Supersymmetry Searches

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Supersymmetry Motivation by Analogy

Doubling the spectrum (particle → sparticle) is a big price. Occam's razor?

→Worked once before: Assembling the electron (Murayama, TASI Lectures)

Electron q=1.6x10^{-19} Coul , radius < 10^{-19}m

[200GeV ~ 10^{-18}m ➔ r_e < 10^{-18}m (from g_e), LEP 2006: 10 TeV contact interaction ➔ r_e < 10^{-20}m]

$E_{assembly}$ ~ $+q^2/r_e$ ~ 10,000 MeV but m_e~ 0.5 MeV

➔Large *negative* "bare mass"

m_e = 0.5 MeV = -9999.5 MeV + 10,000 MeV

FIX: Double the particle spectrum! positron i.e., new physics at ~100fm ~1MeV

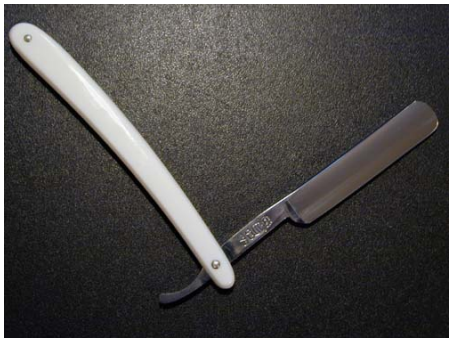
Weisskopf (1939): $E_{assembly}$ ~ $+q^2/r_e$ cancelled by $E_{vacuum\ pair}$ ~ $-q^2/r$ (e^+ from vacuum)

$$(m_e c^2)_{obs} = (m_e c^2)_{bare}\left[1 + \frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

Occam's Razor: Particle Physics Version

We like doubling the particle spectrum.

Single Blade (electron)

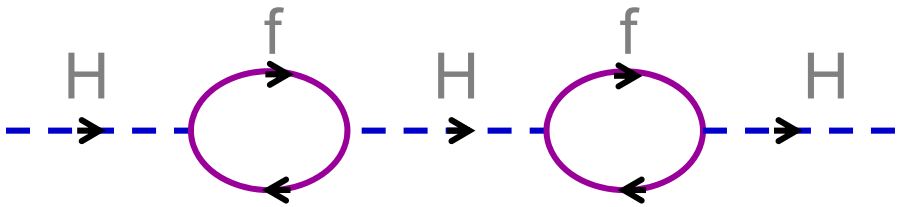


Twin Blade
(electron & positron)

Multiple Blades
(electron, positron, selectron?...)

SUSY: Why?

Today: Higgs has the same hierarchy problem.



Radiative loops: $M_H \sim 10^{15}$ GeV, but Higgs at 100 GeV (EW scale)

Delicate cancellations at 10^{15} GeV

OR

SUSY at TeV scale

- top loops cancelled by stop loops → "hierarchy problem" solution

But SUSY is badly broken. m(selectron) >> 0.5MeV

SUSY-Breaking Defines Phenomenology

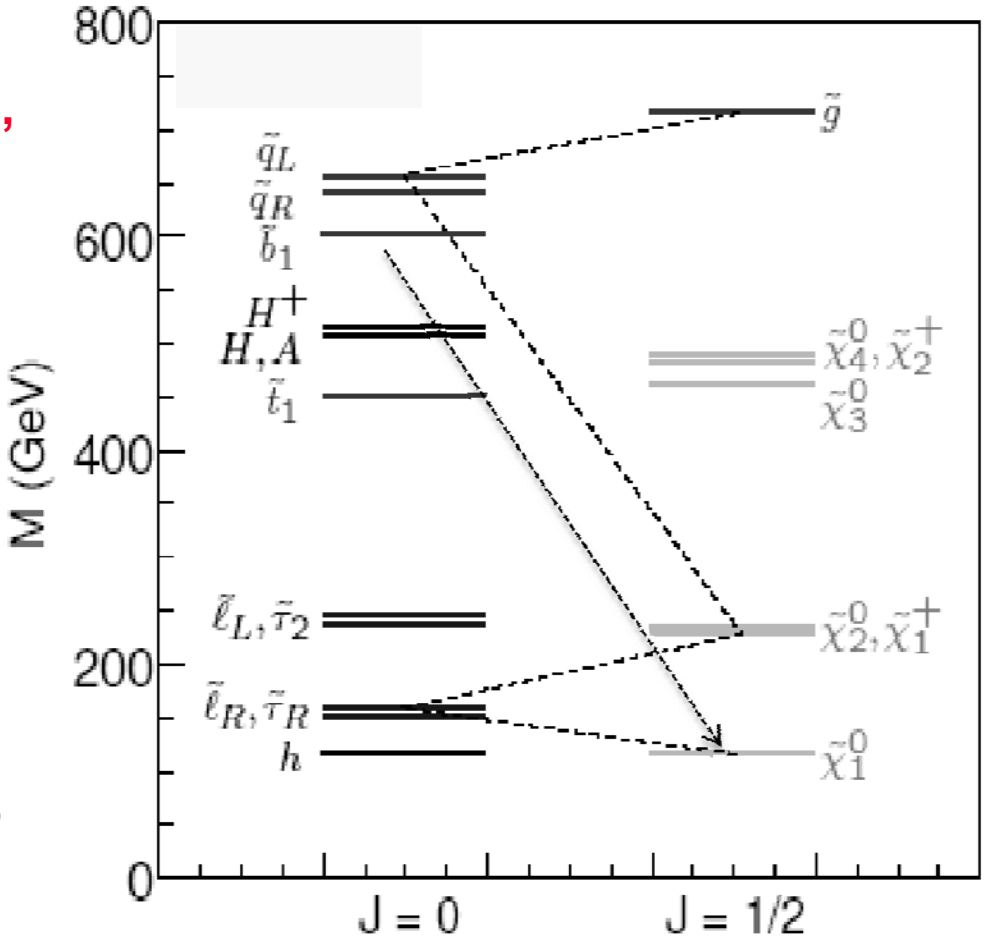
- **Signatures depend on SUSY breaking, mass hierarchy and mixing**

Many but not all models:
RGE running →

- **Strongly interacting particles heavy**
- **Weakly interacting (middle)**

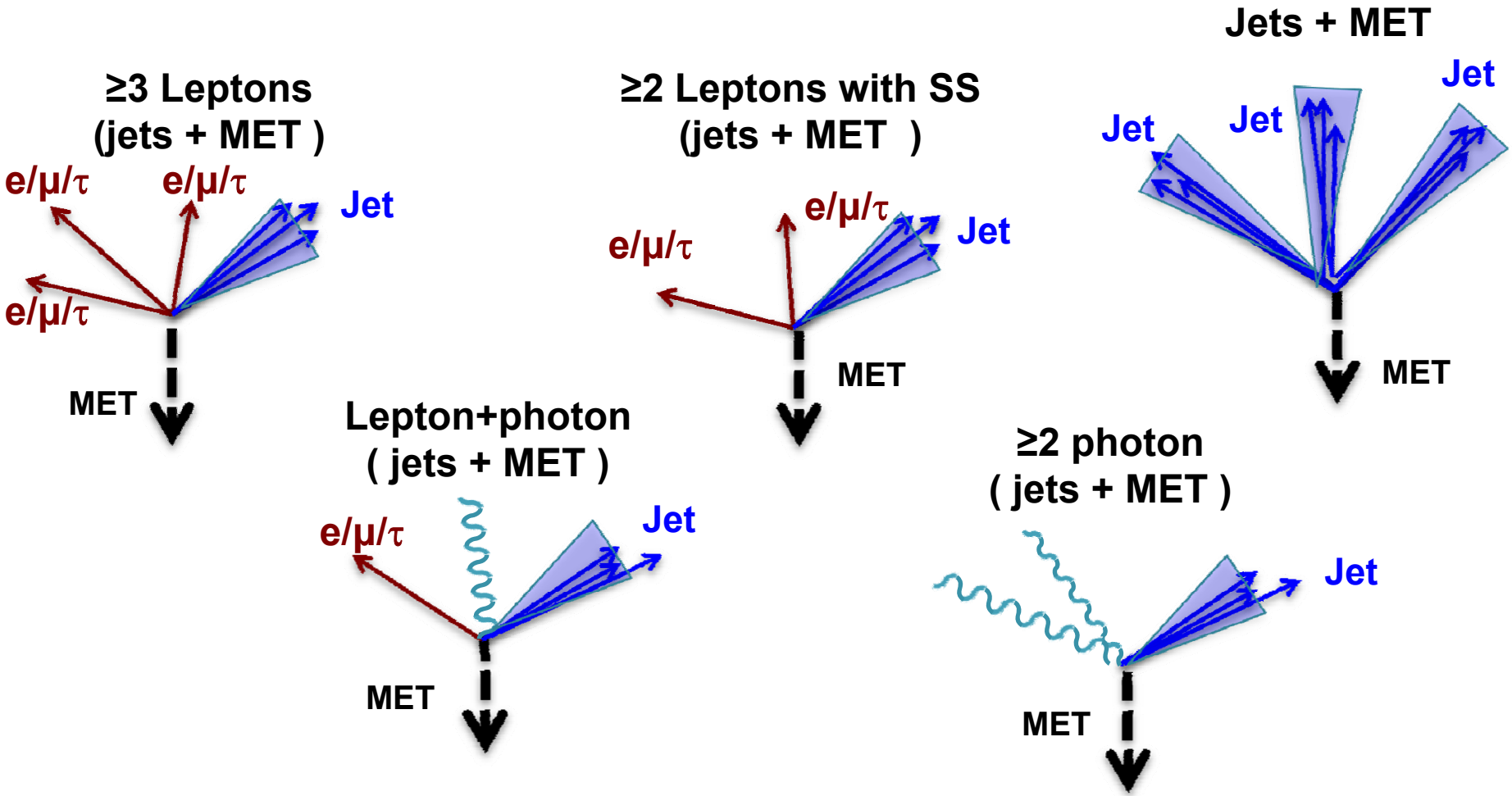
e.g. with R-parity, Stable Lightest Supersymmetric Particle (LSP)

→ Missing E_T (MET) signature (from LSP and neutrinos)



Conventional SUSY Search Axes

(MET or jets/HT etc not guaranteed!)



Experimental Toolkit

- Muons: CMS's middle name. Electrons & γ's done well.
- (Underlying) tracking: Jets, p_T, (also, timing)
- Jets: H_T , b-tag and even top-tag (high pt)
- Hermeticity: MET.
- Effective mass scale: $S_T = \Sigma$ Lepton & jet pt's & MET
- (Hadronic) τ's (isolated tracks, $+\pi^0$,3-tracks, $+\pi^0$)
- Good resolution (Invariant mass reconstruction → Resonant Searches)

→Signatures (recipes)

→Models

SUSY Searches: Where do we stand?

* NOT a systematic survey, just sample searches.
* The heart of a search is background determination.

  Too detailed for this talk → Parallel Session

- Talk organized by signatures, not interpretation

  ** If a search team discovers new physics with a given signature, it is extremely unlikely that it will be the physics they were looking for.

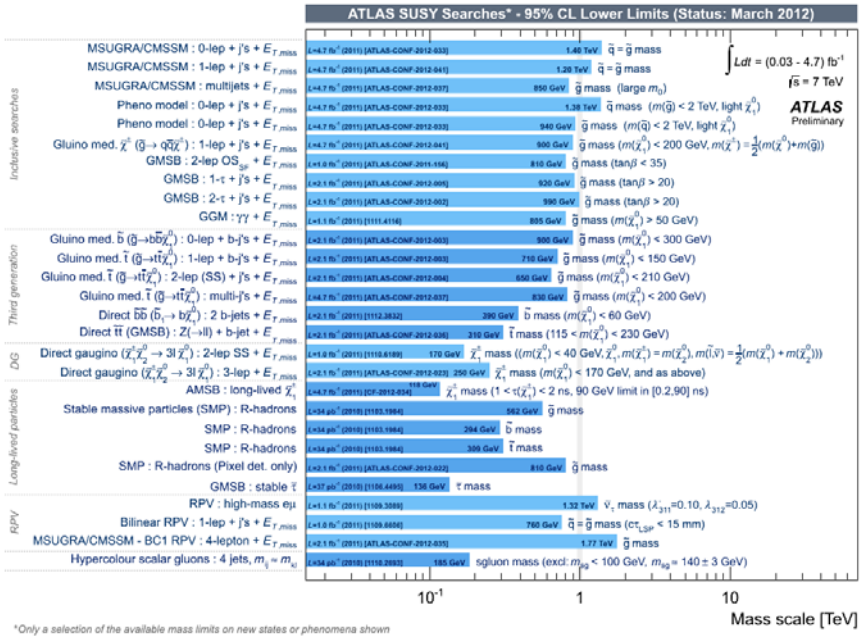
Before we round up the usual suspects

(generic strong production)

→→

LHC vs SUSY Models

e.g. ATLAS SUSY Results



LHC

This is a sugra free talk

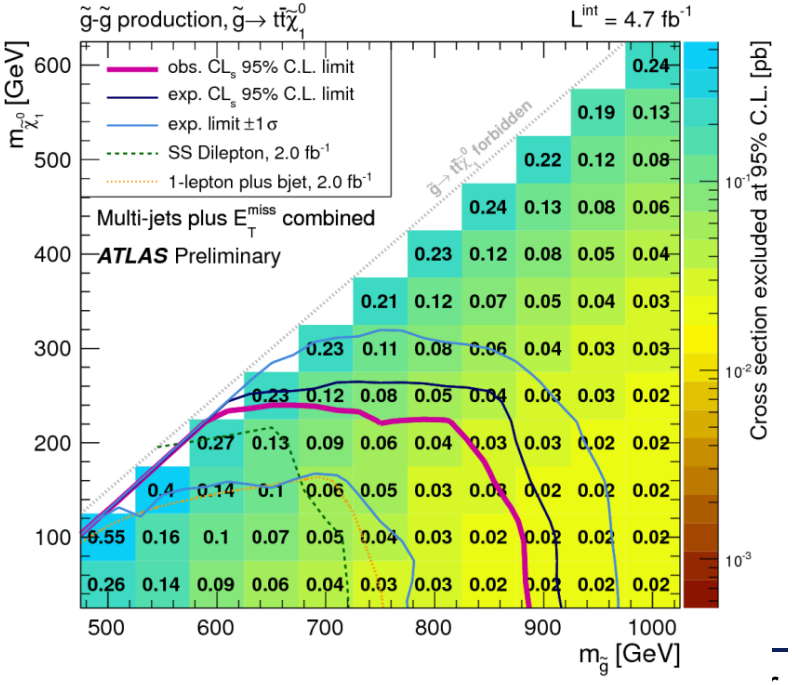
Slide Credit: Stephen Martin

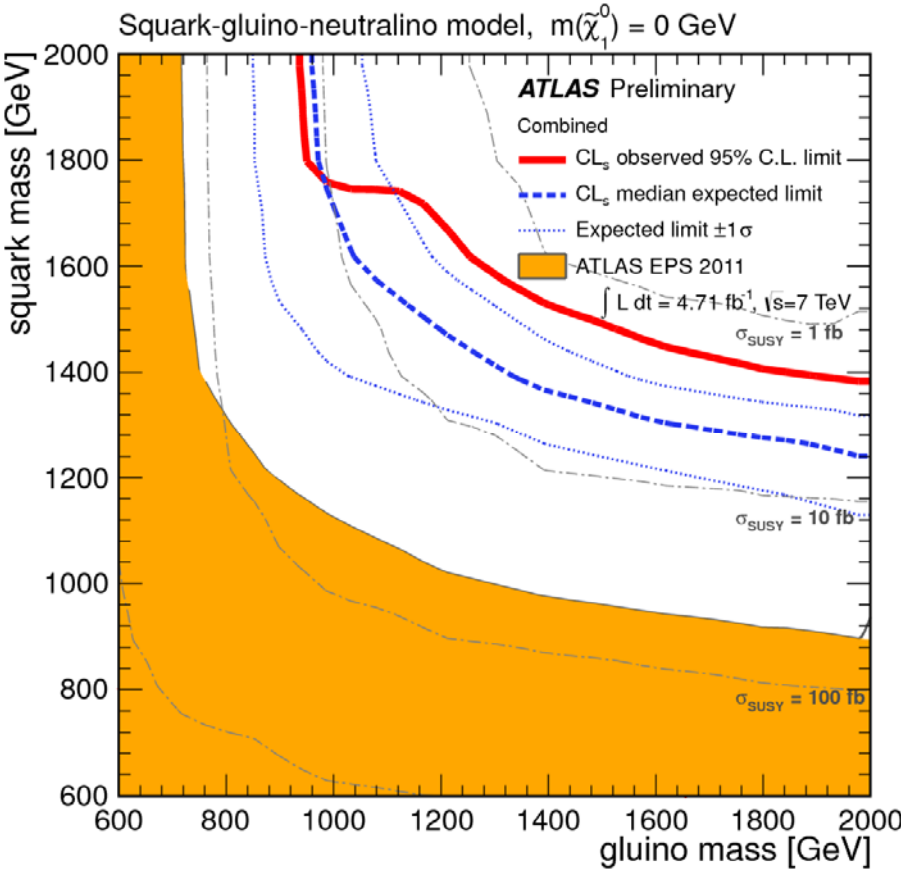
Simple-minded Squarks & Gluinos are getting heavier

ATLAS (4.7/fb)

- Strong production
- Inclusive JET-MET, no leptons
- Several sub-searches with MET, Njet, m_{eff} (=S_T=H_T+MET)
- Backgrounds: W+jets, (Invisible) Z + jets
  ttbar, dibosons, QCD, tau decays

Result: Simplified production of gluinos and Gen1,2 squarks decaying to jets +LSP





ATLAS also does ≥6 jets+MET

← Simplified model cross section limits

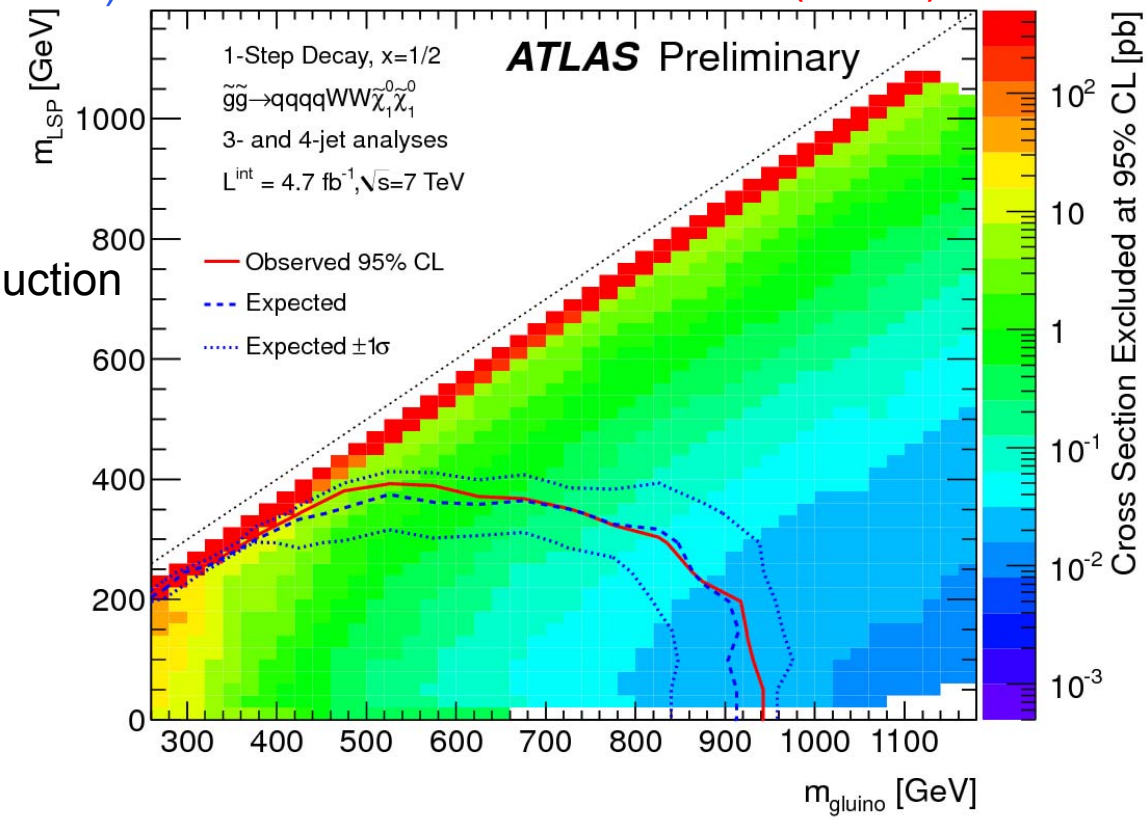
Excellent reach for a non-optimized search

Add a lepton (e/μ)

- Inclusive JET-MET, one lepton. MET >250 GeV
- Sub-searches with 3-jets, 4-jets etc
- Lepton ➔ Transverse mass (>100GeV).
- ST > 1200 or 800 GeV
- Backgrounds: W/Z+jets, ttbar

- Result for 3/4-jet channels
  Simplified model: gluino pair production
  & gluino → qq W* +LSP

ATLAS (4.7/fb)



Add a photon (or two): Photon(s)+Jet(s)+ MET

- 40/25 GeV photons with at least one jet and MET> 50 GeV

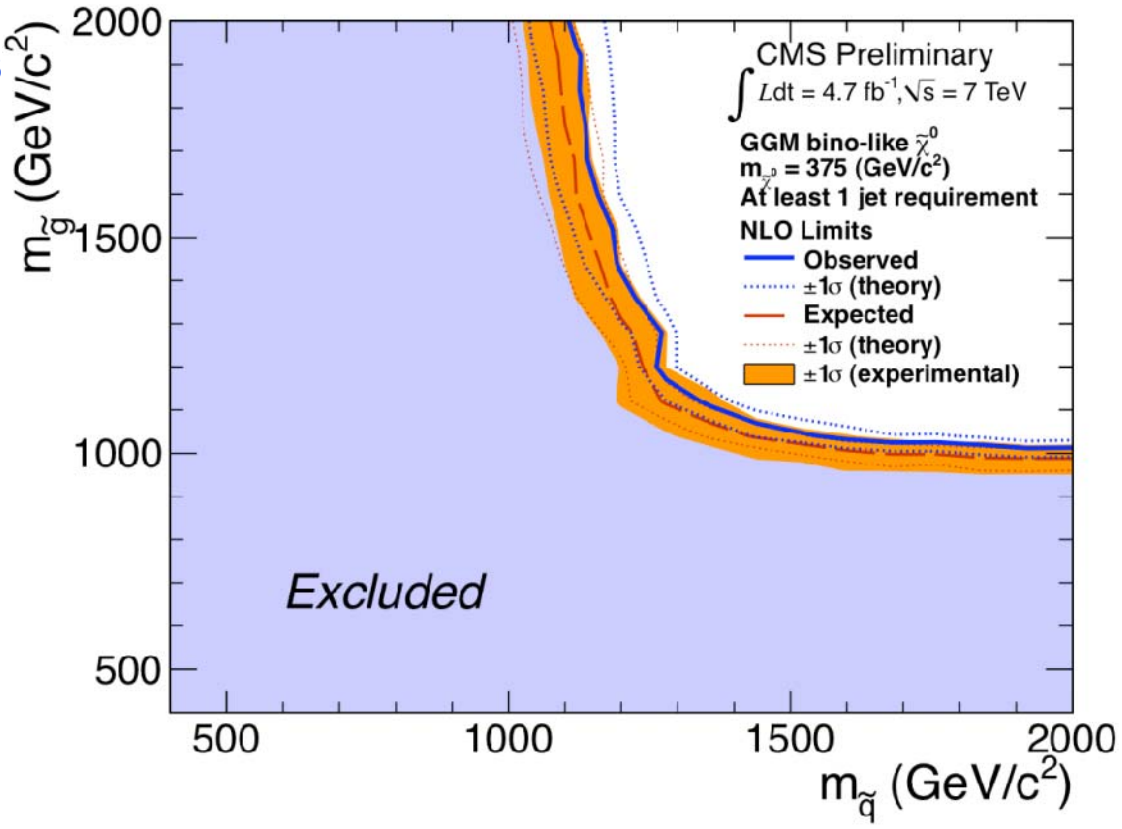
  OR

- 80 GeV photon with at least 2 jets MET> 100 GeV

- Backgrounds: Mis-ID photons and bad MET

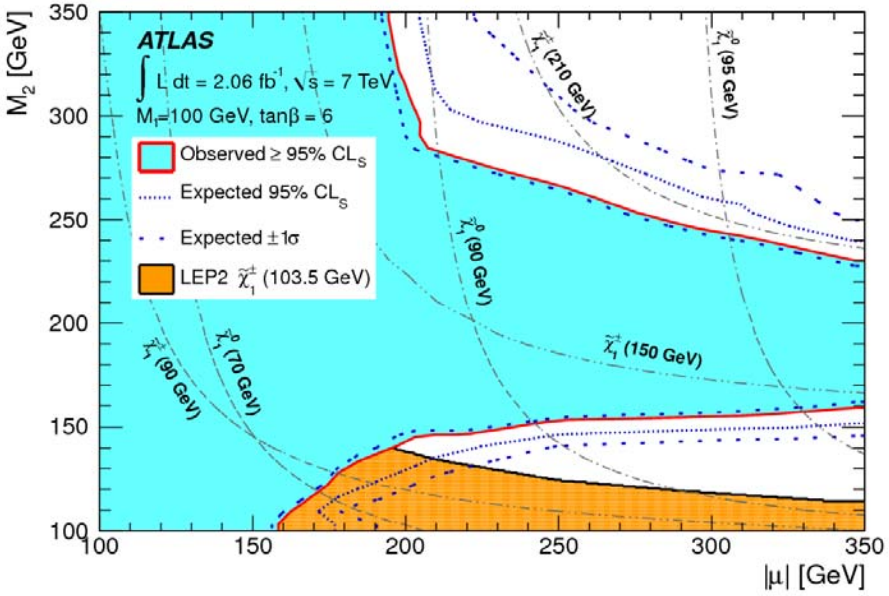
- Results: GMSB

CMS (4.7/fb)

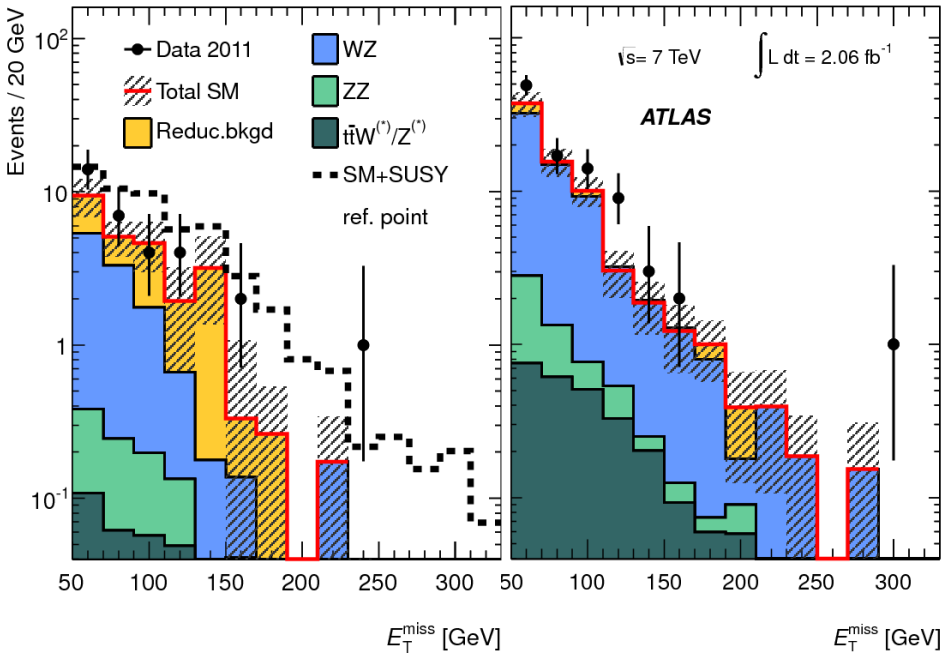


Three leptons with MET : ATLAS

- Three electrons or muons
- MET> 50
- Backgrounds: WZ,ttbar, ttW/Z,
- WW/Z+jets+photons
- Result: pMSSM μ and M2 ~250GeV



Event MET



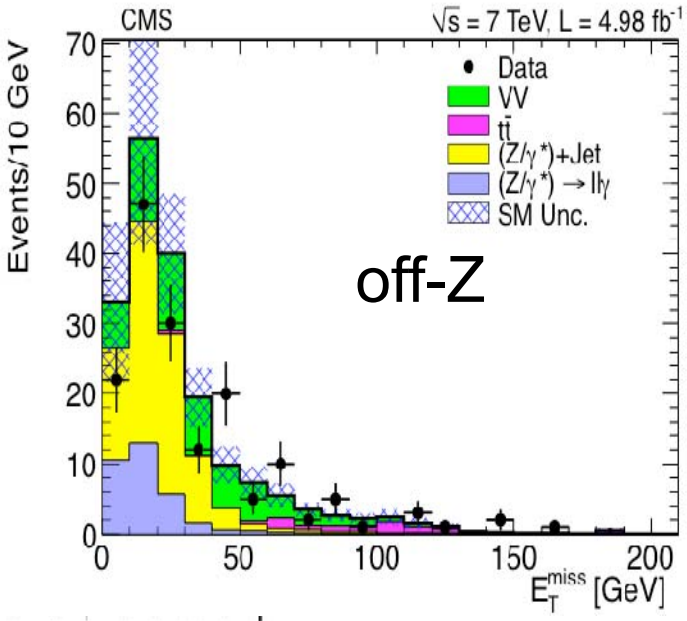
Off-Z (OSSF pair) on-Z

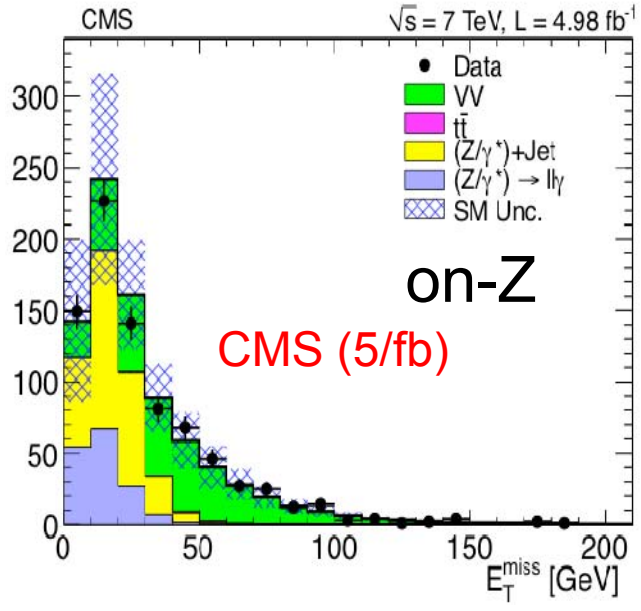
ATLAS (2.05/fb)

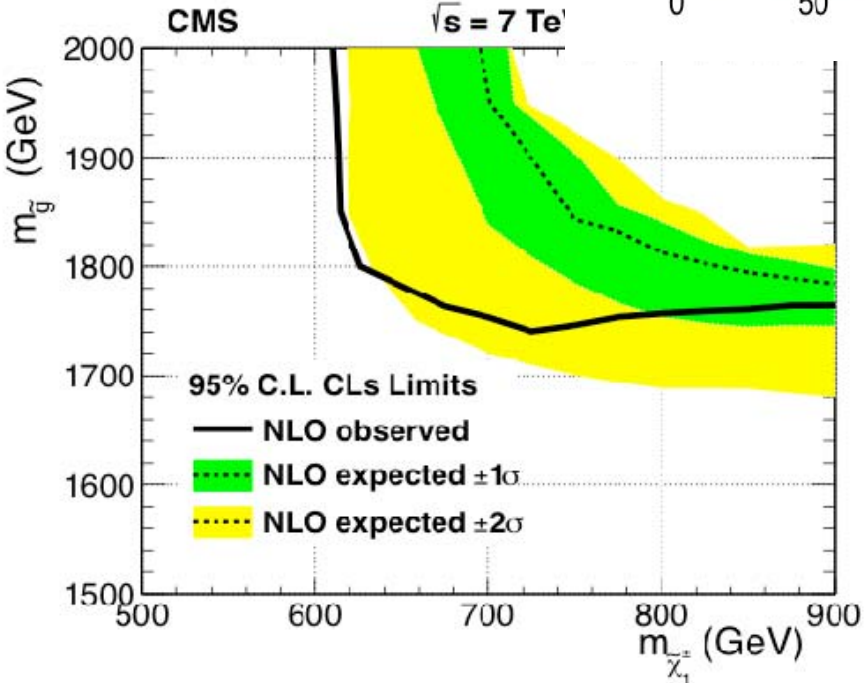
Three leptons in CMS

Part of a wider multilepton search. More later.

Event MET







SLEPTON CONLSP GMSB
Gluino vs Squark Mass

Sleptons share the role of Next to lightest super partner (NLSP) above the gravitino. This results in a multilepton signal. Strong production dominates

SUSY Searches: Where do we stand?

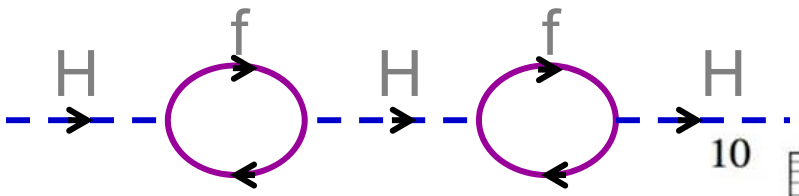
OK, the LHC beampipe didn't melt due to strongly produced SUSY.

Expectations: Search for Strong Production of Supersymmetry Using Precision Thermometry of the LHC Beam Pipe.

It is not the end of the world.

Plenty other possibilities and ongoing searches.

3rd generation

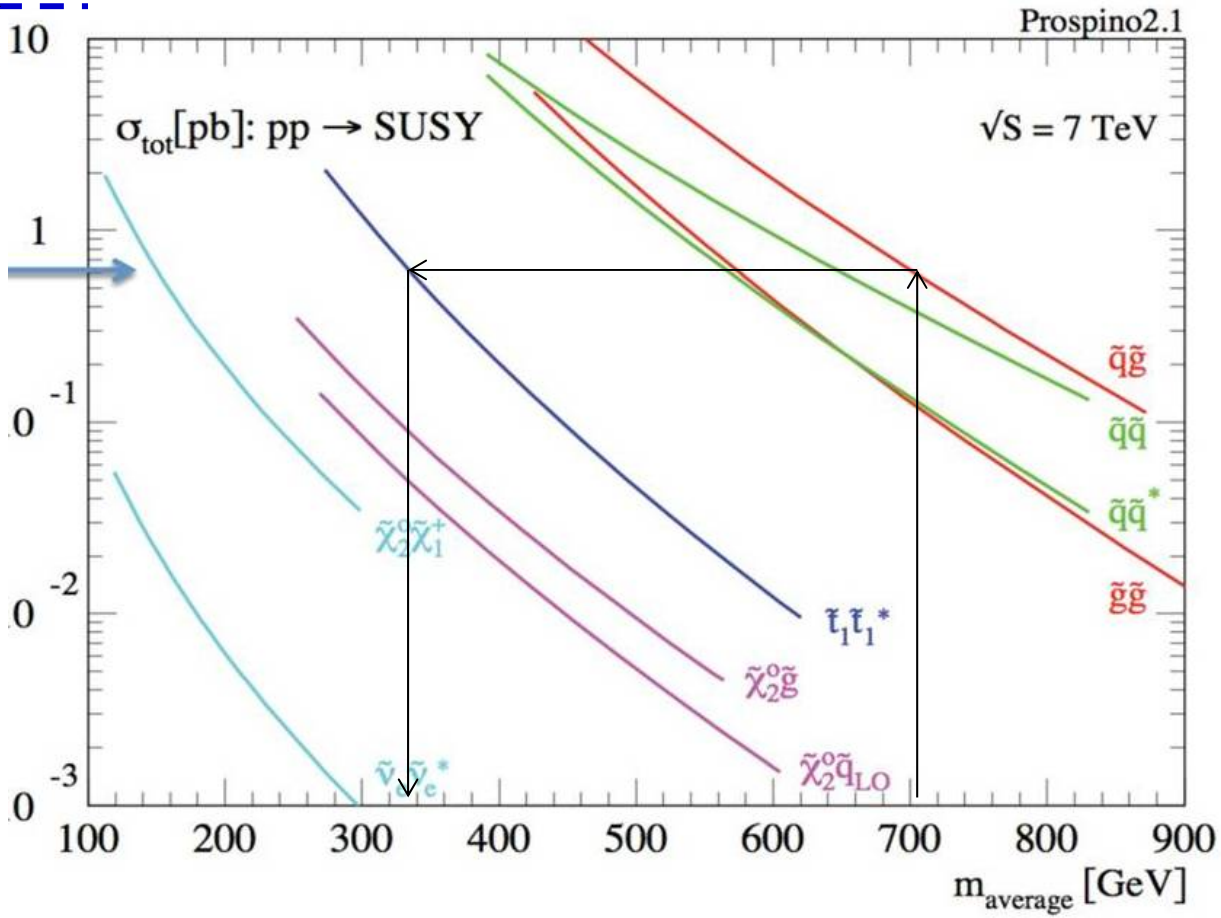


Hierarchy:

Cancelling top loop

→ m_{top} ~m_{stop}

→ Relatively light 3rd generation

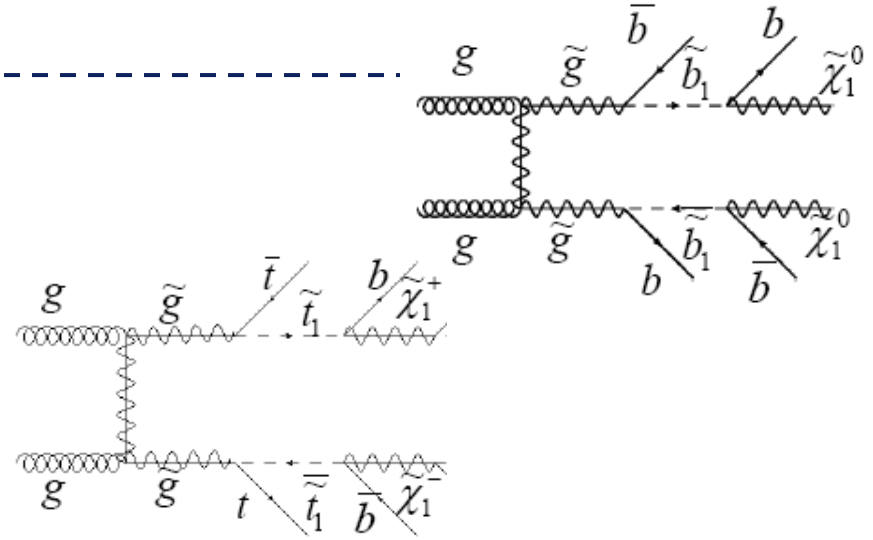


170 GeV is "light"?? Youth these days…

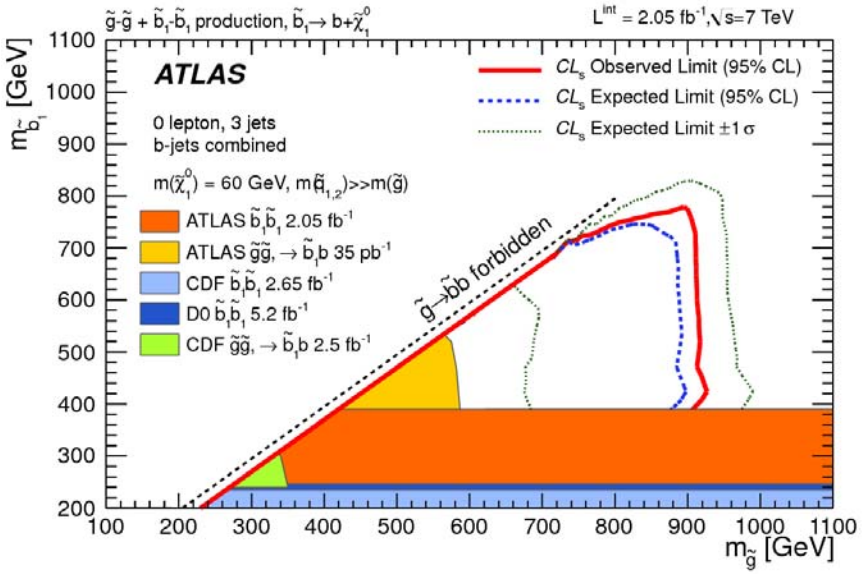
MET and b-jet (gluino mediated 3rd gen)

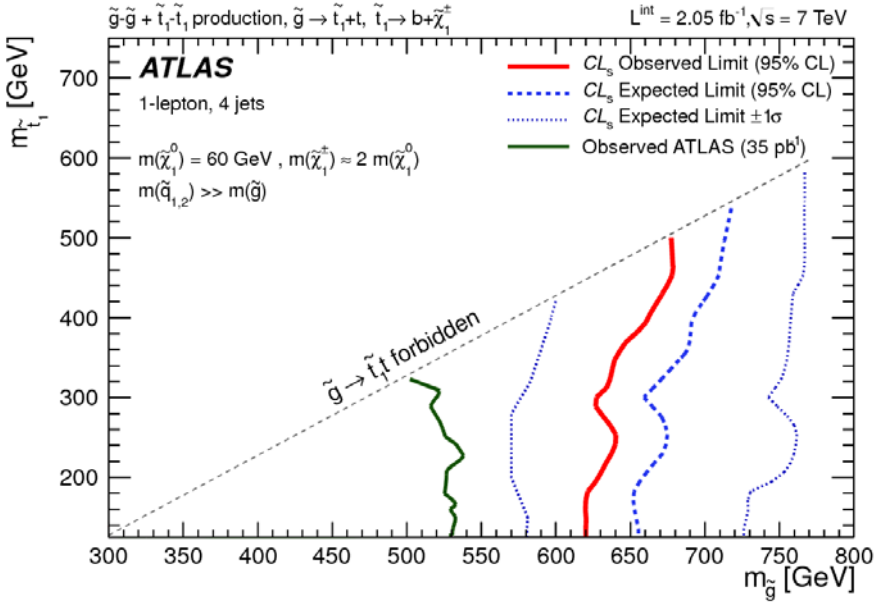
ATLAS (2.05/fb)

- Up to one lepton allowed
- 1st jet pt>130GeV, two more jets, at least one b-jet, MET>130GeV, ST at least 500-900GeV
- 1-lepton channels: four jets, MET>100/200GeV, mT > 100 GeV, ST > 700 GeV
- Backgrounds: top+X, W/Z+jets, multijet/diboson



Result: gluino cascades to 3rd generation



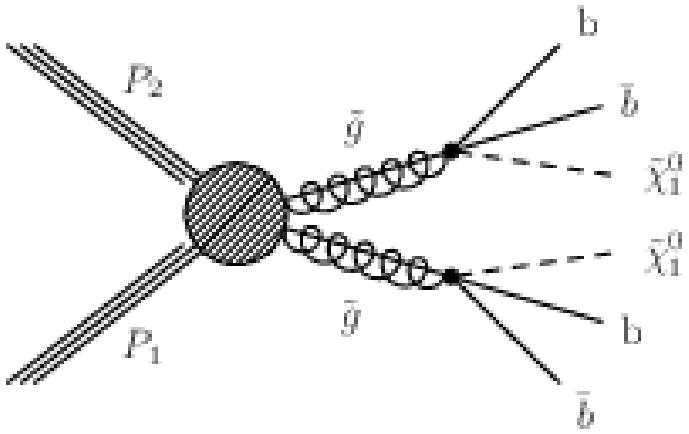


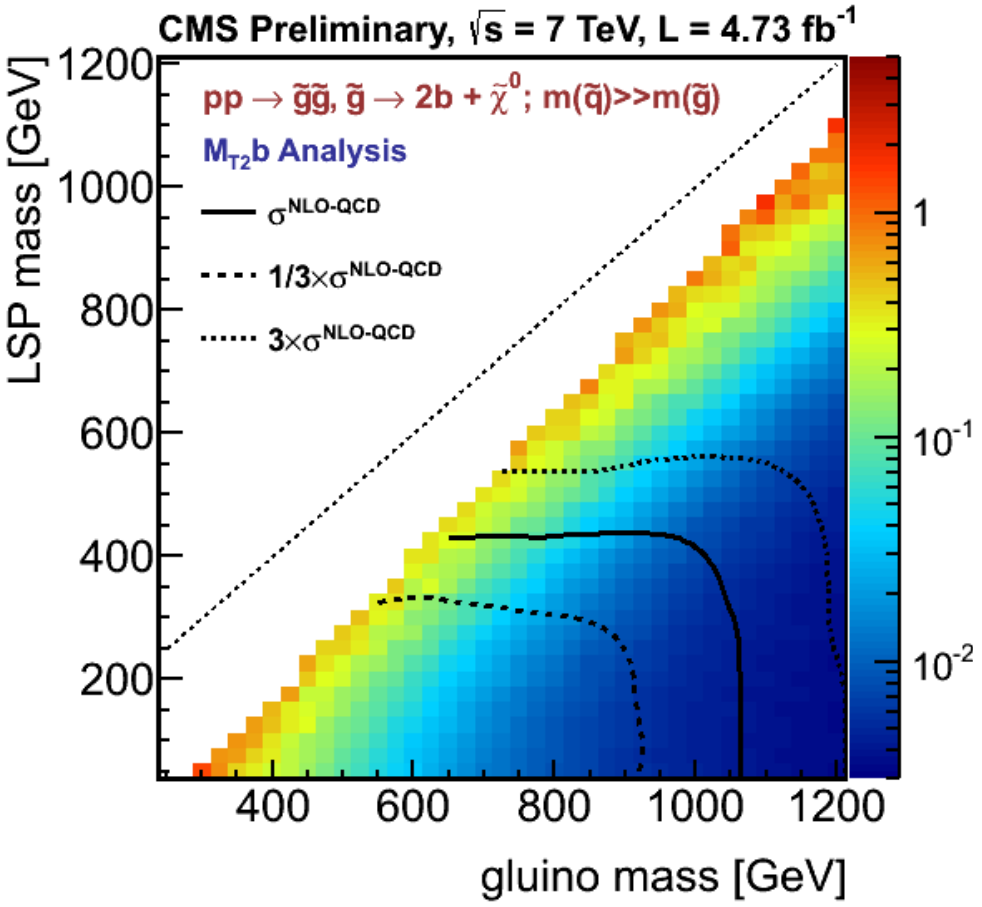
“MT2” with b-jets

CMS (5/fb)

- Hadronic MT2 analysis with b-jets
- MT2> 125GeV. At least 4 jets, one b-jet
- Lead jet > 150 GeV, HT > 750 (950) GeV
- Backgrounds: ttbar

Result: Simple Model of Gluino to bbX pairs

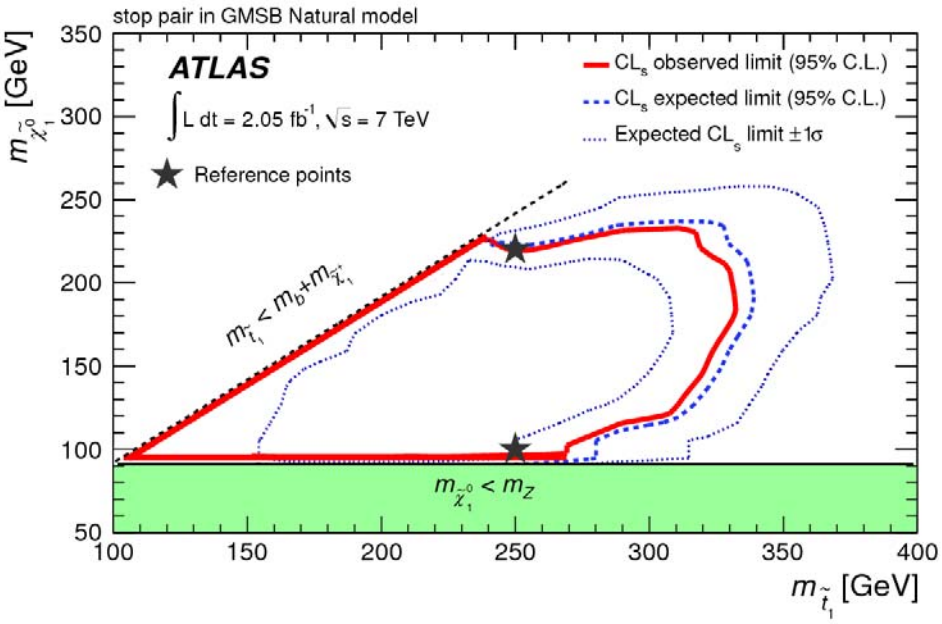


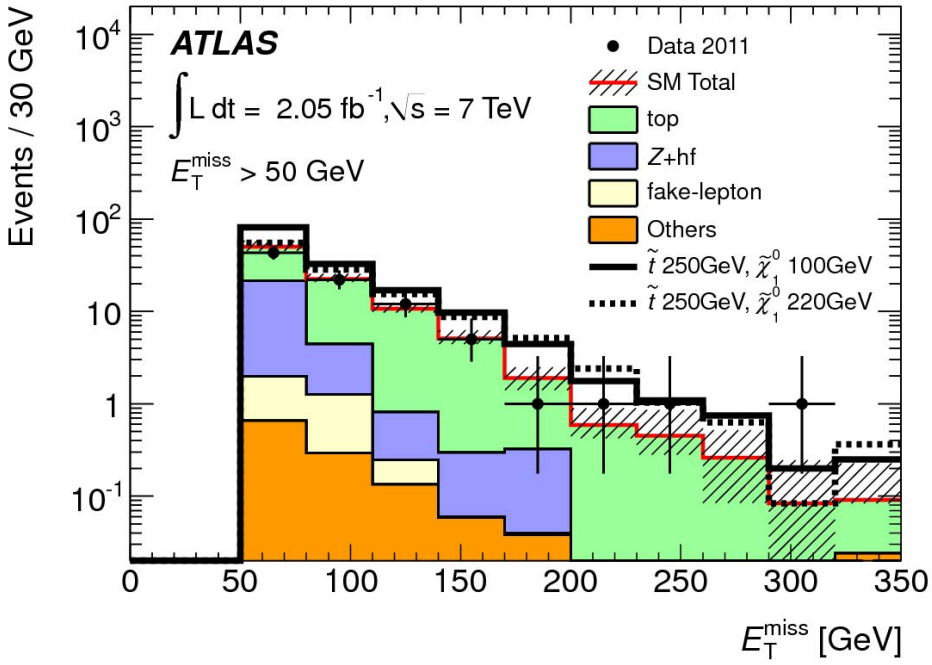


Scalar Top Pair Production in Z + MET + (b) jets

- OSSF electron or muon pair on Z
- MET> 50 or MET>80
- At least two jets, at least one b-jet
- Backgrounds: ttbar, single top, Z+heavy-flavor

- Result: GMSB with neutralino NLSP. (Hence the Z)
  Reaching ~330 GeV exclusion



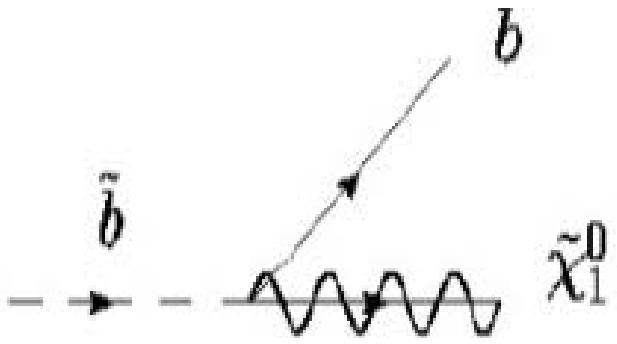


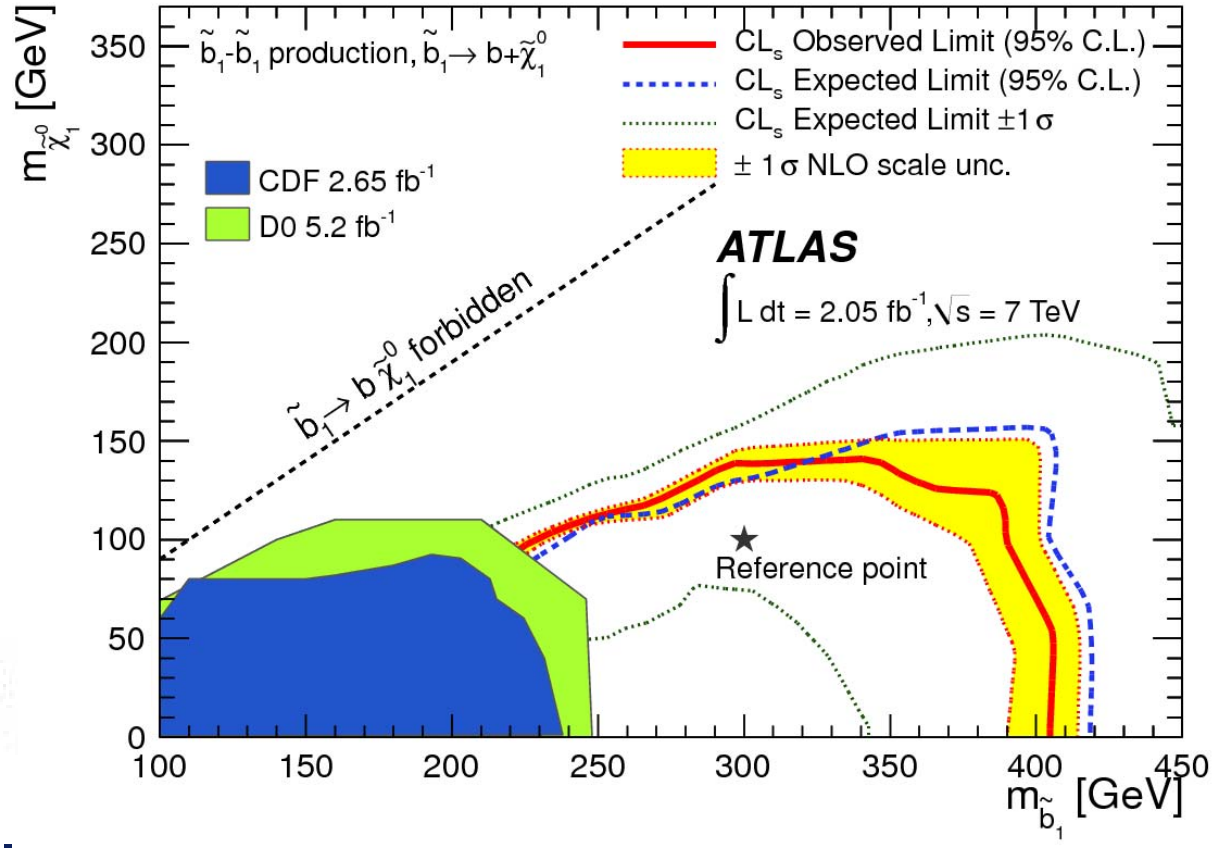
ATLAS (2.05/fb)

MET and 2 b-jets (direct sbottom)

- Up to one lepton allowed
- 1st b-jet pt>130GeV, 2nd >50GeV, MET>130GeV,
- 2-body transverse mass > 100,150,200 GeV
- Backgrounds: top+X

ATLAS (2.05/fb)



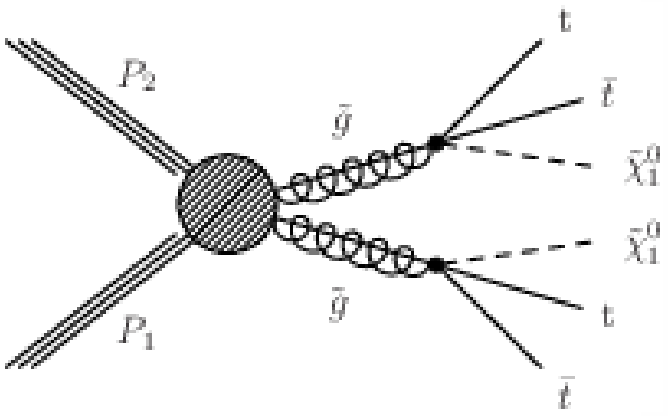


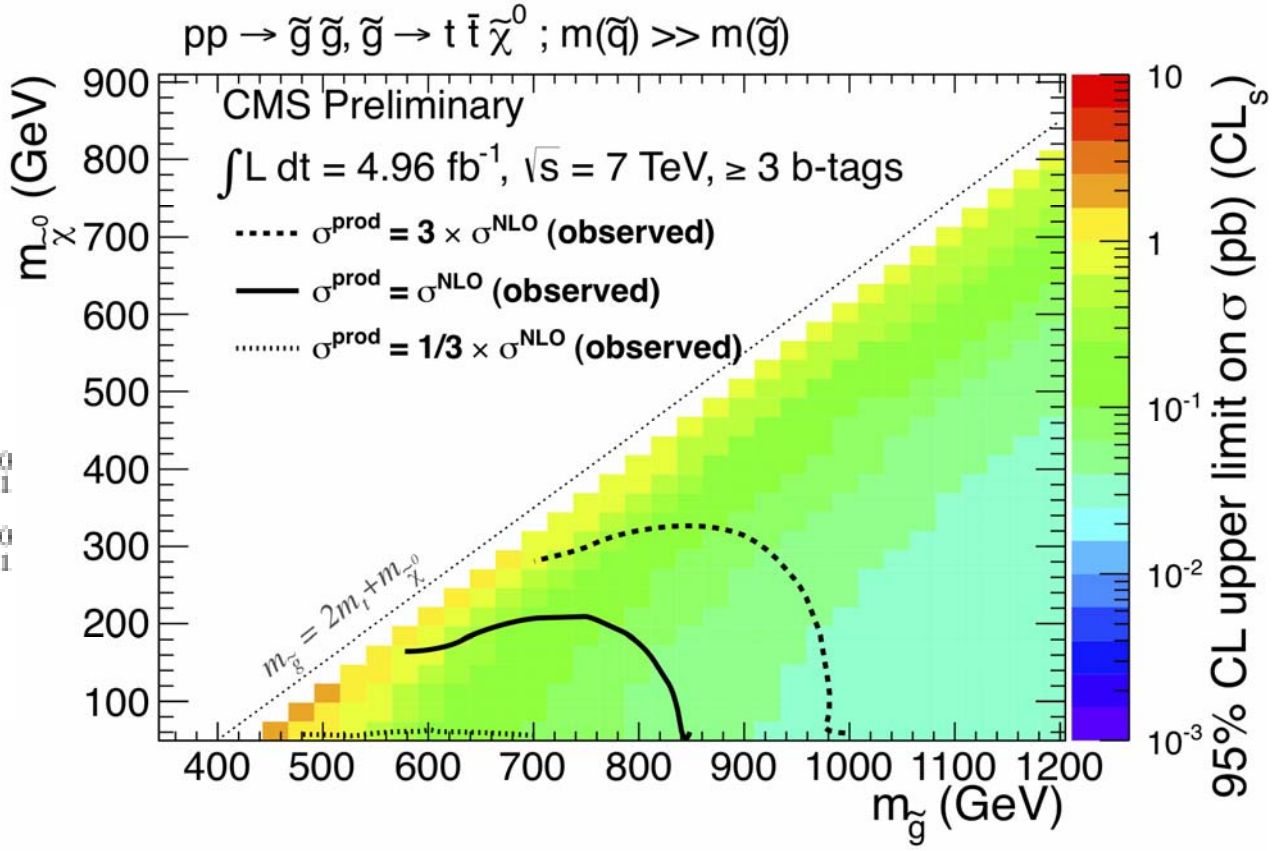
Single Lepton, b-jet and MET/HT

- Lepton + at least 4 jets, MET> 60GeV and HT > 375GeV
- Regions with various # of b-tags. Background: top

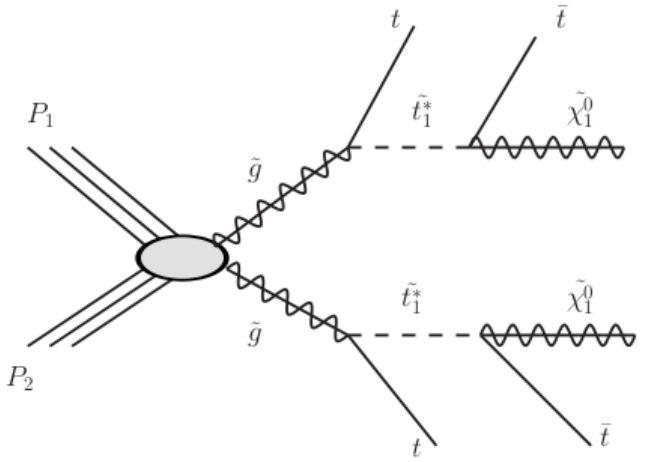
Results: Simple Model gluino pair decays to two ttbar pairs.

CMS (5/fb)





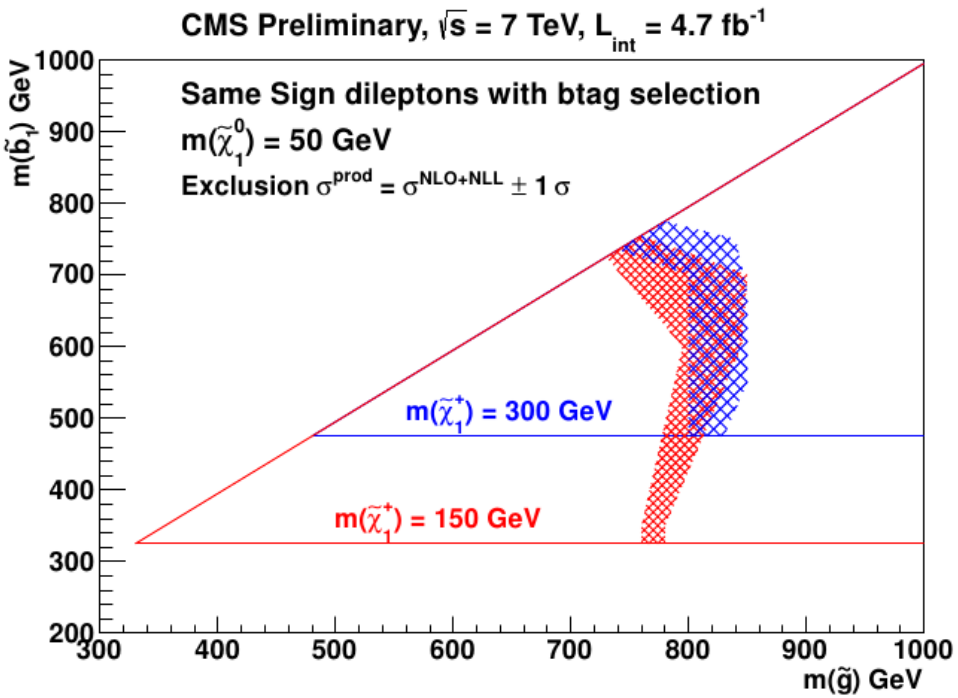
Same-sign Leptons and b-jet

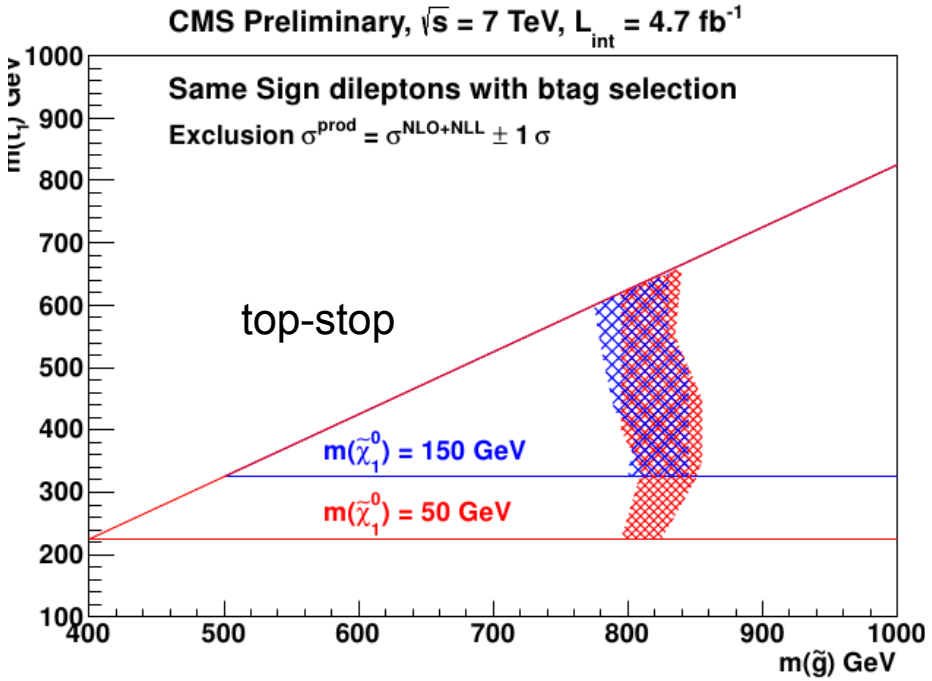


CMS (5/fb)

- SS leptons with at least two b-jets, pt>40GeV
- Various MET-HT's. (0-120, 80-320) GeV
- Backgrnd: ttX, "fake" leptons, electron charge flip

Results: gluino to top-stop OR bottom-sbottom





Another Escape Valve: R-Parity Violation

- Squarks and gluinos getting heavier in simple scenarios

  BUT

- R-Parity Violation can pull the rug from under searches requiring MET because the Lightest Supersymmetric Particle (LSP) decays.

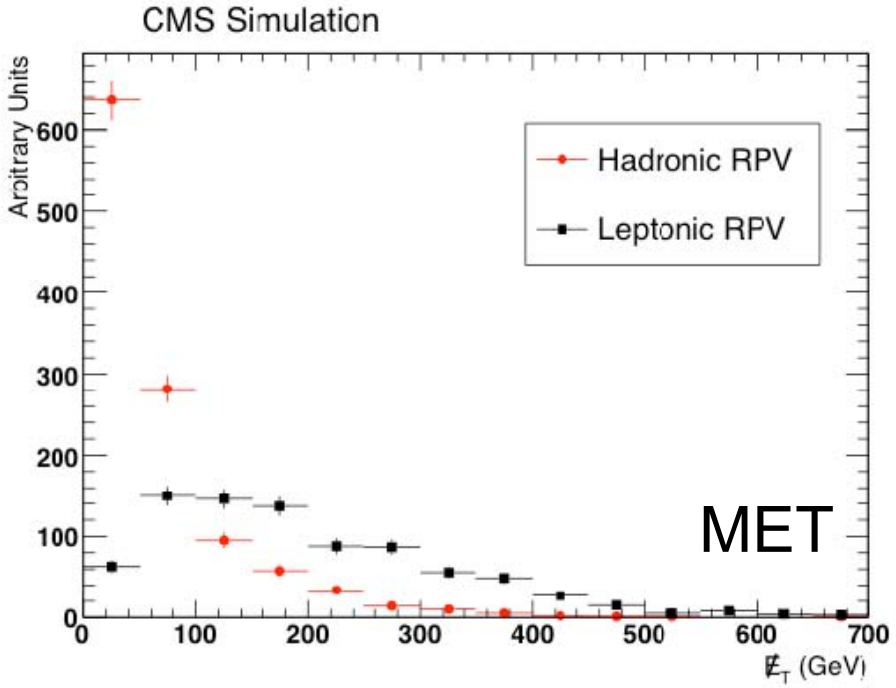
Also, possibly finite lifetimes depending on RPV couplings.

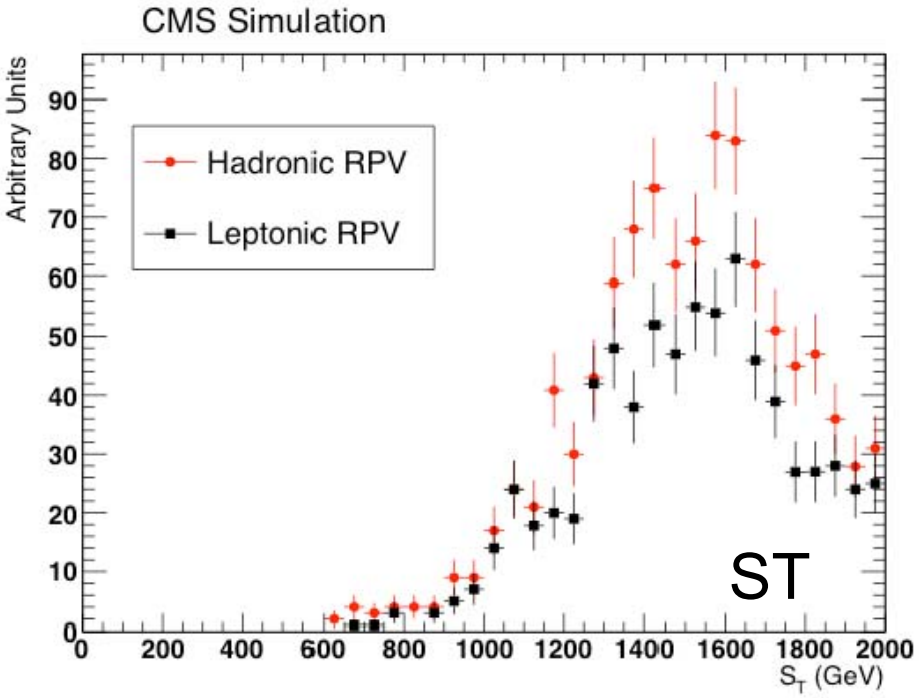
RPV can be tricky

- A CMS multilepton study.
- Two RPV signals:
  no MET in hadronic RPV

- Examine ST instead
  (ST = sum of jet+lepton
  pt's and MET)
  (Also, "effective mass")

- ST recovers the low-MET
  signal



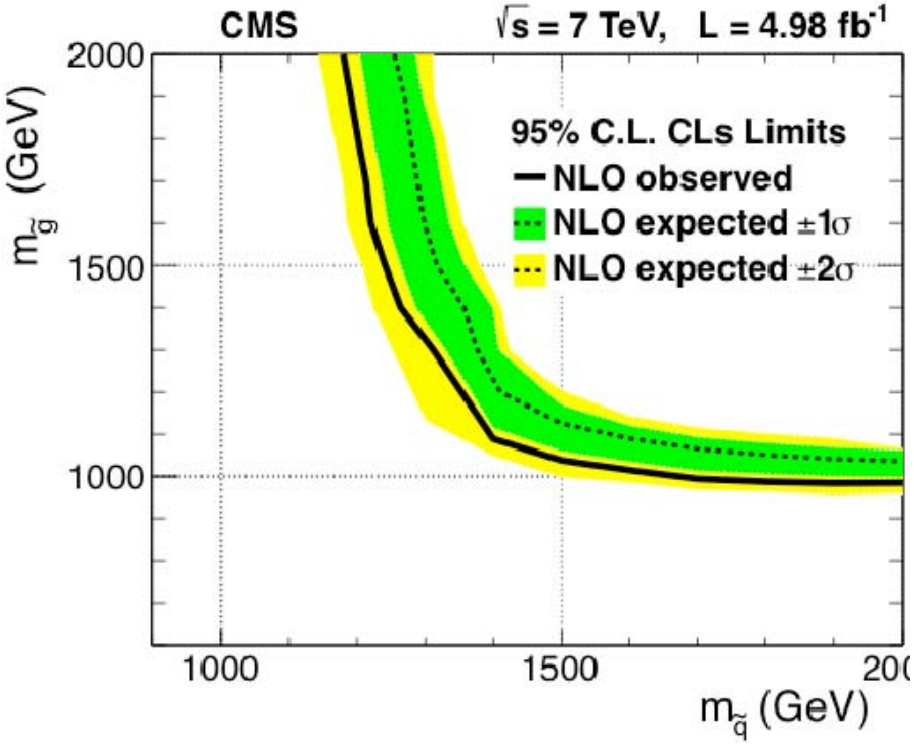


GMSB topologies by Scott Thomas

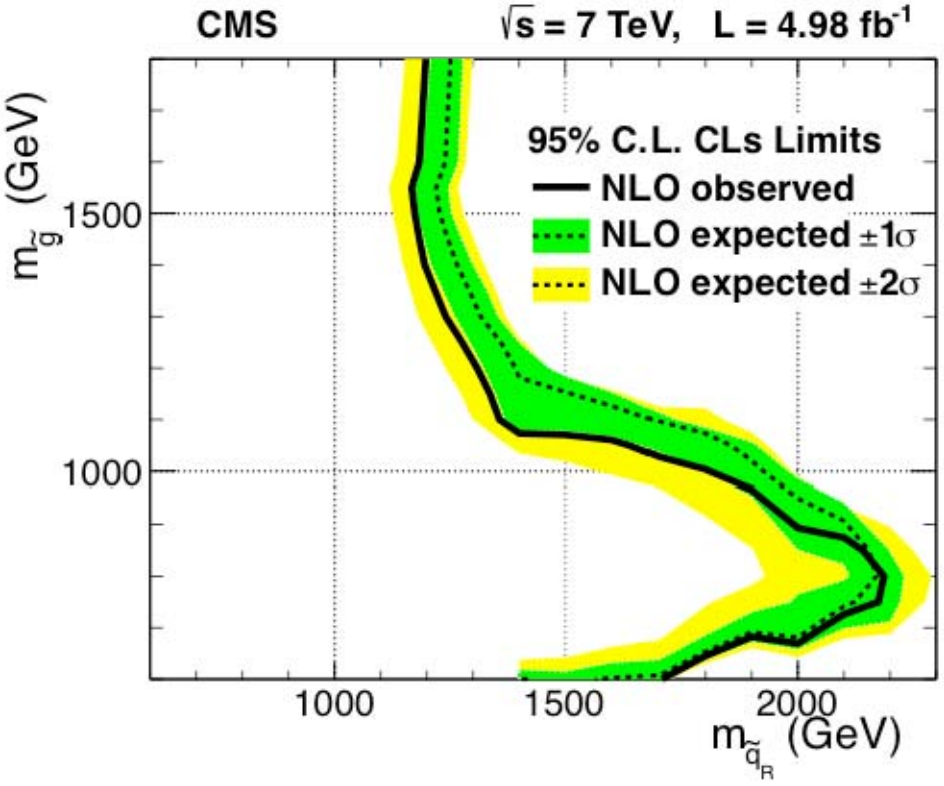
Leptonic and Hadronic RPV in Multileptons

CMS (5/fb)

Gluino vs Squark masses in GMSB RPV
(obtained using ST distribution)



$\lambda_{e\mu\tau}$ L-RPV



λ_{uds} H-RPV

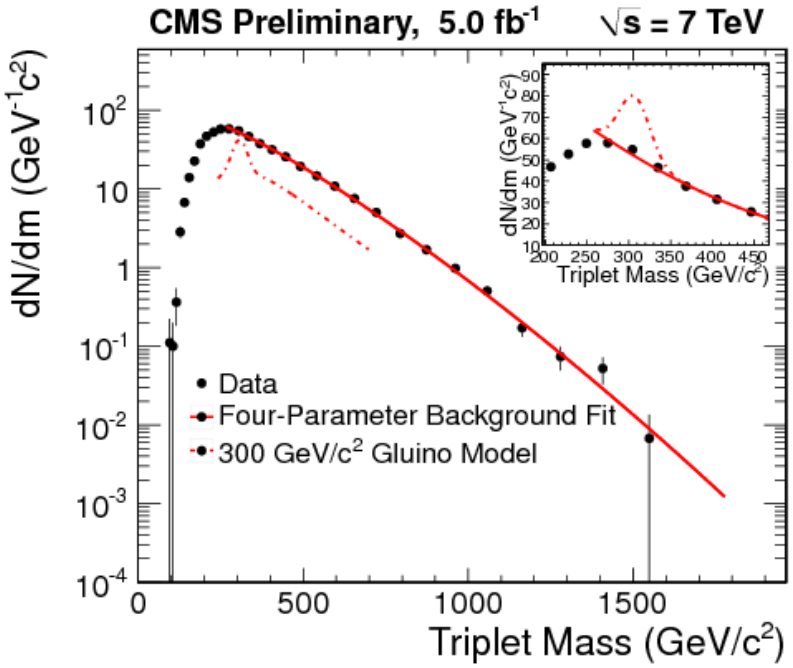
Gluino (etc) RPV Decay to 3 jets (Resonance).

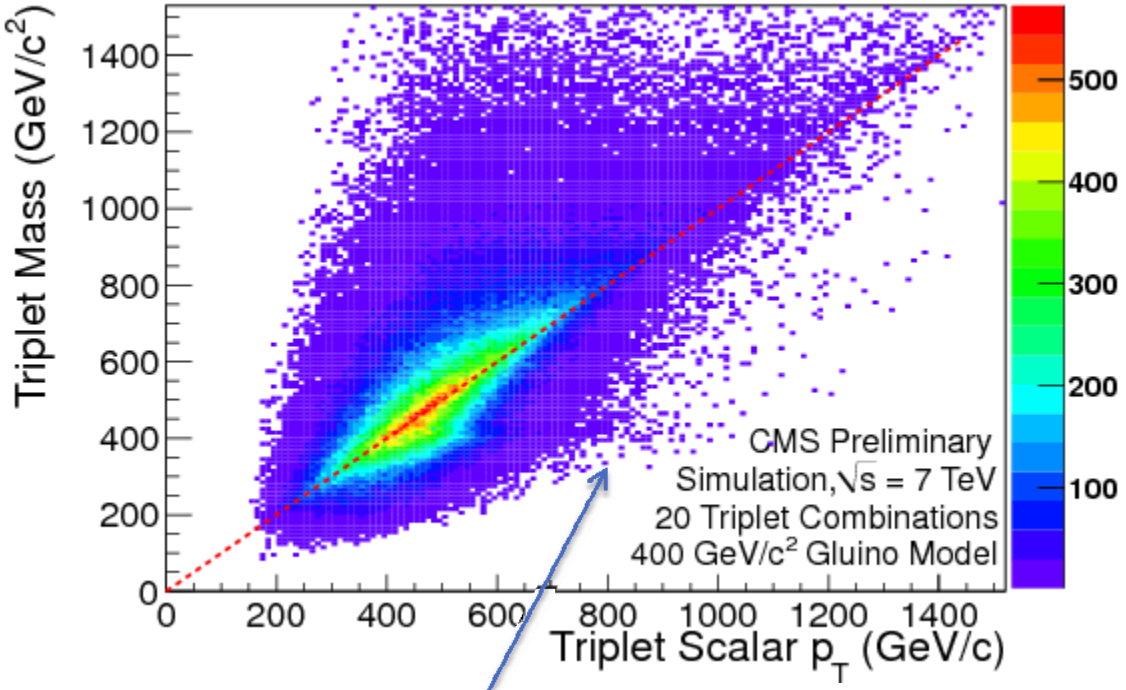
CMS (5/fb)

- No leptons
  → plenty of strong signal (and bkgnd)
- Many jets, look for triplet jet resonances.

$$(\tilde{q})(\tilde{q}) \rightarrow (jjj)(jjj)$$

Signal

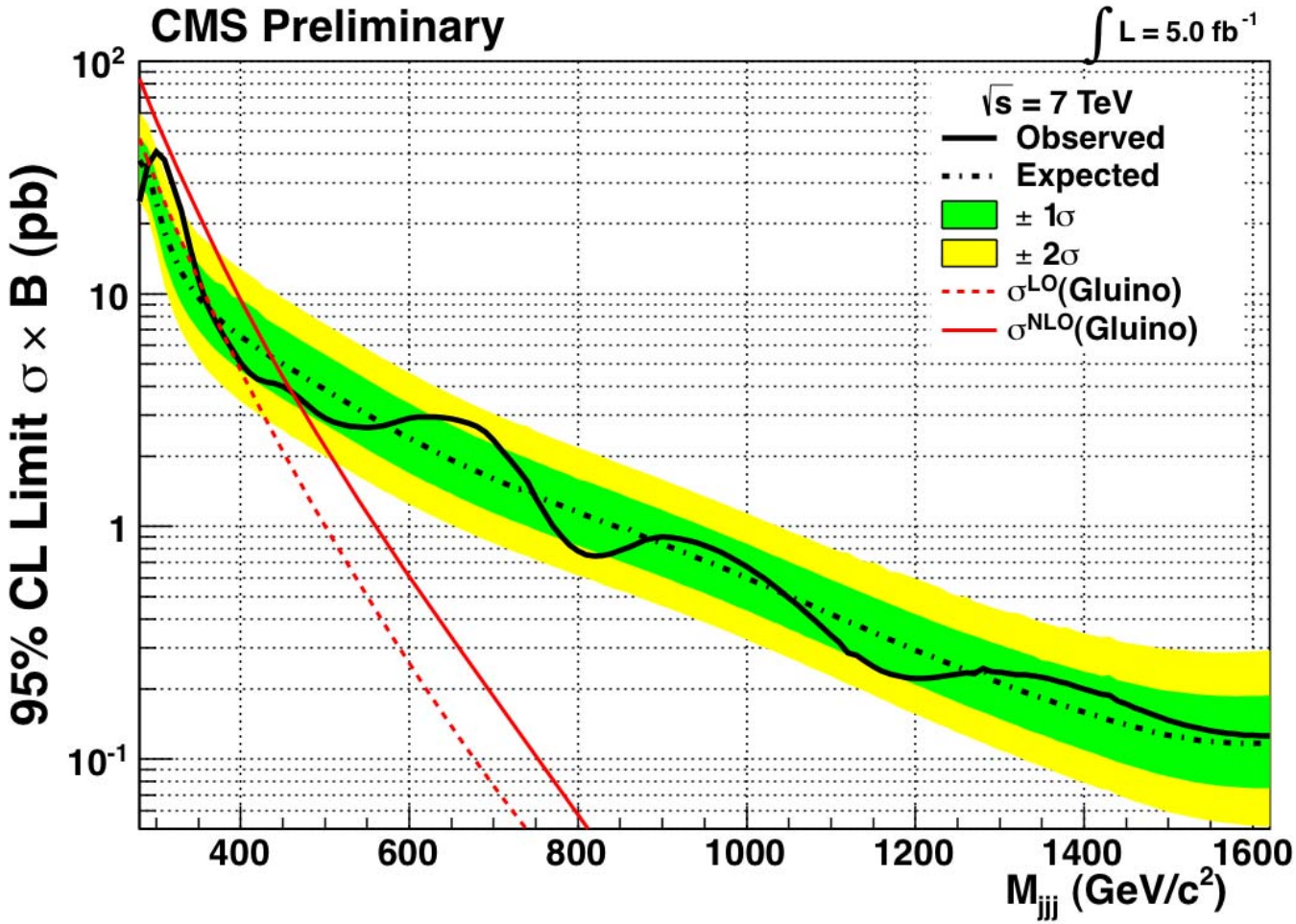




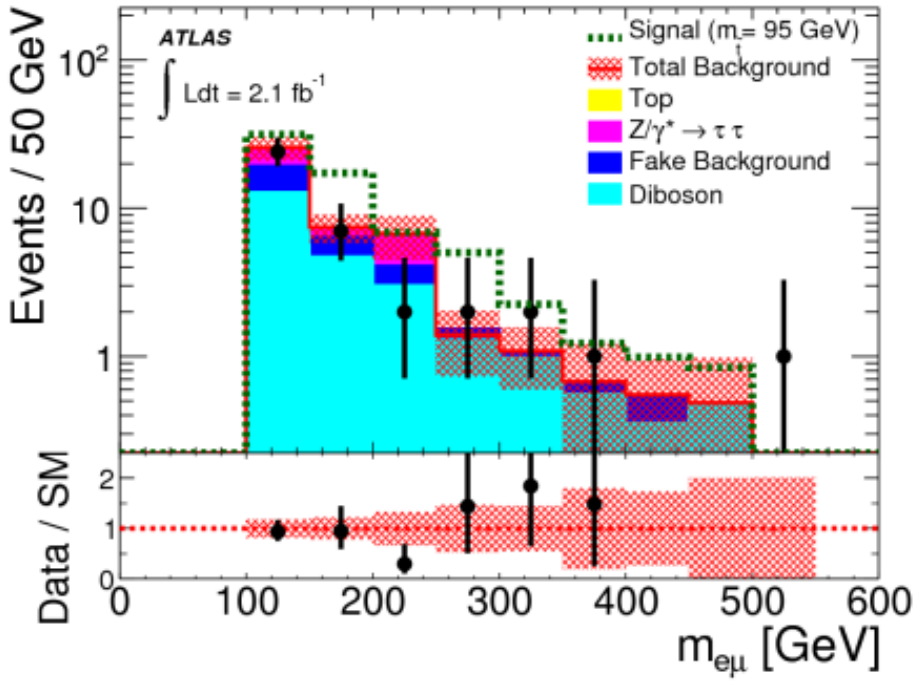
Note

Gluino RPV Decay to 3-jet Resonance, Contd.

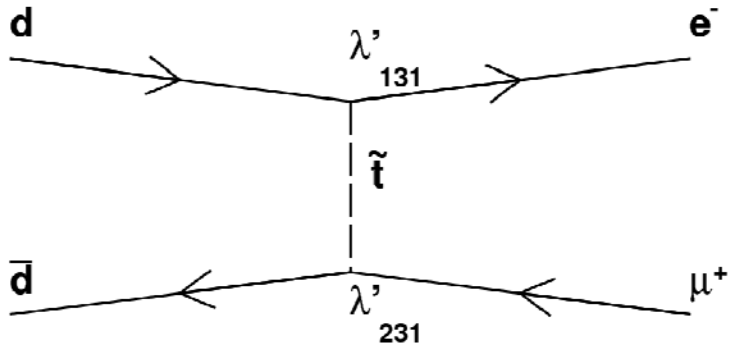
CMS (5/fb)

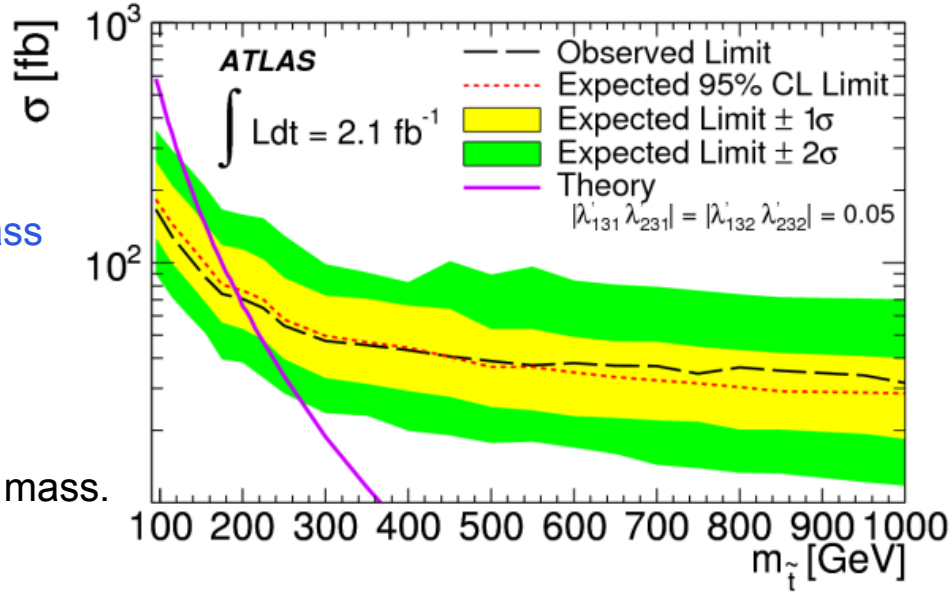


3rd Gen, RPV & Lepton-Flavor Violating (LFV) Scalar Top



ATLAS (2.1/fb)





- > 25 GeV electron-muon pairs with invariant mass >100GeV
- No jets and MET ***less than*** 25 GeV
- Backgrounds: WW, Z → ττ , fakes

- Result: cross section as a function of scalar top mass.

Electroweak Production

- Squarks and gluinos getting heavier in simple scenarios
- What if weak production beats strong production?

→Electroweak production to the rescue?

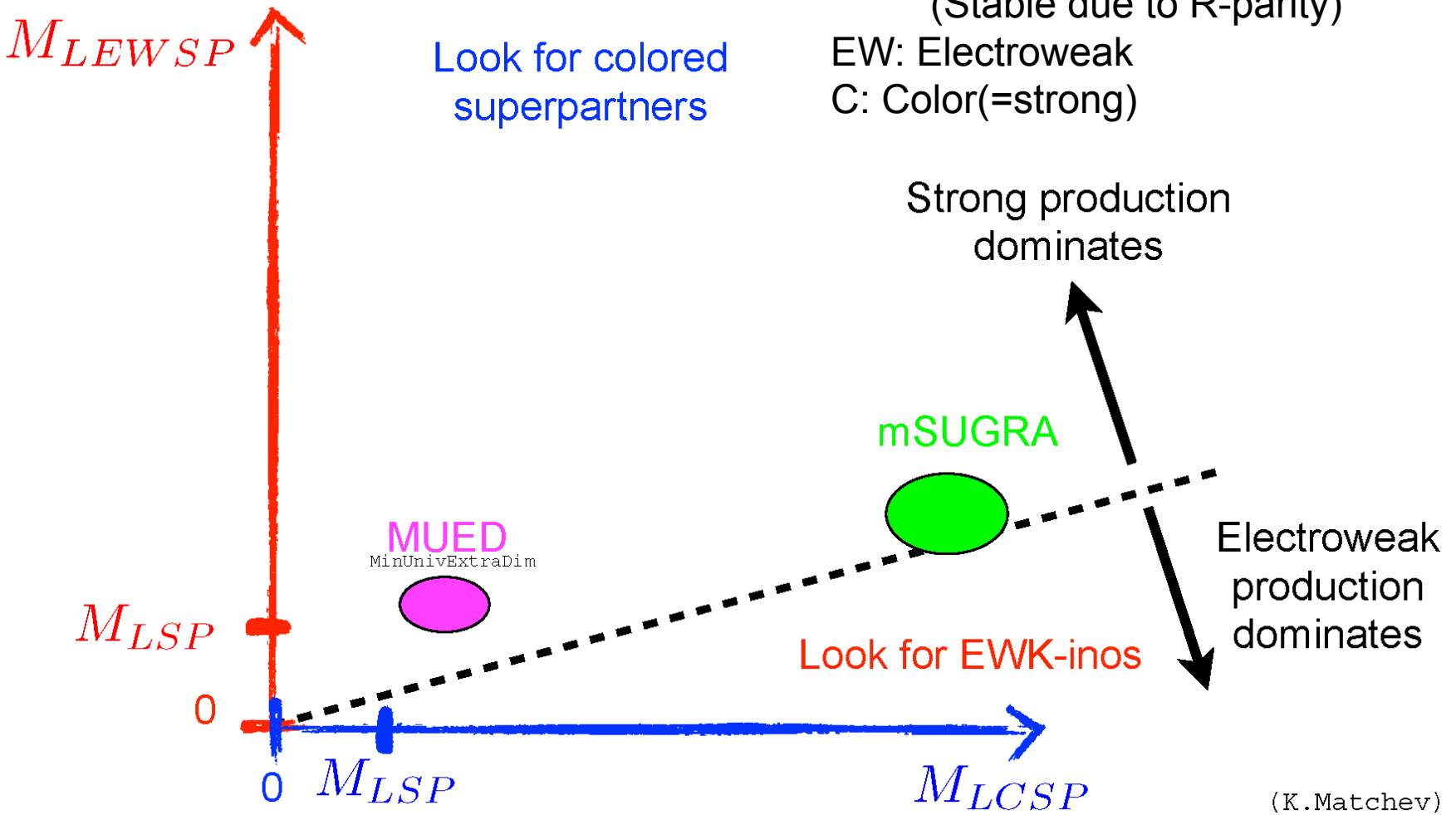
Less copious, so lesser reach in mass. (smass?)

Less hadronic activity (!)

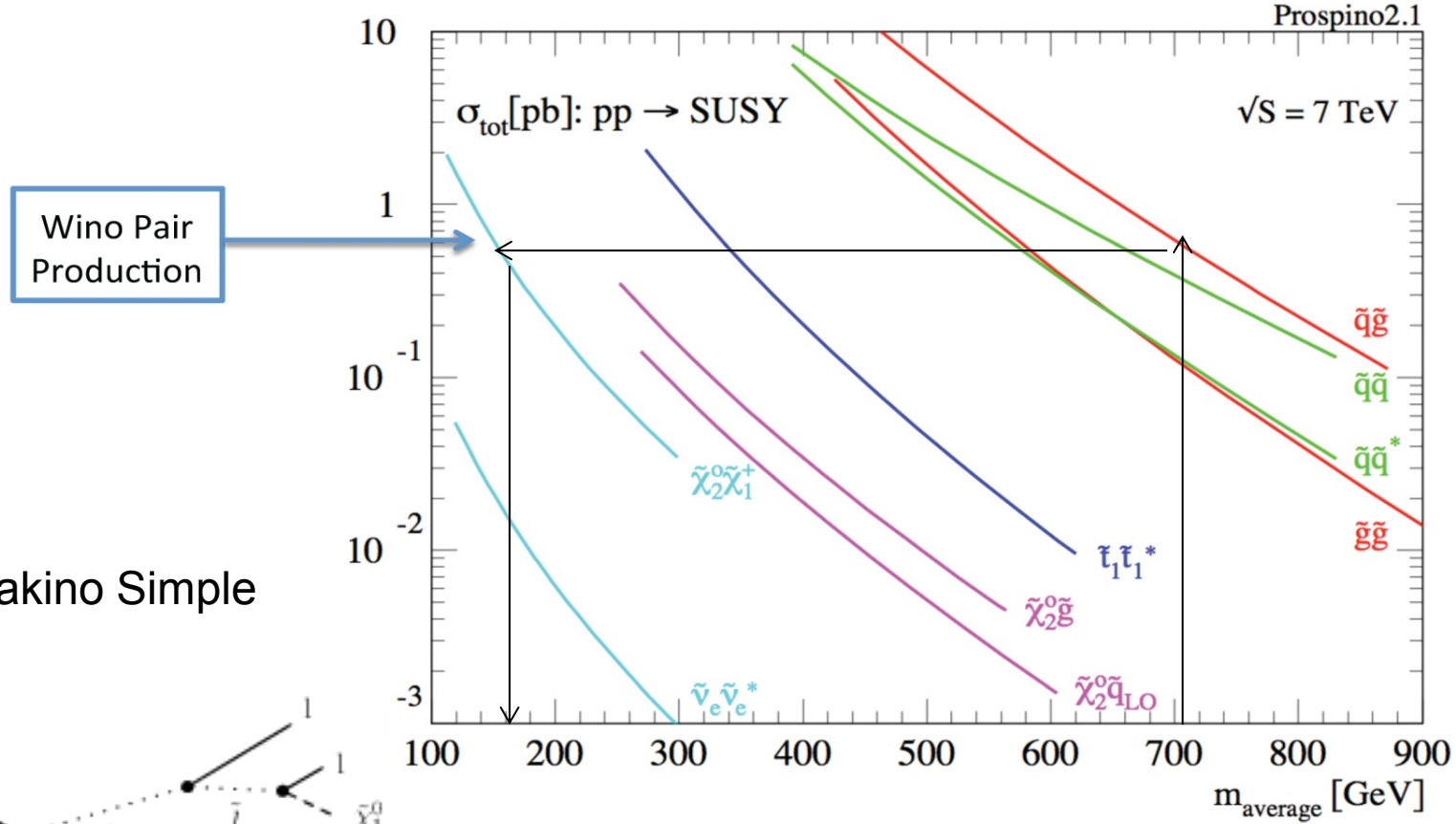
(cf: classic trilepton SUSYsignature from Tevatron Run II).

Electroweak Production

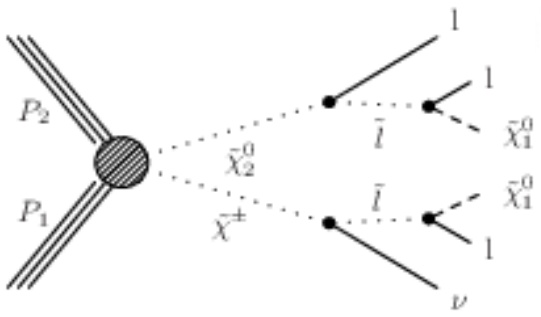
LSP: Lightest Supersymmetric Particle
(Stable due to R-parity)
EW: Electroweak
C: Color(=strong)



Strong vs Weak Super-Partner Production



Electroweakino Simple topology



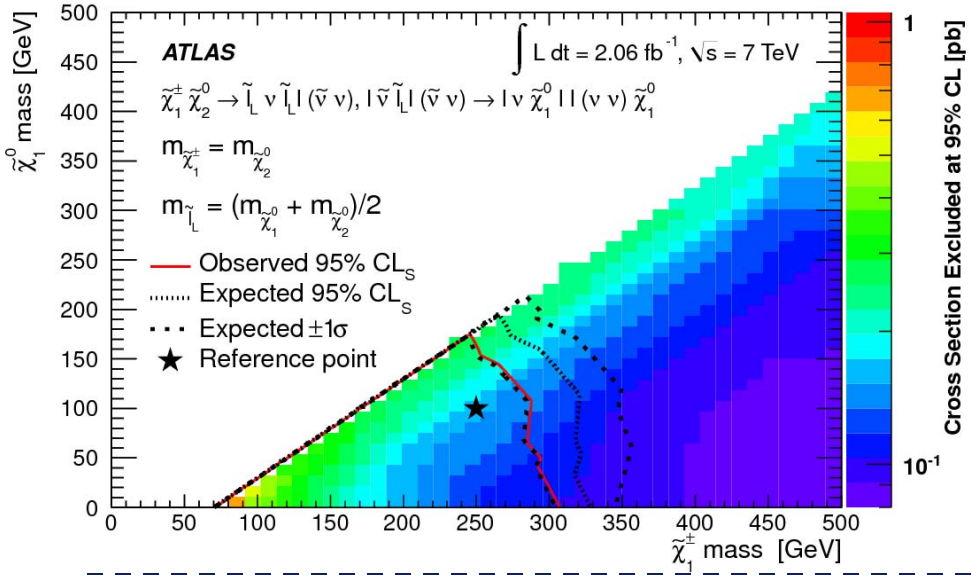
Search: Require *less* hadronic activity (CDF trileptons, ~2008)

Three leptons with MET

- ATLAS (shown before)Three electrons or muons, MET> 50

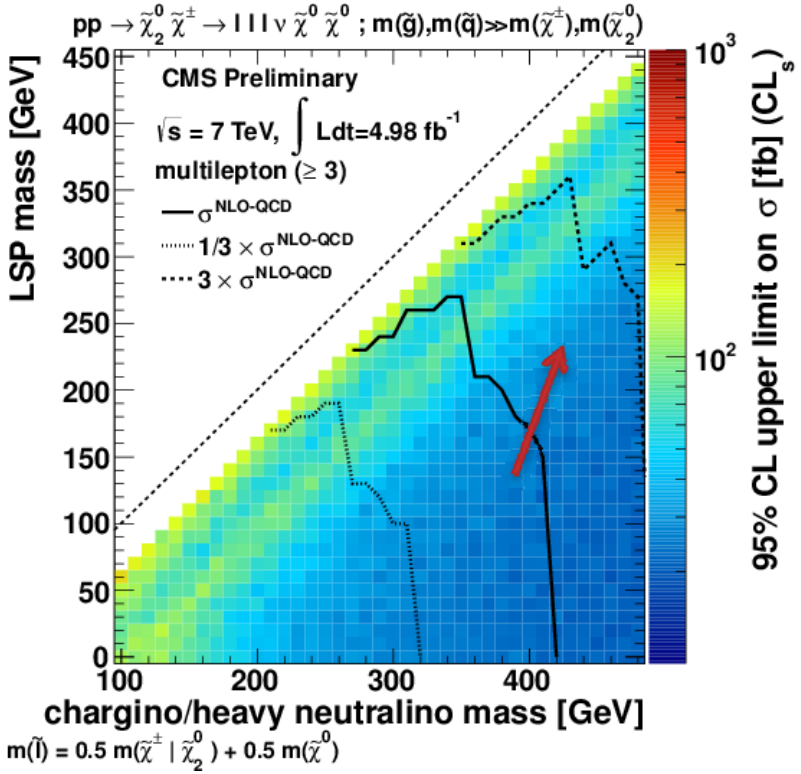
- Result: Simplified model ~300GeV Chargino

ATLAS (2.05/fb)



CMS (5/fb)

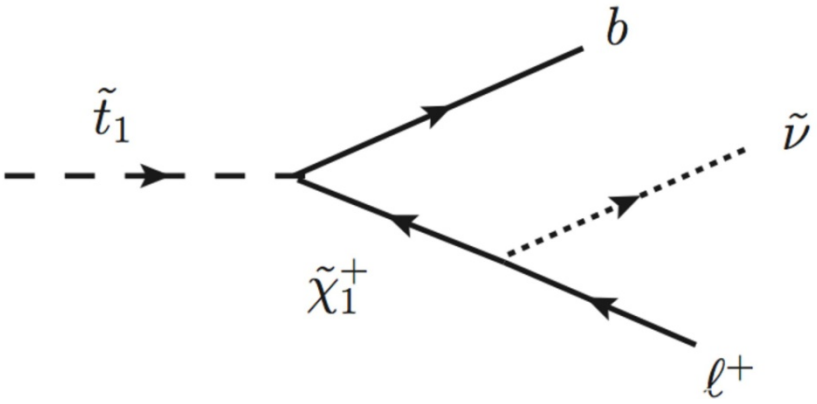
Cut-and-count multileptons



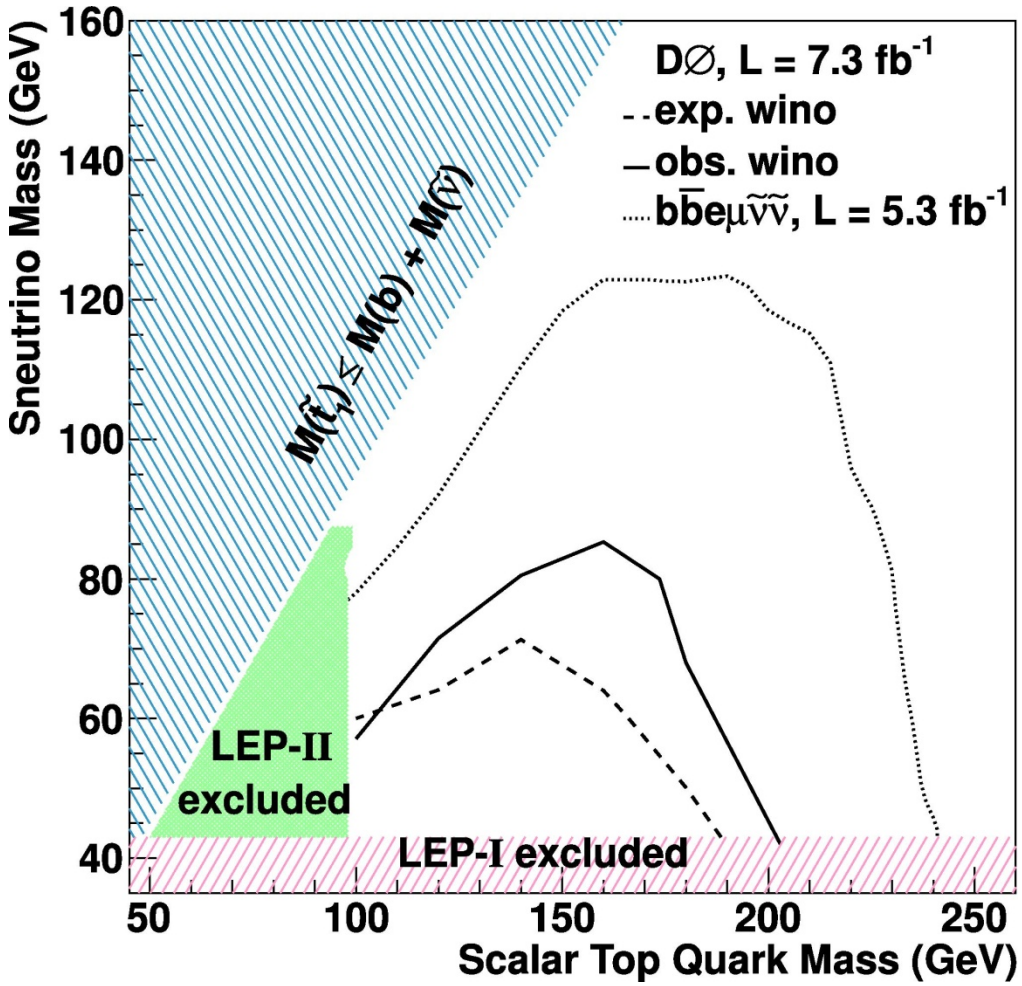
Tan(β) not small: The tau penalty

- Squarks and gluinos getting heavier in simple scenarios
- High tan(β) : Tau reconstruction is difficult.

3rd Generation and Tau's: D0 search

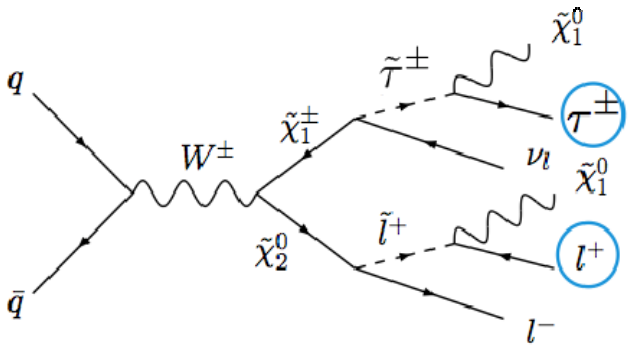


D0 (7.3/fb)



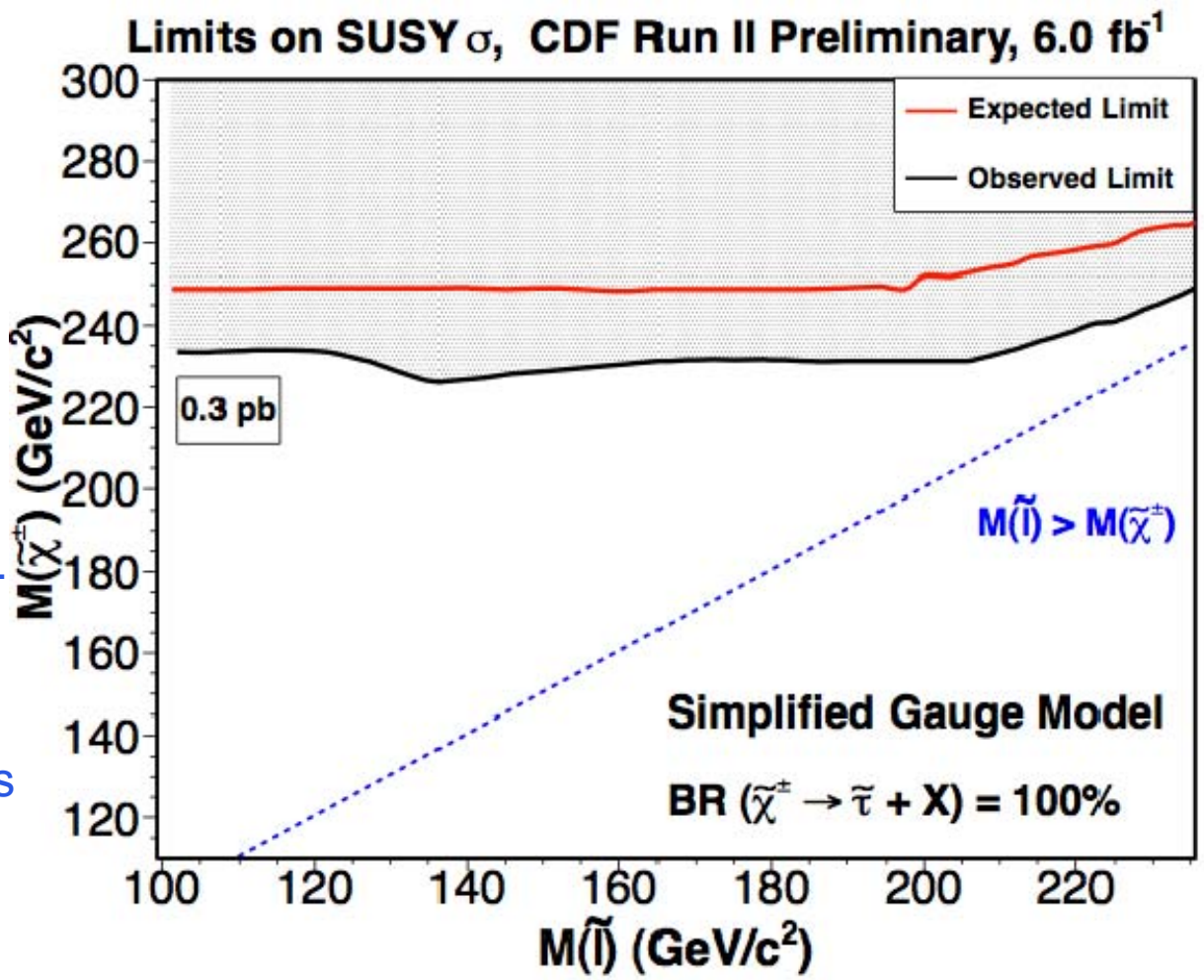
- Higgsino like chargino
  → enhanced tau coupling.
- 2 b-jets, muon and a tau
- MET
- Backgrnd: Z → ττ and W+jets

Tau's: CDF Same-Sign Dilepton Search



- High tan(beta)
  → enhanced tau coupling.
- Require one (hadronic) tau
- MET > 20 GeV
- Backgrnd: Jets faking tau's

CDF (6/fb)



CMS Multileptons: Example of a Broad Search

Three or more electrons, muons or taus. Up to two tau's reconstructed.

54-channel ST table and 52 channel MET/HT results on and off Z

Signal (low-bkgnd) and control (high bkgnd) channels treated uniformly.

CMS multileptons in this talk:

a) Strong production GMSB slepton co-NLSP

b) R-parity Violation (Leptonic)

c) Sensitive to accidents of spectrum (strong production captured by lepton sector)

d) Missing MET: e.g. RPV (Hadronic): S_T comes handy

e) Electroweak Production: cut-and-count (shown), [fitting MET/MT in progress]

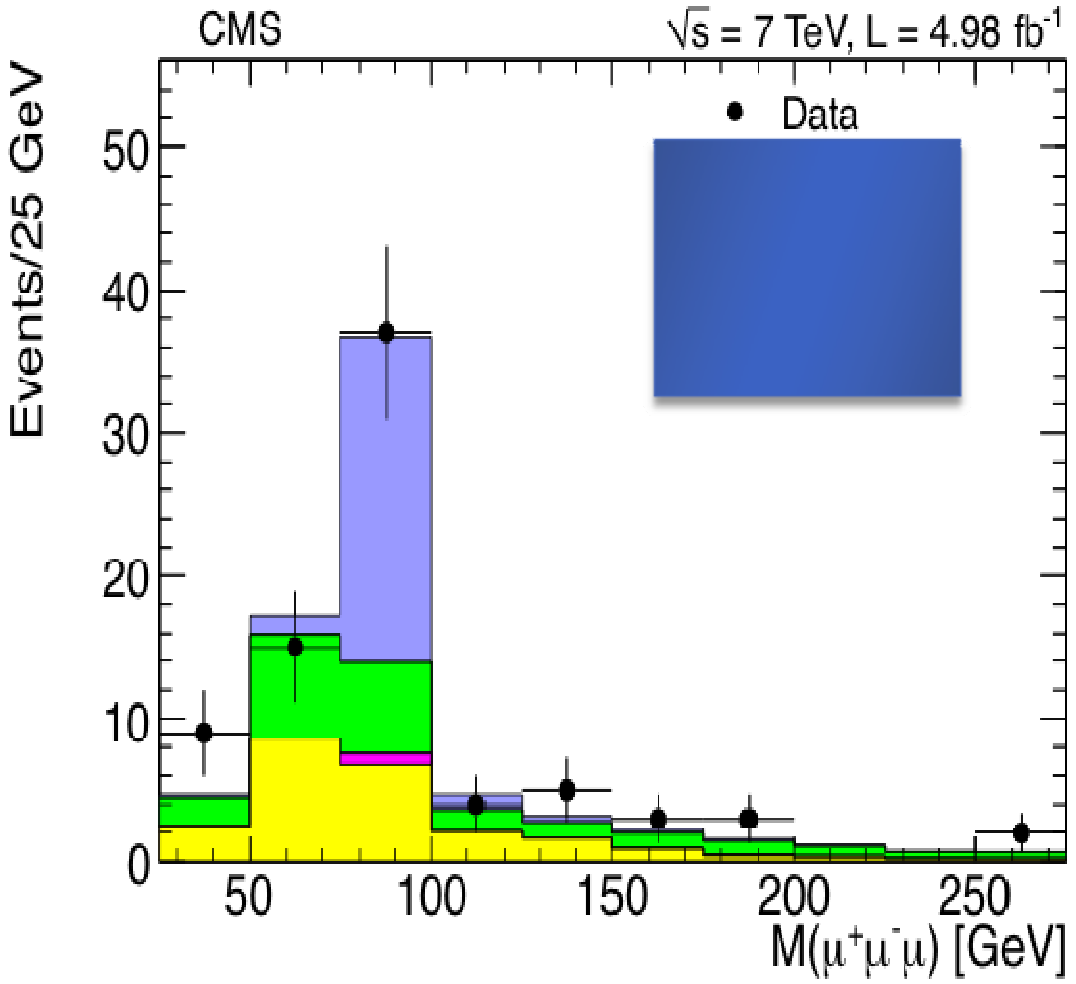
SURPRISES (detailed background studies)

- CMS pristine di-Z event ~5/pb (2010)
- Very rare four lepton event(s) in 2011, still outstanding.
- Next: Trimuon Z (!!!???) and impact on Higgs

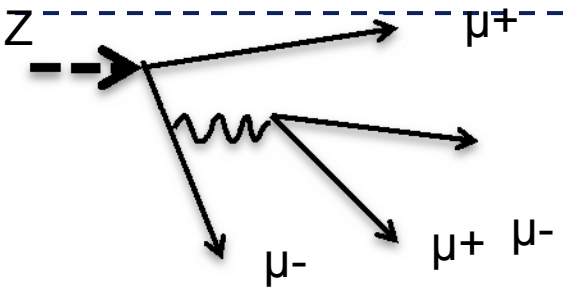
Example of a surprise

Note: Muons!

Note again: 3 muons!!



Z→3μ - Asymmetric Internal (Dalitz) Photon Conversions



Observation of Z→(3)4μ

Feynman level (γ*) gives

e+e- and μ+μ-

Analogous to π^0 → e+e-γ

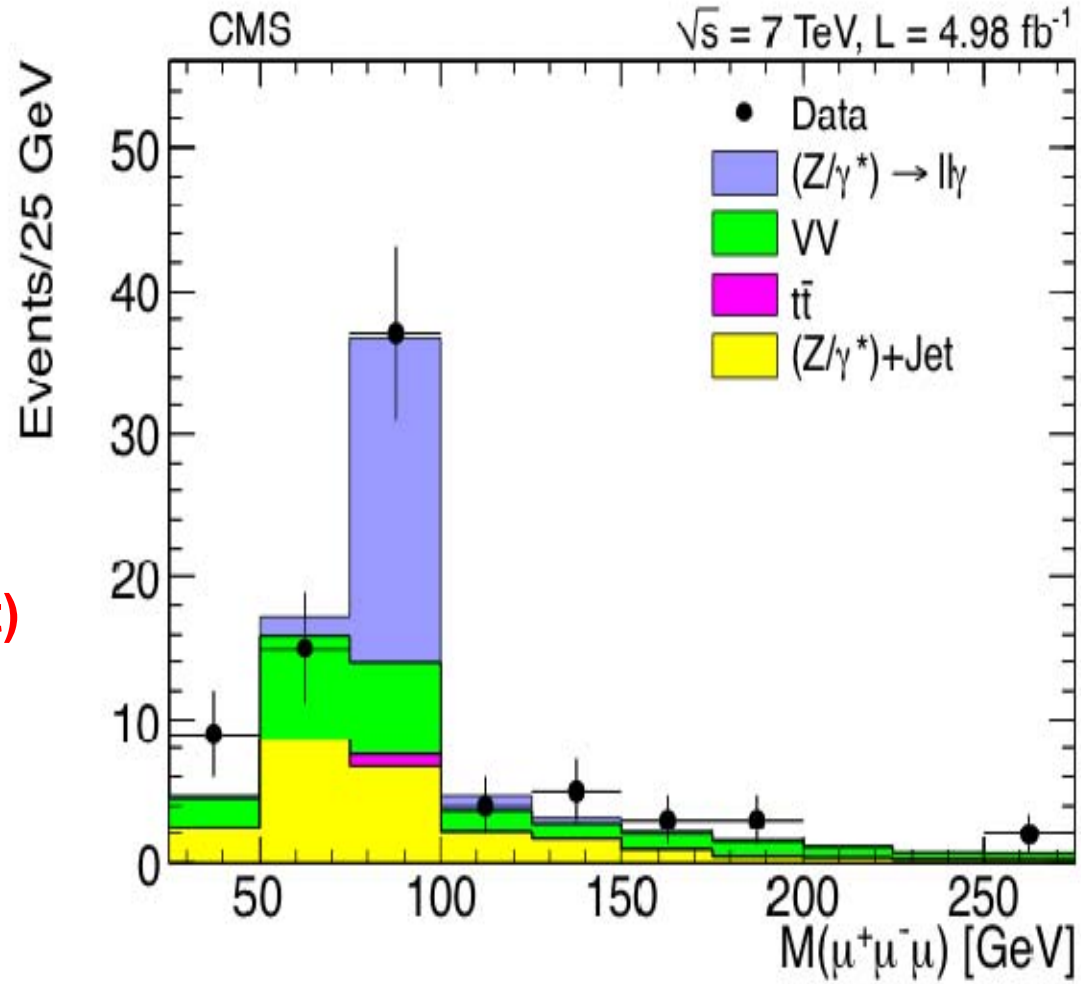
Observe 3μ Z peak (4th μ soft)

Also W→2μ (Higgs!)

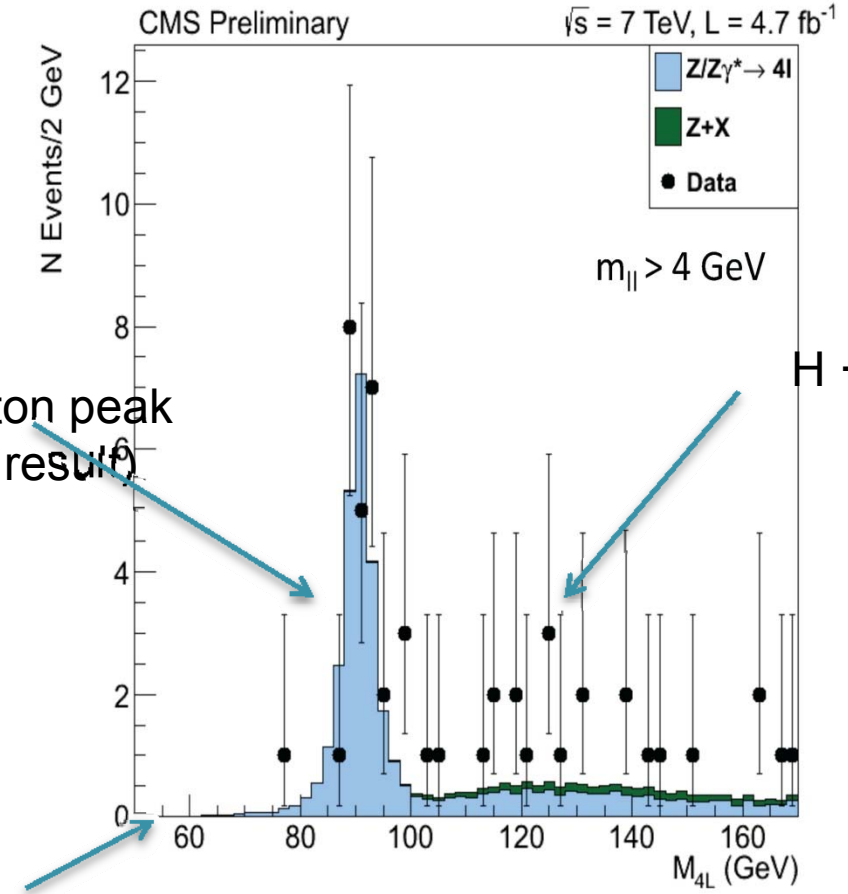
Wg* was not in Higgs WW searches

arXiv:1110.1368 R. C. Gray et. al.

Important for Higgs ~125 GeV



A textbook plot of tomorrow?



Z → 4-lepton peak (CMS result)

H → ZZ → 4-lepton peak here?

π^0 → e^+e^- e^+e^- Double-Dalitz peak (~1960(Plano et al) Parity)

4-lepton mass

Nontrivial SUSY Scenarios

- Unusual mass spectra, e.g. squeezed spectra
- Accidents of Spectrum – e.g. strong production hijacked by leptons
- Top as a massive blanket hiding new physics
- Finite sparticle lifetimes….

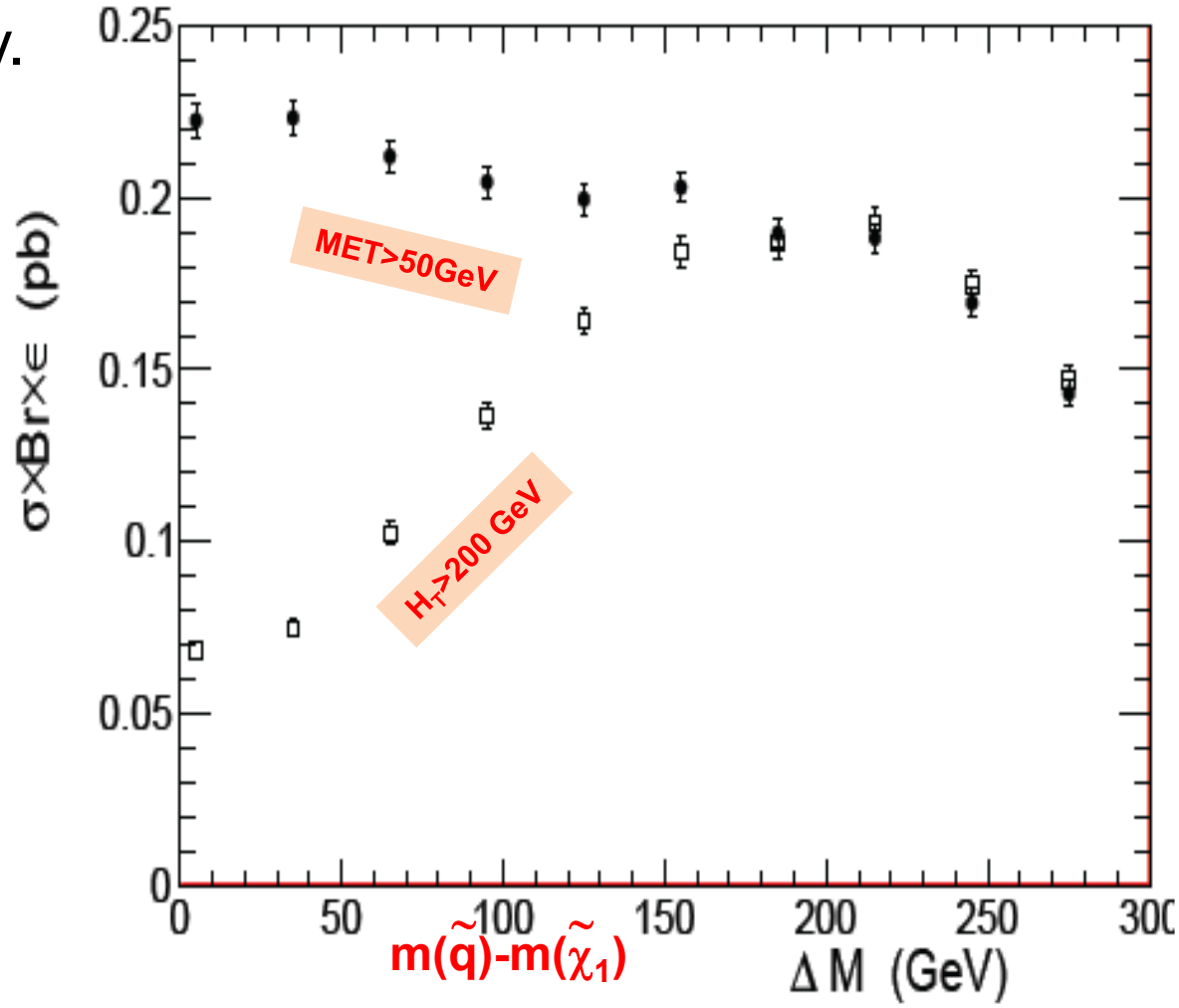
→Many more *exotic* scenarios in Monica's talk coming up soon.

Nontrivial SUSY Scenarios

- A CMS multilepton study.
- ***Strong*** production but NO JETS or HT!

- Strong production captured by Lepton Sector

Slepton co-NLSP GMSB topology by Scott Thomas

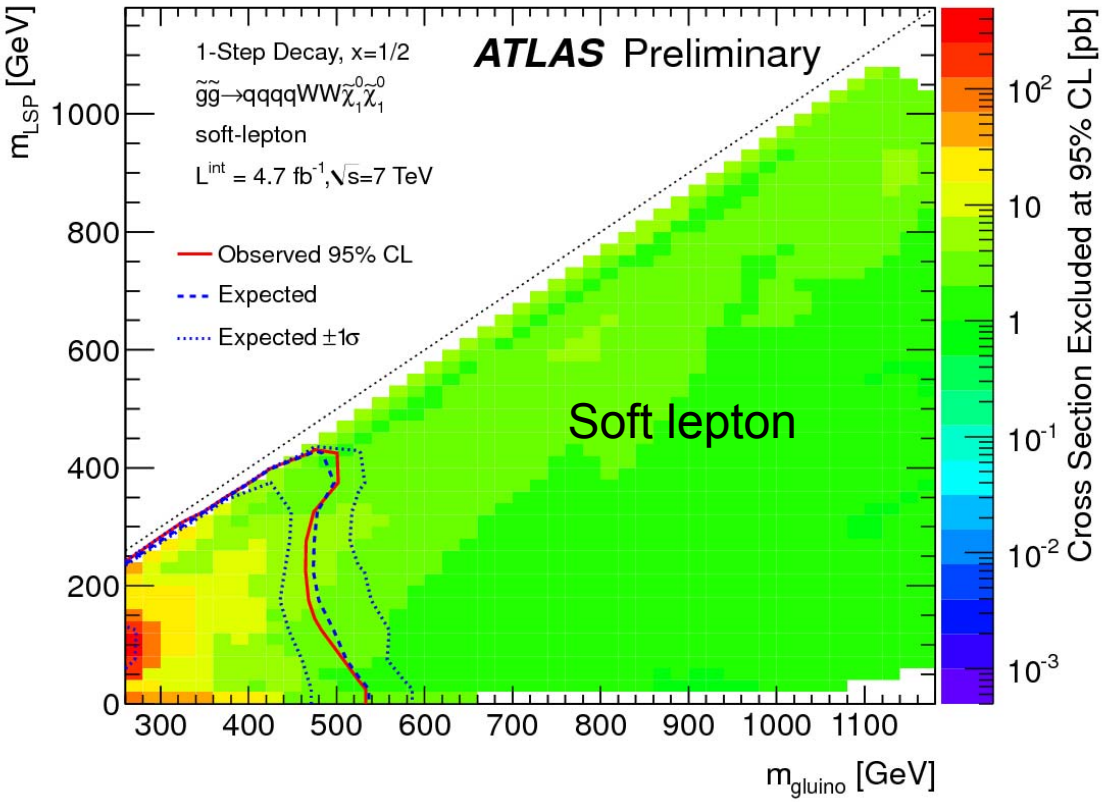


JET-MET + lepton (e/μ) (shown before)
Soft Lepton Case (to cover spectrum accidents)

- Strong production
- Inclusive JET-MET, one lepton. MET >250 GeV
- soft lepton case
  7-25GeV e, 6-20GeV mu.
  (for squeezed spectrum)
- Transverse mass >100GeV
- ST > 1200 or 800 GeV
- Backgrounds: W/Z+jets, ttbar

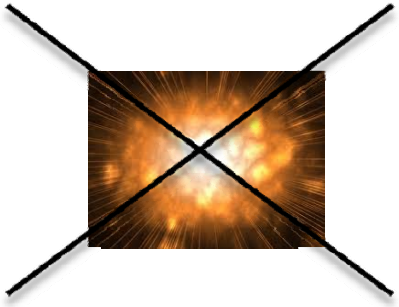
- Result for 3/4-jet channels
  Simplified model: gluino pair pro
  & gluino → qq W* +LSP

ATLAS (4.7/fb)



Long-lived Sparticles

- There is more to life than a hadronic “boom!”

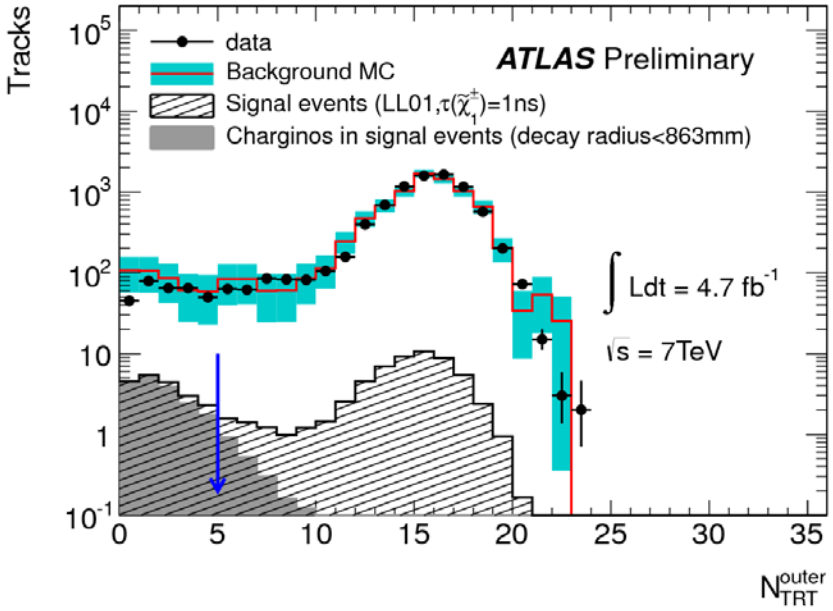


- Displaced or high dE/dx tracks, out-of-time particles, non-pointing photons

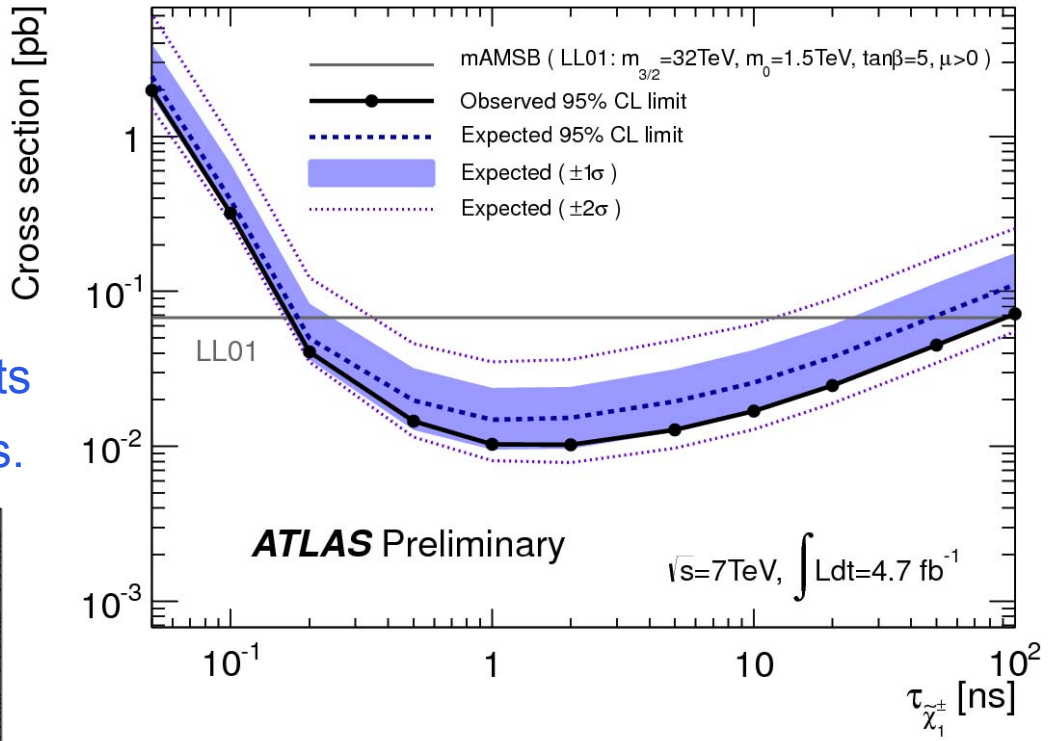
- SUSY, hidden valley, etc.

The Case of the Missing Track

- Strong production followed by decay of the “Chargino” in the detector
- An inner track that vanishes.
- Backgrounds: charged hadrons in jets interacting with material, tau decays.



ATLAS (4.7/fb)

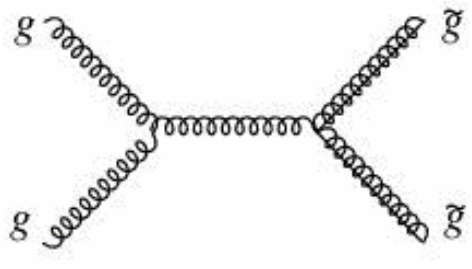


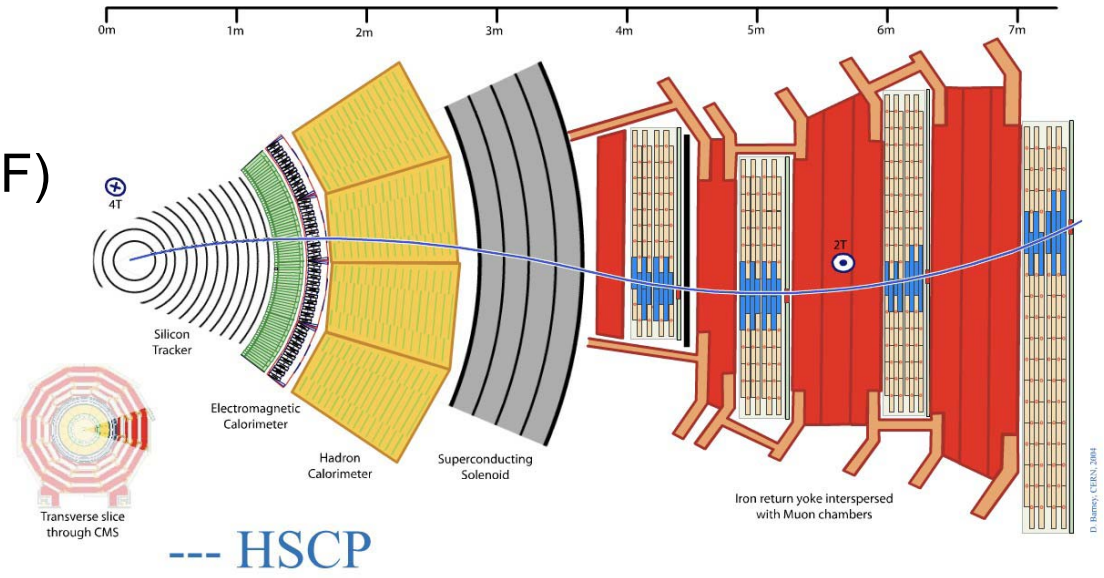
Cross section limit vs lifetime for a 90GeV “chargino”.
0.2 to 90 ns range

5.0fb^{-1} CMS PAS-EXO-11-022

Searches for Heavy Stable Charged Particles

- R-hadrons: squarks or gluinos hadronize with quarks/gluons
- Long-lived NLSP - Split-SUSY,GMSB etc.
- Characteristic: High momentum, but v/c < 1
  - Tracker hits show high dE/dx
    → particle mass
  - Late arrival
    → Long Time Of Flight (TOF) to the muon system



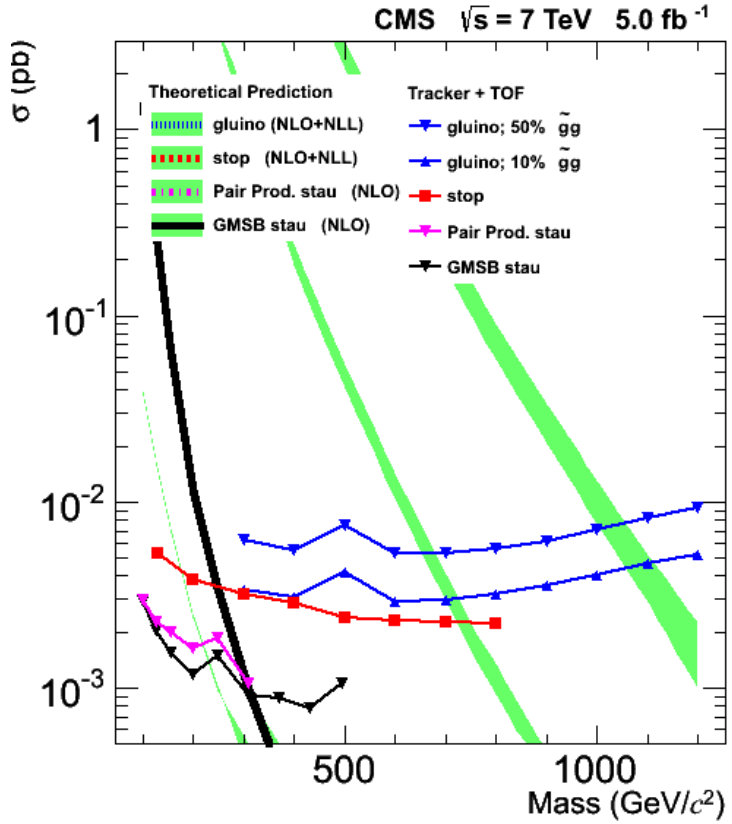


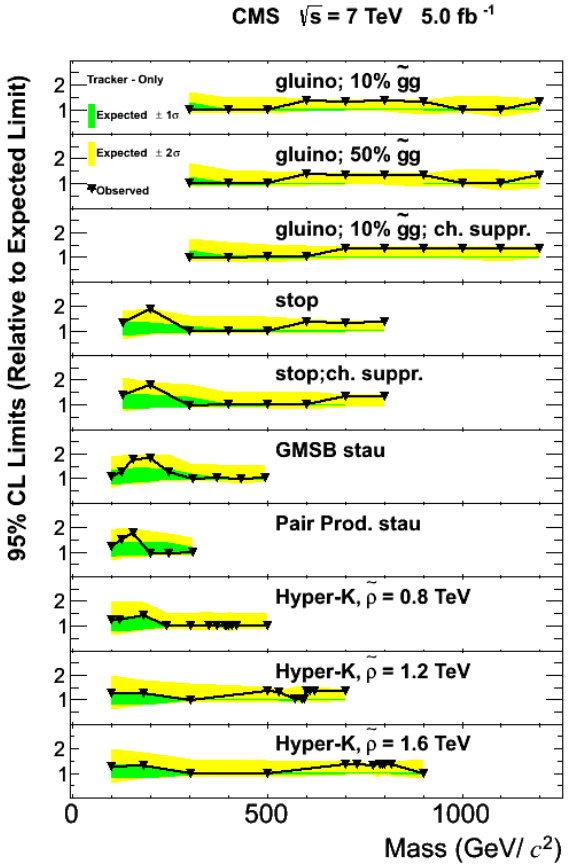
--- HSCP

5.0 fb^{-1} CMS PAS-EXO-11-022

Searches for Heavy Stable Charged Particles

Data consistent with estimated data-driven backgrounds



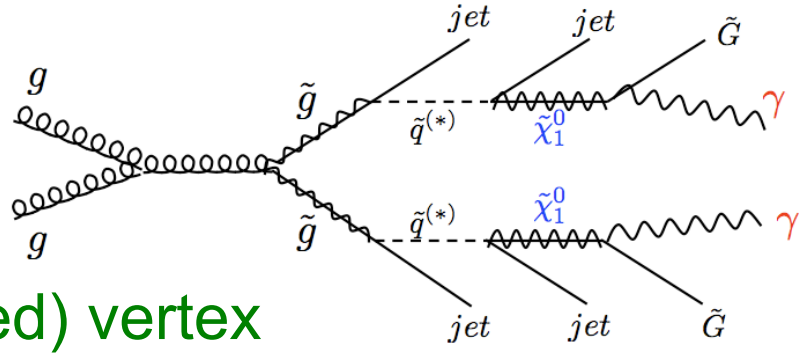


M(gluino)>1091 GeV, M(scalar top)>734 GeV, M(scalar tau) > 221 GeV

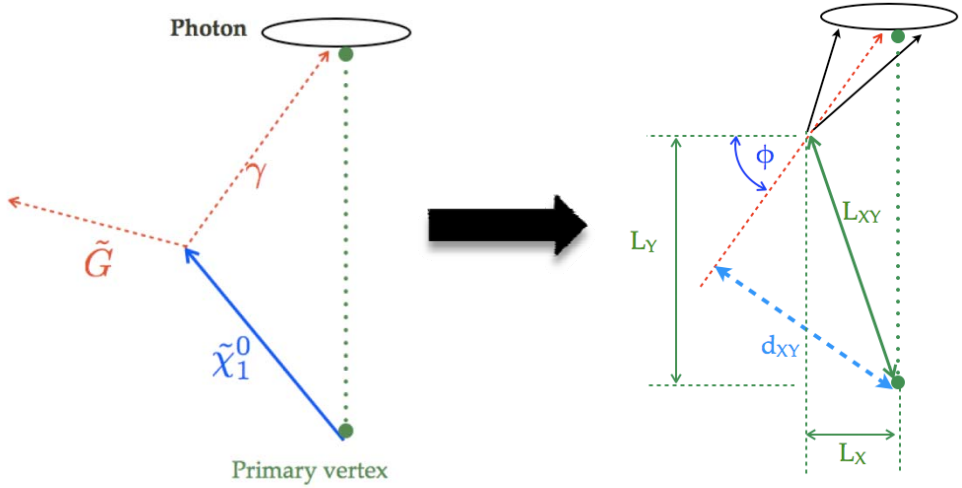
Somewhat Lazy Photons

2.1 fb^{-1}

- Long-lived neutral → Non-prompt Photon + invisibles (MET)
  - $c\tau$ not that large, ~2 to 20cm, e.g. GMSB neutralino
  - Pair production (diphotons)
  - Accompanying jets
  - Converted photon → (displaced) vertex

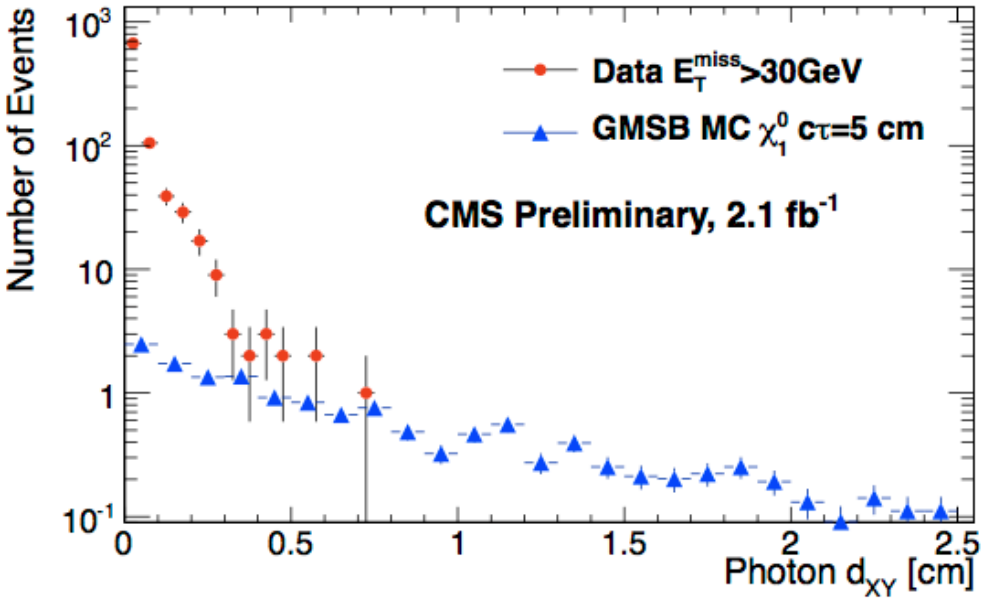


Technique:

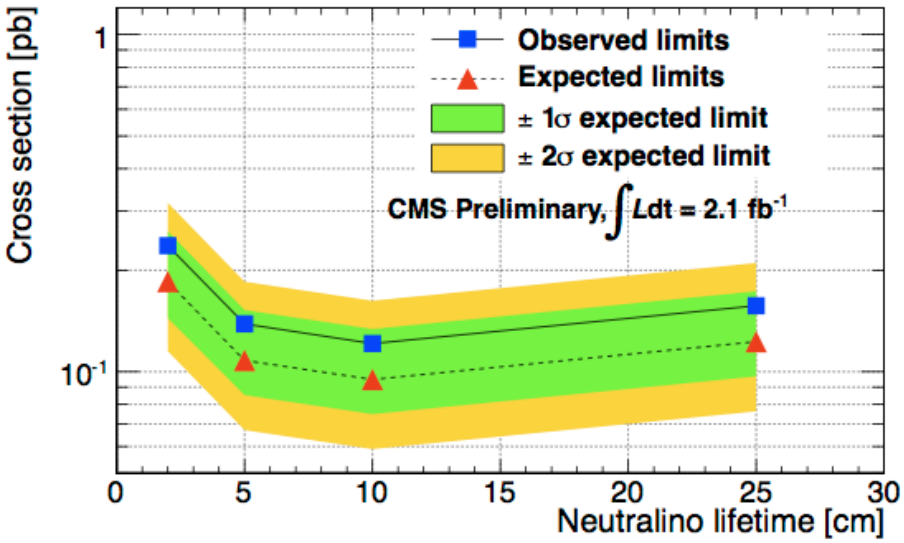


Sensitive to lifetimes O(0.1ns)

Non-prompt (mildly displaced) photons 2.1 fb^{-1}



Select:
$E_T(\gamma)$ > 45 GeV
≥ 2 jets (80/50 GeV)
MET > 30 GeV



Backgrounds:
Photon + jets, Misid jets
Evaluated in MET<20 GeV region

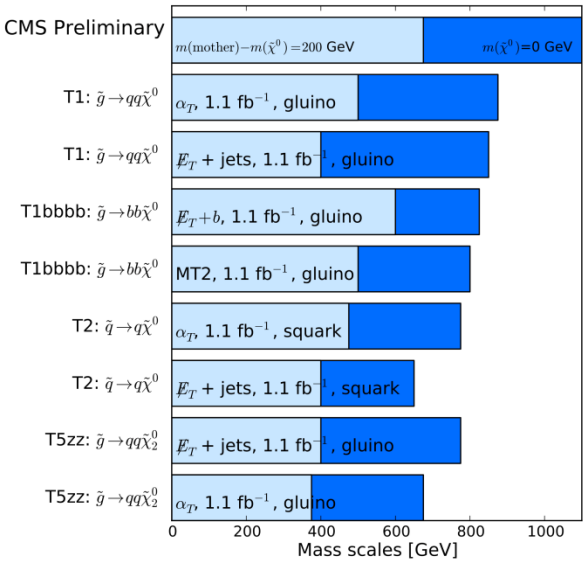
Limits on neutralino cross section as a function of neutralino lifetime

Where do we stand?

- Squarks and gluinos are getting heavier in simple scenarios →electroweak production and 3rd generation under further scrutiny.
- R-Parity Violation can also pull the rug from under us (leptonic or hadronic). MET can vanish.
- High tan(β) : Tau reconstruction is challenging.
- Nontrivial scenarios: unusual mass spectra (no jets despite strong production, e.g.), top as a massive blanket hiding new physics, finite sparticle lifetimes
- If a search team discovers something, a very small chance that it will be the physics model they were looking for.

Reprise: LHC vs SUSY Models

CMS SUSY Results



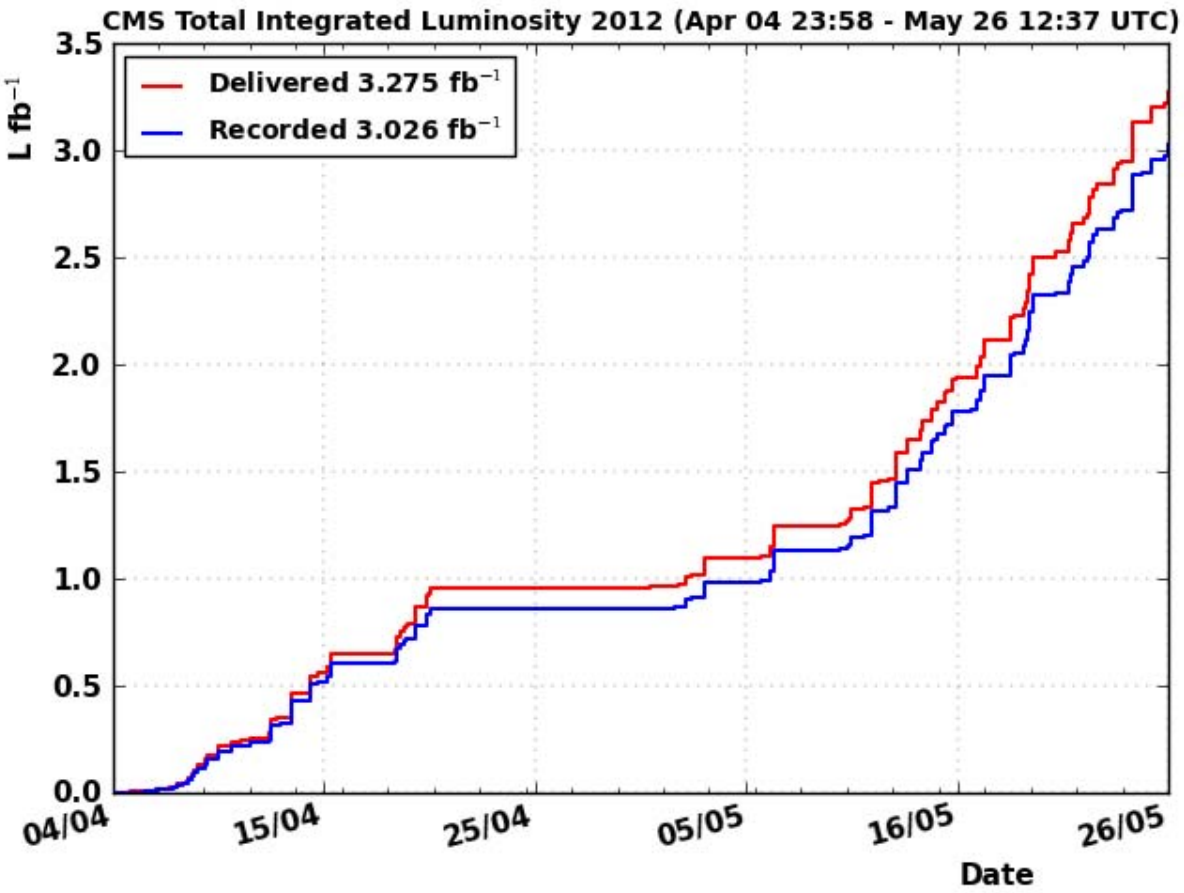
BUT....

Slide Credit: Stephen Martin

New Physics Possibilities: Ways to go

Nascent SUSY

2012 LHC p-p Run @8 TeV



+ 5 fb^{-1} @7TeV from 2011

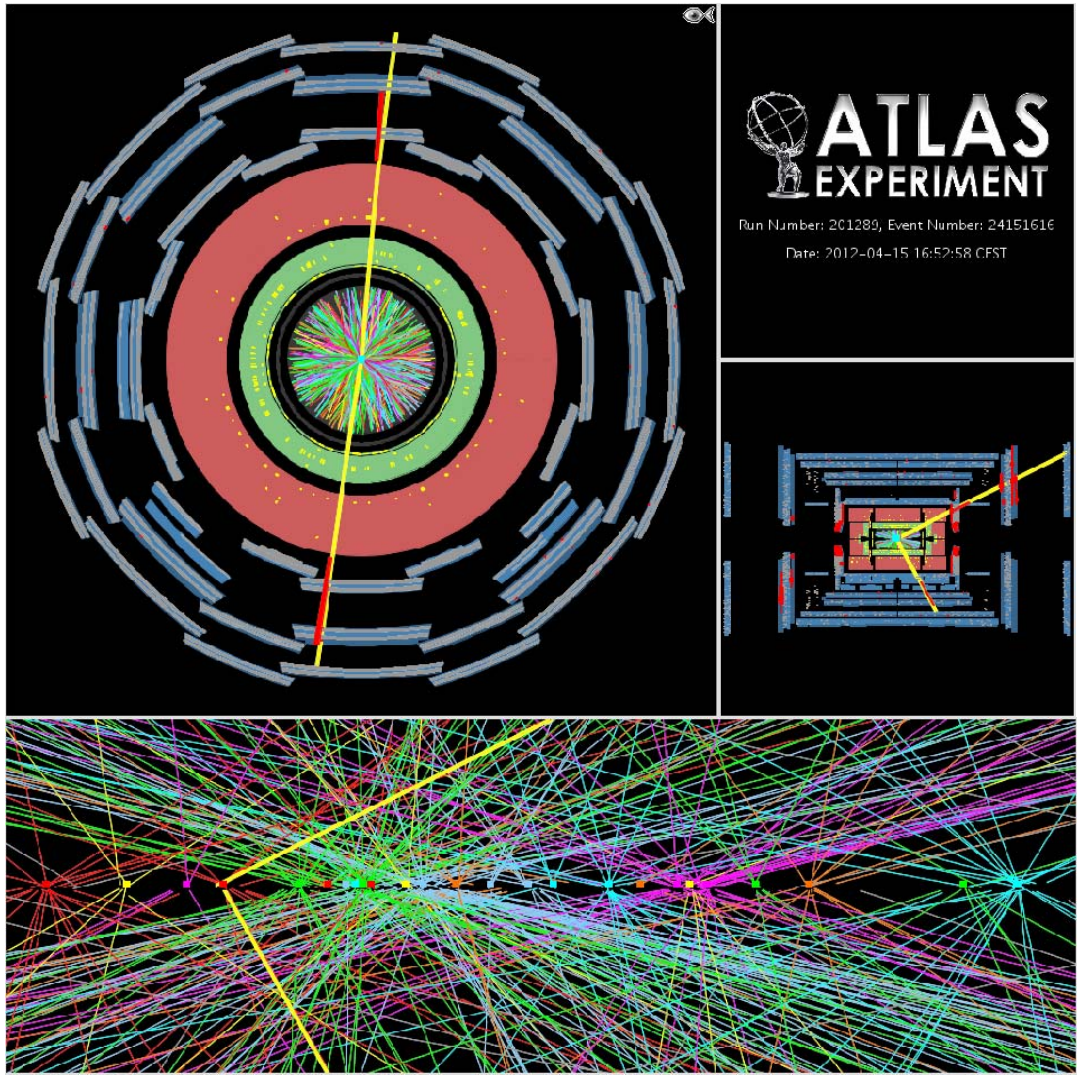
2012 LHC p-p Run @8 TeV

High pileup in 2012

ATLAS Z → μμ

•25 reconstructed vertices.
•Tighter hit requirements than 2011

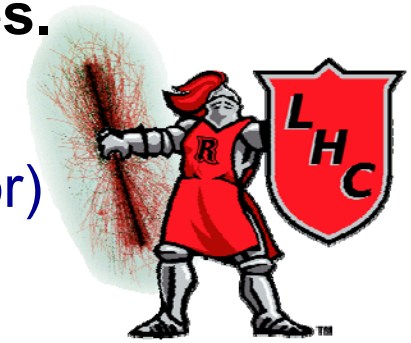
Display:
0.4 GeV track pT threshold



To Conclude…

- **Masses are getting heavy in simple schemes**
- **All fox holes hardly explored. The hunt continues.**

Rutgers Particle Knight
© Scott Thomas



- More off-the-beaten-path ideas coming into focus.
  (The particle knight has to step out of the clunky armor)
- Back to the fox chase (rat race?) with 8TeV
- 2013-14 should bring plenty of fresh insights as well.
- To be followed by a new energy regime in 2015.

→Rumors of SUSY's demise are greatly exaggerated.

- Exciting times are here and ahead.

Come, Watson, come! The game is afoot.

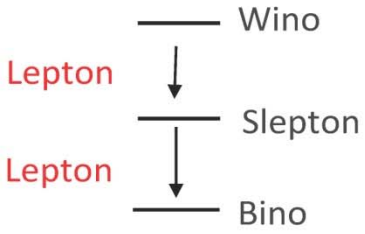
Credits

- Blois organizers !!
- Richard Gray, Scott Thomas, Monica D'Onofrio, Hitoshi Murayama, Stephen Martin, Konstantin Matchev.
- LHC staff.
- ATLAS,CMS,CDF & D0 SUSY collaborators, conveners and leaders.
- Unknown photographers of penguins and painters of foxes.

Extra Slides

Multilepton MET/HT SUSY Signals

Tri-Lepton + MET Signatures



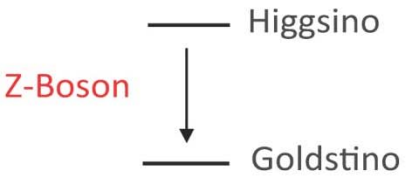
Tri-Lepton + MET

Di-Lepton + Tau + MET

Tri-Tau + MET

Sensitivity Ranges from
Just Beginning to m_{Wino} 500+ GeV

Di-Z-Boson + MET Signatures

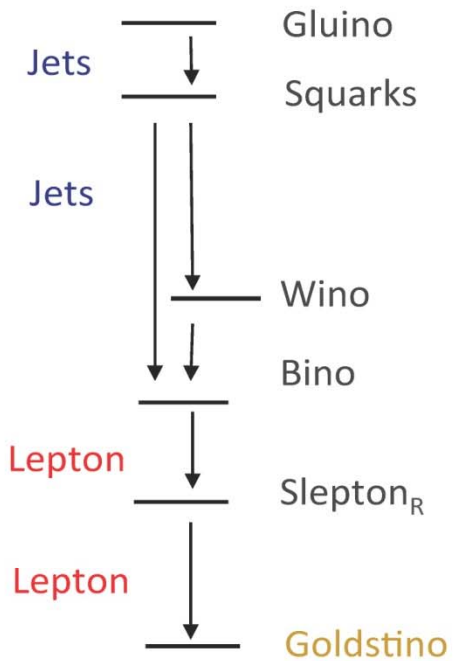


Quad-Lepton + MET

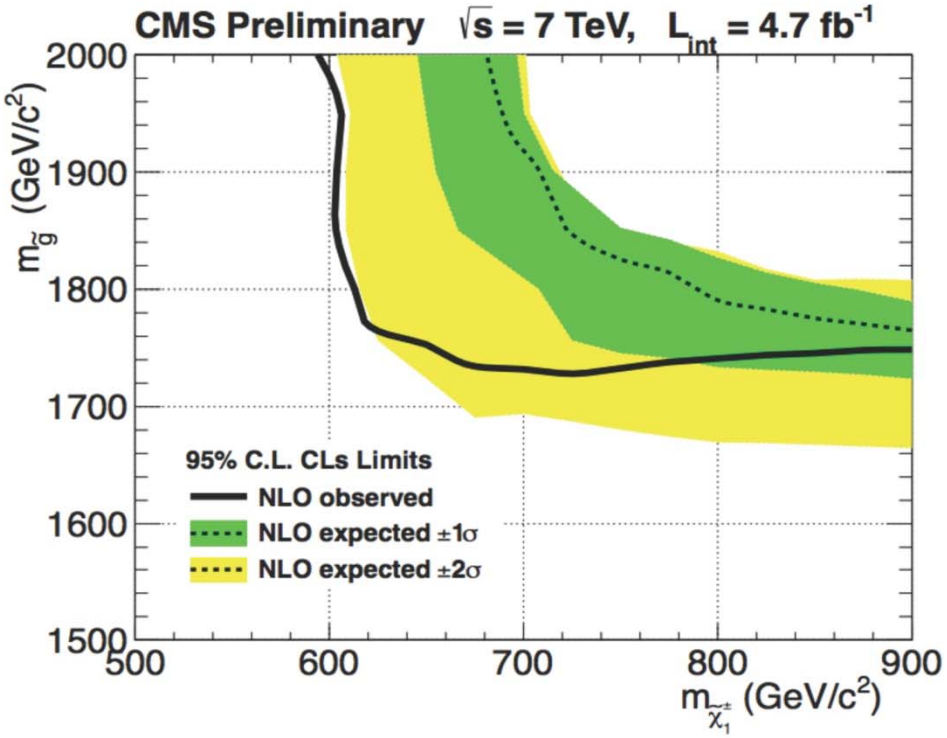
Sensitivity Just Beginning

GMSB Slepton CO-NLSP Exclusion

Slepton Co-NLSP - Prompt Decay to Goldstino
with Strong Production



Stau NLSP,
Leptonic RPV and
No-MET Hadronic RPV
Topologies also …



$m_q = 0.8\ m_g$, $m_{lR} = 0.3\ m_C$, $m_N = 0.5\ m_C$

Strong vs Weak Production

GMSB co-NLSP

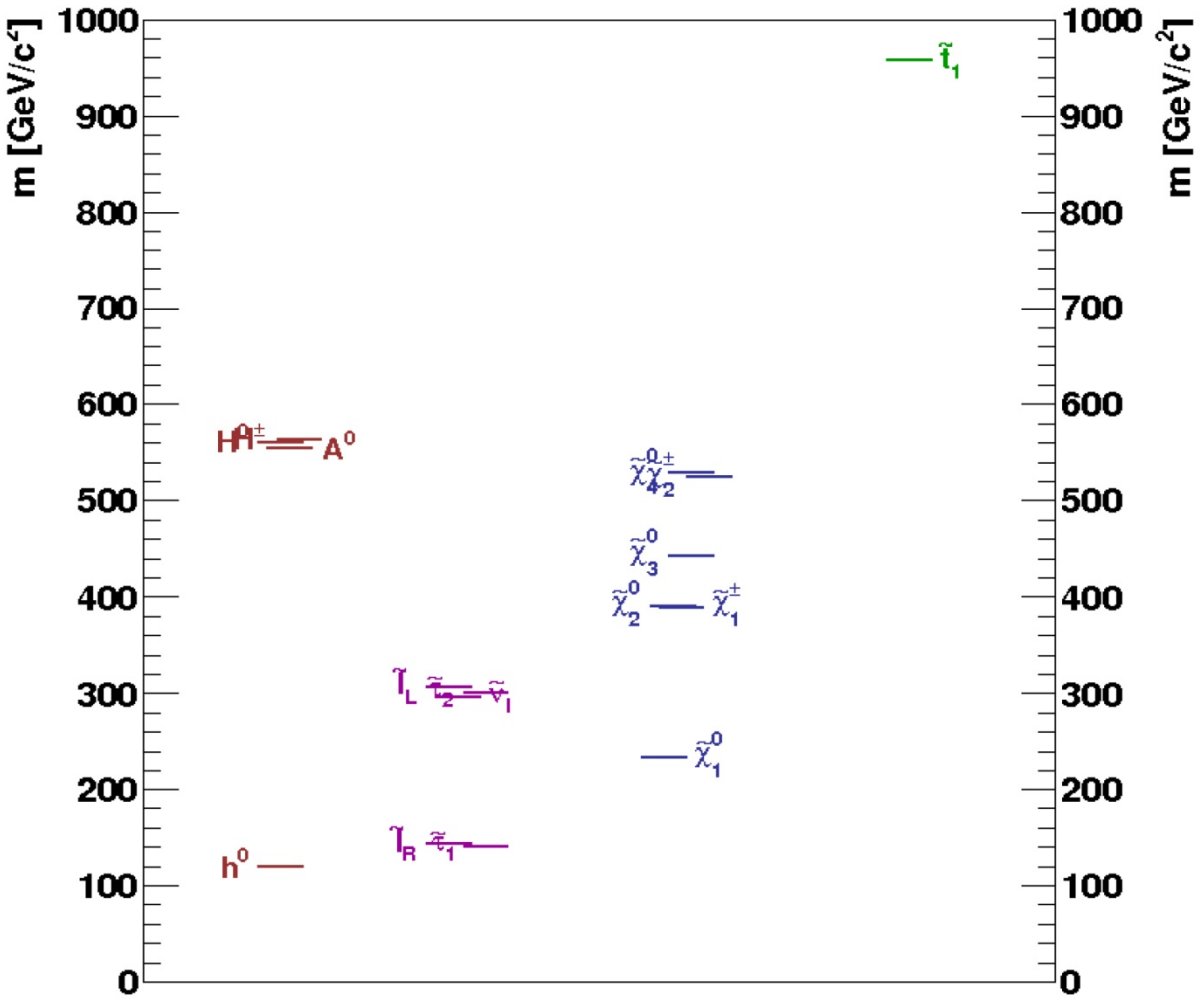


Figure 1: MGM slepton Co-NLSP spectrum with $\Lambda = \Lambda_L = \Lambda_d = 35$ TeV, $N_5 = 5$, $\tan\beta = 3$,$M/\Lambda = 3$, $\mathrm{sgn}(\mu) = +$, and $\mu/m_2 = 0.95$. All strongly interacting superpartners except for the lightest stop are heavier than 1 TeV. The essentially massless Goldstino is not shown. This plot was produced with the spectrum.py script from

MT2

by the unknown LSP transverse momenta, $p_T^{\chi(i)}$. In analogy with the transverse mass used for the W mass determination, we can define two transverse masses ($i = 1,2$)

$$(m_T^{(i)})^2 = (m^{vis(i)})^2 + m_\chi^2 + 2\left(E_T^{vis(i)} E_T^{\chi(i)} - \vec{p}_T^{\,vis(i)} \cdot \vec{p}_T^{\,\chi(i)}\right) \quad (1)$$

These have the property (like for W decay) that for the true LSP mass their distribution cannot exceed the mass of the parent particle of the decay and they present an endpoint at the value of the parent mass. The momenta $p_T^{\chi(i)}$ of the unseen particles are not experimentally accessible individually and only their sum, the missing transverse momentum p_T^{miss}, is known. Therefore, in the context of SUSY, a generalization of the transverse mass is needed and the proposed variable is M_{T2}. It is defined as

$$M_{T2}(m_\chi) = \min_{p_T^{\chi(1)} + p_T^{\chi(2)} = p_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right], \quad (2)$$