SUSY searches at the LHC Run 2

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Seminar - Albert-Ludwig-Universität Freiburg
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Supersymmetry (SUSY)

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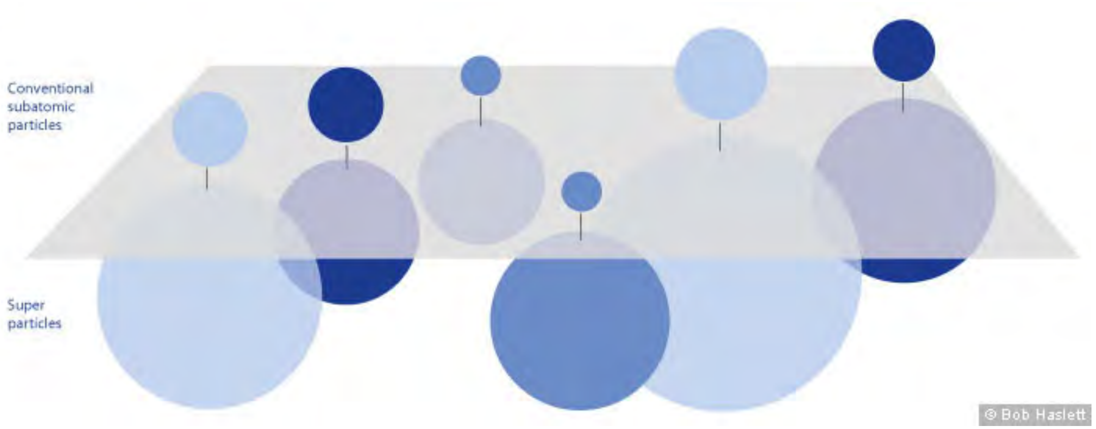
- SUSY is a hypothetical (broken) **symmetry** that relates bosons and fermions
  - a **new set of fields** differing in spin **by 1/2 w.r.t. the SM partners**



SUSY is not an exact symmetry

Sparticle masses ≠ particle masses

Minimal SUSY extension of SM (MSSM)

- Recipe: **supersymmetrise** the SM lagrangian, then **add SUSY breaking terms:**
  - $L_{SUSY} = L_{SUSY\ conserving} + L_{SUSY\ soft\ breaking}$

$$W \ni \frac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k + \mu_iL_iH_u$$

R-parity = $(-1)^{3(B-L)+2s}$
-1 for sparticles
1 for particles

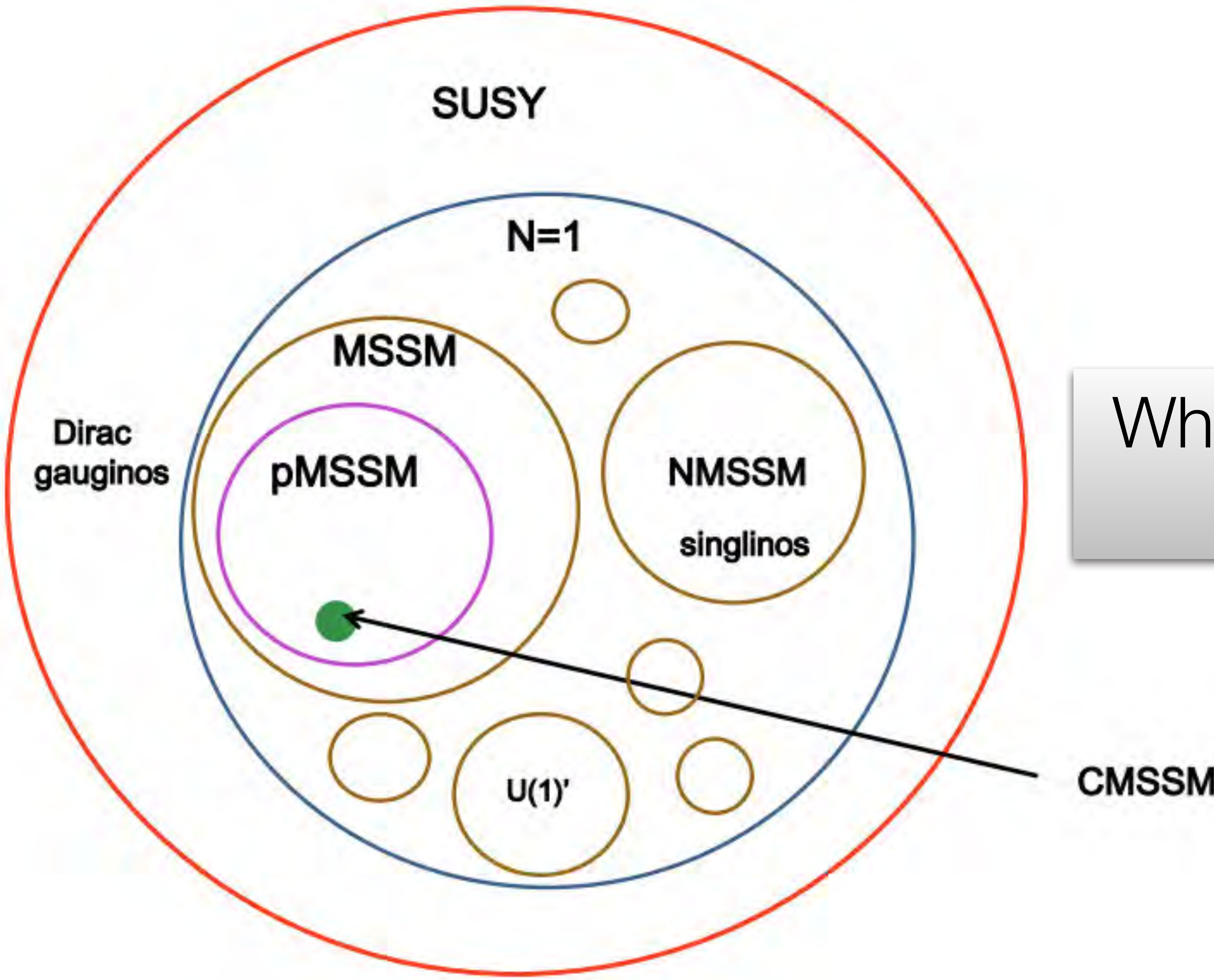
Lepton and baryon number violation allowed → proton decay
If R-parity conserved, the Lightest Supersymmetric Particle (LSP) is stable

MSSM parameters:

SUSY conserving sector	SUSY breaking sector
3 coupling constants for SU(3)xSU(2)sU(1)	5 3x3 hermitian mass matrices (one per EW multiplet)
4 Yukawa couplings per generation	3 complex 3x3 matrices (Higgs trilinear couplings to sfermions)
	3 mass terms for the Higgs sector + 2 additional off-diagonal terms
	Higgs VEV expectation angle β

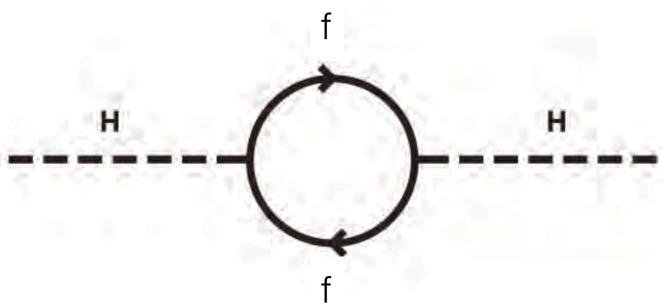
A total of 124 parameters: too much?

Beyond MSSM

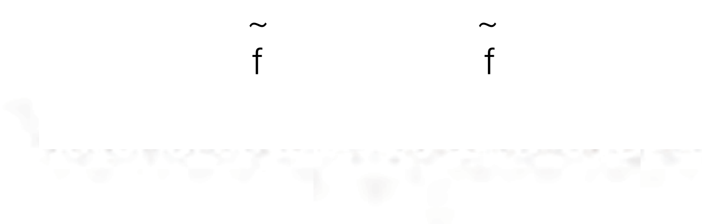


Why SUSY at the LHC energy scale?

Higgs boson mass stability in a nutshell



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



$$\Delta m_H^2 = 2 \times \frac{|\lambda_f|^2}{16\pi^2}\Lambda_{\rm UV}^2 + ...$$

Higgs mass has **a quadratic dependency** from physics at a higher scale

With SUSY, quadratic effects are cancelled exactly

Searching for EW scale SUSY?

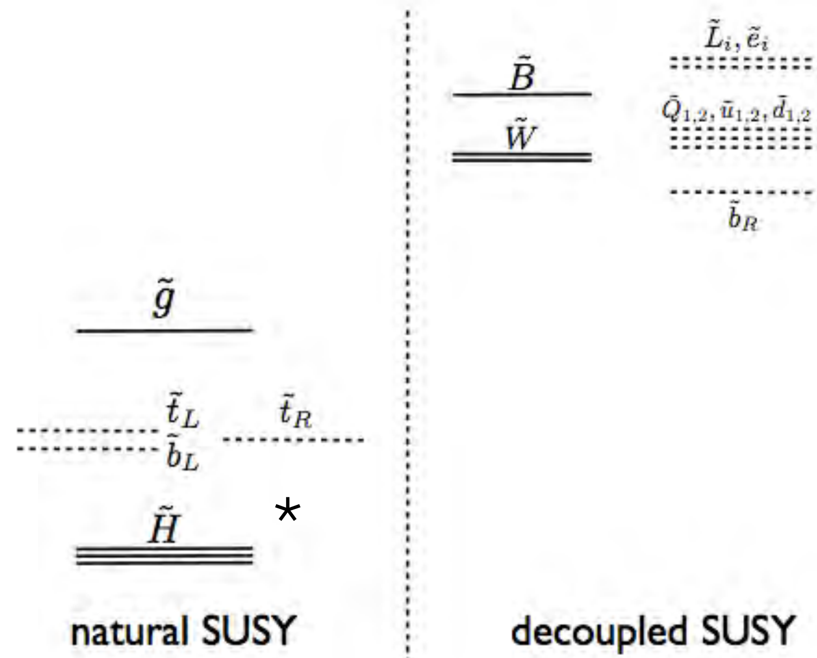
- Residual logarithmic corrections set a **(rough and subjective)** scale of **~ TeV** for the mass of **some** SUSY particles

More of **a guideline** than an actual upper limit.

Superpartners of quarks and gluons have **large production cross sections** at LHC

Strong **pre-LHC** expectation for **"fast" discovery** of squarks and gluinos at LHC

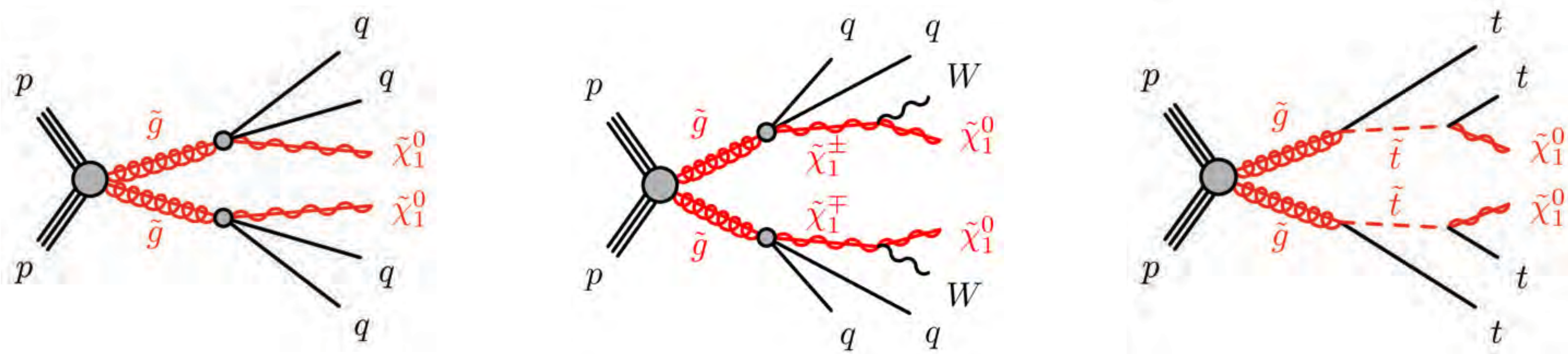
M.Papucci, J.Ruderman, A. Weiler



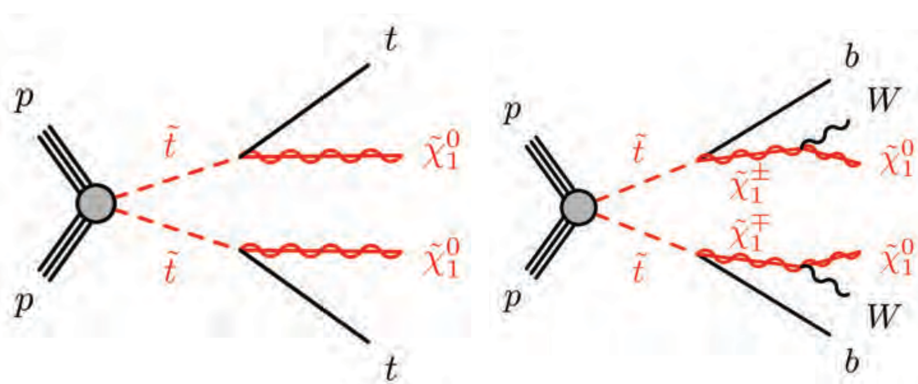
* This implies two light neutralinos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and one chargino $\tilde{\chi}_1^\pm$

What do we expect to measure?

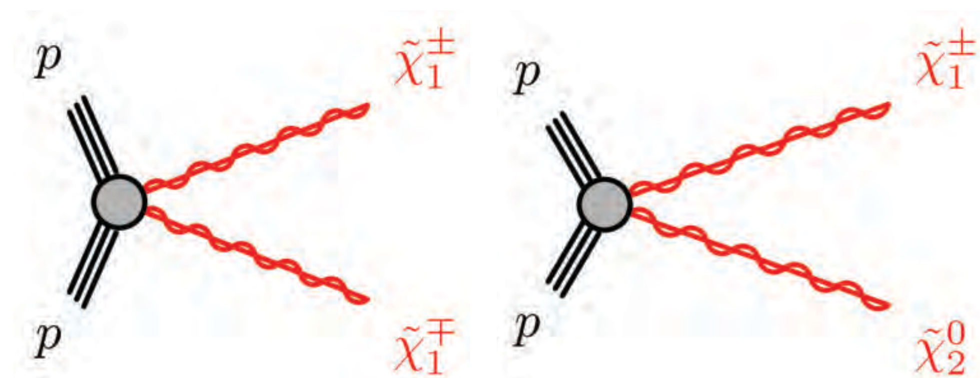
Gluino pair production



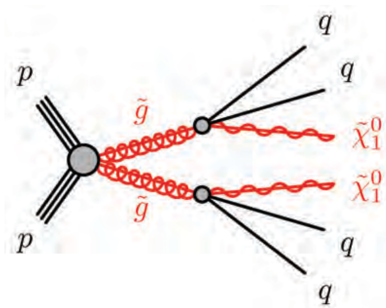
Stop pair production



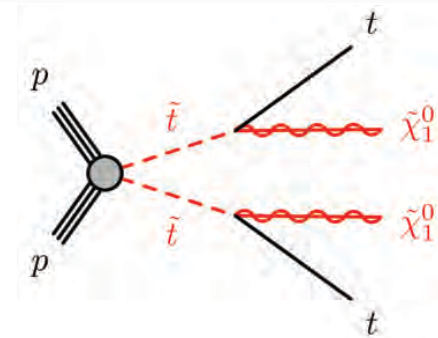
Higgsino pair production



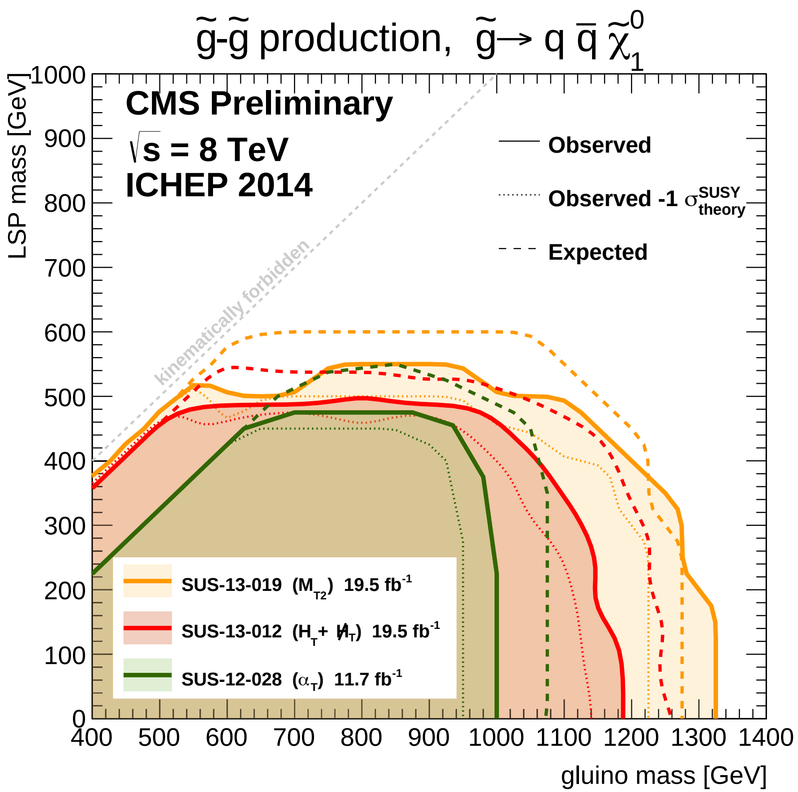
But…



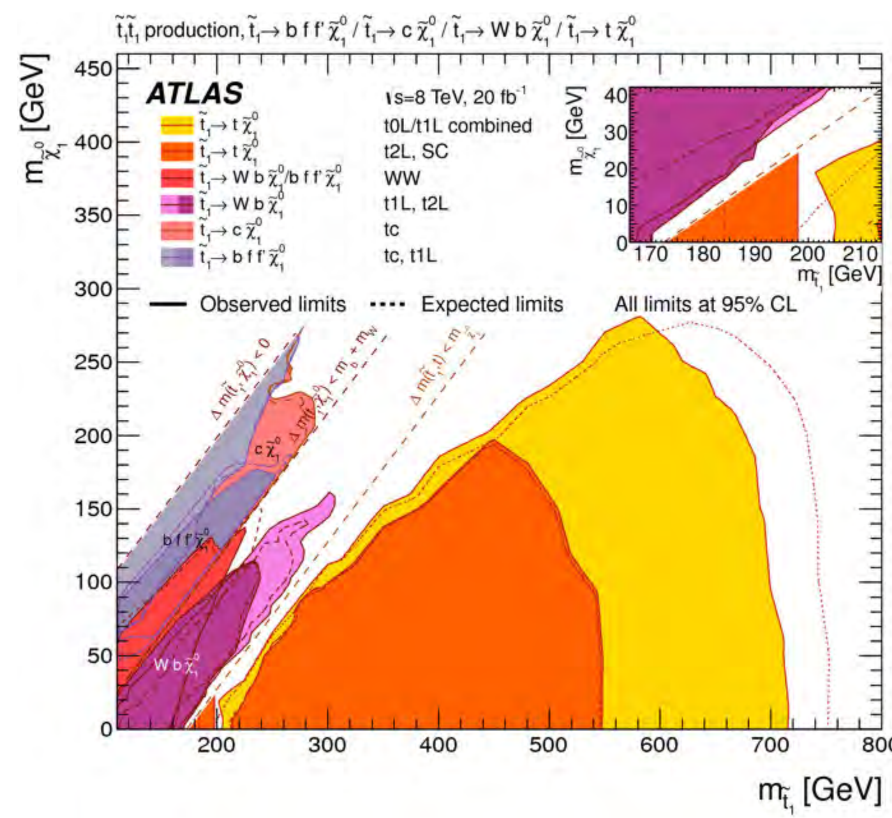
p
p
q
q
q
q



p
p
t
t



g̃-g̃ production, g̃→ q q̄ χ̃$_1^0$
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ$^{SUSY}_{theory}$
Expected
kinematically forbidden
SUS-13-019 (M$_{T2}$) 19.5 fb^{-1}
SUS-13-012 (H$_T$+ H̸$_T$) 19.5 fb^{-1}
SUS-12-028 (α$_T$) 11.7 fb^{-1}
LSP mass [GeV]
gluino mass [GeV]



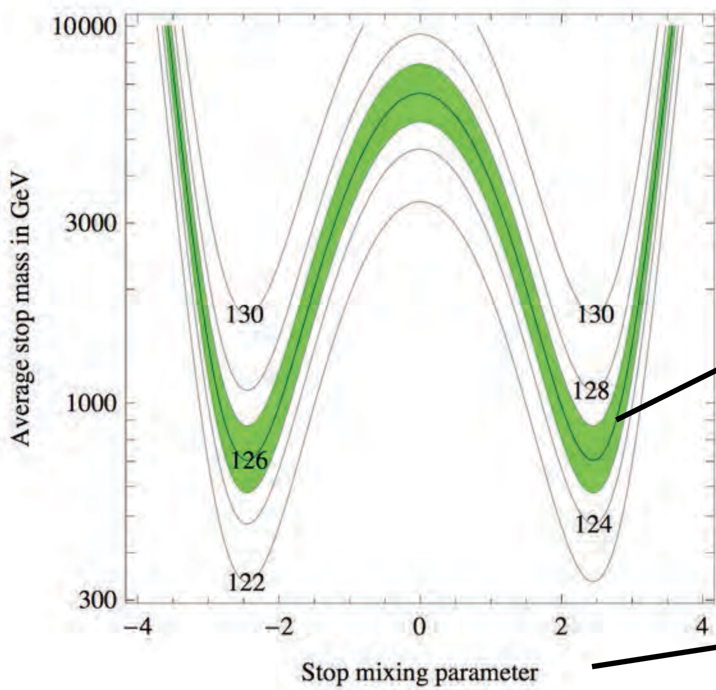
t̃$_1$t̃$_1$ production, t̃$_1$→ b f f' χ̃$_1^0$ / t̃$_1$→ c χ̃$_1^0$ / t̃$_1$→ W b χ̃$_1^0$ / t̃$_1$→ t χ̃$_1^0$
ATLAS
√s=8 TeV, 20 fb^{-1}
t0L/t1L combined
t2L, SC
WW
t1L, t2L
tc
tc, t1L
Observed limits
Expected limits
All limits at 95% CL
m$_{\tilde\chi_1^0}$ [GeV]
m$_{\tilde t_1}$ [GeV]

But…

- The Higgs boson mass is a bit on the "high" side for the MSSM

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$

This is M_S in the formula



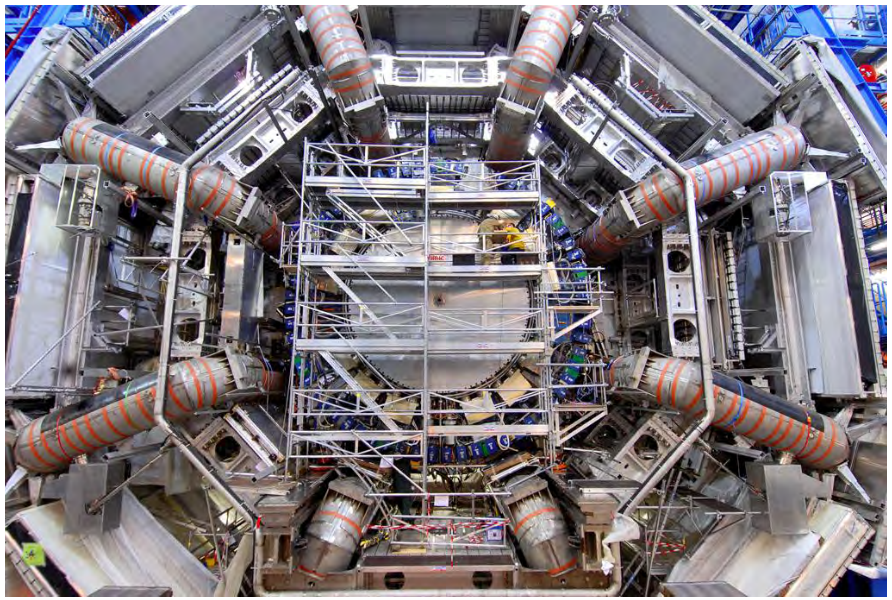
In green the allowed band for m_h = 125 GeV (actually 126, the paper is a bit old)

This is X_t in the formula

From arXiv:1212.6847

Experimental setup

ATLAS and CMS

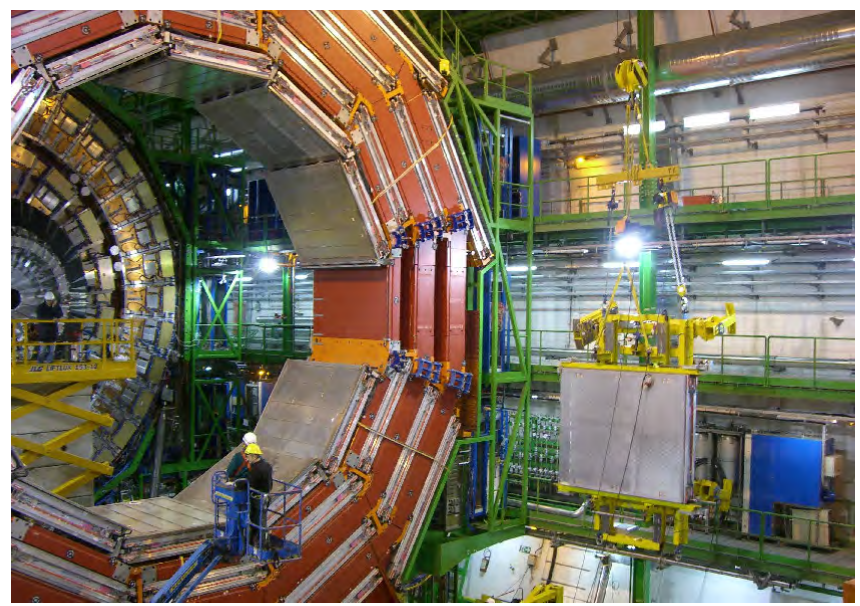


ATLAS

- high-granularity “pointing” EM calorimeter
- good resolution for hadronic calorimetry
- good tracking in ID and muon spectrometer

CMS

- high-resolution EM calorimeter
- excellent tracking performance in ID and muon spectrometer, heavily used for jet and MET measurement as well



LHC - performance of the machine

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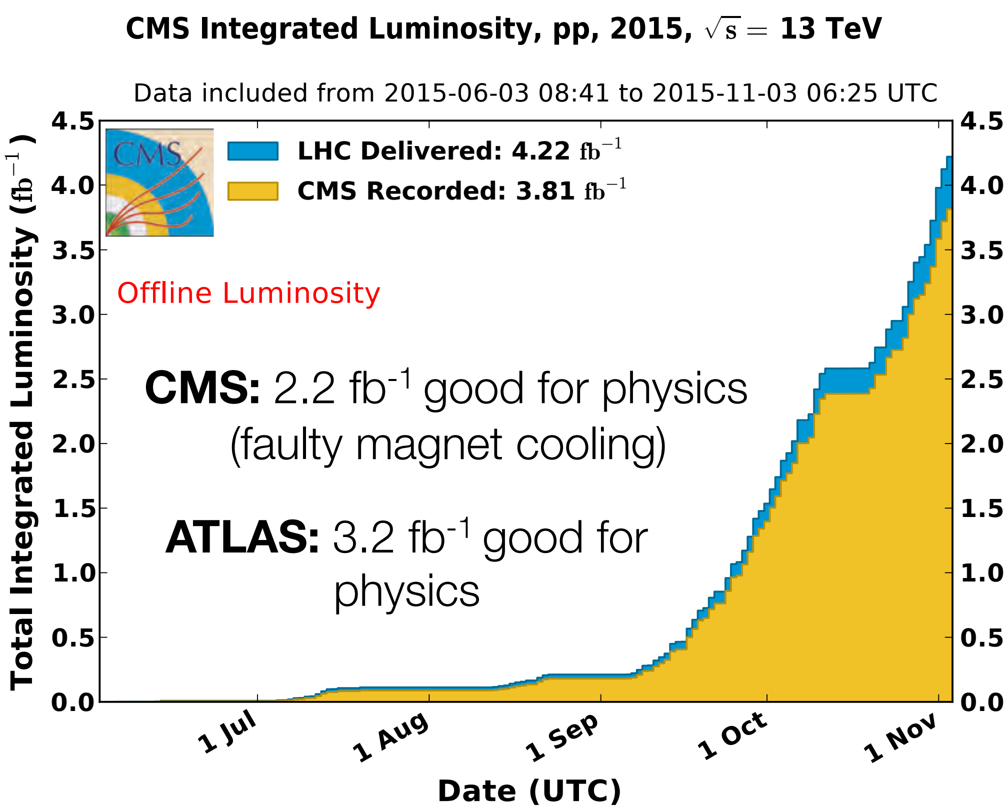
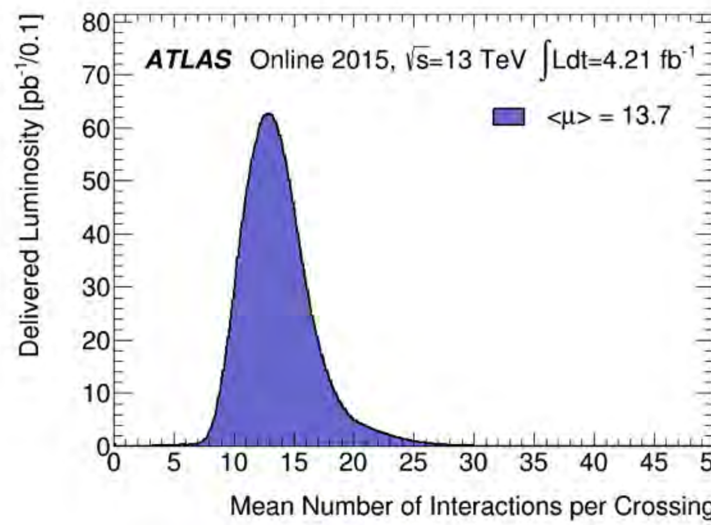
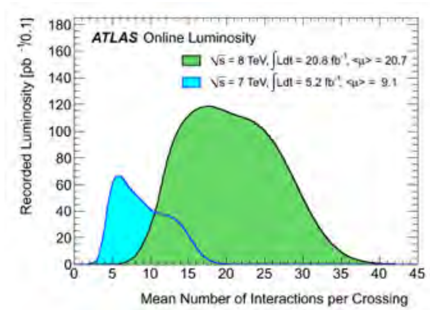


CMS: 2.2 fb^{-1} good for physics (faulty magnet cooling)

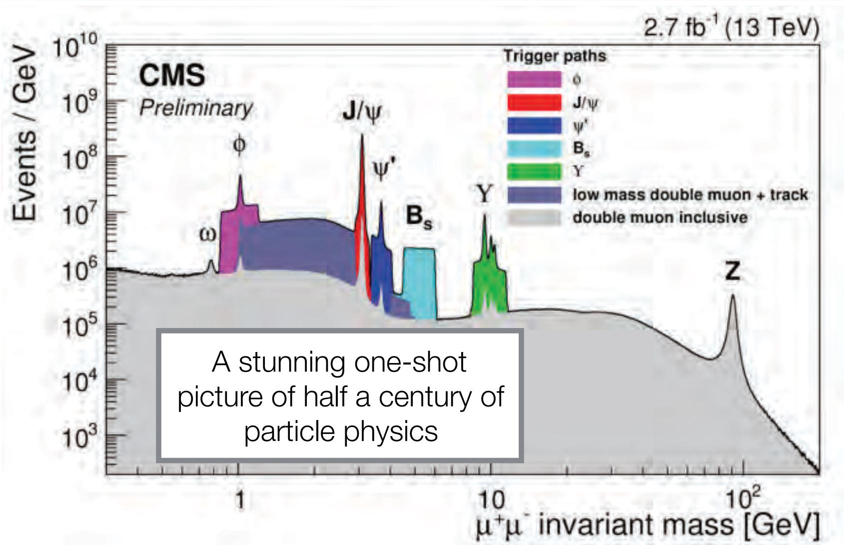
ATLAS: 3.2 fb^{-1} good for physics

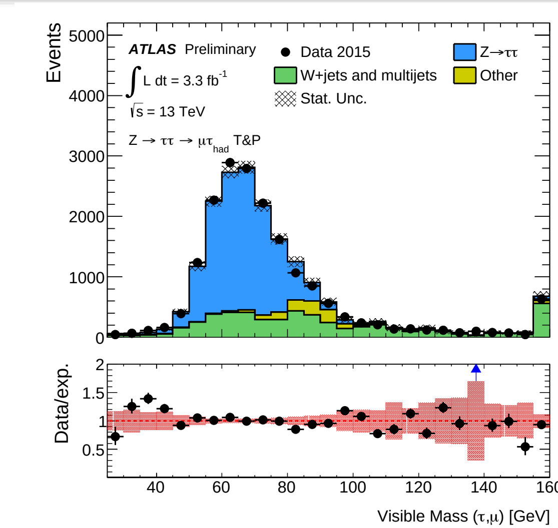


Pileup conditions more relaxed than at $\sqrt{s}$ = 8 TeV

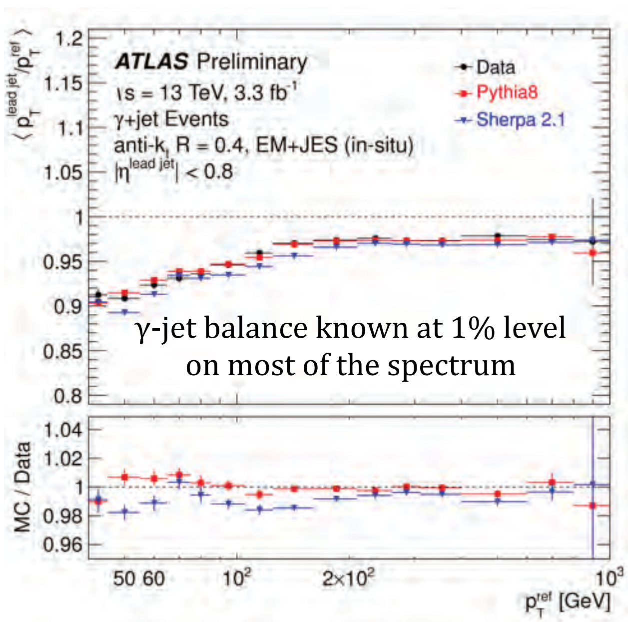


Detector performance

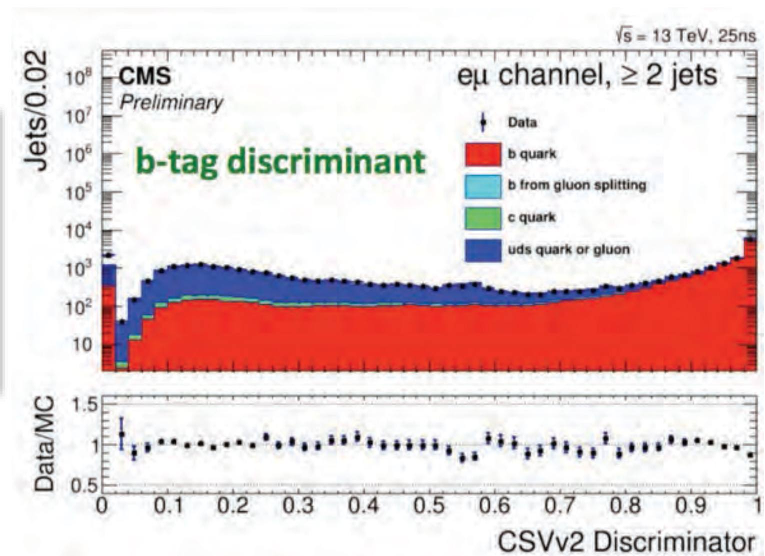


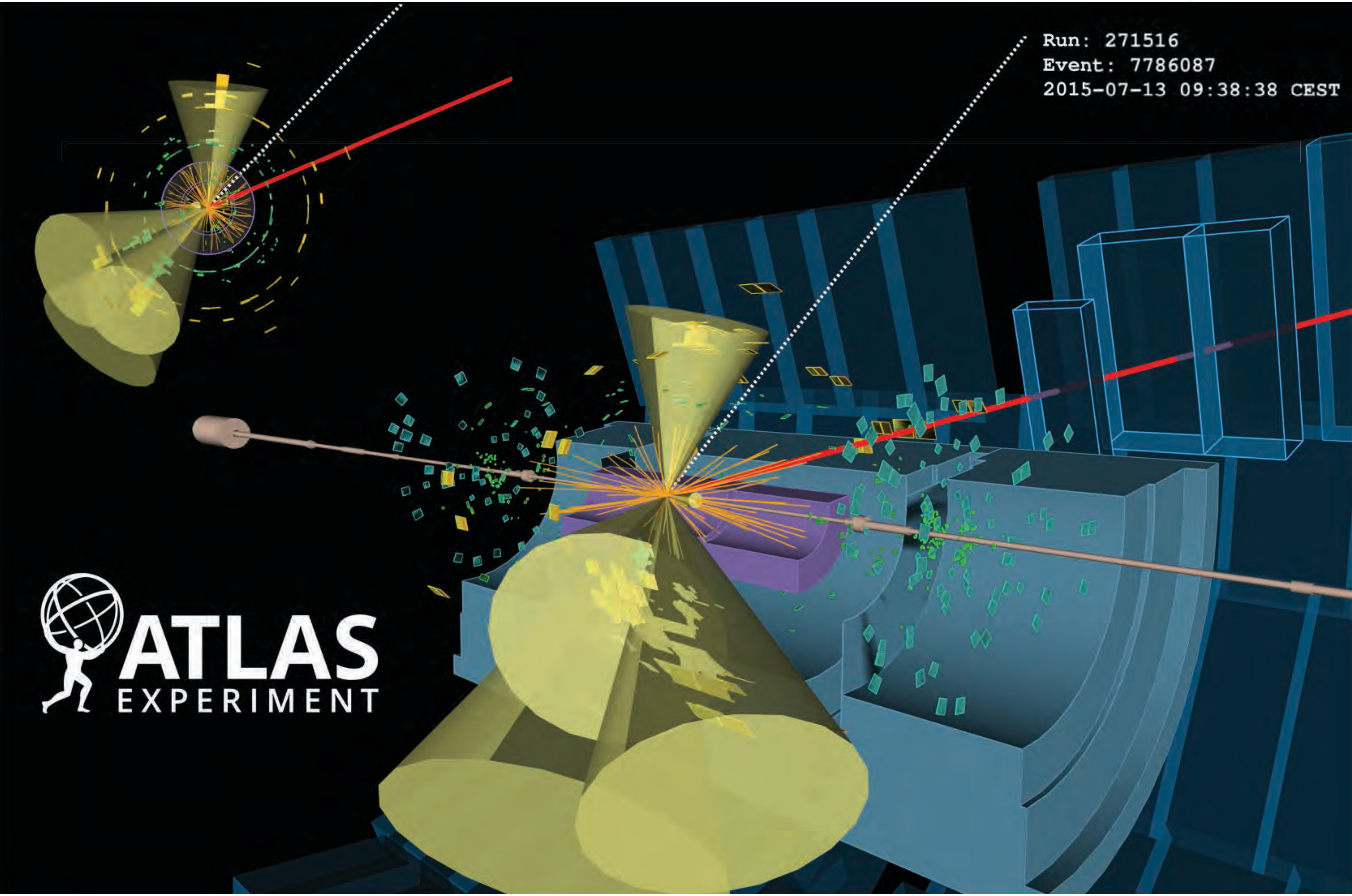


τ lepton performance cross-checked with the Z peak



Detector performance quickly **reached (and surpassed)** those of Run 1



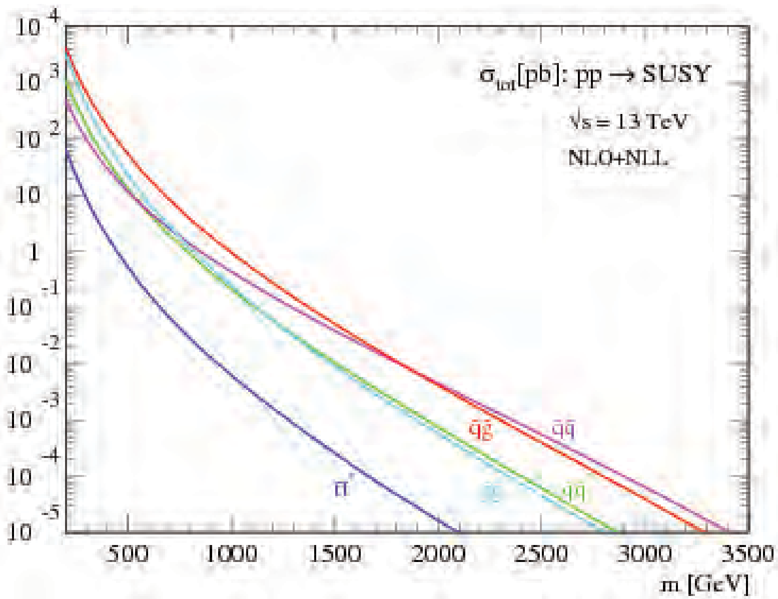

Run: 271516
Event: 7786087
2015-07-13 09:38:38 CEST
ATLAS
EXPERIMENT

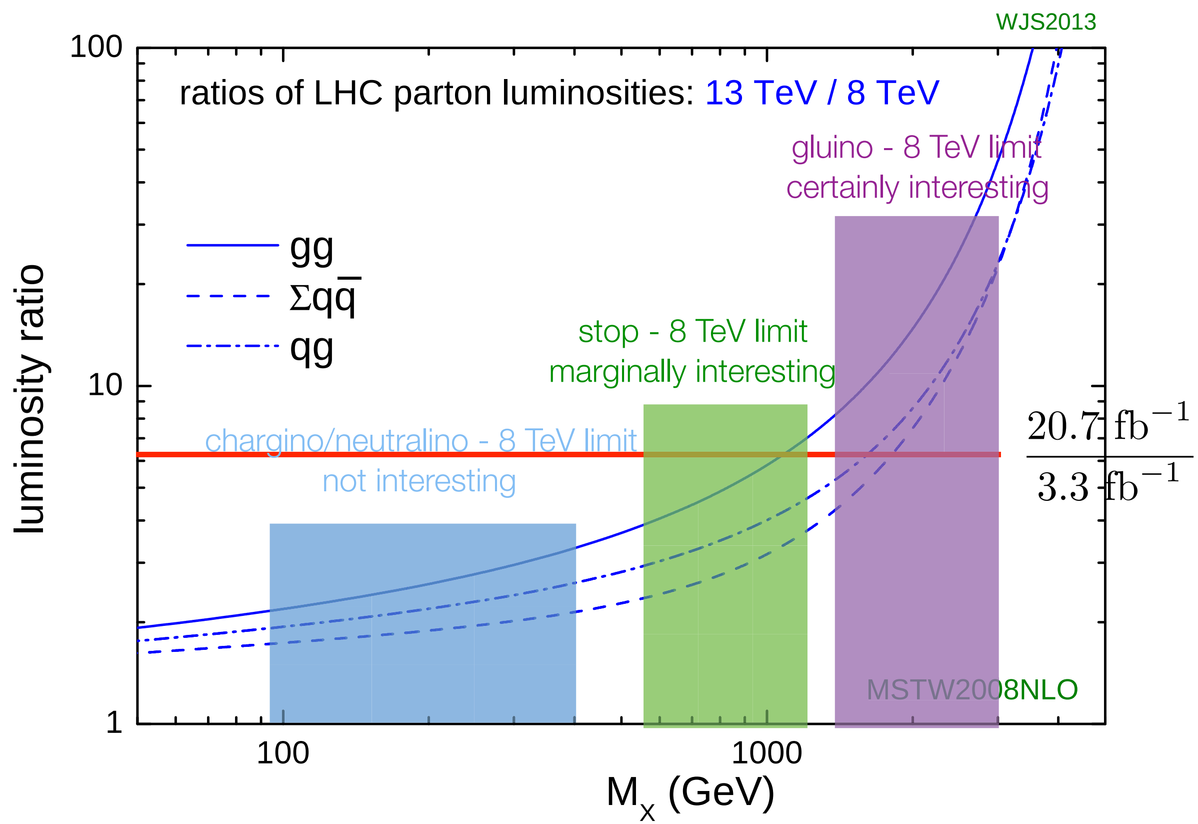
SUSY searches at 13 TeV

Is Run 2 better than Run 1?

Parton luminosities at $\sqrt{s}$ =13 TeV are **larger** than at $\sqrt{s}$=8 TeV

For **heavy final states** the new Run 2 dataset is **already beating Run 1**





(2 M_X for pair-produced particles)

The full list of analyses

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- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

conference notes

Short Title of preliminary conference note		Date	√s (TeV)	L (fb^{-1})	Document	Plots
0L 2-6 jets NEW	*	012/2015	13	3.2	ATLAS-CONF-2015-062	Link
0L 7-10 jets jets NEW		012/2015	13	3.2	ATLAS-CONF-2015-077	Link
1L + jets NEW		012/2015	13	3.2	ATLAS-CONF-2015-076	Link
2L Z+MET NEW	*	012/2015	13	3.2	ATLAS-CONF-2015-082	Link
SS/3L NEW	*	012/2015	13	3.2	ATLAS-CONF-2015-078	Link
multi b-jets NEW		012/2015	13	3.2	ATLAS-CONF-2015-067	Link
2b + MET NEW		012/2015	13	3.2	ATLAS-CONF-2015-066	Link

about 40 signal regions in total

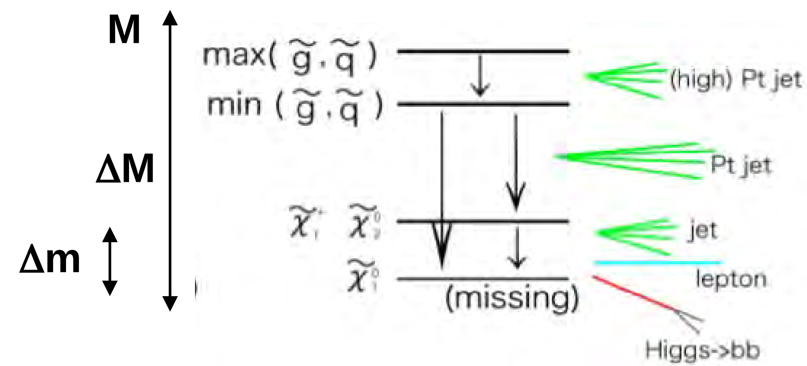
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LHC-Jamboree-2015/SUS.html

CMS-PAS-SUS-15-002	Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV	
CMS-PAS-SUS-15-003	Search for new physics in the all-hadronic final state with the M_{T2} variable	*
CMS-PAS-SUS-15-005	Search for new physics in final states with jets and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the α_T variable	
CMS-PAS-SUS-15-004	Inclusive search for supersymmetry using the razor variables at $\sqrt{s} = 13$ TeV	
CMS-PAS-SUS-15-007	Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV in the single-lepton final state using the sum of masses of large radius jets	*
CMS-PAS-SUS-15-008	Search for SUSY in same-sign dilepton events at $\sqrt{s} = 13$ TeV	
CMS-PAS-SUS-15-011	Search for new physics in final states with two opposite-sign same-flavor leptons, jets and E_T^{miss} in pp collisions at $\sqrt{s} =$ 13 TeV	*

about 400 signal regions in total

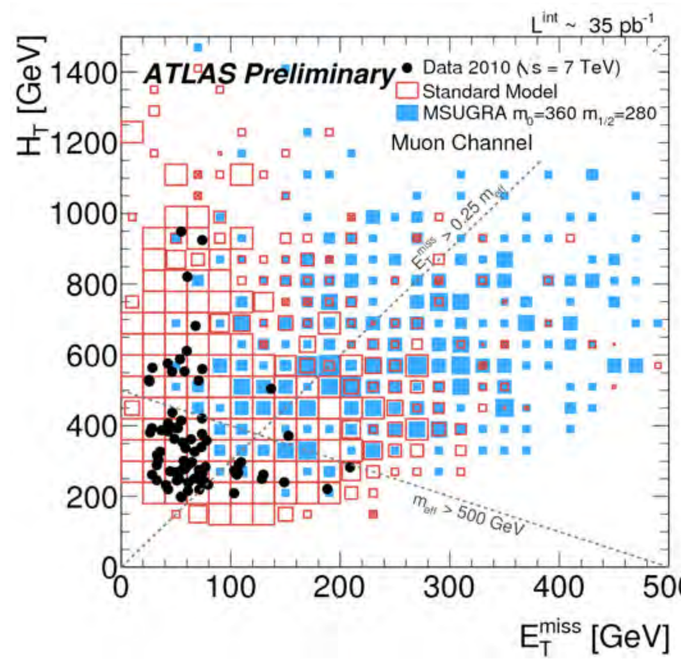
What we are typically doing

- Heavy sparticles produced in the primary collision
- They decay into lighter objects, emitting (high) P_T jets and possibly other objects (leptons, photons) and MET (LSP)
- A "typical" SUSY event will have large MET and large H_T
- Useful variables:

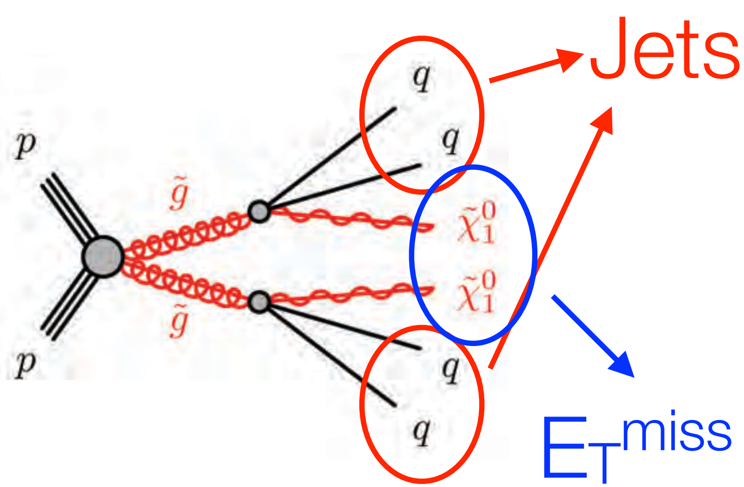


$$H_T = \sum_{jets} p_T^{jets} (+ \sum_{l} p_T^{l} + ...)$$

$$M_{eff} = E_T^{miss} + H_T$$

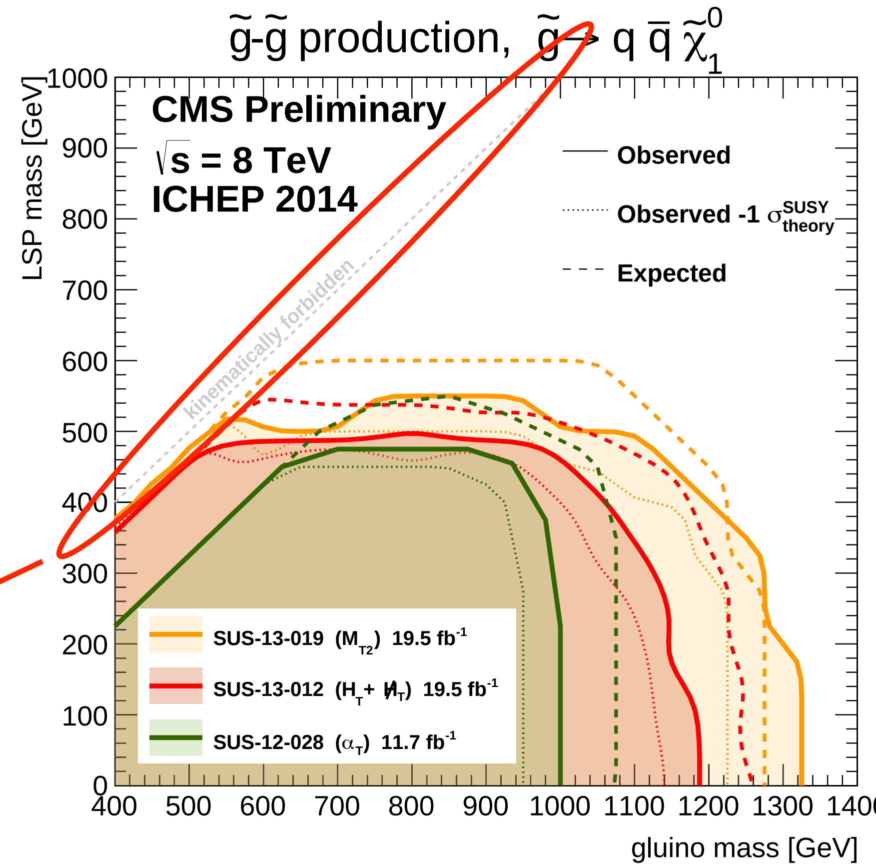


Intermezzo



Neutralinos and jets have low p_T, unless in presence of ISR

Compressed kinematics, **lower p_T** for quarks and neutralinos

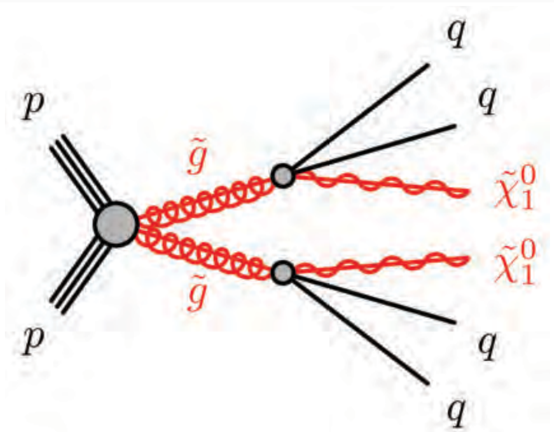


QCD production cross section quickly **decreases with the increasing mass** of the final state produced

Final object boost **increases**

CMS M_{T2} search

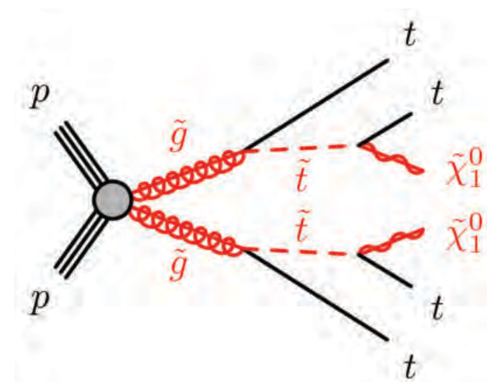
https://cds.cern.ch/record/2114816/files/SUS-15-003-pas.pdf



Underlying idea:
- Collect all hadronic decay products into two jets j1, j2.
- Then M_{T2}(j1,j2,E_T^{miss}) has an endpoint at m_{gluino}
- Typically $M_{T2} << m_{gluino}$ for the background

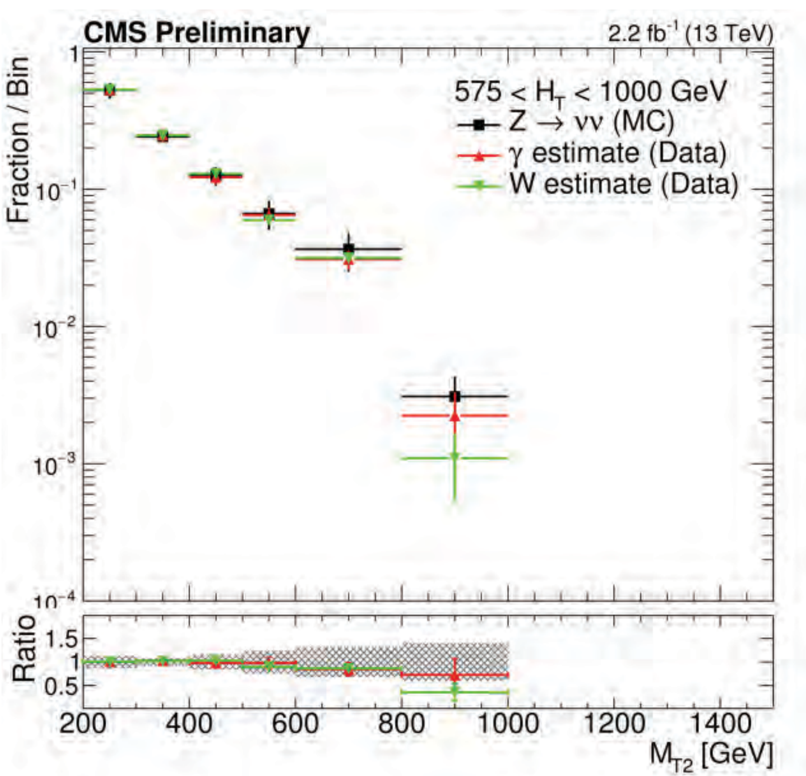
$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_T+\mathbf{r}_T=\mathbf{p}_T^{miss}} \left\{ \max[\, m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T)\,] \right\}$$

- About 250 signal regions classified according to N_{jet}, N_{bjet}, H_T (scalar sum of jet p_T), M_{T2}
- Background processes:
  - "Lost lepton" (W+jets, top pair production)
  - "Irreducible" (mainly Z->$\nu\nu$)
  - "Instrumental" (fake E_T^{miss} - mostly multijet)



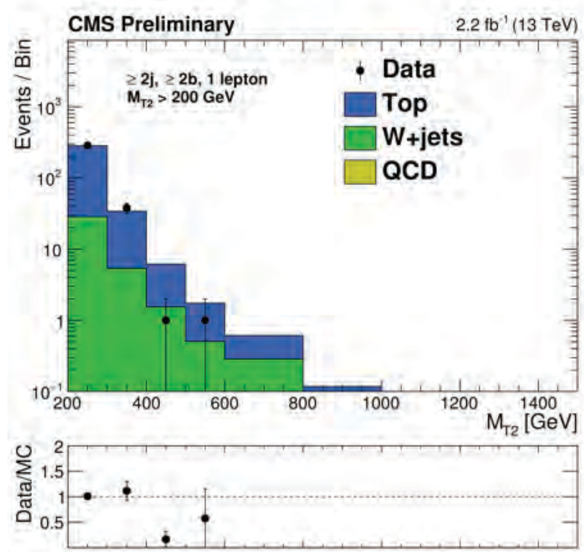
CMS M_{T2} search

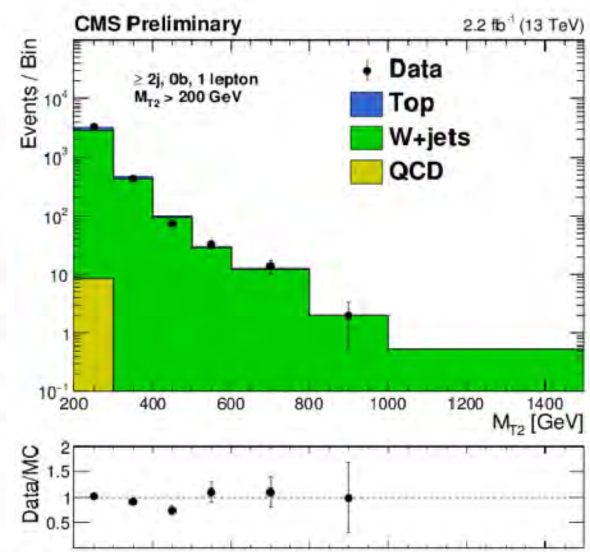
$Z \to \nu\nu$ estimated from γ+jets events in each bin of N_{jet}, N_b, H_T



"Lost lepton" background estimated with **1-lepton control regions** (CR)

- an upper cut on $m_T(lep, E_T^{miss})$ ensures no signal contamination
- **b-jet veto** for the **W** CR, **one b-jet** for the **top pair** production CR





CMS M_{T2} search - result

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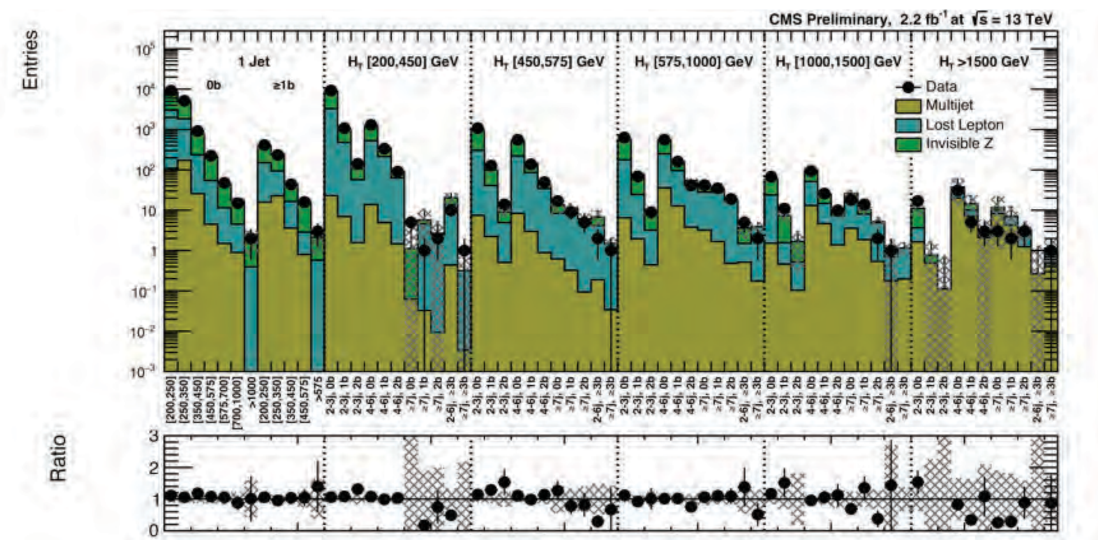
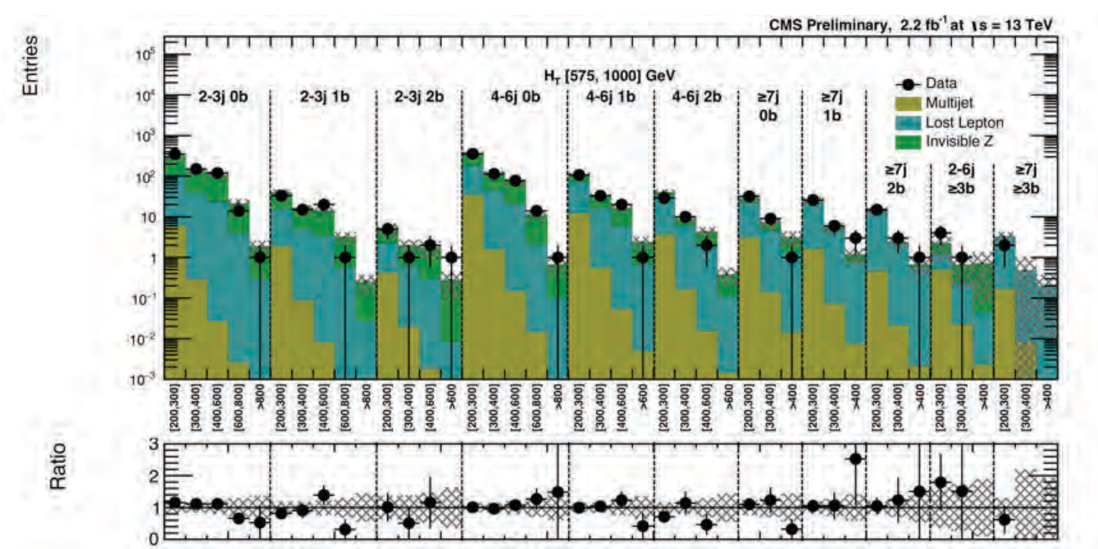
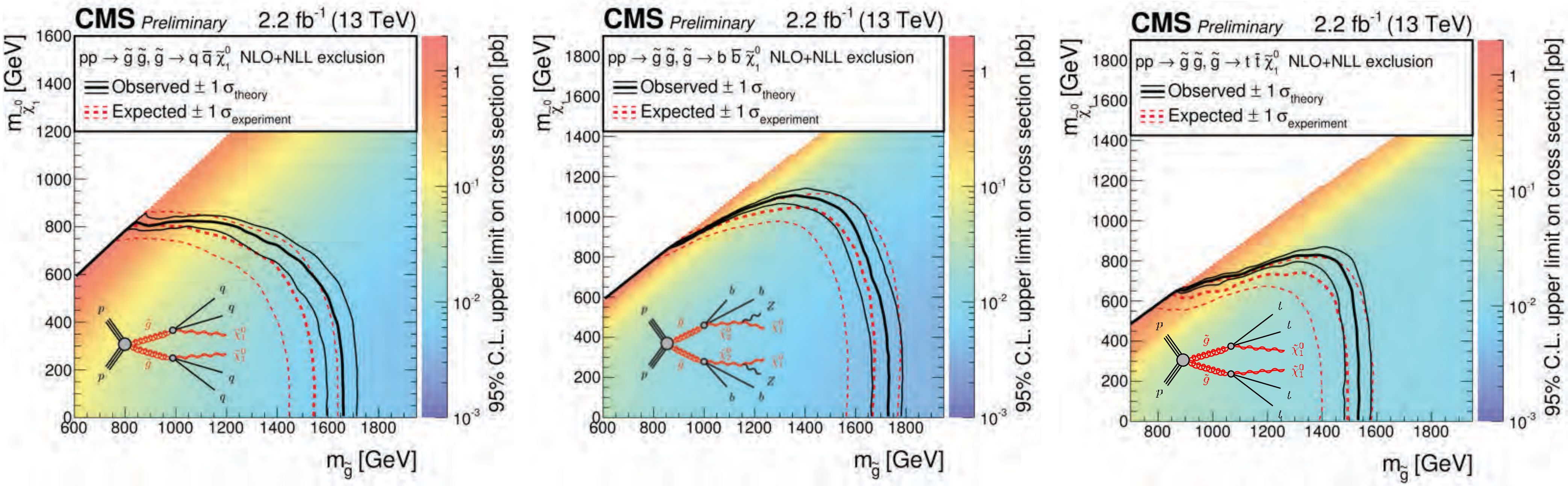
No significant excess above SM expectations





CMS M_{T2} search



Exclusion limits obtained from the **statistical combination** of the signal regions

Interpreted in **gluino pair production** with three **different decay patterns** assumed

Gluino pair production excluded **up to m_{gluino} = 1650 GeV** (depending on assumptions)

ATLAS 0L

ATLAS-CONF-2015-062

Freiburg contribution

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- **KISS** (Keep It Stupid Simple) (and as **model independent** as possible)
- Very different approach: **7 signal regions**
  - defined mainly by **jet multiplicity** and **$m_{eff} = H_T + E_T^{miss}$**

trigger

signal definition

multijet rejection

main discriminant

Requirement	Signal Region						
	2jl	**2jm**	**2jt**	**4jt**	**5j**	**6jm**	**6jt**
E_T^{miss} [GeV] >	200						
$p_T(j_1)$ [GeV] >	200	300	200				
$p_T(j_2)$ [GeV] >	200	50	200	100			
$p_T(j_3)$ [GeV] >	–			100			
$p_T(j_4)$ [GeV] >	–			100			
$p_T(j_5)$ [GeV] >	–				100		
$p_T(j_6)$ [GeV] >	–					100	
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{miss})_{min}$ >	0.8	0.4	0.8	0.4			
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{miss})_{min}$ >	–			0.2			
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	15		20	–			
Aplanarity >	–			0.04			
$E_T^{miss}/m_{eff}(N_j)$ >	–			0.2	0.25		0.2
m_{eff}(incl.) [GeV] >	1200	1600	2000	2200	1600	1600	2000

ATLAS 0L

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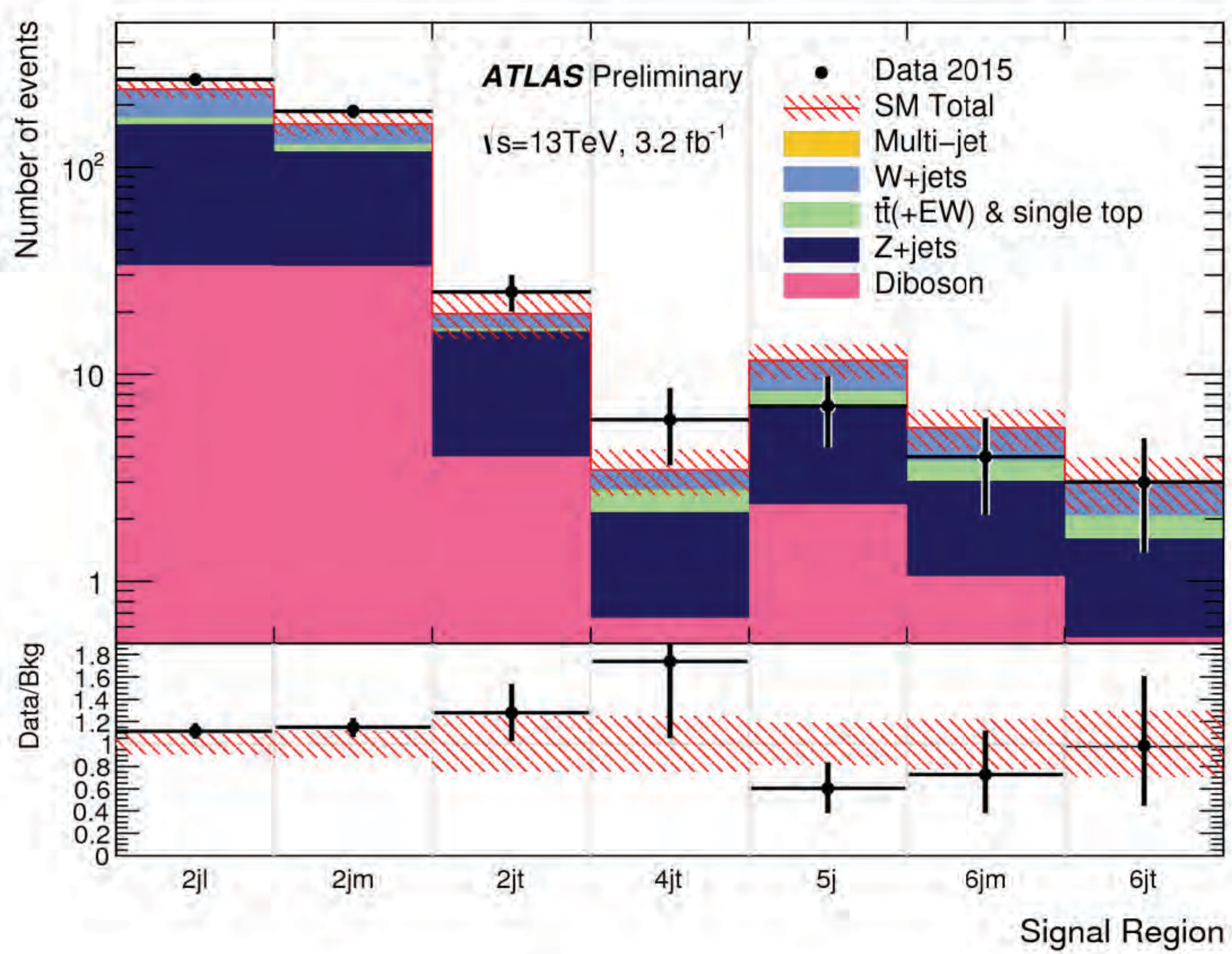
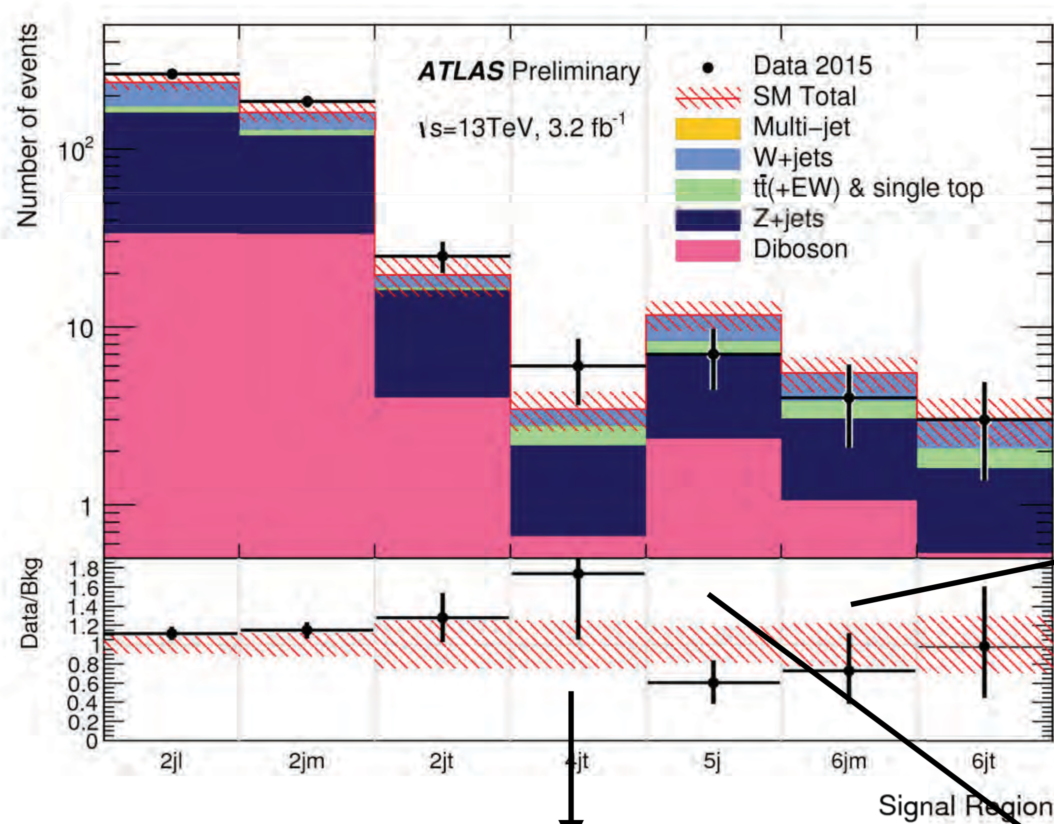
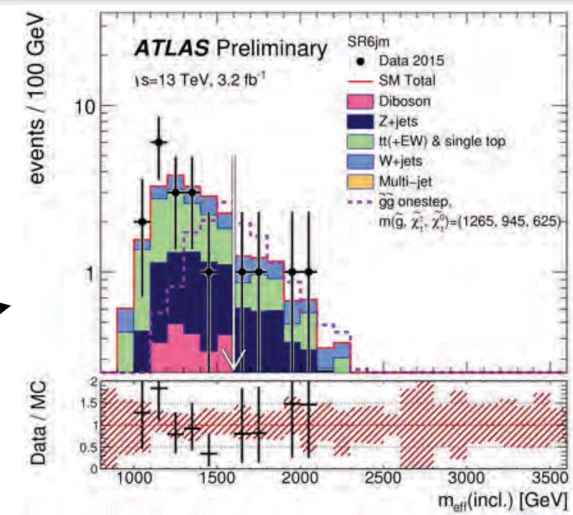
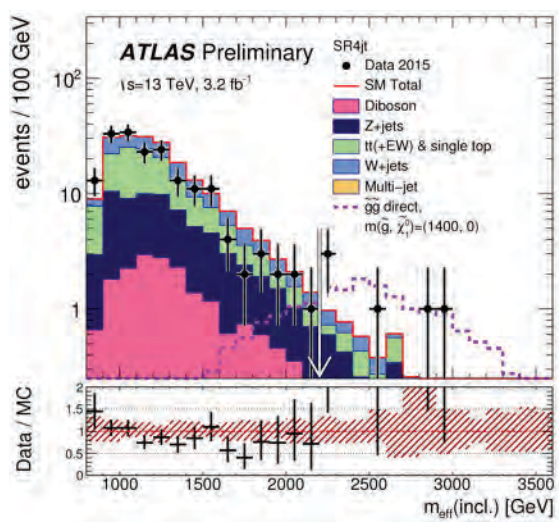
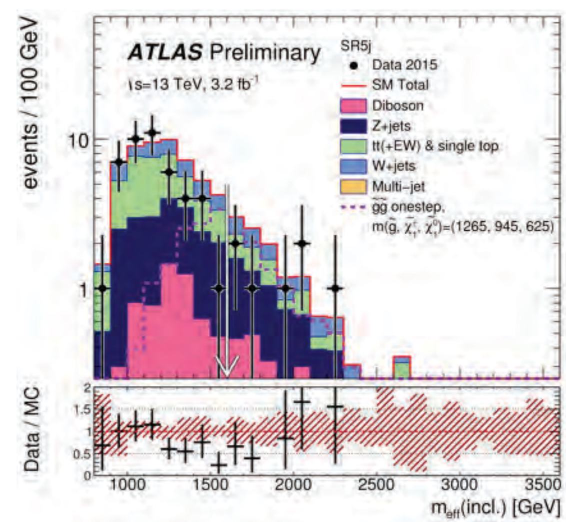



ATLAS Preliminary
√s=13TeV, 3.2 fb-1
Data 2015
SM Total
Multi–jet
W+jets
tt̄(+EW) & single top
Z+jets
Diboson
Number of events
Data/Bkg
2jl
2jm
2jt
4jt
5j
6jm
6jt
Signal Region


ATLAS Preliminary
√s=13 TeV, 3.2 fb-1
SR6jm
Data 2015
SM Total
Diboson
Z+jets
tt(+EW) & single top
W+jets
Multi–jet
g̃g̃ onestep,
m(g̃, χ̃1±, χ̃1⁰)=(1265, 945, 625)
events / 100 GeV
Data / MC
meff(incl.) [GeV]


ATLAS Preliminary
√s=13 TeV, 3.2 fb-1
SR4jt
Data 2015
SM Total
Diboson
Z+jets
tt(+EW) & single top
W+jets
Multi–jet
g̃g̃ direct,
m(g̃, χ̃1⁰)=(1400, 0)
events / 100 GeV
Data / MC
meff(incl.) [GeV]

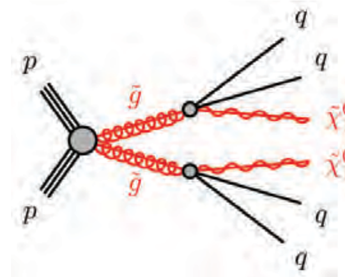

ATLAS Preliminary
√s=13 TeV, 3.2 fb-1
SR5j
Data 2015
SM Total
Diboson
Z+jets
tt(+EW) & single top
W+jets
Multi–jet
g̃g̃ onestep,
m(g̃, χ̃1±, χ̃1⁰)=(1265, 945, 625)
events / 100 GeV
Data / MC
meff(incl.) [GeV]

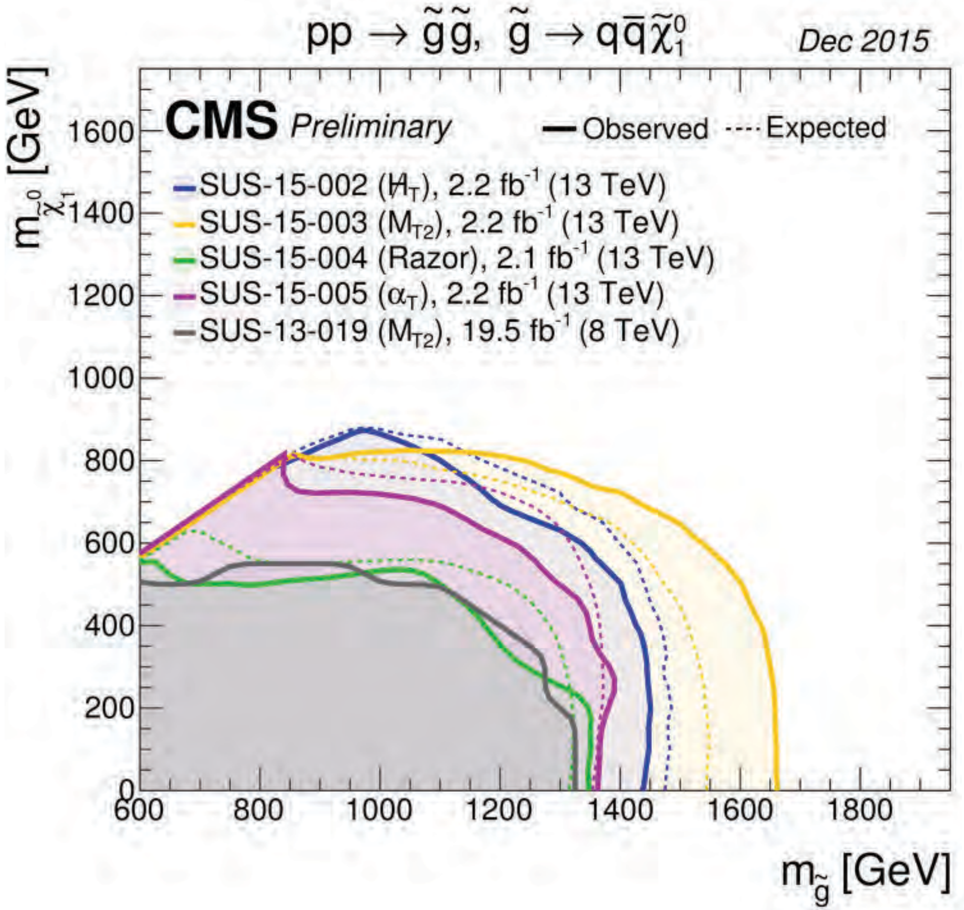
Model independent limits

Signal Region	**2jl**	**2jm**	**2jt**	**4jt**	**5j**	**6jm**	**6jt**
			MC expected events				
Diboson	33	33	4.0	0.7	2.4	1.1	0.5
Z/γ^*+jets	151	94	12	1.8	4.9	2.5	1.3
W+jets	72	42	4.5	0.9	3.0	1.6	0.9
$t\bar{t}$(+EW) + single top	18	17	1.2	0.9	2.7	1.6	1.1
Multi-jet	0.6	0.8	0.03	–	–	–	–
Total MC	275	188	22	4.3	13	6.7	3.8
			Fitted background events				
Diboson	33 ± 17	33 ± 17	4.0 ± 2.0	0.67 ± 0.35	2.4 ± 1.3	1.1 ± 0.6	0.5 ± 0.4
Z/γ^*+jets	127 ± 12	85 ± 8	12 ± 4	1.5 ± 0.6	4.5 ± 1.3	2.0 ± 0.7	1.1 ± 0.6
W+jets	61 ± 4	32 ± 5	2.9 ± 0.8	0.7 ± 0.4	3.3 ± 1.0	1.7 ± 0.7	1.0 ± 0.6
$t\bar{t}$(+EW) + single top	14.6 ± 2.9	10.5 ± 2.6	0.7 ± 0.5	0.6 ± 0.4	1.4 ± 0.5	0.8 ± 0.4	0.46 ± 0.33
Multi-jet	0.51 ± 0.06	0.6 ± 0.5	–	–	–	–	–
Total bkg	237 ± 22	163 ± 20	20 ± 5	3.5 ± 0.8	11.7 ± 2.2	5.5 ± 1.2	3.1 ± 0.9
Observed	264	186	25	6	7	4	3
$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$ [fb]	24	21	5.9	2.5	2.0	1.6	1.6
$S^{95}_{\rm obs}$	76	67	19	8.2	6.3	5.3	5.0
$S^{95}_{\rm exp}$	52^{+22}_{-15}	46^{+19}_{-12}	$14.1^{+5.1}_{-3.1}$	$5.7^{+2.2}_{-1.6}$	$8.5^{+3.3}_{-2.1}$	$6.5^{+2.5}_{-1.6}$	$5.0^{+2.3}_{-1.4}$
p_0 (Z)	0.11 (1.20)	0.12 (1.15)	0.18 (0.93)	0.14 (1.08)	0.5 (0.0)	0.5 (0.0)	0.5 (0.0)

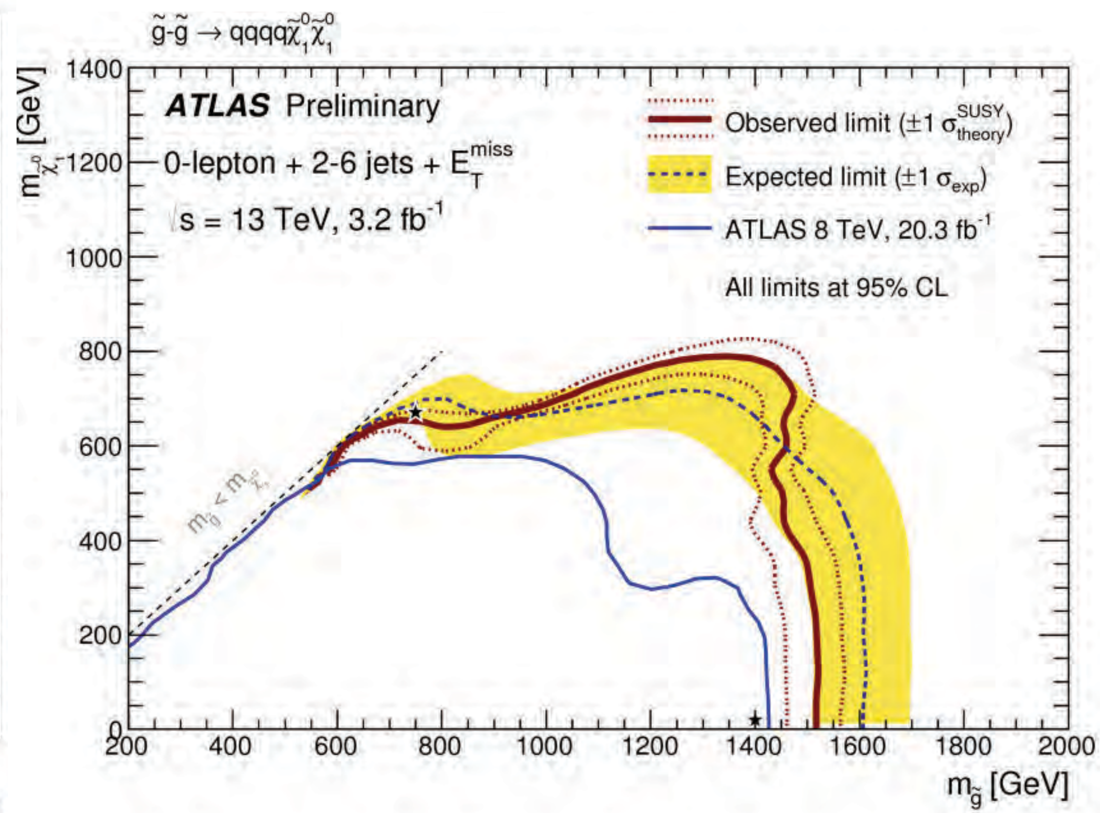
- Answers the question: what cross section is excluded, assuming efficiency x acceptance = 100%?

CMS Vs ATLAS





$pp \to \tilde{g}\tilde{g}, \ \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$
Dec 2015
CMS Preliminary
Observed
Expected
SUS-15-002 (H_T), 2.2 fb^{-1} (13 TeV)
SUS-15-003 (M_{T2}), 2.2 fb^{-1} (13 TeV)
SUS-15-004 (Razor), 2.1 fb^{-1} (13 TeV)
SUS-15-005 (α_T), 2.2 fb^{-1} (13 TeV)
SUS-13-019 (M_{T2}), 19.5 fb^{-1} (8 TeV)
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]

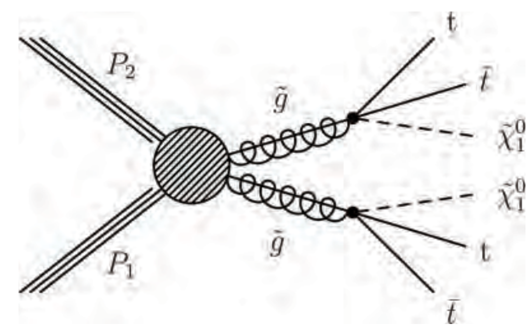


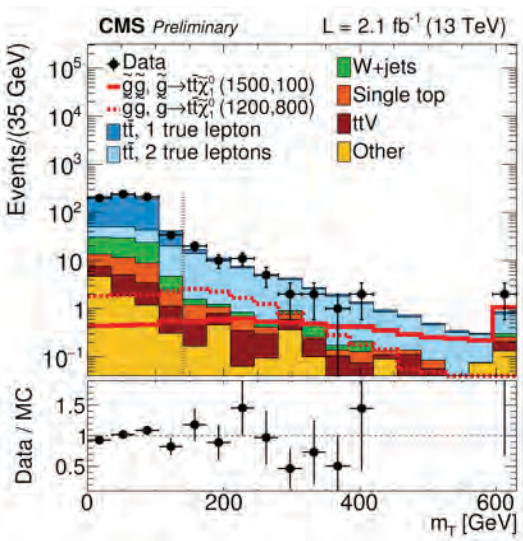
$\tilde{g}$-$\tilde{g} \to qqqq\tilde{\chi}_1^0\tilde{\chi}_1^0$
ATLAS Preliminary
0-lepton + 2-6 jets + E_T^{miss}
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Observed limit ($\pm 1\ \sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\ \sigma_{exp}$)
ATLAS 8 TeV, 20.3 fb^{-1}
All limits at 95% CL
$m_{\tilde{g}} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]

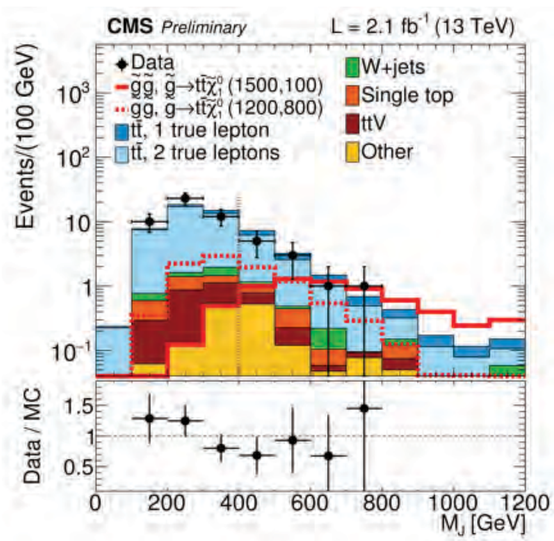
CMS 1-lepton multijets

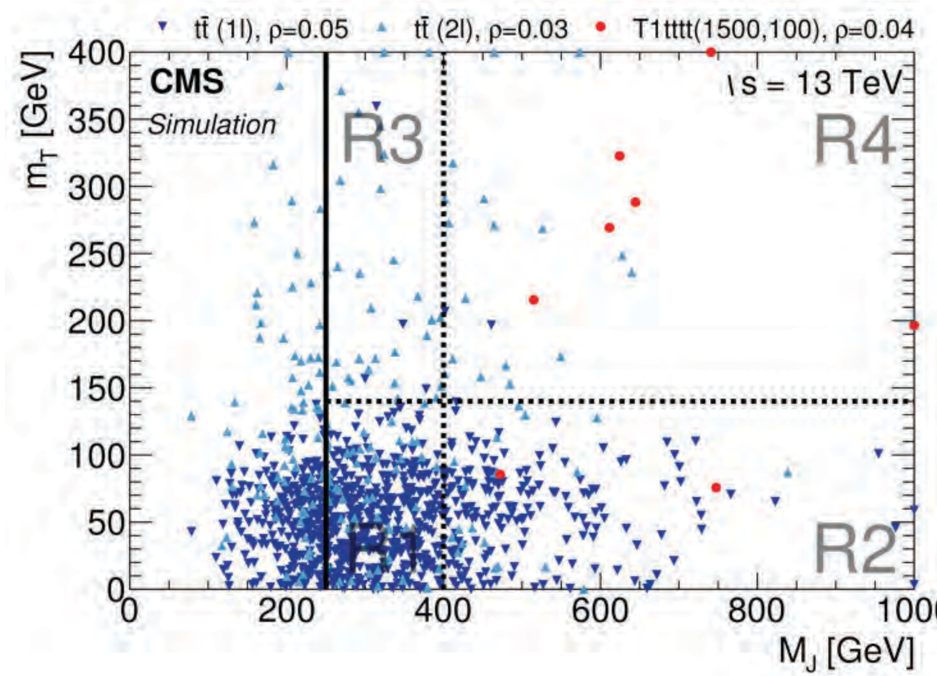
CMS-PAS-SUS-15-007

- **Basic idea:**
  - Reconstruct **R=1.2 Anti-k_T** jets. The sum of their masses M_J is **sensitive to signal** and **independent on m_T(lep,E_T^{miss})**



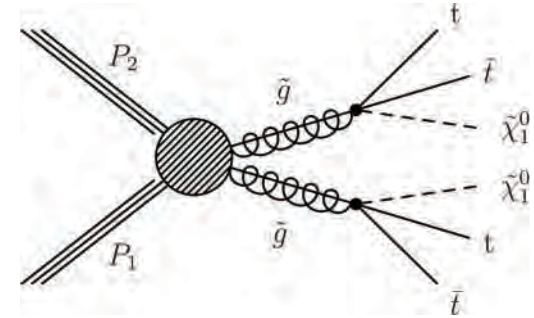


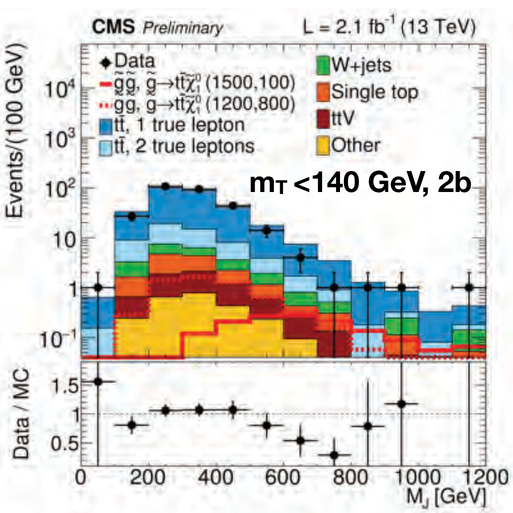


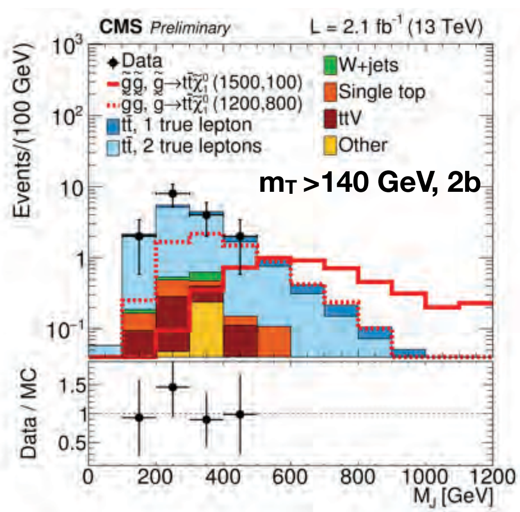


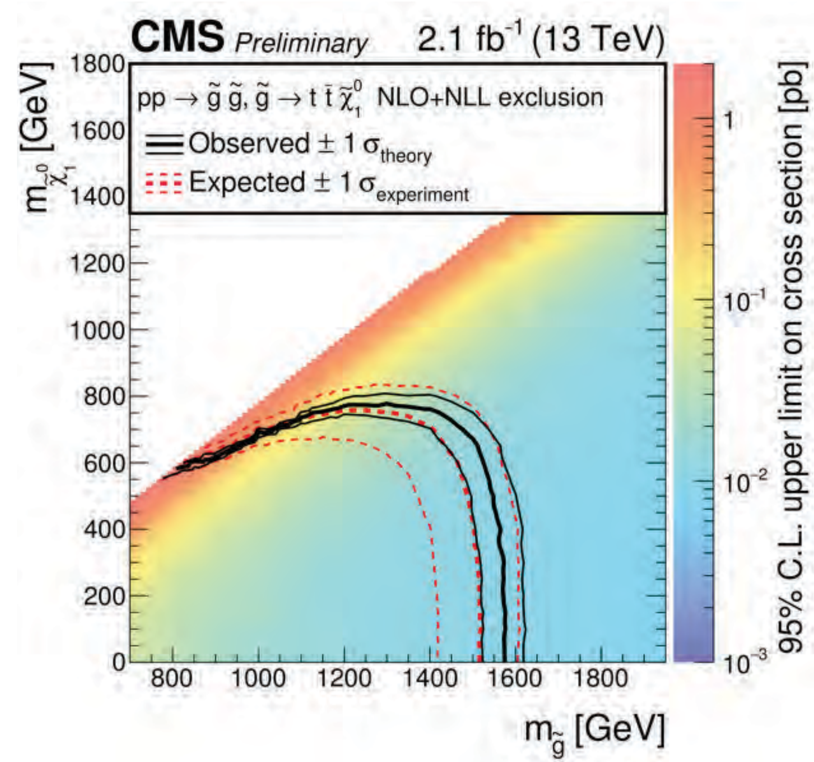
CMS 1-lepton multijets

Bin	κ	Sig. NC	Sig. C	Bkg. Pred. (PF)	Bkg. Pred. (GF)	Obs.
			$200 < \text{MET} \leq 400$ GeV			
R1: all n_j, n_b	–	0.1	2.9	330.1 ± 18.2	329.4 ± 18.0	330
R2: $6 \leq n_j \leq 8$, $n_b = 1$	–	0.1	0.2	47.1 ± 6.9	49.4 ± 6.8	47
R2: $n_j \geq 9$, $n_b = 1$	–	0.1	0.3	6.0 ± 2.4	6.6 ± 2.5	6
R2: $6 \leq n_j \leq 8$, $n_b = 2$	–	0.1	0.3	42.0 ± 6.5	41.0 ± 6.2	42
R2: $n_j \geq 9$, $n_b = 2$	–	0.1	0.5	7.0 ± 2.6	6.5 ± 2.5	7
R2: $6 \leq n_j \leq 8$, $n_b \geq 3$	–	0.1	0.2	12.0 ± 3.5	11.1 ± 3.2	12
R2: $n_j \geq 9$, $n_b \geq 3$	–	0.1	0.6	1.0 ± 1.0	0.9 ± 0.9	1
R3: all n_j, n_b	–	0.2	3.5	21.0 ± 4.6	21.6 ± 4.2	21
R4: $6 \leq n_j \leq 8$, $n_b = 1$	$1.12 \pm 0.09 \pm 0.42$	0.2	0.2	3.4 ± 1.4	3.6 ± 1.0	6
R4: $n_j \geq 9$, $n_b = 1$	$0.91 \pm 0.05 \pm 0.82$	0.1	0.3	0.3 ± 0.3	0.4 ± 0.2	1
R4: $6 \leq n_j \leq 8$, $n_b = 2$	$1.12 \pm 0.05 \pm 0.42$	0.3	0.3	3.0 ± 1.2	3.0 ± 0.8	2
R4: $n_j \geq 9$, $n_b = 2$	$1.04 \pm 0.10 \pm 0.94$	0.3	0.6	0.5 ± 0.3	0.4 ± 0.2	0
R4: $6 \leq n_j \leq 8$, $n_b \geq 3$	$1.25 \pm 0.11 \pm 0.75$	0.3	0.3	1.0 ± 0.5	0.9 ± 0.3	0
R4: $n_j \geq 9$, $n_b \geq 3$	$1.04 \pm 0.09 \pm 0.96$	0.3	0.7	0.1 ± 0.1	0.1 ± 0.1	0
			$\text{MET} > 400$ GeV			
R1: all n_j, n_b	–	0.1	0.4	15.0 ± 3.9	16.2 ± 3.9	15
R2: $6 \leq n_j \leq 8$, $n_b = 1$	–	0.1	0.1	8.0 ± 2.8	6.7 ± 2.5	8
R2: $n_j \geq 9$, $n_b = 1$	–	0.1	0.2	1.0 ± 1.0	1.7 ± 1.2	1
R2: $6 \leq n_j \leq 8$, $n_b \geq 2$	–	0.4	0.2	3.0 ± 1.7	2.5 ± 1.4	3
R2: $n_j \geq 9$, $n_b \geq 2$	–	0.4	0.5	1.0 ± 1.0	0.9 ± 0.9	1
R3: all n_j, n_b	–	0.4	0.8	4.0 ± 2.0	2.8 ± 1.4	4
R4: $6 \leq n_j \leq 8$, $n_b = 1$	$1.15 \pm 0.17 \pm 0.44$	0.6	0.2	2.4 ± 1.9	1.2 ± 0.7	0
R4: $n_j \geq 9$, $n_b = 1$	$1.01 \pm 0.15 \pm 0.92$	0.4	0.3	0.3 ± 0.3	0.3 ± 0.3	1
R4: $6 \leq n_j \leq 8$, $n_b \geq 2$	$1.28 \pm 0.19 \pm 0.50$	1.8	0.4	1.0 ± 0.9	0.5 ± 0.4	0
R4: $n_j \geq 9$, $n_b \geq 2$	$0.90 \pm 0.13 \pm 0.81$	1.5	0.9	0.2 ± 0.3	0.1 ± 0.1	0





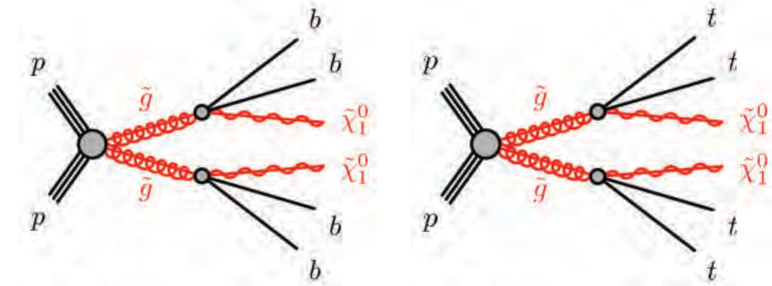


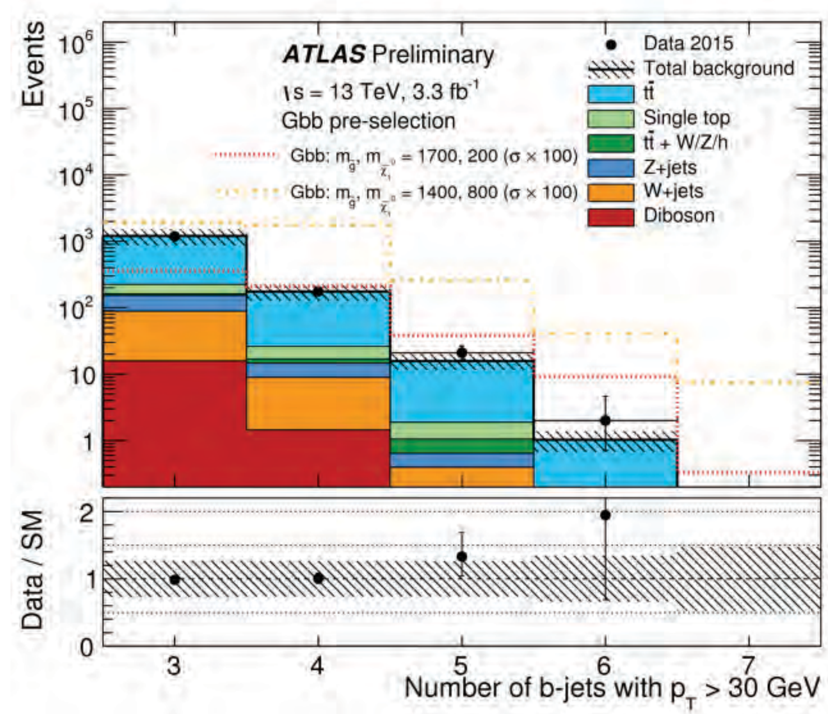


ATLAS multi-b

ATLAS-CONF-2015-067

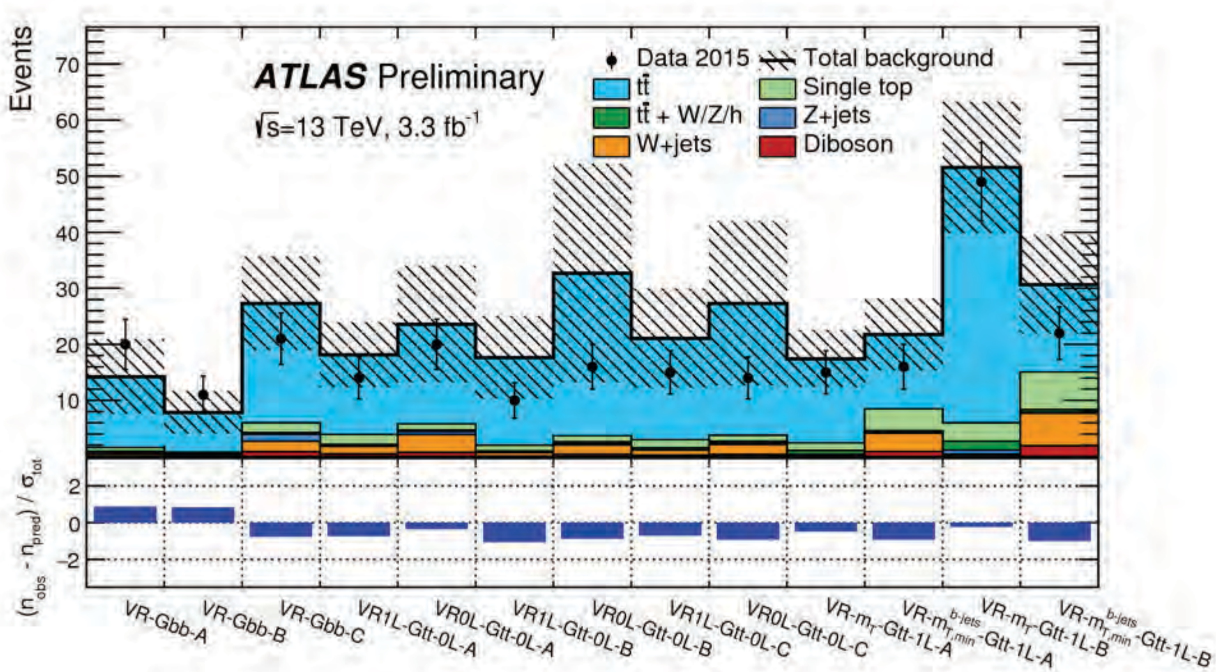
- **Main idea:**
  - gluino mediated stop and sbottom production yields **high jet multiplicity** and **b-jet multiplicity**
- **Three sets** of signal regions (with **at least 3 b-jets**):
  - **G→bbχ_1^0:** 4 jets, 3 b-jets, different E_T^{miss} and m_{eff} selections
  - **G→ttχ_1^0: 0- and 1-lepton** regions, 3 or 4 b-jets, different $m_T(b,E_T^{miss})$, $m_T(l,E_T^{miss})$, E_T^{miss}, m_{eff} selections
  - **Boosted top candidate** for large $\Delta m(g, \chi_1^0)$





ATLAS multi-b

- Control region for **top pair production**: 1-lepton and upper $m_T(l,E_T^{miss})$ cut
- A set of **validation regions** to validate **all extrapolations** from CR to SR
- Main systematic uncertainties: **top pair production** modelling and **mistag rate**



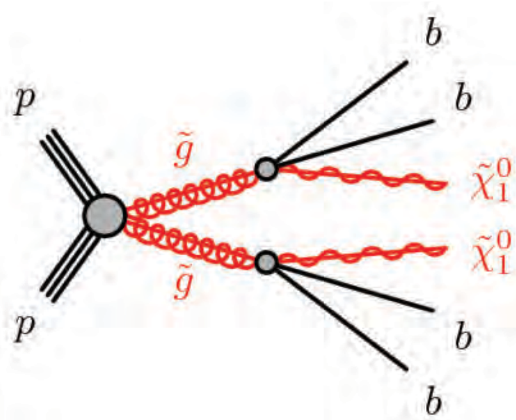
	SR-Gbb-A	SR-Gbb-B	SR-Gbb-C
Observed events	0	1	5
Fitted background events	1.4 ± 0.7	1.5 ± 0.5	7.5 ± 1.4
$t\bar{t}$	0.7 ± 0.5	0.83 ± 0.32	3.9 ± 1.0
Z+jets	0.25 ± 0.26	0.25 ± 0.22	1.4 ± 0.6
W+jets	0.19 ± 0.10	0.15 ± 0.06	0.95 ± 0.34
Single-top	0.22 ± 0.10	0.16 ± 0.15	0.67 ± 0.33
$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, $t\bar{t}t\bar{t}$	< 0.1	< 0.1	0.18 ± 0.10
Diboson	–	< 0.1	0.43 ± 0.25
MC-only prediction	1.7	1.6	7.1
$\mu_{t\bar{t}}$	0.7 ± 0.3	0.9 ± 0.4	1.1 ± 0.4

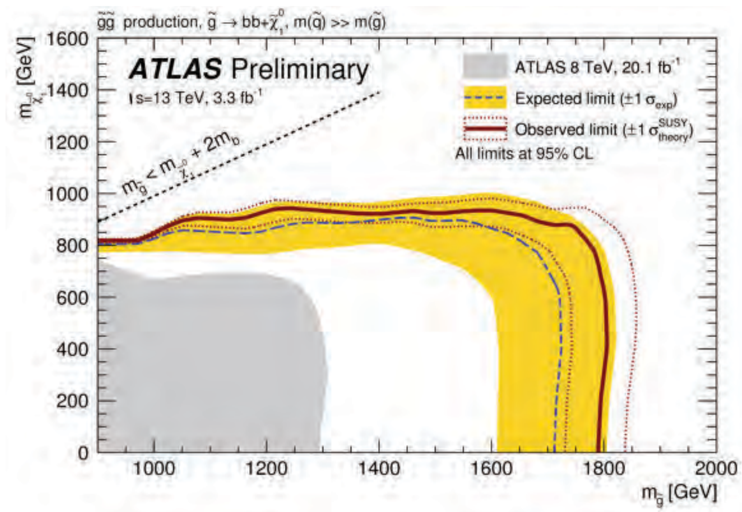
	SR-Gtt-0l-A	SR-Gtt-0L-B	SR-Gtt-0L-C
Observed events	1	1	1
Fitted background events	2.0 ± 0.7	2.8 ± 1.7	3.2 ± 1.7
$t\bar{t}$	1.3 ± 0.6	2.2 ± 1.6	2.4 ± 1.7
Z+jets	0.24 ± 0.17	0.13 ± 0.13	0.16 ± 0.09
W+jets	0.21 ± 0.14	0.15 ± 0.16	0.20 ± 0.21
Single-top	0.14 ± 0.16	0.15 ± 0.13	0.18 ± 0.16
$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}h$, $t\bar{t}t\bar{t}$	< 0.1	0.10 ± 0.06	0.11 ± 0.06
Diboson	< 0.1	< 0.1	0.18 ± 0.18
MC-only prediction	1.8	1.9	2.6
$\mu_{t\bar{t}}$	1.2 ± 0.4	1.7 ± 0.7	1.4 ± 0.6

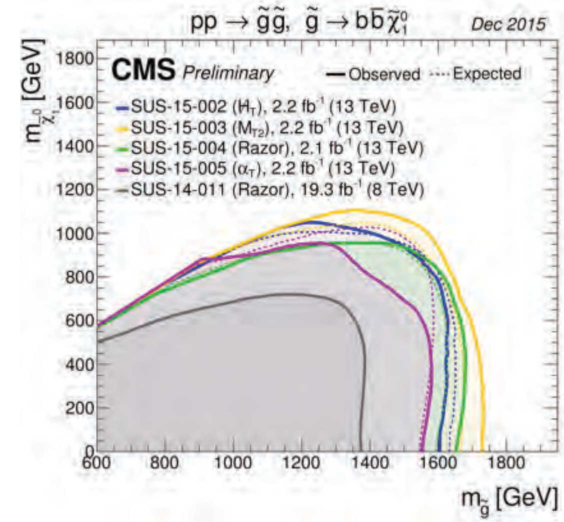
	SR-Gtt-1L-A	SR-Gtt-1L-B
Observed events	2	0
Fitted background events	1.3 ± 0.4	1.1 ± 0.6
$t\bar{t}$	0.91 ± 0.33	0.8 ± 0.5
Z+jets	–	–
W+jets	< 0.1	< 0.1
Single-top	0.19 ± 0.15	0.15 ± 0.13
$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}h$, $t\bar{t}t\bar{t}$	0.18 ± 0.10	0.18 ± 0.10
Diboson	–	–
MC-only prediction	1.3	1.2
$\mu_{t\bar{t}}$	1.0 ± 0.3	0.9 ± 0.3

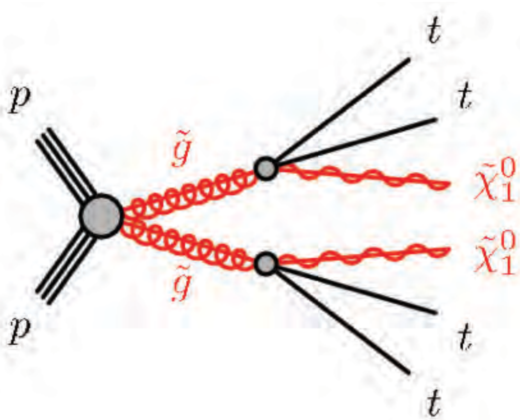
Exclusion limits

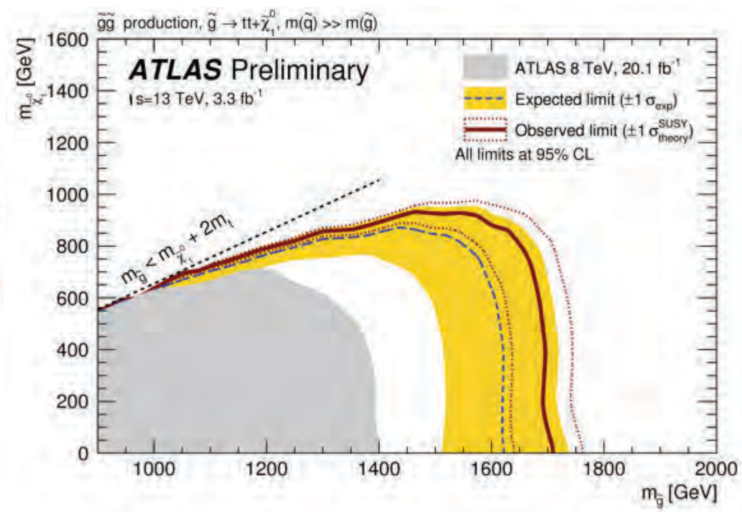
ATLAS-CONF-2015-067

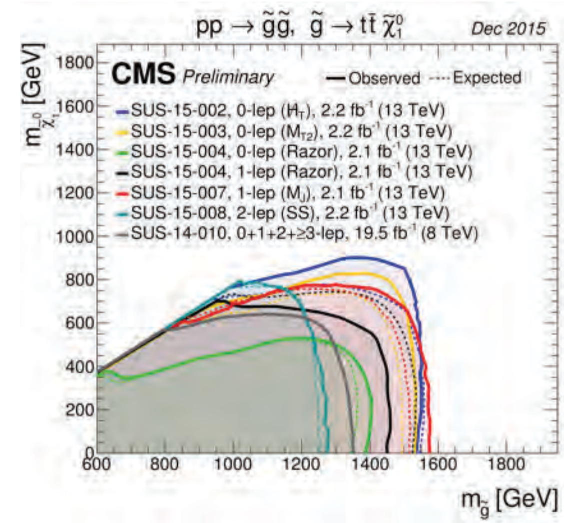












ATLAS-CONF-2015-067

SS/3L analyses

ATLAS-CONF-2015-078

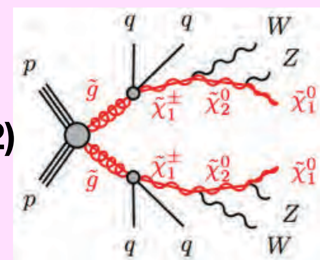
Freiburg contribution

University of Sussex

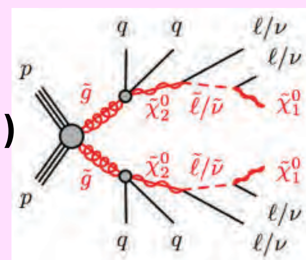
- Gluinos are **majorana fermions** → increased (w.r.t. background) probability of SS leptons
- In general, very low SM background → sensitive to new processes

ATLAS

2)



1)



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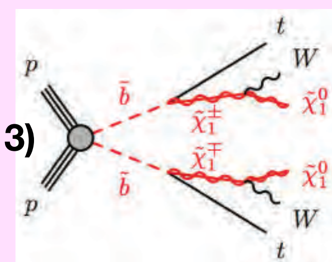
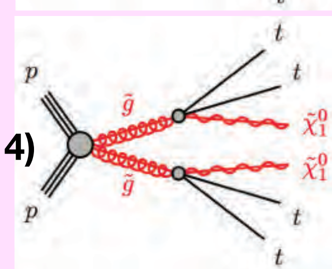


4)

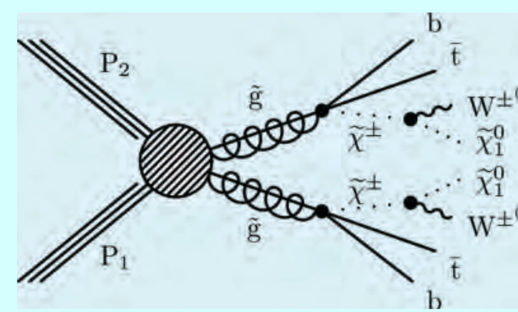


Signal region	$N_{\text{lept}}^{\text{signal}}$	N_{bjets}^{20}	N_{jets}^{50}	E_T^{miss} [GeV]	m_{eff} [GeV]
1) SR0b3j	≥3	=0	≥3	>200	>550
2) SR0b5j	≥2	=0	≥5	>125	>650
3) SR1b	≥2	≥1	≥4	>150	>550
4) SR3b	≥2	≥3	-	>125	>650

CMS

64 signal regions divided by the p_T of leptons, H_T, E_T^{miss}, M_T^{min}

One more interpretation on top of those done by ATLAS



Fake lepton background estimate

US
University of Sussex

- General approach to **fake lepton background estimation** based on a loose/tight matrix method
- Example with 1 lepton (easily extendable to multi-lepton signatures):

- A fake lepton lepton can arise from:
  - Jet mis-identification
  - Off-axis HF semileptonic decays
  - Photon conversion

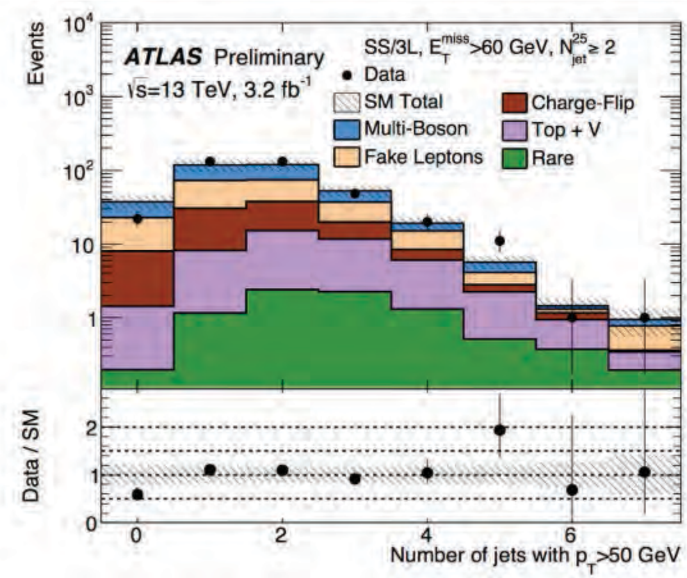
- Strategy: **define a "loose"** (pre-selected) **and a "tight"** (signal) lepton selection.
- Then, solve the following system of equations

$$
\begin{aligned}
N^{loose} &= N^{loose}_{real} + N^{loose}_{fake} \\
N^{tight} &= \varepsilon_{real} N^{loose}_{real} + \varepsilon_{fake} N^{loose}_{fake}
\end{aligned}
$$

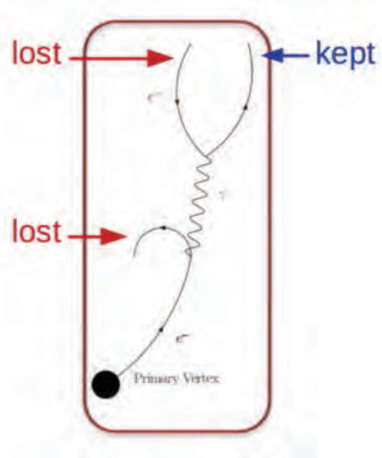
Need to be measured independently from data

Simply count how many of them

$$N^{tight}_{fake} = \frac{\varepsilon_{fake}}{\varepsilon_{real} - \varepsilon_{fake}} \left(N^{loose} \varepsilon_{real} - N^{tight} \right)$$

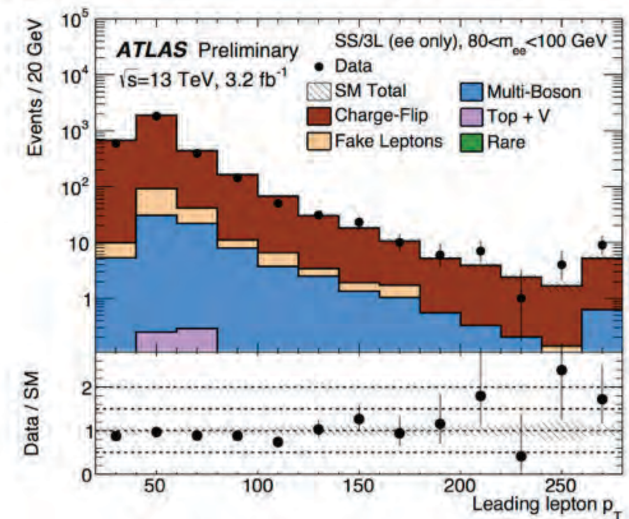


SS/3L

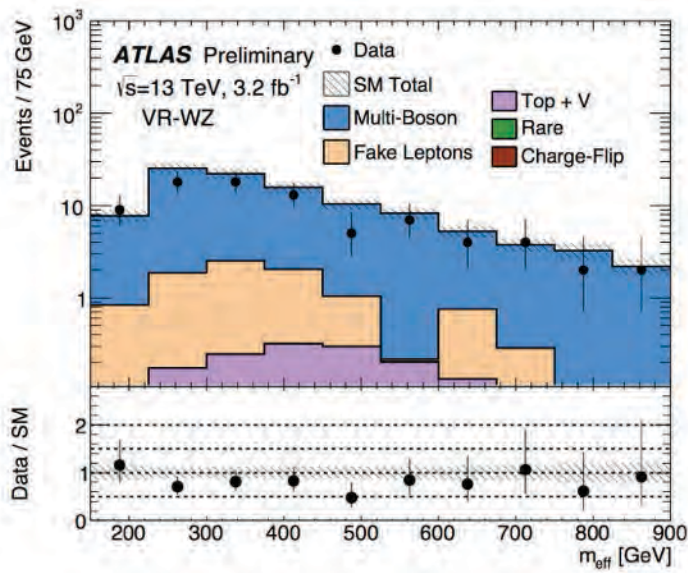


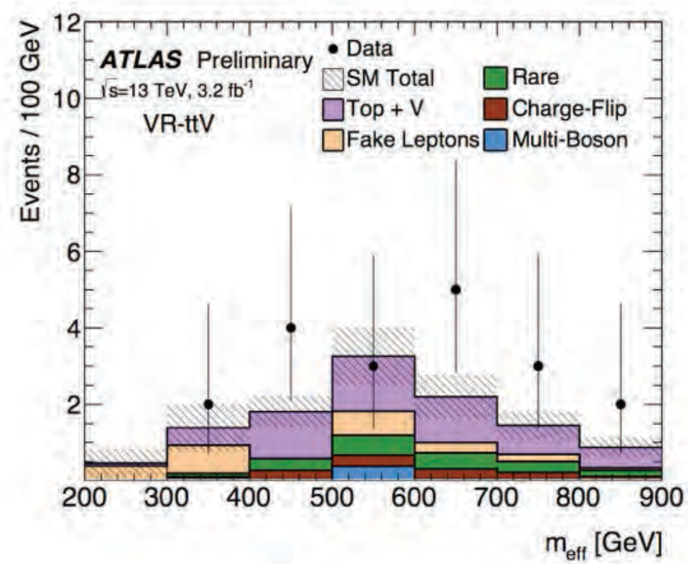
Charge flip background estimated from the **Z → ee peak** (with two electrons with SS)

Obviously irrelevant for muons



Dedicated **validation regions** for irreducible background

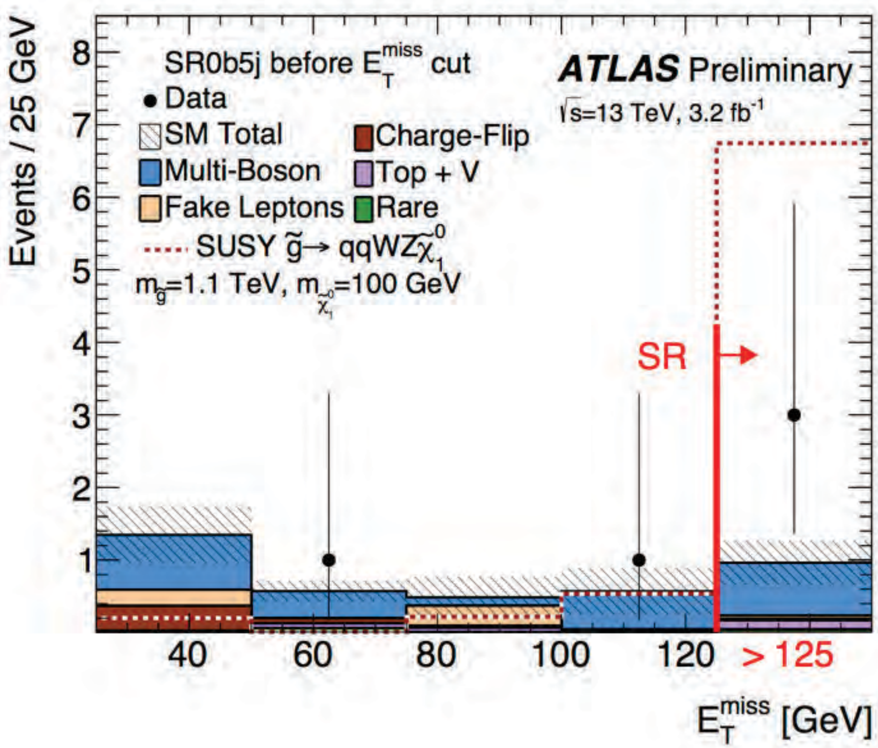


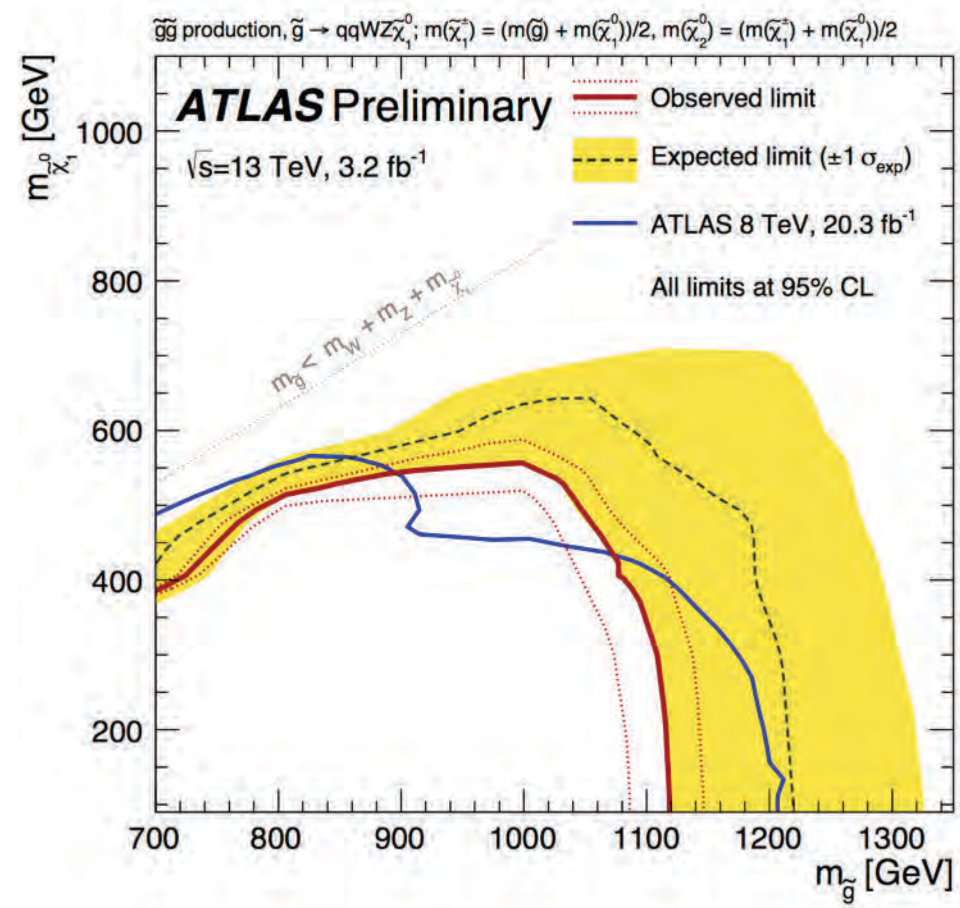


SS/3L - SR example

University of Sussex

No significant excess found in any of the **four signal regions**

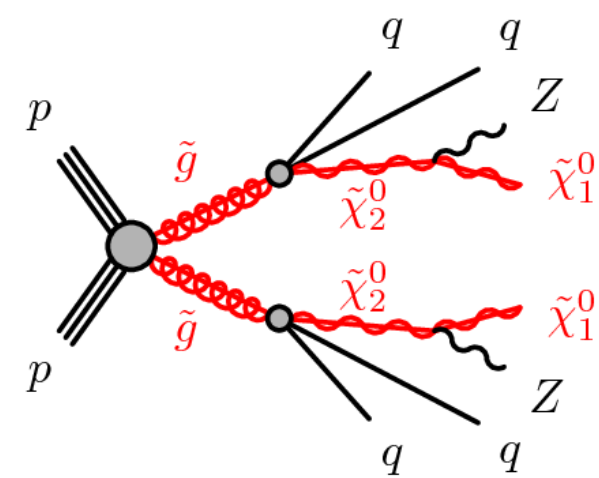




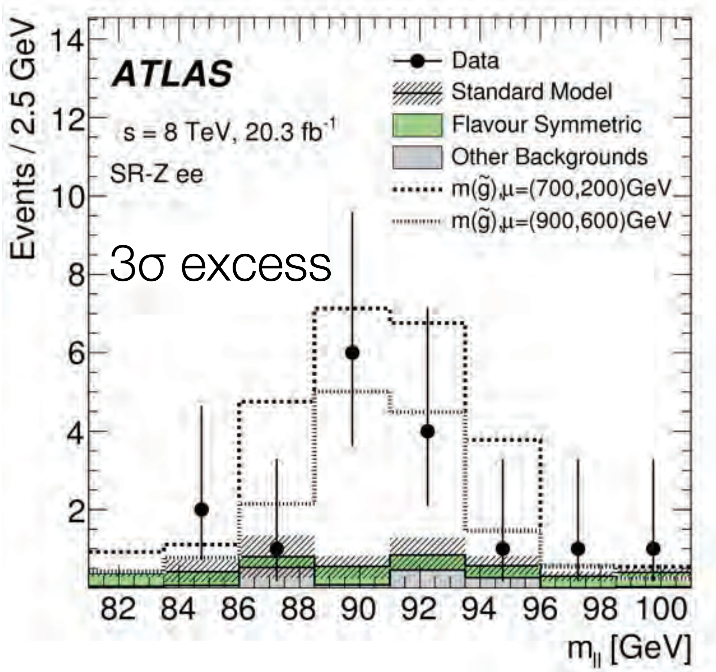
ATLAS Z+E_T^{miss}

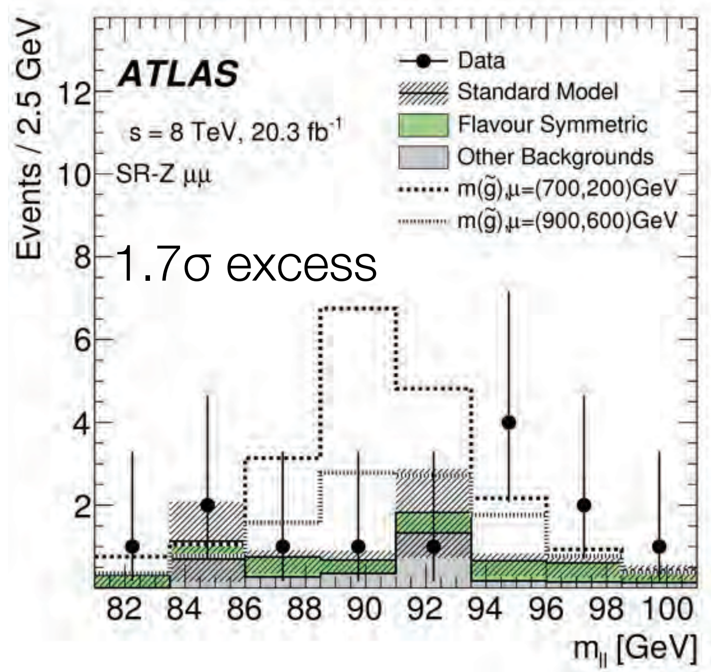
ATLAS-CONF-2015-082

- **Basic idea:** Z boson + E_T^{miss} is a final state with **very limited SM background** (essentially WZ and ZZ production)
- Selection: 2 jets, E_T^{miss} > 225 GeV, H_T > 600 GeV



arXiv:1503.03290



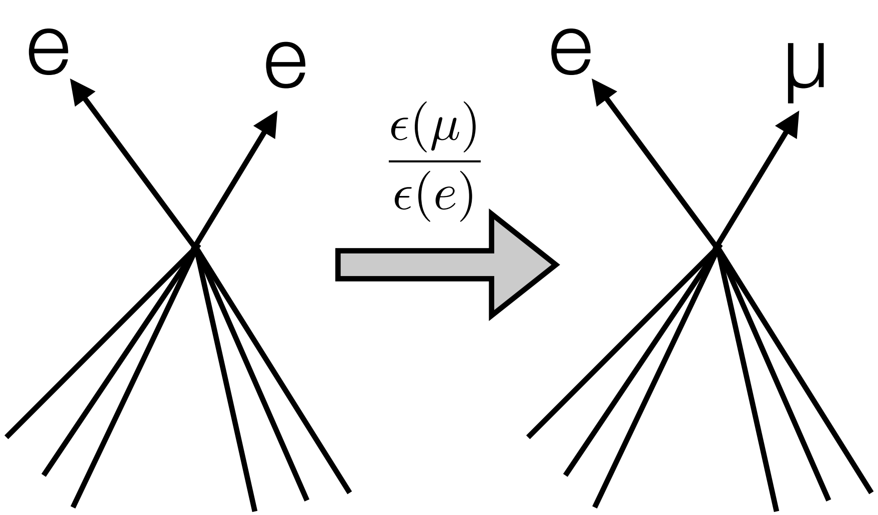


Excess in run 1

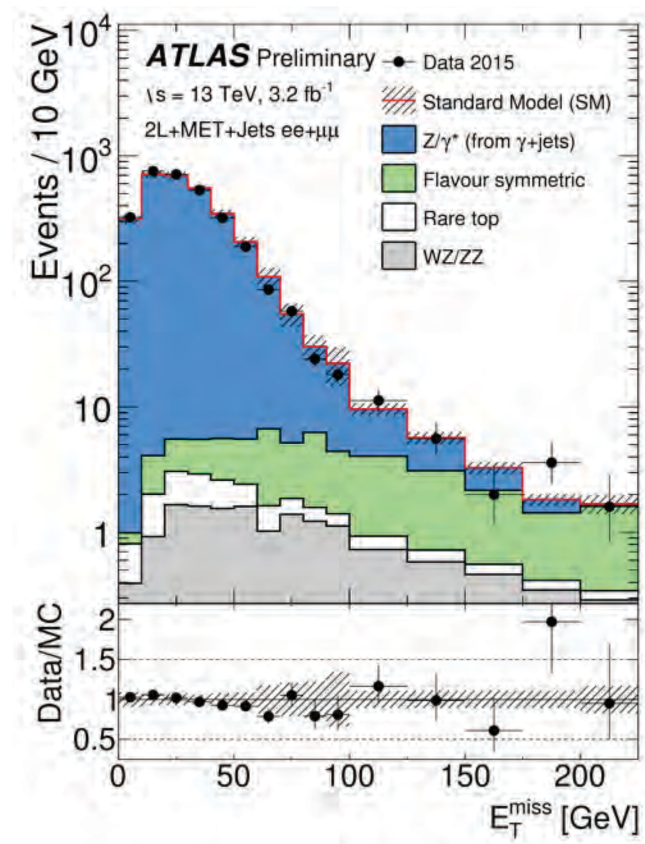
non-resonant background dominated by flavour symmetric processes (mainly ttbar)

ATLAS Z+E_T^{miss}

- **Flavour symmetric** background (top pair production, WW, etc.): ee:μμ:eμ events are in ratio 1:1:2
- Validated with a sideband fit to m_{ll}

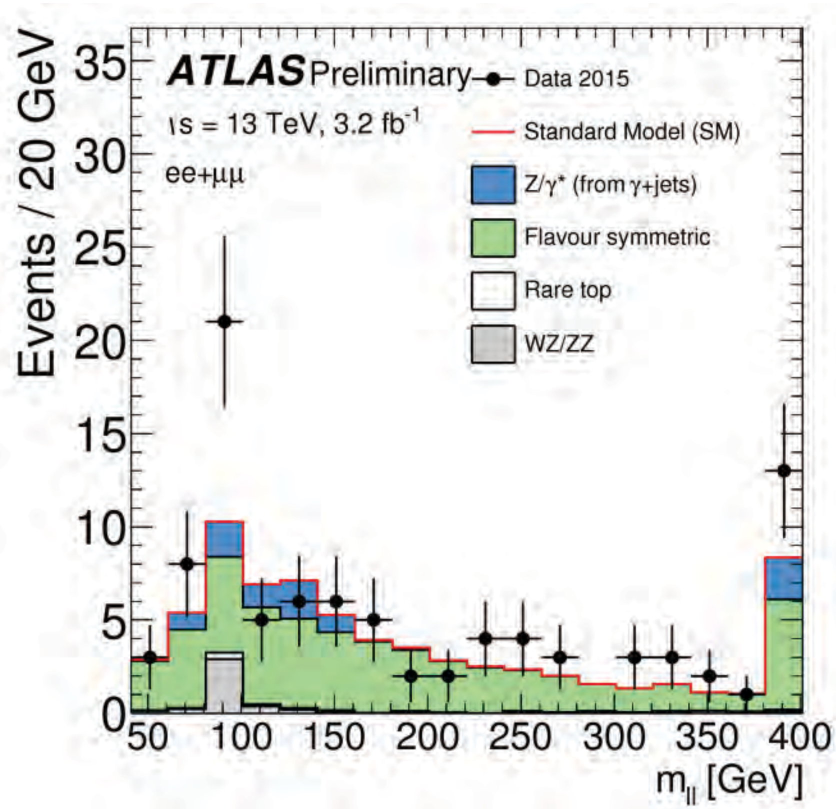


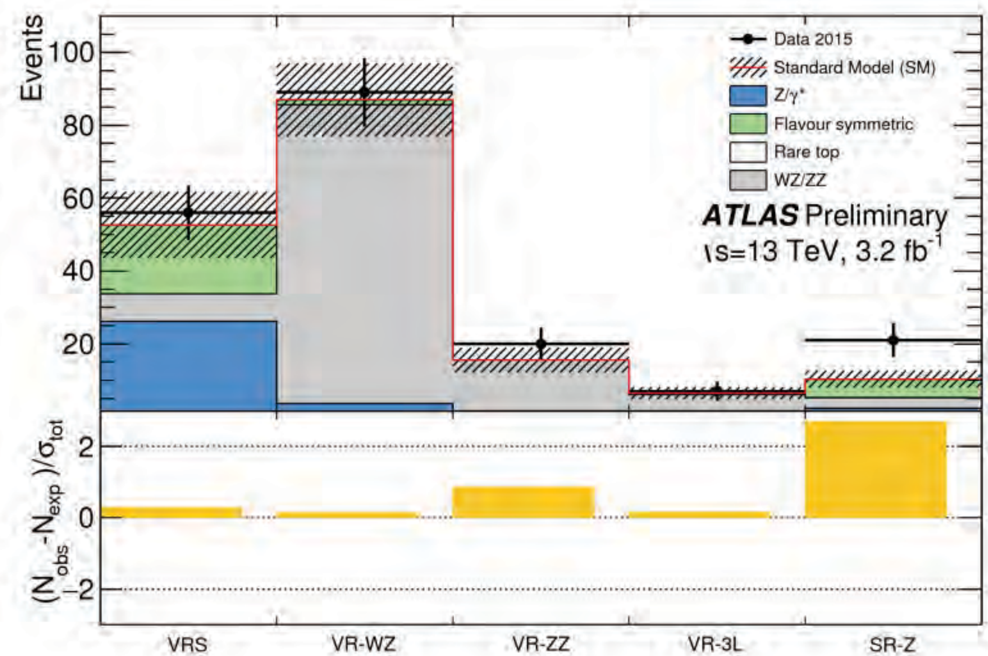
- **Z+E_T^{miss} background** tricky (it mainly comes from detector effects)
- Estimated from γ+jets events
  - idea: γ+jets and Z+jets events are the same (beside Z mass and lepton/photon resolution
  - measure E_T^{miss} shape in γ+jets and use it to predict signal region yields



ATLAS Z+E_T^{miss}

Excess still there in run 2!





Expected events: **10.3 ±2.3**

Observed: **21 (2.2σ)**

10 in ee, 11 in μμ

What does CMS say?

CMS-PAS-SUS-15-011

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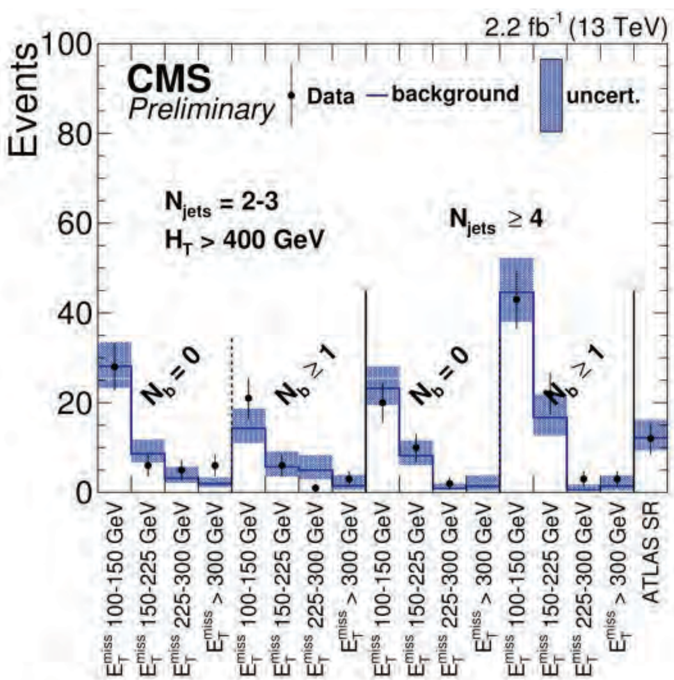
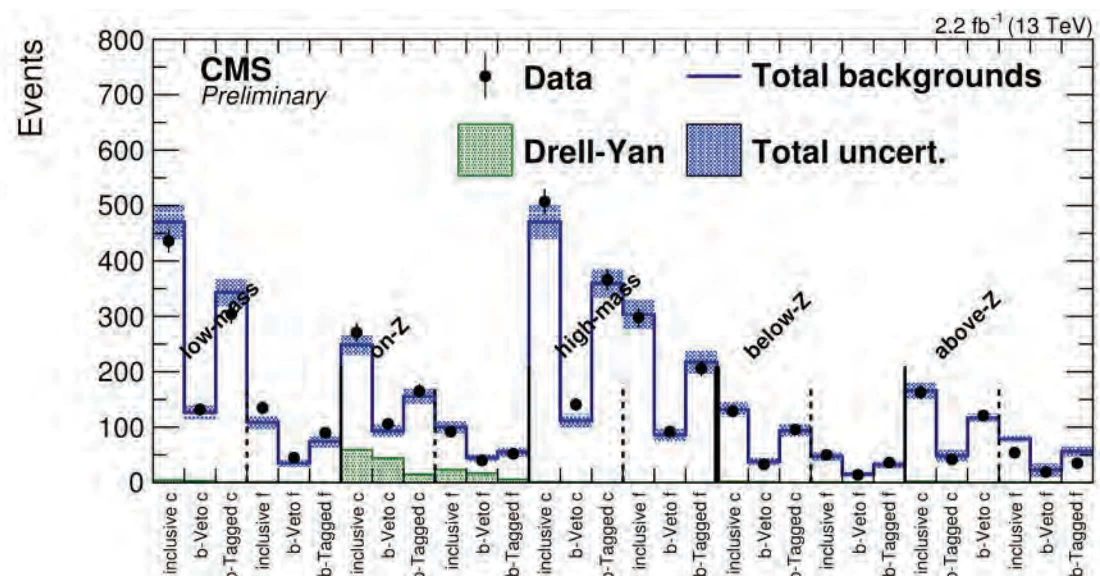
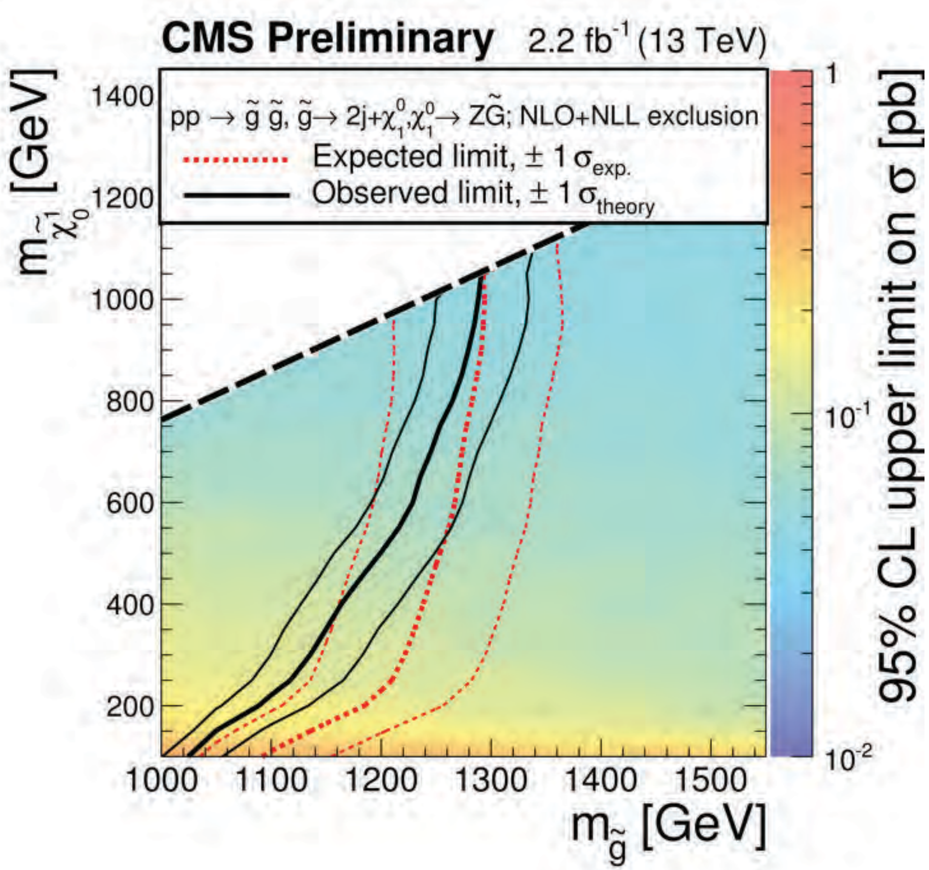
- **47 signal regions**, looking on- and off-Z (CMS had 2.6 σ below the Z peak)
  - Defined with different **jet and b-jet multiplicity, E_T^{miss}, H_T, m_{ll}**
  - Background estimation **similar to the ATLAS case**.

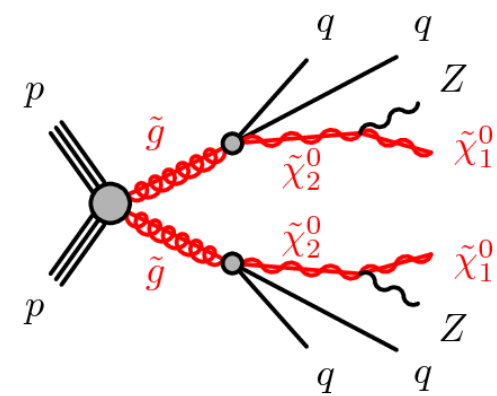


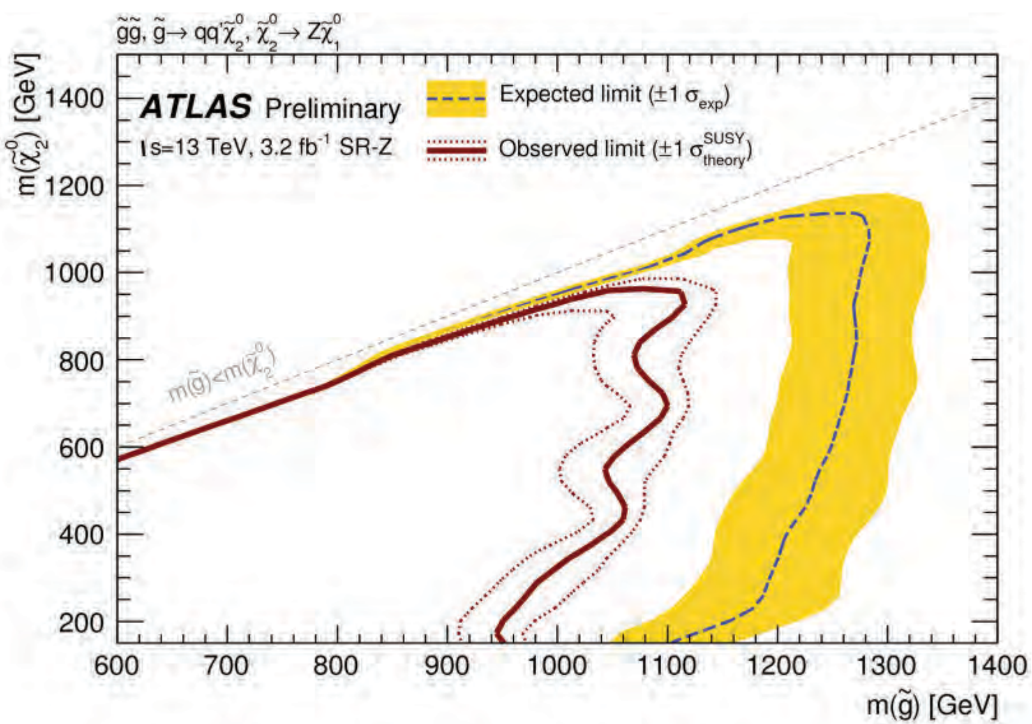


This is identical to the ATLAS selection

CMS Vs ATLAS


CMS Preliminary
2.2 fb^{-1} (13 TeV)
pp → g̃ g̃, g̃→ 2j+χ̃$_1^0$,χ̃$_1^0$→ ZG̃; NLO+NLL exclusion
Expected limit, ± 1 σ$_{exp.}$
Observed limit, ± 1 σ$_{theory}$
95% CL upper limit on σ [pb]
m$_{\tilde{g}}$ [GeV]
m$_{\tilde{\chi}_1^0}$ [GeV]


p
p
q
q
q
q
Z
Z
$\tilde{g}$
$\tilde{g}$
$\tilde{\chi}_2^0$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$


g̃g̃, g̃→ qq'χ̃$_2^0$, χ̃$_2^0$→ Zχ̃$_1^0$
ATLAS Preliminary
√s=13 TeV, 3.2 fb^{-1} SR-Z
Expected limit (±1 σ$_{exp}$)
Observed limit (±1 σ$^{SUSY}_{theory}$)
m(g̃)<m(χ̃$_2^0$)
m(χ̃$_2^0$) [GeV]
m(g̃) [GeV]

Summarising

Conclusions

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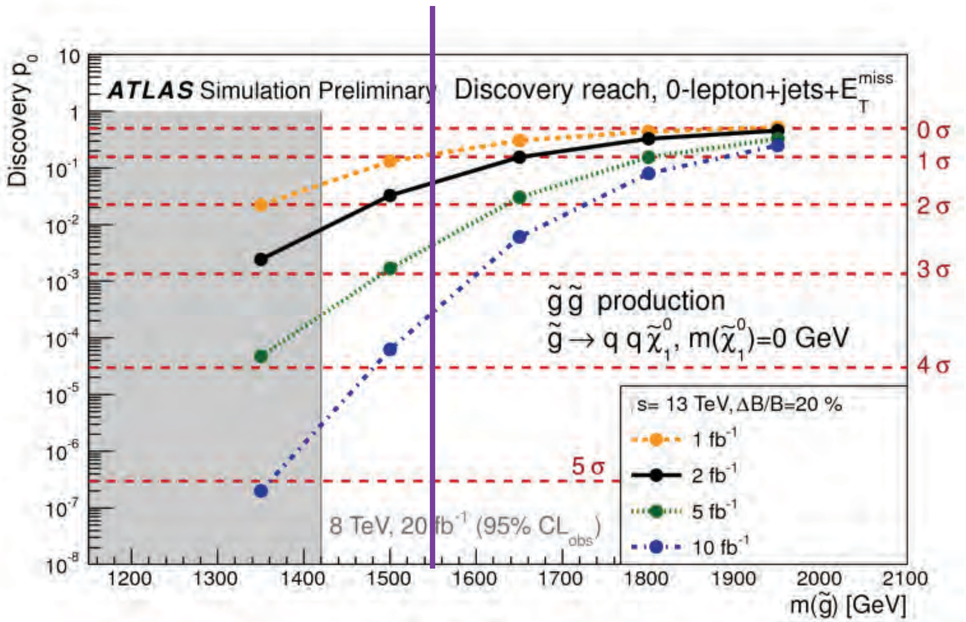
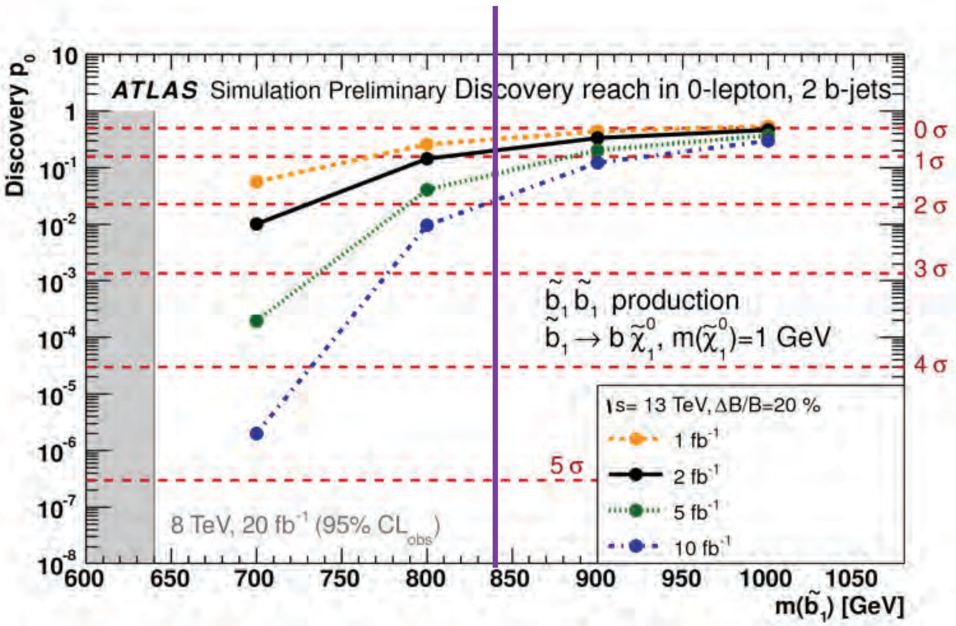
- A nice **restart of the LHC**
- SUSY searches **sensitive to gluino production** mostly
- No discovery, but **some interesting excess** to be followed up
- 2016 (30 fb^{-1} foreseen) **will overcome SUSY sensitivity** for all production mechanisms





BACKUP

Z+jets excess

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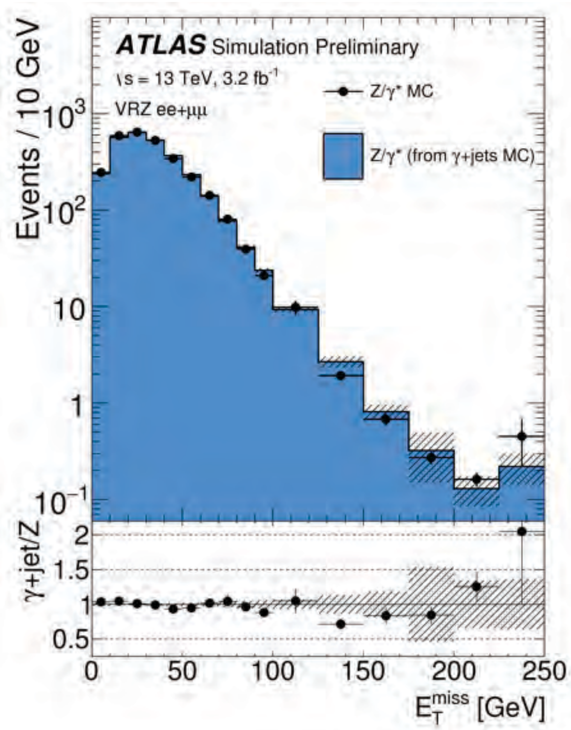
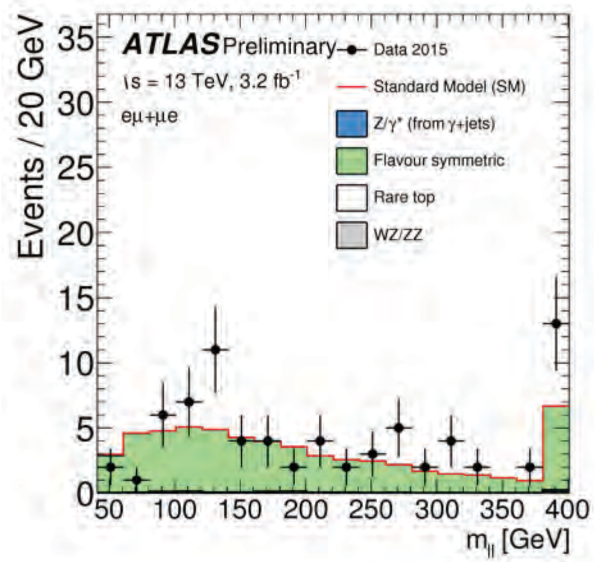
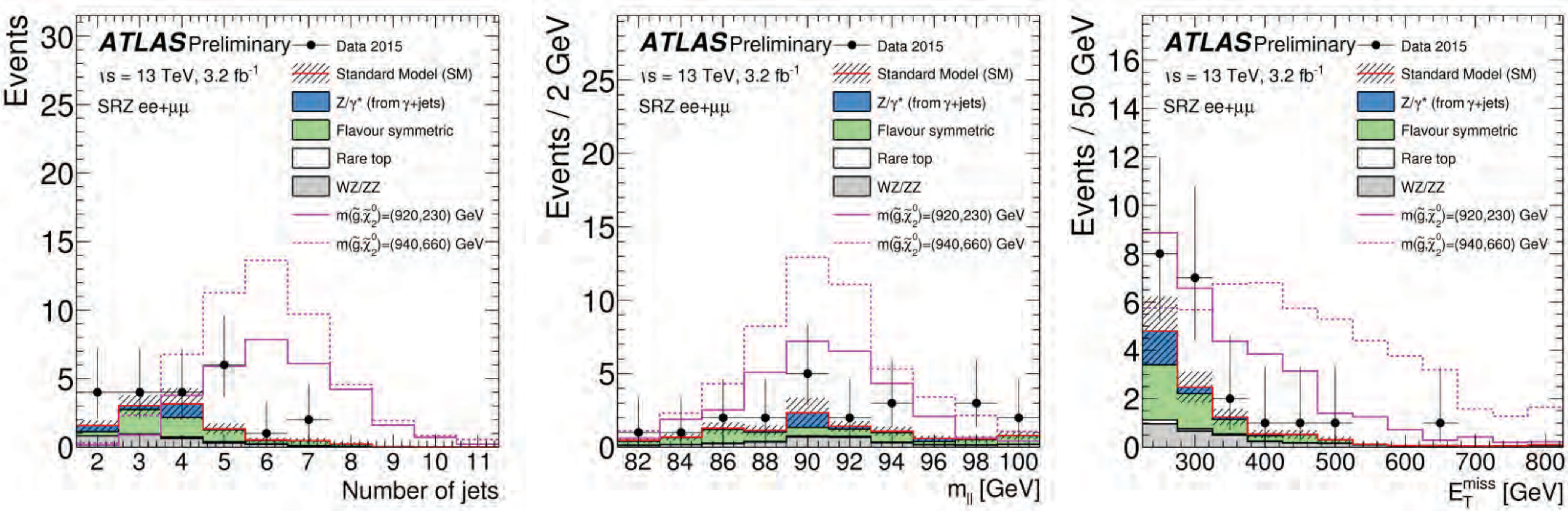
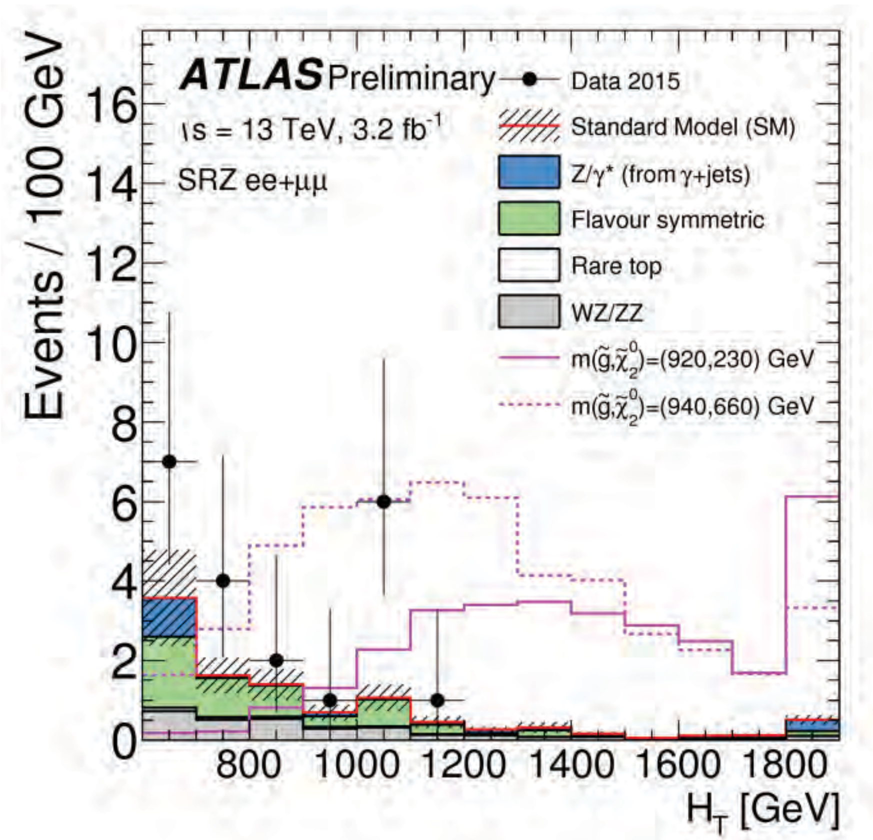
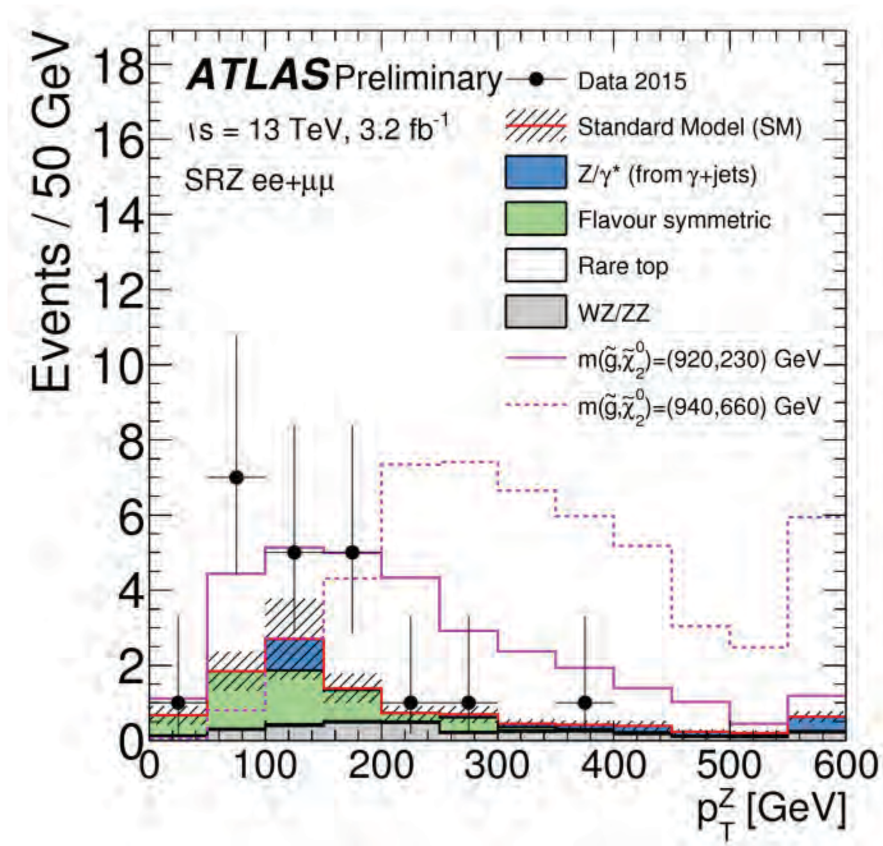






ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
SRZ ee+μμ
Data 2015
Standard Model (SM)
Z/γ* (from γ+jets)
Flavour symmetric
Rare top
WZ/ZZ
m(g̃,χ̃20)=(920,230) GeV
m(g̃,χ̃20)=(940,660) GeV
Events
Number of jets
Events / 2 GeV
m_ll [GeV]
Events / 50 GeV
E_T^miss [GeV]


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
SRZ ee+μμ
Data 2015
Standard Model (SM)
Z/γ* (from γ+jets)
Flavour symmetric
Rare top
WZ/ZZ
m(g̃,χ̃20)=(920,230) GeV
m(g̃,χ̃20)=(940,660) GeV
Events / 100 GeV
H_T [GeV]
0
2
4
6
8
10
12
14
16
800
1000
1200
1400
1600
1800


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
SRZ ee+μμ
Data 2015
Standard Model (SM)
Z/γ* (from γ+jets)
Flavour symmetric
Rare top
WZ/ZZ
m(g̃,χ̃20)=(920,230) GeV
m(g̃,χ̃20)=(940,660) GeV
Events / 50 GeV
p_T^Z [GeV]
0
2
4
6
8
10
12
14
16
18
100
200
300
400
500
600

Region	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	H_{T} [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	$\Delta\phi(\mathrm{jet}_{12}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})$	$m_{\mathrm{T}}(\ell_3, E_{\mathrm{T}}^{\mathrm{miss}})$ [GeV]	$n_{\mathrm{b\text{-}jets}}$
Signal regions								
SRZ	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	-	-
Control regions								
Z normalisation	< 60	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	-	-
CR-FS	> 225	> 600	≥ 2	$61 < m_{\ell\ell} < 121$	DF	> 0.4	-	-
CRT	> 225	> 600	≥ 2	$m_{\ell\ell} \notin [81, 101]$	SF	> 0.4	-	-
Validation regions								
VRZ	< 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	-	-
VRT	100–200	> 600	≥ 2	$m_{\ell\ell} \notin [81, 101]$	SF	> 0.4	-	-
VRS	100–200	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	-	-
VR-FS	100–200	> 600	≥ 2	$61 < m_{\ell\ell} < 121$	DF	> 0.4	-	-
VR-WZ	100–200	-	-	-	3ℓ	-	< 100	0
VR-ZZ	< 100	-	-	-	4ℓ	-	-	0
VR-3L	60–100	> 200	≥ 2	$81 < m_{\ell\ell} < 101$	3ℓ	> 0.4	-	-

	VRS	VR-WZ	VR-ZZ	VR-3L
Observed events	56	89	20	7
Total expected background events	52.6 ± 9.1	87 ± 10	15.5 ± 3.4	6.5 ± 1.6
Flavour symmetric ($t\bar{t}$, Wt, WW and $Z \rightarrow \tau\tau$) events	18.9 ± 4.8	1.3 ± 0.4	0	0.3 ± 0.2
WZ/ZZ events	7.5 ± 1.7	82 ± 10	15.5 ± 3.4	4.9 ± 1.6
$Z/\gamma^* +$ jets events	24.8 ± 7.6	2.7 ± 2.8	0	0.2 ± 0.2
Rare top events	1.4 ± 0.2	0.9 ± 0.4	0.04 ± 0.02	1.0 ± 0.1

Region	Flavour-symmetry	Sideband fit
SRZ	5.1 ± 2.0	6.1 ± 1.7
VRS	18.9 ± 4.8	20.5 ± 5.6

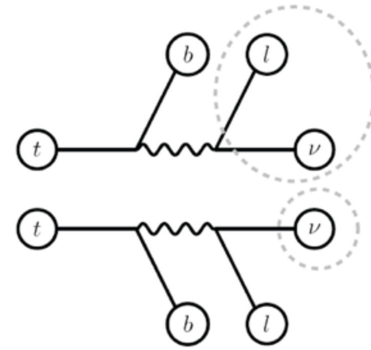
	SRZ
Observed events	21
Total expected background events	10.3 ± 2.3
Flavour symmetric ($t\bar{t}$, Wt, WW and $Z \rightarrow \tau\tau$) events	5.1 ± 2.0
WZ/ZZ events	2.9 ± 0.8
$Z/\gamma^* +$ jets events	1.9 ± 0.8
Rare top events	0.4 ± 0.1
p-value	0.013
Significance	2.2
Observed (Expected) S^{95}	$20.0\ (10.2^{+4.4}_{-3.0})$

Source	Relative systematic uncertainty [%]
	SRZ
Total systematic uncertainty	22
Flavour symmetry (statistical)	14
Flavour symmetry (systematic)	12
$Z/\gamma^* +$ jets (systematic)	7.8
WZ generator uncertainty	7.6
$Z/\gamma^* +$ jets (statistical)	2.2

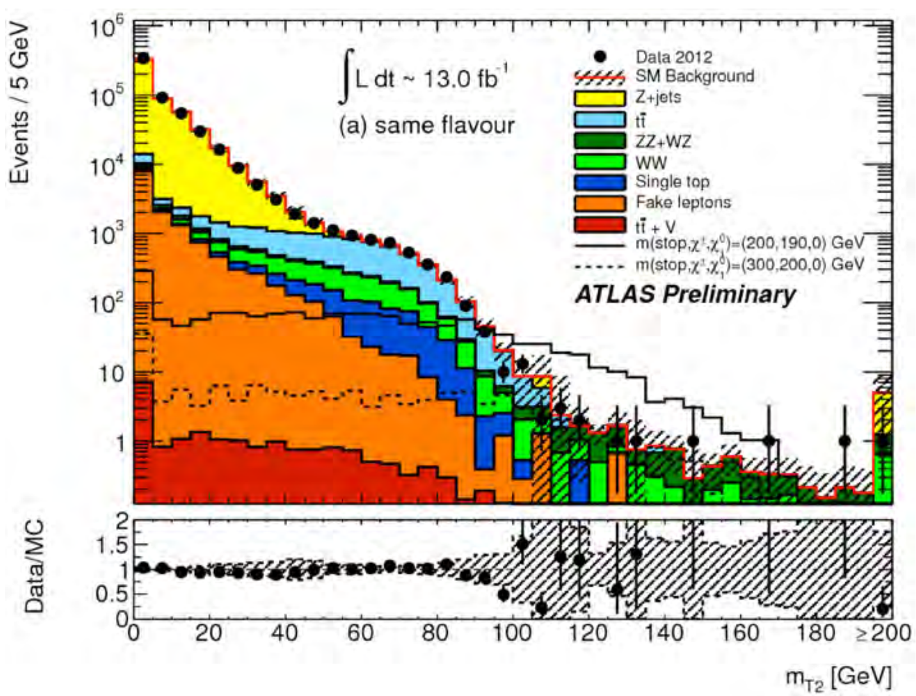
Heavy use of kinematical end-points

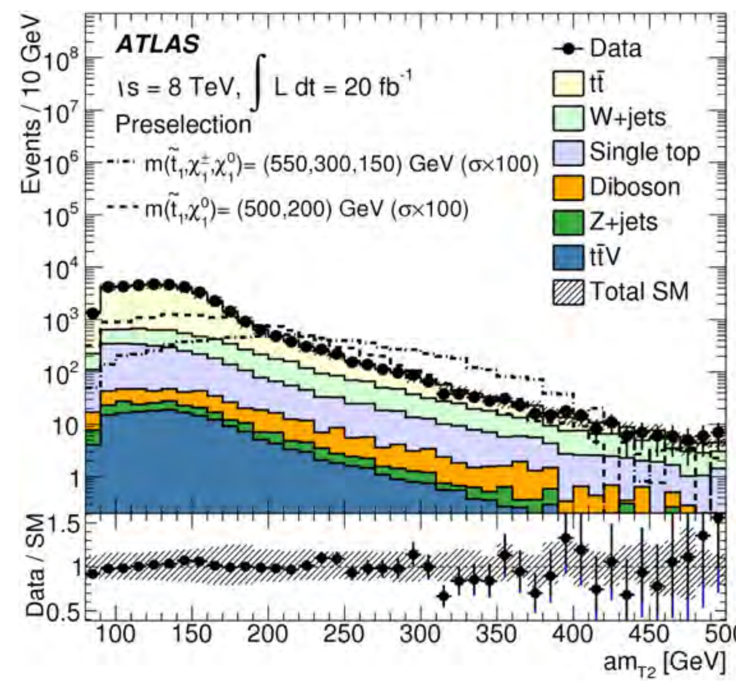
- mT2: an extension of the transverse mass variable

$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{\text{miss}}} \left\{ \max[\, m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T)\,] \right\}$$



- amT2: a generalisation of the mT2





Parameters and masses

Neutralinos

$$\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0)$$

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\widetilde{N}} \psi^0 + \text{c.c.}$$

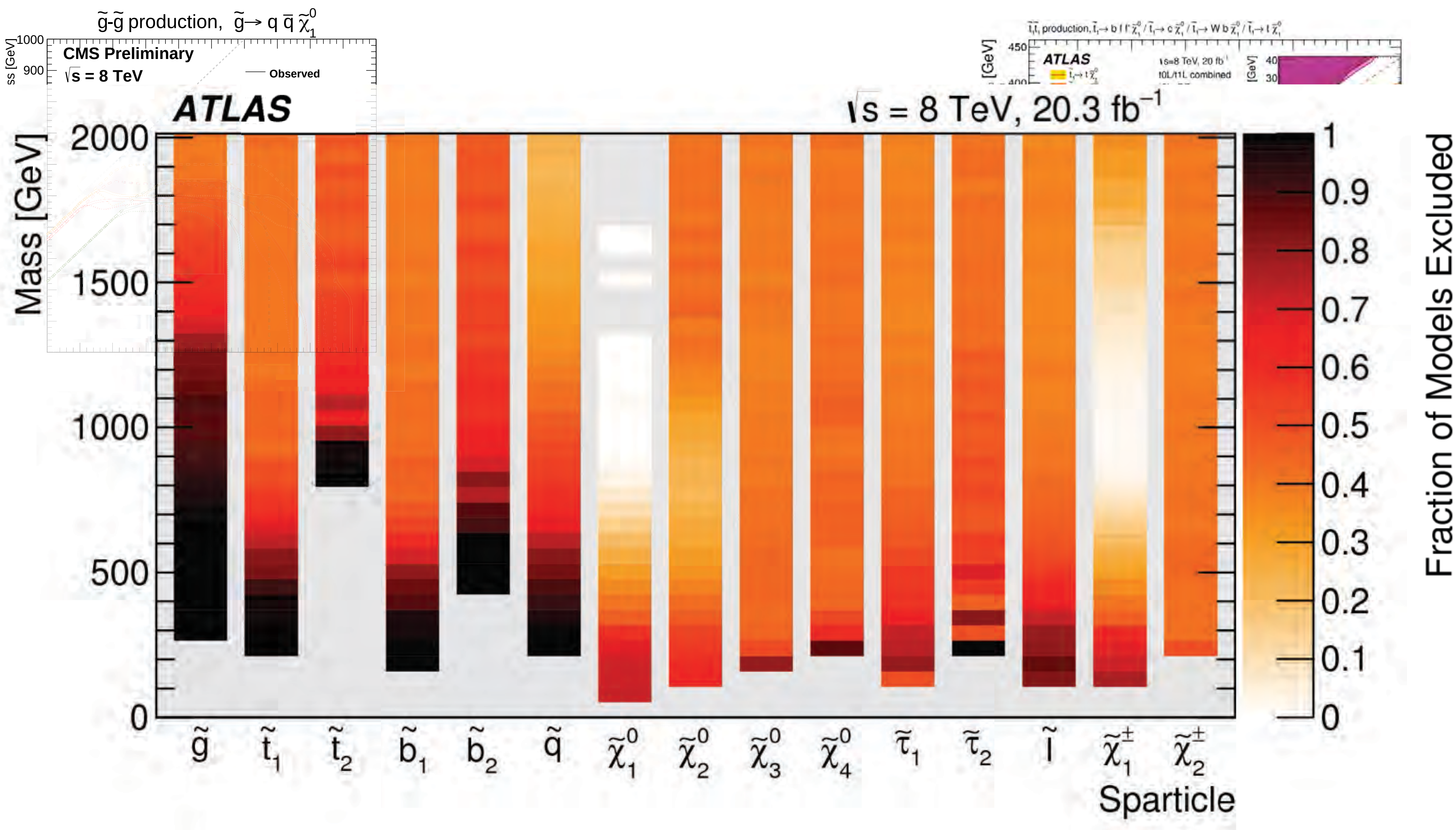
$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

Stops and sbottoms

$$\mathbf{m}^2_{\tilde{\mathbf{t}}} = \begin{pmatrix} m^2_{Q_3} + m_t^2 + \Delta_{\tilde{u}_L} & v(a_t^* \sin\beta - \mu y_t \cos\beta) \\ v(a_t \sin\beta - \mu^* y_t \cos\beta) & m^2_{\overline{u}_3} + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}$$

$$\mathbf{m}^2_{\tilde{\mathbf{b}}} = \begin{pmatrix} m^2_{Q_3} + \Delta_{\tilde{d}_L} & v(a_b^* \cos\beta - \mu y_b \sin\beta) \\ v(a_b \cos\beta - \mu^* y_b \sin\beta) & m^2_{\overline{d}_3} + \Delta_{\tilde{d}_R} \end{pmatrix}$$

But…



g̃-g̃ production, g̃→ q q̄ χ̃$_1^0$
CMS Preliminary
√s = 8 TeV
Observed
ATLAS
√s = 8 TeV, 20.3 fb^{-1}
Mass [GeV]
2000
1500
1000
500
0
g̃
t̃$_1$
t̃$_2$
b̃$_1$
b̃$_2$
q̃
χ̃$_1^0$
χ̃$_2^0$
χ̃$_3^0$
χ̃$_4^0$
τ̃$_1$
τ̃$_2$
l̃
χ̃$_1^\pm$
χ̃$_2^\pm$
Sparticle
Fraction of Models Excluded
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0