietrich, Sannino, Tuominen hep-ph/0510217

Dietrich, Sannino hep-ph/0611341

ν critical exponent

N_f^c critical number of techniflavors for conformality

- Dilaton effective theories/SM — Goldberger et al. 08; Campbell, Ellis, Olive 11
- Holography — Vecchi 10; Elander, Nuñez, Piai 10
- Technidilaton — Haba, Matsuzaki, Yamawaki 10

Scent of Light Walking Higgs

Grinstein, Uttayarat 1105.2370

Antipin, Mojaza, Sannino 1107.2932

Scalar window & the dilaton

$$Tr\left[-\frac{1}{2}F^{\mu\nu}F_{\mu\nu}+i\bar{\lambda}\not{D}\lambda+\overline{Q}i\not{D}Q+\partial_\mu H^\dagger\partial^\mu H+y_H\overline{Q}HQ\right]$$

$$-u_1(Tr[H^\dagger H])^2-u_2Tr(H^\dagger H)^2\,.$$

Fields	$[SU(N_c)]$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
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$\widetilde{q}$	$\overline{\square}$	1	$\square$	$-\frac{N_f-N_c}{N_c}$	$-\frac{N_c}{N_f}$
H	1	$\square$	$\overline{\square}$	0	$\frac{2N_c}{N_f}$
G_μ	Adj	1	1	0	0

Antipin, Mojaza, Sannino 1107.2932

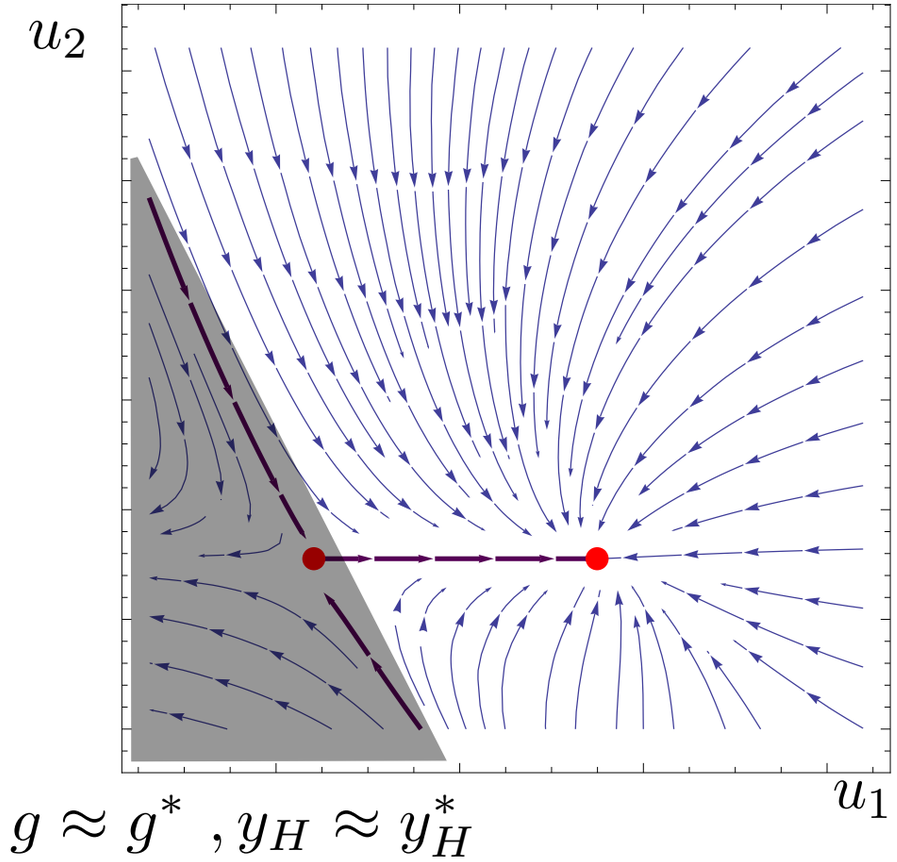
IR scalar instability

Perturbative IR stable fixed point (a la Banks-Zaks)

$$N_f/N_c \equiv x = x_{\rm AF}(1-\epsilon) < x_{\rm AF}$$

$$\{{g^*}^2, {y_H^*}^2, u_1^*, u_2^*\} \sim \epsilon$$

IR conformal or ?



RG improved potential

$$\mathcal{L} = \mathcal{L}_K(F_{\mu\nu}, \lambda, \psi, H; g) + \sqrt{\frac{a_H}{N_f}}\bar{\psi} H \psi - \frac{z_1}{N_f^2}\left(\mathrm{Tr} H^\dagger H\right)^2 - \frac{z_2}{N_f}\mathrm{Tr}\left(H^\dagger H\right)^2$$

Coleman - Weinberg

H. Yamagishi, 1980

$$\frac{dV_{\mathrm{eff}}^{\mathrm{RG}}}{d\mu} = \left(\mu\frac{\partial}{\partial\mu} + \sum_i \beta(g_i)\frac{\partial}{\partial g_i} + \gamma_\phi \phi_c \frac{\partial}{\partial \phi_c}\right) V_{\mathrm{eff}}^{\mathrm{RG}} = 0$$

$$H_{ij}^c = \phi_c \delta_{ij}$$

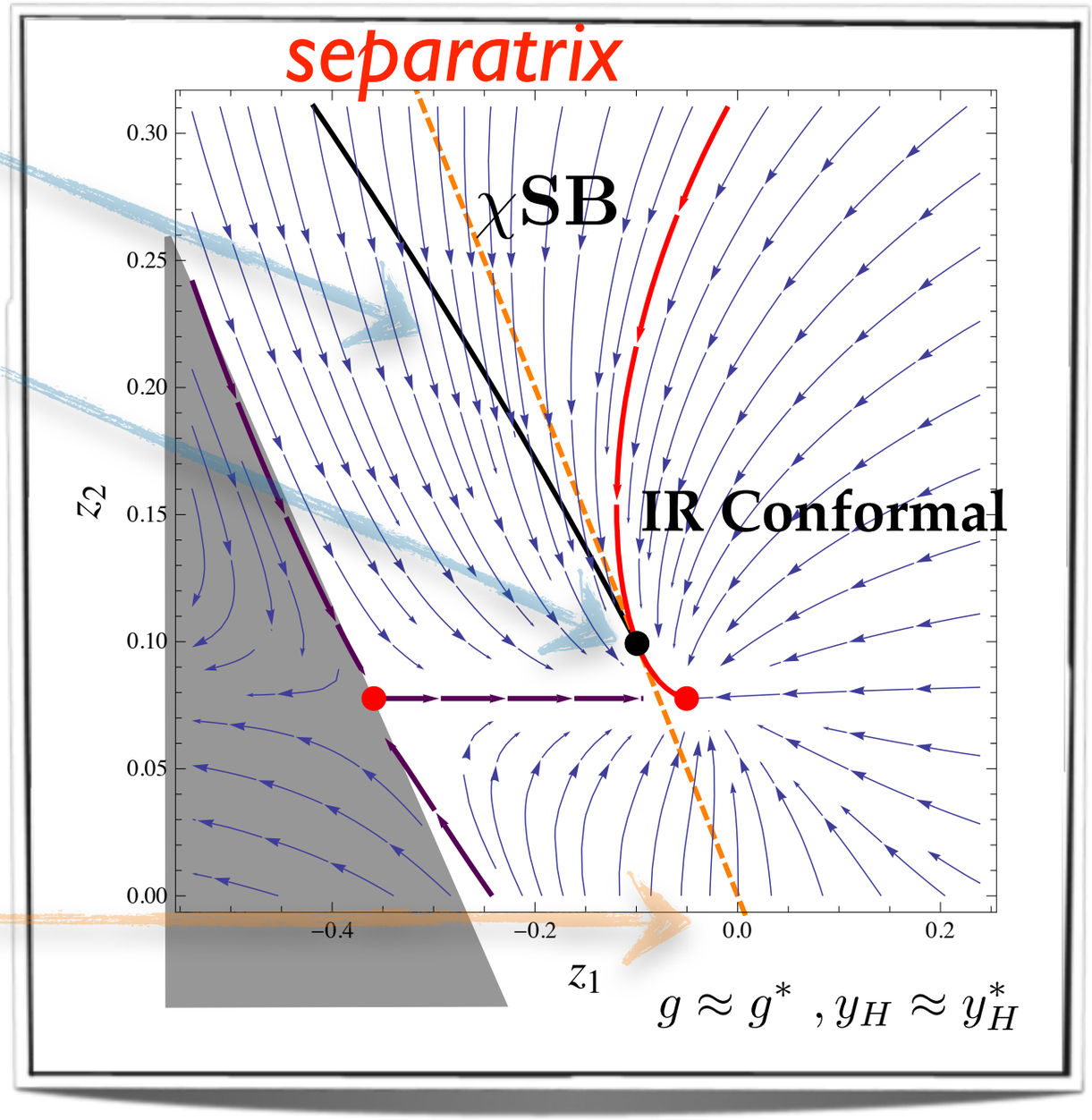
Stability

$$V_{\rm eff}^{\rm RG\,\prime}(\phi_c) = 0$$

$$V_{\rm eff}^{\rm RG\,\prime\prime}(\phi_c) = 0 \Rightarrow$$

$$m_\phi^{(1)\,2} \propto 4z_2^2 - x a_H = 0$$

$$V_{\rm eff}^{\rm RG}(\phi_c) = 0$$



ϕ light by tuning $4z_2^2 - x a_H = \delta$ small

Light dilaton

$$\langle D|\partial_\mu D^\mu|0\rangle = -f_D m_D^2$$

$$\Theta^\mu_\mu = \frac{\beta(g)}{g}(F_{\mu\nu})^2 + \beta(y_H)(qH\widetilde{q} + \text{h.c.})$$
$$- \beta(u_1)\left(\text{Tr}[HH^\dagger]\right)^2 - \beta(u_2)\text{Tr}\left[(HH^\dagger)^2\right]$$

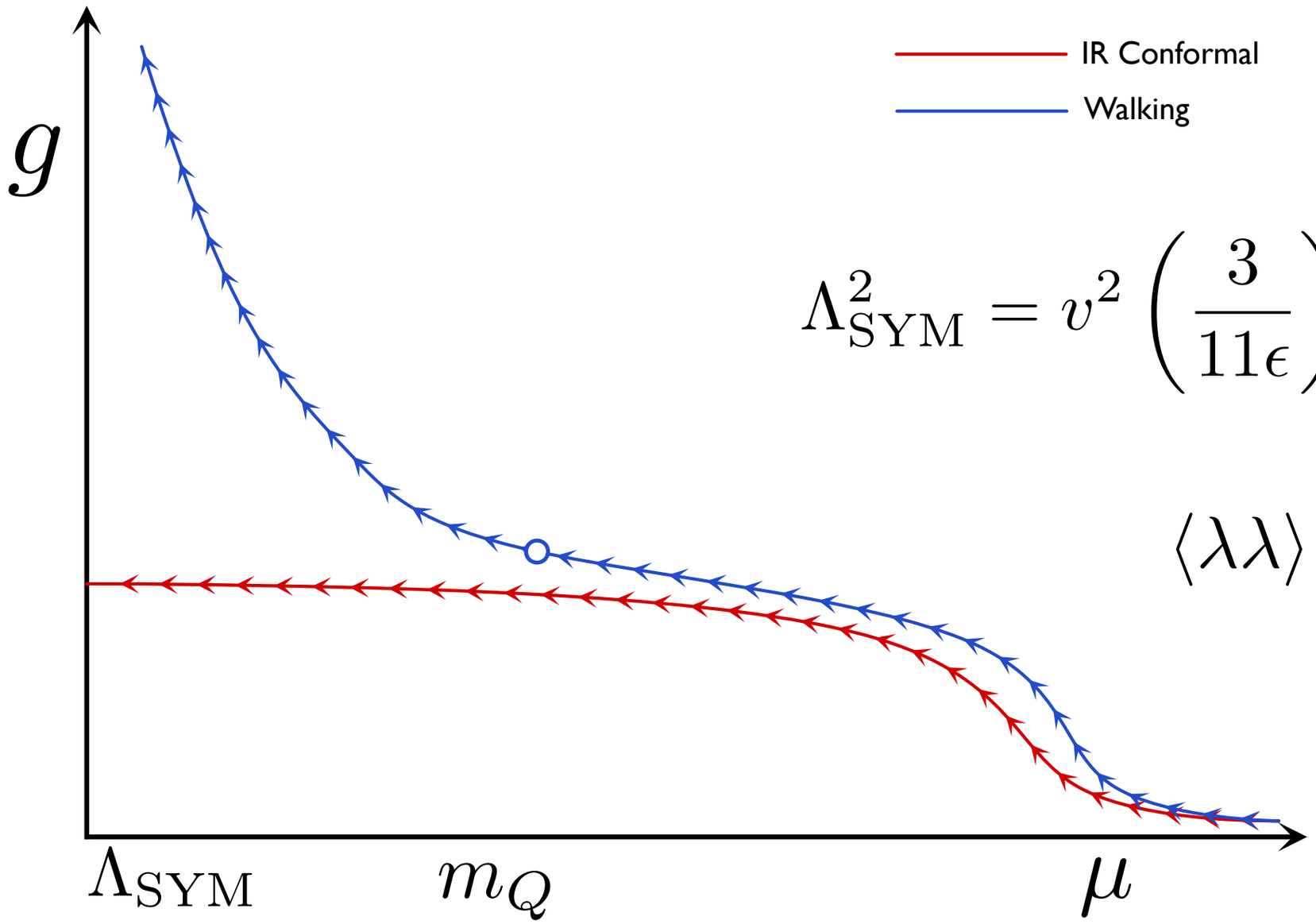
$$\langle 0|\Theta^\mu_\mu|D\rangle\big|_{M_0} = -\frac{32\pi^2 v^3}{N_f^2}\left[4(z_2^0)^2 - x(a_H^0)^2\right] = -vm_d^2 \equiv -f_D m_D^2$$

Is the dilaton the lightest state?

Nope: Ultra light SYM

Gluons and adjoint massless at the condensate scale

Super Yang-Mills in the deep IR



$$\Lambda^2_{\rm SYM} = v^2 \left(\frac{3}{11\epsilon}\right)^{2/3} \exp\left(-\frac{6}{22\epsilon}\right)$$

$$\langle \lambda\lambda \rangle = -\frac{9}{32\pi^2}\Lambda^3_{SYM}$$

Full spectrum



EW

$m_Q^2 \sim m_h^2 \sim \epsilon$

$N_f^2 - 1$ Massive Scalars

$N_f \times N_c$ Massive Dirac Quarks

Higgs

$m_d^2 \sim \delta\epsilon$

Pseudo dilaton

Light DM

$m^2_{\rm SYM} \sim e^{-1/\epsilon}$

Super glueballs

$m^2_{\rm NBG} = 0$

N_f^2 Goldstones

Similar to MWT Spectrum [Talk by K. Rummukainen and A. Rago]

Pheno Proposals

Minimal TC

- Minimal WT

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

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

- Next to MWT

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

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Orthogonal

$SO(4)_{TC}$ $\square$ **U** **D**

Frandsen, Sannino 09

- Ultra MT

$SU(2)_{TC}$ $\square$ **U** **D**

Ryttov & Sannino 08

Vanilla TC

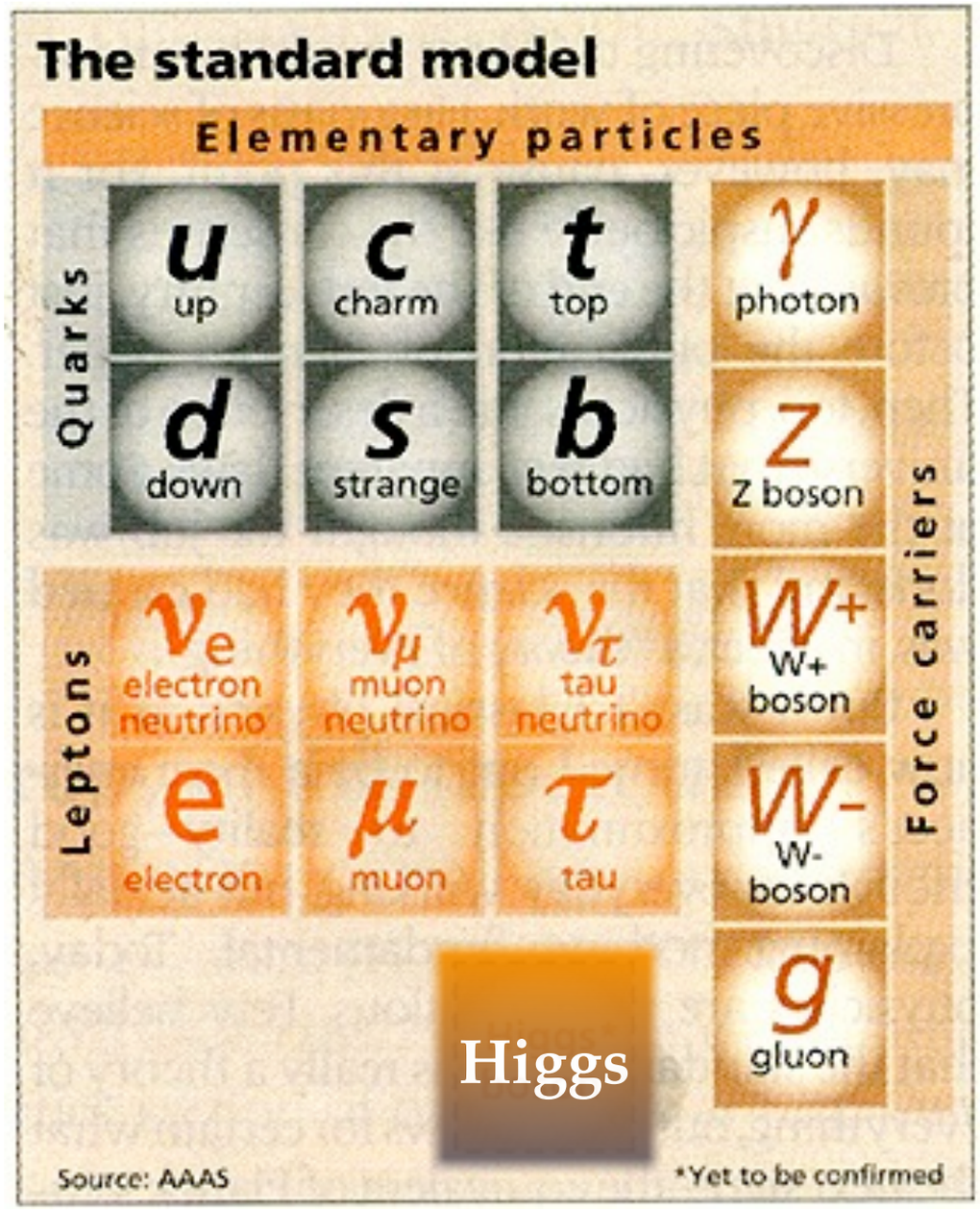
(Next) Minimal Walking Technicolor

- Minimal Walking TC + Strong ETC

  Catterall & Sannino;
  Del Debbio, Lucini Patella, Pica, Rago
  Hietanen, Rummukainen, Tuominen
  Catterall, Giedt, Sannino

- Next to minimal is (just) outside the conformal window

  Fodor, Holland, Kuti, Nogradi, Schroeder, Wong



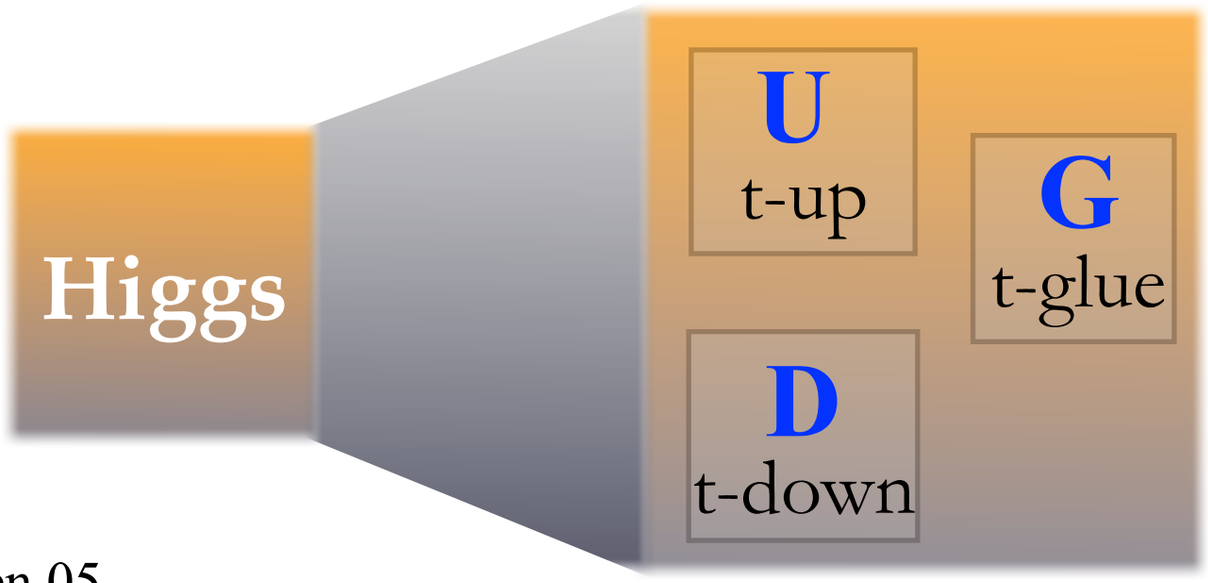
N
Extra Neutrino

ζ
Extra Electron

U(1)

SU(2)

SU(3)



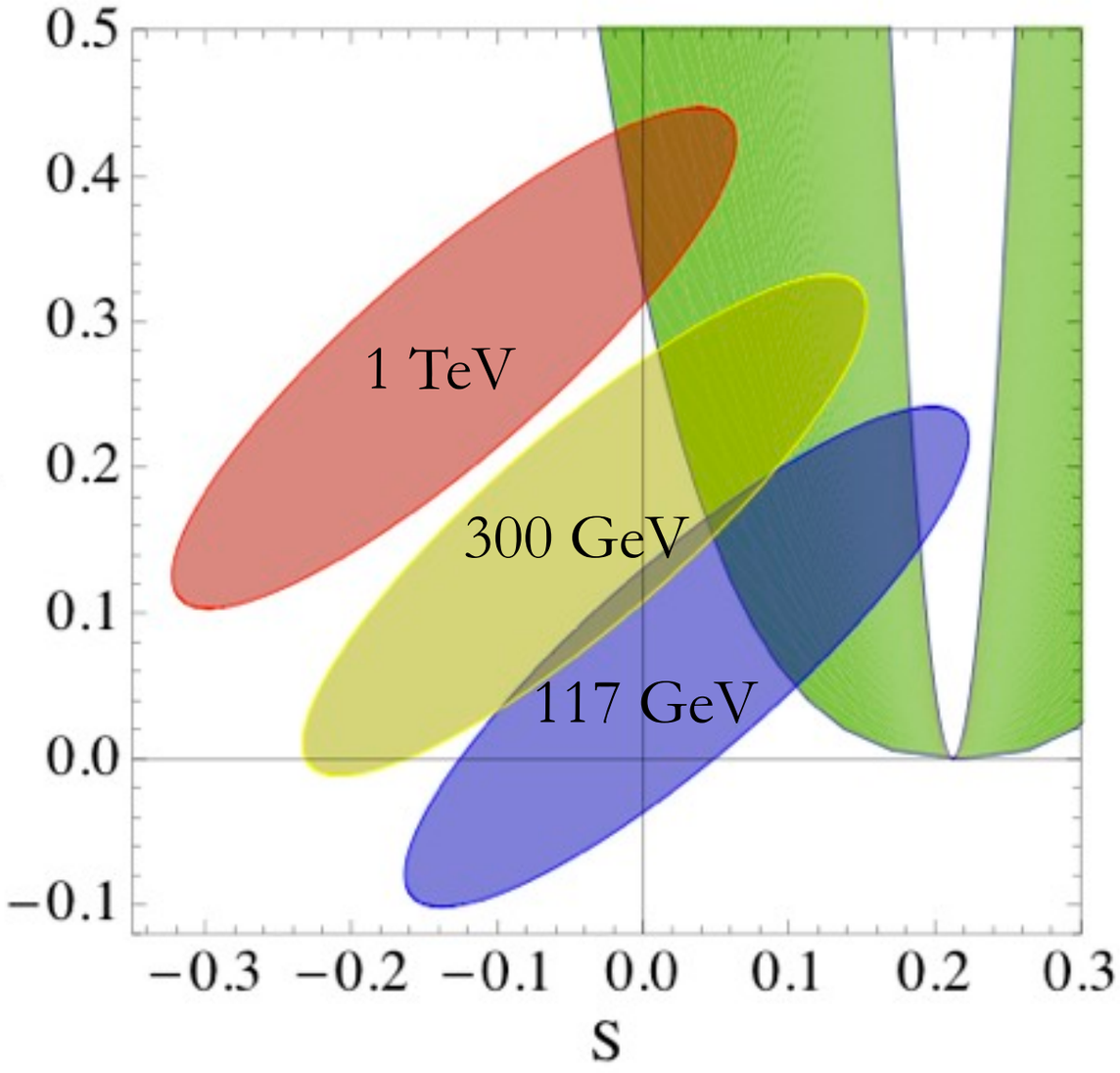
SU(2)

F.S. + Tuominen 04

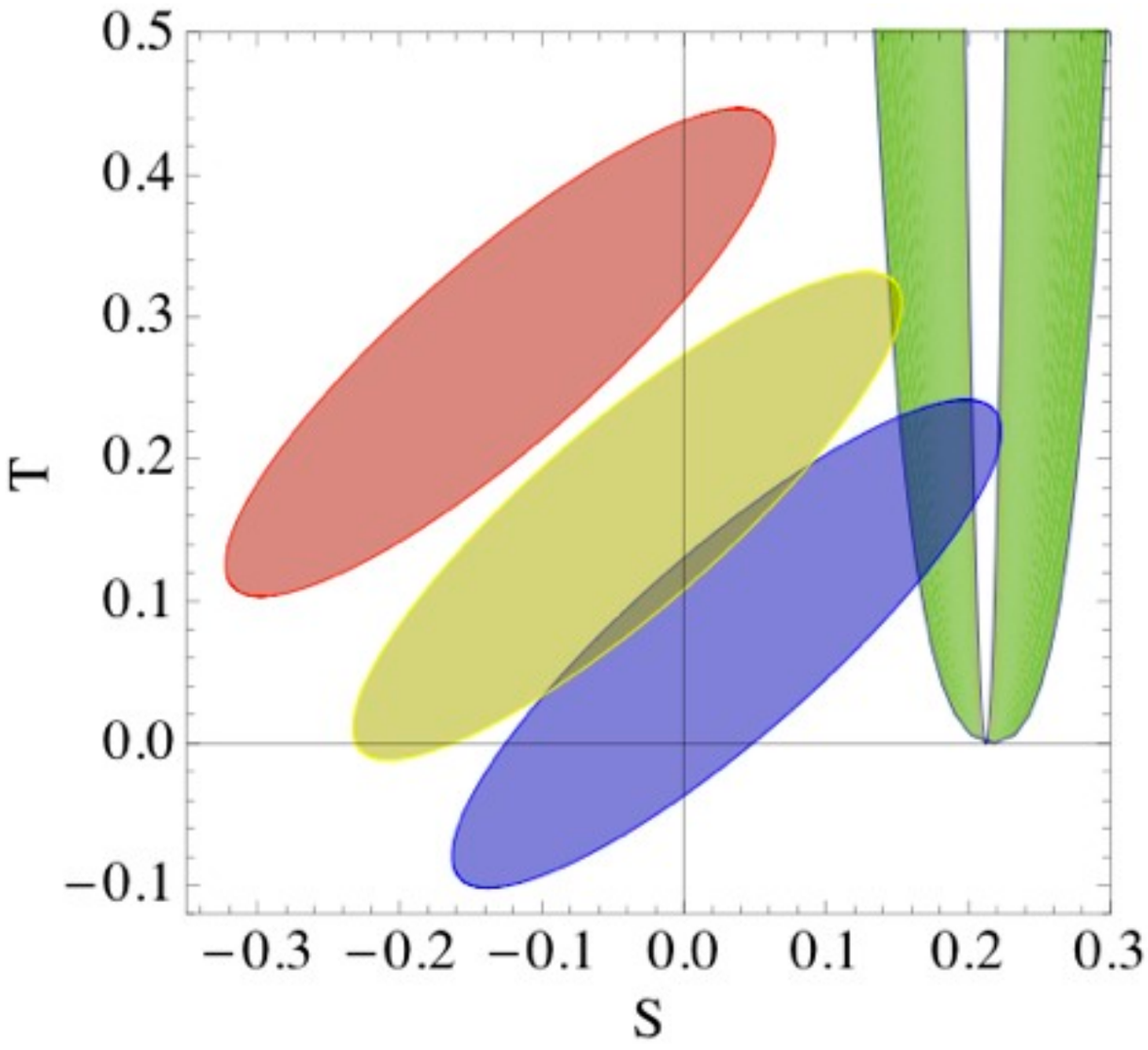
Dietrich, F.S., Tuominen 05

U and D: Adj of SU(2)

New Leptons & Precision Data



Exotic Leptonic hypercharge Y=-3/2



Standard Model Leptonic hypercharge

MWT Lagrangian

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

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

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g_{\rm TC}\epsilon^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu \qquad a,b,c = 1,2,3$$

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

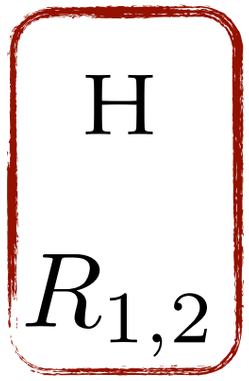
What you see is *not* what LHC will see

MWT Effective Lagrangian

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

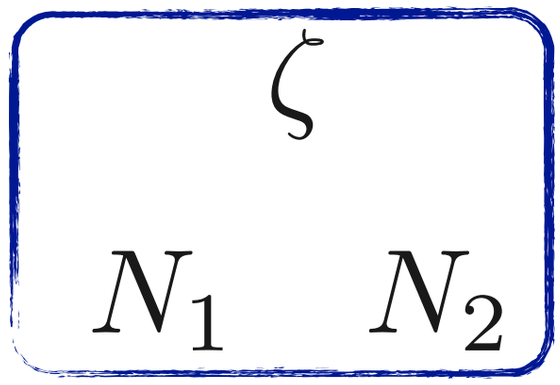
Composite Higgs

Composite Axial - Vector States



Heavy Electron

2 Heavy Majoranas

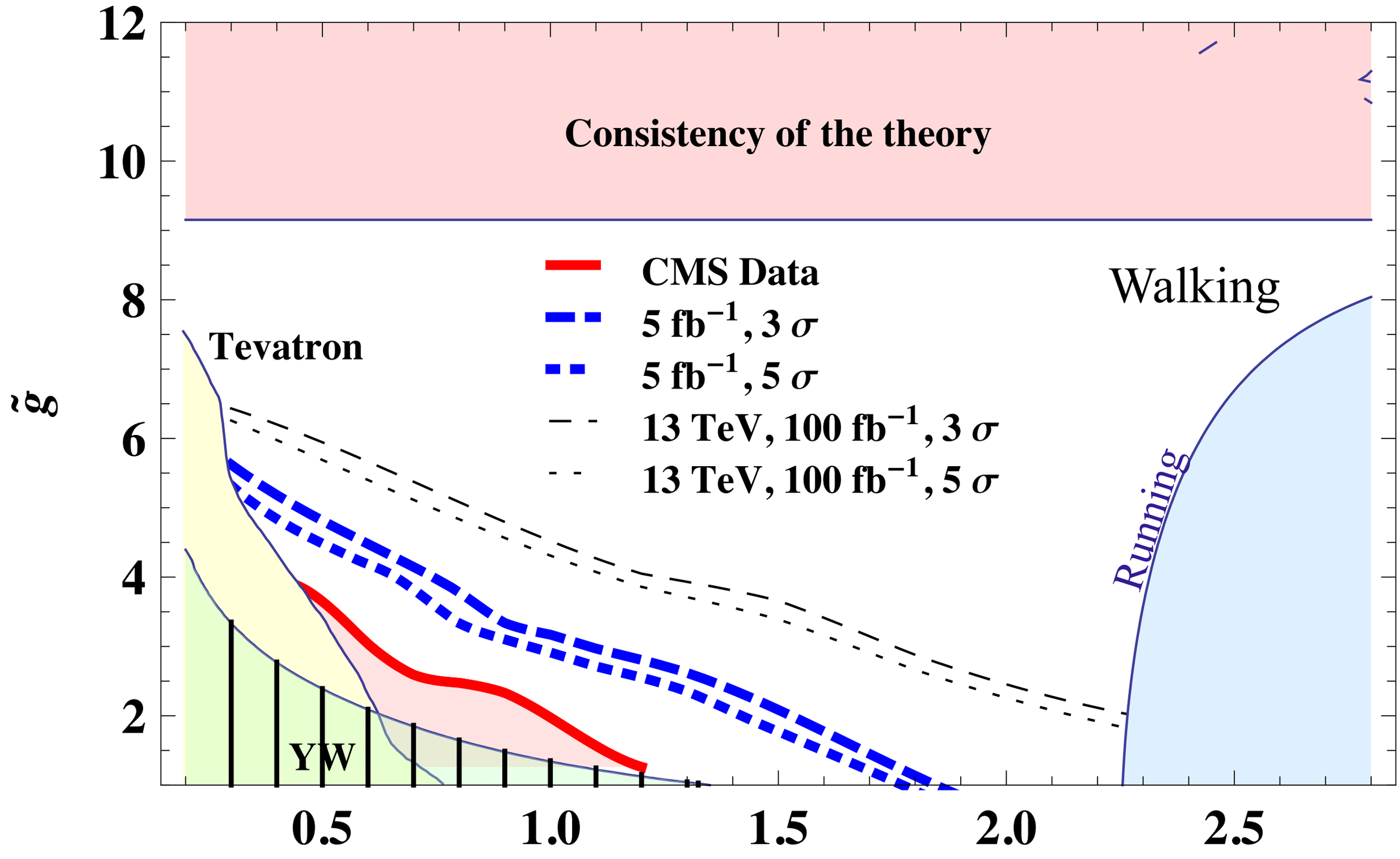


Frandsen, Masina, Sannino 09

Hapola, Masina, Sannino 11

Foadi, Frandsen, Ryttov & F.S. 07

Constraining MWT



Andersen, Hapola, Sannino 11

Belyaev, Foad, Frandsen, Jarvinen, Pukhov, Sannino 08

Conclusions

- Has LHC discovered the lightest composite state?
- Technicolor & X Compositeness
- Example of dilaton & walking
- Minimal TC models
- New era for strong dynamics