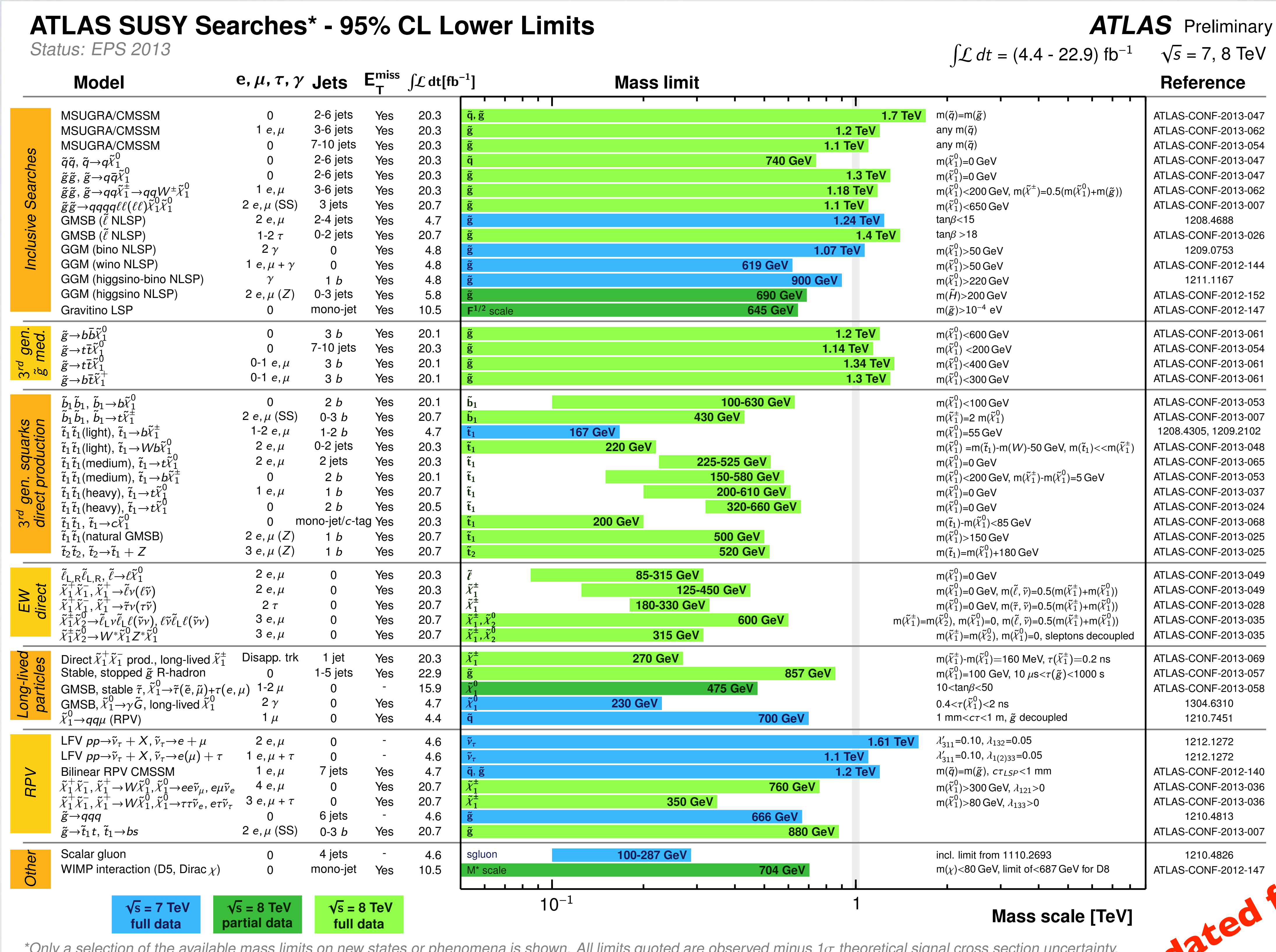
Inclusive searches for squarks and gluinos with the ATLAS detector

Alex Koutsman (TRIUMF)
18 July 2013
EPSHEP 2013, Stockholm

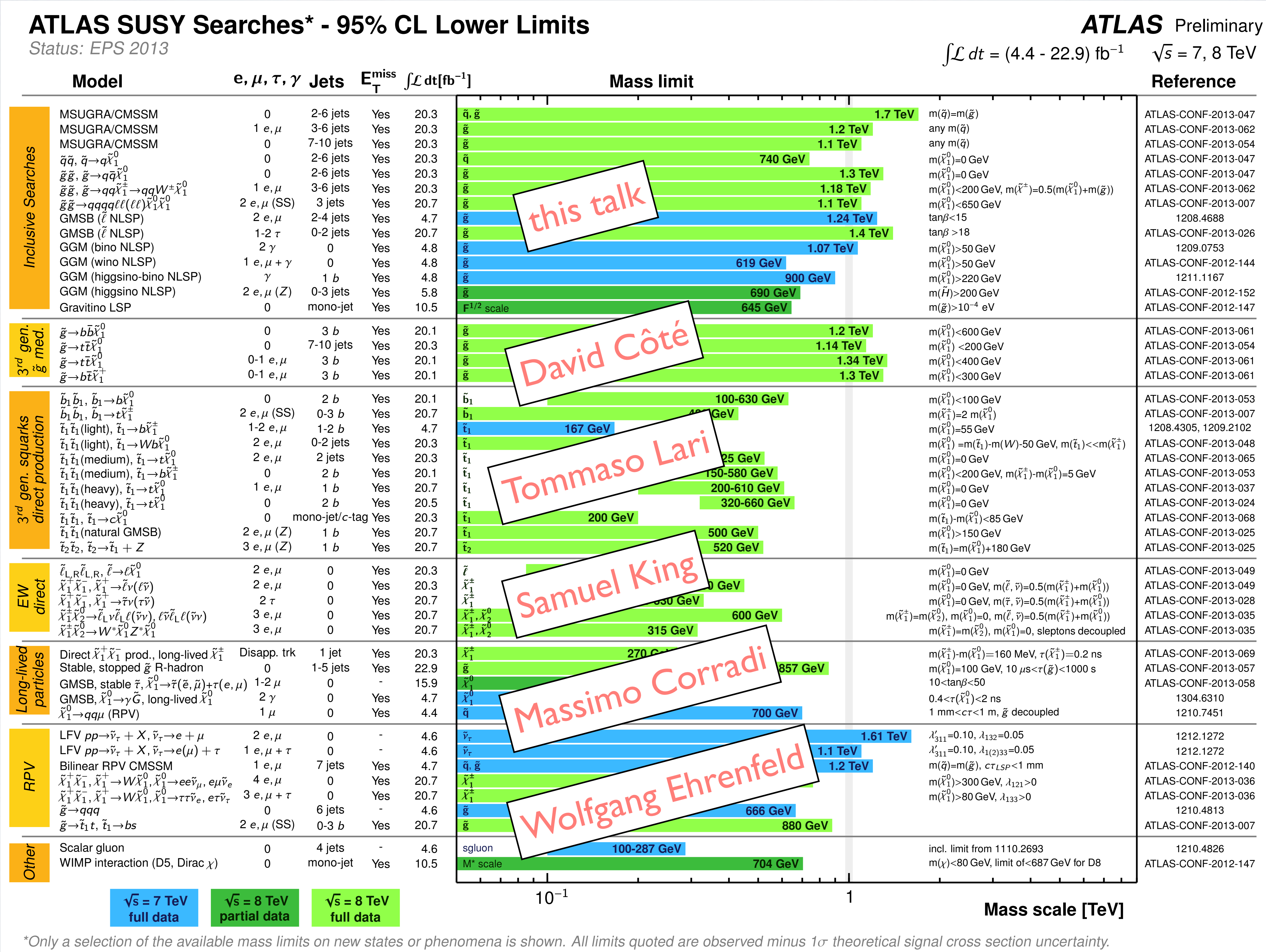
SUPERSYMMETRY IN ATLAS



updated for EPS

- Strategy ATLAS SUSY group: cover a wide range of final states and processes

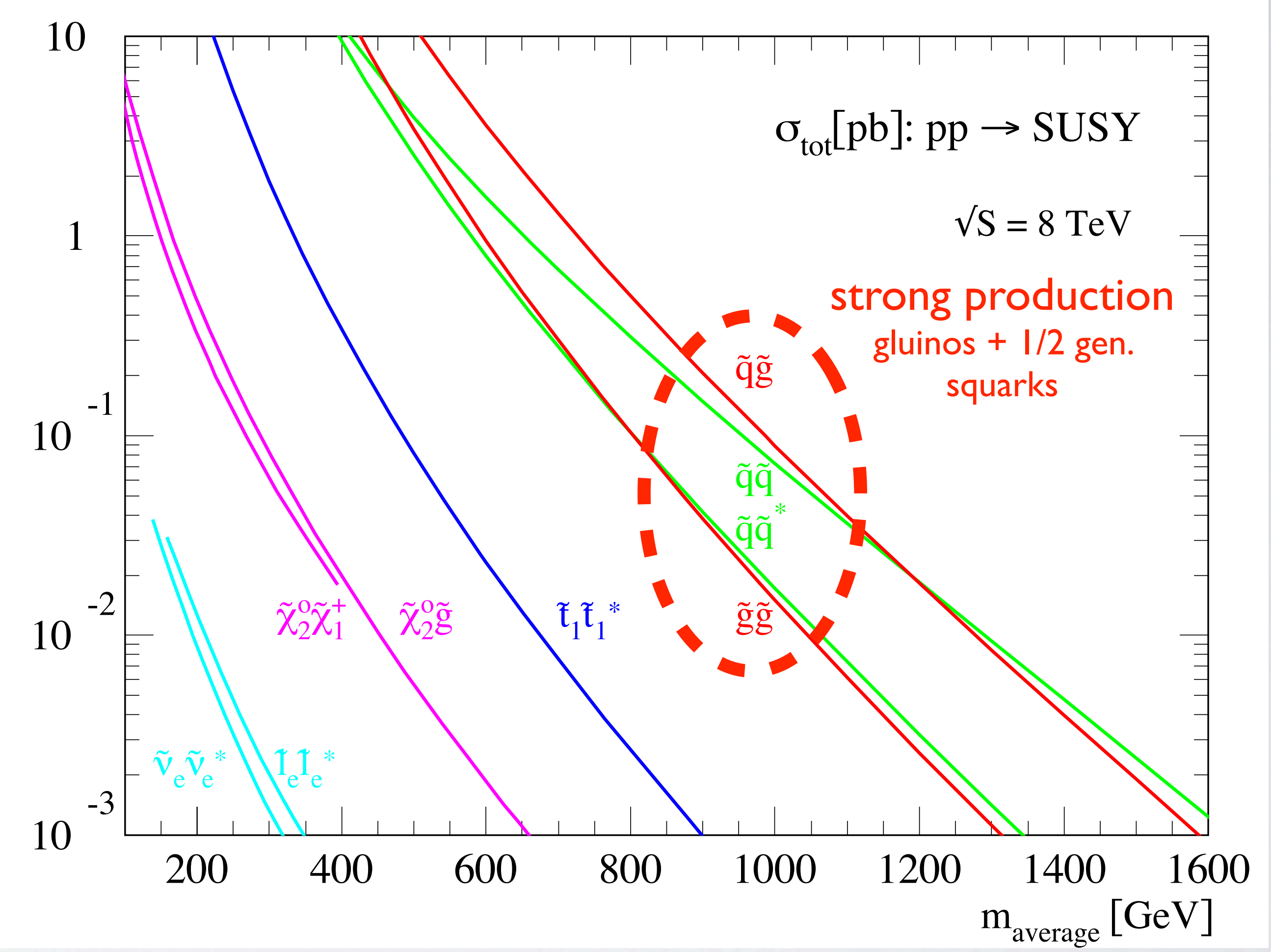
SUPERSYMMETRY IN ATLAS



- A large number of posters presenting more details

OVERVIEW

- Motivation inclusive searches:
  - SUSY predicts existence of new colored particles
  - If present at TeV-scale, "high discovery potential" at LHC
    - Benchmark for LHC/ATLAS performance
  - R-parity conserving (RPC) models:
    - LSP stable (dark matter candidate)
    - Many energetic decay products:
      - multiple jets
      - large missing ET (MET)
      - possibly lepton(s)
        - hard: pT(lep) ≥ 25 GeV
        - soft: pT(lep) < 25 GeV



- Focus (on newest results) on inclusive RPC SUSY strong production searches:
  - 1-2 leptons + 3-6 jets + MET: ***ATLAS-CONF-2013-062***
  - 0 leptons + 2-6 jets + MET: ***ATLAS-CONF-2013-047***
  - 0 leptons + 7-10 jets + MET: ***ATLAS-CONF-2013-054***

  - All ATLAS SUSY public results ***AtlasPublic/SupersymmetryPublicResults***

- Outline of this talk:
  - Analyses + Backgrounds + Signal Regions
  - Results
  - Interpretation

ANALYSES
+
BACKGROUNDS
+
SIGNAL REGIONS

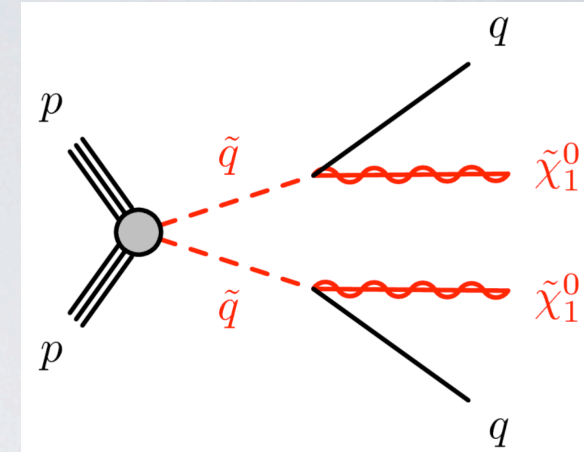
BACKGROUND - **0L** + 2-6J + MET

[***ATLAS-CONF-2013-047***]

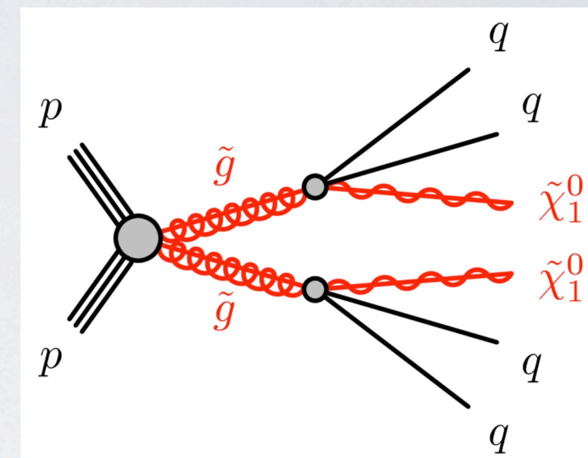
- **MET + jets:** "high discovery potential" of strong production SUSY at hadron collider
- Very powerful, even in busy LHC environment

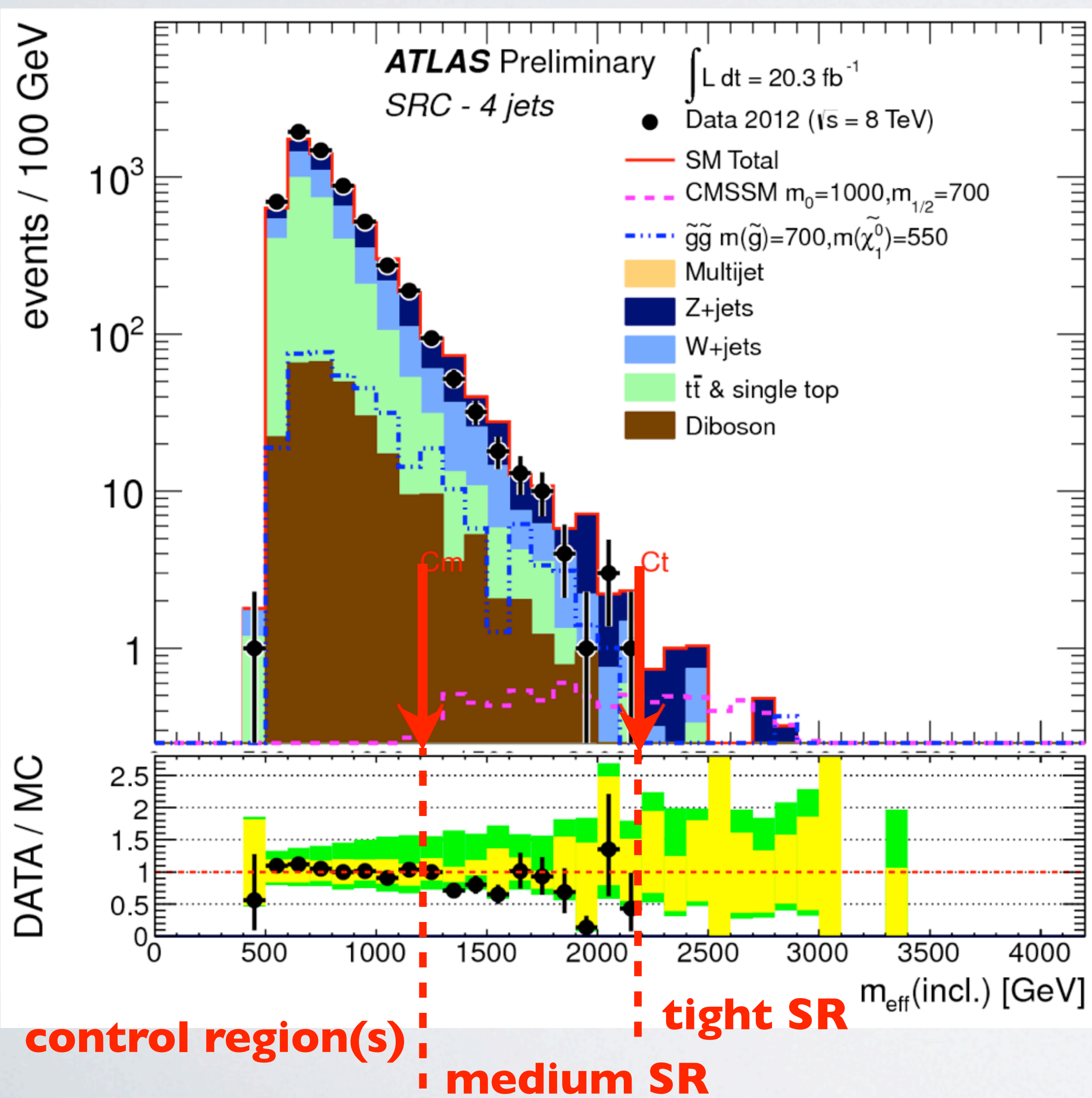
$$m_{\mathrm{eff}} \equiv \sum_{i=1}^{n} |\mathbf{p}_{\mathrm{T}}^{(i)}| + E_{\mathrm{T}}^{\mathrm{miss}}$$

- Main discriminating variables: MET + effective mass **meff**
- ***0-lepton*** analysis focus: short/medium/long decay chains



- Five inclusive channels based on jet multiplicity - 2 / 3 / 4 / 5 / 6 jets + lepton veto
  - optimized for squark or gluino pair (or mixed) production
- Up to three ***signal regions (SR)*** per channel, based on tighter meff *(details in backup)*





4 jets channel

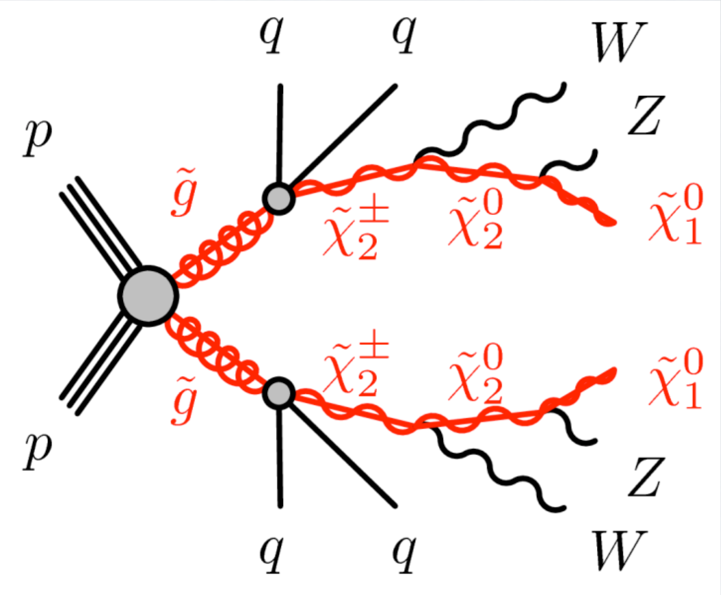
- Irreducible dominant backgrounds estimated with **Combined Fit Method**:
  (1) Bkg-only fit: Normalize Monte Carlo (MC) to data in simultaneous fit of control regions (CR)
  (2) Include systematic experimental/theoretical uncertainties as nuisance parameters
  (3) Exclusion fit: Signal model can be included in signal/control regions for exclusion
  - Used in all discussed analyses

Poster: Valerio Consorti

BACKGROUND - 0L + **7-10J** + MET

ATLAS-CONF-2013-054

- What if SUSY mass/decay spectrum more complex?
- ***0-lepton + multijets*** analysis targets very long decay chains

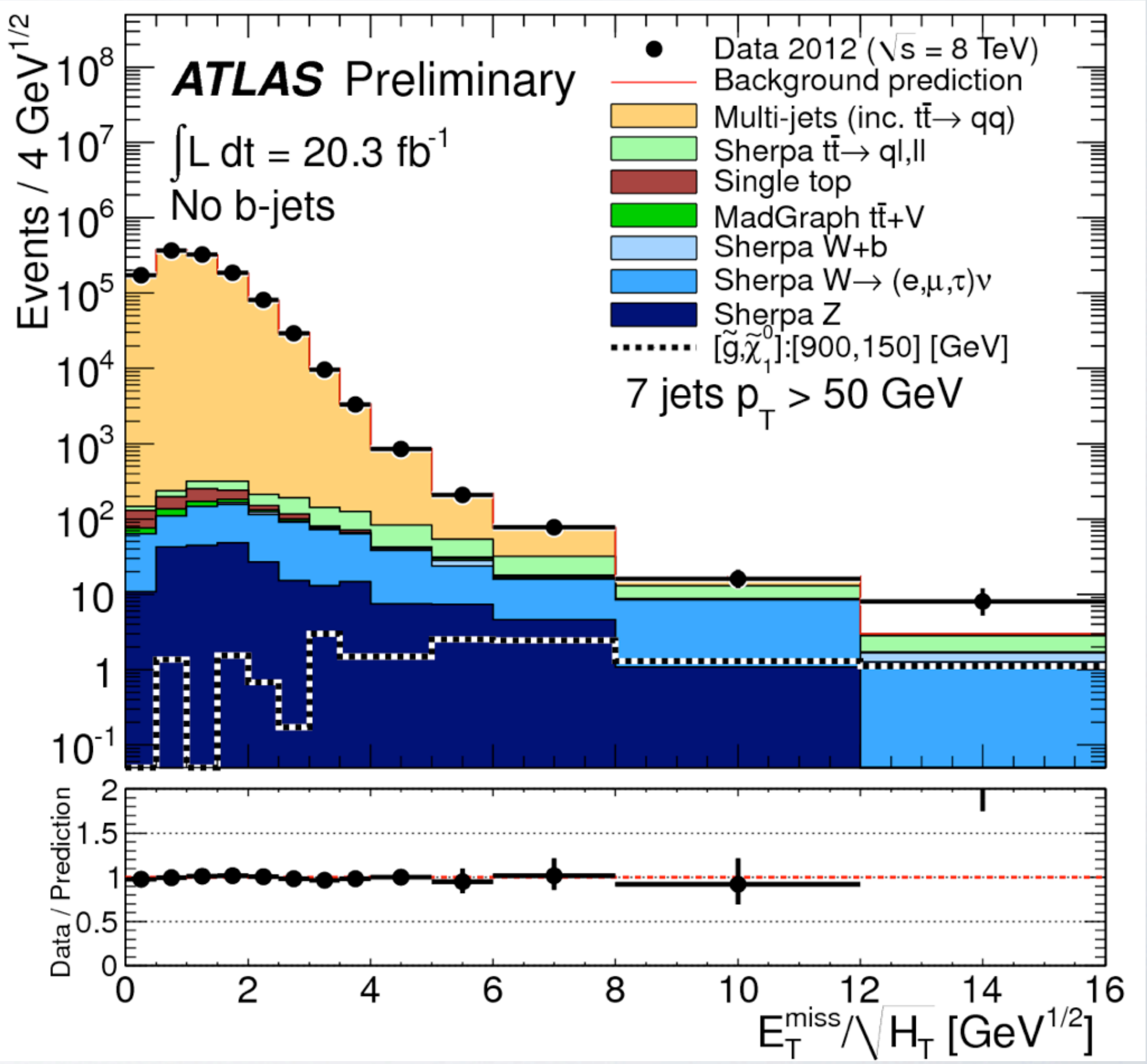


- Multijet production - QCD, ttbar/W+jets/Z+jets fully hadronic - estimated with a dedicated ***data-driven*** method, based on the observation that:
  - MET resolution proportional to √HT in jet dominated events
    ⇛ MET/√HT ~ independent of jet multiplicity
    - HT = scalar sum of pT of all jets with pT > 40 GeV
    - stochastic variations in measured jet energies

➡ Use lower jet multiplicity to retrieve MET/√HT shape from data

➡ Use lower MET/√HT to normalize background to data

MET/√HT shape
7 jets control region

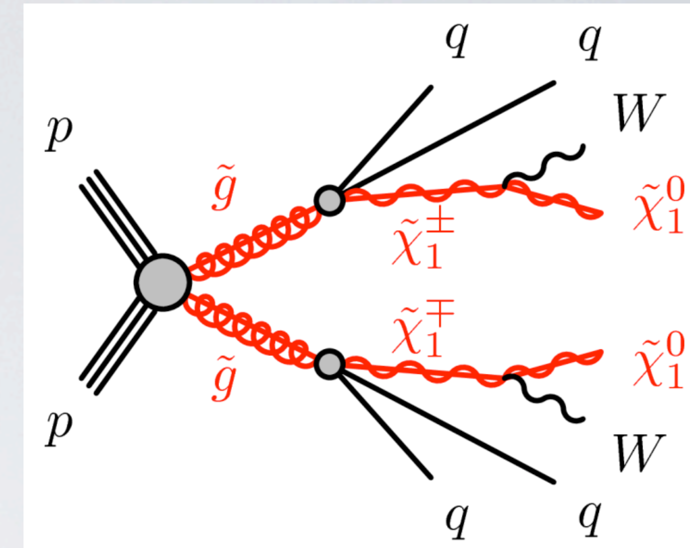


- ***Signal regions*** defined by:
  - MET/√HT > 4 √GeV
  - jet multiplicity 7 / 8 / 9 / ≥10 jets
    - pT(jet) > 50 (80) GeV

BACKGROUND - **HARD 1L** + 3-6J + MET

ATLAS-CONF-2013-062

- Trigger / detectors / world not perfect → leptons help in LHC environment
- Leptonic final state cleaner, easier to trigger, but rare (W/Z/slepton in decay chain)
- Leptonic analyses target different decay modes, rejected by 0-lepton analyses

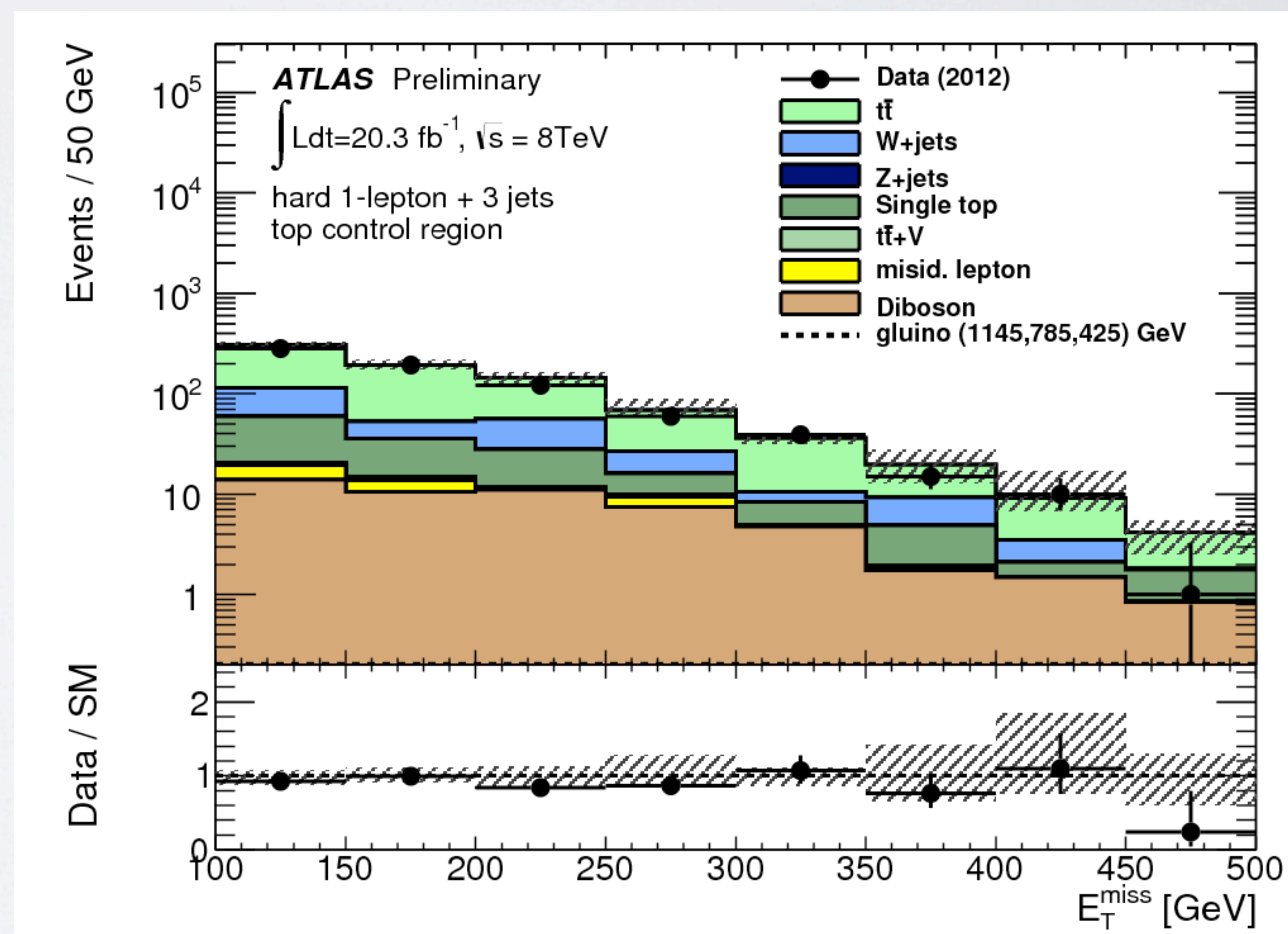


- Extra variables help distinguish backgrounds from signal:
  - Transverse Mass *MT* (using angular information):

$$m_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos(\Delta\phi(\vec{\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})))}.$$

- Hard 1 lepton (electron or muon) ***signal regions***, pT(lep) > 25 GeV defined as:
  - 3 / 5 / 6 jets + high MT + high MET + high meff

- Control regions in leptonic searches typically:
  - At lower MET/MT
  - Subdivided into b-tagged (ttbar enriched) and b-vetoed (W+jets enriched) regions



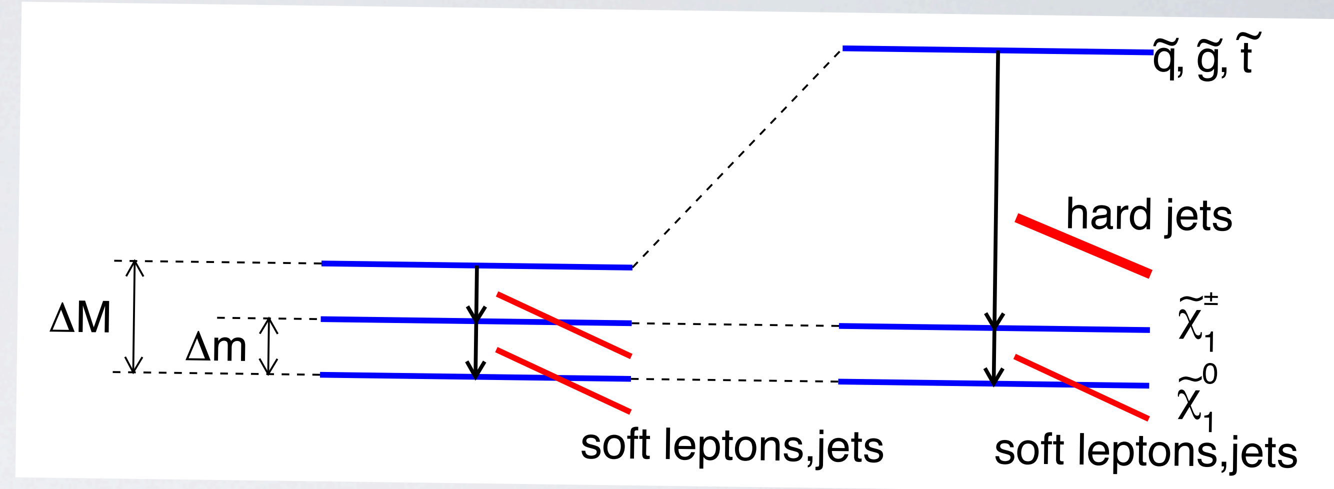
3 jets top control region

Poster: Jeanette Lorenz

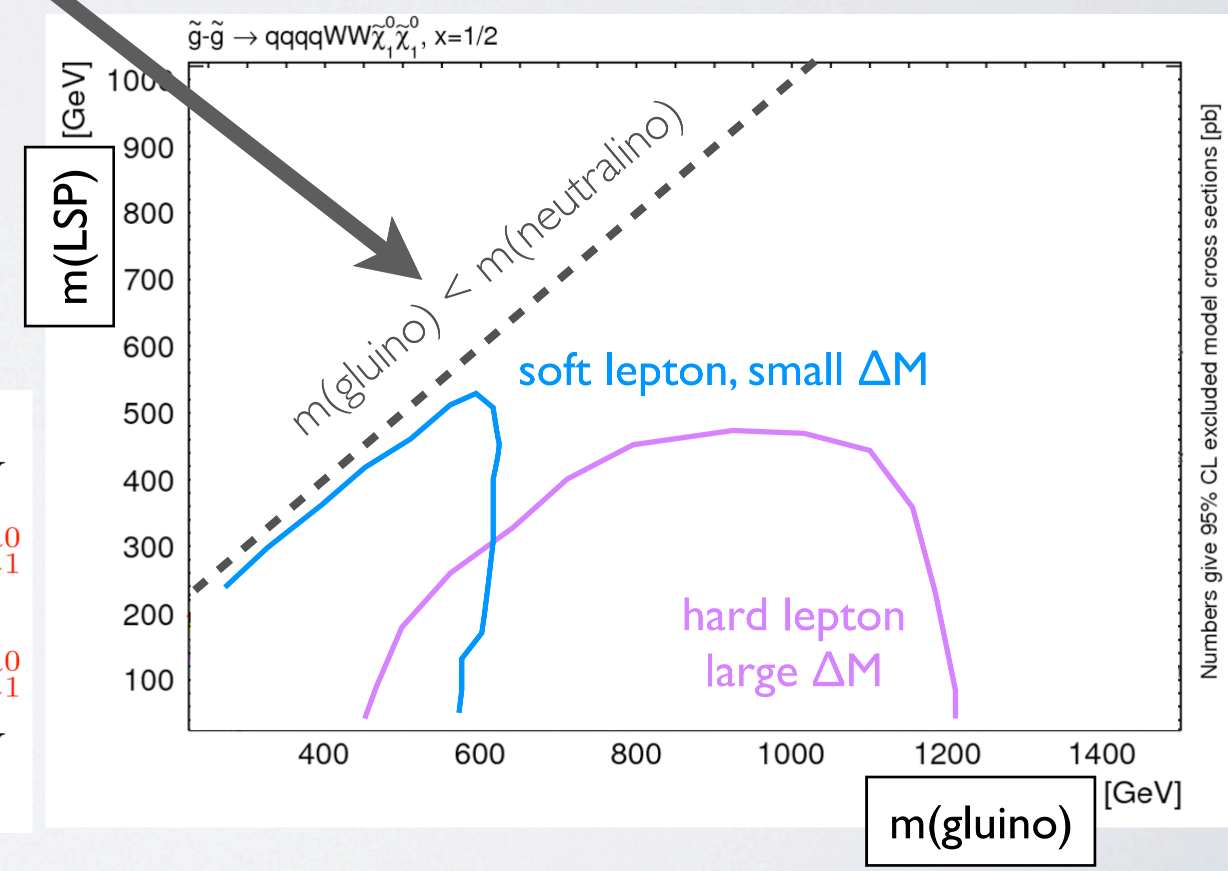
BACKGROUND - **SOFT 1L** + 2-5J + MET

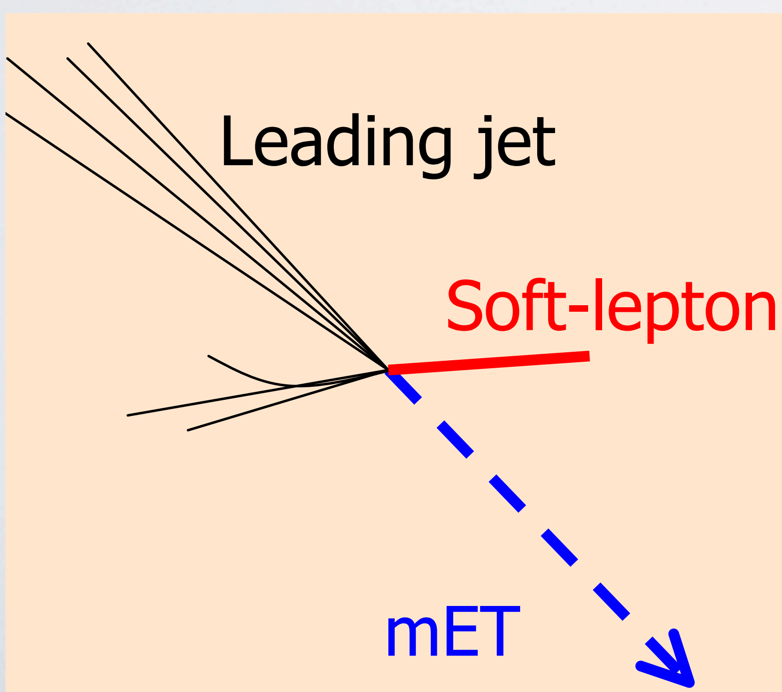
ATLAS-CONF-2013-062

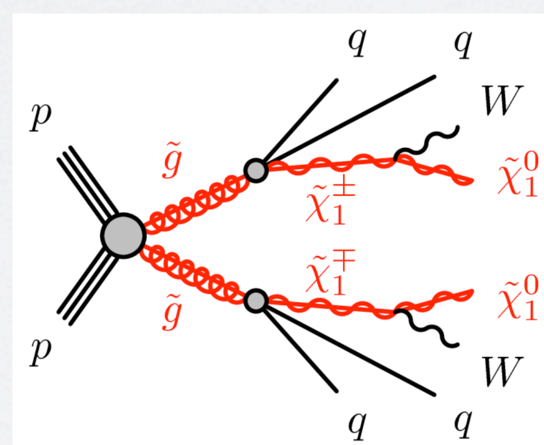
- What if SUSY is not "simple" strong production?
- In ***compressed*** SUSY spectra, leptons in decay chain expected to be soft
  - Fully compressed spectrum: small ΔM
  - Compressed chargino/neutralino sector: small Δm



- Soft 1 lepton ***signal regions***
  6[μ](10[e]) < pT(lep) < 25 GeV:
  - 3 jets / 5 jets + high MET + high MT
- Complimentary to hard 1-lepton → "hard-to-reach" diagonal
- Experimentally challenging → need hard **ISR jet**:
  - Trigger signal (MET trigger)
  - Boost fully compressed spectra







Poster: Ljiljana Morvaj

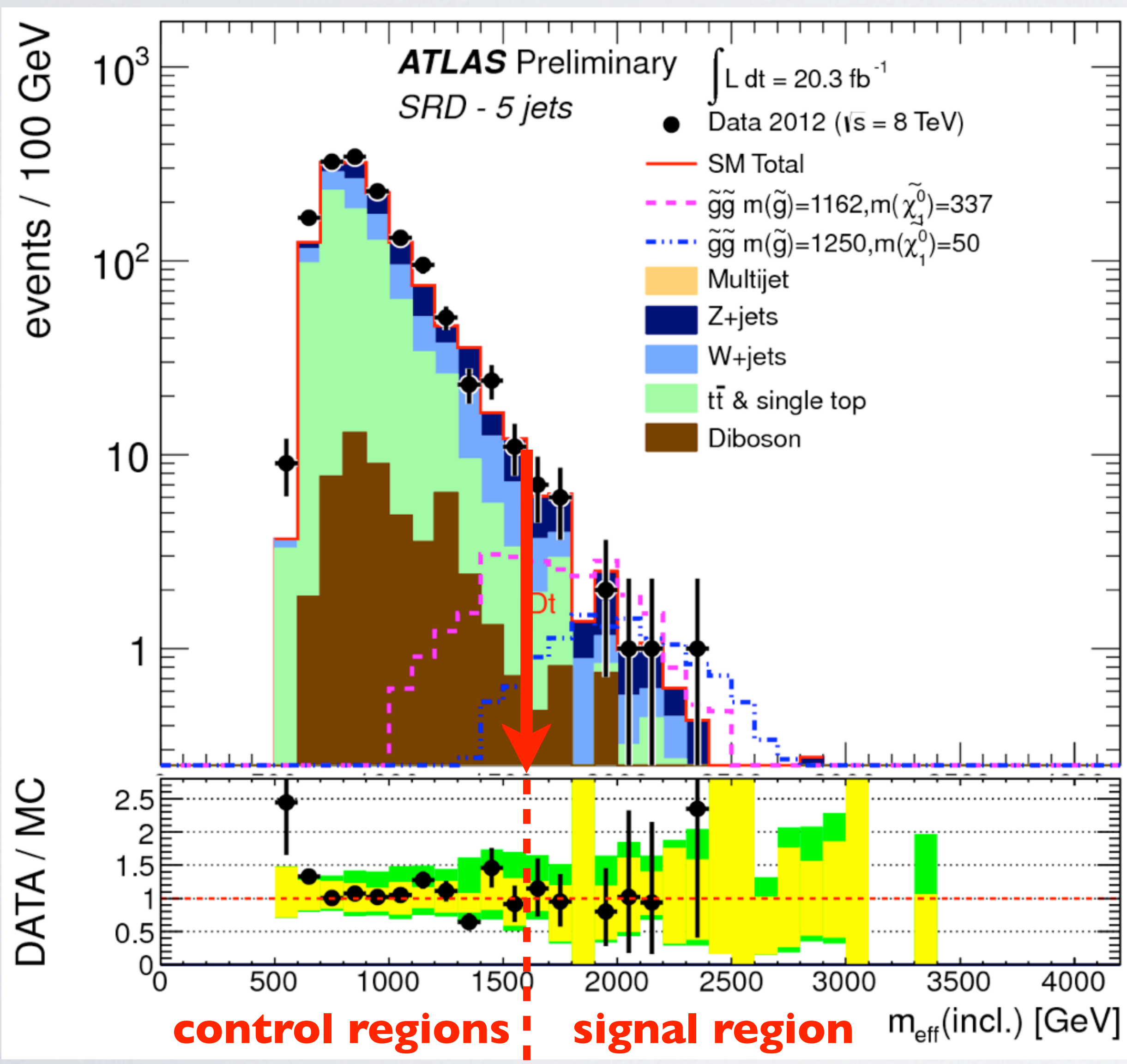
RESULTS

RESULTS - 0 LEPTON

- No significant excess in any signal region *(details in back up)*
- Data and estimated backgrounds used to set ***model-independent limits*** on visible BSM cross section
  - No signal model used, in contrast to model interpretations *(next)*
  - σ(vis) < 0.12 fb
    - σ(vis) = σ(BSM) × Acceptance × efficiency

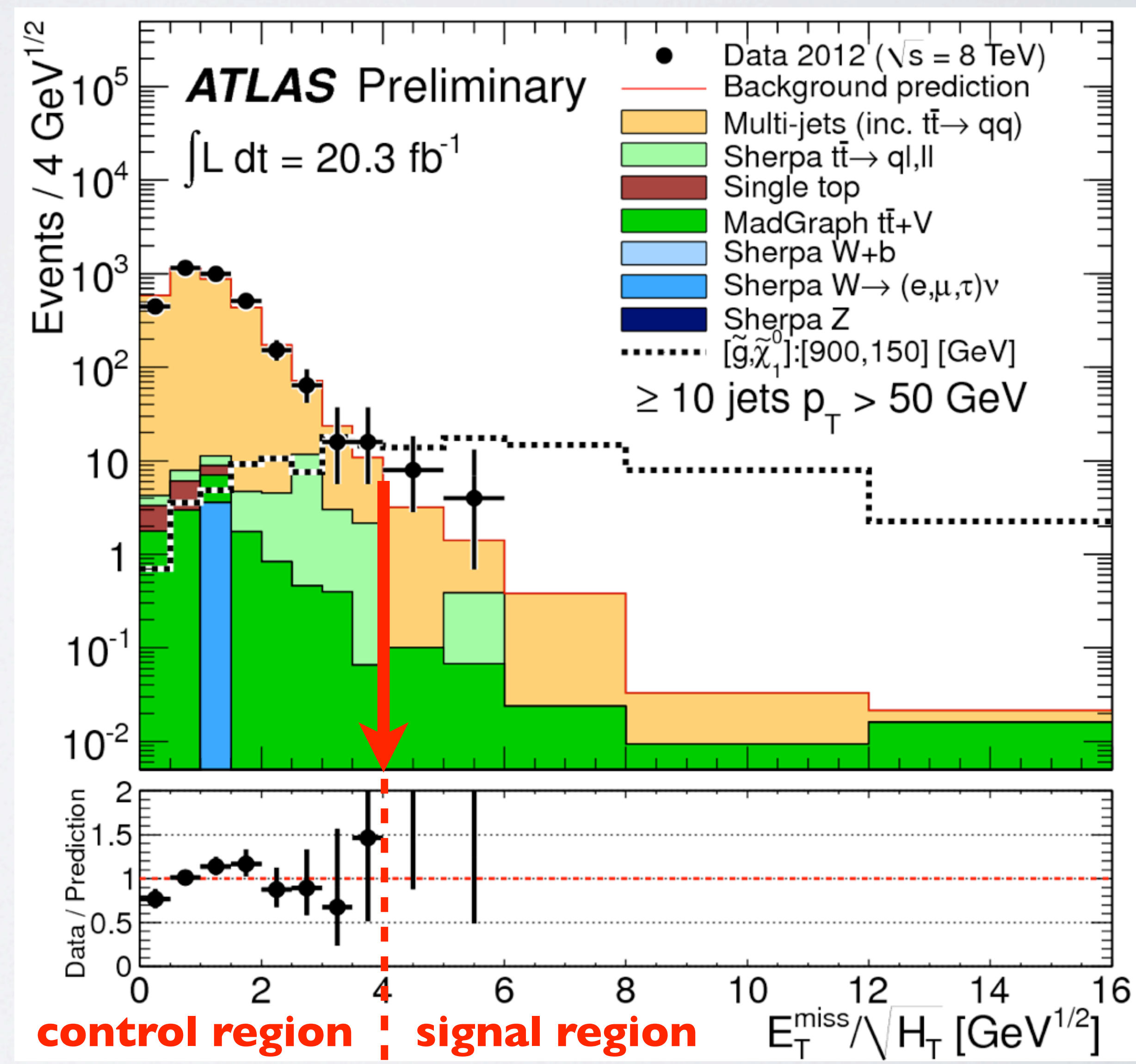
0L+2-6J+MET

5 jets CR/SR



0L+7-10J+MET

≥10 jets CR/SR

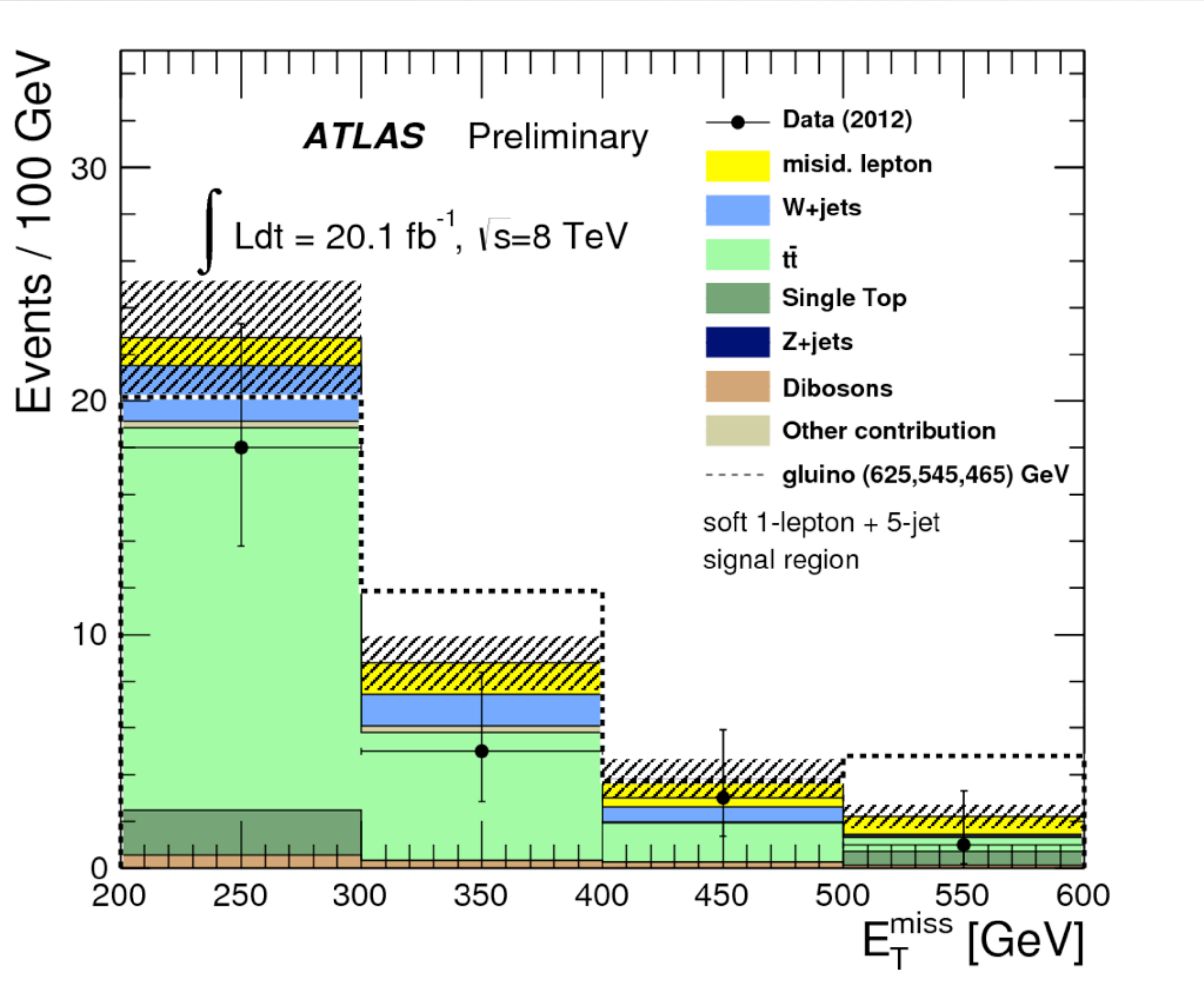


RESULTS - 1 LEPTON

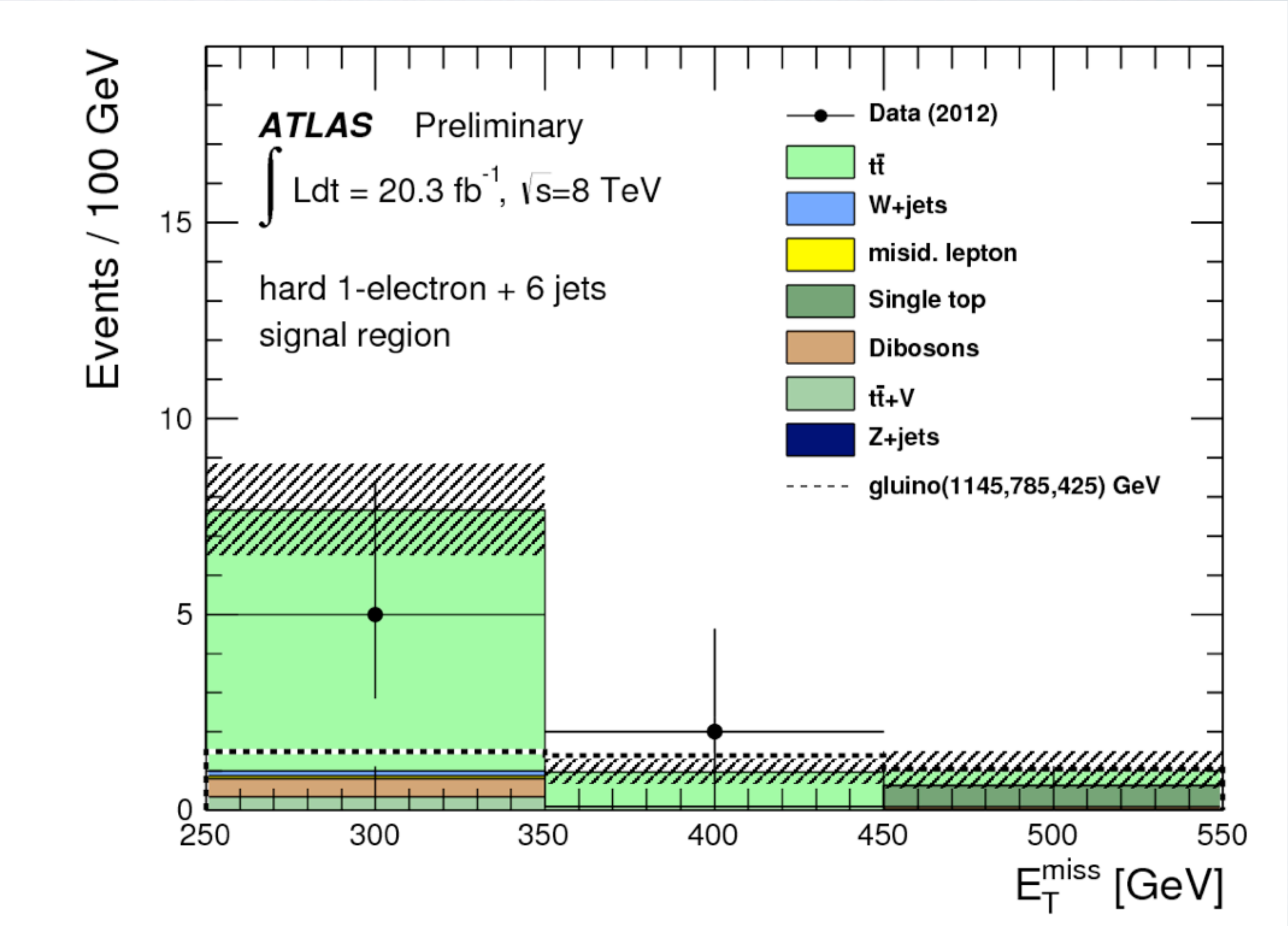
- No significant excess in any signal region *(details in back up)*
- Data and estimated backgrounds used to set ***model-independent limits*** on visible BSM cross section
  - σ(vis) < 0.15 fb

1/2L+2-6J+MET

soft 1-lepton
5 jets SR



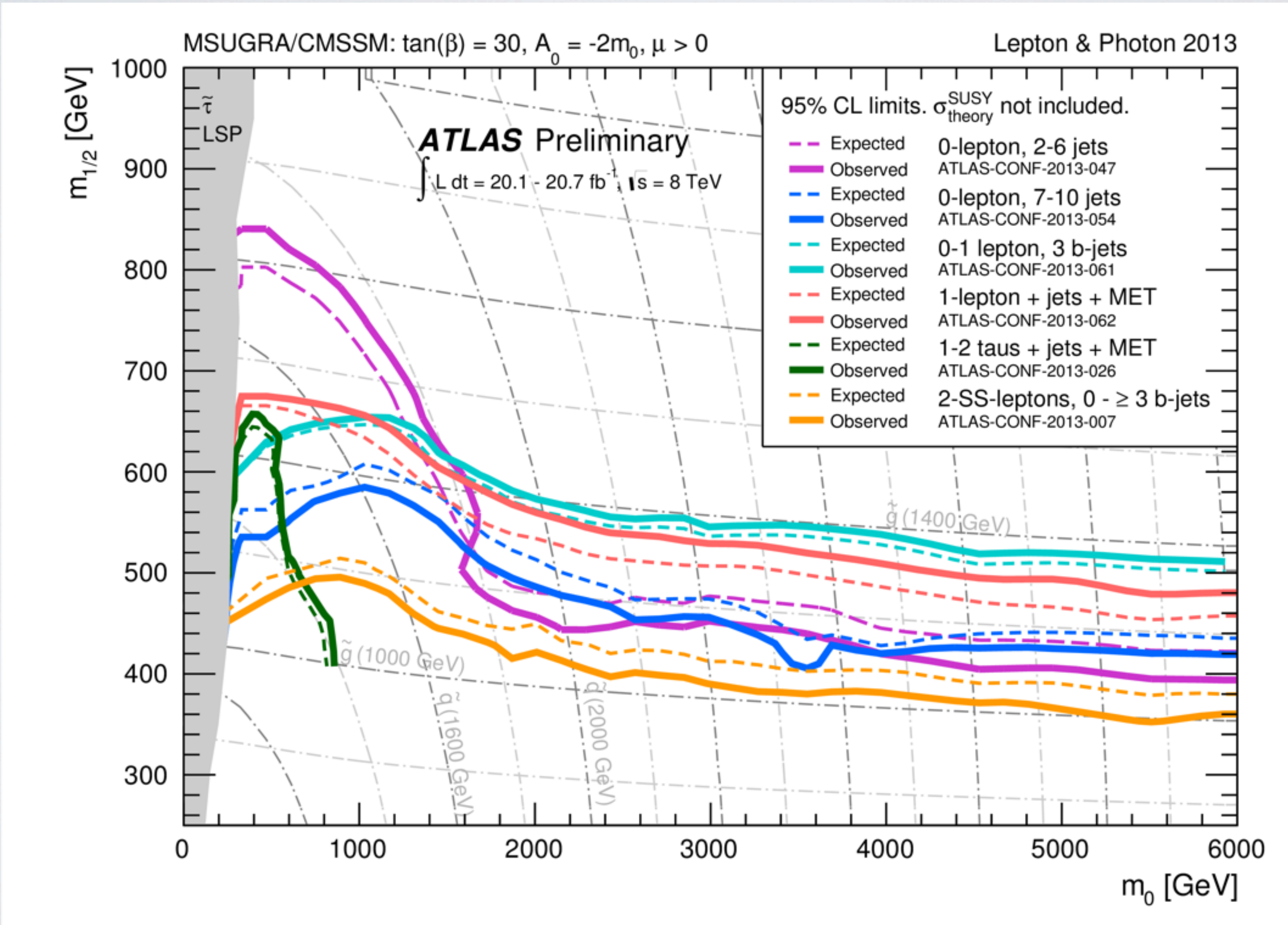
hard 1-lepton
6 jets electron SR



INTERPRETATIONS

MSUGRA/CMMSM

- "Higgs-aware" MSUGRA/CMSSM plane
- Gluino masses below ~1.35TeV excluded for all squark masses



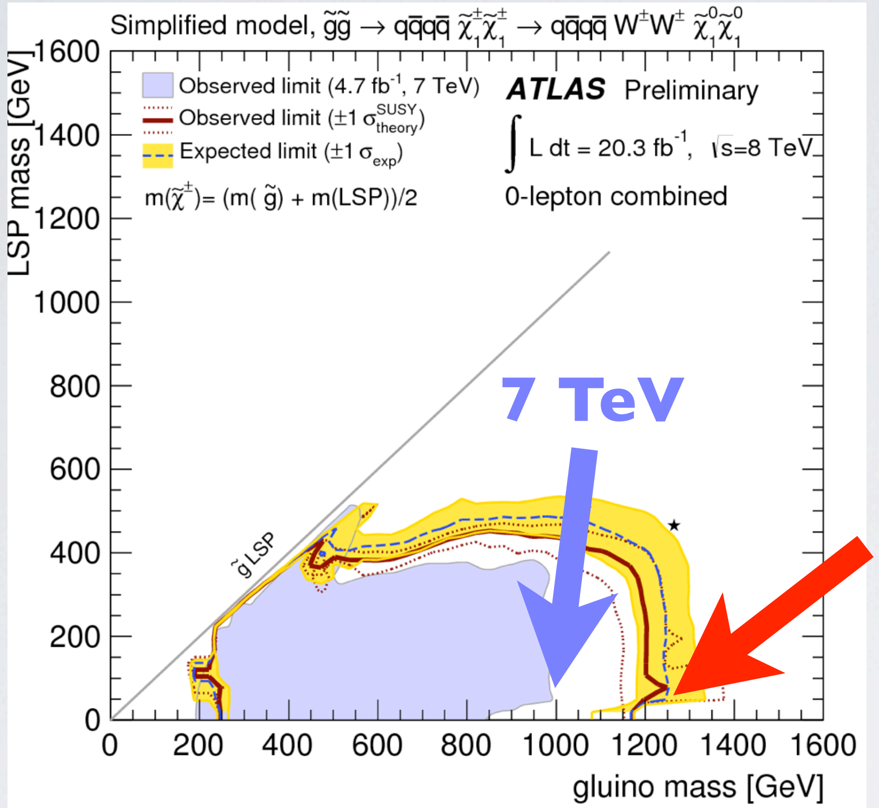
0L+2-6J+MET

0L+7-10J+MET

1/2L+2-6J+MET

SIMP. MODELS: GLUINO VIA CHARGINO

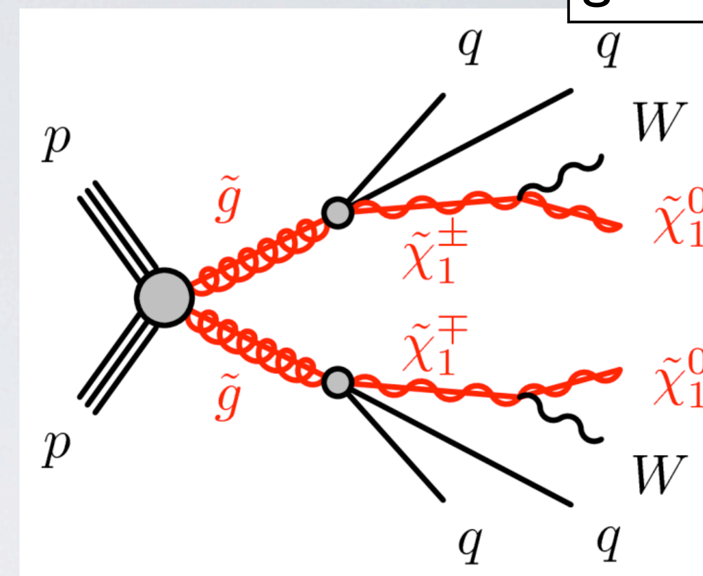
0L+2-6J+MET



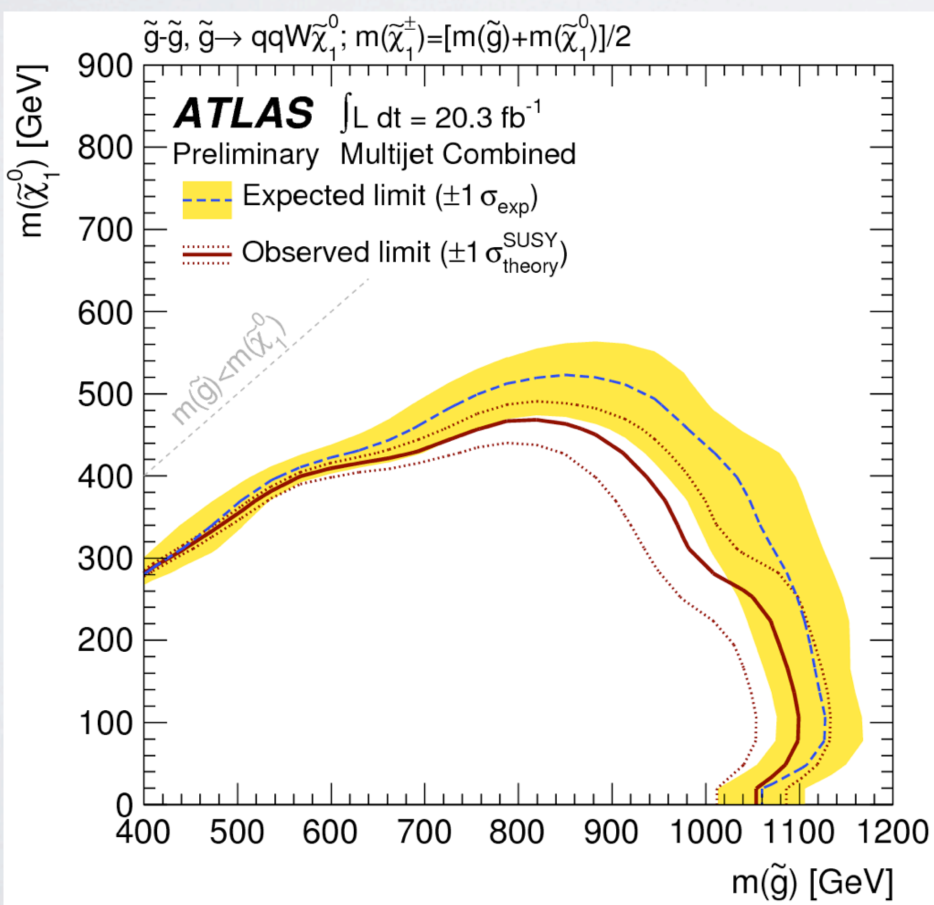
7 TeV

8 TeV

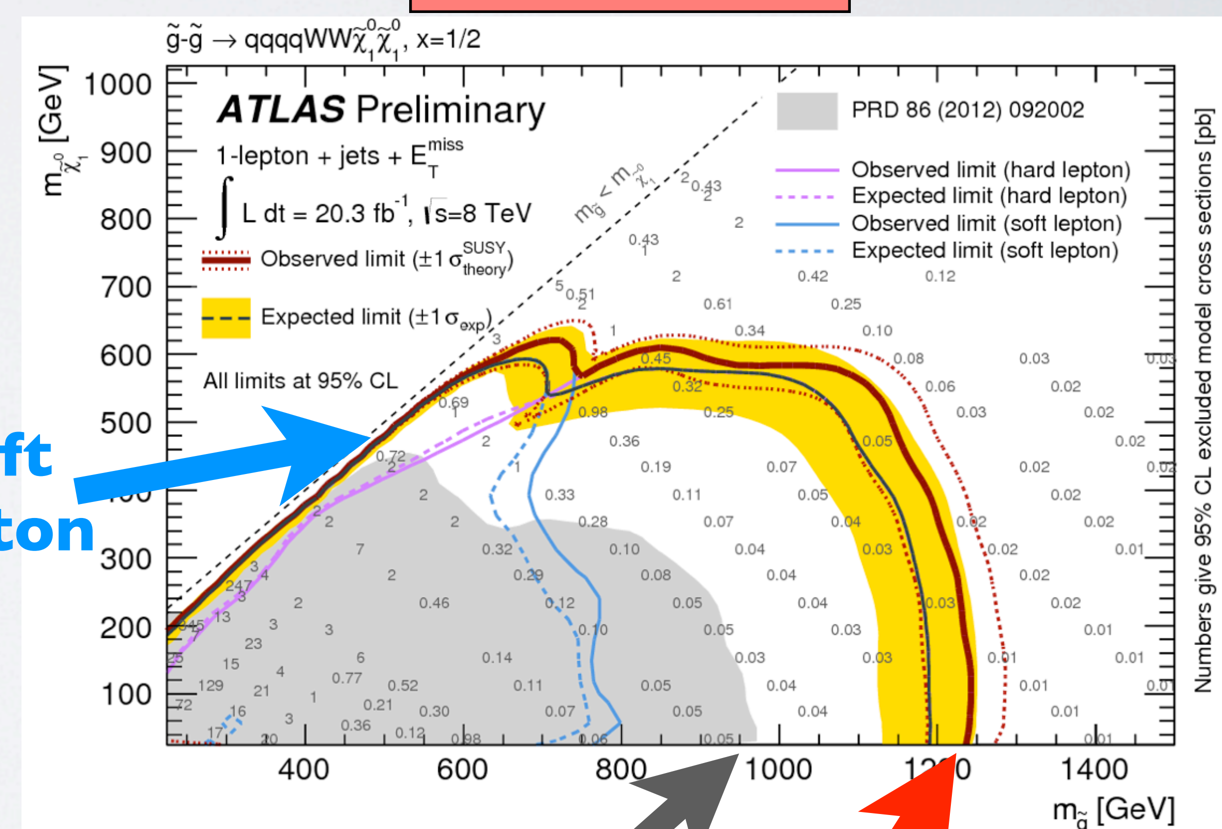
gluino pair



0L+7-10J+MET



1/2L+2-6J+MET



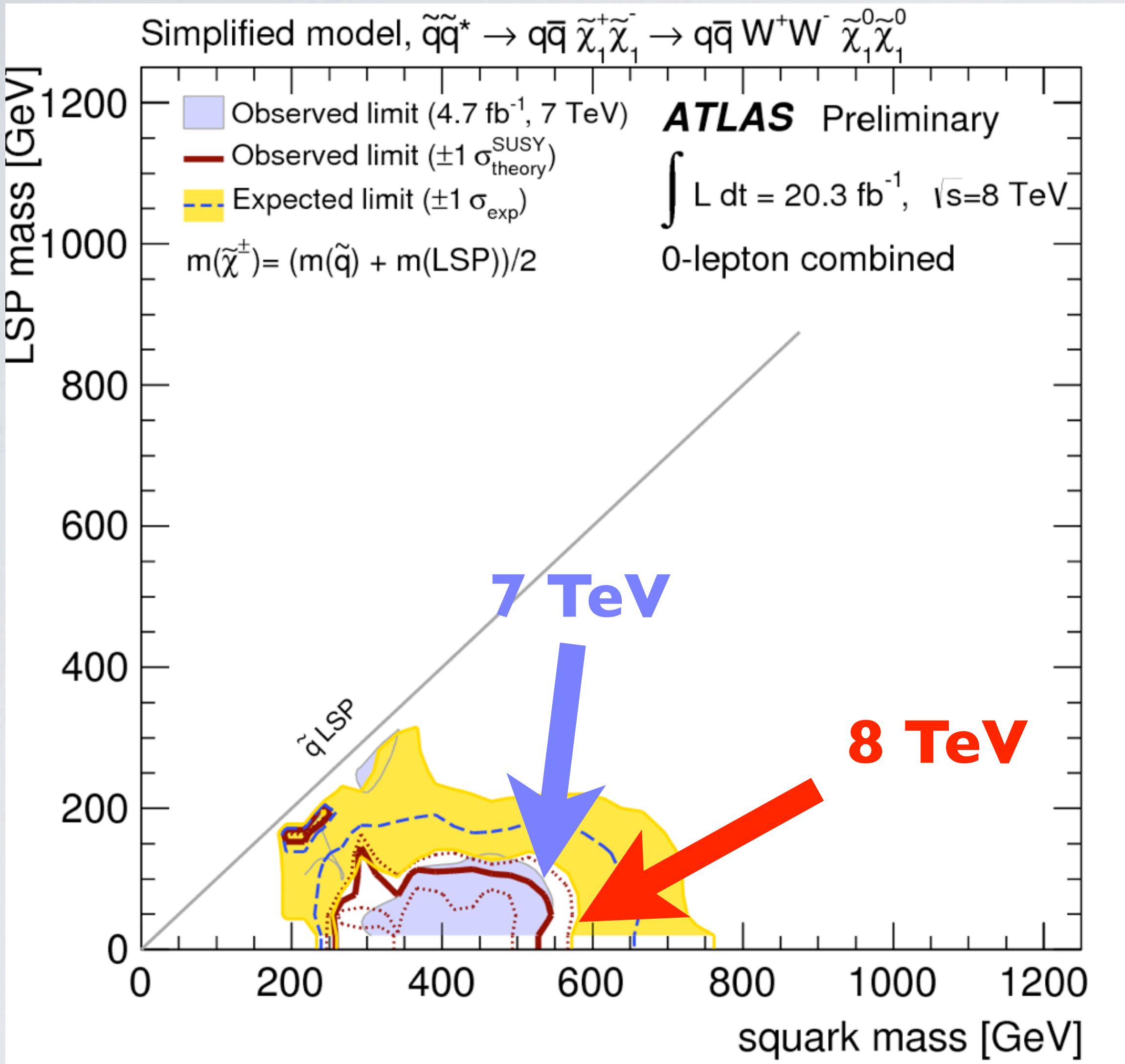
soft lepton

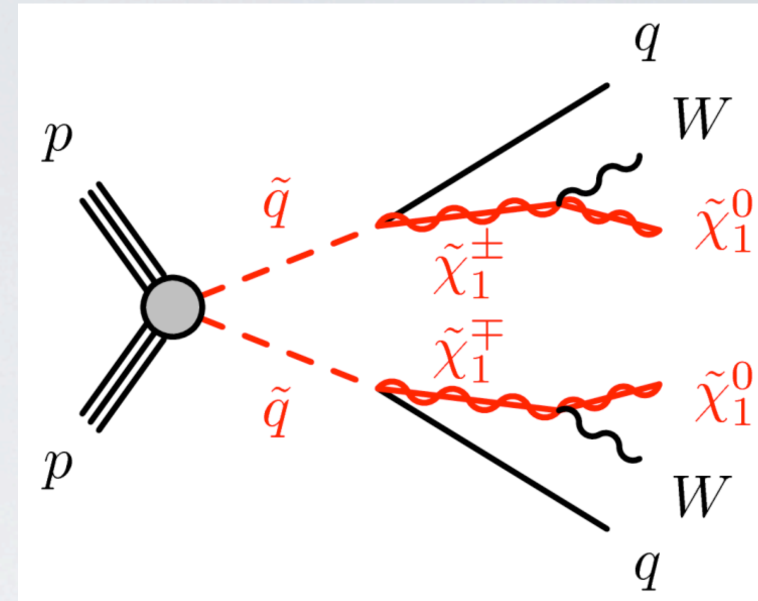
7 TeV

8 TeV

SIMP. MODELS: SQUARK VIA CHARGINO

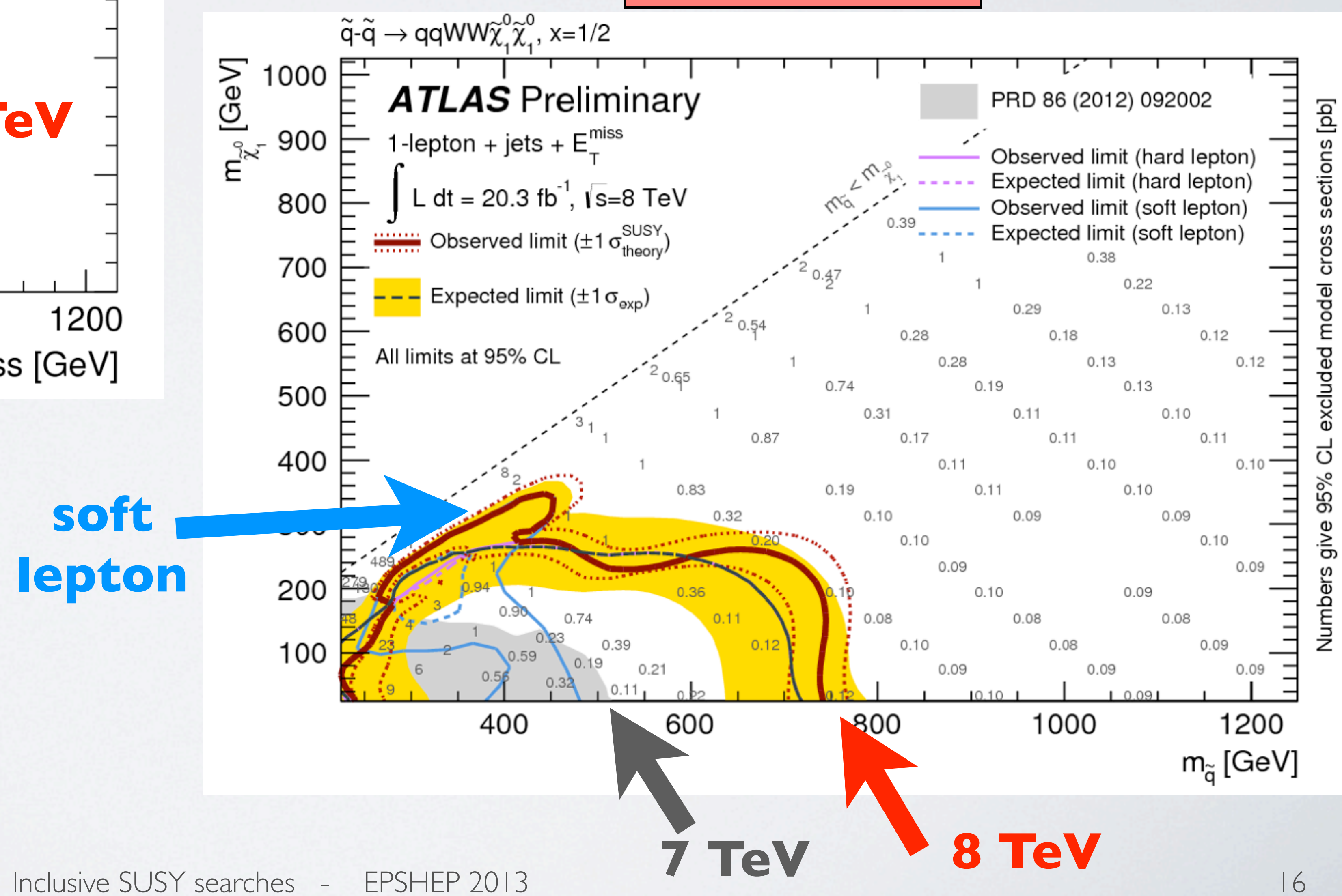
0L+2-6J+MET





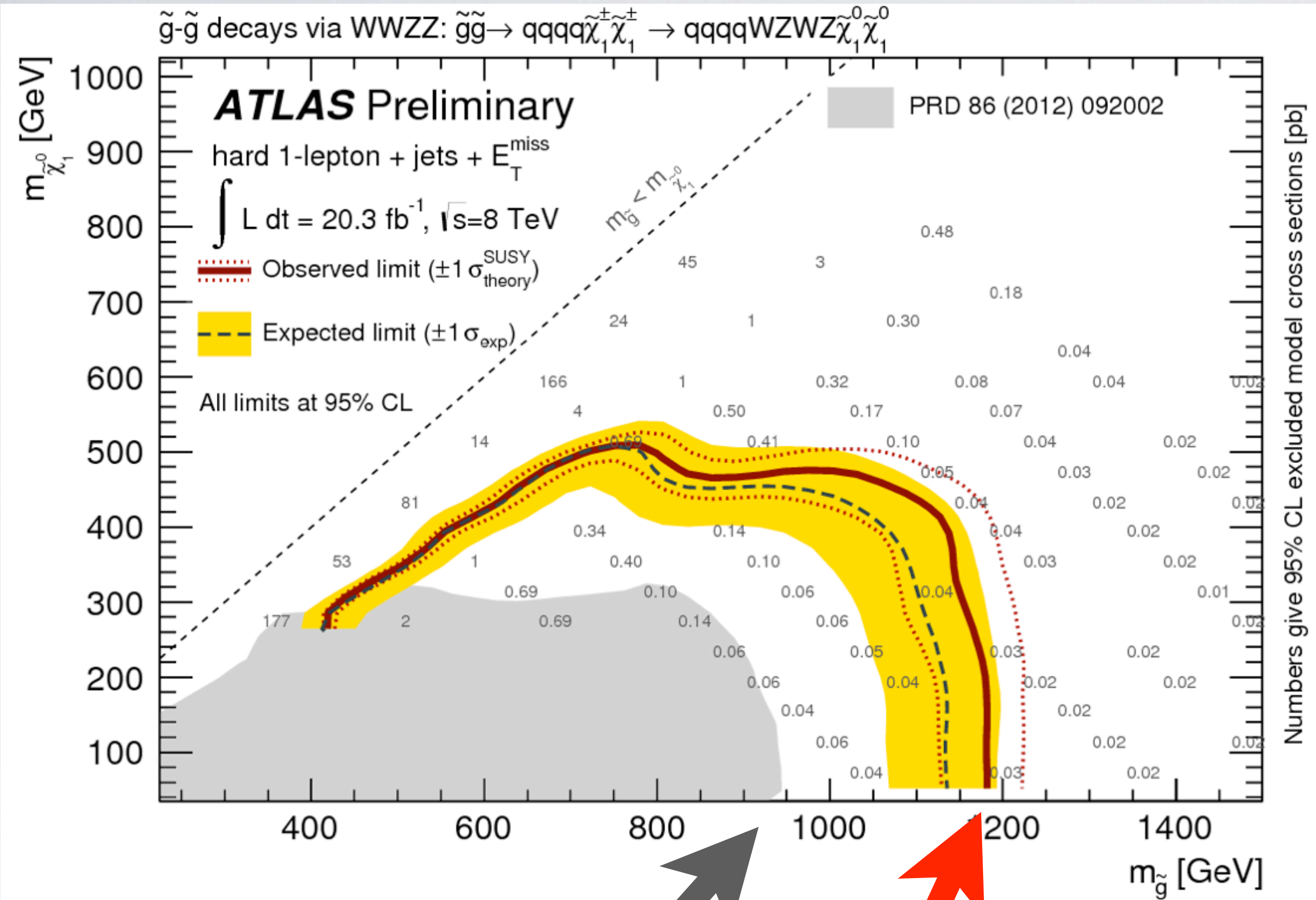
squark pair

1/2L+2-6J+MET



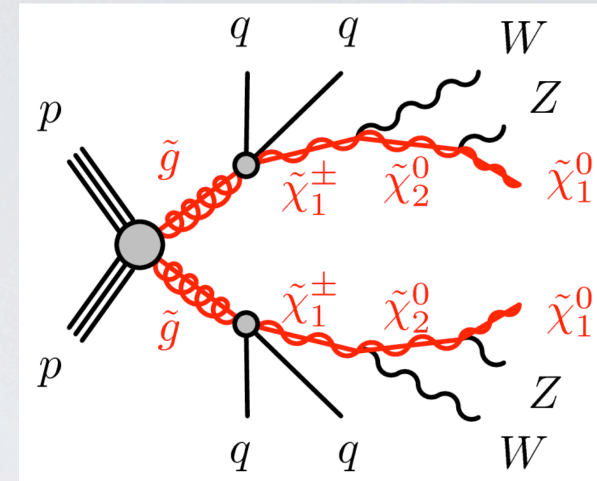
SIMP. MODELS:VIA CHARGINO/NETRALINO2

1/2L+2-6J+MET



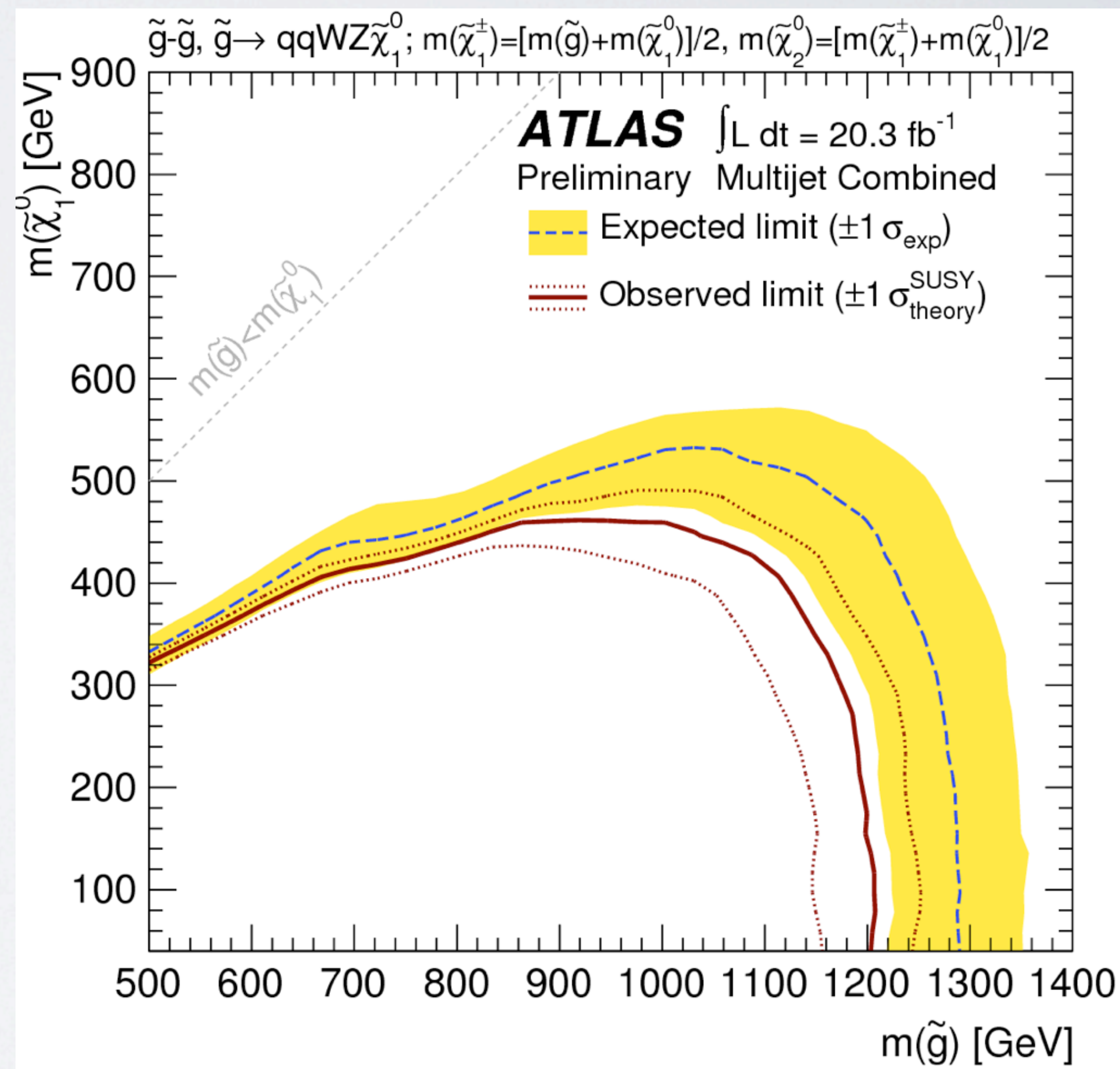
7 TeV

8 TeV



gluino pair

0L+7-10J+MET



SUMMARY

- LHC and ATLAS very powerful pairing in search for SUSY
- Unfortunately no sign of supersymmetric phenomena yet

- Excluding gluinos (squarks) with masses up to ~1.3 (0.75) TeV in studied models
- Model-independent limits on visible cross section for BSM physics as low as 0.12 fb

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147

- <u>Next steps</u>:
  - Finalize all ongoing 8 TeV analyses on full 2012 dataset
  - Move forward to produce combined 0L + 1L + 2L + ... exclusions by full statistical analyses combination
  - 13~14 TeV: the big next step in mass reach for inclusive searches for squarks and gluinos (fingers crossed)

FOUND IT

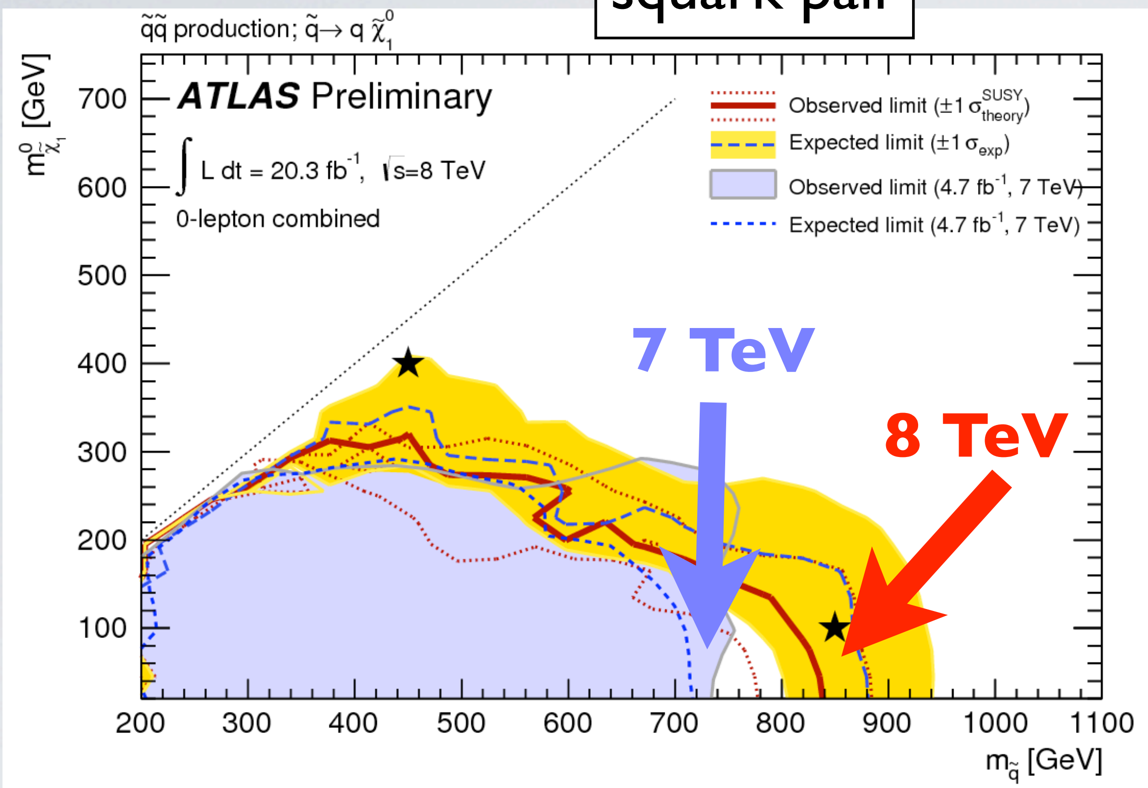
Los Roques, Venezuela
June 2013

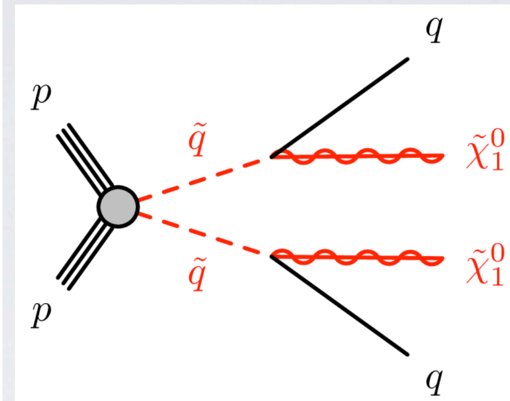
BACK UP

SIMPLIFIED MODELS: DIRECT PRODUCTION

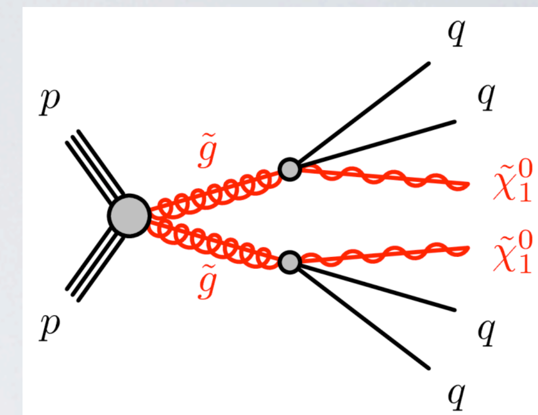
0L+2-6J+MET

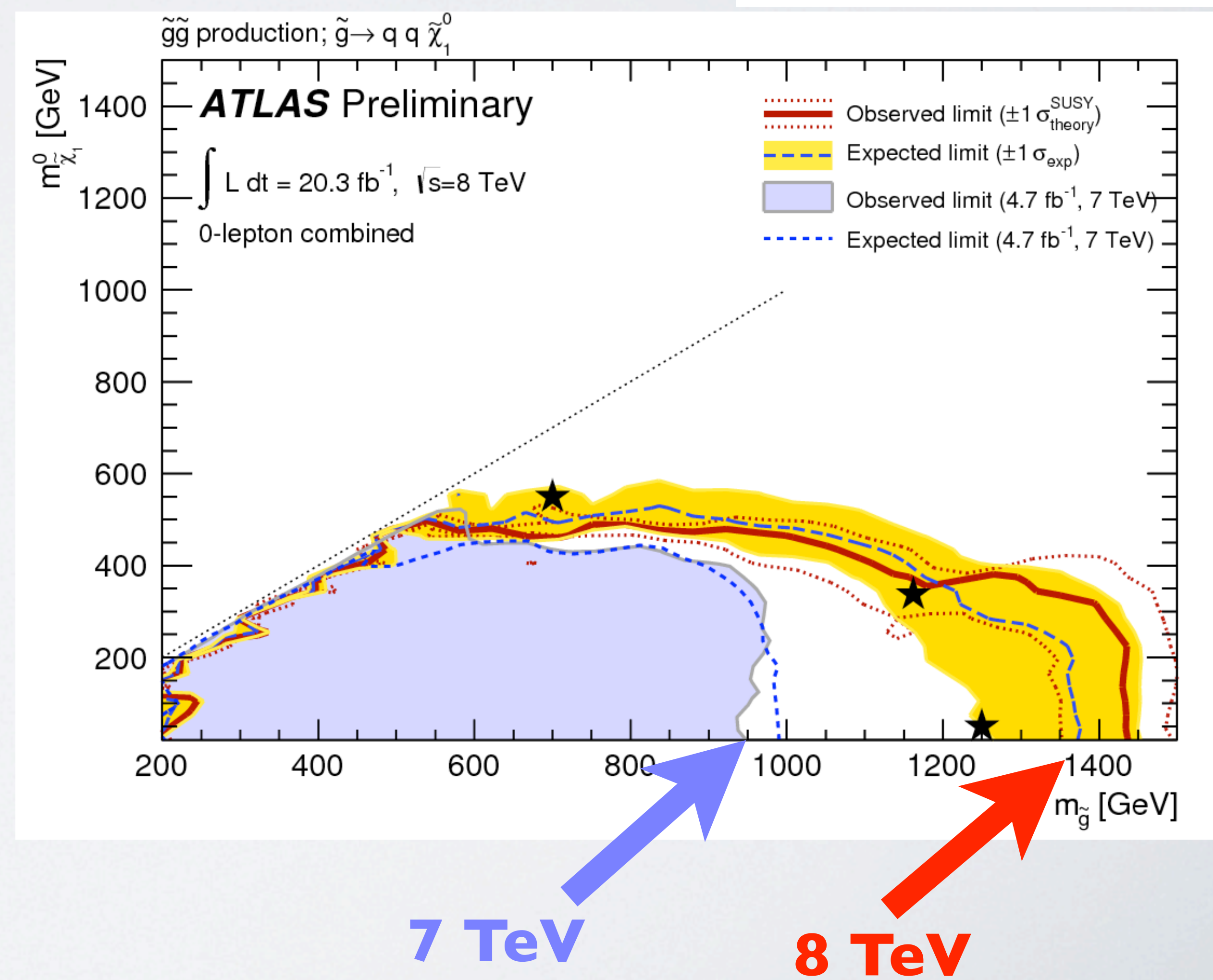
squark pair



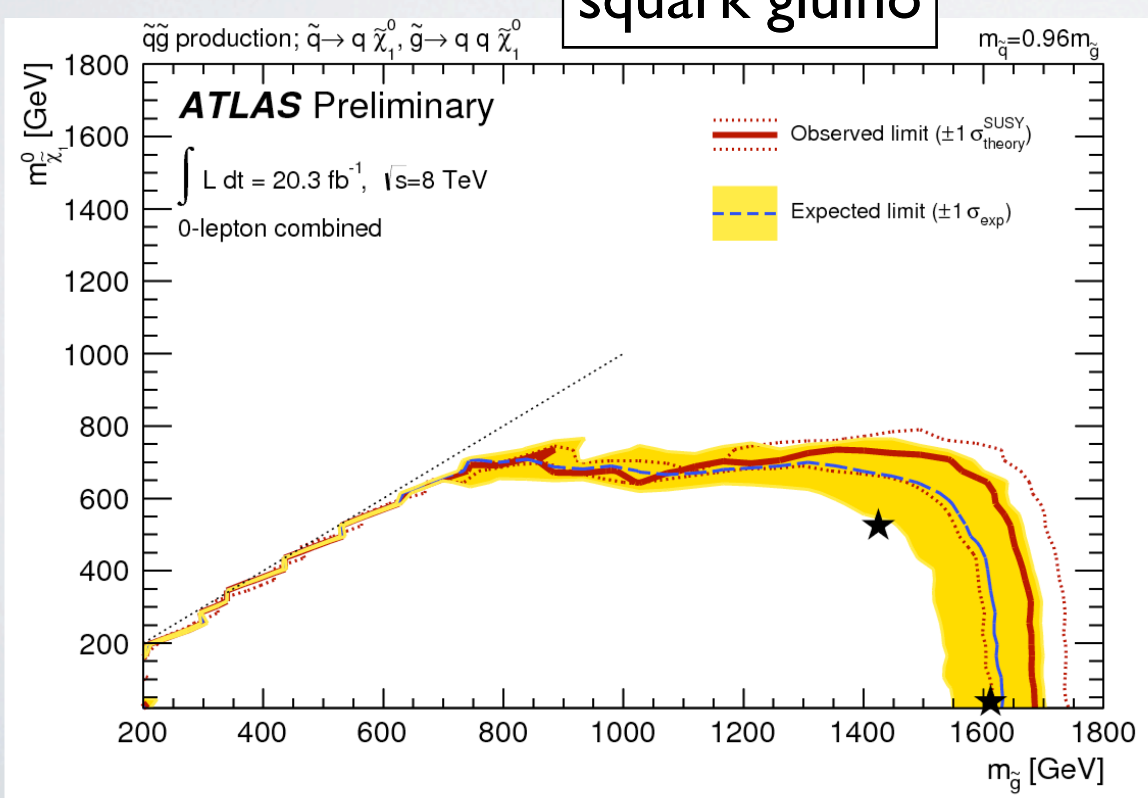


gluino pair





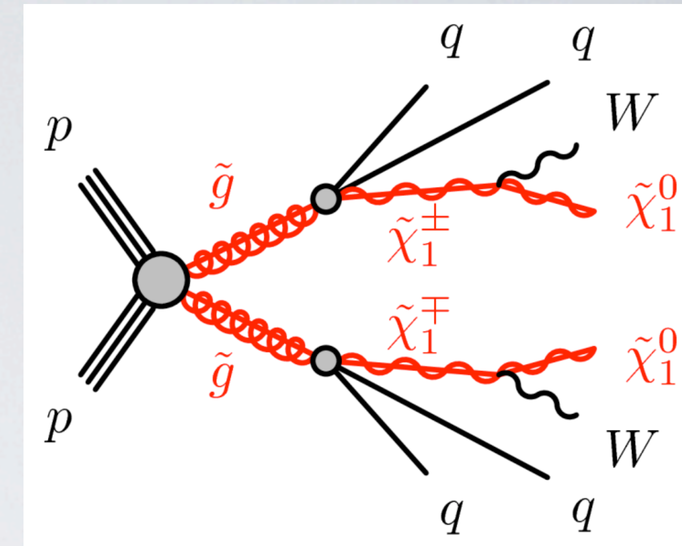
squark gluino



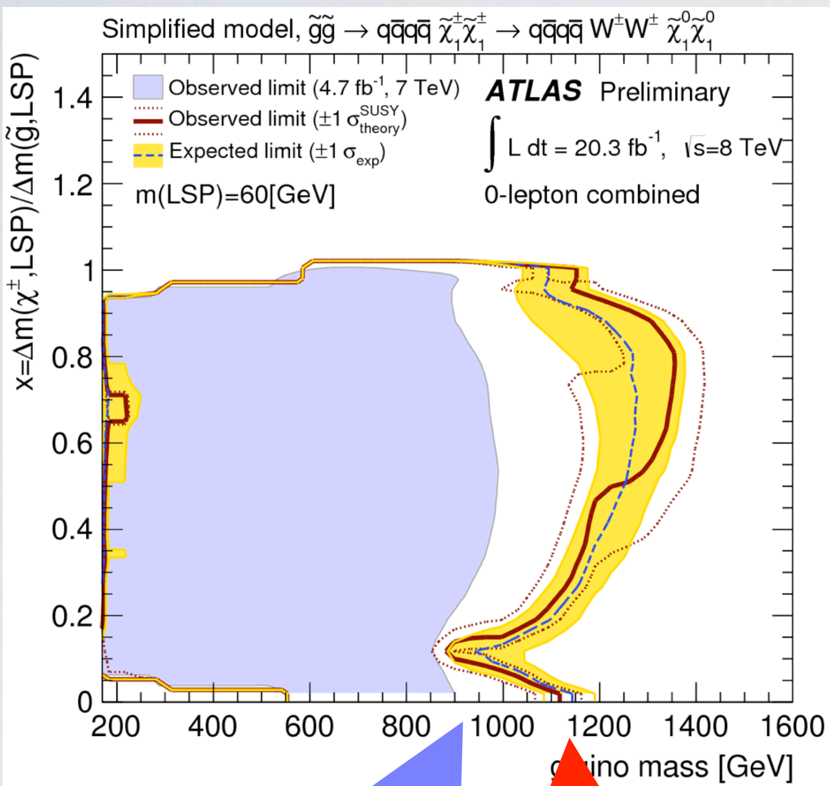
SIMP. MODELS: GLUINO - GRID-X

- Limits in 1-step (intermediate chargino) gluino pair production *simplified models*
- Same decay, different grid: new variable X defined as $x = \frac{m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)}{m(\tilde{g}) - m(\tilde{\chi}_1^0)}$
    - mass splitting ratio

gluino pair

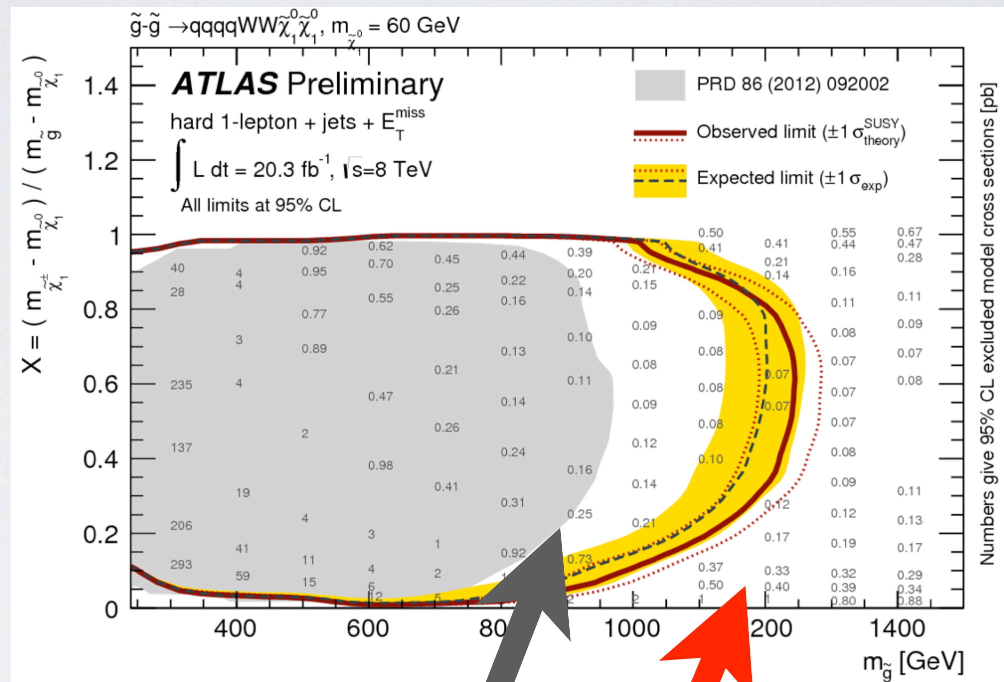


0L+2-6J+MET



7 TeV

8 TeV

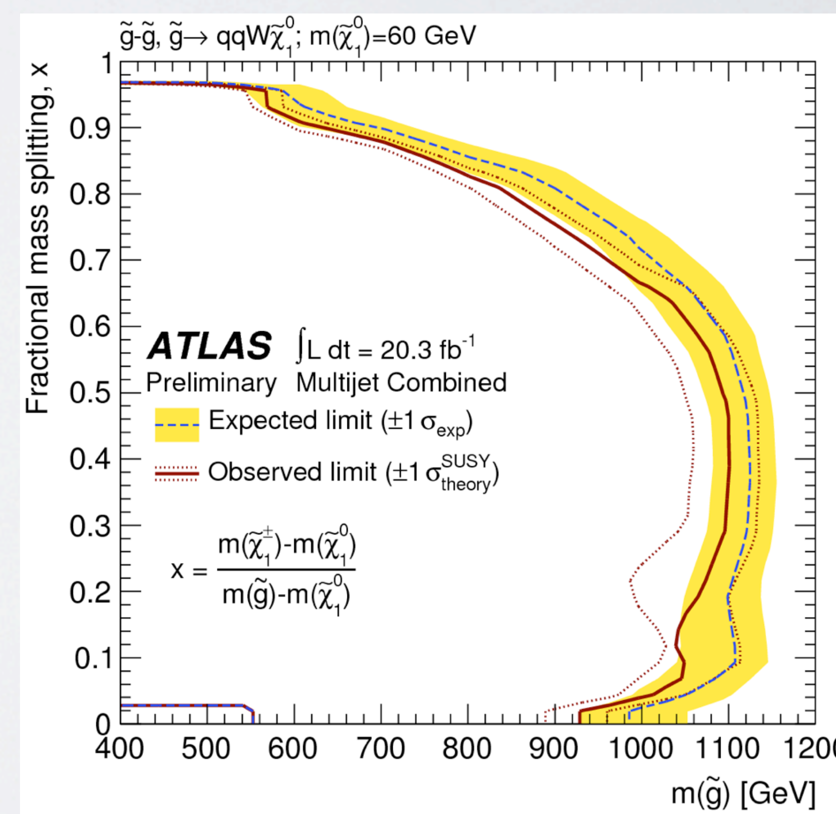


7 TeV

8 TeV

1/2L+2-6J+MET

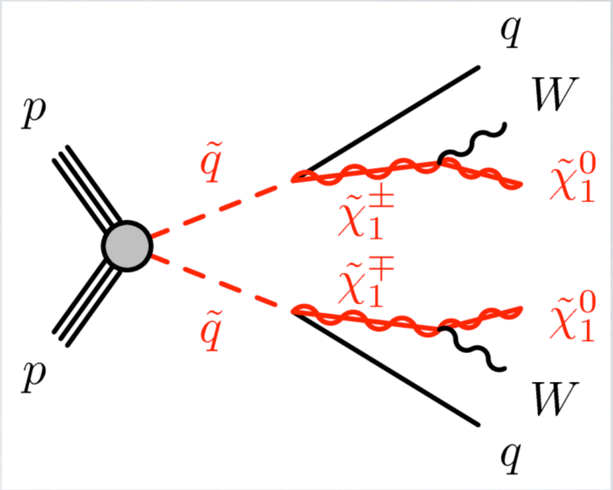
0L+7-10J+MET



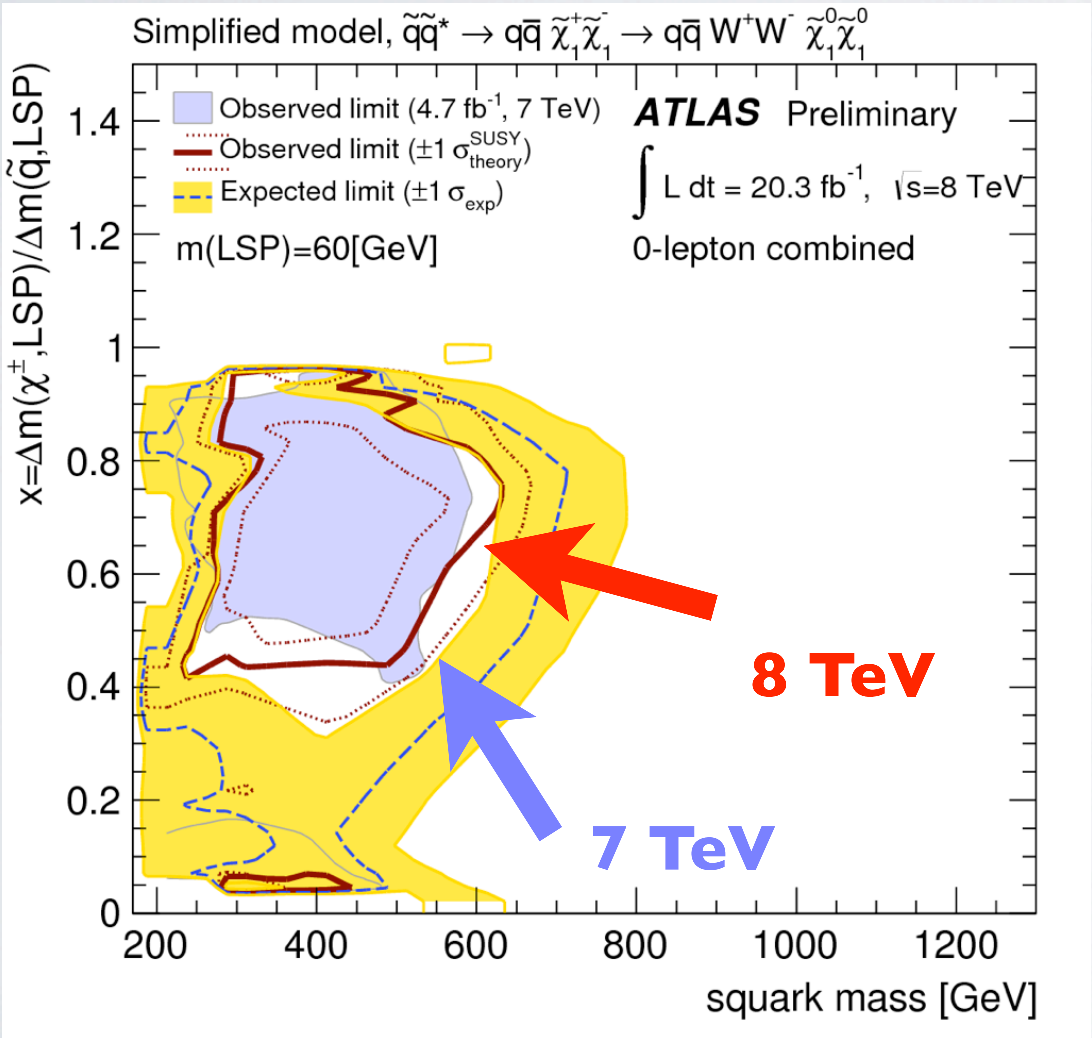
SIMP. MODELS: SQUARK - GRID-X

squark pair

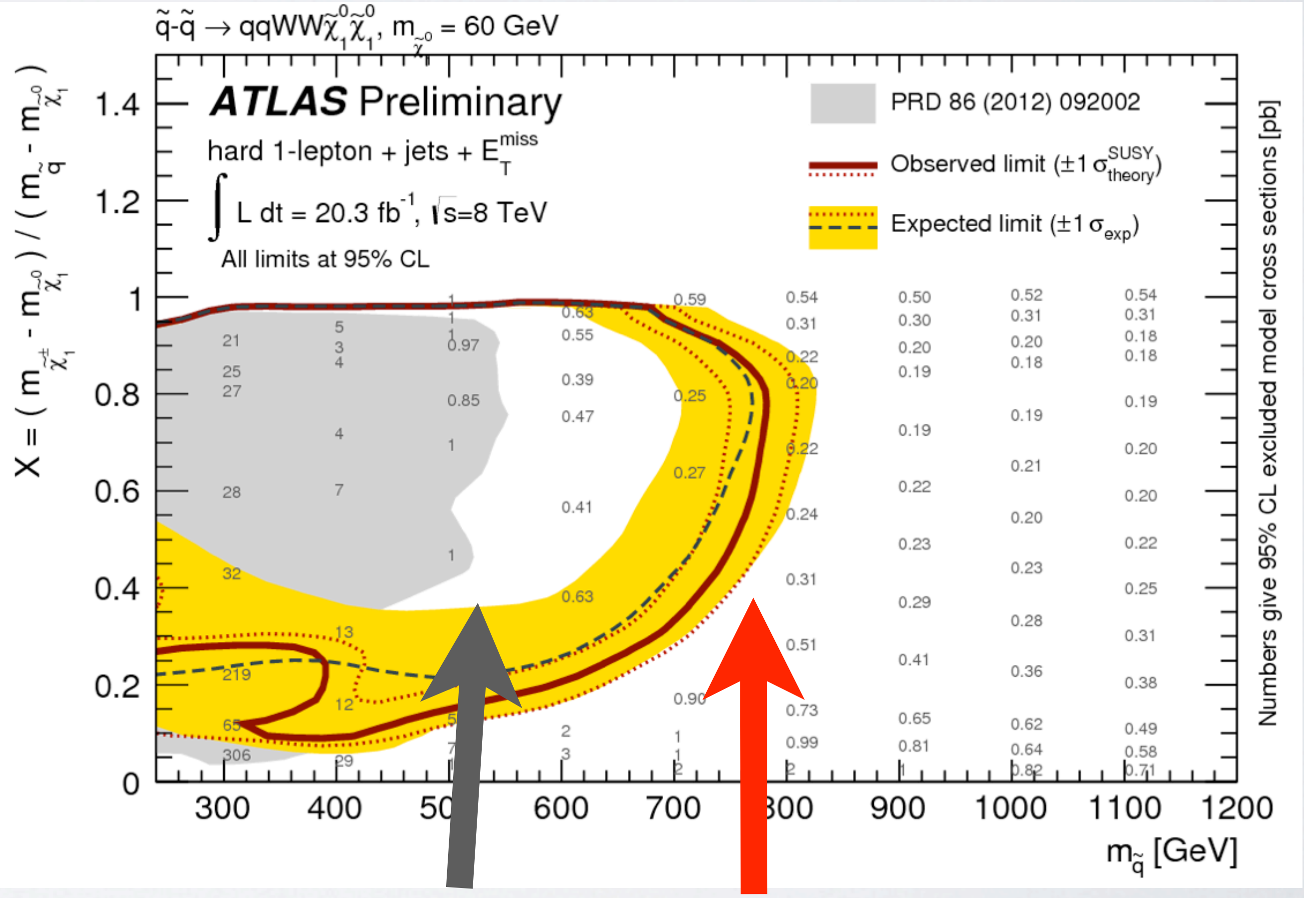
- Limits in 1-step (intermediate chargino) squark pair production *simplified models*
- Same decay, different grid: new variable X defined as $x = \frac{m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)}{m(\tilde{g})-m(\tilde{\chi}_1^0)}$
  - mass splitting ratio



0L+2-6J+MET



1/2L+2-6J+MET

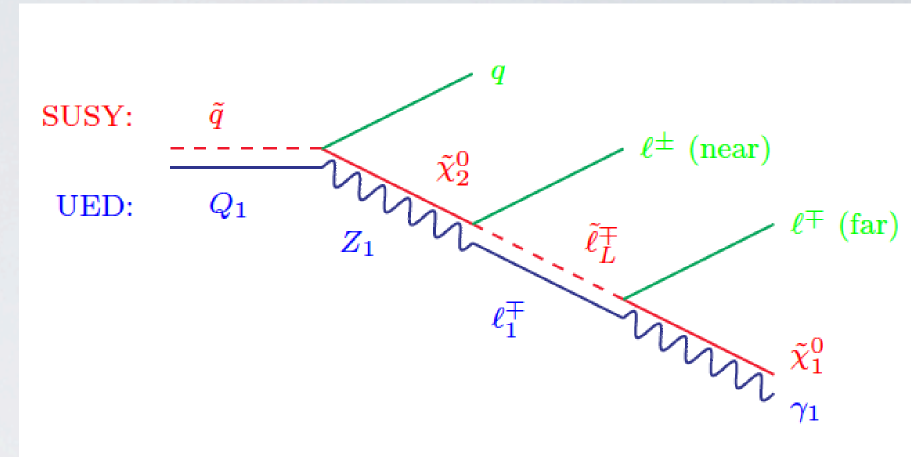


7 TeV 8 TeV

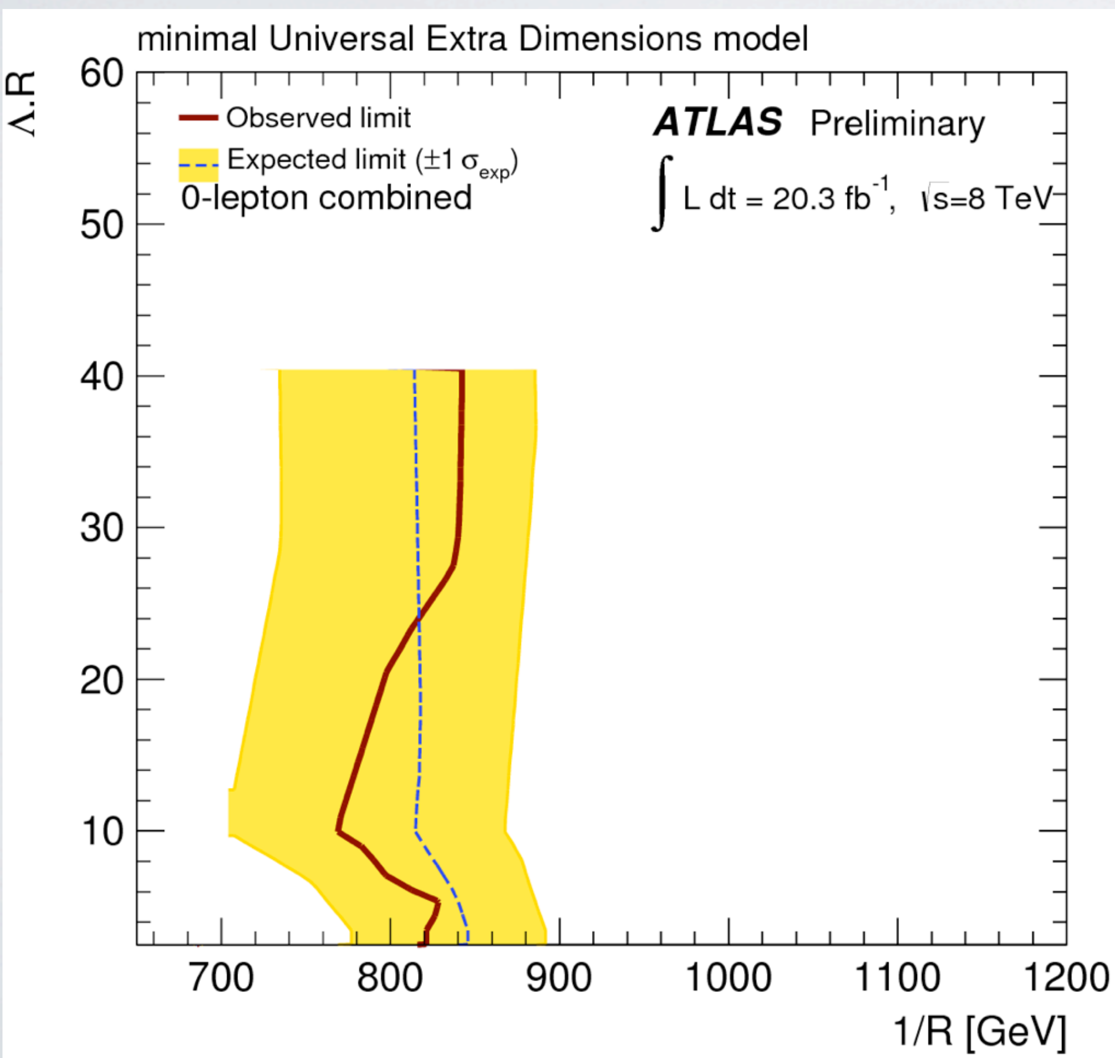
MINIMAL UED

- Limits in minimal Universal Extra Dimensions (mUED)
- Signal region: 2 soft muons + 2 jets + high MET + high MT + Z-veto
- Comparable expected limits, but observed limit worse for 2L because of slight excess

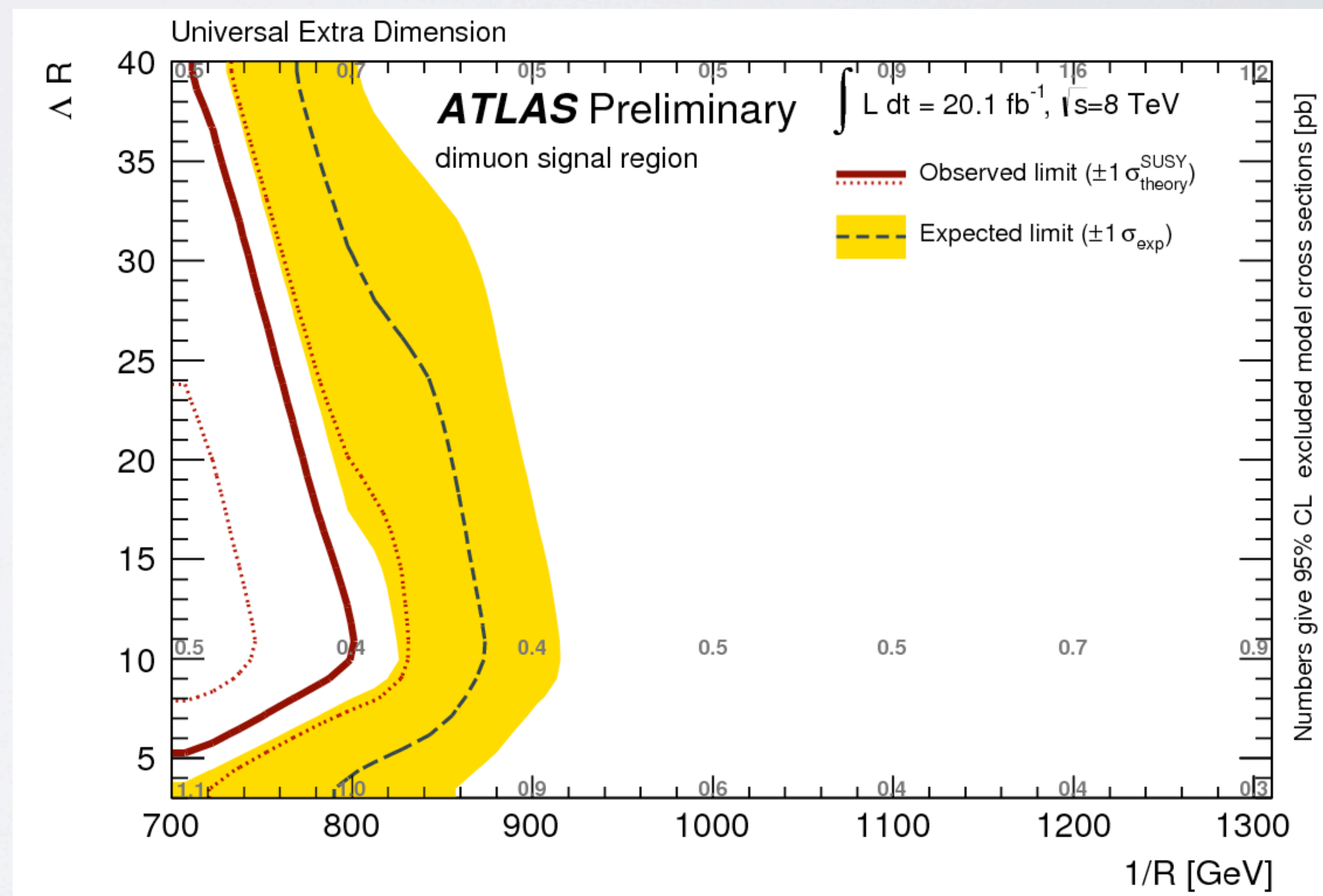
decay chain



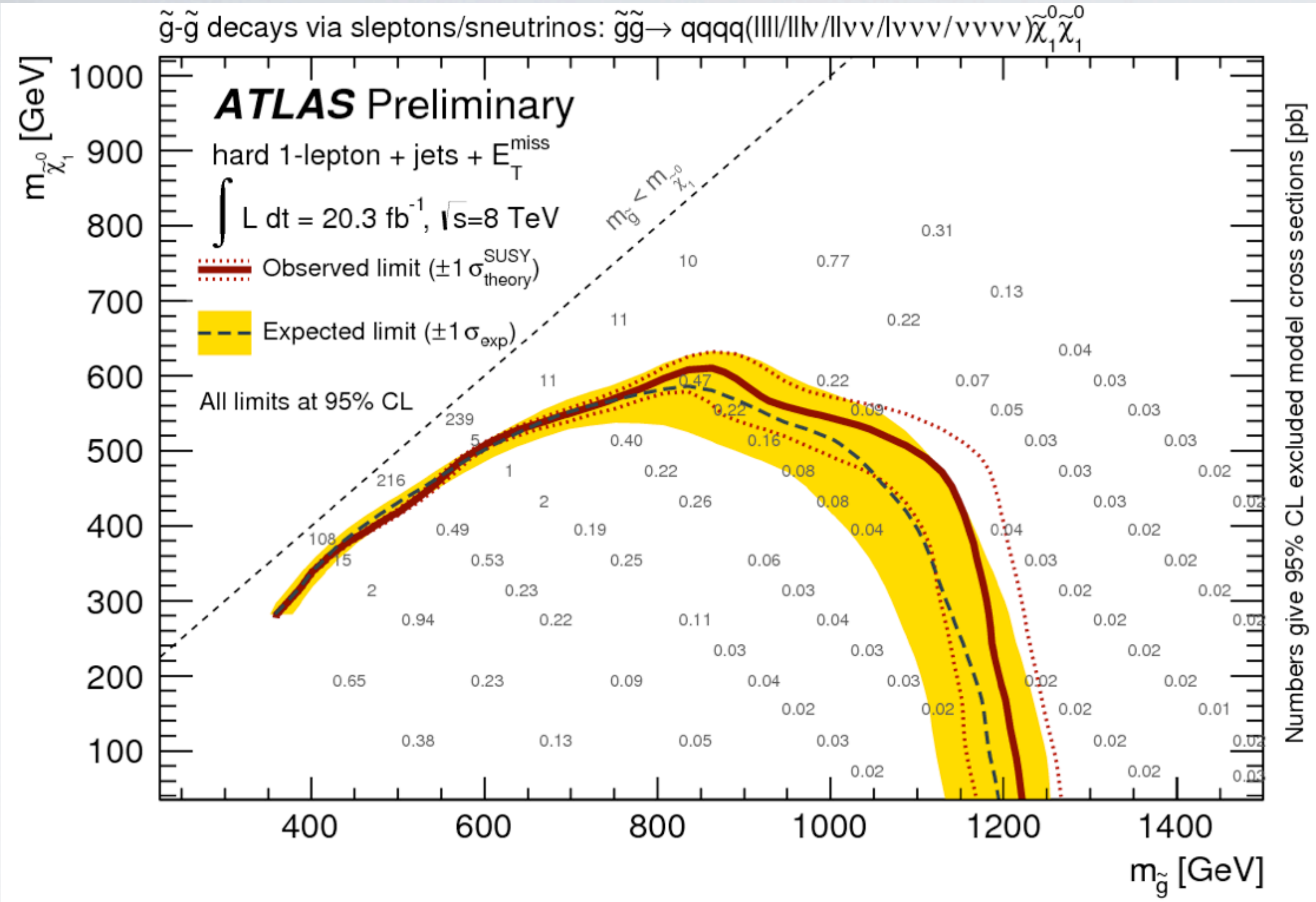
0L+2-6J+MET



1/2L+2-6J+MET

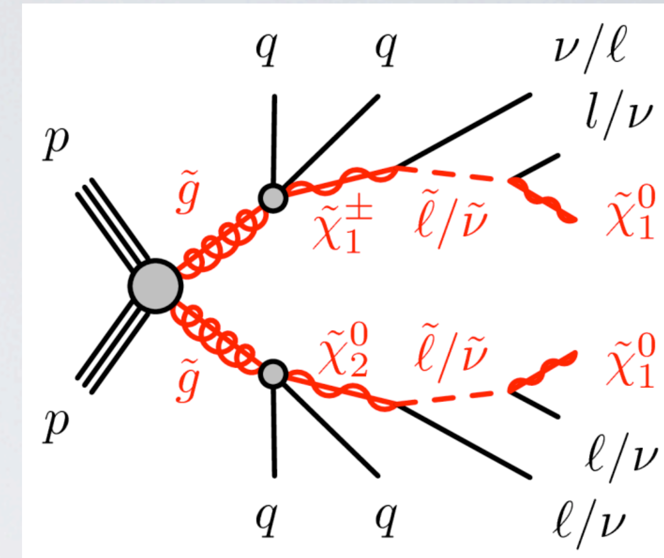


SIMP. MODELS: GLUINO VIA SLEPTON



1/2L+2-6J+MET

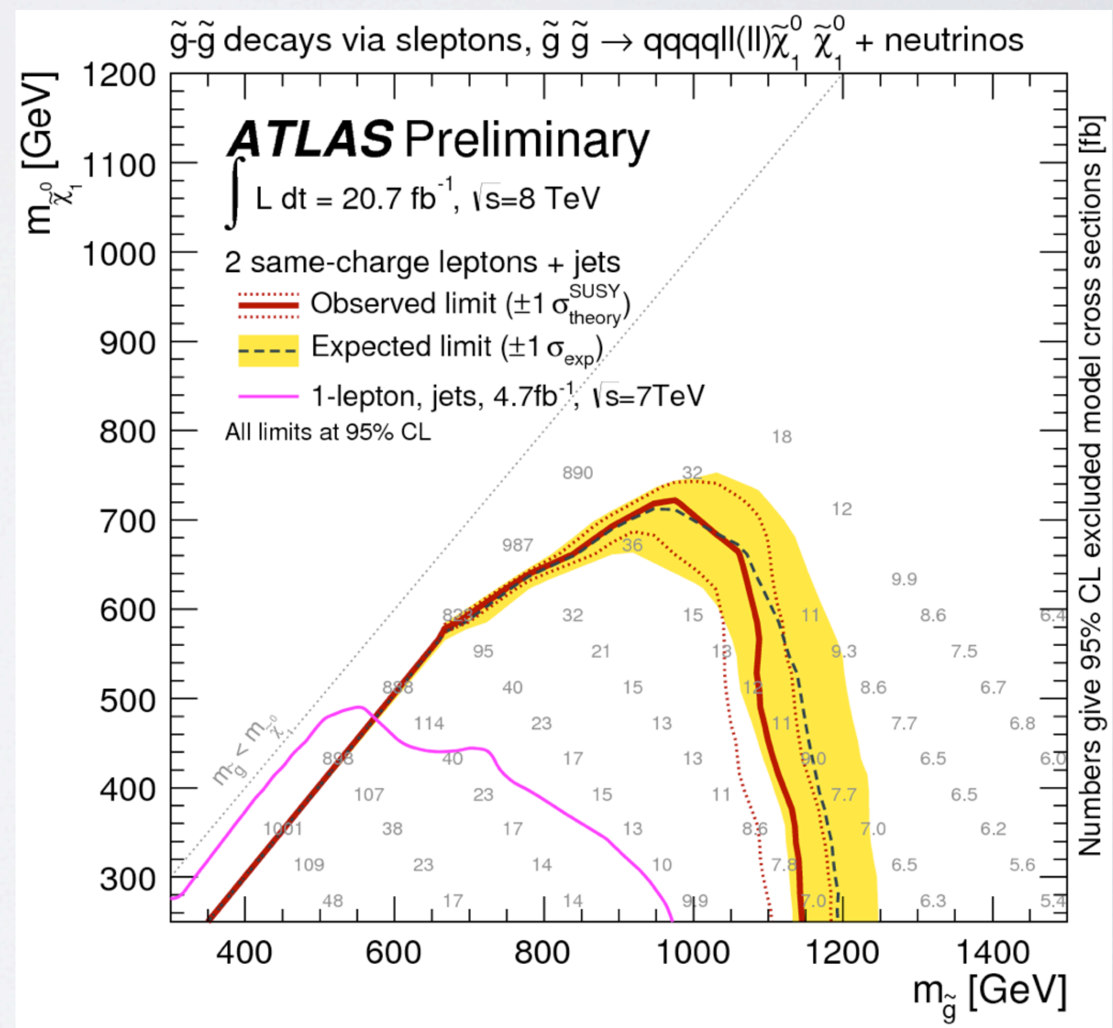
gluino pair



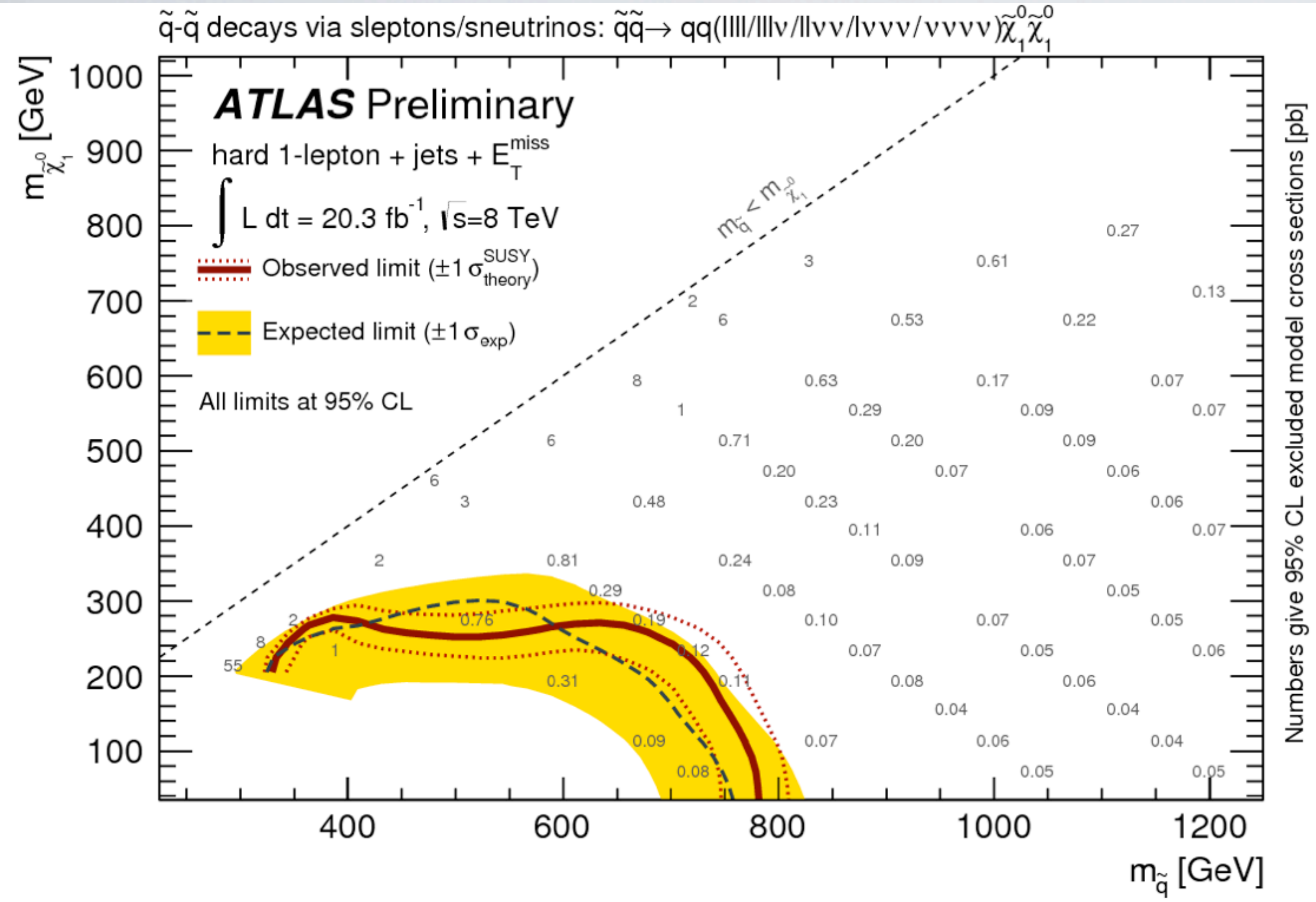
ATLAS-CONF-2013-007

Discussed by David Côté
on gluino-mediated 3rd gen.

2L Same Sign+0-3 b-jets+MET

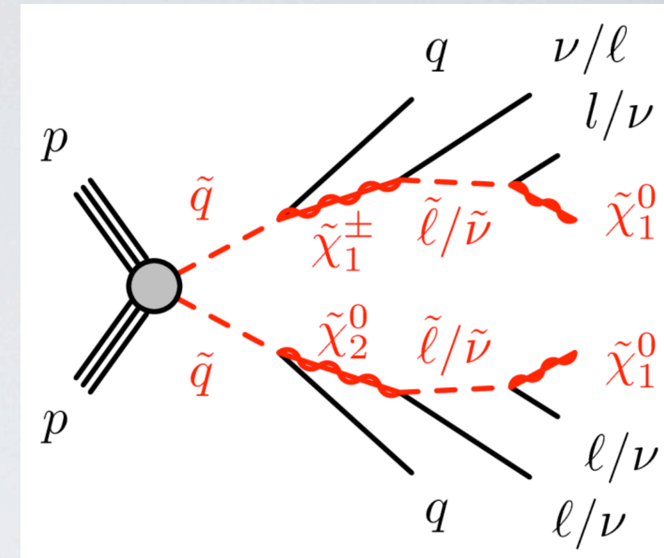


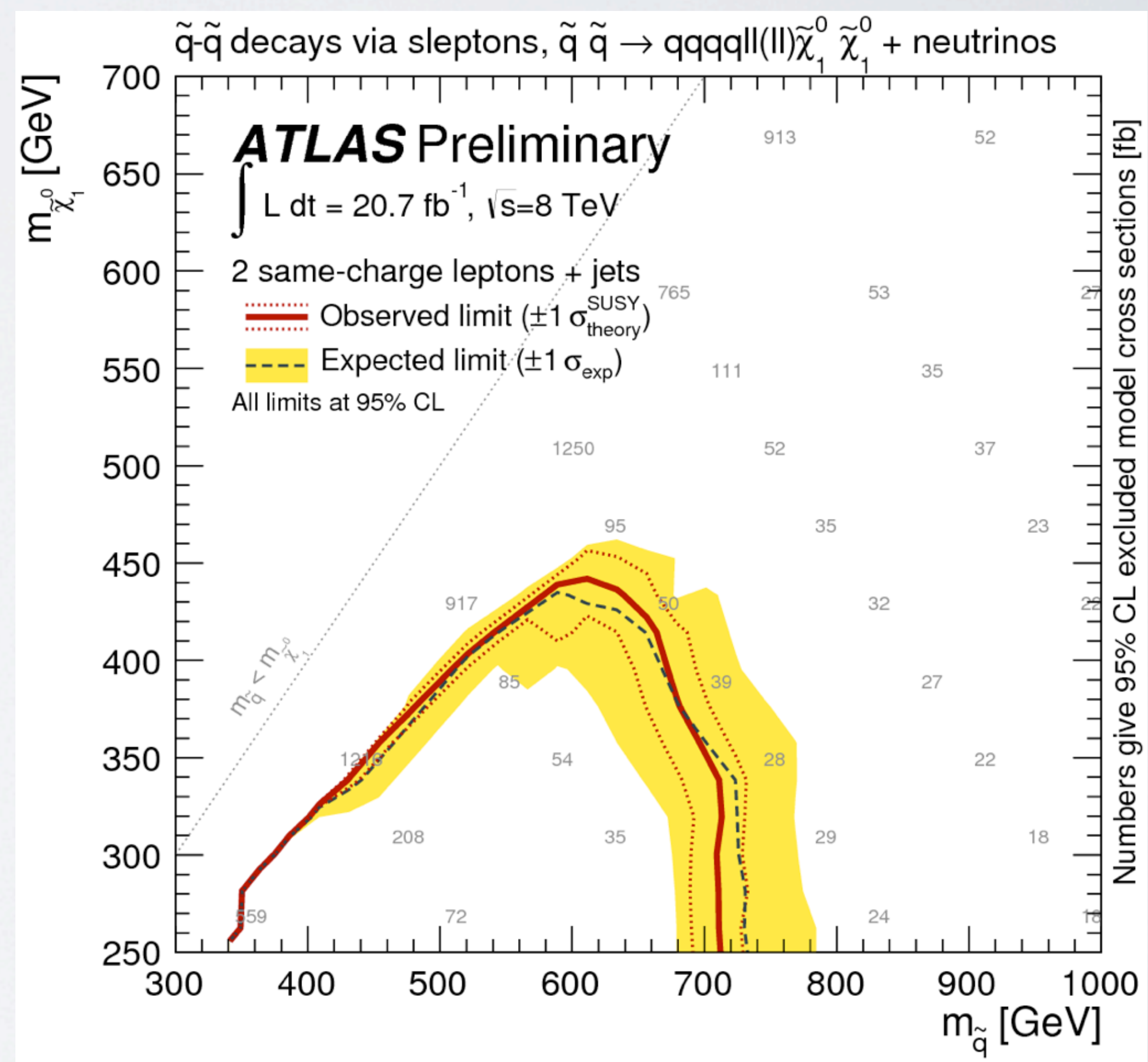
SIMP. MODELS: SQUARK VIA SLEPTON



1/2L+2-6J+MET

squark pair





ATLAS-CONF-2013-007

Discussed by David Côté on gluino-mediated 3rd gen.

2L Same Sign+0-3 b-jets+MET

COMBINED FIT METHOD

- Combined Fit Method:
  - (1) Take shape of variable (MET,MT) distributions from Monte Carlo
  - (2) Combine all backgrounds in a likelihood model with free normalization parameters for dominant backgrounds
  - (3) Select signal-free *control* regions and fit model to data
  - (4) Extrapolate to signal regions using MC shape and fitted normalizations
  - (5) Systematic experimental/theoretical uncertainties included as Gaussian constraints
  - (6) Systematics can be constrained if enough information in fit → "profiling"
  - (7) MC statistical uncertainties can be included as Poisson errors
  - (8) Signal can be included in signal regions for exclusion
  - (9) Shape information (binned fit) easily added for better discriminating power
  - (10) Statistically independent *validation* regions used to cross check SM predictions/extrapolation with data

- Combining all useful information into a global Likelihood:

$$\boxed{L(\mathbf{n}|s,\mathbf{b},\boldsymbol{\theta}) = P_{\mathrm{S}} \times P_{\mathrm{W}} \times P_{\mathrm{T}} \times C_{\mathrm{Syst}},}$$

  - **n** = number of observed events
  - **s** = SUSY signal to be tested
  - **b** = background normalization parameters, shared between all fit regions
  - **θ** = systematic uncertainties, treated as nuisance parameters with a Gaussian constraint
  - **$P_{S\,(W,T)}$** = (Poisson) probability density functions (pdfs) for event counts in signal/control regions
  - **C_{Syst}** = constraints on systematic uncertainties, proper treatment of correlations
- Simultaneous fit of multiple control (+signal) regions normalizes the backgrounds (and signal)

SIGNAL REGIONS 1L + 2-6J + MET

- Hard 1 lepton *signal* regions, pT(lep) > 25 GeV:
  - 3 jets / 5 jets / 6 jets + high MET + high MT + high Meff

ATLAS-CONF-2013-062

	inclusive (binned) hard single-lepton		
	3-jet	**5-jet**	**6-jet**
N_ℓ	1 (electron or muon)		
p_T^ℓ(GeV)	> 25		
$p_T{}^{\text{add. }\ell}$ (GeV)	< 10		
N_{jet}	≥ 3	≥ 5	≥ 6
$p_T{}^{\text{jet}}$(GeV)	> 80, 80, 30	> 80, 50, 40, 40, 40	> 80, 50, 40, 40, 40, 40
$p_T{}^{\text{add. jets}}$(GeV)	– (< 40)	– (< 40)	–
E_T^{miss} (GeV)	>500 (300)	>300	>350 (250)
m_T (GeV)	> 150	> 200 (150)	> 150
$E_T^{\text{miss}}/m_{\text{eff}}^{\text{excl}}$	> 0.3	–	–
$m_{\text{eff}}^{\text{incl}}$ (GeV)	> 1400 (800)		> 600

- Soft 1 lepton signal regions, **6**[μ]**(10**[e]**)** < pT(lep) < 25 GeV:
  - 3 jets / 5 jets + high MET + high MT
- Soft 2 muons signal region (target mUED):
  - high MET + high MT + Z-veto

	soft single-lepton		soft dimuon
	3-jet	**5-jet**	**2-jet**
N_ℓ	1 (electron or muon)		2 (muons)
p_T^ℓ(GeV)	[10,25] (electron) , [6,25] (muon)		[6,25]
$p_T{}^{\text{add. }\ell}$ (GeV)	< 7 (electron), < 6 (muon)		
$m_{\mu\mu}$ (GeV)	–	–	>15 and $\lvert m_{\mu\mu} - m_Z \rvert$ > 10
N_{jet}	[3,4]	≥ 5	≥ 2
$p_T{}^{\text{leading jet}}$(GeV)	> 180		>70
$p_T{}^{\text{subleading jets}}$(GeV)	> 25		
$N_{b-\text{tag}}$	–	–	0
E_T^{miss} (GeV)	>400	>300	>170
m_T (GeV)	> 100		> 80
$E_T^{\text{miss}}/m_{\text{eff}}^{\text{incl}}$	> 0.3		–
ΔR_{min}(jet, ℓ)	> 1.0	–	> 1.0

Example: 3 jets, after fit

SIGNAL REGIONS 0L + 2-10J + MET

ATLAS-CONF-2013-047

- Five inclusive channels based on jet multiplicity - 2-6 jets - optimized for squark/gluino pair (mixed) production
  - Up to three signal regions for each channel based on tighter meff cuts

    → TOTAL: *10* signal regions (SR)

Requirement	Channel									
	A (2-jets)		B (3-jets)		C (4-jets)		D (5-jets)	E (6-jets)		
	L	M	M	T	M	T	–	L	M	T
E_T^{miss}[GeV] >	160									
$p_T(j_1)$ [GeV] >	130									
$p_T(j_2)$ [GeV] >	60									
$p_T(j_3)$ [GeV] >	–		60		60		60	60		
$p_T(j_4)$ [GeV] >	–		–		60		60	60		
$p_T(j_5)$ [GeV] >	–		–		–		60	60		
$p_T(j_6)$ [GeV] >	–		–		–		–	60		
$\Delta\phi(\text{jet}_i, \mathbf{E}_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, (3 \text{ if } p_T(j_3) > 40 \text{ GeV})\}$)				0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_T > 40$ GeV jets)					
$E_T^{miss}/m_{eff}(Nj)$ >	0.2	–[a]	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
m_{eff}(incl.) [GeV] >	1000	1600	1800	2200	1200	2200	1600	1000	1200	1500

ATLAS-CONF-2013-054

- Signal regions defined by:
  - jet multiplicity (7 - ≥10 jets)
    - b-tagged jet multiplicity
    - MJΣ = mass of large-radius jet
  - MET/√HT > 4 √GeV

    → TOTAL *19* signal regions

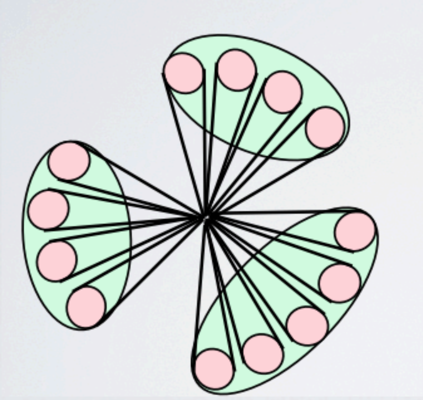
	Multi-jet + flavour stream					Multi-jet + M_J^Σ stream		
Identifier	**8j50**	**9j50**	**≥ 10j50**	**7j80**	**≥ 8j80**	**≥ 8j50**	**≥ 9j50**	**≥ 10j50**
Jet $\lvert\eta\rvert$	< 2.0			< 2.0		< 2.8		
Jet p_T	> 50 GeV			> 80 GeV		> 50 GeV		
Jet count	$= 8$	$= 9$	≥ 10	$= 7$	≥ 8	≥ 8	≥ 9	≥ 10
b-jets ($p_T > 40$ GeV, $\lvert\eta\rvert < 2.5$)	0 | 1 | ≥ 2	0 | 1 | ≥ 2	—	0 | 1 | ≥ 2	0 | 1 | ≥ 2	—		
M_J^Σ [GeV]	—			—		> 340 and > 420 for each case		
$E_T^{miss}/\sqrt{H_T}$	> 4 GeV$^{1/2}$			> 4 GeV$^{1/2}$		> 4 GeV$^{1/2}$		

Example: 3 jets, after fit

LARGE-RADIUS JET MASS

- Highly boosted particles expected to form large-radius ('composite') massive jets

ATLAS-CONF-2013-054



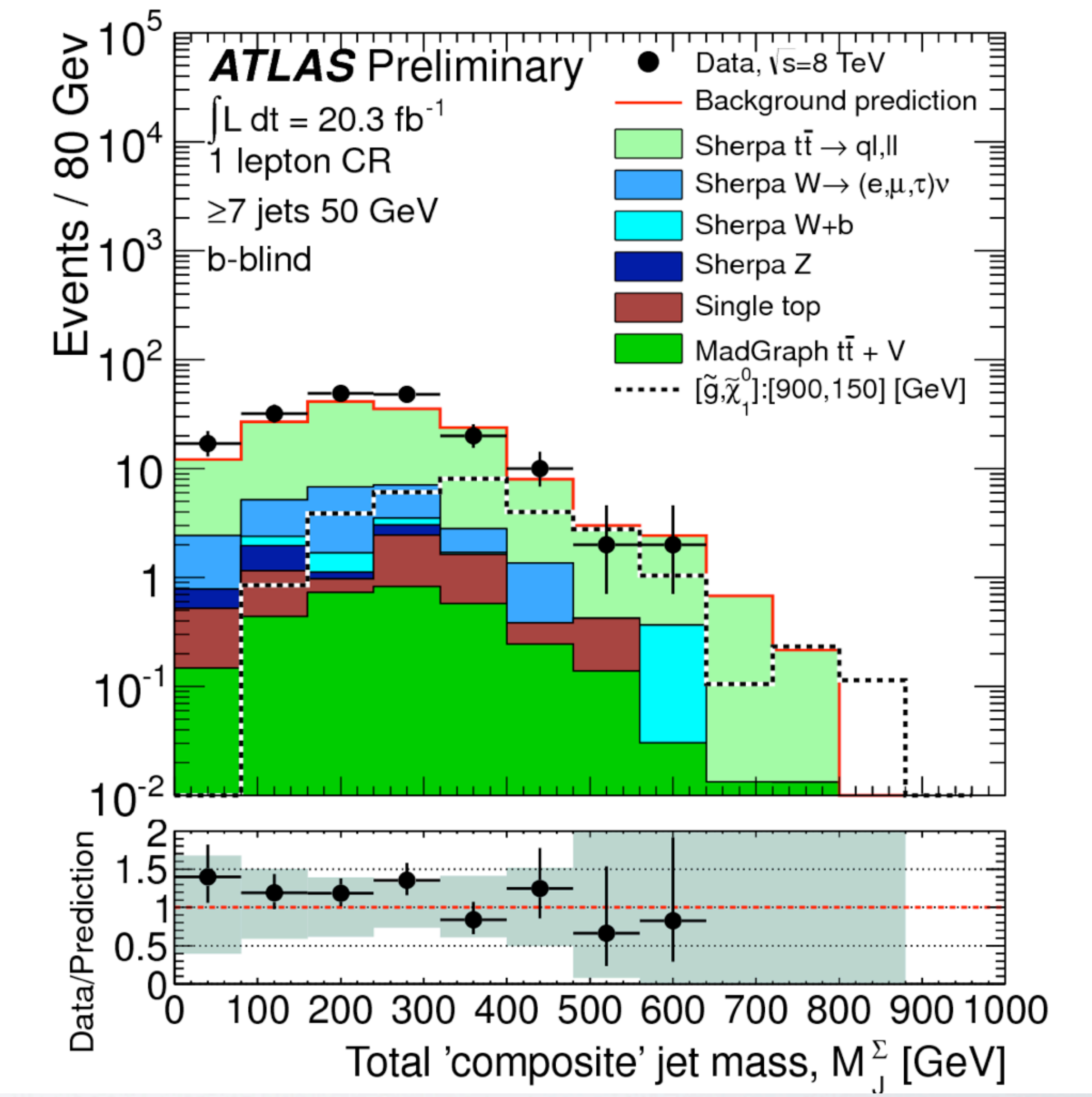
- Form large radius (R=1.0) anti-*kt* jets from nominal R=0.4 jets
- MJΣ = sum of the masses of composite jets:

$$M_J^{\Sigma} \equiv \sum_j m_j^{R=1.0}$$

  - pT(R=1.0 jet) > 100 GeV
  - |eta (R=1.0 jet)| < 1.5

- ***Signal regions*** defined for two MJΣ thresholds:
  - MJΣ > 340 GeV
  - MJΣ > 420 GeV
  - jet multiplicity - 8 / 9 / ≥10 jets - pT(jet) > 50 GeV

MJΣ shape
7 jets CR
0 b-tagged jets



RESULTS

- No significant excess in any signal region
- Data and estimated backgrounds used to set *model-independent* limits on visible BSM cross section
  - σ(vis) = σ(BSM) × Acceptance × efficiency
  - p0 = p(s=0) = p-value of background-only hypothesis

1/2L+2-6J+MET

	inclusive hard single-lepton					
	3-jet		5-jet		6-jet	
	electron	muon	electron	muon	electron	muon
Observed events	4	5	4	2	2	0
Fitted background events	3.9 ± 1.0	2.7 ± 0.9	3.6 ± 1.0	2.5 ± 0.8	2.0 ± 0.7	1.7 ± 0.6
Fitted $t\bar{t}$ events	1.4 ± 0.5	1.6 ± 0.5	2.7 ± 0.8	2.0 ± 0.7	1.3 ± 0.5	1.3 ± 0.5
Fitted W+jets events	0.9 ± 0.4	0.6 ± 0.5	0.11 ± 0.08	0.08 ± 0.08	0.00 ± 0.00	$0.07^{+0.15}_{-0.07}$
Fitted diboson events	0.8 ± 0.5	0.4 ± 0.2	0.7 ± 0.4	0.10 ± 0.05	0.06 ± 0.04	0.00 ± 0.00
Fitted misidentified lepton events	$0.15^{+0.17}_{-0.15}$	0.00 ± 0.02	0.00 ± 0.01	0.00 ± 0.01	0.00 ± 0.00	0.00 ± 0.00
Fitted other background events	0.6 ± 0.3	0.09 ± 0.05	0.12 ± 0.07	0.3 ± 0.1	0.7 ± 0.3	0.3 ± 0.1
MC expected SM events	4.2 ± 1.1	2.9 ± 1.0	3.6 ± 0.9	2.4 ± 0.7	2.1 ± 0.8	1.9 ± 0.7
MC expected $t\bar{t}$ events	1.3 ± 0.4	1.5 ± 0.4	2.6 ± 0.7	1.9 ± 0.6	1.4 ± 0.5	1.4 ± 0.5
MC expected W+jets events	1.3 ± 0.5	0.9 ± 0.7	0.2 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	$0.1^{+0.2}_{-0.1}$
MC expected diboson events	0.8 ± 0.5	0.4 ± 0.2	0.7 ± 0.4	0.10 ± 0.05	0.07 ± 0.04	0.00 ± 0.00
data-driven misidentified lepton events	$0.15^{+0.17}_{-0.15}$	0.00 ± 0.02	0.00 ± 0.01	0.00 ± 0.01	0.00 ± 0.00	0.00 ± 0.00
MC expected other background events	0.6 ± 0.3	0.09 ± 0.05	0.13 ± 0.07	0.3 ± 0.1	0.6 ± 0.3	0.3 ± 0.1

	soft single-lepton		soft dimuon
	3-jet	5-jet	2-jet
Observed events	7	9	7
Fitted background events	5.6 ± 1.6	14.8 ± 3.7	1.6 ± 1.0
Fitted $t\bar{t}$ events	1.3 ± 1.0	7.8 ± 3.3	1.2 ± 1.0
Fitted W+jets events	2.6 ± 0.7	2.1 ± 0.9	-
Fitted diboson events	0.6 ± 0.4	0.7 ± 0.4	0.4 ± 0.3
Fitted misidentified lepton events	$0.00^{+0.05}_{-0.00}$	3.3 ± 1.4	$0.0^{+0.3}_{-0.0}$
Fitted other background events	1.1 ± 0.5	0.9 ± 0.5	$0.01^{+0.06}_{-0.01}$
MC expected SM events	6.3 ± 1.9	15.9 ± 3.8	1.9 ± 1.2
MC expected $t\bar{t}$ events	1.4 ± 1.1	7.8 ± 3.0	1.5 ± 1.2
MC expected W+jets events	3.1 ± 0.9	3.2 ± 0.9	-
MC expected diboson events	0.6 ± 0.4	0.7 ± 0.4	0.4 ± 0.3
data-driven misidentified lepton events	$0.00^{+0.05}_{-0.00}$	3.3 ± 1.4	$0.0^{+0.3}_{-0.0}$
MC expected other background events	1.1 ± 0.6	0.9 ± 0.4	$0.01^{+0.06}_{-0.01}$

Signal channel	$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	S^{95}_{obs}	S^{95}_{exp}	CL_B	$p(s=0)$
soft single-lepton channels					
3-jet	0.40 (0.39)	8.1 (8.1)	$7.3^{+2.7}_{-1.8}$ $(6.8^{+3.3}_{-2.1})$	0.67 (0.66)	0.36 (0.31)
5-jet	0.35 (0.33)	7.1 (6.8)	$10.0^{+3.6}_{-3.0}$ $(9.8^{+4.2}_{-2.9})$	0.15 (0.15)	0.50 (0.50)
soft dimuon channel	0.57 (0.54)	11.5 (11.1)	$5.9^{+2.1}_{-1.0}$ $(6.5^{+3.1}_{-1.9})$	0.98 (0.92)	0.01 (0.02)
inclusive hard single-lepton channels					
3-jet (electron)	0.30 (0.28)	6.0 (5.7)	$5.7^{+2.2}_{-1.5}$ $(5.6^{+2.9}_{-1.8})$	0.56 (0.51)	0.48 (0.48)
3-jet (muon)	0.38 (0.37)	7.7 (7.5)	$5.1^{+2.0}_{-1.5}$ $(5.1^{+2.7}_{-1.7})$	0.89 (0.82)	0.13 (0.13)
5-jet (electron)	0.30 (0.29)	6.0 (5.9)	$5.4^{+2.3}_{-1.5}$ $(5.5^{+2.9}_{-1.7})$	0.60 (0.56)	0.43 (0.43)
5-jet (muon)	0.22 (0.21)	4.6 (4.2)	$4.7^{+1.9}_{-1.2}$ $(4.7^{+2.5}_{-1.6})$	0.44 (0.41)	0.50 (0.50)
6-jet (electron)	0.23 (0.22)	4.6 (4.4)	$4.4^{+1.9}_{-0.8}$ $(4.4^{+2.5}_{-1.5})$	0.56 (0.49)	0.50 (0.50)
6-jet (muon)	0.15 (0.12)	3.0 (2.5)	$4.1^{+1.3}_{-1.1}$ $(3.8^{+2.3}_{-1.3})$	0.13 (0.16)	0.50 (0.50)

0L+2-6J+MET

Signal Region	**D**	**E-loose**	**E-medium**	**E-tight**
MC expected events				
Diboson	2.0	5.5	1.7	0.0
Z/γ^*+jets	8.5	19.6	6.3	1.9
W+jets	4.8	23.1	5.2	0.8
$t\bar{t}$(+EW) + single top	5.0	67.3	16.8	1.5
Fitted background events				
Diboson	2.0 ± 2.0	5.5 ± 2.1	1.7 ± 0.8	–
Z/γ^*+jets	3.8 ± 2.5	12 ± 7	2.9 ± 2.6	0.4 ± 0.6
W+jets	3.3 ± 2.5	18 ± 7	4.9 ± 2.7	0.7 ± 0.5
$t\bar{t}$(+EW) + single top	5.8 ± 2.1	76 ± 19	20 ± 6	1.7 ± 1.4
Multi-jets	–	1.0 ± 1.0	–	–
Total bkg	15 ± 5	113 ± 21	30 ± 8	2.9 ± 1.8
Observed	18	166	41	5
$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	0.77	4.55	1.41	0.41
S^{95}_{obs}	15.5	92.4	28.6	8.3
S^{95}_{exp}	$13.6^{+5.1}_{-3.5}$	$57.3^{+20.0}_{-14.4}$	$21.4^{+7.6}_{-5.8}$	$6.5^{+3.0}_{-1.9}$
p_0 (Z_n)	0.32 (0.5)	0.03 (1.9)	0.14 (1.1)	0.22 (0.8)

Signal Region	**A-loose**	**A-medium**	**B-medium**	**B-tight**	**C-medium**	**C-tight**
MC expected events						
Diboson	428.6	15.0	4.3	0.0	25.5	0.0
Z/γ^*+jets	2044.4	83.1	20.6	2.3	119.4	2.6
W+jets	2109.0	58.8	16.4	2.1	88.7	1.0
$t\bar{t}$(+EW) + single top	785.9	8.2	2.0	0.3	45.9	0.3
Fitted background events						
Diboson	430 ± 190	15 ± 7	4.3 ± 2.0	–	26 ± 11	–
Z/γ^*+jets	1870 ± 320	57 ± 11	16 ± 5	0.2 ± 0.5	80 ± 29	$0.0^{+0.6}_{-0.0}$
W+jets	1540 ± 260	42 ± 11	10 ± 4	1.6 ± 1.2	55 ± 18	0.7 ± 0.9
$t\bar{t}$(+EW) + single top	870 ± 180	7.8 ± 2.8	2.2 ± 2.0	0.6 ± 0.7	50 ± 11	0.9 ± 0.9
Multi-jets	33 ± 33	–	0.1 ± 0.1	–	–	–
Total bkg	4700 ± 500	122 ± 18	33 ± 7	2.4 ± 1.4	210 ± 40	1.6 ± 1.4
Observed	5333	135	29	4	228	0
$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	66.07	2.52	0.73	0.33	4.00	0.12
S^{95}_{obs}	1341.2	51.3	14.9	6.7	81.2	2.4
S^{95}_{exp}	$1135.0^{+332.7}_{-291.5}$	$42.7^{+15.5}_{-11.4}$	$17.0^{+6.6}_{-4.6}$	$5.8^{+2.9}_{-1.8}$	$72.9^{+23.6}_{-18.0}$	$3.3^{+2.1}_{-1.2}$
p_0 (Z_n)	0.45 (0.1)	0.27 (0.6)	0.50 (0.0)	0.34 (0.4)	0.34 (0.4)	0.50 (0.0)

0L+7-10J+MET

Signal region	**8j50**	
M_J^{Σ} [GeV]	340	420
Observed events	69	37
Total events after fit	75 ± 19	45 ± 14
Fitted $t\bar{t}$	17 ± 11	16 ± 13
Fitted W+jets	$0.8^{+1.3}_{-0.8}$	$0.4^{+0.7}_{-0.4}$
Fitted others	$5.2^{+4.0}_{-2.5}$	$2.8^{+2.9}_{-1.6}$
Total events before fit	85	44
$t\bar{t}$ before fit	27	14
W+jets before fit	0.8	0.4
Others before fit	5	2.8
Multi-jets	52 ± 15	27 ± 7
$N^{95\%}_{\mathrm{BSM}}$ (exp)	40	23
$N^{95\%}_{\mathrm{BSM}}$ (obs)	35	20
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (exp) [fb]	1.9	1.1
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	1.7	1.0
p_0	0.60	0.7

Signal region	**9j50**		**10j50**	
M_J^{Σ} [GeV]	340	420	340	420
Observed events	13	9	1	1
Total events	17 ± 7	11 ± 5	$3.2^{+3.7}_{-3.2}$	2.2 ± 2.0
$t\bar{t}$	5 ± 4	$3.4^{+3.6}_{-3.4}$	$0.8^{+0.8}_{-0.8}$	$0.6^{+0.9}_{-0.6}$
W+jets	–	–	–	–
Others	$0.58^{+0.54}_{-0.33}$	$0.39^{+0.32}_{-0.30}$	0.12 ± 0.12	0.06 ± 0.06
Multi-jets	12 ± 4	7.0 ± 2.3	$2.3^{+3.6}_{-2.3}$	$1.6^{+1.8}_{-1.6}$
$N^{95\%}_{\mathrm{BSM}}$ (exp)	13	11	5	5
$N^{95\%}_{\mathrm{BSM}}$ (obs)	11	10	4	4
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (exp) [fb]	0.7	0.5	0.23	0.23
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	0.5	0.5	0.2	0.2
p_0	0.7	0.6	0.8	0.7

Signal region	**8j50**			**9j50**			**10j50**
b-jets	0	1	≥ 2	0	1	≥ 2	—
Observed events	40	44	44	5	8	7	3
Total events after fit	35 ± 4	40 ± 10	50 ± 10	3.3 ± 0.7	6.1 ± 1.7	8.0 ± 2.7	1.37 ± 0.35
Fitted $t\bar{t}$	2.7 ± 0.9	11.8 ± 3.0	23.0 ± 5.0	0.36 ± 0.18	1.5 ± 0.5	3.2 ± 1.1	$0.06^{+0.09}_{-0.06}$
Fitted W+jets	$2.0^{+2.6}_{-2.0}$	$0.62^{+0.81}_{-0.62}$	$0.20^{+0.28}_{-0.20}$	–	$0.24^{+0.65}_{-0.24}$	–	–
Fitted others	$2.9^{+1.8}_{-1.8}$	$1.7^{+1.5}_{-1.2}$	$2.8^{+2.3}_{-2.0}$	0.03 ± 0.03	0.38 ± 0.25	$0.40^{+0.60}_{-0.24}$	0.08 ± 0.08
Total events before fit	36	48	59	3.4	6.6	8.9	1.39
$t\bar{t}$ before fit	3.5	15	30	0.41	1.8	4	0.08
W+jets before fit	2.9	1.0	0.29	–	0.40	–	–
Others before fit	2.4	1.8	2.8	0.03	0.34	0.4	0.08
Multi-jets	27 ± 3	30 ± 10	26 ± 10	3.0 ± 0.6	4.0 ± 1.4	4.4 ± 2.2	1.23 ± 0.32
$N^{95\%}_{\mathrm{BSM}}$ (exp)	16	23	26	5	7	8	4
$N^{95\%}_{\mathrm{BSM}}$ (obs)	20	23	22	7	9	7	6
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (exp) [fb]	0.8	1.2	1.3	0.26	0.36	0.40	0.19
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	0.97	1.1	1.1	0.34	0.43	0.37	0.29
p_0	0.24	0.5	0.7	0.21	0.28	0.6	0.13

Signal region	**7j80**			**8j80**		
b-jets	0	1	≥ 2	0	1	≥ 2
Observed events	12	17	13	2	1	3
Total fitted events	11.0 ± 2.2	17 ± 6	25 ± 10	0.9 ± 0.6	1.5 ± 0.9	3.3 ± 2.2
Fitted $t\bar{t}$	$0.00^{+0.26}_{-0.00}$	5.0 ± 4.0	12 ± 9	$0.10^{+0.14}_{-0.10}$	$0.32^{+0.67}_{-0.32}$	$1.5^{+1.9}_{-1.5}$
Fitted W+jets	$0.07^{+0.38}_{-0.07}$	$0.29^{+0.37}_{-0.29}$	–	–	–	–
Fitted others	$1.9^{+1.1}_{-0.9}$	$0.71^{+0.31}_{-0.25}$	$2.6^{+1.7}_{-1.1}$	0.02 ± 0.02	0.02 ± 0.02	$0.32^{+0.36}_{-0.21}$
Total events before fit	11.7	16	23	0.8	1.8	3.3
$t\bar{t}$ before fit	0.34	4	10	0.08	0.6	1.5
W+jets before fit	0.46	0.29	–	–	–	–
Others before fit	1.8	0.89	3.0	0.02	0.02	0.35
Multi-jets	9.1 ± 1.6	11 ± 4	10 ± 4	0.75 ± 0.56	1.2 ± 0.5	1.4 ± 1.0
N^{95}_{BSM} (exp)	10	17	14	4	4	6
N^{95}_{BSM} (obs)	10	16	12	5	3.5	6
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (exp) [fb]	0.5	0.8	0.7	0.18	0.18	0.31
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	0.5	0.8	0.6	0.24	0.17	0.31
p_0	0.5	0.6	0.8	0.19	0.6	0.5

RESULTS - TRIMMED

- No significant excess in any signal region *(too much to discuss now)*
- Data and estimated backgrounds used to set *model-independent* limits on visible BSM cross section
  - No signal model used, in contrast to model interpretations *(next)*
  - σ(vis) < 0.12 fb (range between 0.12 - 66.07 fb)
    - σ(vis) = σ(BSM) × Acceptance × efficiency
  - p0 = p(s=0) = p-value of background-only hypothesis

1/2L+2-6J+MET

	inclusive hard single-lepton					
	3-jet		5-jet		6-jet	
	electron	muon	electron	muon	electron	muon
Observed events	4	5	4	2	2	0
Fitted background events	3.9 ± 1.0	2.7 ± 0.9	3.6 ± 1.0	2.5 ± 0.8	2.0 ± 0.7	1.7 ± 0.6

	soft single-lepton		soft dimuon
	3-jet	5-jet	2-jet
Observed events	7	9	7
Fitted background events	5.6 ± 1.6	14.8 ± 3.7	1.6 ± 1.0

Signal channel	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$[fb]	$p(s=0)$
inclusive hard single-lepton channels		
3-jet (electron)	0.30 (0.28)	0.48 (0.48)
3-jet (muon)	0.38 (0.37)	0.13 (0.13)
5-jet (electron)	0.30 (0.29)	0.43 (0.43)
5-jet (muon)	0.22 (0.21)	0.50 (0.50)
6-jet (electron)	0.23 (0.22)	0.50 (0.50)
6-jet (muon)	0.15 (0.12)	0.50 (0.50)
soft single-lepton channels		
3-jet	0.40 (0.39)	0.36 (0.31)
5-jet	0.35 (0.33)	0.50 (0.50)
soft dimuon channel	0.57 (0.54)	0.01 (0.02)

0L+2-6J+MET

Signal Region	A-loose	A-medium	B-medium	B-tight	C-medium	C-tight
Total bkg	4700 ± 500	122 ± 18	33 ± 7	2.4 ± 1.4	210 ± 40	1.6 ± 1.4
Observed	5333	135	29	4	228	0
$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$[fb]	66.07	2.52	0.73	0.33	4.00	0.12
p_0 (Z_n)	0.45 (0.1)	0.27 (0.6)	0.50 (0.0)	0.34 (0.4)	0.34 (0.4)	0.50 (0.0)

Signal Region	D	E-loose	E-medium	E-tight
Total bkg	15 ± 5	113 ± 21	30 ± 8	2.9 ± 1.8
Observed	18	166	41	5
$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$[fb]	0.77	4.55	1.41	0.41
p_0 (Z_n)	0.32 (0.5)	0.03 (1.9)	0.14 (1.1)	0.22 (0.8)

0L+7-10J+MET

Signal region	8j50	
M_J^Σ [GeV]	340	420
Observed events	69	37
Total events after fit	75 ± 19	45 ± 14
$\sigma^{95\%}_{\text{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	1.7	1.0
p_0	0.60	0.7

Signal region	9j50		10j50	
M_J^Σ [GeV]	340	420	340	420
Observed events	13	9	1	1
Total events	17 ± 7	11 ± 5	$3.2^{+3.7}_{-3.2}$	2.2 ± 2.0
$\sigma^{95\%}_{\text{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	0.5	0.5	0.2	0.2
p_0	0.7	0.6	0.8	0.7

Signal region	8j50			9j50			10j50
b-jets	0	1	≥ 2	0	1	≥ 2	—
Observed events	40	44	44	5	8	7	3
Total events after fit	35 ± 4	40 ± 10	50 ± 10	3.3 ± 0.7	6.1 ± 1.7	8.0 ± 2.7	1.37 ± 0.35
$\sigma^{95\%}_{\text{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	0.97	1.1	1.1	0.34	0.43	0.37	0.29
p_0	0.24	0.5	0.7	0.21	0.28	0.6	0.13

Signal region	7j80			8j80		
b-jets	0	1	≥ 2	0	1	≥ 2
Observed events	12	17	13	2	1	3
Total fitted events	11.0 ± 2.2	17 ± 6	25 ± 10	0.9 ± 0.6	1.5 ± 0.9	3.3 ± 2.2
$\sigma^{95\%}_{\text{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	0.5	0.8	0.6	0.24	0.17	0.31
p_0	0.5	0.6	0.8	0.19	0.6	0.5