Where do we go from here?

Ben Gripaios

Cambridge

April 2013

A cautionary tale
cf. Observational Geography, c. 1953

Newcastle Journal
North Mail
No. 33,336 TUESDAY JUNE 2 1953 A KEMSLEY NEWSPAPER 2d
6 AM

Britain on top of the world on this Elizabeth II day

EVEREST IS CONQUERED

Queen awakened to hear of climbers' triumph

4-PAGE TV AND RADIO GUIDE INSIDE

COMMENTARY

Queen of all hearts

THIS is a great day. Once more we British make plain to the world that we hold firmly to our way of life.

And, most appropriately, last night brought great news to back the claim that our way usually takes us, in the end, to the top.

At the third attempt, the sixth British expedition, under Col. John Hunt, has conquered Everest. It is the happiest of omens.

Skill, tenacity, courage, and great endurance have overcome the terribly powerful defences of the mightiest mountain on earth.

Right instinct

THE significance of Everest may be clearer to the mass of our people than is the symbolism of the Coronation ceremony.

But they know instinctively that the underlying concern is always for them; for their welfare, their protection, their rights and liberties.

They know, too, something which baffles other peoples: that the Crown has gained in influence far more than has been surrendered in direct power.

Yet, ordinarily, they make no parade whatever of their

2 REACH SUMMIT ON 11th EXPEDITION

THE QUEEN WAS WAKENED AT BUCKINGHAM PALACE LATE LAST NIGHT TO BE TOLD THAT THE BRITISH EXPEDITION HAS CONQUERED MOUNT EVEREST.

This great news, on the eve of the Coronation, reached London last night in a message to "The Times" from Col. John Hunt in charge of the expedition.

MR. E. P. HILLARY
He reached the summit.

The climb was made on Friday and Col. Hunt has reported that "all is well."

The successful assault was made by Mr. E. P. Hillary, a New Zealander, and the Sherpa porter named Tensing Bhutia.

This great feat of the new Elizabethans flashed round the world adding still further joy to the heightening Coronation fever.

Mr. Hillary, aged 34, is a bee-keeper in New Zealand. His climbing experience was gained in the Southern Alps in the South Island, a range that has attracted mountaineers from all over the world because of the difficulty of the climbs.

New route

He was an originator of winter ski mountaineering in New Zealand. During the war he served in the Royal New Zealand Air Force.

He had experience in the Himalayas two years ago, when he was a member of the expedition which, led by Eric Shipton, found a way into the Western Cwm.

This discovery opened up a new route for attacks on Everest, and it has been by following up the pioneering work done by Shipton's and other expeditions of the last two years that success has been achieved this time.

Tensing, the "King" of the Sherpa porters of Mount

1 a.m. AND ROYAL ROUTE BARRIERS ARE CLOSED

CROWD barriers were closed hours before schedule early this morning as tens of thousands of sight-seers camped along the Coronation route.

Fifty thousand people jammed in Trafalgar-

CORONATION GOWN

GIRL, 16, STABBED, FRIEND MISSING

AN attractive girl of 16, found dead in the Thames at Richmond yesterday, was murdered and her body flung in the river near Teddington Lock on Sunday night, police decided after a post-mortem examination last night.

There was a gash on her forehead, but death was due to three stab wounds in the back.

Blood-stains were found on the grassy and wooded verge of the river towpath near the lock a mile and a half away.

WENT CYCLING

Police later feared that they had a double murder to contend with.

The dead girl was identified by her mother as Barbara Songhurst, of Princess Road, Teddington. She was an assistant in a chemist's shop.

On Sunday, she went out with her friend, Christine Reed (18), of Roy Crescent, Hampton Hill, for a cycle ride. Christine Reed has now been reported as missing.

Earlier, detectives had been puzzled by two pairs of women's shoes beside the towpath.

Neither cycle has been found.

Duke will watch

1953 - The high energy frontier

1953 - The high energy frontier (of gravitational potential).

1953 - Where do we go from here?

Nowhere.

2013 - Where do we go from here?

2013 - The high energy frontier (of particle physics).

Where is ‘here’?

UNIVERSITY OF CAMBRIDGE

NATURAL SCIENCES TRIPOS **Part IB & II (General)**

Tuesday, 31 May, 2011 9:00 am to 12:00 pm

Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) +
\end{gathered}
$$

$$
\begin{aligned}
&igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \\
&\bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
&1 - \gamma^5)u_j^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
&\gamma^5)u_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + \\
&m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1 - \\
&\gamma^5)u_j^\kappa] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5u_j^\lambda) - \\
&\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5d_j^\lambda) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \\
&\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
&\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \\
&igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

$$\mathscr{L}_{SM}$$

$$\mathscr{L}_{?} = \mathscr{L}_{SM} + \sum \frac{\mathscr{O}_n}{\Lambda^n}$$

- Effects of $\mathscr{O}_n$, $\sim (\frac{E}{\Lambda})^n$.
- What is Λ?

- LHC, all $\mathscr{O}_n$
- LEP & al., $\mathscr{O}_6 = (H^\dagger D_\mu H)^2, \ldots$
- flavour mixing, $\mathscr{O}_6 = (\bar{s}\gamma_\mu d)^2, \ldots$
- proton decay, $\mathscr{O}_6 = qqql, u^c u^c d^c e^c, \ldots$

Probes of generic new physics:

- LHC, $\Lambda \gtrsim$ TeV
- LEP & al., $\Lambda \gtrsim 1 - 10$ TeV
- flavour mixing, $\Lambda \gtrsim 10^{3-5}$ TeV
- proton decay, $\Lambda \gtrsim 10^{13}$ TeV

$\exists$ 1 measurement of Λ:

- ν masses, $\mathscr{O}_5 = (LH)^2$
- $\implies \Lambda \sim 10^{10}$ TeV

This is evidence for, not against, the SM!

Other 'evidence' for Λ:

- Dark Energy $\implies \Lambda \sim 10^{-3}$ eV!
- Dark Matter: $\frac{\Delta\Lambda}{\Lambda} \sim 10^{80}$!
- Baryogenesis $\implies \Lambda \lesssim M_P$!

So why did we build the LHC?!

We built the LHC to answer two qq:

- How is electroweak symmetry broken?
- Is the weak scale natural?

We built the LHC to answer two qq:

- How is electroweak symmetry broken? Via the Higgs mechanism.
- Is the weak scale natural?

Is the weak scale natural?

An answerable question.

$\exists$ 1 troublesome operator

- $\mathscr{O}_2 = H^\dagger H$
- $\mathscr{L} \supset \Lambda^2 H^\dagger H \implies \Lambda \sim 100$ GeV
- naturalness vs. fine-tuning/anthropics ...

- LHC, $\Lambda \gtrsim$ TeV
- LEP & al., $\Lambda \gtrsim 1 - 10$ TeV
- flavour mixing, $\Lambda \gtrsim 10^{3-5}$ TeV
- proton decay, $\Lambda \gtrsim 10^{13}$ TeV

LHC new physics cannot be generic.

Rules out, e.g., a theory with

- 100s of sub-TeV particles
- sizable couplings
- new flavour structures $\neq y^u, y^d, y^e$
- no accidental B or L symmetry

a.k.a. SUSY!

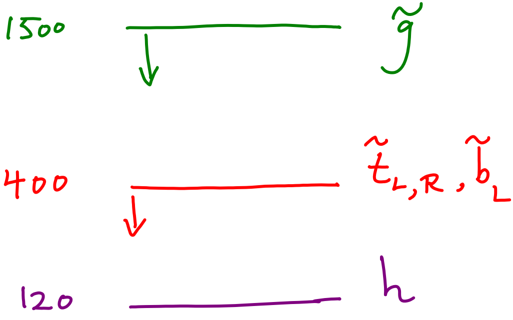
Our predicament requires baroque new physics . . .

e.g. 1/2: unnatural SUSY

Dimopoulos & Giudice

The Mona Lisa of Physics

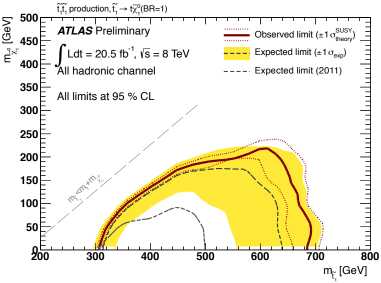
Cumpulsory Natural SUSY

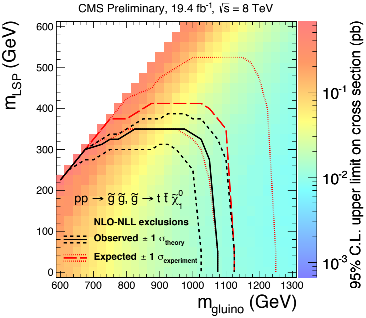


Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

Arkani-Hamed, CERN talk, 2011

Unnatural SUSY





ATLAS-CONF-2013-024 & CMS-SUS-12-024

e.g. 2/2: composite Higgs

e.g. 2/2: composite Higgs

- as plausible as SUSY
- similar resources should be devoted to it

A rhetorical question: What if $\nexists$ Higgs?

What if $\nexists$ Higgs?

- An 'almost perfect' rendition of EWSB!
- QCD has a natural scale $\sim$ GeV
- Global χSB: $SU(2)_L \times SU(2)_R \to SU(2)_V$
- Gauge $\supset SU(2)_L \times U(1)_Y \to U(1)_{em}$
- (But $m_{W,Z} \sim$ GeV)

QCD Colour $\rightarrow$ Technicolour

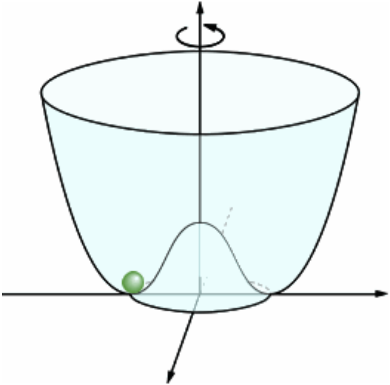
- natural scale $\sim$ 100 GeV
- Global $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- Gauge $\supset SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$
- A perfect, natural rendition of EWSB
- (But no Higgs, flavour, EWPT, ...)

Technicolour $\rightarrow$ Composite Higgs

Kaplan & Georgi, 84 ...

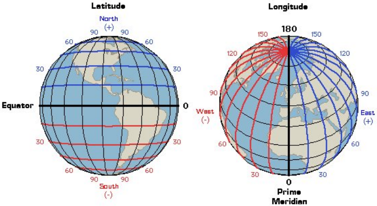
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ is equivalent to $SO(4) \rightarrow SO(3)$
- Generalize to $SO(n+1) \rightarrow SO(n) \ldots$

Geography of $SO(n+1) \to SO(n)$ via proof by example.



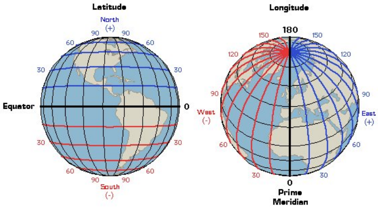
Consider $SO(2) \to SO(1)$:

- There is 1 Goldstone boson: an angle



Consider $SO(3) \to SO(2)$:

- There are 2 Goldstone bosons: latitude and longitude.



Now gauge $SO(2) \subset SO(3)$:

- Rotations about a preferred direction, cf. Earth's axis
- Goldstone boson $\rightarrow$ pseudo-GB
- Gets potential and coupling to gauge fields
- cf. temperature on Earth

Consider $SO(5) \to SO(4)$:

- There are 4 Goldstone bosons: angles of S^4
- they are a $2_{\frac{1}{2}}$ of $SU(2) \times U(1)_Y \subset SO(4)$, viz. the Higgs field, H
- Gauging $SU(2) \times U(1)_Y$ plus coupling to t generates $V(H)$ and $HWW, H\gamma\gamma$ etc
- a.k.a. the Minimal Composite Higgs model

Agashe, Contino, & Pomarol, 0412089

The minimal composite Higgs model

- $\Delta S \propto \theta^2 \implies$ 20 % tuning
- This is a lot better than SUSY

Phenomenology of composite Higgs models

- Natural because strongly-coupled
- We cannot compute!
- Use same tricks for QCD: symmetry, chiral Lagrangians, . . .
- Simplified models

Phenomenology of composite Higgs models: bad news

- Departures from SM in e.g. H couplings $\propto \theta^2 \sim 20$ %
- Generic resonance masses $\sim 4\pi v/\theta \sim$ few TeV

Phenomenology of composite Higgs models: good news

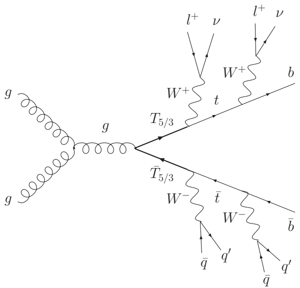
- Naturalness $\Longrightarrow$ light, fermionic top partner

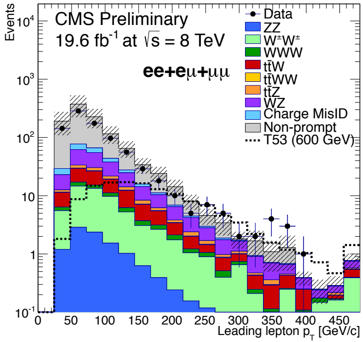
Contino, da Rold & Pomarol, 0612048

- dof: $SO(4)/SO(5)$ reps, compositeness, mass, few couplings
- e.g. $\mathbf{1} = T$ or $\mathbf{4} = (B, T, T', X^{\frac{5}{3}})$ of $SO(4)$

De Simone et al., 1211.5663

Pair production of $X^{\frac{5}{3}}$

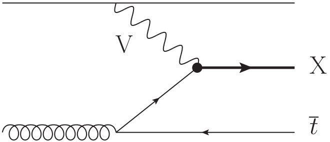


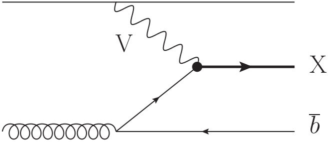


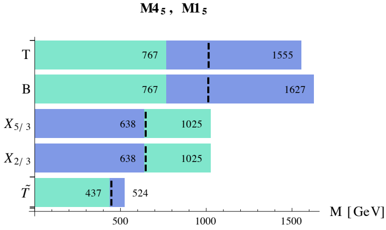
$m > 770 GeV$

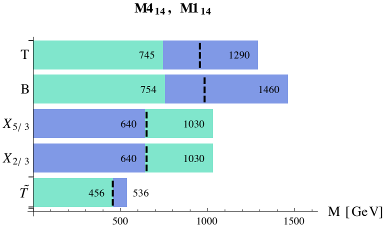
CMS-B2G-12-012

Single production dominates at high mass/coupling









Optimize 4th gen. searches for forward jets

De Simone et al., 1211.5663

- a huge amount of work to be done, by theorists and experimentalists
- we must do the best we can with LHC14

What if we come up empty-handed?

We will, nevertheless, have answered both questions.

We built the LHC to answer two qq:

- How is electroweak symmetry broken? Via the Higgs mechanism.
- Is the weak scale natural? No.

At least our hubris will be profound.

“So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value.” Spanish Royal Commision, 1490

"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.... Our future discoveries must be looked for in the sixth place of decimals." Michelson, 1894