DIAS
Danish Institute
for Advanced Study

University of Southern Denmark

Technicolor after the Higgs Discovery

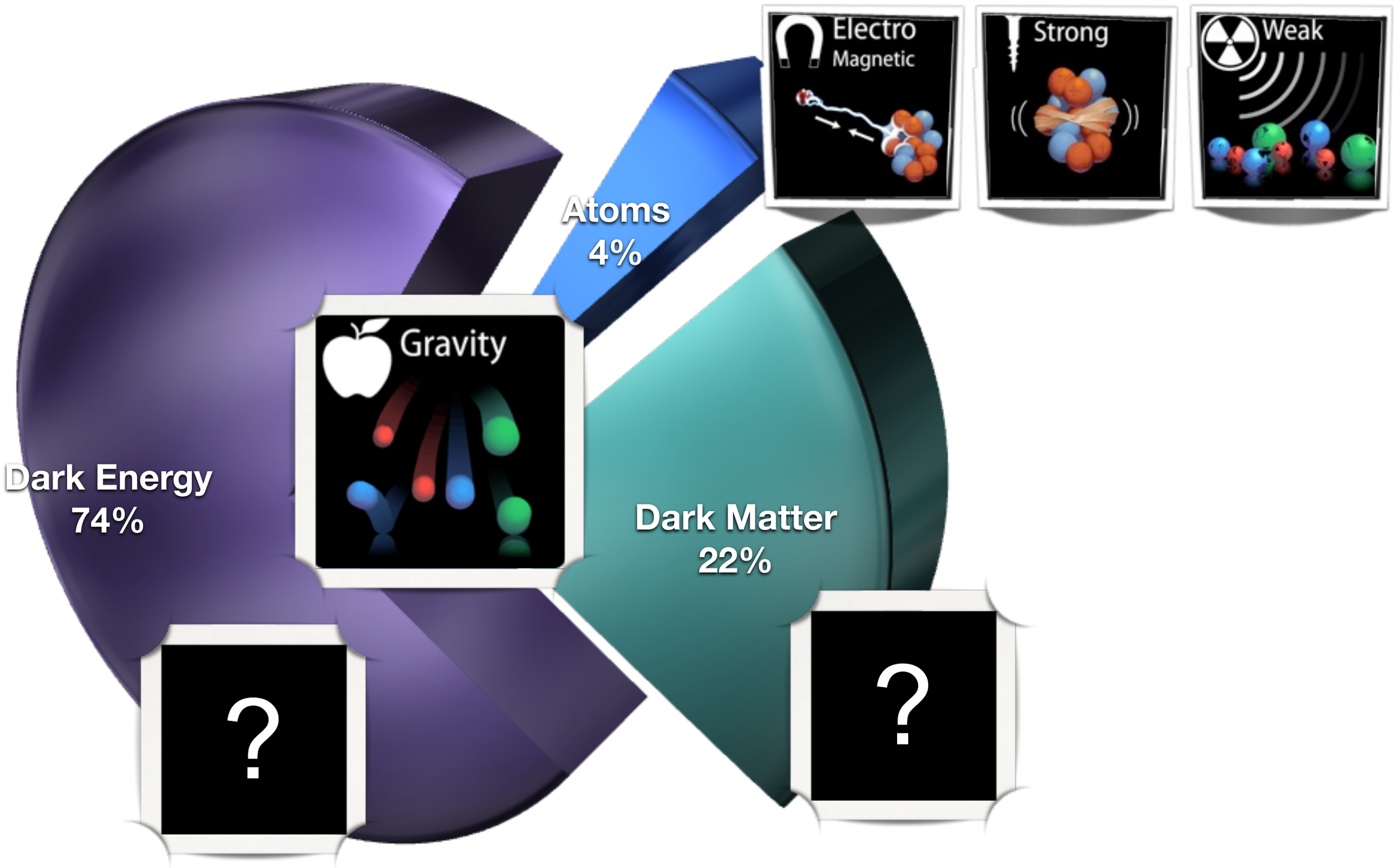
Francesco Sannino

CP³ - Origins

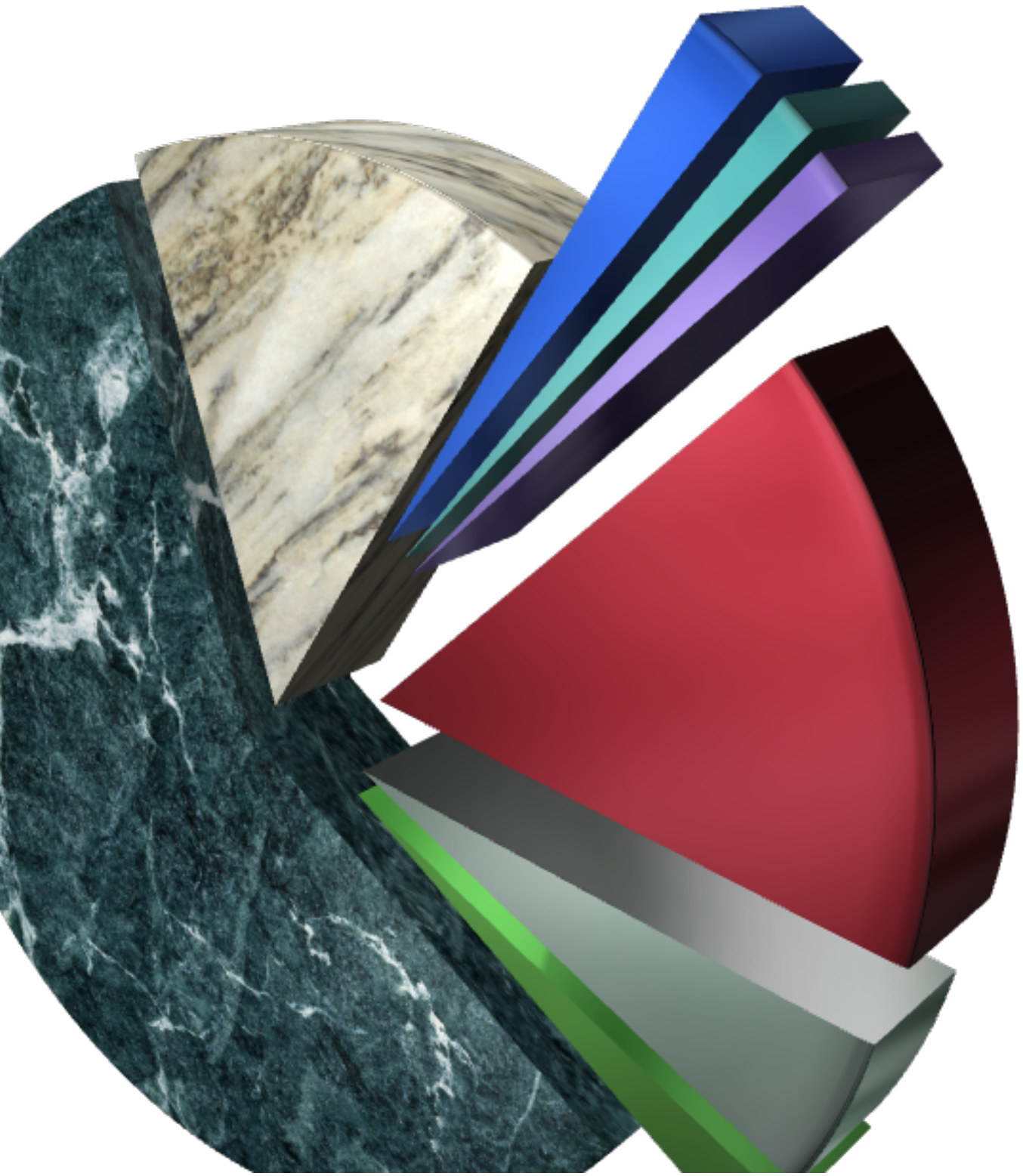
Particle Physics & Cosmology

SCGT12 @ Nagoya 2012

Now


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

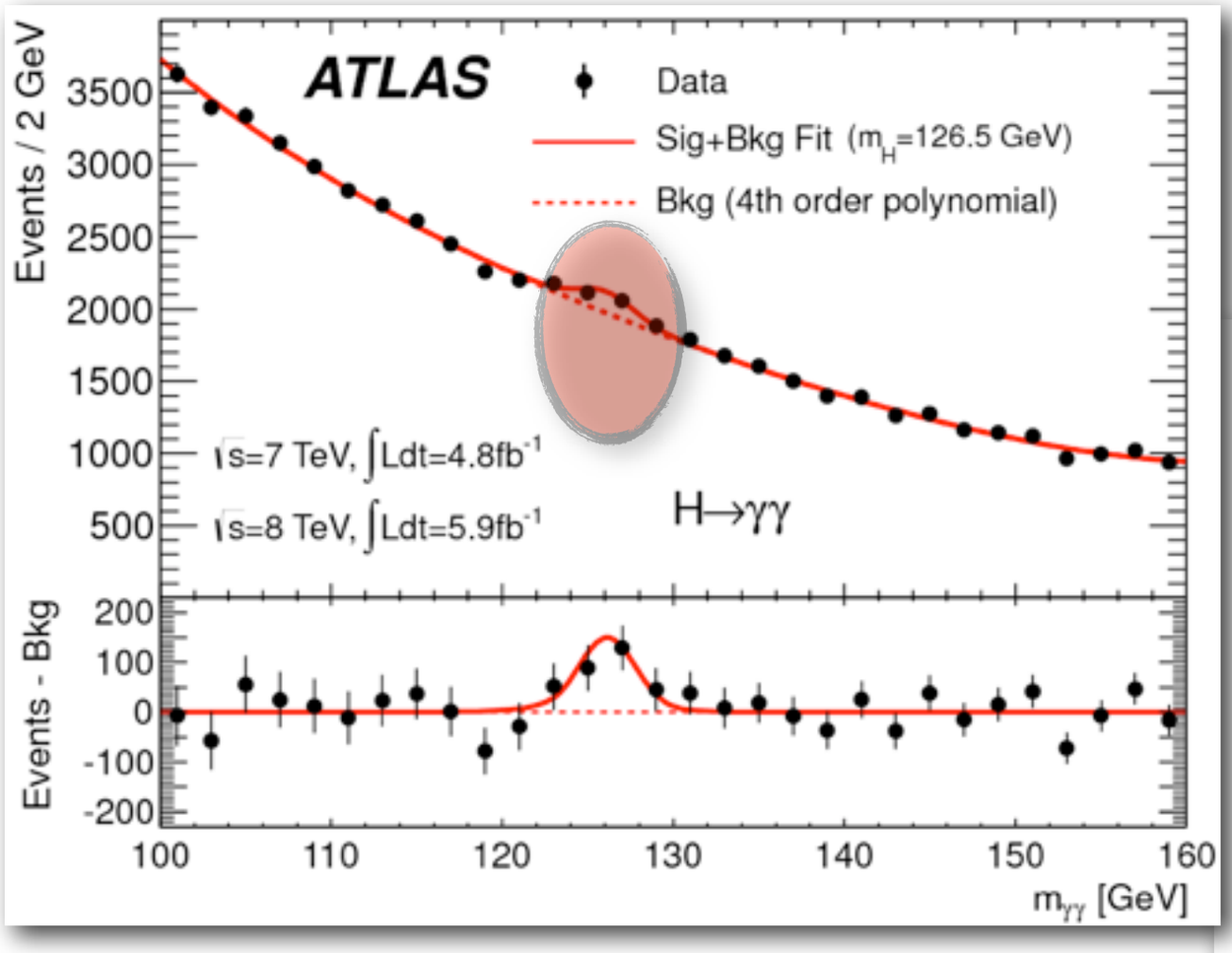
Future pie ?

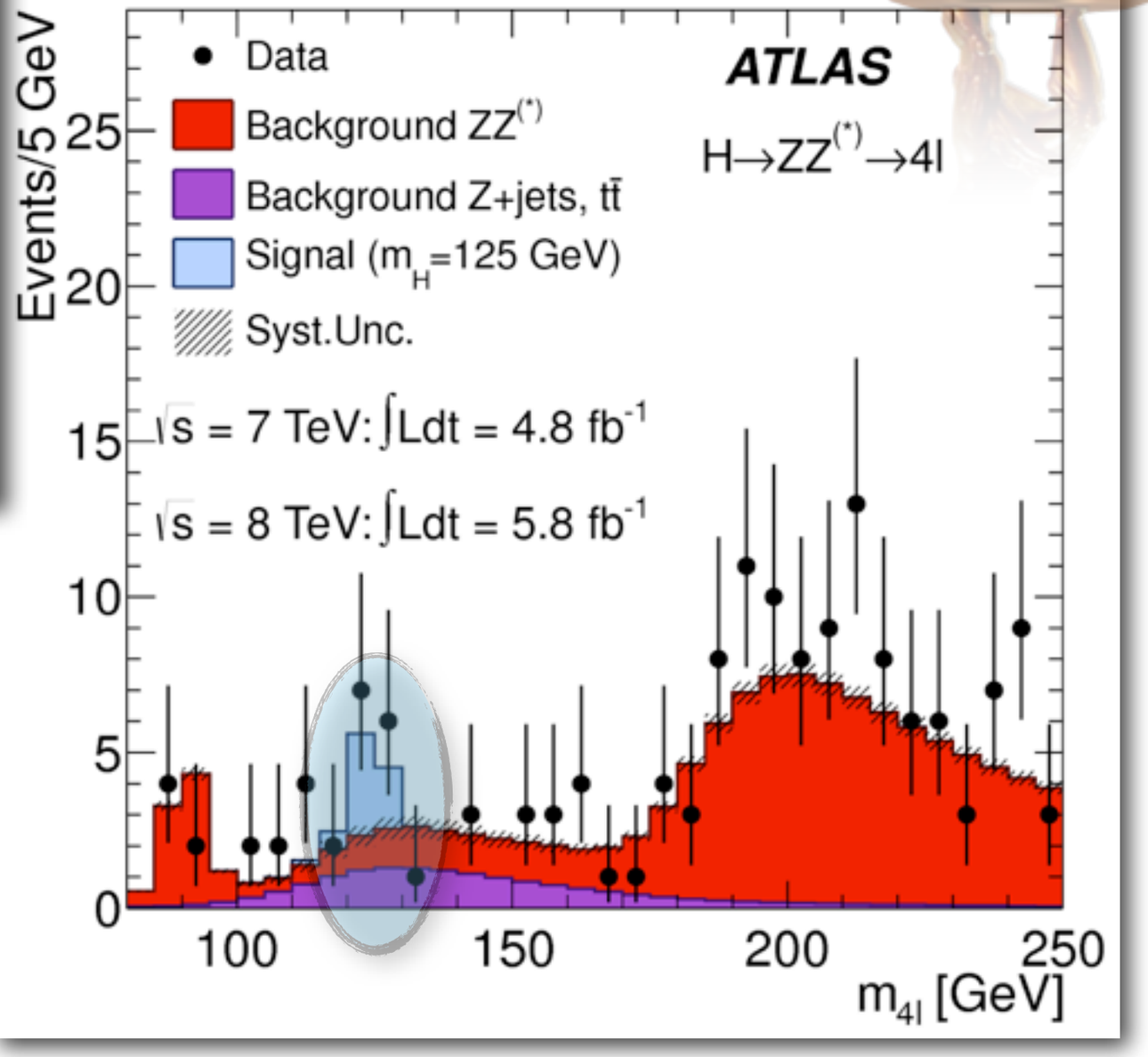


- New weak & strong forces
- Composite Higgs/SM
- Composite dark matter
- Composite inflation
- ....

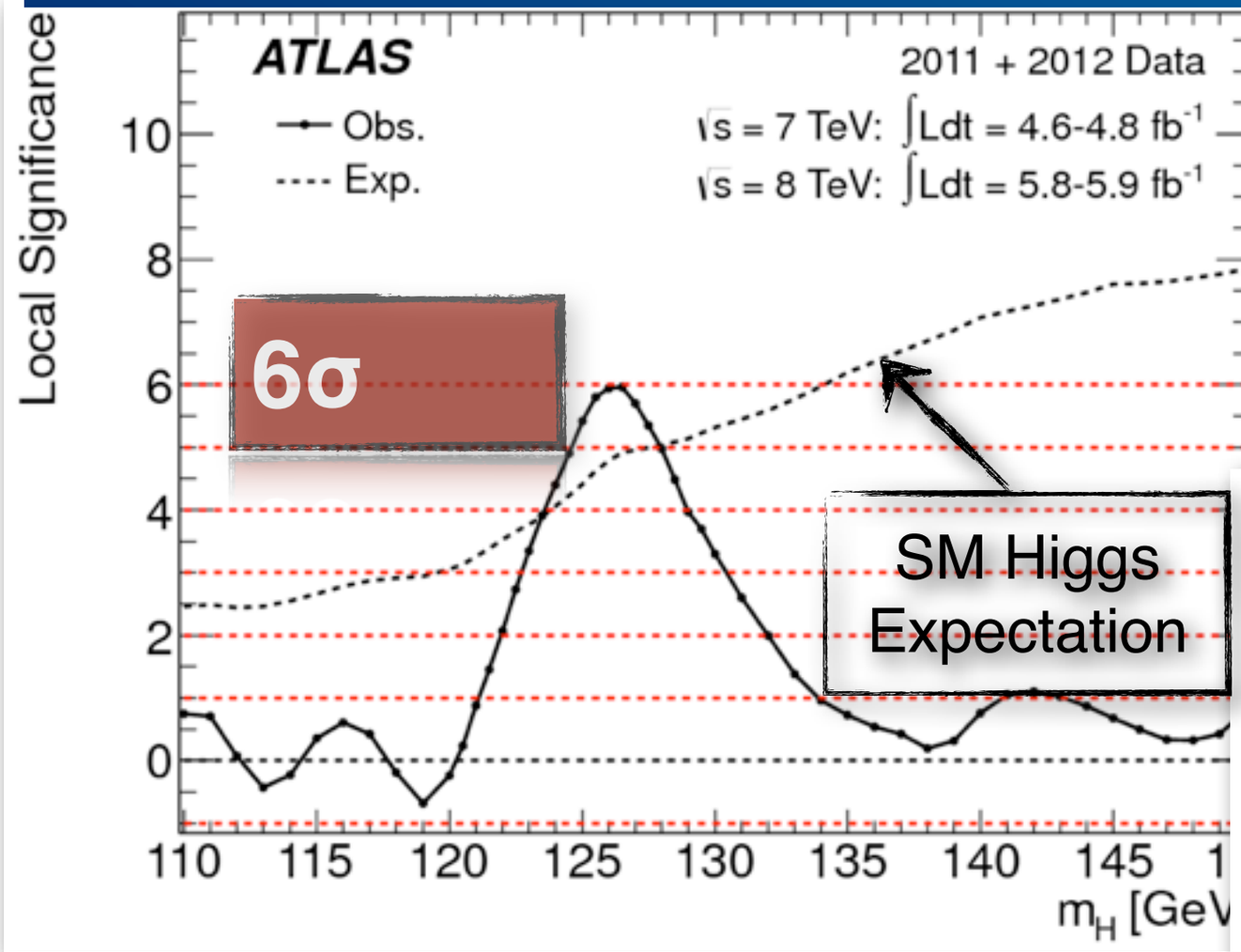
The scent of the Higgs

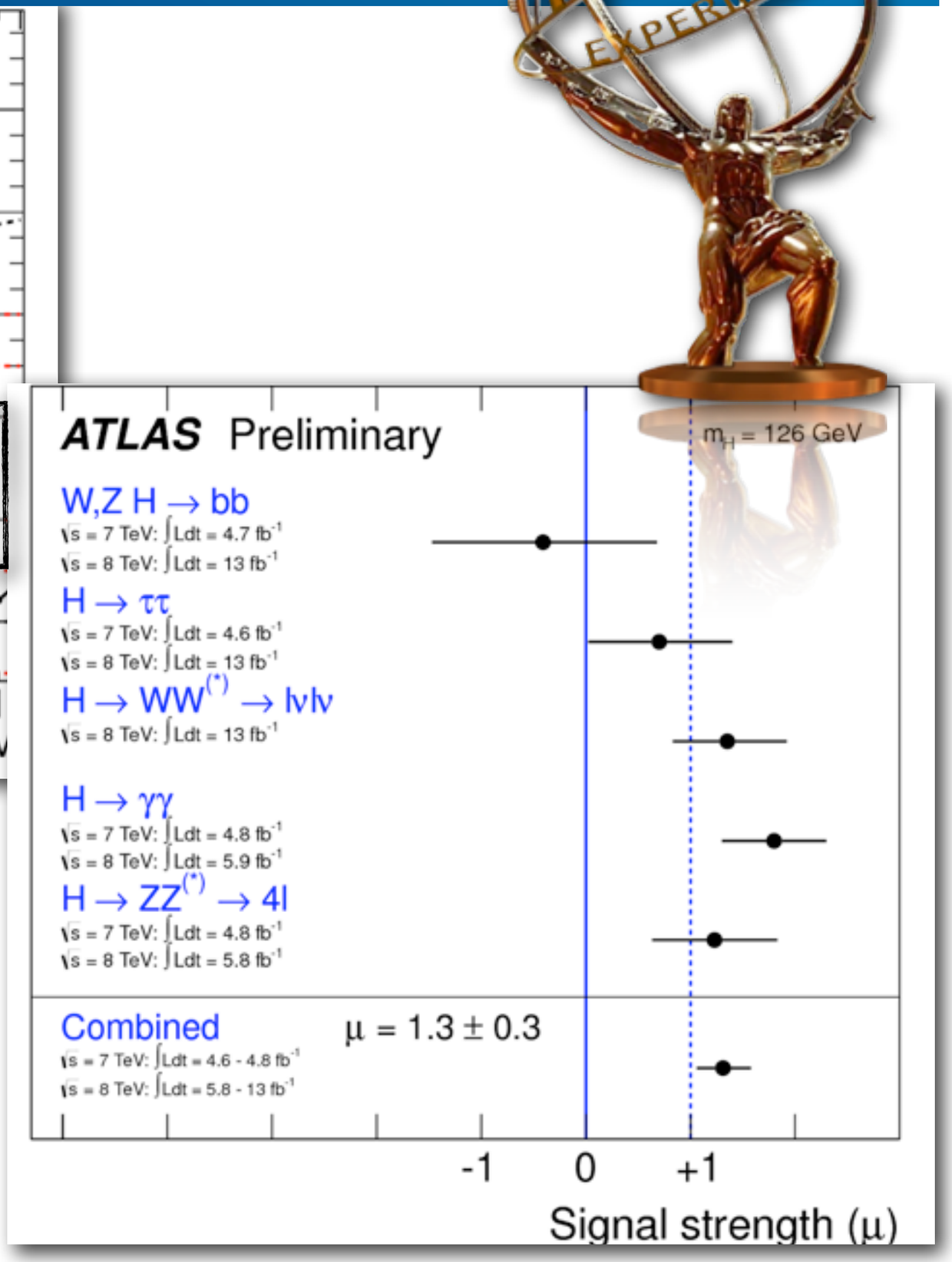
2 bumps


ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int$Ldt=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int$Ldt=5.9fb^{-1}
H→γγ
Events / 2 GeV
Events - Bkg
$m_{\gamma\gamma}$ [GeV]


Data
Background ZZ$^{(*)}$
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Syst.Unc.
$\sqrt{s}$ = 7 TeV: $\int$Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int$Ldt = 5.8 fb^{-1}
ATLAS
H→ZZ$^{(*)}$→4l
Events/5 GeV
m_{4l} [GeV]

Higgs discovery ?



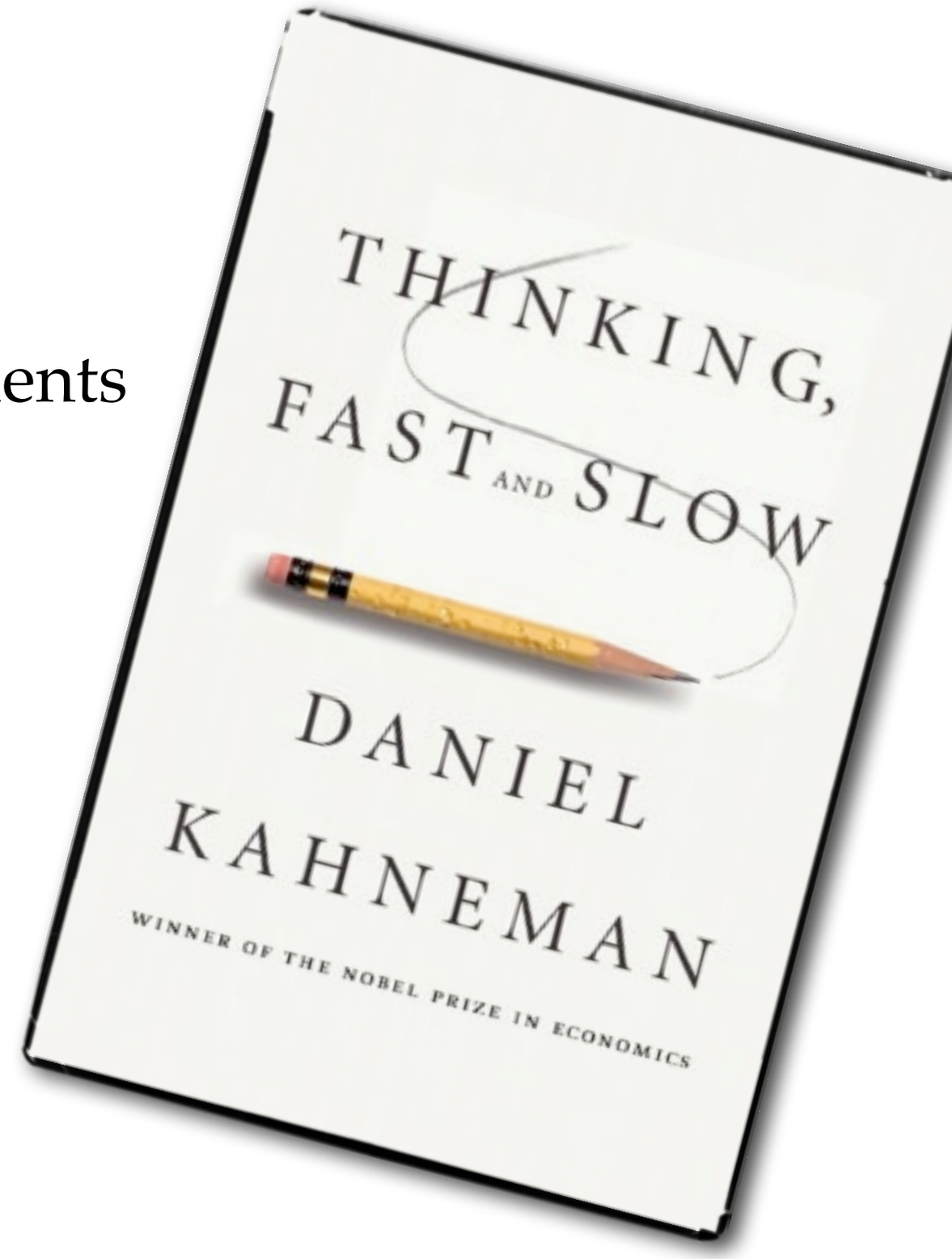


Fundamental ?

- Would be the first time
- Spinors are space-time constituents
- Scalars are derived
- Susy? Can be emergent

  In <4d: Sung-Sik Lee 06

  4d: Antipin, Mojaza, Pica, Sannino 10



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

What LHC has not seen, yet!

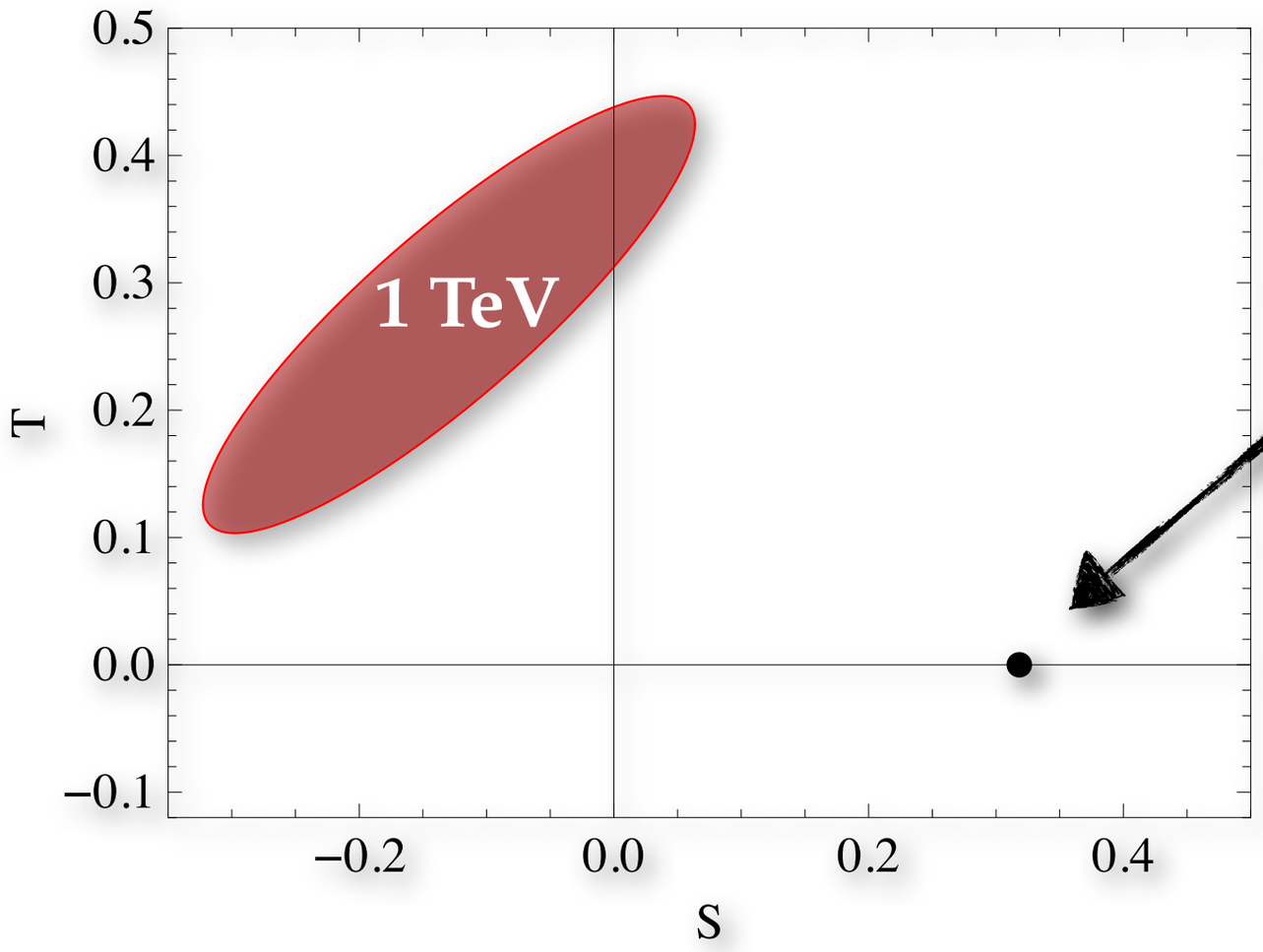
- Extra large, small or medium dimensions [kk states,..]
- Any sign of supersymmetry [gluino,...]
- Extra, mini, large Black-Holes [low scale gravity]

In line with:

Composite dynamics

Technicolor

Is "Old" Technicolor dead?



SU(3) + 1 Fund. Doublet

Weinberg, Susskind

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

TC alone = massless SM fermions

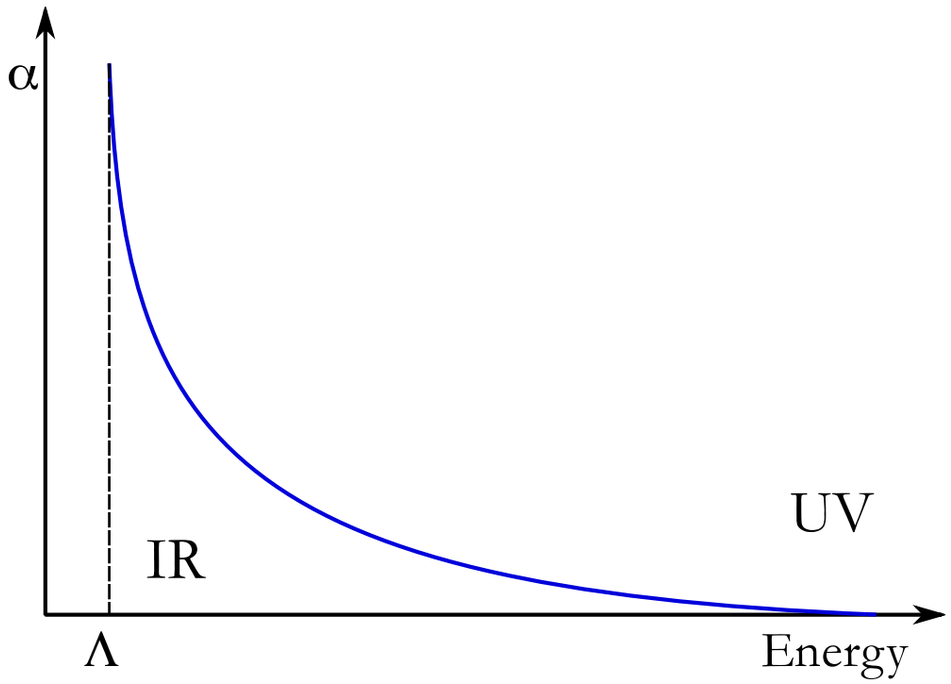
Extend TC to generate fermion masses [Eichten & Lane]

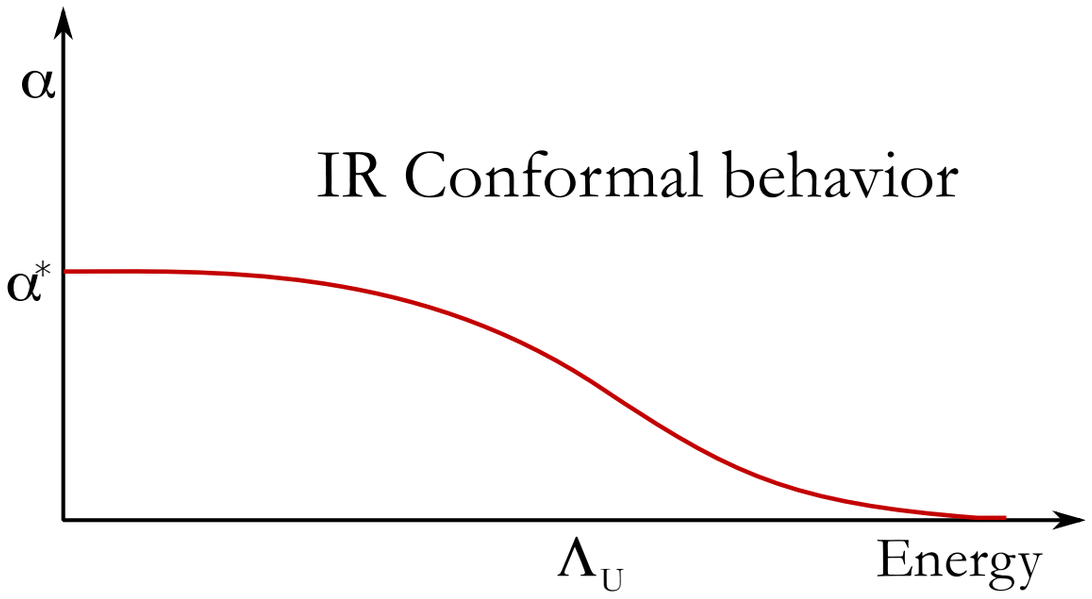
Old TC was dead 2 decades ago!

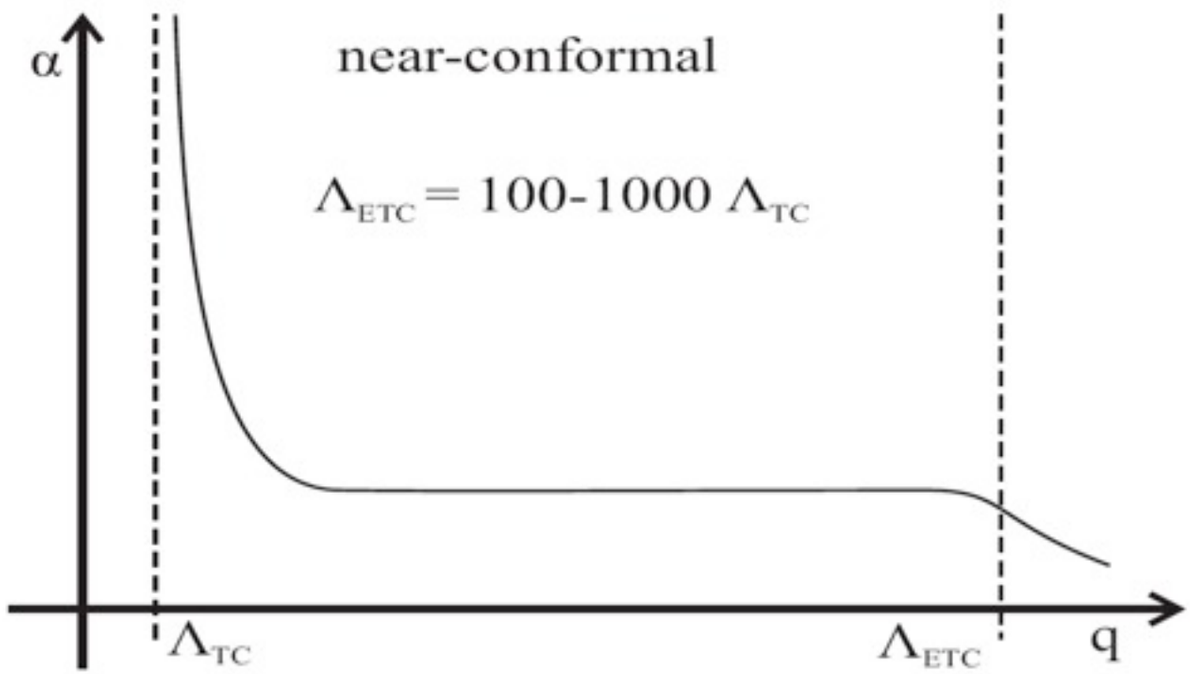
Need to go beyond QCD

- TC-fermion condensate enhancement/FCNC decoupling
- Minimal Technicolor passing precision tests
- Need a Technicolor Higgs
- Dark matter candidates

Walking







Holdom,

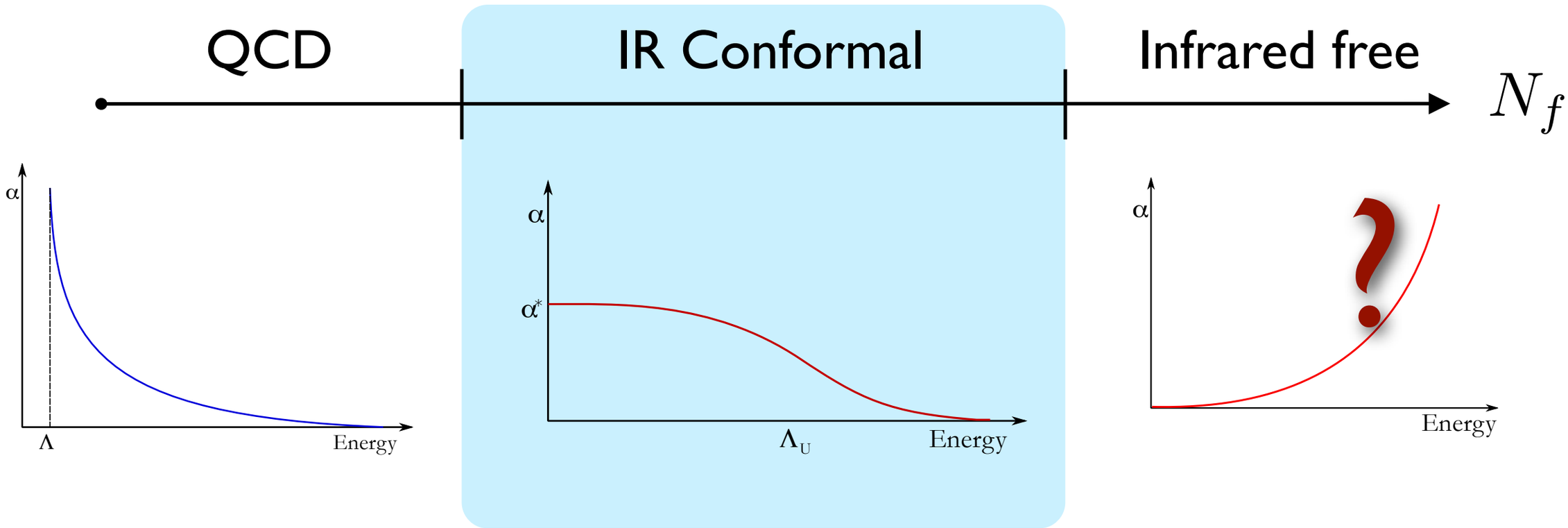
Appelquist, Miranski, Yamawaki, Wijewardhana...

Knobs

Gauge Group: SU, SO, SP, Exceptional

Matter Representation

# of Flavors per Representation



A novel phase @ large Nf

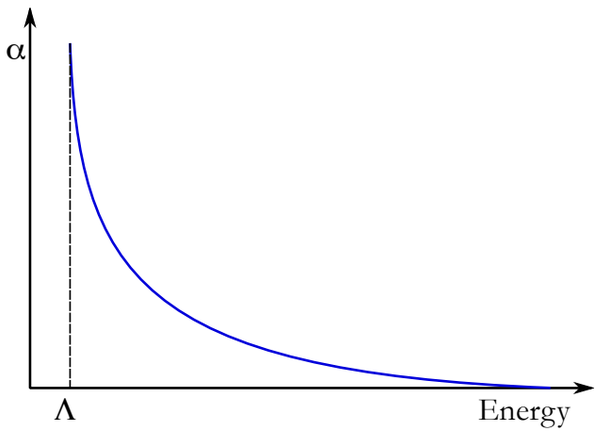
Interesting structure at large Nf

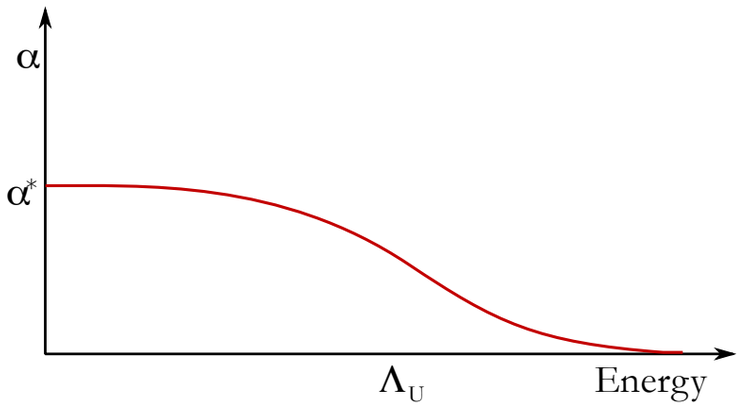
Pica & Sannino 10

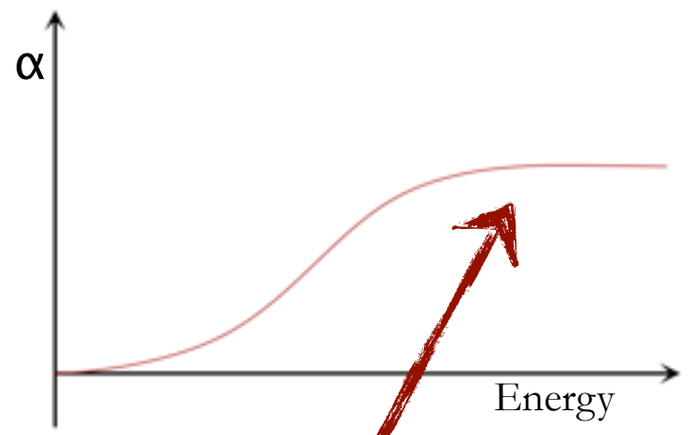
First coefficients at large Nf are known

Ciuchini, Derkachov, Gracey, Manashov ‘99

QCD | IR Conformal | Asymp. Safe — N_f



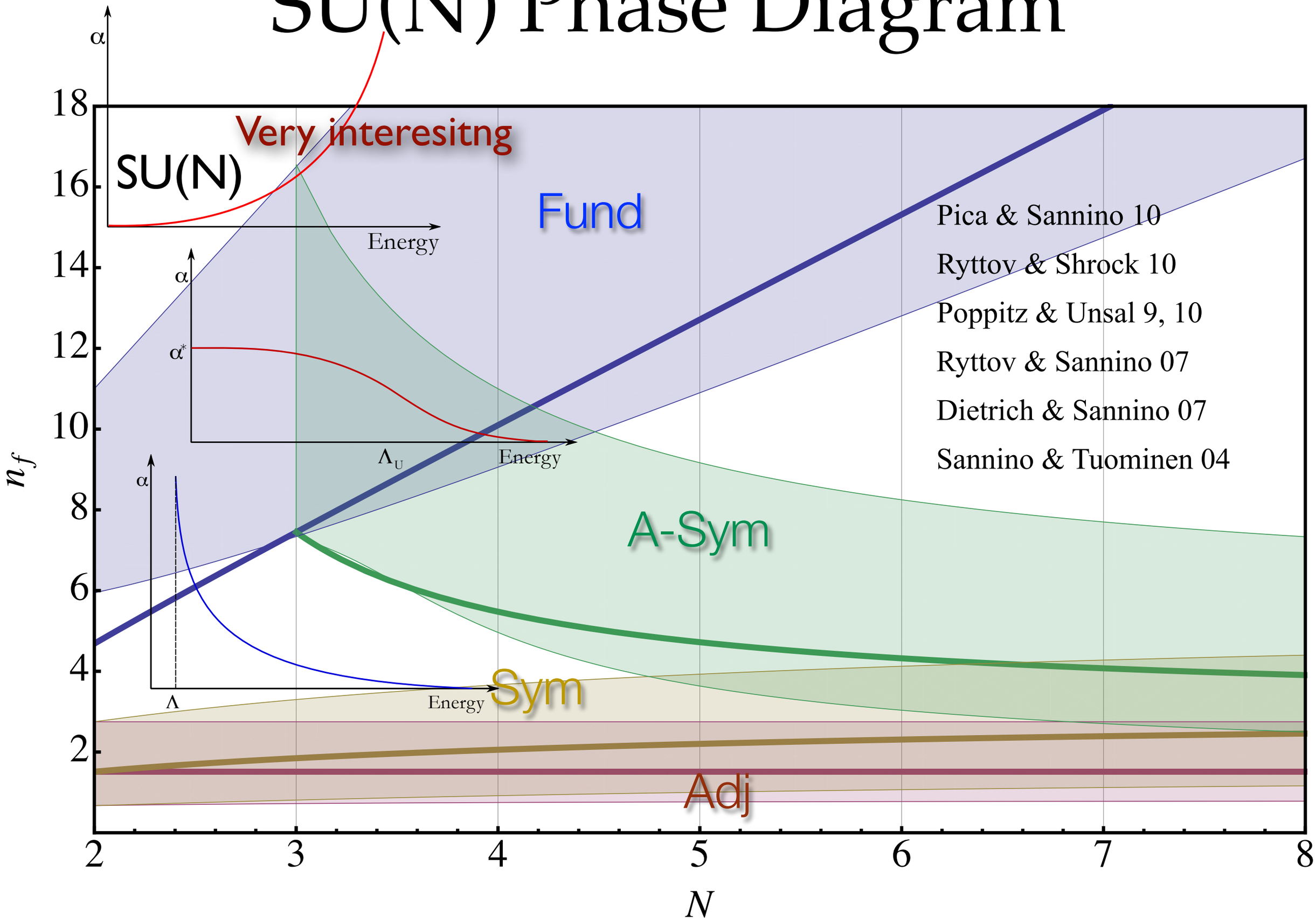




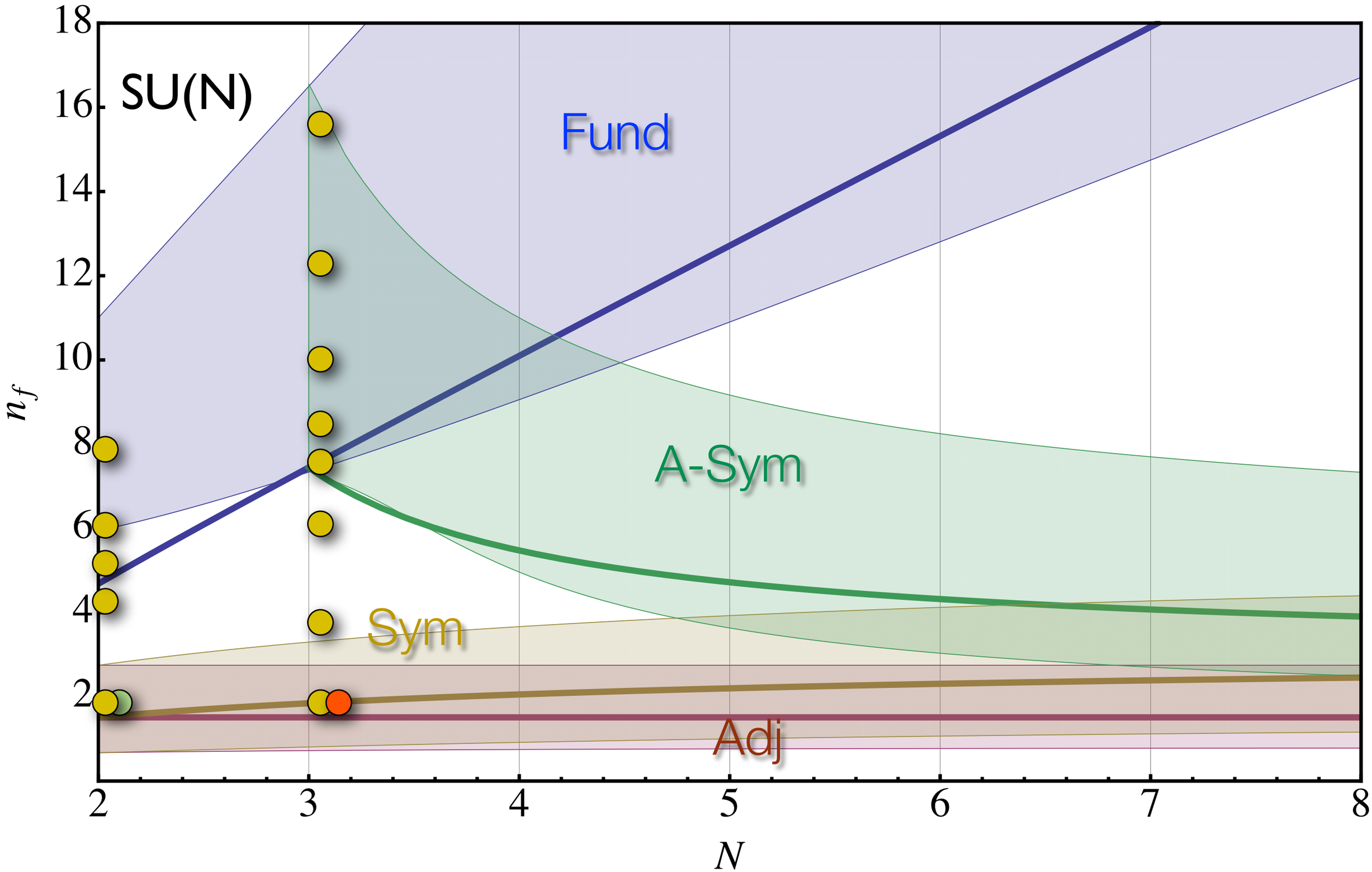
$$\alpha_{UV} = \frac{3\pi}{T_F N_f}$$

Universal Picture

SU(N) Phase Diagram



Lattice SU(N) Diagram



SO(N)

Sannino 09

Pica & Sannino 10

SO(2n+2)

Mojaza, Pica, Ryttov Sannino 12

Ladder

Four Loops $\gamma^*=1$

All Orders $\gamma^*=1$

SO(2n+1)

Mojaza, Pica, Ryttov Sannino 12

Ladder

Four Loops $\gamma^*=1$

All Orders $\gamma^*=1$

n_f

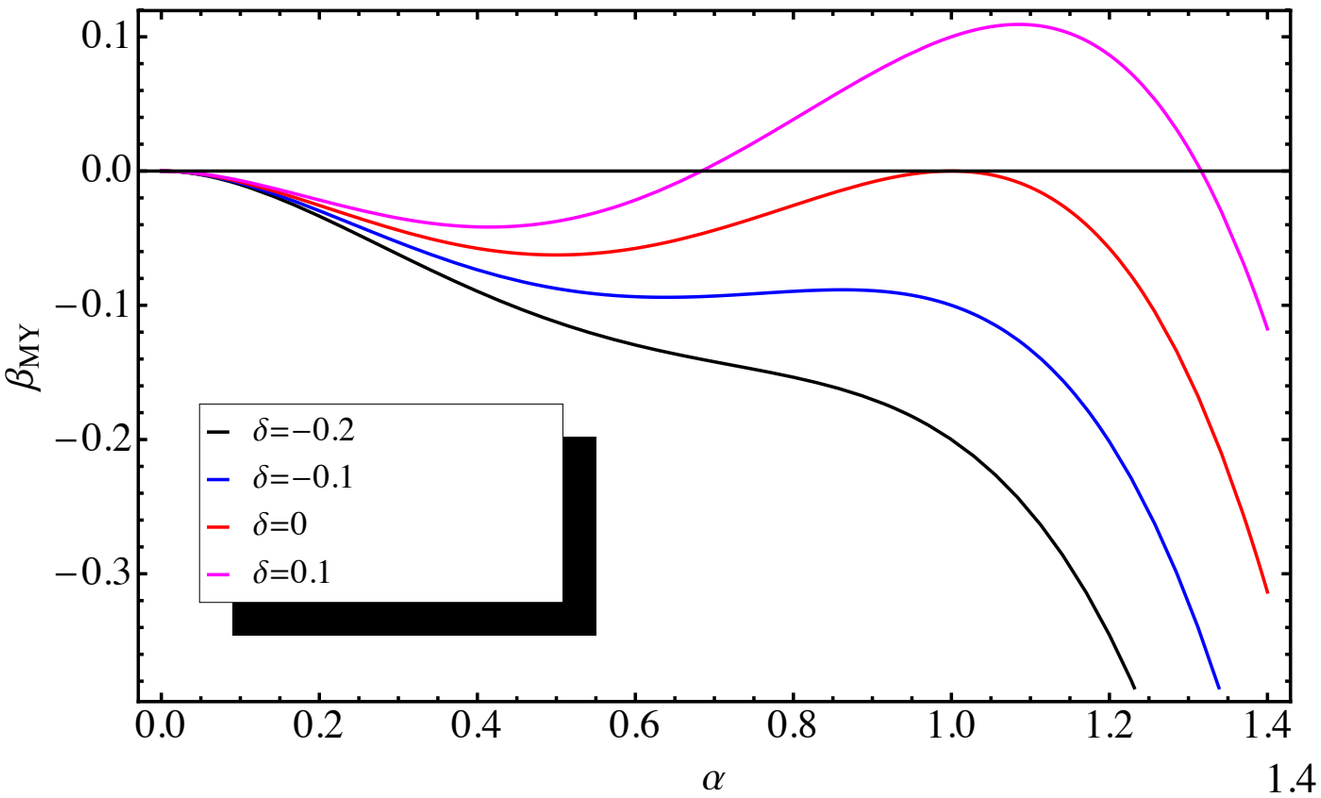
G_2 F_4 E_6 E_7 E_8 / Ad

Mojaza, Pica, Ryttov Sannino 12

Exceptional

Walk or Jump ?

Walking



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

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

Sannino 2012

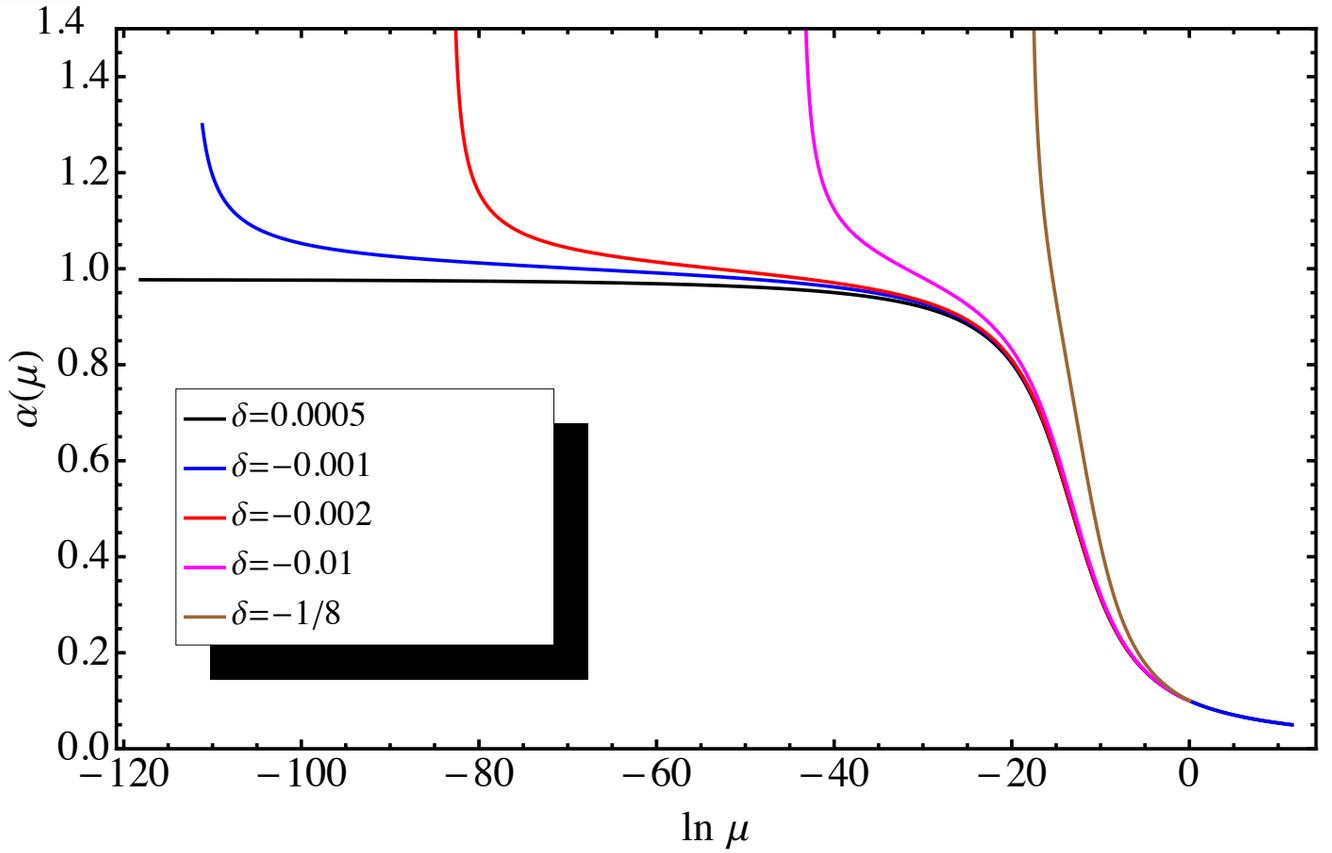
Miransky 85

Miransky & Yamawaki 89

Miransky & Yamawaki 97

Yamawaki, Bando, Matumoto 86

Appelquist, Karabali, Wijewardhana 86

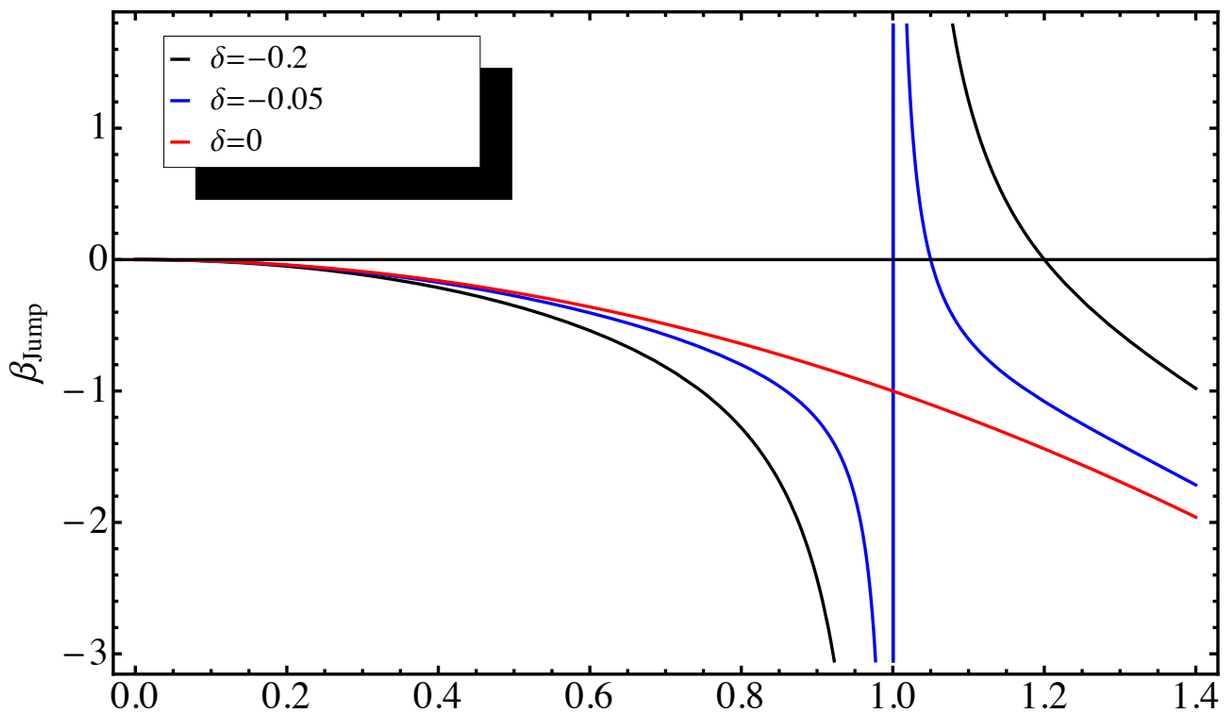


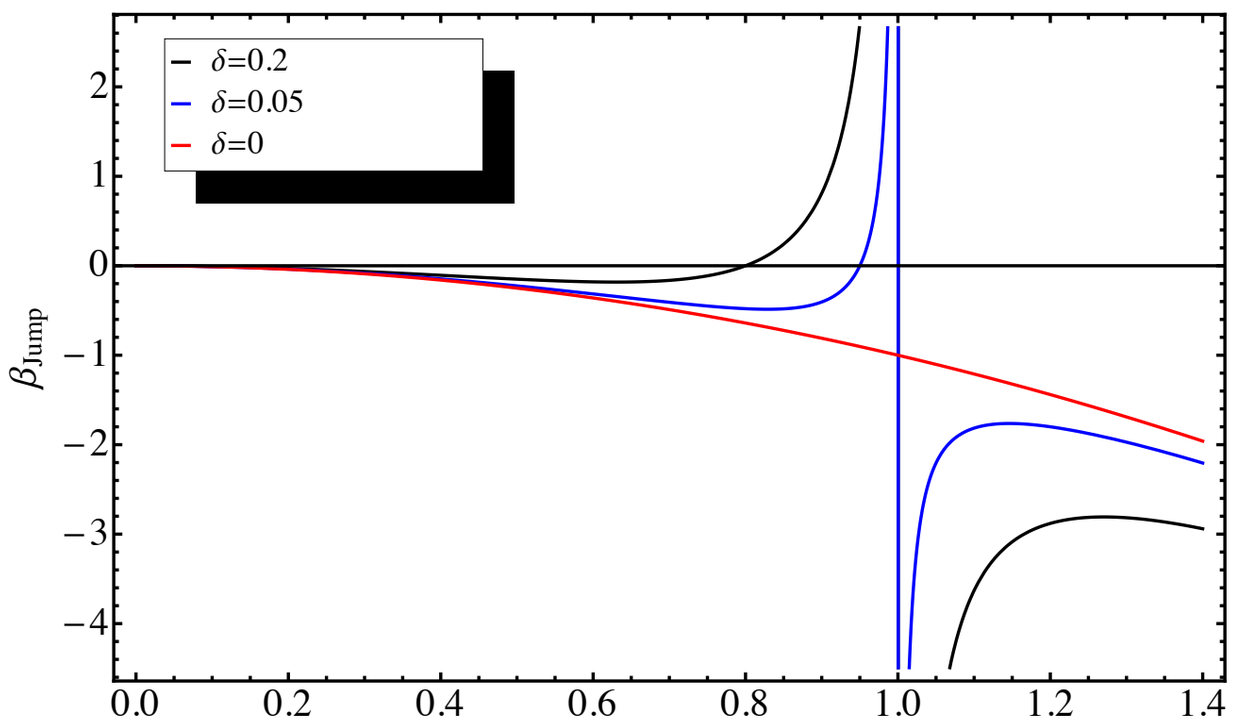
Condensate Enhancement

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

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

Jumping



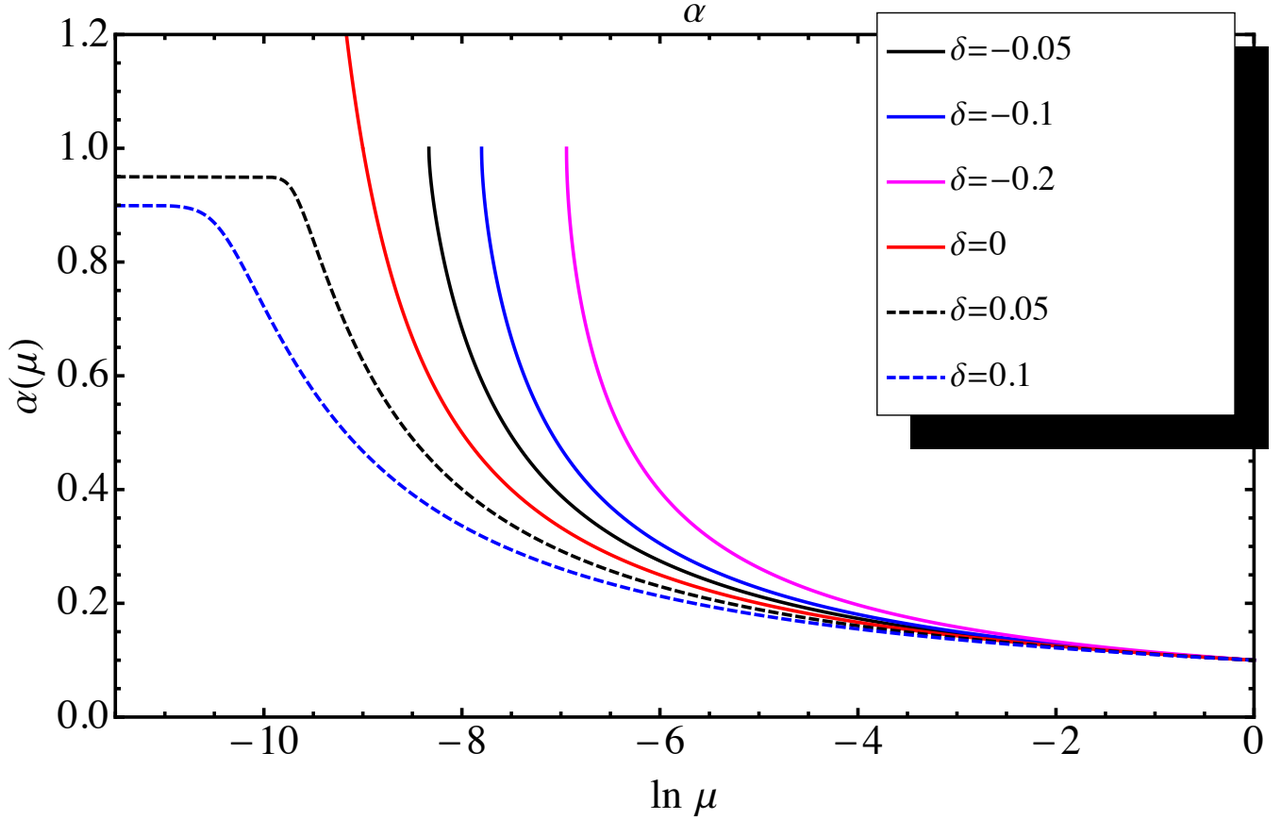


$$\beta_{Jump} = -\alpha^2 \frac{1-\delta-\alpha}{1-\alpha}$$

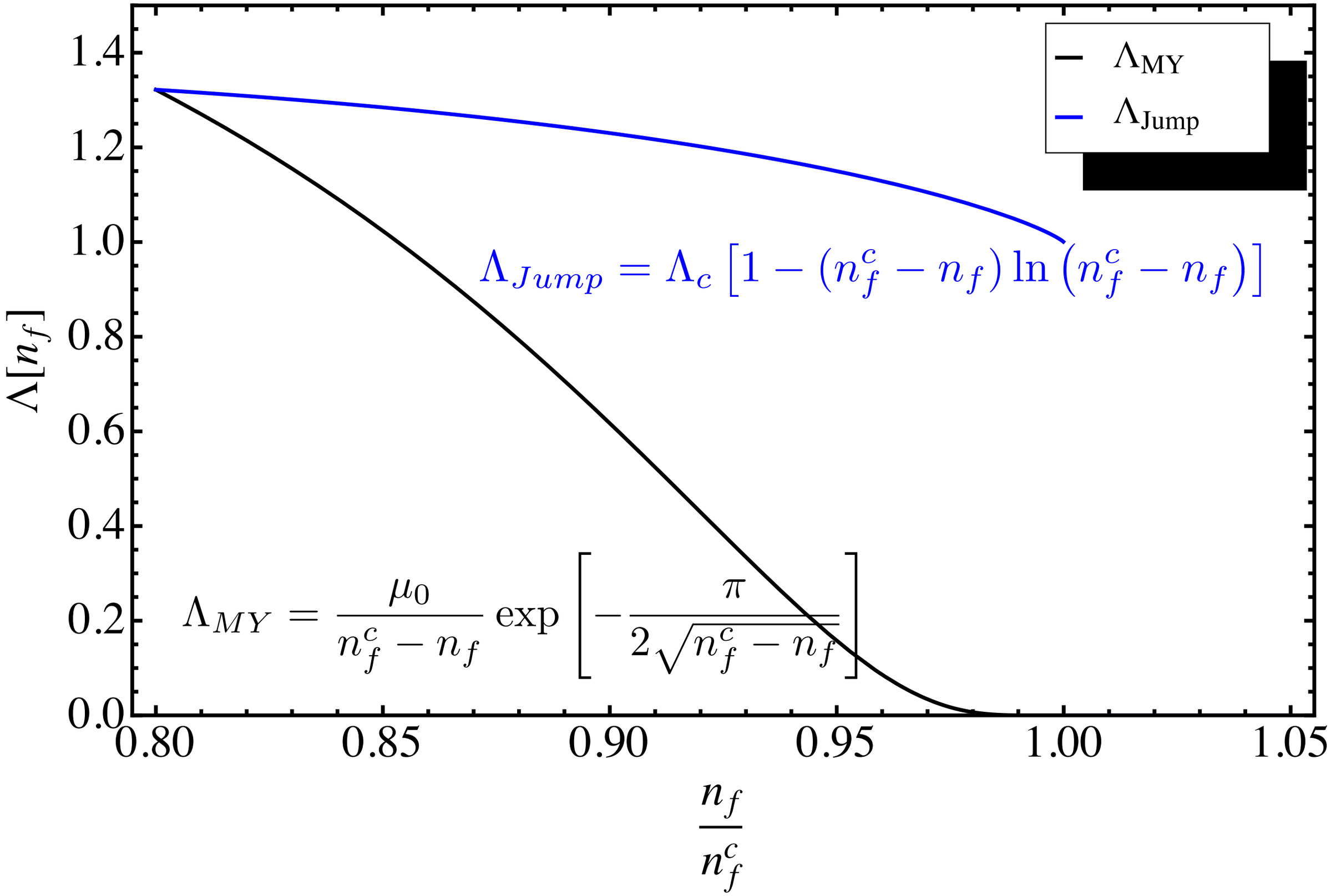
$$\delta = n_f - n_f^c$$

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

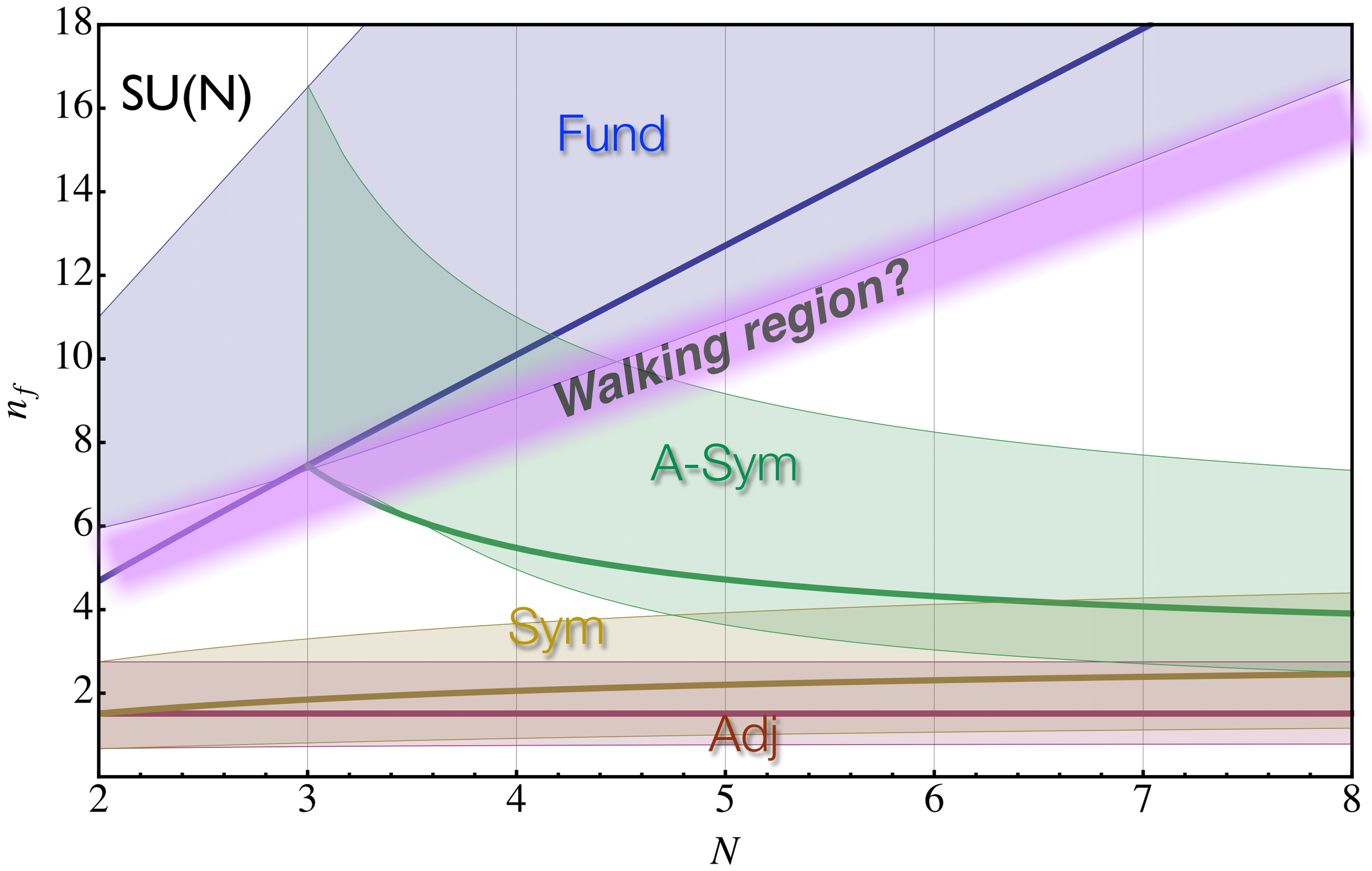
Sannino 2012



Walking or Jumping?



SU(N) Phase Diagram



Calculable 4D Walking Example

Antipin, Di Chiara, Mojaza, Mølgaard, Sannino 1205.6157

Grinstein, Uttayarat 1105.2370
Antipin, Mojaza, Sannino 1107.2932

Walking 4D Gauge theory

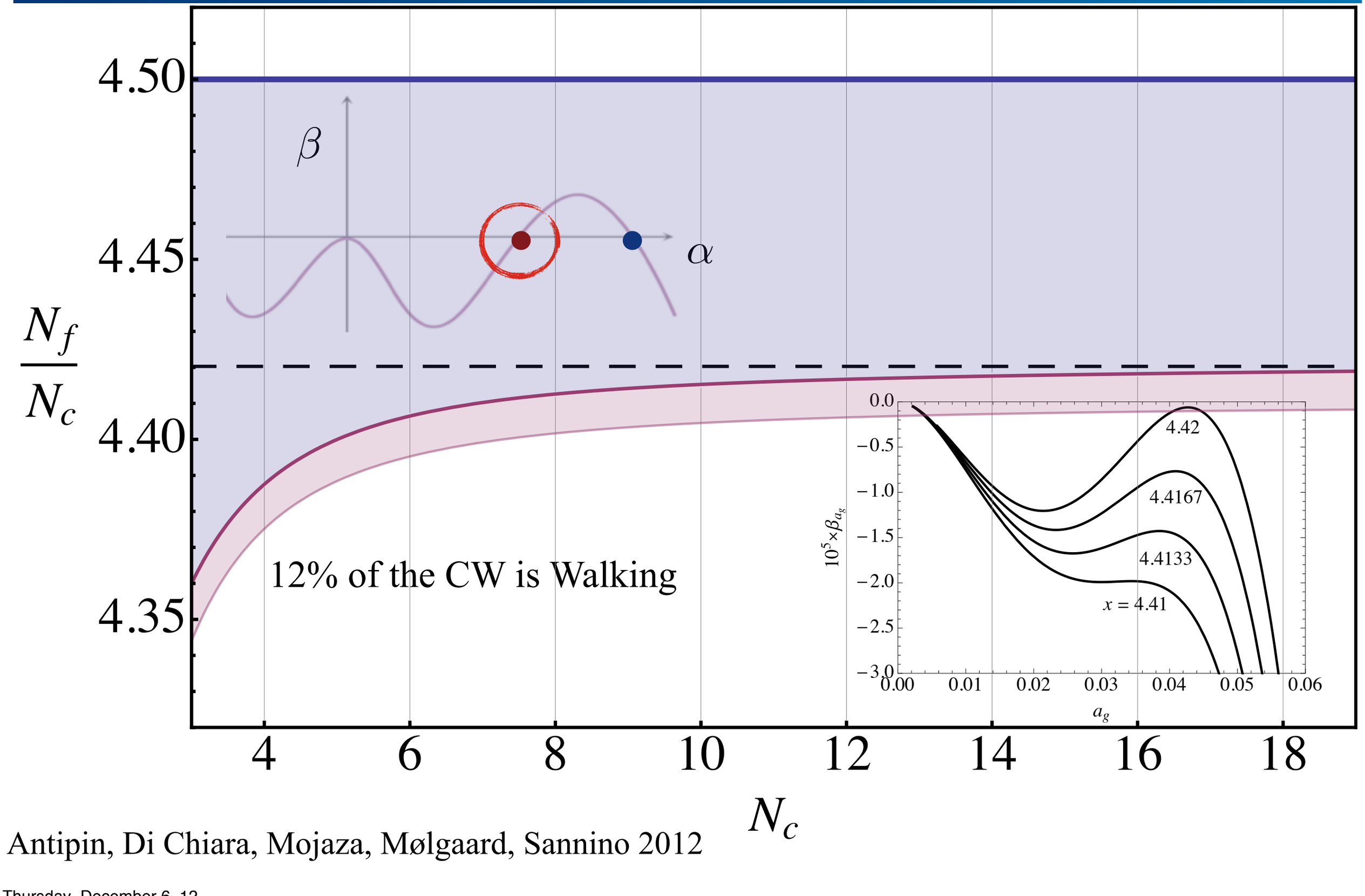
$$Tr\left[-\frac{1}{2}F^{\mu\nu}F_{\mu\nu} + i\bar{\lambda}\not{D}\lambda + \overline{Q}i\not{D}Q + \partial_\mu H^\dagger \partial^\mu H + y_H \overline{Q} H Q\right]$$

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

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

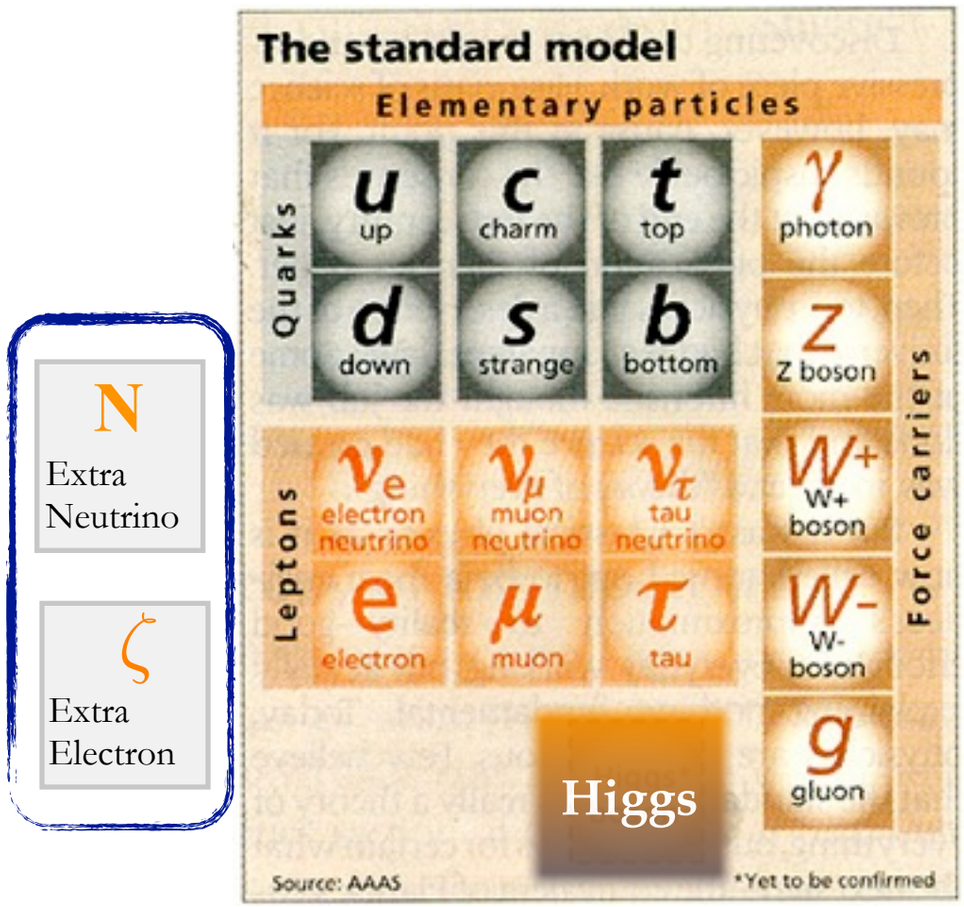


Antipin, Di Chiara, Mojaza, Mølgaard, Sannino 2012

A Minimal TC template

Since 2004 - Minimal WTC is Higgsfull

[Original Name: Light Composite Higgs]



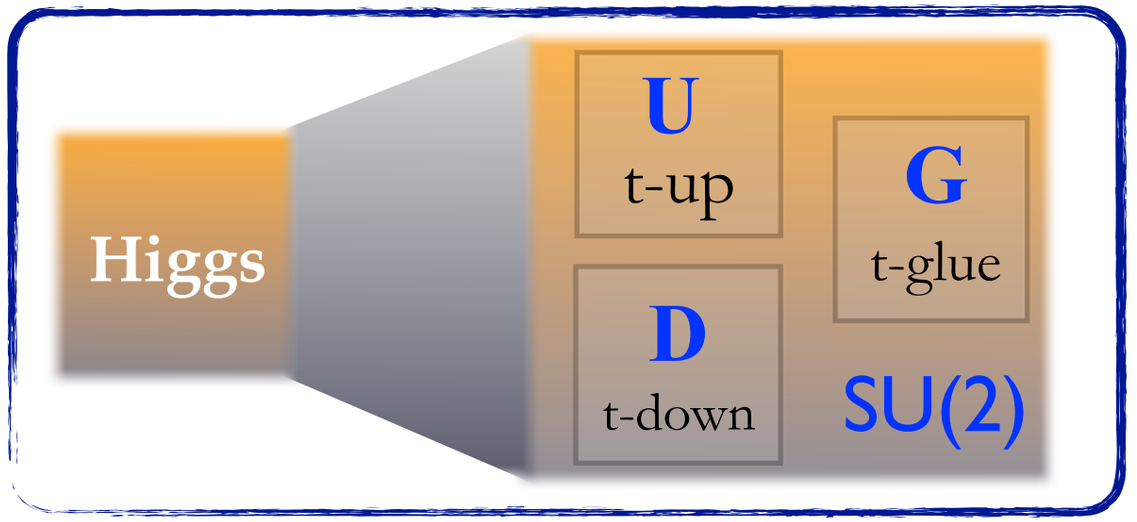
N
Extra Neutrino

ζ
Extra Electron

Sannino, Tuominen 04

Hong, Hsu, Sannino 04

Dietrich, Sannino, Tuominen 05



U(1)

SU(2)

SU(3)

- Can feature Light TC/Dilaton Higgs
- Smallest S-parameter & FCNC
- Dark matter candidates

Being analyzed by ATLAS & CMS

TC Higgs

TC - Higgs is the lightest spin-0 scalar made of TC-fermions

$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}Q\bar{Q}Q + \cdots$$

Will contain also a techniglue component

QCD lightest scalar is $f_0(500)$ with mass ~ 400-550 MeV

Sannino & Schechter 95 PRD [‘t Hooft 1/N, crossing, chiral, pole mass]
Harada, Sannino & Schechter 95 PRD [$f_0(980)$], 96PRL
Pelaez - Confinement X - lecture

Higgs Effective Theory

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\overline{\rm SM}} + \left(1 + \frac{2r_\pi}{v}H + \frac{s_\pi}{v^2}H^2\right)\frac{v^2}{4}\mathrm{Tr}\; D_\mu U^\dagger D^\mu U + \frac{1}{2}\,\partial_\mu H\;\partial^\mu H \\
&- m_t\left(1+\frac{r_t}{v}H\right)\left[\overline{q}_L\; U\;\left(\frac{1}{2}+T^3\right)\;q_R + \mathrm{h.c.}\right] \\
&- m_b\left(1+\frac{r_b}{v}H\right)\left[\overline{q}_L\; U\;\left(\frac{1}{2}-T^3\right)\;q_R + \mathrm{h.c.}\right] + \cdots \\
&- \Delta S\; W^a_{\mu\nu}B^{\mu\nu}\;\mathrm{Tr}\; T^a U T^3 U^\dagger + \mathcal{O}\left(\frac{1}{M_\rho}\right) \qquad\qquad q \equiv (t,b)
\end{aligned}
$$

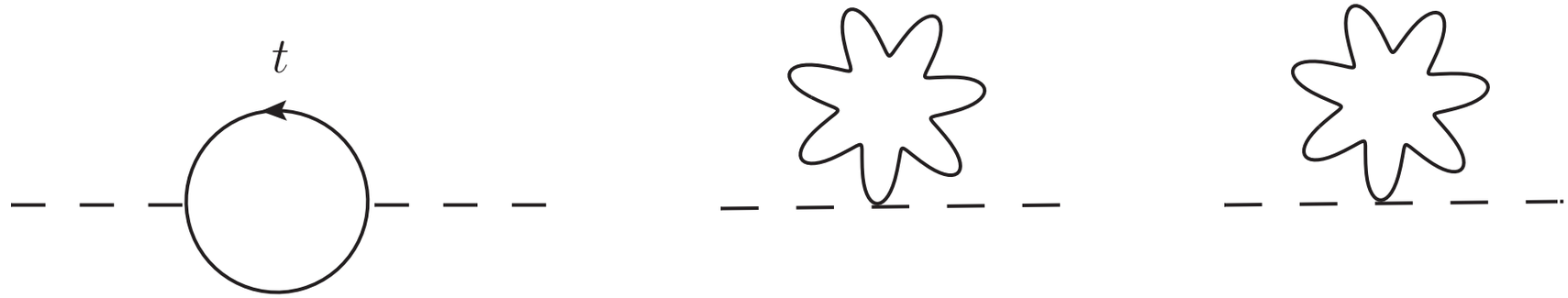
$$U = \exp\left(i\pi^a T^a/v\right) \qquad\qquad v \simeq 246\ \mathrm{GeV}$$

$$D_\mu U \equiv \partial_\mu U - igW^a_\mu T^a U + ig' U B_\mu T^3$$

EW - corrections

$$\mathcal{L}_H \supset \frac{2\, m_W^2\, r_\pi}{v}\, H\, W_\mu^+\, W^{-\mu} + \frac{m_Z^2\, r_\pi}{v}\, H\, Z_\mu\, Z^\mu - \frac{m_t\, r_t}{v}\, H\, \bar{t}\, t$$

$$+ \frac{m_W^2\, s_\pi}{v^2}\, H^2\, W_\mu^+\, W^{-\mu} + \frac{m_Z^2\, s_\pi}{2\, v^2}\, H^2\, Z_\mu\, Z^\mu$$



$$M_H^2 = (M_H^{\rm TC})^2 + \frac{3(4\pi\kappa F_\Pi)^2}{16\pi^2 v^2}\left[-4r_t^2 m_t^2 + 2s_\pi\left(m_W^2 + \frac{m_Z^2}{2}\right)\right] + \Delta_{M_H^2}(4\pi\kappa F_\Pi)$$

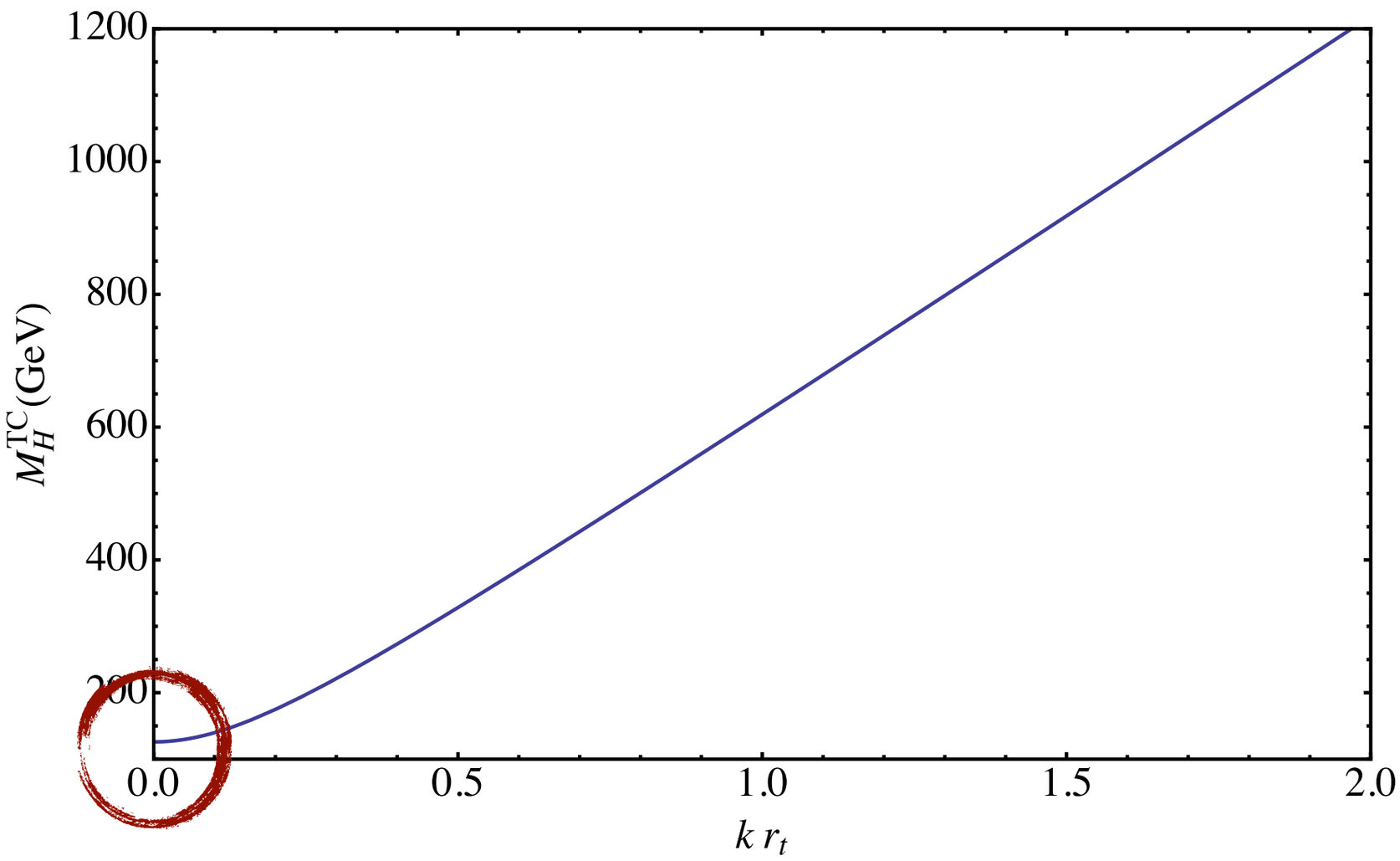
Foadi, Frandsen, Sannino, 12

How light is the TC-Higgs ?

$$(M_H^{\rm TC})^2 \simeq M_H^2 + 12\ \kappa^2 r_t^2 m_t^2$$

$k\ r_t \sim$ TC x ETC

$$F_\Pi = v$$



Not too light!

Geometric not too light **TC** Higgs

Modify underlying gauge geometric structure

Change # of TC-colors, matter repr., EW doublets

By geometric scaling QCD $f_0(500)$ to EW we have

$$M_H^{TC} \simeq 1.8 \frac{1}{\sqrt{N_D d(R_{TC})}} \text{ TeV}$$

$$d(2 - \text{index}_{TC}) = N_{TC} \frac{N_{TC} \pm 1}{2}$$

Physical Higgs mass via gauge geometry

Sannino 08

Sannino & Schechter 07

Foadi, Frandsen, Sannino 12

Minimal TC states to discover

Higgs - like

TC Axial - Vector States

$$H \quad R_{1,2}$$

Beyond minimal: (E)TC model dependent

TC pions

TC composite fermions

Elementary Leptons

Unexpected .....

$$\Pi \quad \Psi \quad L \quad U$$

LHC Search **Strategy**

- Indirect hint of heavy states
  - Modified Higgs couplings wrt SM
  - Study Higgs in association with W/Z
- Direct discovery of heavy states
  - Drell-Yan production of TC-rho/axial
  - (exotic) pions
  - composite fermions
  - 4th heavy lepton family

Higgs to γγ

Sensitive TC-fermion content

$$\Gamma(H \to \gamma\gamma) \sim \left(r_t - 7 r_W + \frac{3}{4} \sum_{Q_{\rm TC}} d(R_{\rm TC}) e_{\rm TC}^2 \right)^2$$

and to the H-tt coupling r_t (Extended TC)

$$pp \to H \sim r_t^2$$

H to $\gamma\gamma$ can help discriminate different models

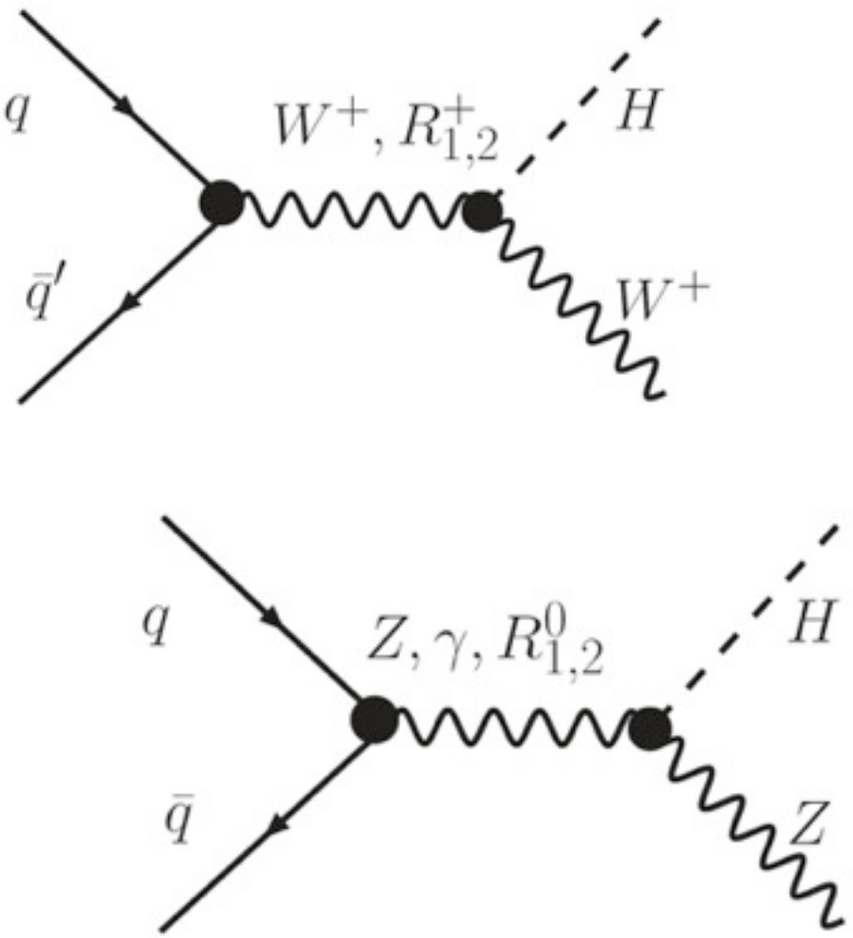
$$\mathcal{L}_H \supset \frac{2\ m_W^2\ r_W}{v}\ H\ W_\mu^+\ W^{-\mu} - \frac{m_t\ r_t}{v}\ H\ \bar{t}\ t$$

Associate production

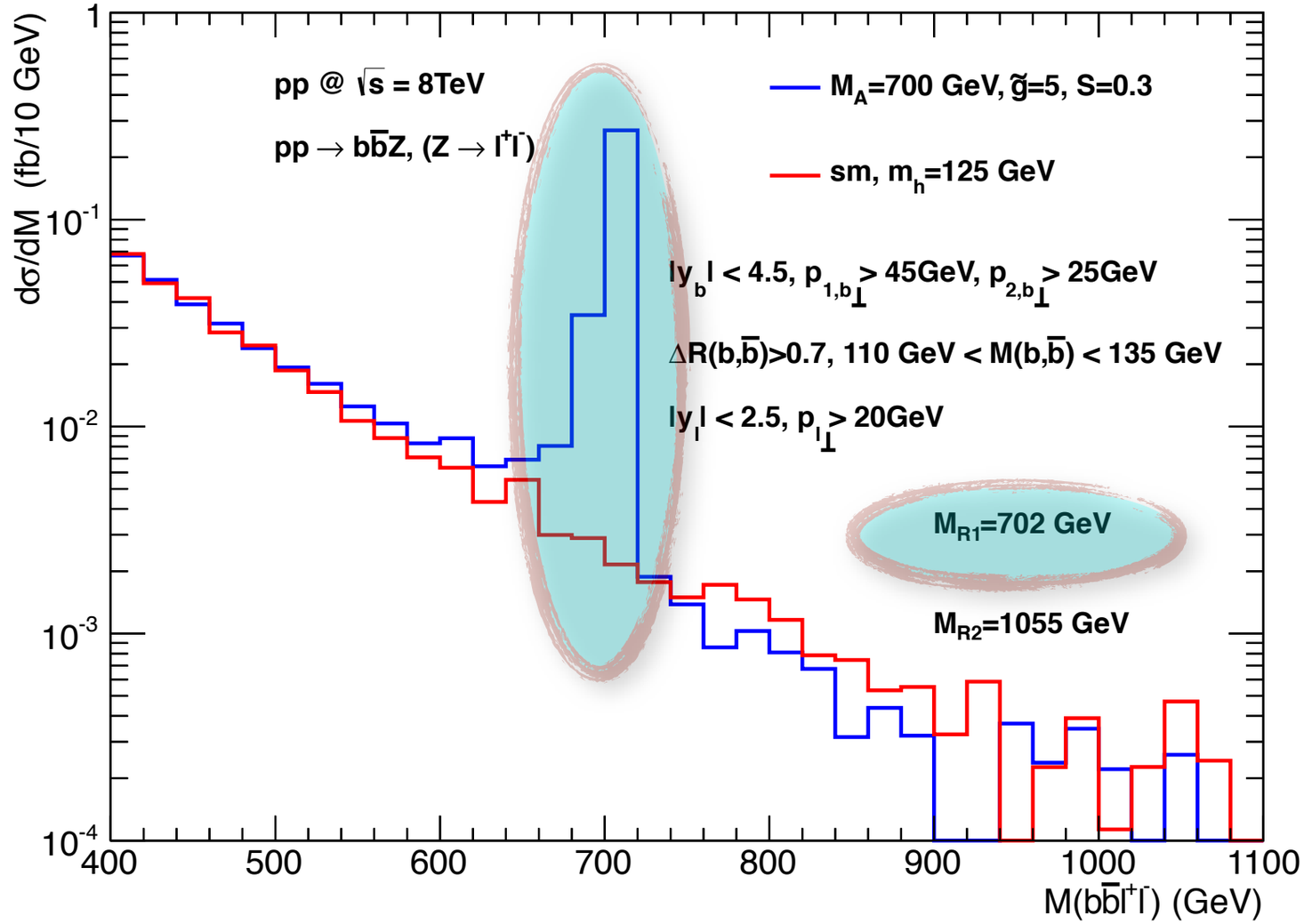
Potential discovery of composite dynamics at the LHC

Composite spin-1 mesons like QCD ϱ & a_1

Belyaev, Foadi, Frandsen, Jarvinen & Sannino 08



$$pp \to HZ^{\pm} \to \bar{b}b + 2\ell$$



Preliminary MWTC - theoretical updated analysis by T. Hapola

Conclusions

- Discovered the TC Higgs?
- New phase diagrams
- Walking & jumping
- 125 Higgs via a heavy TC Higgs!
- Minimal TC & LHC signatures
- New era for strong dynamics

Lots of fun ahead !