BSM for LHC run II

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Cambridge

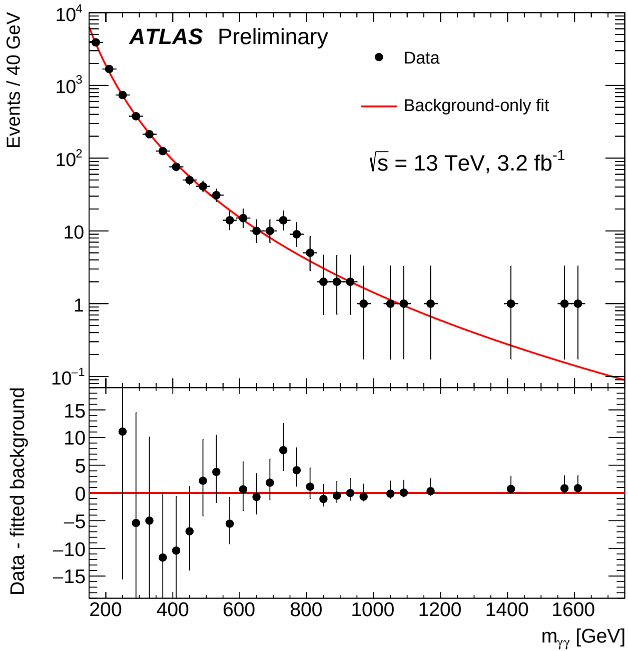
January 2016

Outline

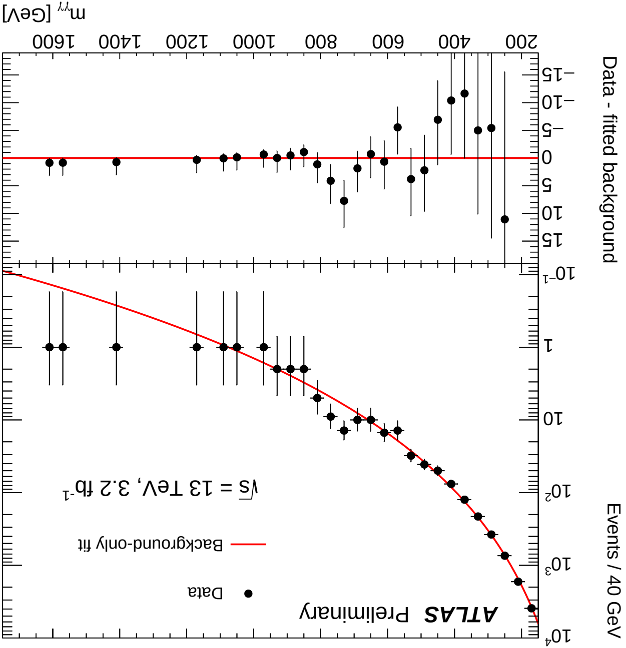
- Di-photon anomaly
- Composite Higgs
- Other anomalies: di-bosons and B-decays

Things that go bump in the night . . .

ATLAS 13 TeV 3.2 /fb: 14 events at 750 GeV



Sanity checks . . .



ATLAS-CONF-2015-081

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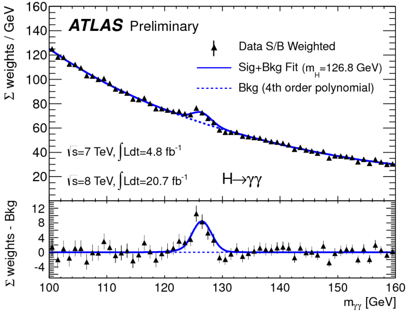
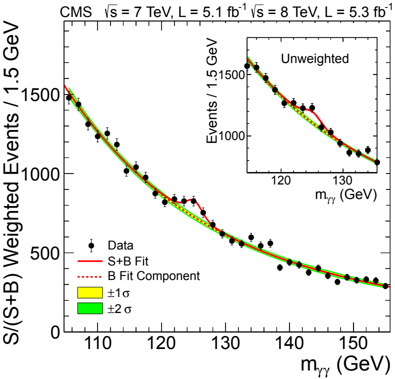
The ‘S/B weighted’ game is apparently no longer considered cricket.





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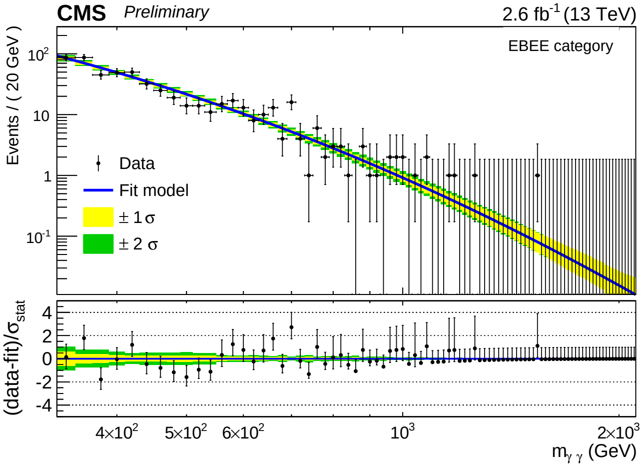
ATLAS 3.2/fb: 3.9σ local, 2.3σ global

ATLAS-CONF-2015-081

CMS 2.6/fb: 10 events at 760 GeV



CMS-EXO-15-004

What is the $\gamma\gamma$ resonance at 750 GeV?

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<polemic>


THE Sun
30p
FA CUP
SOUTHEND........1
CHELSEA...........4
PREMIER LEAGUE
MAN UTD............1
WIGAN...............0
SEE SUNSPORT
SAVE
£5.20
OFF SHOPPING WITH CAPTAIN CRUNCH
VOUCHERS: PAGES 36 & 37
Ski girl
dies in
icy river
By NEIL SYSON
NASA'S HISTORIC DISCOVERY OF METHANE ON THE RED PLANET
LIFE
ON MARS

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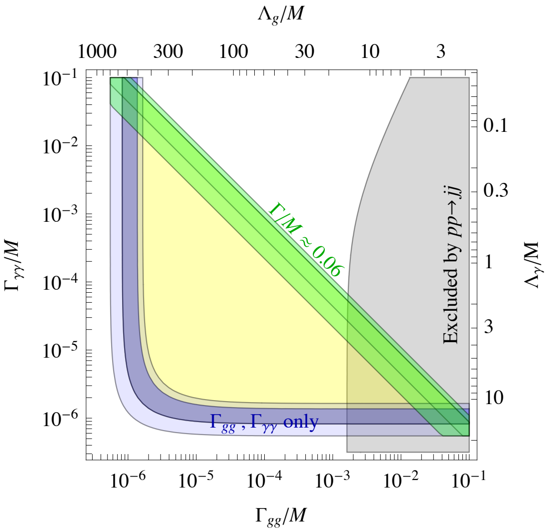
Qualitatively

- Big $\sigma \times BR$
- Excess in 2 bins $\implies$ wide
- $\implies$ strong interactions?
- $\implies$ inconsistent with 8 TeV?
- $\times$5 pdf gain for 2σ compatibility $\implies$ gg or QQ production modes

Franceschini et al. et al. et al., 1512.04933

$$\frac{\Gamma_{\gamma\gamma}}{M}\,\frac{\Gamma_{gg}}{M} \approx 1.1 \times 10^{-6}\;\frac{\Gamma}{M} \approx 6 \times 10^{-8}$$



Franceschini et al. et al. et al., 1512.04933

Couplings from EW invariants:

$$\frac{g_3^2}{\Lambda_3}\eta\, G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{g_2^2}{\Lambda_2}\eta\, W^{\mu\nu}\tilde{W}_{\mu\nu} + \frac{g_1^2}{\Lambda_1}\eta\, B^{\mu\nu}\tilde{B}_{\mu\nu}$$

BB: $\frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)} = 2\tan^2\theta_{\rm W} \approx 0.6, \qquad \frac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)} = \tan^4\theta_{\rm W} \approx 0.08.$

$$\frac{\Gamma(S \to WW)}{\Gamma(S \to \gamma\gamma)} = \frac{2}{\sin^4\theta_{\rm W}} \approx 40,$$

WW: $\frac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)} = \frac{1}{\tan^4\theta_{\rm W}} \approx 12, \qquad \frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)} = \frac{2}{\tan^2\theta_{\rm W}} \approx 7.$

Franceschini et al. et al. et al., 1512.04933

Composite Higgs overview

Composite Higgs $\equiv$ modern incarnation of natural EWSB via strong dynamics.

Why not EWSB via weak dynamics, i.e. SUSY?

Why haven't we seen any superpartners?

- generic SUSY theory predicts $> O(10^2)$ superpartners
- sprinkled around the weak scale $\sim 100 GeV$
- cf. bounds $\sim TeV$
- Avoid this by: reintroducing a tuning. Ugh!
- Or by tuning in theory space. Ugh!

n.b. ‘Natural’ SUSY $\equiv$ Unnatural SUSY!

So, what about strong EWSB?

A solution to the hierarchy problem that is <u>literally</u> natural.

To see this, consider the SM minus the Higgs . . .

To see this, consider the SM minus the Higgs ...

- QCD coupling still runs much the same way
- confines at GeV
- $SU(2)_L \times SU(2)_R$ chiral symmetries of quarks get broken to $SU(2)_V$
- $\implies SU(2)_L \times U(1)_Y \to U(1)_{em}$

To see this, consider the SM minus the Higgs ...

- $W^{\pm}, Z^0$ bosons get masses by eating $\pi^{\pm}, \pi^0$
- Even m_W/m_Z comes out right!
- $f_\pi \sim 100 MeV \implies m_W \sim 30 MeV$ comes out wrong!

The seed of a beautiful (but wrong) idea . . . technicolour

The seed of a beautiful (but wrong) idea ... technicolour

- Assume there is another strong force
- But that it confines at 100 GeV

But technicolour is killed by a treble whammy:

- Flavour physics
- Electroweak precision tests
- It predicts no Higgs!

Flavour physics problems

Natural hierarchy $\implies d[\mathscr{O}] \gtrsim 4$

Two ways to get fermion masses:

- Bi-linear:

$$\mathscr{L} = y f_L \mathscr{O}_H f_R, \;\; \mathscr{O}_H \sim (1,2)_{\frac{1}{2}}$$

- Linear:

$$\mathscr{L} = y_L f_L \mathscr{O}_R + y_R f_R \mathscr{O}_L + m \mathscr{O}_L \mathscr{O}_H \mathscr{O}_R, \;\; \mathscr{O}_R \sim (3,2)_{\frac{1}{6}}$$

D. B. Kaplan, 1991

Bi-linear fermion masses

$$\mathscr{L} = \frac{f_L \mathscr{O}_H f_R}{\Lambda_F^{d-1}} + \frac{f_L f_R f_L f_R}{\Lambda_F^2}$$

$$\text{FCNC} \implies \Lambda_F \gtrsim 10^{3-4}\, TeV \implies d \lesssim 1.2 - 1.3$$

- TC: $d \sim 3$
- WTC: $d \sim 2$
- SM: $d \sim 1$ (but then $d[\mathscr{O}_H^\dagger \mathscr{O}_H] \sim 2$)

Strassler, 0309122

Luty & Okui, 0409274

Rattazzi, Rychkov & Vichi, 0807.0004

Rychkov & Vichi, 0905.2211

Linear fermion masses

$$\mathscr{L} = y_L f_L \mathscr{O}_R + y_R f_R \mathscr{O}_L + m \mathscr{O}_{L,R} \mathscr{O}_H \mathscr{O}_{L,R}$$

- $\mathscr{O}_{L,R}$ can be relevant
- Flavour can be decoupled
- RS-GIM

Gherghetta & Pomarol, 0003129

Huber & Shafi, 0010195

Agashe, Perez & Soni, 0406101

Agashe, Perez & Soni, 0408134

Agashe, Contino & Pomarol, 0412089

‘Flavour can be decoupled’ $\neq$ ‘Flavour is decoupled’
To settle this needs knowledge of strong dynamics.

EWPT problems

Contributions to EWPT $\sim \frac{m_W^2}{m_\rho^2}$ are too large in technicolour.

EWPT problems

Strongest constraints from

- T (a.k.a. m_W/m_Z) $\implies m_\rho \gtrsim$ 10 TeV
- $\Gamma(Z \to b\bar{b}) \implies m_\rho \gtrsim$ couple TeV
- $S \implies m_\rho \gtrsim$ couple TeV

EWPT problems

- T is fine: custodial symmetry $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V} = \frac{SO(4)}{SO(3)}$

  Sikivie, Susskind, Voloshin & Zakharov, 1980

- $\Gamma(Z \to b\bar{b})$ can also be protected by a symmetry

  Agashe, Contino, Da Rold & Pomarol, 0605341

- But there is no (unbroken) symmetry for S!

EWPT problems

There is a broken symmetry for S: $SU(2)_L$

Inami, Lim & Yamada, 1992

- v is a 2, S is a 3 $\implies S \sim v^2/\Lambda^2$
- $v \ll \Lambda$?
- Try $SO(4)/SO(3) \to SO(5)/SO(4)$

Georgi, Kaplan, others, 1980s

Agashe, Contino & Pomarol, 0412089

- NGBs a **4** of $SO(4)$, viz. H
- $SO(5)$ is not exact $\implies$ potential for H
- Gauging stabilizes origin; fermions destabilize it.
- Small tuning between the two $\implies$ small v/Λ

This is still a $O(20\%)$ tuning!

Recap: 'The Minimal Composite Higgs Model'

Agashe, Contino & Pomarol, 0412089

- Assume new strong sector with global symmetry $SO(5)$
- broken to subgroup $SO(4)$ by strong dynamics at TeV scale
- Fermion masses arise by partial compositeness
- Weak gauging of $SU(2)_L \times U(1)_Y \subset SO(4)$
- EWPT satisfied by a combination of symmetries and a small tuning

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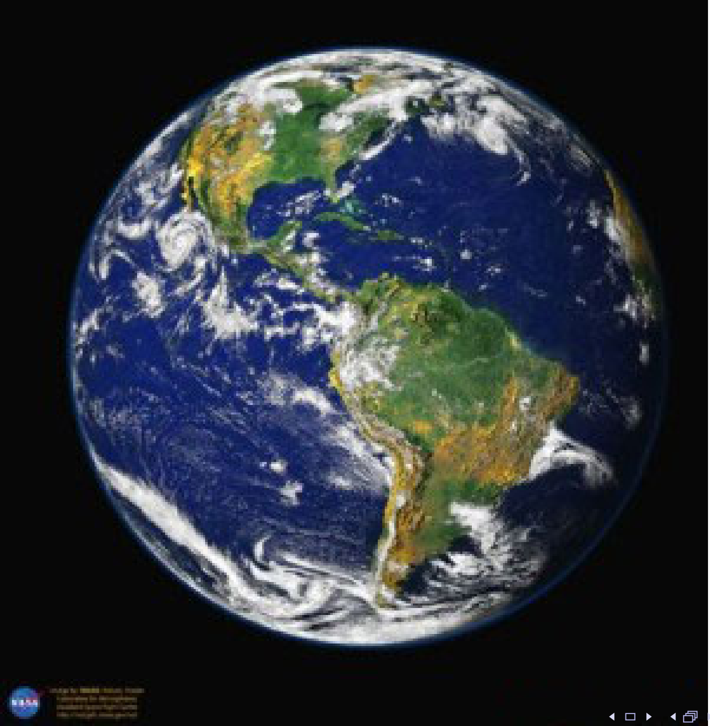
$SO(5)/SO(4)$ is not so mysterious. It is S^4.
Similarly, $SO(n)/SO(n-1) \simeq S^{n-1}$.



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The Minimal Composite Higgs Model @ LHC

- Light d. o. f.: SM Higgs
- Expect small deviations from SM couplings

Giudice, Grojean, Pomarol & Rattazzi,0703164

Falkowski, 0711.0828

Low, Rattazzi & Vichi, 0907.5413

- Best to look for light (top) partners?

Contino & Servant, 0801.1679

de Simone & al., 1211.5663

BMG, Muller, Parker & Sutherland, 1406.5957

Beyond The Minimal Composite Higgs Model?

BMG, A. Pomarol, F. Riva, J. Serra, 0902.1483

Why go beyond?

- Nature doesn't always choose minimal option
- $SO(n)$ is hard to get as a global symmetry.
- $SU(n)$ is much easier.

Any G/H with $SO(5) \subset G$ and $SO(4) \subset H$ seems it will do
$\implies$ extended Higgs sector

But extra states that transform under $SO(4)$ will contribute to T if they get a vev.

$G/H = SO(n)/SO(n-1)$ yields SM Higgs + $n-5$ EW singlets.

$SO(6)/SO(5)$ is unique because $SO(6) \simeq SU(4)$.

Focus on $SO(6)/SO(5)$:

BMG, A. Pomarol, F. Riva, J. Serra, 0902.1483

- A single Higgs doublet plus a singlet!
- Singlet mass is roughly $m_\eta = \frac{f}{v} m_h \gtrsim 600 GeV$!

Another key feature of PC models: Colour

BMG, arXiv:0910.1789

- *PC* $\implies$ every SM state has a strong sector partner
- $\implies$ The strong sector is charged under $SU(3)$ colour
- $\implies$ η couples to everything, including *gg*
- (not such a surprise: so does *H*)
- couplings to fermions scale like Higgs Yukawas
- Plausible explanation of di-photon anomaly

Run 2 agenda

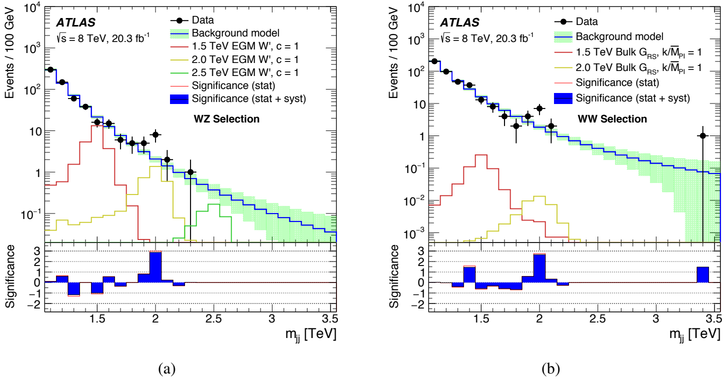
- Confirm excess
- Look for couplings to $Z\gamma$, ZZ and $SU(2) \times U(1)$ consistency
- Look for couplings to everything else (fermions)
- Look for all the other strong sector resonances (TeV . . .)

What about the other anomalies?

Di-boson anomaly

ATLAS

- seeks 2, 2-prong fat jets with $m_j \in [69.4, 95.4]$ (a ' W') or $\in [79.8, 105.8]$ (a ' Z')
- finds bumps at 2 TeV in 'WW', 'WZ', & 'ZZ' of 2.6, 3.4, & 2.9 σ bzw.



ATLAS, 1506.00962

More questions than answers …

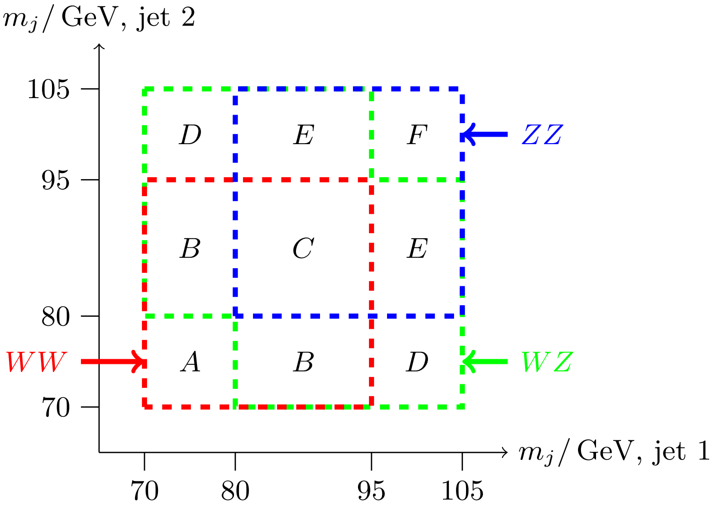
- $m_j \in [69.4, 95.4]$ (a ‘ W’) or $\in [79.8, 105.8]$ (a ‘ Z’) $\Longrightarrow$ signals overlap
- How many events are common?
- What is the true local/global significance?
- Are these (likely) Ws or Zs?
- …

Start by trying to answer some of these qq ...

... by a poor man's (i.e. theorist's) likelihood analysis.

Allanach, BMG & Sutherland, 1507.01638
cf. Brehmer & al., 1507.00013
cf. Fichet & von Gersdorff, 1508.04814

1. In an ancillary file far, far away, we are told the numbers in the ‘WW+ZZ’ and ‘WW+WZ+ZZ’ regions



$$WW = A + B + C,$$
$$ZZ = C + E + F,$$
$$WZ = B + C + D + E,$$
$$WW + ZZ = A + B + C + E + F,$$
$$WW + WZ + ZZ = A + B + C + D + E + F.$$

Even a theorist can't solve 5 eqns in 6 unknowns!
For the 3 bins around 2 TeV:

	A	B	C	D	E	F
$n_i^{\mathrm{obs},1}$	2	6	5	0	4	0
$n_i^{\mathrm{obs},2}$	1	7	5	0	3	1
$n_i^{\mathrm{obs},3}$	0	8	5	0	2	2
μ_i^{SM}	2.09	2.72	1.00	2.43	0.46	0.34

2. Read off probabilities (from ATLAS model simulation) for bosons from a 2 TeV resonance to fall in the signal regions:

	W jet tag only	W and Z jet tag	Z jet tag only
true W	0.25	0.36	0.04
true Z	0.11	0.39	0.21

M_{ji}	A	B	C	D	E	F
true WW	0.063	0.182	0.132	0.018	0.025	0.001
true WZ	0.028	0.139	0.143	0.057	0.090	0.007
true ZZ	0.012	0.087	0.155	0.047	0.165	0.044

3. Use ATLAS' reported efficiencies, branching ratios, etc, to compute a final Poisson likelihood:

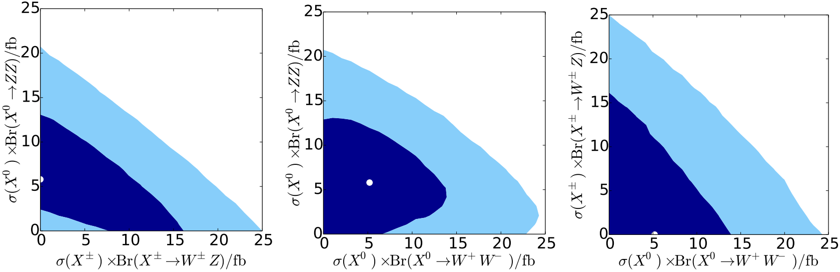
$$p(\{n_i^{\mathrm{obs},\alpha}\}|s_{WW},\ s_{WZ},\ s_{ZZ}) =$$

$$\sum_{\alpha=1}^{3} \frac{\exp\left[-\sum_{i\in\{A,B,C,D,E,F\}}\left(\mu_i^{SM} + \epsilon\sum_{j=1}^{3} b_i s_j M_{ji}\right)\right]}{\prod_{i\in\{A,B,C,D,E,F\}} n_i^{\mathrm{obs},\alpha}!}$$

$$\prod_{i\in\{A,B,C,D,E,F\}} \left(\mu_i^{SM} + \epsilon\sum_{j=1}^{3} b_i s_j M_{ji}\right)^{n_i^{\mathrm{obs},\alpha}},$$

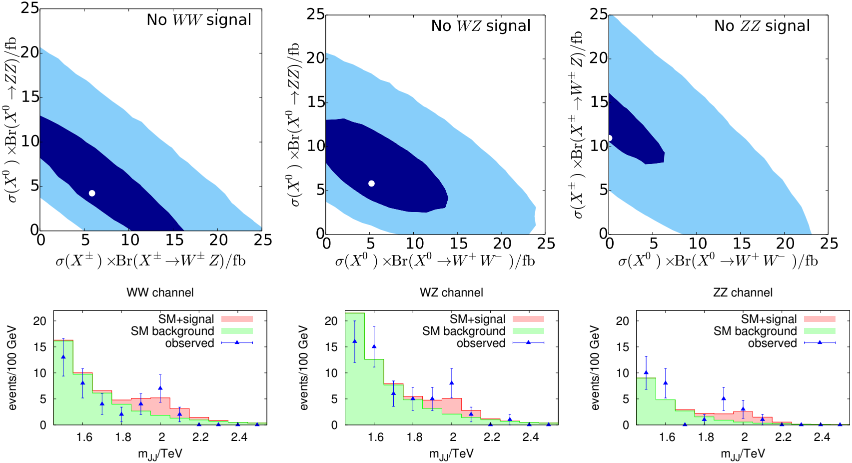
Likelihood results:

- In terms of $\sigma \times BR$ of WW, WZ, and ZZ components
- Best fit at 5.2, 0, 5.8 fb, bzw.
- But pretty flat!



Likelihood results II:

- SM has p-value of 6×10^{-4} ($4\ \sigma$)
- Likelihood with one channel forced to vanish ($\Delta\chi^2 < 1$)



More questions than answers ...

- How many events are common? 13/17, 15/17, 9/17.
- What is the combined local significance? 4σ $(3.4 < 4 < 5.2)$
- Are these (likely) Ws or Zs? Likely equal WW and ZZ with no WZ

2 likely models: EFTs of an $SU(2)_L$ or an $SU(2)_R$ triplet vector boson

Allanach, BMG & Sutherland, 1507.01638

Can either explain the anomaly without conflict with other searches?

e.g. $SU(2)_L$ triplet.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}\rho^a_{\mu\nu}\rho^{a\mu\nu} + (\frac{1}{2}m^2_\rho + \frac{1}{4}g^2_m H^\dagger H)\rho^a_\mu\rho^{a\mu}$$
$$-2g\epsilon^{abc}\partial_{[\mu}\rho^a_{\nu]}W^{b\mu}\rho^{c\nu} - g\epsilon^{abc}\partial_{[\mu}W^a_{\nu]}\rho^{b\mu}\rho^{c\nu}$$
$$+(\frac{1}{2}ig_\rho\rho^a_\mu H^\dagger\sigma^a D^\mu H + \mathrm{h.c.}) + g_q\rho^a_\mu\overline{Q_L}\gamma^\mu\sigma^a Q_L$$

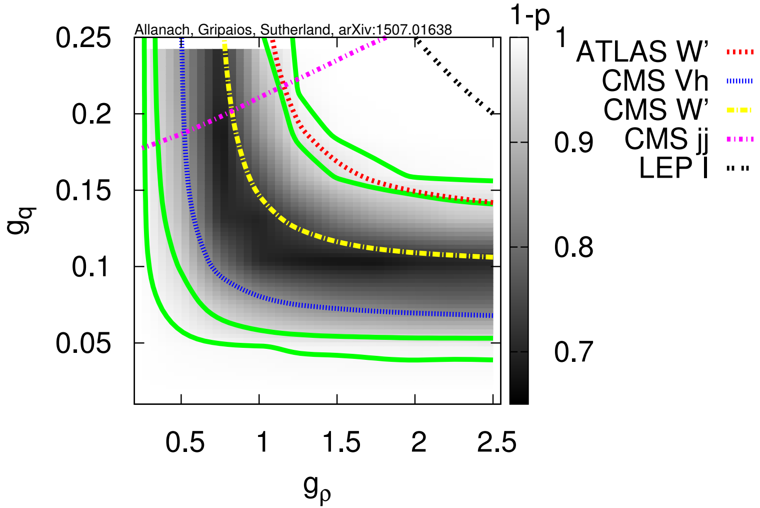
Callan, Coleman, Wess & Zumino

e.g. $SU(2)_L$ triplet.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\rho^a_{\mu\nu}\rho^{a\mu\nu} + (\frac{1}{2}m_\rho^2 + \frac{1}{4}g_m^2 H^\dagger H)\rho^a_\mu\rho^{a\mu}$$
$$-2g\epsilon^{abc}\partial_{[\mu}\rho^a_{\nu]}W^{b\mu}\rho^{c\nu} - g\epsilon^{abc}\partial_{[\mu}W^a_{\nu]}\rho^{b\mu}\rho^{c\nu}$$
$$+(\frac{1}{2}ig_\rho\rho^a_\mu H^\dagger\sigma^a D^\mu H + \text{h.c.}) + g_q\rho^a_\mu\overline{Q_L}\gamma^\mu\sigma^a Q_L$$

Callan, Coleman, Wess & Zumino

e.g. $SU(2)_L$ triplet.



ATLAS, 1409.6190
CMS, 1506.01443
CMS, 1405.1994
CMS, 1501.04198
Pomarol & Riva, 1308.2803

Can this be described by a composite Higgs model?

- Yes!
- recall: $PC \implies$ every SM state has a strong sector partner
- In fact CH with custodial symmetry features both $L-$ and $R-$ triplet partners
- Either will do!

Thamm & al., 1506.08688

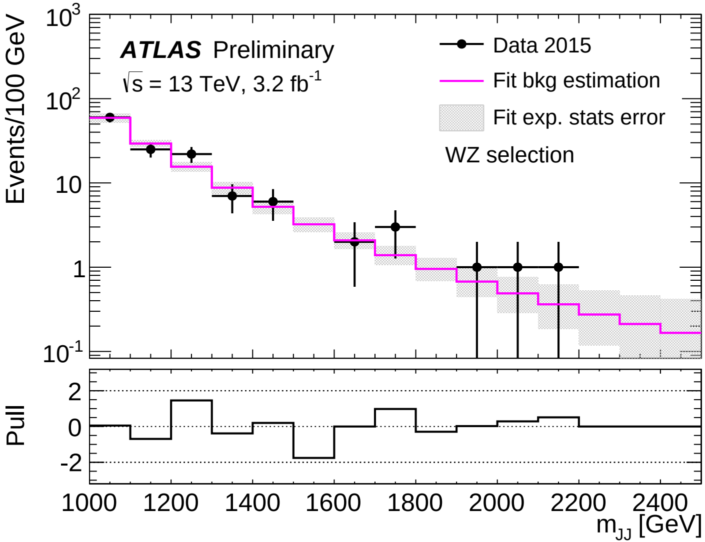
Low & al., 1507.07557

Niehoff & al., 1508.00569

- PC $\implies$ region with small g_q

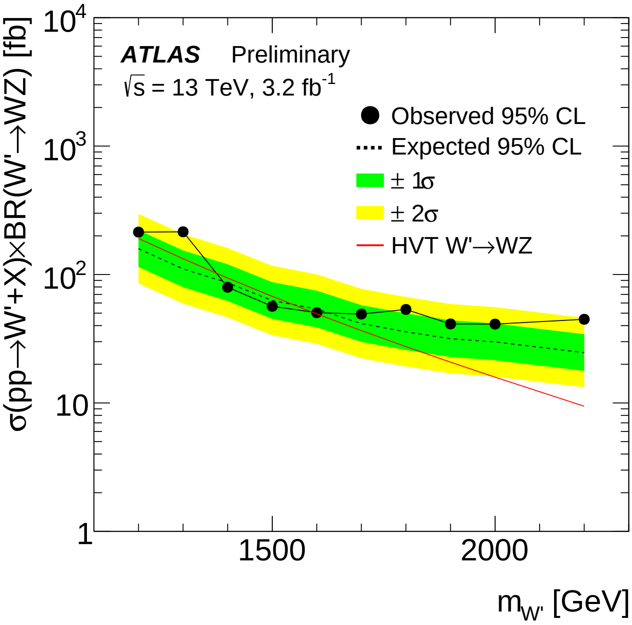
First ATLAS 13 TeV results (3.2/fb)!

ATLAS-CONF-2015-073



Fit W' with $m = 2TeV$, $\sigma \times BR = 7.6$fb:

ATLAS-CONF-2015-073



Run 2 prospects ... . . .

- No hint in other channels

llqq: ATLAS-CONF-2015-071

$l\nu qq$: ATLAS-CONF-2015-075

$l(\nu)l(\nu)bb$ ATLAS-CONF-2015-074

- CMS similar

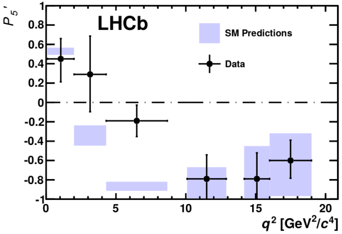
CMS-EXO-15-002

- not inconsistent
- if it is CH, look for other couplings implied by PC
- other resonances close by (esp. top partners)

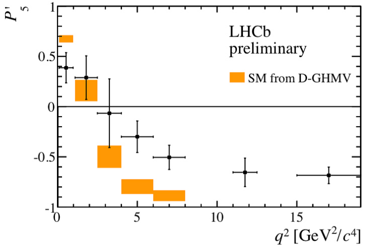
B-physics anomalies

Anomalies in B decays I: $B \to K^* \mu\mu$

2013: LHCb measures anomalies in angular observables in $B \to K^* \mu\mu$ decays with 1fb^{-1} LHCb, 1308.1707, particularly in an optimized observable called P_5' ($\sim 3.7\sigma$)



2015: Confirmed with full 3fb^{-1} data from Run I LHCb-CONF-2015-002



Anomalies in B decays: R_K and branching ratios

2014: 2.6σ anomaly seen in observable R_K: LHCb, 1406.6482

$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

Uncertainties cancel in theory prediction of R_K:
$R_K^{SM} = 1.0003 \pm 0.0001$ Bobeth & al. 0709.4174

Also tensions in some other $b \to s\mu\mu$ observables, eg.: Straub, Moriond 2015

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

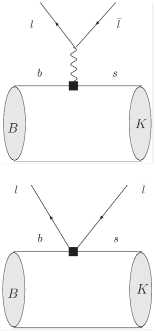
Model-independent NP interpretation

Effective hamiltonian for $b \to s\ell\ell$ transitions $\mathscr{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} (V_{ts}^* V_{tb}) \sum_i C_i^\ell \mathscr{O}_i^\ell$ where $((\ell = e, \mu, \tau))$, $\mathscr{O}_i^\ell$ are:

$$\mathscr{O}_7^{(\prime)} = \qquad \text{DIPOLE}$$

$$\mathscr{O}_9^{\ell(\prime)} = \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \ell\right) \qquad \text{VECTOR}$$

$$\mathscr{O}_{10}^{\ell(\prime)} = \qquad \text{AXIAL VECTOR}$$

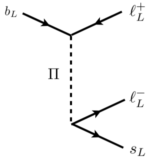


Data are best fit by: e.g. Altmannshofer & Straub 1411.3161, Straub Moriond 2015, Matias Moriond 2015

- Negative contribution to C_9^μ:
  $C_9^{NP,\mu} \in [-1.65, -0.95]$
  (A bit silly, since only $C_9^{NP} = \mp C_{10}^{NP}$ are plausible.)
- Contributions of opposite sign to C_9^μ and C_{10}^μ:
  $C_9^{NP,\mu} = -C_{10}^{NP,\mu} \in [-0.74, -0.29]$

Leptoquark-mediated $b \to s\mu\mu$

A leptoquark Π with SM quantum numbers $(\bar{\mathbf{3}}, \mathbf{3}, \frac{1}{3})$ can mediate the process $b \to s\ell\ell$ Hiller & Schmaltz, 1408.1627



Couplings to s, b, and μ suggested to explain anomalies, with

$$\frac{|\lambda_{\mu b}^{*}\lambda_{\mu s}|}{M^2} \approx \frac{1}{(48\mathrm{TeV})^2}$$

Generates $C_9^{NP,\mu} = -C_{10}^{NP,\mu} \approx -0.5$

What have leptoquarks got to do with the composite Higgs?

Another key feature of PC models: Colour

BMG, arXiv:0910.1789

- $PC \implies$ every SM state has a heavy partner
- $\implies$ The strong sector is charged under $SU(3)$ colour
- $\implies$ the strong sector contains coloured, EW-charged fermions
- $\implies$? the strong sector contains coloured, EW-charged scalars
- Leptoquarks coupled mostly to 3rd generation quarks and leptons.
- If chiral, consistent with all pre-LHC flavour constraints!

Leptoquarks in CH models

BMG, arXiv:0910.1789

- Can even be light, if PNGBs
- With G/H given by

$$\frac{SO(9)\times SO(5)}{SU(4)\times SU(2)_\Pi\times SU(2)_H\times SU(2)_R}.$$

get PNGBs $H\sim(\mathbf{1},\mathbf{2},\frac{1}{2})$ and LQ $\Pi\sim(\bar{\mathbf{3}},\mathbf{3},\frac{1}{3})$!

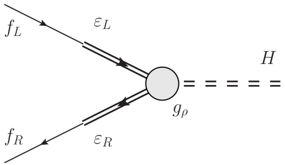
BMG, Nardecchia, & Renner, 1412.1791

- All other resonances of the new strong dynamics around m_ρ
- Leptoquark mass term comes mostly from QCD, so

$$m_\Pi^2\sim\frac{\alpha_s}{4\pi}m_\rho^2\sim\left(\frac{1}{10}m_\rho\right)^2$$

Partial Compositeness & LQ couplings

$$\mathscr{L} \supset \varepsilon^q \overline{\mathscr{O}}^q q + \varepsilon^u \overline{\mathscr{O}}^u u + m_\rho \left(\overline{\mathscr{O}}^q \mathscr{O}^q + \overline{\mathscr{O}}^u \mathscr{O}^u \right) + g_\rho \overline{\mathscr{O}}^q H \mathscr{O}^u .$$



$\Longrightarrow$ Yukawa couplings

$$(Y_u)_{ij} \sim g_\rho \varepsilon_i^q \varepsilon_j^u , \qquad (Y_d)_{ij} \sim g_\rho \varepsilon_i^q \varepsilon_j^d .$$

Partial Compositeness & LQ couplings II

BMG, Nardecchia, & Renner, 1412.1791

10 params. in quark Yukawa sector: $g_\rho, \varepsilon_i^q, \varepsilon_i^u, \varepsilon_j^d$.

Choose ε_i^q, ε_i^u, and ε_i^d to reproduce quark masses and CKM:

$$g_\rho v \varepsilon_i^q \varepsilon_i^u \sim m_i^u, \qquad g_\rho v \varepsilon_i^q \varepsilon_i^d \sim m_i^d$$
$$\frac{\varepsilon_1^q}{\varepsilon_2^q} \sim \lambda, \qquad \frac{\varepsilon_2^q}{\varepsilon_3^q} \sim \lambda^2, \qquad \frac{\varepsilon_1^q}{\varepsilon_3^q} \sim \lambda^3,$$

8 relations $\implies$ 2 leftover parameters: g_ρ and ε_3^q.

Lepton sector: more arbitrary; assume $\varepsilon_i^e \approx \varepsilon_i^\ell$ to minimise $\mu \to e\gamma$.

Fixes lepton mixings:

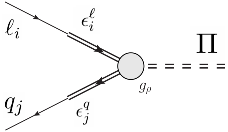
$$Y_i^\ell = g_\rho (\varepsilon_i^\ell)^2 \implies \varepsilon_i^\ell = \sqrt{\frac{Y_i^\ell}{g_\rho}}$$

Also: mass of leptoquark M

Partial Compositeness & LQ couplings III

BMG, Nardecchia, & Renner, 1412.1791

The LQ couples much the same way as the Higgs



So its couplings to SM fermions are:

$$\lambda_{ij} = g_\rho c_{ij} \varepsilon_i^\ell \varepsilon_j^q$$

Quarks $\lambda^3 \; : \; \lambda^2 \; : \; 1$

Leptons $\sqrt{Y_\ell}$

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

c_{ij} are unknown O(1) coefficients $\Longrightarrow$ predictions of the model

Fit to $b \to s\ell\ell$ anomalies

BMG, Nardecchia, & Renner, 1412.1791

$$C_9^{NP\mu} = -C_{10}^{NP\mu} \in [-0.74, -0.36] \quad (\text{at } 1\sigma)$$

$$\implies \mathrm{Re}(c_{22}^* c_{23}) \in [1.50, 3.08] \left(\frac{4\pi}{g_\rho}\right) \left(\frac{1}{\varepsilon_3^q}\right)^2 \left(\frac{M}{\mathrm{TeV}}\right)^2 \quad (\text{at } 1\sigma)$$

So since the c_{ij} should be $O(1)$:

- $\varepsilon_3^q \sim 1$ (i.e maximal)
- $g_\rho \sim 4\pi$ (i.e maximal)
- $\implies M \sim 1$ TeV (i.e. in LHC reach!)

n.b. R_K: Automatically accommodated with PC: contributions to decay $B^+ \to K^+ e^+ e^-$ are negligible.

We now have no free parameters, and 1000s of flavour constraints to satisfy (at O(1))! All are (just about) ok. $\mu \to e\gamma$ most challenging ($\implies$ heavy resonances).

Summary

- Composite Higgs – literal naturalness
- Di-photon anomaly – $\eta \in SO(6)/SO(5)$?
- Di-boson anomaly – $SU(2)_L \times SU(2)_R$ partners?
- B-physics anomalies – leptoquarks from partial compositeness?
- Highly unlikely that all 3 persist
- Just 1 would be nice!