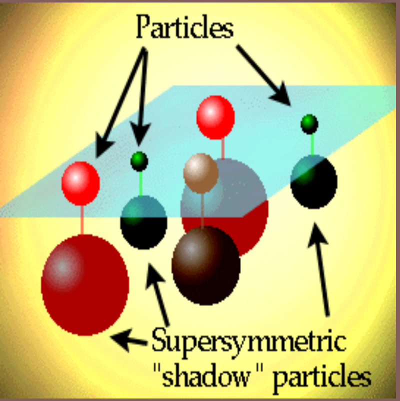
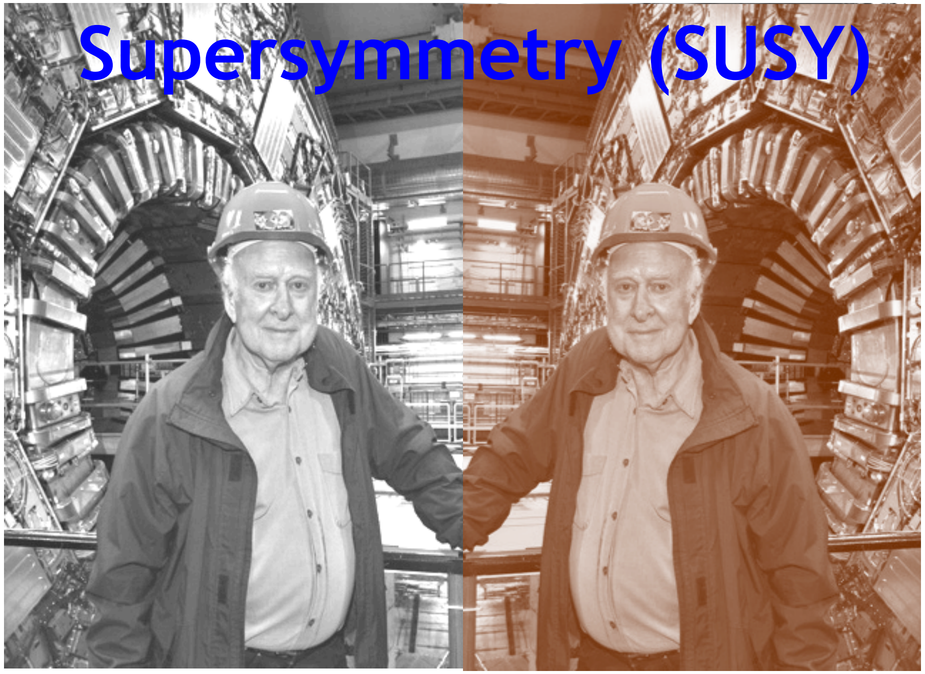



Supersymmetry (SUSY)

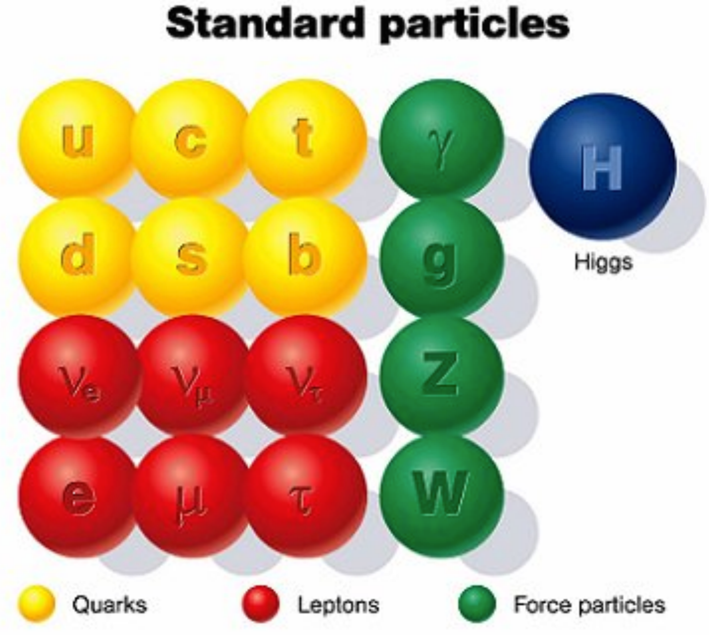
SUSY SEARCHES AT LHC AND BEYOND

Xuai Zhuang (庄胥爱)
xuai.zhuang@cern.ch
IHEP, Beijing, China

18-21 Jan. 2016, HK

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Standard Model and Supersymmetry



- **Standard Model (SM)**

  Very successful description of phenomena at TeV scale, but some shortcomings:

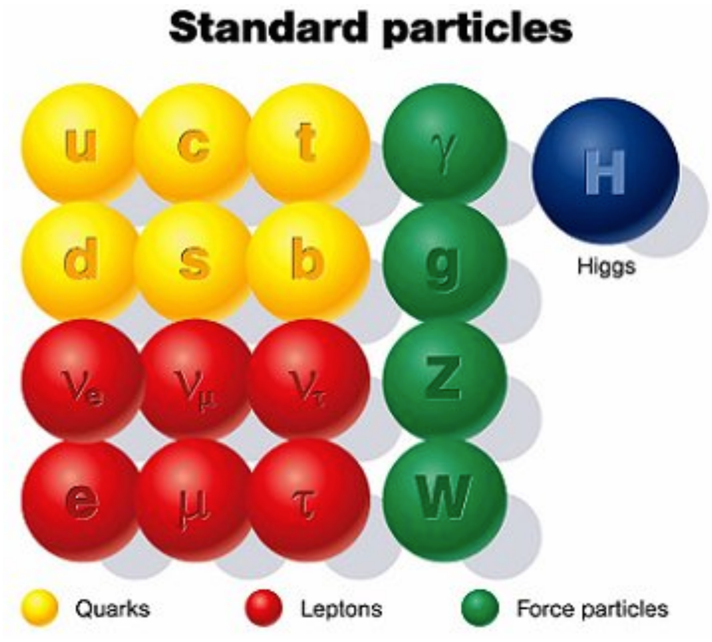
  ☐ Hierarchy problem

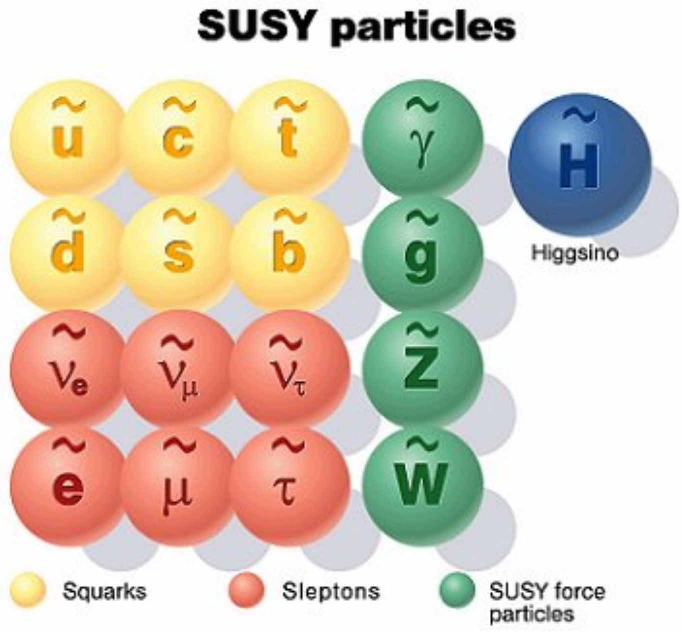
  ☐ Can not unify gauge couplings

  ☐ No dark matter (DM)

  ☐ …

Standard Model and Supersymmetry





- **Standard Model (SM)**

  Very successful description of phenomena at TeV scale, but some shortcomings:

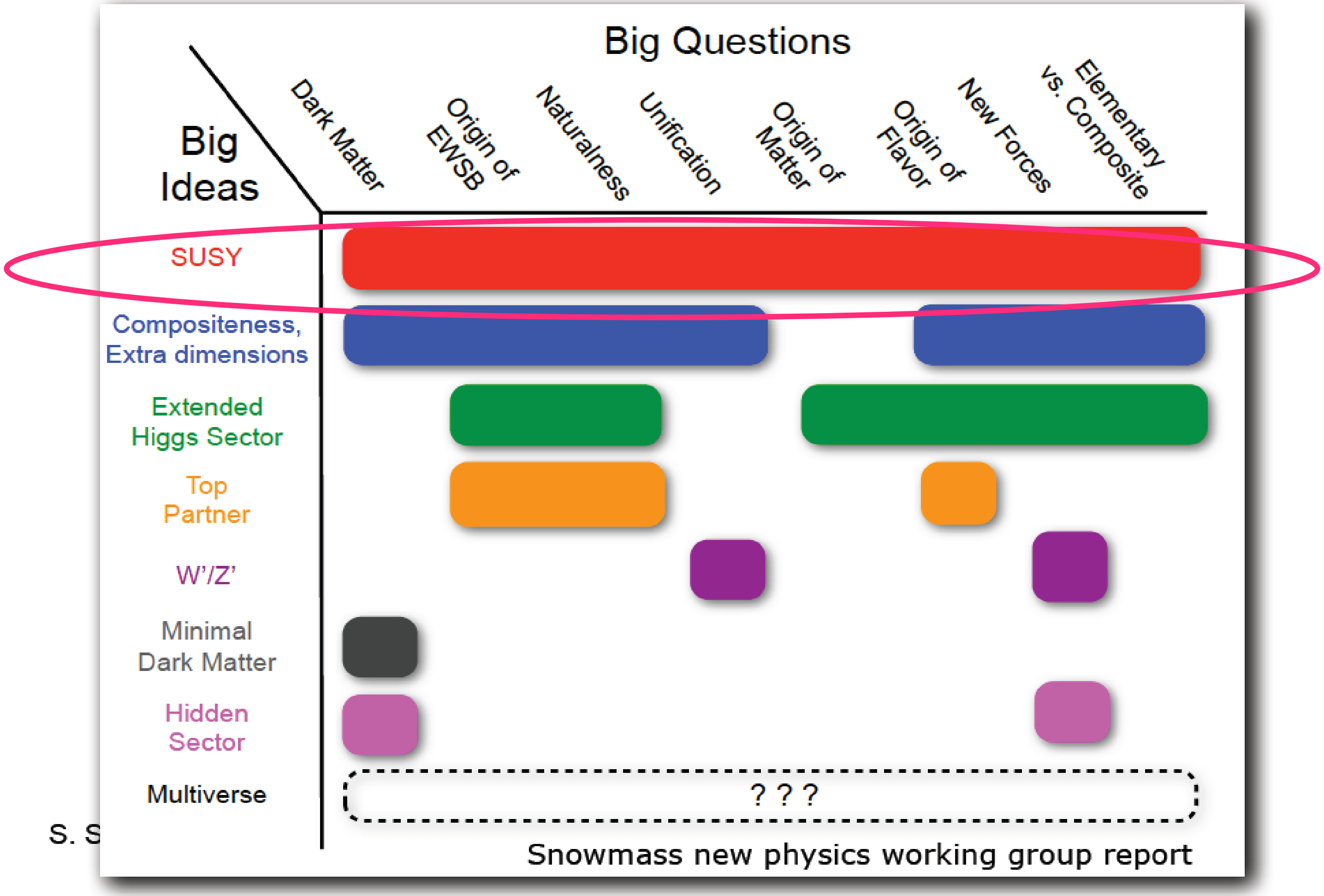
  - Hierarchy problem
  - Can not unify gauge couplings
  - No dark matter (DM)
  - …

- **Supersymmetry (SUSY)**

  Unique extension of Poincare spacetime symmetry

  - Moderate the hierarchy problem
  - Grand unification of gauge couplings
  - Provide excellent DM candidate
  - …

New Physics beyond the SM

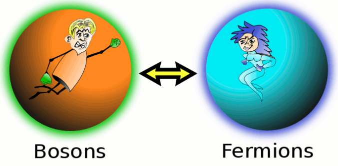


Snowmass new physics working group report

S. S

- If SUSY is at TeV scale, it will be produced copiously at LHC
- SUSY search is one of the most hot topic at LHC and beyond

SUSY Introduction

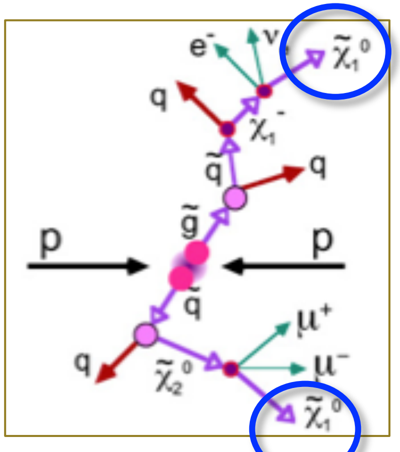


- **A symmetry which unified fermions (mater) and bosons (forces)** -> A fundamental theory
- **Conserved R parity (RPC):** (originally introduced for stability of proton)

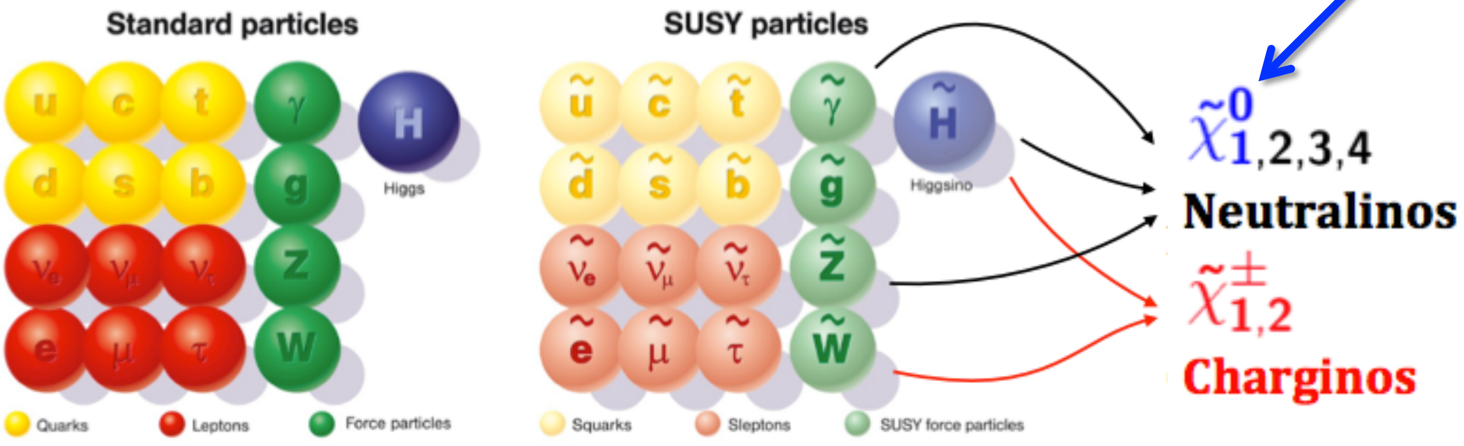
$$R = (-1)^{3(B-L)+2S}$$

R=+1 (SM)
R=-1 (SUSY)

  - SUSY particles produced/annihilated in pairs
  - Lightest SUSY particle (LSP) stable (DM candidate)
  - Typical signature: jets/leptons/photons + **MET**

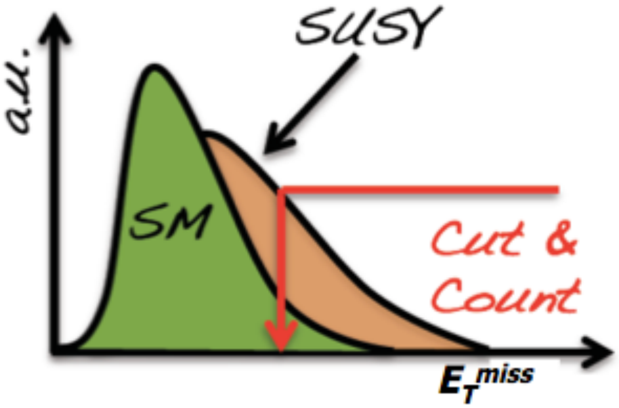


- **Violated R parity (RPV):** no Dark Matter candidate



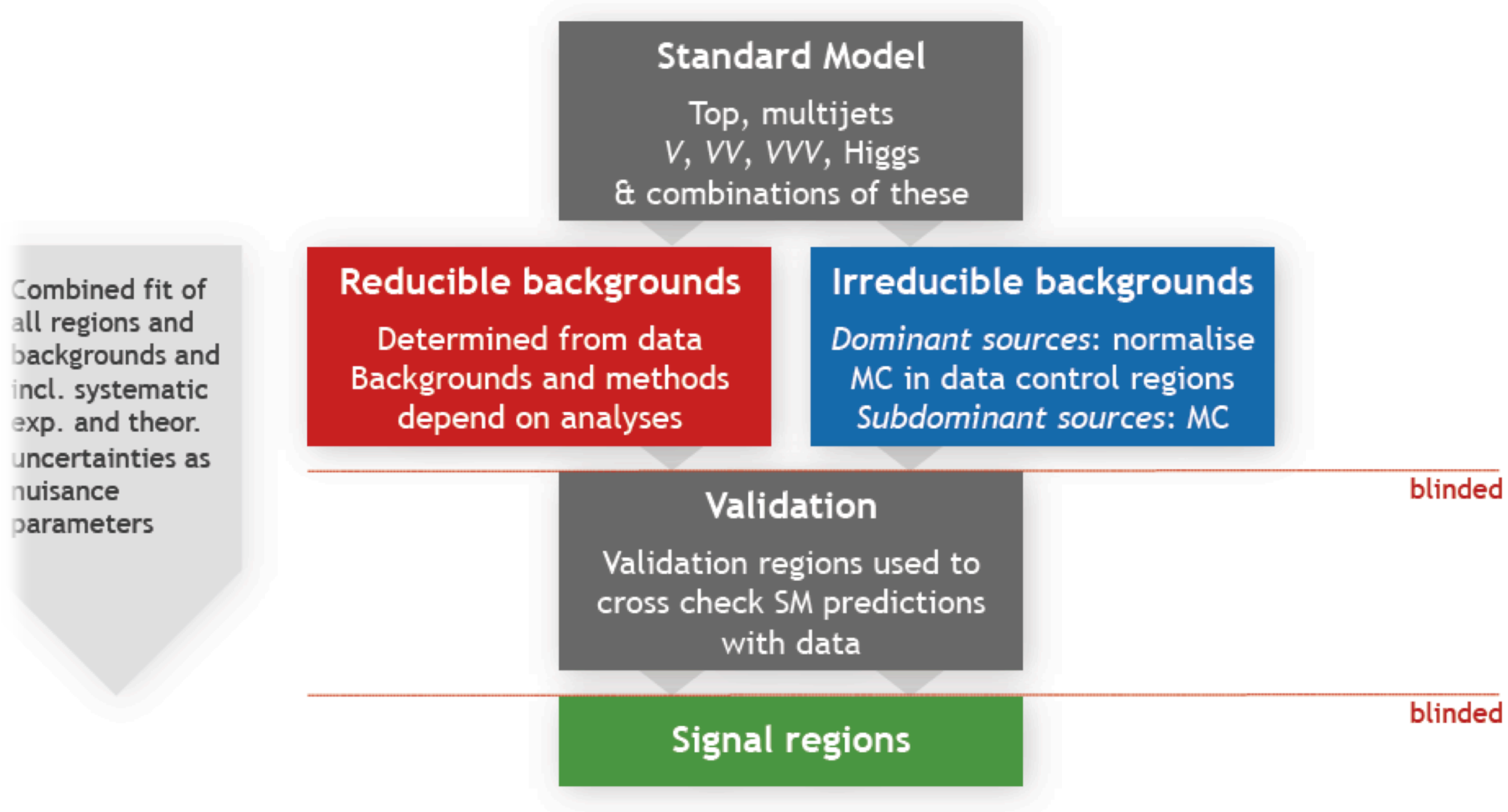
SUSY Search Strategy

- **SUSY search strategy:** search for deviation from SM
- **SUSY sensitive variables:** Try to establish excess of events in some sensitive kinematic distribution (E_T^{miss}, Meff, mT …)
- **SM background:** SUSY searches rely on accurate modeling of the Standard Model backgrounds



SM Background Modeling

- **SUSY searches rely on accurate modeling of the Standard Model backgrounds**



Combined fit of all regions and backgrounds and incl. systematic exp. and theor. uncertainties as nuisance parameters

Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

blinded

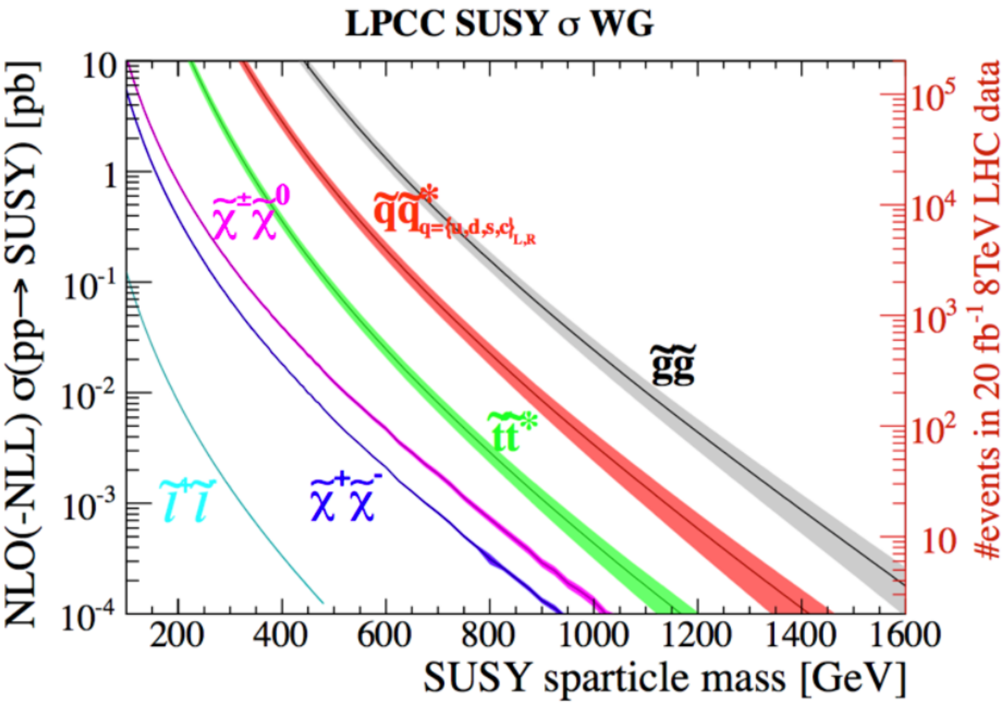
Validation

Validation regions used to cross check SM predictions with data

blinded

Signal regions

SUSY Search @ LHC



Strong production:

- ❑ targeting gluinos and 1st and 2nd generation squarks
- ❑ by far largest cross-sections

3rd generation:

- ❑ targeting stop and sbottoms
- ❑ Should be lowest mass squarks for naturalness reasons

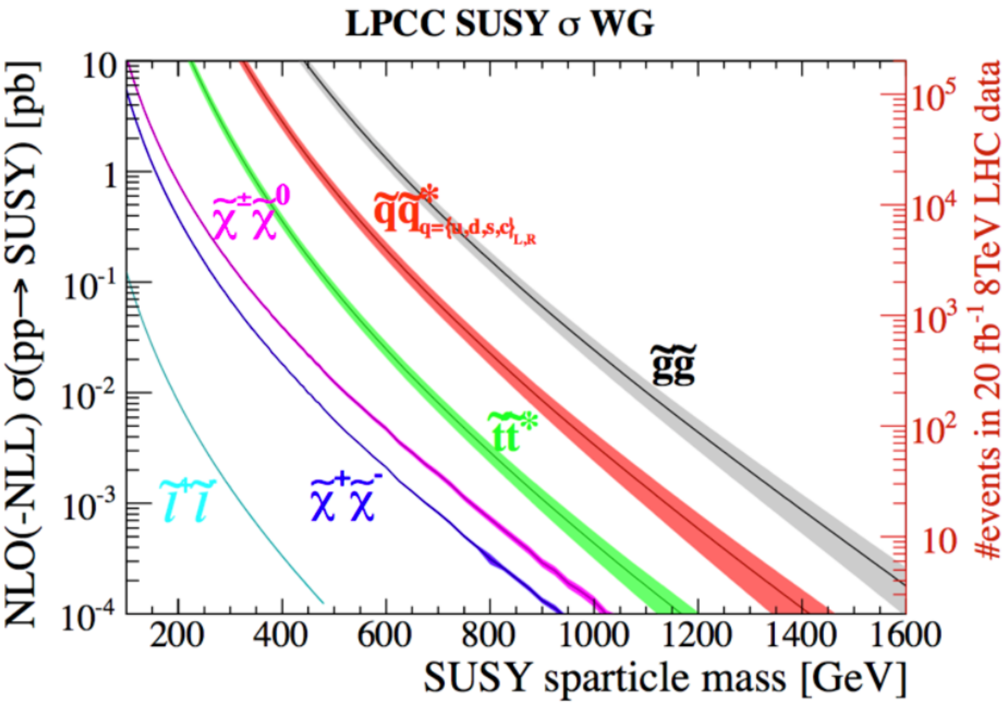
Electroweak production:

- ❑ targeting Electroweakinos, sleptons
- ❑ Lowest mass sparticles, clean signature

RPV/LL:

- ❑ targeting R-parity violating models and long lived sparticles
- ❑ More exotic models

SUSY Search @ LHC

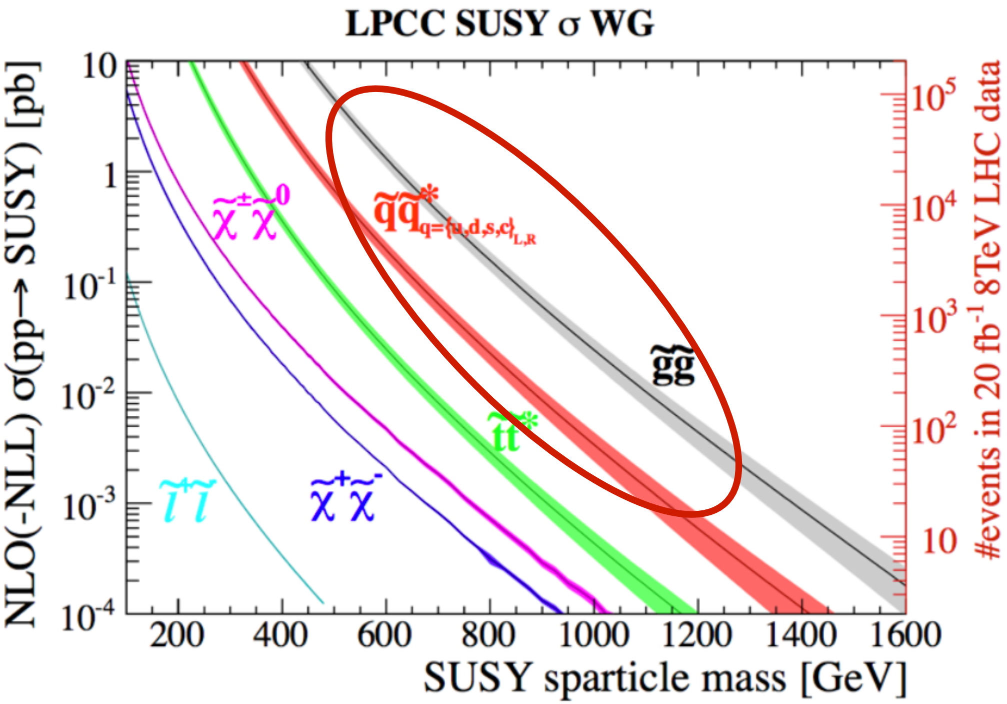


Outline:

- ➔ SUSY Search from real data @ LHC (8-13 TeV)

- ➔ Longer term prospects @ LHC and Future Collider (14, 33, 100 TeV)

SUSY Search @ LHC (Run1+2)



The results are based on 3.3 fb^{-1} @ 13 TeV (Run2)

Strong production:

- ☐ targeting gluinos and 1st and 2nd generation squarks
- ☐ by far largest cross-sections

3rd generation:

- ☐ targeting stop and sbottoms
- ☐ Should be lowest mass squarks for naturalness reasons

Electroweak production:

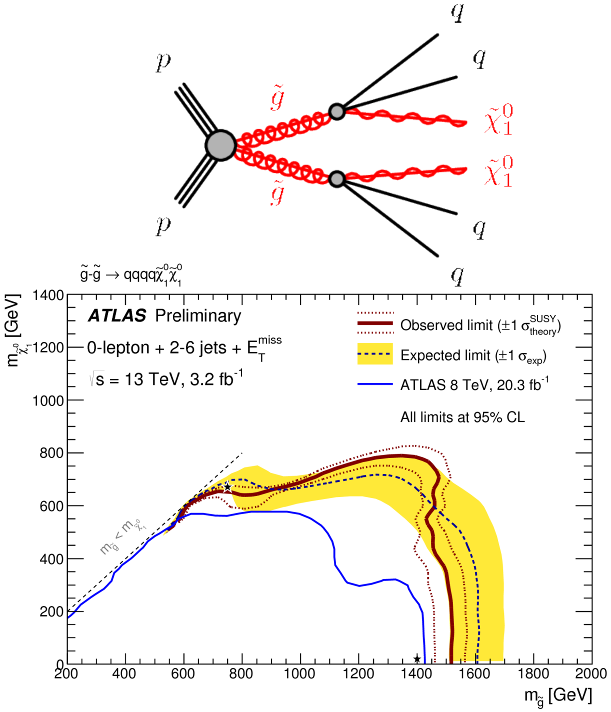
- ☐ targeting Electroweakinos, sleptons
- ☐ Lowest mass sparticles, clean signature

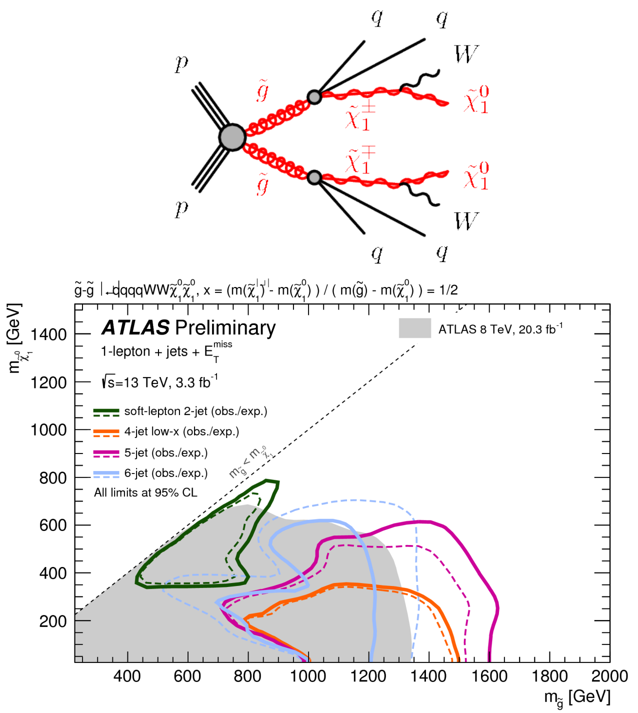
RPV/LL:

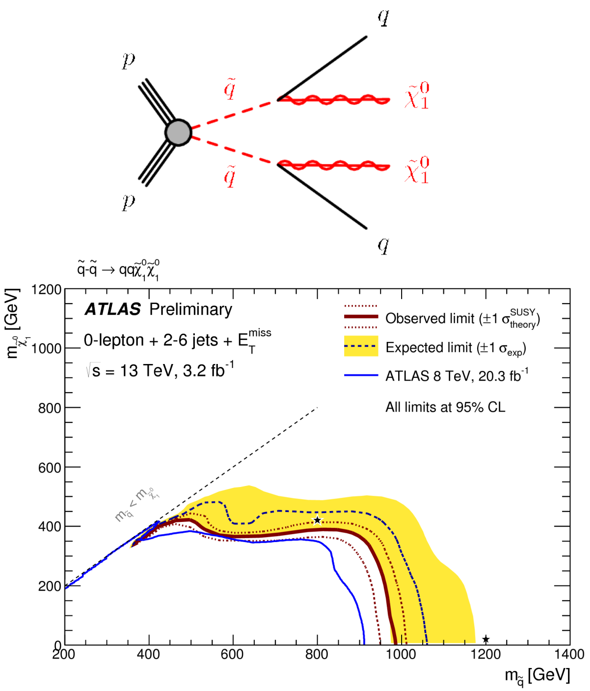
- ☐ targeting R-parity violating models and long lived sparticles
- ☐ More exotic models

Strong Production: 0-1L+jets+MET

- Search for **gluinos and 1st and 2nd generation squarks**
- Final states with jets, missing transverse momentum and **no or one isolated lepton (e/μ)** **(IHEP: 1L channel)**
- Signal to BG discrimination based on: **Meff, MET, mT**
- 28 signal regions defined targeting different search scenarios
- **Excludes gluino masses up to 1.6 TeV, squark mass up to 980 GeV**



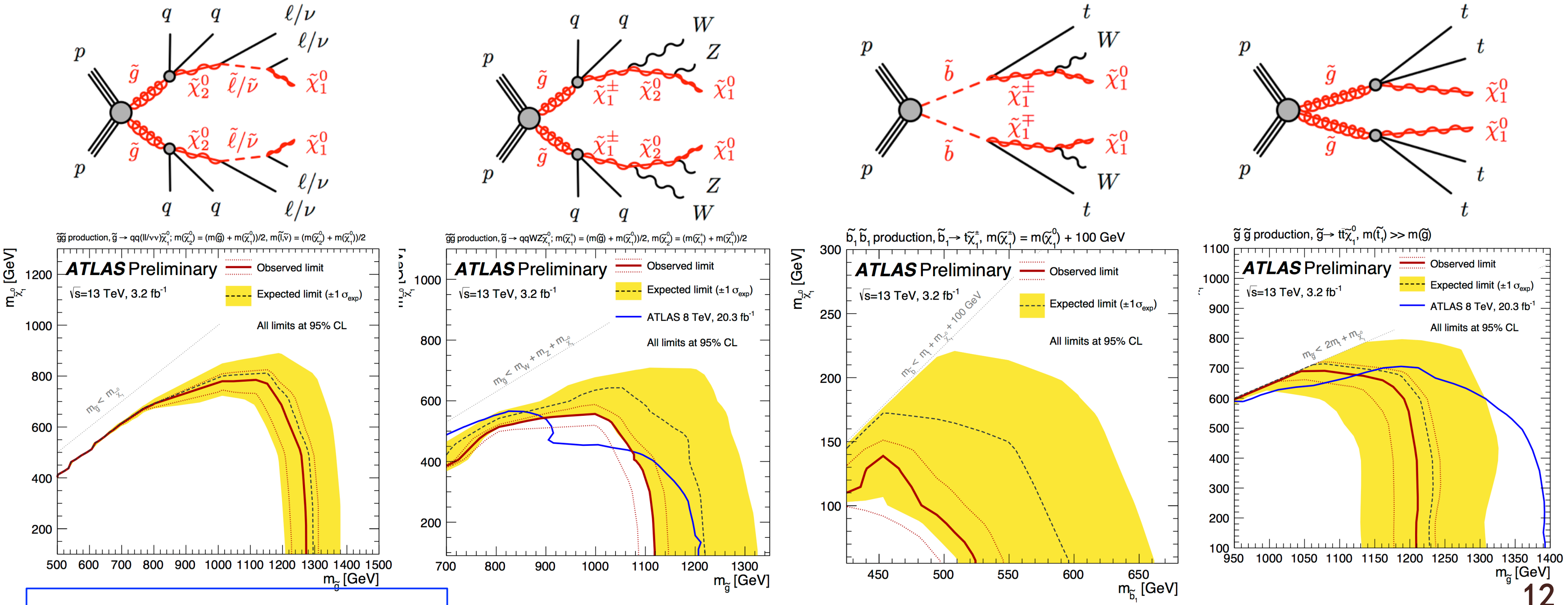




ATLAS-CONF-2015-062(0L 2-6J), ATLAS-CONF-2015-076(1L), ATLAS-CONF-2015-077(0L 7-10J)

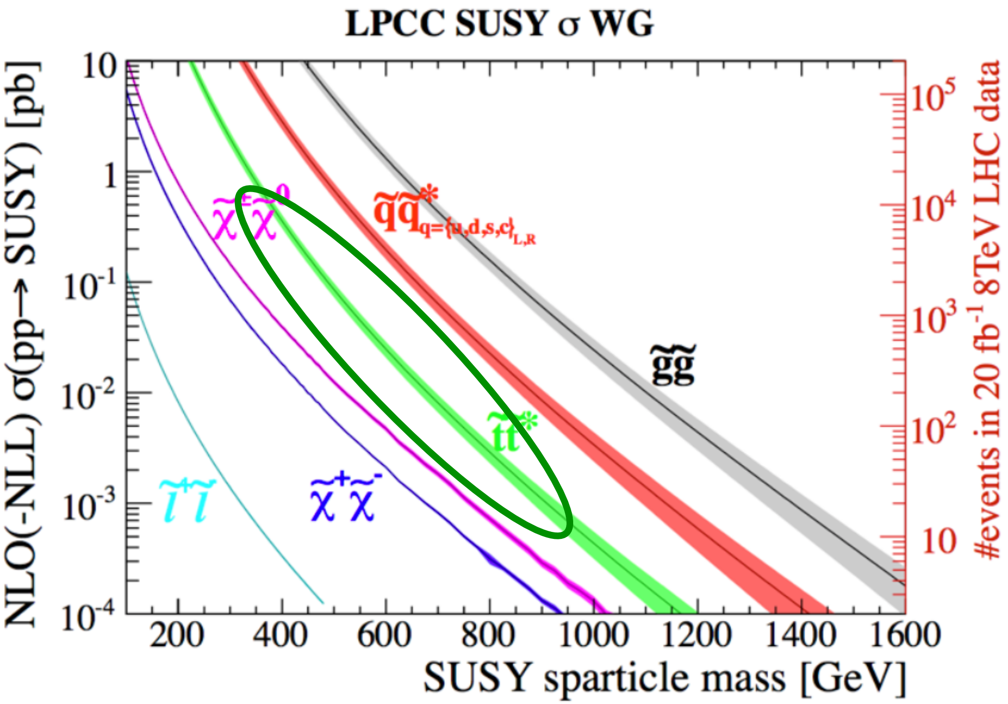
Strong Production: SS/3L+jets+MET

- Search for **squarks/gluinos** via long decay chain in **SS/3L (IHEP)**
  - Sensitive for a wide range of models (Fig. 1)
  - Very clean channels with only tiny SM bg (mainly top+V, diboson, triboson) → **A good probe for new physics**
- 4 SRS defined, targeting specific scenarios
- Gluino mass <1.1-1.3 TeV and LSP mass < 550-800 GeV are excluded for gluino pair production



ATLAS-CONF-2015-078

SUSY Search @ LHC



The results are based on 3.3 fb^{-1}@ 13 TeV (Run2) for sbottom,
20 fb^{-1} @ 8 TeV (Run1) for stop

Strong production:

- ☐ targeting gluinos and 1st and 2nd generation squarks
- ☐ by far largest cross-sections

3rd generation:

- ☐ targeting stop and sbottoms
- ☐ Should be lowest mass squarks for naturalness reasons

Electroweak production:

- ☐ targeting Electroweakinos, sleptons
- ☐ Lowest mass sparticles, clean signature

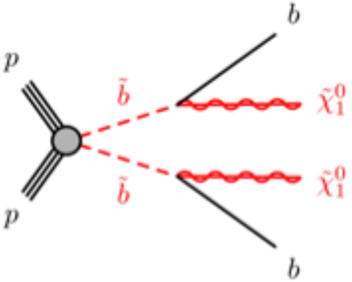
RPV/LL:

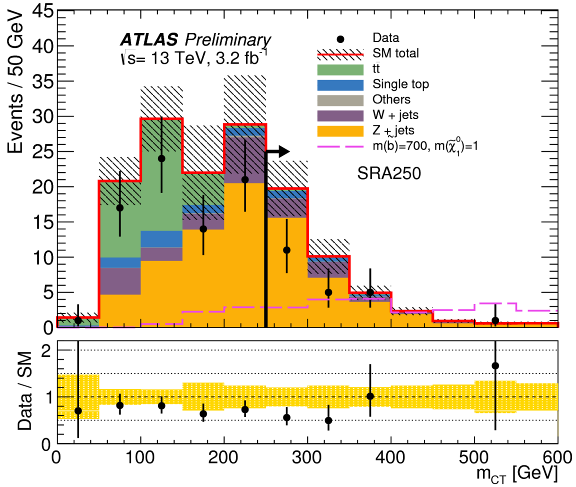
- ☐ targeting R-parity violating models and long lived sparticles
- ☐ More exotic models

Run2

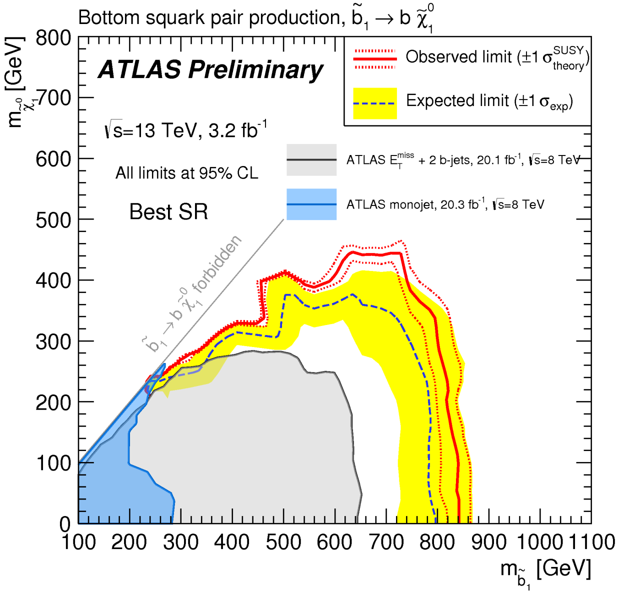
Strong Production: ~b~b

- Search for sbottom directly from ~b~b production with a 2b + MET FS





- Discriminate variables: mCT, MET
- 2 signal regions defined with 2 b-jets and medium or tight MET cut
- No significant excessed observed
- Excludes sbottom masses up to 850 GeV



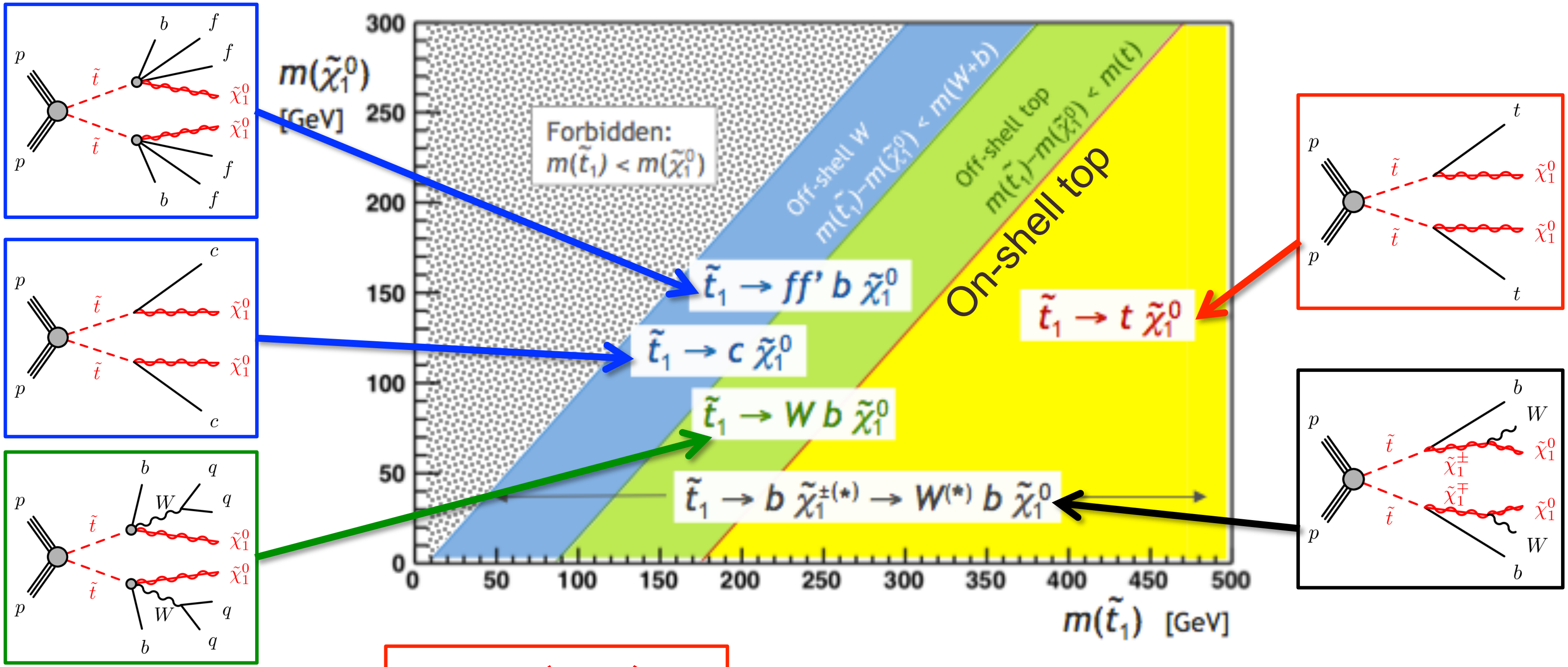
$$m_{CT}^2(v_1,v_2) = [E_T(v_1)+E_T(v_2)]^2 - [p_T(v_1)-p_T(v_2)]^2$$

ATLAS-CONF-2015-066

Run1

Strong Production: ~t~t

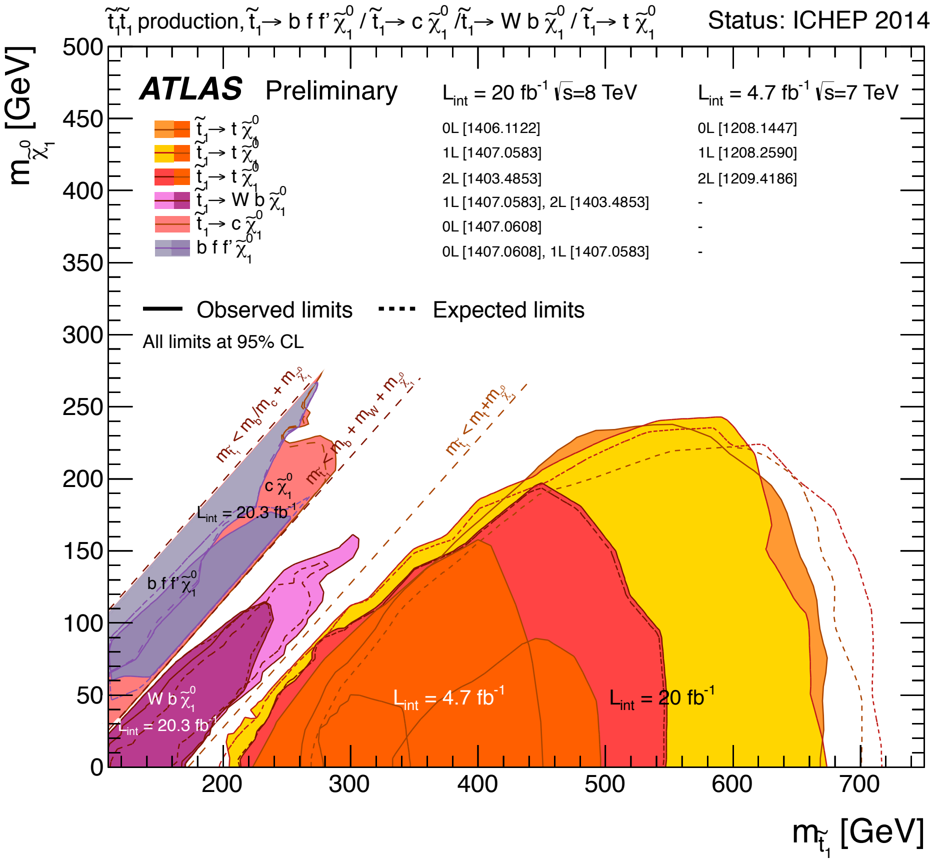
- Search for **stop** directly from ~t~t production
- **Large spectrum of possible stop decays**, covering range from low to heavy stop mass, various decay modes.

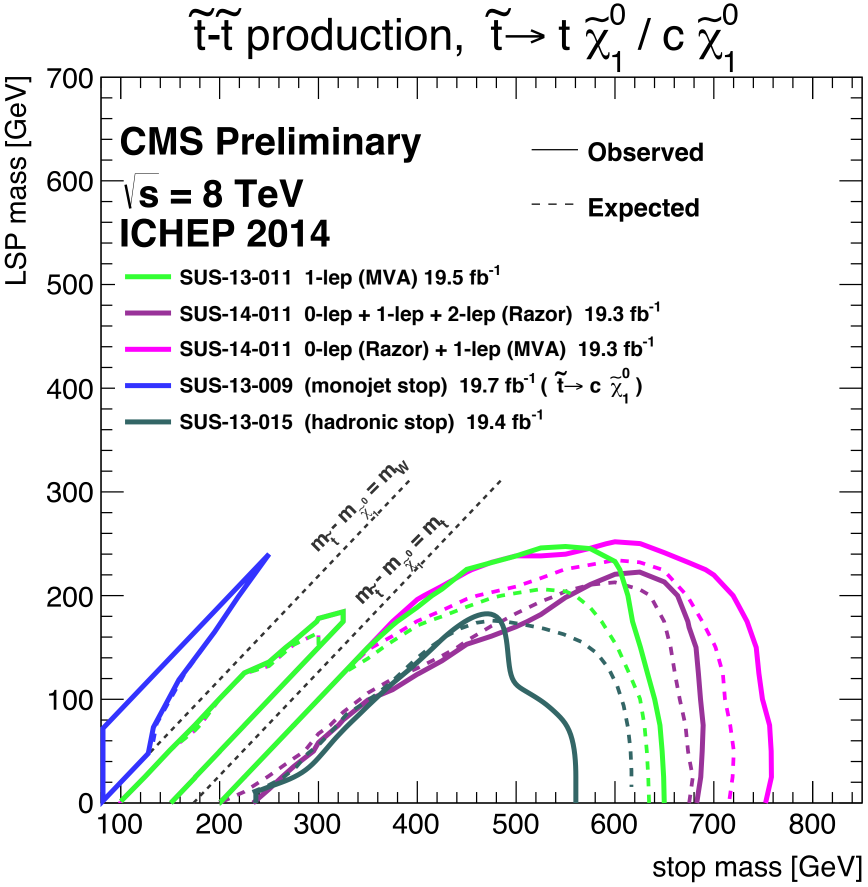


JHEP 11 (2014) 118

Run1

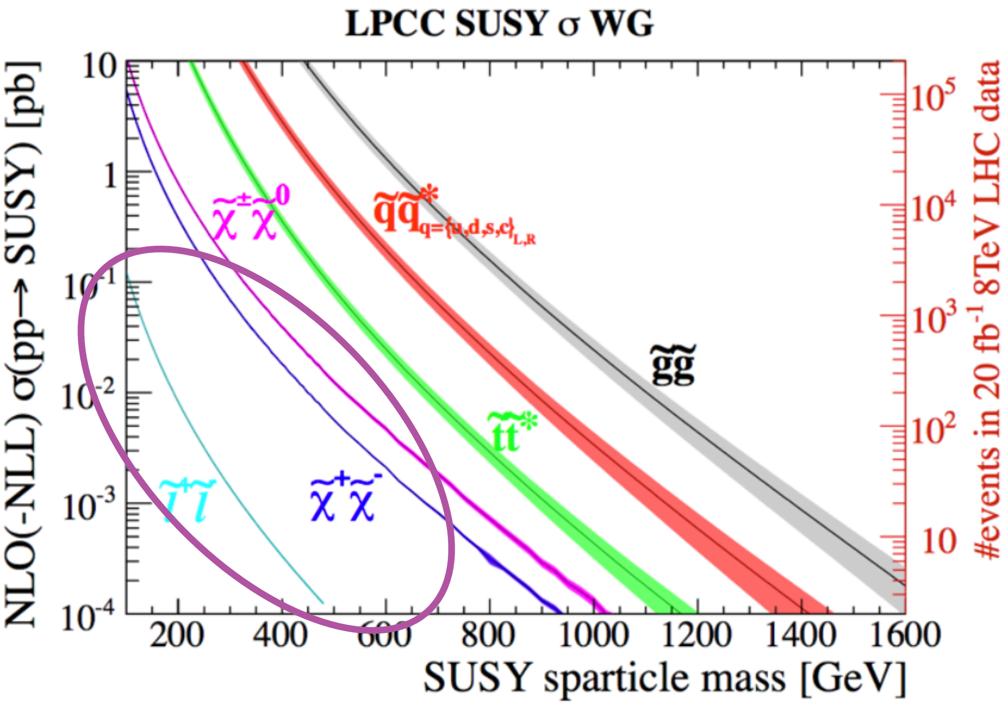
Direct stop pair production Summary





- Exclusion for m(~t1) < ~660GeV for massless LSP, exclusion up to m(LSP) ~250 GeV

SUSY Search @ LHC



The results are based on 20 fb^{-1} @ 8 TeV (Run1)

Strong production:

- ☐ targeting gluinos and 1st and 2nd generation squarks
- ☐ by far largest cross-sections

3rd generation:

- ☐ targeting stop and sbottoms
- ☐ Should be lowest mass squarks for naturalness reasons

Electroweak production:

- ☐ targeting Electroweakinos, sleptons
- ☐ Lowest mass sparticles, clean signature

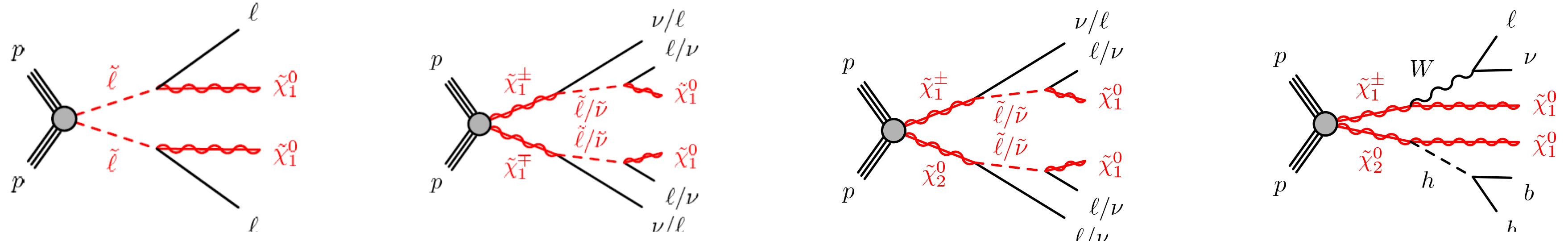
RPV/LL:

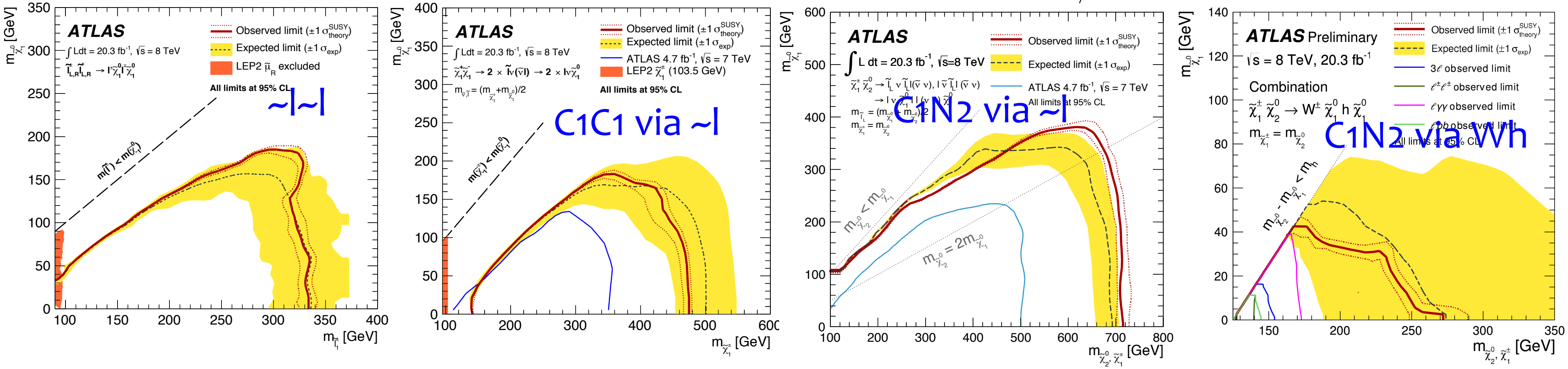
- ☐ targeting R-parity violating models and long lived sparticles
- ☐ More exotic models

EWK Production: 1-3L+MET

- Search for **sleptons** with **2L (e/μ) + MET** FS → **~l > 330 GeV**
- Search for **charginos and neutralinos** with **2-3L (e/μ) + MET** FS

  → **Excludes electroweakino masses up to 400-700 GeV**
- Search for **charginos and neutralinos via higgs decay (Wh→1l +bb, γγ, ll, ττ)** → **Excludes electroweakino masses up to 250 GeV**



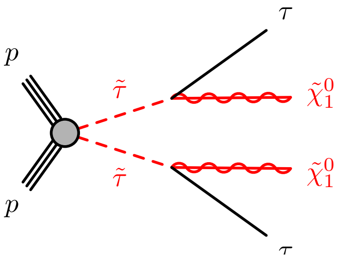


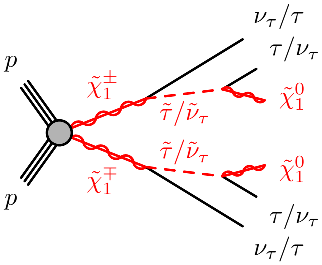
JHEP 05 (2014) 071, JHEP 04 (2014)169, ATLAS-CONF-2014-062

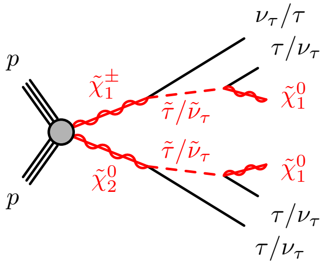
EWK Production: 2tau+MET

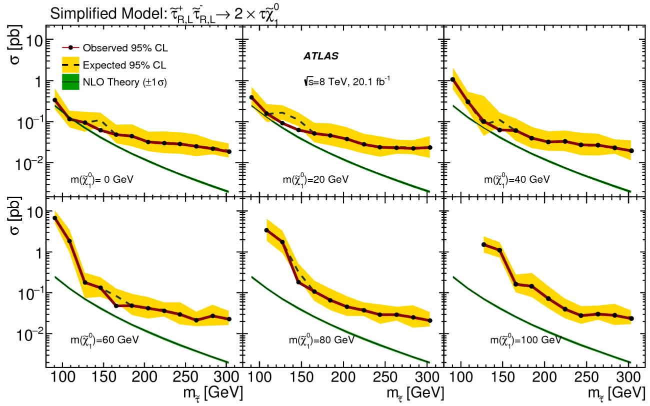
- IHEP member firstly proposed the search for stau and gaugino with final state: ≥2tau + MET, which is also the first search in LHC experiment.
- **4SRs** targeting different scenarios

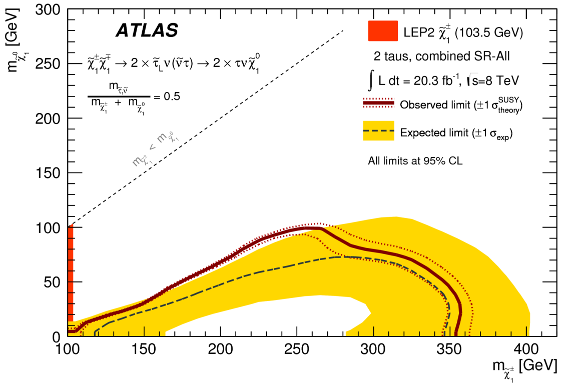
→ Excludes electroweakino masses up to 350-400 GeV

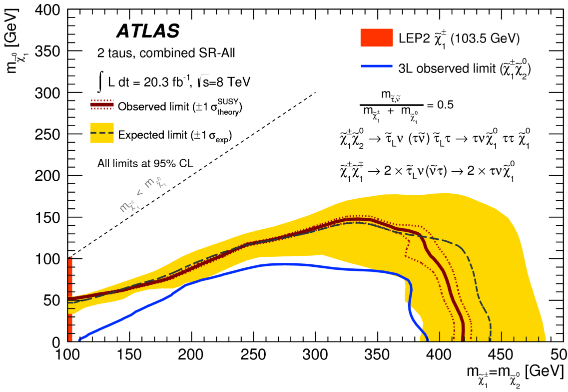






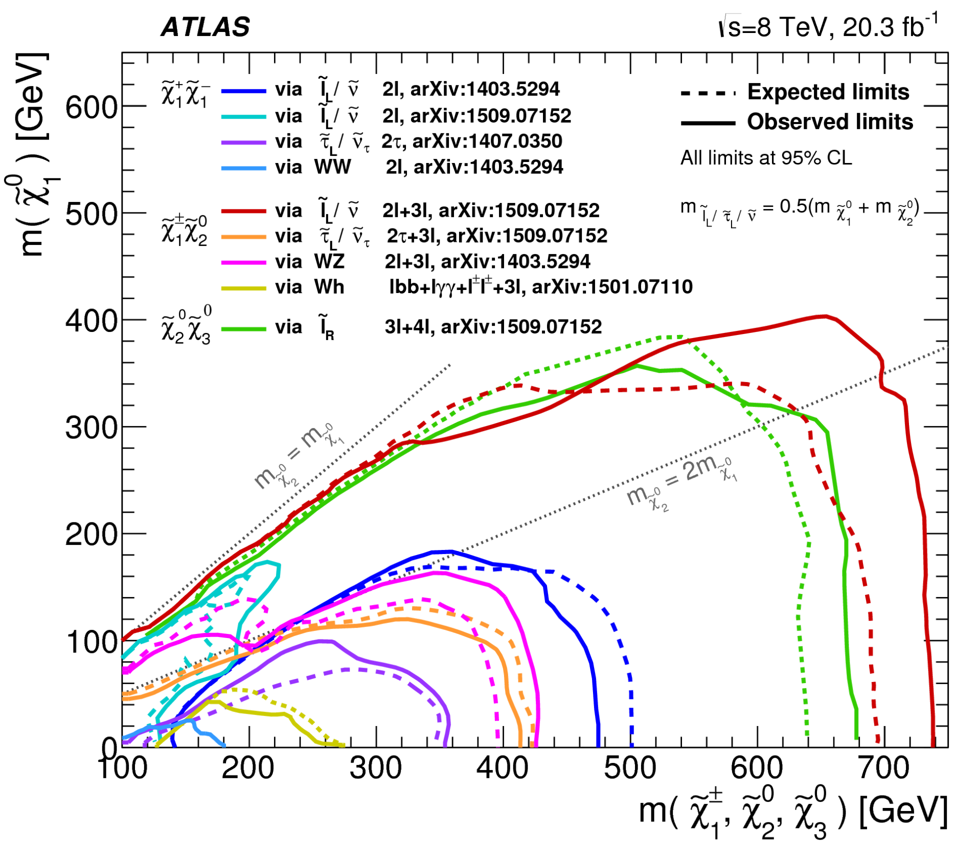


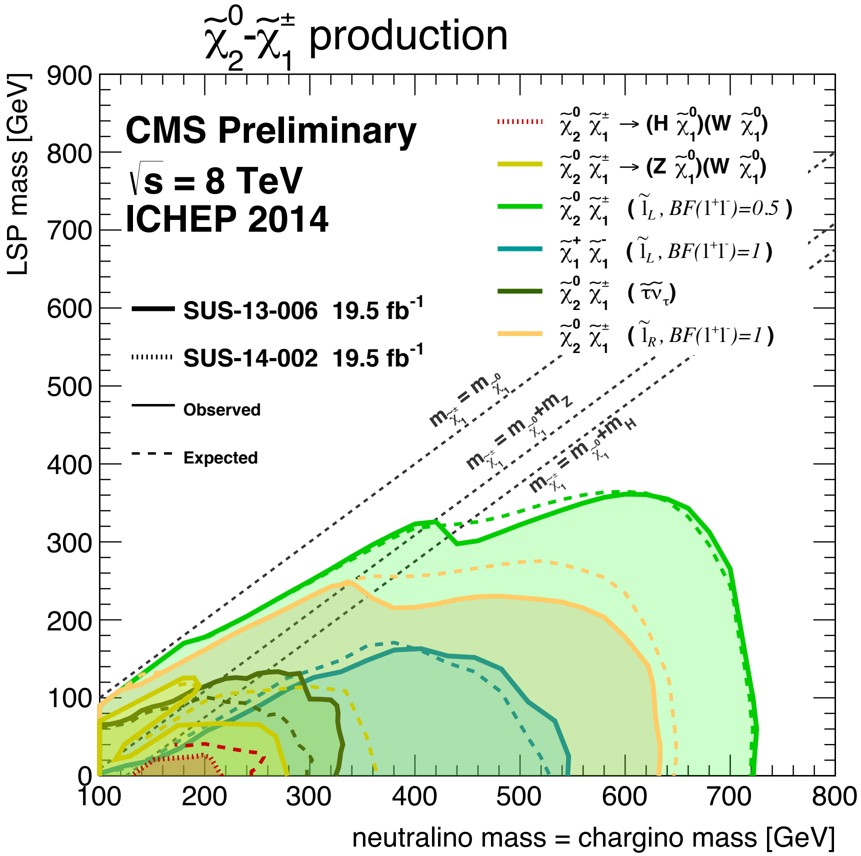




JHEP 10 (2014) 096, arXiv:1509.07152

EWK Production Summary

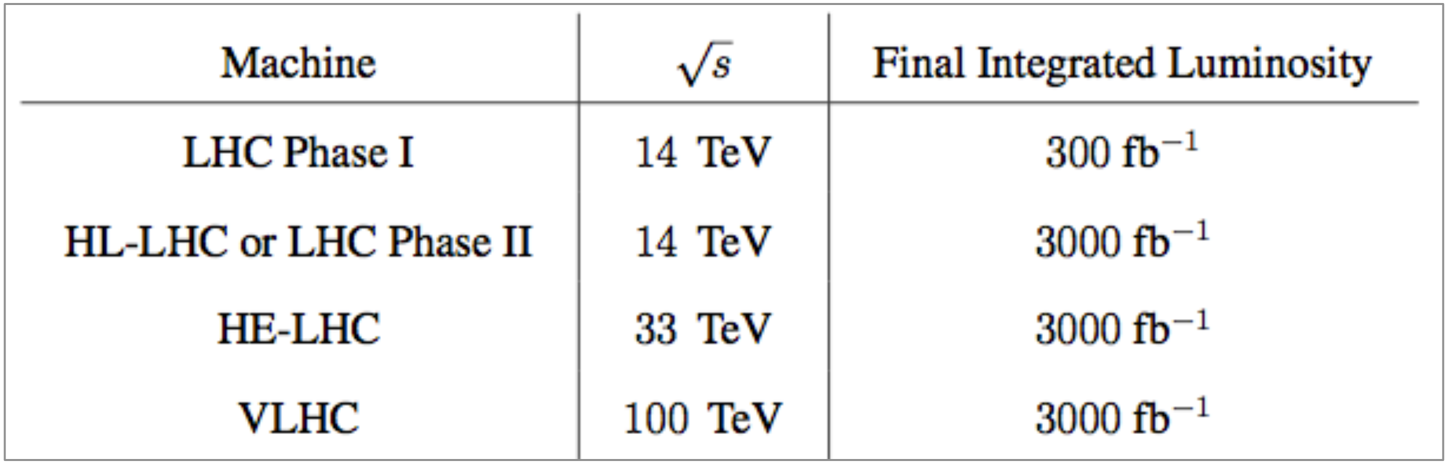




- Comparable for C1N2 via slepton
- CMS: no results on C1C1 via stau and WW

Prospects at Future Proton Colliders

arXiv:1311.6480

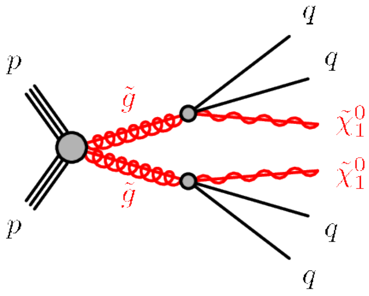


Machine	$\sqrt{s}$	Final Integrated Luminosity
LHC Phase I	14 TeV	300 fb^{-1}
HL-LHC or LHC Phase II	14 TeV	3000 fb^{-1}
HE-LHC	33 TeV	3000 fb^{-1}
VLHC	100 TeV	3000 fb^{-1}

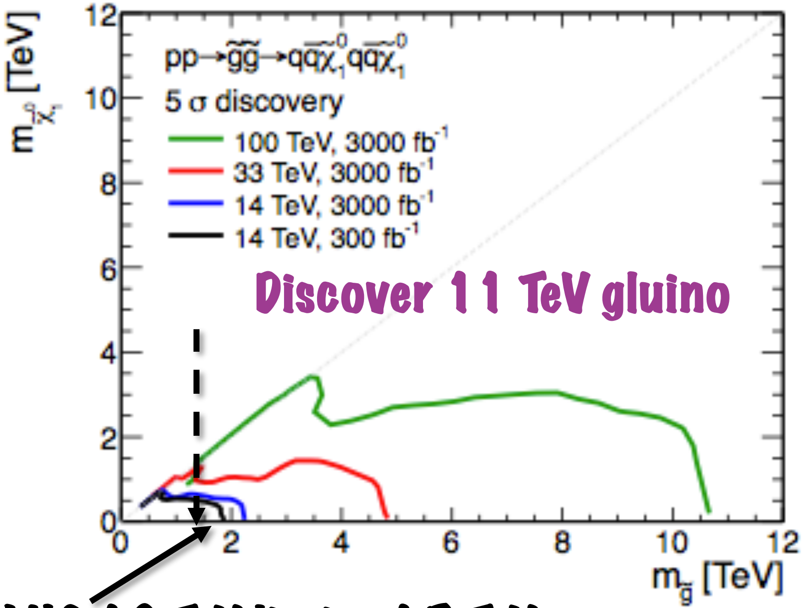
- Long term prospects for 4 collider scenarios have been studied (14, 33, 100 TeV @3000 fb^{-1})
- Use same search strategy as Run1@LHC
- Use simple analysis strategies, avoid assumption, on detector design, pileup sensitivity, etc

Gluino-Neutralino Signature

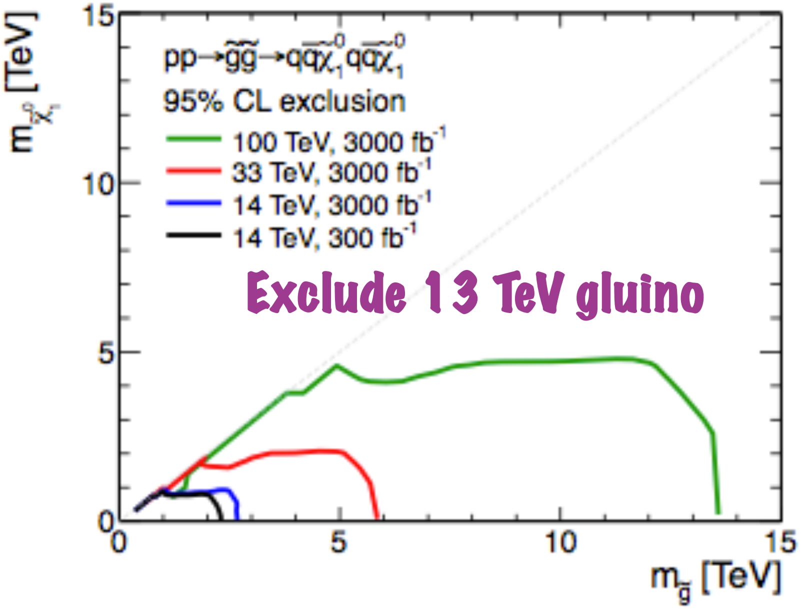
- Search for gluinos with no lepton, multi-jets, large missing transverse momentum
- Signal to BG discrimination based on: MET, HT (Σjet pt)
- Discover (Exclude) 11 (13) TeV gluino
- Increasing the center-of-mass energy has a tremendous impact on the experimentally available parameter space (~5 x beyond 14 TeV @100 TeV)



arXiv: 1311.6480



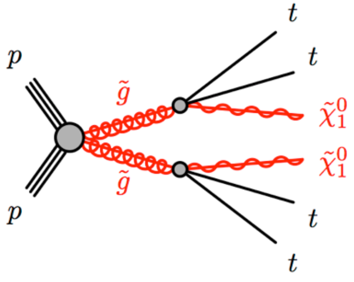
LHC 13 TeV limit ~1.5 TeV



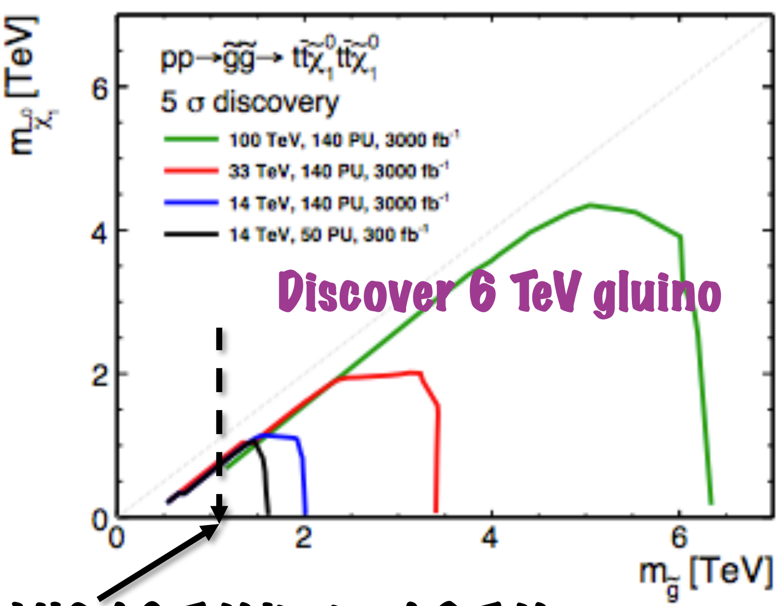
20% systematic uncertainty, no pileup

Gluino-Neutralino Signature – heavy flavor

- Search for gluinos with Same Sign 2 lepton, 2b-jets, large missing transverse momentum
- Signal to BG discrimination based: MET, HT, meff, mT2
- Discover (Exclude) 6 (8) TeV gluino
- Increasing the center-of-mass energy has a tremendous impact on the experimentally available parameter space (~3 x beyond 14 TeV @100 TeV)

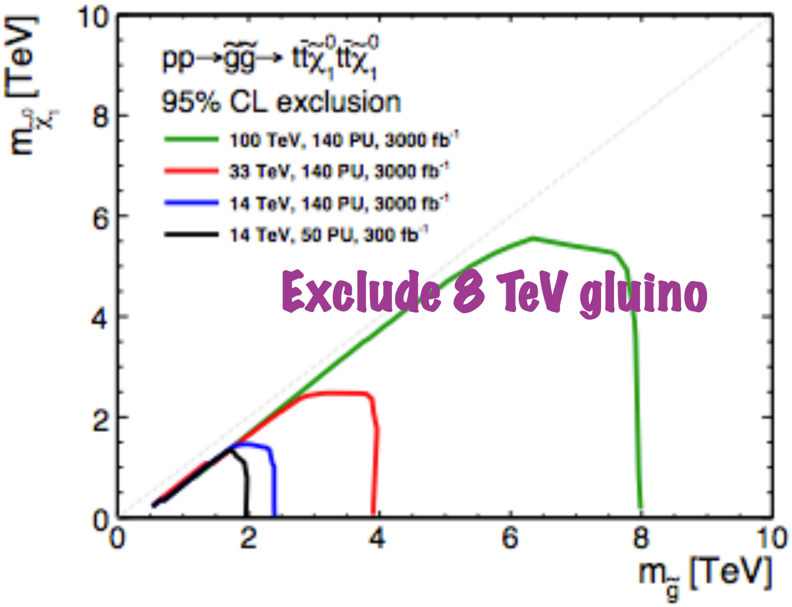


arXiv: 1311.6480



Discover 6 TeV gluino

LHC 13 TeV limit ~1.2 TeV

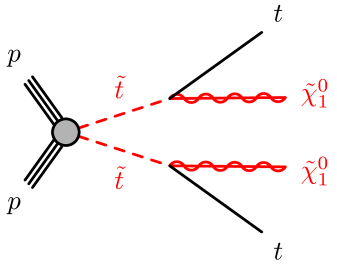


Exclude 8 TeV gluino

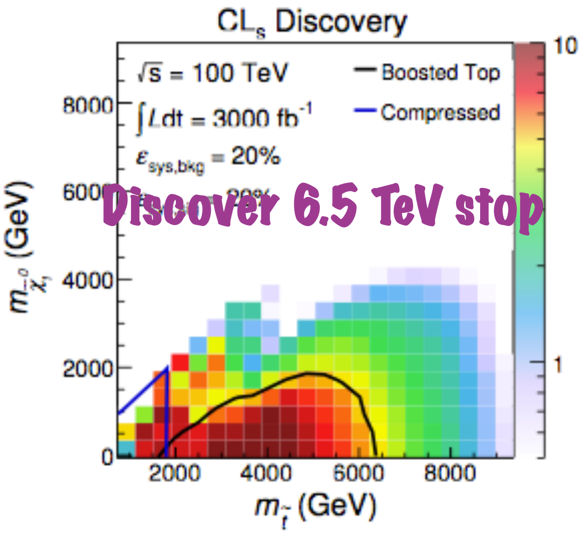
20% systematic uncertainty, no pileup

Stop-Neutralino Signature

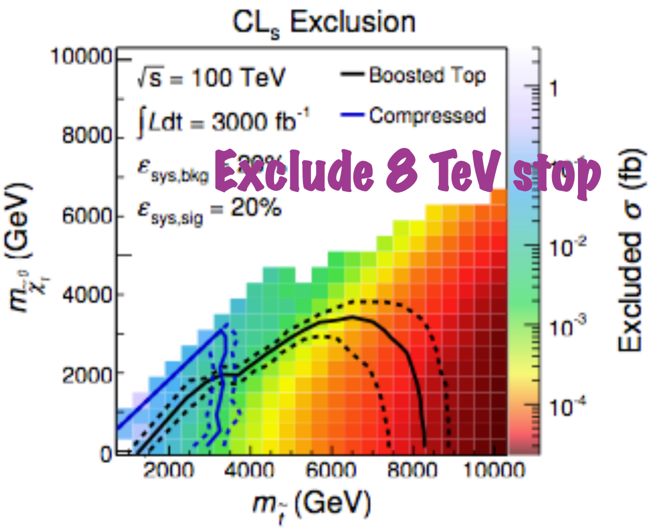
- Search for stop with on-shell top decay @ 100 TeV
- Tops are very boosted at 100 TeV, the search strategy with isolated leptons, b-tags or top-tagging are sensitive to detector granularity/performance, pileup conditions etc. → So use simple handles with hard jets, MET and muon-in-jet
- Two scenarios with high mass stop and compressed region designed
- Discover (Exclude) 6.5 (8) TeV stop @100TeV



arXiv: 1406.4512

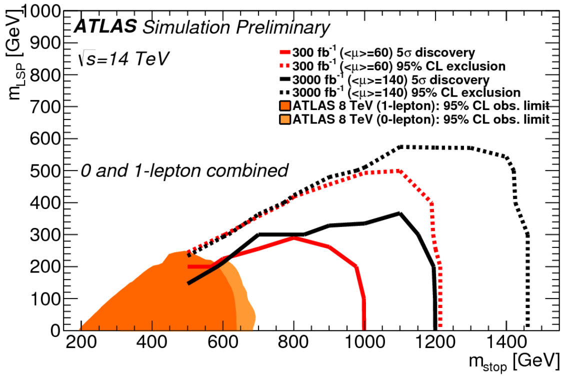


Discover 6.5 TeV stop



Exclude 8 TeV stop

LHC 14:
Exclude 1. 4 TeV stop

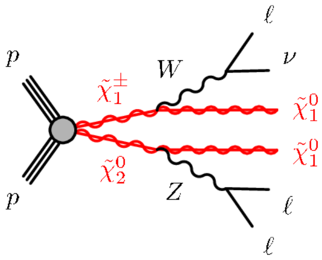


ATL-PHYS-PUB-2014-010

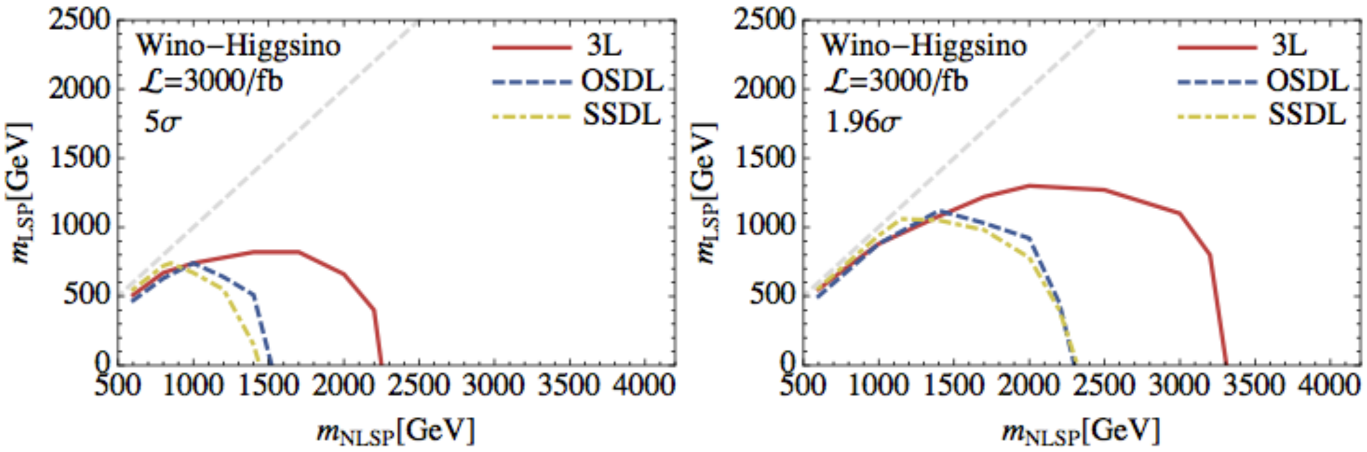
LHC 8: ~ 700 GeV

EWK Signature

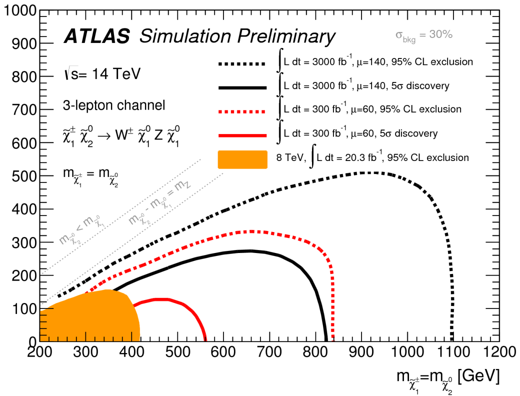
- Increasing bounds on colored SUSY particles, maybe only electroweakinos in the low energy spectrum. LHC has limited reach for direct produced EWK particles
- Potential search for electroweakinos with multi-lepton signatures: 3L || OS2L || SS2L @100 TeV
- Discover (Exclude) 2.1 (3.2) TeV electroweakinos for wino NLSP



arXiv: 1410.6287



LHC 14:
Exclude 1. 1 TeV stop



ATL-PHYS-PUB-2013-011

LHC 8: ~ 400 GeV

Summary

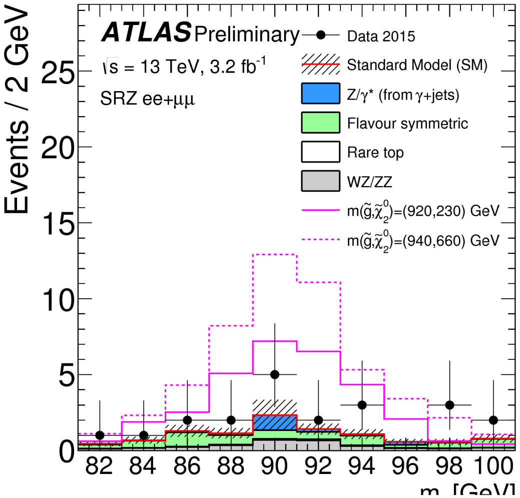
- [LHC 8 TeV ~20 fb^{-1}] In canonical scenarios, sensitivity is achieved to ~1.2 TeV gluinos, ~700 GeV stops and ~400 GeV EWK-inos
- [LHC 14 TeV ~3000 fb^{-1}] Discovery potential up to 2.2 TeV gluinos, 1.2 TeV stop and 800 GeV EWK-inos
- [100 TeV ~3000 fb^{-1}] Discover (Exclude) 11 (13) TeV gluino, 6.5 (8) TeV stop, 2.1 (3.2) TeV EWK-inos

→[LHC 13 TeV ~3.3 fb-1] some extensions for squark and gluino sensitivity with 2015 RUN2 data, some small excess hints observed but still weak, need more data! Looking forward for 2016 and beyond!

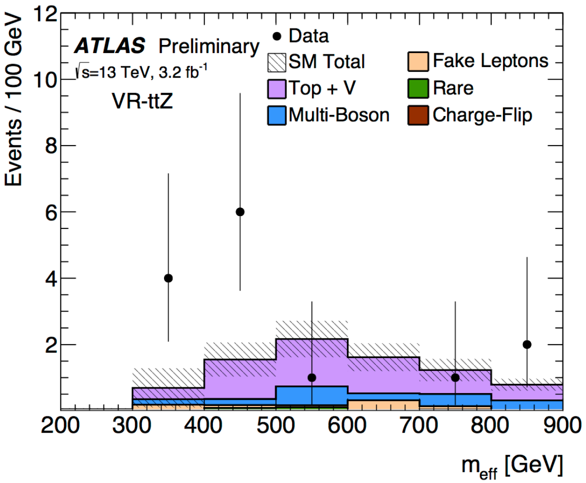
Thanks for your attention!

Run2

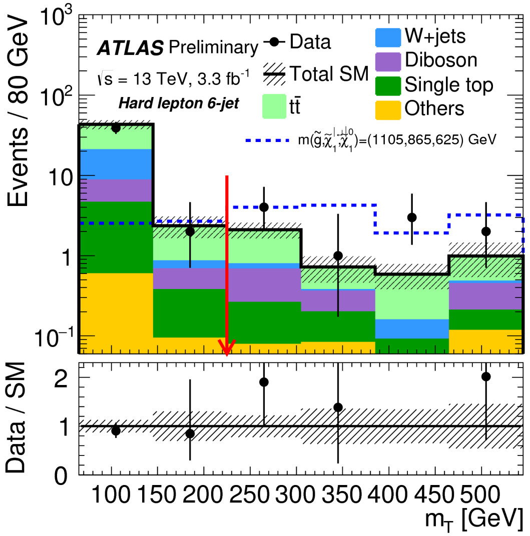
Excess Hints in Run2



Z+MET: a mild excess 2.2σ in 2L (Z+MET) analysis (same SR as run1, where a 3σ excess was found)



SS/3L: an excess in ttZ VR (see 3.5σ excess in 3l+3b VR in run1, will revisit in run2)



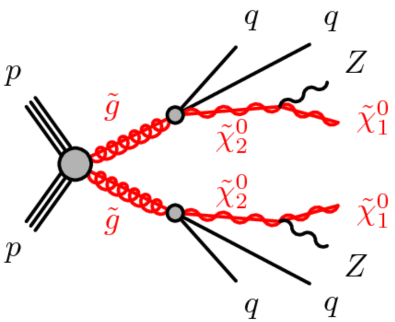
1L: mT distribution disagrees in 6J SR (~2σ)

- There are some excess hints in 3 SUSY analyses (1L, SS/3L, Z+MET)
  →Exciting prospects for 2016!

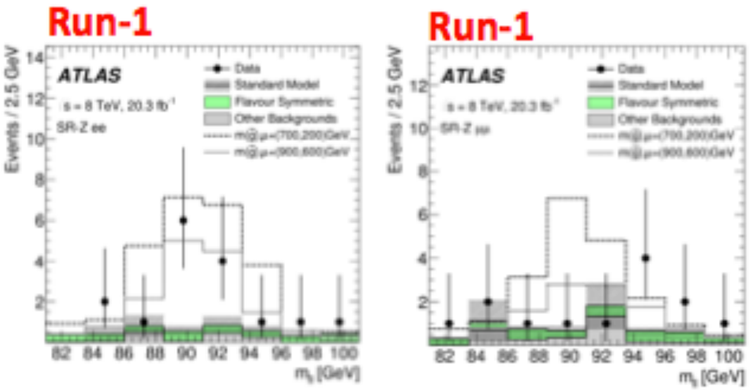
Strong Production: Z(ll)+MET

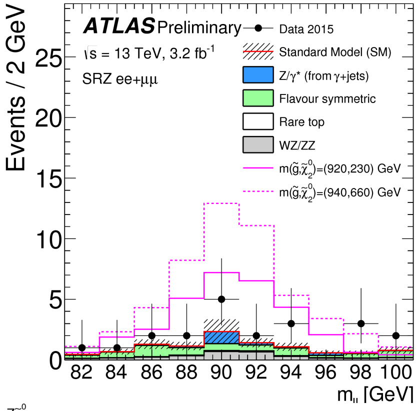
ATLAS-CONF-2015-082

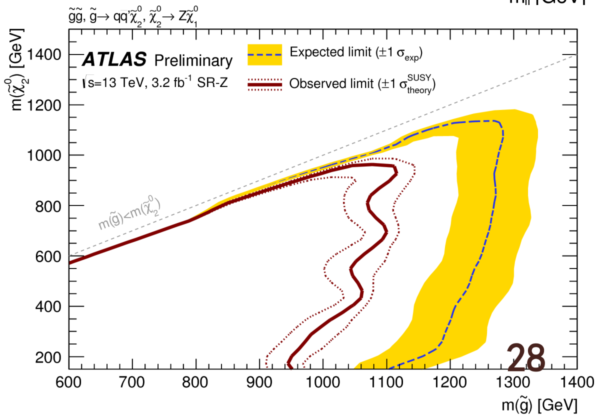
- Search for gluinos with a Z + jets + MET signature



- There is an excess (3σ) at ATLAS Run1 (not as CMS): obs. 29, exp. 10.8+-2.2 ()
- Check it with Run2 using run1-like SR: Z (ll), 2jets, MET>225 GeV, HT>600 GeV
- a mild excess seen in Run2: obs. 21, exp. 10.4+-2.4 (2.2σ in intermediate MET)
- Excludes gluino masses up to 1.1 TeV





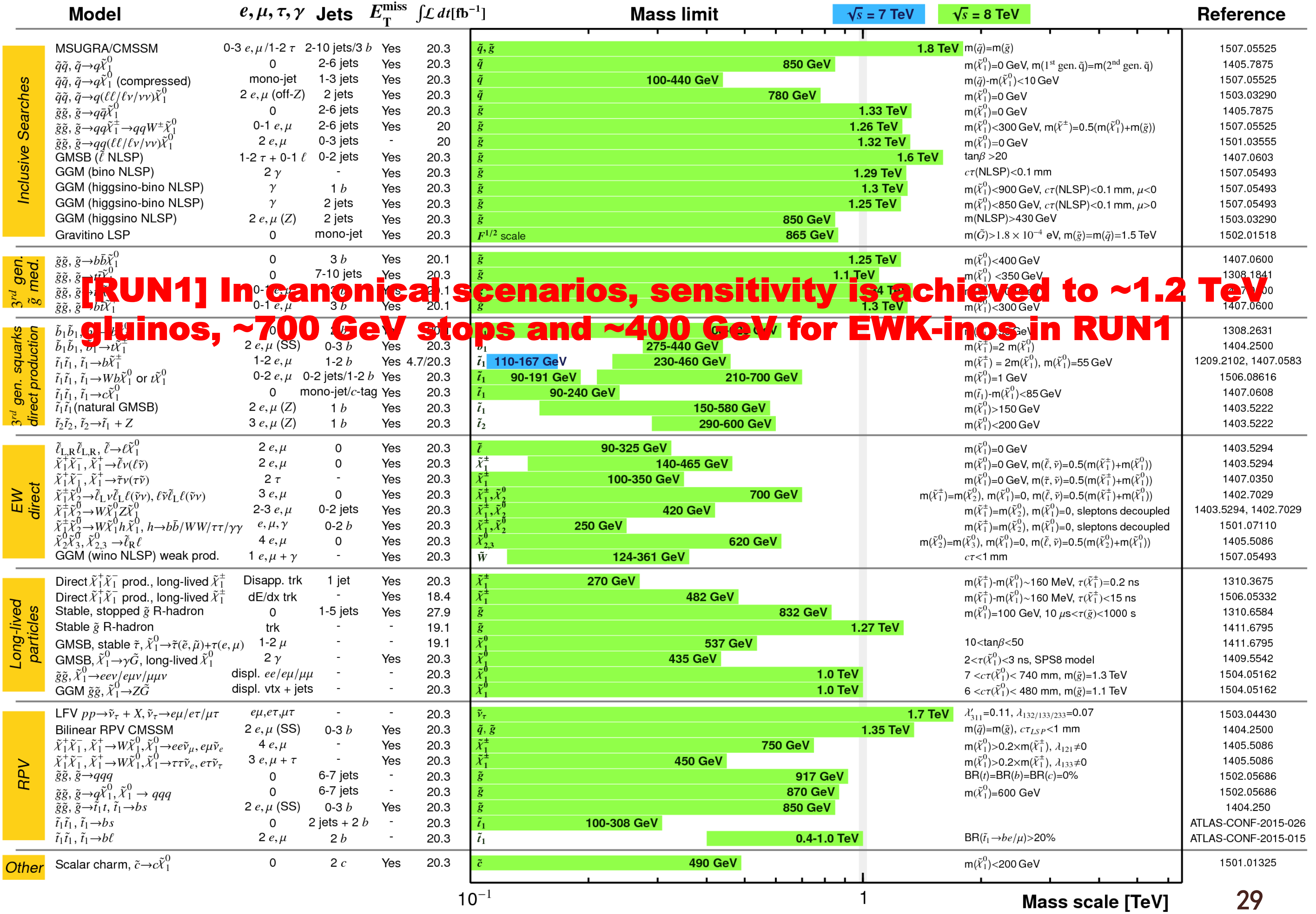


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

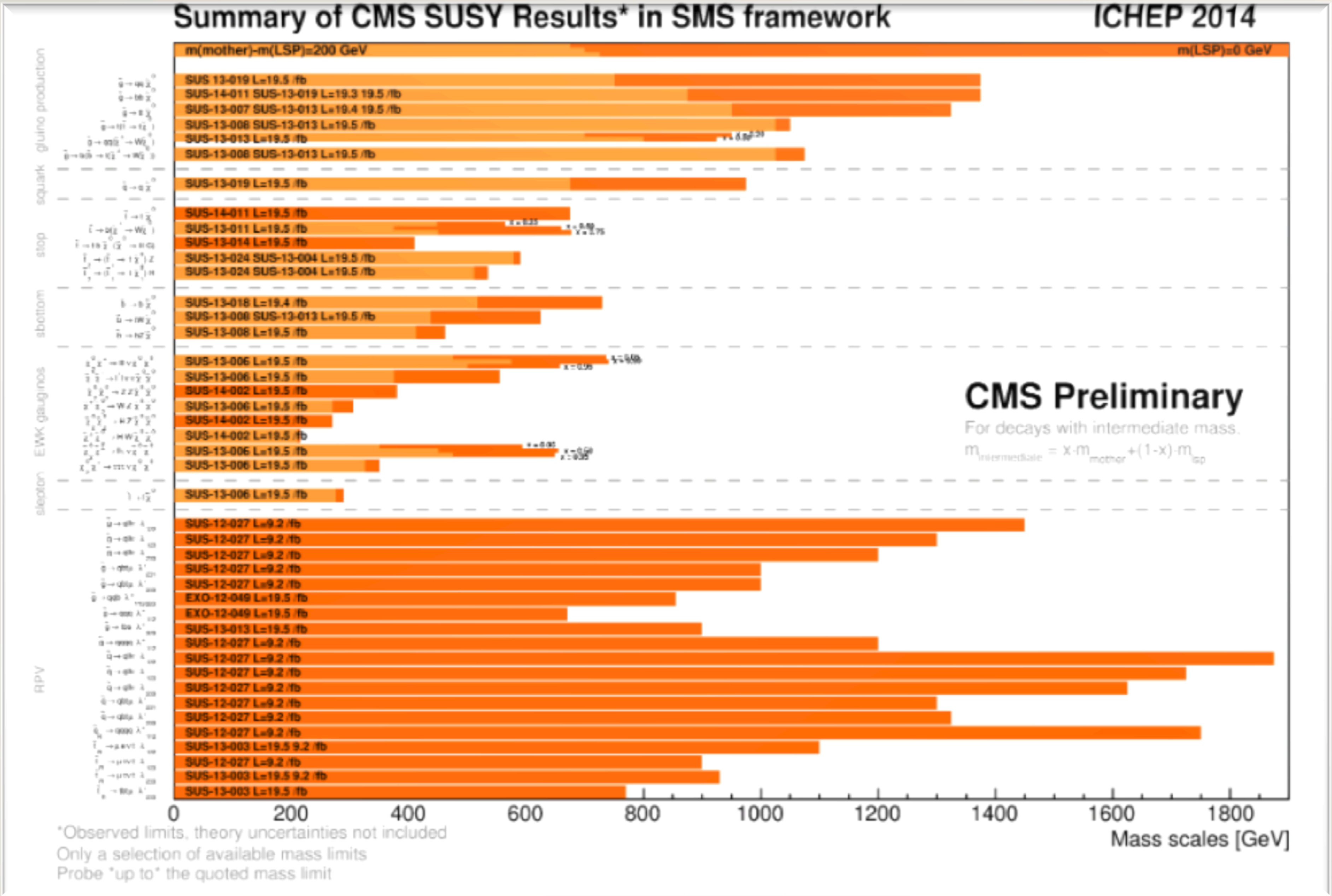
$\sqrt{s}$ = 7, 8 TeV



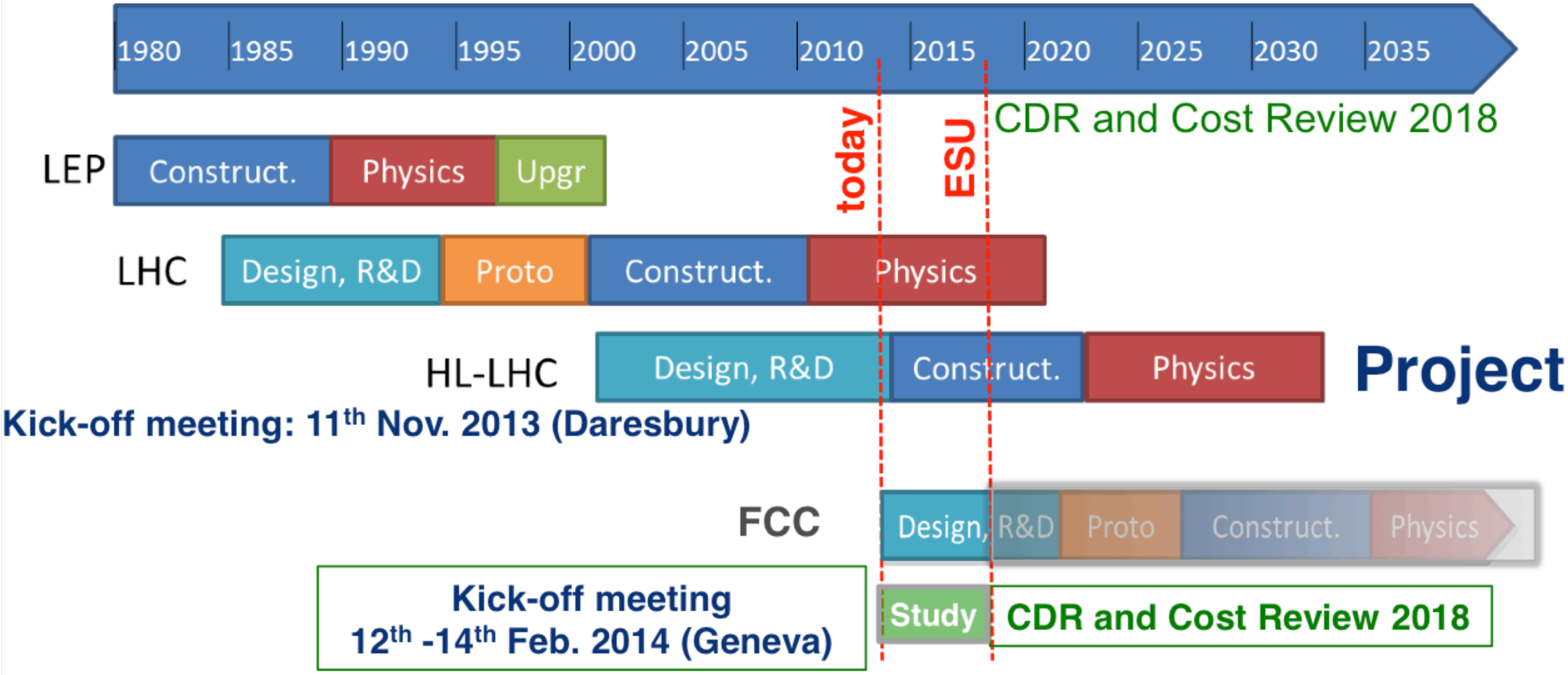
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
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	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 110-167 GeV 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 210-700 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 482 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to q\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	$m(\tilde{\chi}_1^0)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

[RUN1] In canonical scenarios, sensitivity is achieved to ~1.2 TeV gluinos, ~700 GeV stops and ~400 GeV for EWK-inos in RUN1

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-019 L=19.5 /fb
SUS-14-011 L=19.5 /fb
SUS-13-011 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.05
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
EXO-12-049 L=19.5 /fb
EXO-12-049 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-13-003 L=19.5 /fb
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} + (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

CERN and FCC timelines



Kick-off meeting: 11th Nov. 2013 (Daresbury)

Kick-off meeting
12th -14th Feb. 2014 (Geneva)

CDR and Cost Review 2018

- LHC and HL-LHC operation until ~2035
- Must start now developing FCC concepts to be ready in time

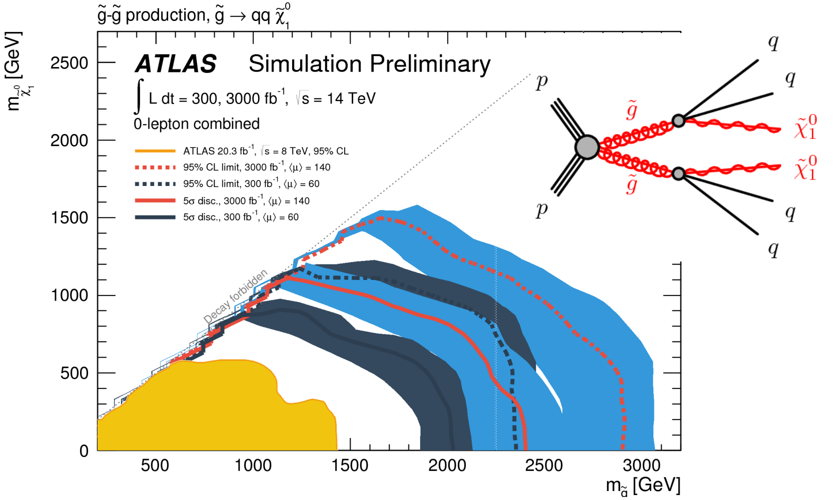
SUSY models: good sale in market

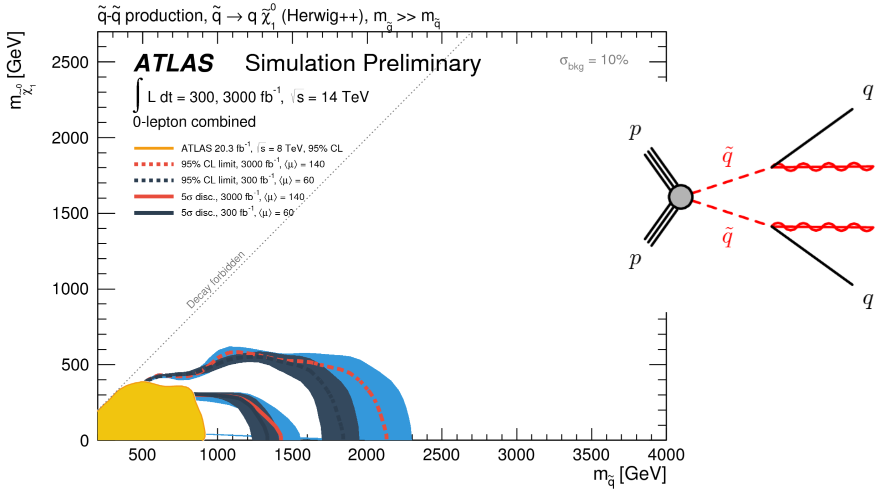
- Simplified Models:
  - Not really a model (Br~100%, most masses fixed at high scales)
  - Important tool for interpretation
- Phenomenological models:
  - pMSSM: captures "most" of phenomenologic features of R-parity conserving MSSM
    - 19 free parameters: M1,M2,M3 ; tan β, μ and $m_{A;}$ 10 sfermion mass parameters; A_t, A_b and A_τ
    - Comprehensive and computationally realistic approximation of the MSSM with neutralino LSP
  - GGM (gravitino)
- Complete SUSY models: mSUGRA, GMSB …

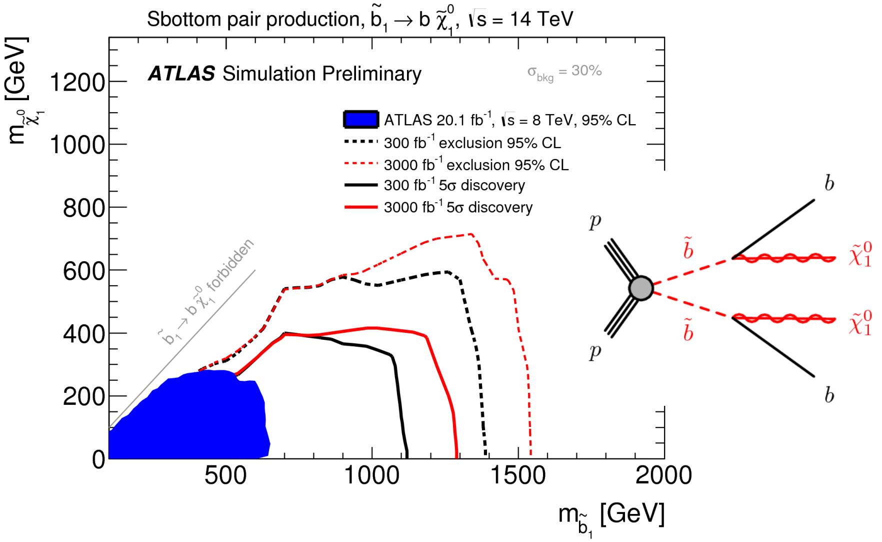
Long term prospects

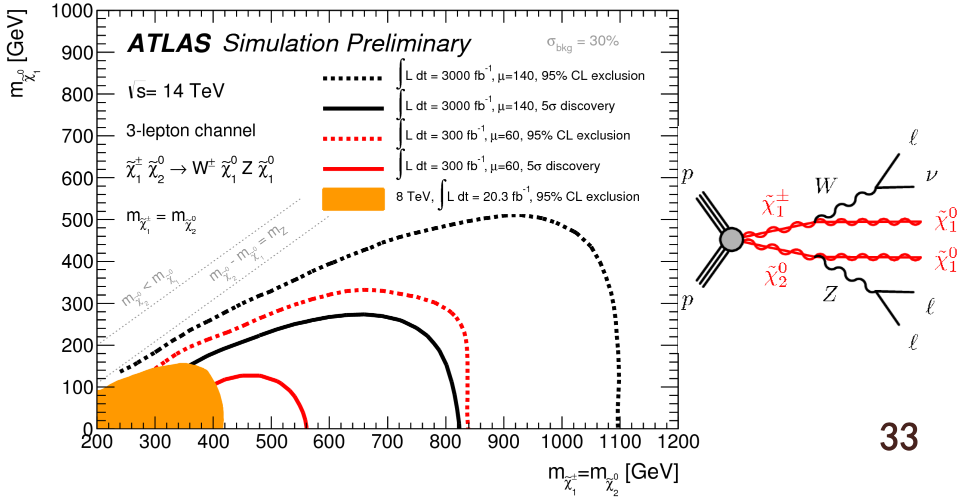
ATL-PHYS-PUB-2014-010

- ATLAS studied long term prospects for the (HL-)LHC with 300, 3000 fb^{-1}@14 TeV
- Discovery potential up **to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom and 800 GeV Electroweakinos**



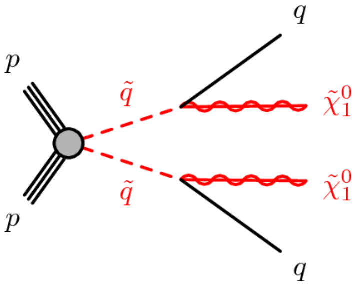




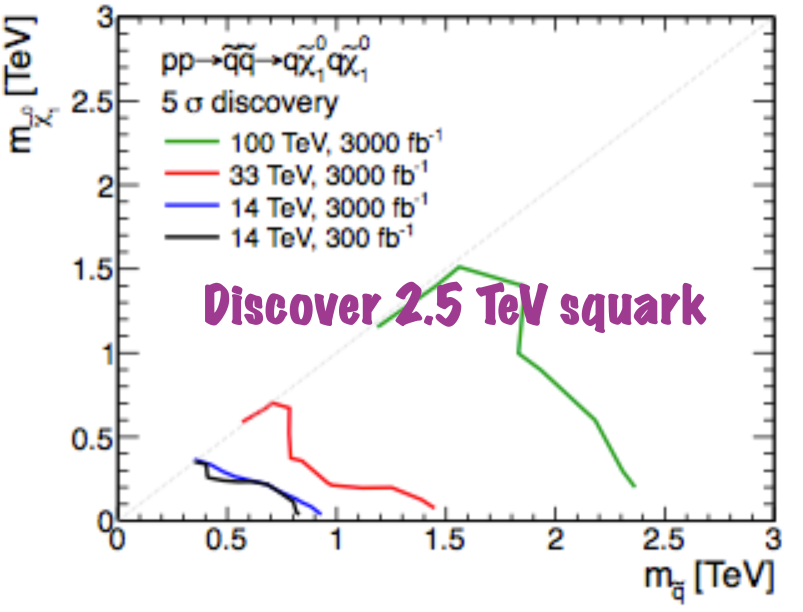


Squark-Neutralino Signature

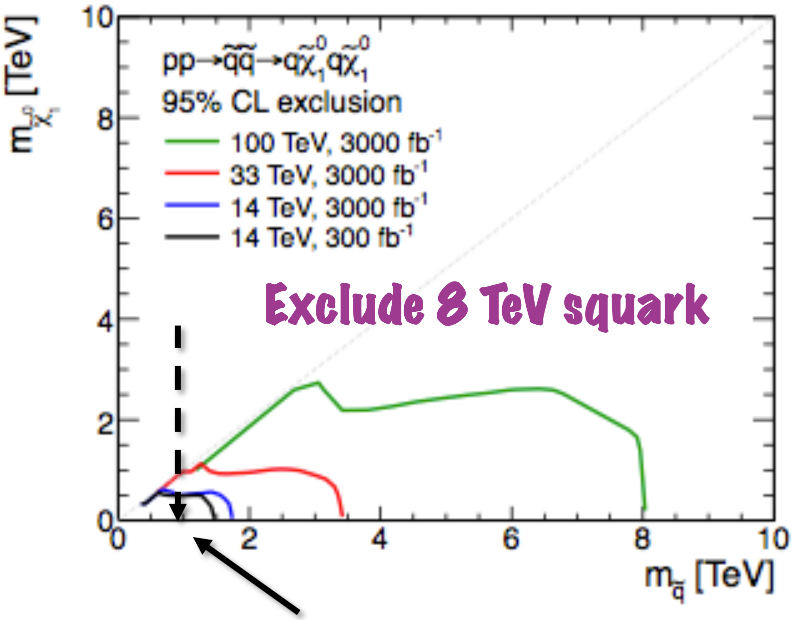
- Search for squarks with no lepton, multi-jets, large missing transverse momentum
- Signal to BG discrimination based on: MET, HT (Σjet pt)
- Discover (Exclude) 2.5 (8) TeV squark
- Increasing the center-of-mass energy has a tremendous impact on the experimentally available parameter space (~3 x beyond 14 TeV @100 TeV)



arXiv: 1311.6480



Discover 2.5 TeV squark



Exclude 8 TeV squark

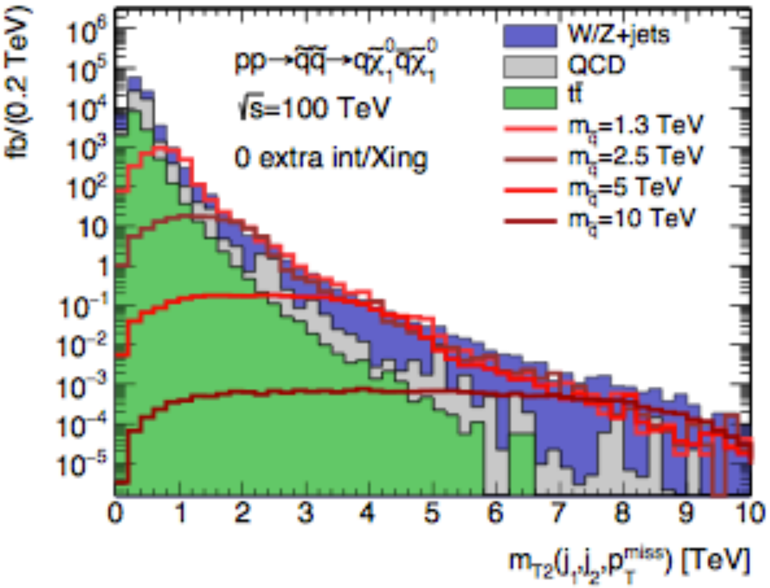
20% systematic uncertainty, no pileup

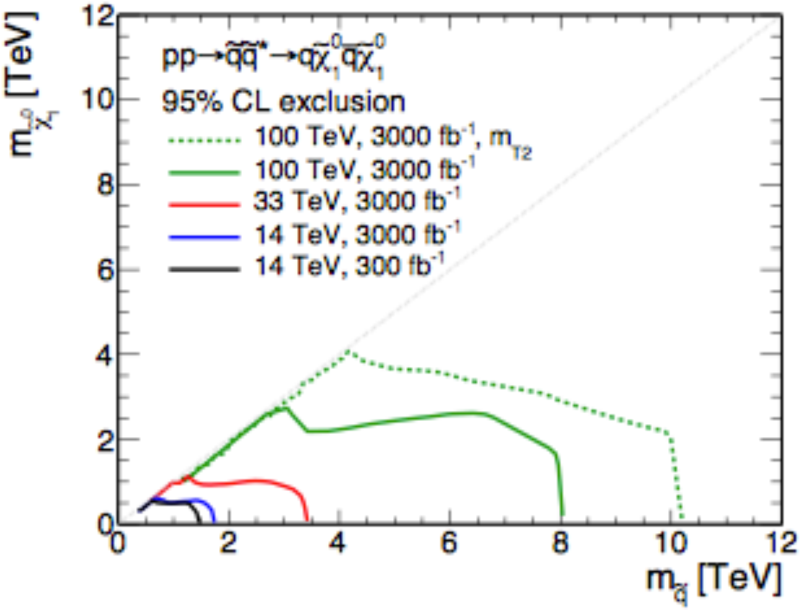
LHC 13 TeV limit ~1 TeV

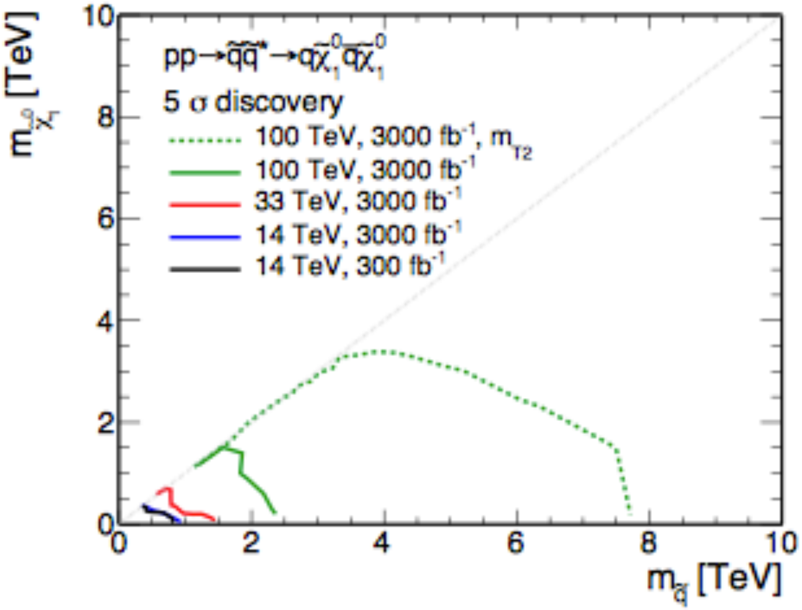
$pp \to \tilde{q}\tilde{q}^* \to q\tilde{\chi}^0_1\bar{q}\tilde{\chi}^0_1$– Updates

Jets+E_T^{miss} strategy not optimal for dijet+E_T^{miss} topology

- Use CMS approach from LHC8 (PAS-SUS-13-019):
  - Bin in H_T^{jets}
  - Optimize cuts on m_{T2} (leading jets + p_T^{miss})

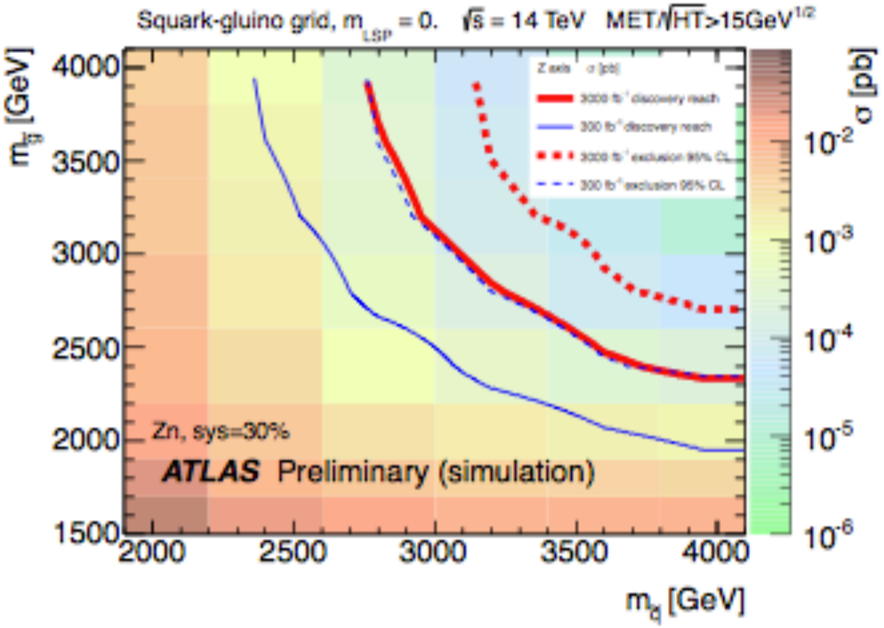


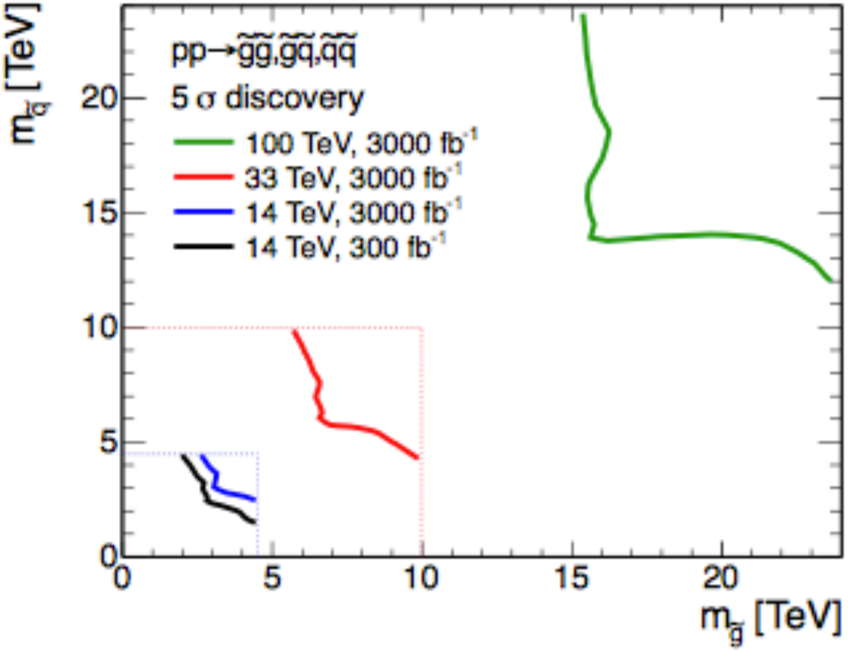




$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$

Assume massless LSP, vary $m_{\tilde{g}}$ and $m_{\tilde{q}}$:





Multijets+$E_{\mathrm{T}}^{\mathrm{miss}}$ gives good sensitivity, but richer topologies are also likely:

- Naturalness suggests $m_{\tilde{t}} < m_{\tilde{q}}$, so decays via off-shell $\tilde{t}$ are more likely than light-flavor squarks

So... what if $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$?

Gluino-Neutralino Signature

Impact of Systematic Uncertainties

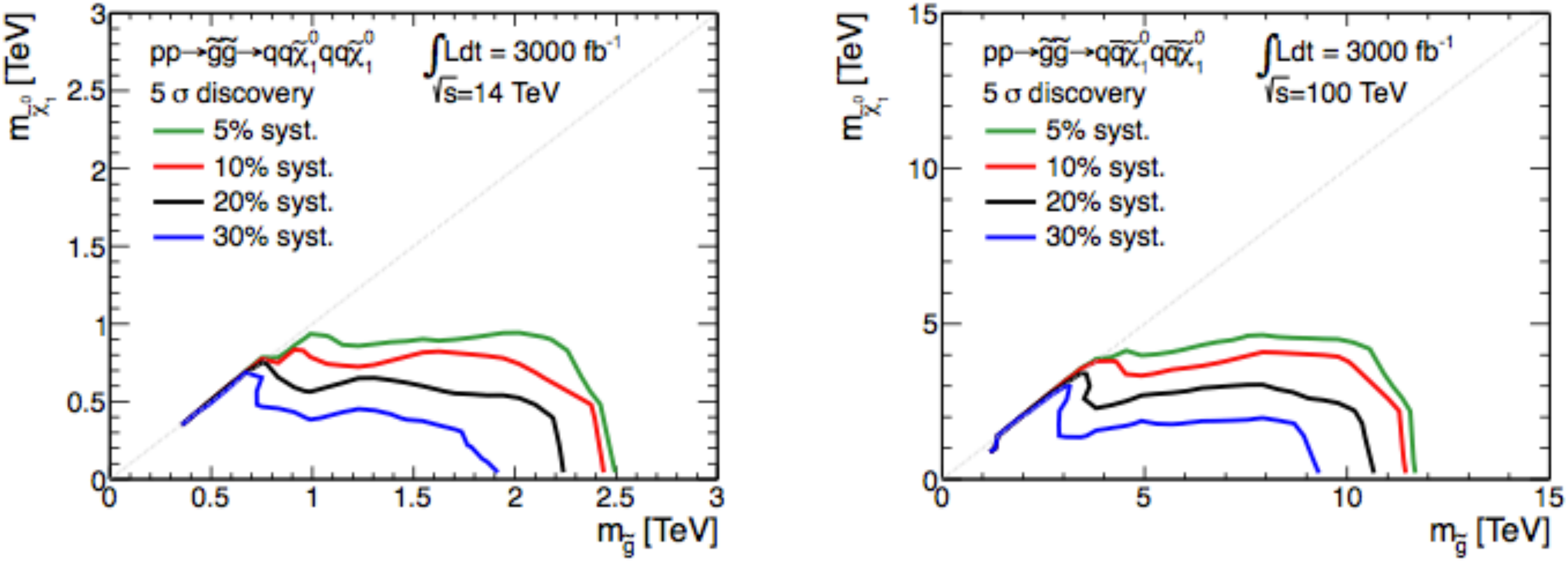


Figure 12: Expected 5σ discovery contours for the $\sqrt{s} = 14$ TeV LHC [left] and a 100 TeV proton collider [right] with 3000 fb^{-1}. The different curves correspond to various assumptions for the systematic uncertainty on the background: 5% [green], 10% [red], 20% [blue], and 30% [black].

- It is likely that the experiments will significantly reduce these uncertainties with larger datasets and an improved understanding of their detectors
- Varying the systematic background uncertainty from 30% to 5%, the discovery reach increases by roughly 600 GeV (3.4 TeV) in m(~g) at 14 TeV (100 TeV) and the coverage in LSP direction is roughly doubled

Impact of Pileup

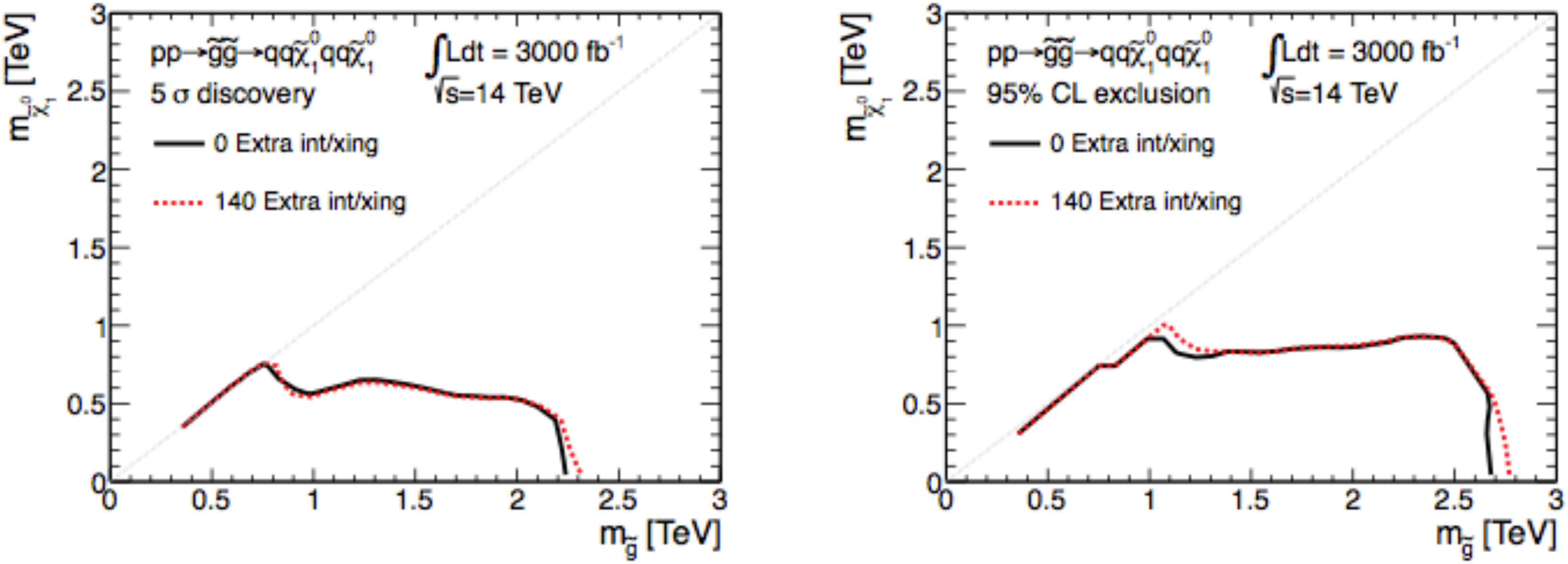
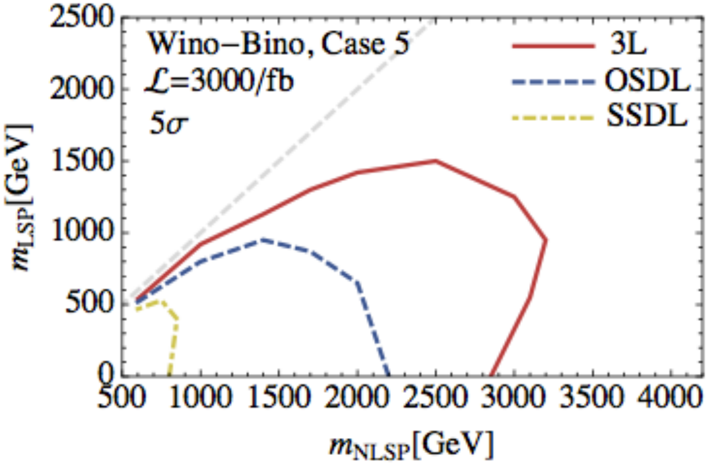
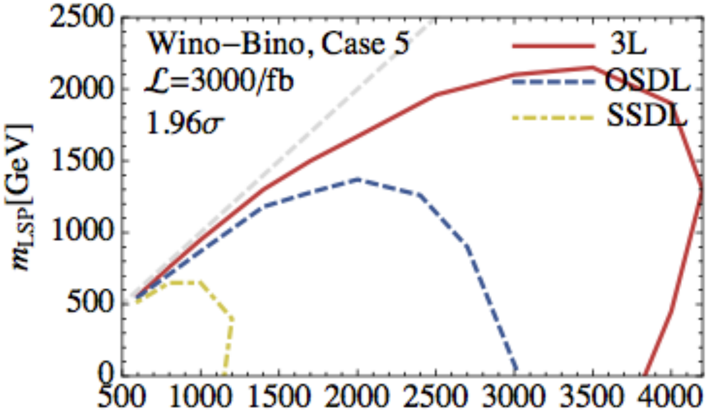


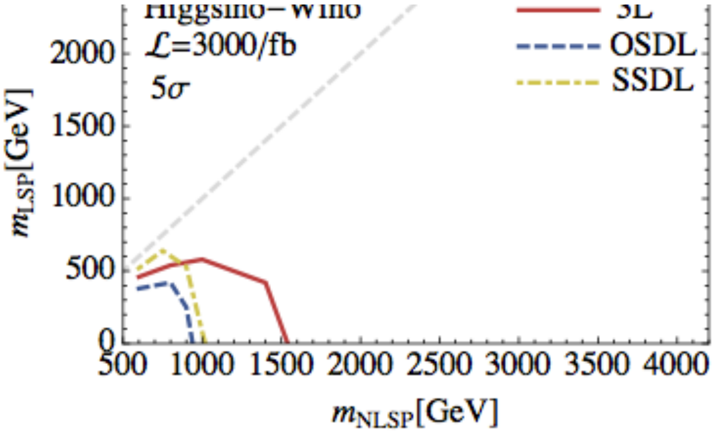
Figure 14: Discovery contours [right] and expected limits [left] for the analyses performed with [red, dotted] and without [black, solid] pileup at the 14 TeV LHC with 3000 fb^{-1} integrated luminosity.

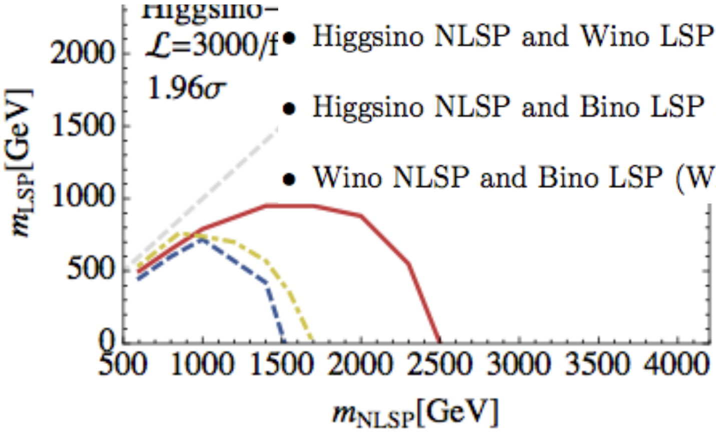
- Compared the results with 140 additional minimum-bias interactions
- The Delphes based Snowmass simulation includes a pileup suppression algorithm that primarily impacts the Emiss resolution (Snowmass detector:ArXiv:1309.1057)
- Given that the HT and ETmiss distributions are effectively unchanged, it is not surprising that the results are very similar with and without pileup

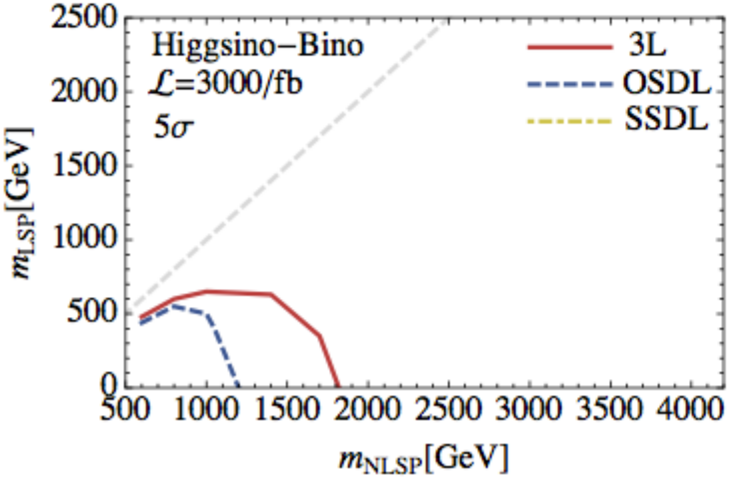


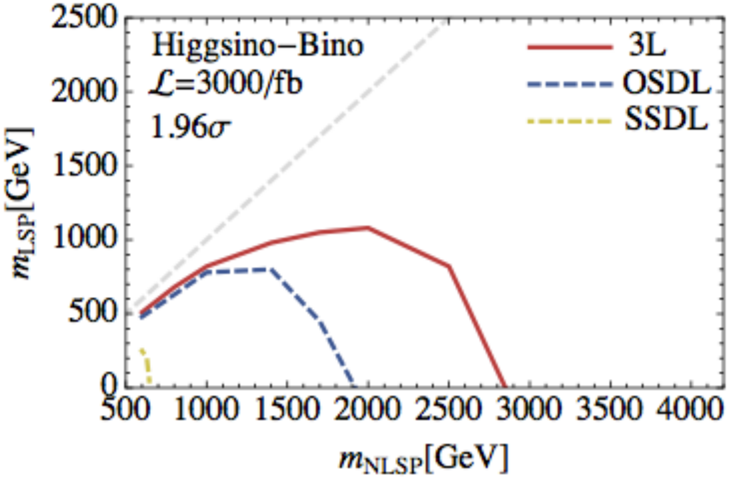


- Wino NLSP and Higgsino LSP (Wino-Higgsino) : $M_1 \gg M_2 > \mu$,
- Higgsino NLSP and Wino LSP (Higgsino-Wino) : $M_1 \gg \mu > M_2$,
- Higgsino NLSP and Bino LSP (Higgsino-Bino) : $M_2 \gg \mu > M_1$,
- Wino NLSP and Bino LSP (Wino-Bino) : $\mu \gg M_2 > M_1$.





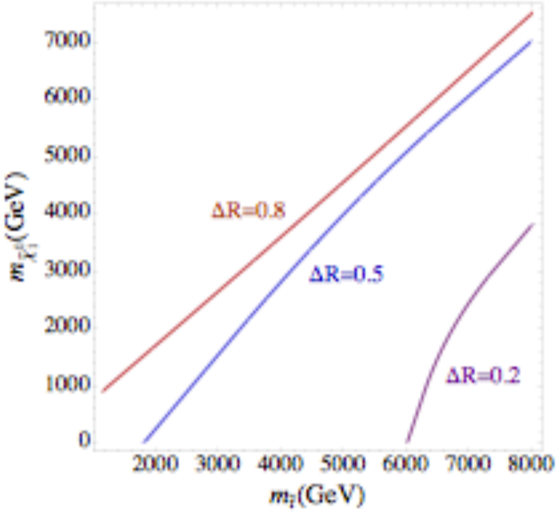


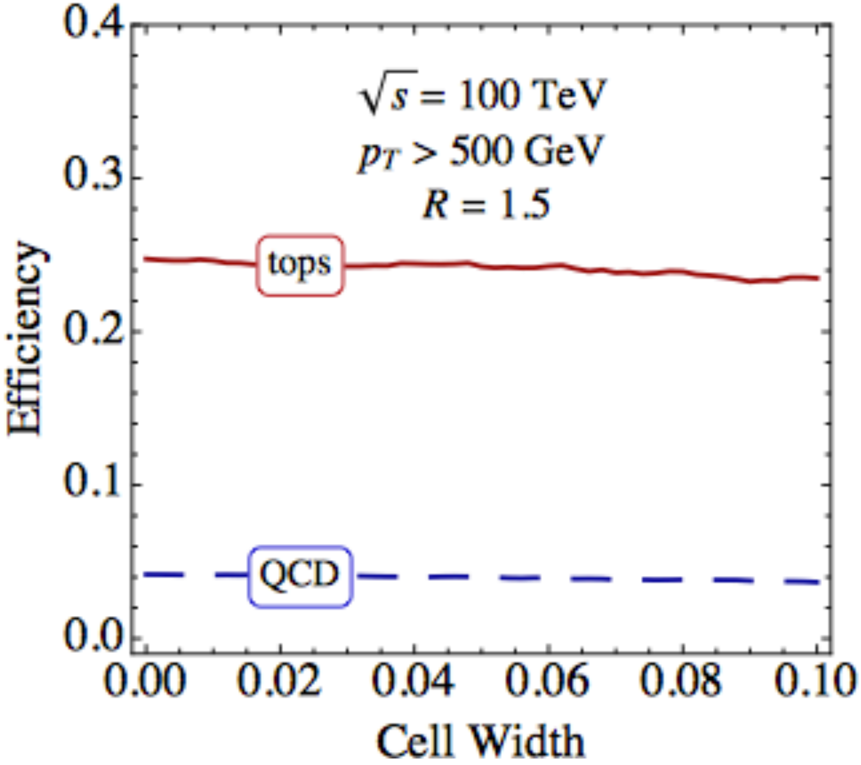


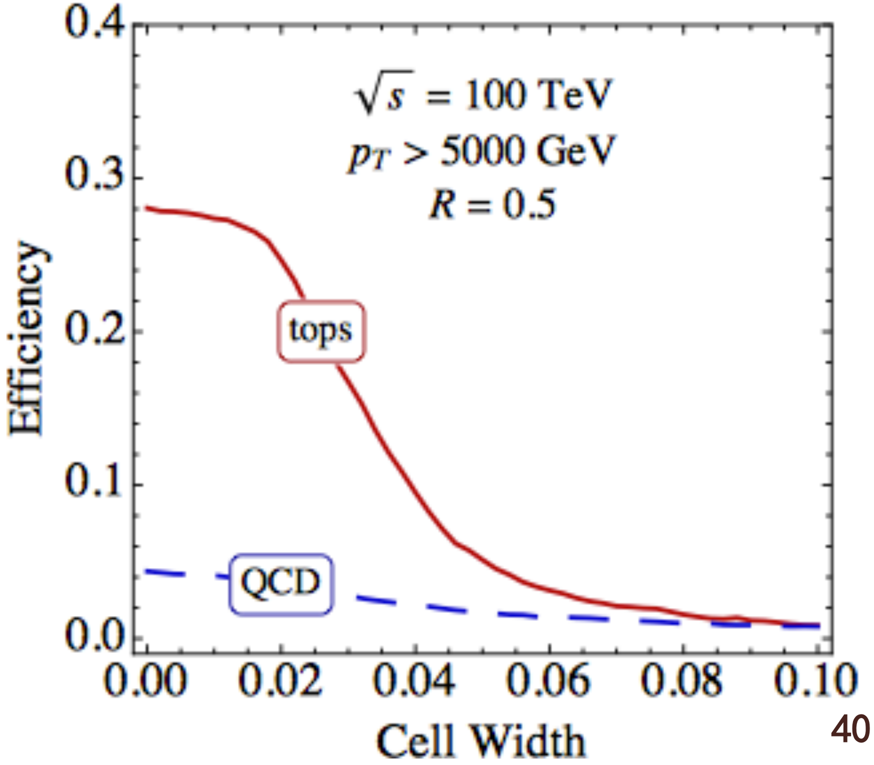
Direct Stop Search – Top Tagging?

Top-tagging at 100 TeV?

- Tops are **very** boosted
- Efficiency depends on detector granularity
- Requires lots of assumptions about calorimeters, trackers, etc
- **What's possible with a simpler approach?**





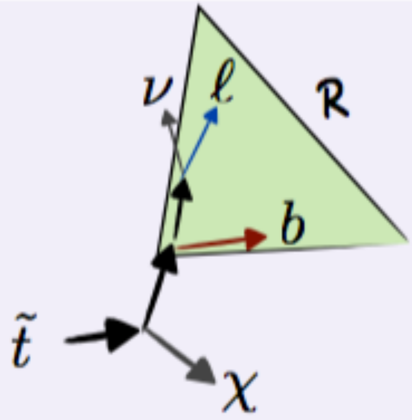


Stop-Neutralino Signature

8 TeV

650 GeV stop

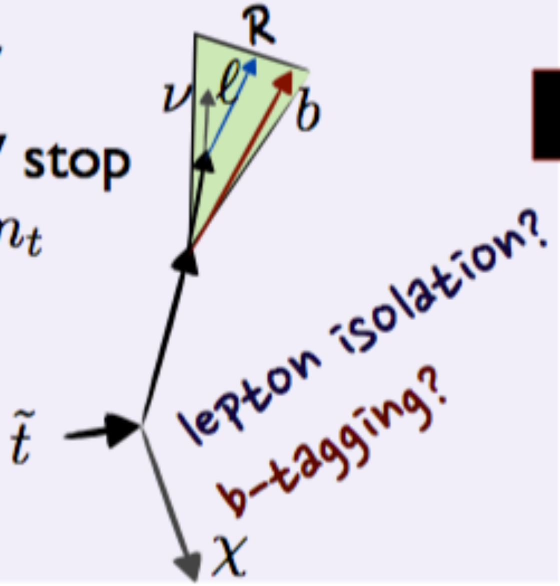
$m_{\tilde{t}} \sim 3m_t$



100 TeV

7000 GeV stop

$m_{\tilde{t}} \sim 30m_t$



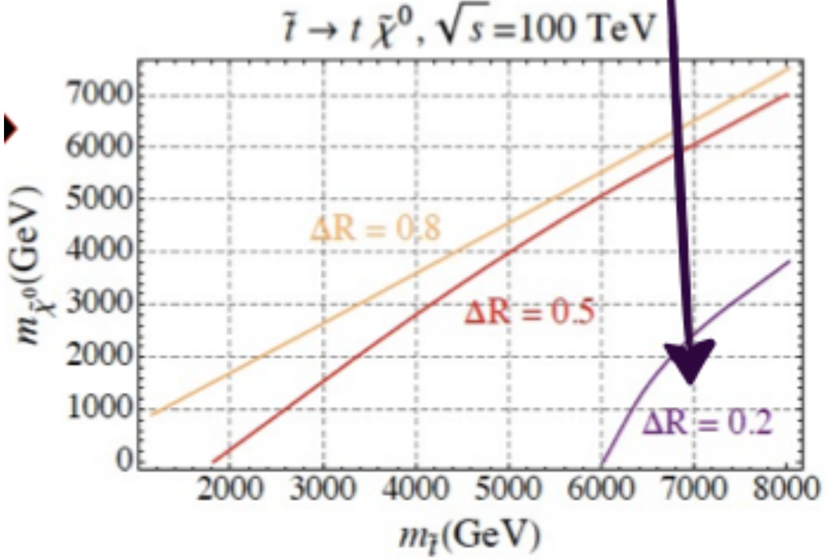
lepton isolation?

b-tagging?

Typical decay radius R < 0.2

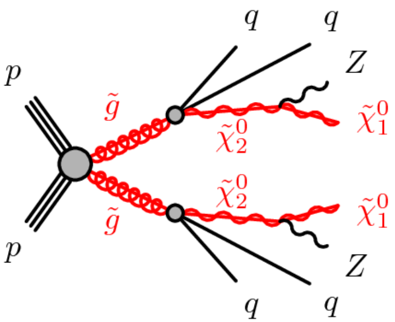
(for light neutralino)

$$R \sim 8/(\pi\gamma_t)$$

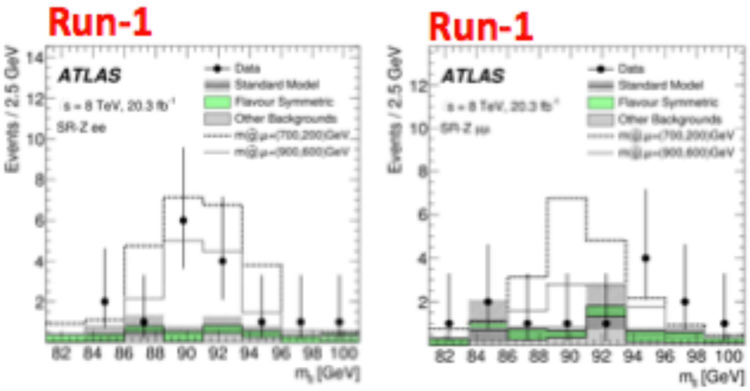


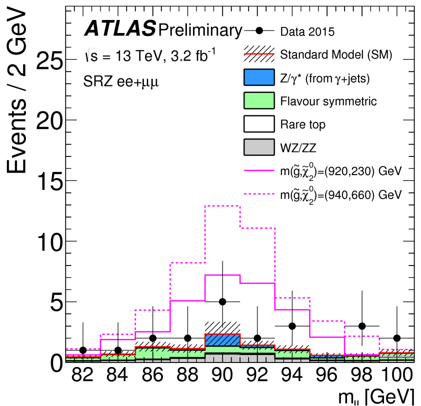
Strong Production: Z(ll)+MET

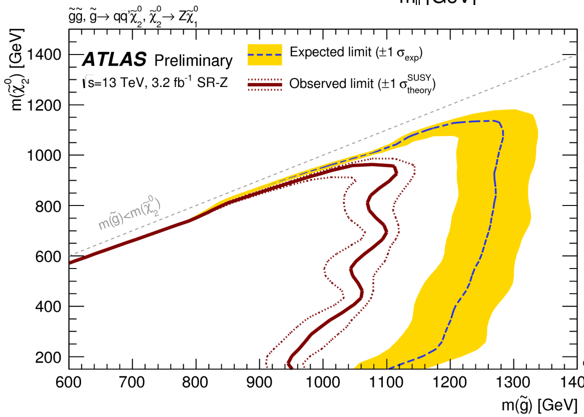
- **Search for gluinos with a Z + jets + MET signature**



- **There is an excess (3σ) at ATLAS Run1 (not at CMS): obs. 29, exp. 10.8+-2.2**
- **Check it with Run2 using run1-like SR: Z (ll), 2jets, MET>225 GeV, HT>600 GeV**
- **a mild excess seen in Run2: obs. 21, exp. 10.4+-2.4 (2.2σ in intermediate MET)**
- **Excludes gluino masses up to 1.1 TeV**





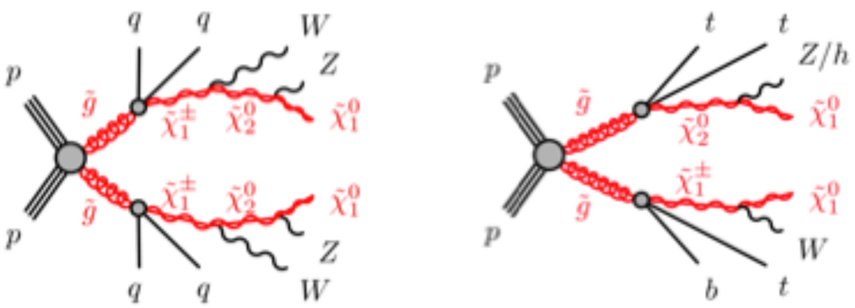


ATLAS-CONF-2015-082

Strong Production: 0L+7-10j+MET

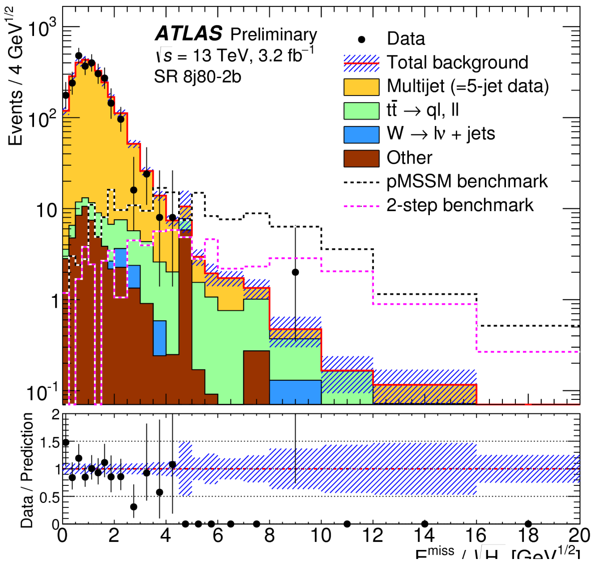
ATLAS-CONF-2015-077

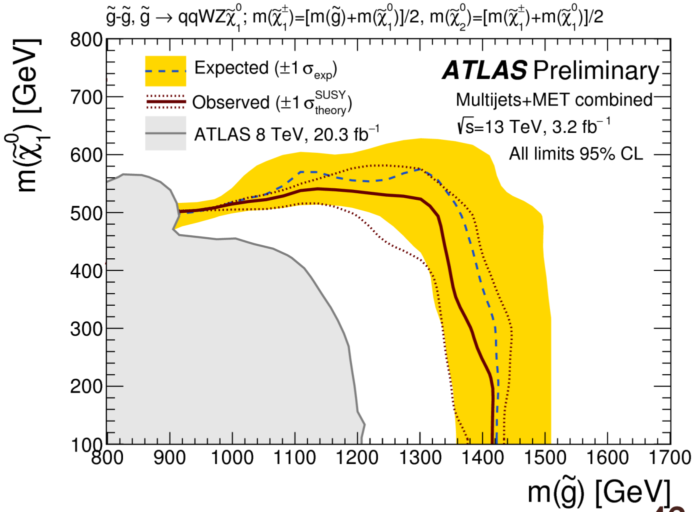
- **Search for gluinos and squarks aiming at more complex decay chains**



- **Signal to BG discrimination based on: MET/$\sqrt{H_T}$**
- **15 signal regions defined based on jet multiplicity 7-10 and b-jet multiplicity**
- **Excludes gluino masses up to 1.4 TeV, significantly extending run1 reach**

No significant excess





1-lepton stop search: 2/3/4-body decay to LSP

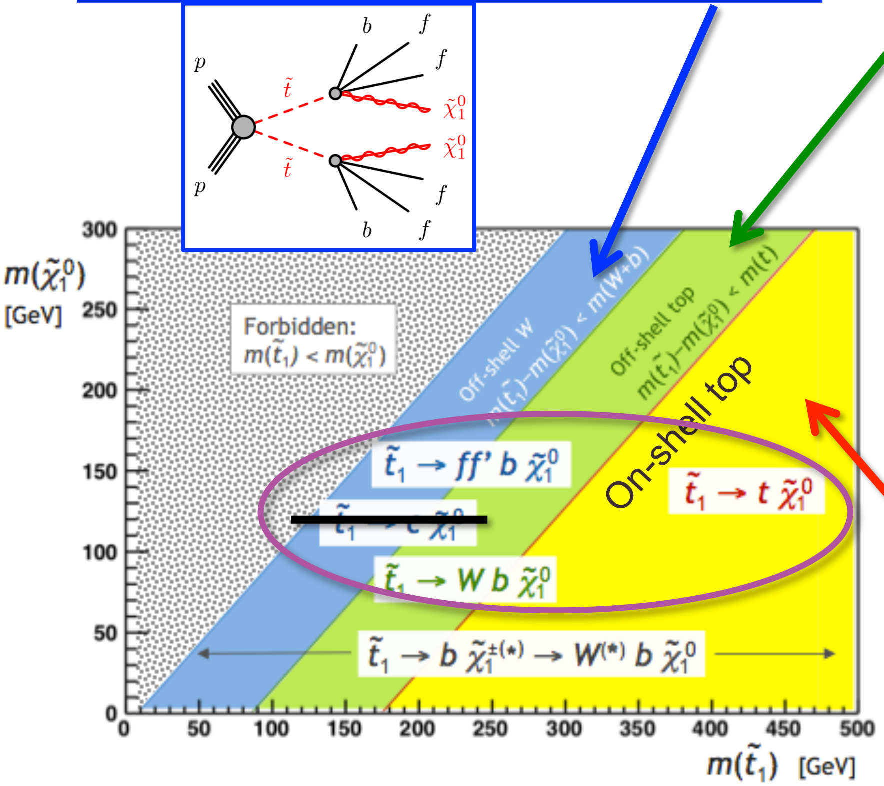
JHEP 11 (2014) 118

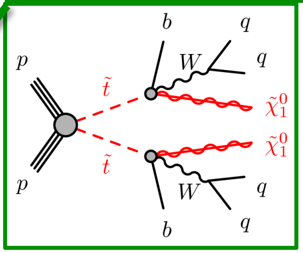
Stop 4-body decay:

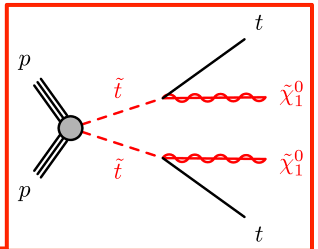
- **1 soft lepton** (6/7 GeV mu/e), **hard ISR jet**, ≥ 1 b-jet, MET cut
- Shape fit in lepton p_T

Stop 3-body decay:

- 1 lepton, ≥ 4 jets, ≥ 1 b-jet, MET cut
- Softer thresholds on MET, MT…
- 2-D shape fit in m_T and m_{T2}







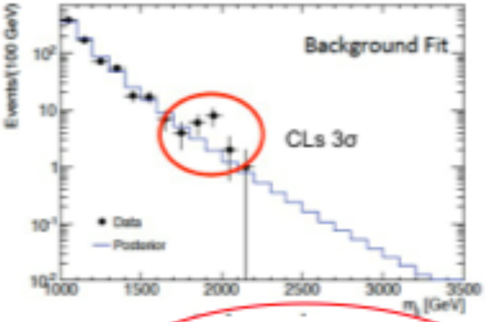
Stop➔top+neutralino decay:

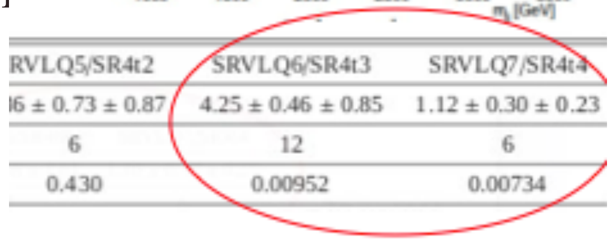
- 1 lepton, ≥ 4 jets, ≥ 1 b-jet, MET cut
- Large-R jets (collect decay products of boosted top in heavy stop search)
- Shape fit for diagonal

Dominant BG: tt, W (MC normlized to data)

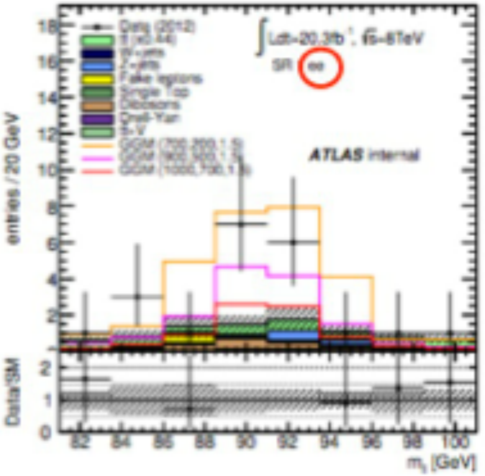
Excesses seen in RUN1 (Exotics, SUSY)

- For a more detailed review, see the physics plenary talk (July 18th) by T. Golling
- **Mono-jet** CDS link
  - ~1.7σ / 2.4σ excess above BG in the two highest MET SRs
  - High MET SRs dropped for paper (very low stat in CR)
- **VV→JJ** CDS link
  - Mass of fat jets each consistent with W,Z mass
- **Same-sign leptons / 3-leptons + b-jets** CDS link
- **3-leptons + 3 b-jets** CDS link (obs. 9, exp. 1.29+-0.65)
  - ~3.5σ in a validation region of the 3-lepton search
  - Plan a dedicated SR for run2
- **Z+jets + MET** CDS link
  - Peaking at Z mass, BG dominated by non-Z (tt)



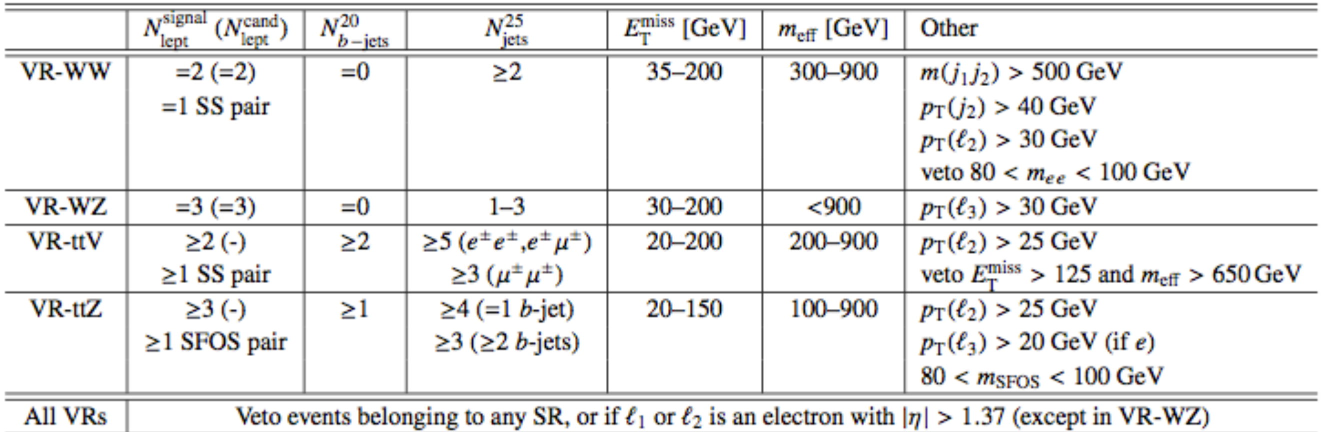


RVLQ5/SR4t2	SRVLQ6/SR4t3	SRVLQ7/SR4t4
6 ± 0.73 ± 0.87	4.25 ± 0.46 ± 0.85	1.12 ± 0.30 ± 0.23
6	12	6
0.430	0.00952	0.00734

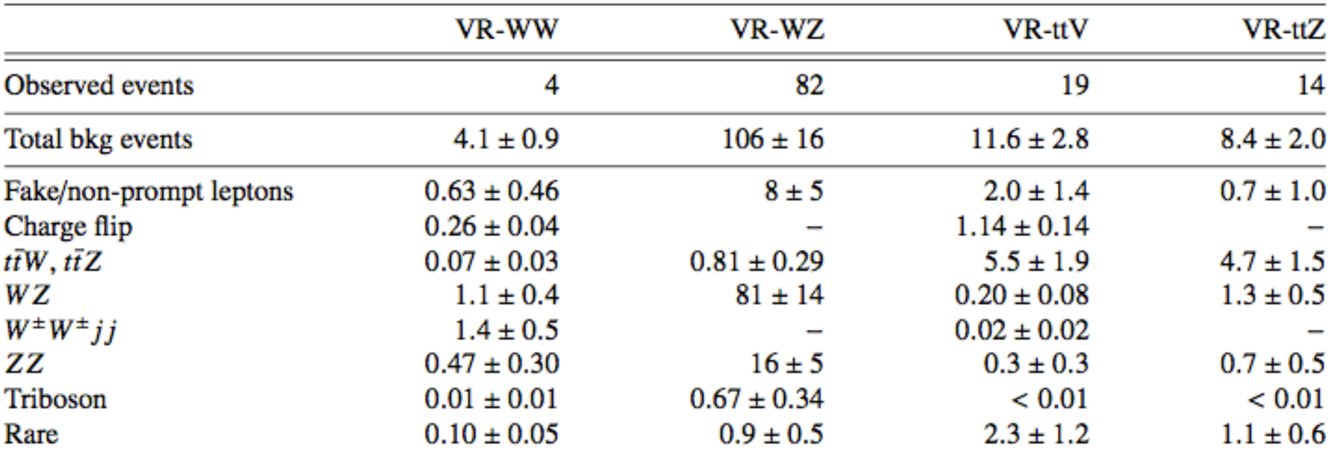


SUSY: https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/SusyDiscrepancies
Exotics: https://twiki.cern.ch/twiki/bin/view/AtlasProtected/ExoticsExcessSummary

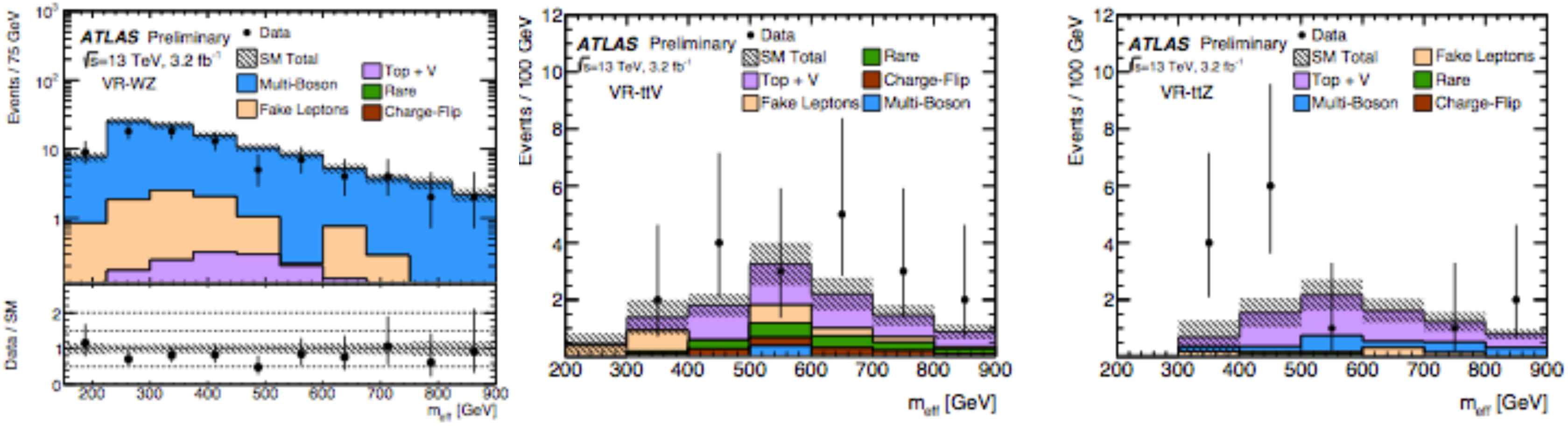
SS/3L



	$N_{\text{lept}}^{\text{signal}}$ ($N_{\text{lept}}^{\text{cand}}$)	$N_{b-\text{jets}}^{20}$	N_{jets}^{25}	E_T^{miss} [GeV]	m_{eff} [GeV]	Other
VR-WW	=2 (=2) =1 SS pair	=0	≥2	35–200	300–900	$m(j_1 j_2) > 500$ GeV $p_T(j_2) > 40$ GeV $p_T(\ell_2) > 30$ GeV veto $80 < m_{ee} < 100$ GeV
VR-WZ	=3 (=3)	=0	1–3	30–200	<900	$p_T(\ell_3) > 30$ GeV
VR-ttV	≥2 (-) ≥1 SS pair	≥2	≥5 ($e^\pm e^\pm$,$e^\pm \mu^\pm$) ≥3 ($\mu^\pm \mu^\pm$)	20–200	200–900	$p_T(\ell_2) > 25$ GeV veto $E_T^{\text{miss}} > 125$ and $m_{\text{eff}} > 650$ GeV
VR-ttZ	≥3 (-) ≥1 SFOS pair	≥1	≥4 (=1 b-jet) ≥3 (≥2 b-jets)	20–150	100–900	$p_T(\ell_2) > 25$ GeV $p_T(\ell_3) > 20$ GeV (if e) $80 < m_{\text{SFOS}} < 100$ GeV
All VRs	Veto events belonging to any SR, or if ℓ_1 or ℓ_2 is an electron with $\lvert\eta\rvert > 1.37$ (except in VR-WZ)					



	VR-WW	VR-WZ	VR-ttV	VR-ttZ
Observed events	4	82	19	14
Total bkg events	4.1 ± 0.9	106 ± 16	11.6 ± 2.8	8.4 ± 2.0
Fake/non-prompt leptons	0.63 ± 0.46	8 ± 5	2.0 ± 1.4	0.7 ± 1.0
Charge flip	0.26 ± 0.04	–	1.14 ± 0.14	–
$t\bar{t}W$, $t\bar{t}Z$	0.07 ± 0.03	0.81 ± 0.29	5.5 ± 1.9	4.7 ± 1.5
WZ	1.1 ± 0.4	81 ± 14	0.20 ± 0.08	1.3 ± 0.5
$W^\pm W^\pm jj$	1.4 ± 0.5	–	0.02 ± 0.02	–
ZZ	0.47 ± 0.30	16 ± 5	0.3 ± 0.3	0.7 ± 0.5
Triboson	0.01 ± 0.01	0.67 ± 0.34	< 0.01	< 0.01
Rare	0.10 ± 0.05	0.9 ± 0.5	2.3 ± 1.2	1.1 ± 0.6



(d) m_{eff} in WZ validation region

(e) m_{eff} in $t\bar{t}V$ validation region

(f) m_{eff} in $t\bar{t}Z$ validation region

SS/3L

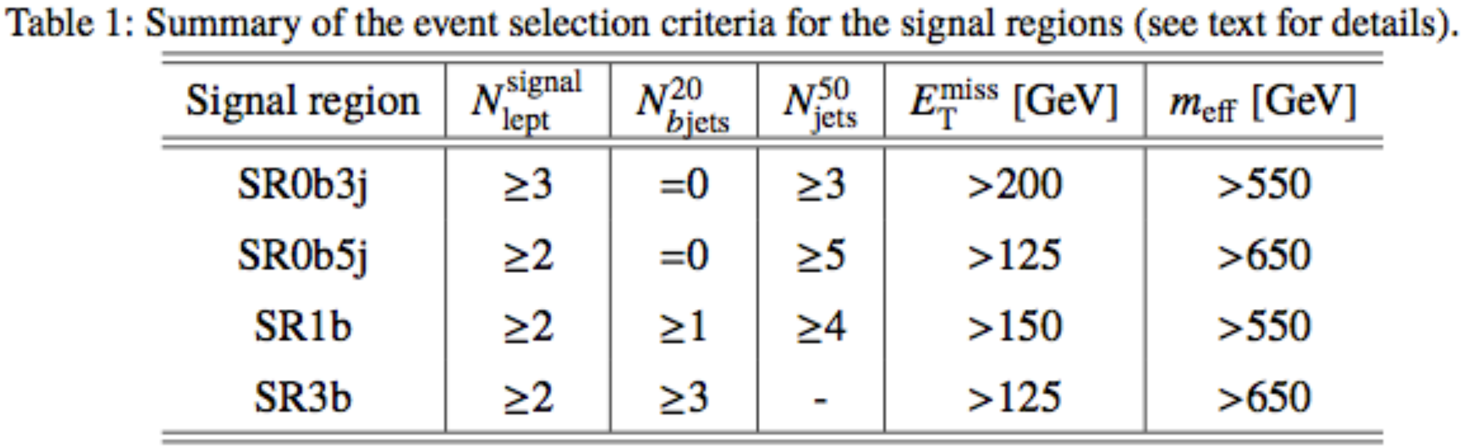


Table 1: Summary of the event selection criteria for the signal regions (see text for details).

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

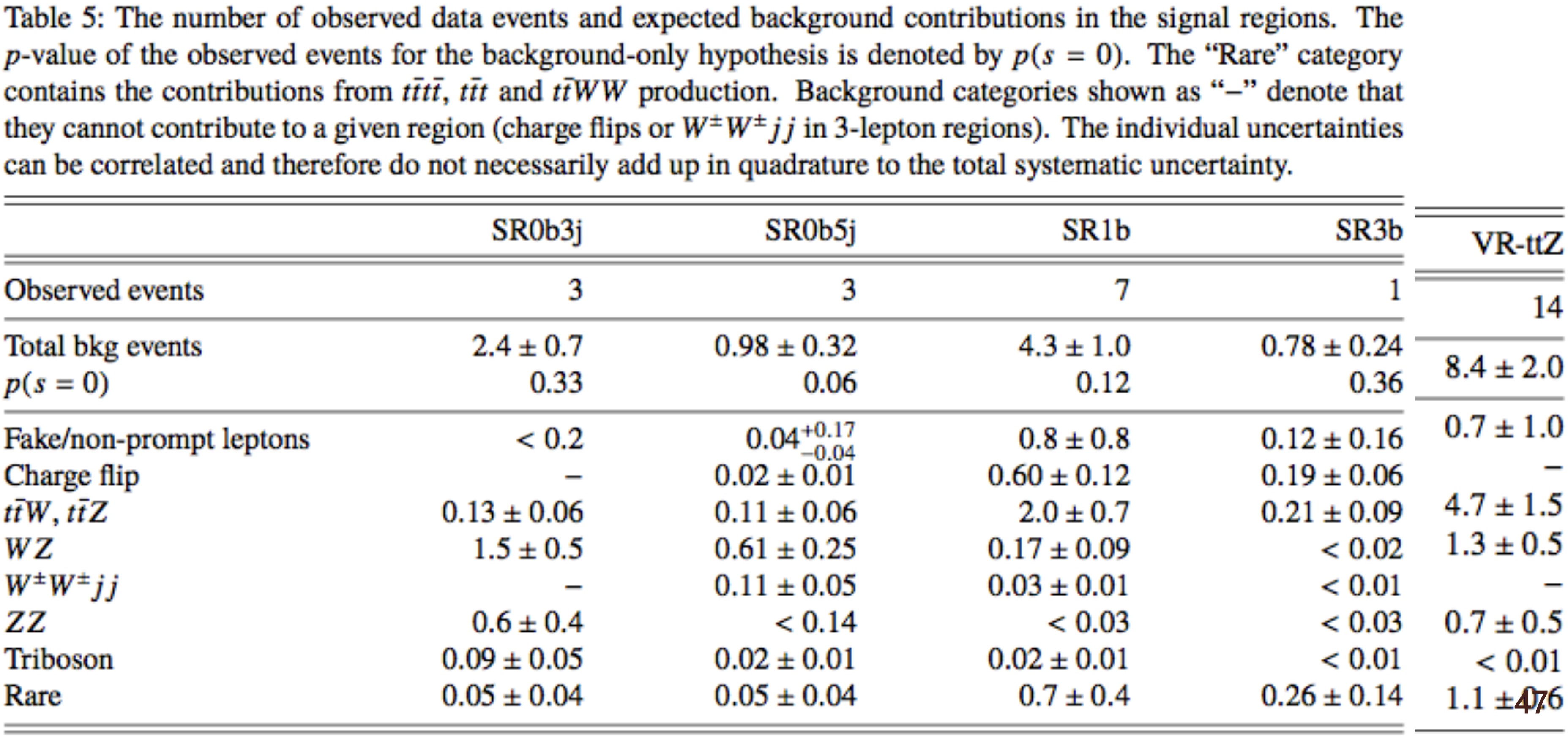


Table 5: The number of observed data events and expected background contributions in the signal regions. The p-value of the observed events for the background-only hypothesis is denoted by $p(s = 0)$. The "Rare" category contains the contributions from $t\bar{t}t\bar{t}$, $t\bar{t}t$ and $t\bar{t}WW$ production. Background categories shown as "–" denote that they cannot contribute to a given region (charge flips or $W^{\pm}W^{\pm}jj$ in 3-lepton regions). The individual uncertainties can be correlated and therefore do not necessarily add up in quadrature to the total systematic uncertainty.

	SR0b3j	SR0b5j	SR1b	SR3b	VR-ttZ
Observed events	3	3	7	1	14
Total bkg events	2.4 ± 0.7	0.98 ± 0.32	4.3 ± 1.0	0.78 ± 0.24	8.4 ± 2.0
$p(s = 0)$	0.33	0.06	0.12	0.36	
Fake/non-prompt leptons	< 0.2	$0.04^{+0.17}_{-0.04}$	0.8 ± 0.8	0.12 ± 0.16	0.7 ± 1.0
Charge flip	–	0.02 ± 0.01	0.60 ± 0.12	0.19 ± 0.06	–
$t\bar{t}W$, $t\bar{t}Z$	0.13 ± 0.06	0.11 ± 0.06	2.0 ± 0.7	0.21 ± 0.09	4.7 ± 1.5
WZ	1.5 ± 0.5	0.61 ± 0.25	0.17 ± 0.09	< 0.02	1.3 ± 0.5
$W^{\pm}W^{\pm}jj$	–	0.11 ± 0.05	0.03 ± 0.01	< 0.01	–
ZZ	0.6 ± 0.4	< 0.14	< 0.03	< 0.03	0.7 ± 0.5
Triboson	0.09 ± 0.05	0.02 ± 0.01	0.02 ± 0.01	< 0.01	< 0.01
Rare	0.05 ± 0.04	0.05 ± 0.04	0.7 ± 0.4	0.26 ± 0.14	1.1 ± 0.6

pMSSM Interpretations

ATLAS JHEP 10 (2015) 134

Study the impact of the full set of ATLAS SUSY searches on the pMSSM.

Use 19-parameter pMSSM

- Minimal flavor violation with no new source of CP violation
- Degenerate 1st and 2nd generation squarks and sleptons
- No RPV and the LSP is the $\tilde{\chi}_1^0$

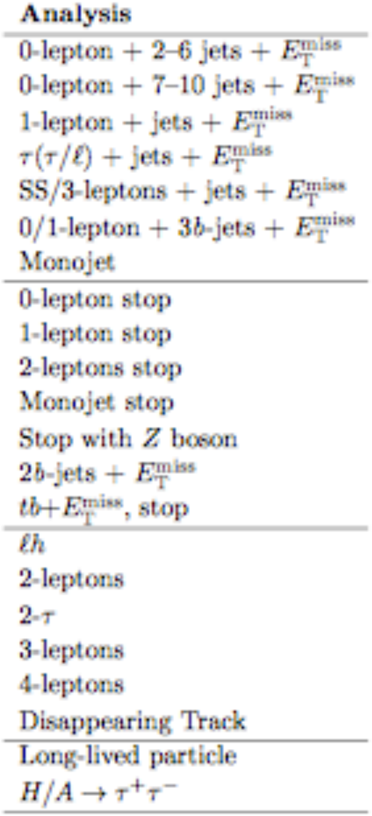
500×10^6 models in the pMSSM are randomly sampled.
300×10^3 models survive theory and non-LHC constraints *(precision EW, LEP, Higgs, DM)*

22 ATLAS Run 1 RPC SUSY searches are reinterpreted in the pMSSM ⇒ **200 SR!**
Best expected SR used for exclusion.
Makes full use of ATLAS simulation, reconstruction and analysis.

$>30\times10^9$ events generated for truth-based analysis.

$>600\times10^6$ events simulated & reconstructed.

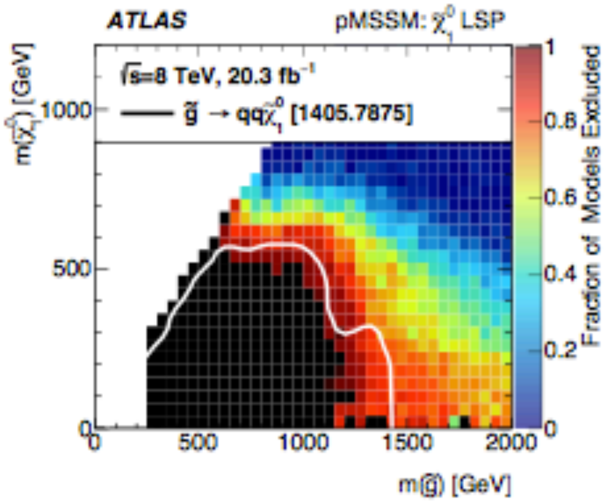
Most comprehensive results from ATLAS on SUSY to date



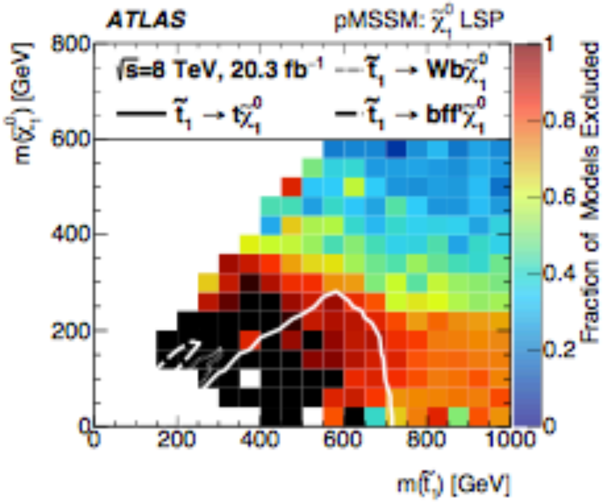
Analysis
0-lepton + 2–6 jets + E_T^{miss}
0-lepton + 7–10 jets + E_T^{miss}
1-lepton + jets + E_T^{miss}
$\tau(\tau/\ell)$ + jets + E_T^{miss}
SS/3-leptons + jets + E_T^{miss}
0/1-lepton + 3b-jets + E_T^{miss}
Monojet
0-lepton stop
1-lepton stop
2-leptons stop
Monojet stop
Stop with Z boson
2b-jets + E_T^{miss}
tb+E_T^{miss}, stop
ℓh
2-leptons
2-τ
3-leptons
4-leptons
Disappearing Track
Long-lived particle
$H/A \to \tau^+\tau^-$

pMSSM Interpretations

ATLAS JHEP 10 (2015) 134

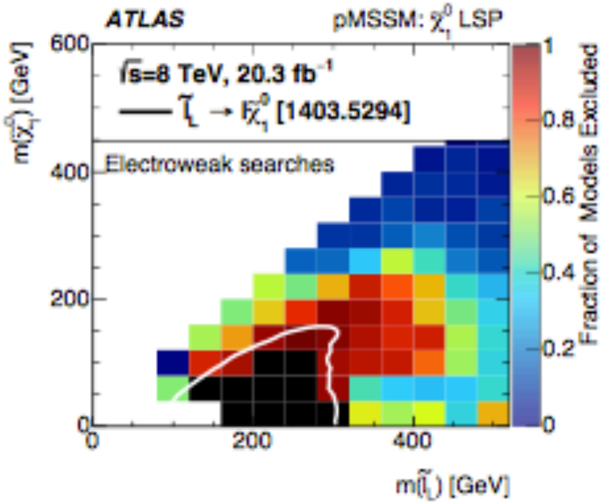


Good agreement with simplified models. Diagonal excluded by mono-jet analysis. Intermediate sparticles reduce exclusion for heavy $\tilde{g}$.

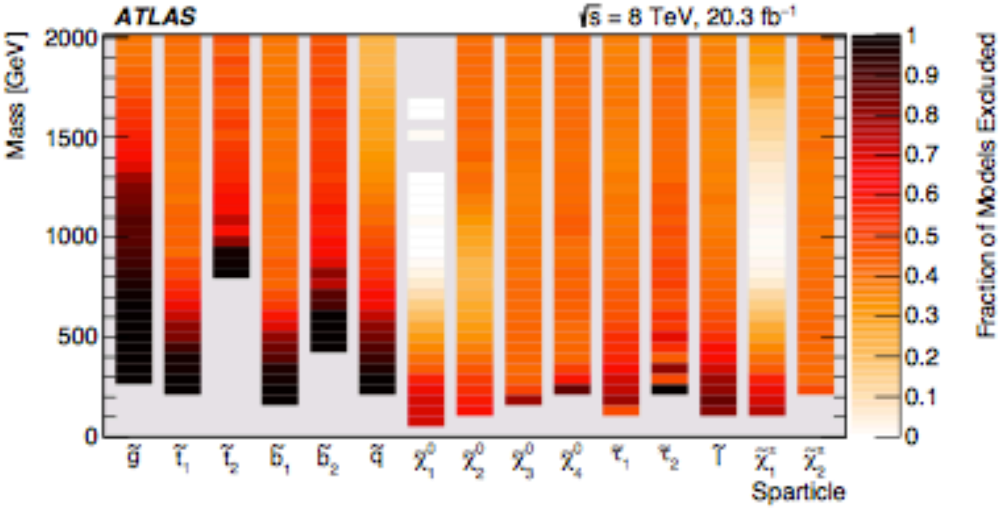


Simplified model overestimates reach (100% BR). Higgs mass constraint excludes light $\tilde{t}_1$ models.

Heavy $\tilde{t}_1$ models with long-lived $\tilde{\chi}_1^{\pm}$ excluded by disappearing track analysis.



Good agreement with simplified models.



- Highest sensitivity to strong processes.
- Simplified models ↔ pMSSM models (some differences observed).
- Good complementarity between different searches and with direct detection experiments (see paper for details).

Interpretation strategy

Based on the number of observed, expected events in all regions with all uncertainties: Probability density function (PDF)

Likelihood function: L(μ,θ)

μ: signal strength (POI);

θ: nuisance parameters(NP)

Profile Likelihood: constrain uncertainty (NP) as part of a likelihood fit

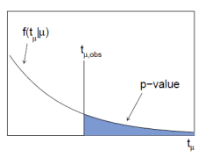
Construct test statistics t_μ based on likelihood ratio λ:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0, \\ \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \end{cases}$$

$$t_\mu = -2\ln\lambda(\mu)$$

Find the observed test statistic for tested μ: $t_{\mu,\text{obs}}$

Construct the PDF of test statistic $t_{\mu:}$ generate toy Monte Carlo or using asymptotic formula



From the constructed distribution of test statistic for s+b, find the p-value of the observation

$$p_\mu = \int_{t_{\mu,\text{obs}}}^{\infty} f(t_\mu|\mu)\, dt_\mu$$

If CLs<0.05: the value of signal is excluded at 95% CL……….

$$\text{CL}_\text{s} = \frac{\text{CL}_\text{s+b}}{\text{CL}_\text{b}} = \frac{p_{s+b}}{1-p_b}$$

The above check has been done for each signal grid points on the SUSY model.

The line can be drawn for the area where points are excluded