THE UNIVERSITY of ADELAIDE

Experimental SUSY searches (~LHC)
Lecture 2

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Reminder of lecture 1

• We have no idea exactly what SUSY will look like at the LHC

  - naturalness is nice, but doesn't give us many clues
  - the Higgs boson discovery complicates matters
  - null observation so far is perfectly consistent with both SUSY and the Higgs mass

• Lots of potential options to look for:

  - high multiplicity final states, or low multiplicity

  - lots of missing energy or not very much missing energy

• LHC detectors give us:

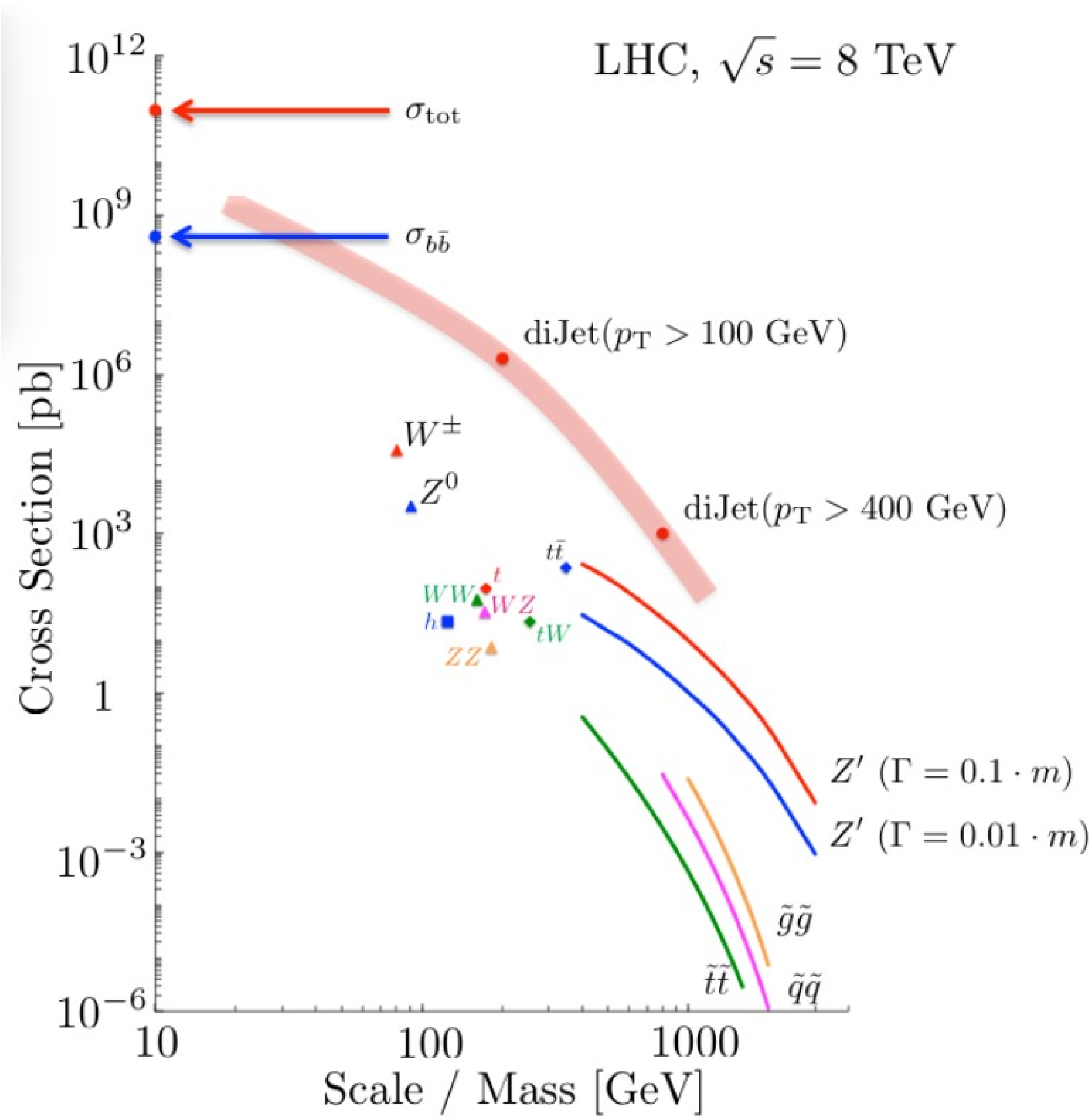
  - particle ID and four vectors for jets, leptons and photons

  - tau and b tagging

  - missing transverse energy

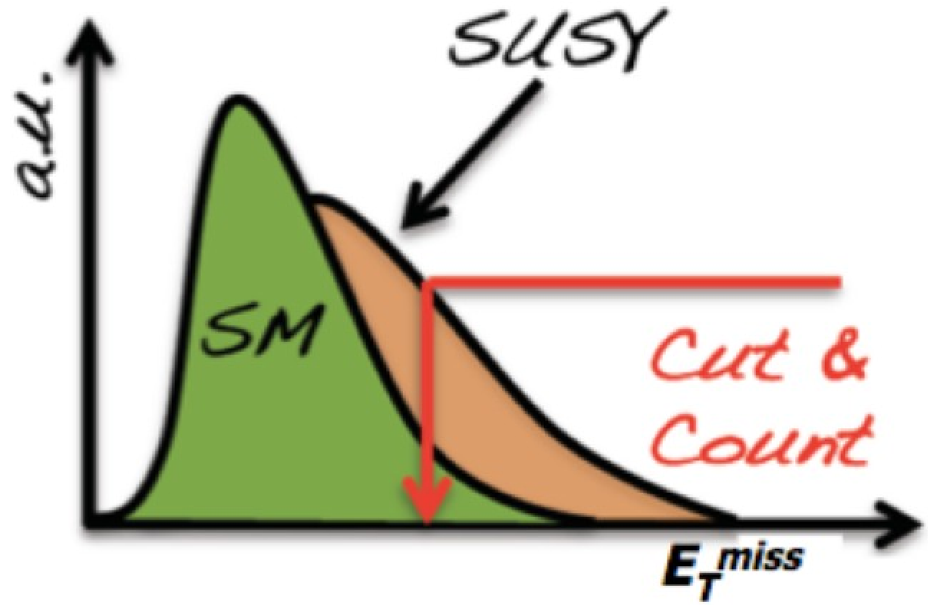
This lecture: How do we use this information to discover SUSY?!

SM backgrounds



- SUSY signal is usually much smaller than SM background
- Can also be topologically similar

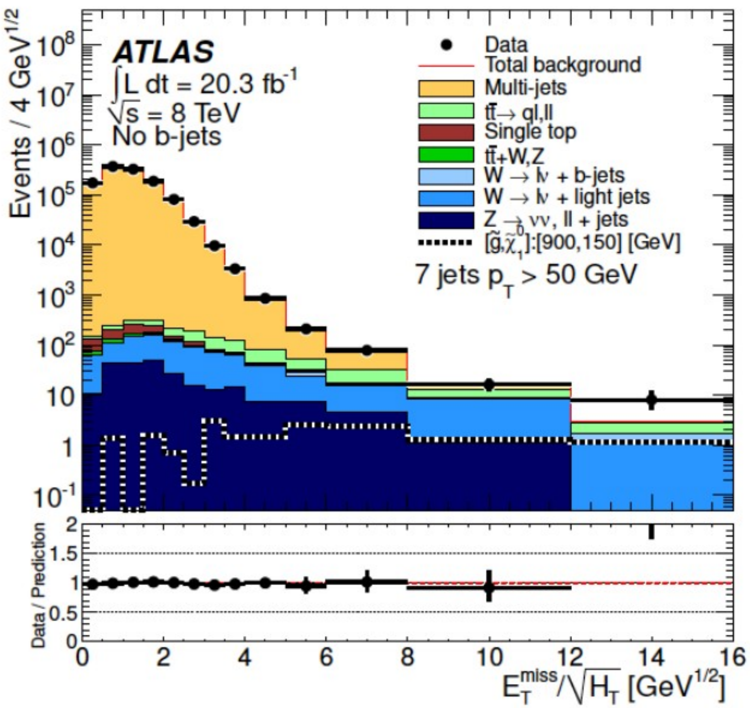
General strategy (cut and count analysis)



• Look for functions of four vectors that discriminate between SM and SUSY

• Cut away the SM background as much as possible without hurting the expected signal

This relies on a signal model. So at this point, the analysis only works for some scenarios.



• Carefully measure the SM background in the signal region

- try and minimise systematic uncertainties

• See nothing

- set a nice limit

(alright- I'm joking: KEEP THE DREAM ALIVE!)

Look for several functions of four vectors

- A typical LHC analysis has lots of cuts

  - each cut targets a specific background
  - final acceptance is very small for e.g. multilepton searches
  - this is really **extreme optimisation**

- Extreme optimisation is probably necessary however:

  - what else do you do if the signal is much smaller than the SM background and looks similar?

- Will give some recent examples of useful variables in the next few slides

  - this is very much a non-exhaustive list
  - there is still an effort to invent and investigate more
  - you should be reading hep-ph daily to try and find more (or invent them yourself!)

Simple variables

- Basic event objects + kinematics:
  - missing transverse energy
  - leading and sub-leading jet and lepton p_T values
  - number of jets
  - number of leptons
  - number of photons
  - number of b jets
  - number of taus

Simple combinations of variables

- m_{eff} = scalar sum of E_T^{miss} and p_T's of leading N jets (see papers for definition)
- $\mathbf{H_T}$ = scalar sum of p_T's of all jets (with p_T over some value)
- $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$
- $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$
- $\Delta\phi(\mathrm{jet}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ (very popular for multijet rejection)
- m_{ll} (in case of 2 or more leptons)
- $M_{\mathrm{T}} = \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{l} (1 - \cos\Delta\phi_{l, E_{\mathrm{T}}^{\mathrm{miss}}})}$ (helps remove W + jets & WZ backgrounds)
- Various scalar sums of lepton and jet p_T's

Let a particle with mass M decay to two particles labelled 1 and 2

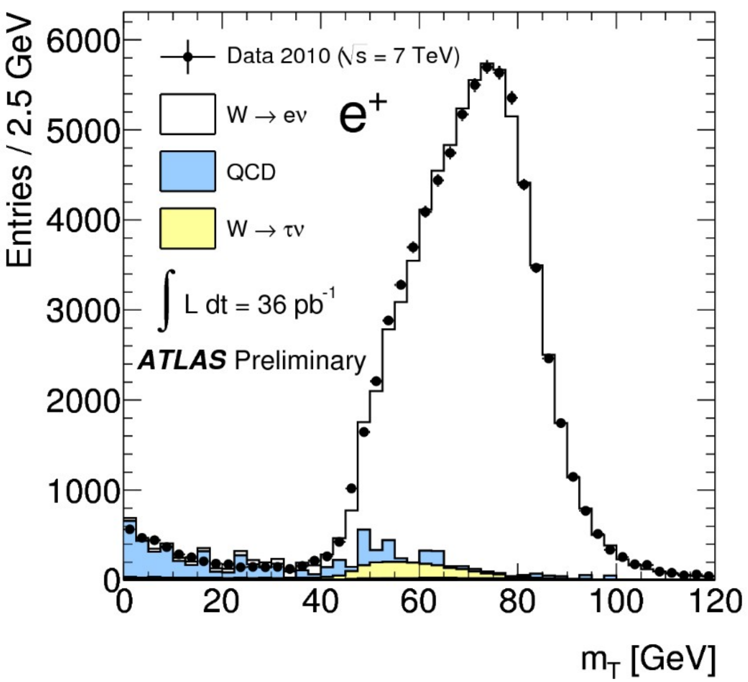
$$M_T^2 \equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2$$
$$= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)]$$

Where $p_T(1)$ is the invisible p_T (the missing E_T), $p_T(2)$ is the visible p_T (lepton p_T).
If the two decay products are massless:

$$M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$$

Has a maximum at *M*

This is *invariant* under boosts along the z direction



M_{T2}

Question: Similar definition as transverse mass M_T for more than one massive escaping particles, e.g. LSP?

$$m_{\tilde{l}}^2 = m_l^2 + m_{\tilde{\chi}}^2 + 2(E_T^l E_T^{\tilde{\chi}} \cosh \Delta\eta - p_T^l \cdot p_T^{\tilde{\chi}})$$

For arbitrary momenta:

Since $\cosh \Delta\eta \geq 1$

$$m_{\tilde{l}}^2 \geq m_T^2(p_T^l, p_T^{\tilde{\chi}}) = m_l^2 + m_{\tilde{\chi}}^2 + 2(E_T^l E_T^{\tilde{\chi}} - p_T^l \cdot p_T^{\tilde{\chi}})$$

If both LSP momenta are known

$$m_{\tilde{l}}^2 \geq \max\{m_T^2(p_T^{l^-}, p_T^{\tilde{\chi}_a}), m_T^2(p_T^{l^+}, p_T^{\tilde{\chi}_b})\}$$

Not usable, since both neutralinos contribute

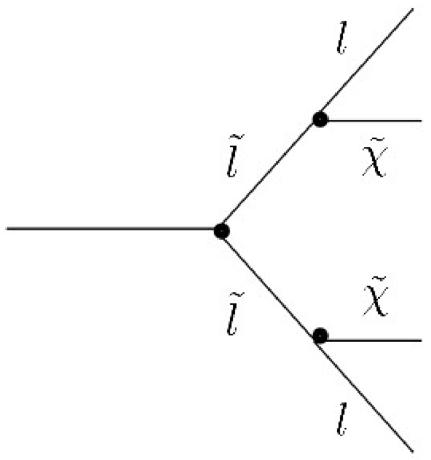
$$\not{E}_T = p_T^{\tilde{\chi}_a} + p_T^{\tilde{\chi}_b}$$

Since splitting not known, the best one can do is:

$$m_{\tilde{l}}^2 \geq M_{T2}^2 = \min_{\not{p}^a + \not{p}^b = \not{p}_T} \{\max\{m_T^2(p_T^{l^-}, \not{p}_T^a), m_T^2(p_T^{l^+}, \not{p}_T^b)\}\}$$

Useful, if enough events populate region near end-point

Lester & Summers 99



α_T

- Kinematic variable independent of E_T^{miss}
- Use pseudojets from event hemispheres

$$\alpha_T = \frac{E_T^{2nd}}{M_T} = \frac{E_T^{2nd}}{\sqrt{2p_T^{1st}p_T^{2nd}(1-\cos\phi_{12})}}$$

- For a perfectly measured dijet event → $\alpha_T = 0.5$
- For events with mismeasured jets, $\alpha_T < 0.5$
- For events with $\alpha_T > 0.5$:

  - QCD with jets below pT threshold
  - events with genuine E_T^{miss}

Define

$$M_R = \sqrt{(|\vec{p}_{q1}| + |\vec{p}_{q2}|)^2 - (p_{z,q1} + p_{z,q2})^2}$$

and

$$M_T^R = \sqrt{\frac{E_T^{\rm miss}(p_T^{q1} + p_T^{q2}) - \vec{E}_T^{\rm miss}(\vec{p}_t^{\,q1} + \vec{p}_T^{\,q2})}{2}}$$

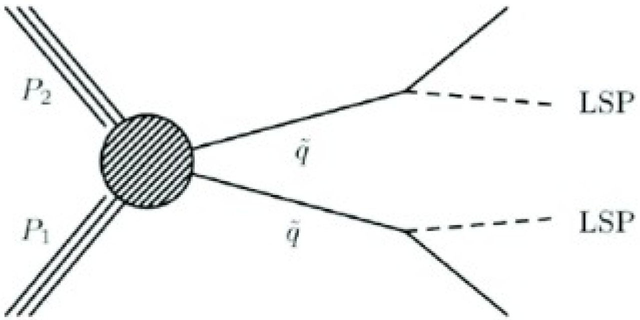
Define **the "Razor"**:

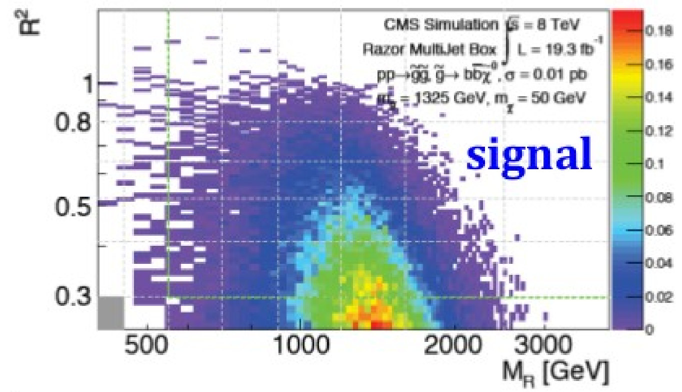
$$R = \frac{M_T^R}{M_R}$$

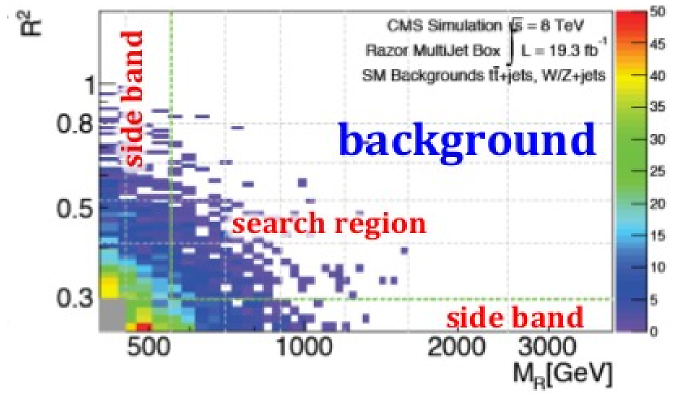
- For signal: M_R has peak and $M_T{}^R$ has endpoint at

$$M_\Delta = \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}_1^0}^2}{M_{\tilde{q}}}$$

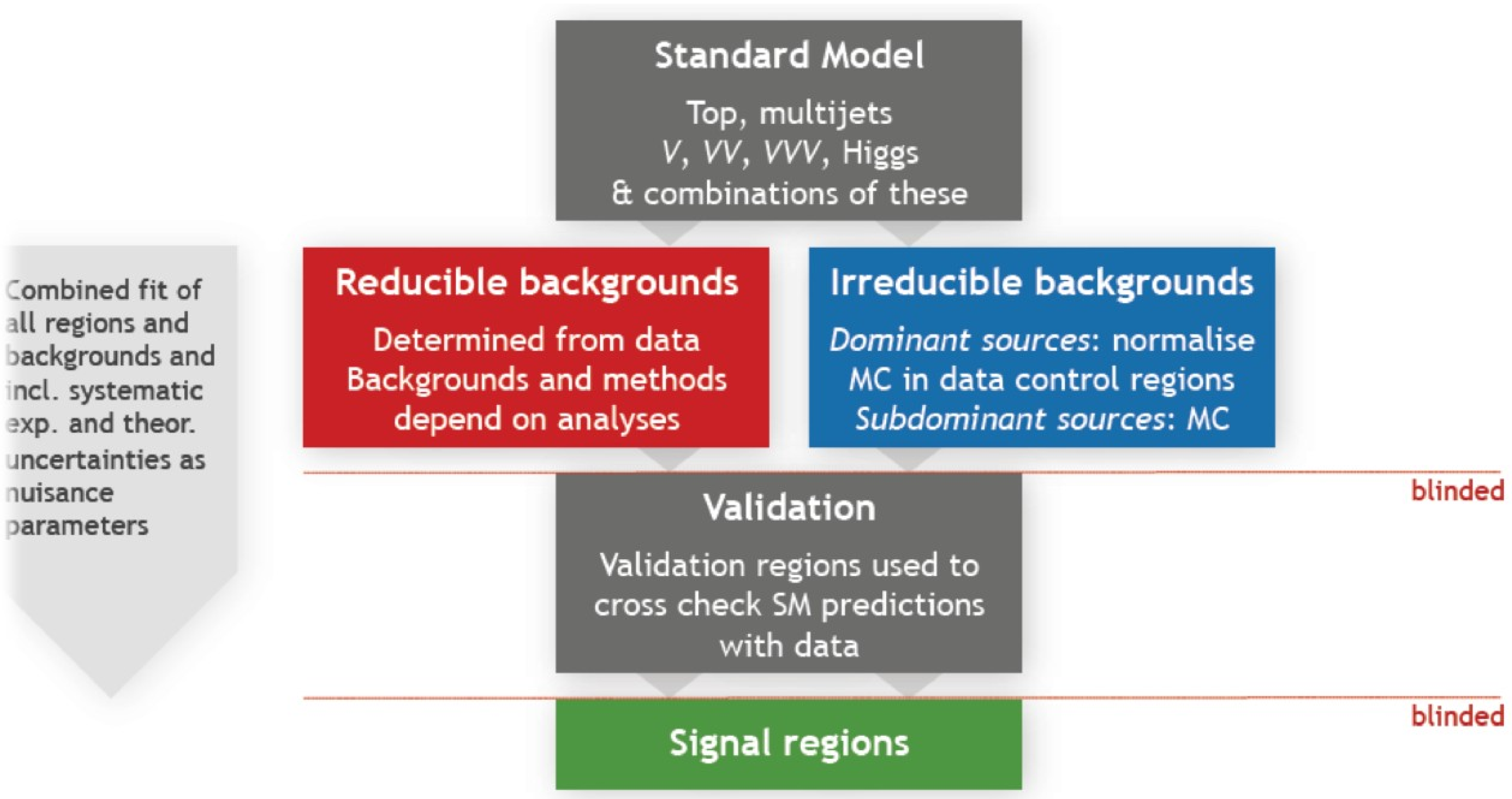
(See conference talk by **Chris Rogan**)

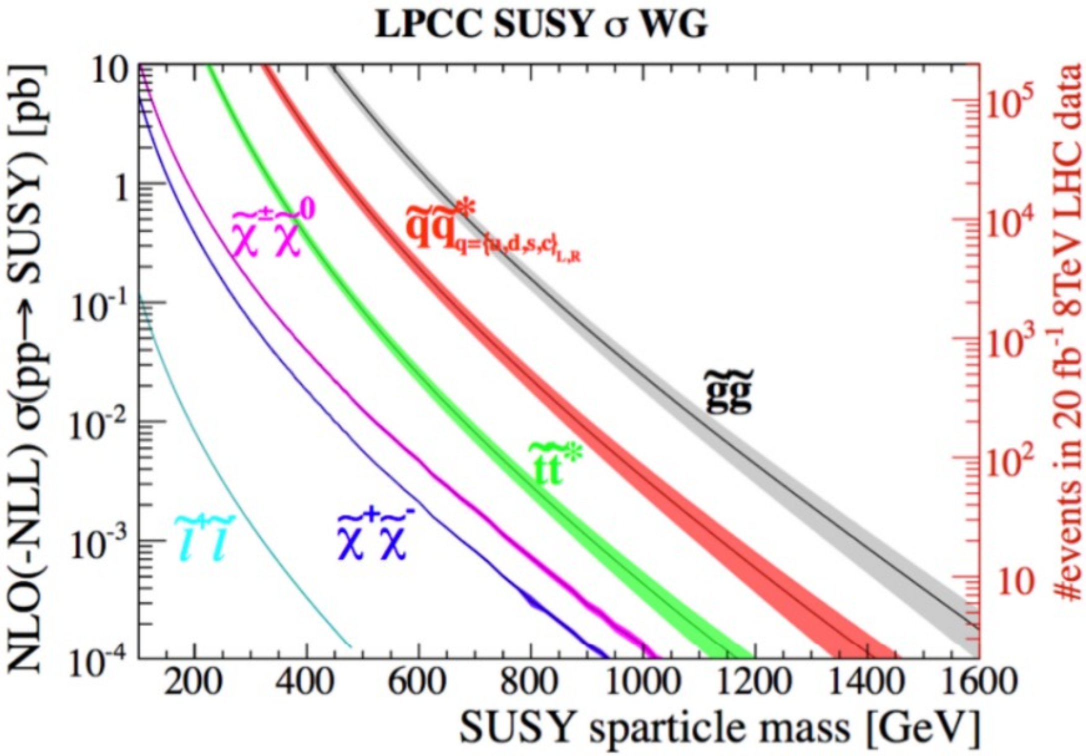






Background measurements: general strategy





Within each category, organise results by final state objects

Strong production:

- targeting gluinos and 1st and 2nd generation squarks
- by far largest cross-sections

3rd generation:

- targeting stop and sbottoms
- Should be lowest mass squarks for naturalness reasons

Electroweak production:

- targeting Electroweakinos, sleptons
- Lowest mass sparticles, clean signature

RPV/LL:

- targeting R-parity violating models and long lived sparticles
- More exotic models

Example: Run I ATLAS 0 lepton search

Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s} = 8$ TeV proton–proton collision data

The ATLAS Collaboration

- Let's now walk through one analysis in detail

- The above example would dominate the limits in the case of:

  - lots of light squarks and a light gluino
  - this is really the canonical “try and discover SUSY immediately” search

Why jets plus missing E_T?

- The simplest squark decay is $\tilde{q} \rightarrow q\tilde{\chi}_1^0$
- The simplest gluino decay is $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$
- If the gluino and lots of squarks are light

  - will have a high cross-section for $(\tilde{g}\tilde{g},\ \tilde{q}\tilde{q},\ \tilde{q}\tilde{g})$ production

  - squark pair events will have at least 2 jets

  - gluino pair events will have at least 4 jets

  - long cascade decays would have even higher multiplicities

  - branching ratios to leptons are usually sub-dominant

- Thus look for at least 2 jets, possibly more, plus missing E_T

Main SM backgrounds

- Z + jets

  - mostly irreducible: $Z \rightarrow \nu\nu$

- W + jets

  - mostly $W \rightarrow \tau\nu$ with hadronic τ decay
  - can also have $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ with a missed lepton

- Top quark pairs (plus single top production)

  - $t\bar{t} \rightarrow b\bar{b}\tau\nu qq'$ with hadronic τ decay

- Multijet

  - anomalous missing ET generated by mis-reconstruction of jet energies
  - neutrino production in semileptonic decays of heavy-flavour quarks

Trigger

- Use jet + MET trigger (matches the final state)
  - requires a jet with p_T > 80 GeV (at the trigger level)
  - requires missing E_T > 100 GeV (at the trigger level)
- The trigger only reaches maximum efficiency for the following reconstruction-level cuts:
  - requires a jet with p_T > 130 GeV
  - requires missing E_T > 160 GeV
- Note that the trigger already removes sensitivity to compressed mass spectra
  - separate searches are performed for this scenario
- Note also that other triggers are often used to select control region events
  - single electron trigger (p_T > 24 GeV)
  - single muon trigger (p_T > 24 GeV)
  - single photon trigger (p_T > 120 GeV)

Signal region definitions

Requirement	Signal Region					
	2jl	**2jm**	**2jt**	**2jW**	**3j**	**4jW**
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] $>$	160					
$p_{\mathrm{T}}(j_1)$ [GeV] $>$	130					
$p_{\mathrm{T}}(j_2)$ [GeV] $>$	60					
$p_{\mathrm{T}}(j_3)$ [GeV] $>$	–				60	40
$p_{\mathrm{T}}(j_4)$ [GeV] $>$	–					40
$\Delta\phi(\mathrm{jet}_{1,2,(3)}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$	0.4					
$\Delta\phi(\mathrm{jet}_{i>3}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$	–					0.2
W candidates	–			$2(W \to j)$	–	$(W \to j) + (W \to jj)$
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] $>$	8	15		–		
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(N_{\mathrm{j}}) >$	–			0.25	0.3	0.35
m_{eff}(incl.) [GeV] $>$	800	1200	1600	1800	2200	1100

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Trigger requirements

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Reduces multijet background

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Reconstruct W candidates to look for cascade decays that produce W bosons

Signal region definitions

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Main discriminant variable for sq-sq production

Signal region definitions

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$m_{\rm eff}$(incl.) [GeV] $>$	800	1200	1600	1800	2200	1100

Main discriminant variable for other processes

More signal region definitions

<table>
<tr><th rowspan="2">Requirement</th><th colspan="9">Signal Region</th></tr>
<tr><th>4jl-</th><th>4jl</th><th>4jm</th><th>4jt</th><th>5j</th><th>6jl</th><th>6jm</th><th>6jt</th><th>6jt+</th></tr>
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<tr><td>m_{eff}(incl.) [GeV] $>$</td><td>700</td><td>1000</td><td>1300</td><td>2200</td><td>1200</td><td>900</td><td>1200</td><td>1500</td><td>1700</td></tr>
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Measuring SM backgrounds

• Basic strategy for most SUSY analyses is to use *control regions*

- define regions dominated by specific backgrounds
- normalise yield
- extrapolate to signal region

$$N(\mathrm{SR, scaled}) = N(\mathrm{CR, obs}) \times \left[\frac{N(\mathrm{SR, unscaled})}{N(\mathrm{CR, unscaled})}\right]$$

Transfer factor (TF)

• Standard procedure in recent searches is to derive TF's via a likelihood fit

- use similar equations for inter-CR transfer factors
- enables coherent normalisation across all CRs associated with an SR
- fit derives the central value plus the uncertainty for each TF (including correlations)

Choosing good control regions (general advice)

• Some uncertainties more or less cancel in the TF (due to the ratio), e.g.

- jet energy scale
- theoretical uncertainties in MC cross-sections

• Residual uncertainties can be reduced by:

- making the kinematic selections as similar as possible for SR and CR
- this must be done whilst minimising signal contamination of the SR!

0 lepton control regions

CR	SR background	CR process	CR selection
CRγ	$Z(\to \nu\nu)$+jets	γ+jets	Isolated photon
CRQ	Multi-jets	Multi-jets	SR with reversed requirements on (i) $\Delta\phi(\text{jet}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ and (ii) $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(N_{\mathrm{j}})$ or $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$
CRW	$W(\to \ell\nu)$+jets	$W(\to \ell\nu)$+jets	30 GeV $< m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) <$ 100 GeV, b-veto
CRT	$t\bar{t}$ and single-t	$t\bar{t} \to b\bar{b}qq'\ell\nu$	30 GeV $< m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) <$ 100 GeV, b-tag

- Four CRs are defined per SR (60 in total!)

  - each CR selects a single dominant background source for its corresponding SR
  - use similar meff(incl) selection → minimise systematic uncertainties
  - note: some differences in SR cuts apply (see paper)

- Most TFs are obtained using MC events except:

  - multijet events: apply a resolution function to well-measured multijet events
  - (gives many more events than would be possible using MC approach)

- For CRγ , use photon + jet events and pretend that the photon is contributing to missing ET

  - for $p_T(\gamma) > m_Z$, these events strongly resemble *Z* + jets events
  - correction is applied to TF to account for LO γ + jet cross-sections (see paper)

Using transverse mass for W and top regions

Let a particle with mass M decay to two particles labelled 1 and 2

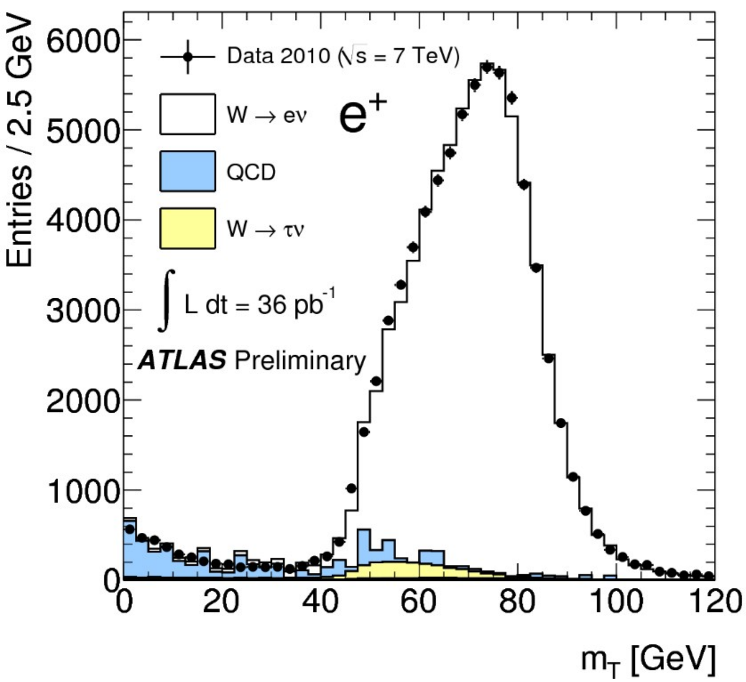
$$M_T^2 \equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2$$
$$= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)]$$

Where $p_T(1)$ is the invisible p_T (the missing E_T), $p_T(2)$ is the visible p_T (lepton p_T).
If the two decay products are massless:

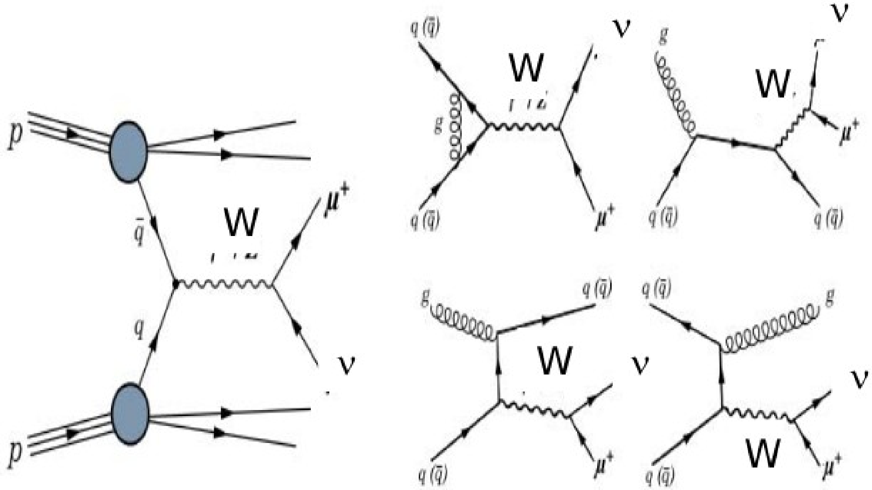
$$M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$$

Has a maximum at *M*

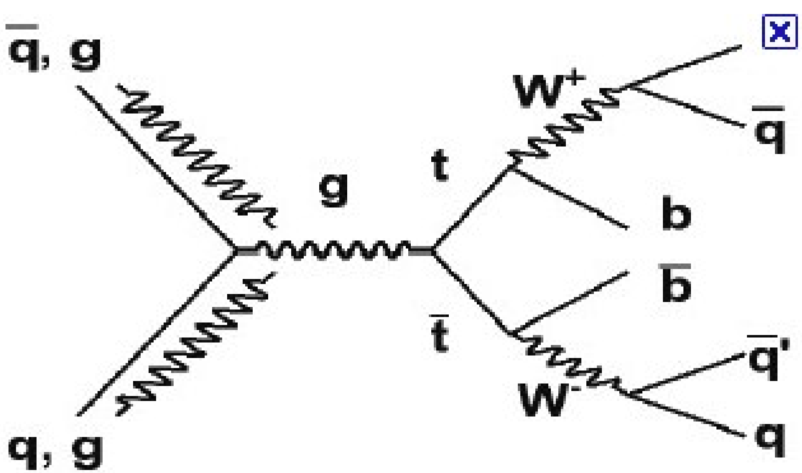
This is *invariant* under boosts along the z direction



b veto or *b* tag



W + jets events will not typically have a *b* jet in, hence the *b* veto in the CR definition



Top events will have a W boson in, but also *b* jets, hence the *b* tag requirement in the CR definition

Validation regions

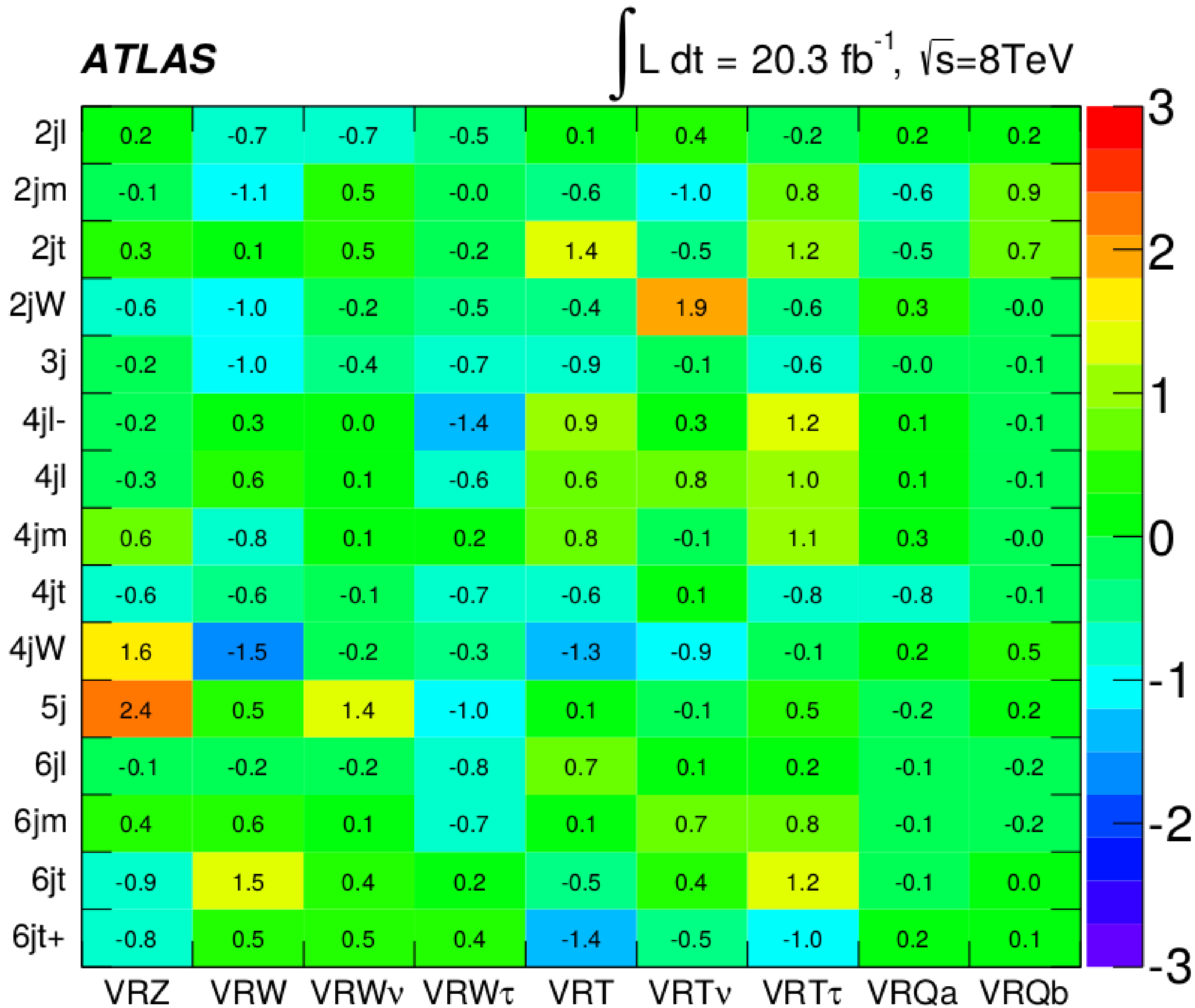
- Can validate the background measurement using *validation regions*

  - select regions that are orthogonal to the CRs (and SR)
  - low signal contamination is also crucial

- e.g. for Z+jets background:

  - use $Z(\rightarrow ll)$ + jets events, require m_{ll} within 25 GeV of m_Z
  - pretend that the leptons are missing E_T

Validation regions



Systematic uncertainties

- A long list of experimental and systematic uncertainties affect the final yields
- Typically, the experimentalist will be given recipes for these
  - combined performance groups give specific recommendations
  - theoretical procedures defined in consulation with theory/pheno community
- Usually need to run analysis code multiple times with each systematic variation applied
  - e.g. jet energy scale up, then jet energy scale down
  - repeat for other systematics
  - final fit takes these values as inputs, can be used to derive bounds on nuisance parameters

Common experimental systematics

- Jet energy scale, resolution and mass scale uncertainties
- Lepton resolution, reconstruction efficiency and energy scale uncertainties
- Photon resolution, reconstruction efficiency and energy scale uncertainties
- MET contribution uncertainties
- b tagging uncertainties
- Trigger efficiency uncertainties
- Luminosity uncertainty

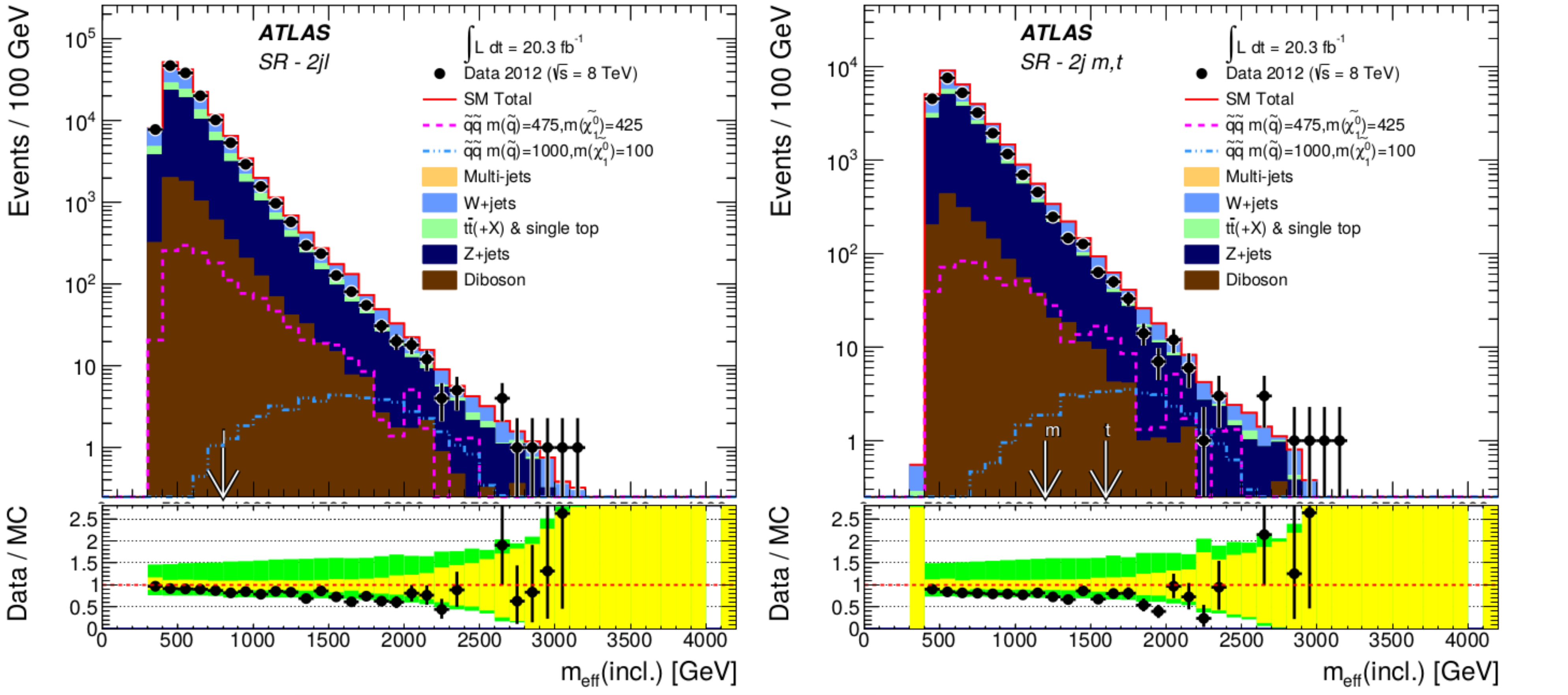
Common theoretical systematics

- Cross-section uncertainties
- MC generator differences (usually compare different generators at truth level)
- Renormalisation scale (usually increase and decrease by a factor of two)
- Factorisation scale (usually increase and decrease by a factor of two)
- Parton distribution function uncertainties

0 lepton systematic uncertainties

Channel	**2jl**	**2jm**	**2jt**	**2jW**	**3j**
Total bkg	13000	760	125	2.3	5.0
Total bkg unc.	±1000 [8%]	±50 [7%]	±10 [8%]	±1.4 [61%]	±1.2 [24%]
CR stats: Z/γ^*+jets	±100 [0.8%]	±15 [2.0%]	±5 [4.0%]	±0.4 [17.4%]	±0.7 [14.0%]
CR stats: W+jets	±300 [2.3%]	±21 [2.8%]	±5 [4.0%]	±0.7 [30.4%]	±0.8 [16.0%]
CR stats: top quark	±200 [1.5%]	±5 [0.7%]	±1.6 [1.3%]	±0.35 [15.2%]	±0.5 [10.0%]
CR stats: multi-jets	–	–	±0.1 [0.1%]	–	±0.1 [2.0%]
MC statistics	±130 [1.0%]	±6 [0.8%]	±2.1 [1.7%]	±0.34 [14.8%]	±0.35 [7.0%]
Jet/MET	±140 [1.1%]	±8 [1.1%]	±0.7 [0.6%]	±0.27 [11.7%]	±0.23 [4.6%]
Leptons	±80 [0.6%]	±2.5 [0.3%]	±0.6 [0.5%]	±0.04 [1.7%]	±0.06 [1.2%]
Z/γ TF	±500 [3.8%]	±35 [4.6%]	±5 [4.0%]	±0.028 [1.2%]	±0.14 [2.8%]
Theory: Z/γ^*+jets	±800 [6.2%]	±5 [0.7%]	±4 [3.2%]	±0.03 [1.3%]	±0.29 [5.8%]
Theory: W+jets	±270 [2.1%]	±10 [1.3%]	±1.4 [1.1%]	±0.1 [4.3%]	±0.35 [7.0%]
Theory: top quark	±13 [0.1%]	±1.8 [0.2%]	±0.11 [0.1%]	±0.9 [39.1%]	±0.05 [1.0%]
Theory: diboson	±400 [3.1%]	±40 [5.3%]	±6 [4.8%]	±0.2 [8.7%]	±0.18 [3.6%]
Theory: scale unc.	±90 [0.7%]	±4 [0.5%]	±0.7 [0.6%]	±0.13 [5.7%]	±0.12 [2.4%]
Multi-jets method	±140 [1.1%]	±1.4 [0.2%]	±0.4 [0.3%]	±0.04 [1.7%]	±0.06 [1.2%]
Other	±32 [0.2%]	±0.6 [0.1%]	±0.4 [0.3%]	±0.24 [10.4%]	±0.02 [0.4%]

Finally: look in signal region!



Likelihood fits

- Background only fit:

  - use only observed event yields from CRs, do not include SRs
  - assume no signal contamination of CRs
  - can then test the significance of any observed excess in the SRs

- Model-independent fit:

  - same as above, except add number of observed events in SRs to the fit
  - add BSM signal strength (constrained to be > 0) is added as a free parameter
  - gives generic upper limit on number of possible BSM signal events in each SR

- SUSY model exclusion fit

  - set limits on signal cross-sections for specific models
  - same as model-independent fit, but now with SR contamination included in the SRs
  - also include theoretical and experimental uncertainties on SUSY event predicitions
  - also include correlation between signal and background uncertainties

In each case, use a Frequentist statistical fitting procedure (details vary between experiments)

- Given s expected signal events, b background events and o observed events:

$$L = e^{-(s+b)}(s+b)^{o} \div o!$$

- Systematics can be handled via:

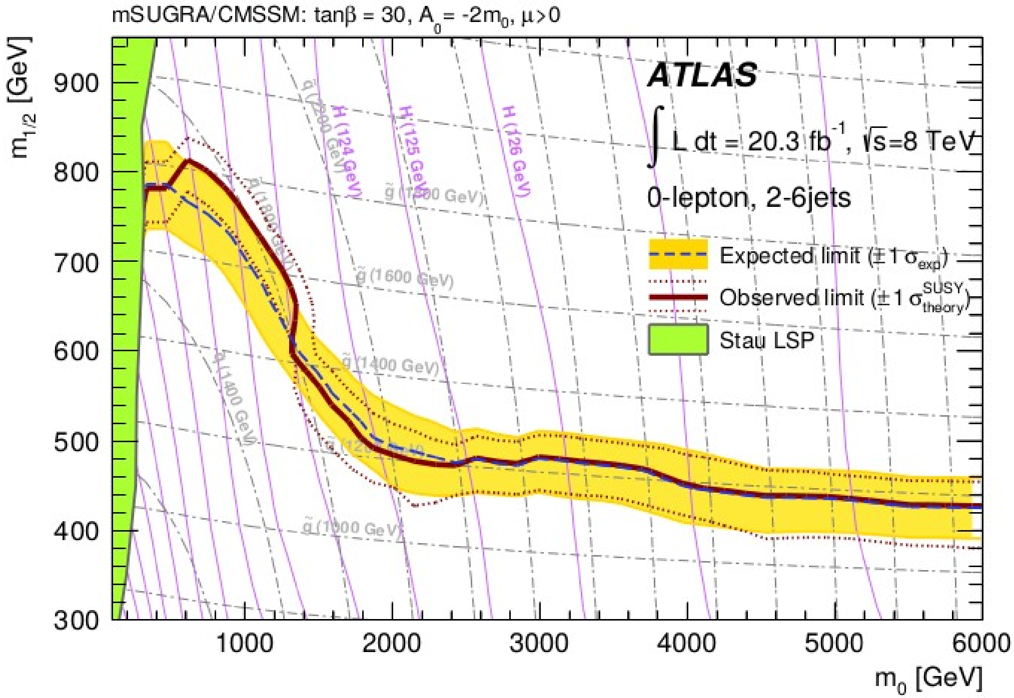
$$\mathcal{L}(n|s,b) = \int_0^\infty \frac{[\xi(s+b)]^n \, e^{-\xi(b+s)}}{n!} P(\xi)\mathrm{d}\xi$$

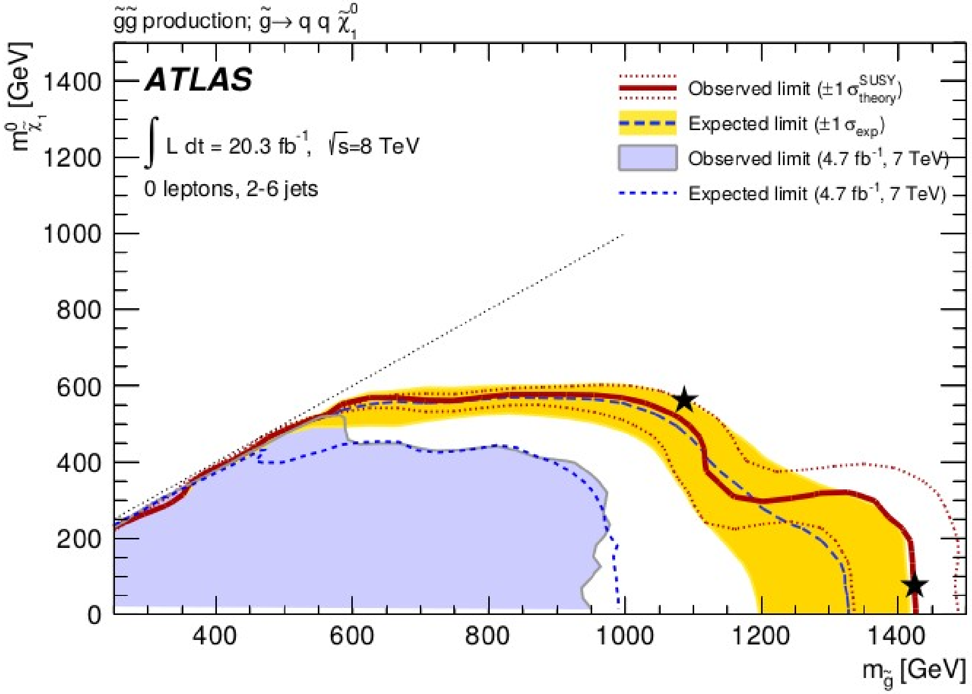
- With, e.g. , $P(\xi|\sigma_\xi) = \frac{1}{\sqrt{2\pi}\sigma_\xi} \exp\left[-\frac{1}{2}\left(\frac{1-\xi}{\sigma_\xi}\right)^2\right]$

- Typically have multiple Gaussian nuisance likelihoods for systematics

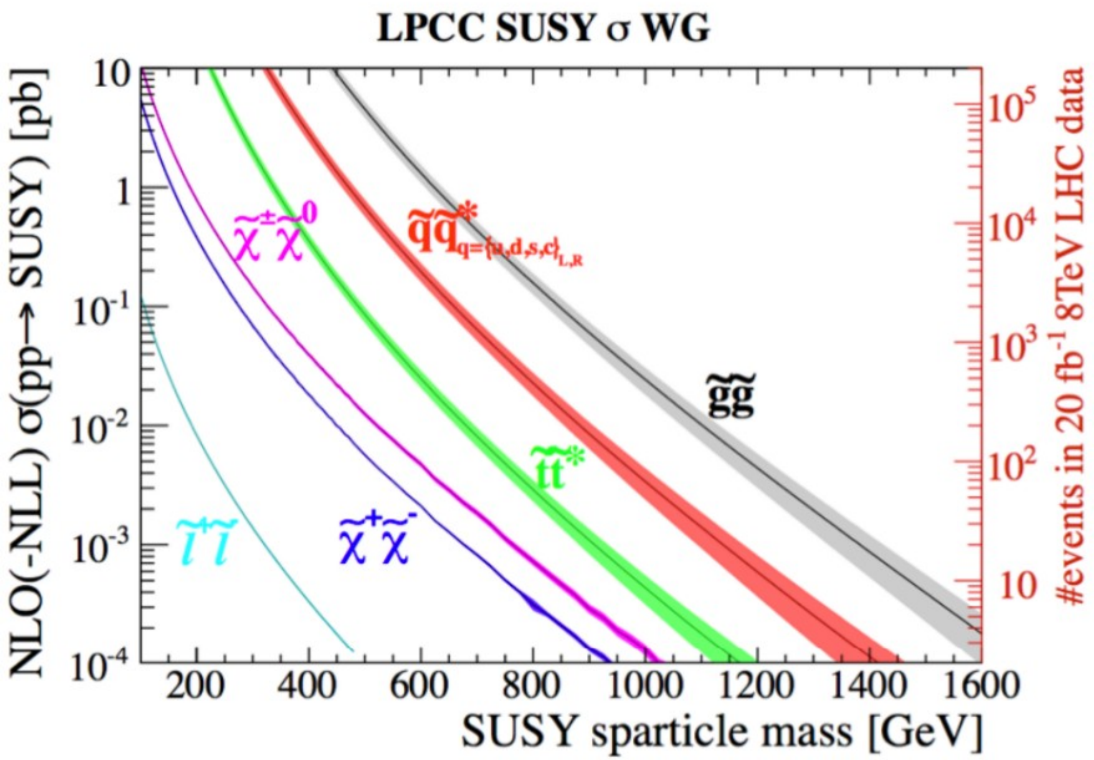
  - final result can be obtained by profiling them out

Exclusion limits





Other SUSY searches



Strong production:

- targeting gluinos and 1st and 2nd generation squarks
- by far largest cross-sections

3rd generation:

- targeting stop and sbottoms
- Should be lowest mass squarks for naturalness reasons

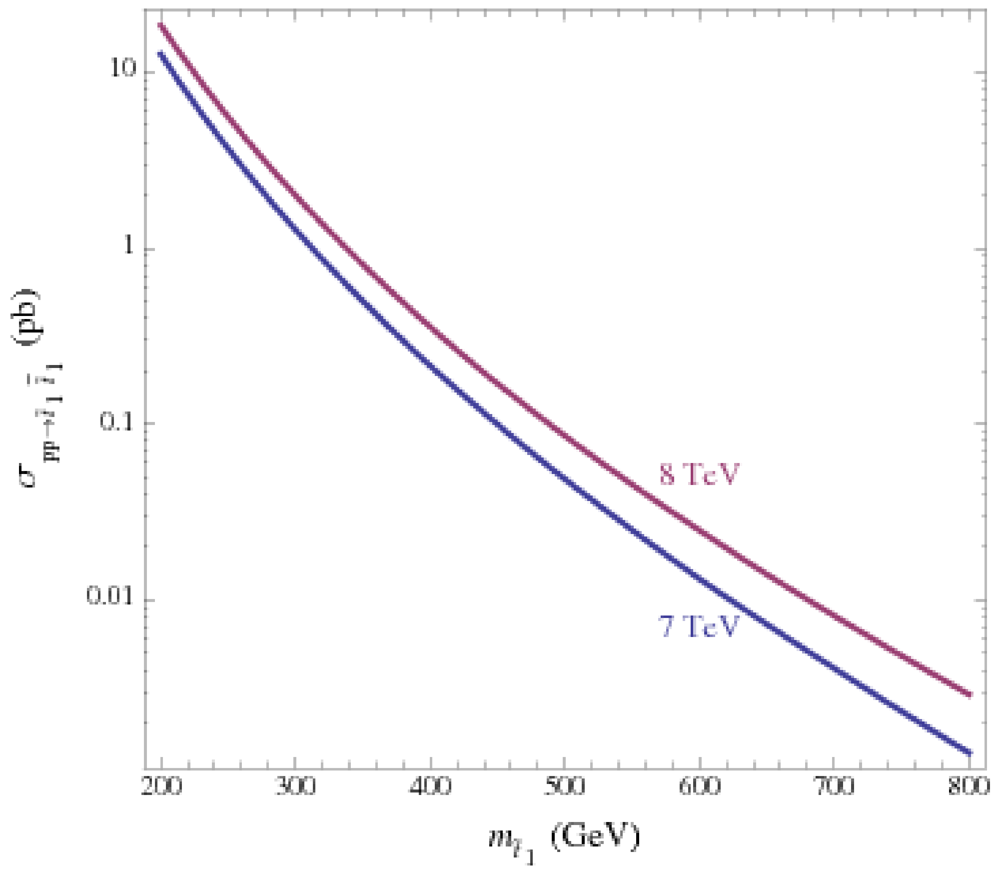
Electroweak production:

- targeting Electroweakinos, sleptons
- Lowest mass sparticles, clean signature

RPV/LL:

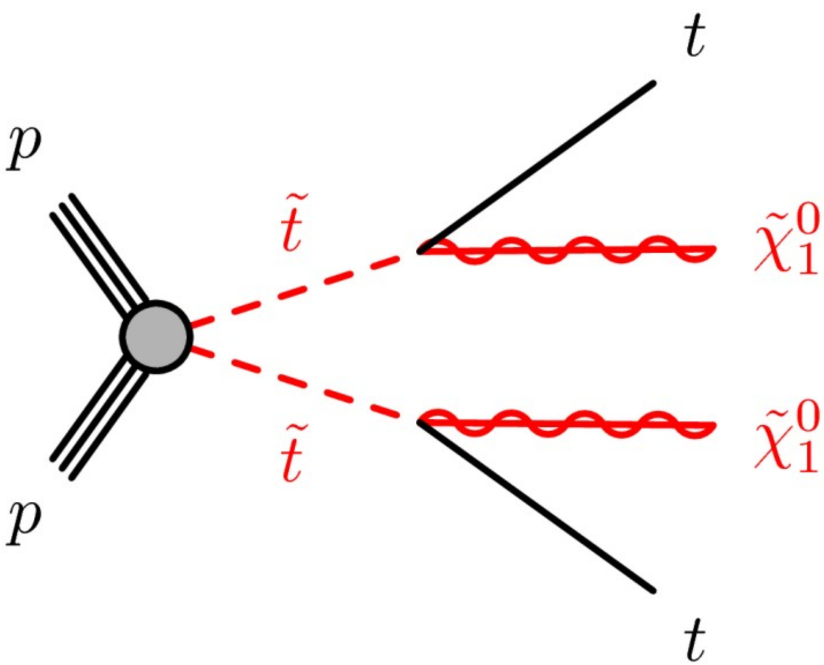
- targeting R-parity violating models and long lived sparticles
- More exotic models

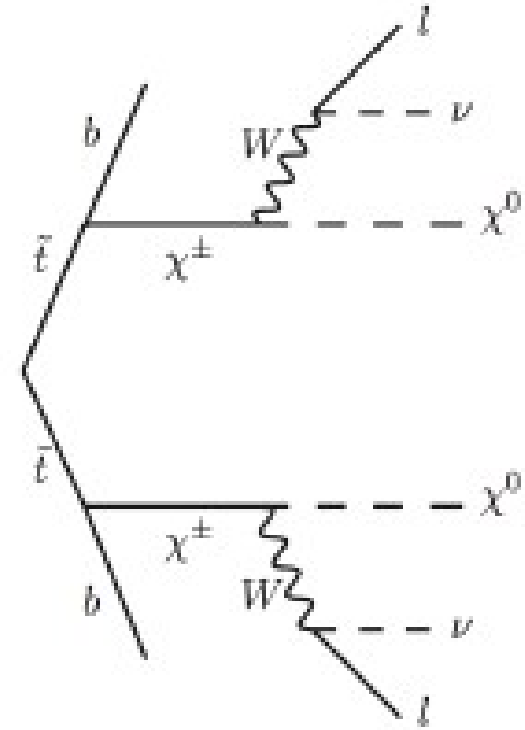
Stop searches: why they are tricky



(Top pair production cross-section ~ 170 pb)

General ATLAS approach





- Perform dedicated searches for dominant stop decay modes
  - include extra searches for compressed spectra and other special cases
  - mostly optimised on specific decays, though some work has now looked at mixed cases

- Divide searches by final state (number of leptons, number of *b* jets, etc)

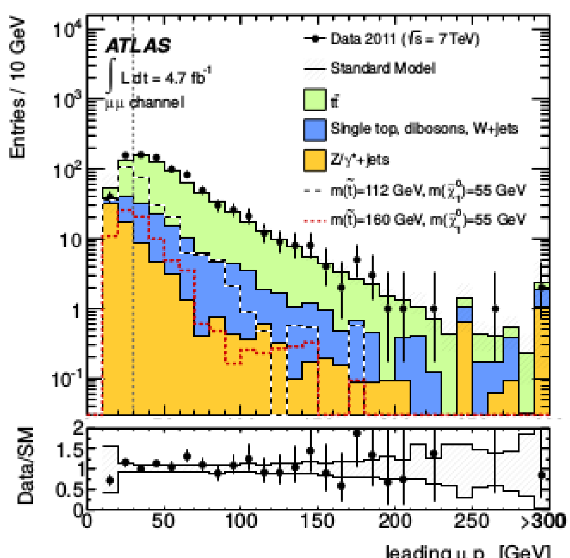
- Perform data-driven SM background estimates for all dominant backgrounds
  - e.g. normalise MC in kinematically similar control and validation regions
  - use pure data-driven QCD estimates

7 TeV dilepton search for very light stops

$$m(t) > m(\tilde{t}_1) > m(\tilde{\chi}_1^{\pm})$$

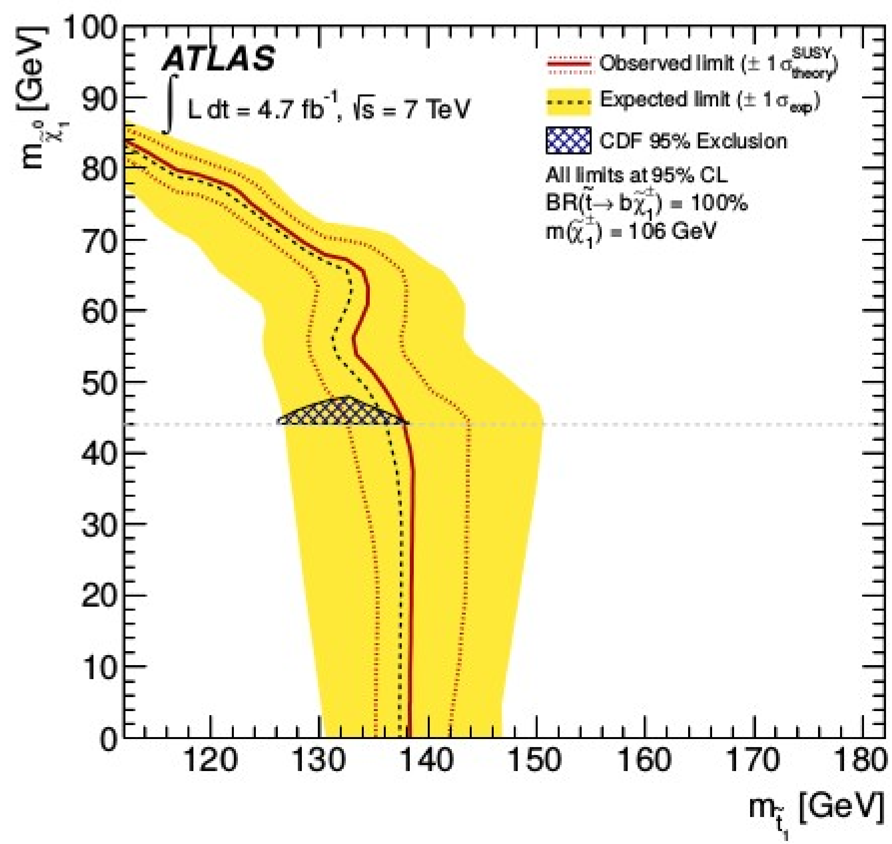
$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$$
$$\tilde{\chi}_1^{\pm} \rightarrow W^{(*)}\tilde{\chi}_1^0$$

Requirement	ee channel	$\mu\mu$ channel	$e\mu$ channel
Signal Region			
lepton p_T	> 17 GeV	> 12 GeV	$> 17(12)$ GeV for $e(\mu)$
leading lepton p_T	< 30 GeV		
m_{ll}	> 20 GeV and Z veto		> 20 GeV
jet p_T	≥ 1 jet, $p_T > 25$ GeV		
E_T^{miss}	> 20 GeV		
$E_T^{miss,sig}$	> 7.5 GeV$^{1/2}$		



- Background estimation:
  - semi-data-driven estimate using top and Z/γ^* control regions

- Dominant systematics: jet energy scale, jet energy resolution, theory errors on top estimate



7 TeV dilepton search for stops around the top mass

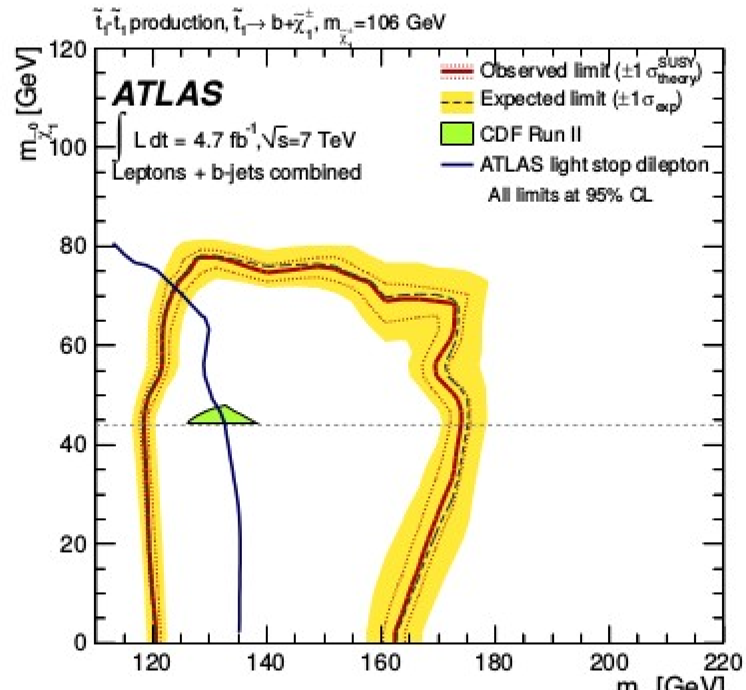
1 lepton search

- 1 lepton, $p_T > 25$ GeV (20 GeV) for e (μ)
- ≥ 4 jets, 2 *b*-tagged
- MET > 40 GeV
- $m_T = \sqrt{2 p_T^{\ell} E_T^{\rm miss} - 2 \mathbf{p}_T^{\ell} \cdot \mathbf{p}_T^{\rm miss}}$, > 30 GeV
- Use invariant mass of hadronic top decay products (use probability weight to reduce combinatorics)

2 lepton search

- 2 OS leptons, 1st $p_T > 25$ GeV (20 GeV) for e (μ)
- ≥ 2 jets, 1 *b*-tagged
- MET > 40 GeV
- 30 GeV $< m_{ll} <$ 81 GeV
- Cut on:

$$\sqrt{s}_{\rm min}^{\rm (sub)} = \left\{ \left(\sqrt{m_{\rm (sub)}^2 + p_{T\,\rm (sub)}^2} + \sqrt{(m^{\rm miss})^2 + (E_T^{\rm miss})^2} \right)^2 - \left(\mathbf{p}_{T\,\rm (sub)} + \mathbf{p}_T^{\rm miss} \right)^2 \right\}^{\frac{1}{2}},$$



(c)

8 TeV 0 lepton search

- One of the "flagship" ATLAS stop searches
- Was originally designed to target $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$ decays (both tops decay hadronically)

  - later paper included optimisations for events with different stop decays

$$\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0 \qquad\qquad \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$$

  - also included optimisations for boosted tops where not all decay products are visible

Main Backgrounds

- Semileptonic tt with one missing (or hadronic tau) lepton: normalise with 1-lepton control region (CR) in data
- Z(νν)+jets normalise with Z(ll) CR

Table 1. Selection criteria common to all signal regions.

Trigger	E_T^{miss}
N_{lep}	0
b-tagged jets	≥ 2
E_T^{miss}	> 150 GeV
$\left\|\Delta\phi\left(\text{jet}, \mathbf{p}_T^{miss}\right)\right\|$	$> \pi/5$
$\left\|\Delta\phi\left(\mathbf{p}_T^{miss}, \mathbf{p}_T^{miss,track}\right)\right\|$	$< \pi/3$
$m_T^{b,min}$	> 175 GeV

8 TeV 0 lepton search: signal regions

Table 2. Selection criteria for SRA, the fully resolved topology, with ≥ 6 anti-k_t $R = 0.4$ jets.

	SRA1	SRA2	SRA3	SRA4
anti-k_t $R = 0.4$ jets	≥ 6, $p_T > 80, 80, 35, 35, 35, 35$ GeV			
m^0_{bjj}	< 225 GeV		[50,250] GeV	
m^1_{bjj}	< 250 GeV		[50,400] GeV	
$\min[m_T(\text{jet}^i, \mathbf{p}_T^{\text{miss}})]$	–		> 50 GeV	
τ veto	yes			
E_T^{miss}	> 150 GeV	> 250 GeV	> 300 GeV	> 350 GeV

- Fully resolved case
- Form two top candidates and use invariant mass as discriminant (plus MET)
- m_T cut ensures jets are well separated from MET direction

Table 3. Selection criteria for SRB, the partially resolved topology, with four or five anti-k_t $R = 0.4$ jets, reclustered into anti-k_t $R = 1.2$ and $R = 0.8$ jets.

	SRB1	SRB2
anti-k_t $R = 0.4$ jets	4 or 5, $p_T > 80, 80, 35, 35, (35)$ GeV	5, $p_T > 100, 100, 35, 35, 35$ GeV
$\mathcal{A}_{m_t}$	< 0.5	> 0.5
$p^0_{T\,\text{jet},R=1.2}$	–	> 350 GeV
$m^0_{\text{jet},R=1.2}$	> 80 GeV	$[140, 500]$ GeV
$m^1_{\text{jet},R=1.2}$	$[60, 200]$ GeV	–
$m^0_{\text{jet},R=0.8}$	> 50 GeV	$[70, 300]$ GeV
$m_T^{\min}$	> 175 GeV	> 125 GeV
$m_T(\text{jet}^3, \mathbf{p}_T^{\text{miss}})$	> 280 GeV for 4-jet case	–
$E_T^{\text{miss}}/\sqrt{H_T}$	–	$> 17\sqrt{\text{GeV}}$
E_T^{miss}	> 325 GeV	> 400 GeV

- Partially resolved case
- Recluster jets with larger *R*
- Use mass of fat jets as discriminant

8 TeV 0 lepton search: signal regions

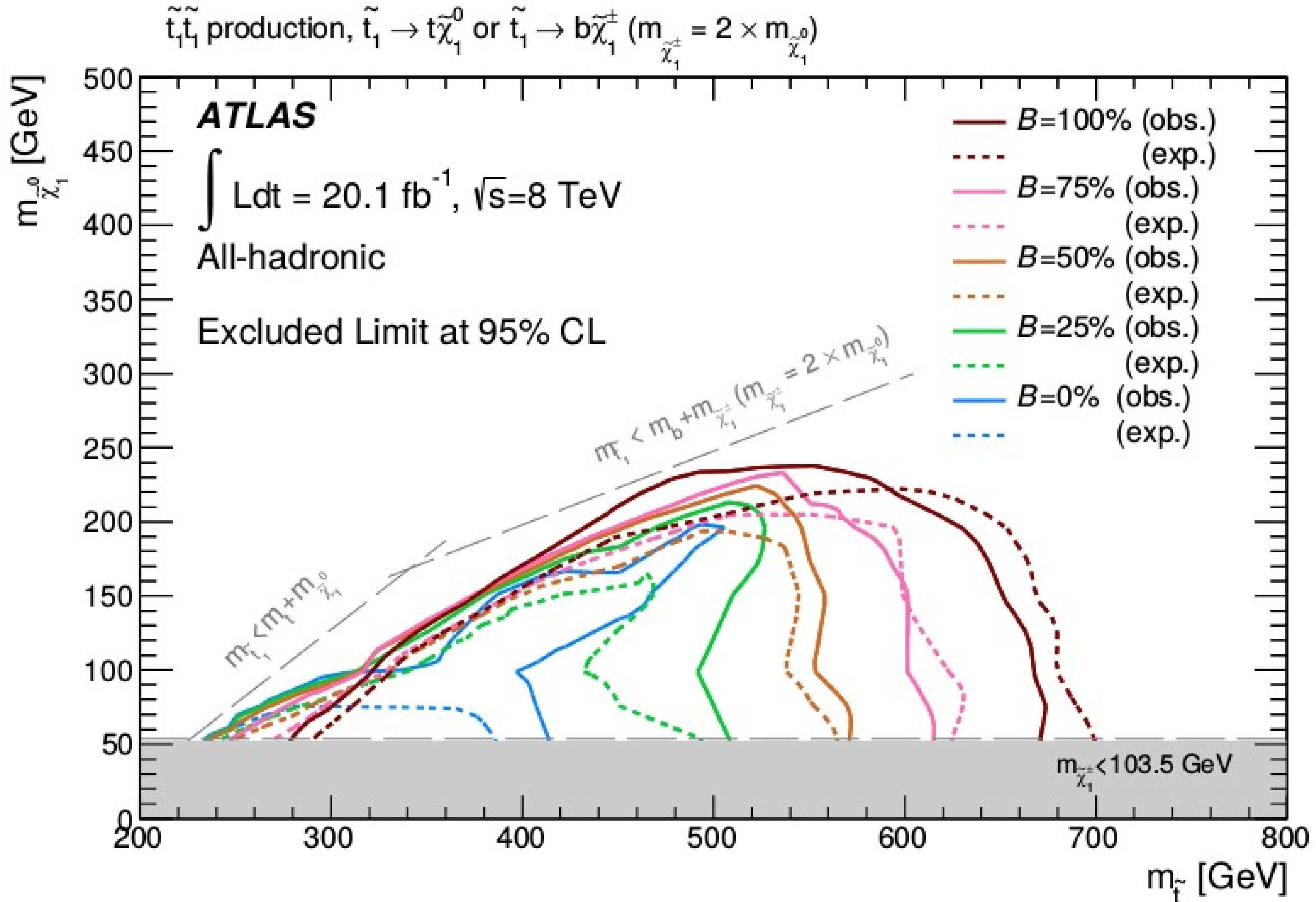
Table 4. Selection criteria for SRC, targeting the scenario in which one top squark decays via $\tilde{t} \to b\tilde{\chi}_1^{\pm}$, with five anti-$k_t$ $R = 0.4$ jets.

	SRC1	SRC2	SRC3
anti-k_t $R = 0.4$ jets	5, $p_{\mathrm{T}} > 80, 80, 35, 35, 35$ GeV		
$\lvert\Delta\phi\,(b,b)\rvert$	$> 0.2\pi$		
$m_{\mathrm{T}}^{b,\min}$	> 185 GeV	> 200 GeV	> 200 GeV
$m_{\mathrm{T}}^{b,\max}$	> 205 GeV	> 290 GeV	> 325 GeV
τ veto	yes		
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 160 GeV	> 160 GeV	> 215 GeV

- Mixed case (assume non-trivial relative branching ratio for $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$
- Require only 5 jets
- Tighten transverse mass cuts to compensate for increased background

8 TeV 0 lepton search: results

	SRA1	SRA2	SRA3	SRA4	SRB	SRC1	SRC2	SRC3
Observed events	11	4	5	4	2	59	30	15
Total SM	15.8 ± 1.9	4.1 ± 0.8	4.1 ± 0.9	2.4 ± 0.7	2.4 ± 0.7	68 ± 7	34 ± 5	20.3 ± 3.0



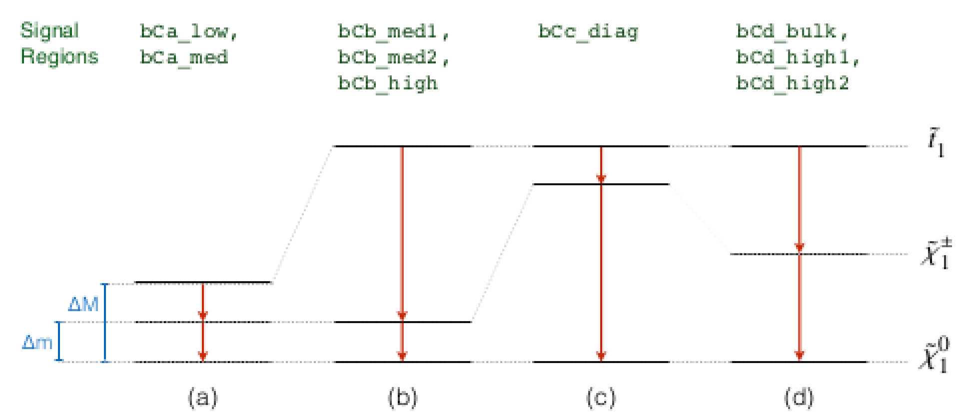
(b)

8 TeV 1 lepton search

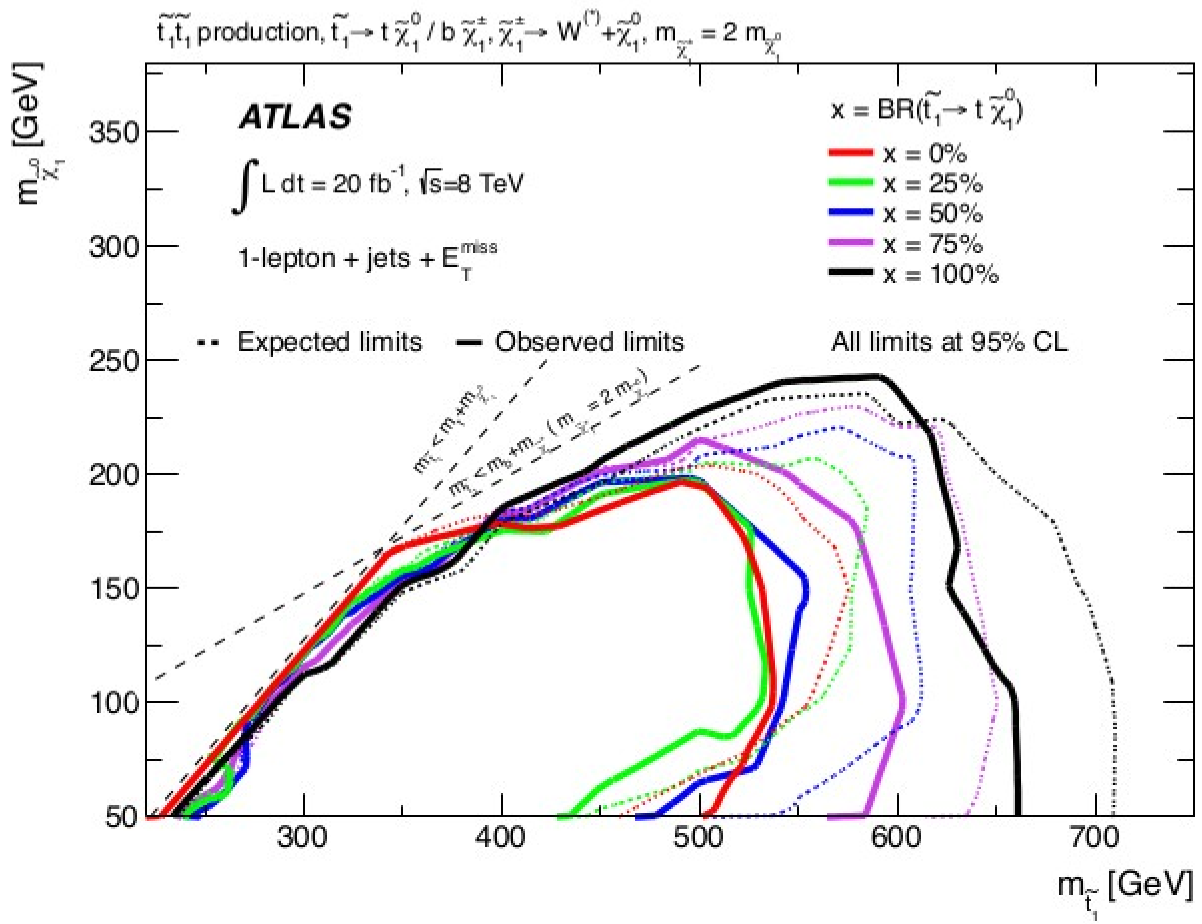
- Very complex search with lots of signal regions
- Includes searches for top neutralino and b chargino final states, plus mixed cases
- Extra optimisations for 3 and 4 body decays, and various mass difference limits

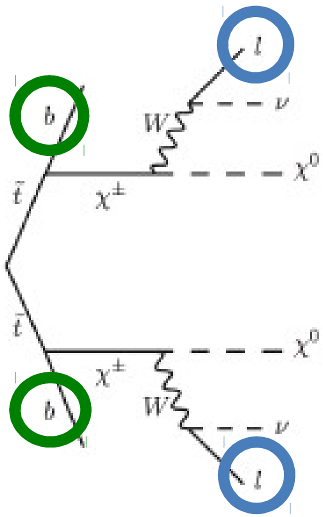
SR	Signal scenario	Exclusion technique	Table
tN_diag	$\tilde{t}_1 \to t\tilde{\chi}_1^0$, $m_{\tilde{t}_1} \gtrsim m_t + m_{\tilde{\chi}_1^0}$	shape-fit (E_T^{miss} and m_T)	4
tN_med	$\tilde{t}_1 \to t\tilde{\chi}_1^0$, $m_{\tilde{t}_1} \sim 550$ GeV, $m_{\tilde{\chi}_1^0} \lesssim 225$ GeV	cut-and-count	4
tN_high	$\tilde{t}_1 \to t\tilde{\chi}_1^0$, $m_{\tilde{t}_1} \gtrsim 600$ GeV	cut-and-count	4
tN_boost	$\tilde{t}_1 \to t\tilde{\chi}_1^0$, $m_{\tilde{t}_1} \gtrsim 600$ GeV, with a large-R jet	cut-and-count	4
bCa_low	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\Delta M \lesssim 50$ GeV	shape-fit (lepton p_T)	5
	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$		
bCa_med	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, 50 GeV$\lesssim \Delta M \lesssim 80$ GeV	shape-fit (lepton p_T)	5
	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$		
bCb_med1	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\Delta m \lesssim 25$ GeV, $m_{\tilde{t}_1} \lesssim 500$ GeV	shape-fit (am_{T2})	5
bCb_high	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\Delta m \lesssim 25$ GeV, $m_{\tilde{t}_1} \gtrsim 500$ GeV	shape-fit (am_{T2})	5
bCb_med2	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\Delta m \lesssim 80$ GeV, $m_{\tilde{t}_1} \lesssim 500$ GeV	shape-fit (am_{T2} and m_T)	6
bCc_diag	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_1^{\pm}}$	cut-and-count	6
bCd_bulk	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $(\Delta M, \Delta m) \gtrsim 100$ GeV, $m_{\tilde{t}_1} \lesssim 500$ GeV	shape-fit (am_{T2} and m_T)	6
bCd_high1	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $(\Delta M, \Delta m) \gtrsim 100$ GeV, $m_{\tilde{t}_1} \gtrsim 500$ GeV	cut-and-count	6
bCd_high2	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\Delta M \gtrsim 250$ GeV, $m_{\tilde{t}_1} \gtrsim 500$ GeV	cut-and-count	6
3body	$\tilde{t}_1 \to bW\tilde{\chi}_1^0$, $m_{\tilde{t}_1} \lesssim 300$ GeV	shape-fit (am_{T2} and m_T)	7
tNbC_mix	non-symmetric ($\tilde{t}_1 \to t\tilde{\chi}_1^0$, $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$)	cut-and-count	7

- Discriminating variables include MT2 (various forms), m_T, “topness” and the hadronic top mass, plus various combinations of MET, H_T and m_{eff}



8 TeV 1 lepton search: results





- For pair-produced particles with identical decay chains the variable

$$m_{T2}^2(p_T^\alpha, p_T^\beta, p_T^{miss}) = \min_{\mathbf{q}_T'^{(1)}+\mathbf{q}_T'^{(2)}=p_T^{miss}} \left[\max\left(M_T^2(\mathbf{p}_T^\alpha, \mathbf{q}_T'^{(1)}; m_\alpha, m_\chi), M_T^2(\mathbf{p}_T^\beta, \mathbf{q}_T'^{(2)}; m_\beta, m_\chi)\right)\right]$$

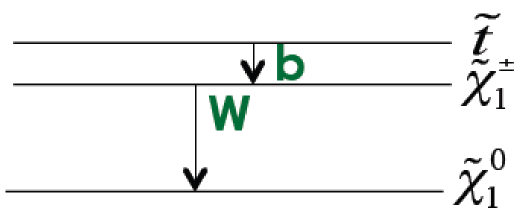
is bounded from above by the parent mass.

$m_{T2}(l_1, l_2, E_T^{Miss})$ bounded by W mass for WW, Wt, $t\bar{t}$

$m_{T2}(b_1, b_2, l_1 + l_2 + E_T^{Miss})$ bounded by top mass for $t\bar{t}$

ATLAS-CONF-2013-048

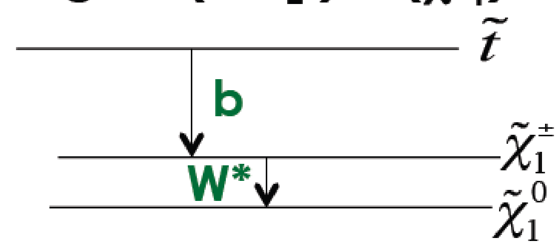
Search for $b\tilde{\chi}^\pm_1$ with large $m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)$



- Asks for large $m_{T2}(l_1, l_2, E_T^{Miss})$
- Four signal regions, one without jets: sensitive also to small $m(\tilde{t}) - m(\tilde{\chi}_1^\pm)$

ATLAS-CONF-2013-065

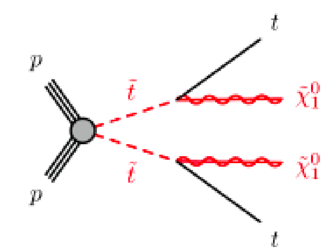
Search for $b\tilde{\chi}^\pm_1$ with large m(stop)-$m(\tilde{\chi}^\pm_1)$



Asks for 2 b-jets and large $m_{T2}(b_1, b_2, l_1 + l_2 + E_T^{Miss})$

ATLAS-CONF-2013-065

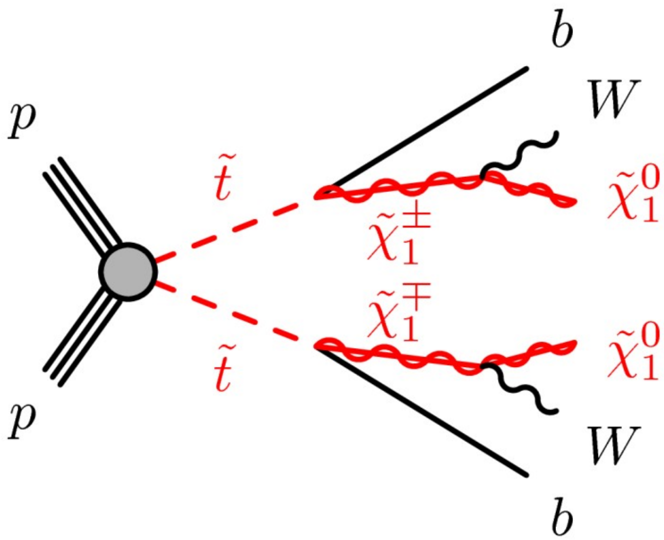
Search for $t\tilde{\chi}^0_1$

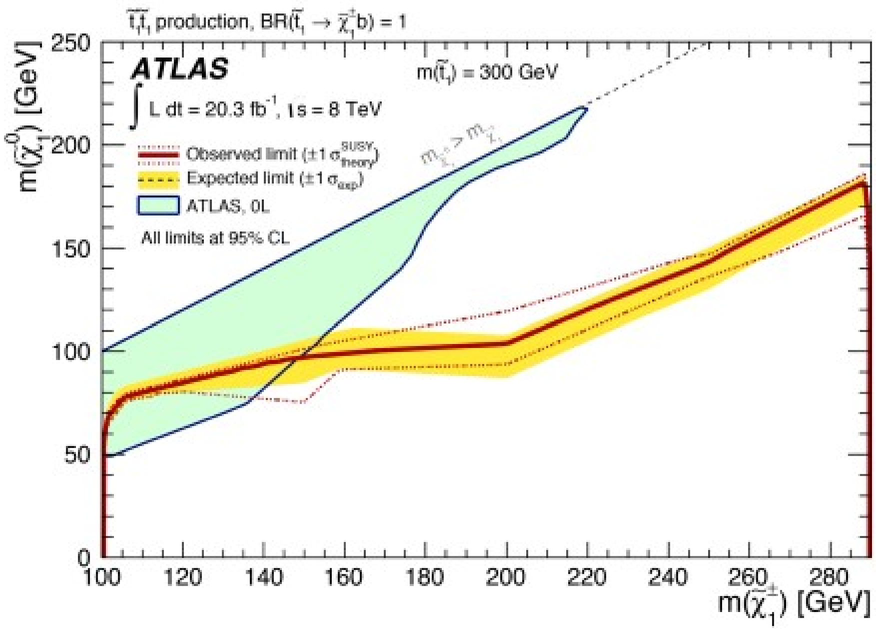


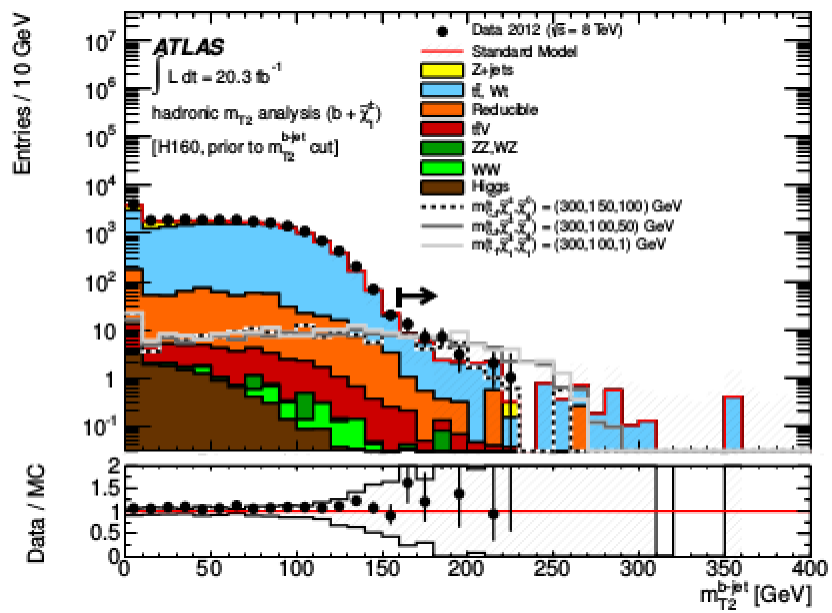
Multivariate analysis using 7 variables (one of them $m_{T2}(l, l, E_T^{Miss})$) to discriminate signal and SM background

15

2 lepton search

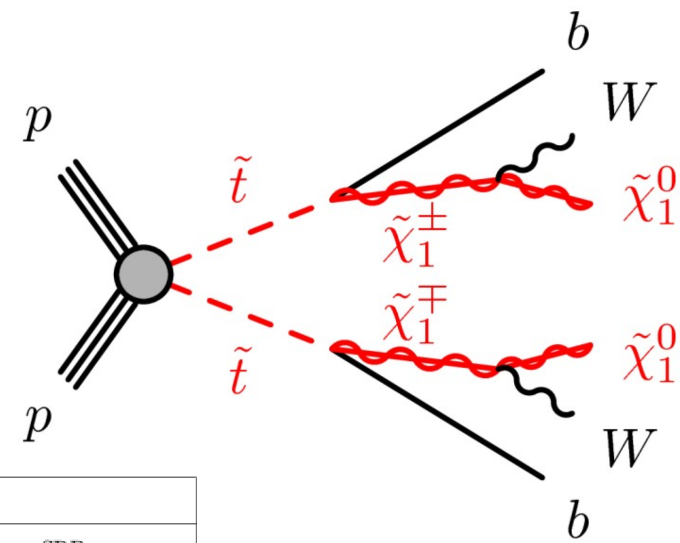






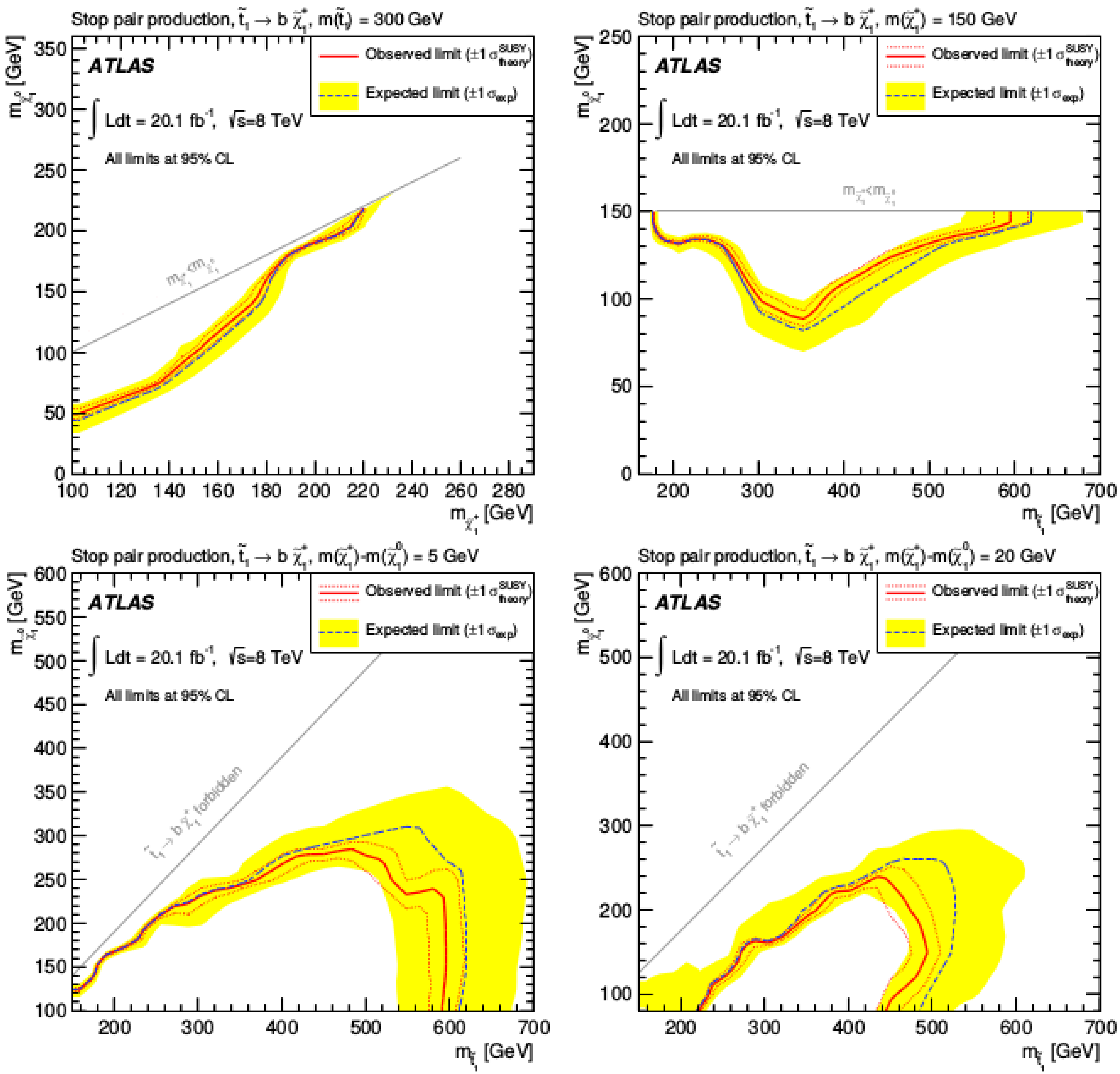
2b jets + MET search

- In the case of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$ with a small chargino-neutralino mass difference, one should see two b jets plus MET
- The same signature would be generated by sbottom pair production
- The ATLAS 2 b jets plus MET search thus can fill in the gaps of the more highly optimised stop searches

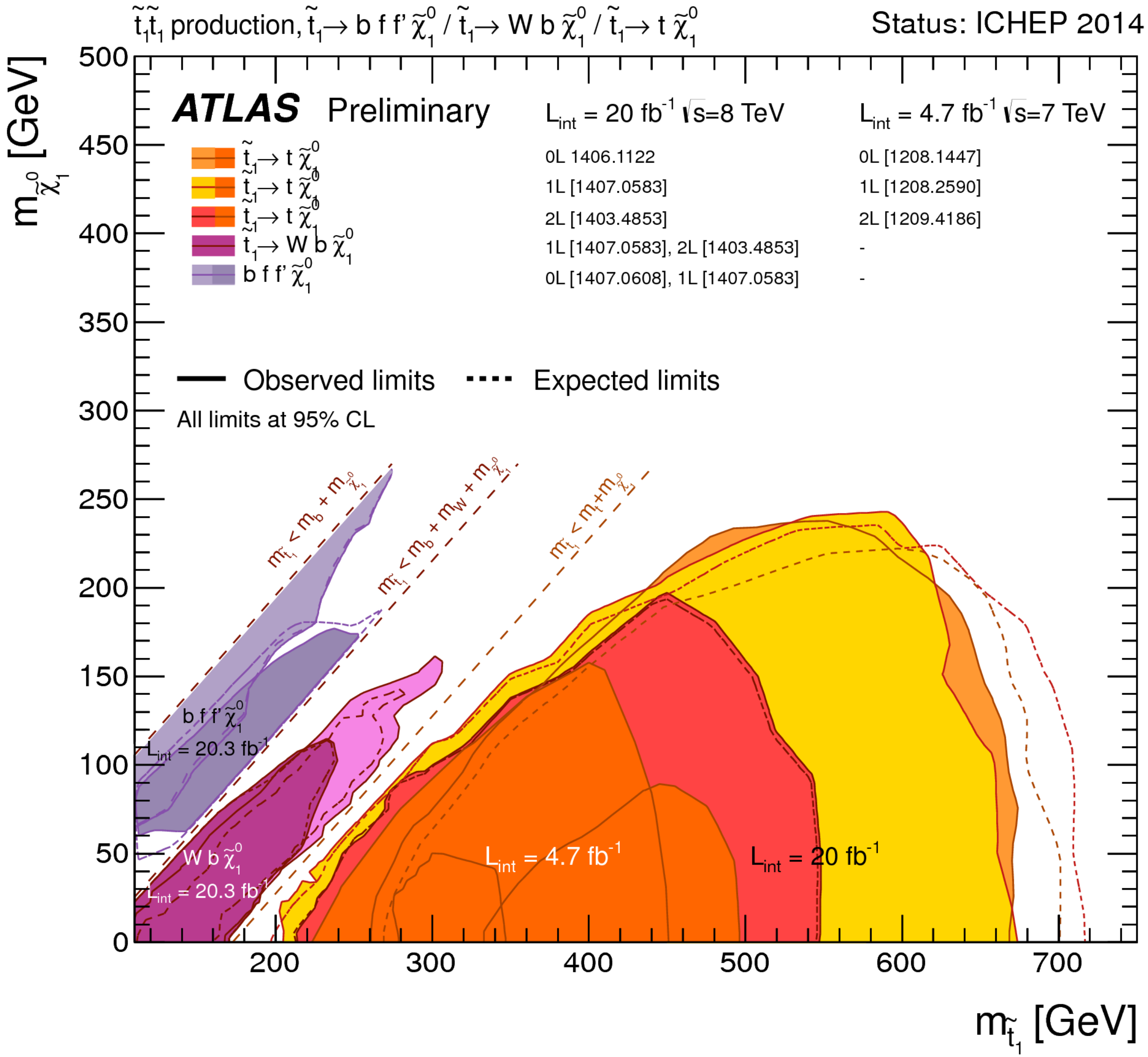


Description	Signal Regions SRA	Signal Regions SRB
Event cleaning	Common to all SR	
Lepton veto	No e/μ after overlap removal with $p_T > 7(6)$ GeV for $e(\mu)$	
E_T^{miss}	> 150 GeV	> 250 GeV
Leading jet $p_T(j_1)$	> 130 GeV	> 150 GeV
Second jet $p_T(j_2)$	> 50 GeV,	> 30 GeV
Third jet $p_T(j_3)$	veto if > 50 GeV	> 30 GeV
$\Delta\phi(p_T^{miss}, j_1)$	-	> 2.5
b-tagging	leading 2 jets ($p_T > 50$ GeV, $\lvert\eta\rvert < 2.5$)	2nd- and 3rd-leading jets ($p_T > 30$ GeV, $\lvert\eta\rvert < 2.5$)
	$n_{b\text{-jets}} = 2$	
$\Delta\phi_{min}$	> 0.4	> 0.4
$E_T^{miss}/m_{eff}(k)$	$E_T^{miss}/m_{eff}(2) > 0.25$	$E_T^{miss}/m_{eff}(3) > 0.25$
m_{CT}	$> 150, 200, 250, 300, 350$ GeV	-
$H_{T,3}$	-	< 50 GeV
m_{bb}	> 200 GeV	-

2b jets + MET search: Results



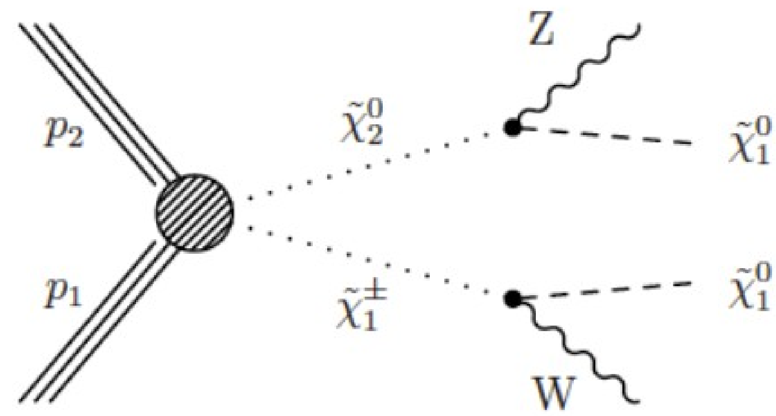
Stop search summary

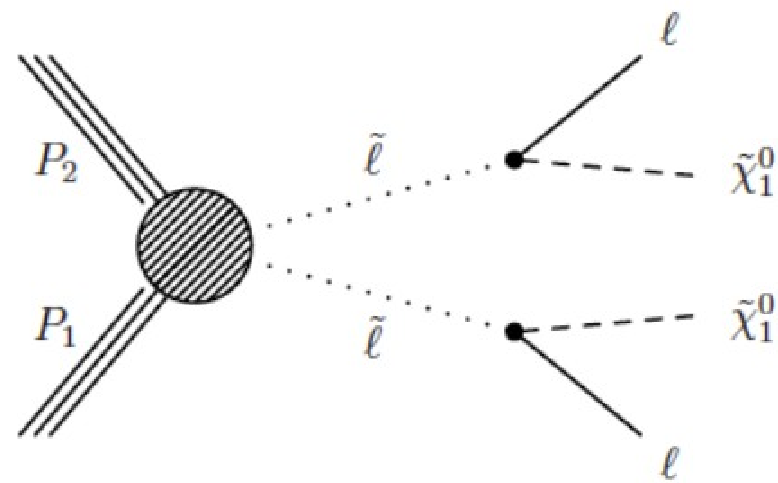


- If coloured sparticles much heavier than EW partners
  - direct chargino/neutralino/slepton production
- Leptonic decay modes provide clean signature:
  - many leptons (up to 4) + MET
  - possibly taus
  - possibly OSSF lepton pairs with $m_{ll} = m_Z$
  - low jet activity
  - in case of WZ + MET final state use:

$$M_{\mathrm{T}} = \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{l} (1 - \cos \Delta\phi_{l, E_{\mathrm{T}}^{\mathrm{miss}}})}$$

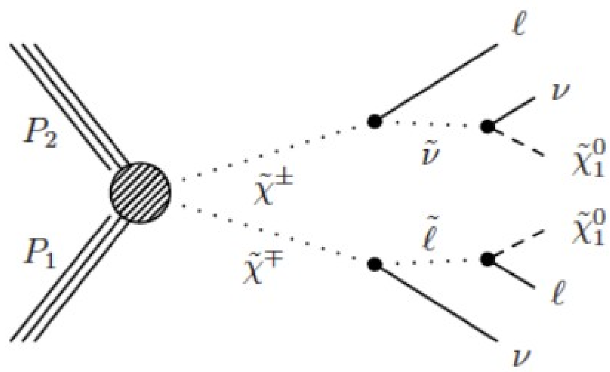
Example processes:

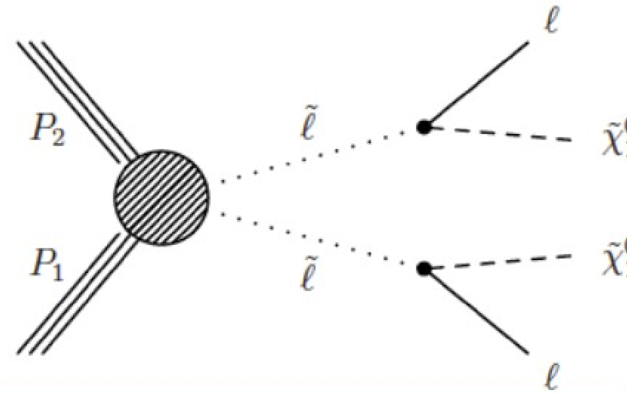


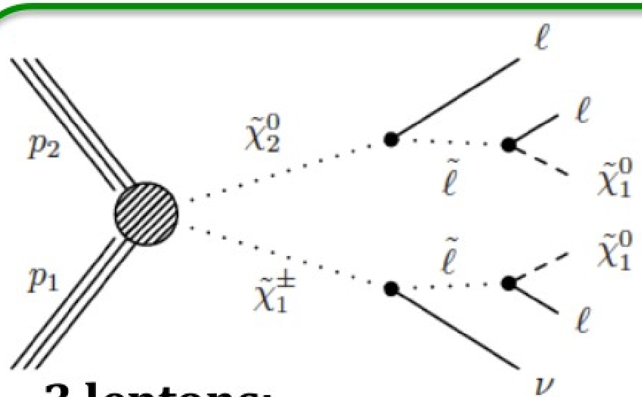


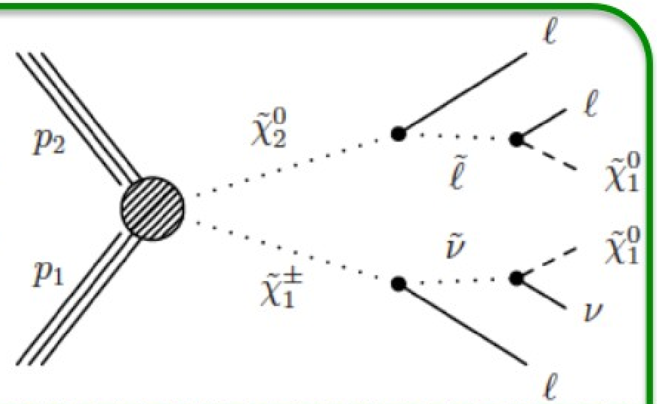
Expected signatures

Mostly **2 leptons:**
- Possibly 1 OSSF pair







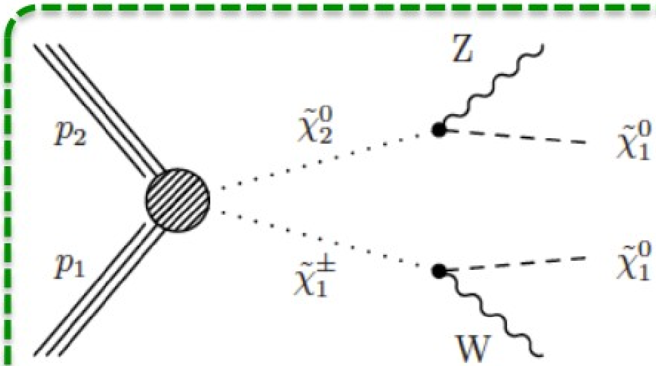


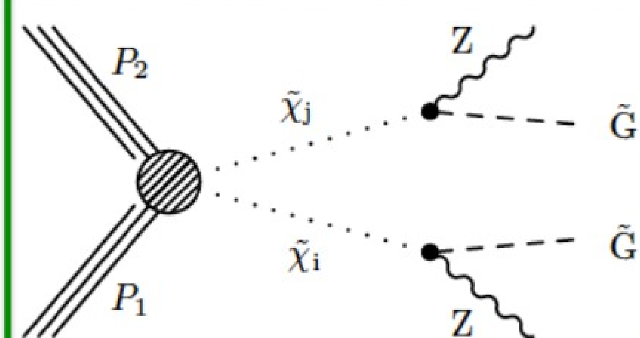
3 leptons:
- Possibly 1 OSSF pair
- Possibly $m_{\ell\ell} \sim m_Z$
- Possibly SS leptons (if one lepton is "lost")

Also: **2 leptons + 2 jets**

Up to **four leptons**
- Up to 2 OSSF

Also: **2 leptons + 2 jets**





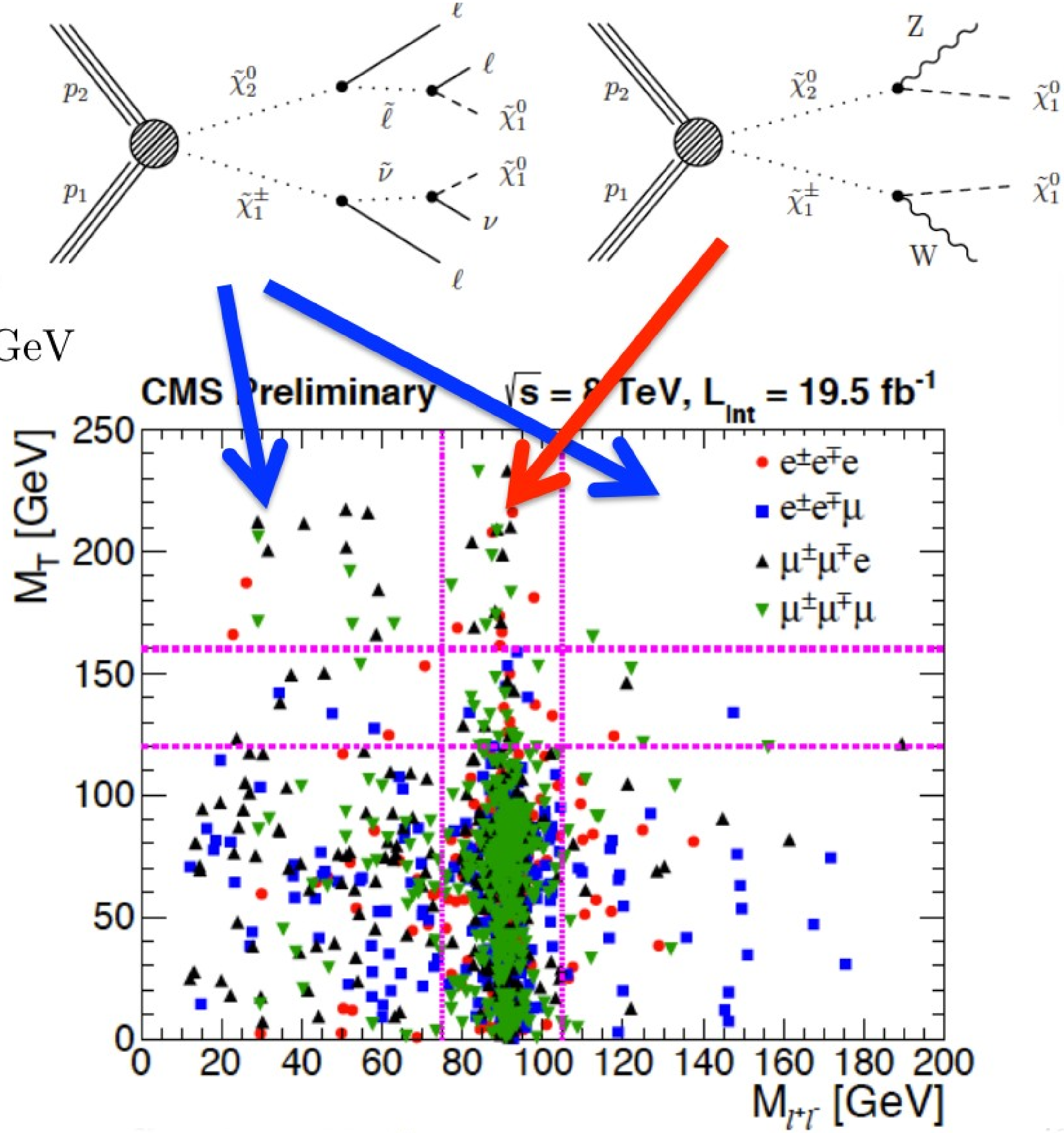
Analysis example: CMS-SUS-13-006

Example selection:

- $N_{\text{leptons}} = 3$
- $N_{b\text{-tag}} = 0$ (suppress $t\bar{t}$)
- MET > 50 GeV (suppress Z+jets)
- Reject events with $m_{l^+l^-} < 12$ GeV
- Search binned in
  - Lepton flavours
  - MET
  - M_{T}
  - $m_{\ell\ell}$ below/on/above Z mass

Backgrounds:

- WZ : MC simulation + data driven MET correction
- $t\bar{t}$: data driven "fake" rate methods



Summary

- There are lots and lots of LHC SUSY searches

- We have viewed one “canonical” example in detail

- Have briefly sketched strategies for other scenarios

    - EW searches

    - 3rd generation searches

- Pay attention to the experimental results talks next week

    - hopefully you now have the knowledge to digest the details
    - will get a comprehensive overview on Run II searches