Explaining CMS Leptons/Jets Excesses With New Physics

Ben Allanach (University of Cambridge)

Talk outline

- Various LHC excesses at the 2.Nσ level
- SUSY explanations
- Non-SUSY explanations

Please ask questions while I'm talking

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

Some CMS Anomalies

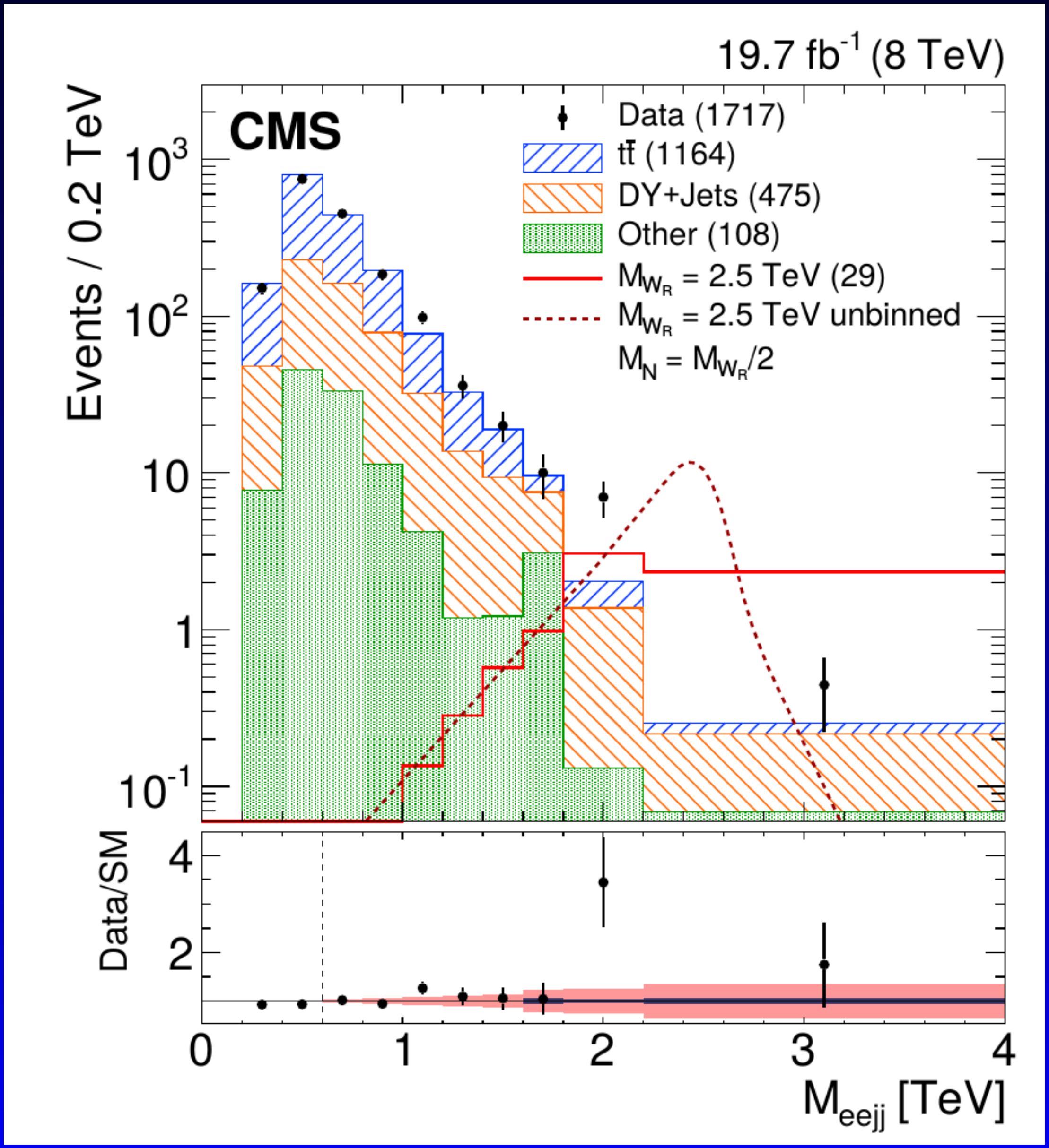
The anomalies were all in 20 fb^{-1} of data taken at 8 TeV.

- One anomaly was in a W_R search
- Two anomalies in a search for di-leptoquark production
- An anomaly in a classic SUSY search $lljj$ missing E_T

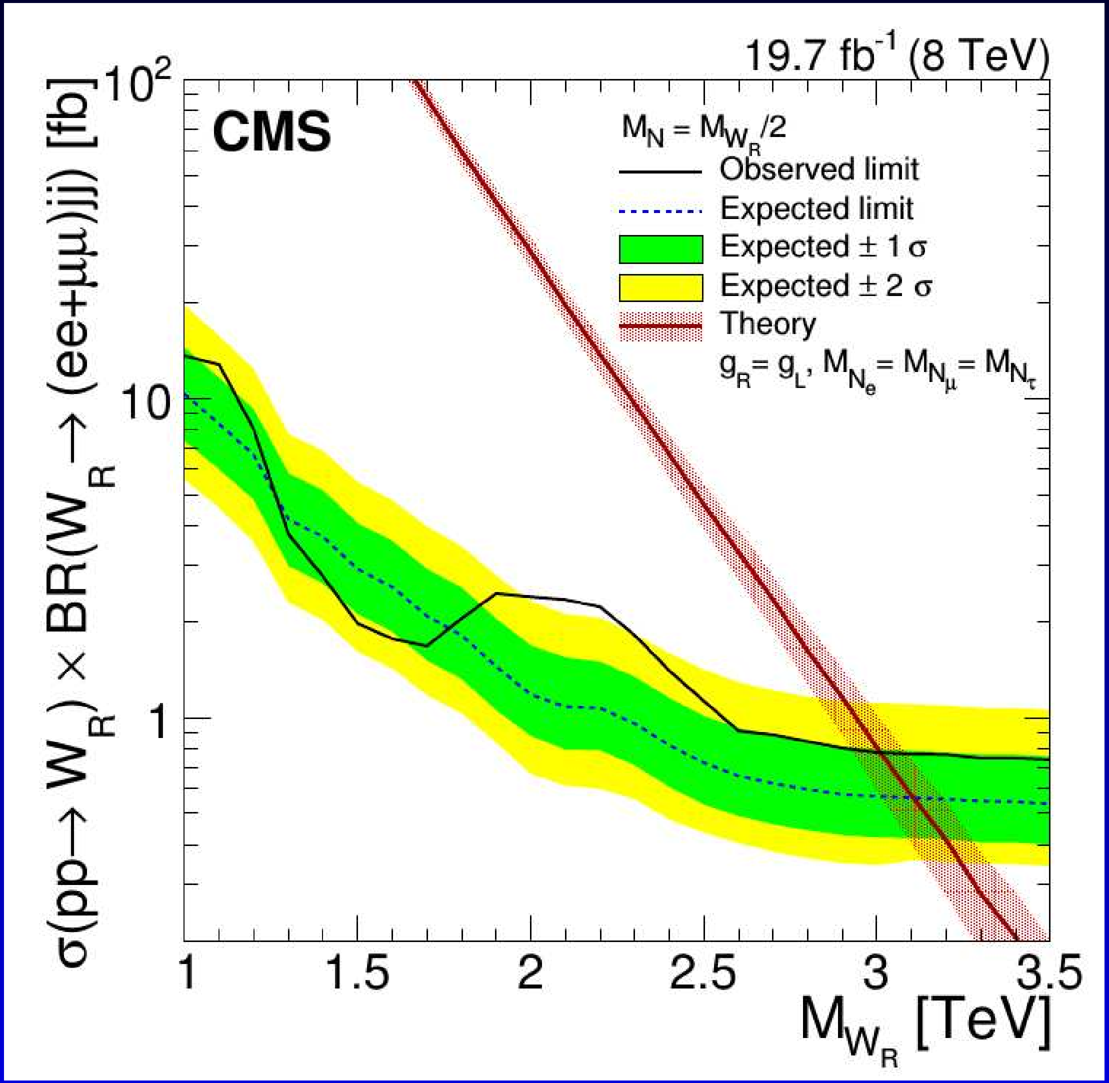
NB We often deal with *invariant masses*, eg

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

CMS $W_R \to l_1 N_l \to l_1 l_2 W_R \to l_1 l_2 q\bar{q}$ Search: **2.8σ**

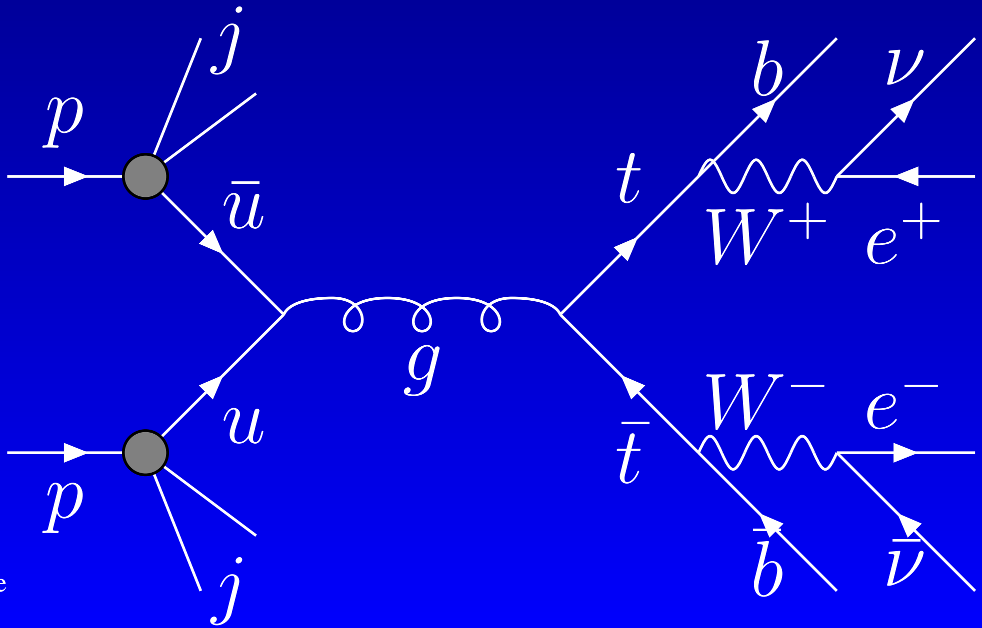


W_R: Inferred Limits



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.

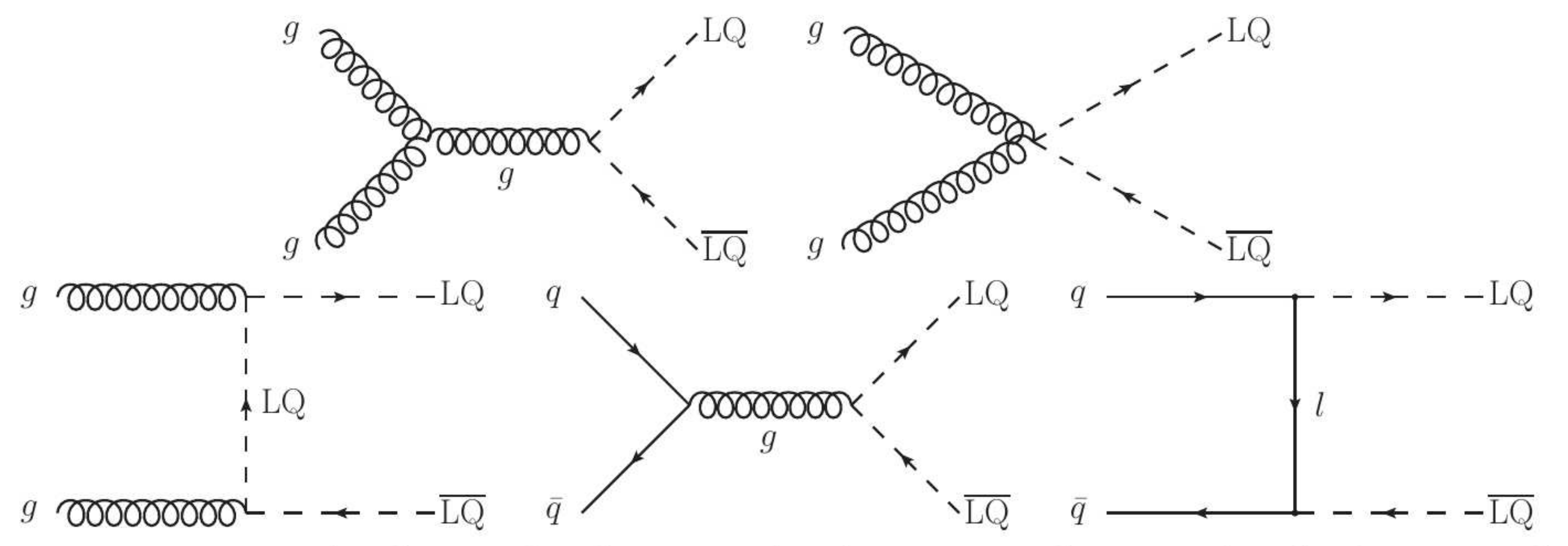


Figure 1: Dominant leading order diagrams for the pair production of scalar leptoquarks.

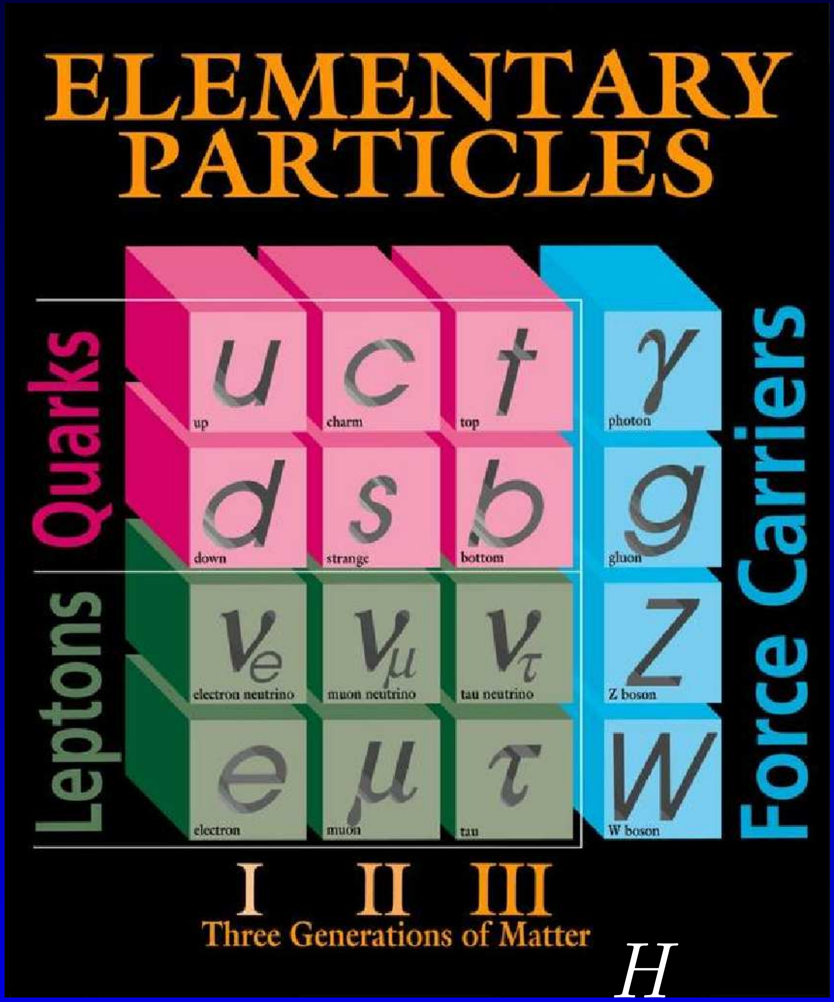
The signals they go for then are:

- $eejj$ 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

Our Proposal

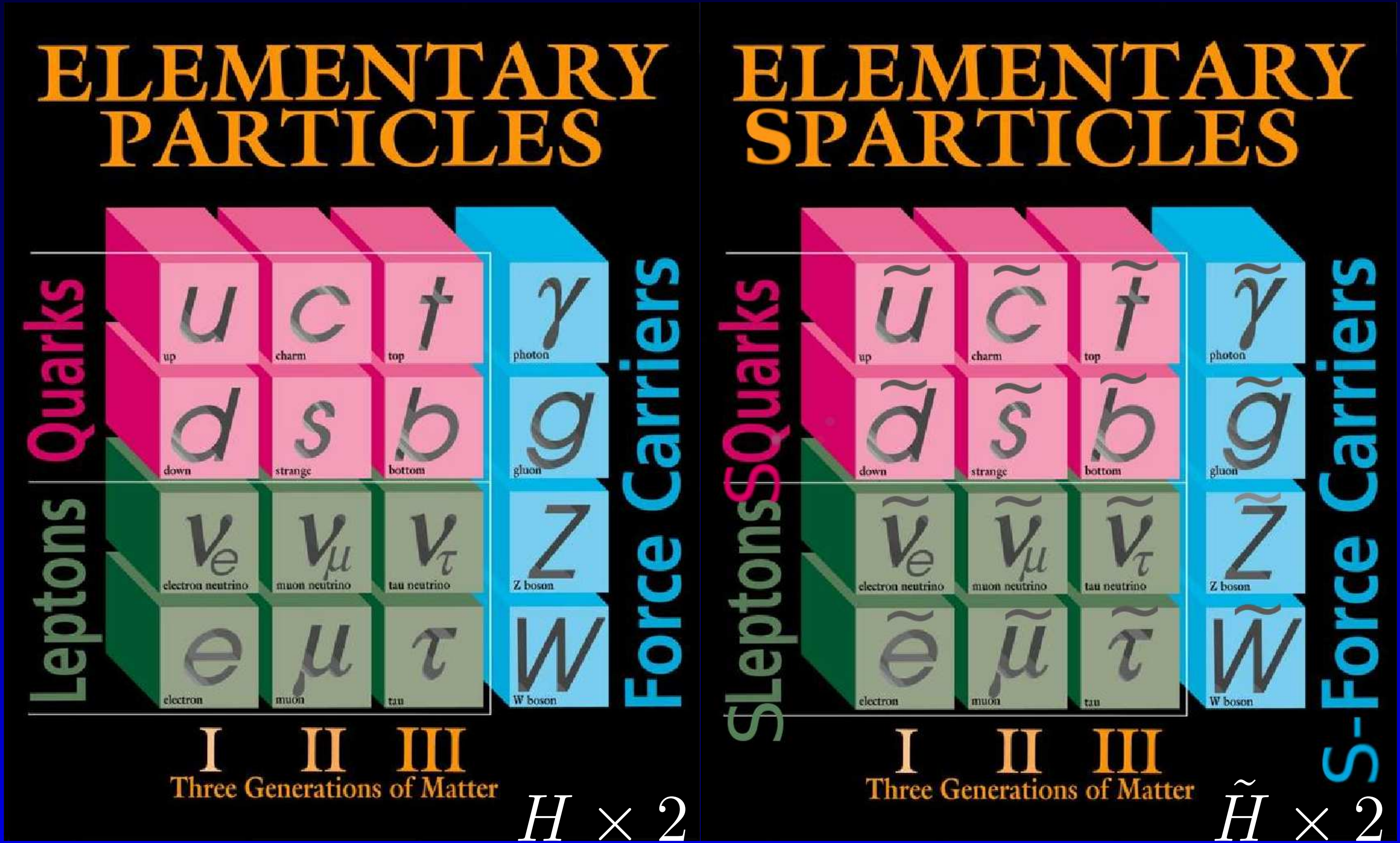
We explain these three excesses with a supersymmetric model with $R-$parity violation in BCA, Biswas, Mondal, Mitra, `arXiv:1408.5439`; *ibid* `arXiv:1410.5947`

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 $W_{\not R_P}$ normally banned?
$\mathcal{A}$: By defining discrete symmetry R_p

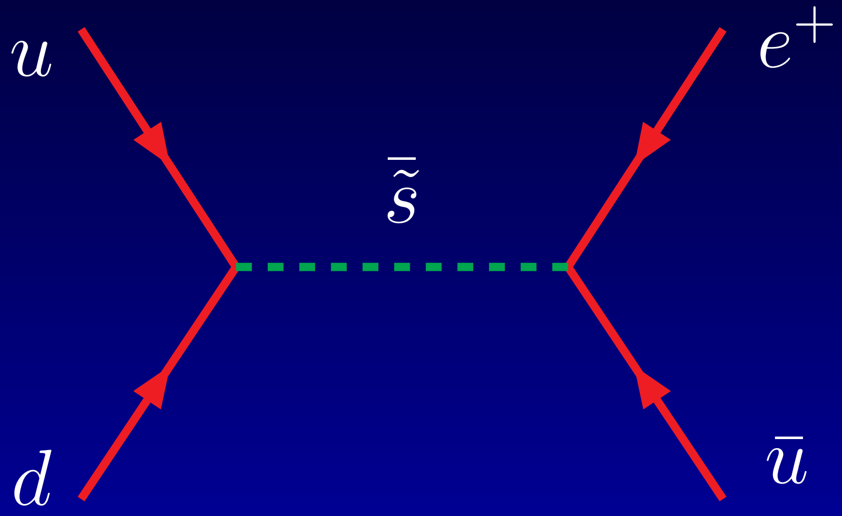
$$R_p = (-\mathbf{1})^{3B+L+2S}.$$

$\rightarrow$ 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

$\not{R}_p$ terms are lepton number L, or baryon number B violating.

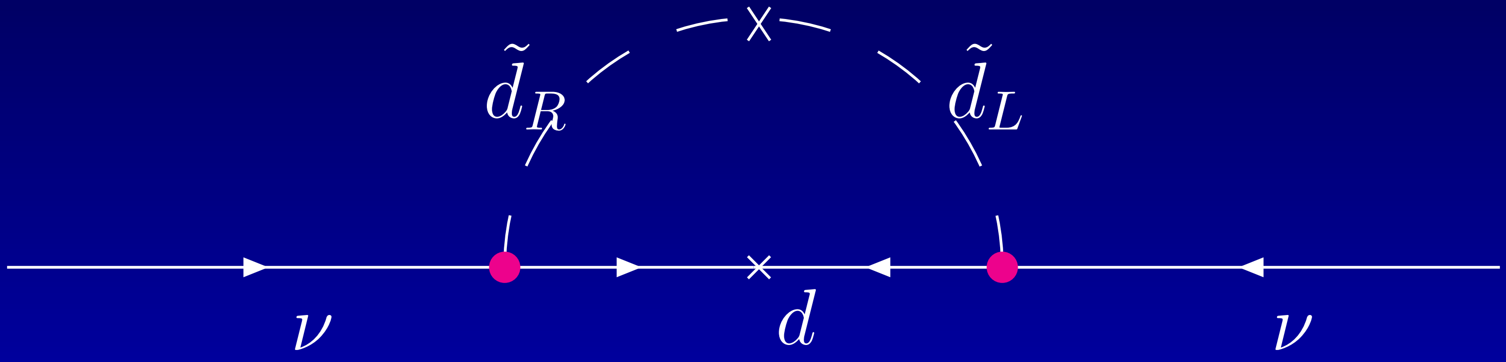


$$\Gamma(p \to e^+\pi^0) \approx \frac{\lambda'^2_{11k}\lambda''^2_{11k}}{16\pi^2 \tilde{m}^4_{d_k}} M^5_{proton}.$$

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

Motivation for $\not{R}_p$

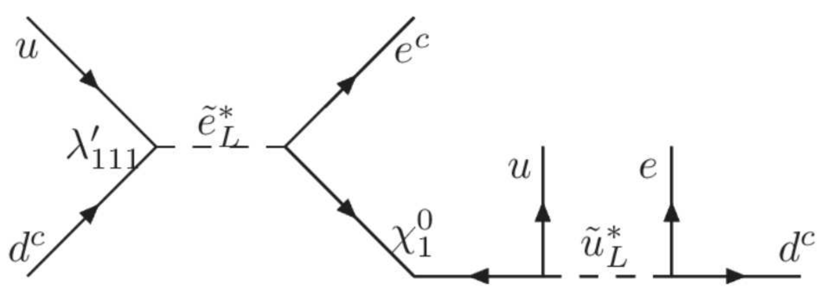
- It has additional search possibilities.
- Neutrino masses and mixings testable at LHC

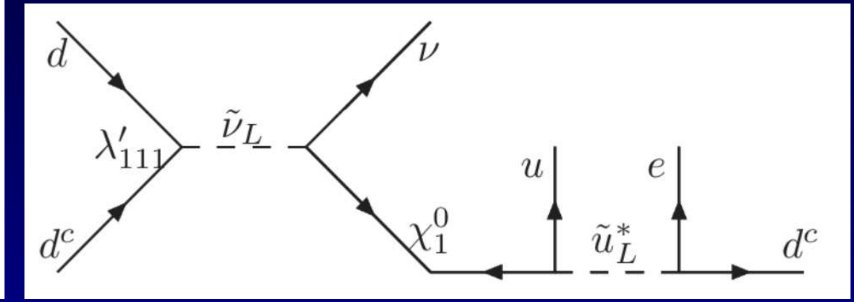


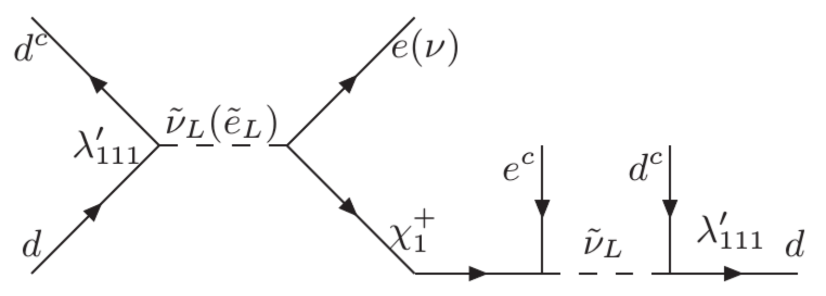
$$(m_\nu)_{11} = \frac{3}{32\pi^2} m_d {\lambda'_{111}}^2 \sin 2\theta_d \ln \frac{m^2_{\tilde{d}_L}}{m^2_{\tilde{d}_R}}$$

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

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







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

With this hypothesis, we can fit the W_R search and the $di - LQ$ searches but *not* the classic SUSY search

Neutralino mass matrix

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

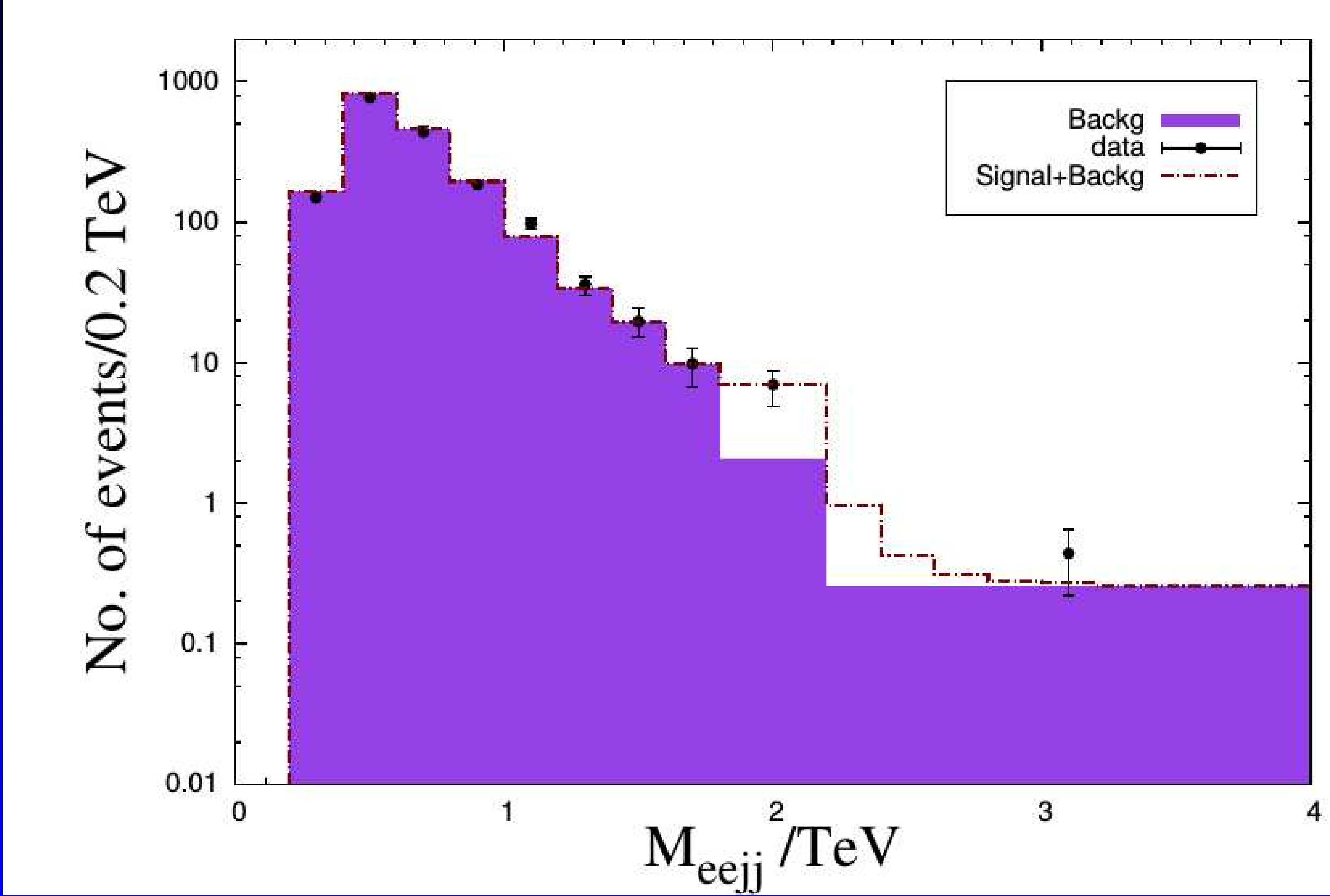
$$\left[\begin{array}{cccc} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{array}\right]$$

Mass eigenstates are labelled χ_1^0, χ_2^0, χ_3^0, χ_4^0 in increasing mass order.

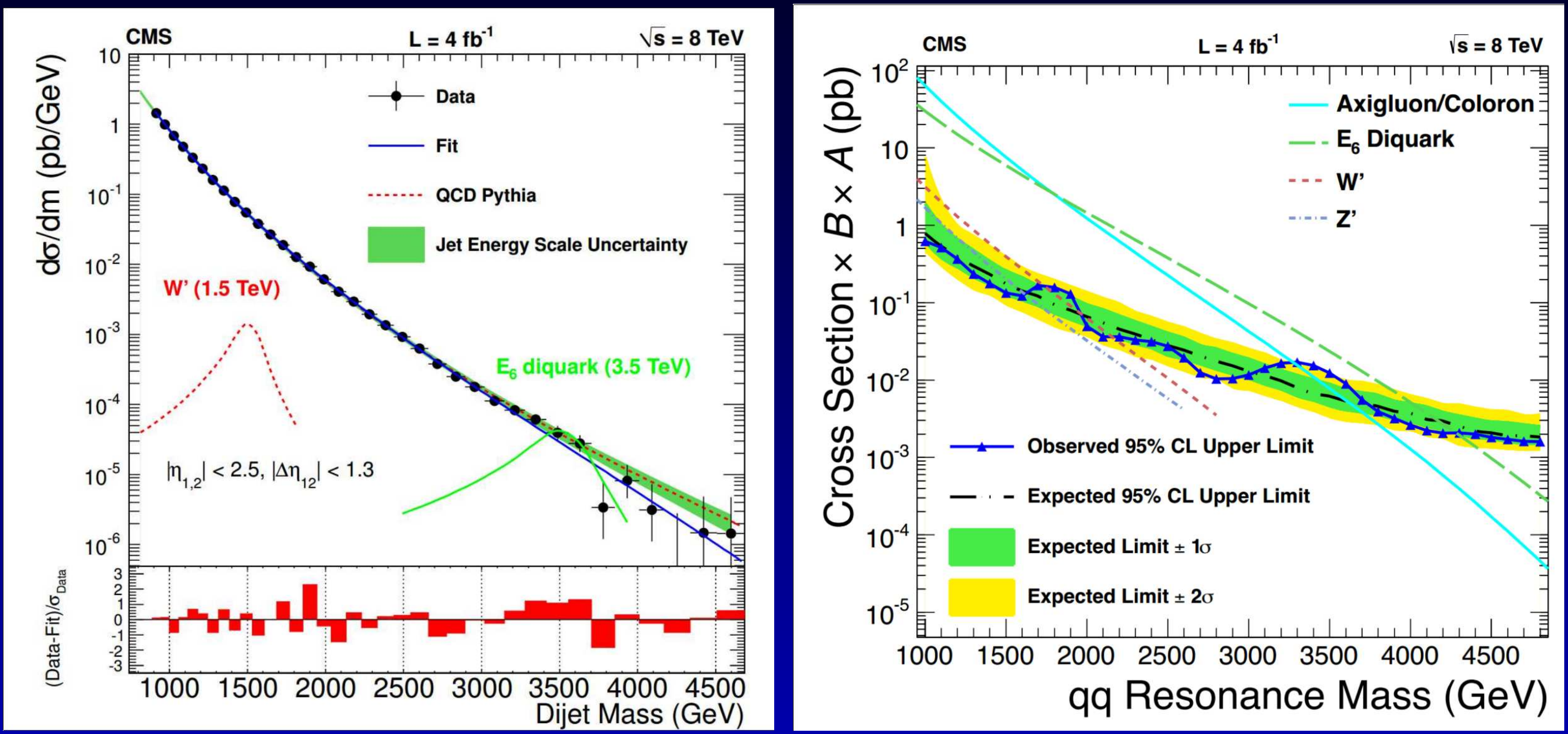
Decays into/from neutralinos are affected by their *composition*.

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

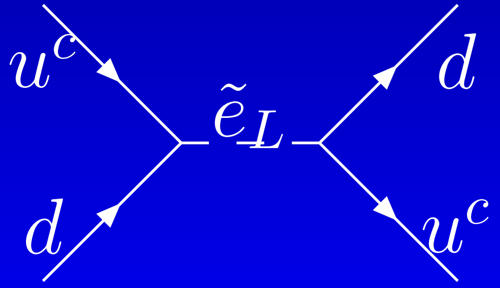
W_R Mass Distribution



Other Constraints

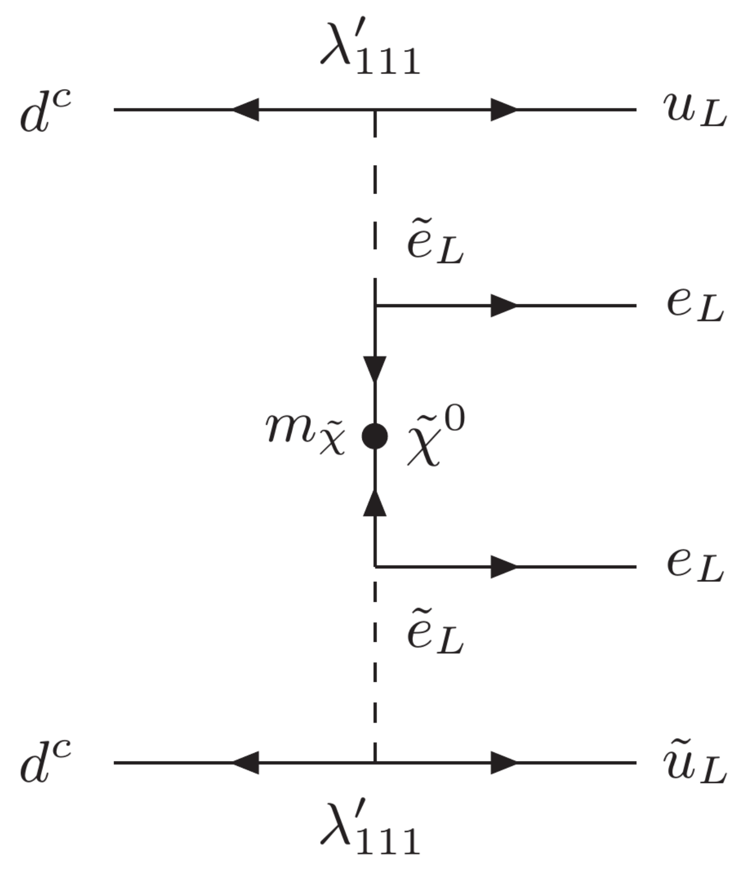


CMS `arXiv:1302.4794`



Neutrinoless Double Beta Decay

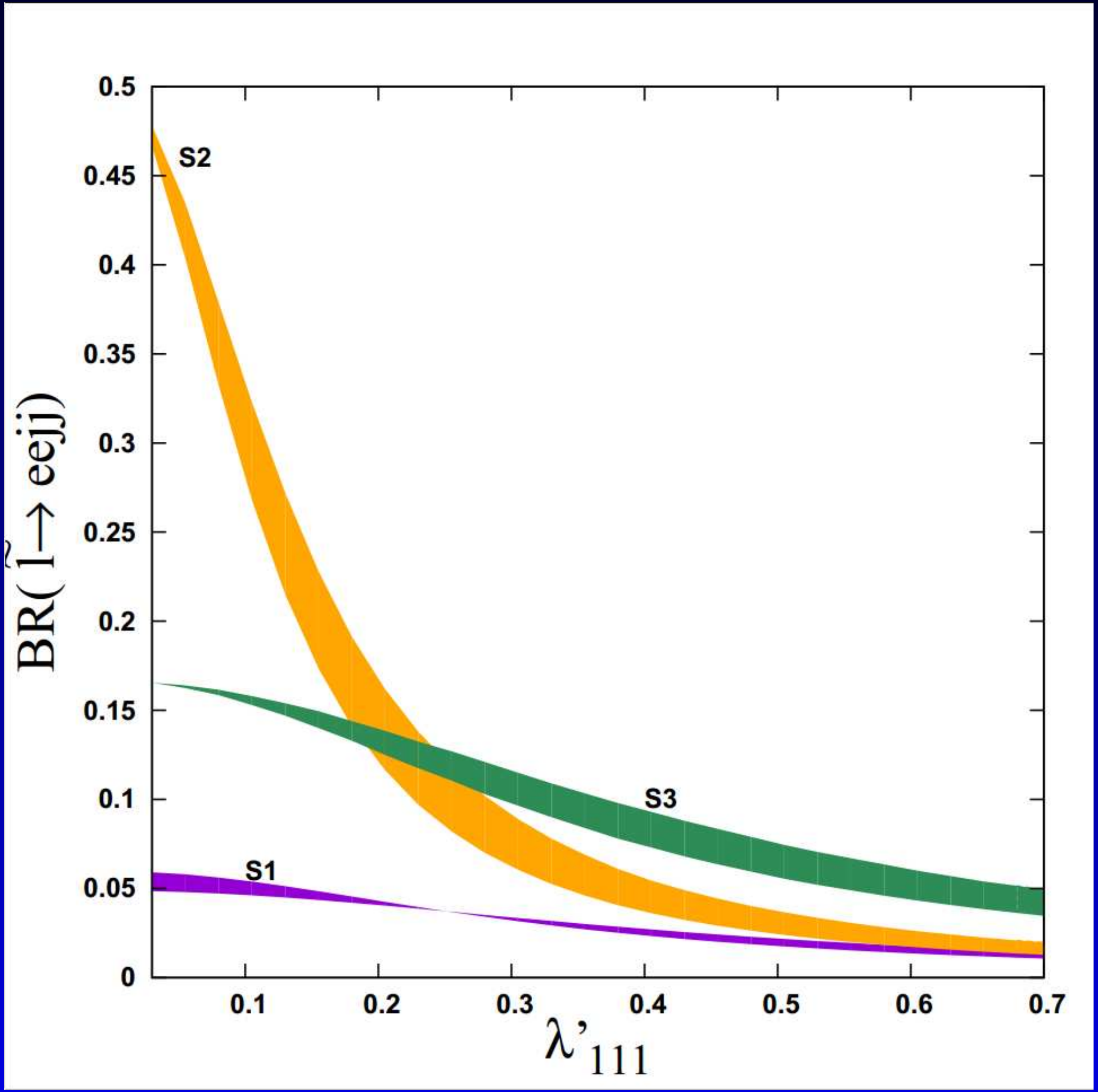
Is *banned* in the Standard Model because it breaks lepton number: $Z \to (Z+2)e^- e^-$ Present bound from GERDA is $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr. It should increase by a factor 10 in the next year or so.



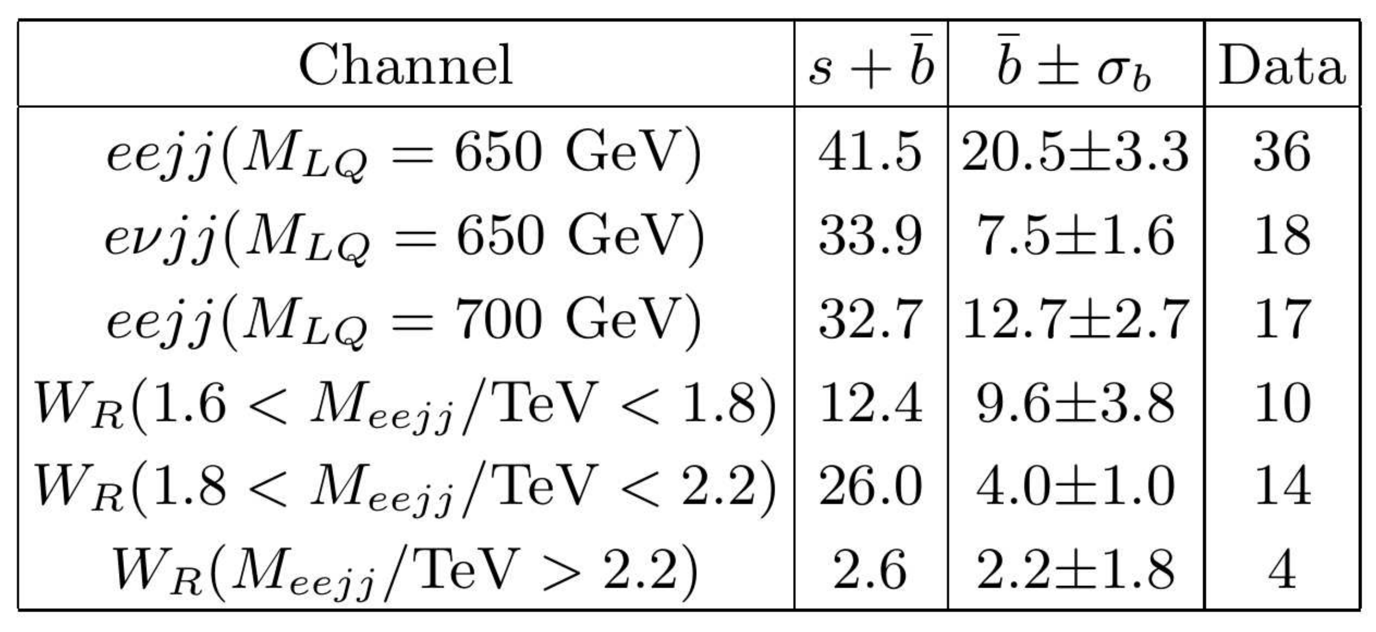
Three Neutralino Scenarios

- **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



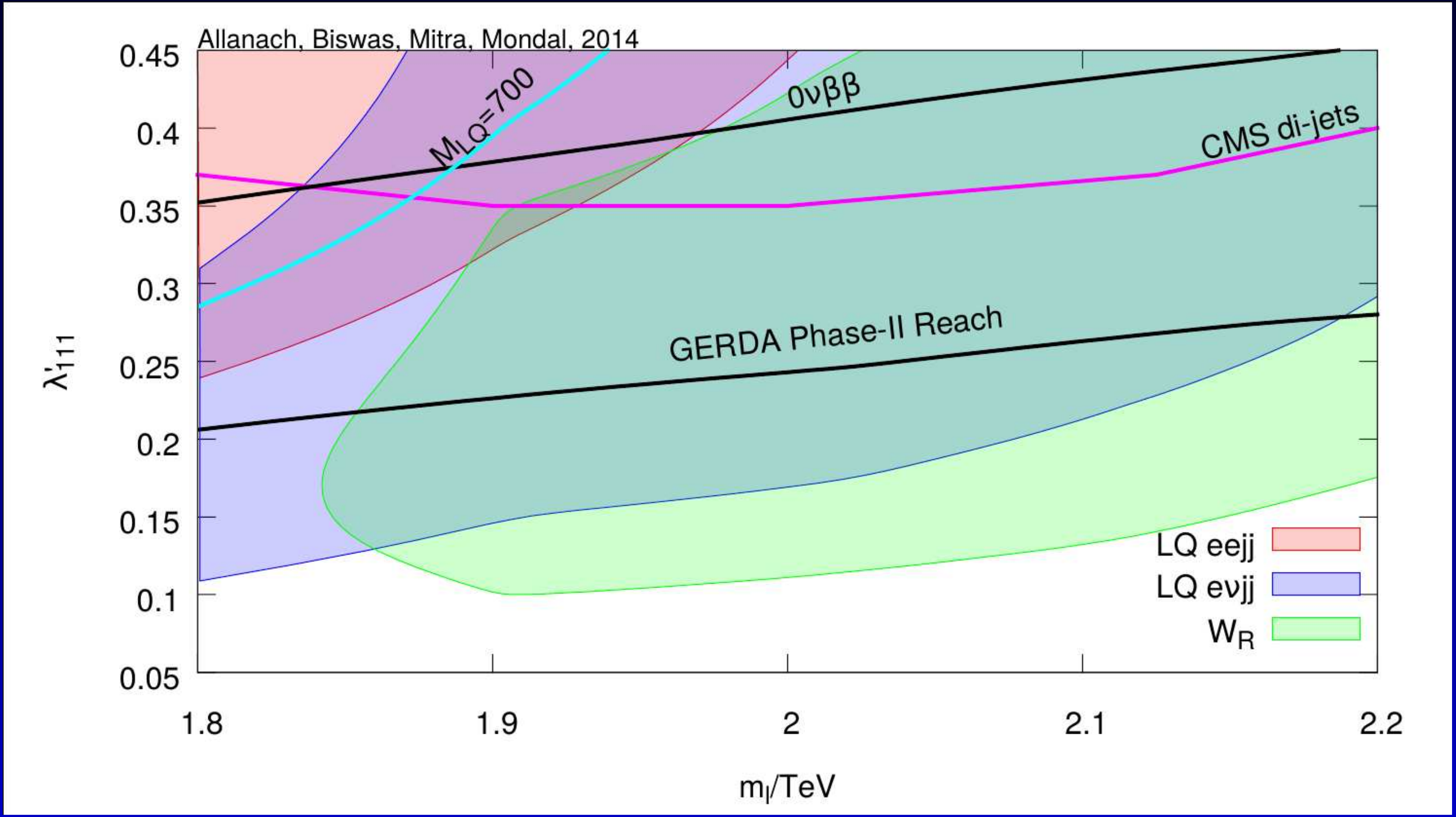
Event Numbers



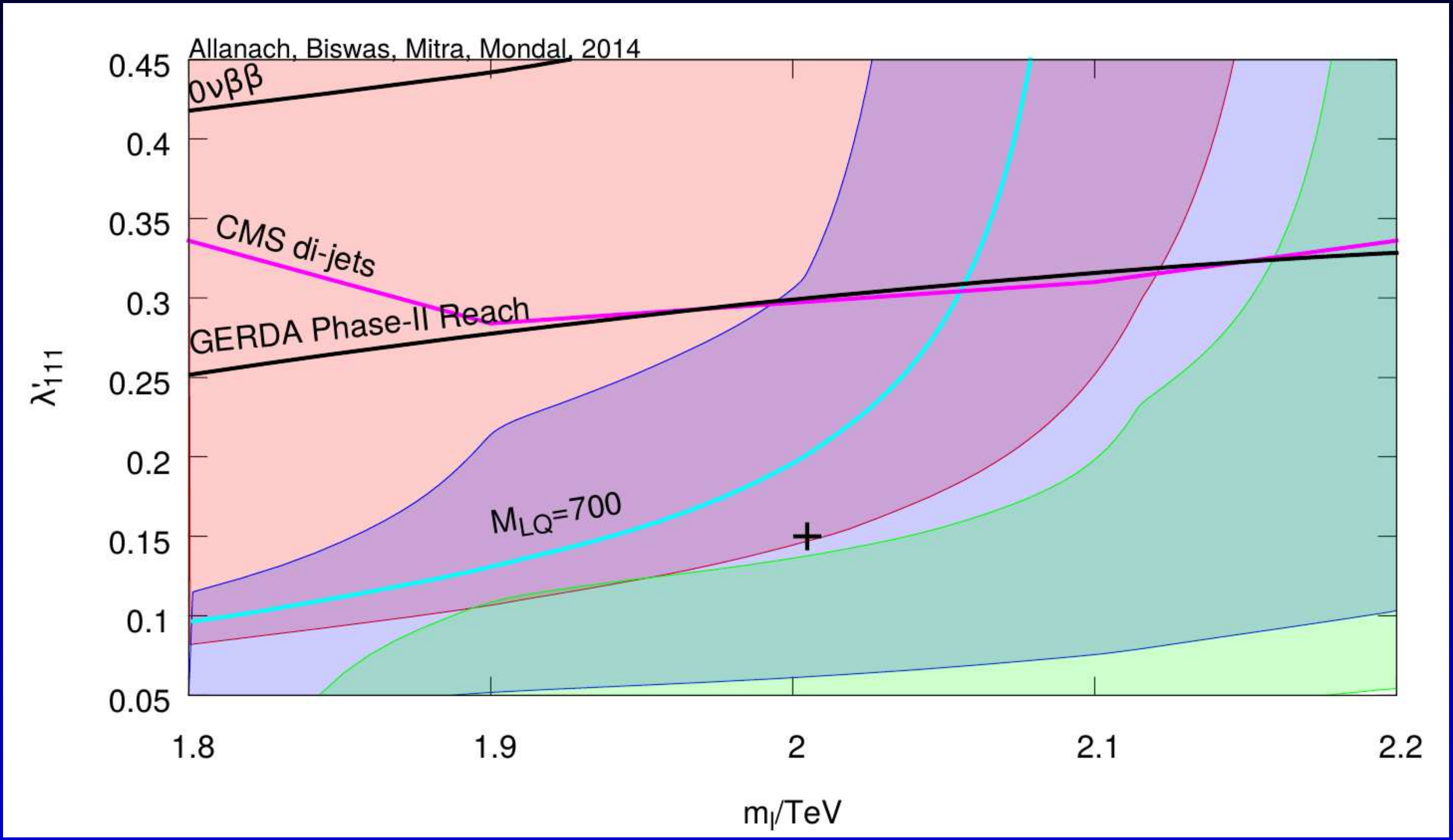
Channel	$s+\bar{b}$	$\bar{b} \pm \sigma_b$	Data
$eejj(M_{LQ} = 650 \text{ GeV})$	41.5	20.5±3.3	36
$e\nu jj(M_{LQ} = 650 \text{ GeV})$	33.9	7.5±1.6	18
$eejj(M_{LQ} = 700 \text{ GeV})$	32.7	12.7±2.7	17
$W_R(1.6 < M_{eejj}/\text{TeV} < 1.8)$	12.4	9.6±3.8	10
$W_R(1.8 < M_{eejj}/\text{TeV} < 2.2)$	26.0	4.0±1.0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

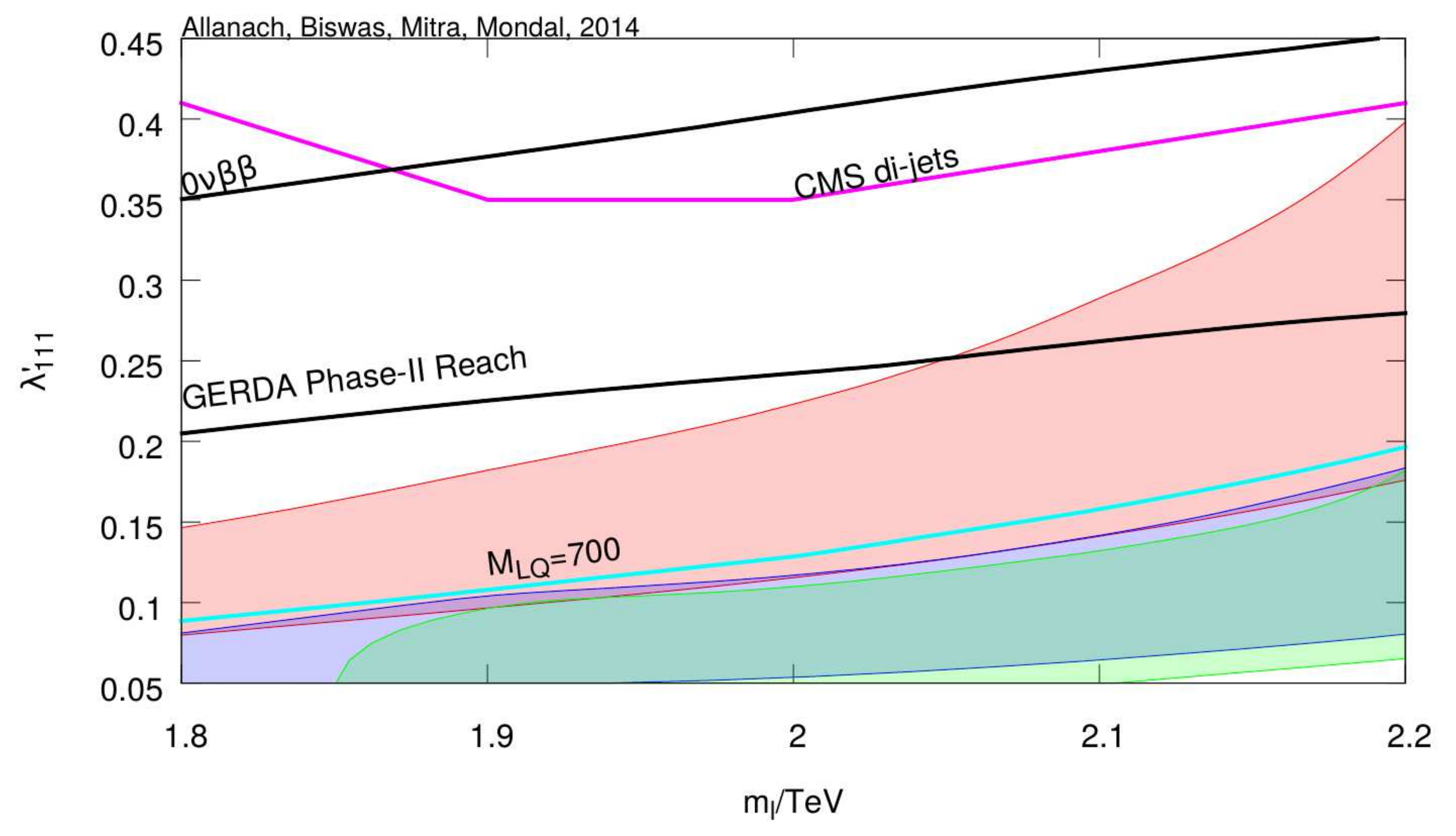
Parameter Space: S1



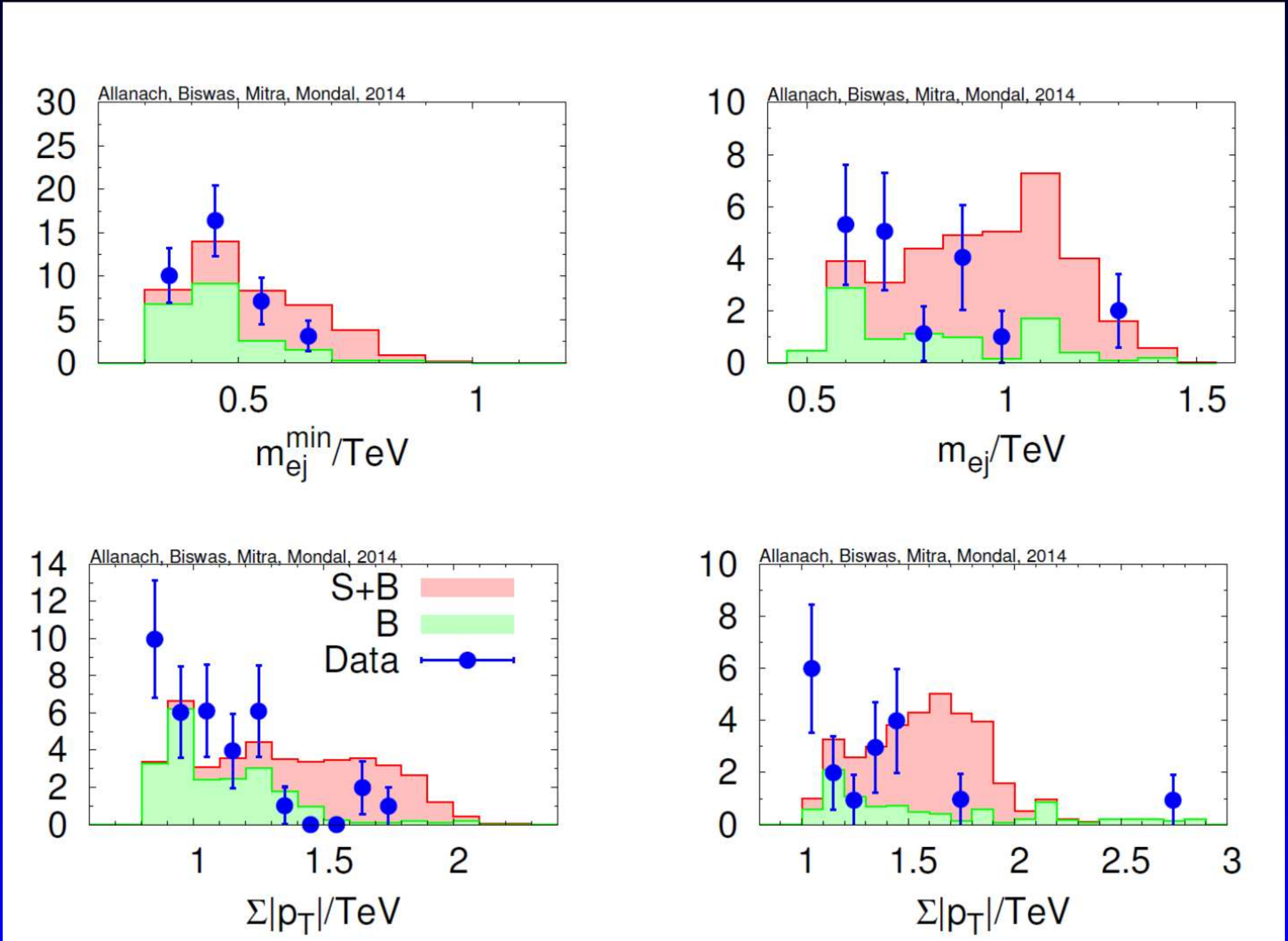
Parameter Space: S2



Parameter Space: S3



Kinematical Distributions: LQ



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: R_p MSSM

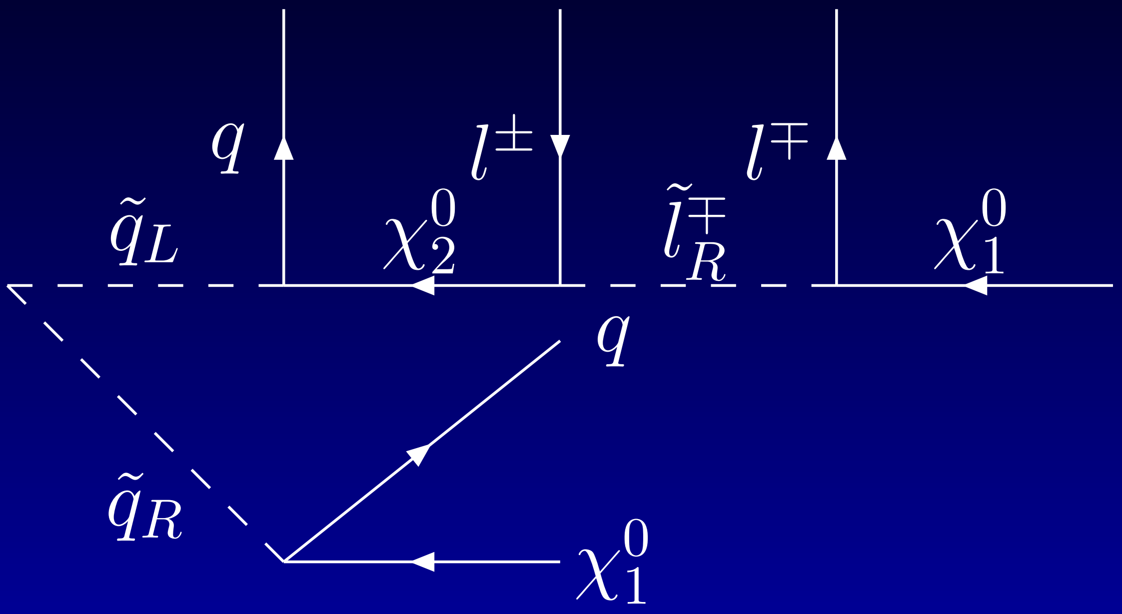
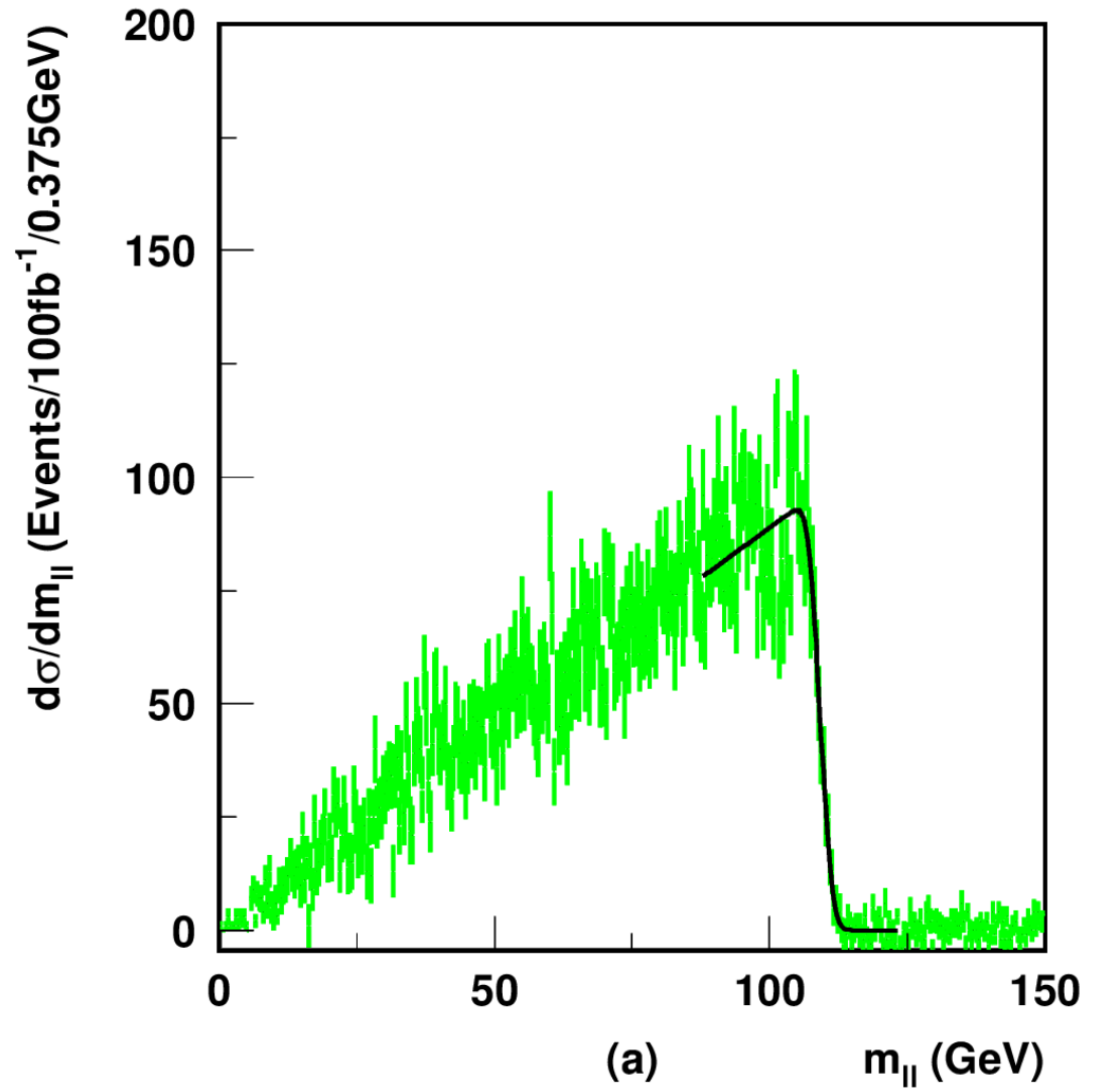


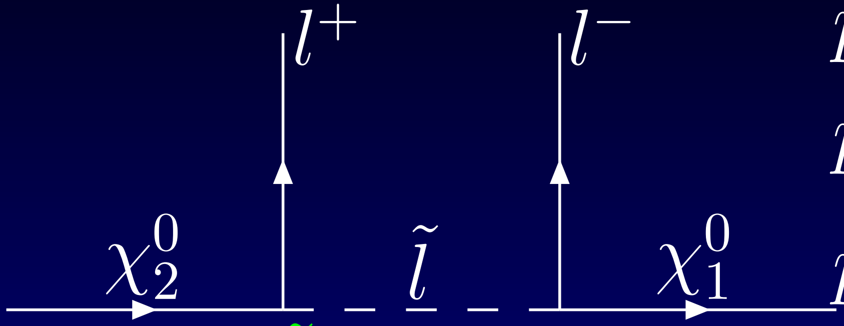
Figure 1: Feynman diagram for the golden cascade decay: opposite sign same flavour leptons (OSSF)

Simplified model: Decouple all sparticles not needed. Important mass parameters: M_1, M_2, $m_{\tilde{q}}$, $m_{\tilde{l}_L} = 2m_{\tilde{l}_R}$. Fix $\tan\beta = 10$ for now.

A Sharp Invariant Feature



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

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

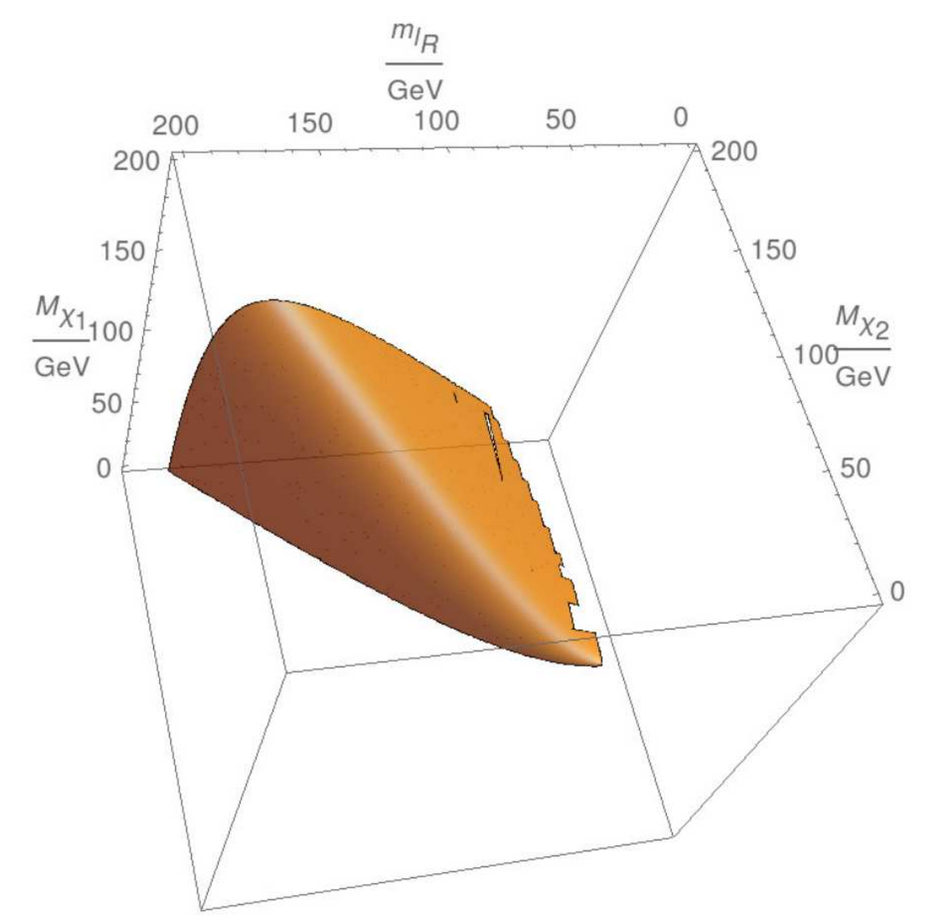
Momentum conservation:

$$\Rightarrow \underline{p}_{\chi^0_2} + \underline{p}_{l^+} = \underline{0}, \qquad \underline{p}_{l^-} + \underline{p}_{\chi^0_1} = \underline{0}.$$

Energy conservation: $\sqrt{{m_{\chi^0_2}}^2 + |\underline{p}_{\chi^0_2}|^2} = m_{\tilde{l}} + |\underline{p}_{l^+}|$,

$$\Rightarrow |\underline{p}_{l^+}| = \frac{m^2_{\chi^0_2} - m^2_{\tilde{l}}}{2m_{\tilde{l}}}.$$ Similarly $$|\underline{p}_{l^-}| = \frac{m^2_{\tilde{l}} - m^2_{\chi^0_1}}{2m_{\tilde{l}}}.$$

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

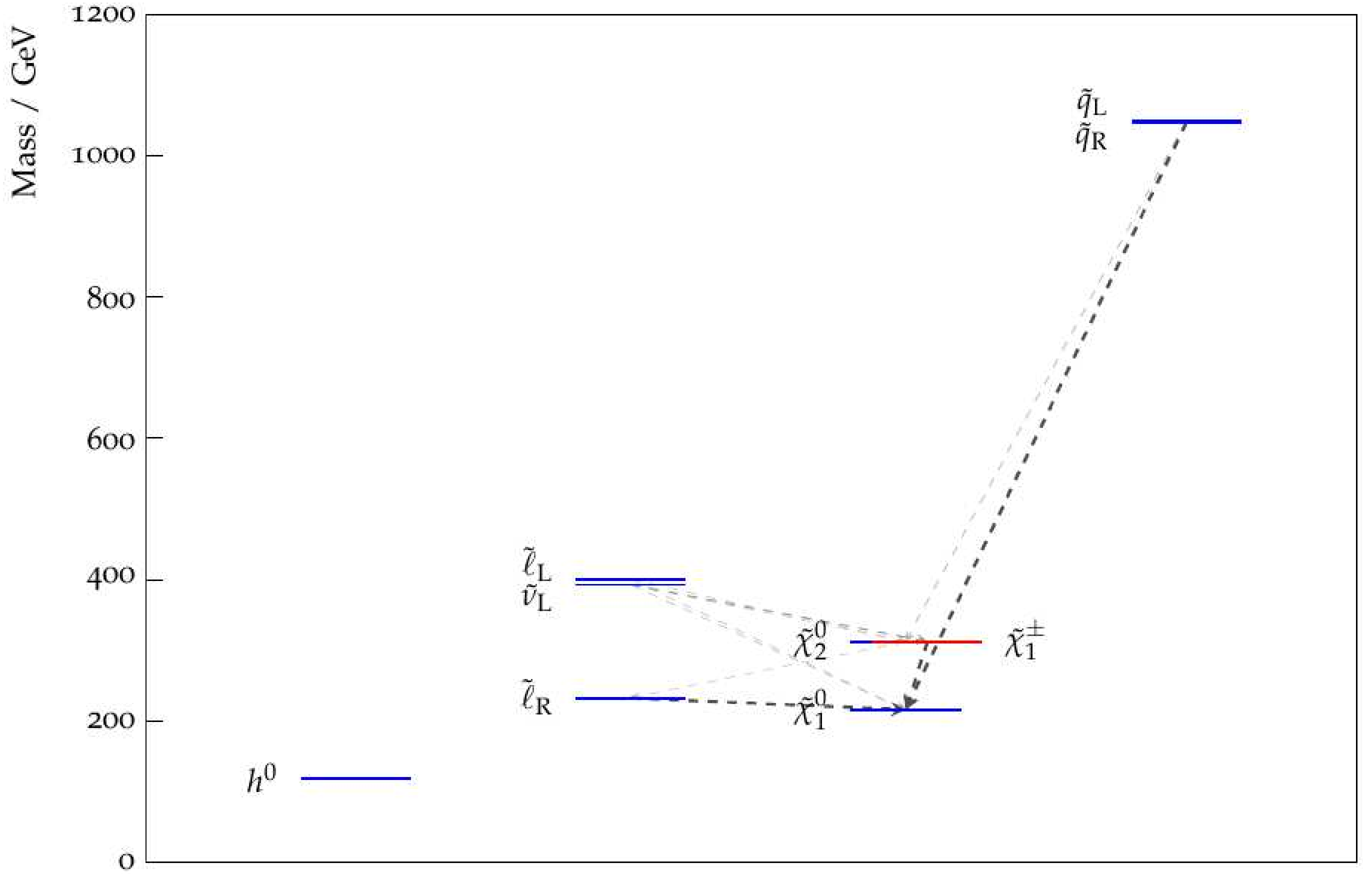
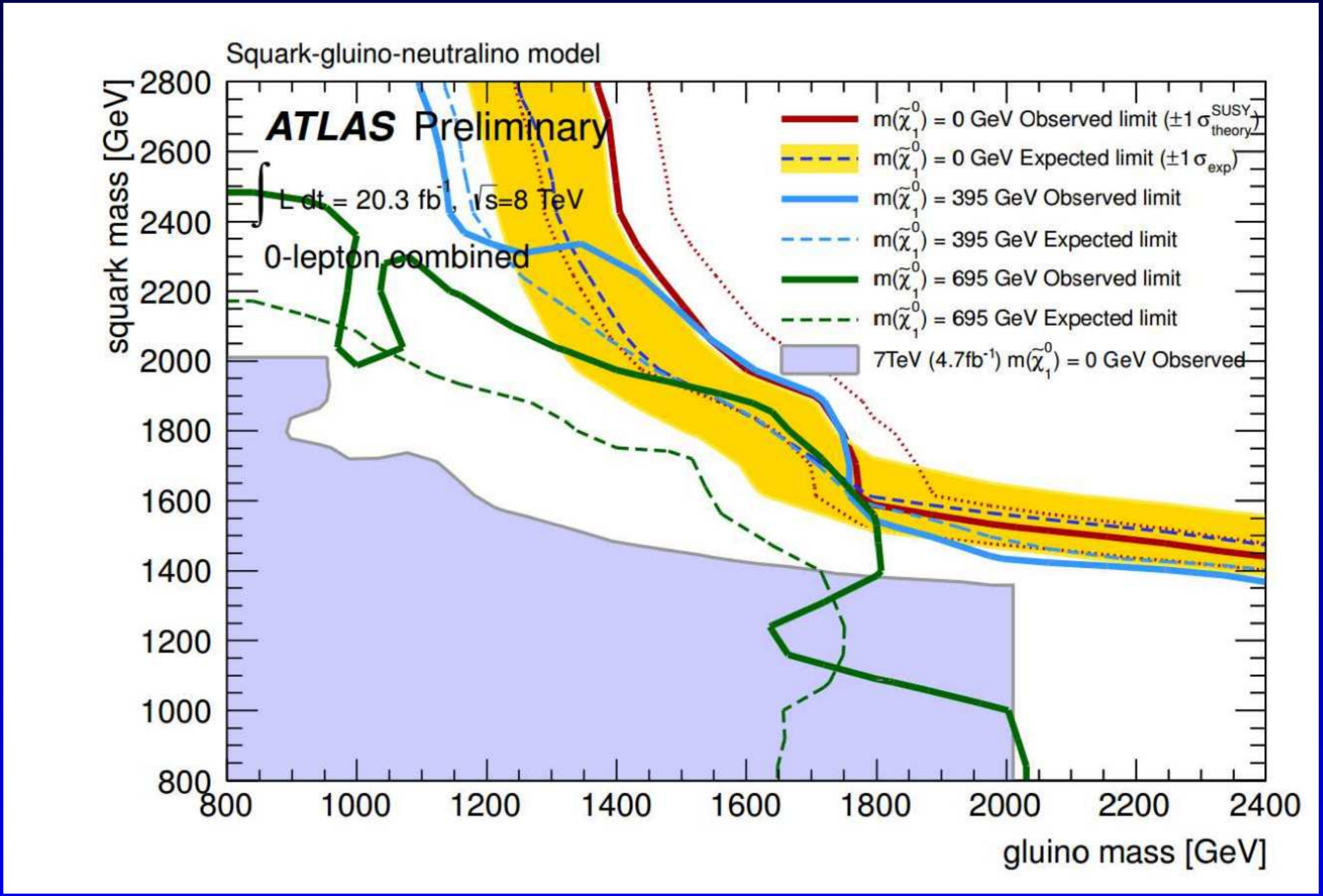


FIG. 4. Example signal point that fits the central CMS rate and edge inferences: $M_2 = 300$ GeV, $m_{\tilde{l}_R} = 200$ GeV, $m_{\tilde{q}} = 1050$ GeV. Prominent decays with branching ratios higher than 10% are shown as arrows.

LHC Constraints

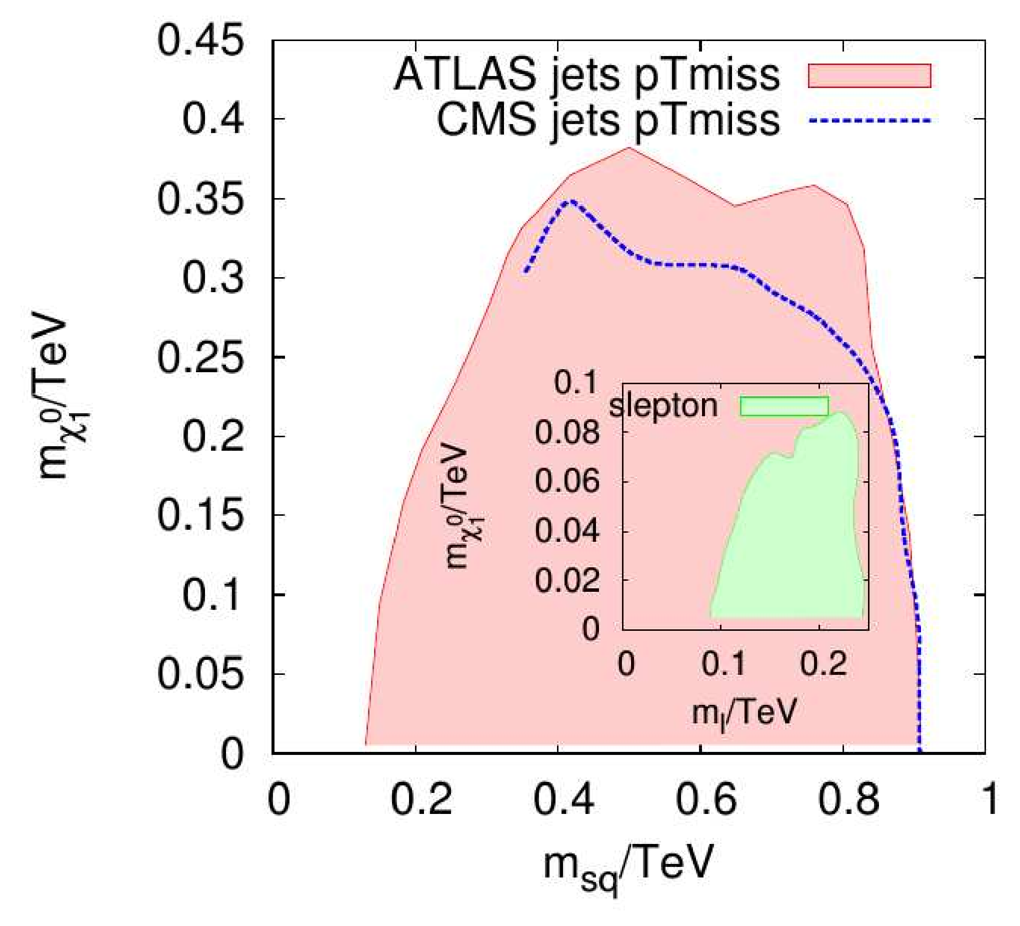
We shall see squark masses of around a TeV being predicted.



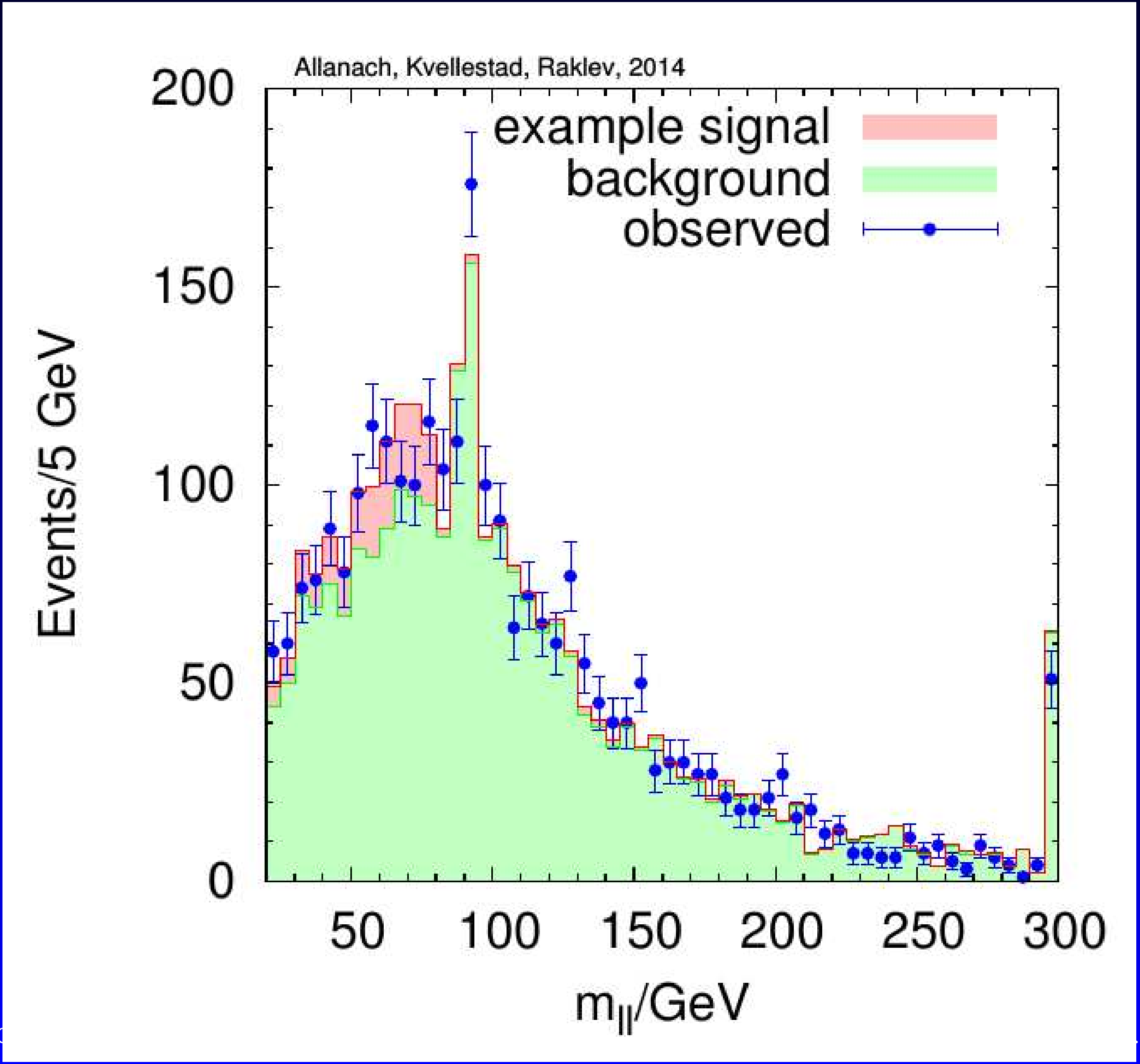
Other Constraints

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

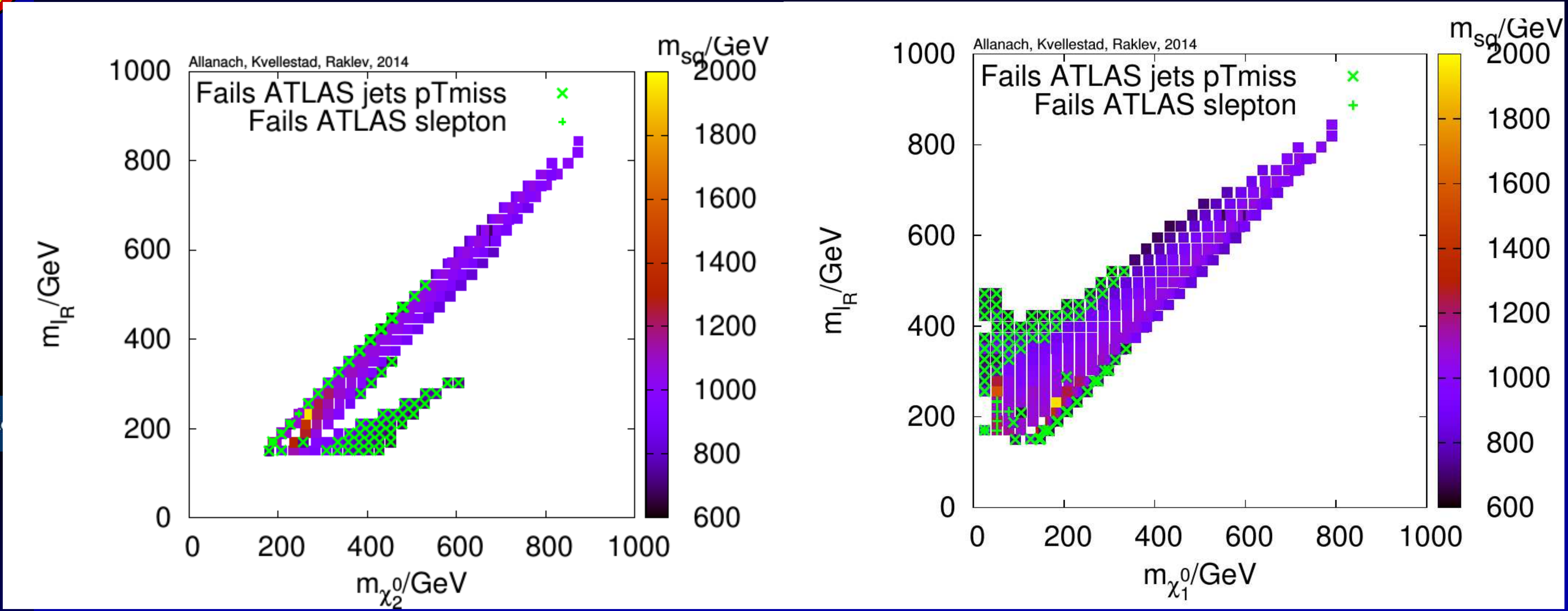
ATLAS(2014), `arXiv:1405.7875`; CMS JHEP **1406** (2014) 055, `arXiv:1402.4770`.



m_{ll} Distribution



Viable Parameter Space

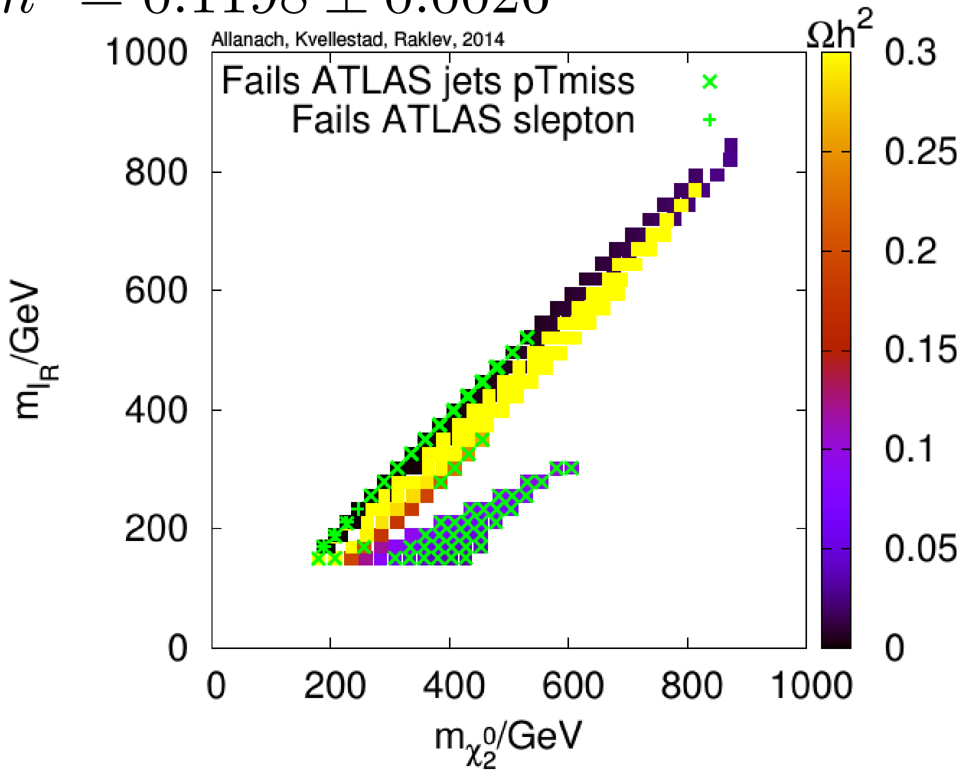


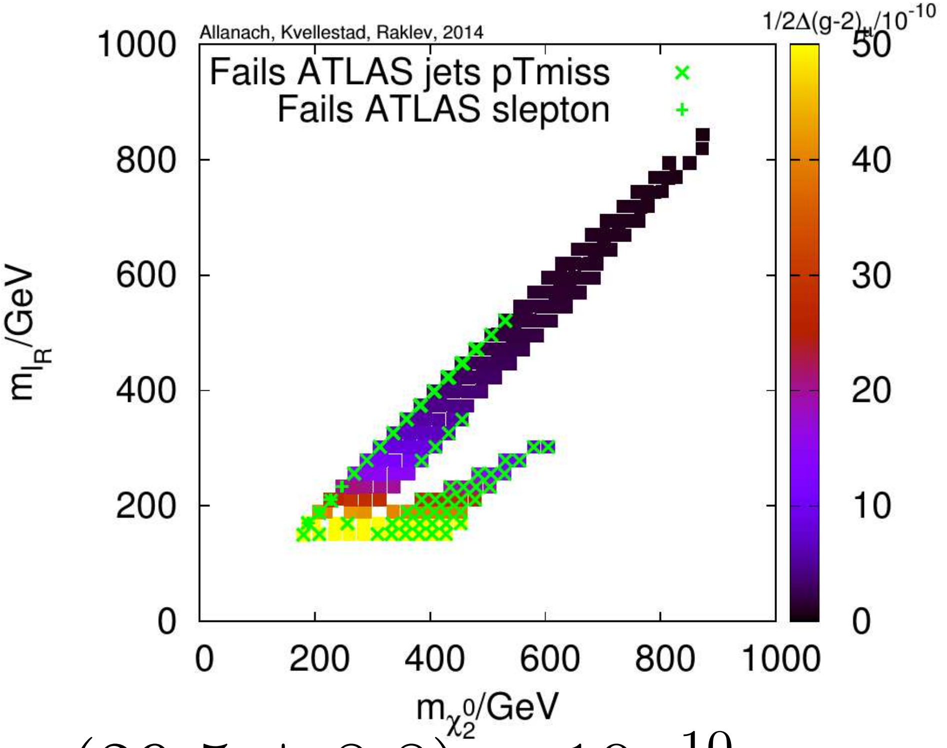
Parameter space fitting the central rate edge measurement.

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

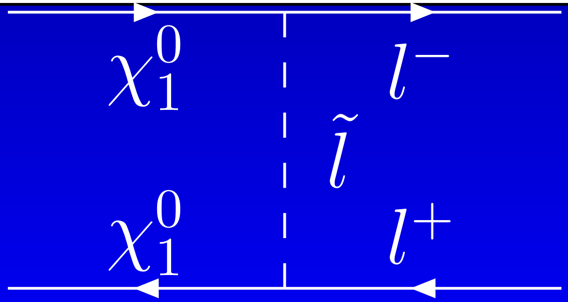
$$\Omega h^2 = 0.1198 \pm 0.0026$$

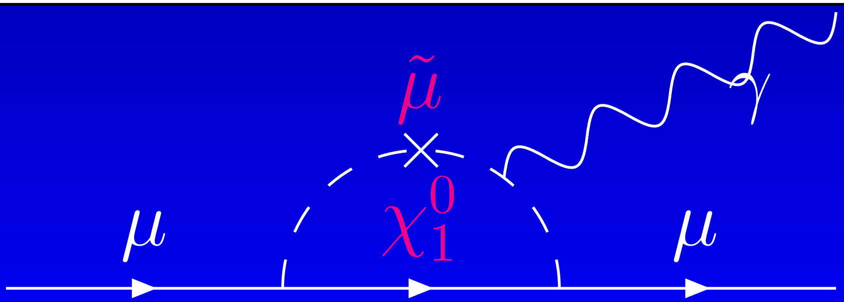
$$\frac{\delta(g-2)_\mu}{2} \sim 13 \times 10^{-10} \left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 \tan\beta$$





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





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 $\chi = (1, 1, 0)_-$.

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

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

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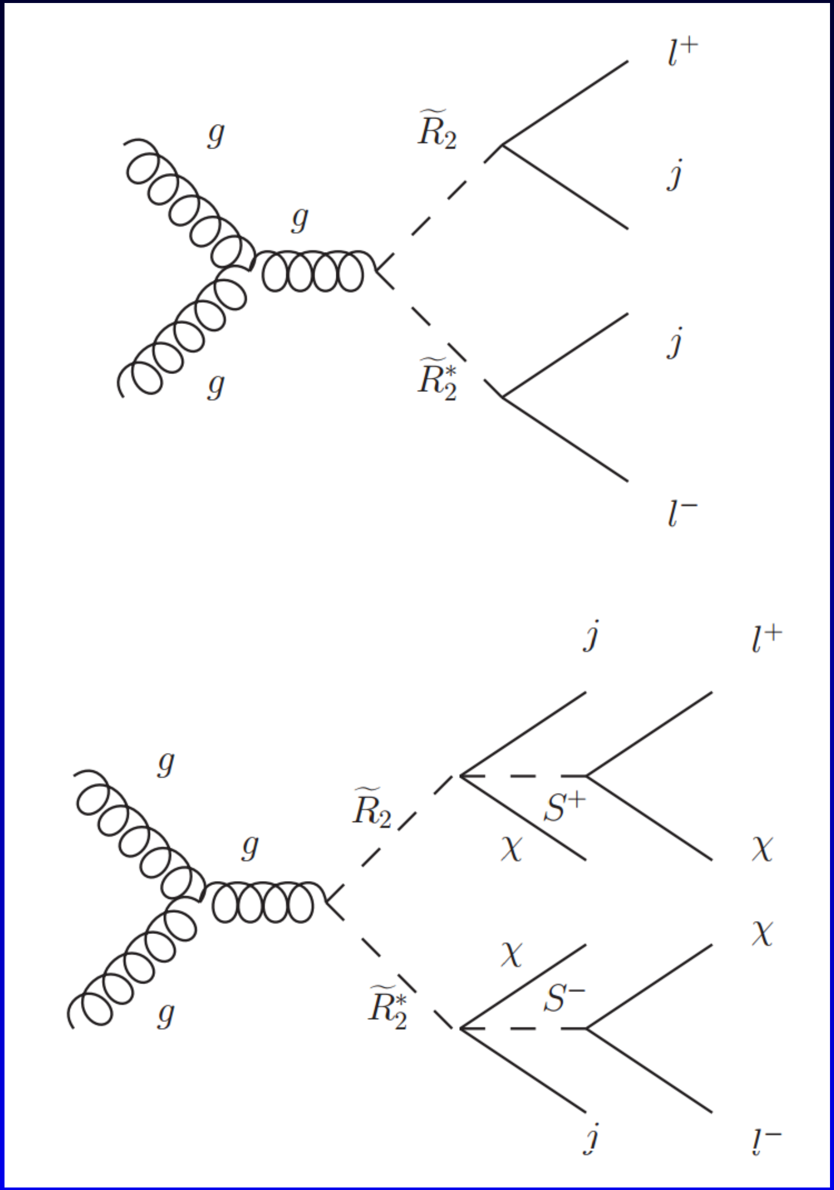
[a] Queiroz, Sinha, Strumia, `arXiv:1409.6301`; BCA, Alves, Queiroz, Sinha, Strumia, `arXiv:1501.03494`

Production at the LHC

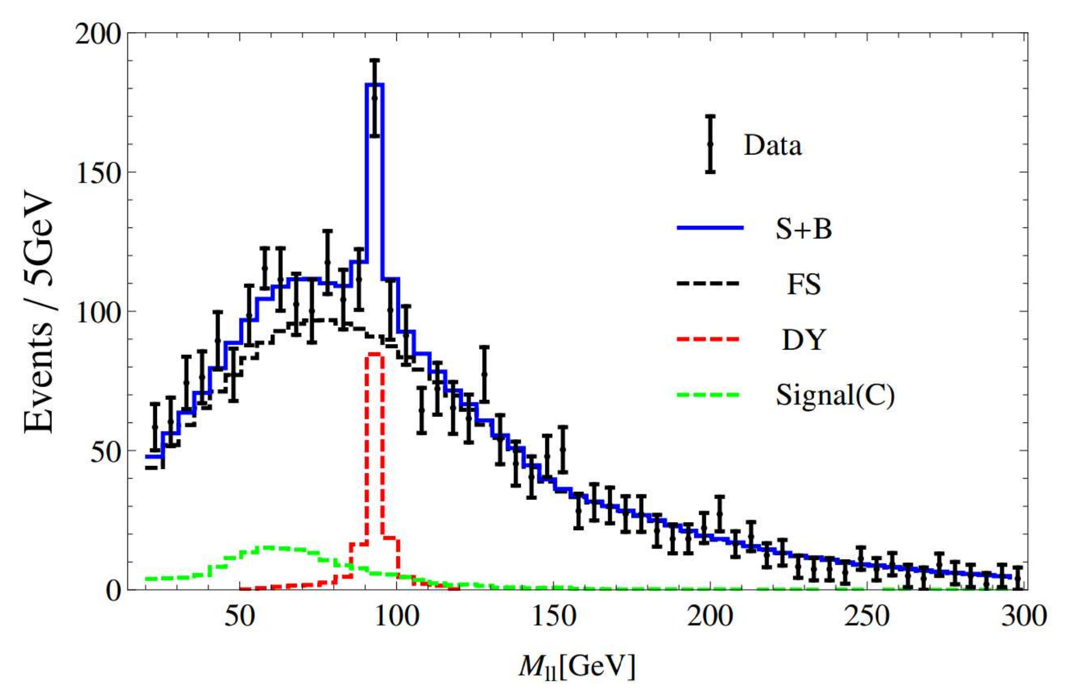


Upper diagram can explain $eejj$ excess.

Lower diagram can explain $l^+l^-jj\not{E}_T$ excess.

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.

$$\begin{aligned}\mathcal{L} &= \bar{\chi}(i\not\partial - M_\chi)\chi + \frac{1}{\Lambda}\left(vh + \frac{1}{2}h^2\right) \\ &\quad [\bar{\chi}\chi\cos\xi + \bar{\chi}i\gamma_5\chi\sin\xi] +\end{aligned}$$

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.

Summary

- LHC run II starts at 13 TeV, *half the data* is expected (10 fb^{-1}). Should expect *similar signal strengths*.
- RPV model fits 3 of the excesses. It has interesting predictions for *neutrinoless double beta decay*.
- Alternatively, a R_p conserving model fits the other one, and has nice dark matter and $(g-2)_\mu$ properties.
- A home-grown leptoquark model can fit *all four* of the excesses.

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.