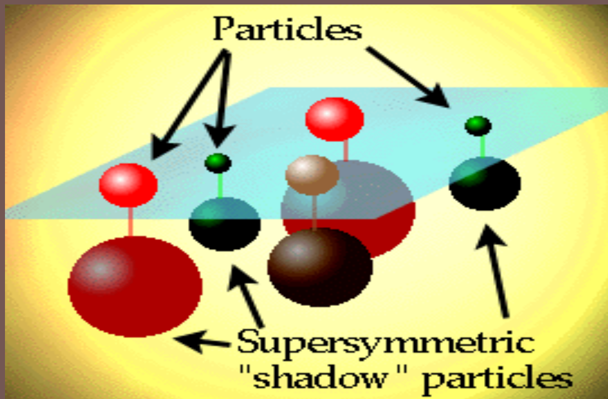

中國科學院高能物理研究所
Institute of High Energy Physics
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Supersymmetry (SUSY)

SUSY Search at LHC and Beyond

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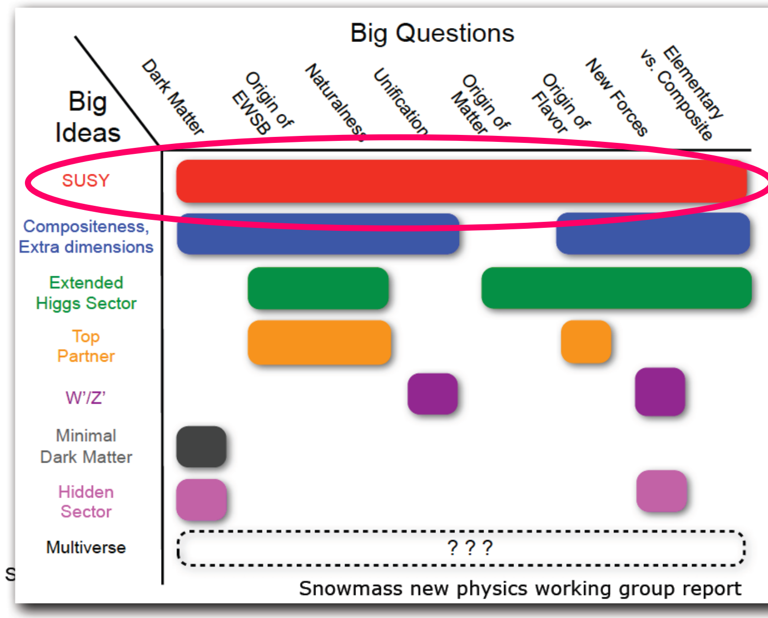
CHEP 2018, Shanghai, 20-22 Jun. 2018

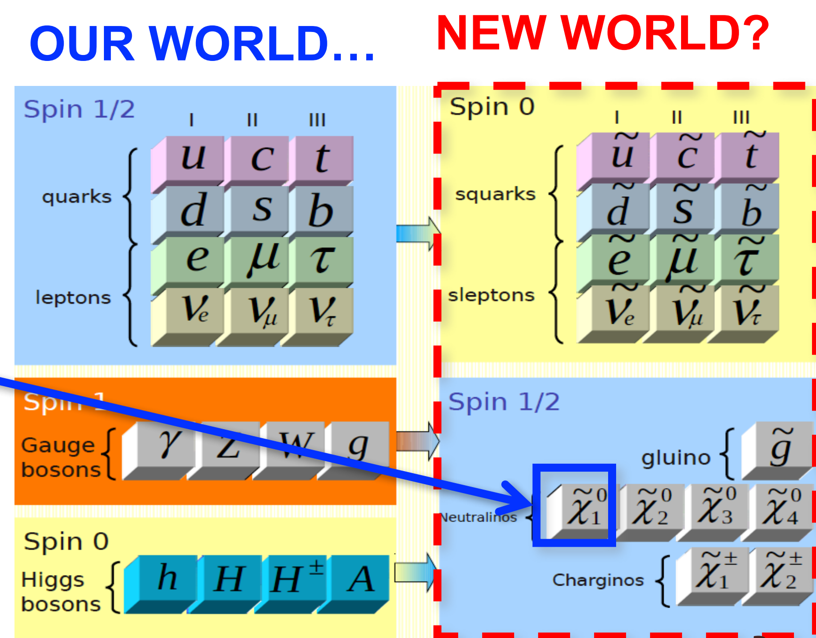
Introduction

- **SM fits the experimental data very well in EW scale, while has problem in Planck scale.**
- **Need a more fundamental theory in which SM is only a low-energy approximation ➔ New Physics.**
- **SUSY establishes a symmetry between fermions (matter) and bosons (forces)**
  - Unification
  - Solves deep problems of the SM
  - Provide Dark Matter candidate
  - …

➔ SUSY search is one of the most hot topic at LHC and beyond

New Physics beyond the SM

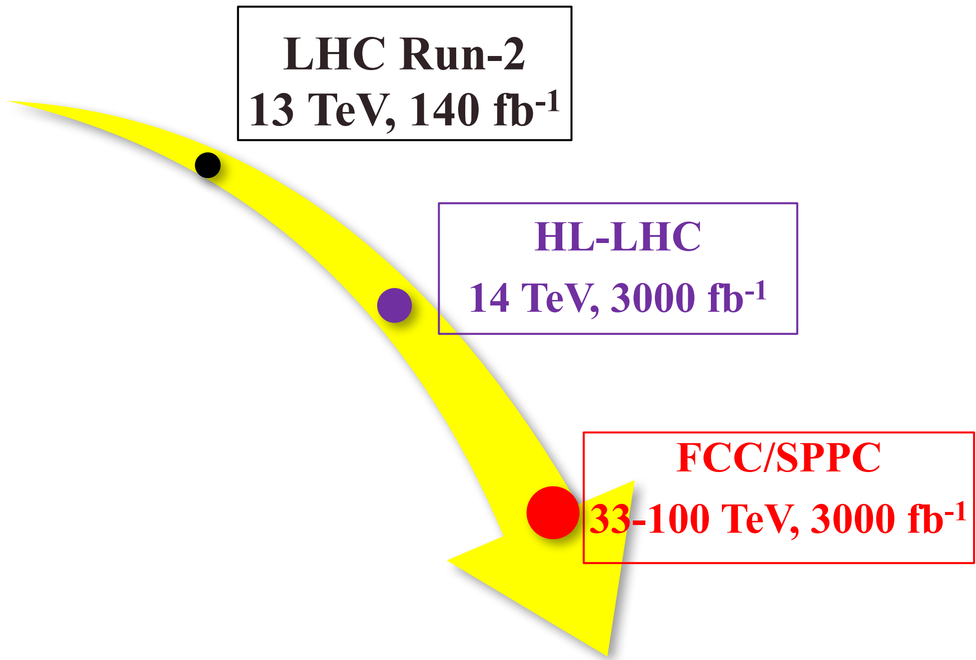




Outline

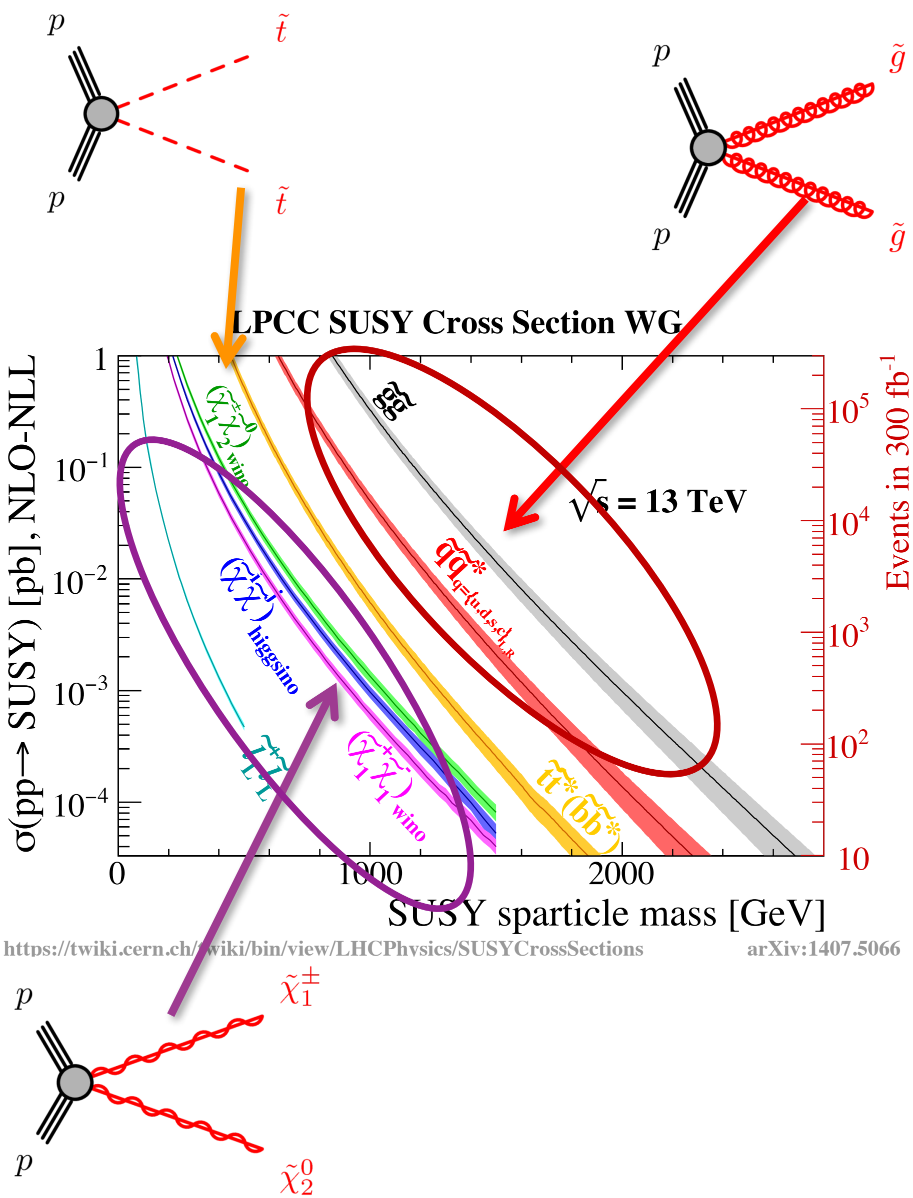
2015-2016 ~ 36 fb^{-1}
2015-2017 ~ 80 fb^{-1}
2015-2018 ~ 140 fb^{-1}

- SUSY Search at LHC (13 TeV, 36-80 fb^{-1})
- Prospects at HL-LHC (14 TeV)
- Prospects at Future Colliders (33, 100 TeV)



SUSY Search @ LHC

[ATLAS public link](#)
[CMS public link](#)



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:

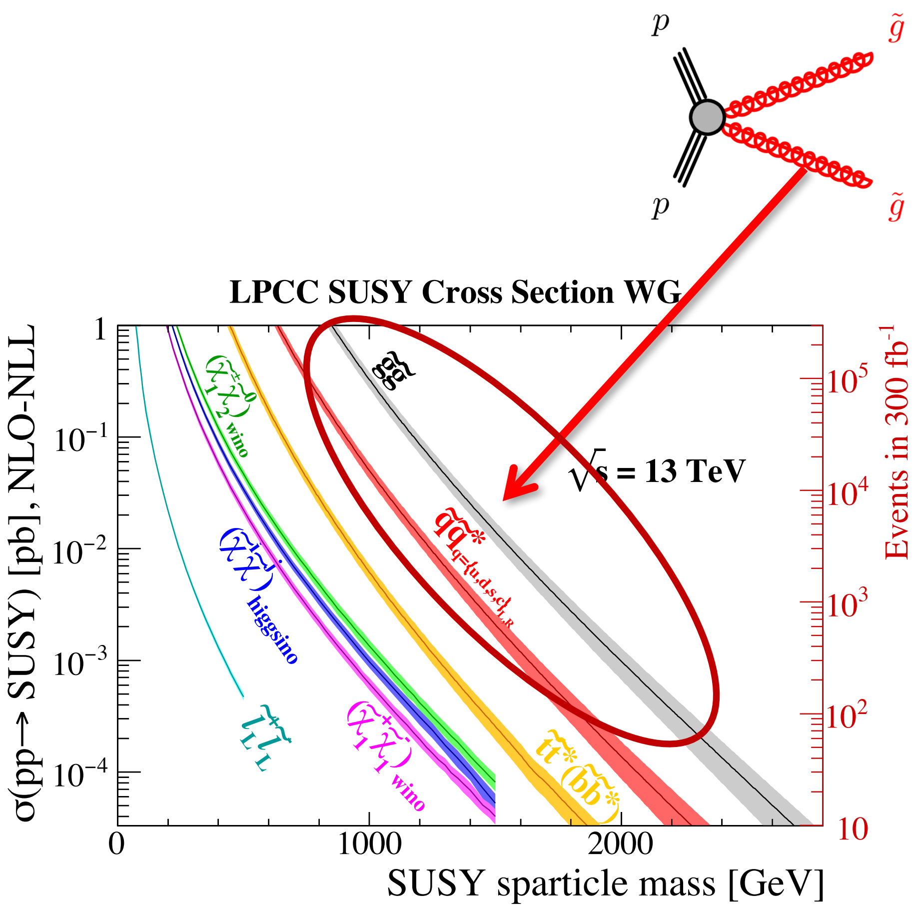
- targeting Electroweakinos, sleptons
- Lowest mass sparticles, clean signature

RPV/LL:

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

SUSY Search @ LHC

ATLAS public link
CMS public link



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1407.5066

Strong production:
- targeting gluinos and 1st and 2nd generation squarks
- by far largest cross-sections

3rd generation:
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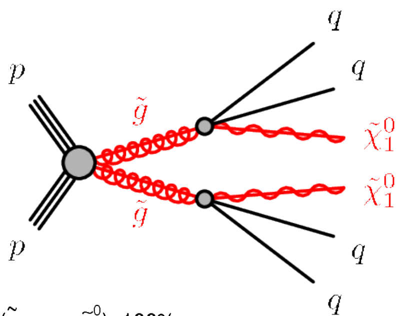
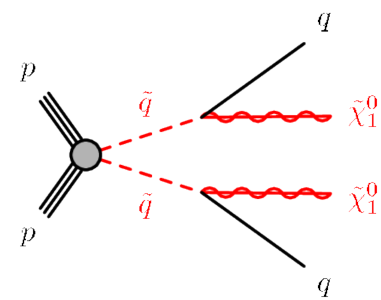
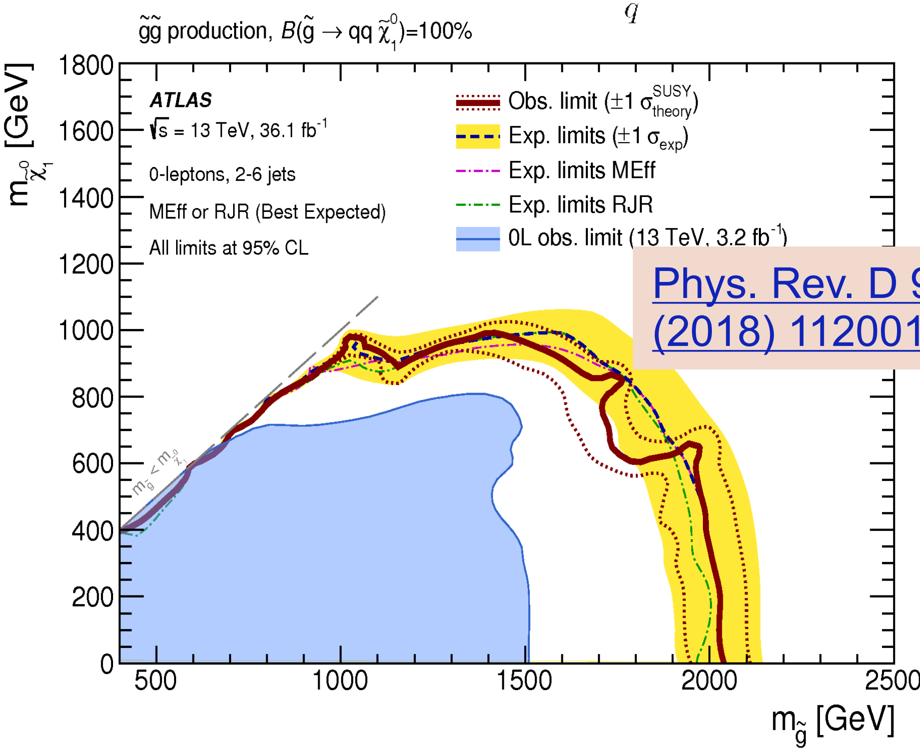
- More exotic models

Direct squark & gluino decays (all had.)

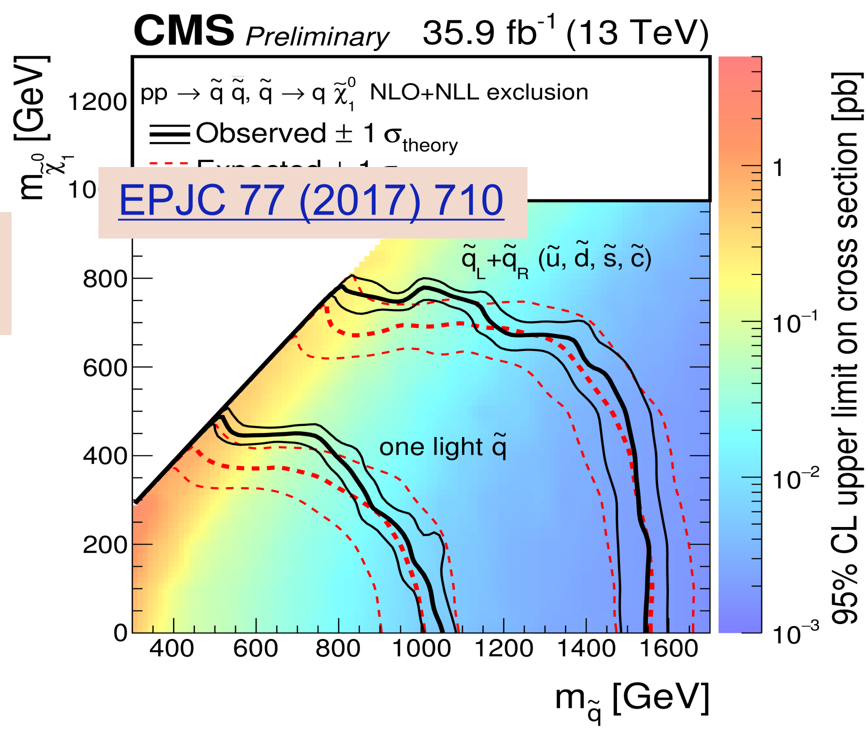


Signal: jets and missing energy





[Phys. Rev. D 97 (2018) 112001]

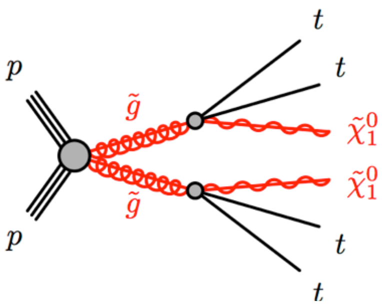


[EPJC 77 (2017) 710]

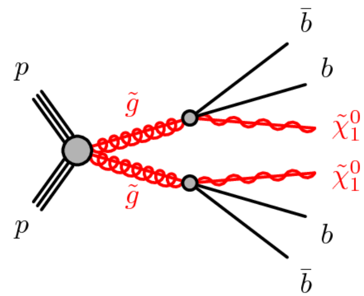
Corresponding sparticle mass limits for **BF=100%**:

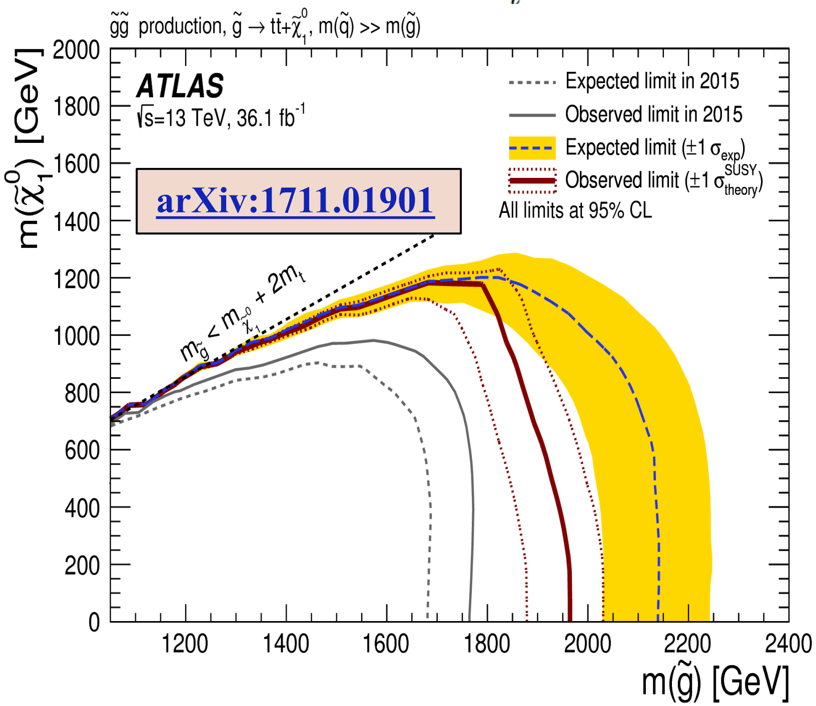
- Squarks: up to 1.55 TeV assuming 8-fold squark degeneracy
- Gluinos: up to 2.05 TeV with neutralinos up to 1.1 TeV

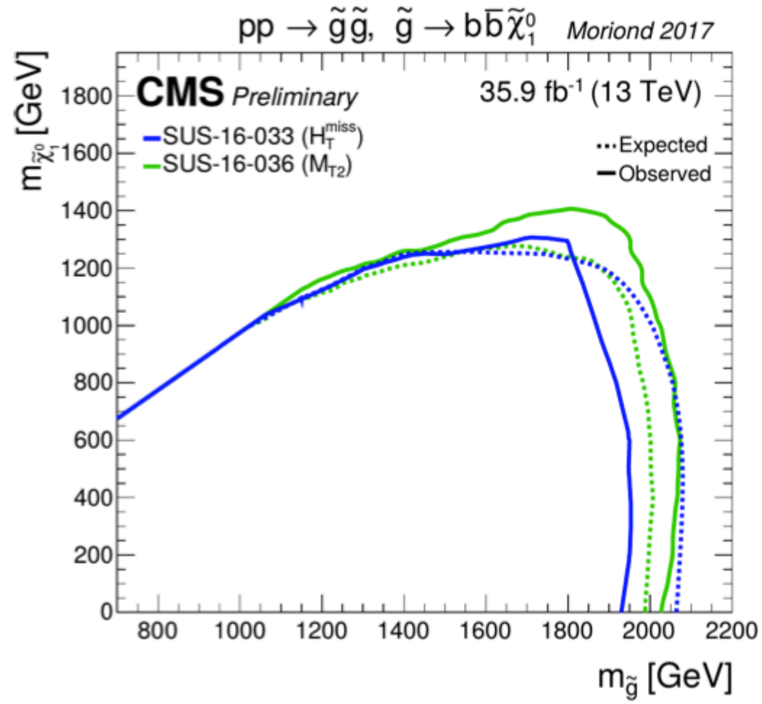
Gluino decays to 3rd Gen. squarks



Signal: 4b-jets (right) up to 4 top quarks (left)





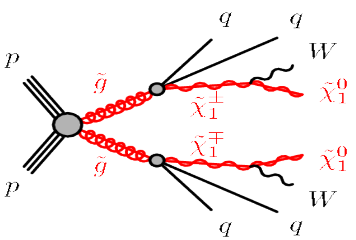


Corresponding sparticle mass limits for **BF=100%**:

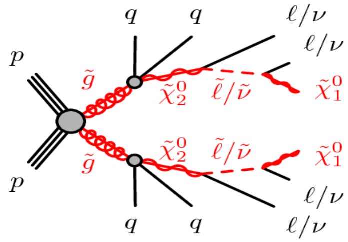
- Gtt: Gluinos up to 1.97 TeV with neutralinos up to 1.19 TeV
- Gbb: Gluinos up to 2.05 TeV with neutralinos up to 1.2 TeV

Multi-step decays

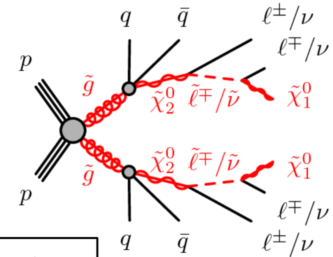
Signal: 1 or 2/3 leptons, jets and MET



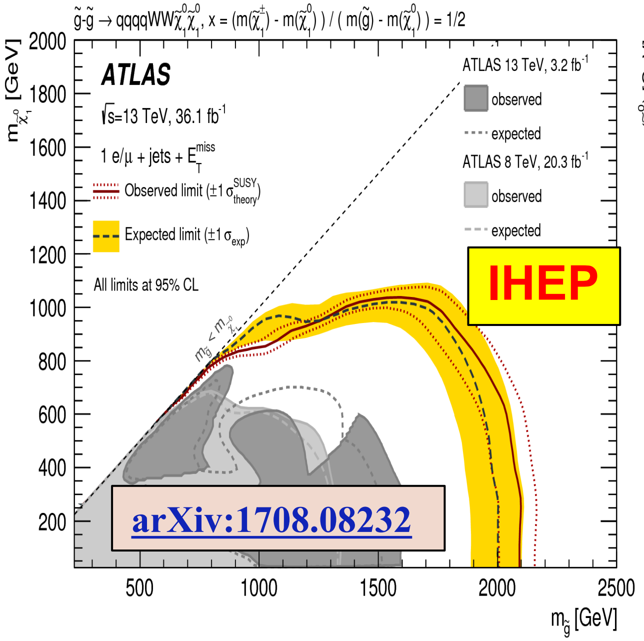
Single lept.

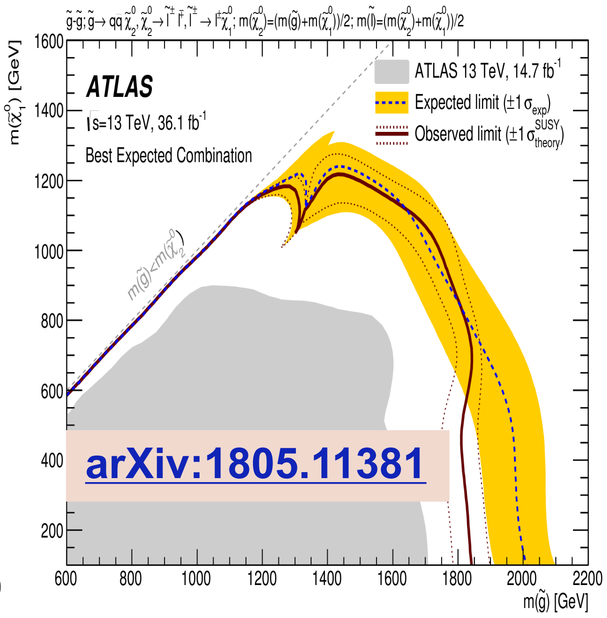


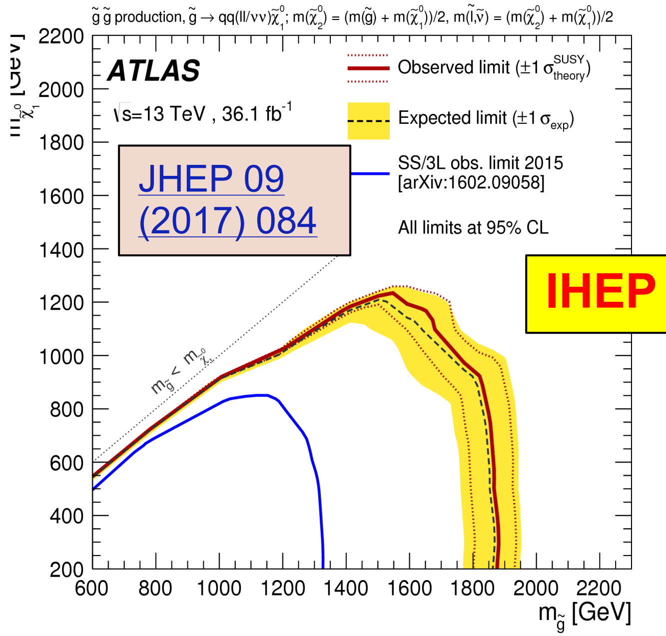
OS Di-lept.



SS Di-lept.



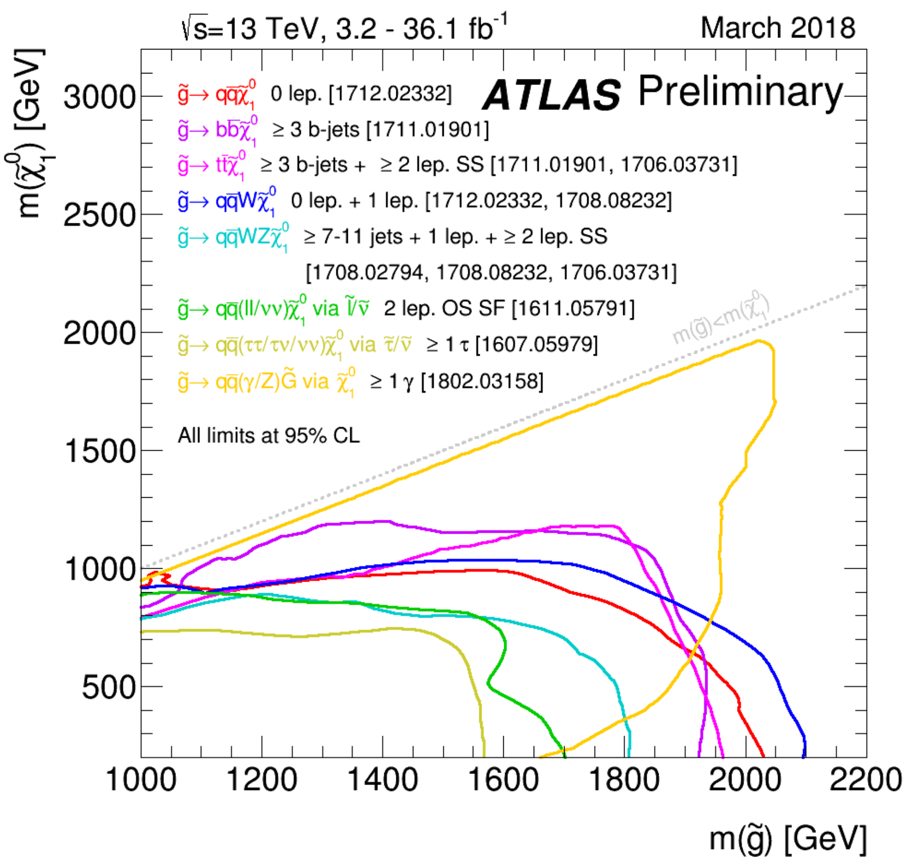


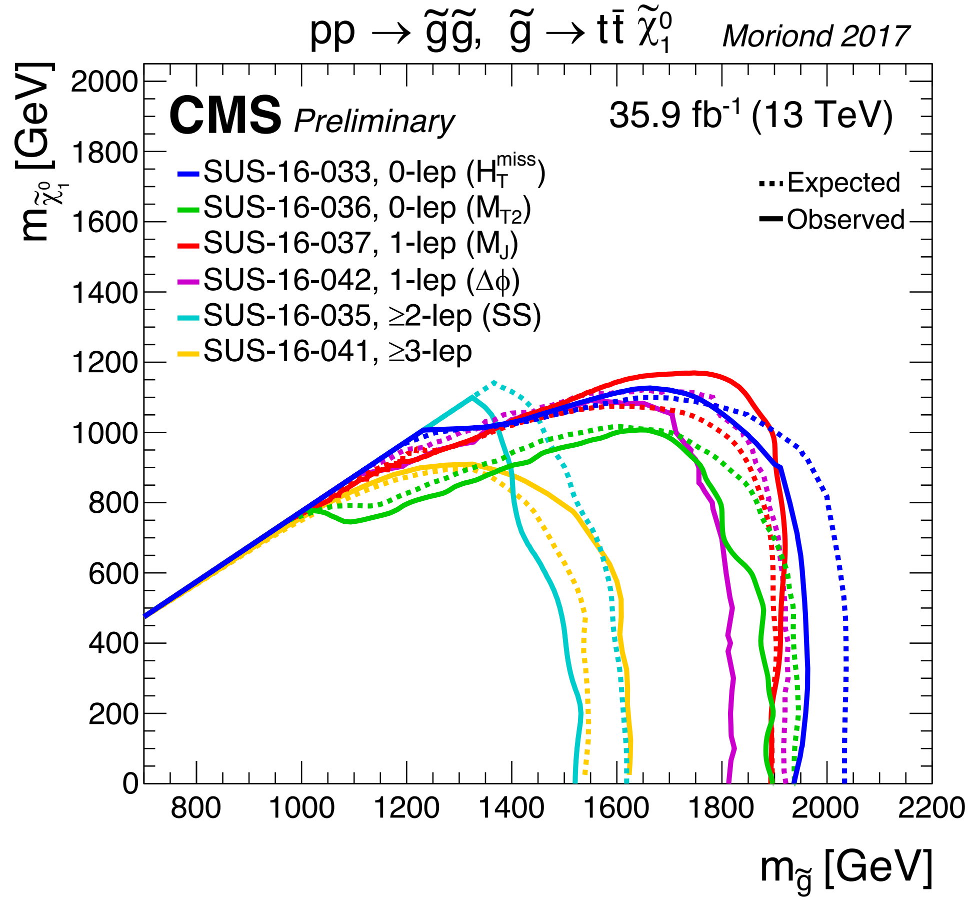


Corresponding sparticle mass limits for **BF=100%**:

- Gluino mass up to 1.8-2 TeV, LSP up to 1-1.2 TeV

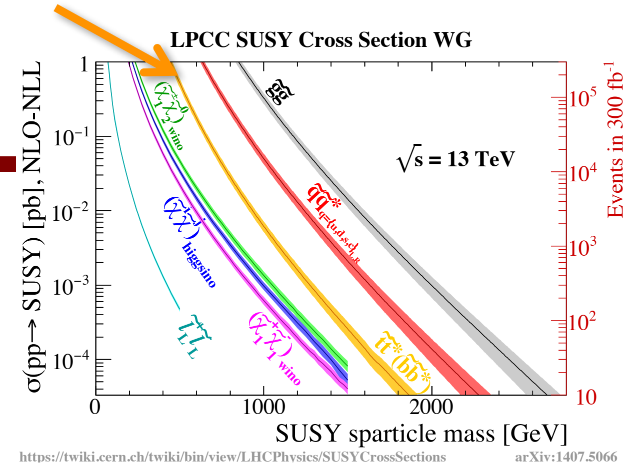
Strong Production *(summary)*

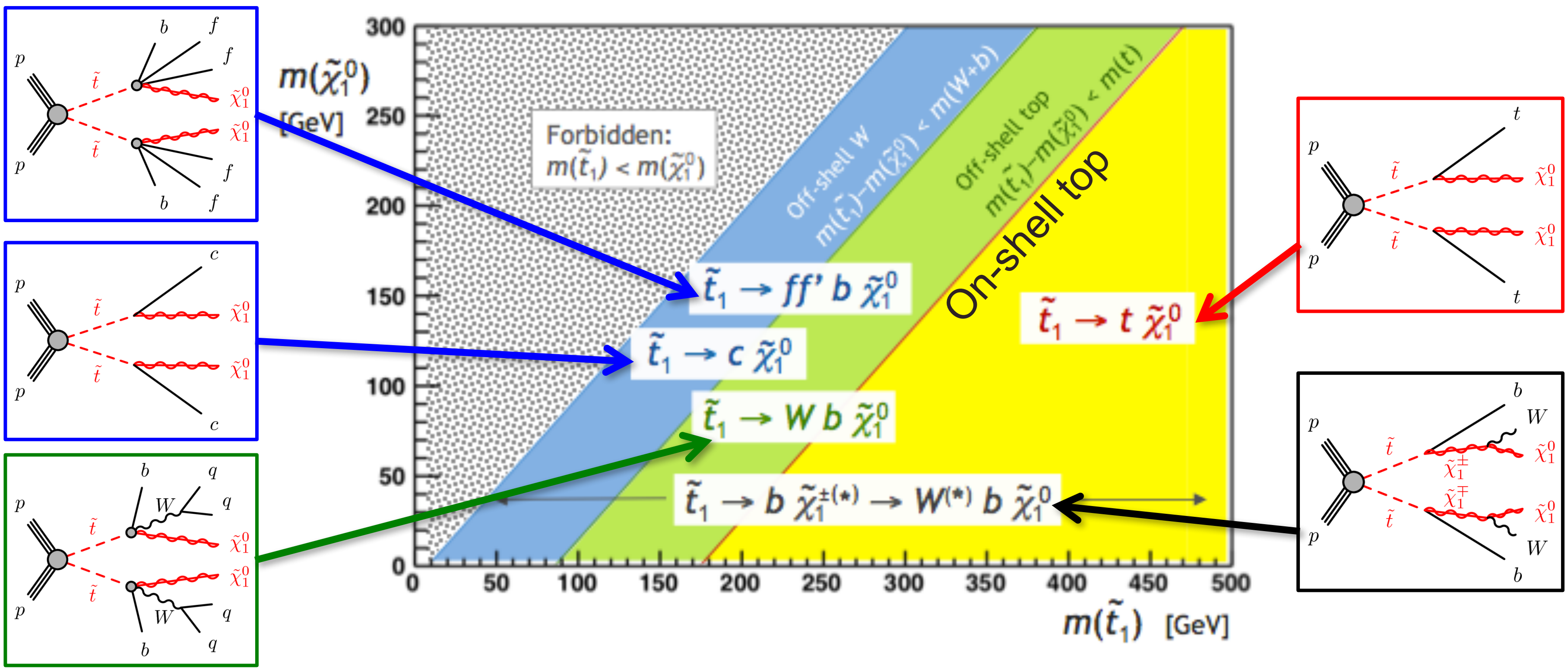




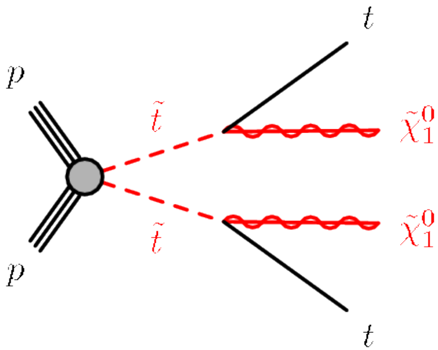
3rd Generation: stop

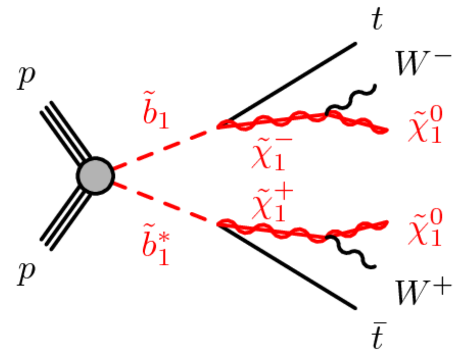
- ❑ Search for stop directly from ~t~t production
- ❑ **Large spectrum of possible stop decays**, covering range from low to heavy stop mass, various decay modes.

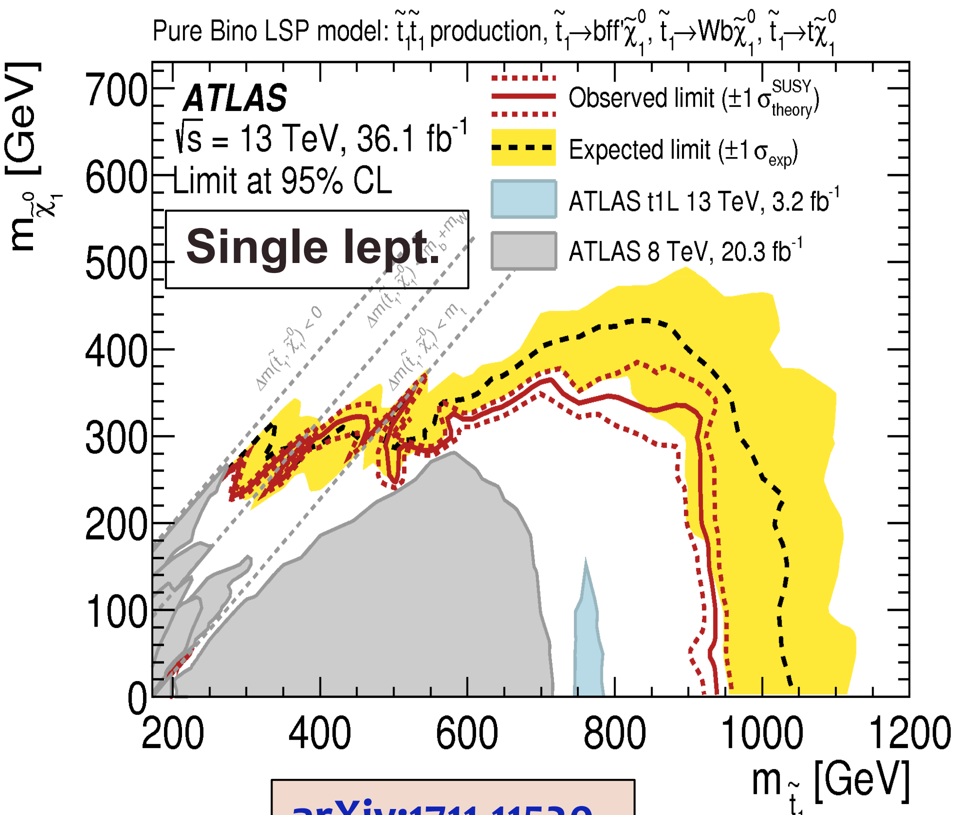


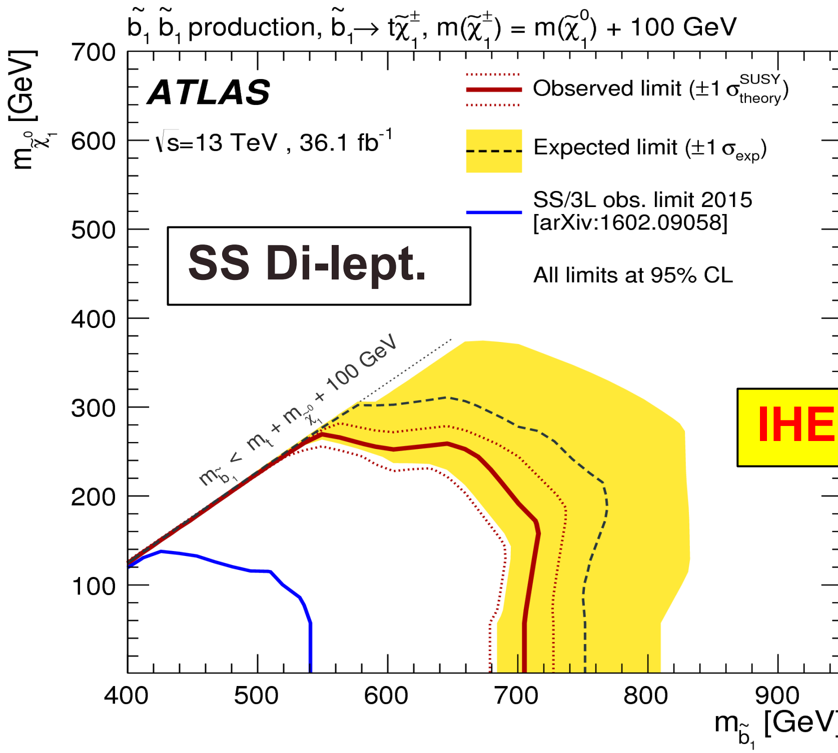


3rd Generation: stop/sbottom (leptonic)









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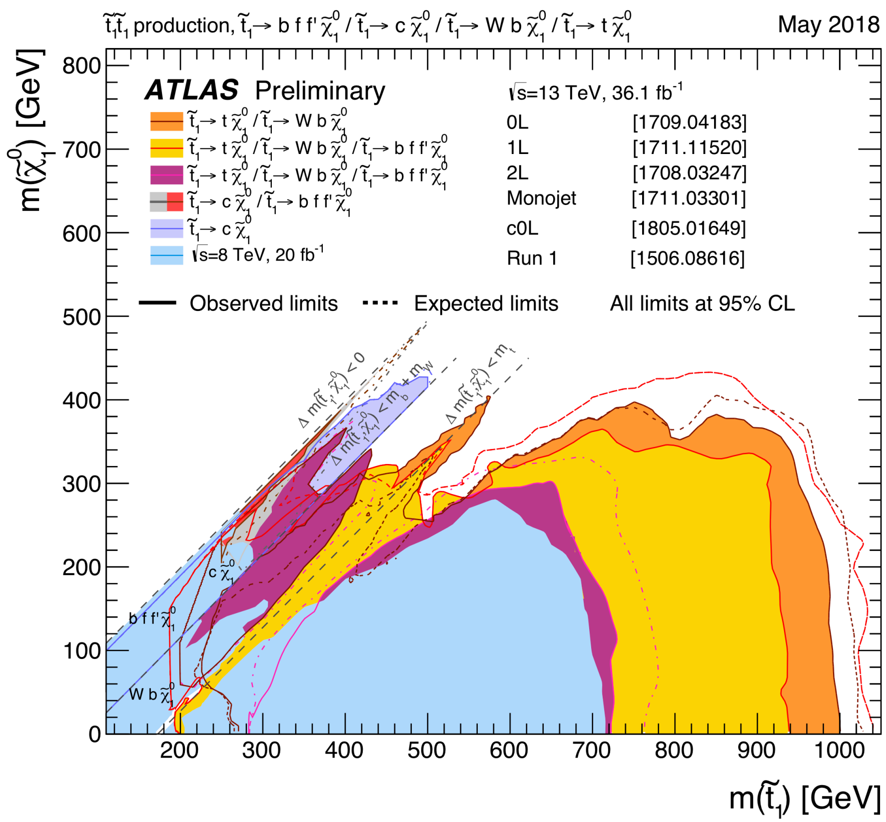
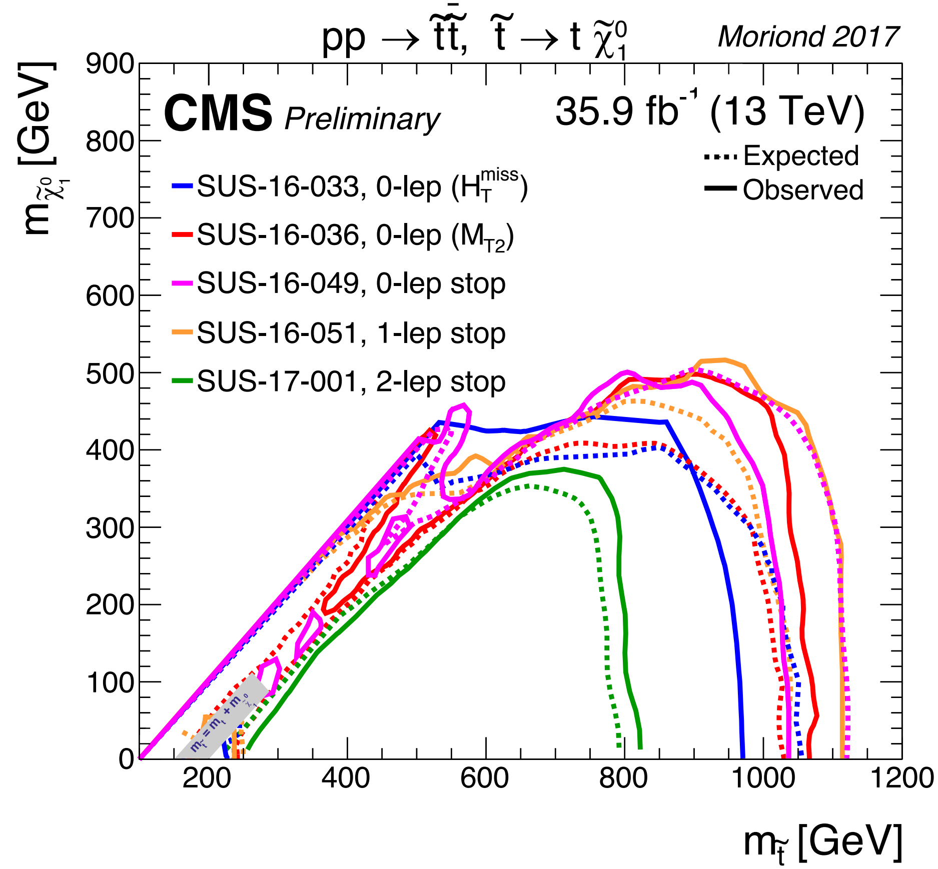
arXiv:1711.11520

JHEP 09 (2017) 084

3rd Generation *(summary)*

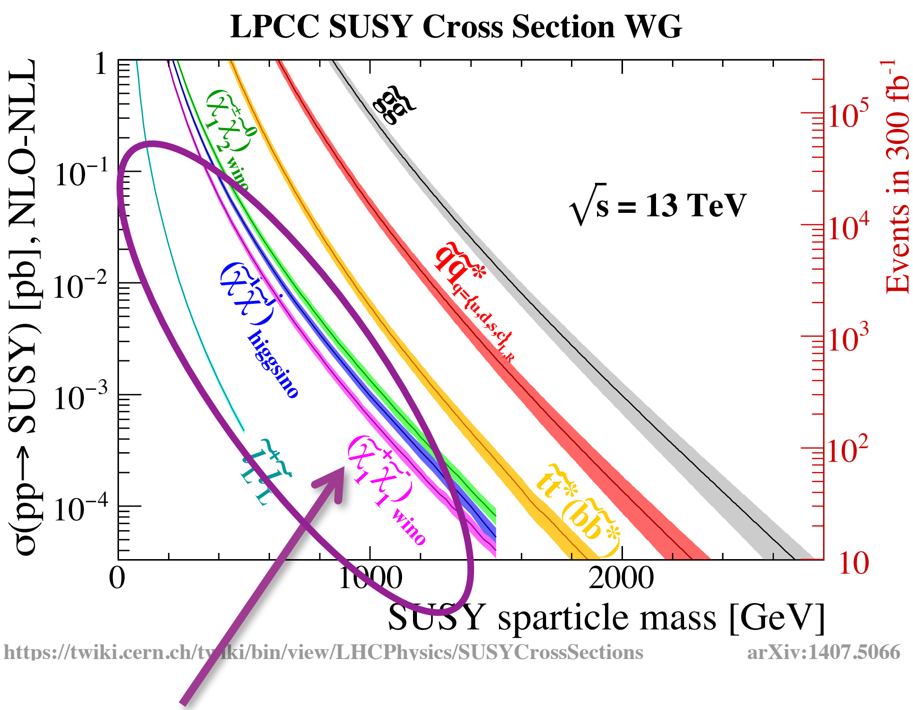


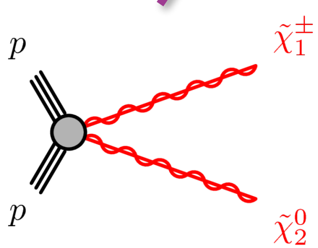


- For **bottom squarks**: exclusion limits beyond **1 TeV** (CMS-PAS-SUS-16-032)
- Still **<600 GeV** for **compressed region**, also for **stop→charm+MET** (ATLAS-CONF-2017-038)

SUSY Search @ LHC

[ATLAS public link](#)
[CMS public link](#)





Strong production:

- ❑ targeting gluinos and 1st and 2nd
- ❑
- 3r
- ❑
- ❑ Should be lowest mass squarks for naturalness reasons

If coloured sparticles much heavier than EW partners, EWK prod. will dominant at LHC

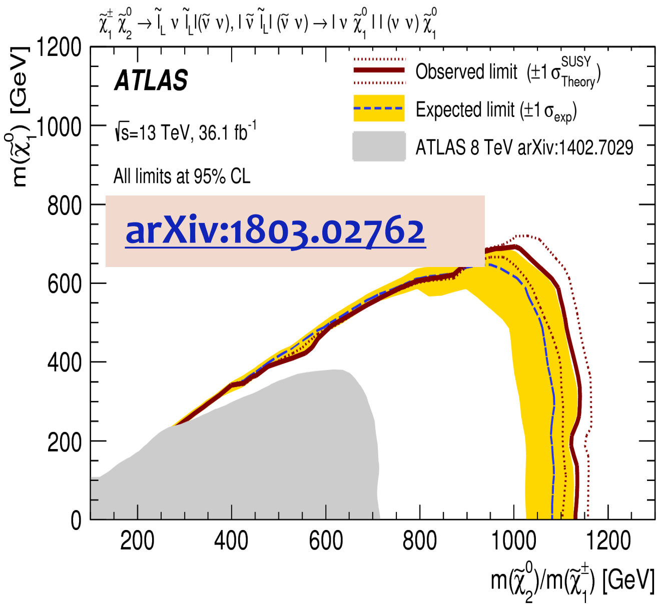
Electroweak production:

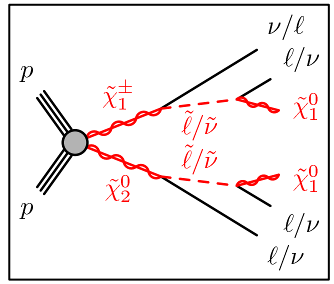
- ❑ targeting Electroweakinos, sleptons
- ❑ Lowest mass sparticles, clean signature

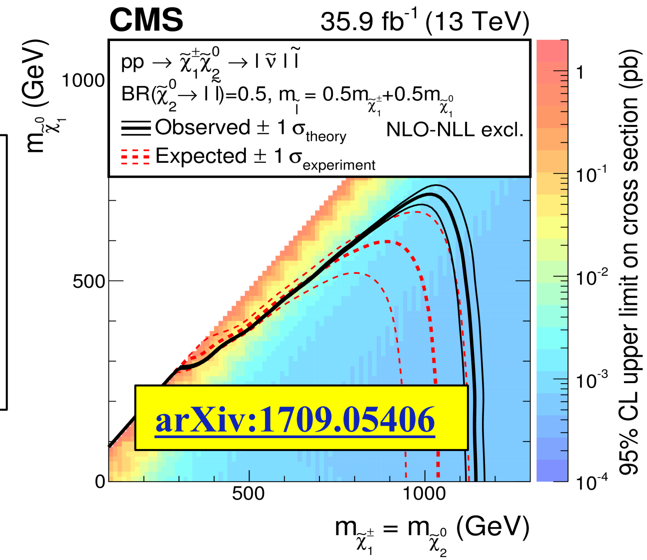
RPV/LL:

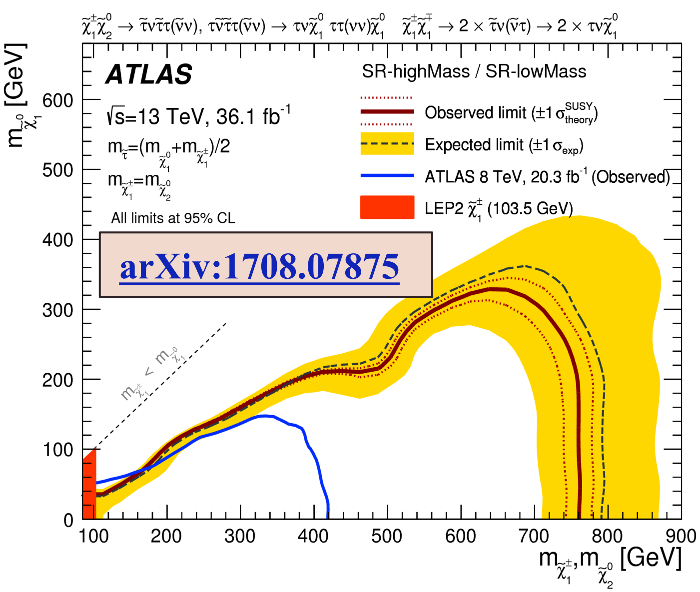
- ❑ targeting R-parity violating models and long lived sparticles
- ❑ More exotic models

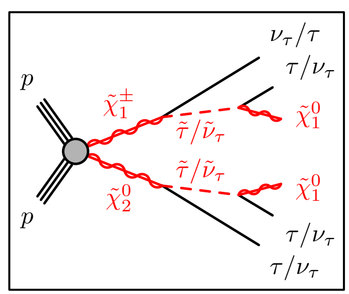
C1N2: via slepton decay (2l/3l)

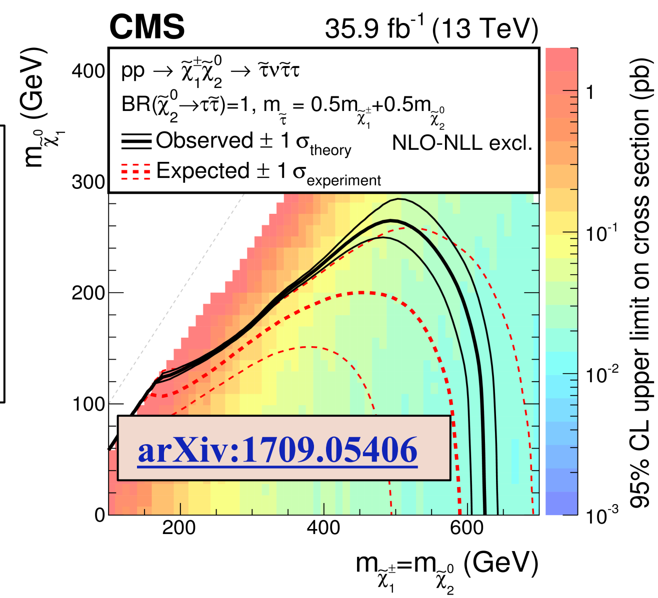












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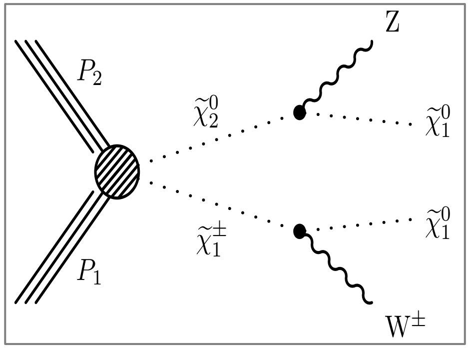
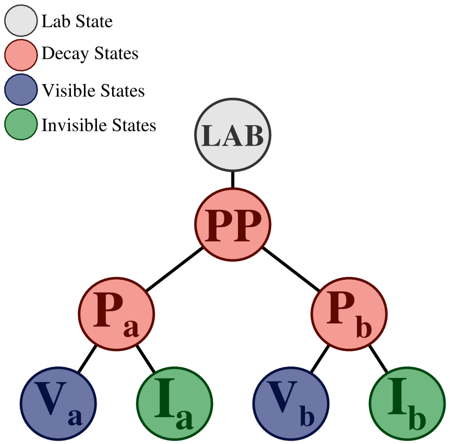
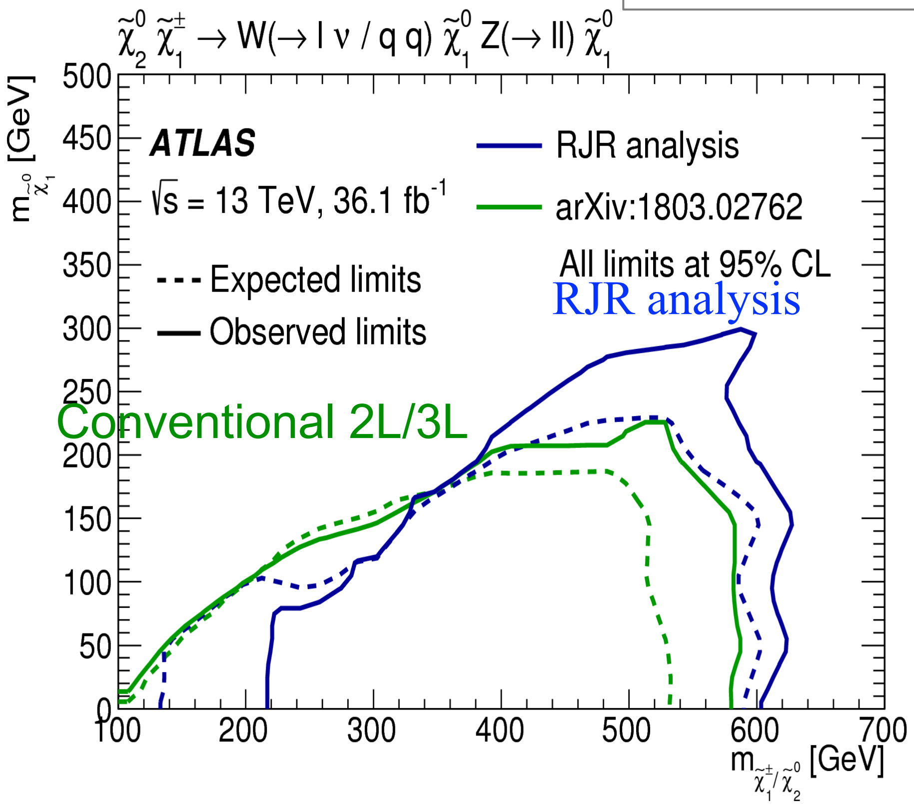
C1N2: via WZ decay (2l/3l)

arXiv:1806.02293





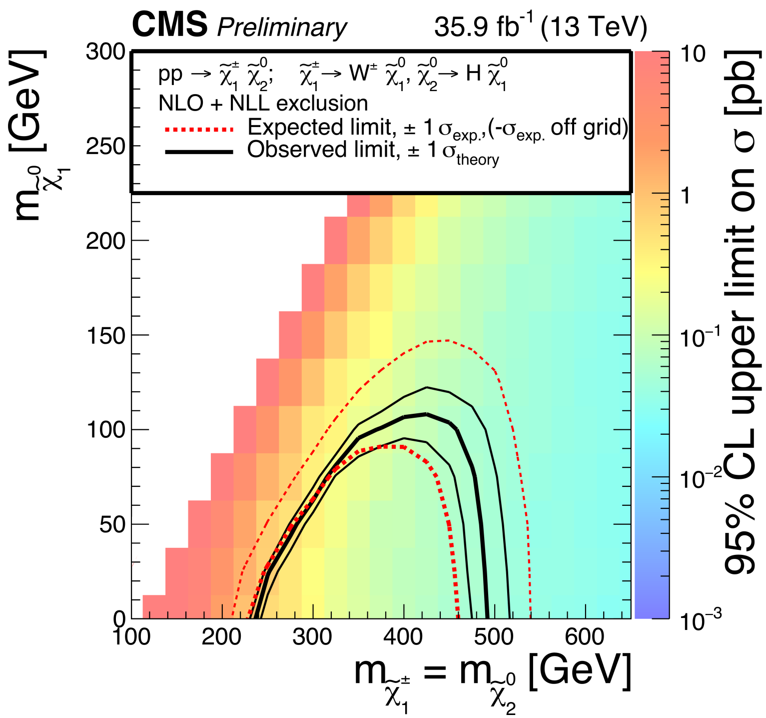


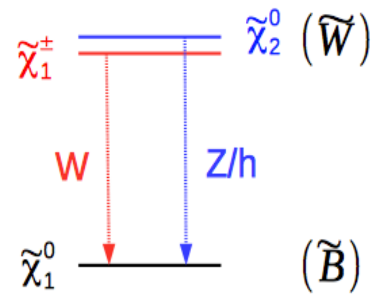
RJR (Recursive Jigsaw Reconstruction): reconstruction of intermediate rest-frames

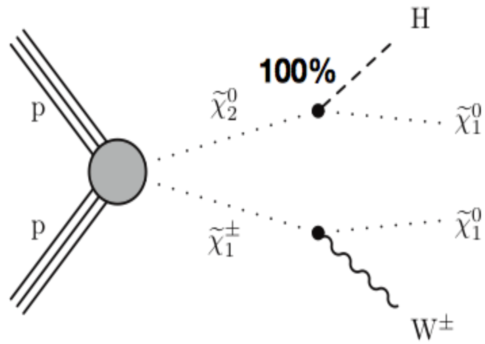
- **~ 3s excesses seen in the SRs targeting low mass-splitting for RJR analysis**
- **Not seen in the conventional search targeting the same signal model**

C1N2: via WH decay (1lbb)

JHEP 11 (2017) 029



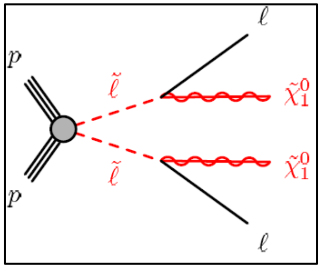


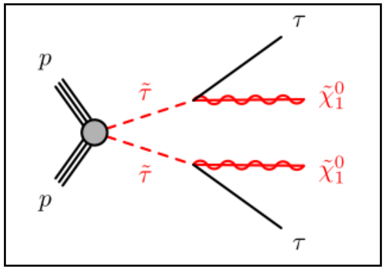


- Wino-like mass spectrum: large xSec.
- Dedicated search for WH topology
- 1 lepton(e/mu)+bb: clean final states, large BR from H→bb
- Probe chargino mass up to 550 GeV

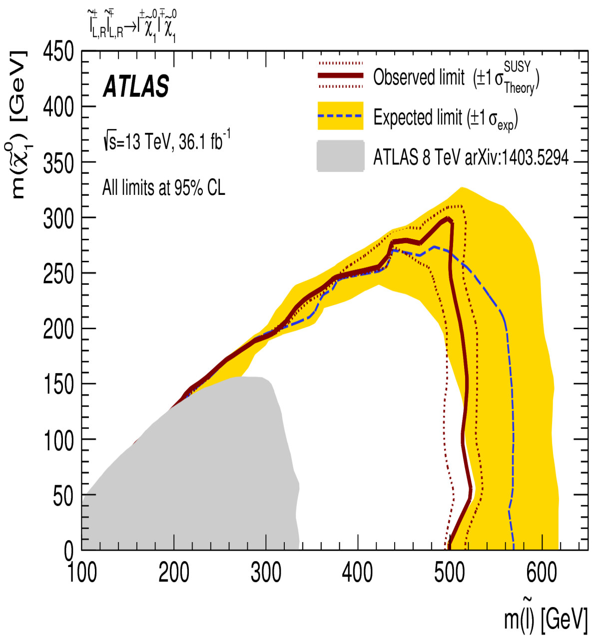
IHEP is working on Wh (1lττ) analysis.

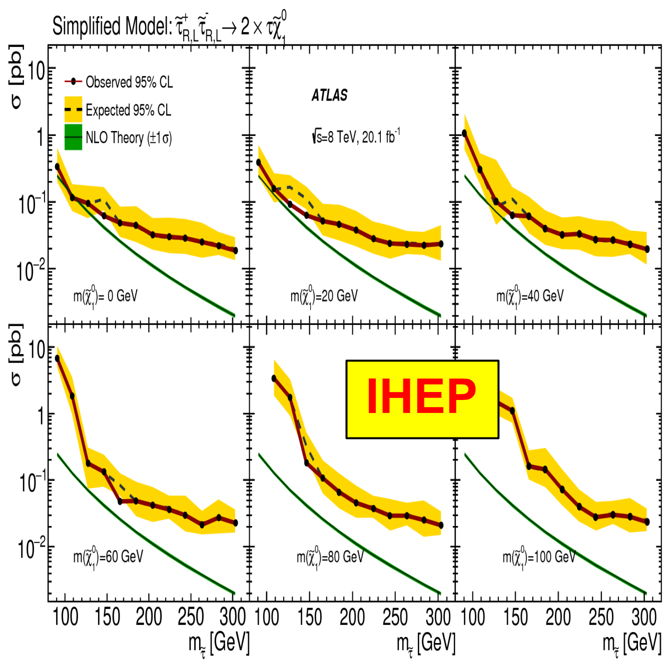
Direct slepton pair

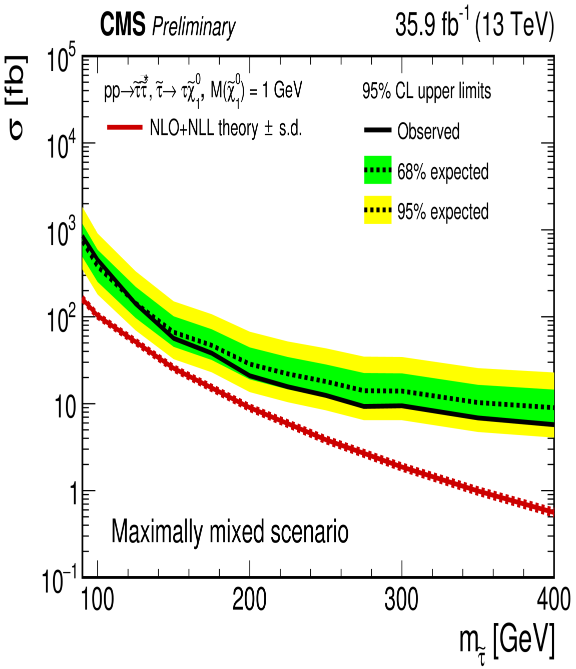




Staus are challenging and are interesting NLSP for DM coannihilation







arXiv:1803.02762

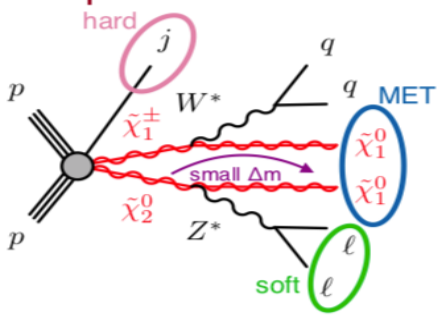
Phys. Rev. D 93, 052002 (2016)

CMS-PAS-SUS-17-003

PRD97(2018)052010

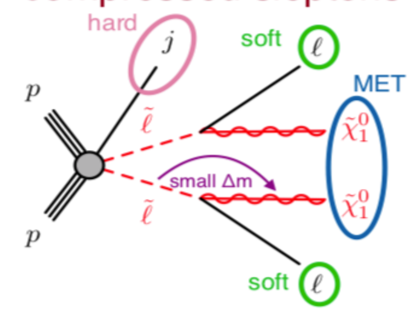
Compressed scenarios with soft leptons

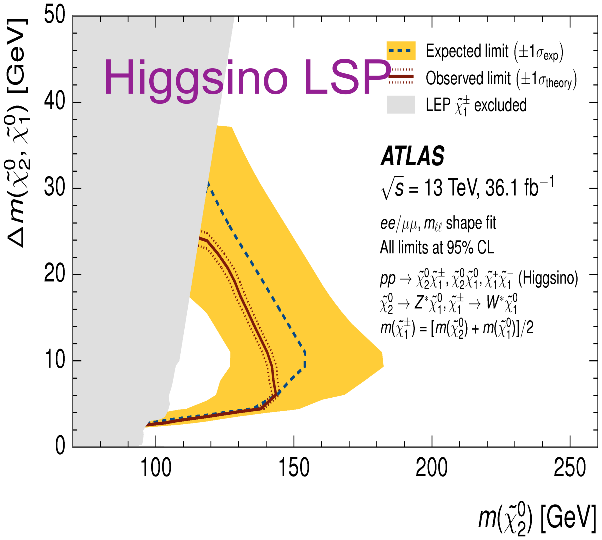
compressed EWKinos

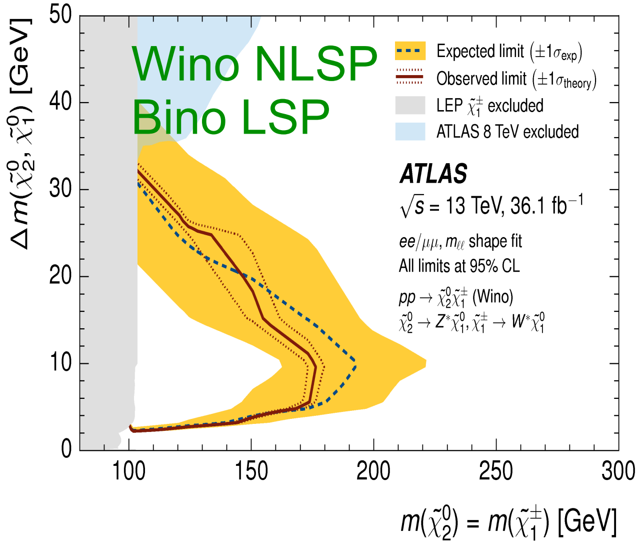


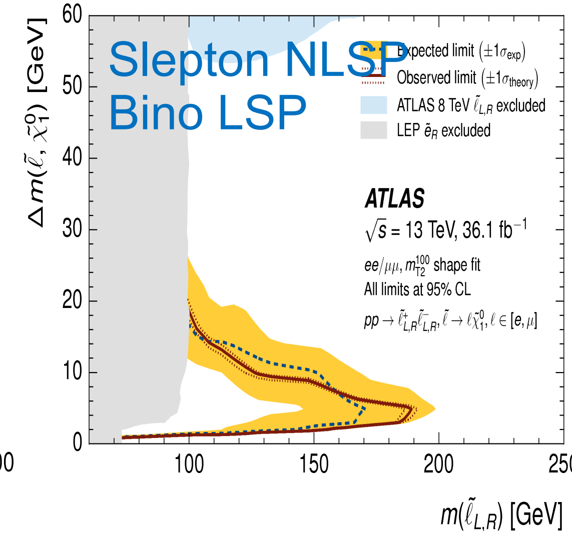
- Soft leptons pt: 4-5 GeV
- ISR jet to get the system boosted (met trigger)
- ***First direct limits on Higgsino since LEP! (also from CMS: SUS-16-048)***

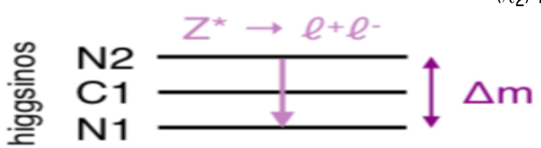
compressed sleptons

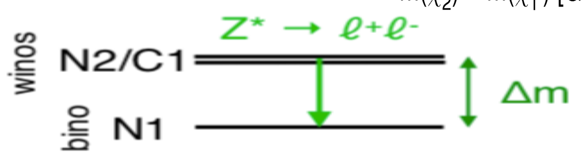








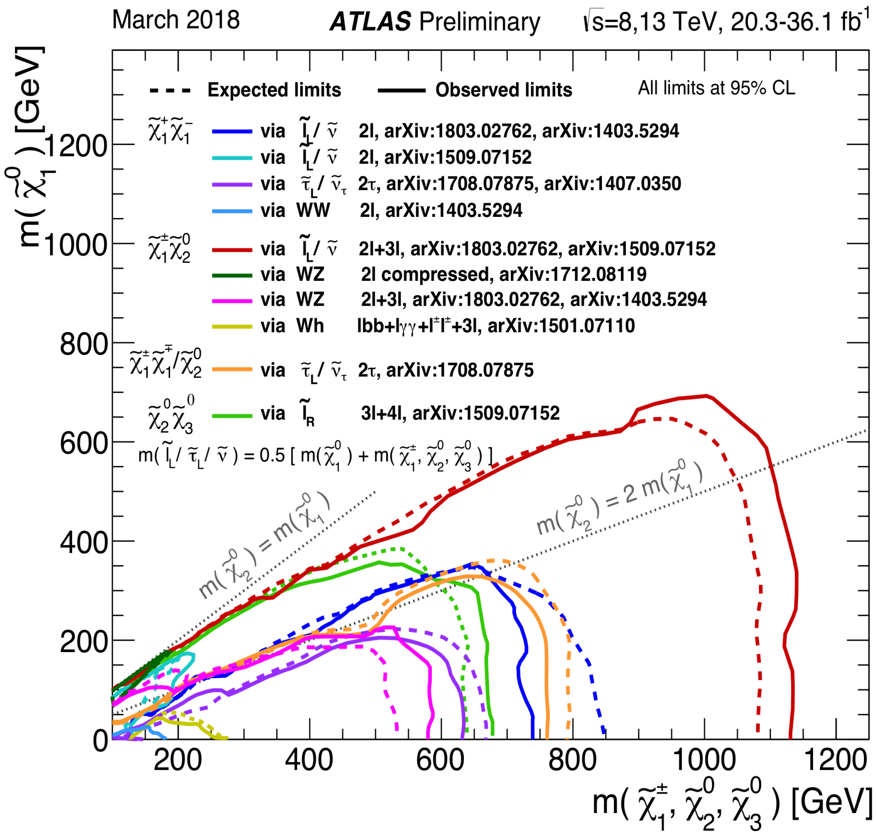


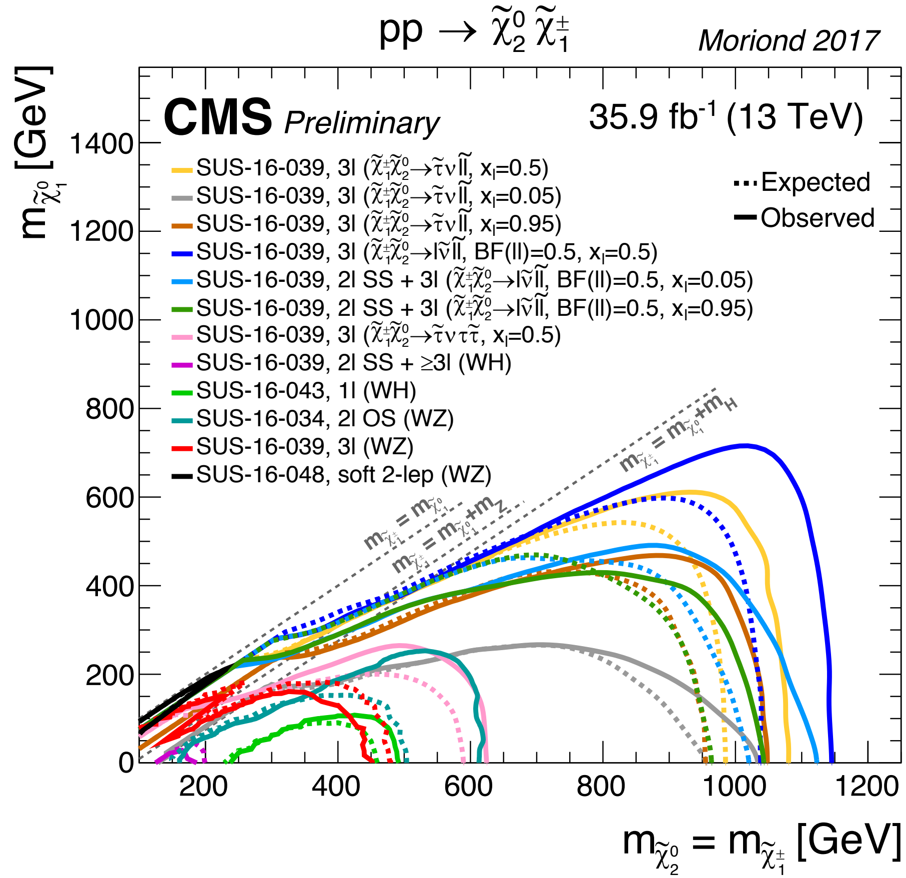


Δm as low as 3 GeV | Δm as low as 2.5 GeV | Δm as low as 1 GeV

EWKino upto 145 GeV | EWKino upto 180 GeV | Slepton upto 190 GeV

EWK Production *(summary)*





- Powerful exclusions in decays **via sleptons** (C1/N2 up to **0.6-1.1** TeV)
- Exclusions is not so large in decays via **bosons** (up to **150-600** GeV)
- Mass limit on **selectron/smuon** up to **500** GeV, not yet on **staus**

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

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

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

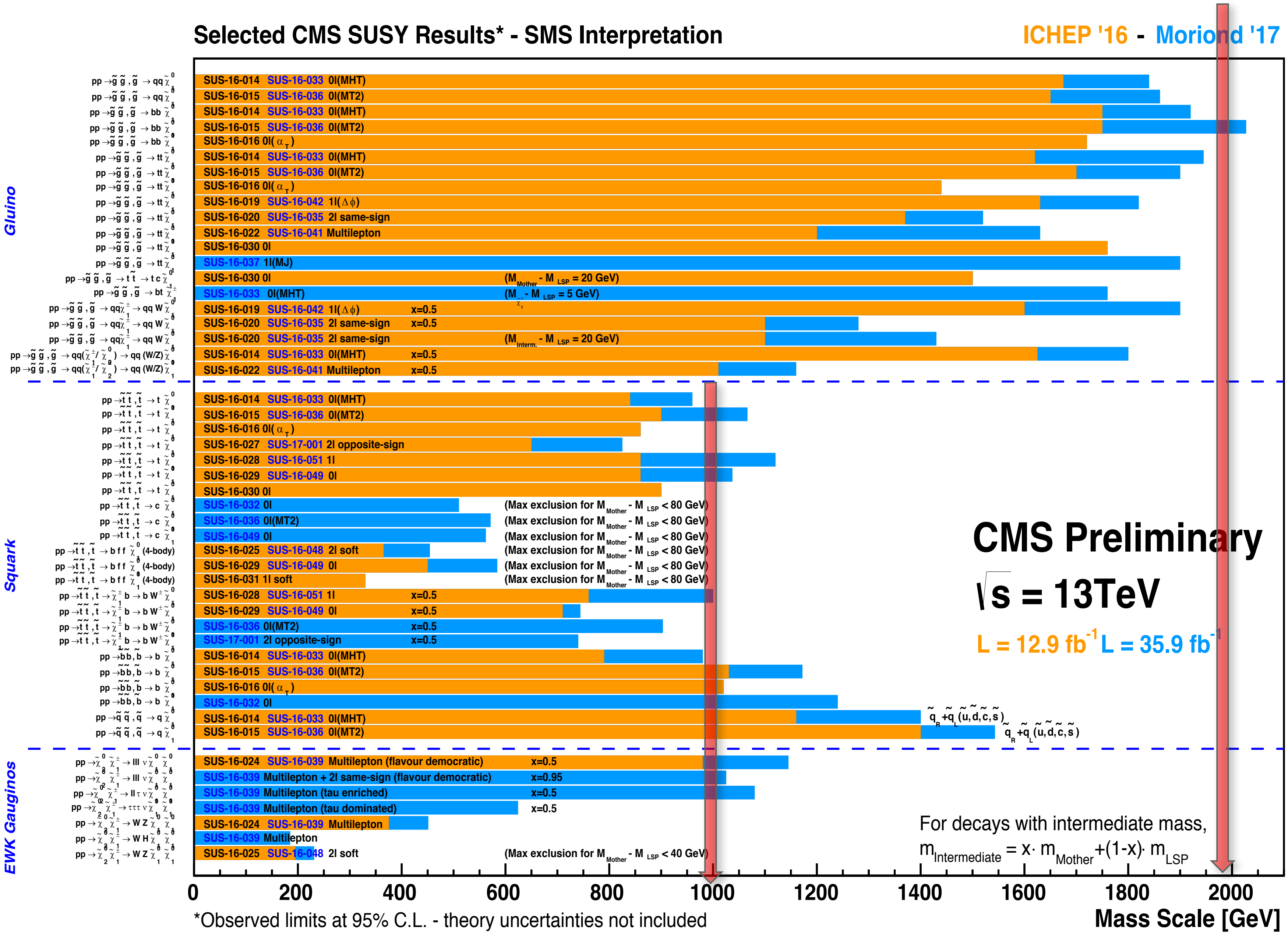
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q \to q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde q$ 1.57 TeV	$m(\tilde\chi^0_1)$<200 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1712.02332
	$\tilde q\tilde q$, $\tilde q \to q\tilde\chi^0_1$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde q$ 710 GeV	$m(\tilde q)$-$m(\tilde\chi^0_1)$<5 GeV	1711.03301
	$\tilde g\tilde g$, $\tilde g \to q\bar q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde g$ 2.02 TeV	$m(\tilde\chi^0_1)$<200 GeV	1712.02332
	$\tilde g\tilde g$, $\tilde g \to qq\tilde\chi^\pm_1 \to qqW^\pm\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde g$ 2.01 TeV	$m(\tilde\chi^0_1)$<200 GeV, $m(\tilde\chi^\pm)$=0.5($m(\tilde\chi^0_1)$+$m(\tilde g)$)	1712.02332
	$\tilde g\tilde g$, $\tilde g \to q\bar q(\ell\ell)\tilde\chi^0_1$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde g$ 1.7 TeV	$m(\tilde\chi^0_1)$<300 GeV,	1611.05791
	$\tilde g\tilde g$, $\tilde g \to qq(\ell\ell/\nu\nu)\tilde\chi^0_1$	3 e,μ	4 jets	-	36.1	$\tilde g$ 1.87 TeV	$m(\tilde\chi^0_1)$=0 GeV	1706.03731
	$\tilde g\tilde g$, $\tilde g \to qqWZ\tilde\chi^0_1$	0	7-11 jets	Yes	36.1	$\tilde g$ 1.8 TeV	$m(\tilde\chi^0_1)$ <400 GeV	1708.02794
	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	36.1	$\tilde g$ 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde g$ 2.05 TeV	$m(\tilde\chi^0_1)$=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	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
3rd gen. $\tilde g$ med.	$\tilde g\tilde g$, $\tilde g \to b\bar b\tilde\chi^0_1$	0	3 b	Yes	36.1	$\tilde g$ 1.92 TeV	$m(\tilde\chi^0_1)$<600 GeV	1711.01901
	$\tilde g\tilde g$, $\tilde g \to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde g$ 1.97 TeV	$m(\tilde\chi^0_1)$<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1 \to b\tilde\chi^0_1$	0	2 b	Yes	36.1	$\tilde b_1$ 950 GeV	$m(\tilde\chi^0_1)$<420 GeV	1708.09266
	$\tilde b_1\tilde b_1$, $\tilde b_1 \to t\tilde\chi^\pm_1$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde b_1$ 275-700 GeV	$m(\tilde\chi^0_1)$<200 GeV, $m(\tilde\chi^\pm_1)$= $m(\tilde\chi^0_1)$+100 GeV	1706.03731
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to b\tilde\chi^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde t_1$ 117-170 GeV; 200-720 GeV	$m(\tilde\chi^\pm_1)$ = 2$m(\tilde\chi^0_1)$, $m(\tilde\chi^0_1)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde t_1$ 90-198 GeV; 0.195-1.0 TeV	$m(\tilde\chi^0_1)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to c\tilde\chi^0_1$	0	mono-jet	Yes	36.1	$\tilde t_1$ 90-430 GeV	$m(\tilde t_1)$-$m(\tilde\chi^0_1)$=5 GeV	1711.03301
	$\tilde t_1\tilde t_1$(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
	$\tilde t_2\tilde t_2$, $\tilde t_2 \to \tilde t_1 + Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde t_2$ 290-790 GeV	$m(\tilde\chi^0_1)$=0 GeV	1706.03986
	$\tilde t_2\tilde t_2$, $\tilde t_2 \to \tilde t_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde t_2$ 320-880 GeV	$m(\tilde\chi^0_1)$=0 GeV	1706.03986
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell \to \ell\tilde\chi^0_1$	2 e,μ	0	Yes	36.1	$\tilde\ell$ 90-500 GeV	$m(\tilde\chi^0_1)$=0	ATLAS-CONF-2017-039
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1 \to \tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	36.1	$\tilde\chi^\pm_1$ 750 GeV	$m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$)	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2$, $\tilde\chi^+_1 \to \tilde\tau\nu(\tau\tilde\nu)$, $\tilde\chi^0_2 \to \tilde\tau\tau(\nu\tilde\nu)$	2 τ	-	Yes	36.1	$\tilde\chi^\pm_1$ 760 GeV	$m(\tilde\chi^0_1)$=0, $m(\tilde\tau,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$)	1708.07875
	$\tilde\chi^\pm_1\tilde\chi^0_2 \to \tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	36.1	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 1.13 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-2017-039
	$\tilde\chi^\pm_1\tilde\chi^0_2 \to W\tilde\chi^0_1 Z\tilde\chi^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 580 GeV	$m(\tilde\chi^\pm_1)$=$m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $\tilde\ell$ decoupled	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^0_2 \to W\tilde\chi^0_1 h\tilde\chi^0_1$, $h \to b\bar b/WW/\tau\tau/\gamma\gamma$	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
	$\tilde\chi^0_2\tilde\chi^0_3$, $\tilde\chi^0_{2,3} \to \tilde\ell_R\ell$	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., $\tilde\chi^0_1 \to \gamma\tilde G$	1 e,μ + γ	-	Yes	20.3	$\tilde W$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde\chi^0_1 \to \gamma\tilde G$	2 γ	-	Yes	36.1	$\tilde W$ 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde\chi^\pm_1$ 460 GeV	$m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$~160 MeV, $\tau(\tilde\chi^\pm_1)$=0.2 ns	1712.02118
	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, $\tau(\tilde\chi^\pm_1)$<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<$\tau(\tilde g)$<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
	Metastable $\tilde g$ R-hadron, $\tilde g \to qq\tilde\chi^0_1$	displ. vtx	-	Yes	32.8	$\tilde g$ 2.37 TeV	$\tau(\tilde g)$=0.17 ns, $m(\tilde\chi^0_1)$ = 100 GeV	1710.04901
	GMSB, stable $\tilde\tau$, $\tilde\chi^0_1 \to \tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde\chi^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde\chi^0_1 \to \gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	20.3	$\tilde\chi^0_1$ 440 GeV	1<$\tau(\tilde\chi^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi^0_1 \to ee\nu/e\mu\nu/\mu\mu\nu$	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
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	$\tilde\nu_\tau$ 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
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1 \to W\tilde\chi^0_1$, $\tilde\chi^0_1 \to ee\nu, e\mu\nu, \mu\mu\nu$	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
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1 \to W\tilde\chi^0_1$, $\tilde\chi^0_1 \to \tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	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
	$\tilde g\tilde g$, $\tilde g \to qq\tilde\chi^0_1$, $\tilde\chi^0_1 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde g$ 1.875 TeV	$m(\tilde\chi^0_1)$=1075 GeV	SUSY-2016-22
	$\tilde g\tilde g$, $\tilde g \to tt\tilde\chi^0_1$, $\tilde\chi^0_1 \to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde g$ 2.1 TeV	$m(\tilde\chi^0_1)$= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde g\tilde g$, $\tilde g \to \tilde t_1 t$, $\tilde t_1 \to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde g$ 1.65 TeV	$m(\tilde t_1)$= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to bs$	0	2 jets + 2 b	-	36.7	$\tilde t_1$ 100-470 GeV; 480-610 GeV		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to b\ell$	2 e,μ	2 b	-	36.1	$\tilde t_1$ 0.4-1.45 TeV	BR($\tilde t_1 \to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde c \to c\tilde\chi^0_1$	0	2 c	Yes	20.3	$\tilde c$ 510 GeV	$m(\tilde\chi^0_1)$<200 GeV	1501.01325

10^{-1} — 1 — Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17



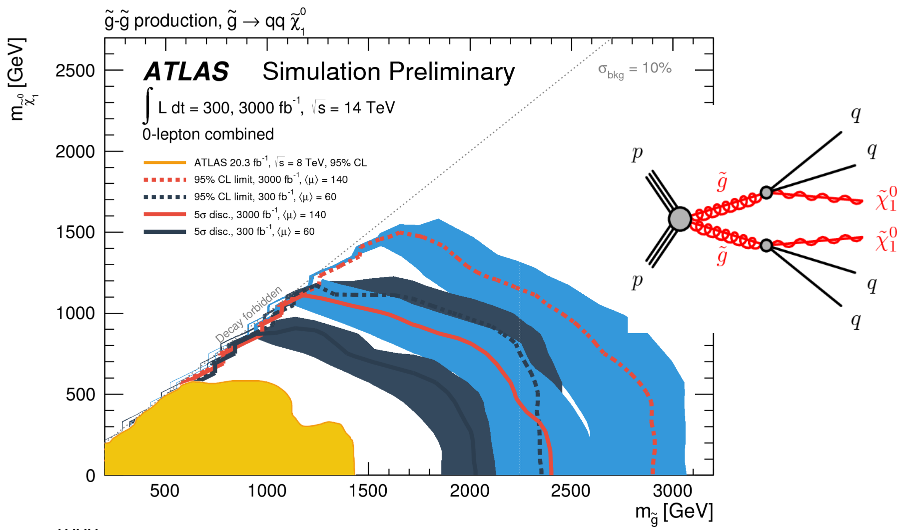
*Observed limits at 95% C.L. - theory uncertainties not included

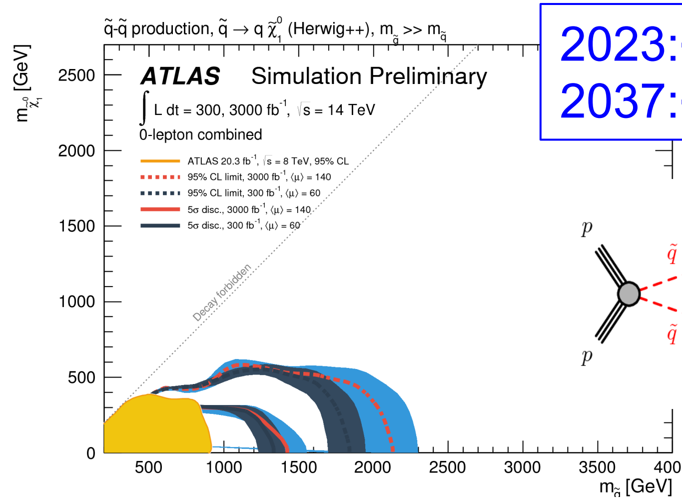
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

Prospects at HL-LHC

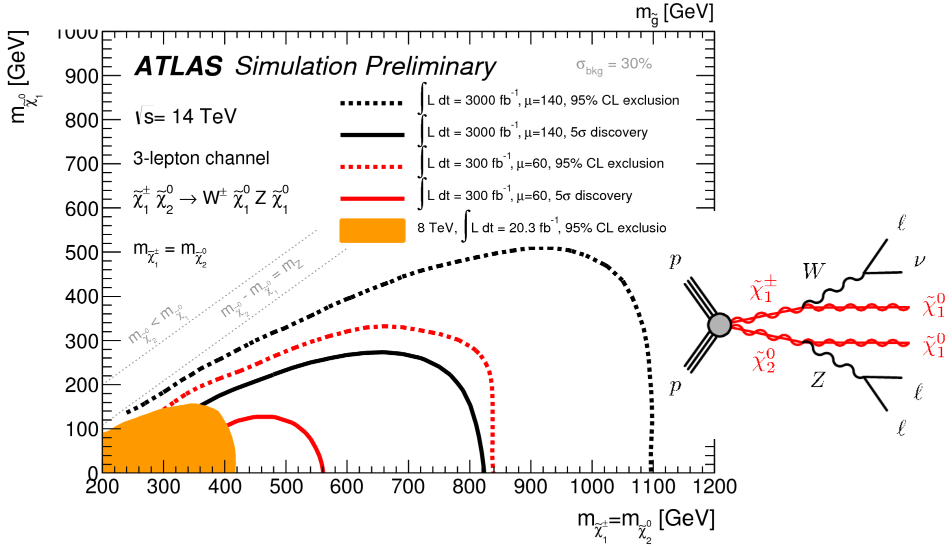
ATL-PHYS-PUB-2014-010

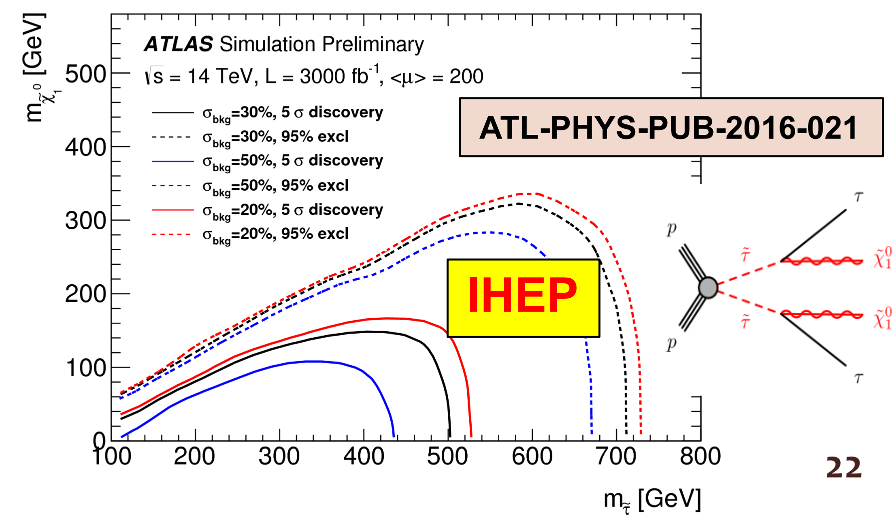
- ATLAS studied long term prospects for the (HL-)LHC with 300, 3000 fb^{-1}@14TeV
- **Discovery potential up to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom and 800 GeV Electroweakinos, 500 GeV stau with 3000 fb^{-1}.**





2023:~300 fb^{-1}
2037:~3000 fb^{-1}



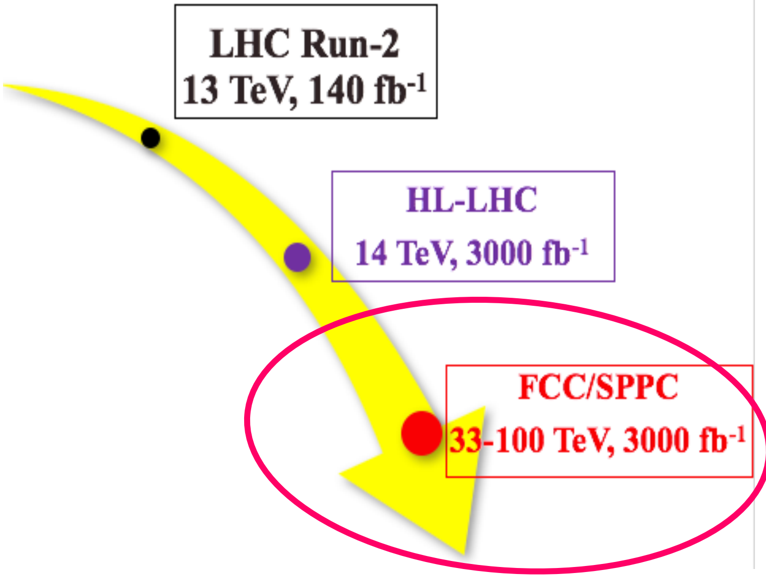


ATL-PHYS-PUB-2016-021

IHEP

Prospects at Future Collider

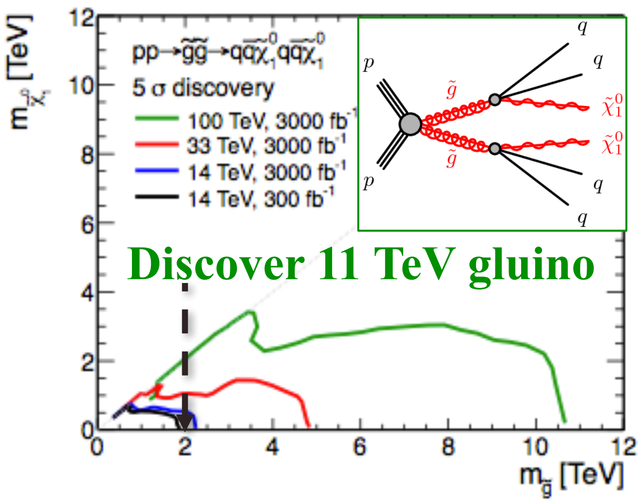
- **Long term prospects for 2 more collider scenarios have been studied (33, 100 TeV @3000 fb^{-1})**
- **Use same search strategy as 8-13TeV @LHC**
- **Use simple analysis strategies, assume 20% syst. uncertainty, avoid assumption on detector design, pileup sensitivity, etc**

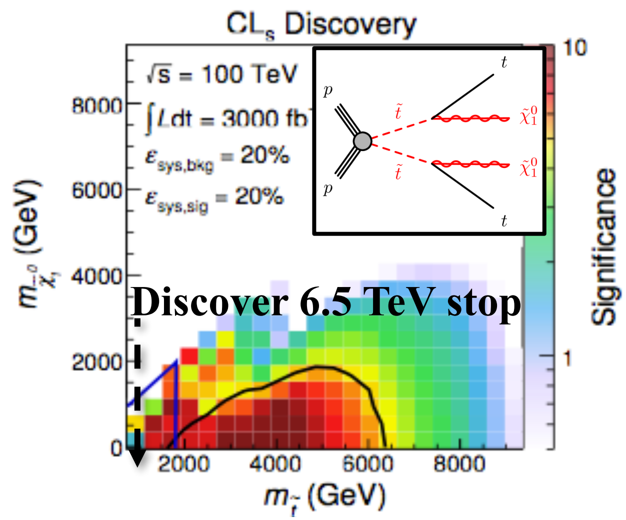


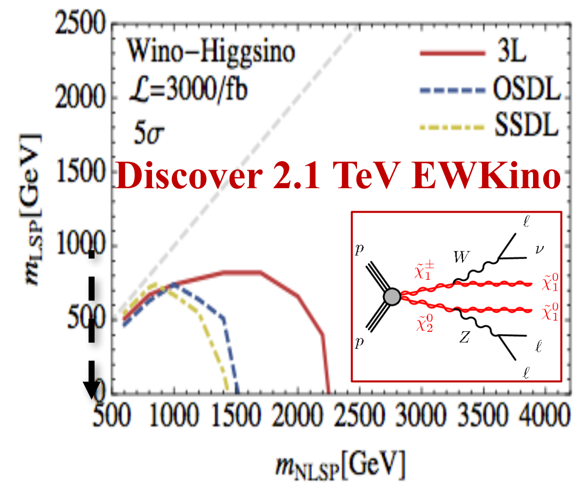
arXiv:1311.6480, 1406.4512, 1410.6287

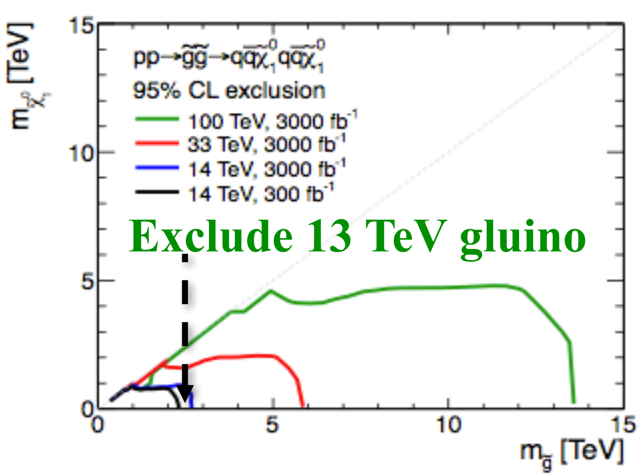
Prospects at Future Collider

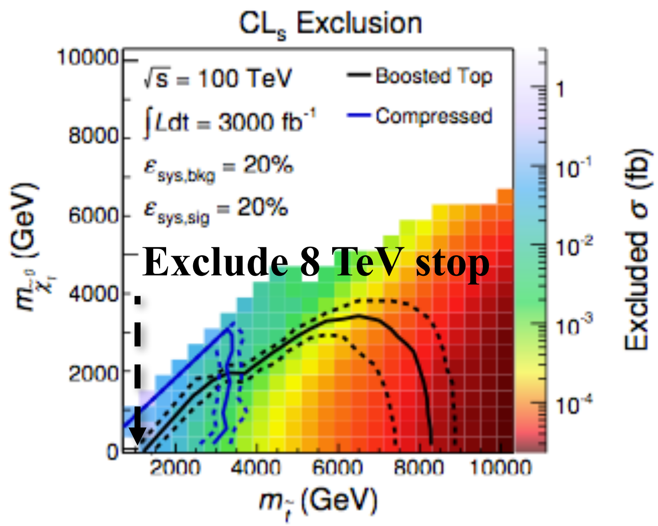
- Discovery potential (exclusion) up to **11 (13) TeV gluinos, 6.5 (8) TeV squarks/sbottom and 2.1 (3.2) TeV Electroweakinos.**

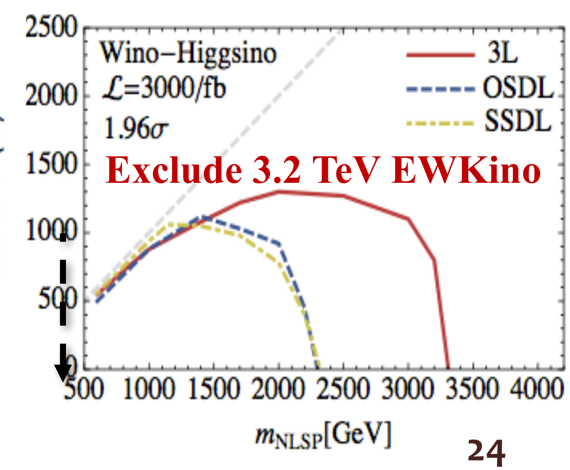




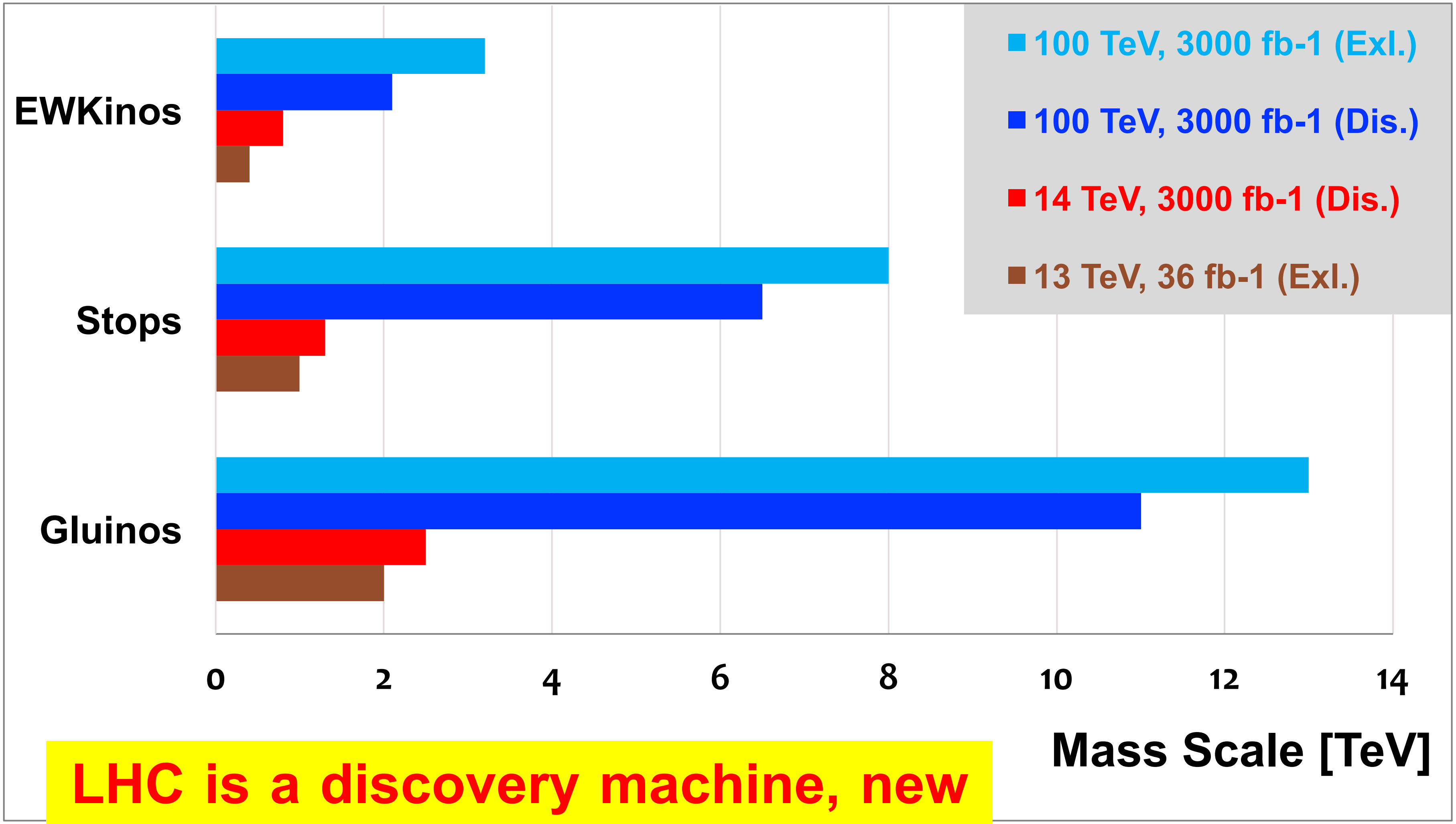








Summary and Outlook

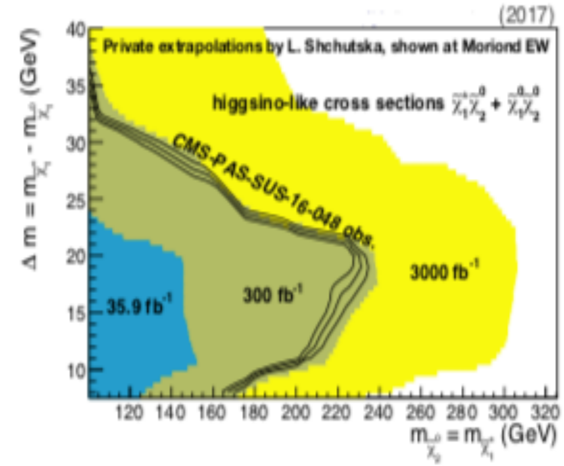


LHC is a discovery machine, new physics may come at any time , stay tuned!

THANKS FOR YOUR ATTENTION!

☺

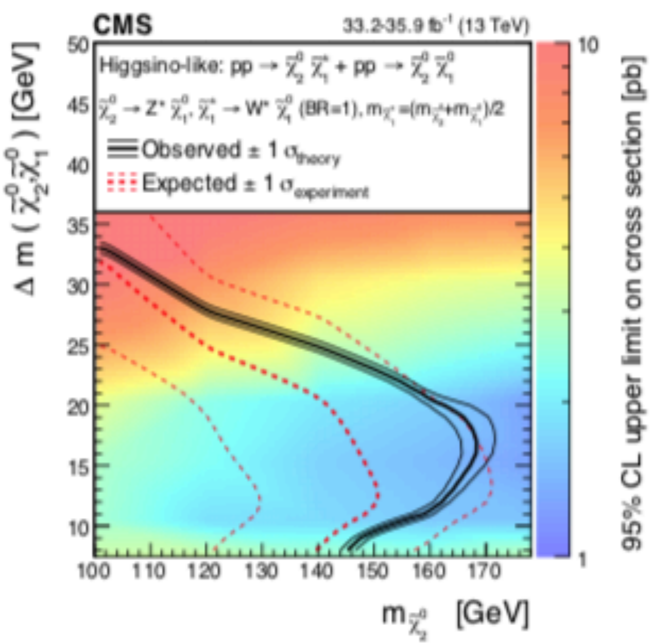
Compressed scenarios with soft leptons

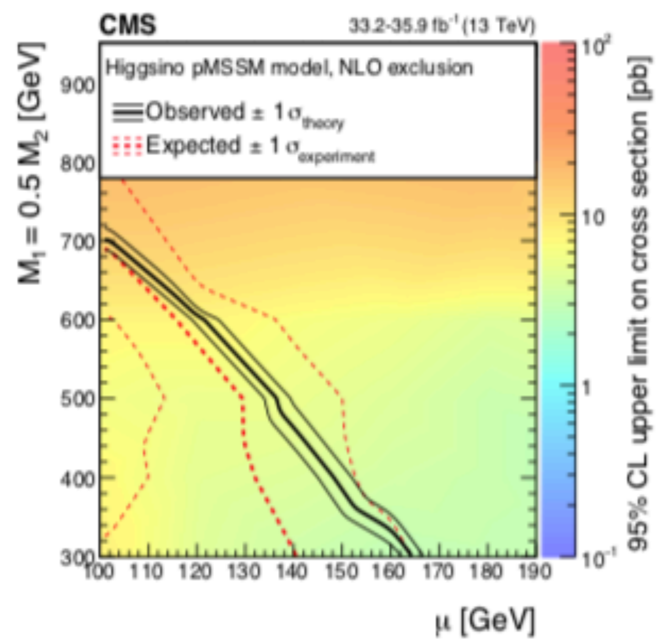


- when it comes to natural SUSY, particular interest lies upon higgsinos!
  - i.e. charginos and neutralinos with dominant higgsino component
- re-interpretation of the WZ-like model with dominant higgsino component (left)
  - improvement of the LEP limit (~ 100 GeV) for the first time!
- also interpretation in pMSSM framework as function of M_1=(1/2)M_2 and μ (right)

Higgsino LSP

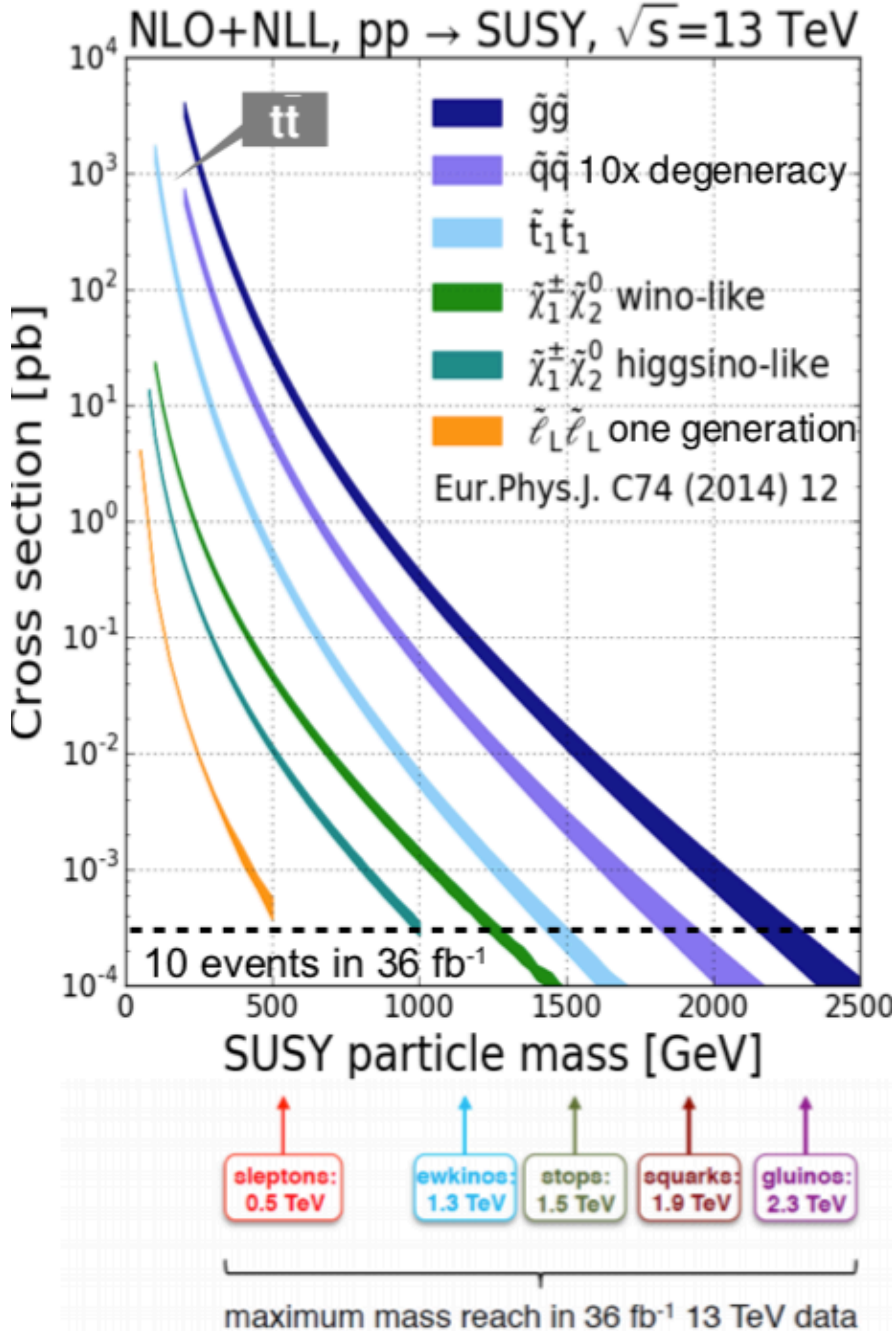
SUS-16-048

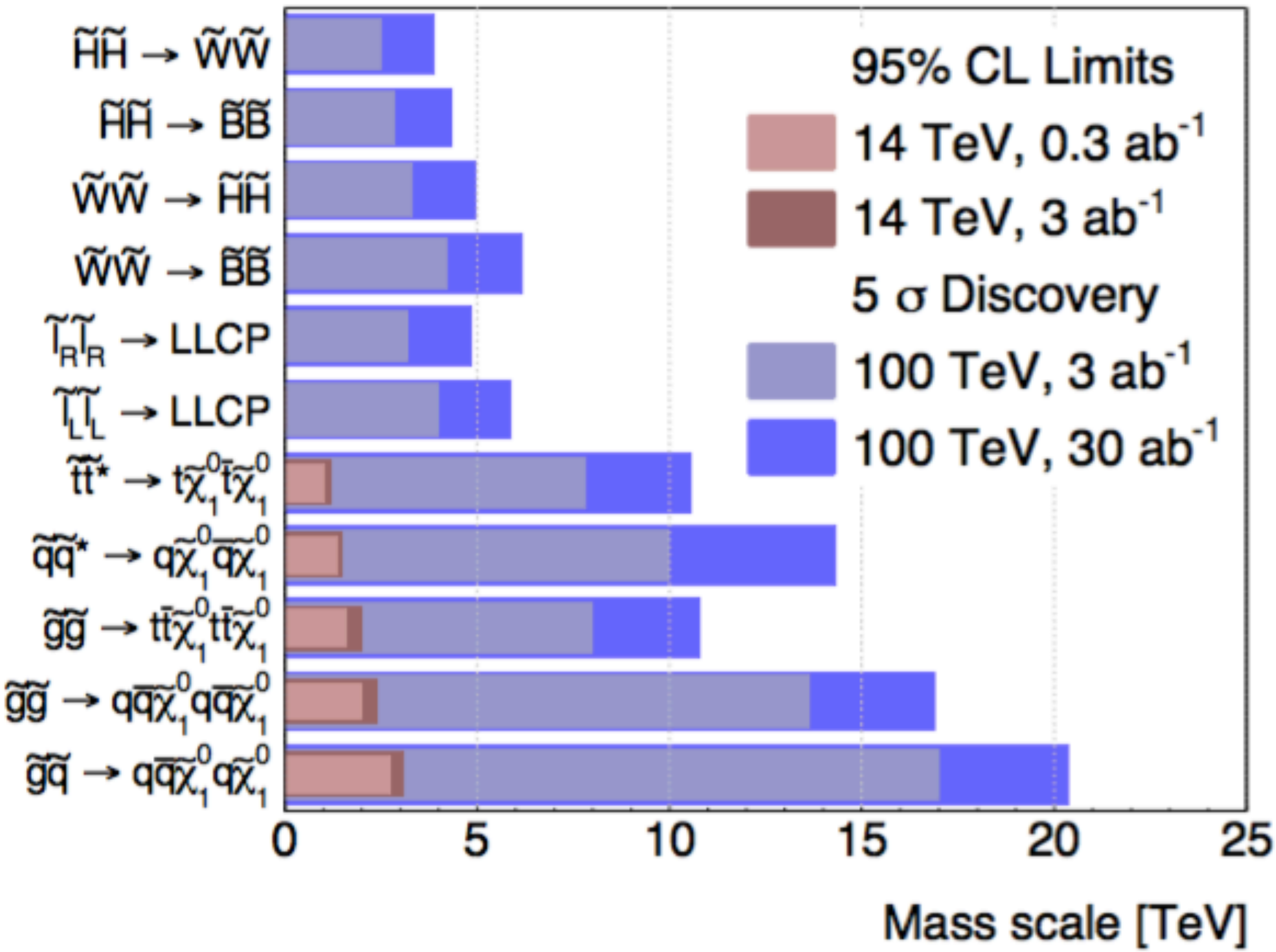




MASS PARAMETERS:
μ = higgsinos
M_1 = bino
M_2 = wino
M_3 = gluino (decoupled)

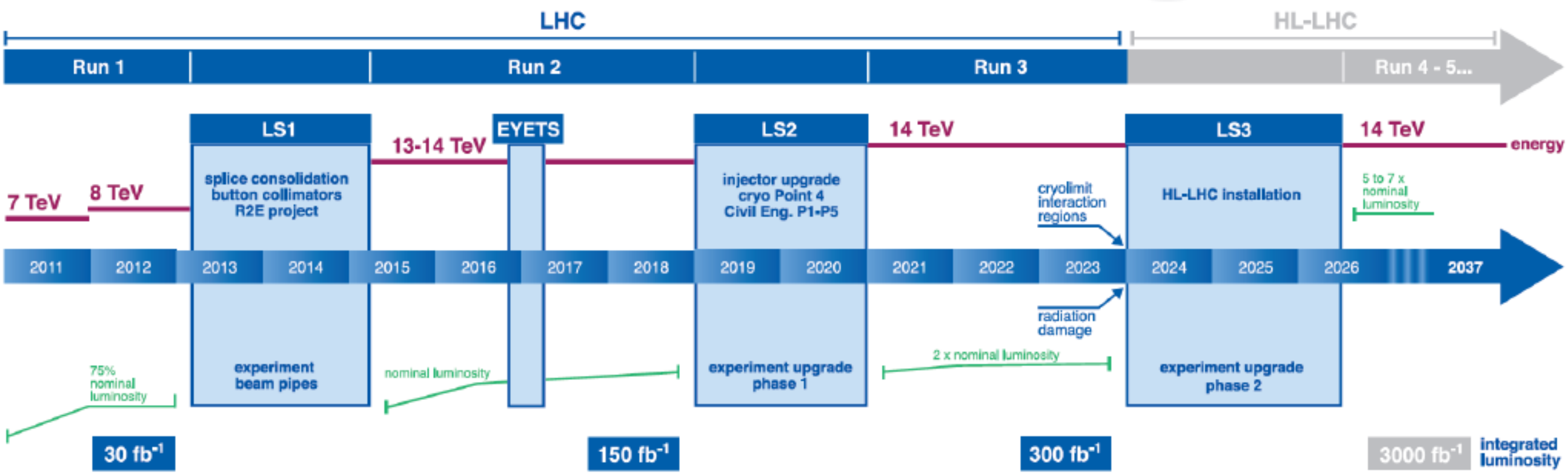
SUS-16-048

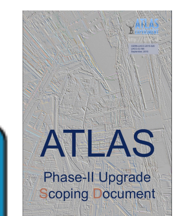

NLO+NLL, pp → SUSY, √s=13 TeV
tt̄
g̃g̃
q̃q̃ 10x degeneracy
t̃1t̃1
χ̃1±χ̃20 wino-like
χ̃1±χ̃20 higgsino-like
ℓ̃Lℓ̃L one generation
Eur.Phys.J. C74 (2014) 12
10 events in 36 fb-1
Cross section [pb]
SUSY particle mass [GeV]
sleptons: 0.5 TeV
ewkinos: 1.3 TeV
stops: 1.5 TeV
squarks: 1.9 TeV
gluinos: 2.3 TeV
maximum mass reach in 36 fb-1 13 TeV data



95% CL Limits
14 TeV, 0.3 ab^{-1}
14 TeV, 3 ab^{-1}
5 σ Discovery
100 TeV, 3 ab^{-1}
100 TeV, 30 ab^{-1}
$\tilde{H}\tilde{H} \to \tilde{W}\tilde{W}$
$\tilde{H}\tilde{H} \to \tilde{B}\tilde{B}$
$\tilde{W}\tilde{W} \to \tilde{H}\tilde{H}$
$\tilde{W}\tilde{W} \to \tilde{B}\tilde{B}$
$\tilde{l}_R\tilde{l}_R \to$ LLCP
$\tilde{l}_L\tilde{l}_L \to$ LLCP
$\tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$
$\tilde{q}\tilde{q}^* \to q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
$\tilde{g}\tilde{q} \to q\bar{q}\tilde{\chi}_1^0 q\tilde{\chi}_1^0$
0
5
10
15
20
25
Mass scale [TeV]

LHC / HL-LHC Plan





ATLAS Phase-0

New inner pixel layer
Detector consolidation
2015: FTK deployment

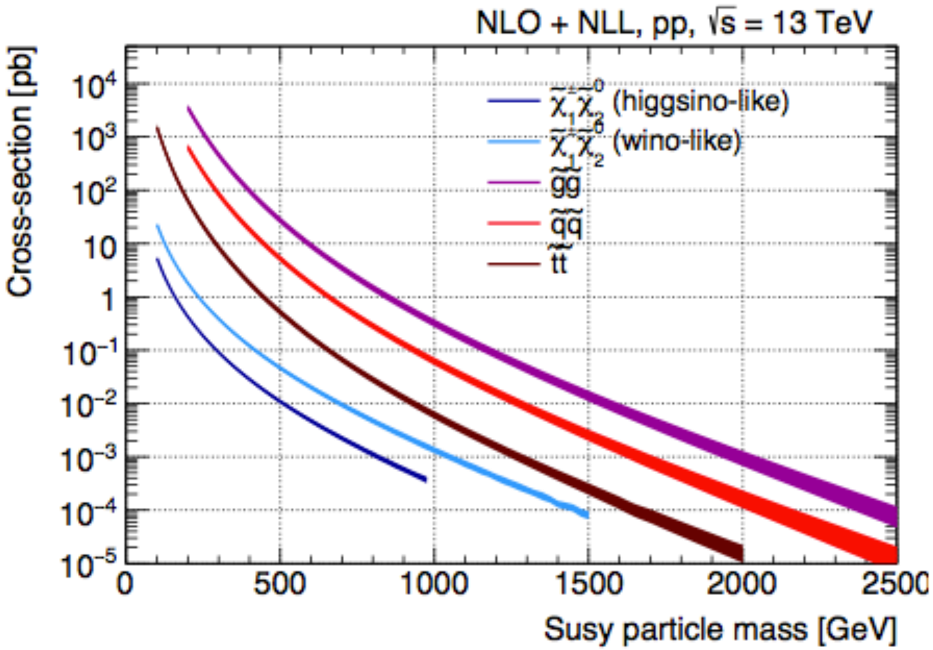
ATLAS Phase-1

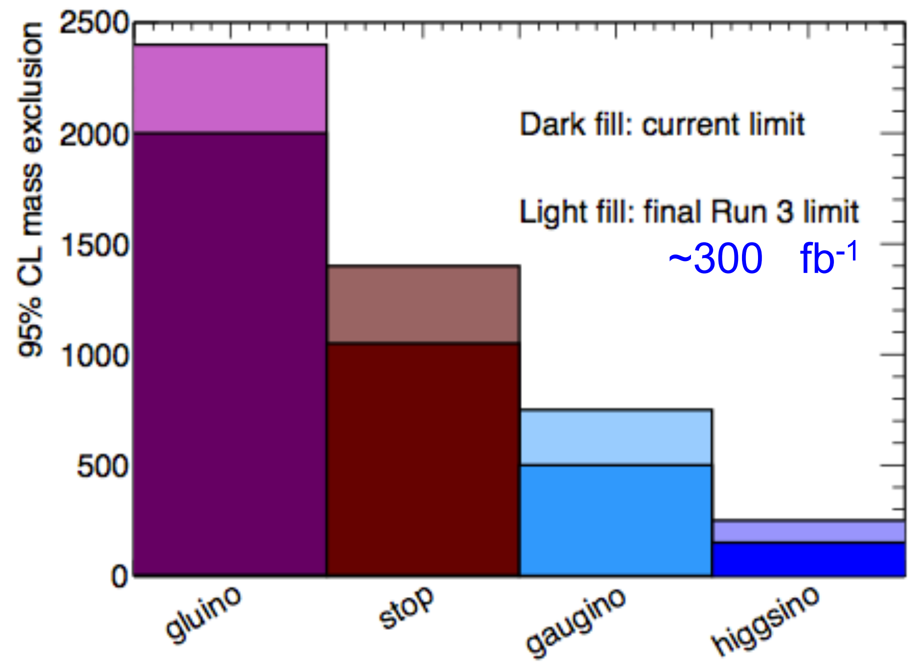
Improve L1 Trigger, NSW and LAr electronics to cope with higher rates

ATLAS Phase-2

Prepare for 140-200 pile-up events
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics
Upgrade of DAQ detector readout

2015+2016 – A milestone for SUSY





This means:

- We explored 85% of our mass reach for gluino pair production, about 75% for stop
- ~60% for gauginos, and just above 50% for higgsinos

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 …

SUSY Signature & Search Strategy

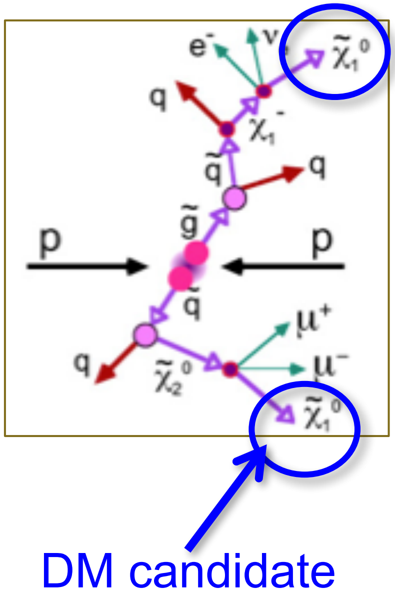
- **R parity:** originally introduced for stability of proton $R = (-1)^{3(B-L)+2S}$

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

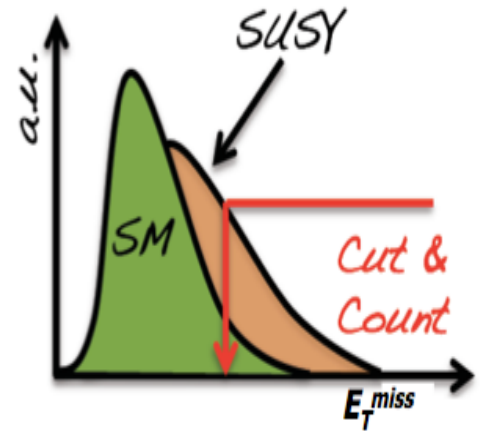
  - **Conserved R parity (RPC):**

    Provide Dark Matter (DM) candidate

    Typical signature: jets/leptons/photons + MET
  - **Violated R parity (RPV): no DM candidate**



- **SUSY search strategy: search for deviation from SM**
  - **SUSY sensitive variables: E_T^{miss}, Meff …**
  - **Accurate modeling of SM background**



SM Background Modeling

Combined fit of all regions and bgs, and including systematic exp. and theory uncertainty 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*:
  - Mulit-jet: data-driven
  - Non-Multi-jet: normalise MC in data control regions
- *Subdominant sources*: MC

Validation

Validation regions used to cross check SM predictions with data

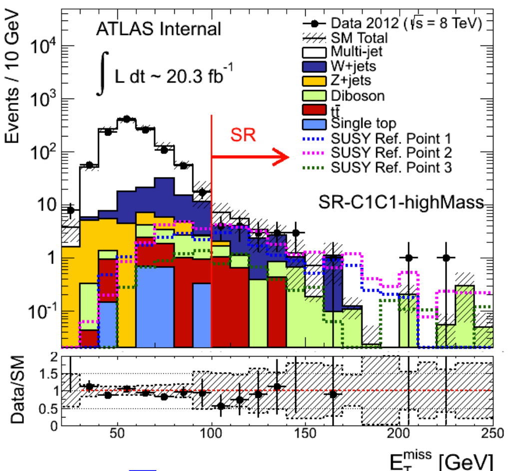
blinded

Signal regions

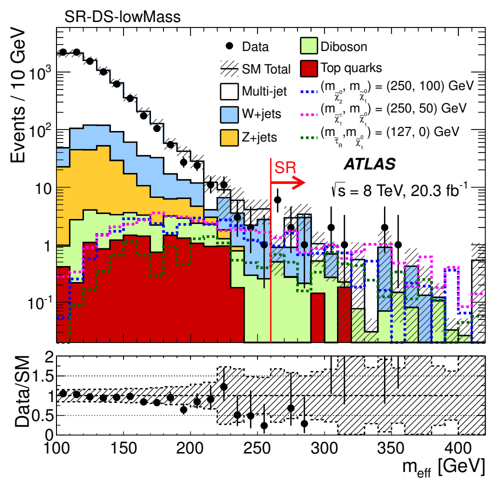
blinded

SUSY Sensitive Variables

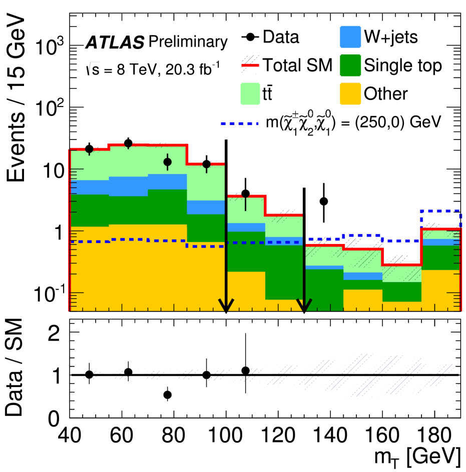
E_T^{miss}



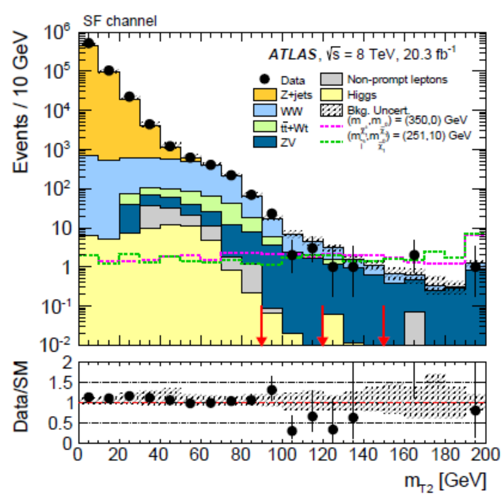
M_{eff}



mT



mT2



- E_T^{miss} from escaping LSP, to suppress bg from mis-measured jets and oth. SM BG
- Related to the sparticle mass scale, like effective mass (**M_{eff}**)

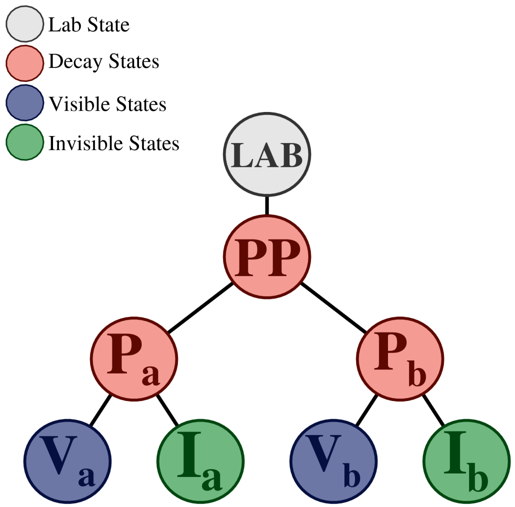
$$M_{\mathrm{eff}} \equiv \sum_{i=1}^{N_{\mathrm{jets}}} p_{\mathrm{T}}^{\mathrm{jet},i} + \sum_{j=1}^{N_{\mathrm{lep}}} p_{\mathrm{T}}^{\mathrm{lep},j} + E_{\mathrm{T}}^{\mathrm{miss}}$$

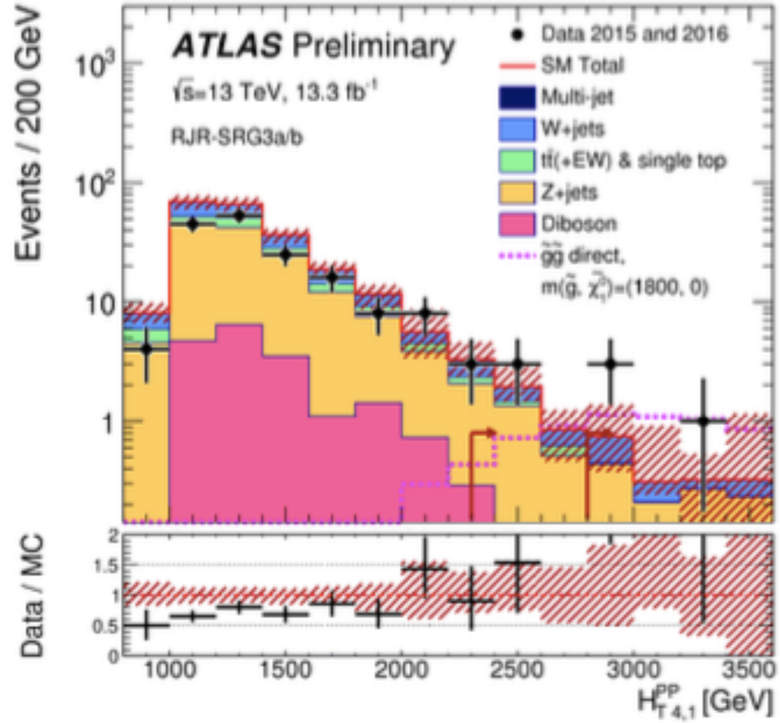
- **mT, mT2** (stransverse mass): suppress BG with Ws

$$m_{\mathrm{T2}} = \min_{\mathbf{q}_{\mathrm{T}}}\left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell 1}, \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell 2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}})\right)\right]$$

- Many others …

RJigsaw





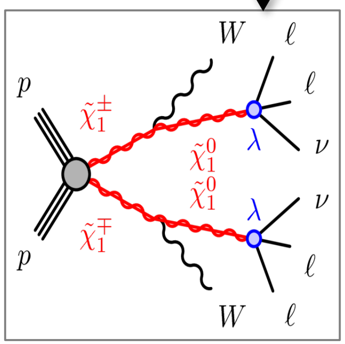
the complementary search using the **Recursive Jigsaw Reconstruction (RJR) techniques** in the construction of a discriminating variable set ('RJR-based search'). By using a dedicated set of selection criteria, the RJR-search improve the sensitivity to supersymmetric models with small mass splittings between the sparticles (models with compressed spectra).

Recursive jigsaw reconstruction
- based on assumption of decay tree
- fix set of rules to resolve combinatorics and unknowns in invisible system
- can form set of variables in the rest frame of each level in the decay tree

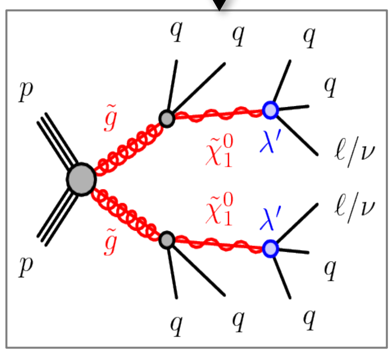
RPV SUSY

- Precision SM measurements support baryon and lepton number conservation, while some MSSM couplings do not
- Search for R-parity Violating SUSY
- Super-potential with RPV of lepton or baryon number

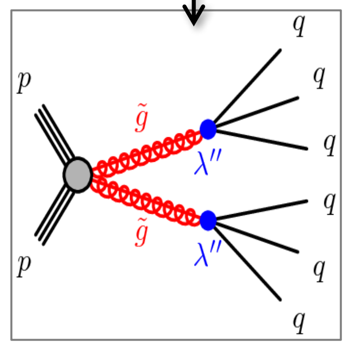
$$W_{\not R_p} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$



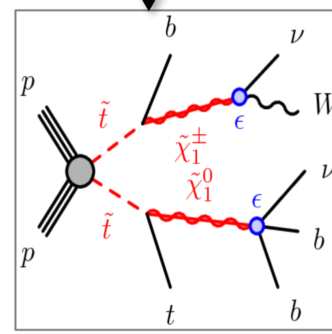
LLE



LQD



UDD



Bilinear LH

- RPV SUSY signatures:
  - Decaying LSP → lower Missing Transverse Energy (MET)
  - Many jets (or leptons) in the final states

SUSY RPV: 1L + multi-jets

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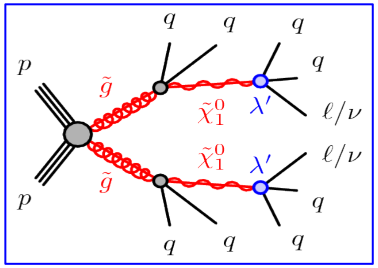
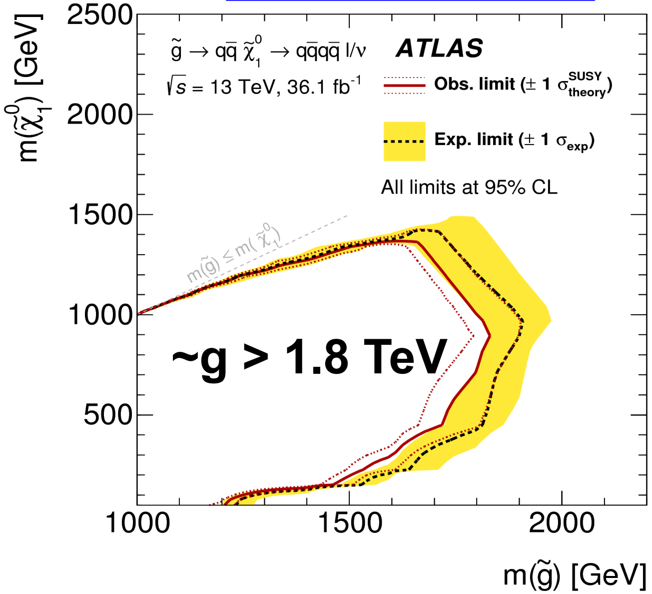
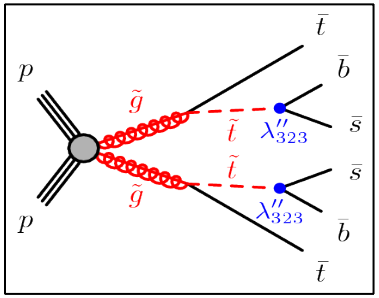
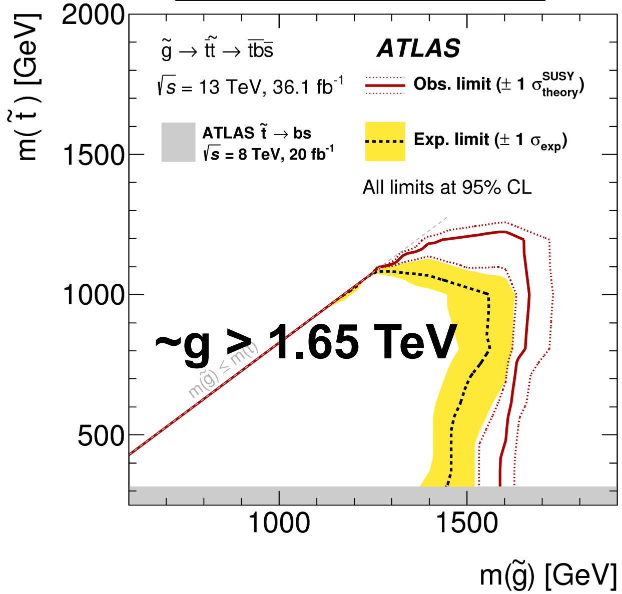
- **RPV SUSY signatures:**
  - Decaying LSP → lower Missing Transverse Energy (MET)
  - Many jets (or leptons) in the final states
  - Signatures showed: 1lepton + multi-jets (≥8-12) and (0, ≥3) bjets

LQD

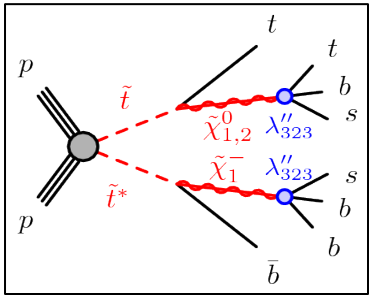


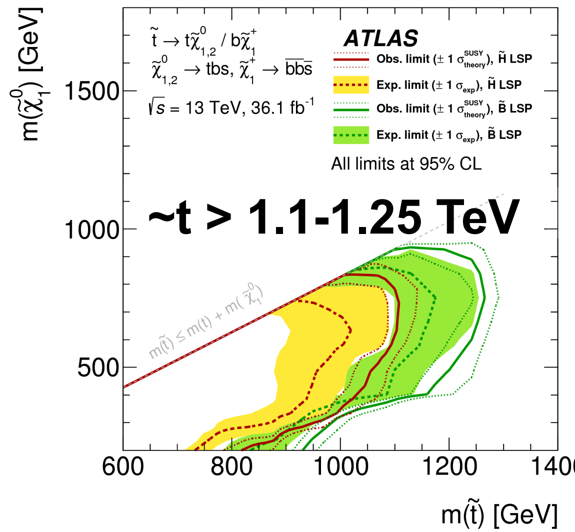






UDD

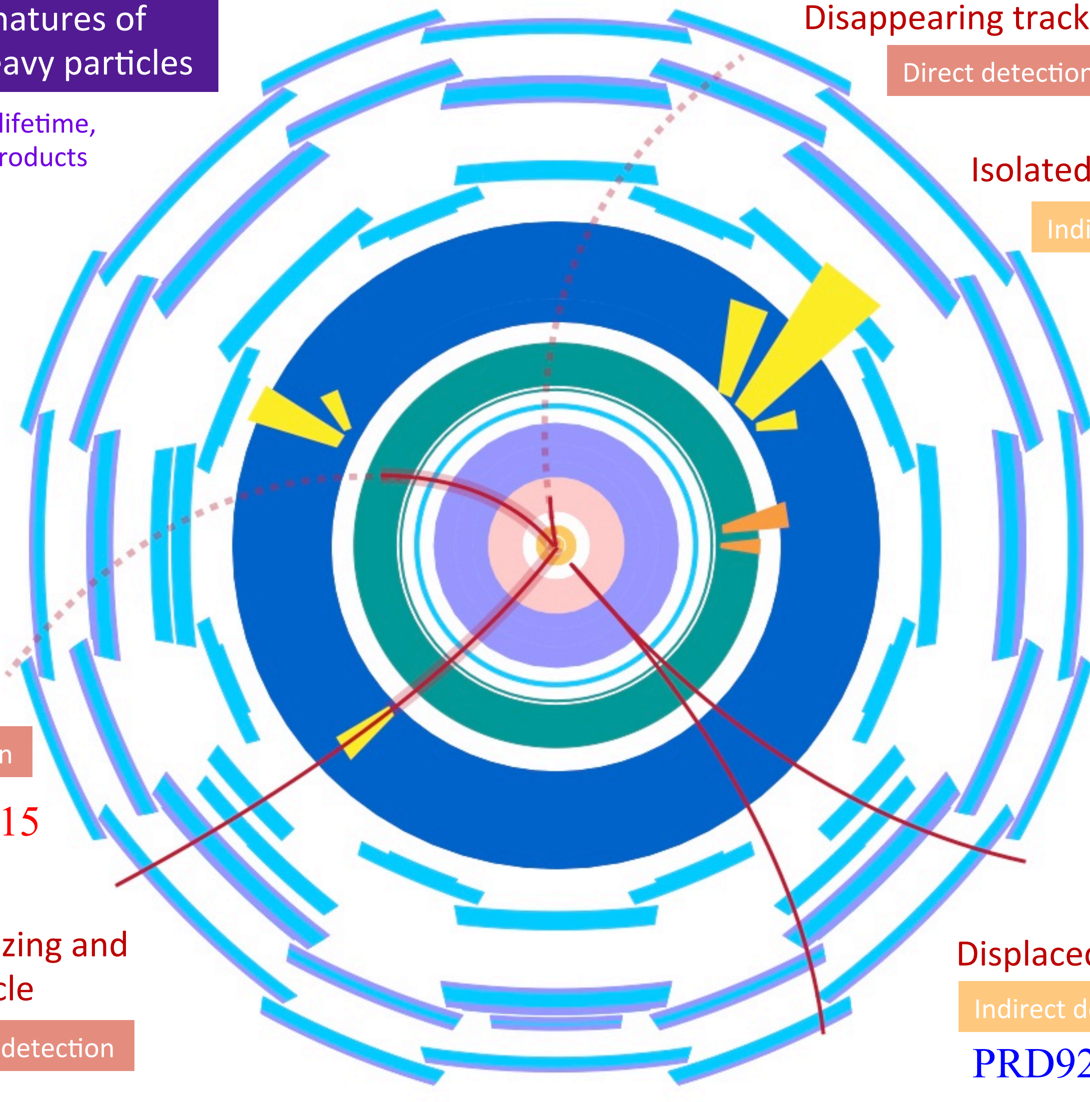




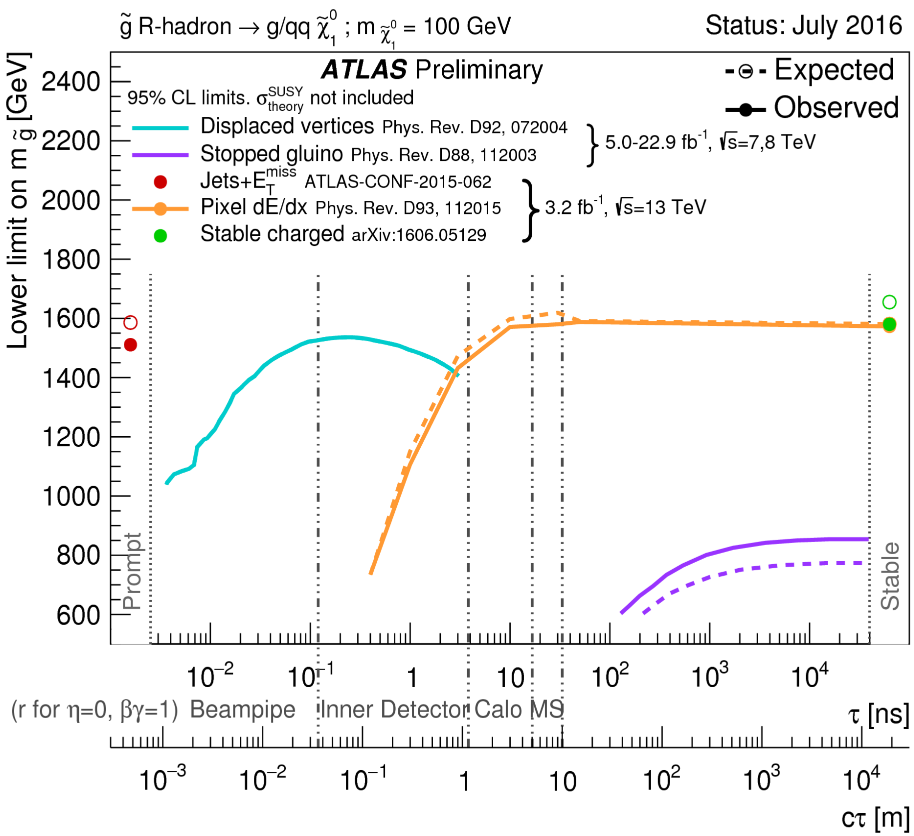
Long-Lived particles in SUSY

Detector signatures of long-lived heavy particles

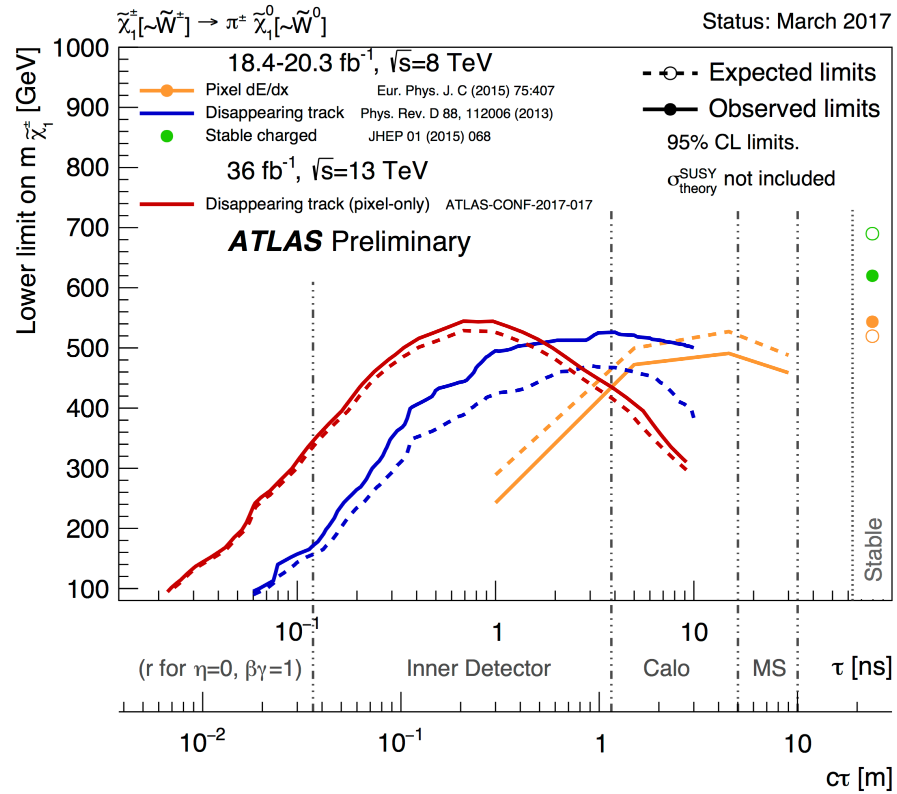
depends on LLP lifetime, mass, & decay products



Long-Lived particles in SUSY



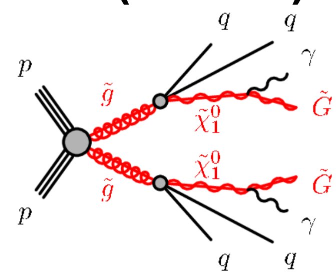
Long-lived R-hadron production



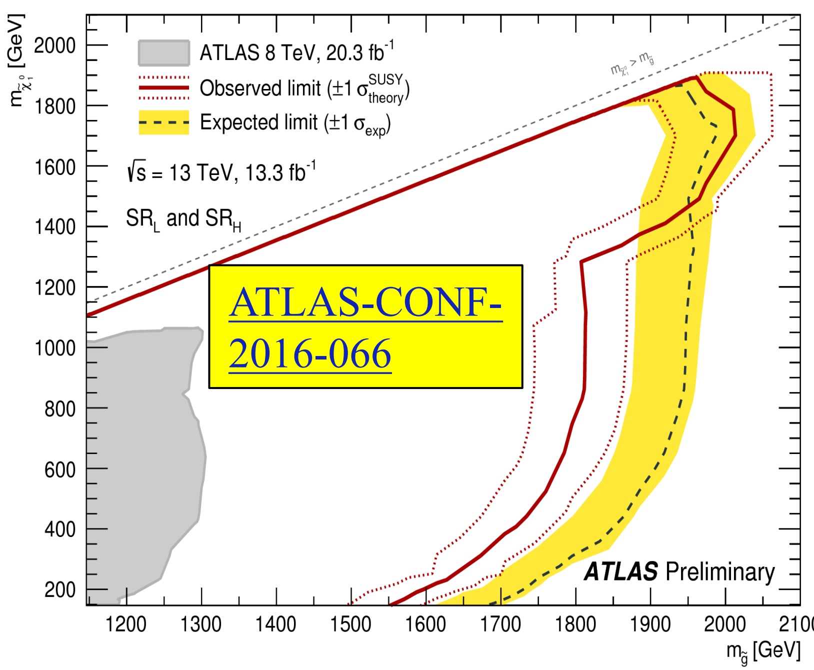
Long lived chargino

Strong Production: photonic signatures

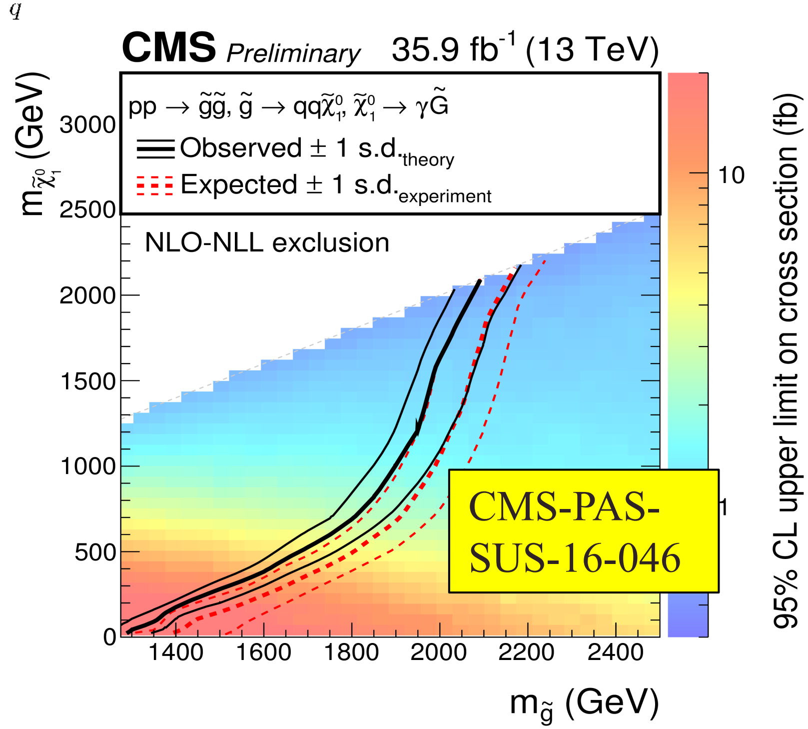
- We can use photon(s) to probe for strong production signals
  - → suppressed hadronic backgrounds
  - → N-photons + jets+ MET (N >= 1)



photons

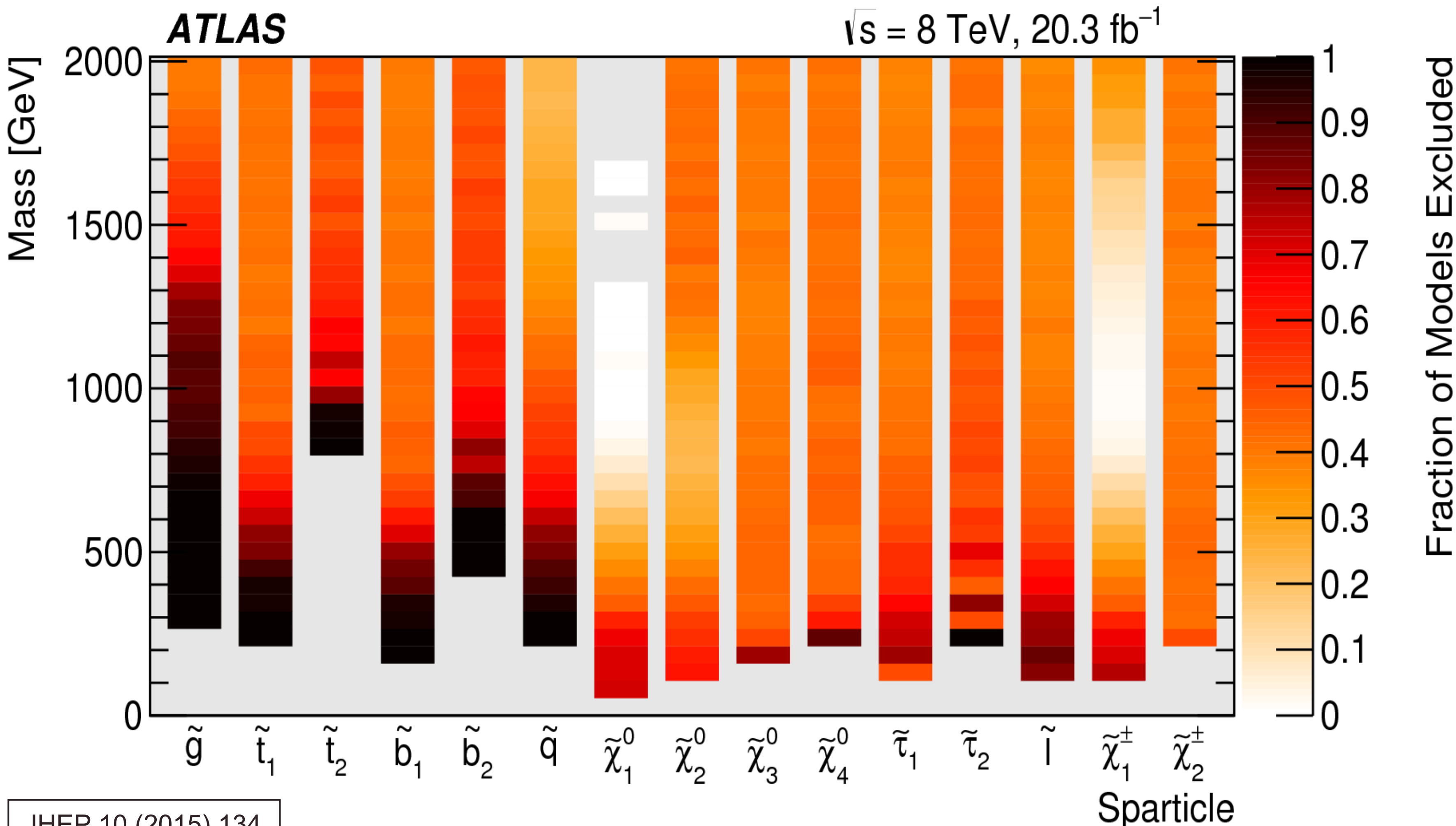


ATLAS-CONF-2016-066



CMS-PAS-SUS-16-046

An attempt to map out the SUSY model space with all the ATLAS analyses, giving an impression of where SUSY could still hide …



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Gluino-Neutralino Signature

Impact of Systematic Uncertainties

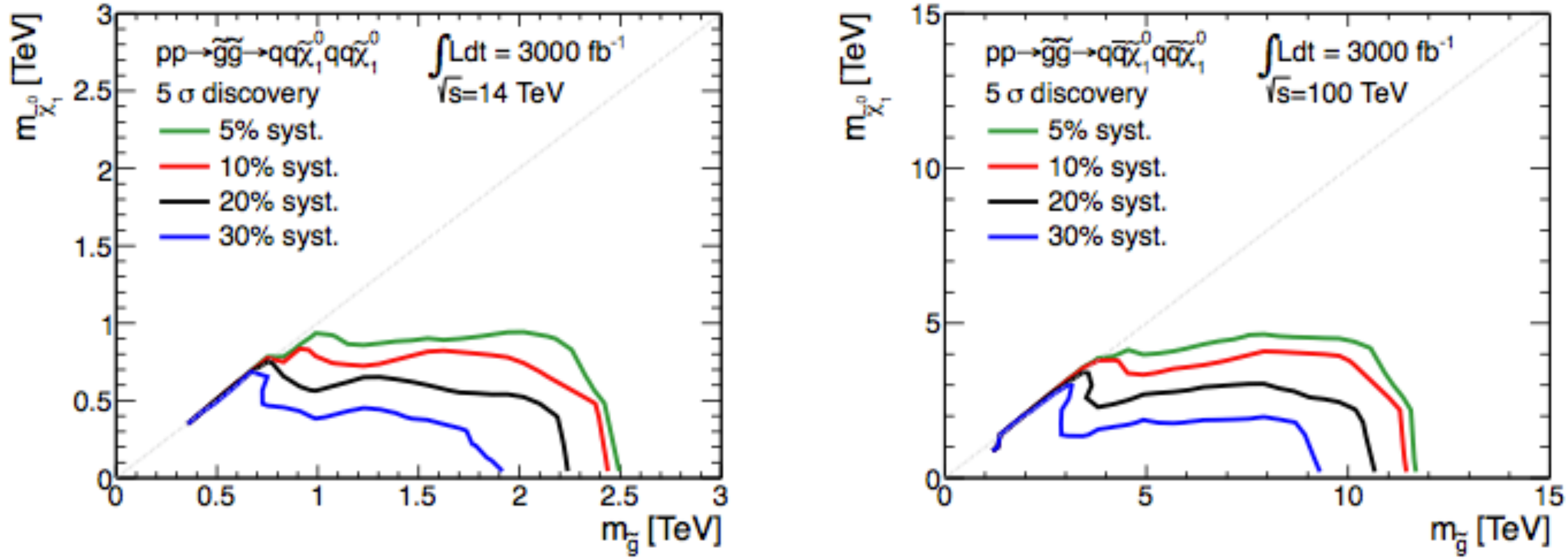


Figure 12: Expected 5σ discovery contours for the $\sqrt{s} = 14$ TeV LHC [left] and a 100 TeV proton collider [right] with 3000 fb^{-1}. The different curves correspond to various assumptions for the systematic uncertainty on the background: 5% [green], 10% [red], 20% [blue], and 30% [black].

- 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

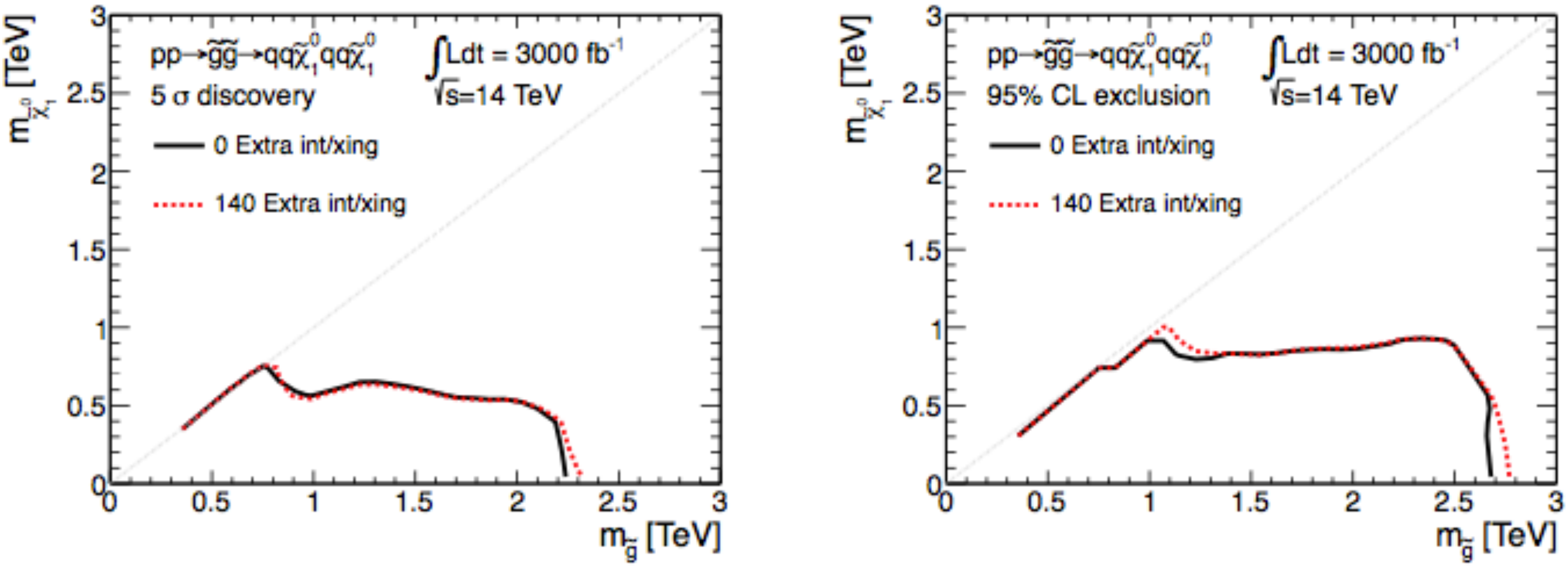
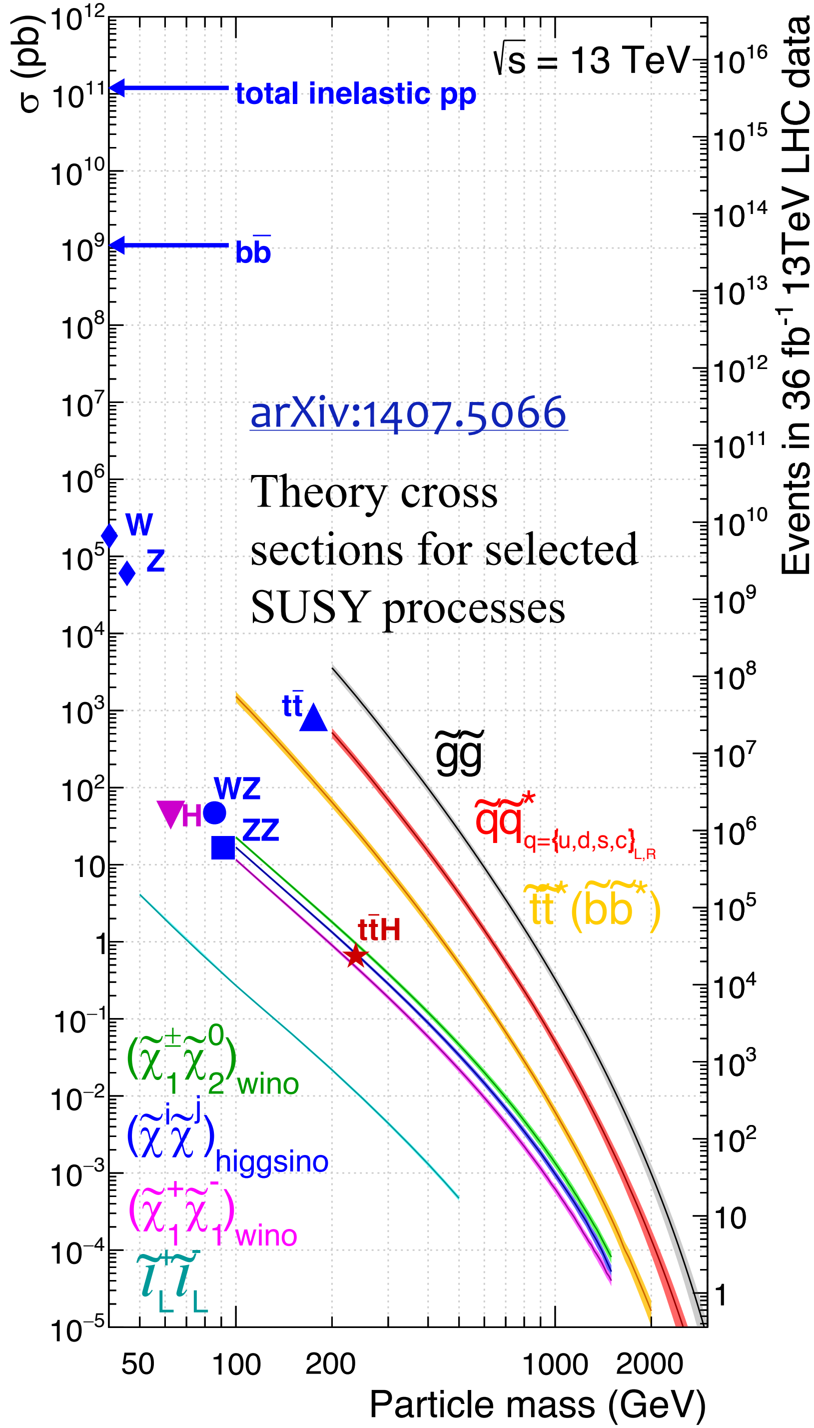
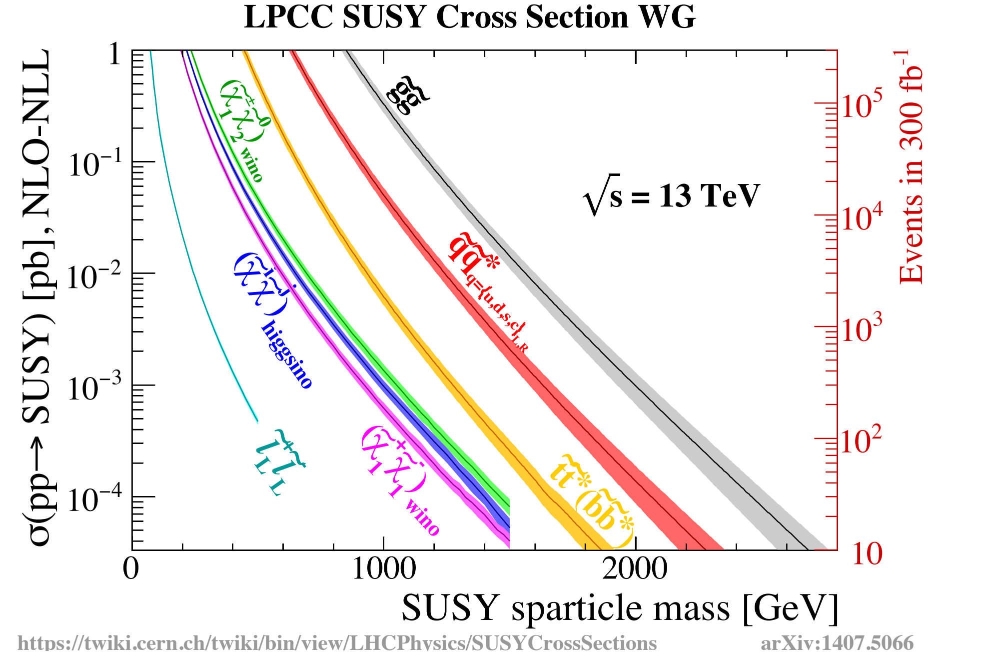
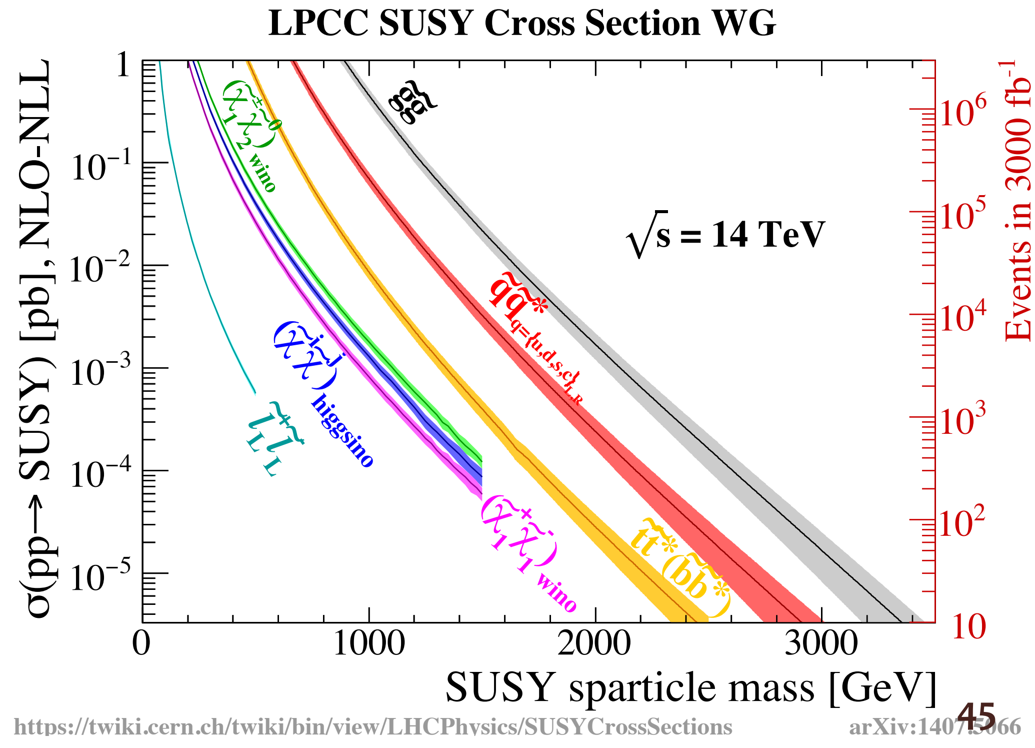


Figure 14: Discovery contours [right] and expected limits [left] for the analyses performed with [red, dotted] and without [black, solid] pileup at the 14 TeV LHC with 3000 fb^{-1} integrated luminosity.

- 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


σ (pb)
√s = 13 TeV
total inelastic pp
bb̄
Events in 36 fb⁻¹ 13TeV LHC data
arXiv:1407.5066
Theory cross sections for selected SUSY processes
W
Z
tt̄
WZ
H
ZZ
tt̄H
g̃g̃
q̃q̃* q={u,d,s,c} L,R
t̃t̃* (b̃b̃*)
(χ̃±1χ̃02)wino
(χ̃iχ̃j)higgsino
(χ̃+1χ̃-1)wino
l̃+L l̃-L
Particle mass (GeV)


LPCC SUSY Cross Section WG
σ(pp→ SUSY) [pb], NLO-NLL
√s = 13 TeV
Events in 300 fb⁻¹
SUSY sparticle mass [GeV]
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections
arXiv:1407.5066


LPCC SUSY Cross Section WG
σ(pp→ SUSY) [pb], NLO-NLL
√s = 14 TeV
Events in 3000 fb⁻¹
SUSY sparticle mass [GeV]
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections
arXiv:1407.5066