

New Physics Explanations for Recent LHC Excesses

Ben Allanach (University of Cambridge)



- Anatomy of the Run I di-boson excess
- Heavy vector triplet explanation
- Resonant sneutrino explanation in RPV
- Resonant sneutrino explanation for di-photons

Particle physics Life and Physics

Ambulance-chasing Large Hadron Collider collisions

Ben Allanach on the impure fun of rapid-response physics



Speed is important Photograph: MACIEJ NOSKOWSKI/Getty Images

Ben Allanach

Wednesday 17 September 2014 07.01 BST



Shares

194

Comments

18

Selection Bias

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

| Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L} dt [\text{fb}^{-1}]$ | Mass limit | Reference | | |
|---|---|--|---------------------|--|-------------------------|---|---|--|
| Inclusive Searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | \tilde{q}, \tilde{g} 1.7 TeV | $m(\tilde{g})=m(\tilde{q})$ | 1405.7875 |
| | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | \tilde{q} 850 GeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$ | 1405.7875 |
| | $\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed) | 1 γ | 0-1 jet | Yes | 20.3 | \tilde{q} 250 GeV | $m(\tilde{g})-m(\tilde{\chi}_1^0) = m(c)$ | 1411.1559 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | \tilde{g} 1.33 TeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ | 1405.7875 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$ | 1 e, μ | 3-6 jets | Yes | 20 | \tilde{g} 1.2 TeV | $m(\tilde{\chi}_1^0) < 300 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | 1501.03555 |
| | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 e, μ | 0-3 jets | - | 20 | \tilde{g} 1.32 TeV | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ | 1501.03555 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 20.3 | \tilde{g} 1.6 TeV | $\tan\beta > 20$ | 1407.0603 |
| | GGM (bino NLSP) | 2 γ | - | Yes | 20.3 | \tilde{g} 1.28 TeV | $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ | ATLAS-CONF-2014-001 |
| | GGM (wino NLSP) | 1 e, μ + γ | - | Yes | 4.8 | \tilde{g} 619 GeV | $m(\tilde{\chi}_1^0) > 50 \text{ GeV}$ | ATLAS-CONF-2012-144 |
| | GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | \tilde{g} 900 GeV | $m(\tilde{\chi}_1^0) > 220 \text{ GeV}$ | 1211.1167 |
| GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | \tilde{g} 690 GeV | $m(\text{NLSP}) > 200 \text{ GeV}$ | ATLAS-CONF-2012-152 | |
| Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $R^{1/2}$ scale 865 GeV | $m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$ | 1502.01518 | |
| 3 rd gen. \tilde{g} med. | $\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 20.1 | \tilde{g} 1.25 TeV | $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ | 1407.0600 |
| | $\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | \tilde{g} 1.1 TeV | $m(\tilde{\chi}_1^0) < 350 \text{ GeV}$ | 1308.1841 |
| | $\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^\pm$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} 1.34 TeV | $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ | 1407.0600 |
| | $\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^\pm$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} 1.3 TeV | $m(\tilde{\chi}_1^0) < 300 \text{ GeV}$ | 1407.0600 |
| 3 rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 20.1 | \tilde{b}_1 100-620 GeV | $m(\tilde{\chi}_1^0) < 90 \text{ GeV}$ | 1308.2631 |
| | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$ | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{b}_1 275-440 GeV | $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$ | 1404.2500 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ | 1-2 e, μ | 1-2 b | Yes | 4.7 | \tilde{t}_1 110-167 GeV 230-460 GeV | $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 55 \text{ GeV}$ | 1209.2102, 1407.0583 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 2 e, μ | 0-2 jets | Yes | 20.3 | \tilde{t}_1 90-191 GeV 215-530 GeV | $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ | 1403.4853, 1412.4742 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ | 0-1 e, μ | 1-2 b | Yes | 20 | \tilde{t}_1 210-640 GeV | $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ | 1407.0583, 1406.1122 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ | 0 | mono-jet/c-tag | Yes | 20.3 | \tilde{t}_1 90-240 GeV | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0) < 85 \text{ GeV}$ | 1407.0608 |
| | $\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_1 150-580 GeV | $m(\tilde{\chi}_1^0) > 150 \text{ GeV}$ | 1403.5222 |
| | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ | 3 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_2 290-600 GeV | $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ | 1403.5222 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\ell}$ 90-325 GeV | $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ | 1403.5294 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$ | 2 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 140-465 GeV | $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{\ell}, \bar{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ | 1403.5294 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$ | 2 τ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 100-350 GeV | $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{\tau}, \bar{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ | 1407.0350 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\bar{\nu}\nu), \tilde{\nu}\tilde{\ell}_L\ell(\bar{\nu}\nu)$ | 3 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV | $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \bar{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ | 1402.7029 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ | 2-3 e, μ | 0-2 jets | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV | $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \text{ sleptons decoupled}$ | 1403.5294, 1402.7029 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$ | e, μ, γ | 0-2 b | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 250 GeV | $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \text{ sleptons decoupled}$ | 1501.07110 |
| | $\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell$ | 4 e, μ | 0 | Yes | 20.3 | $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ 620 GeV | $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \bar{\nu}) = 0.5(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0))$ | 1405.5086 |
| | Long-lived particles | Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 270 GeV | $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$ |
| Stable, stopped \tilde{g} R-hadron | | 0 | 1-5 jets | Yes | 27.9 | \tilde{g} 832 GeV | $m(\tilde{\chi}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ | 1310.6584 |
| Stable \tilde{g} R-hadron | | trk | - | - | 19.1 | \tilde{g} 1.27 TeV | - | 1411.6795 |
| GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$ | | 1-2 μ | - | - | 19.1 | $\tilde{\chi}_1^0$ 537 GeV | $10 < \tan\beta < 50$ | 1411.6795 |
| GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | | 2 γ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 435 GeV | $2 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$ | 1409.5542 |
| $\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV) | | 1 μ , displ. vtx | - | - | 20.3 | \tilde{q} 1.0 TeV | $1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu) = 1, m(\tilde{\chi}_1^0) = 108 \text{ GeV}$ | ATLAS-CONF-2013-092 |
| RPV | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$ | 2 e, μ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.61 TeV | $\lambda'_{311} = 0.10, \lambda_{132} = 0.05$ | 1212.1272 |
| | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$ | 1 e, μ + τ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.1 TeV | $\lambda'_{311} = 0.10, \lambda_{1(2)33} = 0.05$ | 1212.1272 |
| | Billinear RPV CMSSM | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{q}, \tilde{g} 1.35 TeV | $m(\tilde{g}) = m(\tilde{q}), c\tau_{LS} < P < 1 \text{ mm}$ | 1404.2500 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 e, μ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 750 GeV | $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{121} \neq 0$ | 1405.5086 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 e, μ + τ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 450 GeV | $m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm), \lambda_{133} \neq 0$ | 1405.5086 |
| | $\tilde{g} \rightarrow qq\tilde{q}$ | 0 | 6-7 jets | - | 20.3 | \tilde{g} 916 GeV | $\text{BR}(l) = \text{BR}(b) = \text{BR}(c) = 0\%$ | ATLAS-CONF-2013-091 |
| $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$ | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{g} 850 GeV | - | 1404.2500 | |
| Other | Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$ | 0 | 2 c | Yes | 20.3 | \tilde{c} 490 GeV | $m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ | 1501.01325 |

$\sqrt{s} = 7 \text{ TeV}$ full data
 $\sqrt{s} = 8 \text{ TeV}$ partial data
 $\sqrt{s} = 8 \text{ TeV}$ full data

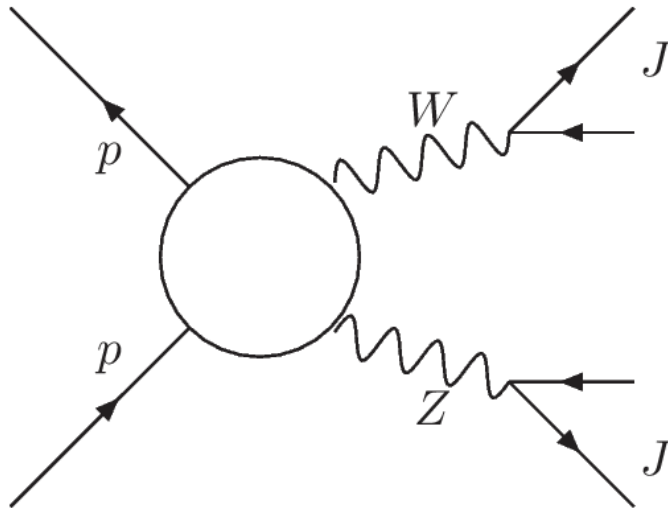
10^{-1}

1

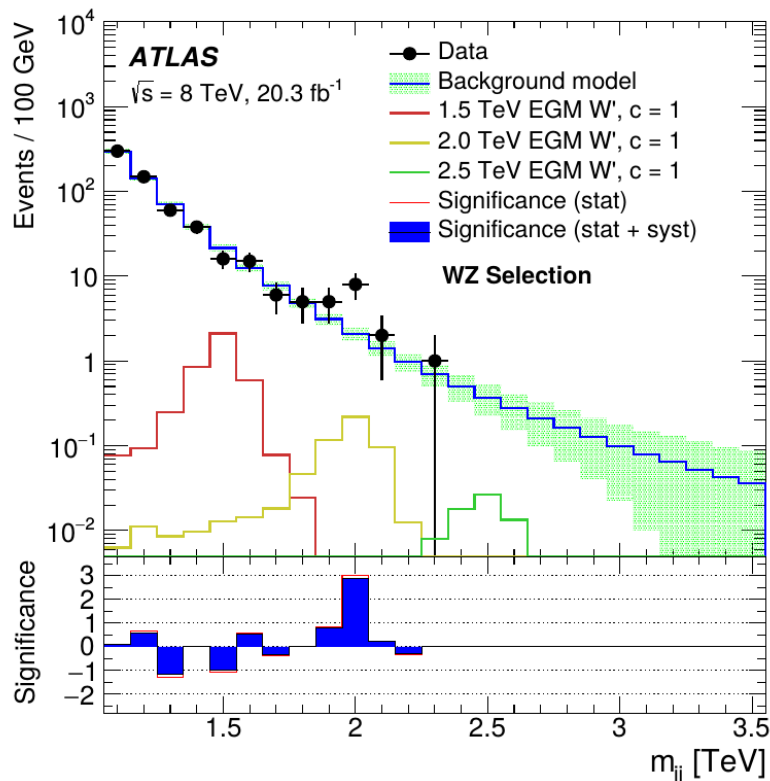
Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

ATLAS di-boson excess

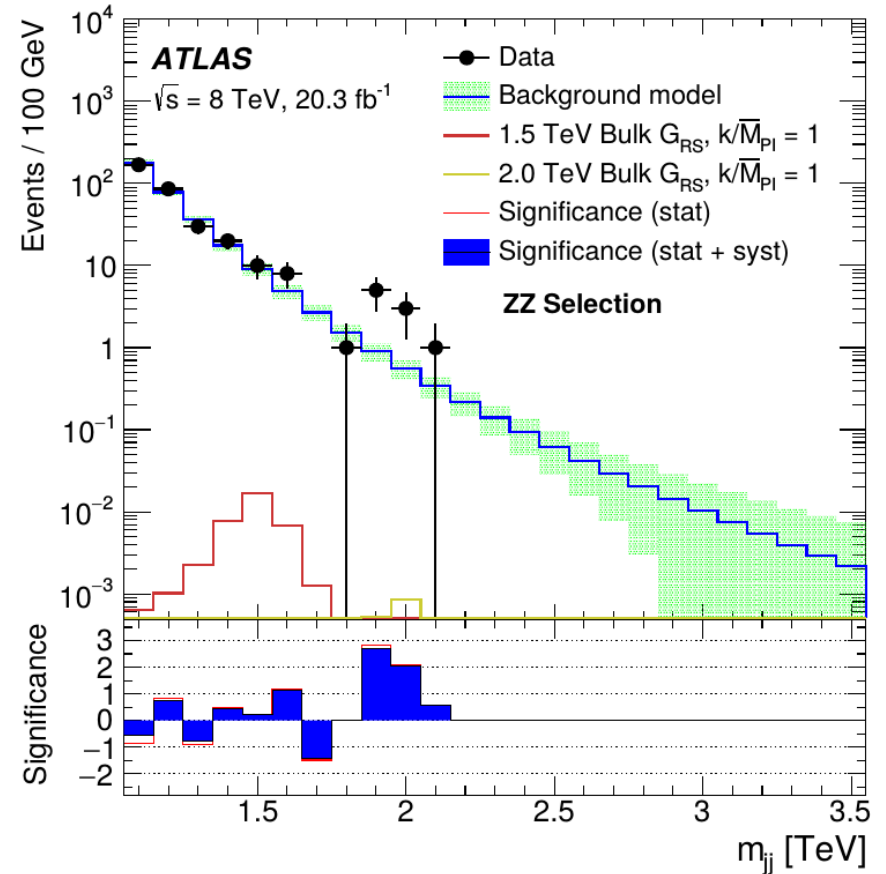
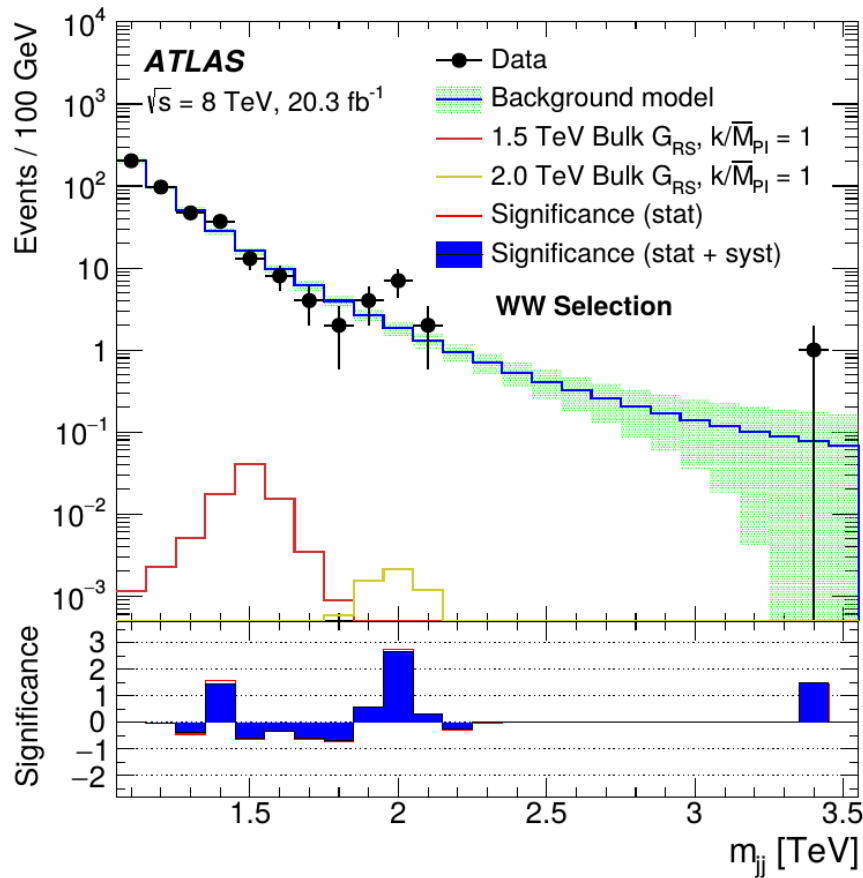


Dig fat jets J made out of two smaller jets j with **jet substructure** techniques. $69.4 < m_J/\text{GeV} < 95.4$ is called a 'W', whereas $79.8 < m_J/\text{GeV} < 105.8$ is called a 'Z'.

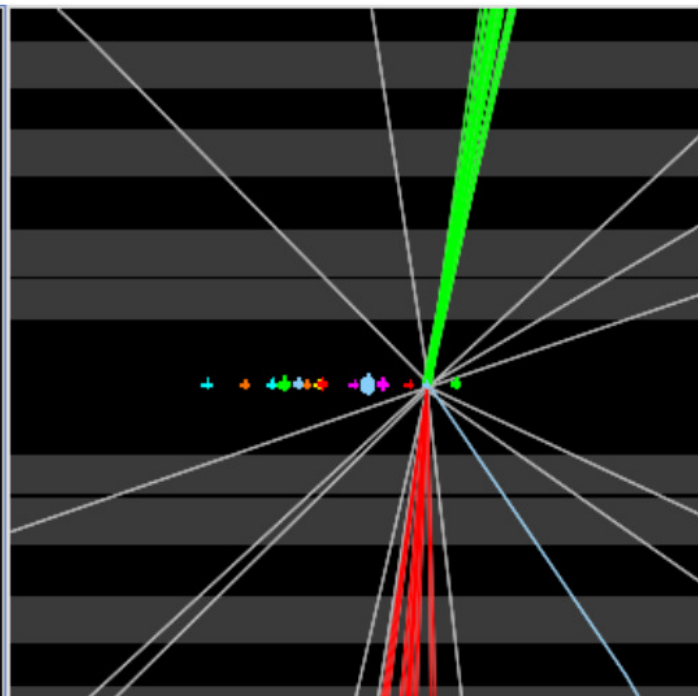
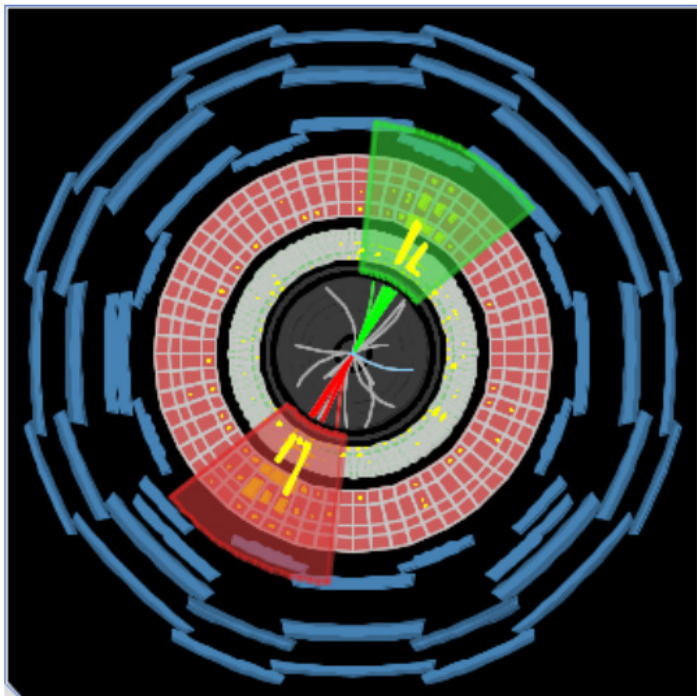


Global excess 2.5σ in WZ channel.
(Local significance is 3.4σ). CMS finds 1.9σ around 1.9-2 TeV in a boosted search for $WH \rightarrow l\nu jj$. **ATLAS, arXiv:1506.00962; CMS, CMS-PAS-EXO-14-010.**

Other channels

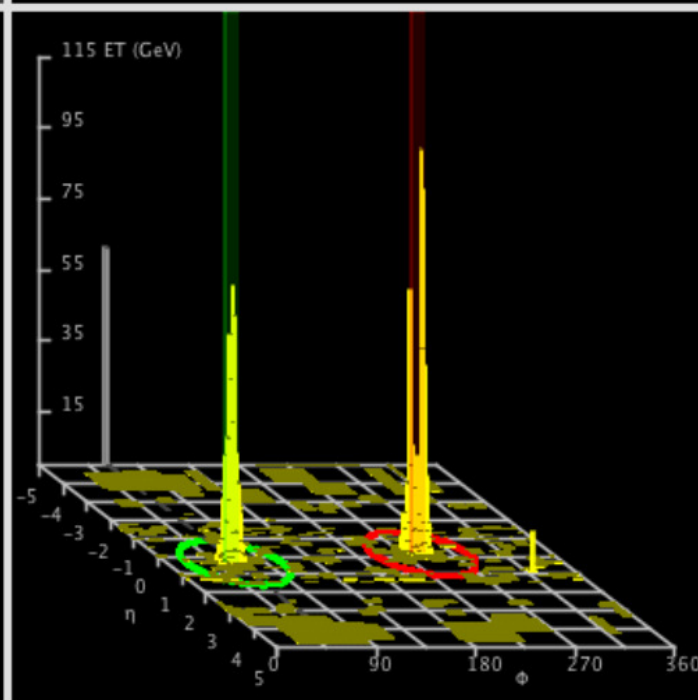
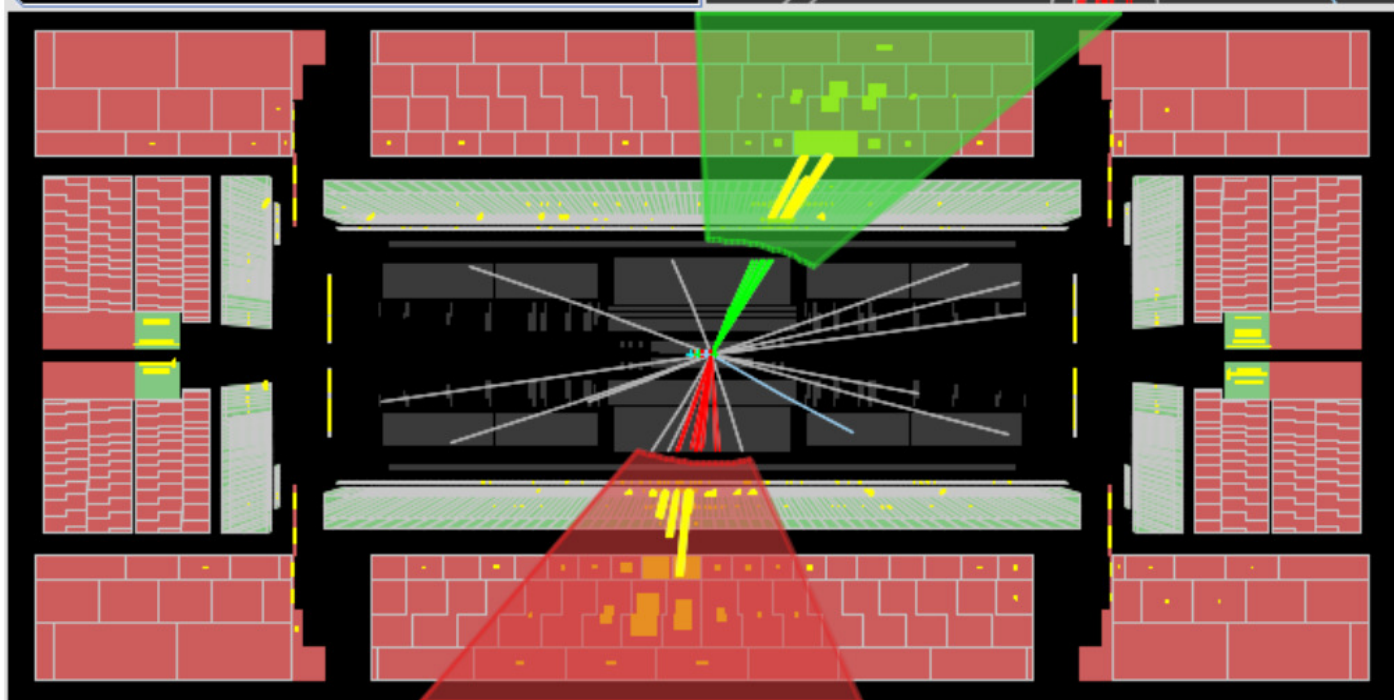


Local significances: 2.6σ (WW), 2.9σ (ZZ), again: all around 2 TeV.



ATLAS EXPERIMENT

Run Number: 207749, Event Number: 36414089
Date: 2012-07-31 01:30:57 CEST



Analysis Details

Cambridge-Aachen jets: iteratively replace nearest elements with their combination until all remaining pairs are separated by more than $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 1.2$.

Jets then *groomed* to find 2 subjets: reverse pairwise construction. At each step, lower-mass subjet is discarded, the higher mass one being considered to be the jet until

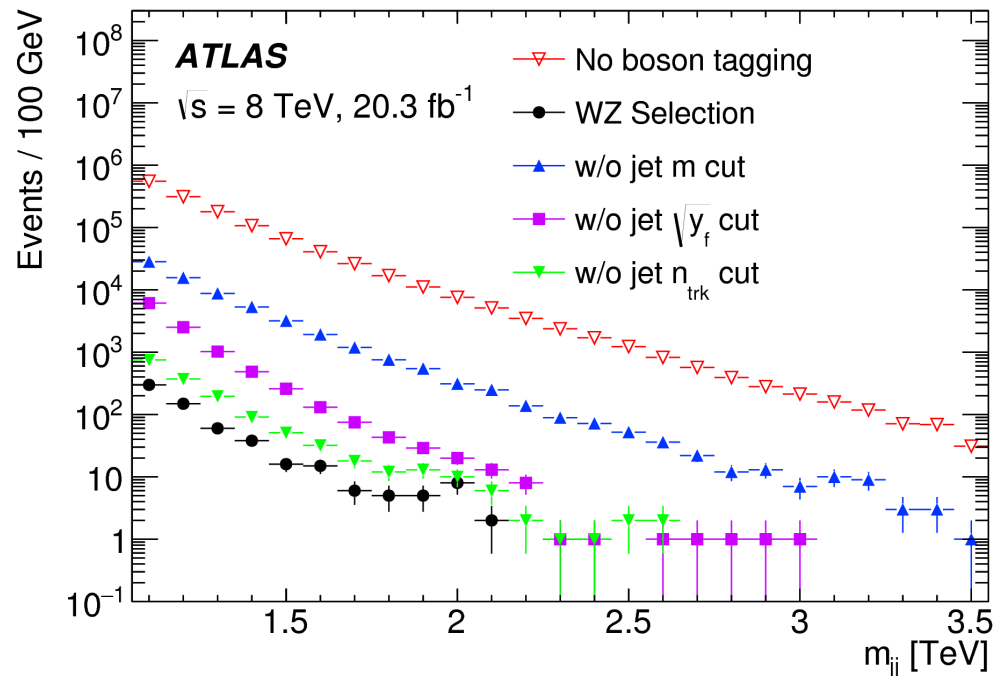
$$\sqrt{y} \equiv \min(p_T(j_1), p_T(j_2)) \frac{\Delta R(j_1, j_2)}{m_0} \geq \sqrt{0.2}$$

where m_0 is the mass of the parent jet.

Details II

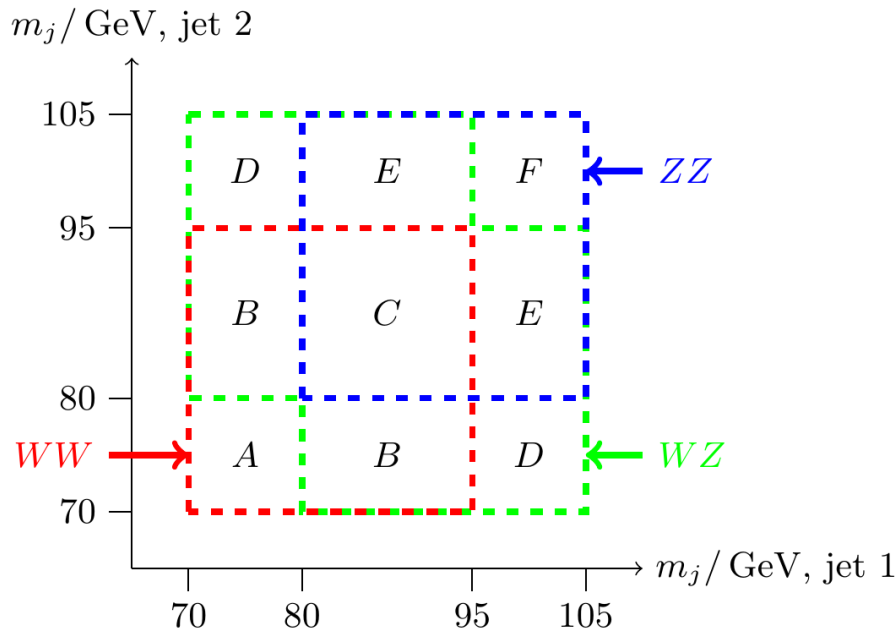
Selected pair of subjects is then *filtered*: subjects reconstructed with $R = 0.3$ and all but 3 of highest p_T are discarded.

$\sqrt{y} \geq 0.45$ at subjects level to discriminate against soft QCD radiation, $n_{\text{tracks}} < 30$ as well.



Overlap

BCA, Gripaio, Sutherland, arXiv:1507.01638



$$WW = A + B + C,$$

$$ZZ = C + E + F,$$

$$WZ = B + C + D + E,$$

$$WW + ZZ = A + B + C + E + F,$$

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

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

Summed
over 3
bins: three
possibilities

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

Likelihood analysis

How may we take overlap into account?

$$\mu_i = \mu_i^{SM} + \sum_{j=1}^3 \epsilon b_j s_j M_{ji} \quad (1)$$

$i \in \{A, B, C, D, E, F\}$. $b_j = \{0.45, 0.47, 0.49\}$ are the totally hadronic branching fractions. $s_j = \{s_{WW}, s_{WZ}, s_{ZZ}\}$ is the number of “truth” signal pairs.

| 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 |

TABLE III. Probability of different diboson candidates from a 2 TeV resonance being tagged in each signal region.

Joint likelihood

$$p(\{n_i\}|\{\mu_i\}) = \prod_{i \in \{A,B,C,D,E,F\}} P(n_i|\mu_i),$$

$$P(n|\mu) = \frac{e^{-\mu} \mu^n}{n!},$$

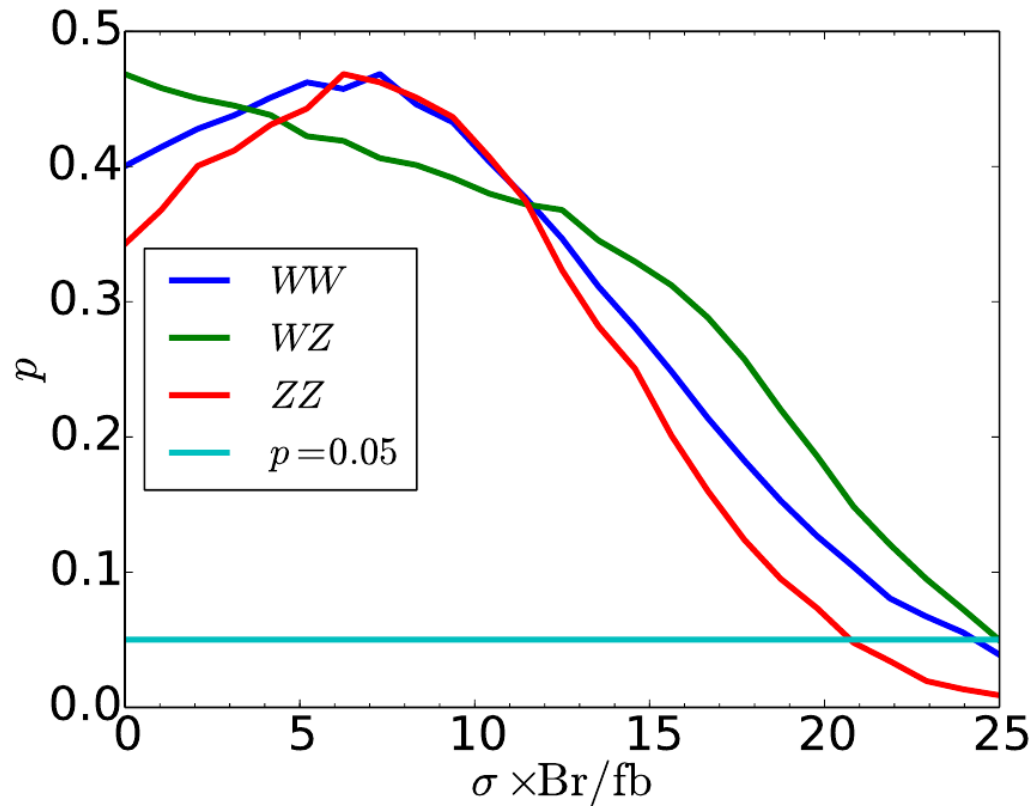
$$p(\{n_i^{\text{obs},\alpha}\} | s_{WW}, s_{WZ}, s_{ZZ}) =$$

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

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

Multi-dimensional likelihood

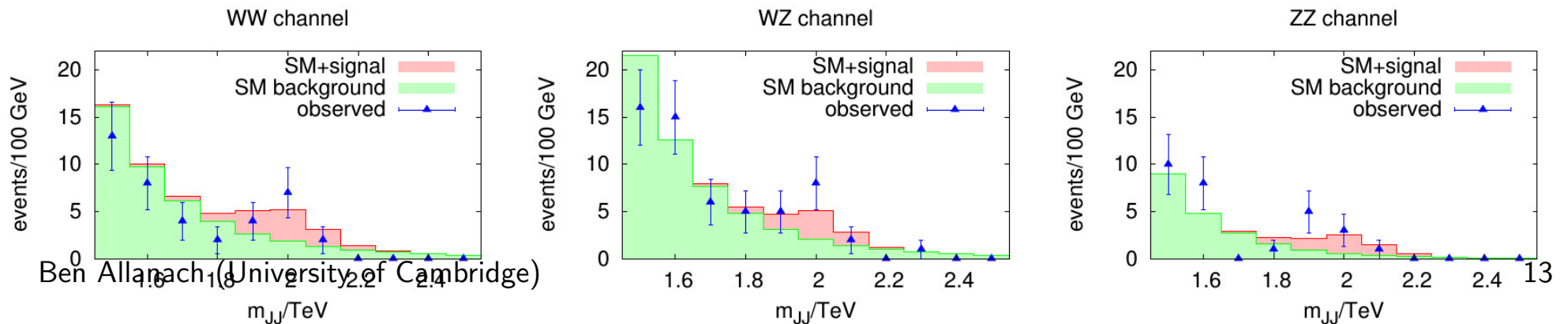
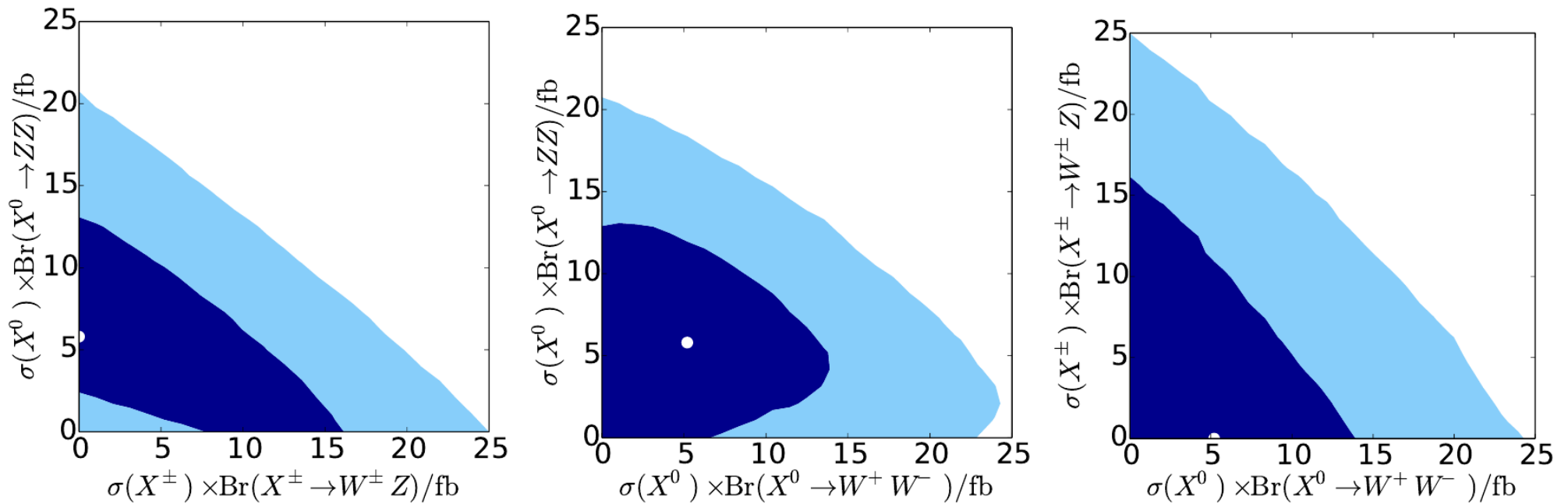
This is turned into a $\chi^2 = -2 \log p(\{n_i^{\text{obs},\alpha}\} | s_{WW}, s_{WZ}, s_{ZZ})$



SM is 4.0σ discrepant (local).

Joint Constraints

Similar results to a global analysis [Brehmer *et al*, arXiv:1507.00013](#)



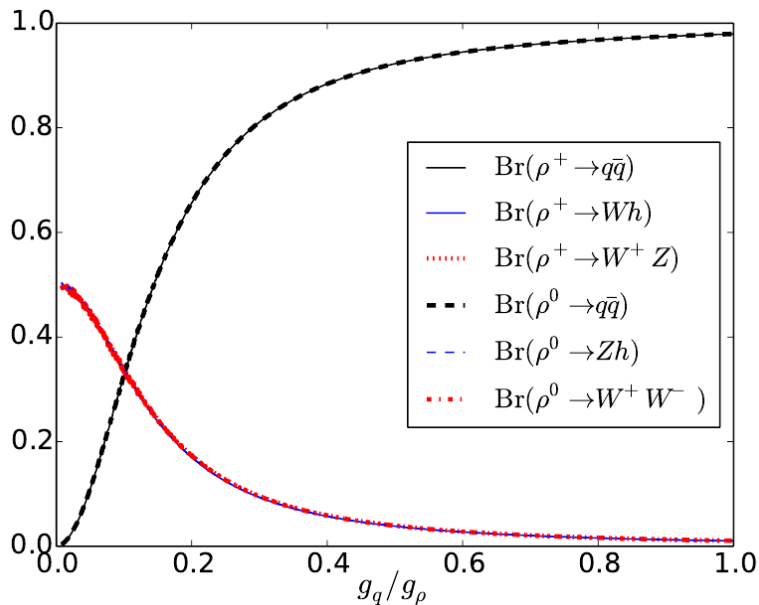
Ben Allanach (University of Cambridge)

New Physics Decalogue

- Require SM symmetry broken by h
- Sizeable signal $\Rightarrow D \leq 4$ in production
- Integral spin j
- $D \leq 4 \Rightarrow j \leq 1$
- $j = 0$ needs EW charge to couple to W/Z . But it would get a VEV $\Rightarrow m_q$ too big
- EFT $j = 1$: gauge field with EW charge
- $\rho \approx 1 \Rightarrow SU(2)_L \times SU(2)_R$ symmetric: 1 or 3.
- In universal limit, $O(1)$ coupling to quarks is OK.
- (Non-uni couplings correct Γ_Z and CKM unit.).
- Assume flavour-diagonal couplings to 2 light families

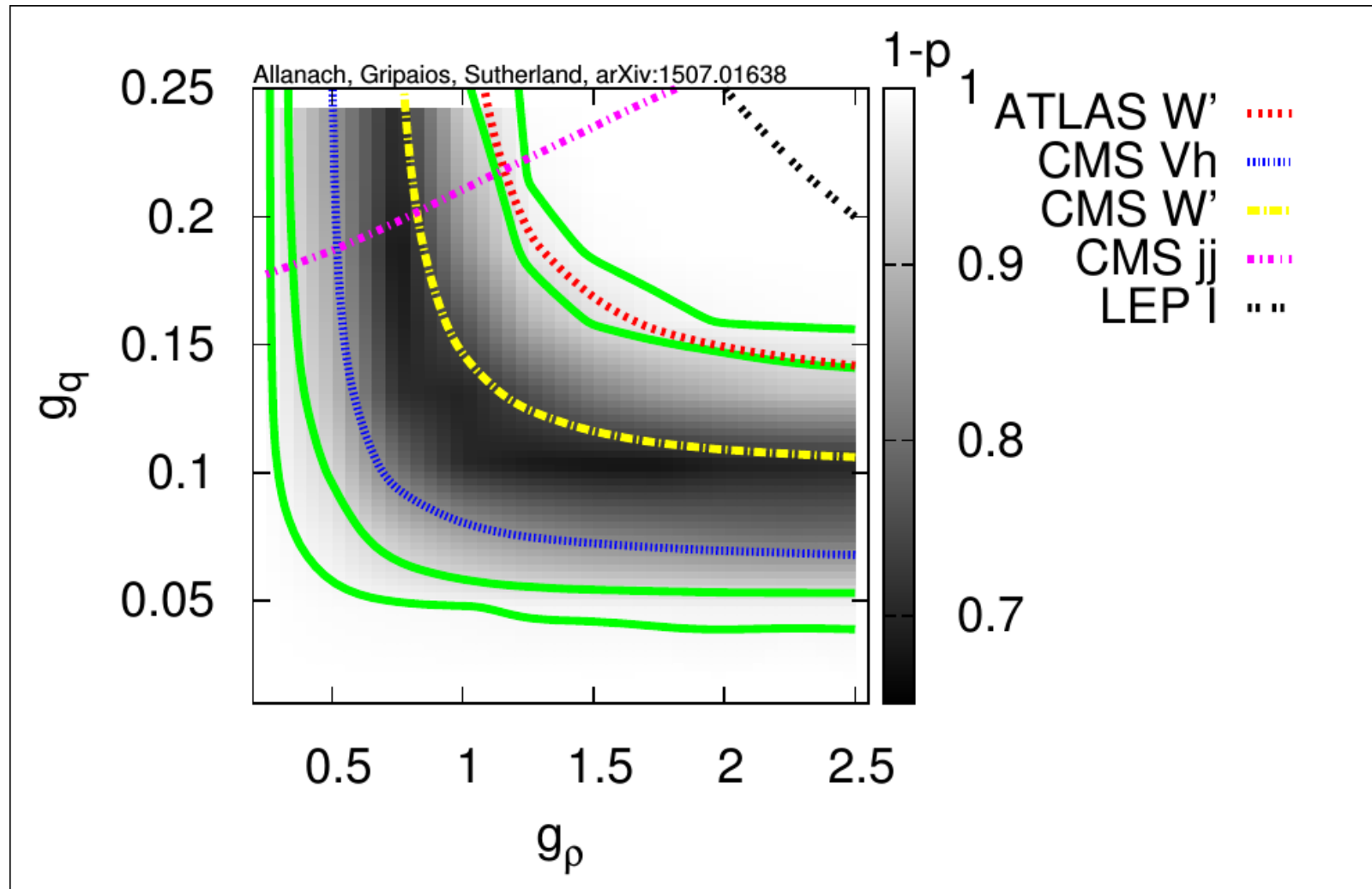
$$Y = 0 \quad \mathbf{SU(2)}_L \quad \mathbf{HVT} \quad \rho_\mu^a$$

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}\rho_{\mu\nu}^a\rho^{a\mu\nu} + \left(\frac{1}{2}m_\rho^2 + \frac{1}{4}g_m^2 H^\dagger H\right)\rho_\mu^a\rho^{a\mu} \\ & -2g\epsilon^{abc}\partial_{[\mu}\rho_{\nu]}^a W^{b\mu}\rho^{c\nu} - g\epsilon^{abc}\partial_{[\mu}W_{\nu]}^a\rho^{b\mu}\rho^{c\nu} \\ & + \left(\frac{1}{2}ig_\rho\rho_\mu^a H^\dagger\sigma^a D^\mu H + \text{h.c.}\right) + g_q\rho_\mu^a\overline{Q}_L\gamma^\mu\sigma^a Q_L \\ & + g_l\rho_\mu^a\overline{L}_L\sigma^a\gamma^\mu L_L + \dots \end{aligned}$$



This model ('HVT') was initially considered by Thamm, Torre, Wulzer, [arXiv:1506.08688](https://arxiv.org/abs/1506.08688). A RH triplet yields very similar results.

Constraints



EW precision: $g_\rho g_q \lesssim 0.5$ is OK.

R –Parity Violation

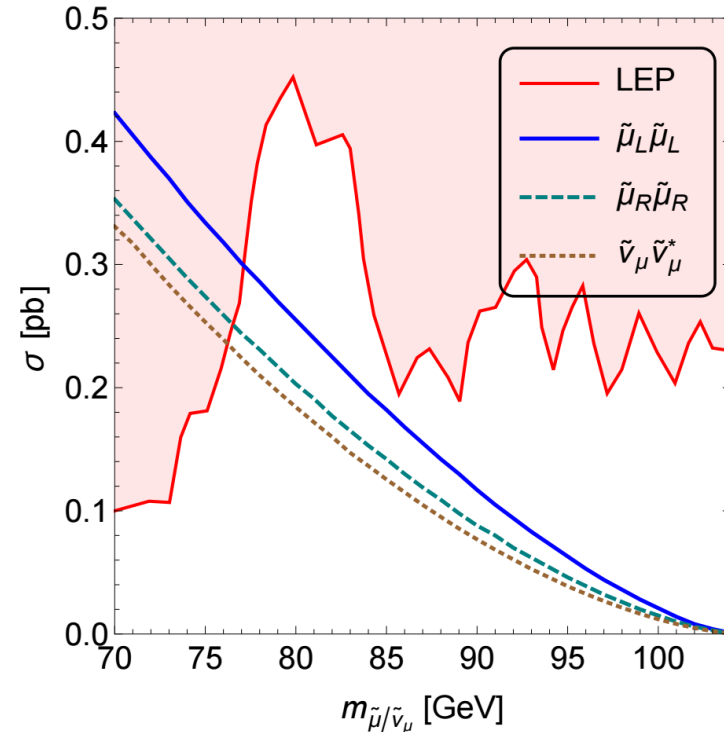
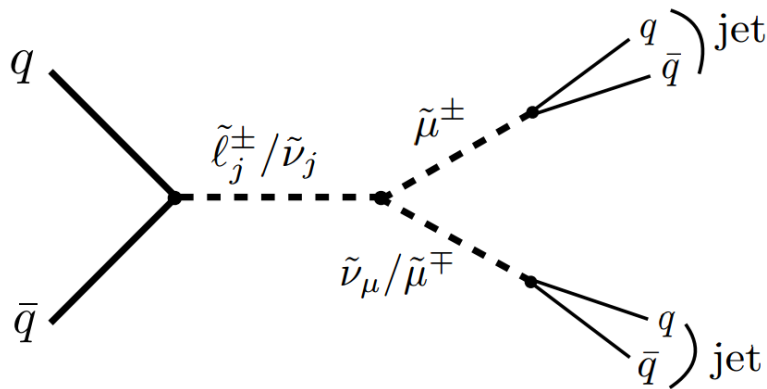
Allanach's conjecture:

“Any excess can be explained with R –parity violating supersymmetry.”

“The Last Refuge of The Scoundrel”

$$W_{LV} = \lambda'_{j11} L_1 Q_1 \bar{D}_1 + \lambda'_{2kl} L_2 Q_k \bar{D}_l$$

$$L_{LV}^{soft} = A_{j22} \tilde{l}_j \tilde{l}_2 \tilde{\mu}_R^+ + (H.c.)$$



No leptons in final state

Allanach, Dev, Sakurai arXiv:1511.01483

Consistency

$$d(m_{\tilde{\ell}}^2)_{22}/d \ln \mu = -2|A_{j22}|^2/(16\pi^2) + \dots$$

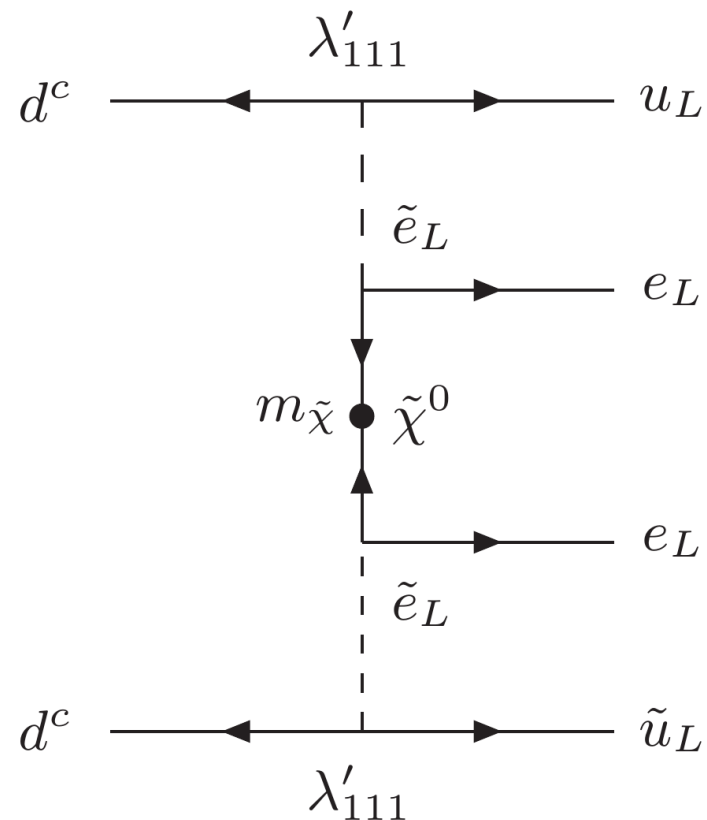
can turn smuon mass negative. Also, a correction to quartic \tilde{l}_j coupling may be non-perturbative from box with smuons running in the loop:

$$\Delta\lambda_{\tilde{l}_j} \approx -\frac{1}{384\pi^2} \left(\frac{A_{j22}}{\tilde{m}} \right)^4. \quad (2)$$

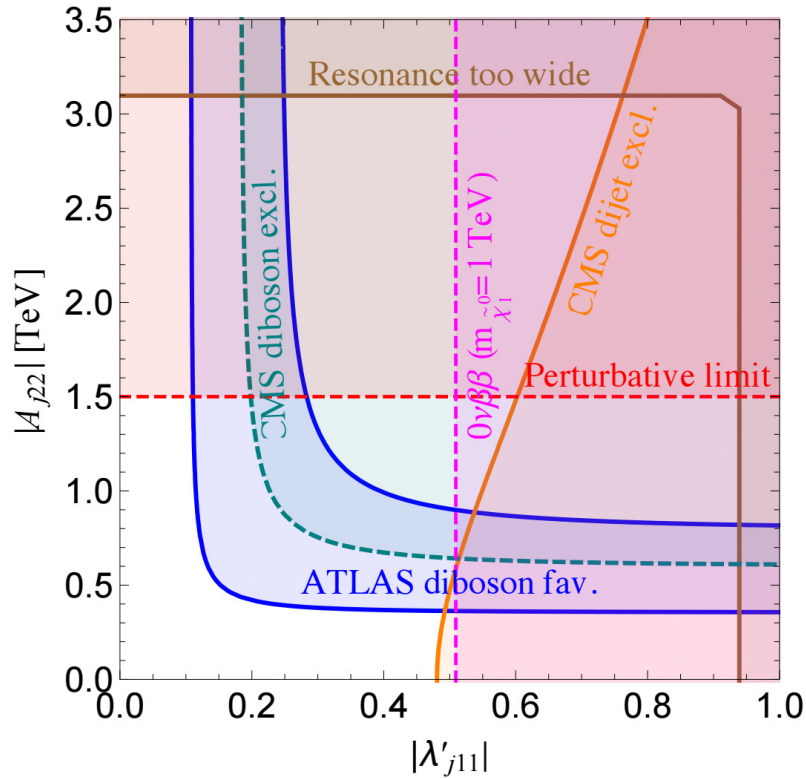
- *No leptonic/semi-leptonic states*
- *No WH states*
- Could have a stau instead of a smuon

Neutrinoless Double β Decay

Is *banned* in the Standard Model because it breaks lepton number: $Z \rightarrow (Z + 2)e^-e^-$ Present bound from GERDA is $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr. It should increase by a factor **10** in the next year or so.

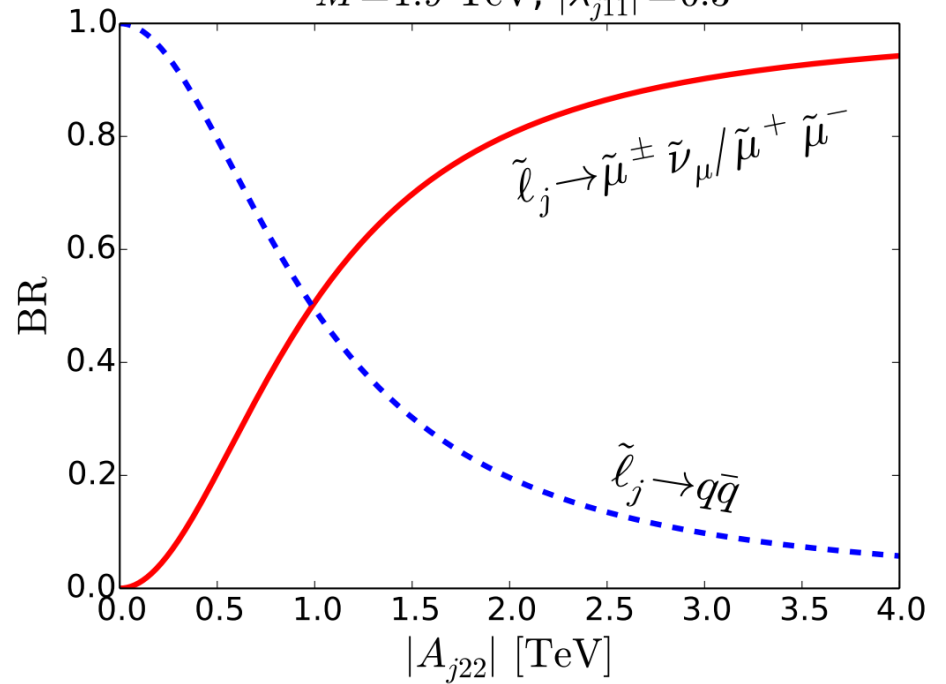


Parameters and $(g - 2)_\mu$

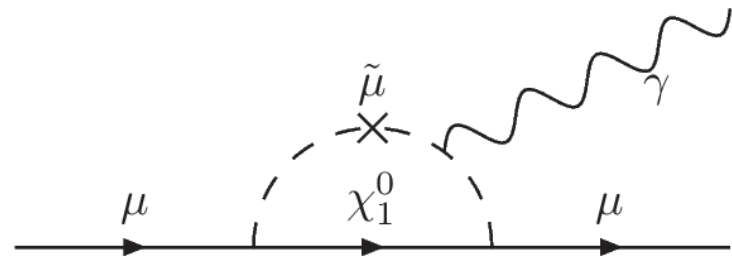


$$\frac{\delta(g-2)_\mu}{2} \sim 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{\chi_1^0}} \right)^2 \tan \beta$$

$M = 1.9 \text{ TeV}, |\lambda'_{j11}| = 0.3$



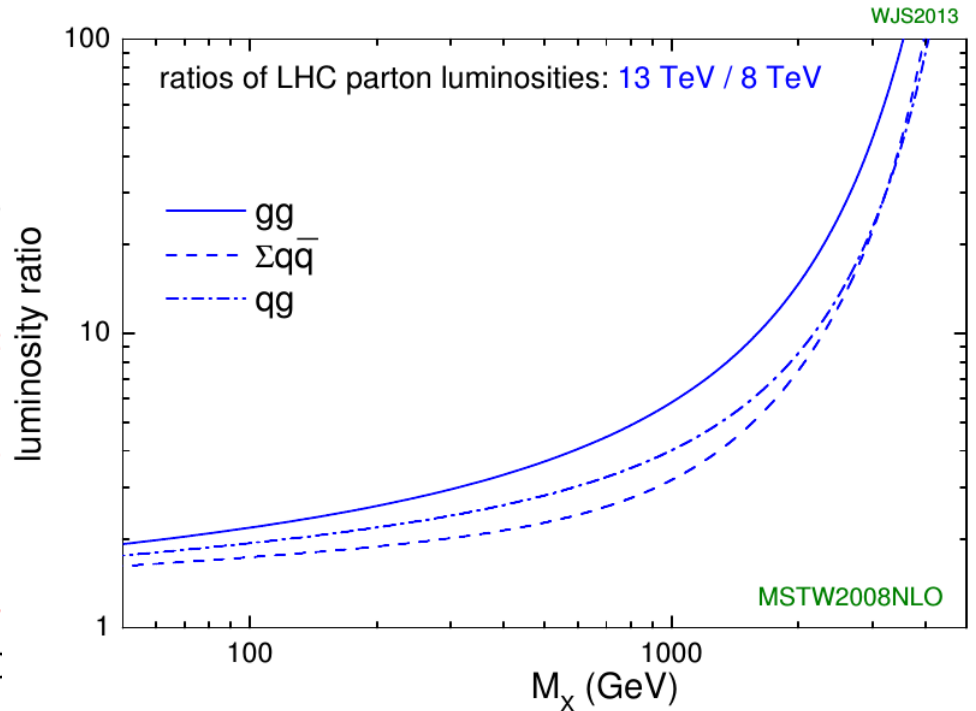
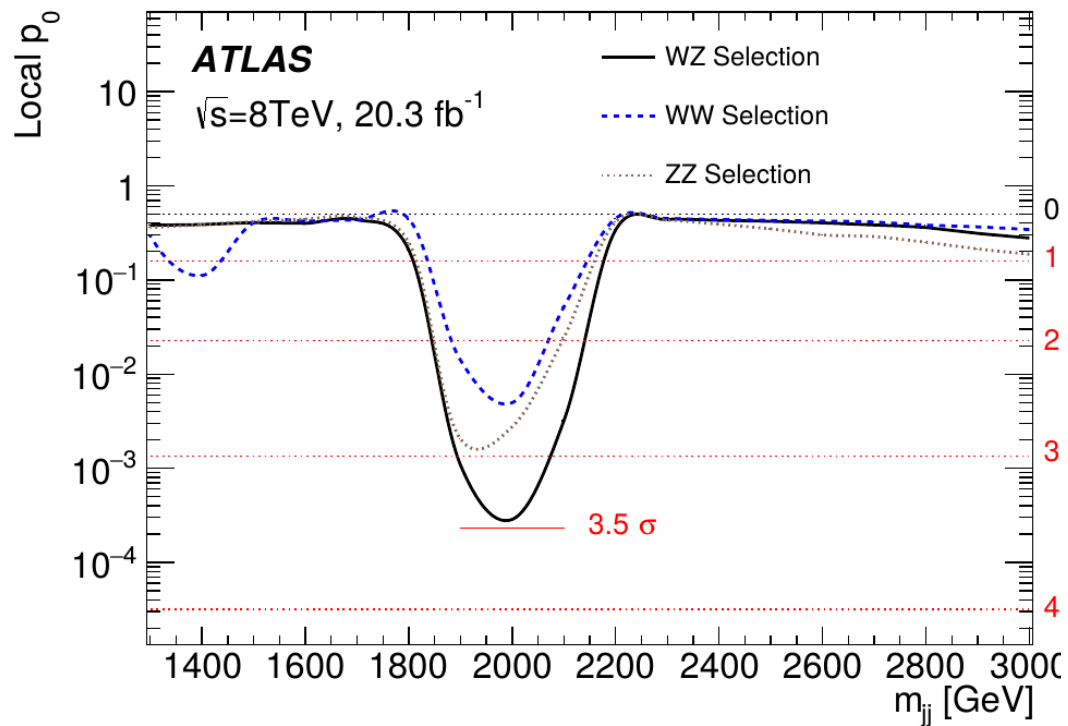
$$(29 \pm 8) \times 10^{-10}$$



Other Models

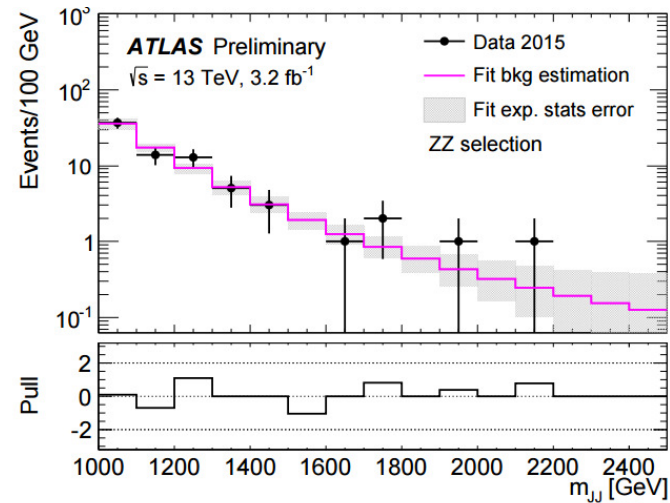
- Other initial models: W' , Z' models *Alves et al*, [arXiv:1506.06767](#); Hisano, Nagata and Omura, [arXiv:1506.03931](#); Cheung *et al*, [arXiv:1507.06064](#); Xue, [1506.05994](#); Dobrescu and Liu, [arXiv:1506.06737](#); Aguilar-Saavedra, [arXiv:1506.06739](#); Cao, Yan and Zhang, [1507.00268](#); Cacciapaglia and Frandsen, [arXiv://1507.00900](#); Brehmer *et al*, [arXiv:1507.000013](#).
- Vector resonances motivated by composite dynamics *Franzosi, Frandsen and Sannino*, [1506.04392](#); *Thamm, Torre and Wulzer*, [arXiv:1506.08688](#)
- After the vectors (and our paper) came the scalars and some spin 2 interpretations.

ATLAS Run I Excesses

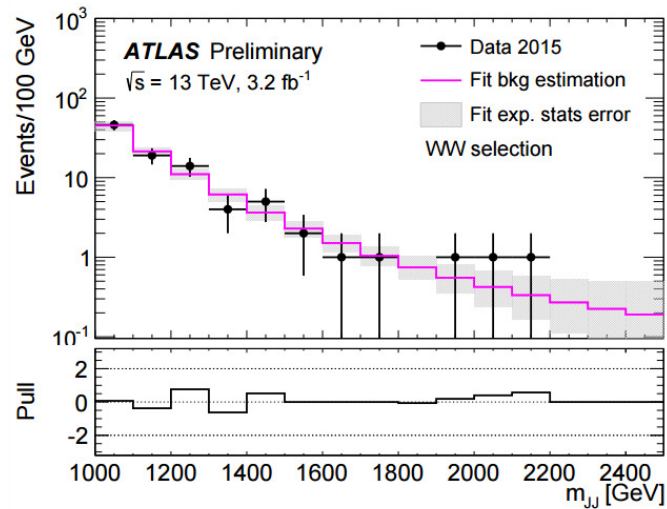


ATLAS claims 2.5σ including LEE from all channels.

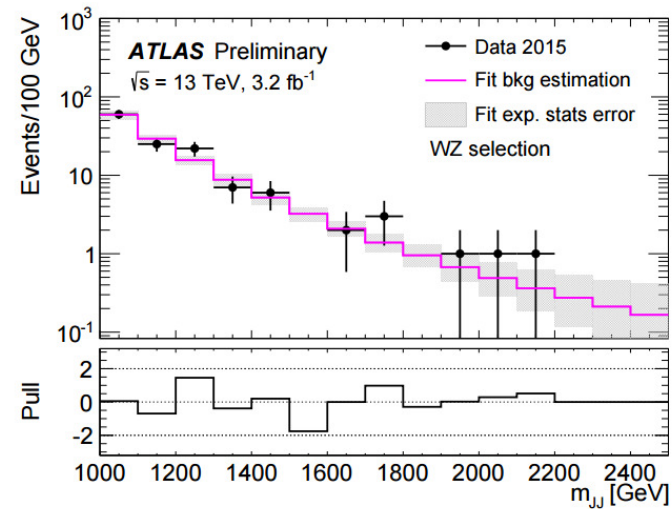
Run II Search: ATLAS 13 TeV 3.2fb^{-1} $l\nu J$



(a)

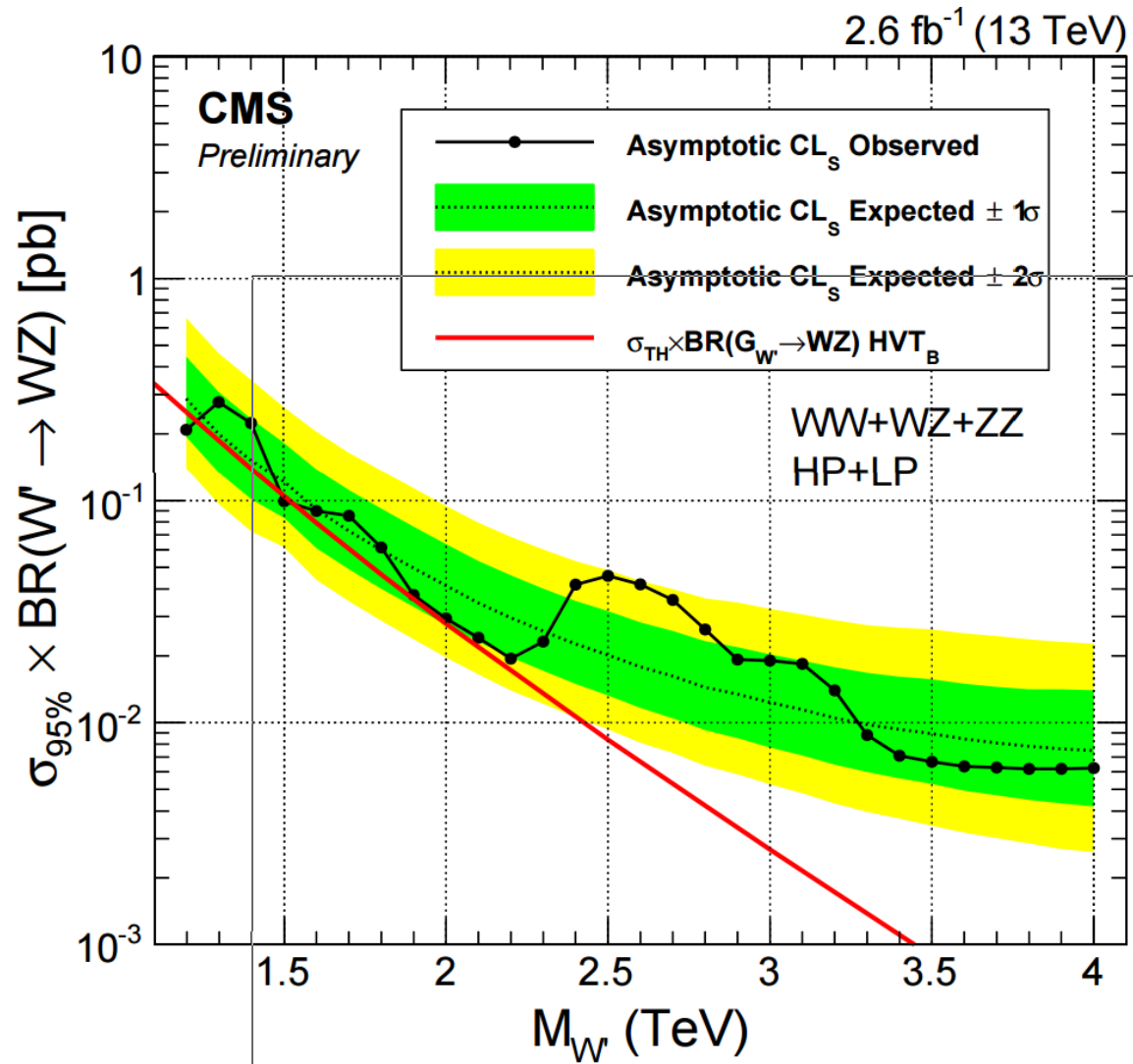


(b)



(c)

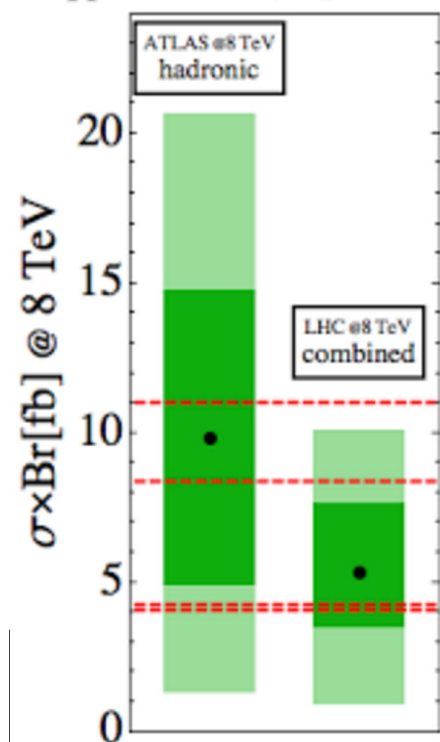
CMS 13 TeV 2.6 fb⁻¹: $l\nu qq + 4q$ EXO-15-002



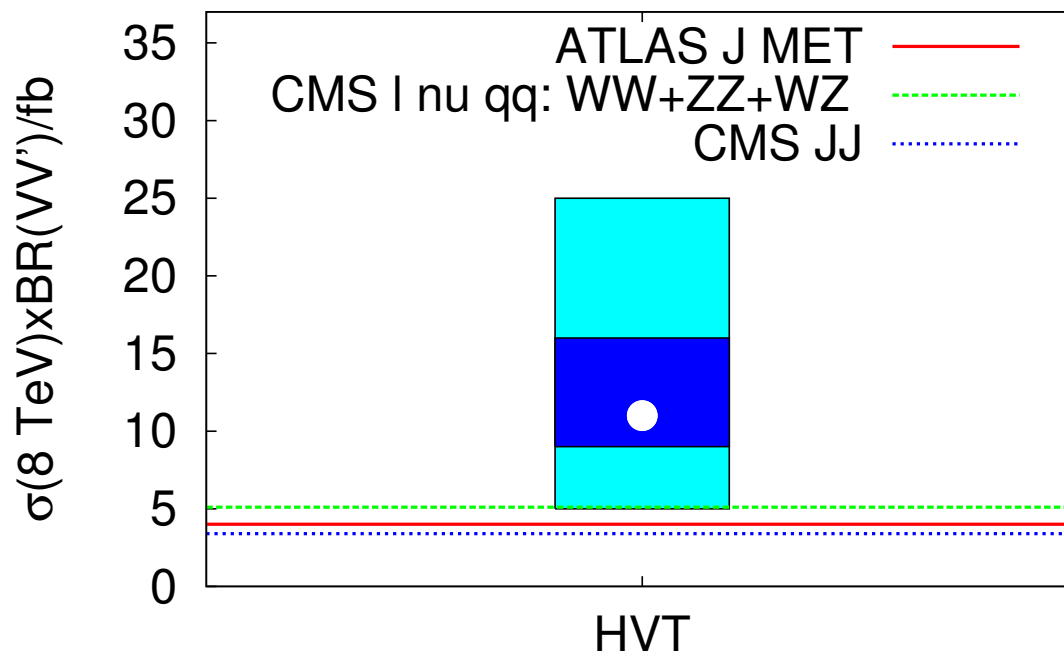


Run II: 2 TeV HVT In Trouble

$pp \rightarrow W' \rightarrow WZ, m_{W'} = 1.9 \text{ TeV}$



Run II constraints on HVT

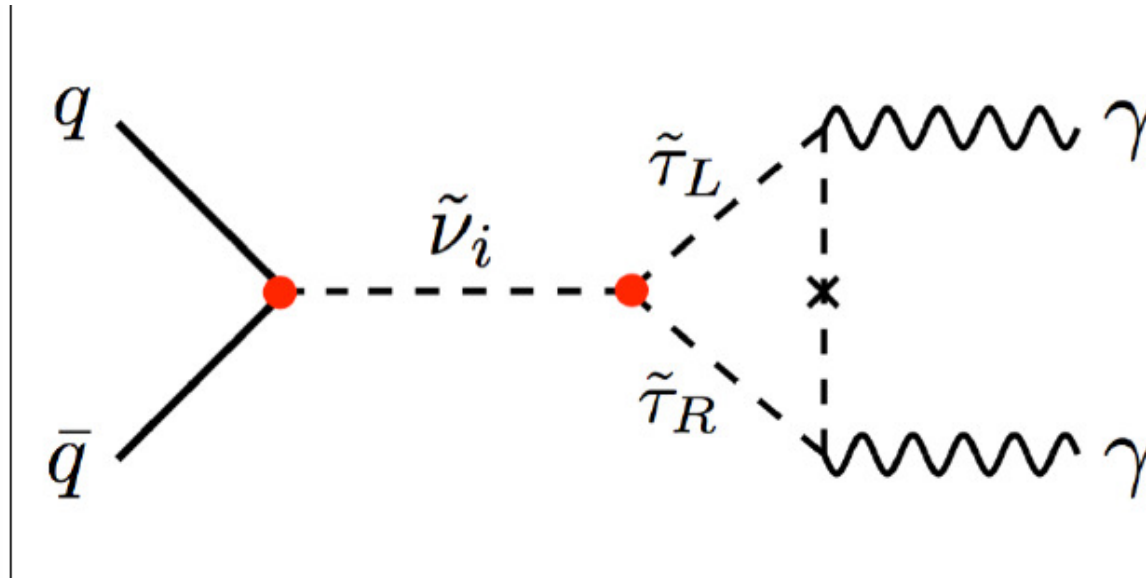


But note: sneutrino is OK because of its hadronic-only decays

Di-Photon Explanation

A 750 GeV resonant sneutrino with a coupling to quarks:

$$W_{RPV} = \lambda'_{i11} L_1 Q_1 \bar{D}_1 \quad \mathcal{L}_{RPV}^{\text{soft}} = A_{i33} \tilde{l}_i \tilde{l}_3 \tilde{\tau}_R^+ + H.c.$$



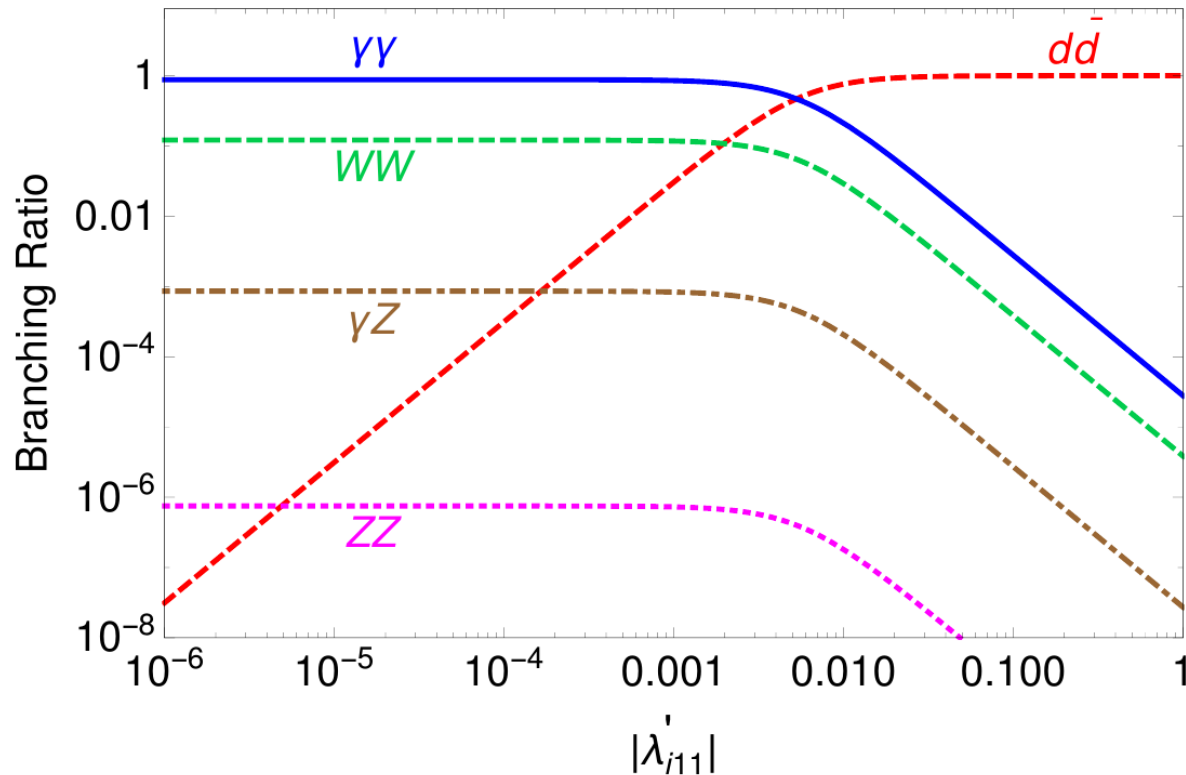
We shall need the staus heavier than 750 / 2 GeV.

BCA, Dev, Renner, Sakurai, [arXiv:1601.03007](https://arxiv.org/abs/1601.03007)

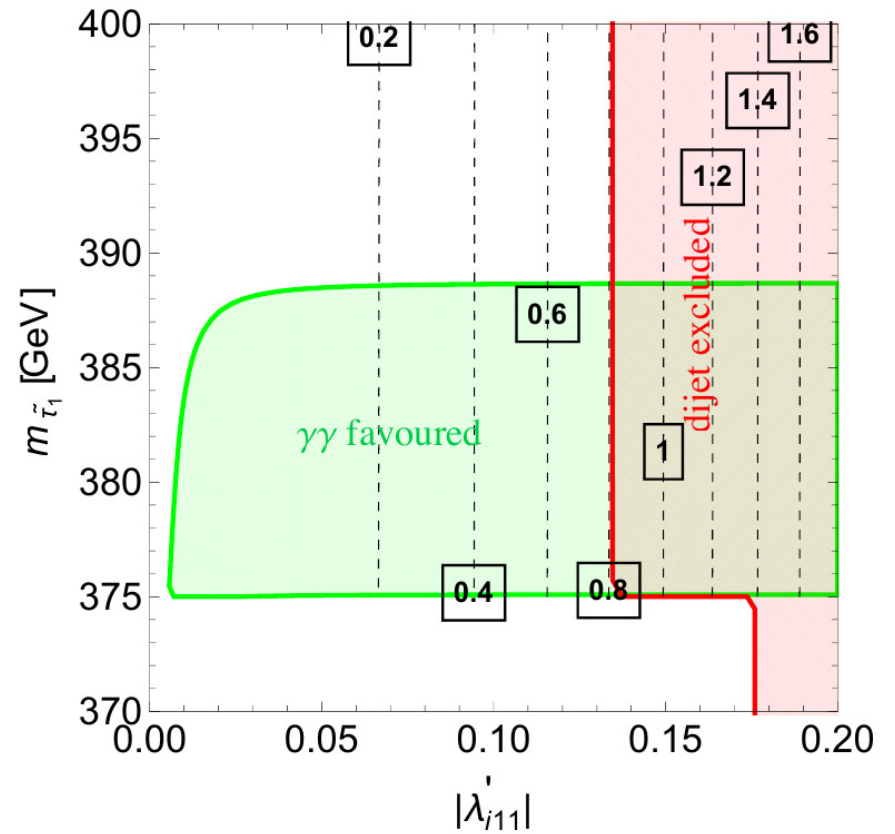
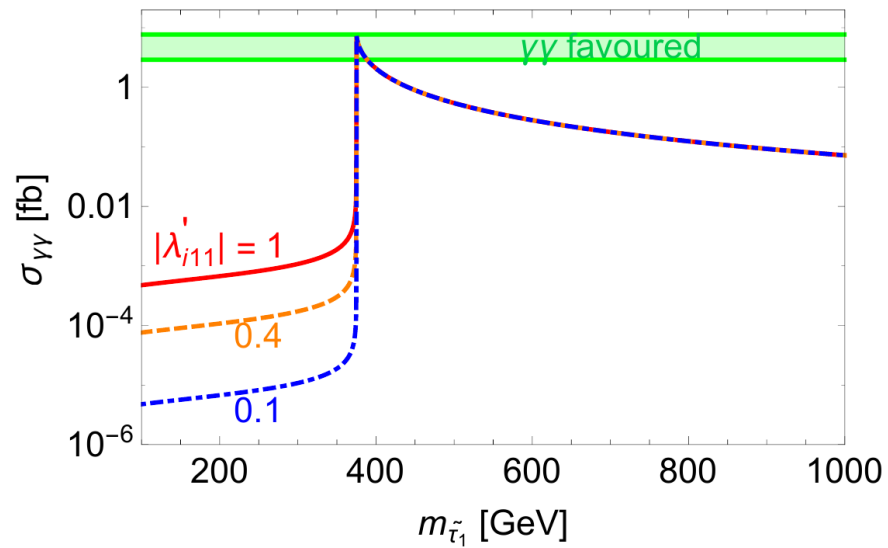
Decays

$$\Gamma_{WW} \equiv \Gamma(\tilde{\nu}_i \rightarrow W^+W^-) = \frac{\alpha_w^2 m_{\tilde{\nu}_i}^3}{1024\pi^3} \frac{|\bar{A}_{i33}|^2}{m_{\tilde{\tau}_1}^4} \sin^4 \theta \left(1 - \frac{4m_W^2}{m_{\tilde{\nu}_i}^2}\right)^{1/2}$$

$$\times \left[\frac{|F|^2}{16\tau_{\tilde{\tau}}^2} \left(12 - \frac{4m_{\tilde{\nu}_i}^2}{m_W^2} + \frac{m_{\tilde{\nu}_i}^4}{m_W^4}\right) - \frac{|F \cdot G|}{2\tau_{\tilde{\tau}}} \left(8 - \frac{6m_{\tilde{\nu}_i}^2}{m_W^2} + \frac{m_{\tilde{\nu}_i}^4}{m_W^4}\right) + |G|^2 \left(16 - \frac{8m_{\tilde{\nu}_i}^2}{m_W^2} + \frac{m_{\tilde{\nu}_i}^4}{m_W^4}\right) \right],$$



Parameter Space



Summary

- Heavy vector triplets explanation of ATLAS Run I di-boson excess is *ruled out* by Run II searches involving leptons
- RPV explanation of di-boson excess is *alive* still because it only predicts hadronic channels
- RPV explanation of di-photon excess works fine and requires: a 750 GeV sneutrino and staus around 375-385 GeV.
- Can the RPV explanations be joined up into one explanation?

“The road of excess leads to the palace of wisdom.”



William Blake, *The Marriage of Heaven and Hell*

Hint of new particle at CERN's Large Hadron Collider?

Particle theorist [Ben Allanach](#) gives his reaction to yesterday's seminar, where ATLAS and CMS reported on what we have (and have not yet) learned from a year of the highest-energy particle collisions ever achieved



Not that event. Photograph: Fabrice Coffrini/AFP/Getty Images

Ben Allanach

Wednesday 16 December 2015 09.26 GMT



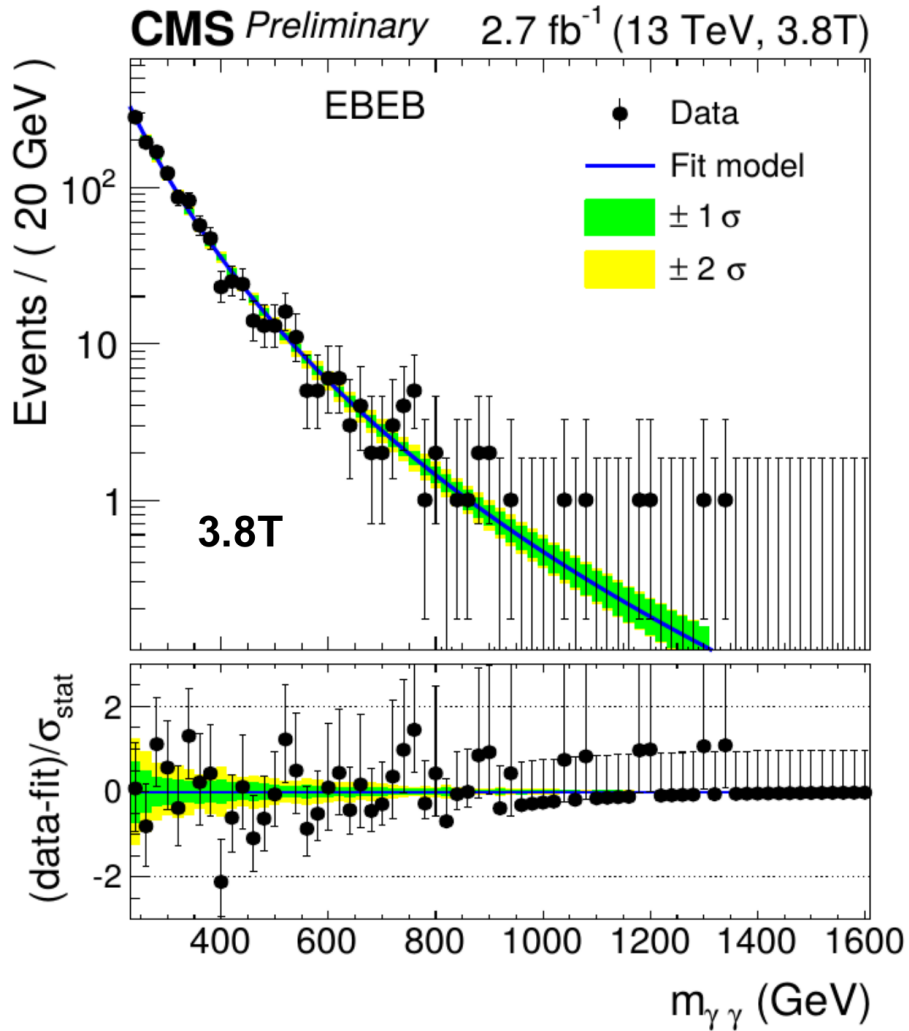
Save for later

Shares
220

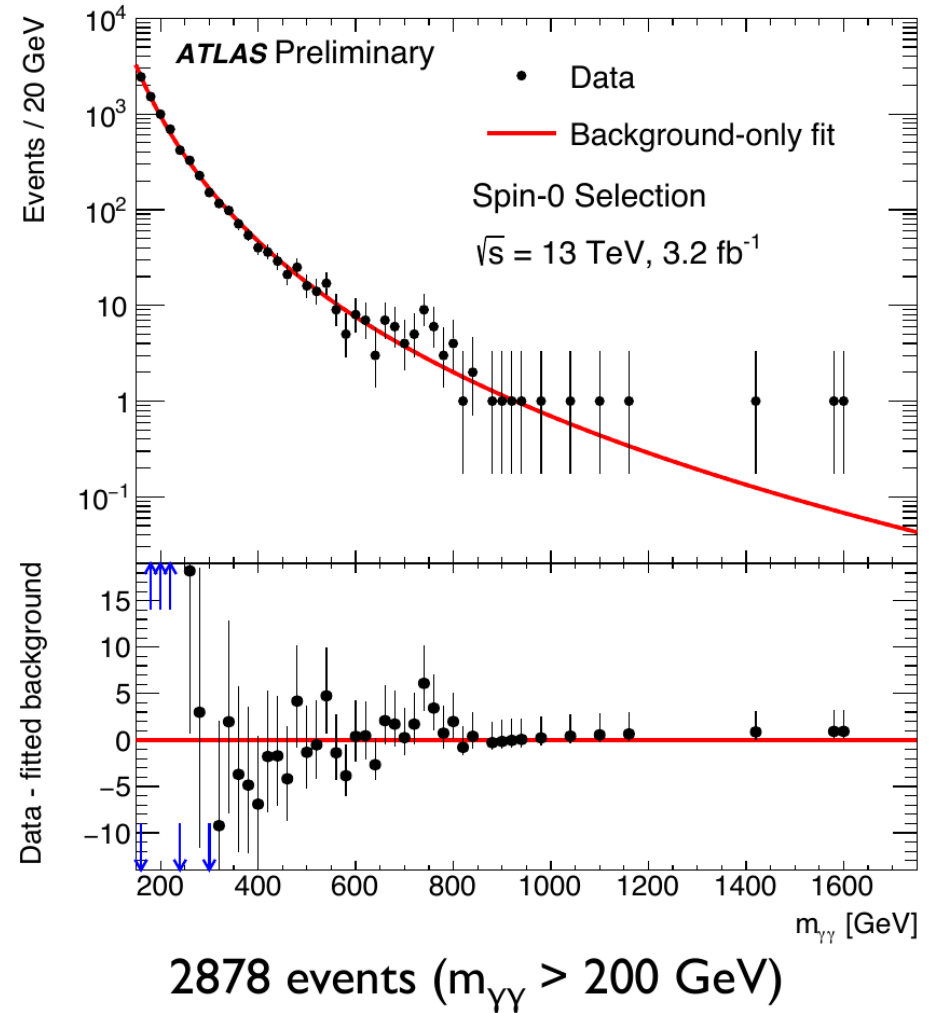
Comments
36

I've just finished watching the ATLAS and CMS experiments give their end of year seminars, presenting some analyses of data taken this year at the highest collision energy, 13 TeV. Being a "beyond the Standard Model" theorist, I was most

750 GeV Di-Photon

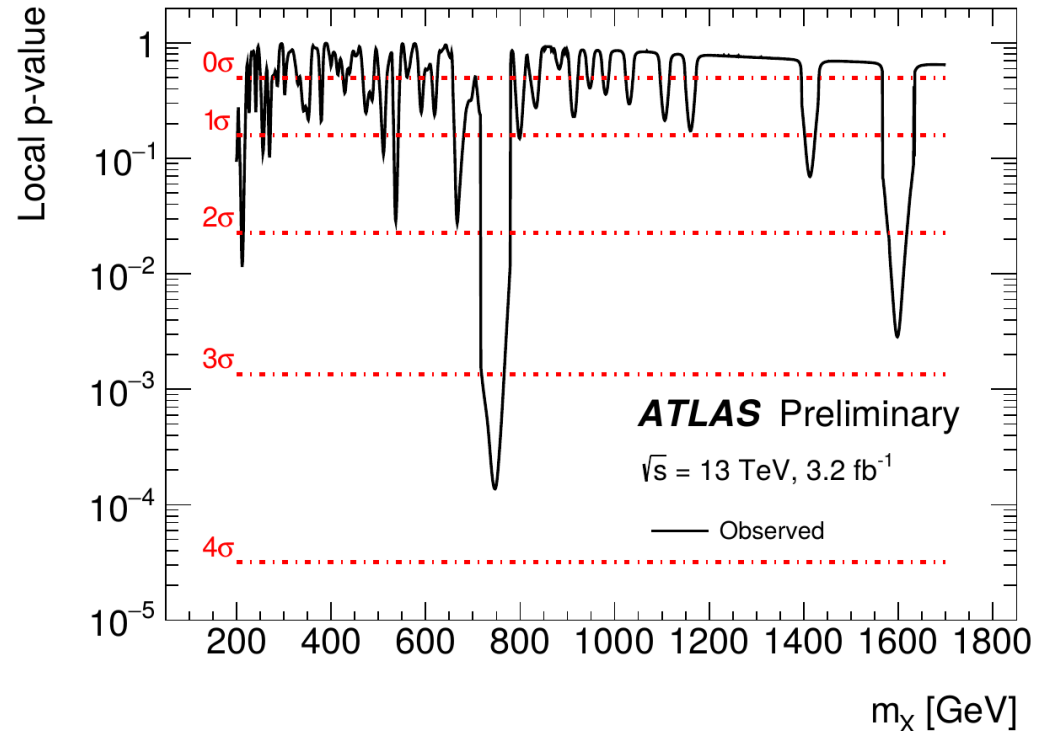
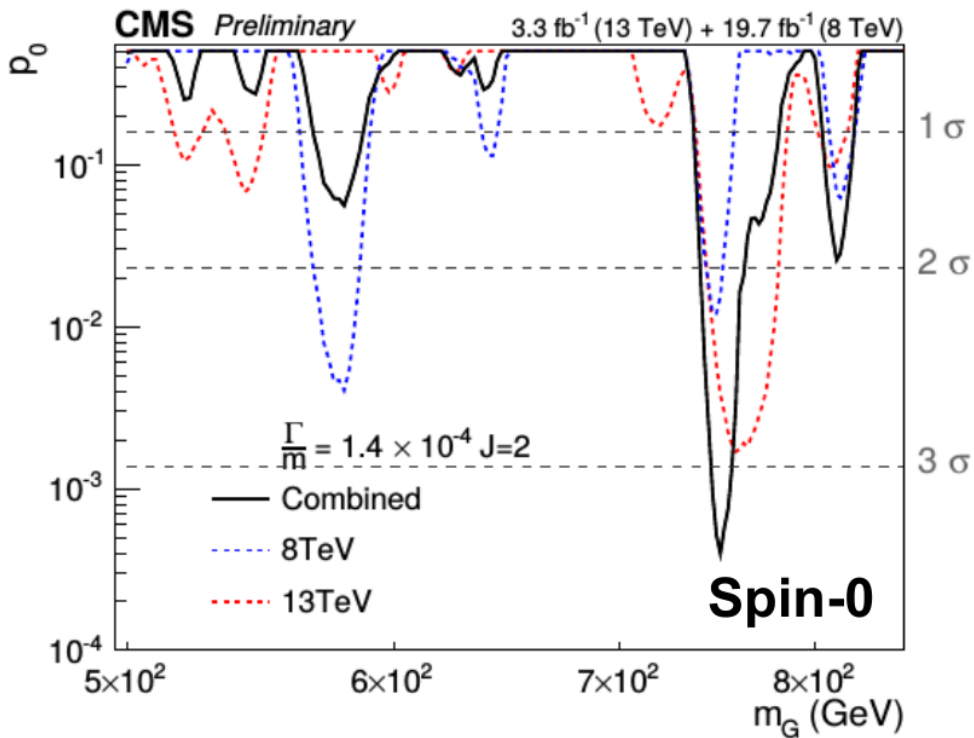


CMS (2.6 fb^{-1})



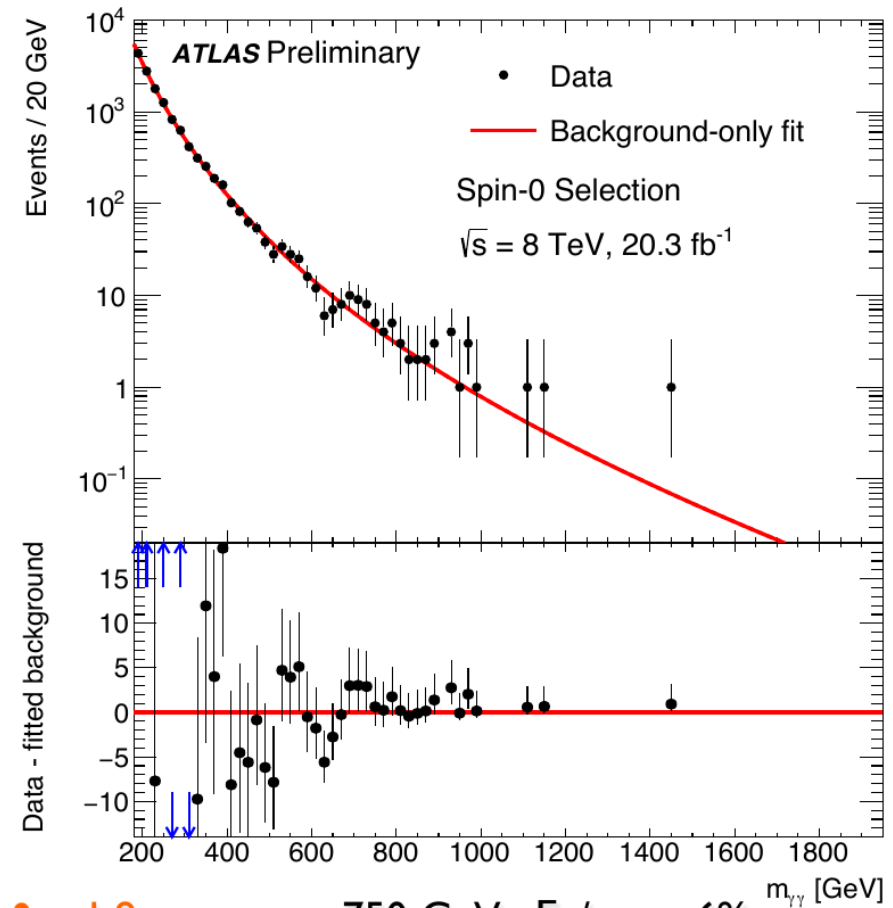
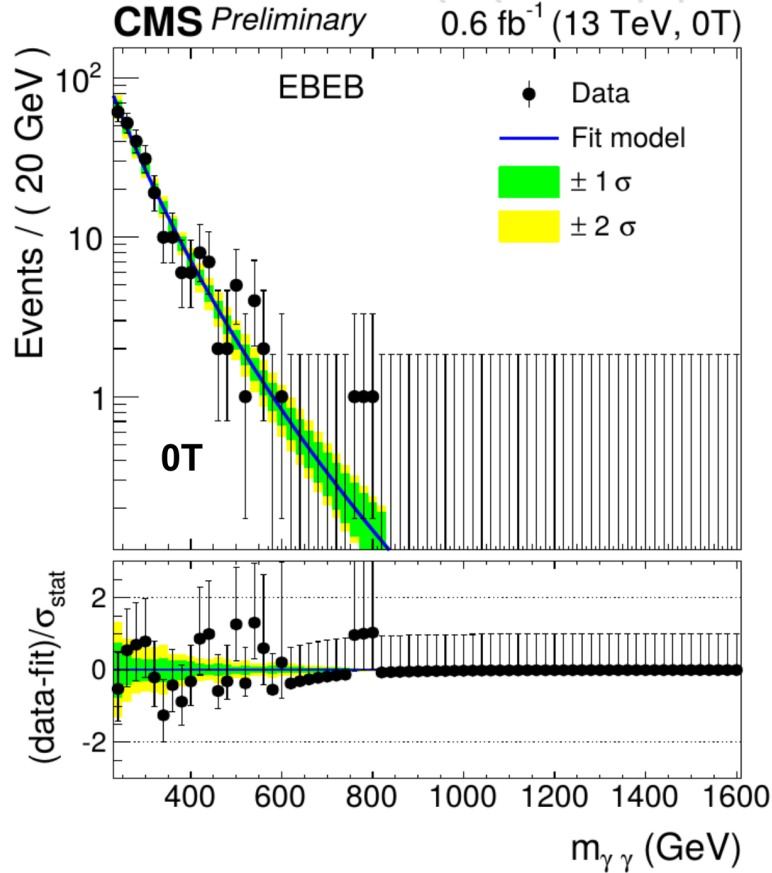
ATLAS (3.2 fb^{-1})

n -values: Run I



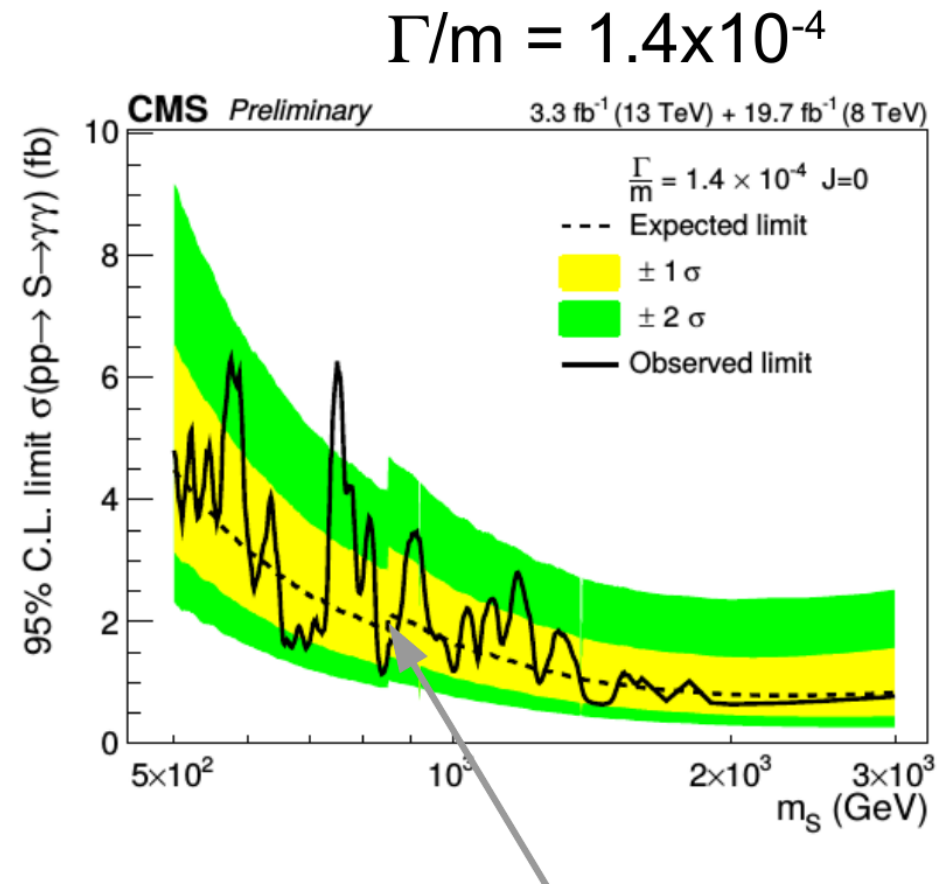
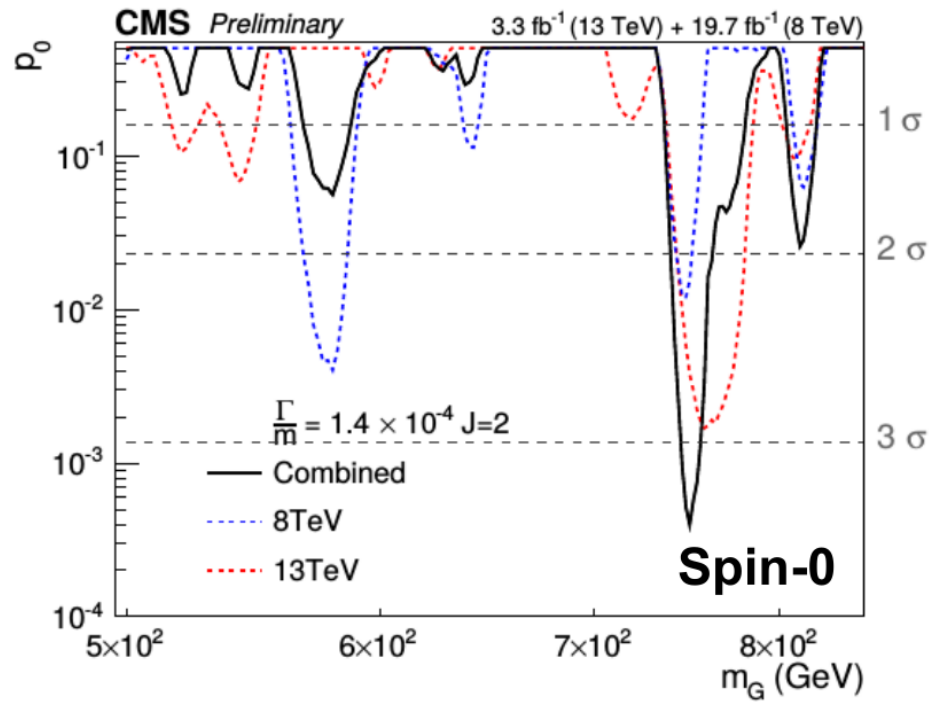
ATLAS: favours width of 45 GeV over narrow width to 0.3σ . Local(global) significance of **NWA** is 3.9 (2.3) σ .
 CMS: slightly favours narrow width. Local (global) significance is 2.6 (1.2) σ .

8 TeV Data from Moriond



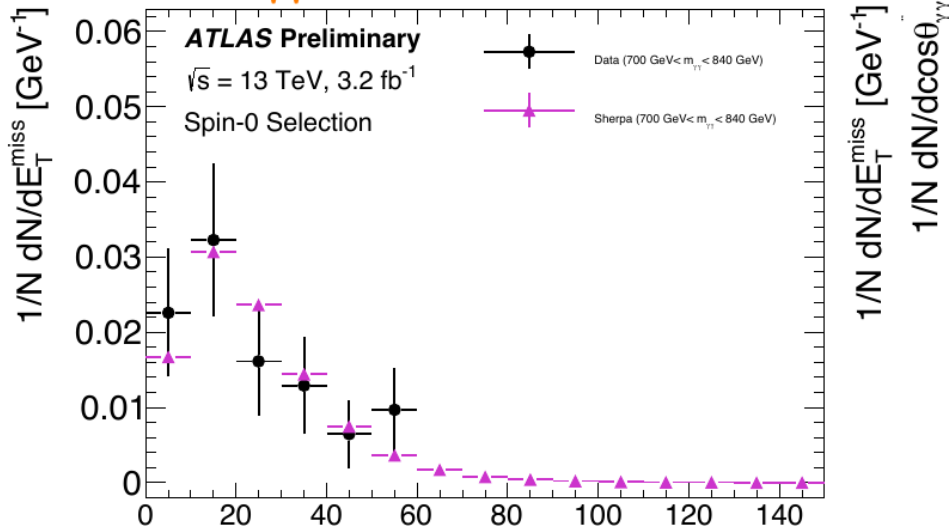
CMS: excess goes from 2.6σ to 3.4σ local
 ATLAS (1.9σ) excess, $gg \Rightarrow 1.2\sigma$, $qq \Rightarrow 2.1\sigma$

CMS 8+13 TeV

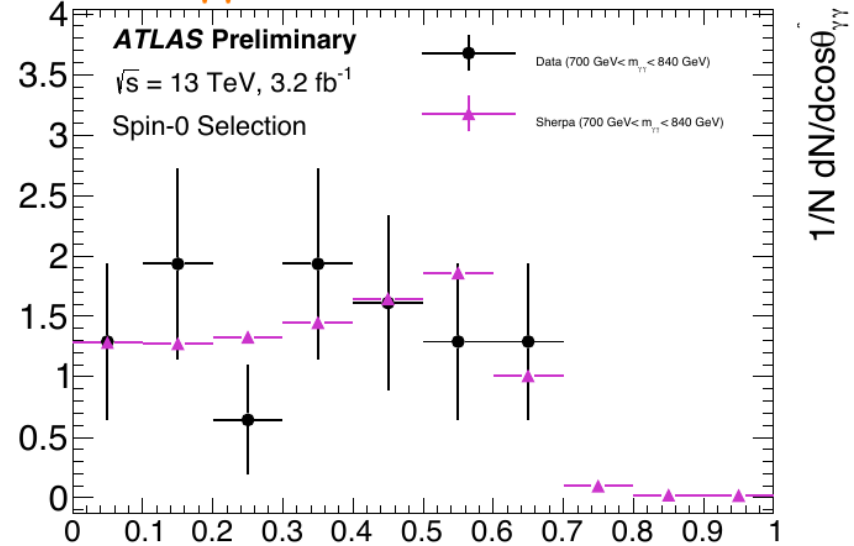


ATLAS Objects

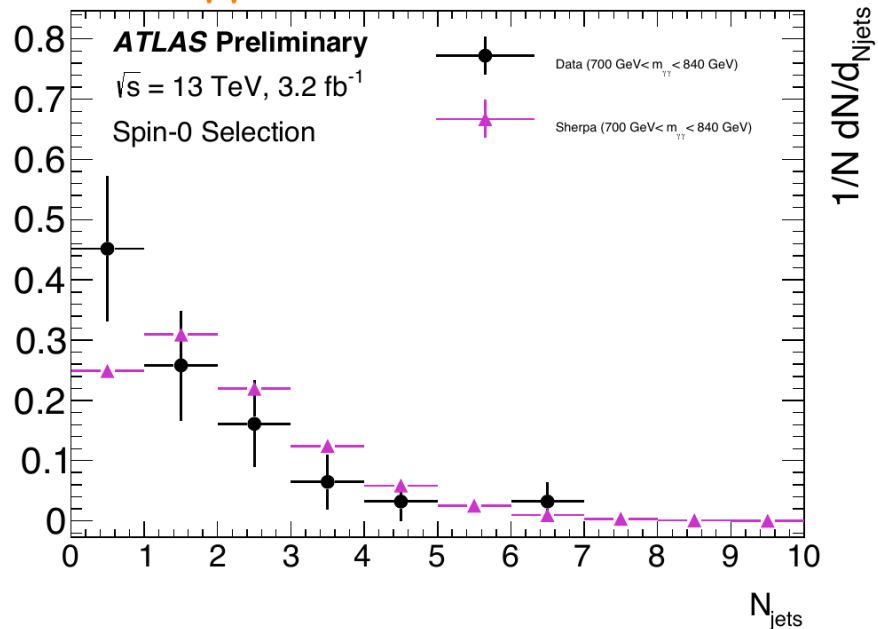
$m_{\gamma\gamma} = [700-840]$ GeV



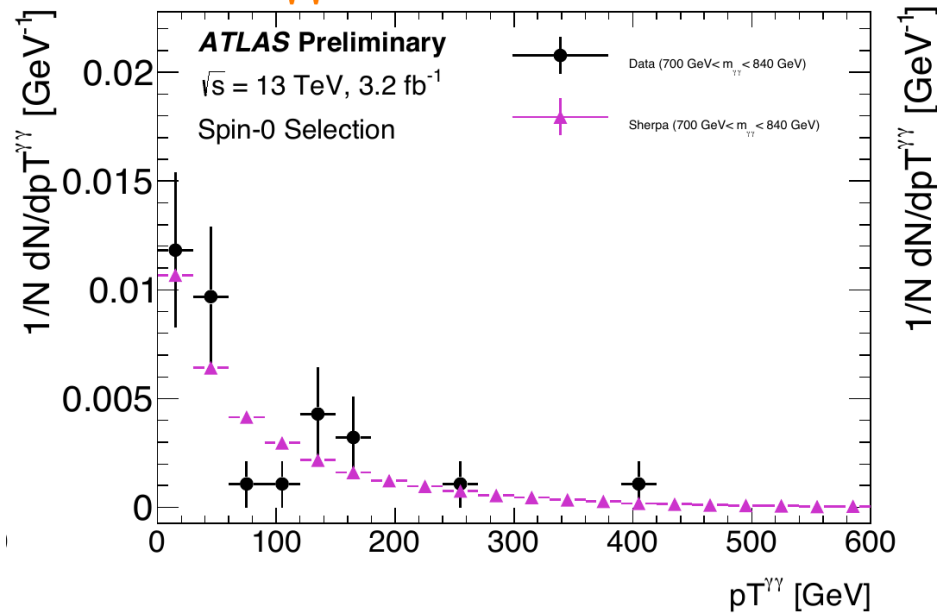
$m_{\gamma\gamma} = [700-840]$ GeV



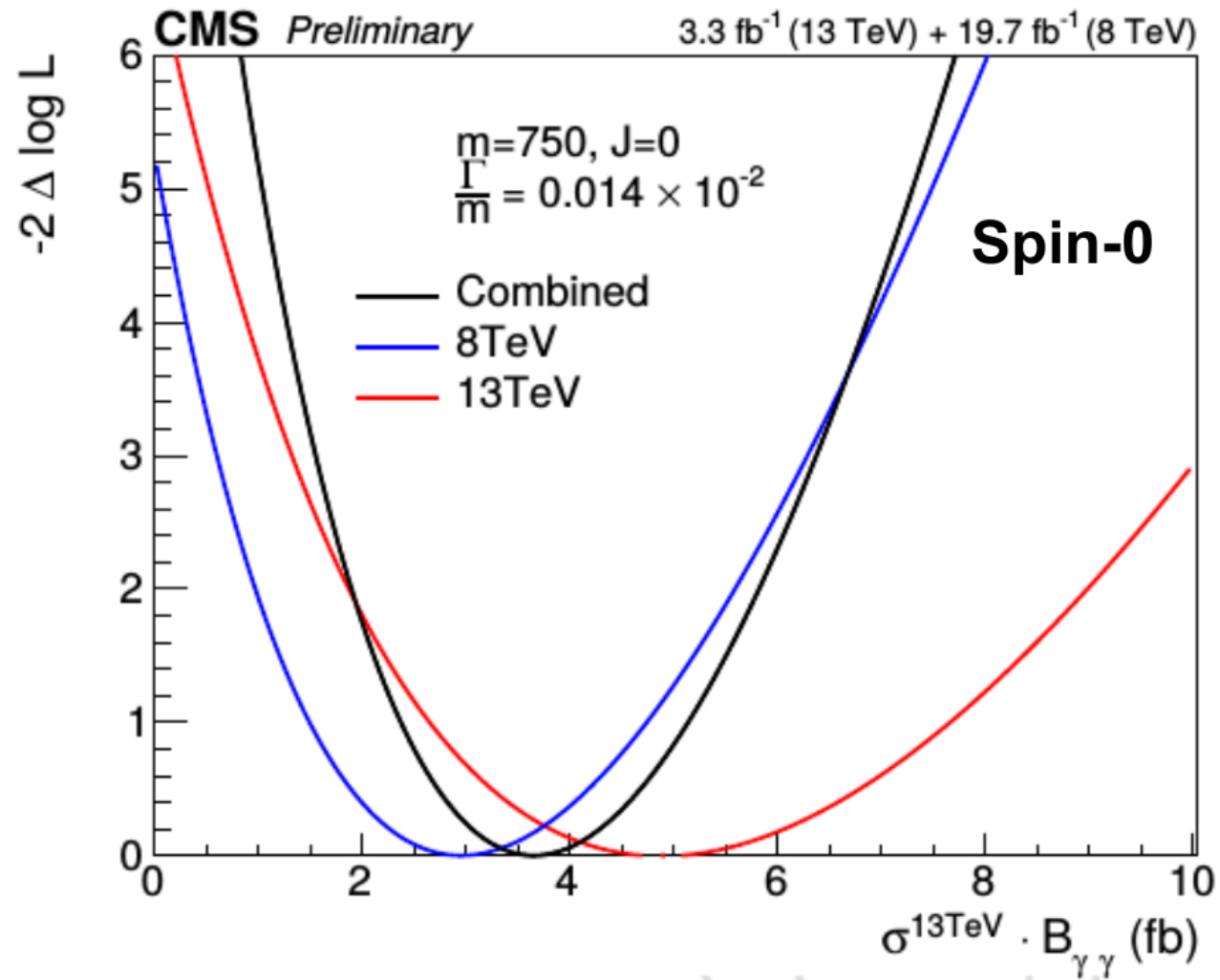
$m_{\gamma\gamma} = [700-840]$ GeV



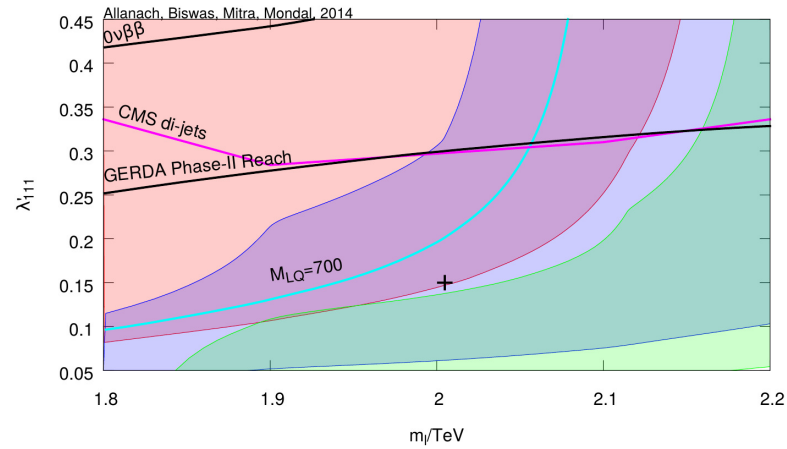
$m_{\gamma\gamma} = [700-840]$ GeV



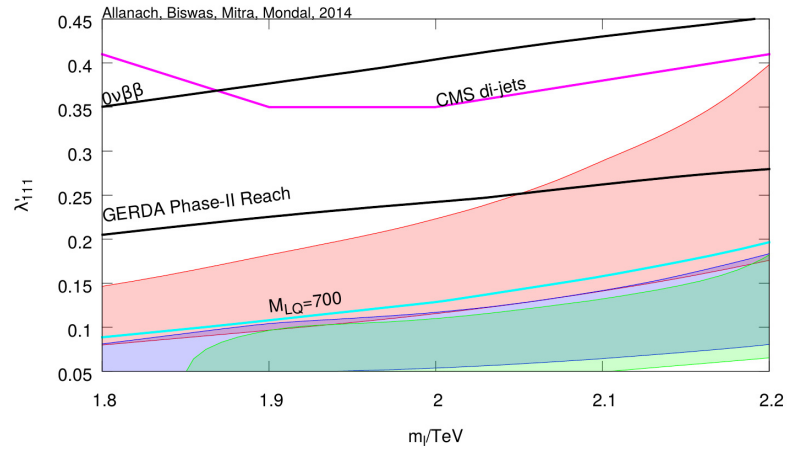
Cross section



Parameter Space: S2



Parameter Space: S3



CMS Excesses

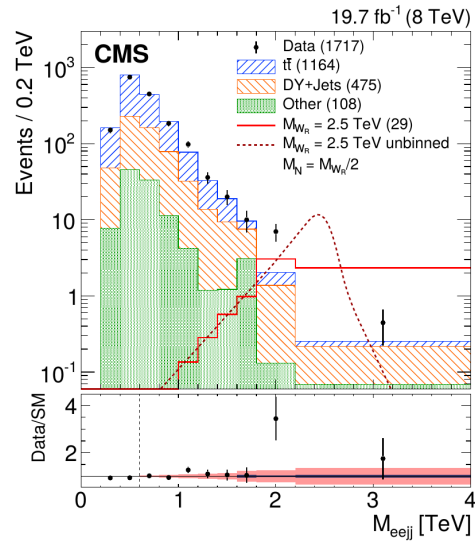
The anomalies were all in 20 fb^{-1} of data taken at 8 TeV.

- One anomaly was in a W_R search [arXiv:1407.3683](#)
- Two anomalies in a search for **di-leptoquark** production
[CMS PAS EXO-12-041](#)

NB We often deal with *invariant masses*, eg

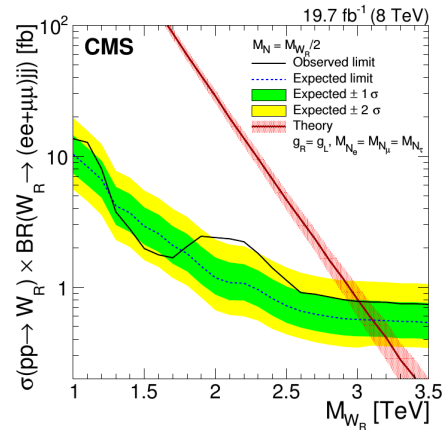
$$M_{lljj}^2 = (p(l_1) + p(l_2) + p(j_1) + p(j_2))^\mu (p(l_1) + p(l_2) + p(j_1) + p(j_2))_\mu$$

CMS W_R Search: 2.8σ



$$W_R \rightarrow l_1 N_l \rightarrow l_1 l_2 W_R^* \rightarrow ee q \bar{q}$$

W_R : Inferred Limits



A W_R model with reduced couplings could explain it

Deppisch *et al*, arXiv:1407.5384; Heikinheimo *et al*, arXiv:1407.6908;

Dobrescu *et al* arXiv:1408.1082; Aguilar-Saavedra *et al*, arXiv:1408.2456.

W_R Search Important Features

- No excess in $\mu\mu jj$
- The excess is at invariant masses of 2 TeV: this is consistent with a particle of mass 2 TeV decaying into $eejj$. There were 14 measured events on a background of 4.0 ± 1.0 .
- Of these 14, 1 was a *same-sign* pair and 13 were *opposite sign*. **Standard Model backgrounds:**

$$\begin{array}{cc}
 p & j \\
 & \bar{u} \\
 & \\
 p & u \\
 & j \\
 & \\
 & g \\
 & \\
 & t \bar{t} \\
 & W^+ W^- \\
 & b \bar{b} \\
 & \nu \bar{\nu}
 \end{array}$$

CMS Di-Leptoquark Search

Assume that $LQ \rightarrow ej$ or νj .

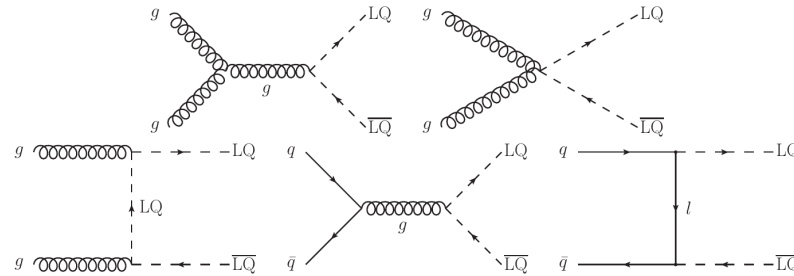


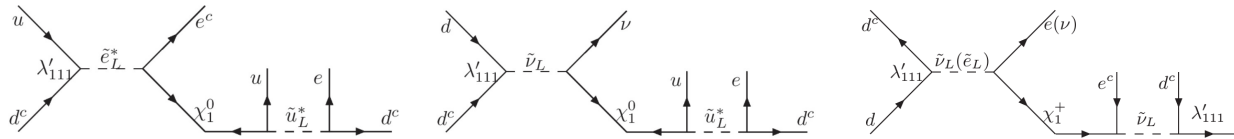
Figure 1: Dominant leading order diagrams for the pair production of scalar leptoquarks.

The signals they go for then are:

- $eejj$ 2.4σ : $S_T > 850$ GeV, $M_{eej} > 155$ GeV, $m_{ej}^{min} > 360$ GeV
- $e\nu jj$ 2.6σ : $S_T > 1040$ GeV, $M_{ejj} > 555$ GeV, $\cancel{E}_T > 145$ GeV, $M_T(e\nu) > 270$ GeV

Proposal: $W = \lambda'_{111} L Q d^c$

2 TeV left-handed selecton which decays via the λ'_{111} :

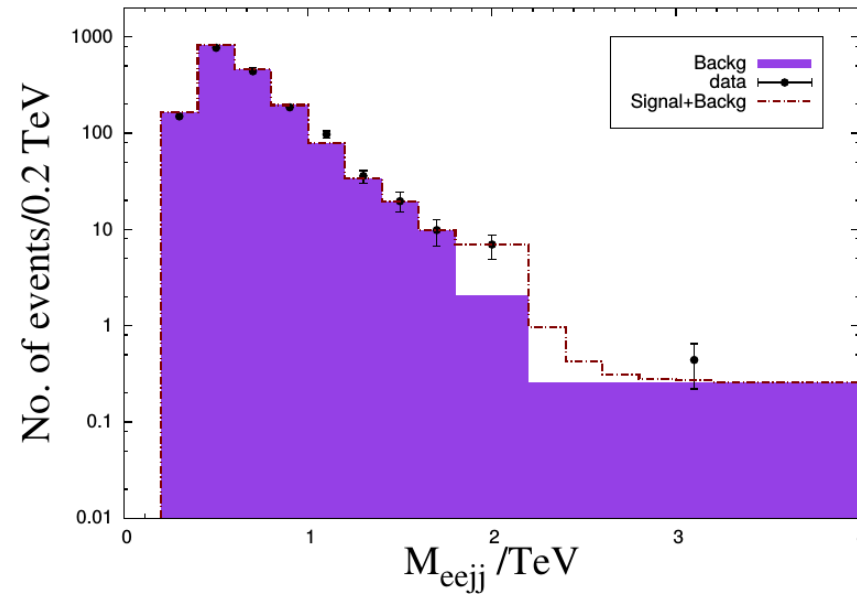


$$m_{\tilde{e}_L}^2 = m_{\tilde{\nu}_L}^2 + M_W^2 \cos 2\beta$$

Resolves W_R , di- LQ anomalies BCA, Biswas, Mondal, Mitra,

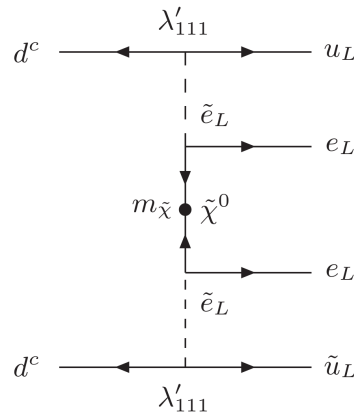
arXiv:1408.5439; *ibid* arXiv:1410.5947

W_R Mass Distribution

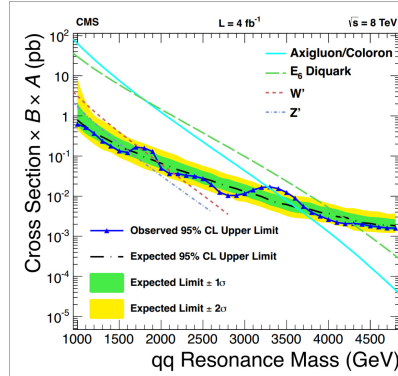
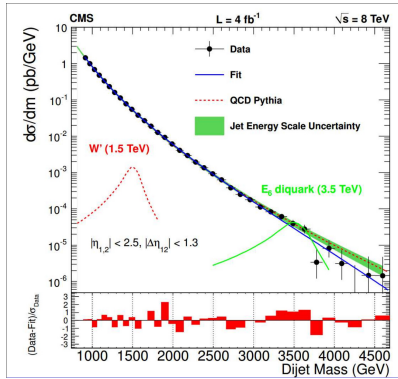


Neutrinoless Double Beta Decay

Is *banned* in the Standard Model because it breaks lepton number:
 $Z \rightarrow (Z + 2)e^-e^-$ Present bound from GERDA is $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr. It should increase by a factor **10** in the next year or so.



Other Constraints



CMS [arXiv:1302.4794](https://arxiv.org/abs/1302.4794)

u^c
 d

\tilde{e}_L

d
 u^c

Neutralino mass matrix

In the basis $[-i\tilde{B}, -i\tilde{W}^3, \tilde{H}_1, \tilde{H}_2]^T$

$$\begin{bmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{bmatrix}$$

Mass eigenstates are labelled $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$ in increasing mass order.

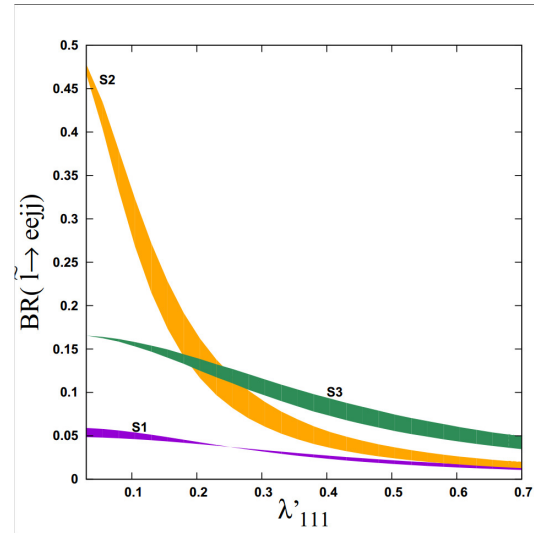
Decays into/from neutralinos are affected by their *composition*.

$\tan \beta = s_\beta/c_\beta$ is the ratio of the two Higgs VEVs.

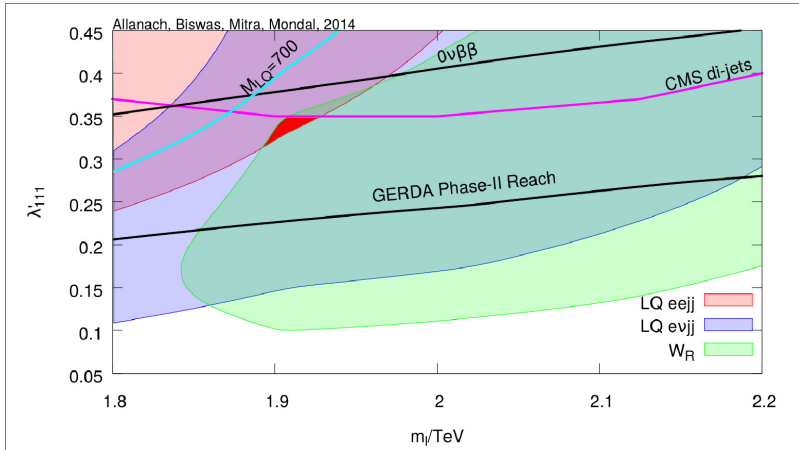
Three Neutralino Scenarios

- **S1:** $M_2 = M_1 + 200 < \mu$. \tilde{B} LSP. \tilde{e} can decay to χ_2^0 or χ_1^\pm . Predicts $R = OS/SS = 1$.
- **S2:** $M_1 < \mu < M_2$. \tilde{B} LSP, but increased BR for $\tilde{l} \rightarrow \chi_1^0 l$. Predicts $R = 1$.
- **S3:** $M_2 \ll M_1$. \tilde{W} LSP. $\tilde{l}_L \rightarrow \chi_1^\pm$ but χ_1^\pm decays via λ'_{111} too. Predicts $R = 3$.

Branching Ratios



Parameter Space: S1



The red triangle here will be covered by GERDA Phase-II

Event Numbers

| Channel | $s + \bar{b}$ | $\bar{b} \pm \sigma_b$ | Data |
|--|---------------|------------------------|------|
| $eejj(M_{LQ} = 650 \text{ GeV})$ | 41.5 | 20.5 ± 3.3 | 36 |
| $e\nu jj(M_{LQ} = 650 \text{ GeV})$ | 33.9 | 7.5 ± 1.6 | 18 |
| $eejj(M_{LQ} = 700 \text{ GeV})$ | 32.7 | 12.7 ± 2.7 | 17 |
| $W_R(1.6 < M_{eejj}/\text{TeV} < 1.8)$ | 12.4 | 9.6 ± 3.8 | 10 |
| $W_R(1.8 < M_{eejj}/\text{TeV} < 2.2)$ | 26.0 | 4.0 ± 1.0 | 14 |
| $W_R(M_{eejj}/\text{TeV} > 2.2)$ | 2.6 | 2.2 ± 1.8 | 4 |

Signal model point: **S2** with $\lambda'_{111} = 0.175$, $m_{\tilde{l}} = 2\text{TeV}$
and $M_{\chi_1^0} = 900 \text{ GeV}$.

ATLAS On-Z Analysis

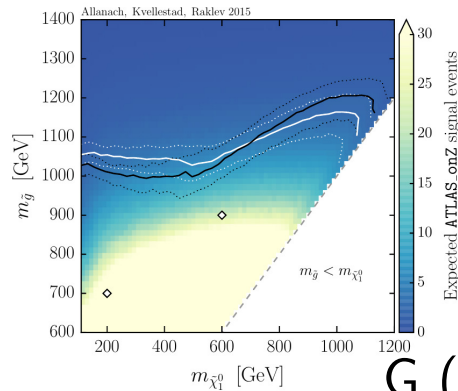
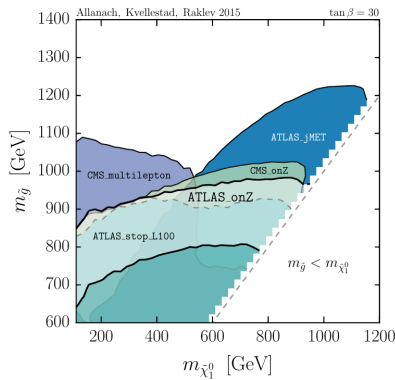
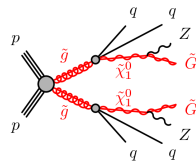
| | |
|-----------------|----------------|
| observed | 29 |
| background | 10.6 ± 3.2 |
| number of sigma | 3.0 |
| s (95% CL) | 7.1-31.8 |

$\cancel{E}_T > 225$ GeV, $H_T > 600$ GeV, $81 < m_{ll}/\text{GeV} < 101$,
OSSF leptons, $p_T(j_{1,2}) > 35$ GeV.

CMS sees no excess, but has **different** cuts: OSSF,
 $81 < m_{ll}/\text{GeV} < 101$, $p_T(j_{1,2}) > 40$ GeV,
 $\cancel{E}_T/\text{GeV} = [100 - 200, 200 - 300, > 300]$.

Have to check on a model-by-model basis whether they are compatible

Combined Constraints



G (Barenboim *et al* also had this interpretation in [arXiv:1503.04184](https://arxiv.org/abs/1503.04184)).

Less¹ than 6(7) events for $\tan \beta = 1.5(30)$.

¹BCA, Kvellestad, Raklev, [arXiv:1504.02752](https://arxiv.org/abs/1504.02752)

CMS $l^+l^-jj\cancel{E}_T$ 2.6σ Excess

Search in m_{ll} : for **O**pposite **S**ign **S**ame **F**lavour leptons (either e or μ). Demand $\cancel{E}_T > 100$ GeV.

The dominant $t\bar{t}$ background produces $e^\pm\mu^\mp$ at the same rate as **OSSF** (e^+e^- or $\mu^+\mu^-$) and so it is used to measure the background.

Background estimate: 730 ± 40 events, but there were **860** measured: an excess of 130^{+48}_{-49} .

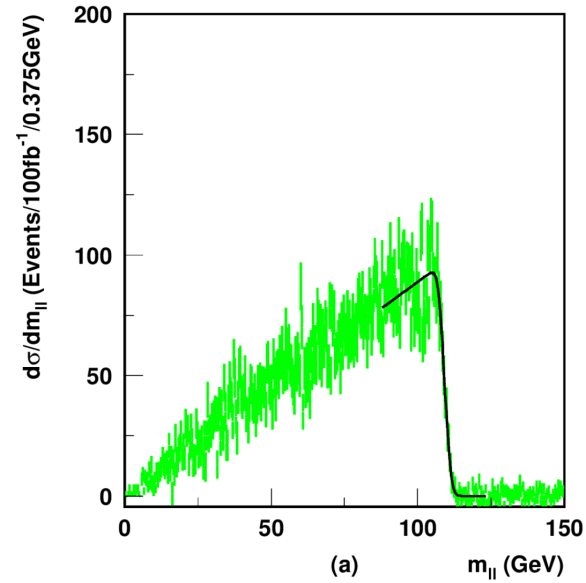
Explanation: Supersymmetry

$$\begin{array}{cccc} \tilde{q}_L^q & \chi_2^{b^\pm} & \tilde{l}_R^{\mp} & \chi_1^0 \\ \tilde{q}_R & & & \chi_1^0 \end{array}$$

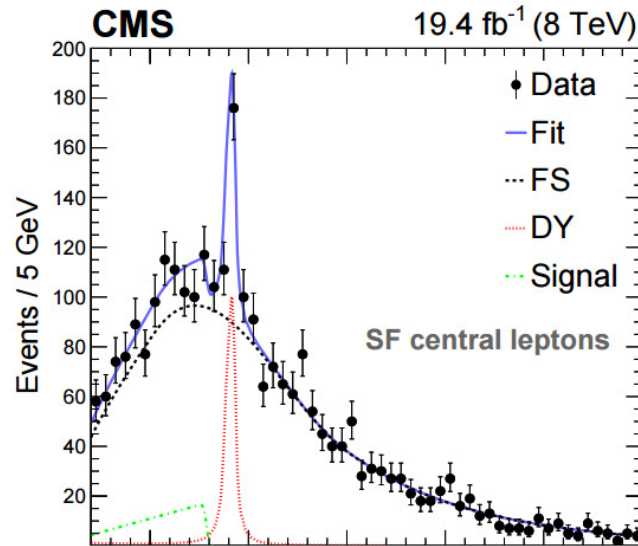
Figure 1: Feynman diagram for the golden cascade decay: opposite sign same flavour leptons (OSSF)

BCA, Raklev, Kvellestad, [arXiv:1409.3532](https://arxiv.org/abs/1409.3532); Huang Wagner PRD 90 015014
[arXiv:1410.4998](https://arxiv.org/abs/1410.4998); Grothaus, Sakurai [arXiv:1502.05712](https://arxiv.org/abs/1502.05712)

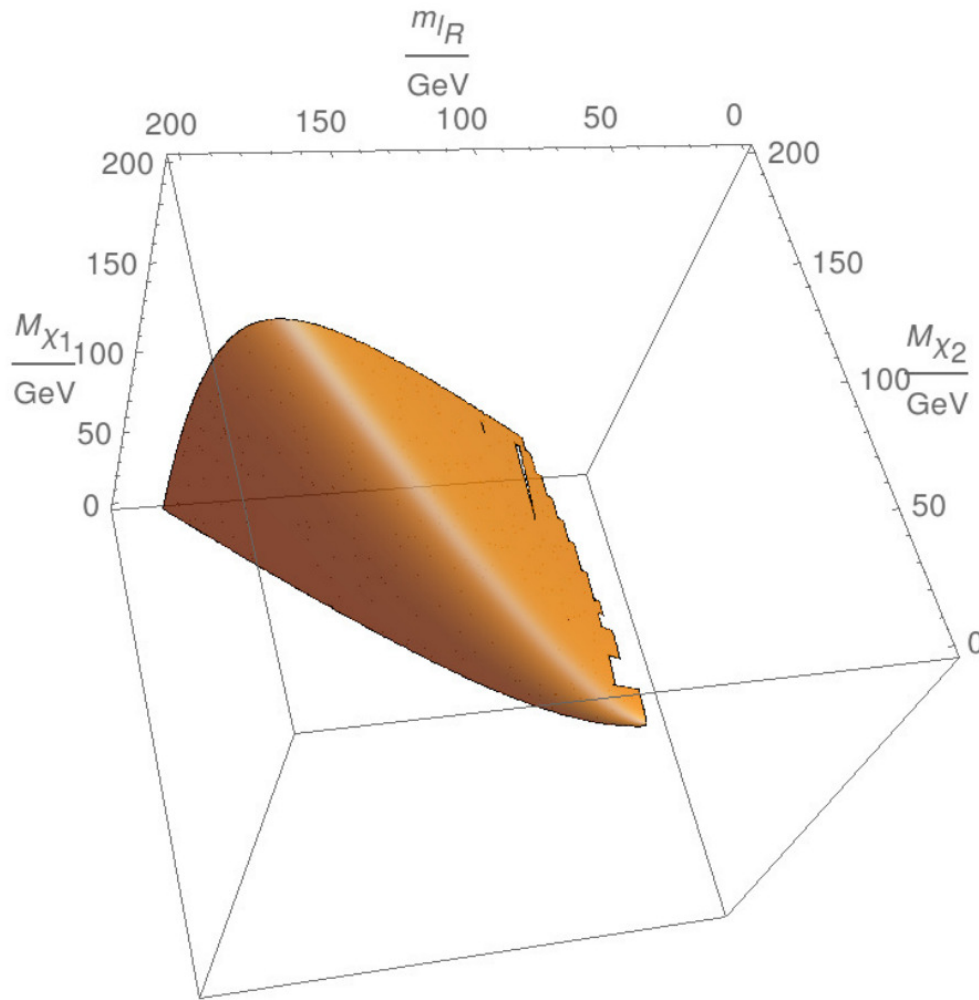
A Sharp Invariant Feature



m_{ll} Distribution



Edge Interpretation



The signal **rate** determines $m_{\tilde{q}}$,

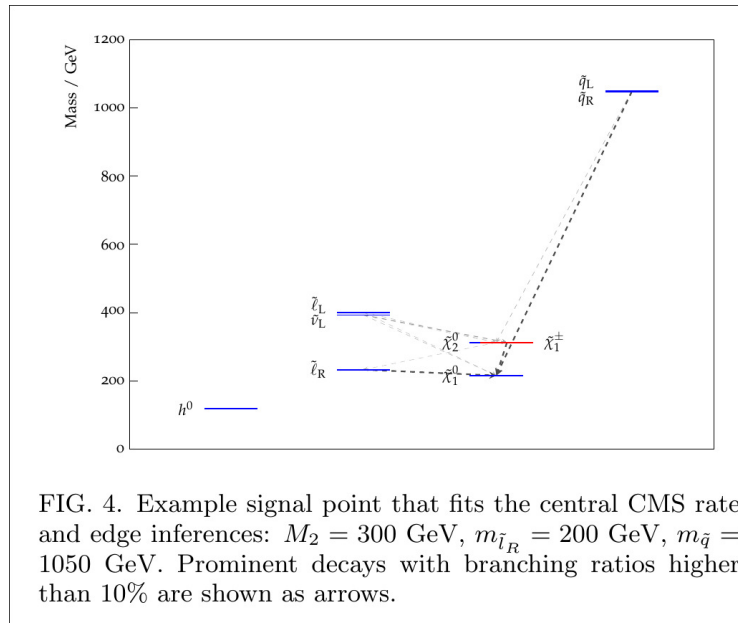
$$m_{ll}^{max} = 78.4 \pm 1.4$$

GeV we fit to

$$\sqrt{\frac{(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}}$$

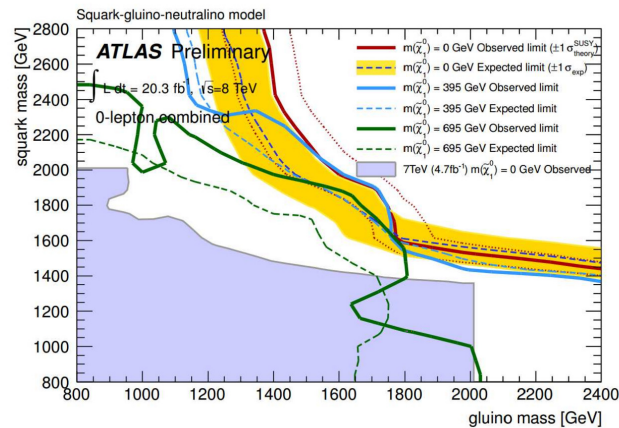
We choose $m_{\tilde{l}}, M_2$ then vary M_1 in order to predict the correct m_{ll}^{max} . Sometimes, $M_1 > M_2$.

Example Spectrum



LHC Constraints

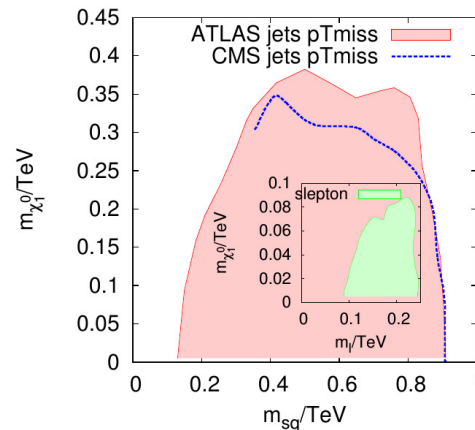
We shall see squark masses of around a TeV being predicted.



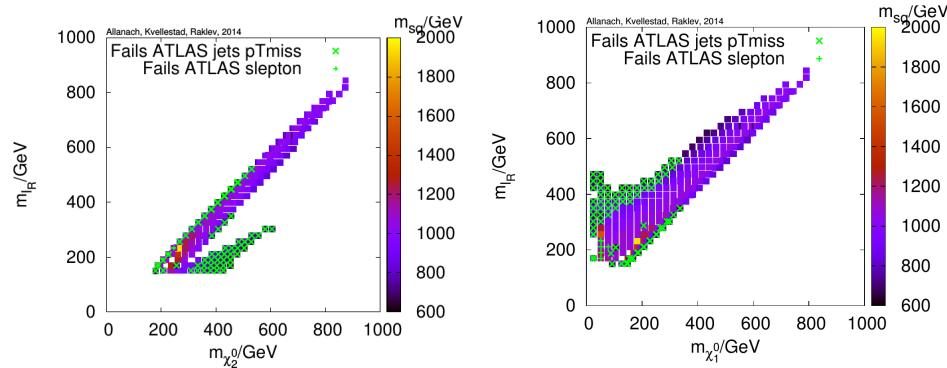
Other Constraints

We shall see squark masses of around a TeV being predicted.

ATLAS(2014), [arXiv:1405.7875](#); CMS JHEP **1406** (2014) 055,
[arXiv:1402.4770](#).



Viability Parameter Space

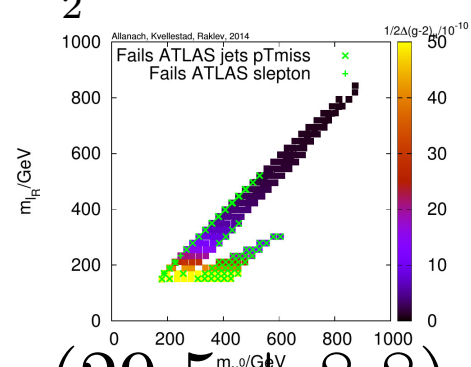
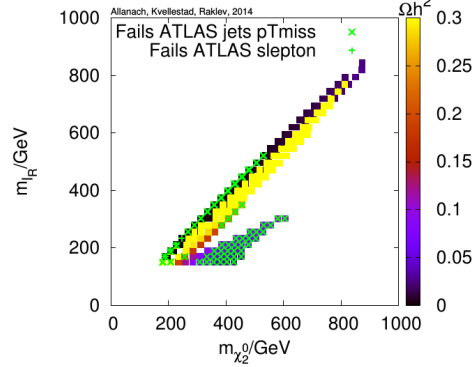


Parameter space fitting the central rate edge measurement.

Constraints from ATLAS and 4-lepton \cancel{E}_T searches currently underway

$(g - 2)_\mu$ and Dark Matter

$$\Omega h^2 = 0.1198 \pm 0.0026 \frac{\delta(g-2)_\mu}{2} \sim 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{SUSY}} \right)^2 \tan \beta$$

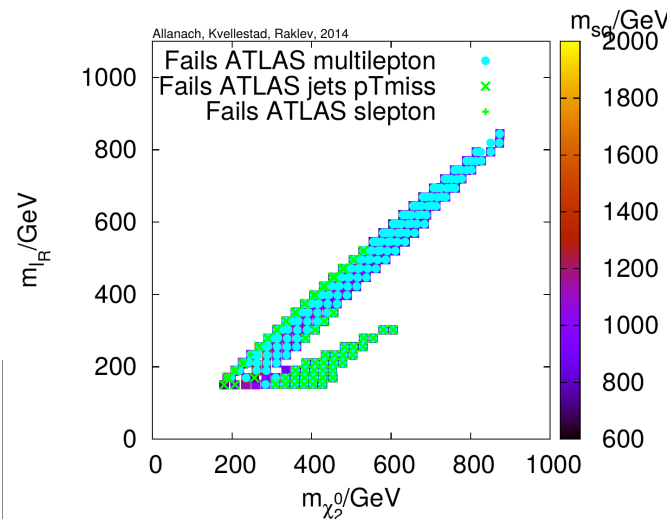


$$(29.5 \pm 8.8) \times 10^{-10}$$

$$\begin{matrix} \chi_1^0 & \tilde{l}^- \\ \chi_1^0 & \tilde{l}^+ \end{matrix}$$

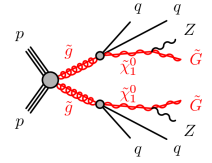
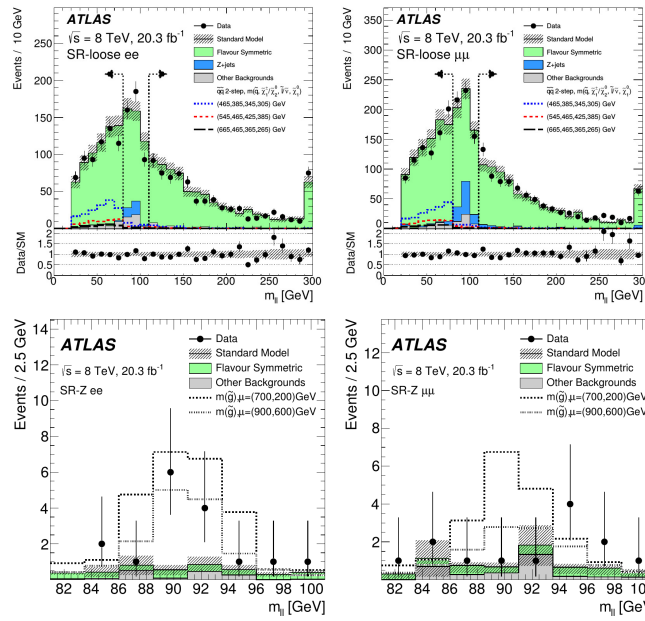
$$\begin{matrix} \tilde{\mu}_0 & \gamma \\ \mu & \mu \end{matrix}$$

CMS 4-lepton \cancel{E}_T (*preliminary*)

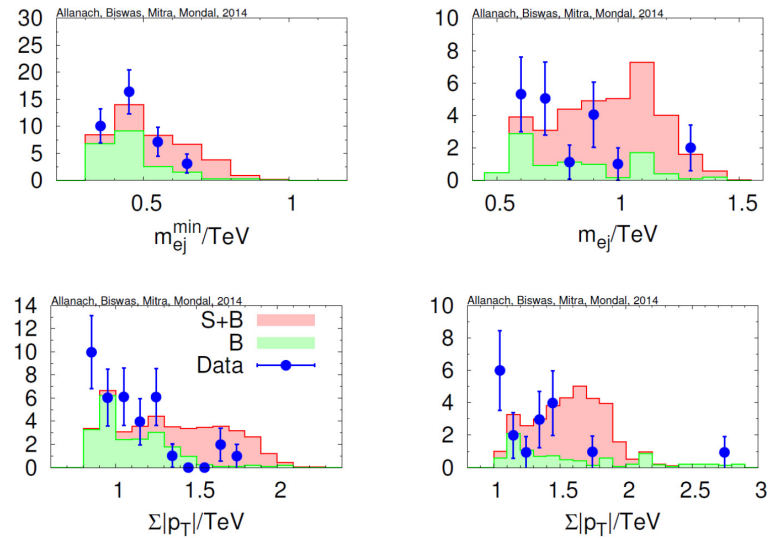


ATLAS Disagrees

arXiv:1503.03290



Kinematical Distributions: LQ



Cascade Decay

$$\begin{array}{l} l^+ \quad l^- \\ \chi_2^0 \quad \tilde{l} \quad \chi_1^0 \end{array} \quad \begin{array}{l} p_{\tilde{l}}^\mu = (m_{\tilde{l}}, 0) \\ p_{l^\pm}^\mu = (|\underline{p}_{l^\pm}|, \underline{p}_{l^\pm}) \\ p_{\chi_{1,2}^0}^\mu = \left(\sqrt{m_{\chi_{1,2}^0}^2 + |\underline{p}_{\chi_{1,2}^0}|^2}, \underline{p}_{\chi_{1,2}^0} \right) \end{array}$$

Work in \tilde{l} rest frame.

The invariant mass of the l^+l^- pair is

$$\begin{aligned} m_{ll}^2 &= (p_{l^+} + p_{l^-})^\mu (p_{l^+} + p_{l^-})_\mu = p_{l^+}^2 + p_{l^-}^2 + 2p_{l^+} \cdot p_{l^-} \\ &= 2|\underline{p}_{l^+}| |\underline{p}_{l^-}| (1 - \cos \theta) \leq 4|\underline{p}_{l^+}| |\underline{p}_{l^-}|. \end{aligned}$$

Momentum conservation:

$$\Rightarrow \underline{p}_{\chi_2^0} + \underline{p}_{l^+} = \underline{0}, \quad \underline{p}_{l^-} + \underline{p}_{\chi_1^0} = \underline{0}.$$

Energy conservation: $\sqrt{m_{\chi_2^0}^2 + |\underline{p}_{\chi_2^0}|^2} = m_{\tilde{l}} + |\underline{p}_{l^+}|,$

$$\Rightarrow |\underline{p}_{l+}| = \frac{m_0^2 - m_{\tilde{l}}^2}{2m_{\tilde{l}}}. \text{ Similarly } |\underline{p}_{l-}| = \frac{m_{\tilde{l}}^2 - m_0^2}{2m_{\tilde{l}}}.$$

Statistics

$\bar{b} \pm \sigma_b$ background events:

$$p(b|\bar{b}, \sigma_b) = \begin{cases} B e^{-(b-\bar{b})^2/(2\sigma_b^2)} & \forall b > 0 \\ 0 & \forall b \leq 0 \end{cases}$$

Marginalise over b to take confidence limits:

$$P(n|n_{exp}, \bar{b}, \sigma_b) = \int_0^\infty db p(b|\bar{b}, \sigma_b) \frac{e^{-n_{exp}} n_{exp}^n}{n!}.$$

The CL is then $P(n < n_{obs}|n_{exp}, \bar{b}, \sigma_b)$.

Simulations

- SUSY spectrum `SOFTSUSY3.5.1` modified to iterate and hit the edge measurement
- Sparticle decays `SUSYHIT1.4`
- LHC signal events `PYTHIA8.186`
- Backgrounds `CMS`
- Dark matter and anomalous magnetic moment of the muon `micrOMEGAs3.6.9.2`
- All linked together with the SLHA.

A New Leptoquark Model

Does not lead² to proton decay, and has:

- A scalar $\tilde{R}_2 = (3, 2, 1/6)_+$
- A scalar $S = (1, 3, 0)_-$
- A dark matter fermion $\chi = (1, 1, 0)_-$.

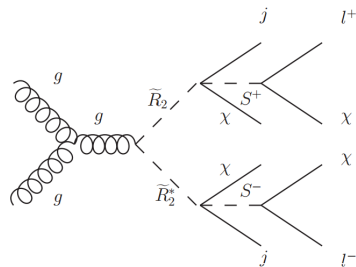
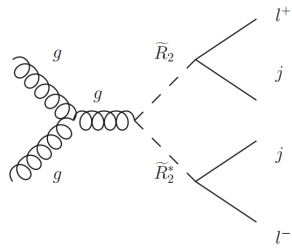
$$\mathcal{L} = -\lambda_d^{ij} \bar{d}_R^i \tilde{R}_2^T \epsilon L_L^j + hc - \frac{h_i}{\Lambda} S \bar{Q}_i \chi \tilde{R}_2 - \frac{h'_i}{\Lambda_2} S \bar{l}_i \chi \tilde{H} +$$

$$BR(\tilde{R}_2 \rightarrow lj) \sim 15\%, \quad BR(\tilde{R}_2 \rightarrow S^0 j \chi \rightarrow j \cancel{E}_T) \sim 25\%, \\ BR(\tilde{R}_2 \rightarrow S^\pm j \chi \rightarrow l^\pm j \cancel{E}_T) \sim 65\%.$$

²Queiroz, Sinha, Strumia, [arXiv:1409.6301](https://arxiv.org/abs/1409.6301); BCA, Alves, Queiroz, Sinha, Strumia, [arXiv:1501.03494](https://arxiv.org/abs/1501.03494)

Production at the LHC

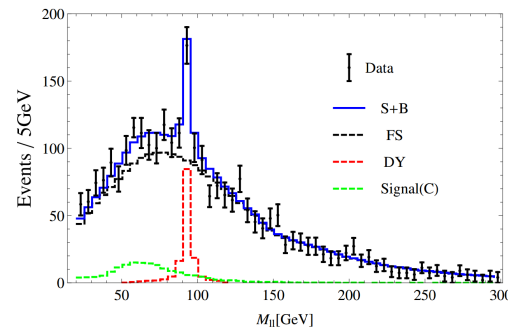
Upper
 diagram
 can
 explain
 W_R
 and di-
 leptoquark
 excesses.



Lower
 diagram
 can
 explain
 CMS
 SUSY
 search

Constraints on the masses

- $j\cancel{E}_T$ searches imply $M_S + M_\chi > 300$ GeV for LQs around 500 GeV.
- To get the m_{ll} spectrum right in the CMS $l^+l^-jj\cancel{E}_T$ excess, $m_S - m_\chi \sim 20 - 40$ GeV.



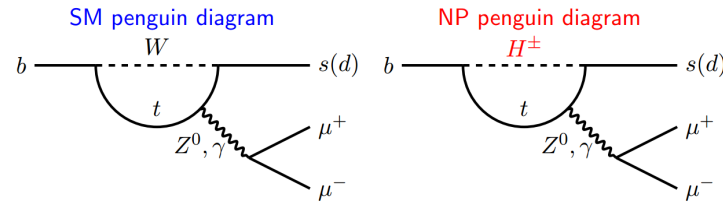
Dark Phenomenology

DM stability is guaranteed by a discrete Z_2 . χ has a significant pseudoscalar coupling to the Higgs, resulting in a dominant spin-*dependent* scattering cross-section.

$$\mathcal{L} = \bar{\chi}(i/\partial - M_\chi)\chi + \frac{1}{\Lambda} \left(vh + \frac{1}{2}h^2 \right) \\ [\bar{\chi}\chi \cos \xi + \bar{\chi}i\gamma_5\chi \sin \xi] +$$

Direct searches (eg LUX) imply that $m_\chi > 100$ GeV is allowed for $\sin^2 \xi > 0.7$ and $\Lambda = 1 - 5$ TeV. We pick $m_\chi \sim 140$ GeV.

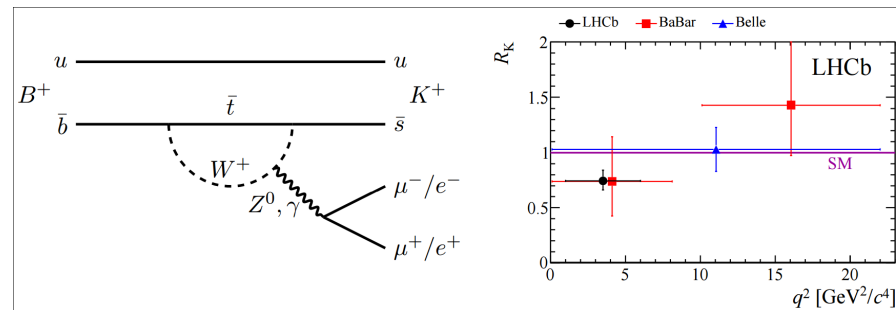
B Meson Rare Decays



- FCNC decays loop suppressed and rare in the Standard Model
- New heavy particles in could appear in competing diagrams can affect the branching ratio and angular distributions

$R_K: 2.6 \sigma$

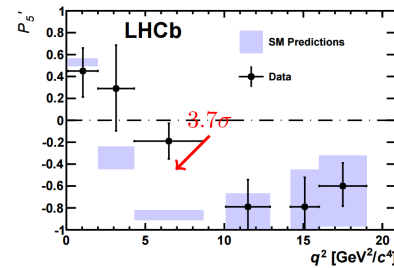
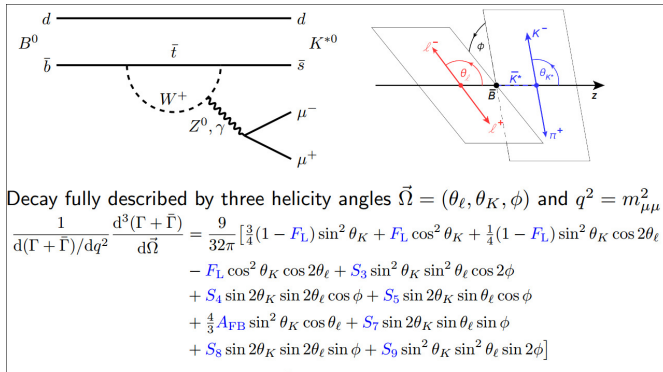
$$R_K \equiv \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B \rightarrow K^+ e^+ e^-)} \quad R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$



$$R_K(SM) = 1.00$$

Indicates lepton flavour non-universality

$$B^0 \rightarrow K_*^0(\rightarrow K^+\pi^-)\mu^+\mu^-$$



$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)},$$

leading FF
uncertainties
cancel.

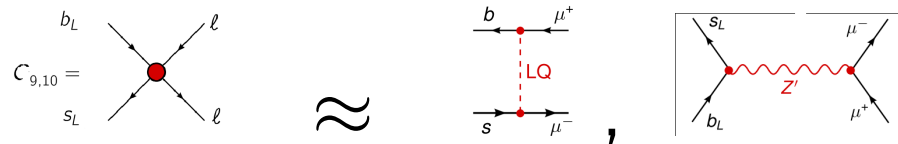
Tension
already in
 1 fb^{-1} and
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LHCb-CONF-2015-002

New Physics: Effective Operators

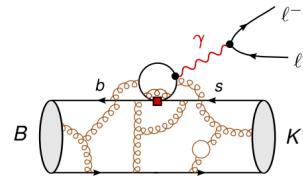
Altmannshofer, Straub arXiv:1411.3161



$$\mathcal{L} = C_9(\bar{s}_L\gamma^\mu b_L)(\bar{l}\gamma_\mu l) + C_{10}(\bar{s}_L\gamma^\mu b_L)(\bar{l}\gamma_\mu\gamma_5 l) + \dots$$

Fitting many operators to 76 B -physics observables, a non-zero fit to C_9^μ is preferred at the 4.3σ level.

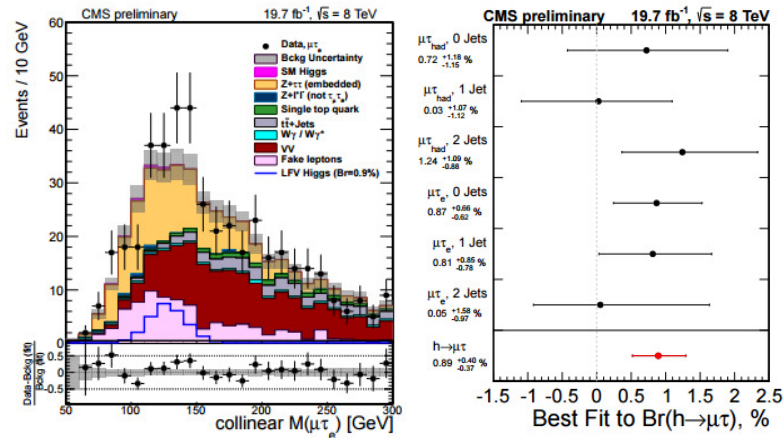
- ▶ Hadronic effects like charm loop are photon-mediated \Rightarrow vector-like coupling to leptons just like C_9



- ▶ How to disentangle NP \leftrightarrow QCD?
 - ▶ Hadronic effect can have different q^2 dependence
 - ▶ Hadronic effect is lepton flavour universal ($\rightarrow R_K!$)

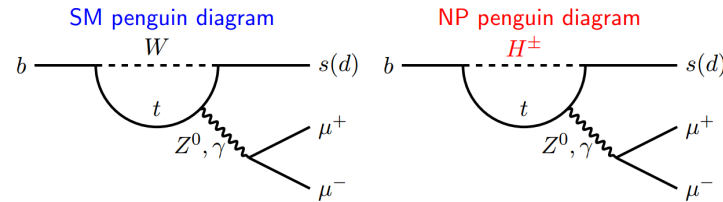
CMS $h \rightarrow \tau\mu$: 2.6σ

There is no lepton flavour violation in the Standard Model, so you should see none of these decays³. Various models use flavour symmetries, but also 2 Higgs doublet models (2HDM) work.



³CMS-PAS-HIG-14-005

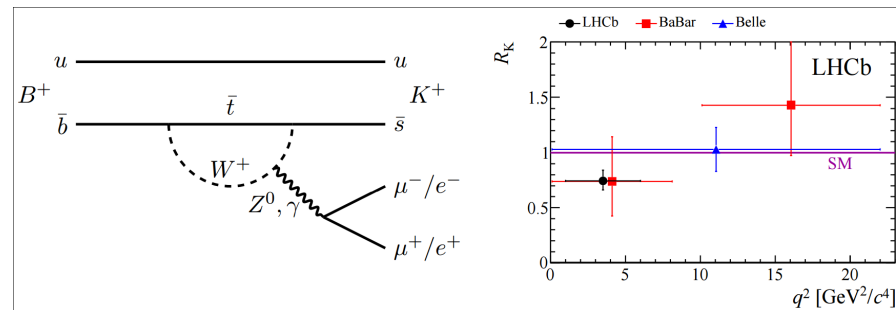
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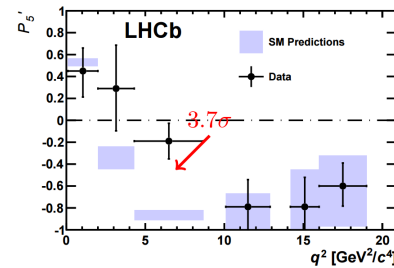
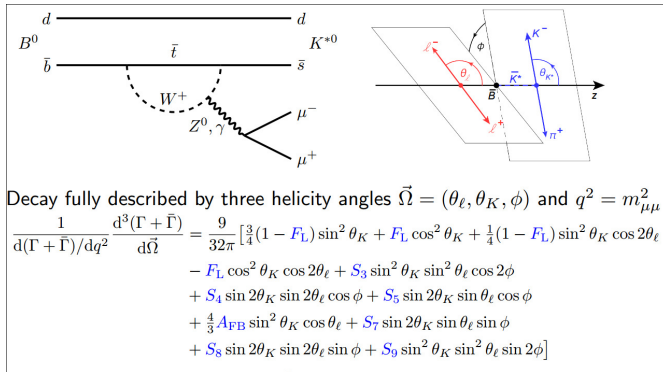
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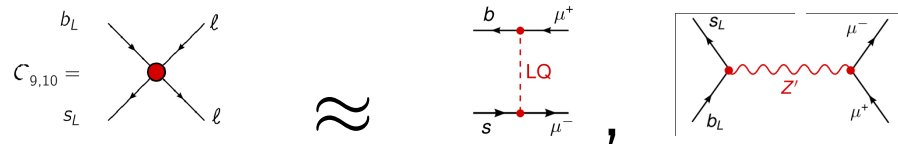
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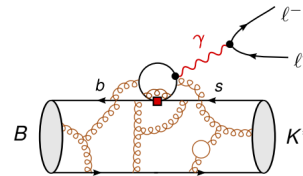
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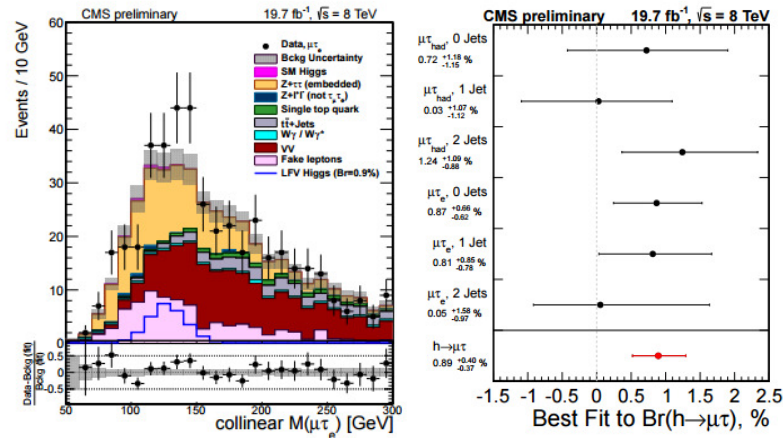
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