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R-parity Violation and SUSY Searches at the LHC

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Physikshow trip to CERN Sept. 2010

OUTLINE

- **R-parity Violation** equally well motivated **R-Parity Conservation**
- **Should** dedicate comparable effort at the LHC
- What has been done?
- Top R-parity Violating Signatures (work in progress: T. Stefaniak, W. Porod)

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)

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

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

  - Superpotential $\longrightarrow$

SUPERPOTENTIAL

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

- These terms give mass to quarks and leptons.

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

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

R-Parity MSSM

Advantages:

- Proton stable (Well should really consider P_6 instead of R_p)
- Automatic dark matter candidate: $\tilde{\chi}_1^0$

Disadvantages:

- Must add ν_R and Majorana scale $\mathsf{M}_\mathsf{M} > 10^{11}$ GeV
- No solution to strong CP problem

R-Parity MSSM & Axion

Advantages:

- Proton stable (Well should really consider P_6 instead of R_p)
- Automatic dark matter candidate: $\tilde{\chi}_1^0$
- Peccei Quinn axion solution to strong CP problem

Disadvantages:

- Must add ν_R and Majorana scale $\mathrm{M_M} > 10^{11}\,\mathrm{GeV}$

Baryon Triality (B_3) SSM

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

Advantages:

- Proton stable
- Automatic light neutrino masses
  - $\kappa L H_u \Longrightarrow$ ν_i and $\tilde{\chi}^0_j$ mix $\Longrightarrow$ 1 massive neutrino
  - at 1–loop ($LL\bar{E}$, $LQ\bar{D}$) generate other neutrino masses

Disadvantages:

- No dark matter candidate
- No solution to strong CP problem

B_3 SSM & Axion

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

Advantages:

- Proton stable
- Automatic light neutrino masses
- Automatic dark matter candidate: axion or axino

Disadvantages:

Theory Motivation

- Krauss & Wilczek: Discrete symmetries violated by quantum gravity

- Unless remnant of spont. broken gauge symmetry

$\Longrightarrow$ "discrete gauge symmetry"

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

$\Longrightarrow$ conditions on the remnant discrete symmetry

$\Longrightarrow$ "anomaly-free discrete gauge symmetry"

- HD,Luhn,Thormeier: syst. study of all $\mathbf{Z}_N$ with MSSM particle content

$\Longrightarrow$ only 3 anomaly-free discrete gauge symmetries: P_6, R_p, B_3

Unification

- P_6 and B_p not compatible with simple unbroken GUT gauge group

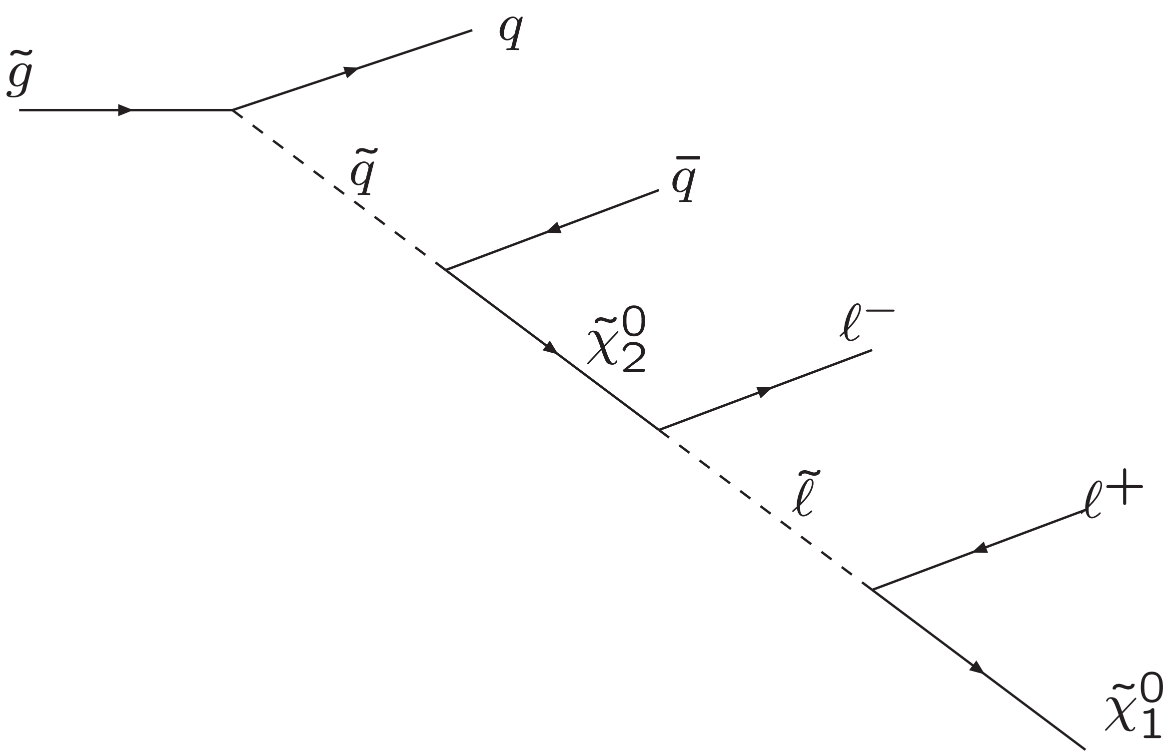
- R_p dangerous dim-5 proton decay operators

Summary

R-parity Violation	equally well motivated	R-Parity Conservation

R-Parity LHC Phenomenology

- SUSY Pair Production: $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$
- Lightest SUSY Particle (LSP) stable: $\tilde{\chi}_1^0$
- Signature: jets + missing transverse energy (MET) + leptons



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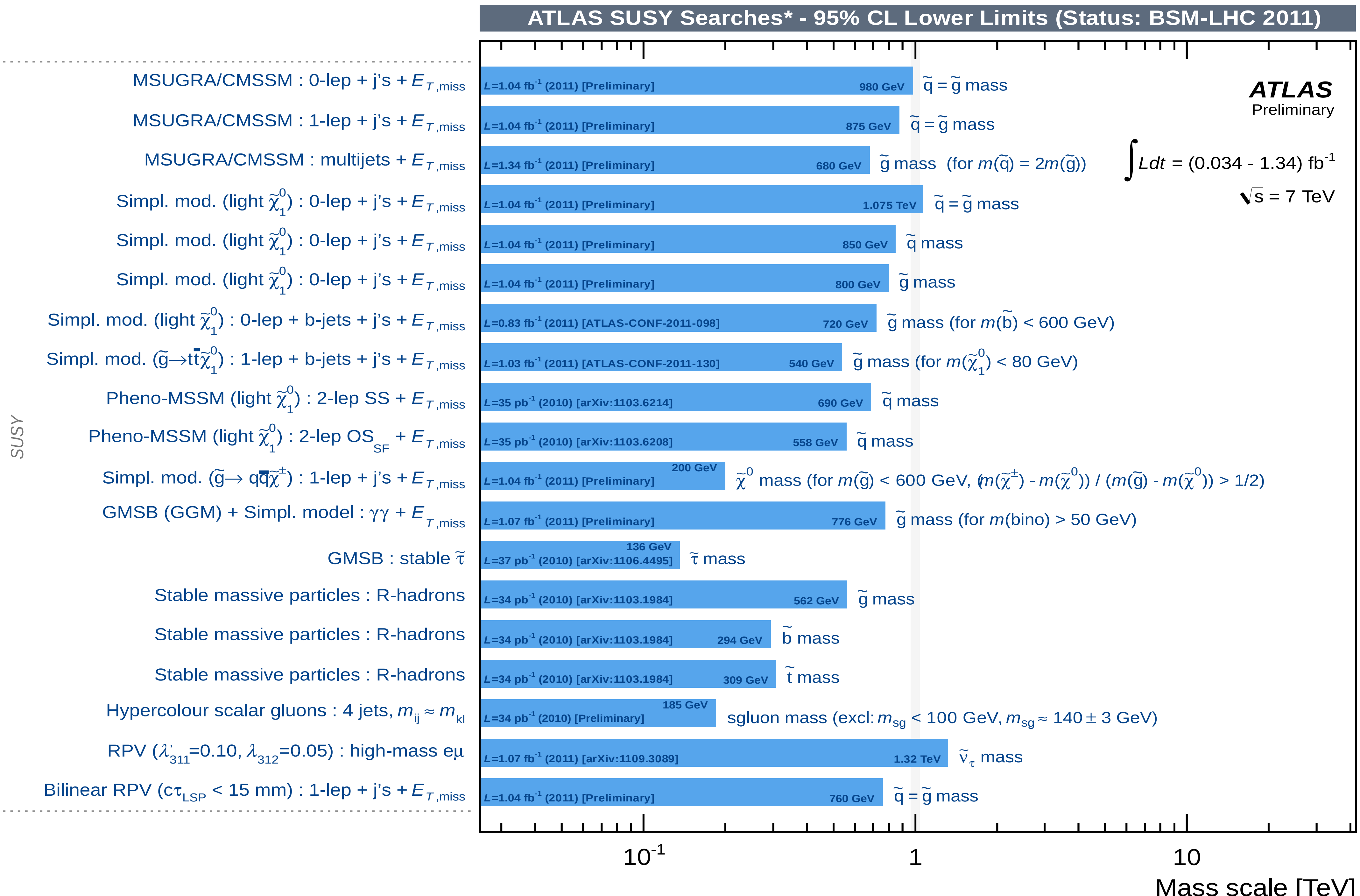
RPC SUSY Searches at the LHC

- **Signatures:** (ATLAS & CMS)
  - jets + MET
  - b-jets + MET
  - 1 lepton + jets + MET
  - 2 leptons + MET
  - 2 photons + MET
  - 1 lepton + 1 photon + MET
  - stable colored particle(s)



*Only a selection of the available results leading to mass limits shown

B_3-Phenomenology: Lepton Number Violation

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

LOW-ENERGY BOUNDS ON λ, λ' (2σ):

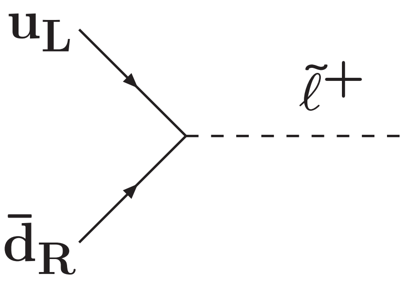
	$\lambda_{ijk}L_iL_j\bar{E}_k$	$\lambda'_{1jk}L_1Q_j\bar{D}_k$	$\lambda'_{2jk}L_2Q_j\bar{D}_k$	$\lambda'_{3jk}L_3Q_j\bar{D}_k$
weakest	0.07	0.28	0.56	0.52
strongest	0.05	$5.\cdot 10^{-4}$	0.06	0.11

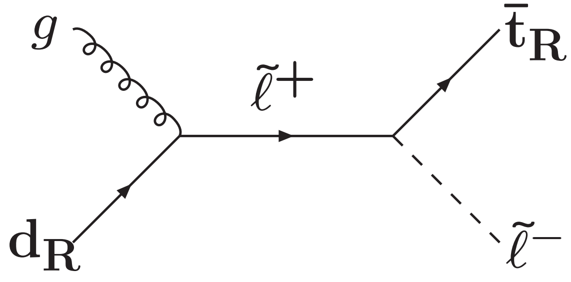
- One operator at a time

- (almost all) Bounds scale with $(\tilde{m}/100)$ GeV

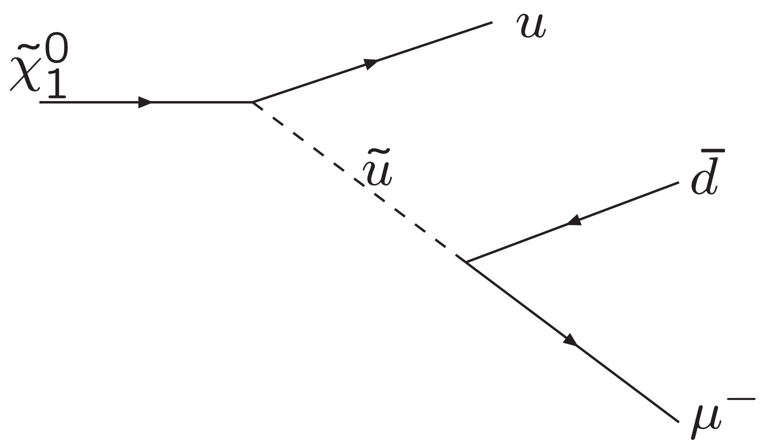
B_3-Phenomenology: Main Changes

1. Resonant/Associated Single SUSY Production possible





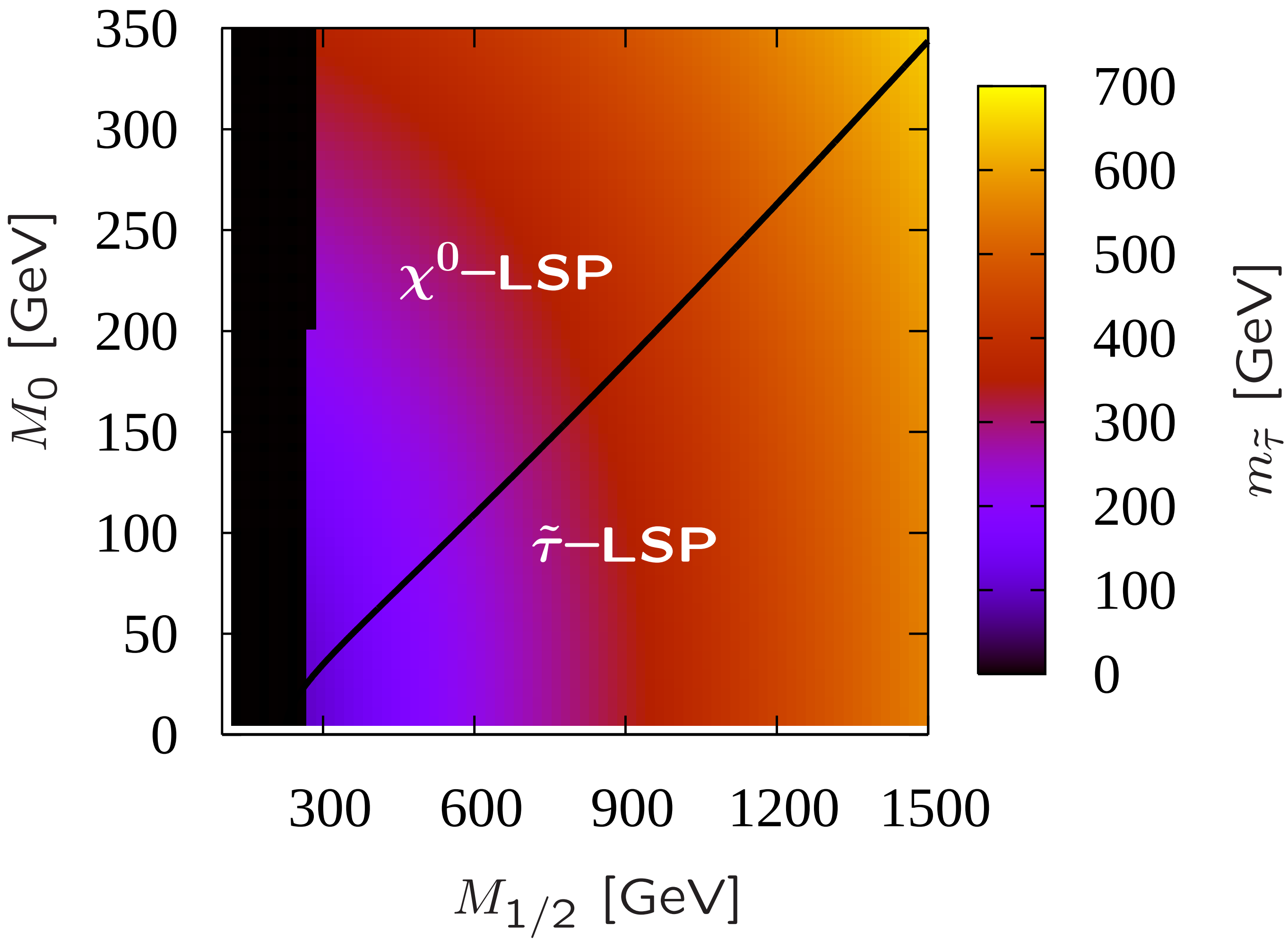
2. LSP is no longer stable



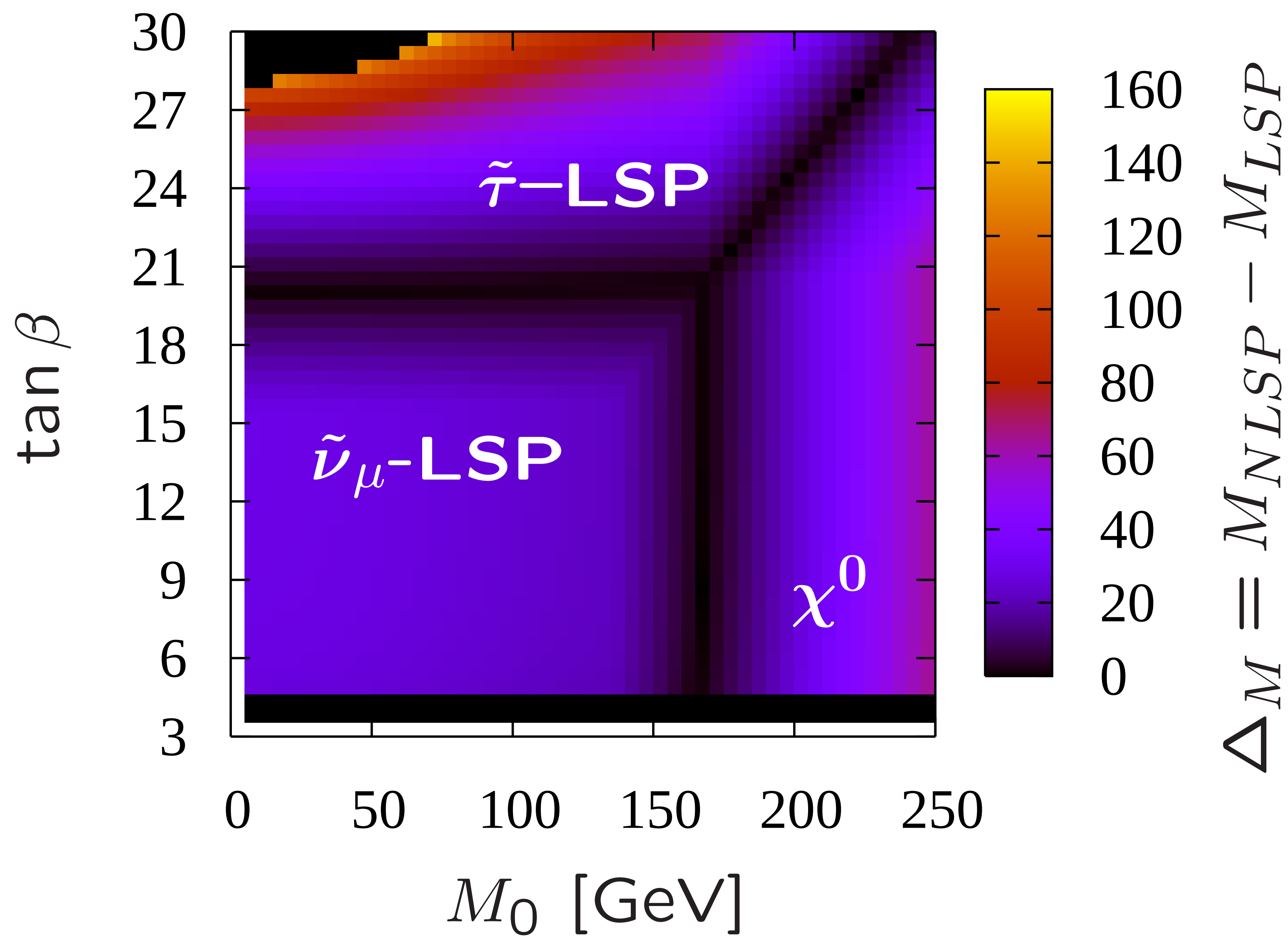
3. LSP $\in \{\chi_1^0, \chi_1^+, \tilde{\nu}_L, \tilde{\ell}^{\pm}_{L,R}, \tilde{\tau}_1^{\pm}, \tilde{q}_{L,R}, \tilde{g}\}$

4. In CMSSM/mSUGRA spectrum can differ

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



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



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

Plethora of new Signatures

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

- With one dominant operator something like 441 possibilities
- Where to start?
- mSUGRA/RGEs; possible LSPs: $(\tilde{\chi}_1^0, \tilde{\tau})$, $(\tilde{\nu}, \tilde{\ell}_R)$

First Step: $\tilde{\chi}_1^0$–LSP

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

- $\tilde{\chi}_1^0$–LSP: $\tilde{\chi}_1^0 \rightarrow \begin{cases} \ell^\pm + \ell^\mp + \not{p}_T & L_1 L_{2,3} \bar{E}_{1,2},\ L_2 L_3 \bar{E}_1 \\ \ell^\pm + \tau^\mp + \not{p}_T & L_{1,2} L_3 \bar{E}_3 \\ \ell^\pm + 2\,\text{jets} & L_{1,2} Q_i \bar{D}_k \\ \ell^\pm + 2\,\text{jets} & L_{1,2} Q_i \bar{D}_k \end{cases}$ $\qquad \ell = e, \mu$

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

  like–sign dileptons + $\not{p}_T$ + jets $\quad (\ell^+ \ell^+ + \text{jets})$

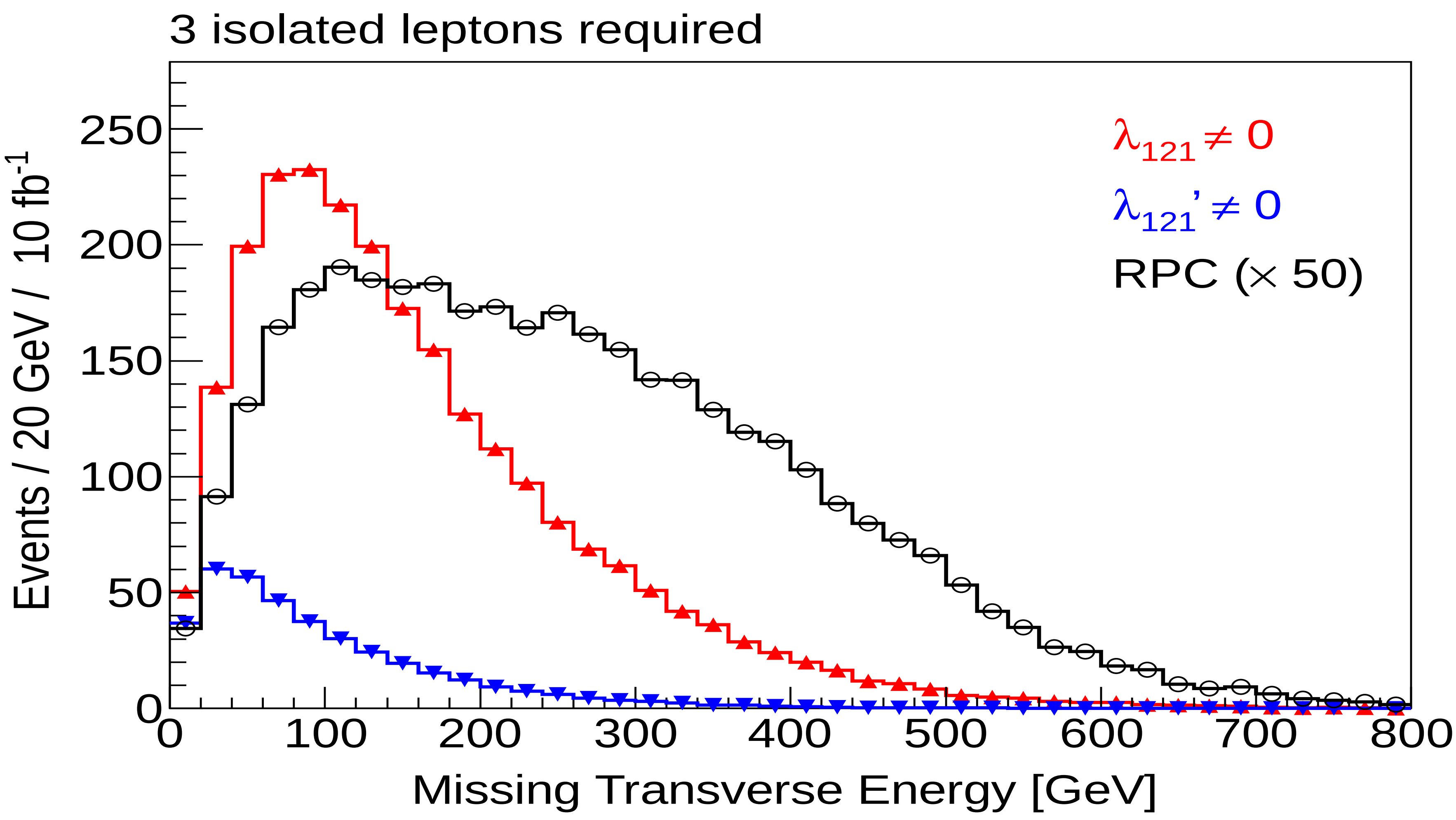
LSP Decays in Detector

- Missing transverse energy diluted or absent
- Neutralino LSP decays:
  - $LL\bar{E}$: $\tilde{\chi}_1^0 \to \begin{pmatrix} ee \\ e\mu \\ e\tau \\ \mu\mu \\ \mu\tau \end{pmatrix} + \nu$
  - $LQ\bar{D}$: $\tilde{\chi}_1^0 \to \begin{pmatrix} e, \mu, \tau \\ \nu \end{pmatrix} + 2\,\text{jets}$
- Very few R-parity violating searches performed to–date
- Can maybe still use MET searches?

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

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

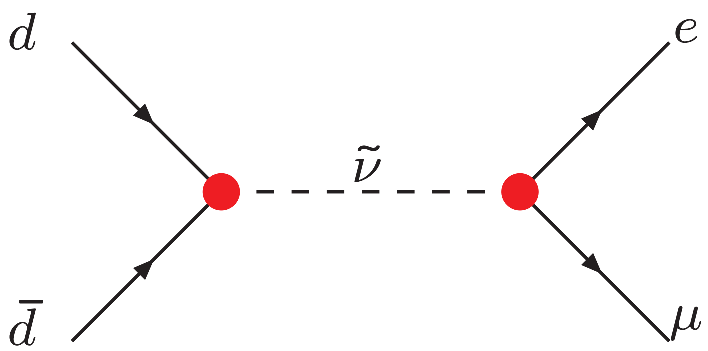
Tim Stefaniak



$M_{\tilde\chi_1^0} = 162\,,\ M_{\tilde\tau_1} = 214\,,\ M_{\tilde t_1} = 650\,,\ M_{\tilde q} = 865\,,\ M_{\tilde g} = 935\,\text{GeV}$

ATLAS Search

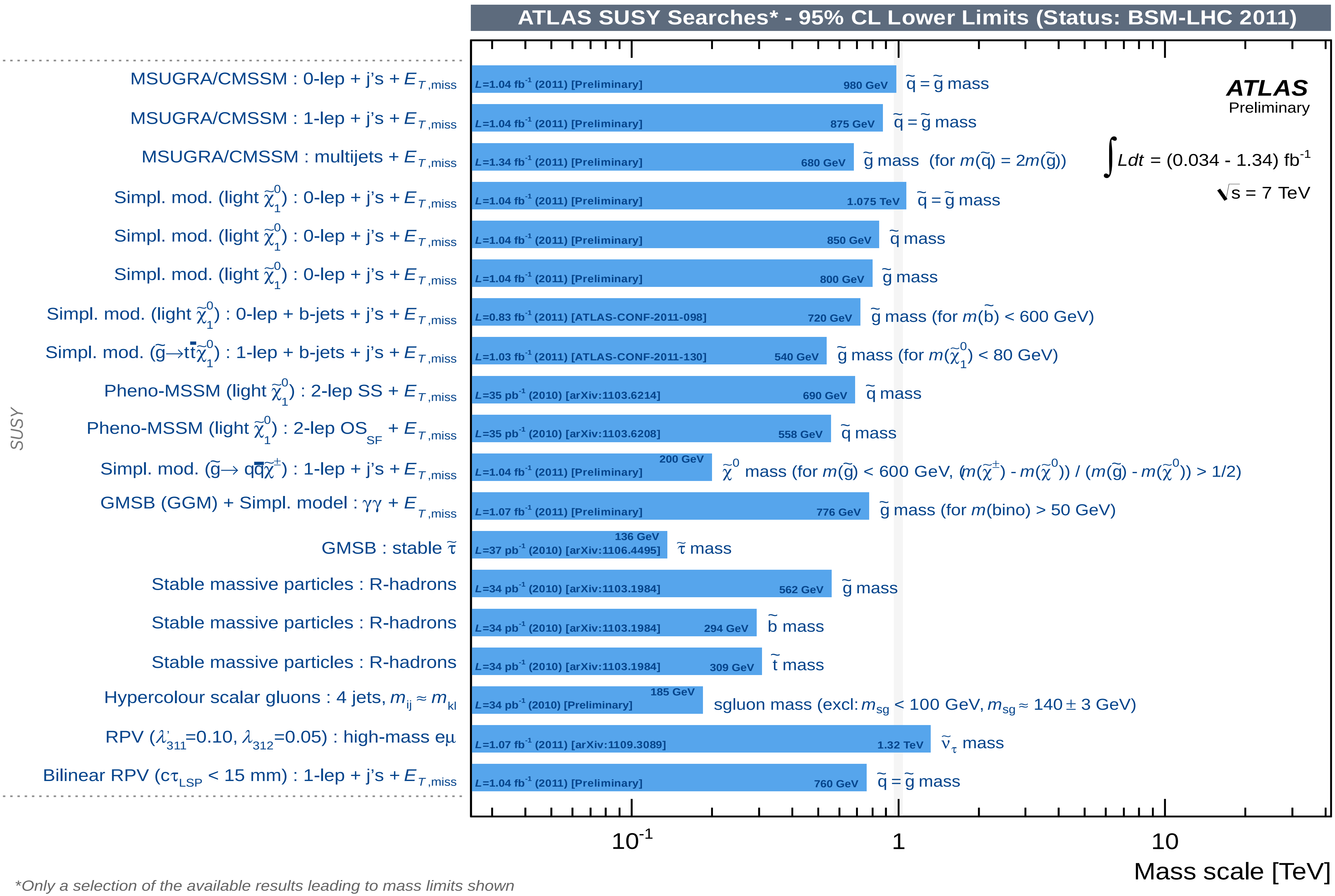
- Resonant sneutrino production, followed by leptonic decay



$L_i Q_1 \bar{D}_1 \qquad L_i L_1 \bar{E}_2$

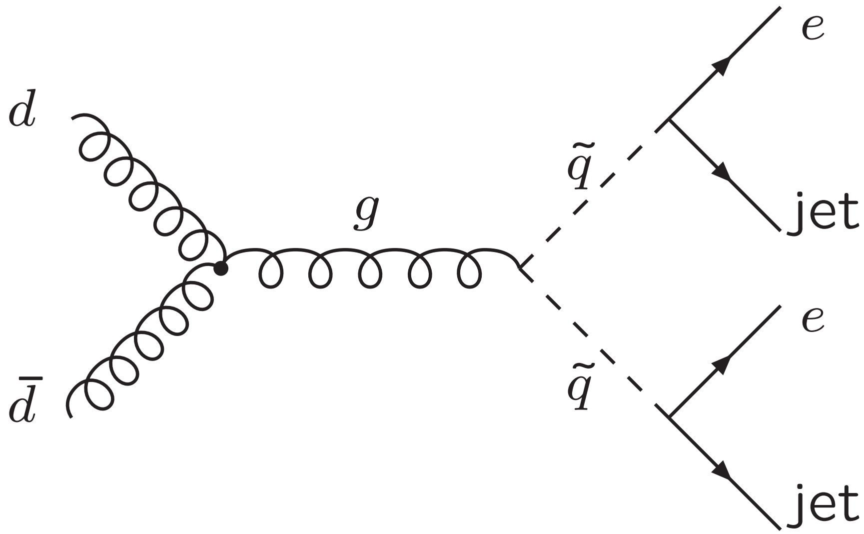
- This requires two dominant operators

- Assume sneutrino is the LSP (or decay to LSP suppressed)

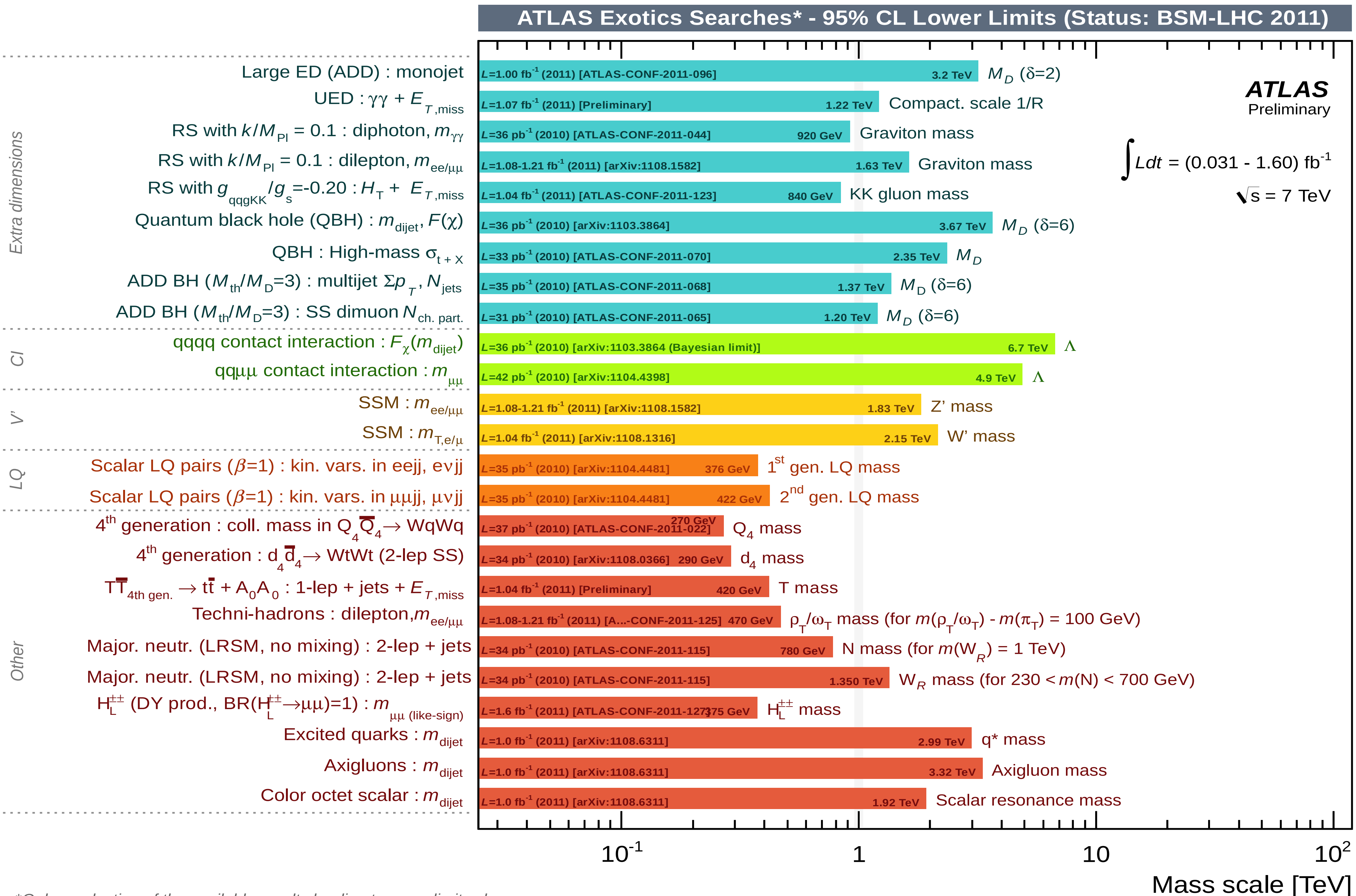

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)
ATLAS
Preliminary
∫Ldt = (0.034 - 1.34) fb^-1
√s = 7 TeV
SUSY
MSUGRA/CMSSM : 0-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
980 GeV
q̃ = g̃ mass
MSUGRA/CMSSM : 1-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
875 GeV
q̃ = g̃ mass
MSUGRA/CMSSM : multijets + E_T,miss
L=1.34 fb^-1 (2011) [Preliminary]
680 GeV
g̃ mass (for m(q̃) = 2m(g̃))
Simpl. mod. (light χ̃₁⁰) : 0-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
1.075 TeV
q̃ = g̃ mass
Simpl. mod. (light χ̃₁⁰) : 0-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
850 GeV
q̃ mass
Simpl. mod. (light χ̃₁⁰) : 0-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
800 GeV
g̃ mass
Simpl. mod. (light χ̃₁⁰) : 0-lep + b-jets + j's + E_T,miss
L=0.83 fb^-1 (2011) [ATLAS-CONF-2011-098]
720 GeV
g̃ mass (for m(b̃) < 600 GeV)
Simpl. mod. (g̃→tt̄χ̃₁⁰) : 1-lep + b-jets + j's + E_T,miss
L=1.03 fb^-1 (2011) [ATLAS-CONF-2011-130]
540 GeV
g̃ mass (for m(χ̃₁⁰) < 80 GeV)
Pheno-MSSM (light χ̃₁⁰) : 2-lep SS + E_T,miss
L=35 pb^-1 (2010) [arXiv:1103.6214]
690 GeV
q̃ mass
Pheno-MSSM (light χ̃₁⁰) : 2-lep OS_SF + E_T,miss
L=35 pb^-1 (2010) [arXiv:1103.6208]
558 GeV
q̃ mass
Simpl. mod. (g̃→ qq̄χ̃^±) : 1-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
200 GeV
χ̃^0 mass (for m(g̃) < 600 GeV, (m(χ̃^±) - m(χ̃^0)) / (m(g̃) - m(χ̃^0)) > 1/2)
GMSB (GGM) + Simpl. model : γγ + E_T,miss
L=1.07 fb^-1 (2011) [Preliminary]
776 GeV
g̃ mass (for m(bino) > 50 GeV)
GMSB : stable τ̃
L=37 pb^-1 (2010) [arXiv:1106.4495]
136 GeV
τ̃ mass
Stable massive particles : R-hadrons
L=34 pb^-1 (2010) [arXiv:1103.1984]
562 GeV
g̃ mass
Stable massive particles : R-hadrons
L=34 pb^-1 (2010) [arXiv:1103.1984]
294 GeV
b̃ mass
Stable massive particles : R-hadrons
L=34 pb^-1 (2010) [arXiv:1103.1984]
309 GeV
t̃ mass
Hypercolour scalar gluons : 4 jets, m_ij ≈ m_kl
L=34 pb^-1 (2010) [Preliminary]
185 GeV
sgluon mass (excl: m_sg < 100 GeV, m_sg ≈ 140 ± 3 GeV)
RPV (λ'_311=0.10, λ_312=0.05) : high-mass eμ
L=1.07 fb^-1 (2011) [arXiv:1109.3089]
1.32 TeV
ν̃_τ mass
Bilinear RPV (cτ_LSP < 15 mm) : 1-lep + j's + E_T,miss
L=1.04 fb^-1 (2011) [Preliminary]
760 GeV
q̃ = g̃ mass
10^-1
1
10
Mass scale [TeV]
*Only a selection of the available results leading to mass limits shown

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 $\mu\mu jj$ ($L_\mu QD$)



*Only a selection of the available results leading to mass limits shown

$\tilde{\tau}$-LSP Phenomenology

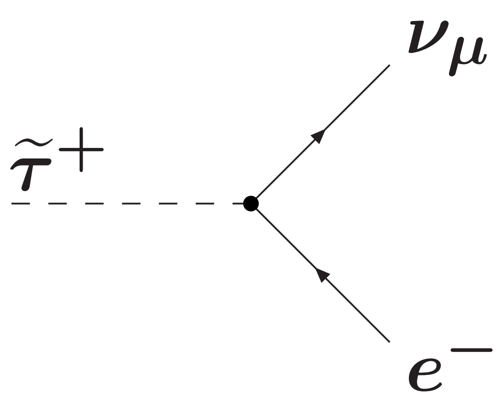
- Dominant production mechanisms @ LHC: $\tilde{q}\tilde{q},\ \tilde{g}\tilde{g},\ \tilde{q}\tilde{g}$

- Signature determined by cascade decays:

$$\tilde{q} \longrightarrow \ldots \longrightarrow \chi_1^0 \longrightarrow \tau^{\pm}\,\tilde{\tau}^{\mp}$$

- How does the $\tilde{\tau}$–LSP decay?

- Depends on dominant operator, e.g. $\boldsymbol{\lambda_{231} L_\mu L_\tau E_e}$

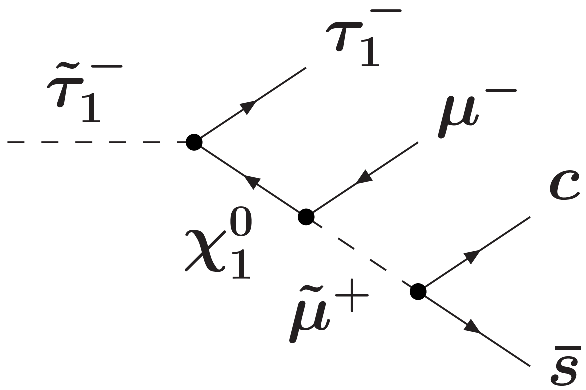


Simple leptonic two-body decay; easy to detect

- Get like-sign dilepton signature + extra τ's

4-Body $\tilde{\tau}$-Decays

- How about if $\lambda'_{211} L_\mu Q_2 \bar{D}_2$? Would expect a 4-body decay



- But through RGEs generate couplings $\lambda_{233} L_\mu L_\tau \bar{E}_\tau$, which violates μ-number, but conserves τ-number.

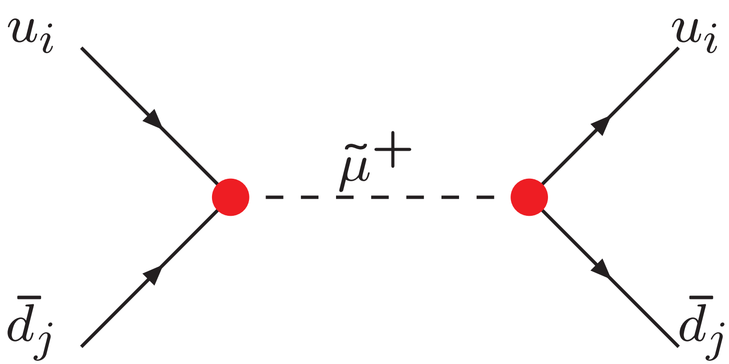
- Must calculate case by case if 4-body or 2-body decay dominates

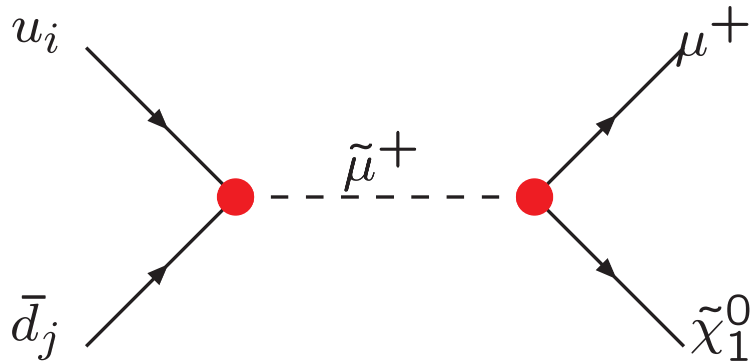
- Work in progress by ATLAS (Bonn group involved: Desch, Fleischmann, ...)

2 More Searches: Resonant $\tilde{\ell}$, $\tilde{\nu}$ Production

with Tim Stefaniak

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



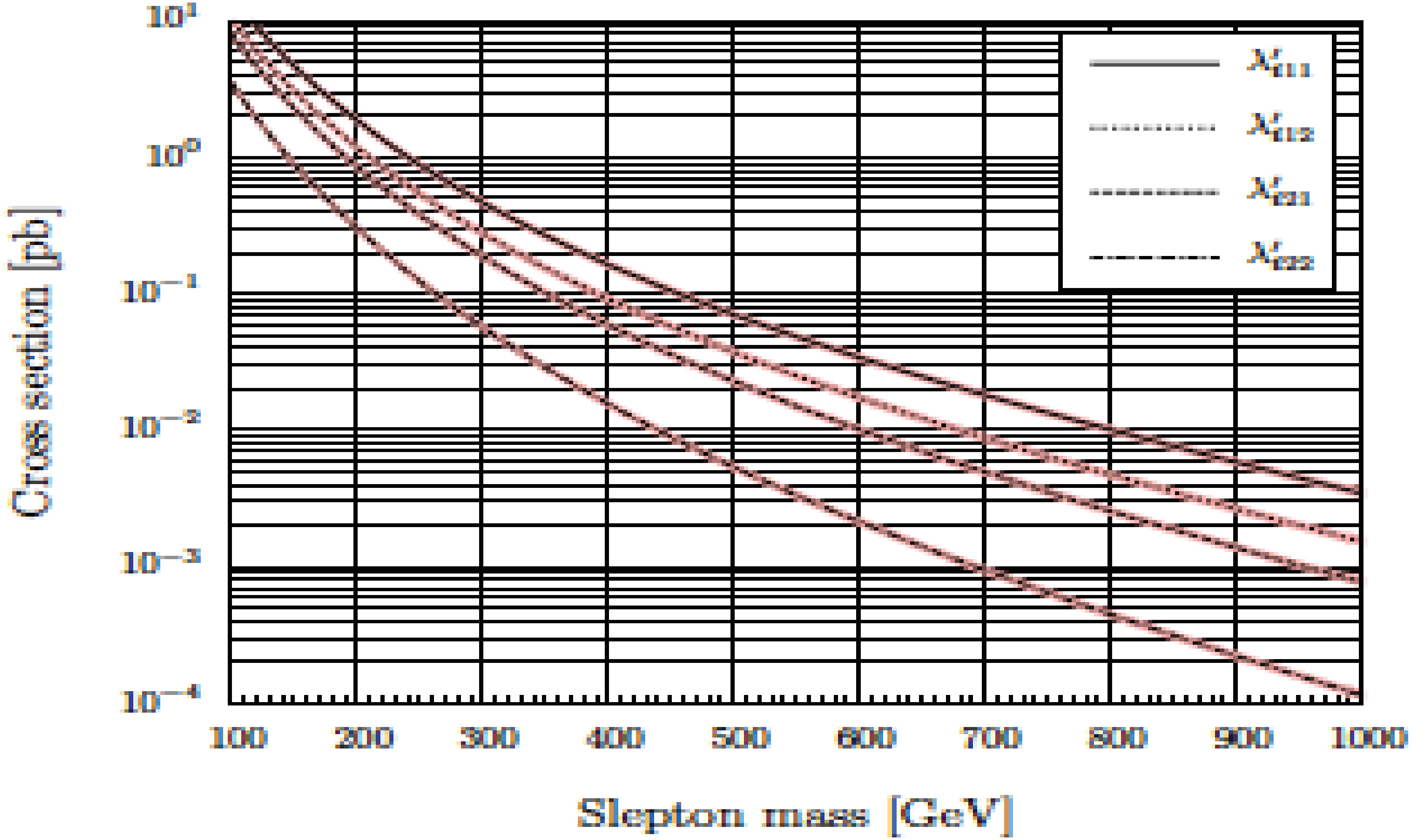


$\tilde{\chi}_1^0 \to \mu^+ + 2\,\text{jets}$

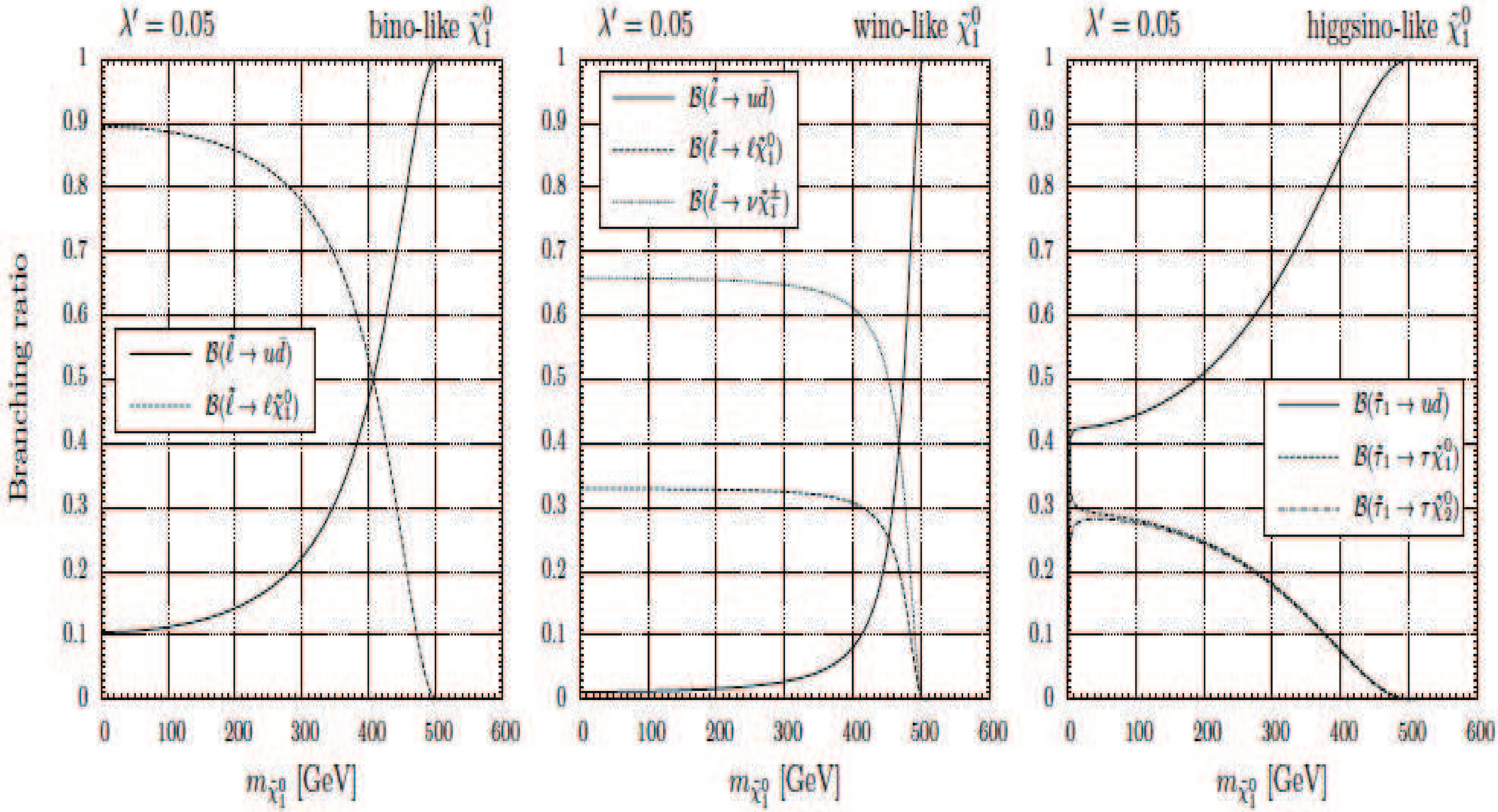
- Dijet resonance: compare with ATLAS and CMS searches ($1\,\text{fb}^{-1}$)

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

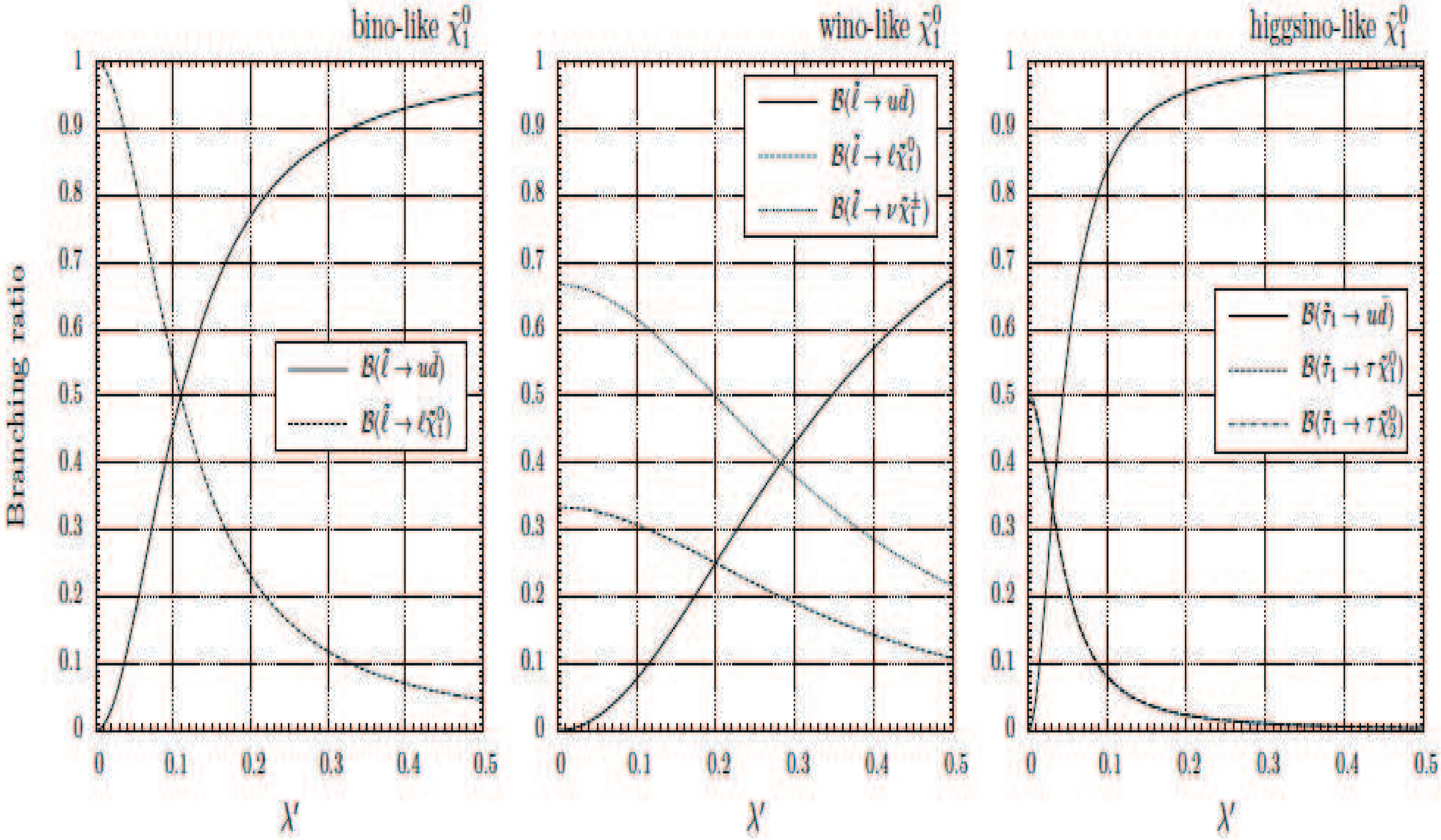
Resonant Slepton Production Xsection



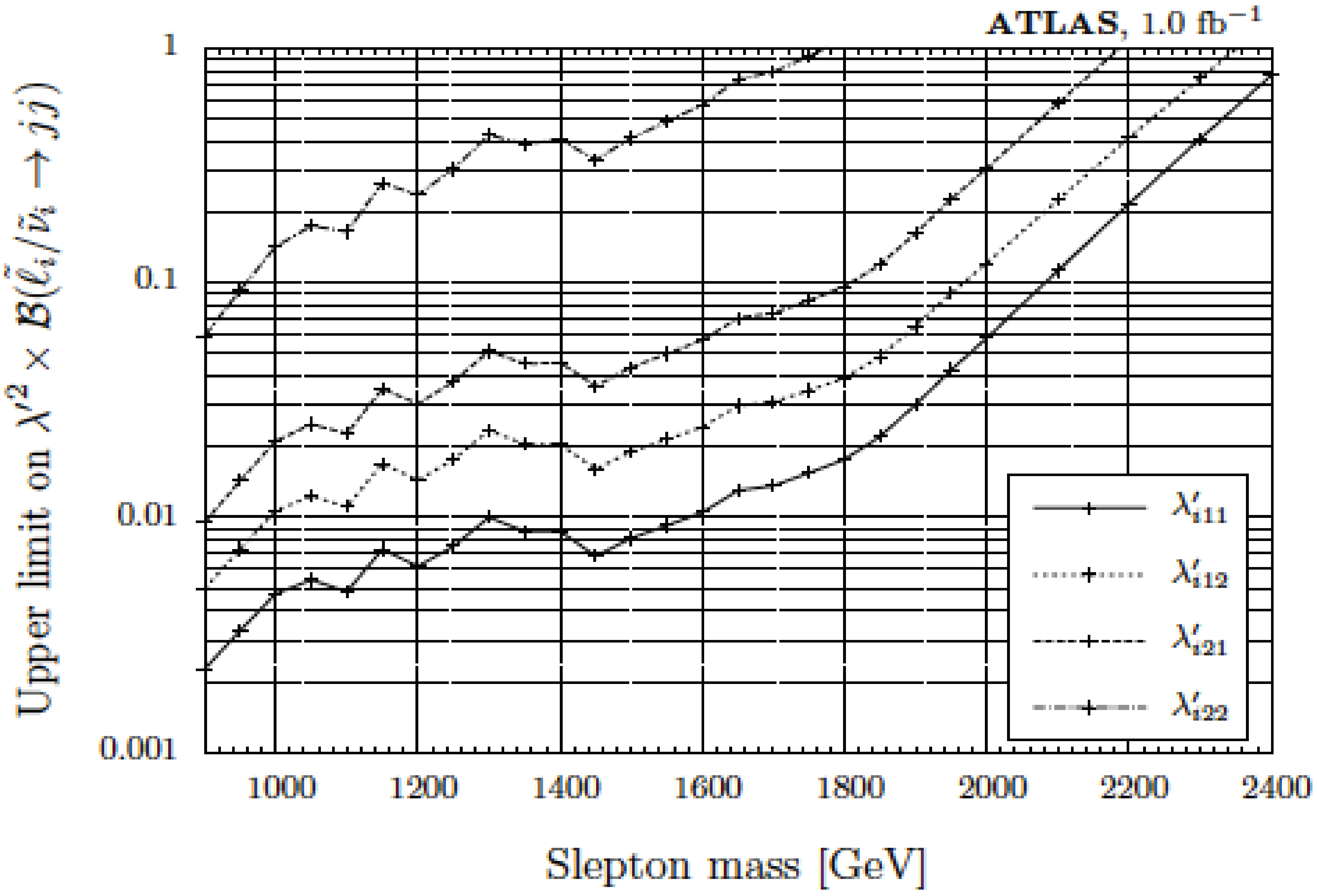
- $\lambda' = 0.01$
- CTEQ6m PDFs



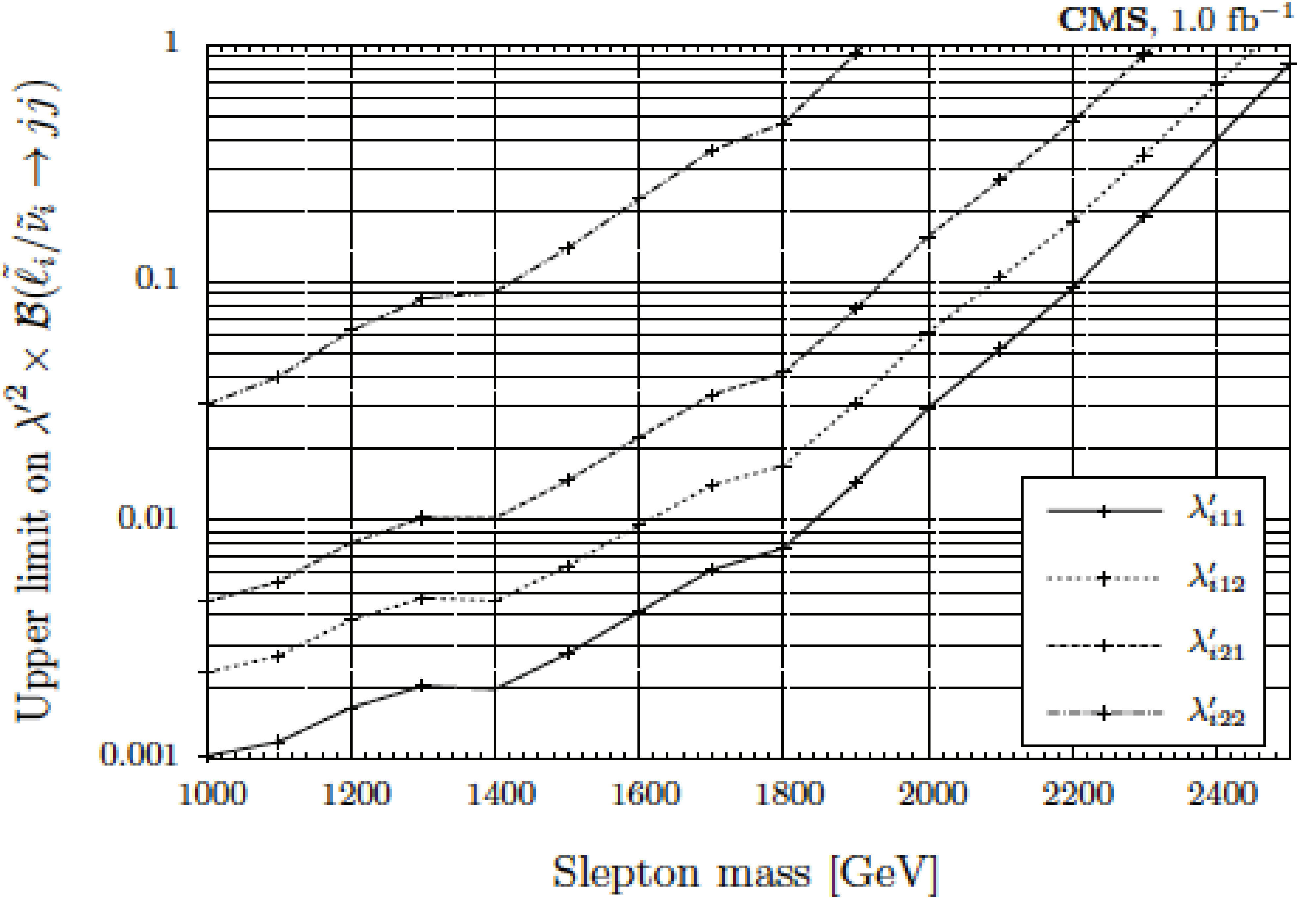
$\lambda' = 0.05$
bino-like $\tilde{\chi}_1^0$
$\lambda' = 0.05$
wino-like $\tilde{\chi}_1^0$
$\lambda' = 0.05$
higgsino-like $\tilde{\chi}_1^0$
Branching ratio
$\mathcal{B}(\tilde{\ell} \to u\bar{d})$
$\mathcal{B}(\tilde{\ell} \to \ell\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\ell} \to \nu\tilde{\chi}_1^\pm)$
$\mathcal{B}(\tilde{\tau}_1 \to u\bar{d})$
$\mathcal{B}(\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\tau}_1 \to \tau\tilde{\chi}_2^0)$
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
500
600
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



bino-like $\tilde{\chi}_1^0$
wino-like $\tilde{\chi}_1^0$
higgsino-like $\tilde{\chi}_1^0$
Branching ratio
λ'
$\mathcal{B}(\tilde{\ell} \to u\bar{d})$
$\mathcal{B}(\tilde{\ell} \to \ell\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\ell} \to \nu\tilde{\chi}_1^\pm)$
$\mathcal{B}(\tilde{\tau}_1 \to u\bar{d})$
$\mathcal{B}(\tilde{\tau}_1 \to \tau\tilde{\chi}_1^0)$
$\mathcal{B}(\tilde{\tau}_1 \to \tau\tilde{\chi}_2^0)$



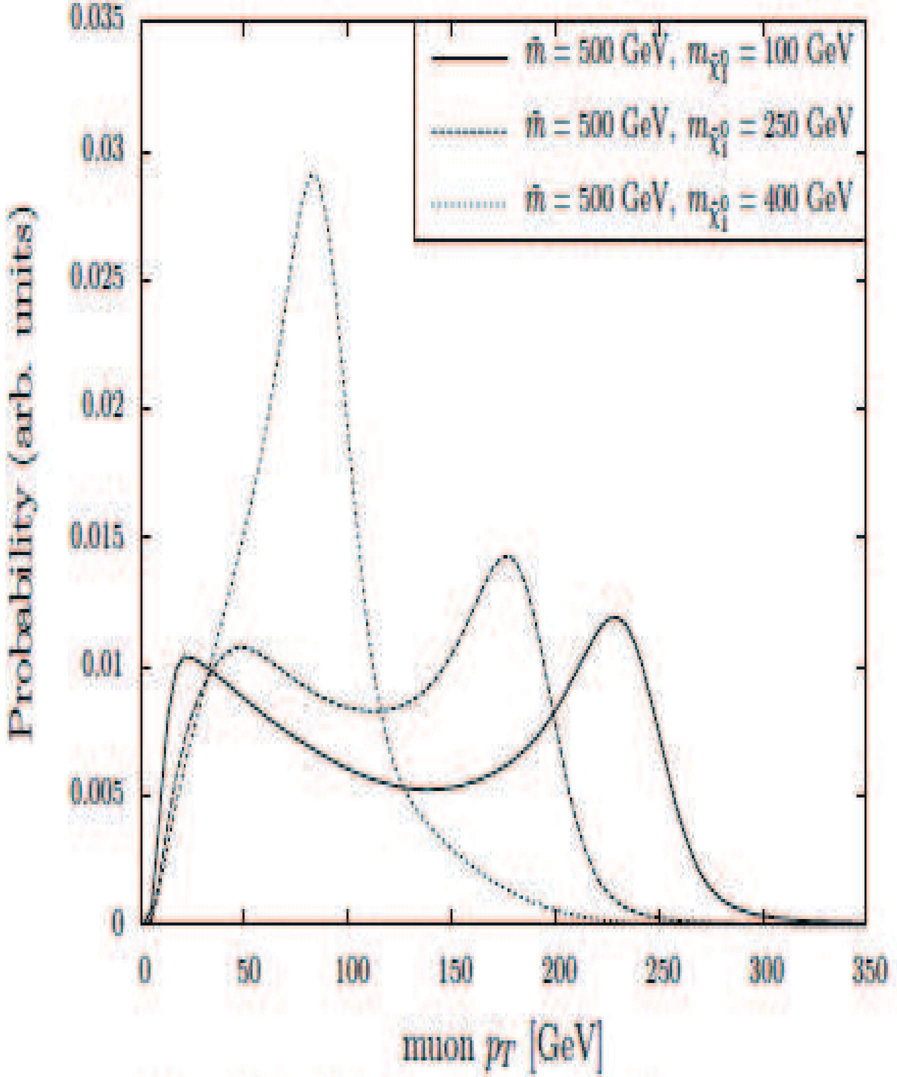
ATLAS, 1.0 fb^{-1}
Upper limit on $\lambda'^2 \times \mathcal{B}(\tilde{\ell}_i/\tilde{\nu}_i \to jj)$
1
0.1
0.01
0.001
1000
1200
1400
1600
1800
2000
2200
2400
Slepton mass [GeV]
λ'_{i11}
λ'_{i12}
λ'_{i21}
λ'_{i22}


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

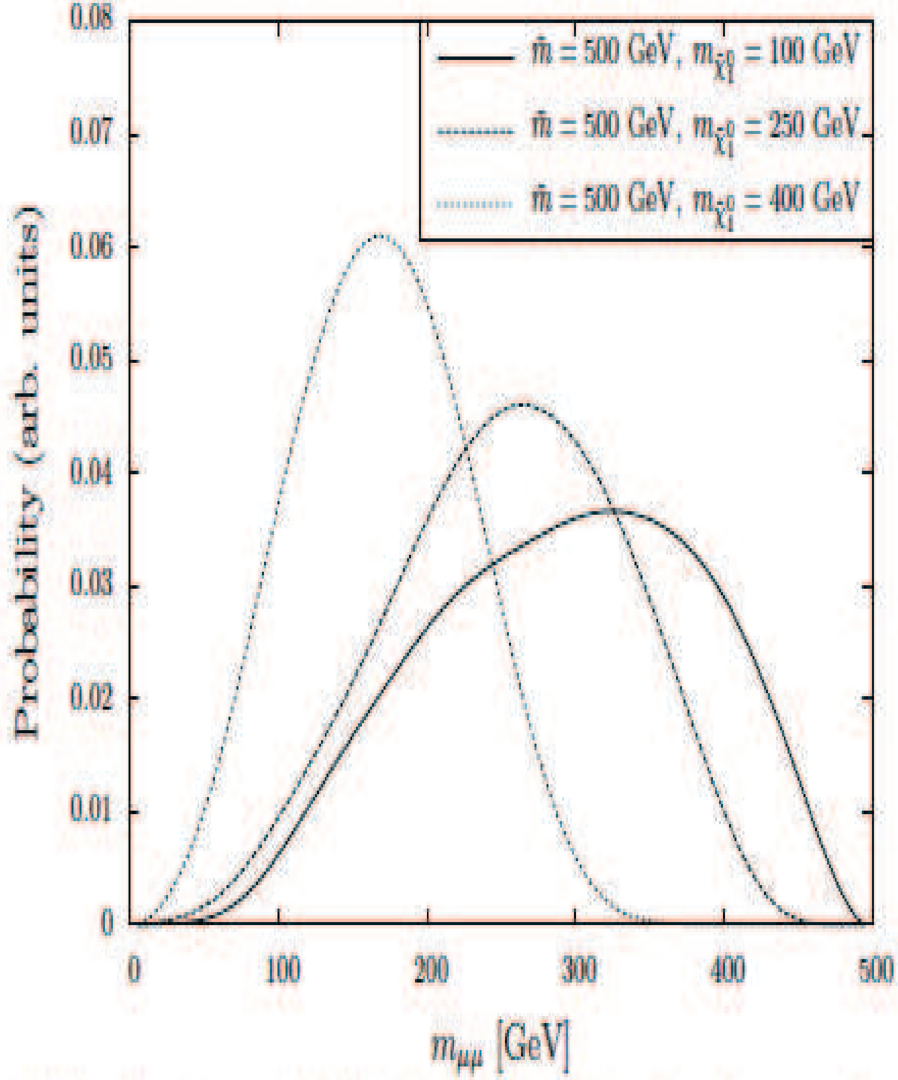
Resonant Dijet Search

- Mass range search ATLAS (CMS) 0.9 TeV (1 TeV)- 4.0 TeV (4.1 TeV)

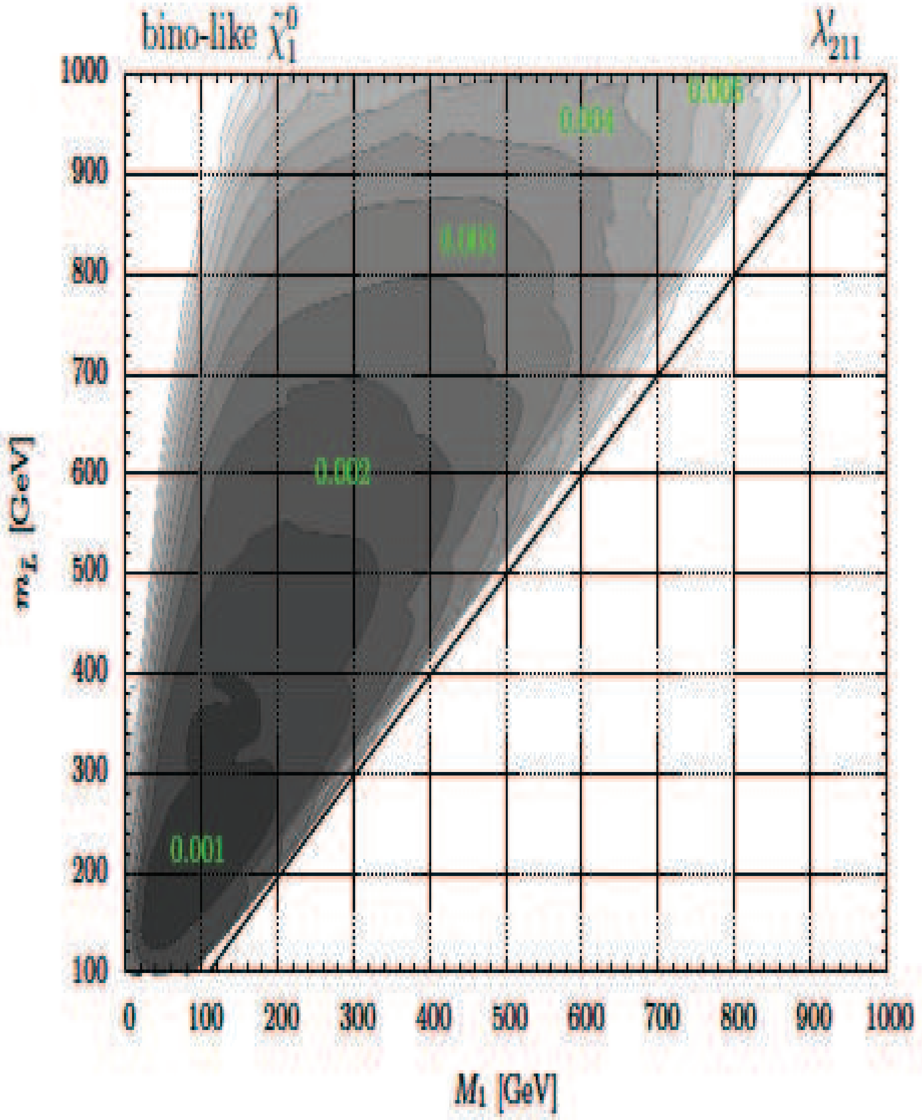
- Simulated 25,000 signal events for each slepton mass



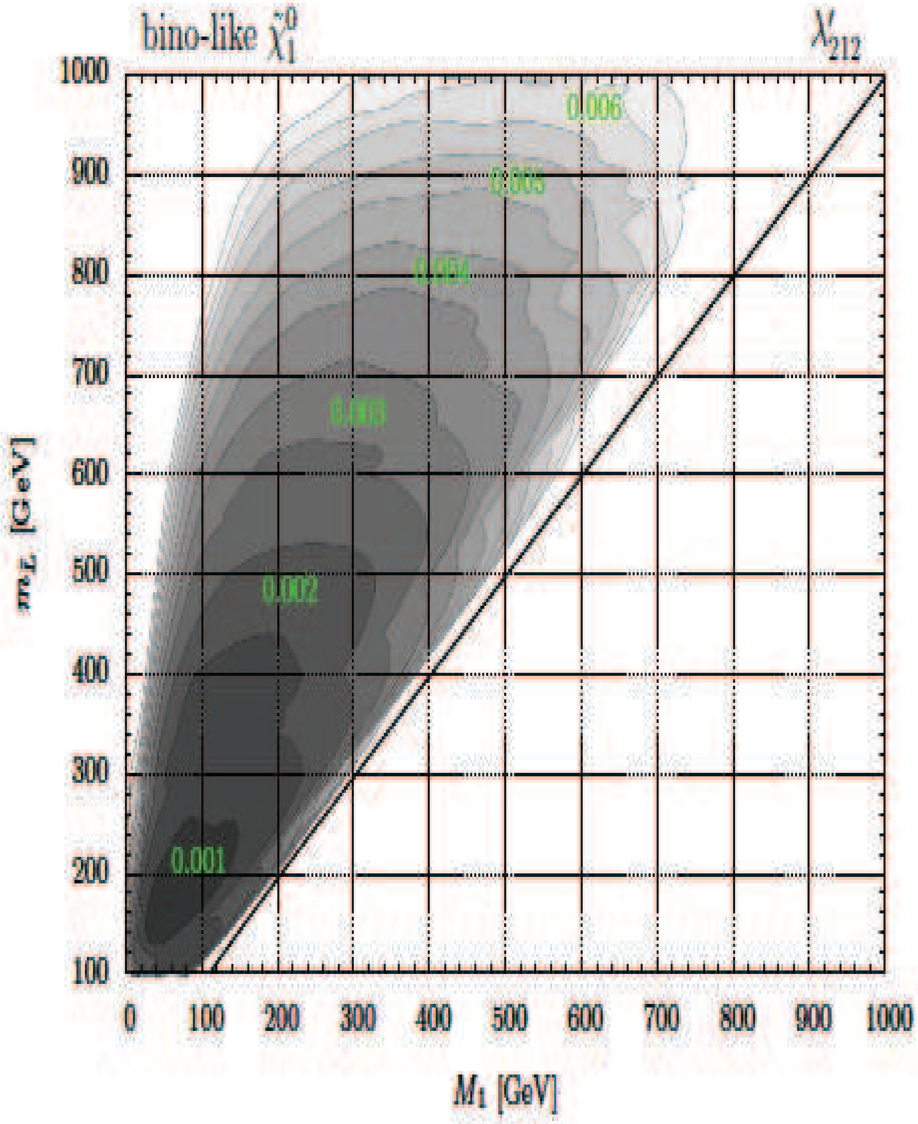
(a)p_T distrubution of the isolated muons.



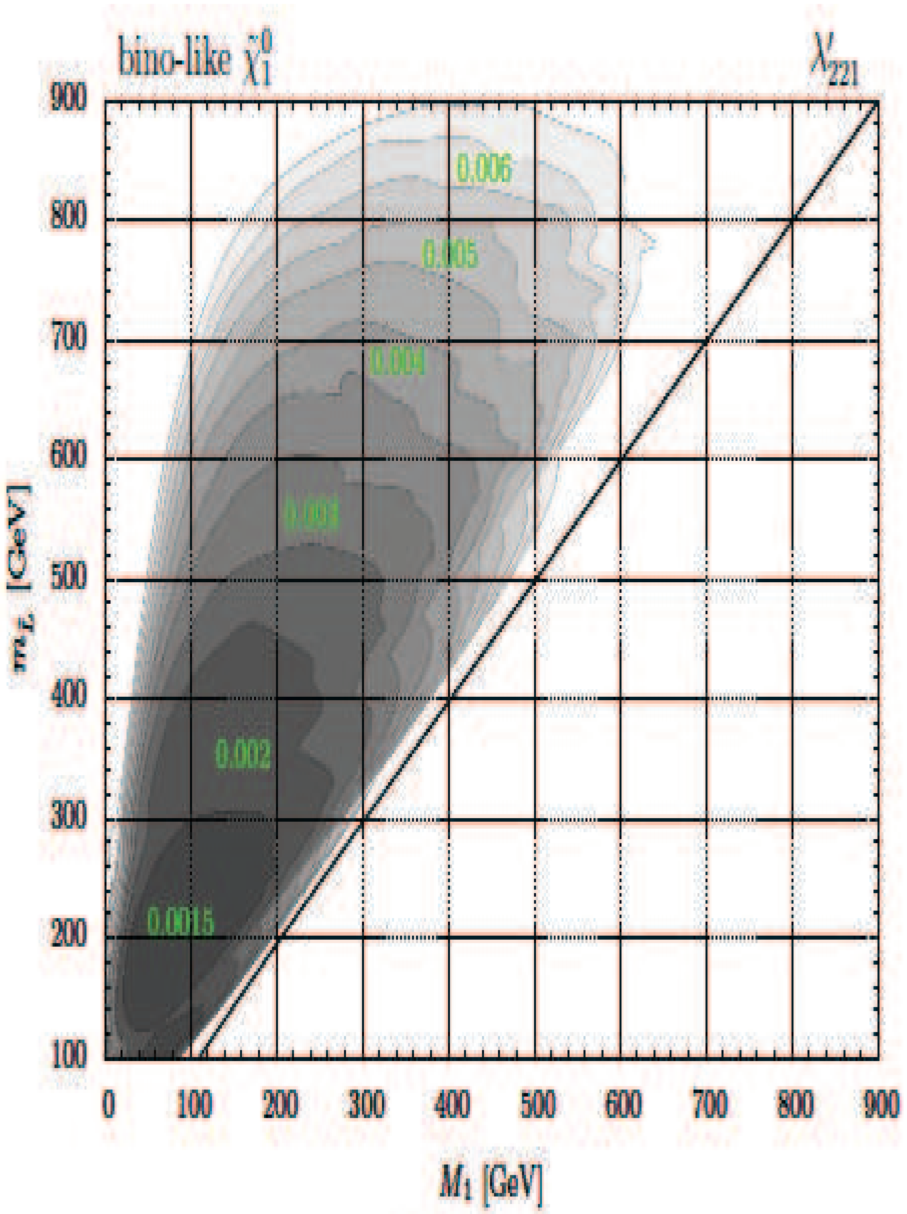
(b)Invariant mass distribution of the like–sign dimuon pairs.



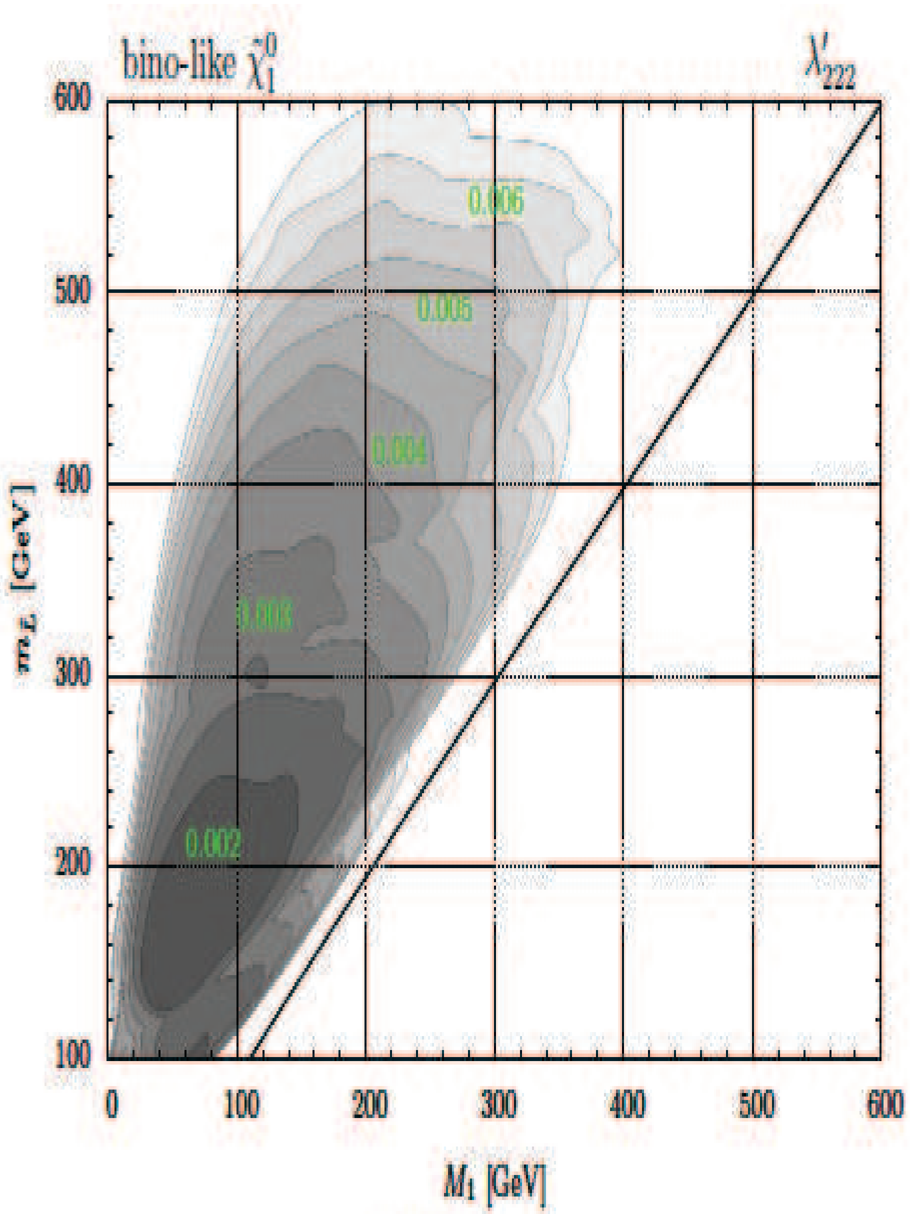
(a)λ'_{211}.



(b)λ'_{212}.



(c)λ'_{221}.



(d)λ'_{222}.

TOP (10) RPV MODELS

(Work in progress: Tim Stefaniak, Werner Porod, Ben Allanach)

- **LLE:** (a) $(\tilde{\chi}_1^0, \tilde{\tau})$–LSP

  (b) pair production

  (c) detached vertices

- **LQD:** (a) $(\tilde{\chi}_1^0, \tilde{\tau})$–LSP

  (b) pair production

  (c) resonant production

  (d) detached vertices

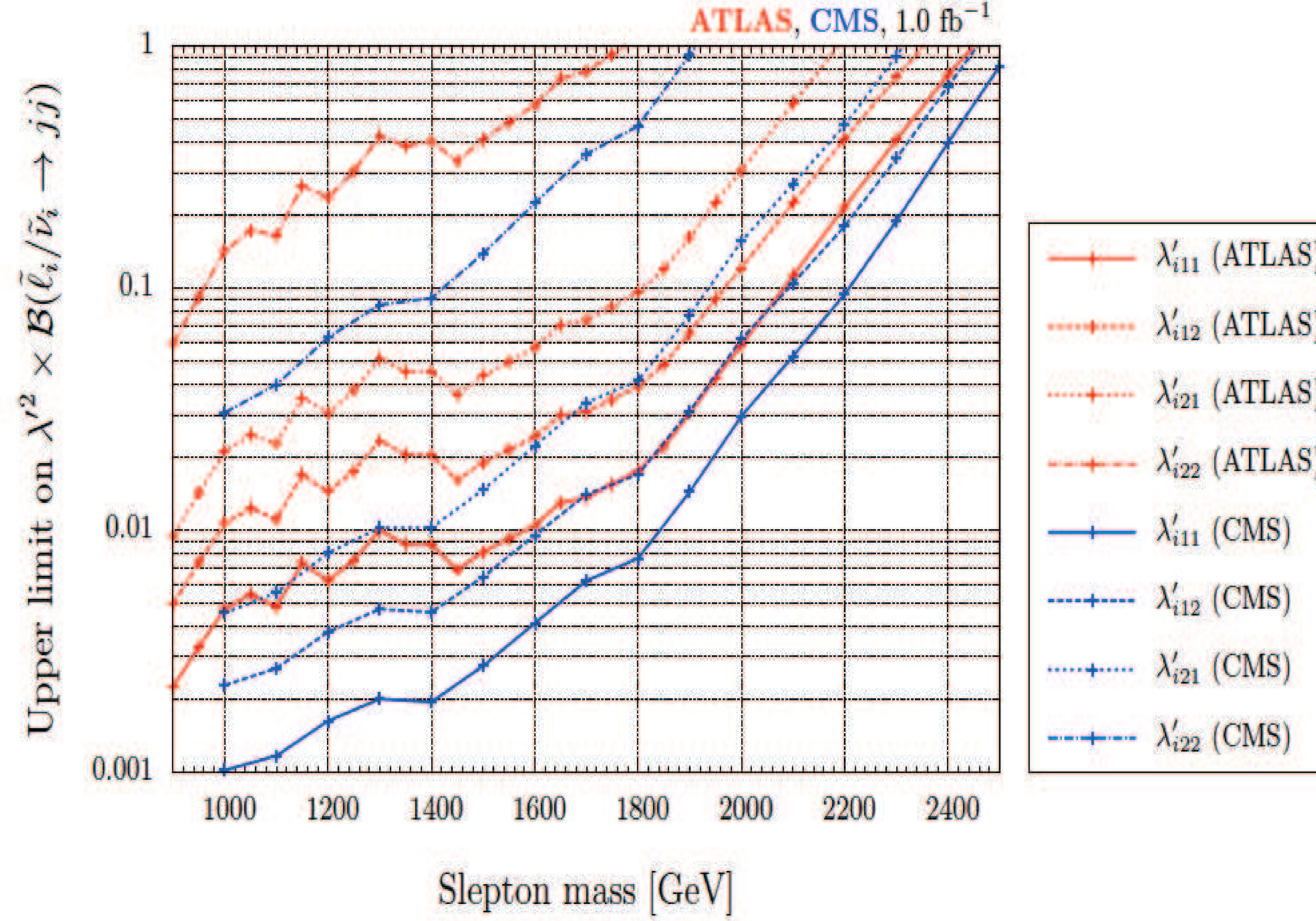
- **UDD**: ?

Conclusions & Outlook

- Tried to argue that RPC and RPV equally well motivated
- Experimental effort almost exclusively on RPC so far
- Shown some simple well motivated signatures: multileptons, like-sign dileptons, dijet resonance bumps
- Compared resonant slepton production directly to existing ATLAS and CMS searches
- Outline of a top 10 list of signatures

Physikshow trip to Berlin: Weltmaschine Exhib.

Totally Unexpected



ATLAS, 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} (ATLAS)
λ'_{i12} (ATLAS)
λ'_{i21} (ATLAS)
λ'_{i22} (ATLAS)
λ'_{i11} (CMS)
λ'_{i12} (CMS)
λ'_{i21} (CMS)
λ'_{i22} (CMS)