Explaining CMS Leptons/Jets Excesses With Supersymmetry

by

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Talk outline[a]

- Excess at 2.6σ in $lljj\not{E}_T$
- Completely standard interpretation: MSSM
- Other 2.4-2.8σ excesses in $lljj$ and $ljj\not{E}_T$: RPV

Please ask questions while I'm talking

[a] BCA, Kvellestad, Raklev, arXiv:1409.3532, BCA, Biswas, Mondal, Mitra, arXiv:1408.5439

First Excess in $lljj\not{E}_T$: Golden Cascade

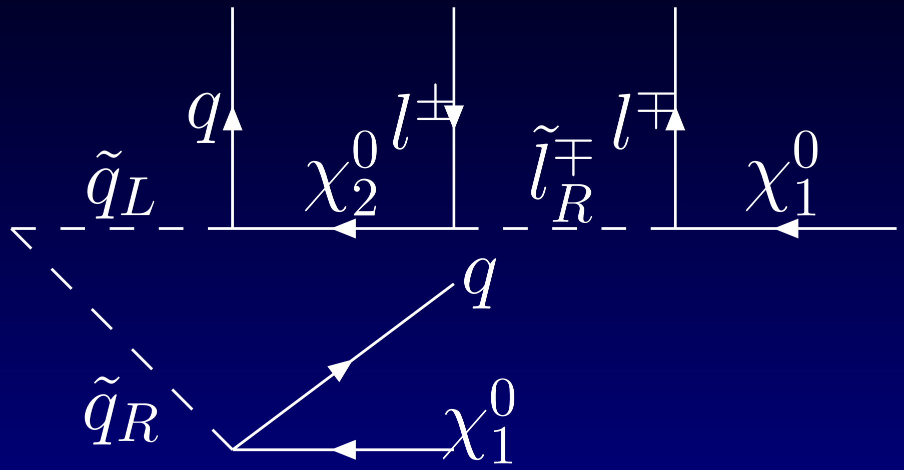
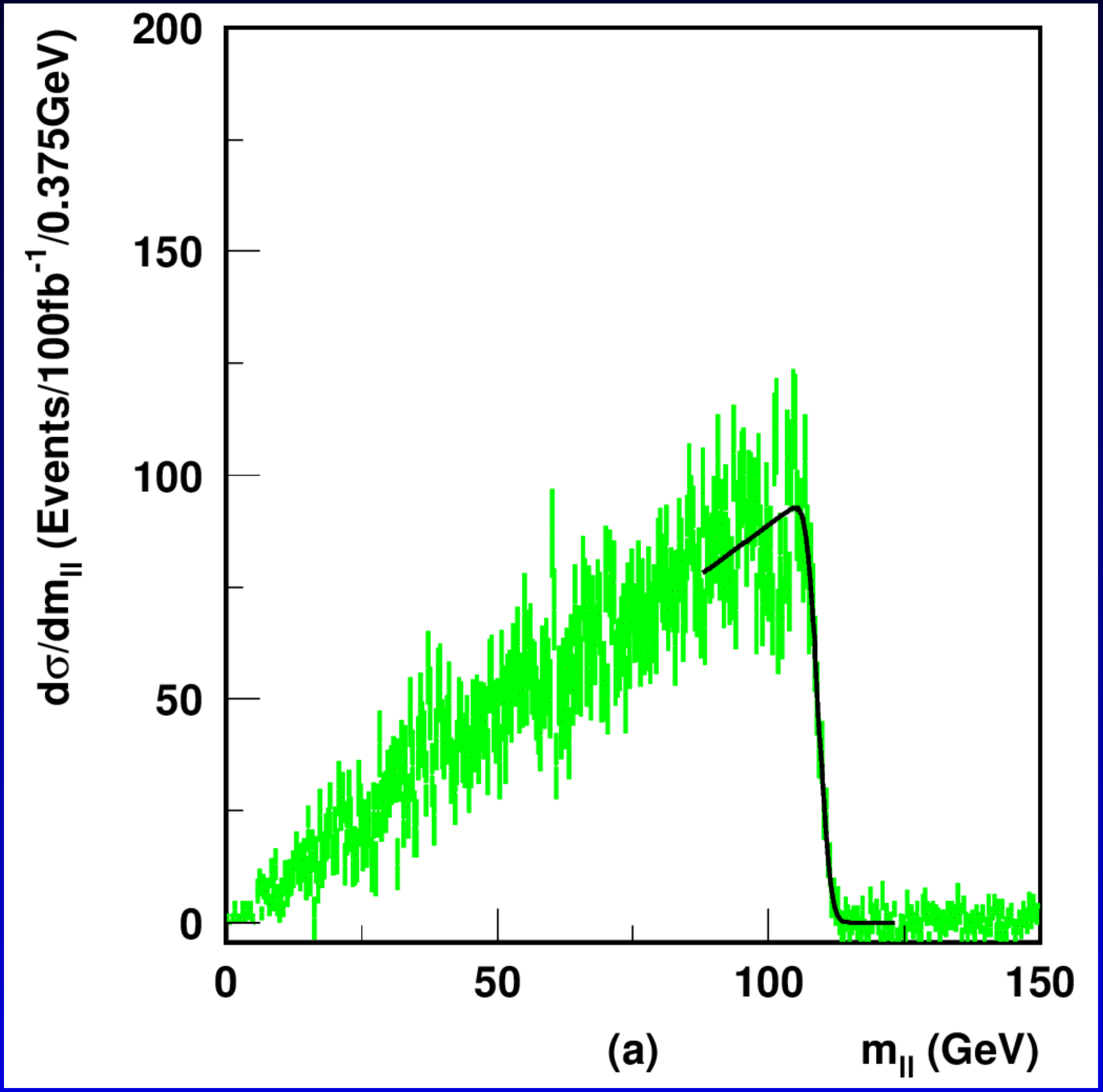


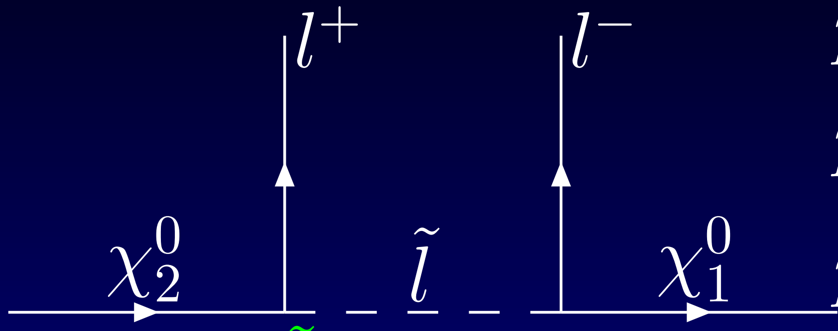
Figure 1: Feynman diagram for the golden cascade decay: opposite sign same flavour leptons (OSSF)

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

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

Momentum conservation:

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

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

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

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Neutralino Mass Matrix

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

(1)

Fix M_1, M_2 to determine $M_{\chi_1^0}, M_{\chi_2^0}$ and assume the higgsinos are decoupled by large $|\mu|$.

$$\tan\beta = v_2/v_1$$

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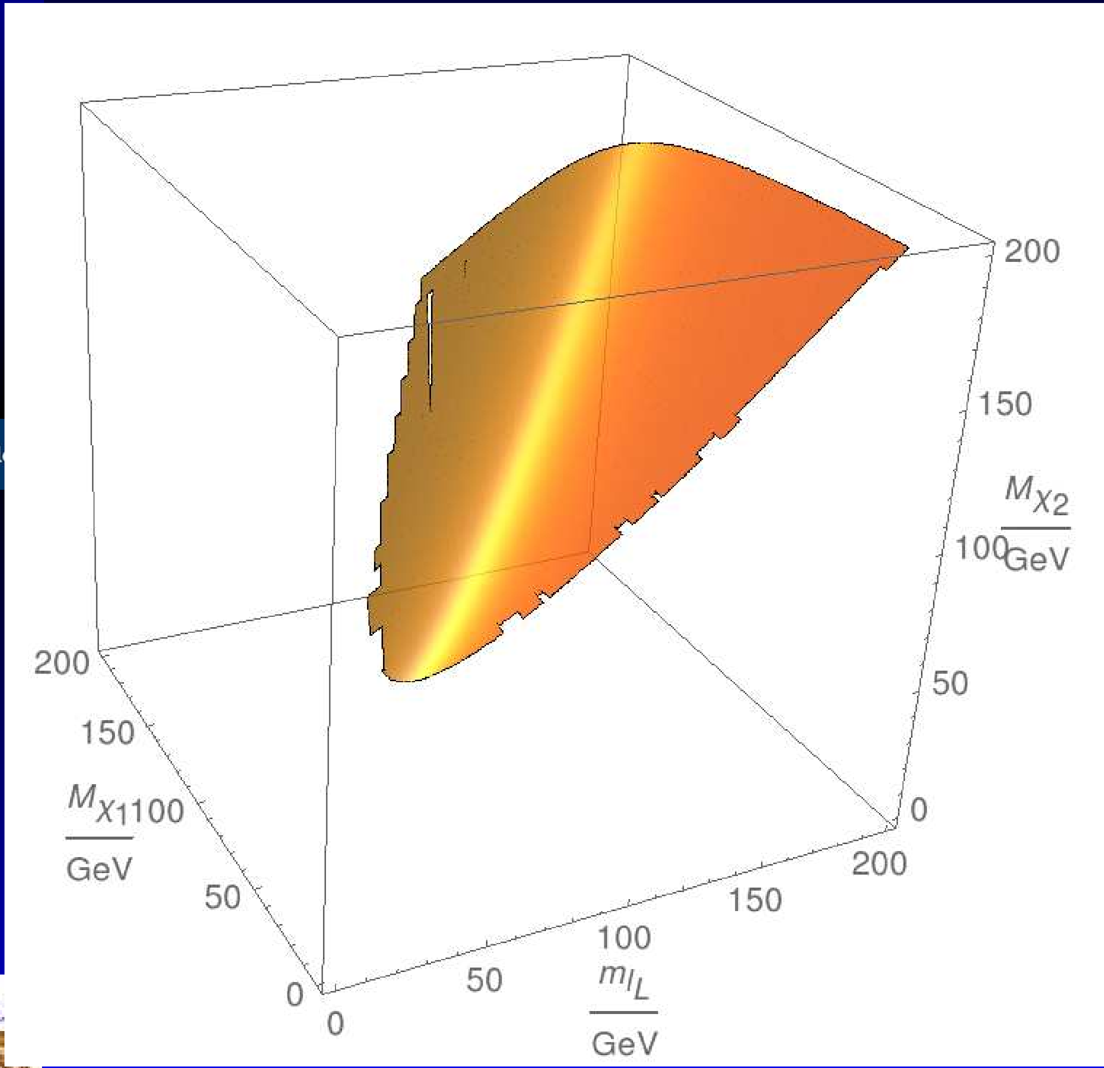
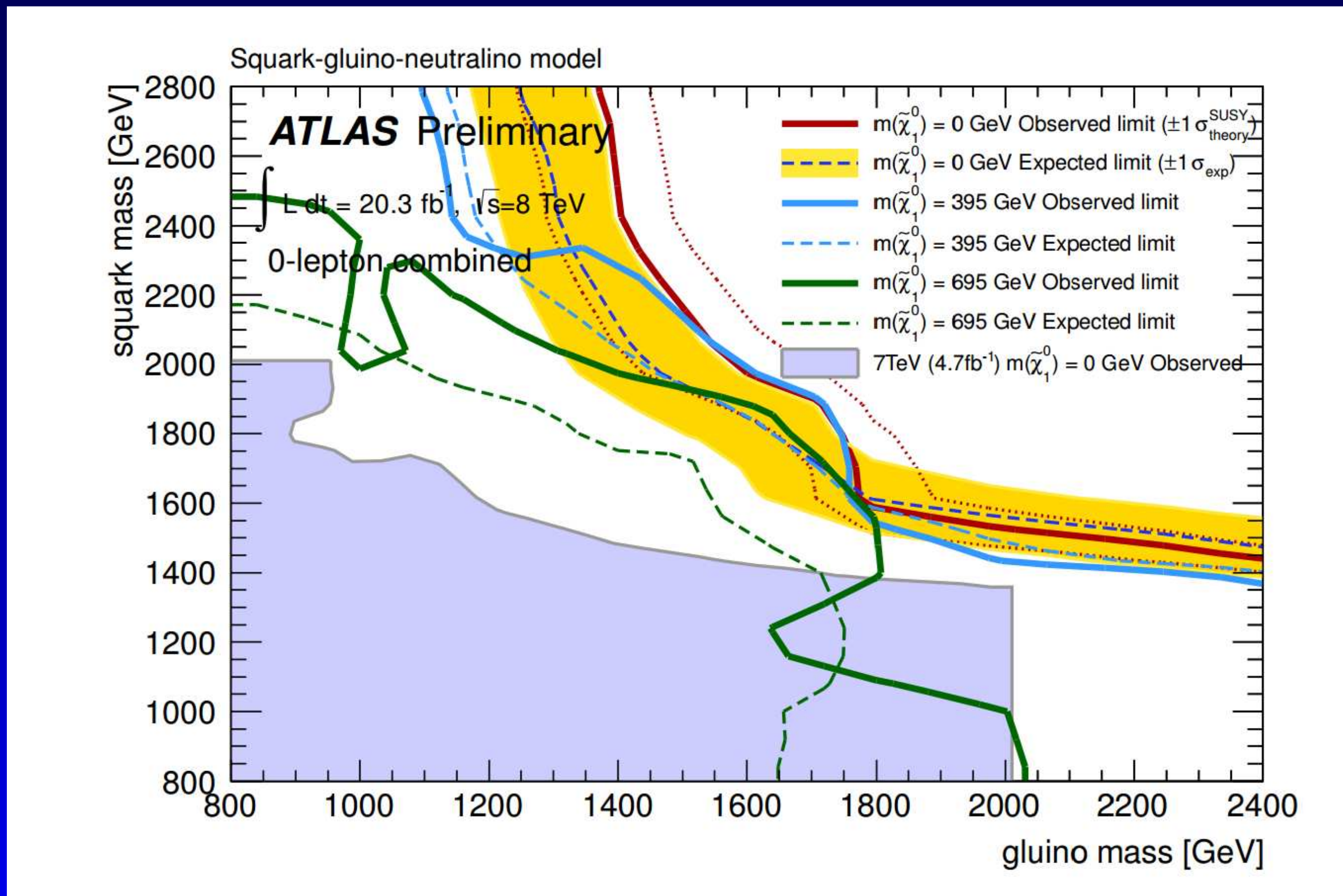
Edge Interpretation



The signal rate determines $m_{\tilde{q}}$, $m_{ll}^{max} = 78.4 \pm 1.4$ GeV which we fit to $\sqrt{\frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}}}}$. We choose $m_{\tilde{l}}$, M_2 then vary M_1 in order to predict the correct m_{ll}^{max}. Sometimes, $M_1 > M_2$.

LHC Constraints

We shall see squark masses around a TeV being predicted ATLAS (2014), `arXiv:1405.7875`; CMS JHEP **1406** (2014) 055, `arXiv:1402.4770`.



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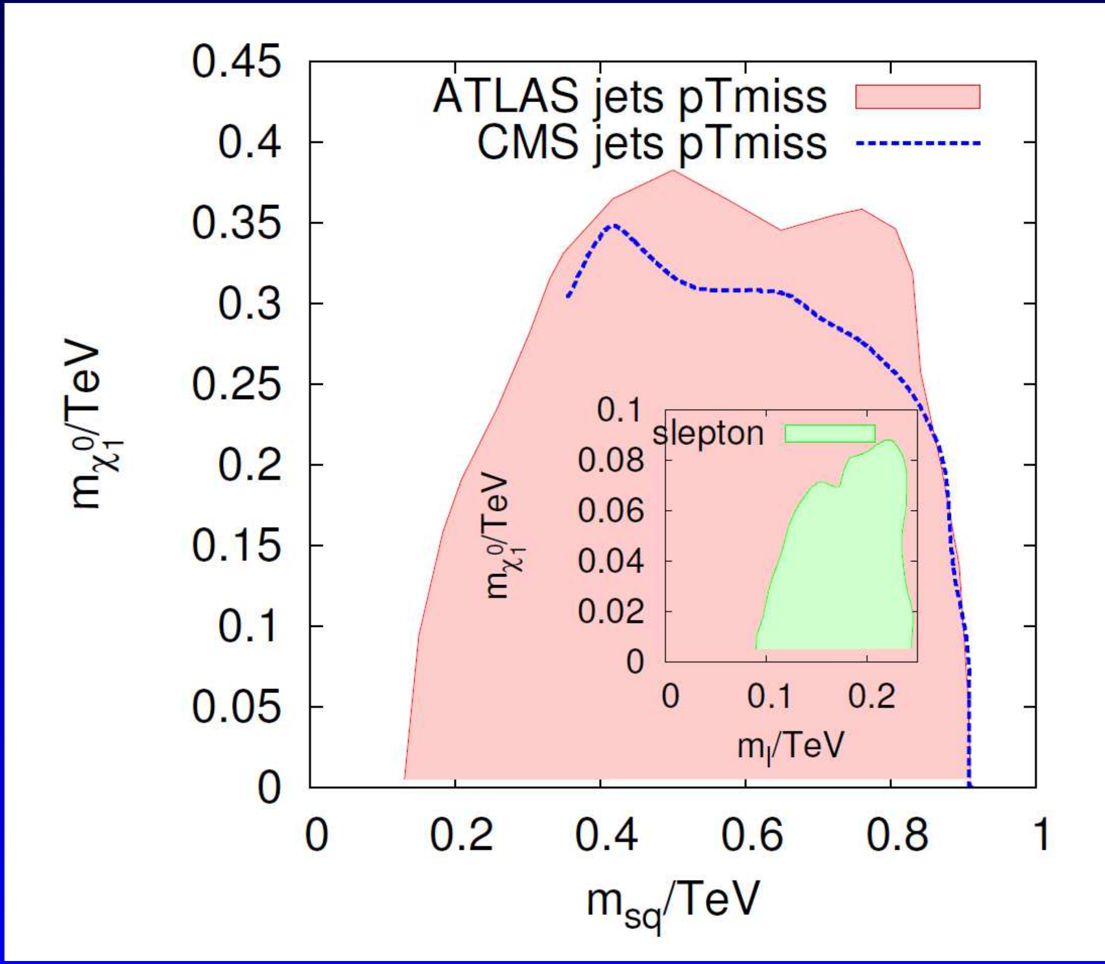

Simulations

- 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`

Example Point

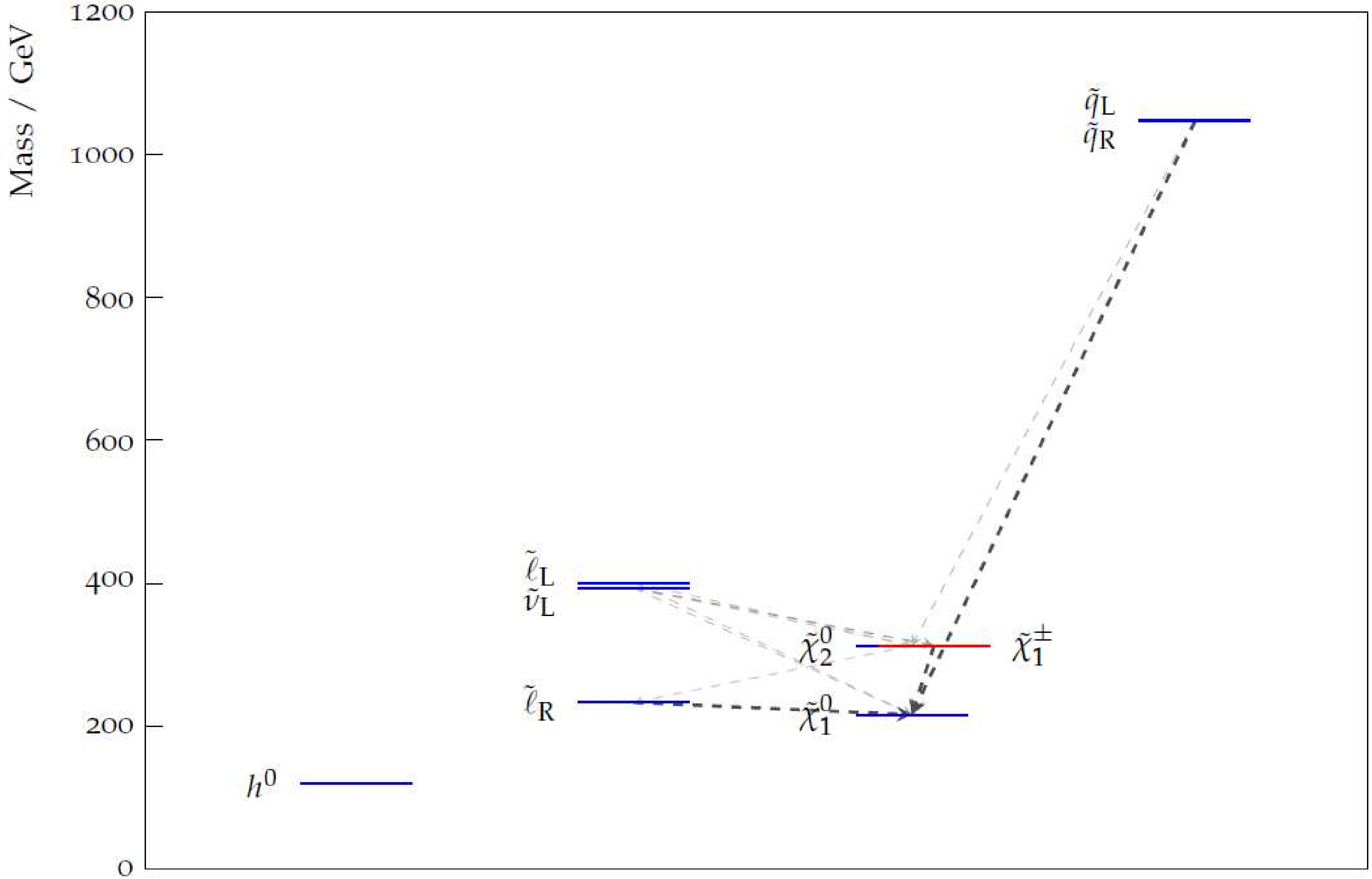

FIG. 4. Example signal point that fits the central CMS rate and edge inferences: $M_2 = 300$ GeV, $m_{\tilde{l}_R} = 200$ GeV, $m_{\tilde{q}} = 1050$ GeV. Prominent decays with branching ratios higher than 10% are shown as arrows.

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m_{ll} Distribution

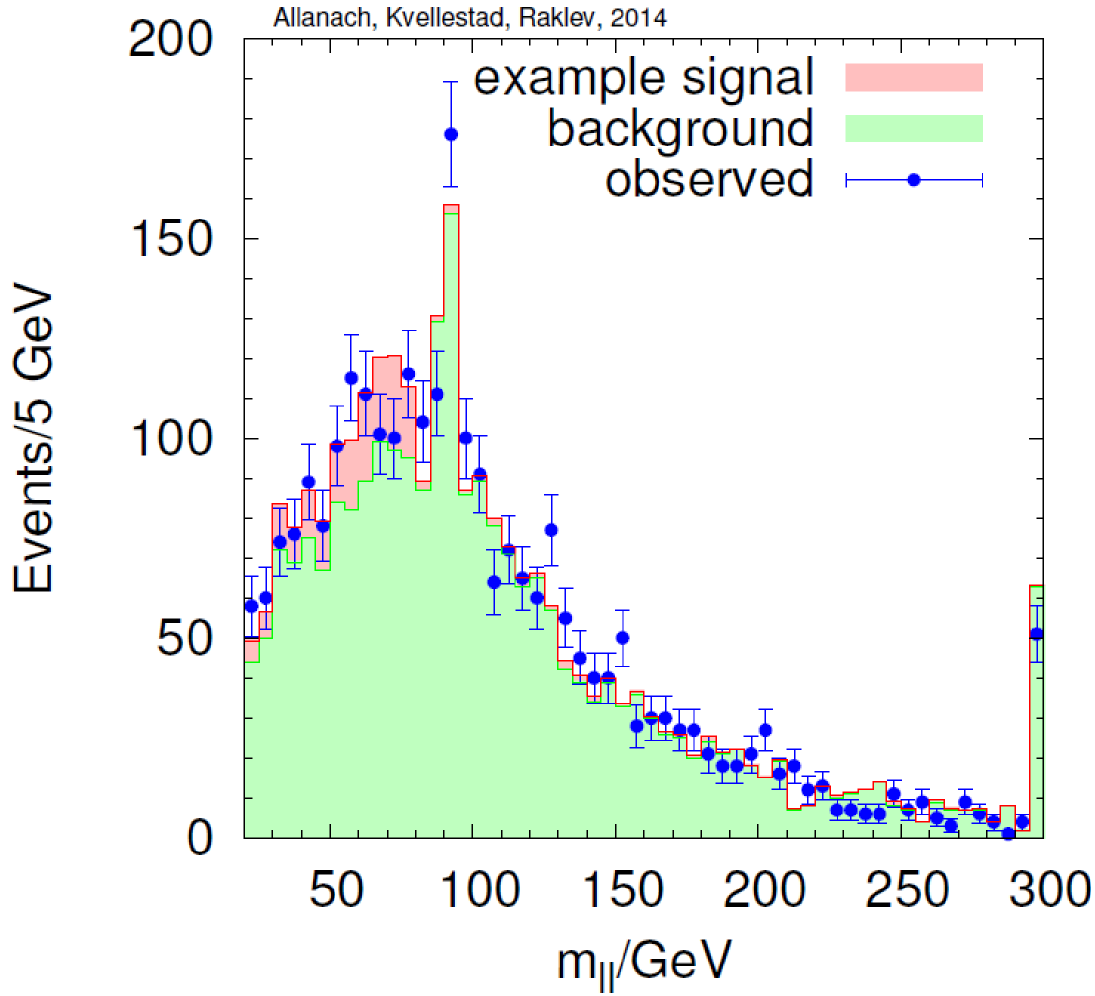
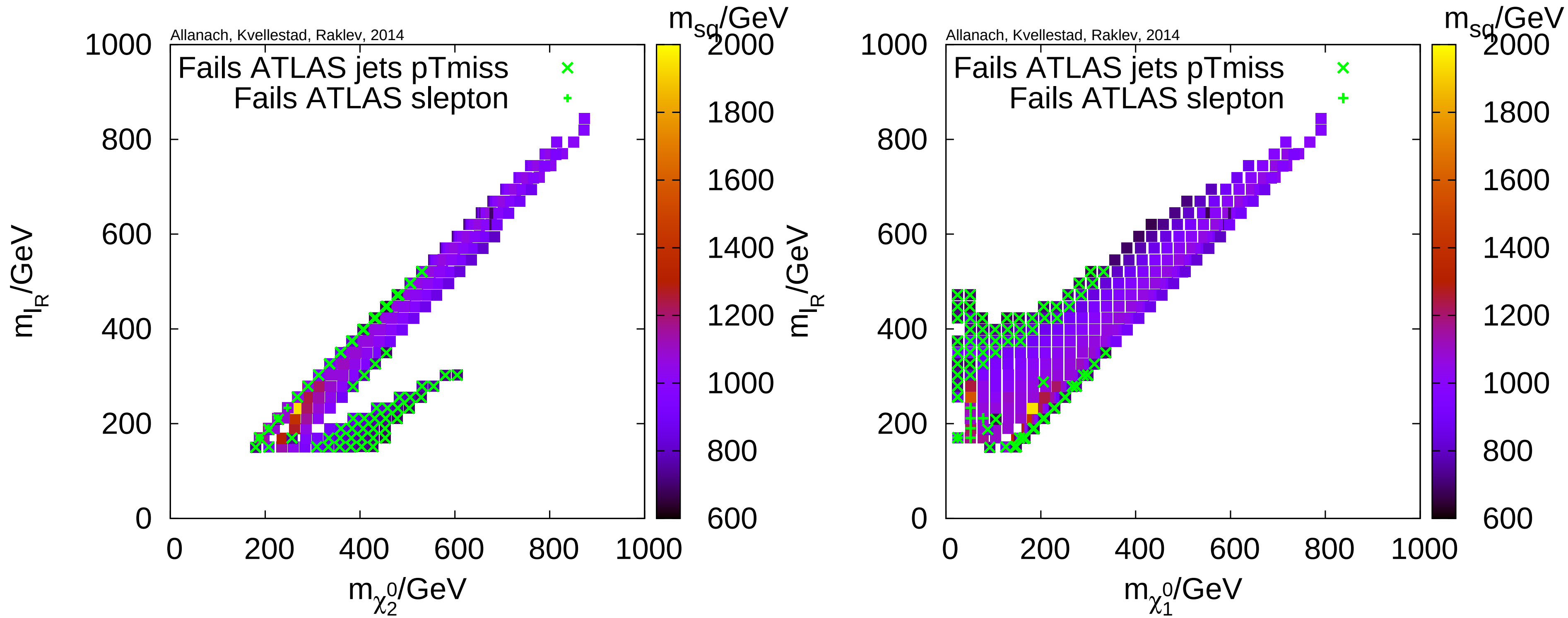


FIG. 1. Invariant mass distribution of OSSF in the CMS selection after cuts. The Standard Model background is shown, which is calculated from data by using OSOF events, as well as the observed data and an example signal point in our pa-

Viable Parameter Space

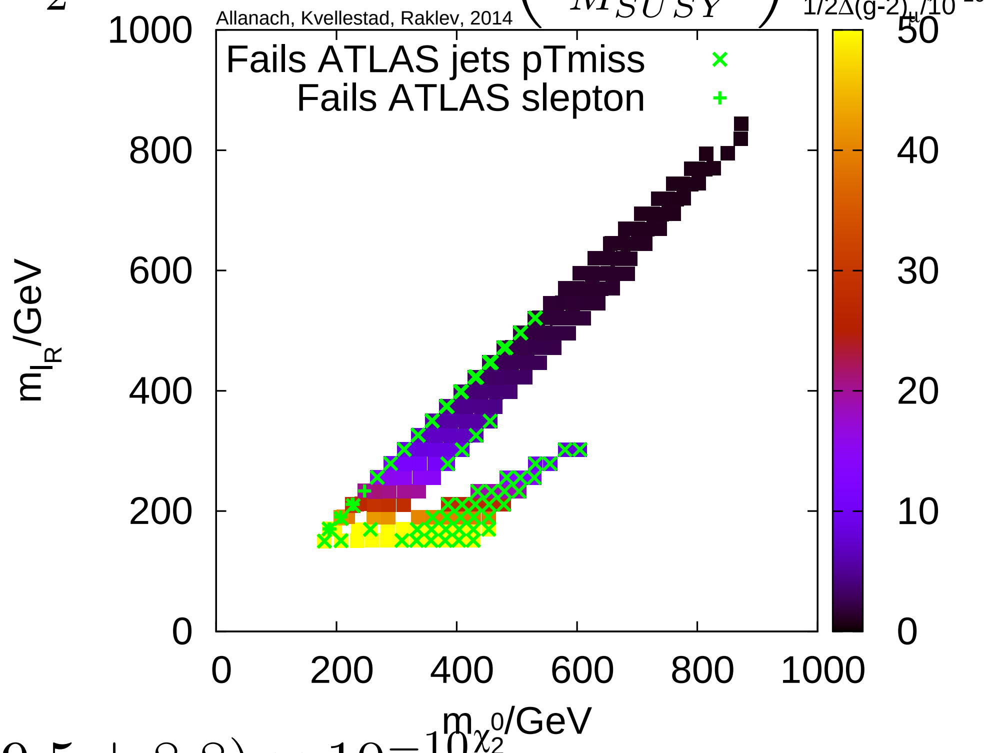


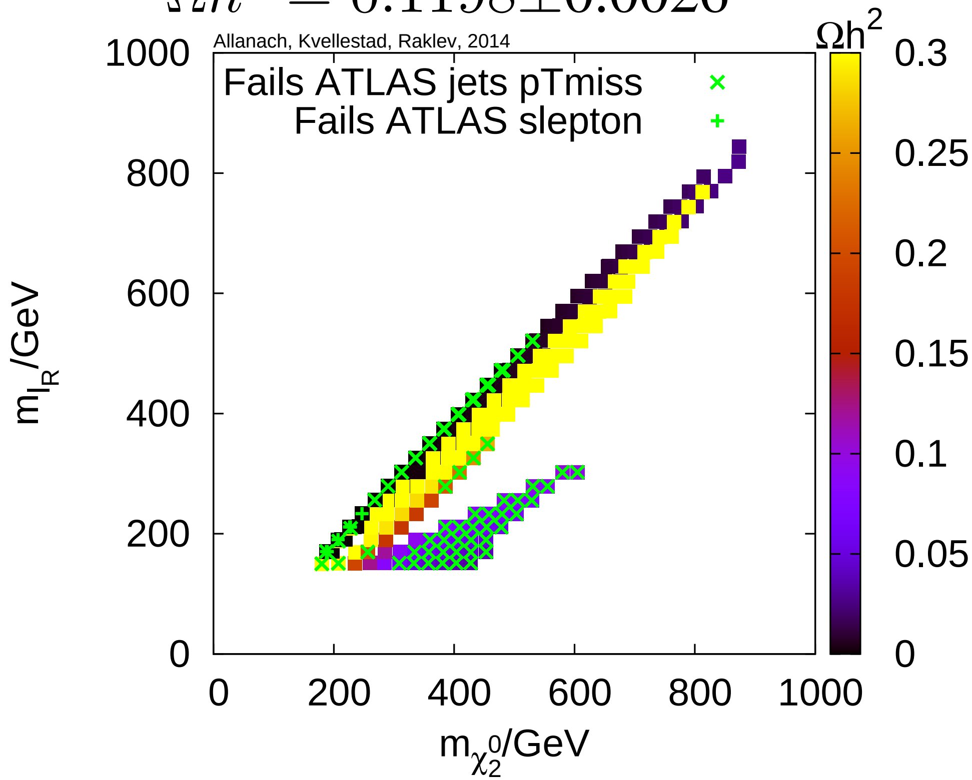
Parameter space fitting the central rate edge measurement.

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

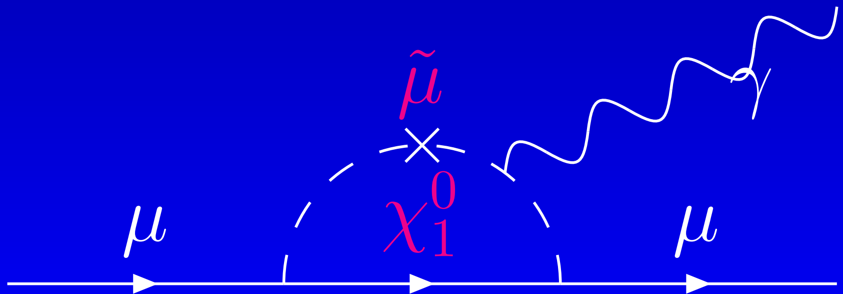
$$\frac{(g-2)_\mu}{2} \sim 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{SUSY}}\right)^2 \tan\beta$$

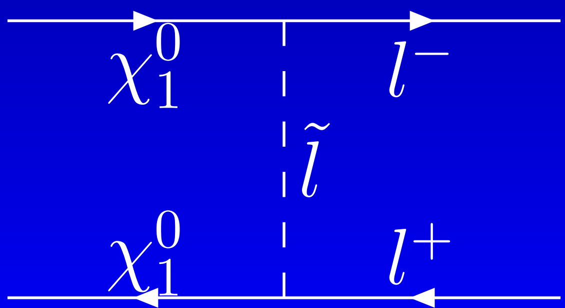
$$\Omega h^2 = 0.1198 \pm 0.0026$$



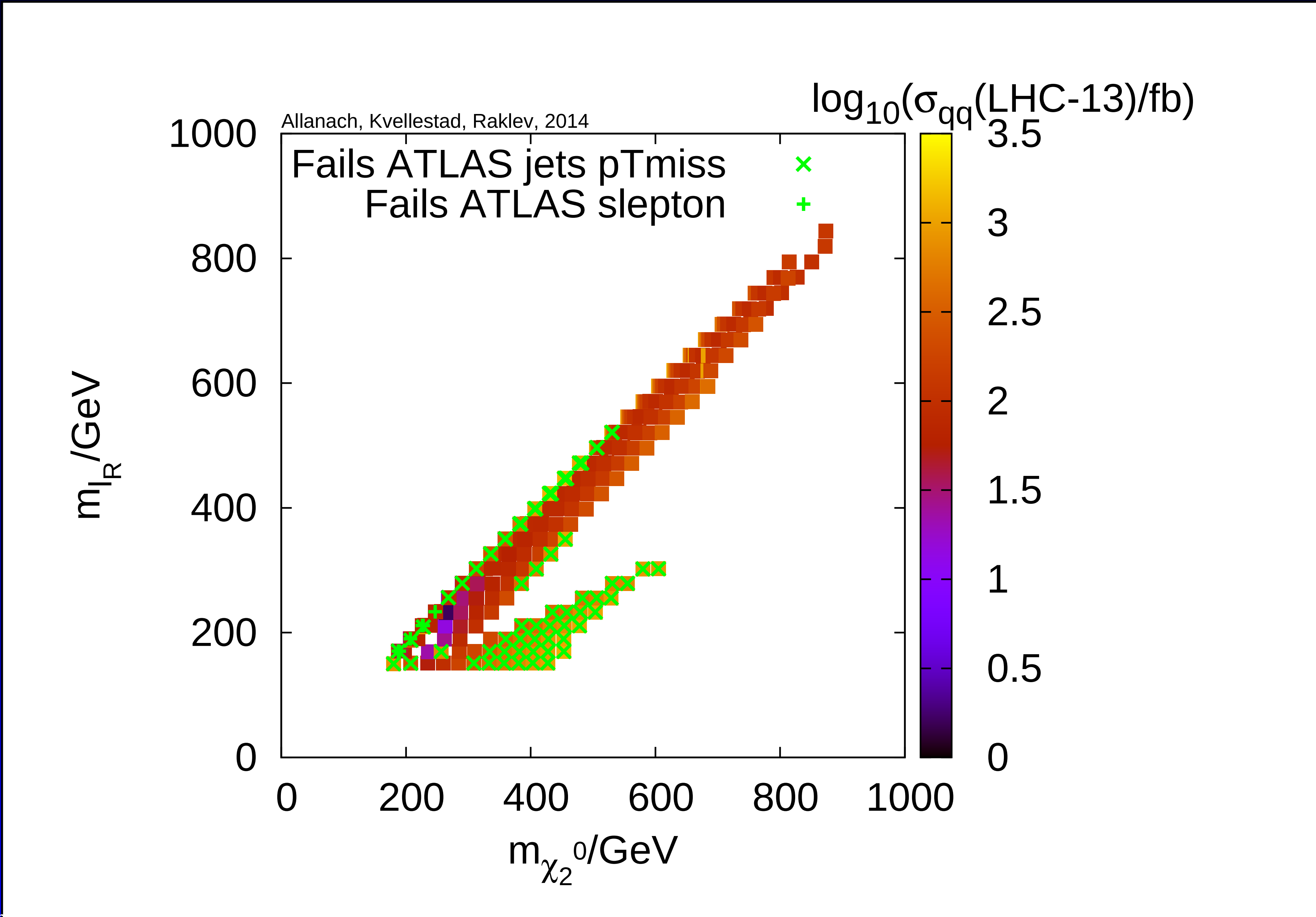


$(29.5 \pm 8.8) \times 10^{-10}$





NLO Predictions for LHC13



Other CMS Anomalies

All in $\approx 20\ \mathrm{fb}^{-1}$ at 8 TeV:

channel		cuts
$eejj(W_R)$	2.8σ	$M_{eejj} = [1.8,\ 2.2]$ TeV
$eejj(LQ)$	2.4σ	$S_T > 850$ GeV, $M_{ee} > 155$ GeV, $m_{ej}^{min} > 360$ GeV
$ejj\not{E}_T(LQ)$	2.6σ	$S_T > 1.04$ TeV, $M_{ej} > 555$ GeV, $\not{E}_T > 145$ GeV, $M_T(e\nu) > 270$ GeV

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Event numbers

Channel	S+B	B	Data
$eejj(M_{LQ} = 650 \text{ GeV})$	41.5	20.5±3.3	36
$e\not{E}_T jj(M_{LQ} = 650 \text{ GeV})$	33.9	7.5±1.6	18
$W_R(1.6 < (M_{eejj}) < 1.8)$ TeV	12.4	9.6±3.8	10
$W_R(1.8 < (M_{eejj}) < 2.2)$ TeV	26.0	4.0±1.0	14
$W_R(2.2 < (M_{eejj}))$ TeV	2.6	2.2±1.8	4

Table 1: 19.6 fb^{-1} and 8 TeV center of mass energy.

S2 assuming $\lambda'_{111} = 0.18$ and $m_{\tilde{l}} = 2$ TeV.

CMS-PAS-EXO-12-041; CMS, arXiv:1407.3683

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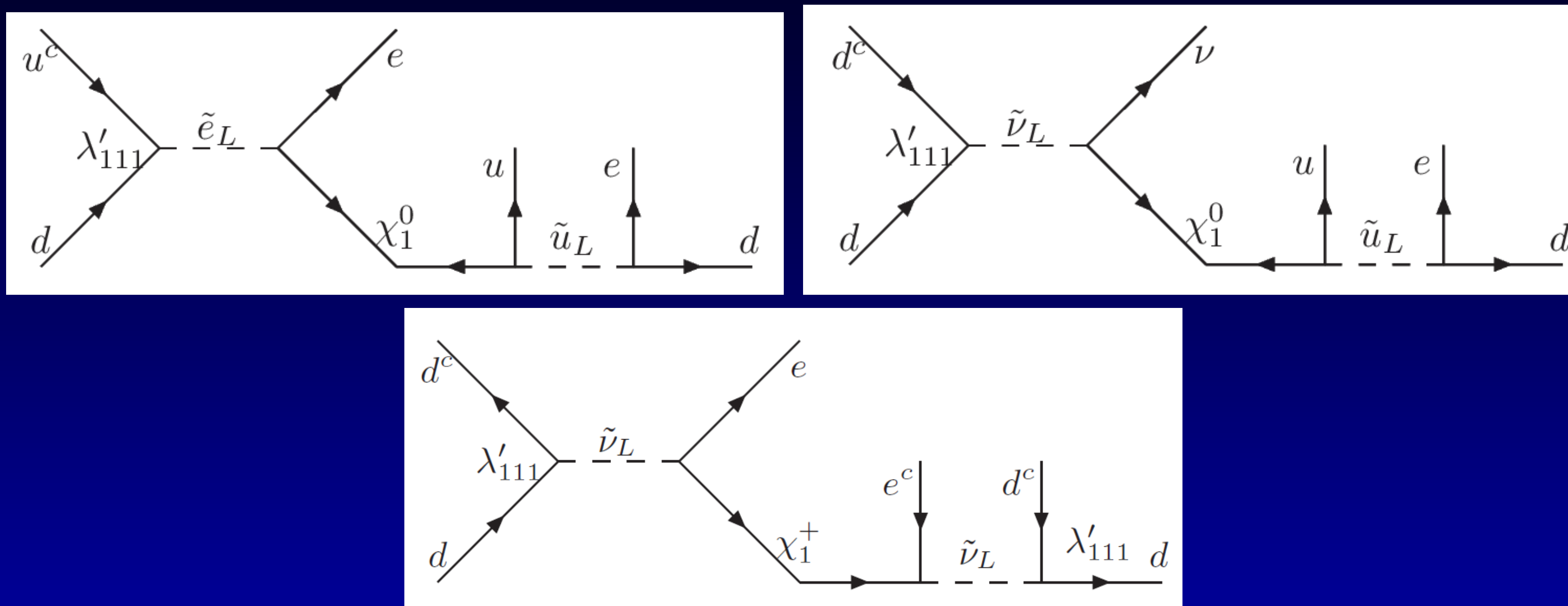
Our Proposal $W = \lambda'_{111} LQd^c$



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

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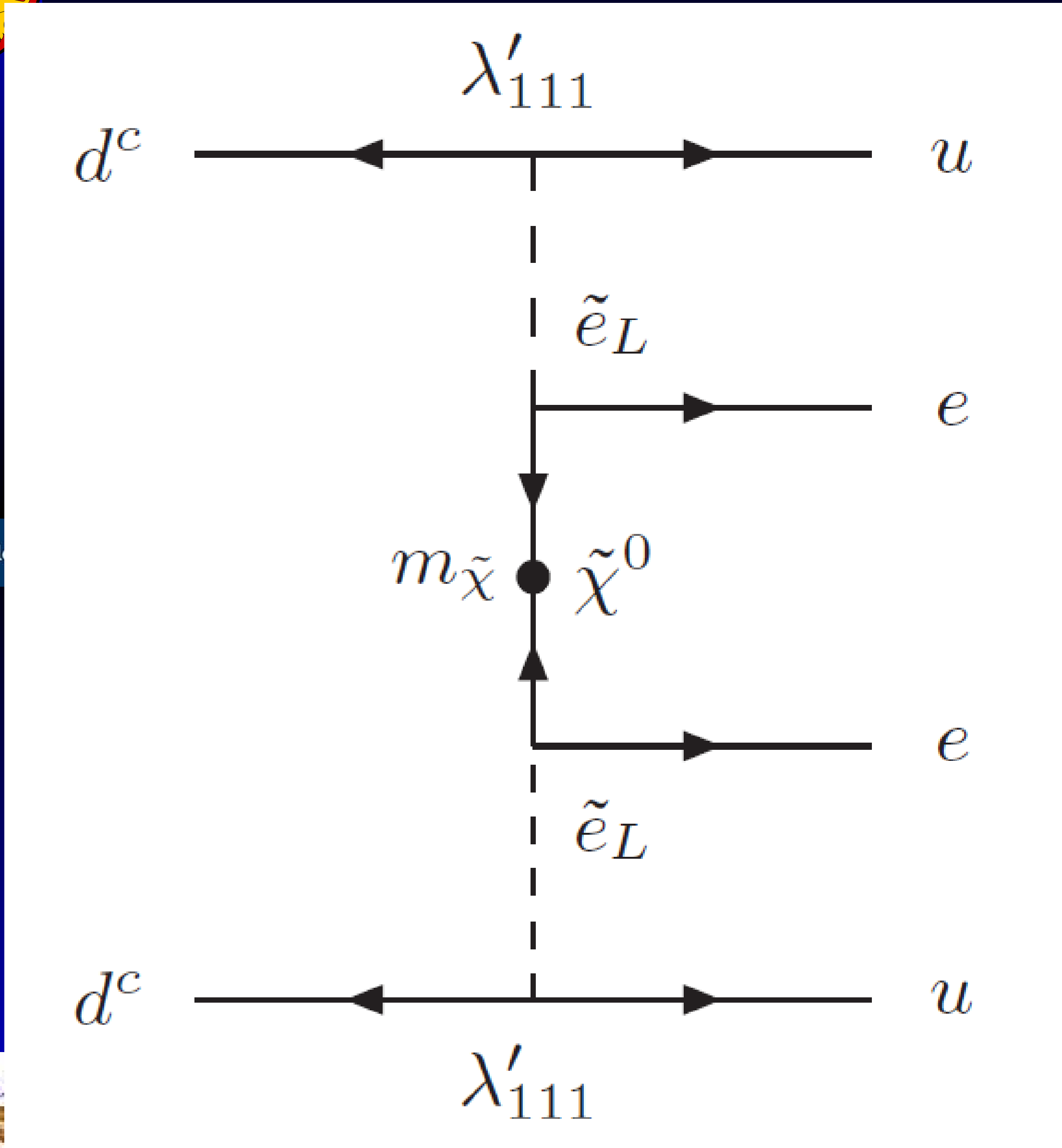
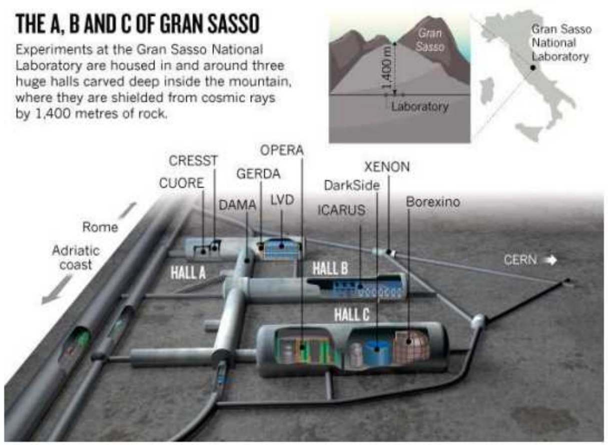
$0\nu\beta\beta$



Currently, $T^{0\nu}_{1/2}(Ge^{76}) > 2.1 \times 10^{25}$ yr 90%CL. GERDA Phase-II should reach $\sim 2 \times 10^{26}$ yr.

The low background experiment GERDA



Setup and background shielding (1):

- Overburden of 3500 m w.e. at Hall A of LNGS
  → Reduction of cosmic-muon flux by six orders of magn. down to $\sim 1\,\mu/(m^2 \cdot h)$ (PB)
- Water tank and plastic scintillator
  - R=5 m, h=9.0 m, 590 m^3 ultra-pure water
  → water acts as neutron moderator/absorber (PB)
  → both components act as muon Cherenkov veto (AB)
- Large volume cryostat:
  - R=2 m, h=5.9 m, 64 m^3 LAr
  → LAr acts as cooling medium for diodes
  → LAr attenuates external radiation (PB)
  → LAr scintillation light planned to be used as a background rejection (AB)
- GERmanium Detector Array:
  - 1-string and 3-string arms, each string with 3 detectors (Phase I)
  - Up to ∼12 strings (depending on final design for Phase II)
  - Handling of diodes within a glovebox flushed mit N2 gas (PB)
  - Operating bare diodes in LAr using low-mass holders (PB)
  → $0\nu\beta\beta$ source = Detector, enriched in ^{76}Ge
  - coincidence mode and pulse shape tracing (AB)

PB = passive background rejection
AB = active background rejection
All construction materials close to detectors screened for radiopurity

GERDA Phase II: Towards a higher sensitivity

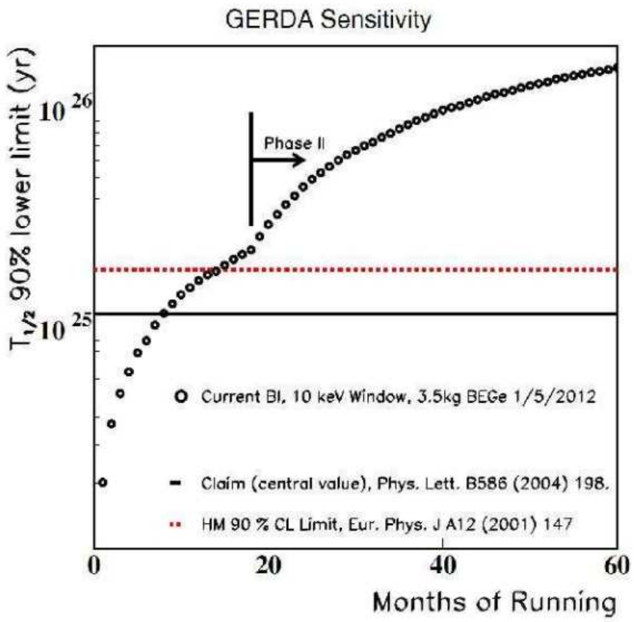
Sensitivity expressed in terms of half-life

$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, \quad \text{(if background is present)}$$

where:

- f_{76}: Abundance of $0\nu\beta\beta$ candidate isotope
  → Enrichment
- ϵ: Efficiency
  → precise characterisation via dedicated acceptance tests
- **M**: Mass
  → Increasing target mass
- **T**: DAQ livetime → high duty cycle
- **ΔE**: Energy resolution
  → Novel detector technology with improved resolution
- **B**: Background:
  → Keep exposure to cosmogenic radiation low
  → Apply pulse shape discrimination techniques to reject background events
  → Read-out LAr scintillation light to discriminate background events

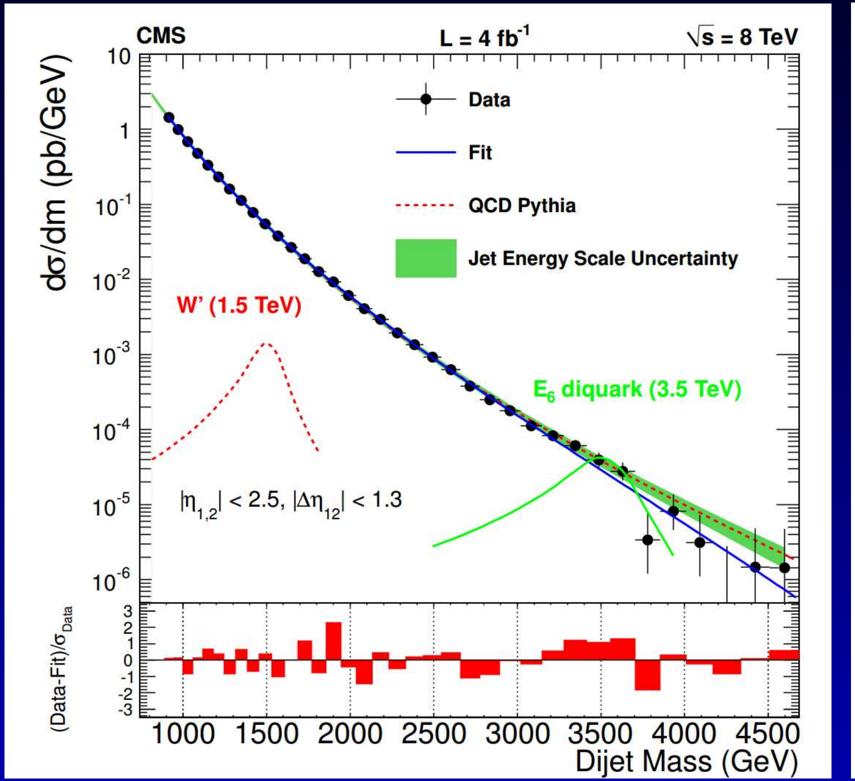
Expected sensitivity of GERDA Phase I-II

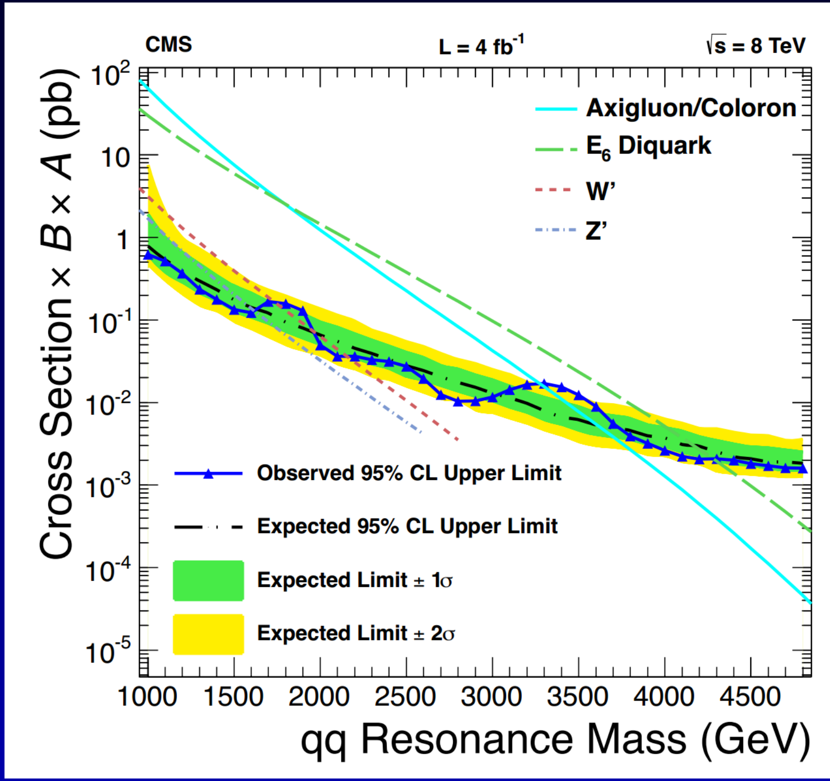


Neutralino Scenarios

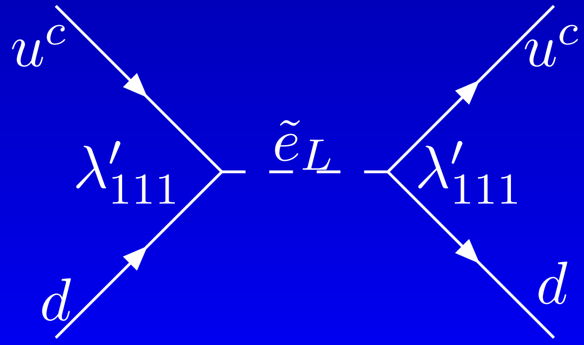
- **S1:** $M_2 = M_1 + 200 < \mu$: $\tilde{B}$ LSP $\tilde{l}$ can decay to χ_2^0 or $\chi_1^\pm$. Predicts $R = OS/SS = 1$.
- **S2:** $M_1 < \mu < M_2$: $\tilde{B}$ LSP but increases BR for $\tilde{l} \to \chi_1^0 l$. Predicts $R = 1$.
- **S3:** $M_2 \ll M_1$: $\tilde{W}$ LSP $\tilde{l}_L \to \chi_1^\pm$,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

CMS Di-jet constraints

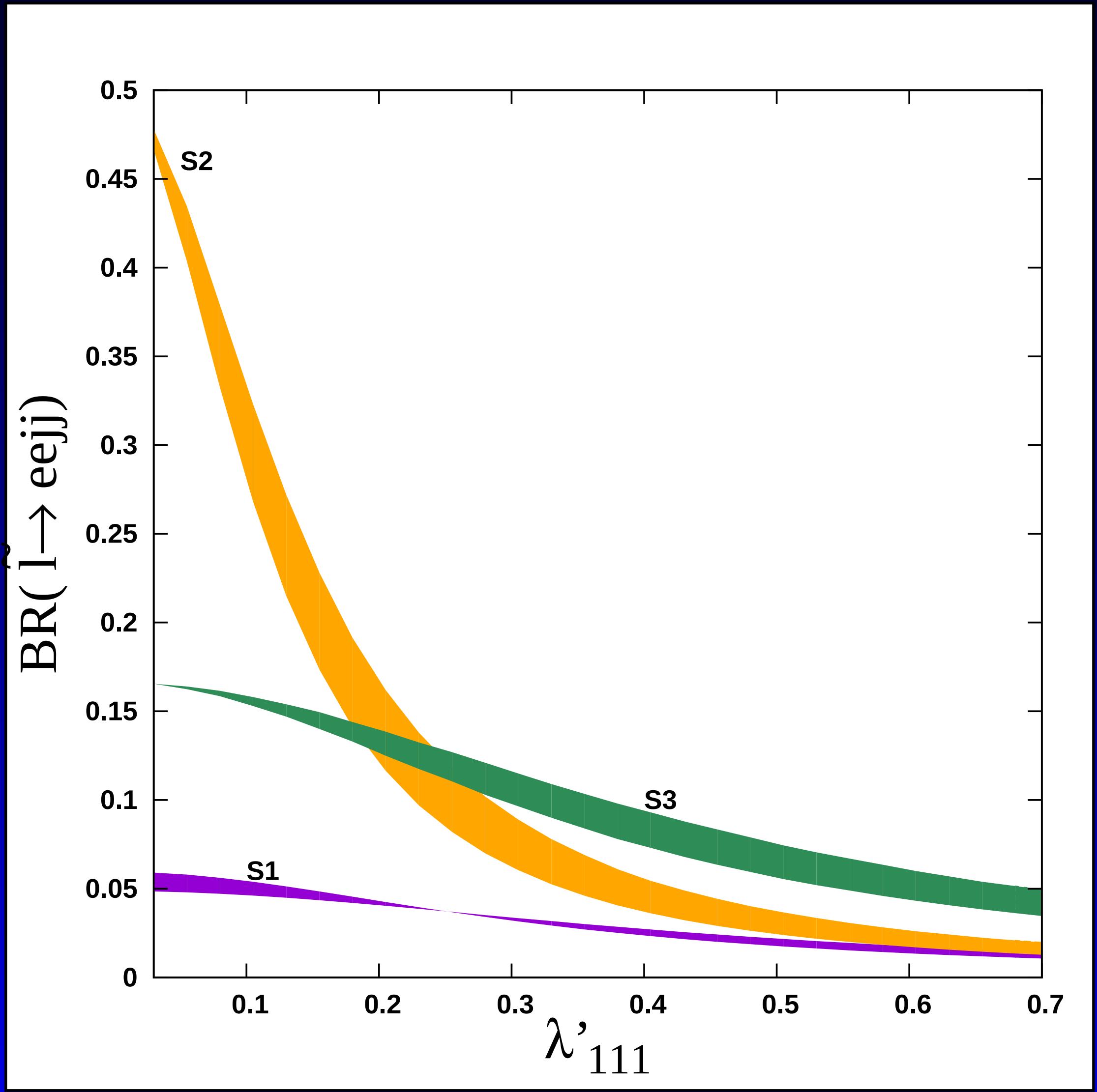




CMS, arXiv:1302.4794



Branching Ratios



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:

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

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

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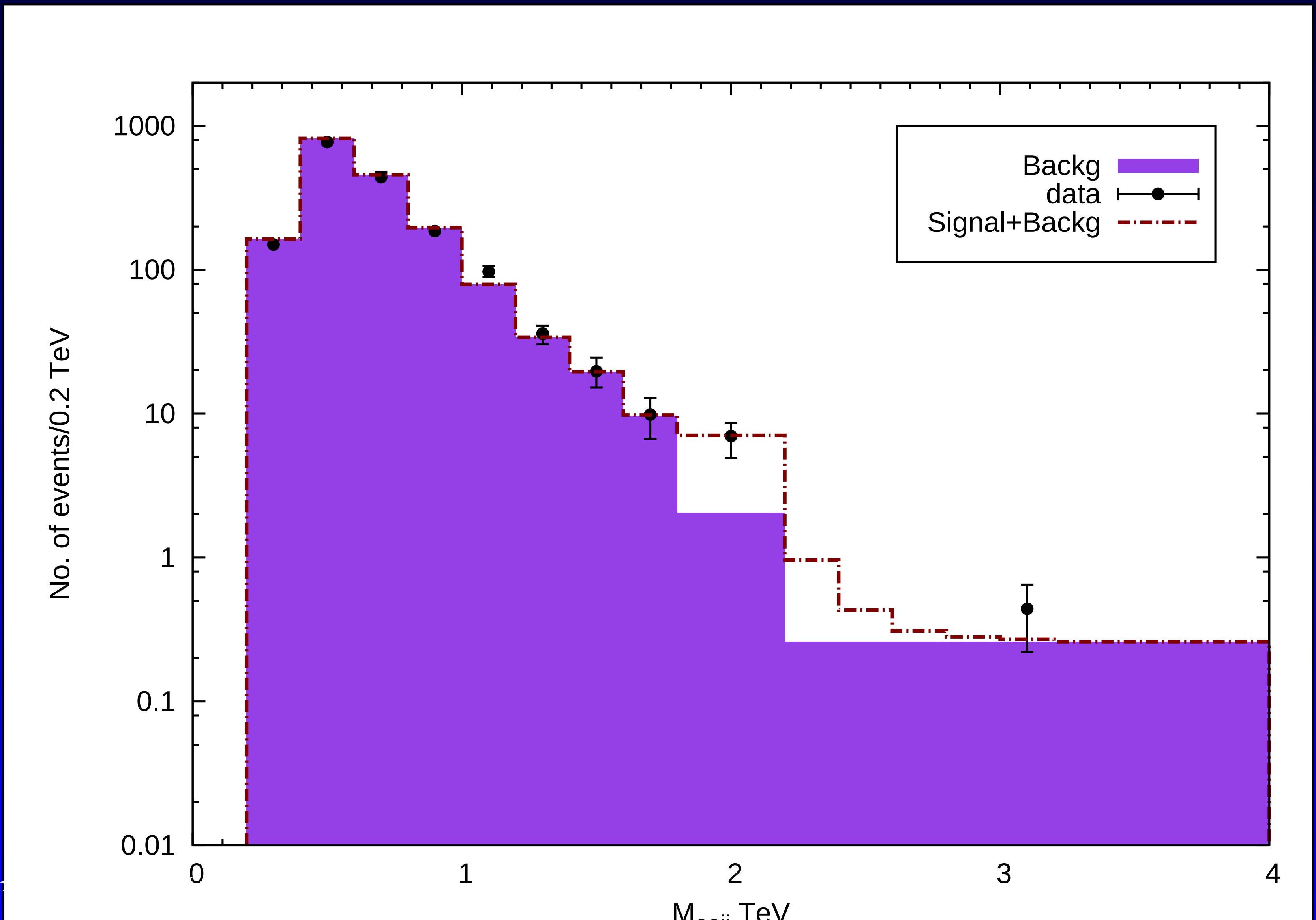
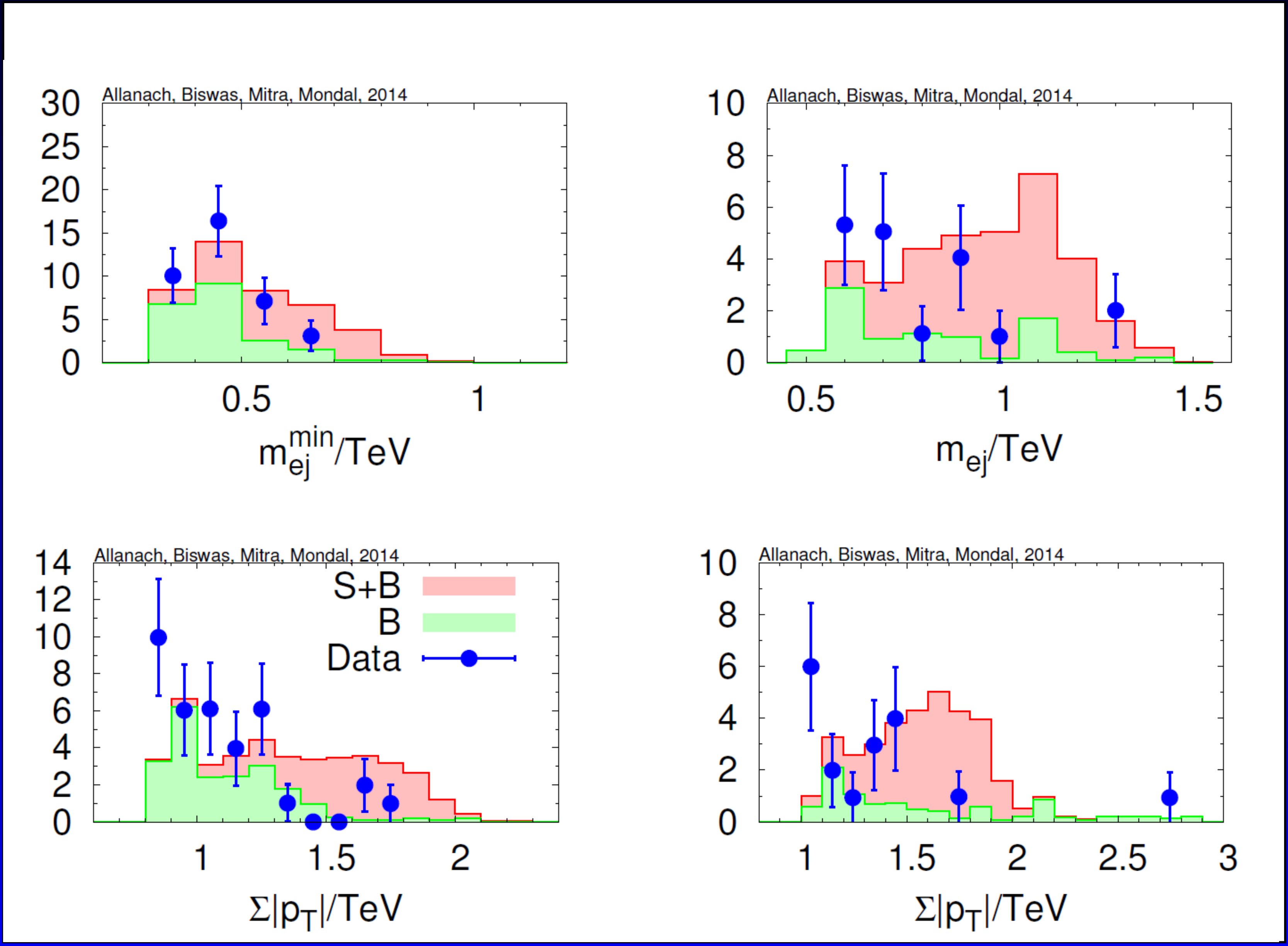
Kinematical Distributions: W_R

Backgrounds: $t\bar{t}$, DY+jets

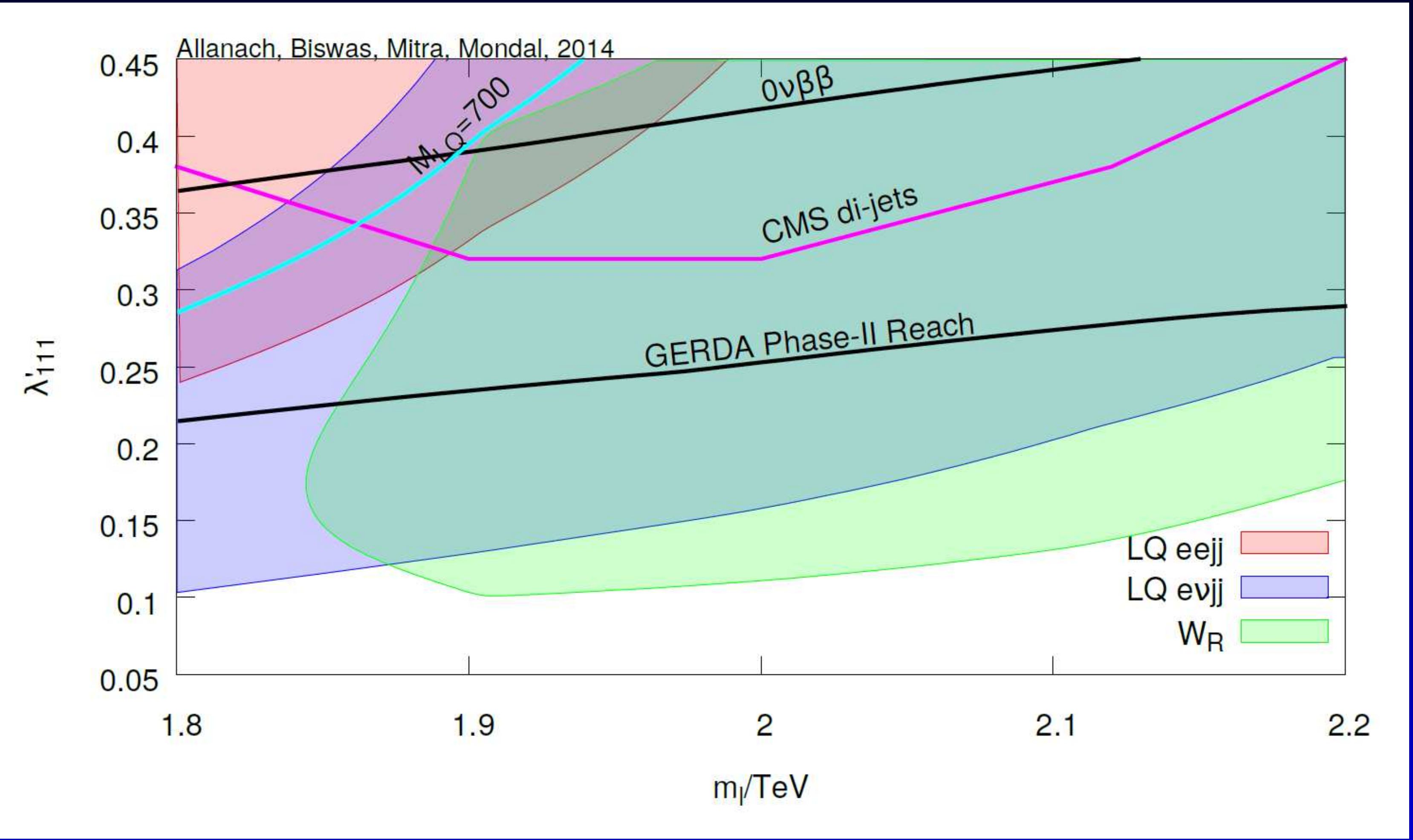
CMS measure 1SS and 13 OS ll in excess bin.



Kinematical Distributions: LQ

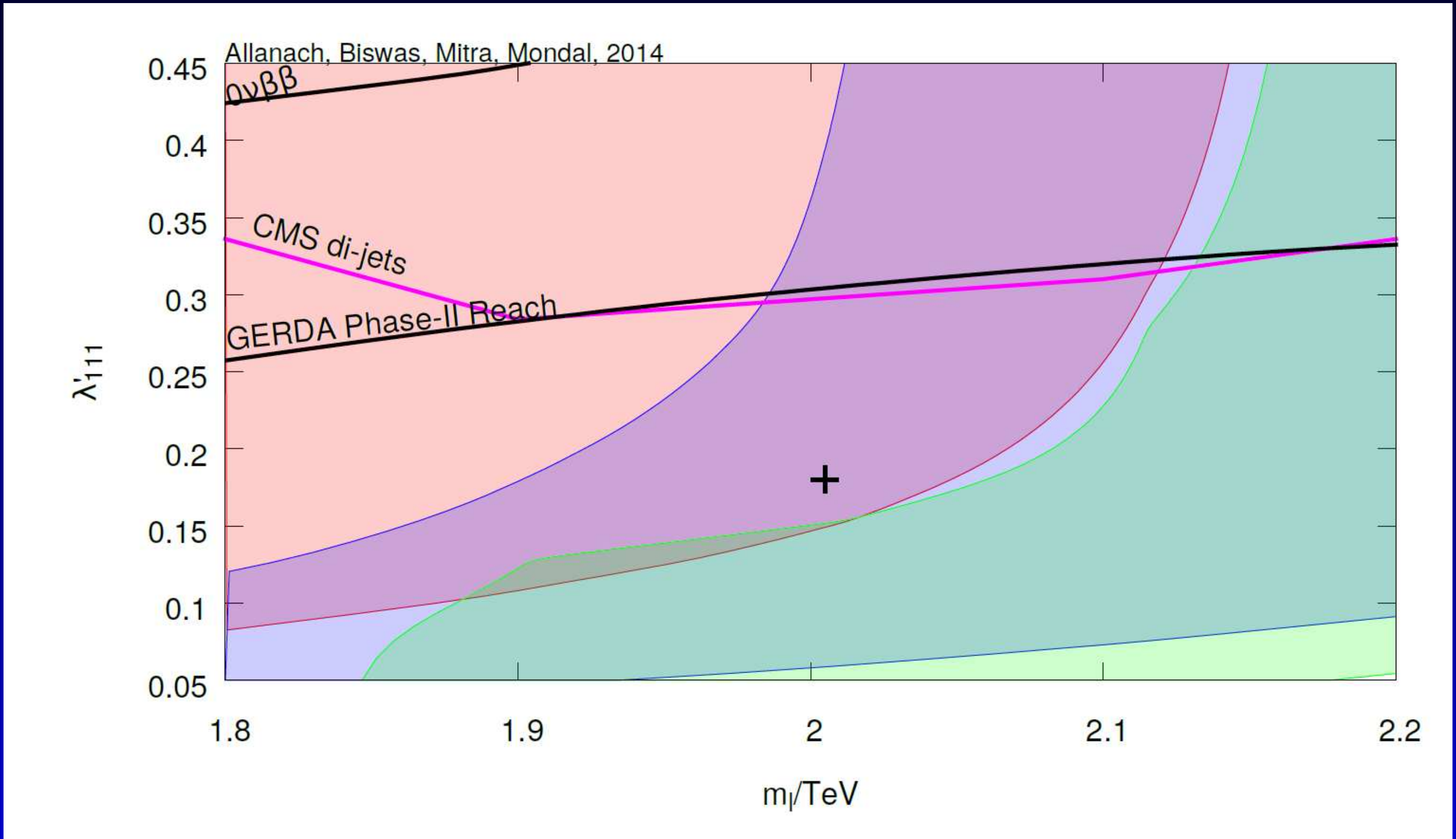


Constraints: S1



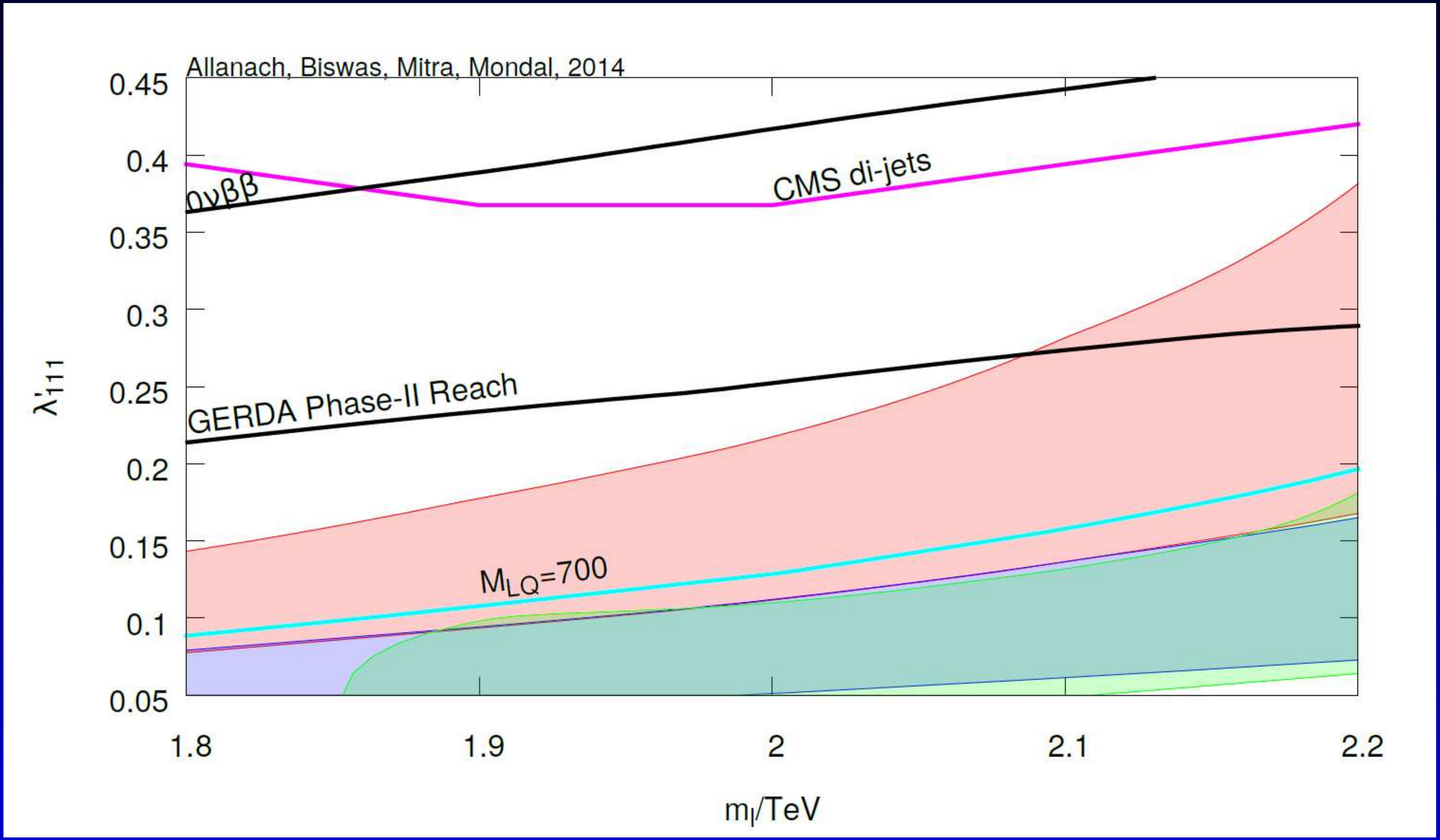
S1: $M_2 = M_1 + 200 < \mu$: $\tilde{B}$ LSP $\tilde{l}$ can decay to χ_2^0 or $\chi_1^\pm$

Constraints: S2



S2: $M_1 < \mu < M_2$: $\tilde{B}$ LSP but increases BR for $\tilde{l} \rightarrow \chi_1^0 l$

Constraints: S3

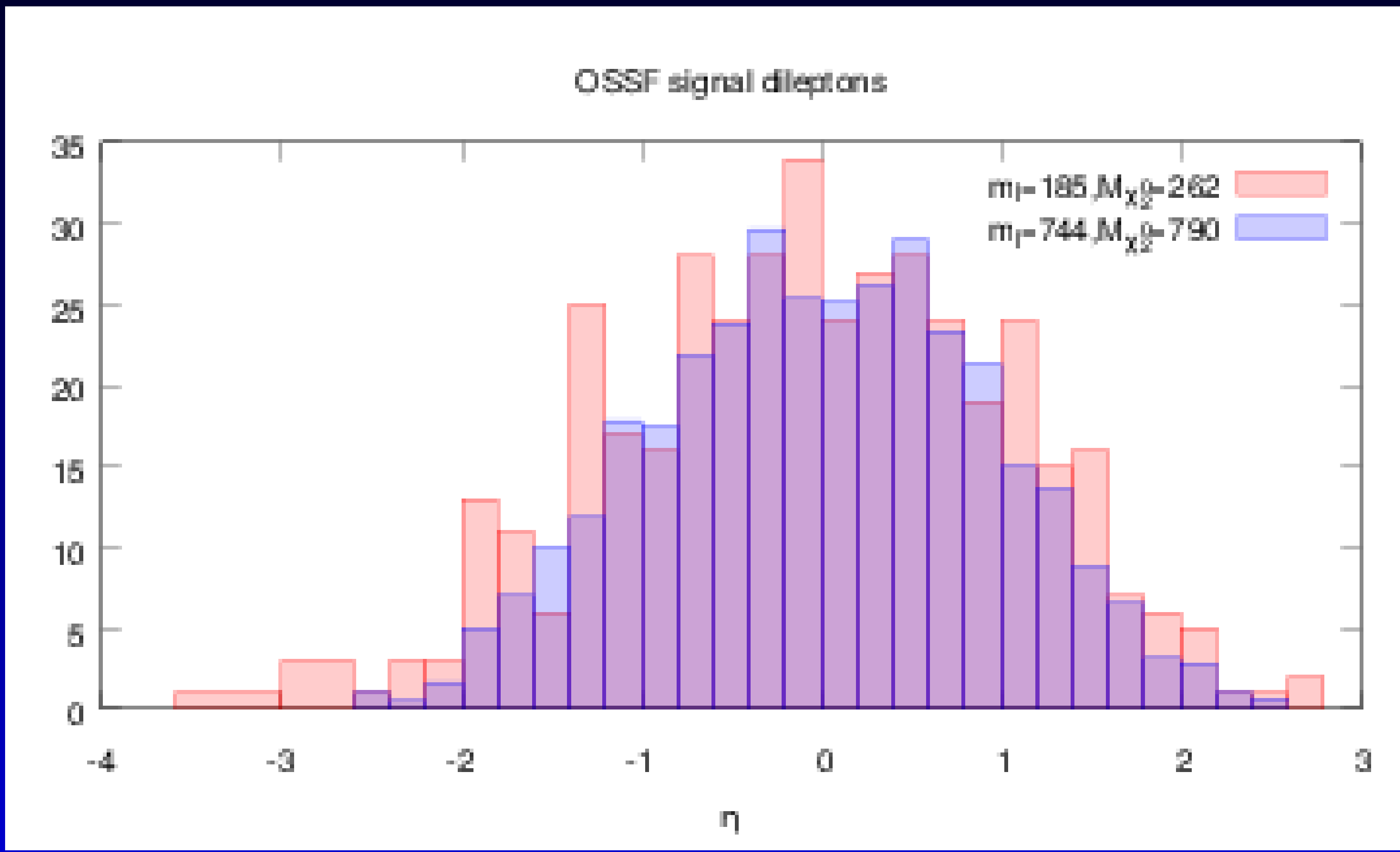


S3: $M_2 \ll M_1$: $\tilde{W}$ LSP $\tilde{l}_L \to \chi_1^\pm$, but $\chi_1^\pm$ decays via λ'_{111} too.

Summary

- Standard SUSY *with decoupled gluinos* can explain the $lljj\not{E}_T$ excess with $\not{E}_T$.
- Another possibility to try is to bring the gluinos lighter and decouple the squarks.
- To explain three other excesses in $lljj$ and $ljj\not{E}_T$, we invoke RPV. We can explain all three, and there are possibilities for measuring $0\nu\beta\beta$ in the next years.

Pseudorapidity of Leptons



UV Limit of Decoupled Gluinos