Some LHC Excesses: di di di

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

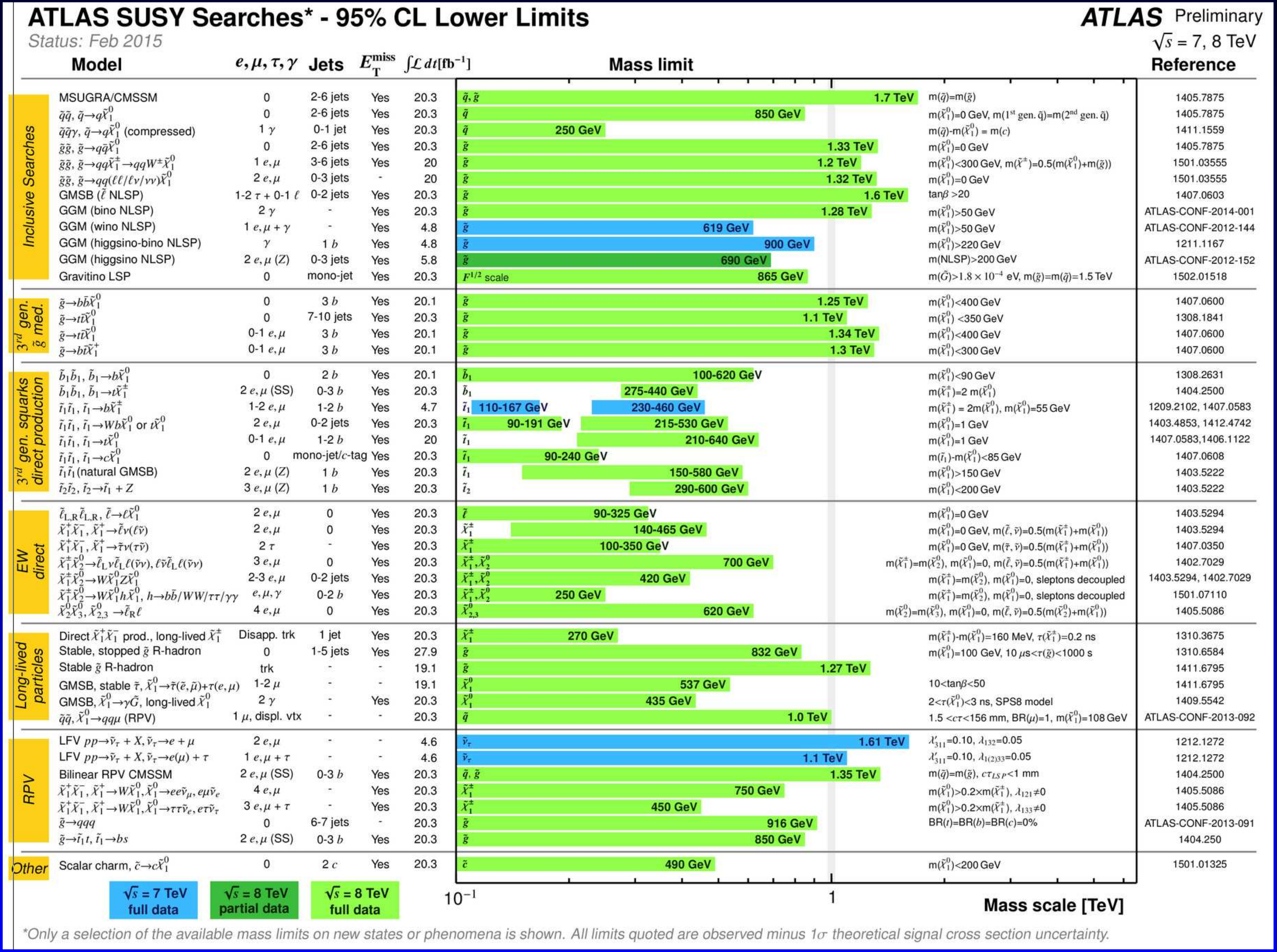
Ambulance-chasing Large Hadron Collider collisions

Ben Allanach on the impure fun of rapid-response physics

Speed is important Photograph: MACIEJ NOSKOWSKI/Getty Images

Ben Allanach

Selection Bias



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

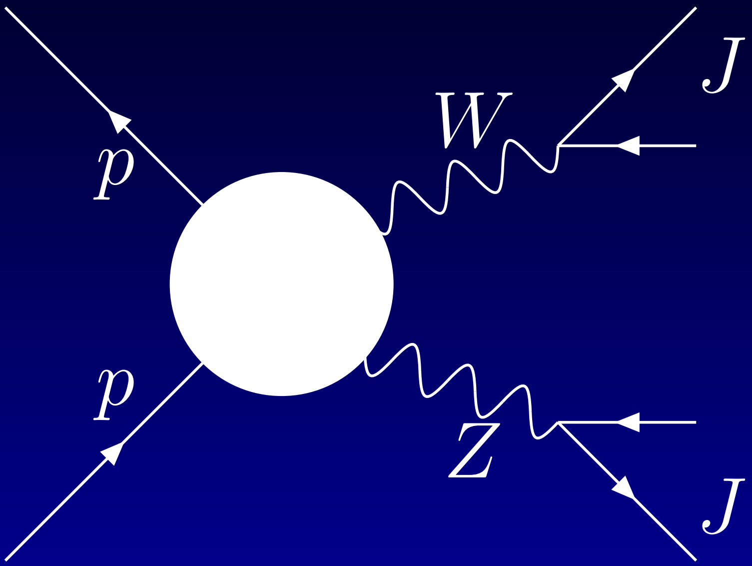
ATLAS Preliminary

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

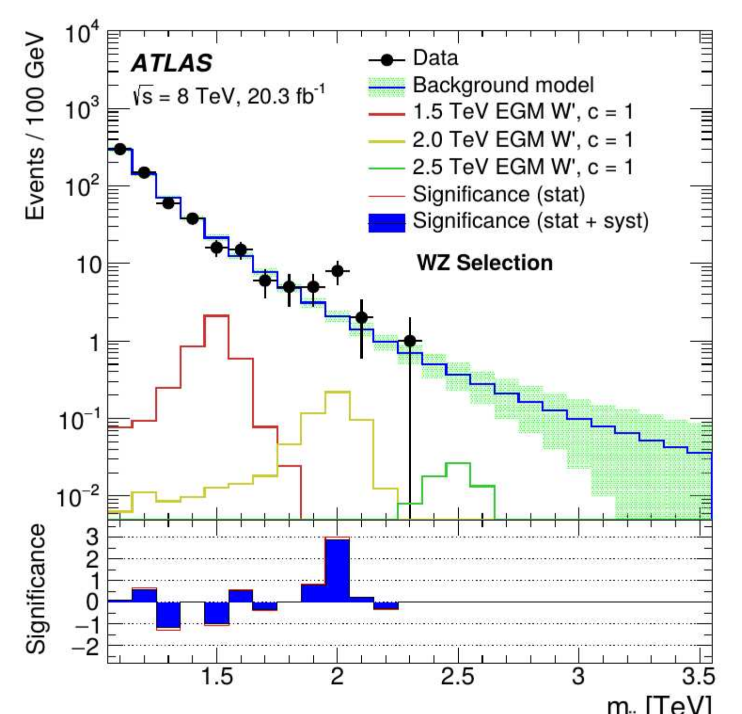
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$\text{m}(\tilde{q})=\text{m}(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$\text{m}(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{\text{q}}$)=m(2nd gen. $\tilde{\text{q}}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$\text{m}(\tilde{q})\text{-m}(\tilde{\chi}_1^0) = \text{m}(c)$	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$\text{m}(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$\text{m}(\tilde{\chi}_1^0)$<300 GeV, $\text{m}(\tilde{\chi}^{\pm})=0.5(\text{m}(\tilde{\chi}_1^0)+\text{m}(\tilde{g}))$	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$\text{m}(\tilde{\chi}_1^0)$=0 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	$\text{m}(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$\text{m}(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$\text{m}(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$\text{m}(\tilde{G})>1.8\times10^{-4}$ eV, $\text{m}(\tilde{g})=\text{m}(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$\text{m}(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$\text{m}(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$\text{m}(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$\text{m}(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$\text{m}(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$\text{m}(\tilde{\chi}_1^{\pm})=2\,\text{m}(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV 230-460 GeV	$\text{m}(\tilde{\chi}_1^{\pm}) = 2\text{m}(\tilde{\chi}_1^0)$, $\text{m}(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 215-530 GeV	$\text{m}(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$\text{m}(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$\text{m}(\tilde{t}_1)\text{-m}(\tilde{\chi}_1^0)$<85 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	$\text{m}(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$\text{m}(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$\text{m}(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$\text{m}(\tilde{\chi}_1^0)$=0 GeV, $\text{m}(\tilde{\ell},\tilde{\nu})=0.5(\text{m}(\tilde{\chi}_1^{\pm})+\text{m}(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$\text{m}(\tilde{\chi}_1^0)$=0 GeV, $\text{m}(\tilde{\tau},\tilde{\nu})=0.5(\text{m}(\tilde{\chi}_1^{\pm})+\text{m}(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_{\text{L}}\nu\tilde{\ell}_{\text{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\text{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$\text{m}(\tilde{\chi}_1^{\pm})=\text{m}(\tilde{\chi}_2^0)$, $\text{m}(\tilde{\chi}_1^0)$=0, $\text{m}(\tilde{\ell},\tilde{\nu})=0.5(\text{m}(\tilde{\chi}_1^{\pm})+\text{m}(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$\text{m}(\tilde{\chi}_1^{\pm})=\text{m}(\tilde{\chi}_2^0)$, $\text{m}(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	$\text{m}(\tilde{\chi}_1^{\pm})=\text{m}(\tilde{\chi}_2^0)$, $\text{m}(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\text{R}}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$\text{m}(\tilde{\chi}_2^0)=\text{m}(\tilde{\chi}_3^0)$, $\text{m}(\tilde{\chi}_1^0)$=0, $\text{m}(\tilde{\ell},\tilde{\nu})=0.5(\text{m}(\tilde{\chi}_2^0)+\text{m}(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$\text{m}(\tilde{\chi}_1^{\pm})\text{-m}(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$\text{m}(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $\text{m}(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$\text{m}(\tilde{q})=\text{m}(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$\text{m}(\tilde{\chi}_1^0)>0.2\times\text{m}(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$\text{m}(\tilde{\chi}_1^0)>0.2\times\text{m}(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$\text{m}(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*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



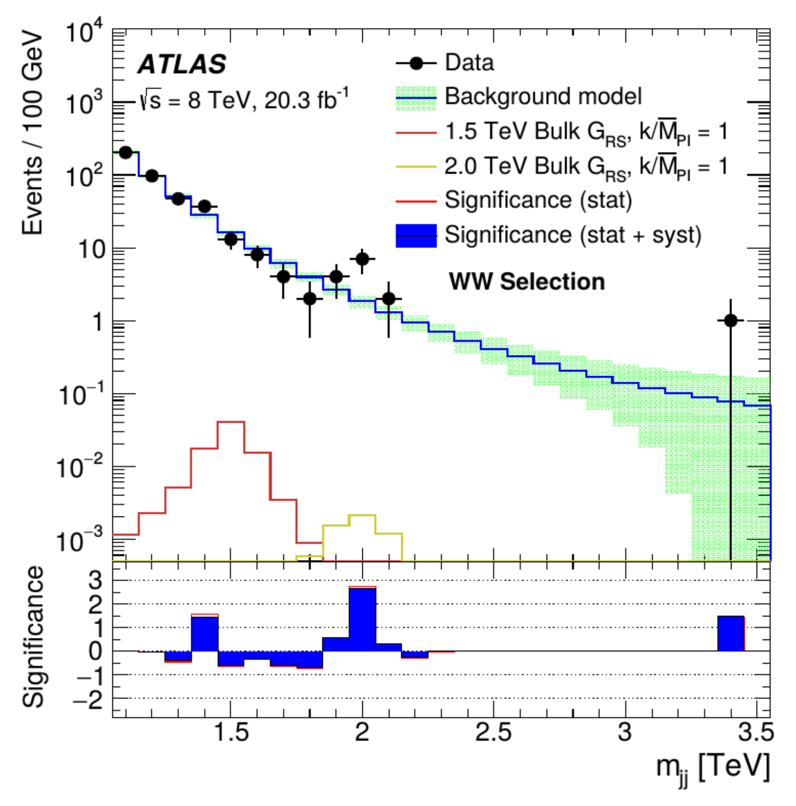
Dig fat jets J made out of two smaller jets j with jet substructure techniques. $69.4 < m_J/\text{GeV} < 95.4$ is called a ‘W’, whereas $79.8 < m_J/\text{GeV} < 105.8$ is called a ‘Z’.

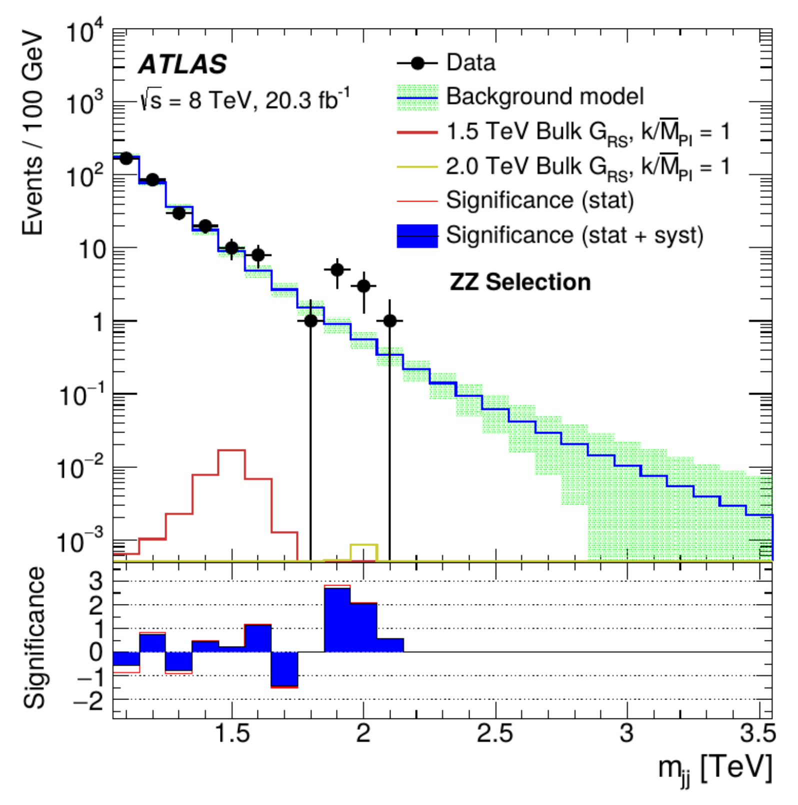


Global excess 2.5σ in WZ channel. (Local significance is 3.4σ). CMS finds 1.9σ around 1.9-2 TeV in a boosted search for $WH \to l\nu jj$.

ATLAS, `arXiv:1506.00962`; CMS, CMS-PAS-EXO-14-010.

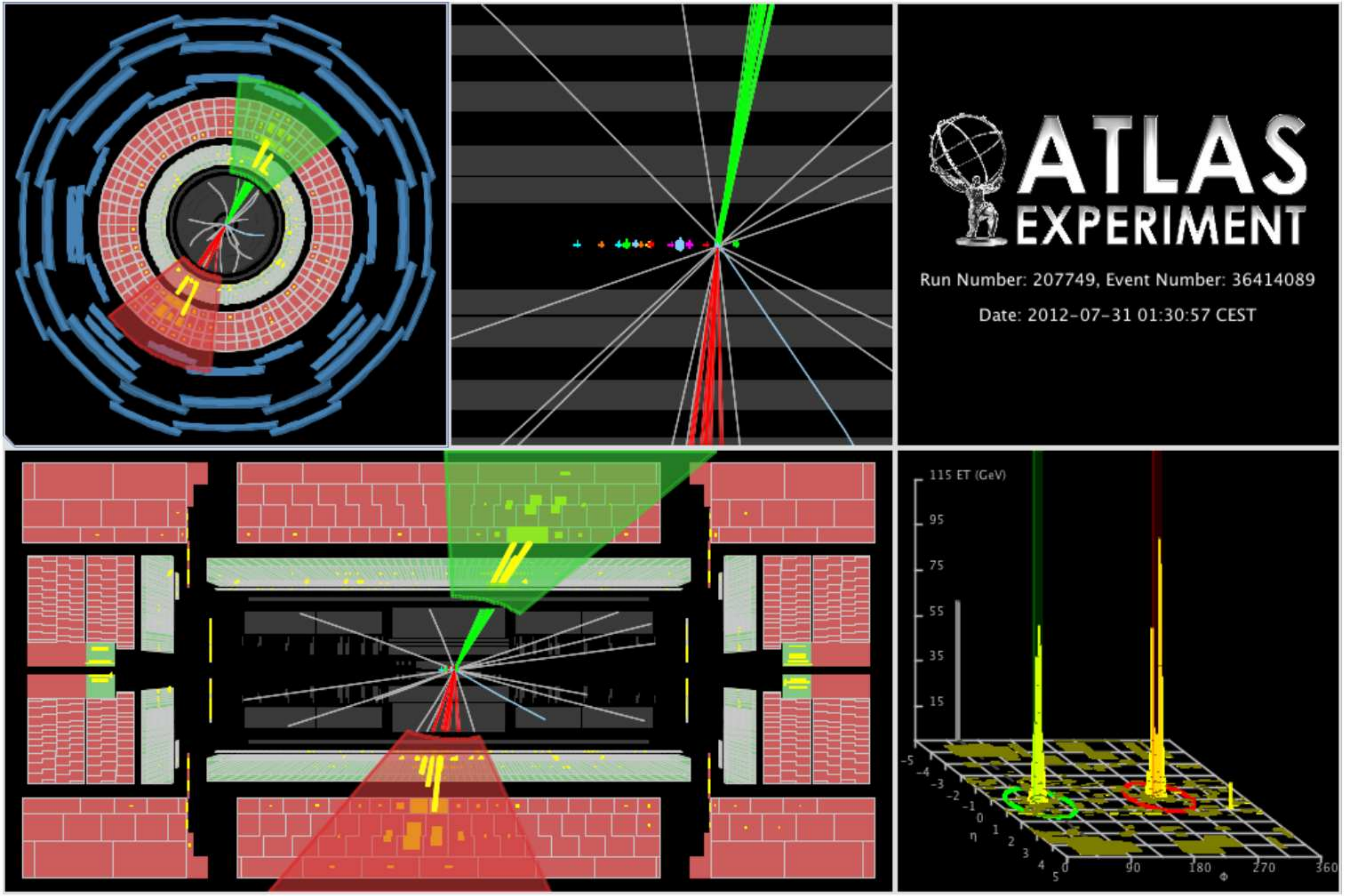
Other channels





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

Event display



Analysis Details

Cambridge-Aachen jets: iteratively replace nearest elements with their combination until all remaining pairs are seperated 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

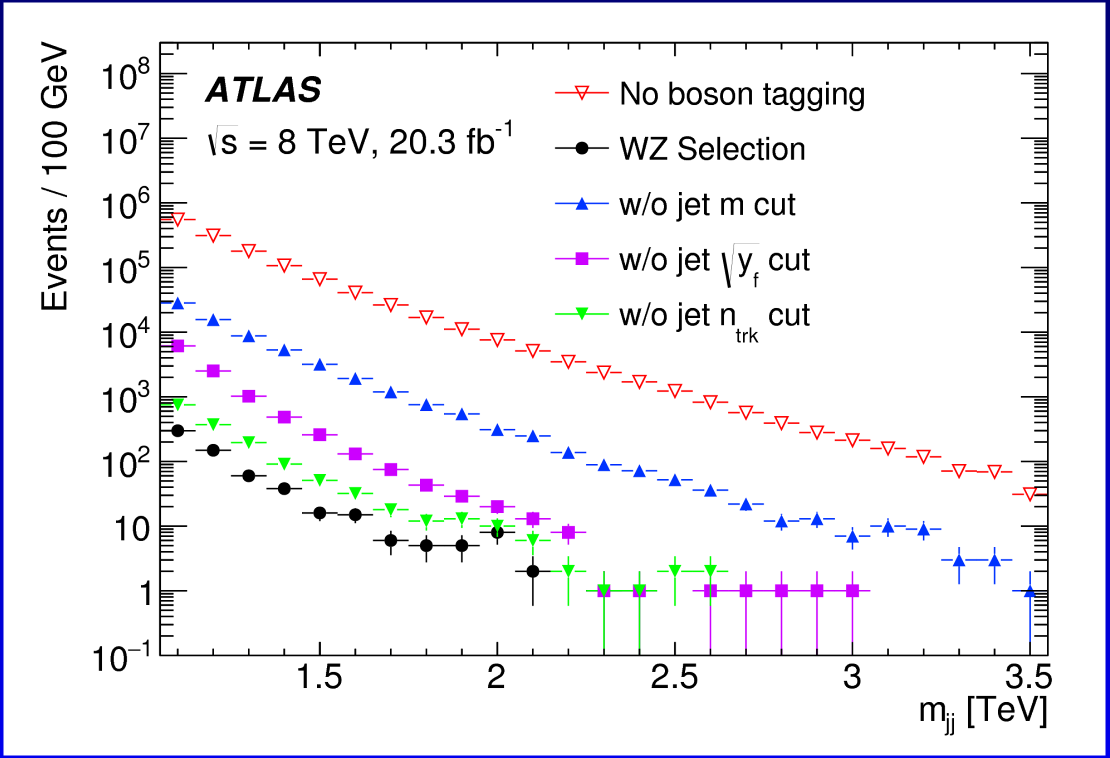
$$\sqrt{y} \equiv \min(p_T(j_1), p_T(j_2)) \frac{\Delta R(j_1, j_2)}{m_0} \geq \sqrt{0.2}$$

where m_0 is the mass of the parent jet.

Details II

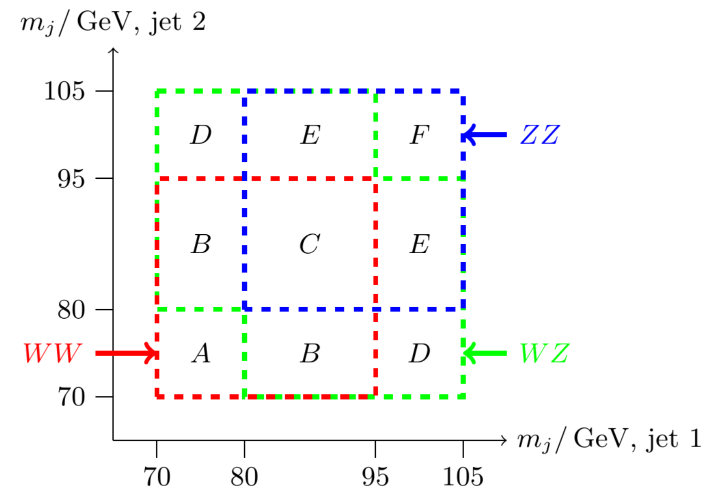
Selected pair of subjets is then *filtered*: subjets reconstructed with $R = 0.3$ and all but 3 of highest p_T are discarded.

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



Overlap

BCA, Gripaios, Sutherland, `arXiv:1507.01638`



$$
\begin{aligned}
WW &= A+B+C,\\
ZZ &= C+E+F,\\
WZ &= B+C+D+E,\\
WW+ZZ &= A+B+C+E+F,\\
WW+WZ+ZZ &= A+B+C+D+E+F.
\end{aligned}
$$

	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
true Z	0.11	0.39	0.21

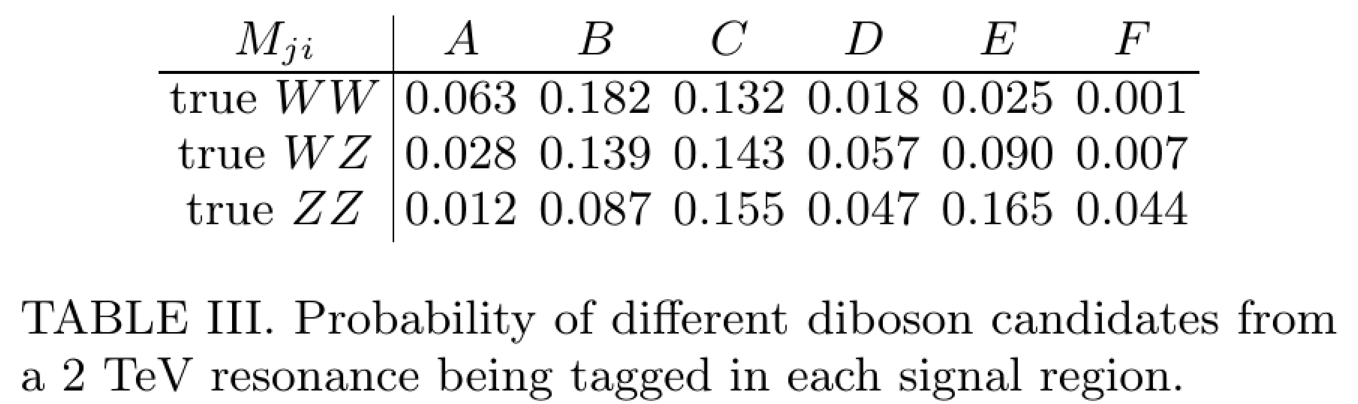
Probabilities

Likelihood analysis

How may we take overlap into account?

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

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

$$
\begin{aligned}
p(\{n_i\}|\{\mu_i\}) &= \prod_{i\in\{A,B,C,D,E,F\}} P(n_i|\mu_i), \\
P(n|\mu) &= \frac{e^{-\mu}\mu^n}{n!},
\end{aligned}
$$

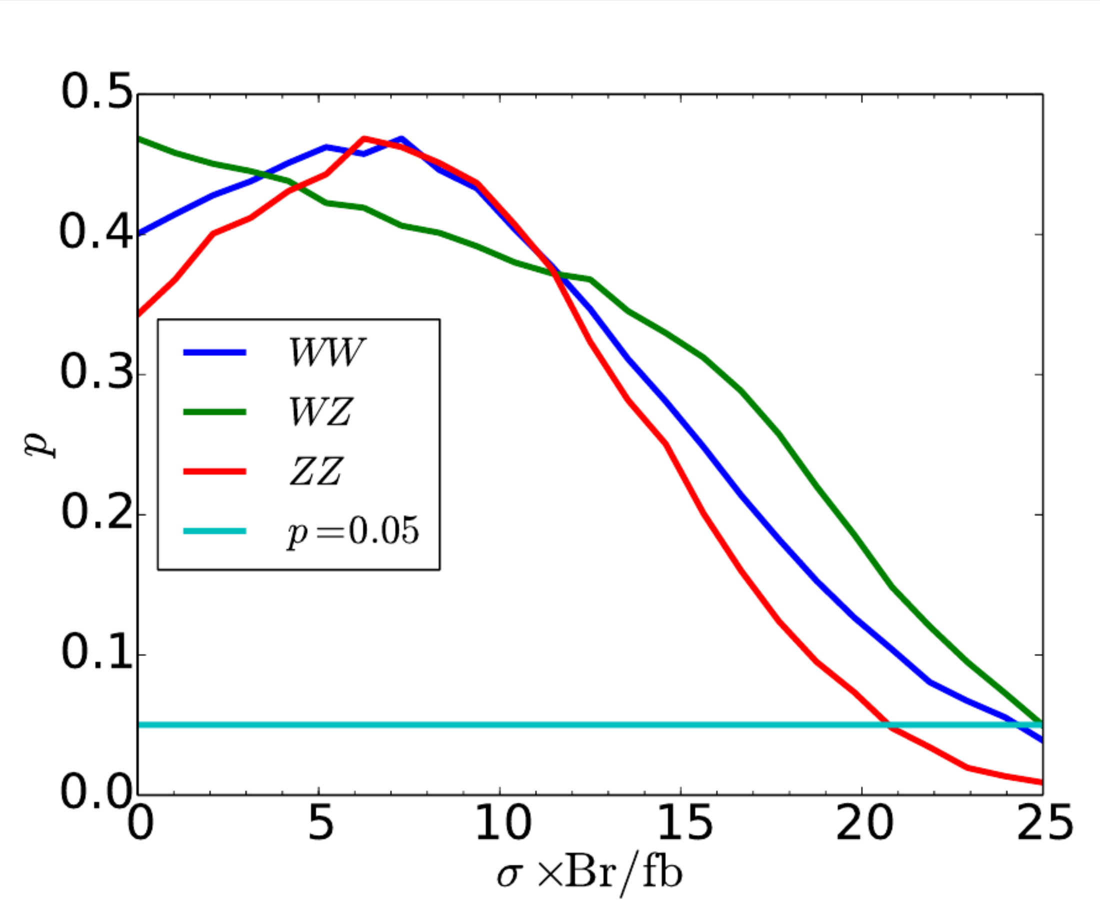
$$
p(\{n_i^{\text{obs},\alpha}\}|s_{WW},\ s_{WZ},\ s_{ZZ}) =
$$

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

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

Multi-dimensional likelihood

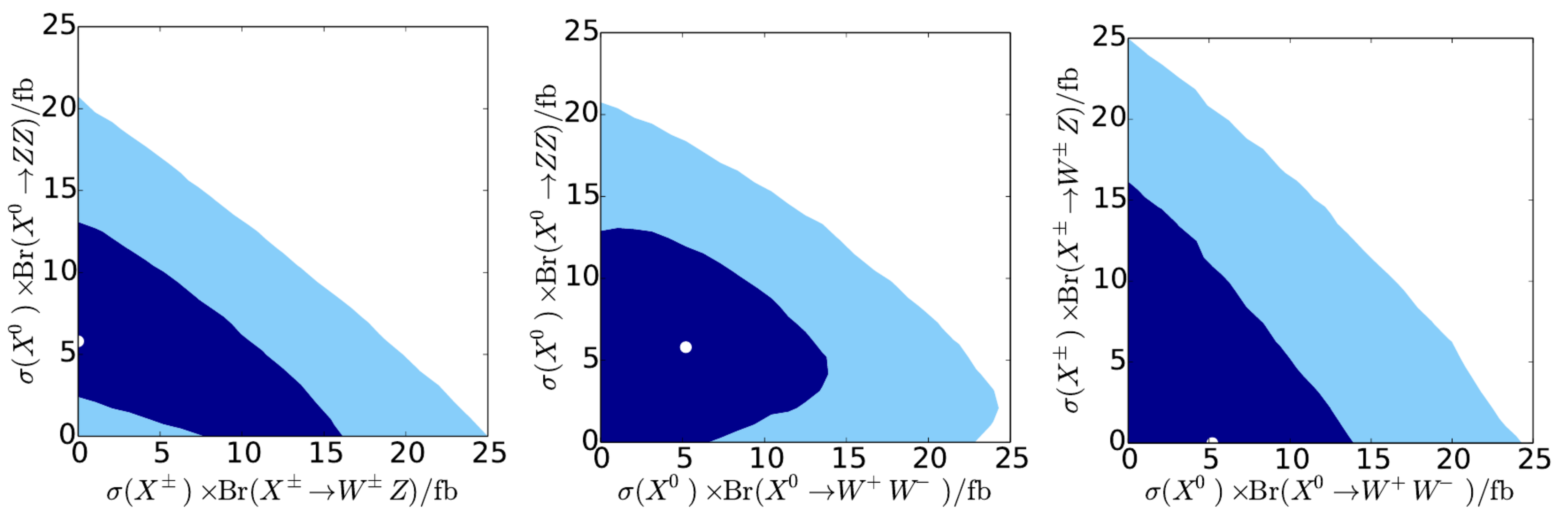
This is turned into a $\chi^2 = -2 \log p(\{n_i^{\text{obs},\alpha}\}|s_{WW},\ s_{WZ},\ s_{ZZ})$, or a $p-$value:

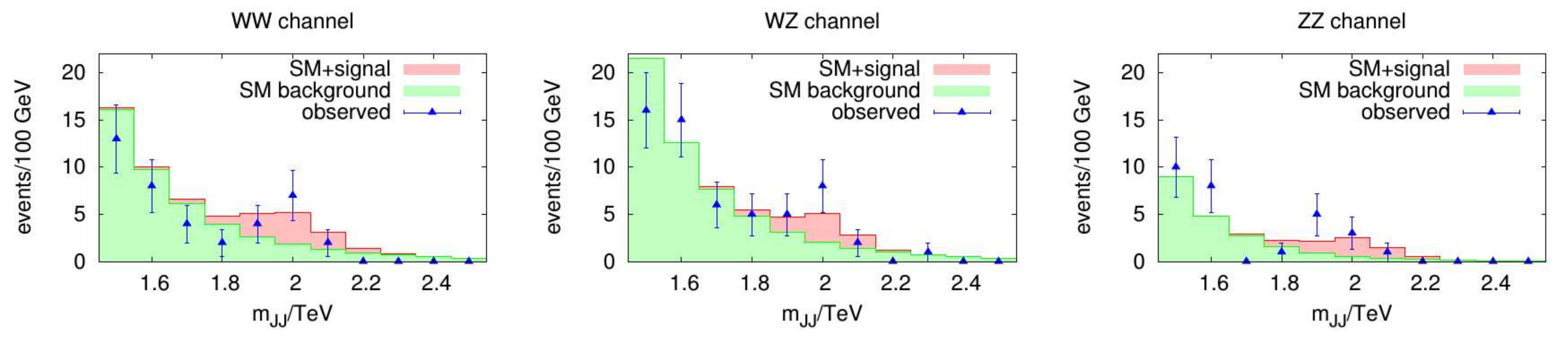


SM is 4.0σ discrepant (local).

Joint Constraints

Similar results to a global analysis Brehmer *et al*, `arXiv:1507.00013`



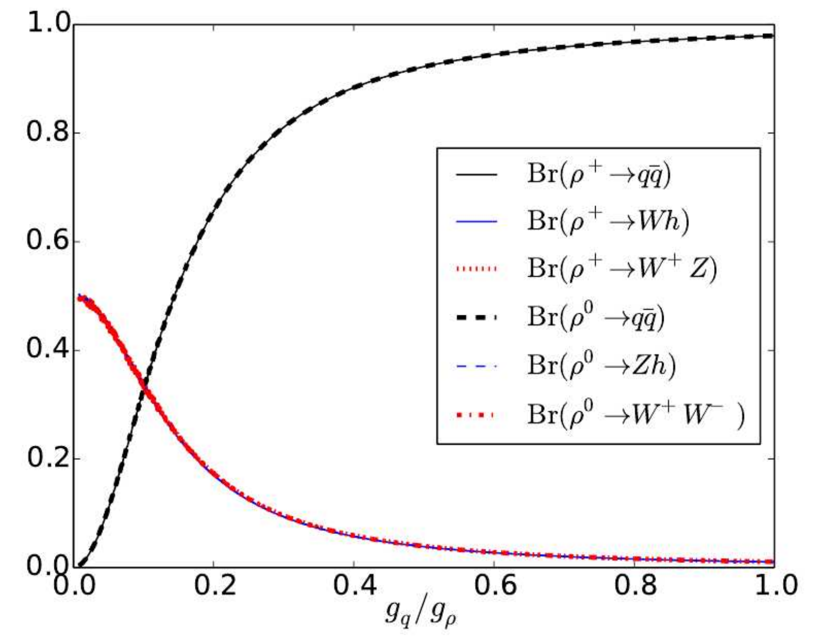


New Physics Decalogue

- 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 coupings correct Γ_Z and CKM unit.).
- Assume flavour-diagonal couplings to 2 light families

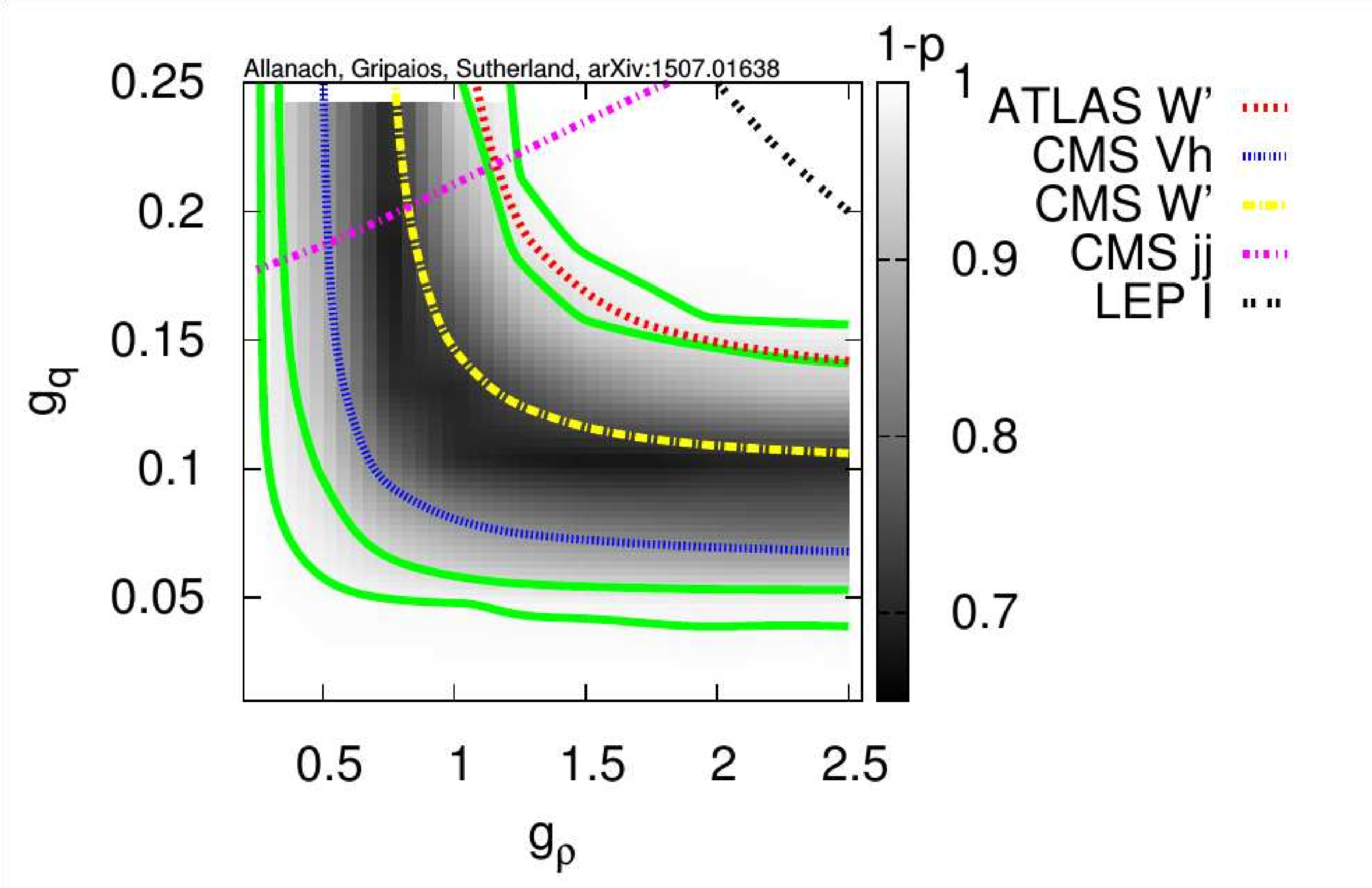
$Y = 0$ SU(2)$_L$ Vector Triplet ρ^a_μ

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



This model was initially considered by Thamm, Torre, Wulzer, `arXiv:1506.08688`. A RH triplet yields *very* similar results.

Constraints

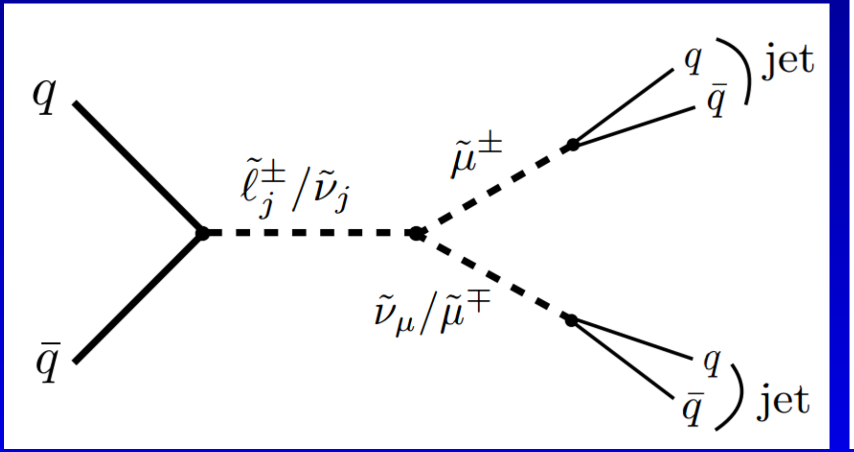


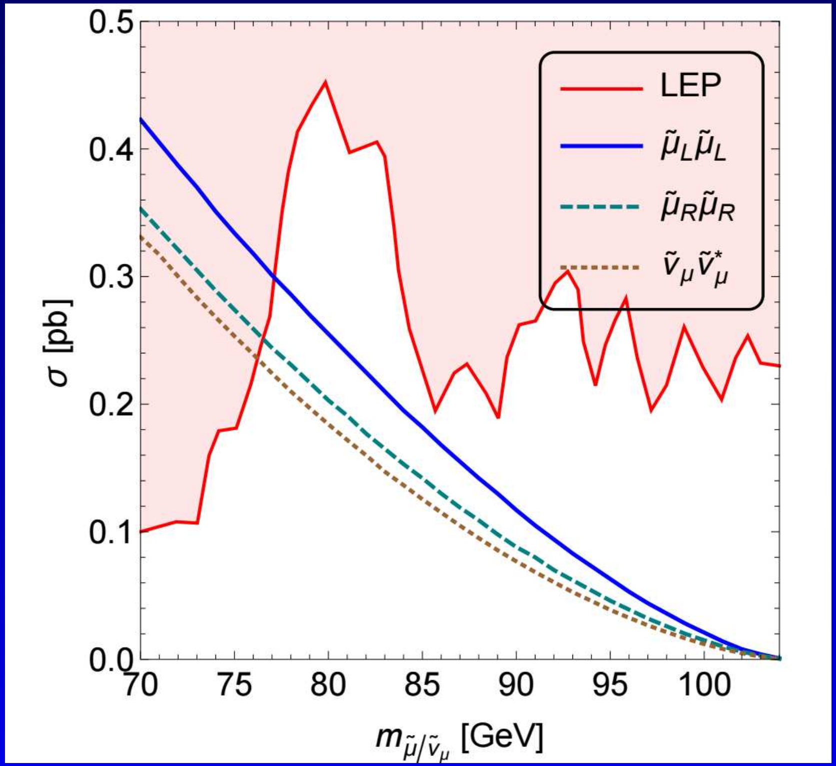
EW precision: $g_\rho g_q \lesssim 0.5$ is OK.

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, Dey, Sakurai `arXiv:1511.01483`

Consistency

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

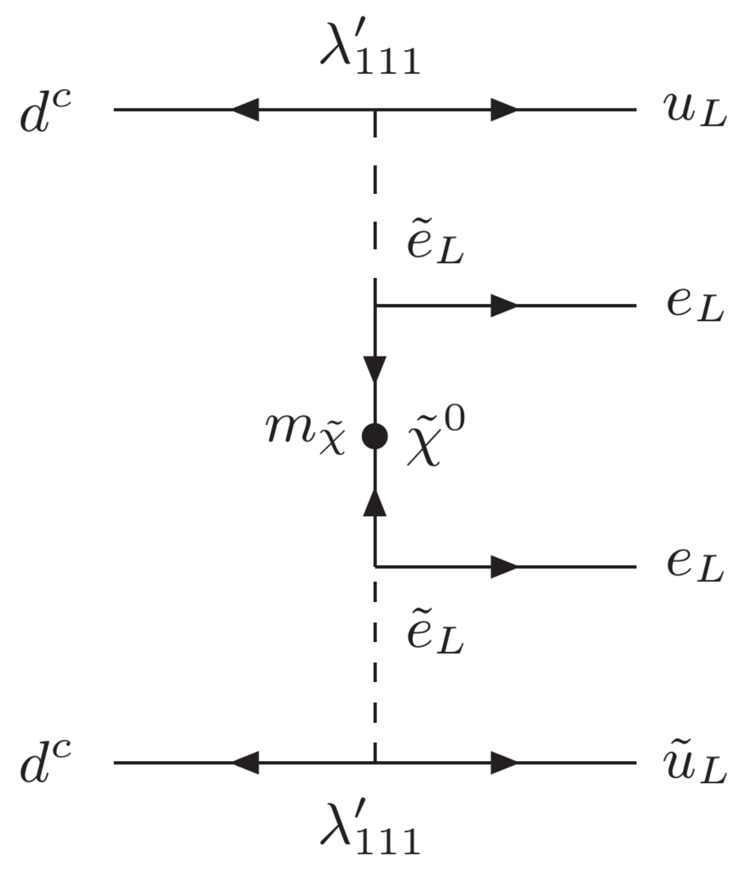
can turn smuon mass negative. Also, a correction to quartic $\tilde{l}_j$ coupling may be non-perturbative from box with smuons running in the loop:

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

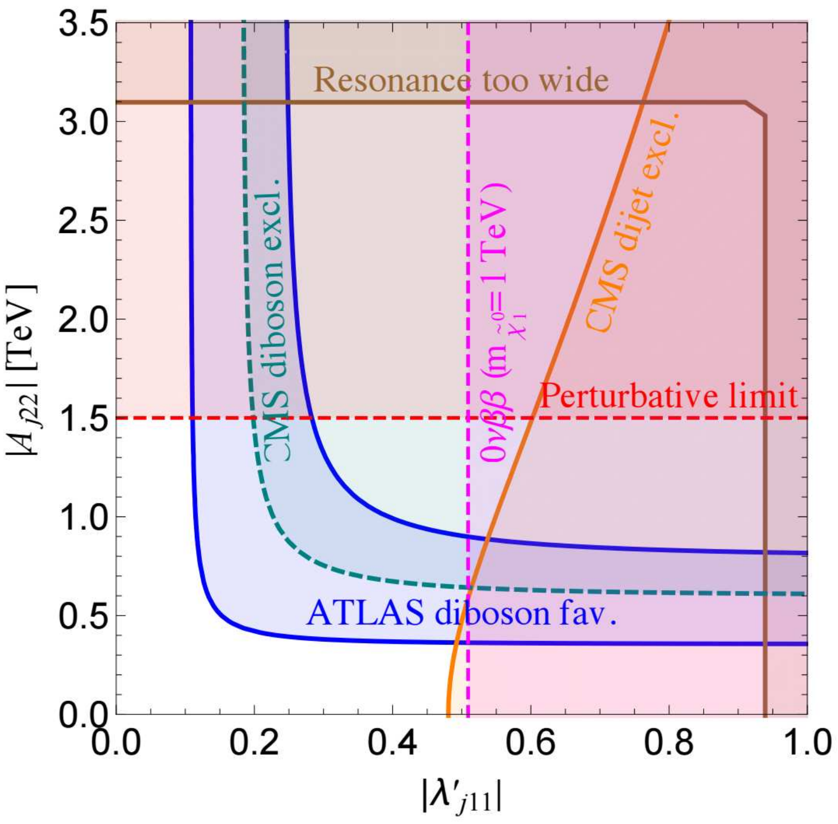
- *No leptonic/semi-leptonic states*
- *No WH states*
- Could have a stau instead of a smuon

Neutrinoless Double Beta Decay

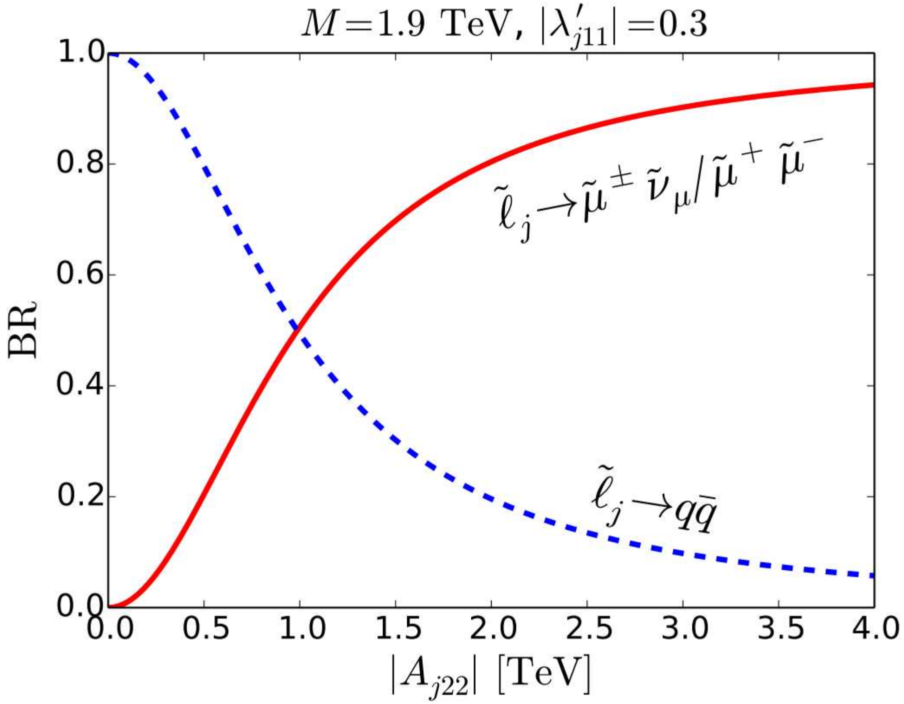
Is *banned* in the Standard Model because it breaks lepton number: $Z \to (Z+2)e^-e^-$ Present bound from GERDA is $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr. It should increase by a factor 10 in the next year or so.



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



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

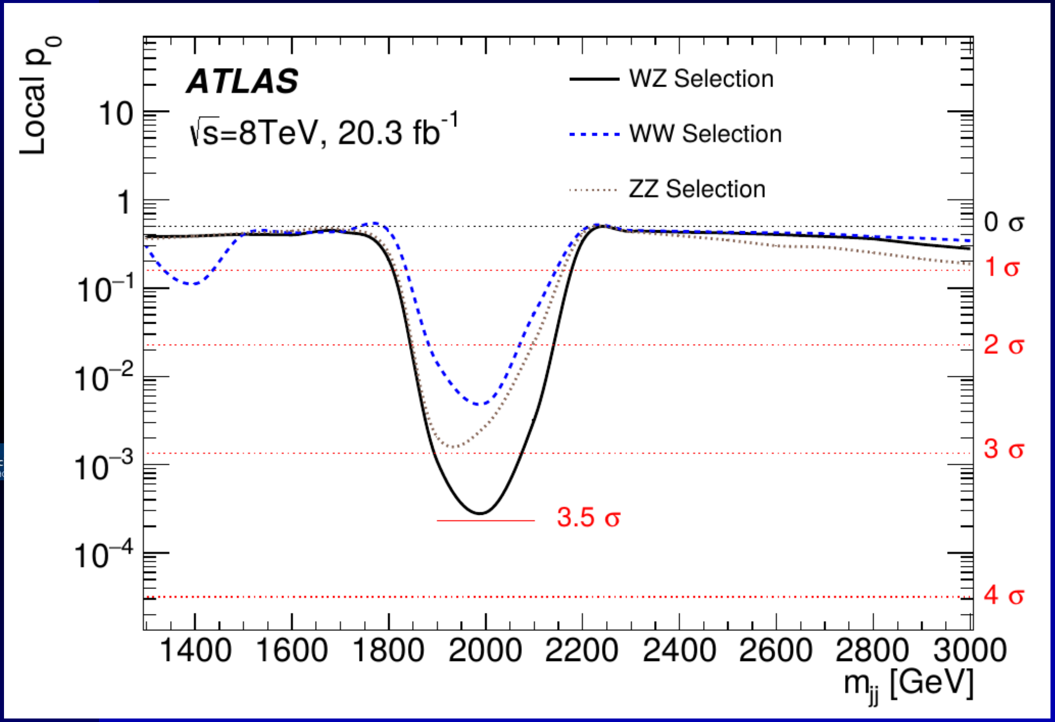


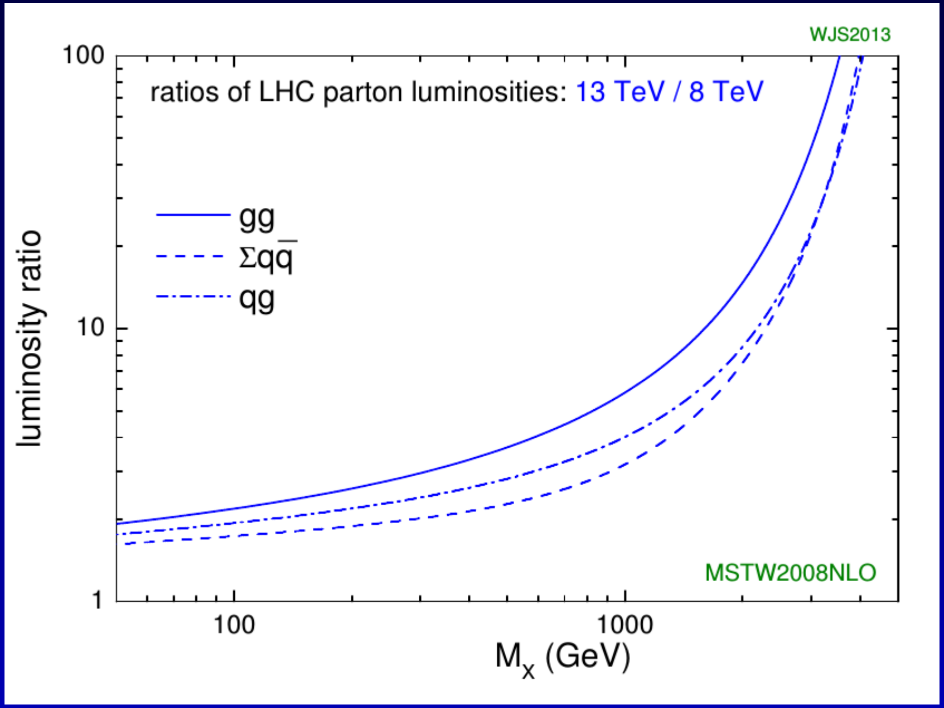
$$(29 \pm 8) \times 10^{-10}$$

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.

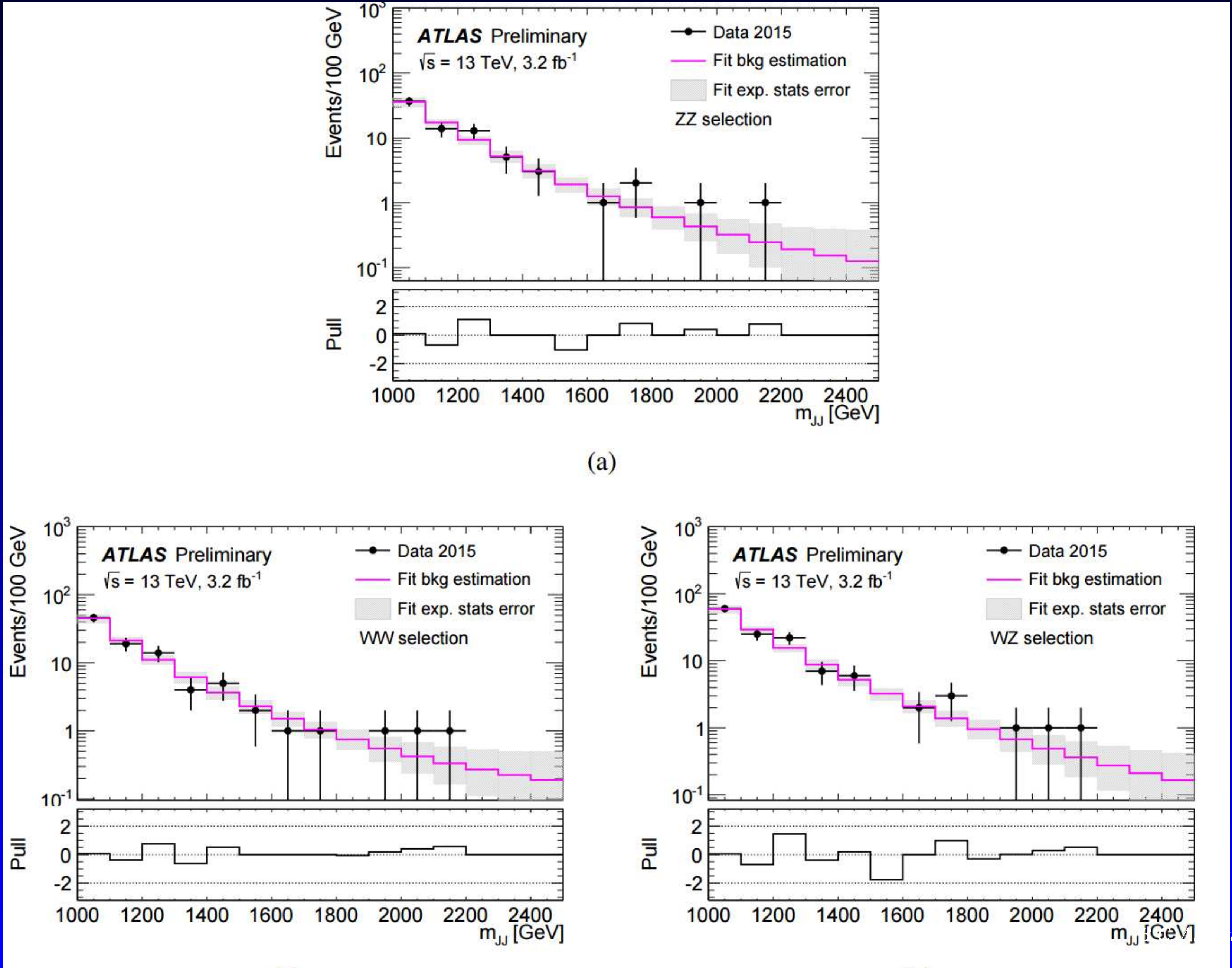
ATLAS Run I Excesses





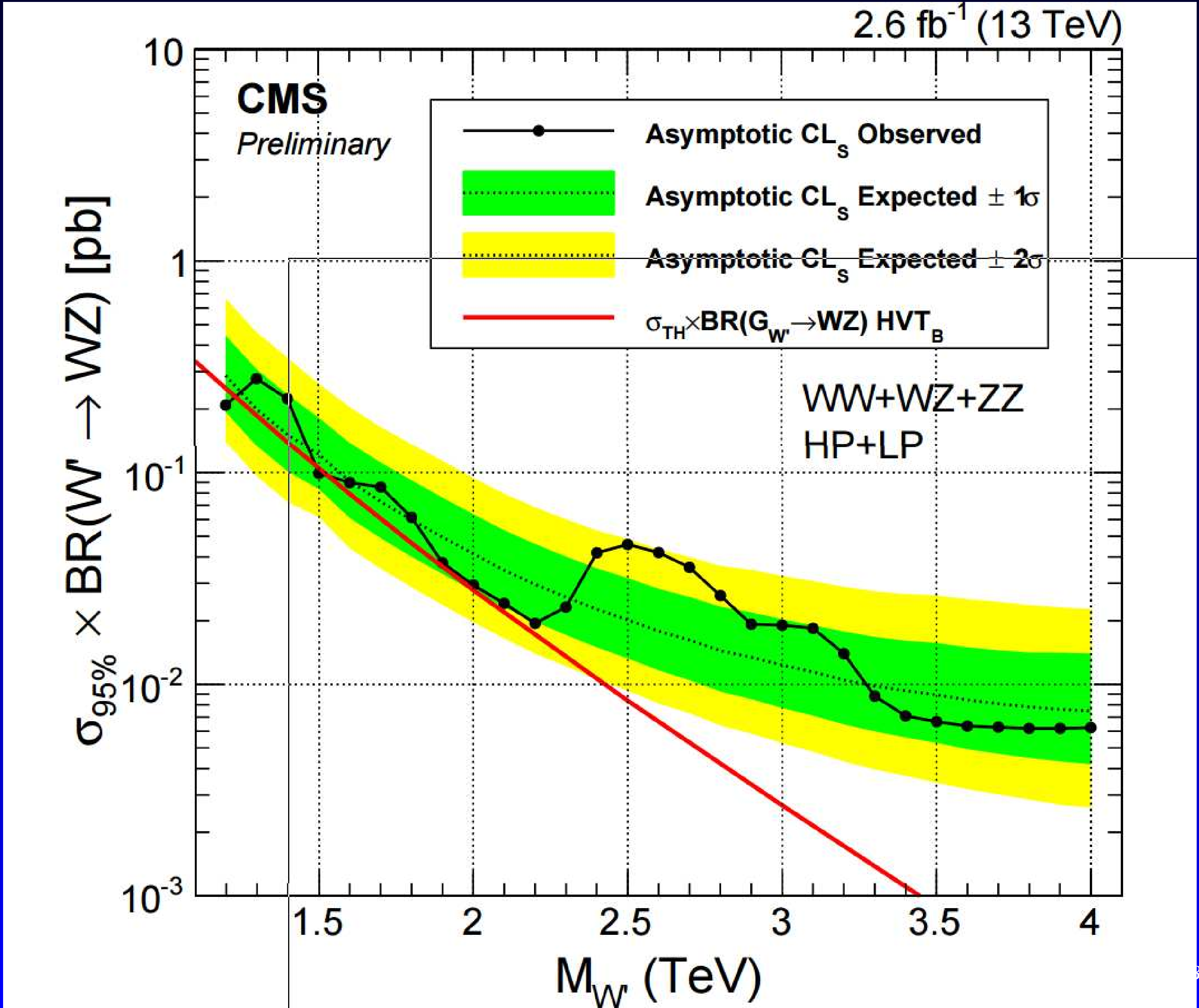
ATLAS claims 2.5σ including LEE from all channels.

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

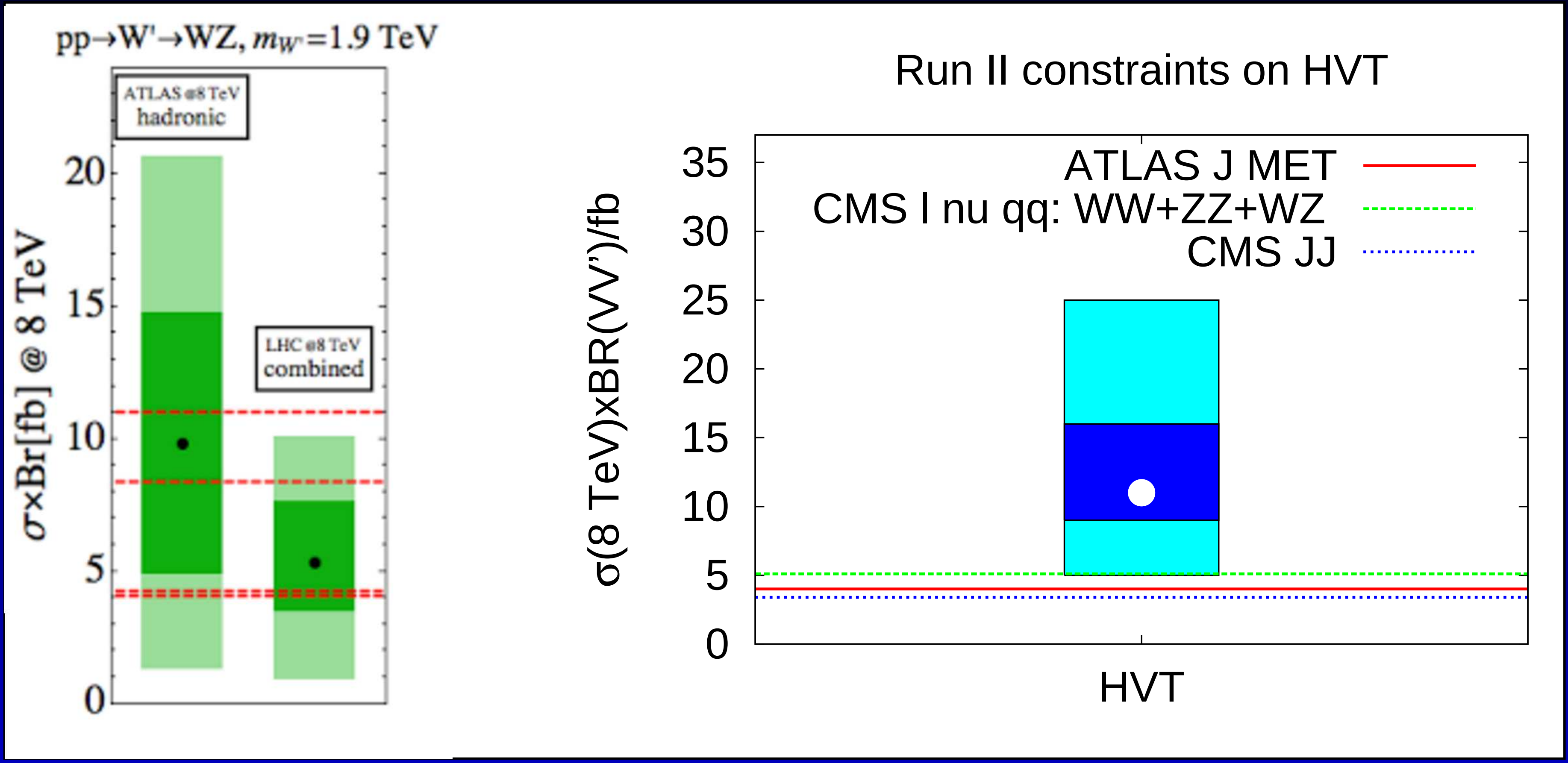


(a)

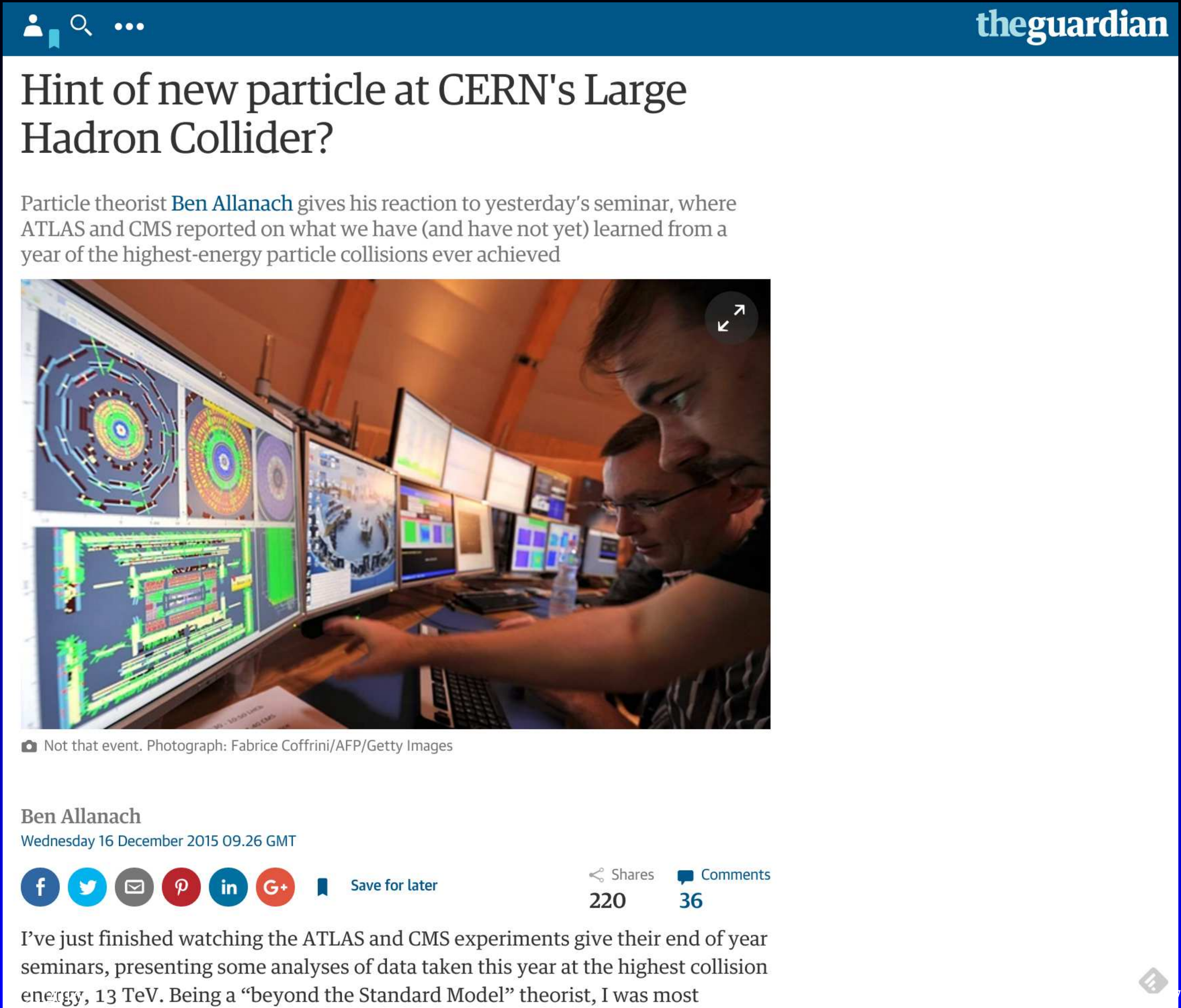
CMS 13 TeV 2.6 fb^{-1}: $l\nu qq + 4q$



Run II: 2 TeV HVT In Trouble



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



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

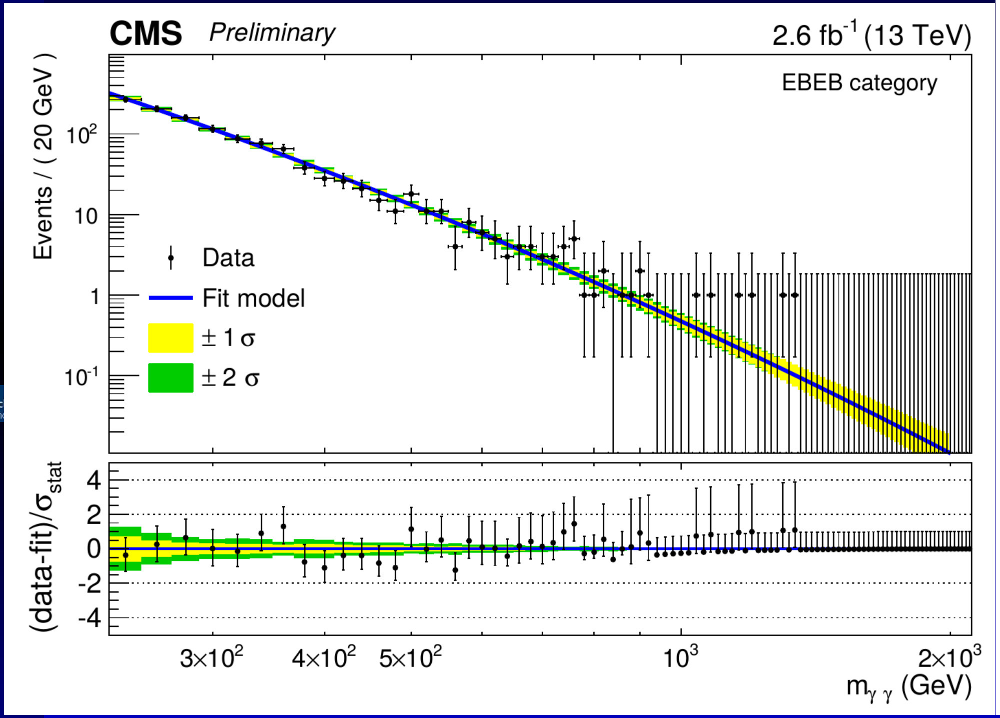
Particle theorist Ben Allanach gives his reaction to yesterday's seminar, where ATLAS and CMS reported on what we have (and have not yet) learned from a year of the highest-energy particle collisions ever achieved

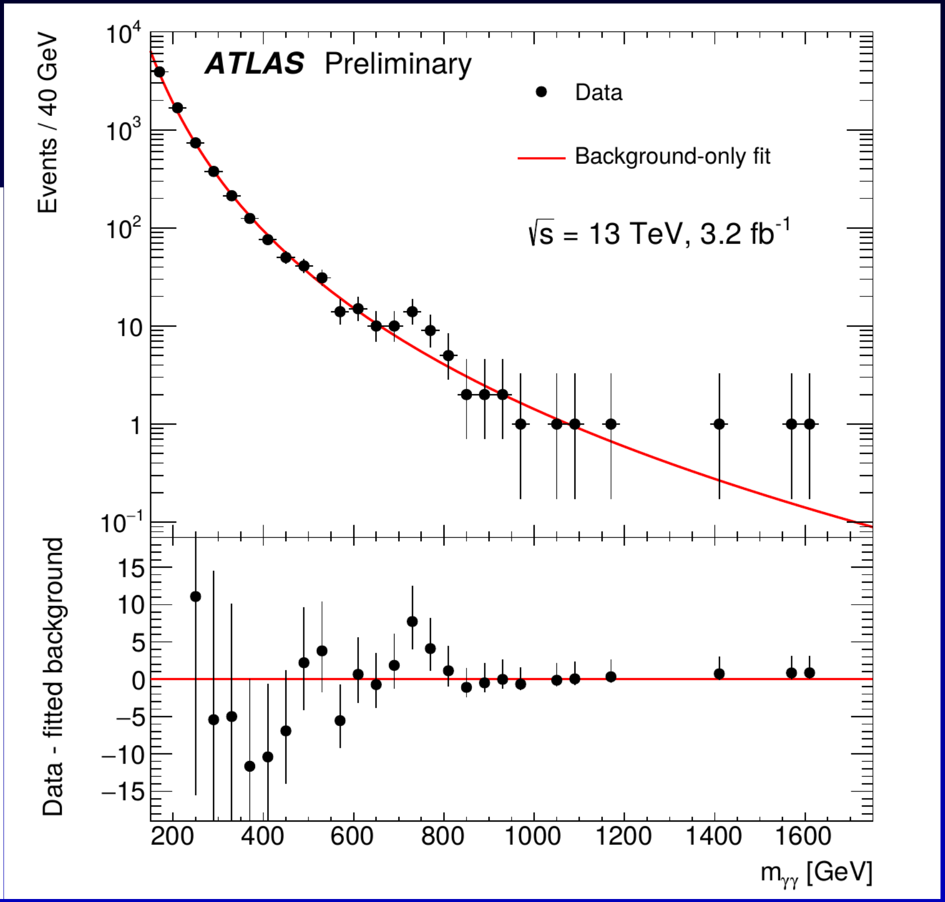
Not that event. Photograph: Fabrice Coffrini/AFP/Getty Images

Ben Allanach
Wednesday 16 December 2015 09.26 GMT

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 Resonance at 13 TeV

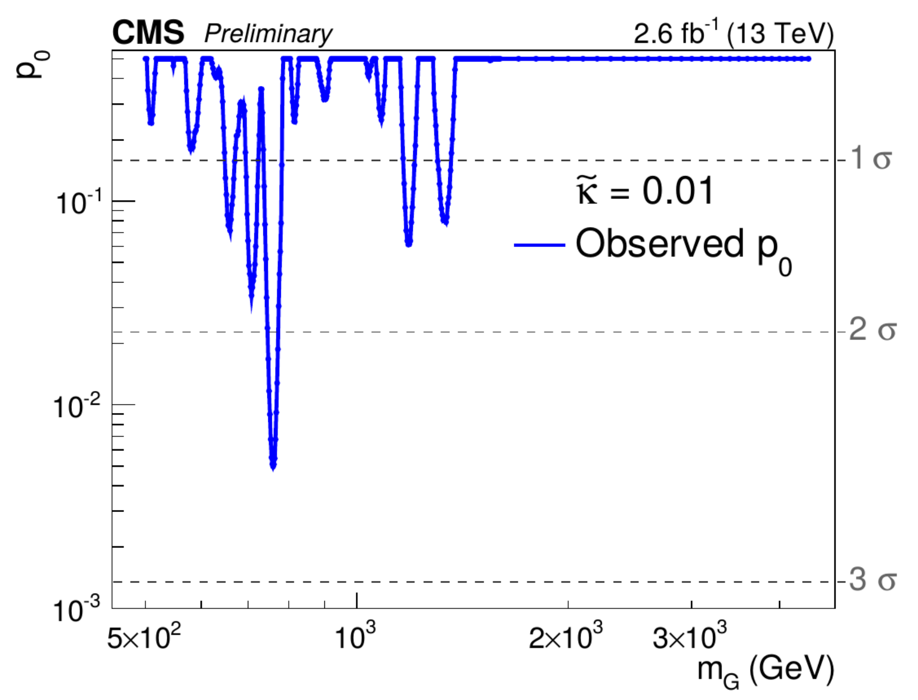


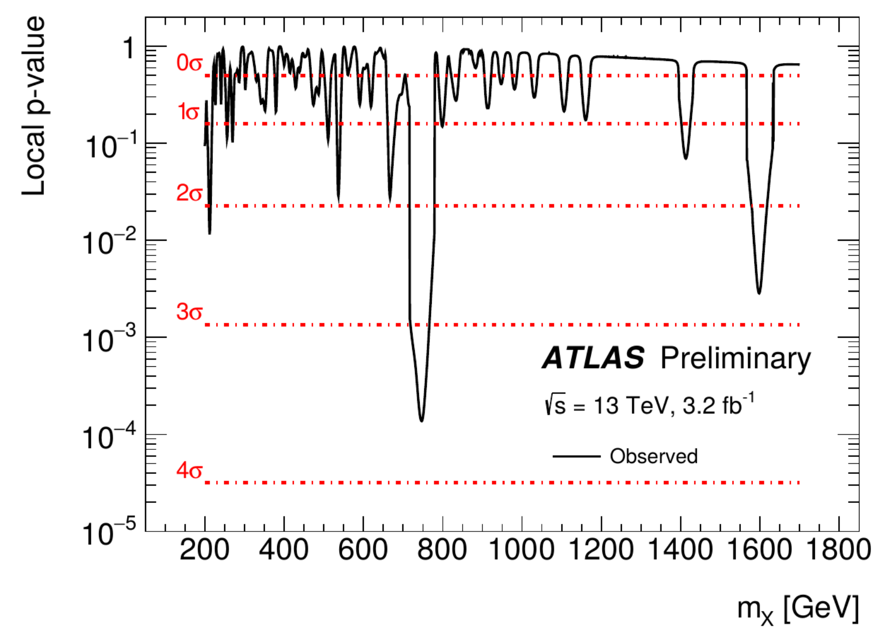


CMS (2.6 fb^{-1})

ATLAS (3.2 fb^{-1})

$p-$values



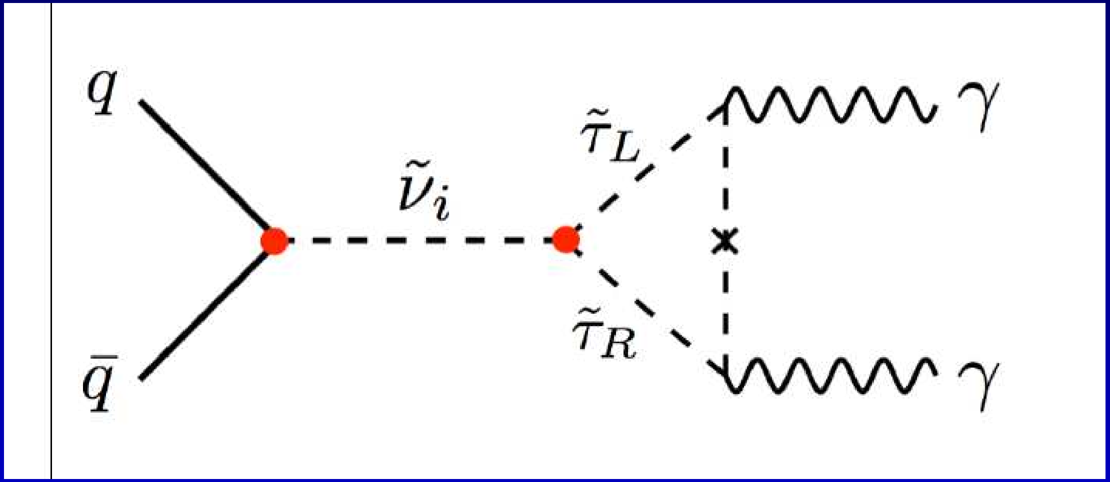


ATLAS: favours width of 45 GeV over narrow width to the tune of 0.3σ. Local(global) significance of NWA is 3.9 (2.3) σ.
CMS: slightly favours narrow width. Local (global) significance is 2.6 (1.2) σ.

Explanation for Di-Photon Excess

A 750 GeV resonant sneutrino with a coupling to quarks:

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



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

BCA, Dev, Renner, Sakurai, `arXiv:1601.03007`

Decays

$$\Gamma_{\gamma\gamma} \equiv \Gamma(\tilde{\nu}_i \to \gamma\gamma) = \frac{\alpha^2 m_{\tilde{\nu}_i}^3}{256\pi^3} \frac{|\bar{A}_{i33}|^2}{m_{\tilde{\tau}_1}^4} \left|A_0(\tau_{\tilde{\tau}})\right|^2, \quad (5)$$

$$\Gamma_{\gamma Z} \equiv \Gamma(\tilde{\nu}_i \to \gamma Z) = \frac{\alpha^2 m_{\tilde{\nu}_i}^3}{256\pi^3} \frac{|\bar{A}_{i33}|^2}{m_{\tilde{\tau}_1}^4} \left(1 - \frac{m_Z^2}{m_{\tilde{\nu}_i}^2}\right)^3 \times \left|\lambda_{Z\tilde{\tau}_1\tilde{\tau}_1} A_{0Z}(\tau_{\tilde{\tau}}^{-1}, \tau_Z^{-1})\right|^2, \quad (6)$$

$$\Gamma_{ZZ} \equiv \Gamma(\tilde{\nu}_i \to ZZ) = \frac{\alpha^2 m_{\tilde{\nu}_i}^3}{256\pi^3} \frac{|\bar{A}_{i33}|^2}{m_{\tilde{\tau}_1}^4} \left(1 - \frac{4m_Z^2}{m_{\tilde{\nu}_i}^2}\right)^3 \times \left|\lambda_{Z\tilde{\tau}_1\tilde{\tau}_1}^2 A_{0Z}(\tau_{\tilde{\tau}}^{-1}, \tau_Z^{-1})\right|^2, \quad (7)$$

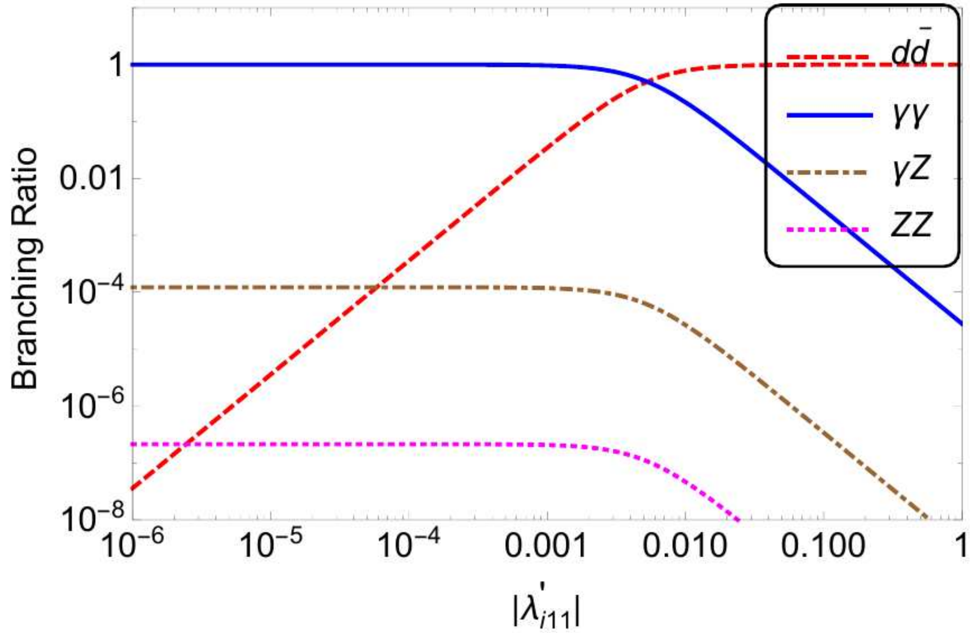
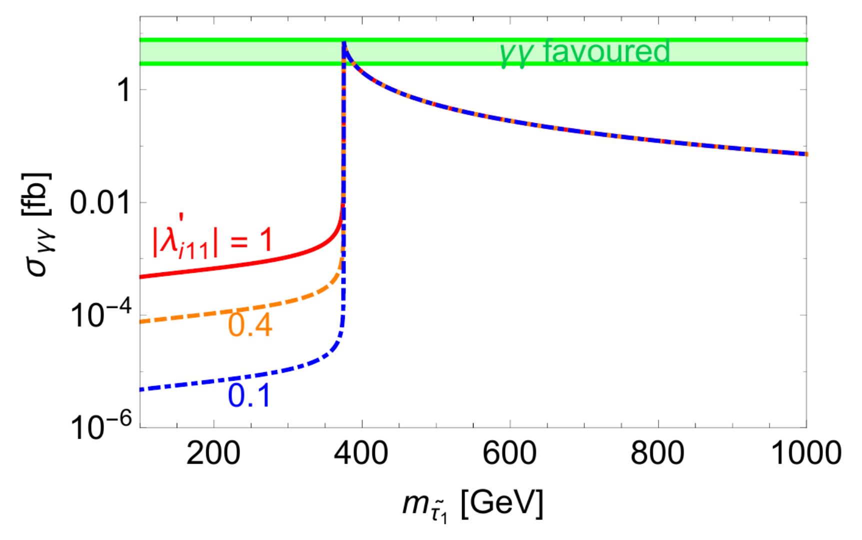
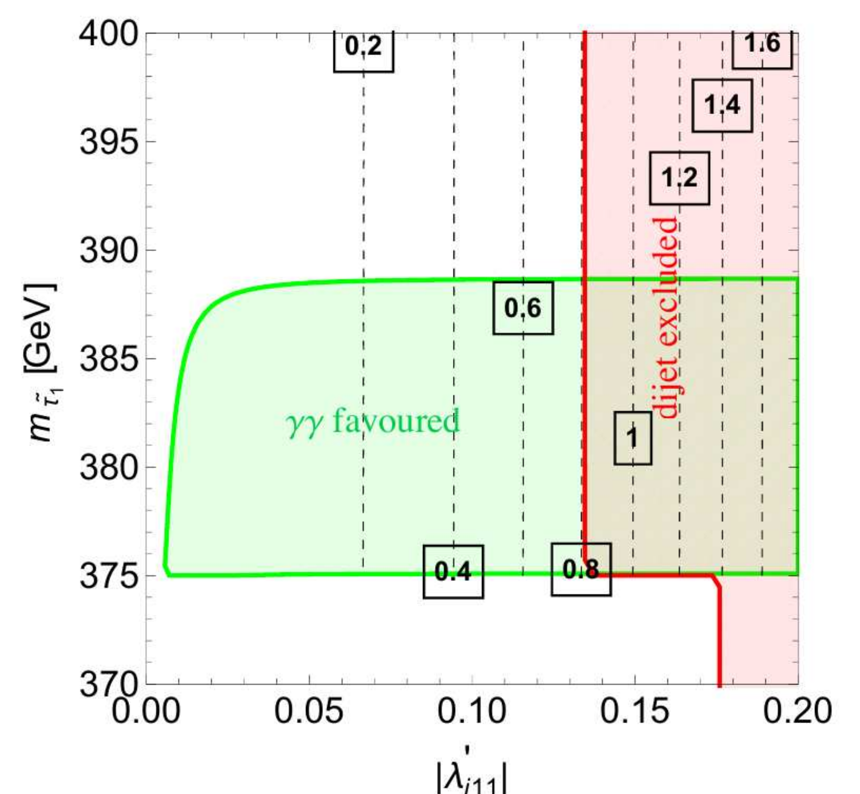


FIG. 2. The branching ratios of the sneutrino decay to $d\bar{d}$, $\gamma\gamma$, γZ and ZZ. Here we have chosen $m_{\tilde{\nu}_i} = 750$ GeV, $m_{\tilde{\tau}_1} = 380$ GeV and $A_{i33} = 14\, m_{\tilde{\tau}_1}$.

Parameter Space

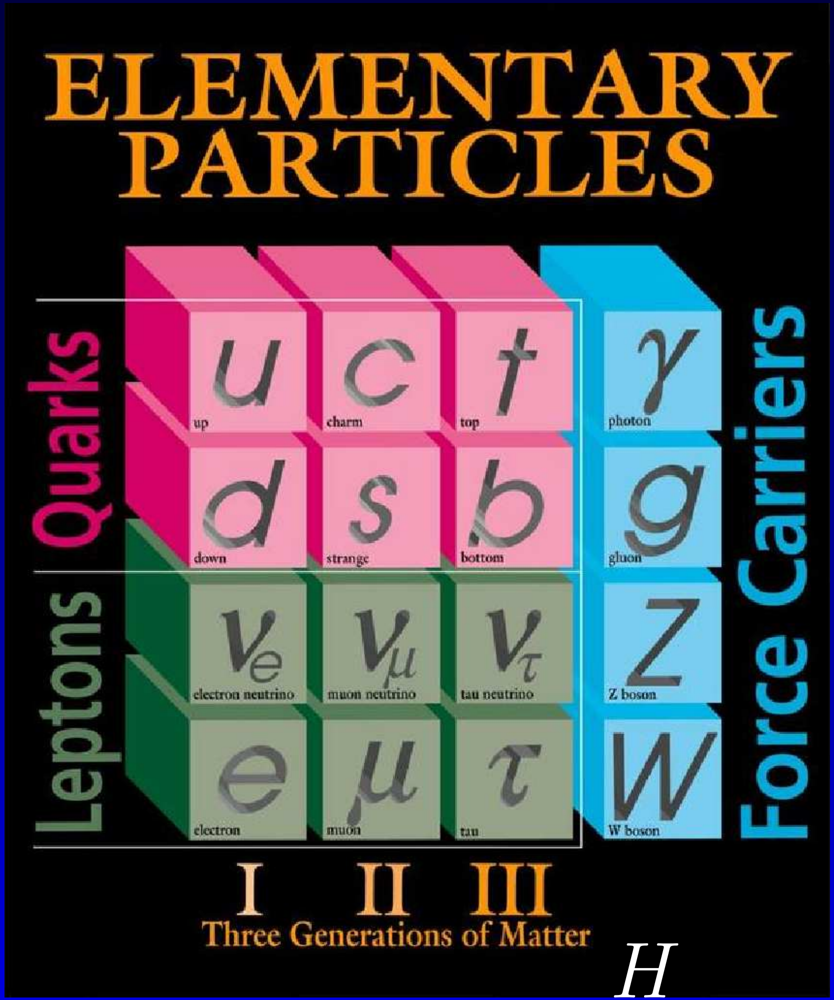




Summary

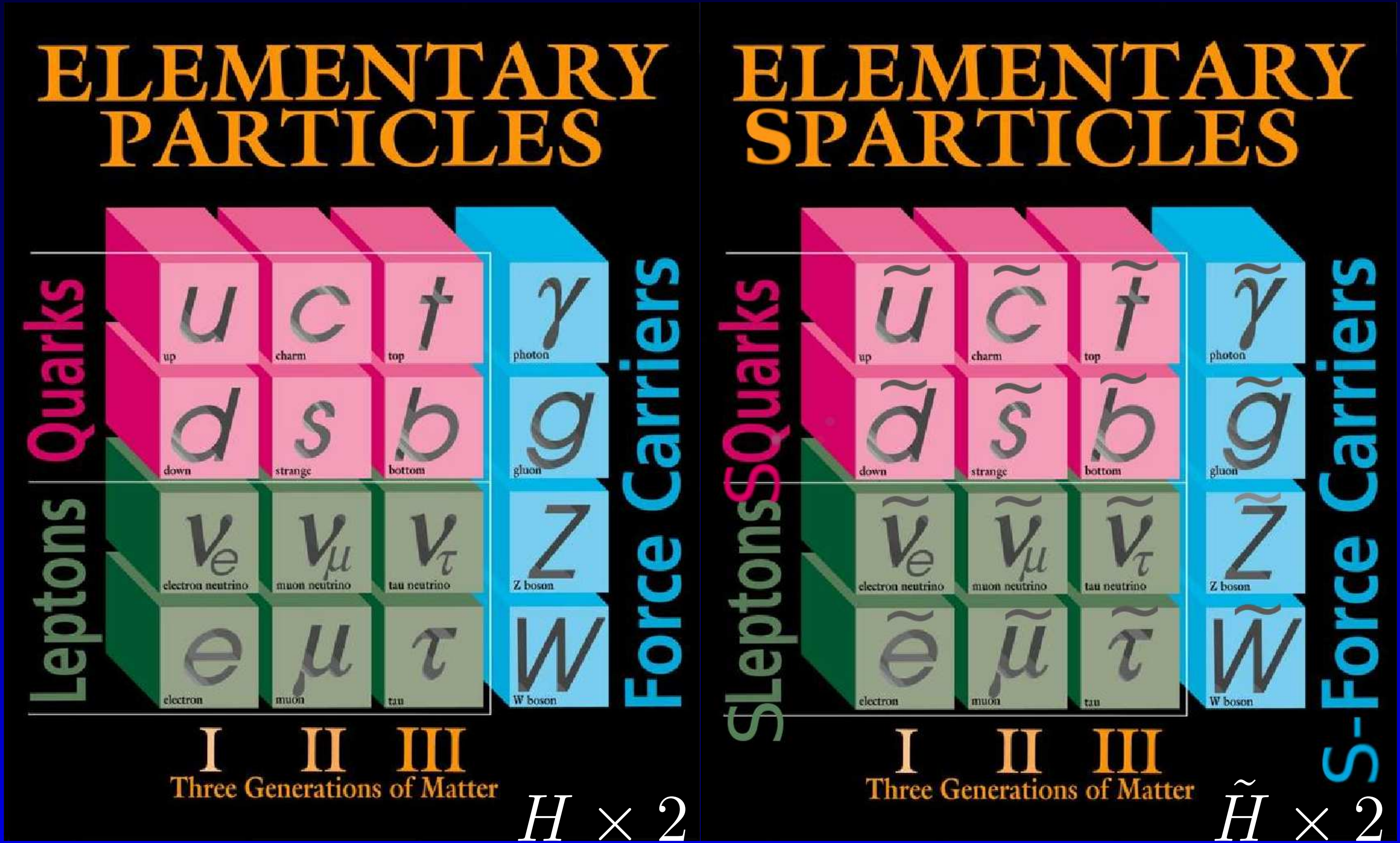
- Heavy vector triplets explanation of ATLAS Run I di-boson excess is *ruled out* by Run II searches involving leptons
- RPV explanation of di-boson excess is *alive* still because it only predicts hadronic channels
- RPV explanation of di-photon excess works fine and requires: a 750 GeV sneutrino and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

Supersymmetric Copies



H

Supersymmetric Copies



$H \times 2$ $\tilde{H} \times 2$

Review of R-Parity

The superpotential of the MSSM can be seperated into two parts:

$$
\begin{aligned}
W_{R_p} &= h^e_{ij} L_i H_1 \bar{E}_j + h^d_{ij} Q_i H_1 \bar{D}_j \\
&\quad + h^u_{ij} Q_i H_2 \bar{U}_j + \mu H_1 H_2, \\
W_{\not R_P} &= \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k \\
&\quad + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2.
\end{aligned}
$$

W_{R_p} is what is usually meant by the MSSM.

$\mathcal{Q}$: Why ban $W_{\not R_P}$?

$\mathcal{A}$: “Proton decay”

Definition of R-Parity

Q: How is $W_{R\!\!\!/_P}$ normally banned?
$\mathcal{A}$: By defining discrete symmetry R_p

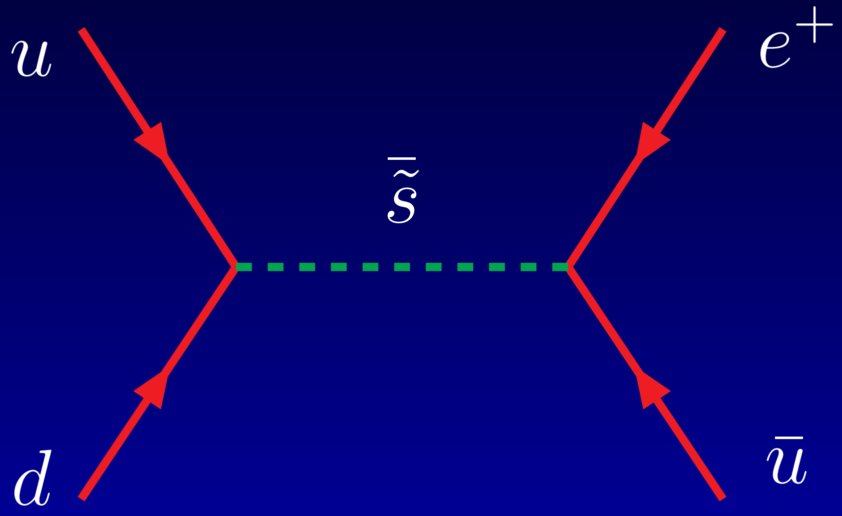
$$R_p = (-\mathbf{1})^{3B+L+2S}.$$

→ SM fields have $R_p = +1$ and superpartners have $R_p = -1$. There are two important consequences:

- Because initial states in colliders are R_p EVEN, we can only pair produce SUSY particles
- The *lightest superpartner is stable*

Proton decay

$R\!\!\!/_p$ terms are lepton number L, or baryon number B violating.

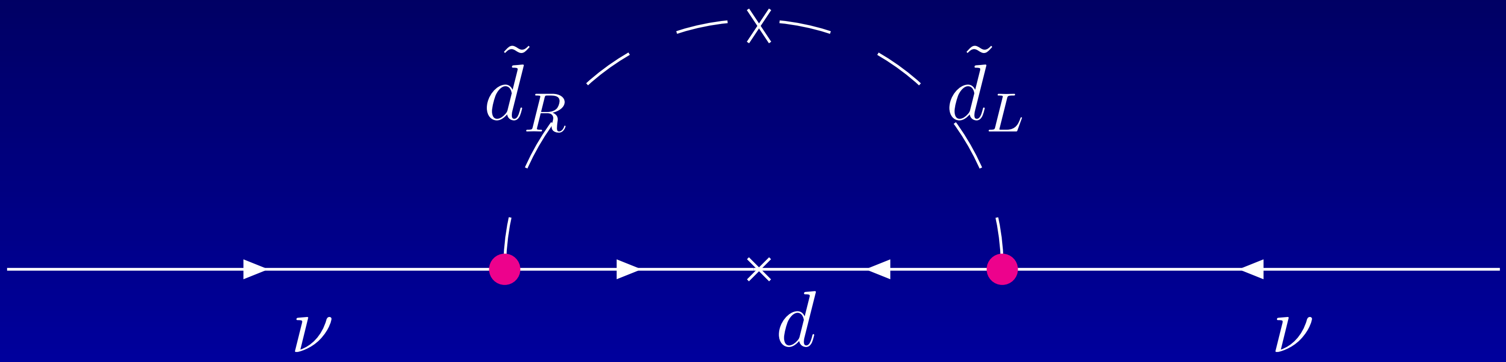


$$\Gamma(p \to e^+\pi^0) \approx \frac{\lambda'^2_{11k}\lambda''^2_{11k}}{16\pi^2 \tilde{m}^4_{d_k}} M^5_{proton}.$$

$$(p \to \nu K^+) > 7 \cdot 10^{32}\, yr \Rightarrow \lambda'_{11k} \cdot \lambda''_{11k} \lesssim 10^{-27} \left(\frac{\tilde{m}_{d_k}}{100 \text{ GeV}} \right)^2 .$$

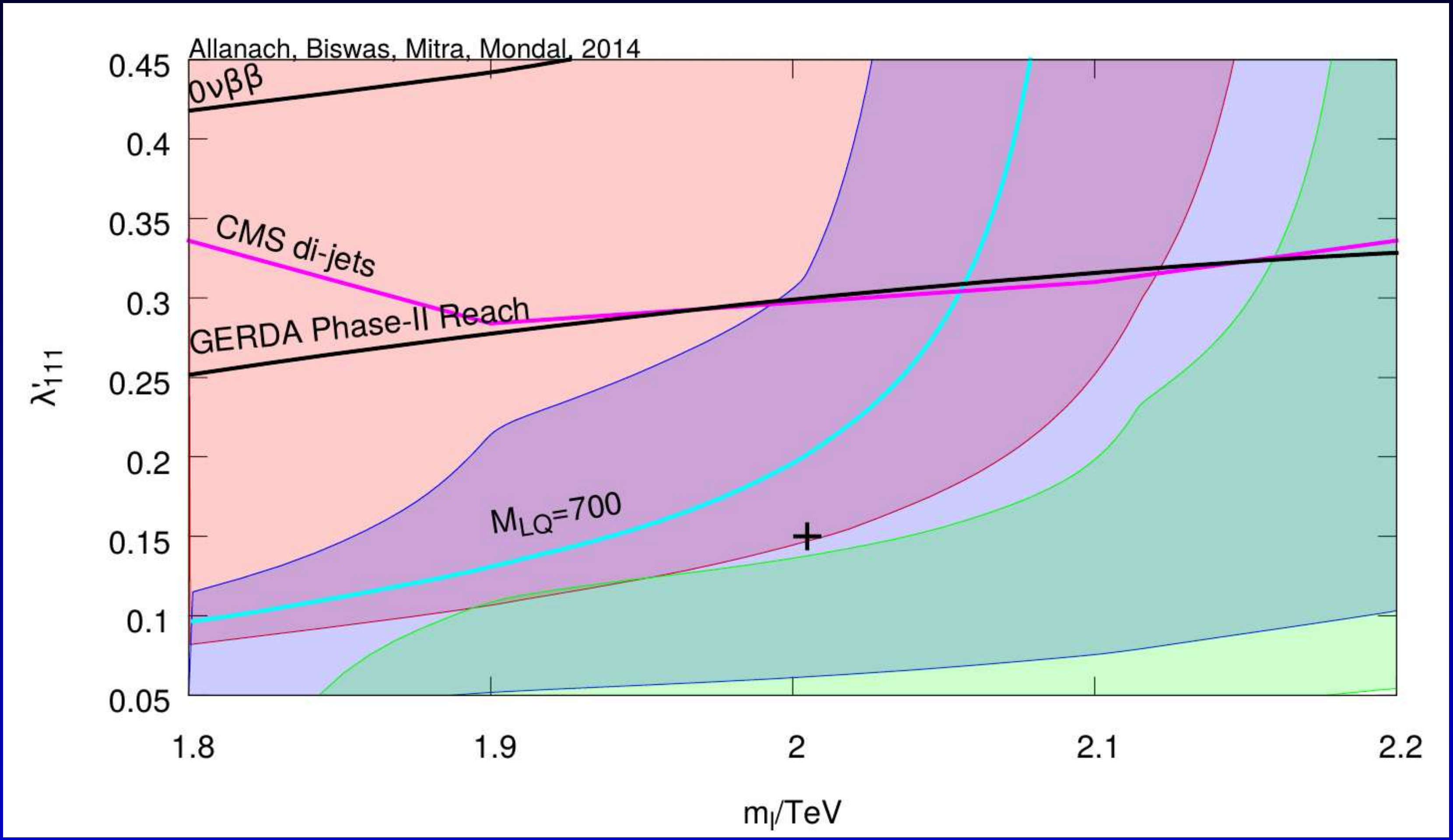
Motivation for $\not{R}_p$

- It has additional search possibilities.
- Neutrino masses and mixings testable at LHC

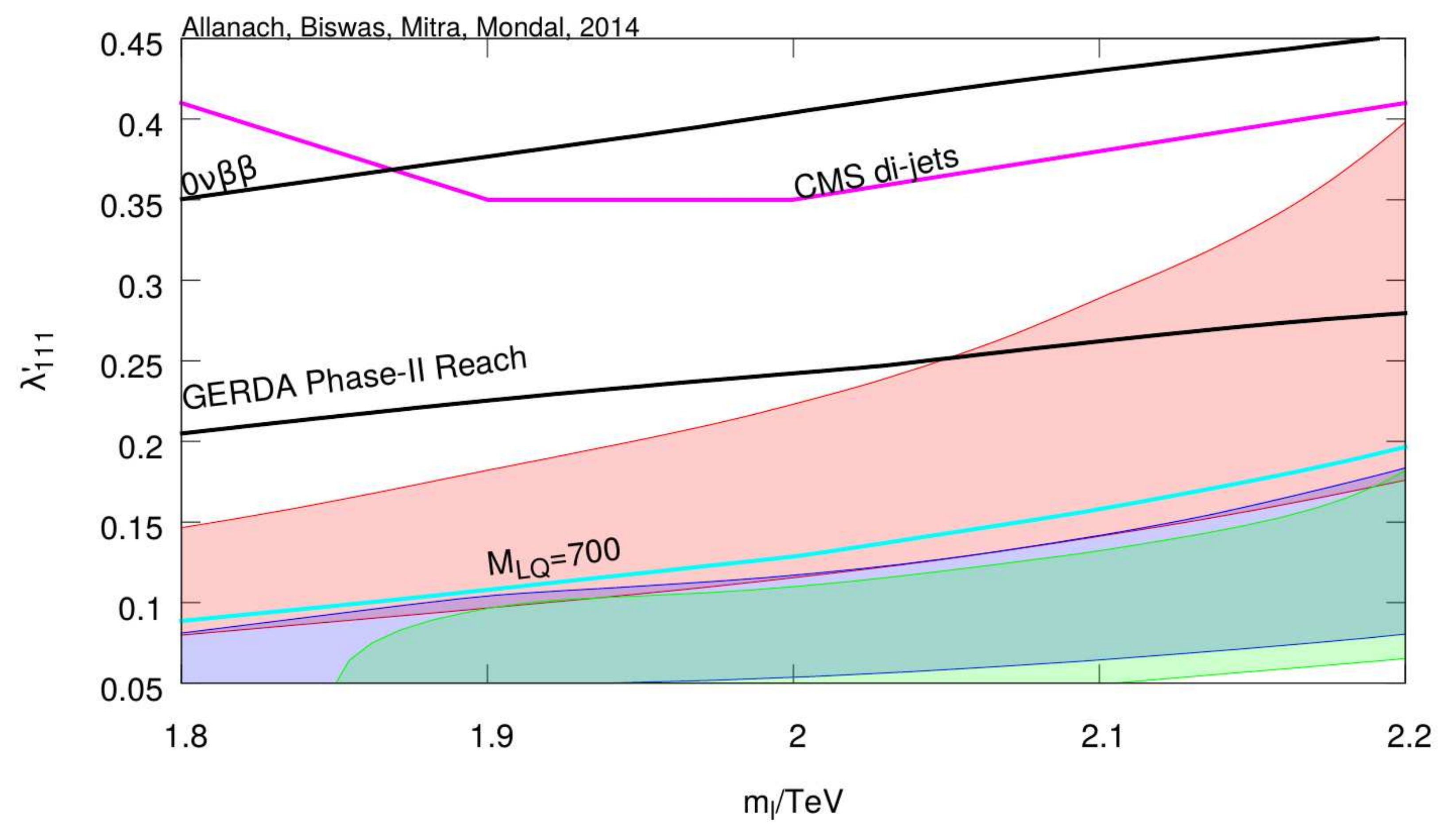


$$(m_\nu)_{11} = \frac{3}{32\pi^2} m_d {\lambda'_{111}}^2 \sin 2\theta_d \ln \frac{m^2_{\tilde{d}_L}}{m^2_{\tilde{d}_R}}$$

Parameter Space: S2



Parameter Space: S3



CMS Excesses

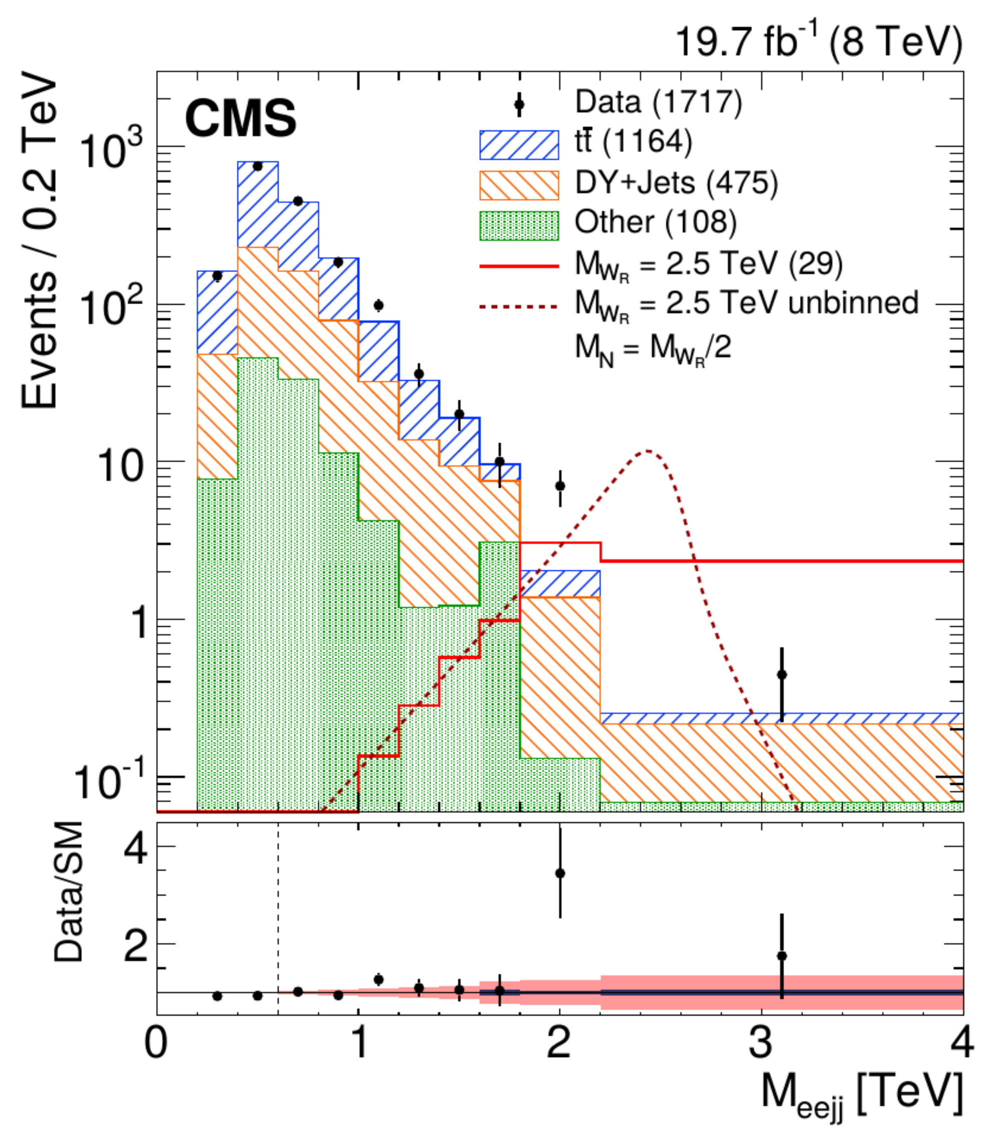
The anomalies were all in 20 fb^{-1} of data taken at 8 TeV.

- 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

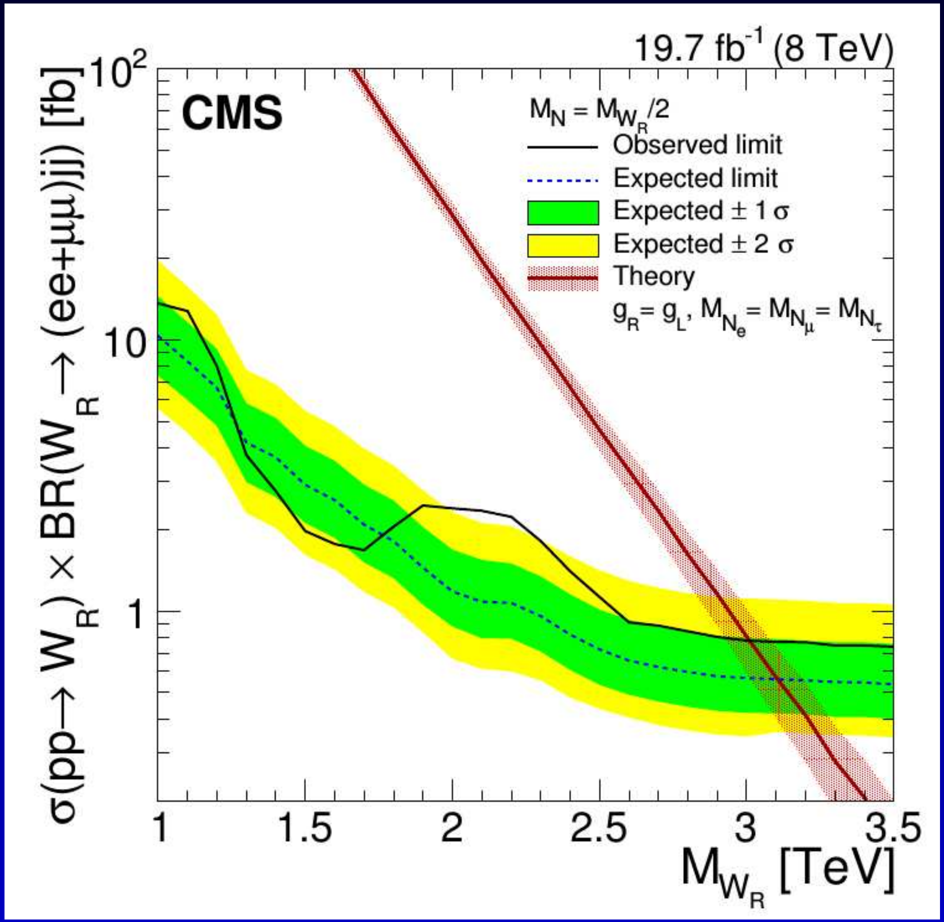
$$\begin{aligned} M^2_{lljj} &= (p(l_1)+p(l_2)+p(j_1)+p(j_2))^\mu \\ &\quad (p(l_1)+p(l_2)+p(j_1)+p(j_2))_\mu \end{aligned}$$

CMS W_R Search: 2.8σ



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

W_R: Inferred Limits

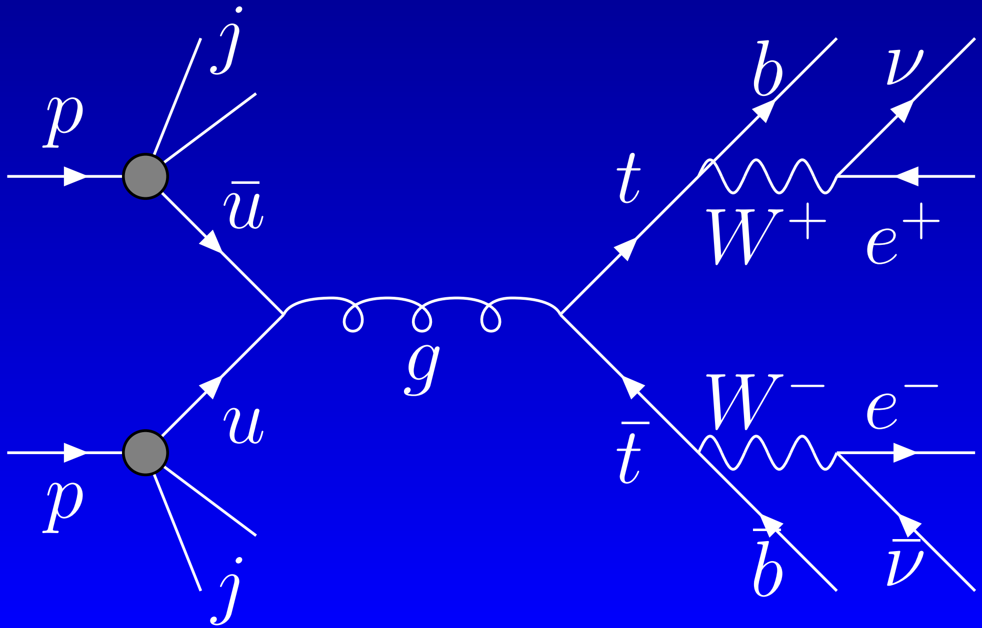


A W_R model with reduced couplings could explain it

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:



CMS Di-Leptoquark Search

Assume that $LQ \to ej$ or νj.

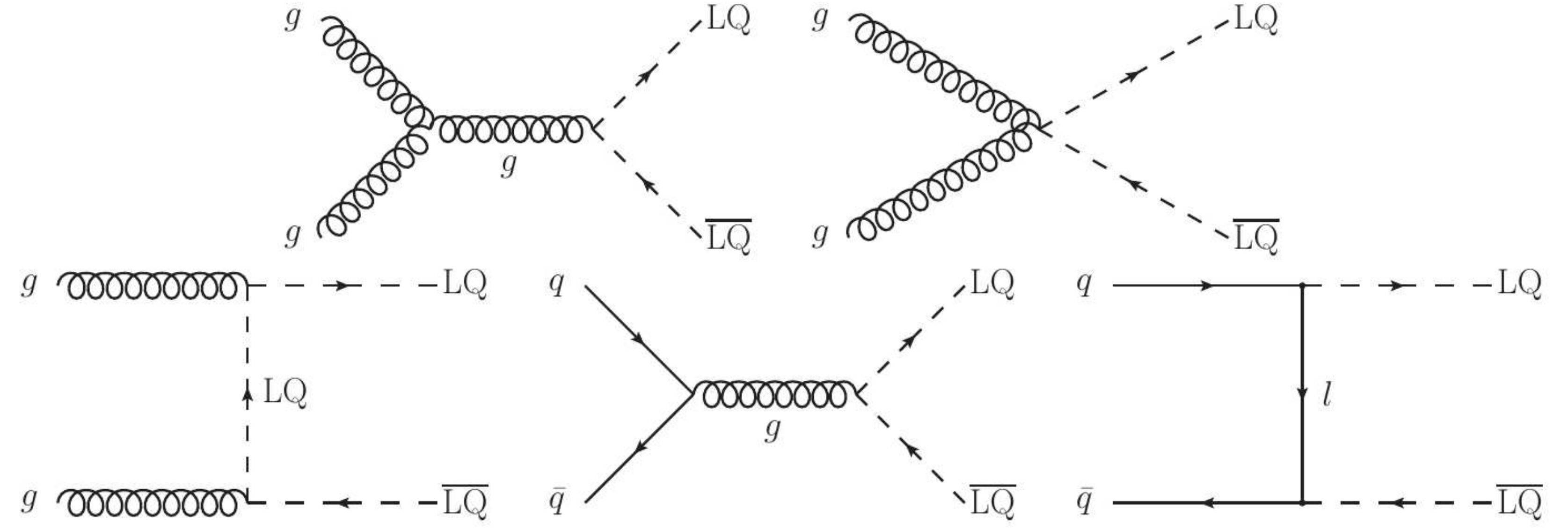


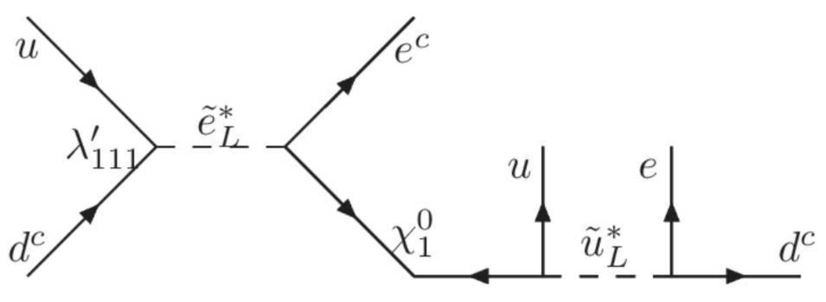
Figure 1: Dominant leading order diagrams for the pair production of scalar leptoquarks.

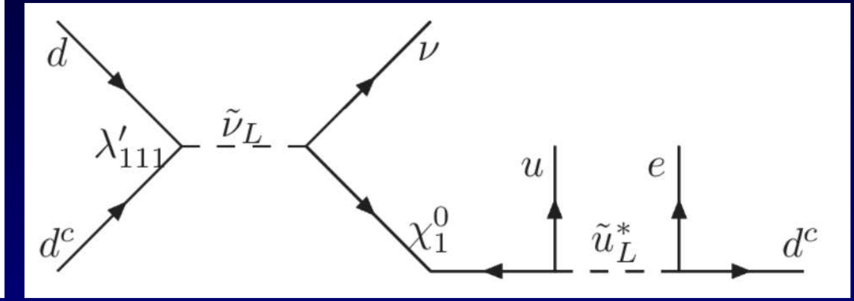
The signals they go for then are:

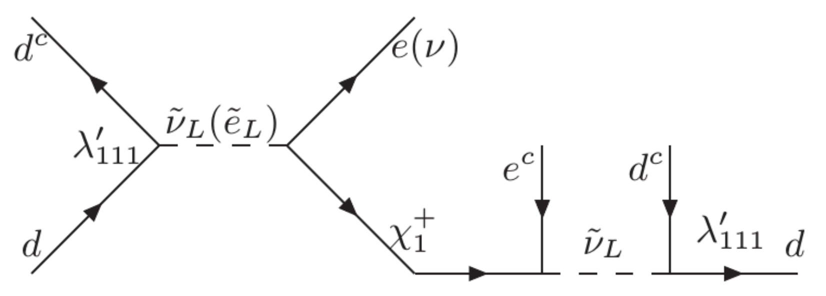
- $eejj$ 2.4σ: $S_T > 850$ GeV, M_{ee}>155 GeV, $m_{ej}^{min} > 360$ GeV
- $e\nu jj$ 2.6σ: $S_T > 1040$ GeV, M_{ej}>555 GeV, $\not{E}_T > 145$ GeV, $M_T(e\nu) > 270$ GeV

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

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



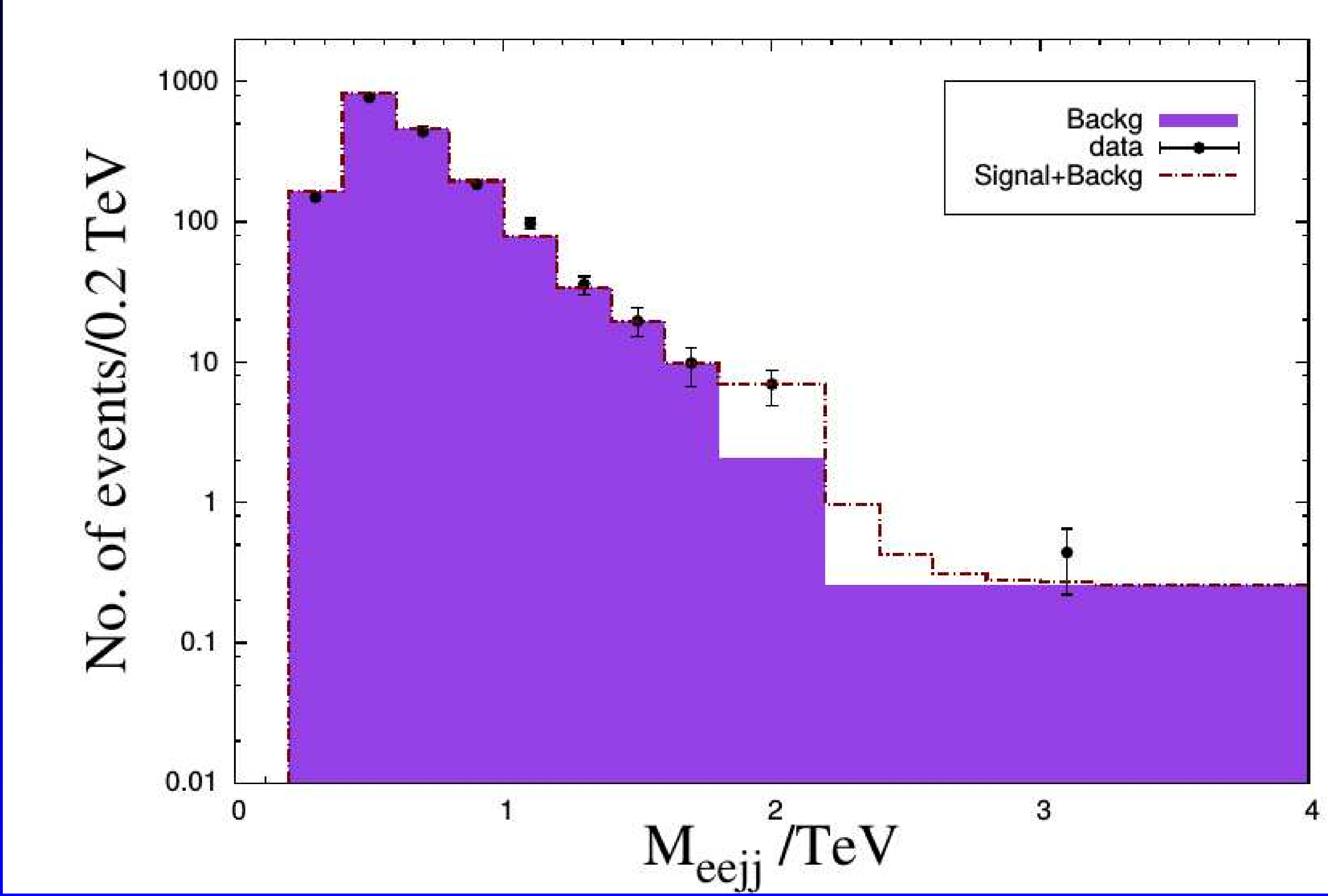




$$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_L} + M^2_W \cos 2\beta$$

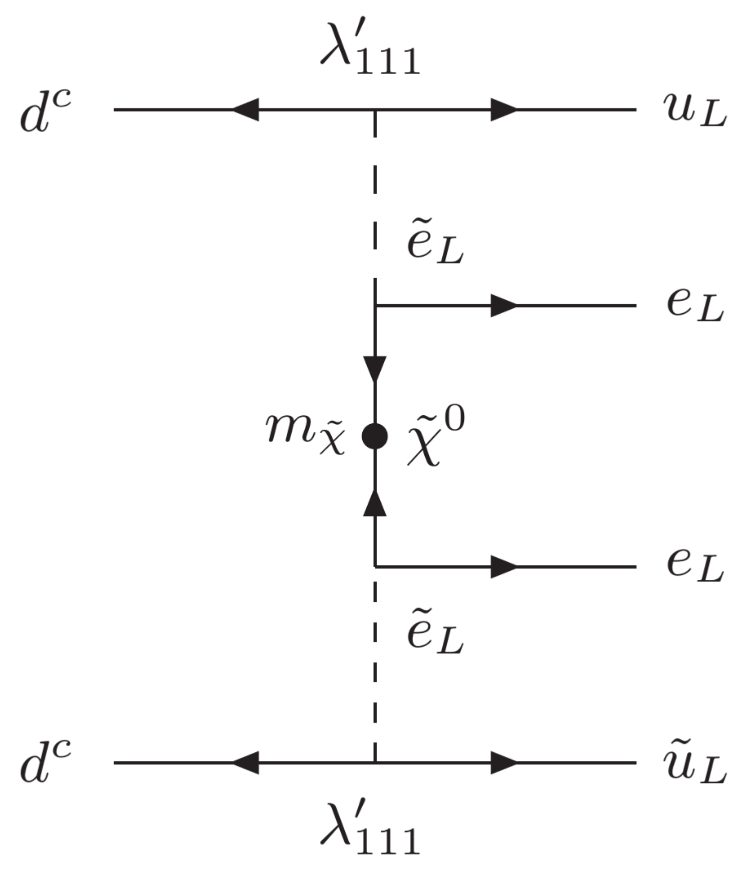
Resolves W_R, di-LQ anomalies BCA, Biswas, Mondal, Mitra, `arXiv:1408.5439`; *ibid* `arXiv:1410.5947`

W_R Mass Distribution

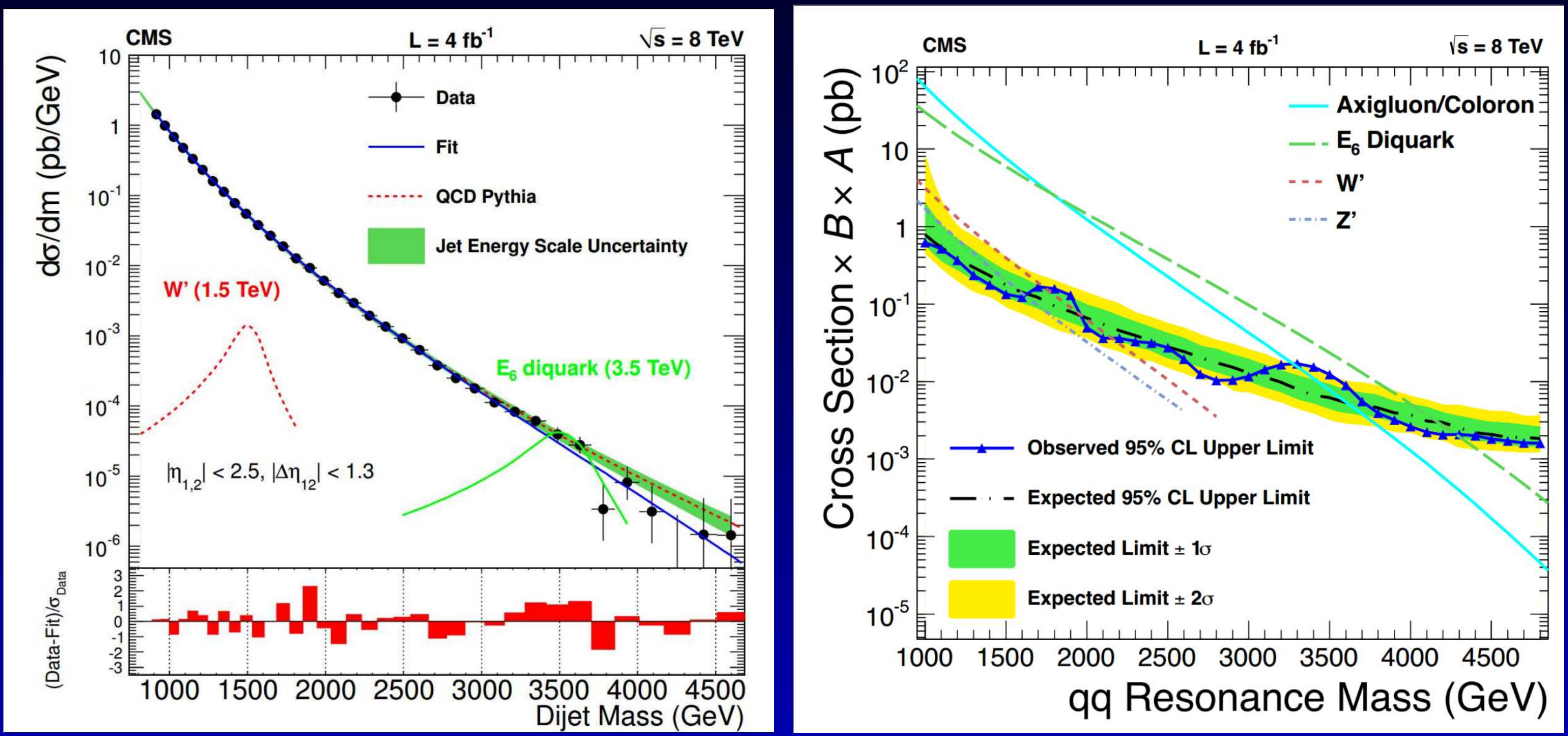


Neutrinoless Double Beta Decay

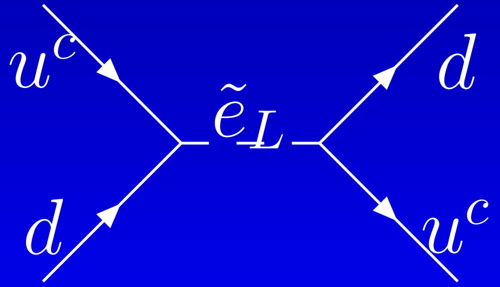
Is *banned* in the Standard Model because it breaks lepton number: $Z \to (Z+2)e^-e^-$ Present bound from GERDA is $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr. It should increase by a factor 10 in the next year or so.



Other Constraints



CMS `arXiv:1302.4794`



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 χ_1^0, χ_2^0, χ_3^0, χ_4^0 in increasing mass order.

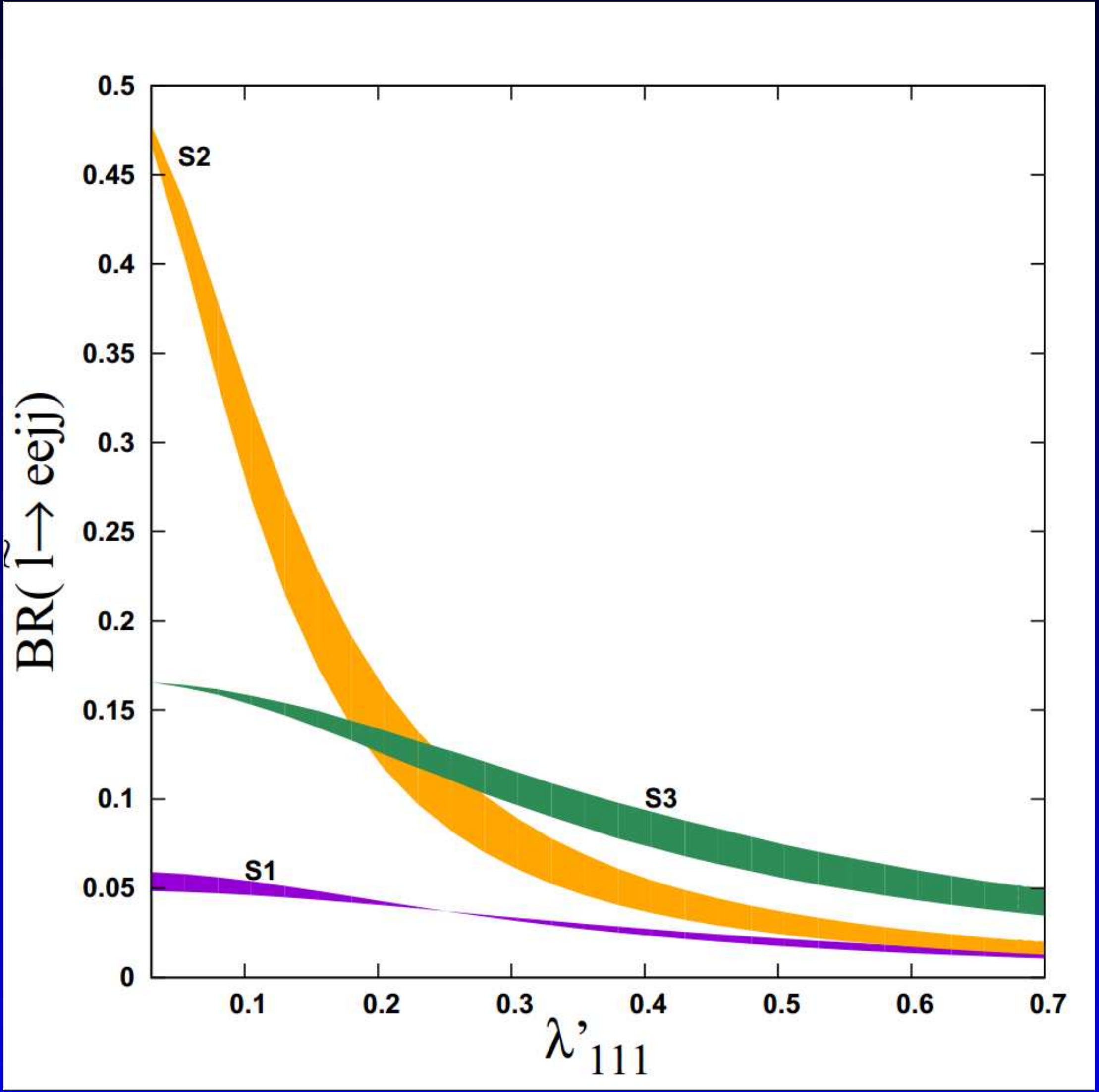
Decays into/from neutralinos are affected by their *composition*.

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

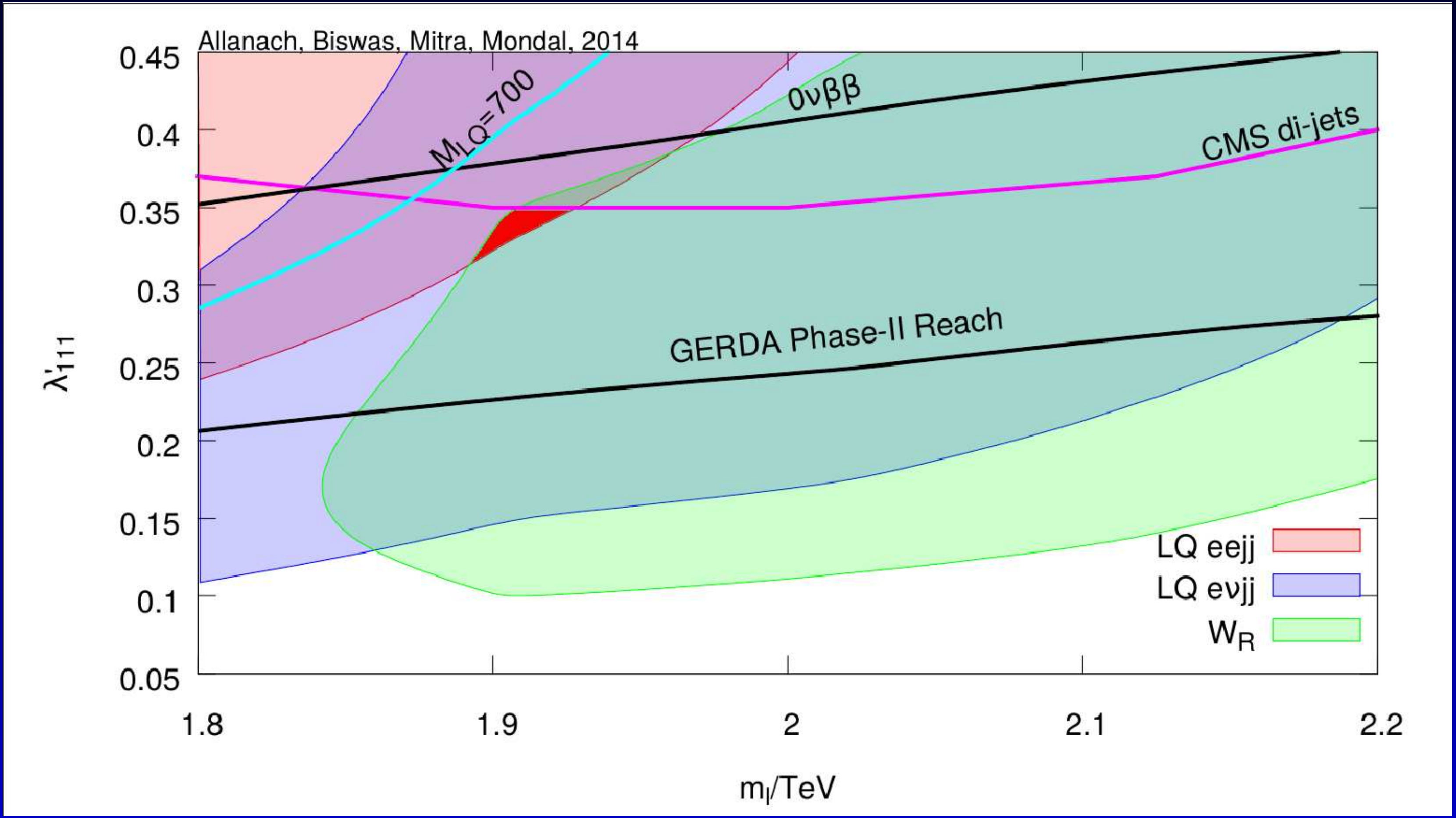
Three Neutralino Scenarios

- **S1:** $M_2 = M_1 + 200 < \mu$. $\tilde{B}$ LSP. $\tilde{e}$ can decay to χ_2^0 or $\chi_1^\pm$. 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 $\chi_1^\pm$ decays via λ'_{111} too. Predicts $R = 3$.

Branching Ratios

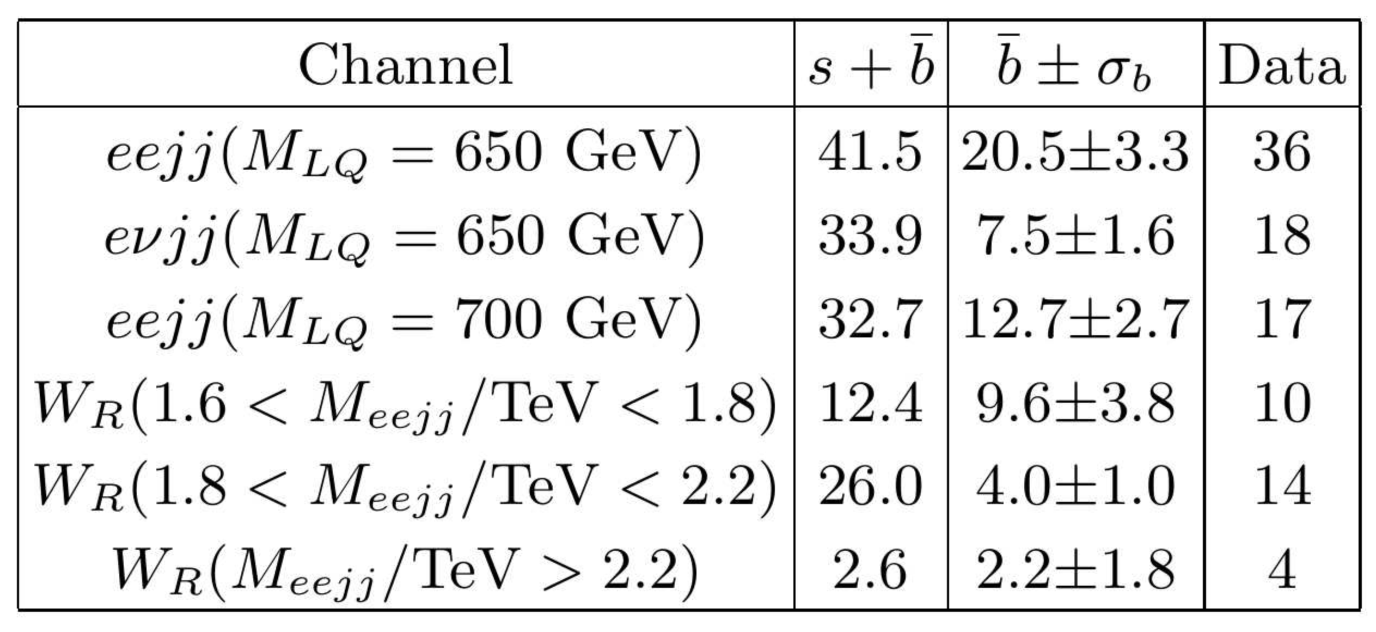


Parameter Space: S1



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

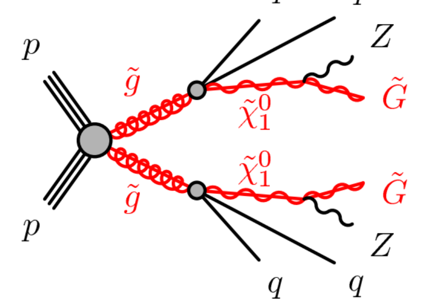
Signal model point: **S2** with $\lambda'_{111} = 0.175$, $m_{\tilde{l}} = 2TeV$ and $M_{\chi_1^0} = 900$ GeV.

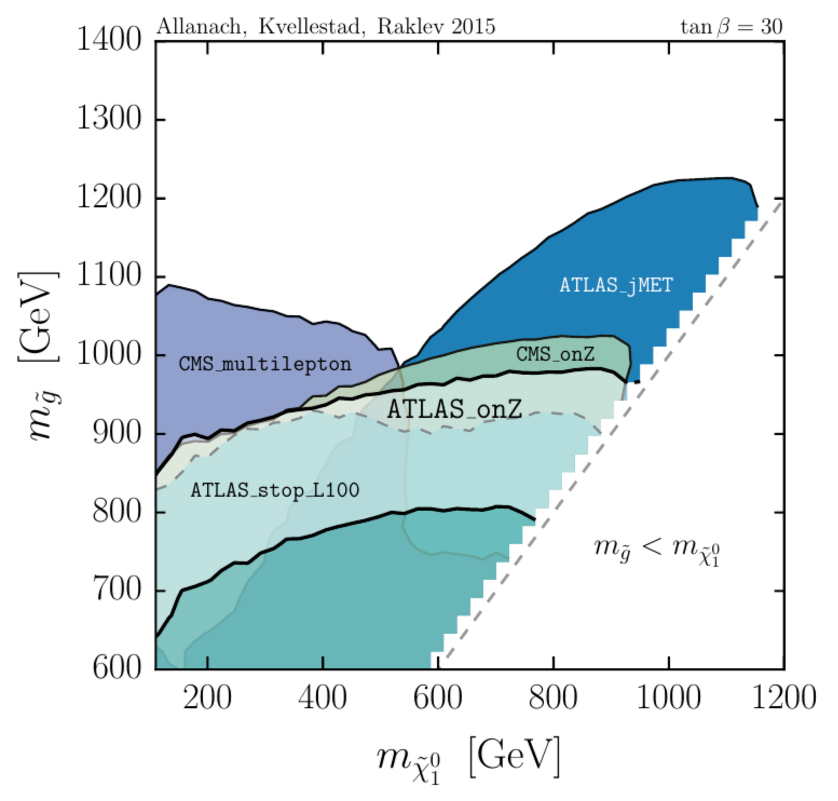
ATLAS On-Z Analysis

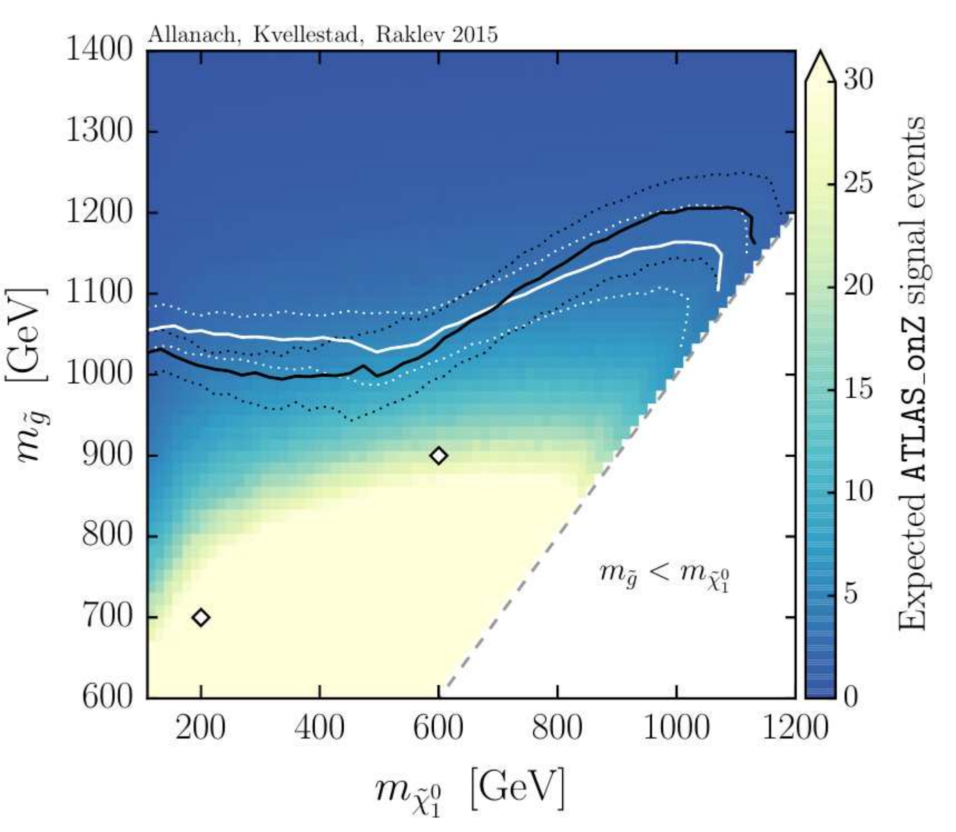
observed	29
background	10.6±3.2
number of sigma	3.0
s (95% CL)	7.1-31.8

$\not{E}_T > 225$ 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,
$\not{E}_T/\text{GeV} = [100 - 200,\ 200 - 300,\ > 300]$.
Have to check on a model-by-model basis whether they are compatible

Combined Constraints







(Barenboim *et al* also had this interpretation in arXiv:1503.04184).

Less^a than 6(7) events for $\tan\beta = 1.5(30)$.

---

[a] BCA, Kvellestad, Raklev, arXiv:1504.02752

CMS $l^+l^-jj\not{E}_T$ 2.6σ Excess

Search in m_{ll}: for Opposite Sign Ssame Flavour leptons (either e or μ). Demand $\not{E}_T > 100$ 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

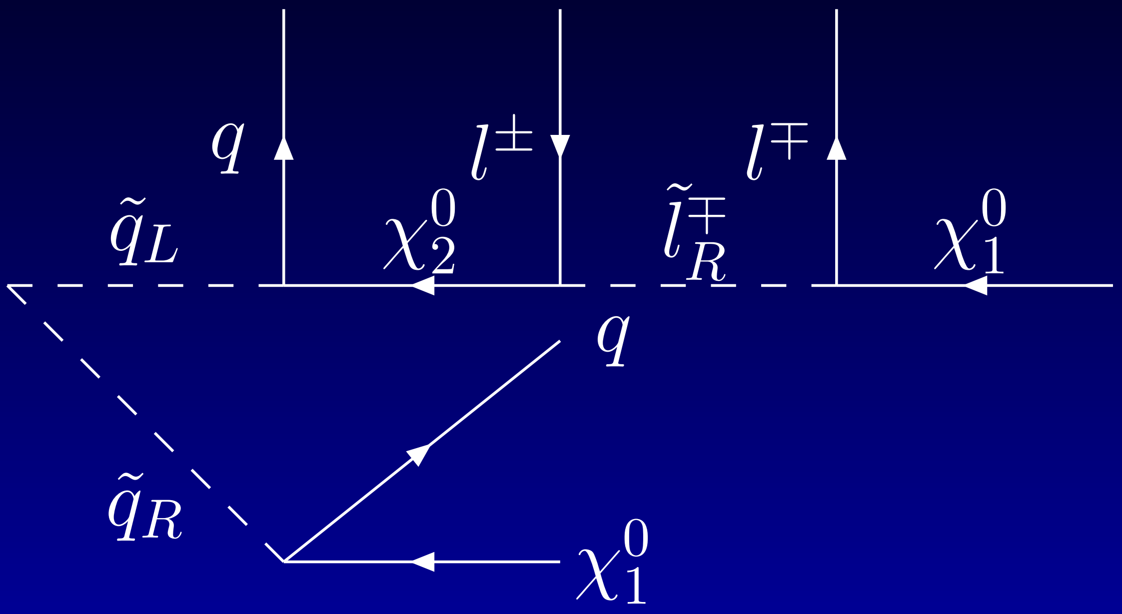
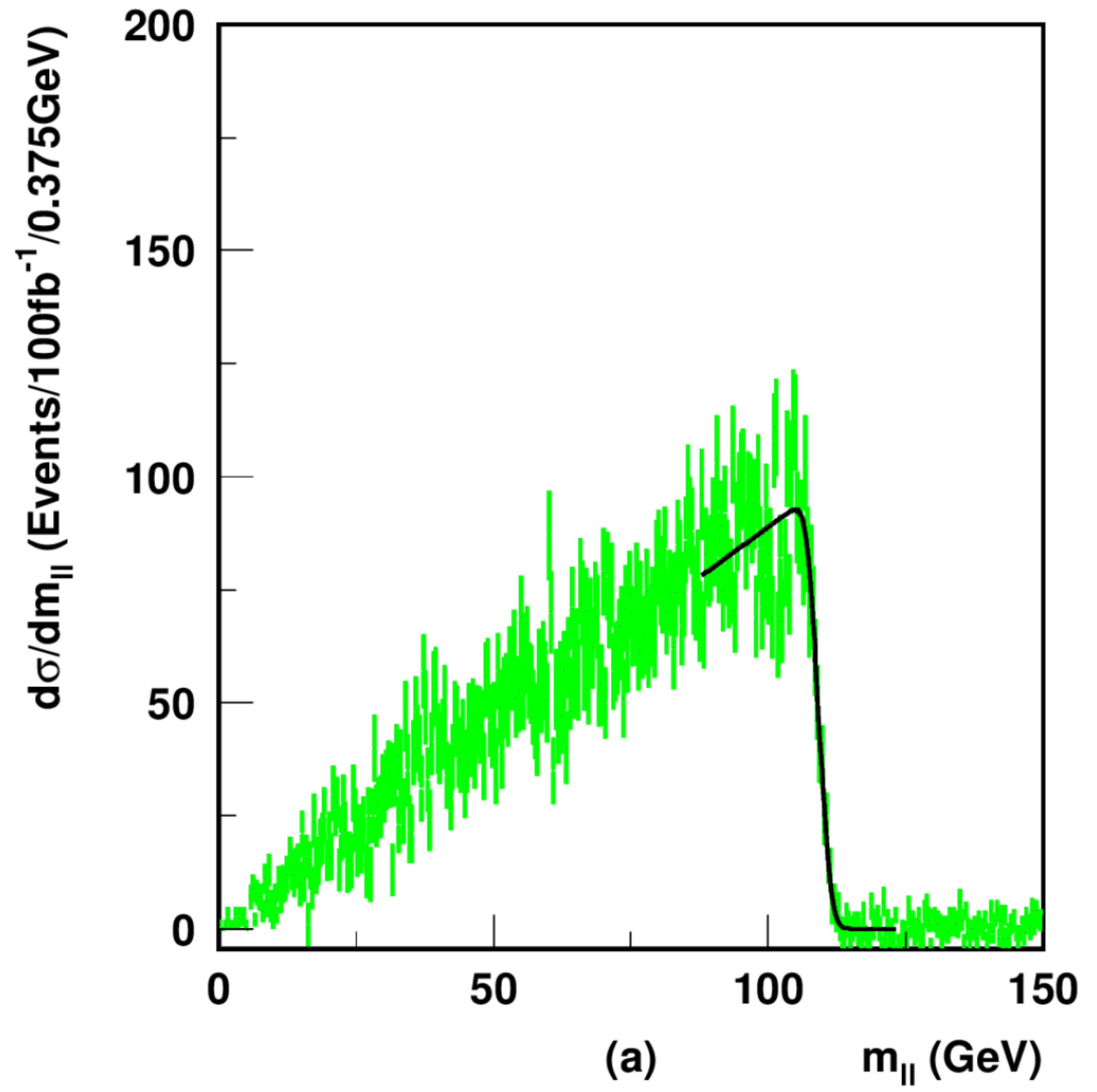


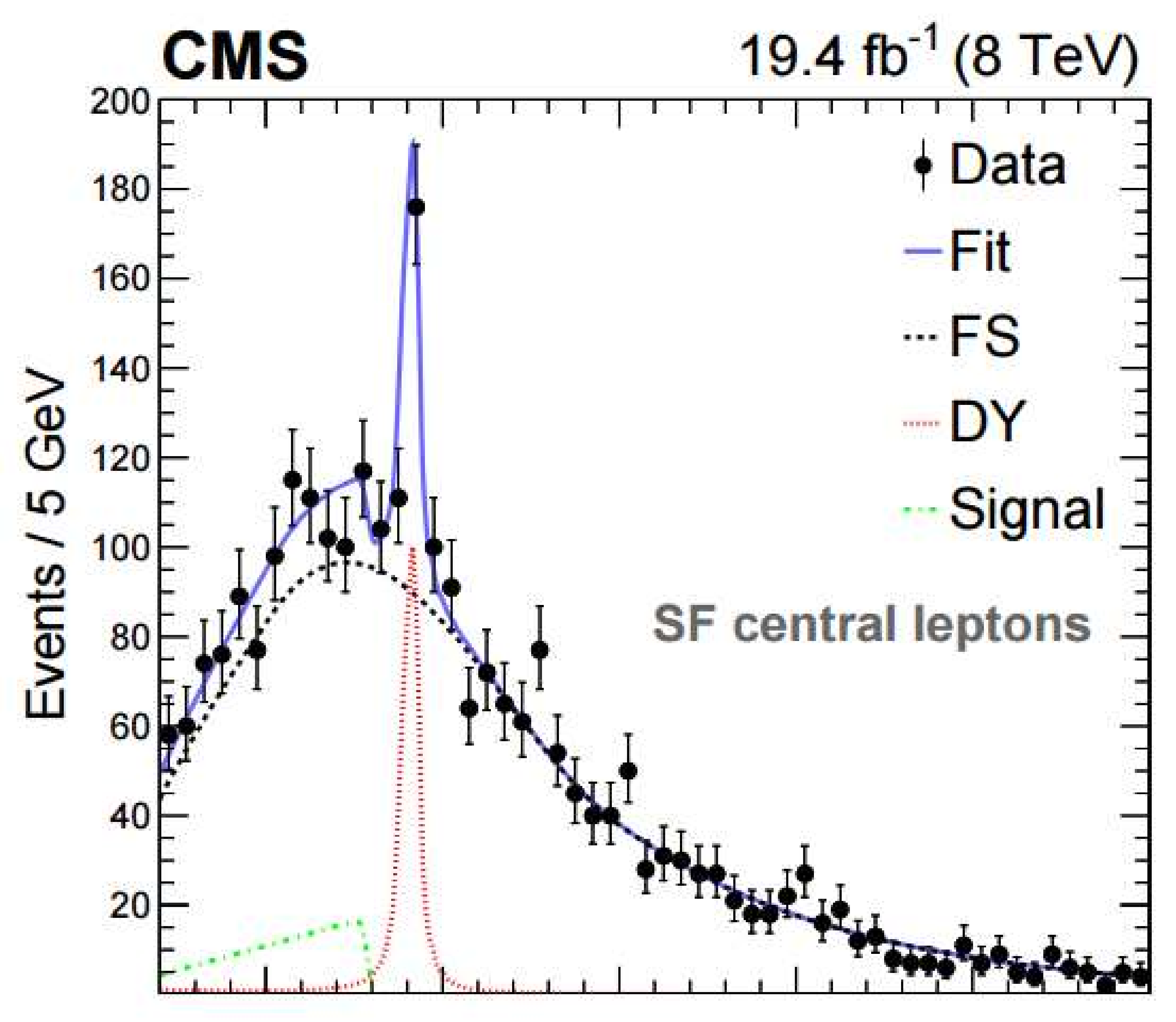
Figure 1: Feynman diagram for the golden cascade decay: opposite sign same flavour leptons (OSSF)

BCA, Raklev, Kvellestad, `arXiv:1409.3532`; Huang Wagner PRD 90 015014 `arXiv:1410.4998`; Grothaus, Sakurai `arXiv:1502.05712`

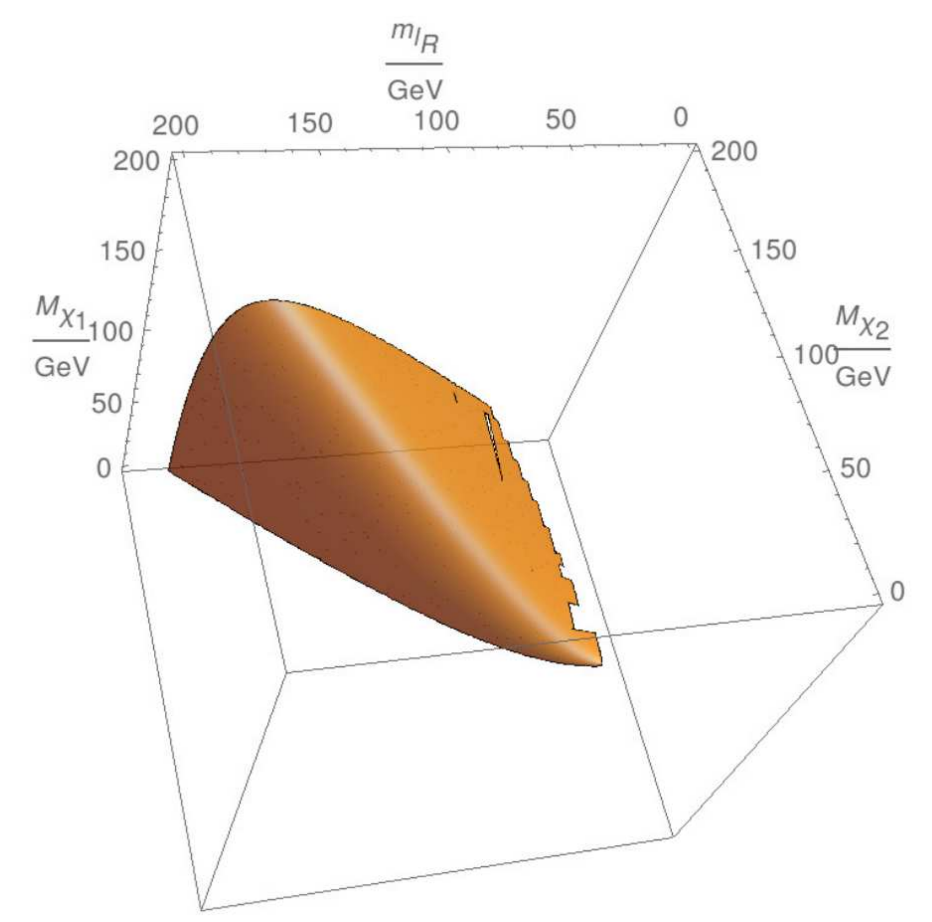
A Sharp Invariant Feature



m_{ll} Distribution



Edge Interpretation



The signal rate determines $m_{\tilde{q}}$, $m_{ll}^{max} = 78.4 \pm 1.4$ GeV we fit to $\sqrt{\frac{(m^2_{\chi^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\chi^0_1})}{m^2_{\tilde{l}}}}$.

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

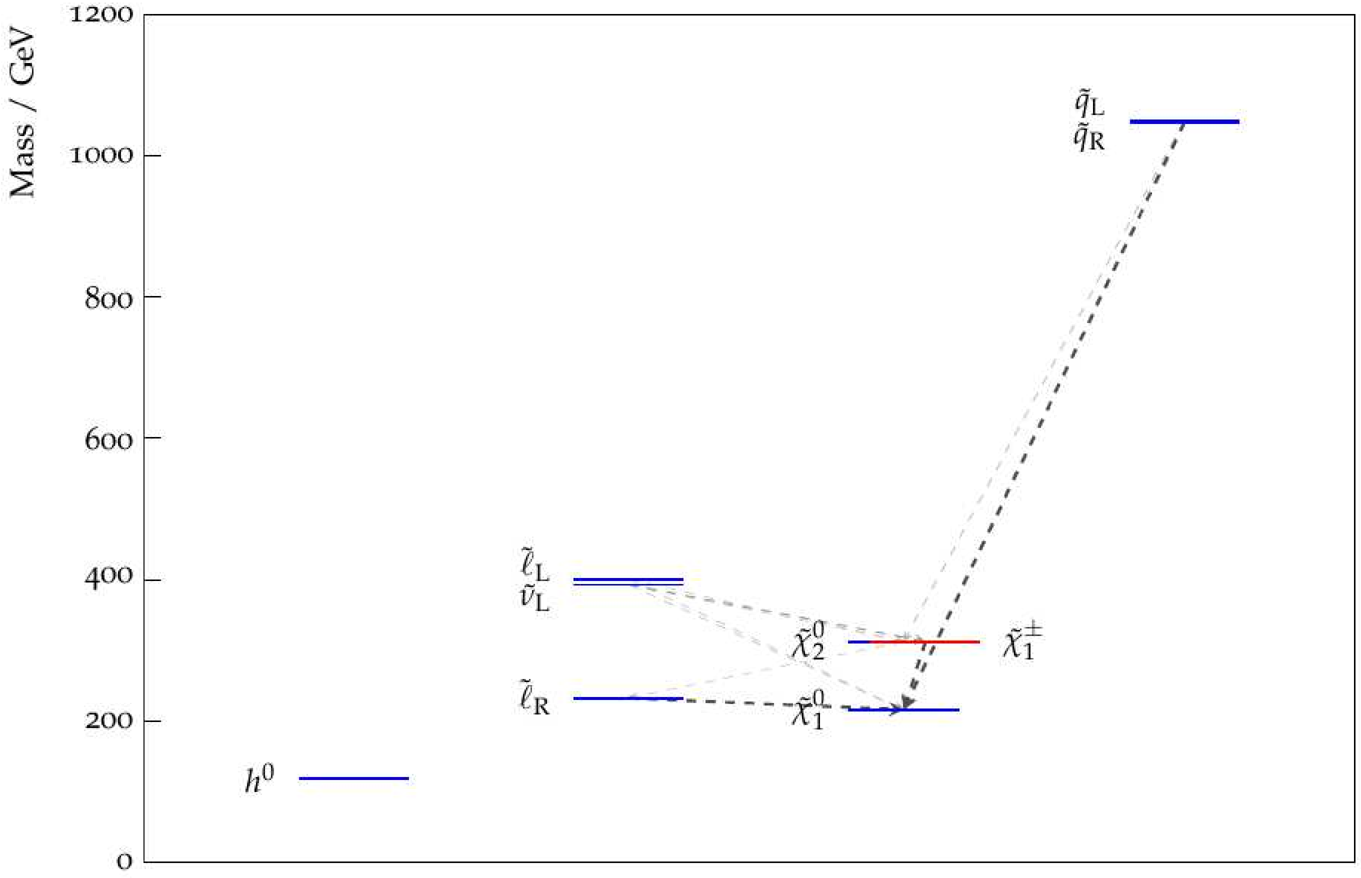
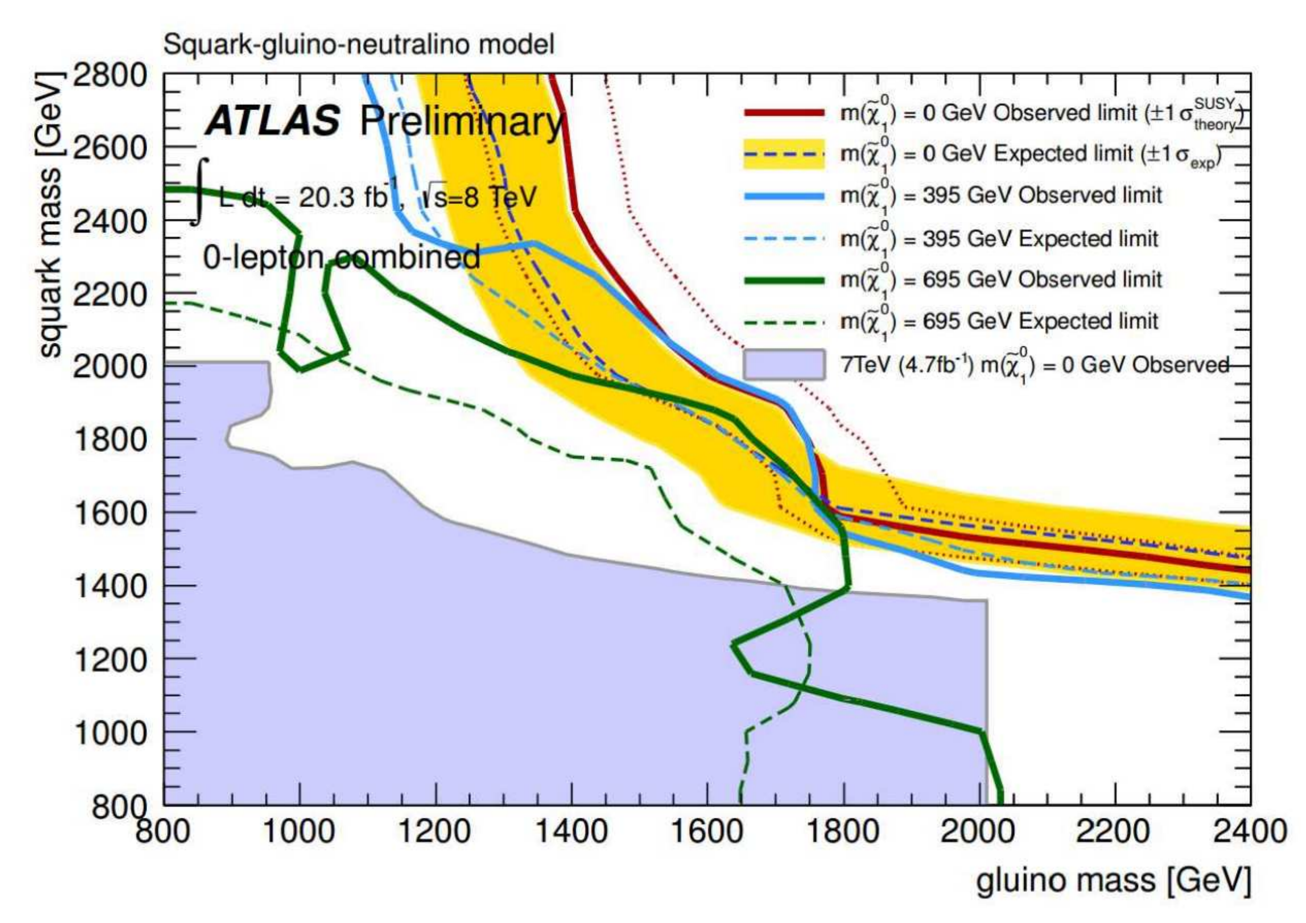


FIG. 4. Example signal point that fits the central CMS rate and edge inferences: $M_2 = 300$ GeV, $m_{\tilde{l}_R} = 200$ GeV, $m_{\tilde{q}} = 1050$ GeV. Prominent decays with branching ratios higher than 10% are shown as arrows.

LHC Constraints

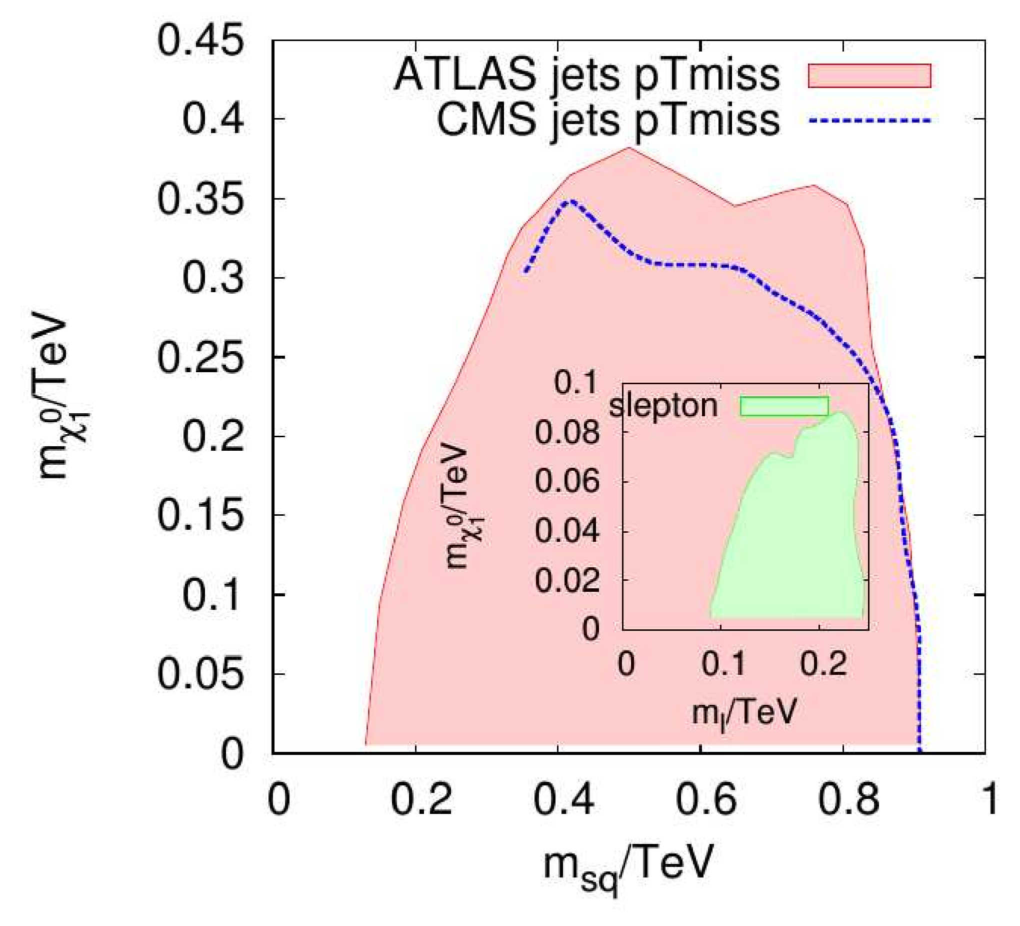
We shall see squark masses of around a TeV being predicted.



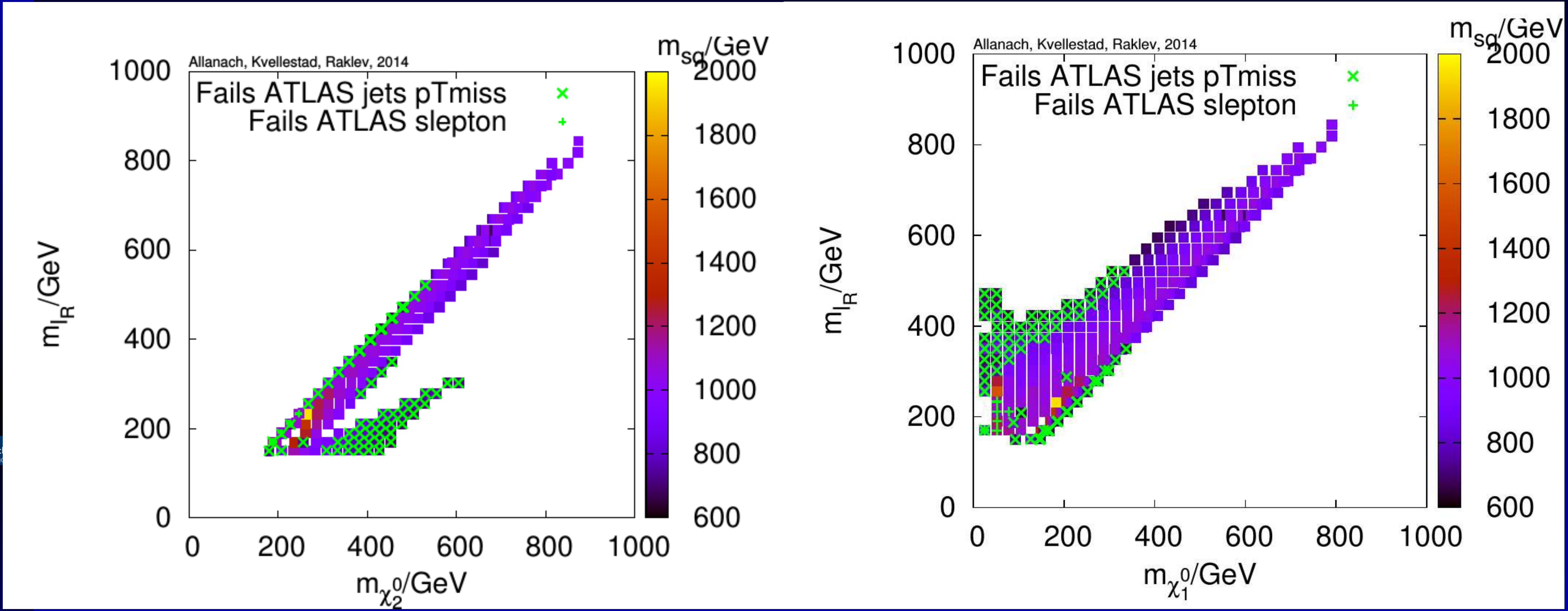
Other Constraints

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

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



Viable Parameter Space



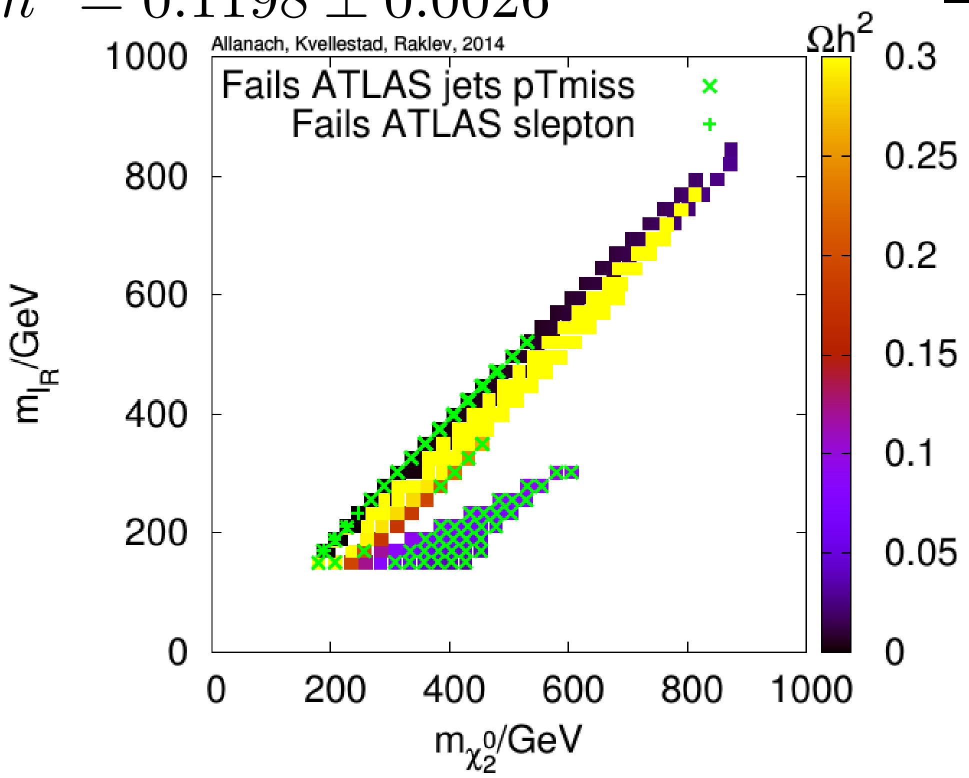
Parameter space fitting the central rate edge measurement.

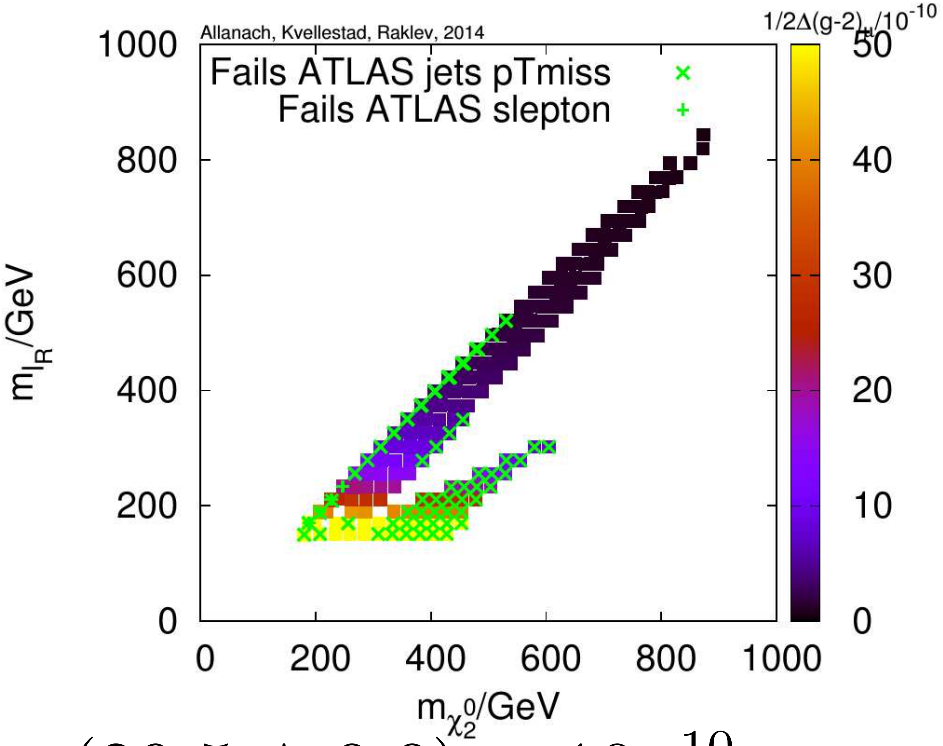
Constraints from ATLAS and 4-lepton $\not{E}_T$ searches currently underway

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

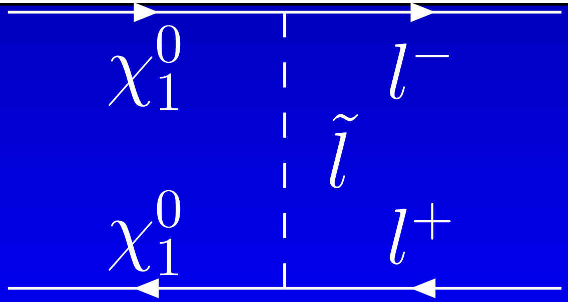
$\Omega h^2 = 0.1198 \pm 0.0026$

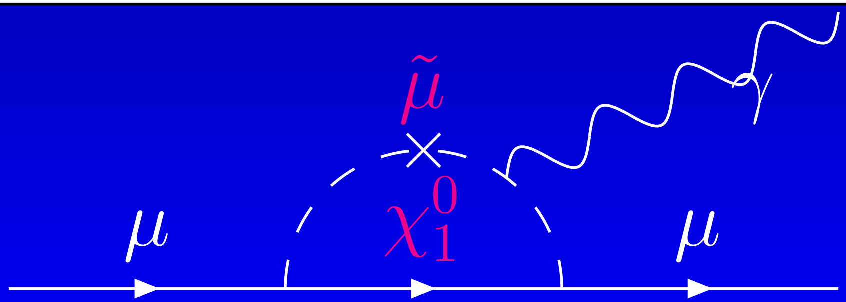
$$\frac{\delta(g-2)_\mu}{2} \sim 13 \times 10^{-10} \left(\frac{100\text{ GeV}}{M_{SUSY}}\right)^2 \tan\beta$$


Allanach, Kvellestad, Raklev, 2014

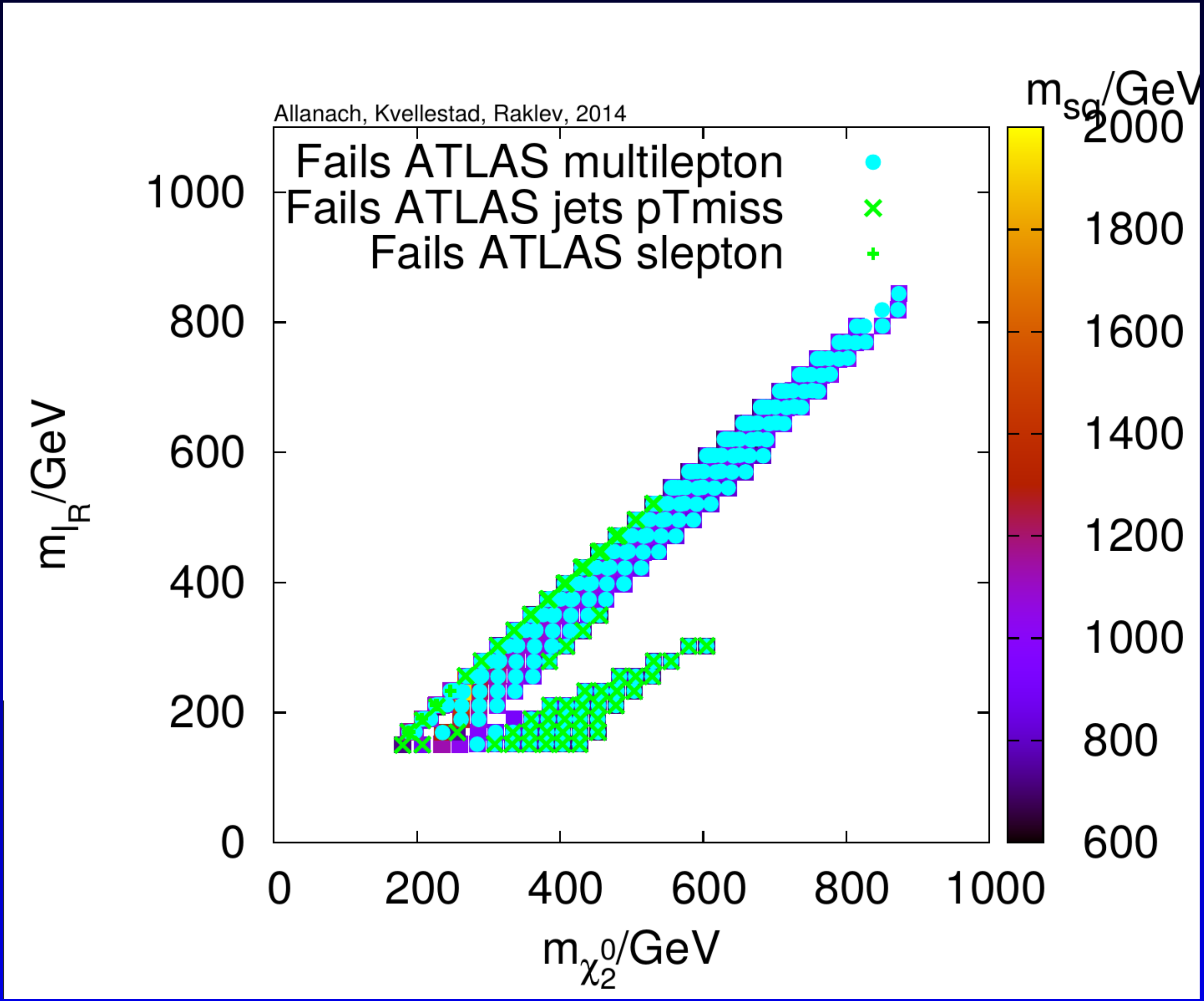

Allanach, Kvellestad, Raklev, 2014

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

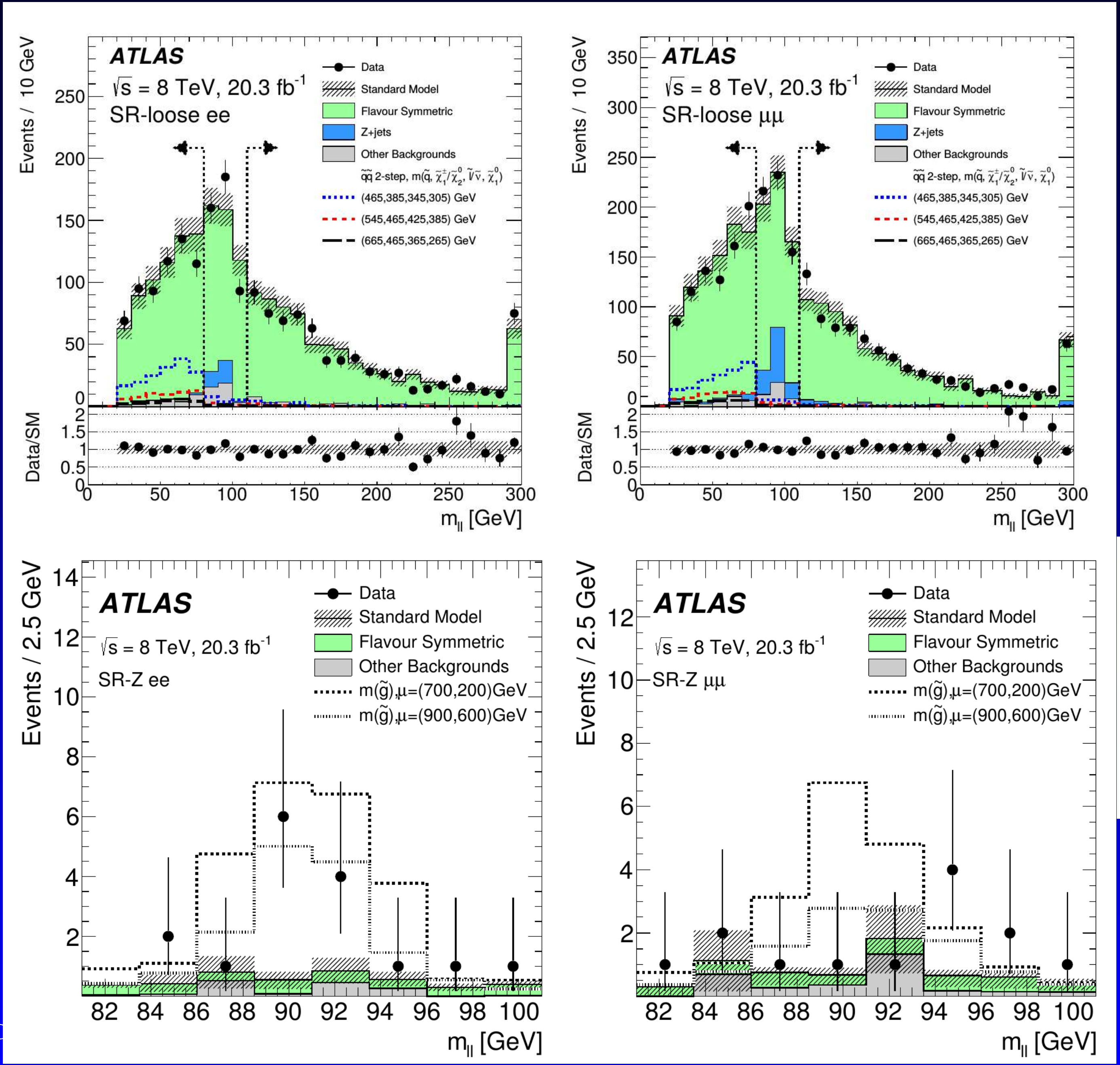


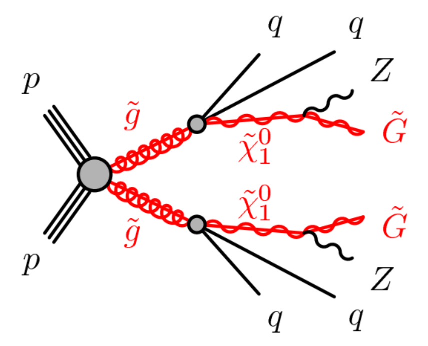


CMS 4-lepton $\not\!\!E_T$ (*preliminary*)

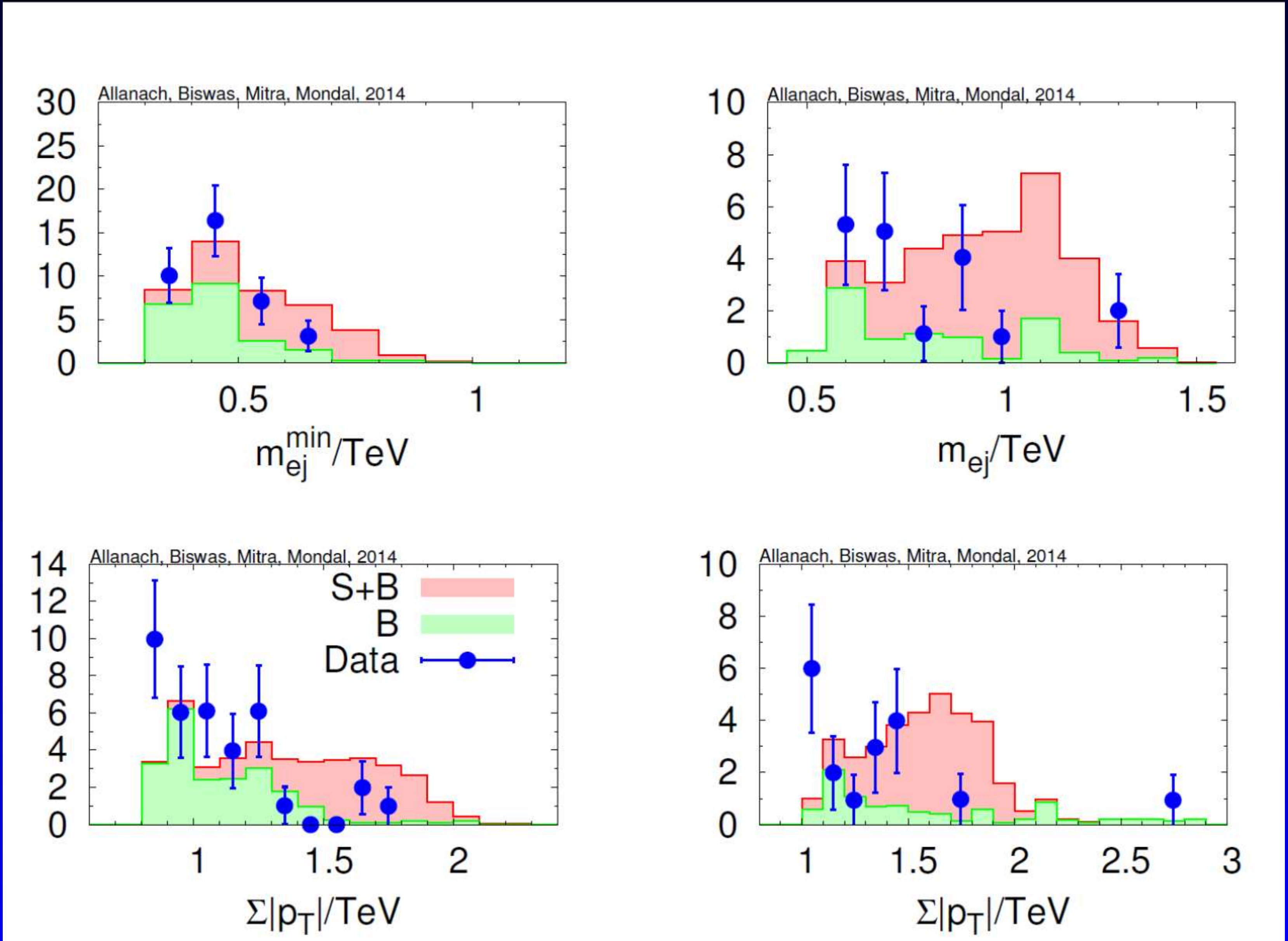


ATLAS Disagrees `arXiv:1503.03290`

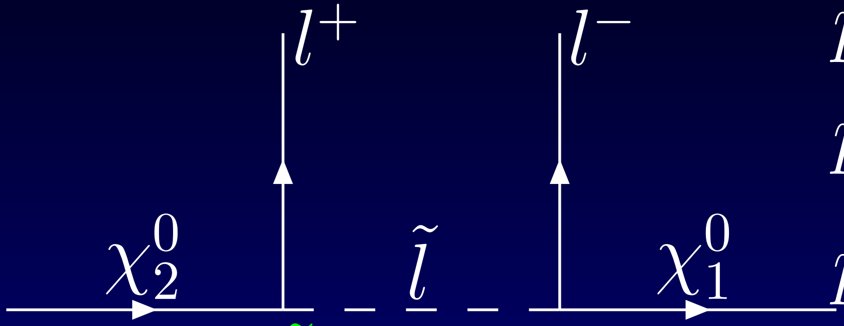




Kinematical Distributions: LQ



Cascade Decay



$$p^\mu_{\tilde{l}} = (m_{\tilde{l}}, \underline{0})$$
$$p^\mu_{l\pm} = (|\underline{p}_{l\pm}|, \underline{p}_{l\pm})$$
$$p^\mu_{\chi^0_{1,2}} = \left(\sqrt{{m_{\chi^0_{1,2}}}^2 + |\underline{p}_{\chi^0_{1,2}}|^2}, \underline{p}_{\chi^0_{1,2}}\right)$$

Work in $\tilde{l}$ rest frame.

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

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

Momentum conservation:

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

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

$$\Rightarrow |\underline{p}_{l^+}| = \frac{m^2_{\chi_2^0} - m^2_{\tilde{l}}}{2 m_{\tilde{l}}}. \text{ Similarly } |\underline{p}_{l^-}| = \frac{m^2_{\tilde{l}} - m^2_{\chi_1^0}}{2 m_{\tilde{l}}}.$$

Statistics

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

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

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 lead[a] to proton decay, and has:

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

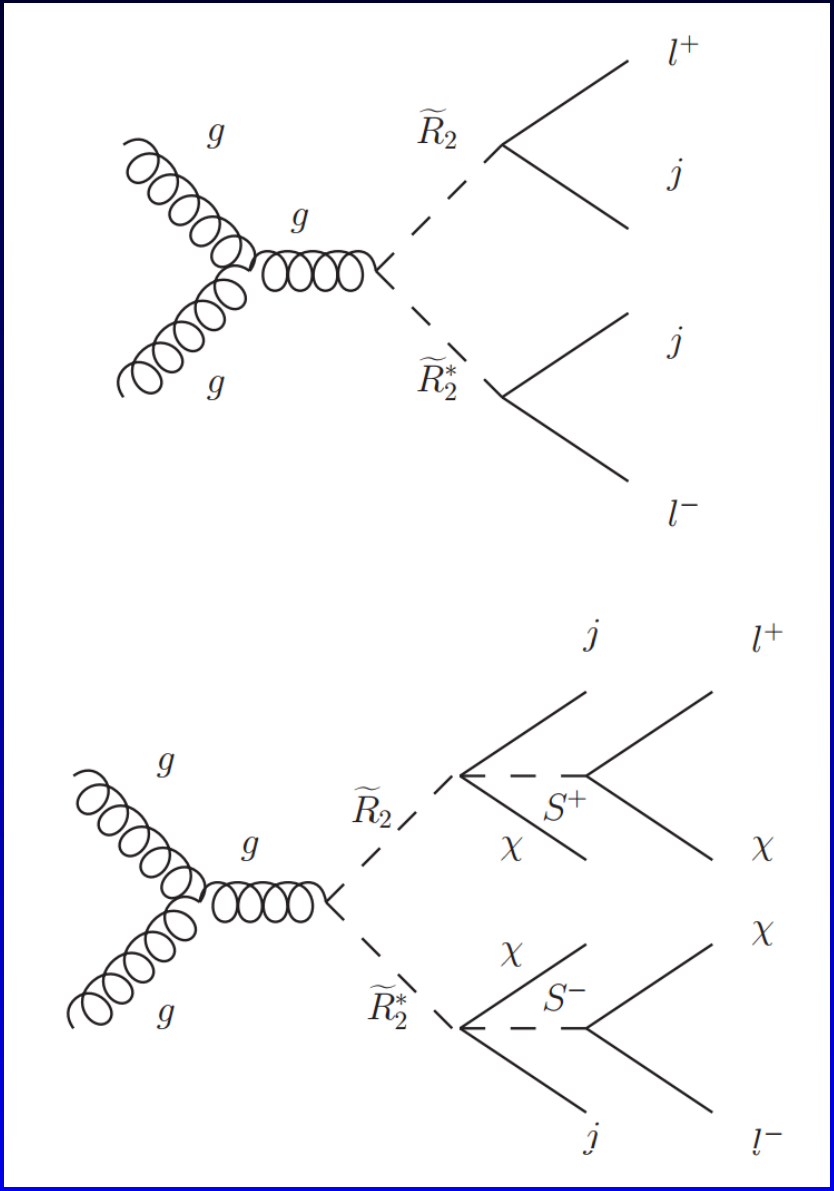
$$\mathcal{L} = -\lambda_d^{ij} \bar{d}^i_R \tilde{R}_2^T \epsilon L^j_L + hc - \frac{h_i}{\Lambda} S \bar{Q}_i \chi \tilde{R}_2 - \frac{h'_i}{\Lambda_2} S \bar{l}_i \chi \tilde{H} +$$

$$BR(\tilde{R}_2 \to lj) \sim 15\%,$$
$$BR(\tilde{R}_2 \to S^0 j\chi \to j\not{E}_T) \sim 25\%,$$
$$BR(\tilde{R}_2 \to S^{\pm} j\chi \to l^{\pm} j\not{E}_T \sim 65\%.$$

---

[a] Queiroz, Sinha, Strumia, `arXiv:1409.6301`; BCA, Alves, Queiroz, Sinha, Strumia, `arXiv:1501.03494`

Production at the LHC

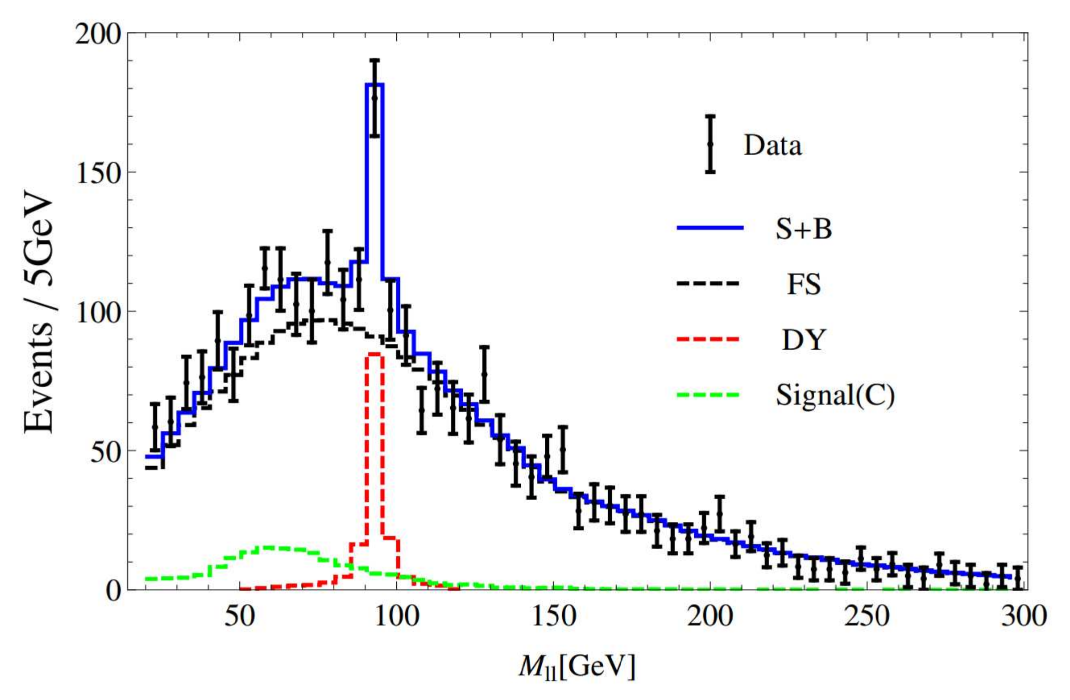


Upper diagram can explain W_R and di-leptoquark excesses.

Lower diagram can explain CMS SUSY search excess (but not ATLAS).

Constraints on the masses

- $j\not{E}_T$ searches imply $M_s + M_\chi > 300$ GeV for LQs around 500 GeV.
- To get the m_{ll} spectrum right in the CMS $l^+l^-jj\not{E}_T$ excess, $m_S - m_\chi \sim 20 - 40$ GeV.



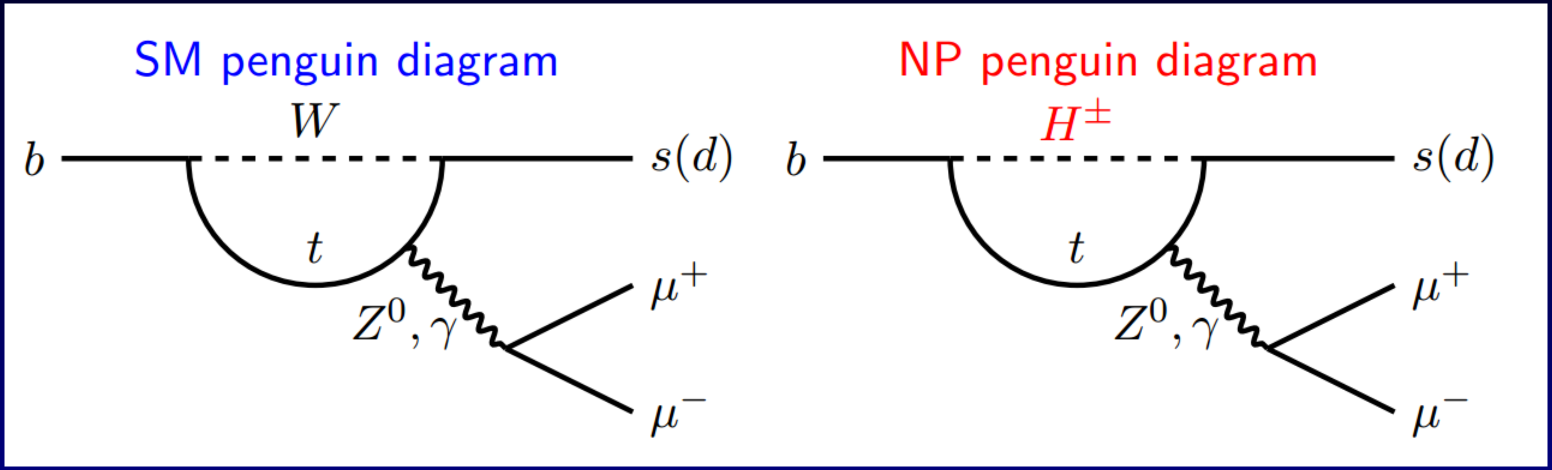
Dark Phenomenology

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.

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

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.

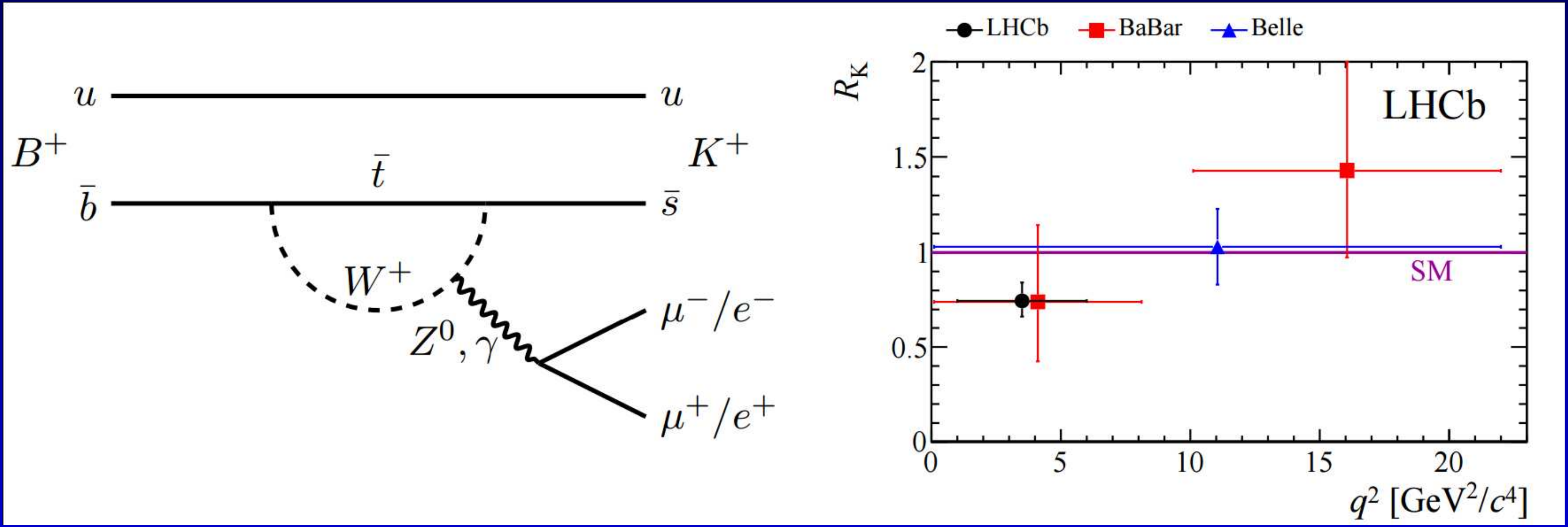
B Meson Rare Decays



- 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 σ**

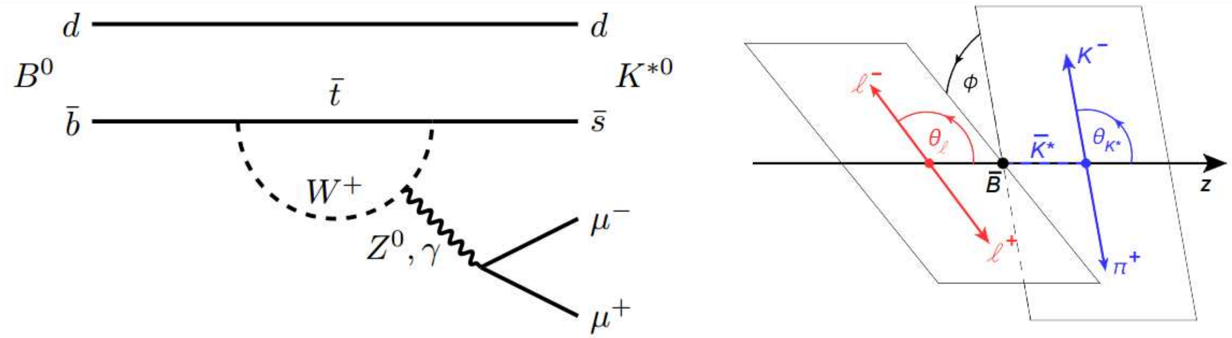
$$R_K \equiv \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B \to K^+e^+e^-)} \quad R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$



$$R_K(SM) = 1.00$$

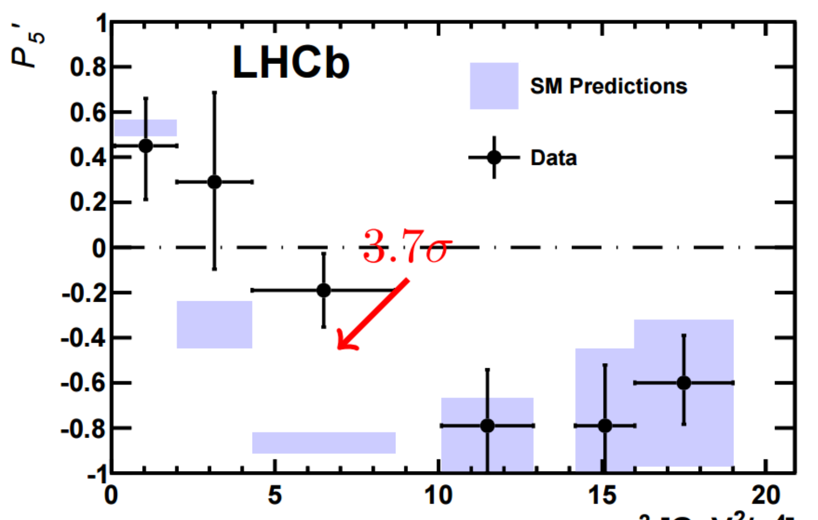
Indicates lepton flavour non-universality

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



Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

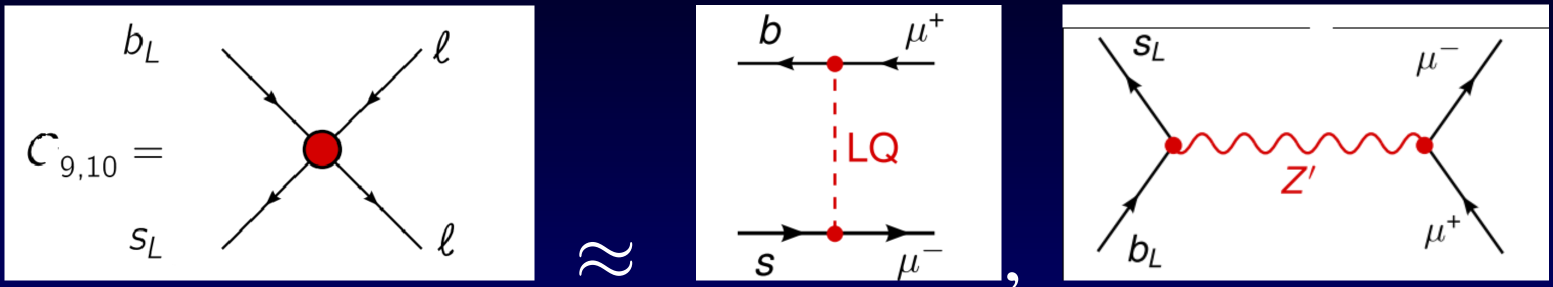
$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\ &- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\ &+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\ &+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\big]\end{aligned}$$



$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading FF uncertainties cancel. Tension already in 1 fb^{-1} and confirmed in 3 fb^{-1} last week

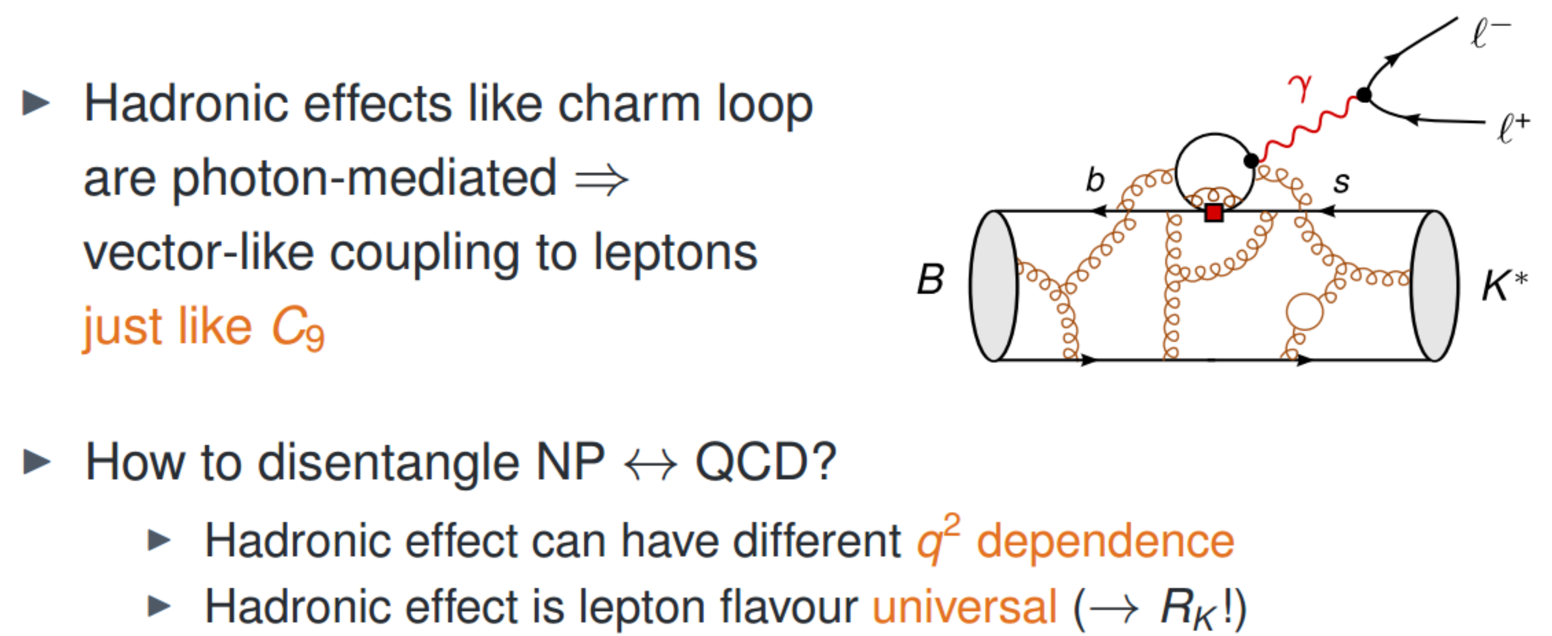
`LHCb-CONF-2015-002`

New Physics: Effective Operators **Altmannshofer, Straub** `arXiv:1411.3161`



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

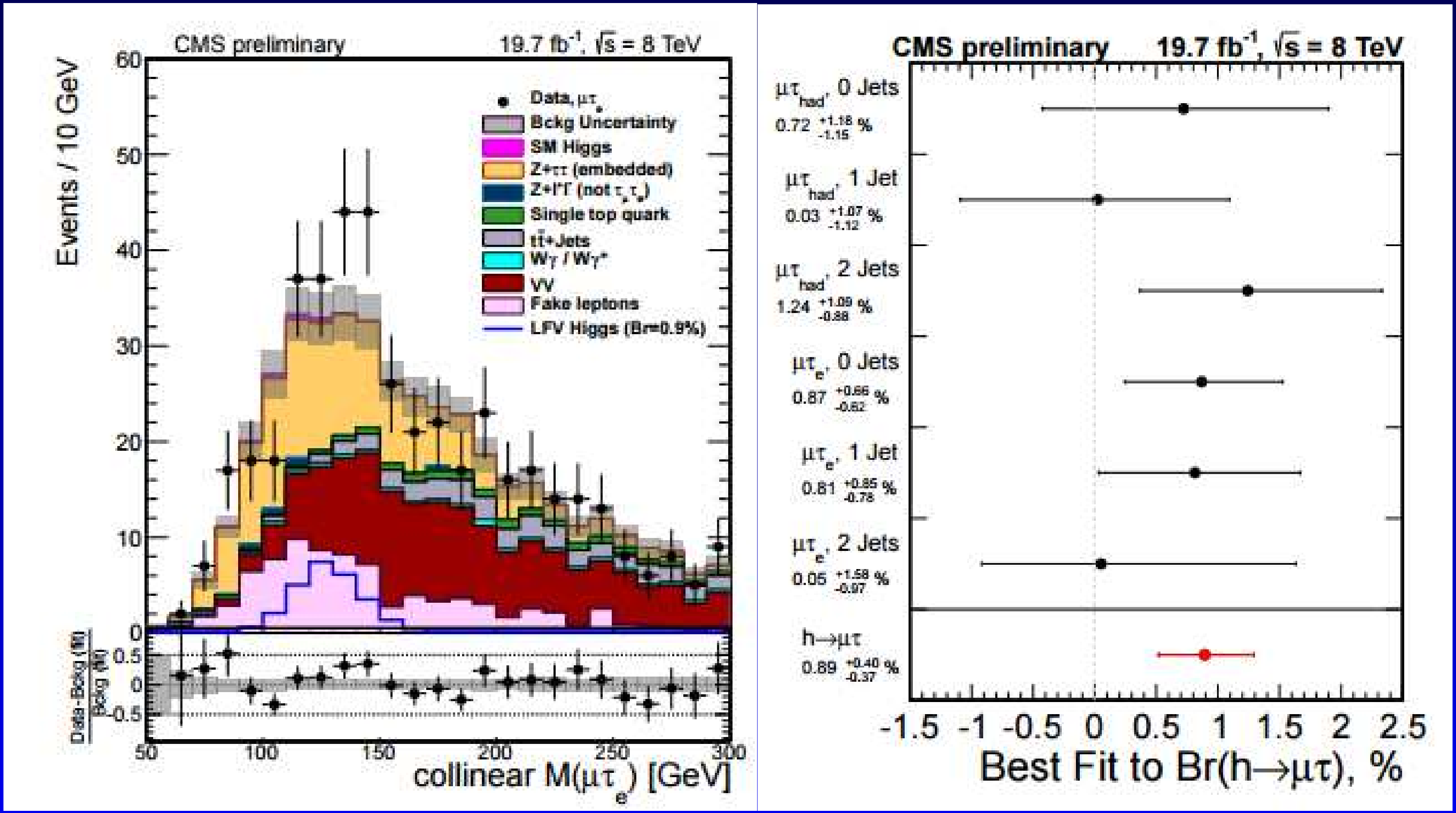
Fitting many operators to 76 $B-$physics observables, a non-zero fit to C_9^μ is preferred at the 4.3σ level.



- Hadronic effects like charm loop are photon-mediated ⇒ vector-like coupling to leptons just like C_9
- How to disentangle NP ↔ QCD?
  - Hadronic effect can have different q^2 dependence
  - Hadronic effect is lepton flavour universal ($\rightarrow R_K$!)

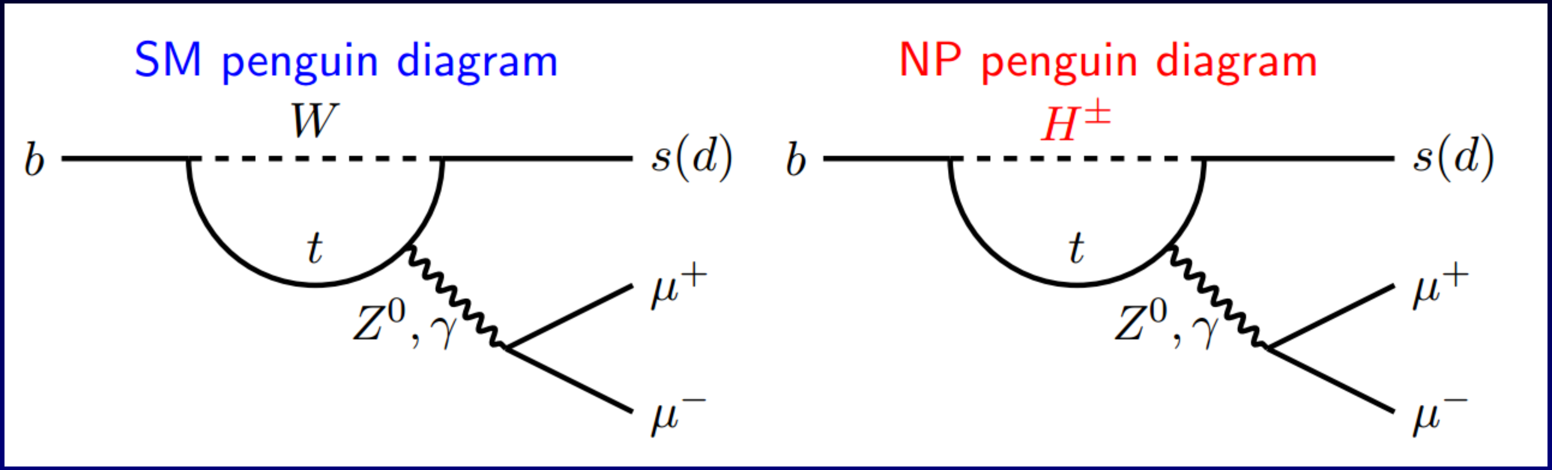
CMS $h \to \tau\mu$: 2.6σ

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



CMS-PAS-HIG-14-005

B Meson Rare Decays



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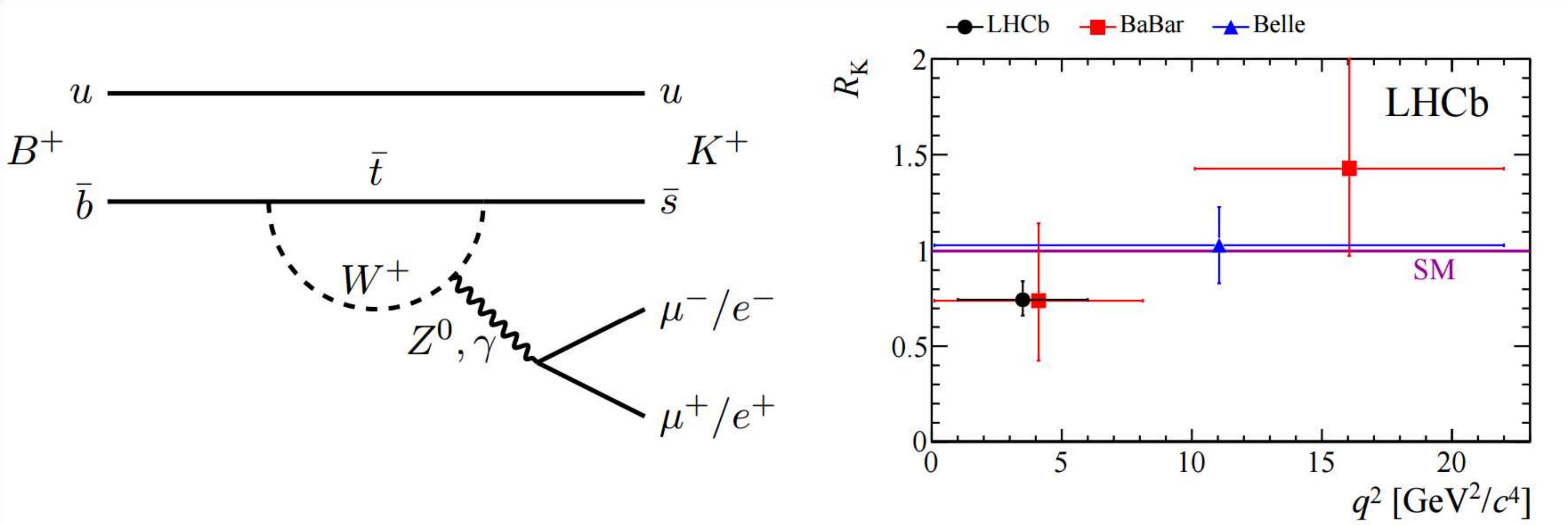

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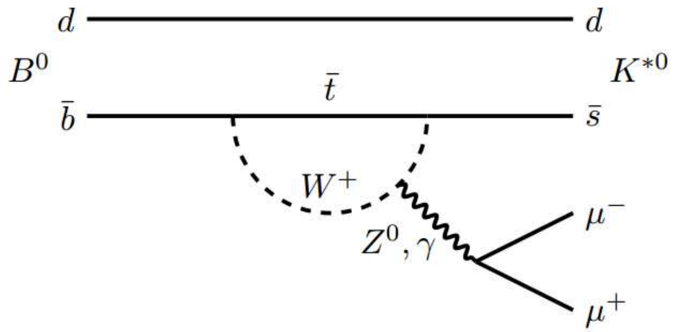

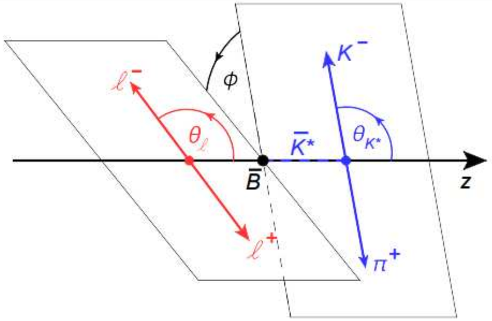

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$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
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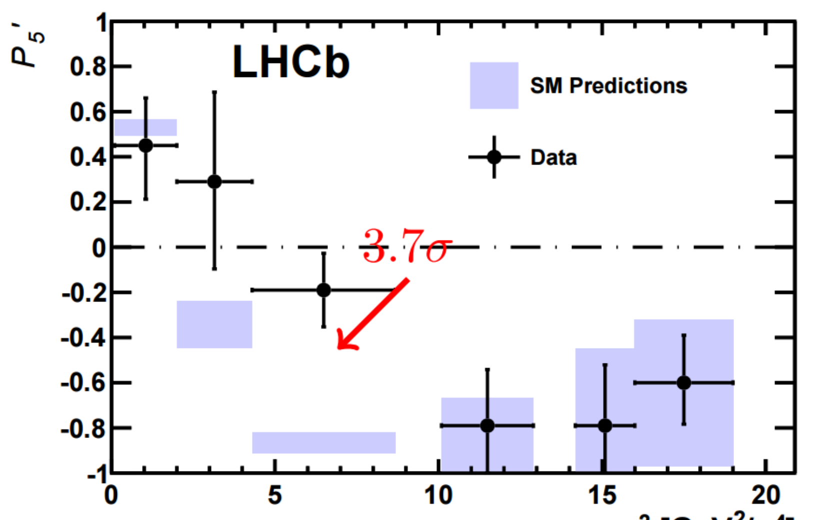

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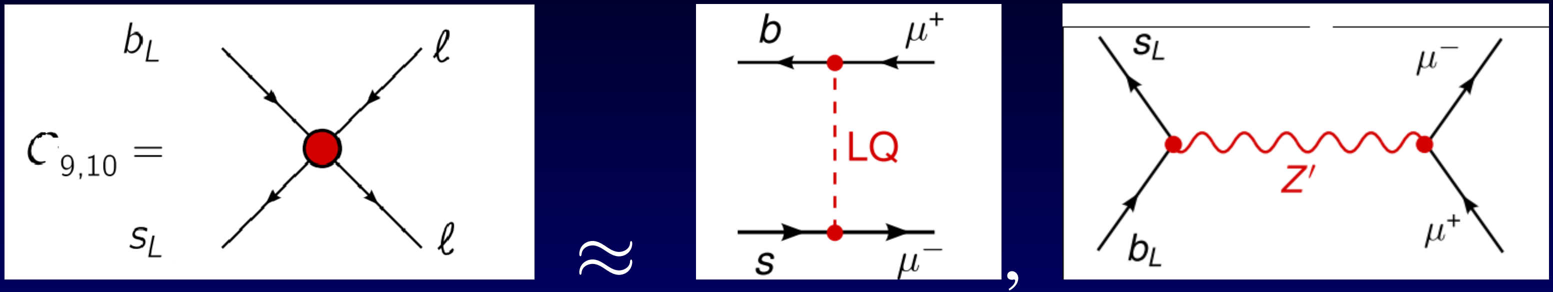
LHCb-CONF-2015-002

New Physics: Effective Operators **Altmannshofer, Straub** `arXiv:1411.3161`



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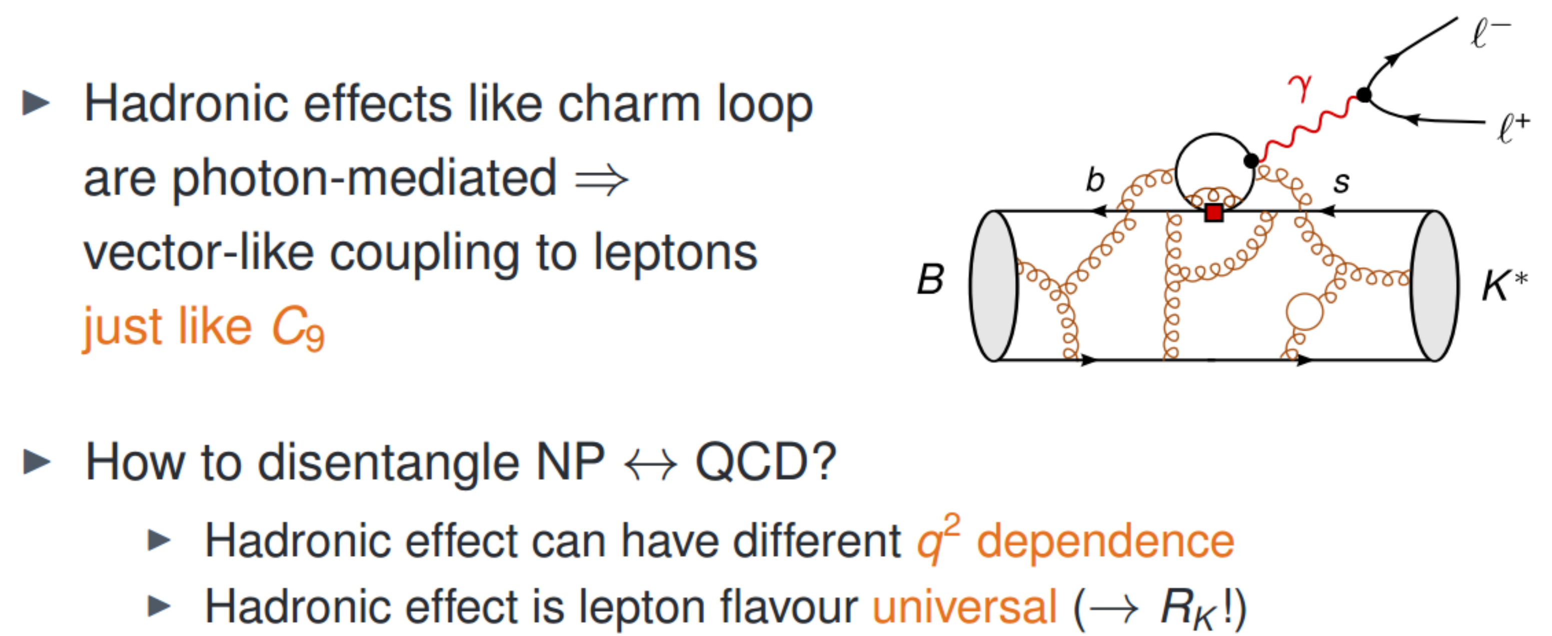

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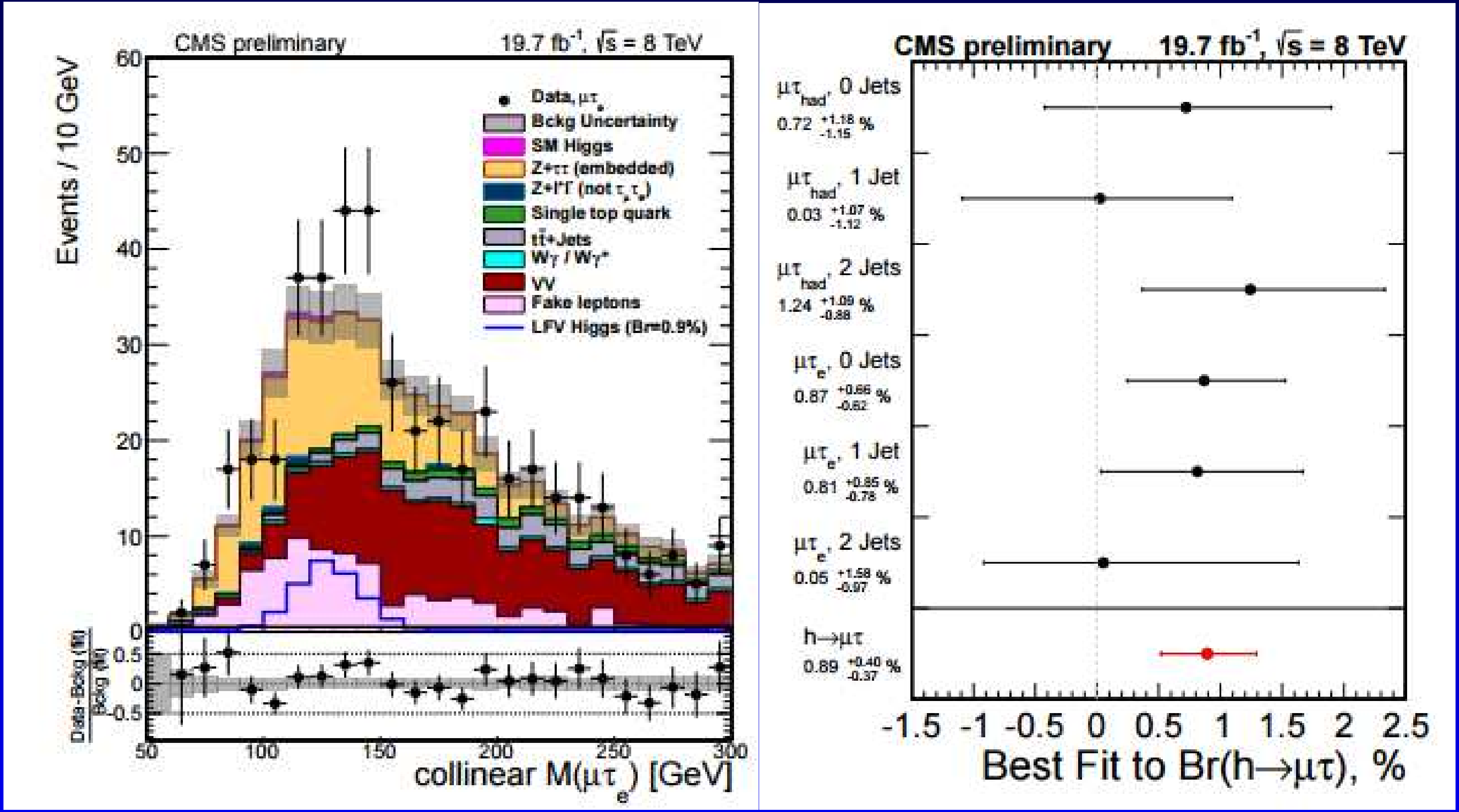

CMS-PAS-HIG-14-005