SUperSYmmetry
A Report from the Front

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Outline

- ☐ Introduction
- ☐ What is supersymmetry?
- ☐ What have we learned?
- ☐ Summary & Conclusions

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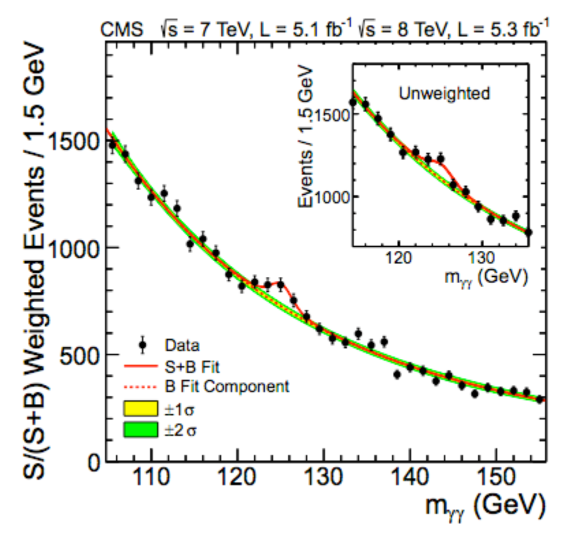
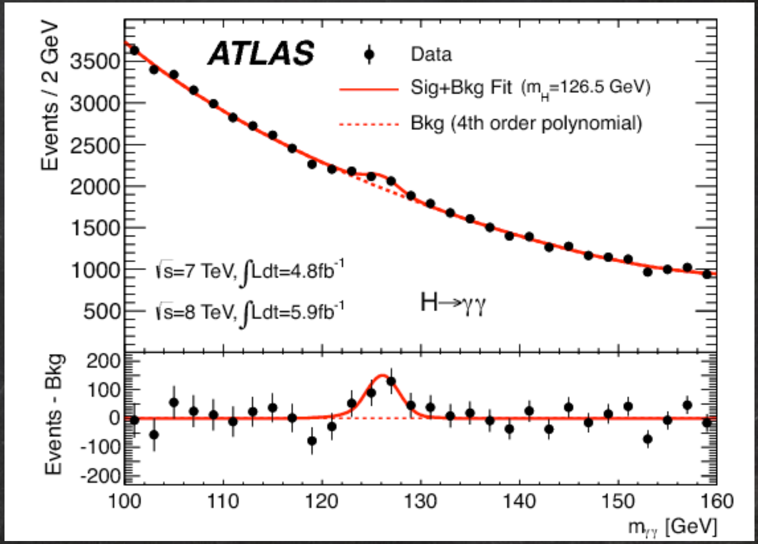
Introduction

The most significant result from the LHC is clearly the discovery of the neutral scalar Higgs boson.





$m_H = 125.09 \pm 0.21 \pm 0.11$ GeV

CMS & ATLAS, Phys. Rev. Lett. **114**, 191803 (2015)

Introduction

But, also of potentially monumental significance is the absence (so far) of credible evidence for new physics, in particular, for supersymmetry.

If, by the end, of the LHC era it is shown that supersymmetry is irrelevant at the TeV scale, this would be a profound discovery. It might signal that an understanding of physics the TeV scale requires an understanding of physics at a scale many orders of magnitude greater.

Takemichi Okui

Introduction

But, we are not yet able to dismiss the supersymmetry hypothesis and many particle physicists remain gung-ho about it!

Keep the (S)Faith!

John Ellis

KING'S College LONDON

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What is Supersymmetry?

- A supersymmetry operation Q transforms a bosonic state into a fermionic one and vice versa:

  Q |boson> = |fermion>

  Q |fermion> = |boson>

- By adding appropriate structures to the Standard Model, it is possible to create versions of it that are invariant under this operation. The simplest such model is called the minimal supersymmetric extension of the SM (MSSM).

But, why do this? The SM is, after all, spectacularly successful.

What is Supersymmetry?

Here are the principal reasons:

1. In the SM, the quantum correction to the Higgs boson mass is given by

$$m_H^2 = -m_{\text{bare}}^2 + \frac{y_t^2}{16\pi^2}\Lambda^2 + \cdots$$

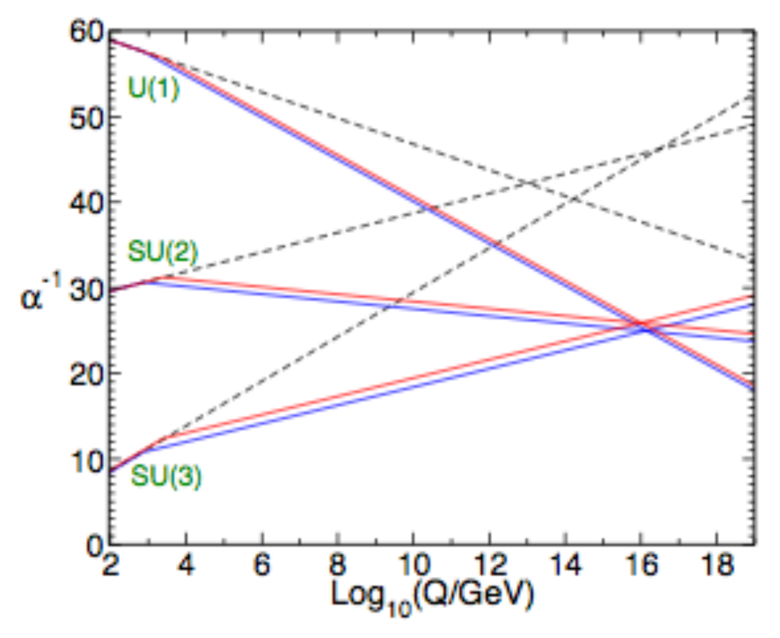
m_{bare}	Langrangian parameter
y_t	top Yukawa coupling
Λ	cut-off

Since, in principle, $\Lambda \sim 10^{18}$ GeV, one has to fine-tune the bare mass parameter with enormous precision in order to get the measured value of the Higgs boson mass.

However, fine-tuning is unnecessary in a theory invariant under supersymmetry because such terms cancel *exactly*.

What is Supersymmetry?

2. In a supersymmetric theory, it is possible to arrange for the coupling constants of the three forces to unify at a scale ~ O(10^{16}) GeV.



Stephen P. Martin, https://arxiv.org/pdf/hep-ph/9709356.pdf

The MSSM

The quantum number (R-parity)

$$R = (-1)^{3(B-L) + S}$$

B = Baryon number
L = Lepton number
S = Spin

is +1 for every SM particle and -1 for every supersymmetric particle (or super-particle, or sparticle)

In the usual definition of the MSSM, R-parity is conserved. Consequently, super-particles are predicted to be created in *pairs* and the lightest is absolutely stable. If the lightest super-particle (LSP) is *neutral* and *weakly* interacting, it is a dark matter candidate.

The MSSM

Supersymmetric Particle Content:

neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$1/2$	
charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$1/2$	Fermions
gluinos	$\tilde{g}$	$1/2$	
Higgs bosons	$h^0, H^0, A^0, H^\pm$	0	
sleptons	$\tilde{e}_{L,R}, \tilde{\mu}_{L,R}, \tilde{\tau}_{1,2}$	0	
	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	0	Bosons
squarks	$\tilde{u}_{L,R}, \tilde{c}_{L,R}, \tilde{t}_{1,2}$	0	
	$\tilde{d}_{L,R}, \tilde{s}_{L,R}, \tilde{b}_{1,2}$	0	

The MSSM

Hadron collider reactions:

Electroweak

$$q\vec{q} \rightarrow \tilde{\chi}_i^+\tilde{\chi}_j^-, \quad \tilde{\chi}_i^0\tilde{\chi}_j^0, \quad \tilde{l}_i^+\tilde{l}_j^-, \quad \tilde{\nu}_l\tilde{\nu}_l^*$$

$$u\bar{d} \rightarrow \tilde{\chi}_i^+\tilde{\chi}_j^0, \quad \tilde{l}_L^+\tilde{\nu}_l$$

$$d\bar{u} \rightarrow \tilde{\chi}_i^-\tilde{\chi}_j^0, \quad \tilde{l}_L^-\tilde{\nu}_l^*$$

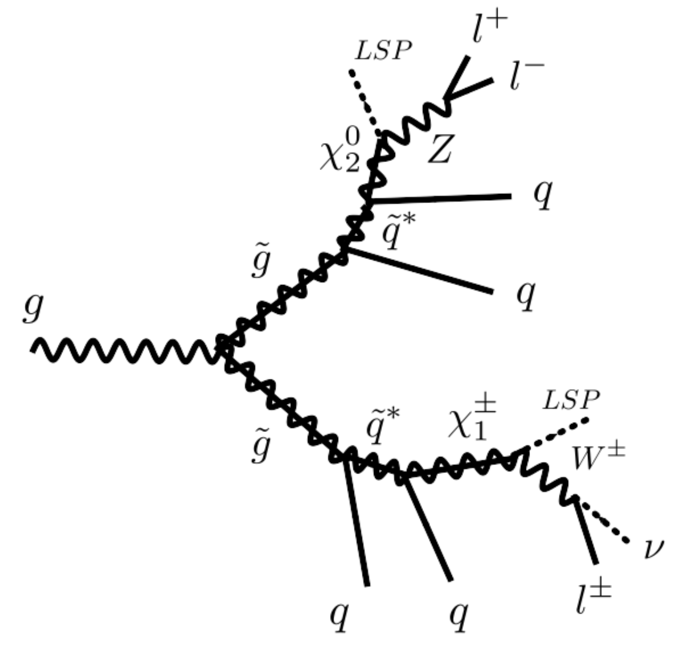
Strong

$$gg \rightarrow \tilde{g}\tilde{g}, \quad \tilde{q}_i\tilde{q}_j^*$$

$$q\vec{q} \rightarrow \tilde{g}\tilde{g}, \quad \tilde{q}_i\tilde{q}_j^*$$

$$gq \rightarrow \tilde{g}\tilde{q}_i$$

$$qq \rightarrow \tilde{q}_i\tilde{q}_j$$



* antiparticles

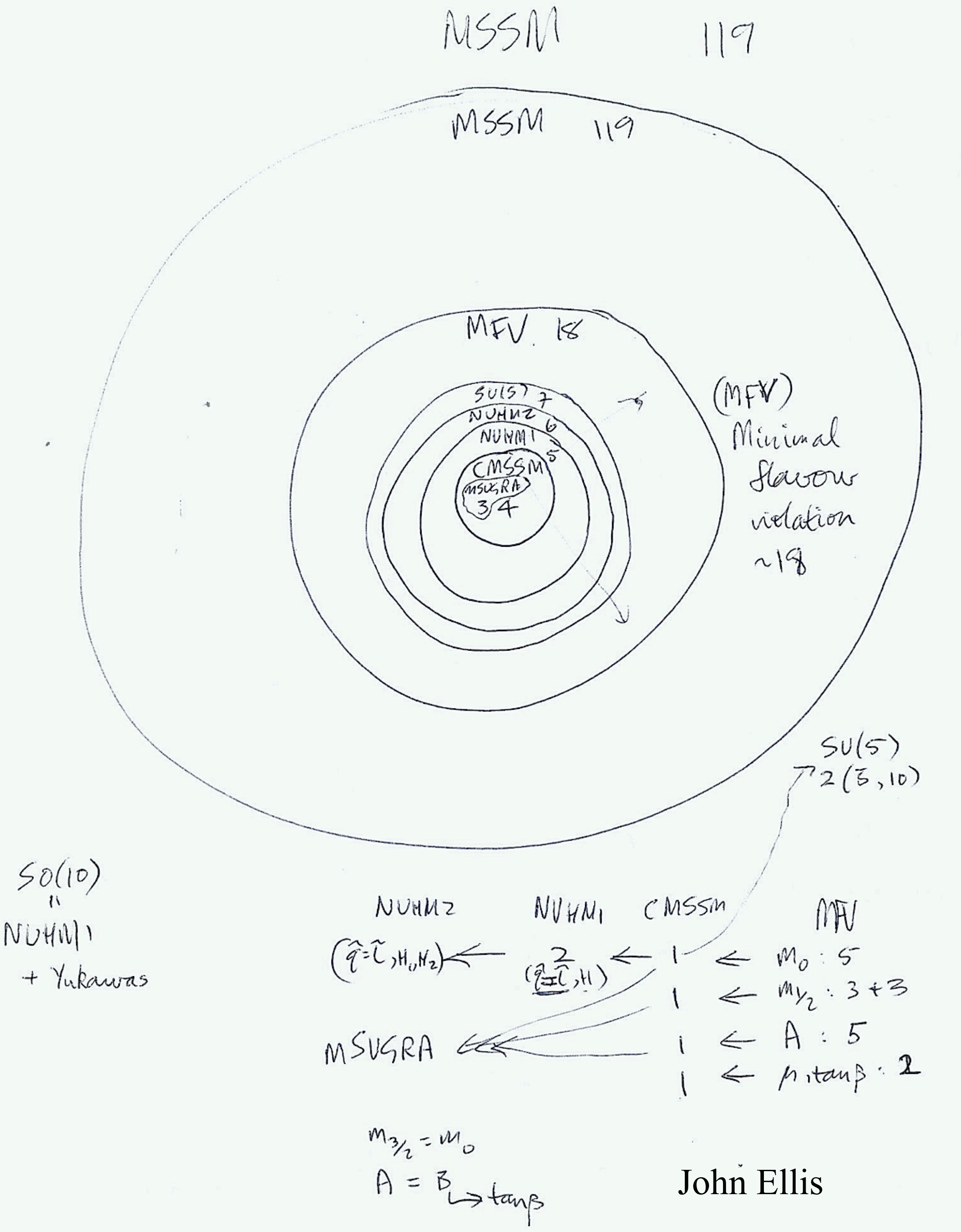
The MSSM

No supersymmetric particles with the same mass as the corresponding SM particle have been found, therefore, the ground state of the Universe is clearly not supersymmetric.

In order to accommodate this fact, extra structure has been added to the MSSM (and its variants), consistent with the symmetry of the SM, that breaks (or hides) the supersymmetry.

Alas, this causes the number of parameters to explode from the 19 of the SM to the 19 + 105 = 124 of the MSSM!

Model	**# Pars.**
mSUGRA	3
CMSSM	4
NUHM1	5
NUHM2	6
SU(5)	7
pMSSM	19
MSSM	124



John Ellis

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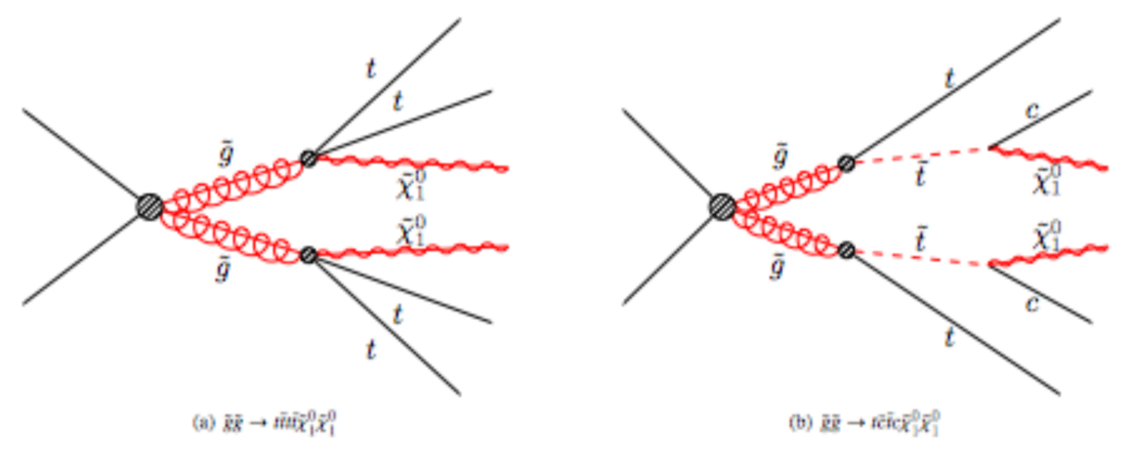
Interpretation Using Simplified Models

Supersymmetry search results at the LHC are often interpreted in terms of simplified models (SMS) or models that posit specific SUSY-breaking schemes, e.g., the constrained MSSM (CMSSM).



(a) $\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$

(b) $\tilde{g}\tilde{g} \rightarrow t\bar{c}\bar{t}c\tilde{\chi}_1^0\tilde{\chi}_1^0$

simplified models

Typical Hadron Observables

$$\vec{p}_T^{\,\text{miss}} + \sum_{\text{jets}} \vec{p}_{T,i} + \sum_{\text{leptons}} \vec{p}_{T,i} + \sum_{\text{photons}} \vec{p}_{T,i} = 0, \quad E_T^{\text{miss}} = \left|\vec{p}_T^{\,\text{miss}}\right|$$

$$H_T = \sum_{\text{jets}} \left|\vec{p}_{T,i}\right|$$

$$S_T = \sum_{\text{jets}} \left|\vec{p}_{T,i}\right| + E_T^{\text{miss}}$$

$$m_T = \sqrt{2 p_{T,l} E_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{p}_{T,i}, \vec{p}_T^{\,\text{miss}})]}$$

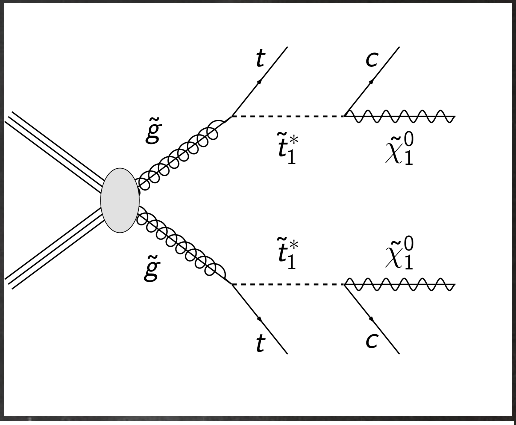
$$M_R = \sqrt{(p_{j1} + p_{j2})^2 - (p_{j1,z} + p_{j2,z})^2}$$

$$R^2 = \left(E_T^{\text{miss}} (p_{j1,T} + p_{j2,T}) - \vec{p}_T^{\,miss} \cdot (\vec{p}_{j1} + \vec{p}_{j2})\right) / \left(2 M_R^2\right)$$

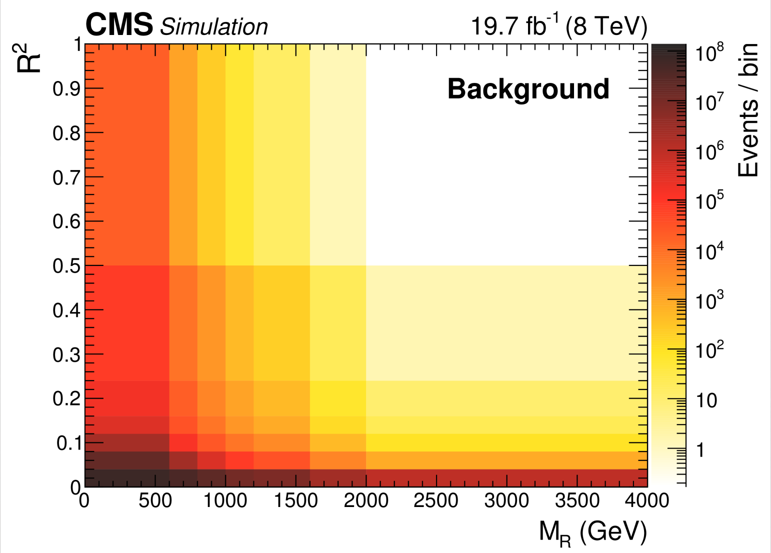
Chris Rogan, “Kinematical variables towards new dynamics at the LHC” arXiv:1006.2727v2

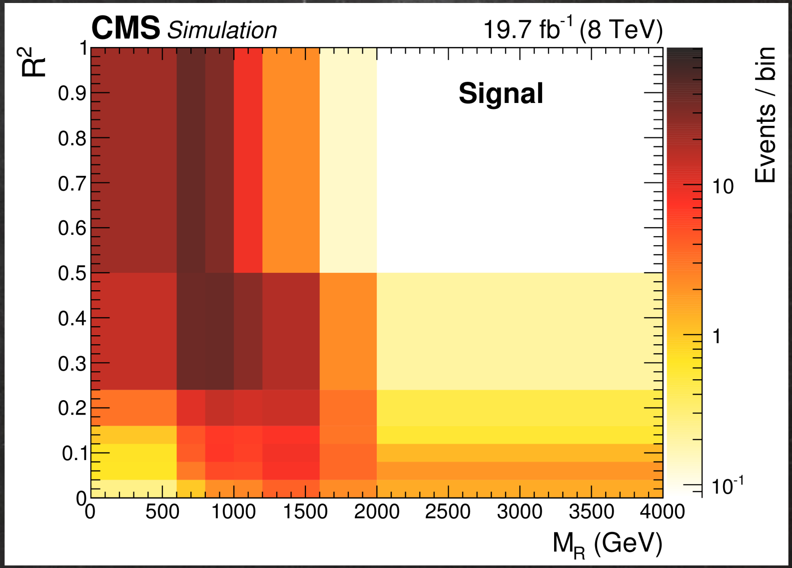
Example: CMS Search Using Razor

Search using boosted W bosons and razor variables



$$m_{\tilde{g}} = 1\text{ TeV}, m_{\tilde{t}_1} = 0.325\text{ TeV}, m_{\tilde{\chi}_1^0} = 0.300\text{ TeV}$$





CMS collaboration, "Search for supersymmetry in pp collisions at √s= 8 TeV in final states with boosted W bosons and b jets using razor variables", Phys. Rev. D **93** (2016) 092009

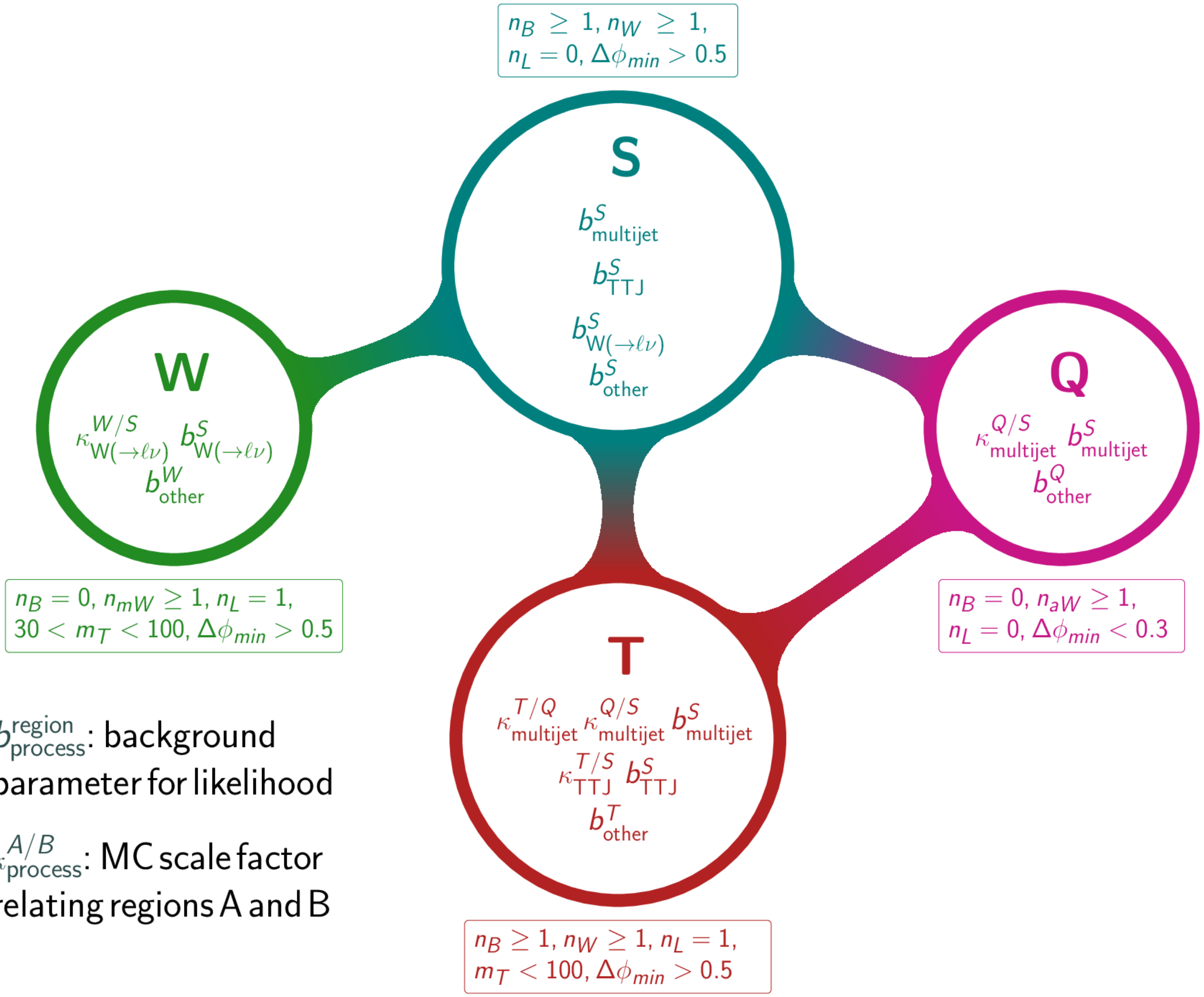
Signal Region

S

Control Regions

W	W boson
Q	QCD
T	top

Control regions used to model background in signal region



$n_B \geq 1, n_W \geq 1,$
$n_L = 0, \Delta\phi_{min} > 0.5$

S

b^S_{multijet}
b^S_{TTJ}
$b^S_{\text{W}(\to\ell\nu)}$
b^S_{other}

W

$\kappa^{W/S}_{\text{W}(\to\ell\nu)}$ $b^S_{\text{W}(\to\ell\nu)}$
b^W_{other}

$n_B = 0, n_{mW} \geq 1, n_L = 1,$
$30 < m_T < 100, \Delta\phi_{min} > 0.5$

Q

$\kappa^{Q/S}_{\text{multijet}}$ b^S_{multijet}
b^Q_{other}

$n_B = 0, n_{aW} \geq 1,$
$n_L = 0, \Delta\phi_{min} < 0.3$

T

$\kappa^{T/Q}_{\text{multijet}}$ $\kappa^{Q/S}_{\text{multijet}}$ b^S_{multijet}
$\kappa^{T/S}_{\text{TTJ}}$ b^S_{TTJ}
b^T_{other}

$n_B \geq 1, n_W \geq 1, n_L = 1,$
$m_T < 100, \Delta\phi_{min} > 0.5$

$b^{\text{region}}_{\text{process}}$: background parameter for likelihood

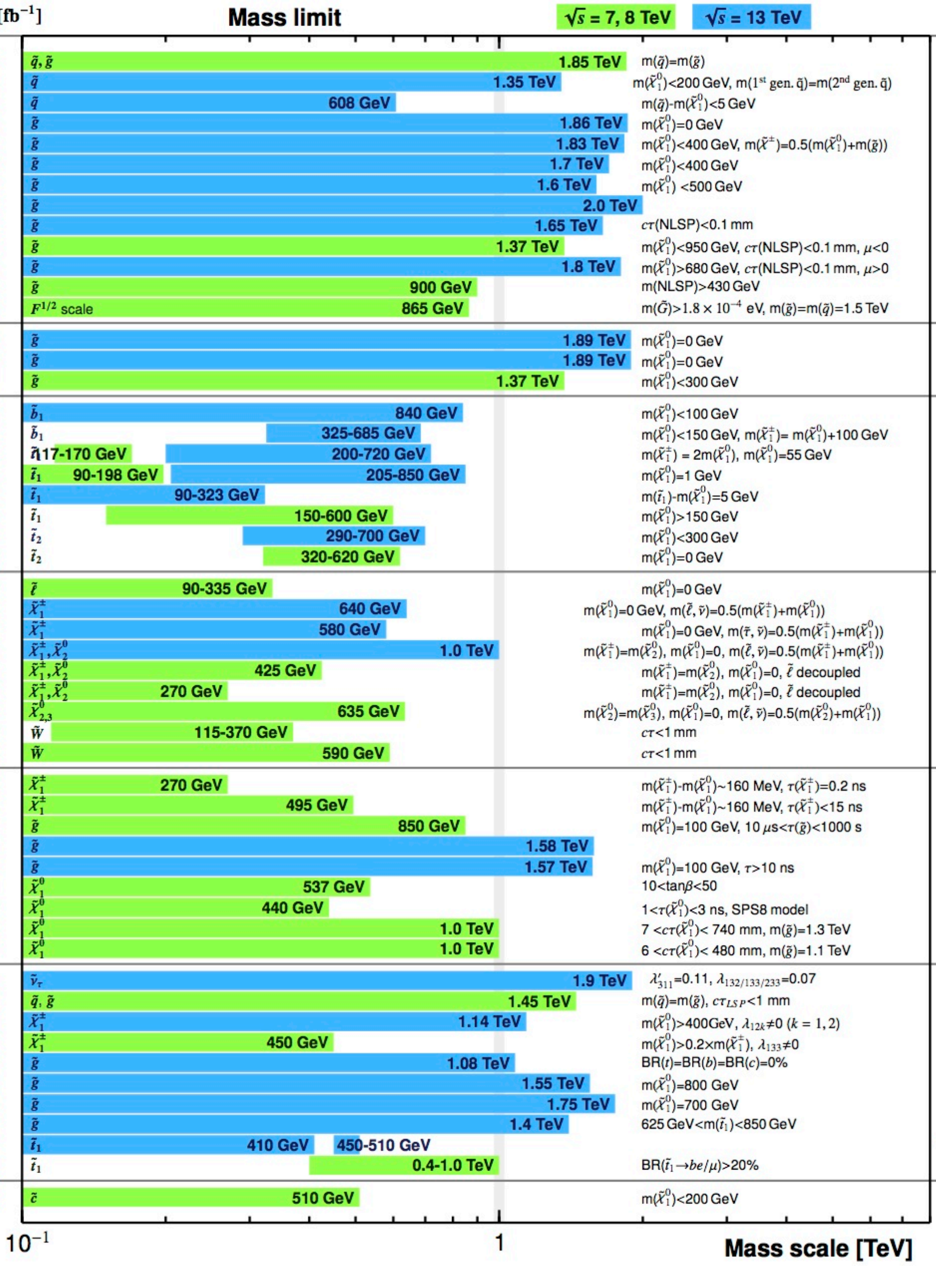
$\kappa^{A/B}_{\text{process}}$: MC scale factor relating regions A and B

CMS collaboration, "Search for supersymmetry in pp collisions at √s= 8 TeV in final states with boosted W bosons and b jets using razor variables", Phys. Rev. D **93** (2016) 092009

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

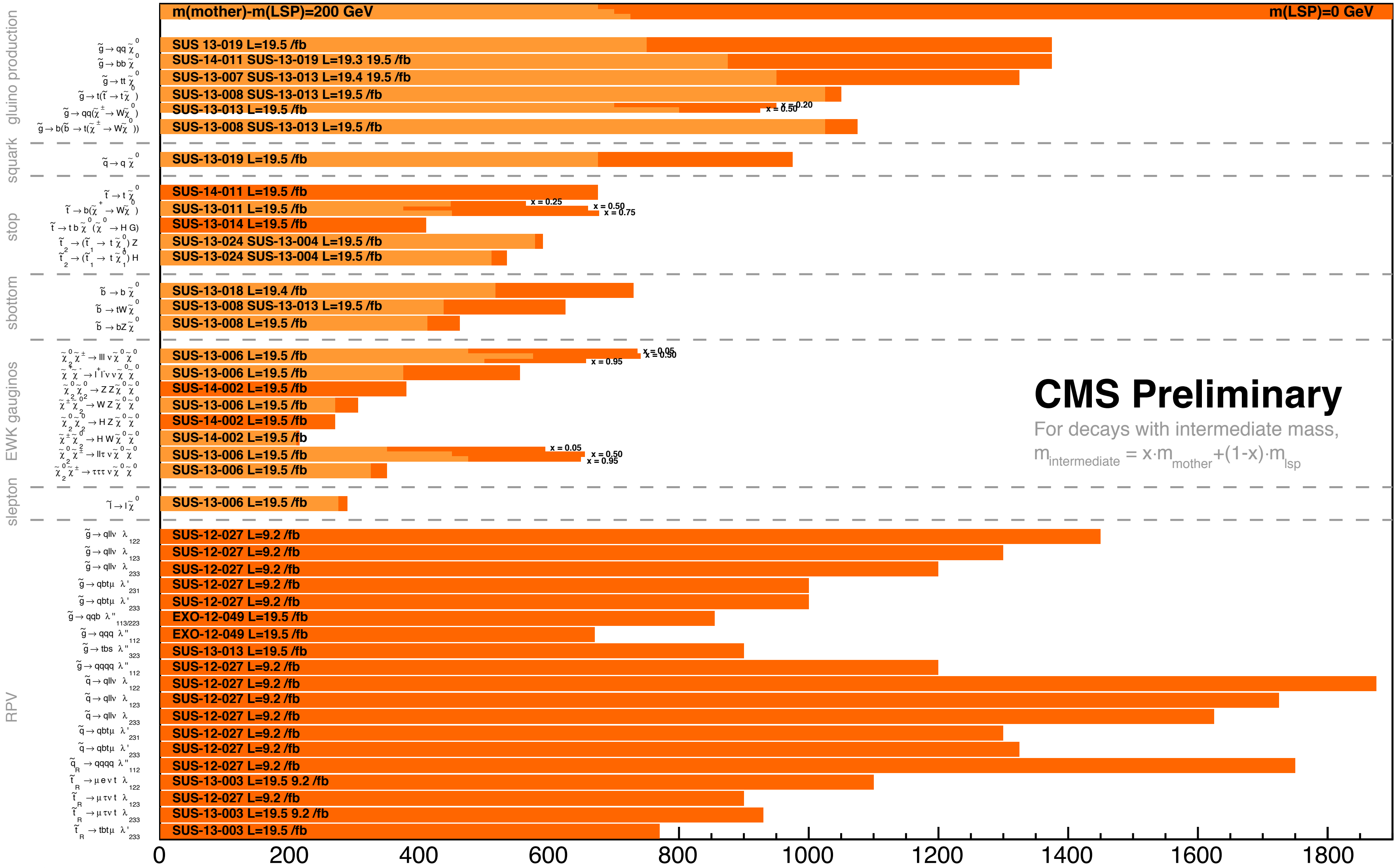


	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{q}$ 1.35 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.86 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^{\pm}_1\rightarrow qqW^{\pm}\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$ 1.83 TeV	m($\tilde{\chi}^0_1$)<400 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	13.2	🟦 $\tilde{g}$ 1.7 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}^0_1$	2 e,μ (SS)	0-3 jets	Yes	13.2	🟦 $\tilde{g}$ 1.6 TeV	m($\tilde{\chi}^0_1$) <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	14.8	🟦 $\tilde{g}$ 1.89 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$ 840 GeV	m($\tilde{\chi}^0_1$)<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}^{\pm}_1$	2 e,μ (SS)	1 b	Yes	13.2	🟦 $\tilde{b}_1$ 325-685 GeV	m($\tilde{\chi}^0_1$)<150 GeV, m($\tilde{\chi}^{\pm}_1$)= m($\tilde{\chi}^0_1$)+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}^{\pm}_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	🟩 $\tilde{t}_1$ 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}^{\pm}_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	🟩 $\tilde{t}_1$ 90-198 GeV 🟦 205-850 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	13.3	🟦 $\tilde{t}_2$ 290-700 GeV	m($\tilde{\chi}^0_1$)<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$ 320-620 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-335 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^{\pm}_1$ 640 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-096
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	🟦 $\tilde{\chi}^{\pm}_1$ 580 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-093
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_2$ 1.0 TeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-096
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\rightarrow W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_2$ 425 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\rightarrow W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_2$ 270 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^0_{2,3}$ 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	Disapp. trk	1 jet	Yes	20.3	🟩 $\tilde{\chi}^{\pm}_1$ 270 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}^{\pm}_1$ 495 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}^0_1$ 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	6 <$c\tau$($\tilde{\chi}^0_1$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}$, $\tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow ee\nu$, $e\mu\nu$, $\mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}^{\pm}_1$ 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow\tau\tau\nu_e$, $e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	🟩 $\tilde{\chi}^{\pm}_1$ 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^{\pm}_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	m($\tilde{\chi}^0_1$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow qqq$	1 e,μ	8-10 jets/0-4 b	-	14.8	🟦 $\tilde{g}$ 1.75 TeV	m($\tilde{\chi}^0_1$)=700 GeV	ATLAS-CONF-2016-094
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	1 e,μ	8-10 jets/0-4 b	-	14.8	🟦 $\tilde{g}$ 1.4 TeV	625 GeV<m($\tilde{t}_1$)<850 GeV	ATLAS-CONF-2016-094
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$ 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\rightarrow be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

**Only a selection of the available mass limits on new states or phenomena is shown.*

Summary of CMS SUSY Results* in SMS framework

ICHEP 2014

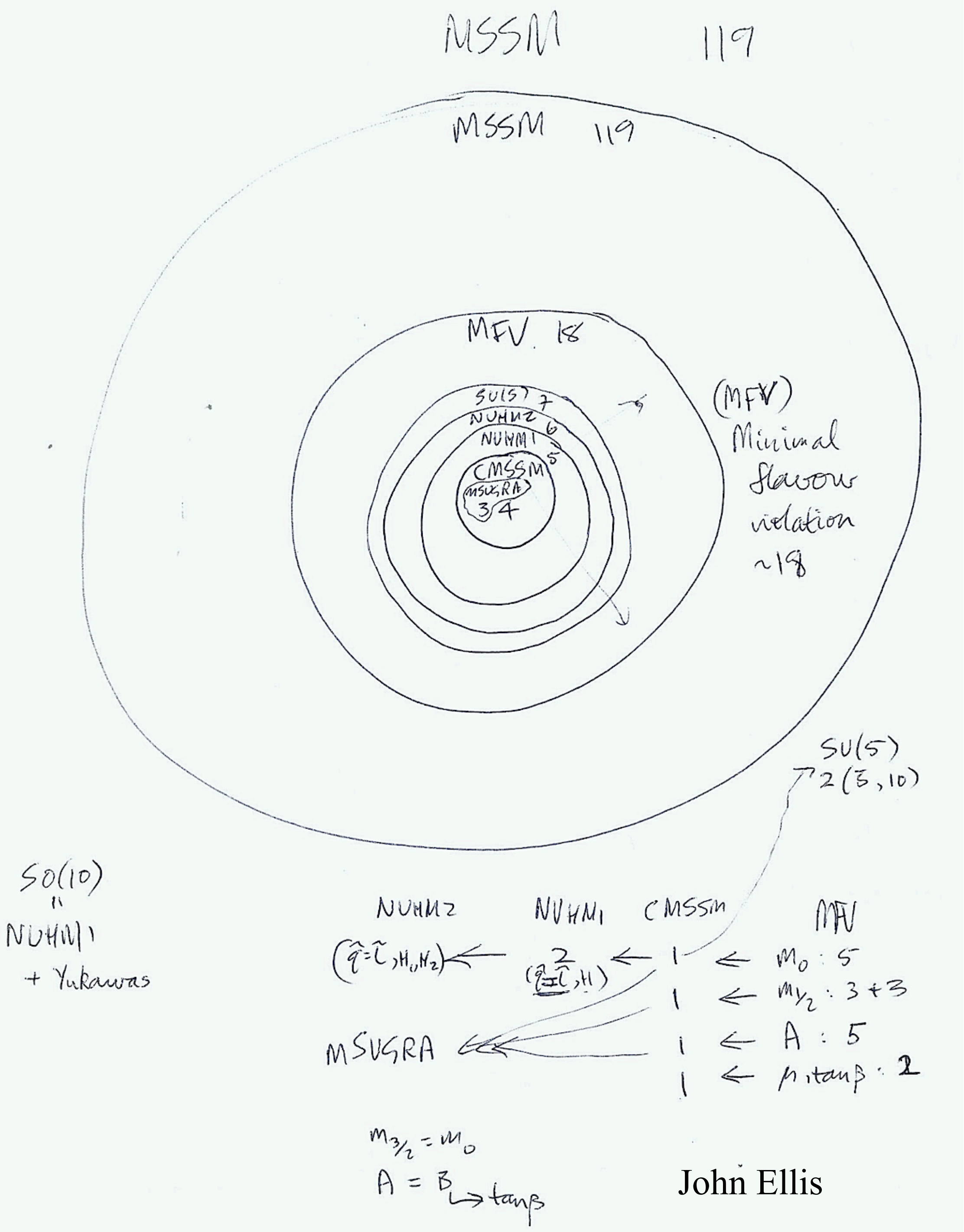


*Observed limits, theory uncertainties not included

Only a selection of available mass limits

Probe *up to* the quoted mass limit

Model	**# Pars.**
mSUGRA	3
CMSSM	4
NUHM1	5
NUHM2	6
SU(5)	7
pMSSM	19
MSSM	124



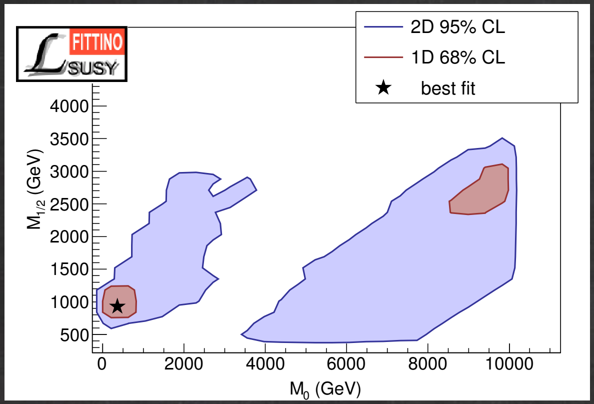
John Ellis

The CMSSM

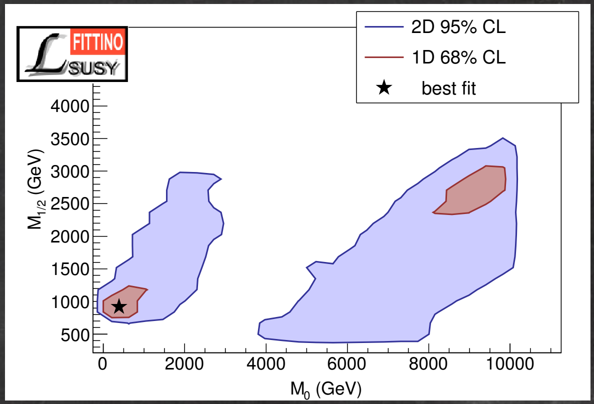
There have been many studies of the CMSSM assessing its status after the 7 and 8 TeV runs of the LHC, including:

1. “The CMSSM and NUHM1 after LHC Run 1”, O. Buchmueller *et al*., Eur. Phys. J. **C74** (2014), 2922
2. “Experimental status of supersymmetry after the LHC Run-1”, C. Autermann, Prog. Part. Nucl. Phys. **90** (2016) 125
3. “Killing the cMSSM softly”, P. Bechtle *et al.*, Eur. Phys. J. **C76** (2016), 96

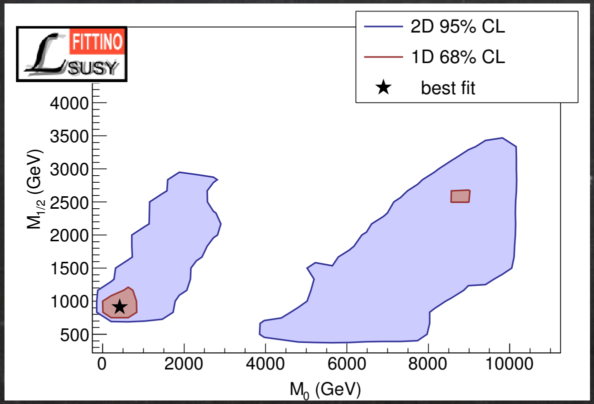
Best Fit to CMSSM



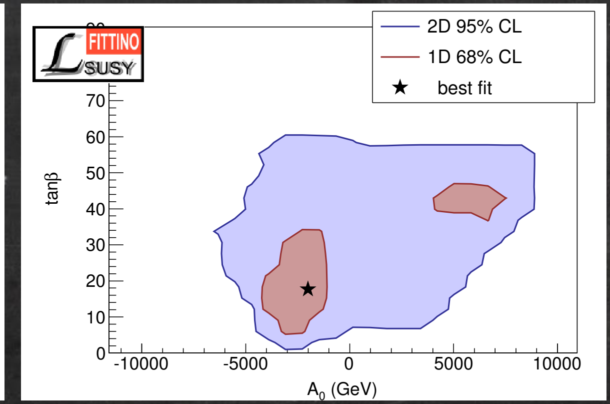
(a) 1 σ and 2 σ contour plot in in the $(M_0, M_{1/2})$–plane for the Small Observable Set.



(b) 1 σ and 2 σ contour plot in in the $(M_0, M_{1/2})$–plane for the Medium Observable Set.



(c) 1 σ and 2 σ contour plot in the $(M_0, M_{1/2})$–plane for the Large Observable Set.



(d) 1 σ and 2 σ contour plot in the $(A_0, \tan\beta)$–plane for the Medium Observable Set.

"Killing the cMSSM softly", P. Bechtle *et al.*, Eur. Phys. J. **C76** (2016), 96

Best Fit to CMSSM

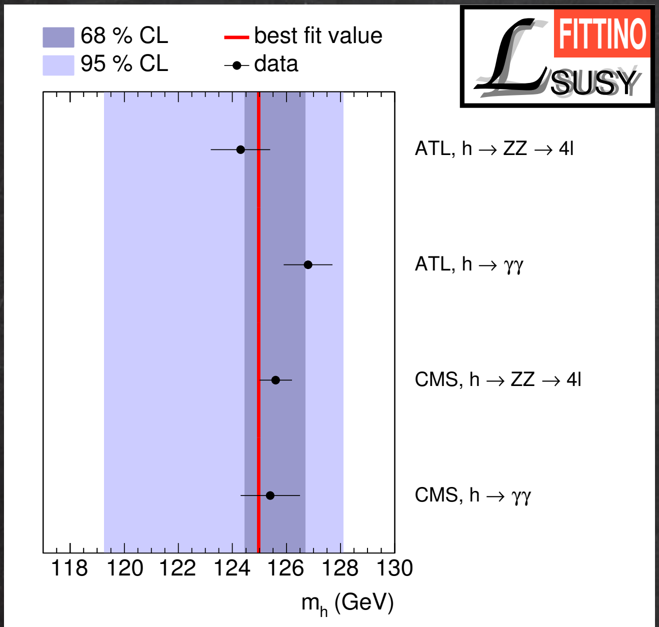


Fig. 6 Our predicted mass of the light Higgs boson, together with the $1\,\sigma$ and $2\,\sigma$ ranges. The LHC measurements used in the fit are shown as well. Note that the correlated theory uncertainty of $\Delta m_{h_{theo}} = 3\,\mathrm{GeV}$ is not shown in the the plot. The relative smallness of the 68% CL region of the fitted mass of $\Delta m_{h_{fit}} = 1.1\,\mathrm{GeV}$ is caused by constraints from other observables.

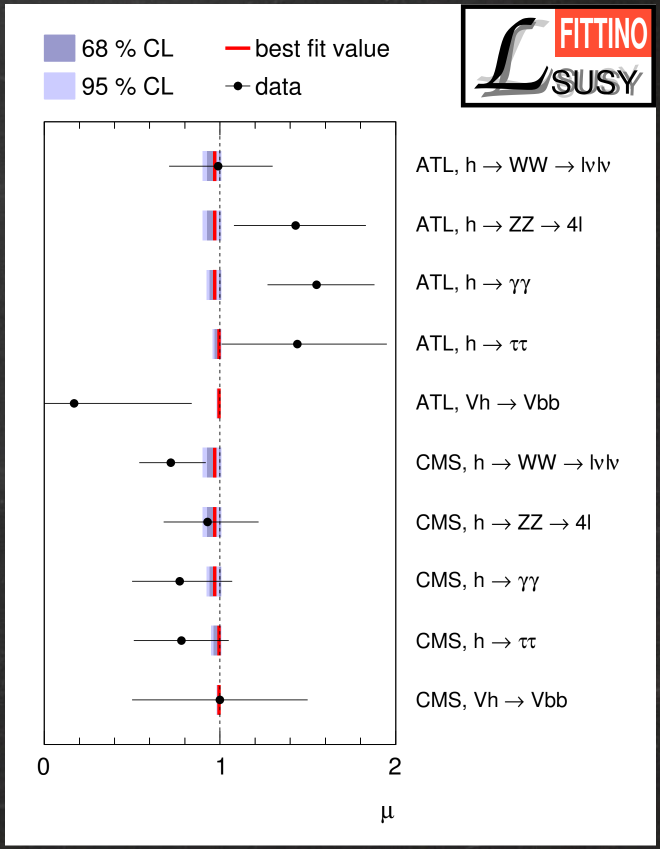


Fig. 8 Our predicted μ values of the light Higgs boson relative to the SM value for a Higgs boson with the same mass. The measurements used in the fit are shown as well.

“Killing the cMSSM softly”, P. Bechtle *et al.*, Eur. Phys. J. **C76** (2016), 96

“*Although the standard CMSSM … is still viable, there remain only restricted regions of the parameter space of the CMSSM … in which a successful prediction for* m_h *can be reconciled with the measured cold dark matter density*”*

Indeed, Bechtle *et al*. exclude the CMSSM at 90% CL.

* “Beyond the CMSSM without an Accelerator: Proton Decay and Direct Dark Matter Detection”, J. Ellis *et al*., Eur. Phys. J. **C76** (2016), 8

Model	# Pars.
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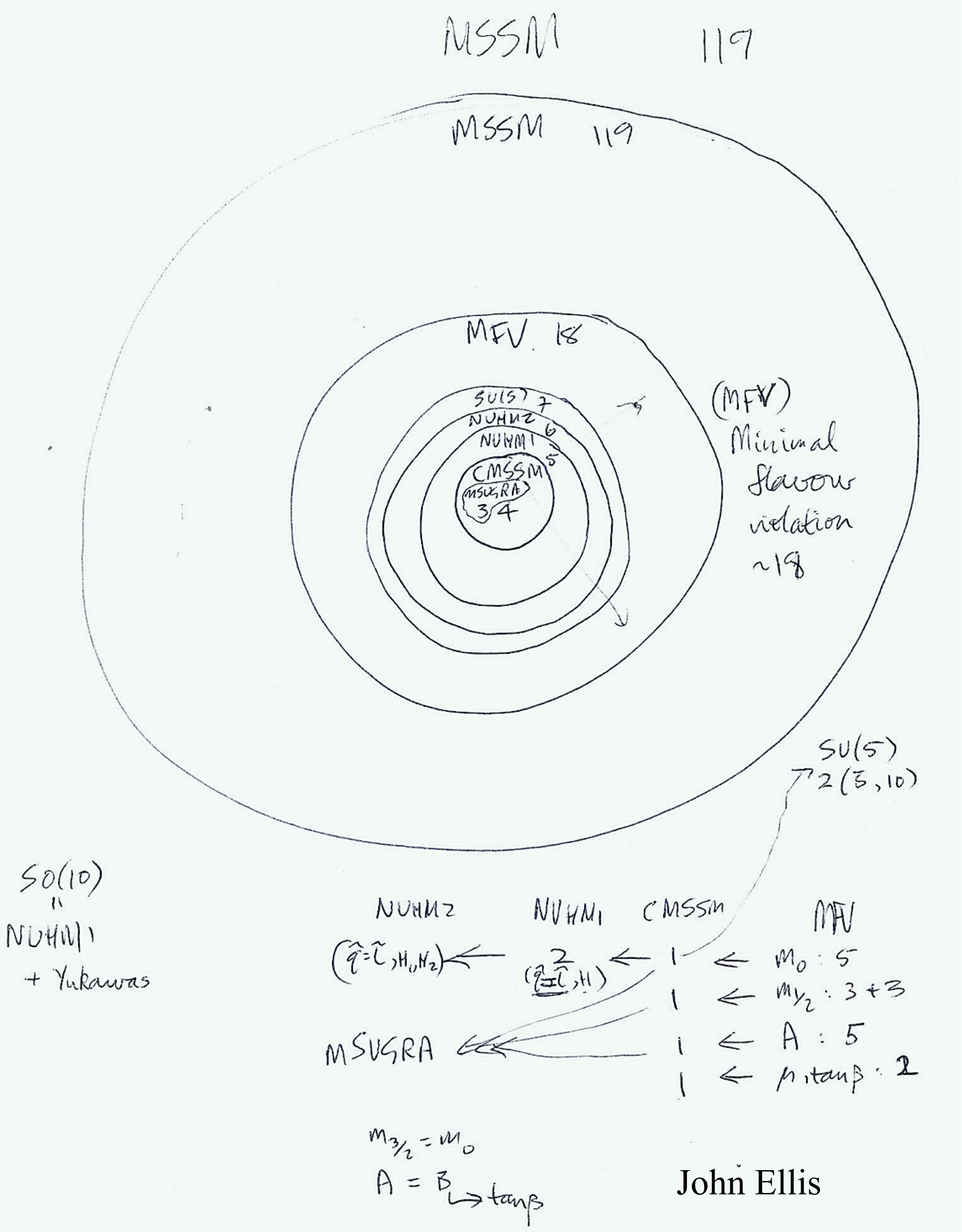


John Ellis

The pMSSM

3 gaugino mass parameters M_1, M_2, M_3

1 ratio of Higgs vacuum expectation values $\tan\beta = v_2 / v_1$

1 higgsino mass parameter μ

1 pseudoscalar Higgs boson mass m_A

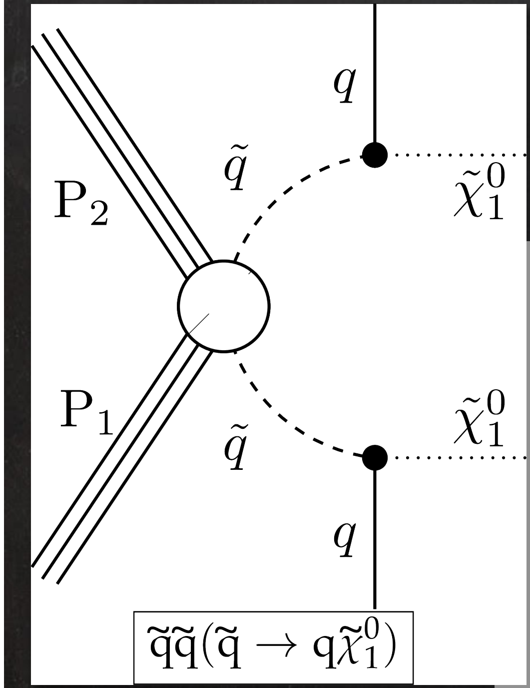
10 sfermion mass parameters $m_{\tilde{F}}$

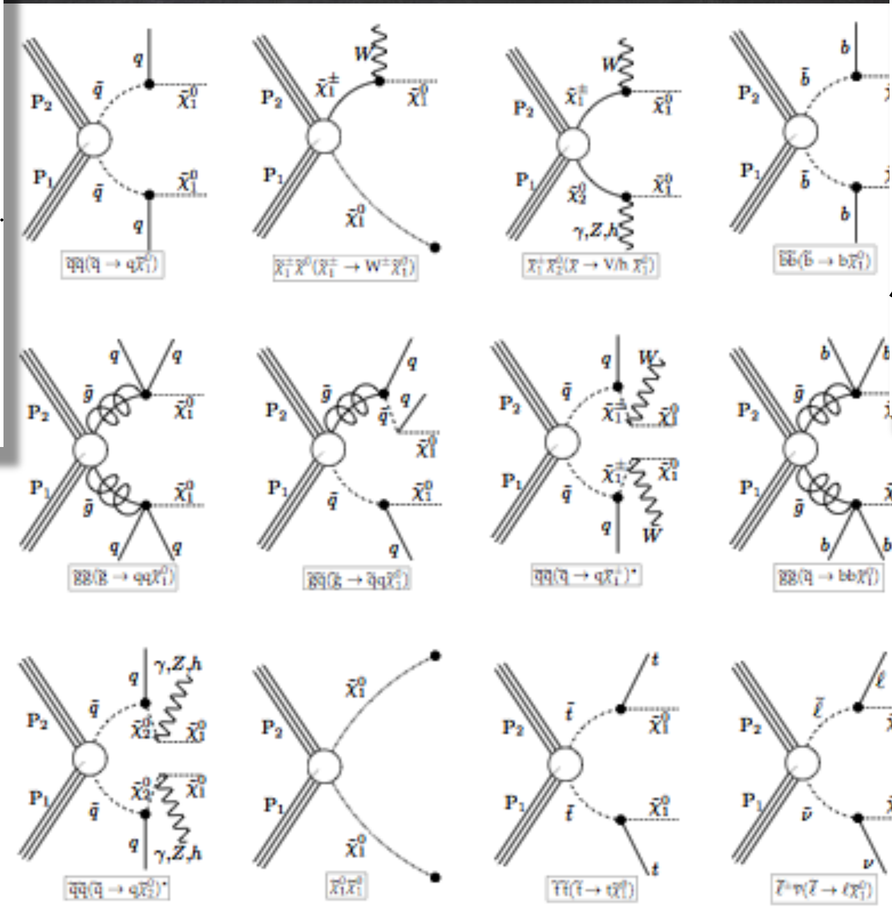
3 trilinear couplings A_t, A_b, A_τ

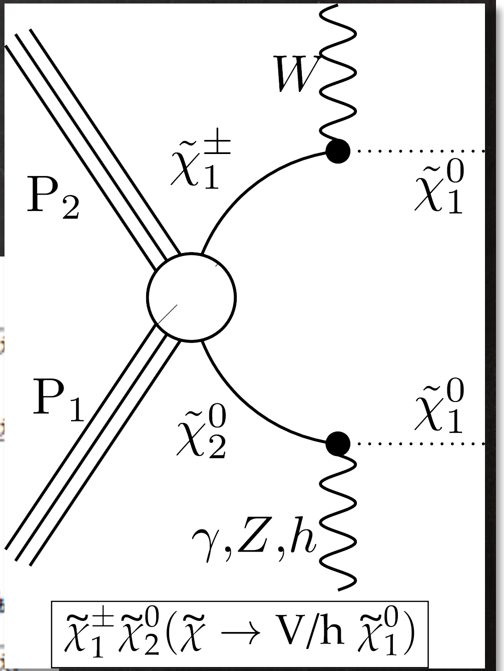
ATLAS collaboration, “Summary of the ATLAS experiment’s sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM”, JHEP 1510 (2015) 134

CMS collaboration, “Phenomenological MSSM interpretation of CMS searches in pp collisions at sqrt(s) = 7 and 8 TeV”, JHEP 1610 (2016) 129

pMSSM: Twelve Principal Processes

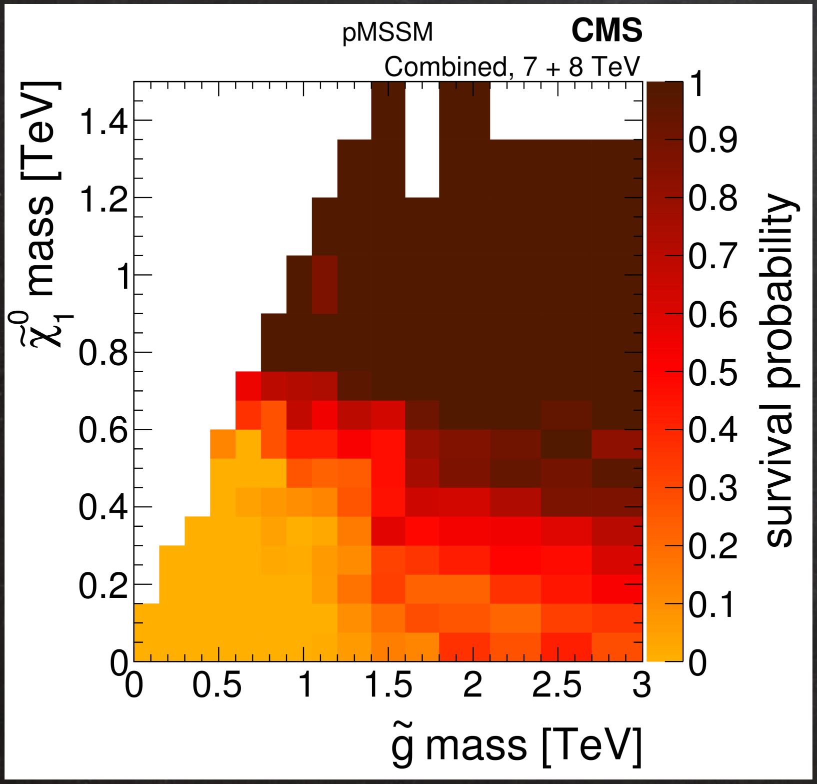


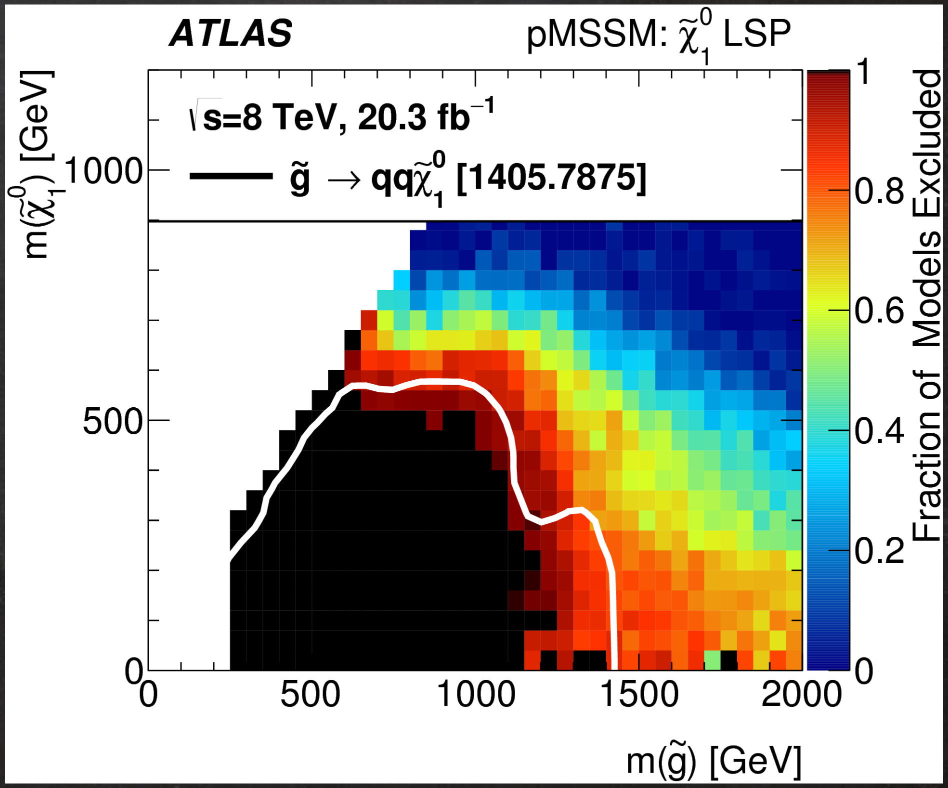




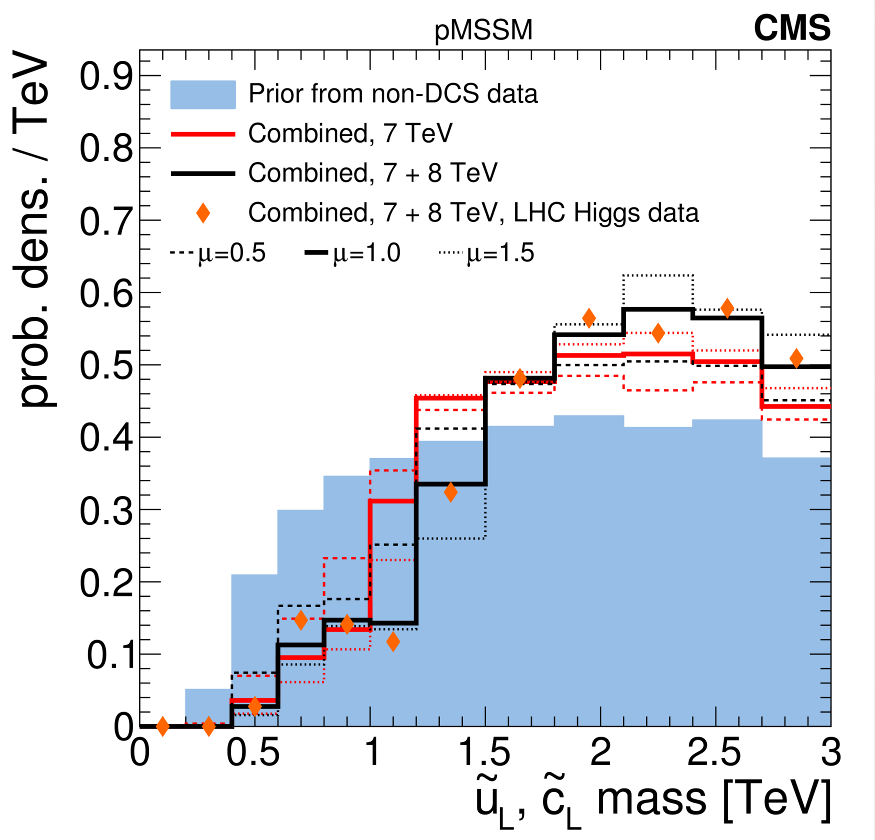
The pMSSM: Gluino and LSP

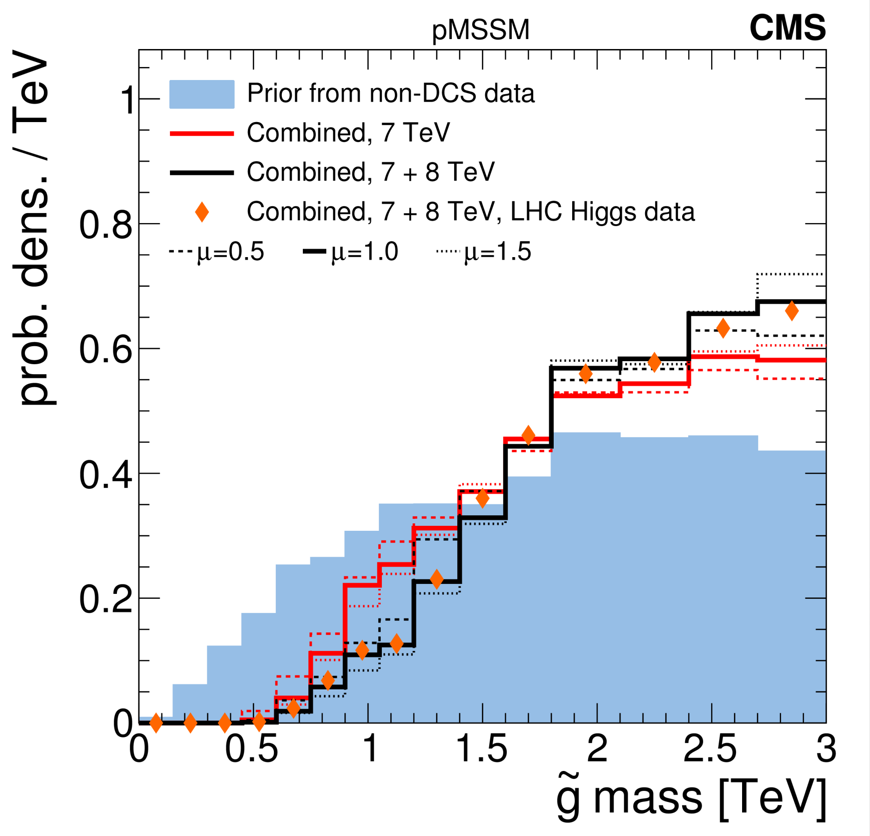
CMS and ATLAS reach similar conclusions regarding the gluino and lightest neutralino.





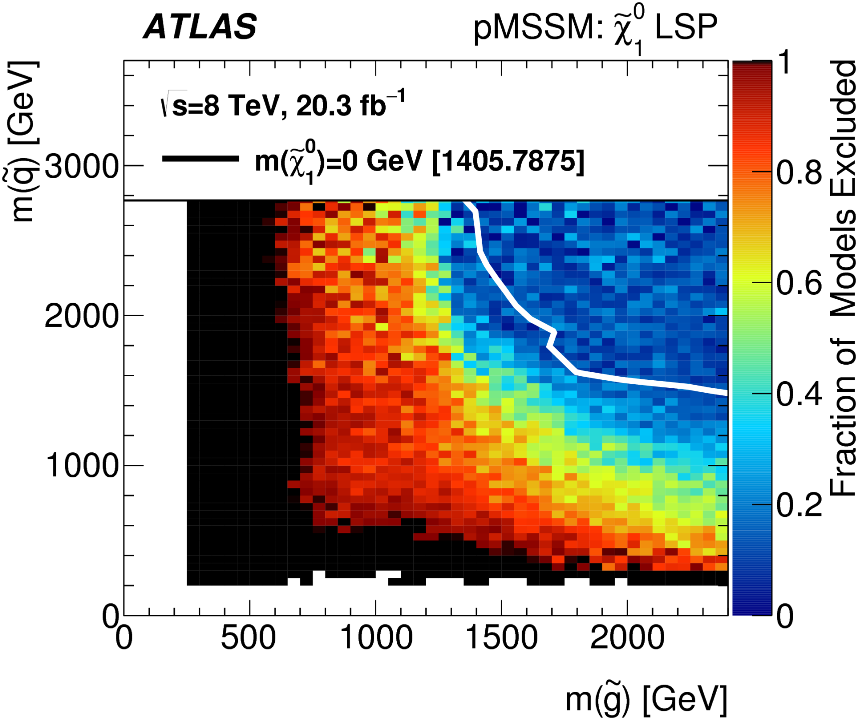
pMSSM: Squarks

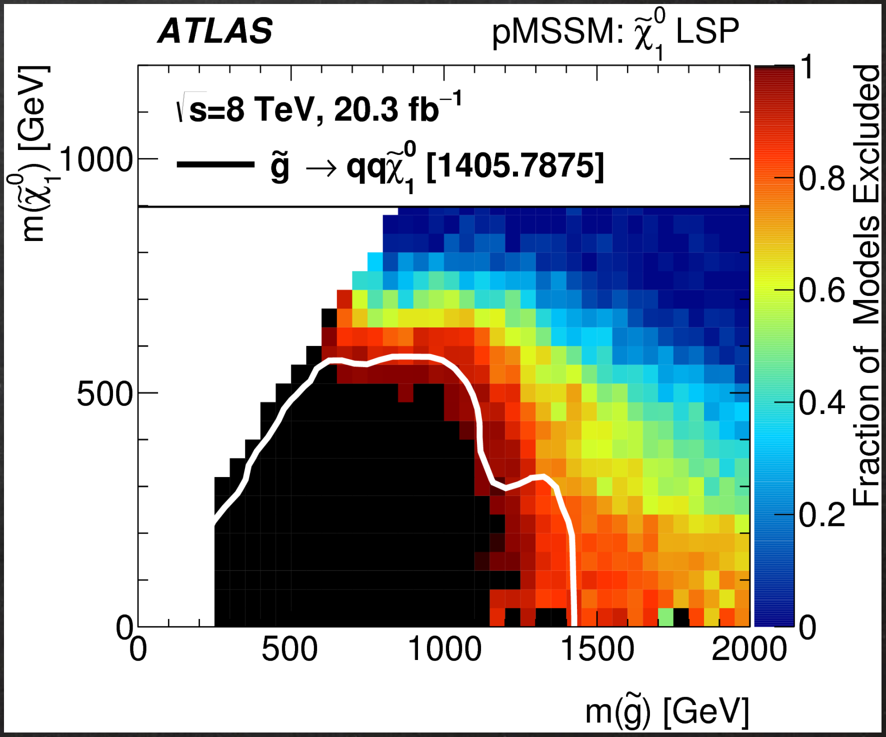




SMS vs pMSSM

Here is an illustration, from ATLAS, of why some caution is needed in drawing conclusions from simplified models.

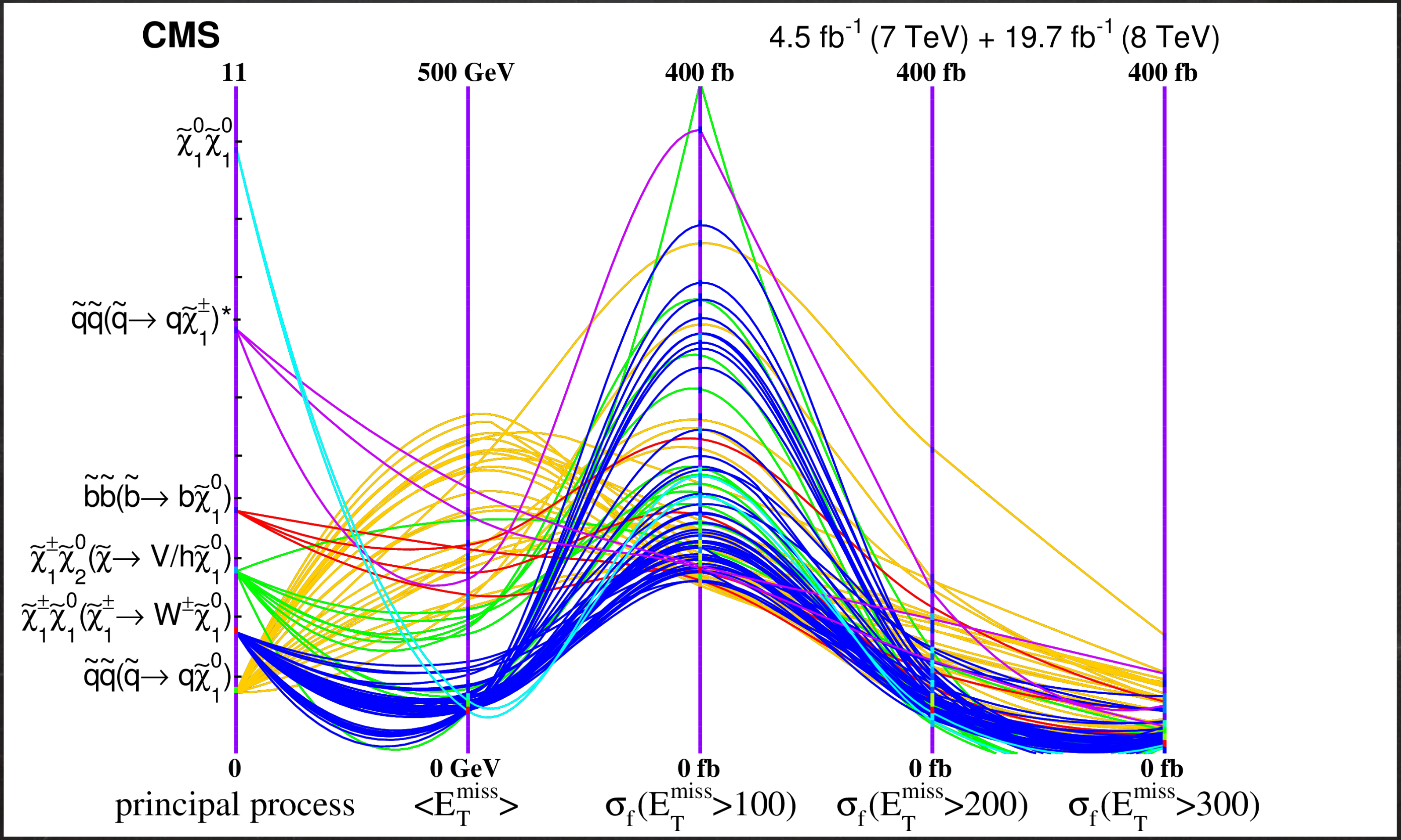




pMSSM: Summary

- Gluino masses < 500 GeV excluded.
- Neutralino and chargino masses < 300 GeV strongly disfavored.
- A relatively light supersymmetric top is still viable.
- About half of the potentially accessible pMSSM parameter space excluded.
- Of the surviving points, about half have cross sections exceeding ~ 10fb and tend to yield events with missing E_{T} lower than typical missing E_{T} analysis cuts.

Beyond Low-Hanging Fruit



Outline

- ☐ Introduction
- ☐ What is supersymmetry?
- ☐ What have we learned
- ☐ **Summary & Conclusions**

Summary and Conclusions

- The CMSSM has been excluded at 90% CL.
- In the pMMSM (a good MSSM proxy), about half of the parameter space, potentially accessible at the LHC, remains.
- Of the remaining model points, about half have cross sections exceeding 10fb.
- The gluino mass > 500 GeV, a light stop is still possible, but squarks and neutralinos with mass < 300 GeV are strongly disfavored.
- Conclusion: weak-scale supersymmetry remains viable!