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R-parity Violation and SUSY Searches at the LHC

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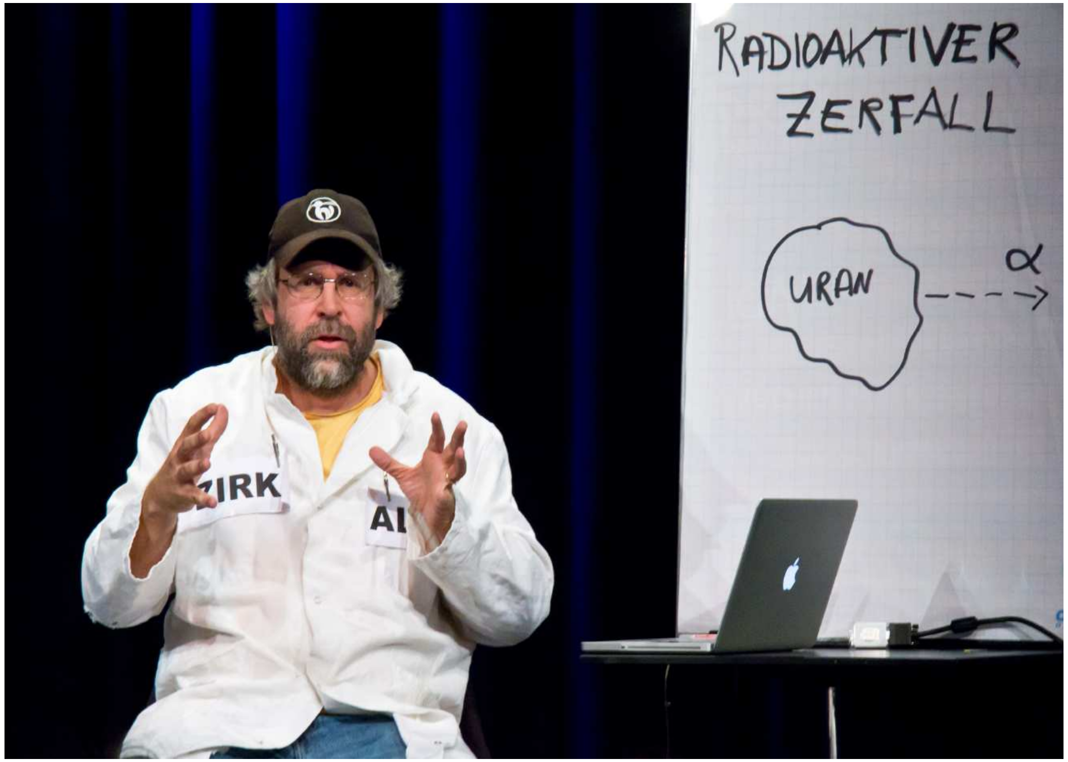


OUTLINE

- LHC SUSY Searches mainly focused on a fairly narrow set of signatures
  - R-parity conservation (RPC)
  - Missing transverse momentum (MET, or $\not{E}_T$)
- Motivation for R-Parity Conservation $\leftrightarrow$ R-parity Violation (RPV)
- Outline status of CMSSM – using `FITTINO` results
- Top-10 “RPV-CMSSM” Signatures
- Generalized RPC and RPV Signatures

SUSY SPECTRUM

Standard Model + SUSY $\Longrightarrow$ Double Spectrum (+2 Higgs Doublets)

e^- (spin $= \frac{1}{2}$)	$\longleftrightarrow$	$\tilde{e}$ $(s=0)$	scalar electron
top t $(s=\frac{1}{2})$	$\longleftrightarrow$	$\tilde{t}$ $(s=0)$	scalar top
$W^\pm$ $(s=1)$	$\longleftrightarrow$	$\tilde{W}^\pm$ $(s=0)$	Wino
$H^\pm$ $(s=0)$	$\longleftrightarrow$	$\tilde{H}^\pm$ $(s=\frac{1}{2})$	Higgsino
γ, Z^0 $(s=1)$	$\longleftrightarrow$	$\tilde{\gamma}$, $\tilde{Z}^0$ $(s=\frac{1}{2})$	Photino, Zino
H^0, h^0 $(s=0)$	$\longleftrightarrow$	$\tilde{H}^0$, $\tilde{h}^0$, $\tilde{A}^0$ $(s=\frac{1}{2})$	Higgsino
$g_{a=1,\ldots,8}$ $(s=1)$	$\longleftrightarrow$	$\tilde{g}_a$ $(s=\frac{1}{2})$	Gluino

SUSY LAGRANGIAN

- SUSY Lagrangian fixed by
  - gauge group: SU(3)xSU(2)xU(1)
  - particle content: L_i, $\bar{E}_i$, Q_i, $\bar{U}_i$, $\bar{D}_i$, H_u, H_d (chiral superfields)

$$L = \begin{pmatrix} N \\ E \end{pmatrix}_L \sim \begin{pmatrix} \phi_{\tilde{\nu}} + \epsilon\psi_\nu \\ \phi_{\tilde{e}} + \epsilon\psi_e \end{pmatrix}_L, \quad E^c \sim \phi^*_{\tilde{e}} + \epsilon\psi^c_{e_R}$$

$$Q = \begin{pmatrix} U \\ D \end{pmatrix}_L \sim \begin{pmatrix} \phi_{\tilde{u}} + \epsilon\psi_u \\ \phi_{\tilde{d}} + \epsilon\psi_d \end{pmatrix}_L, \quad U^c \sim \phi^*_{\tilde{u}} + \epsilon\psi^c_{u_R}, \quad D^c \sim \phi^*_{\tilde{d}} + \epsilon\psi^c_{d_R}$$

  - Yukawa-related interactions: Superpotential $\longrightarrow$

SUPERPOTENTIAL

- These terms give mass to quarks and leptons.

$$W_{\text{MSSM}} = (h_e)_{ij}\, L_i H_d E_j^c + (h_d)_{ij}\, Q_i H_d D_j^c + (h_u)_{ij}\, Q_i H_u U_j^c + \mu H_d H_u$$

- Automatically get extra terms

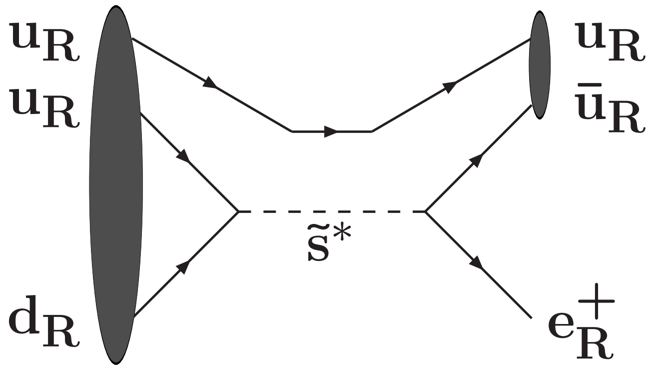
$$W_{\text{RPV}} = \underbrace{\lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \kappa_i L_i H_u}_{\text{Lepton Number Violating}} + \underbrace{\lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k}_{\text{Baryon Num. Viol.}}$$

- Do you only consider W_{MSSM} or include some or all of W_{RPV}?

- Problem: proton decay

PROTON DECAY

- **LQD and UDD $\longrightarrow$ Proton Decay:** $p \to \pi^0 + e^+$



$$\lambda'_{11j} \cdot \lambda''_{11j} < 2 \cdot 10^{-27} \left(\frac{M_{\tilde{d}_j}}{100\,\mathrm{GeV}} \right)^2 , \quad i = 1, 2\,, \; j \neq 1\,,$$

- The supersymmetric SM is excluded!

- Must add a symmetry to kill at least one coupling

Discrete Symmetries – by Hand

- **R-parity:** $(-1)^{3B+L+2S}$,
- Discrete $\mathbf{Z}_2$ multiplicative symmetry $[R_p(e^-) = e^-; \;\; R_p(\tilde{e}^-) = -\tilde{e}^-]$
- This prohibits all extra operators: UDD, LLE, LQD, LH_u
- Lepton- and Baryon-number are conserved
- The proton is stable
- All SUSY particles produced in pairs
- Lightest SUSY particle (LSP) stable......
  - dark matter
  - $\not{E}_T$ signatures

OTHER SIMPLE OPTIONS

- **BARYON PARITY:** Prohibits UDD Terms

$$(Q, U^c, D^c) \longrightarrow -(Q, U^c, D^c)$$
$$(L, E^c, H_1, H_2) \longrightarrow +(L, E^c, H_1, H_2)$$

- **LEPTON PARITY:** Prohibits LLE, LQD, LH Terms

$$(L, E^c) \longrightarrow -(L, E^c)$$
$$(Q, U^c, D^c, H_1, H_2) \longrightarrow +(Q, U^c, D^c, H_1, H_2)$$

- **BARYON TRIALITY (B_3):** Prohibits UDD Terms

$$\Psi_j \to e^{i\alpha_j 2\pi/3}\Psi_j$$

	Q	U^c	D^c	L	E^c	H_d	H_u
α_j	0	2	1	2	2	2	1

- Proton always stable

Analysis of Discrete Symmetries

- `Krauss & Wilczek:` expect all global symmetries to be violated by quantum gravity effects, also for discrete symmetries
- Exception: discrete symmetry is the remnant of a spontaneously broken gauge symmetry

$\Longrightarrow$ "discrete gauge symmetry"

- `Ibanez & Ross:` if the original U(1) gauge symmetry is anomaly-free

$\Longrightarrow$ conditions on the remnant discrete symmetry

$\Longrightarrow$ "anomaly-free discrete symmetry"

- `Ibanez & Ross:` systematic study of all $\mathbf{Z}_{2,3}$ with MSSM particle content

$\Longrightarrow$ only two anomaly-free discrete symmetries: R_p, B_3

- R_p: dangerous dim-5 proton decay operators

General Analysis

HD, Christoph Luhn, Marc Thormeier

- We extended the Ibanez & Ross analysis to all $\mathbf{Z}_N$ symmetries

- Find four $\mathbf{Z}_6$, nine $\mathbf{Z}_9$, and nine $\mathbf{Z}_{18}$ as new fundamental anomaly-free symmetries

- Require:

1. $\mu H_1 H_2$ in Lagrangian

2. No dim-5 proton decay operators

3. See-saw neutrino mass term: LH_2LH_2

- Only **proton-hexality**: P_6, and **baryon-triality**: B_3 remain

(• R-parity allows dim-5 proton decay operators)

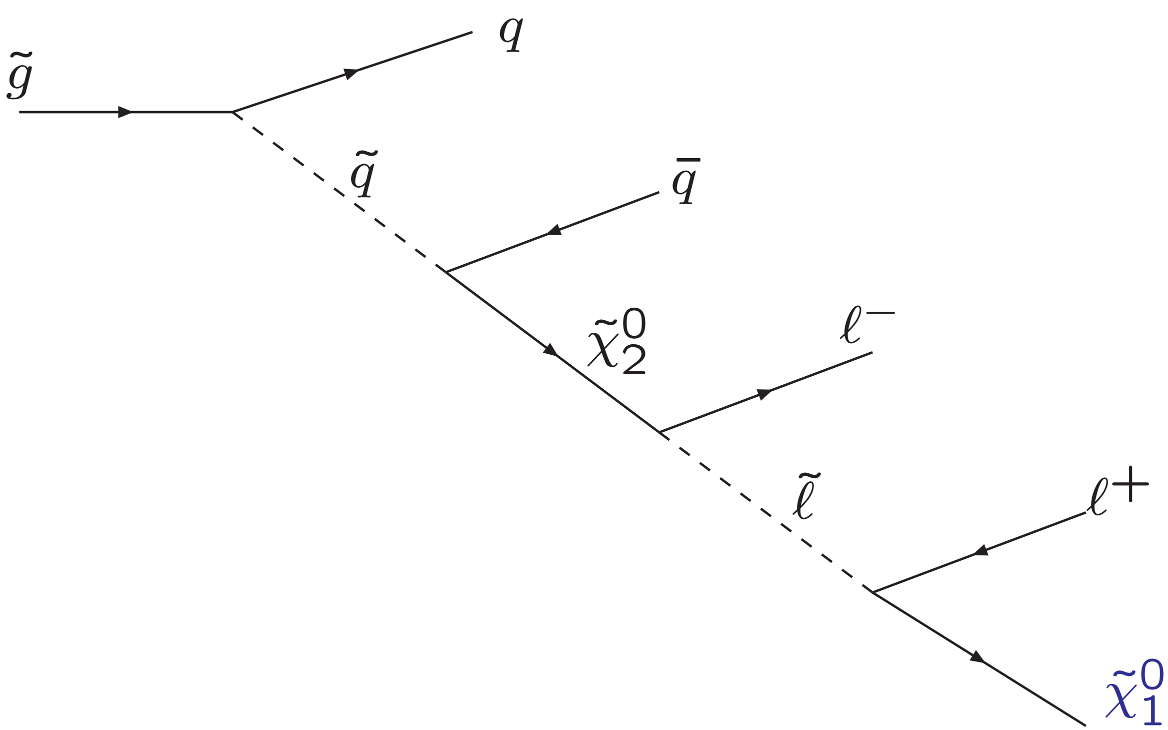
R-Parity MSSM

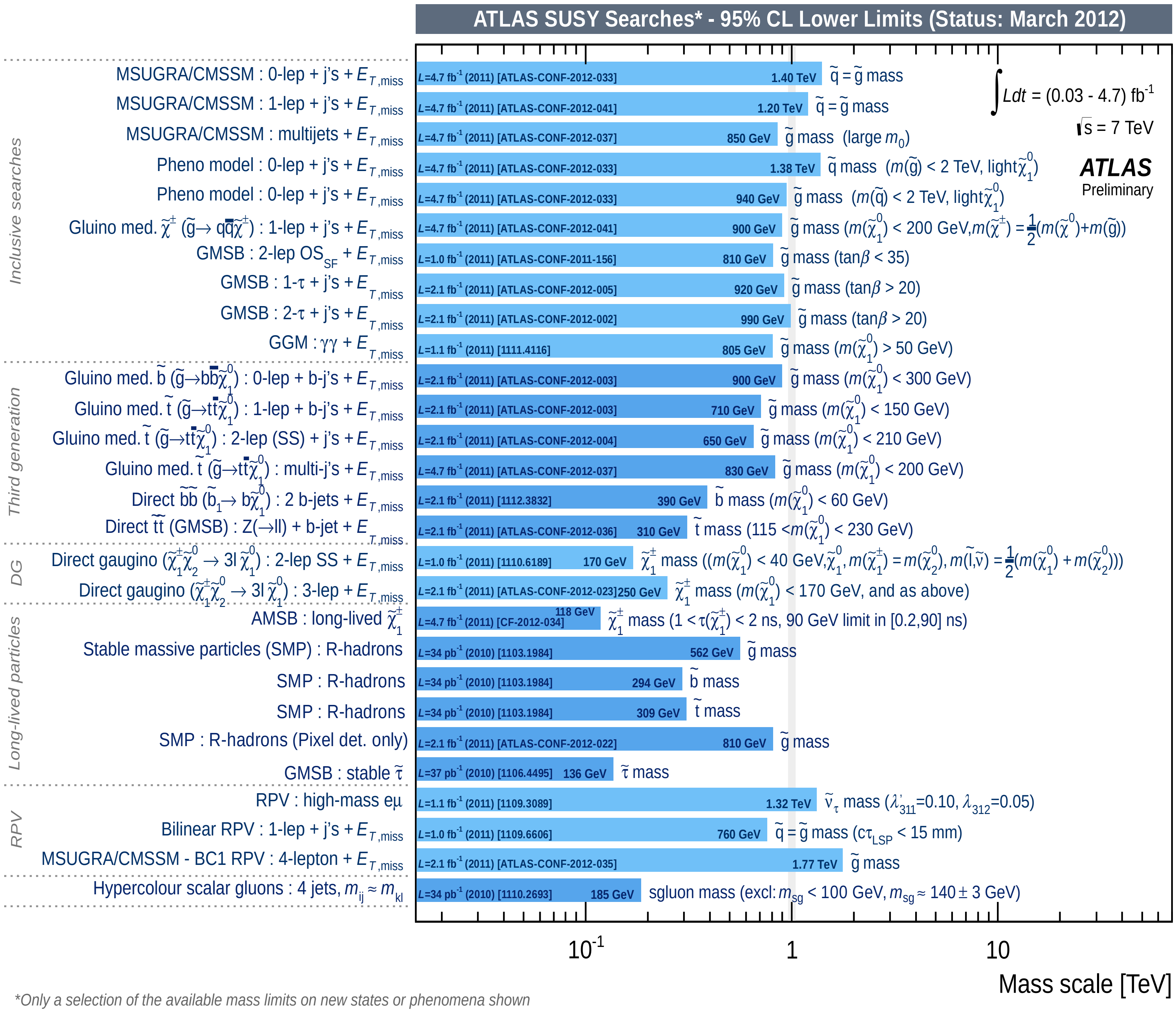
- Low-energy R_p and P_6 equivalent

$$W_{\mathsf{MSSM}} = (h_e)_{ij}\, L_i H_d E^c_j + (h_d)_{ij}\, Q_i H_d D^c_j + (h_u)_{ij}\, Q_i H_u U^c_j + \mu H_d H_u$$

- SUSY particles only produced in pairs: $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{q}$ (dominant)

- LSP stable: focus on parameter regions where LSP=χ^0_1, MET



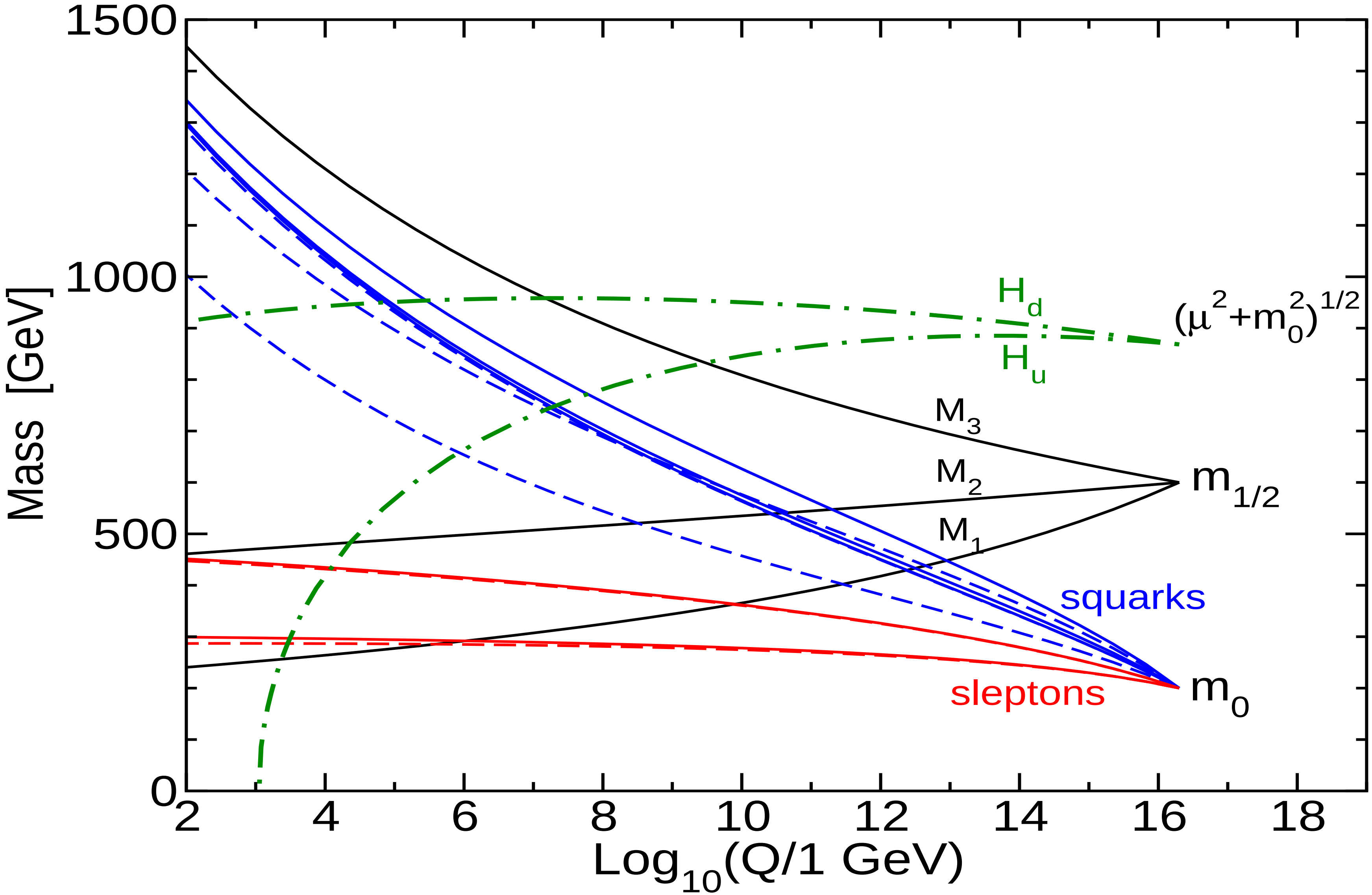


*Only a selection of the available mass limits on new states or phenomena shown

Simple Model: CMSSM

- Universal soft supersymmetry breaking parameters at unification scale
  - scalar SUSY masses: $m_{\tilde{\ell}} = m_{\tilde{q}} = M_0$
  - gaugino masses: $M_1 = M_2 = M_3 = M_{1/2}$
  - trilinear scalar couplings: $A_e = A_\mu = ... = A_t = A_0$
- Ratio of Higgs vacuum expectation values: $\tan\beta$
- The sign of the Higgs mass coupling: $\text{sgn}\mu$
- **Important:** Assume R-parity is conserved, LSP stable, MET

SUSY Spectrum



From: A Supersymmetry primer; S. P. Martin, hep-ph/9709356

CMSSM Fit without LHC exclusions

Bechtle, Bringmann, Desch, HD, Hamer, Hensel, Krämer, Porod, Prudent, Sarrazin, Uhlenbrock, Wienemann: `FITTINO: arXiv:1204.4199 [hep-ph]`

Input:

- Indirect constraints

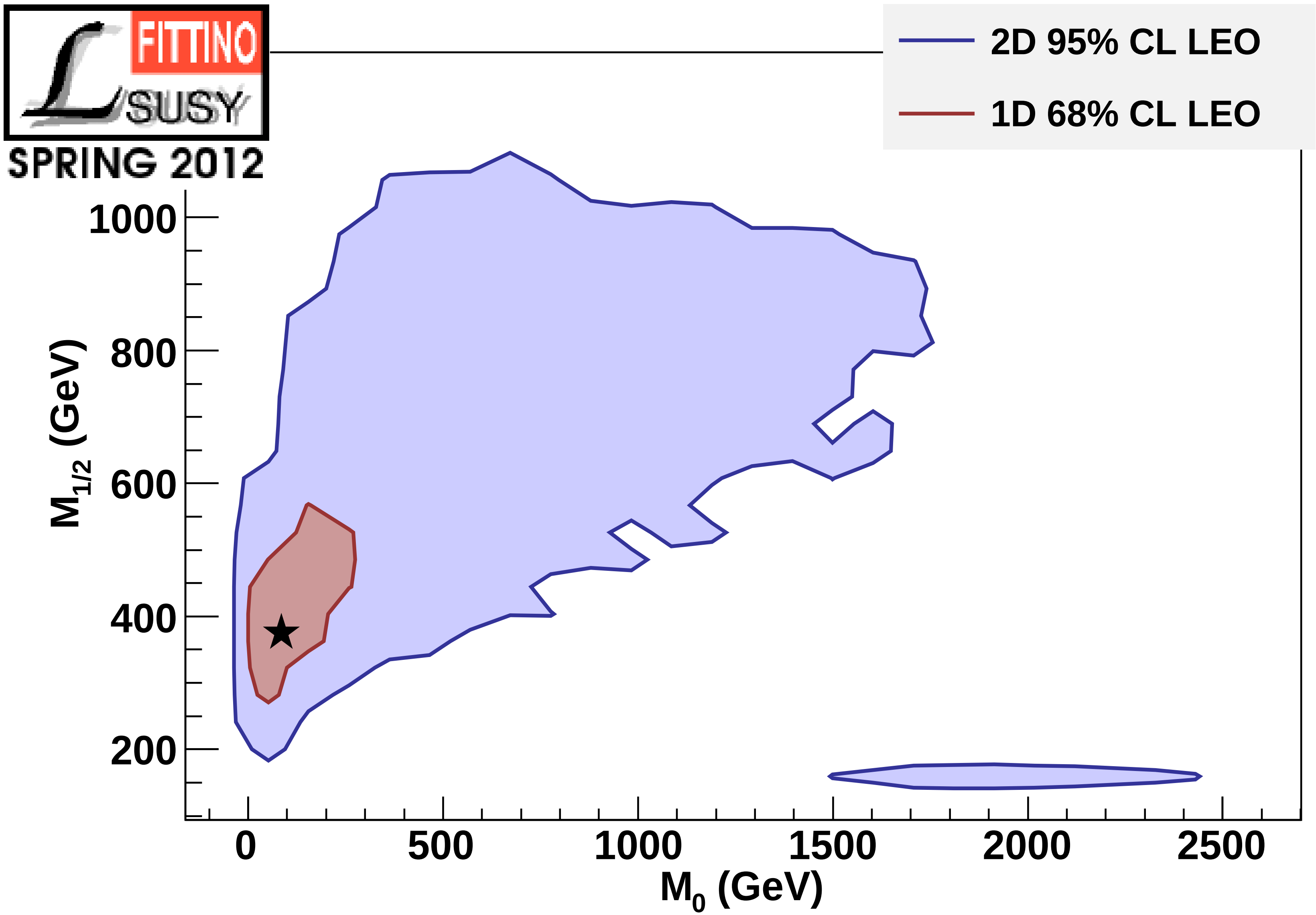
$\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu\mu)$, $\mathrm{BR}(B \to \tau\nu)$, Δm_{B_s}, $(g-2)_\mu$, m_W, $\sin^2\theta_{\mathrm{eff}}$

- Constraints from astrophysical observations

Ω_{DM}, direct and indirect detection limits

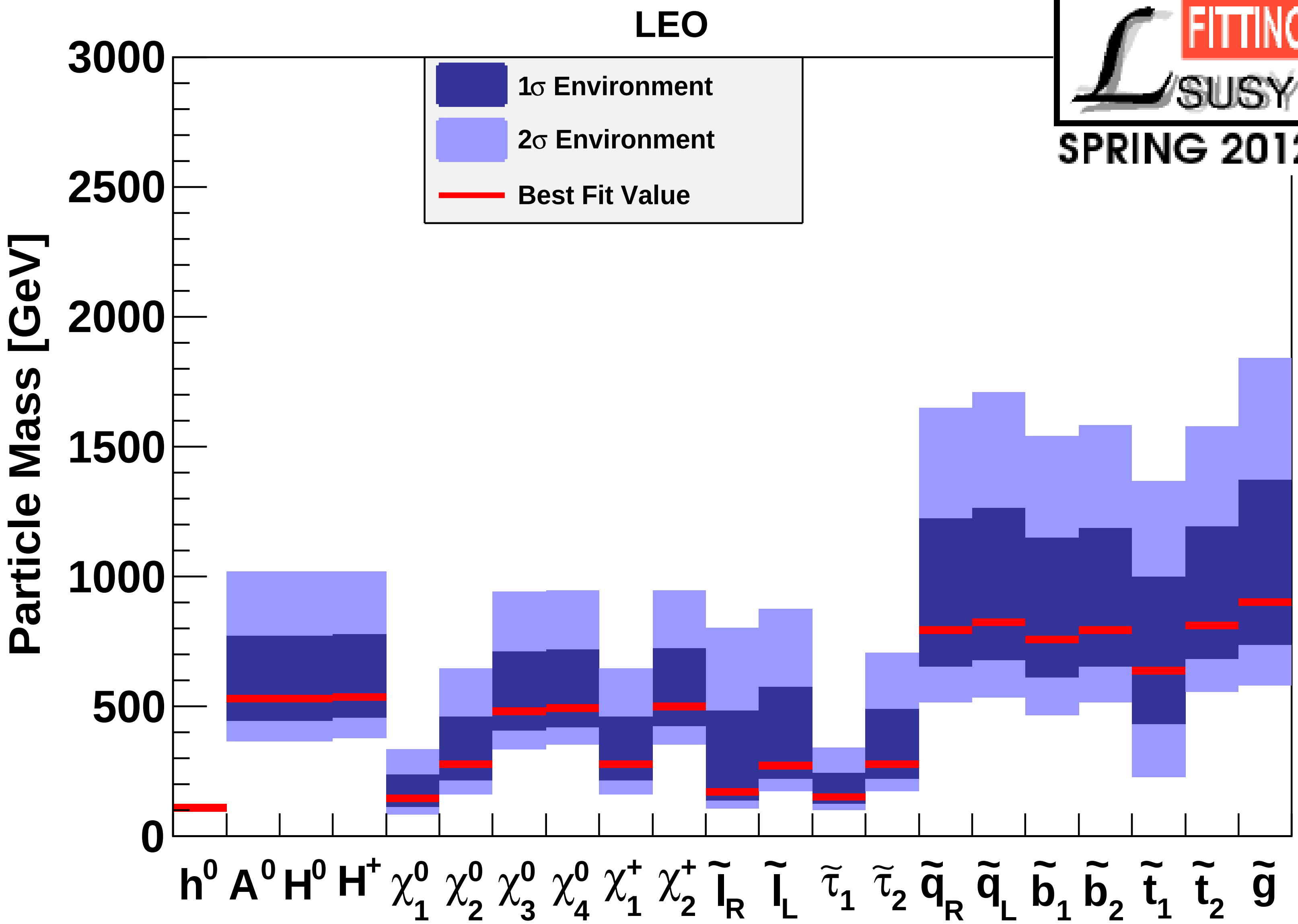
- Direct Sparticle and Higgs search limits from colliders

$m_{\chi^\pm}$, limits on MSSM Higgs boson masses from `HiggsBounds`



Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	tan β	A_0	χ^2/ndf
LEO	$84.4^{+144.6}_{-28.1}$	$375.4^{+174.5}_{-87.5}$	$14.9^{+16.5}_{-7.2}$	$186.3^{+831.4}_{-843.7}$	10.3/8

Best Fit LEO Spectrum

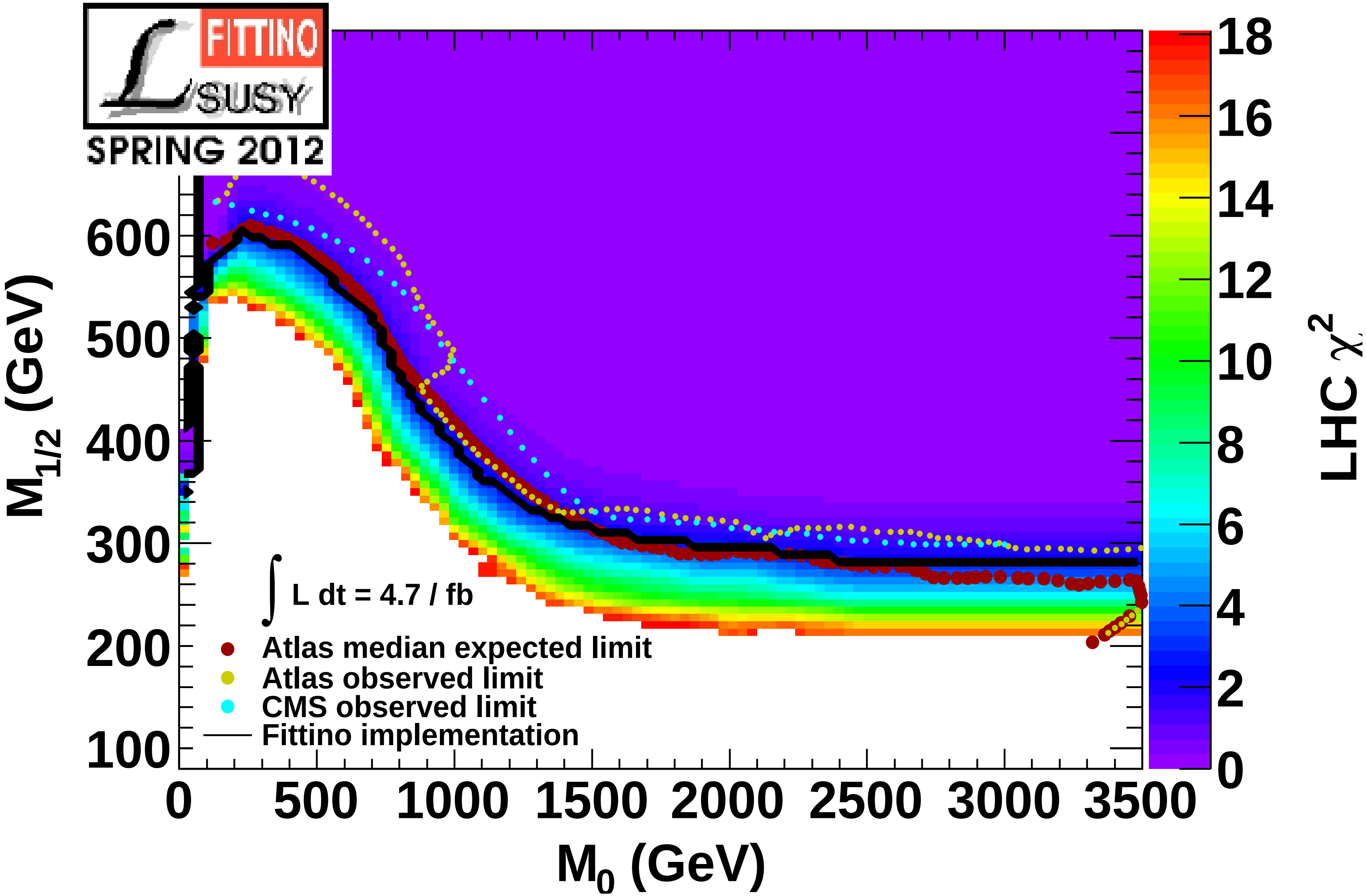


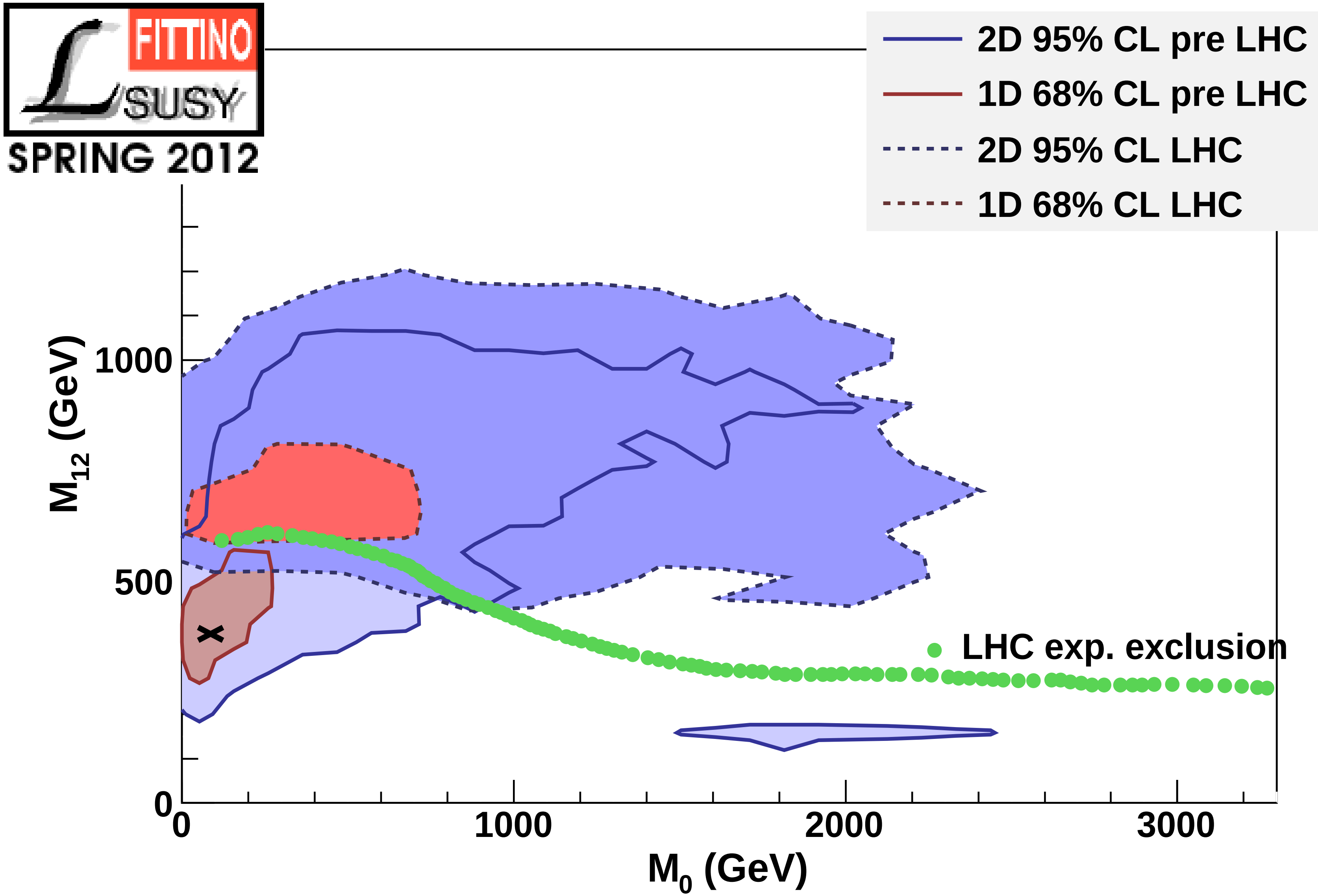
Include LHC Data

- We follow a recent ATLAS analysis in the jets+0l+$E_{T\text{miss}}$ signature.
- We have calculated the CMSSM signal for a grid in $(m_0, m_{1/2})$ using
  - the spectrum generator `SPheno`;
  - the MC generator `Herwig++`;
  - NLO+NLL K-factors;
  - the fast detector simulation `Delphes`.

  and have verified the independence of the signal yield from $\tan\beta$ and A_0.
- The SM background is taken from the ATLAS simulation.

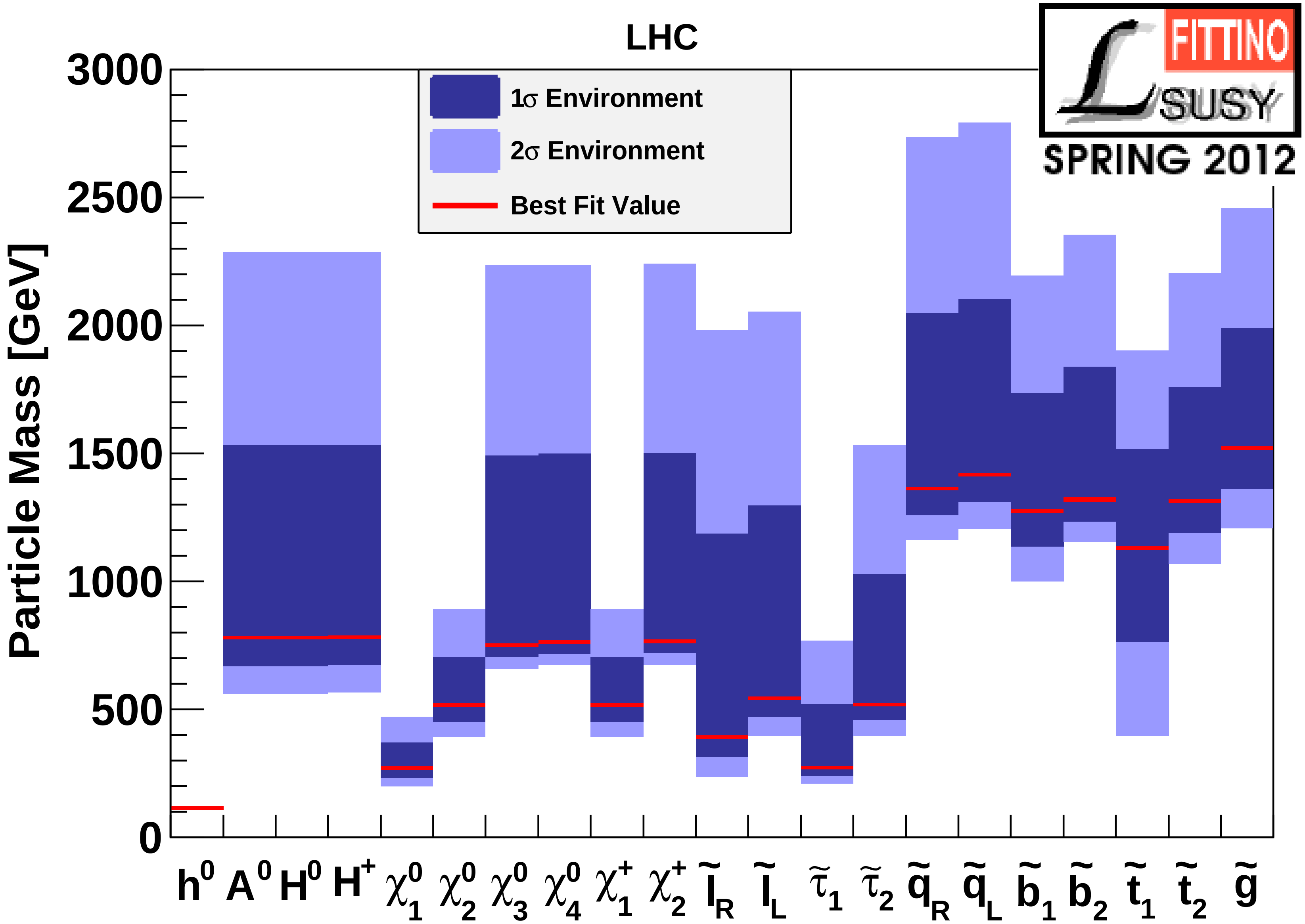
Best Fit LHC 5 fb^{-1} Spectrum

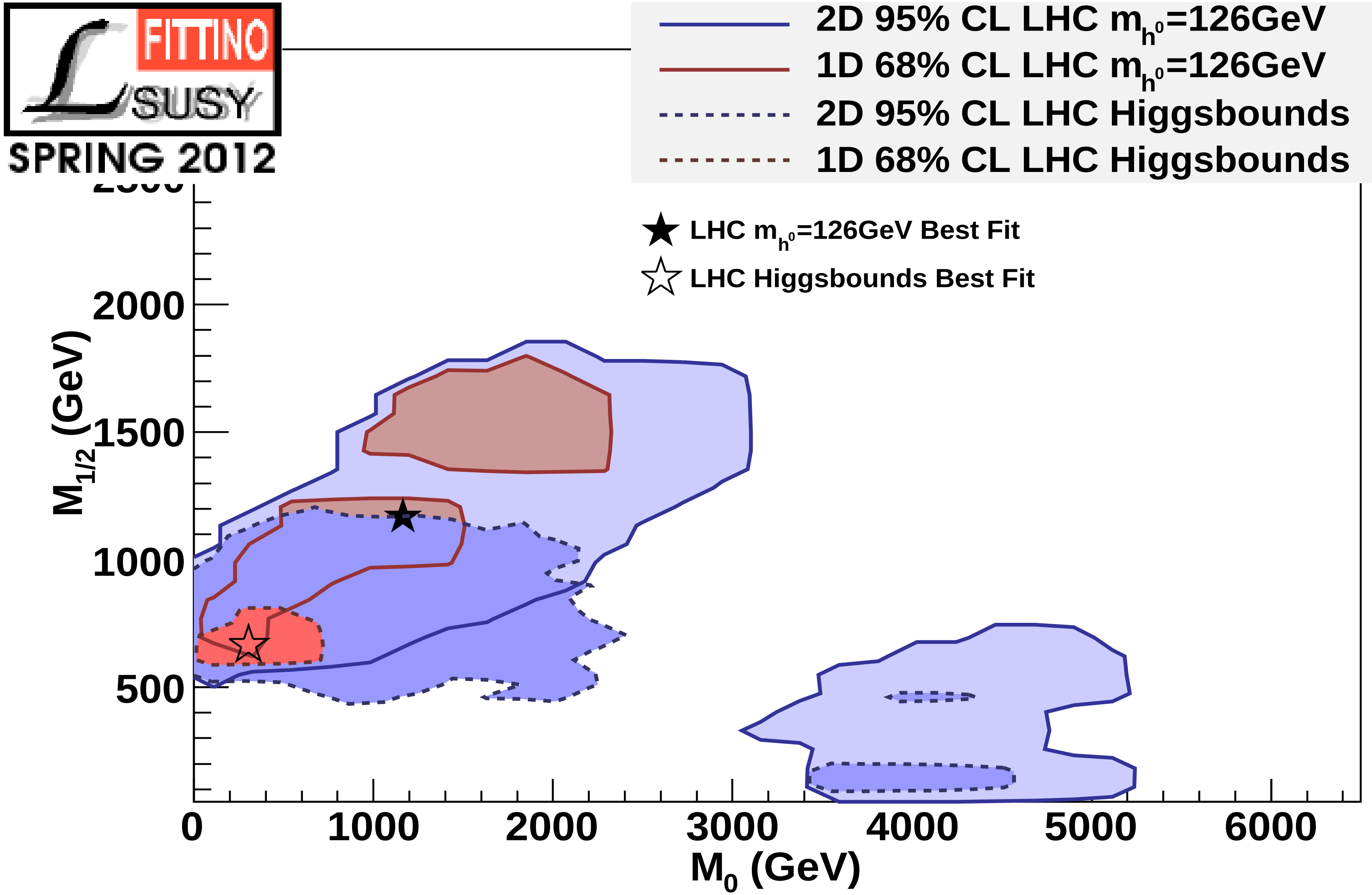




Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	$\tan\beta$	A_0	χ^2/ndf
LHC	$304.3^{+373.7}_{-185.2}$	$664.6^{+138.1}_{-70.9}$	$34.4^{+15.3}_{-21.3}$	$884.76^{+1178.0}_{-974.9}$	13.0/9

Best Fit LHC 5 fb^{-1} Spectrum





Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	tan β	A_0	χ^2/ndf
LHC+$m_h = 126$ GeV	$1163.2^{+1185.3}_{-985.7}$	$1167.4^{+594.0}_{-513.0}$	$39.3^{+16.7}_{-32.7}$	$-2969.1^{+6297.8}_{-1234.9}$	18.4/9

Summary CMSSM Fits

fit	M_0	$M_{1/2}$	$\tan\beta$	A_0	χ^2/ndf
no LHC	$84.4^{+144.6}_{-28.1}$	$375.4^{+174.5}_{-87.5}$	$14.9^{+16.5}_{-7.2}$	$186.3^{+831.4}_{-843.7}$	10.3/8
with LHC	$304.3^{+373.7}_{-185.2}$	$664.6^{+138.1}_{-70.9}$	$34.4^{+15.3}_{-21.3}$	$884.76^{+1178.0}_{-974.9}$	13.0/9
LHC+m_h=126	$1706.5^{+244.7}_{-1499.3}$	$1378.1^{+328.1}_{-689.9}$	$57.1^{+1.5}_{-49.4}$	$-2015.7^{+3408.3}_{-2019.5}$	18.2/9

- including the current LHC exclusion limits leads to tensions within constrained models like the CMSSM
- in particular, Higgs masses $\gtrsim$ 125 GeV are hard to accommodate
- essentially, we have to give up on an improved description of low energy data, like $(g-2)_\mu$
- we should move to more general models, but just from exclusions it is hard to constrain a larger set of free parameters

R-Parity (C)MSSM

Disadvantages:

- Must add ν_R and Majorana scale $\mathrm{M_M} > 10^{11}$ GeV for see-saw neutrino masses
- dim-5 proton decay operators, e.g. QQQL
- Within CMSSM: 125 GeV Higgs mass
- Main problem: haven't found anything yet.

- Peccei - Quinn solution to strong CP problem: axion/axino

Beyond RPC CMSSM

- Drop some CMSSM assumptions
- Here: choose different symmetry: baryon triality

Baryon Triality

- $W = W_{\text{MSSM}} + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \kappa_i L_i H_u$

Advantages:

- Proton stable
- Automatic light neutrino masses (1 Tree: LH; Loop: LLE, LQD)
- Automatic dark matter candidate: axion or axino

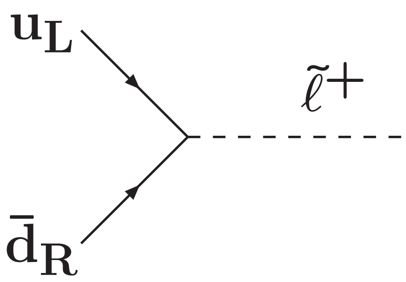
[Gravitino: Buchmüller et al: JHEP 0703 (2007) 037]

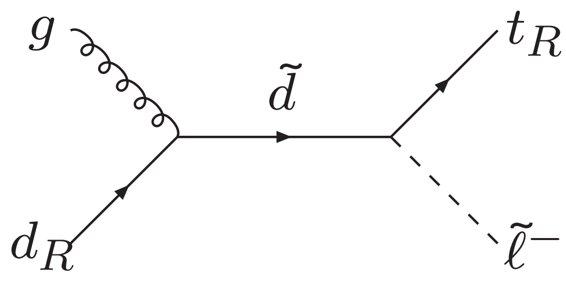
Disadvantages:

- Not observed to date: but haven't looked as hard ... yet

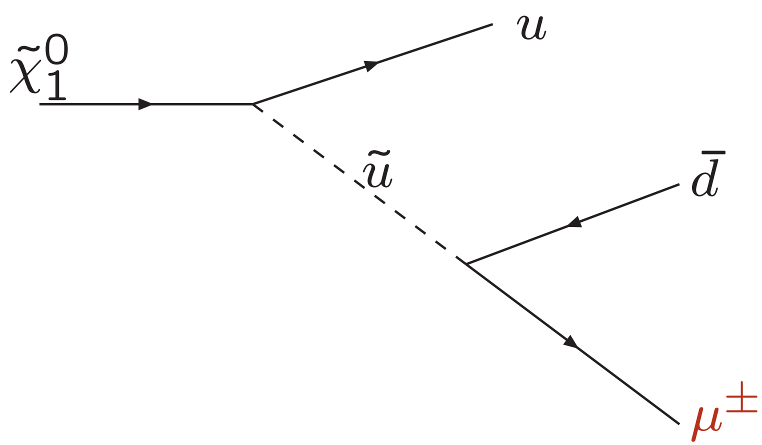
B_3-Phenomenology: Main Changes

1. Resonant/Associated Single SUSY Production possible





2. LSP is no longer stable



3. LSP $\in \{\chi_1^0, \chi_1^+, \tilde{\nu}_L, \tilde{\ell}^\pm_{L,R}, \tilde{\tau}_1^\pm, \tilde{q}_{L,R}, \tilde{t}_1, \tilde{g}\}$

4. In RPV–CMSSM spectrum can differ

Plethora of new Signatures

$$\begin{pmatrix} \text{pair production}: \ \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g} \\ \text{resonant } \tilde{\ell} \text{ production} \end{pmatrix} \otimes \begin{pmatrix} \underline{\textbf{LSP}} \\ \tilde{\chi}_1^0 \\ \tilde{\chi}_1^+ \\ \tilde{\nu}_L \\ \tilde{\ell}^{\pm}_{L,R} \\ \tilde{\tau}_1^{\pm} \\ \tilde{q}_{L,R} \\ \tilde{t}_1 \\ \tilde{g} \end{pmatrix} \otimes \begin{pmatrix} \underline{\textbf{Operator}} \\ L_1 L_2 \bar{E}_1 \\ \vdots \\ L_2 L_3 \bar{E}_3 \\ L_e Q_1 \bar{D}_1 \\ \vdots \\ L_\mu Q_1 \bar{D}_1 \\ \vdots \\ L_\tau Q_3 \bar{D}_3 \\ \bar{U}_i \bar{D}_j \bar{D}_k \end{pmatrix}$$

- With one dominant operator something like 720 possibilities
- Later: even go beyond this and consider general mass hierarchies
- Help! Where to start?

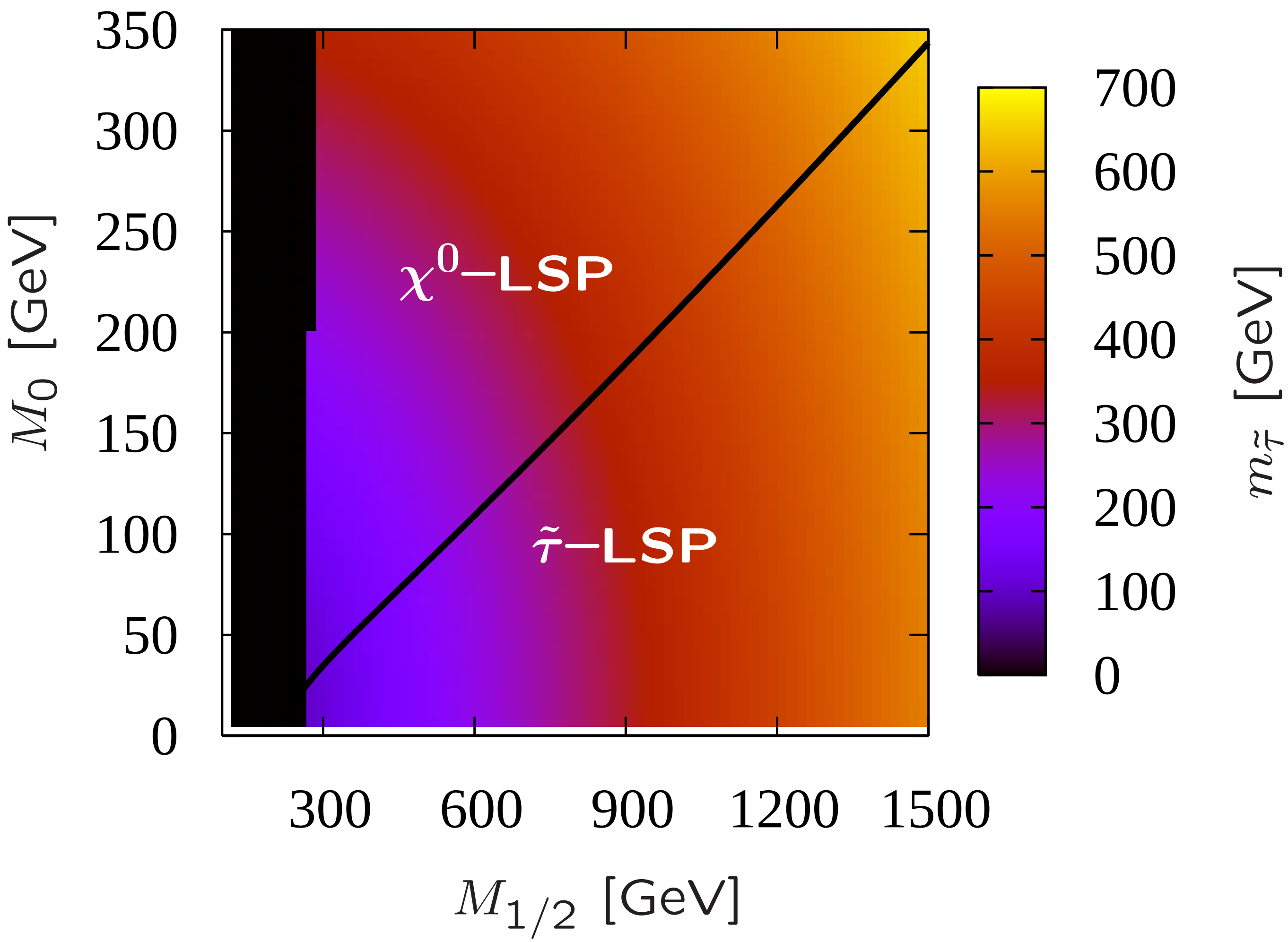
Simplifying Assumptions

- As for RPC MUST make simplifying assumptions, in order to start somewhere.
- First scenario: CMSSM + 1 RPV coupling
- At M_{GUT}: $M_0,\ M_{1/2},\ A_0,\ \tan\beta, \mathrm{sgn}(\mu),\ \Lambda$
- Exactly one coupling: $\Lambda \in \{\lambda_{ijk},\ \lambda'_{ijk},\ \lambda''_{ijk}\}$

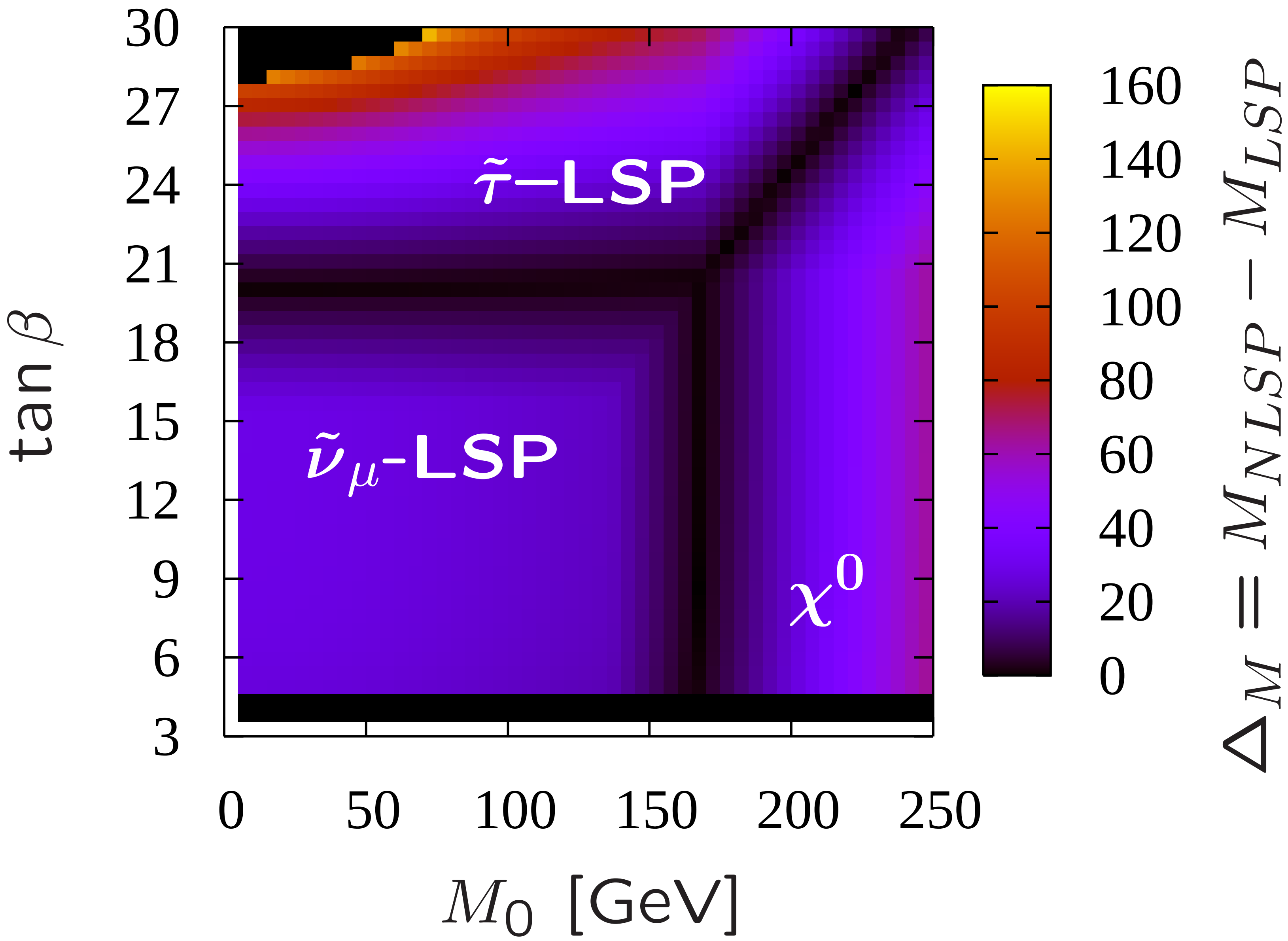
$$W_{\mathrm{RPV}} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

- RGE's change, ie spectrum can change, in particular LSP can change
- Details in: *R parity violating minimal supergravity model*; Allanach, Dedes, HD; Phys.Rev. D69 (2004) 115002

$\tilde{\tau}$-LSP with $\Lambda = 0$



- SPS1a($M_0 = 100$ GeV, $M_{1/2} = 250$ GeV) chosen so χ_1^0 is LSP



$M_{1/2} = 500$ GeV, $A = -500$ GeV, sgn(μ)=+1, $\lambda'_{221} = 0.1$

First Step: $\tilde{\chi}_1^0$–LSP

- Pair production: $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$

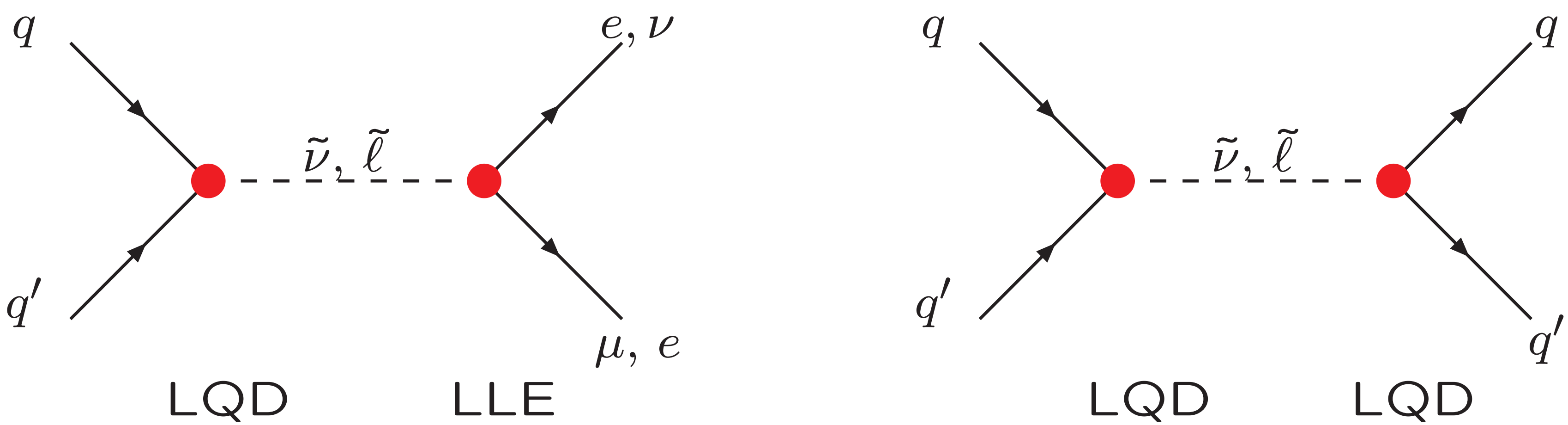
- $\tilde{\chi}_1^0$–LSP: $\tilde{\chi}_1^0 \to \begin{cases} \ell^\pm + \ell^\mp + \not{p}_T & \mathsf{L_1L_{2,3}\bar{E}_{1,2},\ L_2L_3\bar{E}_1} \\ \ell^\pm + \tau^\mp + \not{p}_T & \mathsf{L_{1,2}L_3\bar{E}_3} \\ \ell^\pm + 2\,\mathrm{jets} & \mathsf{L_{1,2}Q_i\bar{D}_k} \\ \ell^\pm + 2\,\mathrm{jets} & \mathsf{L_{1,2}Q_i\bar{D}_k} \end{cases}$ $\qquad \ell = e, \mu$

- Signatures: 4 charged leptons + $\not{p}_T$ + jets $\quad$ ($e^+e^+\mu^-\mu^-$+jets)
  ($e^+e^+\tau^-\tau^-$+jets)

  like–sign dileptons + jets $\quad$ ($\ell^+\ell^+$+jets)

- **UDD:** this is the big challenge; LSP decay: $\chi_1^0 \to 3\,\mathrm{jets}$
  - Use leptons from cascade decay (model dependent)
  - Or jet substr. à la Butterworth et al Phys.Rev.Lett. 103 (2009) 241803

Resonant Production ($\tilde{\chi}_1^0$–LSP)



- Signatures: dilepton resonance: $(e^+e^-,\ \mu^+\mu^-,\ e^+\mu^-,\ e^+\tau^-,\ \mu^+\tau^-)$

  mono lepton: $(e^\pm\nu,\ \mu^\pm\nu,\ \tau^\pm\nu)$

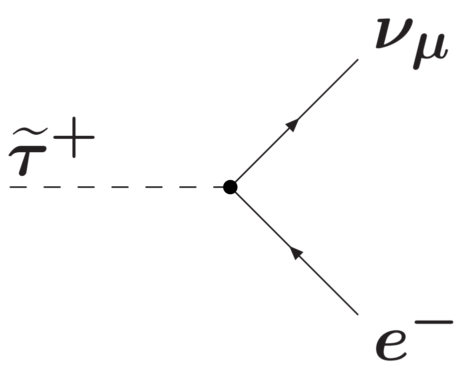
  dijet resonance: (qq')

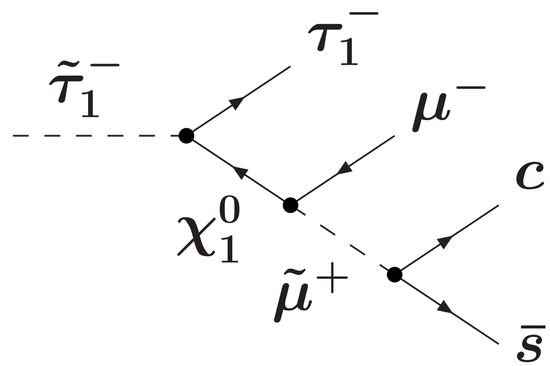
- For cascade slepton decay: $\tilde{\ell}^+ \to \ell^+ + \chi_1^0 \ \to \ell^+ + (\ell^+ + 2\,\text{jets})$

  like–sign dilepton: $(e^+e^+,\ \mu^+\mu^+,\ \tau^+\tau^+)$

Second Step: $\tilde{\tau}$–LSP

- Pair production: $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$
- Cascade decay to $\tilde{\tau}$, via χ_1^0 gives extra τ's: $(\chi_1^0)^* \to \tau^{\pm}\tilde{\tau}^{\mp}$





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$L_iL_j\bar{E}_k$ (i, j, or $k = 3$)

(i, j, AND $k \neq 3$)

- See Desch, Fleischmann, Grab, Wienemann, HD: PRD 83 (2011) 015013
- Paper in progress by ATLAS collaboration

$\tilde{\tau}$–LSP Signatures – Examples

- <u>$LL\bar{E}$:</u> (a) $\tau \in LL\bar{E}$ $\tau^+\tau^+e^-e^-\nu\nu$

  (b) $\tau \notin LL\bar{E}$ $\mu^+\mu^+e^-e^-\nu\nu +$ 4τ's

.

- <u>$LQ\bar{D}$:</u> (a) $\tau \in LQ\bar{D}$ $\tau^+\tau^+ +$ 6 jets, no $\not{p}_T$

  (b) $\tau \notin LQ\bar{D}$ 4τ's $+ \not{p}_T +$ 4 jets

- So similar to χ_1^0–LSP but more τ's in final state
- Details depend on flavor structure of coupling...see paper

Detached Vertices: Signatures

- LSP lifetime proportional to λ^2, λ'^2 or λ''^2
- χ_1^0–LSP decay prompt for λ, λ', $\lambda'' \gtrsim 10^{-5}$ (depends on masses)
- Assuming detached vertex for $c\tau > 1\,\text{cm}$, have about 2 extra orders of magn. in λ, $\lambda'\,\lambda''$
- For λ, $\lambda' \lesssim 10^{-7}$ regain conserved R_p at colliders (not cosmology!)
- New Signatures: long lived χ_1^0, $\tilde{\tau}$, or $(\tilde{q}/\tilde{g})$
- Decays: leptonic, semi-leptonic, or hadronic

Proposed Top 10 LHC RPV Signatures

	Signature	Model
1)	4 charged leptons: $e^+e^+\mu^-\mu^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LL\bar{E}$
2)	2 leptons, 2 taus: $e^+e^+\tau^-\tau^-$	χ_1^0–LSP, $LL\bar{E}$, $\tilde{\tau}$–LSP, $LQ\bar{D}$
3)	6 jets or 2 w/ substructure	χ_1^0–LSP, $\bar{U}\bar{D}\bar{D}$
4)	like-sign dileptons + jets	χ_1^0–LSP, $LQ\bar{D}$
5)	dilepton resonance	$LL\bar{E} \otimes LQ\bar{D}$
6)	mono lepton	$LL\bar{E} \otimes LQ\bar{D}$
7)	dijet resonance	pure $LQ\bar{D}$
8)	like sign ditau's $\tau^-\tau^-$ + 6jets	$\tilde{\tau}$–LSP, $LQ\bar{D}$
9)	late decaying χ_1^0–LSP, $\tilde{\tau}$–LSP	$\lambda \lesssim 10^{-5}$
10)	late decaying $\tilde{q}$ or $\tilde{g}$–LSP	

- Not yet considered bilinear RPV models (w/ W. Porod in progress).

Related Work

- CMS have recently performed a trilepton search without MET ✗
- `HD+Tim Stefaniak`:
  - interpreted `ATLAS`, `CMS` resonant dijet search in RPV
  - interpreted `ATLAS` like-sign di-muon search in RPV
  - detailed flavor structure of Top-10 signatures
  - Lifetime studies
  - Even RPV has MET: use existing work

PRD 84 (2011) 015005, arXiv:1103.1883; arXiv:1201.5014

Generalized Signatures

Konar, Matchev, Park, Sarangi: *How to look for supersymmetry under the lamp post at the LHC*, PRL 105 (2010) 221801

- Consider as distinct particles

$$Q\ (\tilde{u}_L,\ \tilde{d}_L, \tilde{c}_L, ...),\quad U\ (\tilde{u}_R,\ \tilde{c}_r, \tilde{t}_R),\quad D\ (\tilde{d}_R,\ \tilde{s}_r, \tilde{b}_R),$$

$$L\ (\tilde{\nu}_{eL},\ \tilde{e}_L, \tilde{\nu}_{\mu L}, ...),\quad E\ (\tilde{e}_R,\ \tilde{\mu}_r, \tilde{\tau}_R)$$

$$H\ (\tilde{h}^{\pm}, \tilde{h}_u^0, \tilde{h}_d^0)\quad B\ (\tilde{b}^0)\quad W\ (\tilde{w}^{\pm}, \tilde{w}^0)$$

$$G\ (\tilde{g}_a)$$

- Various mass orderings, eg $GQUDHLWEB$ (9! different ones)

(• CMSSM only has 47 different hierarchies in this notation.)

- **What are the dominant collider signatures for each hierarchy?**

Generalized Signatures II

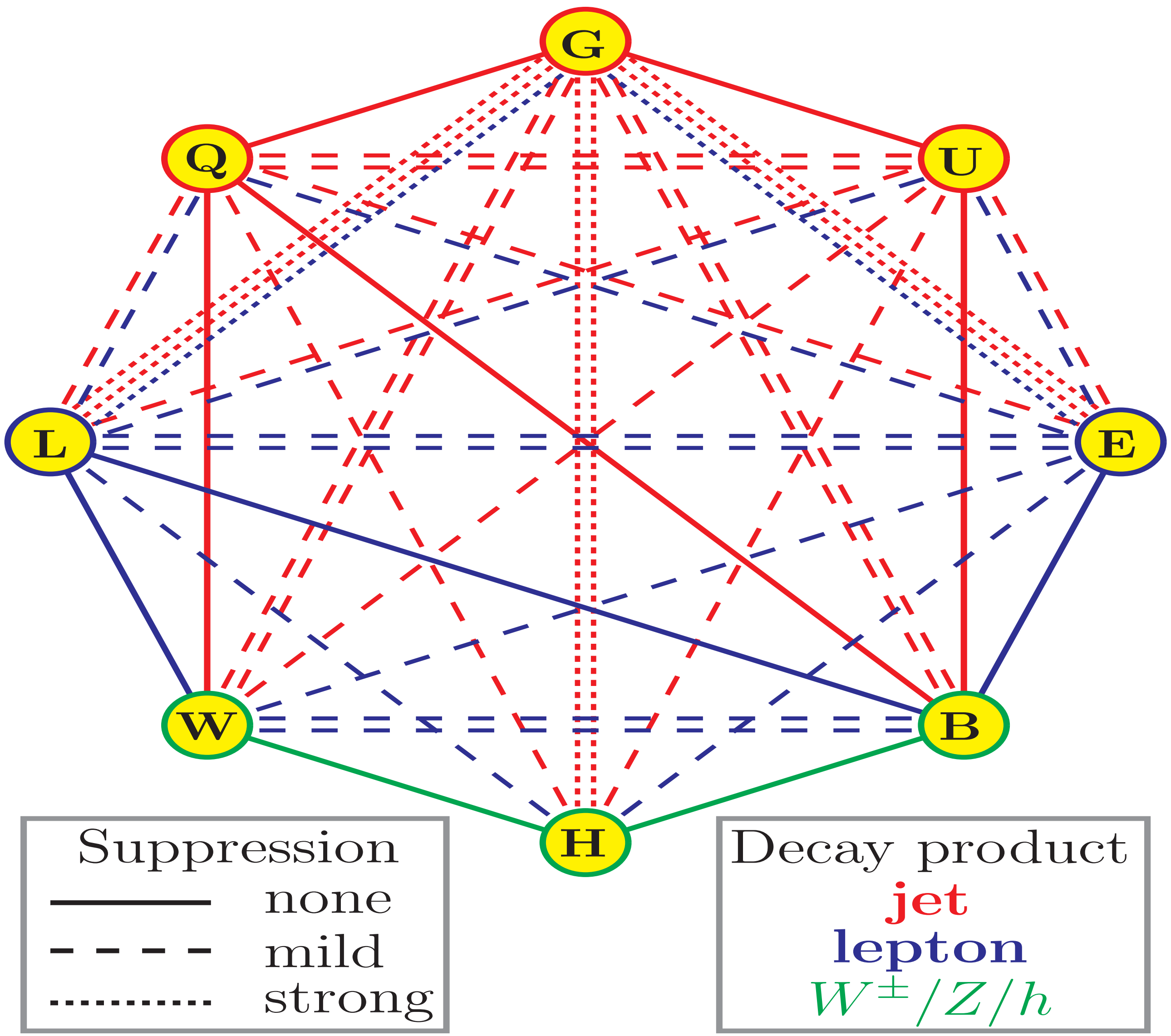
- Sort by LSP: CHAMP, R-Hadrons, MET-LSP
- Lightest colored particle "C" $\in \{G, Q, U, D\}$, hierarchies have form

$$x \ldots x C y \ldots y \mathcal{L}$$

- $\mathcal{L}$: LSP
- Dominant production CC, followed by "dominant" cascade decay(s)

$U \to B$ (+u =jet); $Q \to (B,\, W)$ (+q'=jet)

$W \to (L,\, Q,\, H)$ [+(ℓ, q, V)]



Konar, Matchev, Park, Sarangi, PRL

Results (decay branch)

Konar, Matchev, Park, Sarangi: PRL

	$n_v = 0$		$n_v = 1$		$n_v = 2$	
n_ℓ	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$	$n_j = 1$	$n_j = 2$
0	79296	26880	12768	3360	1344	672
1	30240	10080	1824	480	192	96
2	19770	6030	1500	180	0	0
3	4656	1296	312	72	6	6
4	1656	396	66	6	0	0

- Examples: $x_1 x_2 x_3 x_4 QWBLH$,

a) $(n_l, n_v, n_j) = (0,1,1)$: $\tilde{Q} \to \tilde{W} \to \tilde{H}$ or $\tilde{Q} \to \tilde{B} \to \tilde{H}$; 1 entry in Tab

b) $(n_l, n_v, n_j) = (2,0,1)$: $\tilde{Q} \to \tilde{W} \to \tilde{L} \to \tilde{H}$ or $\tilde{Q} \to \tilde{B} \to \tilde{L} \to \tilde{H}$
1 entry in Tab

- 4 leptons: $x_1 x_2 \tilde{G}\tilde{Q}\tilde{W}\tilde{L}\tilde{B}\tilde{E}\tilde{H}$, 2!

- More entries than hierarchies

Beyond Konar et al

HD, Florian Staub, Werner Porod, Avelinio Vicente: arXiv:1205.0557

- Separate third generation: $\tilde{Q}, \tilde{Q}_3, \tilde{U}, \tilde{U}_3, \tilde{D}, \tilde{D}_3, \tilde{L}, \tilde{L}_3, \tilde{E}, \tilde{E}_3, \tilde{W}, \tilde{H}, \tilde{B}, \tilde{G}$

- 14! hierarchies

- Allow for mass splitting between charged and neutral components of $\tilde{H}$ and $\tilde{W}$ $\longrightarrow$ breaks $SU(2)_L$

  $\Rightarrow$ distinguish charged leptons and MET [$\nu, (\chi^0_1, \tilde{\nu})$−LSP] signatures

- Consider: (a) RPC

  (b) RPV - λ, (c) RPV - λ', (d) RPV - λ''

  (e) Bilinear RPV - ϵ (κ)

- Assume RPV small – subdominant if other decay mode exists

COLORED DECAYS

- Consider all possible decays of the gluino

transition	strength	signat.	transition	strength	signat.	transition	strength	signat.
$\tilde{G} \leftrightarrow \tilde{d}$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{q}$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{u}$	not sup.	j
$\tilde{G} \leftrightarrow \tilde{W}^0$	sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{W}^\pm$	sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{e}$	str. sup.	$2j + l$
$\tilde{G} \leftrightarrow \tilde{H}^0$	str. sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{H}^\pm$	str. sup.	$2j$	$\tilde{G} \leftrightarrow \tilde{l}$	str. sup.	$2j + l$
$\tilde{G} \leftrightarrow \tilde{\nu}$	str. sup.	$2j + l$	$\tilde{G} \leftrightarrow \tilde{t}$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{b}$	not sup.	j
$\tilde{G} \leftrightarrow \tilde{q}_3$	not sup.	j	$\tilde{G} \leftrightarrow \tilde{\tau}_R$	str. sup.	$3j$	$\tilde{G} \leftrightarrow \tilde{\tau}_L$	str. sup.	$3j$
$\tilde{G} \leftrightarrow \tilde{\nu}_\tau$	str. sup.	$2j + \not{E}_T$	$\tilde{G} \leftrightarrow \tilde{B}$	sup.	$2j$			

- If kinematically allowed, the decays to squarks are 2-body and unsuppressed: 1 jet

- Decay $\tilde{G} \to \tilde{W}^0$ is 3-body and suppressed: 2 jets

- Decay $\tilde{G} \to \tilde{\nu}$ is 4-body and strongly suppressed: 2 jets

- As Konar et al, we focus on dominant decays

COLORED DECAYS

transition	strength	signat.	transition	strength	signat.	transition	strength	signat.
$\tilde{u} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{u} \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{u} \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{u} \leftrightarrow \tilde{W}^\pm$	sup.	j	$\tilde{u} \leftrightarrow \tilde{e}$	sup.	$j+l$
$\tilde{u} \leftrightarrow \tilde{H}^0$	sup.	j	$\tilde{u} \leftrightarrow \tilde{H}^\pm$	sup.	j	$\tilde{u} \leftrightarrow \tilde{l}$	sup.	$j+l$
$\tilde{u} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{u} \leftrightarrow \tilde{t}$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{b}$	sup.	$2j$
$\tilde{u} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{u} \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{u} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j + \not{E}_T$	$\tilde{u} \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{t} \leftrightarrow \tilde{G}$	not sup.	j	$\tilde{t} \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{t} \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{t} \leftrightarrow \tilde{W}^\pm$	sup.	j
$\tilde{t} \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{t} \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{t} \leftrightarrow \tilde{H}^\pm$	not sup.	j
$\tilde{t} \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{t} \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{t} \leftrightarrow \tilde{b}$	sup.	$2j$
$\tilde{t} \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{\tau}_R$	sup.	$2j$	$\tilde{t} \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{t} \leftrightarrow \tilde{\nu}_\tau$	sup.	$j + \not{E}_T$	$\tilde{t} \leftrightarrow \tilde{B}$	not sup.	j			

- As mentioned we include 3rd generation separately
- Decay $\tilde{t} \to \tilde{H}^0$ is 2-body and **not** suppressed: 1 jet
- Decay $\tilde{u} \to \tilde{H}^0$ is 2-body and suppressed: 1 jet

SLEPTON DECAYS

transition	strength	signat.	transition	strength	signat.	transition	strength	signat.
$\tilde{\tau}_R \leftrightarrow \tilde{G}$	str. sup.	$3j$	$\tilde{\tau}_R \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{q}$	sup.	$2j$
$\tilde{\tau}_R \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{W}^0$	sup.	j	$\tilde{\tau}_R \leftrightarrow \tilde{W}^\pm$	sup.	$\not{E}_T$
$\tilde{\tau}_R \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{\tau}_R \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{\tau}_R \leftrightarrow \tilde{H}^\pm$	not sup.	$\not{E}_T$
$\tilde{\tau}_R \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{\tau}_R \leftrightarrow \tilde{\nu}$	sup.	$j+\not{E}_T$	$\tilde{\tau}_R \leftrightarrow \tilde{t}$	sup.	$2j$
$\tilde{\tau}_R \leftrightarrow \tilde{b}$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{q}_3$	sup.	$2j$	$\tilde{\tau}_R \leftrightarrow \tilde{\tau}_L$	sup.	$2j$
$\tilde{\tau}_R \leftrightarrow \tilde{\nu}_\tau$	sup.	$j+\not{E}_T$	$\tilde{\tau}_R \leftrightarrow \tilde{B}$	not sup.	j			
$\tilde{\tau}_L \leftrightarrow \tilde{G}$	str. sup.	$3j$	$\tilde{\tau}_L \leftrightarrow \tilde{d}$	sup.	$2j$	$\tilde{\tau}_L \leftrightarrow \tilde{q}$	sup.	$j+\not{E}_T$
$\tilde{\tau}_L \leftrightarrow \tilde{u}$	sup.	$2j$	$\tilde{\tau}_L \leftrightarrow \tilde{W}^0$	not sup.	j	$\tilde{\tau}_L \leftrightarrow \tilde{W}^\pm$	not sup.	$\not{E}_T$
$\tilde{\tau}_L \leftrightarrow \tilde{e}$	sup.	$j+l$	$\tilde{\tau}_L \leftrightarrow \tilde{H}^0$	not sup.	j	$\tilde{\tau}_L \leftrightarrow \tilde{H}^\pm$	sup.	$\not{E}_T$
$\tilde{\tau}_L \leftrightarrow \tilde{l}$	sup.	$j+l$	$\tilde{\tau}_L \leftrightarrow \tilde{\nu}$	sup.	$j+\not{E}_T$	$\tilde{\tau}_L \leftrightarrow \tilde{t}$	sup.	$2j$
$\tilde{\tau}_L \leftrightarrow \tilde{b}$	sup.	$2j$	$\tilde{\tau}_L \leftrightarrow \tilde{q}_3$	sup.	$j+\not{E}_T$	$\tilde{\tau}_L \leftrightarrow \tilde{\tau}_R$	sup.	$2j$
$\tilde{\tau}_L \leftrightarrow \tilde{B}$	not sup.	j						
$\tilde{\nu}_\tau \leftrightarrow \tilde{G}$	str. sup.	$2j+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{d}$	sup.	$j+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{q}$	sup.	$j+\not{E}_T$
$\tilde{\nu}_\tau \leftrightarrow \tilde{u}$	sup.	$j+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{W}^0$	not sup.	$\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{W}^\pm$	not sup.	j
$\tilde{\nu}_\tau \leftrightarrow \tilde{e}$	sup.	$l+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{H}^0$	sup.	$\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{H}^\pm$	not sup.	j
$\tilde{\nu}_\tau \leftrightarrow \tilde{l}$	sup.	$l+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{\nu}$	sup.	$j+l$	$\tilde{\nu}_\tau \leftrightarrow \tilde{t}$	sup.	$j+\not{E}_T$
$\tilde{\nu}_\tau \leftrightarrow \tilde{b}$	sup.	$j+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{q}_3$	sup.	$j+\not{E}_T$	$\tilde{\nu}_\tau \leftrightarrow \tilde{\tau}_R$	sup.	$j+\not{E}_T$
$\tilde{\nu}_\tau \leftrightarrow \tilde{B}$	not sup.	$\not{E}_T$						

- Distinguish $\tilde{\tau}_L \leftrightarrow \tilde{\tau}_R$ and $\tilde{\tau}_L \leftrightarrow \tilde{\nu}$

- Final state τ's treated as jets, note MET in signatures

RPC - Neutral LSP: Results

	$n_v = 0$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	312541986240	117970262784	165342436440
1	67074706080	34779312324	57422656260
2	65174167872	18534736560	51054671976
3	1575226224	2493306468	10912949436
4	2547024480	483080928	2934477432

	$n_v = 1$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	40410334080	18304902216	12747340176
1	4187624400	979516800	3604426884
2	2194158240	1134558324	2327435580
3	187519464	39029940	328568028
4	38201760	18106992	81826620

	$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	3899301120	1072184256	199620876
1	166795200	70155072	172247244
2	49626720	20533032	68802012
3	2162160	2098980	17367492
4	2882880	454896	4965588

- Zeros from Konar et al are filled in: 3rd generation

New Signatures: 3rd generation

- Hierarchy $\tilde{U}\tilde{B}\tilde{H}\tilde{W}^0\tilde{l}\tilde{\nu}_\tau$ gives signature: jvvl(l+MET)=2l, 2v, j+MET

RPC - colored LSP

	$n_v = 0$				$n_v = 1$			$n_v = 2$		
n_l	$n_j = 0$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j \leq 1$	$n_j = 2$	$n_j > 2$	$n_j \leq 1$	$n_j = 2$	$n_j > 2$
0	$3.9\,10^{11}$ 0	$7.4\,10^{10}$ 0	$2.2\,10^{11}$ $1.7\,10^{10}$	$1.4\,10^{11}$ $4.5\,10^{10}$	0 0	$1.5\,10^{10}$ $3.2\,10^{8}$	9468026568 4118797332	0 0	$1.2\,10^{9}$ 66718080	465918336 195361296
1	0 0	0 0	0 $1.1\,10^{10}$	0 $1.6\,10^{10}$	0 0	0 $9.3\,10^{8}$	0 1035229080	0 0	0 $1.1\,10^{8}$	0 68133048
2	0 0	0 0	$5.6\,10^{10}$ $6.1\,10^{9}$	$4.8\,10^{10}$ $1.7\,10^{10}$	0 0	$8.7\,10^{8}$ 77848056	2087854260 1026167004	0 0	$1.5\,10^{8}$ 19274112	126657048 53947968
3	0 0	0 0	0 $4.5\,10^{9}$	0 $5.2\,10^{9}$	0 0	0 77523264	0 227922096	0 0	0 10749024	0 15159648
4	0 0	0 0	$4.3\,10^{9}$ $6.4\,10^{8}$	$5.7\,10^{9}$ $1.9\,10^{9}$	0 0	37065600 2656368	164800584 84705564	0 0	8648640 1482624	12473784 4864080

- Separate table, here many zeros
- Top entry in a cell: **no** $\not{E}_T$, lower entry **with** $\not{E}_T$

Charged Colorless LSP

	$n_v = 0$			$n_v = 1$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	90914503680 54695577024	199786549248 61269389940	197018064984 63438117456	24908083200 10558182528	11170089216 4340060412	12896522496 5214451944
1	145463205888 45077401152	46923606288 30820398288	103720477956 51364952568	3146397696 2250005760	1341596880 2379924300	6502814196 3218399052
2	7442772480 7788263040	38091856608 13132673004	53353013508 24556564692	1234284480 762654456	356185440 371151744	2261412456 1290674736
3	17120353536 5263677936	3950718000 3618848640	21030151800 11792319204	264060000 91768320	107755860 214164552	828194112 497798316
4	0 0	2854028736 369243072	4860902520 1224327540	20386080 3833280	16380000 1011816	141558288 42047532

	$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	1868106240 729451008	954809856 186361344	458198208 182707512
1	539675136 62805600	118295424 157238640	354737592 167907912
2	0 22857120	82158336 18125640	116895888 67810896
3	33359040 6383520	6626880 13149864	49067520 29295096
4	0 0	5765760 494208	10858536 2994600

- Some Zeros, MET from neutrinos
- Top entry in a cell: **no** $\not\!\!E_T$, lower entry **with** $\not\!\!E_T$

RPV: LSP Decays

	ϵ	λ	λ'	λ''
$\tilde{B}$	$h^0\nu$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{W}^\pm$	$Z^0l^\pm$	$3l^\pm$	$l^\pm q\bar{q}$	$qq'q''$
$\tilde{W}^0$	$W^\pm l^\mp$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{G}$	$q\bar{q}'l^\pm$	$q\bar{q}l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{H}^\pm$	$Z^0l^\pm$	$3l^\pm$	$l^\pm q\bar{q}$	$qq'q''$
$\tilde{H}^0$	$W^\pm l^\mp$	$l^+l^-\nu$	$l^\pm q\bar{q}'$	$qq'q''$
$\tilde{q}$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q$	$4q$
$\tilde{d}$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q$	qq'
$\tilde{u}$	$q\nu$	$ql^+l^-\nu$	$l^\pm q\bar{q}'q''$	qq'
$\tilde{l}$	$q\bar{q}'$	$l^\pm\nu$	$q\bar{q}'$	$qq'q''l^\pm$
$\tilde{\nu}$	$q\bar{q}$	l^+l^-	$q\bar{q}$	$qq'q''\nu$
$\tilde{e}$	$l^\pm\nu$	$l^\pm\nu$	$l^\pm l^\pm q\bar{q}'$	$qq'q''l^\pm$
$\tilde{q}_3$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q$	$4q$
$\tilde{b}_R$	$q\nu$	$ql^+l^-\nu$	$q\nu$	qq'
$\tilde{t}_R$	$l^\pm q$	$ql^+l^-\nu$	$l^\pm q\bar{q}'q''$	qq'
$\tilde{\tau}_L$	$q\bar{q}'$	$l^\pm\nu$	$q\bar{q}'$	$qq'q''\tau$
$\tilde{\nu}_\tau$	$q\bar{q}$	l^+l^-	$q\bar{q}$	$qq'q''\nu$
$\tilde{\tau}_R$	$\tau\nu$	$l^\pm\nu$	$l^\pm\nu q\bar{q}$	$qq'q''\tau$

RPV Tables

- Have a table each for λ, λ', λ'', ϵ
- Present here briefly LLE and UDD cases

LLE

n_l	$n_v = 0$, $n_j = 1$	$n_v = 0$, $n_j = 2$	$n_v = 0$, $n_j > 2$	$n_v = 1$, $n_j = 1$	$n_v = 1$, $n_j = 2$	$n_v = 1$, $n_j > 2$
1	0 0	0 130043916288	0 126078094584	0 0	0 5076504576	0 6792674304
2	0 733867579008	12098211840 322809374988	9552173904 611946284436	0 40153740336	2283240960 13533662232	936683280 42548769012
3	181413872640 11815321680	66135199104 68437050756	100760522148 66950801244	34422036480 1101083760	8464603680 3729359340	8852651496 3071850684
4	0 100232869968	4559068800 22535589516	4236078720 176577808008	0 4506797520	127258560 999414984	190131684 6052502688
5	17537160960 3434937264	3070611360 9459788856	20536985256 11432125176	1537889760 130978584	147932928 384495264	930607140 396622128
6	0 4670186400	0 877146672	318288888 13904938128	0 119746080	4530240 19136592	7575432 287912544
7	0 0	0 176061600	308737536 61006956	20386080 0	730080 0	603096 141960

$n_v = 1$, $n_j = 1$	$n_v = 1$, $n_j = 2$	$n_v = 1$, $n_j > 2$	$n_v = 2$, $n_j = 1$	$n_v = 2$, $n_j = 2$	$n_v = 2$, $n_j > 2$
0 0	0 5076504576	0 6792674304	0 0	0 539675136	0 363789504
0 40153740336	2283240960 13533662232	936683280 42548769012	0 4498281216	163088640 1043947008	30798144 2208113844
34422036480 1101083760	8464603680 3729359340	8852651496 3071850684	2639070720 12972960	499520736 128527776	125019960 154994508
0 4506797520	127258560 999414984	190131684 6052502688	0 81956160	9266400 18482256	8760540 388659492
1537889760 130978584	147932928 384495264	930607140 396622128	1853280 2574000	430560 8767044	10575960 20289840
0 119746080	4530240 19136592	7575432 287912544	0 2882880	0 454896	495024 25746192
20386080 0	730080 0	603096 141960	0 0	0 0	0 0

- Top entry in a cell: **no** $\not{E}_T$, lower entry **with** $\not{E}_T$; Many more leptons,

UDD

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 2$	$n_j = 3$	$n_j > 3$	$n_j = 2$	$n_j = 3$	$n_j > 3$	$n_j = 2$	$n_j = 3$	$n_j > 3$
0	$3.0\,10^{11}$	$1.5\,10^{11}$	1210196785824	0	0	134043915720	0	0	9656262720
	0	0	250790698860	0	0	24355637904	0	0	998711688
1	0	0	0	0	0	0	0	0	0
	0	0	261088197468	0	0	17713073232	0	0	943274592
2	0	0	556143064584	0	0	20689566648	0	0	1460694240
	0	0	118354600104	0	0	6920229852	0	0	350075748
3	0	0	0	0	0	0	0	0	0
	0	0	45310166604	0	0	1923262980	0	0	108784248
4	0	0	61062386412	0	0	1597074060	0	0	125687520
	0	0	13933473948	0	0	614916804	0	0	36546144

- Typically many jets
- 2 jets if $(\tilde{U}, \tilde{D}) = C = \mathcal{L}$, 3 jets if $\tilde{G} = C = \mathcal{L}$
- No unique signatures

Unique Dominant and Best Visible Signatures

	$n_v = 0$			$n_v = 1$			$n_v = 2$		
n_l	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$	$n_j = 1$	$n_j = 2$	$n_j > 2$
0	R			c	R		c R	R	
1	R								
2	c			ø			ø		
3	.						R		
4	ø			c			ø		
5	λ λ	λ λ	$\not{R}$ $\not{R}$	$\not{R}$ $\not{R}$	$\not{R}$ $\not{R}$	$\not{R}$ $\not{R}$	$\not{R}$ λ	$\not{R}$ $\not{R}$	$\not{R}$ $\not{R}$
6	ø λ	ø λ	λ λ	ø λ	λ λ	λ λ	ø λ	ø λ	λ λ
7	ø ø	ø λ	λ λ	λ ø	λ ø	λ λ	ø ø	ø ø	ø ø

- R: RPC, (n, c, h): nature of LSP
- ø: not covered by RPC or RPV
- $\not{R}$: RPV, possibly just by one coupling: λ

Not Possible Dominant Signatures

	$n_v=0$			$n_v=1$			$n_v=2$		
n_l	$n_j=1$	$n_j=2$	$n_j>2$	$n_j=1$	$n_j=2$	$n_j>2$	$n_j=1$	$n_j=2$	$n_j>2$
0	$n,\not{R}$ $h,\lambda,\lambda',\lambda''$	$n,\epsilon,\lambda,\lambda'$ λ,λ''	n,λ λ	$n,h,\not{R}$ $h,\lambda,\lambda',\lambda''$	$n,\epsilon,\lambda,\lambda''$ $\lambda,\lambda',\lambda''$	n,λ,λ' λ	$n,h,\epsilon,\lambda,\lambda''$ $h,\not{R}$	$n,\epsilon,\lambda',\lambda,\lambda',\lambda''$ $\lambda,\lambda',\lambda''$	n,λ λ
1	n,h,λ,λ'' $h,\not{R}$	n,h,λ,λ'' $\epsilon,\lambda',\lambda''$	n,h,λ,λ''	$n,h,\lambda,\lambda',\lambda''$ $h,\lambda,\lambda',\lambda''$	$n,h,\lambda,\lambda',\lambda''$ λ',λ''	n,h,λ,λ''	$n,h,\ \lambda,\lambda',\lambda''$ $h,\lambda,\lambda',\lambda''$	$n,h,\ \lambda,\lambda',\lambda''$ λ',λ''	n,h,λ,λ''
2	$n,h,\not{R}$ h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n	$n,h,\not{R}$ h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n	all h,λ',λ''	$n,\ \epsilon,\lambda',\lambda''$ λ',λ''	n
3	$n,h,\epsilon,\lambda',\lambda''$ $h,\epsilon,\lambda',\lambda''$	$n,h,\epsilon,\lambda',\lambda''$ $\epsilon,\lambda',\lambda''$	n,h,λ''	n,h,λ',λ'' h,λ',λ''	n,h,λ',λ'' λ',λ''	n,h,λ''	$n,h,\ \lambda',\lambda''$ $h,\not{R}$	n,h,λ',λ'' λ',λ''	n,h,λ''
4	all c,h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n	$n,h,\not{R}$ h,λ',λ''	$c,\epsilon,\lambda',\lambda''$ λ',λ''	n	all c,h,λ',λ''	$n,\epsilon,\lambda',\lambda''$ λ',λ''	n
5	R,ϵ,λ' R,ϵ,λ'	R,ϵ,λ' R,ϵ,λ'	R R	R,λ' R,λ'	R,λ' R,λ'	R R	R,λ' R,ϵ,λ'	R,λ' R,λ'	R R
6	all $R,\epsilon,\lambda',\lambda''$	all $R,\epsilon,\lambda',\lambda''$	$R,\epsilon,\lambda',\lambda''$ $R,\epsilon,\lambda',\lambda''$	all $R,\epsilon,\lambda',\lambda''$	$R,\epsilon,\lambda',\lambda''$ $R,\epsilon,\lambda',\lambda''$	$R,\epsilon,\lambda',\lambda''$ $R,\epsilon,\lambda',\lambda''$	all $R,\epsilon,\lambda',\lambda''$	all $R,\epsilon,\lambda',\lambda''$	$R,\epsilon,\lambda',\lambda''$ $R,\epsilon,\lambda',\lambda''$
7	all all	all $R,\epsilon,\lambda',\lambda''$	$R,\epsilon,\lambda',\lambda''$ $R,\epsilon,\lambda',\lambda''$	$R,\epsilon,\lambda',\lambda''$ all	$R,\epsilon,\lambda',\lambda''$ all	$R,\epsilon,\lambda',\lambda''$ $R,\epsilon,\lambda',\lambda''$	all all	all all	all all

- Notation:
  - R =RPC, $\not{R}$ =RPV, (n,c,h)=(neutral,charged,colored)-LSP
  - $\lambda, \lambda', \lambda'', \epsilon$: type of RPV

Conclusions

- Have argued that RPC and RPV are theoretically equally well motivated

- CMSSM fits with low-energy and LHC observables have tension

- 125 GeV Higgs hard to accommodate in CMSSM fit

- RPV has many novel signatures

- Listed Top 10 RPV-CMSSM signatures

- Presented analysis of generalized RPC and RPV signatures

Physikshow trip to Berlin: Weltmaschine Exhib.

Physik at the LHC is fun!

Backup Slides

B_3-Phenomenology: Lepton Number Violation

- charge current universality ($\pi^+ \to e^+\nu$)

LOW-ENERGY BOUNDS ON λ, λ' (2σ):

	$\lambda_{ijk} L_i L_j \bar{E}_k$	$\lambda'_{1jk} L_1 Q_j \bar{D}_k$	$\lambda'_{2jk} L_2 Q_j \bar{D}_k$	$\lambda'_{3jk} L_3 Q_j \bar{D}_k$
weakest	0.07	0.28	0.56	0.52
strongest	0.05	$5. \cdot 10^{-4}$	0.06	0.11

- One operator at a time
- (almost all) Bounds scale with ($\tilde{m}/100$) GeV
- Thus for 1 TeV sparticles bounds factor 10 weaker

Signatures: χ_1^0-LSP, Dominant LLE

Operator	Signature
$L_iL_j\bar{E}_i$ $(i \neq j)$	$(\mathbf{2}\ \ell_i^+\ell_i^+\ell_i^-\ell_i^-,\ \mathbf{4}\ \ell_i^+\ell_i^+\ell_i^-\ell_j^-,\ \mathbf{1}\ \ell_i^+\ell_i^+\ell_j^-\ell_j^-,\ \mathbf{1}\ \ell_i^+\ell_i^-\ell_j^+\ell_j^-) + \not{p}_T$
$L_iL_j\bar{E}_k$ $(i \neq j \neq k)$	$(\mathbf{1}\ \ell_i^+\ell_i^+\ell_k^-\ell_k^-,\ \mathbf{1}\ \ell_i^+\ell_i^-\ell_k^+\ell_k^-,\ \mathbf{2}\ \ell_i^+\ell_j^+\ell_k^-\ell_k^-,\ \mathbf{2}\ \ell_i^+\ell_j^-\ell_k^+\ell_k^-,\ \mathbf{1}\ \ell_j^+\ell_j^+\ell_k^-\ell_k^-,$ $\mathbf{1}\ \ell_j^+\ell_j^-\ell_k^+\ell_k^-) + \not{p}_T$

Signatures of neutralino LSP pairs decaying via a dominant $L_iL_j\bar{E}_k$ operator. We include combinatorial factors but neglect slepton mass as well as neutralino decomposition effects on the neutralino branching ratios (*i.e.* we assume $\mathcal{B}(\tilde{\chi}_1^0 \to \tilde{\ell}_L^* \ell) = \mathcal{B}(\tilde{\chi}_1^0 \to \tilde{\ell}_R^* \ell) = \mathcal{B}(\tilde{\chi}_1^0 \to \tilde{\nu}_L^* \nu)$, where $\tilde{\ell}_L^*$, $\tilde{\ell}_R^*$ and $\tilde{\nu}_L^*$ are the intermediate sleptons in the R-parity violating three-body decays of the neutralino.) For each signature there exists the charged conjugated signature.

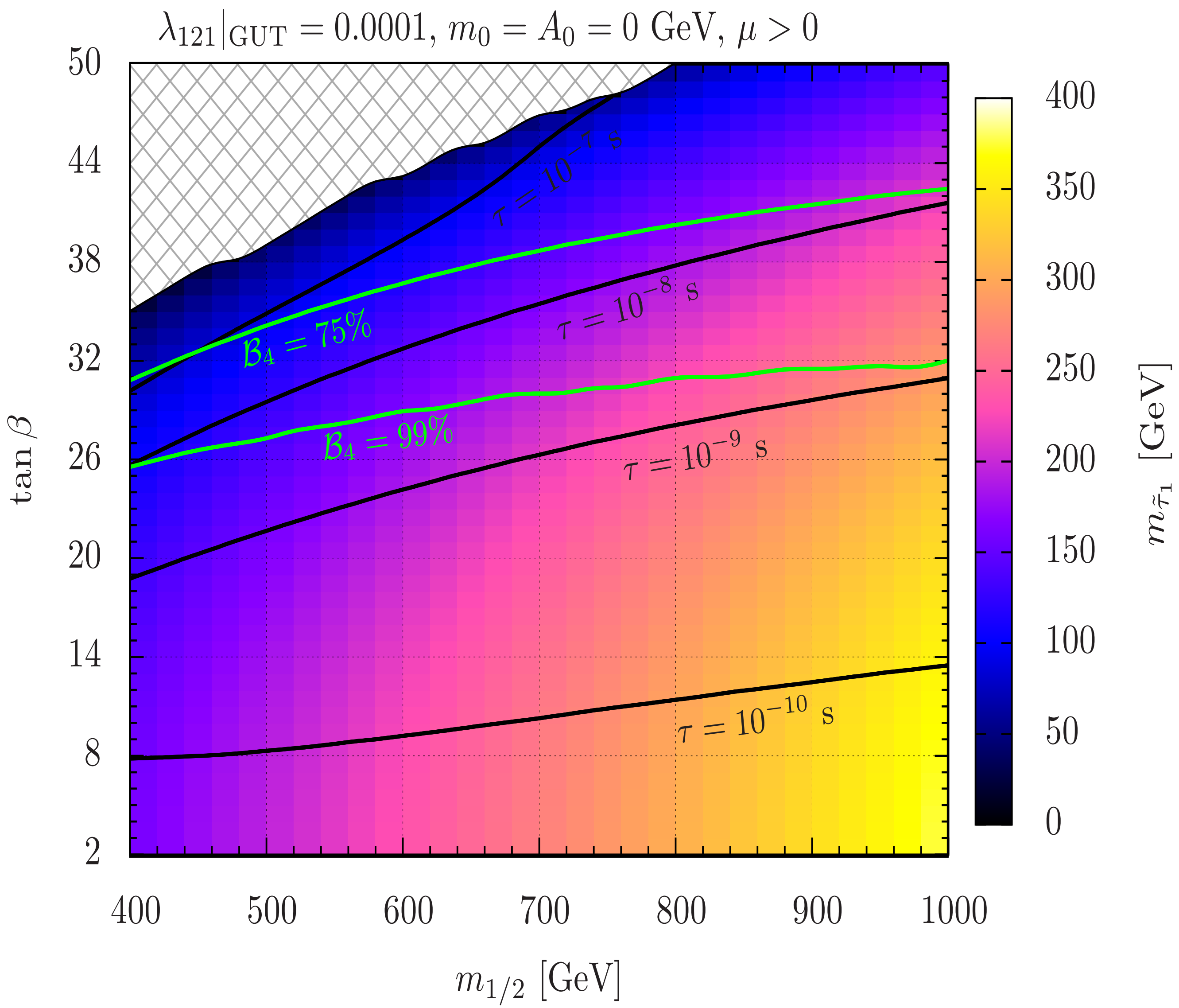
Signatures: χ_1^0-LSP, Dominant LQD, UDD

Operator	Signature
$L_iQ_j\bar{D}_k$ $(j,k \in \{1,2\})$	$(\mathbf{1}\ \ell_i^-\ell_i^-,\ \mathbf{1}\ \ell_i^+\ell_i^-,\ \mathbf{4}\ \ell_i^-\not{p}_T,\ \mathbf{2}\ \not{p}_T) + 4j$
$L_iQ_3\bar{D}_k$ $(k \in \{1,2\})$	$(\mathbf{1}\ \ell_i^-\ell_i^-tt,\ \mathbf{1}\ \ell_i^+\ell_i^-t\bar{t},\ \mathbf{2}\ \ell_i^-tb\not{p}_T,\ \mathbf{2}\ \ell_i^-t\bar{b}\not{p}_T,\ \mathbf{1}\ bb\not{p}_T,\ \mathbf{1}\ b\bar{b}\not{p}_T) + 2j$
$L_iQ_j\bar{D}_3$ $(j \in \{1,2\})$	$(\mathbf{1}\ \ell_i^-\ell_i^-\overline{bb},\ \mathbf{1}\ \ell_i^+\ell_i^-b\bar{b},\ \mathbf{2}\ \ell_i^-\overline{bb}\not{p}_T,\ \mathbf{2}\ \ell_i^-b\bar{b}\not{p}_T,\ \mathbf{1}\ bb\not{p}_T,\ \mathbf{1}\ b\bar{b}\not{p}_T) + 2j$
$L_iQ_3\bar{D}_3$	$\mathbf{1}\ \ell_i^-\ell_i^-tt\overline{bb},\ \mathbf{1}\ \ell_i^+\ell_i^-t\bar{t}b\bar{b},\ \mathbf{4}\ \ell_i^-tb\overline{bb}\not{p}_T,\ \mathbf{2}\ b\bar{b}b\bar{b}\not{p}_T$

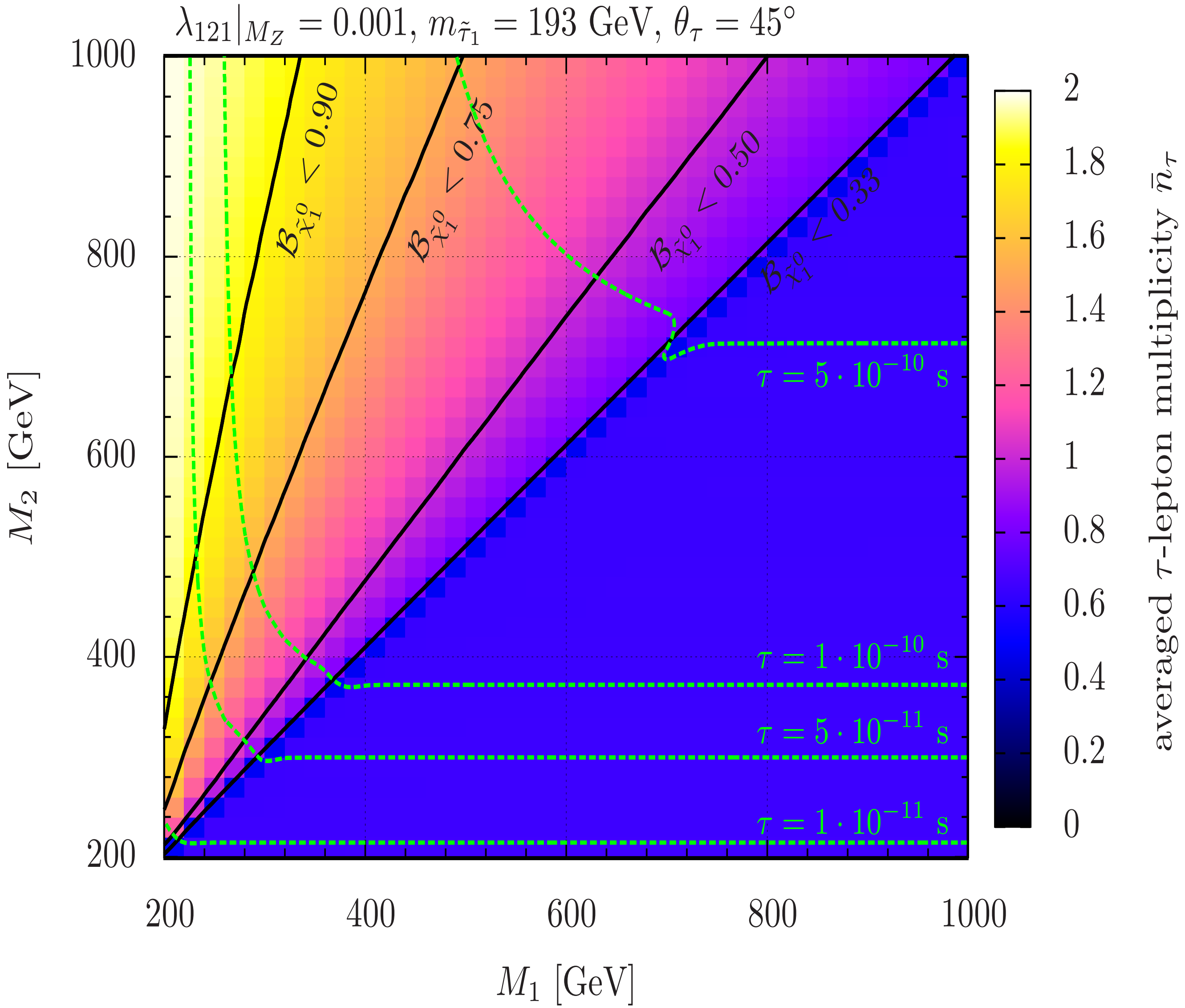
Signatures of neutralino LSP pairs decaying via a dominant $L_iQ_j\bar{D}_k$ operator. We include combinatorial factors assuming equal neutralino branching fractions $\mathcal{B}(\tilde{\chi}_1^0 \to \tilde{\ell}_L^*\ell) = \mathcal{B}(\tilde{\chi}_1^0 \to \tilde{\nu}_L^*\nu)$ and $\mathcal{B}(\tilde{\chi}_1^0 \to \tilde{u}_L^*\bar{u}) = \mathcal{B}(\tilde{\chi}_1^0 \to \tilde{d}_L^*\bar{d})$, where $\tilde{\ell}_L^*$, $\tilde{\nu}_L^*$, $\tilde{u}_L^*$ and $\tilde{d}_L^*$ are the intermediate sleptons and squarks in the R-parity violating three-body decays of the neutralino. For each signature there exists the charged conjugated signature.

Operator	Signature
$\bar{U}_i\bar{D}_j\bar{D}_k$ $(i,j,k \in \{1,2\})$	$6j$
$\bar{U}_3\bar{D}_j\bar{D}_k$ $(j,k \in \{1,2\})$	$(\mathbf{1}\ tt,\ \mathbf{1}\ t\bar{t}) + 4j$
$\bar{U}_i\bar{D}_3\bar{D}_k$ $(i,k \in \{1,2\})$	$(\mathbf{1}\ bb,\ \mathbf{1}\ b\bar{b}) + 4j$
$\bar{U}_3\bar{D}_3\bar{D}_k$ $(k \in \{1,2\})$	$(\mathbf{1}\ ttbb,\ \mathbf{1}\ t\bar{t}b\bar{b}) + 2j$

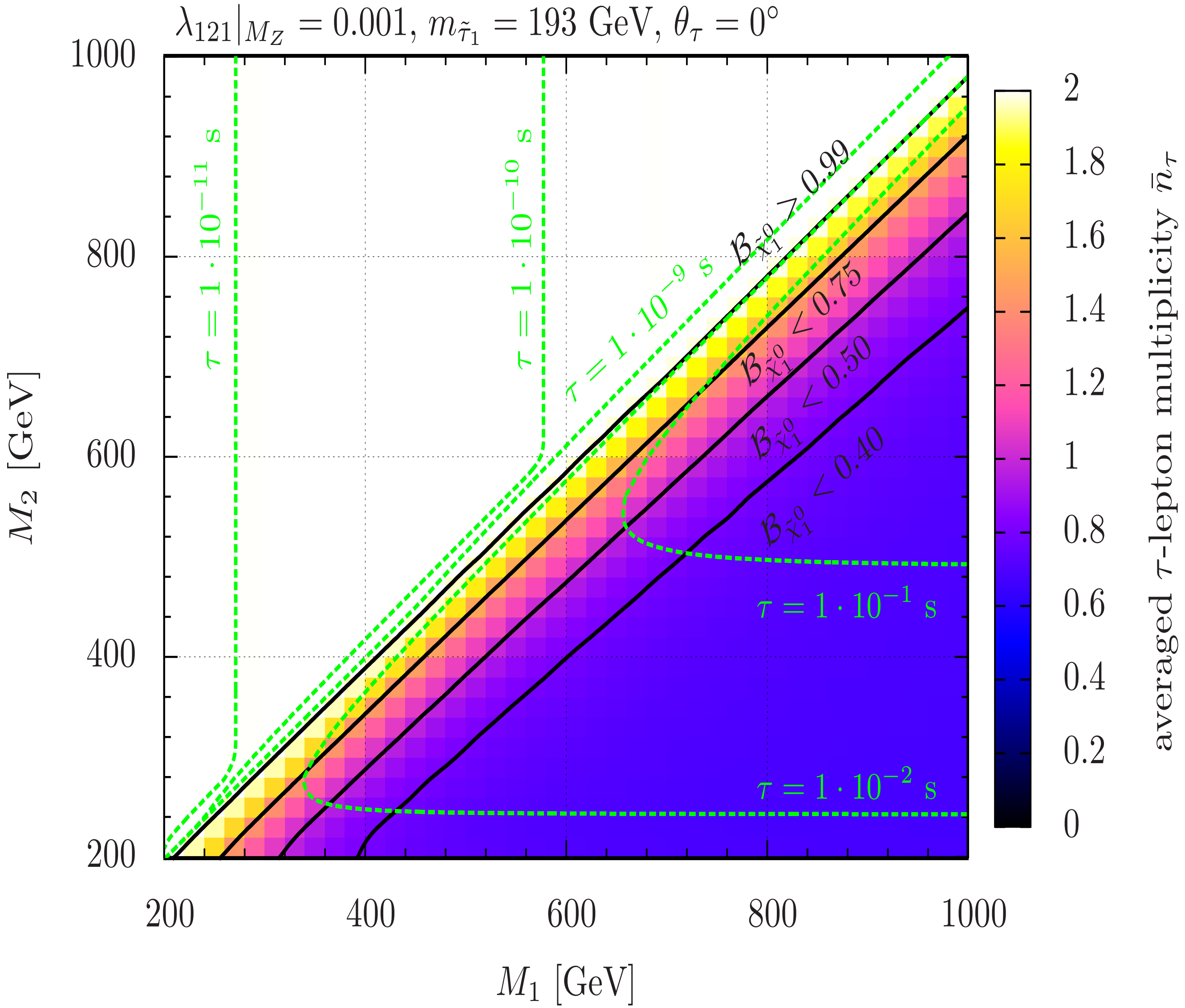
Signatures of neutralino LSP pairs decaying via a dominant $\bar{U}_i\bar{D}_j\bar{D}_k$ operator. The combinatorial factors are independent of the sparticle masses and neutralino nature (since every diagram yields the same final state). For each signature there exists the charged conjugated signature.



Long-lived stau LSP in the CMSSM: The color indicates $m_{\tilde{\tau}_1}$ (in GeV). Here $\lambda_{212}(\mathrm{GUT}) = 0.0001$, which generates $\lambda_{233}(\mathrm{WEAK}) \sim \mathcal{O}(10^{-9}$–$10^{-11})$ (depending on $\tan\beta$). The black contour lines correspond to the stau lifetime, τ (in s). The green contours give the branching fraction of the $\tilde{\tau}_1$ to 4-body final states (via λ_{121}).



Averaged τ-lepton multiplicity from $\tilde{\tau}_1$ pairs decaying purely via four-body decays. $\tilde{m} = 350\,\text{GeV}$, $m_{\tilde{\tau}_1} = 193\,\text{GeV}$. The black lines indicate the branching fraction of 4-body decays mediated by a virtual neutralino. The green dashed contours give the lifetime τ of the lightest stau. ($\tan\beta = 10$, $\mu = 5$ TeV)



Averaged τ-lepton multiplicity from $\tilde{\tau}_1$ pairs decaying via four-body decays for fixed slepton masses. Here $\theta_\tau = 0°$ and $m_{\tilde{\tau}_1} = 193\,\text{GeV}$. The black lines indicate the branching fraction of neutralino mediated decays. The green dashed contours give the lifetime τ of the lightest stau. ($\tan\beta = 10$, $\mu = 5$ TeV) For $M_2 \leq M_1$, the $\tilde{\tau}_1$ becomes long-lived.

χ_1^0 LSP Decays in Detector

- Missing transverse energy diluted or absent

- Neutralino LSP decays:

  - $L L \bar{E}$: $\quad \tilde{\chi}_1^0 \to \begin{pmatrix} ee \\ e\mu \\ e\tau \\ \mu\mu \\ \mu\tau \end{pmatrix} + \nu$

  - $L Q \bar{D}$: $\quad \tilde{\chi}_1^0 \to \begin{pmatrix} e, \mu, \tau \\ \nu \end{pmatrix} + 2\,\text{jets}$

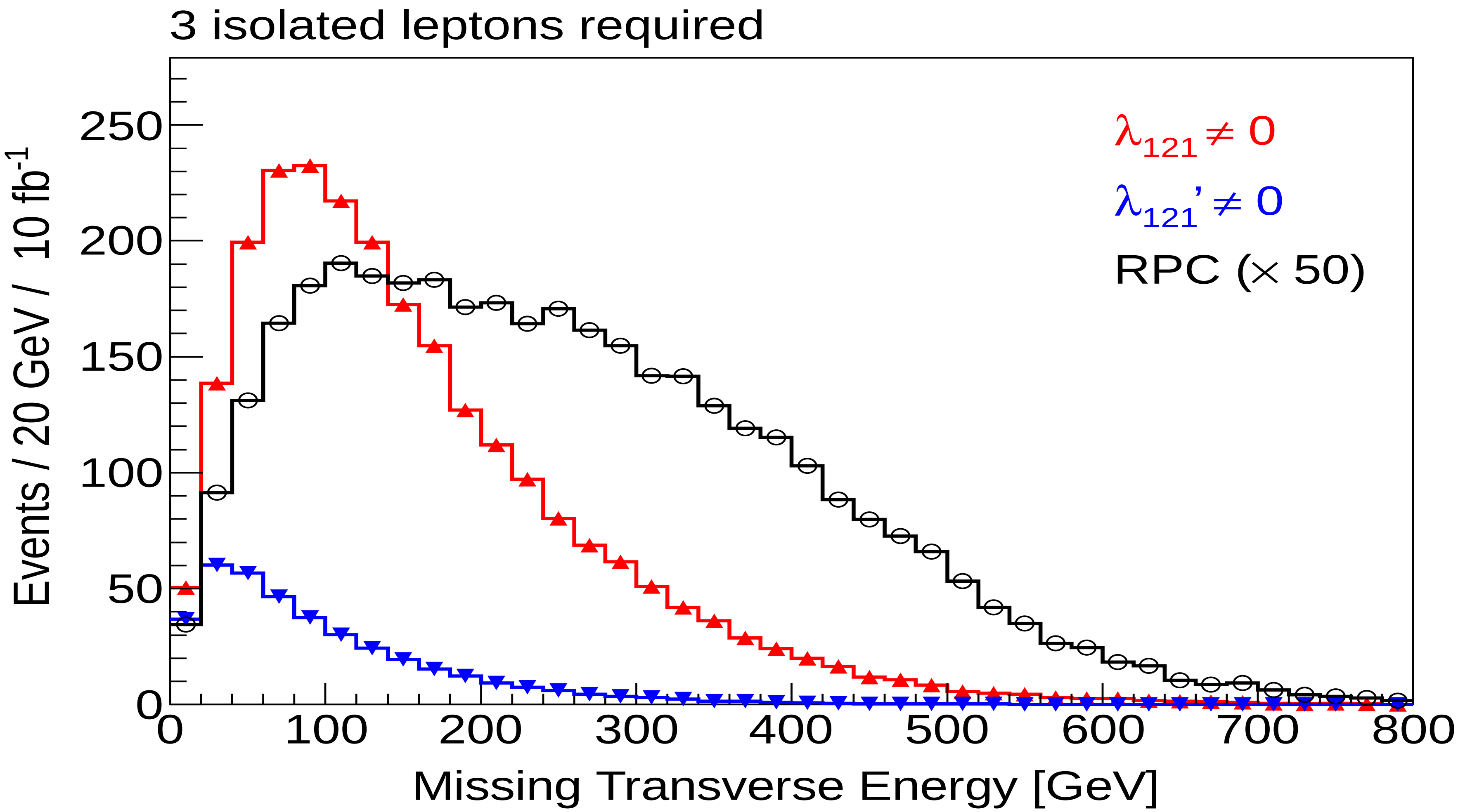
- Very few R-parity violating searches performed to–date

- Can maybe still use MET searches?

$M_0 = 150\,\text{GeV},\ M_{1/2} = 400\,\text{GeV},\ A_0 = 0,\ \tan\beta = 5,\ \text{sgn}(\mu) = +$

$\lambda_{121} = \lambda'_{121} = 0.001$

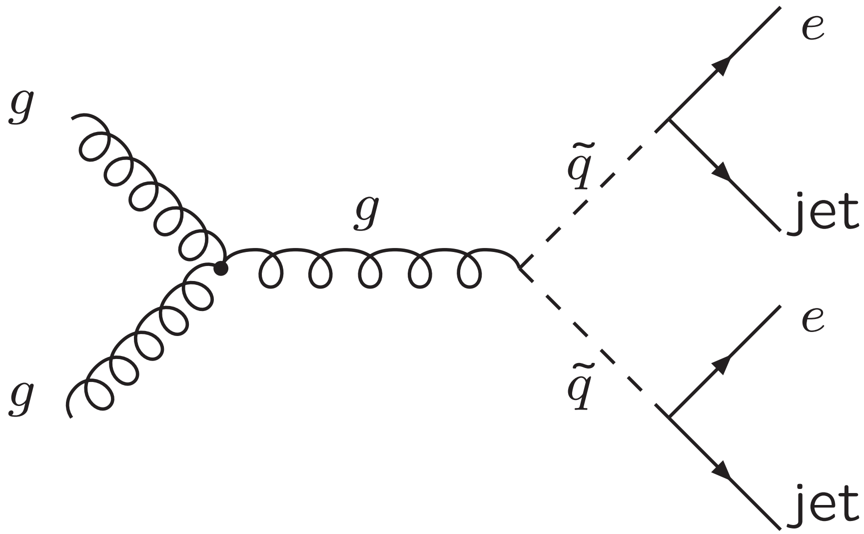
Tim Stefaniak



$M_{\tilde{\chi}_1^0} = 162\,,\ M_{\tilde{\tau}_1} = 214\,,\ M_{\tilde{t}_1} = 650\,,\ M_{\tilde{q}} = 865\,,\ M_{\tilde{g}} = 935\,\text{GeV}$

RPV and Leptoquarks

- Can also consider $\tilde{q}$–LSP
- Dominant $L_e Q_i \bar{D}_j$ operator

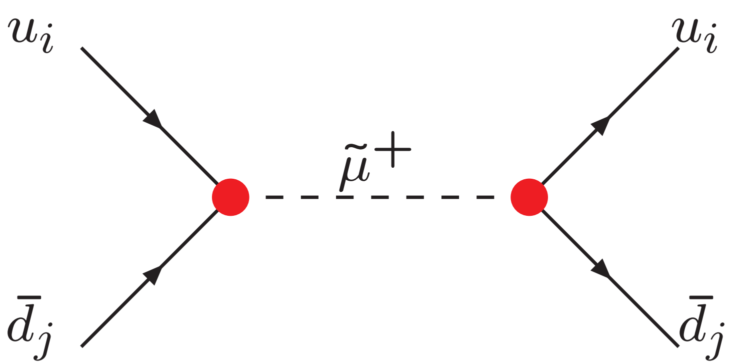


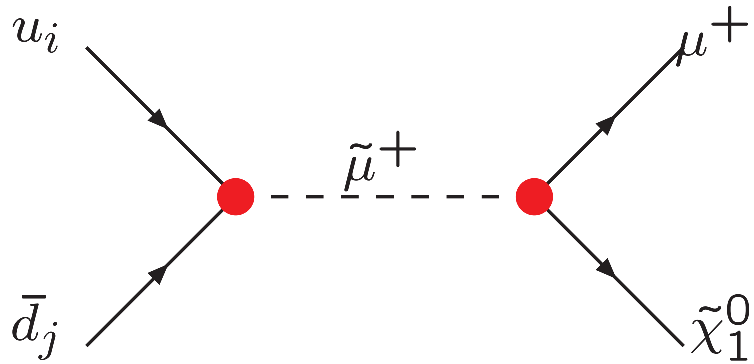
- Signature: $eejj$
- Can also have $\nu\nu jj$, or $\mu\mu jj$ ($L_\mu QD$)

Use existing searches: Resonant $\tilde{\ell}$, $\tilde{\nu}$ Prod.

with Tim Stefaniak

- One dominant operator: $L_2 Q_i \bar{D}_j$



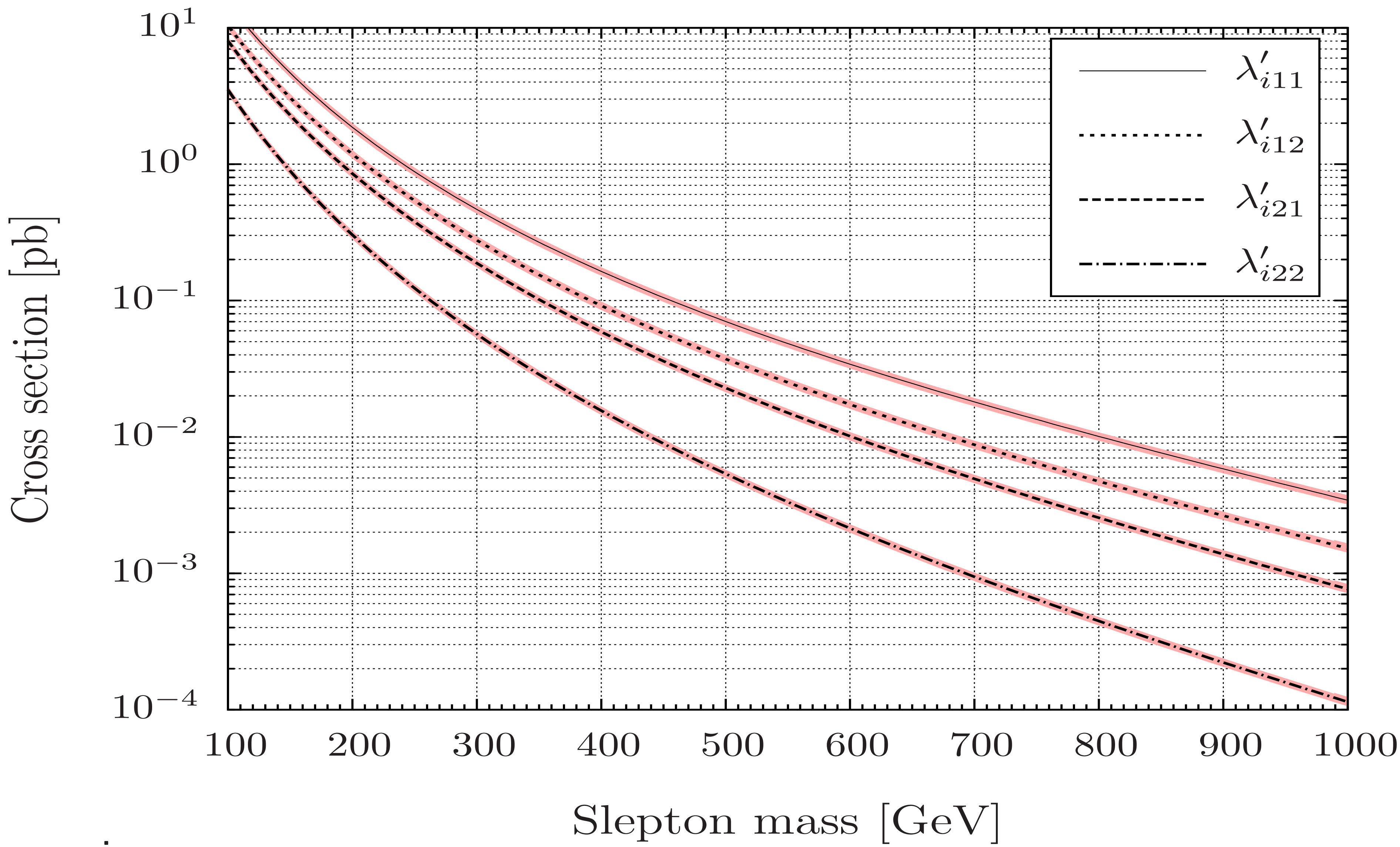


$\tilde{\chi}_1^0 \to \mu^+ + 2\,\text{jets}$

- Dijet resonance: compare with ATLAS and CMS searches (1 fb^{-1})

- Prompt like-sign μ's, compare with ATLAS search

Resonant Slepton Production Xsection



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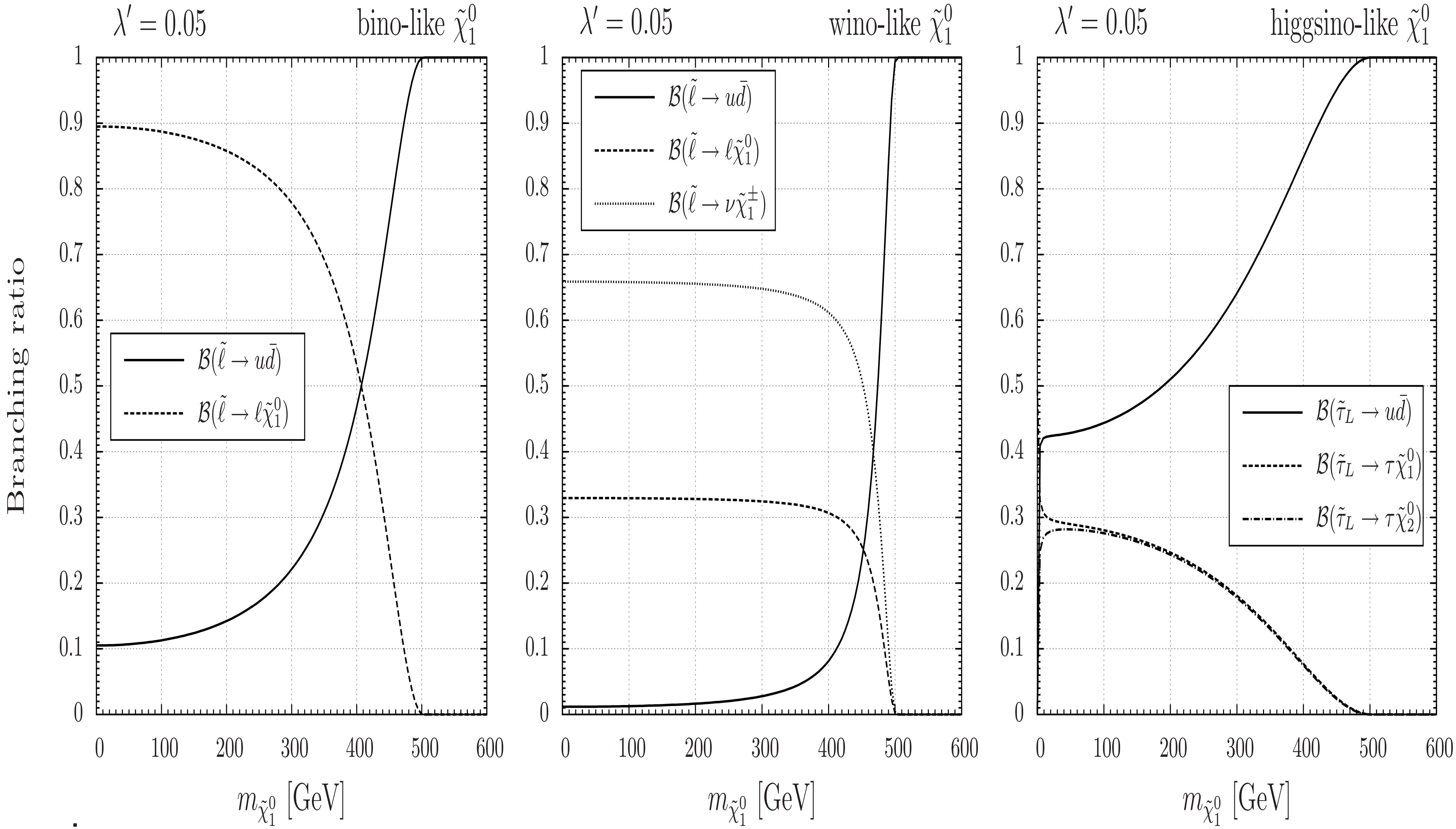
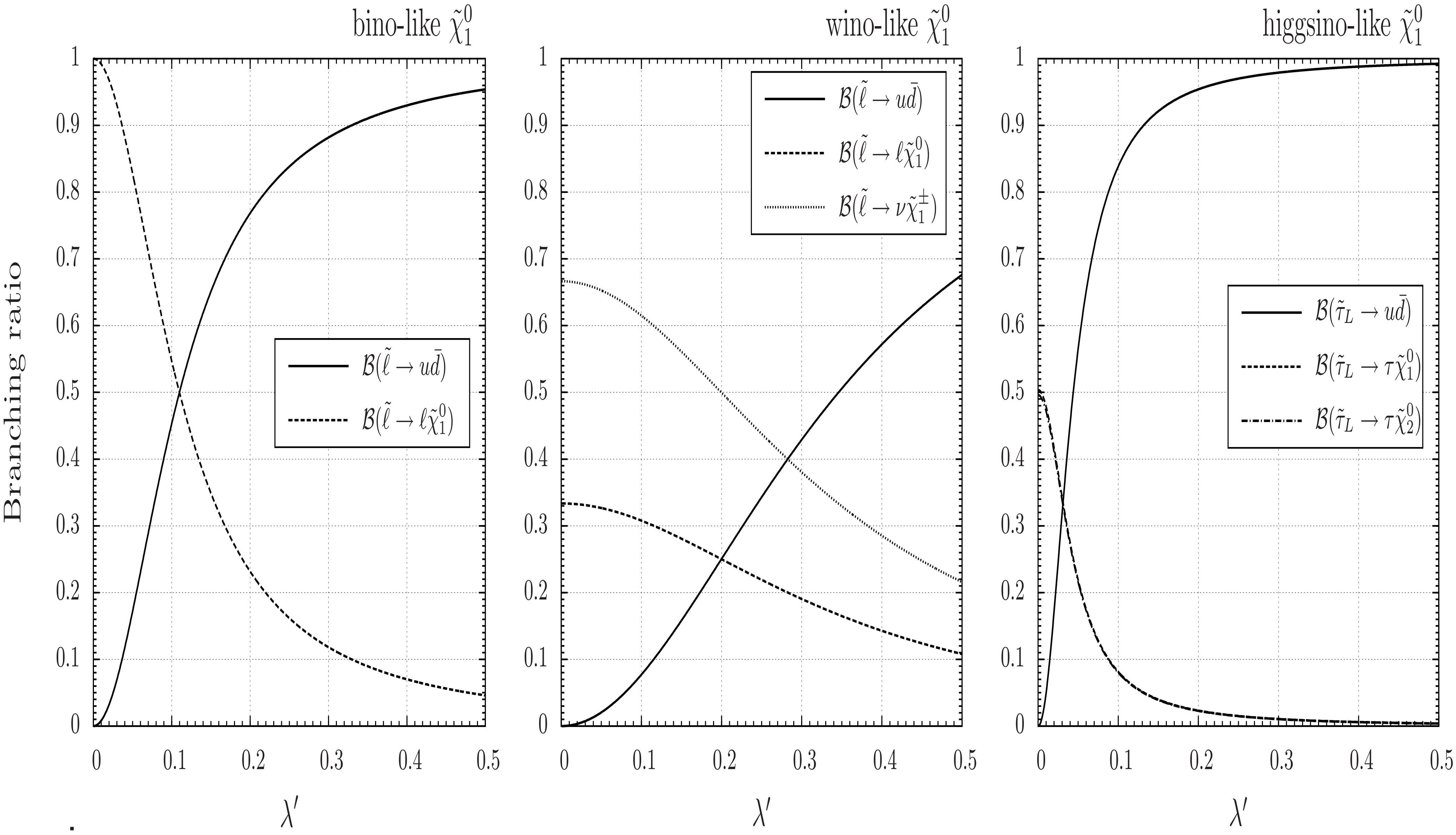
- $\lambda' = 0.01$
- CTEQ6m PDFs



$\lambda' = 0.05$
bino-like $\tilde{\chi}_1^0$
$\mathcal{B}(\tilde{\ell} \to u\bar{d})$
$\mathcal{B}(\tilde{\ell} \to \ell\tilde{\chi}_1^0)$
$\lambda' = 0.05$
wino-like $\tilde{\chi}_1^0$
$\mathcal{B}(\tilde{\ell} \to u\bar{d})$
$\mathcal{B}(\tilde{\ell} \to \ell\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\ell} \to \nu\tilde{\chi}_1^\pm)$
$\lambda' = 0.05$
higgsino-like $\tilde{\chi}_1^0$
$\mathcal{B}(\tilde{\tau}_L \to u\bar{d})$
$\mathcal{B}(\tilde{\tau}_L \to \tau\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\tau}_L \to \tau\tilde{\chi}_2^0)$
Branching ratio
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]



bino-like $\tilde{\chi}_1^0$
wino-like $\tilde{\chi}_1^0$
higgsino-like $\tilde{\chi}_1^0$
Branching ratio
λ'
$\mathcal{B}(\tilde{\ell} \to u\bar{d})$
$\mathcal{B}(\tilde{\ell} \to \ell\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\ell} \to \nu\tilde{\chi}_1^{\pm})$
$\mathcal{B}(\tilde{\tau}_L \to u\bar{d})$
$\mathcal{B}(\tilde{\tau}_L \to \tau\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\tau}_L \to \tau\tilde{\chi}_2^0)$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

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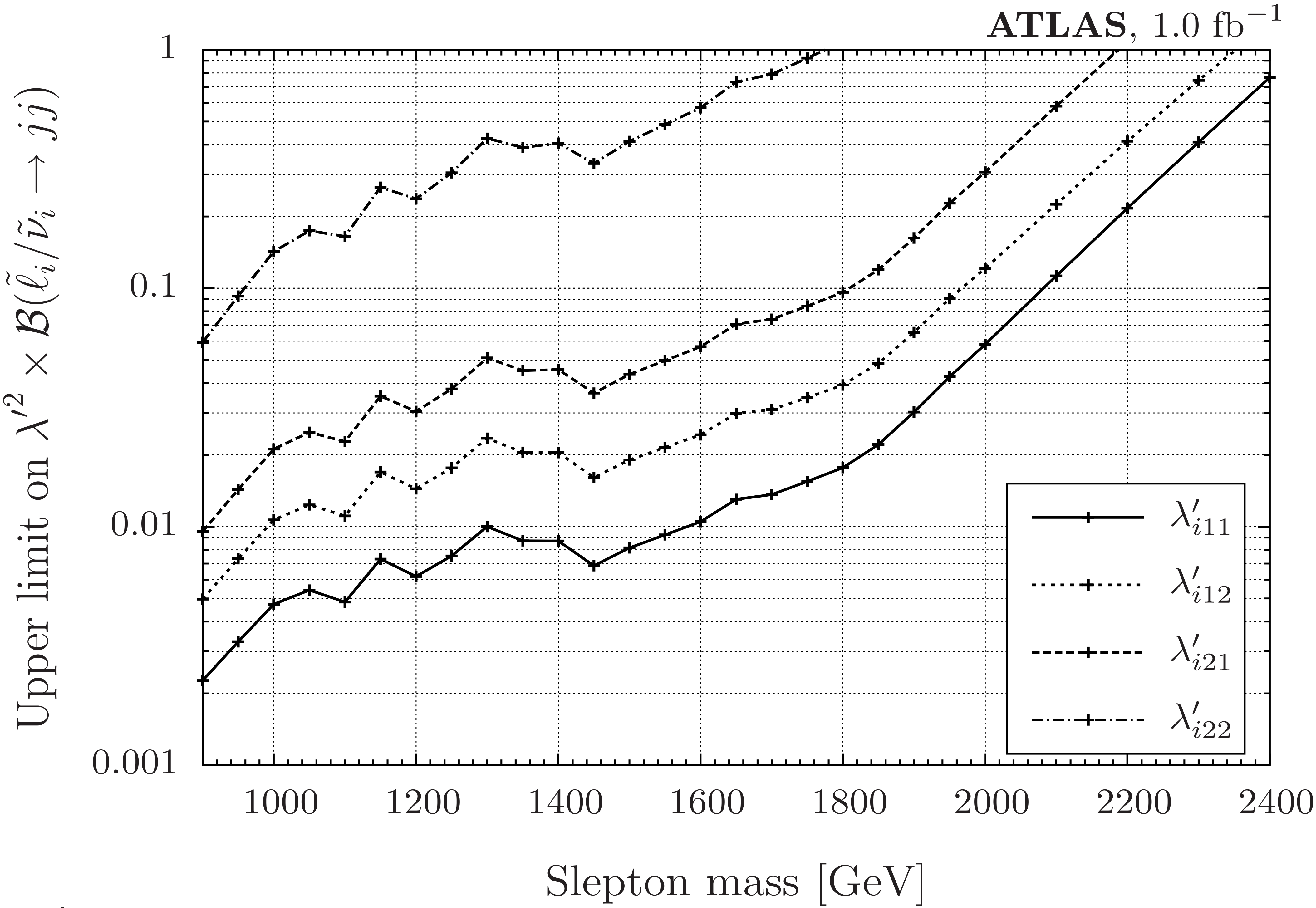
Resonant Dijet Search

- Mass range search ATLAS (CMS) 0.9 TeV (1 TeV)- 4.0 TeV (4.1 TeV)
- Simulated 25,000 signal events for each slepton mass



ATLAS, 1.0 fb^{-1}
Upper limit on $\lambda'^2 \times \mathcal{B}(\tilde{\ell}_i/\tilde{\nu}_i \rightarrow jj)$
Slepton mass [GeV]
1
0.1
0.01
0.001
1000
1200
1400
1600
1800
2000
2200
2400
λ'_{i11}
λ'_{i12}
λ'_{i21}
λ'_{i22}

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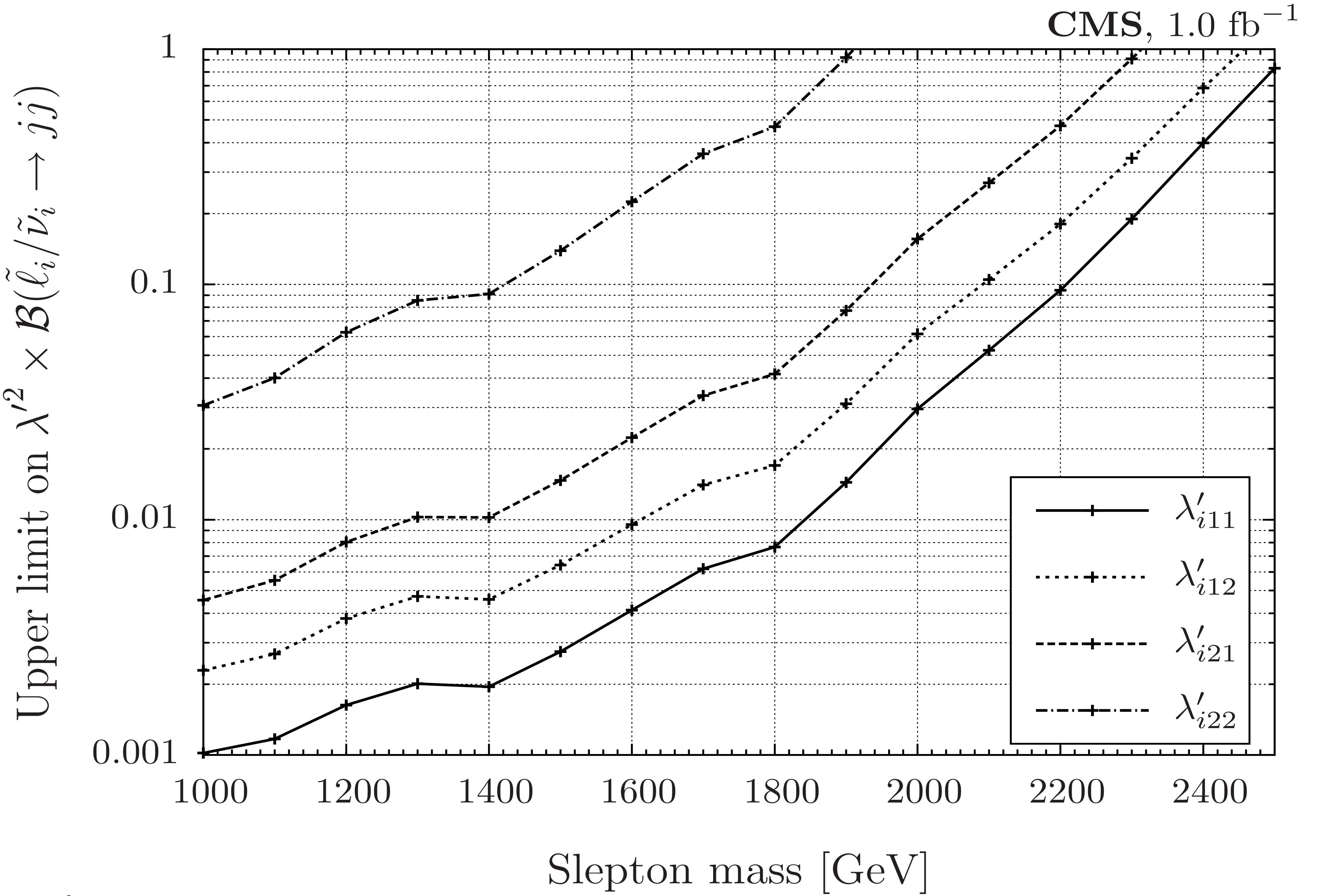

CMS, 1.0 fb^{-1}
Upper limit on $\lambda'^2 \times \mathcal{B}(\tilde{\ell}_i/\tilde{\nu}_i \to jj)$
1
0.1
0.01
0.001
1000
1200
1400
1600
1800
2000
2200
2400
Slepton mass [GeV]
λ'_{i11}
λ'_{i12}
λ'_{i21}
λ'_{i22}

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Like Sign Dileptons from Resonant Slepton Prod.

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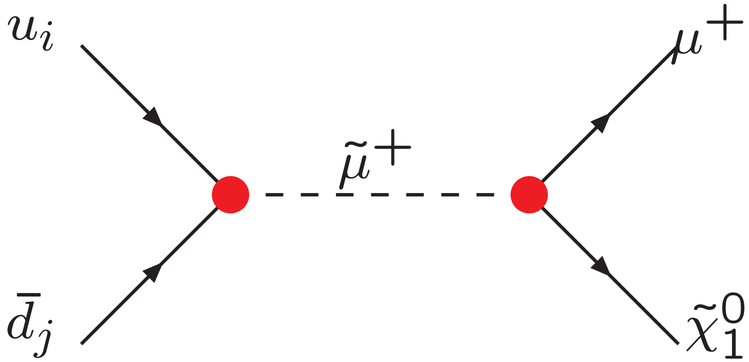
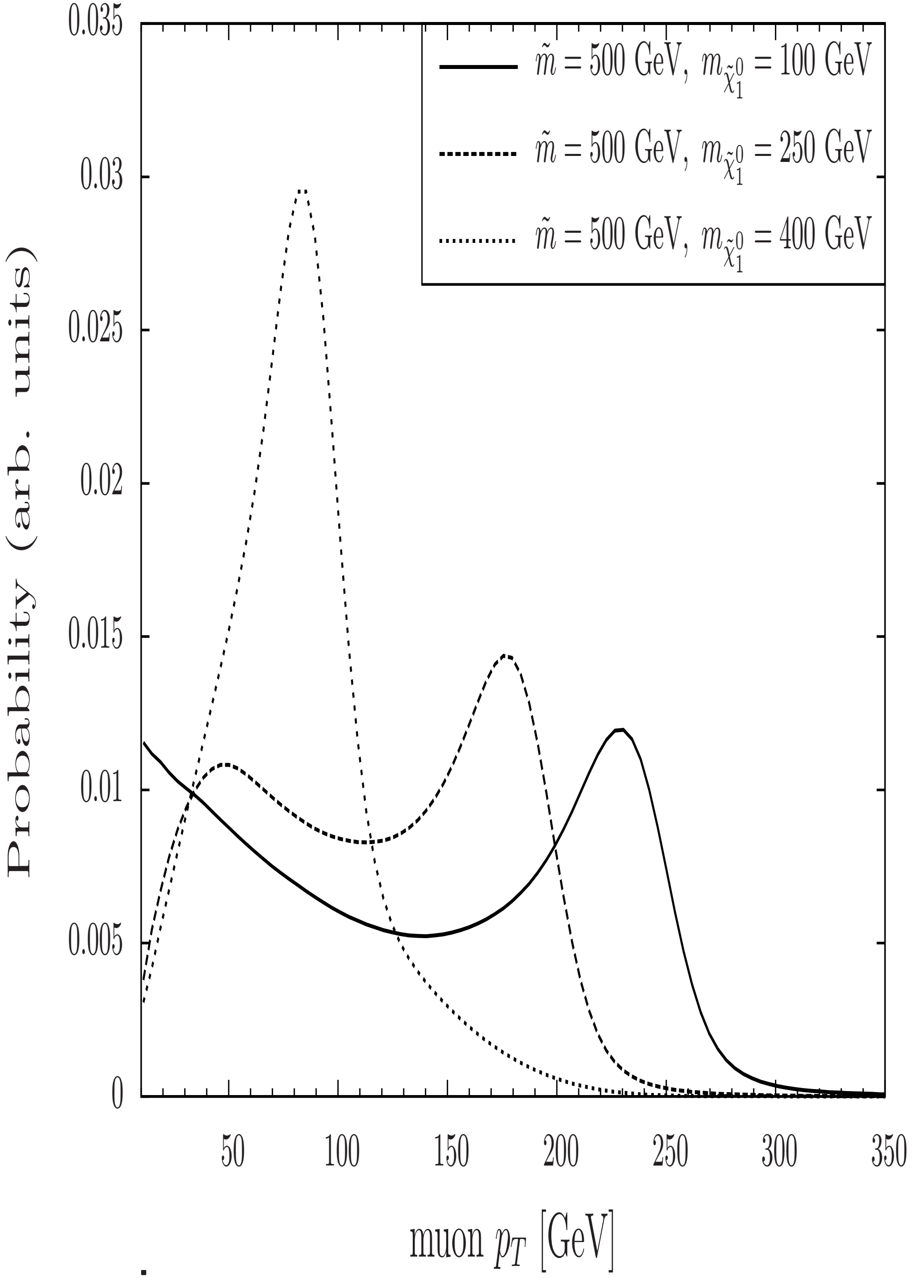
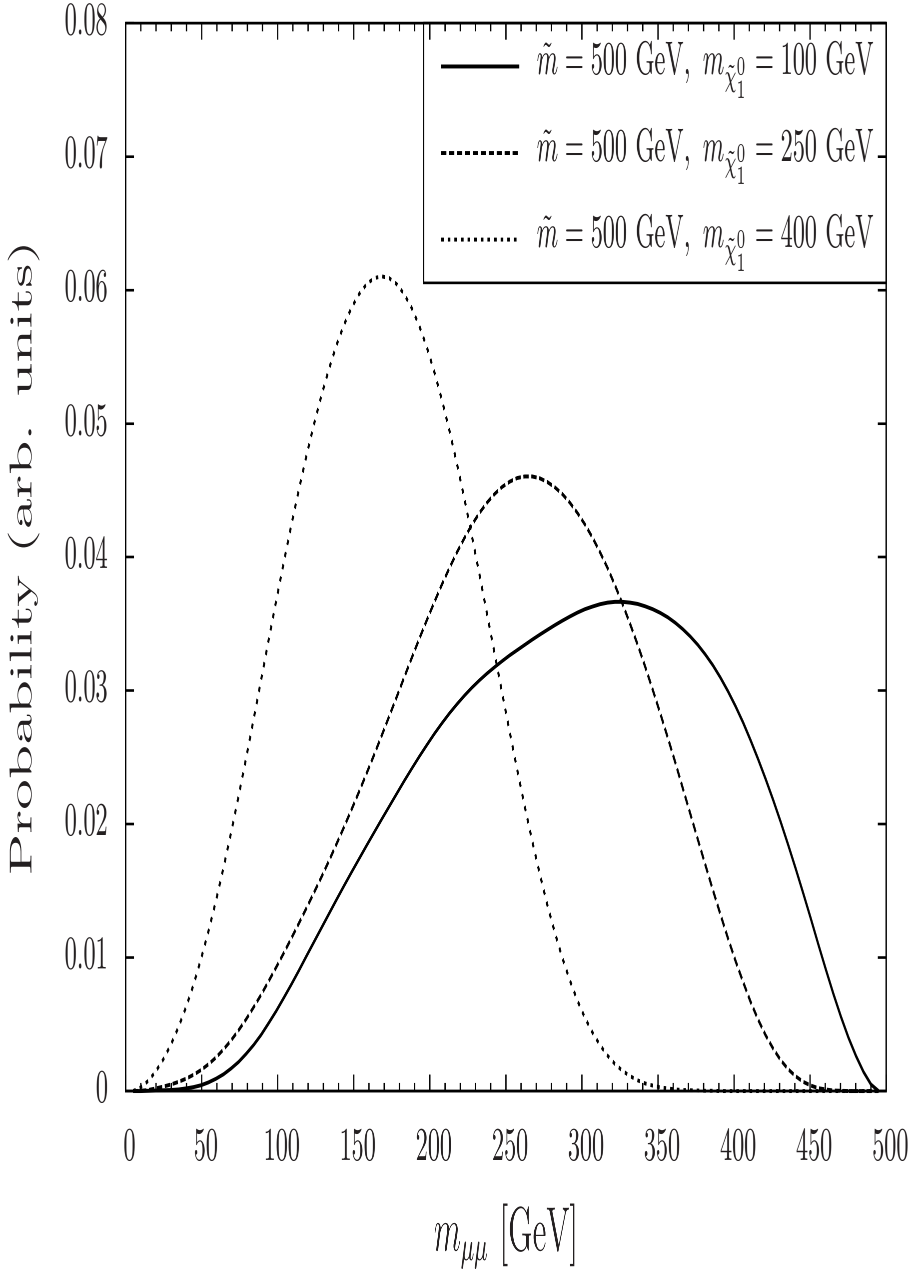


$\tilde{\chi}_1^0 \to \mu^+ + 2\,\mathrm{jets}$

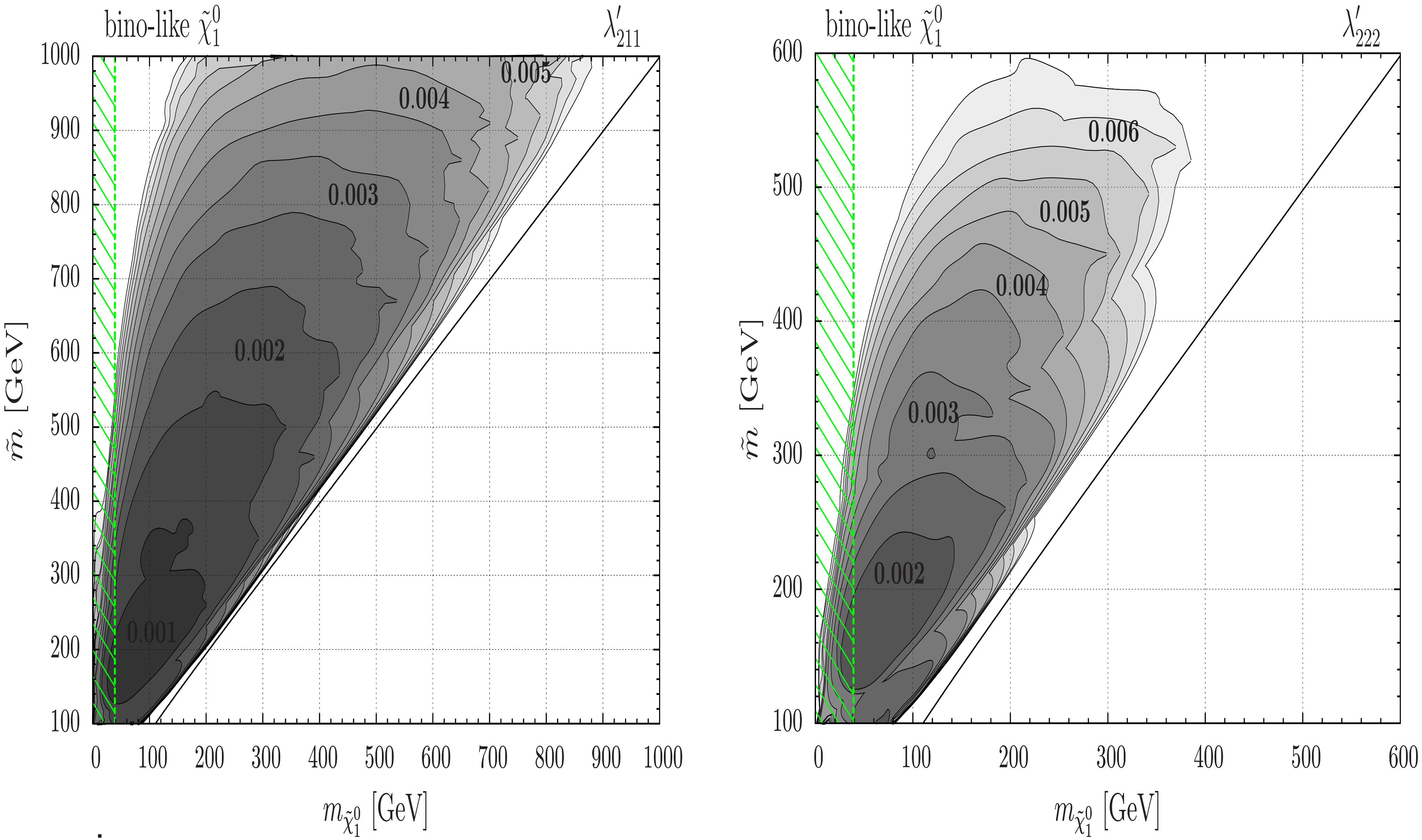
- Prompt like-sign μ's, compare with ATLAS search



(a). p_T distribution of the isolated muons



(b) invariant mass distribution of the like-sign dimuon pairs



bino-like $\tilde{\chi}_1^0$
λ'_{211}
0.001
0.002
0.003
0.004
0.005
$\tilde{m}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]
bino-like $\tilde{\chi}_1^0$
λ'_{222}
0.002
0.003
0.004
0.005
0.006
$\tilde{m}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]