SUSY-After-Higgs Workshhop

UC Davis

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Searching for Supersymmetry with the ATLAS Detector at the LHC

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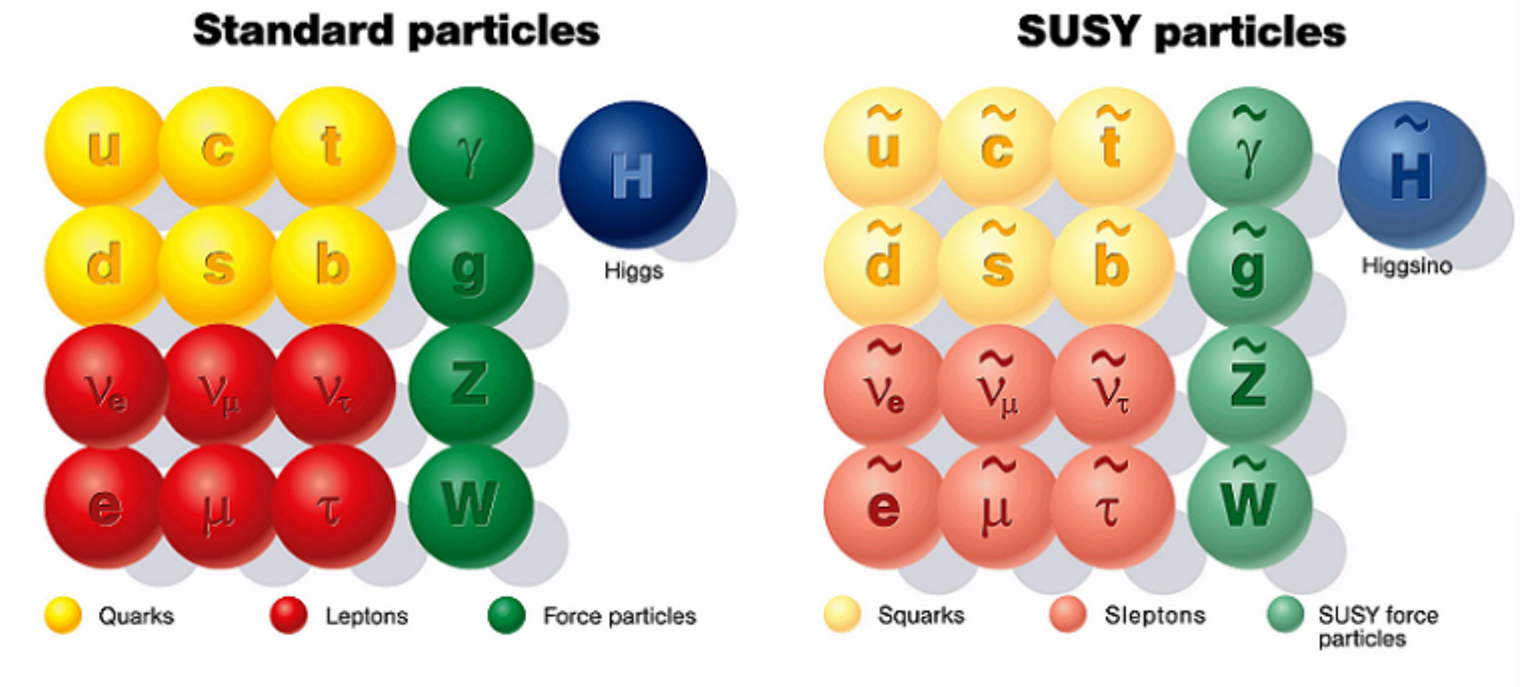
SUSY States

SUSY posits a complete set of mirror states with $S_{SUSY} = |S_{SM} - ½|$



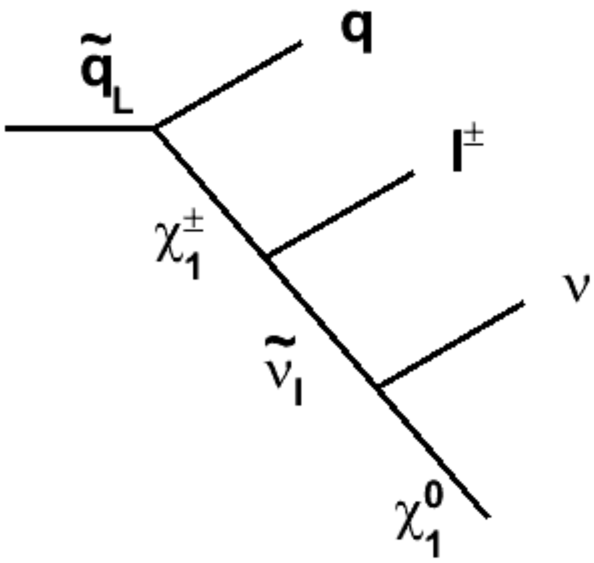
- Stabilize Higgs mass for GUTs
- Can provide reasonable dark-matter candidate
- Minimum of two Higgs doublets

R Parity

To avoid lepton/baryon number violation can require that "SUSYness" is conserved, i.e., preserves an additive "parity" quantum number R such that $R_{SM} = +1$; $R_{SUSY} = -1$

If you can't get rid of SUSYness, then the lightest super-symmetric particle (LSP) must be stable ➔ **dark matter, missing energy**

LSP is typically a "neutralino" (dark matter must be neutral); admixture of $\widetilde{W}^0, \widetilde{\mathbf{B}}^0, \widetilde{H}^0$, Known as "$\chi_1^0$, whose identity is not that relevant to phenomenology



SUSY Breaking

But we know that SUSY is broken…

SUGRA: Local supersymmetry broken by **supergravity** interactions

Phenomenology: LEP (usually χ_1^0) carries missing energy.

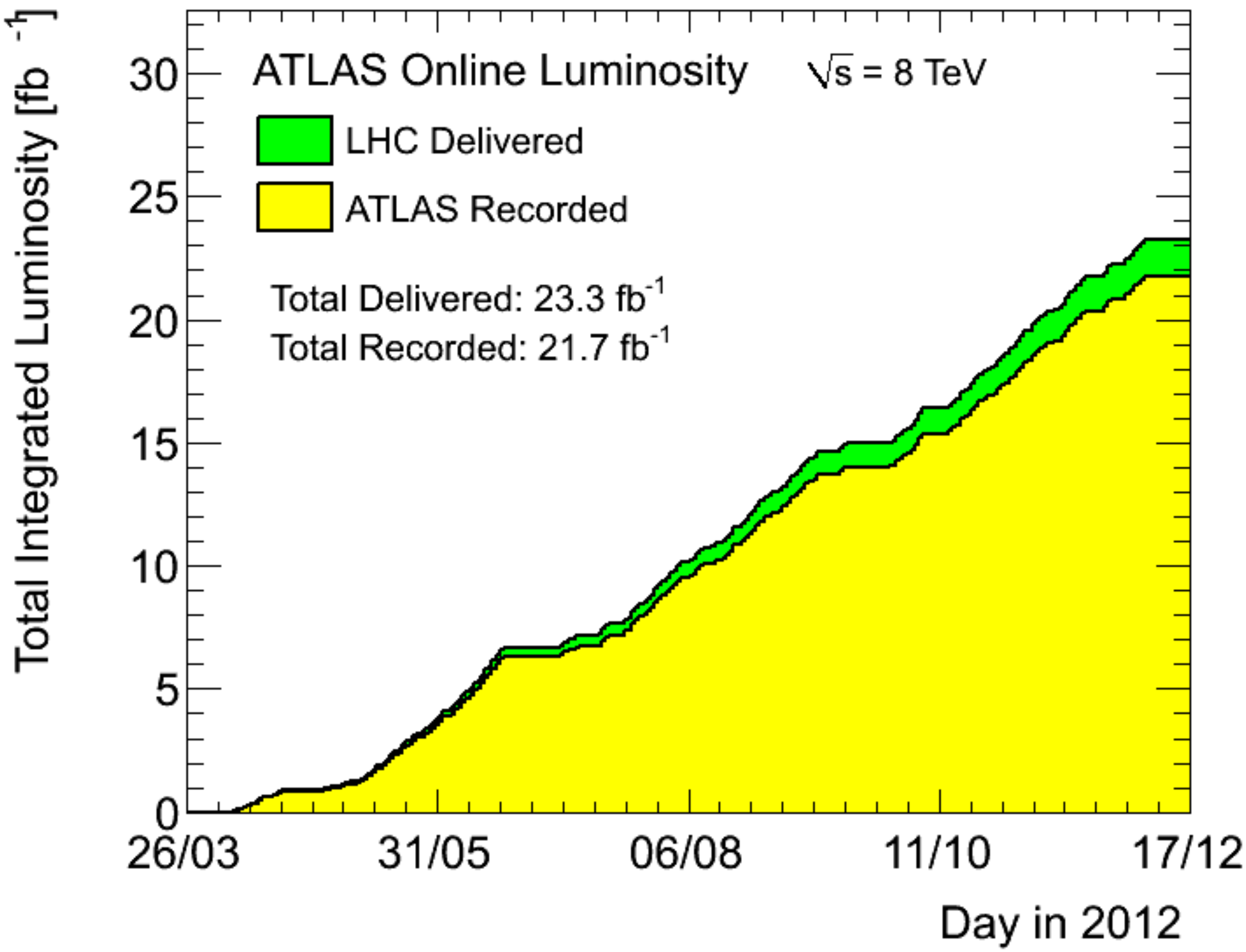
GMSB: Explicit couplings to intermediate-scale ($M_{EW} < \Lambda < M_{GUT}$) "messenger" **gauge** interactions **mediate** SUSY breaking.

Phenomenology: Gravitino ($\widetilde{G}$) LSP; NLSP is χ_1^0 or $\widetilde{\tau}$. Content of χ_1^0 germane.

AMSB: Higher-dimensional SUSY breaking communicated to 3+1 dimensions via "Weyl **anomaly**".

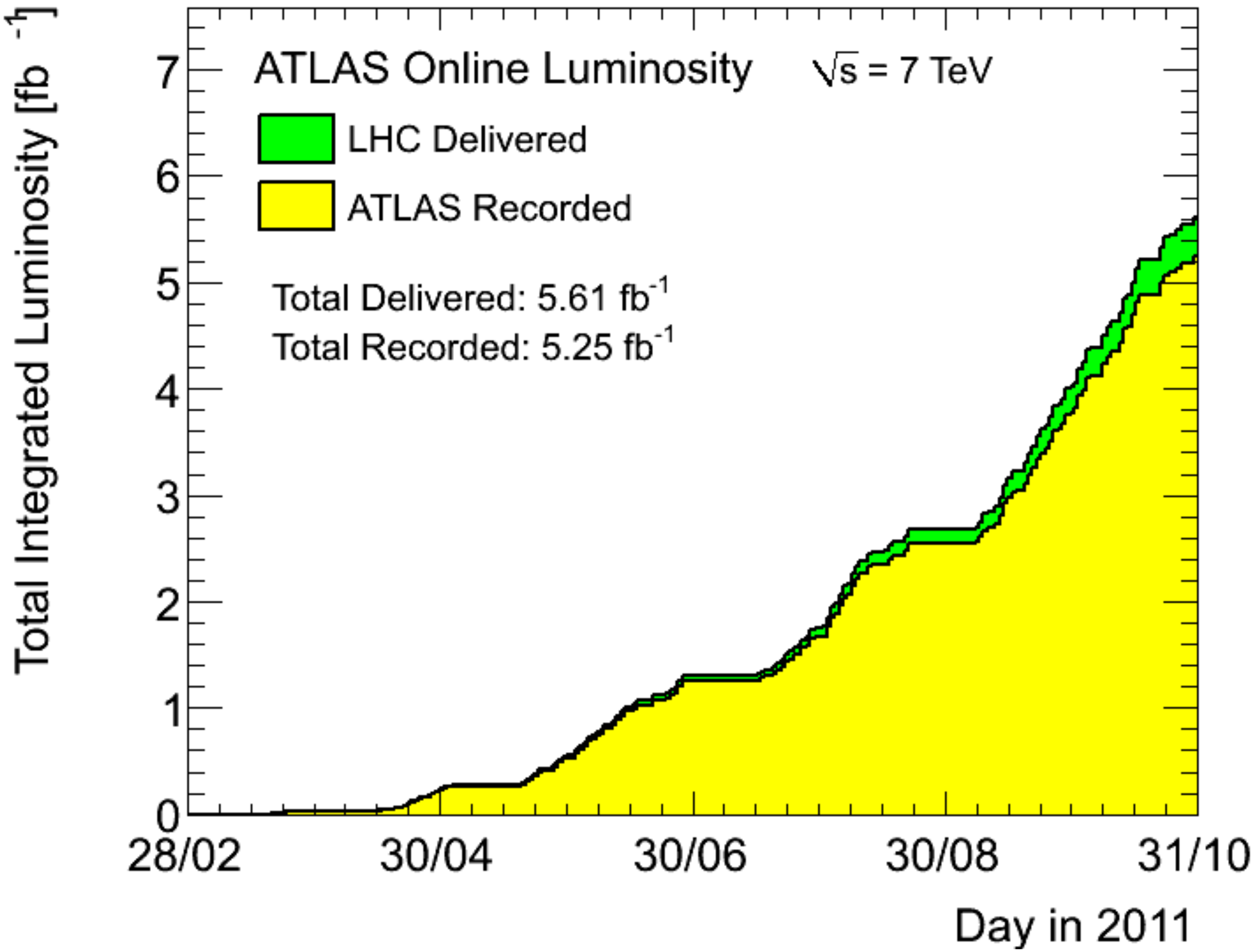
Phenomenology: LSP tends to be $\widetilde{W}$, with χ_1^+, χ_1^0 nearly degenerate.

The 8 TeV (2012) ATLAS Data Set



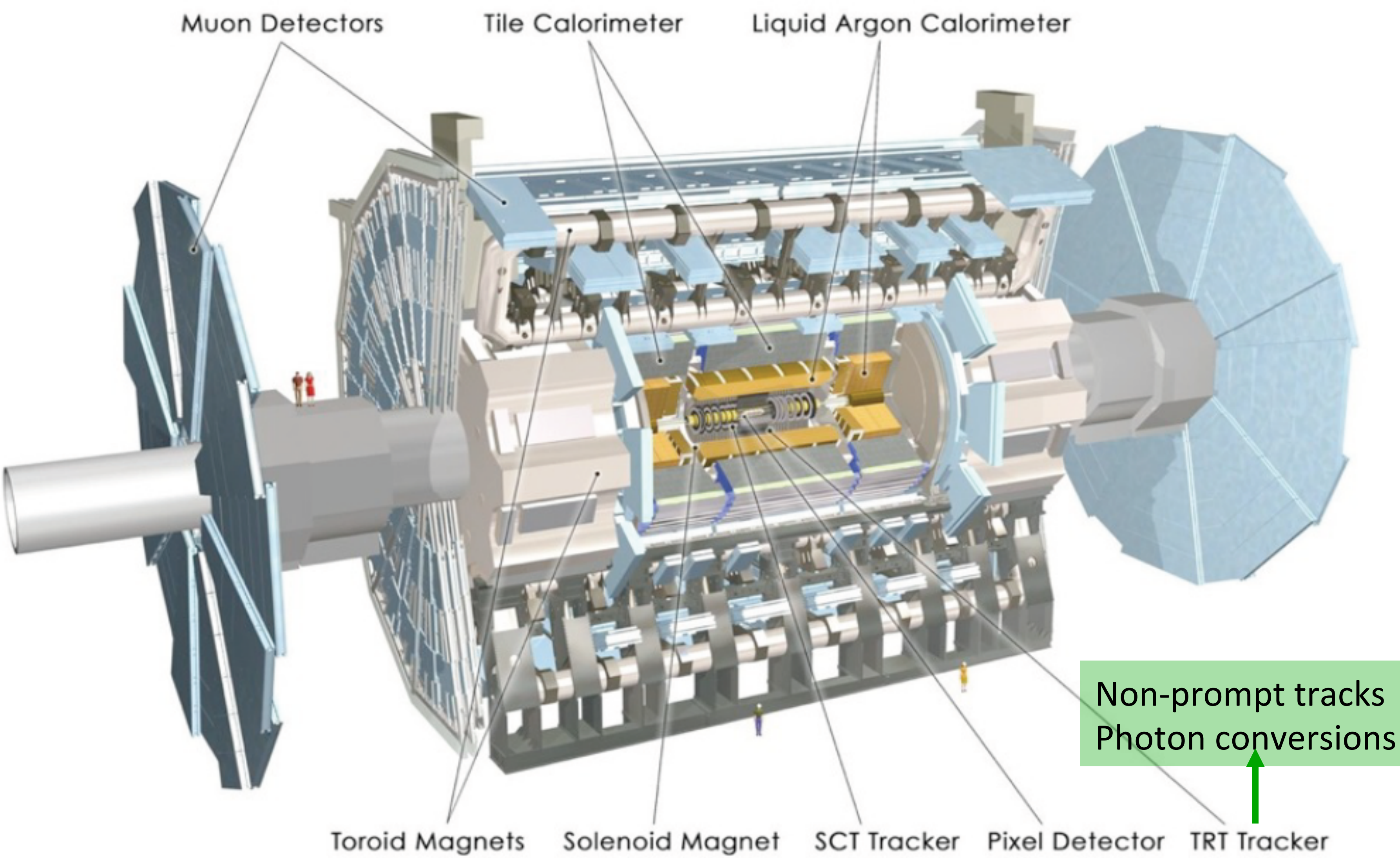
A total of 20.7 fb^{-1} deemed to be adequate for SUSY analyses

The 7 TeV (2011) ATLAS Data Set



A total of 4.7 fb^{-1} deemed to be adequate for SUSY analyses

The ATLAS Detector



Favorite Discriminating Variables

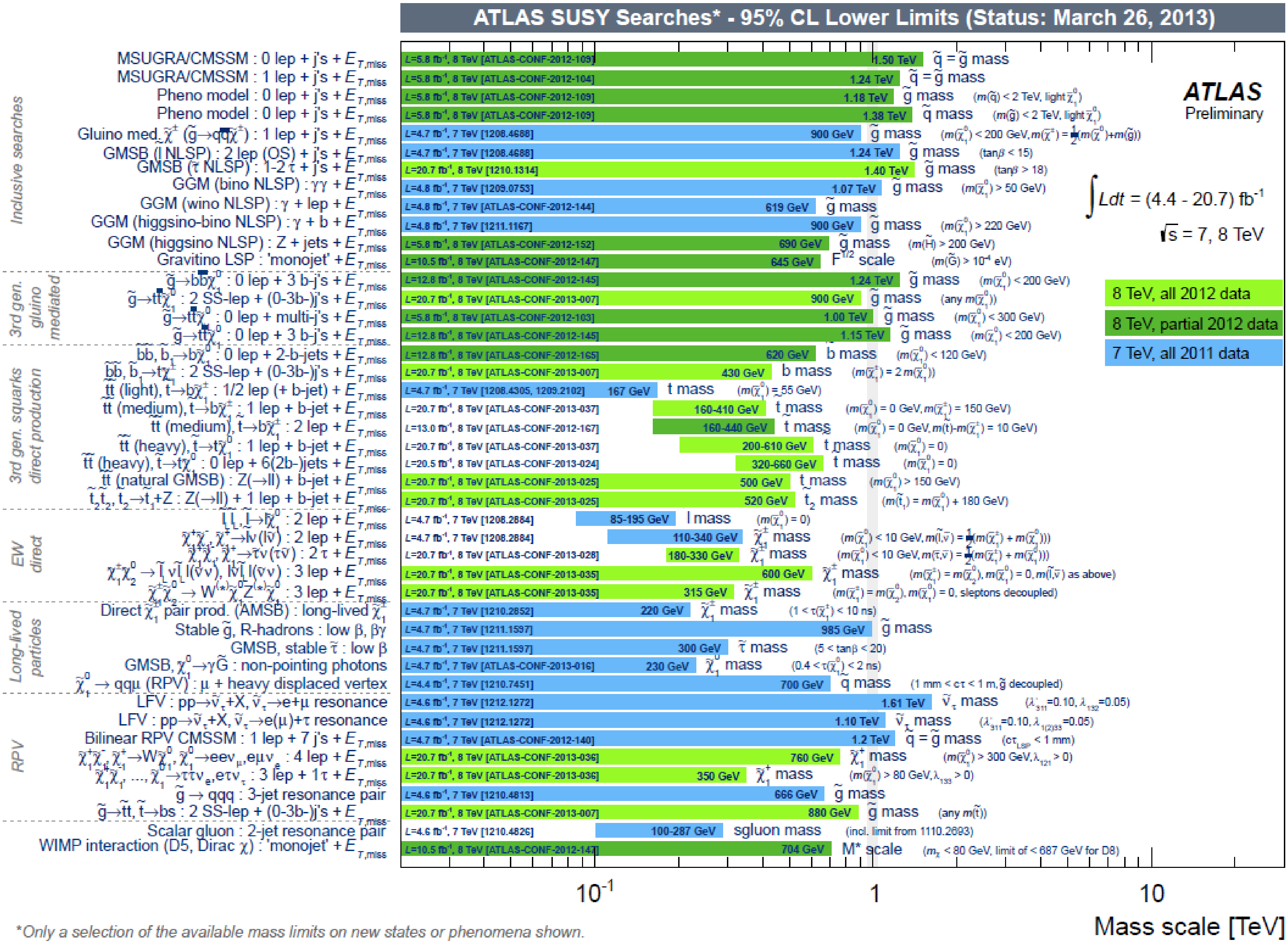
E_T^{miss}: Transverse momentum imbalance
- LSP escapes detection (RP conserving SUSY)

m_{eff}, H_T, etc: Transverse energy scale
- Strong production can reach high mass scales
- "Scale chasing"

m_{t2}, m_{CT}: Generalized (under-constrained) transverse mass
- When two copies of intermediate state are produced

$\Delta\phi_X$: Minimum ϕ separation between E_T^{miss} vector and any object of type X.
- LSP produced in intermediate-to-high mass decay
- Separation between LSP and decay sibling
- Jet backgrounds tend to have small separation

Heavy Flavor: "Natural" preference for 3rd generation
- b jets, τ jets (now also c jets)



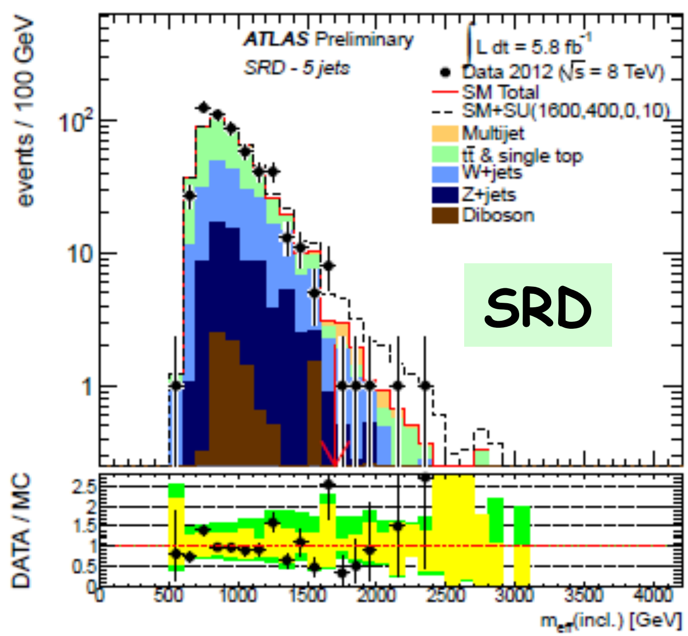
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Jets + MET in Minimal (MSUGRA) Paradigm

- Very basic signature
- Interpreted in fully-constrained model (five fundamental parameters)
- Employs "scale chasing" to limit backgrounds (high m_{eff})
- Maintains some low m_{eff} analyses

Requirement	Channel A 2-jets	Channel B 3-jets	Channel C 4-jets	Channel D 5-jets	Channel E 6-jets
E_T^{miss}[GeV] >	160				
$p_T(j_1)$ [GeV] >	130				
$p_T(j_2)$ [GeV] >	60				
$p_T(j_3)$ [GeV] >	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	60	60
$p_T(j_6)$ [GeV] >	–	–	–	–	60
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ [rad] >	0.4 ($i = \{1, 2, (3)\}$)		0.4 ($i = \{1, 2, 3\}$), 0.2 (p_T > 40 GeV jets)		
$E_T^{miss}/m_{eff}(Nj)$ >	0.3/0.4/0.4 (2j)	0.25/0.3/– (3j)	0.25/0.3/0.3 (4j)	0.15 (5j)	0.15/0.25/0.3 (6j)
m_{eff}(incl.) [GeV] >	1900/1300/1000	1900/1300/–	1900/1300/1000	1700/–/–	1400/1300/1000

6 fb^{-1} at 8 TeV



- Plot shows one of 12 selections (some SRs have loose, medium, tight m_{eff} cut)
- Observed: 5 events; Expected: 6.3 ± 2.1
- σ_{NP} < 1.03 fb; typical for model point (best of 12 is C_{tight} at 0.57 fb)
- At each point in MSUGRA parameter space, choose SR with best expected sensitivity…

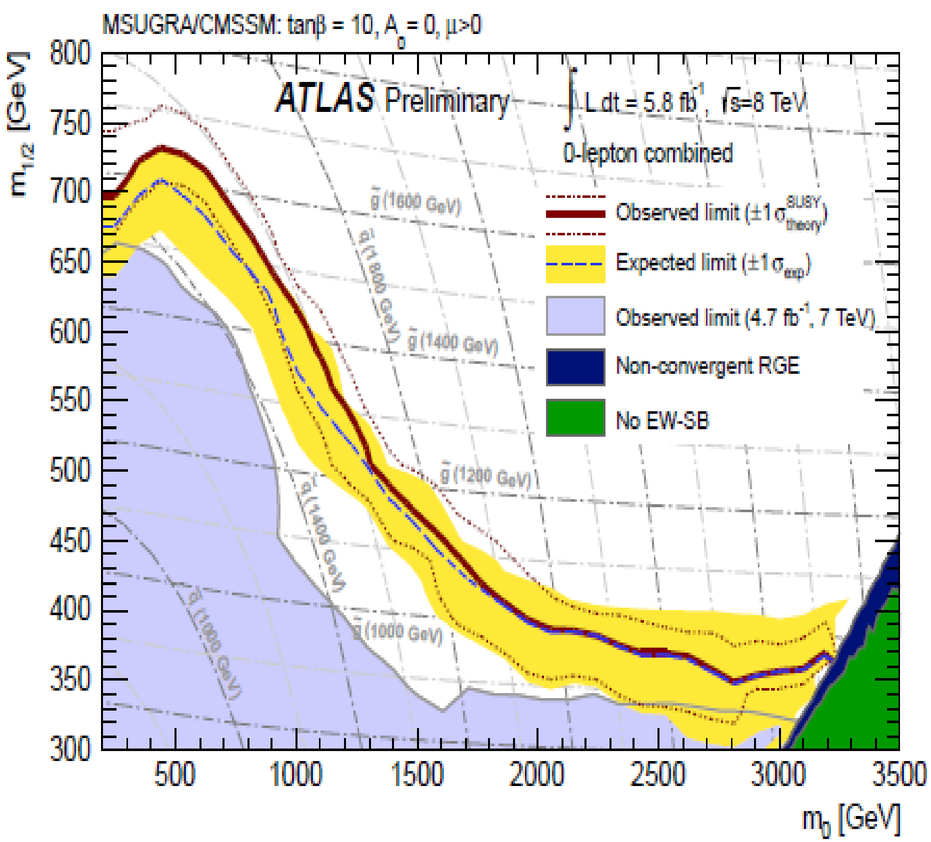
Jets+MET Exclusion in MSUGRA Parameter Space

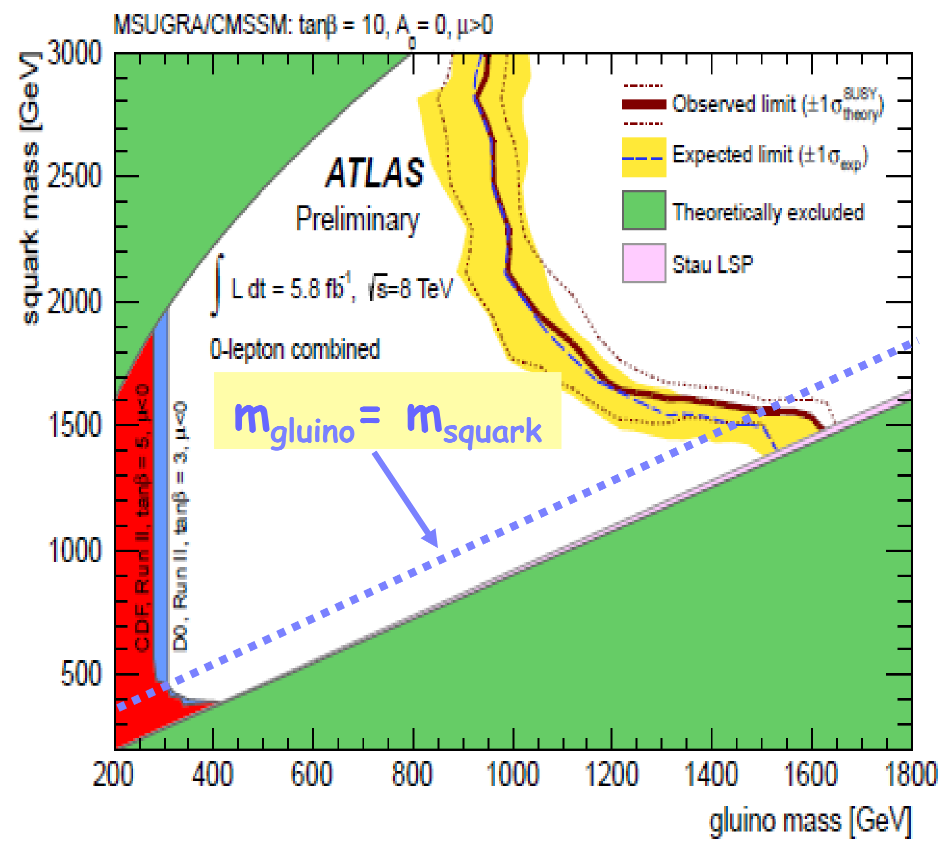
Set limits in MSUGRA parameter space

➔To get a handle on scale, re-cast in MSUGRA-constrained generic squark and gluino mass space

➔Excluded scale at $m_{gluino} = m_{squark}$ is ~ 1500 GeV

But many scenarios for which SUSY can still exist below 1500 GeV!





Looking for the Holes

The gaps in coverage arise from many different considerations.

How do we identify them?

➔ **Reasoning and intuition:** 3^{rd} generation NLSP, no light strong partners, ”compressed” scenarios, etc…

➔ **Brute force:** model-space carpet bombing (e.g. “pMSSM”…)

The pMSSM

M.W. Cahill-Rowley, J.L. Hewett, A. Ismail, T.G. Rizzo

Now an ATLAS associate!

Our p(henomenological)MSSM

- General CP-conserving MSSM with R-parity
- MFV at the TeV scale (CKM)
- Lightest neutralino/gravitino is the LSP.
- 1st/2nd generation sfermions degenerate
- Ignore 1st/2nd generation Yukawa's.
- No assumptions wrt SUSY-breaking

→ the pMSSM with 19/20 parameters

(Flat priors)

$50 \text{ GeV} \le |M_1| \le 4 \text{ TeV}$
$100 \text{ GeV} \le |M_2, \mu| \le 4 \text{ TeV}$
$400 \text{ GeV} \le M_3 \le 4 \text{ TeV}$
$1 \le \tan\beta \le 60$
$100 \text{ GeV} \le M_A, l, e \le 4 \text{ TeV}$
$400 \text{ GeV} \le q_1, u_1, d_1 \le 4 \text{ TeV}$
$200 \text{ GeV} \le q_3, u_3, d_3 \le 4 \text{ TeV}$
$|A_{t,b,\tau}| \le 4 \text{ TeV}$
$1 \text{ eV} \le m_{3/2} \le 1 \text{ TeV}$ (log prior)

Goal: obtain ~225k points in each of these 2 spaces satisfying existing data then study their signatures @ the LHC & elsewhere.. NO FITS!

We're going for breadth not depth ! →→ New low-FT set 5

Minimal (constrained) vs. General Models

Idea #1: Are model-dependent linkages between masses fooling us?

GUT unification: few parameters

- mSUGRA/CMSSM
- mGMSB

"Minimal" Model

e.g. mSUGRA:

m_0: GUT scale common scalar mass

$m_{½}$: GUT scale common gaugino mass

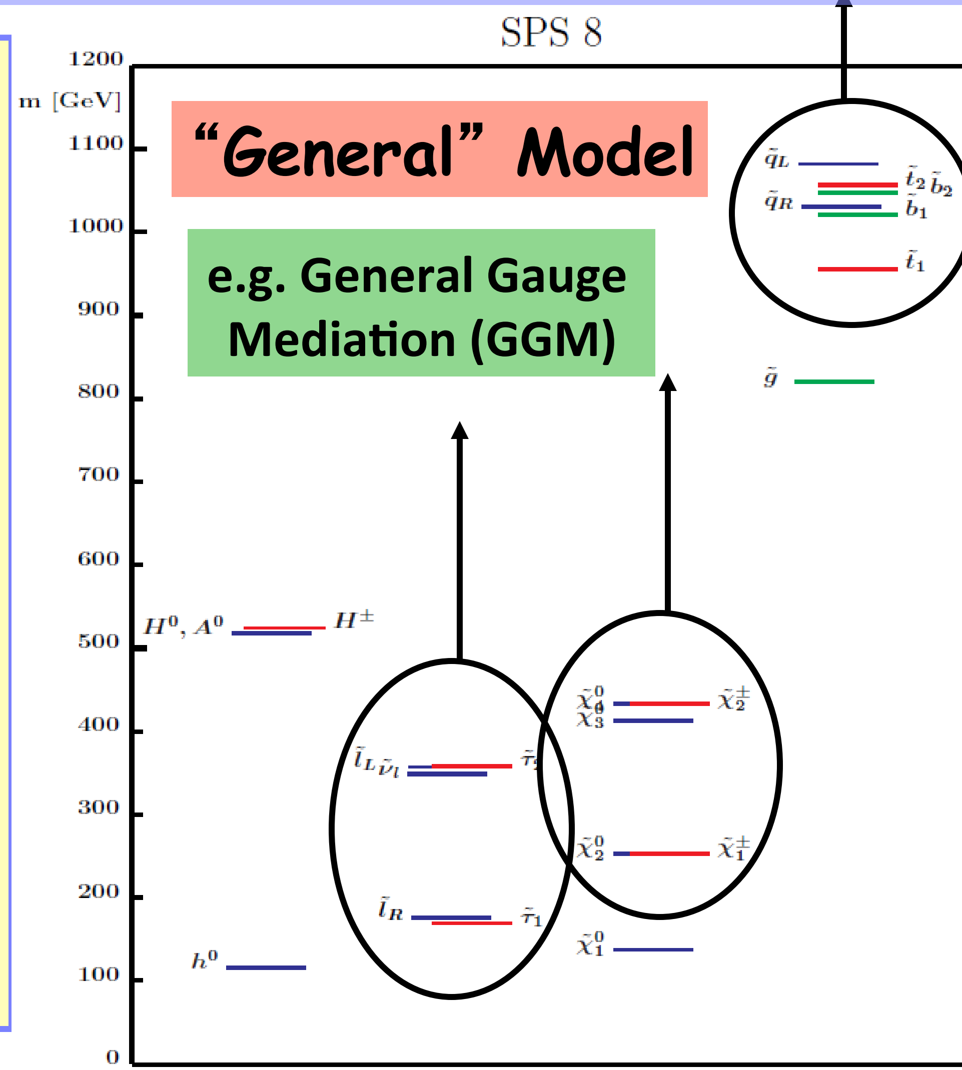
tanβ: Ratio of Higgs doublet VEVs

A_0: Common trilinear coupling

Sgn(μ): Higgs mass term

"General" Model

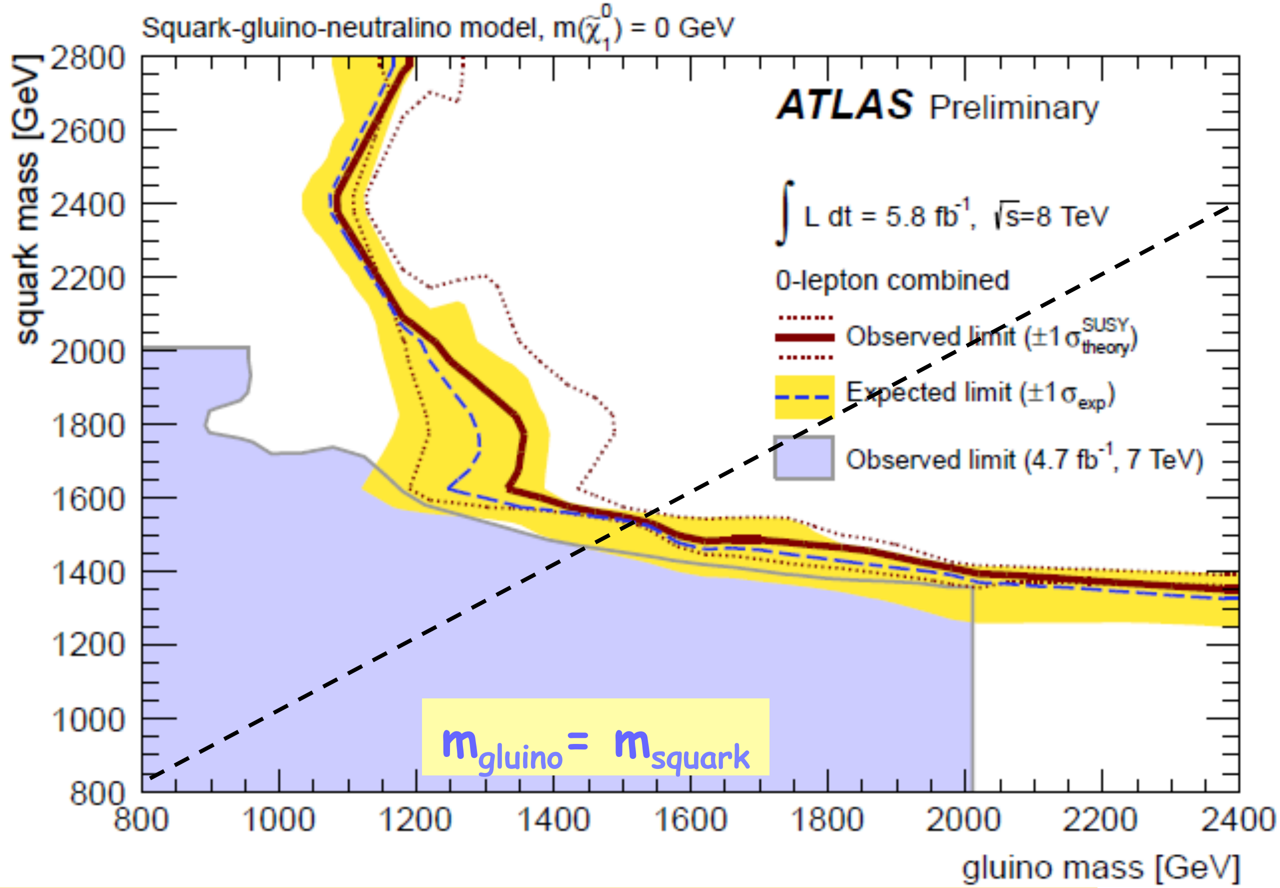
e.g. General Gauge Mediation (GGM)



Jets+MET in a Generalized MSUGRA Scenario

Jets+MET interpreted with simplified model

- generic squark
- generic gluino
- χ^0 LSP
- All other SUSY states decoupled
- Standard decay of SUSY particles to accessible states



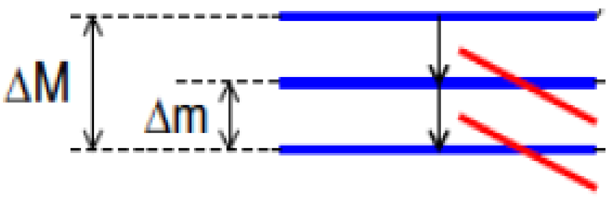
➔ Limits in same range (scenario has at least one accessible strong partner

➔ Again, excluded scale is ~1500 GeV for $m_{squark} = m_{gluino}$ (for light χ_1^0)

Idea #2: Is visible signature too soft to see or trigger on?

Small mass splittings can lead to signature with little visible energy

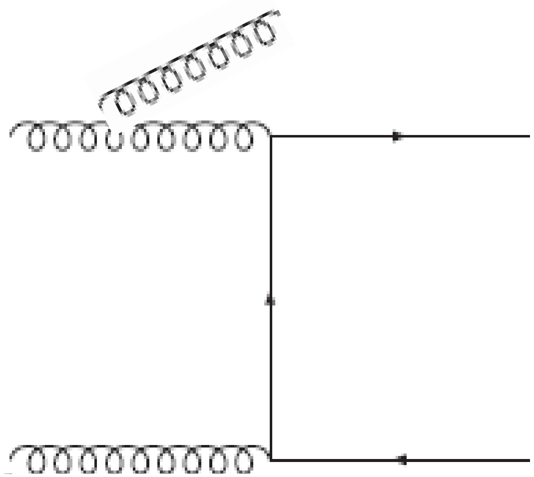
➔Even if E_T^{miss} is large, events can be buried in backgrounds or not even stored on disk
➔ Requires complex triggers (object + E_T^{miss}) and clever analyses



Small $\Delta M < m_W$ (Off-shell W)

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 W^* \rightarrow \tilde{\chi}_1^0 \ell^{\pm} \nu$$

'soft' lepton



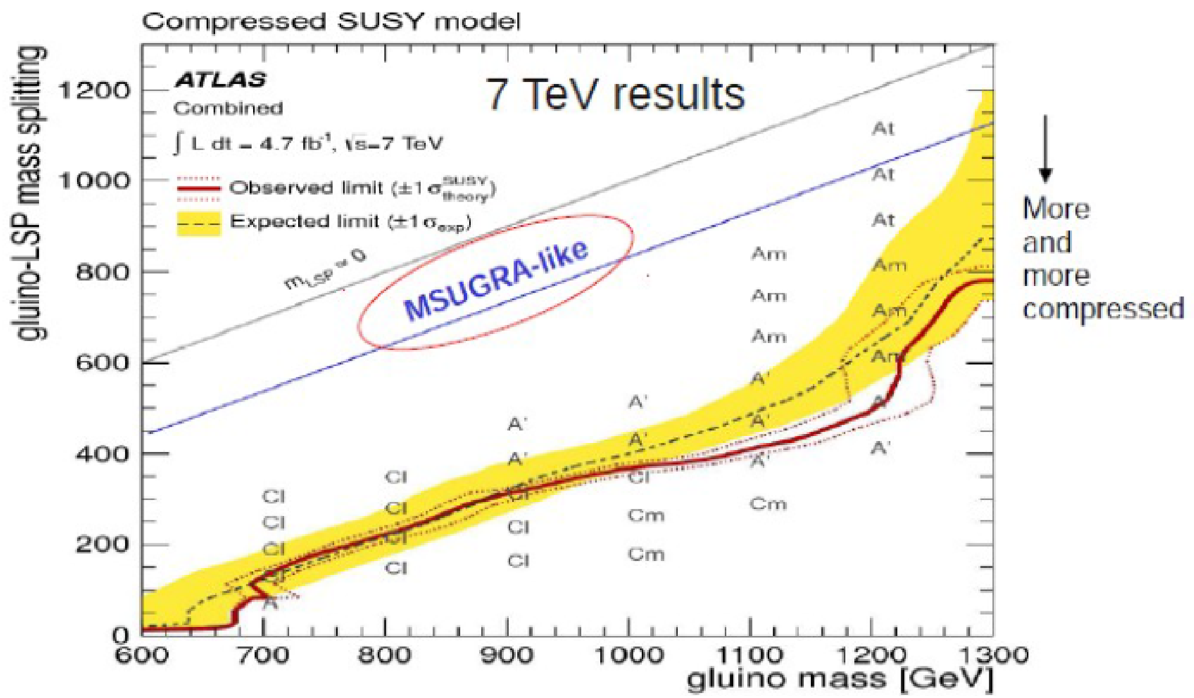
Important weapon: Initial state radiation

- ATLAS is perfecting its modeling of ISR
- Can look for events for which ISR "stiffen" the visible content of the event
- Somewhat "up-and-coming"

Compression and the Jets+MET Analysis

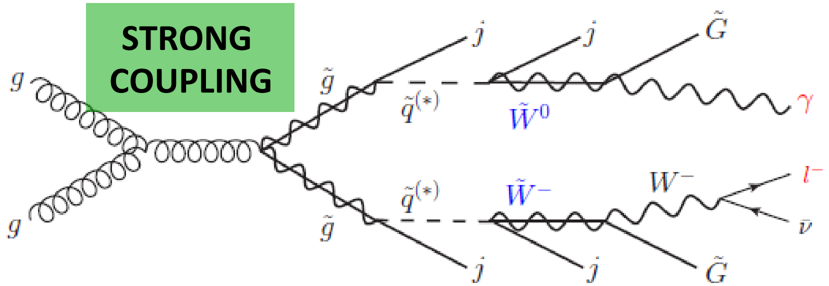
Requirement	Channel				
	A 2-jets	B 3-jets	C 4-jets	D 5-jets	E 6-jets
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ [rad] >	0.4 ($i = \{1, 2, (3)\}$)		0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_T > 40$ GeV jets)		
$E_T^{miss}/m_{eff}(Nj)$ >	0.3/0.4/0.4 (2j)	0.25/0.3/– (3j)	0.25/0.3/0.3 (4j)	0.15 (5j)	0.15/0.25/0.3 (6j)
m_{eff}(incl.) [GeV] >	1900/1300/1000	1900/1300/–	1900/1300/1000	1700/–/–	1400/1300/1000

Removal of m_{eff} cut for some SRs geared towards compressed scenarios

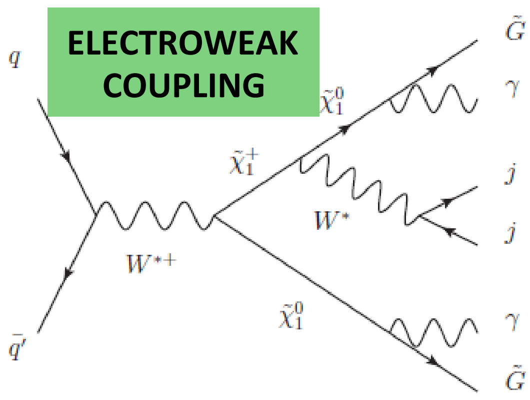


Inspired by LeCompte, Martin, PRD84 (2011) 015004

Strong vs. Electroweak Production



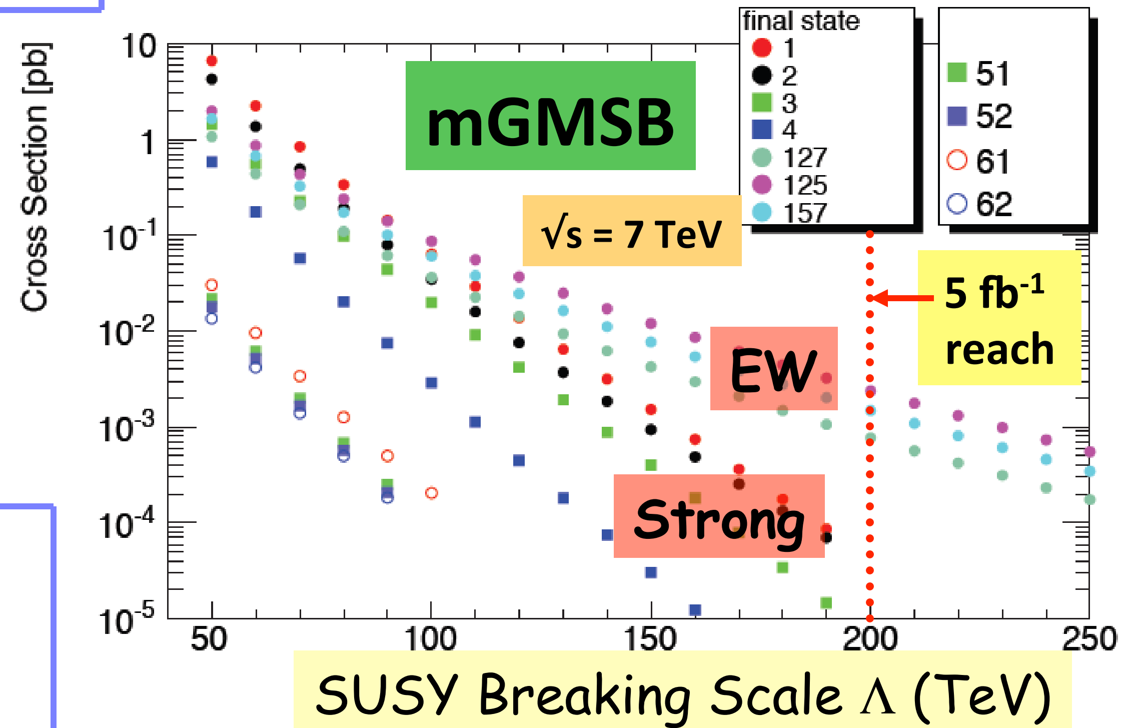
➔ probe high mass scale
➔ steep mass dependence (~M^{-10})
➔ beam energy vs. luminosity
➔ lower backgrounds



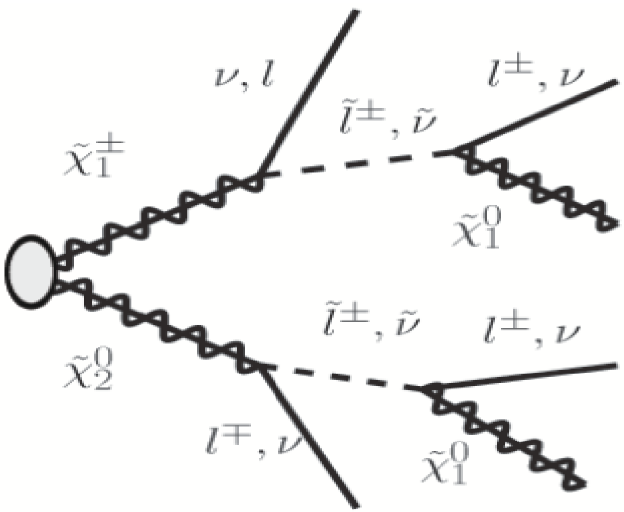
➔ probe intermediate mass scales
➔ higher backgrounds
➔ benefit from high ∫L·dt

However: if colored states are decoupled, EW production will dominate

- Dedicated EW prod. analyses
- Pure-EW simplified models (new!)



Next Idea: Are non-colored states the only accessible states?



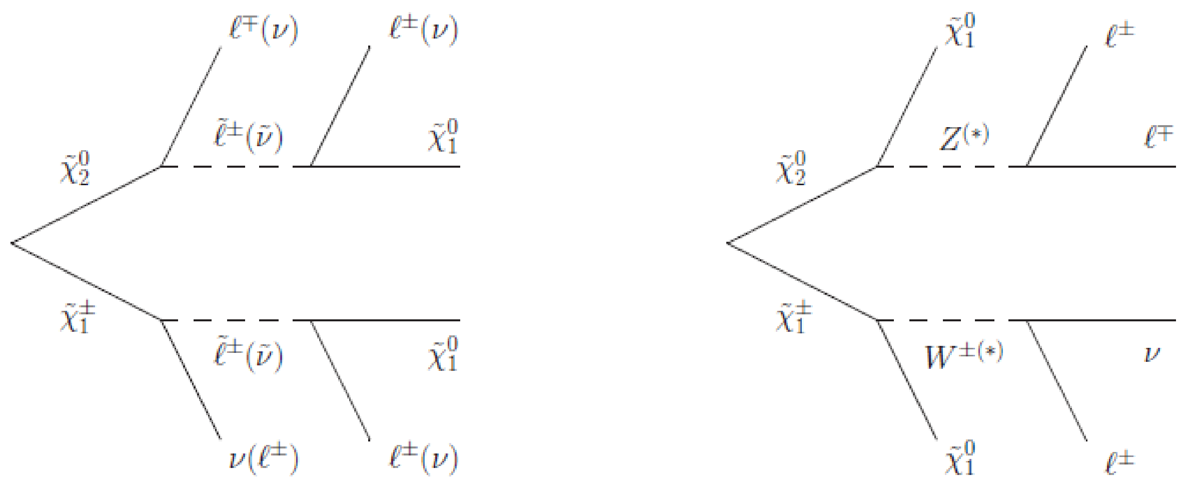
Many "natural" scenarios have few-hundred GeV gauginos, decoupled colored sparticles (except perhaps 3rd generation; see next section)…

- Multi-lepton signals
- E_T^{miss} from ν and χ_1^0
- Simplified model, only gauginos and sleptons light
- Large backgrounds to content with (smaller cross section for given mass scale)

Multi-lepton + MET EW SUSY Searches

➢ Employ simplified models with bino, wino masses as free parameters; all else decoupled

➢ Can also have light sleptons



Example:

- $\chi_1^+ \chi_2^0$ degenerate wino NLSP, χ_1^0 bino LSP
- Two cases: only gauginos light, or also with generic left-handed slepton with mass half-way between bino and wino,
- Produce $\chi_1^+\chi_1^-$ or $\chi_1^+\chi_2^0$; involves opposite-sign, same-flavor lepton pair

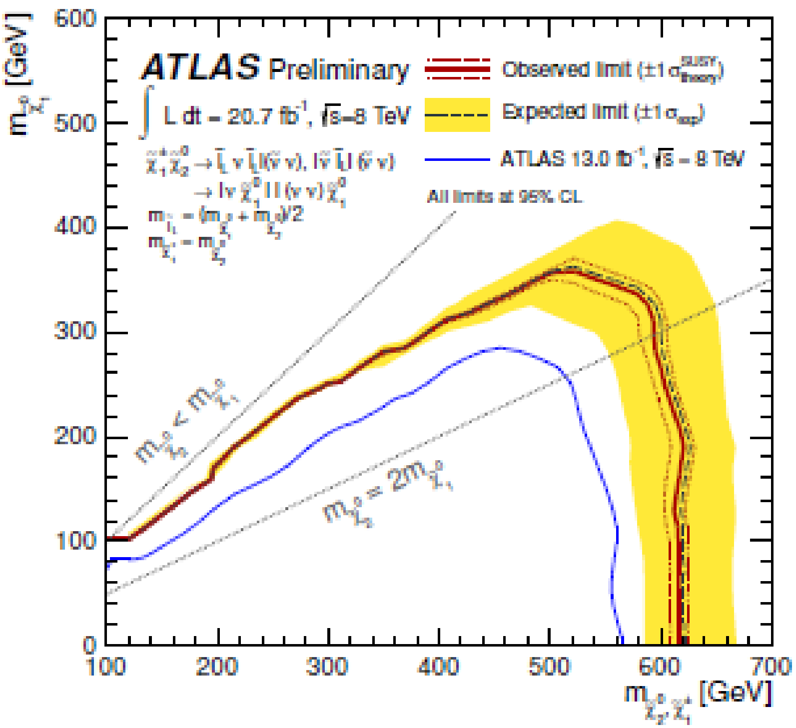
3 Lepton + MET Weak-Production Search

- Search for 3 leptons, including one same-flavor, opposite-sign pair
- Signal regions consider presence (SRZ) or absence (SRnoZ) of on-shell Z
- E_T^{miss}, transverse mass

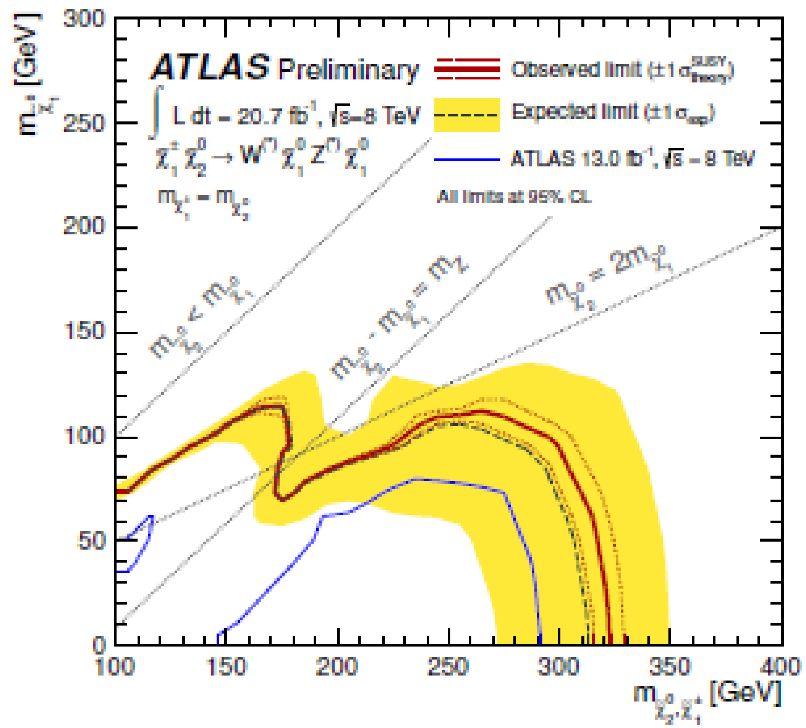
Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
m_{SFOS} [GeV]	<60	60–81.2	<81.2 or >101.2	81.2–101.2	81.2–101.2	81.2–101.2
E_T^{miss} [GeV]	>50	>75	>75	75–120	75–120	>120
m_T [GeV]	–	–	>110	<110	>110	>110
p_T 3rd ℓ [GeV]	>10	>10	>30	>10	>10	>10
SR veto	SRnoZc	SRnoZc	–	–	–	–

Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
Tri-boson	1.7 ± 1.7	0.6 ± 0.6	0.8 ± 0.8	0.5 ± 0.5	0.4 ± 0.4	0.29 ± 0.29
ZZ	14 ± 8	1.8 ± 1.0	0.25 ± 0.17	8.9 ± 1.8	1.0 ± 0.4	0.39 ± 0.28
$t\bar{t}V$	0.23 ± 0.23	0.21 ± 0.19	$0.21^{+0.30}_{-0.21}$	0.4 ± 0.4	0.22 ± 0.21	0.10 ± 0.10
WZ	50 ± 9	20 ± 4	2.1 ± 1.6	235 ± 35	19 ± 5	5.0 ± 1.4
Σ SM irreducible	65 ± 12	22 ± 4	3.4 ± 1.8	245 ± 35	20 ± 5	5.8 ± 1.4
SM reducible	31 ± 14	7 ± 5	1.0 ± 0.4	4^{+5}_{-4}	1.7 ± 0.7	0.5 ± 0.4
Σ SM	**96 ± 19**	**29 ± 6**	**4.4 ± 1.8**	**249 ± 35**	**22 ± 5**	**6.3 ± 1.5**
Data	**101**	**32**	**5**	**273**	**23**	**6**
p_0-value	0.41	0.37	0.40	0.23	0.44	0.5
N_{signal} excluded (exp)	39.3	16.3	6.2	67.9	13.2	6.7
N_{signal} excluded (obs)	41.8	18.0	6.8	83.7	13.9	6.5
$\sigma_{visible}$ excluded (exp) [fb]	1.90	0.79	0.30	3.28	0.64	0.32
$\sigma_{visible}$ excluded (obs) [fb]	2.02	0.87	0.33	4.04	0.67	0.31

3 Lepton + MET Analysis



(a) Decay via sleptons



(b) Decay via gauge bosons

Limits ~600 GeV when sleptons are accessible

Softer limits without sleptons (vector boson BFs)

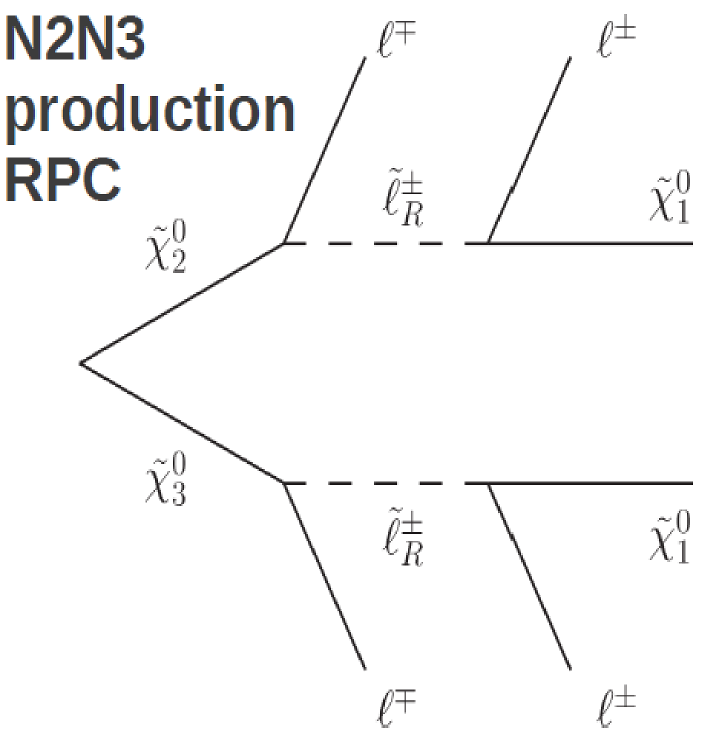
Still at the ~1/2 TeV scale for now

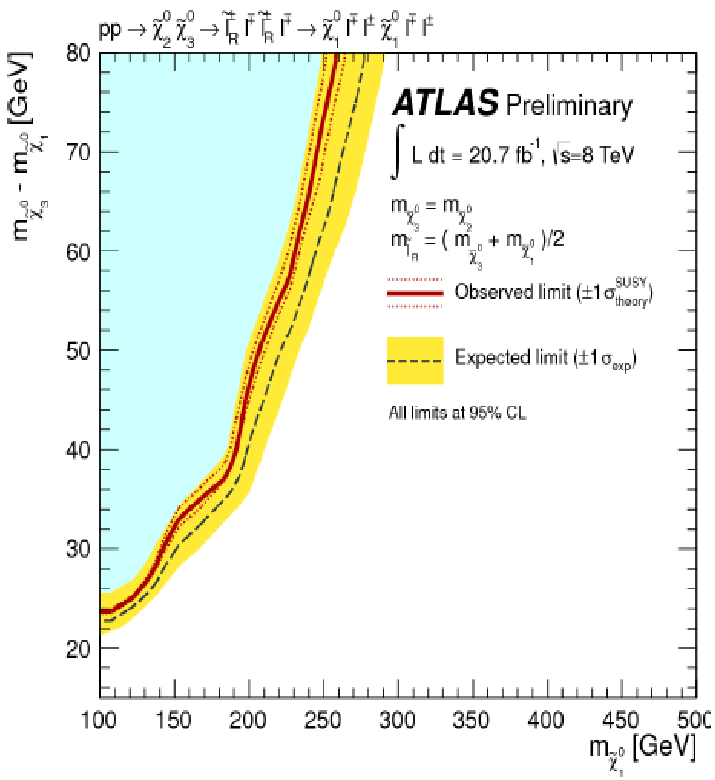
The One that Almost Got Away

Exploration of non-excluded pMSSM points revealed that a Heavy chargino scenario not considered!

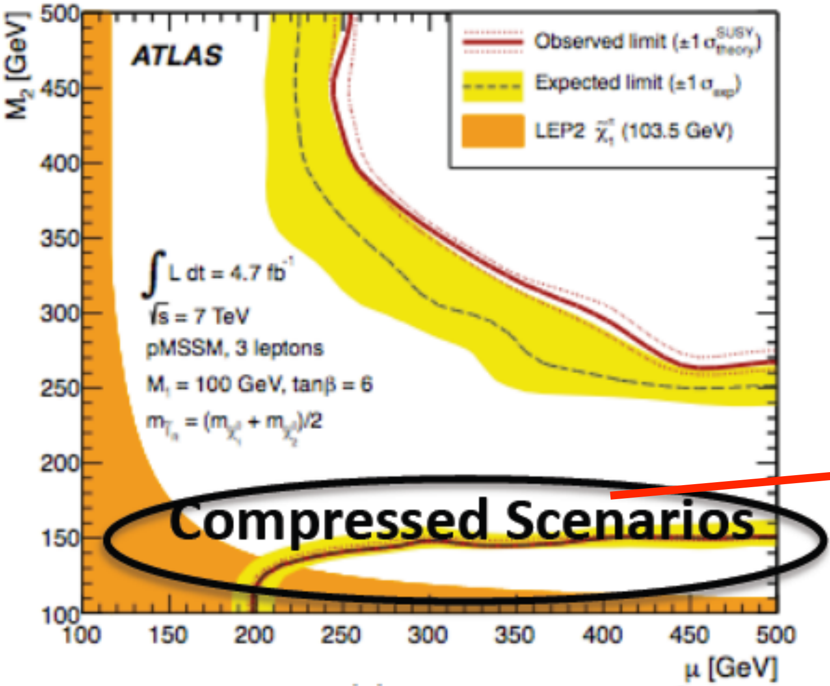
Significant Z-mediated production of $\chi_2^0\chi_3^0$ if they contain significant higgsino admixture

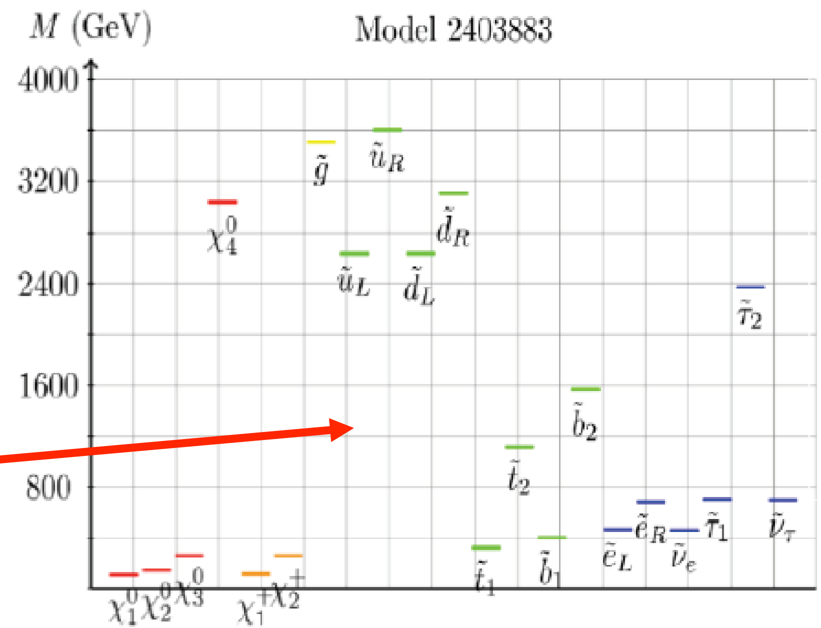
Accessible right-handed sleptons ➔ **4-lepton final state** dominant





Compressed Scenarios in Weak Production





What to improve? (Anadi Canepa, ATLAS)

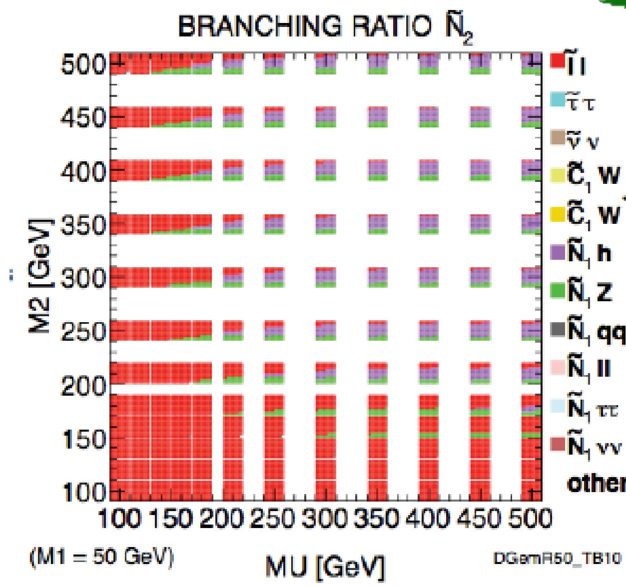
– Coverage of compressed scenarios using
  - low pT leptons
  - SS like search
  - mono-jet like search

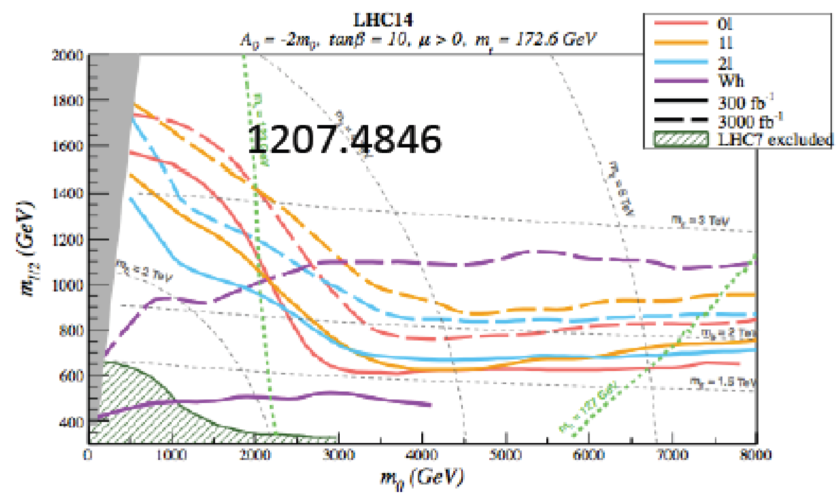
(and perhaps also ISR-enhanced events?)

Higgs in EW SUSY Decay Chains

Very important final state!

- Current sensitivity is very limited so dedicated signal regions are required
- Searches in the bb and tau-tau decay modes of the higgs are on-going
- Combination will be boost the overall sensitivity
- Once finalized, search results should be presented in the context of the pMSSM





In Search Of: Light 3rd Generation

Maximal mixing for 3rd generation: $\tilde{b}_1, \tilde{t}_1, \tilde{\tau}_1$ **naturally lightest sfermions**

Naturalness suggests they might well be accessible

Low cross-section to single chiral state (e.g. $\sigma_{stop\text{-}L} \approx 1/20\ \sigma_{gluino}$)

Challenging signatures with high backgrounds

Look for **leptons, E_T^{miss}, b-tagged jets**

Make use of **kinematic variables** ($\Delta\phi_{jet,MET}$, m_{T2},…)

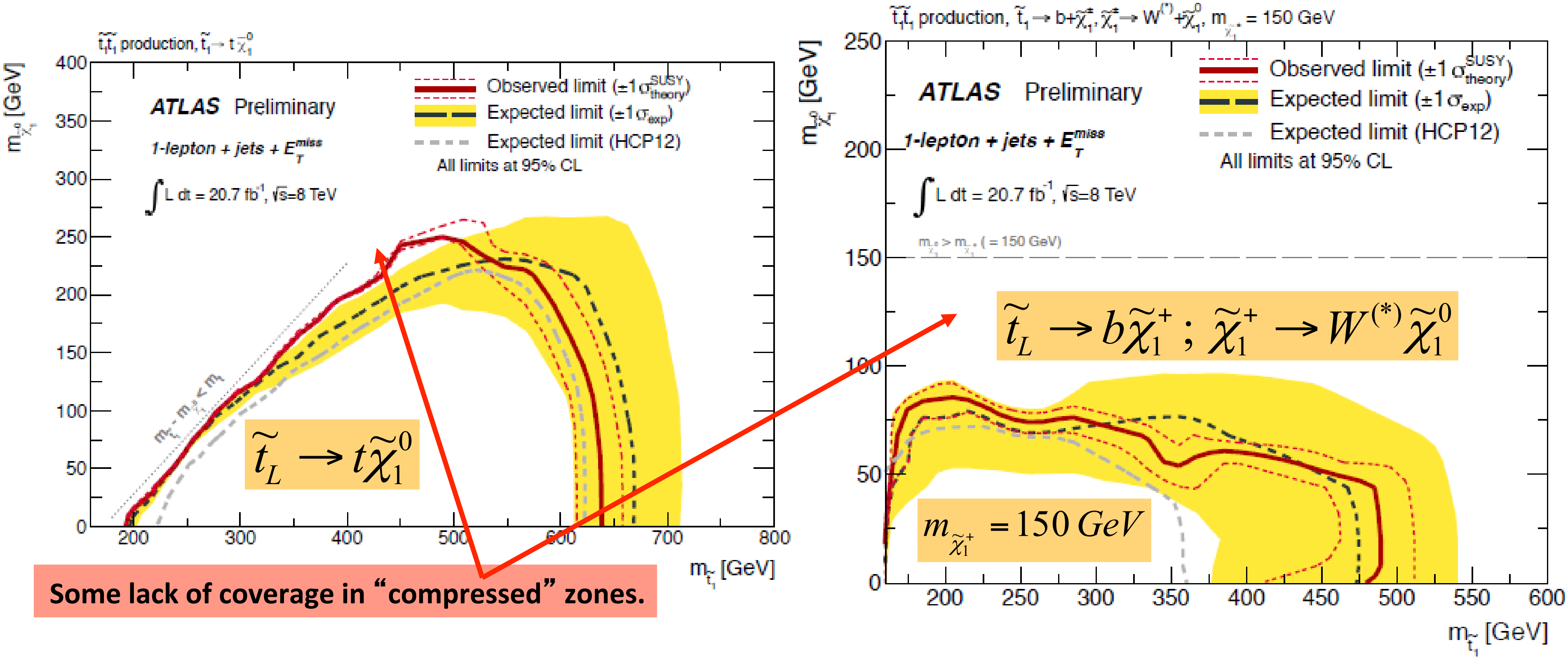
Stop can be more difficult than sbottom (softer jets)

- Gluino mass limits can be compromised if stop dominates decay chain

Direct Stop Production

Assume left-handed stop only accessible colored state. Look for decays through

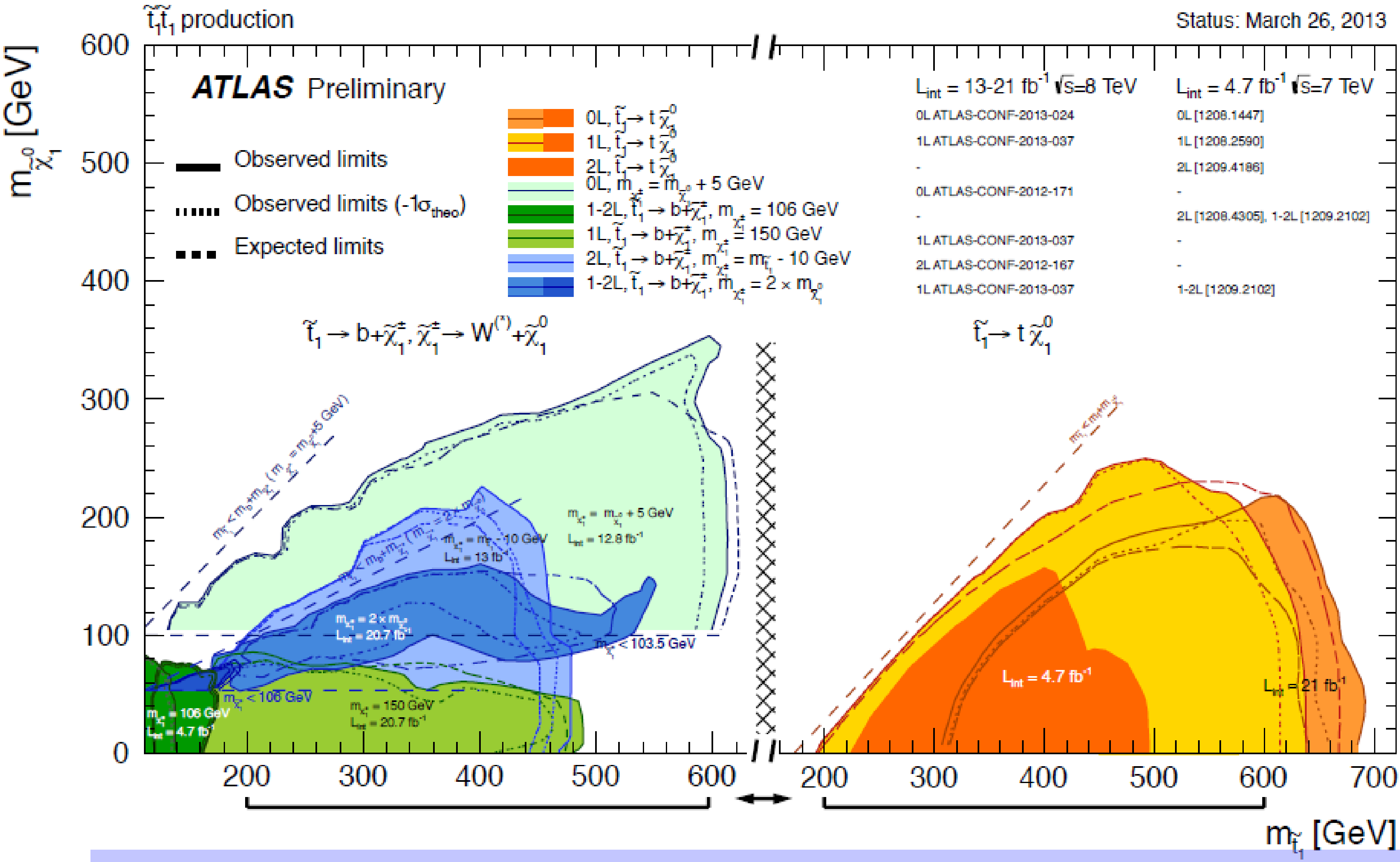
- t χ_1^0
- b χ_1^+ with $\chi_1^+ \rightarrow W^{(*)} \chi_1^0$; assume some χ_1^+ mass (e.g. 150 GeV)



Some lack of coverage in "compressed" zones.

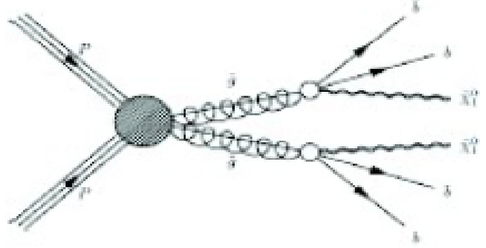
Limits around 600 GeV for $t\chi_1^0$; 500 GeV for $b\chi_1^+$

Summary of Light-Stop Results

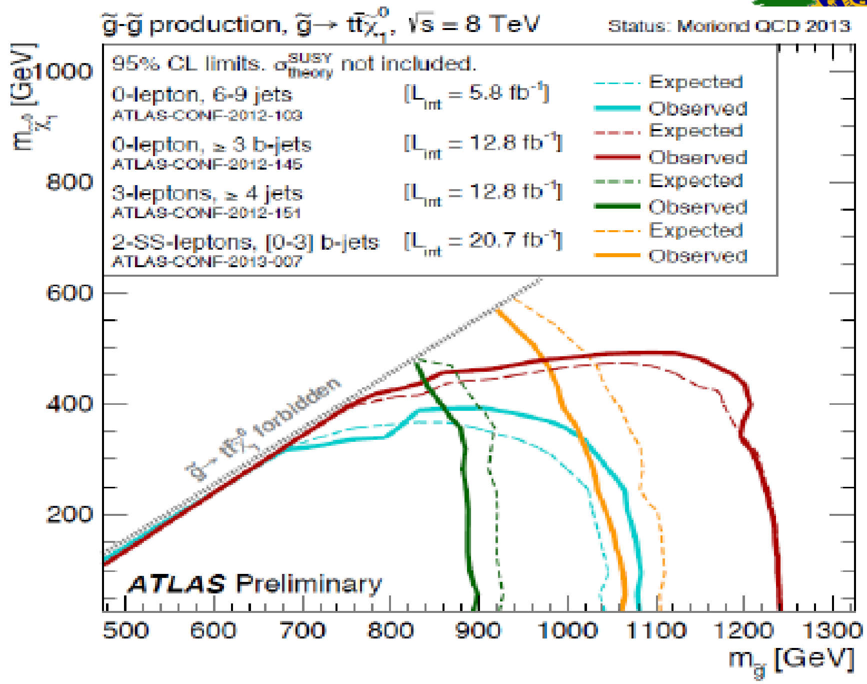


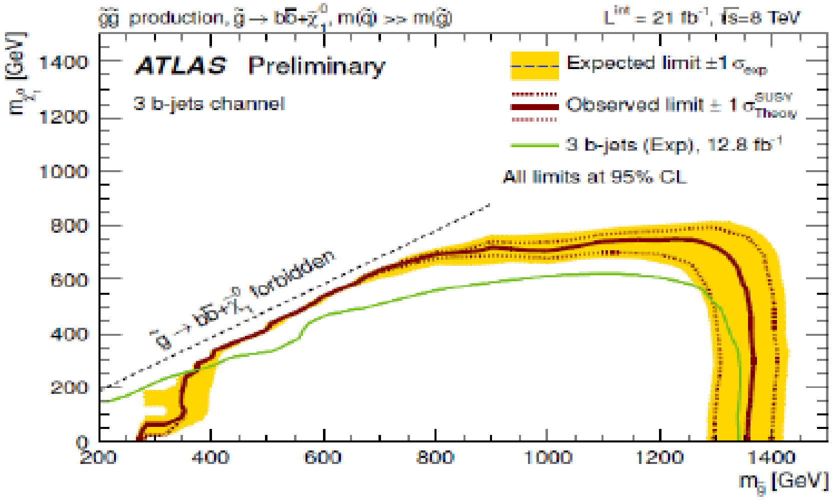
Reach for $b\chi_1^+$ analysis very dependent on χ_1^+ mass, but some sensitivity to regions not probed by $t\chi_1^0$ mass (avoid top in decay chain)

Gluino-Mediated Stop/Sbottom



$$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$$





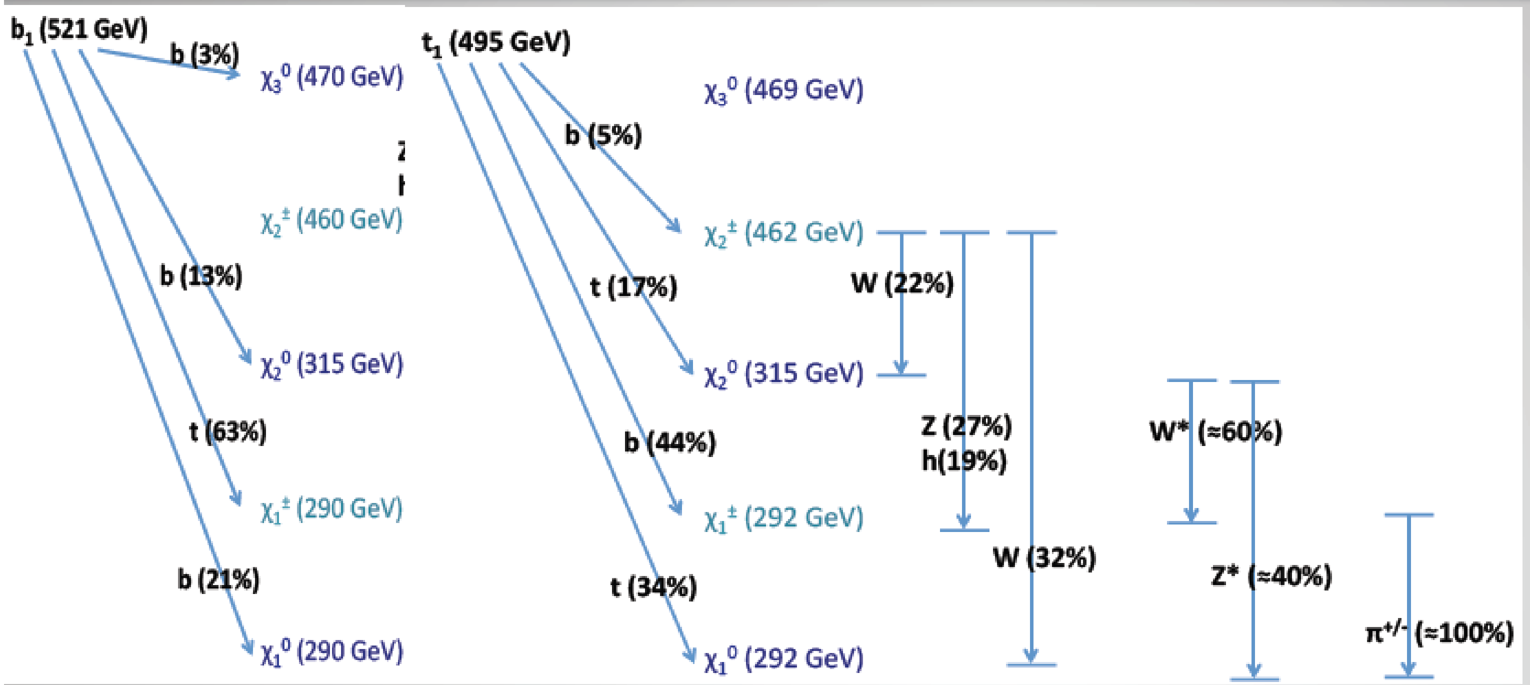
$$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$$

Gluino lower limits soften to ~1300 GeV if decay chain forced to go through sbottom, stop

N.B.: No lower limits on stau from direct stau production (look for 1-2 taus plus E_T^{miss}

The One that Got Away

pMSSM point 402293



- N_1, N_2, C_1 degenerate: sb sb and st st look alike.
- Final states (w/o soft fermions from C_1,N_2 decays)

tb+LSP (44%) tt+LSP (33%), bb+LSP (15%)

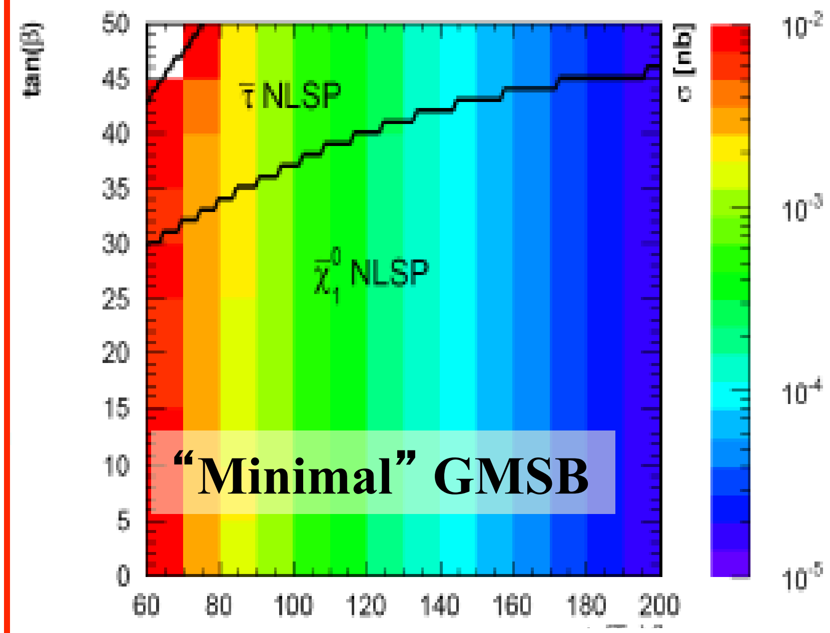
Final State with Photons

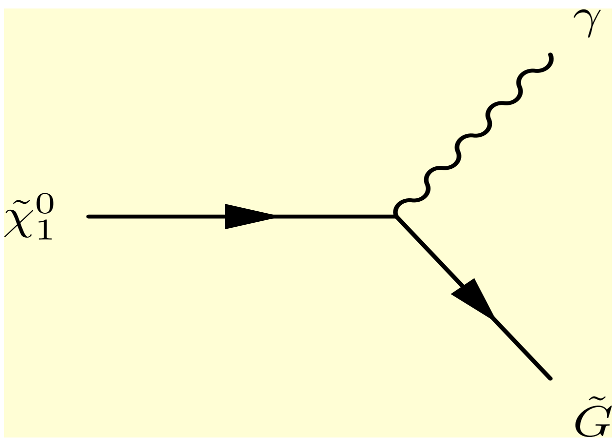
Arise from bino-like NLSP

GMSB has χ_1^0 NLSP over much of parameter space

Pure bino NLSP: $BR(\chi_1^0 \rightarrow \gamma G) = \cos^2\theta_W = 78\%$

Consider both pure bino-NLSP case as well as admixture





Signatures Considered:

Pure bino-like NLSP: **Diphoton + MET** (including non-pointing photons)

Higgsino Admixtue: **Photon + bjet(s) + MET**

Pure Wino NLSP ($BR(\chi_1^0 \rightarrow \gamma G) = \sin^2\theta_W = 22\%$): **Photon + lepton + MET**

Bino-Like NLSP: The Diphoton + MET Search

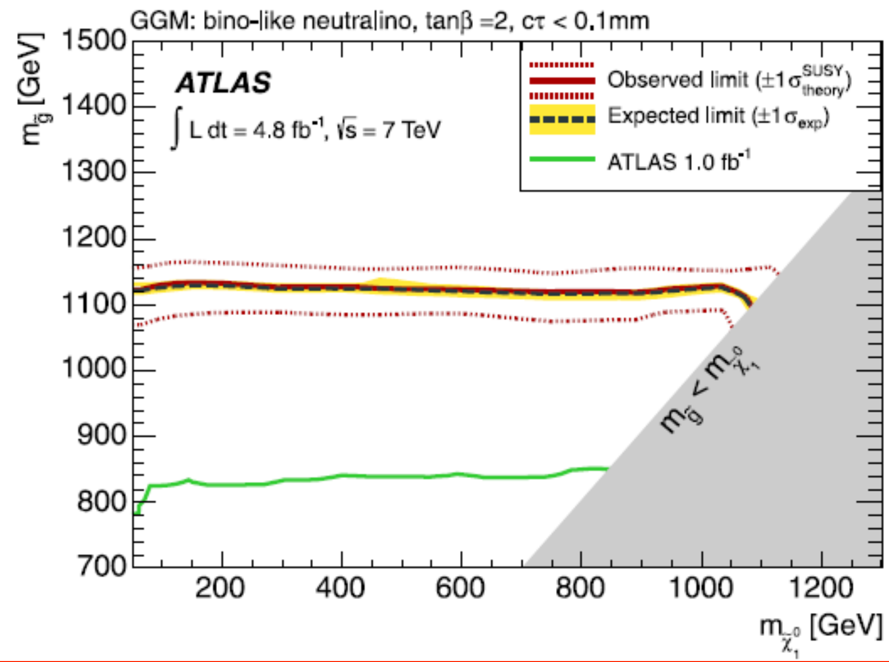
Three signal regions: Two 50 GeV isolated photons plus:

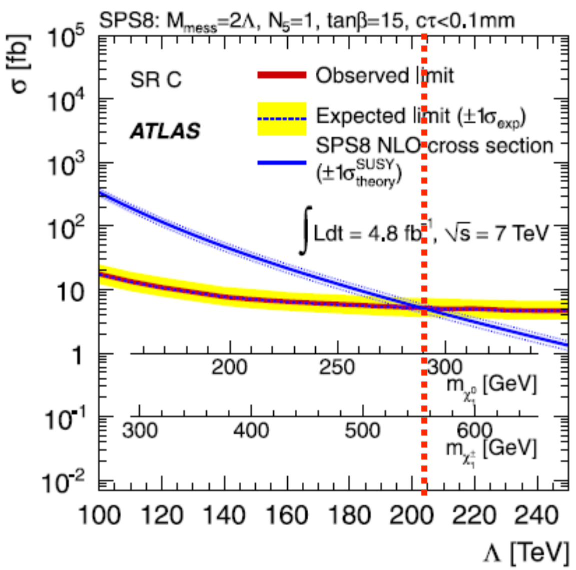
	SR A	SR B	SR C
$E_T^{miss} >$	200 GeV	100 GeV	125 GeV
$H_T >$	600 GeV	1100 GeV	-
$\Delta\phi_{min}(\gamma, E_T^{miss}) >$	0.5	-	0.5

A: Strong production, massive bino

B: Strong production, light bino

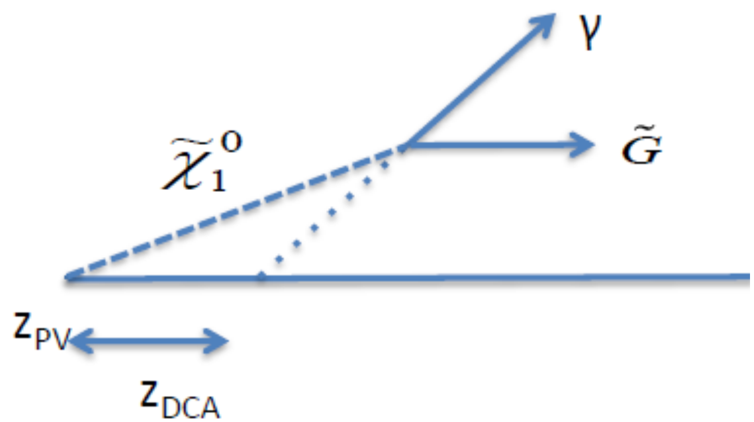
C: Weak production (SPS8 GMSB Model)





- 7 TeV data only
- Gluino limits above 1100 GeV for all bino mass
- SPS8 (minimal GMSB) dominated by EW production ($\chi_2^0\chi_1^\pm$ and $\chi_1^+\chi_1^-$)
- SPS8 limits suggest sensitivity to ~550 GeV gauginos; GGM EW analysis under development for 8 TeV data

New: Non-Pointing Photons (Long-Lived Bino)



Coupling to gravity sector is unconstrained

Long-lived binos natural in cosmological and compressed scenarios

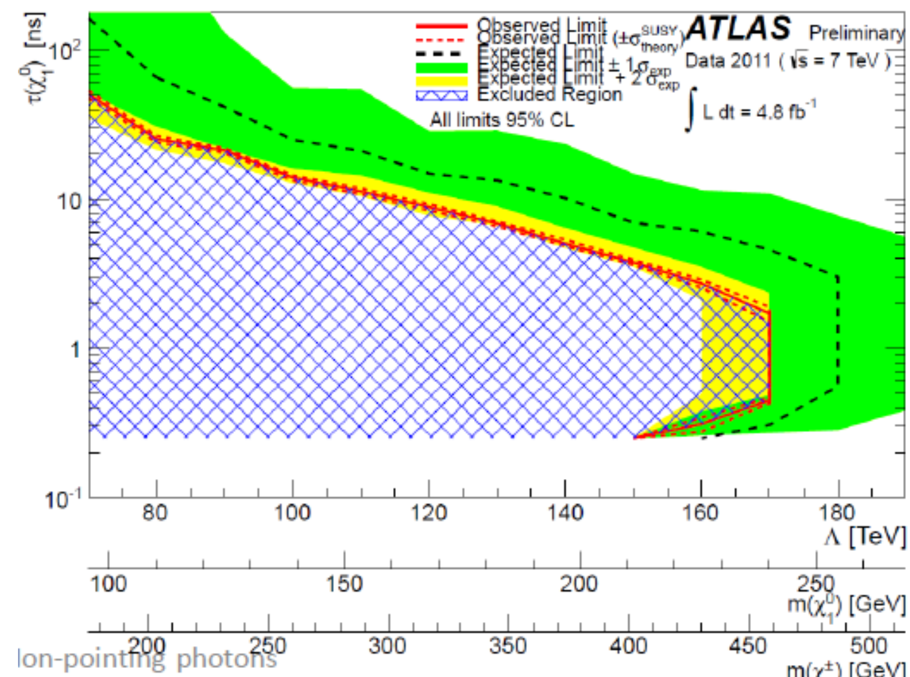
Fine η-segmentation of ATLAS calorimeter very advantageous

7 TeV data only

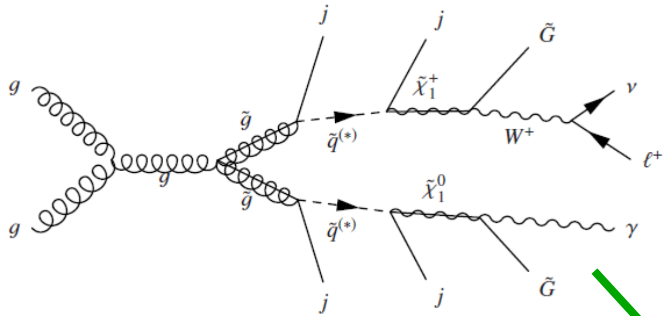
Require 1 tight, 1 loose photon

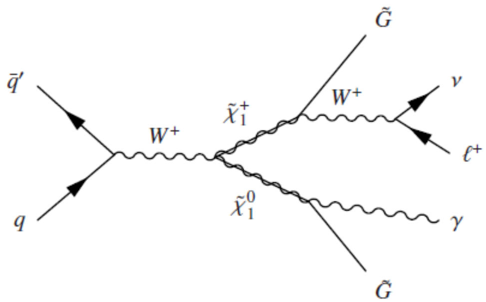
Fit to ZDCA distribution of loose photon

Result begs to be combined with prompt diphoton analysis (soon!)



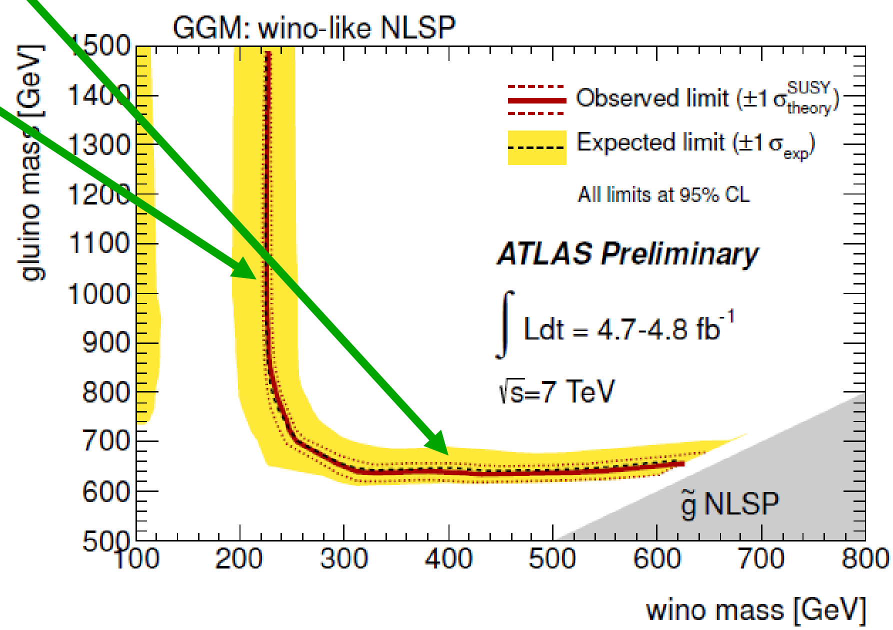
Photon + Lepton + MET: The Wino-Like NLSP



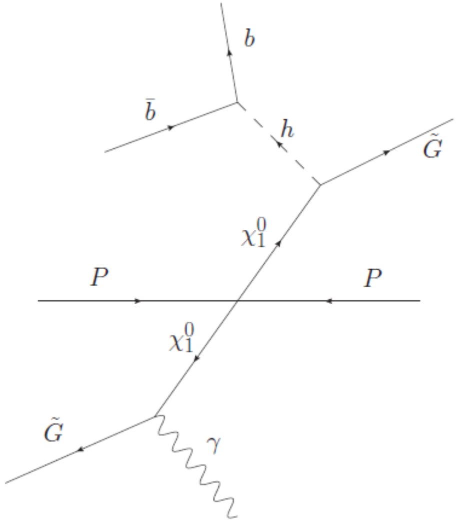


- Can proceed via strong or EW production
- Photon from photino-like component of neutral wino
- Lepton from chargino
- Require E_T^{miss} > 100 GeV; m_T > 100 GeV

Yields	electron channel	muon channel
$W\gamma$	$6.1^{+2.5}_{-2.3}$	$8.6^{+2.9}_{-2.8}$
W + jets	0.5 ± 0.4	$0.3^{+0.4}_{-0.3}$
$t\bar{t}\gamma$	2.2 ± 1.0	2.3 ± 1.0
fully-leptonic $t\bar{t}$	1.5 ± 0.4	$2.3^{+0.6}_{-0.8}$
semi-leptonic $t\bar{t}$	$0.02^{+0.06}_{-0.02}$	$0.03^{+0.17}_{-0.01}$
single top	$0.2^{+0.1}_{-0.2}$	0.4 ± 0.2
WW, WZ, ZZ	0.9 ± 0.2	0.7 ± 0.3
$Z\gamma$	0.2 ± 0.1	0.3 ± 0.1
Z + jets	0.8 ± 0.7	0.1 ± 0.1
diphoton	$0.5^{+0.7}_{-0.5}$	–
γ + jets	0.1 ± 0.3	–
total predicted	13.0 ± 3.4	15.1 ± 3.6
data	15	11



Photon + bjet(s) + MET: Higgs in the Decay Chain!



Also require $E_T^{miss} > 150$ GeV, $m_T > 100$ GeV

Model: Free parameters are gluino, χ_1^0 mass

Adjust M_1, μ (μ < 0) to maintain

$$BR[\chi_1^0 \rightarrow (\gamma,h,Z)G] = (56,33,11)\%$$

Probe strong scales to 900 GeV, weak to 350 GeV

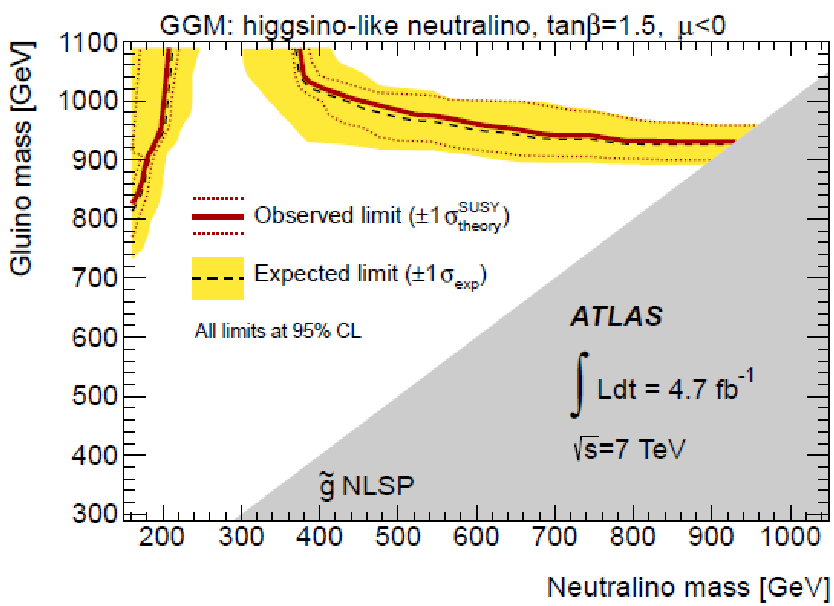
First SUSY analysis with final-state Higgs!

Also can have μ > 0

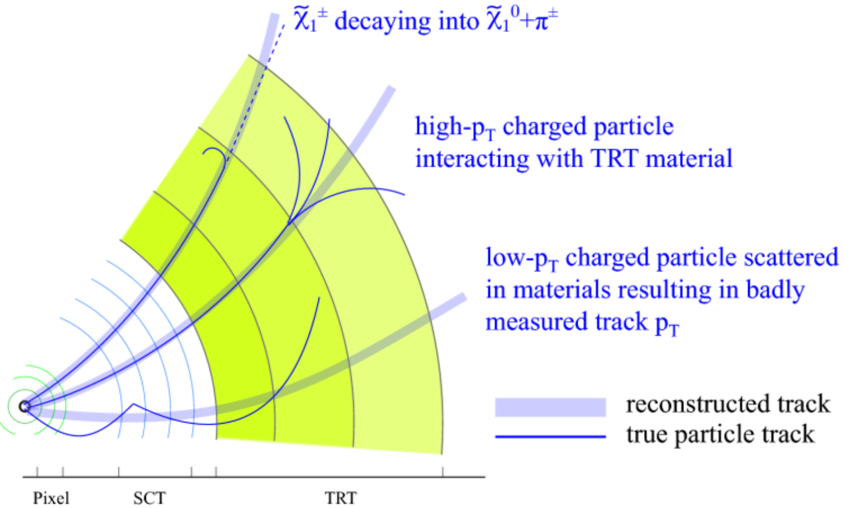
To explore this, are creating grid with $BR[\chi_1^0 \rightarrow (\gamma,h,Z)G] = (50,2,48)\%$

Few b-jets or leptons

➔Photon + njets + MET is final neutralino-NLSP-inspired signature to be explored



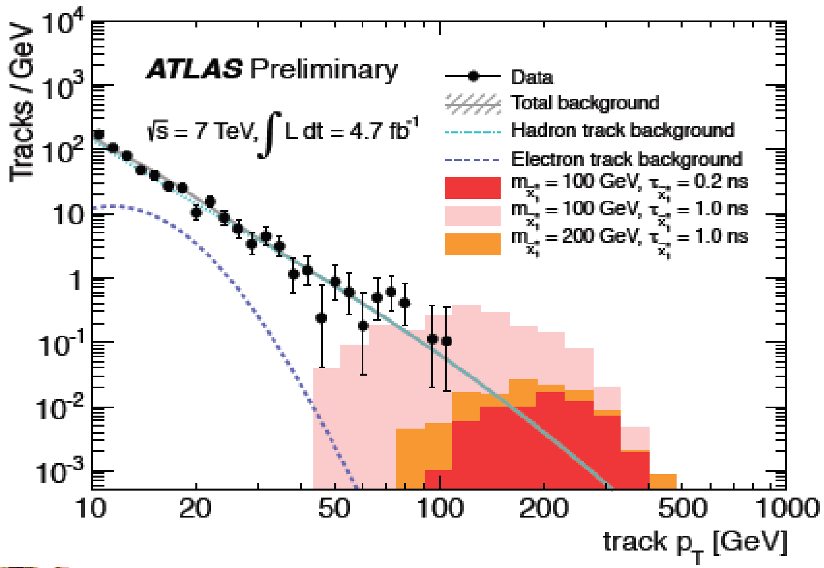
Disappearing Tracks!!! (+ E_T^{miss})



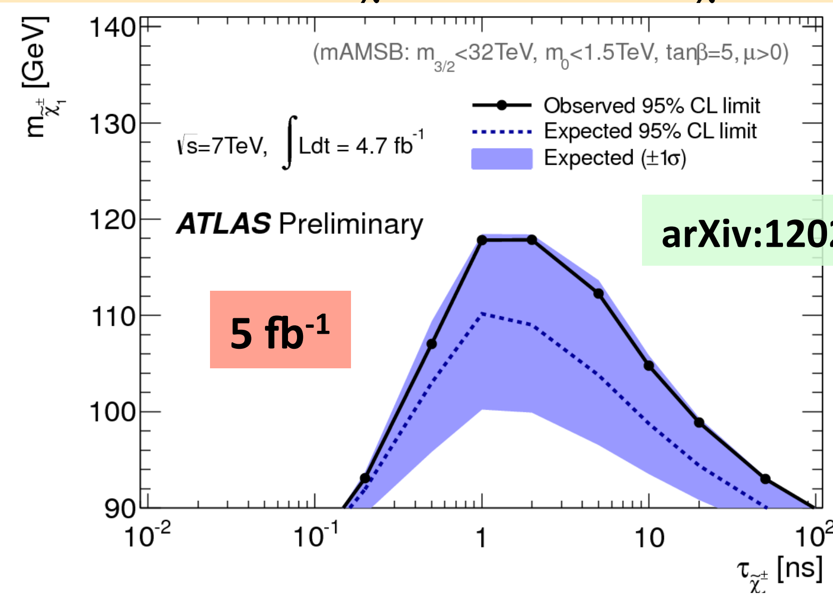
AMSB: Chargino/Neutralino naturally quasi-degenerate

- ➢ Long-lived states
- ➢ Asymmetric decay
- ➔ Disappearing tracks
- ➔ TRT is critical component

Disappearing track ➔ few TRT hits



Exclude 0.2 < $M_{\chi+}$ < 90 ns for $M_{\chi+}$ < 90 GeV



5 fb^{-1}

arXiv:1202.4847

Wrap-Up

- No discoveries claimed
- SUSY scale pushed up to 1500 GeV for standard scenarios
- If only gauginos or 3rd generation squarks accessible, limits in 500-600 GeV range
- Light stau with interediate (~1 TeV) gauginos is a challenge
- Many analyses have yet to update to 20 fb^{-1} at 8 TeV
- Have ~2 years to continue looking for holes in coverage
- As gaps become more contrived, motivation may wane
- 14 TeV will be welcome, but maybe we're getting a little jaded.
- Pray to the Goddess for new states!

Back-Up