Supersymmetry after LHC Run 1

Brian Petersen
CERN

Outline

- Supersymmetry
  What and why?

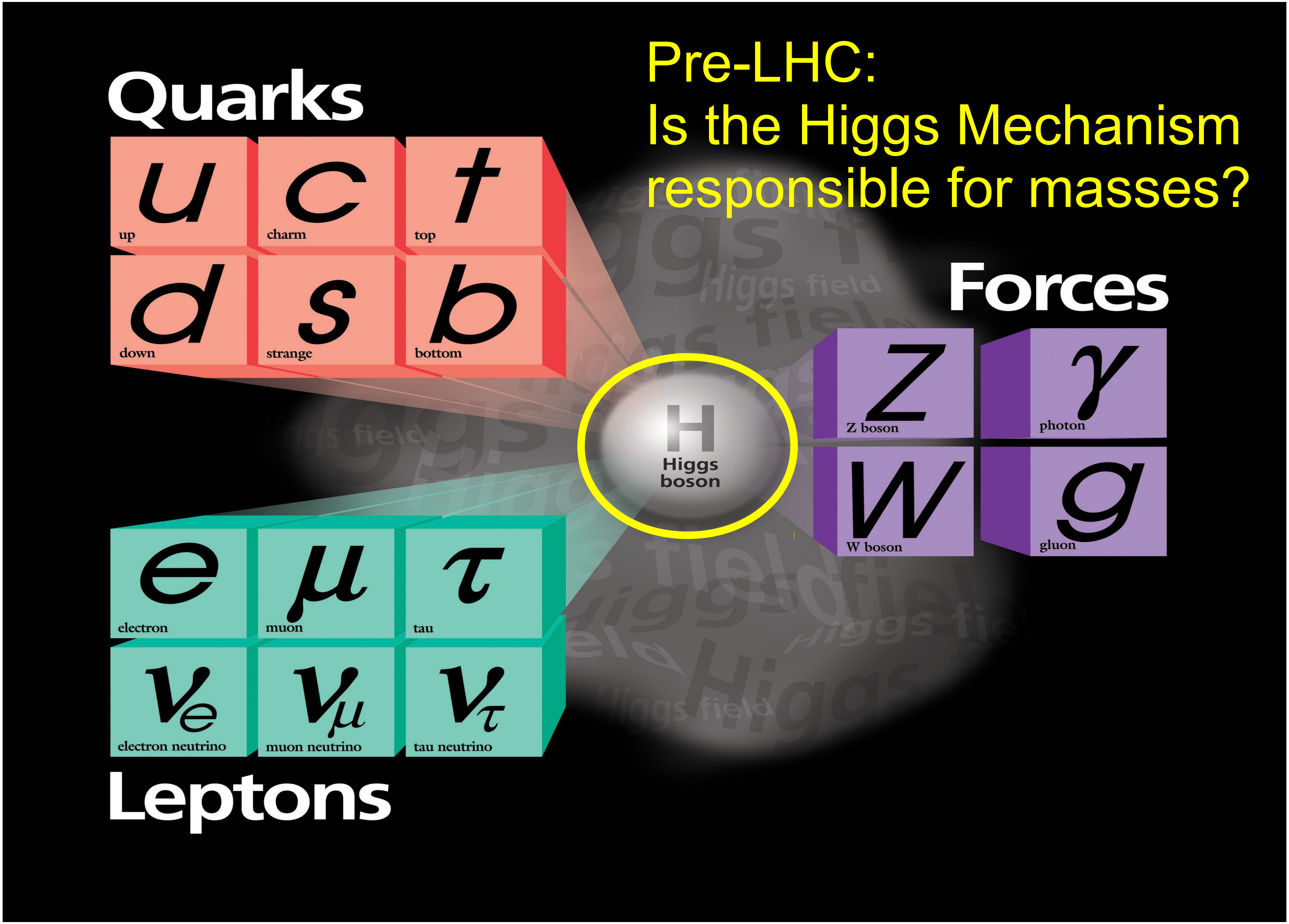
- Searching for Supersymmetry at the LHC
  Brief intro to LHC and the ATLAS experiment and how we search for Supersymmetry there

- Status of Run-1 Supersymmetry searches
  Where did we look? What did we find?
  Will focus mostly on some of the latest results

- Outlook for upcoming data-taking
  What can we expect for 2015 and beyond

Supersymmetry

Standard Model



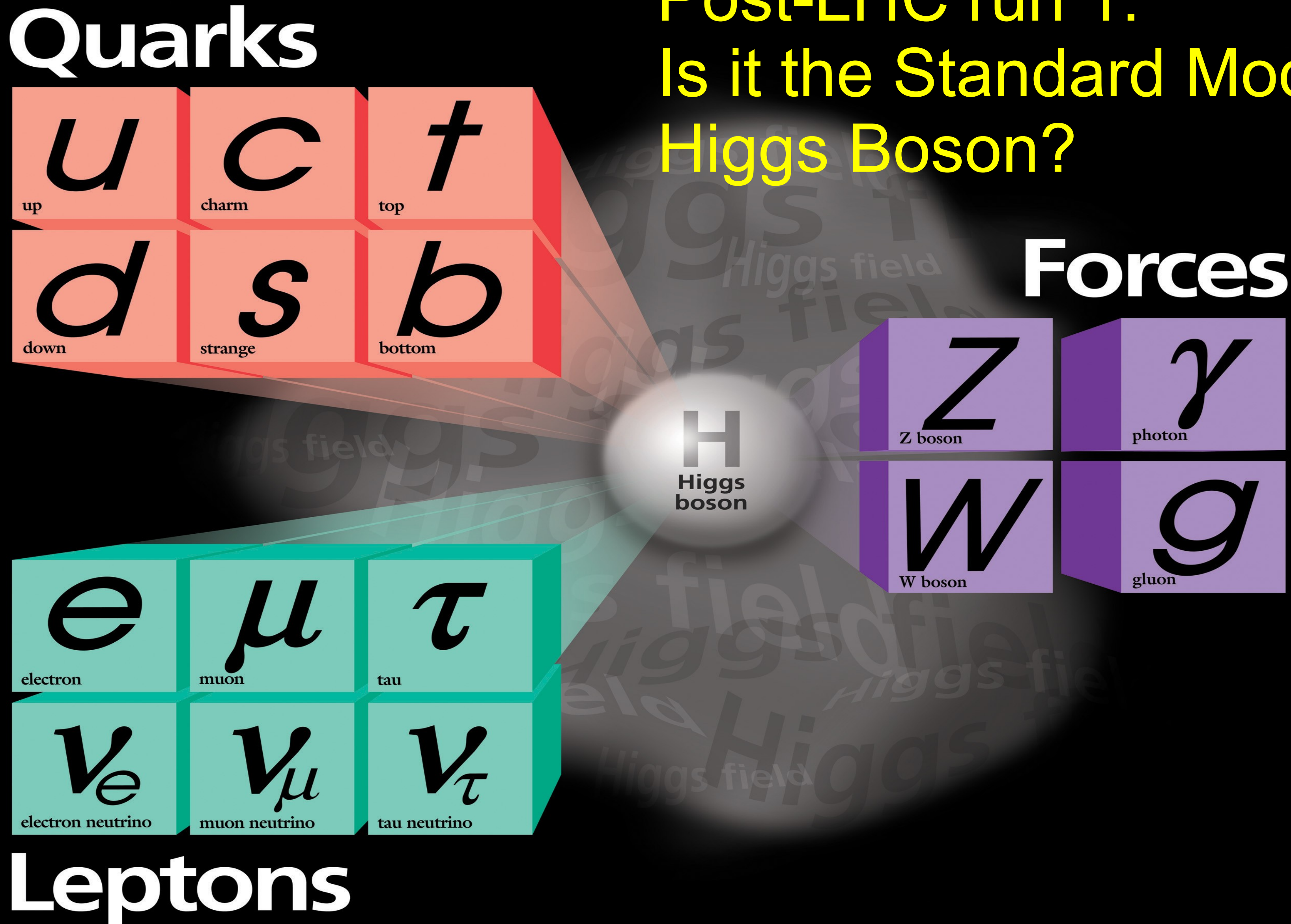
2013 NOBEL PRIZE IN PHYSICS

François Englert
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”

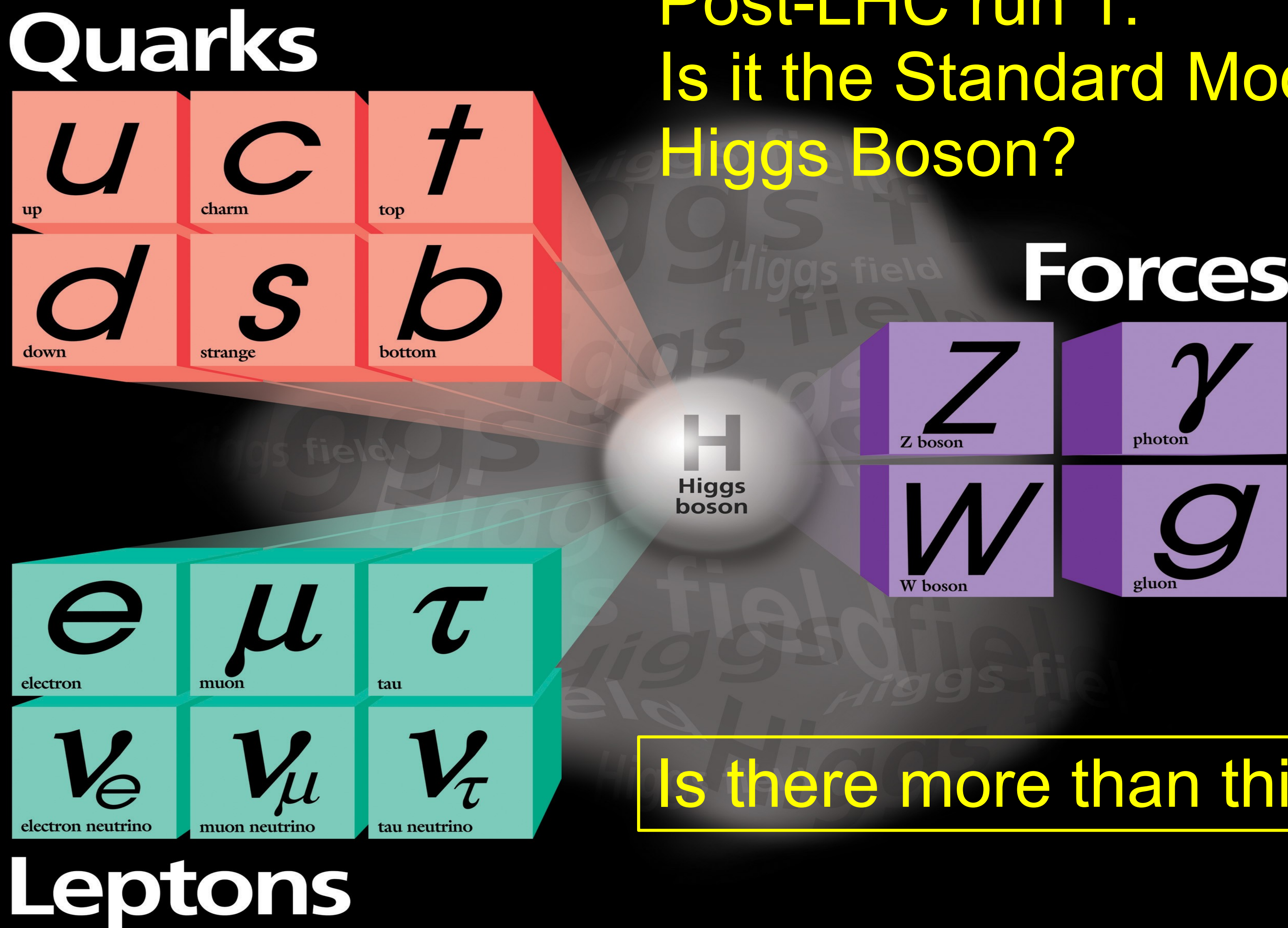
Standard Model Complete?



Post-LHC run 1:
Is it the Standard Model Higgs Boson?

Standard Model Complete?

Post-LHC run 1:
Is it the Standard Model Higgs Boson?

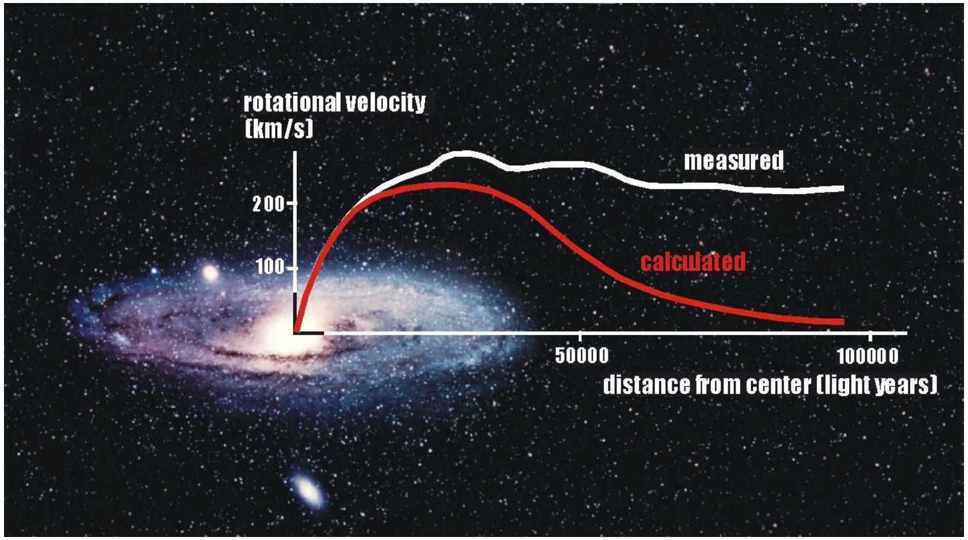


Is there more than this?

Dark Matter

Strong evidence in astrophysics for presence of dark matter

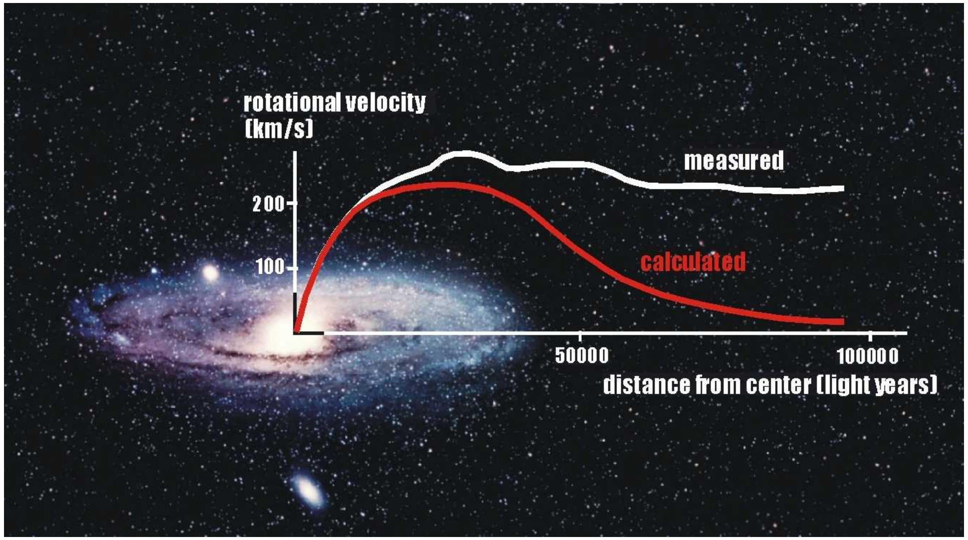
Galaxy rotational curves



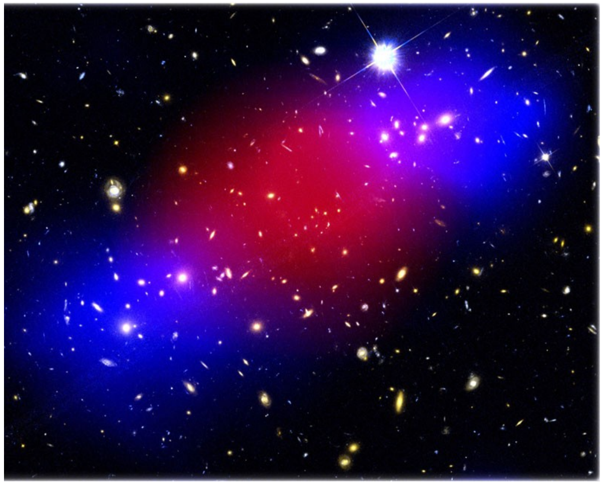
Dark Matter

Strong evidence in astrophysics for presence of dark matter

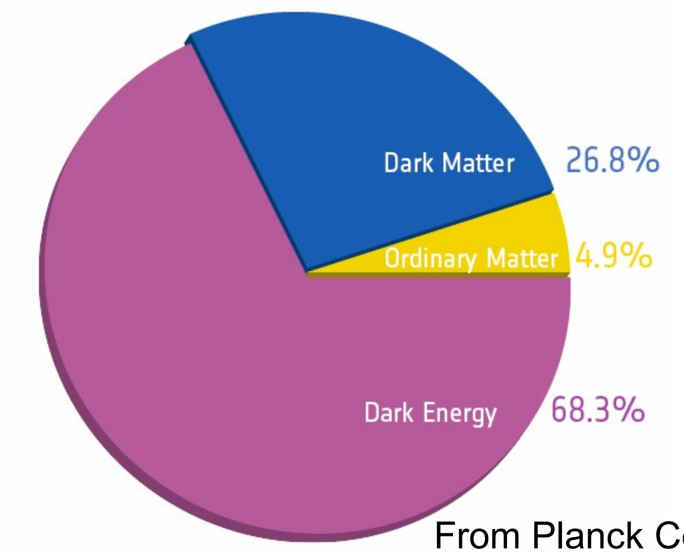
Galaxy rotational curves



Gravitational lensing

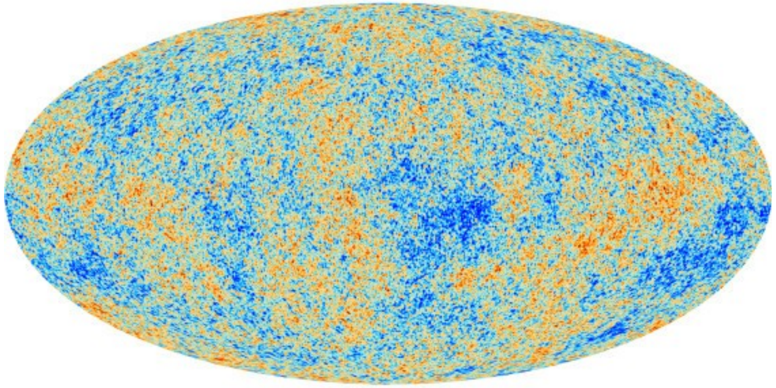


Combined cosmological fit



From Planck Collaboration

Cosmic microwave background



Possible Sources of Dark Matter

Ordinary non-luminous matter?

- A lot of the 5% ordinary matter is not luminous, but present in form of gas etc.
- Cannot account for non-baryonic DM

Neutrinos?

- Can only have small contribution due to large-scale structure formation

Modifying gravity

- Very difficult to explain all the different measurements

Axions?

- Particle resulting from the Peccei-Quinn solution to the strong CP problem
- O(keV) mass – good DM candidate

WIMPs?

- Weakly Interacting Massive Particle
- EW-scale (100-1000 GeV) gives right DM density

Other exotic particles

- Many other options have been proposed

Possible Sources of Dark Matter

Ordinary non-luminous matter?

- A lot of the 5% ordinary matter is not luminous, but present in form of gas etc.
- Cannot account for non-baryonic DM

Neutrinos?

- Can only have small contribution due to large-scale structure formation

Modifying gravity

- Very difficult to explain all the different measurements

Axions?

- Particle resulting from the Peccei-Quinn solution to the strong CP problem
- O(keV) mass – good DM candidate

WIMPs?

- Weakly Interacting Massive Particle
- EW-scale (100-1000 GeV) gives right DM density

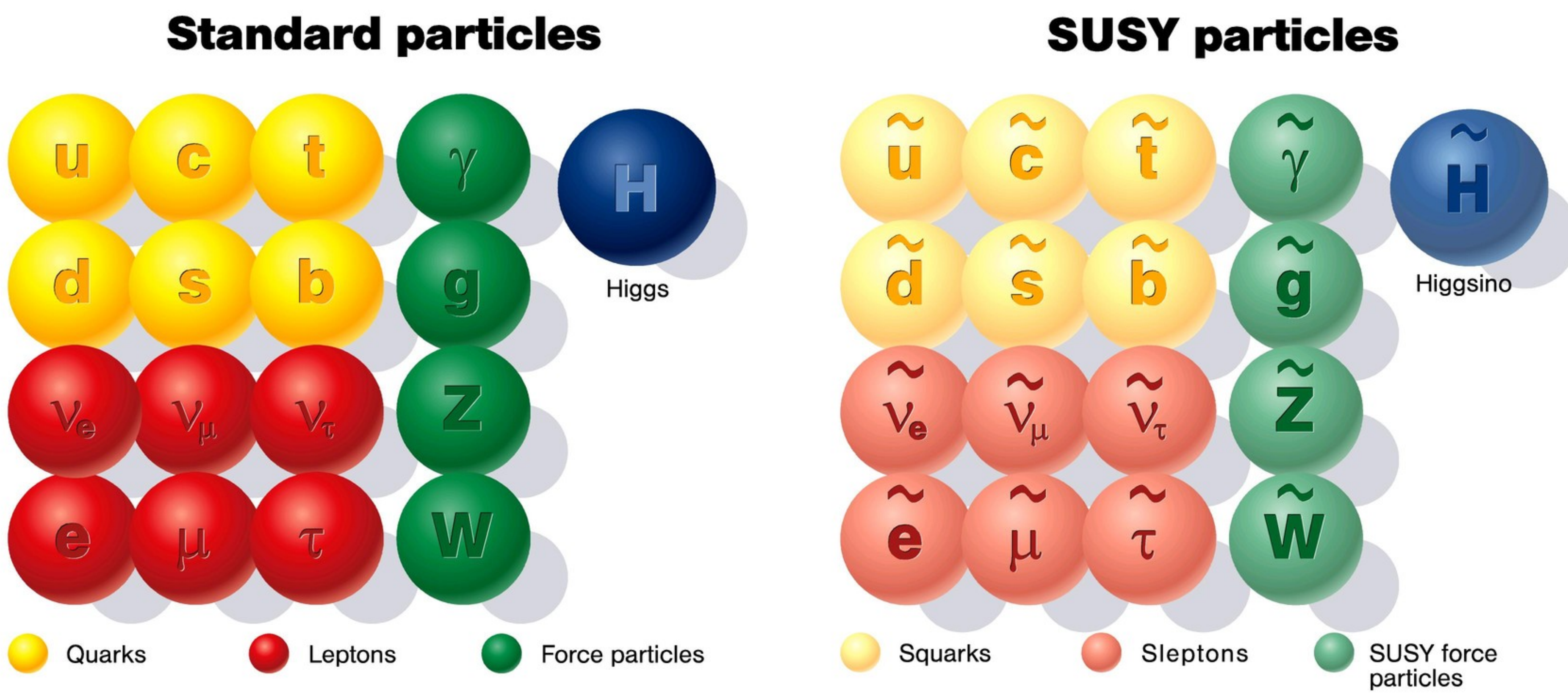
Other exotic particles

- Many other options have been proposed

Supersymmetry

Supersymmetry (SUSY) is a favored source for WIMP

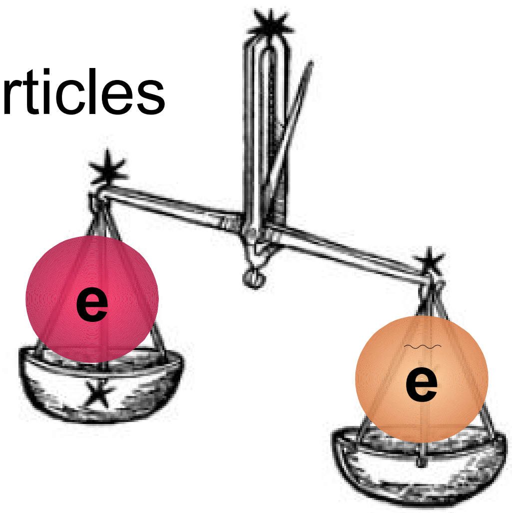
- New symmetry between bosons and fermions
- For every SM particle, introduces partner with Δspin=½



Supersymmetry

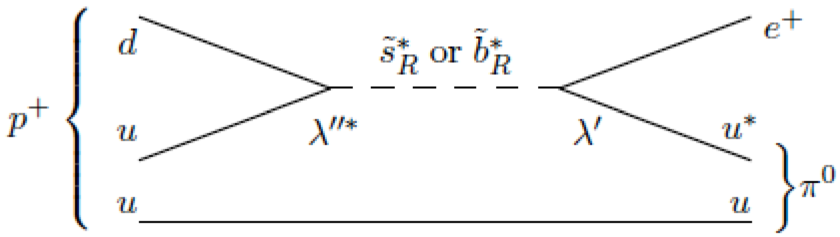
Supersymmetry must be broken symmetry

- If unbroken, would have same mass as SM particles
- Introduce soft breaking terms
- In minimal supersymmetry (MSSM) this introduces 124 new parameters



R-parity

- MSSM introduces baryon and lepton number violating processes
- Protect against proton decays by introducing new discrete symmetry



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

- Implies SUSY particles always produced in pairs
- Lightest SUSY particle (LSP) has to be stable

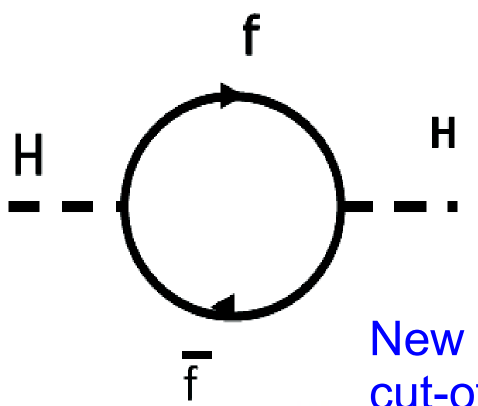
This is an excellent Dark Matter candidate

Supersymmetry Motivation

Dark matter is not the original or only motivation for SUSY
Also provides solutions to several particle theory issues

Hierarchy Problem

- Very large loop corrections to Higgs mass in any SM extension



New physics cut-off

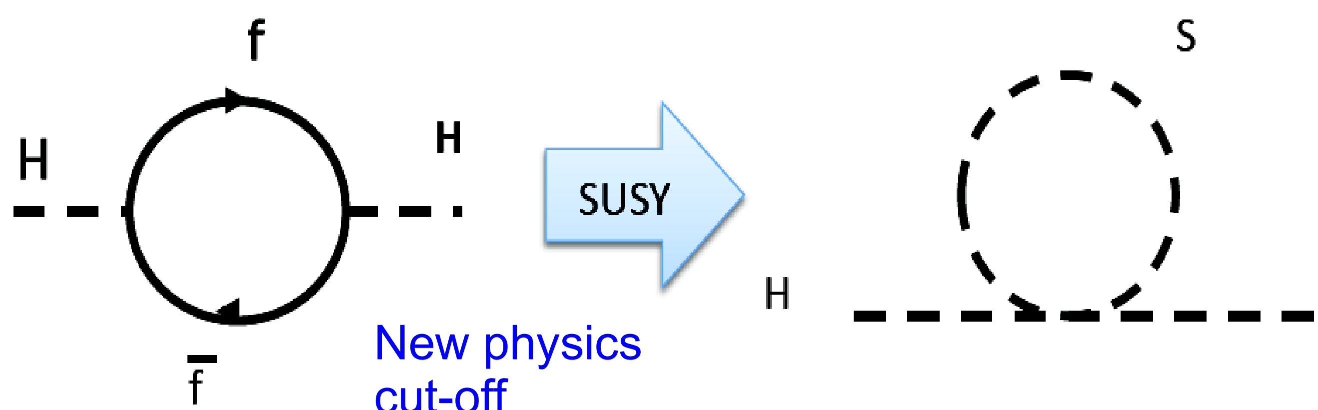
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

Supersymmetry Motivation

Dark matter is not the original or only motivation for SUSY
Also provides solutions to several particle theory issues

Hierarchy Problem

- Very large loop corrections to Higgs mass in any SM extension
- SUSY can stabilize Higgs boson mass without extreme fine-tuning



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots .$$

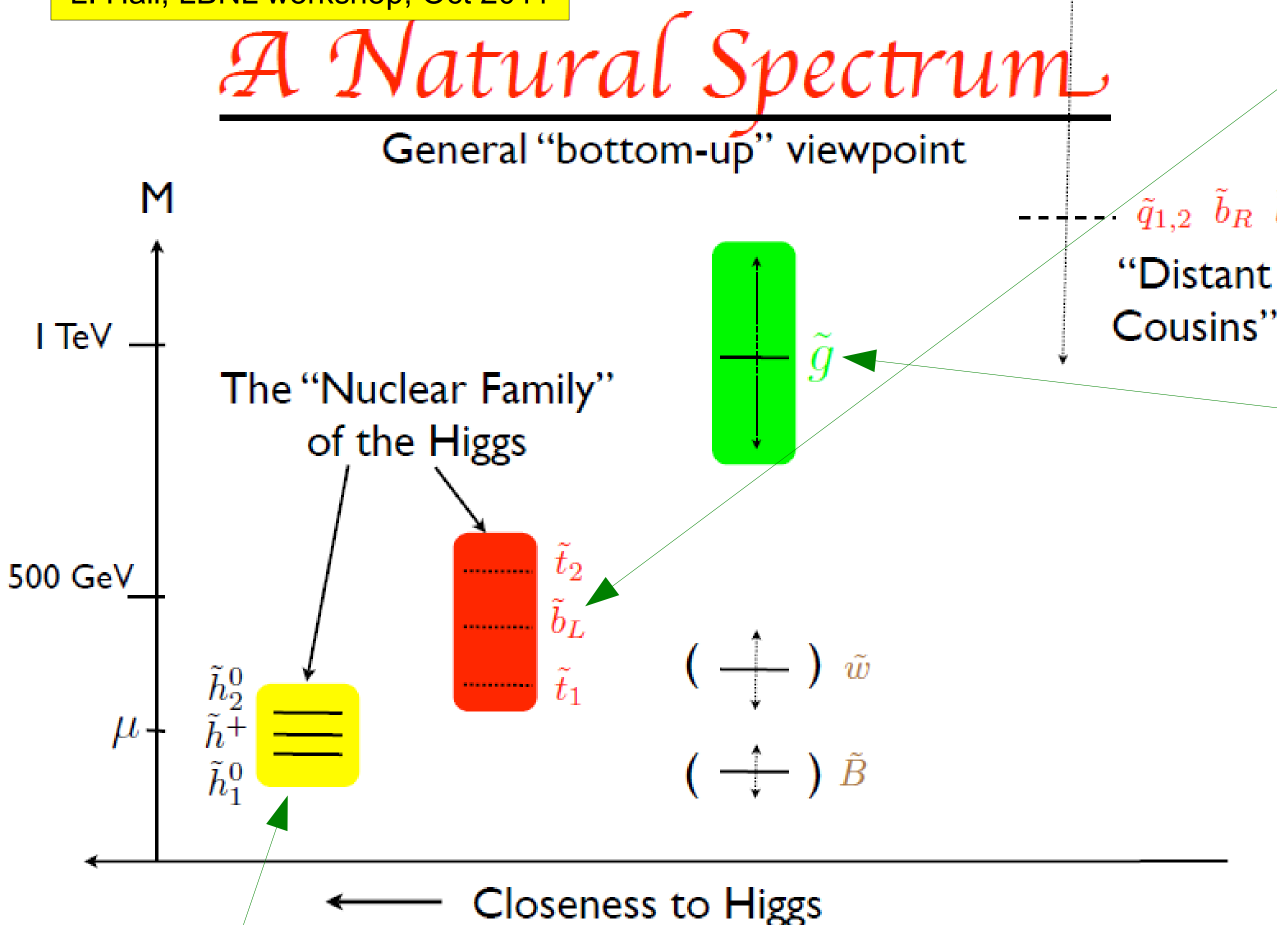
Opposite sign contribution

Requires SUSY particles not to be much heavier, O(TeV), than the Standard Model particles

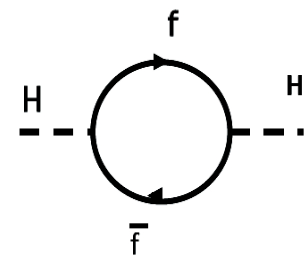
Natural SUSY

Not all SUSY particles need to be light
Focus on the ones that have to be light ("Natural SUSY")

L. Hall, LBNL workshop, Oct 2011



Only light stop needed to regularize light Higgs boson



The gluino should not be too heavy either

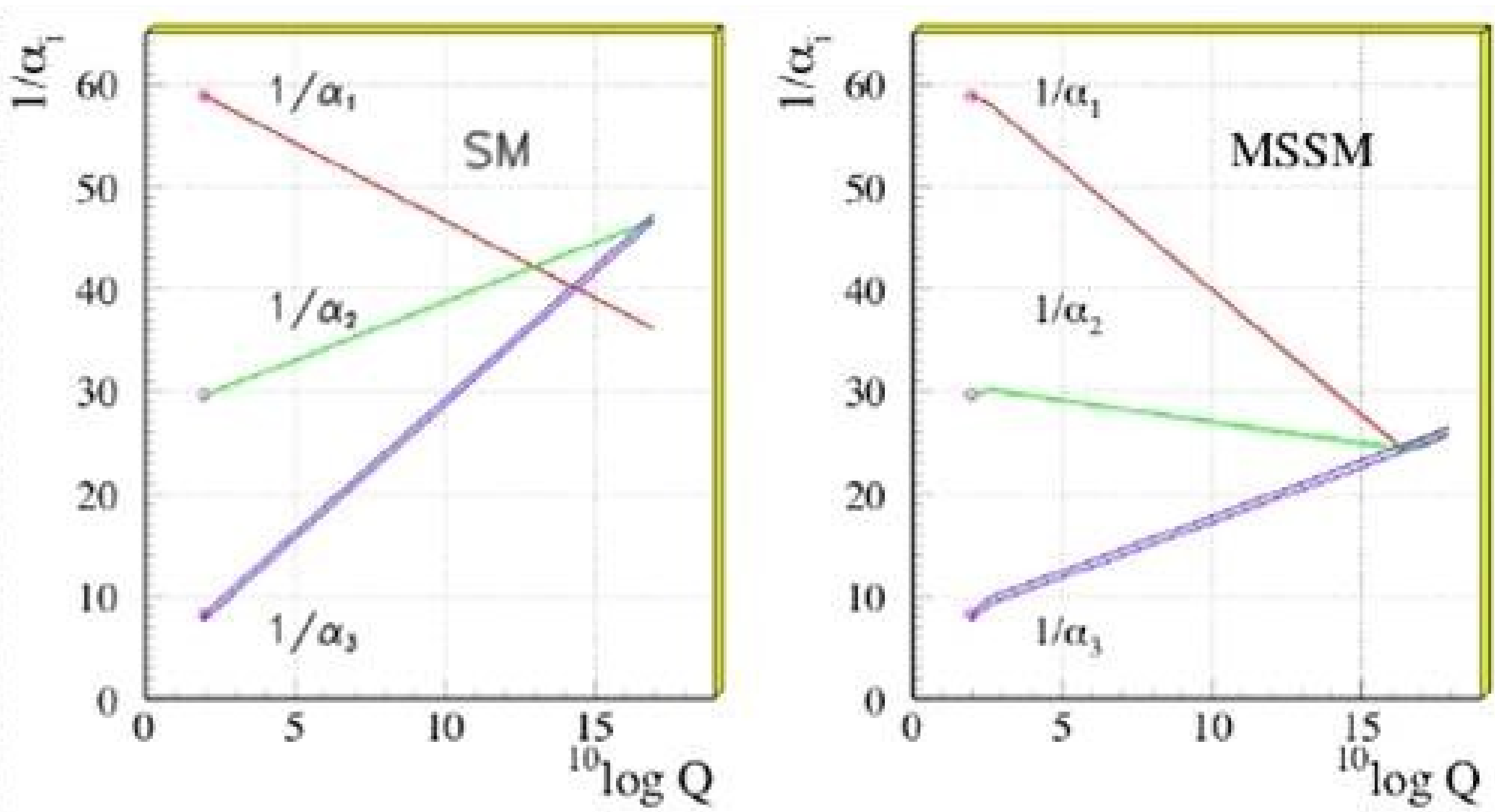
Much attention has been devoted to the search for these in the LHC searches

Light higgsinos as $\mu \sim m_Z$ at tree level

Supersymmetry Motivation

Gauge-coupling Unification

- Couplings run in SM, but do not quite meet as one would expect in a Grand Unified Theory (GUT)
- SUSY changes running of couplings to allow unification of couplings at GUT scale

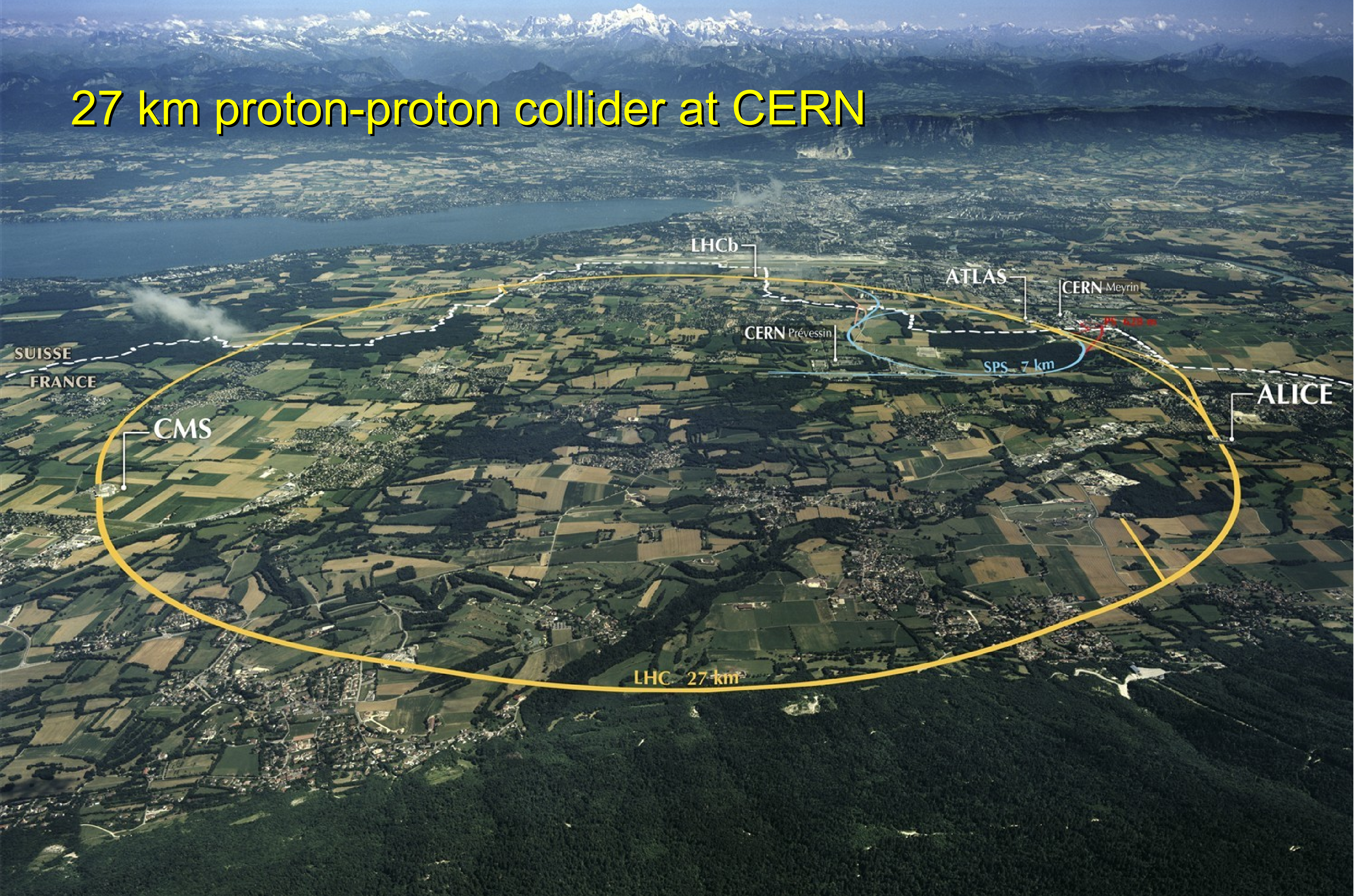


Again requires SUSY at TeV scale

Searching for Supersymmetry at the LHC

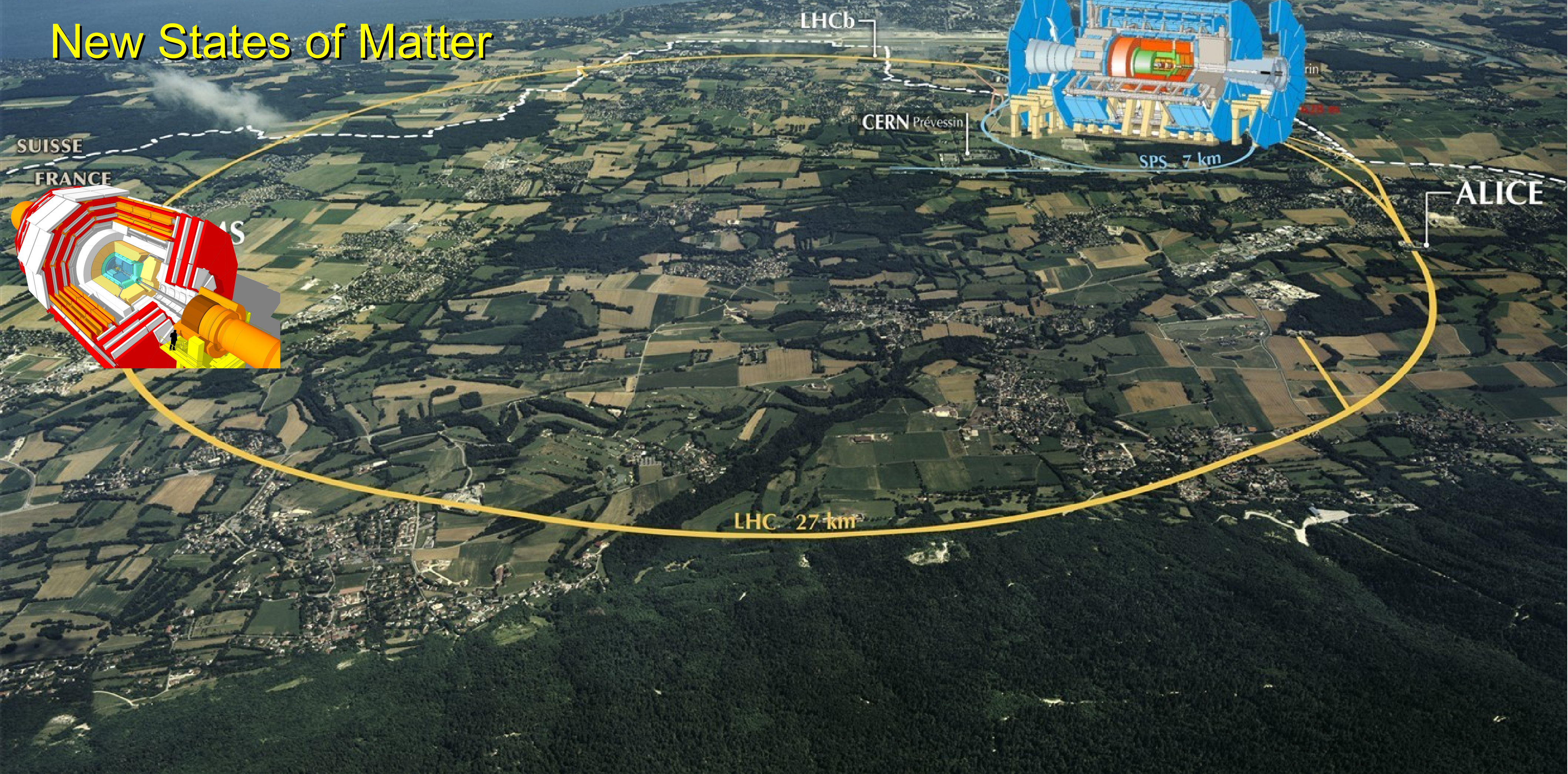
Large Hadron Collider

27 km proton-proton collider at CERN



Large Hadron Collider Goals

- Electroweak Symmetry Breaking
- Beyond SM Physics Searches
- Matter-antimatter Asymmetry
- New States of Matter

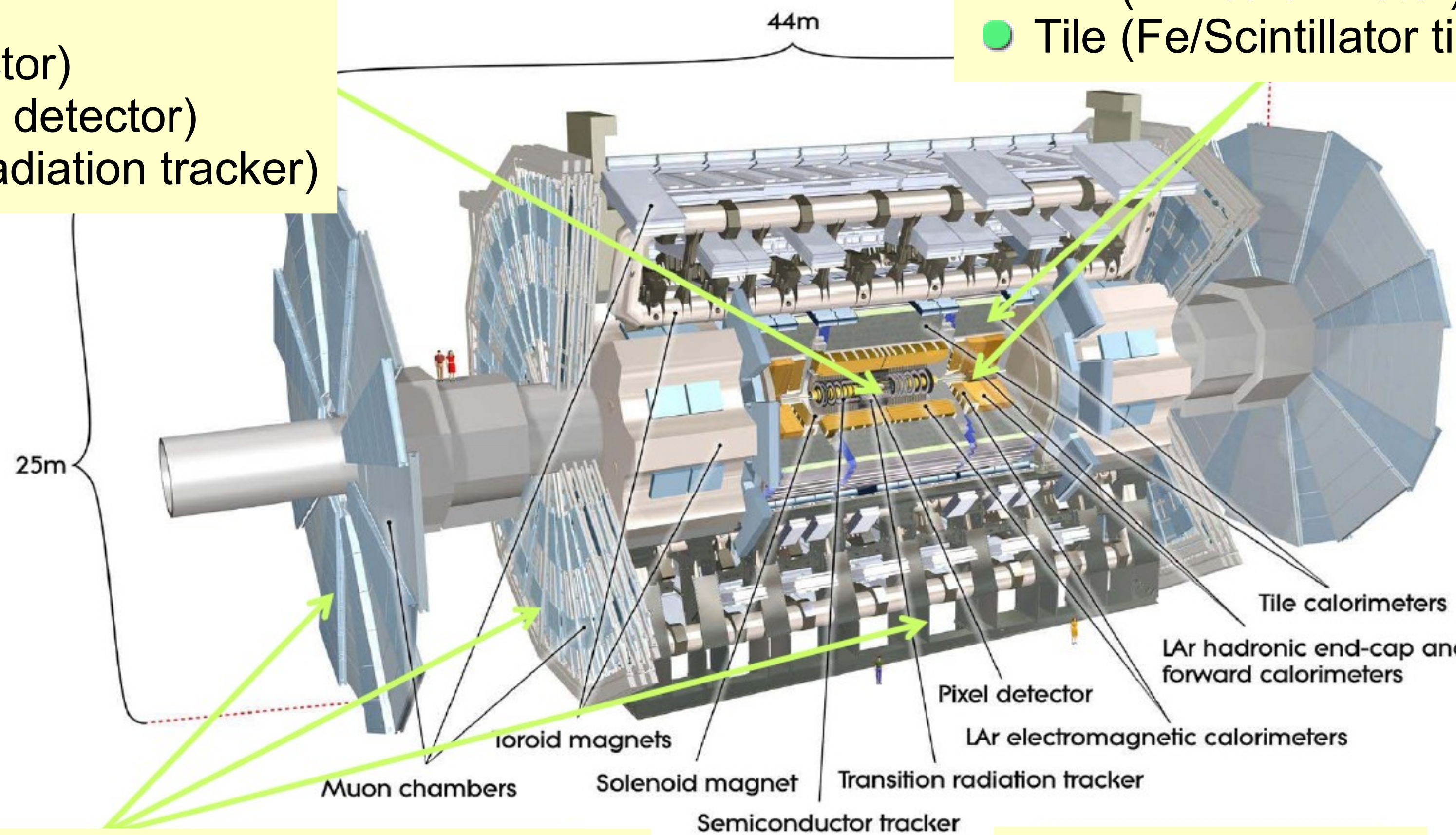


The ATLAS Experiment

Inner Detector
- Pixel (pixel detector)
- SCT (silicon strip detector)
- TRT (transition radiation tracker)

Calorimeter
- LAr (EM calorimeter)
- Tile (Fe/Scintillator tile)

7 TeV proton



Muon Spectrometer
- MDT,CSC (precise momentum measurement)
- RPC,TGC (trigger chambers)

Magnet System
- 2 T solenoid
- 0.5 T toroid

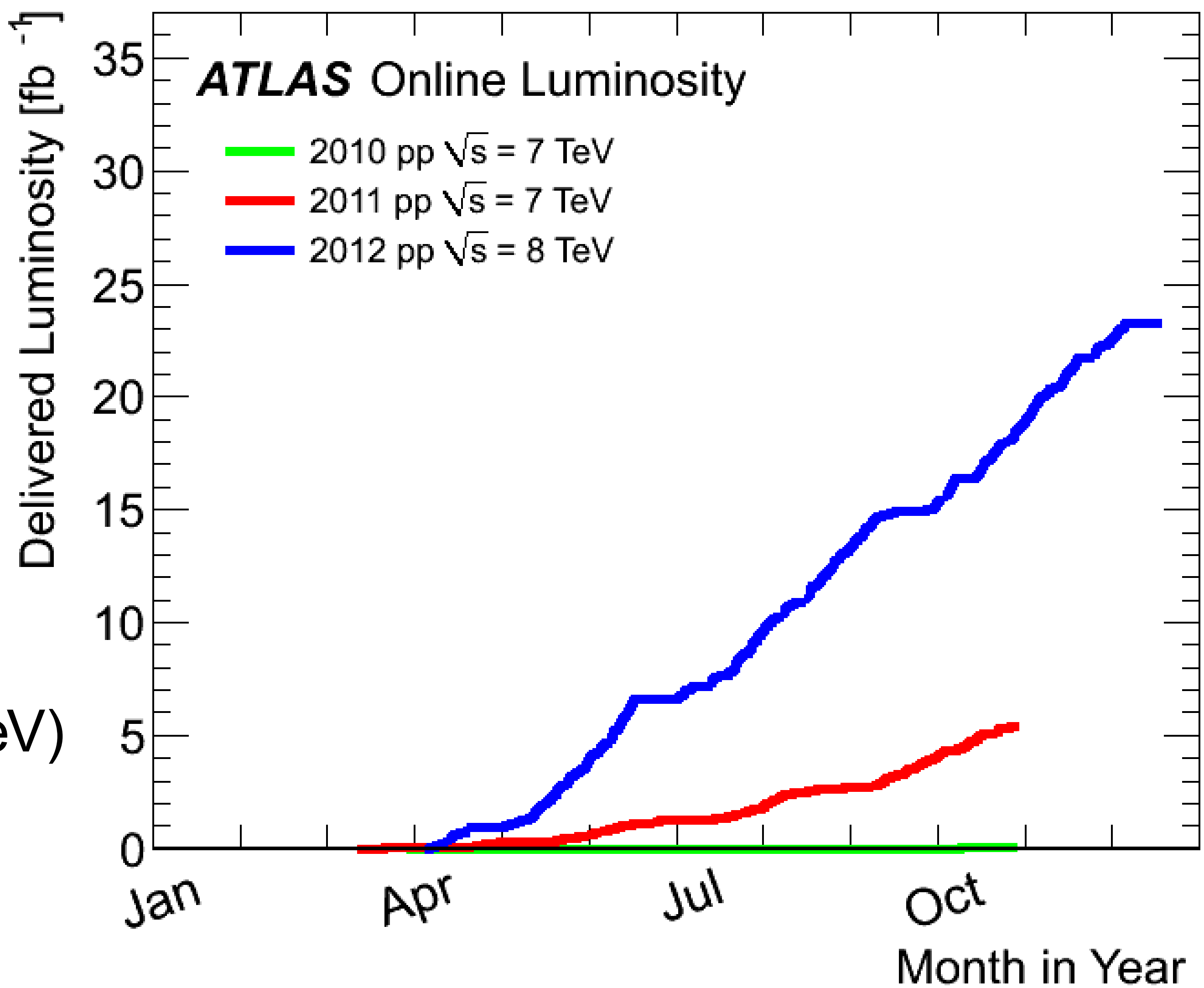
Luminosity

Critical LHC parameter is delivered luminosity:

Rate = Cross-section x Efficiency x Luminosity

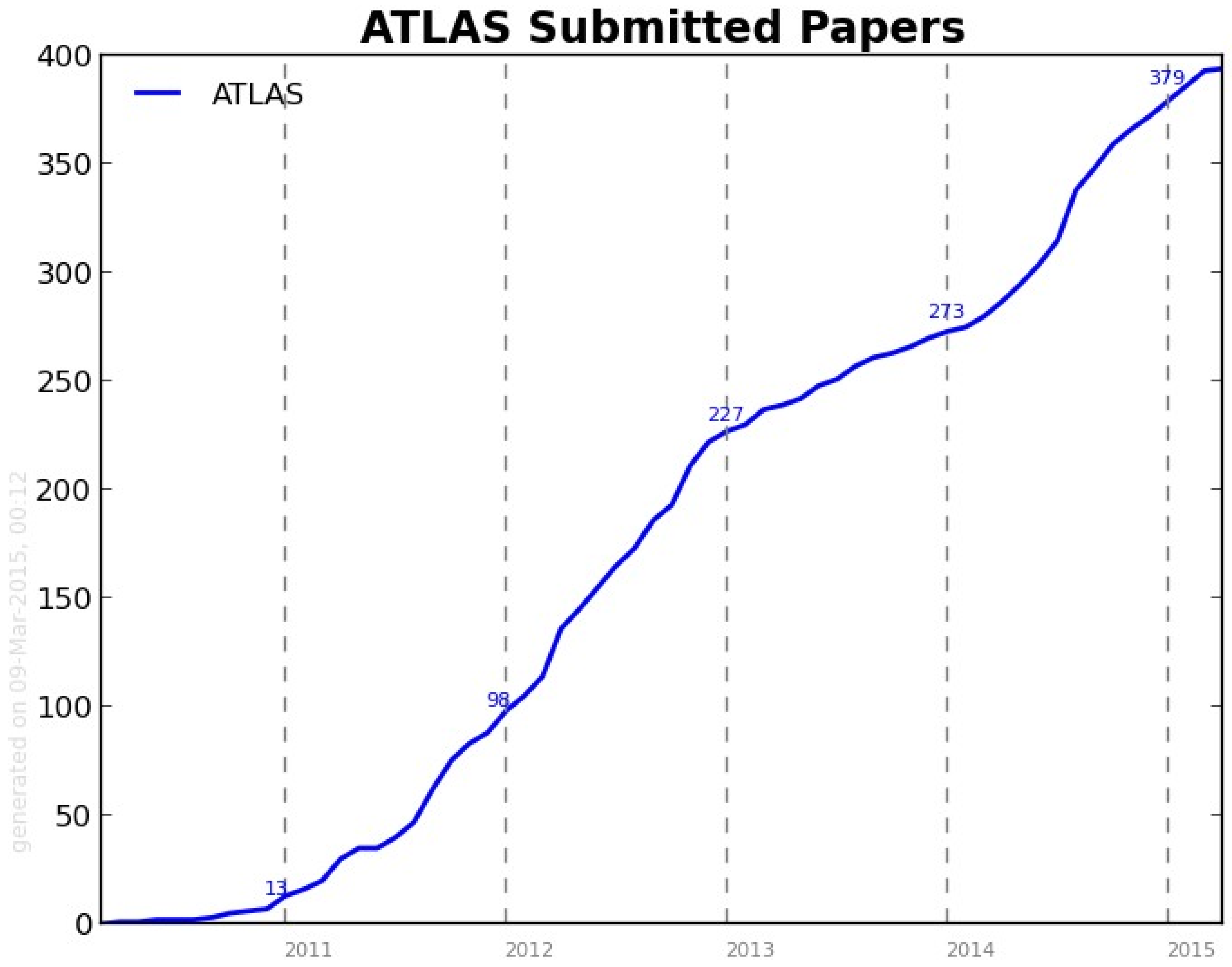
Excellent LHC performance:

- Peak luminosity of $7.7\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$
- Big jumps in integrated luminosity:
  2010: 0.048 fb^{-1}
  2011: 5.6 fb^{-1}
  2012: 23.3 fb^{-1}
  (also increase in energy from 7 to 8 TeV)
- Full sample is called “Run-1”



LHC – A Paper Factory

~400 papers for the first 3 years of data-taking
In addition more than 600 preliminary results



ATLAS Total: 395
on SUSY: 74

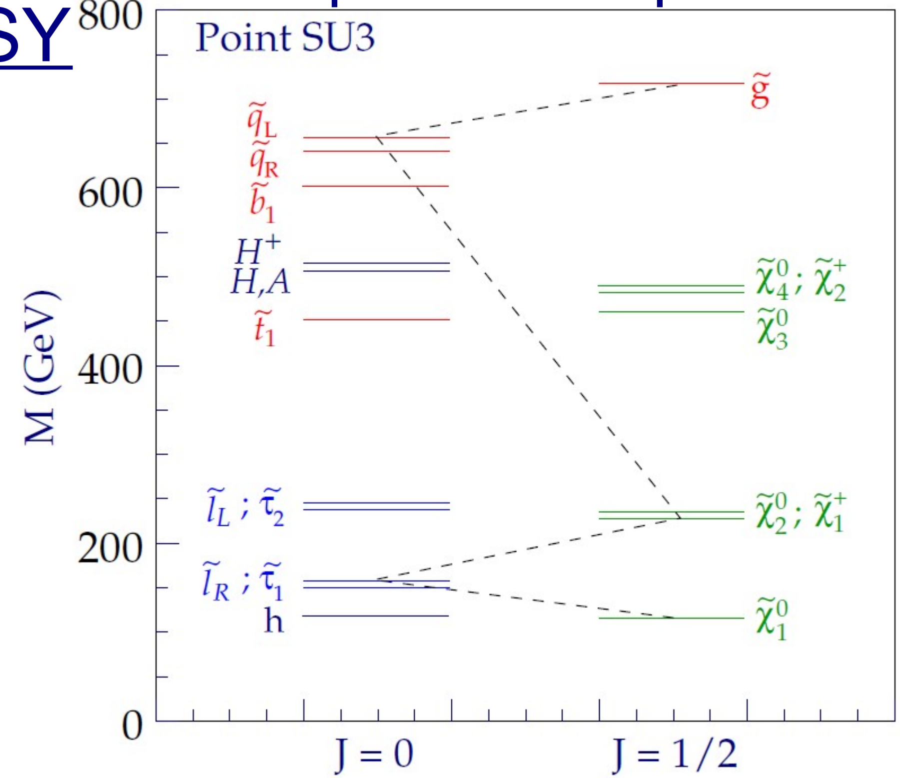
CMS Total: 378
on SUSY: 48

Searching for SUSY at the LHC

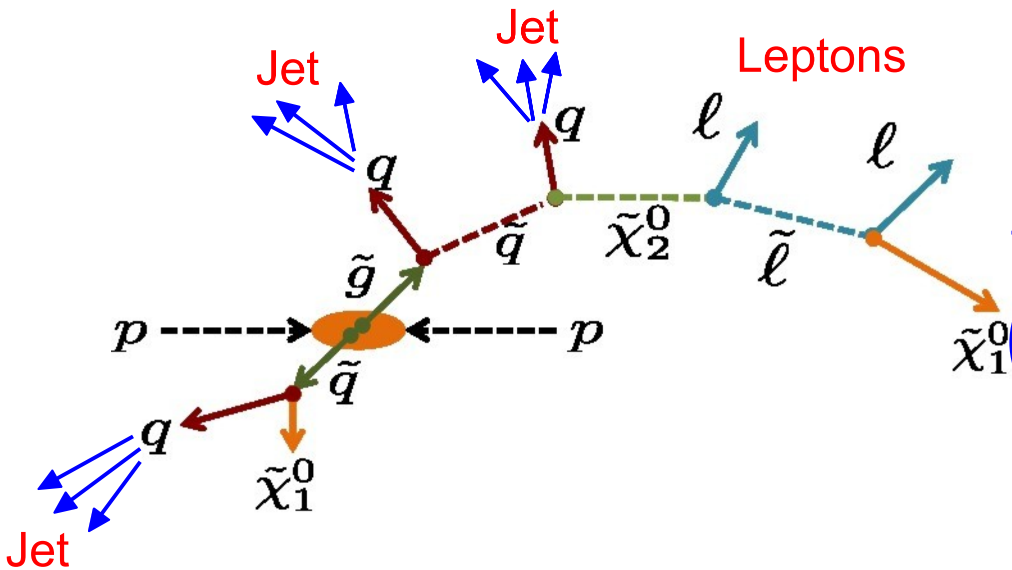
Wide ranging searches for SUSY

- Many different SUSY models with different masses and decays
- Requires to look for many different signatures
- Always pair produced and typically more energetic than SM with multiple decay products

Example SUSY spectrum



A typical SUSY decay chain:



Missing energy

Key signature for all SUSY models with a stable LSP (i.e. Dark Matter candidate)

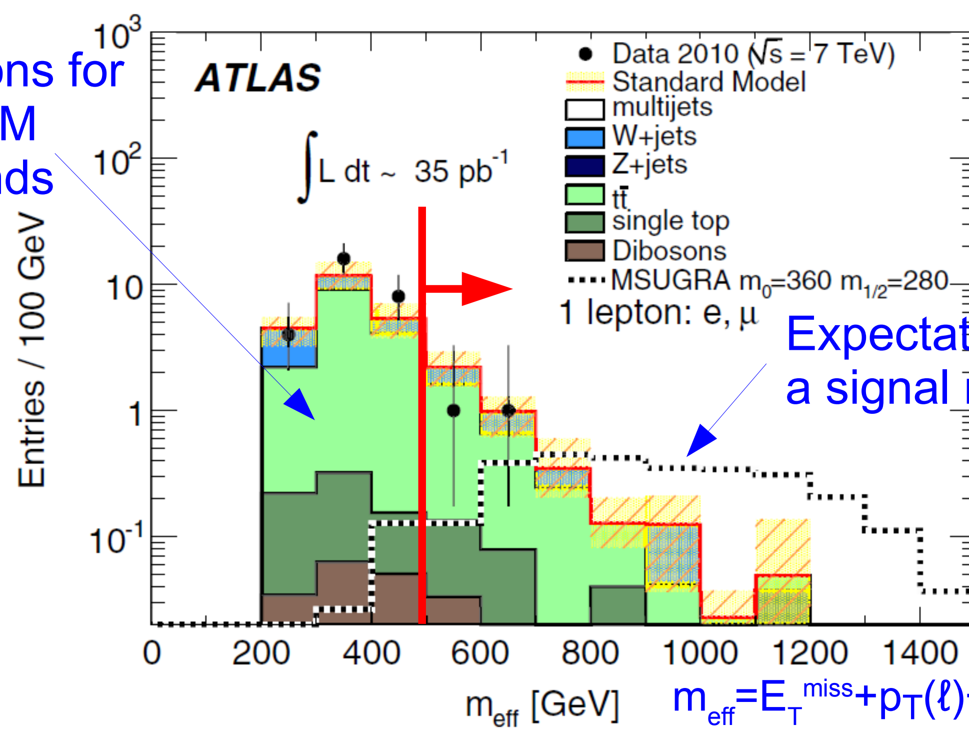
SUSY Analysis and Backgrounds

Typical ATLAS supersymmetry search:

- Count events that has a characteristic SUSY signature and is unlikely to be due to Standard Model processes
  – More than … jets and/or leptons
  – Measured energy above … GeV
  – Missing transverse energy above … GeV

  …
- *Are there more events than expected from the Standard Model?*

Expectations for different SM backgrounds



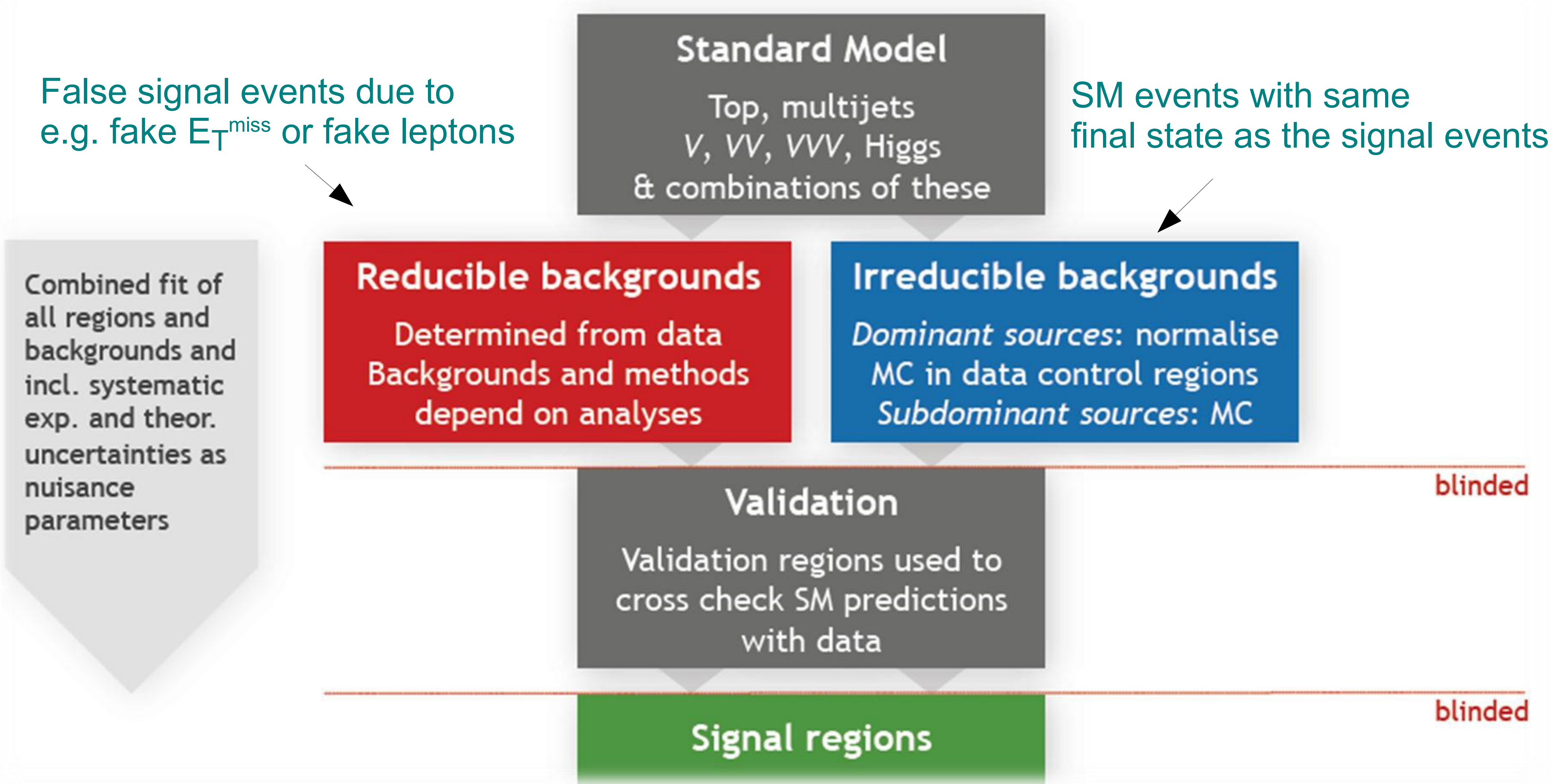
Expectation from a signal model

$m_{eff}=E_T^{miss}+p_T(\ell)+\Sigma\ p_T(jet)$

Critical to have solid understanding of SM backgrounds

Estimating Backgrounds

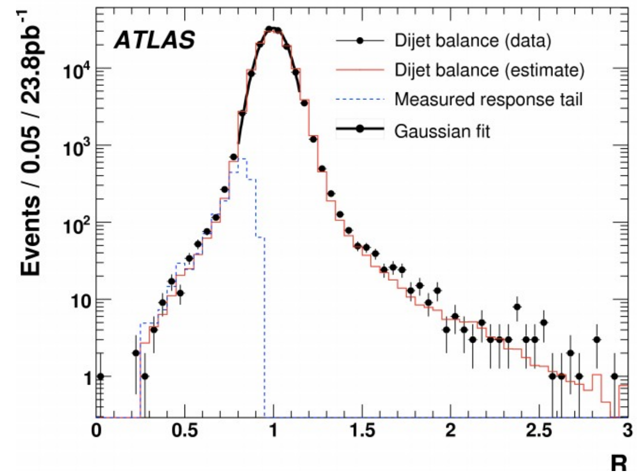
Each analysis typically has multiple source of backgrounds
Estimation of each depends on the nature of the background



Reducible Background – Example

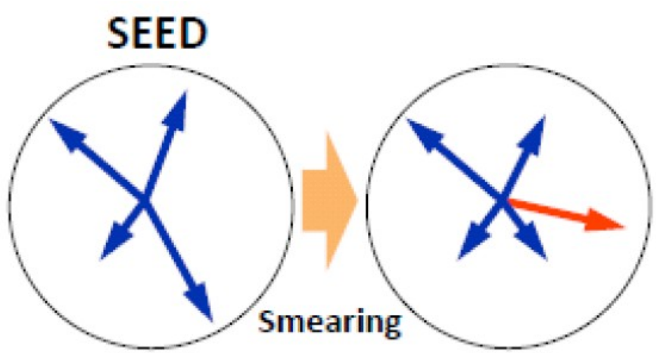
Jet mis-measurement can give large fake E_T^{miss}

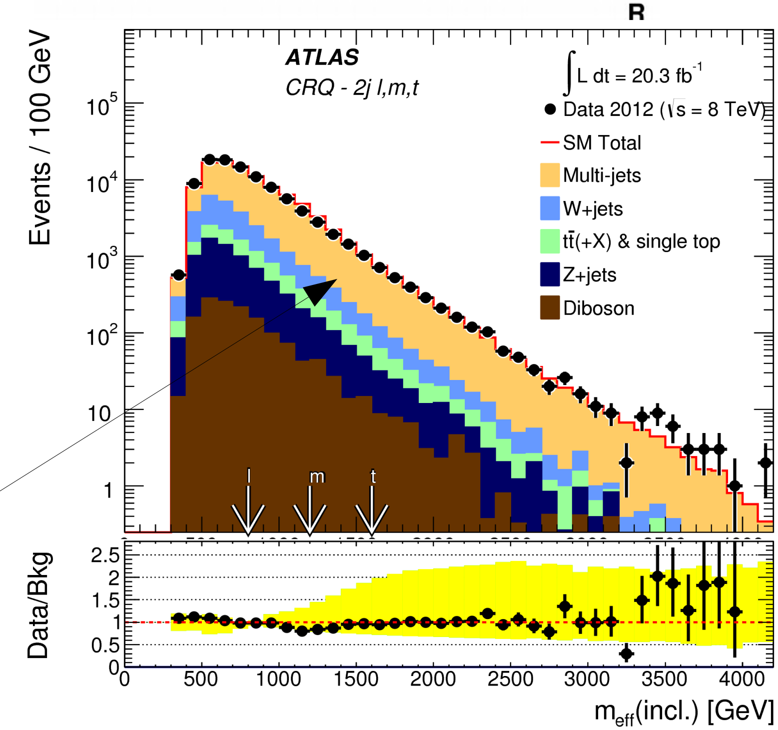
Makes E_T^{miss}-less multi-jet or Z→ll events look like signal



Jet-smearing method

- Jet-response function derived from MC and adjusted to match data in di-jet and three-jet events
- Select low E_T^{miss} events in data and smear the jets with a response function

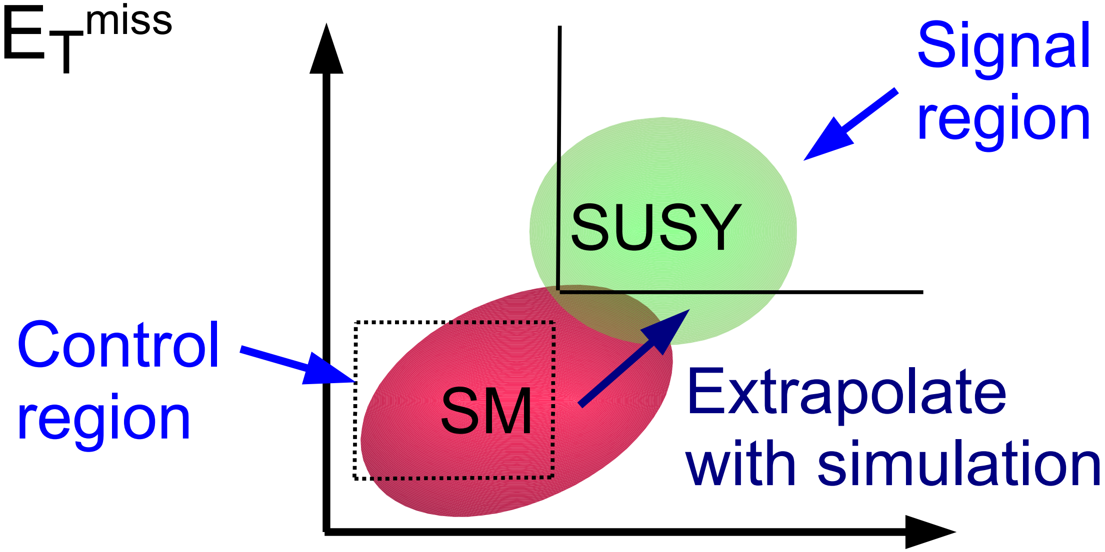




- Provides good estimate of fake E_T^{miss} background as seen in control-region

Irreducible Backgrounds

SM backgrounds with real E_T^{miss} such as $Z \to \nu\nu$ and $W \to l\nu$



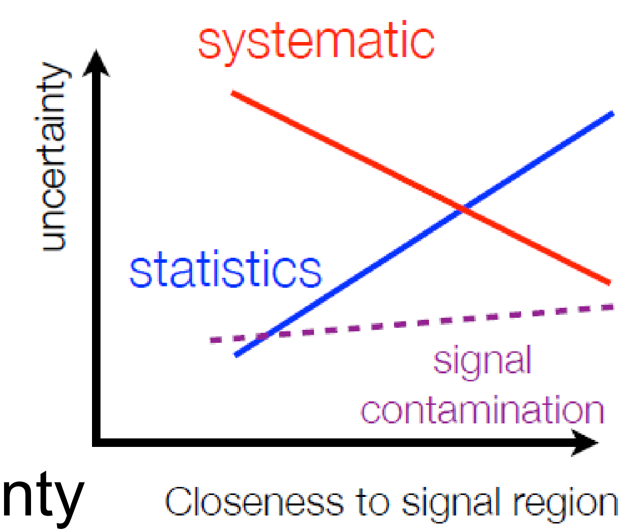
Rely (partly) on simulation

- Small contributions taken directly from simulation
- Larger one normalized to data in signal free region ans extrapolated to signal region

$$N_{SR}^{i} = \frac{N_{SR}^{i,MC}}{N_{CR}^{i,MC}}(N_{CR}^{i,data} - \sum_{j=process} N_{CR}^{j,MC}) = T(N_{CR}^{i,data} - \sum_{j=process} N_{CR}^{j,MC})$$

Minimize uncertainty on background

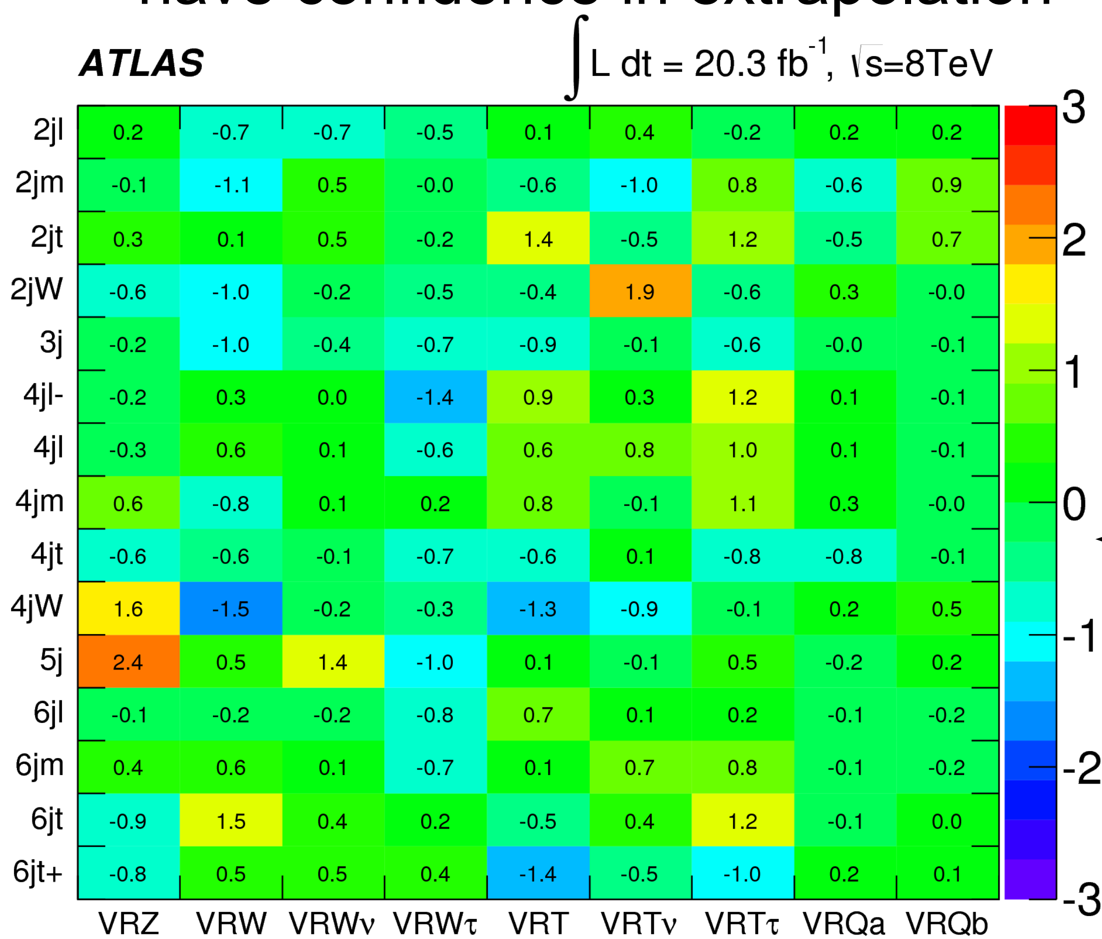
- Systematic uncertainty on extrapolation factor from both theory (modelling) and experimental effects (efficiencies, etc.)
- In some cases can derive extrapolation factor from data or at least correct using data to reduce systematic uncertainty

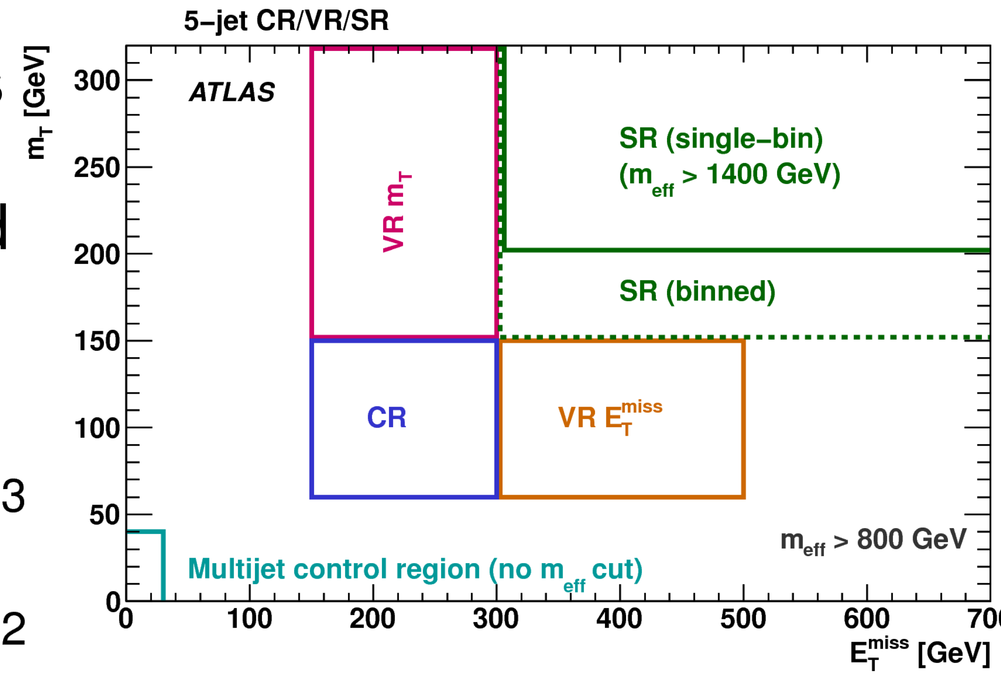


Background Validation

Validate background predictions with dedicated validation regions

- Extrapolate to regions close to signal region, but signal depleted
- If prediction matches the data have confidence in extrapolation





Can get complicated

- 9 validation regions for each of the 15 signal regions in "0-lepton" search
- Deviation from prediction shown in "σ"

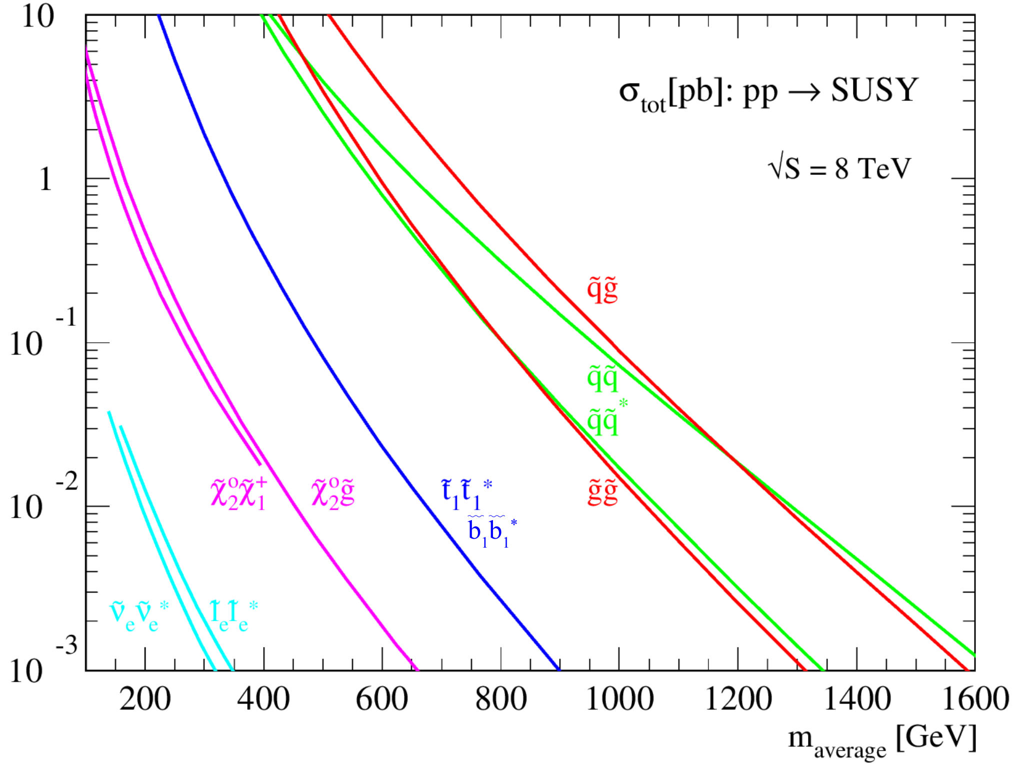
LHC Supersymmetry Search Results

Short Version

Did We Really Look Everywhere?

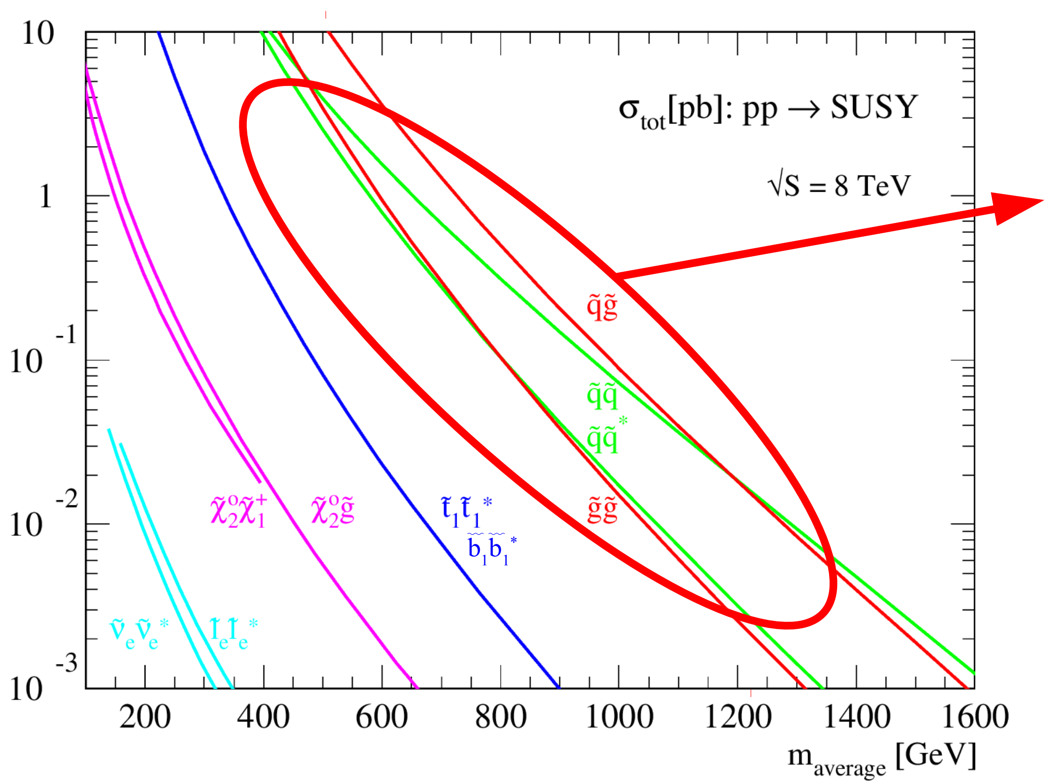
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



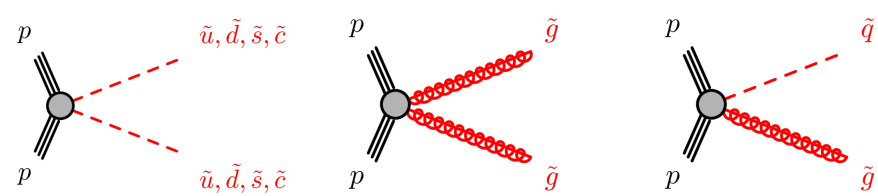
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



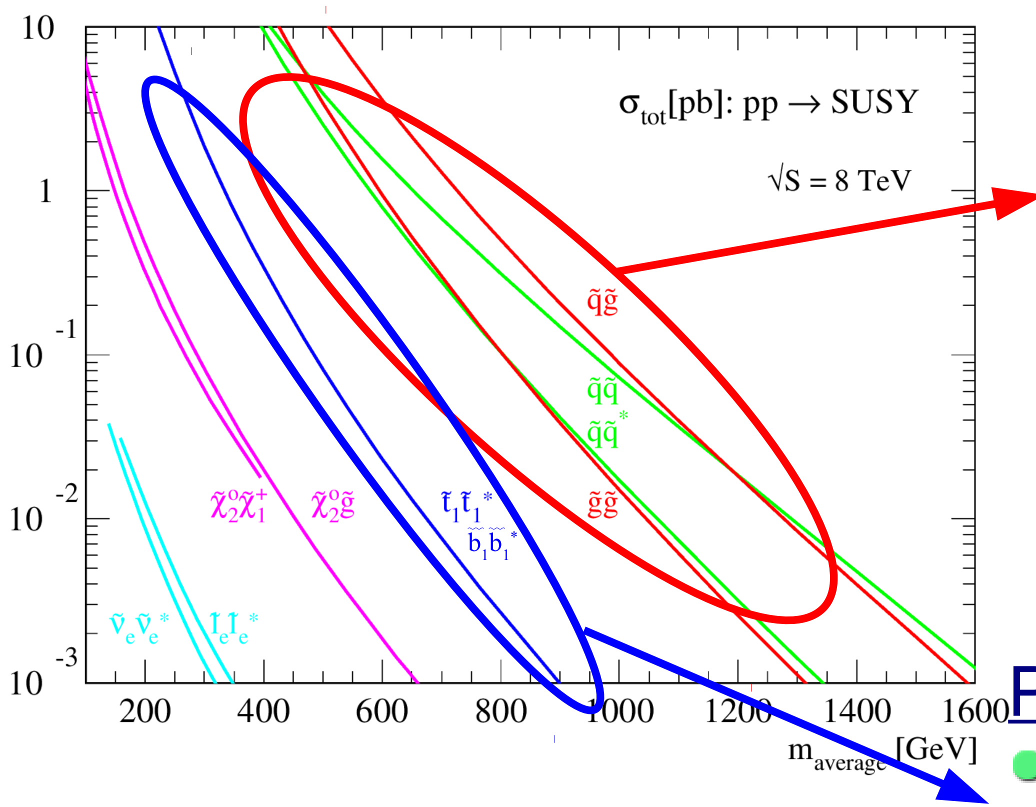
Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is jets and missing energy



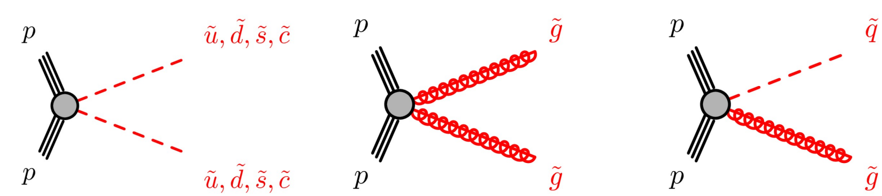
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



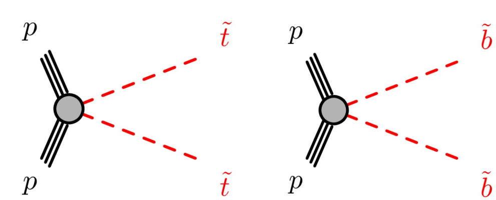
Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is jets and missing energy



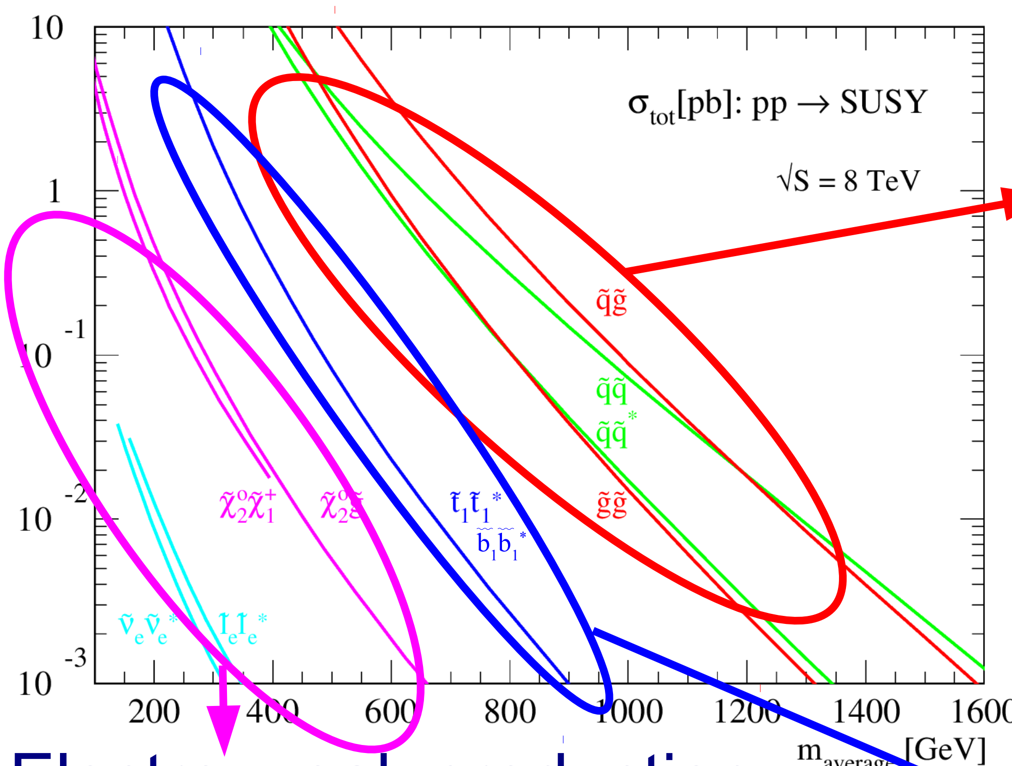
Prod. of 3rd generation squarks:

- Lower cross section,
- Decays chains frequently has top and bottom quarks
- Of great interest to “Natural SUSY”



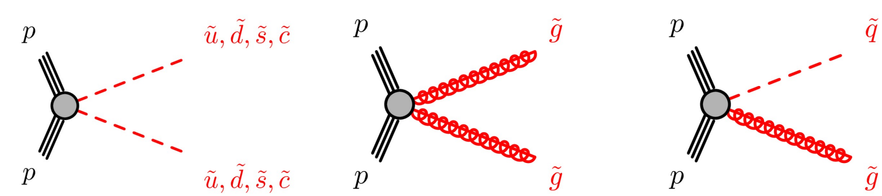
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



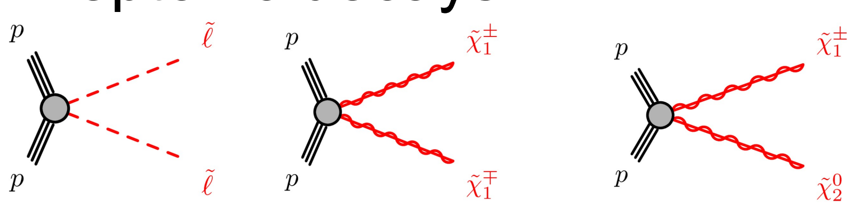
Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is jets and missing energy



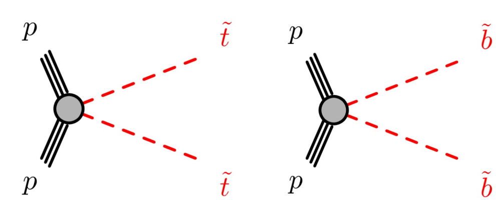
Electro-weak production

- Slepton, neutralino and charginos
- Detectable mostly through leptonic decays



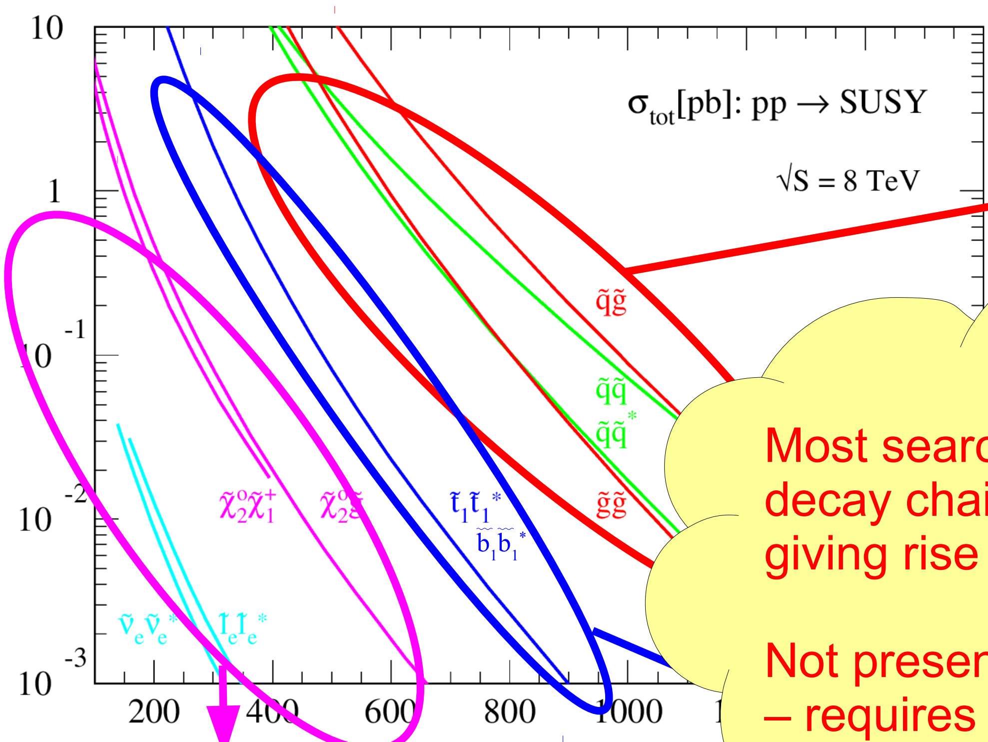
Prod. of 3rd generation squarks:

- Lower cross section,
- Decays chains frequently has top and bottom quarks
- Of great interest to "Natural SUSY"



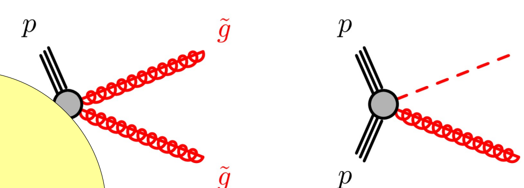
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is ...s and missing energy

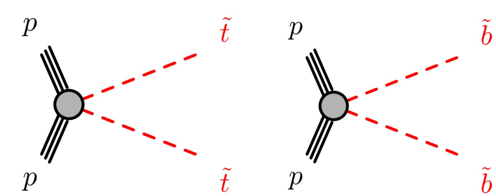


Most searches assume decay chain to stable LSP giving rise to missing energy

Not present in all SUSY models – requires dedicated searches to cover this

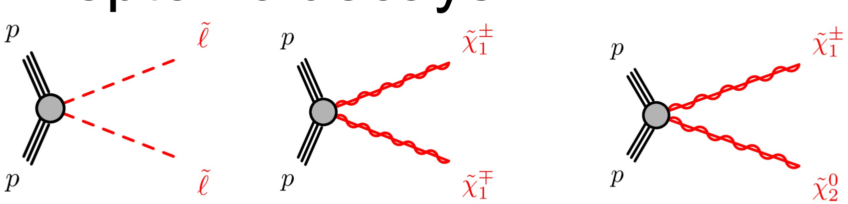
...eration squarks:

- ...ection,
- ...ins frequently has top and bottom quarks
- Of great interest to "Natural SUSY"



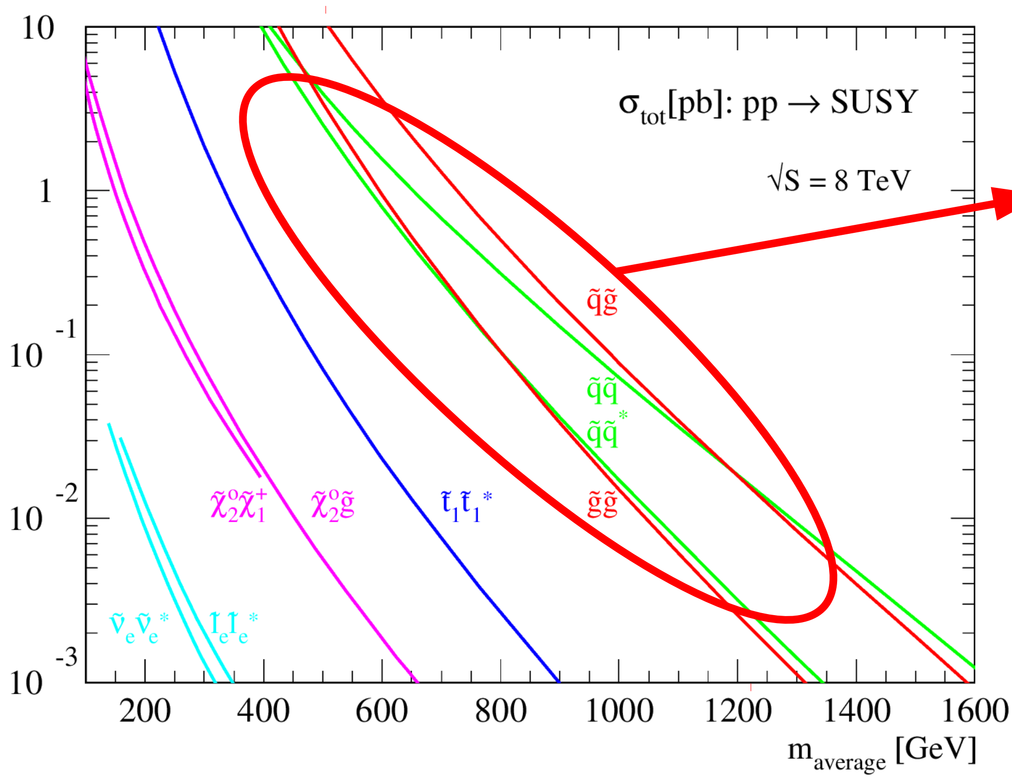
Electro-weak production

- Slepton, neutralino and chargi...
- Detectable mostly through leptonic decays



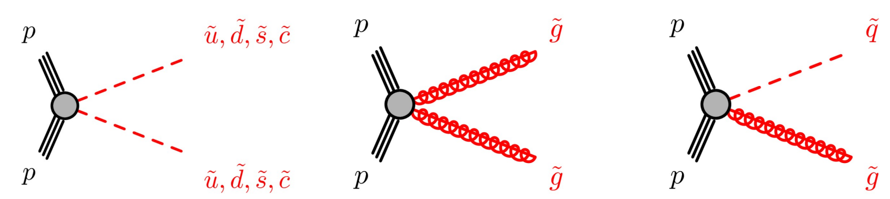
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



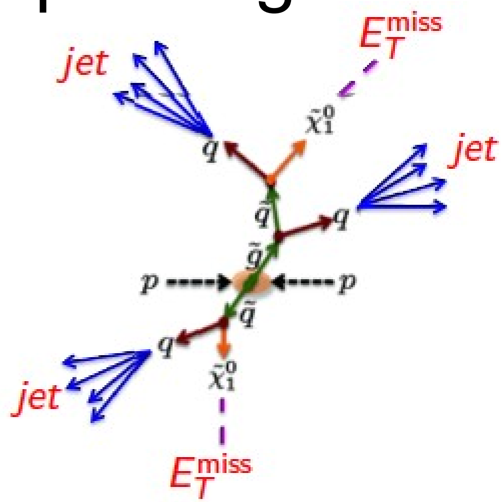
Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is jets and missing energy



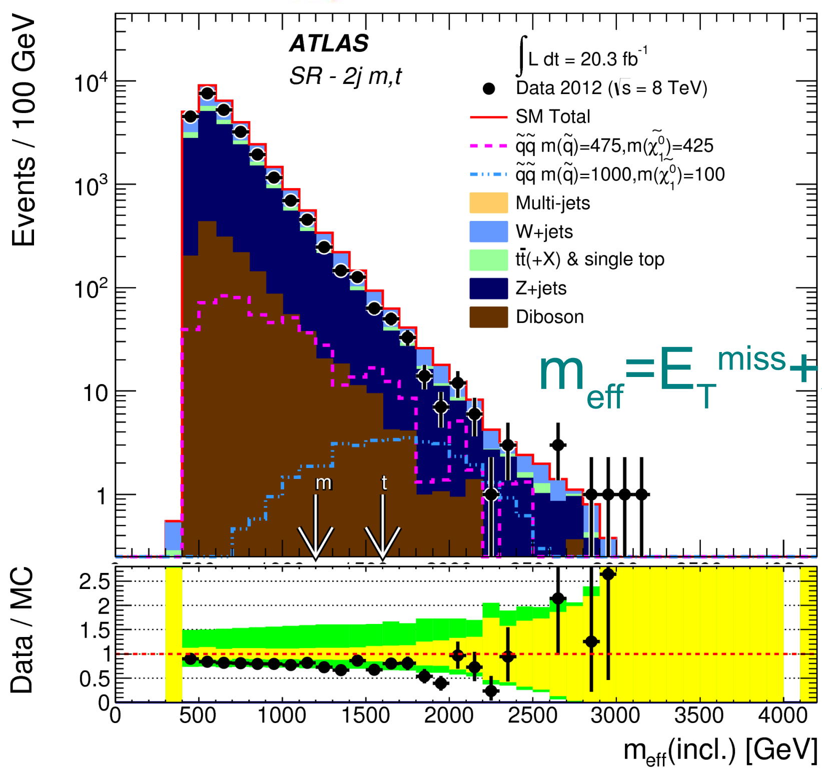
Inclusive 0-Lepton Analysis

Work-horse for searches for squarks/gluinos



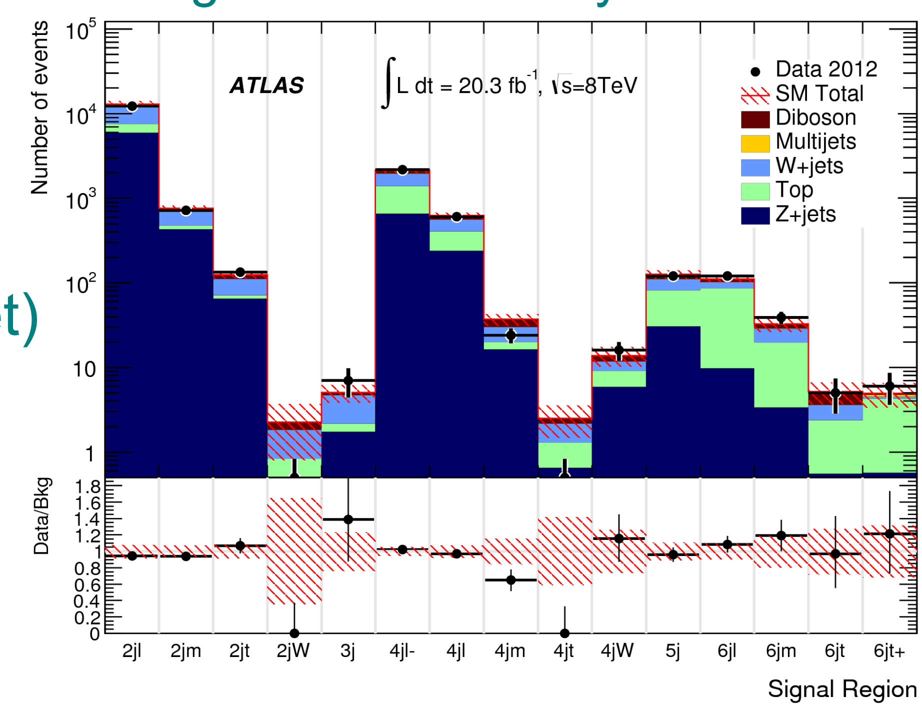
Inclusive selection

- Between 2-6 jets with p_T>60 GeV
- $\Delta\phi(j_i, E_T^{miss})$>0.4(0.2 for i>3)
- No leptons with p_T>10 GeV
- Large E_T^{miss} wrt m_{eff} (>0.15 – 0.4)
- Signal region split by #jets and m_{eff} with two SRs dedicated to W→jets



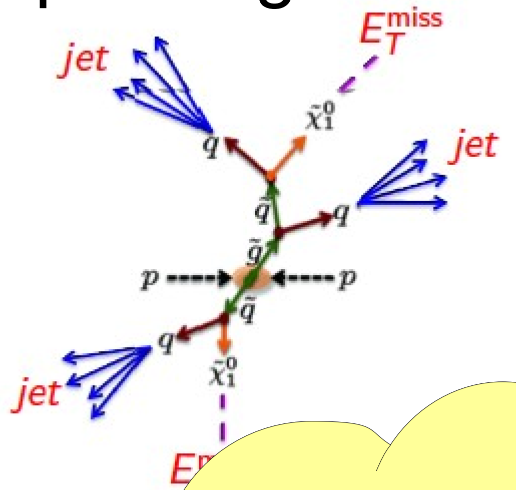
$m_{eff}=E_T^{miss}+\Sigma\, p_T(jet)$

Background and data yields in 15 SRs



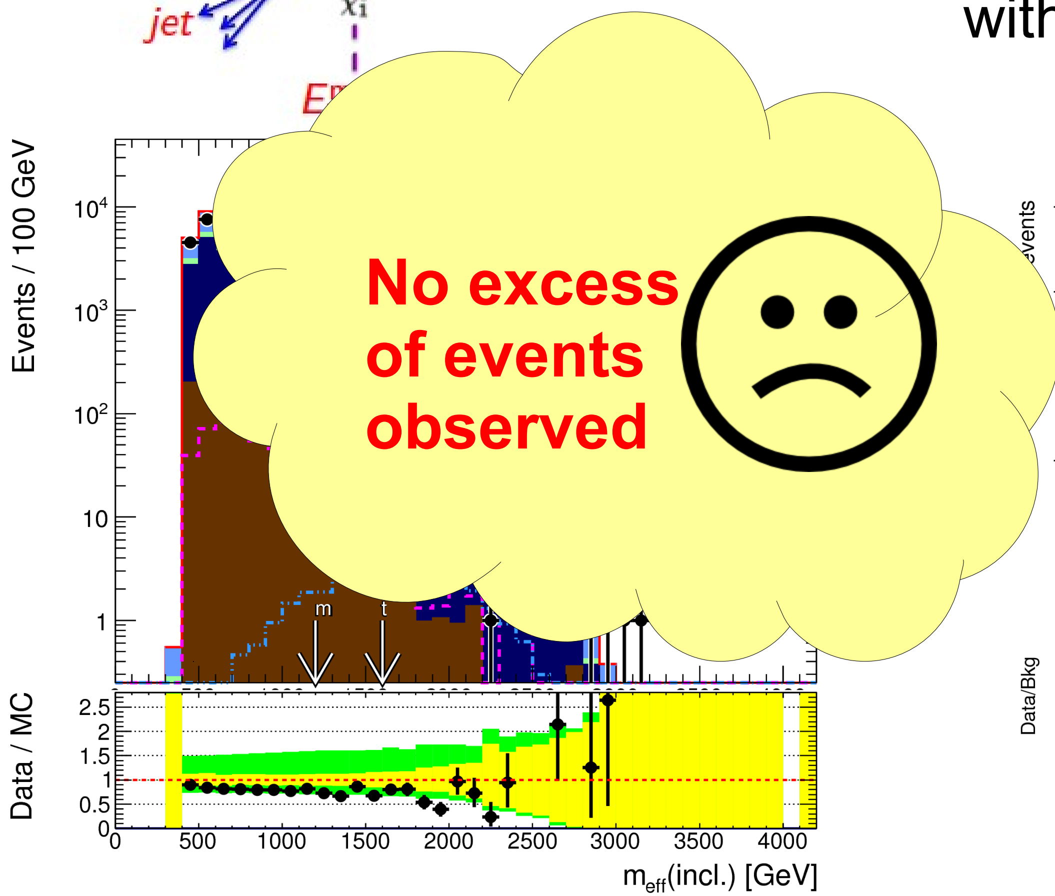
Inclusive 0-Lepton Analysis

Work-horse for searches for squarks/gluinos

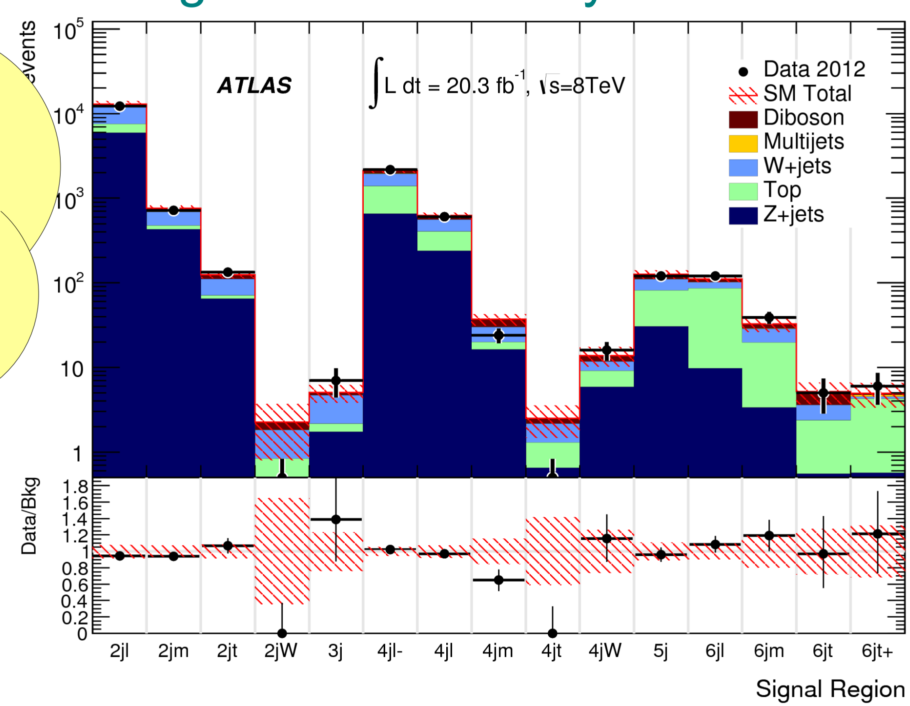


Inclusive selection

- Between 2-6 jets with p_T>60 GeV
- $\Delta\phi(j_i, E_T^{miss})$>0.4(0.2 for i>3)
- No leptons with p_T>10 GeV
- Large E_T^{miss} wrt m_{eff} (>0.15 – 0.4)
- Signal region split by #jets and m_{eff} with two SRs dedicated to W→jets



Background and data yields in 15 SRs



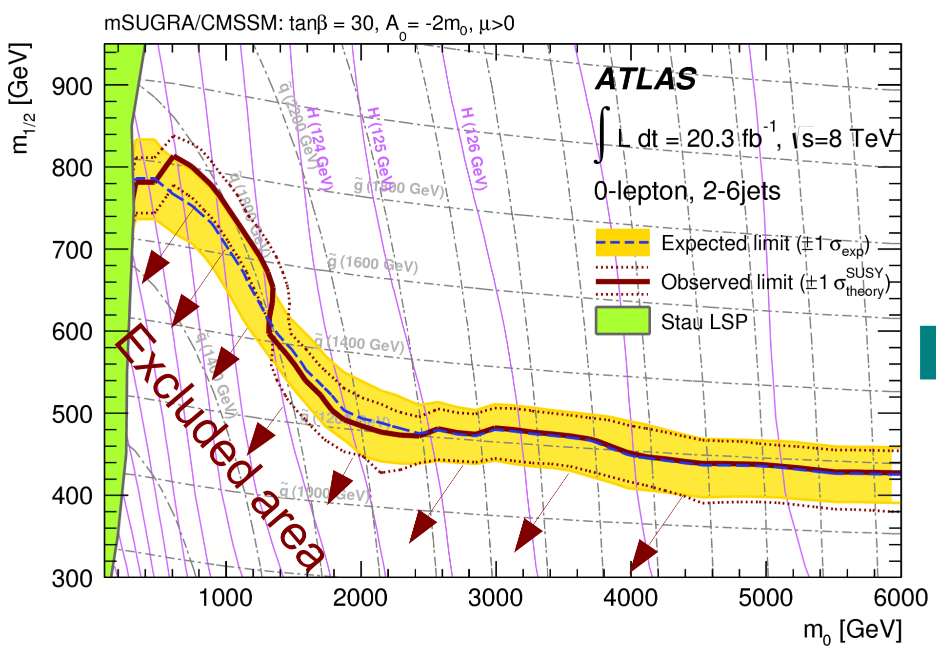
Inclusive 0-Lepton Analysis Results

With no signals observed, proceed to set limits on SUSY models

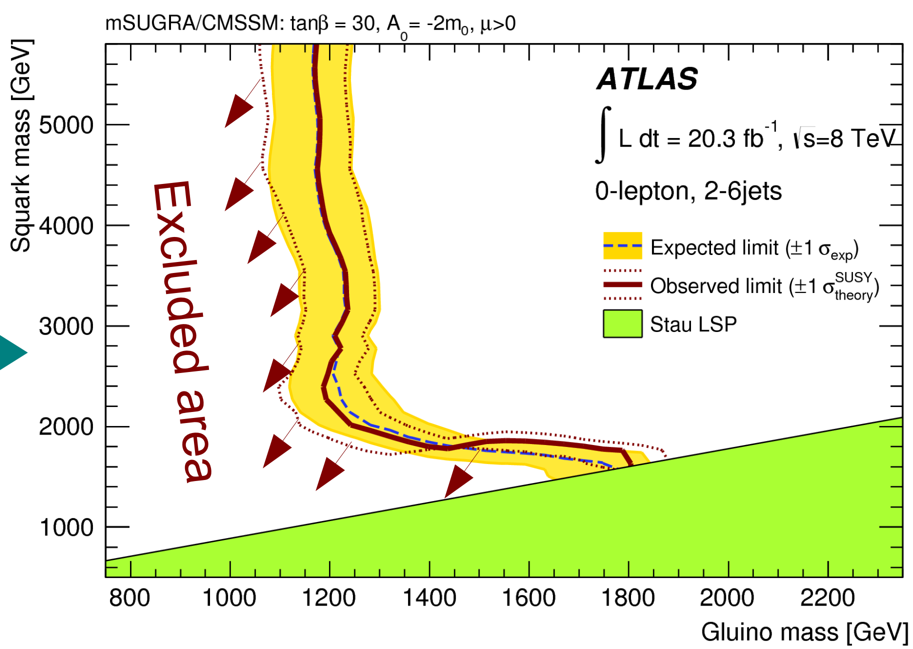
Limit setting procedure

- For each SUSY model calculate expected number of events in each signal region and any leakage to control regions
- Obtain p_0 from simultaneous fit to the signal and control regions
- Limit quoted from best expected signal region
- Typically do this in scan over several SUSY model parameters

Limits on mSUGRA parameters



Limits on squark/gluino masses



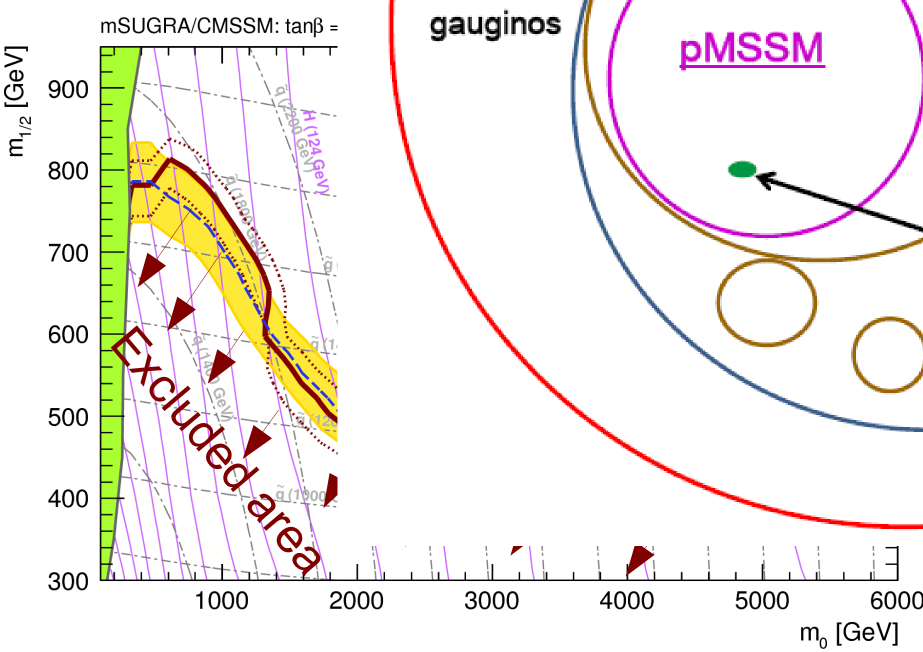
Inclusive 0-Lepton Analysis Results

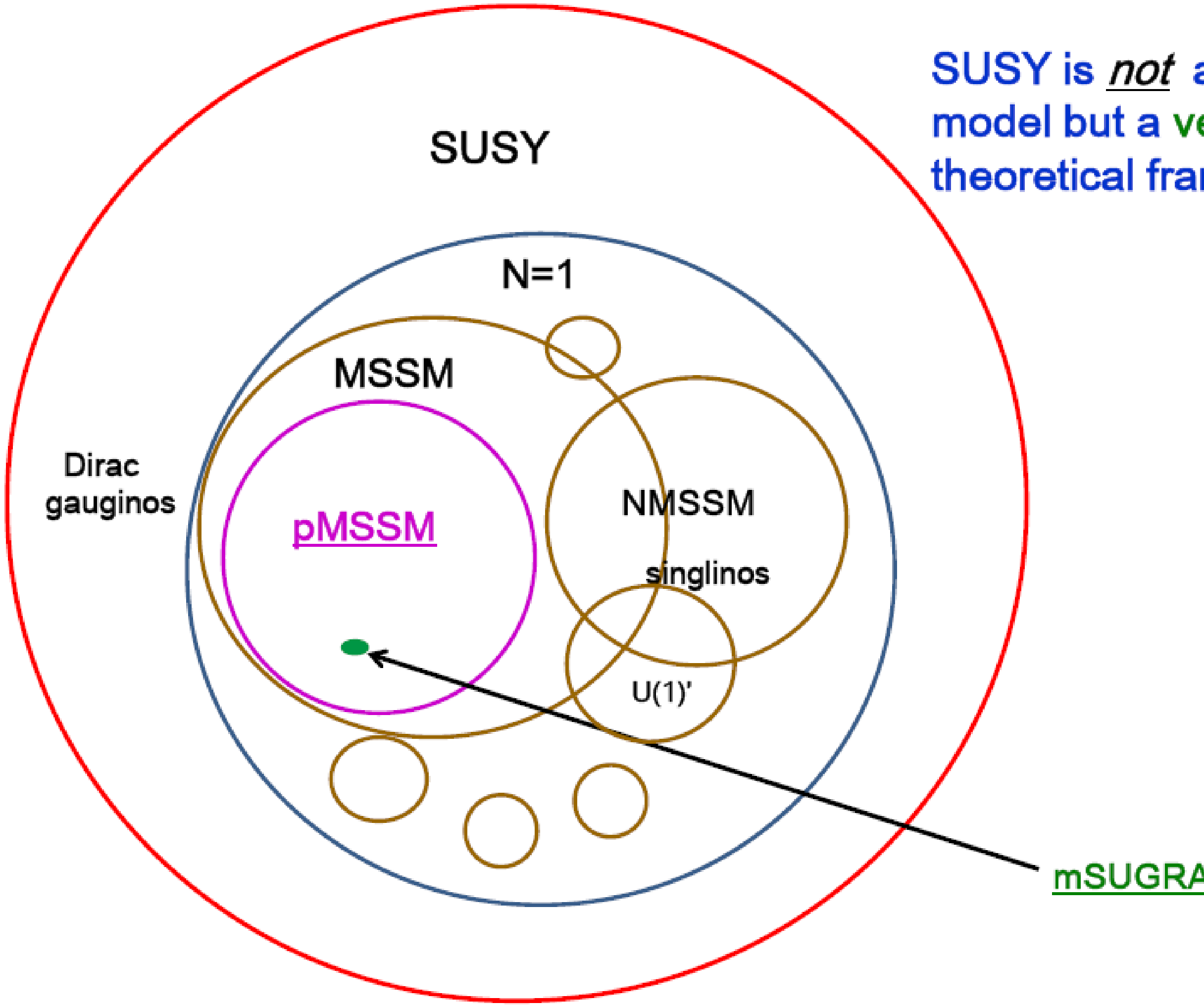
With no signals observed, proceed to set limits on SUSY models

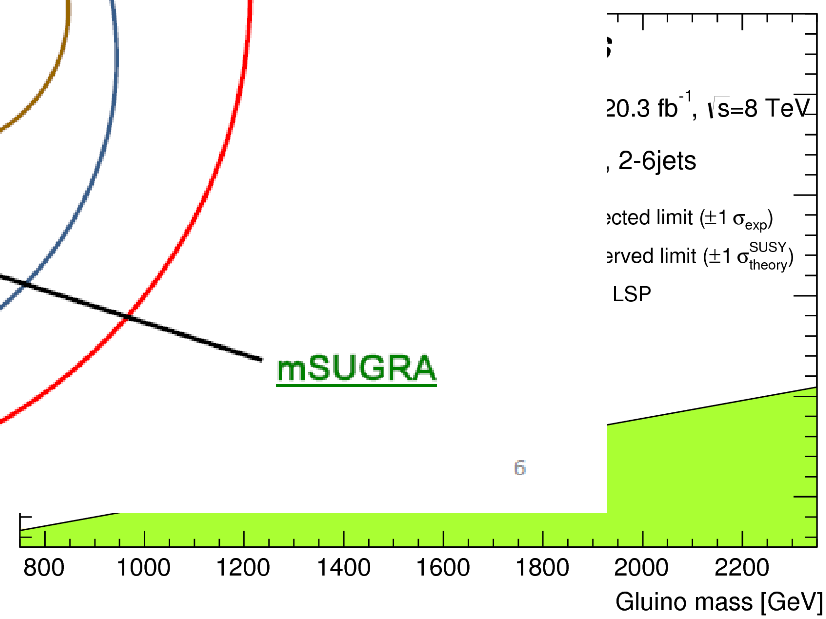
Limit setting procedure

- For ea… of ever… regions
- Obtain …gions
- Limit q
- Typical …eters

Limits on m… …asses







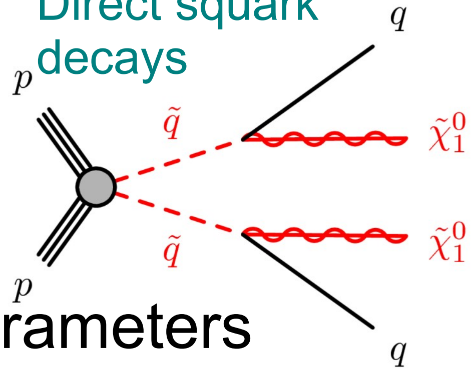
Simplified Model Limits

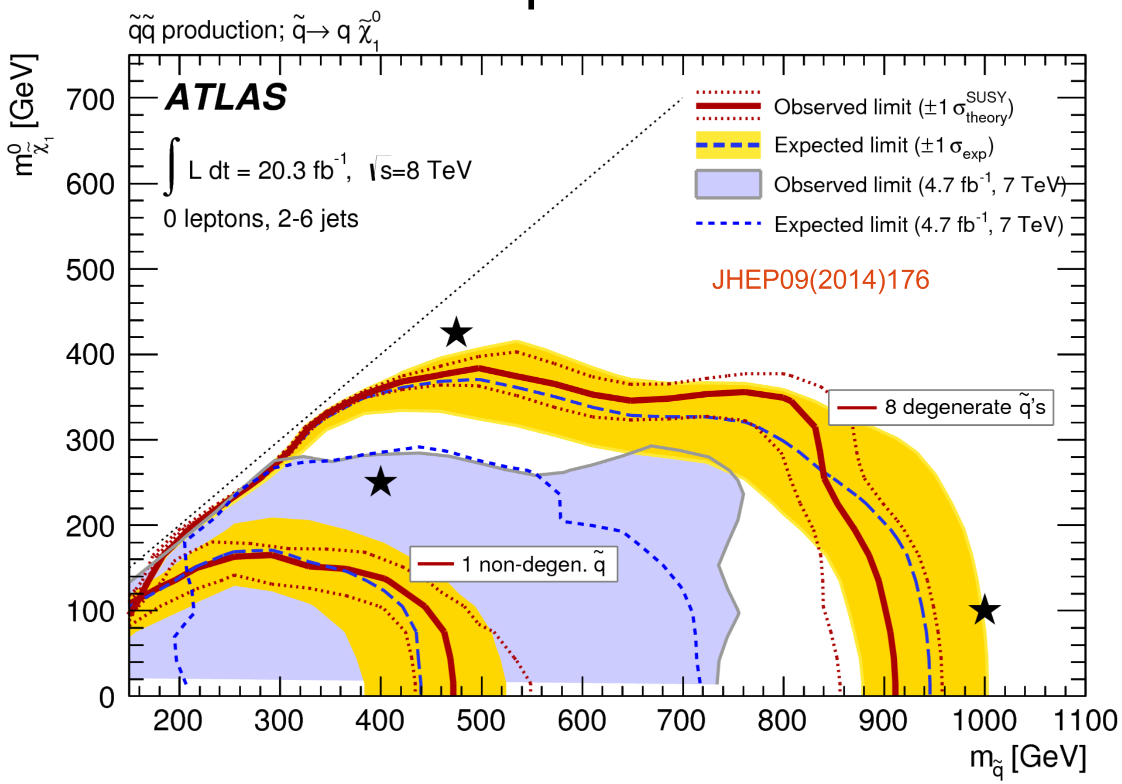
Present results in form of simplified models

Simplified Models

- 1 production channel
- 1 decay channel (BF=100%)
- Minimal amount of parameters
- Assume SUSY production σ, but can reinterpret broader

Direct squark decays





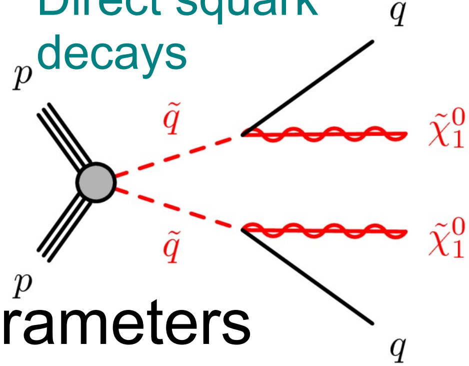
Simplified Model Limits

Present results in form of simplified models

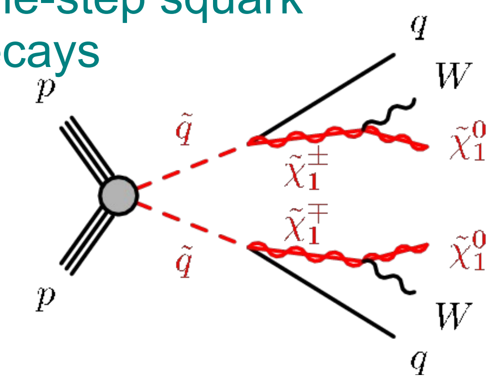
Simplified Models

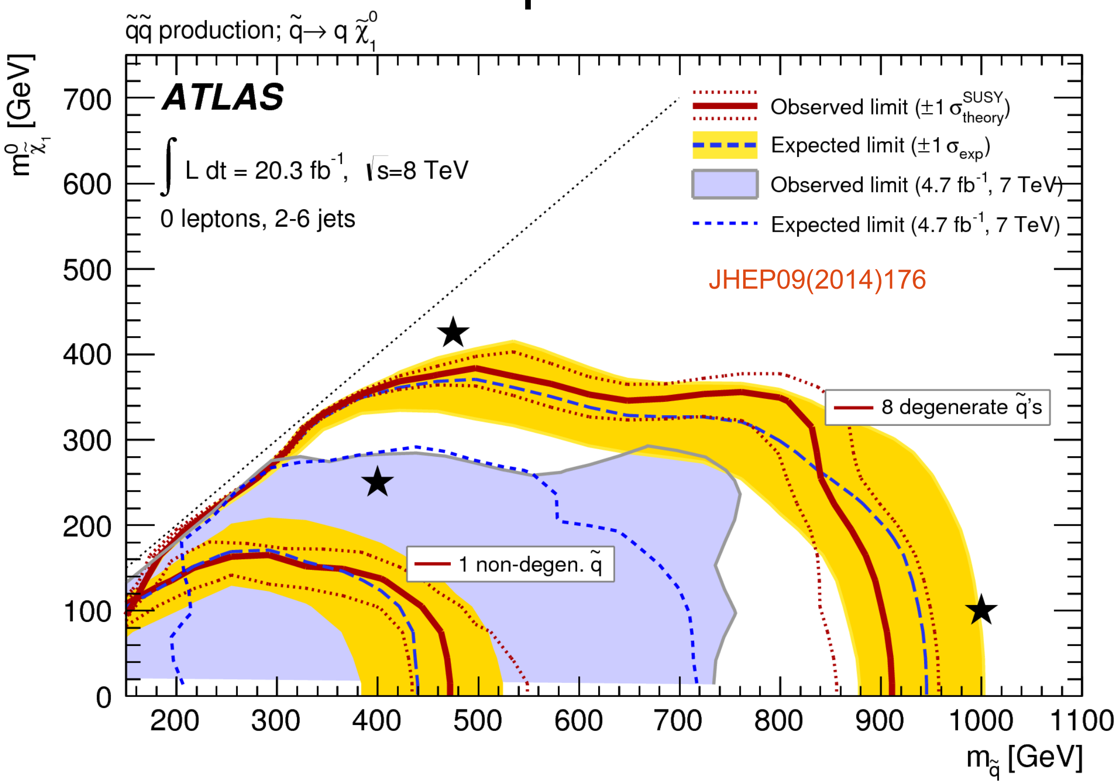
- 1 production channel
- 1 decay channel (BF=100%)
- Minimal amount of parameters
- Assume SUSY production σ, but can reinterpret broader

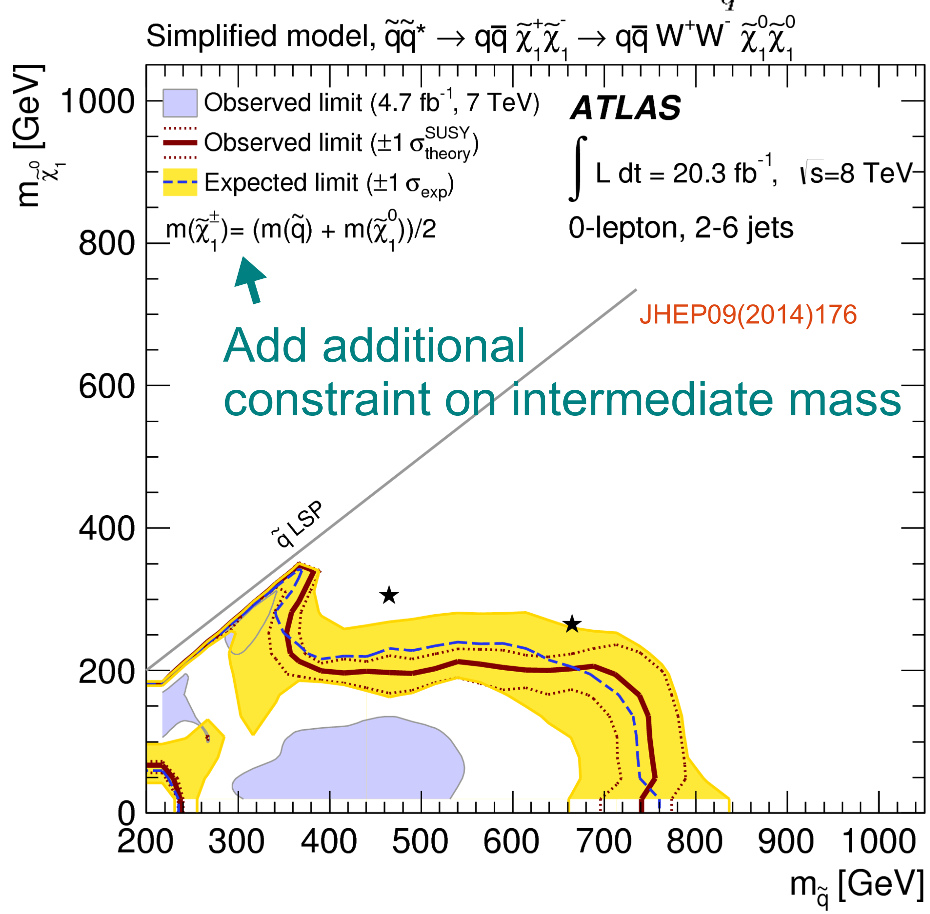
Direct squark decays



One-step squark decays



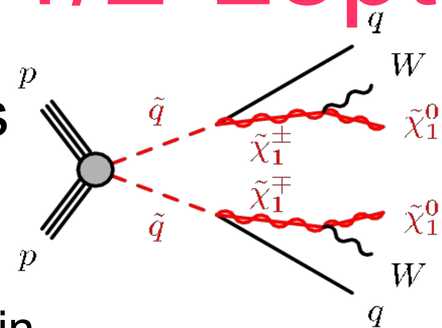


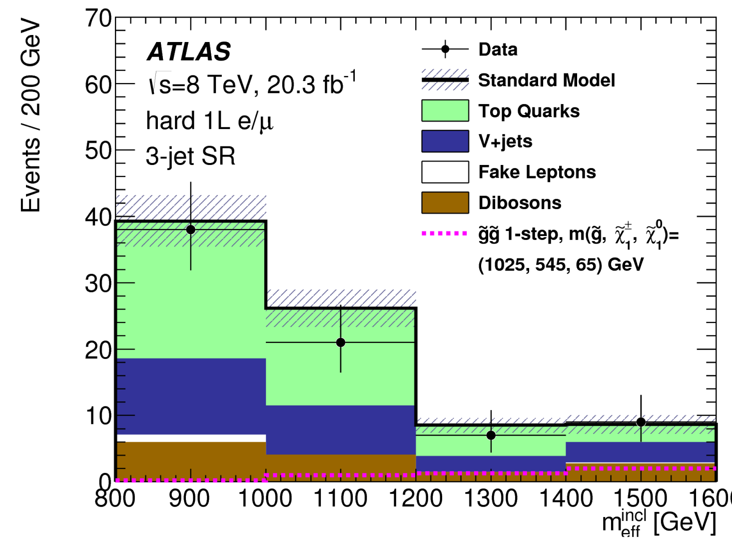


New

Inclusive 1/2-Lepton Analysis

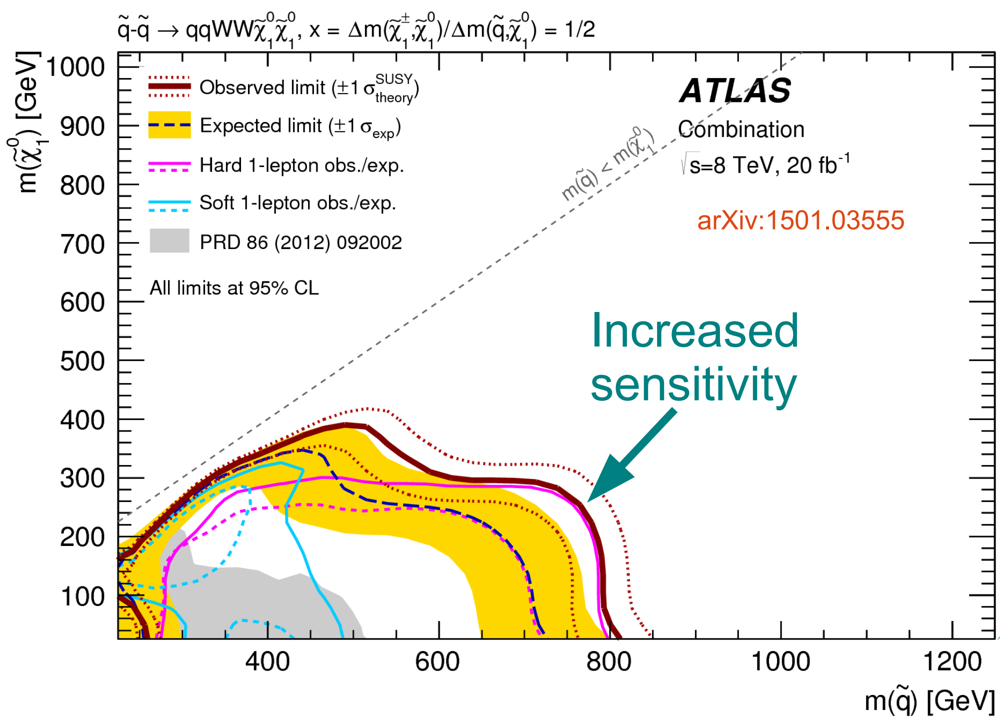
Longer decay chains gives more possible signatures



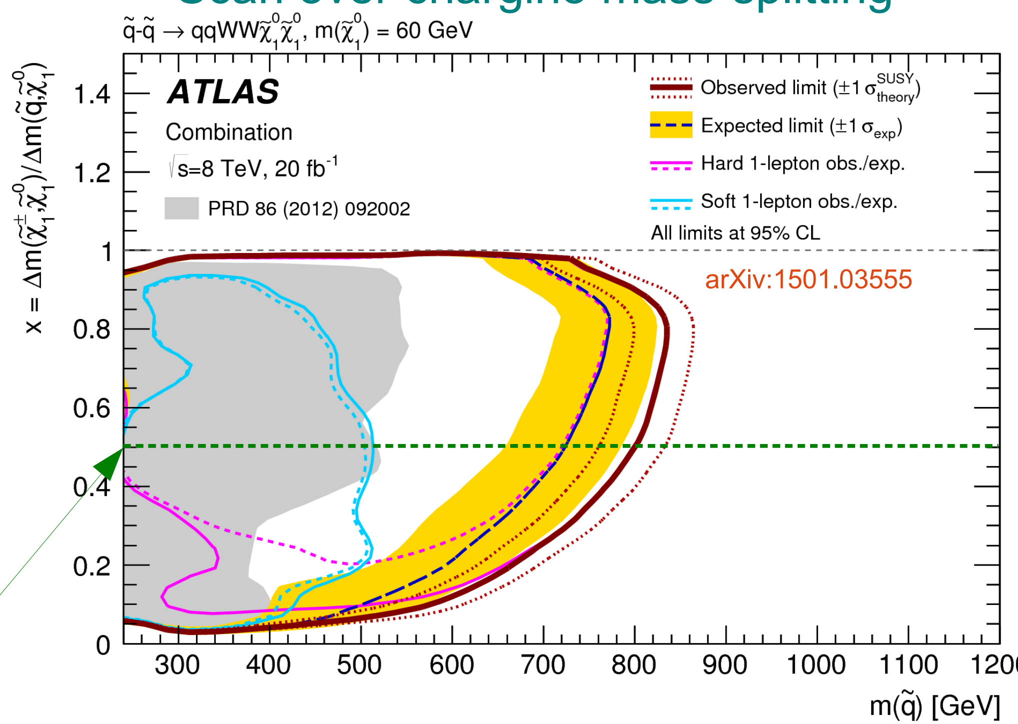


1/2-lepton analysis

- 1 or 2 leptons with p_T>6 GeV, split in hard (pT>25 GeV) and soft (6<pT<25 GeV)
- 3, 5 and 6 jet signal regions (also 2 jets for 2-lepton)
- Large transverse mass, $m_T = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} (1 - \cos[\Delta\phi(\vec{\ell}, \vec{p}_T^{\text{miss}})])}$ to suppress W and top bkg
- Simultaneous fit to multiple bins in m_{eff} or E_T^{miss}/m_{eff} to increase sensitivity



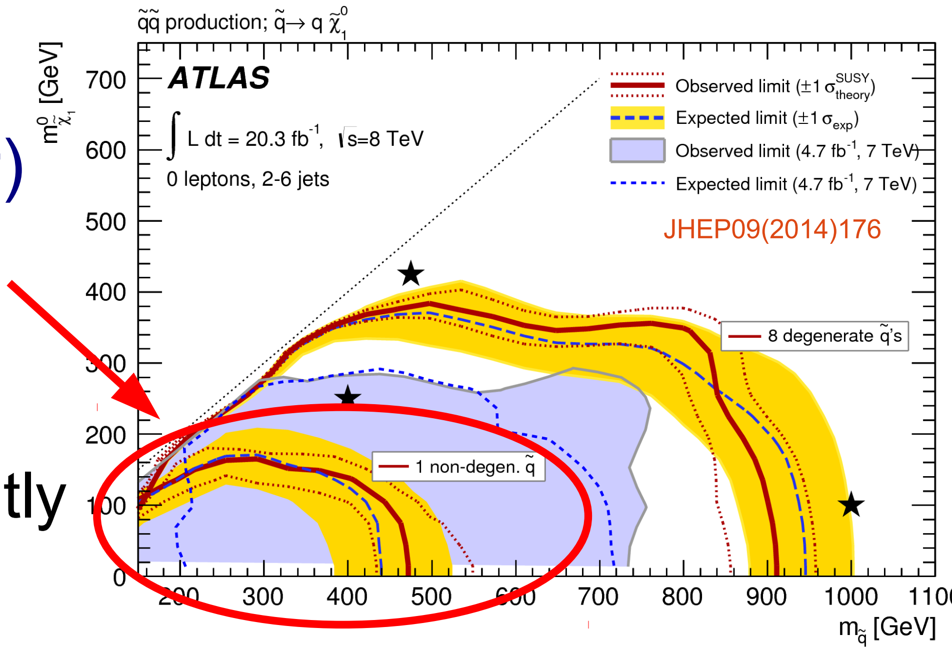
Scan over chargino mass-splitting



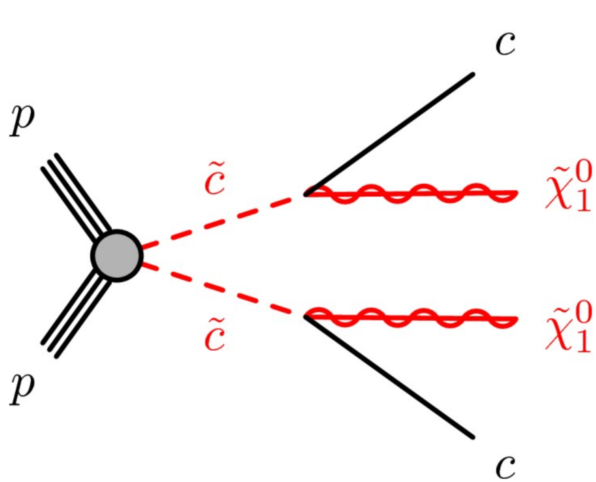
New

Scalar Charm Search

Much weaker squark limit if only one light light-flavor squark (1/8σ)



- Cannot have any light-flavor squark on its own as it would violate flavor-physics constraints
- However, scharm is not significantly constrained from flavor physics and could be lighter than others



New, dedicated scharm search

- Search for direct decay to charm
- Signal is two high-p_T charm jets, high E_T^{miss} and no leptons
- Use dedicated charm-tagger for jets to suppress other jet types

New

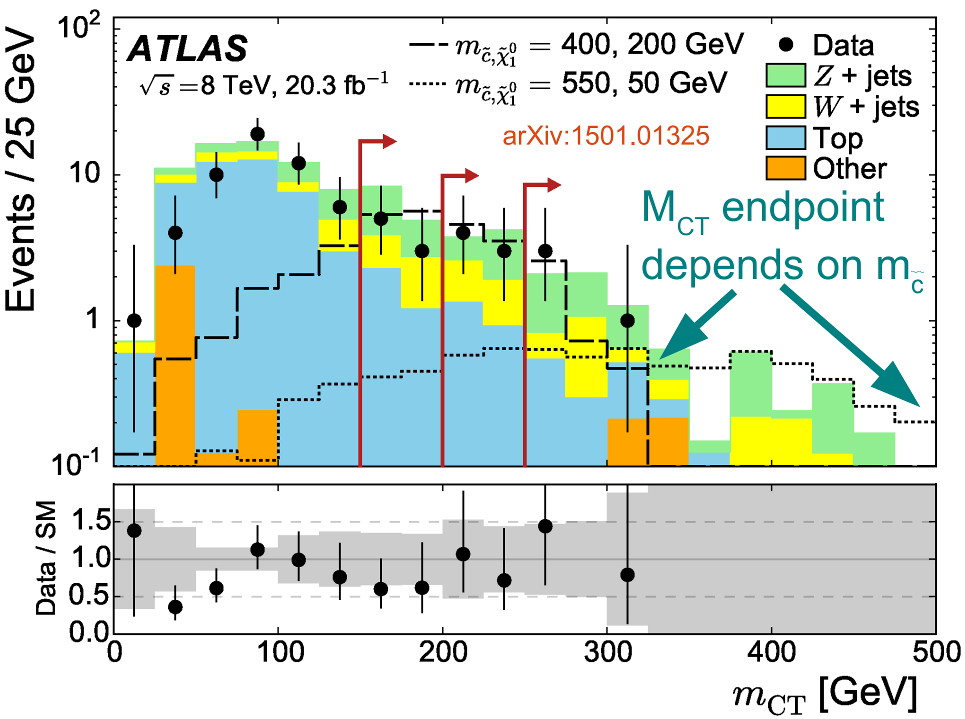
Scalar Charm Search

- Kinematic selection using contransverse mass m_{CT} and charm pair mass m_{cc}

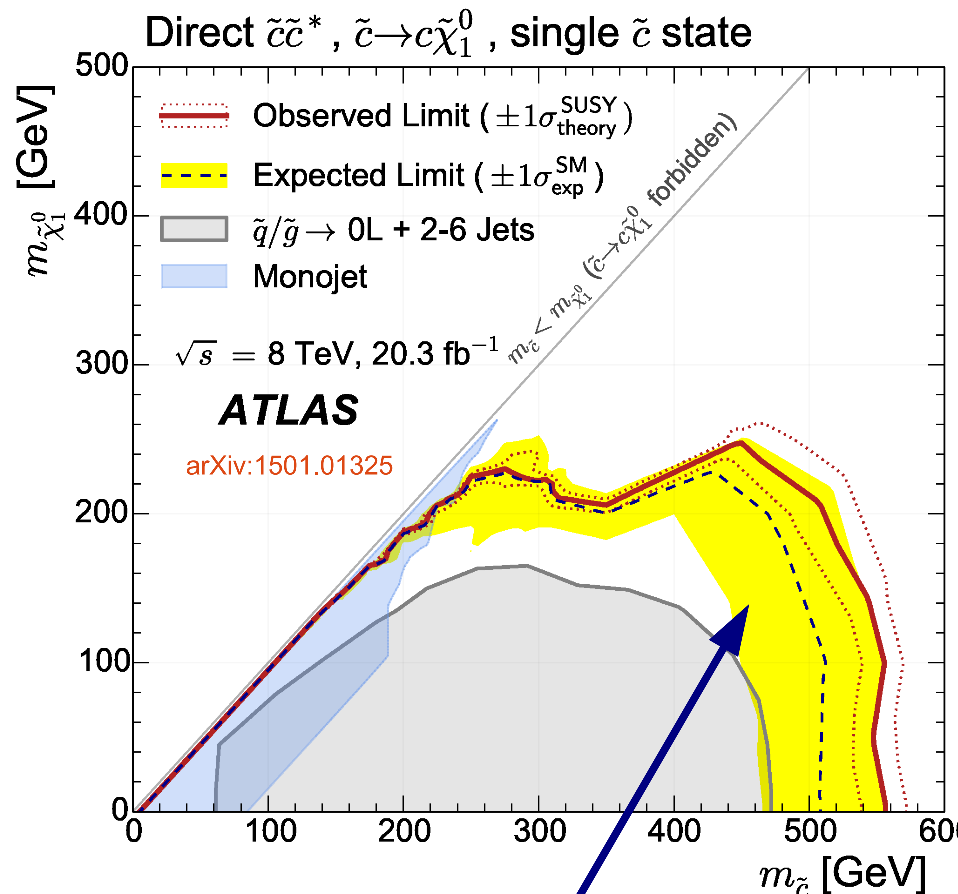
$$m^2_{\mathrm{CT}}(j_1, j_2) = [E_{T,1} + E_{T,2}]^2 - [\mathbf{p}_{T,1} - \mathbf{p}_{T,2}]^2$$

$$E_{\mathrm{T}} = \sqrt{p^2_{\mathrm{T}} + m^2}$$

$$m^{\max}_{\mathrm{CT}} = \frac{m^2(\tilde{c}) - m^2(\tilde{\chi}^0_1)}{m(\tilde{c})}$$



M_{CT} endpoint depends on $m_{\tilde{c}}$

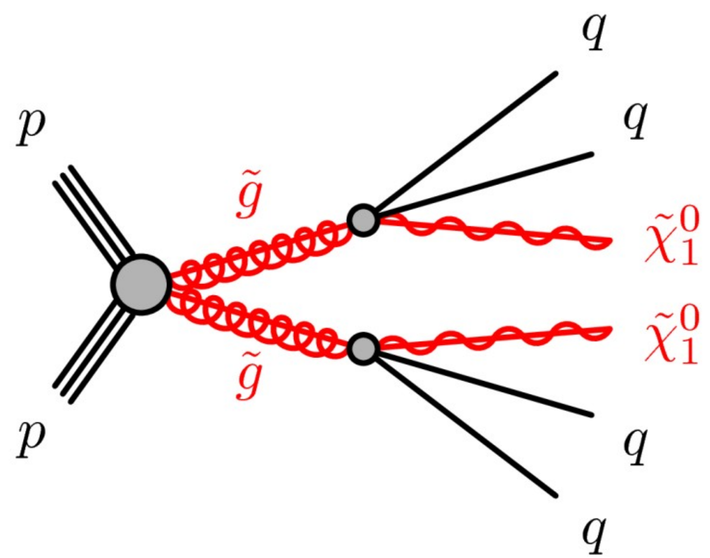


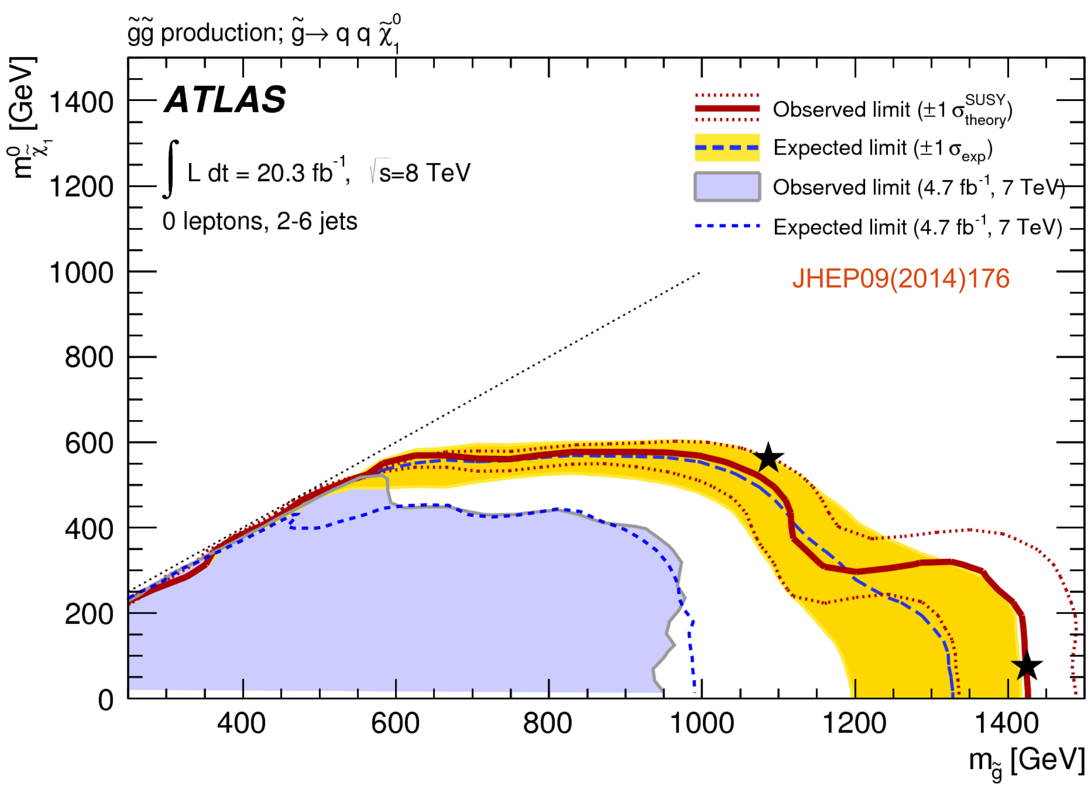
~100 GeV improvement in sensitivity w.r.t. inclusive search

Limits on Gluino Production

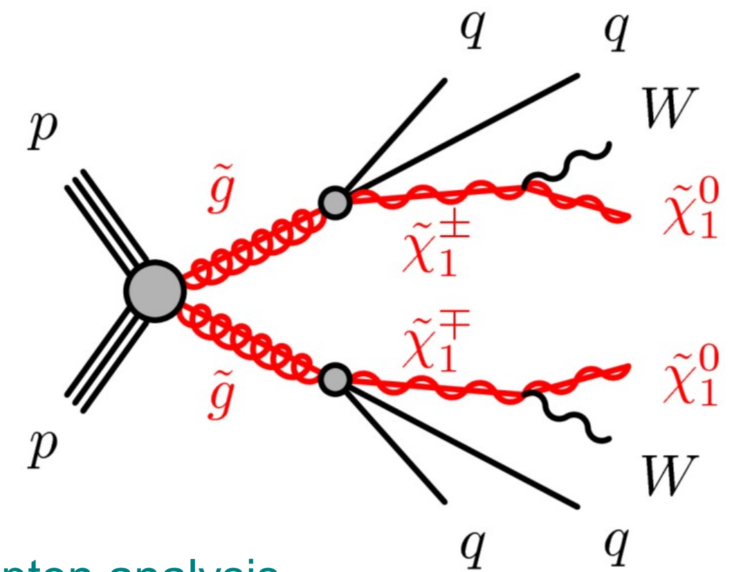
Even stronger limits on gluinos

- Several quarks(=jets) in each decay
- Inclusive 0-lepton analysis sensitive up to 1.3 TeV for direct gluino decays





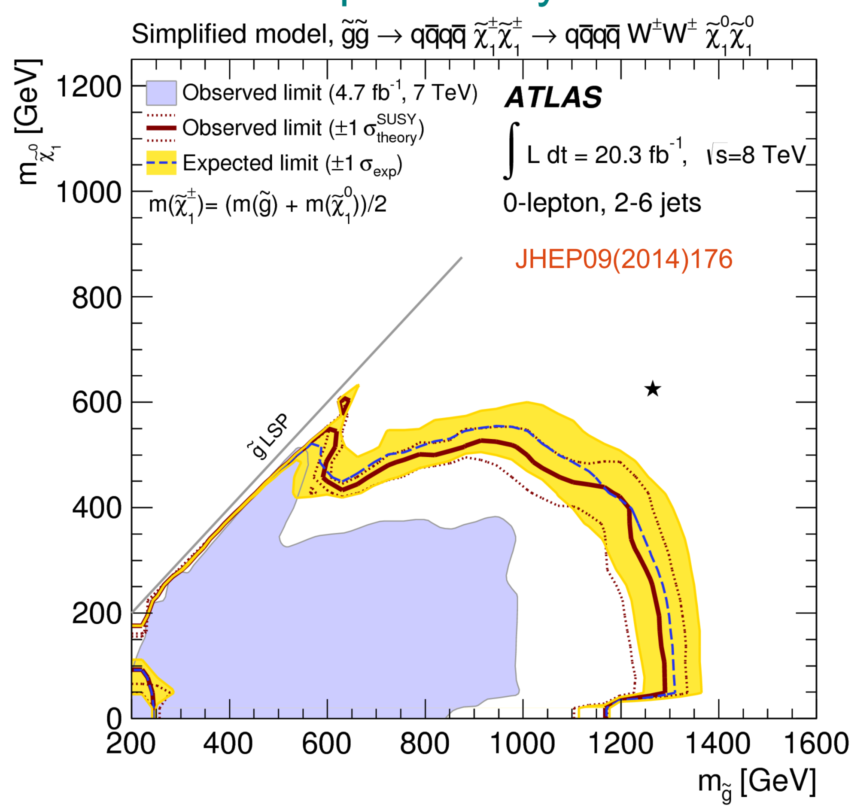
Limits on Gluino Production



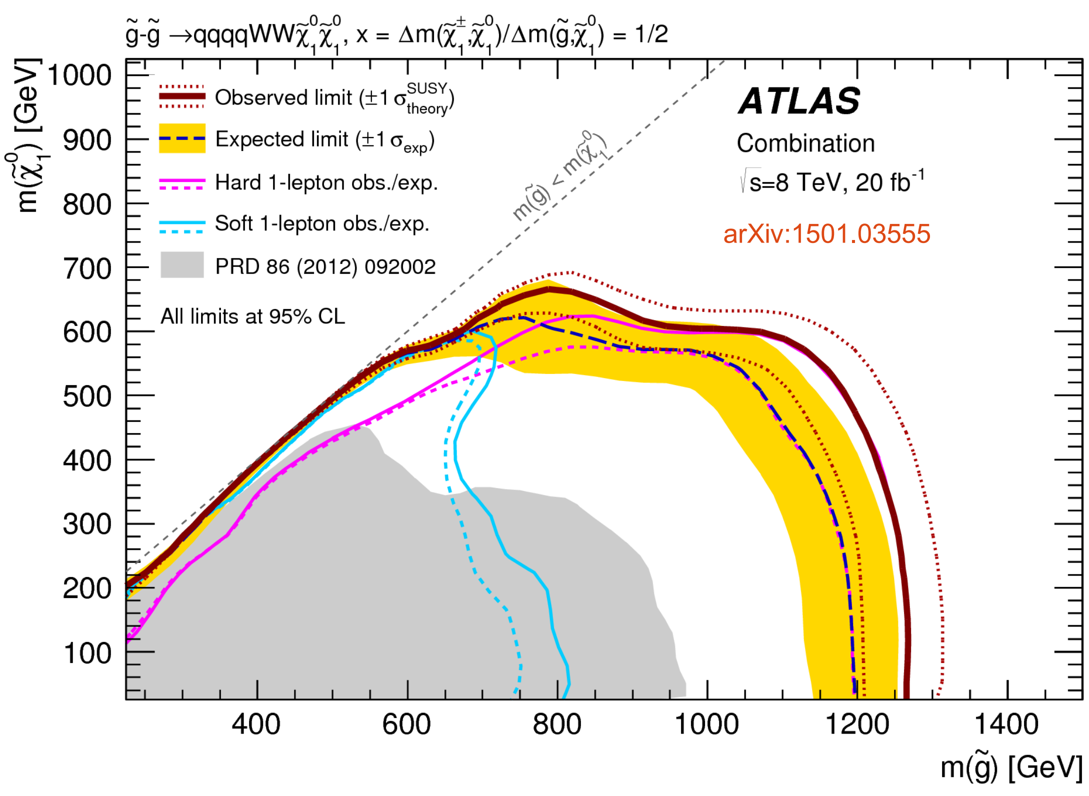
Even stronger limits on gluinos

- Several quarks(=jets) in each decay
- Inclusive 0-lepton analysis sensitive up to 1.3 TeV for direct gluino decays
- For one-step decay, good complementarity with 1-lepton analysis

0-lepton analysis

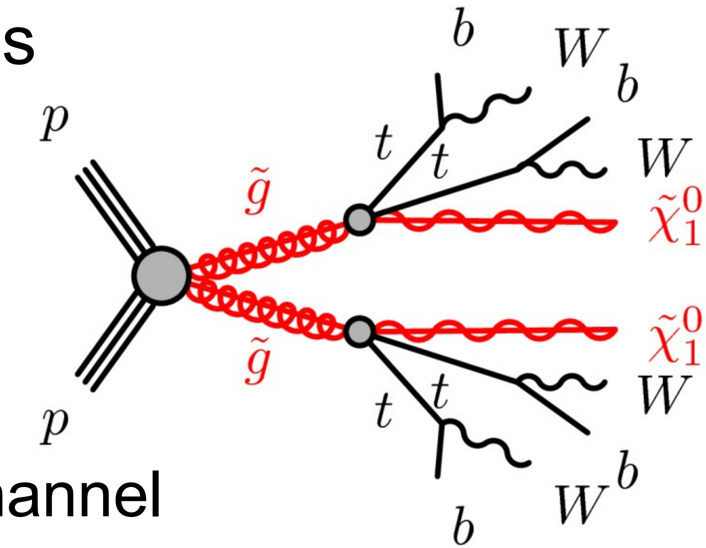


1-lepton analysis



Limits on Gluino Production

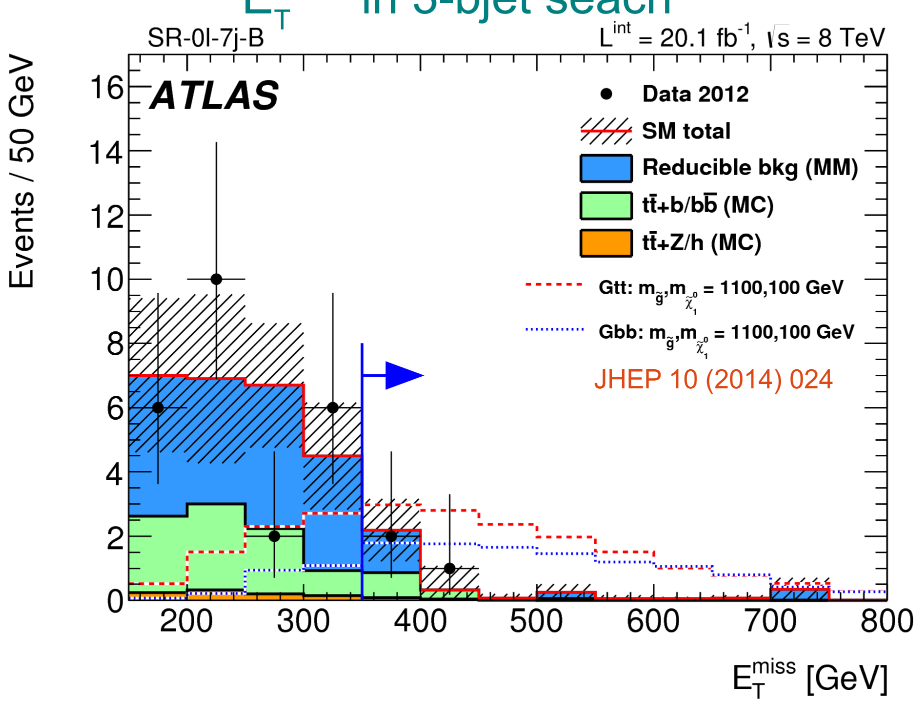
Many more decays possible for gluinos

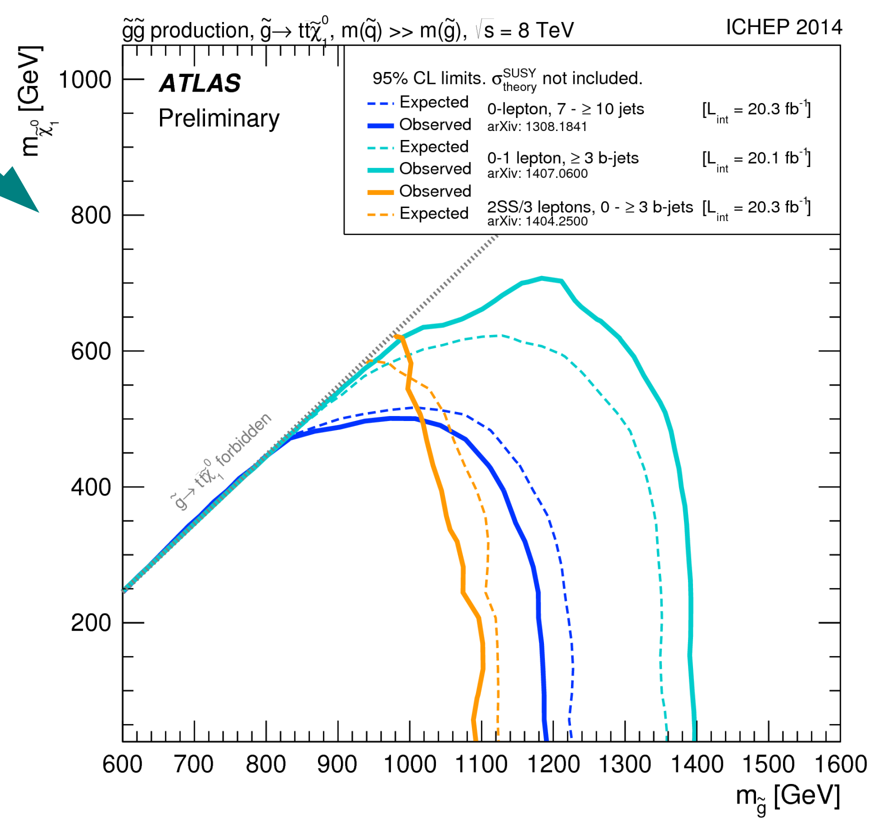


Decays through stop

- If scalar top lighter than other squarks, gluinos will decay to multiple top quarks
- Provides a very rich final state: 4-bjets, up to 4 leptons, up to 12 jets
- Many SUSY searches sensitive to this channel
- Best limit from a search for 3-bjets: Gluino heavier than ~1.4 TeV

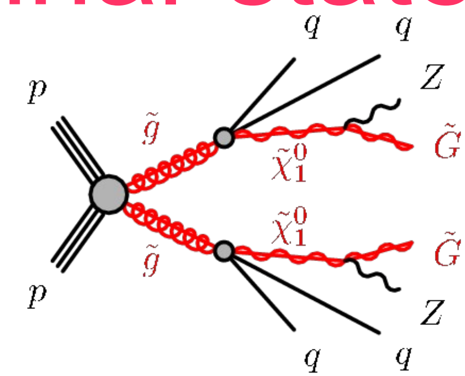
E_T^{miss} in 3-bjet seach





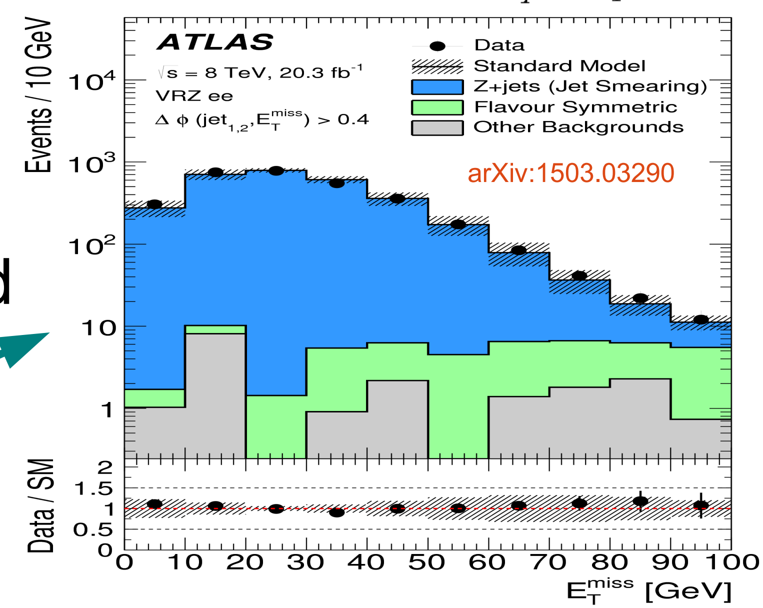
New Search for Di-lepton Final-state

Many more decays possible for gluinos



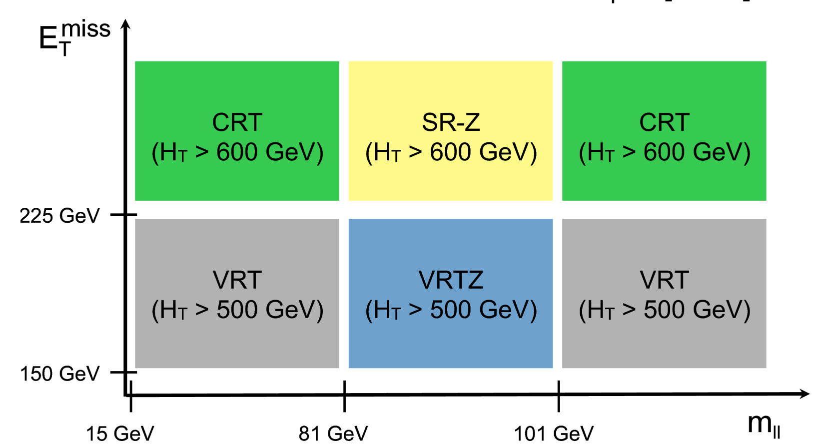
Search for decays through Z→ll:

- Select di-leptons with $|m_{ll}-m_Z|<10$ GeV
- At least two jets ($p_T>35$ GeV)
- $E_T^{miss}>225$ GeV
- $t\bar{t}$ background estimated from data using eμ events
  Cross check in $|m_{ll}-m_Z|>10$ GeV sideband
- Z+fake MET from jet smearing method
- Multiple validation regions at low E_T^{miss}



Signal, control and validation regions

On-Z Region	E_T^{miss} [GeV]	H_T [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	E_T^{miss} sig. [$\sqrt{\text{GeV}}$]	f_{ST}	$\Delta\phi(\text{jet}_{12}, E_T^{miss})$
Signal regions								
SR-Z	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4
Control regions								
Seed region	-	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	< 0.9	< 0.6	-
CReμ	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	DF	-	-	> 0.4
CRT	> 225	> 600	≥ 2	$m_{\ell\ell} \notin [81, 101]$	SF	-	-	> 0.4
Validation regions								
VRZ	< 150	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	-
VRT	150–225	> 500	≥ 2	$m_{\ell\ell} \notin [81, 101]$	SF	-	-	> 0.4
VRTZ	150–225	> 500	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4



New

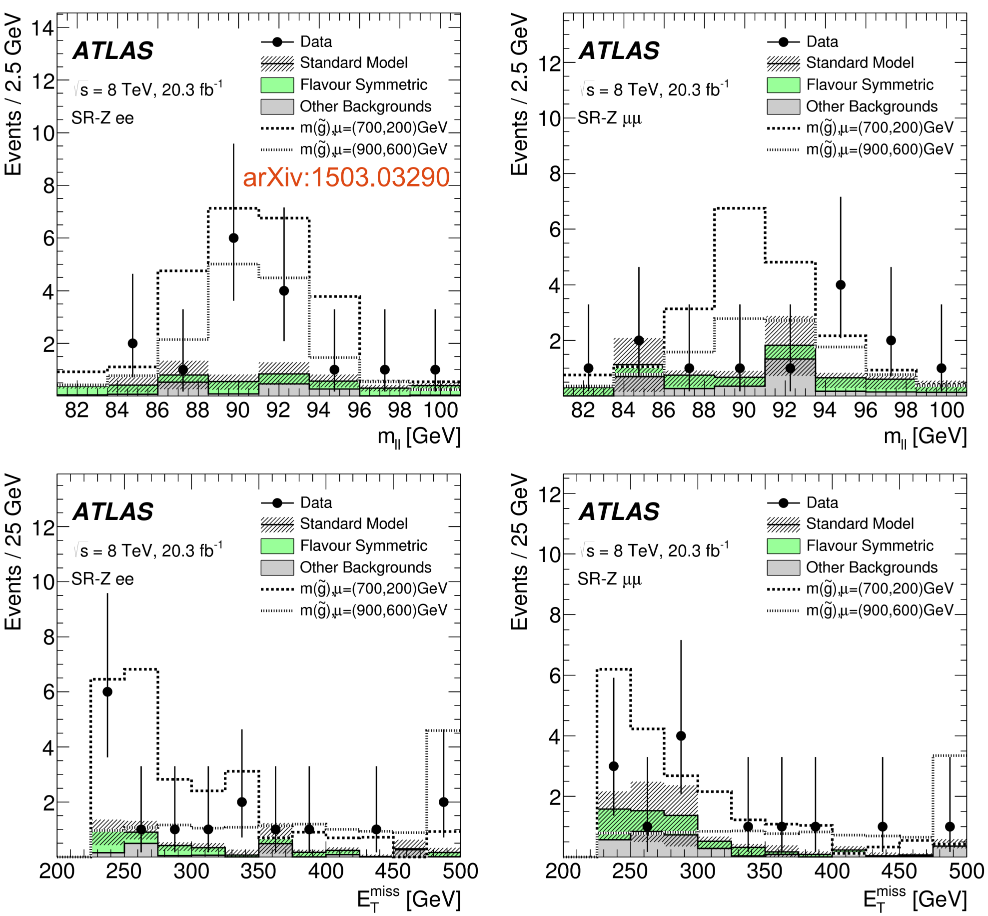
Excess in Z+jets Final-state

Observe an excess in data:

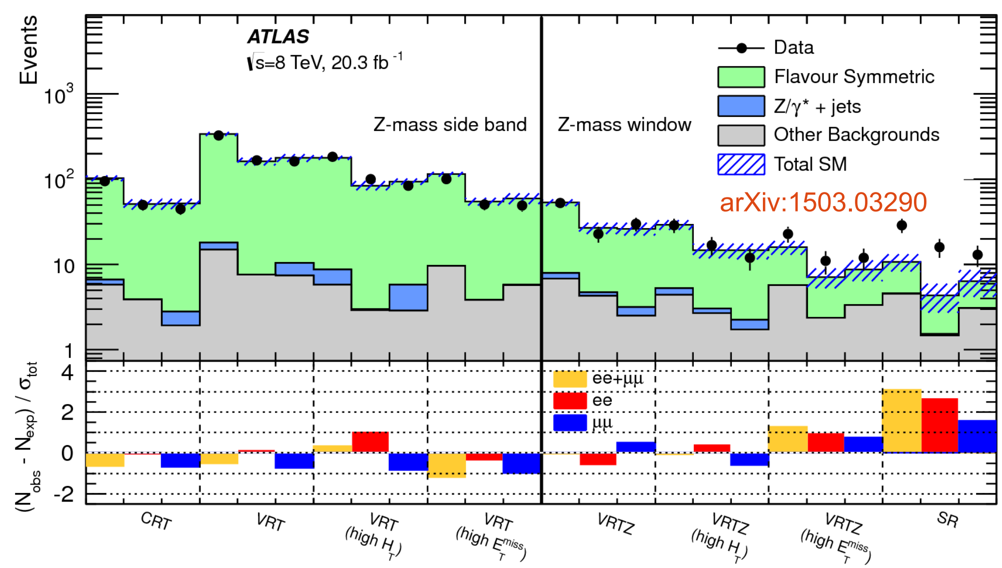
- 3σ significance in ee channel
- 1.7σ in μμ channel
- 3σ significance when combining the two channels

Observed events and expected backgrounds

Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ^* + jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$



Excess of events only in signal region:



New

Excess in Z+jets Final-state

Observe an excess in data:

- 3σ significance in ee channel
- 1.7σ in μμ channel
- 3σ significance when combining the two chan…

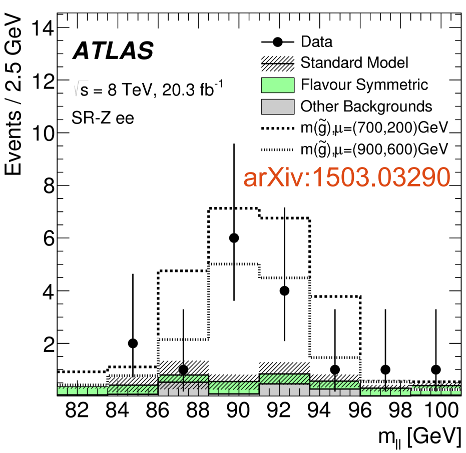
Observed events and expected backgrounds

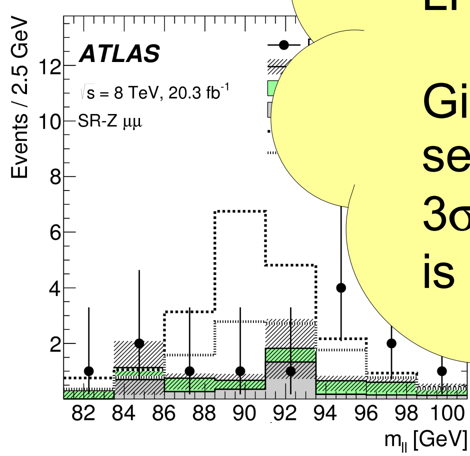
Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ^* + jets (jet-sm…	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
[illegible]	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
[illegible]	…2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
[illegible]	[illegible]	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

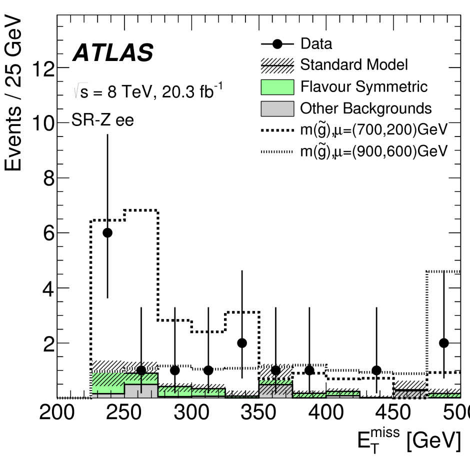
Largest excess seen in LHC SUSY searches

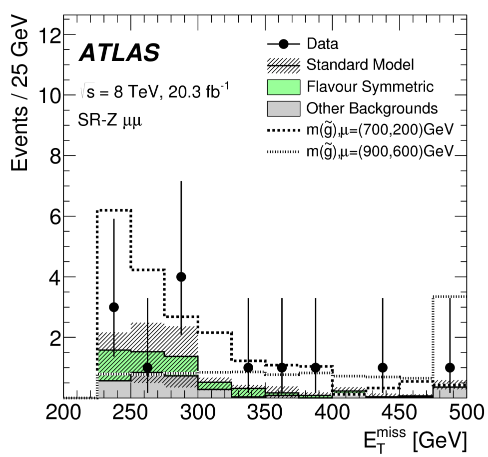
Given large number of searches performed 3σ statistical fluctuation is not unexpected

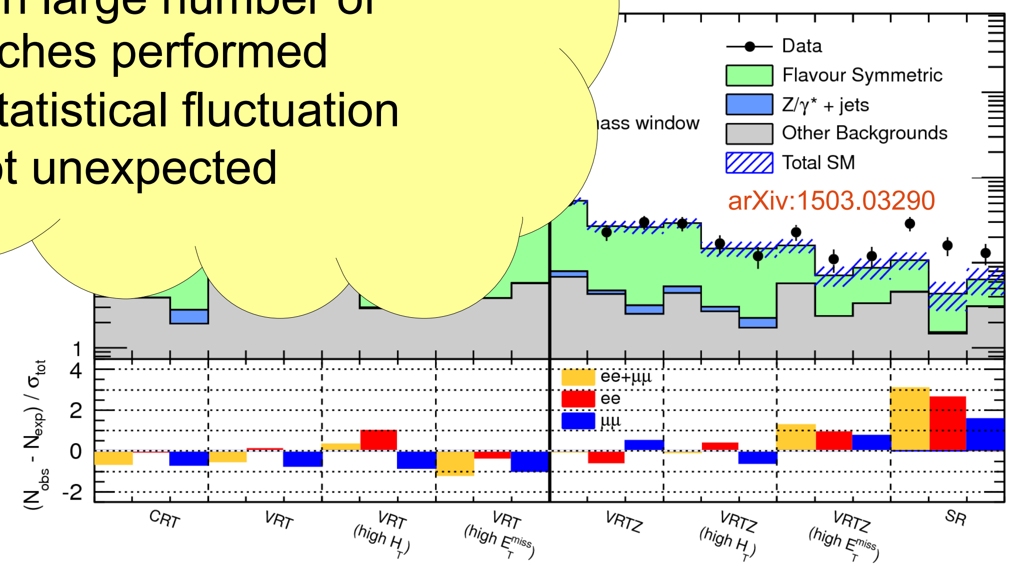
…in signal region:











New

Does CMS See Excess?

Recent similar search in CMS:

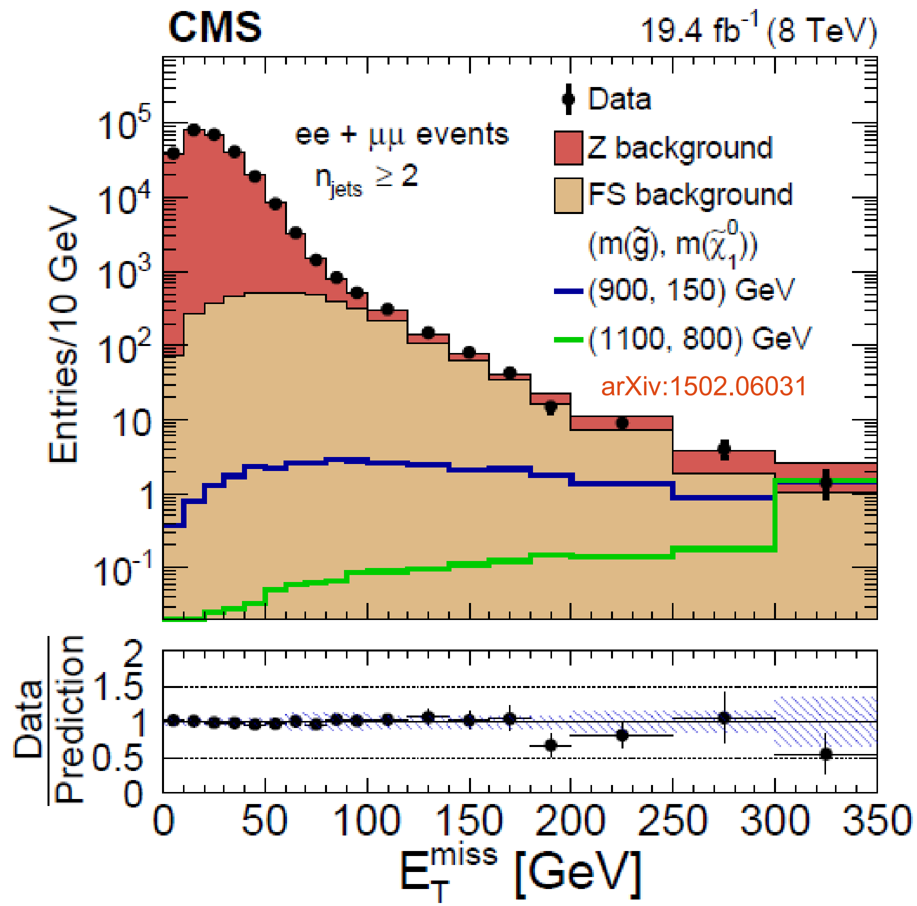
- Similar Z→ll selection
- Counts in bins of E_T^{miss}
- ≥2 (or ≥3) jets above 40 GeV
- No selection on H_T (sum of jet p_T) resulting in increased Z→ll bkg

≥2 jets

E_T^{miss} (GeV)	100–200	200–300	>300
DY background	336 ± 89	28.6 ± 8.6	7.7 ± 3.6
FS background	868 ± 57	45.9 ± 7.3	5.1 ± 2.3
Total background	1204 ± 106	74.5 ± 11.3	12.8 ± 4.3
Data	1187	65	7
GMSB signal yields			
$m_{\tilde{g}} = 900$, $m_{\tilde{\chi}_1^0} = 150$	22.1 ± 0.4	11.1 ± 0.3	7.2 ± 0.2
$m_{\tilde{g}} = 1100$, $m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.6 ± 0.05	7.6 ± 0.1

≥3 jets

E_T^{miss} (GeV)	100–200	200–300	>300
DY background	124 ± 33	12.7 ± 3.8	3.2 ± 1.8
FS background	354 ± 28	26.5 ± 5.4	2.0 ± 1.4
Total background	478 ± 43	39.2 ± 6.6	5.3 ± 2.3
Data	490	35	6
GMSB signal yields			
$m_{\tilde{g}} = 900$, $m_{\tilde{\chi}_1^0} = 150$	22.0 ± 0.4	11.0 ± 0.3	7.1 ± 0.2
$m_{\tilde{g}} = 1100$, $m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.5 ± 0.05	7.4 ± 0.1



No excess seen by CMS

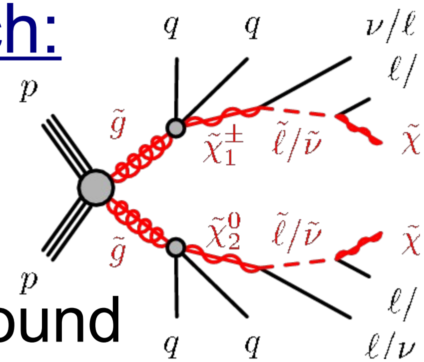
However, only ~30% overlap with ATLAS selection

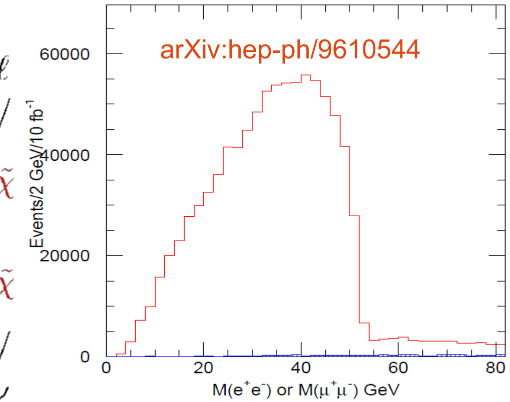
New

CMS Excess in Dilepton Search

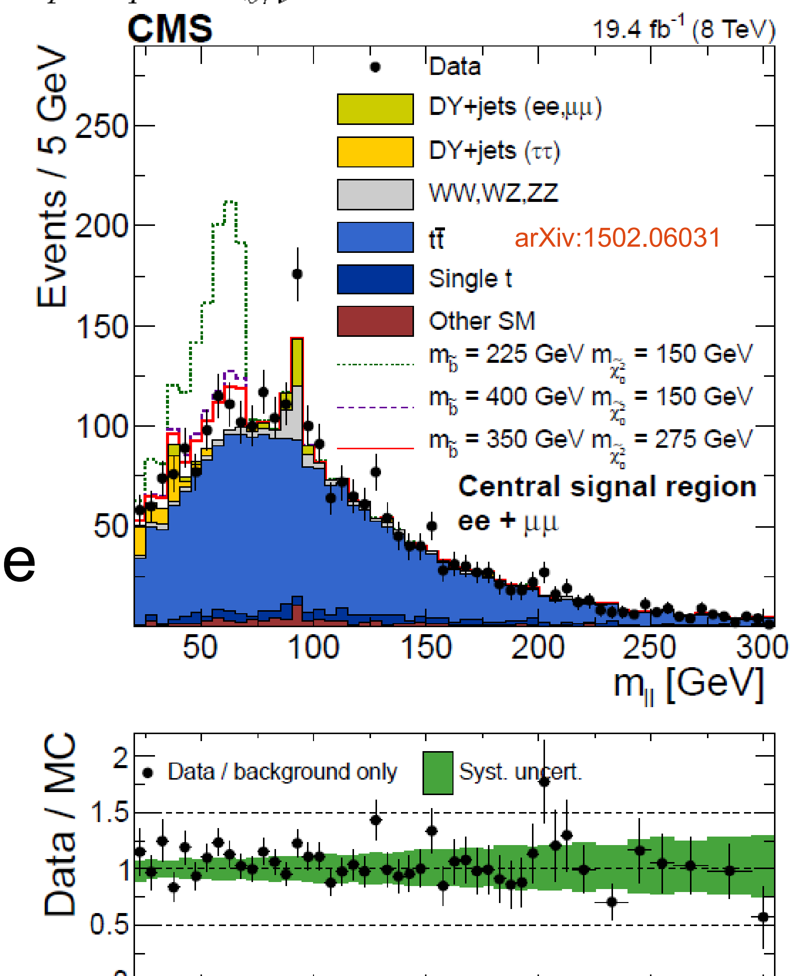
CMS excess in dilepton edge search:

- Decay of heavy neutralino through slepton or off-shell Z gives triangular ll mass distribution with characteristic edge and kinematic bound
- Split in central leptons ($|\eta|<1.4$) and forward leptons ($|\eta|>1.6$)
- 2 jets and $E_T^{miss}>150$ GeV, or 3 jets and $E_T^{miss}>100$ GeV
- Fit to "edge" shape across m_{ll} and count in 3 m_{ll} bins
- See 2.6σ excess at low m_{ll} in central case





	Low-mass		On-Z		High-mass	
	Central	Forward	Central	Forward	Central	Forward
Observed	860	163	487	170	818	368
Flavor-symmetric	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$	$355 \pm 19 \pm 14$	$131 \pm 12 \pm 8$	$768 \pm 28 \pm 31$	$430 \pm 22 \pm 27$
Drell–Yan	8.2 ± 2.6	2.5 ± 1.0	116 ± 21	42 ± 9	2.5 ± 0.8	1.1 ± 0.4
Total estimated	730 ± 40	158 ± 16	471 ± 32	173 ± 17	771 ± 42	431 ± 35
Observed−estimated	130^{+48}_{-49}	5^{+20}_{-20}	16^{+37}_{-38}	-3^{+20}_{-21}	47^{+49}_{-50}	-62^{+37}_{-39}
Significance	2.6σ	0.3σ	0.4σ	$<0.1\sigma$	0.9σ	$<0.1\sigma$



New

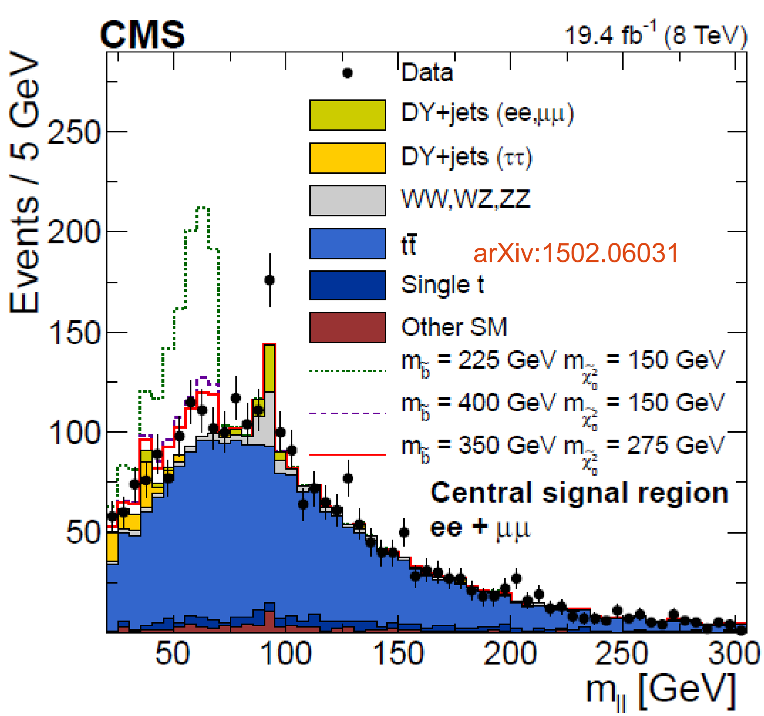
Dilepton Edge in ATLAS

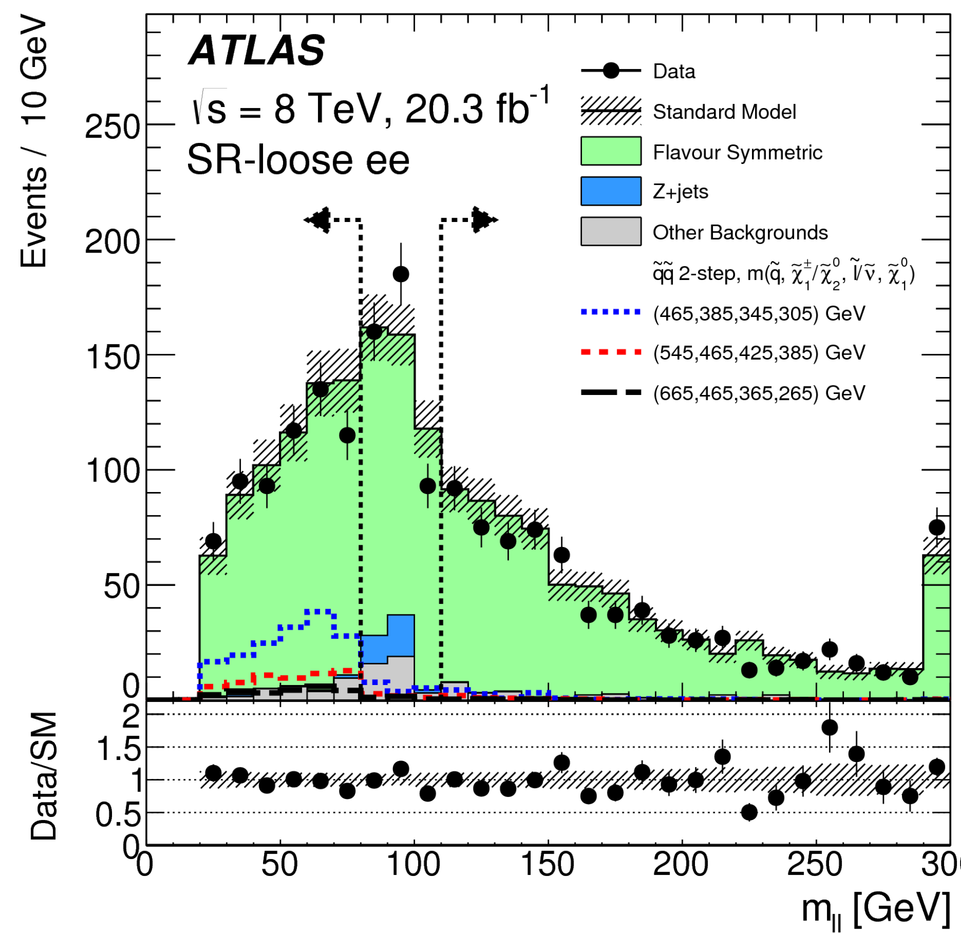
ATLAS also has edge search:

- One set of selection almost identical to CMS
- Additional SRs split in b-jets and no bjets and minimum 2 vs 4 jets

Below-Z ($20 < m_{\ell\ell} < 70$ GeV)	SR-loose ee	SR-loose $\mu\mu$	SR-loose same-flavour combined
Observed events	509	624	1133
Expected background events	$510 \pm 20 \pm 40$	$680 \pm 20 \pm 50$	$1190 \pm 40 \pm 70$
Flavour-symmetric backgrounds	$490 \pm 20 \pm 40$	$650 \pm 20 \pm 50$	$1140 \pm 40 \pm 70$
Z/γ^* + jets	$2.5 \pm 0.8 \pm 3.2$	$8 \pm 2 \pm 5$	$11 \pm 2 \pm 7$
Rare top	$0.3 \pm 0.0 \pm 0.0$	$0.4 \pm 0.0 \pm 0.0$	$0.7 \pm 0.0 \pm 0.0$
WZ/ZZ	$1.1 \pm 0.3 \pm 0.1$	$1.2 \pm 0.2 \pm 0.4$	$2.4 \pm 0.4 \pm 0.4$
Fake leptons	$16 \pm 4 \pm 2$	$23 \pm 5 \pm 1$	$38 \pm 6 \pm 4$

- No excess seen in ATLAS





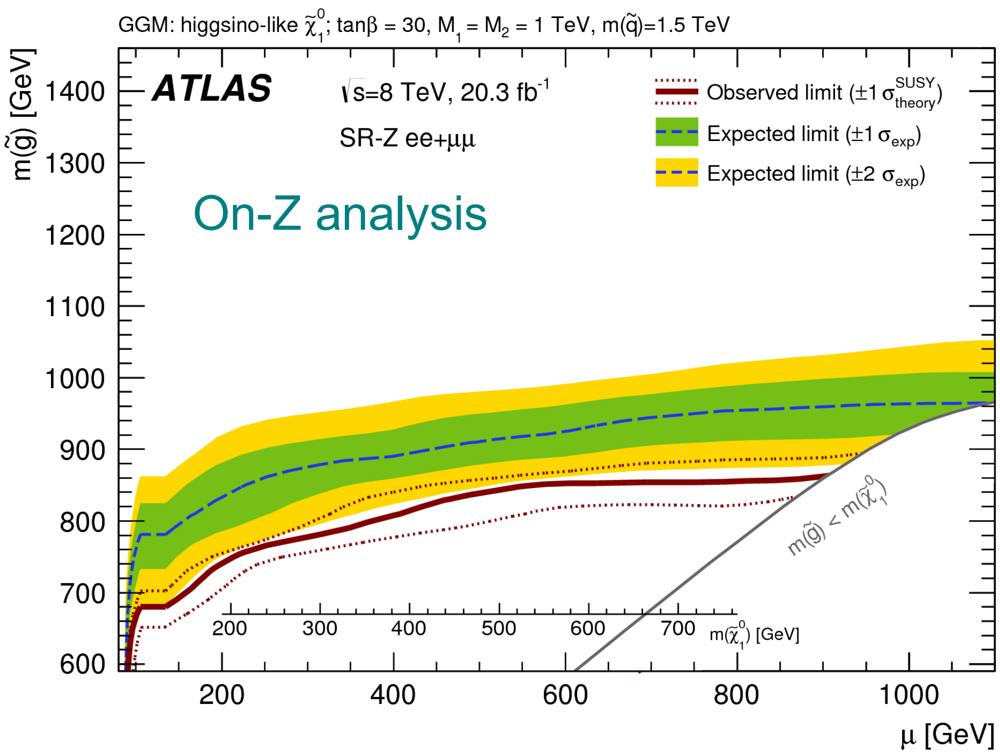
New Gluino Limits with Dileptons

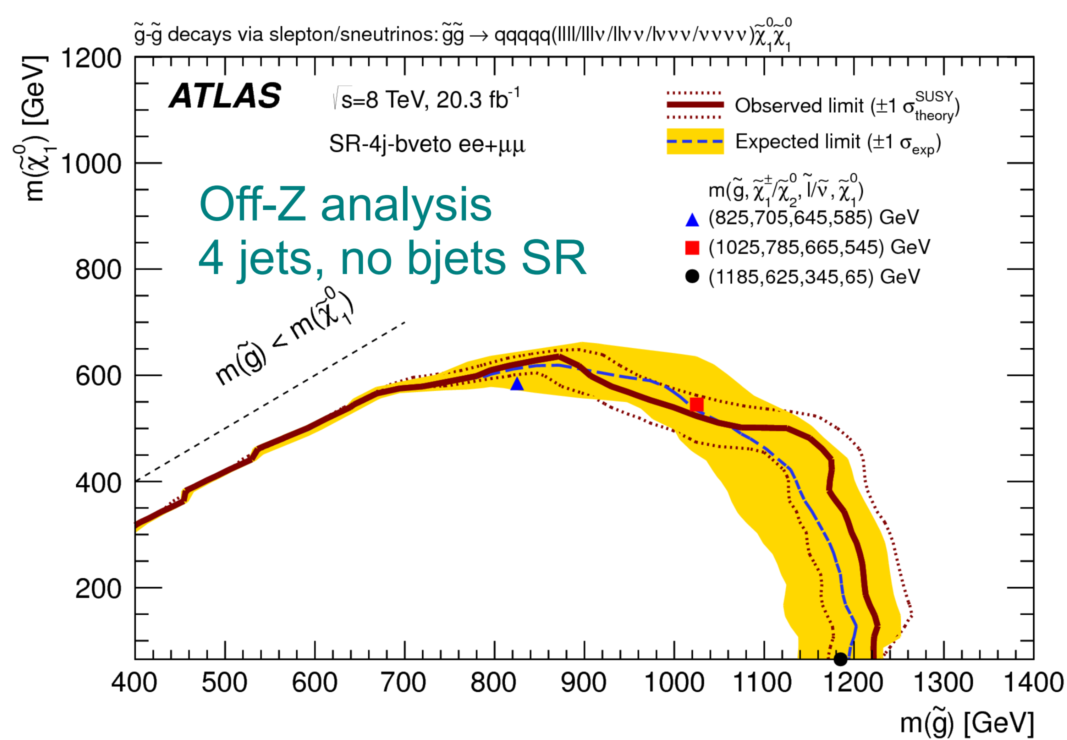
Still put limits on gluinos:

- Analysis results interpreted in both simplified models and Generalized gauge mediated supersymmetry models (GGM)
- Limits weakened due to excess in on-Z search

	Dilepton edge	Z+MET
ATLAS	No excess	3.0σ
CMS	2.6σ	No excess

The ATLAS and CMS edge selections are the same (by design) but the Z+MET are different, only ~30% of our events enter the CMS selection

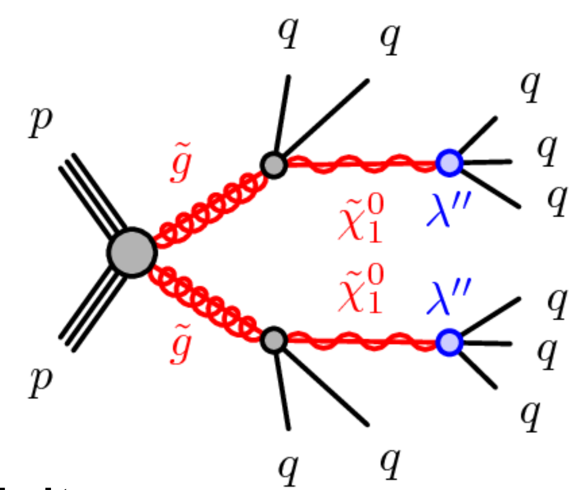


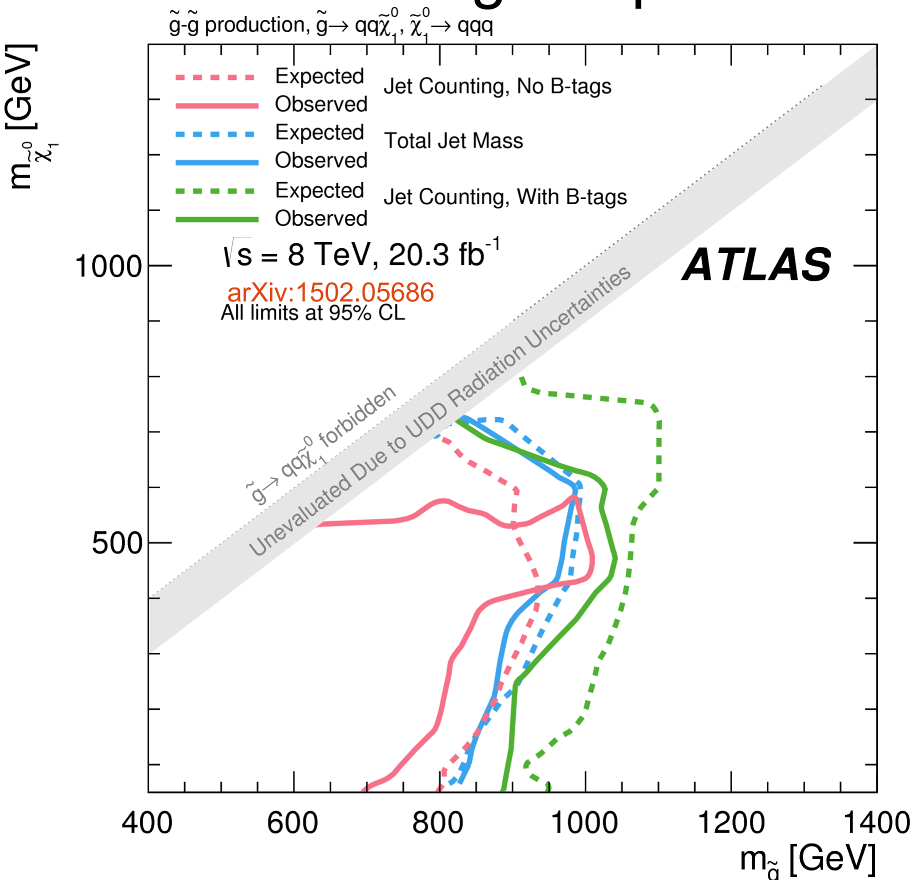


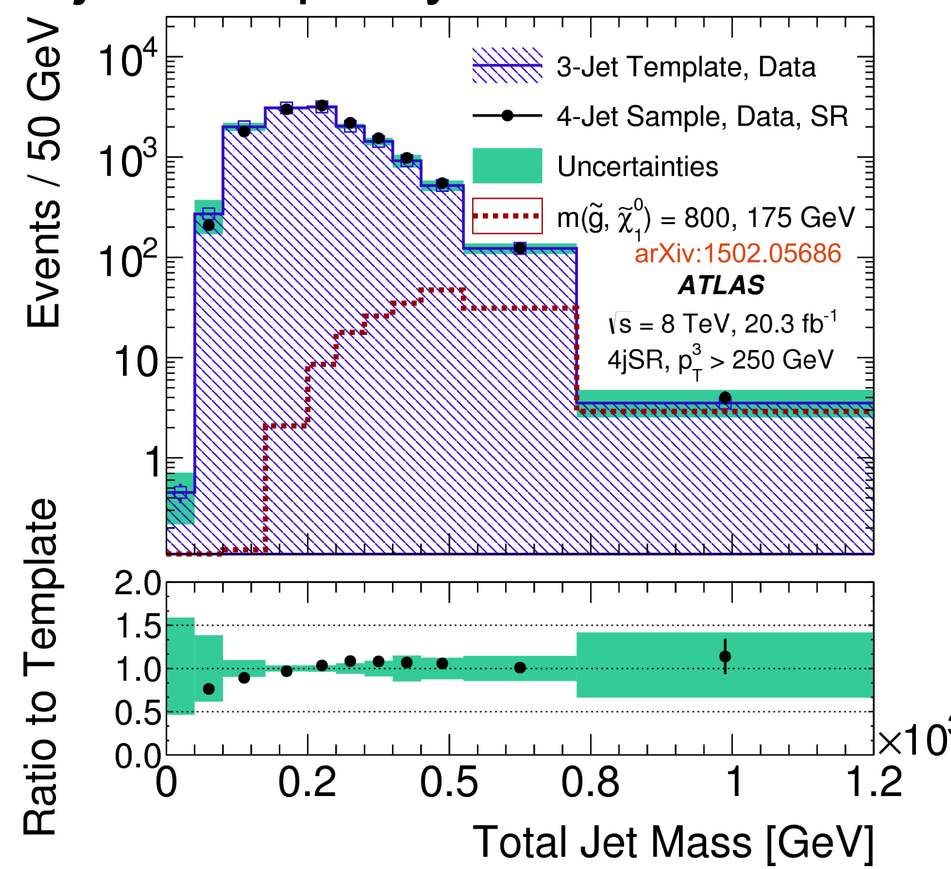
New Gluino Search without E_T^{miss}

Search for E_T^{miss} less gluino decays:

- If R-parity violated can have decays to just jets
- Search uses high jet multiplicity (≥6,7 jets) or large total (fat-)jet mass
- Dominant background from SM multi-jets estimated using templates from lower jet multiplicity

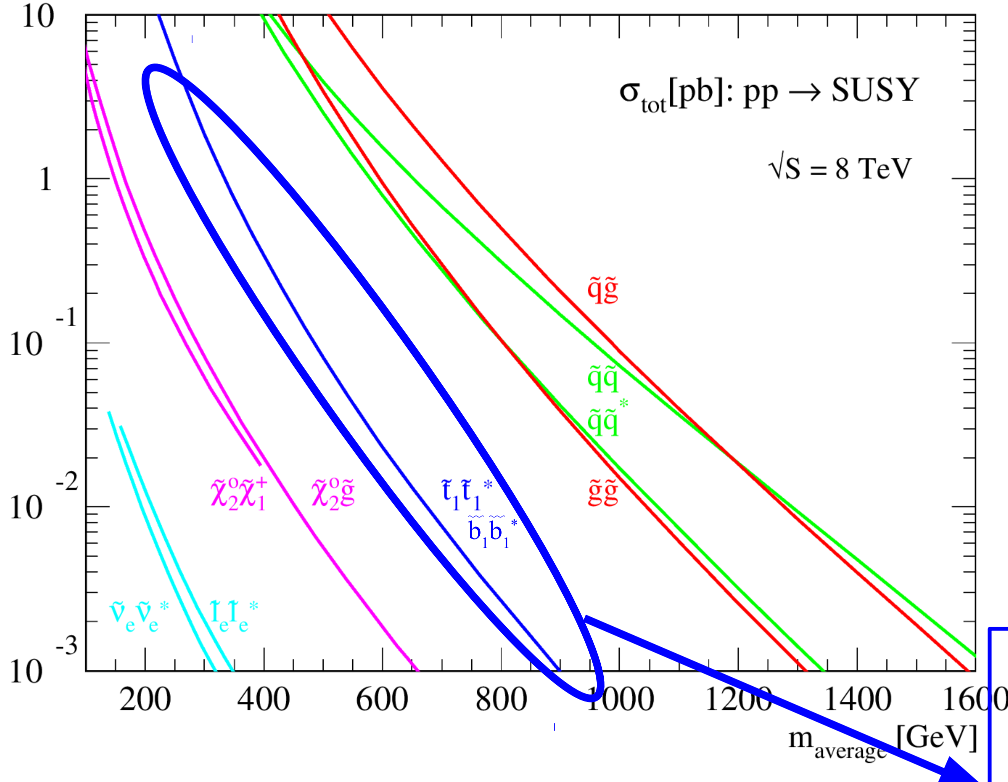






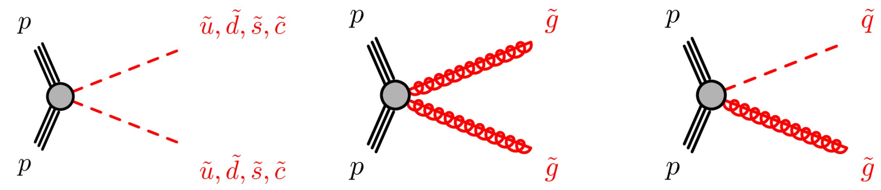
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



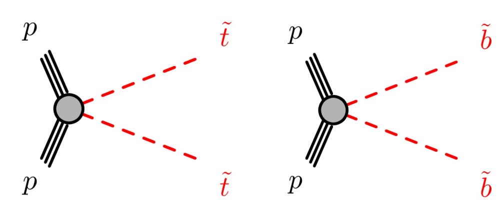
Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is jets and missing energy



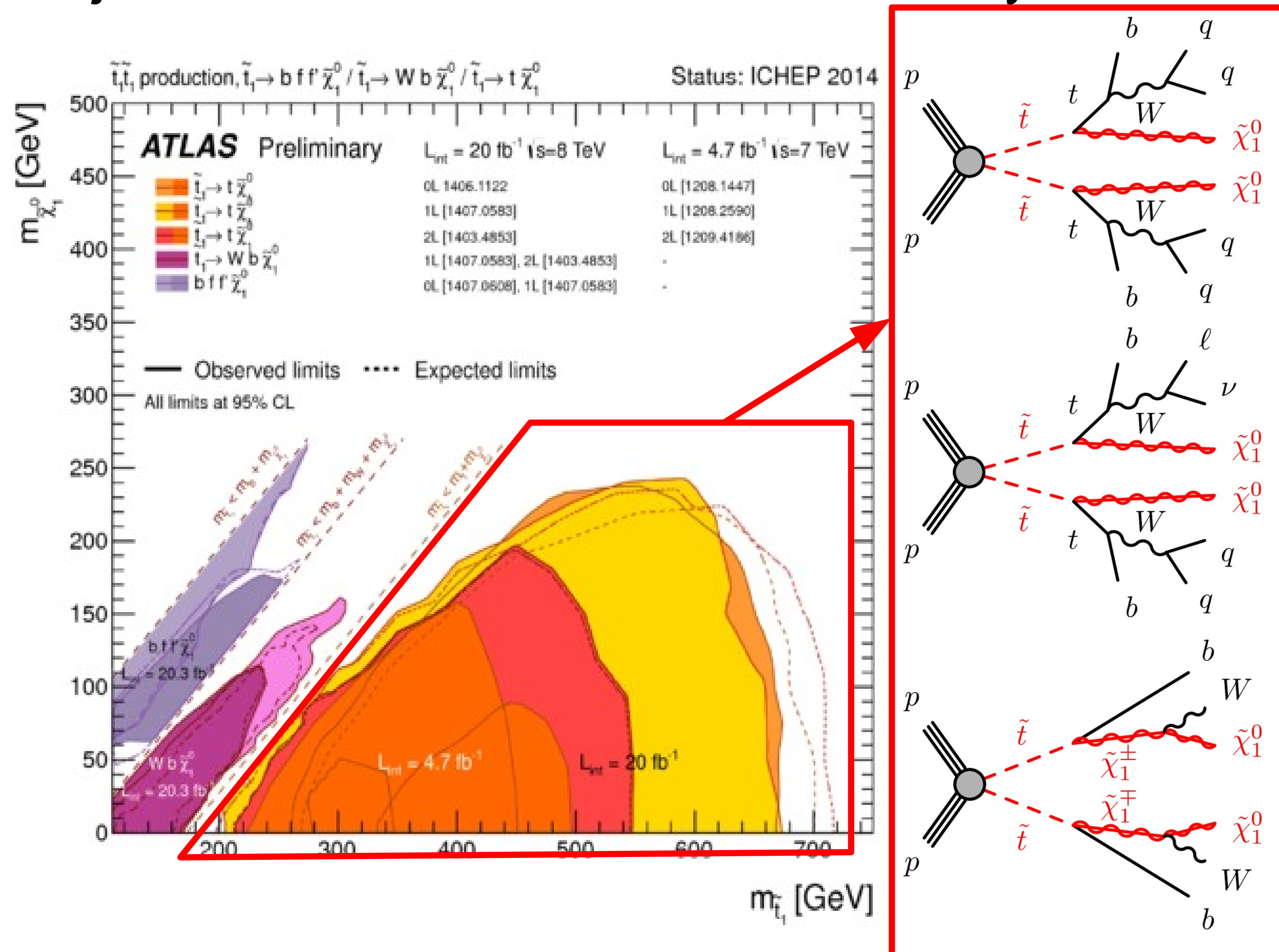
Prod. of 3rd generation squarks:

- Lower cross section,
- Decays chains frequently has top and bottom quarks
- Of great interest to "Natural SUSY"



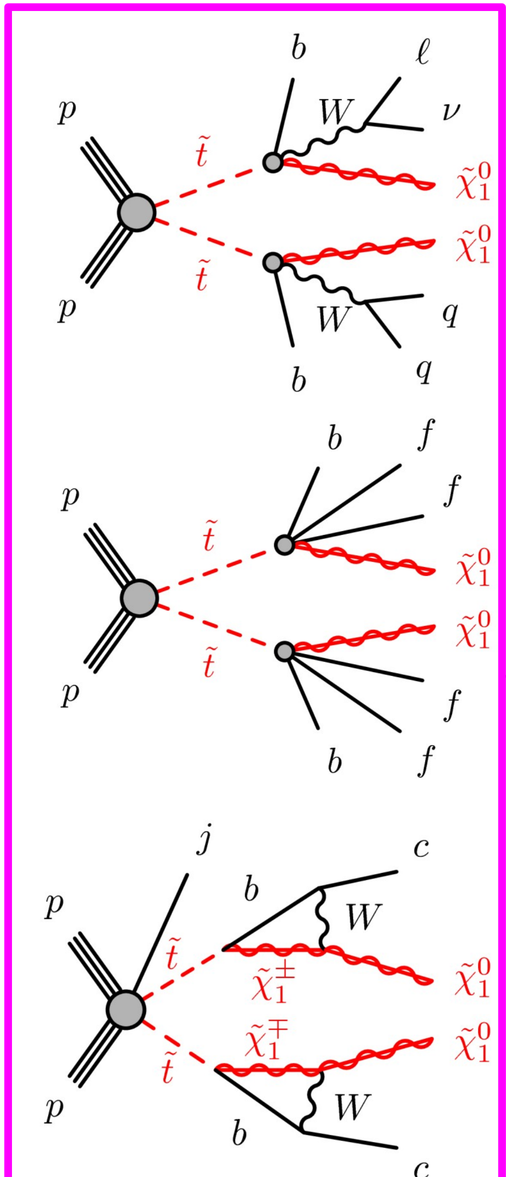
3rd Generation Squark Searches

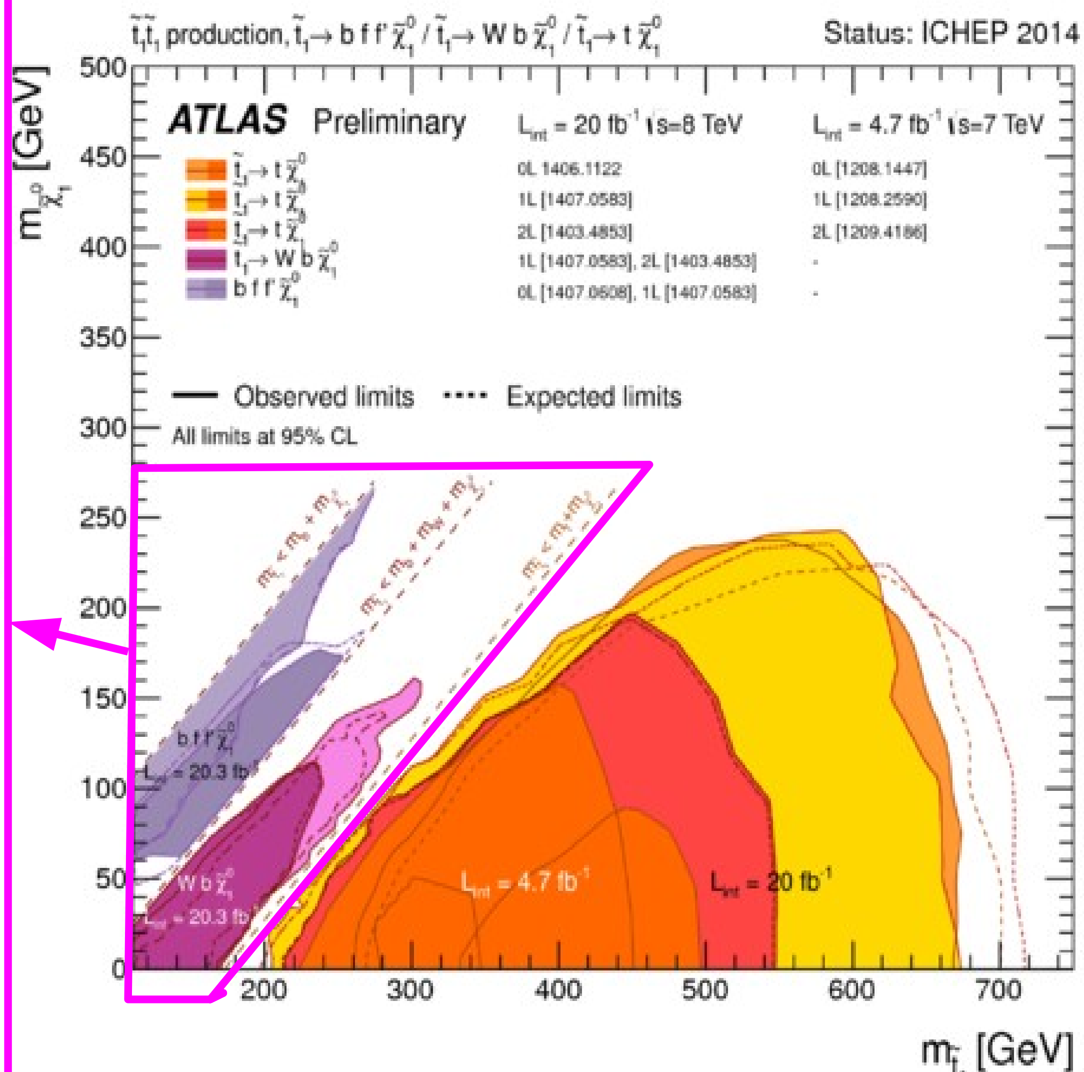
In natural SUSY at least one stop light (m< 1 TeV)
Have been a major focus of SUSY searches in last 3 years

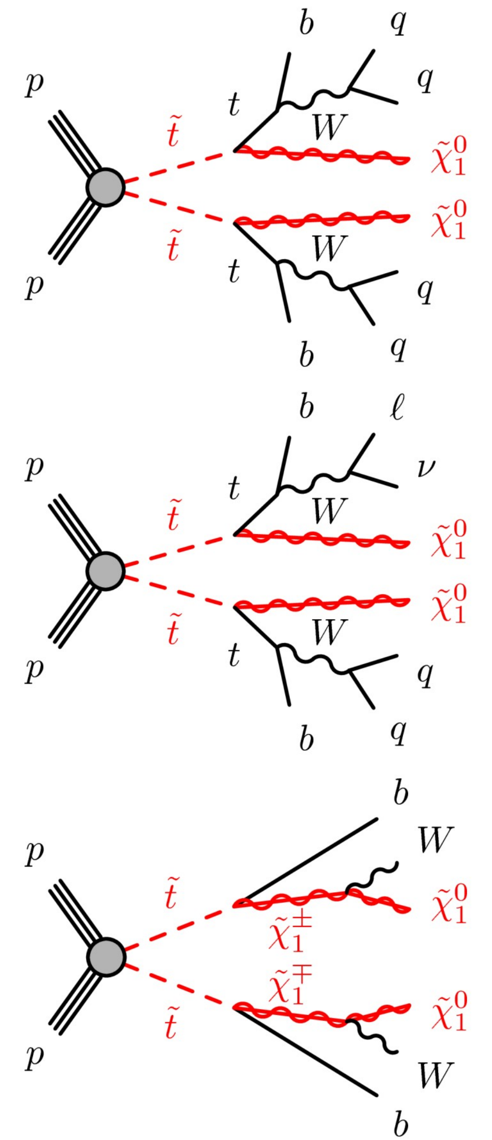


3rd Generation Squark Searches

In natural SUSY at least one stop light (m< 1 TeV)
Have been a major focus of SUSY searches in last 3 years

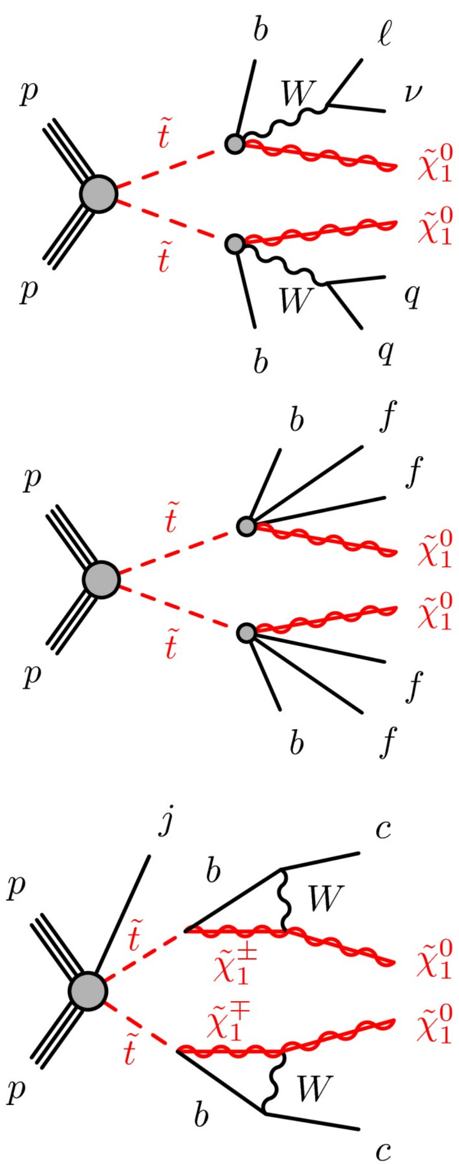


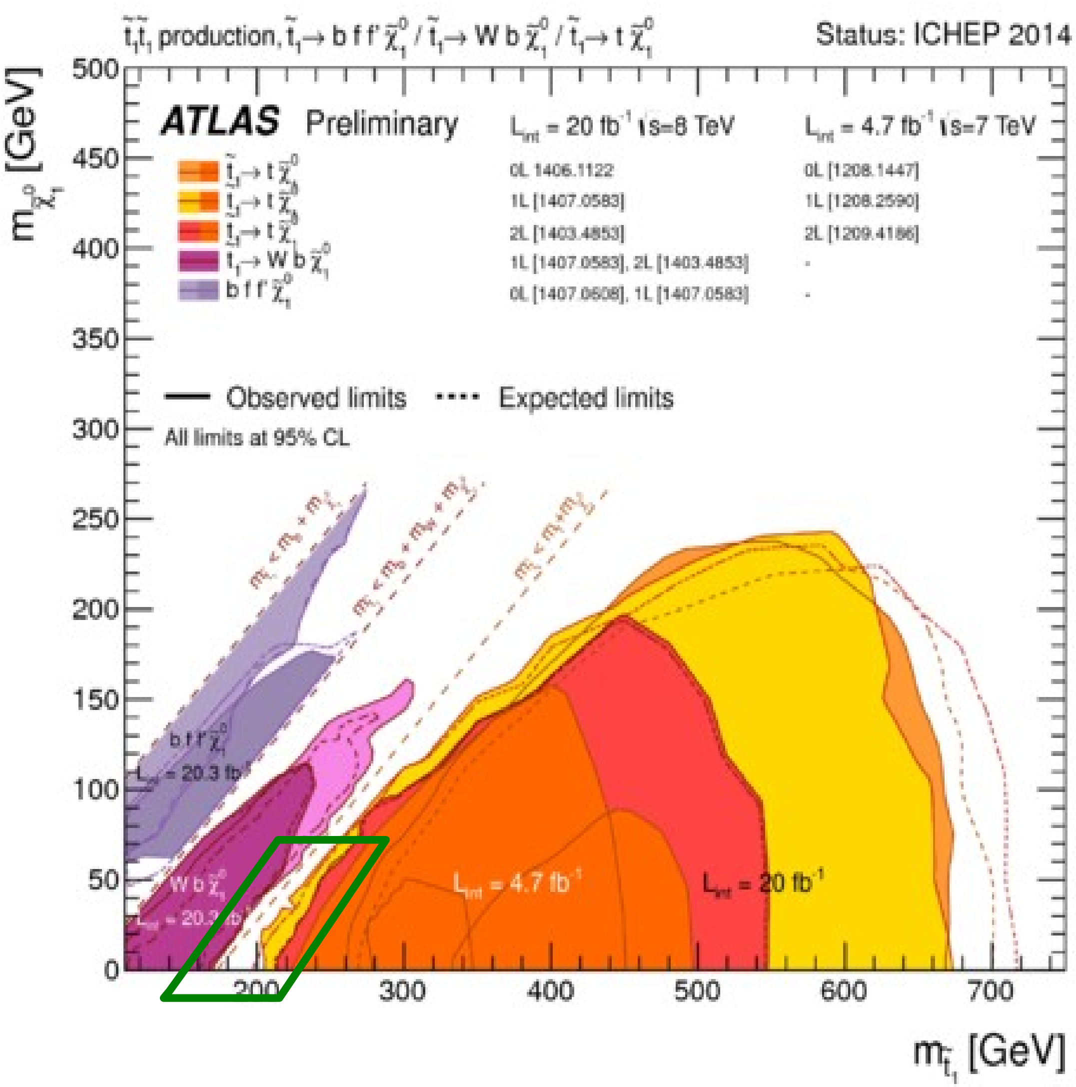


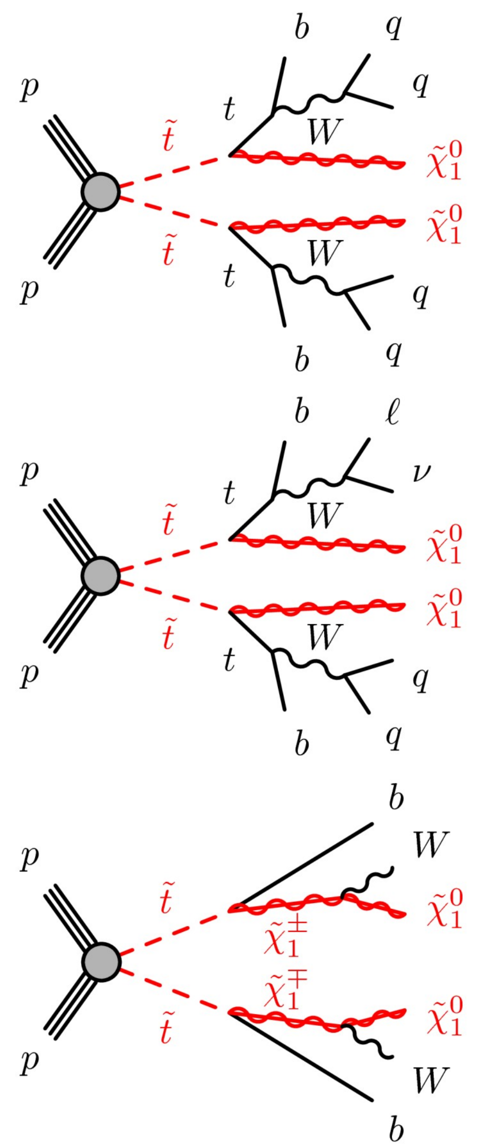


3rd Generation Squark Searches

In natural SUSY at least one stop light (m< 1 TeV)
Have been a major focus of SUSY searches in last 3 years

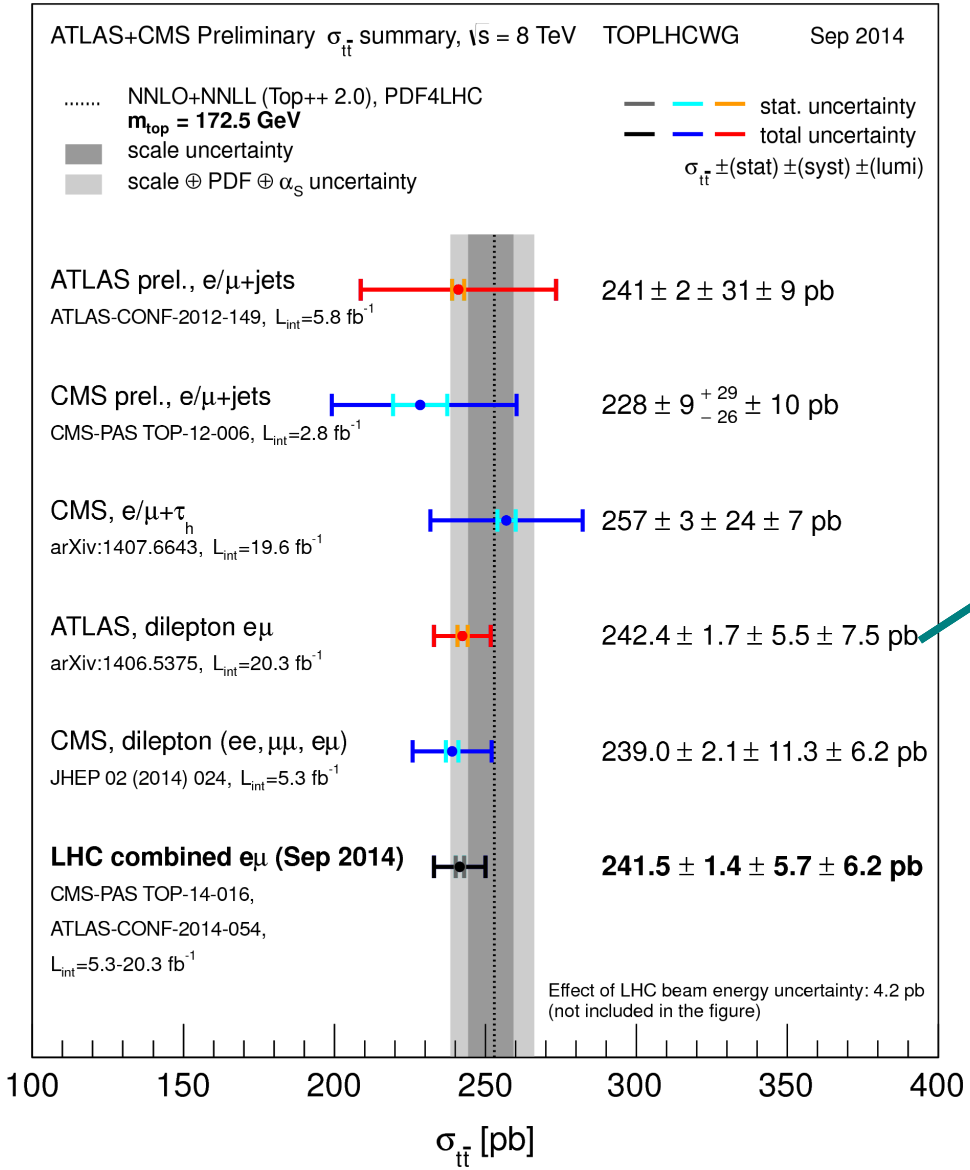




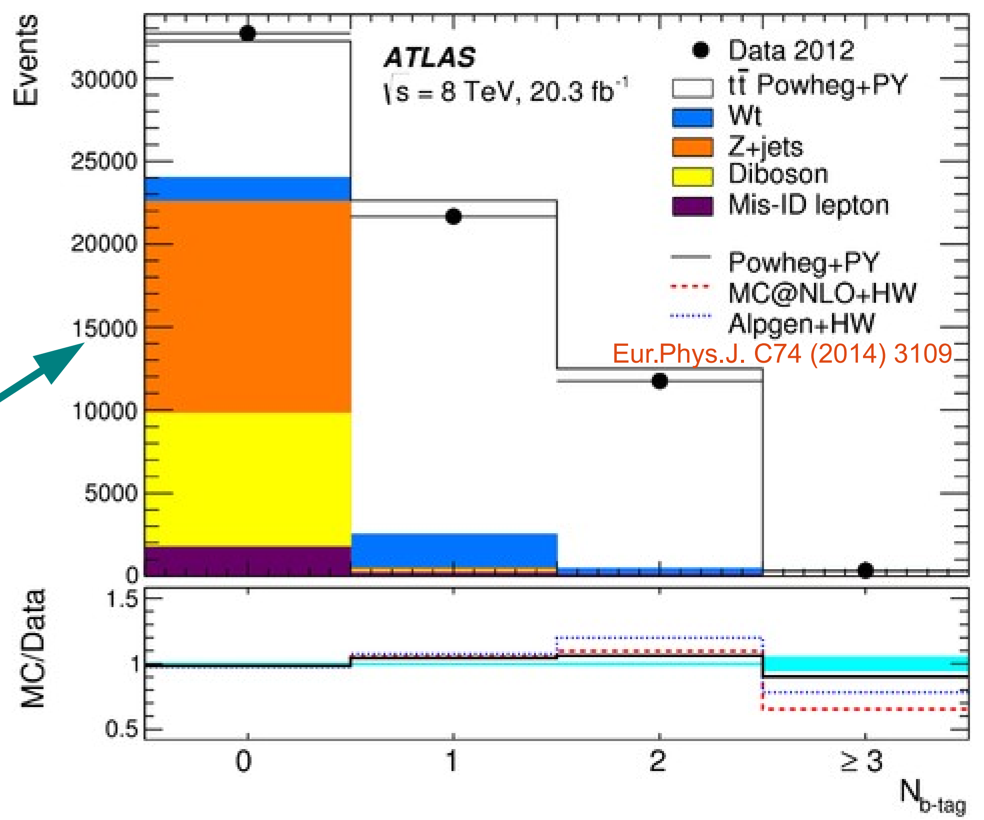


Stop Limit from $t\bar{t}$ cross section

- If $m_{\tilde{t}} \sim m_{top}$, then it is reconstructed as top, increasing cross section
- Precise NNLO+NNLL SM prediction: $177.3^{+11.5}_{-12.0}$ pb (7 TeV)
  $252.9^{+15.3}_{-16.3}$ pb (8 TeV)



ATLAS $t\bar{t}$ dilepton cross section measurement



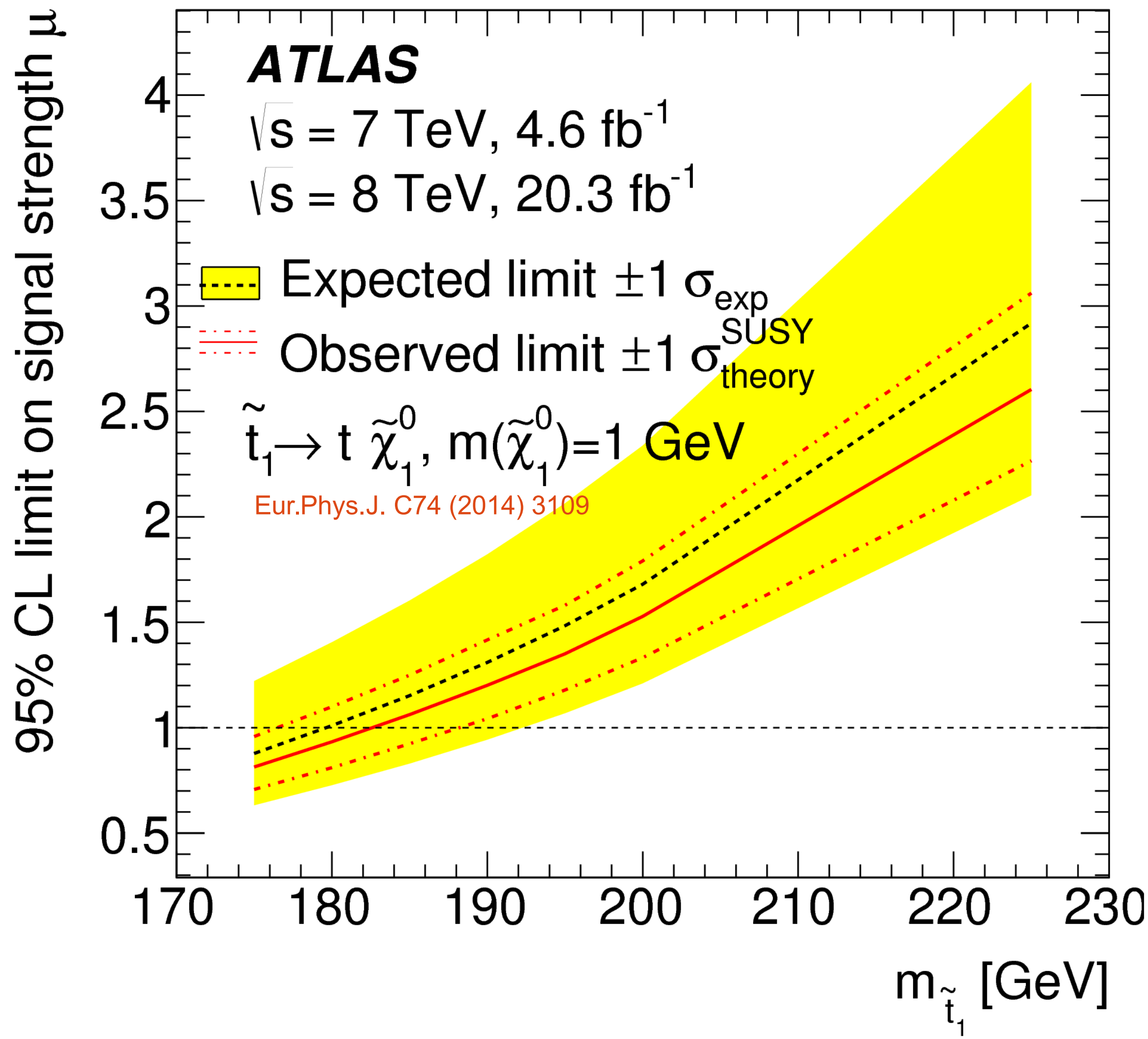
$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\ (\sqrt{s} = 7\,\text{TeV})$$

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}\ (\sqrt{s} = 8\,\text{TeV}),$$

Stop Limit from $t\bar{t}$ cross section

$m_{\tilde{t}} \sim m_{top}$ excluded

- $\sigma_{\tilde{t}\tilde{t}}$ ~40 pb at $m_{\tilde{t}}$=175 GeV,
  $\sigma_{\tilde{t}\tilde{t}}$ ~20 pb at $m_{\tilde{t}}$=200 GeV
- Selection efficiency is very similar to $t\bar{t}$ for right-handed $\tilde{t}$
- Exclude light stop from m_t to 183 (177) GeV before(after) accounting for 15% uncertainty on $\sigma_{\tilde{t}\tilde{t}}$
- Limit assumes BF($\tilde{t}\rightarrow t\tilde{\chi}_1^0$)=100%
- Weakens to 175 GeV if stop is left-handed



- Little dependence on the neutralino mass

New Stop Limit from $t\bar{t}$ Spin Correlation

Can also use difference in spin to put limit on light stop

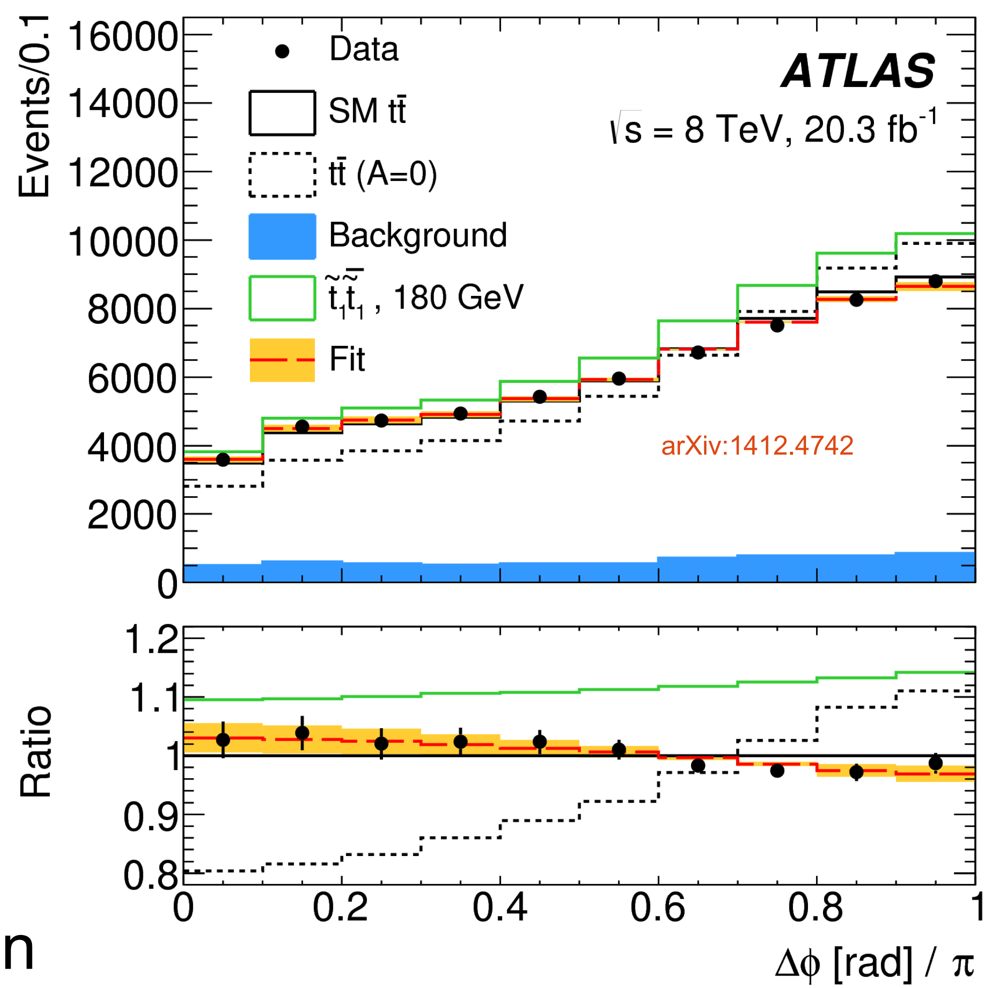
[$t\bar{t}$ spin correlation measurement]

- Opposite-sign dileptons (ee, eμ, μμ) at 8 TeV
- At least two jets, ≥1 b-tagged
- Further kinematic selections on E_T^{miss} and m(ll) to ensure clean top decay samples
- Measure spin-correlation

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

  using azimuthal Δφ(i,j) distribution
- Consistent with SM prediction:

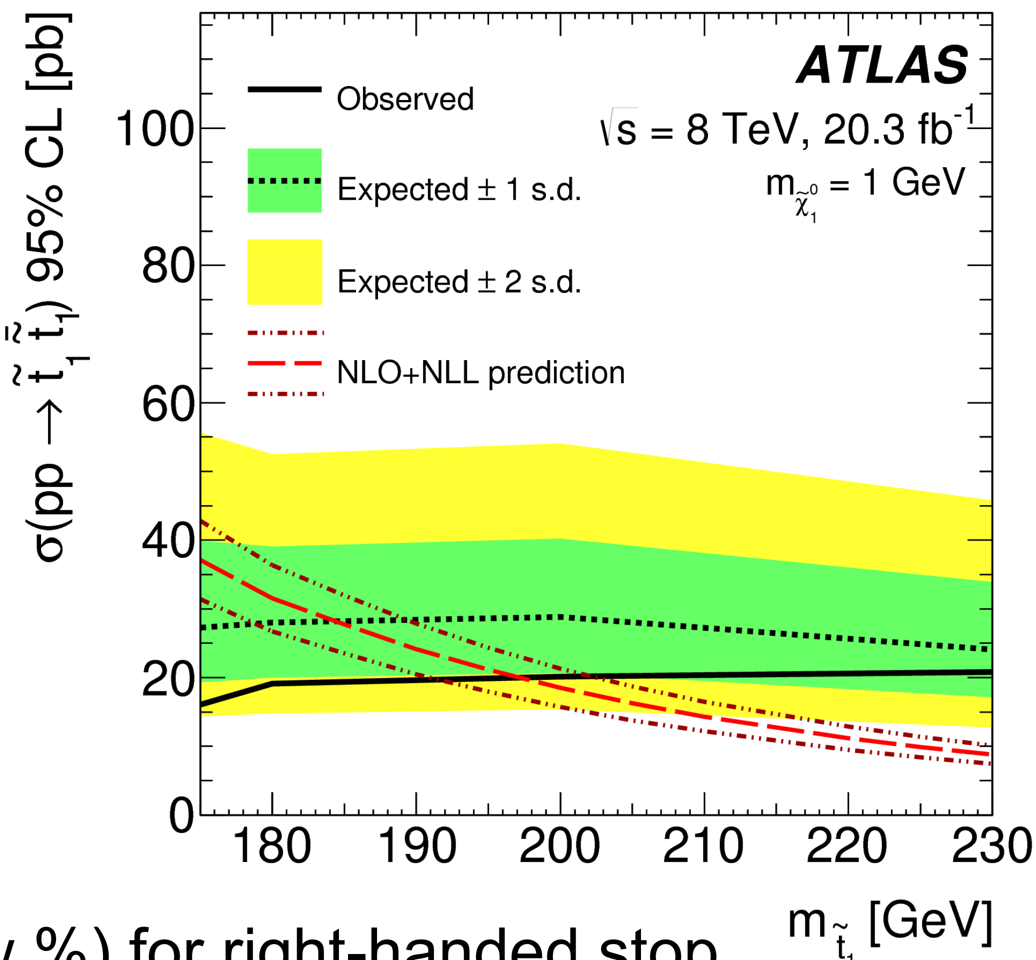
$A_{helicity}$=0.38±0.04 A_{SM}= 0.318±0.005



New Stop Limit from $t\bar{t}$ Spin Correlation

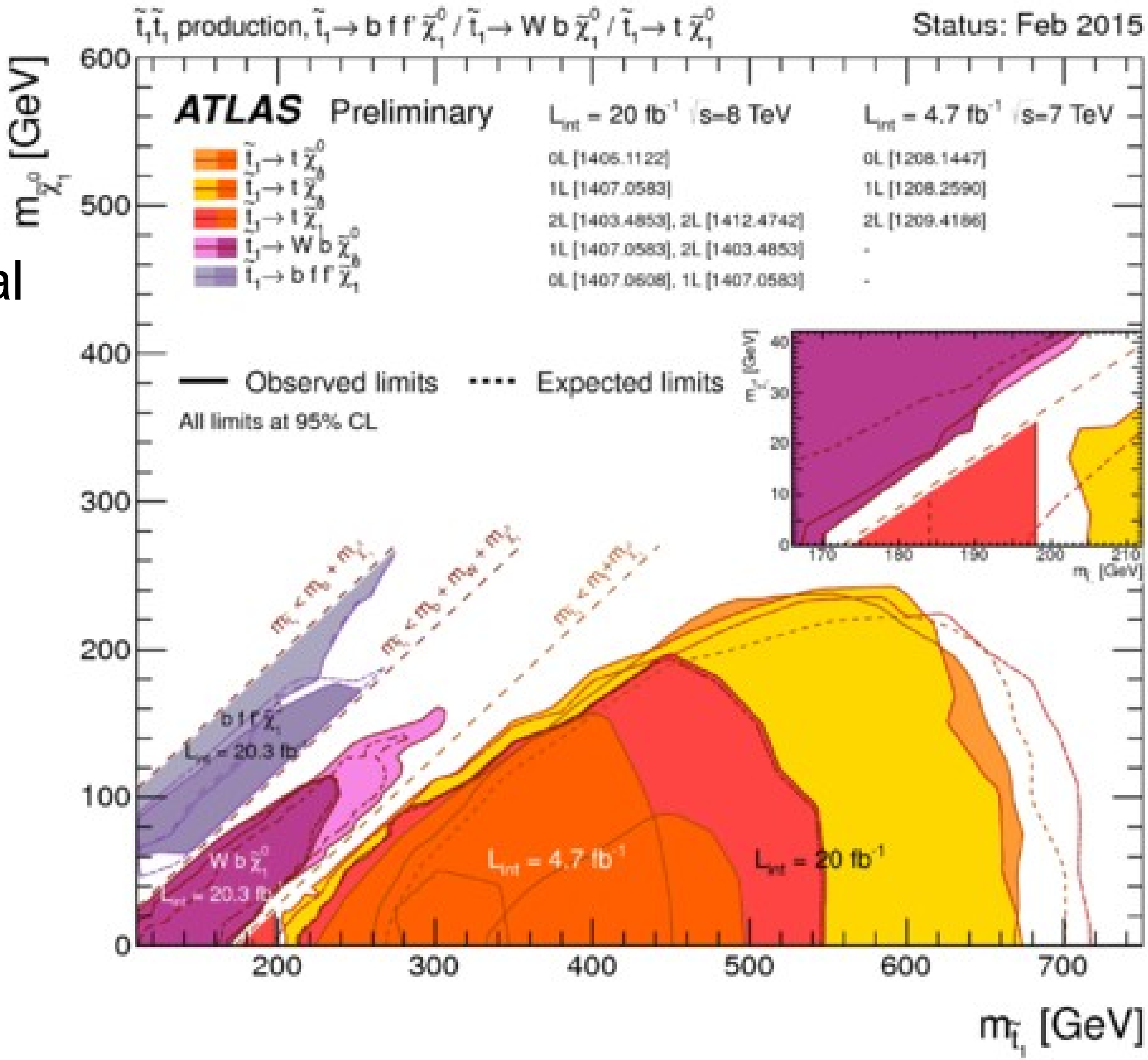
$m_{\tilde{t}} \sim m_{top}$ further excluded

- Simultaneous fit to overall $\sigma_{t\bar{t}}$ and $\Delta\phi(i,j)$ distribution for additional scalar top contribution assuming SM cross section for top
- Exclude light stop from m_t to 197 (191) GeV before(after) accounting for 15% uncertainty on $\sigma_{\tilde{t}\tilde{t}}$
- Limit assumes $BF(\tilde{t} \to t\tilde{\chi}_1^0)$=100% and right-handed stop
- Only slightly weaker limit (few %) for right-handed stop and heavier neutralino



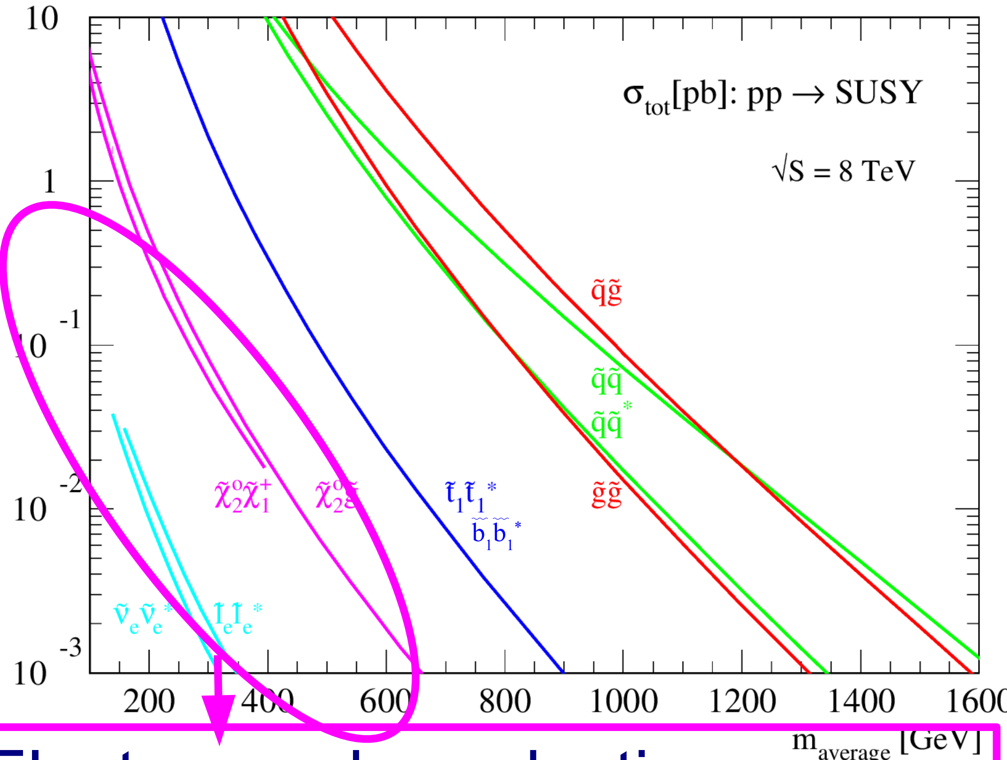
Current Stop Limit Summary

With the additional measurements at top starting to close some of the holes for light stops



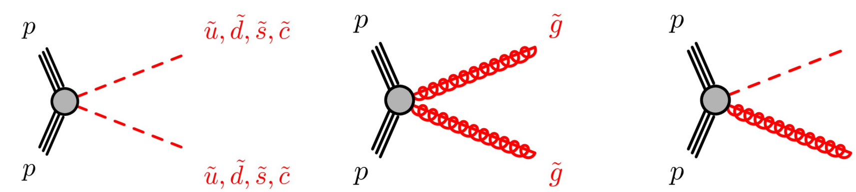
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



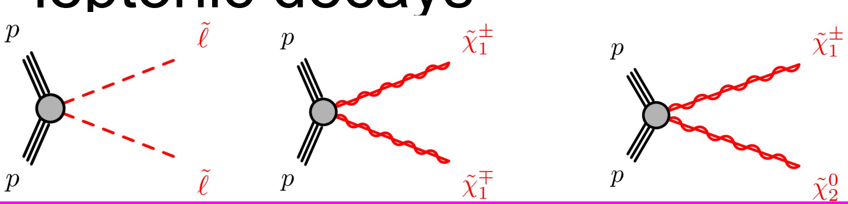
Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is jets and missing energy



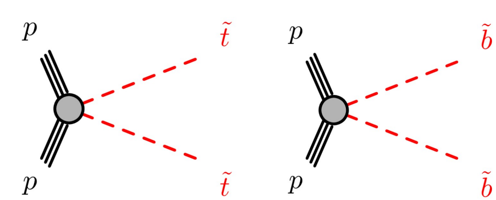
Electro-weak production

- Slepton, neutralino and charginos
- Detectable mostly through leptonic decays



Prod. of 3rd generation squarks:

- Lower cross section,
- Decays chains frequently has top and bottom quarks
- Of great interest to "Natural SUSY"

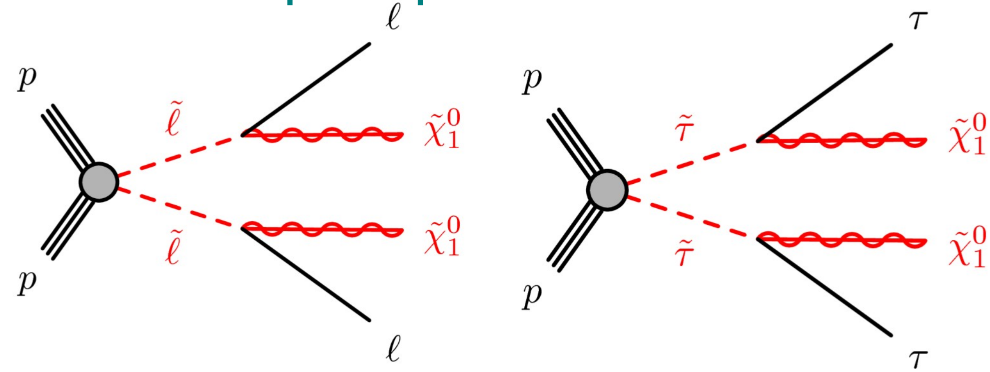


EW Production Search Program

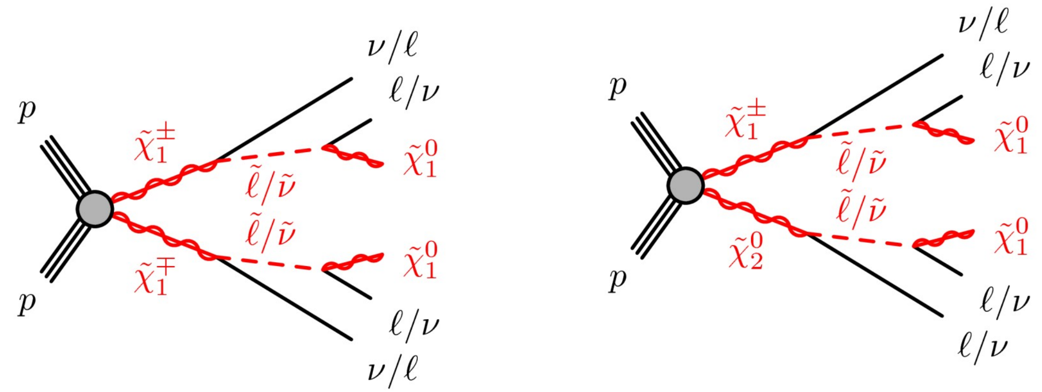
Comprehensive program

- Search for chargino, neutralino and slepton pair production
- Primarily using leptonic final states either through direct decays to leptons or through W/Z decays
- Dedicated searches with τ's

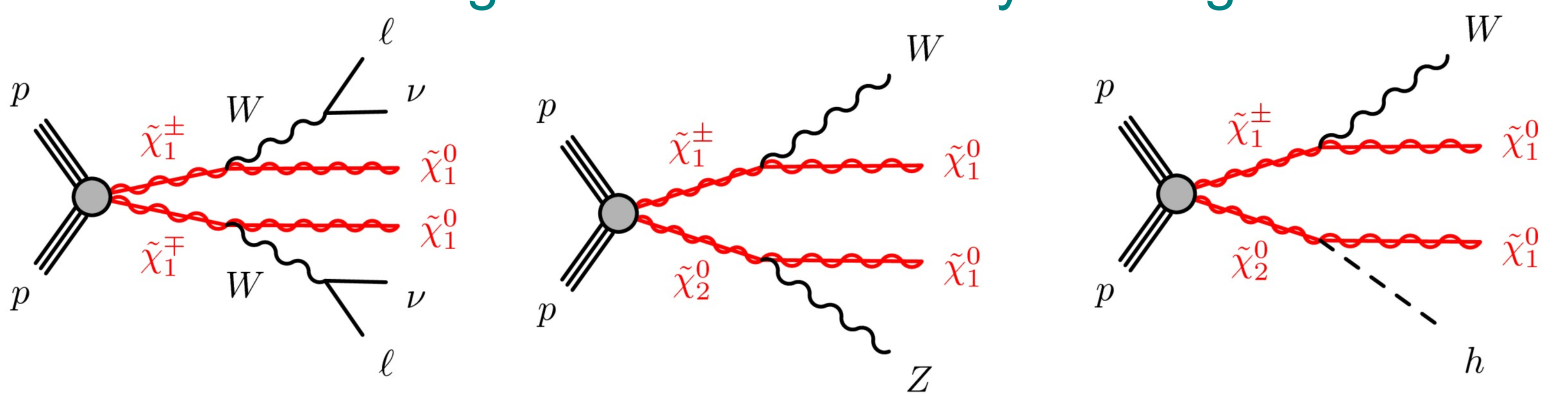
Direct slepton production



Chargino/neutralino decays through sleptons



Direct chargino/neutralino decays through W/Z/h's

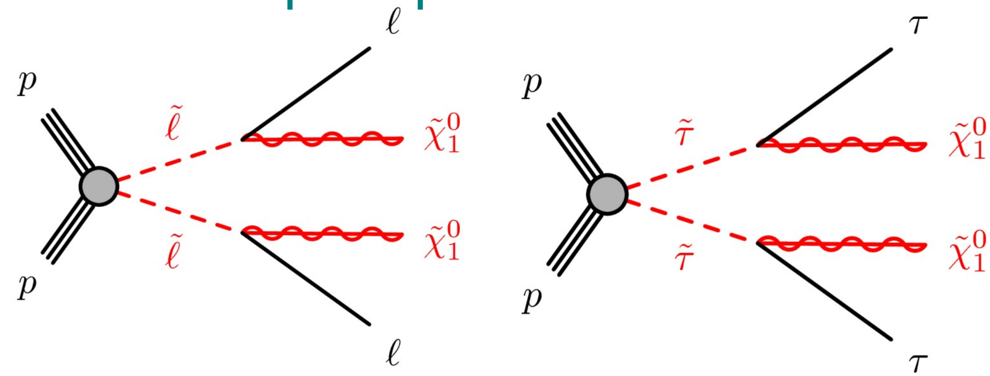


EW Production Search Program

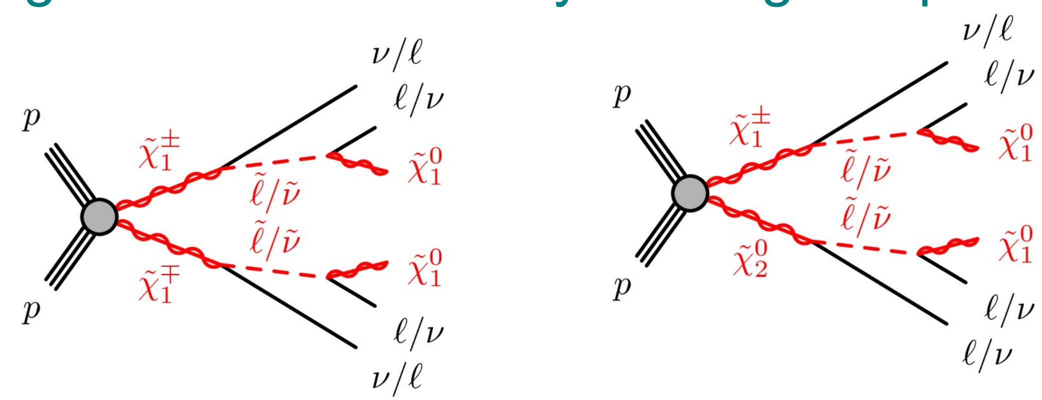
Comprehensive program

- Search for chargino, neutralino and slepton pair production
- Primarily using leptonic final states either through direct decays to leptons or through W/Z decays
- Dedicated searches with τ's

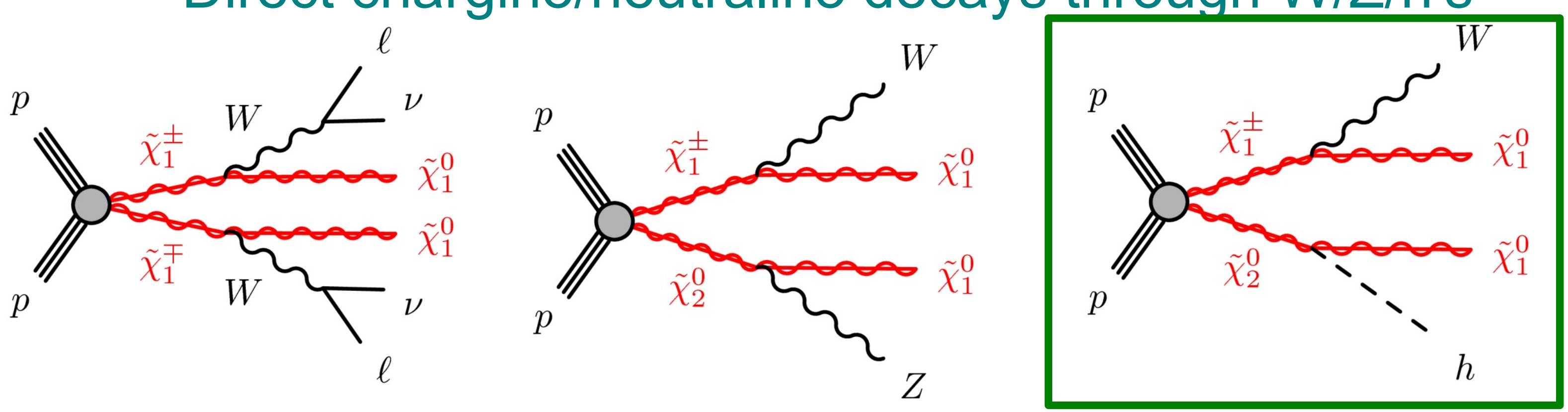
Direct slepton production



Chargino/neutralino decays through sleptons



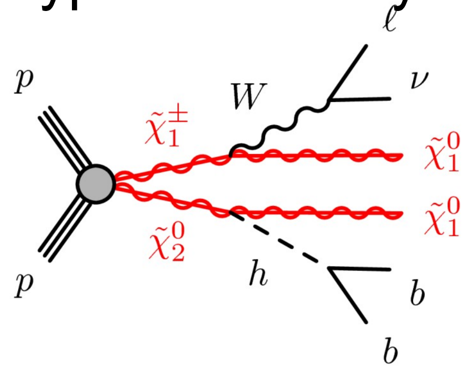
Direct chargino/neutralino decays through W/Z/h's

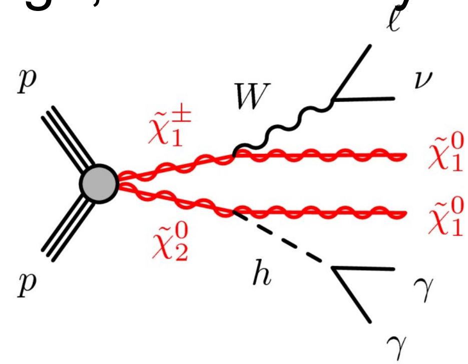


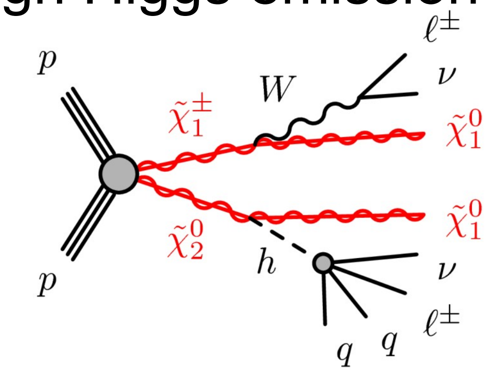
New Search for EW Prod. With Higgs Decay

If $\tilde{\chi}_2^0$ is of wino-type and heavy enough, it will decay through Higgs emission

Searched for in three decay modes in association with $\tilde{\chi}_1^+$ decay



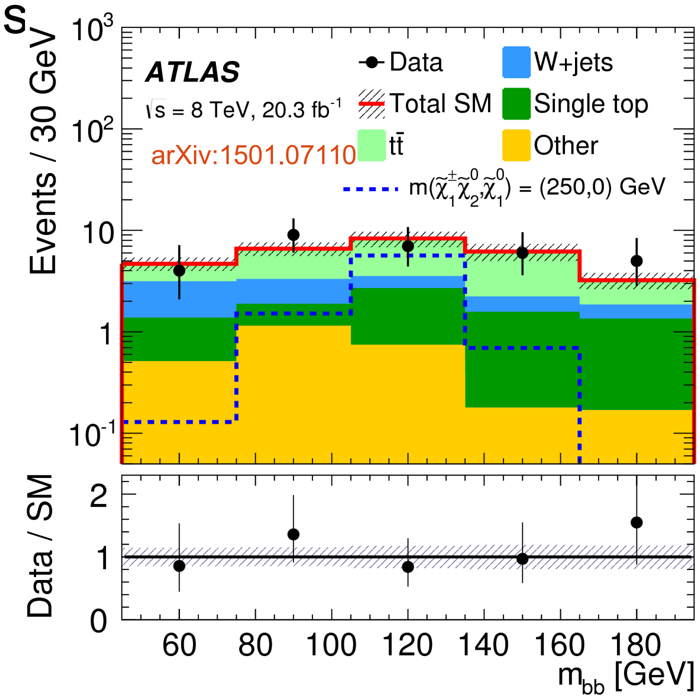




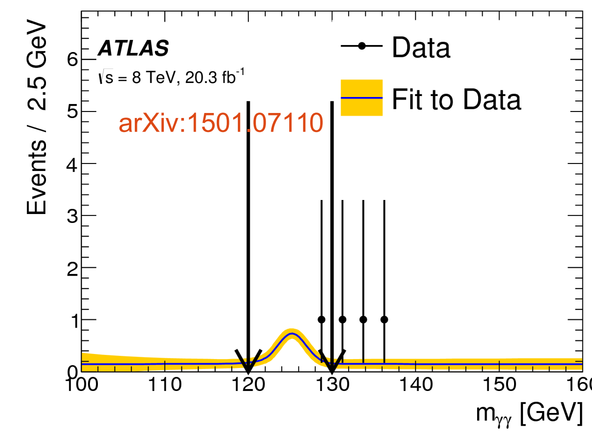
Search Strategy:

- 2 signal regions in $b\bar{b}$ using lepton-E_T^{miss} transverse mass and $m_{CT,b\bar{b}}$ to suppress W+jet and tt backgrounds
- 2 signal regions in $\gamma\gamma$ using W+γ transverse mass and $\Delta\phi(W,\gamma)$ to suppress SM Higgs production
- 6 same-sign lepton signal regions split by flavor and jet multiplicity
- Combine all signal regions for maximal sensitivity

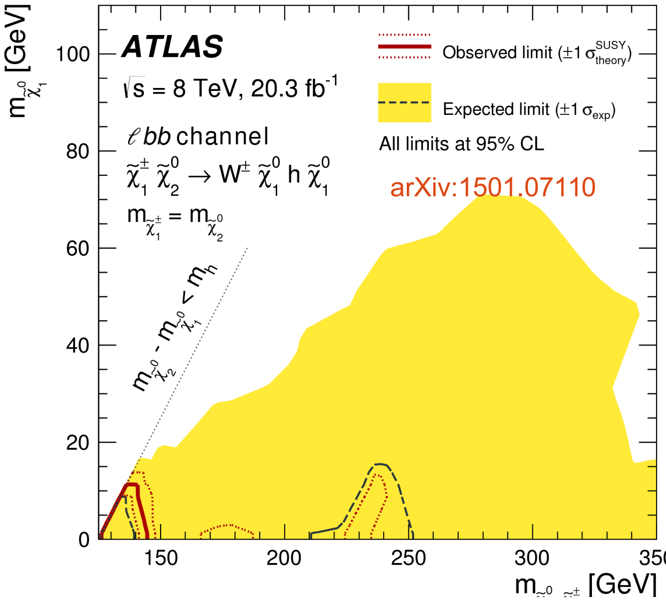
$m_{b\bar{b}}$ in $h \to b\bar{b}$ channel

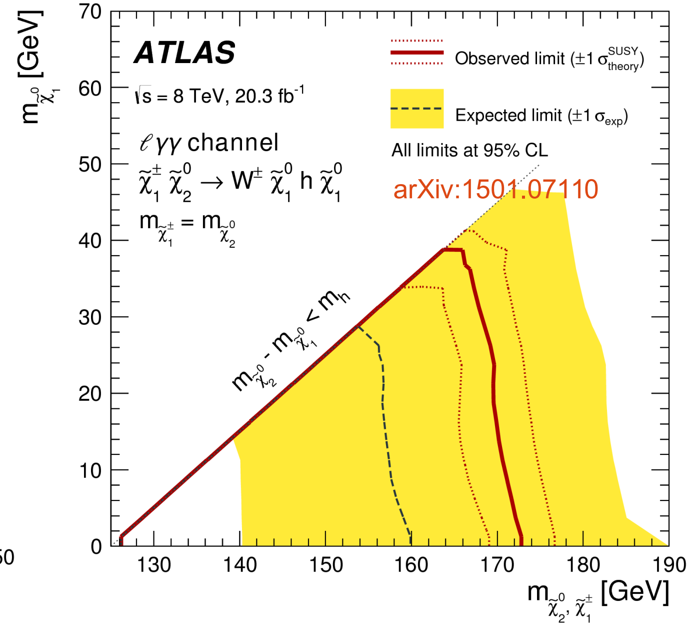


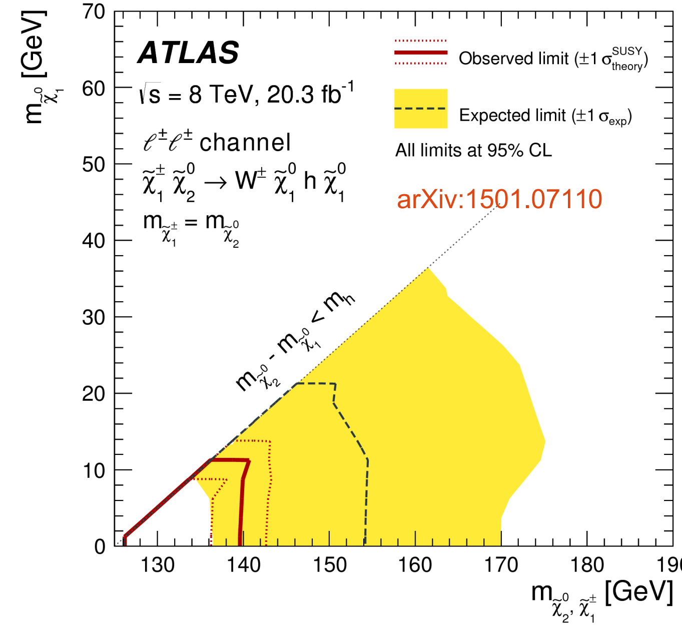
$m_{\gamma\gamma}$ in $h \to \gamma\gamma$ channel

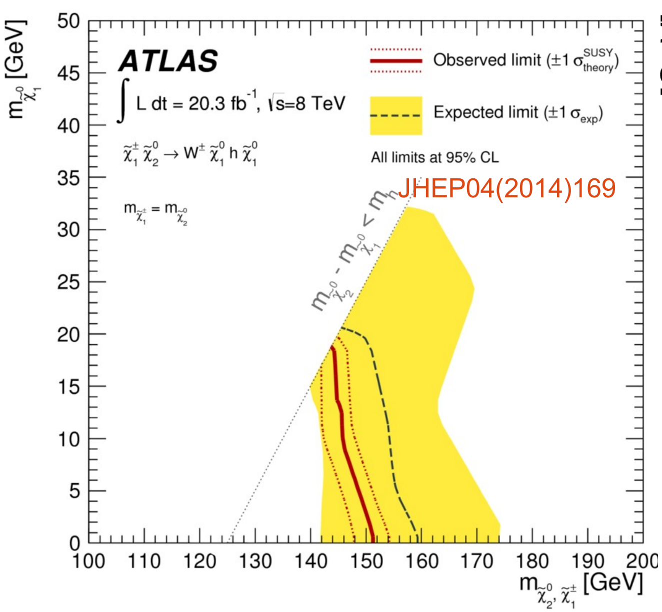


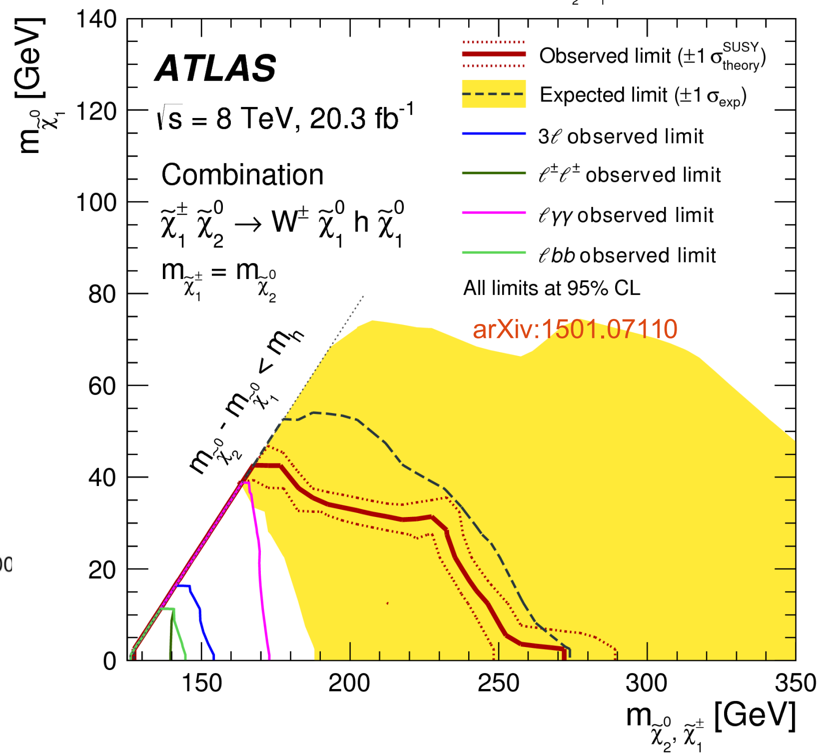
New Search for EW Prod. With Higgs Decay











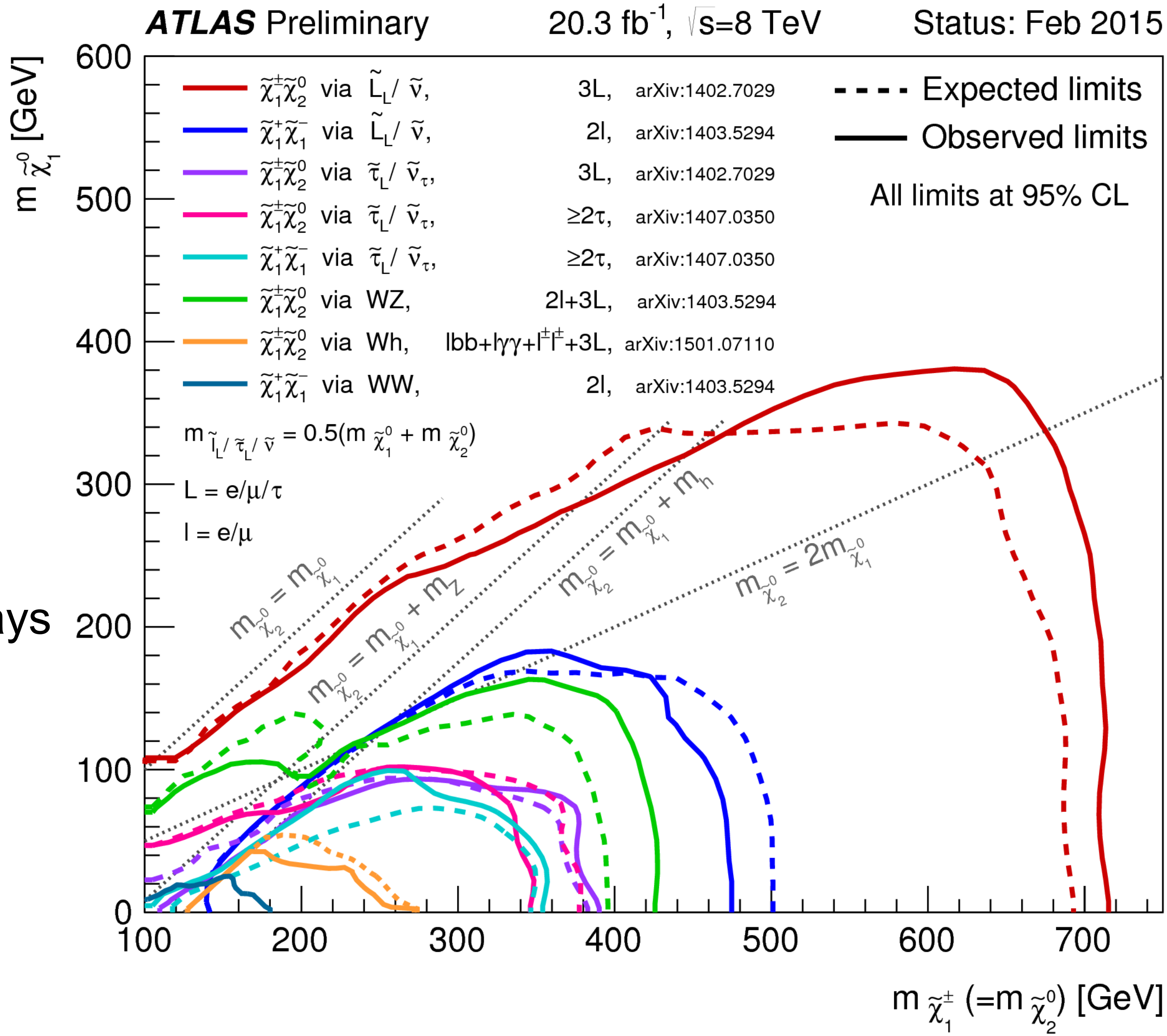
Combined Result

- Combine with older 3-lepton search
- Significant extension of search reach (up to 250 GeV)

Status of EW Production Searches

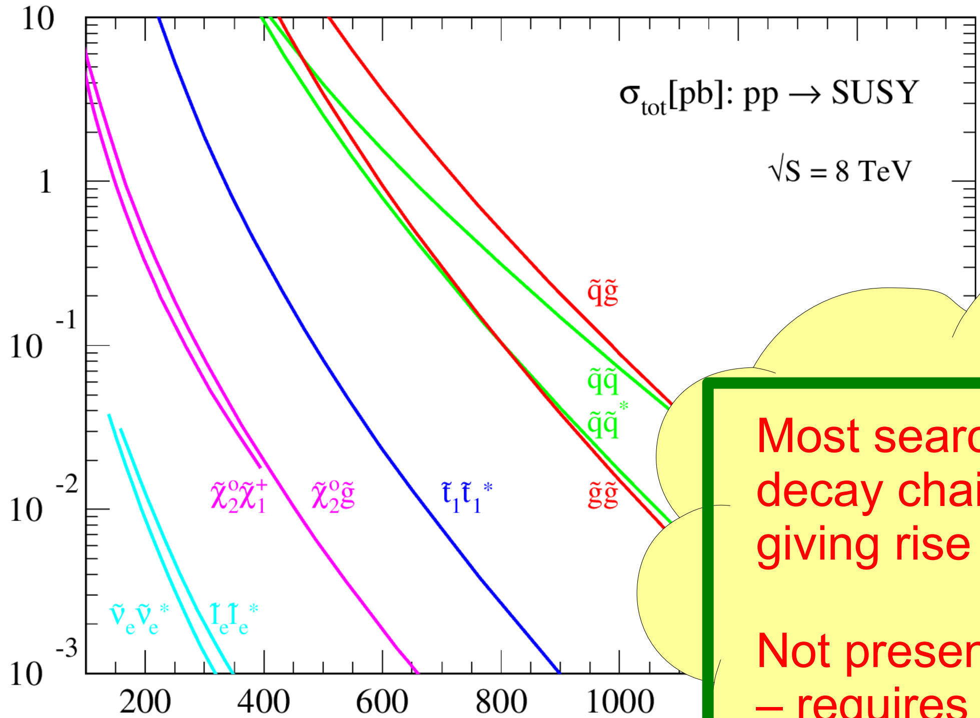
Rather strong limits in case of intermediate sleptons

Still relatively weak limits for direct chargino and neutralino decays



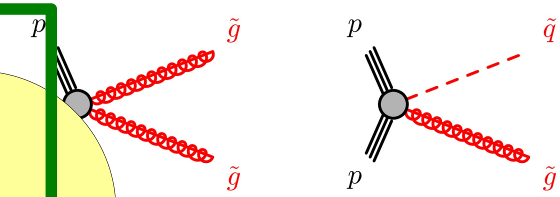
LHC SUSY Searches

At LHC can search for production for almost all SUSY particles, but with different sensitivity as production cross-sections vary



Production of squarks/gluinos:

- Strong coupling gives large sensitivity at the LHC
- Primary signature is ...s and missing energy



Most searches assume decay chain to stable LSP giving rise to missing energy

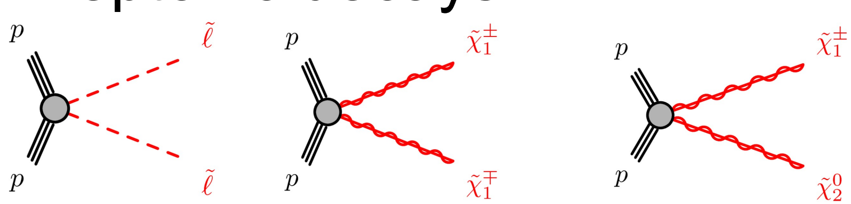
Not present in all SUSY models – requires dedicated searches to cover this

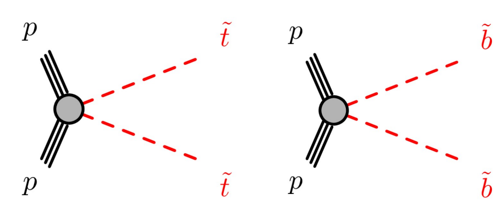
...eration squarks:

- ...ection,
- ...ins frequently has top and bottom quarks
- Of great interest to "Natural SUSY"

Electro-weak production...

- Slepton, neutralino and chargin...
- Detectable mostly through leptonic decays





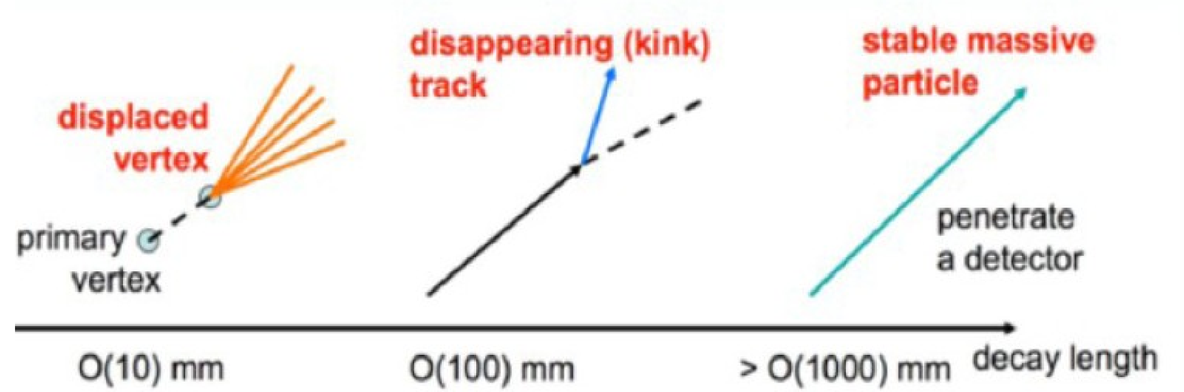
Long-lived SUSY Particles

Long-lived SUSY particles are predicted in wide variety of models: Hidden Sectors, RPV violating decays, Split SUSY, AMSB, GMSB,..

Possible Signatures

- Displaced vertices
- Disappearing tracks
- Non-pointing and delayed photons
- Stopped R-hadrons
- Stable massive particles

Observable signatures depend on lifetime



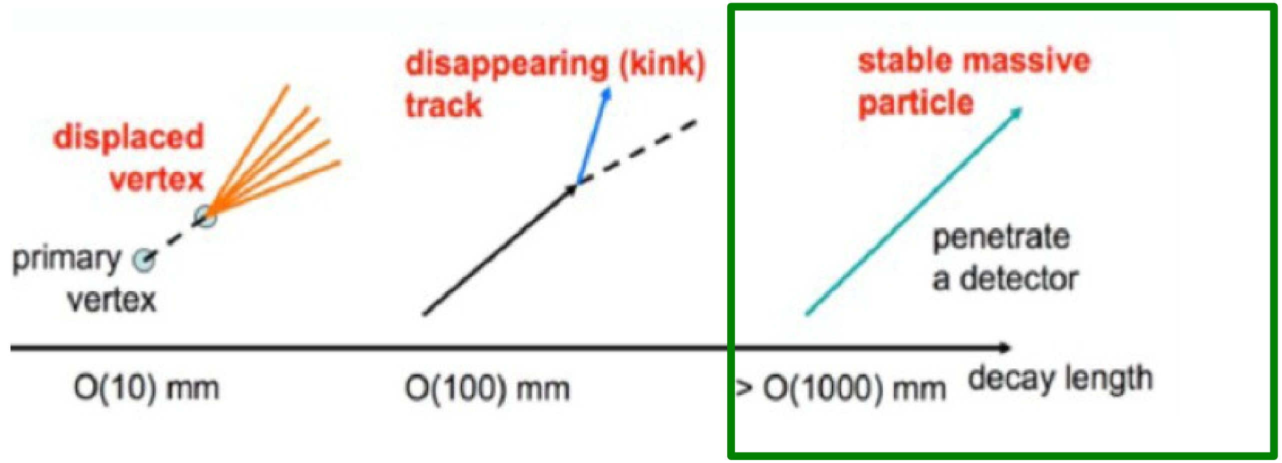
Long-lived SUSY Particles

Long-lived SUSY particles are predicted in wide variety of models: Hidden Sectors, RPV violating decays, Split SUSY, AMSB, GMSB,..

Possible Signatures

- Displaced vertices
- Disappearing tracks
- Non-pointing and delayed photons
- Stopped R-hadrons
- Stable massive particles

Observable signatures depend on lifetime



New

Stable Massive Particle Search

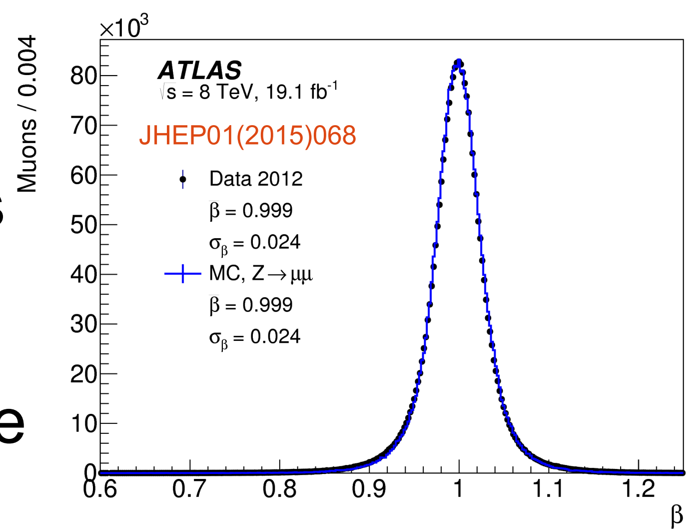
Massive charged particles leave several distinct signatures:

- Energy loss (βγ) measured by pixel detector
- Long time-of-flight measured by calorimeters and muon system
- With momentum measurement get mass estimate: m= p/(βγ)

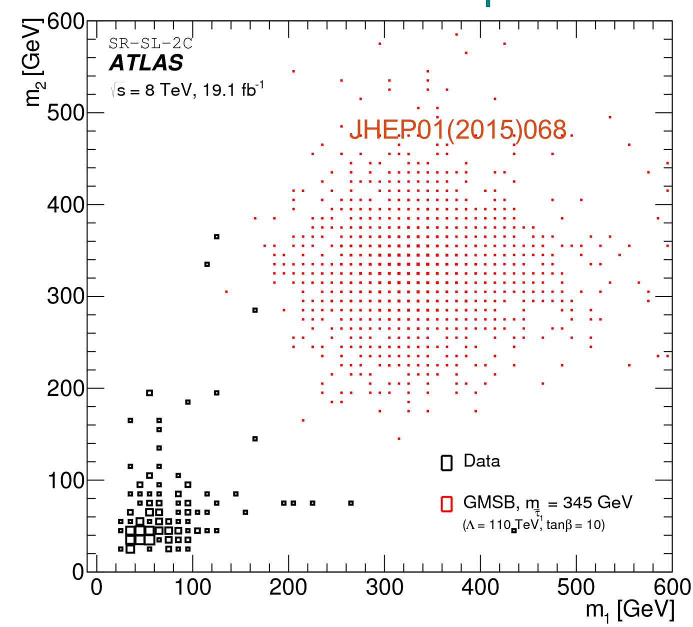
Search strategy:

- Reconstruct particles with $0.2 < \beta < 0.95$
- Determine mass from β measured in muon and calorimeters
- Confirm selection using pixel energy loss
- Either require two loose heavy particles or one tightly selected
- Optimize for different long-lived particle production scenarios

Combined β resolution

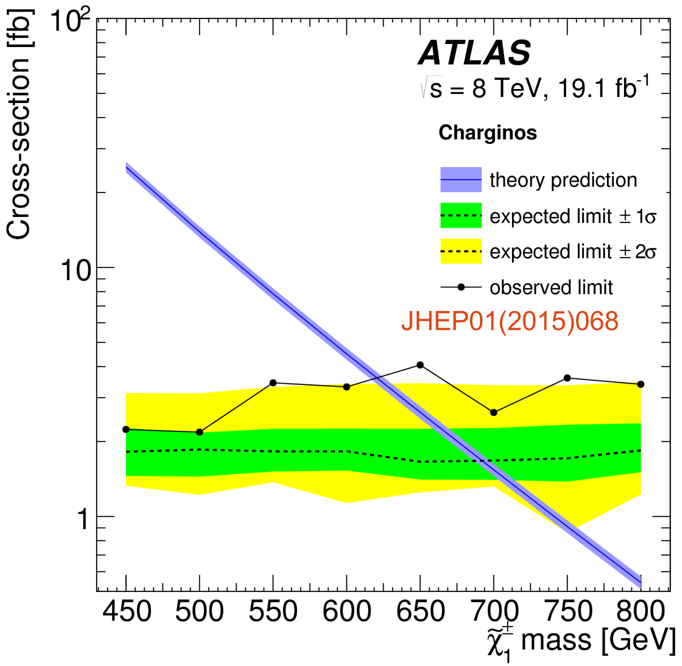


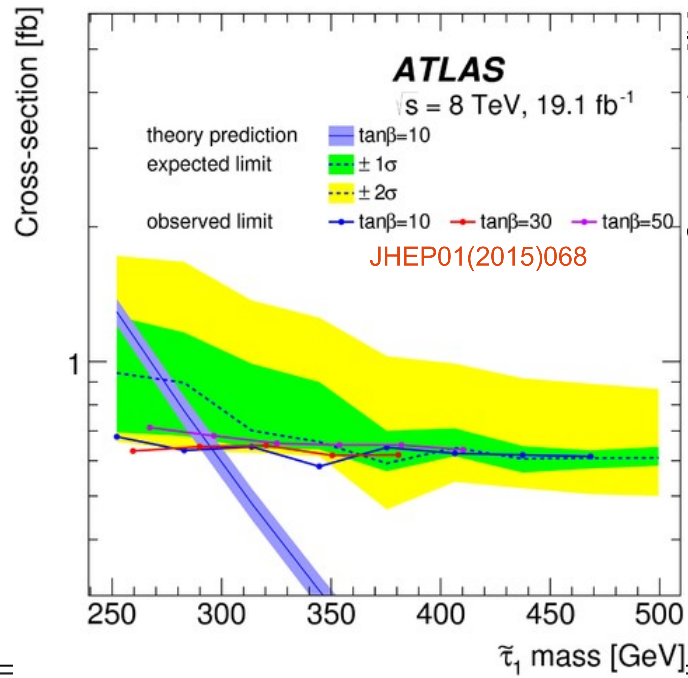
Reconstructed mass distributions for two particles

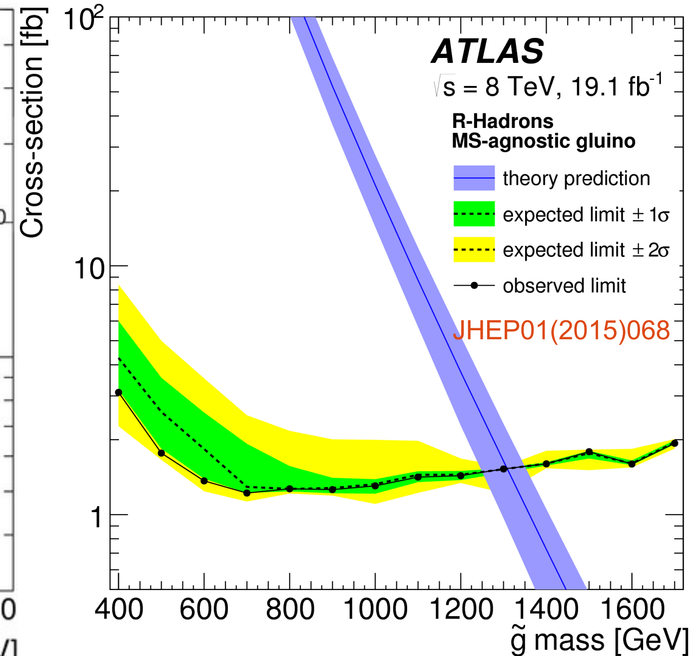


New Stable Massive Particle Search

Interpreted in many different models with long-lived particles







Often limits are stronger than in case of prompt decays

Search	Lower mass limit [GeV]
GMSB sleptons	
· $\tan\beta = 10, 20, 30, 40, 50$	440, 440, 430, 410, 385
· direct $\tilde{\ell}$ production ($m_{\tilde{\ell}} - m_{\tilde{\tau}_1} = 2.7$–$93$ GeV)	377–335
· direct $\tilde{\tau}_1$ production	289
· $\tilde{\chi}_1^0 \tilde{\chi}_1^{\pm}$ decaying to stable $\tilde{\tau}_1$	537
LeptoSUSY	
· $\tilde{q}, \tilde{g}$	1500, 1360
Charginos	
· $\tilde{\chi}_1^{\pm}$	620
R-hadrons	
· $\tilde{g}, \tilde{b}, \tilde{t}$ (full-detector)	1270, 845 and 900
· $\tilde{g}, \tilde{b}, \tilde{t}$ (MS-agnostic)	1260, 835 and 870

ATLAS SUSY Searches* - 95% CL Lower Limits

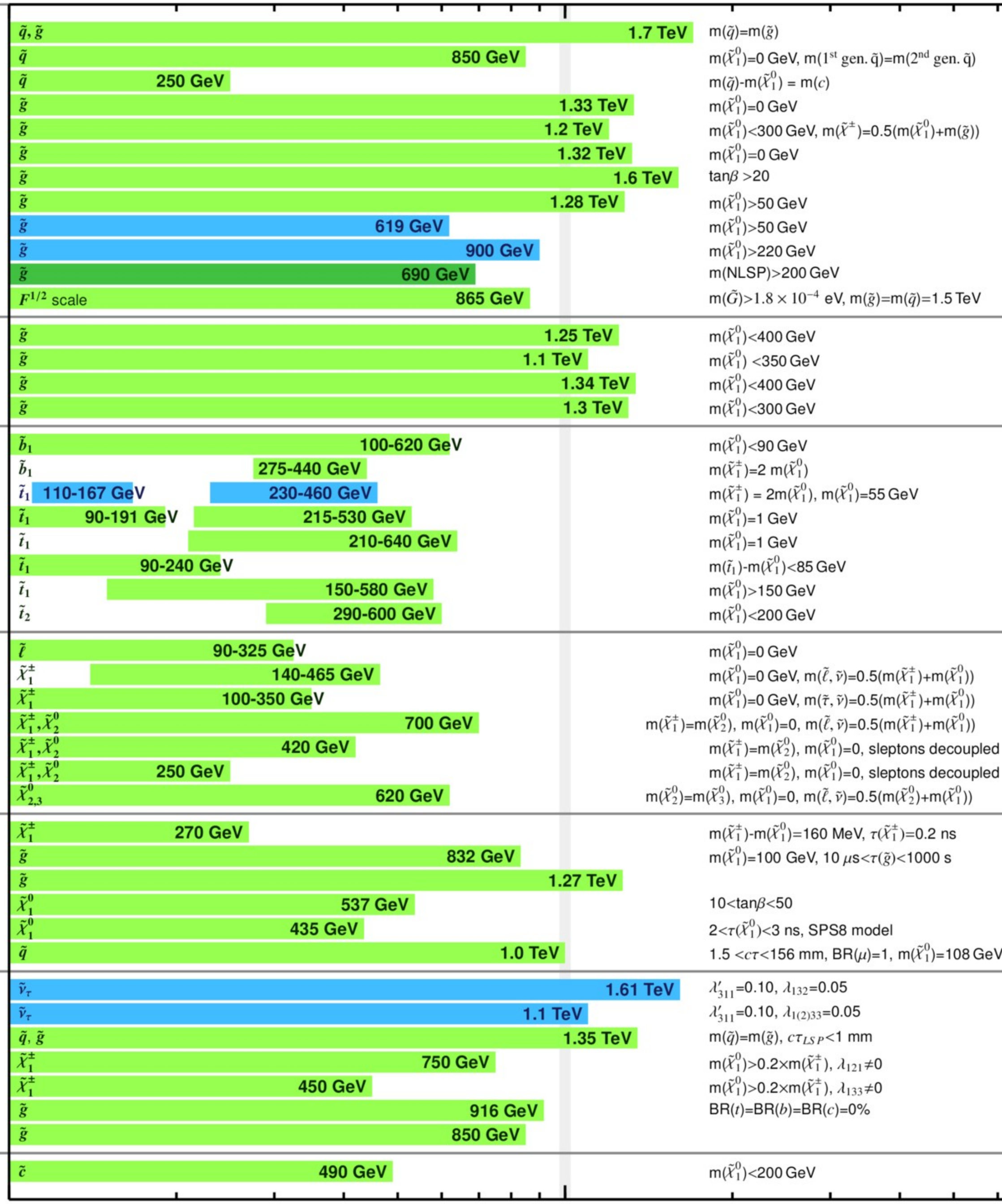
Status: Feb 2015

Full List of Results

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

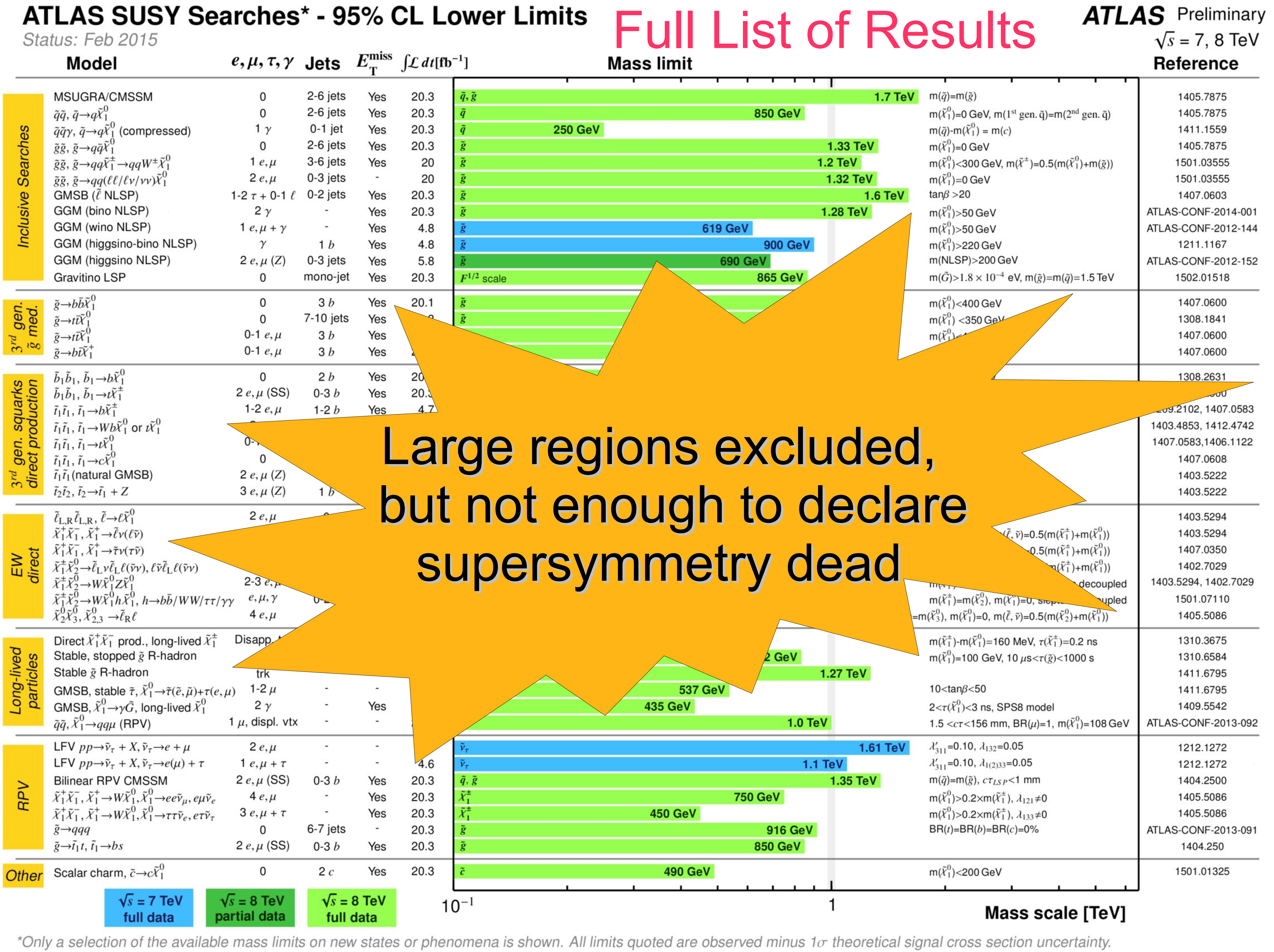
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$ = m(c)	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV; 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV; 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325



$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

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

Full List of Results

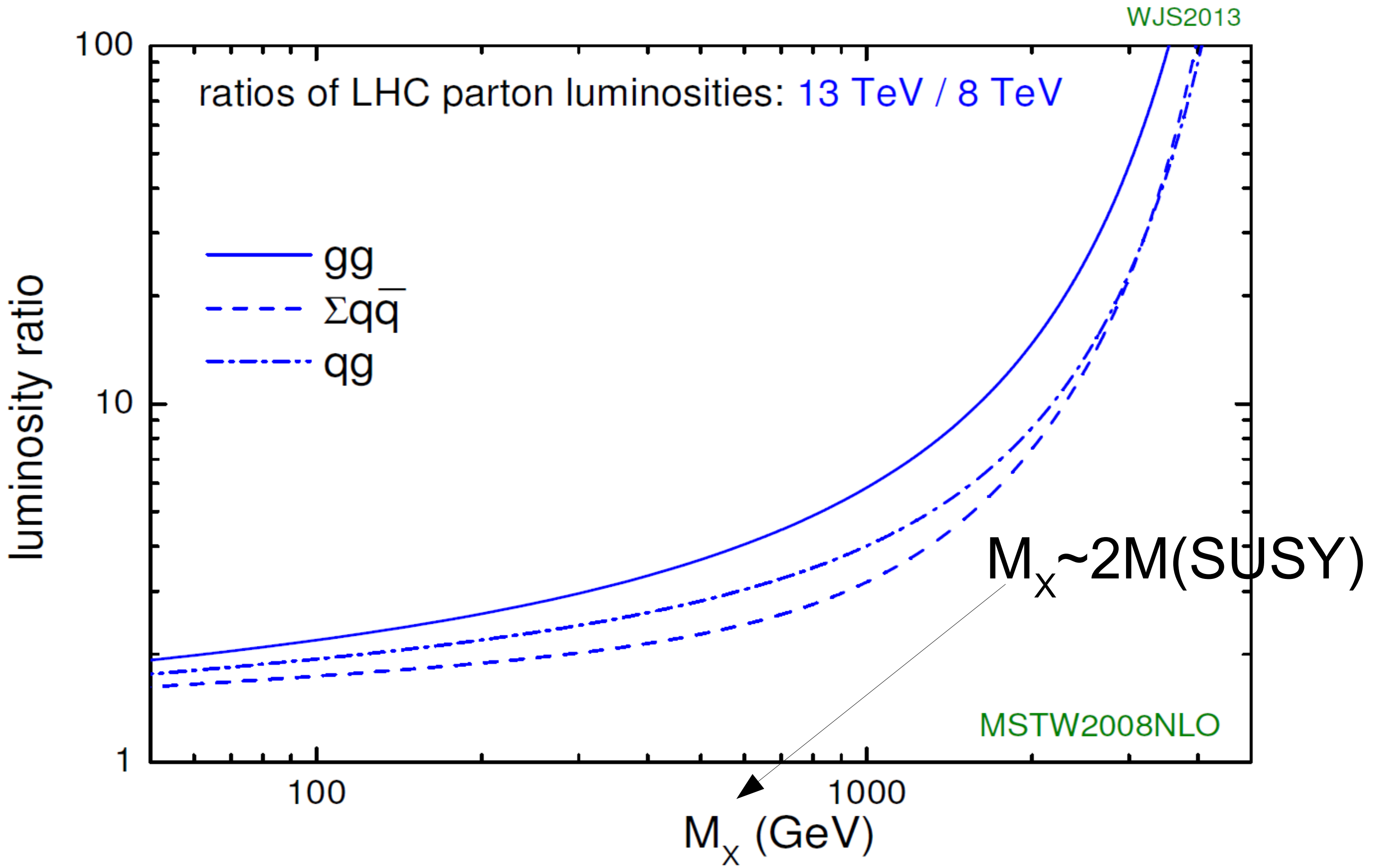


Outlook for Supersymmetry Searches at the LHC

Future LHC Running

Two major improvements coming at the LHC

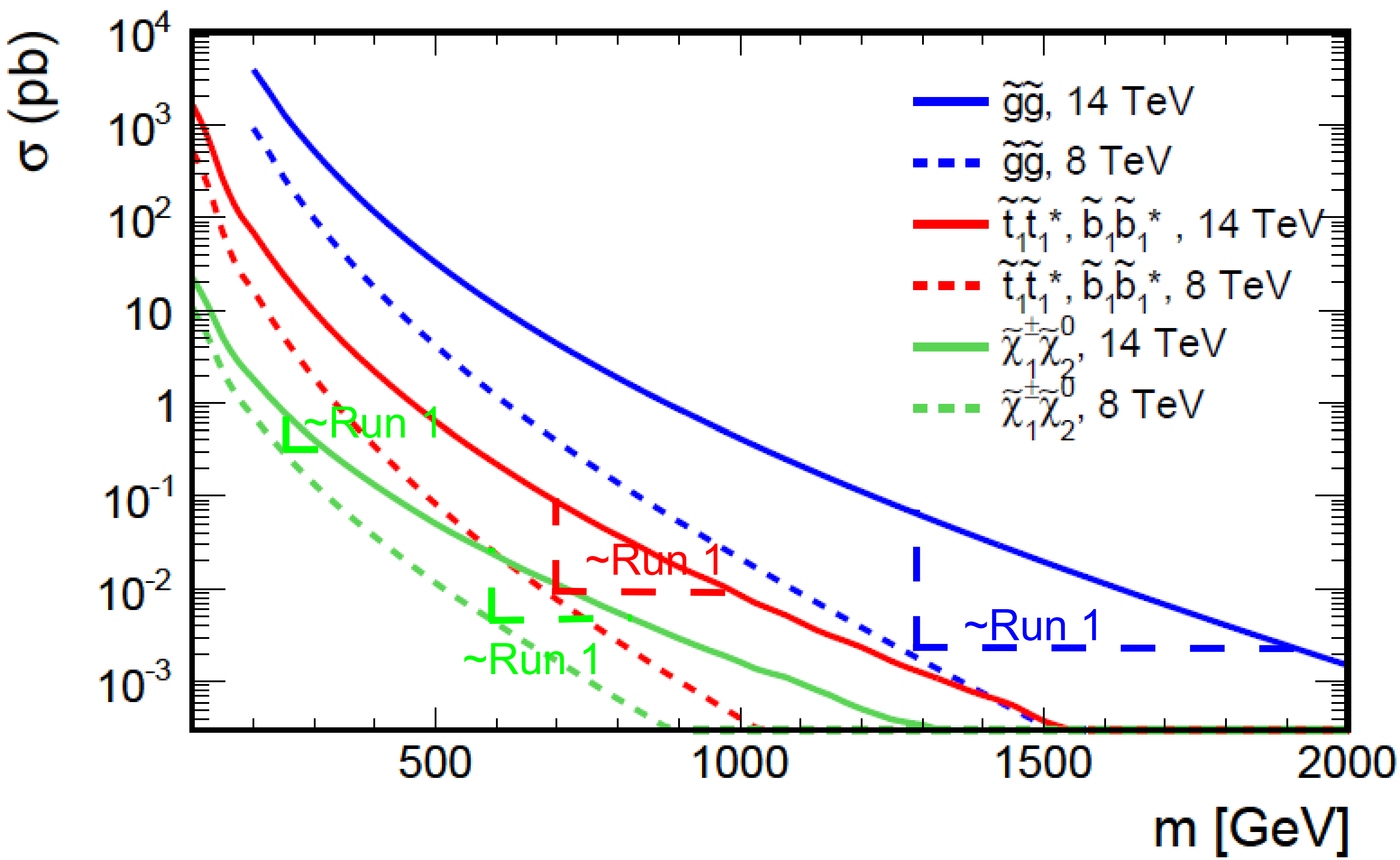
- Increase of collision energy from 8 TeV to 13 TeV this year
  Will eventually increase towards 14 TeV
- Increase in integrated luminosity by O(100) over next ~20 years



Collision Energy Increase

Immediate impact of higher collision energy

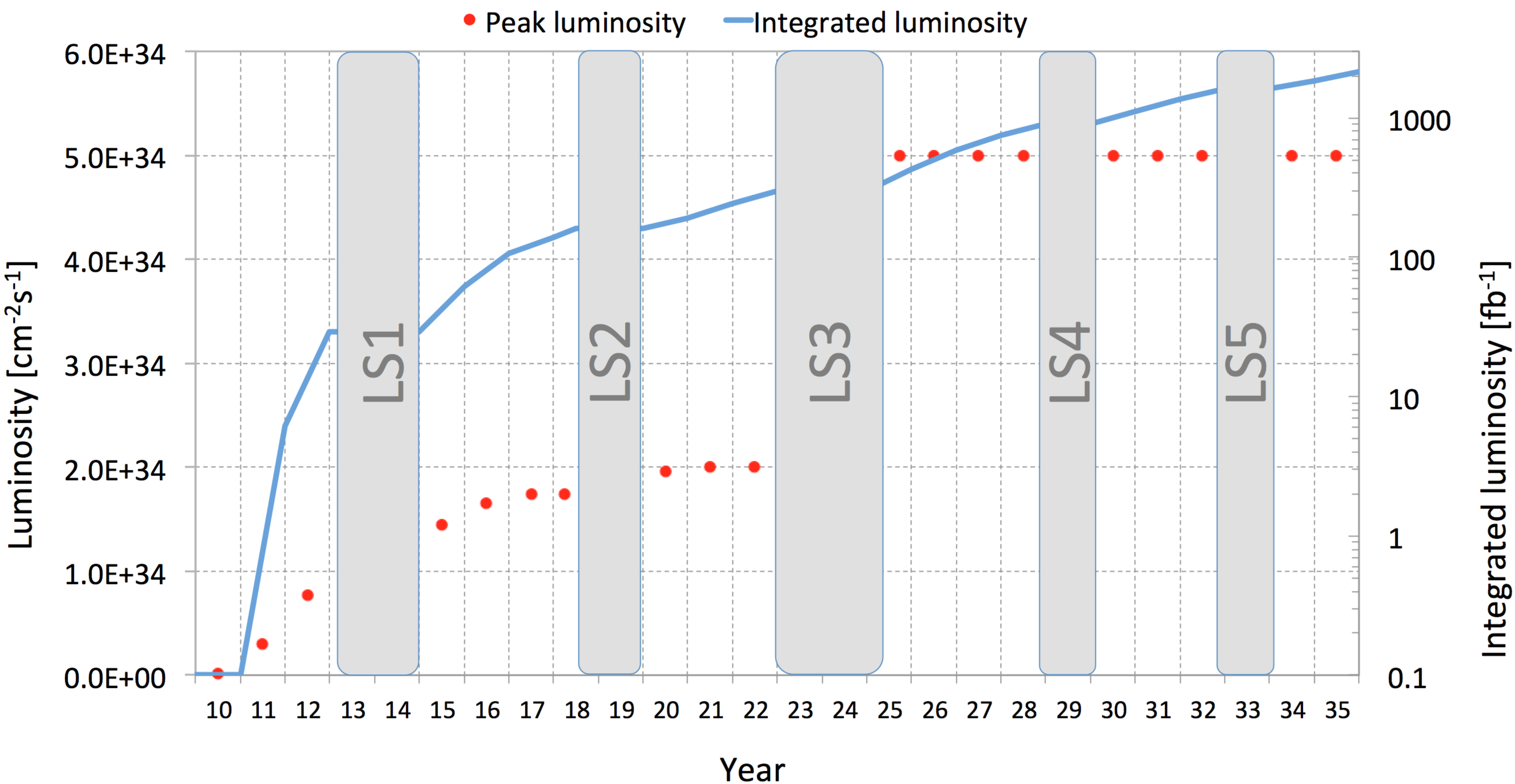
- O(50) increase in cross section for heavy gluinos
- O(10) increase in cross section for heavy stop
- Around factor two increase for EW production cross sections
- SM physics backgrounds also increase by factor 2-4



Luminosity Evolution

Expectations for the LHC

- ~10 fb^{-1} at 13 TeV by end of this year
- ~300 fb^{-1} at 13-14 TeV by 2022
- ~3000 fb^{-1} by 2035



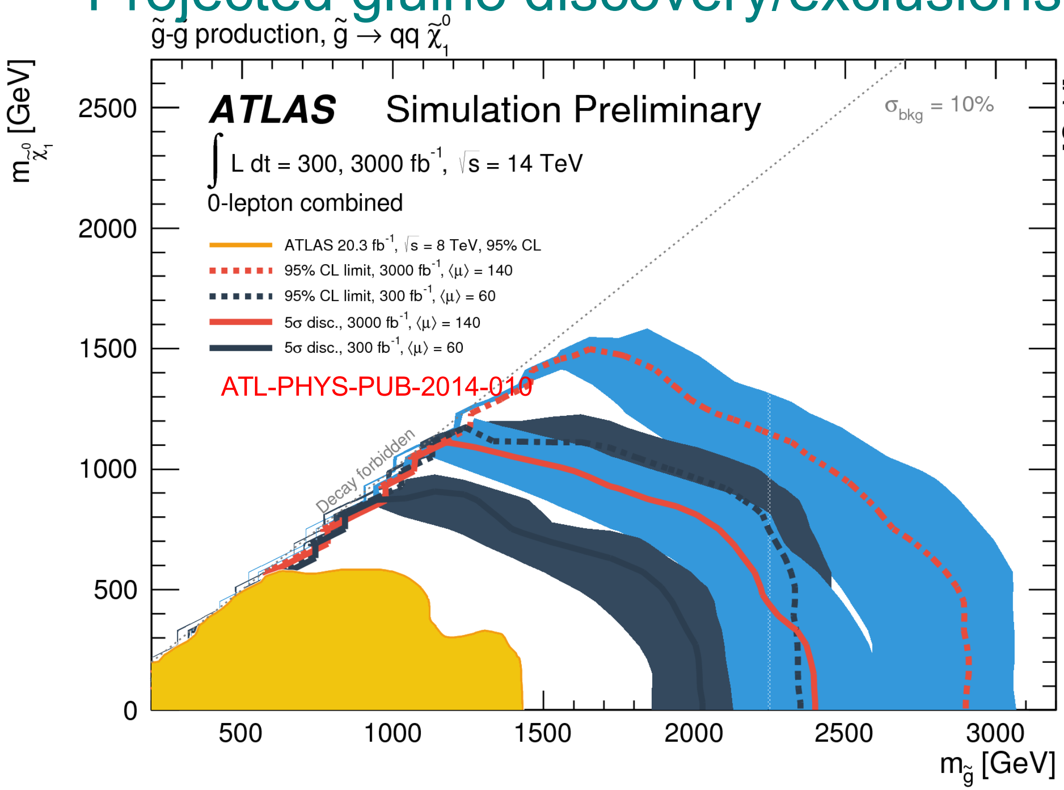
Projections for SUSY Searches

Unfortunately, no public projection for 2015 sensitivity

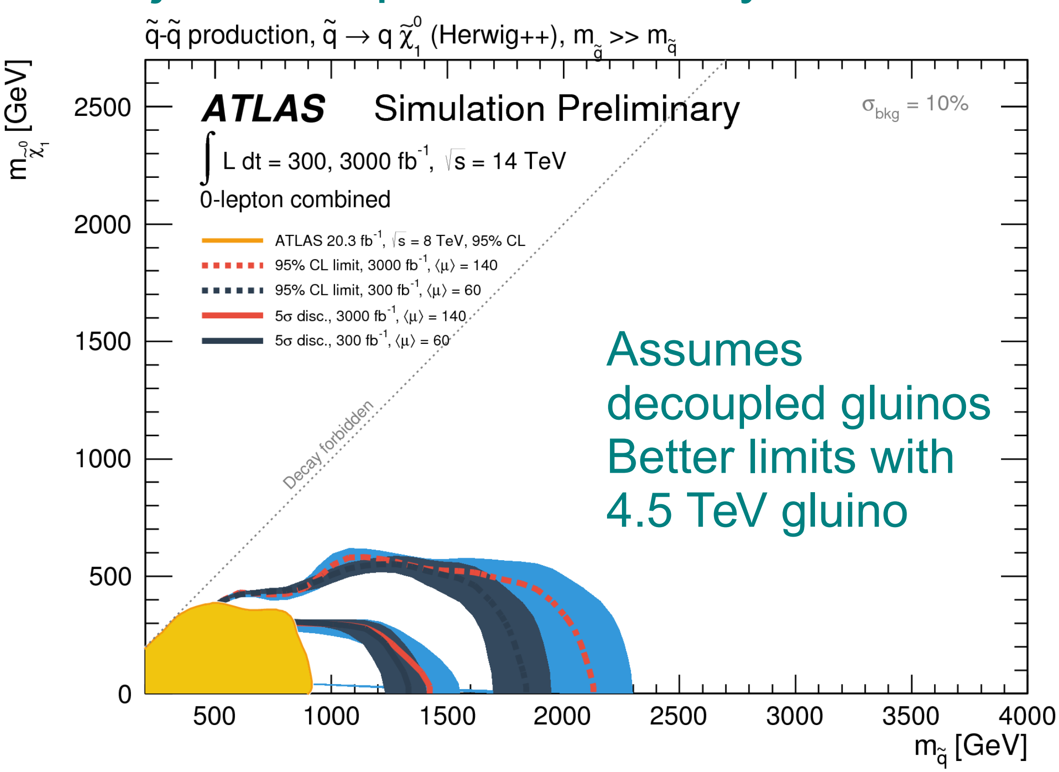
Longer-term sensitivity studied in good detail

- Main backgrounds simulated using parameterized detector response
- Squarks and gluino searches will reach into multi-TeV space
- If no gluinos found by end of LHC, Natural SUSY disfavored
- Already in 2015, expect that just a few fb^{-1} enough to exceed 2012 exclusions levels, particularly for heavy gluinos

Projected gluino discovery/exclusions



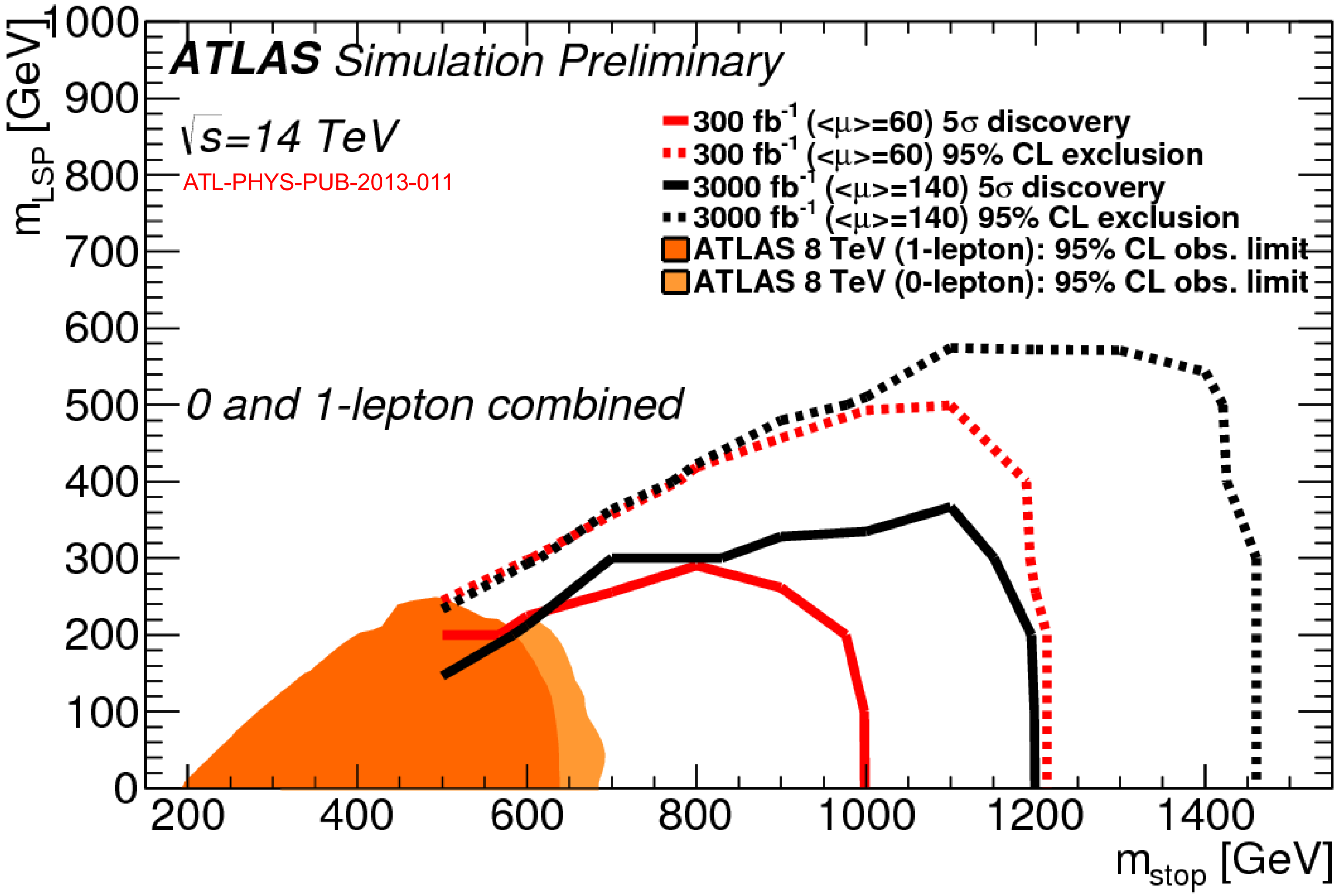
Projected squark discovery/exclusions



3^{rd} Generation Squark Searches

Similar studies done for stop and sbottom production

- Expect to discover stop/sbottom up to 1 TeV with 300 fb^{-1}
- Sensitivity up to almost 1.5 TeV with complete dataset in the favorable decay mode $t \to t\tilde{\chi}_1^0$
- For 2015 will need >5fb^{-1} to excess 2012 high mass limit

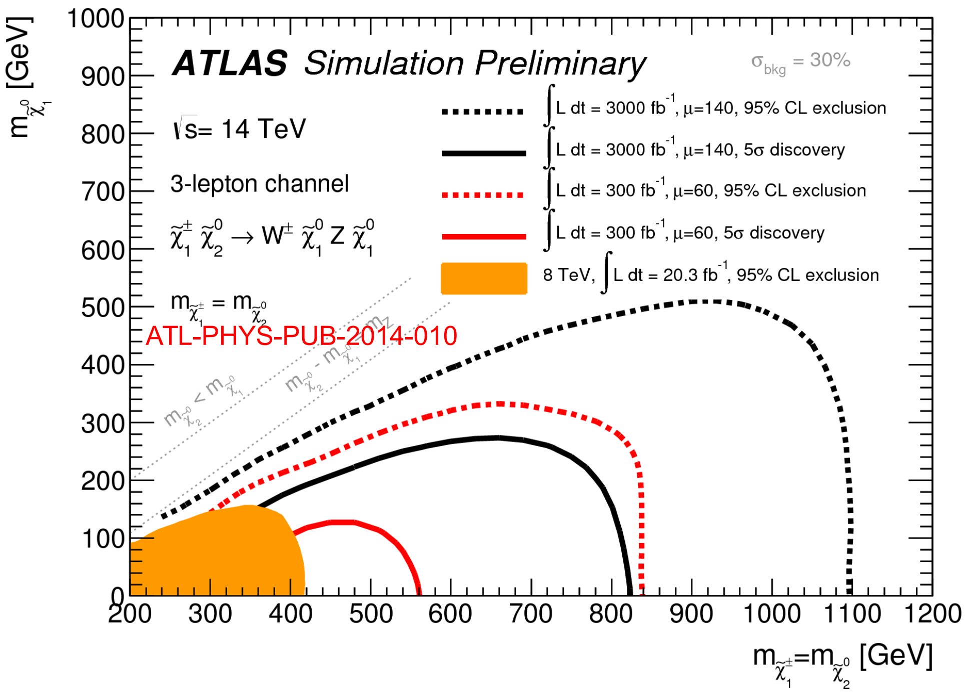


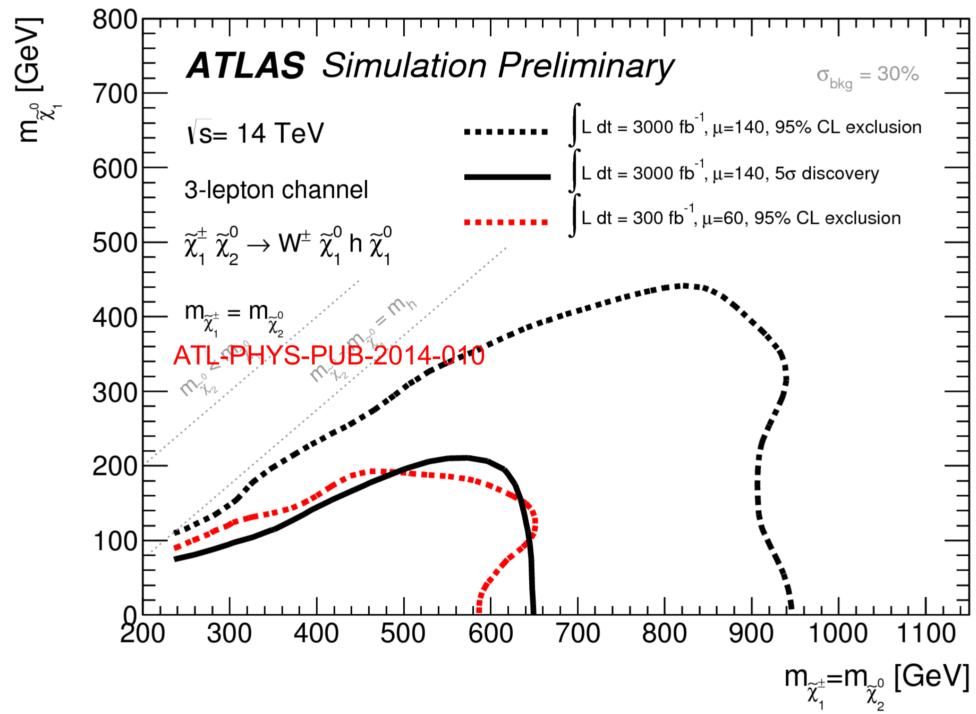
Chargino/Neutralino Searches

Searches for EW production sees little gain from energy increase
Large luminosity needed to really push sensitivity

High luminosity projections for direct chargino/neutralino decays

- Use 3-lepton channel as very low background (primarily WZ)
- Even with 300 fb^{-1} not much possibility of 5σ discovery
- With 3000 fb^{-1}, will approach 1 TeV for exclusion sensitivity, 650-800 TeV discover with a light LSP



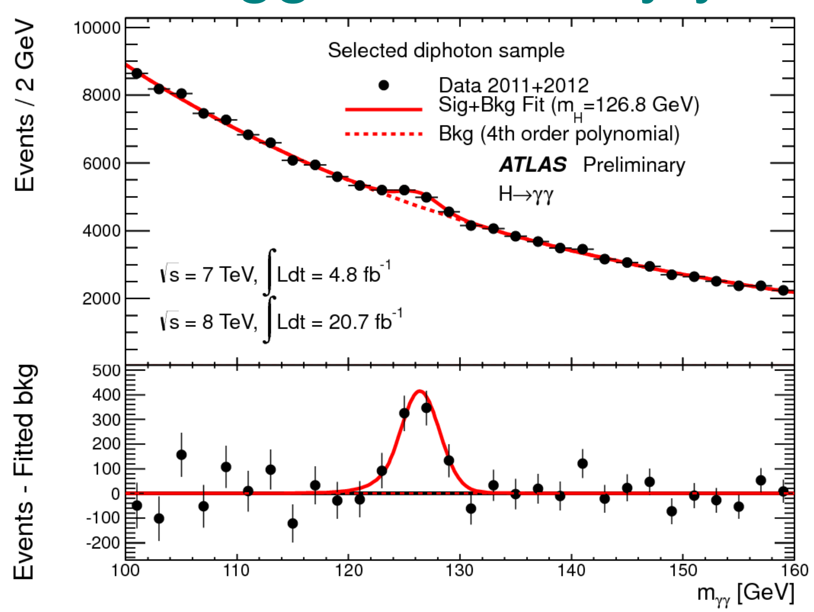


Summary

Summary

- Extensive search for SUSY at the LHC in Run-1
- Provide comprehensive coverage of SUSY detectable with current LHC luminosity and energy
- No significant signals seen, excluding a big chunk of SUSY with sparticles below 1 TeV
  - do have one signal region at 3σ significance
- Even greater sensitivity in upcoming LHC run(s)

2012: Higgs Discovery year



2015: SUSY Discovery year?

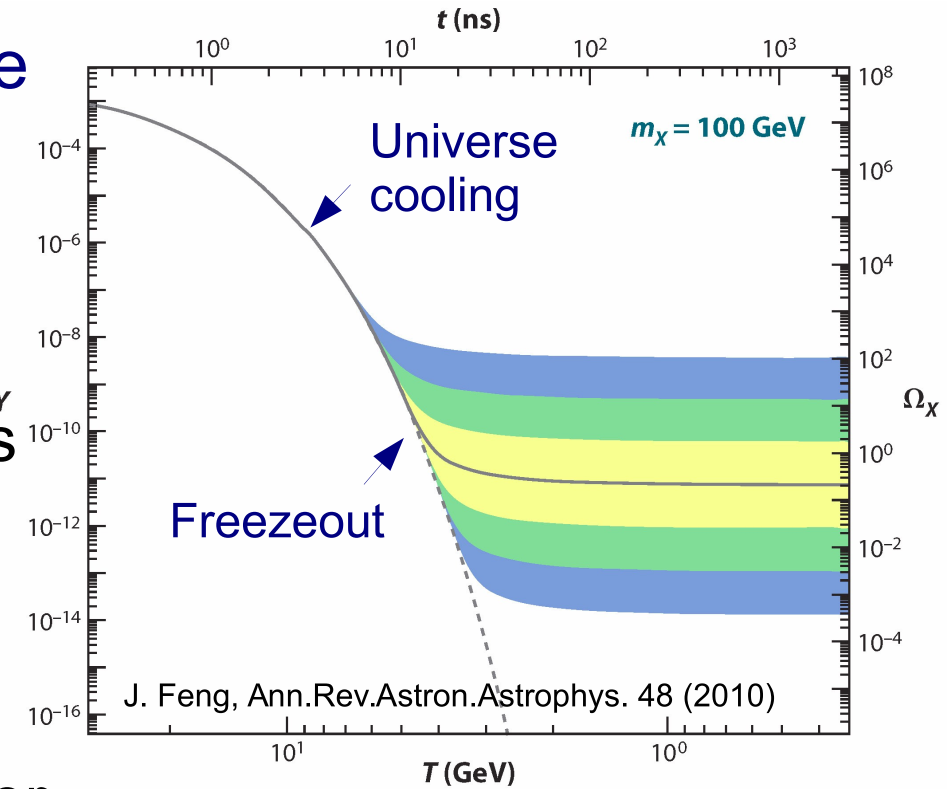
Backup

"WIMP Miracle"

A new, weakly-interacting massive particle (WIMP) is an excellent dark matter candidate

- Assume initial thermal equilibrium
  X X ↔ SM SM
- Density will drop as universe cools
  X X → SM SM
- Annihilation stops as universe expands
  X X ↛ SM SM

  Leaving relic density as dark matter



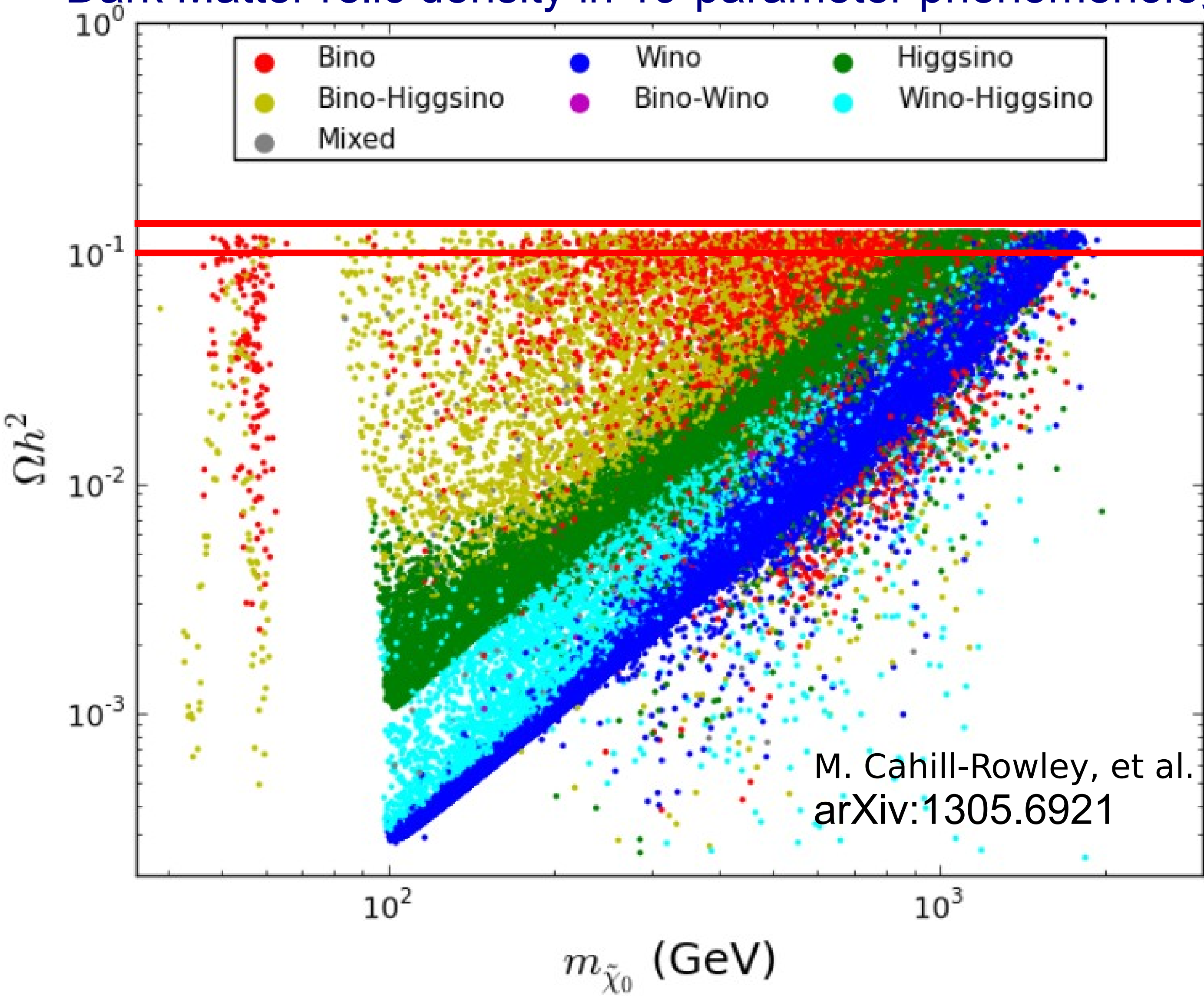
If m_X~100 GeV and has weak-scale interaction, the thermal relic density $\Omega_X \sim \Omega_{DM}$

Supersymmetry provides a natural WIMP in the lightest supersymmetric particle

Supersymmetry and Dark Matter

LSP mass strongly dependent on SUSY model, but should normally be 100 GeV to 2 TeV to match Dark Matter observation

Dark Matter relic density in 19-parameter phenomenological MSSM

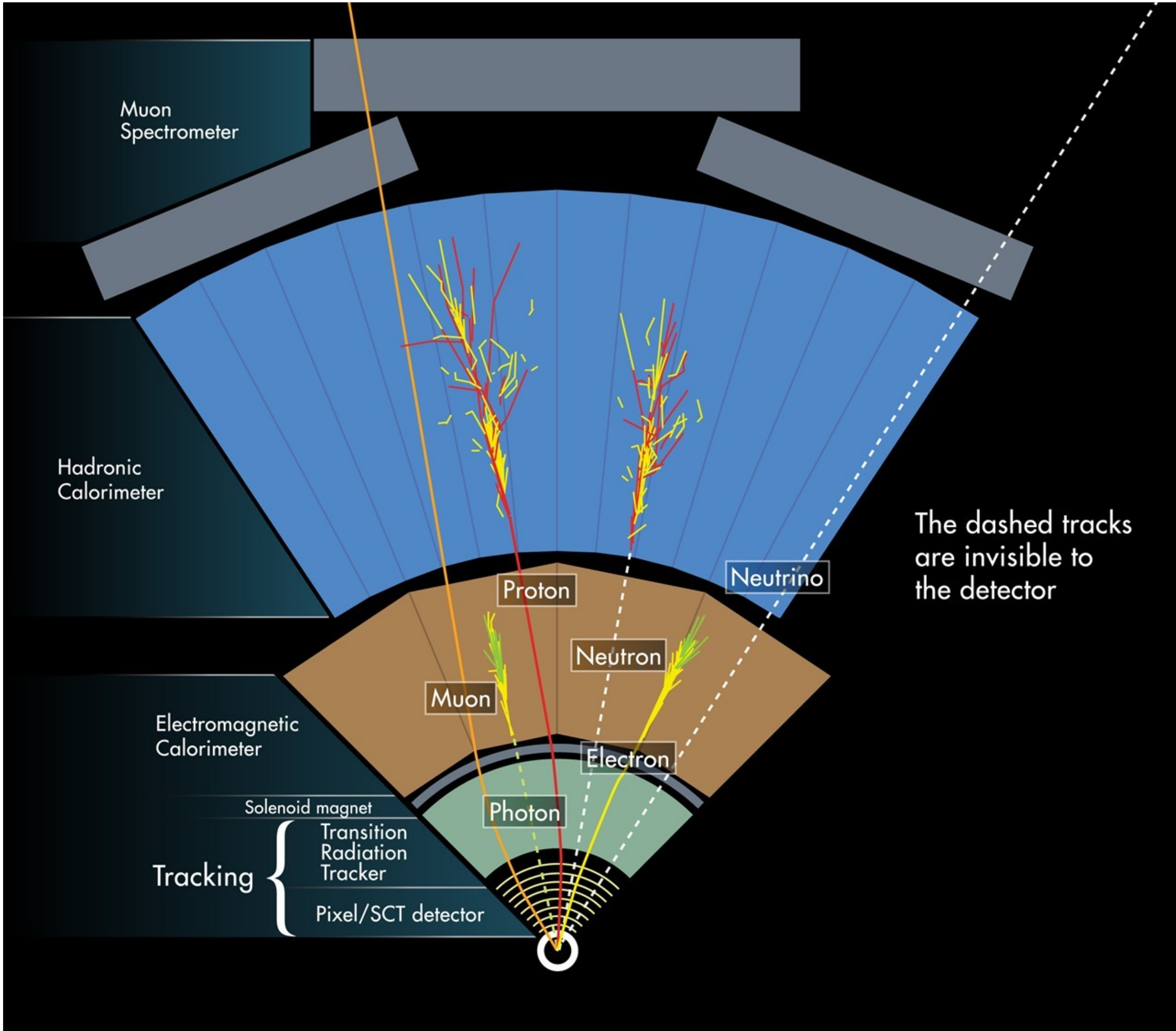


Observed Dark Matter density

All 19 pMSSM model parameters are varied randomly and each model subjected to indirect constraints

Particle Reconstruction and Identification

Schematic view of ATLAS detector



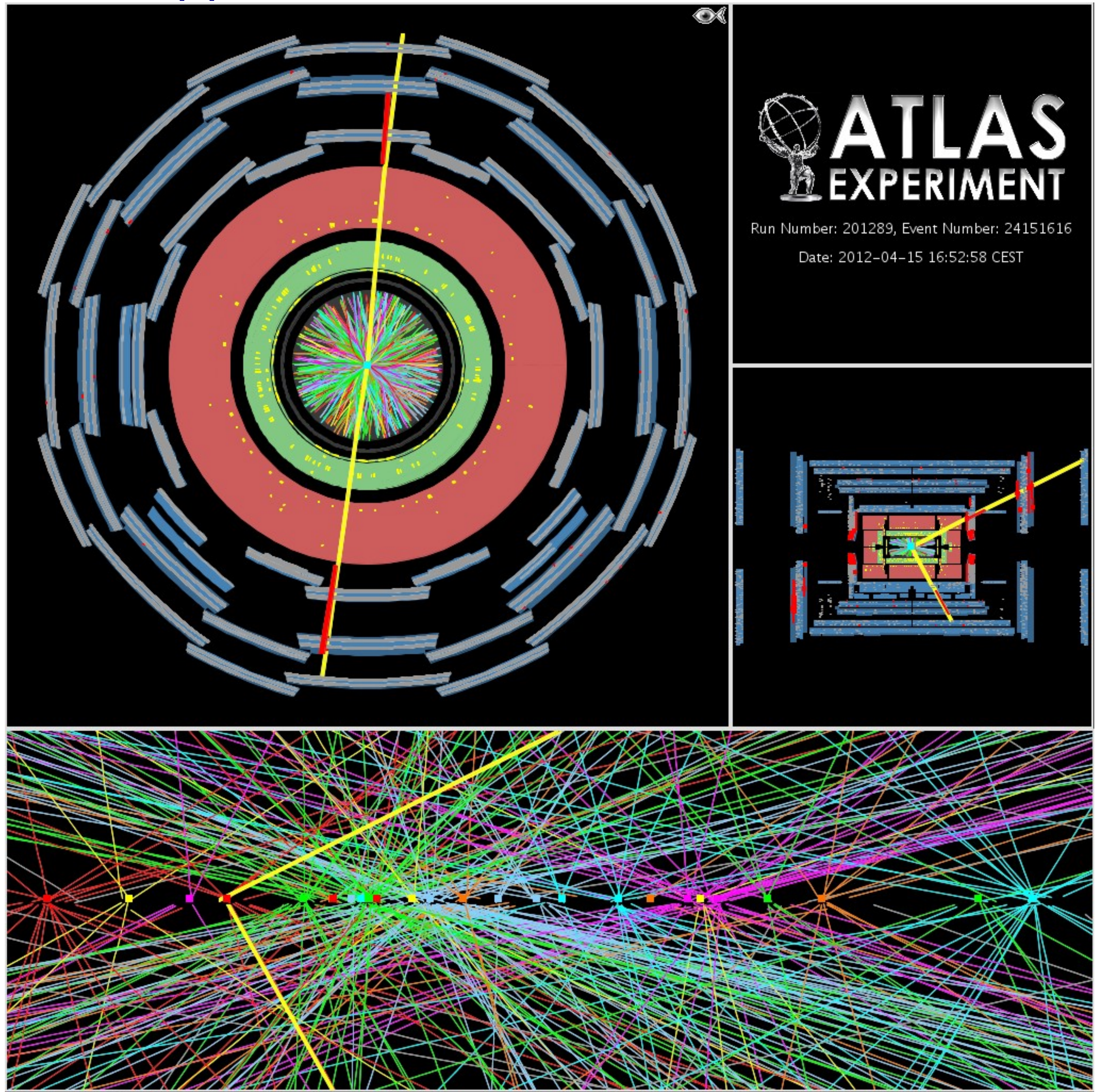
Hermetic Detector

Almost all particles fully reconstructed and identified in one or more sub-detectors

Only weakly-interacting particles pass through undetected

Pileup

Z → μμ event with 25 reconstructed vertices



High luminosity at a cost

Record luminosity achieved by having 20-40 interactions per beam crossing every 50 ns

Design was peak of 23 interaction per 25 ns

Results in degraded performance, but mostly compensated by use of smarter selection algorithms

Inclusive 0-lepton Signal Regions

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

Requirement	Signal Region								
	4jl-	4jl	4jm	4jt	5j	6jl	6jm	6jt	6jt+
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] >	160								
$p_{\mathrm{T}}(j_1)$ [GeV] >	130								
$p_{\mathrm{T}}(j_2)$ [GeV] >	60								
$p_{\mathrm{T}}(j_3)$ [GeV] >	60								
$p_{\mathrm{T}}(j_4)$ [GeV] >	60								
$p_{\mathrm{T}}(j_5)$ [GeV] >	–				60				
$p_{\mathrm{T}}(j_6)$ [GeV] >	–					60			
$\Delta\phi(\mathrm{jet}_{1,2,(3)}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ >	0.4								
$\Delta\phi(\mathrm{jet}_{i>3}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ >	0.2								
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] >	10		–						
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(N_{\mathrm{j}})$ >	–		0.4	0.25	0.2			0.25	0.15
m_{eff}(incl.) [GeV] >	700	1000	1300	2200	1200	900	1200	1500	1700

Top polarisation and Spin Correlations

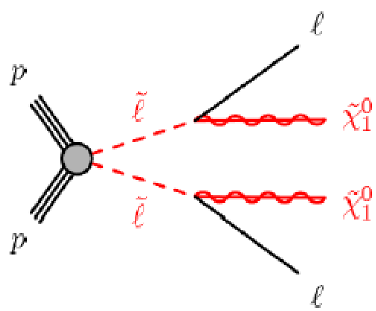
- Top quark lifetime of ~3 10^{-25} sec is much shorter than hadronisation time
  - Top decays as a bare quark, and does not form hadrons
  - Top spin info is not 'corrupted' by QCD interactions, transferred to decay products
- Angular decay distribution: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos(\theta_i)} = (1 + \alpha_i \mathbf{P}\cos(\theta_i))/2$
  - θ_i angle between top decay product i and top polarisation P along chosen axis
  - α_i is spin analysing power: $\sim\pm1$ for charged leptons, -0.966 / -0.393 for d / b quark
  - Normally use helicity basis, chose quantisation axis as top quark momentum direction in tT rest frame
- Negligible polarisation in SM, but spins of t and T are correlated

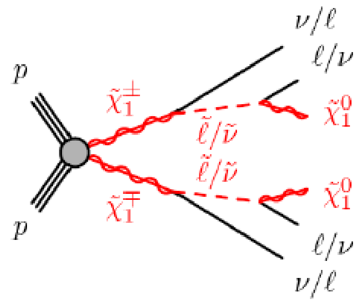
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos(\theta_+)\,d\cos(\theta_-)} = \frac{1}{4}(1 + A\,\alpha_+\alpha_-\cos(\theta_+)\cos(\theta_-)) \qquad A = \frac{N_{\mathrm{like}} - N_{\mathrm{unlike}}}{N_{\mathrm{like}} + N_{\mathrm{unlike}}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow}$$

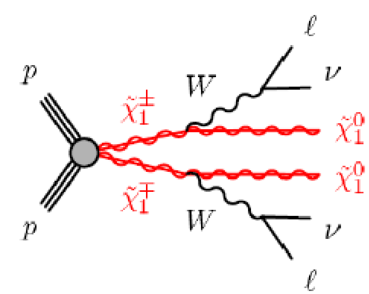
- Can be measured from dilepton $\Delta\phi_{ll}$, or observables involving $\cos\theta_i$
  - $\Delta\phi_{ll}$ is straightforward to measure precisely
  - $\cos\theta_i$ requires full event reconstruction (dilepton or l+jets events)

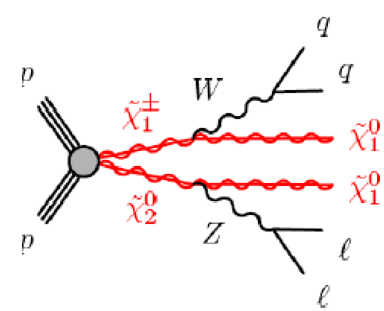
2-lepton EW Search

Direct slepton pair	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via slepton/sneutrino	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$via WZ





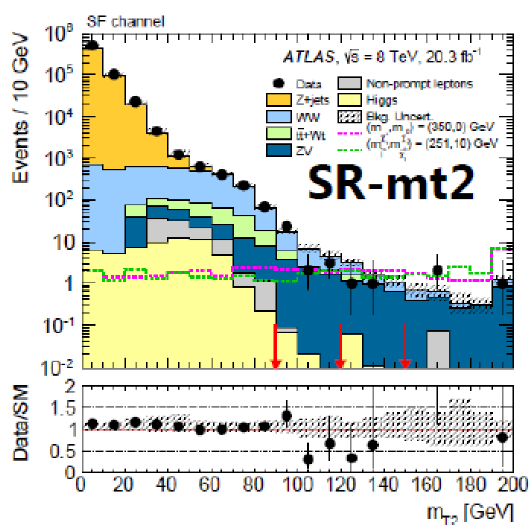


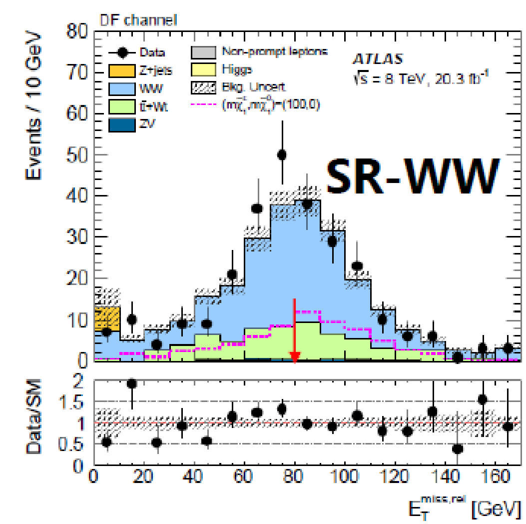


* $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{0}$ (pure wino, mass degenerate);
$\tilde{\chi}_1^{0}$(pure bino)

[SR-mt2] 3SRs: slepton mediated	[SR-WW] 3SRs: WW mediated	[SR-WZ] 1SRs:WZ mediated

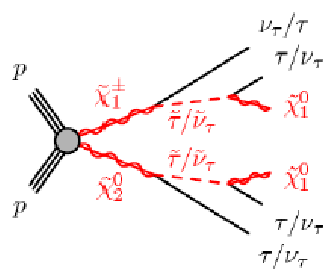
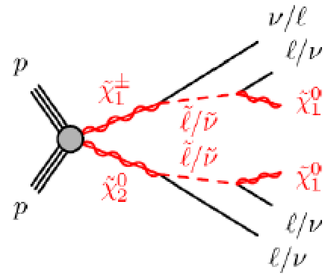
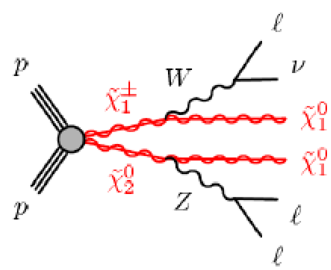
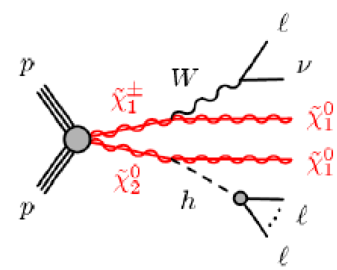
- 7 SRs designed targeting different models.
  - The same flavor and different flavor are considered separately in each SR.
- Main backgrounds: top-quark(ttbar and Wt) and dibosons.
  - For SM ttbar and WW: mt2 has an upper end-point at the W mass.





3 lepton (e/μ/τ) EW Search

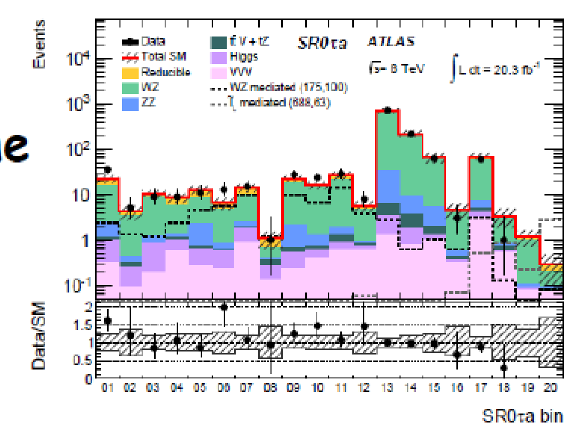
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via stau/sneutrino	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via slepton/sneutrino	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WH

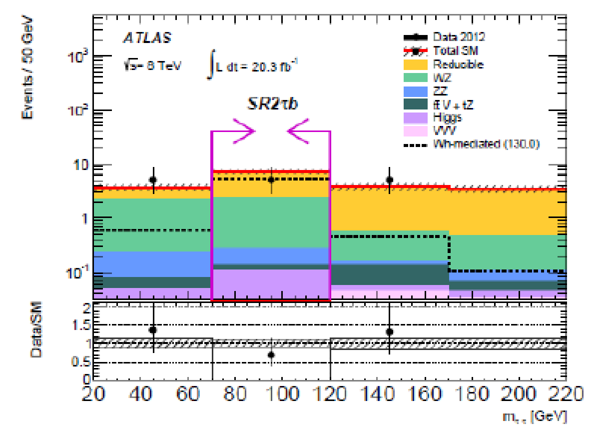





* $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ (pure wino, mass degenerate); $\tilde{\chi}_1^0$(pure bino)

1 SR: 2 taus + light lepton	1 SR: 0 tau + light leptons *characterized by 20 independent bins*	3 SRs: 0,1,2 taus + light leptons

- Analysis includes up to 2 hadronic taus.
- 5 SRs are defined according to the flavor and charge of the leptons, targeting different models.
- Main backgrounds: diboson, triboson, ttbarV, tZ and VH.

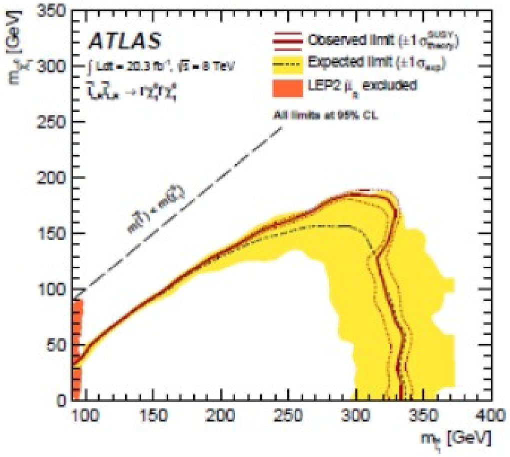




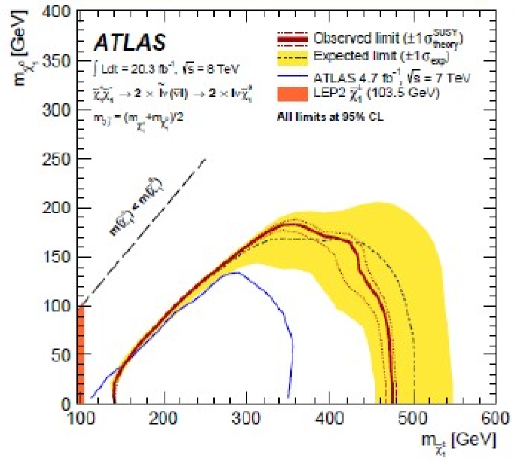
2/3 Lepton Results

2-lepton searches

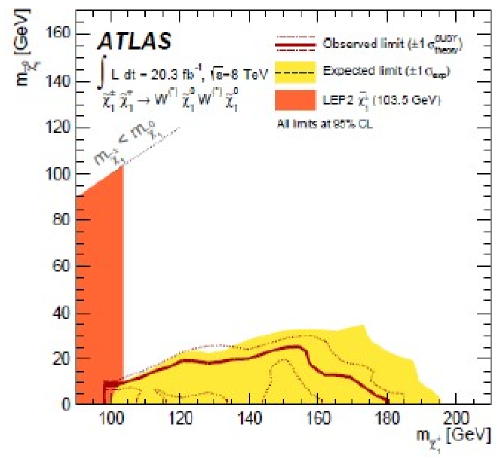
Direct slepton pair



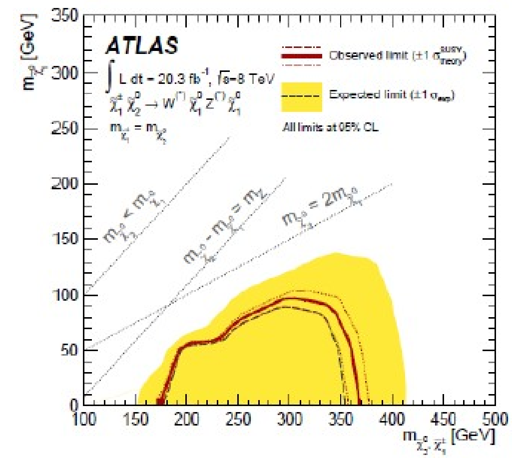
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via slepton/sneutrino



$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW

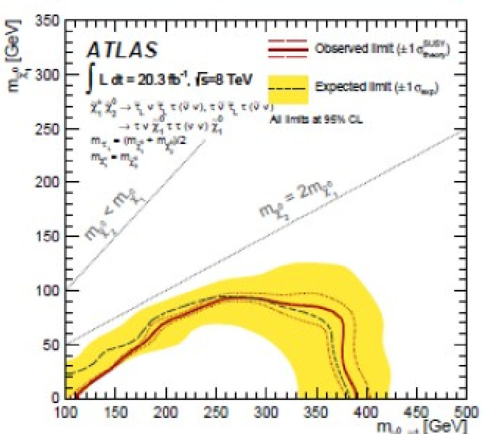


$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ via WZ

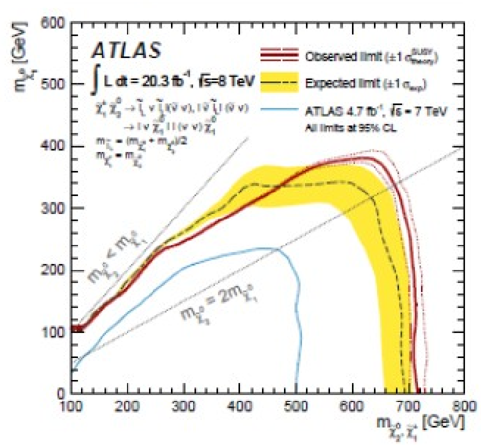


3-lepton searches

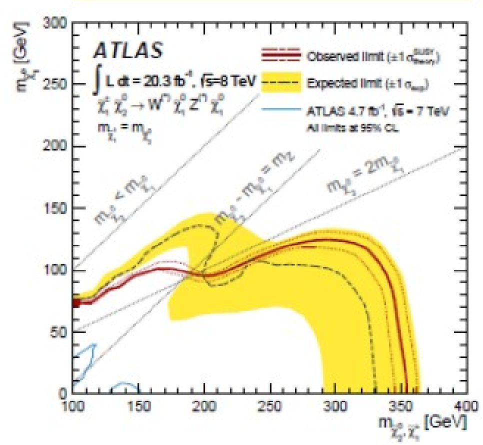
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ via stau/sneutrino



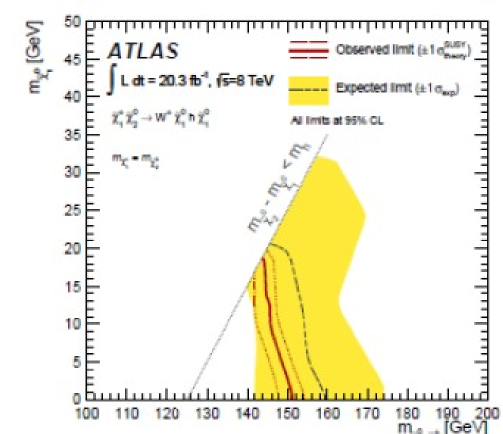
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$via slepton/sneutrino



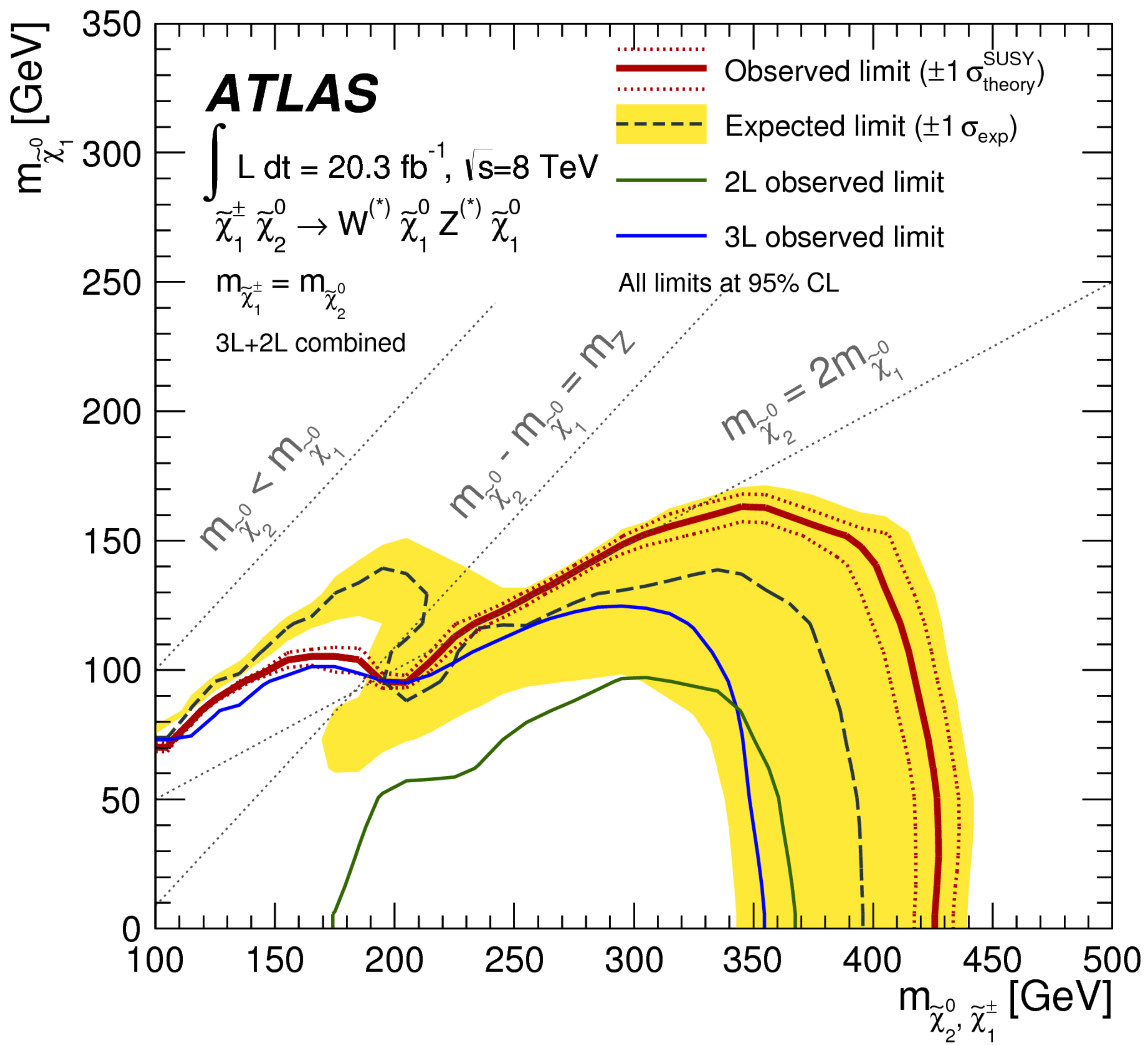
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$via WZ



$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$via WH



Combined 2/3 Lepton Result

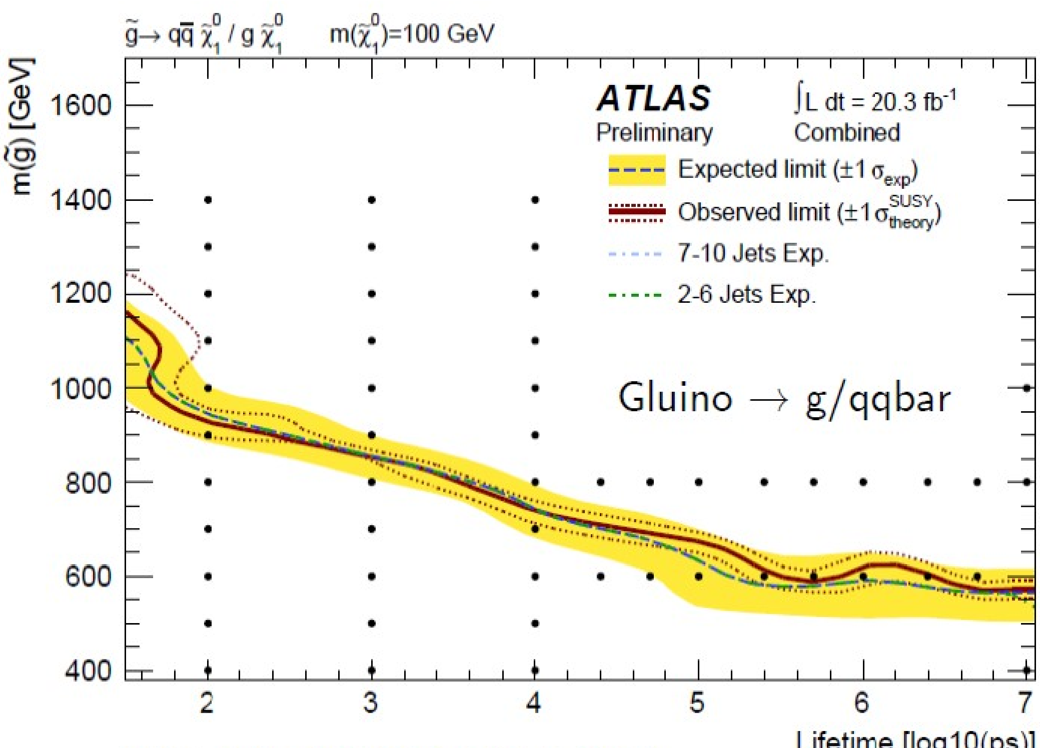


Long-lived

What if gluino is just a little long-lived, about 1 ns? (mini-split SUSY)
Standard jets+MET SUSY searches should still apply (up to what lifetime?)

- Leptons vetos may start to fail impact-parameter cuts (when?)
- Jets will start to be identified as b-jets (when?)
- Jets may fail cleaning cuts using track pT fraction, EM fraction (when?)

First explicit re-interpretation of prompt SUSY searches for long-lived gluinos!



ATLAS-CONF-2014-037