Connecting Flavour & EWSB:
A Heavy Q and a Light 𝒟(ilaton)

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26 Nov @ LIO/Flav-Compo-DM, IPNL, Lyon

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National Taiwan University

Outline

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

4G/$\mathcal{D}$ Loophole; VBF'15? ← Run 2 Verdict

II. Yukawa Couplings & Nondecoupling

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

λ_u λ_t λ_Q

III. Yukawa-dynamic EWSB

Scattering to Self-Energy; Mass Gen. @ Extremum

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

IV. Flavour & CPV

$B_q \to \mu^+\mu^-$; $K_L \to \pi^0 \nu\nu$; ϕ_1/β; $\phi_s \sim 0$; CPV-4-BAU (!)

V. Discussion and Conclusion

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

news & views

SUPERCONDUCTIVITY

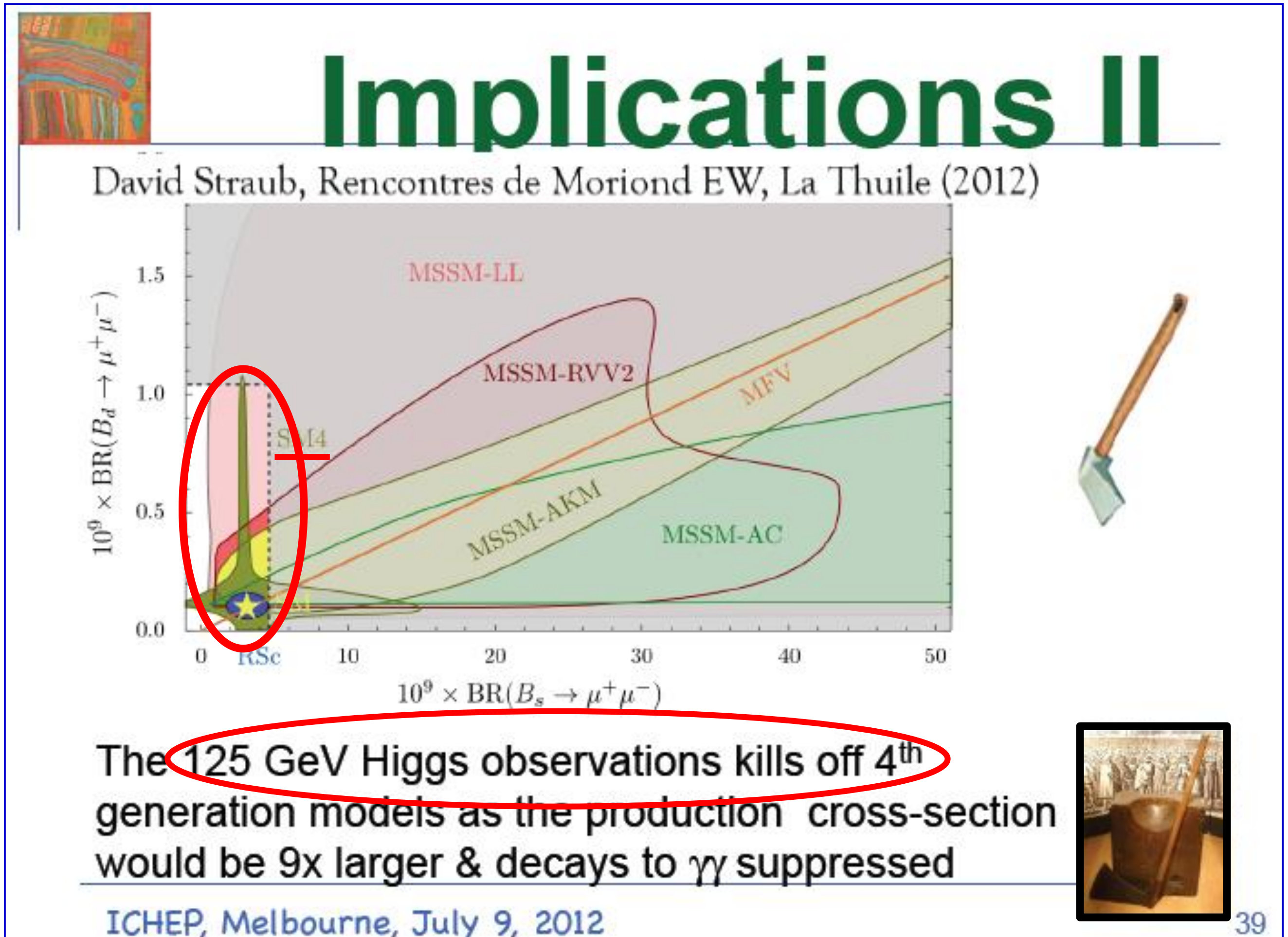
Higgs, Anderson and all that

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

125 GeV Higgs observation “kills off” 4G ?

Sheldon Stone @ ICHEP2012



R.I.P.

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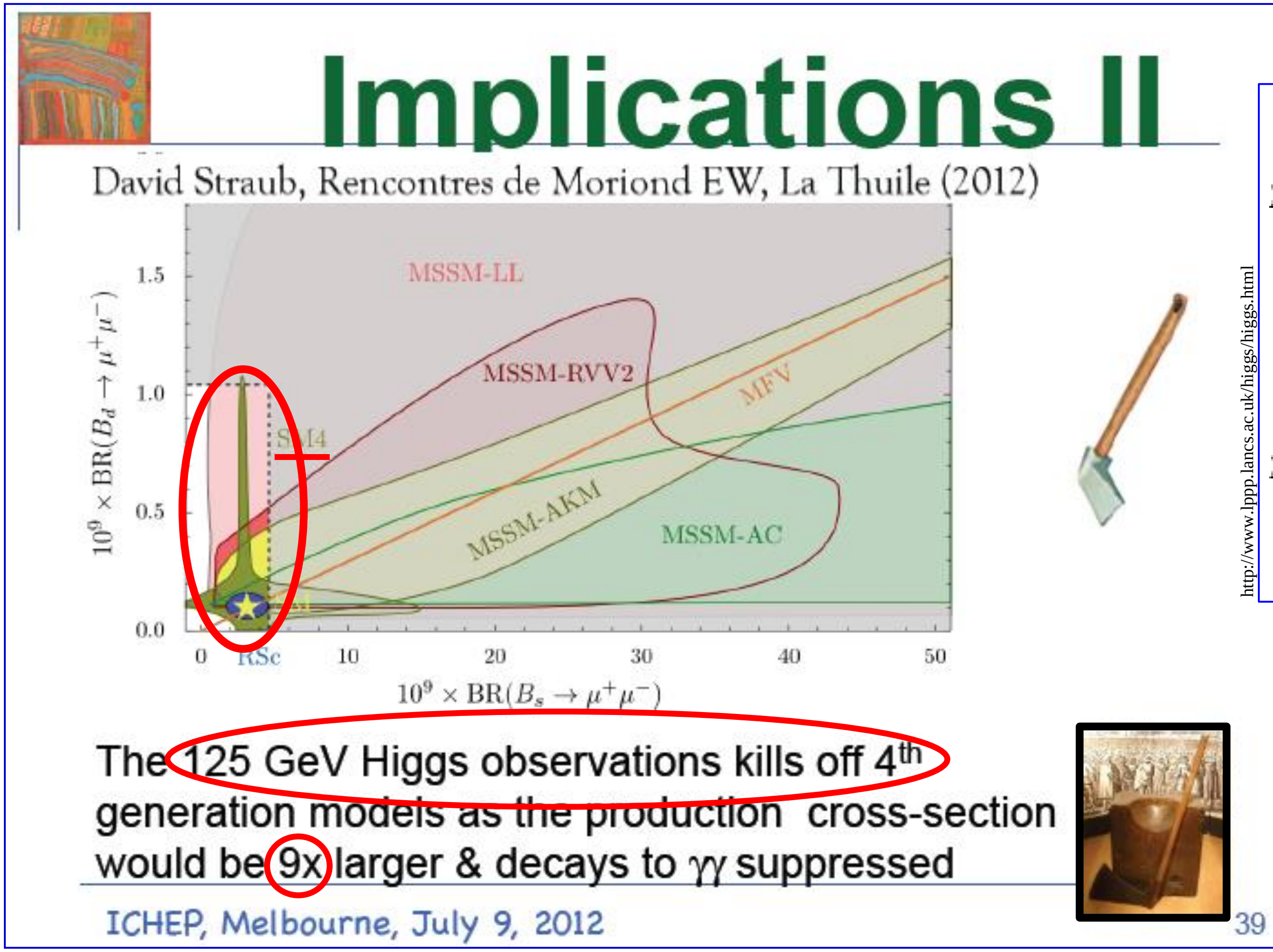
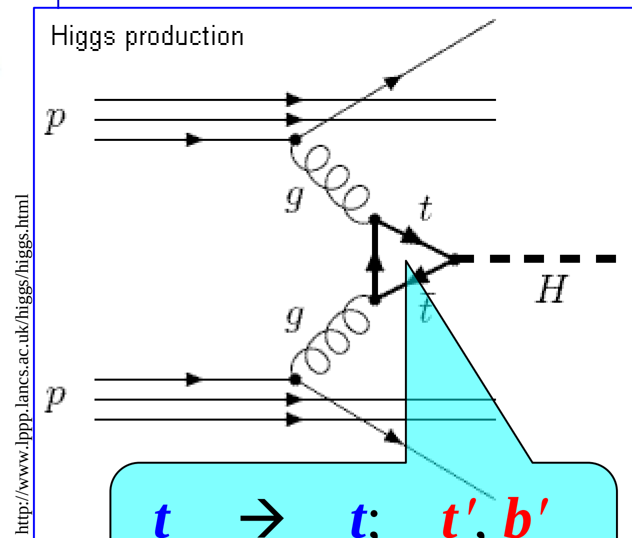


Why?

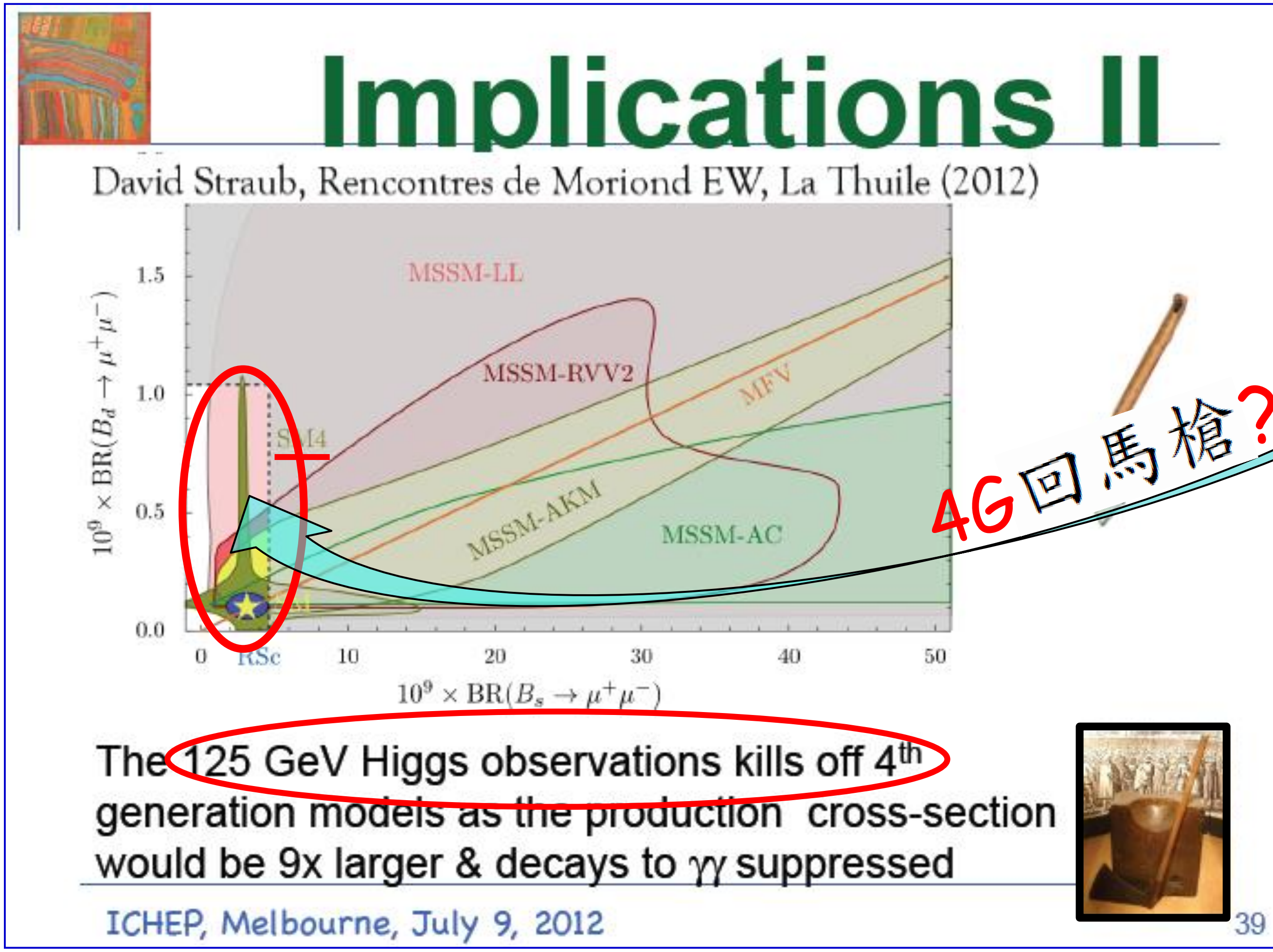


$$\frac{t \;\rightarrow\; t;\;\; t', b'}{1^2 \;\rightarrow\; (1+1+1)^2}$$

R.I.P.

However, SM Higgs is flavor-blind

Sheldon Stone @ ICHEP2012



Flavor people should keep CKM-extension in mind.

Higgs does not enter these loops;

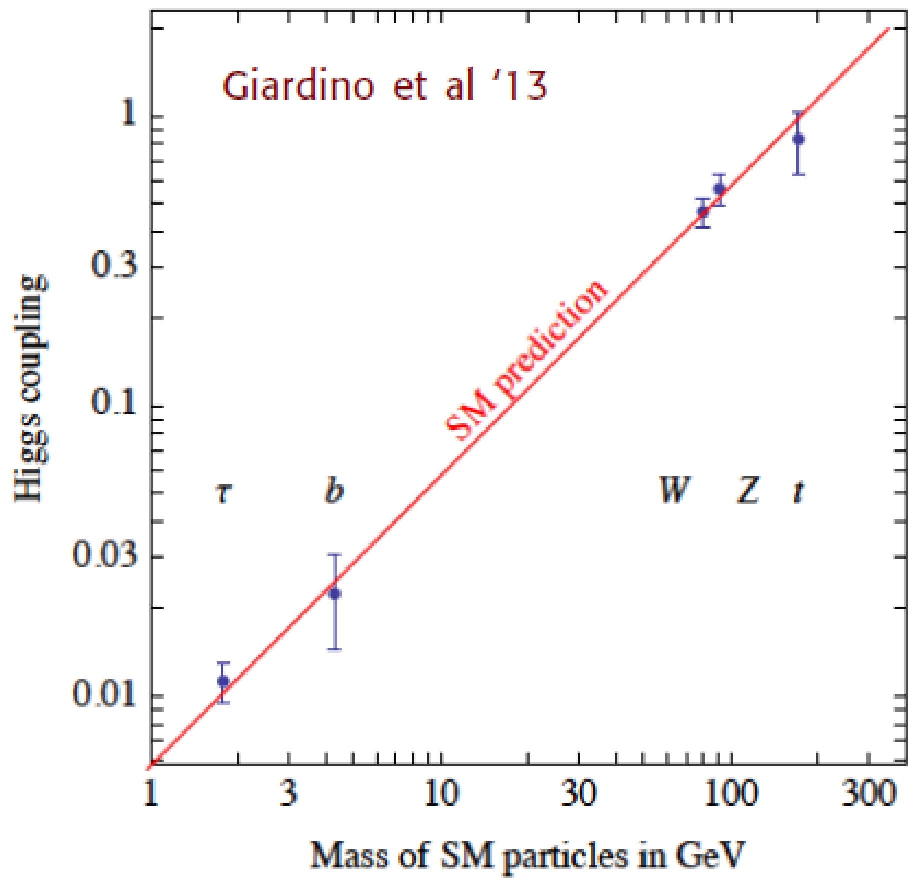
and, 126 GeV boson could be "dilaton" still …

Keep on Searching w/ Gusto!

WSH, Kohda, Xu, PRD'2013

Nothing wrong with 4G quarks,
except this Higgs cross section.

The Higgs couplings are in proportion to masses:
a striking signature [plus specified, gg, $\gamma\gamma$, $Z\gamma$ couplings]



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

v/f

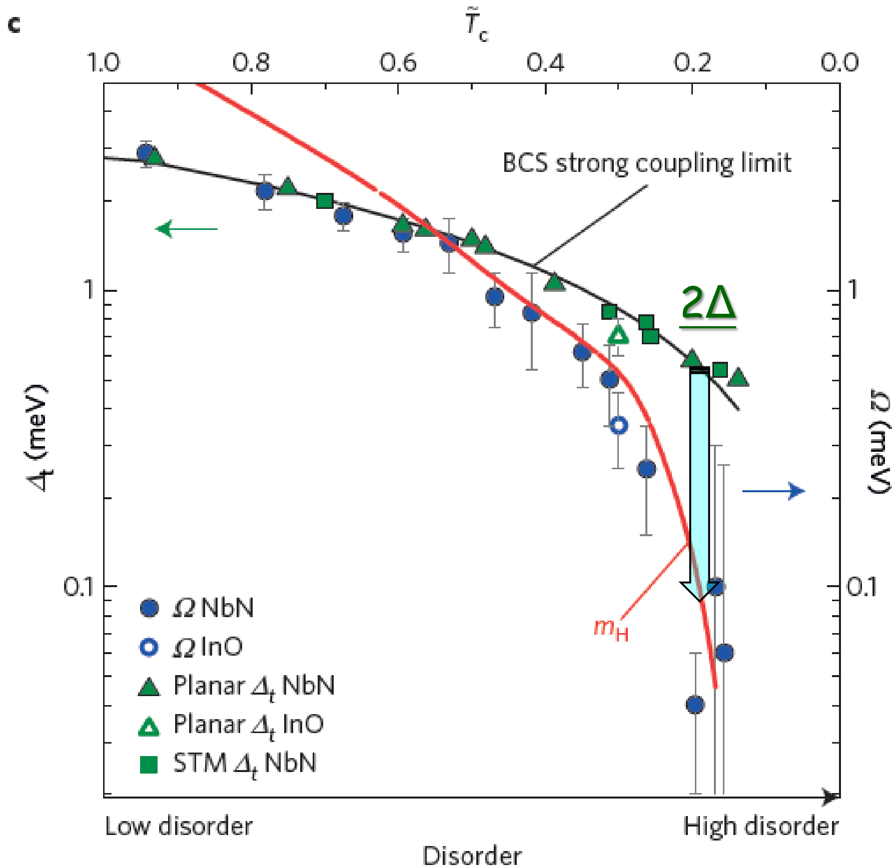
Nearly impossible to reproduce by accident

Agrees with a SM doublet: no Clebsch distortions

Couplings now checked at ~20%

Higgs mode from the "Squalid State"

ARTICLES
NATURE PHYSICS DOI: 10.1038/NPHYS3227



~ 2m in NJL
R.I.P.

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

Phil Anderson (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

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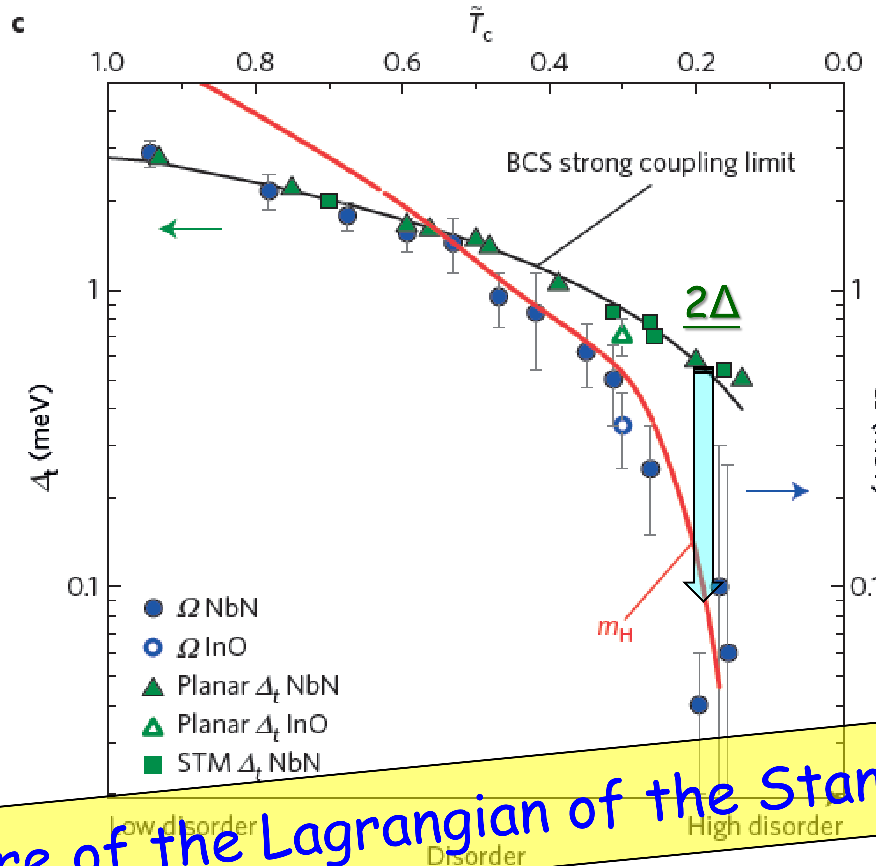

~ 2m in NJL
R.I.P.

→ "Nature of the Lagrangian of the Standard Model."

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

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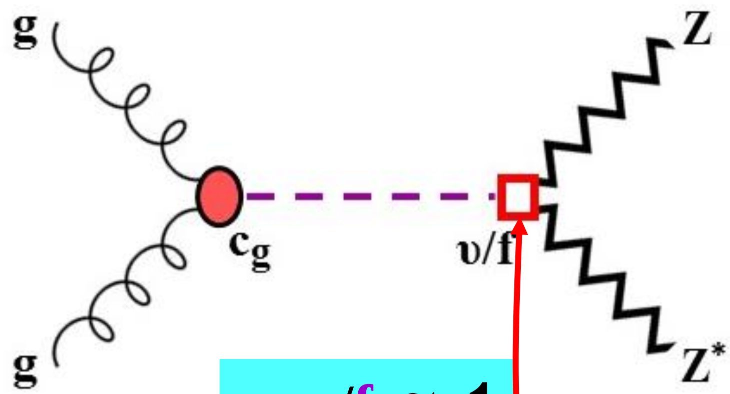
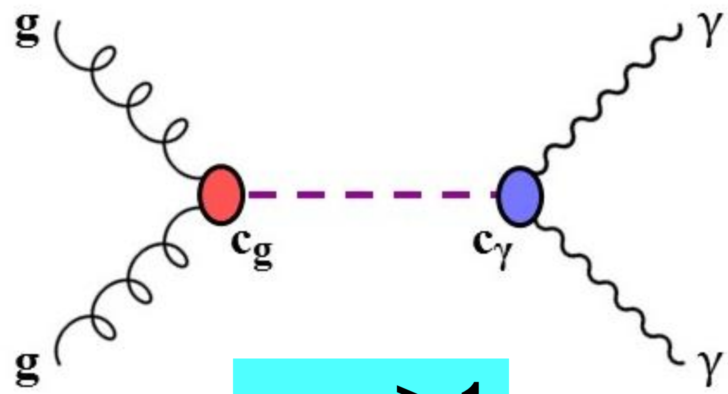
Our "Higgs": Production ⊗ Decay



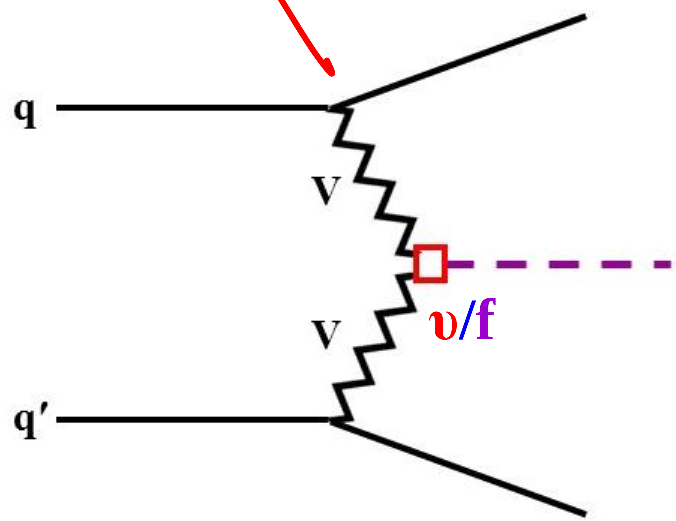


$c_g \upsilon/f \simeq 1$

$c_g c_\gamma \gtrsim 1$

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

Vector Boson Fusion (VBF)



Need Direct Measurement

Coupling determined by BEH Mechanism in SM

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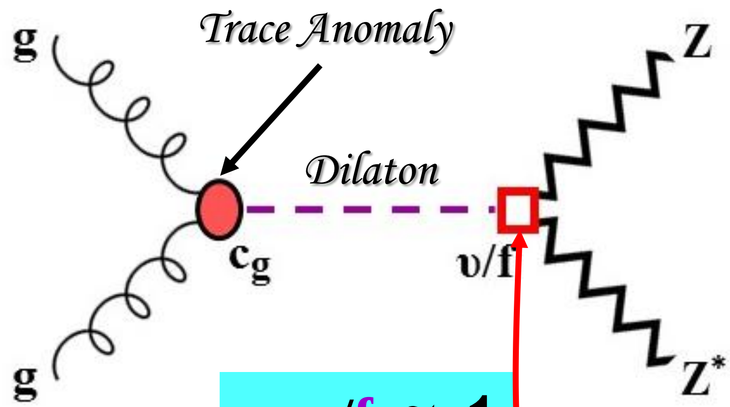

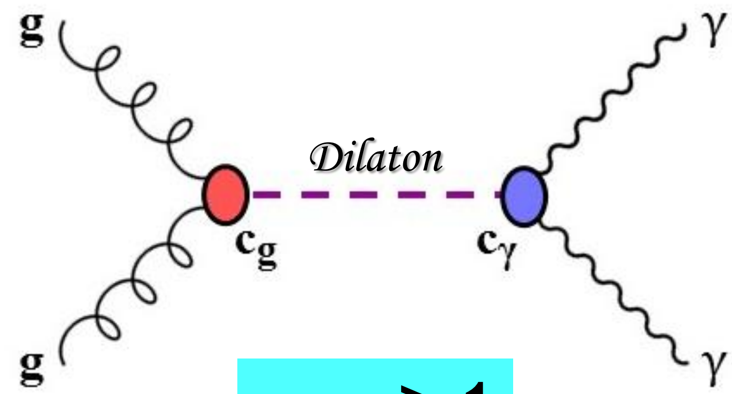

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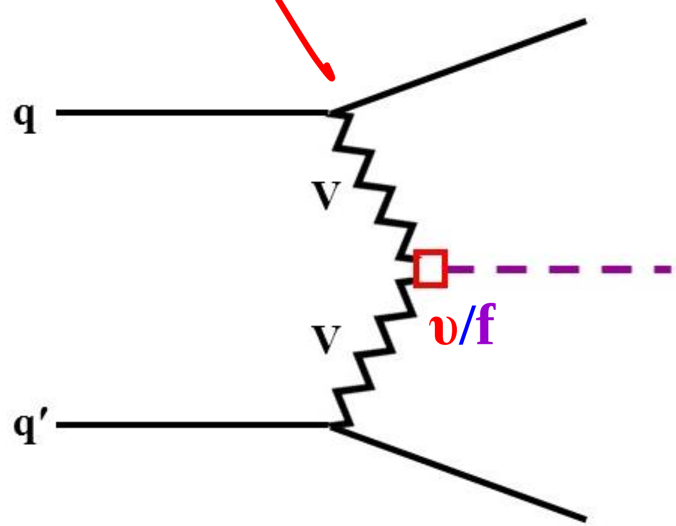


Need Direct Measurement

Coupling determined by BEH Mechanism in SM

Dilaton **still ?**

Dilaton: Goldstone boson of SSB of Scale Invariance

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

Conclusions

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

15th September 2015

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

⋮

Sep 1, 2015 Marco Pieri UC San Diego 32

- 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

II. Empirical Yukawa Couplings & Nondecoupling

Pursuits of my youth …

WSH, Willey, Soni, PRL'87
SM penguin diagram

WSH, Willey, PLB'88
NP penguin diagram

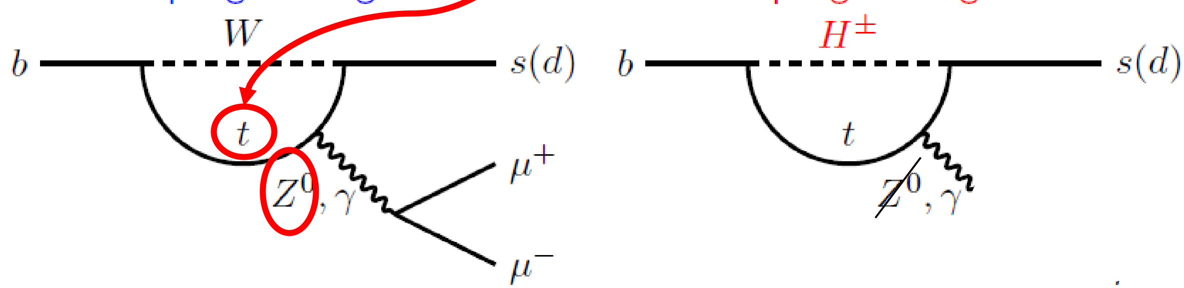
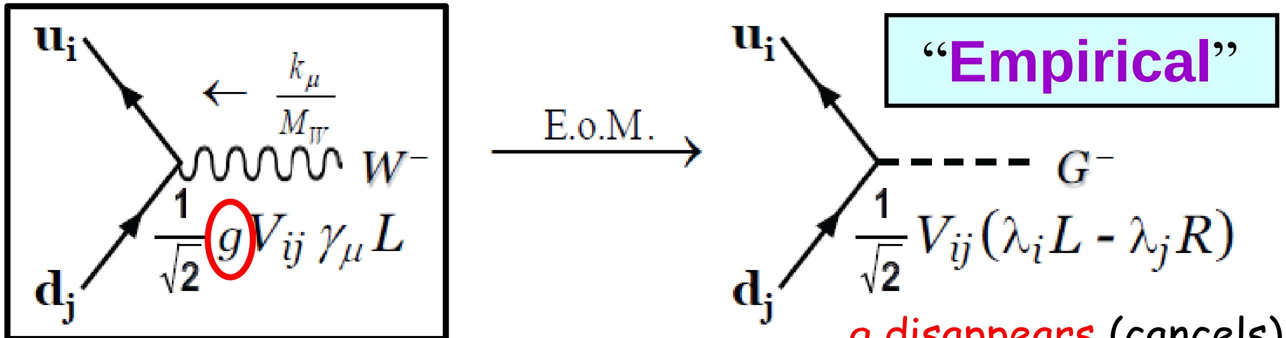


figure doctored from C. Langenbruch

Empirical!

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



g disappears (cancels)

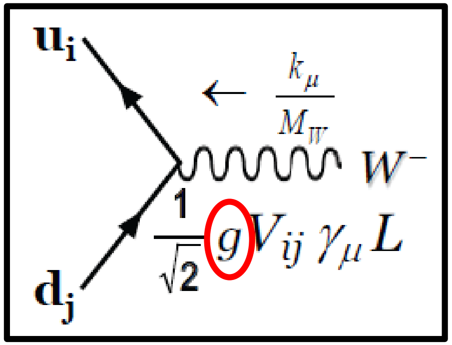
$$\lambda_Q \equiv \frac{\sqrt{2} m_Q}{v}$$

From left-handed (vector) gauge coupling:

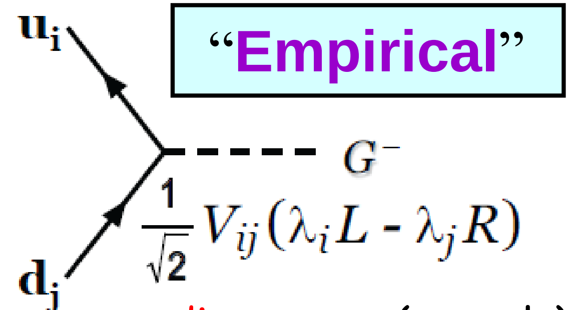
Not Trivial

Empirical!

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



E.o.M. →



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From left-handed (vector) gauge coupling:

Not Trivial

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

complex doublet in Standard Model

Yukawa Coupling: Not Understood, but *Dynamical*

The Enigma: 10^{-5} to $\mathbf{1}$

$\lambda_{u,d,e}$ λ_t $\Rightarrow$

NDA strong ("extremum")

$\frac{4\pi}{\lambda_Q}$ (!?) ← Why Not

Q: $t' \doteq b'$ 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 (Lagangian)

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

III. Yukawa-dynamic EWSB

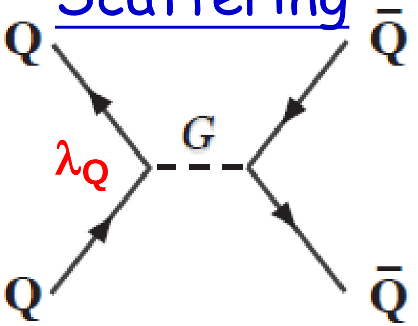
Around Extremum of $\lambda_Q \sim 4\pi$: Emergent

In Pursuit of 4th Generation

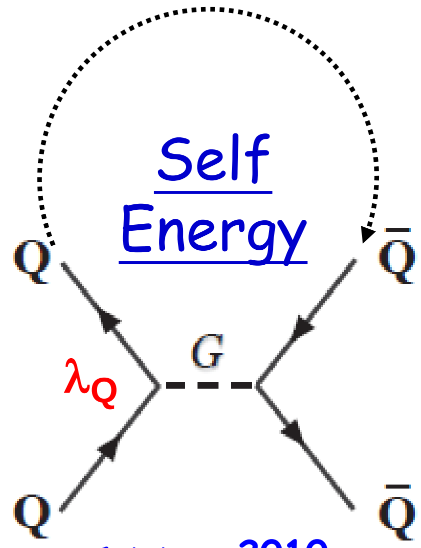
2009 (**Strong Yuk., UBV**)

unitarity bound

Scattering

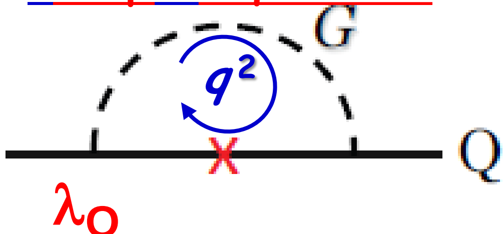


~ $1/M_W$ "long-dist."
(vs $1/m_Q$)



summer 2010,

"Gap" Equation?



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

In Pursuit of 4th Generation

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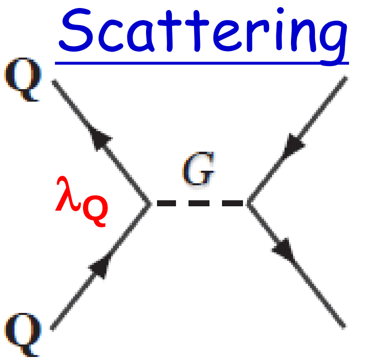

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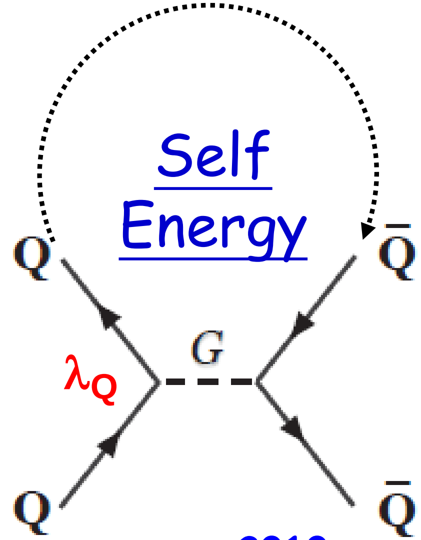
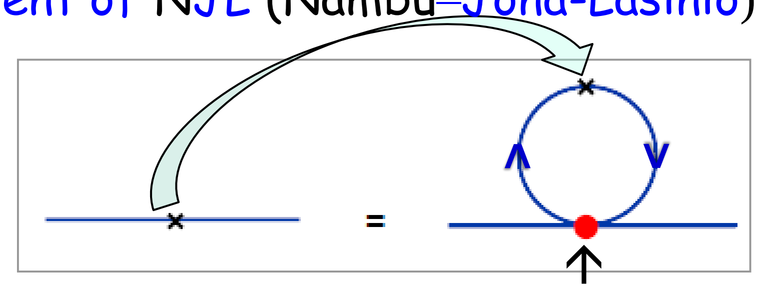
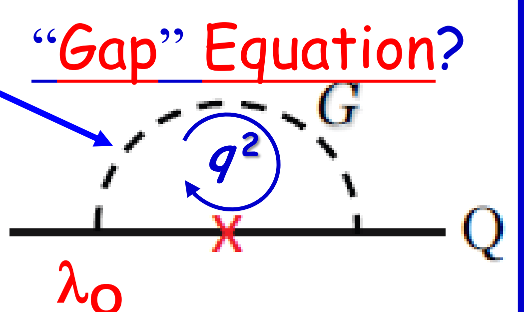


summer 2010,

Reminiscent of NJL (Nambu–Jona-Lasinio)



S.D.



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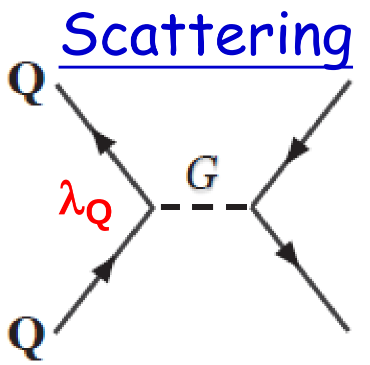

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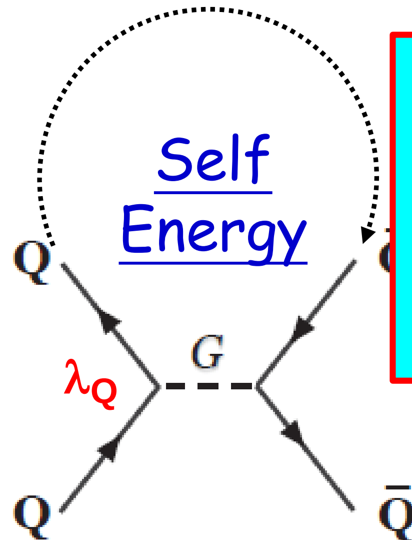


summer 2010,

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

Strong Yuk. Mass Gen.

→ **DSB from *Strong Yuk*.**

a Pairing Mechanism

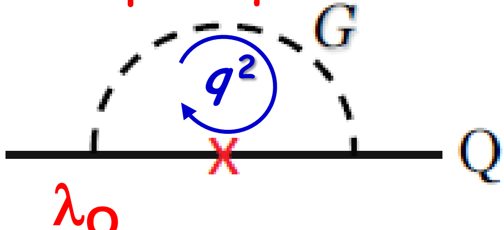
can replace Higgs for v gen.

$\lambda_Q \sim 4\pi$

$m_Q > 2$ TeV!!

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

"Gap" Equation?



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

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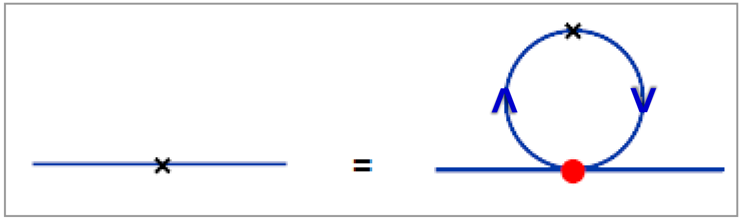


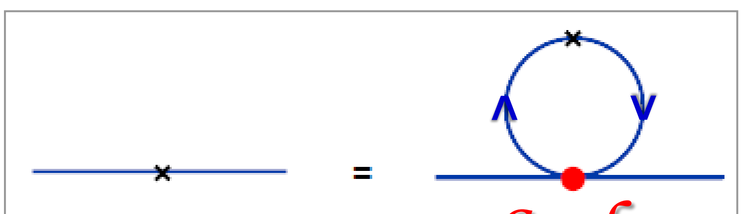
$$\lambda_Q \equiv \frac{\sqrt{2}m_Q}{v}$$

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

⟹ *Allows* Dilation, $\mathcal{D}$, to Emerge.

numerically self-consistent *

Reminiscent of NJL (Nambu–Jona-Lasinio)



Scale

Mimura, WSH, Kohyama
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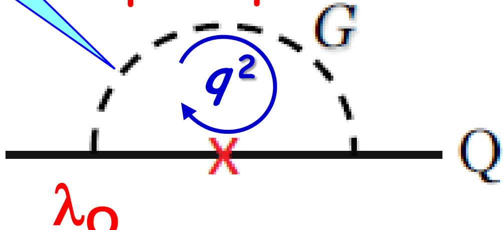

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(Chin. J. Phys., 6/2012)

* backup

$\bar{Q}Q$ Condensation

by *Strong Yukawa*

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

don't quite know why

Dilaton

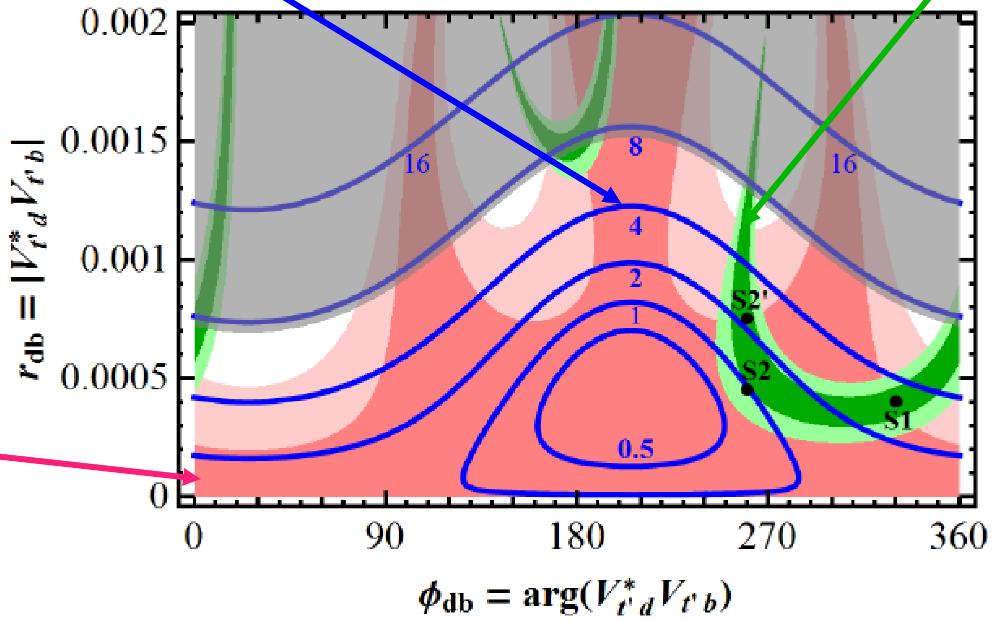
IV. Flavour & CPV

what 4G was "purposed" for ...

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

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.

-0.010 ± 0.039

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

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

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

> ~~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

V. Discussion and Conclusion

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

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

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received August 24, 1949)

π ~ N$\bar{\text{N}}$?

G ~ Q$\bar{\text{Q}}$?

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.

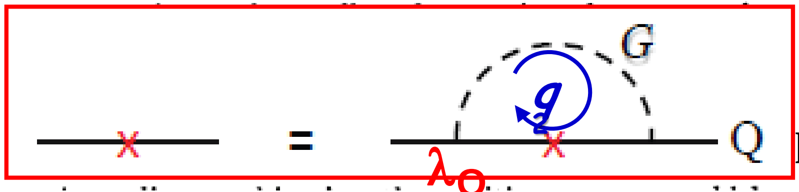
"NDA Strong"

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

Q

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



exact

pointlike

π-N took Path of QCD:
stringy resonances/hadrons

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

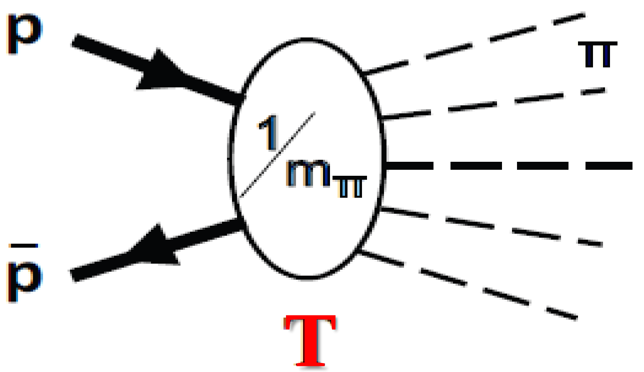
Intriguing: $Q\bar{Q} \to n V_L$ "EW Fireballs"

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

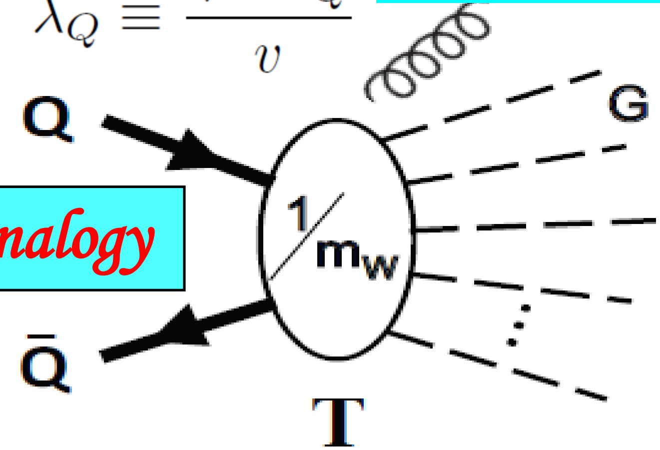
➡ $m_Q \gtrsim 2$ TeV

Boundstate may help

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



Analogy



annihilation "fireball"

- 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.

data

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'2012 [arXiv:1206.1453]

Conclusion

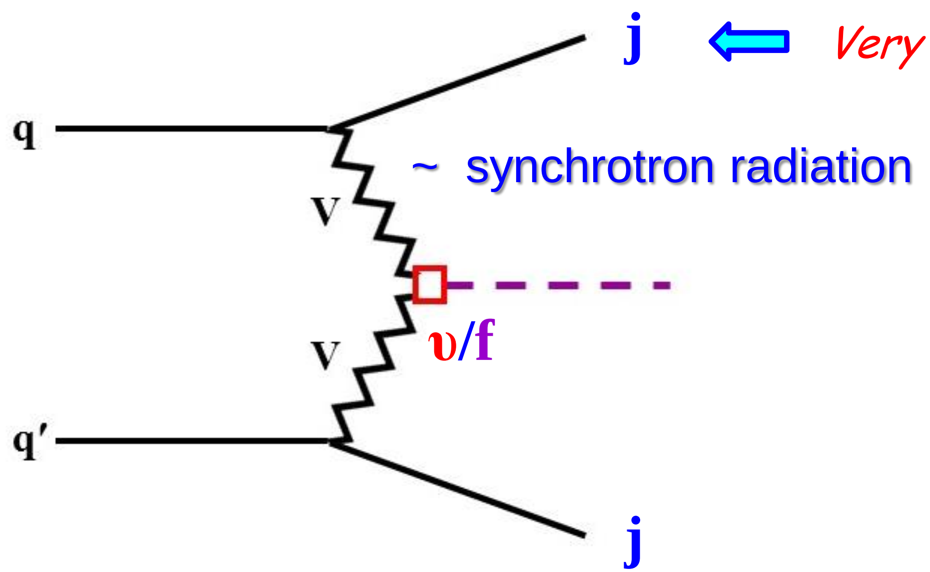
Despite 125 GeV particle, as well as "VBF-like" signal at Run 1, a consistent picture may emerge from confluence of measurements in the next few years ["LHC Run 2"].

Perhaps it would be 4G, rather than SM Higgs ...

- High Purity VBF "Verdict": Higgs/*Dilaton*–ID.
  This is serious, as much as you think it unlikely!
  Agent of EWSB is No Light Matter.
- New "Flavour Anomalies": $B_d \to \mu^+\mu^-$, $K_L \to \pi^0\nu\nu$
  CPV-4-BAU!
- EW Fireball (may have to await higher energy collider)
- What is Direct Signature of Heavy 4G Quarks?

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

Vector Boson Fusion (VBF)



Very Energetic and Forward

Priority Analysis 2015[+], 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

1-2-3 of 2011: No New Physics

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

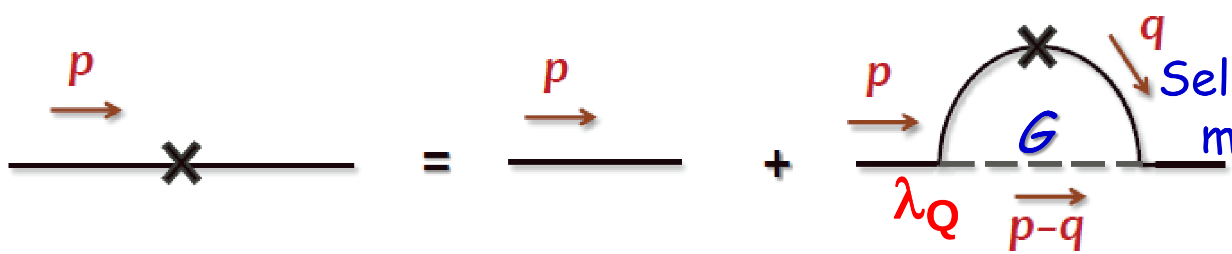
Henri Bachacou, Irfu CEA-Saclay   Lepton-Photon 2011   49

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.) ✓



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

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,

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

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

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

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

the boundary conditions

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

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

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)