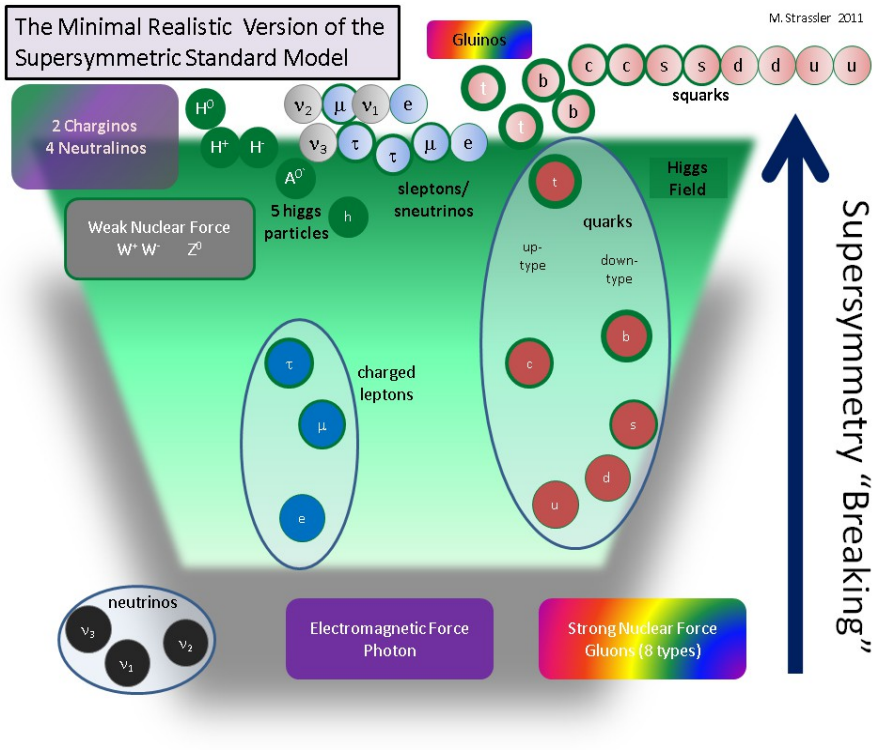
SUSY searches with ATLAS (including non-standard Higgs)

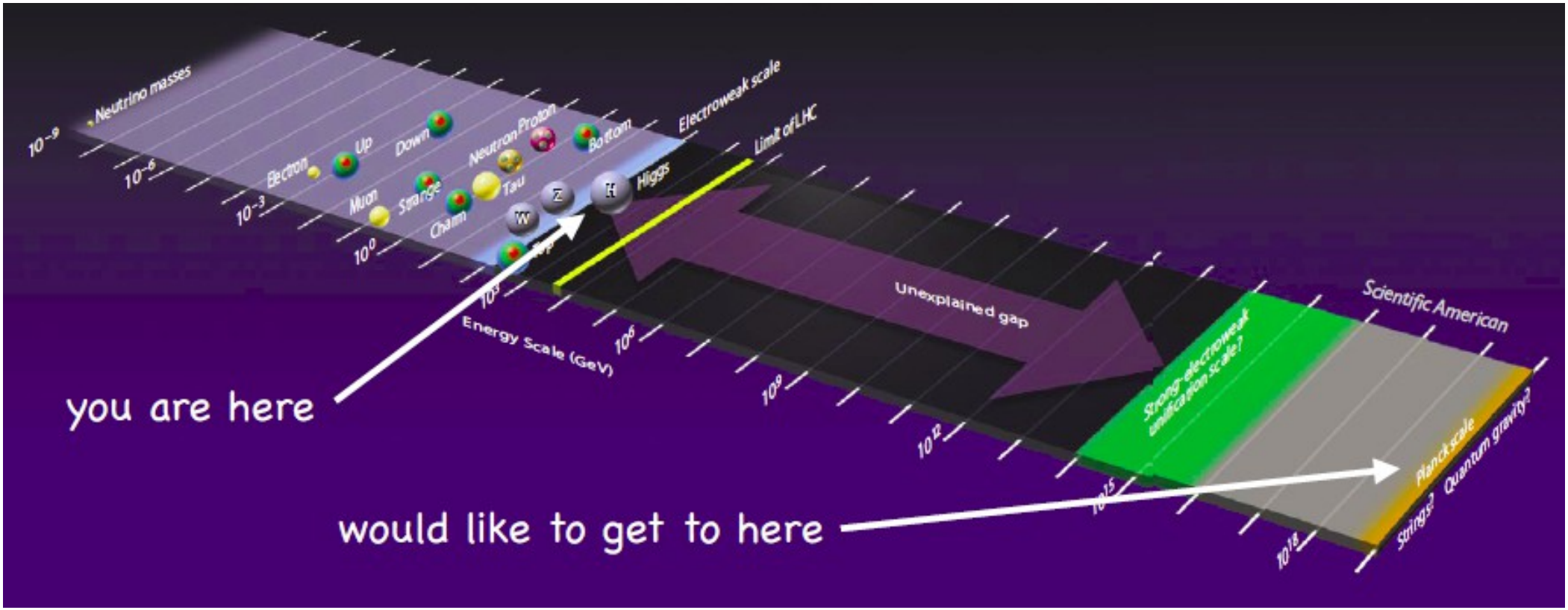
Andy Haas (NYU) on behalf of the ATLAS Collaboration

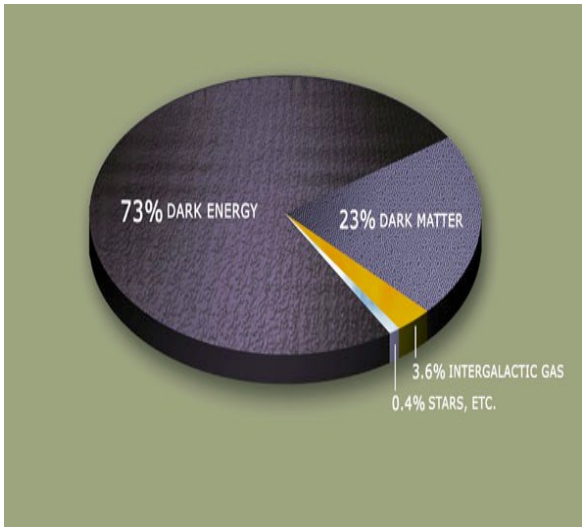
Results and Perspectives in Particle Physics
La Thuile, Italy - March 6, 2015
https://agenda.infn.it/conferenceOtherViews.py?confId=8743&view=standard

NEW YORK UNIVERSITY



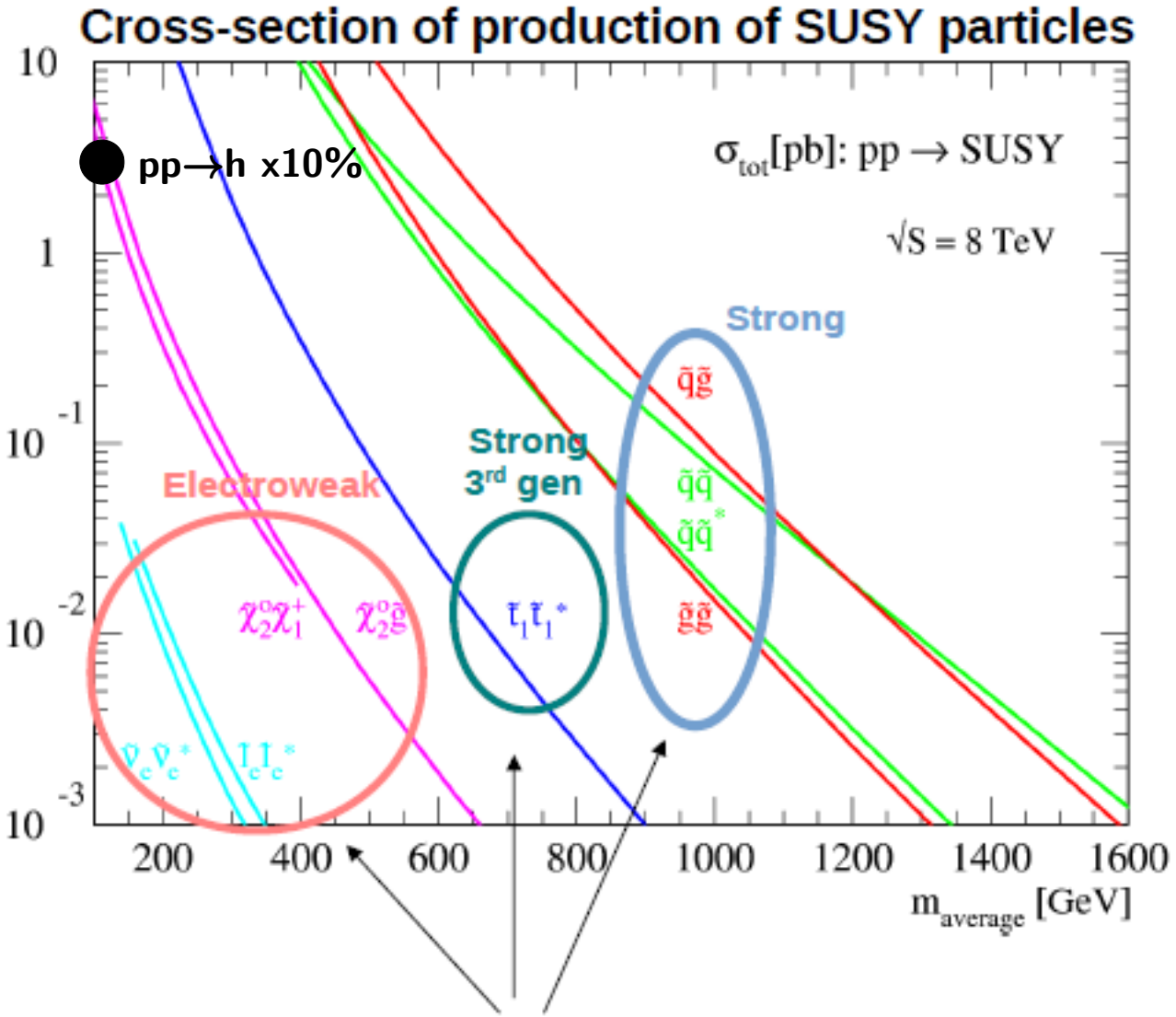
SUSY, Where Art Thou?



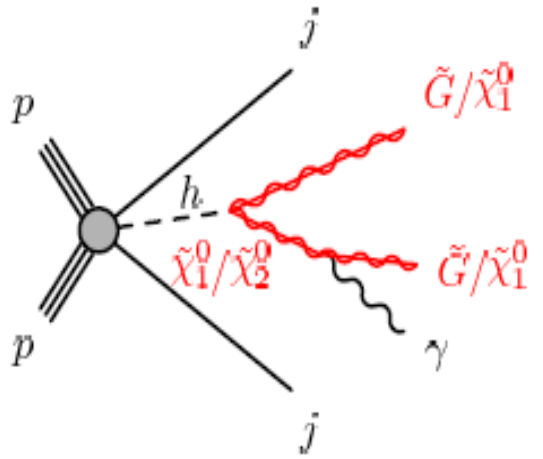


Hierarchy problem
Force unification
Dark matter
...
Should find SUSY near the EW scale?

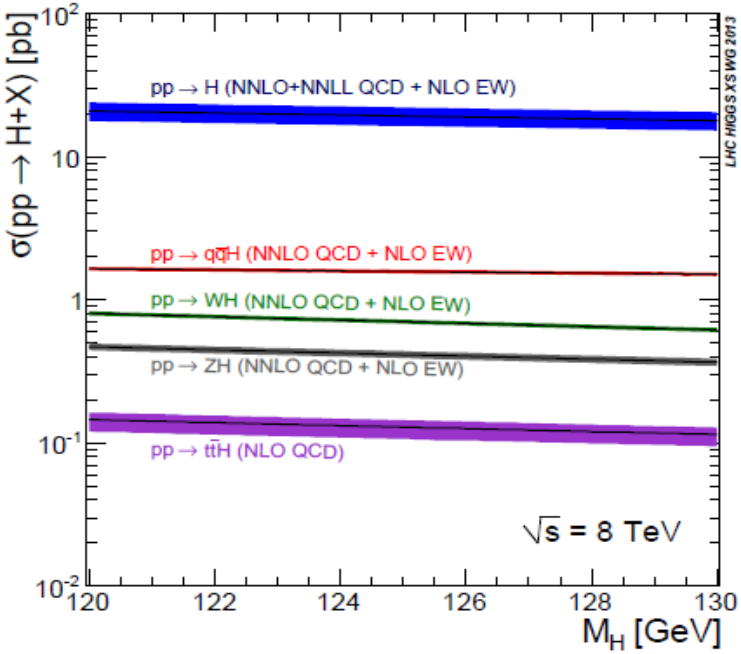
Introduction



Search strategies developed by ATLAS target all these SUSY production modes



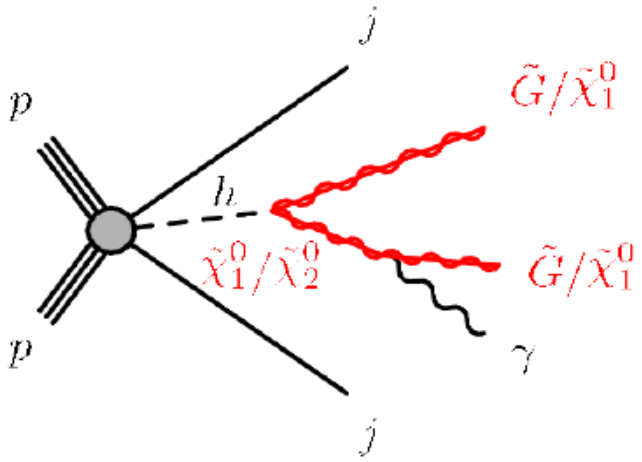
Also consider Higgs → SUSY



NEW! VBF Higgs ATLAS-CONF-2015-001

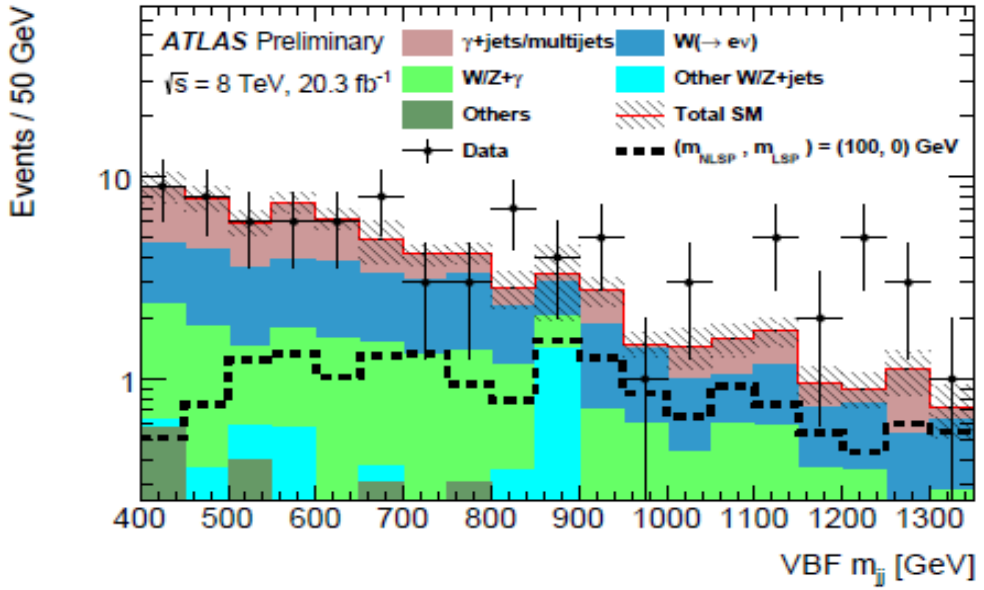
Higgs-boson production via vector-boson-fusion (VBF) decaying into neutralinos and/or gravitinos

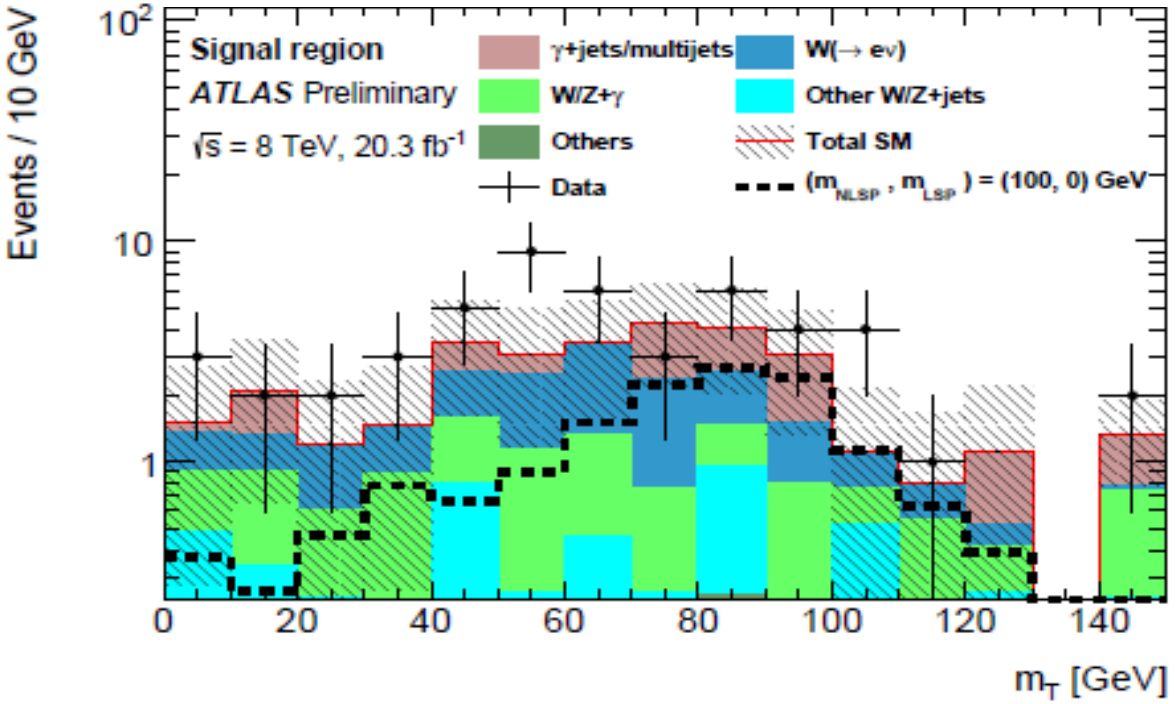
- Interpretation in GMSB and NMSSM models



Analysis Design

- Event Selection:
lepton veto, $\geq$ 2 jets, $\geq$ 1 photon, $E_{\mathrm{T}}^{\mathrm{miss}}$
- event selection optimized to exploit VBF di-jet topology m_{jj}, $\Delta\eta(jj)$
- main backgrounds multi-jets and gamma+jets





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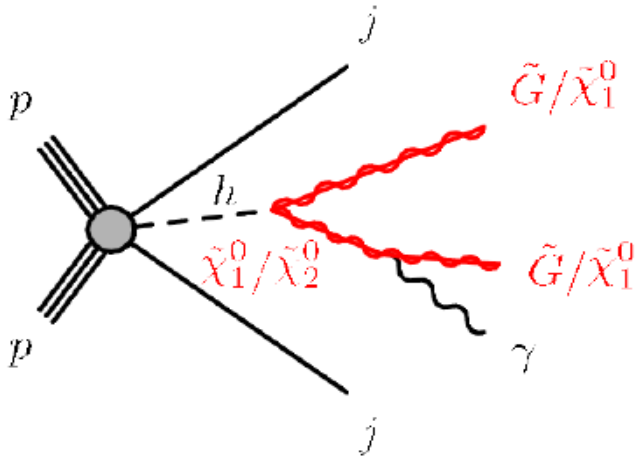

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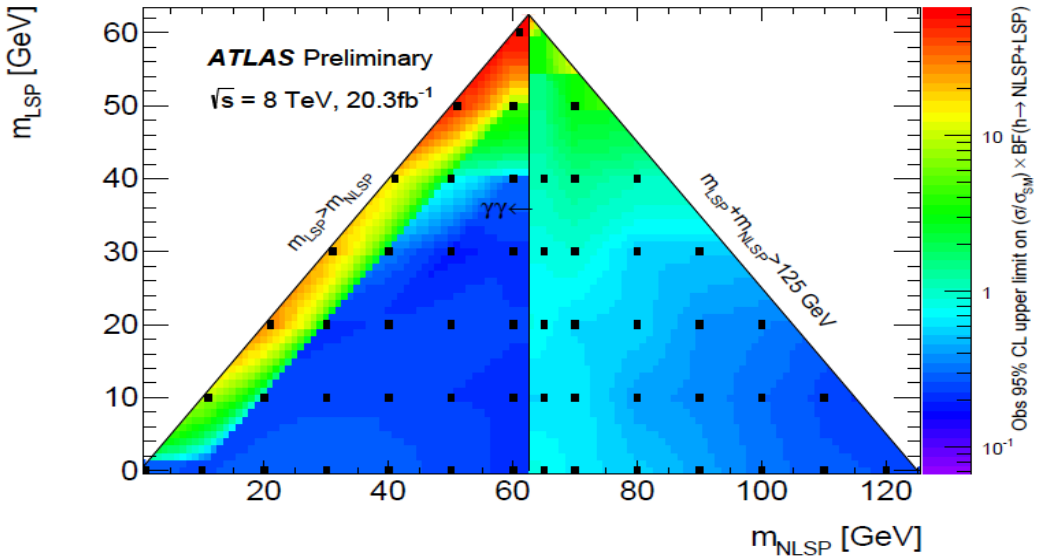
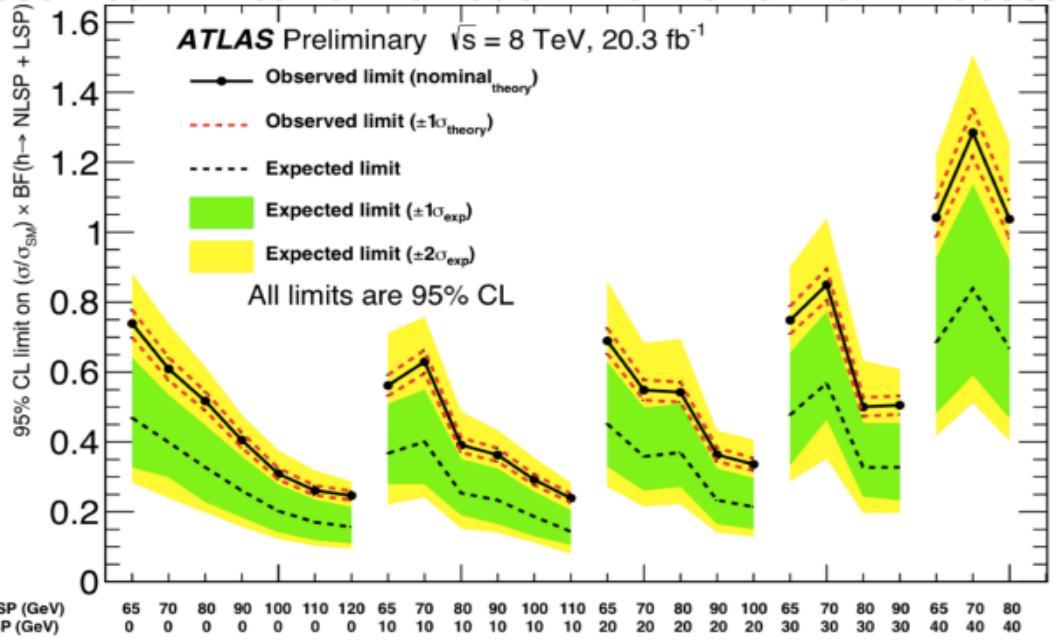
No significant deviation from SM.



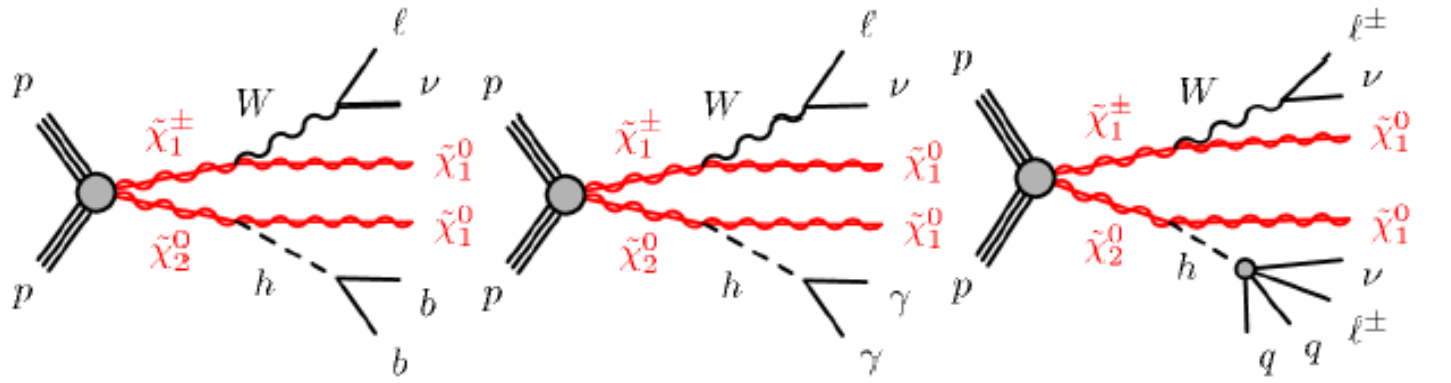
Observed limits for various NLSP and LSP masses.



NEW! *WH* combination

arXiv:1501.07110

$1\ell + 2\,\text{bb} + E_{\text{T}}^{\text{miss}}$ $1\ell + 2\,\text{photons} + E_{\text{T}}^{\text{miss}}$ $\ell^{\pm}\ell^{\pm} + \geq 1\,\text{jet} + E_{\text{T}}^{\text{miss}}$



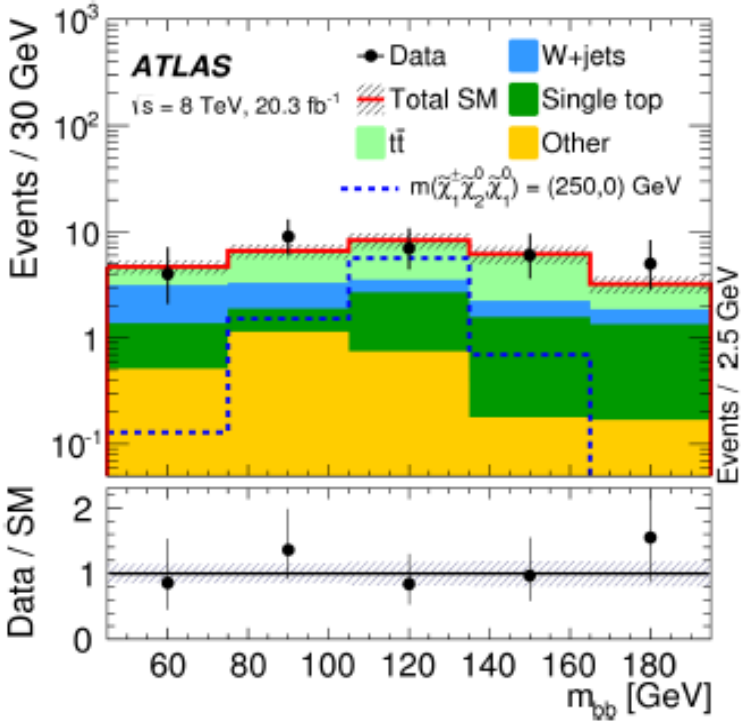
Simplified models:
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ decays via Wh

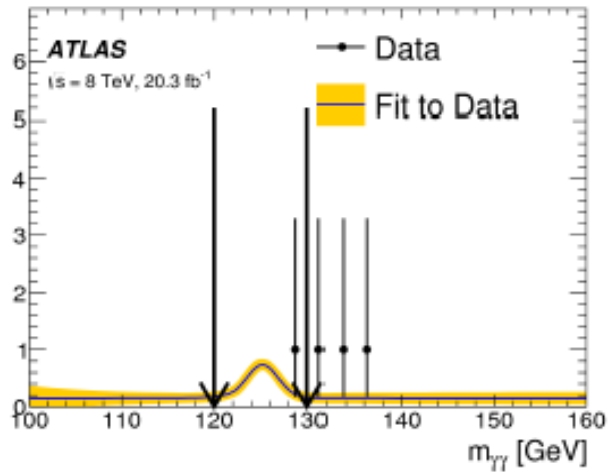
- $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ wino, mass degenerate
- $\tilde{\chi}_1^0$ bino

Strategy

- all 3 signatures combined
- 2 signal regions exploiting m_{T}^{W}, m_{CT} and requiring m_{bb} to be around the Higgs mass
- W+jets and $t\bar{t}$ SM background processes dominate
- 2 signal regions exploiting $m_{\text{T}}^{W\gamma}$, and $\Delta\phi(W,\gamma)$
- VH and $t\bar{t}$H SM background processes dominate
- 6 signal regions exploiting m_{eff}, and m_{T}
- VV and non-prompt lepton SM background processes dominate

Overall very good agreement between data and expectation





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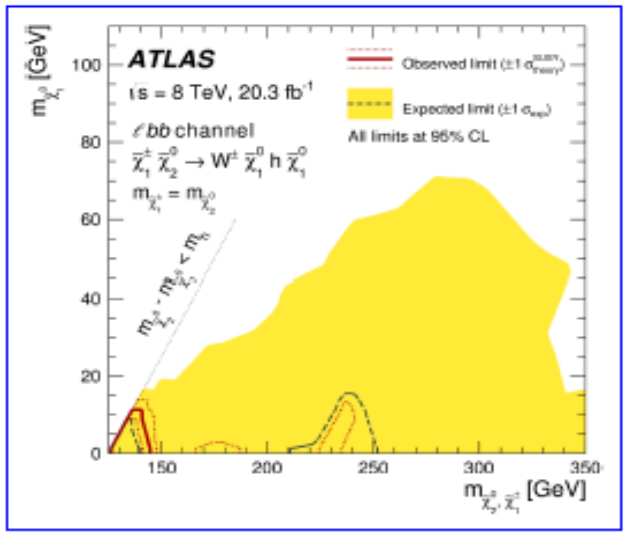

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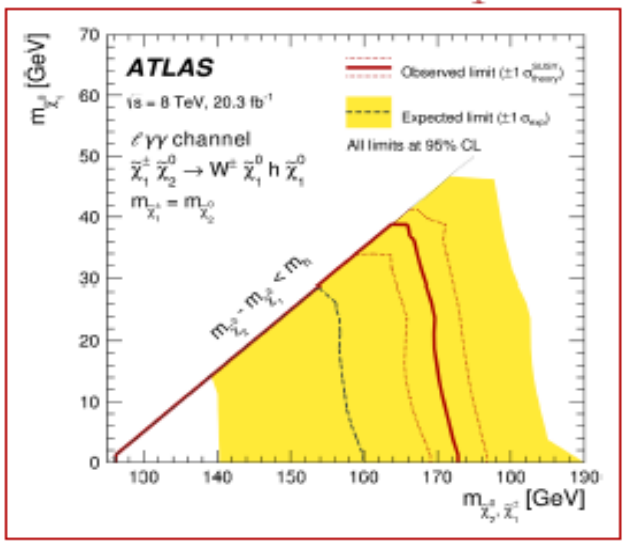
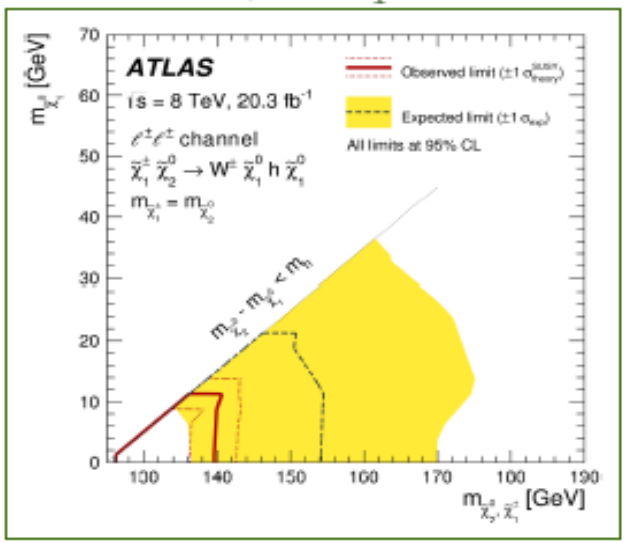
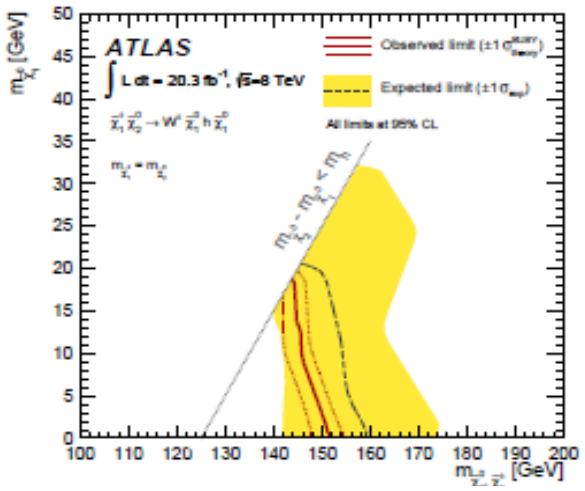


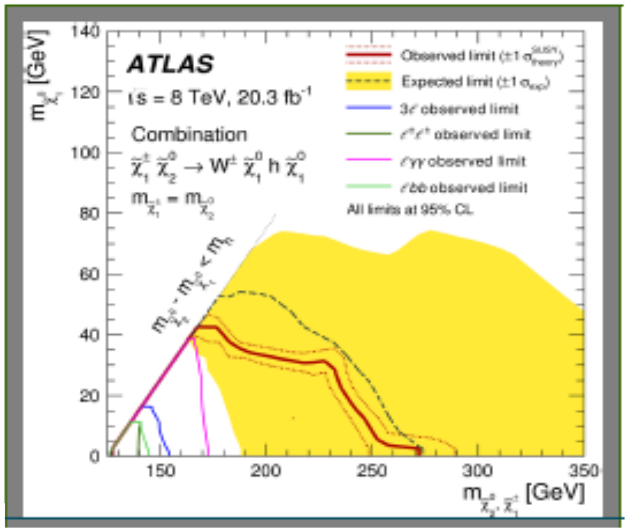
$\ell^{\pm}\ell^{\pm} + \geq 1\,\text{jet} + E_{\text{T}}^{\text{miss}}$



$3\ell + E_{\text{T}}^{\text{miss}}$ (arXiv:1402.7029)



Combination + 3L



- No significant deviation from SM
- **Combination of all 3 channels + 3L analysis shows the best exclusion** (mind the axis range)
- Excluding charginos with mass up to 250 GeV for massless LSP

NEW!

$A \rightarrow Zh$

arXiv:1502.04478

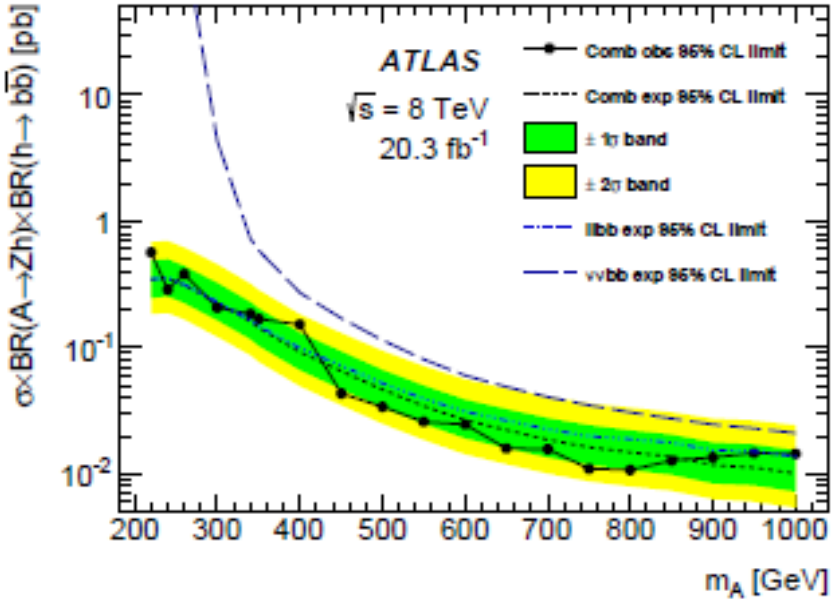
2HDM

Can be dominant A decay, especially for $m_A < 2m_{top}$

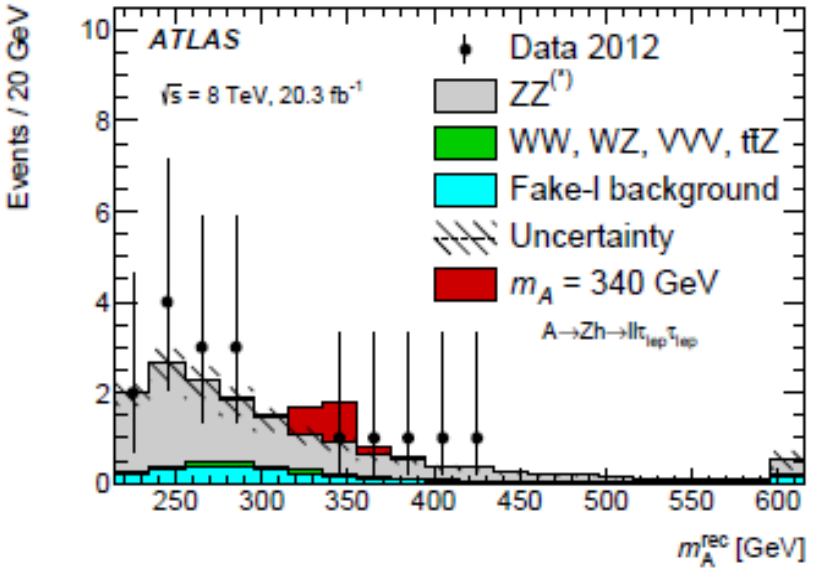
A is a narrow resonance in 220 – 1000 GeV

Look for $Z \rightarrow ll + h \rightarrow bb$ or $\tau\tau$

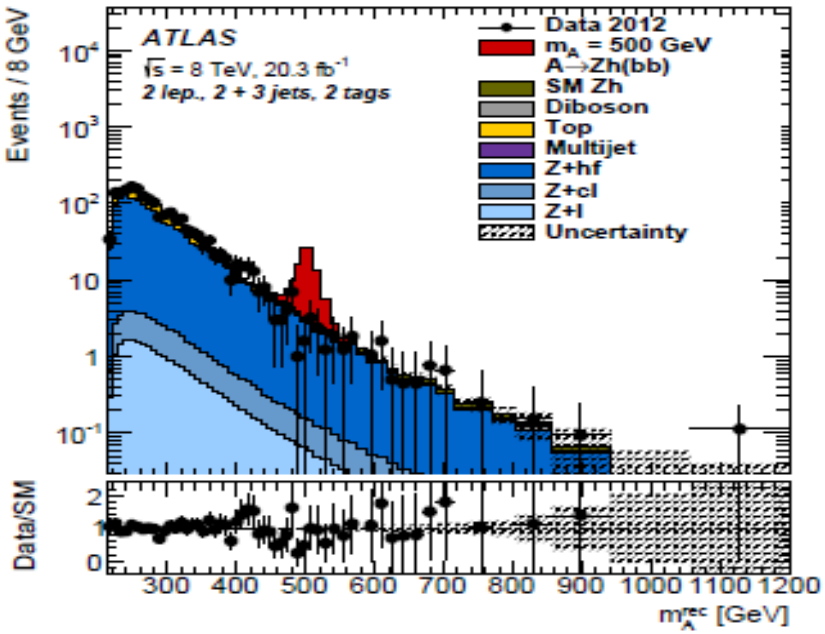
and $Z \rightarrow \nu\nu + h \rightarrow bb$



(b) $A \rightarrow Zh,\ h \rightarrow bb$



(b) $\ell\ell\tau_{\rm lep}\tau_{\rm lep}$



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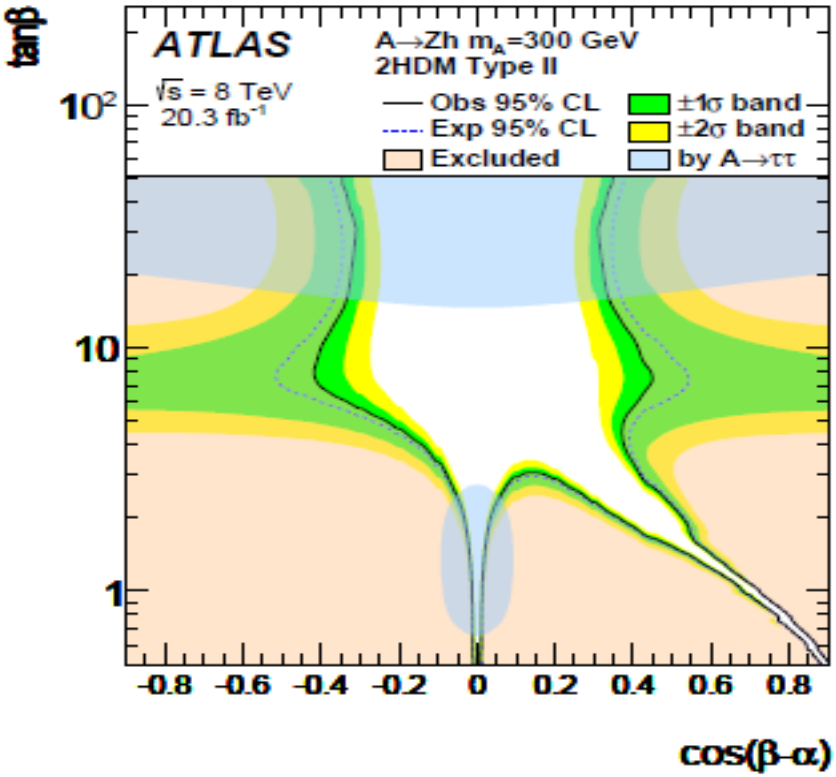

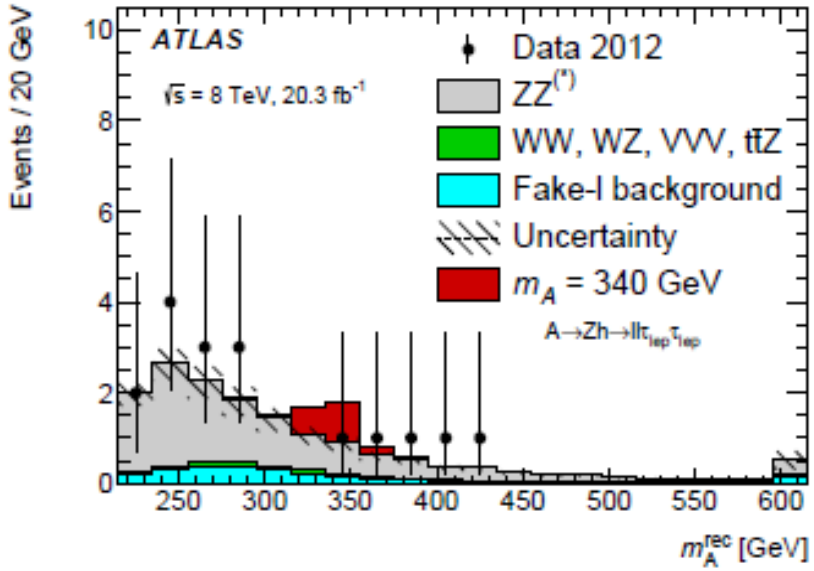

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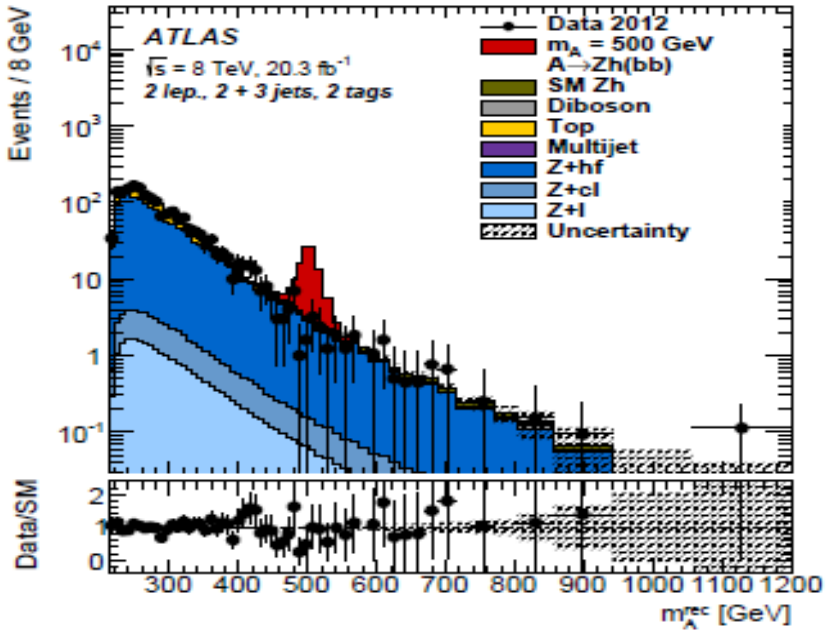


(a) $\ell\ell bb$

NEW!

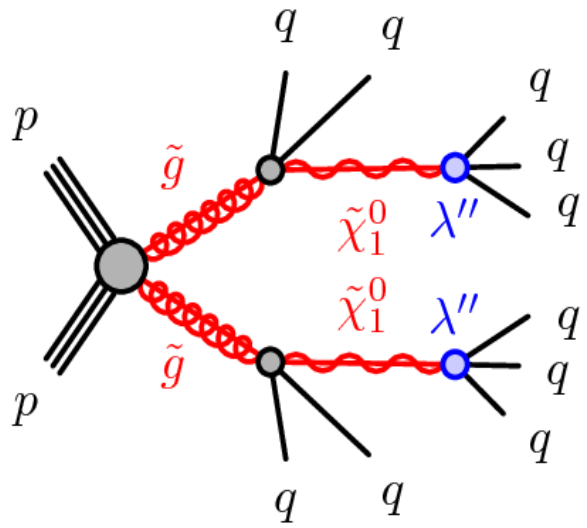
Gluino → multi-jets

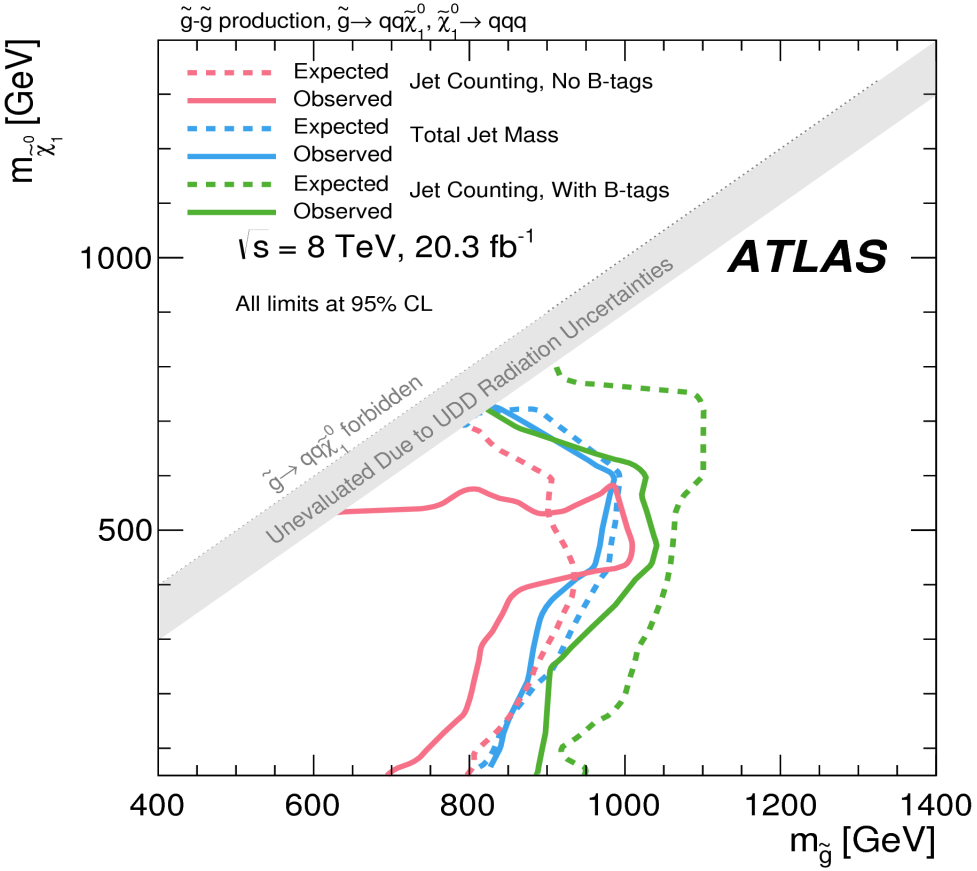
arXiv:1502.05686

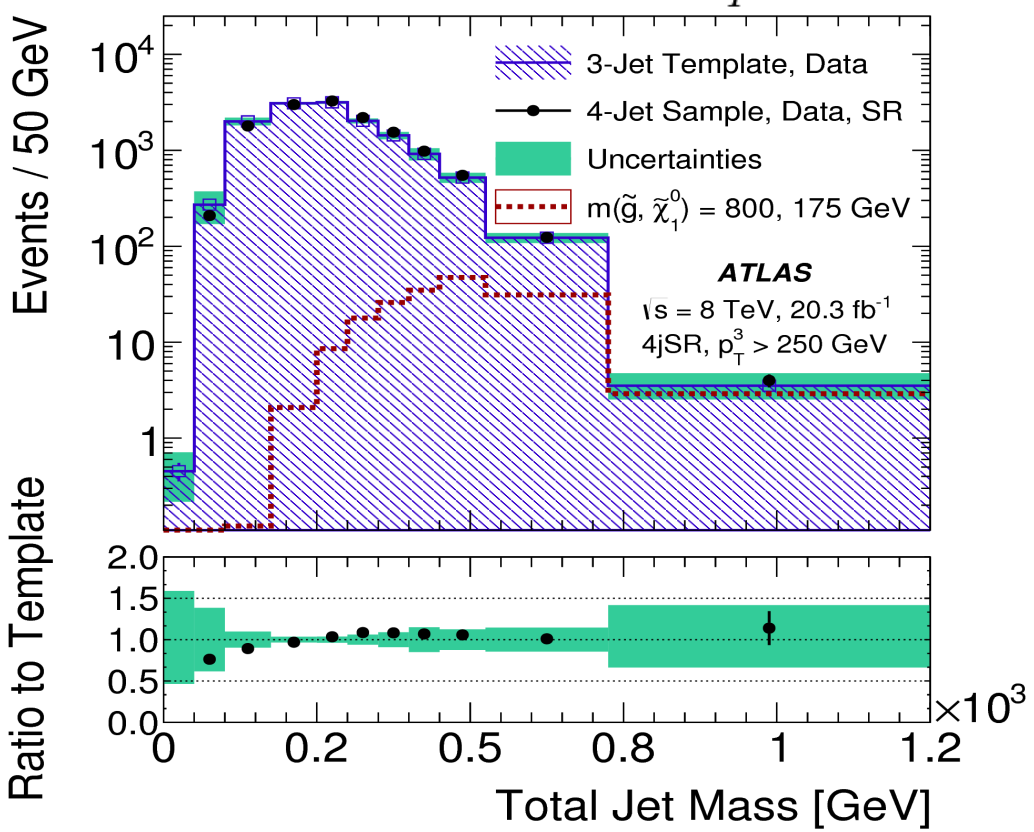
Search for gluino decays to jets through RPV coupling

Dominant QCD background is estimated using templates derived in lower jet multiplicity bins

Excess searched for with ≥6,7 jets or large total (fat-)jet mass







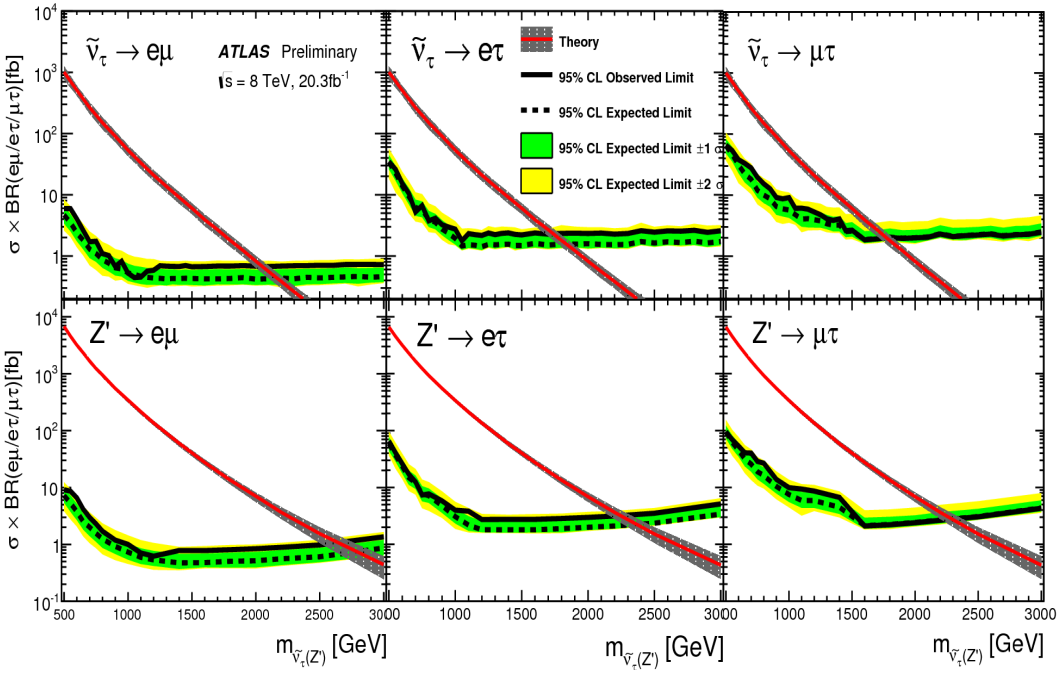
NEW!

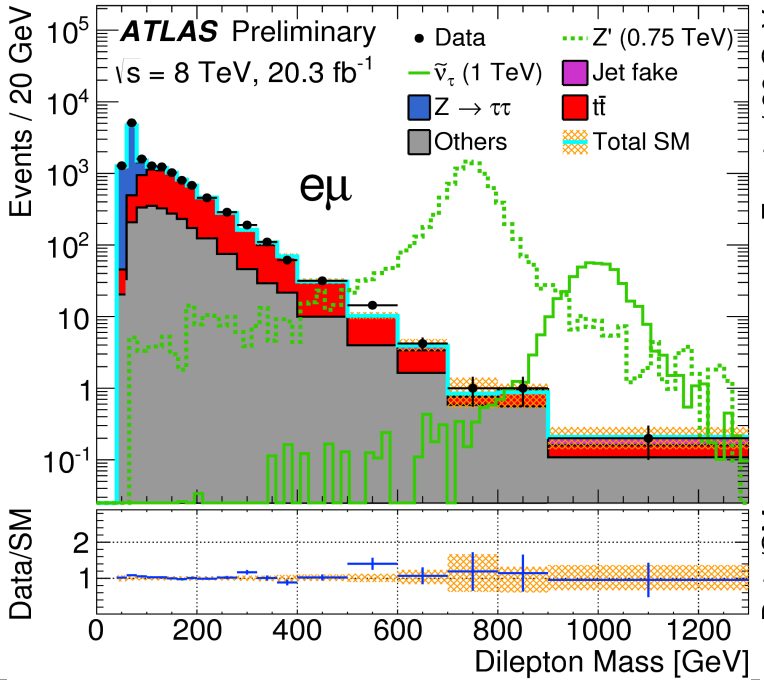
Search for eμ, eτ, or μτ resonances

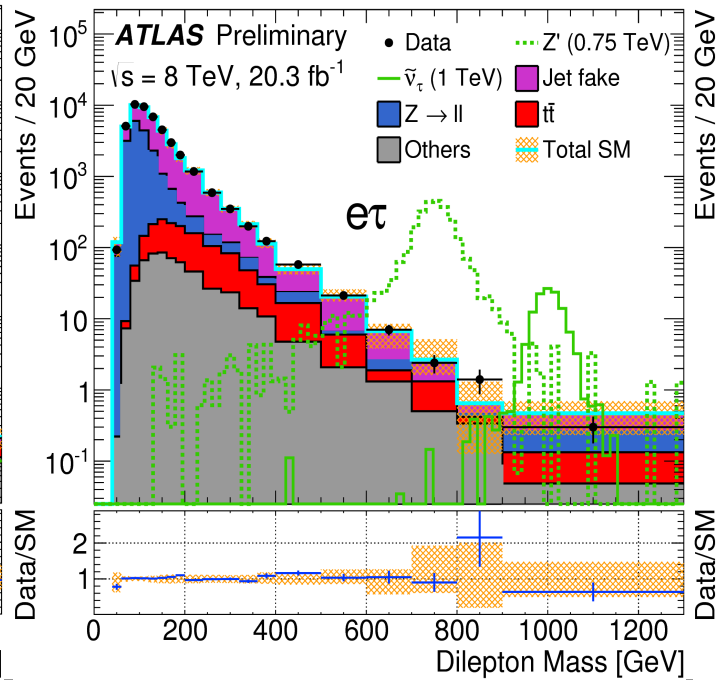
RPV decays of the τ sneutrino
LFV decays of a Z'

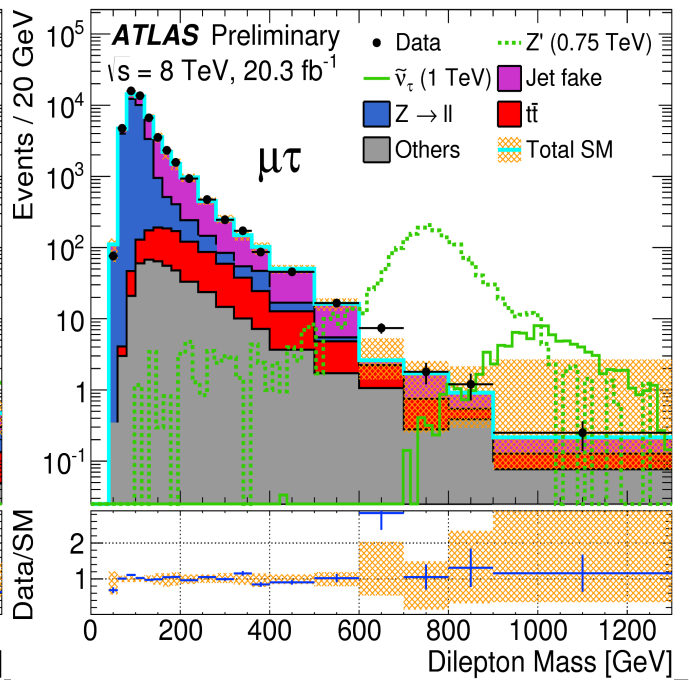
Dominant backgrounds modeled in MC and checked in Control Regions

Excess searched for in mass ranges compatible with signal resolution









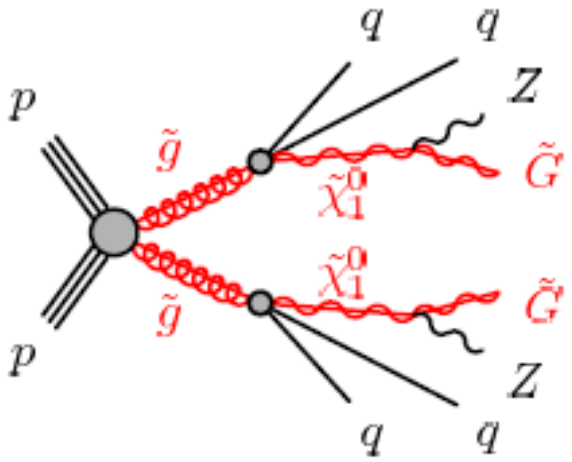
NEW! Search for SUSY with 2l+jets+MET

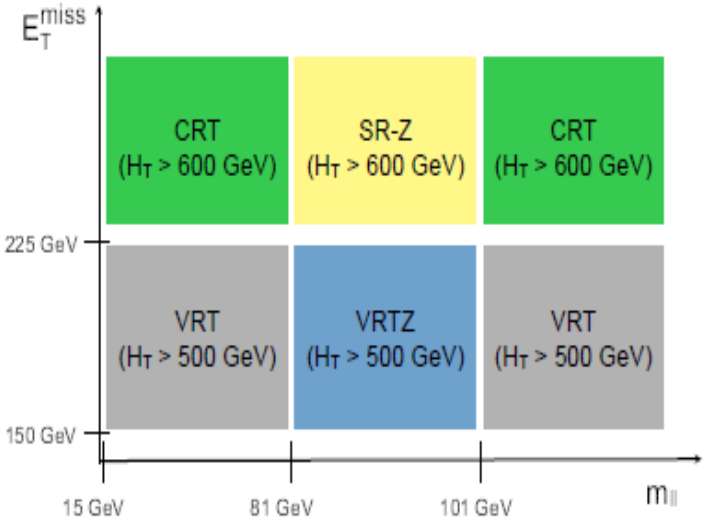
Various SUSY decay chains can give 2l+jets+MET

Look at events with a Z→ll candidate
Signal Region: MET>225GeV and HT>600GeV

Main background (ttbar) is estimated from data using eμ events with the same cuts as the SR.
This is cross checked using the Z side-bands.

3.0σ excess (!) ... 3.0σ for ee, 1.7σ for μμ





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	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

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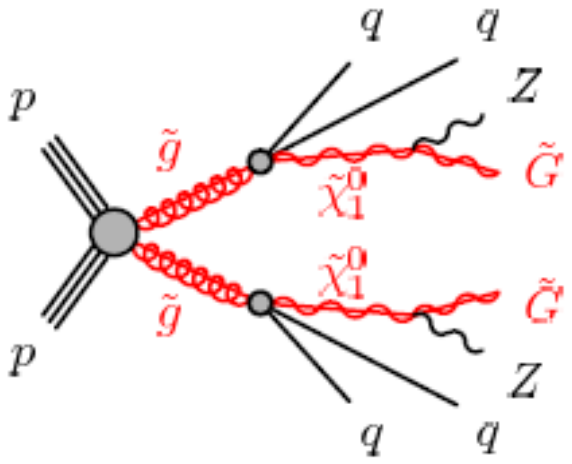
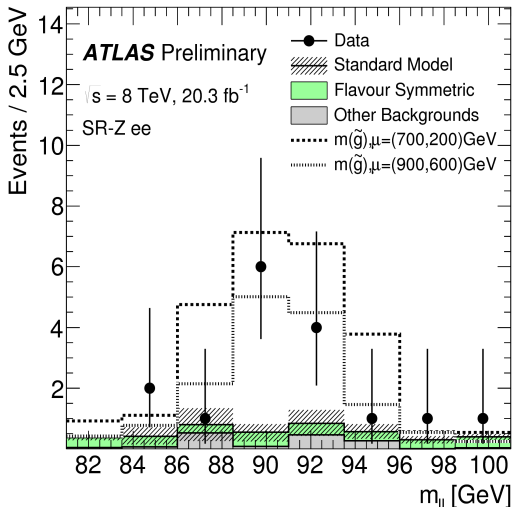
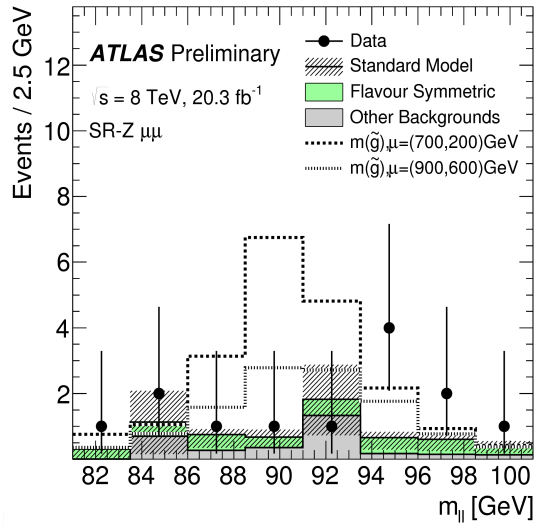
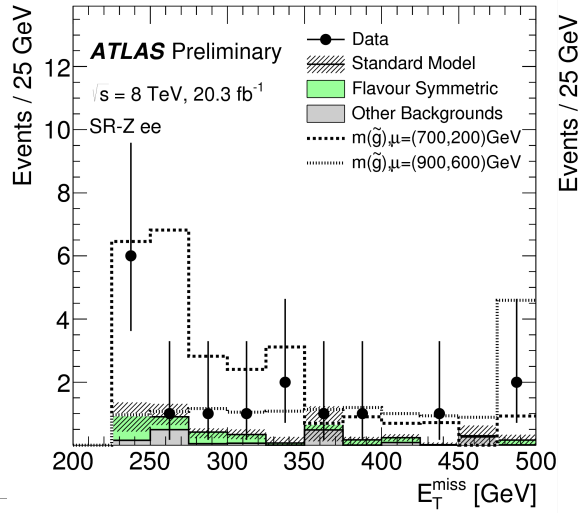
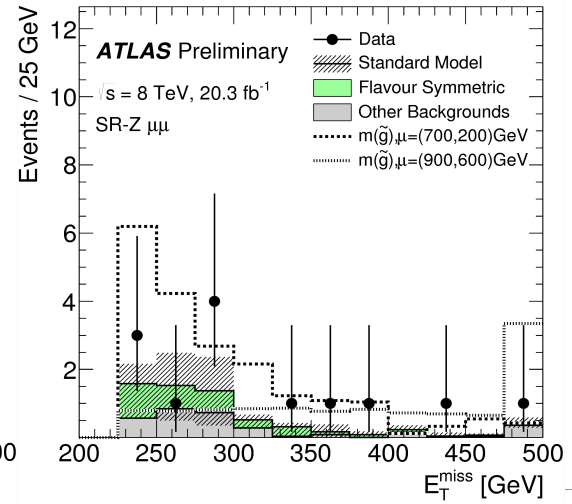
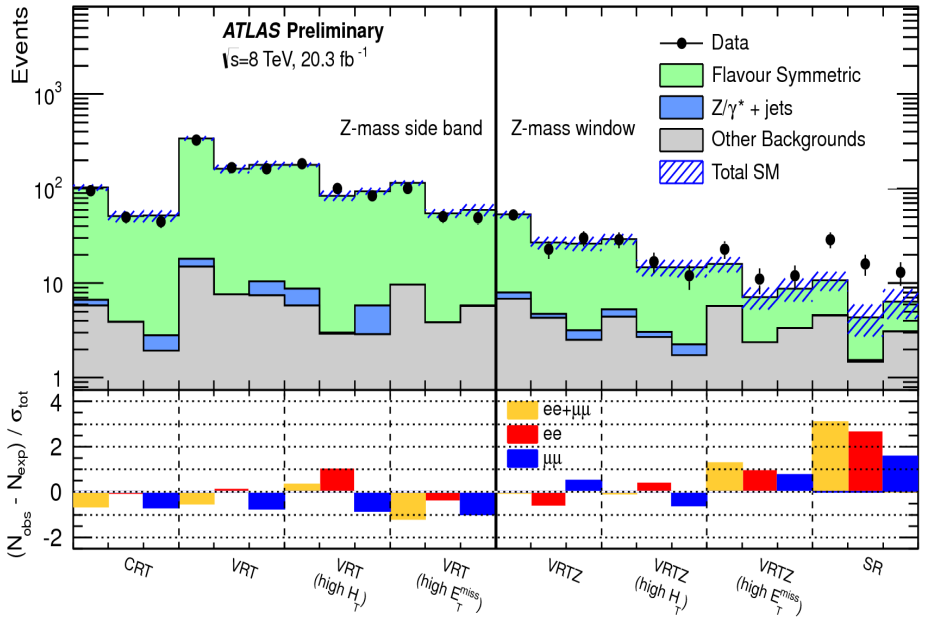












CMS Search for SUSY with 2l+jets+MET: on Z

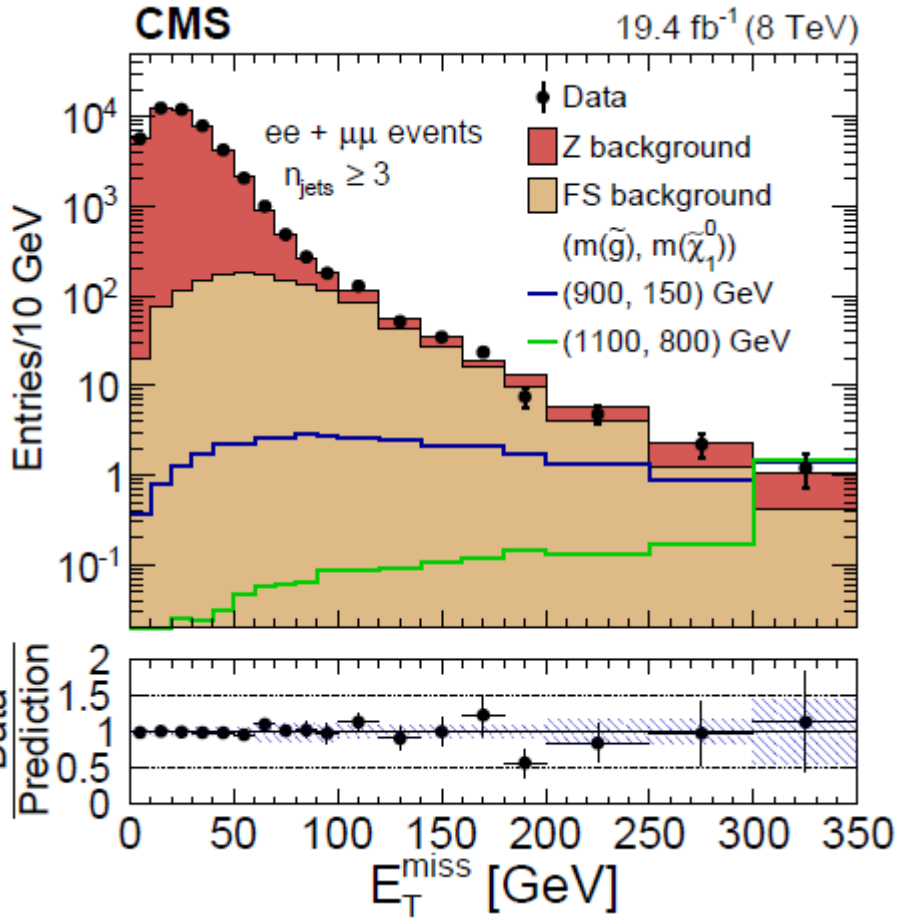
Recall ATLAS Signal Region: MET>225GeV and HT>600GeV

arXiv:1502.06031

CMS has new Signal Region with Njets>2 and large MET

- **No excess seen**
- **More DY background than ATLAS (from looser H_T)**
- **~30% overlap with ATLAS selection**

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

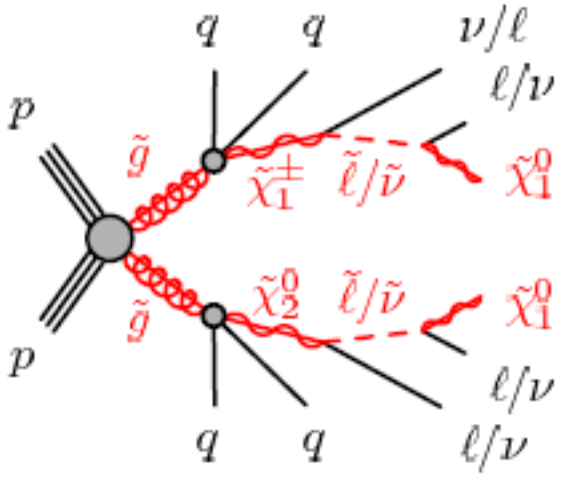


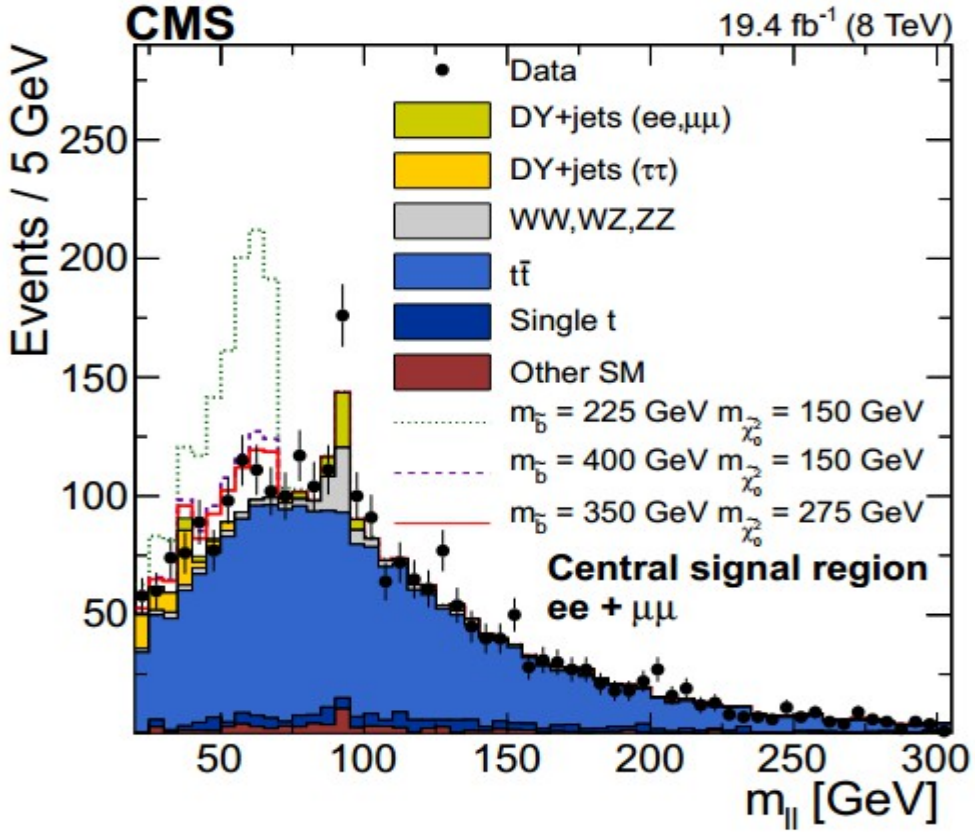
NEW! Search for SUSY with 2l+jets+MET

Various SUSY decay chains can give 2l+jets+MET

Also study off-Z-peak range, with 2 or 4 jets,
with or without b-tags, and CMS-like selection

Recall CMS 2.6σ excess 20<m(ll)<70 GeV with 2/3 jets
(arXiv:1502.06031)





Off-Z Region	E_T^{miss} [GeV]	n_{jets}	$n_{b\text{-jets}}$
Signal regions			
SR-2j-bveto	> 200	≥ 2	$= 0$
SR-2j-btag	> 200	≥ 2	≥ 1
SR-4j-bveto	> 200	≥ 4	$= 0$
SR-4j-btag	> 200	≥ 4	≥ 1
SR-loose	$> (150, 100)$	$(2, \geq 3)$	-

CMS-like selection

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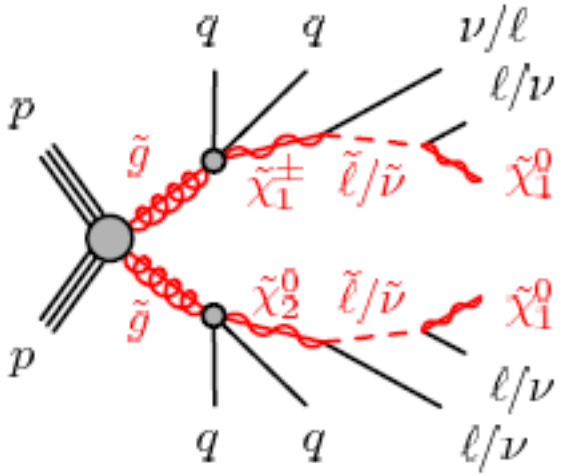
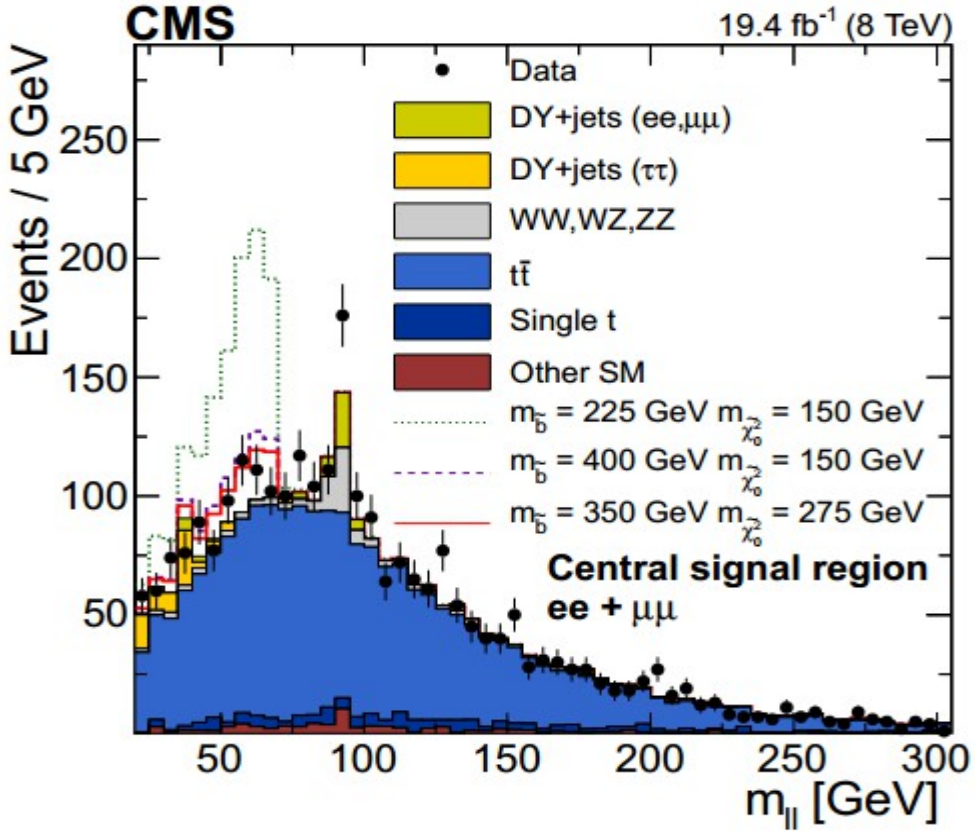
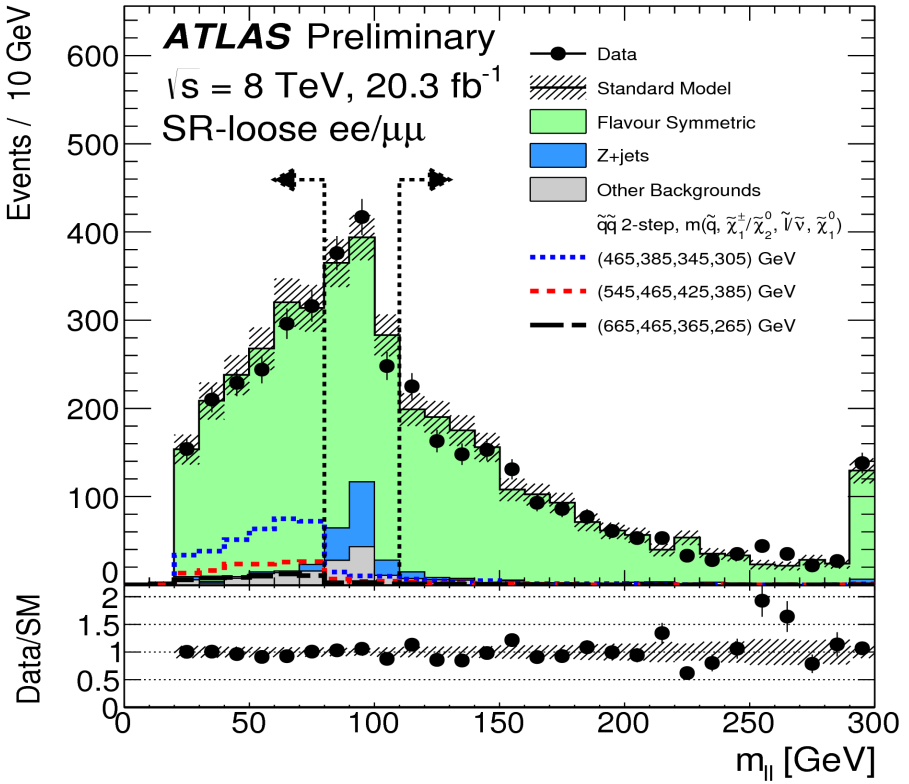
No excess seen in similar ATLAS selection







NEW!

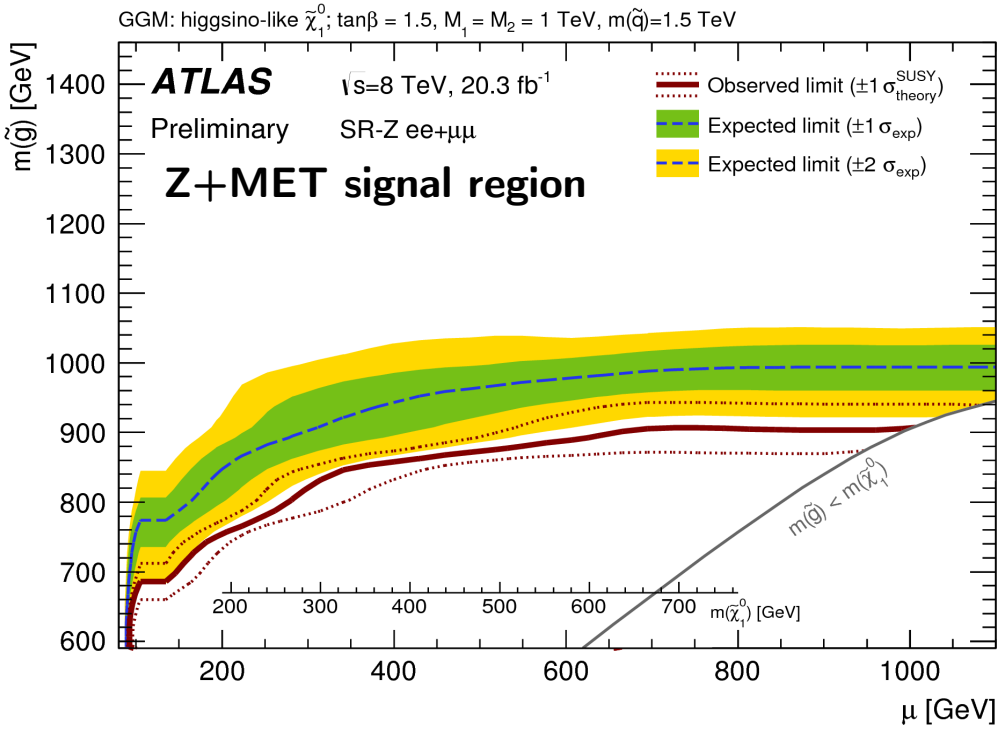
Search for SUSY with 2l+jets+MET

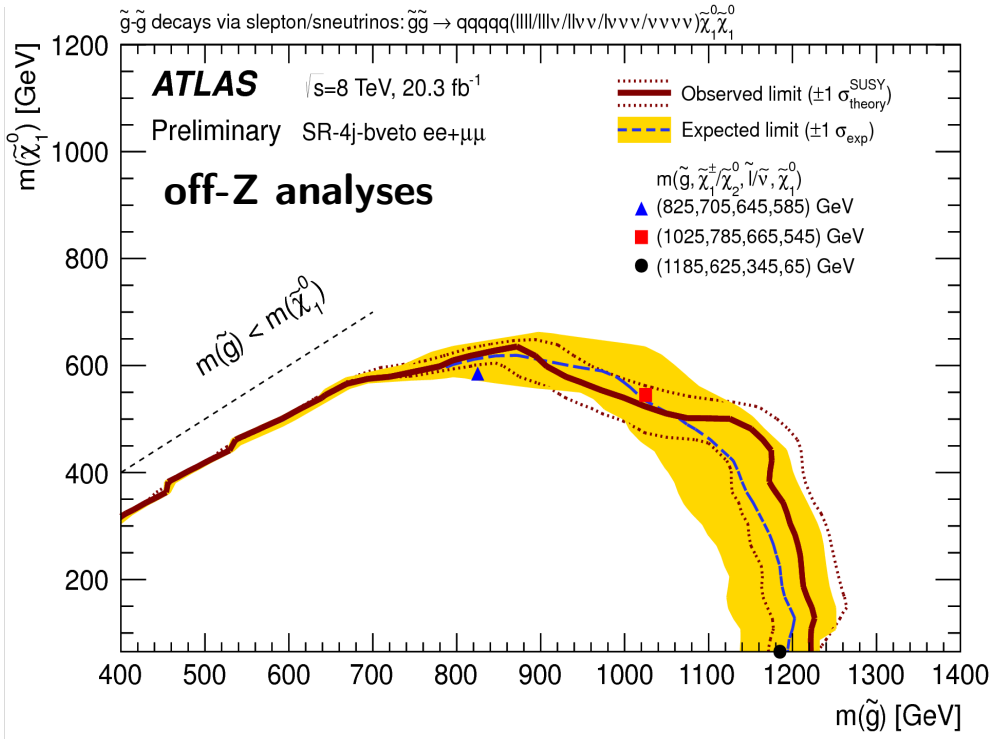
Set limits in GGM models,
as well as squark/gluino decays chains
with neutralinos

3.0 sigma excess in Z+MET at
large HT weakens limits

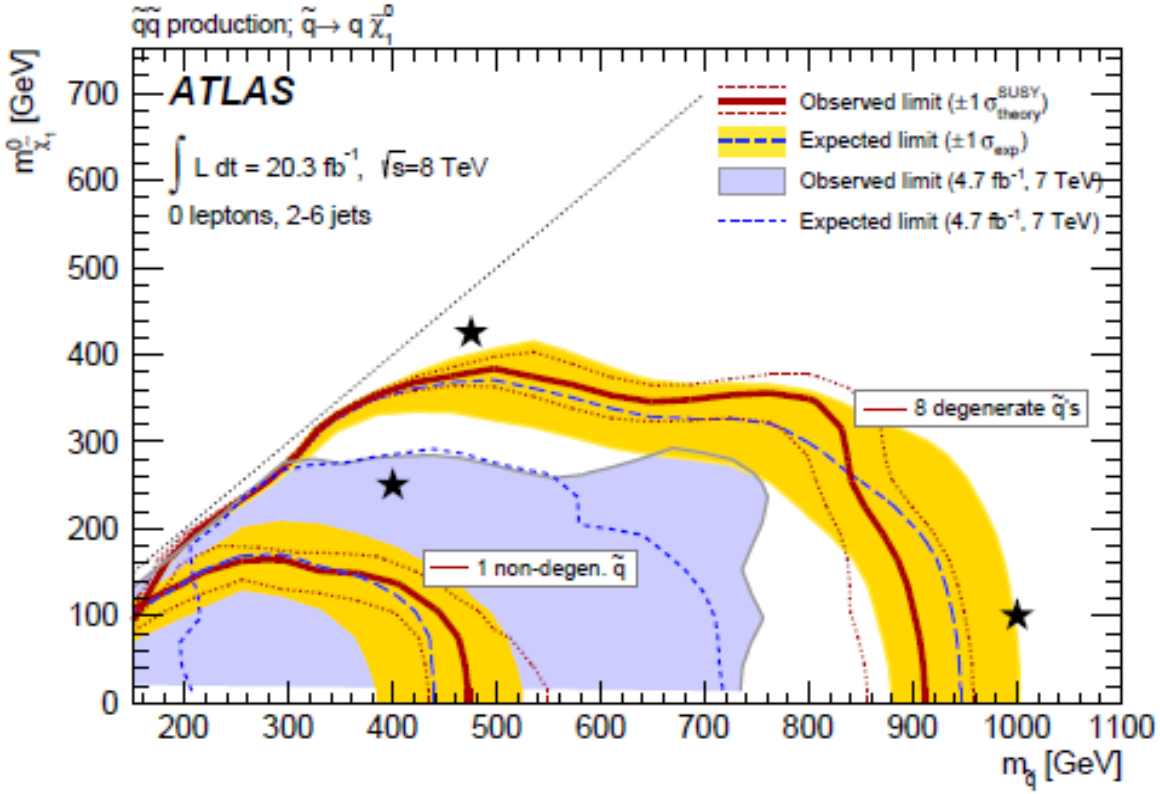
	Dilepton edge	Z+MET
ATLAS	No excess	3.0σ
CMS	2.6σ	No excess

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





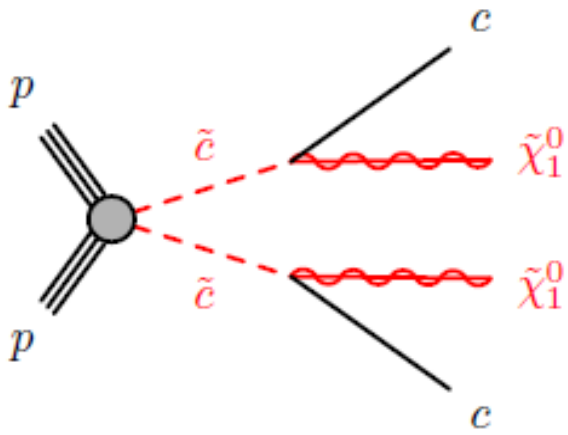
Scalar charm $\rightarrow$ cc + MET



- Inclusive $\tilde{q}$ searches weaker if only one light $\tilde{q}$: $\sigma/8$
- In MSSM squarks can mix
  - Weak flavour physics constraints on $\tilde{t} - \tilde{c}$ mixing
- Charm jet tagging gives improved sensitivity to $\tilde{c}$
- First dedicated search for scalar charm quark

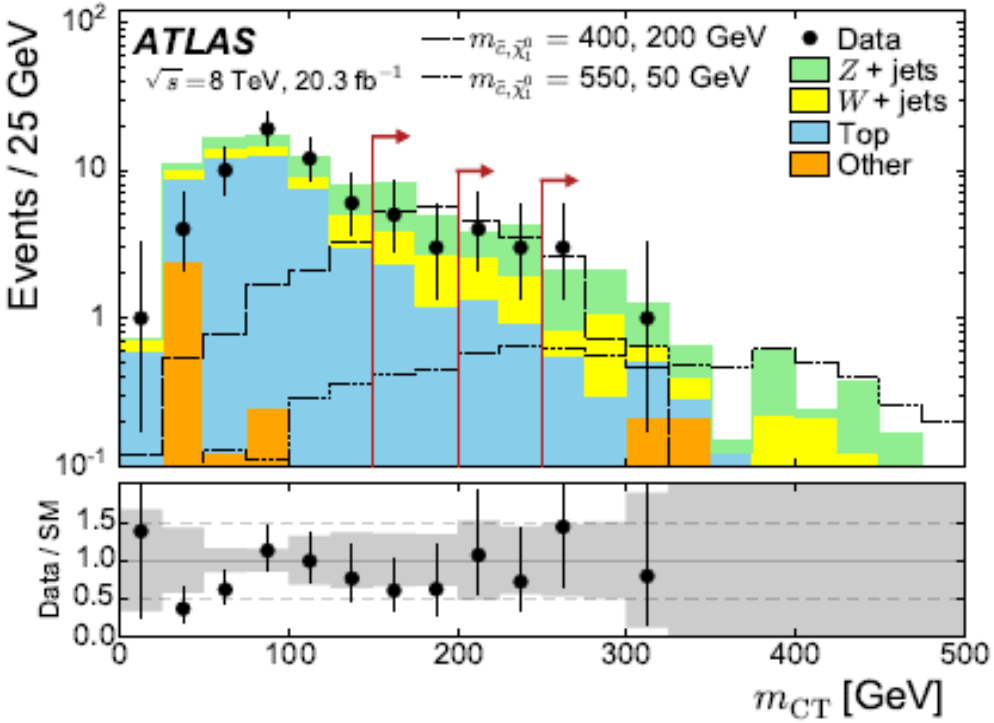
arXiv: 1501.01325 [hep-ex], submitted to PRL

Simplified model $\tilde{c} \rightarrow c\tilde{\chi}_1^0$

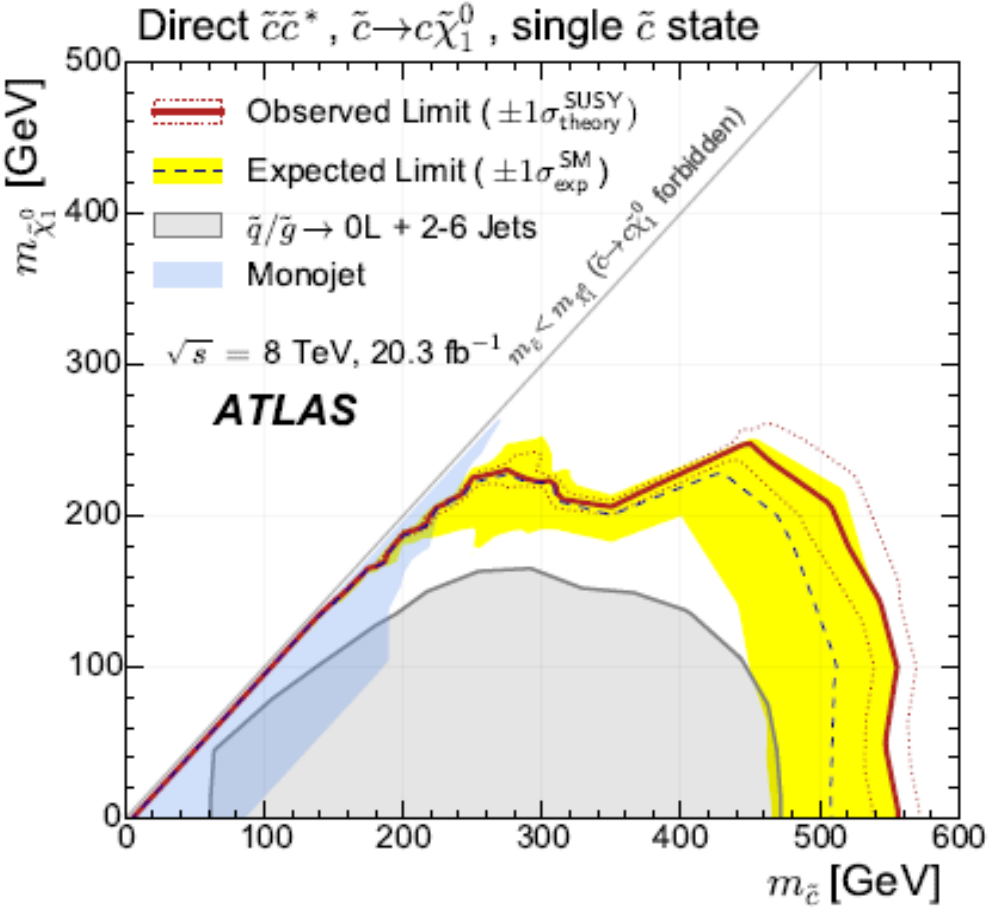


- 2 high-p_{T} c-jets
- High $E_{\mathrm{T}}^{\mathrm{miss}}$
- No leptons

Scalar charm $\rightarrow$ cc + MET



- Kinematic selection (m_{CT} and m_{cc})
- $m_{\mathrm{CT}}^2(j_1, j_2) = [E_{T,1} + E_{T,2}]^2 - [\mathbf{p}_{T,1} - \mathbf{p}_{T,2}]^2$
  - $E_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m^2}$
  - $m_{\mathrm{CT}}^{\mathrm{max}} = \frac{m^2(\tilde{c}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{c})}$



- $\sim$ 100 GeV improvement in exclusion over inclusive $\tilde{q}/\tilde{g}$ (grey)

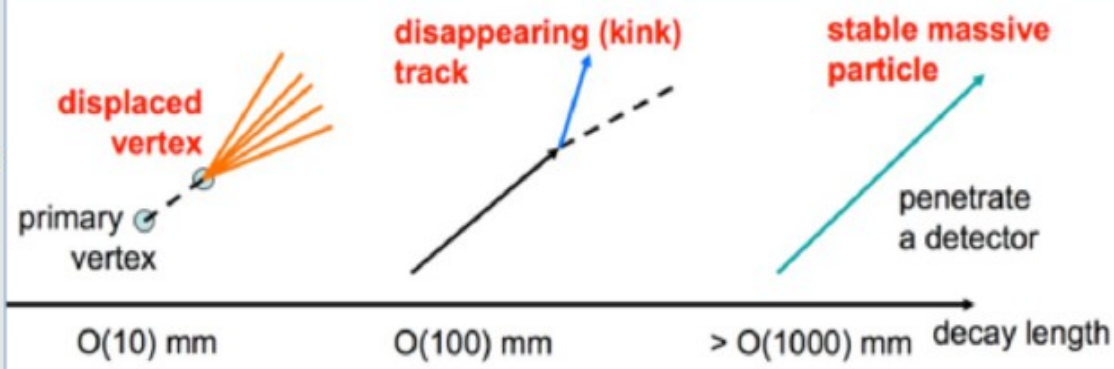
Searches for Long-lived SUSY

Long Lived Particles (LLP) are predicted by a wide variety of models : Hidden Sectors, RPV violating decays, Split-SUSY, AMSB, GMSB,

Signatures include:

- **Disappearing tracks**
- **Stopped gluino or squark R-hadrons**
- **Non-pointing and delayed photons**
- **Stable LLPs**
- **Displaced vertices**

All these signatures depend on lifetime

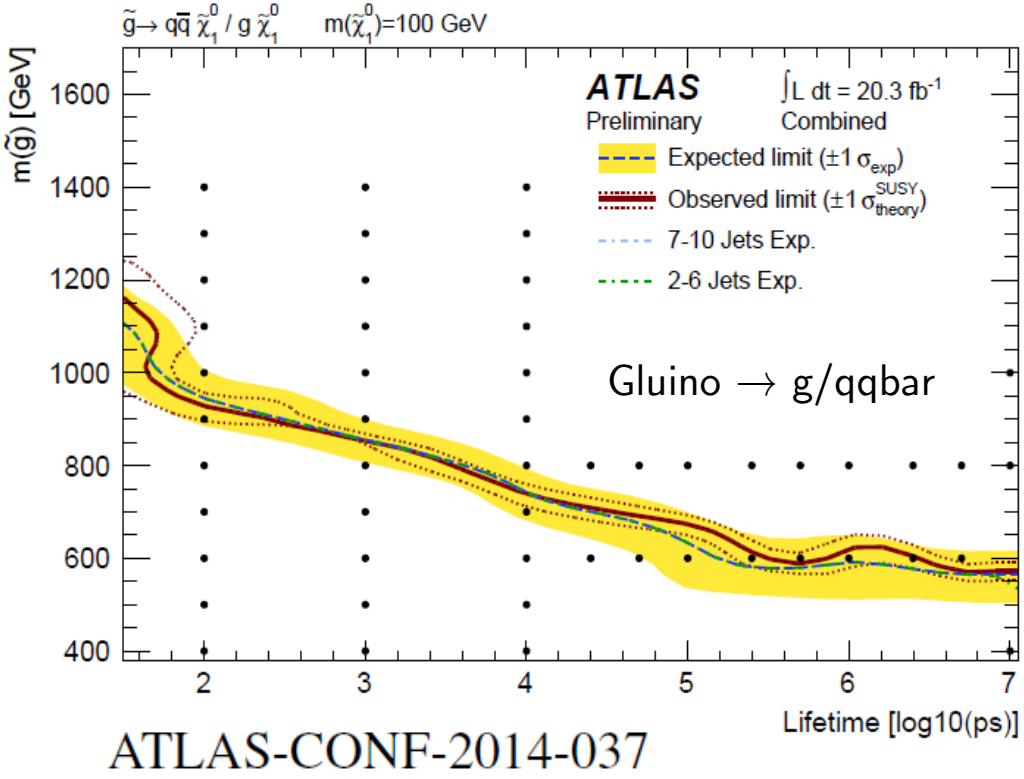


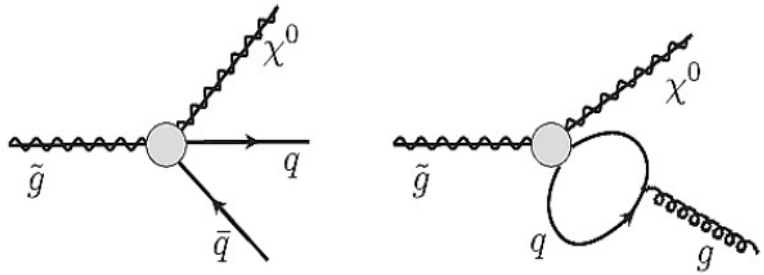
Re-interpretation of Prompt SUSY Searches

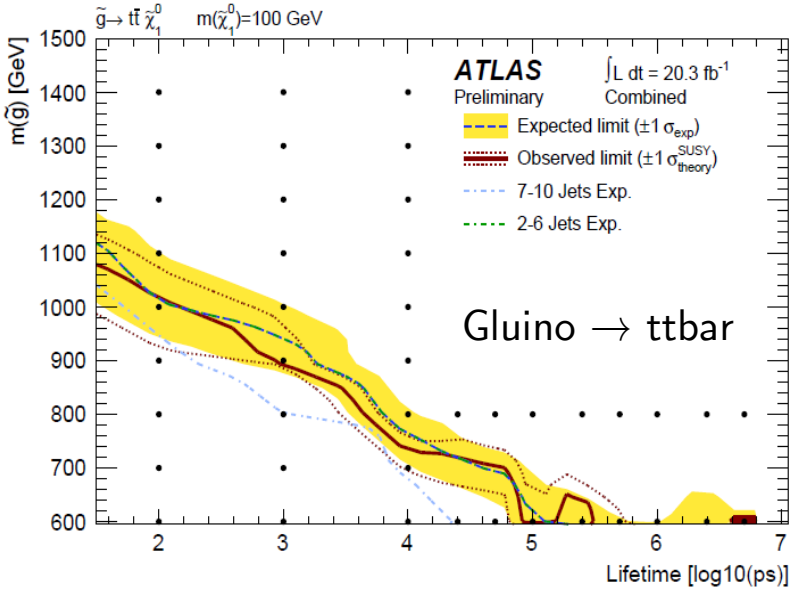
What if gluino is just a little long-lived, about 1 ns? (mini-split SUSY)
Standard jets+MET SUSY searches should still apply (up to what lifetime?)

- 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!



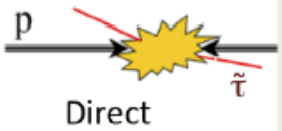




Stable Massive Particles

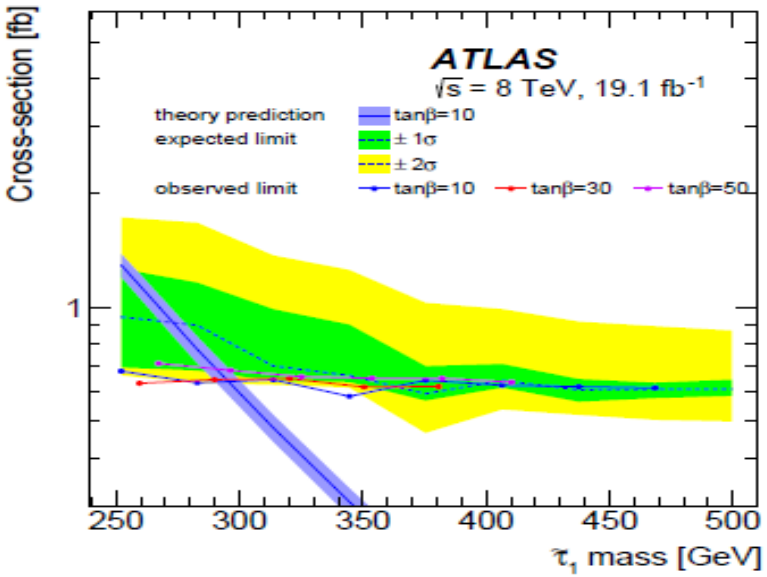
JHEP 01 (2015) 068

GMSB



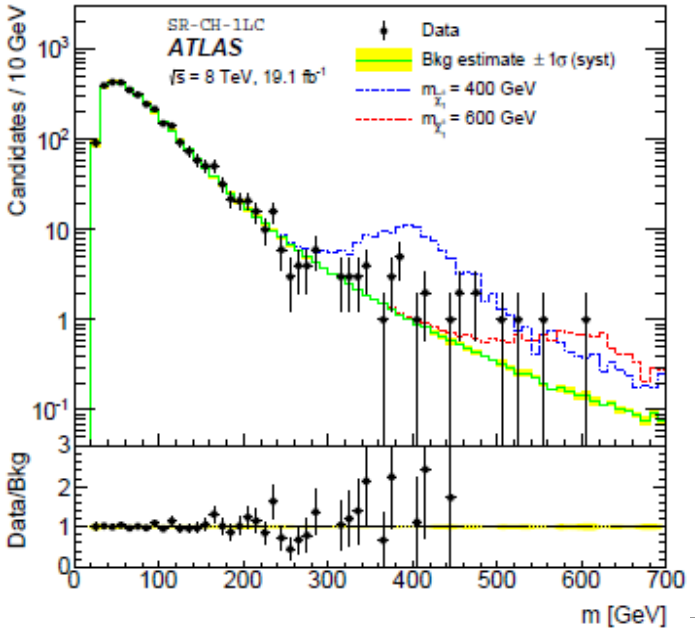
- Interpreted in many SUSY models, e.g. GMSB (τ_1 as NLSP)
- Four different signatures probed: stable sleptons, leptoSUSY, charginos and R-hadrons (bound states composed of the LLP and light SM quarks or gluons)
- GMSB: two muon-like SMPs, high β values
- Signal discrimination using mass measurements ($m = \frac{p}{\beta\gamma}$), with p taken from the charge particle track, time measurement (β) in the calorimeters and muon system, and energy loss ($\beta\gamma$) measured in the pixel detector

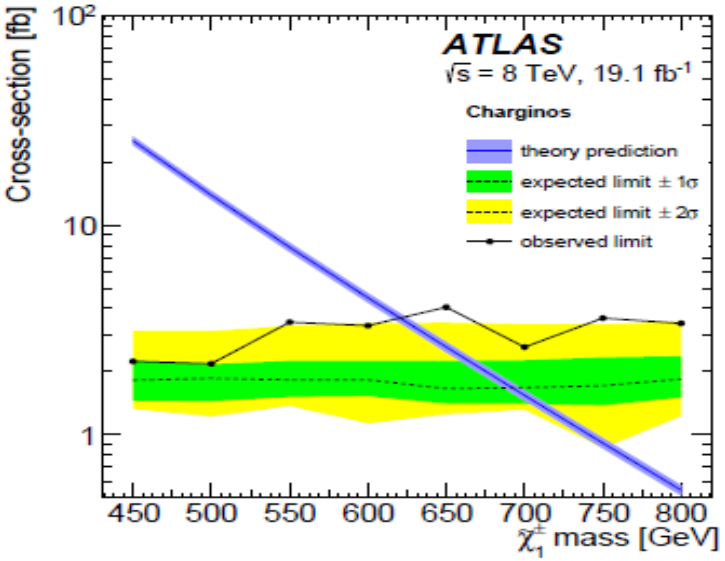
Stau<290 GeV, Chargino < 620 GeV
Gluino Rhadrons < 1270 GeV



Analysis Design

- Events selected with two SMPs and $0.2 < \beta < 0.95$
- High p_T muons with mis-measured β as the dominating background, taken from data
- Discriminating variables: β (taken from ToF), $\beta\gamma$ (can be measured by energy loss $\frac{dE}{dx}$ in pixel detector)

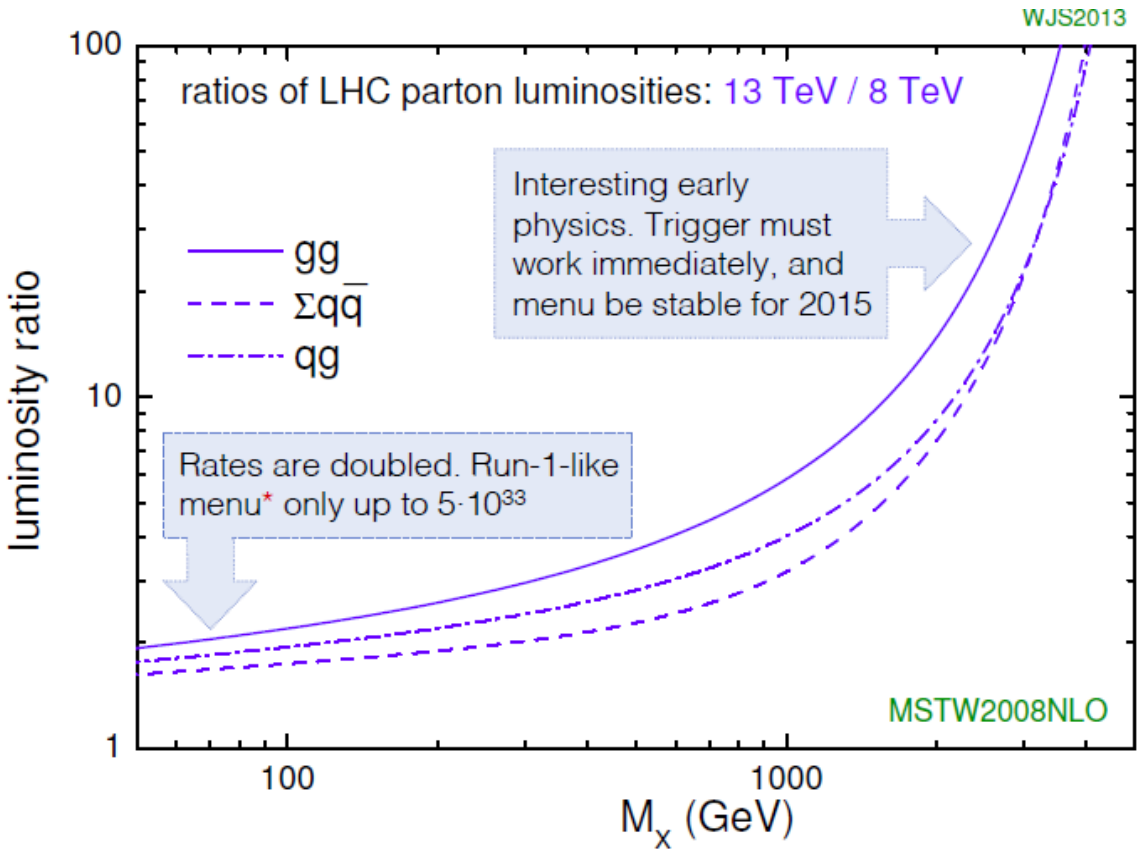




Conclusions

- Large number of new results still being derived from LHC Run 1 !
  - Challenging analyses / filling gaps in previous search coverage

- Excited to finally lay hands on 13 TeV data
- New heavy states could be discovered relatively quickly!

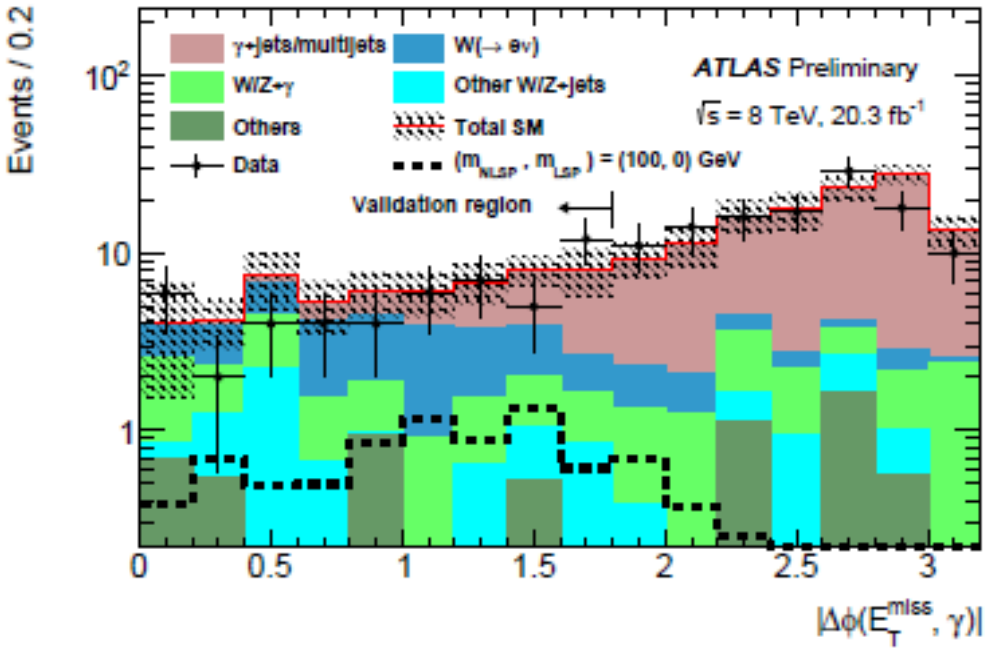


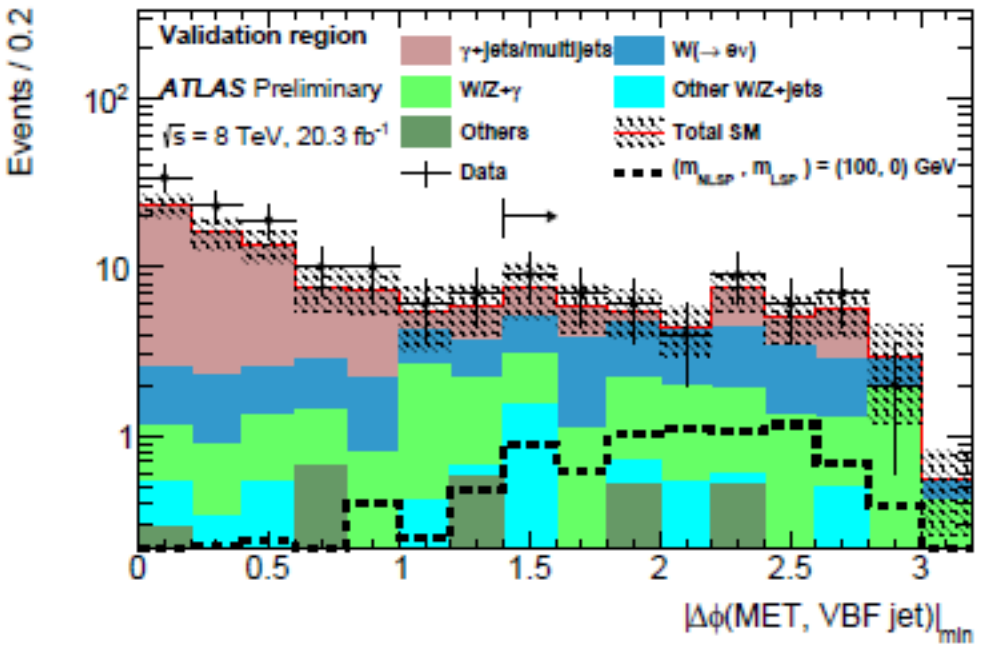
Backup

h → y+MET

Requirement	Data	$(m_{NLSP}, m_{LSP}) = (100, 0)$ GeV signal
Data quality and trigger	1.53×10^7	337±4
Good vertex	1.53×10^7	336±4
$E_T^{\text{miss}} > 50$ GeV	1.26×10^7	279±3
Selected photon $p_T > 40$ GeV	7.41×10^5	128±2
VBF m_{jj} >400 GeV and $\lvert\Delta\eta_{jj}\rvert$ >3.0	3.17×10^4	96.4±1.9
VBF jet $p_T \geq 40$ GeV	6870	58.0±1.5
Lepton veto	6040	57.2±1.5
≤ 1 non-VBF jet	4620	50.4±1.4
$\lvert\Delta\phi(E_{\text{T}}^{\text{miss}}, VBF\ jet)\rvert_{min} > 1.4$	600	30.1±1.1
$\lvert\Delta\phi(E_{\text{T}}^{\text{miss}}, non-VBF\ jet)\rvert_{min} < 2.0$	565	28.2±1.0
OPV	425	27.6±1.0
$\lvert\vec{p}_T^{\,TOT}\rvert \geq 50$ GeV	337	26.9±1.0
$\lvert\Delta\phi(E_{\text{T}}^{\text{miss}}, \gamma)\rvert \leq 1.8$	100	21.6±0.9
VBF m_{jj} >600 GeV and $\lvert\Delta\eta_{jj}\rvert$ >4.0	50	14.6±0.7

h → γ+MET

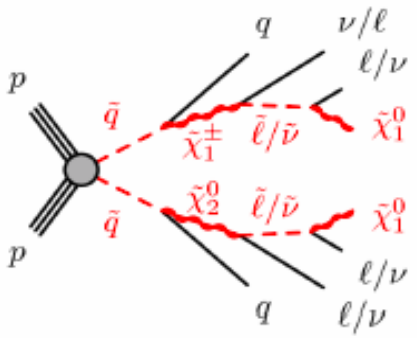

Events / 0.2
γ+jets/multijets
W/Z+γ
Others
Data
W(→ eν)
Other W/Z+jets
Total SM
(m_NLSP , m_LSP) = (100, 0) GeV
ATLAS Preliminary
√s = 8 TeV, 20.3 fb-1
Validation region
|Δφ(E_T^miss, γ)|


Events / 0.2
Validation region
ATLAS Preliminary
√s = 8 TeV, 20.3 fb-1
γ+jets/multijets
W/Z+γ
Others
Data
W(→ eν)
Other W/Z+jets
Total SM
(m_NLSP , m_LSP) = (100, 0) GeV
|Δφ(MET, VBF jet)|min

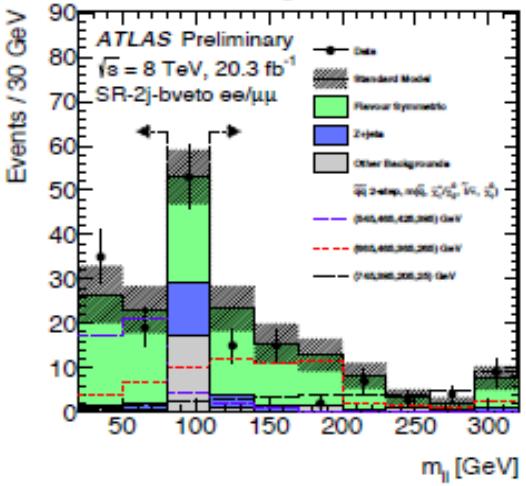
ATLAS Off-Z Results

Define 4 signal regions to target various types of signal models

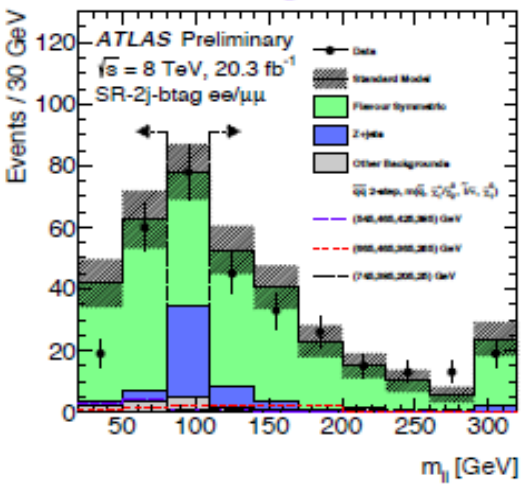
$n_{jets} \geq 2$ (squarks)

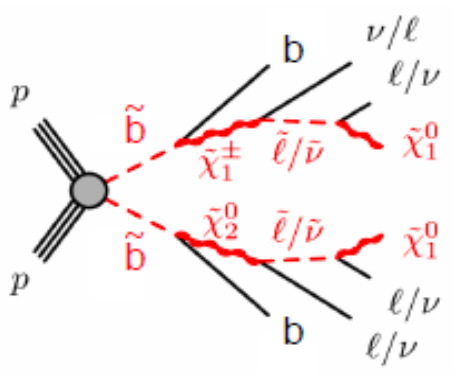


$n_{b\text{-tags}} = 0$

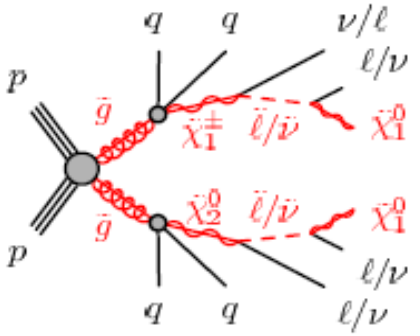


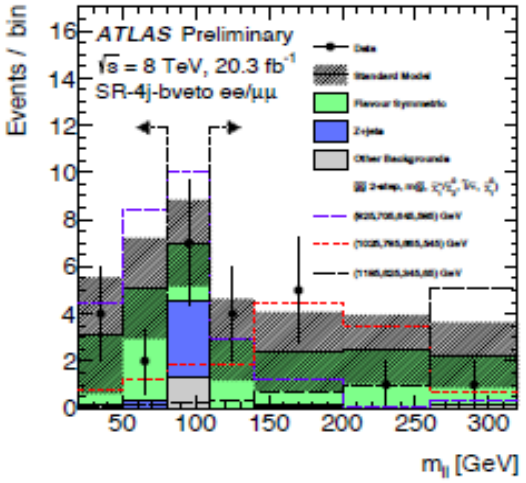
$n_{b\text{-tags}} \geq 1$

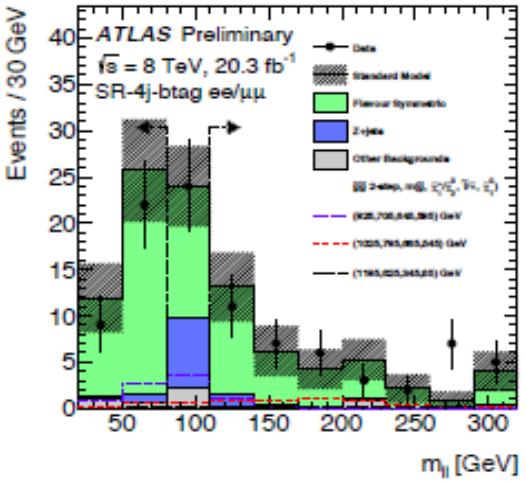


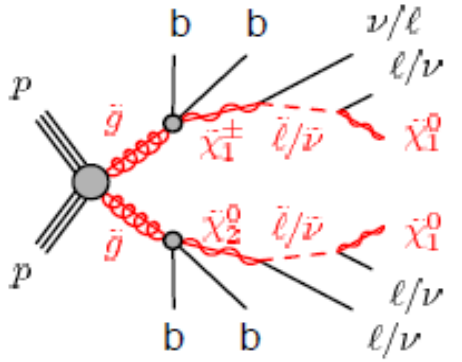


$n_{jets} \geq 4$ (gluinos)

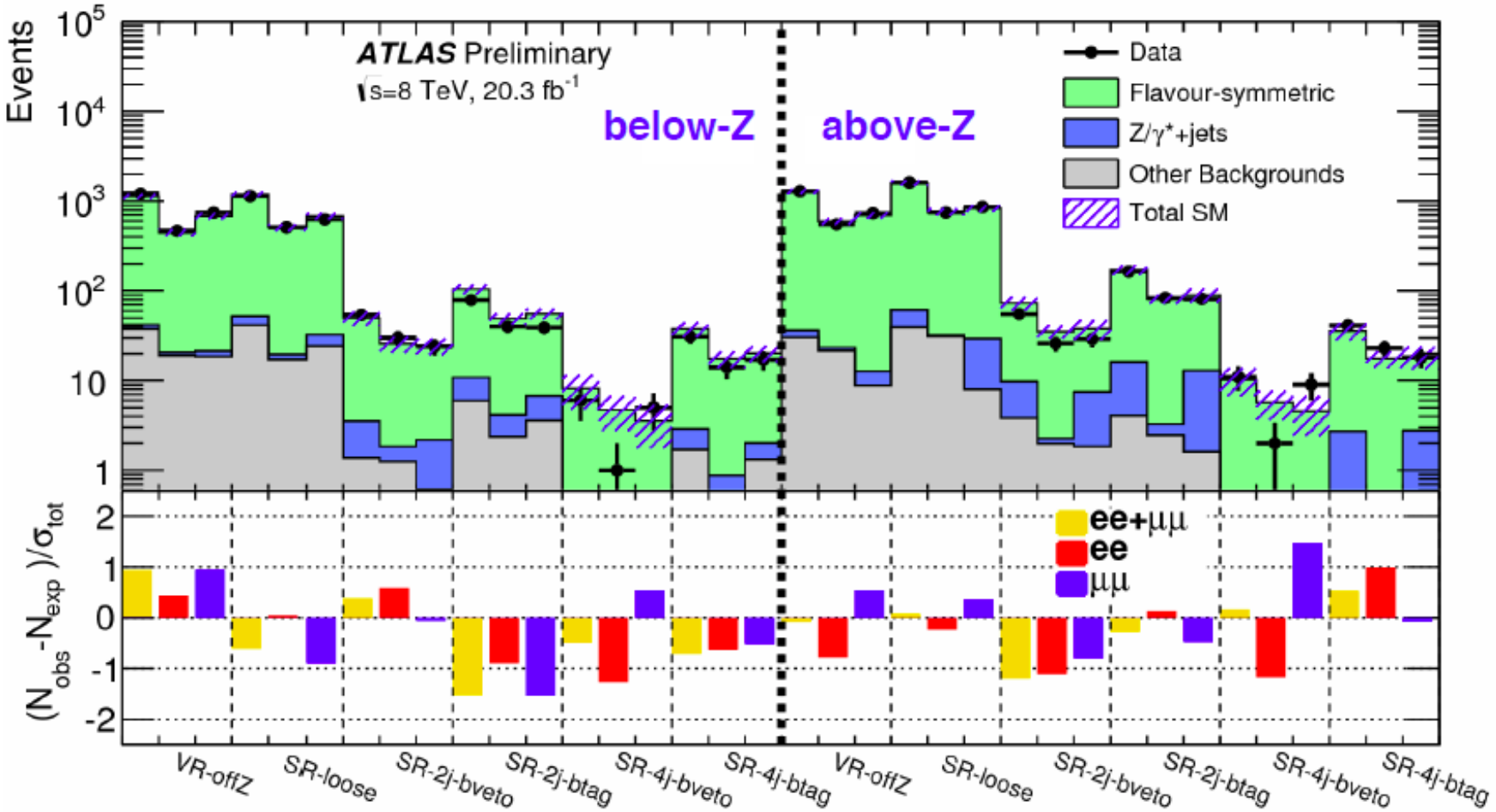




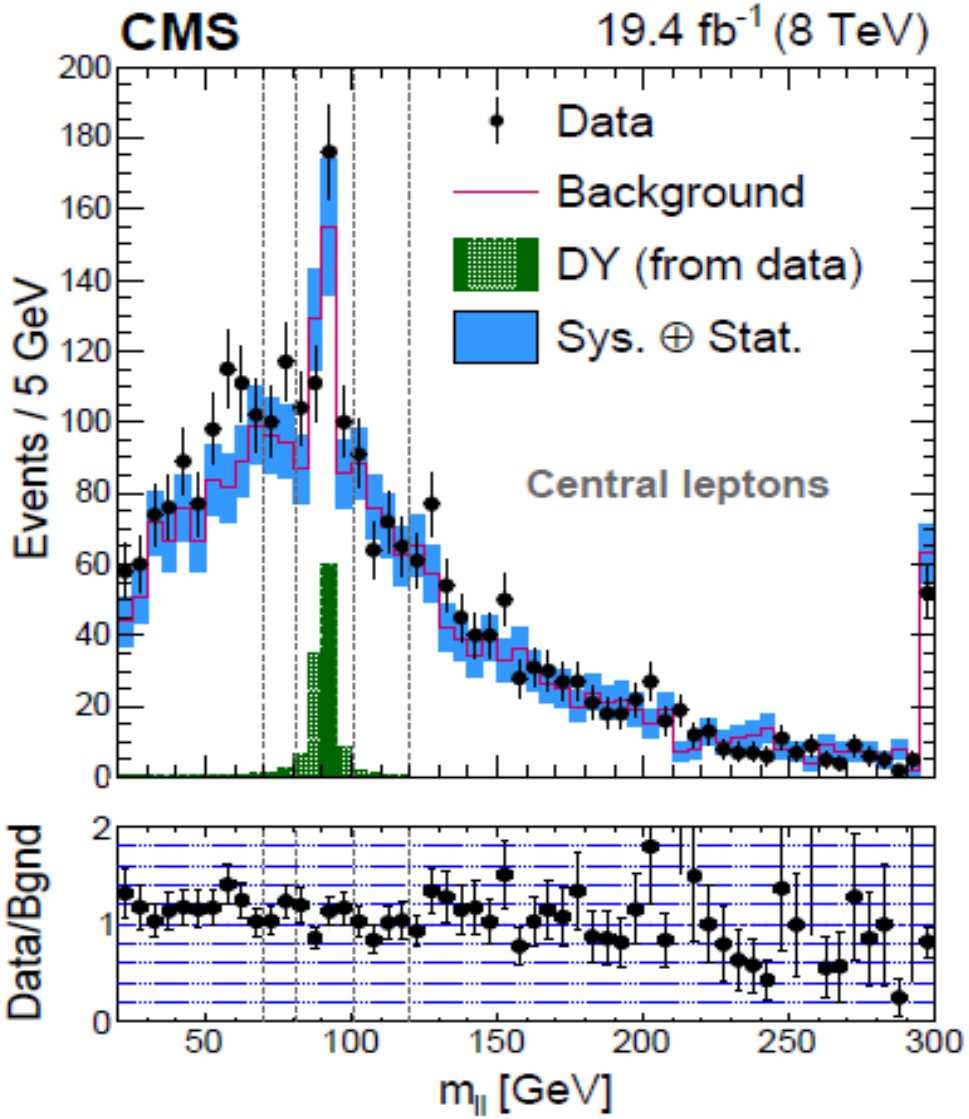


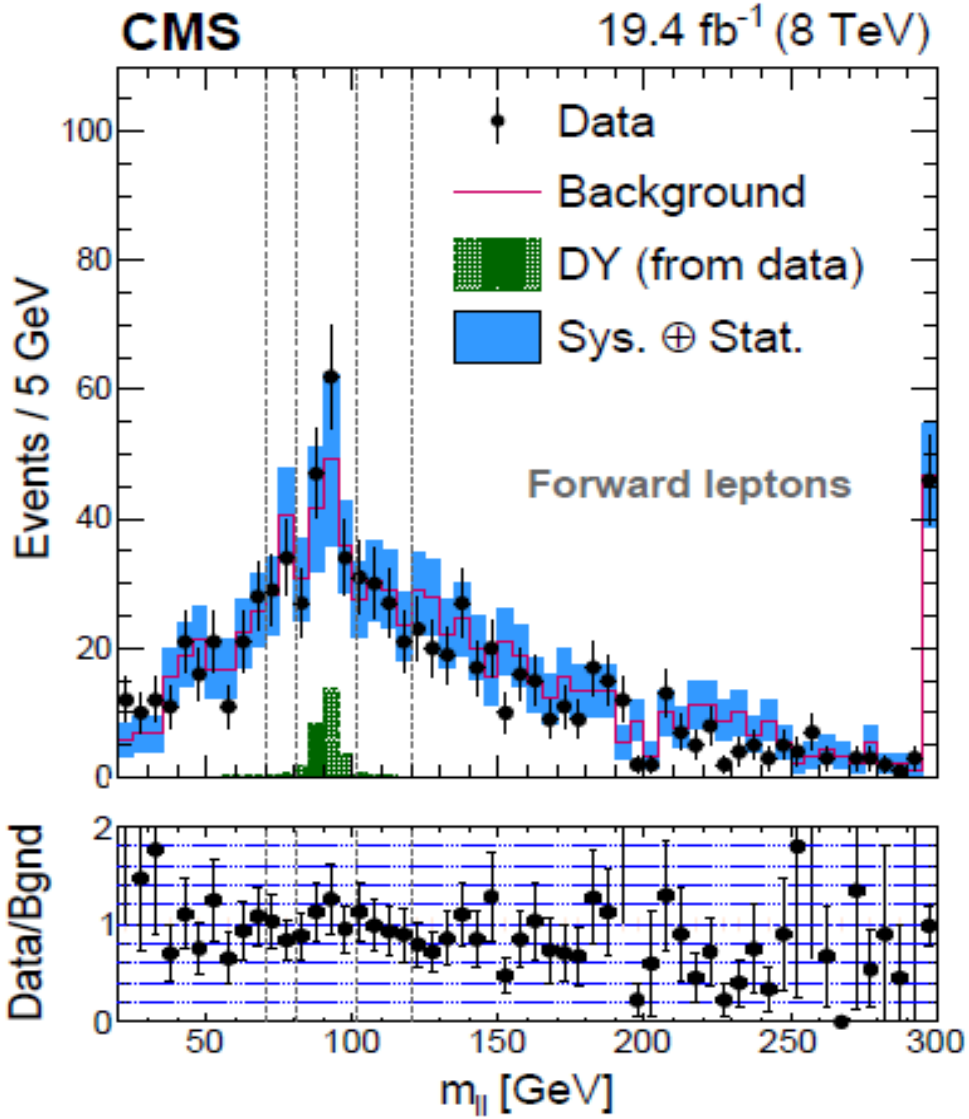


ATLAS Off-Z Summary of Results

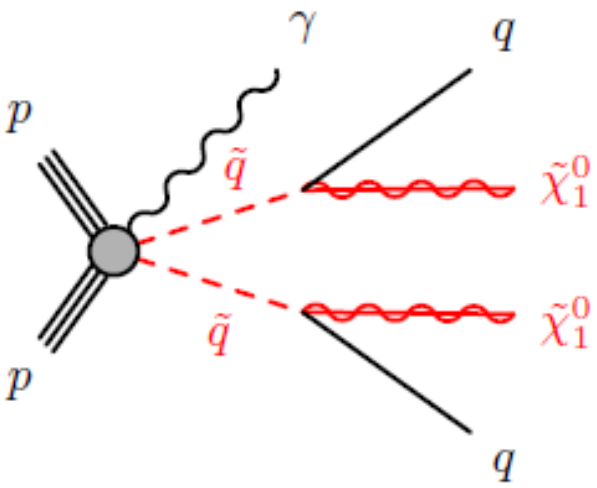


CMS Search for SUSY with 2l+jets+MET: off Z

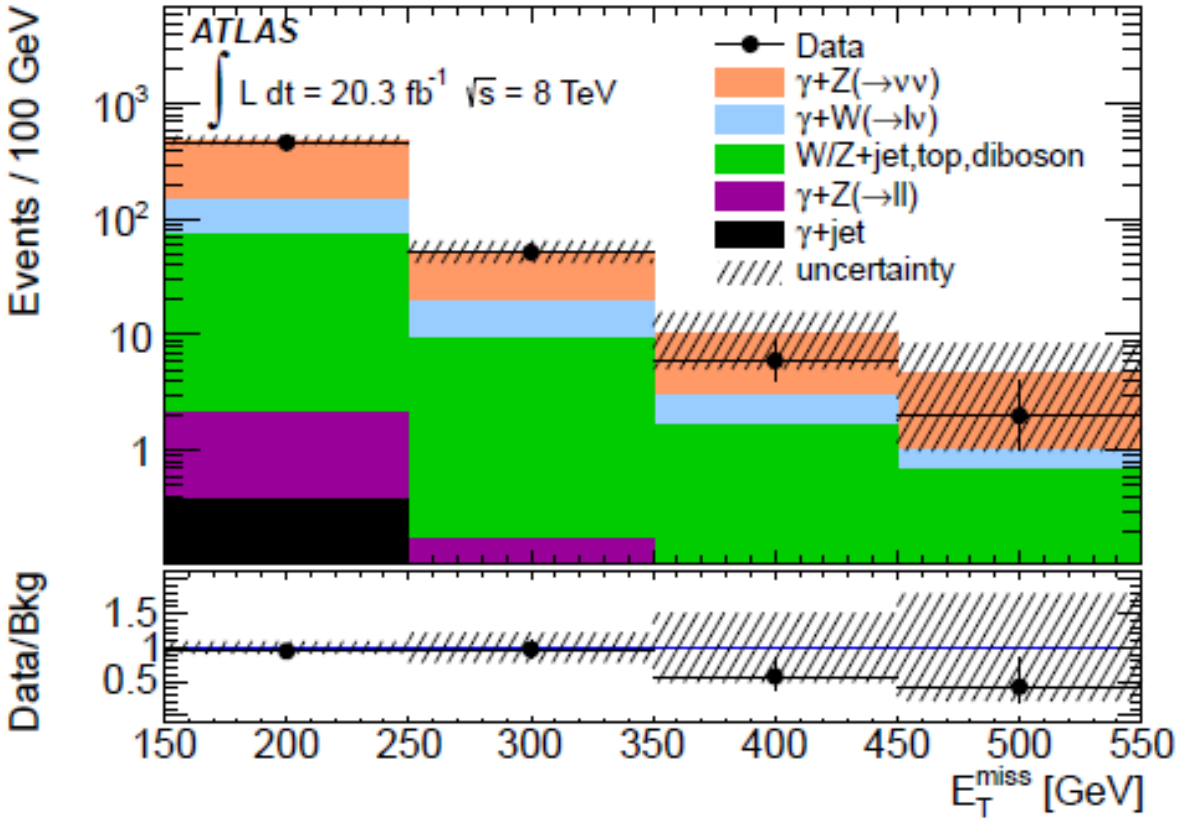




Mono-photon + MET



- arXiv: 1411.1559 [hep-ex], PRD 91, 012008 (2015)
- Compressed spectra $\Rightarrow$ soft decay products, low $E_{\mathrm{T}}^{\mathrm{miss}}$
- ISR photon boosts system $\Rightarrow$ higher $E_{\mathrm{T}}^{\mathrm{miss}}$



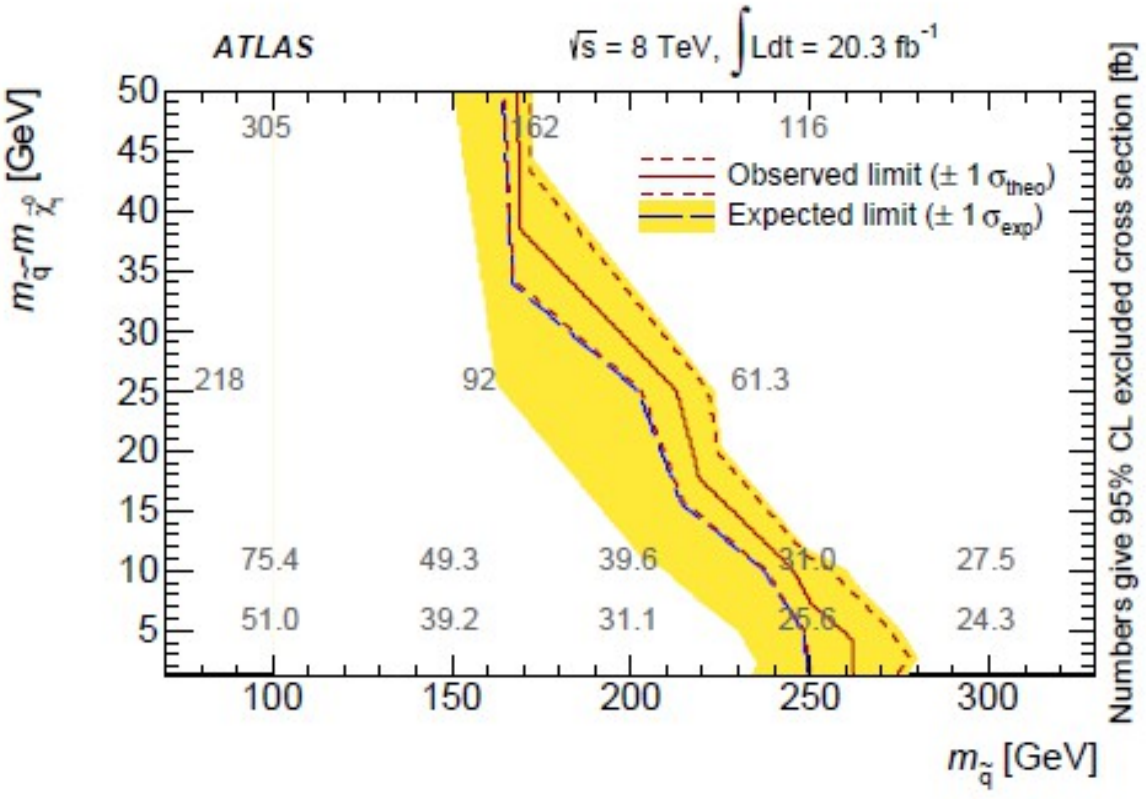
- Veto leptons and >1 jet
- Background $W\gamma$ (15%) and $Z\gamma$ (70%) normalized in lepton CRs

Mono-photon + MET

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

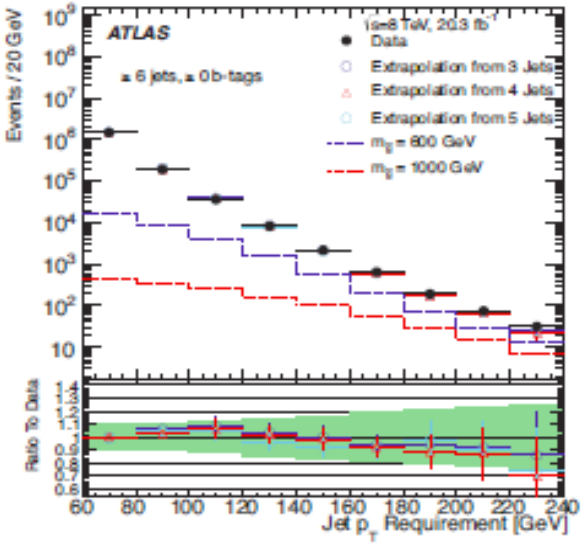
Systematic uncertainties $\sim 15\%$

- CR statistics (6%)
- $e \to \gamma$ mis-ID (5%)

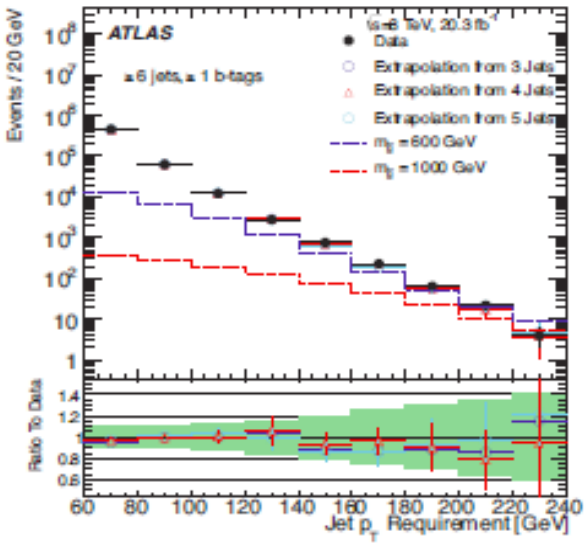


- Best exclusion along 'diagonal'
- Also sets limits for DM and more general models

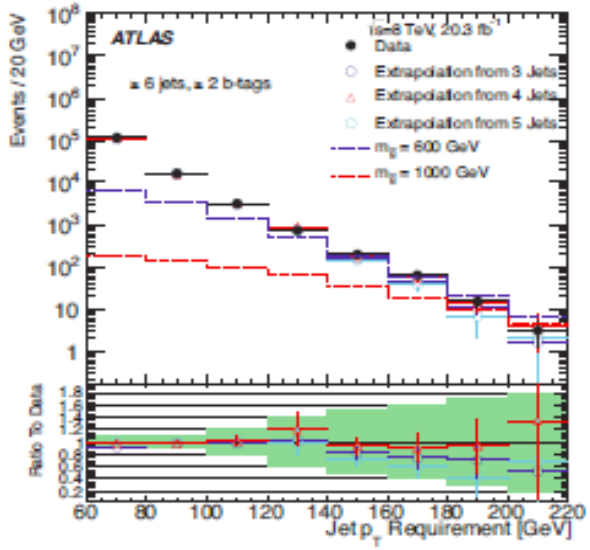
Gluino $\rightarrow$ multi-jets



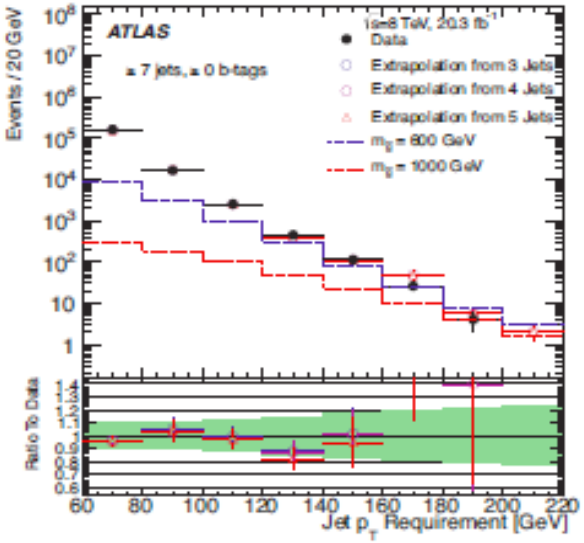
(a) ≥ 6 jets, ≥ 0 b-tagged jets



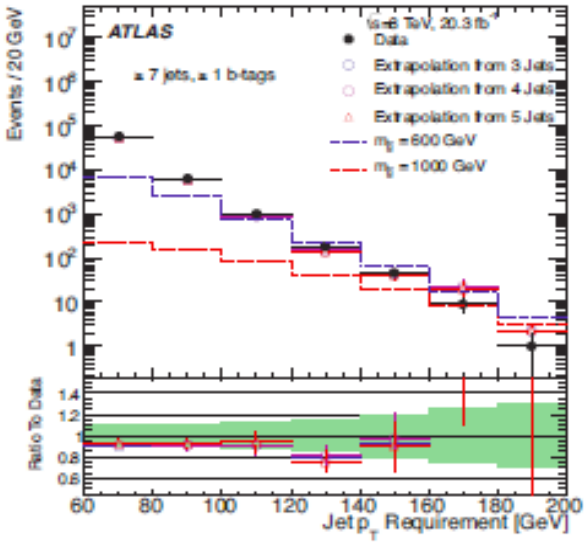
(b) ≥ 6 jets, ≥ 1 b-tagged jet



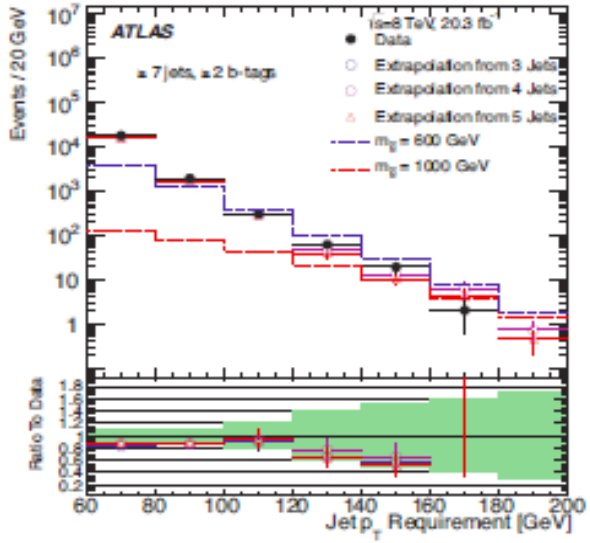
(c) ≥ 6 jets, ≥ 2 b-tagged jets



(d) ≥ 7 jets, ≥ 0 b-tagged jets

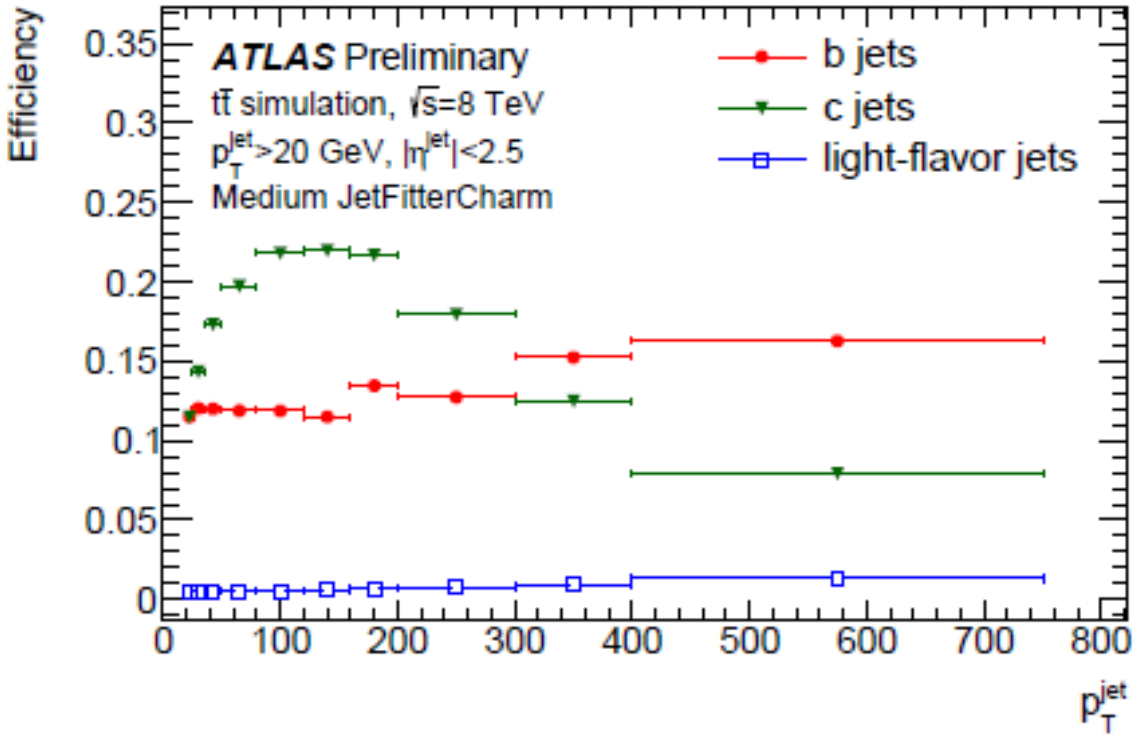


(e) ≥ 7 jets, ≥ 1 b-tagged jet



(f) ≥ 7 jets, ≥ 2 b-tagged jets

Charm tagging



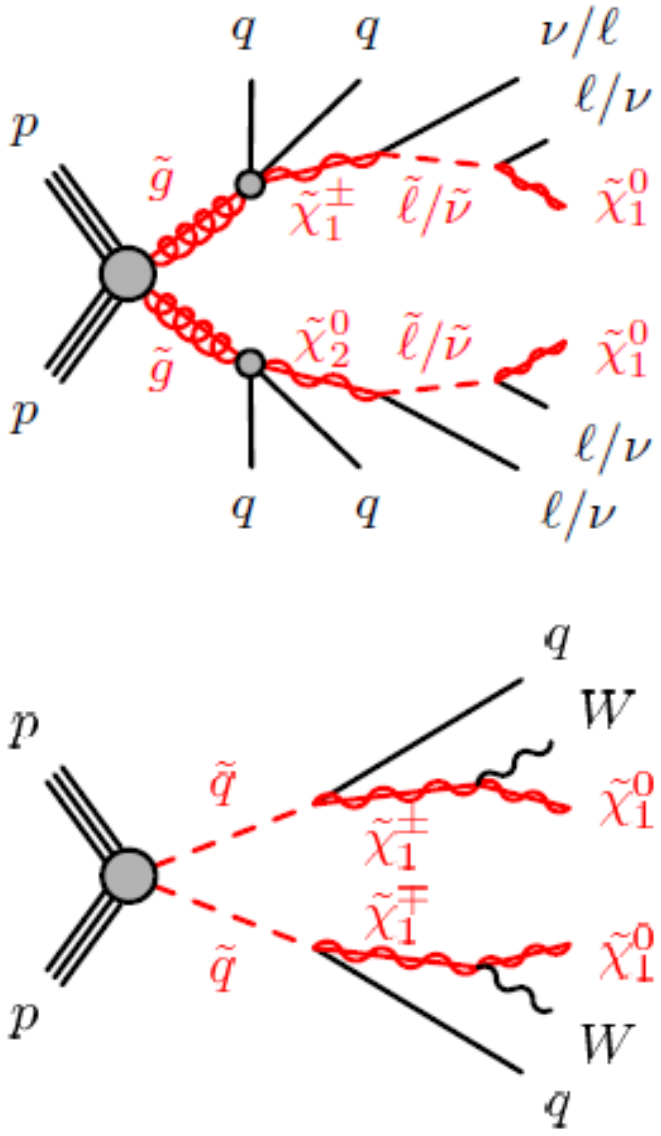
$$\epsilon_c \sim 0.15$$

$$\epsilon_b \sim 0.12$$

$$\epsilon_{\text{light}} \sim 0.008$$

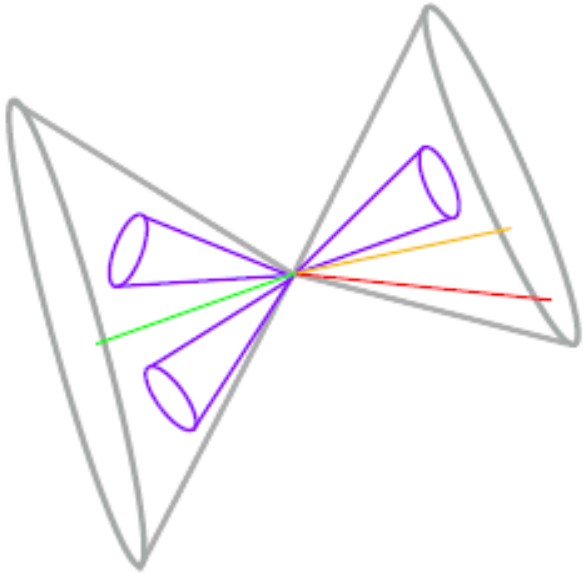
1 or 2 leptons + jets + MET

- arXiv: 1501.03555 [hep-ex], submitted to JHEP
- Many models targeted
  - Gluino ($\tilde{g}$) and squark ($\tilde{q}$) production
  - Decays via charginos ($\tilde{\chi}_1^{\pm}$) and sleptons ($\tilde{l}$) $\rightarrow$ leptons in final state
- Four regions, 1 & 2 leptons (decay chain length), soft and hard (mass splittings)
  - Soft: $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, $p_T^{\ell} < 25$ GeV
  - Hard: Combined $\ell + E_{\mathrm{T}}^{\mathrm{miss}}(+\,\mathrm{jet})$ triggers

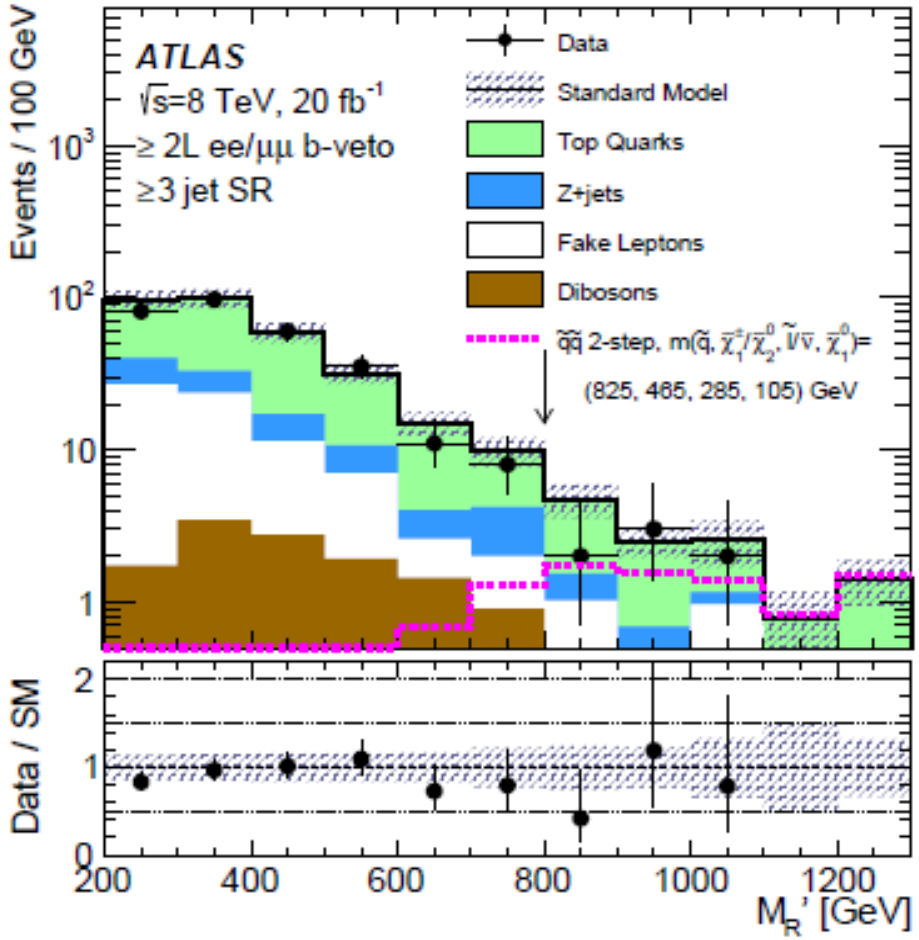


1 or 2 leptons + jets + MET

- Discrimination from N_{jets}, $E_{\text{T}}^{\text{miss}}$, m_T, m_{eff}, topological information
- $m_T = \sqrt{2 p_T^{\ell} E_{\text{T}}^{\text{miss}} (1 - cos[\Delta\phi(\vec{\ell}, \mathbf{p}_T^{\text{miss}})])}$
- $m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + \sum_{i=1}^{N_{\text{jets}}} p_{T,i}^{\text{jet}} \left(+ \sum_{i=1}^{N_{\ell}} p_{T,i}^{\ell} \right)$
- Split event into two 'mega jets'



- Exploit symmetry to approximate rest frame - 'R-frame': 'Razor variables'



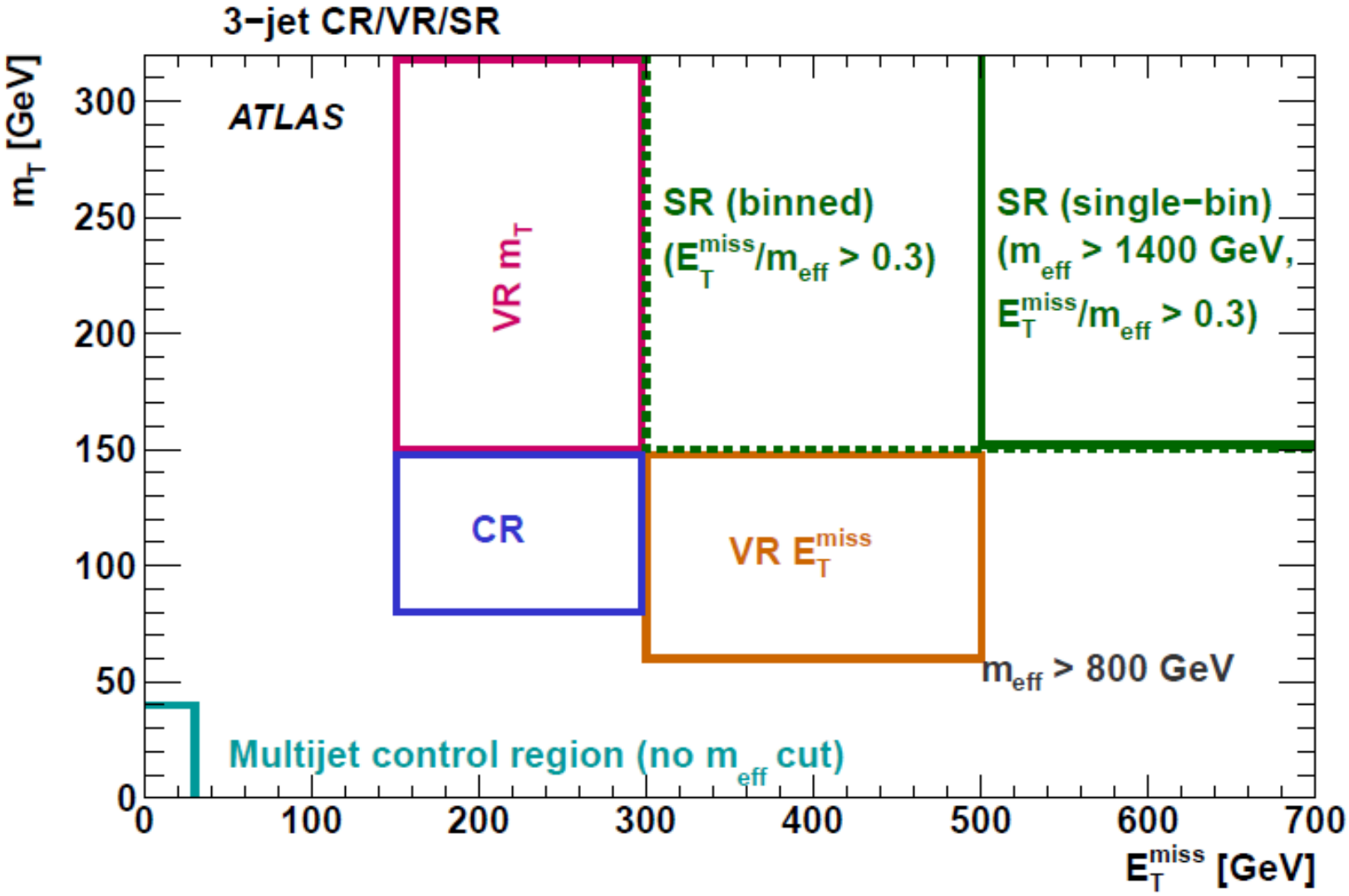
- $M_R' = \sqrt{(j_{1,E} + j_{2,E})^2 - (j_{1,L} + j_{2,L})^2}$

E: Energy in R-frame

L: Longitudinal momentum

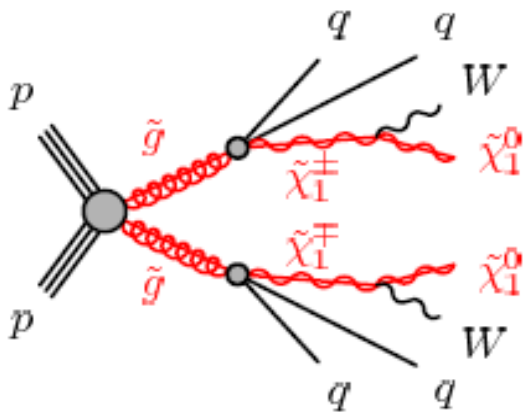
1 or 2 leptons + jets + MET

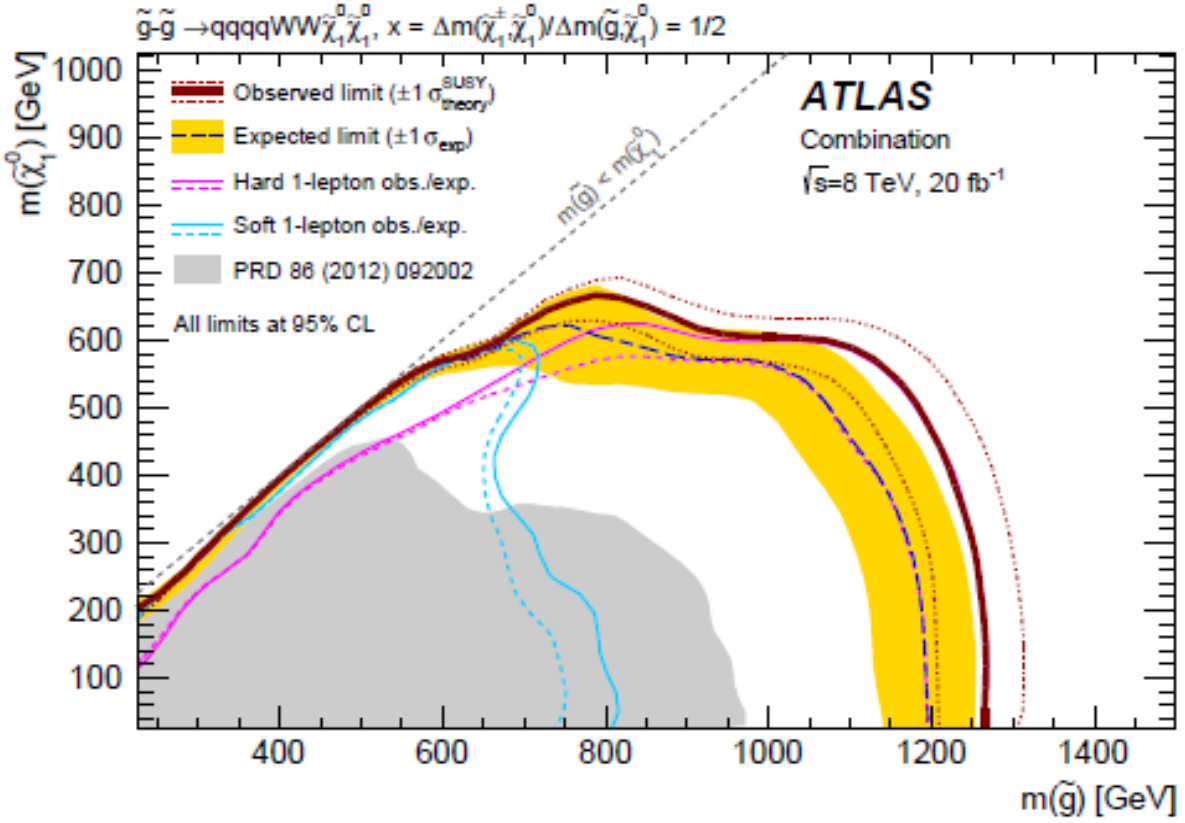
SM backgrounds controlled with semi data-driven estimate



1 or 2 leptons + jets + MET

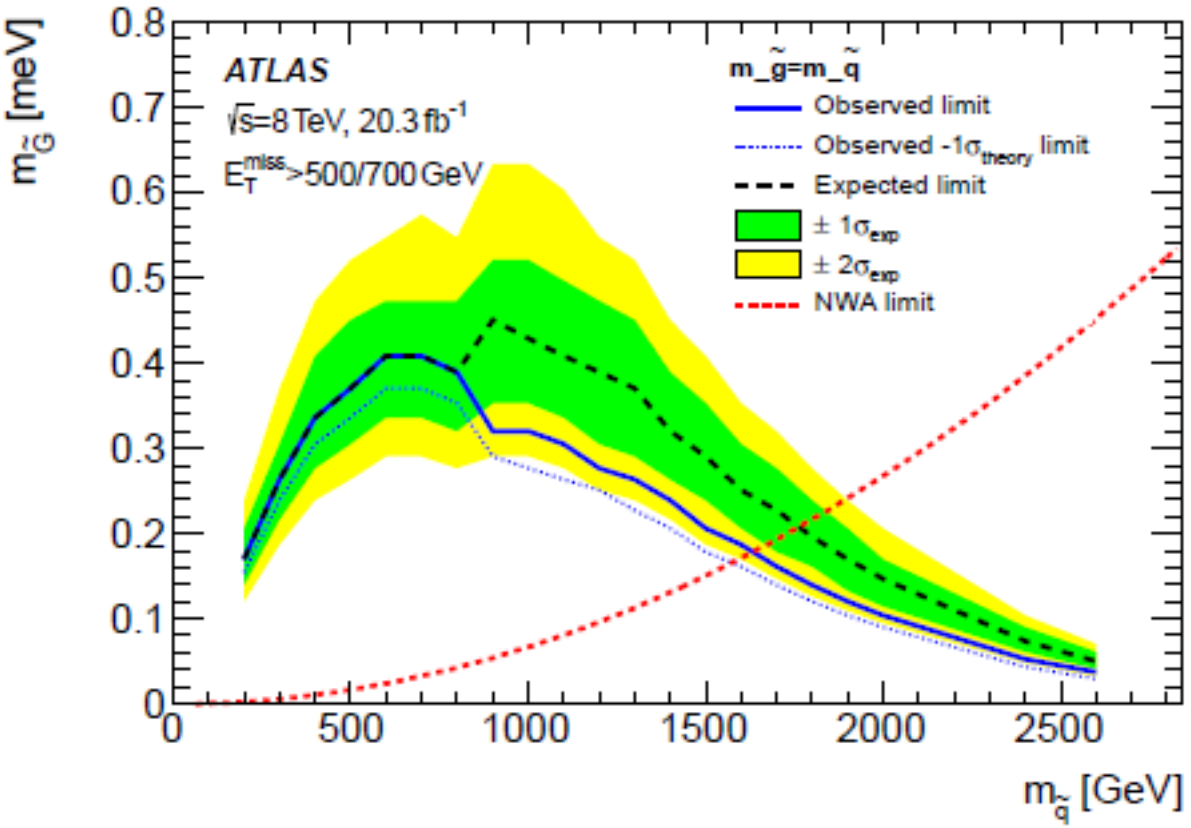
- Interpret results in a variety of models





- Soft lepton regions contribute to improved sensitivity in compressed regions
- Significant improvement over 2011 results

Mono-jet


ATLAS
√s=8 TeV, 20.3 fb-1
E_T^miss>500/700 GeV
m_g̃=m_q̃
Observed limit
Observed -1σ_theory limit
Expected limit
± 1σ_exp
± 2σ_exp
NWA limit
m_G̃ [meV]
m_q̃ [GeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
500
1000
1500
2000
2500

Non-pointing and delayed Photons

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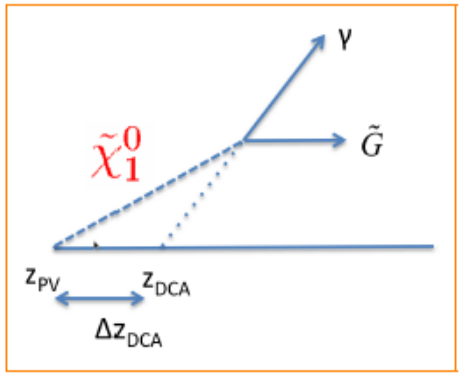
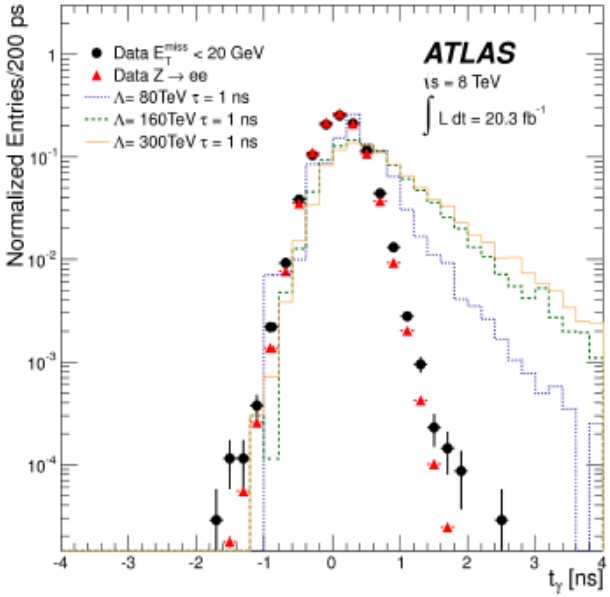
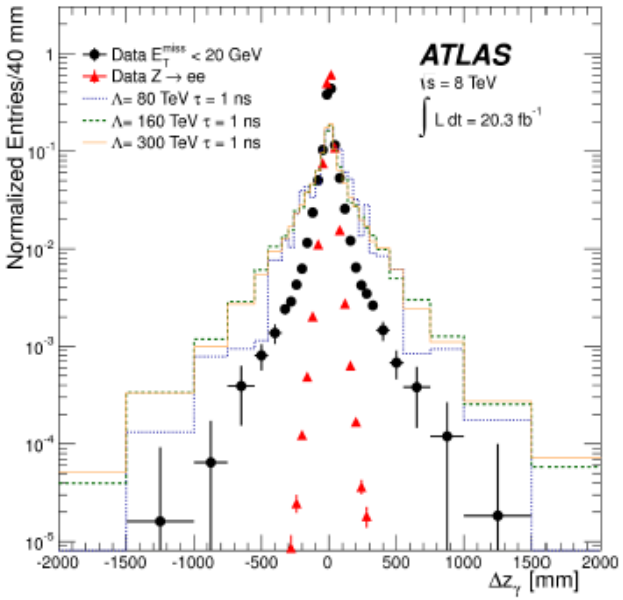
- Interpreted in the context of GMSB ($\tilde{G}$ as LSP)
- Long-lived $\tilde{\chi}_1^0$ NLSP with finite lifetime $>$ 250 ps

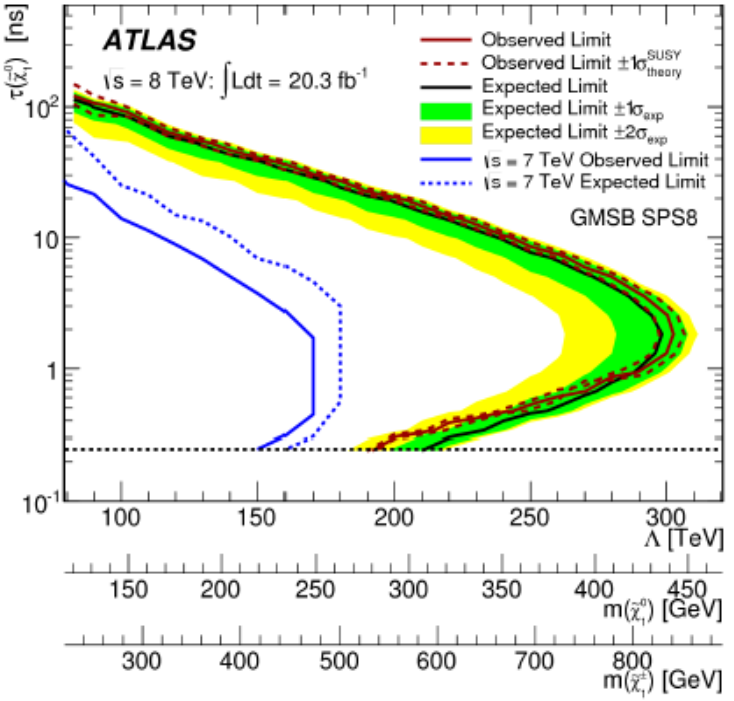


Analysis Design

- Signature: 2 delayed photons (γ) , not pointing back to IP, and high $E_{\mathrm{T}}^{\mathrm{miss}}$
- Dominating background processes from prompt: γ, e, jet
- Optimisation done exploiting Δz_{DCA} and t_γ
- Exploiting the excellent timing and pointing resolution of the ATLAS LAr EM calorimeter







Limits set for the NLSP decaying into a photon and gravitino with a lifetime in the range from 250 ps up to about 100 ns