Connecting Flavour & EWSB:
A Sequential Heavy Quark and a Light $\mathcal{D}$ilaton

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National Taiwan University

7 July @ SUSY 2016, Melbourne

There is a cry in the wilderness:

" Repent! The Higgs boson may be fictitious!"

(Phil Anderson, Nature Physics 2/2015)

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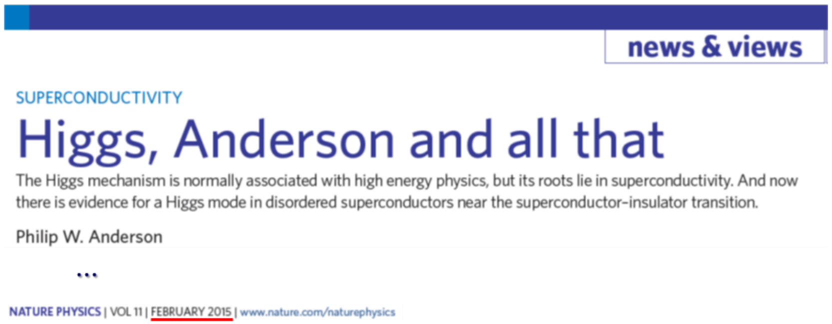

news & views

SUPERCONDUCTIVITY

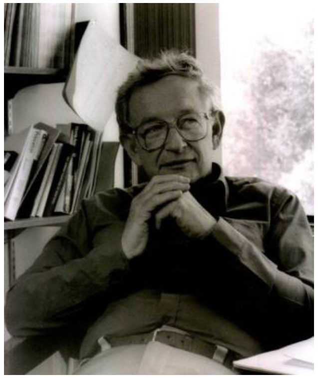
Higgs, Anderson and all that

The Higgs mechanism is normally associated with high energy physics, but its roots lie in superconductivity. And now there is evidence for a Higgs mode in disordered superconductors near the superconductor–insulator transition.

Philip W. Anderson

...

NATURE PHYSICS | VOL 11 | FEBRUARY 2015 | www.nature.com/naturephysics



Outline

I. Intro: Higgs, Anderson, and all that ...

the "Squalid Higgs"; 4G (still !?) / $\mathcal{D}$ (still !? ...)

II. a 125 GeV $\mathcal{D}$ilaton?

VBF @ Run 1? ← Run 2 Verdict

III. Yukawa Coupling is Empirical

Empirical Source of Flavour; 10^{-5} to 1 ⇛ 4π [NDA strong

IV. Yuk.-dynamic EWSB λ_u λ_t λ_Q

Scattering to Self-Energy; Mass Gen. @ Extremum

Beyond NJL ← No-scale ⇛ $\mathcal{D}$ Allowed

V. Discussion and Conclusion

Flavour & CPV; Strong Yukawa G-Q system; Conclusion

WSH, arXiv:1606.0732

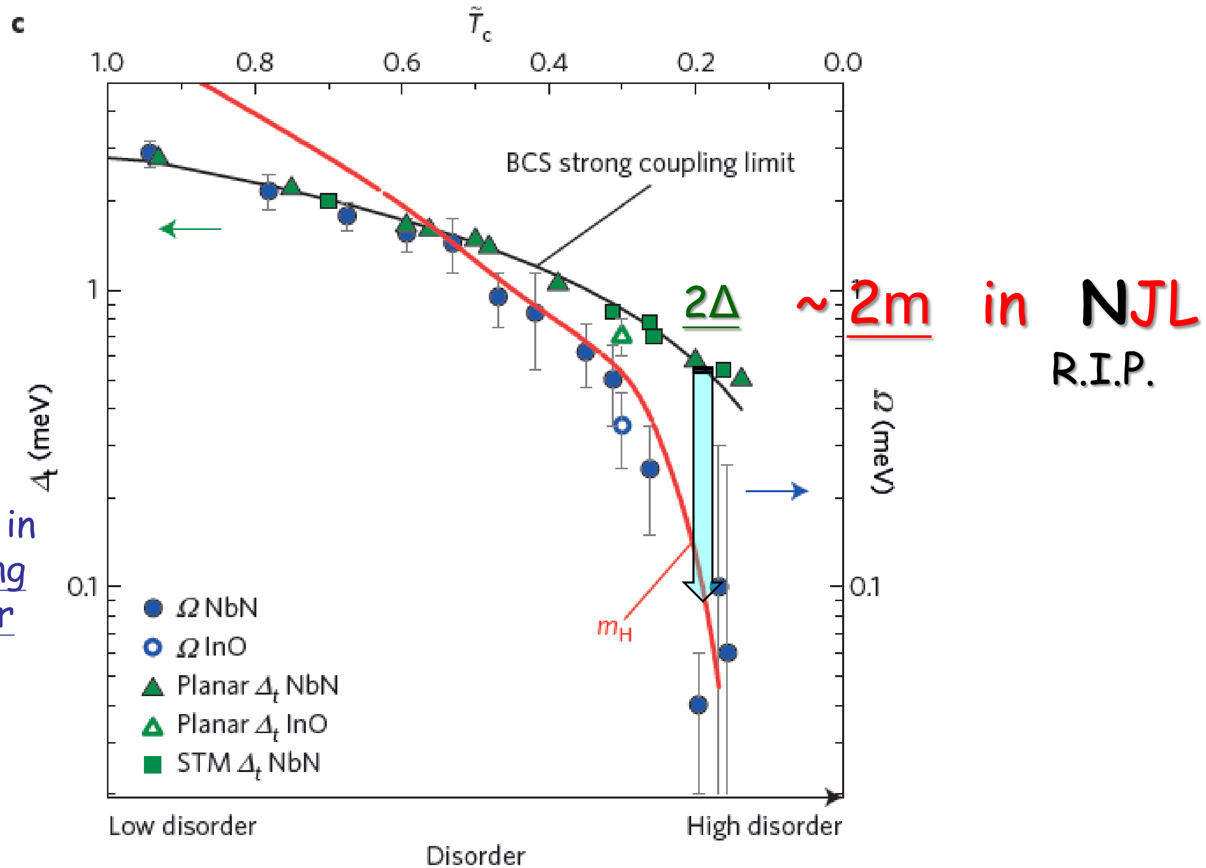
I. Intro: Higgs, Anderson, and all that …

Higgs mode from the "Squalid State"

NR wilderness

ARTICLES
NATURE PHYSICS DOI: 10.1038/NPHYS3227

D. Sherman *et al.*



a "Higgs mode" is observed in disordered SuperConducting films near the SC-insulator quantum critical point

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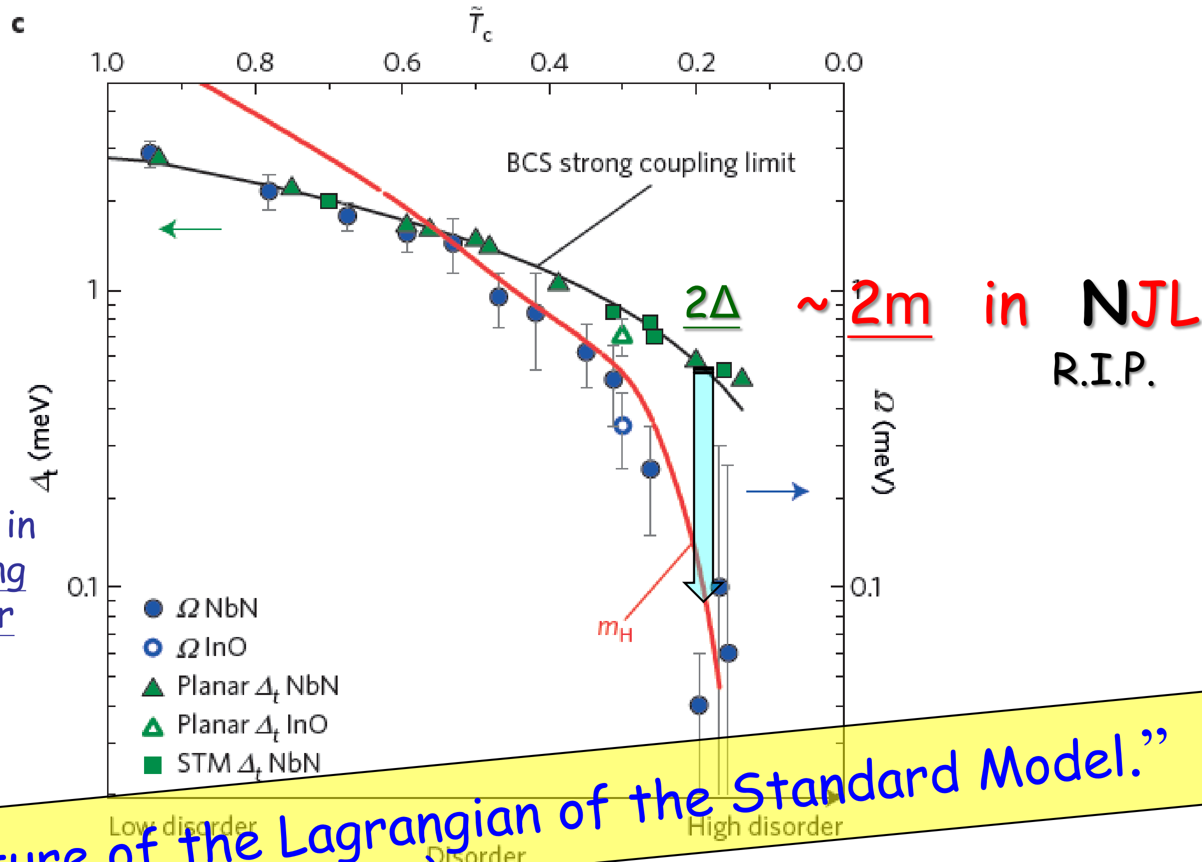

a "Higgs mode" is observed in disordered SuperConducting films near the SC-insulator quantum critical point

→ "Nature of the Lagrangian of the Standard Model." (Higgs)

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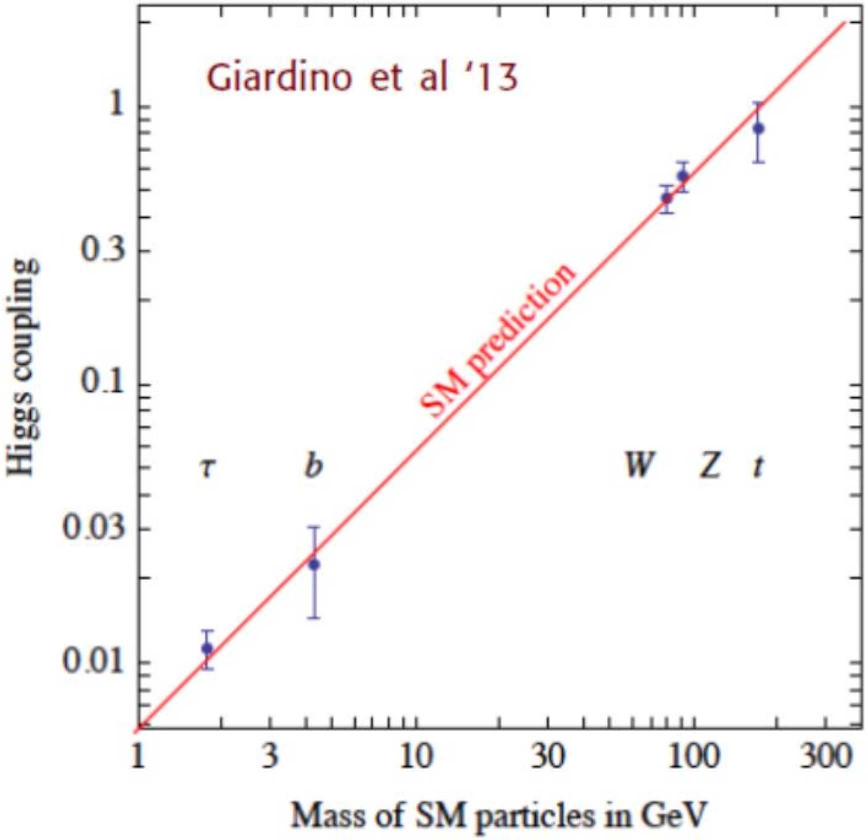
NATURE PHYSICS | VOL 11 | FEBRUARY 2015 | www.nature.com/naturephysics

Phil Anderson (2/2015 @ age 91):
"If superconductivity does not require an explicit Higgs in the Hamiltonian to observe a Higgs mode, might the same be true for the 126 GeV mode?"
... "Maybe the Higgs boson is fictitious!"

NATURE PHYSICS | VOL 11 | FEBRUARY 2015 | www.nature.com/naturephysics
93

The Higgs couplings are in proportion to masses:
a striking signature [plus specified, gg, γγ, Zγ couplings]



[this is also true for a dilaton-like, but up to a common factor]

$\mathcal{D}$

v/f

Nearly impossible to reproduce by accident

Agrees with a SM doublet: no Clebsch distortions

Couplings now checked at ~20%

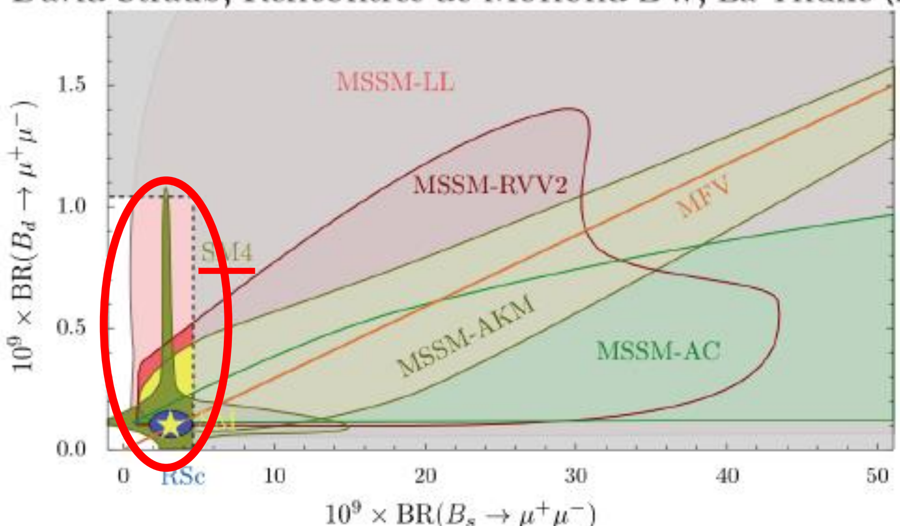
See e.g. Goldberger, Grinstein, Skiba, PRL 100 (2008) 111802

125 GeV Higgs observation "kills off" 4G?

Sheldon Stone @ ICHEP2012

Implications II

David Straub, Rencontres de Moriond EW, La Thuile (2012)



The 125 GeV Higgs observations kills off 4th generation models as the production cross-section would be 9x larger & decays to $\gamma\gamma$ suppressed

ICHEP, Melbourne, July 9, 2012 39

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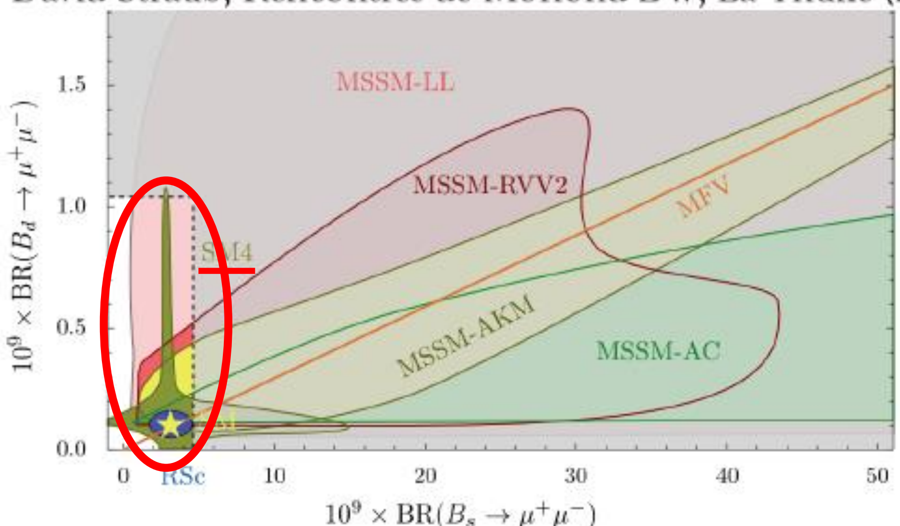

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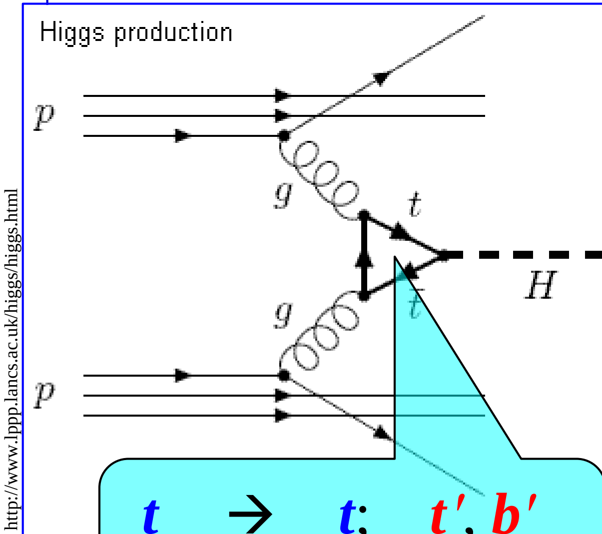
ICHEP, Melbourne, July 9, 2012 39

Why?



$$\frac{t \;\rightarrow\; t;\;\; t',\, b'}{1^2 \;\rightarrow\; (1+1+1)^2}$$

R.I.P.

However, SM Higgs is flavor-blind

Sheldon Stone @ ICHEP2012

Implications II

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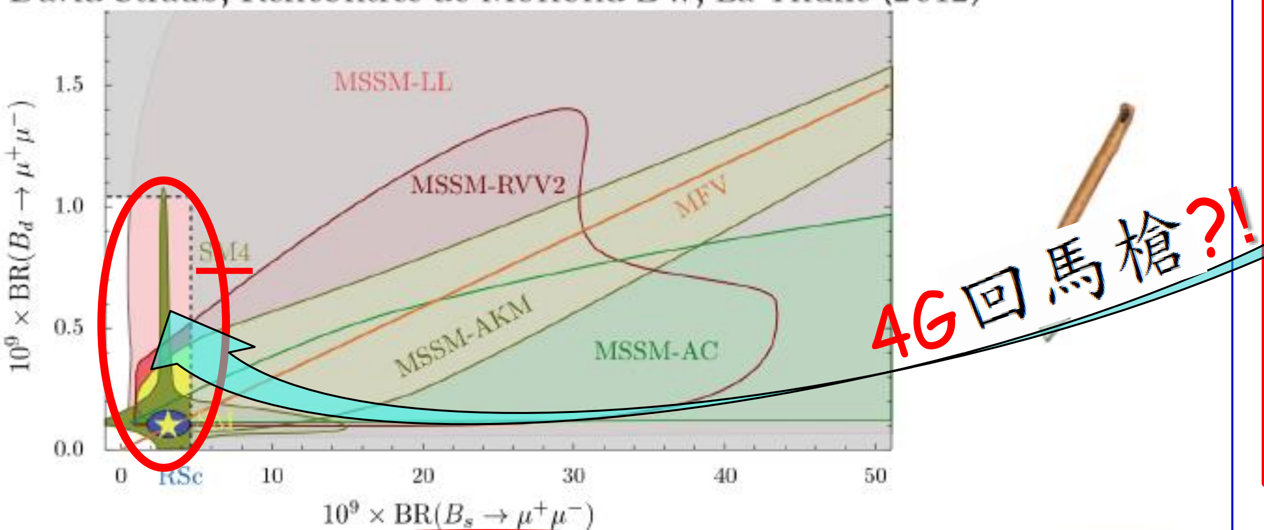

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ICHEP, Melbourne, July 9, 2012 39

Flavor people should keep CKM-extension in mind.

Higgs does not enter these loops;

and, 126 GeV boson could be "dilaton" still ...

R.I.P.

Keep on Searching w/ Gusto!

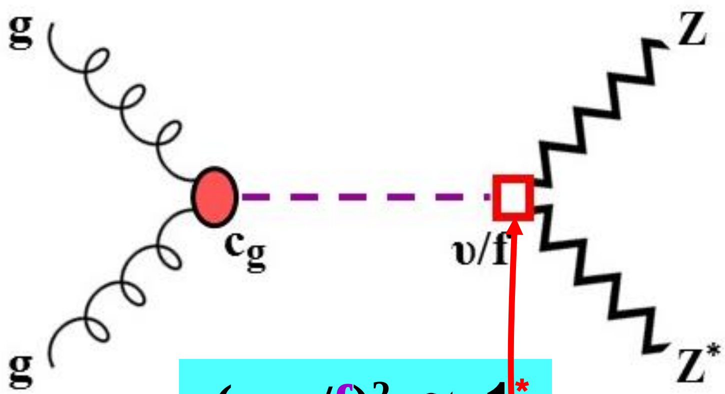
WSH, Kohda, Xu, PRD'2013

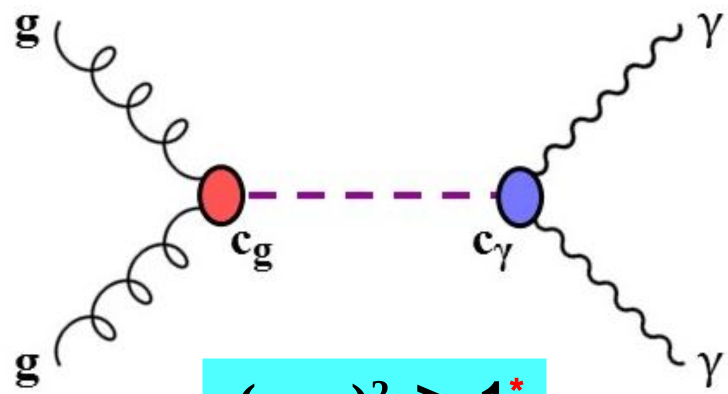
Nothing wrong with 4G Quarks,
except the Higgs cross section.

The true reason for me to return to Melbourne 4 years after ICHEP.

II. a 125 GeV $\mathcal{D}$ilaton?

"Our Higgs": Production ⊗ Decay



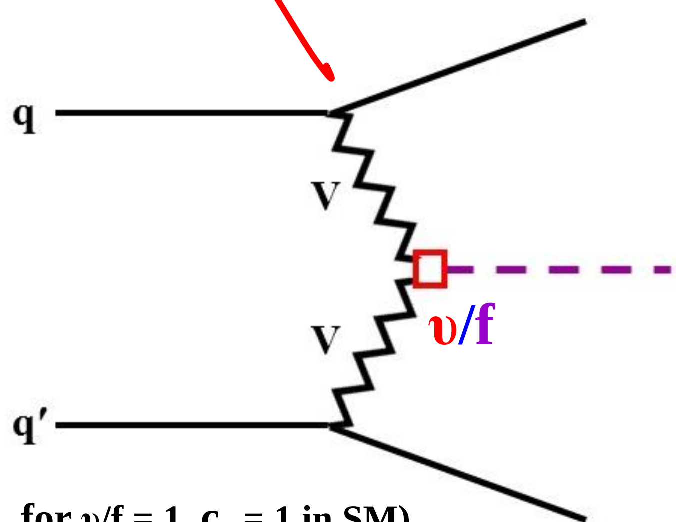


$(c_g \upsilon/f)^2 \simeq \underline{1}^*$

$(c_g c_\gamma)^2 \gtrsim \underline{1}^*$

Product Measured (~ **SM**), but not individual coefficients

Vector Boson Fusion (VBF)

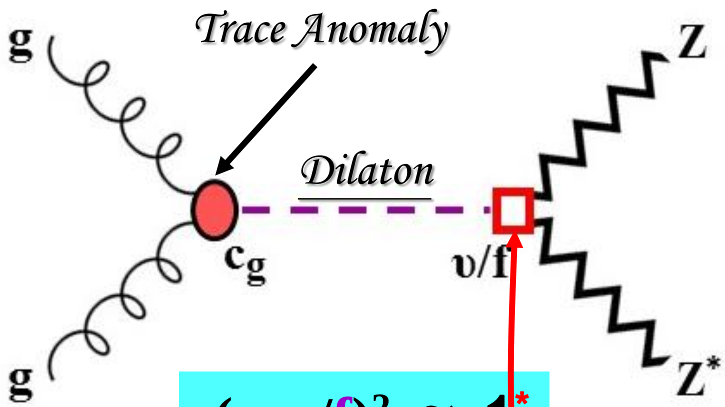


Need Direct Measurement

Coupling determined by BEH Mechanism in SM

* $0.91(\upsilon/f)^2 + 0.087(c_g)^2 \sim \underline{1}$ (e.g. for $\upsilon/f = 1$, $c_g = 1$ in SM)

"Our Higgs": Production ⊗ Decay



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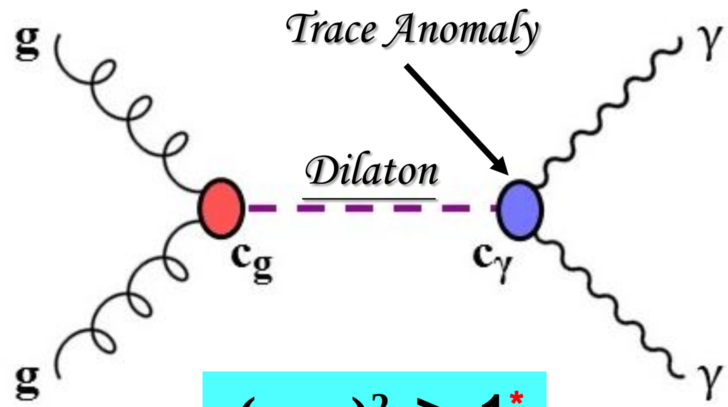

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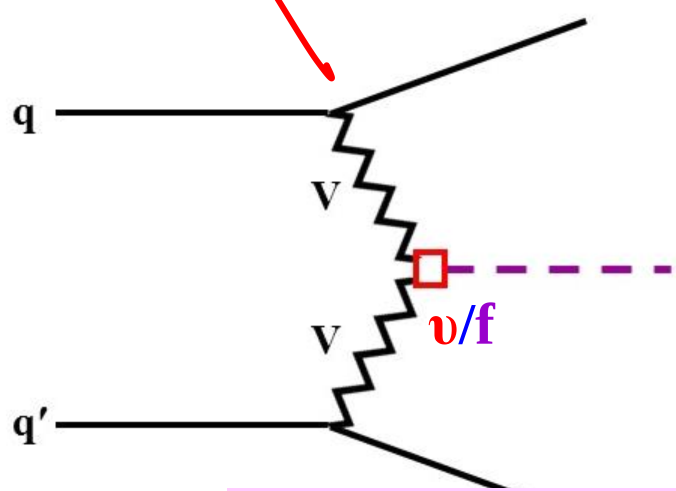


Need Direct Measurement

Coupling determined by BEH Mechanism in SM

Dilaton ***still?***

$^*\ 0.91(\upsilon/f)^2 + 0.087(c_g)^2 \sim \underline{1}$

Dilaton: Goldstone boson of SSB of Scale Invariance

See e.g. Goldberger, Grinstein, Skiba, PRL 100 (2008) 111802

Conclusions

- **ATLAS and CMS Higgs boson results on the mass and the couplings have been combined - sensitivity improved by almost √2**
- The mass of the Higgs boson has been measured at 0.2%:

  $M_H = 125.09 \pm 0.24$ GeV

- **Higgs to ττ and VBF production established at more that 5σ level**

⋮

Sep 1, 2015 Marco Pieri UC San Diego 32

ATLAS+CMS Higgs Combo paper

arXiv:1606.02266

Submitted to: JHEP

CERN-EP-2016-100
8th June 2016

"direct observation of the VBF production process at 5.4σ"

Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC *pp* collision data at $\sqrt{s} = 7$ and 8 TeV

- This is really just "VBF-like" production* ...
- How does one combine (potential) bias(es)?*
- Source of EWSB Too Important to be cavalier!

← Await Run 2 Verdict!

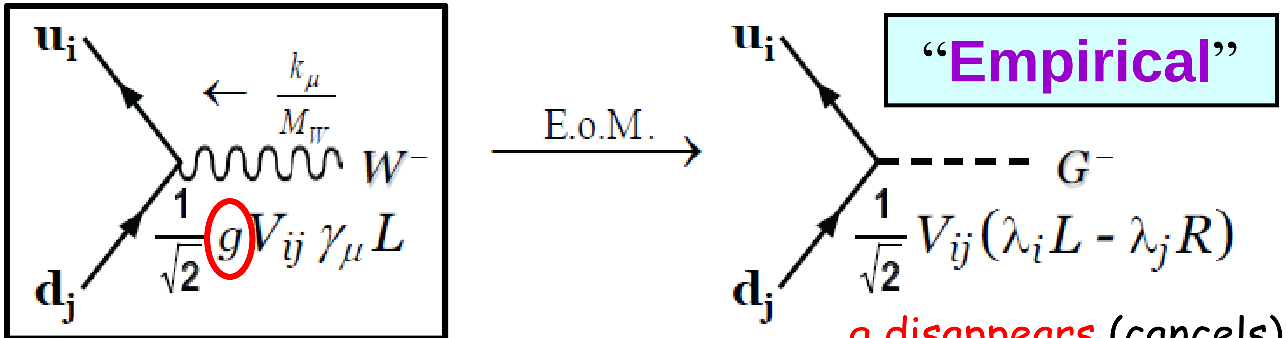
*backup

III. Yukawa Coupling is Empirical

WSH, arXiv:1201.6029 (Chin. J. Phys., 6/2012)

Empirical!

Intuitive:
(ca. 2009)
[live in massive world]



g disappears (cancels)

$$\lambda_Q \equiv \frac{\sqrt{2} m_Q}{v}$$

From left-handed (vector) gauge coupling:

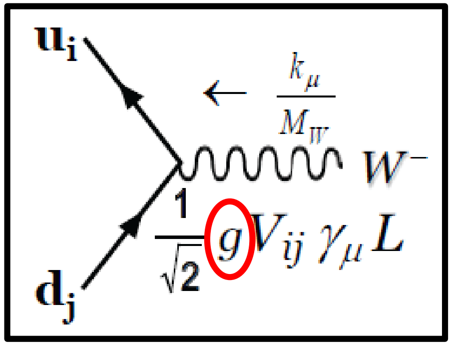
Not Trivial

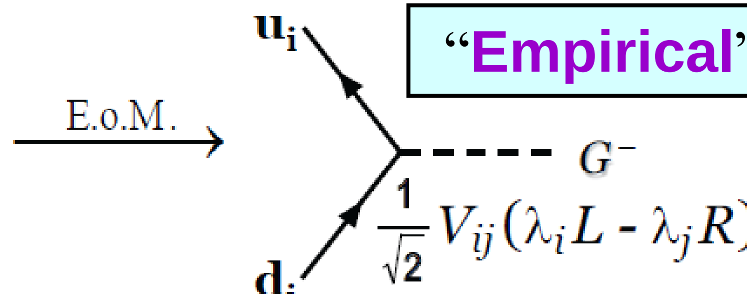
WSH, arXiv:1201.6029 (Chin. J. Phys., 6/2012)

Yukawa Coupling Empirical: "Goldstone" from Gauge

Empirical!

Intuitive:
(ca. 2009)
[live in massive world]





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Yukawa Coupling λ_Q of Goldstone Mode G Expt'lly Established, Independent of Higgs Boson Existence

complex doublet in Standard Model
(*Lagrangian*)

WSH, arXiv:1201.6029 (Chin. J. Phys., 6/2012)

Yukawa Coupling: Not Understood, but *Dynamical*

Naive Dimensional Analysis (Georgi-Manohar)

The Enigma: 10^{-5} to **1**

$\lambda_{u,d,e}$ λ_t

what ⇒ if?

NDA strong ("extremum")
4π (!?) ← Why Not
λ_Q

Q: $t' \doteqdot b'$ near deg. when heavy (EWPO)

From left-handed (vector) gauge coupling:

Not Trivial

$$\lambda_Q \equiv \frac{\sqrt{2} m_Q}{v}$$

Yukawa Coupling λ_Q of Goldstone Mode *G* Expt'lly Established,
Independent of *H*iggs Boson Existence

complex doublet in Standard Model
(*Lagrangian*)

N.B. **Yuk. coupling**, modulated by V_{ij}, is Source of Flavour/CPV.

IV. Yuk.-dynamic EWSB

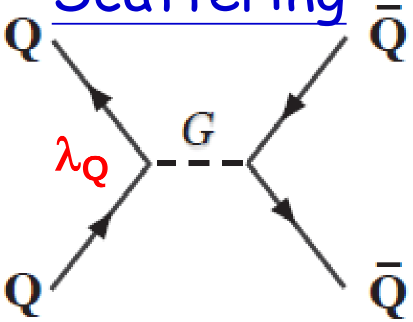
around Extremum of $\lambda_Q \sim 4\pi$: Emergent

In Pursuit of 4th Generation

2009 (**Strong Yuk., UBV**)

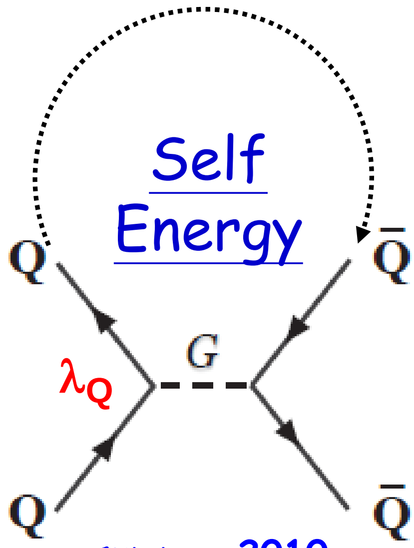
Unitarity Bound

Scattering



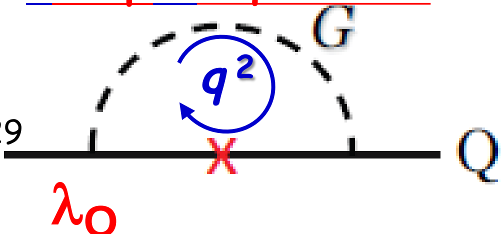
~ $1/M_W$ "long-range"
(vs $1/m_Q$)

Self Energy



summer **2010**

"Gap" Equation?



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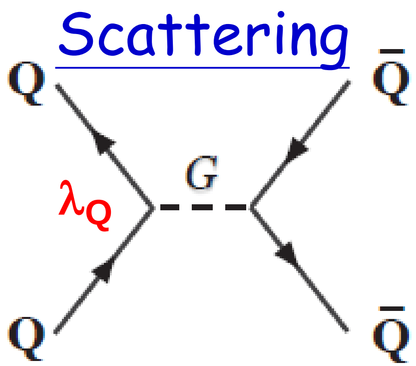

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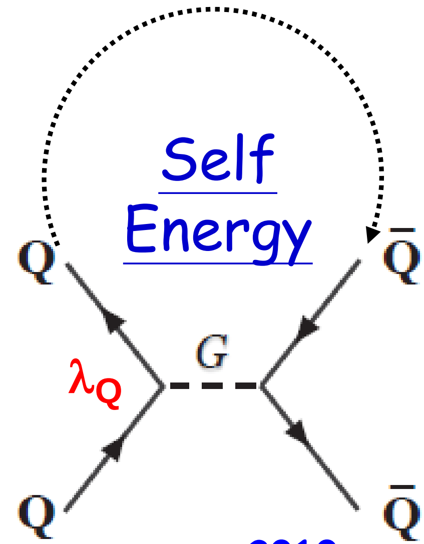
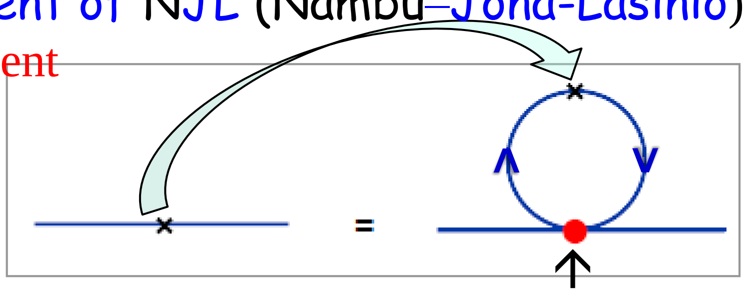


summer 2010

Reminiscent of NJL (Nambu–Jona-Lasinio),

but different

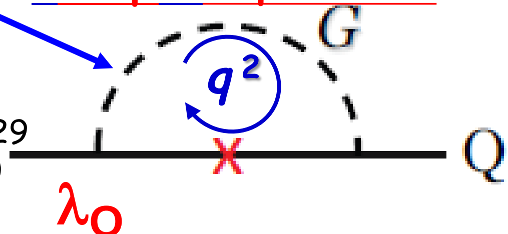


S.D.

WSH, arXiv:1201.6029

(Chin. J. Phys., 6/2012)

"Gap" Equation?

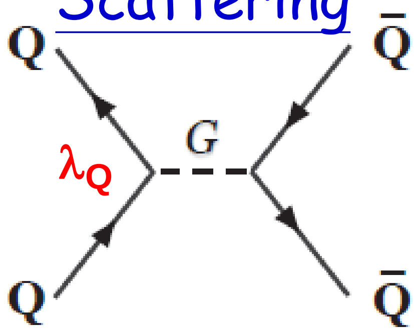


Strong Yukawa: $Q\bar{Q}$ Scattering, *Dynamical* EWSB

In Pursuit of 4th Generation

2009 (Strong Yuk., UBV)
Unitarity Bound

Scattering



~ $1/M_W$ "long-range"
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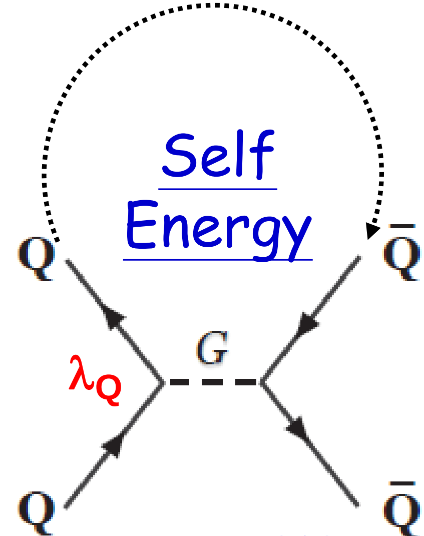
Self Energy



summer 2010

Mimura, WSH, Kohyama
arXiv:1206.6063 → JHEP 1311
numerical sol. * to Gap Equation

Strong Yuk. Mass Gen.

→ **DSB from *Strong Yuk.***

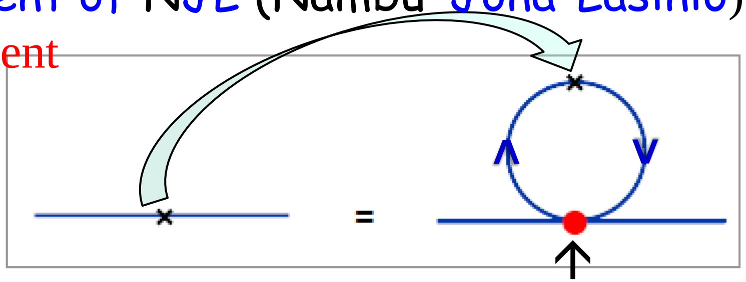
a Pairing Mechanism
can replace Higgs for v gen.

$\lambda_Q \gtrsim 4\pi$

$m_Q > 2$ TeV!!

summer 2011: No New Physics
[ansatz: integrate q up to $2m_Q$]*

Reminiscent of NJL (Nambu–Jona-Lasinio),
but different



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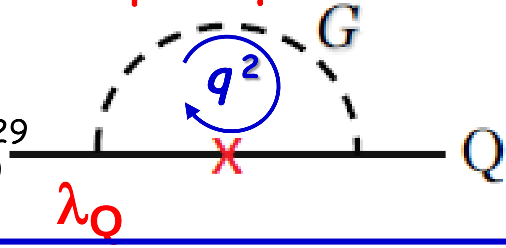

WSH, arXiv:1201.6029
(Chin. J. Phys., 6/2012)

* backup

$$\lambda_Q \equiv \frac{\sqrt{2} m_Q}{v}$$

Empirical, Self-Consistent
No-Scale Equation (def. integral)

Allows Dilaton, $\mathcal{D}$, to Emerge

*numerically self-consistent**

Mimura, WSH, Kohyama
arXiv:1206.6063 → JHEP 1311
*numerical sol.** to Gap Equation

Strong Yuk. Mass Gen.

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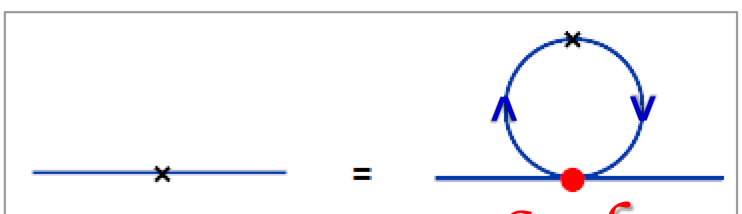
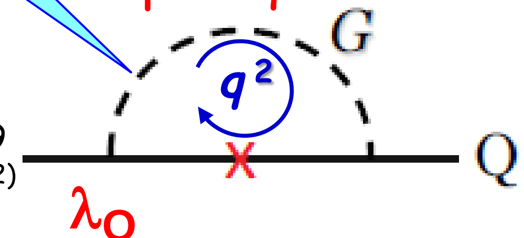


Scale

“Gap” Equation?



arXiv:1201.6029
(Chin. J. Phys., 6/2012)

* backup

$\bar{Q}Q$ Condensation*

by NDA-*Strong Yukawa*

The True Agent of Mass,
and the 125 Boson as New Physics

don't quite know why
(but appeared)

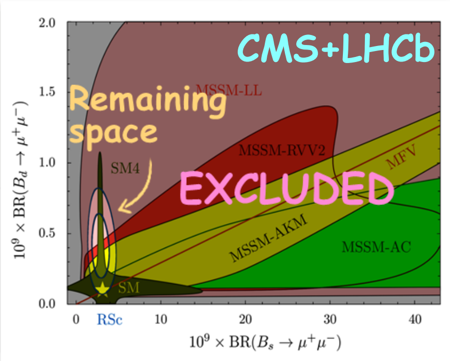
***Dilaton* (from UV)**

*** shielded from UV completion**

V. Discussion and Conclusion

Flavour & CPV

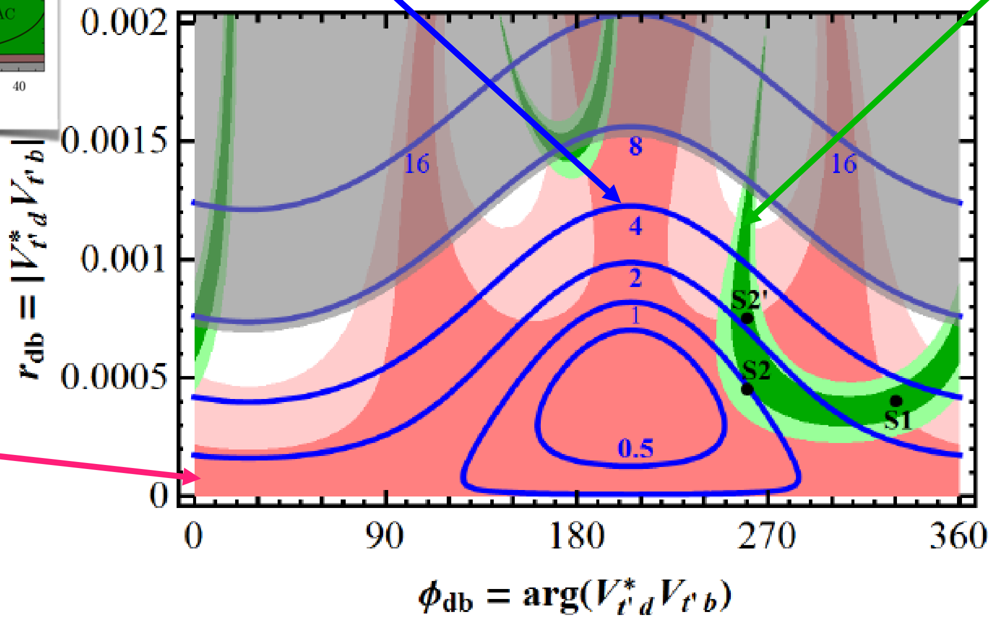
what 4G was "purposed" for ...



$\mathbf{B_d \to \mu^+\mu^-}$, $\mathbf{K_L \to \pi^0 \nu\nu}$ & $\mathbf{\sin 2\phi_1/\beta}$

($\times 10^{-10}$)

WSH, Kohda, Xu, 1411.1988 (PLB'15)



pink: Δm_{B_d}

$B_d \to \mu^+\mu^-$

$\sim 4 \times 10^{-10}$?!

("1" in SM)

The $B_s \to \mu^+\mu^-$ mode has finally been observed, albeit at rate 1.2σ below Standard Model (SM) value, while the rarer $B_d^0 \to \mu^+\mu^-$ decay has central value close to 4 times SM expectation but with only 2.2σ significance. The measurement of CP violating phase ϕ_s has finally reached SM sensitivity. Concurrent with improved measurements at LHC Run 2, $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ decays are being pursued in a similar time frame. We find, whether $B_d^0 \to \mu^+\mu^-$ is enhanced or not, $K_L \to \pi^0 \nu\bar{\nu}$ can be enhanced up to the Grossman-Nir bound in the fourth generation model, correlated with some suppression of $B_s \to \mu^+\mu^-$, and with ϕ_s remaining small.

-0.033 ± 0.033 (HFAG, Spring 2016)

Enough CP Violation 4 Matter Asymm. of Universe!

Sakharov Conditions	EW Theory	KM3	KM4
• Baryon # Violation	't Hooft/Sphaleron	✓	✓
• CP Violation	Kobayashi-Maskawa	✗	✓
• Out of Thermal Equilibrium ("boil")	$m_H \lesssim 50$ GeV	✗	?

Strong

"Weak"?

1-2-3

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\,A$$

Jarlskog Invariant

2-3-4

$$J^{sb}_{(2,3,4)} \simeq (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)\,A^{sb}_{234}$$

$$\sim \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\frac{A^{sb}_{234}}{A}J$$

> ~~10^{+15}~~ 10^{+17}

Strong Yukawa

$\mathcal{O}(1)$

Main (Yukawa!) Enhancement

CPV for Universe w/ spare change?

WSH, arXiv:0803.1234

Chin.J.Phys. 47 (2009) 134

Ultra-Strong Yukawa?

Fermi-Yang Redux: EWSB by Mass Gen.?

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

$$\lambda_Q \equiv \frac{\sqrt{2} m_Q}{v}$$

$\pi \sim N\bar{N}$?

$G \sim Q\bar{Q}$?

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*

Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

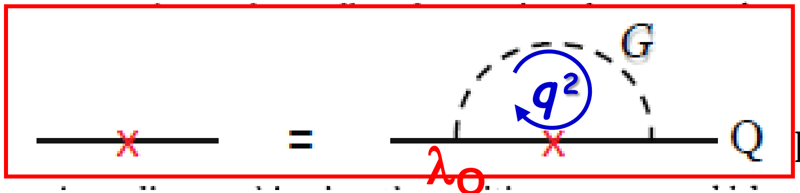
"NDA Strong"

$$g_{\pi NN} \simeq \lambda_{\pi NN} \equiv \sqrt{2} m_N / f_\pi \simeq 14$$

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

We assume that the π-meson is a pair of nucleon and anti-nucleon bound in this way. Since the mass of the

Q



exact

pointlike

π-N took (amazing!) Path of QCD: stringy resonances/hadrons

Could we have 2nd chance w/ non-QCD strong Yukawa?

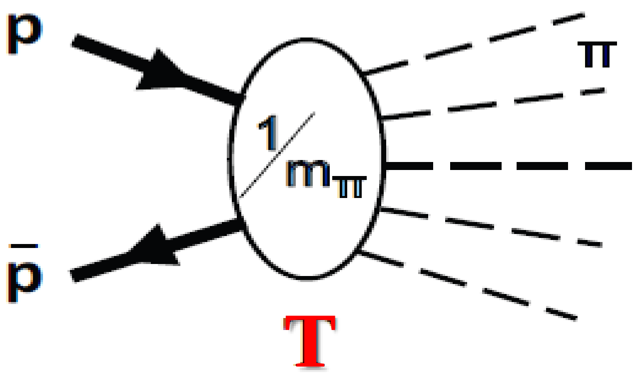
Intriguing: $Q\bar{Q} \to nV_L$ "EW Fireballs"

$$g_{\pi NN} \simeq \lambda_{\pi NN} \equiv \sqrt{2}m_N/f_\pi \simeq 14$$

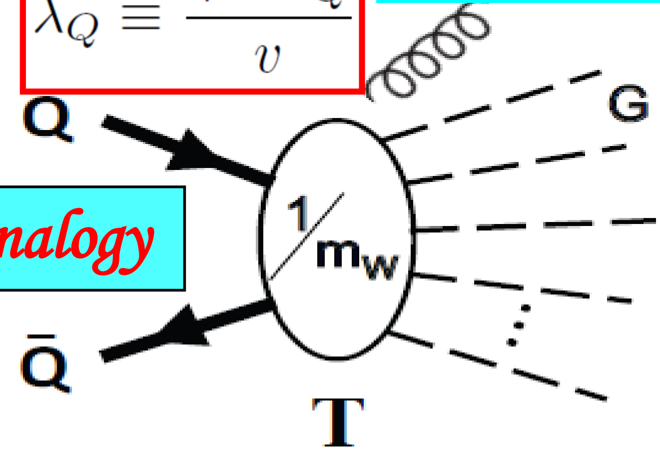
➡ $m_Q \gtrsim 2$ TeV

Boundstate may help

$$\lambda_Q \equiv \frac{\sqrt{2}m_Q}{v}$$



Analogy



annihilation "fireball"

data

- Size of order $1/m_\pi$;
- Temperature $T \simeq 120$ MeV;
- Average number of emitted pions $\langle n_\pi \rangle \simeq 5$;
- A soft-pion p_π^2/E_π^2 factor modulates the Maxwell–Boltzman distribution for the pions.

Example

$$T \sim \frac{2}{3} v \sim 160 \text{ GeV}$$

$$\langle |p_G| \rangle \sim 310 \text{ GeV},$$

$$\langle n_G \rangle \sim 6.25\ (12.5), \quad \mathcal{O}(10)$$

$$P(n_G) \simeq 0.319\, e^{-\frac{(n_G-6.25)^2}{3.13}} \quad \left(0.226\, e^{-\frac{(n_G-12.5)^2}{6.25}}\right)$$

WSH, PRD'12 [arXiv:1206.1453]

Conclusion

Despite 125 GeV particle, as well as "VBF-like" signal at Run 1, a consistent picture may emerge from confluence of measurements in the next few years [**LHC Run 2**]...

... and it could *still* be 4G, rather than SM Higgs ...

- High Purity VBF "Verdict": Higgs/*Dilaton*-ID.

  This is serious, as much as you(/I) think it unlikely!

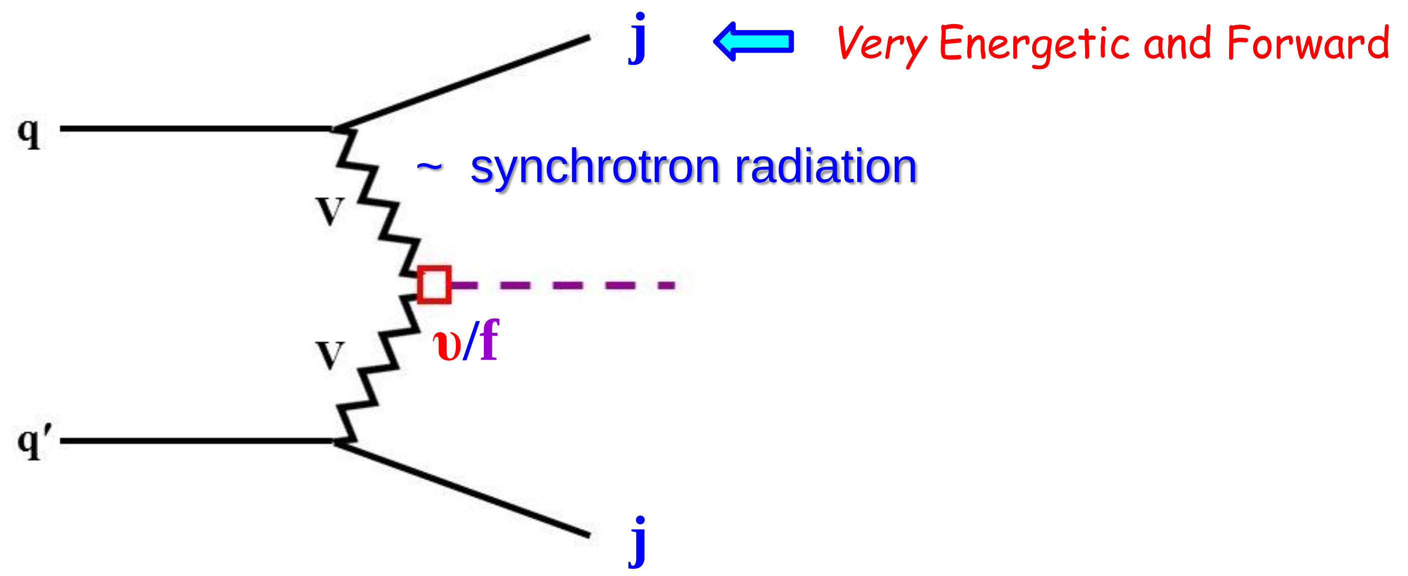
  Agent of EWSB is No Light Matter.
- New "Flavour Anomalies": $\mathbf{B_d \to \mu^+\mu^-}$, $\mathbf{K_L \to \pi^0 \nu\nu}$ CPV-4-BAU!
- EW Fireball (may have to await higher energy collider)

  Genuine "Composite Higgs": Boundstates at Multi-TeV
- What is Direct Signature of Heavy 4G Quarks?

What is "Theory of Yukawa Coupling"?

To have purity, one had insufficient statistics for Run 1 (2011−2012);
to gain statistics, a MVA multi-channel impure analysis was done …

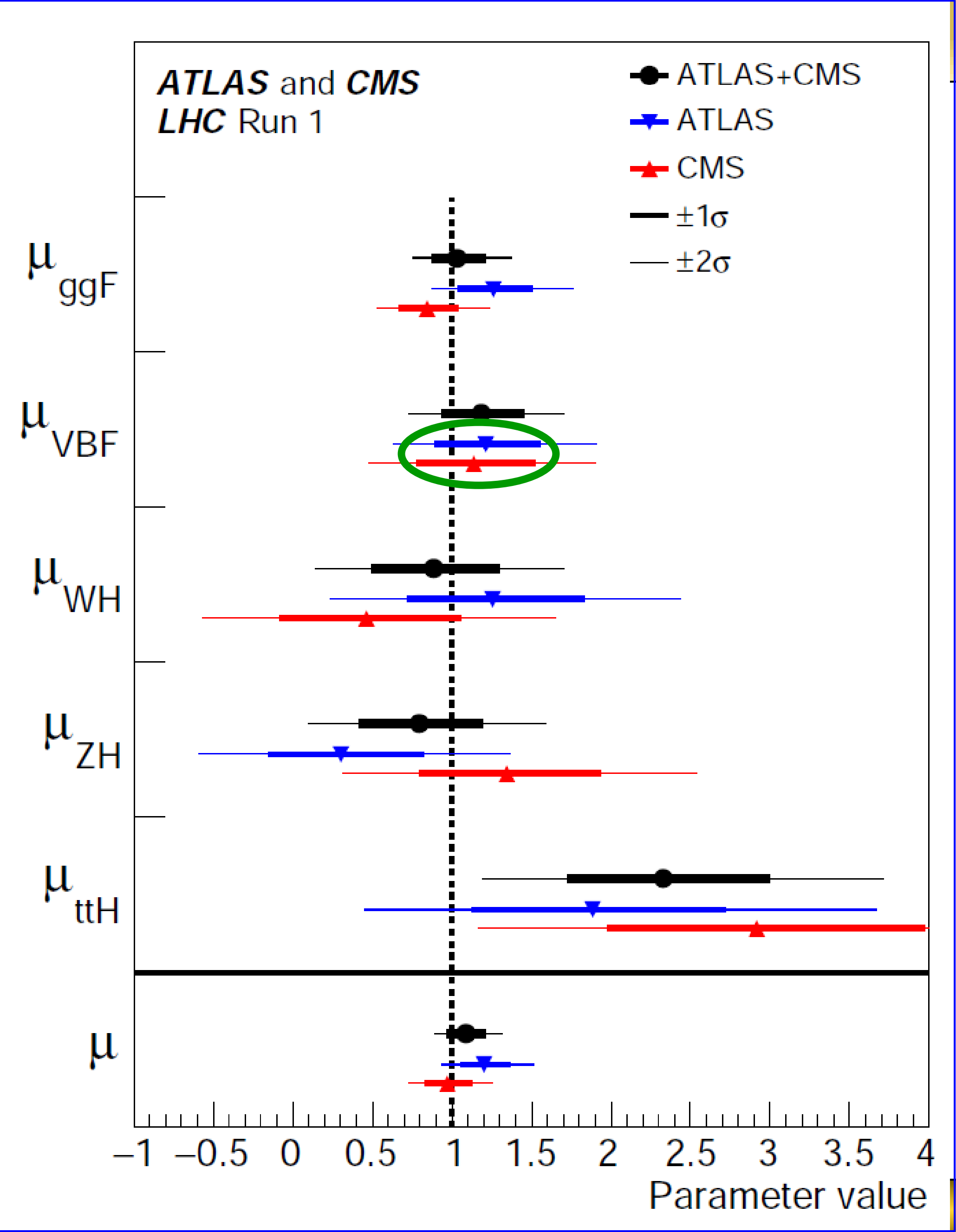
Vector Boson Fusion (VBF)



Priority Analysis 2016⁺, but with clear Conscience,
Run 2 and Vigilance.

Tools: large m_{jj}, large $\Delta\eta_{jj}$; $\Delta\theta_{jj}$
low jet activity in η gap

Central values for μ_{VBF} remarkably "close"



Unfortunately, no hint of New Physics in the LHC data (yet)

	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV

Henri Bachacou, Irfu CEA-Saclay Lepton-Photon 2011 49

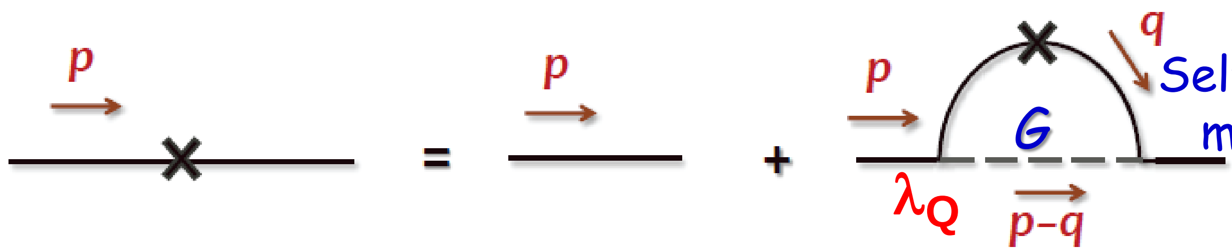
Gap Equation: Scale-inv. Strong Yukawa

Mimura, WSH, Kohyama, JHEP 1311

Gap equation for large Yukawa in the **ladder approx.** (and neglect gauge couplings)

w/ $m_0 = 0$

(gauge inv.) ✔



Self-energy momentum-dep.

$$S(p)^{-1} = A(p^2)\,\not{p} - B(p^2)$$

Goldstone propagator : $D(q) = 1/q^2$

$$B(p^2) = +\frac{3\lambda_Q^2}{2}\int \frac{d^4q}{i(2\pi)^4}\frac{1}{(p-q)^2}\frac{B(q^2)}{A^2(q^2)q^2 - B^2(q^2)}$$

$$-\frac{\lambda_Q^2}{2}\int \frac{d^4q}{i(2\pi)^4}\frac{1}{(p-q)^2 - m_h^2}\frac{B(q^2)}{A^2(q^2)q^2 - B^2(q^2)}$$

"Mass" = B/A

Consistent with dilaton; permits a dilaton.

$$A(p^2)p^2 = p^2 + \frac{3\lambda_Q^2}{2}\int \frac{d^4q}{i(2\pi)^4}\frac{p\cdot q}{(p-q)^2}\frac{B(q^2)}{A^2(q^2)q^2 - B^2(q^2)}$$

$$+\frac{\lambda_Q^2}{2}\int \frac{d^4q}{i(2\pi)^4}\frac{p\cdot q}{(p-q)^2 - m_h^2}\frac{B(q^2)}{A^2(q^2)q^2 - B^2(q^2)}$$

Dropped "Higgs"; **if dilaton, v^2/f^2 suppressed**.
→ self-consistent ✔

N.B. Retain Higgs, m_Q much higher!!

Gap Equation: Scale-inv. Strong Yukawa

Higgs or not, absorbed in κ_b and κ_a

Mimura, WSH, Kohyama, JHEP 1311

So,

$$\begin{cases} B(x) = \kappa_b \left(\frac{1}{x} \int_0^x dy \frac{yB(y)}{yA^2(y)+B^2(y)} + \int_x^{\Lambda^2} dy \frac{B(y)}{yA^2(y)+B^2(y)} \right) \\ A(x) = 1 + \kappa_a \left(\frac{1}{x^2} \int_0^x dy \frac{y^2A(y)}{yA^2(y)+B^2(y)} + \int_x^{\Lambda^2} dy \frac{A(y)}{yA^2(y)+B^2(y)} \right) \end{cases}$$

$$p^2 = x = e^{2t}$$

$$xB'' + 2B' + \frac{\kappa_b B}{xA^2+B^2} = 0,$$

$$xA'' + 3A' + \frac{2\kappa_a A}{xA^2+B^2} = 0,$$

the boundary conditions

$$B'(x)|_{x=\Lambda_{\rm IR}^2} = 0, \ \ (xB'(x) + B(x))\,|_{x=\Lambda^2} = 0,$$

$$A'(x)|_{x=\Lambda_{\rm IR}^2} = 0, \ \ \left(\frac{1}{2}xA'(x) + A(x)\right)|_{x=\Lambda^2} = 1$$

scale invariance used in solving

$$\ddot{B} + 2\dot{B} + \frac{4\kappa_b B}{A^2 + B^2 e^{-2t}} = 0,$$

$$\ddot{A} + 4\dot{A} + \frac{8\kappa_a A}{A^2 + B^2 e^{-2t}} = 0,$$

$$\dot{B}(t_{\rm IR}) = 0, \qquad \dot{B}(t_{\rm UV}) + B(t_{\rm UV}) = 0$$

$$\dot{A}(t_{\rm IR}) = 0, \qquad \frac{1}{4}\dot{A}(t_{\rm UV}) + A(t_{\rm UV}) = 1$$

We find, numerically, $\kappa_b = 2\kappa_a = 3\alpha_Q/8\pi$ ≳ 1.4

→ $\lambda_Q^c \simeq 12$ → $m_Q^c > 2.1$ TeV, !! (No Higgs)