Unified Approach to Composite Higgs Phenomenology

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CP3 - Origins
Particle Physics & Cosmology

DIAS DANISH INSTITUTE FOR ADVANCED STUDY

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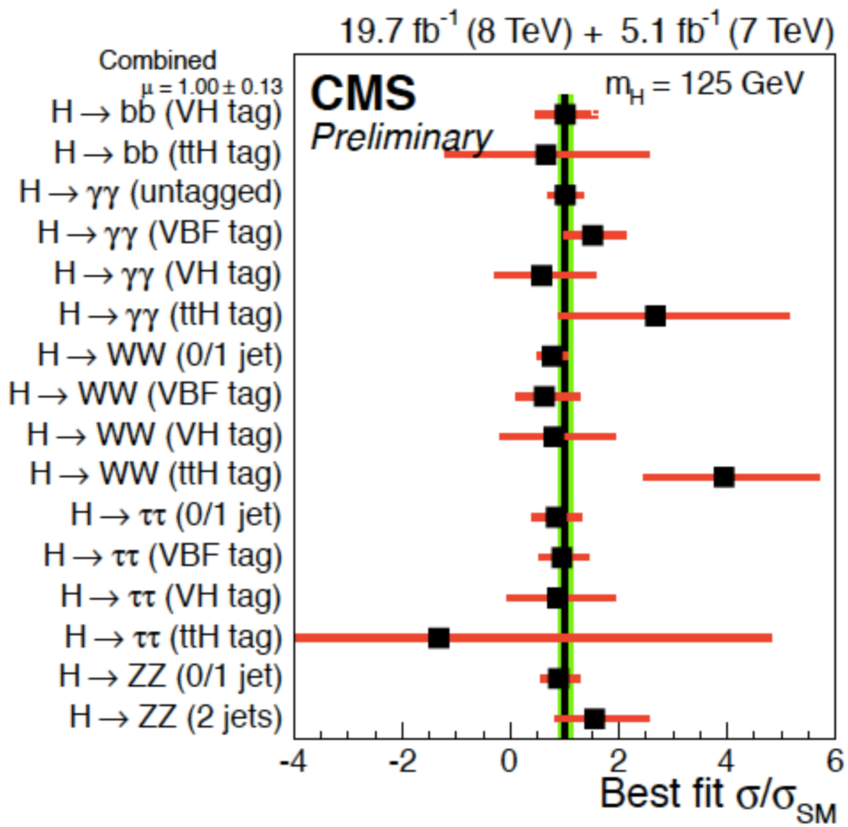
LHC Higgs Searches as of 2014



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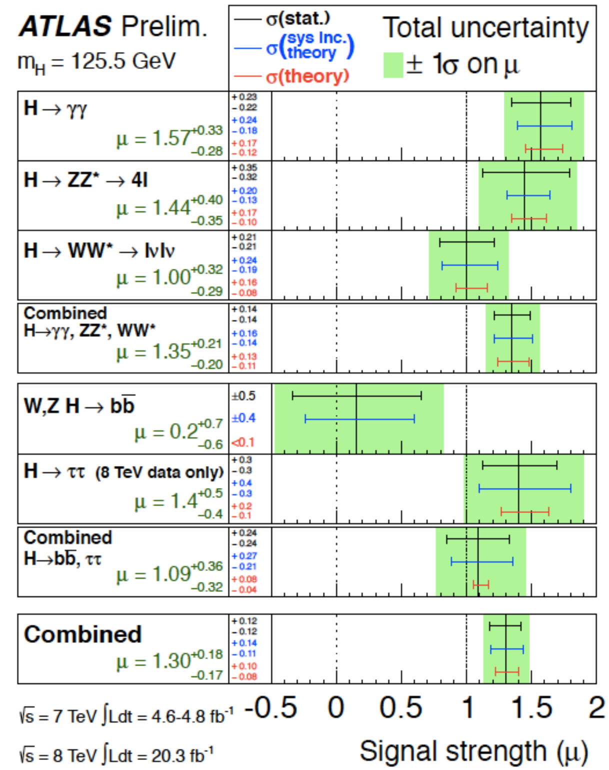
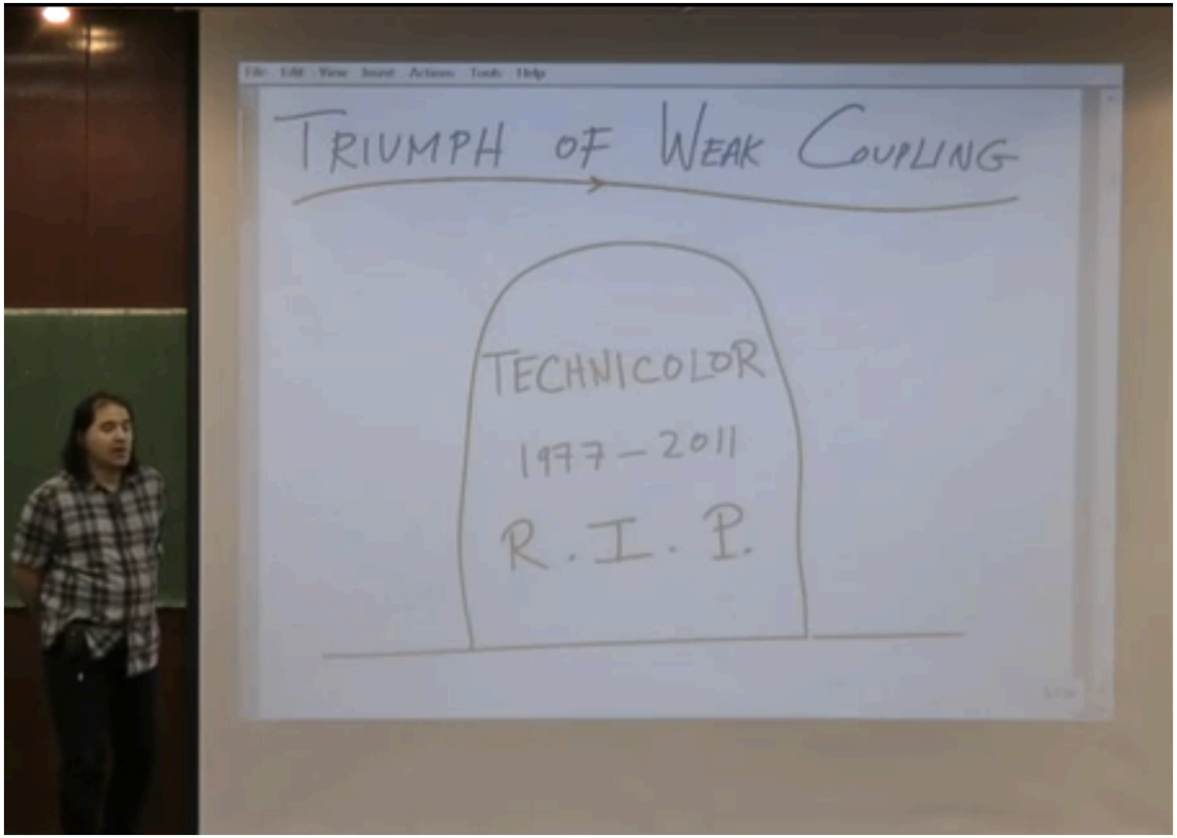


ATLAS-CONF-2014-009

Implications?



The Standard Model

- SM Higgs does not *explain* EWSB
- SM Higgs does not *explain* fermion masses
- SM provides no DM candidate
- etc…

Two time-honoured extensions

- New Strong Dynamics
  - QCD is Strongly Natural -

    Naturalness in Dirac's sense, i.e. no small numbers

- Supersymmetry
  - Susy makes the Higgs technically natural –
    Naturalness in 't hooft's sense, small input numbers symmetry protected

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- Susy makes the Higgs technically natural –
  Naturalness in ’t hooft’s sense, small input numbers symmetry protected (although ’t Hooft had QED and TC in mind)

Two time-honoured extensions

- New Strong Dynamics
  - Expect new states at $4\pi\, f_{strong}$?

- Supersymmetry
  - Expect new states below v_{EW}?

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  - Atleast one state needs to be quite a bit lighter…*known since LEP!*

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  - Nature requires SUSY heavy (and fine-tuned?) since LEP

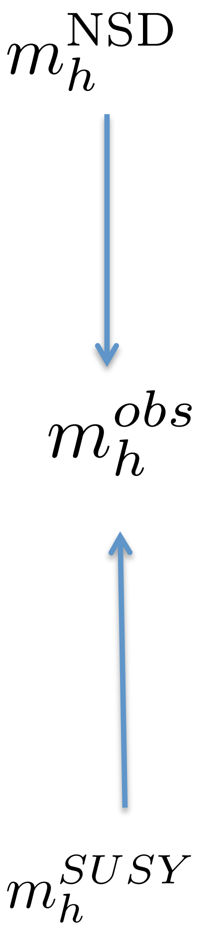
Two time-honoured extensions

▪ New Strong Dynamics

- Expect new states at $4\pi f_{Strong}$?
- Atleast one state needs to be quite a bit lighter…*known since LEP!*
- Finding a light scalar did not change established picture *that* much…

▪ Supersymmetry

- Expect new states below v_{EW}?
- Nature likes SUSY heavy (and fine-tuned?) since LEP



New Strong Dynamics

m_σ^{TC}

- The Technicolor Composite Higgs
  - 'Higgs' is the lightest scalar isospin-0 resonance of strong dynamics
  - Compare with the f_0 (500) in QCD

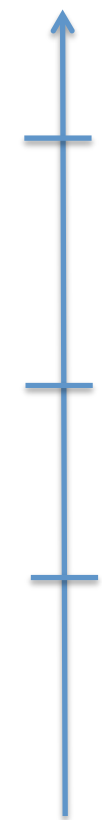
m_h^{obs}

- The *Composite Higgs* Composite Higgs
  - The Higgs doublet arises as goldstone bosons of global symmetry breaking
  - Electroweak symmetry breaks through vacuum misalignment

$m_h^{\rm CH}$

New Strong Dynamics

$$f_{\text{strong}}$$



- 'Composite Higgs Models' $\quad v_{\text{EW}} = \sin(\theta) f_{\text{strong}}$

- Minimal Technicolor (one weak doublet) $\quad v_{\text{EW}} = f_{\text{strong}}$

- Non Minimal Technicolor $\quad v_{\text{EW}} = \sqrt{N_D} f_{\text{strong}}$

Decoupling

f_{strong}

- 'Composite Higgs Models'
  Decoupling, though fine tuned

$$v_{\text{EW}} = \sin(\theta) f_{\text{strong}}$$

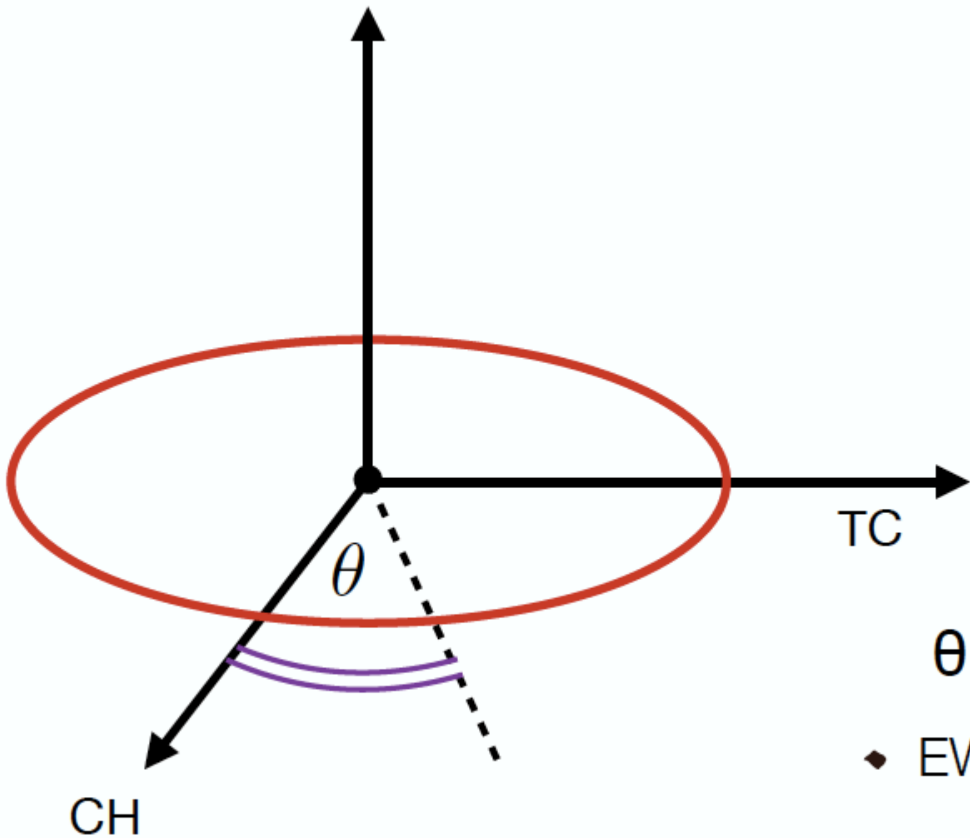
- Minimal Technicolor (one weak doublet)
  No decoupling

$$v_{\text{EW}} = f_{\text{strong}}$$

$$v_{\text{EW}} = \sqrt{N_D} f_{\text{strong}}$$

Technicolor vs Composite Higgs

(Galloway, Evans, Tacchi & Luty ’10
G. Cacciapaglia & F. Sannino ’14)



$\theta = 0$

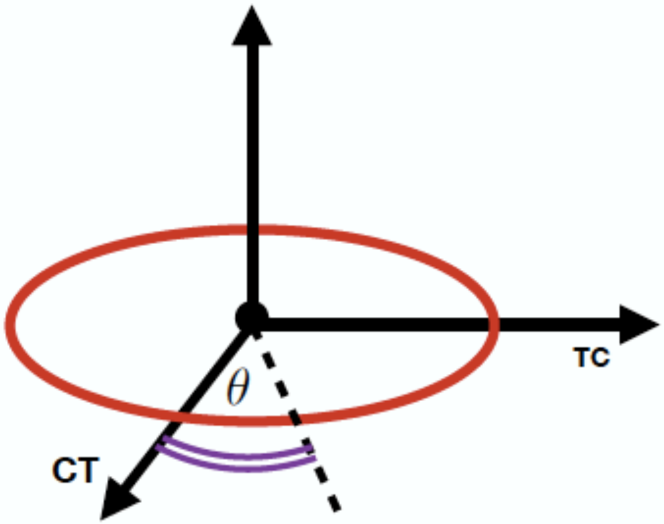
- EW does not break
- Higgs is exact GB

$\theta = \pi/2$

- EW breaks
- Higgs is massive excitation

Vacuum fixed by ‘external’ effects

- Gauge bosons quantum corrections
- Top corrections
- Explicit breaking of global symmetry



New Strong Dynamics

f_{strong}

- 'Composite Higgs Models' $\quad v_{\text{EW}} = \sin(\theta) f_{\text{strong}}$
- Minimal Technicolor (one weak doublet) $\quad v_{\text{EW}} = f_{\text{strong}}$
- Non Minimal Technicolor $\quad v_{\text{EW}} = \sqrt{N_D} f_{\text{strong}}$
- Preons – fermions are composite
- Duality – SM as a 'magnetic dual'
- …

Asymmetric DM from Strong Dynamics

The asymmetric part of DM relic density is simply related to the baryon asymmetry:

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm baryon}} = \frac{m_{\rm DM}}{m_{\rm baryon}} \frac{\eta_{\rm DM}}{\eta_{\rm baryon}}$$

- Strong dynamics provides global stabilizing symmetries, compare baryon number
- Provides, often though not always, large annihilation cross-sections

Does DM arise from new strong dynamics?

New Strong Dynamics

- New strongly interacting gauge group G_{TC}
- New (techni)fermions,
- Vector-like under G_{TC}
- Chiral under G_{EW}
- Fermions condense and break G_{EW} - Technicolor
- *Basic* idea modelled on QCD
- Strongly natural EWSB

New Strong Sector

1. The SM gauge group is augmented:

$$G_{SM} \to SU(3)_{\rm c} \times SU(2)_{\rm W} \times U(1)_{\rm Y} \times G_{\rm SD} \ .$$

(SD=Strong Dynamics/Technicolor)

2. The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \to -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\rm L} \gamma_\mu D^\mu Q_{\rm L} + i\bar{Q}_{\rm R} \gamma_\mu D^\mu Q_{\rm R} + \ldots$$

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \sim F_\Pi^3 \to M_W = \frac{gF_\pi}{2}$$

Minimal chiral symmetries: 3 GB's + Custodial + DM.

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \ .$$

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$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \; .$$

Minimal fermion content:
2 Dirac technifermions in a weak doublet,
TC charge but no QCD charges

$$Q^a_L = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \quad Q^a_R = (U^a_R, D^a_R),$$
$$a = 1, \ldots d(\mathcal{R}_{TC})$$

New Strong Dynamics

- Composite Higgs has decoupling limit
  – not falsifiable without new discoveries
- Technicolor has no decoupling limit
  – falsifiable, except via the 'Composite Higgs limit'

- Both scenarios unified if underlying 4d theories are available

- Interesting to clarify if TC is really ruled out by Higgs discovery
  – If TeV resonances were discovered would point to TC

Light scalar in QCD

- Lightest non-GB resonance in QCD is $f_0(500)$ (σ)

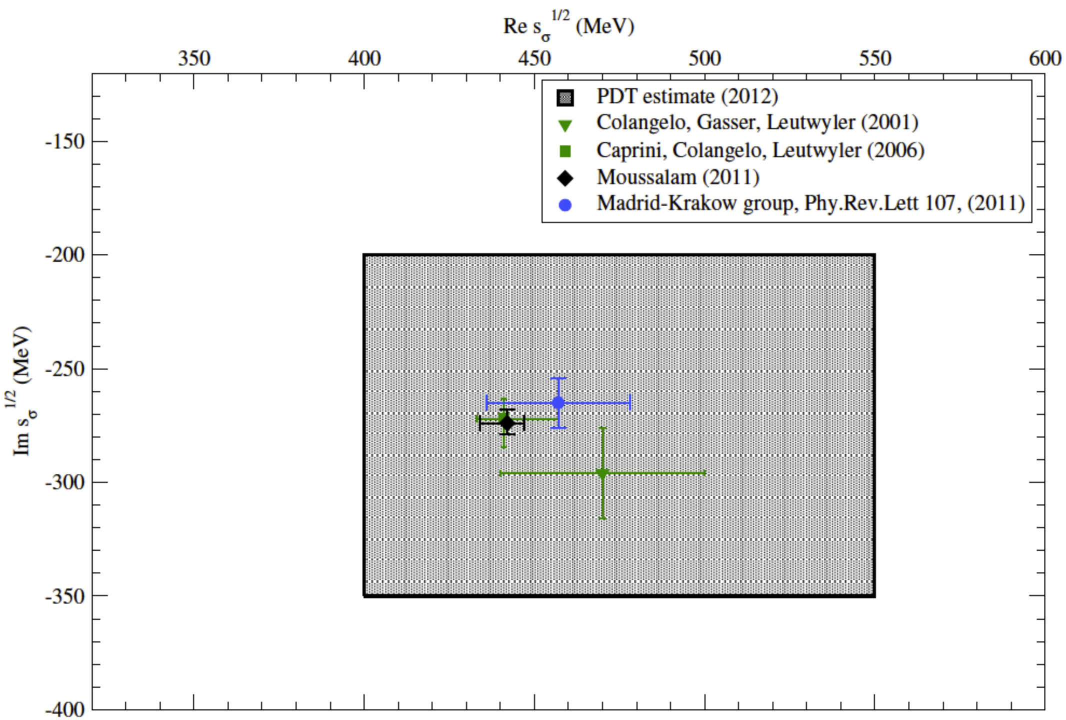
$$\sqrt{s_\sigma} = m_\sigma - i\Gamma_\sigma/2$$

m_σ=400-550 MeV,
Γ_σ=400-700 MeV

(PDG 2012)

m_σ=441 MeV,
Γ_σ=544 MeV

(Caprini, Colangelo & Leutwyler ’06)



(Pelaez ’13)

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

Geometry: Scaling up from QCD

$$(M_H^{TC})^2 = \frac{3}{d(R_{\rm TC})} \frac{1}{N_{\rm TD}} \frac{v^2}{f_\pi^2} m_\sigma^2 \ .$$

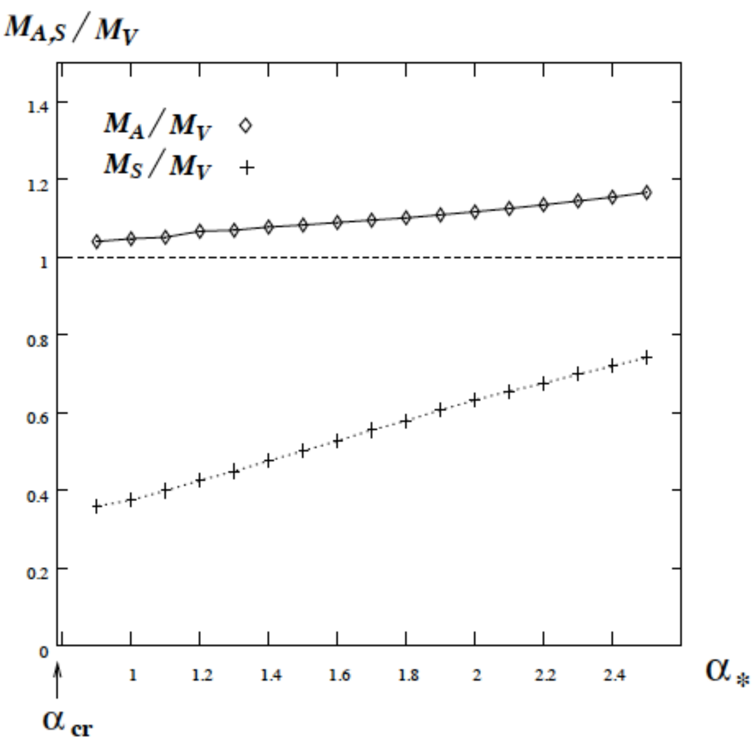
Scalar spectrum in TC

- Trivially the Techni-Higgs can be light with many colors – but conflict with EWPT(?)

$$(M_H^{TC})^2 = \frac{3}{d(R_{\rm TC})} \, \frac{1}{N_{\rm TD}} \, \frac{v^2}{f_\pi^2} \, m_\sigma^2 \ .$$

- Could it be dynamically be light?

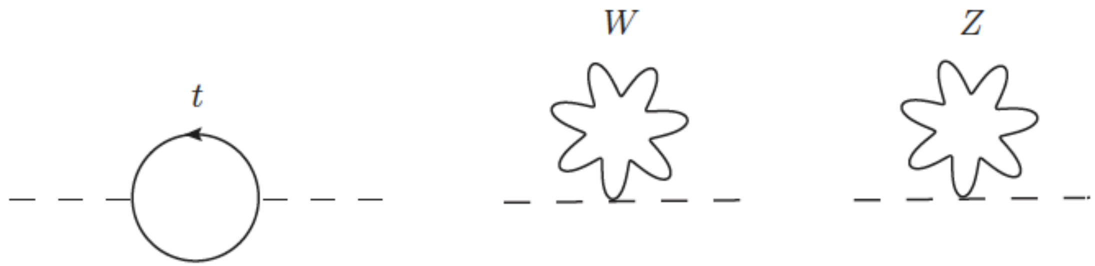
(Sannino & Tuominen ’04; Sanino & Hong ’04;
Dietrich, Sannino & Tuominen ’05
Shrock & Kurachi 06…Appelquist and Bai ’10…)



(Shrock & Kurachi ’06)

EW - corrections

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



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

-> Compare W/Z contribution with pion charge radius

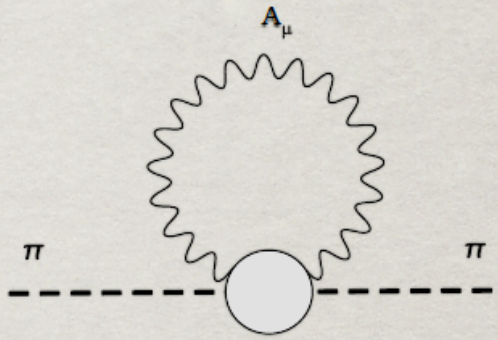
(Foadi, MTF & Sannino '12)

-> In TC contributions are finite due to compositeness

Example: pion mass difference

- EW interactions and Yukawa interactions break the custodial $SU(2)_{V.}$
- EW mass contritution to π^+ proportional to the 'cut-off' m_ρ

The electromagnetic correction
to the pion mass



$$\Delta m_\pi^2 \approx 3 \, \frac{\alpha_{em}}{4\pi} \, m_\rho^2$$

$$m_{\pi^+} - m_{\pi^0} \simeq 5.0\,\mathrm{MeV}$$

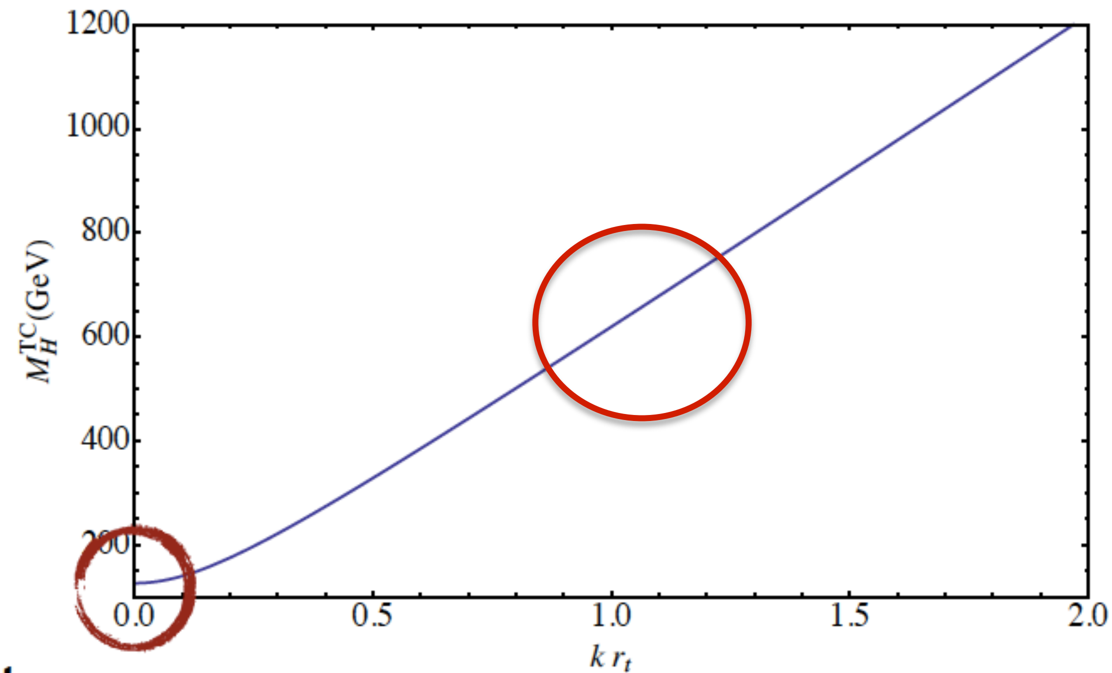
[Das, Guralnik, Mathur, Low, Yang 1967]

Light TC-Higgs from radiative corrections

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

$k\ r_t$ ~ TC x ETC

$$F_\Pi = v$$



Not too light!

(Foadi, MTF & Sannino '12)

Effect correlated with the next TC resonance mass via κ and ETC via r_t

The lightest scalar in QCD

QCD σ-pion interaction Lagrangian

$$\mathcal{L}_{\sigma\pi\pi} = \frac{c_\pi^{\rm QCD}}{f_\pi}\sigma\partial_\mu\pi^a\partial^\mu\pi^a\,, \quad a = 1,2,3,$$

Compare with Higgs-Goldstone boson Lagrangian:

$$\mathcal{L}_{SM} = \frac{m_h^2}{2v}h(h^2 + w_Z^2 + 2w_+w_-) \;= \frac{h}{v}(\partial_\mu w_Z\partial^\mu w_Z + 2\partial_\mu w_+\partial^\mu w_-)$$

From pi-pi scattering data: $c_\pi \sim 1$

(e.g. Harada, Sannino & Schechter ’95; Caprini, Colangelo & Leutwyler ’05; Garcia-Martin et al ’11;)

m_σ (MeV)	$\lvert g_{\sigma\pi\pi}\rvert$ (GeV)	$\lvert c_\pi^{\rm QCD}\rvert$
$457^{+14}_{-13} - i(279^{+11}_{-7})$, [38]	$3.59^{+0.11}_{-0.13}$	1.0169 ± 0.06
$445 \pm 25 - i(278^{+22}_{-18})$, [38]	3.4 ± 0.5	1.0013 ± 0.17
$441^{+16}_{-8} - i(272^{+9}_{-12.5})$ [39]	$3.31^{+0.35}_{-0.15}$	1.0035 ± 0.12
$474 \pm 6 - i(254 \pm 4)$, [40]	3.58 ± 0.03	1.0264 ± 0.024
$443 \pm 2 - i(216 \pm 4)$ [41]	2.97 ± 0.04	1.0479 ± 0.020
$452 \pm 12 - i(260 \pm 15)$ [42]	2.65 ± 0.01	0.8026 ± 0.053
$453 - i271$, [43]	3.5	1.0255

(Belyaev, Brown, Foadi, MTF & Sannino ’13)

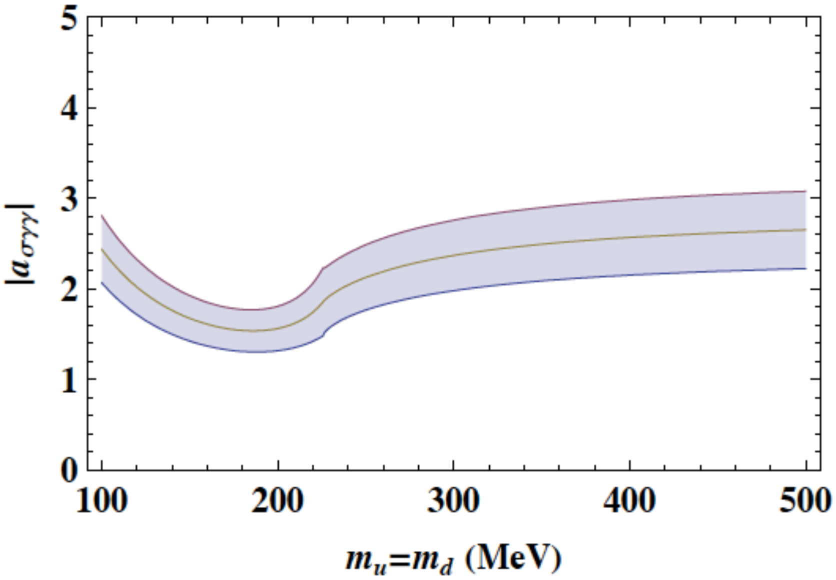
The lightest scalar in QCD

QCD σ-photon model Lagrangian, $a_{\sigma\gamma\gamma}$ composite fudge-factor

$$\Gamma_{\sigma\to\gamma\gamma} = \frac{\alpha^2 \, (\mathrm{Re}\, m_\sigma)^3 \, a_{\sigma\gamma\gamma}^2}{256\pi^3 f_\pi^2} \left| 3\left(\frac{2}{3}\right)^2 F_{1/2}\left(\frac{4m_u^2}{(\mathrm{Re}\, m_\sigma)^2}\right) + 3\left(-\frac{1}{3}\right)^2 F_{1/2}\left(\frac{4m_d^2}{(\mathrm{Re}\, m_\sigma)^2}\right)\right|^2$$

Compare with QCD data:

(Belyaev, Brown, Foadi, MTF & Sannino ’13)



The Techni-Higgs scalar in QCD

Scaled up QCD-like Techni-Higgs would have (diboson) Higgs-like couplings

Coefficient $c_\pi \sim 1$ is independent of number of colors or size of representation

Techni-Higgs photon model Lagrangian

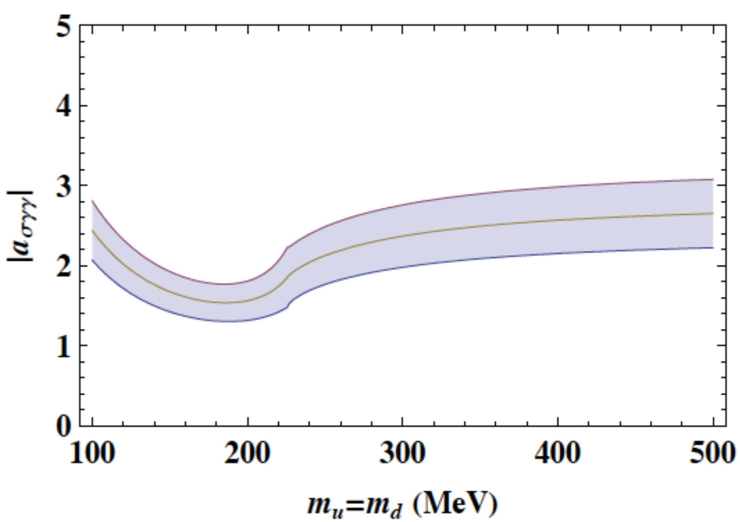
$$g_{H\gamma\gamma}^{\rm TC} = \frac{\alpha}{8\pi}\left| c_\Pi\,[F_1(\tau_W) - 2] + \sum_f c_f\, N_c^f\, Q_f^2\, F_{1/2}(\tau_f) + a_{H\gamma\gamma}\, d(R_{\rm TC}) \sum_F N_c^F\, Q_F^2\, F_{1/2}(\tau_F) \right|$$

The Techni-Higgs scalar in QCD

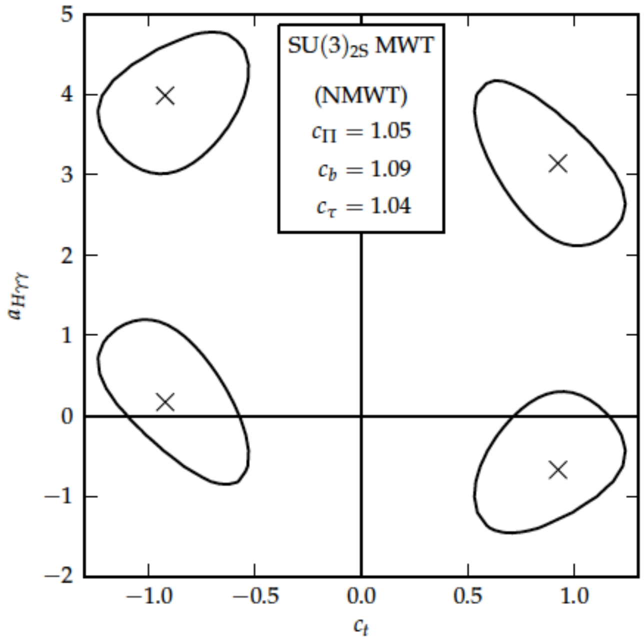
Example fit to LHC Data

$$g_{H\gamma\gamma}^{TC} = \frac{\alpha}{8\pi}\left| c_\Pi\left[F_1(\tau_W) - 2\right] + \sum_f c_f\, N_c^f\, Q_f^2\, F_{1/2}(\tau_f) + a_{H\gamma\gamma}\, d(R_{TC}) \sum_F N_c^F\, Q_F^2\, F_{1/2}(\tau_F)\right|$$

Fit to QCD data



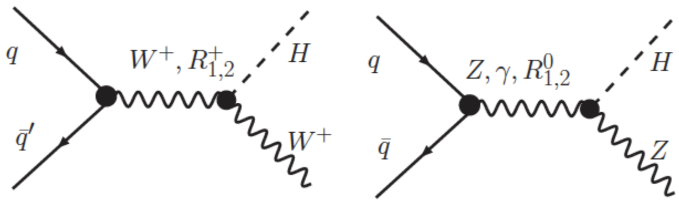
Fit to LHC data



Phenomenology of a light TC Higgs

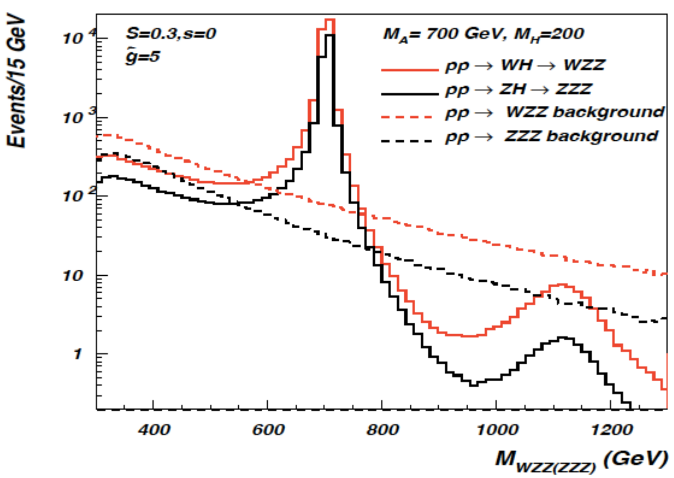
(e.g. A. Belyaev, MTF et al '08, Hapola & Sannino '11; Andersen et al '11; MTF & Sannino '12; Belyaev, Brown, Foadi & MTF)

- Massive vector and fermion couplings can be SM like
- Di-photon decay sensitive to new technifermions
- Resonances coupled to the TC-Higgs

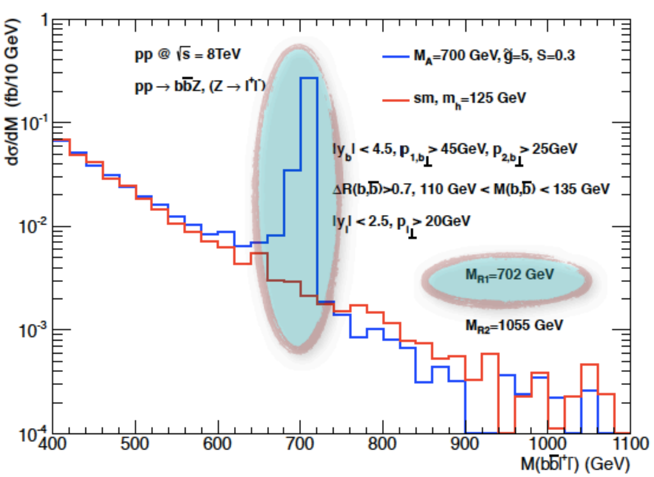


$$pp \to HV \to VVV$$

$$pp \to HZ \to b\bar{b}ll$$



(Belyaev, Foadi, MTF, Jarvinen, Pukhov & Sannino '08)



(T. Hapola preliminary)

Summary: Composite Dynamics

- Technicolor and Composite Higgs are two realizations of *Composite Higgs!* Non-GB vs pNGB

- Studied in a unified manner via vacuum alignment – The Composite Higgs model is a decoupling limit

- The lightest scalar in TC can (perhaps) be SM Higgs-like

- Crucial test is the discovery/non-discovery of new resonances at the (few) TeV from Technicolor