Recent Supersymmetry Results from

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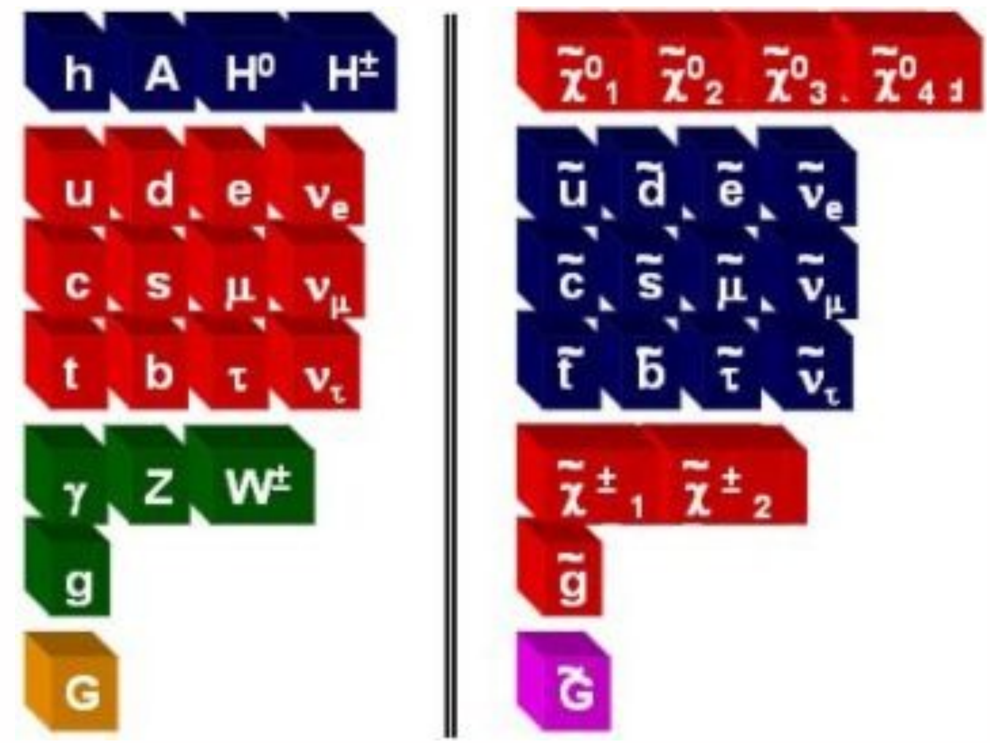
a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

LHC Seminar, November 25, 2014

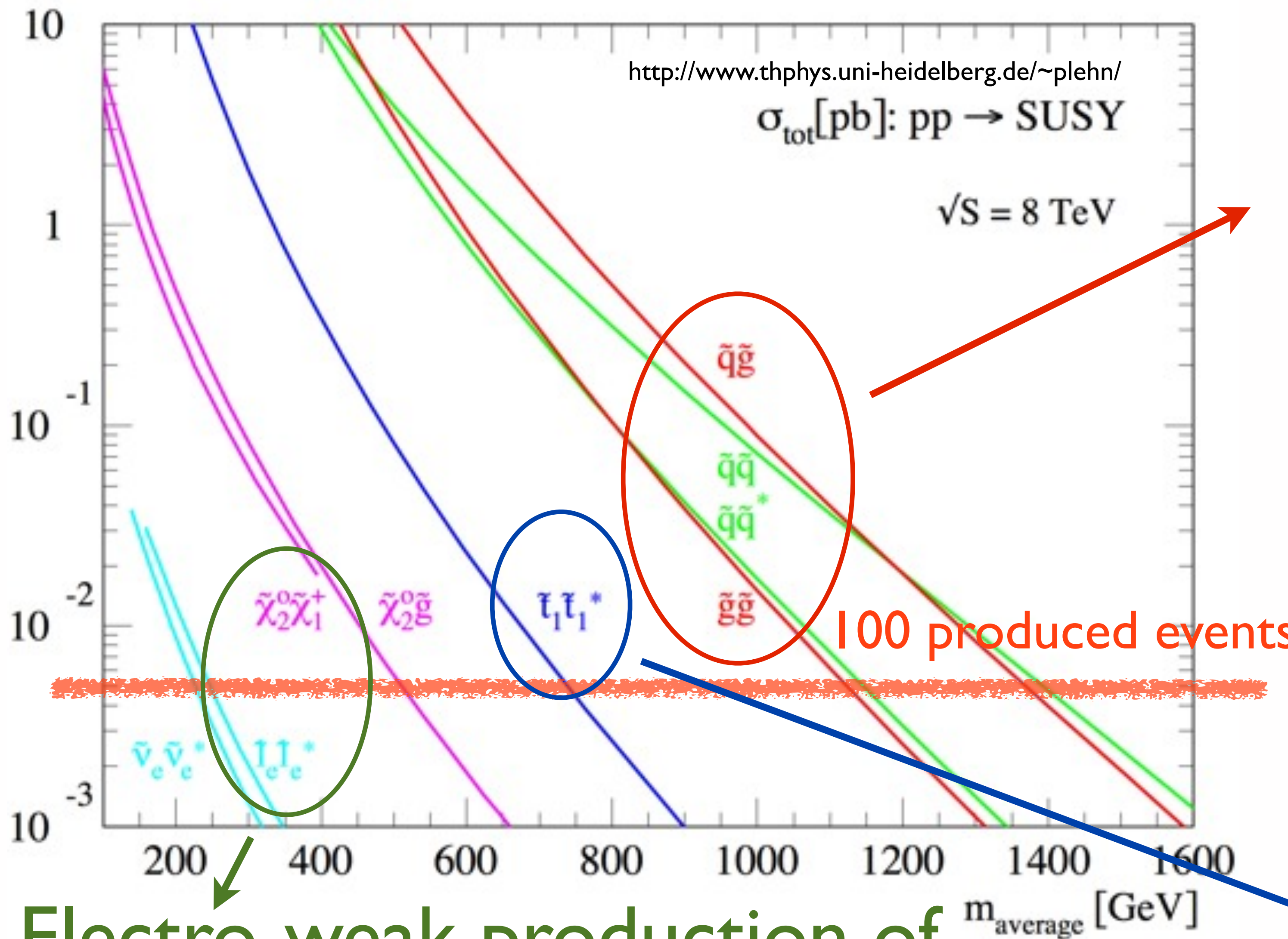
Why SUSY?

- **Theoretically and experimentally motivated**
  - Extends Poincare space-time symmetry
  - Natural grand unified theory
  - Can incorporate gravity
  - Solves hierarchy problem
  - can provide candidate for cold DM
    (if a new parity, R-parity is conserved)
- **MSSM developed in the early ’80 and starting point for searches ever since**
  - More than 100 soft SUSY breaking parameters



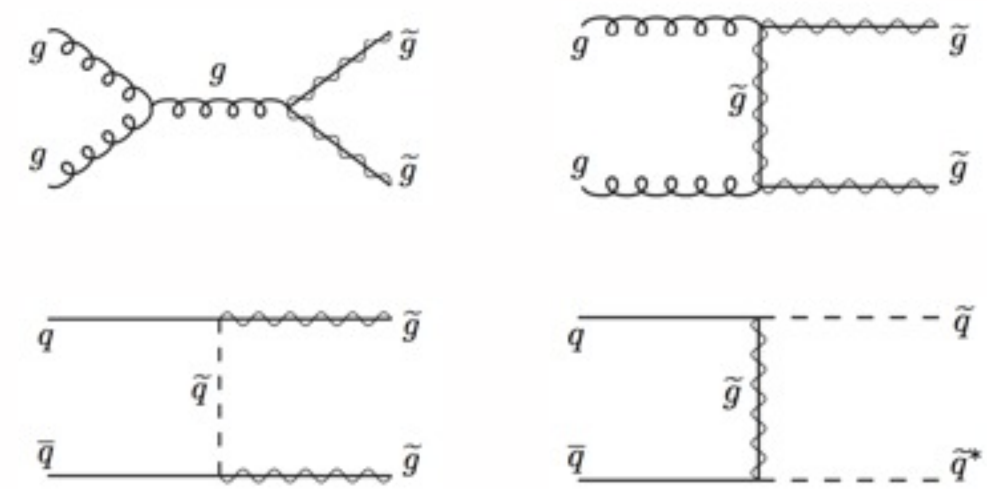
- **Complete SUSY Models:**
  - mSUGRA, AMSB , GMSB
- **Phenomenological Models:**
  - pMSSM: 19 parameters, GGM (gravitino)
- **Simplified Models:**
  - physical masses of SUSY particles
  - fixed branching fractions, pure states

Production of SUSY Particles at the LHC



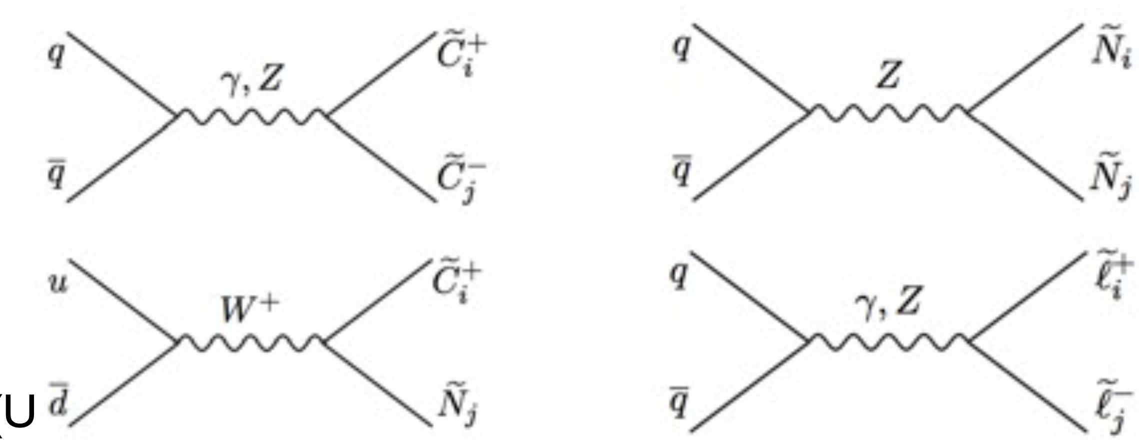
Strong production of gluinos, 1st/2nd generation squarks

expected sensitivity up to ~1.2TeV



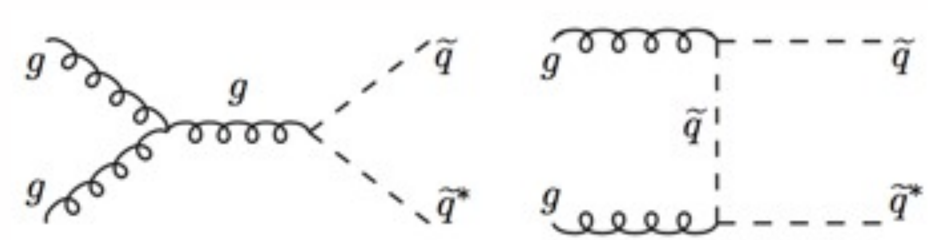
Electro-weak production of electroweakinos and sleptons

expected sensitivity ~0.2-0.5TeV



Strong production of 3rd generation squarks

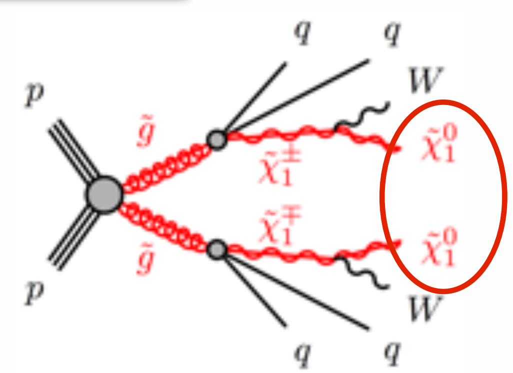
expected sensitivity ~0.7TeV

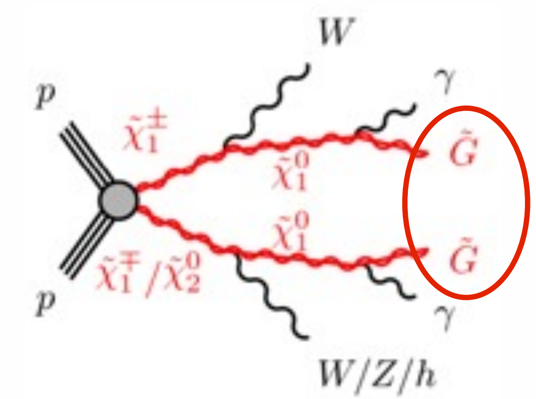


Phenomenology of SUSY

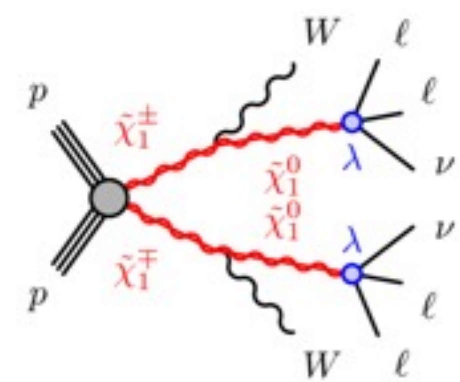
$$P_R = (-1)^{2s+3B+L}$$

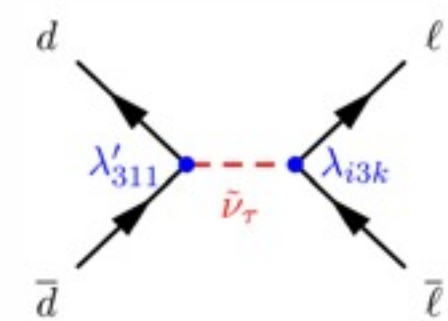
- R-parity conserved (RPC)
  - SUSY particles created in pairs
  - Lightest SUSY particle (LSP) is stable, DM candidate
  - Expect large ETmiss from escaping LSP



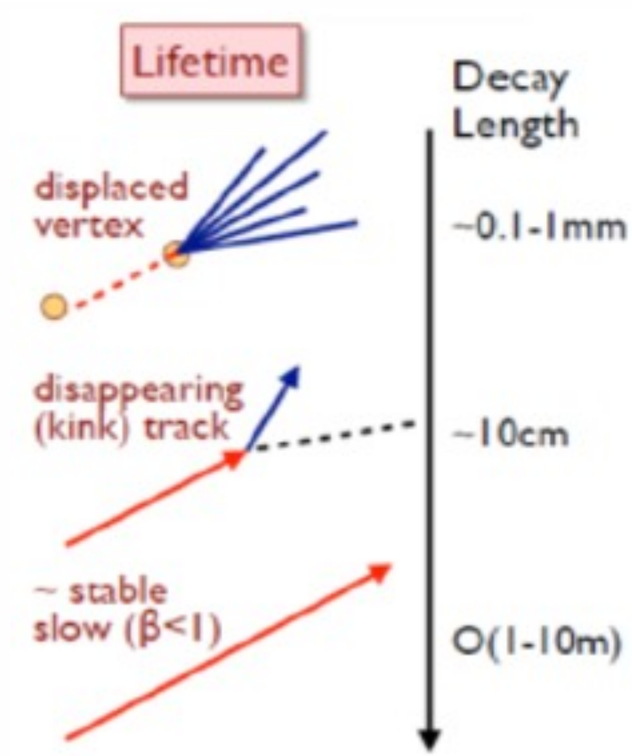


- R-parity violated (RPV)
  - RPC pair-production, but decaying LSP
  - RPV production of a single SUSY particle
  - Loss of ETmiss, but large object multiplicity and resonances



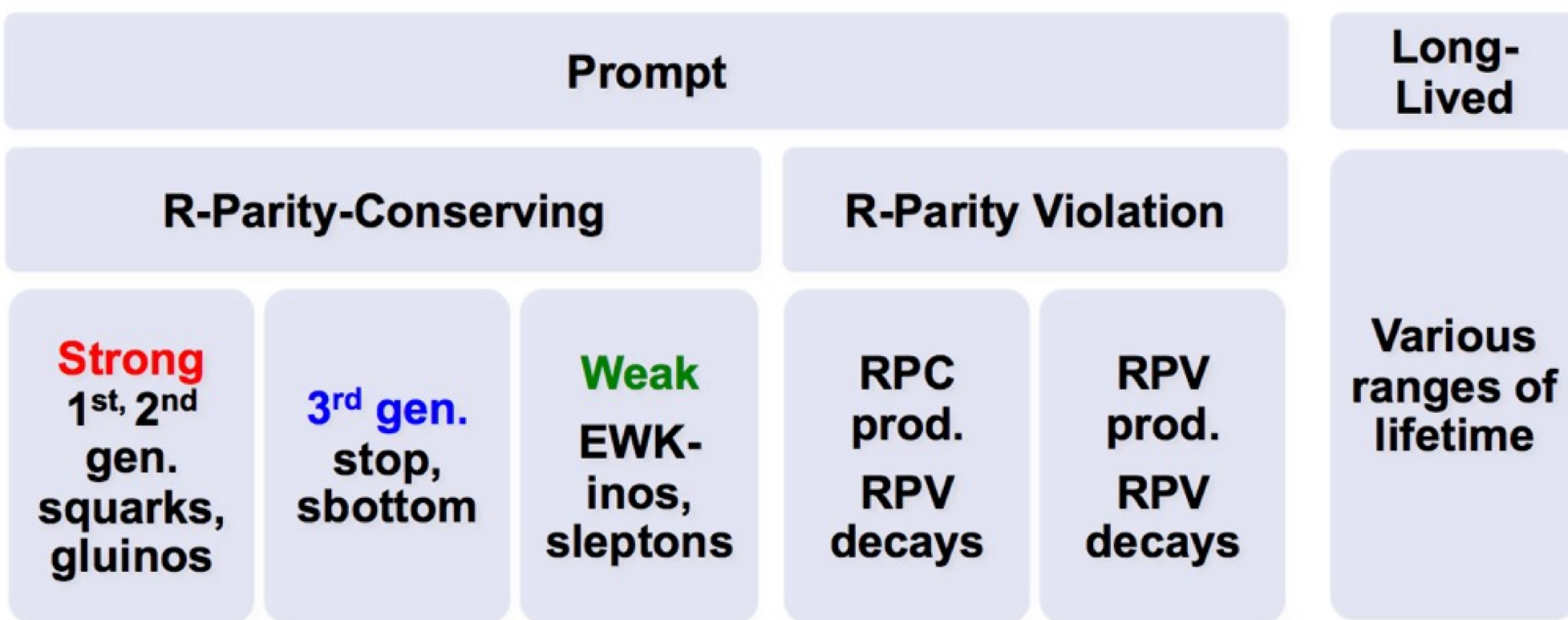


- Long Lived (LL) particles (in both RPC and RPV)
  - R-hadrons from meta-stable gluinos, decaying via very heavy squarks
  - Compressed spectra
  - Meta-stable (N)LSP due to small (Gravitino)RPV coupling



Organization of SUSY Searches in ATLAS

- Searches focus on specific processes rather than final state signatures
  - Higher discovery potential!



Outline: Updates Since SUSY 2014

- Searches for gluinos
    - Search based on 1-2 lepton + jets final states
- Searches for 1st/2nd generation squarks
    - Mono-photon search targeting compressed scenarios
    - Search for charm squarks
- Searches for 3rd generation of squarks
    - Re-interpretation of the measurement of the top spin correlation
- Searches for EWK SUSY
    - Search for chargino and neutralino with Higgs in decays
- Searches for Long Lived Sparticles
    - Search for heavy stable sparticles
    - Re-interpretation of 0-lepton results in search for metastable gluinos
    - Search for GMSB-like scenarios using non-pointing and delayed photons
- Summary and Outlook

New today

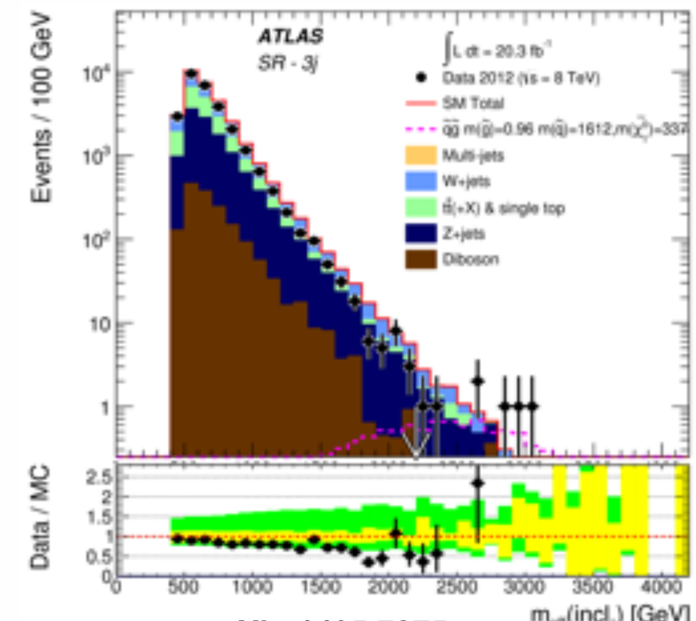
New today

New today

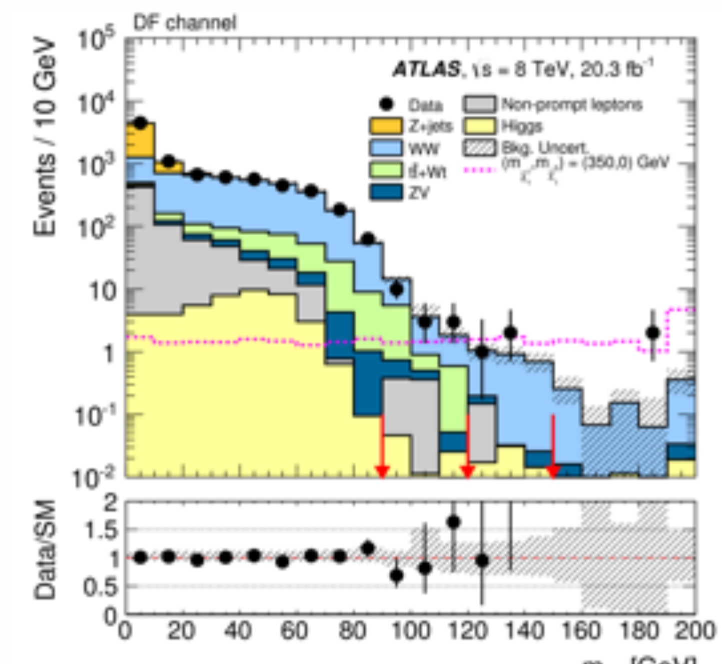
New today

General Analysis Strategy

- Select Signal Regions using discriminating variables
  - ETmiss mostly from escaping LSP, to suppressing backgrounds with mis-measured jets also ETmiss significance = ETmiss/$\sqrt{\sum_{jet} pT}$
  - related to the sparticle mass scale, e.g meff = ETmiss + $\sum_{\text{all objects}} pT$
  - mT and mT2, stranverse mass (generalization of the transverse mass) used to suppress backgrounds with Ws, typically in searches for stops and electroweakinos
  - mCT, razor, ...
- Analyses are usually based on many signal region (SR) bins
- Fake instrumental backgrounds with data-driven methods (matrix, ABCD)
- Remaining backgrounds from MC, usually normalized in Control Regions (CR) in a simultaneous fit in all CR (and SR for limits)
- Signal Regions blind until modeling validated in Validation Regions (VR)

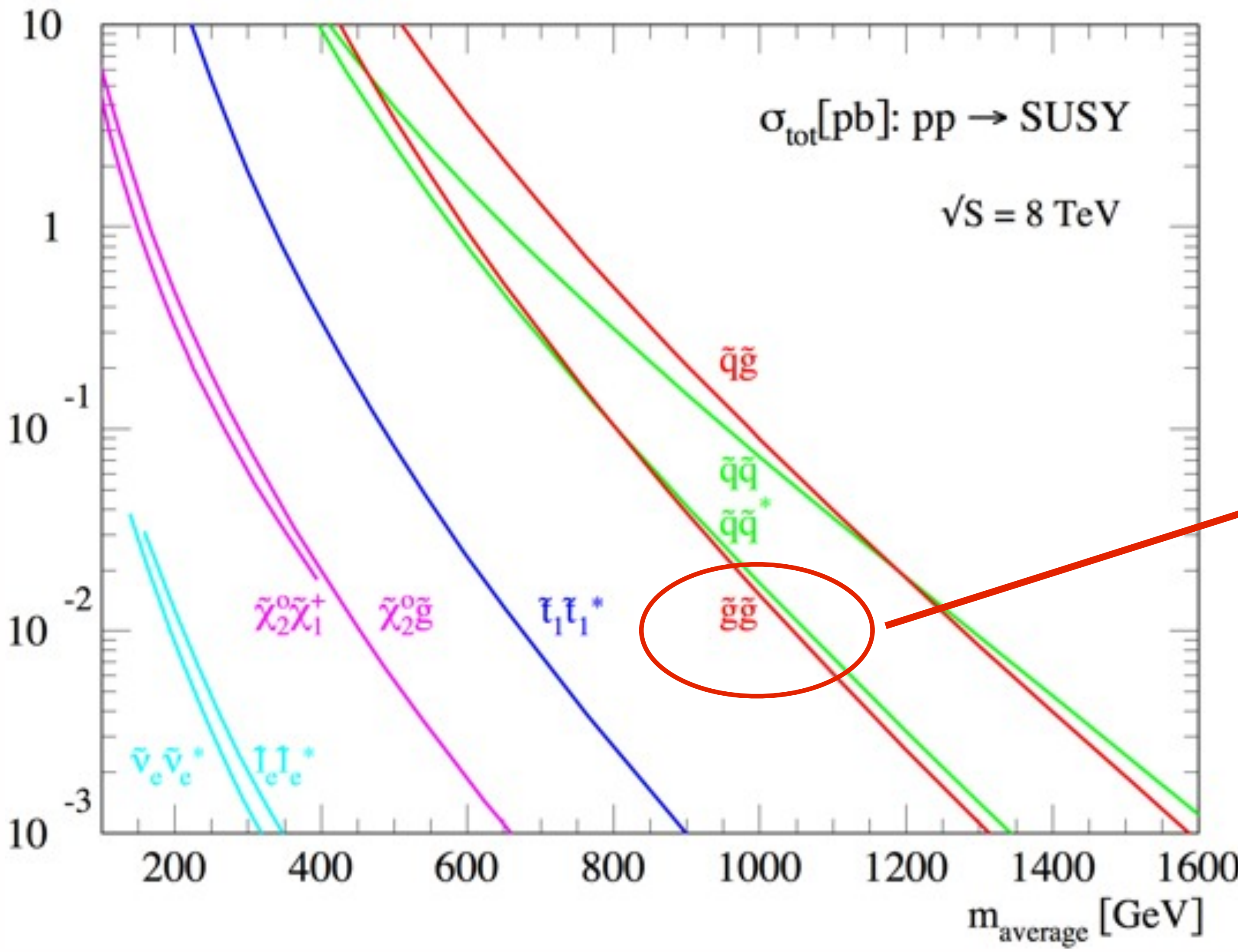


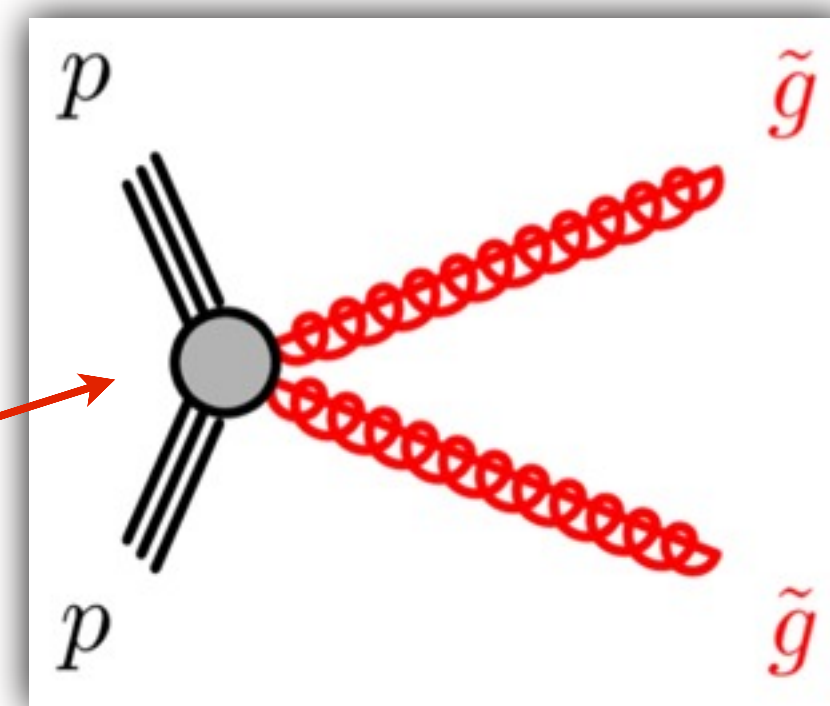
arXiv:1405.7875



arXiv:1403.5294

Searches for Pair Production of Gluinos



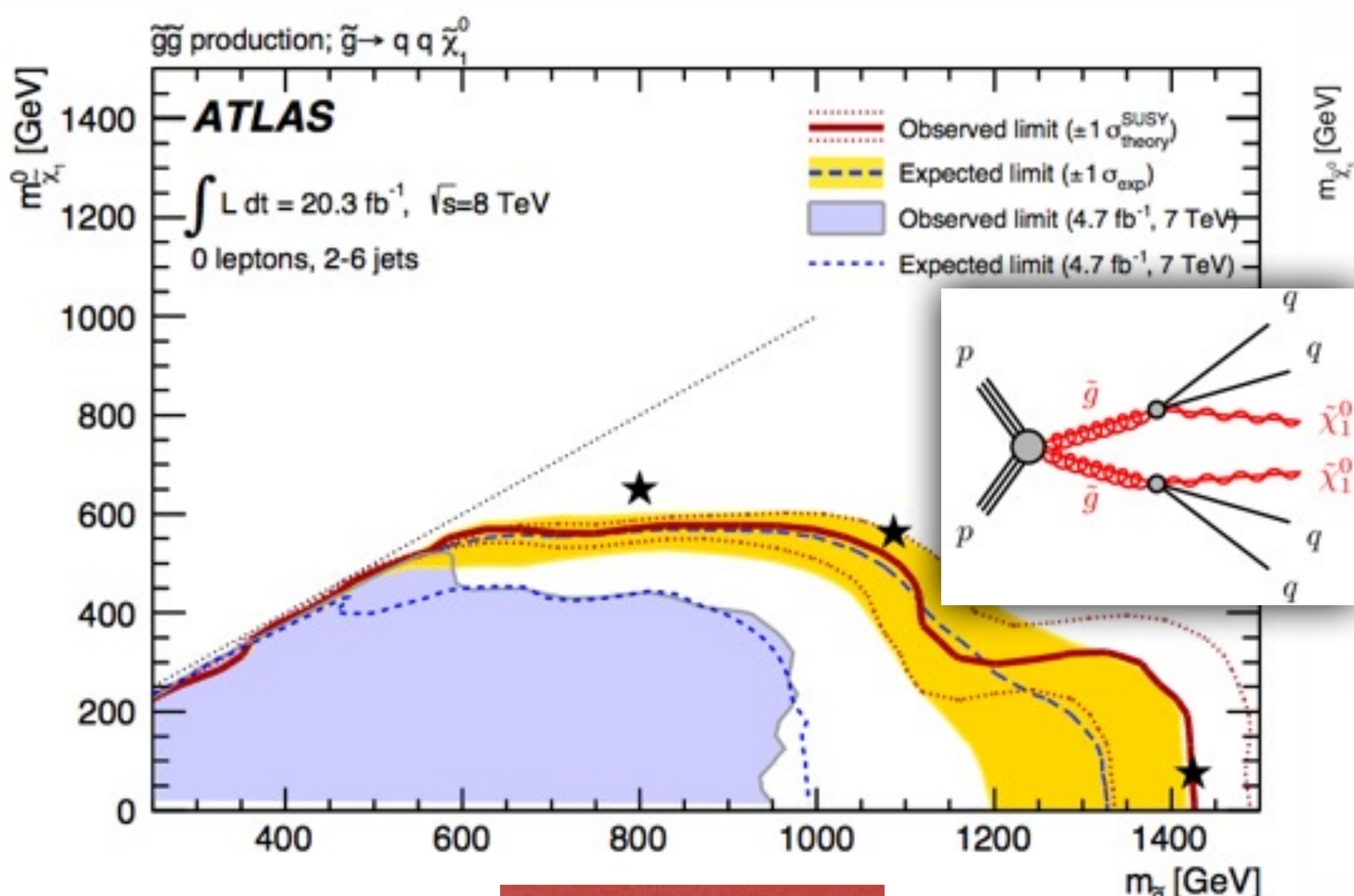


Searches for Gluinos decaying via Virtual Squarks

- Scenarios with gluinos decaying via off-mass shell light-flavor squarks are probed by search using events with 0 leptons, 2-6+ jets, large Meff (up to >1.7TeV) and ETmiss significance

- Scenarios with gluinos decaying via off-mass shell stops lead to rich phenomenology with 4 b-jets and 4Ws in the final state

    - Achieved sensitivity to large mass and compressed spectra using events with 0-1L, 3b-jets;   2SS/3L, b-jets;   0L, 7-10+ jets



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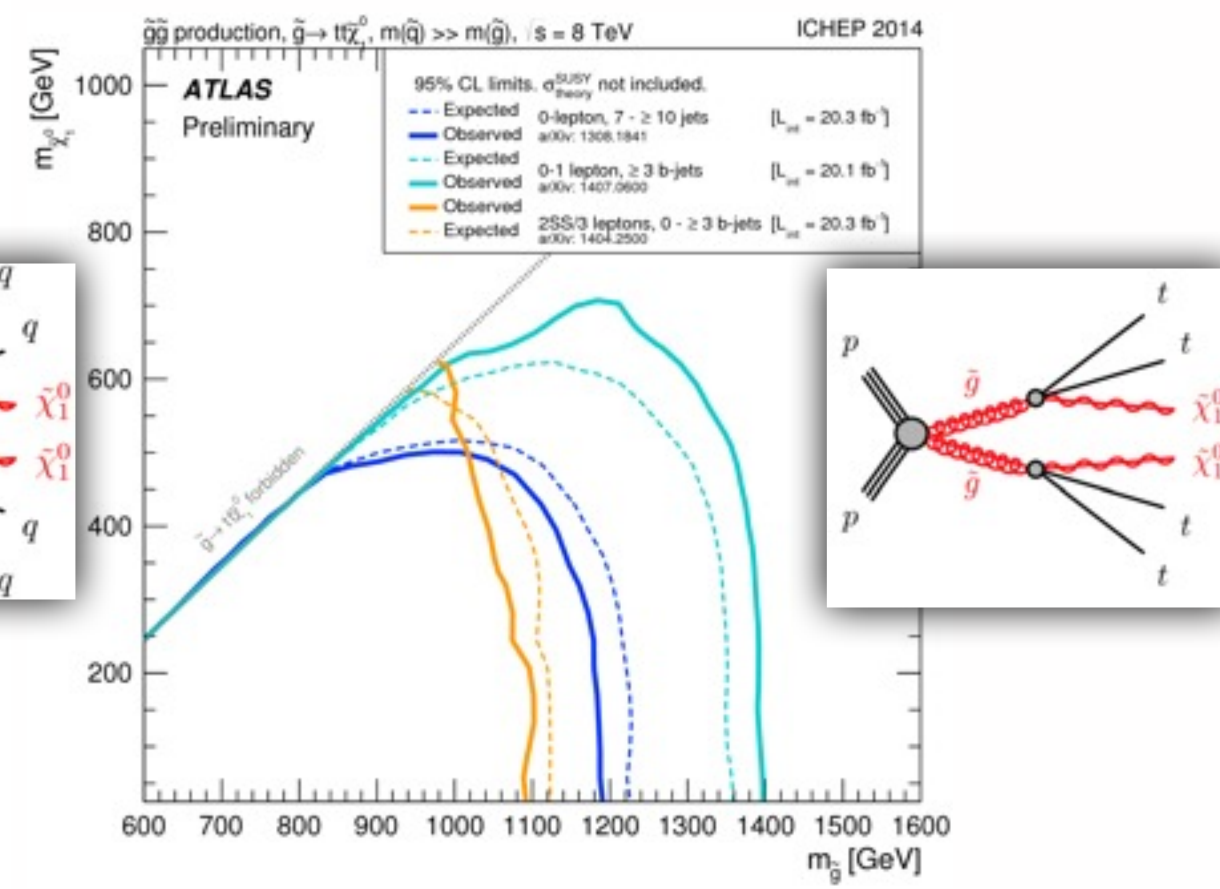


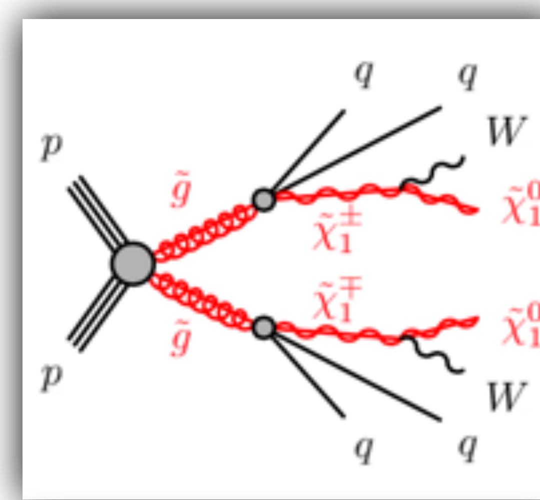
Searches for Gluinos decaying via Charginos and Sleptons

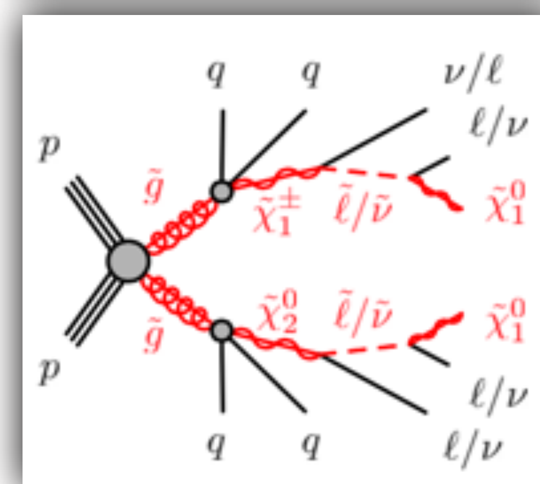
New

- Gluinos can undergo long decay chain through charginos and sleptons leading to final states with leptons

- Four searches targeting
  - compressed scenarios (lepton pT in 6-7 to 25 GeV range, “soft”) using ETmiss trigger
  - scenarios with medium to large mass splittings (lepton pT >25 GeV, “hard”)
  - scenarios with long decay chains (di-lepton, pT >14/10 GeV range, “hard-dilepton”)

- Signal to background discrimination based on:
  - number of jets, ETmiss, Meff, ETmiss/Meff, MT in hard/soft searches
  - number of jets, topological information (“razor”) instead of ETmiss in di-lepton search





“Mega-jets” from all visible objects on each side of the di-sparticle decay

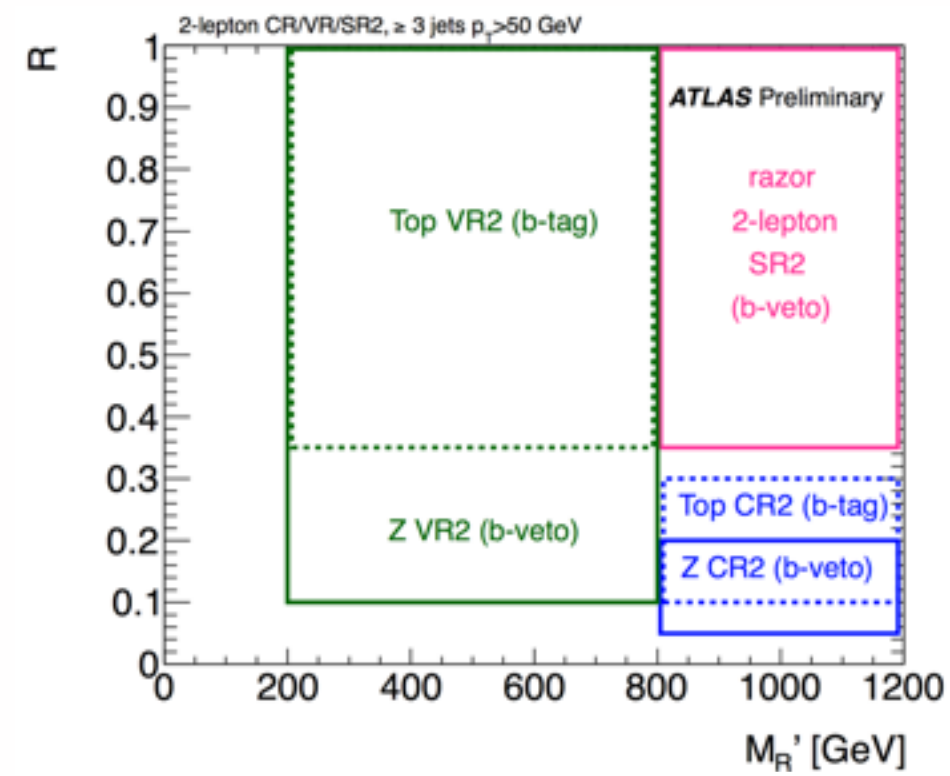
$$M'_R = \sqrt{(j_{1,E} + j_{2,E})^2 - (j_{1,p_L} + j_{2,p_L})^2}$$

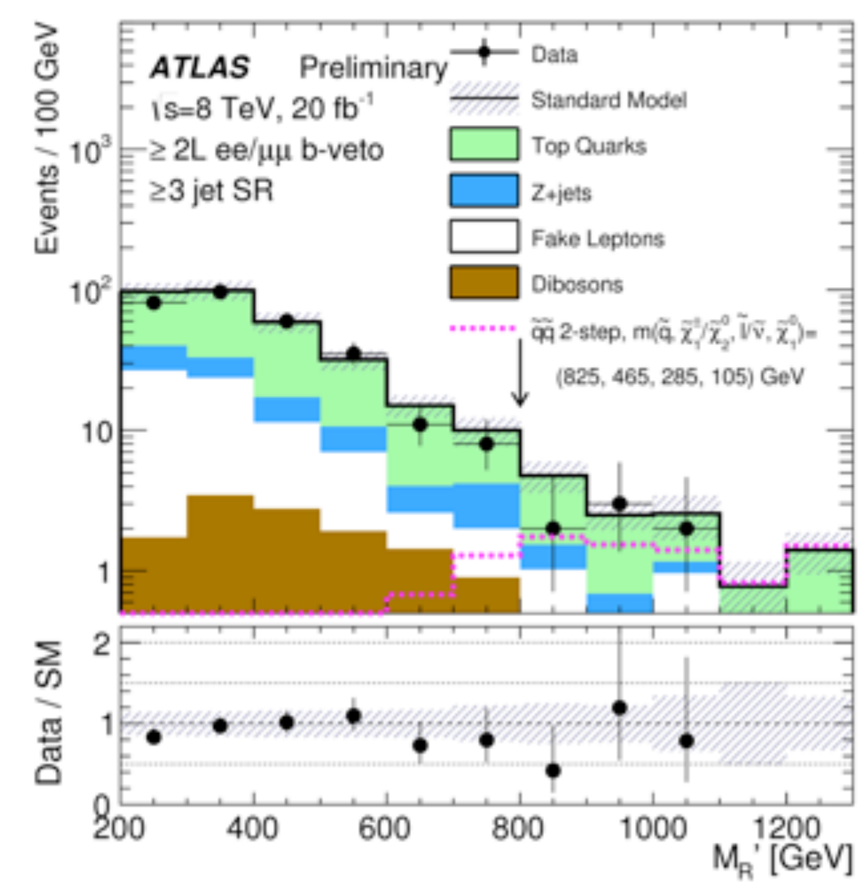
$$M_T^R = \sqrt{\frac{|\vec{E}_T|(|\vec{j}_{1,p_T}| + |\vec{j}_{2,p_T}|) - \vec{E}_T \cdot (\vec{j}_{1,p_T} + \vec{j}_{2,p_T})^2}{2}}$$

Searches for Gluinos decaying via Charginos and Sleptons

New

- For each search, a number of signal regions for discovery and for exclusions are optimized
- The dominant tt and W+jets or Z+jets backgrounds are estimated using a semi data-driven approach
  - MC is fit to data in the Top-dominated and W- or Z-dominated control regions
  - These background contributions are extrapolated to the signal regions using MC
  - The extrapolation is carried out in a **simultaneous fit accounting for potential signal contamination in the control regions and for correlation of systematic uncertainties**
  - The extrapolation to the signal region is cross-checked in validation regions kinematically close to the signal regions but orthogonal to both signal and control regions.
- Observations are in agreement with SM expectations

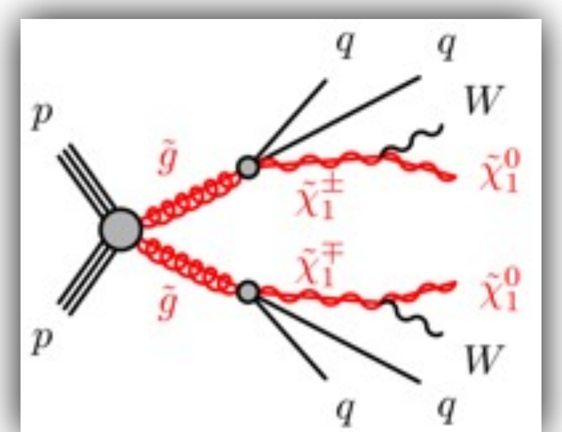


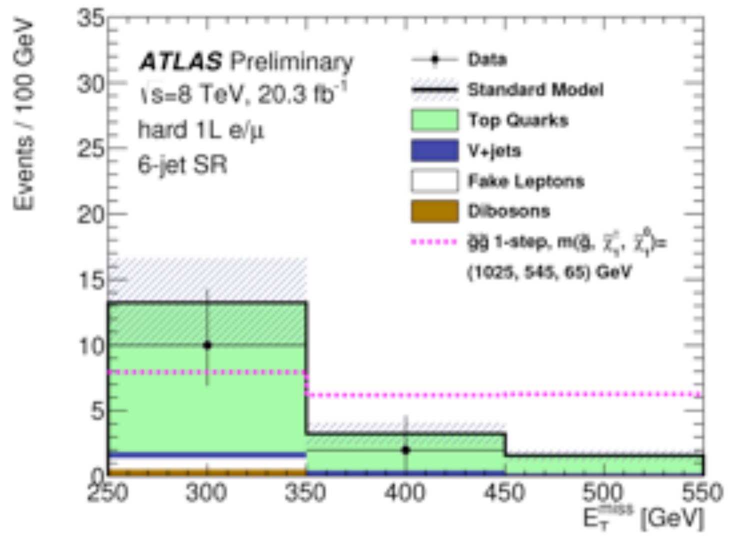


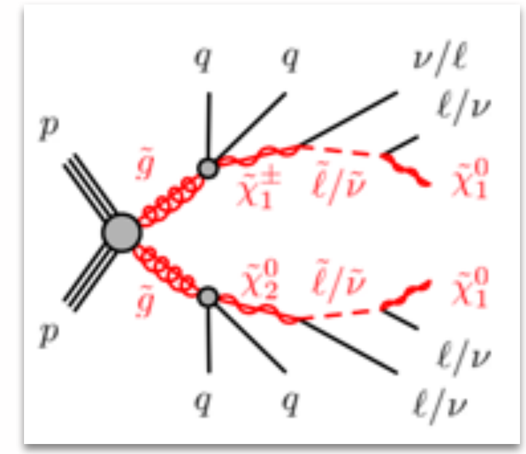
Statistical package “HistFitter” documented in http://arxiv.org/abs/1410.1280

Searches for Gluinos decaying via Charginos and Sleptons

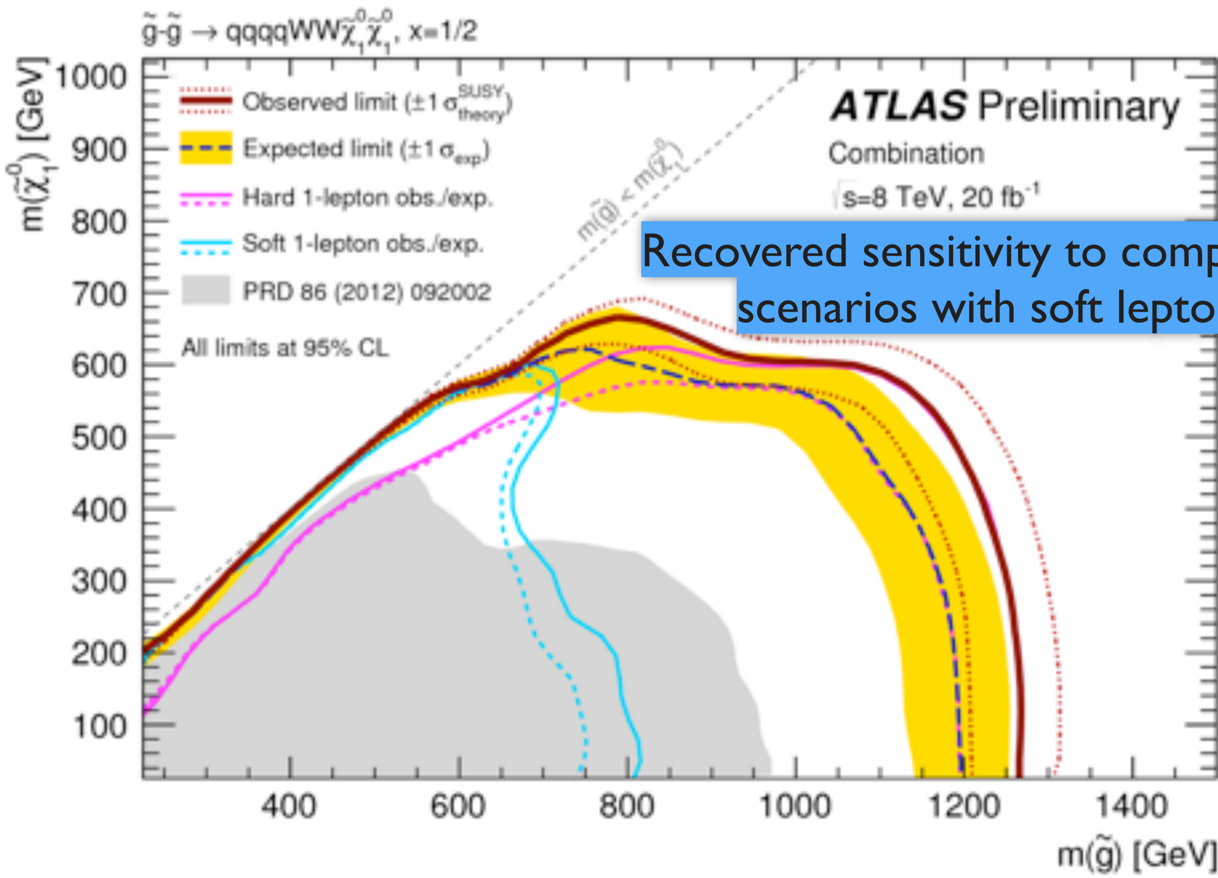
New



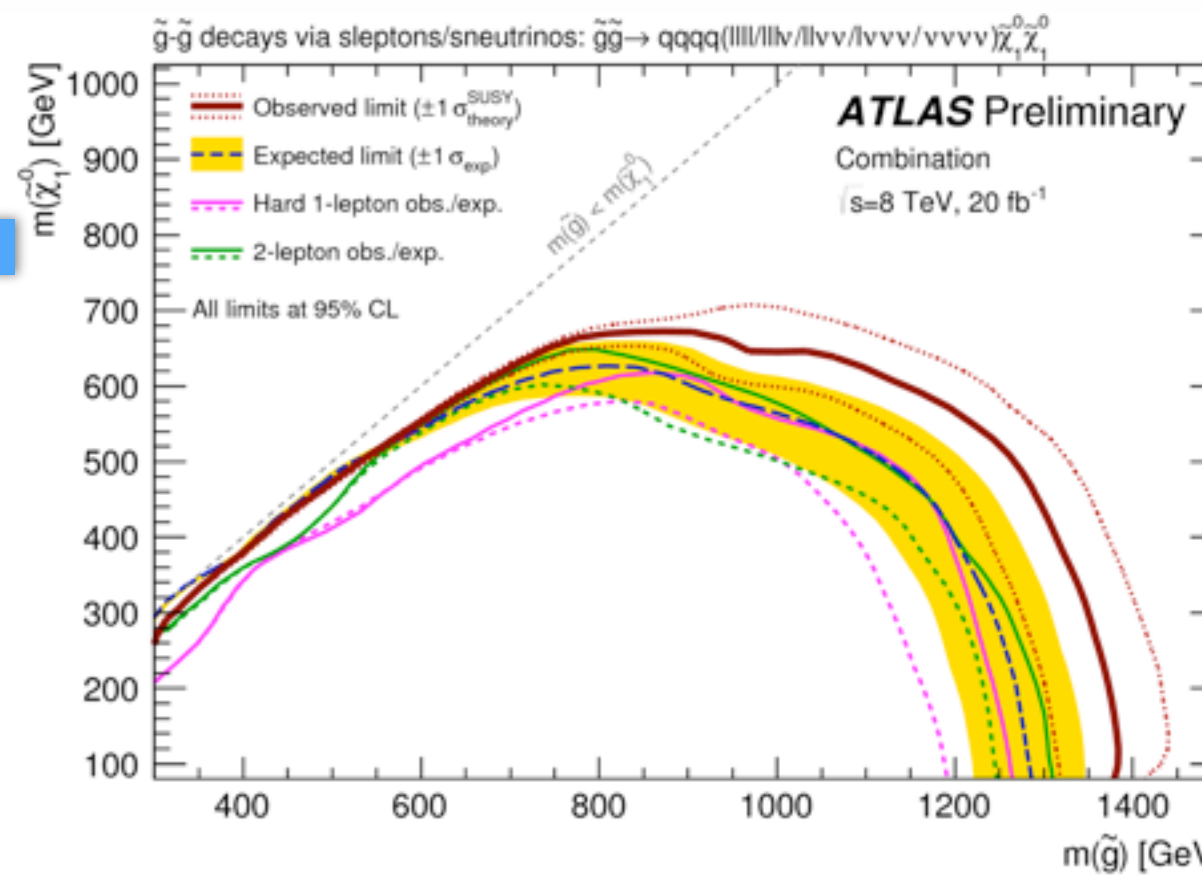




- Non-overlapping signal regions are statistically combined

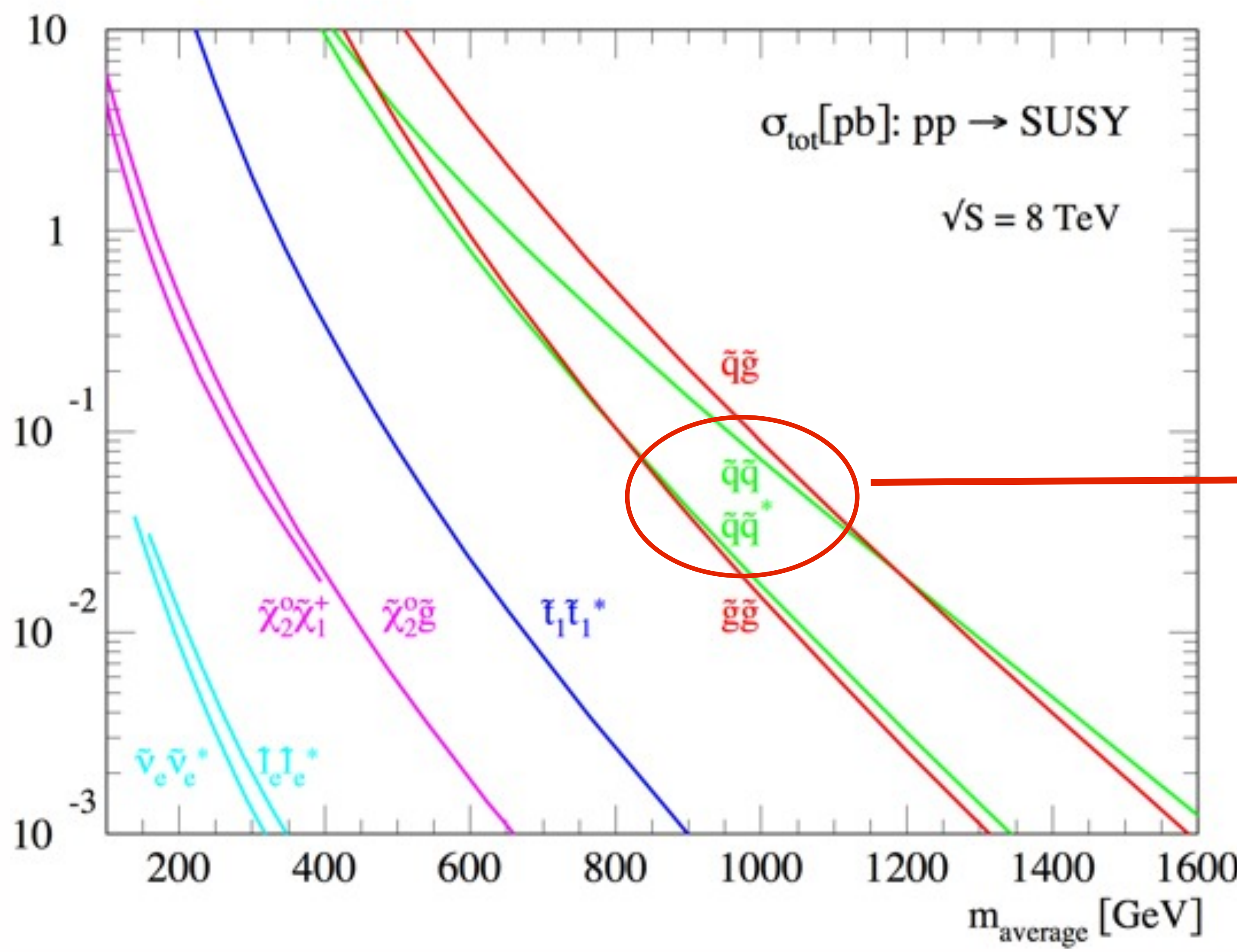


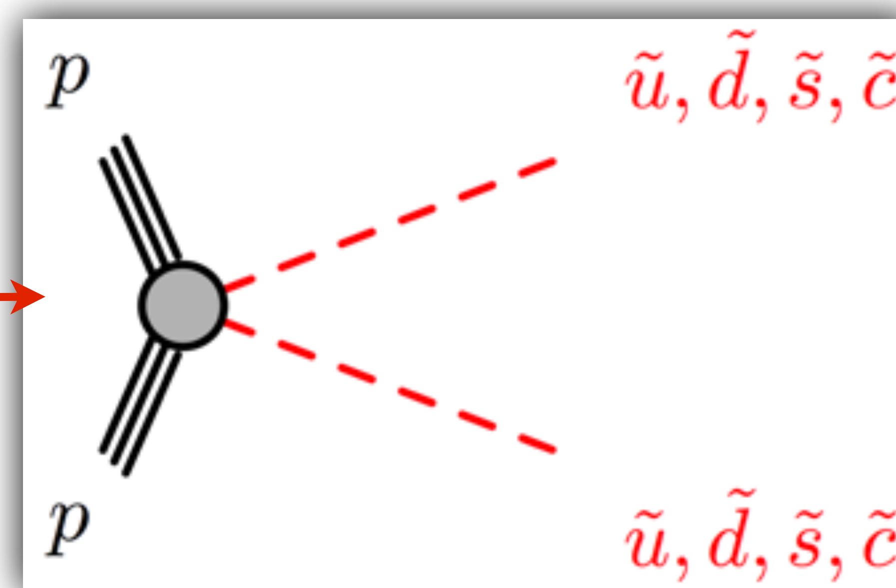
Recovered sensitivity to compressed scenarios with soft leptons



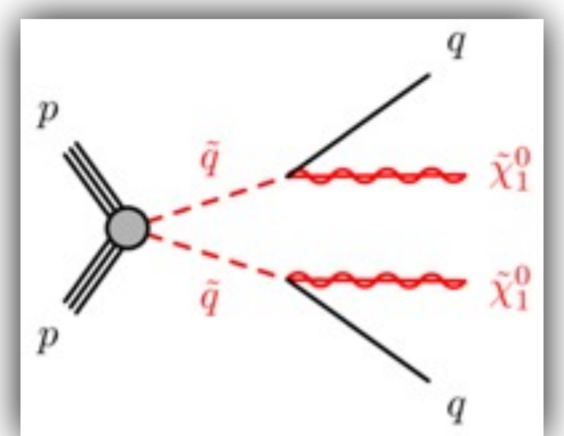
Gluino mass > 1.2TeV for massless LSP, independently of decay modes

Search for Pair Production of 1/2 Generation Squarks

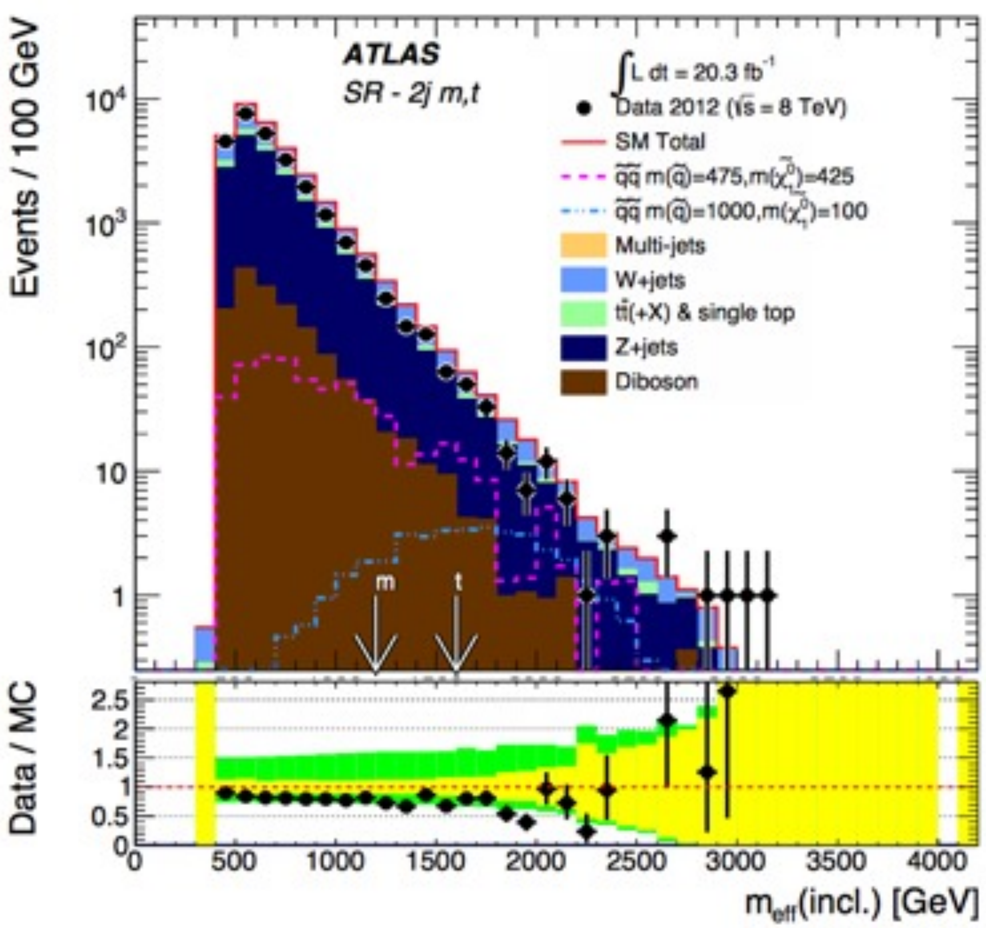




Search for Pair Production of Light-flavor Squarks



- The cross-section for 1st and 2nd generation squarks benefits from 8-fold degeneracy (u, d, c, s) x (left, right)
  - comparable to the gluino pair production cross-section
- Searches using events with 0 leptons, 2-6+ jets



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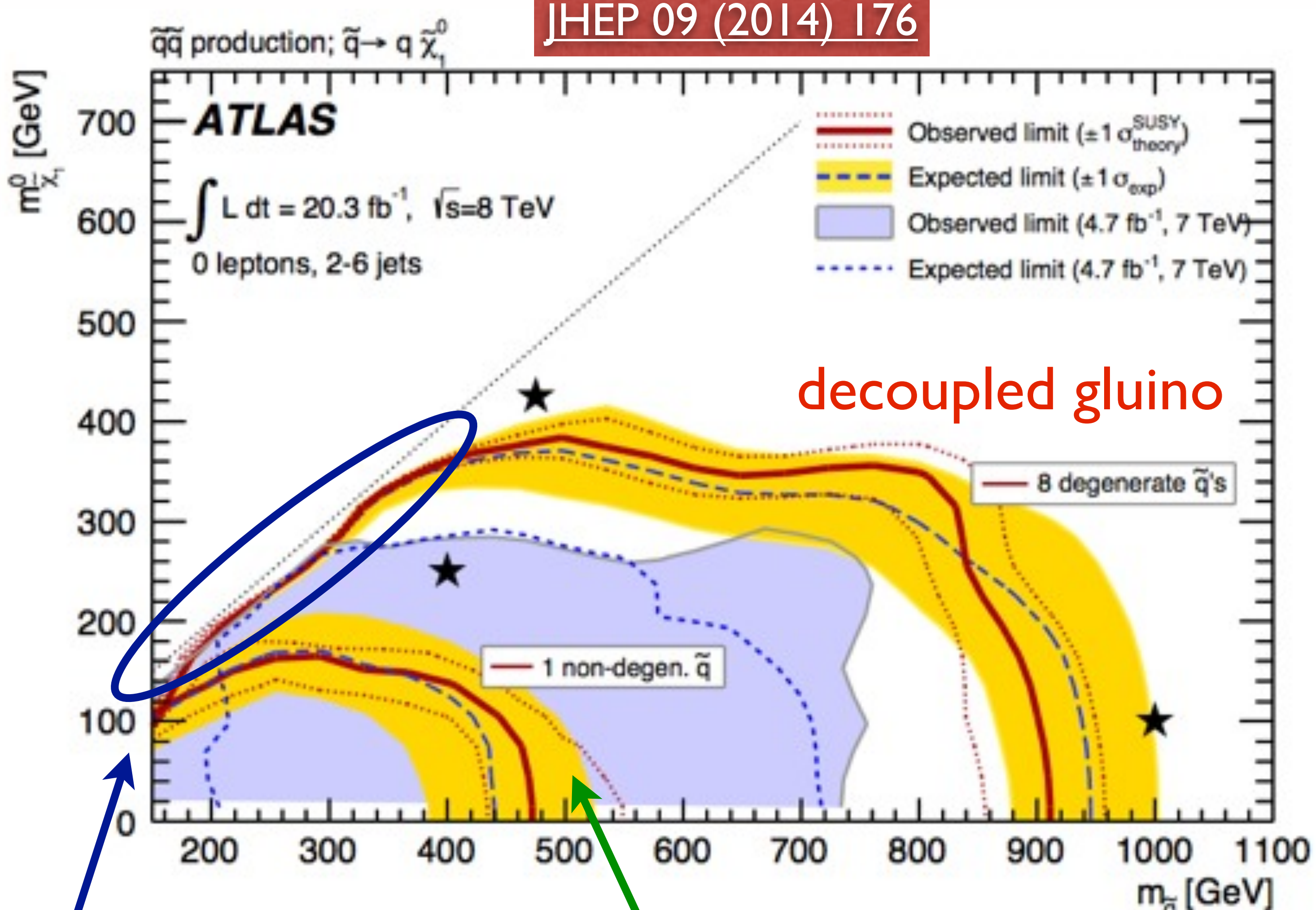


decoupled gluino

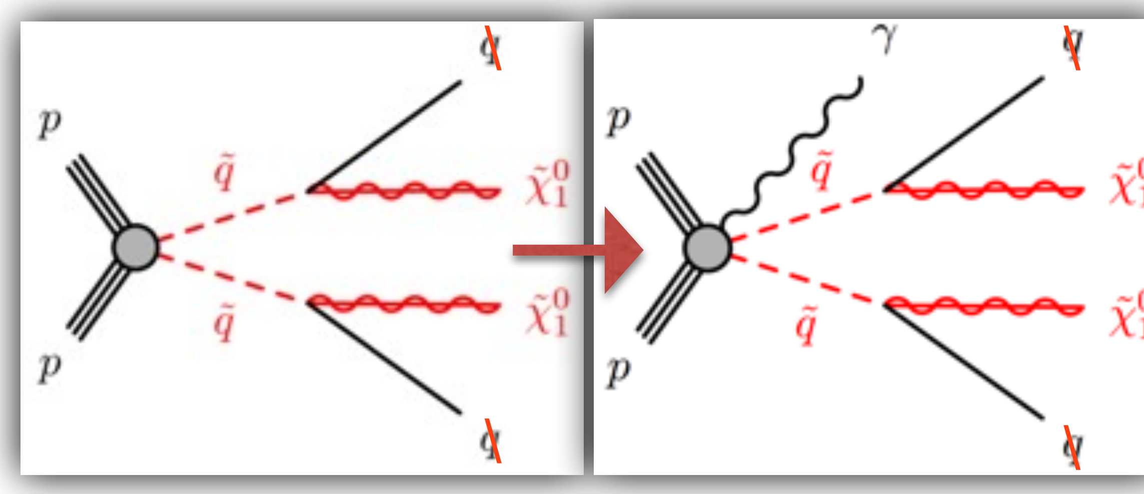
Coverage of compressed scenarios is challenging

Significant drop of sensitivity if only 1 squark is accessible!

Searches for Light-flavor Squarks in Compressed Scenarios

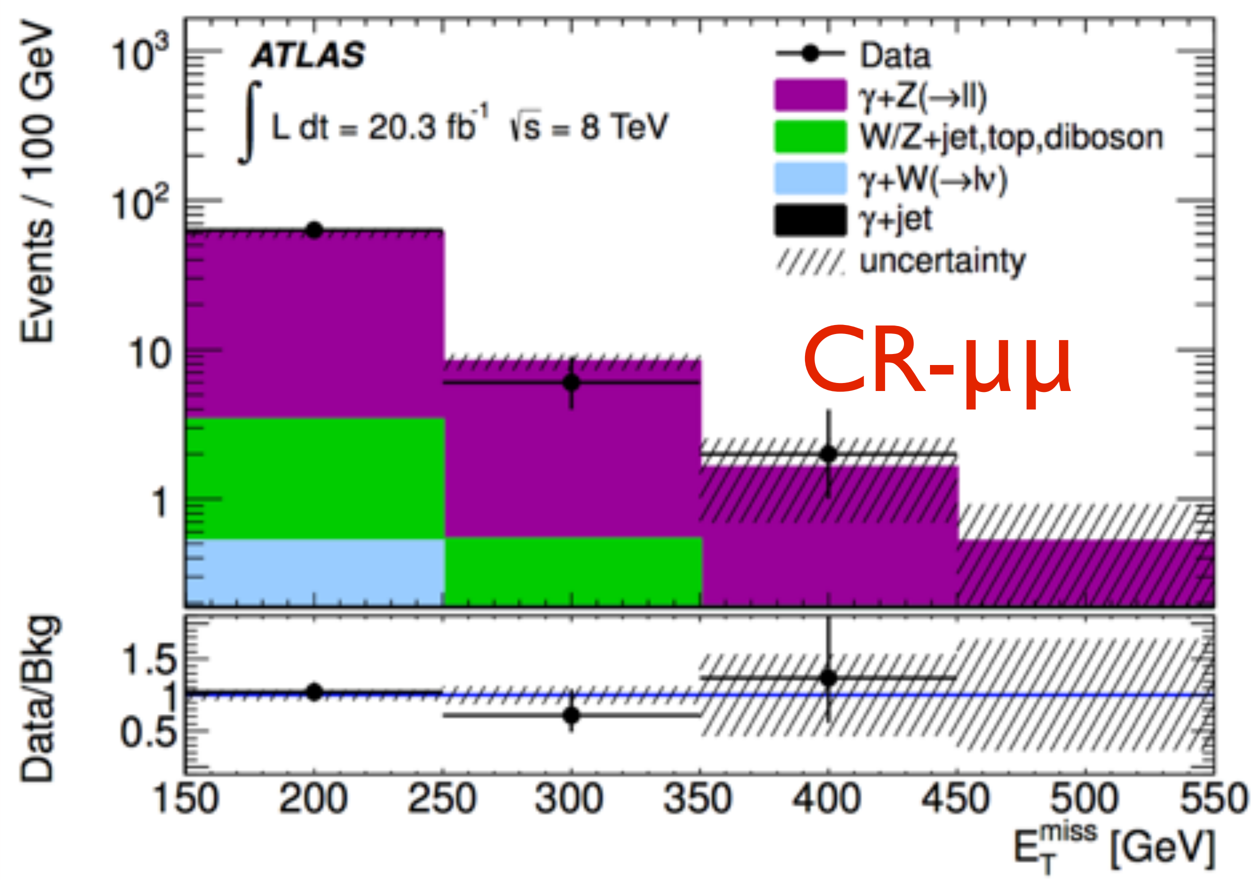
New

- In scenarios with compressed mass spectrum, the outgoing SM quarks are too soft to be detected
  - recovered sensitivity with ISR-like approach
    - jet veto (allow up to one jet with p_T>30 GeV) and lepton veto



- Search is based on events with one energetic photon and mild ETmiss:
  - ETmiss trigger, ETmiss > 150GeV
  - One central photon pT > 125GeV

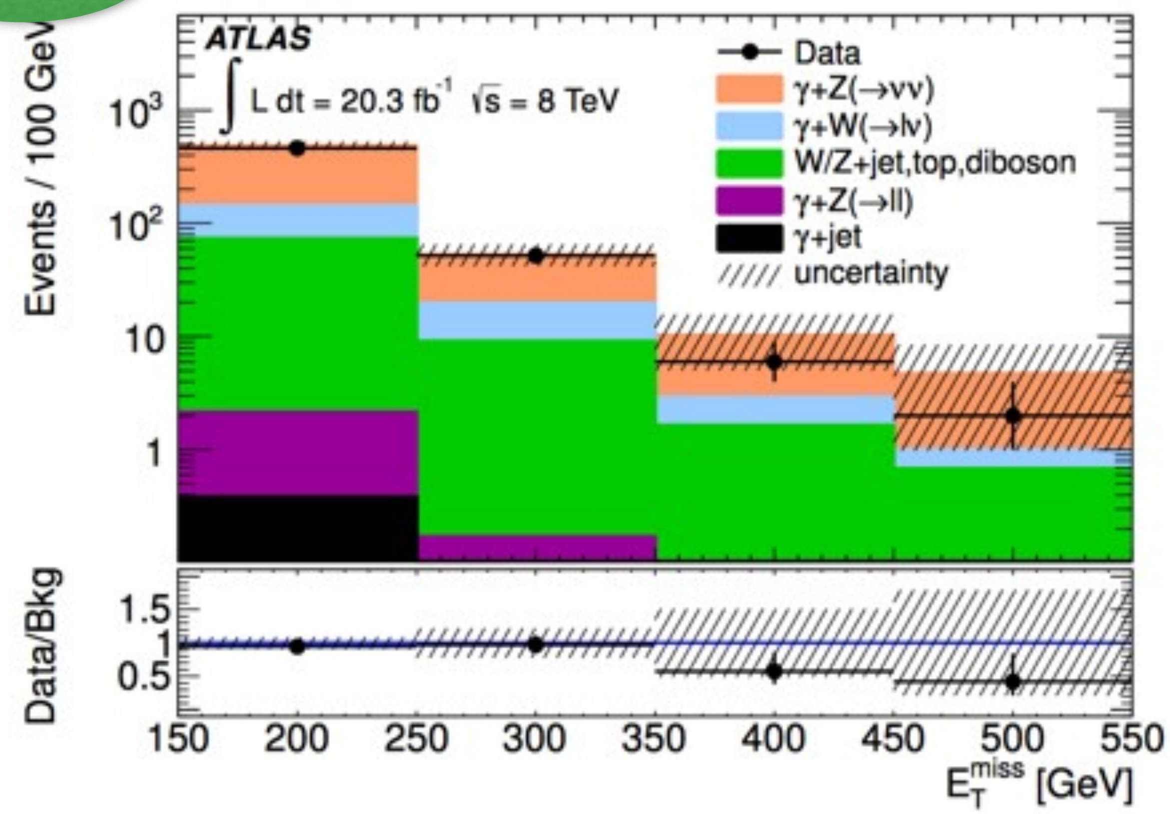
- Wγ (~15%) and Zγ (~70%) normalized in lepton enriched CRs
  - leptons treated as invisible in the ETmiss calculation



arXiv: 1411.1559

Searches for Light-flavor Squarks in Compressed Scenarios

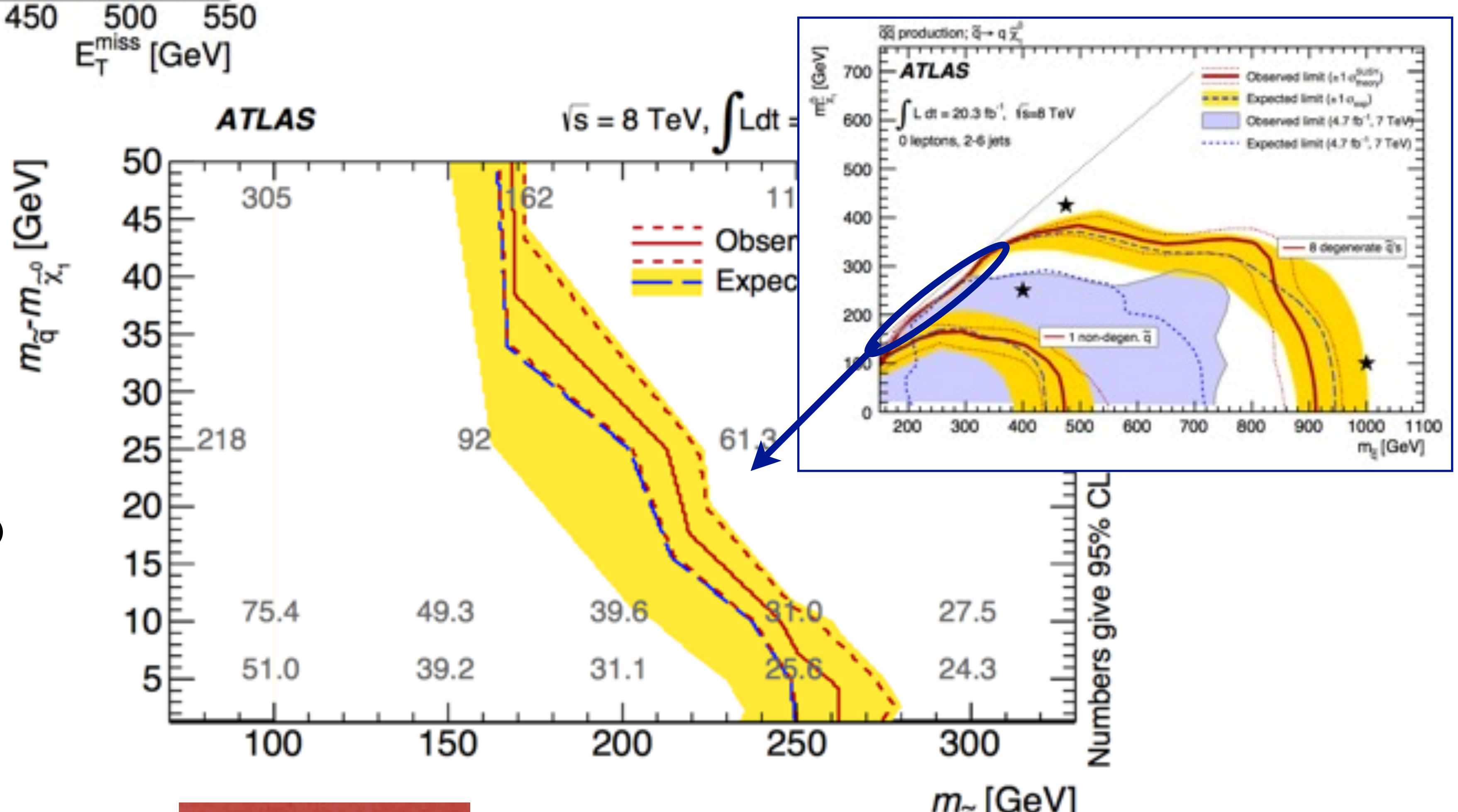
New



Process	Event yield
$Z(\to \nu\nu) + \gamma$	$389 \pm 36 \pm 10$
$W(\to \ell\nu) + \gamma$	$82.5 \pm 5.3 \pm 3.4$
$W/Z + \text{jet}, t\bar{t}, \text{diboson}$	$83 \pm 2 \pm 28$
$Z(\to \ell\ell) + \gamma$	$2.0 \pm 0.2 \pm 0.6$
$\gamma + \text{jet}$	$0.4^{+0.3}_{-0.4}$
Total background	$557 \pm 36 \pm 27$
Data	521

- Dominant systematic uncertainties on the background estimate from:
  - CR statistics (6%)
  - electron into photon mis-ID probability (4.6%)

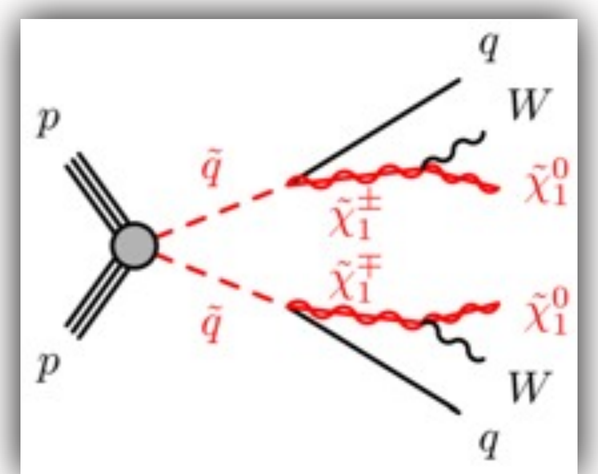
The smaller the splitting the stronger the limit is



Zoltan Gecse (UBC)

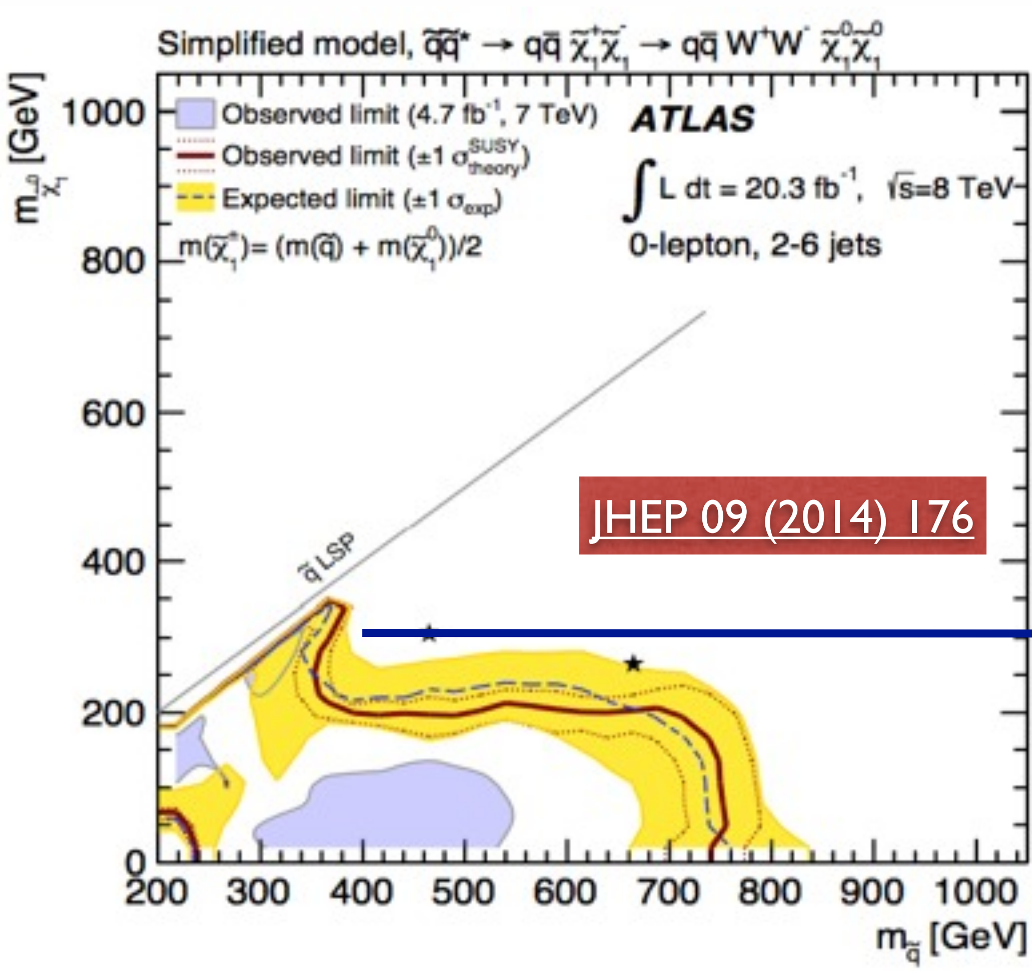
arXiv: 1411.1559

Searches for Light-flavor Squarks decaying via Charginos

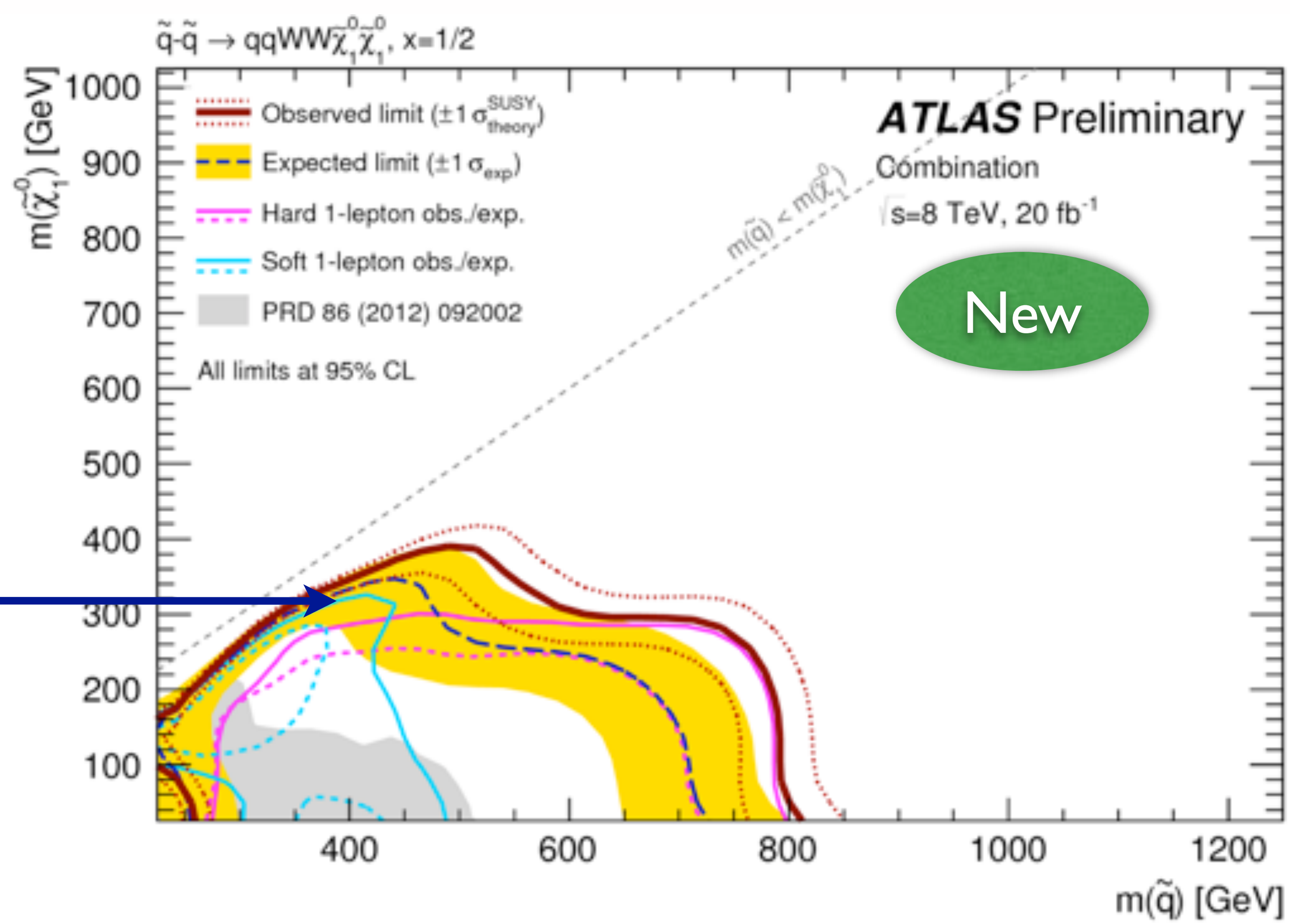


Final states may contain leptons

- Search with 0 leptons, 2-6+jets



- Search in events with 1 lepton recovers sensitivity for more compressed scenarios

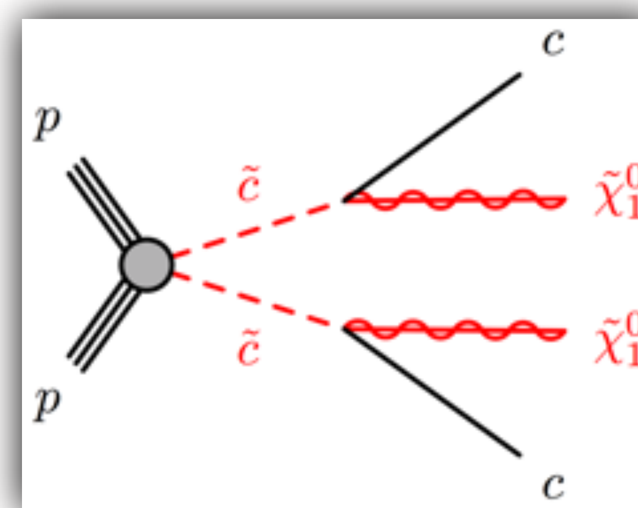


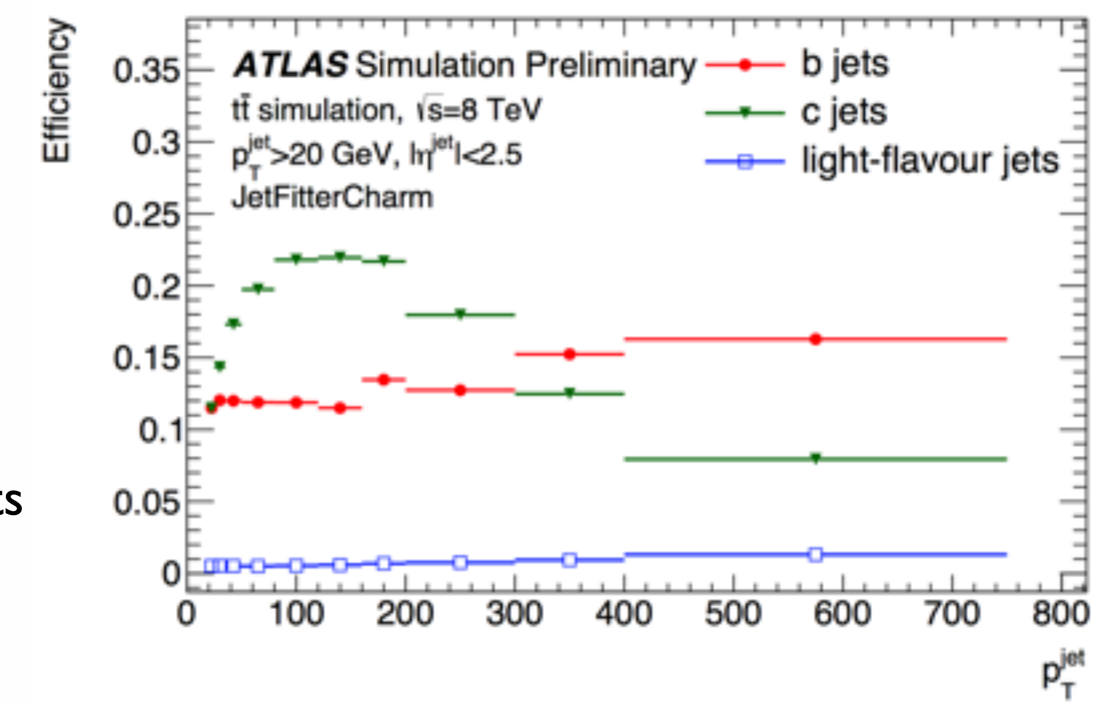
Squark mass > 700 GeV independently of decay modes
if 8 squarks degenerate and massless LSP

Search for Charm Squark, Motivations

New

- Non-degenerate light flavor squarks are well motivated arXiv:1212.3328
    - degenerate squarks not necessary to solve the SUSY flavor problem, SUSY alignment models avoid bounds from CP violating processes
- Limits on a single light-flavor squark are greatly reduced but can be improved if the flavor is charm
- Important for discovery and also probes the flavor structure of the underlying theory
- **New search for charm squark at LHC!**
- **Signal and background discrimination based on c-tagging**
    - Neural Network dedicated to c-jet identification based on impact parameter and secondary vertex information
    - c-jet tagging efficiency and its uncertainty have been calibrated in inclusive jet events over a range of pT using jets with D*

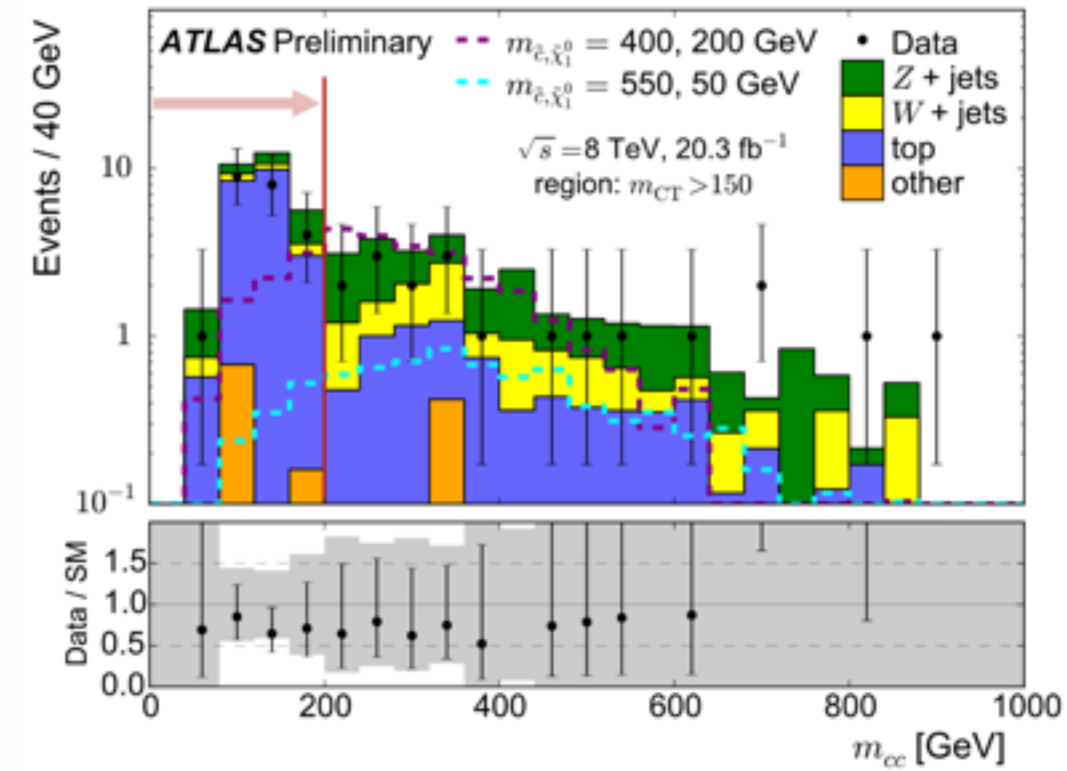


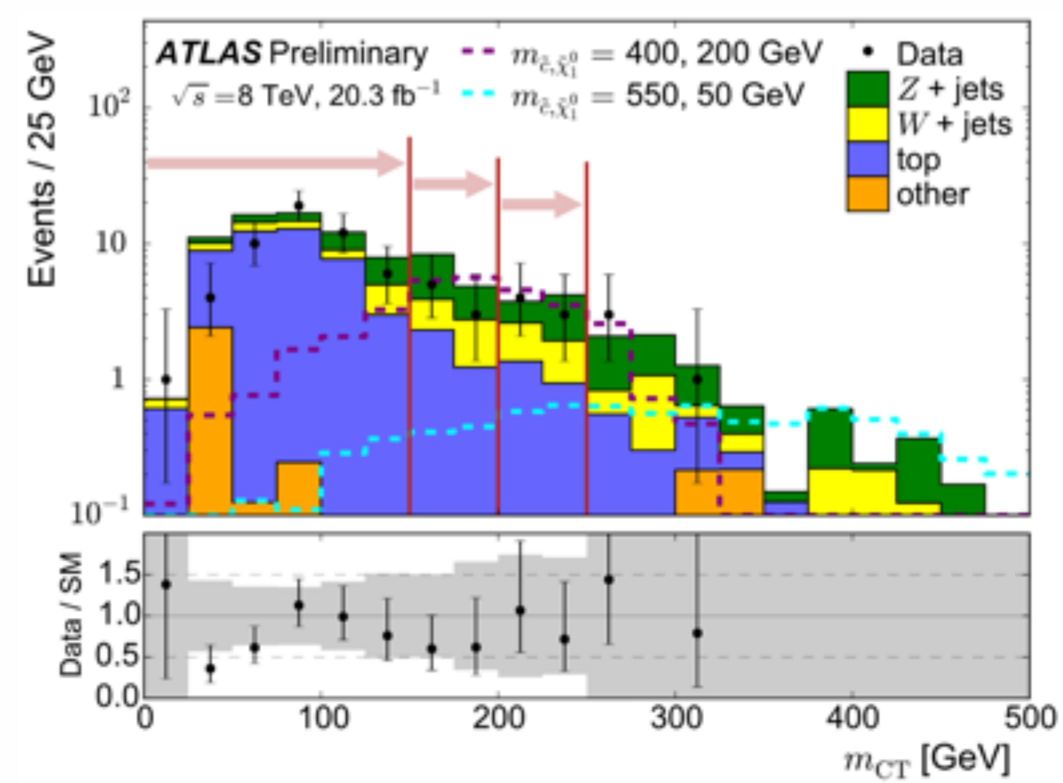


Search for Charm Squark

New

- Search is carried out in events with:
  - ETmiss>150GeV
  - jet1 pT > 130 GeV,   jet2 pT > 100 GeV
  - leading 2 jets c-tagged
  - ETmiss / (ETmiss + pT1 + pT2) > 0.25
  - mcc > 200 GeV   reduces g→cc
  - mCT > 150, 200, 250 GeV   reduces tt
- Dominant backgrounds are normalized in CRs containing events with 2 c-tagged jets:
  - Z(νν)+jets: two $e^+e^-/\mu^+\mu^-$ leptons in Z window
  - top: two $e^+ \mu^-/\mu^+e^-$ leptons
  - W+jets: 1 lepton, mT in W window





$$m_{CT}^2 = \left(E_T^{c_1} + E_T^{c_2}\right)^2 - \left|\mathbf{p}_T^{c_1} - \mathbf{p}_T^{c_2}\right|^2$$

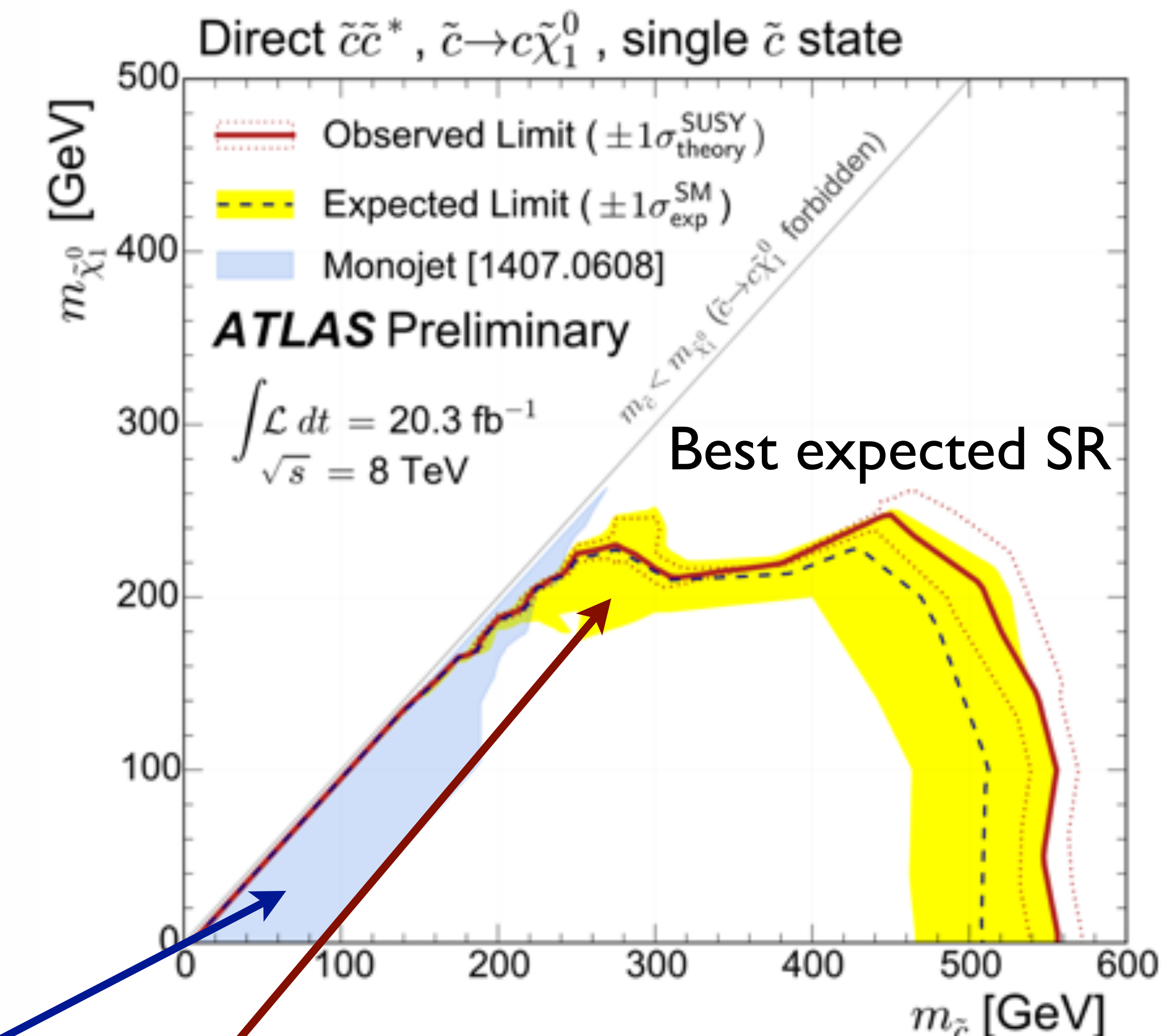
ATLAS-CONF-2014-063

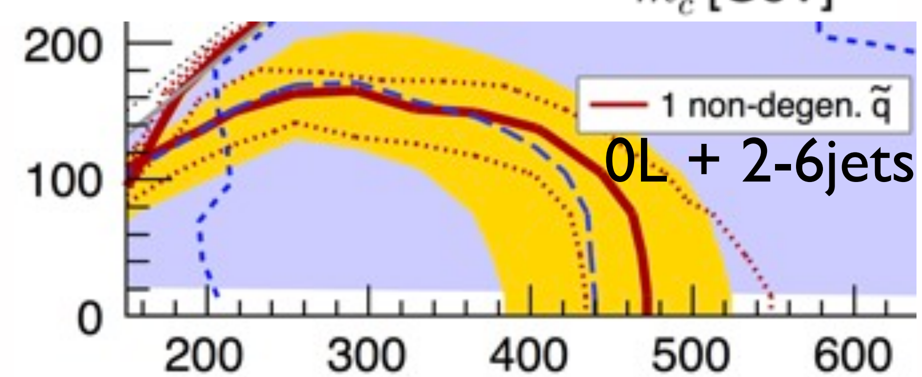
Search for Charm Squark, Results

New

- Dominant uncertainties originate from the limited number of events in the CRs ~20%, jet tagging and mis-tagging ~20%, jet energy scale ~10%

m_{CT} (GeV)	>150	>200	>250
Top	7.4 ± 2.7 (7.1)	3.9 ± 1.6 (3.7)	1.6 ± 0.7 (1.5)
Z+jets	14 ± 3 (13)	7.7 ± 1.7 (7.0)	4.3 ± 1.2 (3.9)
W+jets	7.2 ± 4.5 (7.4)	4.1 ± 2.6 (4.2)	1.9 ± 1.2 (1.9)
Multijets	0.3 ± 0.3	0.2 ± 0.2	0.05 ± 0.05
Others	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
Total	30 ± 6	16 ± 3	8.2 ± 1.9
Data	**19**	**11**	**4**





Overlaying observed limit from the monojet-SR,

combining with c-tagged SR of the $\tilde{t} \to c\tilde{\chi}_1^0$ search

Limit on charm squark mass ~ 540 GeV , for massless LSP
improves significantly on single light flavor squark limit
improved sensitivity for heavier LSP

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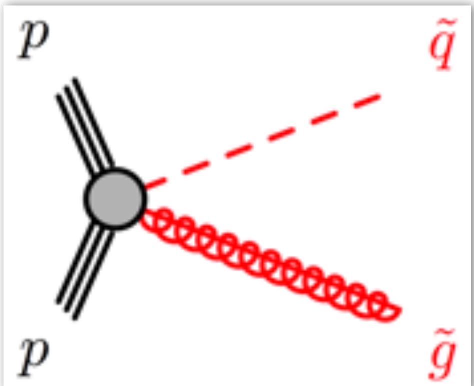
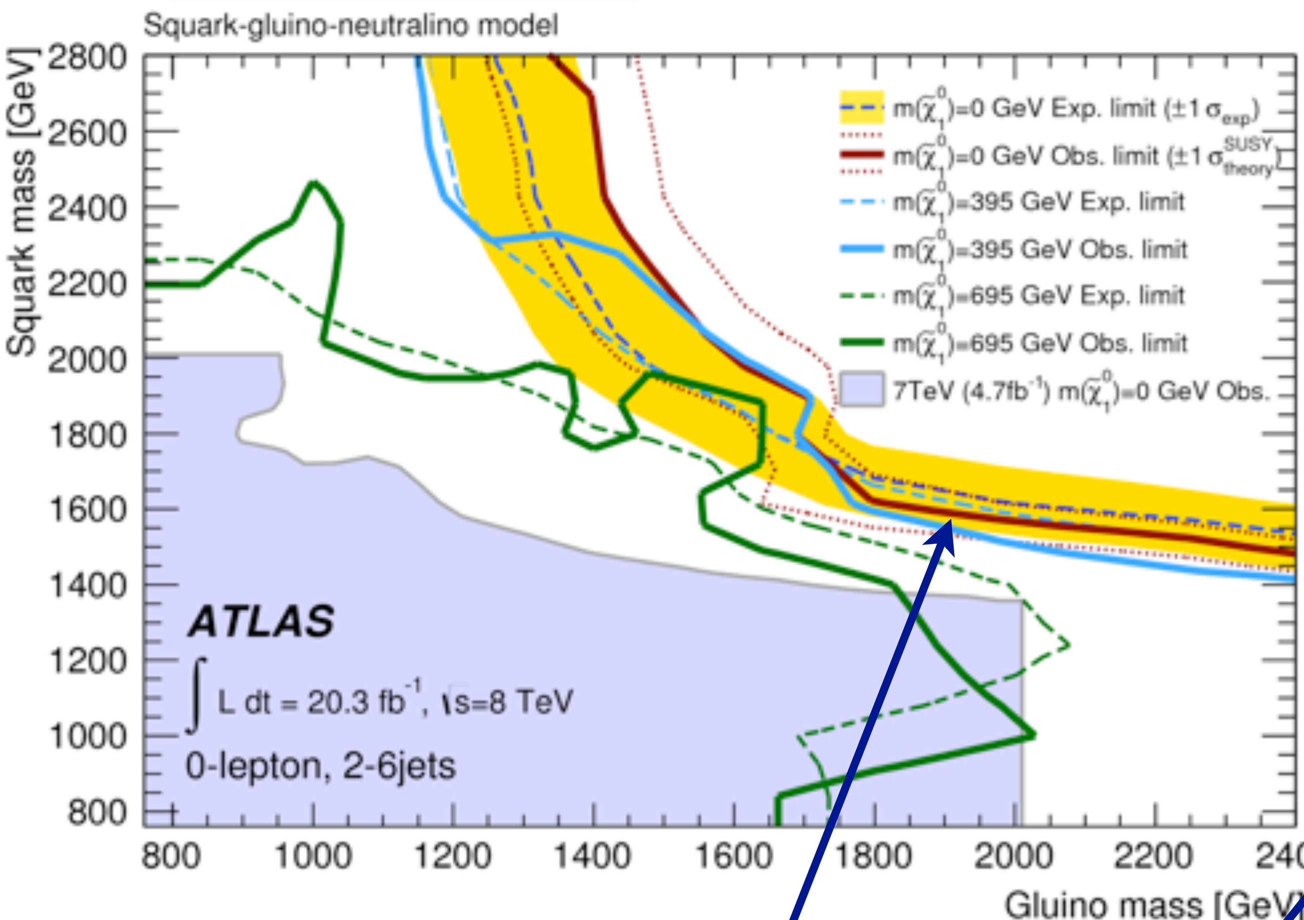
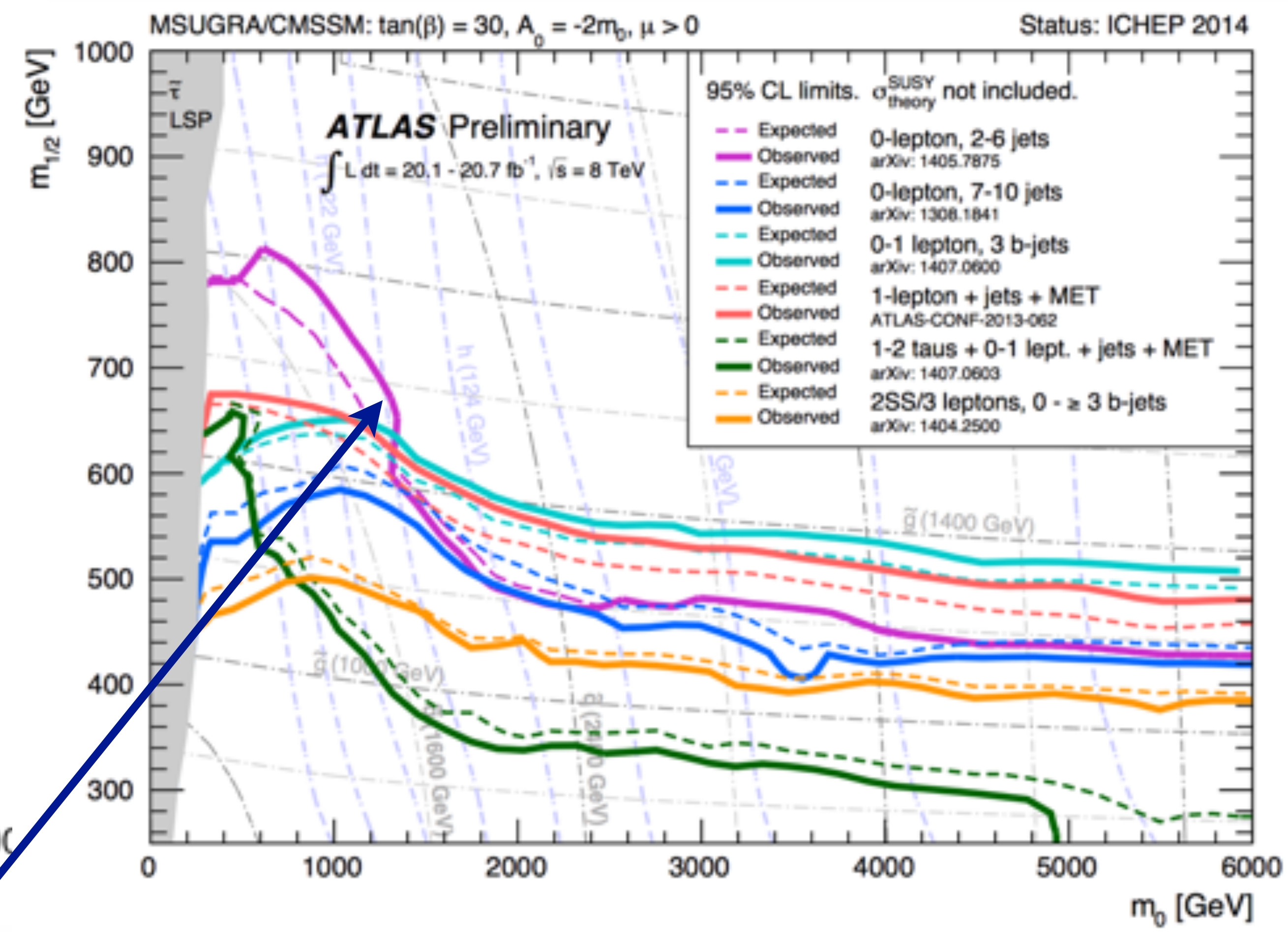
Sensitivity to Gluinos and Squarks



- When gluinos and squarks have similar masses, the associated production of squarks and gluinos is available with cross-sections 1 order of magnitude larger than the gluino production
  - substantial increase of sensitivity to squarks





Compare to ~ 900 GeV in decoupled scenarios

- Full SUSY model with gravity mediated SUSY breaking and with mH ~ 125 GeV
- All SUSY processes are present in the model (only strong production considered in the limit)

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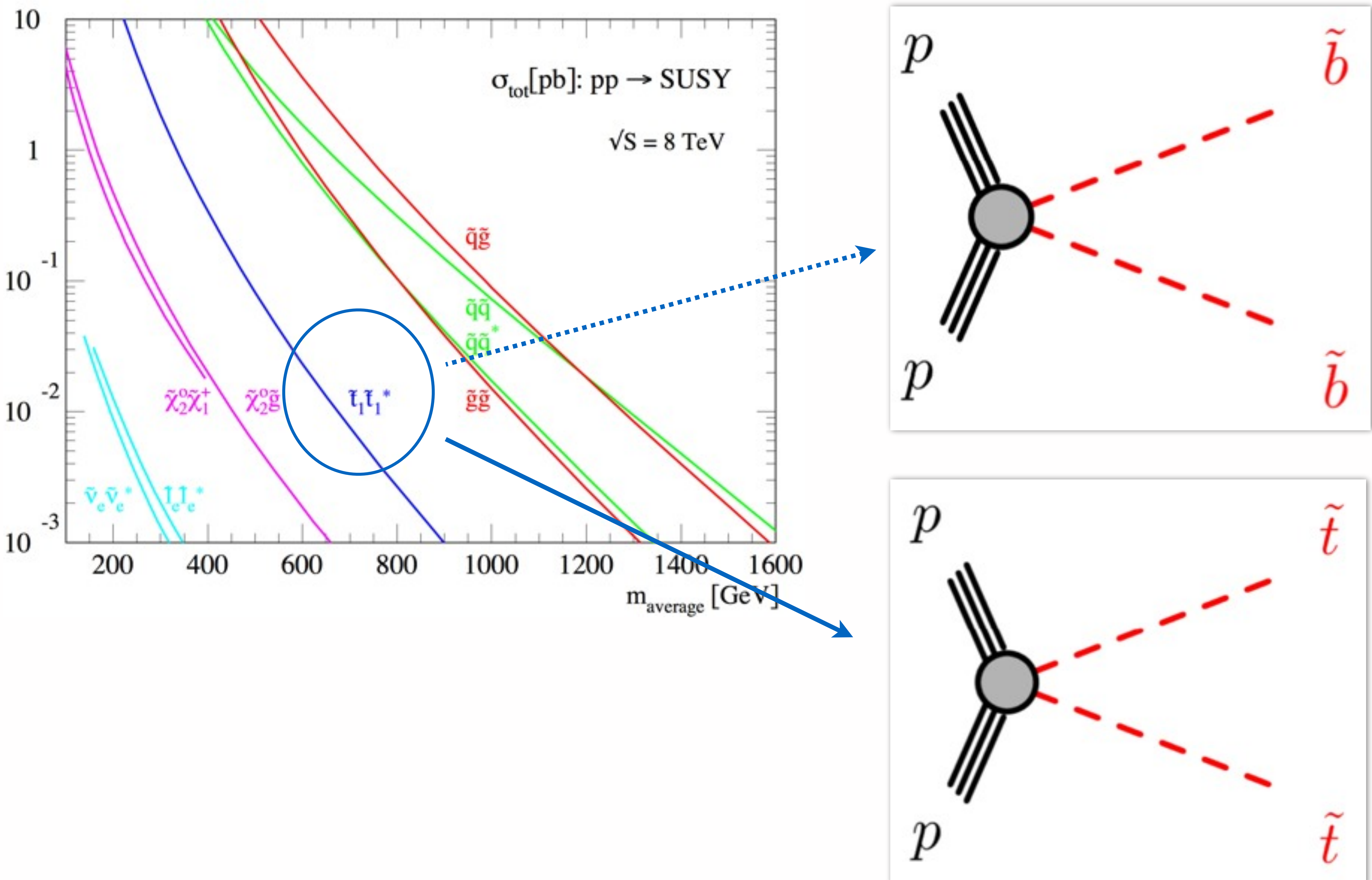
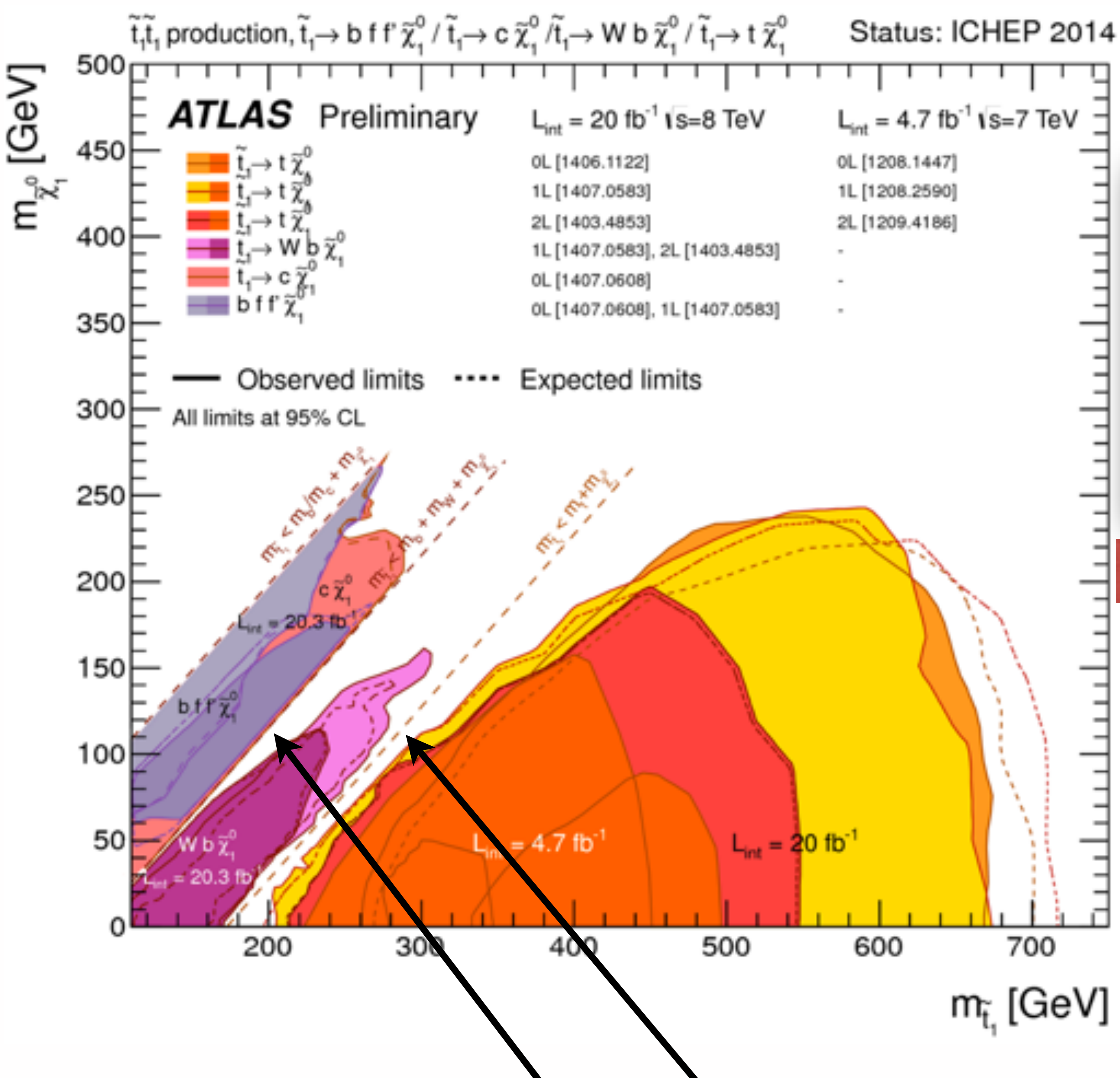
Search for Pair Production of Stops and Sbottoms



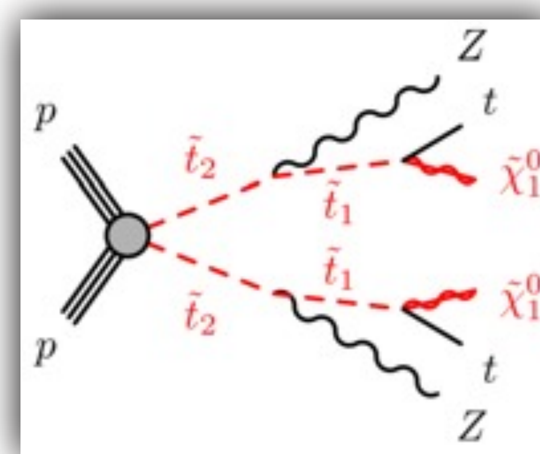
Summary of Stop Searches (No Chargino in Decays)



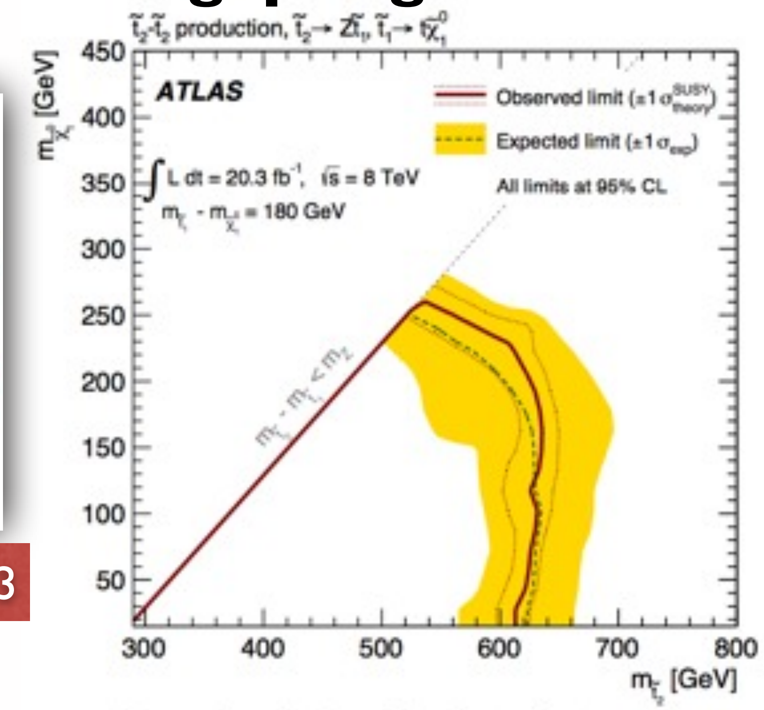
- Signal similar to WW / tt backgrounds

Stop mass > 670 GeV, for massless LSP

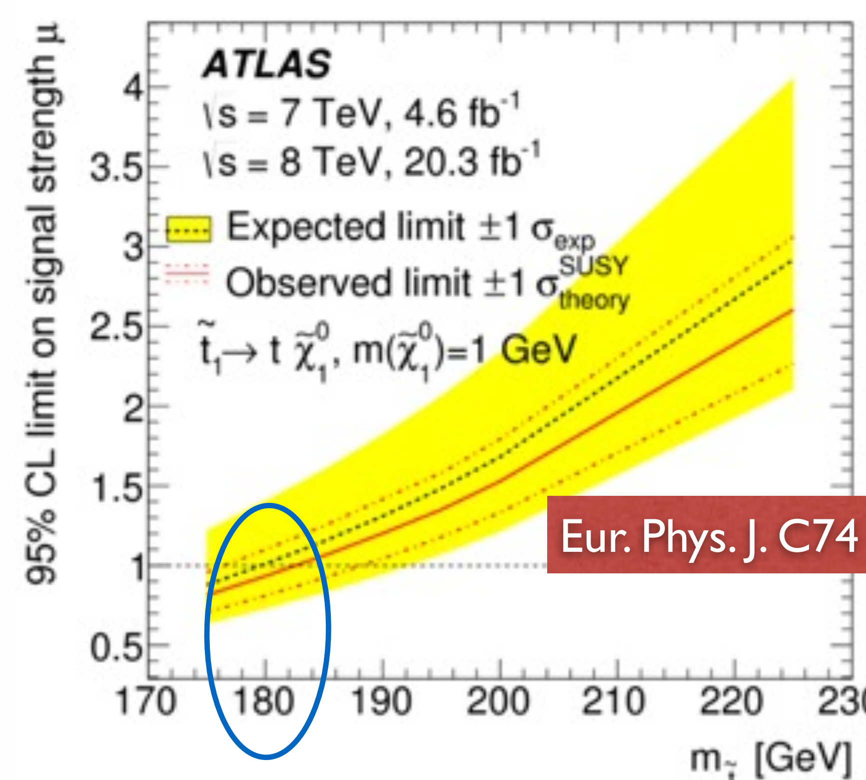
Search for Stop2 with Z in final state to cover gap region



Eur. Phys. J. C (2014) 74:2883



For mStop ~ mTop, constrains from XS measurement



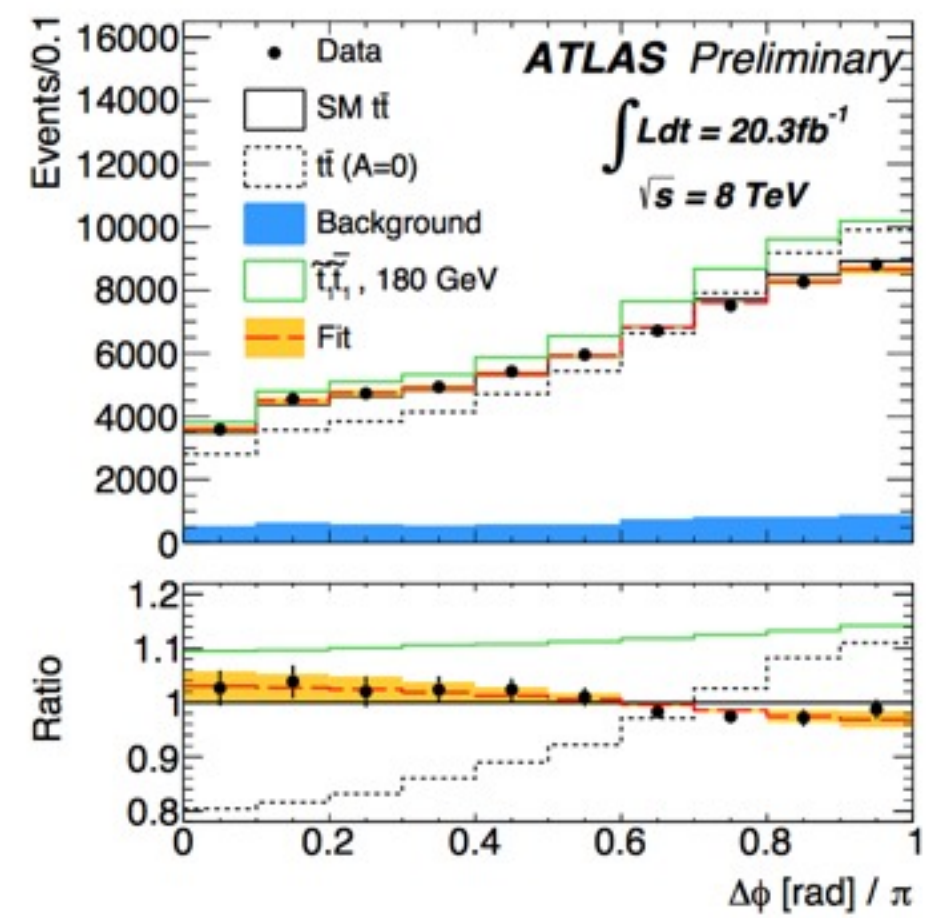
Eur. Phys. J. C74 (2014) 3109

Measurement of Spin Correlation in tt Events

- The measurement of spin correlation A between the t-tbar pair is carried out in events with 2 leptons
  - standard top di-lepton selection applied

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

- The strength is determined from the angular distributions of the top's decay particles, $\Delta\varphi(l+, l-)$, in the lab frame
- Orientation of the top spin of top quarks produced in pairs is sensitive to pairs of stops
- The first measurement of spin correlation in t-tbar pairs at $\sqrt{s}$ = 8 TeV is re-interpreted as a search for stop pair production in a region of parameter space mostly unexplored
  - stop mass ~ top mass
  - stop into RH-top quarks and a light neutralino



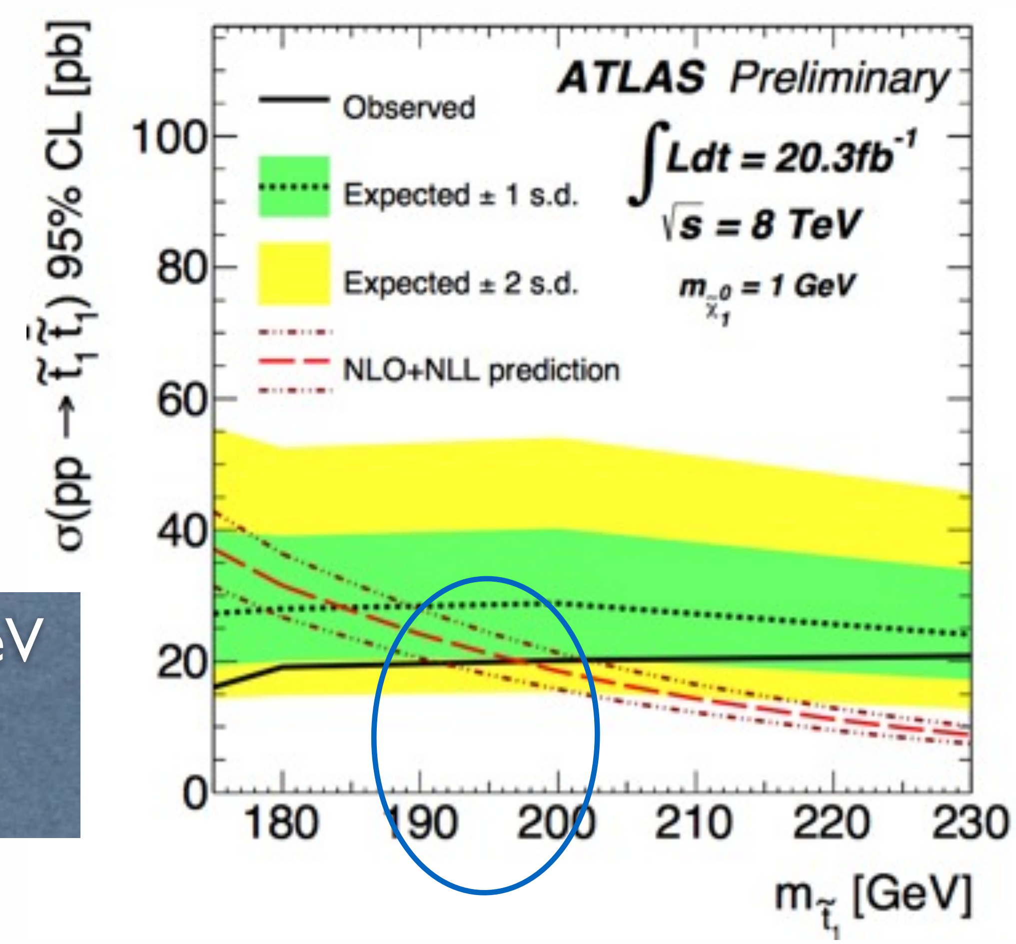
Measurement of Spin Correlation in tt Events

- Two templates, with and without spin correlation, are constructed and fitted to data.
  - Backgrounds modeled from MC
- $A = 0.38 \pm 0.04$, in agreement with the Standard Model prediction (in helicity basis) $A^{\mathrm{SM}}_{\mathrm{helicity}} = 0.318 \pm 0.005$

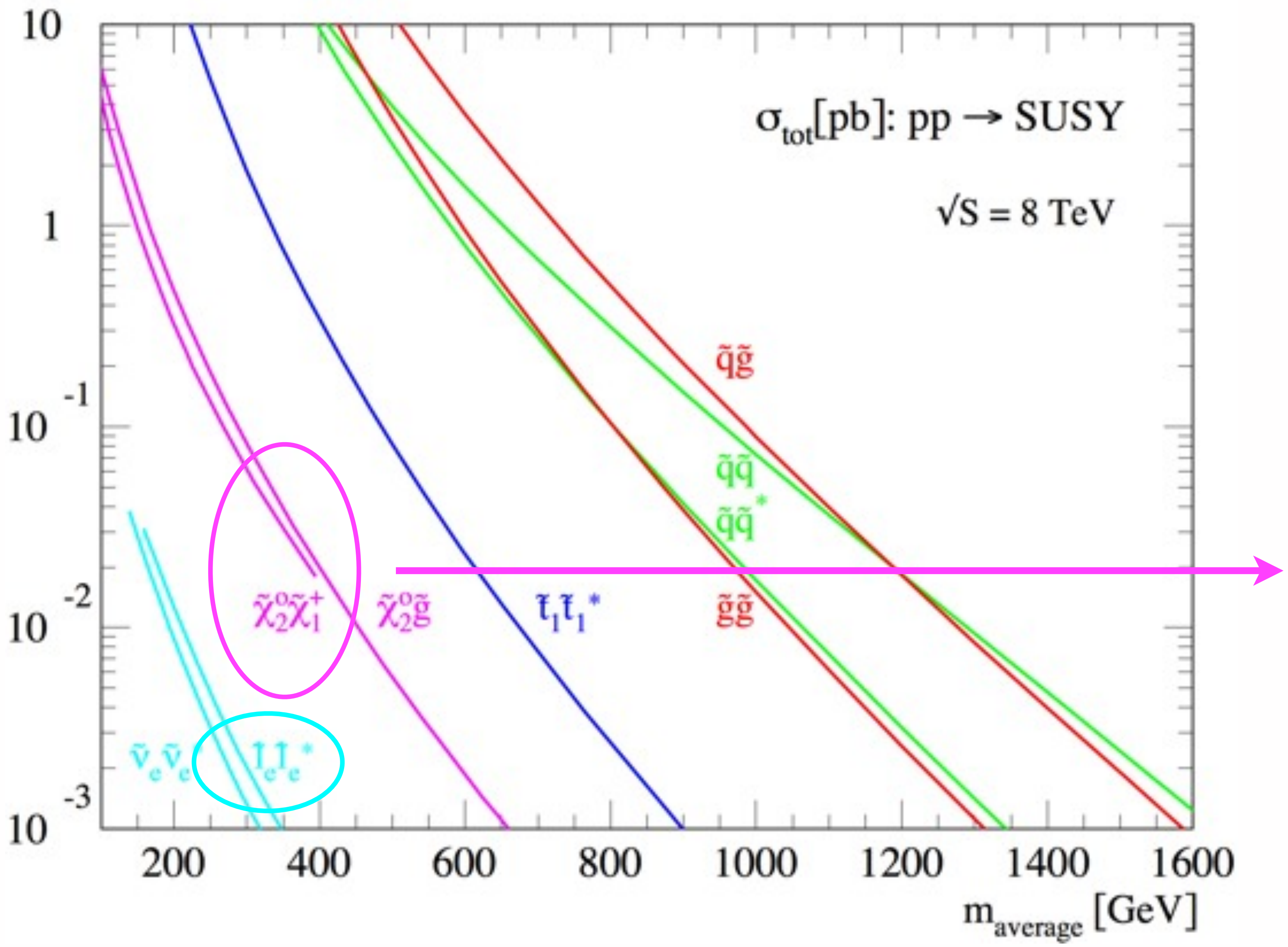
Process	Yield
$t\bar{t}$	54000^{+3400}_{-3600}
Z/γ^{*}+jets	2800 ± 300
tV (single top)	2600 ± 180
$t\bar{t}V$	80 ± 11
WW, WZ, ZZ	180 ± 65
Fake Leptons	780 ± 780
Total non-$t\bar{t}$	6400 ± 860
Expected (E)	60000^{+3500}_{-3700}
Observed (O)	60424
$\tilde{t}_1\bar{\tilde{t}}_1$ ($m_{\tilde{t}_1} = 180$ GeV, $m_{\tilde{\chi}^0_1} = 1$ GeV)	7100 ± 1100

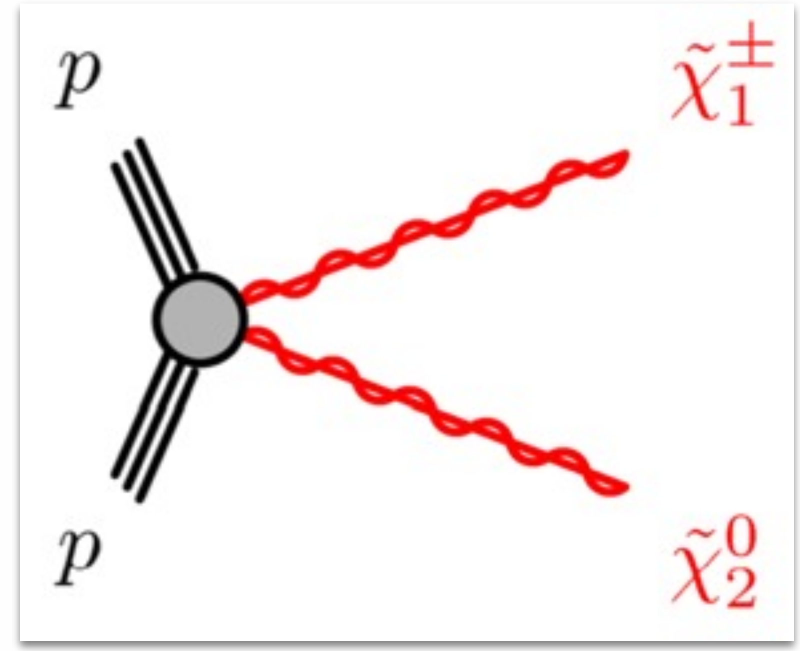
Source of uncertainty	Δf_{SM}
Detector modeling	
Lepton reconstruction	± 0.01
Jet energy scale	± 0.02
Jet reconstruction	± 0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$	< 0.01
Fake leptons	< 0.01
b-tagging	< 0.01
Signal and background modeling	
Renormalization/factorization scale	± 0.05
MC generator	± 0.03
Parton shower and fragmentation	± 0.06
ISR/FSR	± 0.06
Underlying event	± 0.04
Color Reconnection	± 0.01
PDF Uncertainty	± 0.05
Background	± 0.01
MC statistics	± 0.04
Total systematic uncertainty	± 0.13
Data statistics	± 0.05

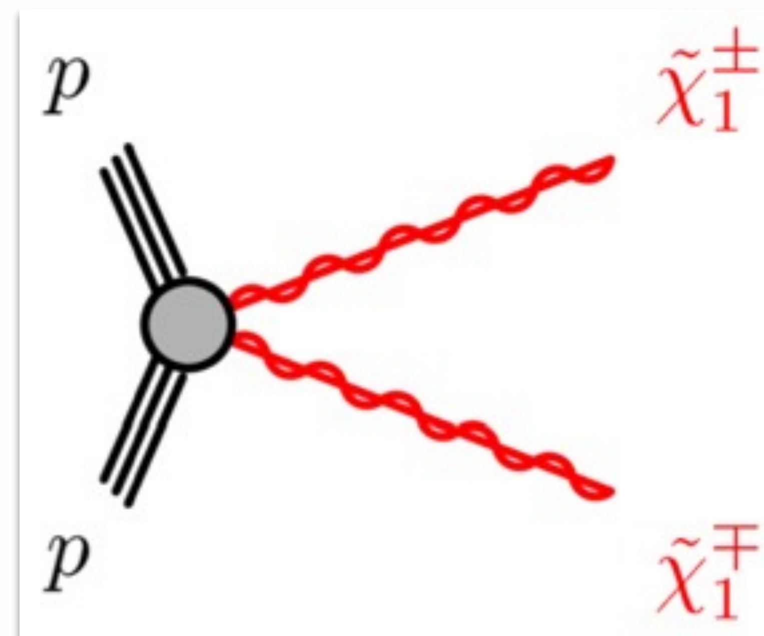
Stop mass below 191 GeV are excluded for mLSP=1GeV



Searches for Electroweak Production

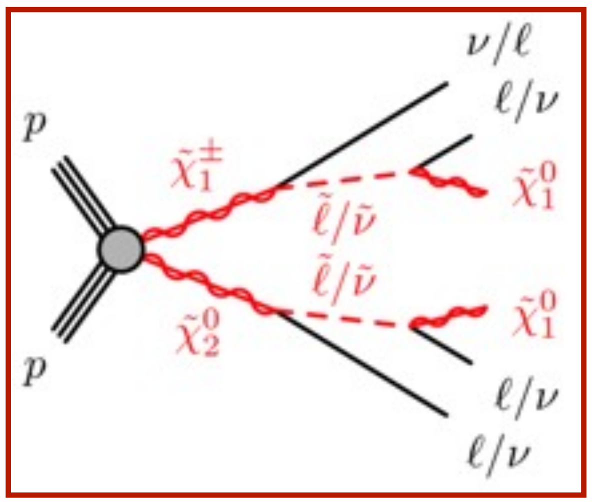


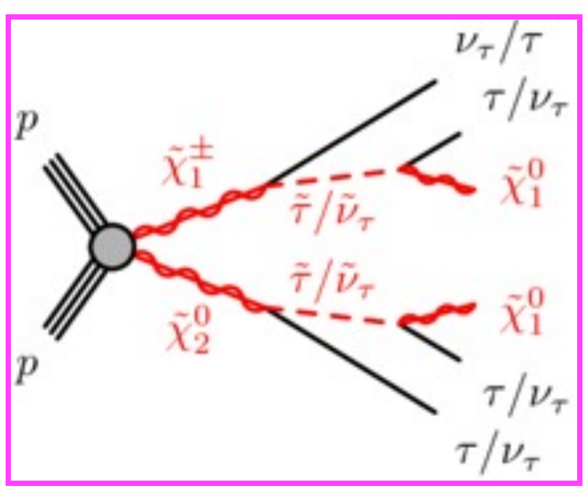


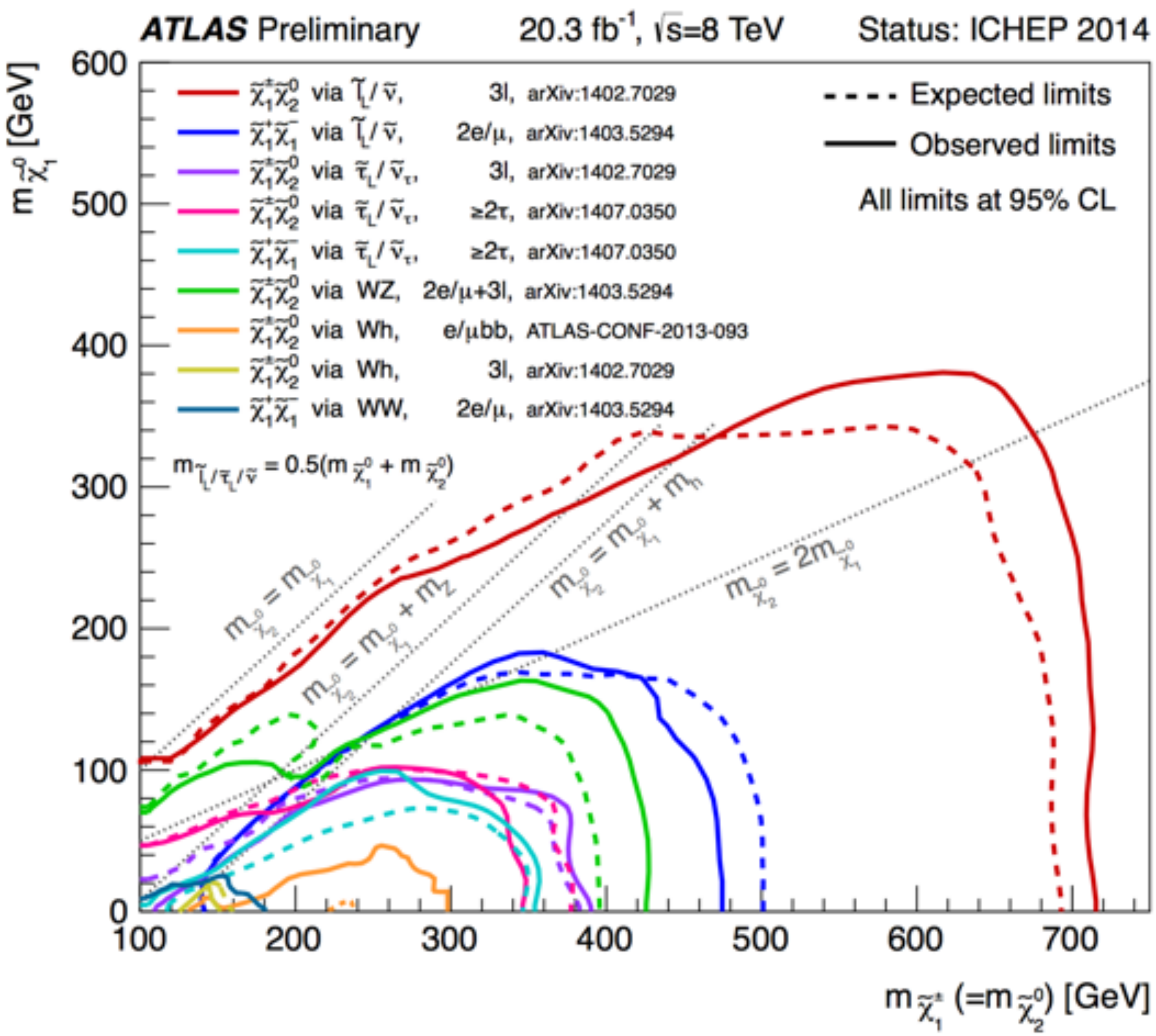


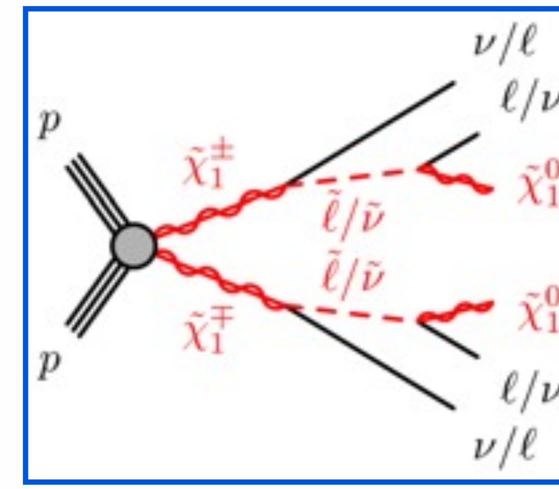
Search for Electroweakinos

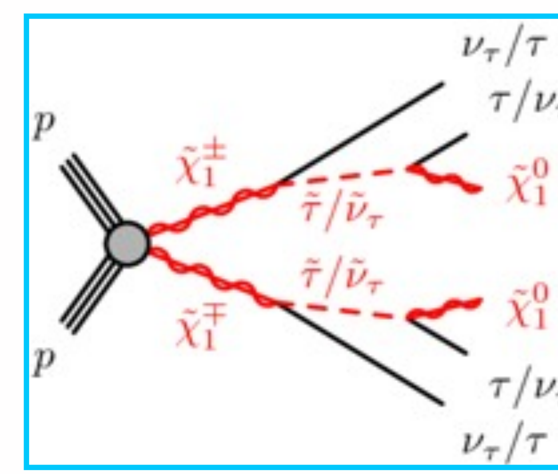
Challenging searches due to very small production cross-section and significant irreducible background from diboson but highly motivated as electroweakinos expected to be light







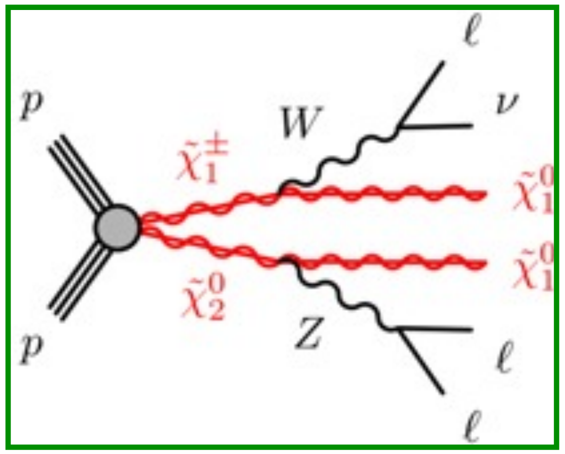


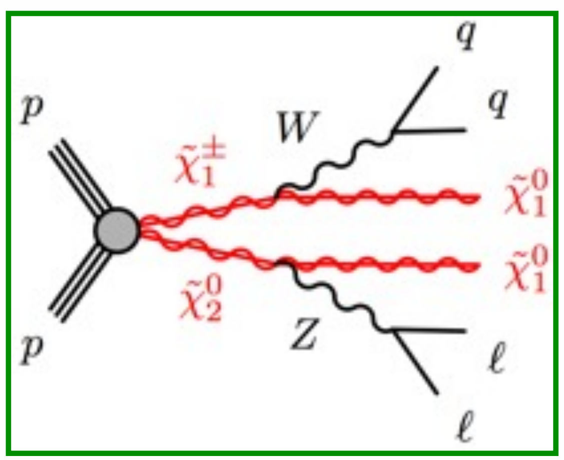


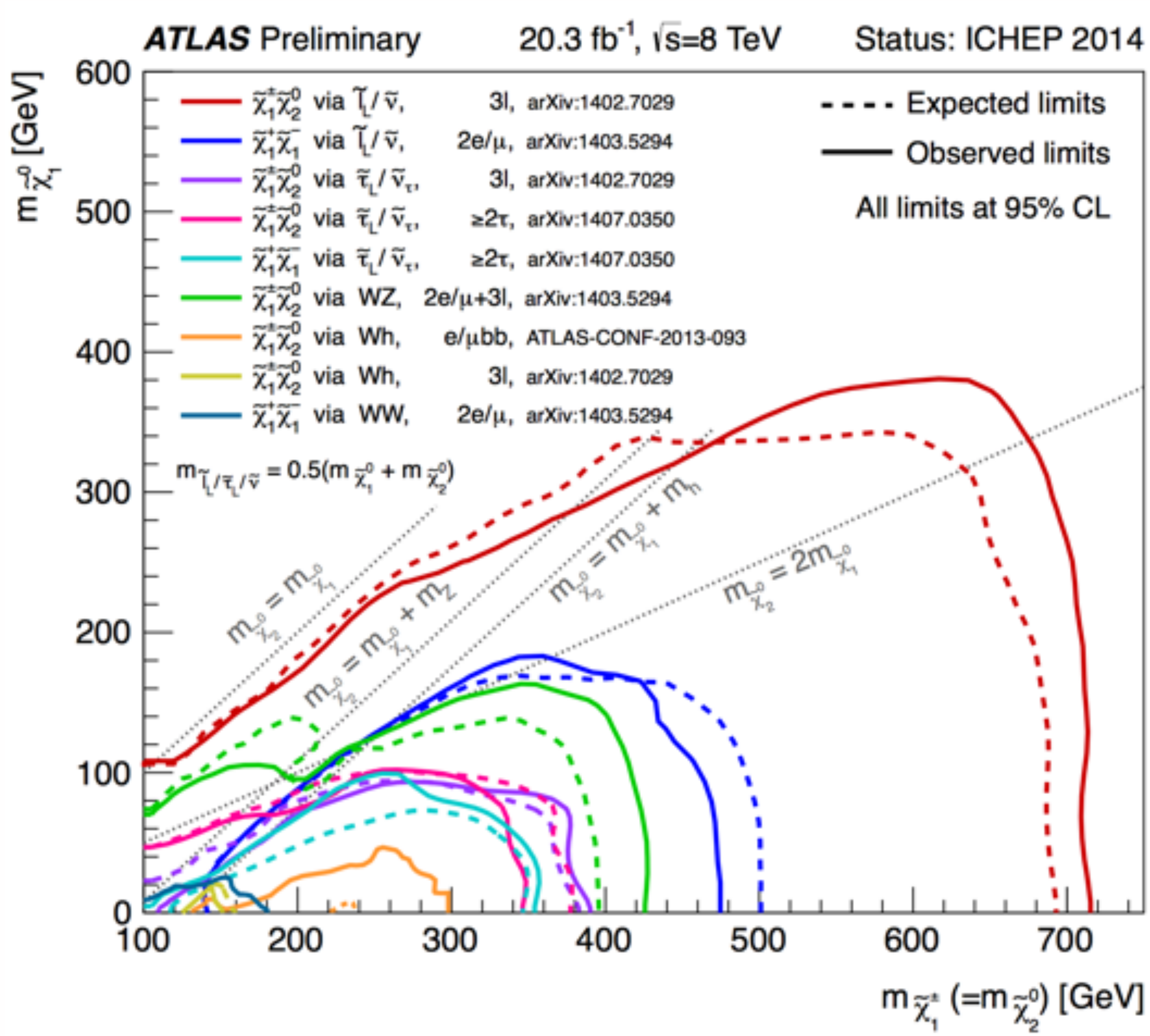
Electroweakino mass > 700 GeV in models with light sleptons
Less stringent constraint at ~400 GeV when only staus are light

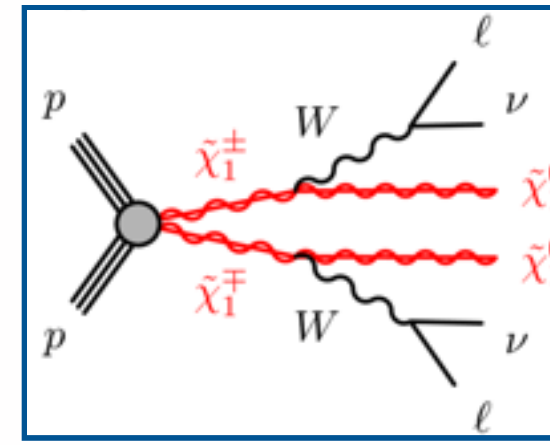
Search for Electroweakinos

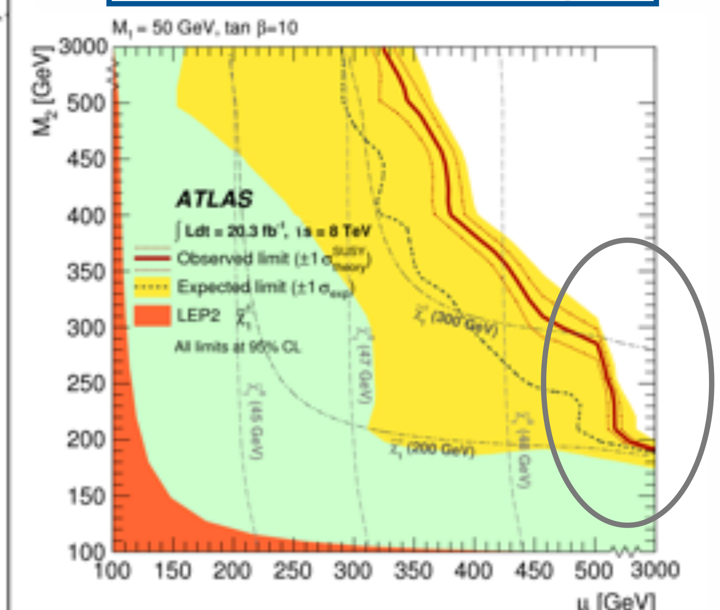
Challenging searches due to very small production cross-section and significant irreducible background from diboson but highly motivated as electroweakinos expected to be light









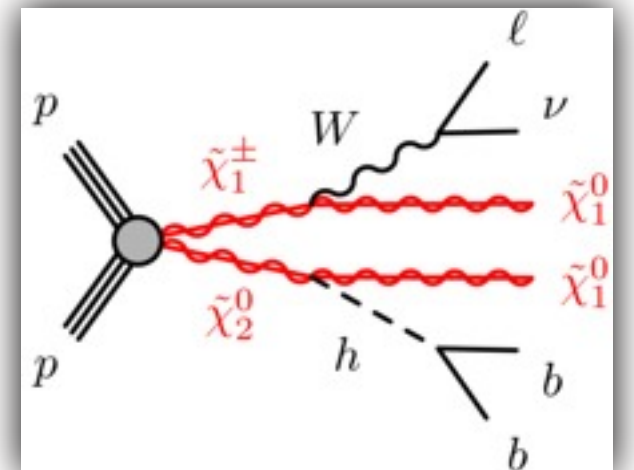


Dedicated search for Higgs in decays needed for wino like EWK-inos

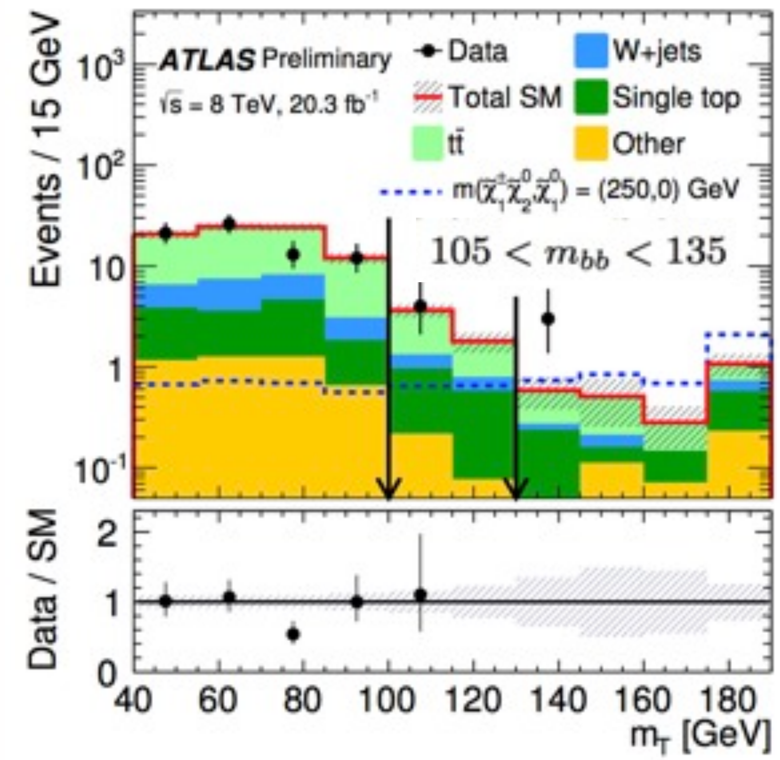
Electroweakino mass > 400 GeV in models with decay via gauge bosons (heavy sleptons)

Higgs Bosons as Probes for EWK SUSY: 1Lbb channel

New



- Search based on events with 1L and two b-tagged jets
- Signal from background discrimination based on ETmiss, mT, and mCT observables and by binning in mbb

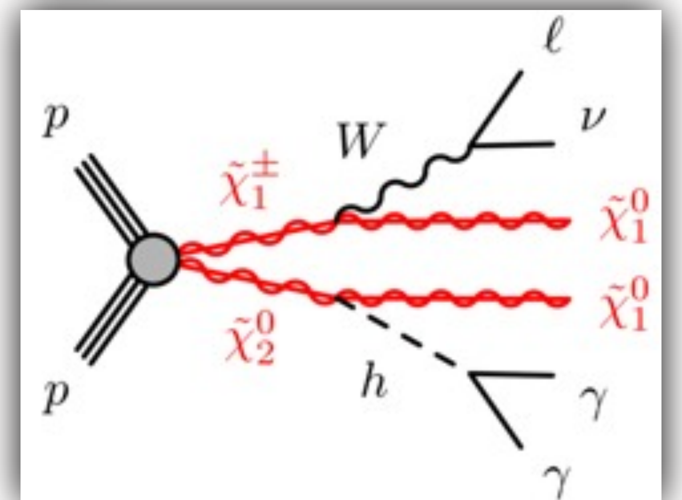


- Dominant backgrounds are tt and W+j determined from simultaneous fit of MC based prediction to data in dedicated control and signal region sidebands
- All systematic uncertainties are accounted for with nuisance parameters constrained within their uncertainties
    - Dominant uncertainty tt modeling ~25%

	SRℓbb-1 ($105 < m_{bb} < 135$)	SRℓbb-2 ($105 < m_{bb} < 135$)	SRℓbb-1 (m_{bb} sidebands)	SRℓbb-2 (m_{bb} sidebands)	CRℓbb-T	CRℓbb-W	VRℓbb-1	VRℓbb-2
Observed events	4	3	14	10	625	1547	885	235
SM expectation	6.0 ± 1.3	2.8 ± 0.8	13.1 ± 2.4	8.9 ± 1.7	642 ± 25	1560 ± 40	880 ± 90	245 ± 17
$t\bar{t}$	3.8 ± 1.2	1.4 ± 0.7	8.0 ± 2.4	3.1 ± 1.4	607 ± 25	680 ± 60	690 ± 90	141 ± 18
W + jets	0.6 ± 0.3	0.2 ± 0.1	2.7 ± 0.5	1.7 ± 0.3	11 ± 2	690 ± 60	99 ± 12	62 ± 8
Single top	1.3 ± 0.4	0.7 ± 0.4	1.9 ± 0.6	2.5 ± 1.1	20 ± 4	111 ± 14	80 ± 10	27 ± 4
Other	0.3 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	1.5 ± 0.2	4 ± 1	76 ± 8	16 ± 2	15 ± 1

Higgs Bosons as Probes for EWK SUSY: 1Lγγ channel

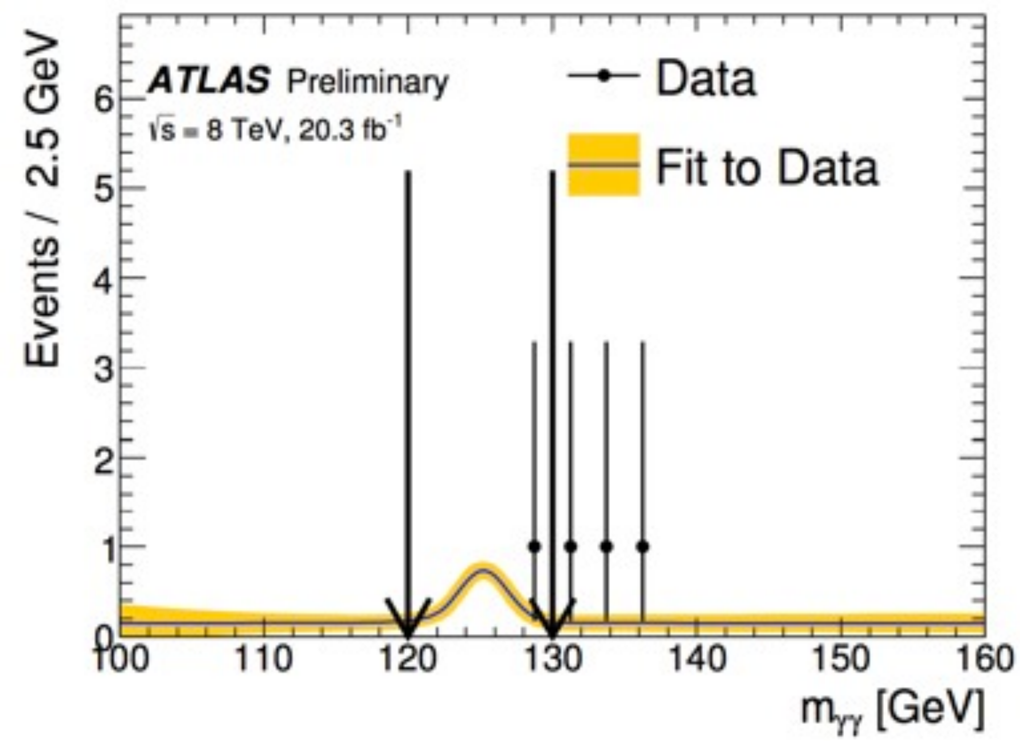
New



- Search based on events with 1L and two photons
  - Primary vertex selection is based on a neural network algorithm based on tracks associated to each vertex and the direction of flight of the photons
- Signal from background discrimination based on ETmiss, mT(Wγi), and Δφ(W, h)

$$m_T^{W\gamma_i} = \sqrt{(m_T^W)^2 + 2E_T^W E_T^{\gamma_i} - 2\vec{p}_T^W \cdot \vec{p}_T^{\gamma_i}}$$

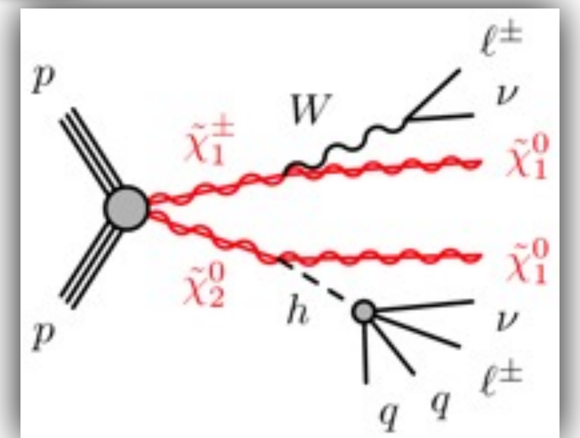
- mγγ distribution of non-Higgs backgrounds is modeled with an exponential function
- Higgs backgrounds are modeled with Crystal Ball function obtained from fit to MC samples
- Results of the background estimate are obtained from the fit to the sidebands only
- Dominant uncertainties are statistical from the mass sidebands



	SRℓγγ-1	SRℓγγ-2	VRℓγγ-1	VRℓγγ-2
Observed events	1	5	30	26
SM expectation	1.6 ± 0.4	3.3 ± 0.8	30.2 ± 2.3	20.4 ± 1.9
Non-Higgs	0.6 ± 0.3	3.0 ± 0.8	29.2 ± 2.3	19.8 ± 1.9
Wh	0.85 ± 0.02	0.23 ± 0.01	0.71 ± 0.02	0.29 ± 0.01
Zh	0.04 ± 0.01	0.02 ± 0.01	0.14 ± 0.02	0.05 ± 0.01
$t\bar{t}h$	0.14 ± 0.01	0.02 ± 0.01	0.11 ± 0.01	0.25 ± 0.01

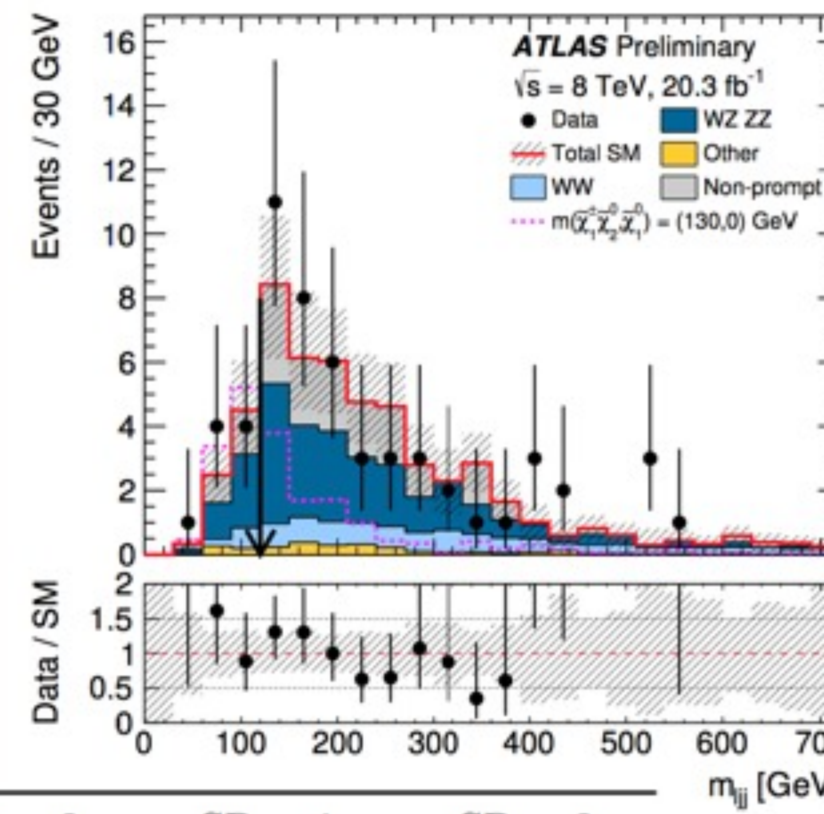
Higgs Bosons as Probes for EWK SUSY: 2 SS channel

New



- Search based on events with 2 same-sign (SS) leptons
  - 1 to 3 central jets, no b-tag with 80% working point, no forward jets
  - Signal and background discrimination based on ETmissRel, meff, mTmax, mlj mljj

- The dominant irreducible background (WZ, ZZ) is determined from MC
- Non-prompt component estimated from data with Matrix Method
- Charge-flip contribution estimated from MC applying charge-flip probability obtained from data
- Background modeling is validated in VRs

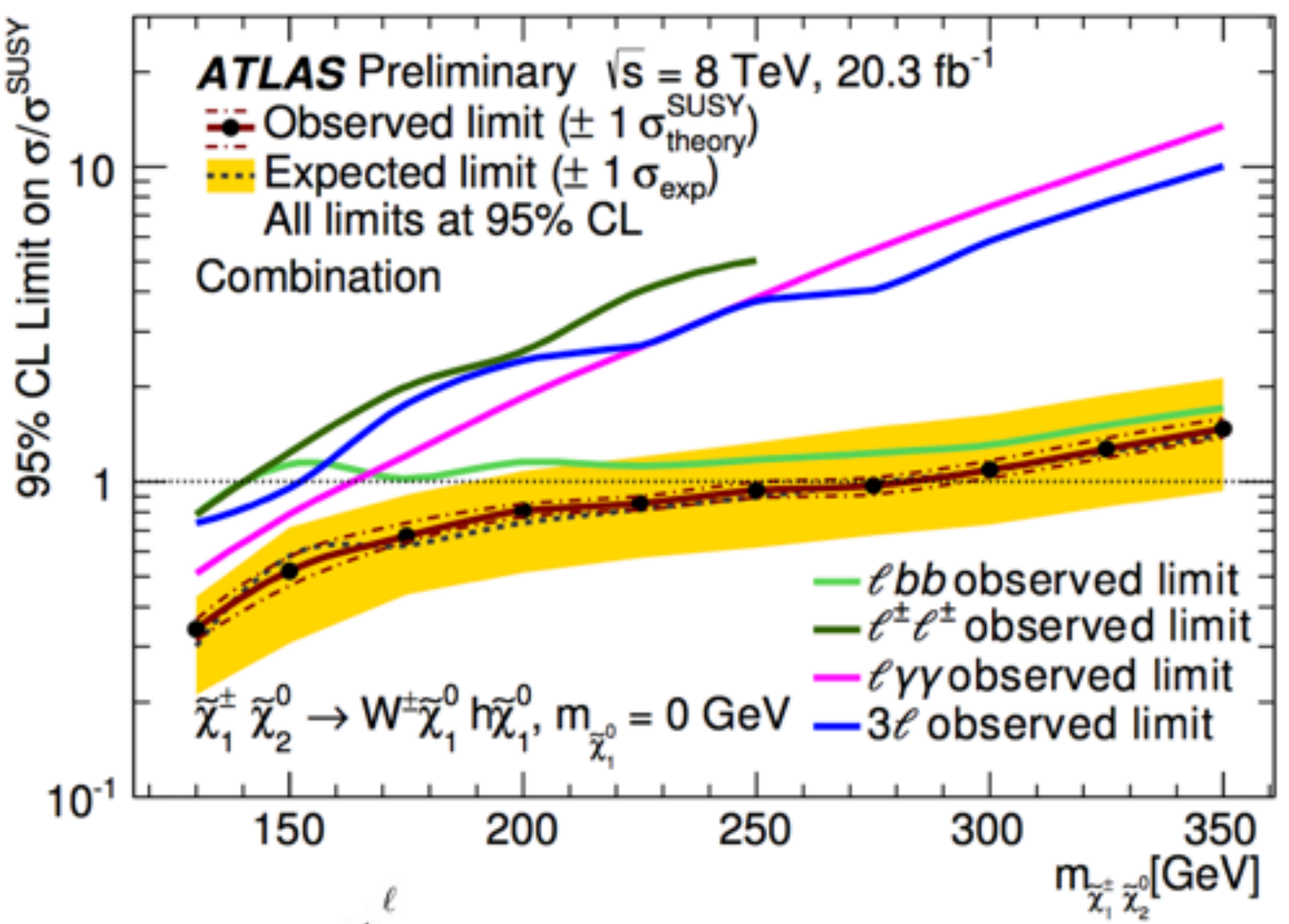


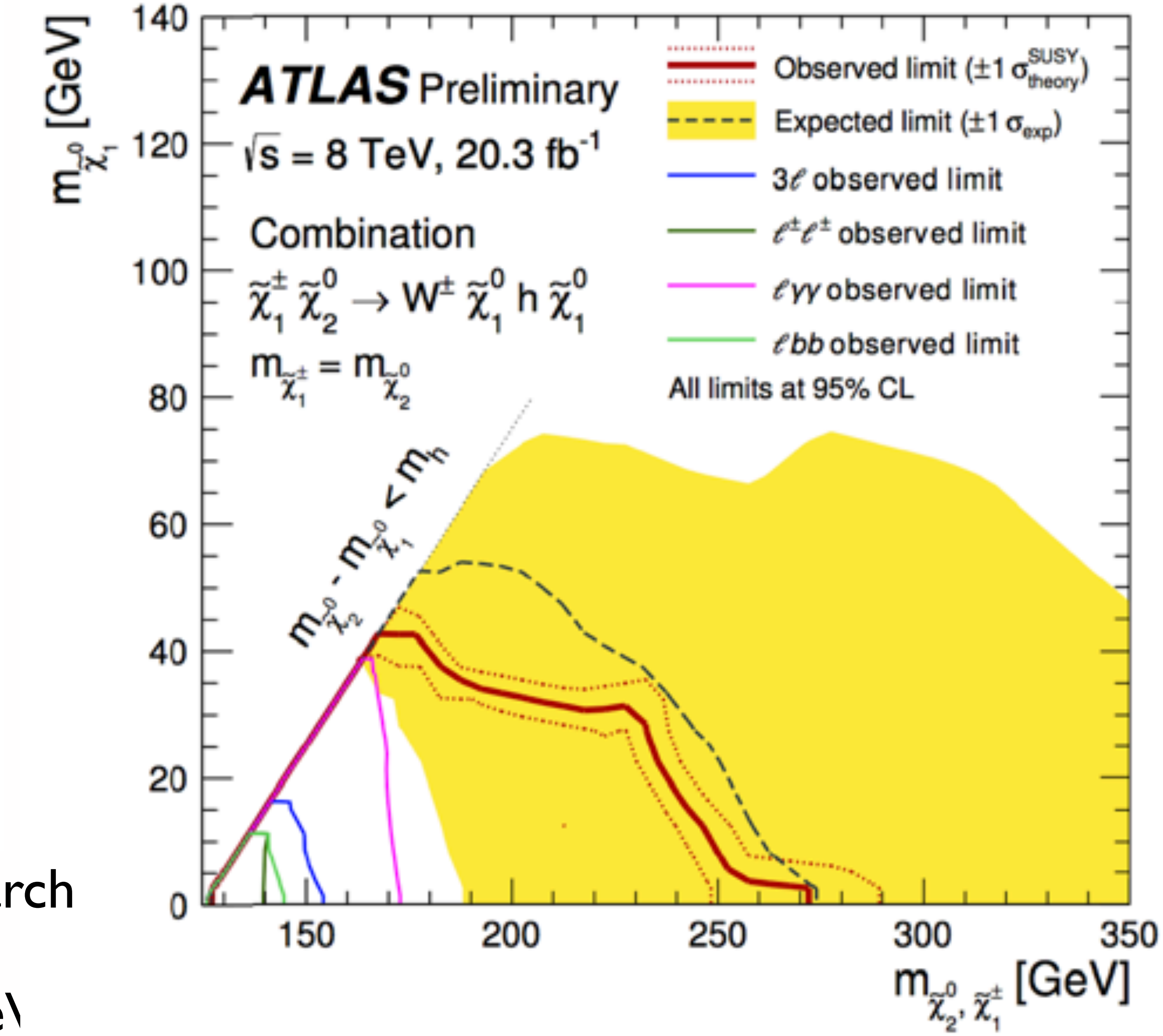
	SRee-1	SRee-2	SR$\mu\mu$-1	SR$\mu\mu$-2	SR$e\mu$-1	SR$e\mu$-2
Observed events	2	1	6	4	8	4
SM expectation	6.0 ± 1.2	2.8 ± 0.8	3.8 ± 0.9	2.6 ± 1.1	7.0 ± 1.3	1.9 ± 0.7
Non-prompt	3.4 ± 1.0	1.6 ± 0.5	0.00 ± 0.20	0.3 ± 0.4	3.0 ± 0.9	0.48 ± 0.28
WZ, ZZ	2.2 ± 0.6	0.7 ± 0.4	3.4 ± 0.8	1.8 ± 0.9	3.3 ± 0.8	1.1 ± 0.5
WW	0.33 ± 0.31	0.22 ± 0.23	0.24 ± 0.29	0.4 ± 0.5	0.4 ± 0.4	0.23 ± 0.26
Other	0.13 ± 0.13	0.31 ± 0.31	0.14 ± 0.14	0.06 ± 0.06	0.19 ± 0.17	0.09 ± 0.08

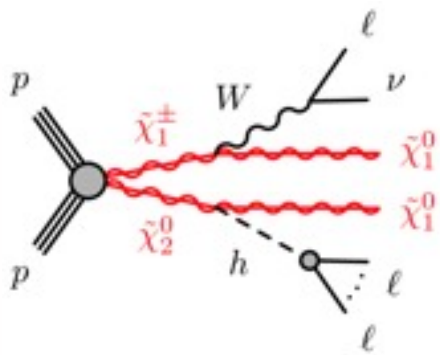
ATLAS-CONF-2014-062

Higgs Bosons as Probes for EWK SUSY

New







Combining 3 channels + 3L search

- For chargino mass < 170 Ge\
- For chargino mass > 170 1L+bb channel dominates
- 1L+bb sensitivity varies slowly due to decreasing XS and increasing acceptance

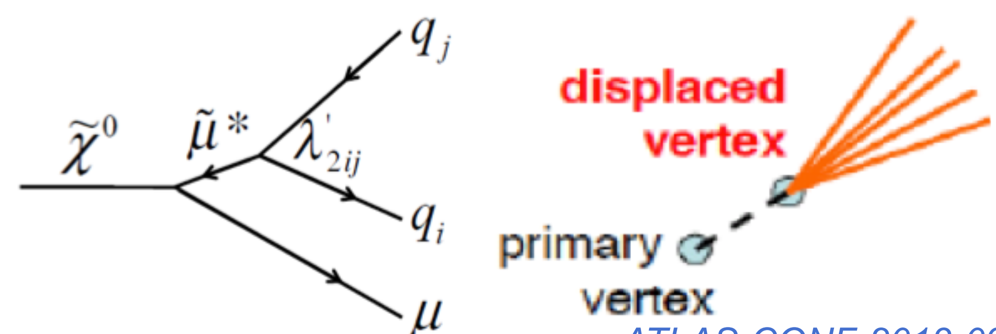
ATLAS-CONF-2014-062

Electroweakino mass > 250 GeV , for massless LSP in models with higgs in decay

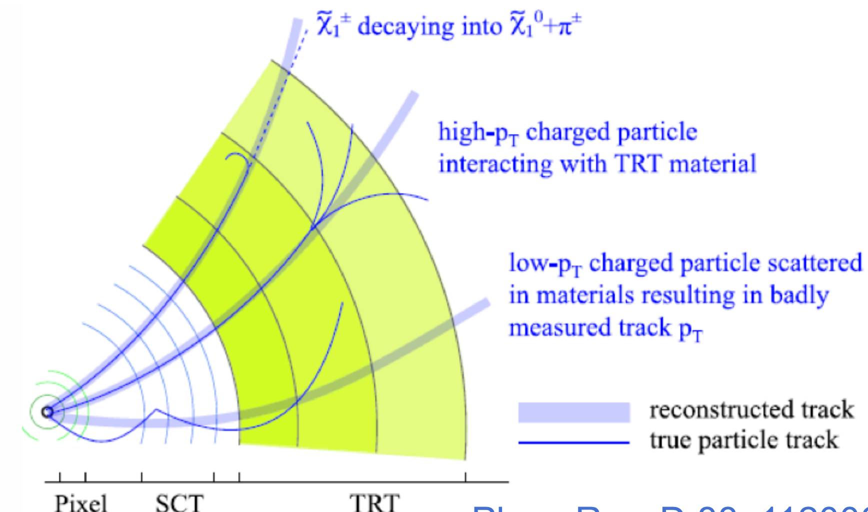
Long Lived SUSY

- **R-parity violating scenarios with lifetime in [0.1-1] ns**
  - long lived neutralinos due to small RPV couplings

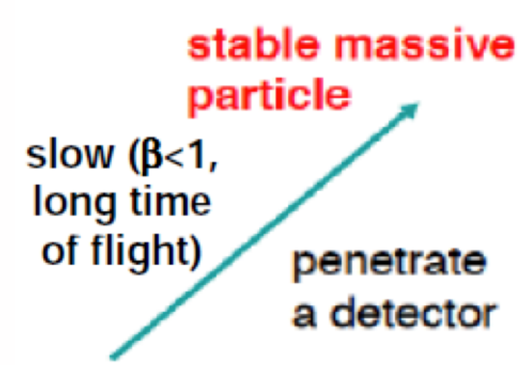
- **R-parity conserving scenarios with lifetime > 0.1 ns**
  - compressed scenarios, small mass gap between EWK-inos (AMSB like)
  - meta-stable and long lived gluinos due to heavy squarks (R-hadrons)
  - Long lived sleptons/neutralinos due to small coupling to gravitino

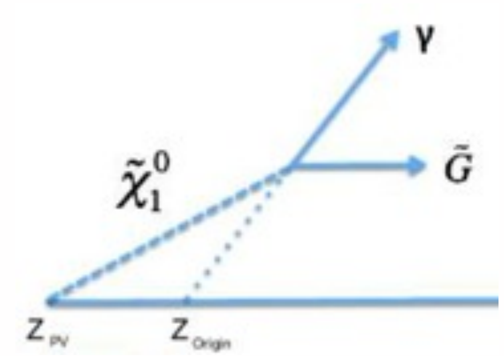


ATLAS-CONF-2013-092



Phys. Rev. D 88, 112006 (2013)



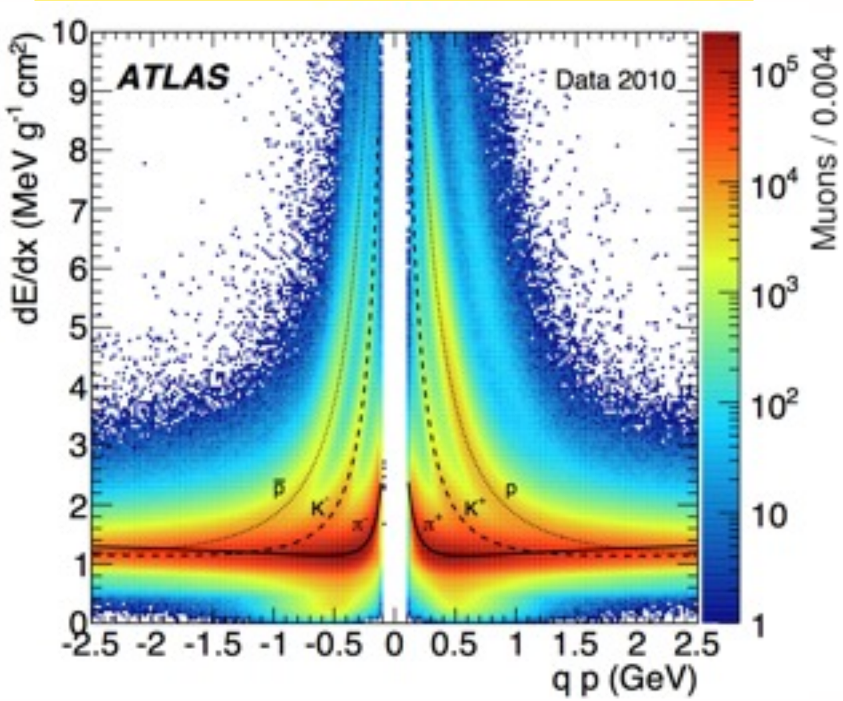


Heavy Long Lived Particles

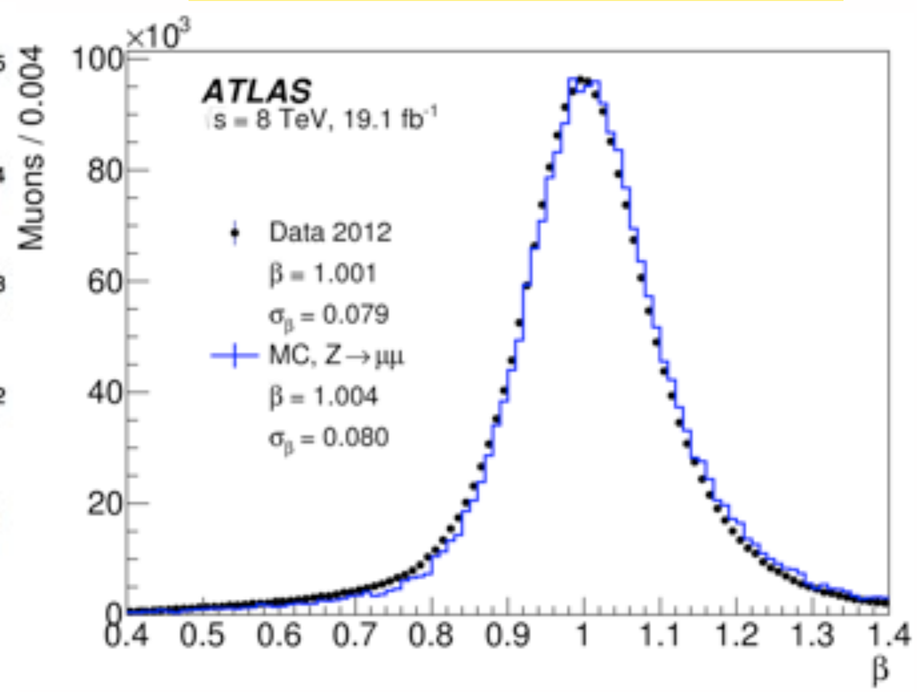
New

- Heavy long lived particles are predicted by Split SUSY, GMSB, LeptoSUSY, ...
- Final states containing long-lived sleptons, gluinos, squarks, charginos
- Heavy candidates move measurably slower than speed of light
- Mass $m=p/\beta\gamma$ used as discriminating observable
- Dedicated timing calibration and MC smearing using $Z \rightarrow \mu\mu$ events

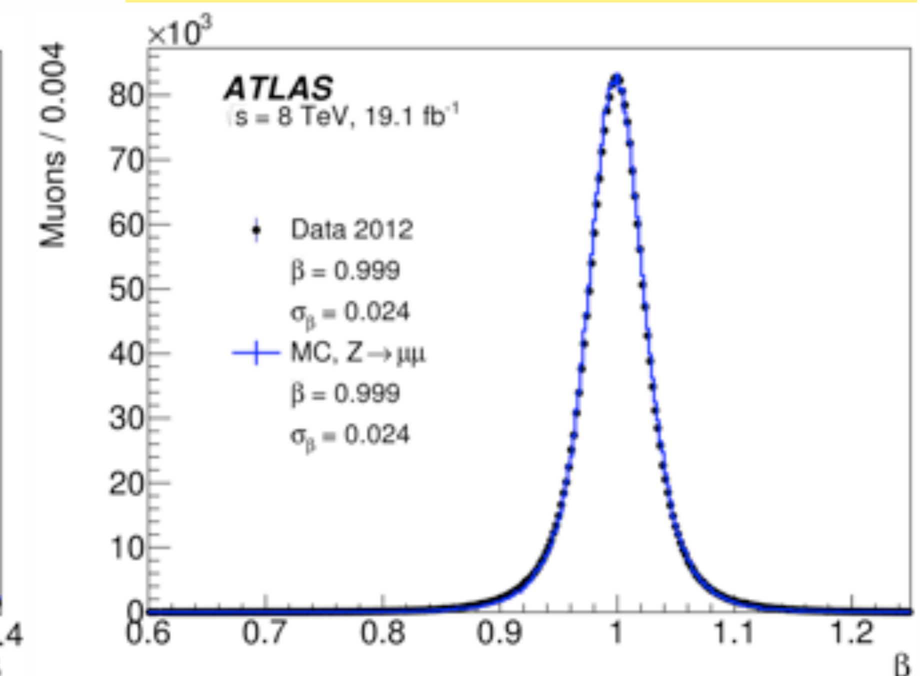
$\beta\gamma$ from dE/dx measurement in Pixel detector



β from time of flight in calorimeter system only



β from time of flight in calorimeter and muon system

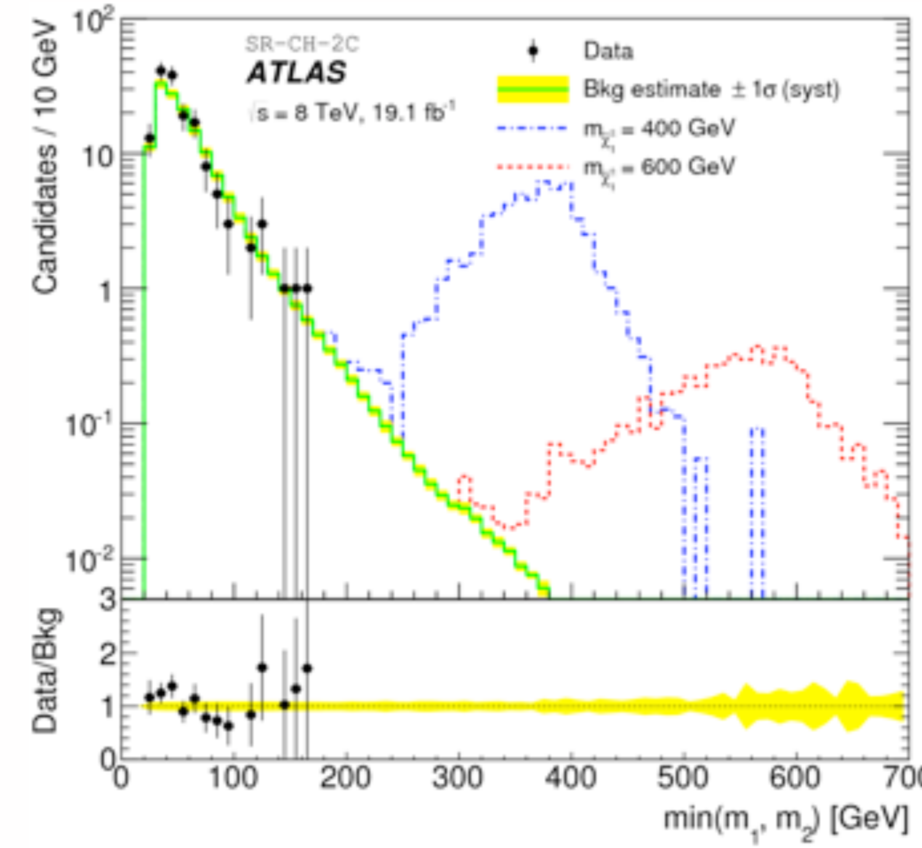


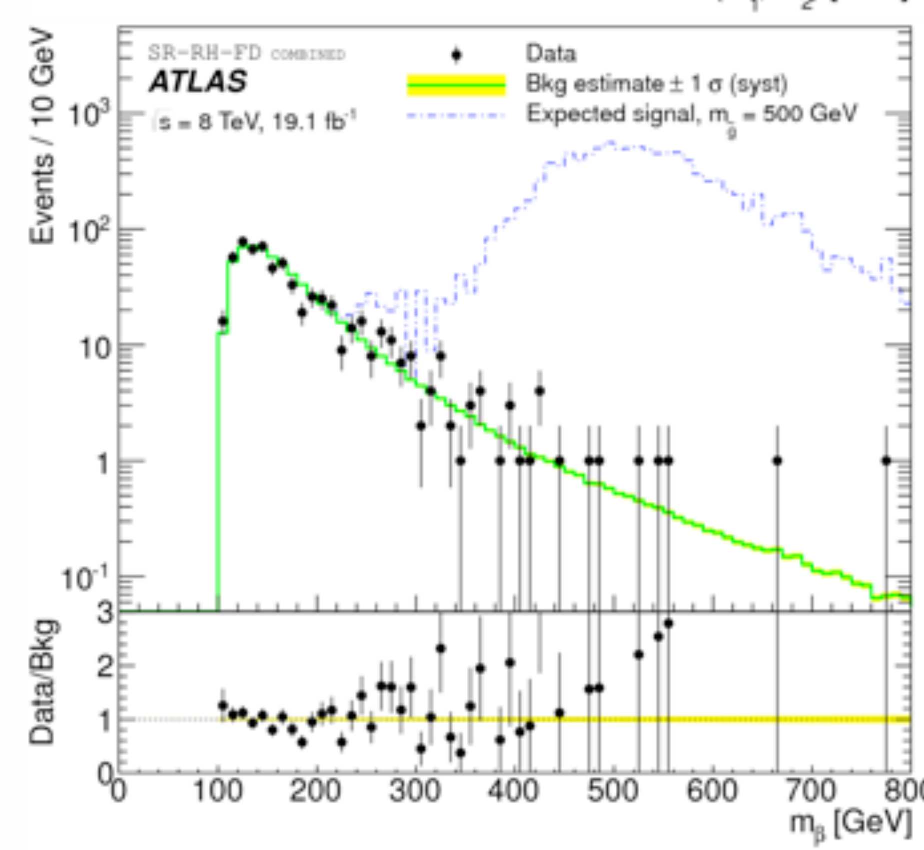
arXiv:1411.6795

Heavy Long Lived Particles

New

- Events selected by ETmiss and muon triggers
- Track pT and quality cuts
- Z-veto, cosmic veto, isolation requirements
- Signal regions with 1/2 candidates and β, βγ, mass cuts
- Background estimation
  - dominant background from high pT mis-measured muons
  - data-driven estimate based on random pairing of p and β
- Systematic uncertainties
  - Trigger efficiency of signal
  - β calibration
  - Initial state radiation for R-hadrons signal
  - ETmiss for charginos signal



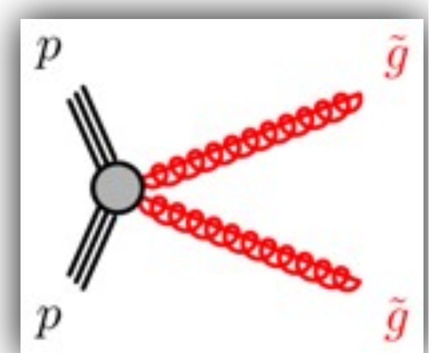


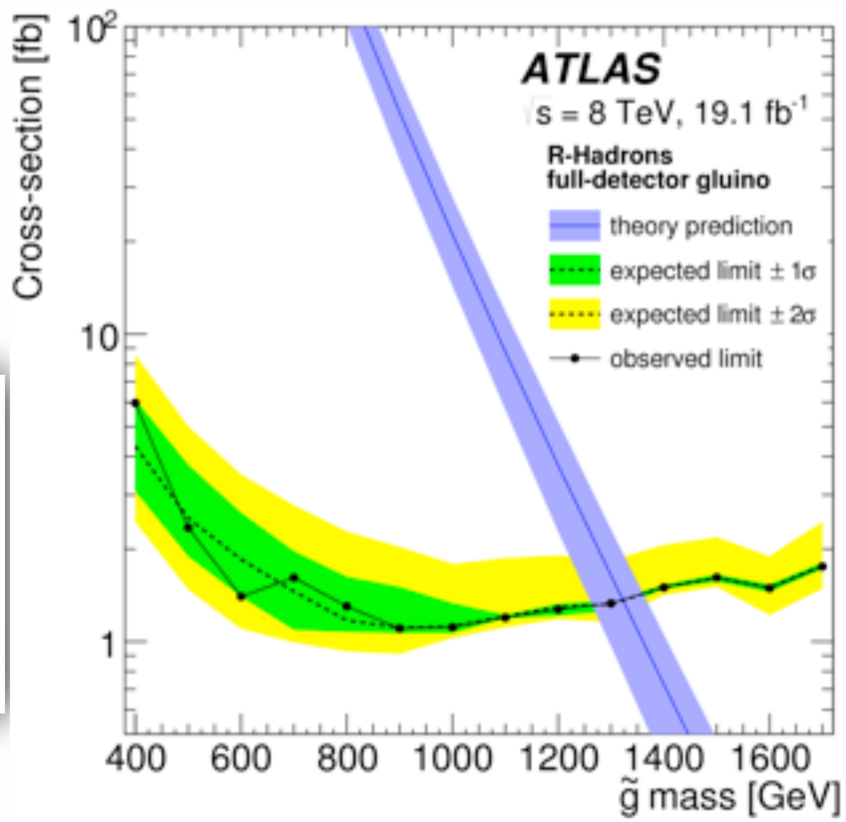
arXiv:1411.6795

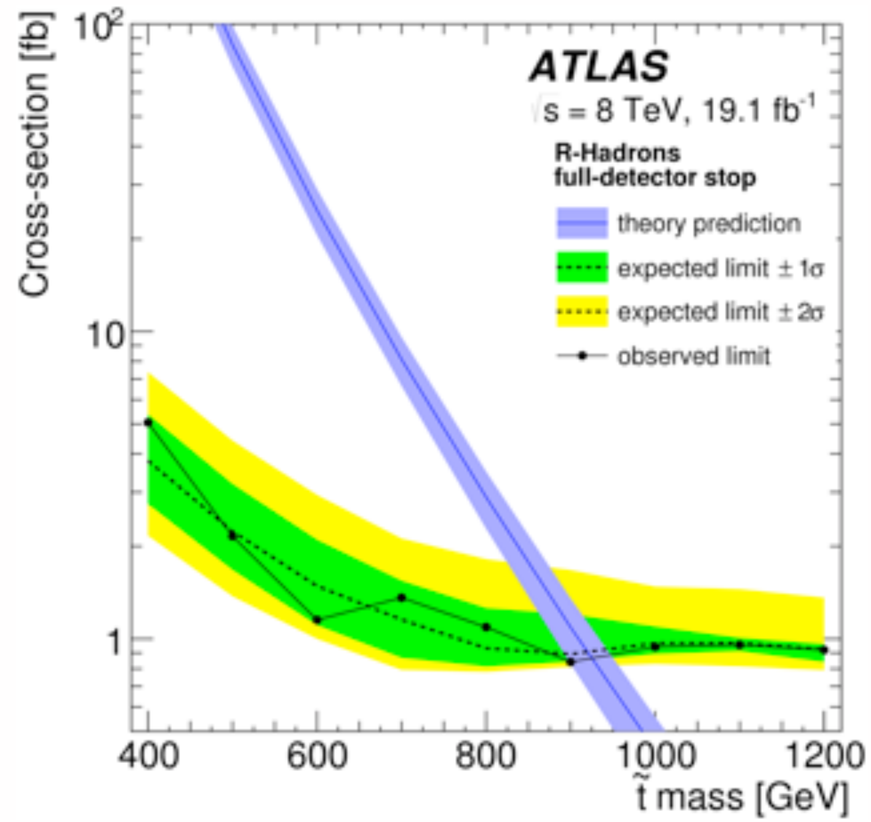
Heavy Long Lived Particles, Results

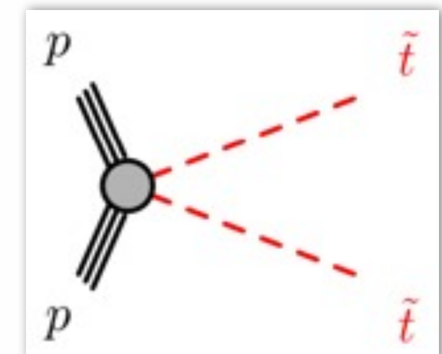
New

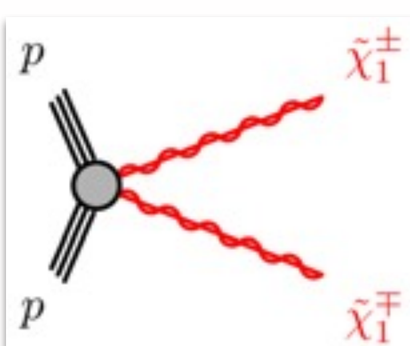
arXiv:1411.6795

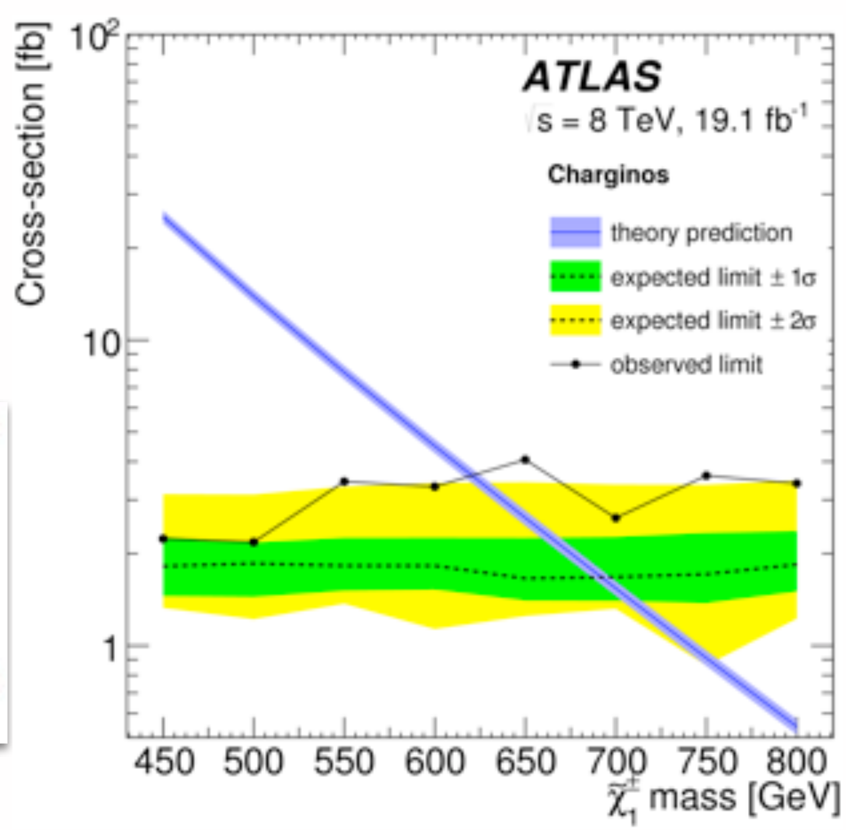


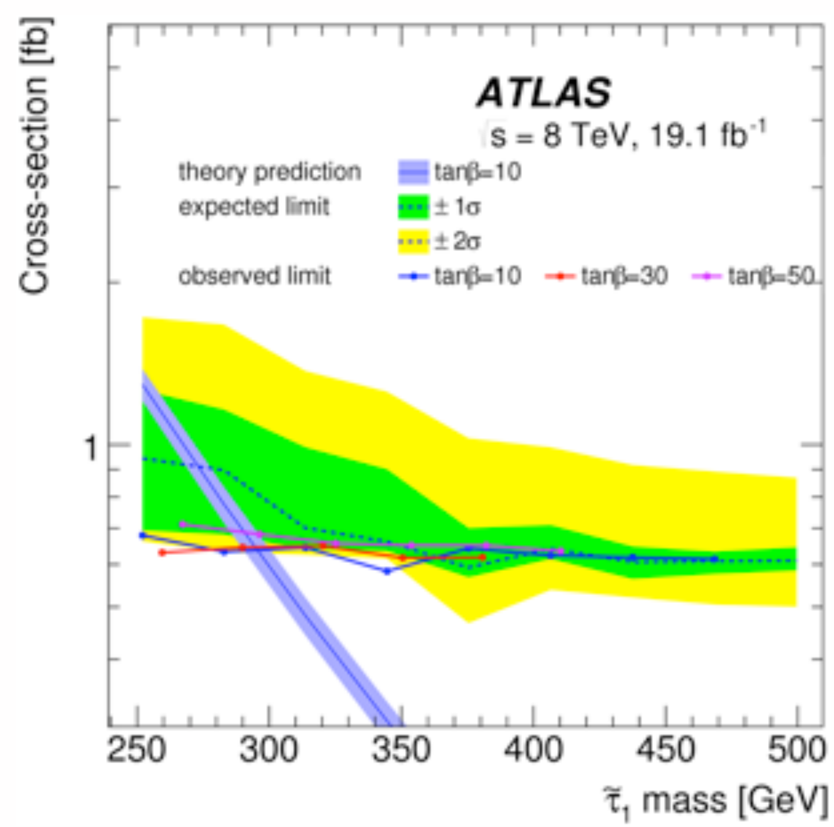


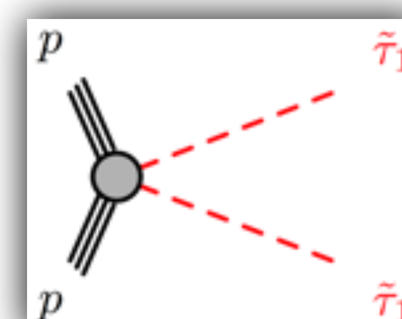








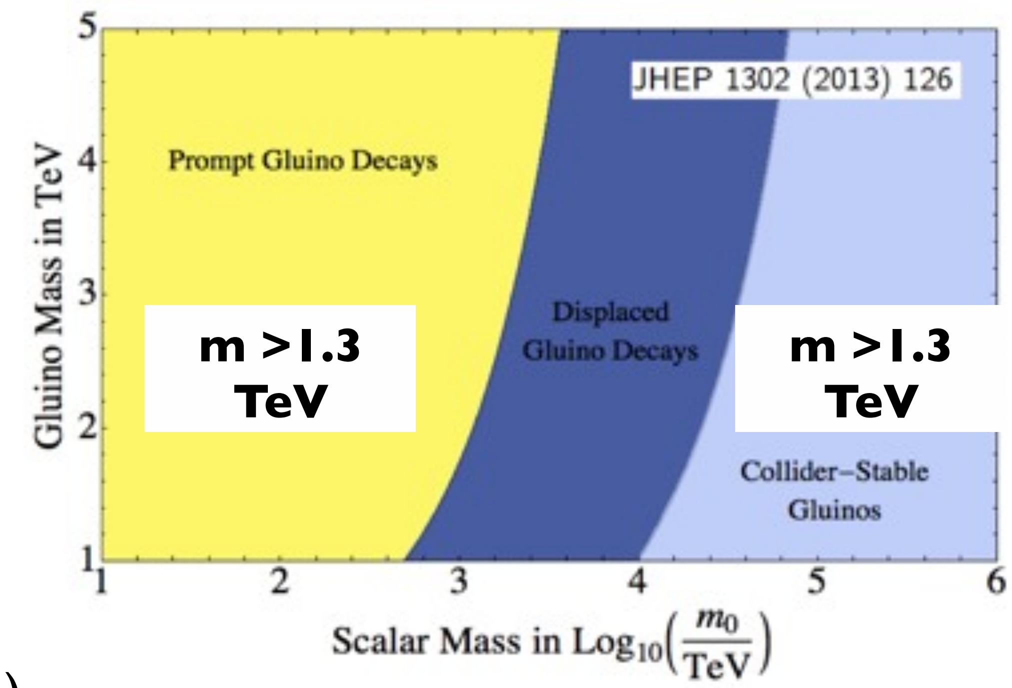


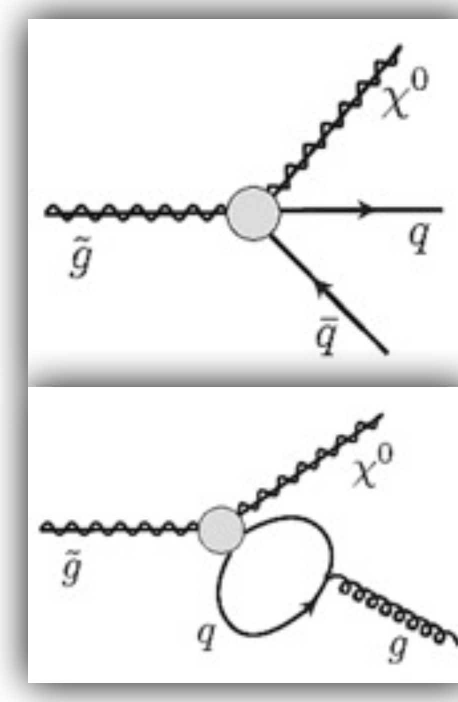


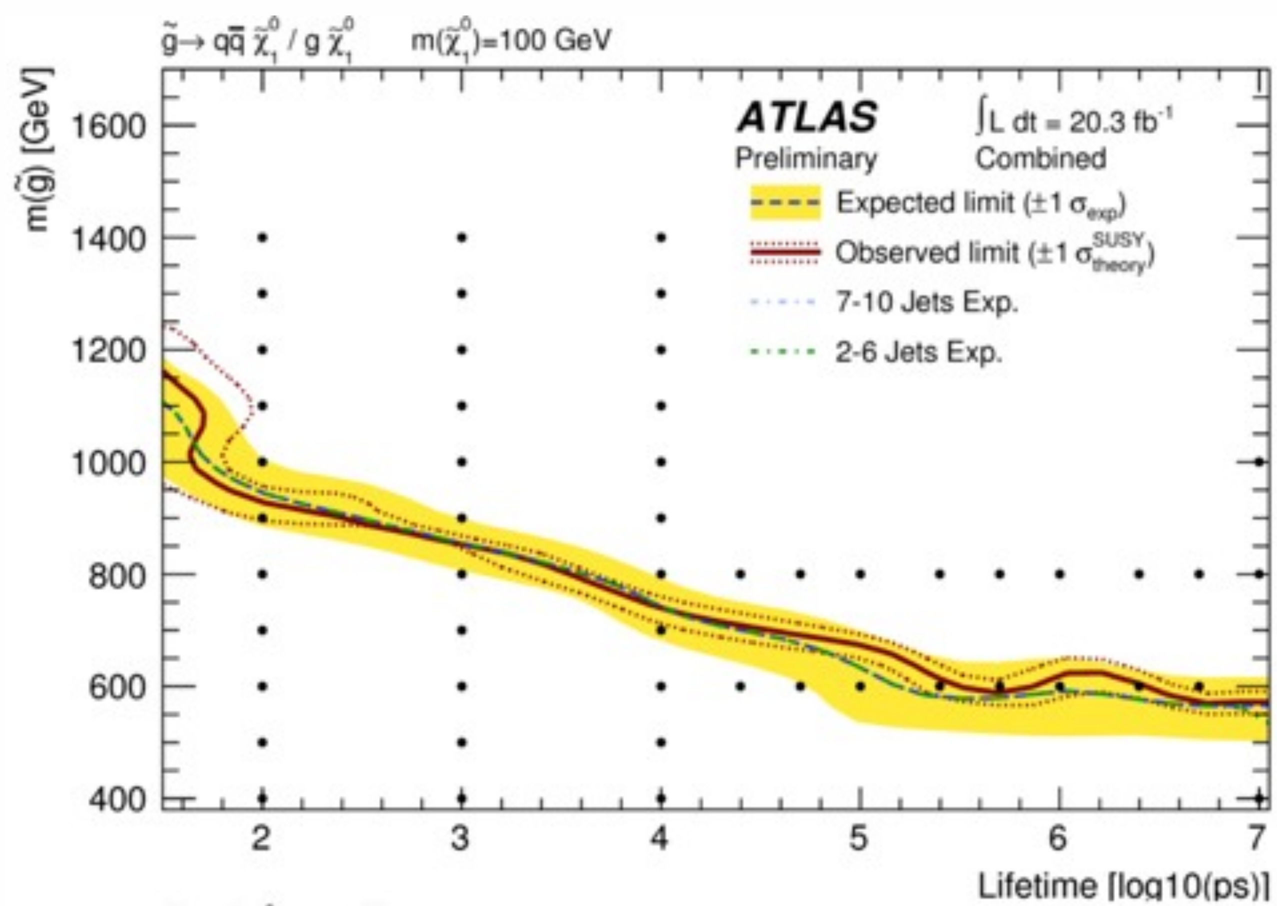
Cross section upper limit of ~1/fb independently of the produced sparticle

Meta-stable Gluinos

- Promptly produced gluinos have been excluded up to m ~ 1.3 TeV
- Split SUSY models predict a metastable gluino
  - gluinos hadronize into color-less R-hadrons
  - gluinos decay into quark pairs (including top) or gluons, and neutralinos
- The canonical search for prompt gluinos in events with 0 leptons provides some sensitivity to metastable gluinos but dedicated search is essential for lifetime > 100 ns
  - drop in sensitivity due to gluinos decaying outside the calorimeter or inefficiency of jet requirements, e.g. charged or EM fractions







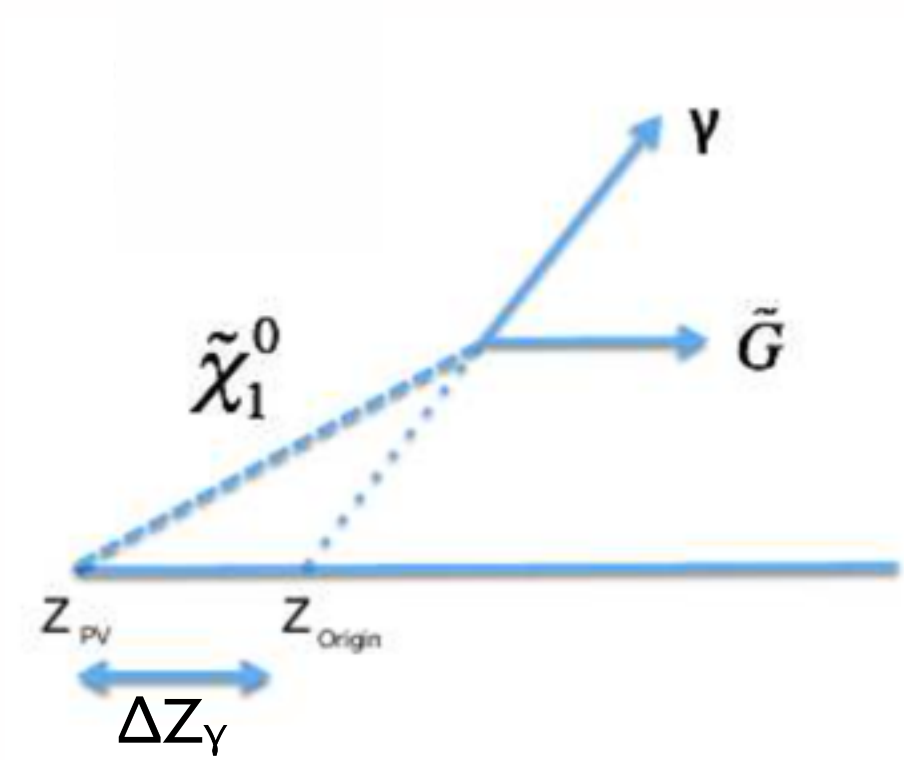
Non-pointing and Delayed Photons probing GMSB SUSY

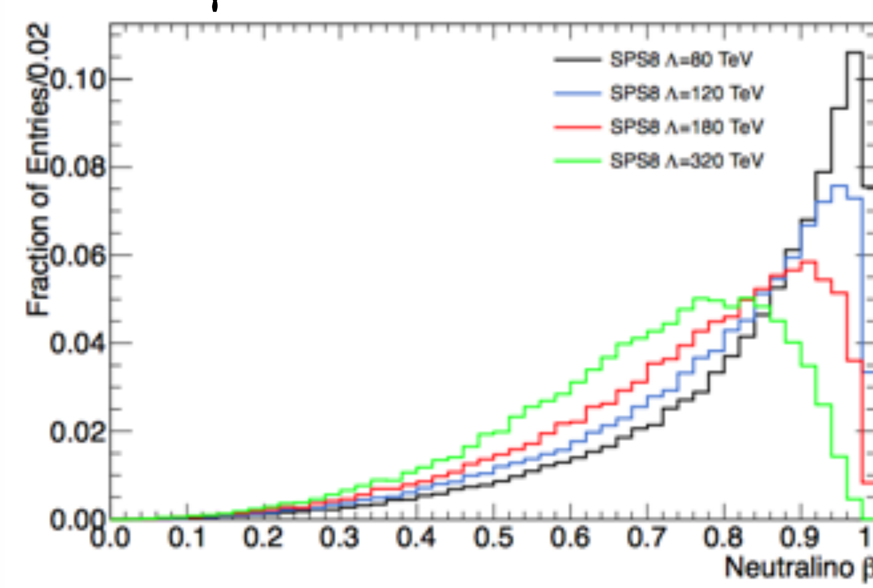
New

$$\Gamma(\tilde{X} \to X\tilde{G}) = \frac{\kappa m_{\tilde{X}}^5}{16\pi F^2}\left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)$$

- Gauge Mediated SUSY Breaking with mass splitting scale F predicts long lived neutralinos decaying into a gravitino and a photon
  - non-prompt decay for large F
  - If decay time > 0.5 ns , decay can occur after first layer of calorimeter
- The non-zero decay angle between long-lived neutralino and photon results in an EM shower that does not point back to the PV
  - The extra path length also results in the photon arriving delayed compared to a photon from the PV
- The neutralino mass increases with SUSY breaking scale $\Lambda \Rightarrow$

  β distribution shifts to lower values

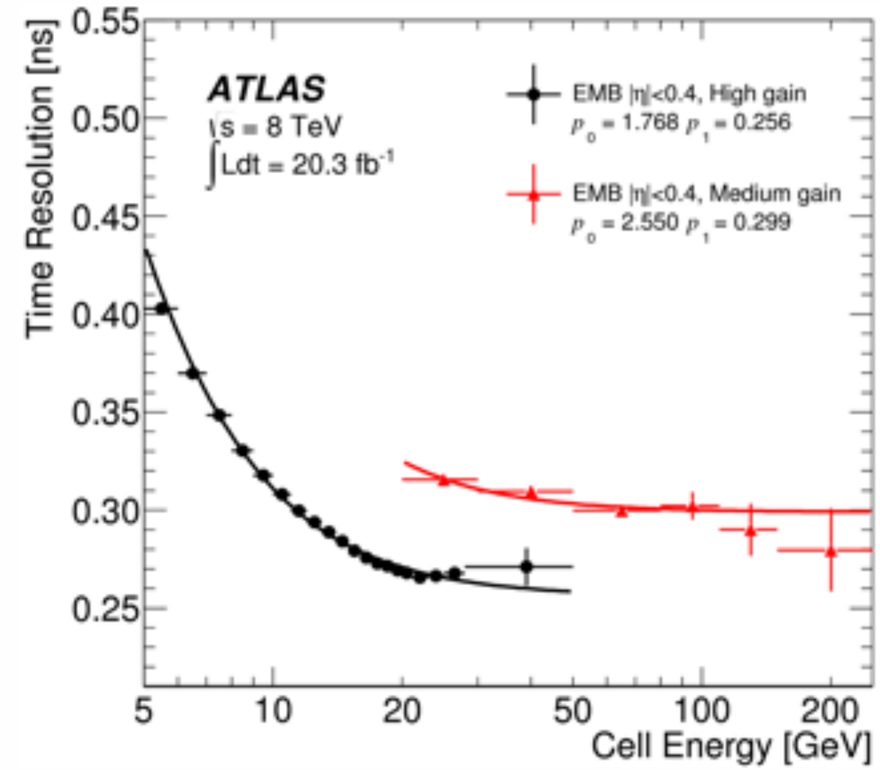


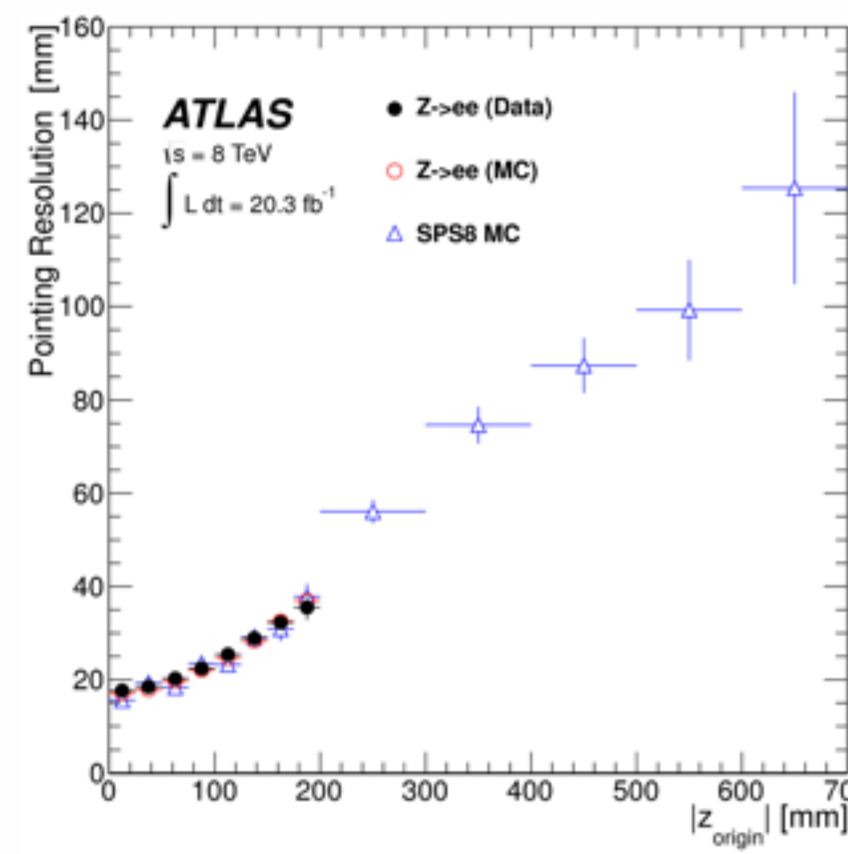


Non-pointing and Delayed Photons probing GMSB SUSY

New

- If long-lived neutralinos produced in SUSY decays, events contain two non-pointing photons, and large ETmiss from gravitinos
- The signal from background discrimination is based on photon pointing and timing information
- LAr Calorimeter has excellent timing resolution
  - Timing measurement is obtained from cell with the maximum energy
  - The resolution is determined to be 300 ps, with 220 ps from the spread of colliding bunches
- Calorimeter pointing resolution estimates the error on the ΔZ_γ measurement using calorimeter shower
- Signal region is defined by ETmiss > 75 GeV
- CRs: 20GeV < ETmiss < 75 GeV



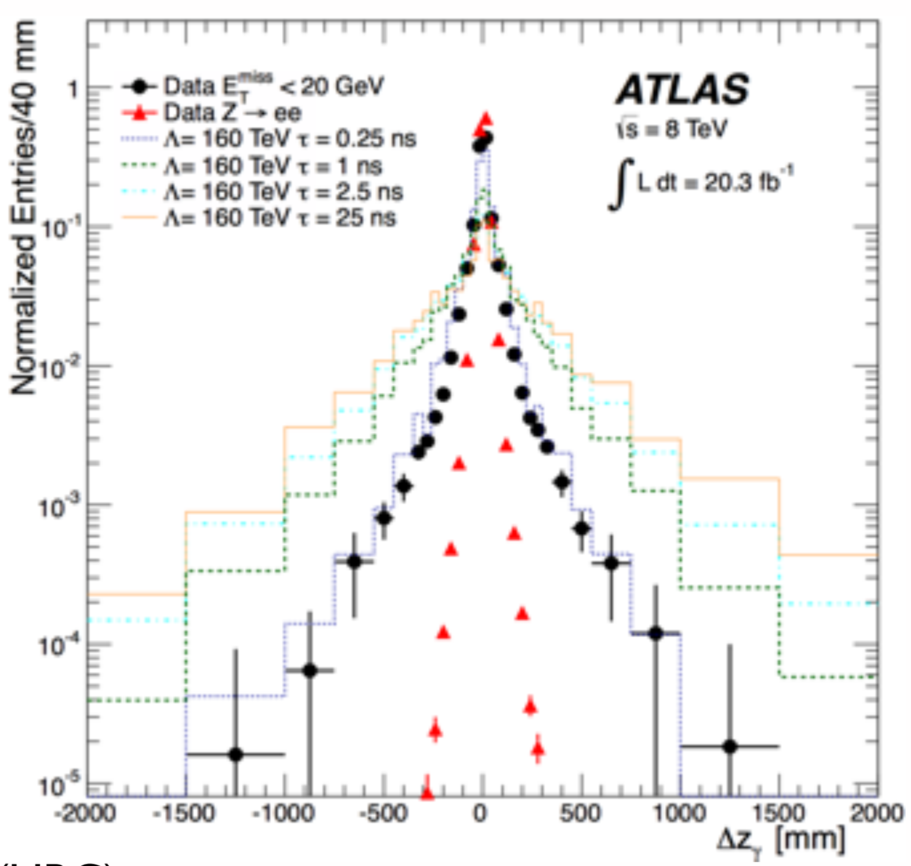


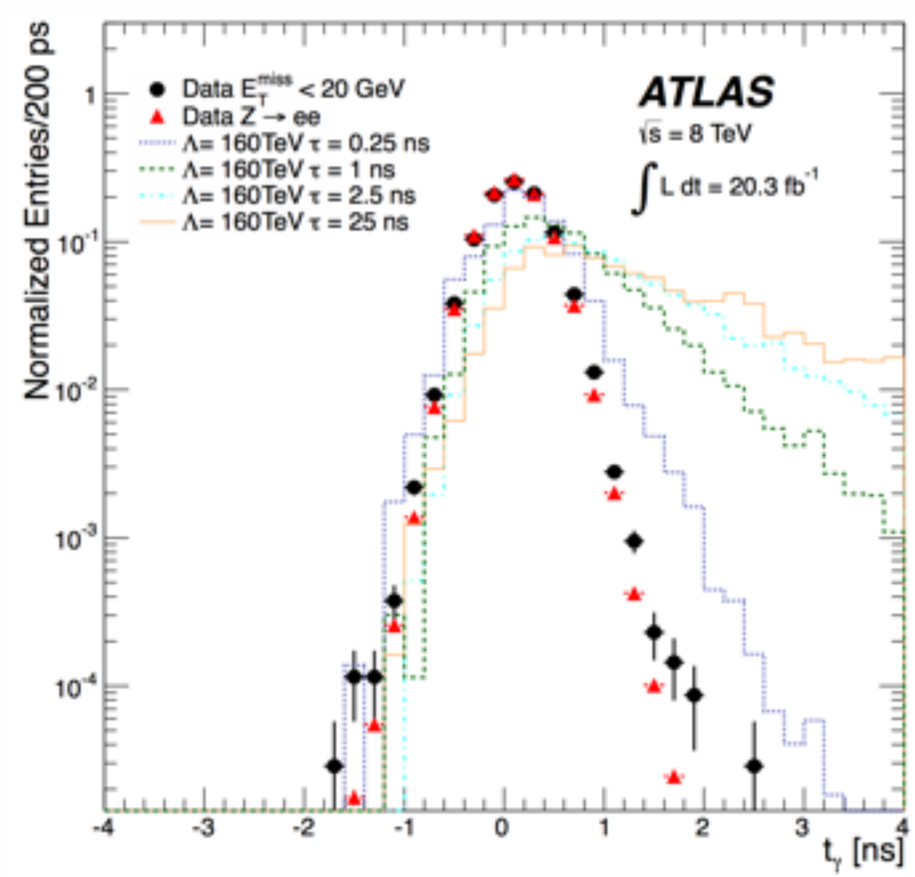
Non-pointing and Delayed Photons probing GMSB SUSY

New

- The signal regions are defined based on ΔZ_γ
- In each signal region, arrival time (t_γ) templates are fitted to data
  - Background templates obtained from ETmiss < 20GeV data
  - Fitting boundaries optimized over signal grid
  - Different boundaries required for neutralino with small and large lifetimes

Source of uncertainty	Value [%]
Integrated luminosity	$\pm$ 2.8
Trigger efficiency	$\pm$ 2
Photon E_T scale/resolution	$\pm$ 1
Photon identification and isolation	$\pm$ 1.5
Non-pointing photon identification	$\pm$ 4
E_T^{miss} reconstruction	$\pm$ 1.1
Signal MC statistics	$\pm$ (0.8–3.6)
Signal reweighting	$\pm$ (0.5–5)
Signal PDF and scale uncertainties	$\pm$ (9–14)





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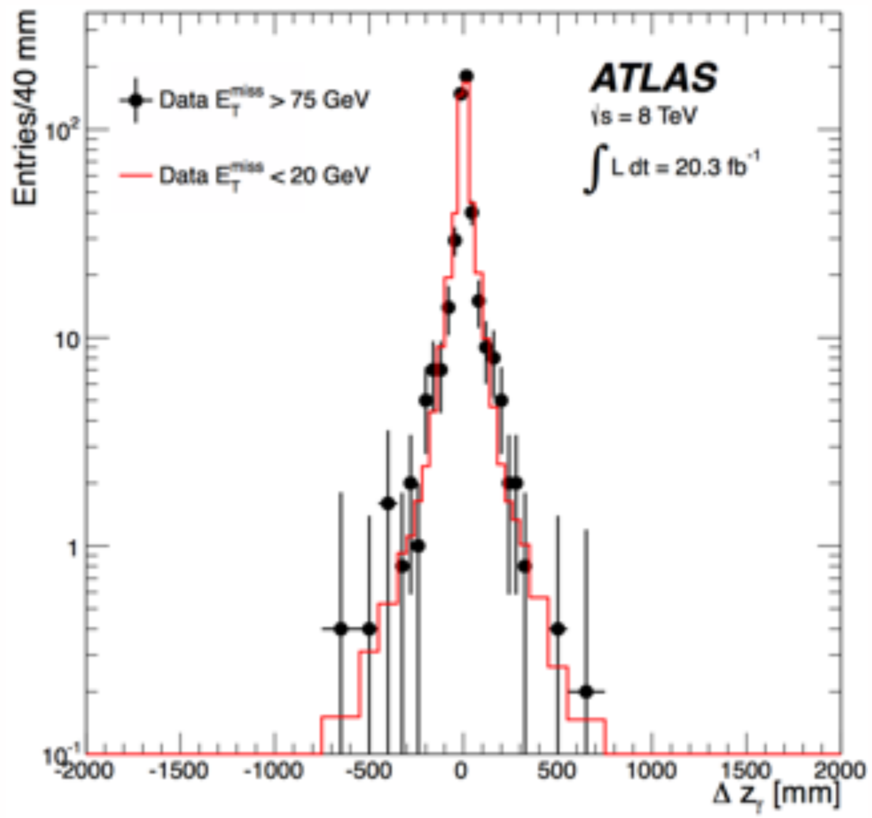
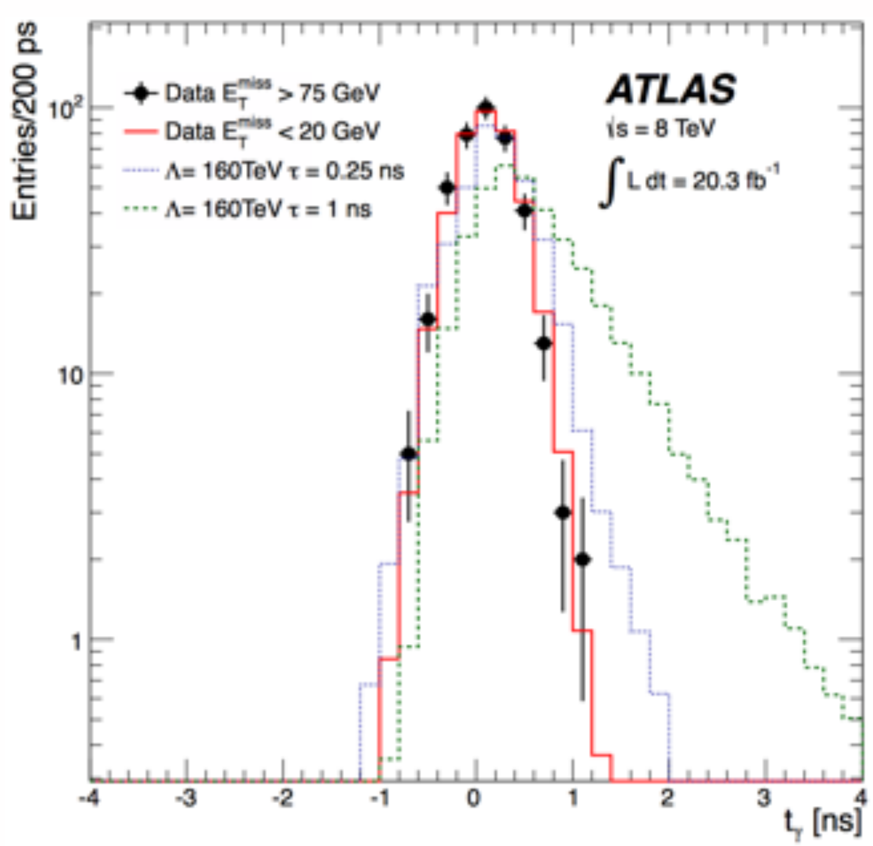
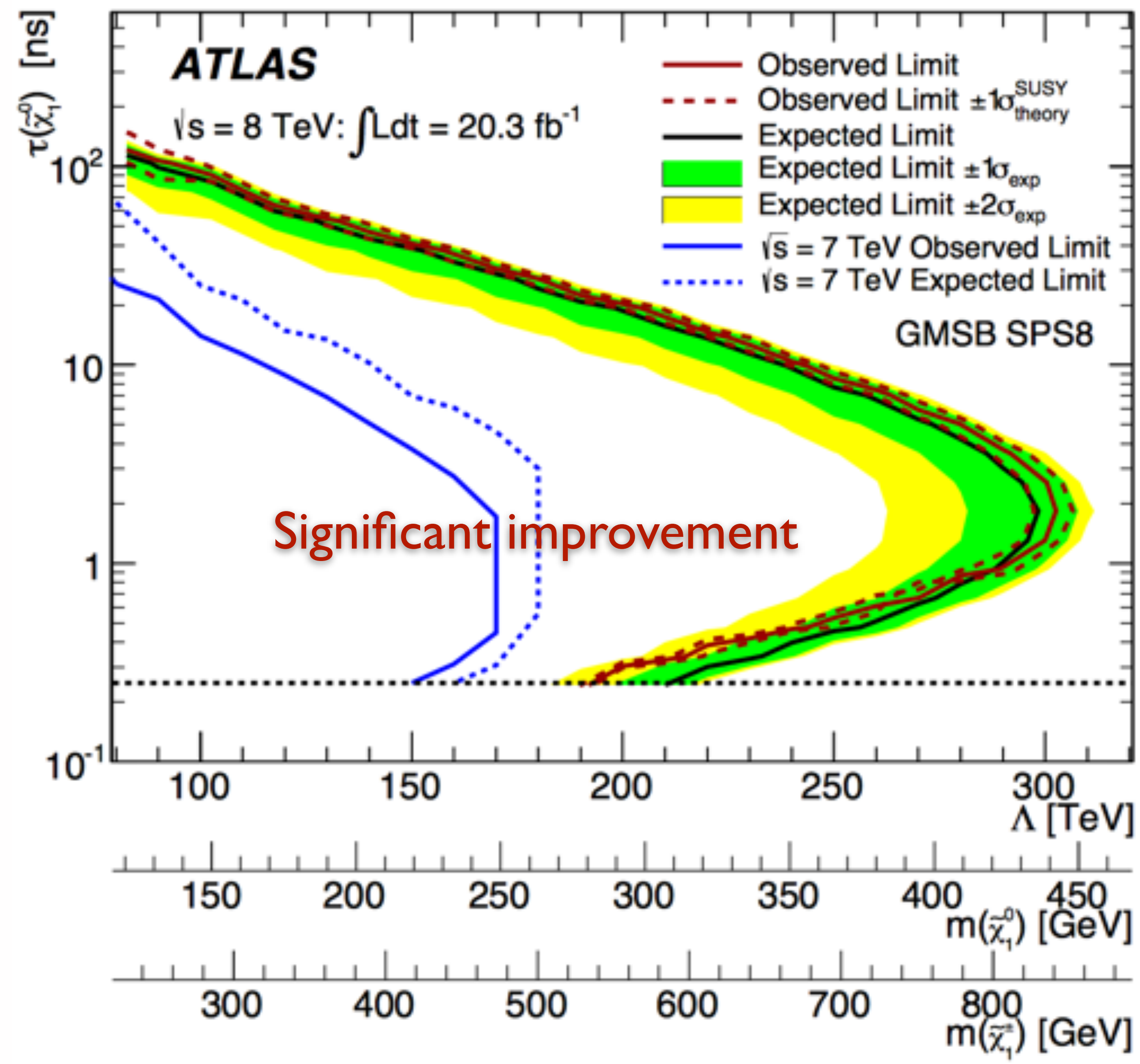
Non-pointing and Delayed Photons probing GMSB SUSY

New



Sample	$E_{\mathrm{T}}^{\mathrm{miss}}$ range [GeV]	Number of events
CR1	$20 < E_{\mathrm{T}}^{\mathrm{miss}} < 50$	50751
CR2	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 75$	3591
SR	$E_{\mathrm{T}}^{\mathrm{miss}} > 75$	386





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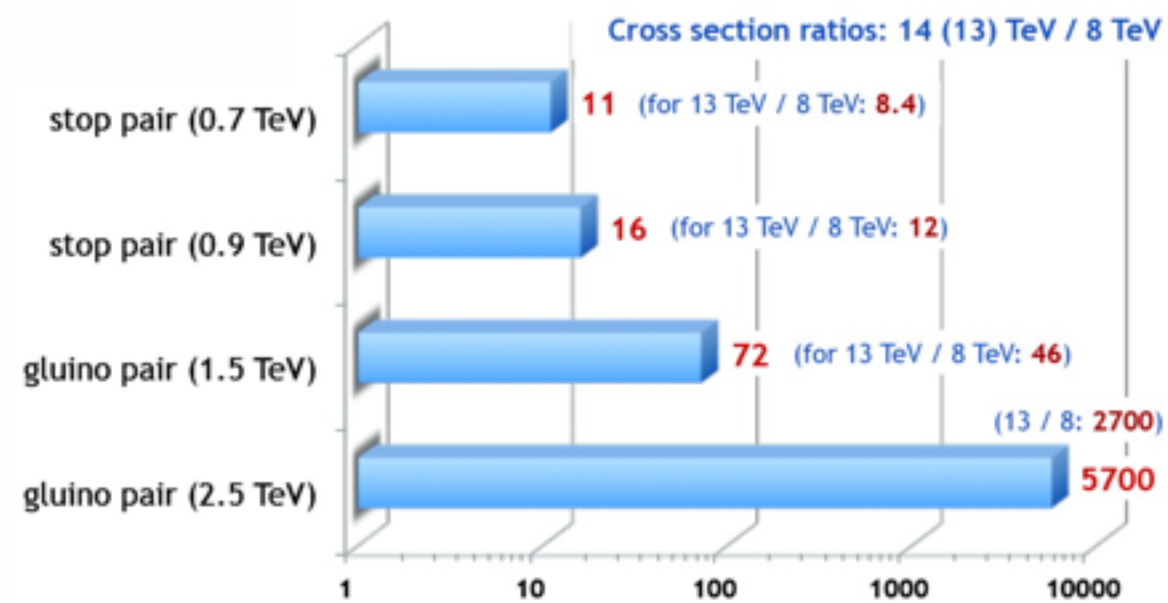
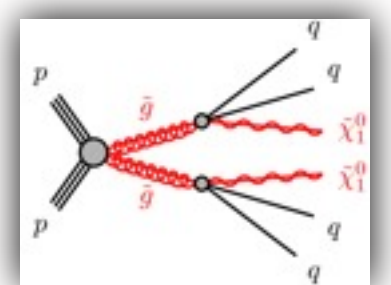
Summary and Outlook

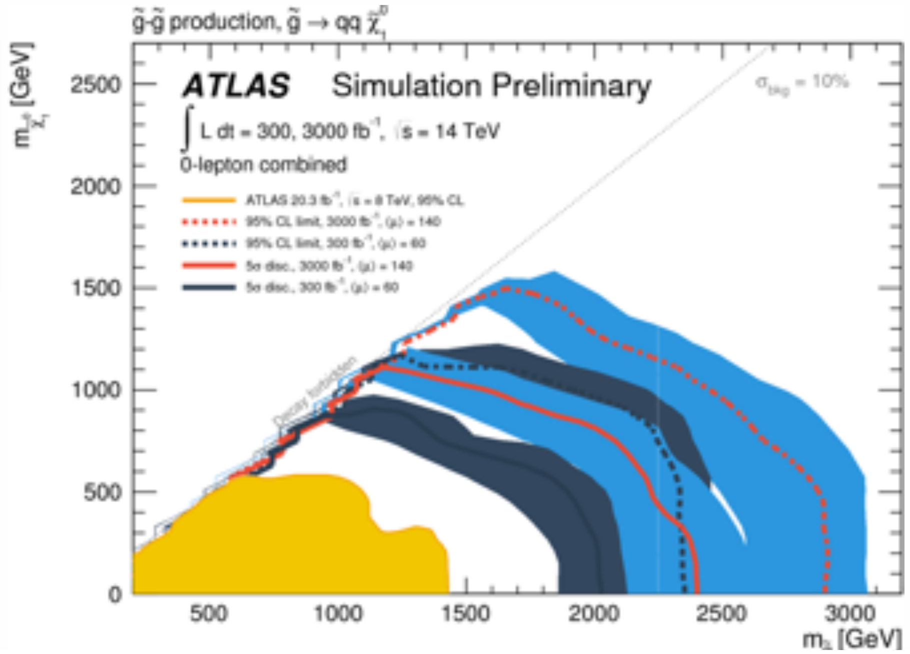
- ATLAS developed a vast program including searches for strongly- and weakly-produced *sparticles* under the assumption of both R-parity conservation (and R-parity violation)
  - scenarios with prompt, metastable, and long lived *sparticles* are explored
  - interpretation of search results is done in the context of simplified, phenomenological, and complete models
- In canonical scenarios, sensitivity is achieved to ~1.2 TeV gluinos, ~700 GeV stops, and of ~400 GeV EWK-inos
  - significant improvement of sensitivity to compressed and challenging scenarios thanks to innovative experimental techniques
- The reach for strongly produced SUSY is expected to increase significantly at Run 2
- The HL-LHC will allow to ultimately probe the TeV scale and Natural SUSY

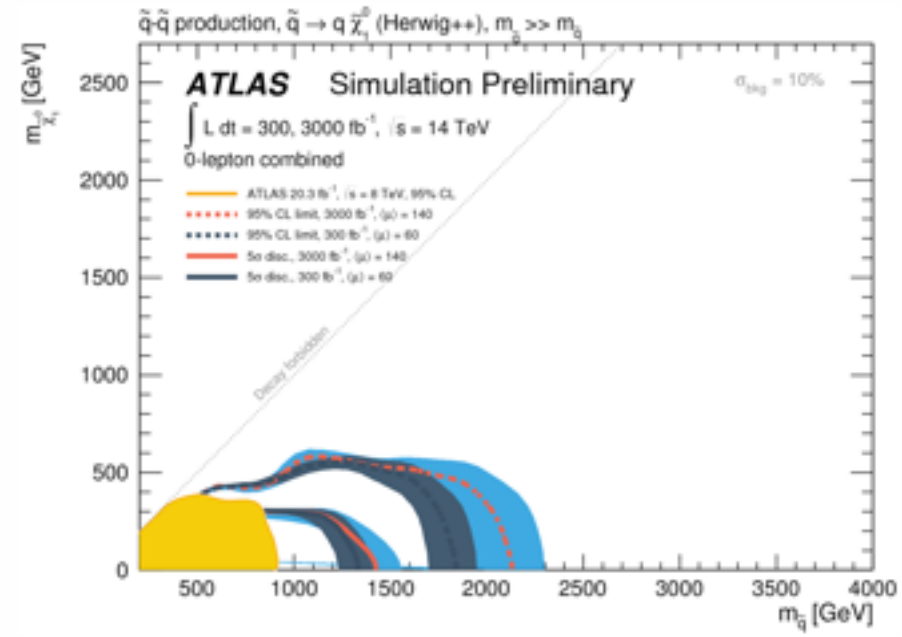


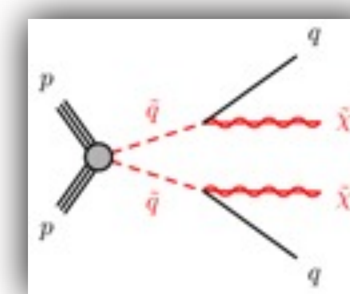
SUSY at Run 3 and HL-LHC

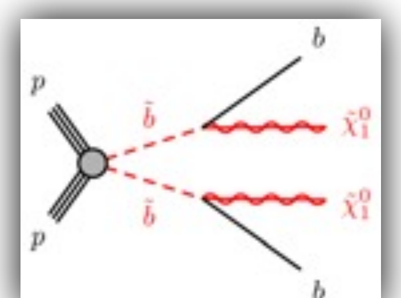
- 14 TeV allows to probe heavier SUSY and 300/3000 fb^{-1} crucial for EWK processes

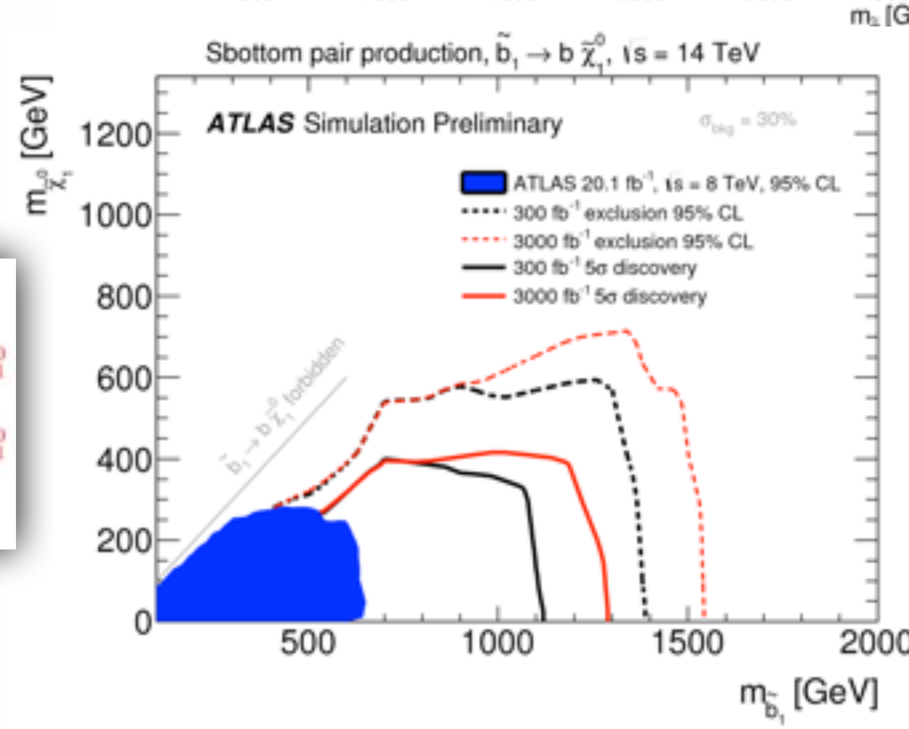


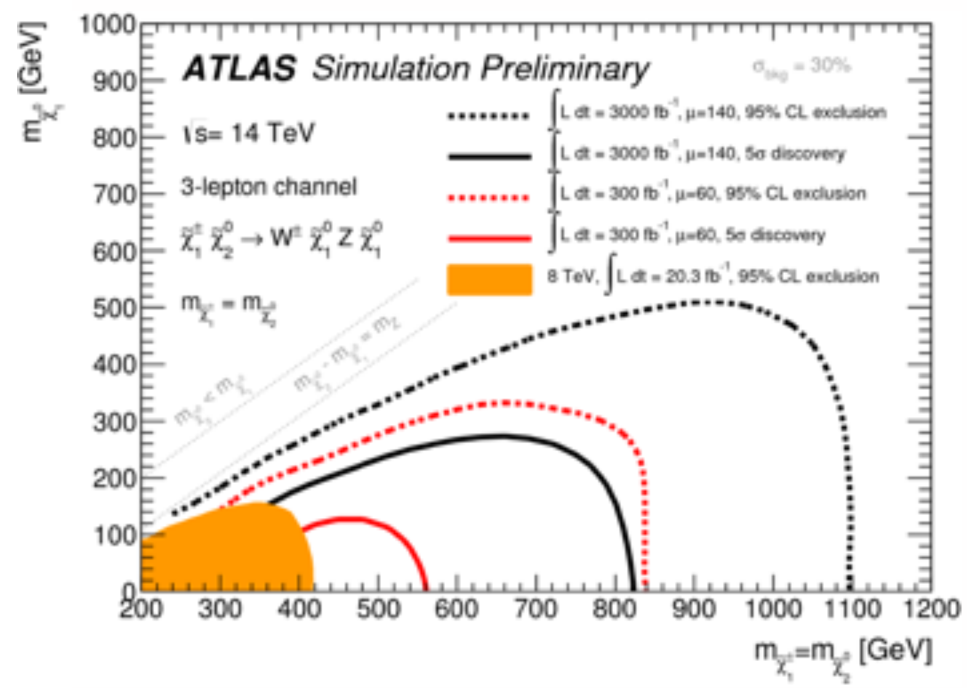


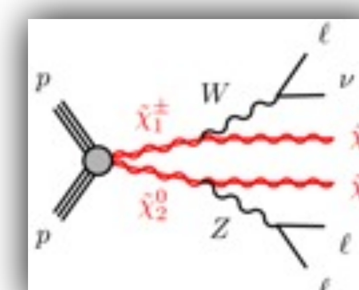












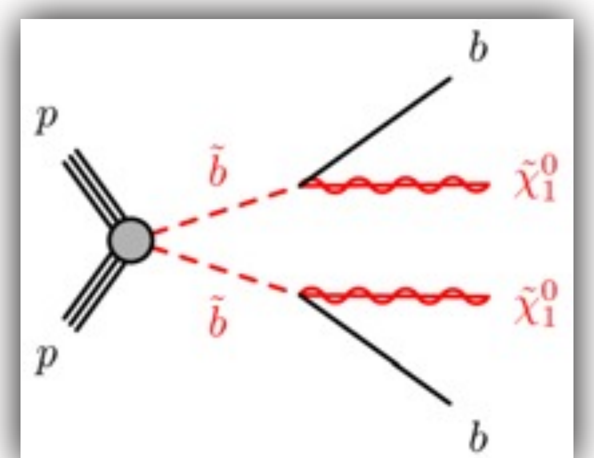
Discovery potential up to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom
800 GeV Electroweakinos, covering 'natural range'

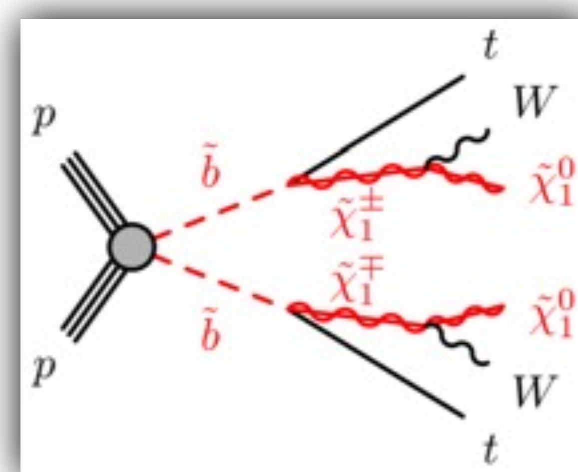
Search for Pair Production of Sbottoms

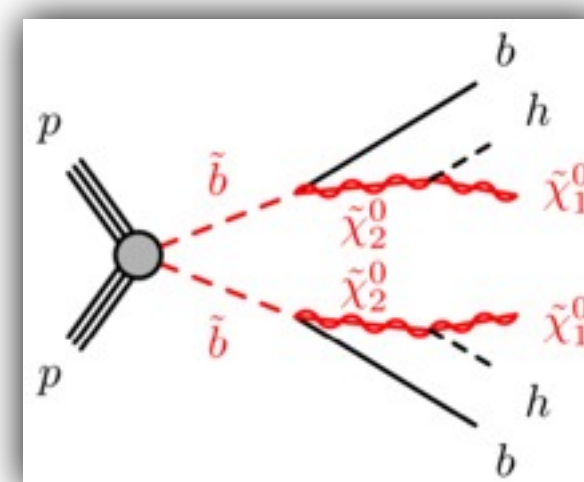
- 2b + ETmiss
- Bins in MCT

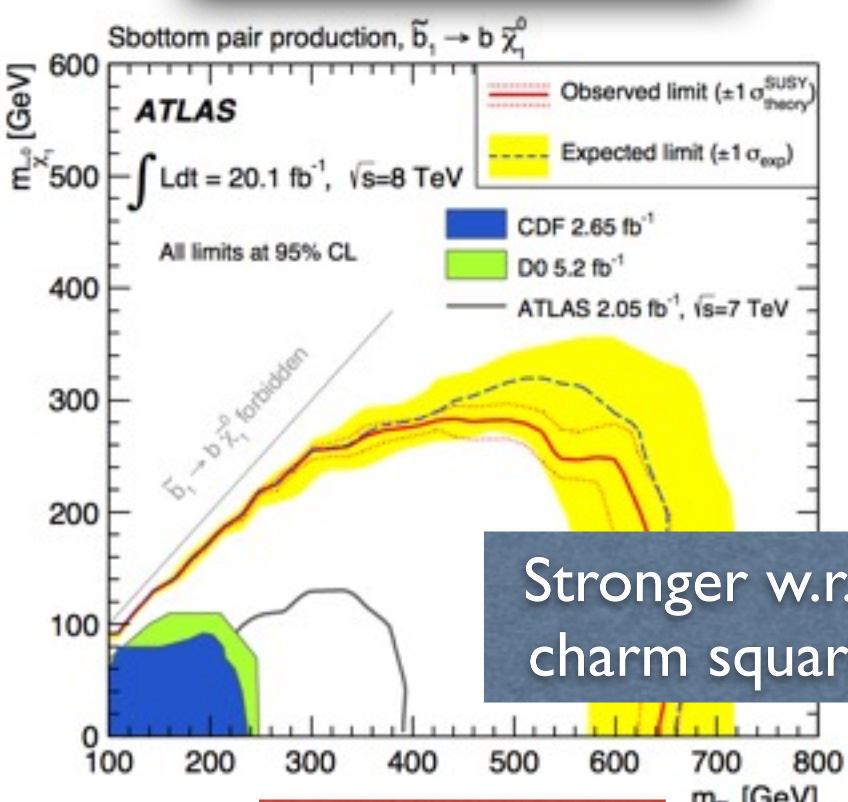
- 2L(SS) + b + ETmiss + Meff
- 3L + ETmiss + Meff

- 0L + 3b + ETmiss + Meff
- Sensitivity limited by ETmiss in compressed region

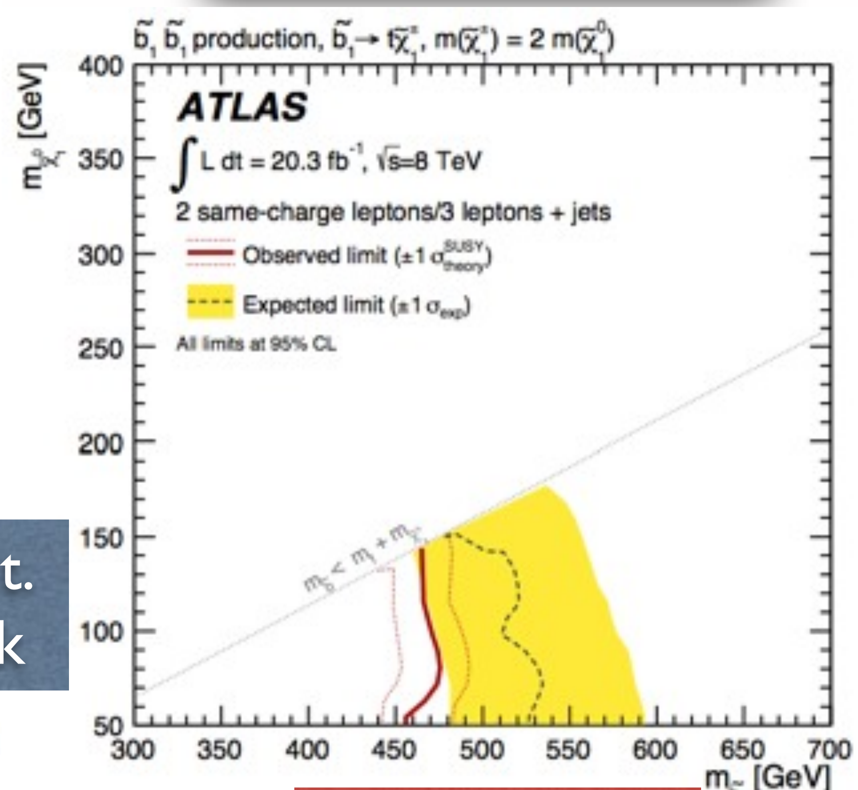


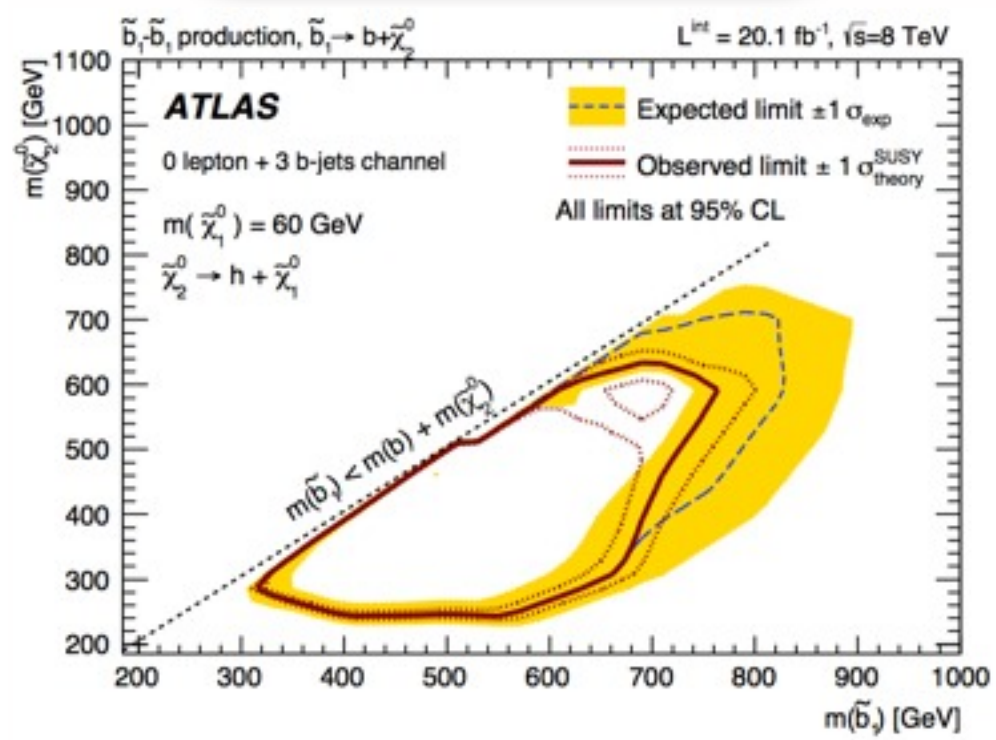






Stronger w.r.t. charm squark





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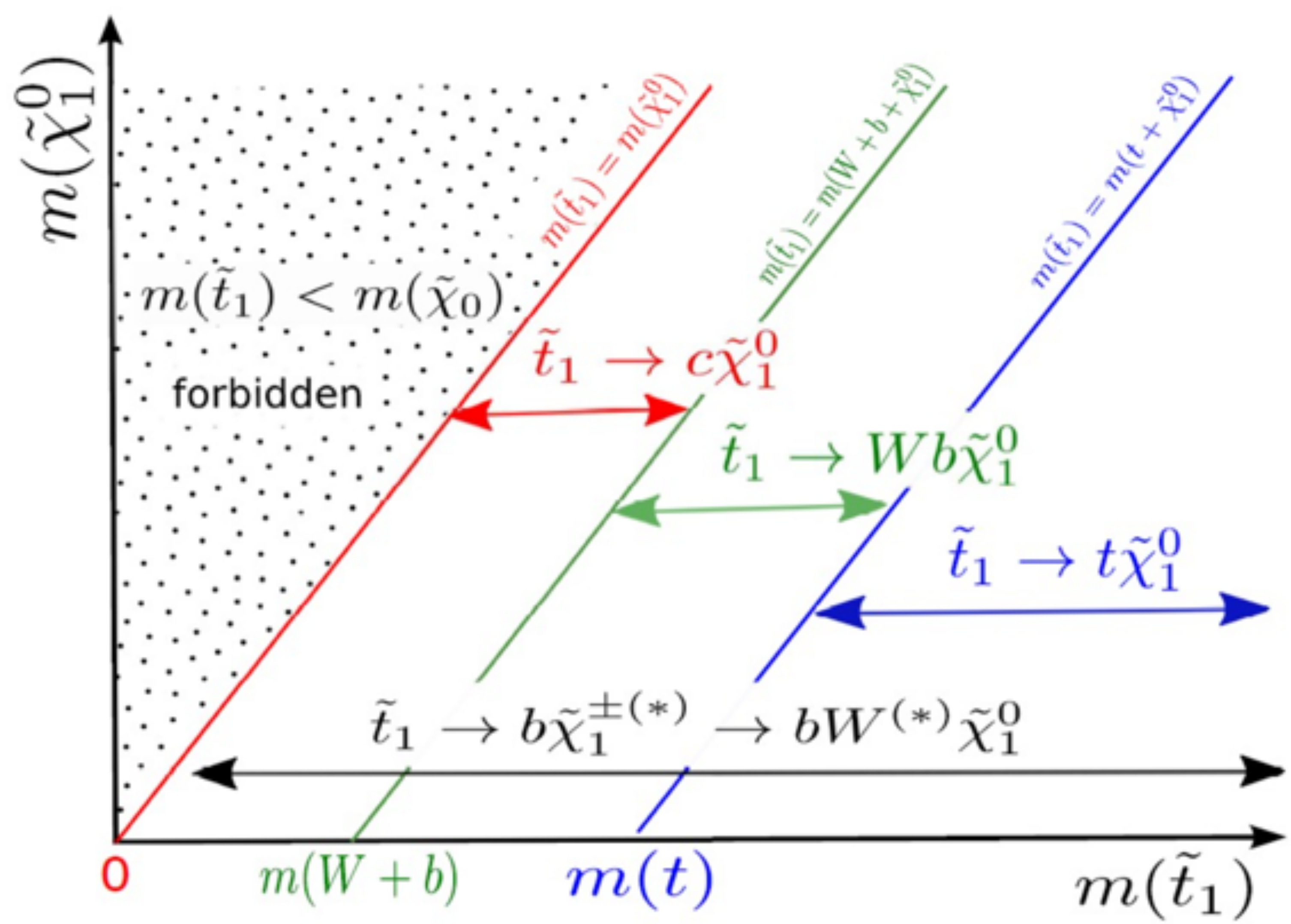
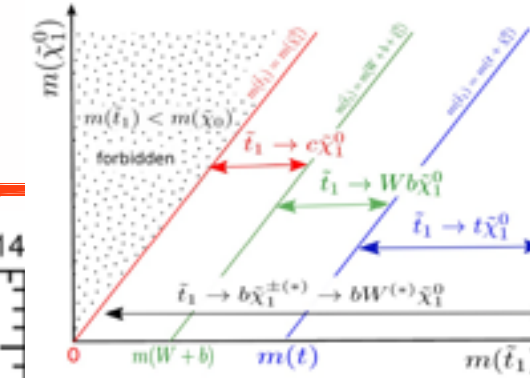
Sbottom mass > 400-700 GeV depending on mass hierarchy

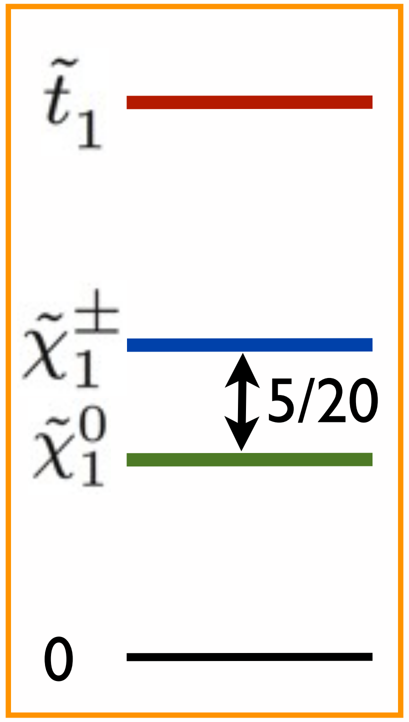
Searches for Pair Production of Stops

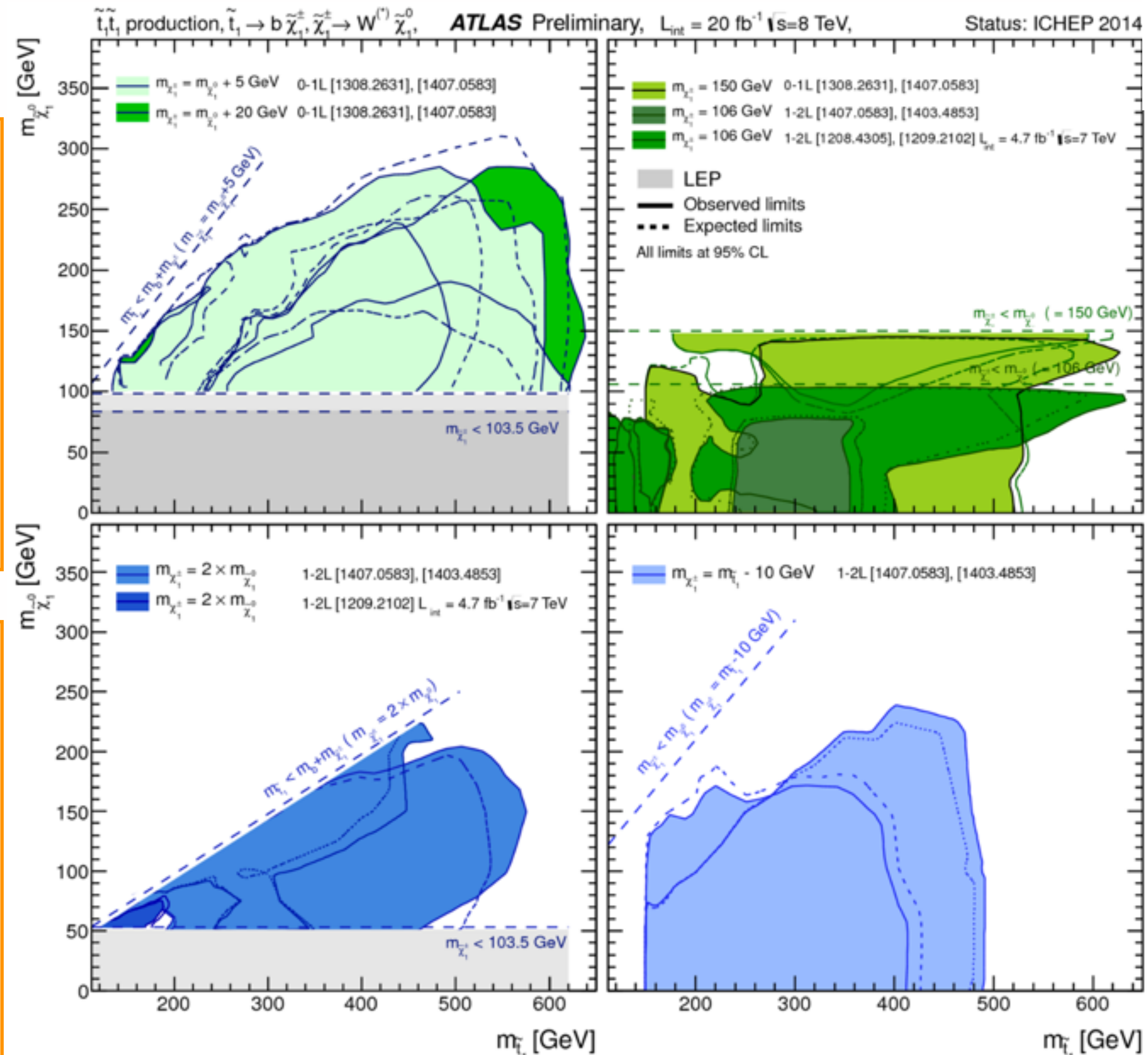
- **Key to naturalness but challenging!**
  - The cross section is suppressed, 10pb to 1fb from 200 to 900 GeV stops
  - The sensitivity is highly dependent on the decay mode, the mass hierarchy of sparticles participating in the decay (and to some extent on the stop "handiness")

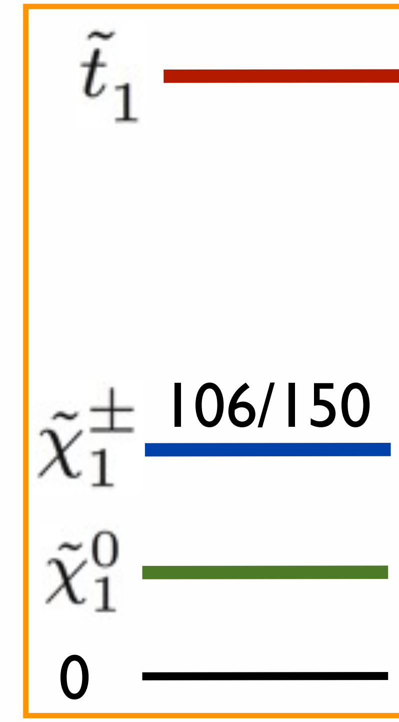


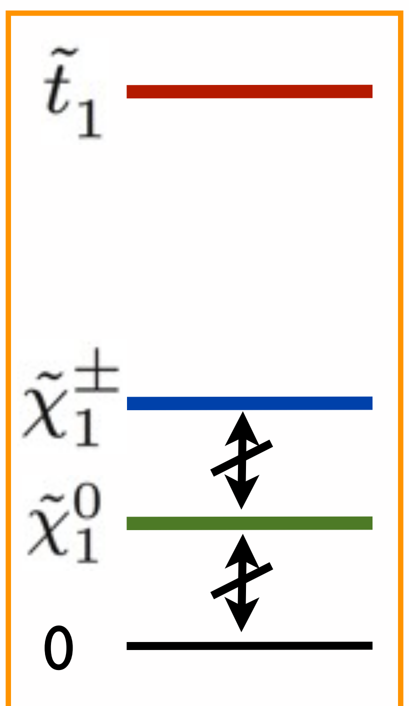
Summary of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$

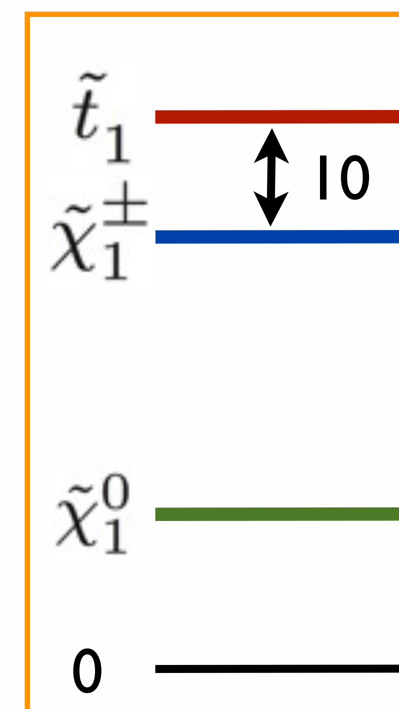






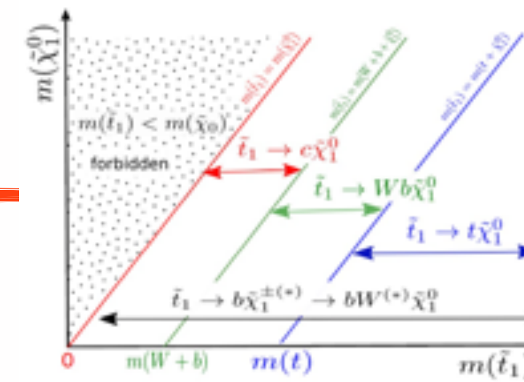






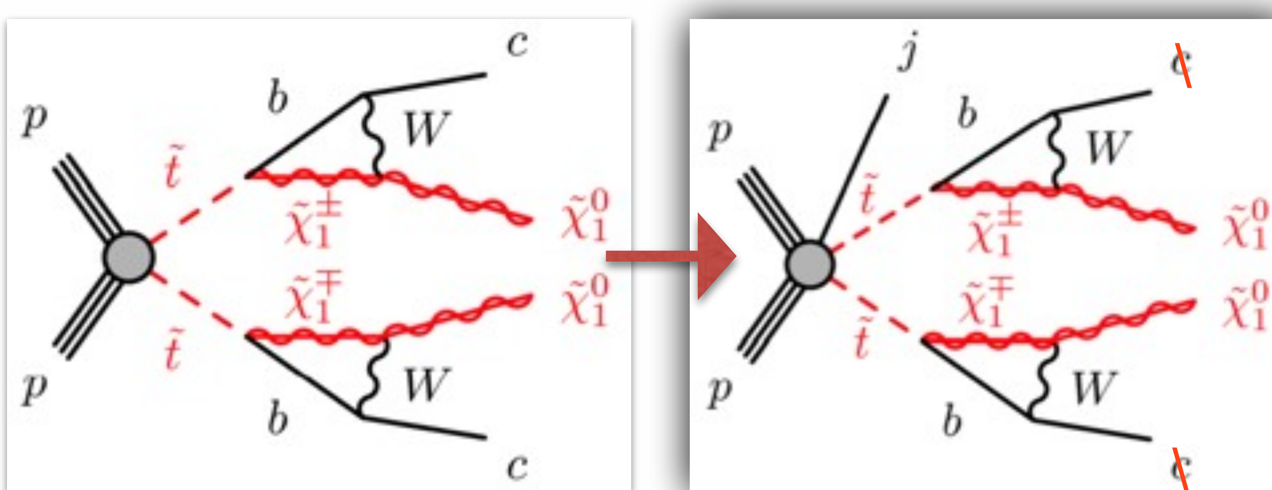
Limits on stop mass in the range of 500-600 GeV

Search for Stop decaying into Charm and LSP

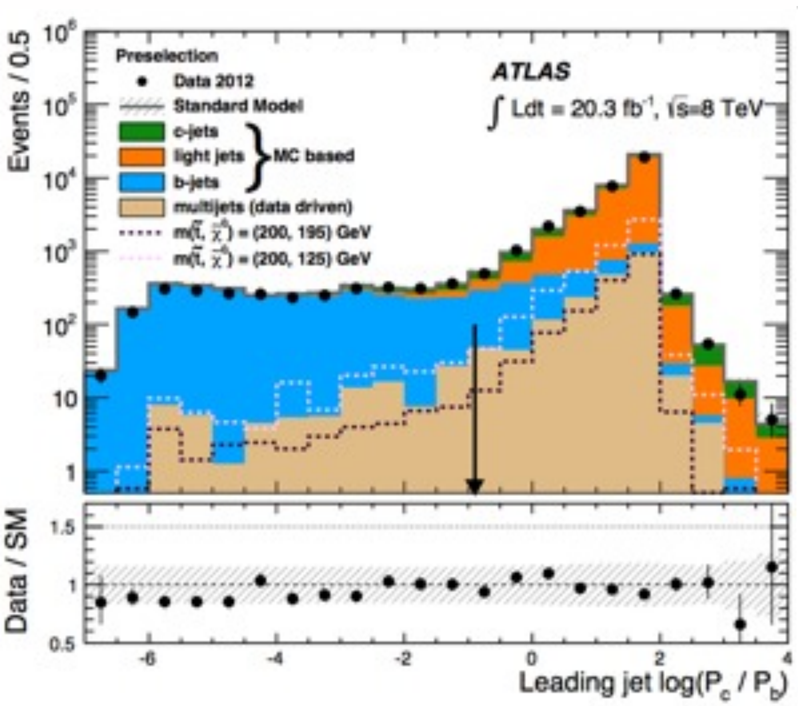


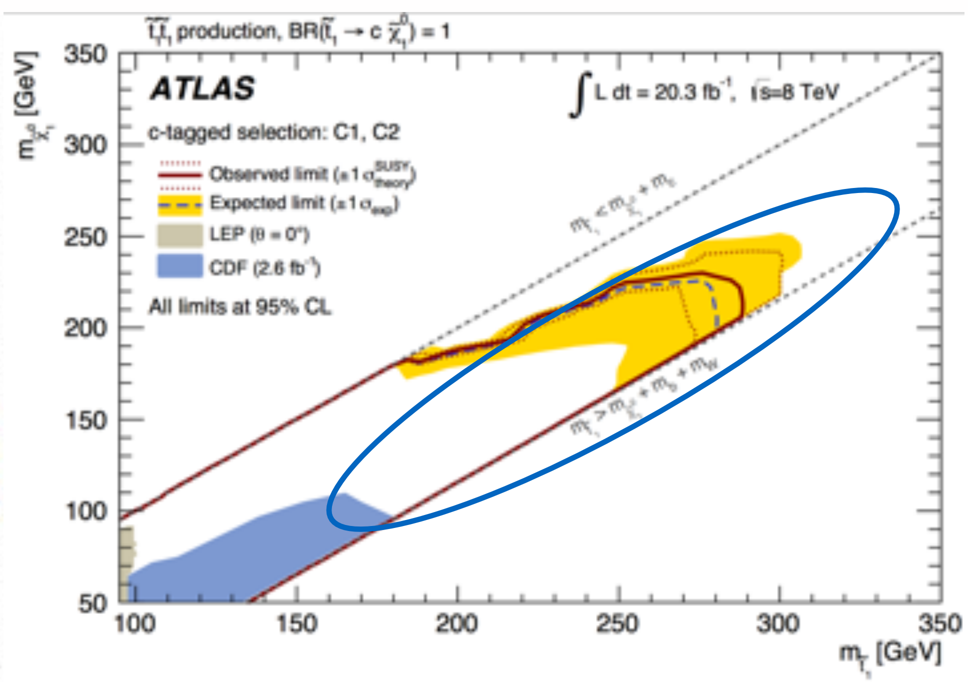
- Search based on requesting one c-tagged jet or Initial State Radiation jet to boost the system

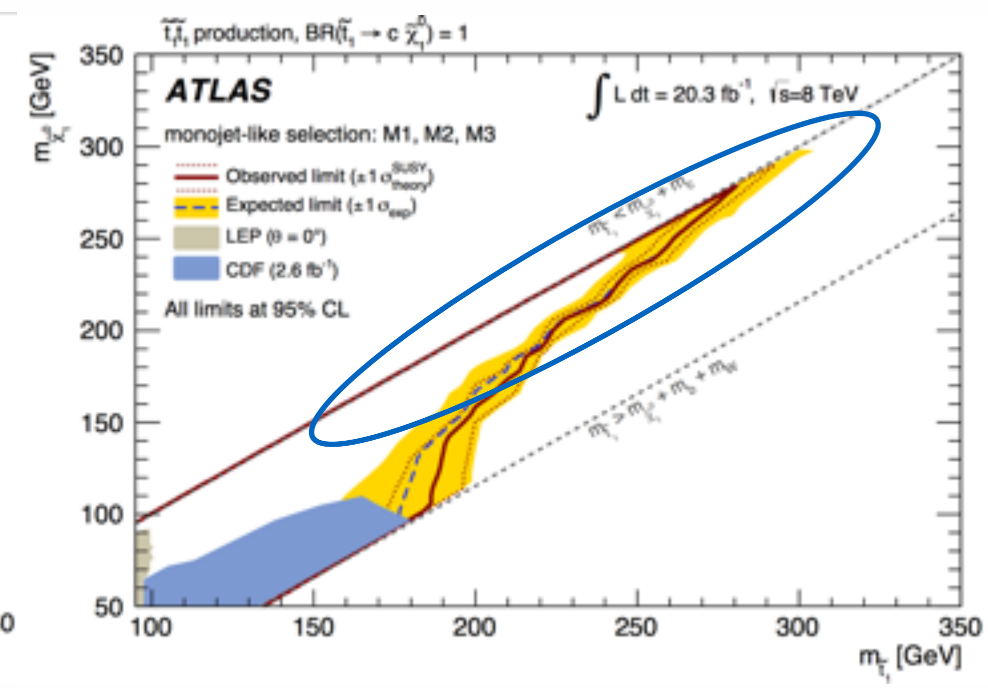
signal region requesting one charm-tagged jet



mono-jet 'like' SR targeting very compressed scenarios

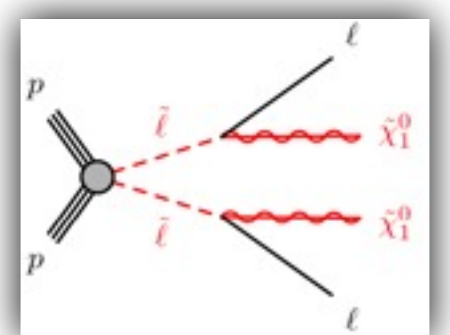


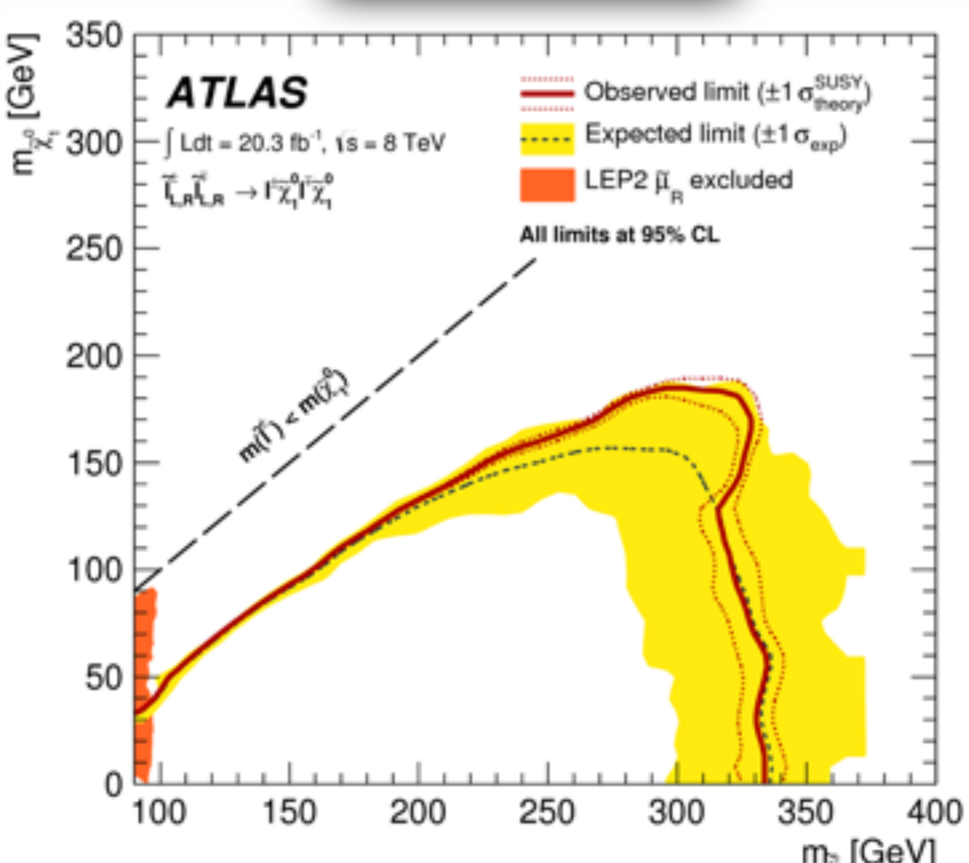


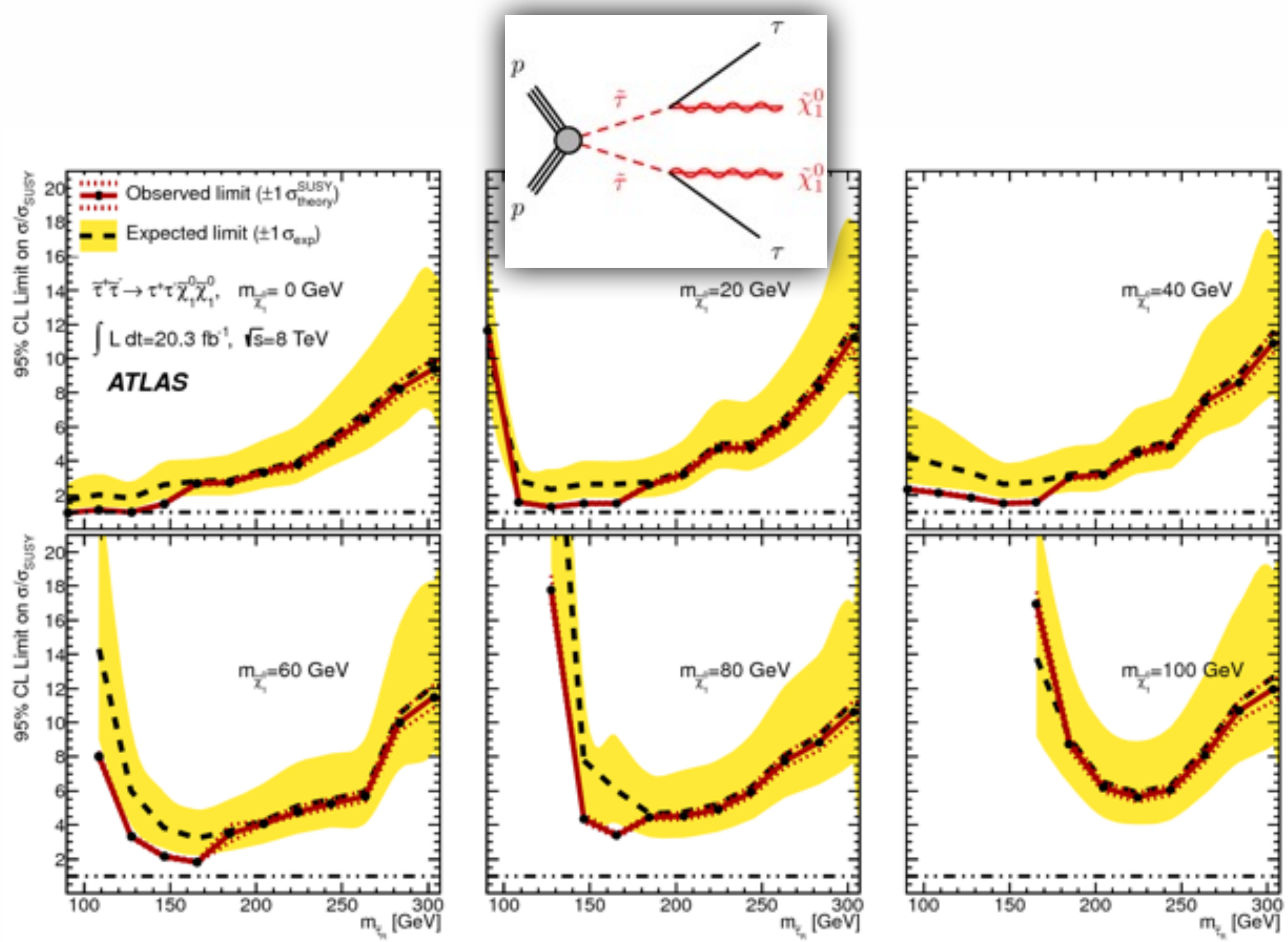


Scenarios with Light Sleptons or Light Staus

- The search for light-flavor sleptons is based on events with two leptons, ETmiss, large ETmissRel, MT2 and the one for staus relies on hadronic taus, ETmiss and MT2







Probing light sleptons beyond LEP at LHC
First sensitivity to pair produced staus at hadron collider

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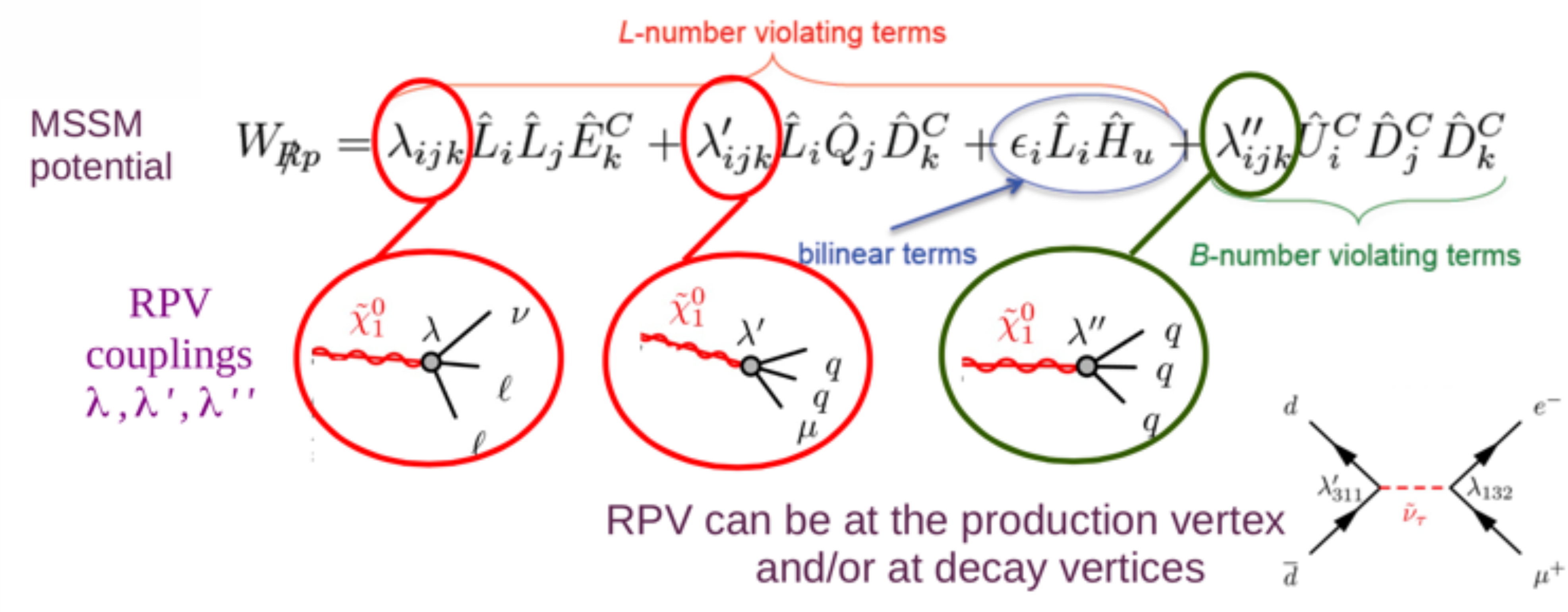
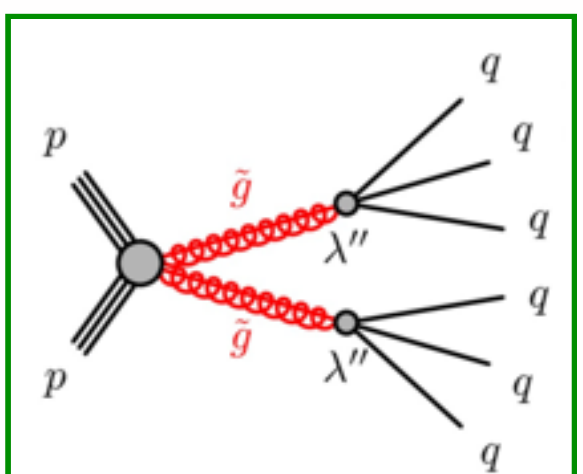
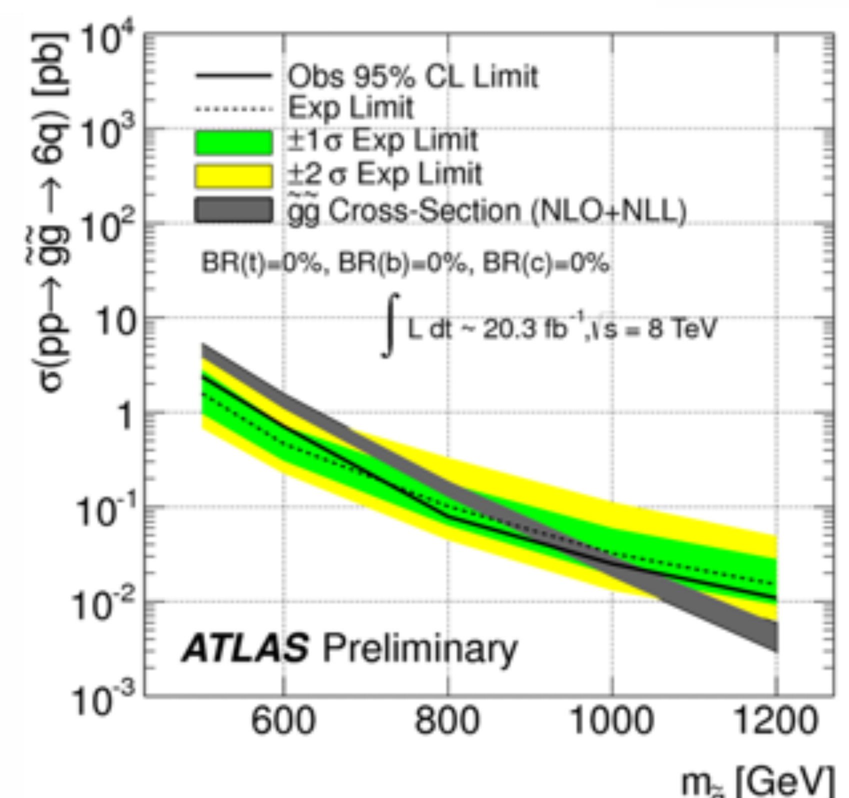
SUSY with R-parity Violation

Violation of R-parity allowed as long as either the lepton or the baryon number is conserved





Search in events with $\geq$ 6 or 7 high p_T jets



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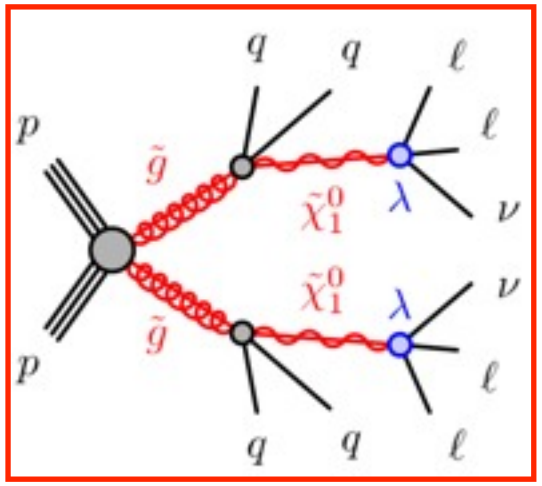
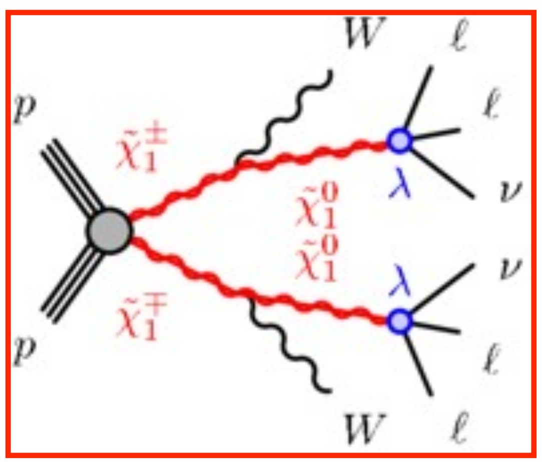
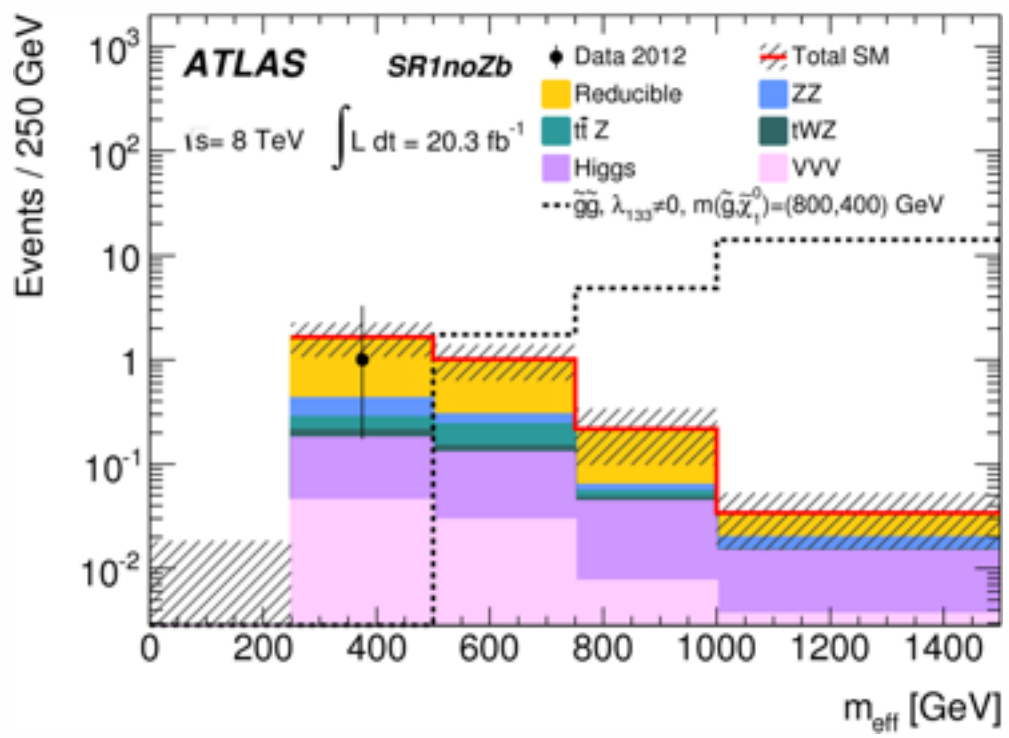
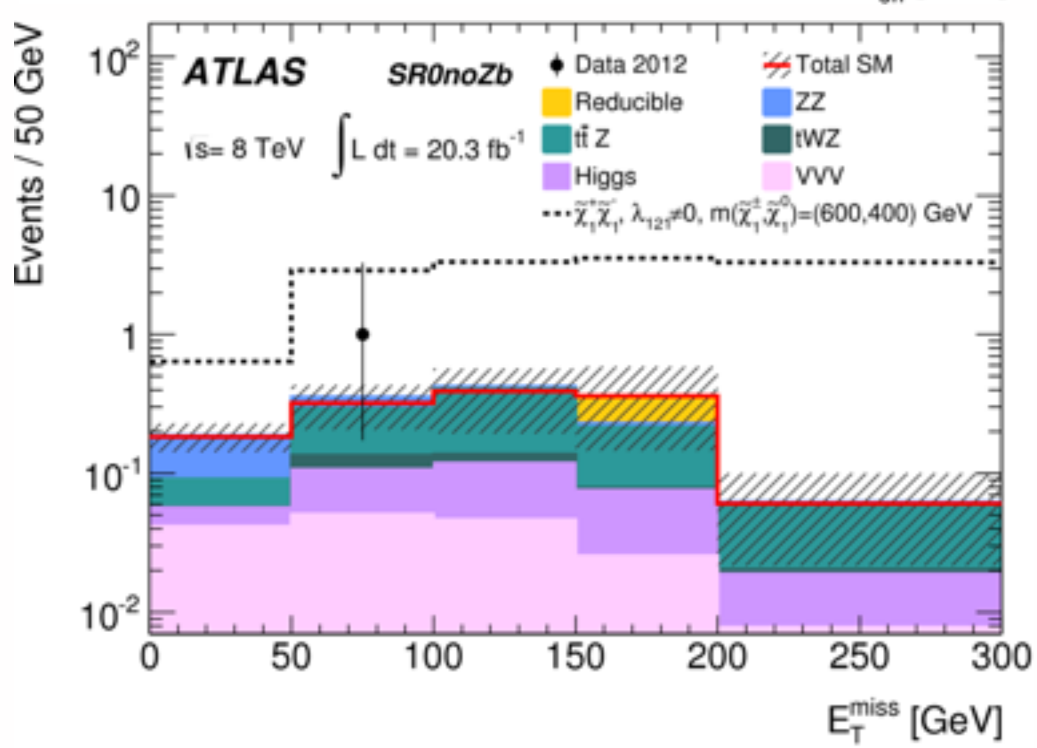
R-parity Violation

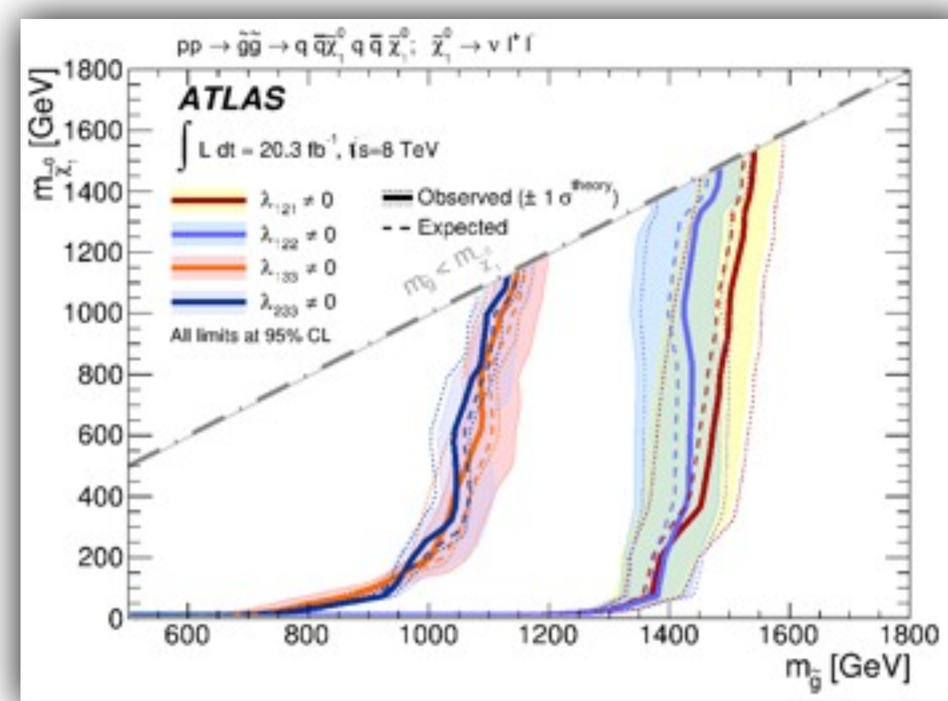
Search in events with ≥ 4 leptons, large MET or MEff

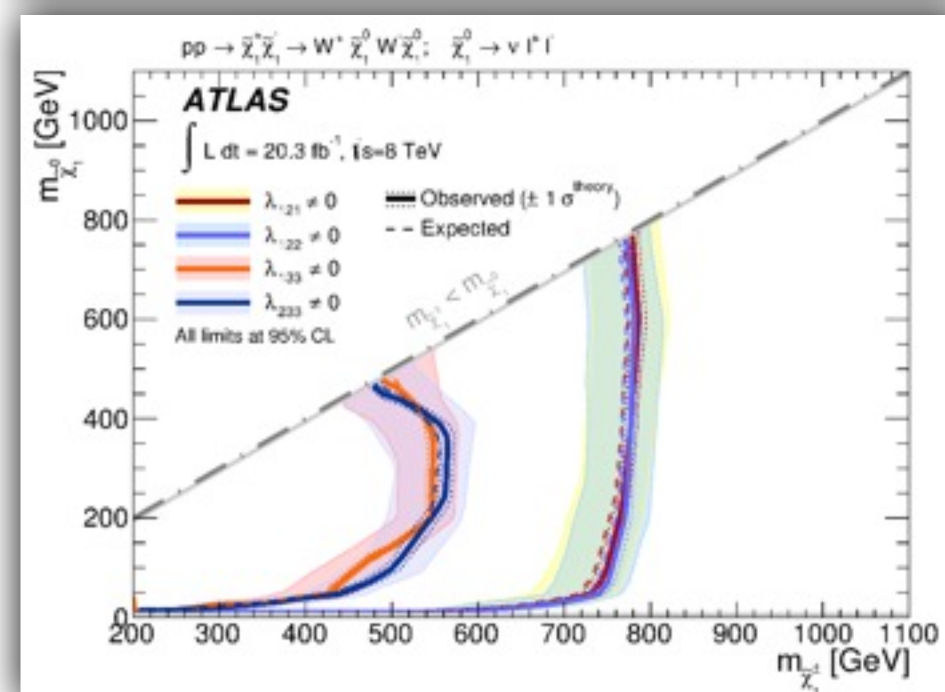












Sensitivity to 1-1.4 TeV gluinos (similar to RPC)
Enhanced sensitivity to charginos

Phys. Rev. D. 90, 052001 (2014)

Grand Summary of SUSY at ATLAS