ATLAS results on searches for Supersymmetry

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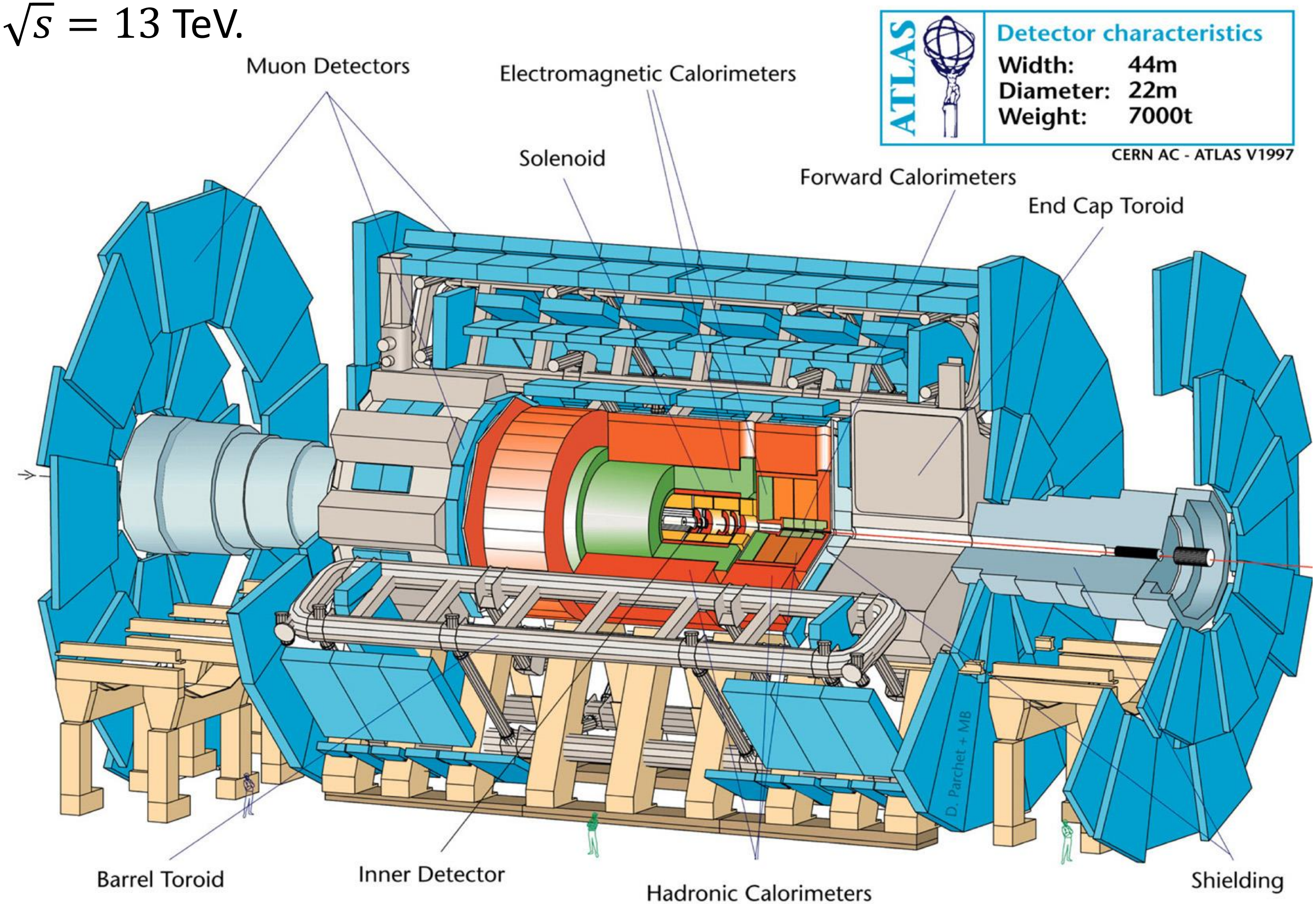
26 March 2018

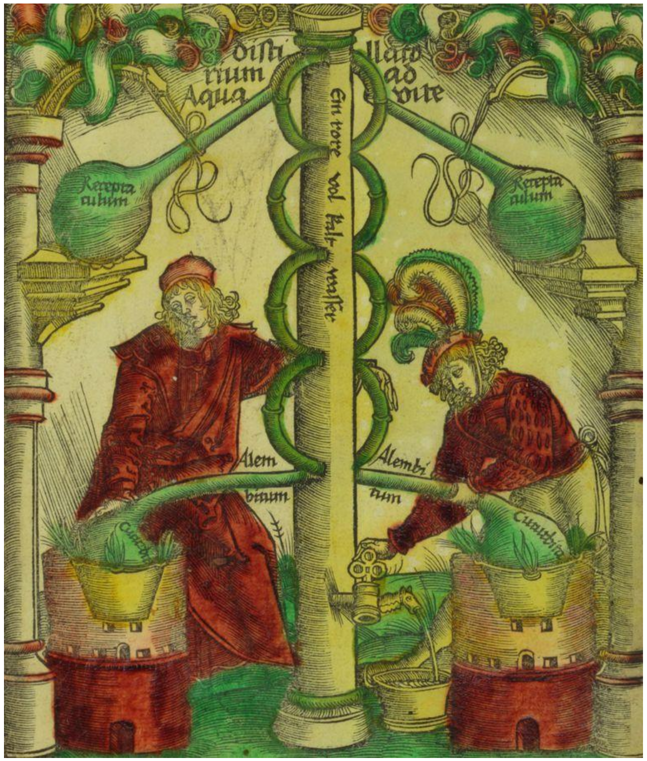
Aspen 2018 – The particle frontier

The ATLAS experiment at the LHC

- Multi-purpose experiment exploring proton-proton (and HI) collisions at $\sqrt{s} = 13$ TeV.

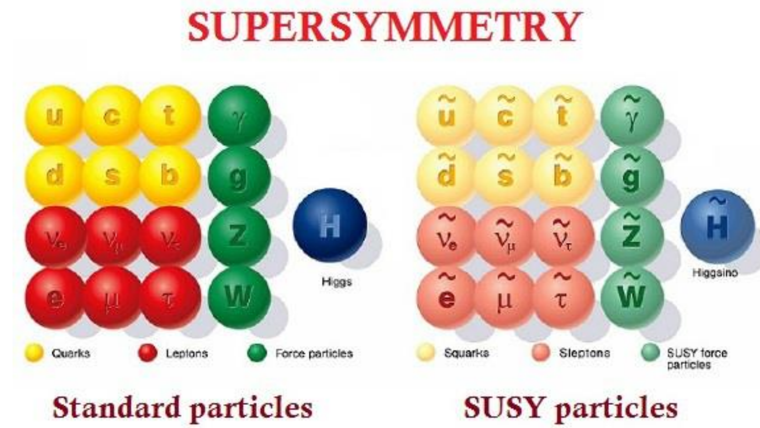


Why SUSY?



"philosopher's stone" enables:

- creation of an elixir of immortality
- transmutation of common substances into gold

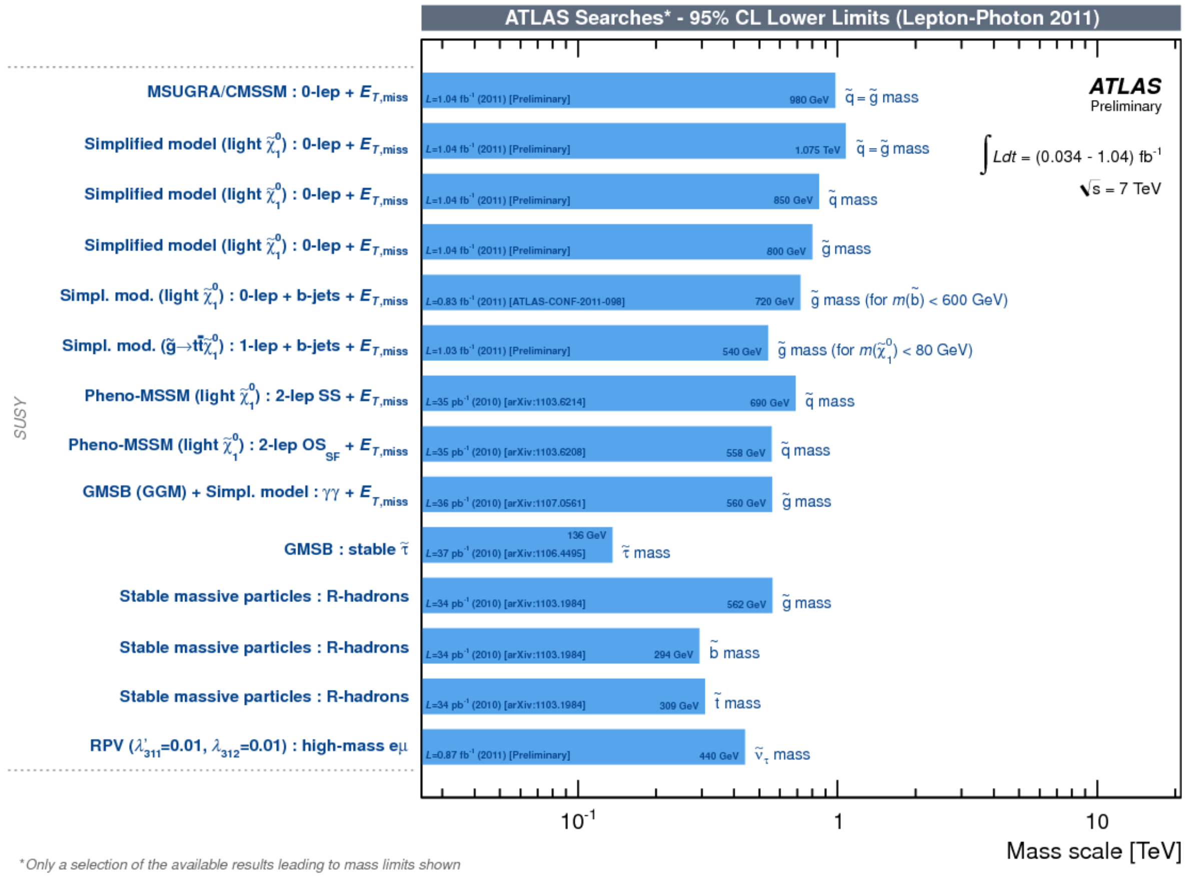


- A supersymmetric extensions of the SM could solve the central issues:
  - Gauge coupling unification
  - Hierarchy problem (e.g. loop corrections to Higgs mass)
  - DM candidate

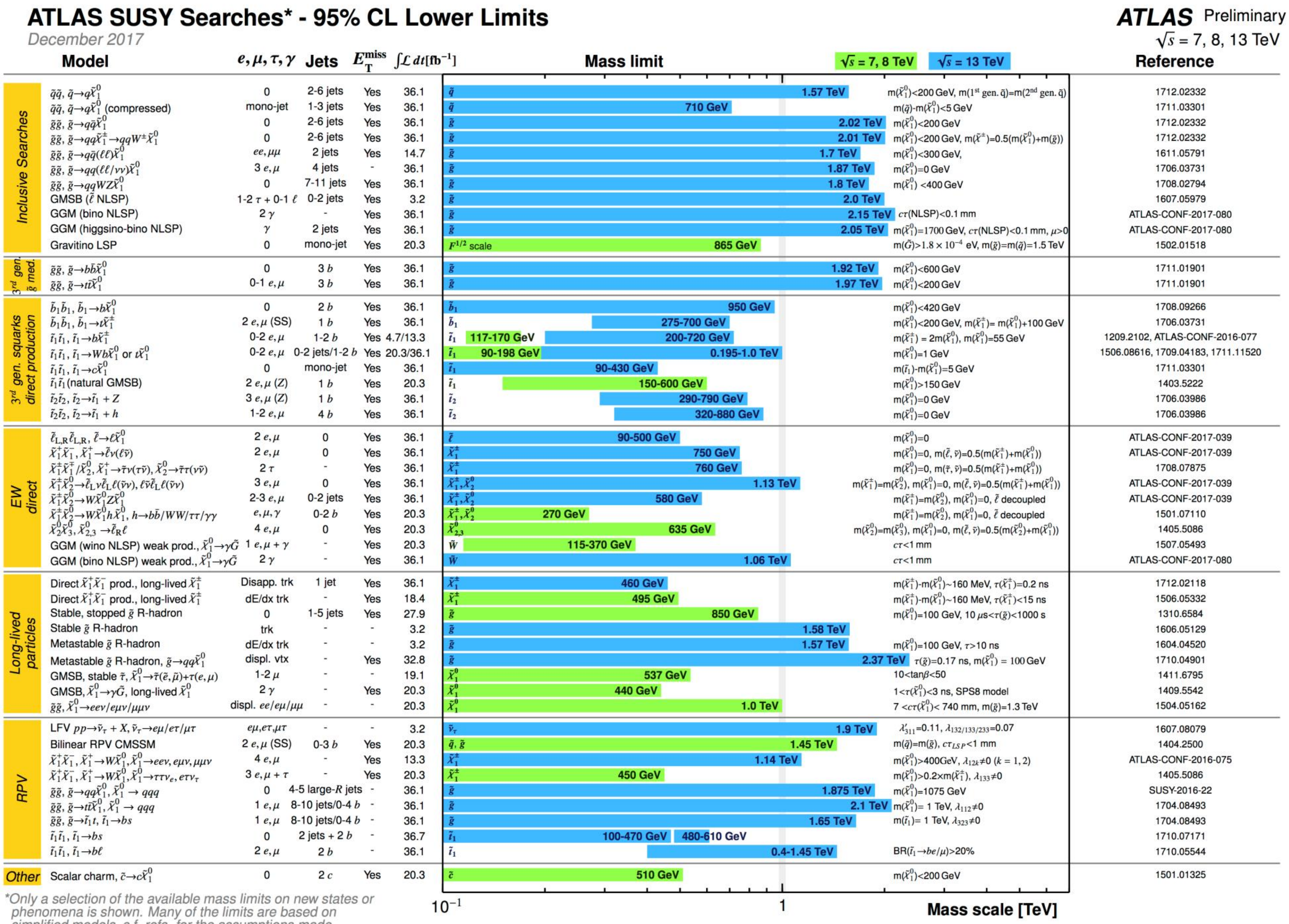
- Half of SUSY particles have been discovered already:
  - SUSY partners to squarks, gluinos, higgsinos, and sleptons

ATLAS searches pre-Higgs (2011)

- The majority of searches were inclusive. They targeted strongly-produced SUSY particles that cascade decay to WIMPS (DM candidates) and generic models like MSUGRA/MSSM/GMSB.
- Searches for the 3rd generation were emerging (e.g. arXiv:1101.1963)



Contemporary search program



Contemporary search program

- The 125 GeV Higgs is considered as “SUSY model killer” (tension with high-scale theories). However, the discovery of Higgs inspired a number of searches for m~O(1 TeV) 3rd generation squarks.
- Overall, the search program is more exciting than ever before.
- Goes even beyond the R-parity conserving models and in the corners of phase space where the mass differences are small (compressed and long-lived).
- Caveat: The data are often interpreted for simplified models so the limits need to be translated carefully for your model of choice.
  - The simplified models may give overly high or low exclusion.

ATLAS SUSY Searches* - 95% CL Lo

December 2017

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2
	GGM (bino NLSP)	2 γ	-	Yes	36.1
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1
	Gravitino LSP	0	mono-jet	Yes	20.3
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	1 b	Yes	36.1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e, μ	1-2 b	Yes	4.7/13.3
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3

Hidetoshi will discuss this later on.

New results since spring of 2017

1.	RPV multijet 1-lepton	1704.08493 [hep-ex]
2.	long-lived reinterpretation	CONF-SUSY-2018-03
3.	displaced vertices	1710.04901 [hep-ex]
4.	disappearing track	PHYS-PUB-2017-019
5.	multijet (7-11)	1708.02794 [hep-ex]
6.	0L inclusive	1712.02332 [hep-ex]
7.	1-lepton + MET + jet	1708.08232 [hep-ex]
8.	stop in Z/h	1706.03986 [hep-ex]
9.	**SS/3L**	**1706.03731 [hep-ex]**
10.	**stop 2L**	**1708.03247 [hep-ex]**
11.	2b+MET	1708.09266 [hep-ex]
12.	**stop 0L**	**1709.04183 [hep-ex]**
13.	stop b-l	1710.05544 [hep-ex]
14.	**multi b-jets**	**1711.01901 [hep-ex]**
15.	stop 2x2	1710.07171 [hep-ex]
16.	**stop 1L**	**1711.11520 [hep-ex]**
17.	Stop in stau	ATLAS-CONF-2017-079
18.	electroweak compressed	1712.08119 [hep-ex]
19.	**SUSY with photons**	**1802.03158 [hep-ex]**
20.	GMSB Higgsinos in 4b	ATLAS-CONF-2017-081
21.	Electroweak di-tau	1708.07875 [hep-ex]
22.	EW 2/3L	1803.02762 [hep-ex]

All these use 2015+2016 data: 36 fb^{-1} at $\sqrt{s} = 13$ TeV

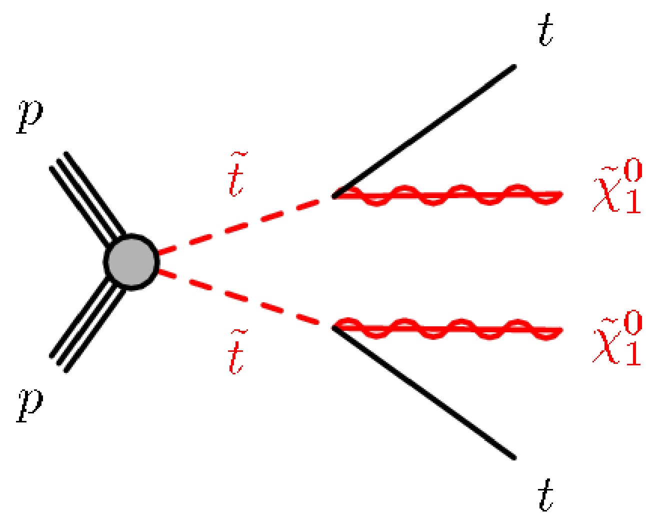
Expect ~150 fb^{-1} in Run2. We already have about 80 fb^{-1}.

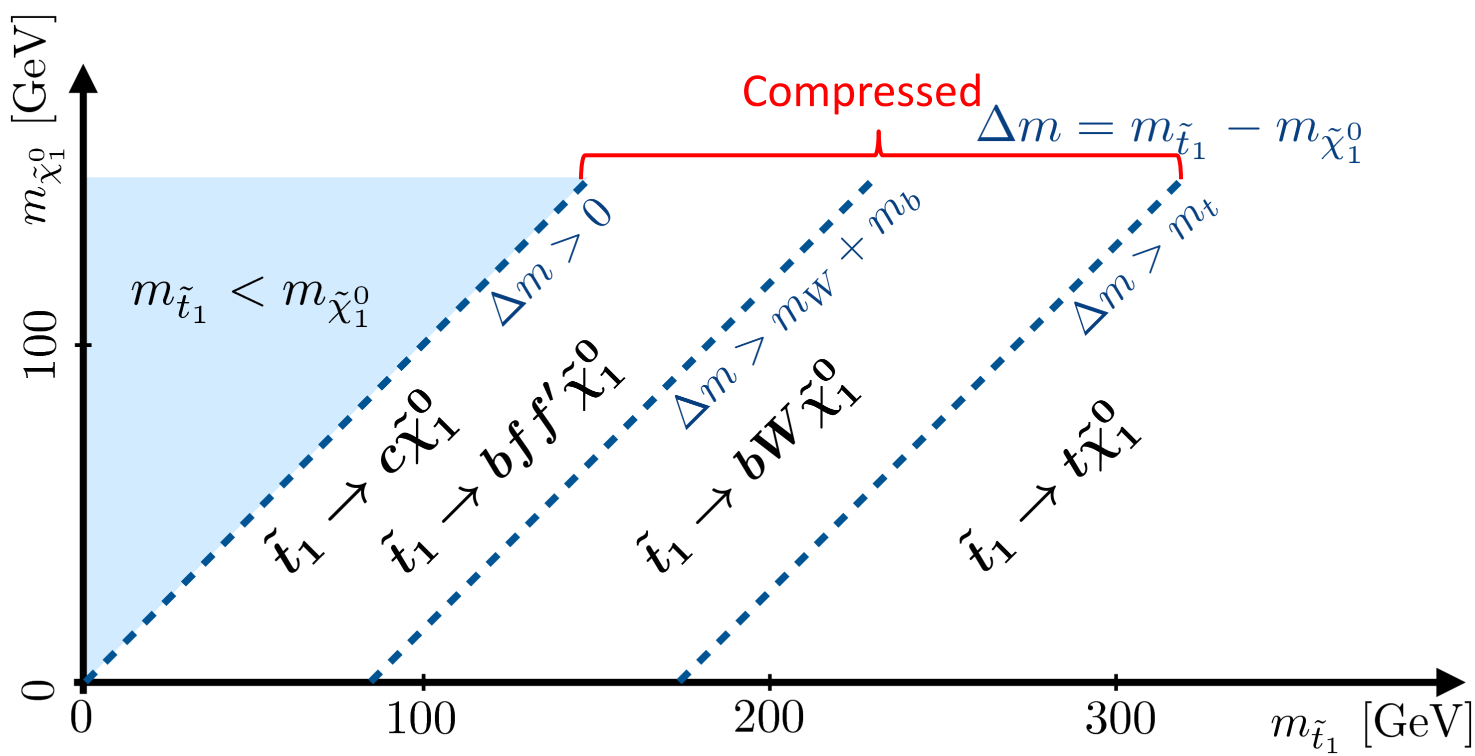
No significant excesses.

Searches in red have slight excess.

Direct stop pair-production

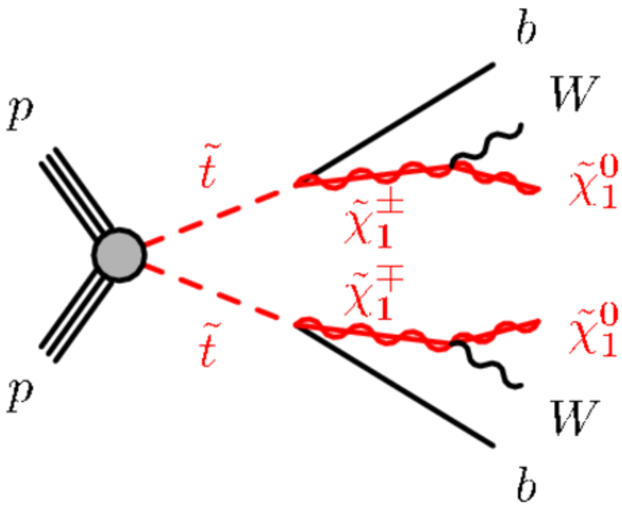
- The Higgs at 125 GeV inspires m ~ O(1TeV) top squarks. The decay chain depends on model parameters and there are a lot of variations.
- The experimental signatures become difficult when the top quarks are off-shell (compressed)

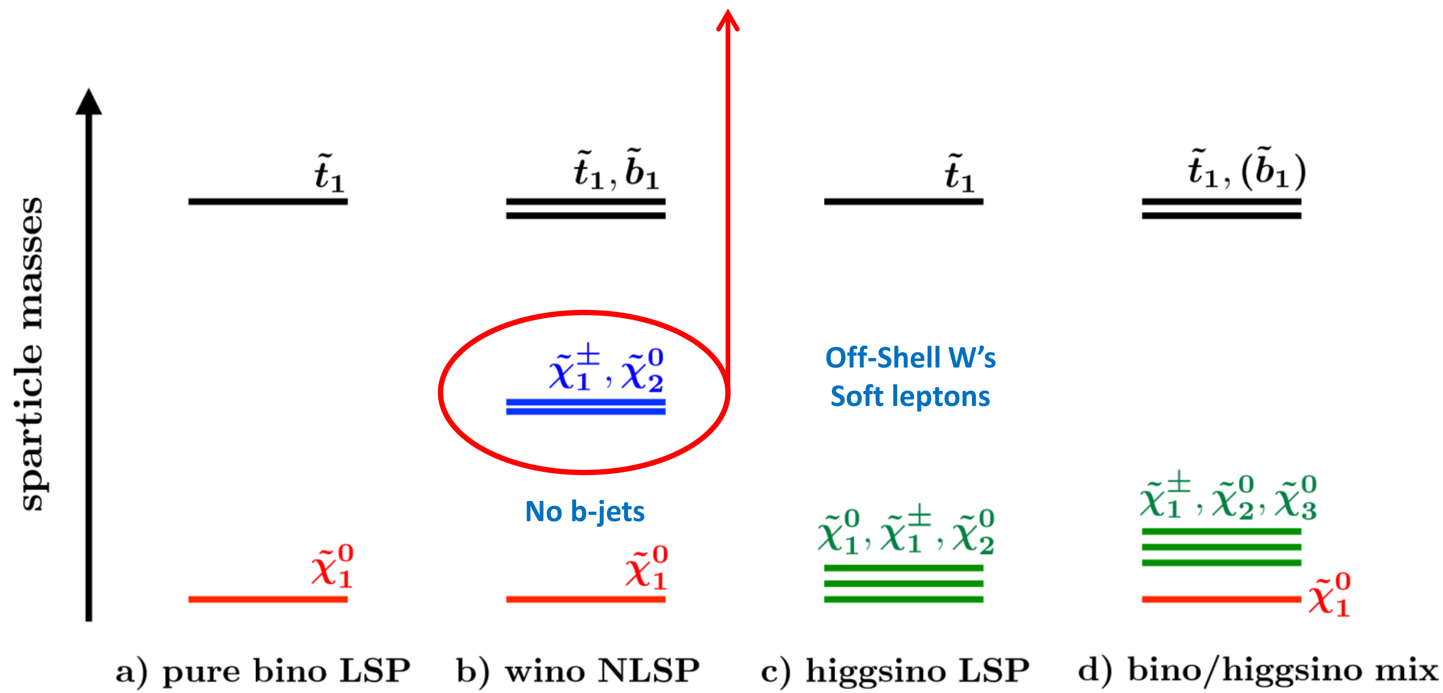




Direct stop pair-production

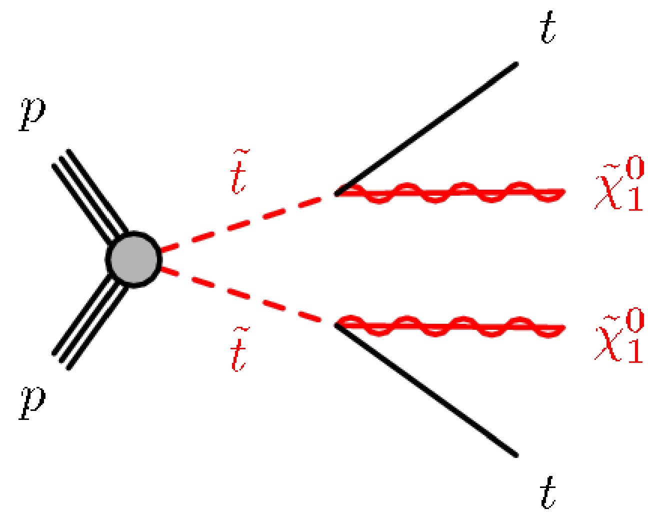
- Complexity of the decay chain can escalate quickly.
- What will happen if the intermediate state is much heavier than a top squark?
- 16 channels are used to target all the scenarios.

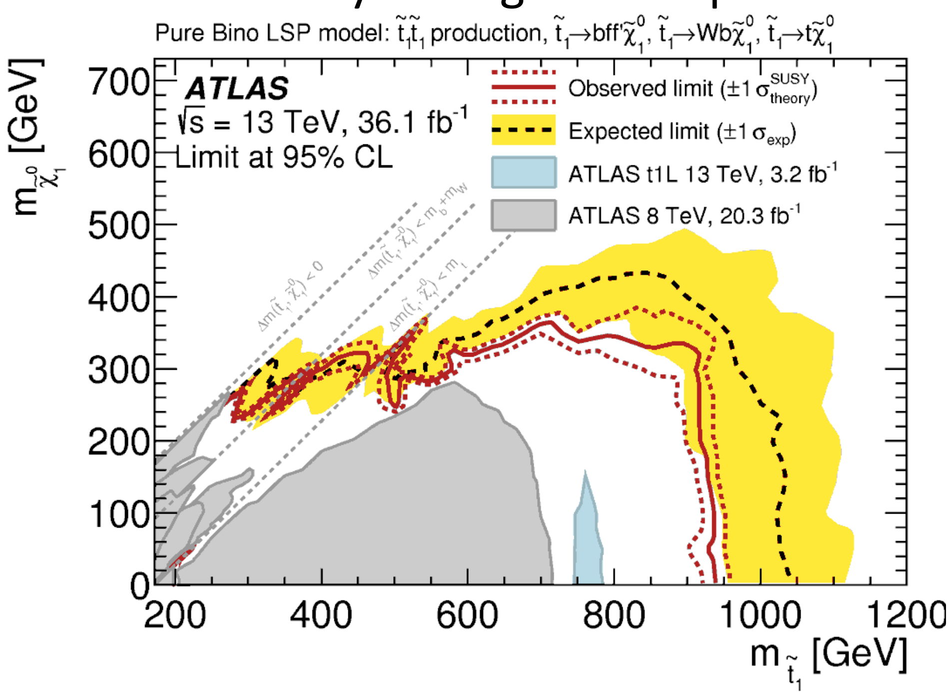


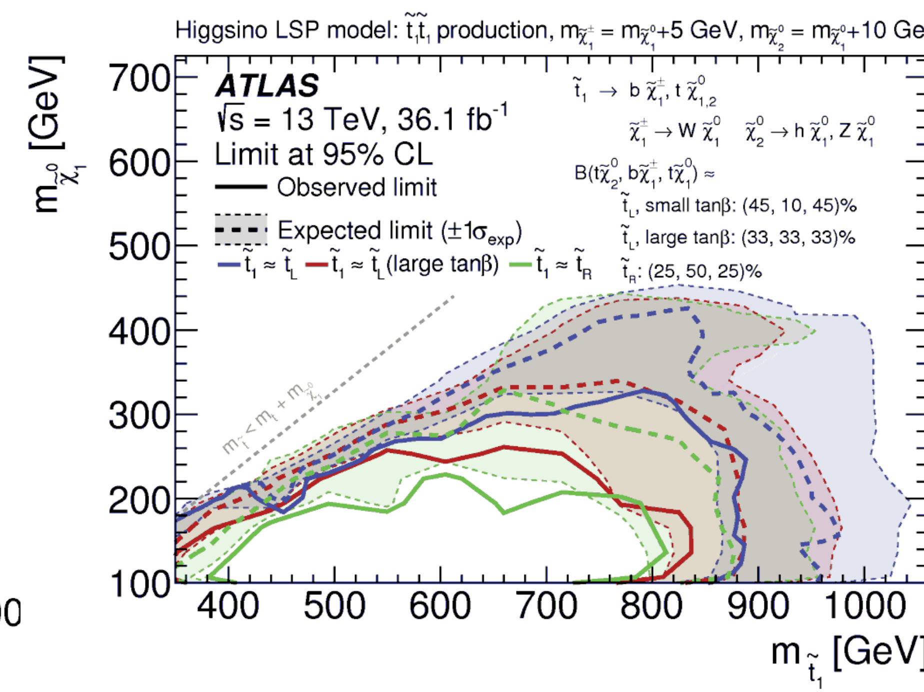


Direct stop pair-production: 1L

- The 13 TeV searches probe the compressed decays (near the $m(\tilde{t}) = m(t) + m(\tilde{\chi}^0)$ diagonal) better than the 8 TeV searches by using events with jet ISR.
- Data is mostly interpreted with simplified models.
- Multiple simultaneous decay chains degrade sensitivity. → Right-hand plot

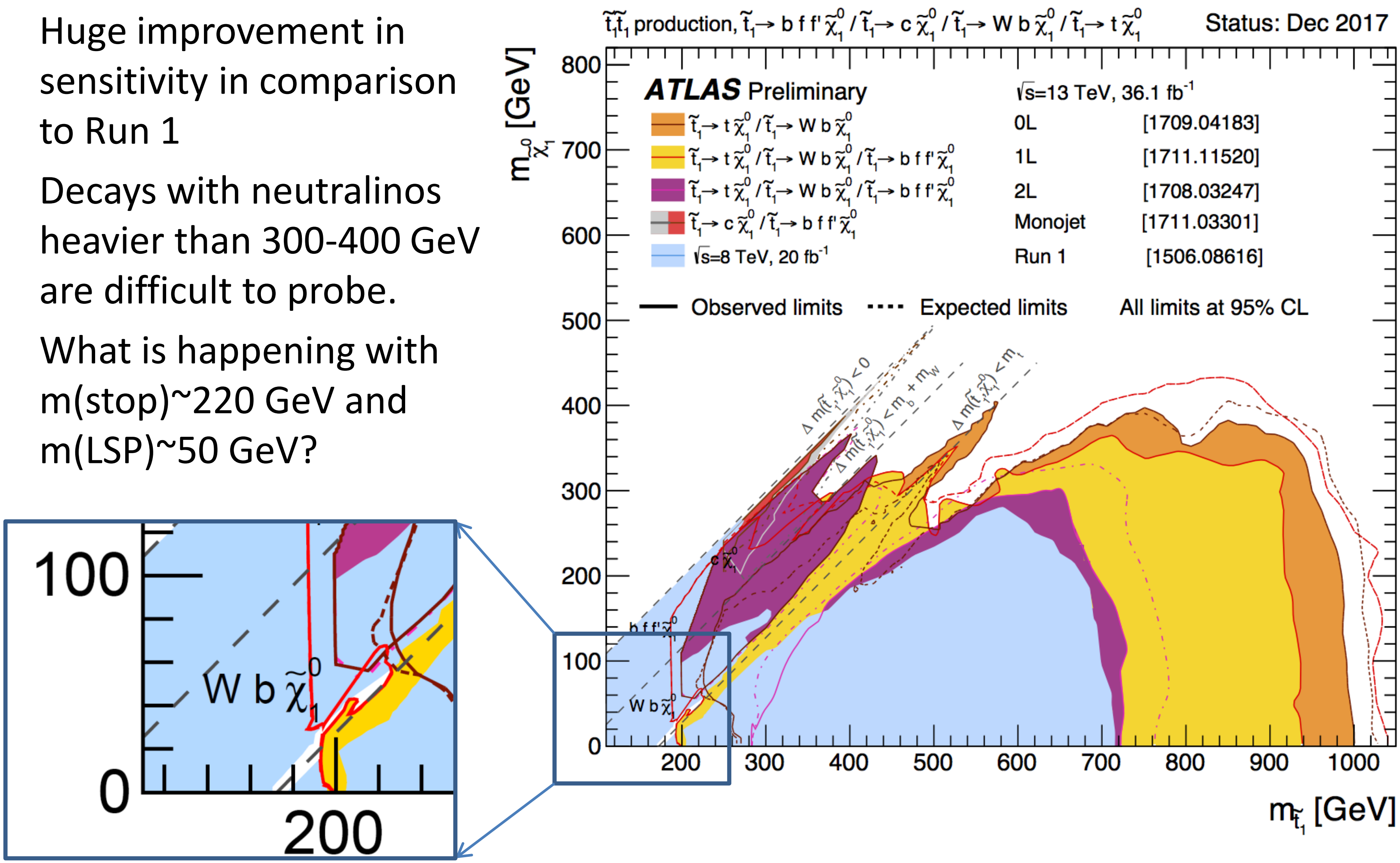






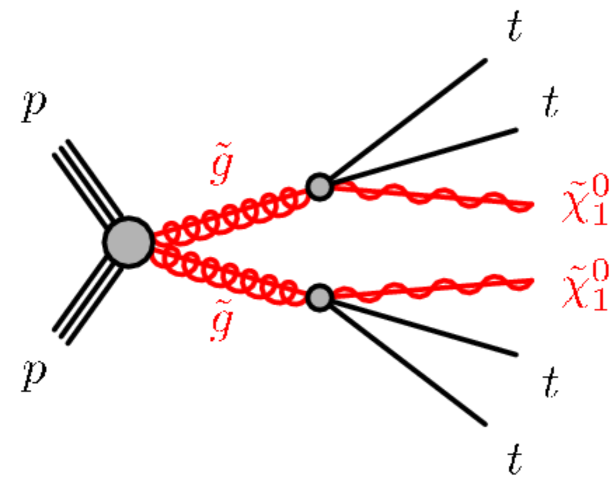
Direct stop pair-production: Overview

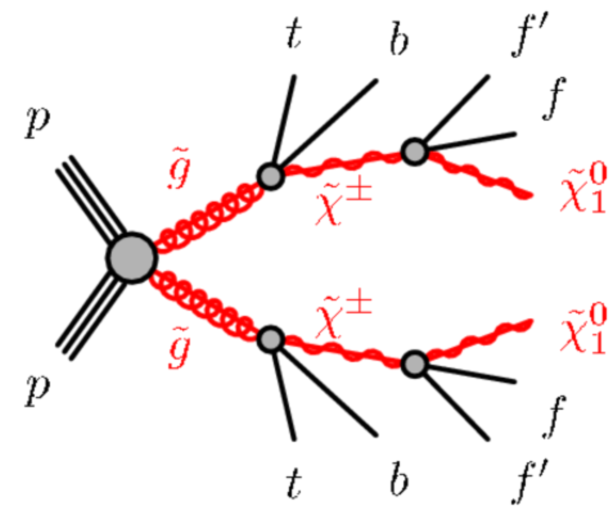
- Huge improvement in sensitivity in comparison to Run 1
- Decays with neutralinos heavier than 300-400 GeV are difficult to probe.
- What is happening with m(stop)~220 GeV and m(LSP)~50 GeV?

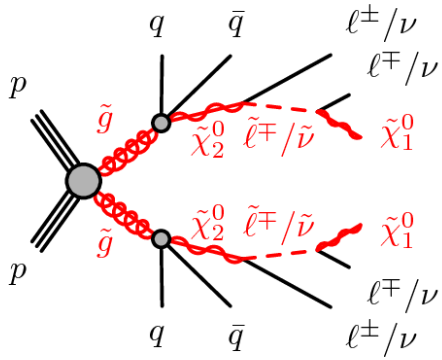


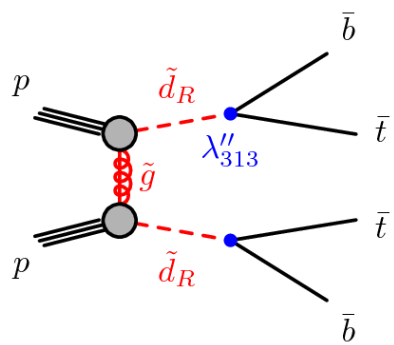
Gluino-mediated stop production

- I learned about this interesting channel in the paper by Gordy Kane, Lian-Tao Wang, and others 1101.1963 [hep-ph]
- Complementary to direct stop pair-production.
- Best when m(glu)<m(stop).
- The stop decays of different complexity are considered.
- There are separate searches with 0 or 1 lepton and b-jets and 2SS or 3 leptons and jets:
  - SS/3L 1706.03731 [hep-ex]
  - multi b-jets 1711.01901 [hep-ex]
- The searches cover a broad range of models. e.g.:



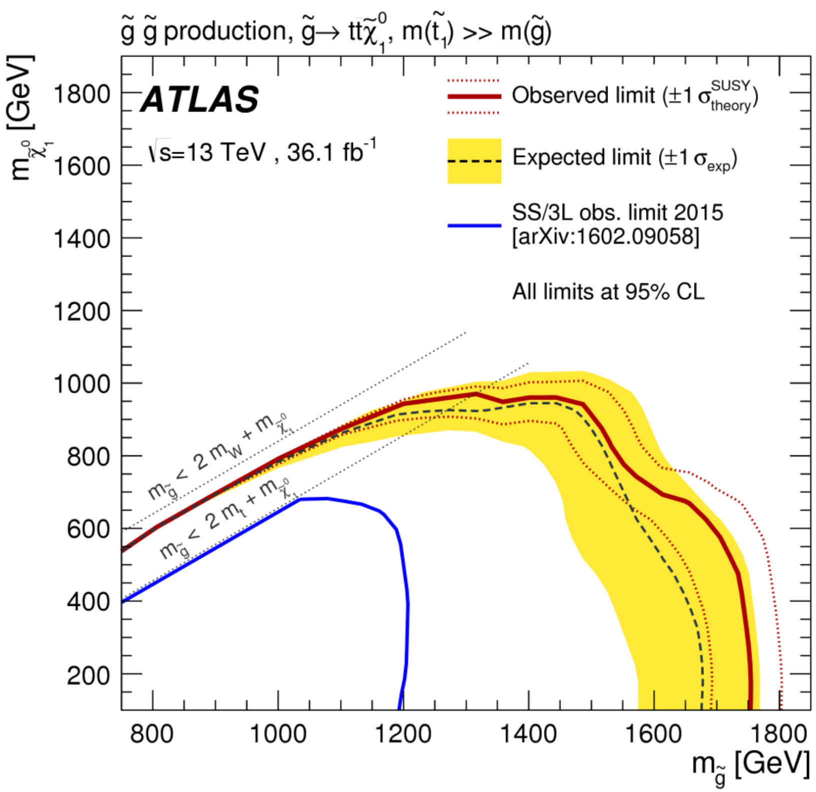


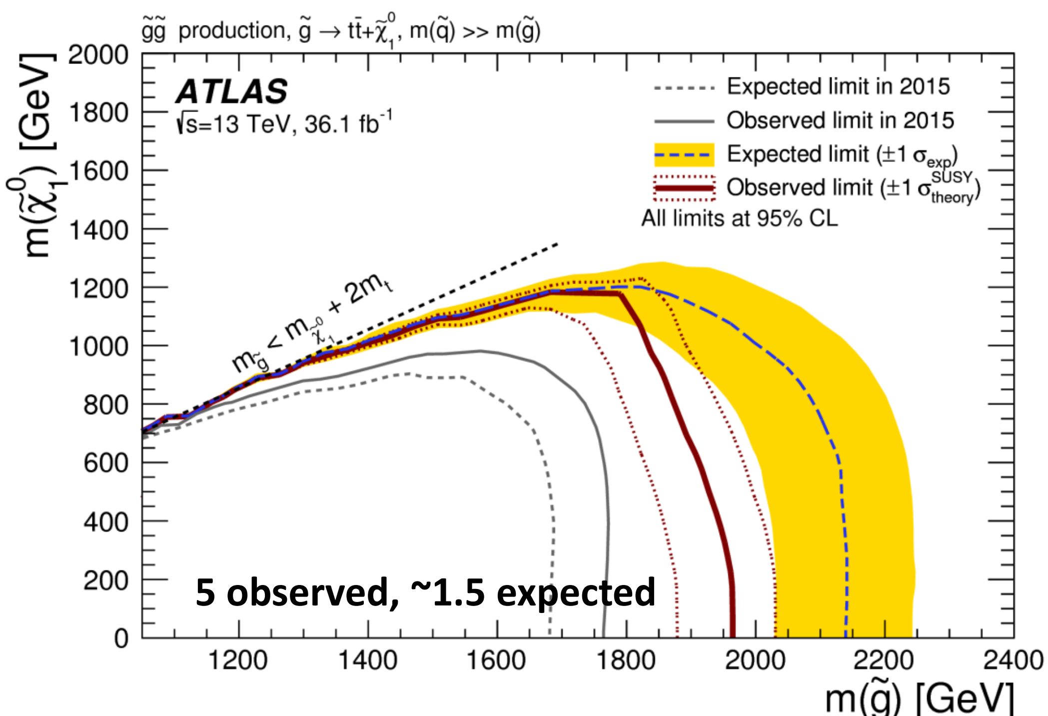




Gluino-mediated stop production

- 0/1L gives better reach for heavy gluinos and 2SS/3L helps in the compressed region.
- Slight excess in the 0/1L multi-b search (right-hand figure).
  - Would a model with m(gluino)=2.3 TeV; m(stop)=220 GeV and m(LSP)=50 GeV be excluded by CMS?

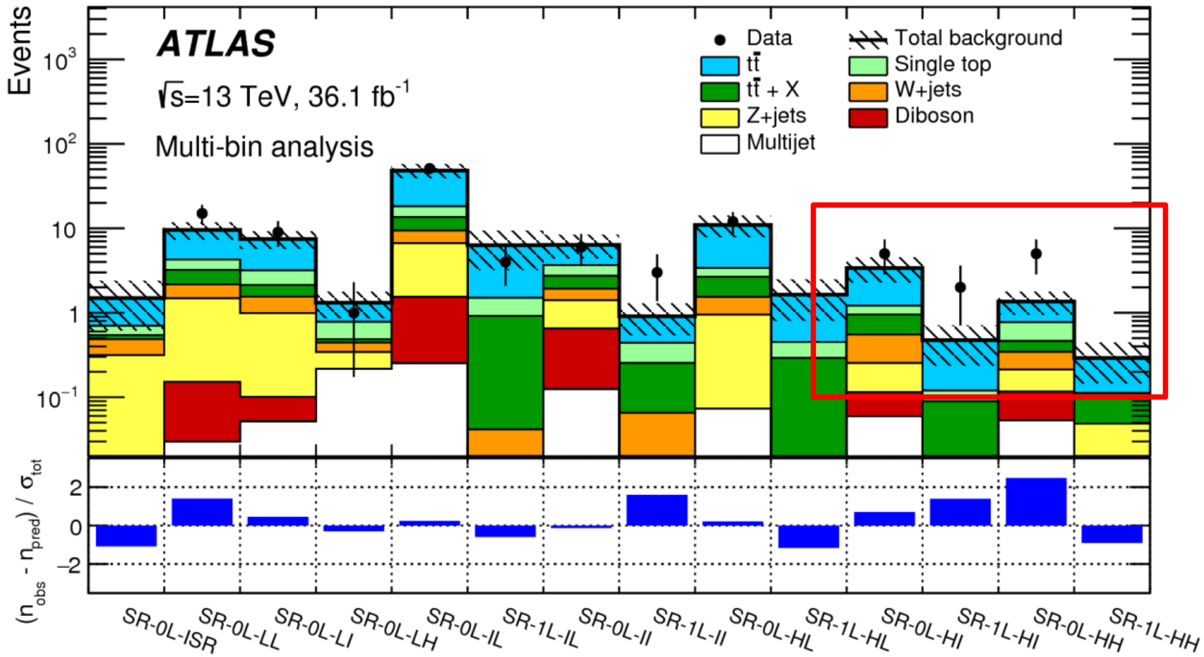




Note how large the theory "uncertainty" is.

Gluino-mediated stop production

- The excess is driven by a small number of events.

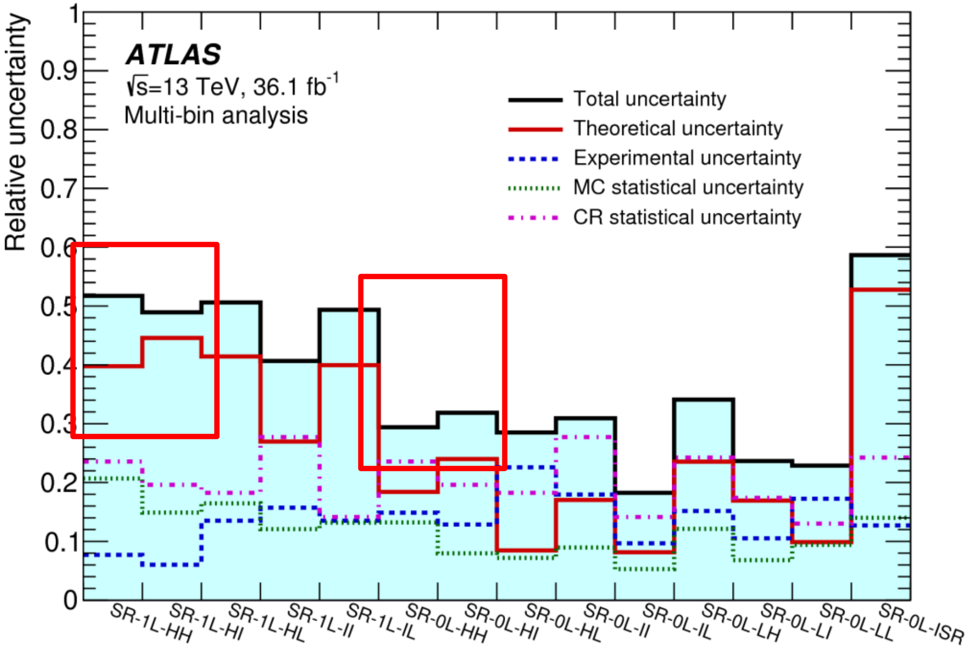


Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $p_T^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$\Delta\phi^{4j}_{\text{min}}$	m_T	N_{jet}	$m^{b\text{-jets}}_{T,\text{min}}$	M^{Σ}_{J}	E^{miss}_{T}	m_{eff}
High-m_{eff} (HH) (Large Δm)	SR-0L	$= 0$	> 0.4	–	≥ 7	> 100	> 200	> 400	> 2500
	SR-1L	≥ 1	–	> 150	≥ 6	> 120	> 200	> 500	> 2300
Intermediate-m_{eff} (HI) (Intermediate Δm)	SR-0L	$= 0$	> 0.4	–	≥ 9	> 140	> 150	> 300	$[1800, 2500]$
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	> 150	> 300	$[1800, 2300]$

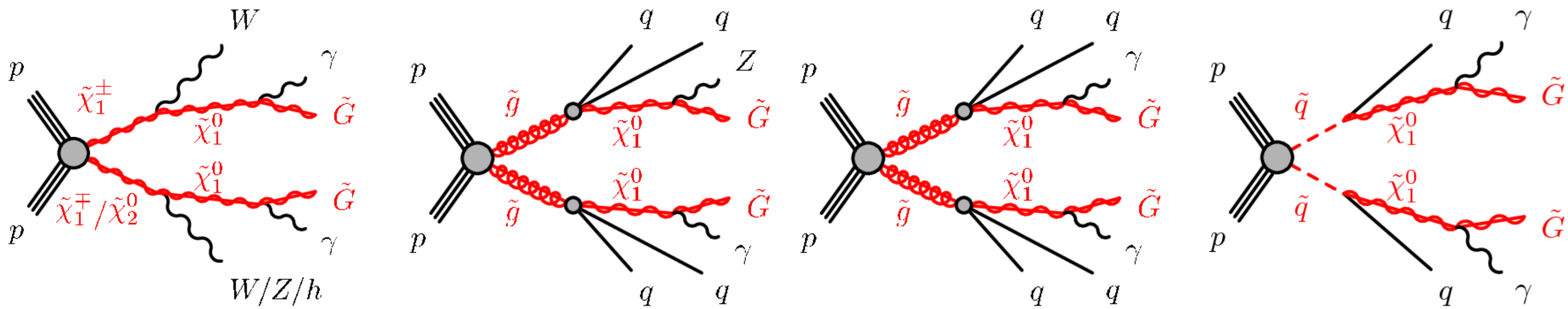
Gluino-mediated stop production

- Background estimation for the multi-jet final states (e.g. ttbar+extra jets) is challenging.
  - Effectively, the backgrounds are extrapolated from control regions to the signal regions using SM predictions.
  - The extrapolation process is verified using the validation regions.
- Often have to rely on parton showering as the ME for ttbar+1p, which can give up to 7 jets (both W's decay hadronically).
  - Control regions are also used to constrain the predictions in situ (background fit).



Photonic signatures

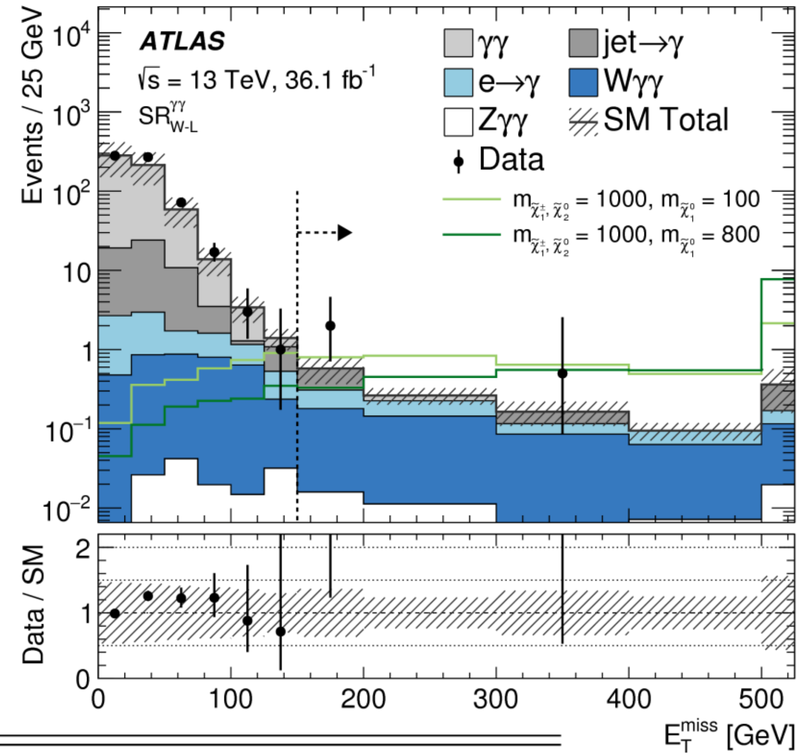
- The search targets models where Gravitiono is the LSP and it is produced in association with a photon.



Signal Region	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{S-L}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{S-H}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-L}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-H}}$	$\mathrm{SR}^{\gamma \mathrm{j}}_{\mathrm{L}}$	$\mathrm{SR}^{\gamma \mathrm{j}}_{\mathrm{L200}}$	$\mathrm{SR}^{\gamma \mathrm{j}}_{\mathrm{H}}$
Number of photons	≥ 2	≥ 2	≥ 2	≥ 2	≥ 1	≥ 1	≥ 1
E_{T}^{γ} [GeV]	> 75	> 75	> 75	> 75	> 145	> 145	> 400
Number of jets	...	...	...	...	≥ 5	≥ 5	≥ 3
Number of leptons	...	...	...	...	0	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 250	> 150	> 250	> 300	> 200	> 400
H_{T} [GeV]	> 2750	> 2000	> 1500	> 1000	...	...	...
m_{eff} [GeV]	...	...	...	...	> 2000	> 2000	> 2400
R_{T}^4	...	...	...	...	< 0.90	< 0.90	...
$\Delta\phi_{\mathrm{min}}(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}})$	> 0.5	> 0.5	> 0.5	> 0.5	> 0.4	> 0.4	> 0.4
$\Delta\phi_{\mathrm{min}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$ $(\Delta\phi(\gamma, E_{\mathrm{T}}^{\mathrm{miss}}))$	...	> 0.5	...	> 0.5	(> 0.4)	(> 0.4)	(> 0.4)

Photonic signatures

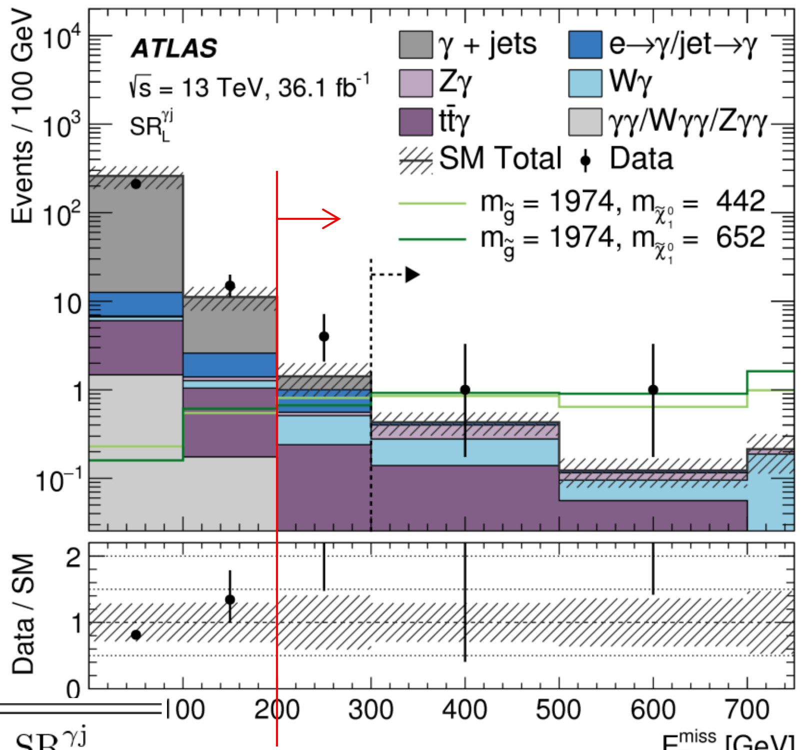
- Deviations between observed events and expected backgrounds are small in the two-photon signal regions.
- The rate of $jet \rightarrow \gamma$ is estimated with data. The rate of $W\gamma\gamma$ is extrapolated from a control region using SM prediction.



Signal Region	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{S-L}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{S-H}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-L}}$	$\mathrm{SR}^{\gamma\gamma}_{\mathrm{W-H}}$
Jet $\rightarrow \gamma$	$0.19^{+0.21}_{-0.19}$	$0.19^{+0.21}_{-0.19}$	0.93 ± 0.67	$0.19^{+0.21}_{-0.19}$
QCD diphoton	$0.00^{+0.17}_{-0.00}$	$0.00^{+0.17}_{-0.00}$	$0.15^{+0.17}_{-0.15}$	$0.00^{+0.17}_{-0.00}$
EW background	0.08 ± 0.04	0.06 ± 0.04	0.88 ± 0.23	0.51 ± 0.15
$(W \rightarrow \ell\nu)\gamma\gamma$	0.22 ± 0.14	0.21 ± 0.13	1.55 ± 0.78	1.08 ± 0.56
$(Z \rightarrow \nu\nu)\gamma\gamma$	0.01 ± 0.01	0.03 ± 0.02	0.15 ± 0.08	0.27 ± 0.13
Expected background events	$0.50^{+0.30}_{-0.26}$	$0.48^{+0.30}_{-0.25}$	3.7 ± 1.1	$2.05^{+0.65}_{-0.63}$
Observed events	0	0	6	1

Photonic signatures

- The deviations are larger in the single-photon signal regions.
- The backgrounds are from various processes.
- It will be interesting to re-visit this channel with 80/150 fb^{-1}.



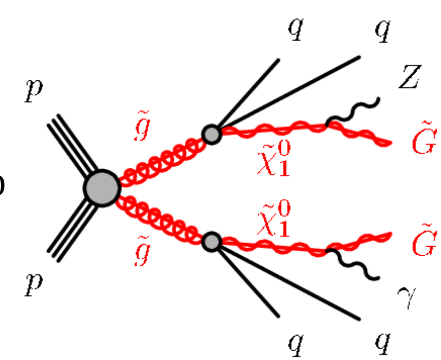
Signal Region	$SR_L^{\gamma j}$	$SR_{L200}^{\gamma j}$	$SR_H^{\gamma j}$
γ + jets (QCD)	$0.00^{+0.21}_{-0.00}$	$0.42^{+0.43}_{-0.42}$	0.14 ± 0.14
$W\gamma$	0.54 ± 0.24	0.81 ± 0.22	0.40 ± 0.26
$Z\gamma$	0.31 ± 0.16	0.36 ± 0.13	0.42 ± 0.19
$t\bar{t}\gamma$	0.30 ± 0.11	0.54 ± 0.17	0.07 ± 0.03
$e \to \gamma$	0.07 ± 0.03	0.16 ± 0.06	0.04 ± 0.04
Jet $\to \gamma$	$0.07^{+0.44}_{-0.07}$	$0.35^{+0.36}_{-0.35}$	$0.01^{+0.50}_{-0.01}$
$\gamma\gamma/W\gamma\gamma/Z\gamma\gamma$	0.03 ± 0.01	0.03 ± 0.01	0.06 ± 0.02
Expected background events	$1.33^{+0.58}_{-0.32}$	$2.68^{+0.64}_{-0.63}$	$1.14^{+0.61}_{-0.36}$
Observed events	4	8	3

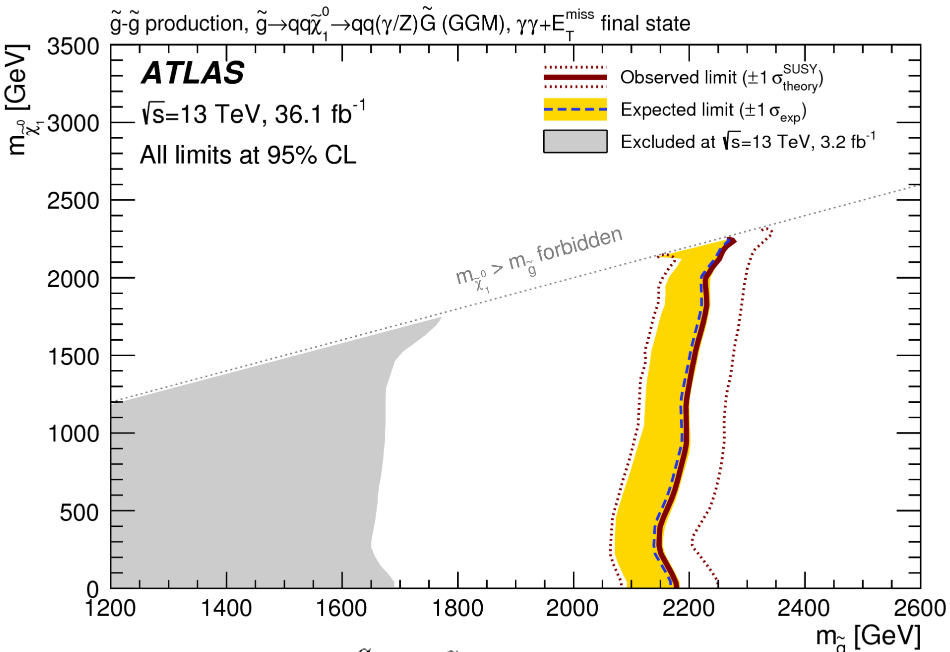
Photonic signatures

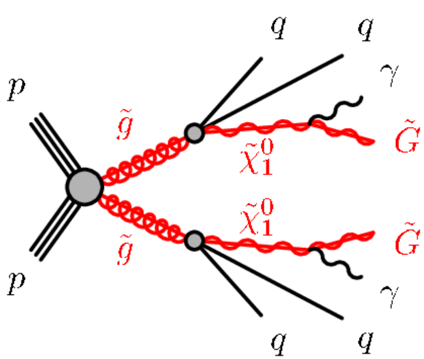
- Good improvement in sensitivity.

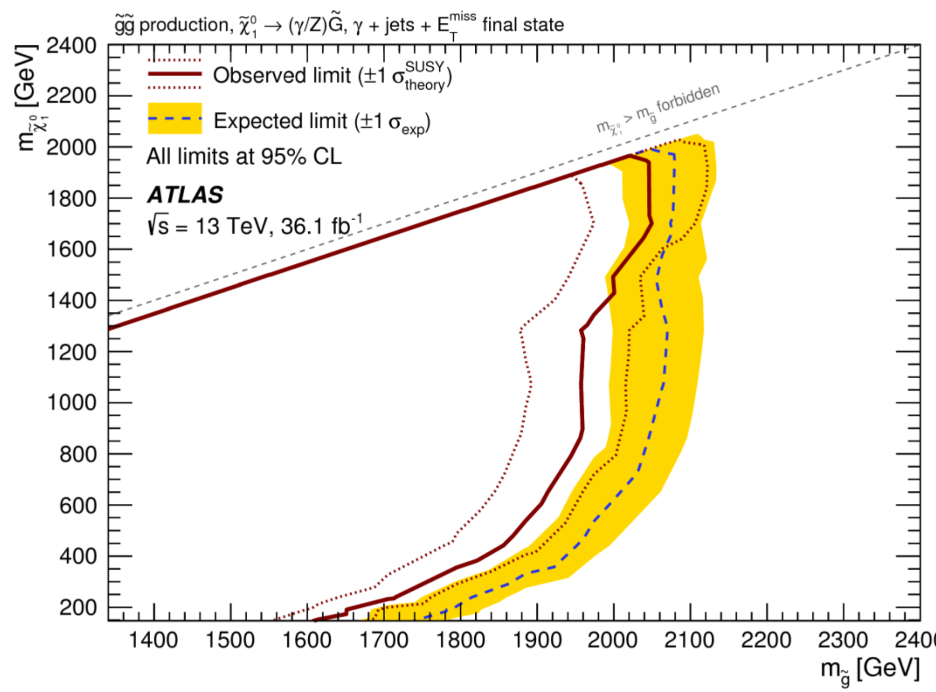
$$Br(\tilde{\chi}_1{}^0 \rightarrow \gamma\tilde{G}) \sim 50\%$$

$$Br(\tilde{\chi}_1{}^0 \rightarrow Z\tilde{G}) \sim 49\%$$

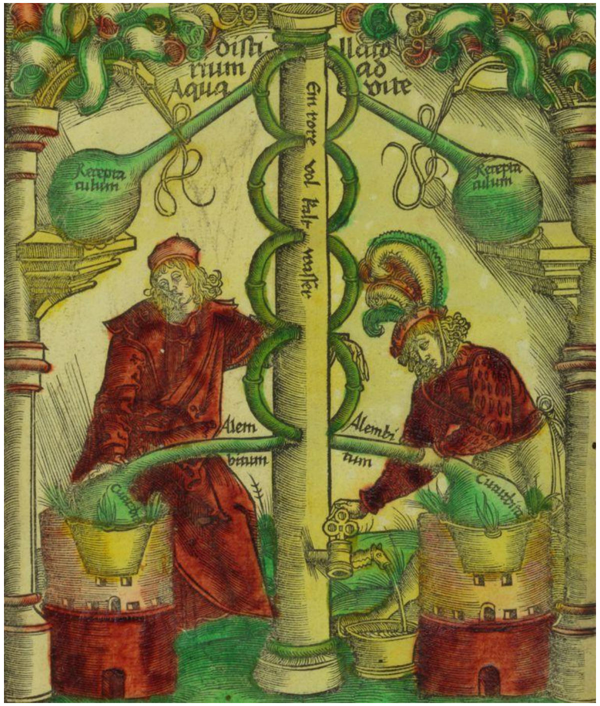


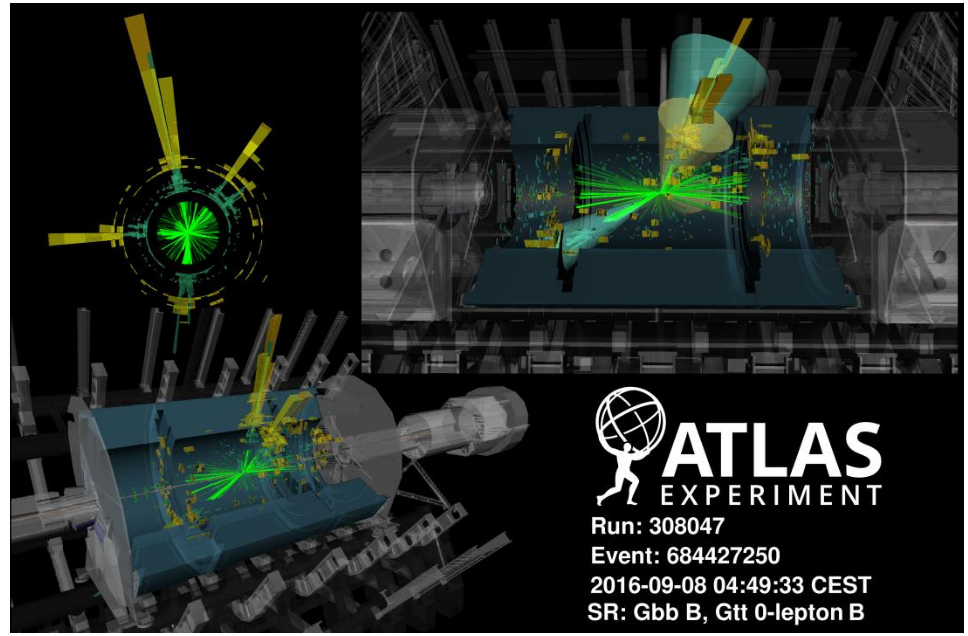






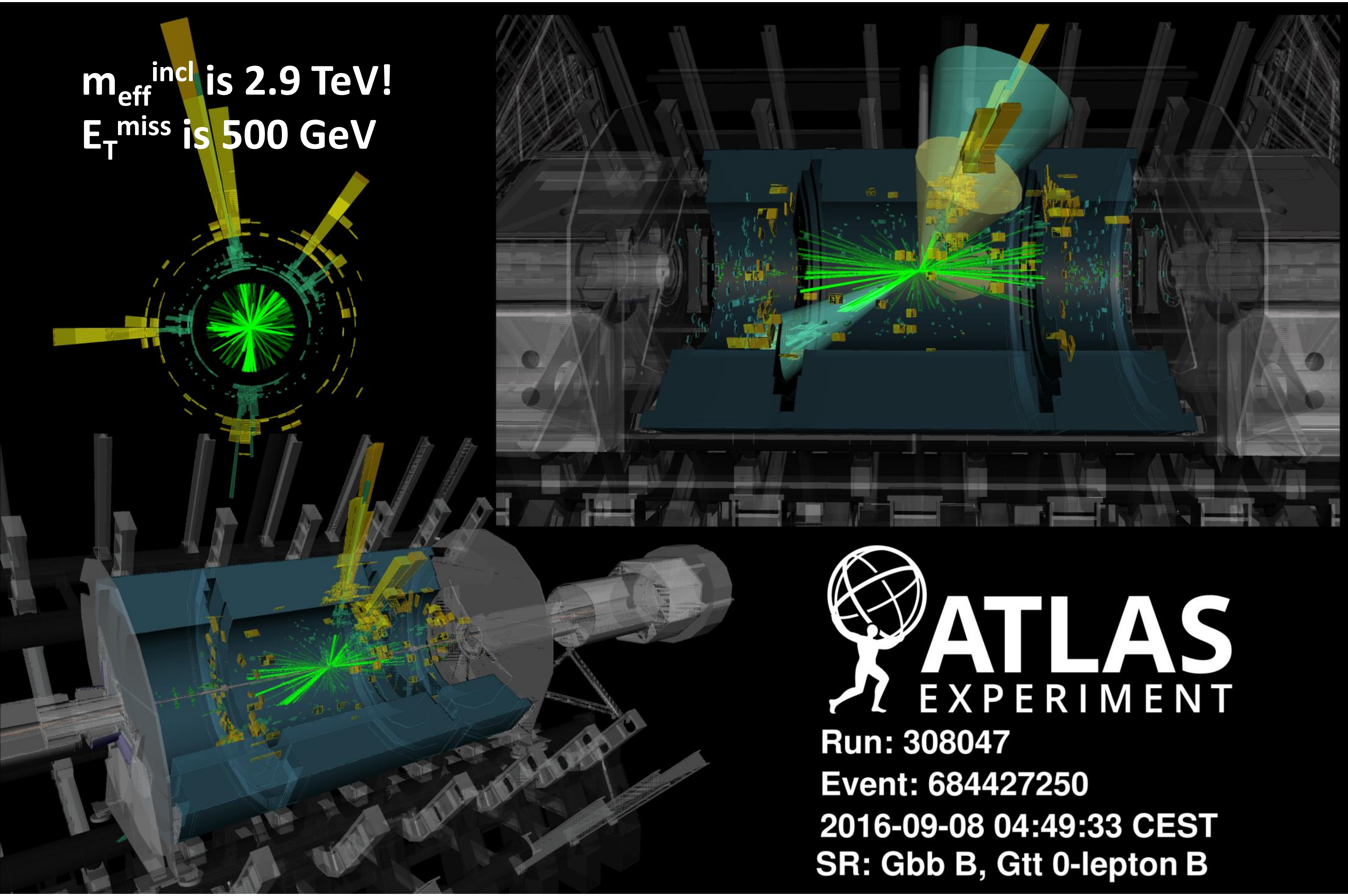
Outlook





- Now we know that the philosopher's stone does not exist. However, the medieval alchemy laid the foundation for development of modern chemistry.

- ATLAS has tremendous sensitivity to a broad range of models but we are not seeing anything big … yet.
- Our tools (SM predictions) and experimental techniques (understanding instrumental effects) are evolving. Every generation of searches covers a broader range of signatures.
- The ultimate sensitivity is not reached yet.


m_{eff}^{incl} is 2.9 TeV!
E_T^{miss} is 500 GeV
ATLAS
EXPERIMENT
Run: 308047
Event: 684427250
2016-09-08 04:49:33 CEST
SR: Gbb B, Gtt 0-lepton B

Thank you!