Displaced Supersymmetry

Prashant Saraswat

arXiv:1204.6038

with Peter Graham, David E. Kaplan and Surjeet Rajendran

Motivations for Low-Energy Supersymmetry

1. The Hierarchy Problem

2. LSP dark matter

3. Gauge coupling unification

Motivations for Low-Energy Supersymmetry

1. The Hierarchy Problem

   Expect superpartner masses at the
   weak scale O(100 GeV)

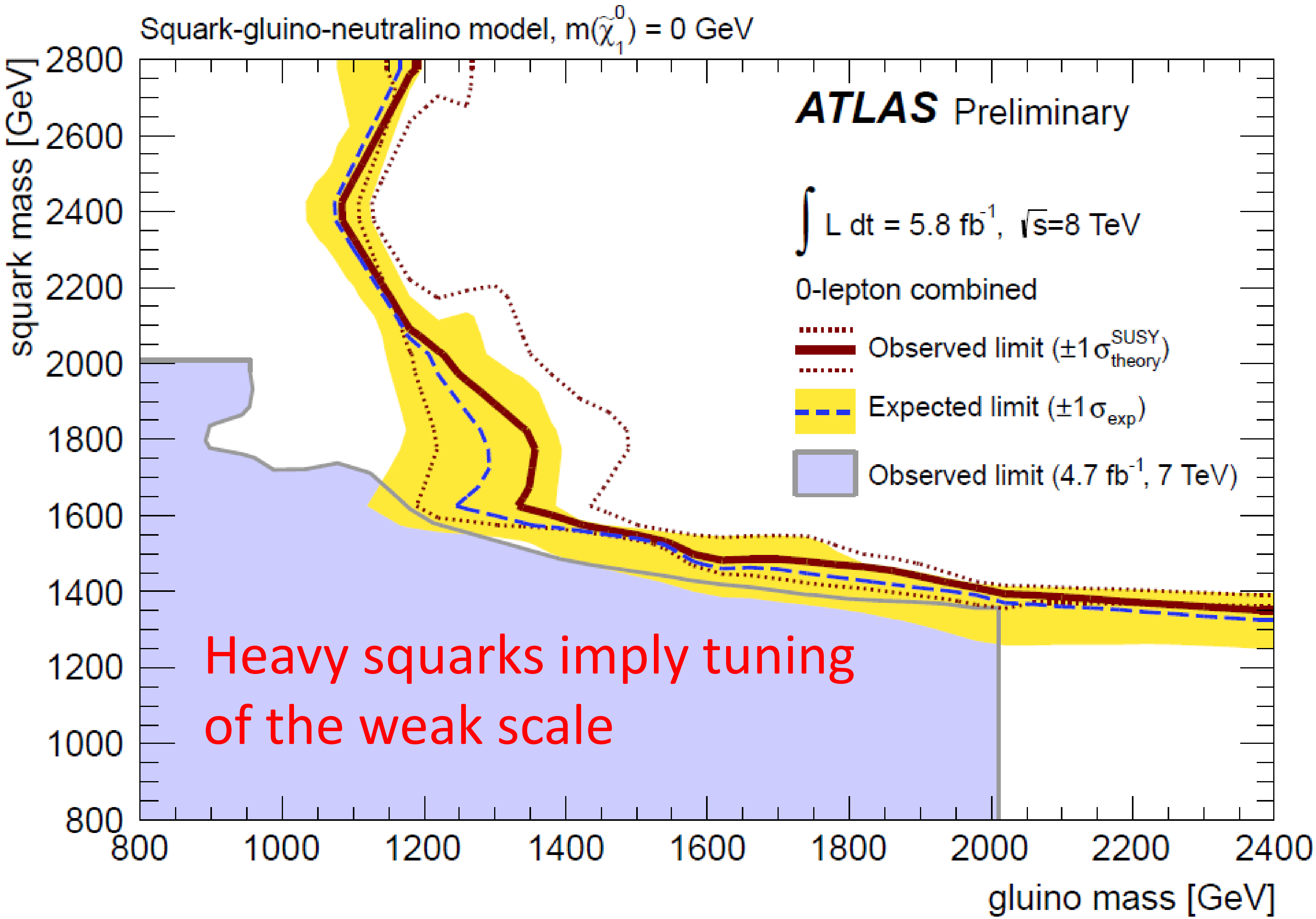
2. LSP dark matter

   Expect LSP to be stable and neutral:
   missing energy signatures

3. Gauge coupling unification

   Less constraining than naturalness,
   allows for split spectrum

The Missing Superpartner Problem



Is there a little hierarchy, or are we not looking for SUSY in the right way?

Some standard assumptions about SUSY collider signatures:

- Large missing transverse energy
- All decays are prompt

Can we relax these assumptions, and what happens to collider constraints if we do?

Outline

- Motivation: Naturalness and gauge unification
- Bilinear R-Parity Violation
- Displaced decays from bilinear RPV
- Collider constraints and light squark masses
- Discovery prospects and search strategies

Motivations for Low-Energy Supersymmetry

1. The hierarchy problem: Stabilize the weak scale

Expect superpartner masses at the weak scale O(100 GeV)

Relax tuning with R-parity violation?

2. ~~LSP dark matter~~

~~Expect the LSP to be stable and neutral: missing energy signatures~~

3. Gauge coupling unification

Less constraining than naturalness, allows for split spectrum

Is RPV consistent with unification?

R-Parity Violating Operators

$$W_{RPV} = \mu_{L,i} L_i H_u +$$

$$\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k$$

SU(5) invariant trilinear operator:

$$\bar{\mathbf{5}}_L \bar{\mathbf{5}}_L \mathbf{10} \to \lambda_{ijk}(L_i L_j E_k + L_i Q_j D_k + U_i D_j D_k)$$

Simultaneous *B* and *L* violation leads to proton decay!

R-parity violation requires *SU*(5) breaking in matter sector

R-Parity Violating Operators from *SU*(5)

$$\bar{\mathbf{5}}_L \mathbf{5}_{H_u} \to \mu_{L,i}(L_i H_u + D_j H_u^c)$$

Doublet-triplet splitting problem: H^c must have *SU*(5)-breaking mass $\sim M_{GUT}$ to suppress proton decay

If colored Higgs decouples, then the bilinear operator essentially violates *L* only

High-scale mediation of RPV

If *R*-parity is broken in a hidden sector by the vev of an operator $\mathcal{O}$, then the trilinear terms are suppressed compared to the bilinear:

$$\frac{\mathcal{O}}{\Lambda^{n-1}}\bar{\mathbf{5}}_L\mathbf{5}_{H_u} \rightarrow \frac{M^n}{\Lambda^{n-1}}\bar{\mathbf{5}}_L\mathbf{5}_{H_u}$$

$$\langle\mathcal{O}\rangle = M^n$$

$$\frac{\mathcal{O}}{\Lambda^{n}}\bar{\mathbf{5}}_L\bar{\mathbf{5}}_L\mathbf{10} \rightarrow \frac{M^n}{\Lambda^{n}}\bar{\mathbf{5}}_L\bar{\mathbf{5}}_L\mathbf{10}$$

Bilinear *R*-Parity Violation

$$W \supset \mu_{L,i}(L_i H_u + D_i H_u^c) + \mu H_d H_u$$

L and H_d mix with angle μ_L/μ, diagonalization gives trilinears

$$W \supset \epsilon_i y^e_{jk} L_i L_j E_k + \epsilon_i y^d_{jk} L_i Q_j D_k \quad \epsilon_i \equiv \frac{\mu_{L,i}}{\mu}$$

Predictive: largest *R*-parity violating effects involve heavier generation particles, particularly bottoms

In an *SU*(5) GUT, *UDD* will obtain contributions

$$\frac{\mu_{L,i}}{M_{H^c}} y^u_{jk} D_i D_j U_k$$

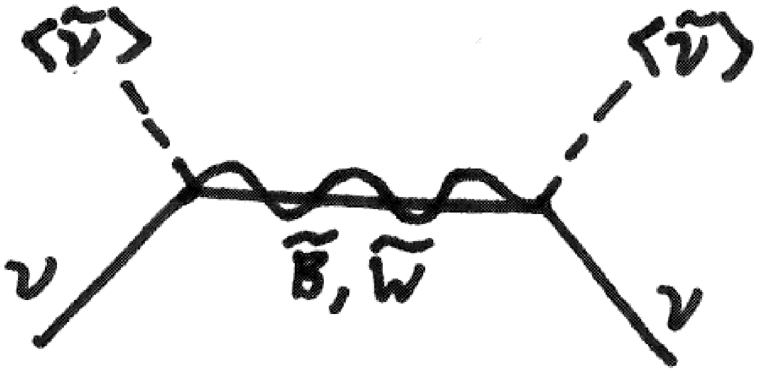
GUT-scale B violation

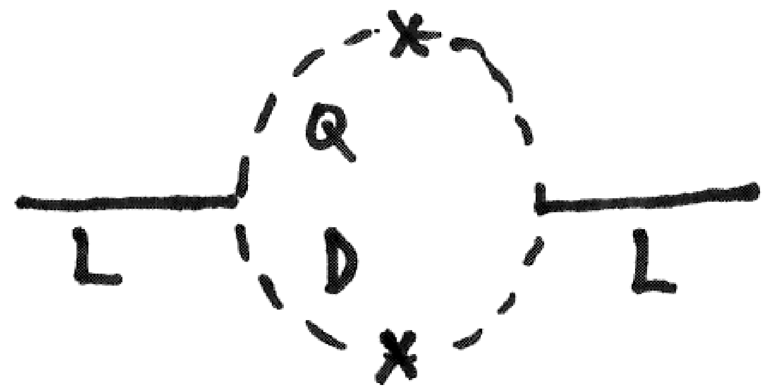
$$\frac{\mu_{L,i}}{\Lambda} D_i D_j U_k$$

Planck Slop

Constraints on Bilinear R-Parity Violation

L violation → Contributions to neutrino masses





Δm_ν depends on SUSY breaking

$$\Delta m_\nu \sim \frac{\epsilon^2 y_b^4}{16\pi^2} v$$

Requires ε < 10^{-3} to not exceed largest neutrino mass splitting. This also avoids proton decay bounds for GUT completions

Signatures of Bilinear RPV

Dominant operators are $\epsilon_i y_b L_i Q_3 D_3, \epsilon_i y_\tau L_i L_3 E_3$

LSP	$\tilde{\chi}$	$\tilde{\nu}$	$\tilde{\tau}$	$\tilde{u}_L$	$\tilde{b}$
Dominant Decays	$\nu b\bar{b},\ \nu\tau l$	$b\bar{b}$	$l^{\pm}\nu$	$l^{\pm}q$	$b\nu$

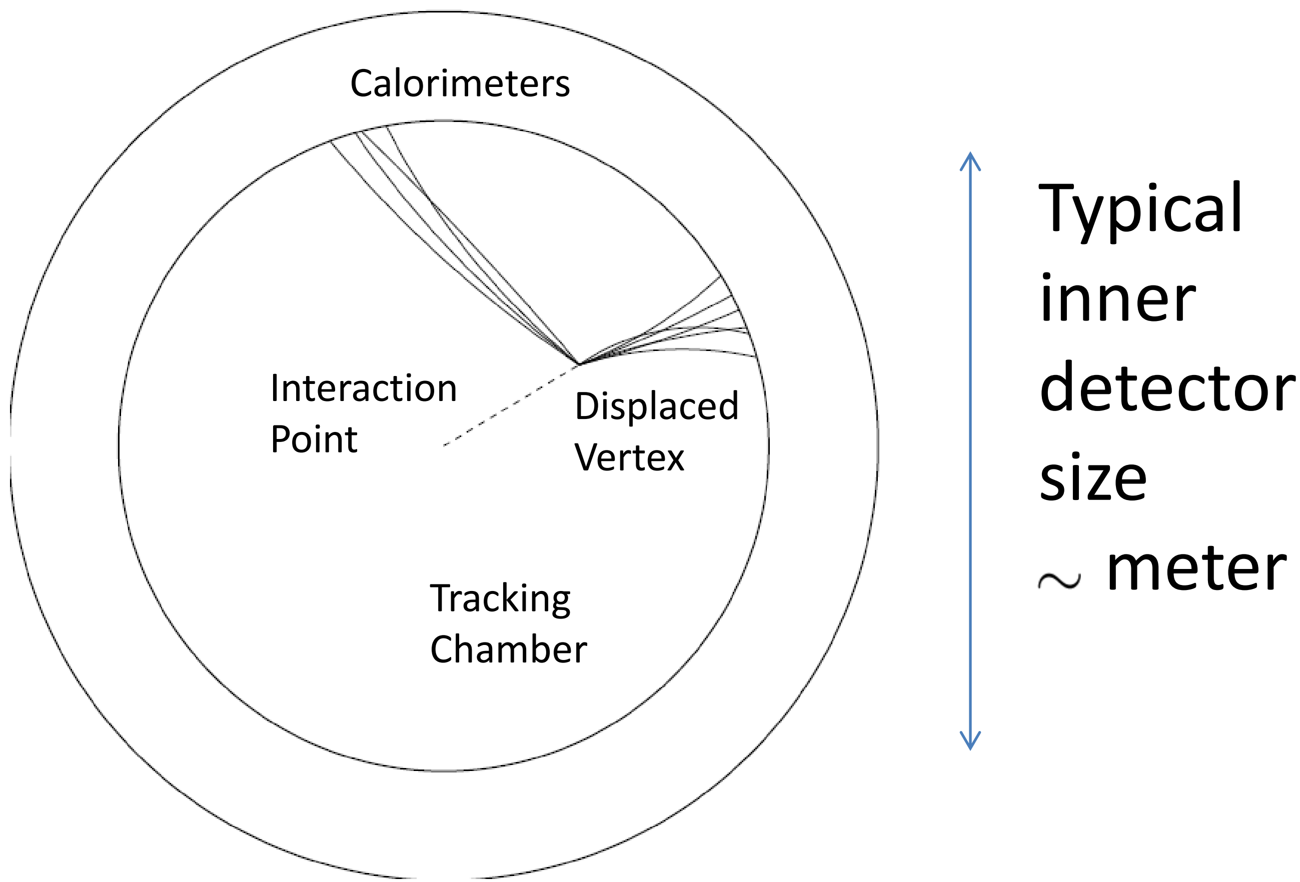
Final states in SUSY events can have

- suppressed, but nonzero, missing energy
- many jets, including *b*-jets
- possibly leptons

Displaced Vertices

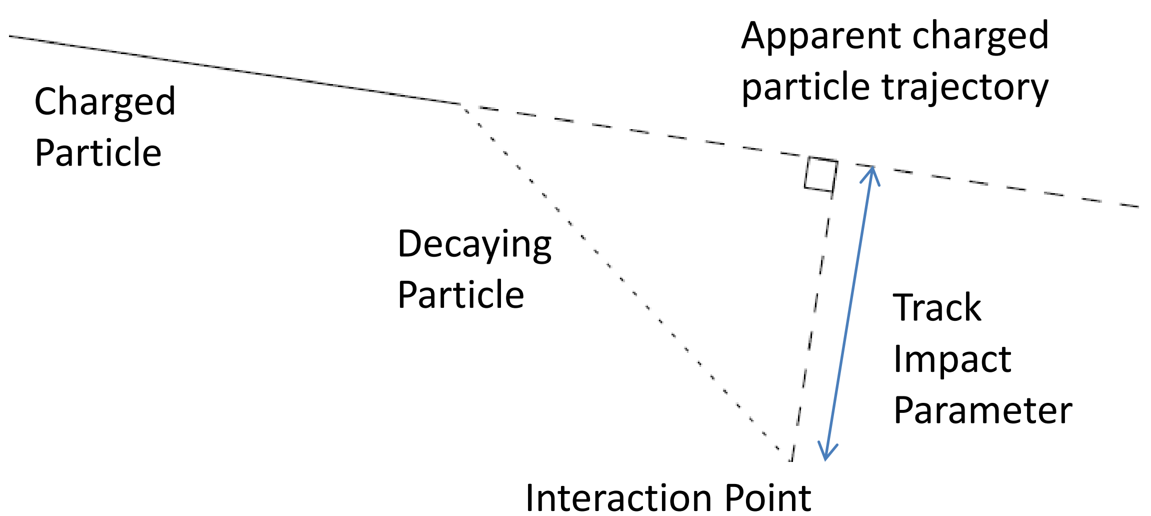
For weak R-parity violation (small ε), the LSP decay length can be macroscopic (> 1 mm)

Unlike any Standard Model signal!



Displaced Vertices

Resulting tracks will have **large impact parameter** (distance of closest approach to interaction point or beamline).



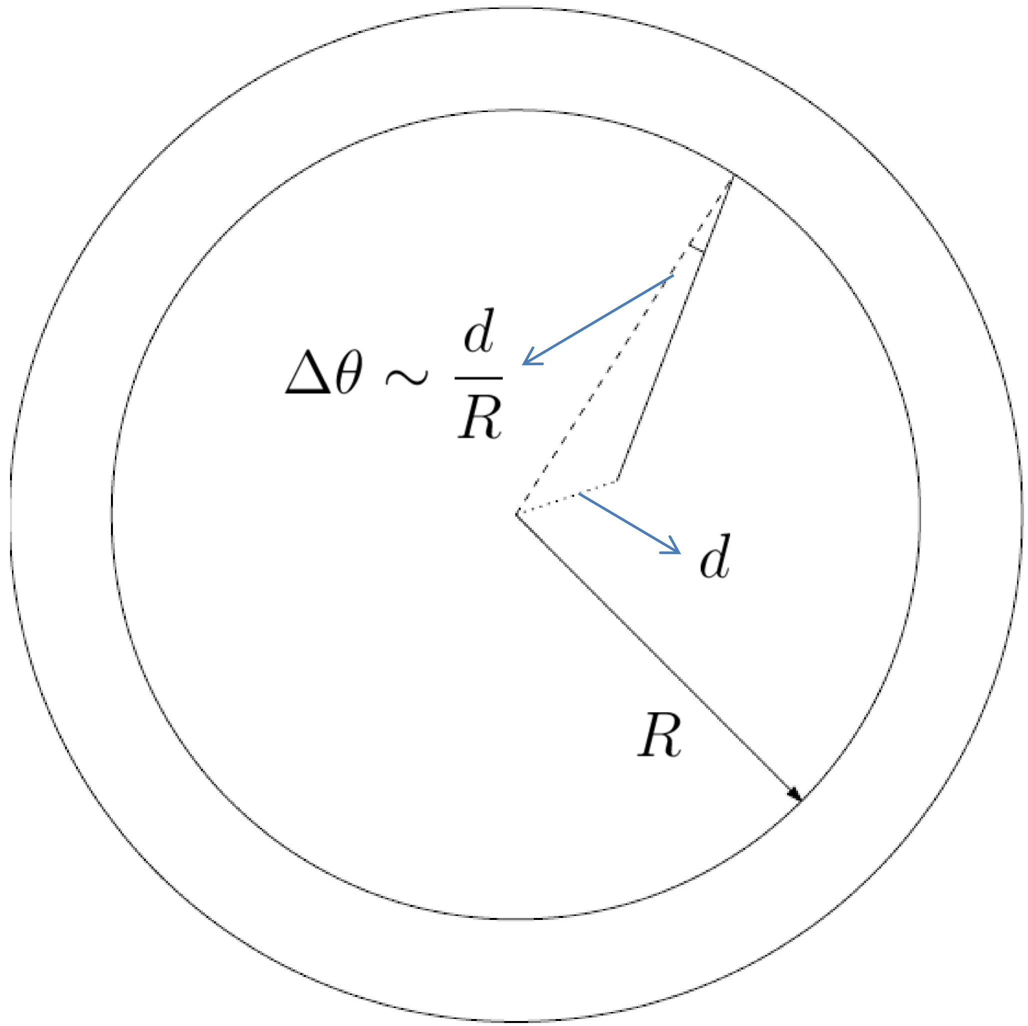
Tracks with IP > 1—2 mm are **not accepted** by the lepton reconstruction and b-tagging algorithms of ATLAS and CMS

Displaced Vertices

Momenta of jets from displaced decay will be mismeasured

Error scales as decay length over detector size

I'll ignore this effect when considering constraints



Existing Collider Constraints on BRPV

Bilinear RPV with displaced decays can avoid constraints from many SUSY searches:

Collider Search	Issues Limiting Sensitivity to Displaced BRPV Decays
Searches in leptons and *b*-jets	Displaced tracks prevent reconstruction
Searches in jets + MET	Highly suppressed missing energy, CMS jets require good tracks
Searches for displaced vertices	Specific decay topologies not yet searched for

Disclaimer

The following constraint plots consider pre-HCP (7 TeV) results ONLY

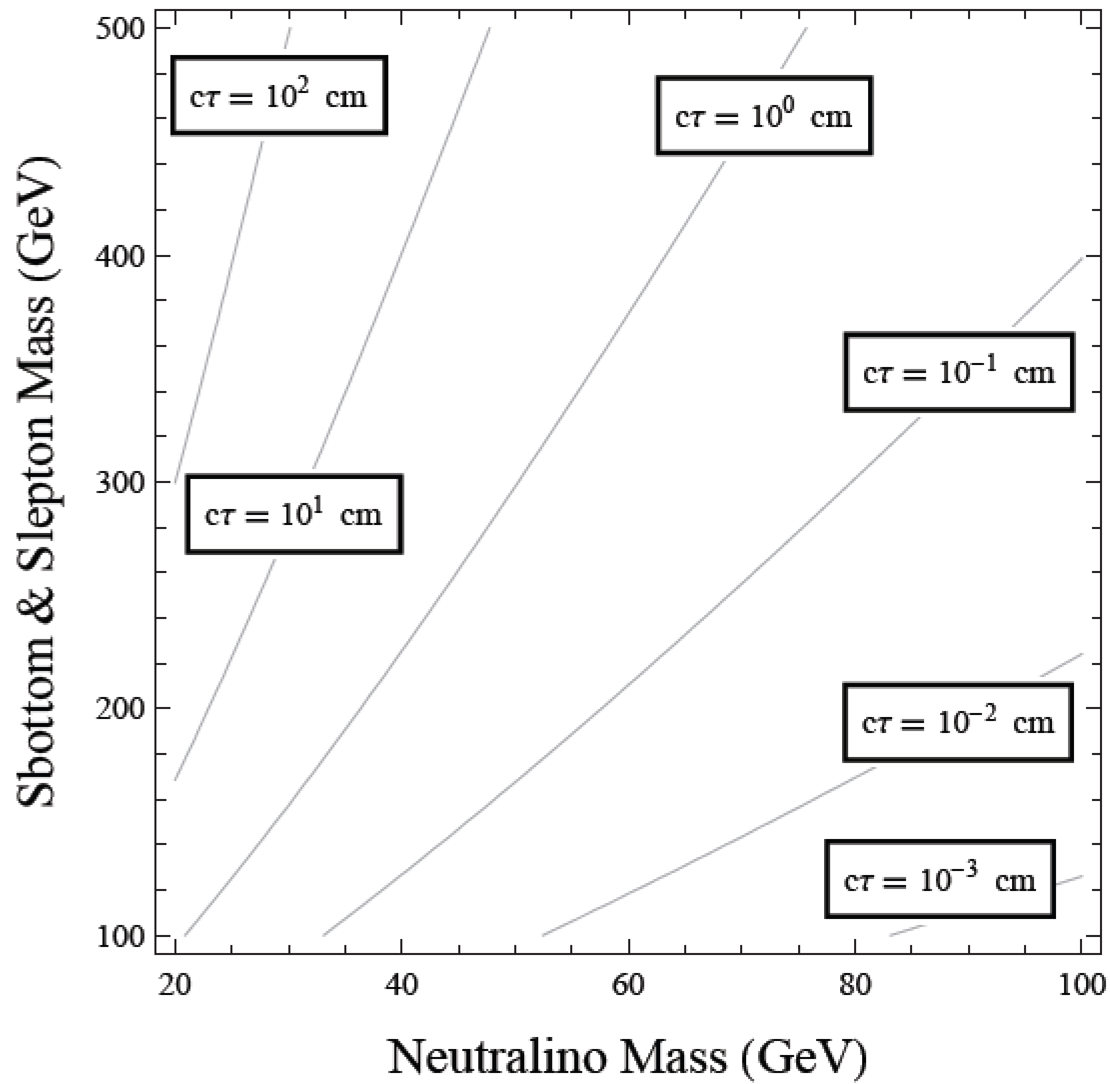
Where appropriate I'll mention the possible impact of newer searches including 8 TeV searches

Neutralino LSP

Neutralino can decay to $\nu b\bar{b}$ or $\nu\tau l$ depending on sfermion masses

ϵ small enough to satisfy neutrino mass constraints implies macroscopic decay length

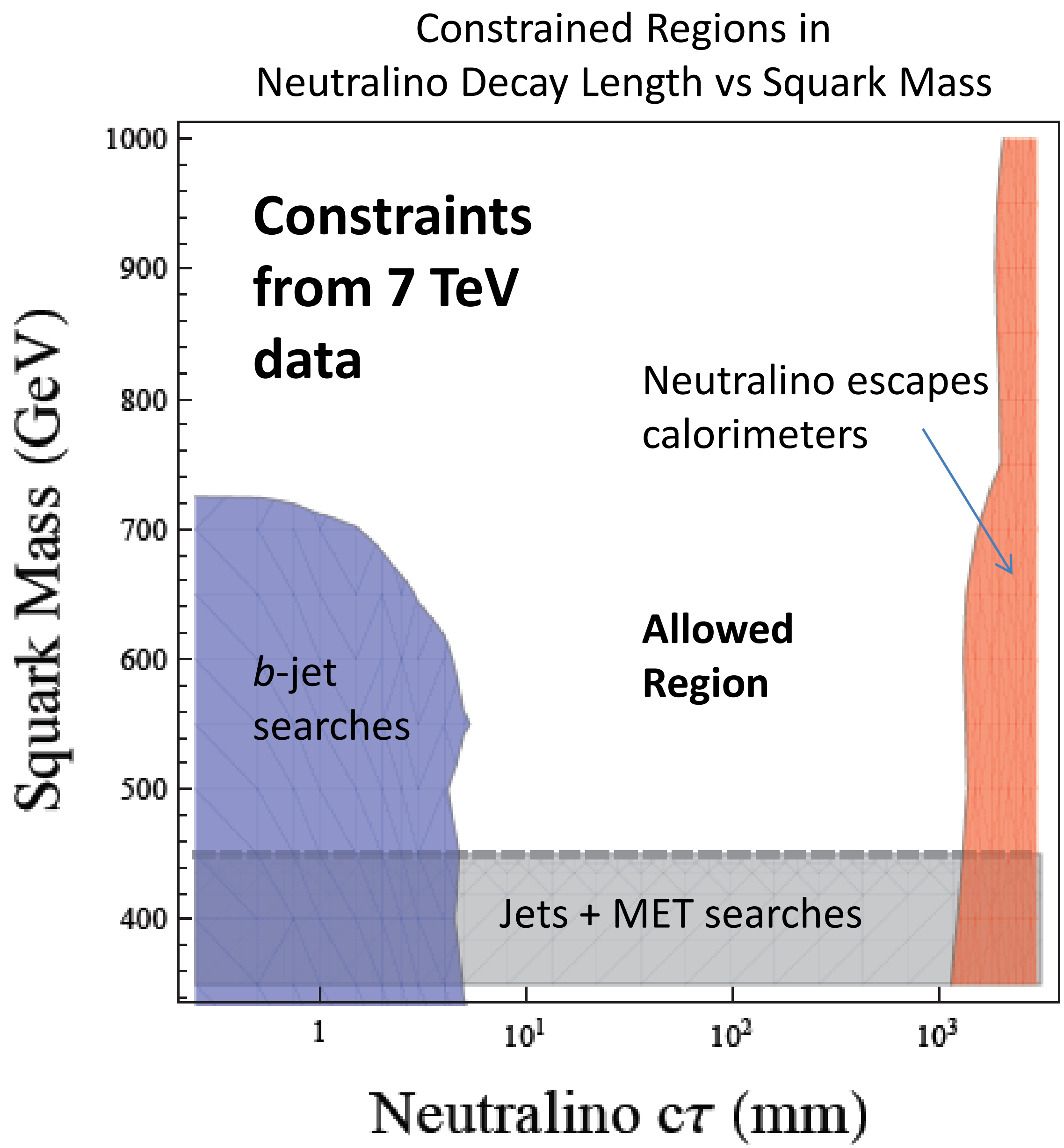
Neutralino Lifetime for $\epsilon_i = 10^{-3}$



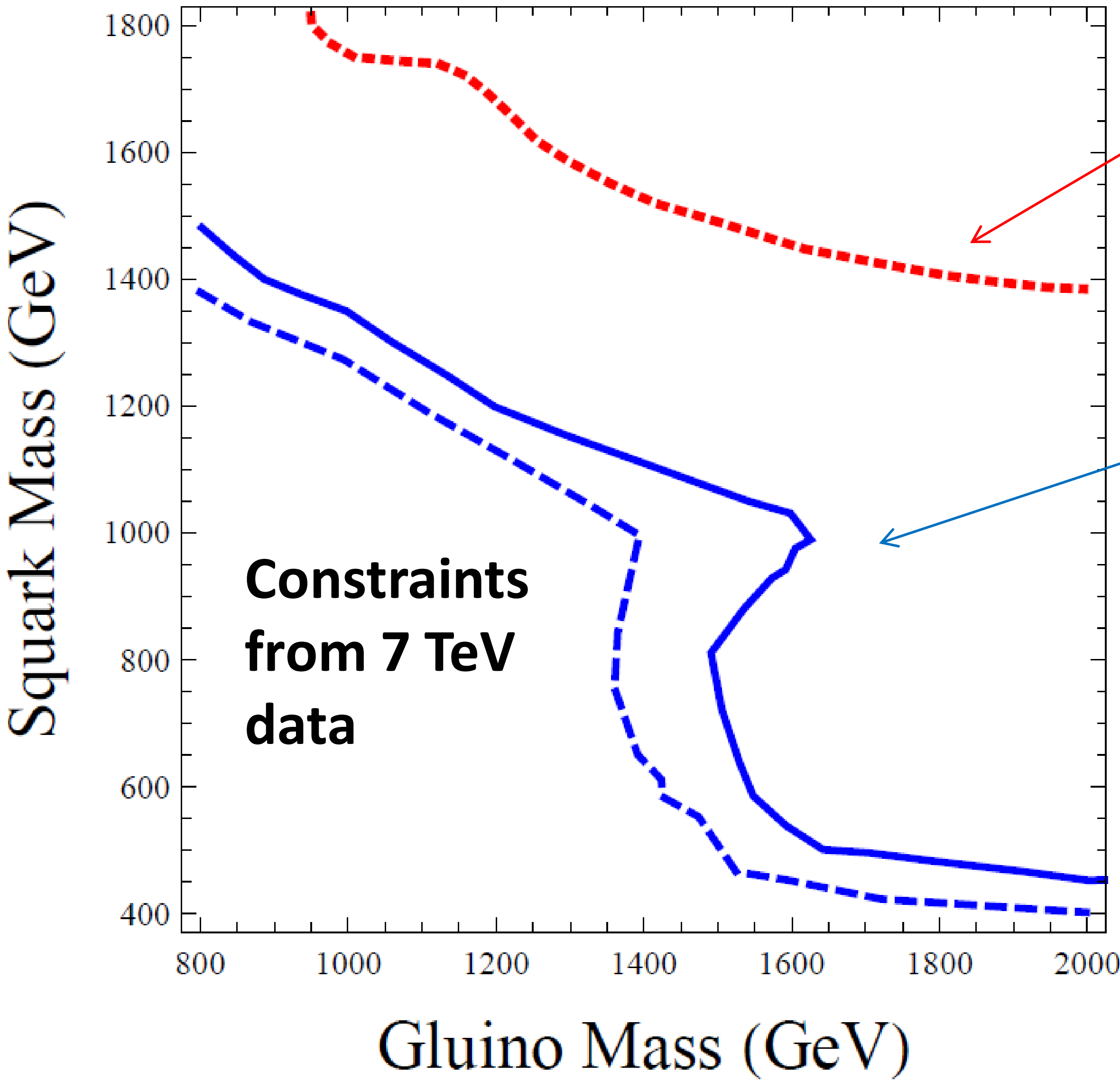
Neutralino LSP

For decay lengths < few mm, *b*-jets and leptons from neutralino decays can be tagged

For decay lengths > 1 meter, neutralinos often escape calorimeters



Constraints on Squark & Gluino Masses



Stable massless neutralino

50 GeV neutralino decaying to $\nu b\bar{b}$ Universal squark masses

With 8 TeV data, squark bound is ≈ 550 GeV

ATLAS Displaced Vertex Searches

A search for displaced vertices in data collected using a high-p_T muon trigger:

Only constrains decay to $\nu\tau l$

35 pb^{-1} search does not constrain squarks heavier than ≈ 400 GeV at all

5 fb^{-1} search requires five or more tracks from displaced vertex– low efficiency for $\nu\tau l$ decay

CMS Displaced Dilepton Search

A search for high-p_T lepton pairs originating from a displaced vertex

Requires decay to $\nu\tau l$ with leptonic tau decay

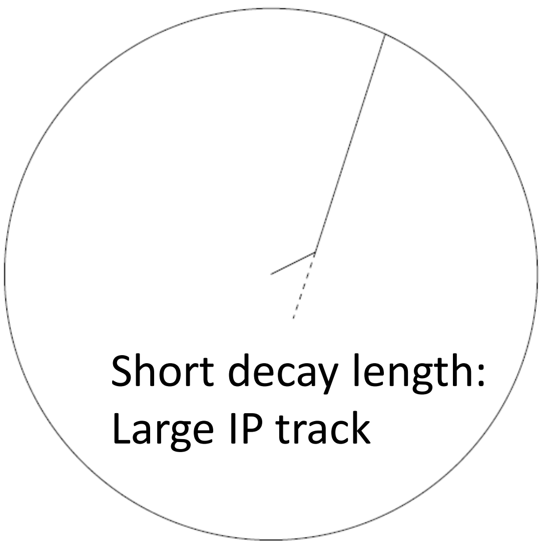
High p_T selection for leptons is inefficient for leptons from taus

BR of neutralino to $\nu\tau\mu$ constrained to be < 3%-- easily possible

Stau LSP

If decay to $\bar{t}b$ is not kinematically allowed, staus decay through *LLE* to νl

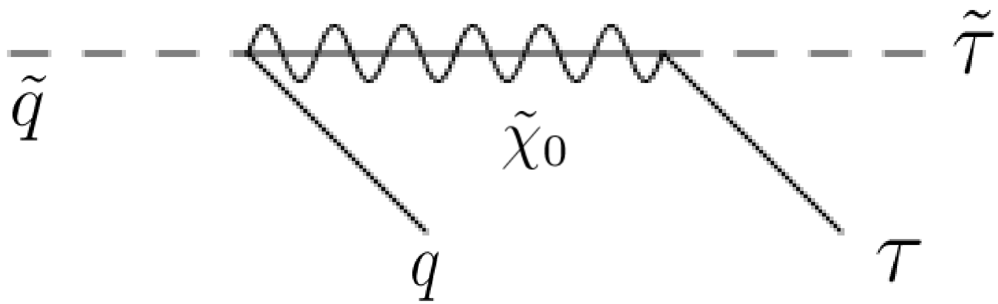
Signal is a *single* kinked or large-impact-parameter track, not a visible displaced vertex



LEP searches for displaced slepton decay require stau mass > 100 GeV.

Constraints on Stau LSP

Prompt taus are often produced in cascade decays to staus



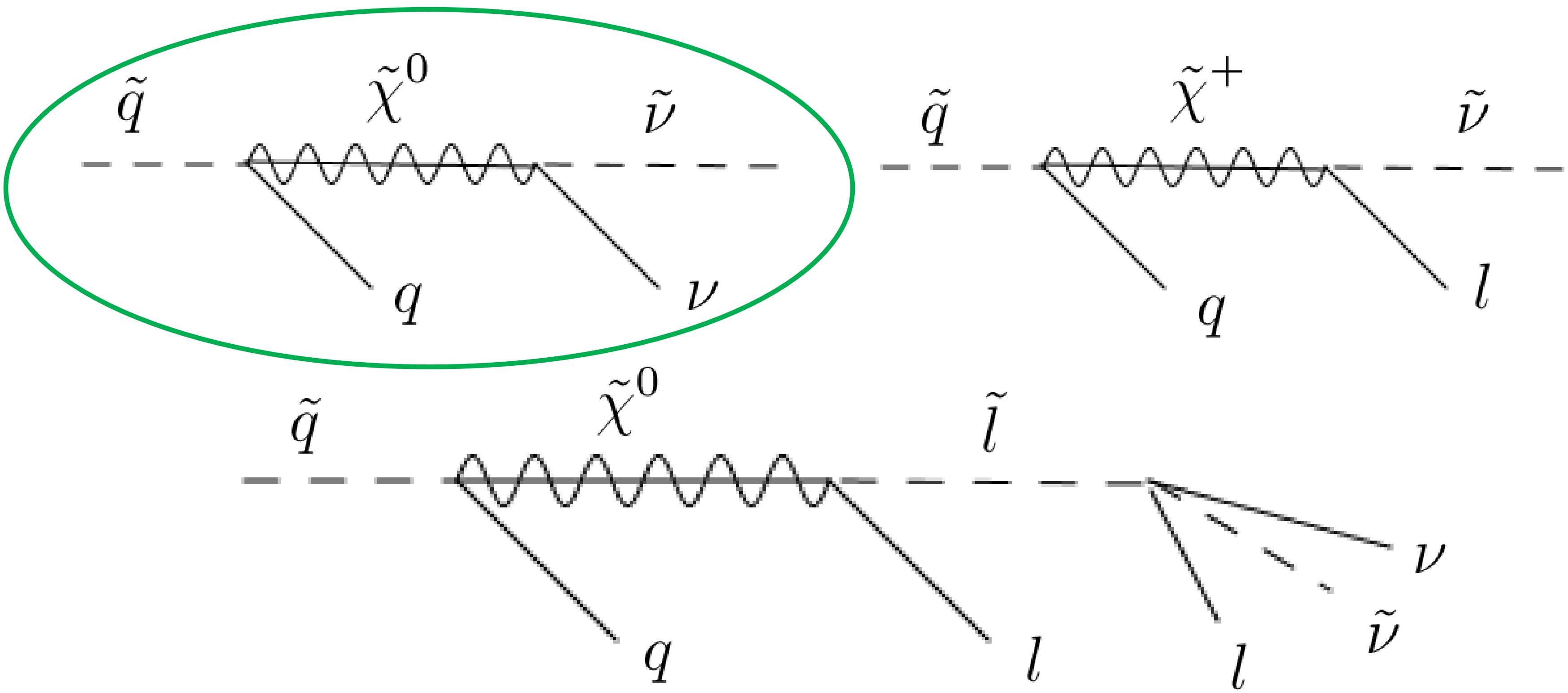
An ATLAS search in jets + MET + taus places strongest constraints

Squarks must be above 600 GeV if neutralino is 200 GeV and stau is 100 GeV

Sneutrino LSP

Sneutrinos decay mostly to $b\bar{b}$, which are not tagged if displaced

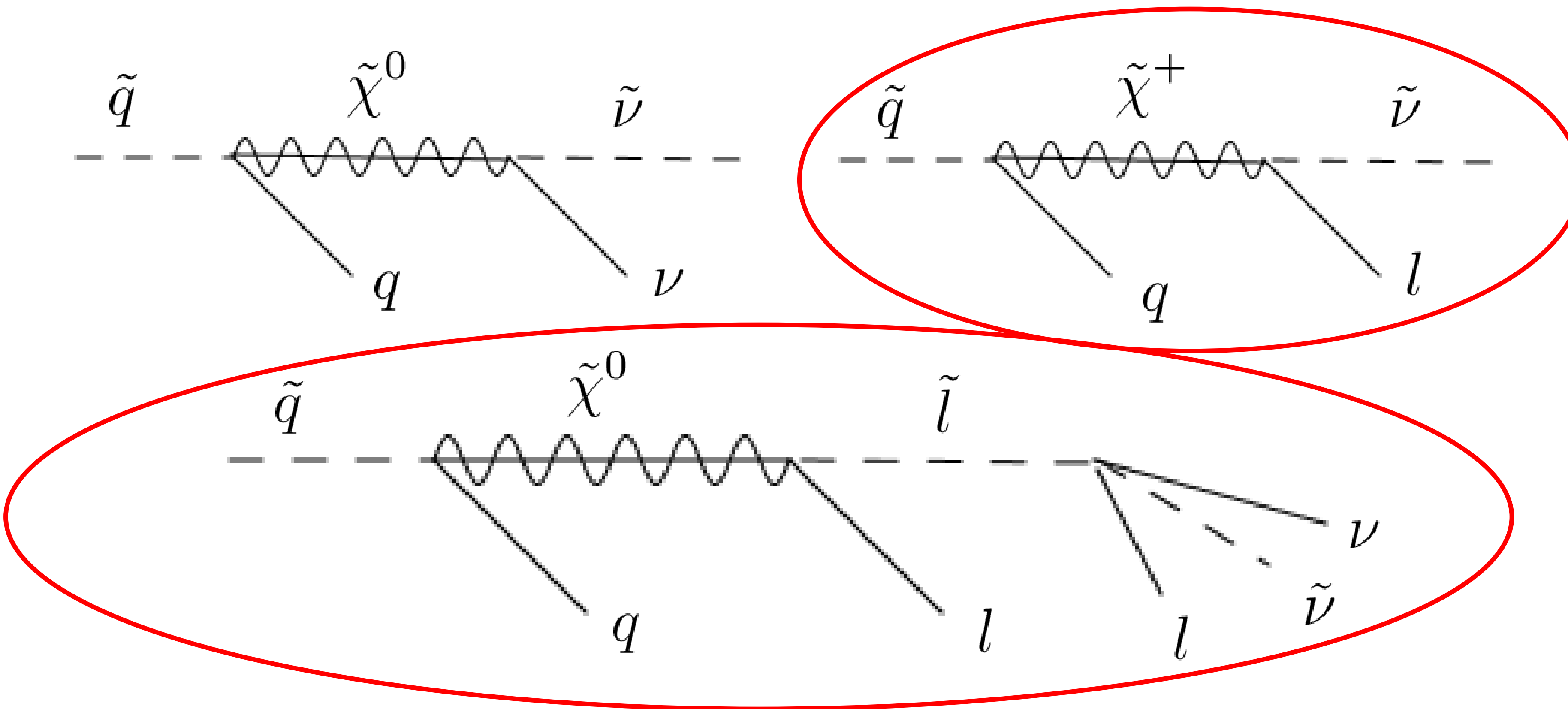
However, cascade decays can produce neutrinos and/or prompt leptons



Sneutrino LSP

Sneutrinos decay mostly to $b\bar{b}$, which are not tagged if displaced

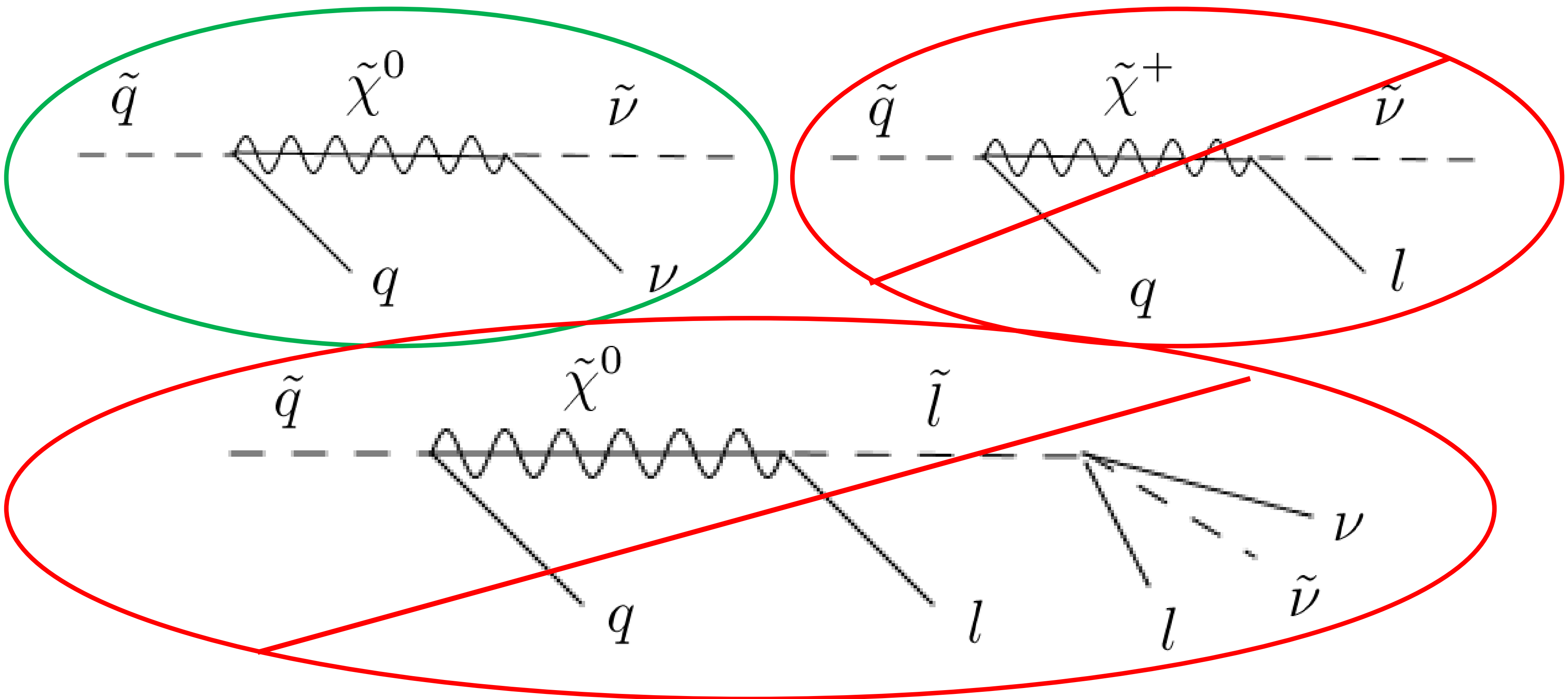
However, cascade decays can produce neutrinos and/or prompt leptons



Sneutrino LSP

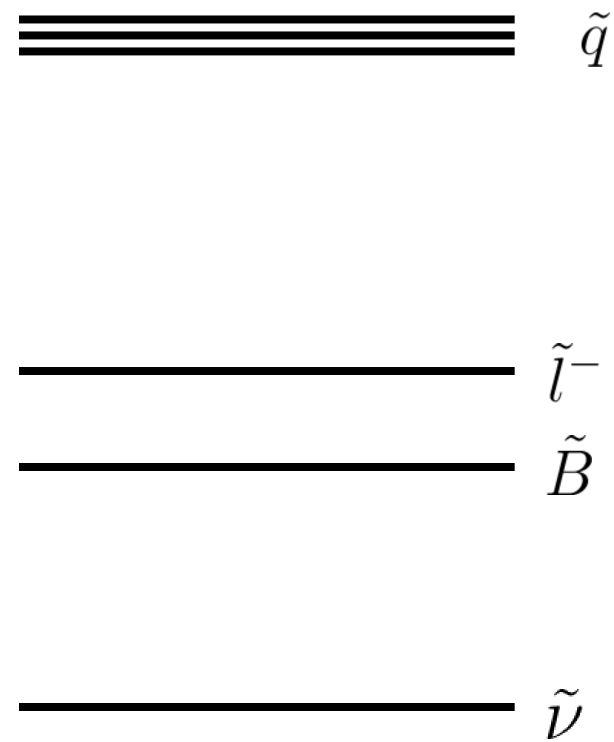
Sneutrinos decay mostly to $b\bar{b}$, which are not tagged if displaced

However, cascade decays can produce neutrinos and/or prompt leptons



Constraints on Sneutrino LSP

To achieve light squark masses, need a spectrum that suppresses decays to leptons



Constraints are then similar to neutralino case

Squarks can be as light as 500 GeV if sneutrino is 50 GeV and neutralino is 80 GeV

Novel Higgs Decays

Displaced BRPV decays make light LSPs possible, allowing for Higgs decays to LSPs

Sfermion LSPs would dominate the width → Sfermions must be heavier than 60 GeV

Higgs BR to neutralinos depends on the Higgsino fraction-- could be subdominant but visible.

Discovery Prospects

SUSY production cross-sections ≈ pb still allowed:

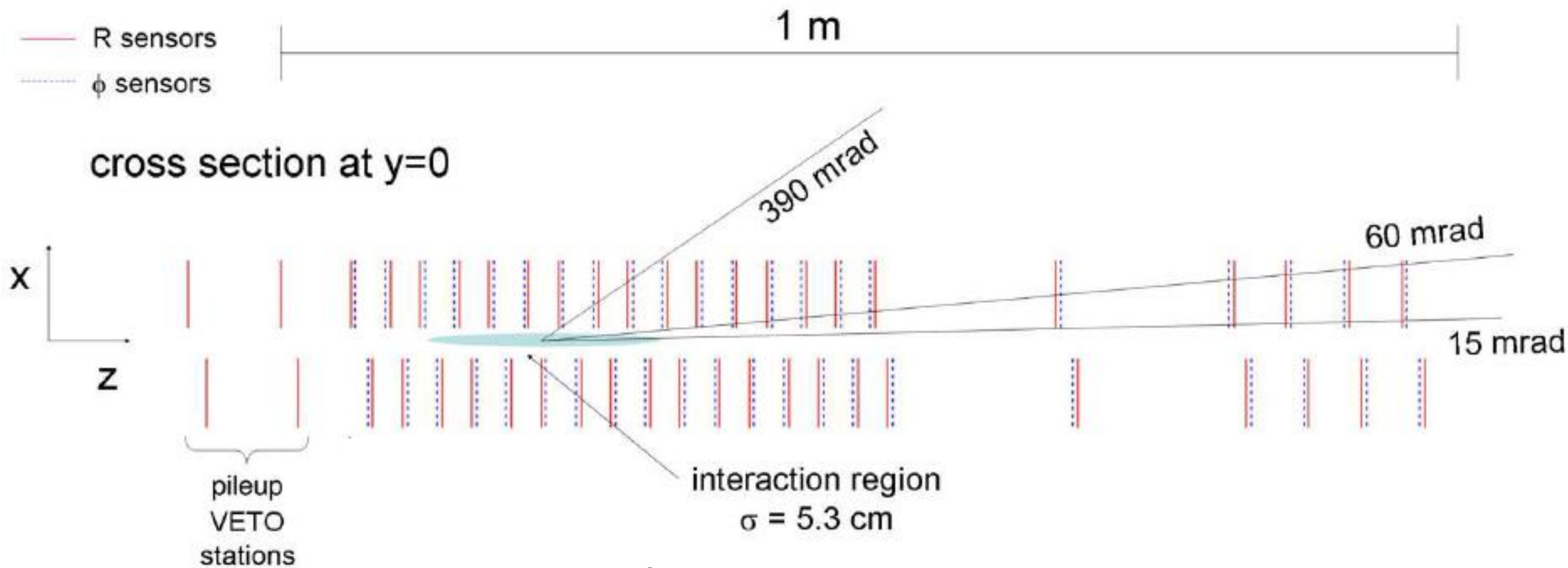
Displaced decay searches have great discovery potential!

Two avenues for searches:

- Trigger on signatures of displaced decays
- Trigger on other aspects in the event and identify displaced decays offline

Triggering on Displaced Decays

LHCb is designed to trigger on displaced vertices in the forward direction, with a vertexing region nearly a meter long



LHCb vertexing region

Triggering on Displaced Decays

At ATLAS and CMS, low-level triggering on displaced vertices is difficult.

ATLAS has developed triggers for decays beyond the tracking regions (“trackless jets”) and in the muon system

Missing energy and multijet triggers can be sensitive to the BRPV decays.

Conclusions

- Bilinear R-parity violation is well-motivated and consistent with low energy constraints
- RPV couplings can naturally be small, giving the LSP a macroscopic decay length
- Such decays greatly relax the constraints from existing searches on supersymmetry and squark mass in particular
- An appropriately designed search can have great discovery potential for these models.