Latest results from SUSY Searches

Rencontres du Vietnam: Windows on the Universe

August 15, 2013

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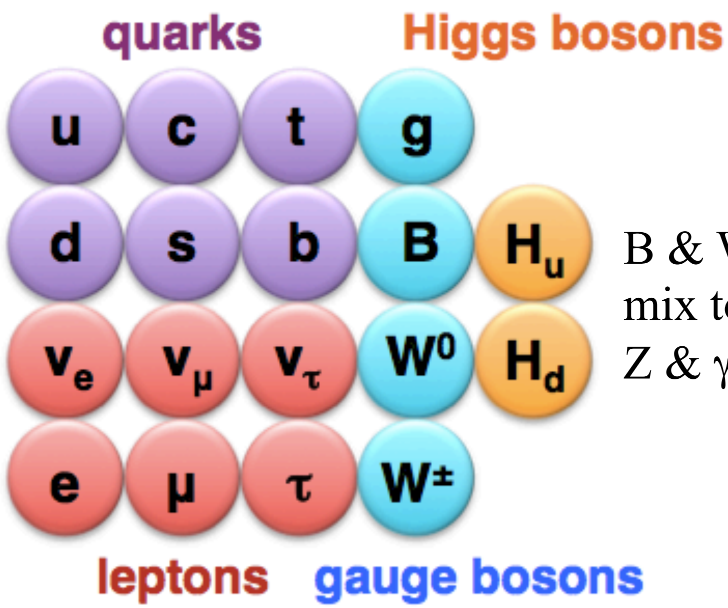
"SUSY 101"

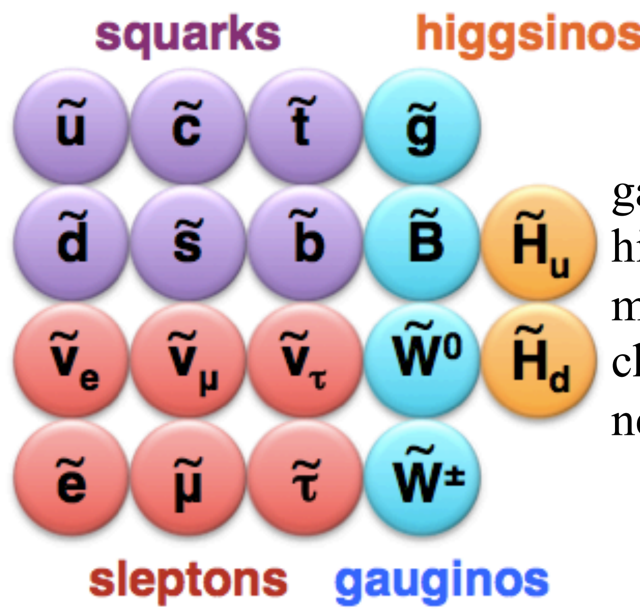
New spin-based symmetry relating fermions and bosons

SM Particles



B & W^0 mix to give Z & γ

SUSY Particles

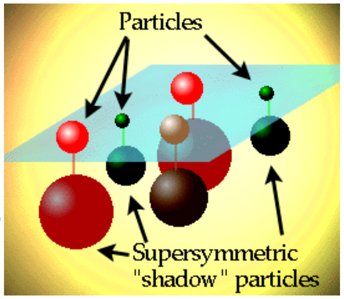


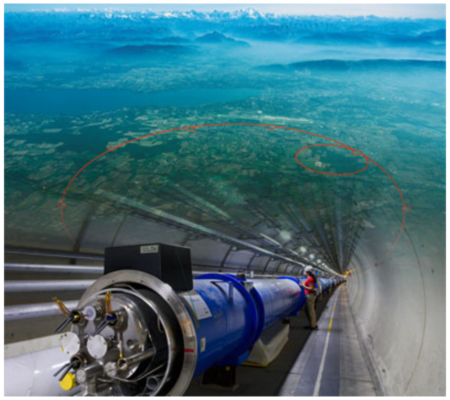
gauginos & higgsinos mix to give charginos & neutralinos

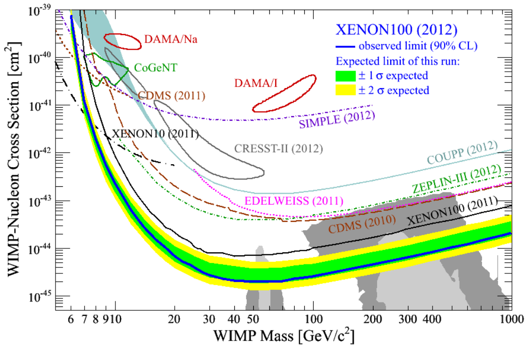
If R-Parity is conserved, provides Dark Matter Candidate (Lightest Supersymmetric Particle or LSP)

- R-parity = $(-1)^{3(B-L)+2s}$ → R = 1 (-1) for SM (SUSY) particles

Searching for SUSY







http://xenon.astro.columbia.edu/XENON100_Experiment/

Why?

- Symmetry between bosons and fermions
- Unification of forces
- Provides a dark matter candidate
- No “fine-tuning” → “natural” scenarios, hierarchy problem

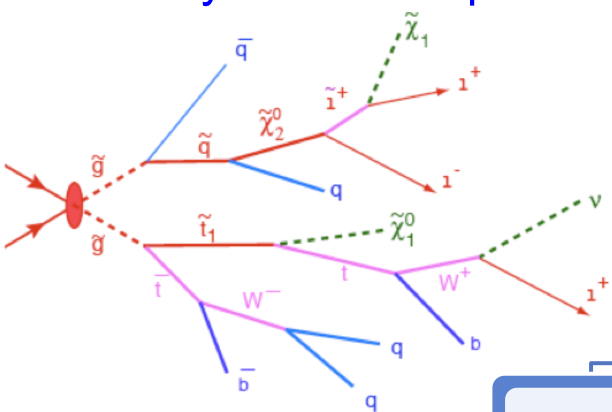
How?

- Colliders
  - e.g. Tevatron & LHC
- Dark Matter Searches **(see talks this afternoon)**
  - Direct searches
    - deep underground: e.g. CDMS, XENON
  - Indirect searches
    - e.g. Fermi/LAT, Pamela

I will mainly focus on latest results from the LHC (ATLAS and CMS) **[Also see parallel talk by C. Ohm]**

How can we search for SUSY?

SUSY yields a rich phenomenology and a broad set of potential signatures

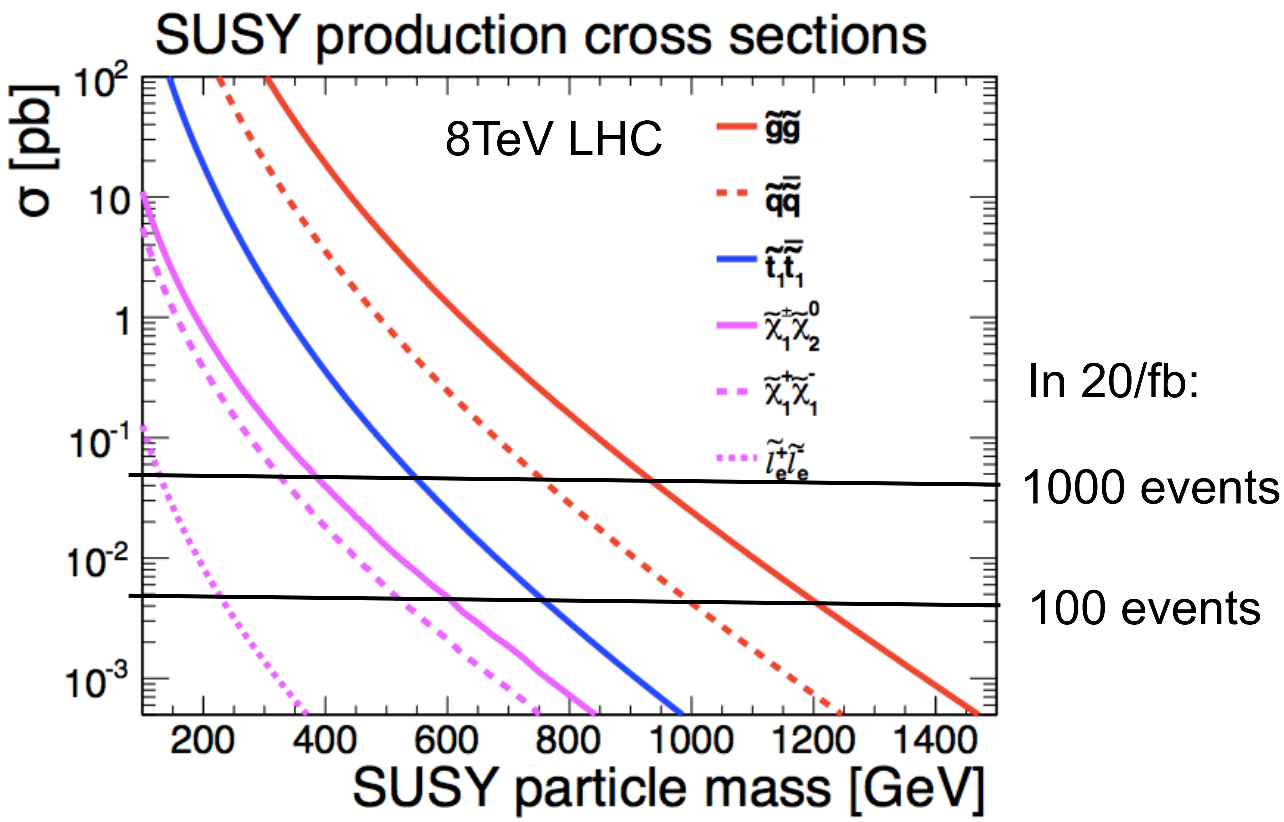


Classifying searches for SUSY

- **Prompt?**
  - **RPC?**
    - **Strong?**
      - **1st and 2nd generation squarks and gluinos**
      - **3rd generation squarks (stops, sbottoms)**
    - **Weak?**
      - **EWK gauginos, sleptons**
  - **RPV?**
- **Long-Lived?**
  - **How long lived?**

I'll touch on the latest results for each of these.
Impossible to cover everything.

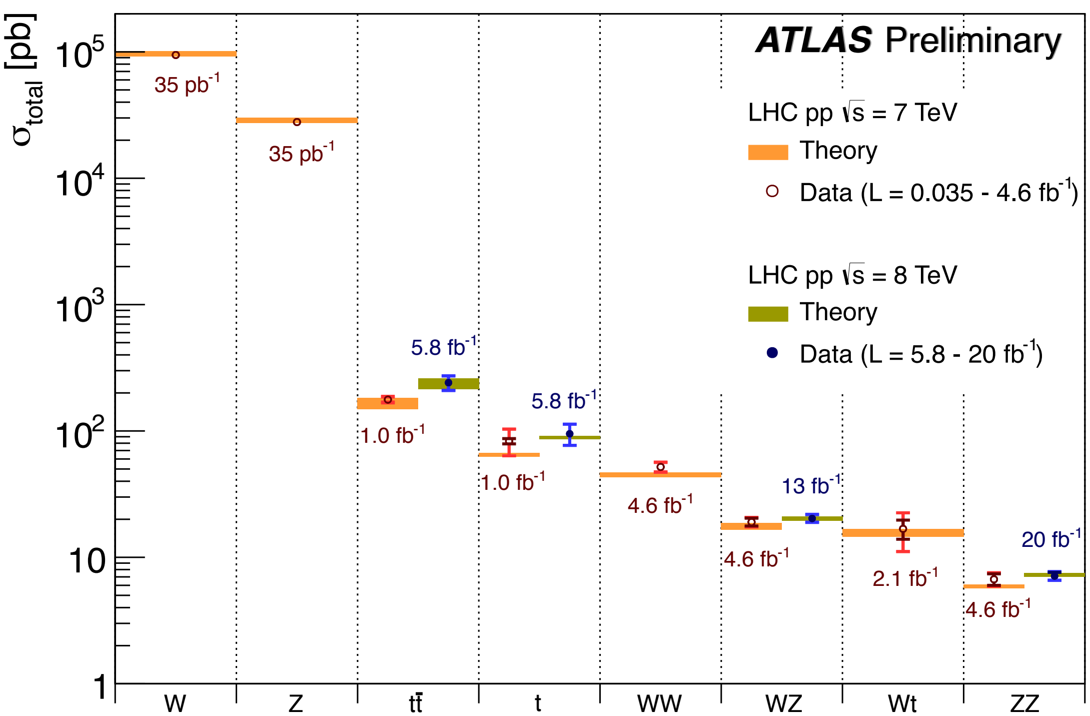
SUSY Particle Production at the LHC



[arXiv:1206.2892]

- Gluinos, 1^{st} & 2^{nd} generation squarks
  - High cross sections
- 3^{rd} generation squarks (stops, sbottoms)
  - Moderate cross sections
- Charginos, neutralinos, sleptons
  - Small cross sections, but feasible

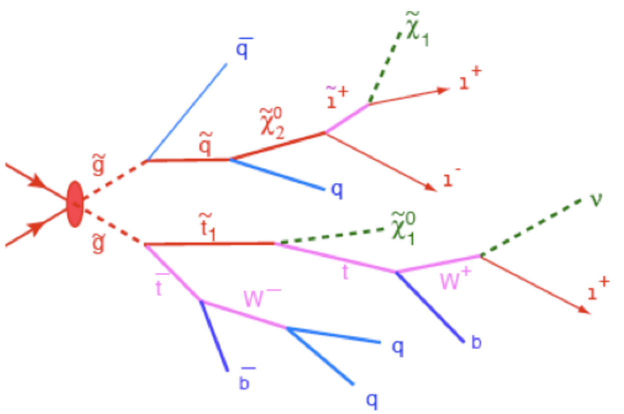
Standard Model Backgrounds

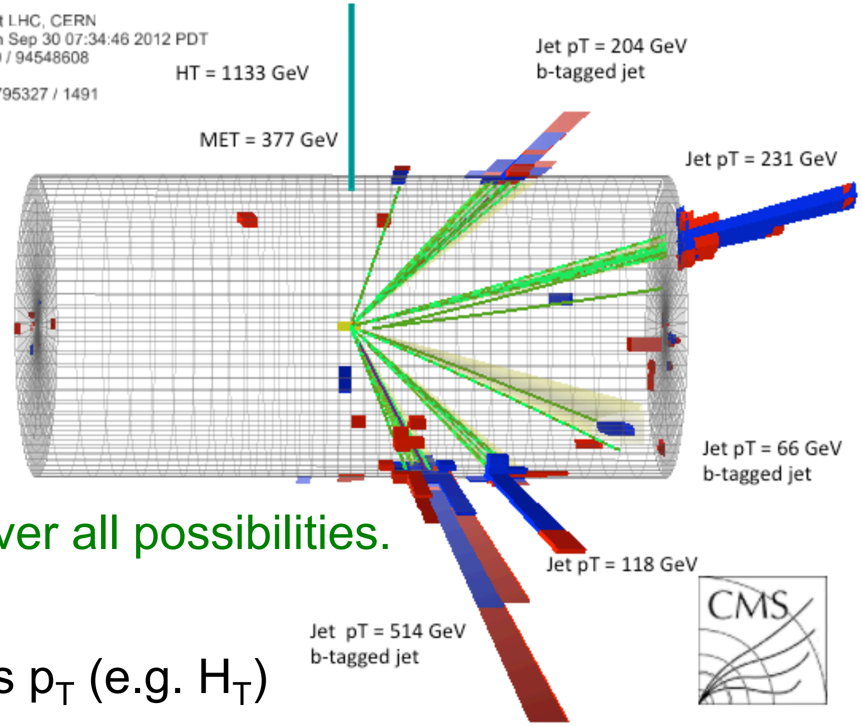


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots

- SM processes measured with very high precision and over many orders of magnitude
- W's, Z's, and top are primary sources of background for most SUSY searches
- Backgrounds mostly estimated from data, or data-driven methods
  - Monte Carlo primarily used for validation of control regions

SUSY Signatures





CMS-PAS-SUS-12-024

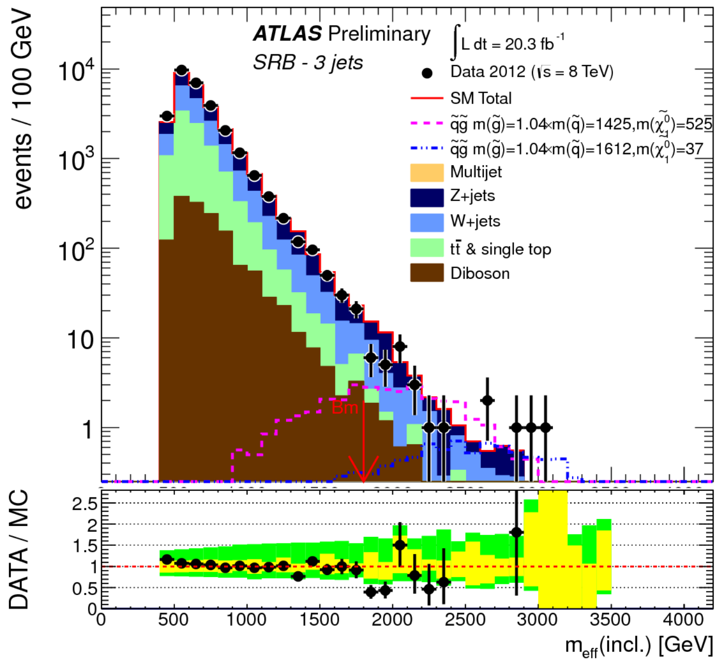
Topology oriented signature strategy. Cover all possibilities.

- Jets
  - Number of jets, Number of b-jets, jets p_T (e.g. H_T)
- Leptons:
  - electrons, muons, taus
  - same sign, opposite sign
- MET (Missing Transverse Energy)
- Photons

Kinematic Search Variables

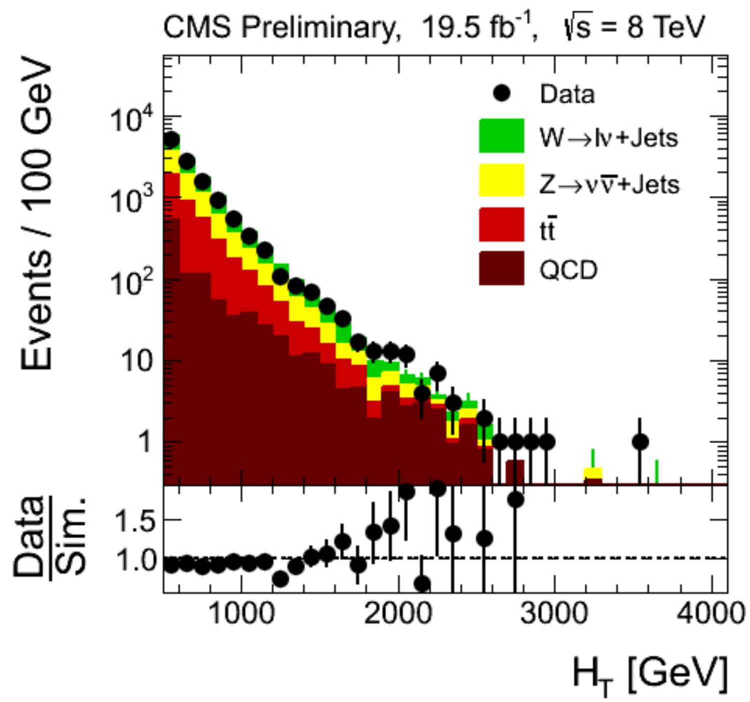
- A variety of discriminating quantities used in these searches
  - Total visible energy (e.g. H_T, M_{eff}), assume 2 LSPs in decay (e.g. MET, M_T, M_{T2}), exploit 2-body nature of decays ($alpha_T$, Razor), particle multiplicities (e.g. N_{jets}, $N_{b\text{-}jets}$), etc…

M_{eff} = MET + Sum p_T jets (leptons)



ATLAS-CONF-2013-047

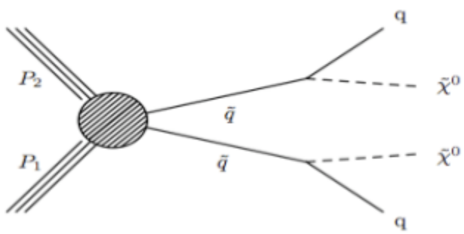
H_T = Sum p_T jets

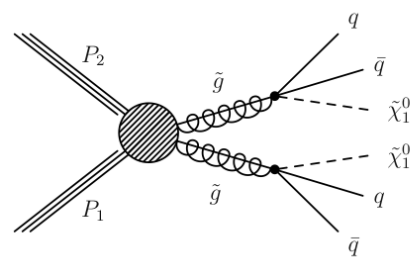


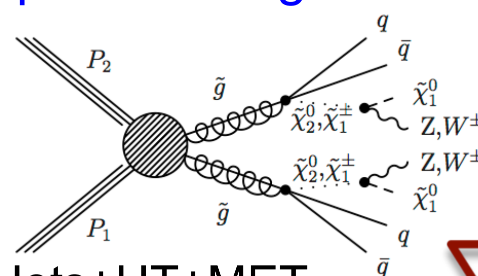
CMS-PAS-SUS-13-012

Inclusive Searches for Squarks and Gluinos

- Comprehensive program of inclusive searches for squarks and gluinos
- Signature: jets + MET + "X"

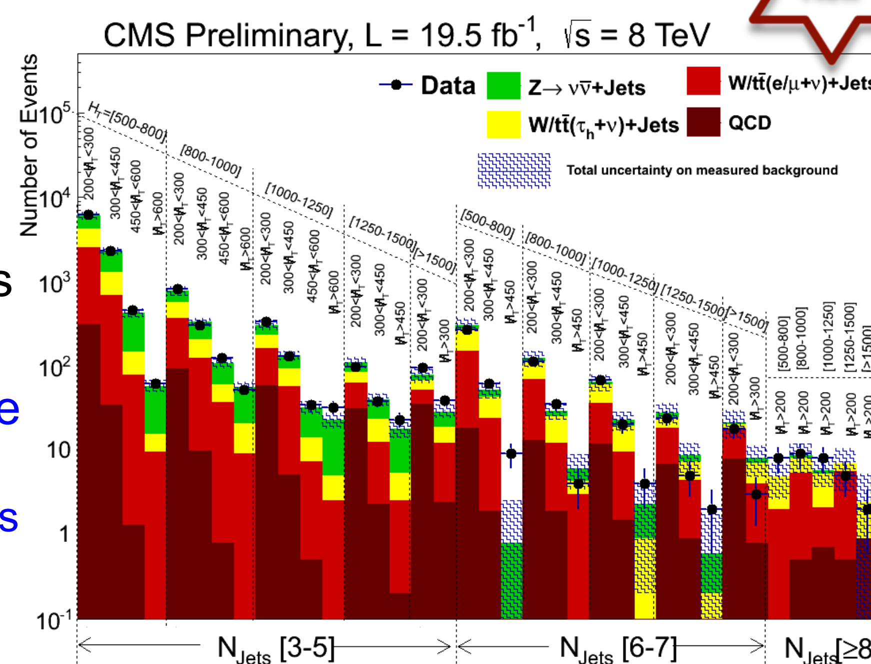






Jets+HT+MET

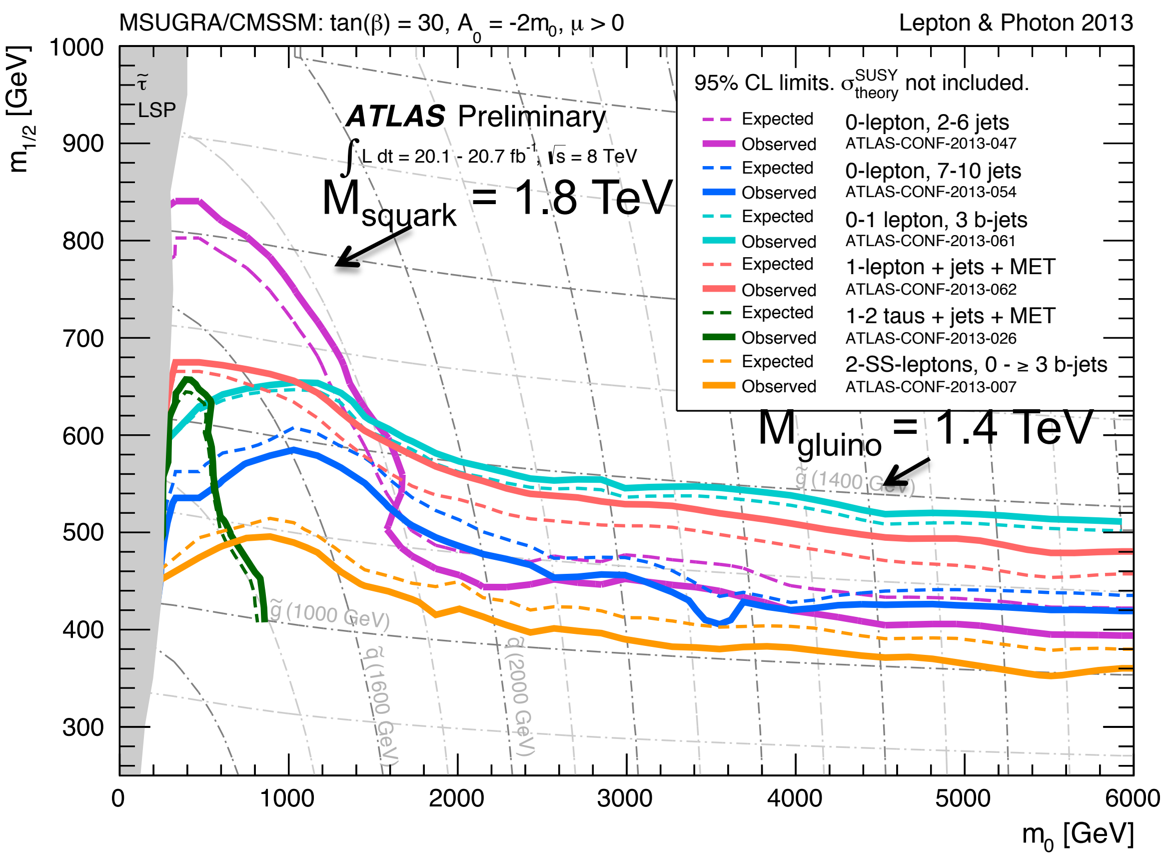
New



- e.g. "X" can be with or without leptons
- e.g. bin in number of jets, b-jets
- Exploit discriminating kinematic variables
  - Each experiment has their "favorites"
    - ATLAS: M_{eff}, MET, MET significance
      - use also MJ (=Sum m(R=0.4)) in searches targeting long decay chains (arXiv:1308.1841)
    - CMS: MET, H_T, $alpha_T$, M_{T2}, Razor

CMS-PAS-SUS-13-012

Interpretations: MSUGRA/CMSSM



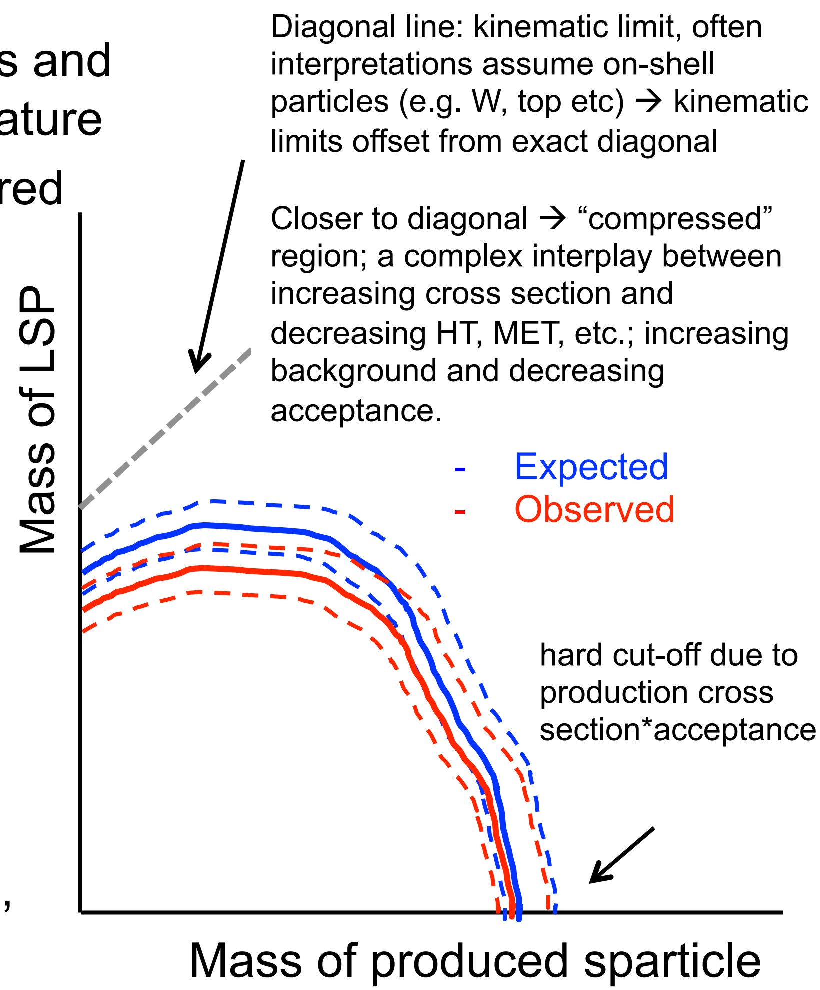
- Results have historically been most commonly presented in the MSUGRA/CMSSM m_0 vs $m_{1/2}$ plane

  ←"Higgs aware" scenario
  - **Shows breadth of analyses/final states explored and large gain in coverage**
  - M_{gluino} below ~1.35 TeV excluded for any M_{squark} [in this model]

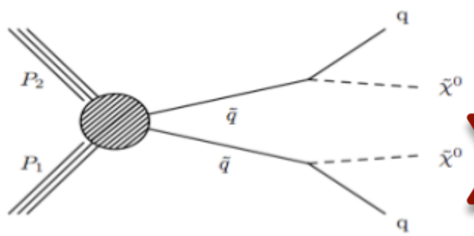
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots#SusyMSUGRASummary

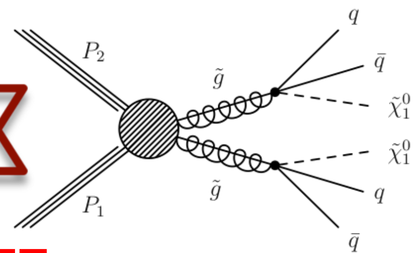
Interpretations: Simplified Models

- Simplified Model Spectra (SMS)
  - Use limited set of new hypothetical particles and decays to produce a given topological signature
  - Assume 100% BR for decay chain considered
- 95% CL upper limits shown
  - Presented in M_{LSP} vs M_{SUSY}
    - M_{SUSY} is mass of the produced sparticle considered
  - Expected, with experimental uncertainty
  - Observed, with theory uncertainty
  - Cross section limits (shown as color map)
- "Typical" systematics
  - Backgrounds: analysis dependent
  - Signal: trigger efficiency, lepton efficiencies, jet energy scale, pileup, ISR, …

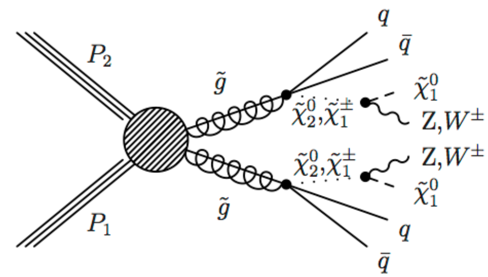


Direct and Gluino Mediated Squark Production

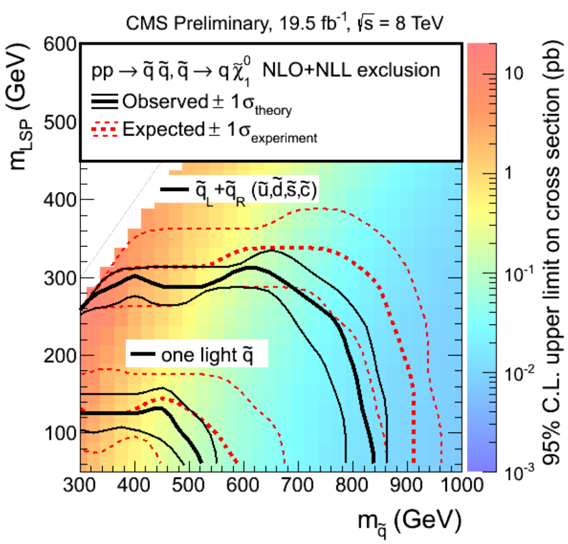


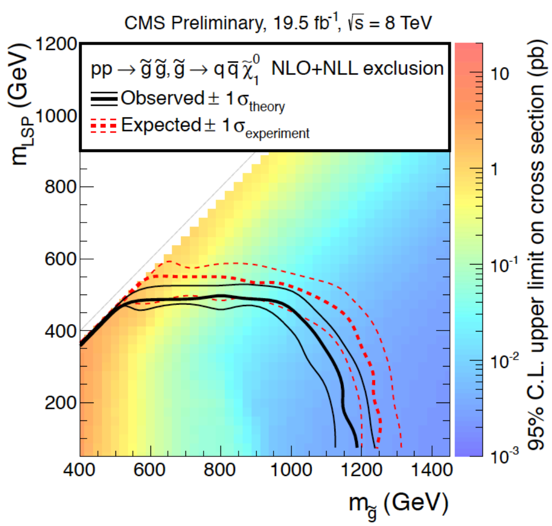


Jets+HT+MET



1-2 leptons + 3-6 jets + MET
→ Soft leptons add sensitivity to "compressed" spectra





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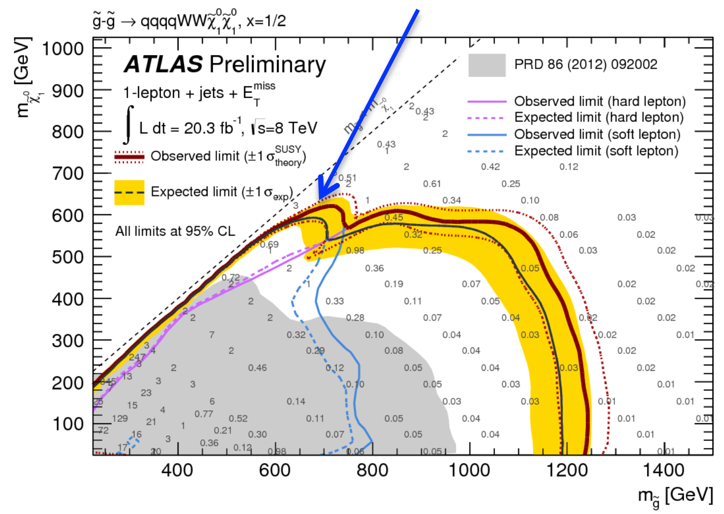
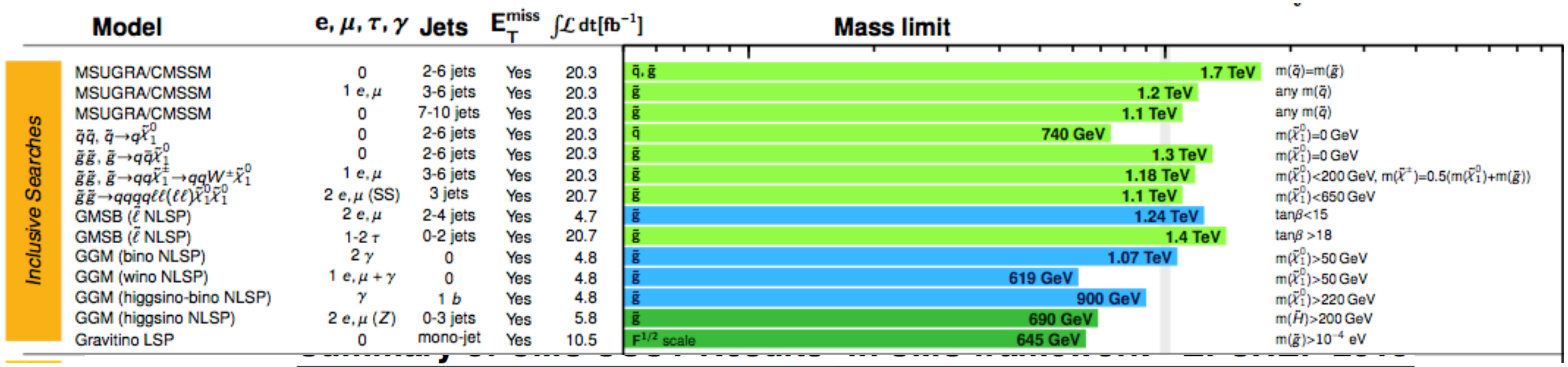
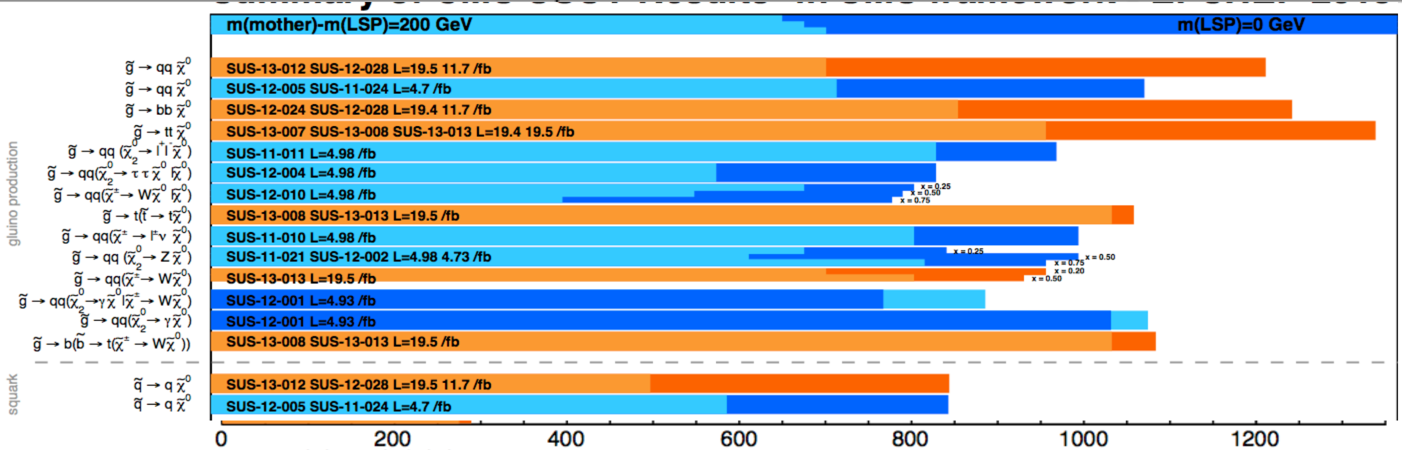


ATLAS-CONF-2013-062

Summary of Inclusive Searches





- "Best" direct squark (1st & 2nd generation) limits ~850 GeV

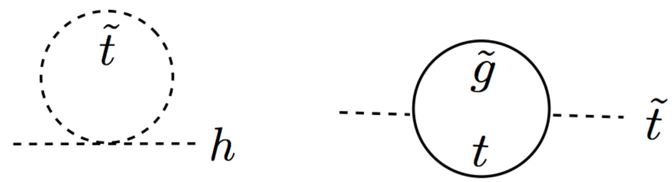
  → assuming eight-fold mass degeneracy (limits also for one light flavor accessible squark)

- "Best" gluino mediated limits ~ 1.2TeV

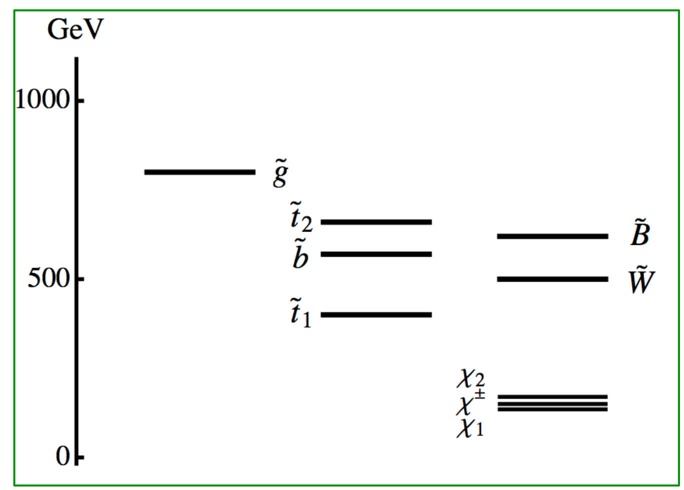
  → assuming 1st and 2nd generation decays for gluinos

"Natural" SUSY Scenarios

- Hierarchy problem:
  - Higgs mass at the weak scale despite the presence of divergent corrections from top quark loops
  - Large cancelations are unnatural
- Solution:
  - SUSY could make this natural
  - top squark adds canceling terms
  - gluino mass should not be too large also so its contributions to the top squark are controlled.



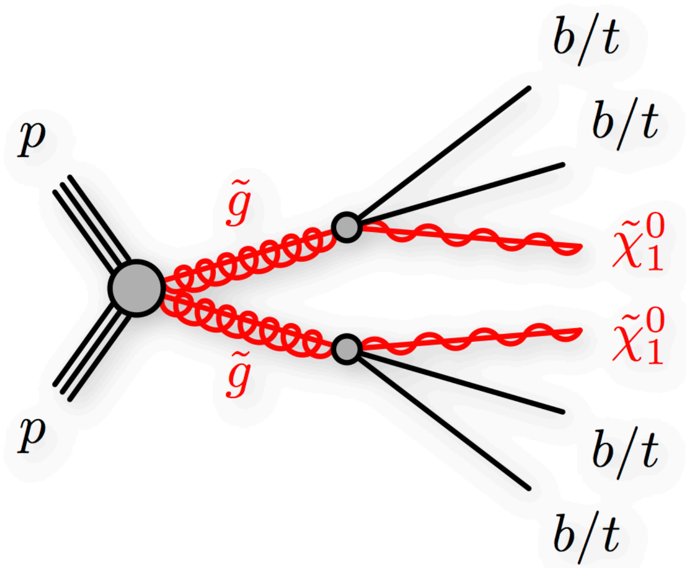
- Leads to "natural" SUSY spectrum:
  - 3rd generation squarks part of "nuclear family", while the other generations can be heavy and decoupled
  - Some charginos and neutralinos (the higgsinos) at ~ the weak scale.



R.Barbieri & D.Pappadopulo JHEP 0910:061,2009

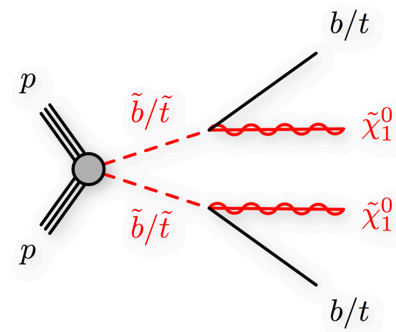
Searches for stops and sbottoms

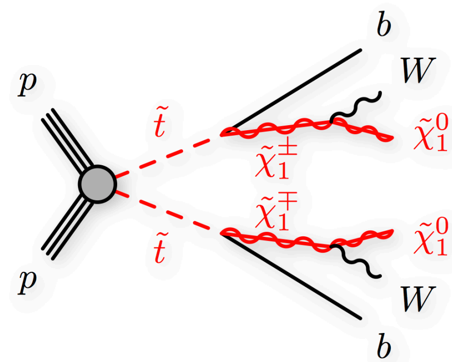
- Gluino mediated searches



Large cross sections.
Spectacular final states.
Many jets and b-jets.

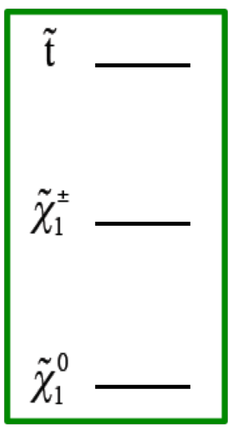
- Direct searches



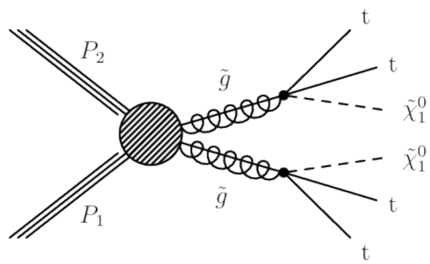


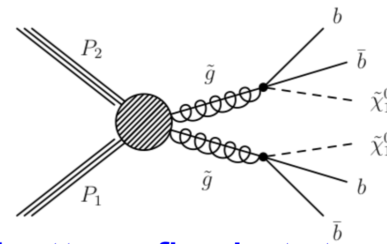
Smaller cross sections.
Many decay modes.
Compressed spectra can make these searches very difficult → close to indistinguishable from top background.

In the decays involving charginos, the stop-chargino-LSP mass hierarchy is important



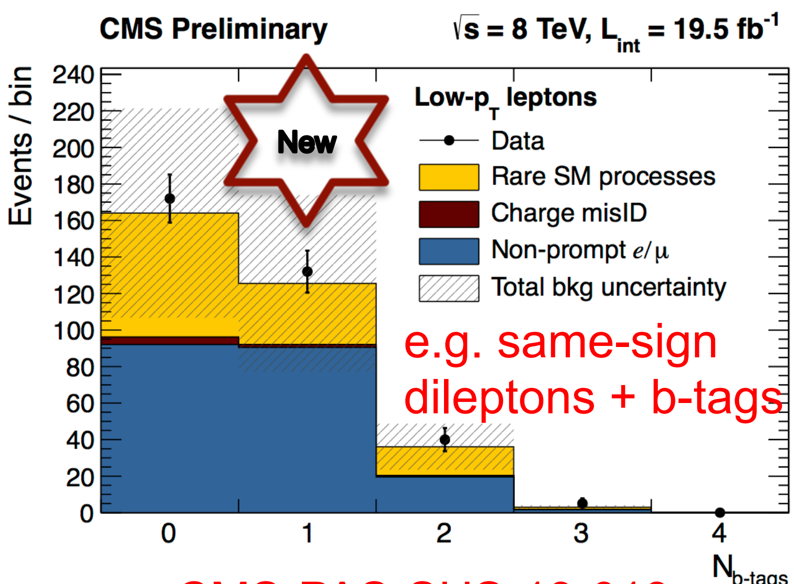
Gluino Mediated Stop and Sbottom Searches



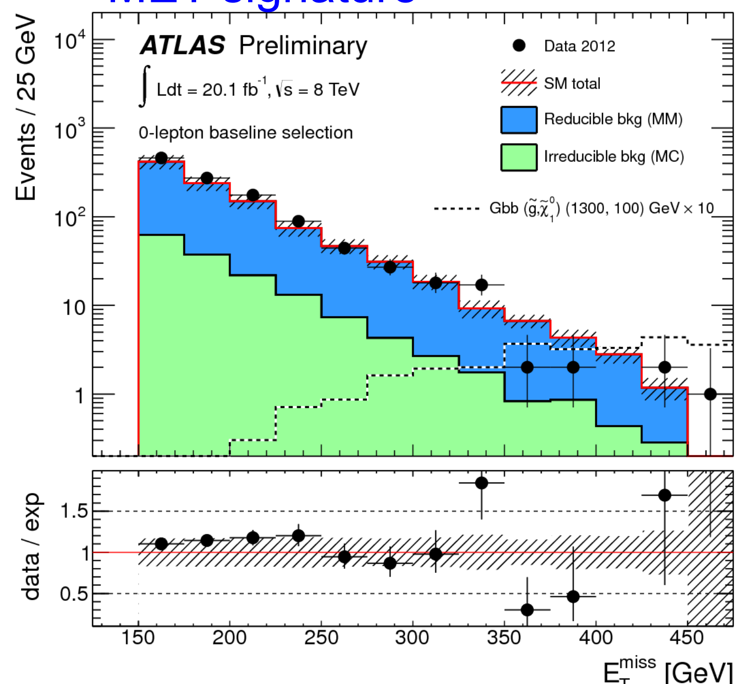


Muti-top final state → searches use 0, 1, 2 leptons + jets + b-jets + MET

Multi-bottom final state → b-jets + MET signature



e.g. same-sign dileptons + b-tags



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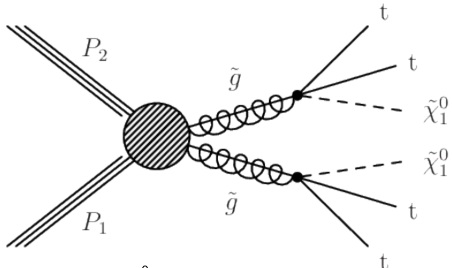
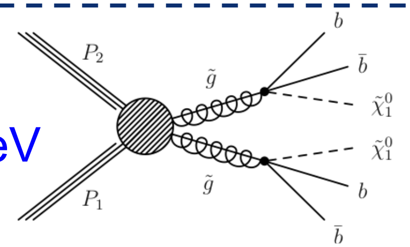
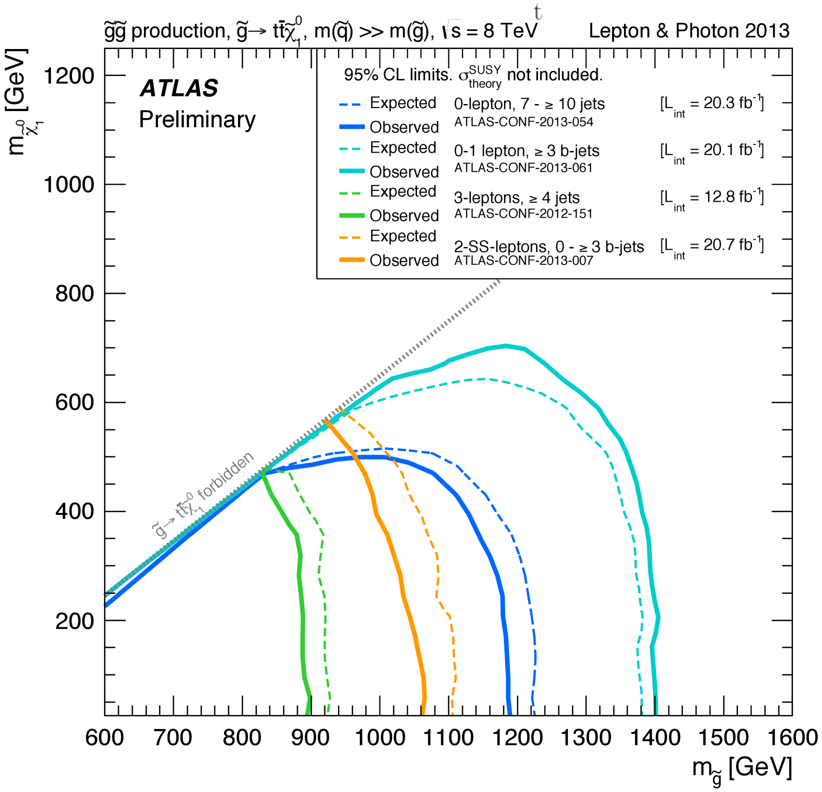
ATLAS-CONF-2013-061

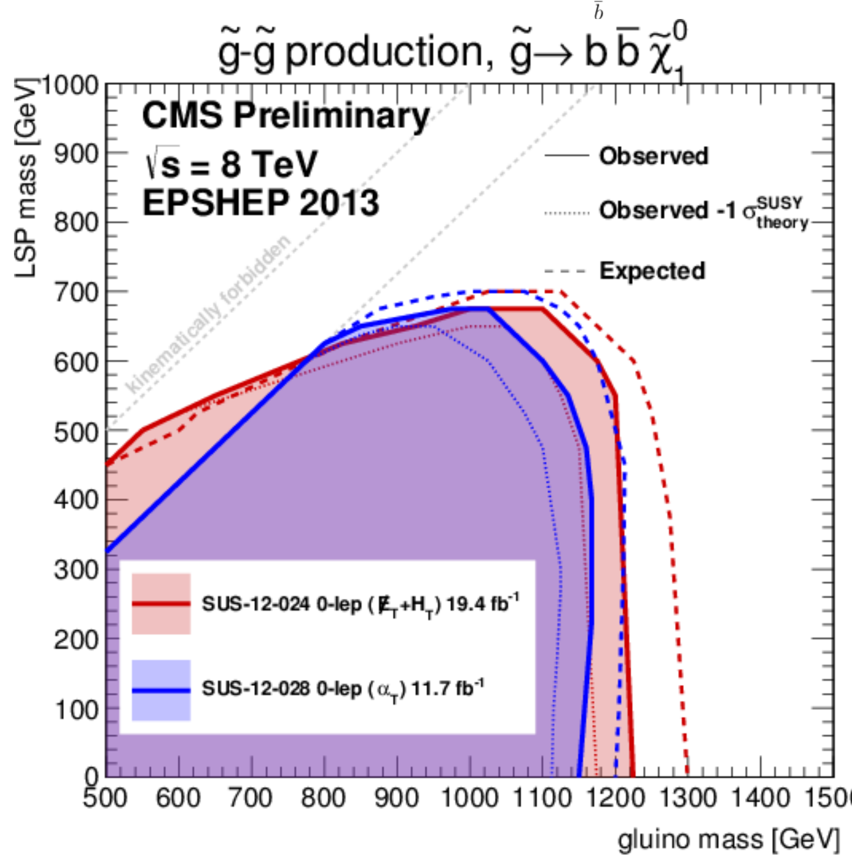
Summary: Gluino Mediated Stop and Sbottom Searches



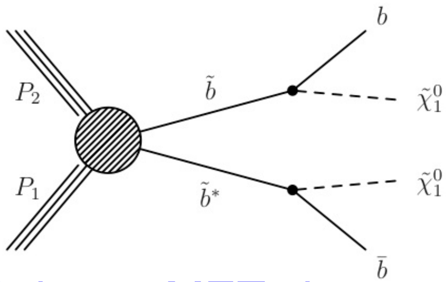
"Best" limits ~1.2-1.4 TeV



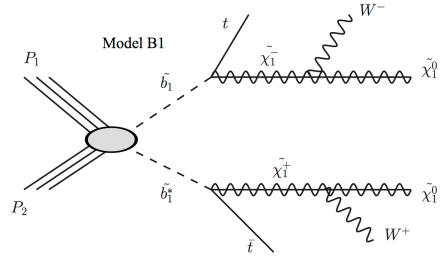




Direct Sbottom Searches



or



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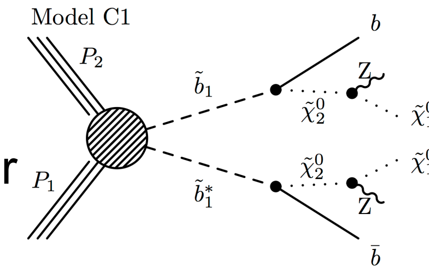
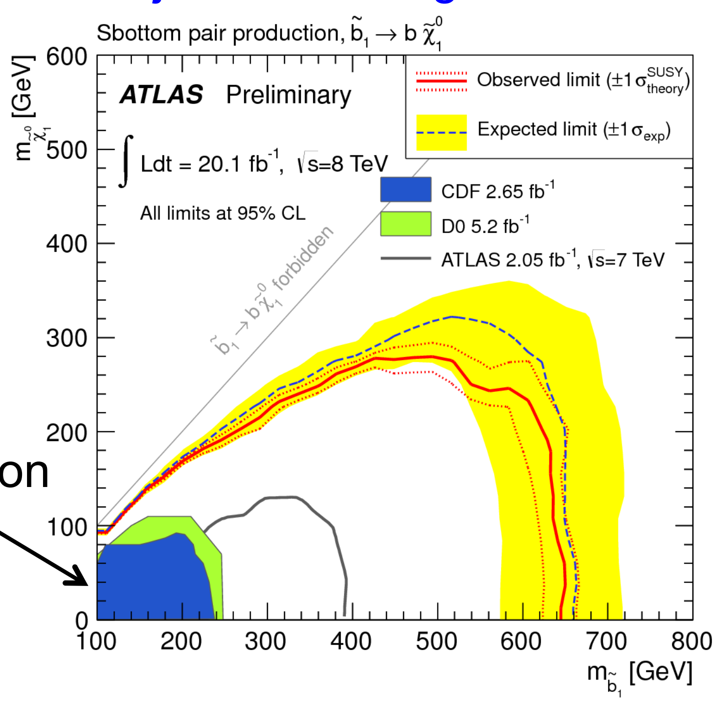
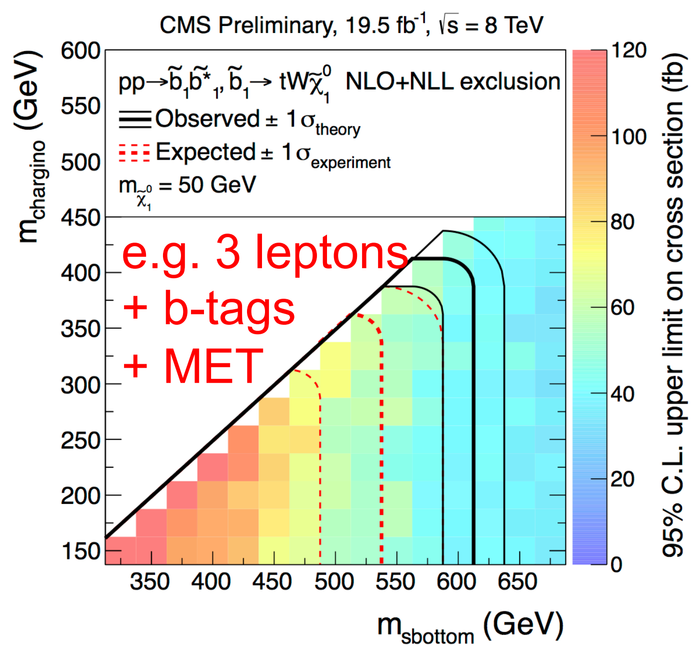


2 b-jets + MET signature

→ leptons + jets + b-jets + MET

Tevatron





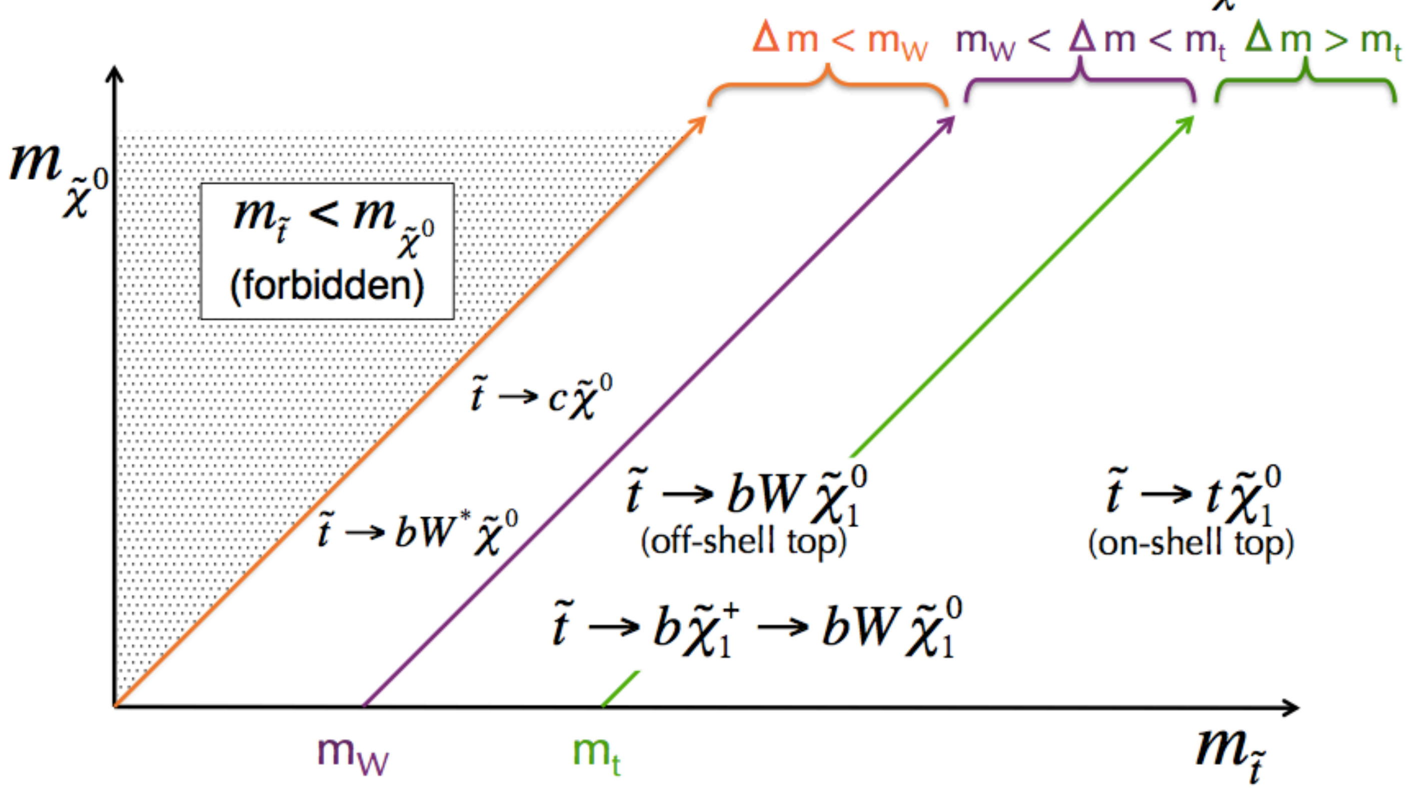
ATLAS-CONF-2013-053

CMS-PAS-SUS-13-008

Direct Stop Searches

- Several decay modes and final states (0, 1, 2 leptons) considered to cover range of kinematic regions
- So far 100% BR considered

$$\Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0}$$

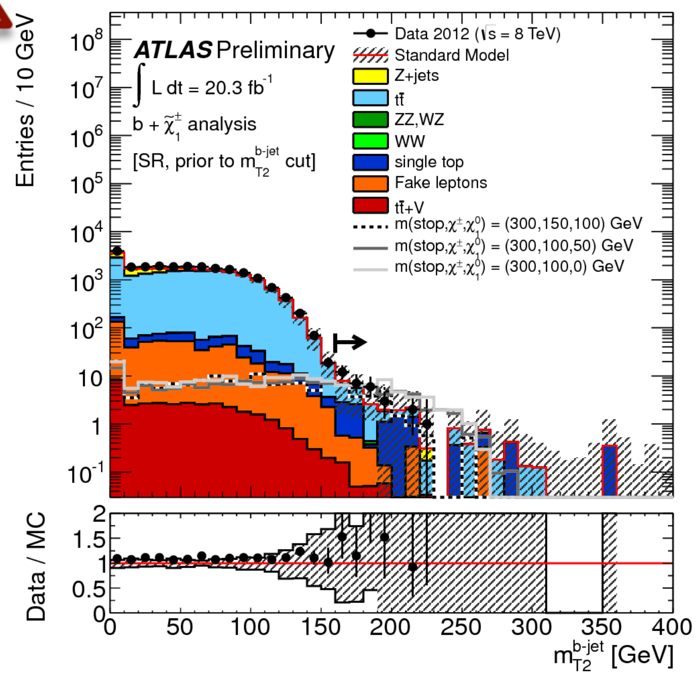


Direct Stop Searches

- Challenging analyses. Dominant backgrounds from top pair production and V+jets.
- Make use of shapes of kinematic variables (e.g. MT2b) and MVA's (e.g. BDT)
- Searches target 2-body/3-body decays & on/off-shell top regions

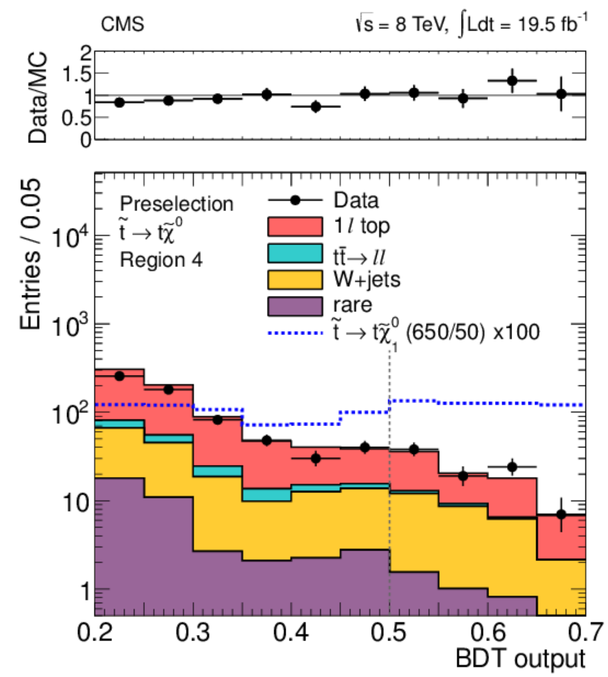
New

2 leptons + b-jets +MET



ATLAS-CONF-2013-065

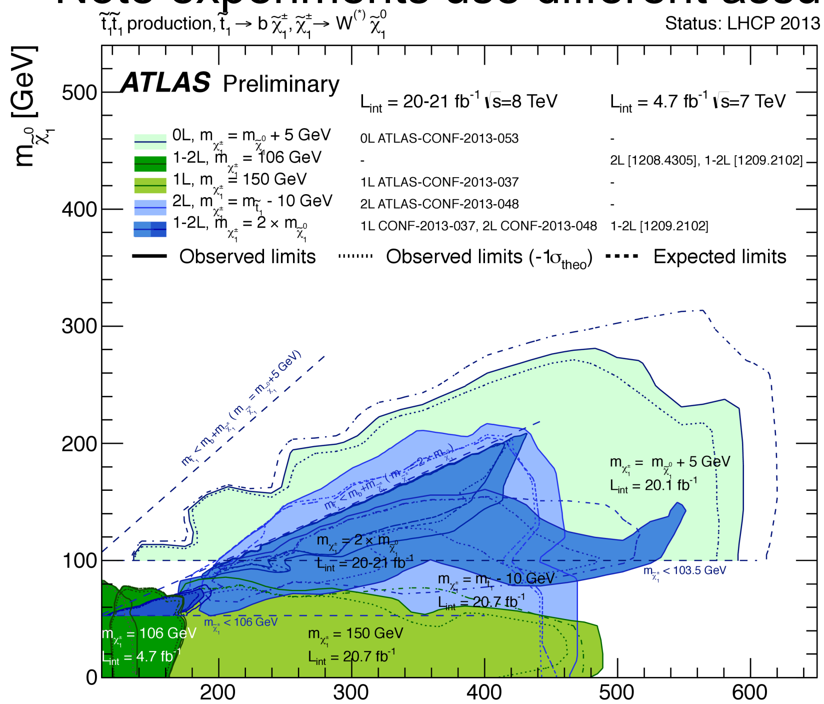
1 lepton + b-jets +MET



CMS-SUS-13-011 arXiv:1308.1586

Stop Results: $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow W^{(*)}\,\tilde{\chi}_1^0$

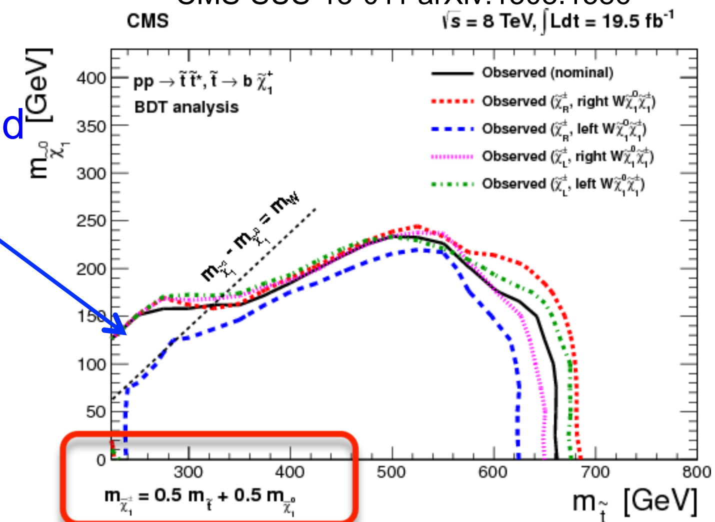
- Results depend on stop-chargino-LSP mass hierarchy
- Results depend on R/L charginos and couplings
- Note experiments use different assumptions

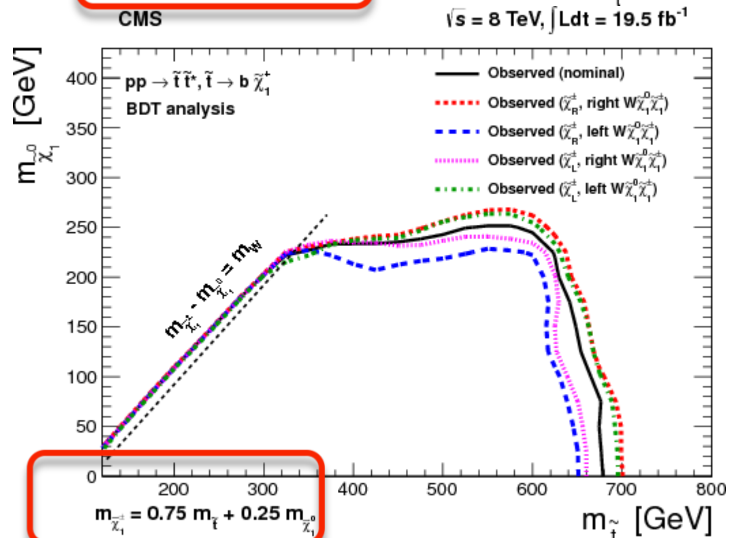


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots#SusyDirectStopSummary

W is virtual (compressed spectrum)

CMS-SUS-13-011 arXiv:1308.1586

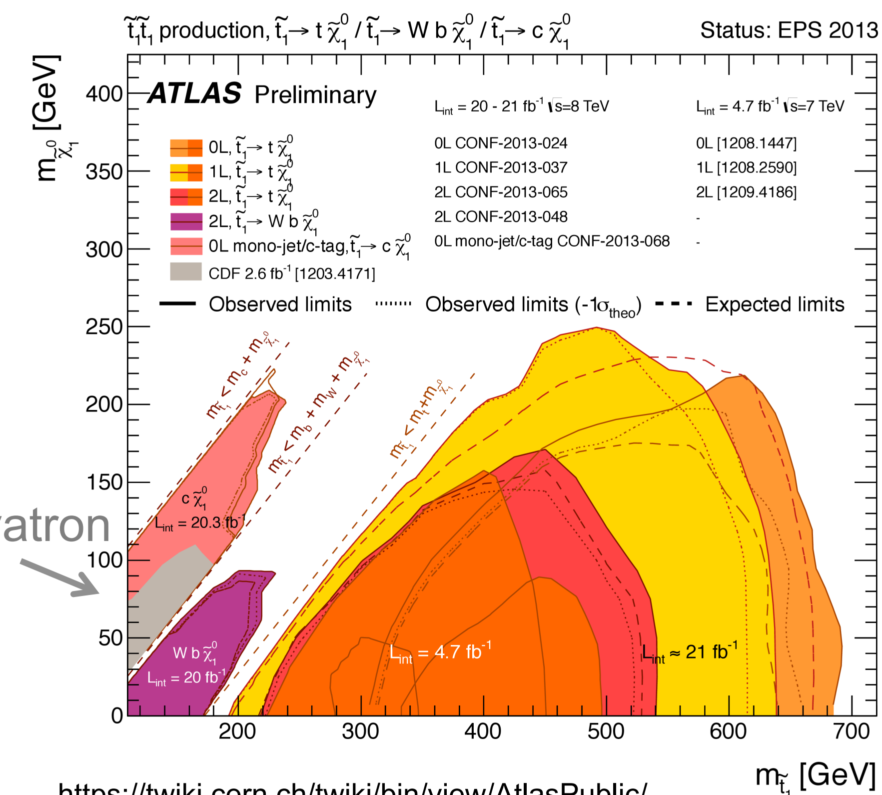




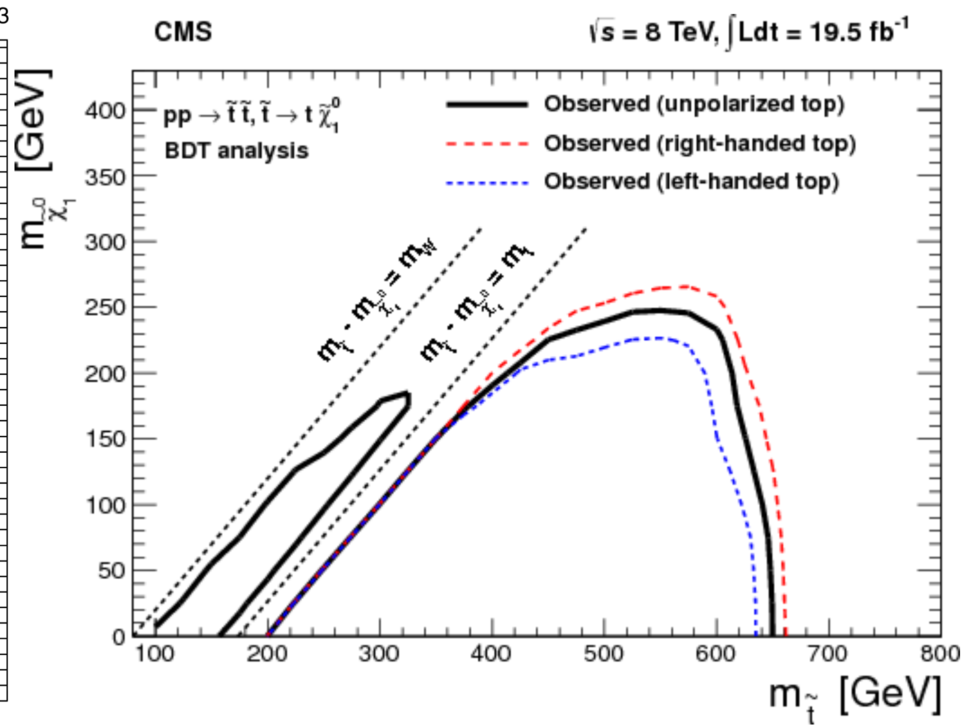
Stop Results: $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$

- Results depend on polarization of top quark
- New results on charm + LSP final state (next slide)

Tevatron

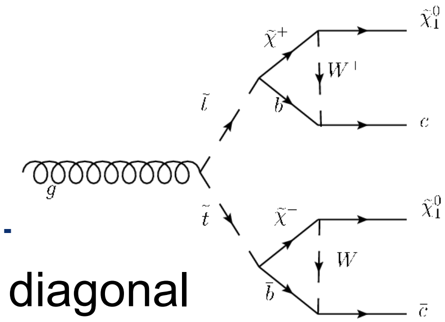


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots#SusyDirectStopSummary

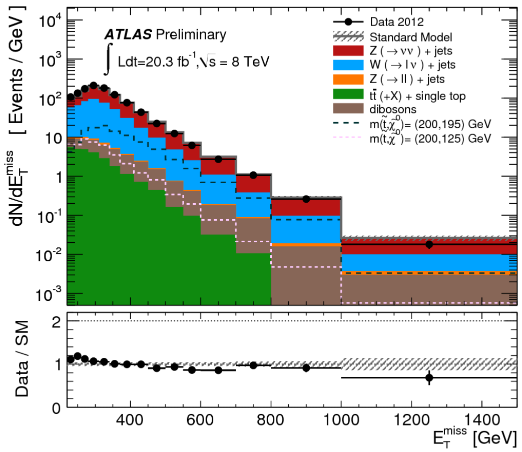


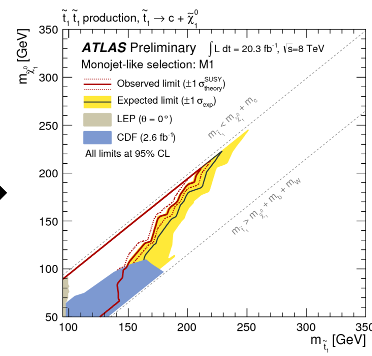
CMS-SUS-13-011 arXiv:1308.1586

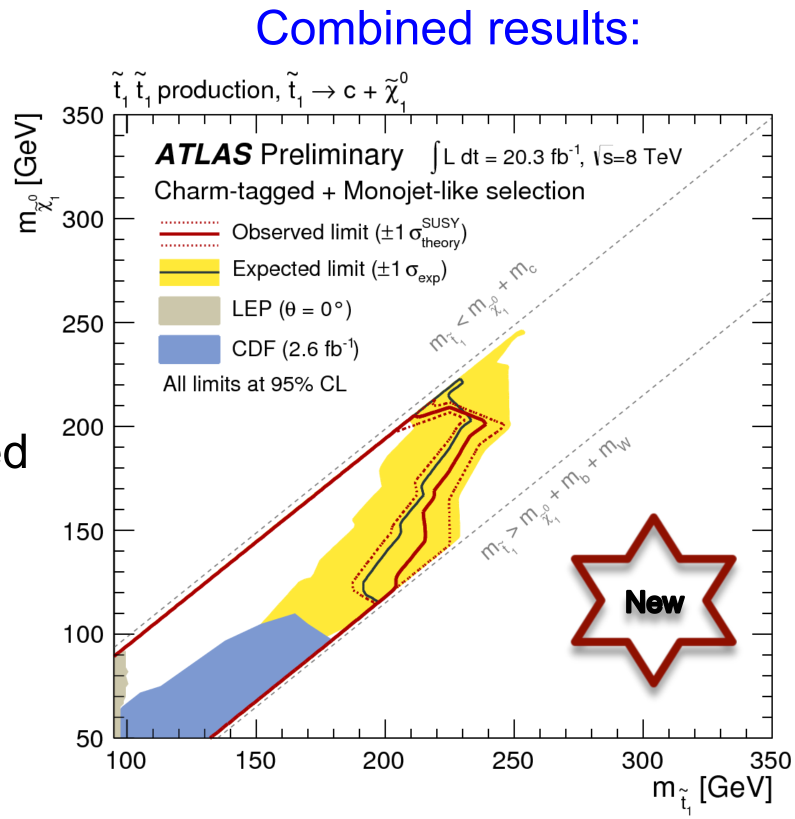
Stop Decay to Charm + LSP



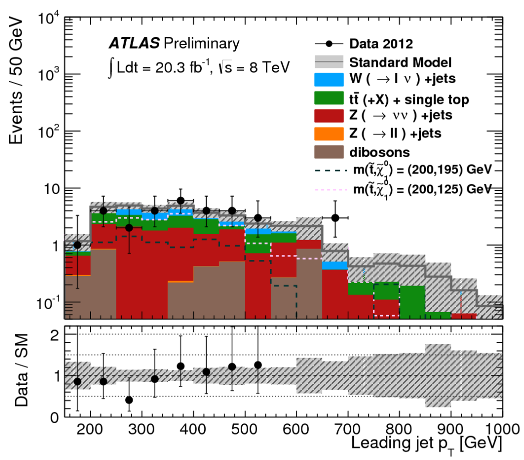
1) Mono-jet signature → use ISR jet to cover region near diagonal

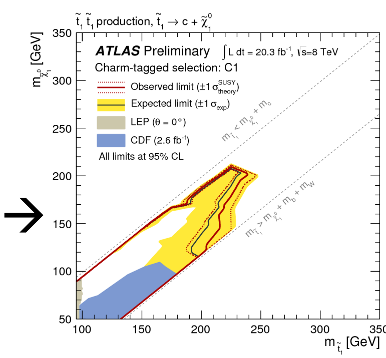






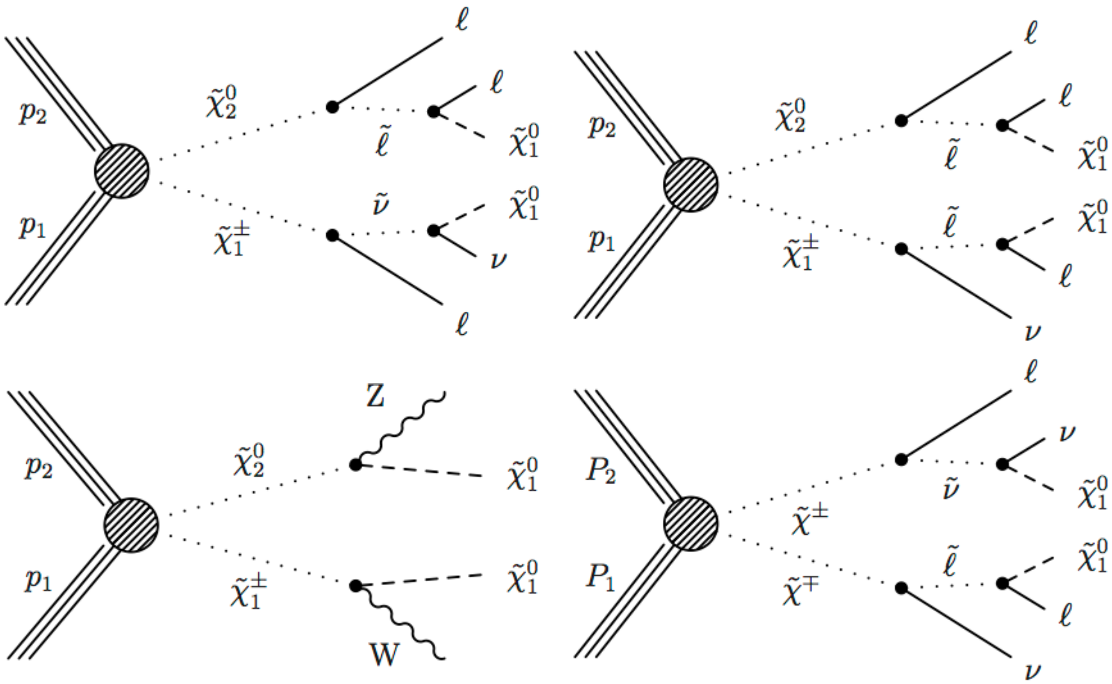
2) MVA based c-tagging → extend region covered





ATLAS-CONF-2013-068

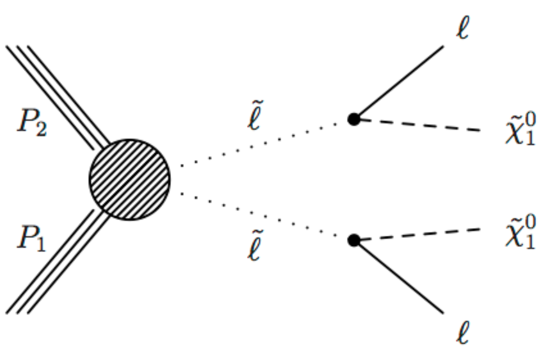
Searches for Production of EWKinos and Sleptons



- Extensive set of searches for chargino and neutralino production
- Final states and search strategy depends on assumption of sleptons masses: e.g. all light, only stau light, all heavy
- Signatures:

  2 (opposite and same sign),

  3, 4 leptons + MET

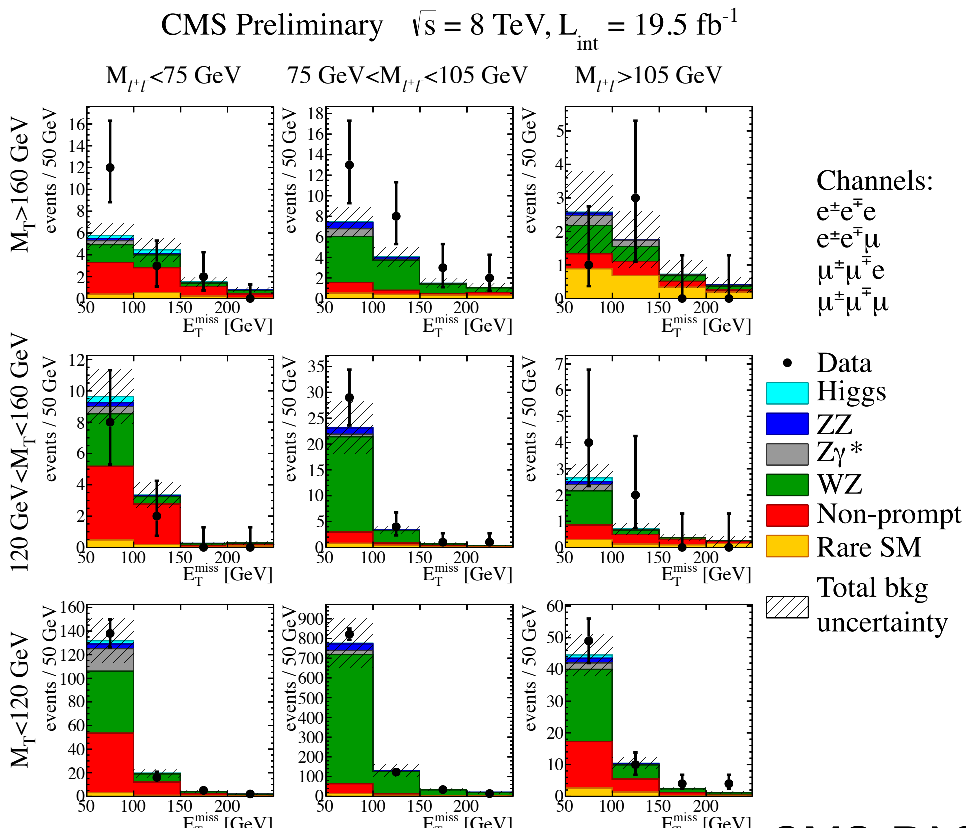


- Direct slepton production:

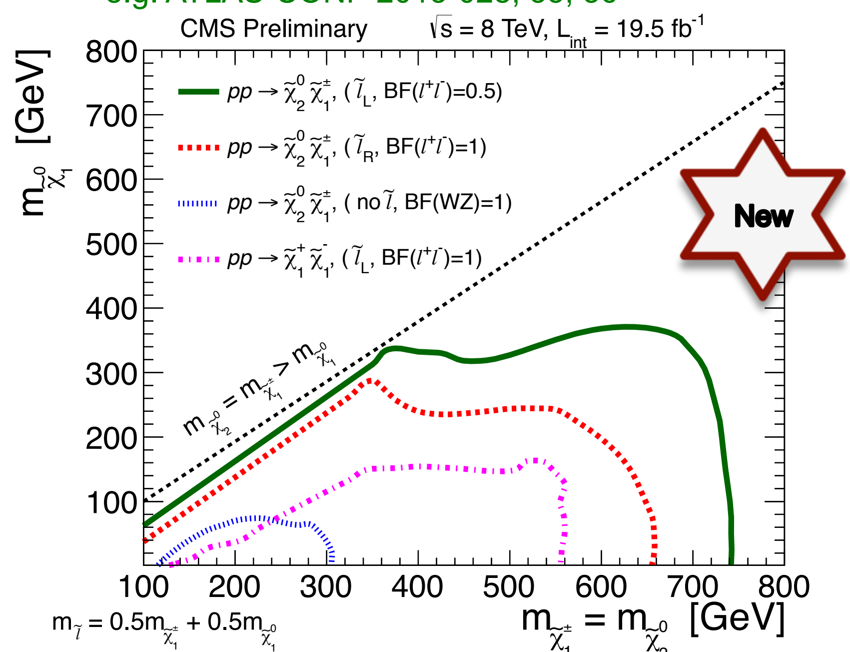
  2 leptons + MET

Summary of EWKino Searches

Example 3 leptons: $e^+e^-\ell$, $\mu^+\mu^-\ell$ signal regions in bins of $M_{\ell\ell}$, M_T and MET



- Results benefit from combining exclusive channels
- Considered flavor democratic, tau enriched/dominated, light/heavy slepton scenarios
- Similar results also from ATLAS
  e.g. ATLAS-CONF-2013-028, 35, 36

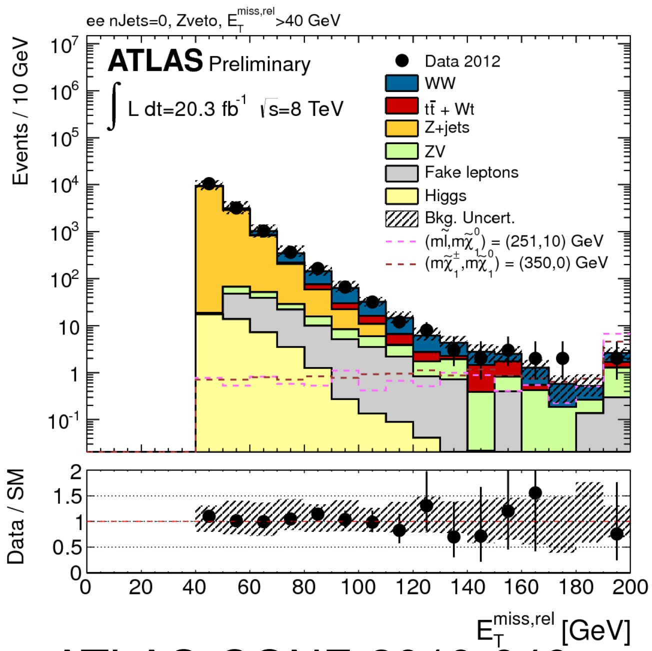


CMS-PAS-SUS-13-006

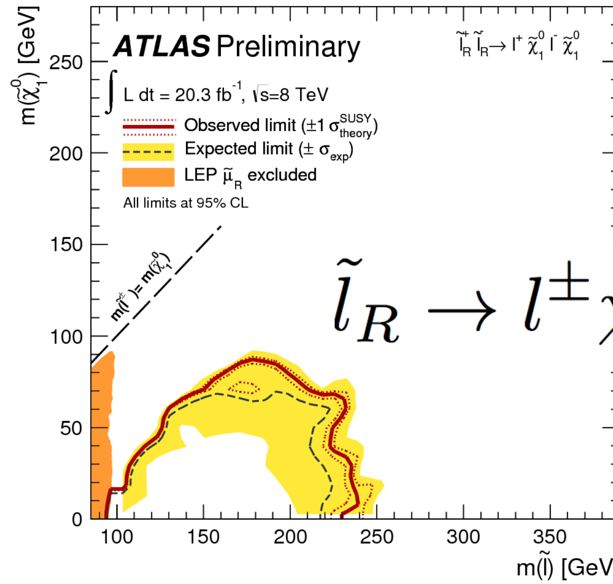
Direct Slepton Searches

- ee or μμ + MET
- Limits for R/L sleptons
  - R-slepton cross section ~2.5x smaller
- Similar results from CMS (for L-slepton)

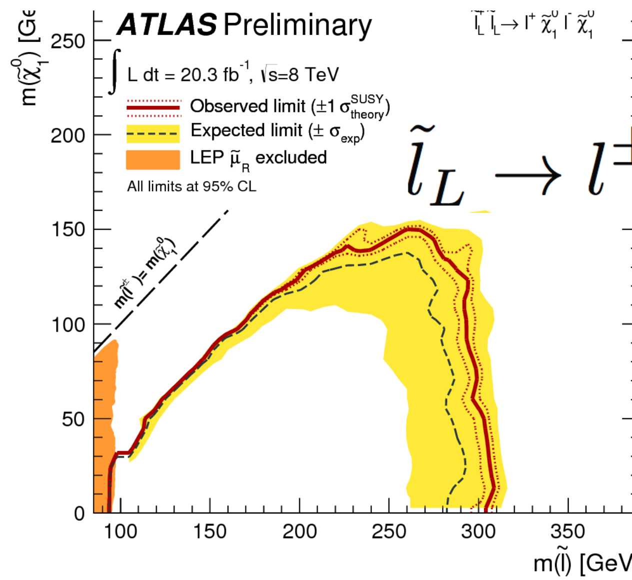
e.g. MET for ee channel



ATLAS-CONF-2013-049



$$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$$



$$\tilde{l}_L \rightarrow l^{\pm}\chi_1^0$$

RPV Searches

- Program of searches for RPV: leptonic, LQD and hadronic RPV
- No dark matter candidate, but could still address naturalness
- Low MET final states; resonances

$$W \propto \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c U_k^c D_k^c + \mu_i H_u L_i$$

Leptonic RPV

LQD ("semi-leptonic") RPV

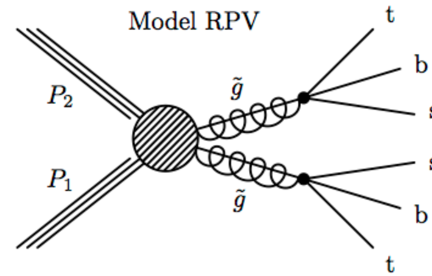
Hadronic RPV

- e.g. Summary of RPV searches from ATLAS. CMS similar.

RPV	LFV $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e + \mu$	$2\ e, \mu$	0	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05
	LFV $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e(\mu) + \tau$	$1\ e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05
	Bilinear RPV CMSSM	$1\ e, \mu$	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}<1$ mm
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	$4\ e, \mu$	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	$3\ e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0
	$\tilde{g} \to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV	
	$\tilde{g} \to \tilde{t}_1 t, \tilde{t}_1 \to bs$	$2\ e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV	

- I will focus on two new results on hadronic RPV

Searches for Hadronic RPV

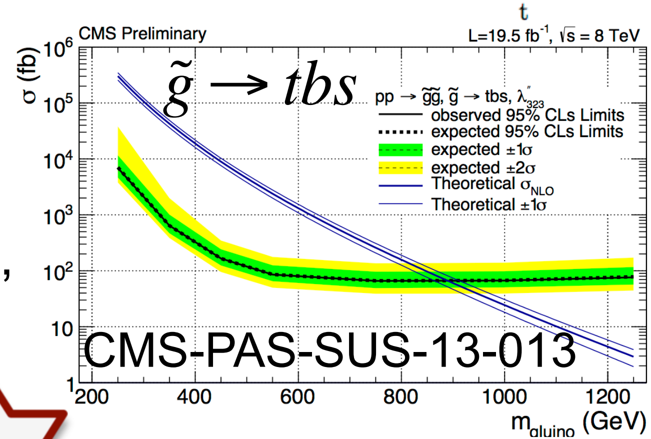


or

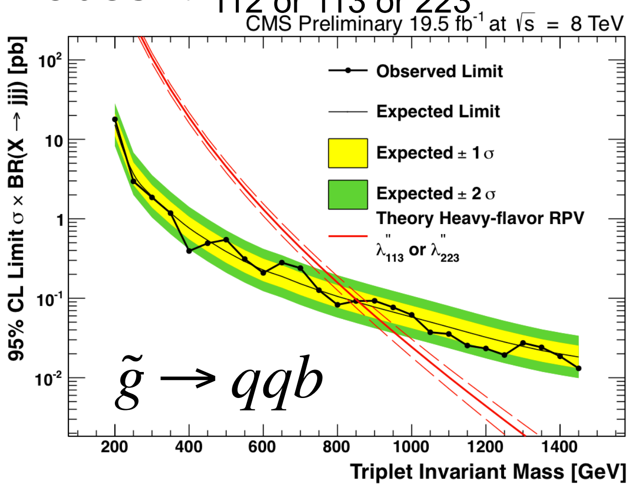
q
q
q (b)
q
q
q (b)

1) Search for $\tilde{g} \rightarrow tbs$ in same sign dilepton final state + jets + b-jets and no MET
   - Clean signature, low backgrounds
   - Probes λ''_{323}

2) Search for $\tilde{g} \rightarrow qqq$ or qqb in 6-jet final state, with and without b-tags
   - Use 3-jet resonance and "jet ensemble" technique to reduce background
   - Probes $\lambda''_{112 \text{ or } 113 \text{ or } 223}$



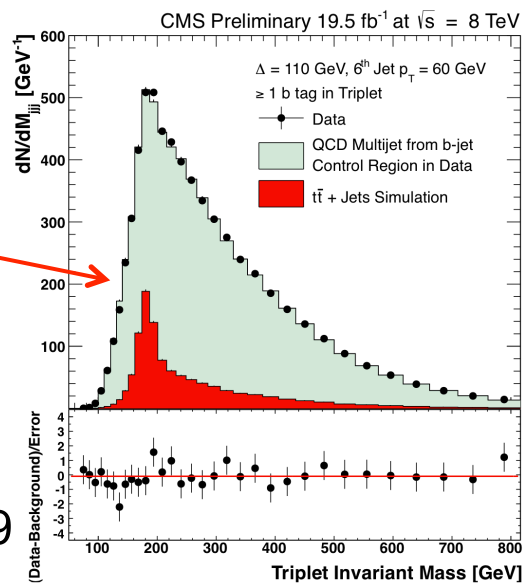
New



Top quark contributes to bkg in heavy flavor analysis

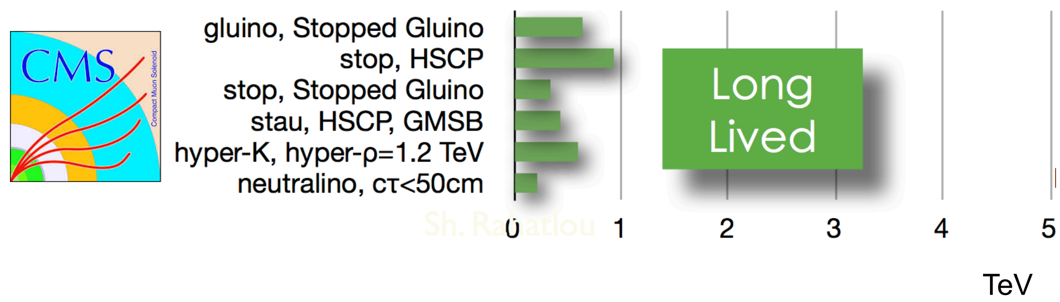
First limits on $\lambda''_{113/223}$

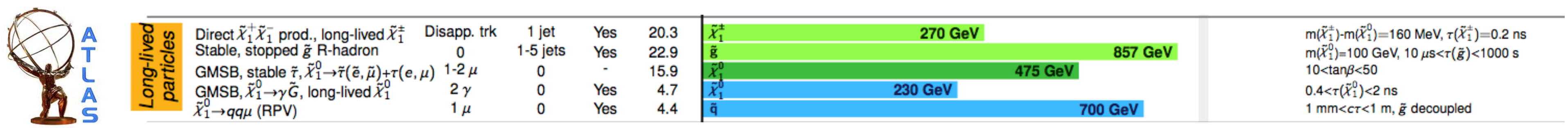
CMS-PAS-EXO-12-049



Long Lived Particles

- Predicted in many extensions of the SM: GMSB, “split” SUSY, hidden valley models, etc.
- Several ways to look for them; typically need specialized algorithms/tools
  - Displaced tracks
  - Highly ionizing tracks
  - Out-of-time particles
  - Non-pointing photons
  - …





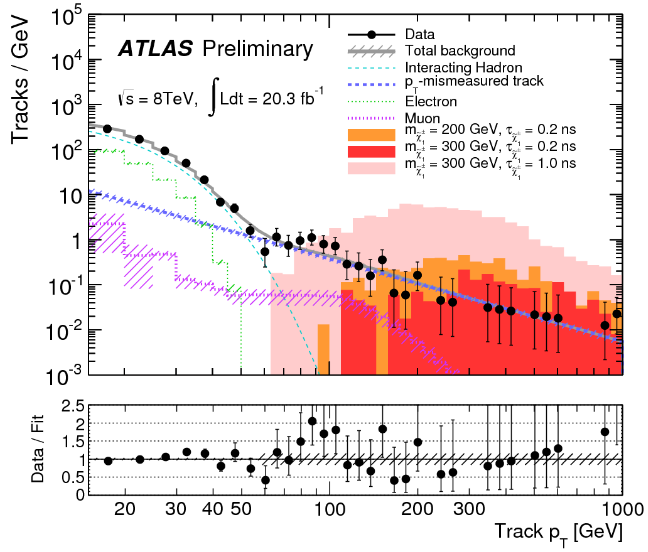
- I will focus on one new result:
  - Long-lived charginos → disappearing tracks [ATLAS]

Search for Disappearing Tracks

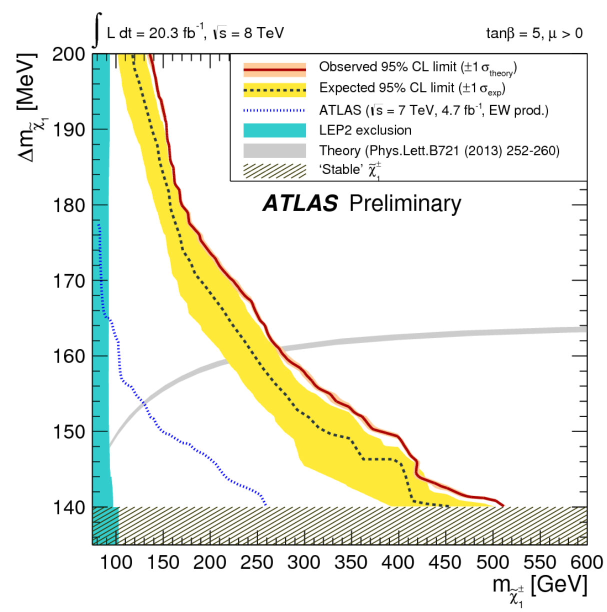
New

- Model: charginos and neutralinos almost mass degenerate (Δm =160MeV)
  - e.g. in Anomaly Mediated SUSY Breaking (AMSB)
  - Metastable chargino with significant lifetime (τ~0.2ns or 6cm)
- Characteristic: disappearing tracks in inner detector
  - i.e. identify tracks with no associated hits in the outer tracker
- $M_{chargino}$ < 270 GeV excluded for model assumptions above

p_T of disappearing track candidates



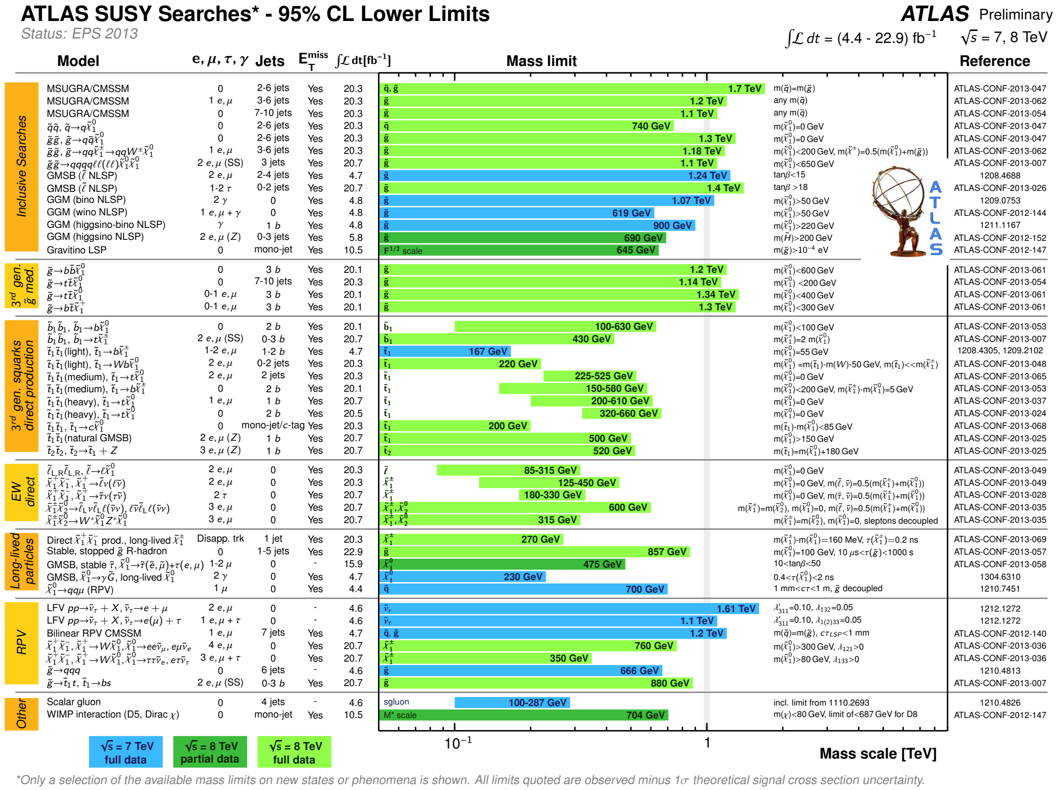
Sensitive to τ ~1-10 ns and masses up ~500 GeV

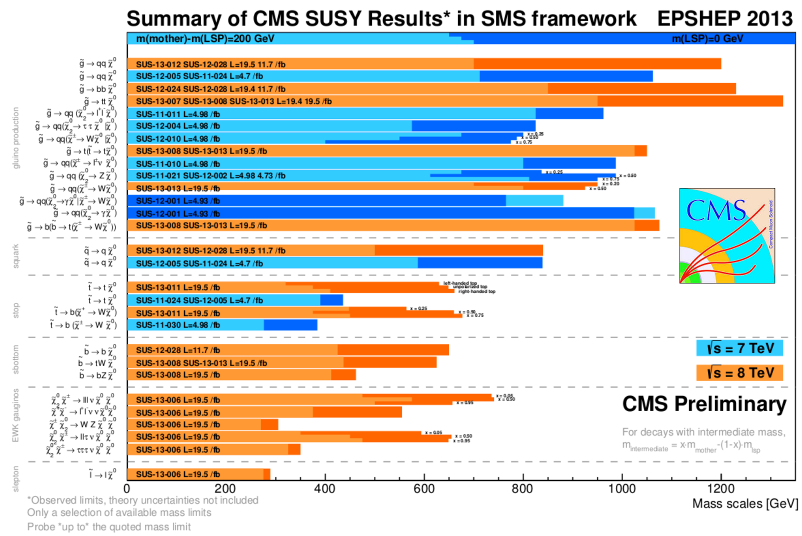


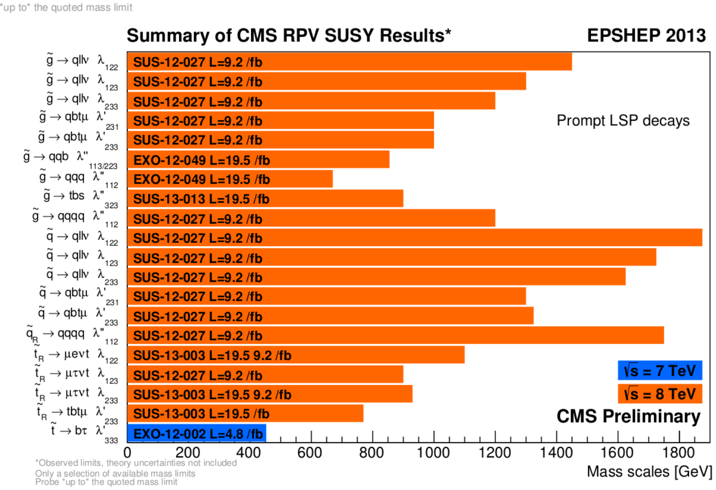
ATLAS-CONF-2013-069

The Big Picture

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS







Probing the Terascale!

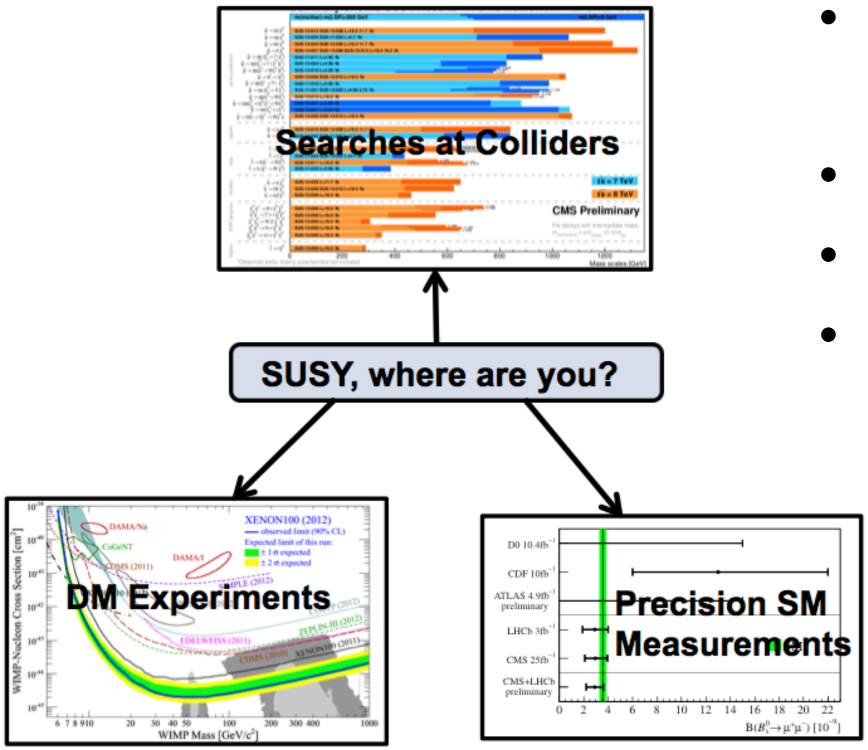
Many other searches that I didn't cover:

e.g. GMSB, pMSSM, DM, …

Many new results to come in the near future …

Summary

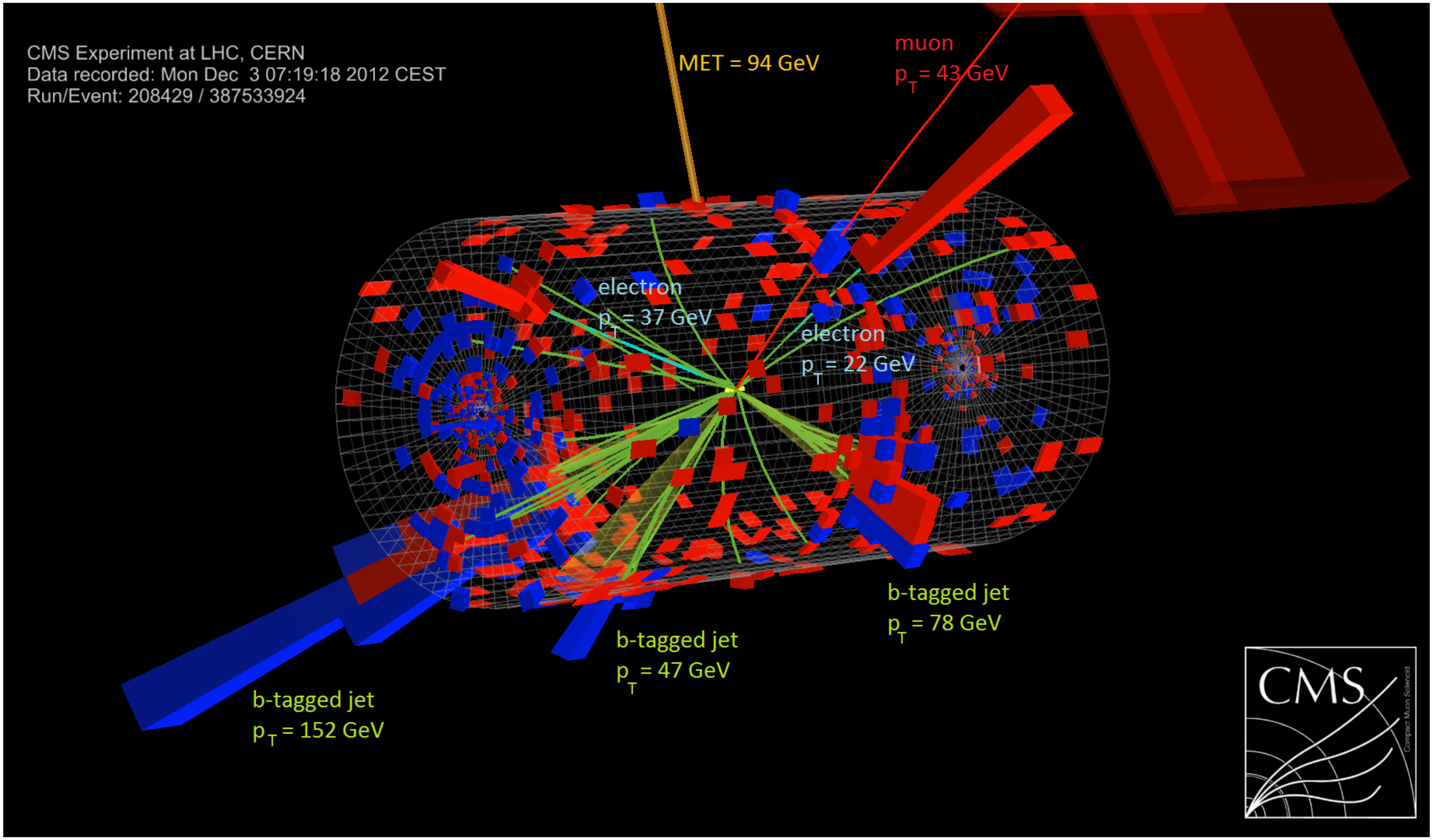
Putting it all together:



- No evidence for SUSY so far.
- Stringent limits placed.
  - With caveats; simplified models
- But, the search for SUSY is far from over!
- We are leaving no stone unturned
- At the LHC:
  - Focusing more and more on "difficult regions", e.g. compressed spectra
  - Combinations of channels will help with big picture and conclusions from 8TeV run
  - Preparing for 2015, and gearing up for (hopefully) discovery!

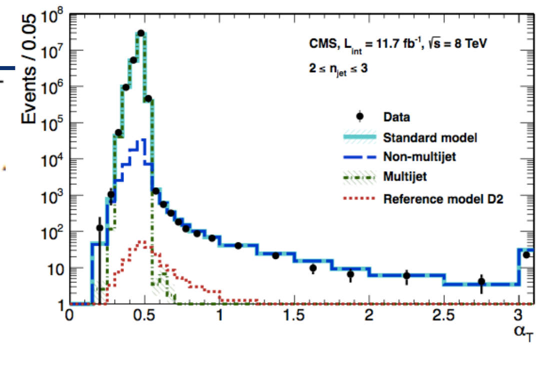
Backup

Spectacular Event with 3 Leptons and 3 b-tags



CMS-PAS-SUS-13-008

Examples of Kinematic Variables



- alpha$_T$ $\alpha_T = E_T^{j2} / M_T = E_T^{j2} / \sqrt{H_T^2 - \not{H}_T^2}$

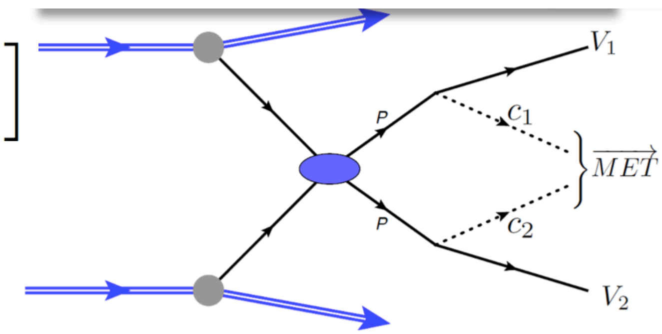
  =0.5 for a perfectly balanced dijet event

  $$H_T = \sum_{i=1}^{N_{jet}} E_T$$

  $$\not{H}_T = \left| \sum_{i=1}^{N_{jet}} \vec{p}_T \right|$$

- M_{T2} $M_{T2} = \min_{p_T^{c1} + p_T^{c2} = \not{p}_T} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right]$

  Kills QCD efficiently.
  ~0 for dijet events



- Razor

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}\,.$$

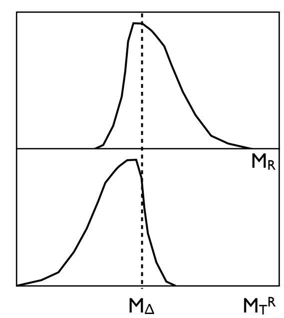
← M_R peaks at M_Δ

$$M_T^R \equiv \sqrt{\frac{\not{E}_T (p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

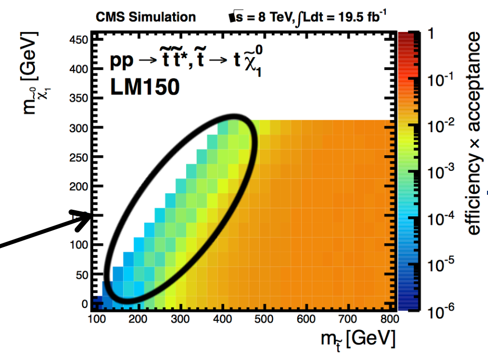
← M_Δ edge in M_T^R

$$R \equiv \frac{M_T^R}{M_R}$$

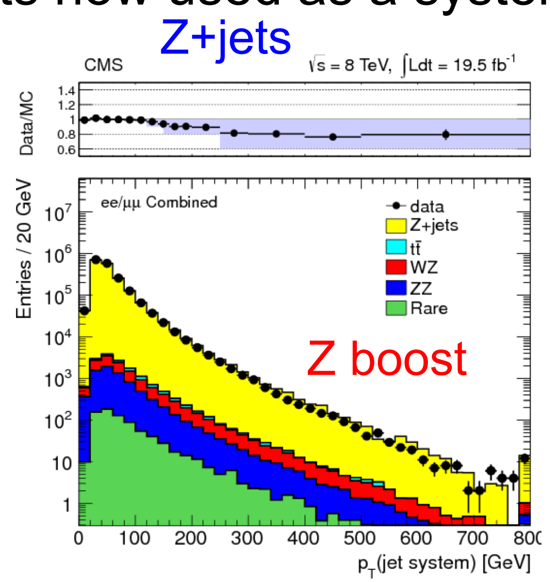
← R is ratio of the two and related to MET

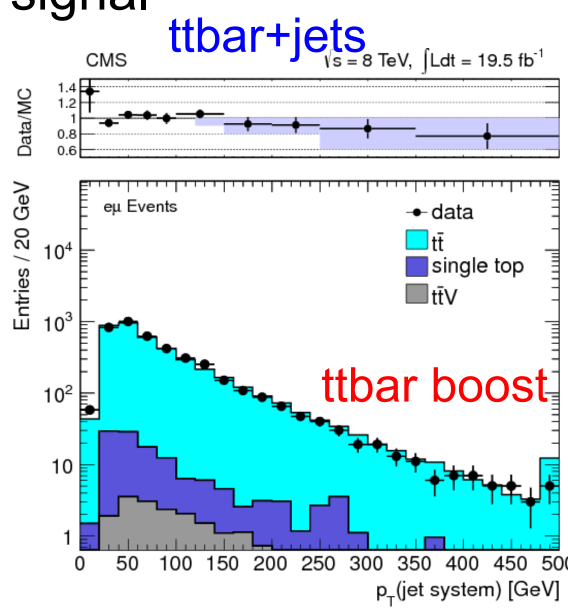


Treatment of ISR



- Signal efficiency for compressed spectra relies on ISR jet production
- At CMS, we studied with data how well the MC accounts for this effect
  - Different initial state partons → consistent results
- Results now used as a systematic for signal



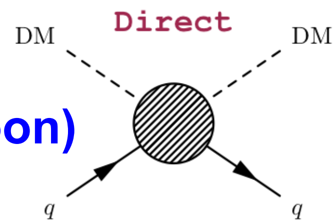


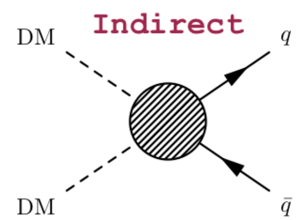
- ATLAS and some CMS analyses also estimate ISR systematic by varying normalization and factorization scales in MC

Searches for Dark Matter Pair Production

- DM Searches:

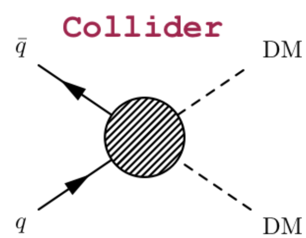
(see talks this afternoon)





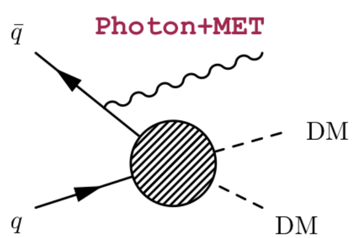
- Collider searches:

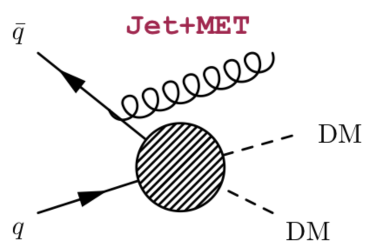
(also see next talk by G. Brooijmans)

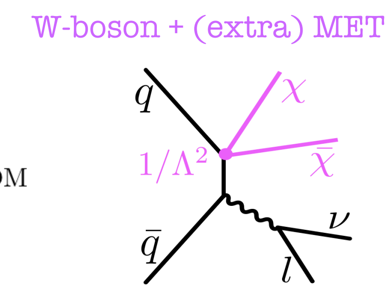


Rotate Feynman diagrams assumed in direct-detection experiments (use s-channel, instead of t-channel mode)

  – How? Use QED/QCD initial state radiation (ISR) of photon, jet or a W/Z boson to "tag" DM events







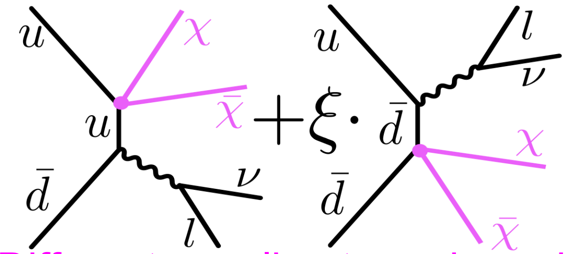
Contact Interaction term:

couplings to χ and q

$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M_M^2}$$

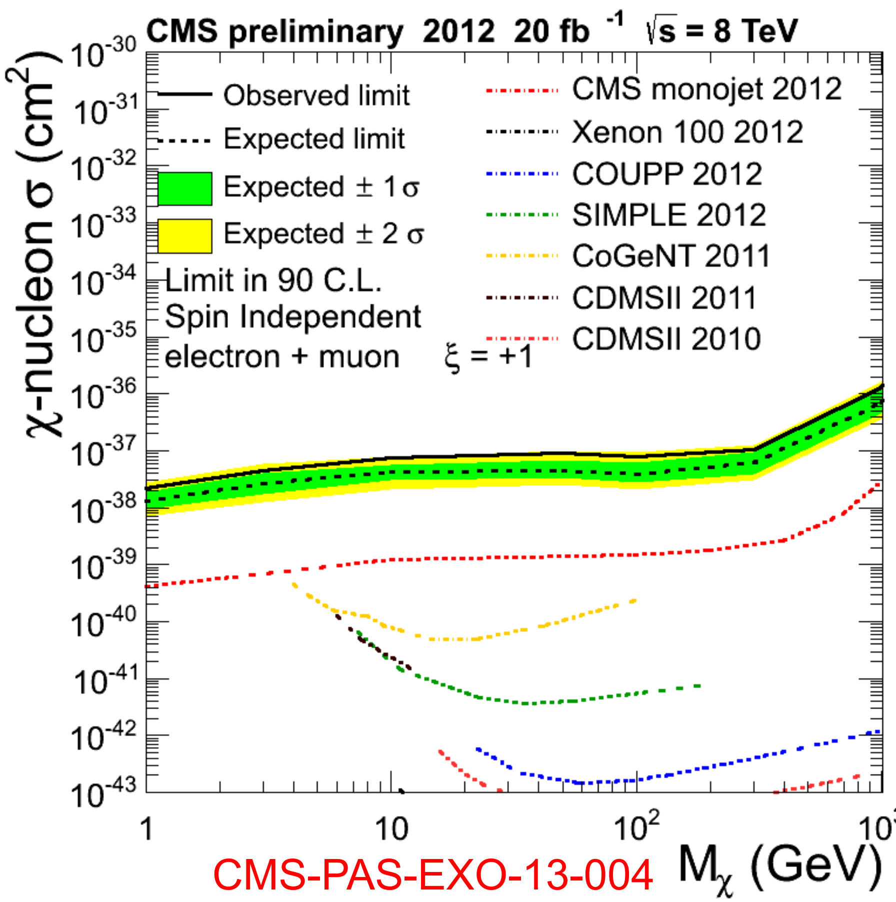
Mono-X DM Searches

New



Different coupling to u, d quarks

Example: Mono-lepton W→ℓν + MET signature



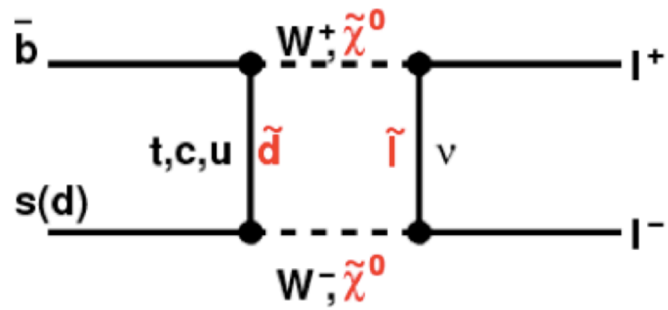
CMS-PAS-EXO-13-004

Both CMS and ATLAS experiments use such searches to set limits on spin independent (vector-like) and spin-dependent (axial-vector-like) scattering

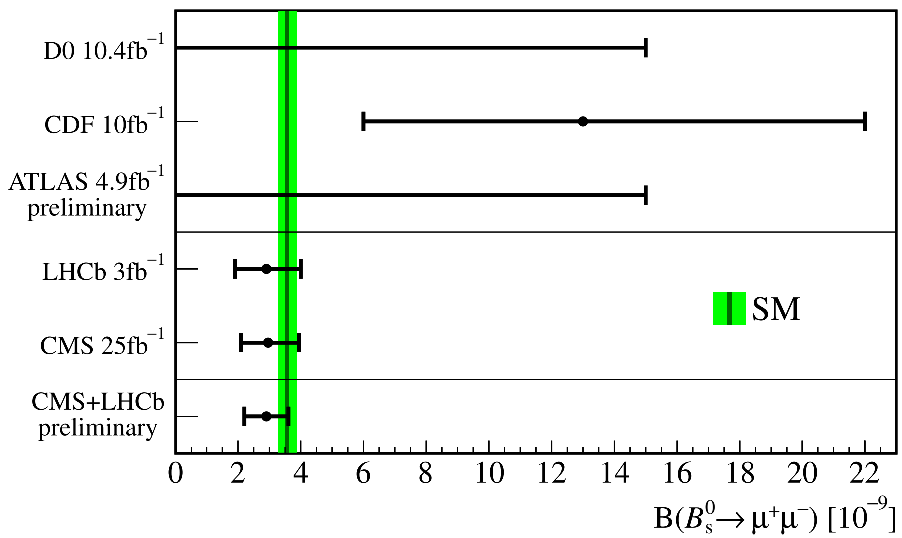
Comparisons to DM experiments

See next talk by G. Brooijmans for more details

Measurement of $B_s \rightarrow \mu\mu$



- $B_S \rightarrow \mu\mu$ rare process in the SM
- Sensitive to new physics, e.g. SUSY
- New results from CMS and LHCb experiments!
  - **First observation of $B_S \rightarrow \mu\mu$!**



CMS 25 fb^{-1}

$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$ 4.3 σ

LHCb 3 fb^{-1}

$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$ 4.0 σ

Combined:

$$BR(B_S^0 \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

Best Mass Limits Summary

EPS 2013 Direct SUSY Searches, O. Buchmüller

Direct squark	$\tilde{q} \to q\chi_1^0$	$\tilde{u}_L \to q\chi_1^0$	$\tilde{b} \to b\chi_1^0$	$\tilde{t} \to t\chi_1^0$
Best limit: [GeV]	~850	~500	~650	~650
No limit for M_{LSP}[GeV]	~ 300	~120	~270	~260

coloured sparticle production

(from O. Buchmueller, EPS2013)

Direct squark	$\tilde{g} \to q\bar{q}\chi_1^0$	$\tilde{g} \to b\bar{b}\chi_1^0$	$\tilde{g} \to t\bar{t}\chi_1^0$
Best limit: [GeV]	~1200	~1200	~1400
No limit for M_{LSP}[GeV]	~480	~650	~700

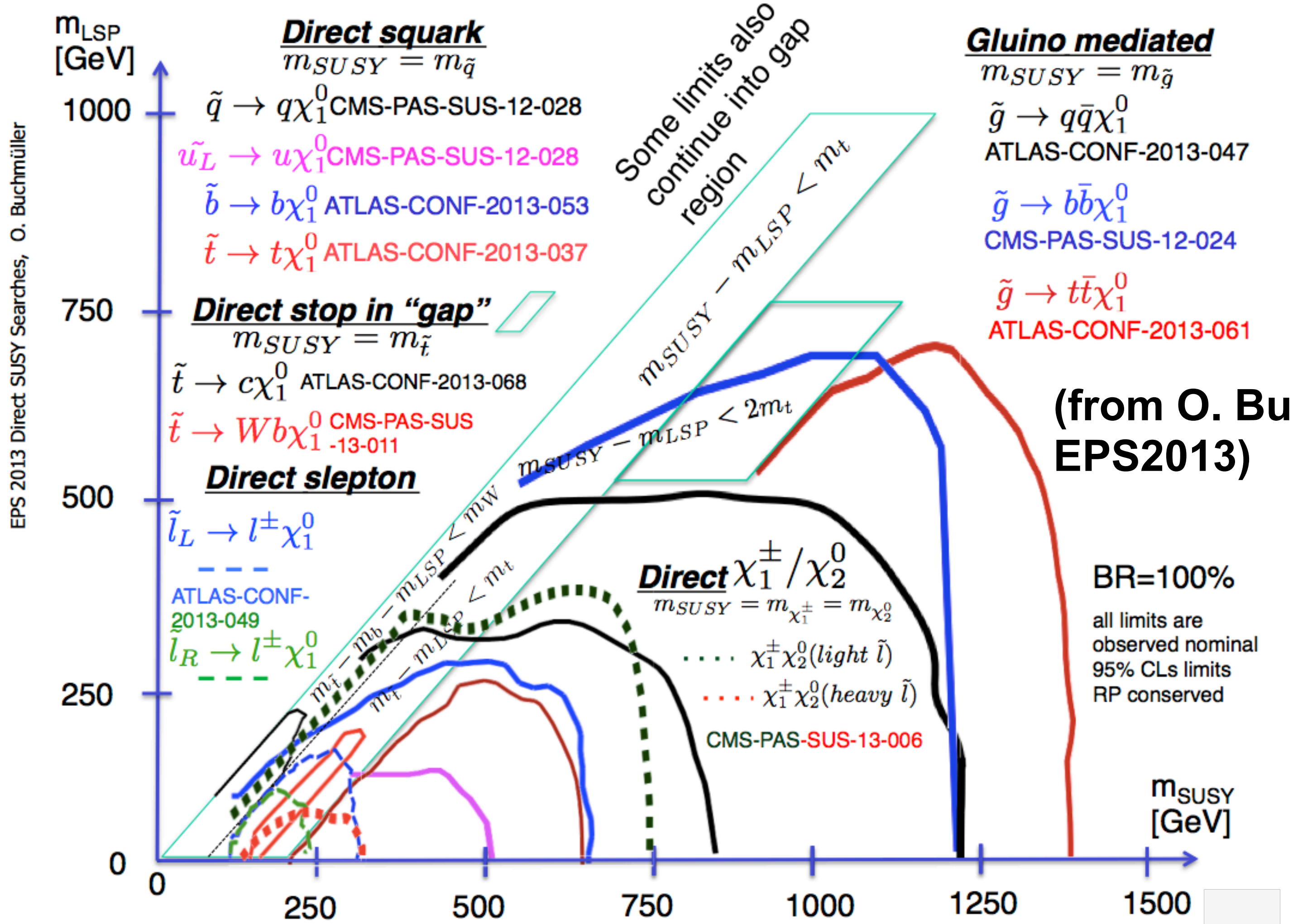
Stop $M_{stop} - M_{Lsp} < M_{top}$	$\tilde{t} \to c\chi_1^0$	$\tilde{t} \to Wb\chi_1^0$
Best limit: [GeV]	~240	~320
No limit for M_{LSP}[GeV]	~210	~190

EWK sparticle production

Direct slepton	$\tilde{l}_L \to l^{\pm}\chi_1^0$	$\tilde{l}_R \to l^{\pm}\chi_1^0$
Best limit: [GeV]	~300	~240
No limit for M_{LSP}[GeV]	~150	~90

$\chi_1^{\pm}\chi_2^0$	*light* $\tilde{l}$	*heavy* $\tilde{l}$
Best limit: [GeV]	~750	~300
No limit for M_{LSP}[GeV]	~350	~60

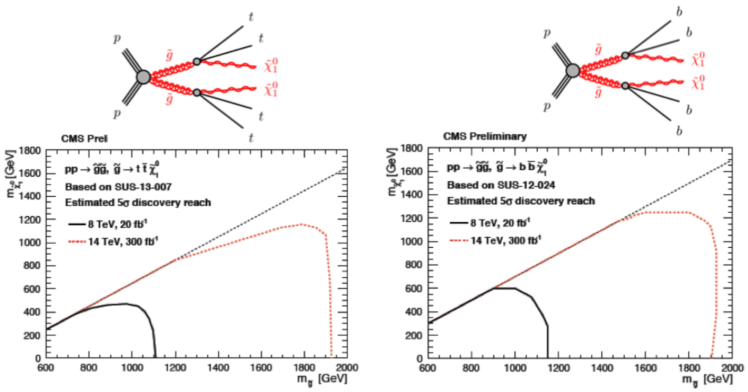
SMS Limits Summary



(from O. Buchmueller, EPS2013)

Recently Shown at Snowmass **(from B. Heinemann)**

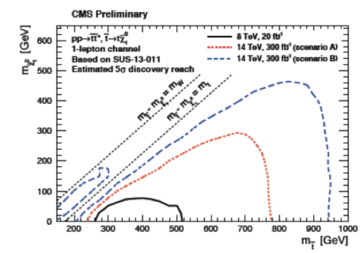
Gluino reach if decay via top/bottom

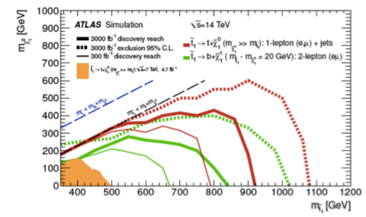


- With 300 fb^{-1} will reach about 2 TeV in gluino mass both in top- and b-decay signatures
  - 3000 fb^{-1} study ongoing

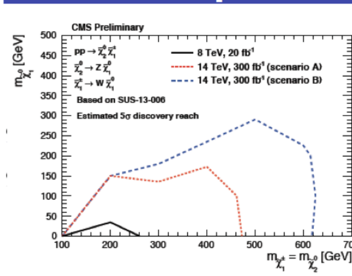
Top squark discovery potential

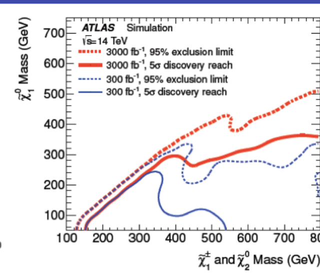
- Challenging analysis due to large top background
  - Systematic uncertainties matter
- 300 fb^{-1}:
  - Discovery up to 800-900 GeV in direct production
- 3000 fb^{-1}:
  - Reach improved by ~140 GeV in m(stop) and ~100 GeV in m(LSP)
- Expect further improvements with reoptimization





Future Prospects for Weak SUSY Production





- Probe chargino masses of ~500 GeV with 300 fb^{-1}
  - for m(LSP)<100-200 GeV
- Dramatic improvement with HL-LHC:
  - Reach >800 GeV for m(LSP)<300 GeV

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