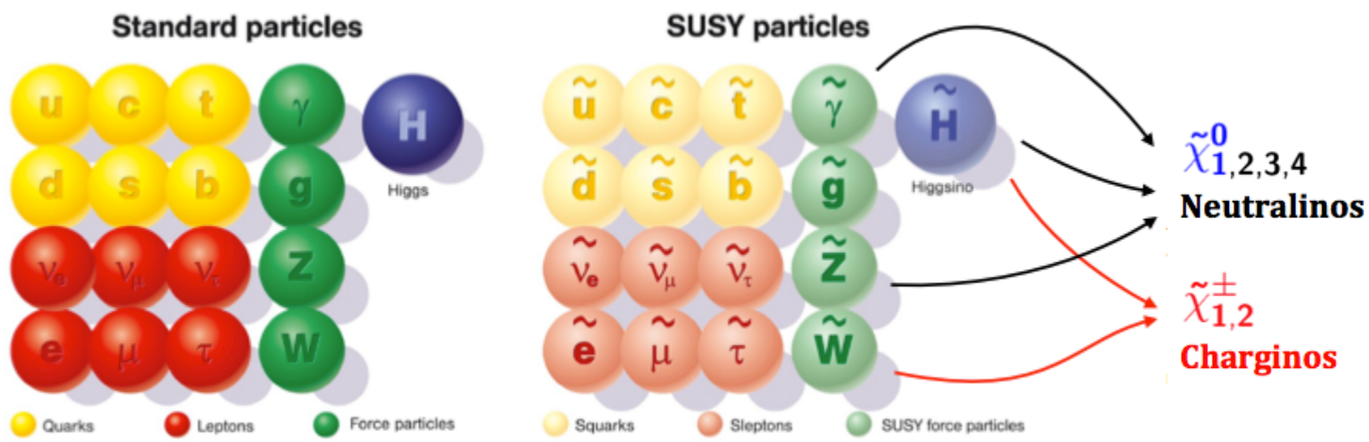
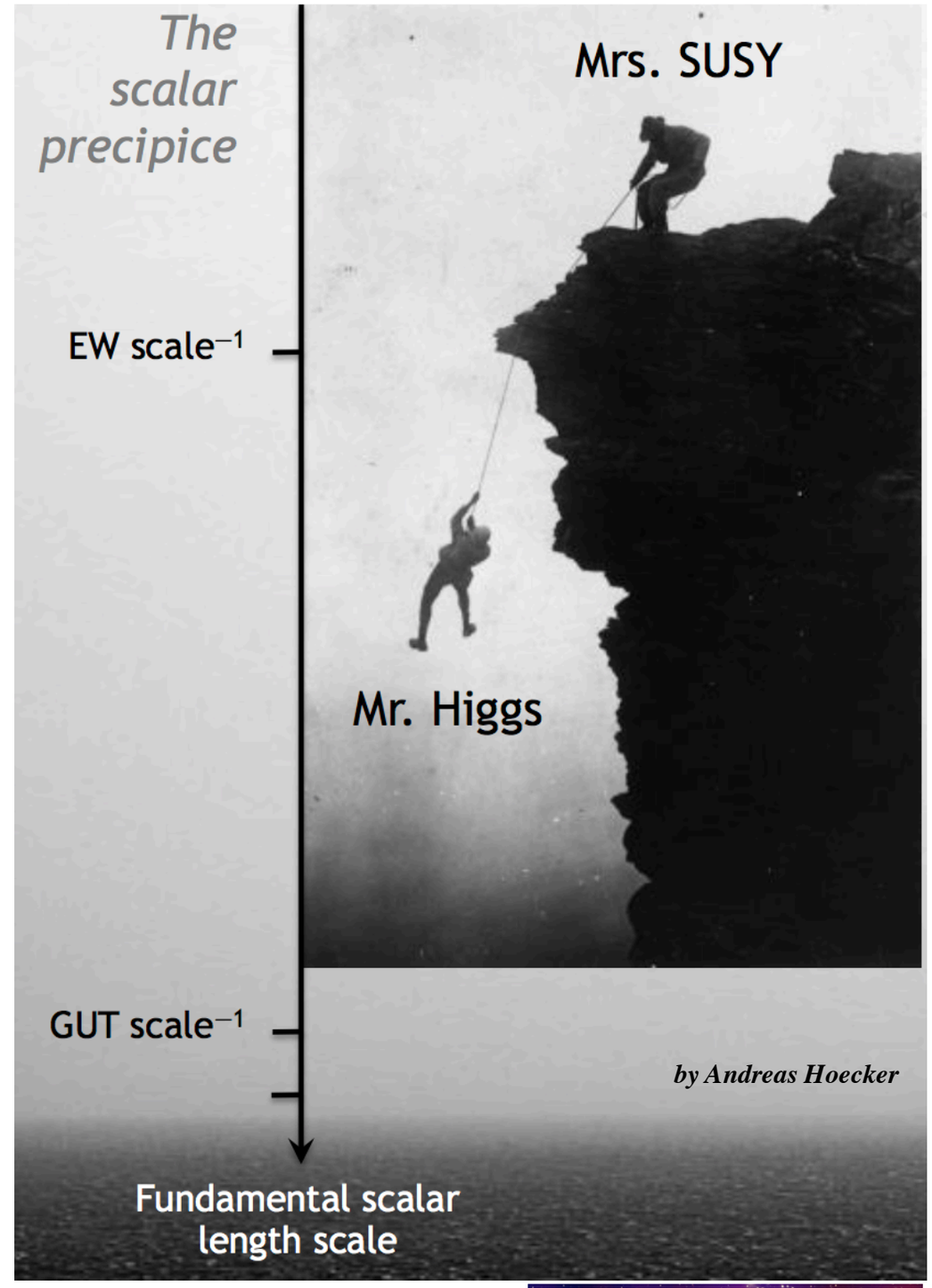
SUSY searches at LHC

Da XU (IHEP, CAS)
On behalf of the ATLAS, CMS and LHCb collaborations
CLHCP2017

Institute of High Energy Physics Chinese Academy of Sciences

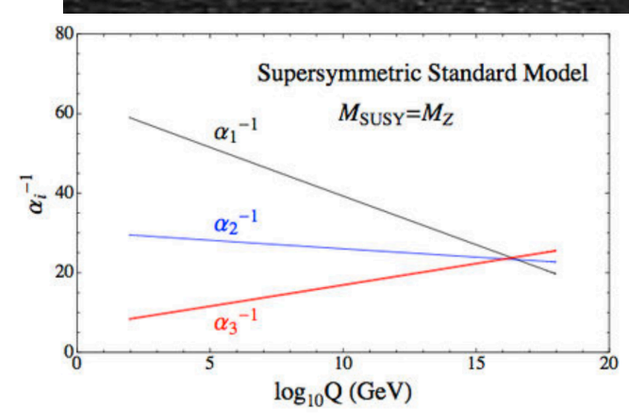
Supersymmetry



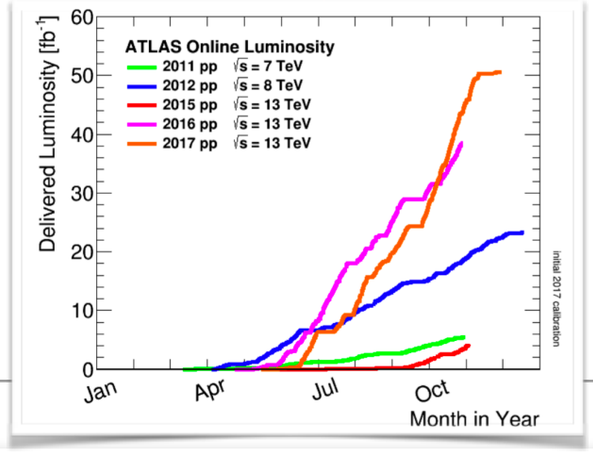


A theory to describe physics beyond standard model, with additional symmetry introduced: fermions ~ bosons

If weak-scale SUSY existed, it could…
Moderate the hierarchy problem
Realize grand unification of gauge couplings
Provide a suitable dark matter candidate



SUSY searches @ LHC

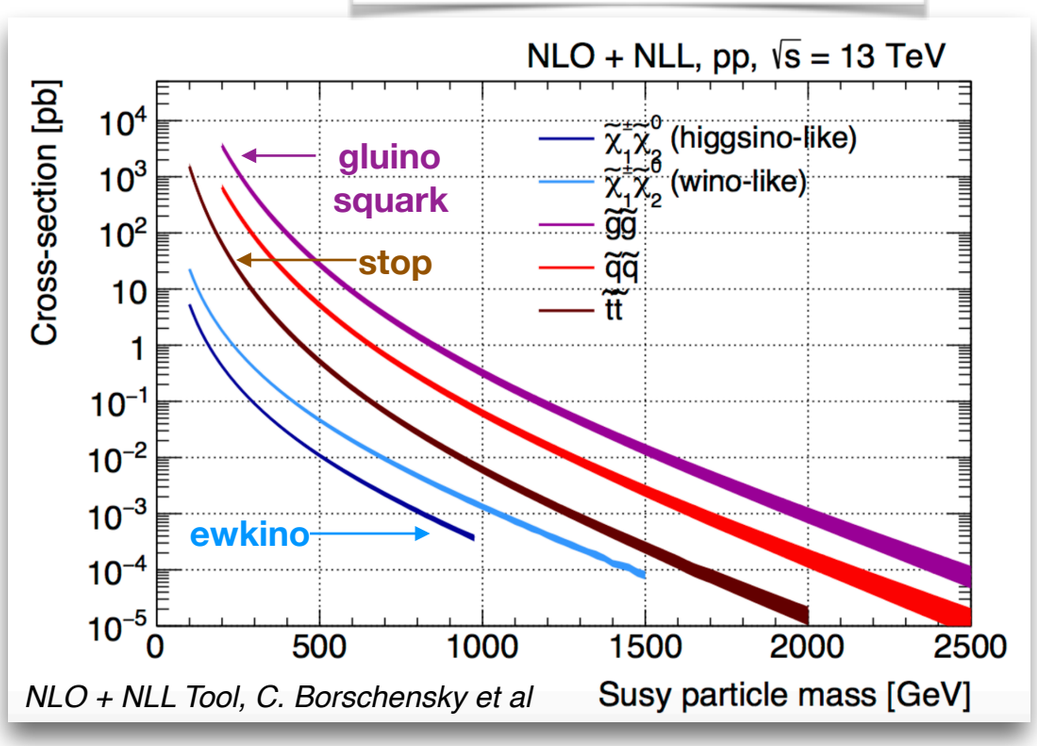


R-parity conserving (RPC)

- Pair produced sparticles
- Decays to lightest SUSY particle (LSP), mostly lightest neutralino or gravitino
- Invisible LSP forms large missing transverse momentum (Etmiss)

R-parity violating (RPV)

- LSP can decay
- Don't feature large Etmiss
- No dark matter candidate



SUSY search strategy is driven by cross-section and luminosity:

- Early analyses are dominated by inclusive searches for gluinos/squarks.
- Increasing luminosity gives access to rare production channels.

SUSY searches @ LHC

SUSY searches rely on the understanding of the SM backgrounds.

Standard Model

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

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

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 searches @ LHC

Exploring kinematic/topological information to separate SM from SUSY signal.

Reconstructed object multiplicities, momenta, energies, e.g. Njet/b-tag/l, pT, Etmiss

Scale variables, e.g. meff=pTlep+pTjet+Etmiss

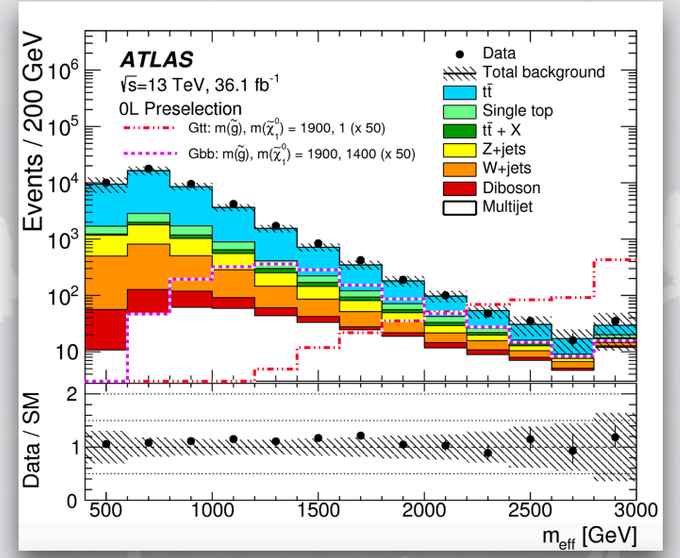
Angular variables, e.g. dPhi

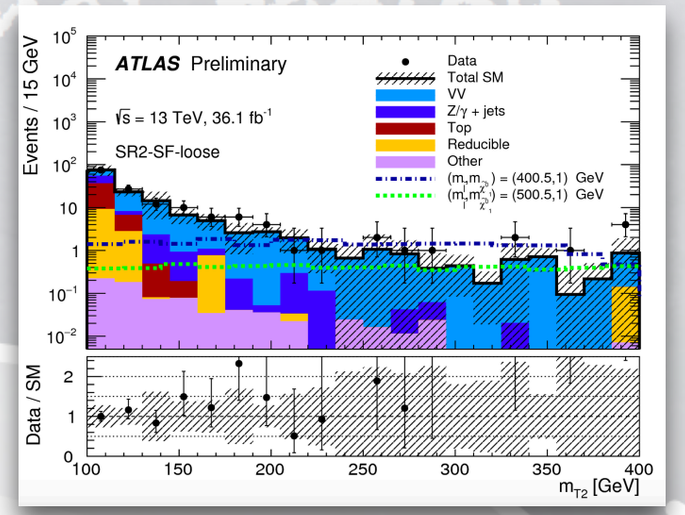
Mass variables, e.g. Mll

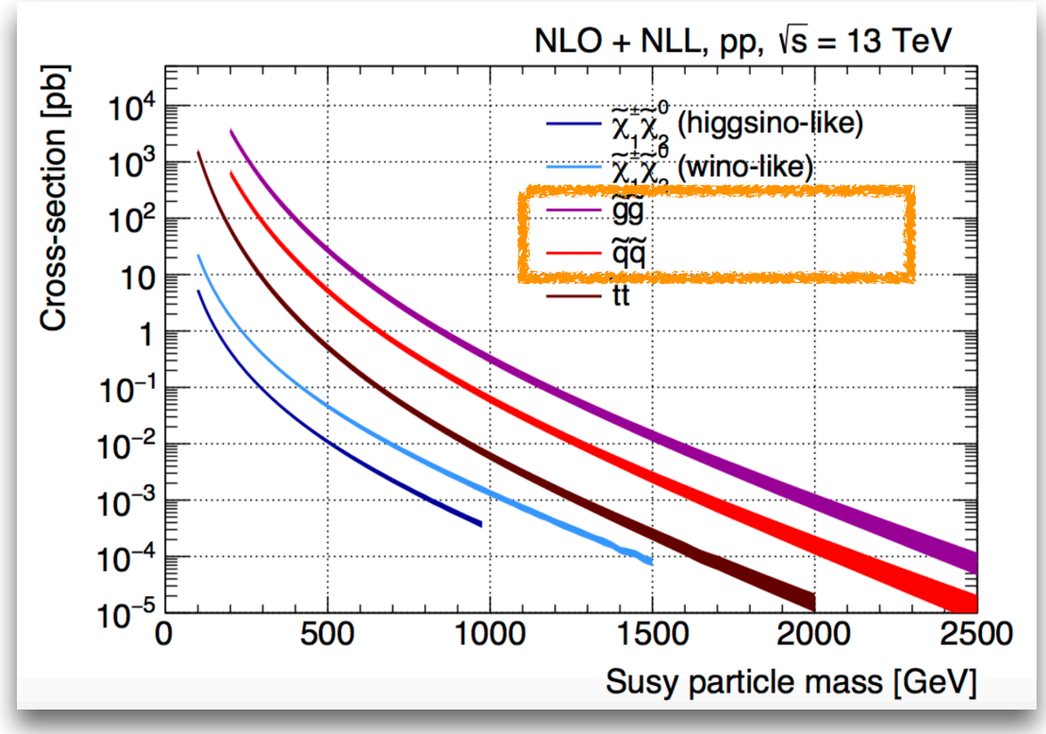
Event shape variables, e.g. aplanarity

Hypothesis-based event variables, e.g. mT2

More complex methods, e.g. recursive jigsaw

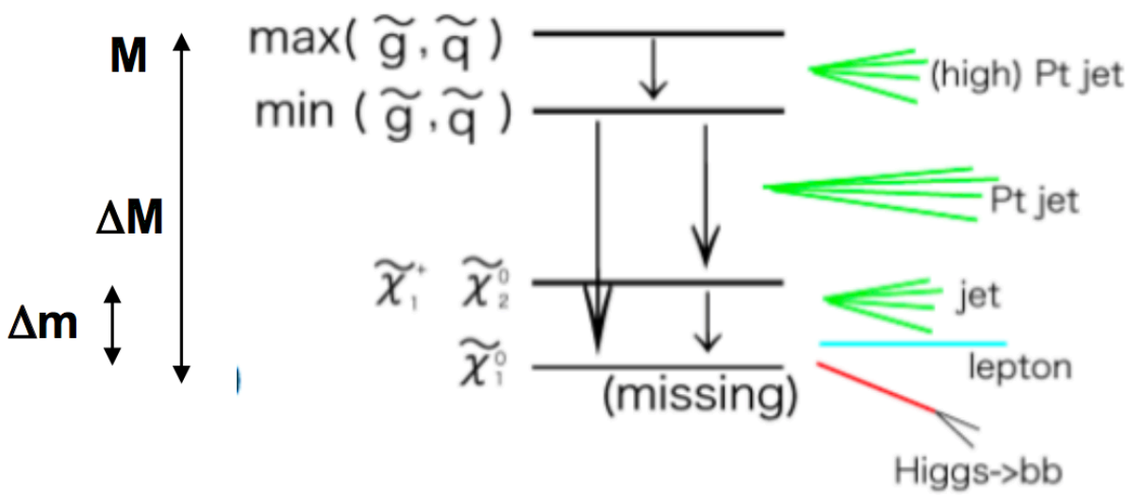




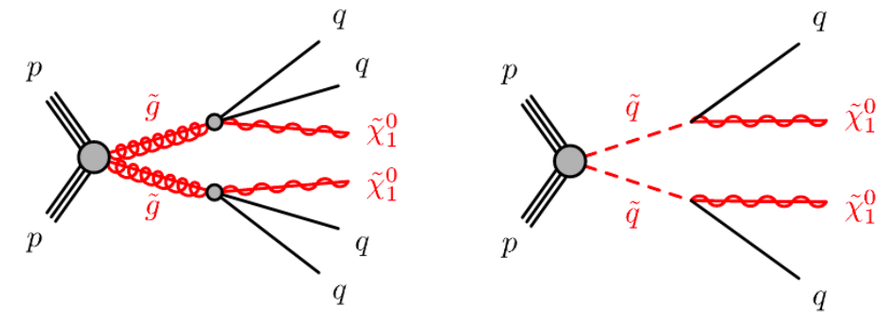


Strong production

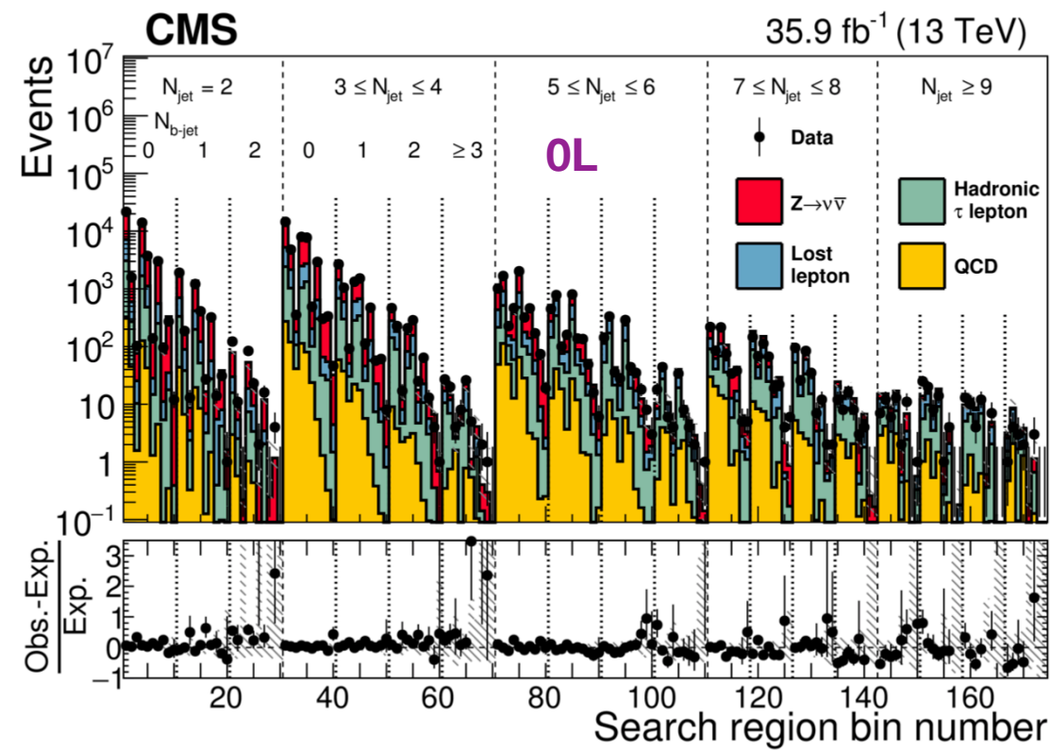
- Abundant production of gluinos and squarks
- Large cross-section
- Generic feature:
  - jets from gluino/squark decay;
  - large Etmiss

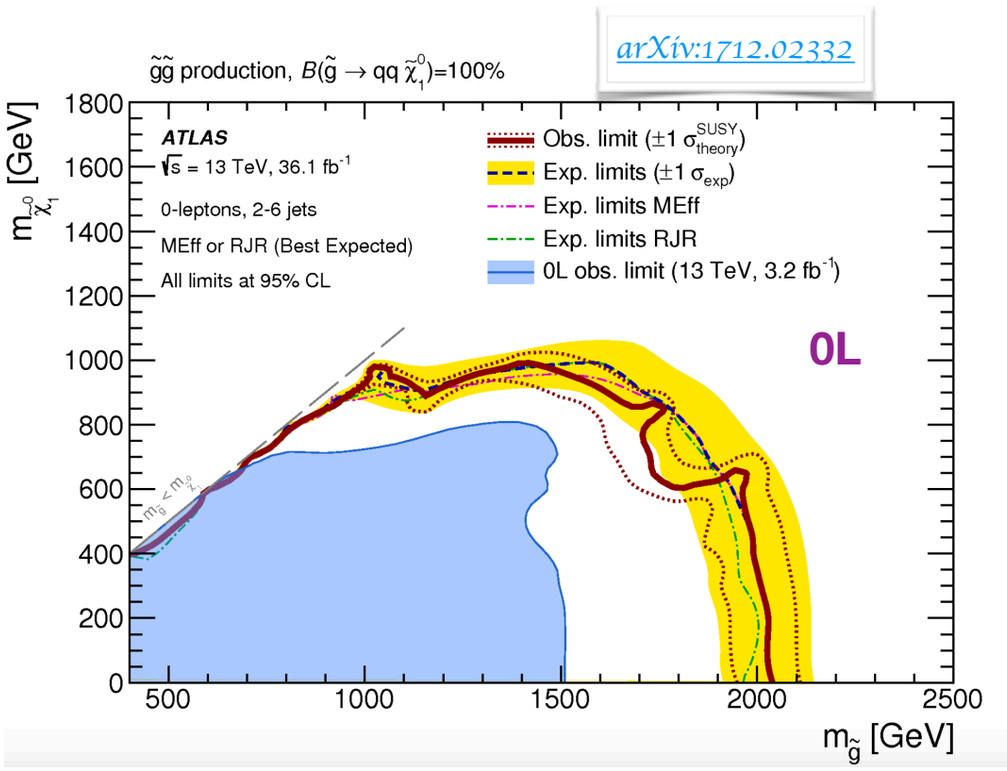


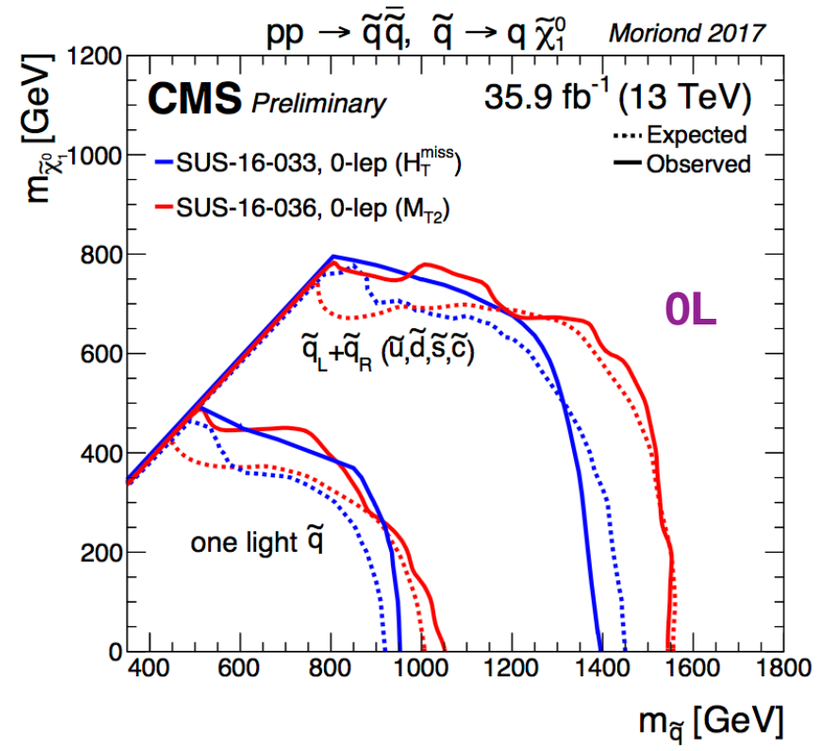
Gluino/squark 0-step decay



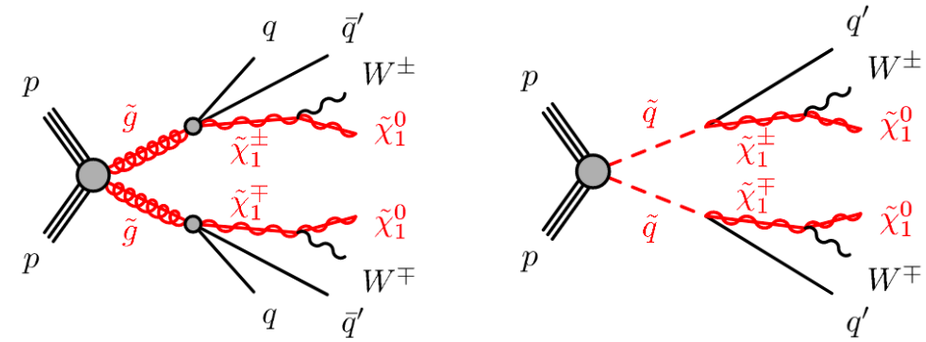
- Search for signal-like phrase space with no lepton.
- Several **0L** searches performed based on different discriminating variables: Htmiss, Meff.
- Signal regions are usually further binned in different jet and b-jet multiplicity.



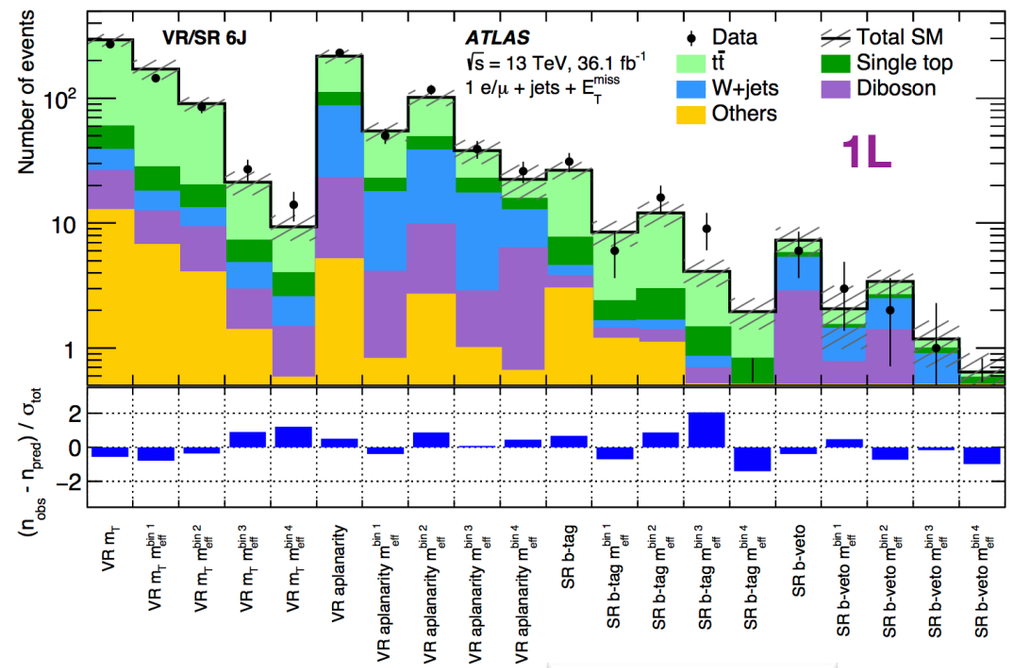




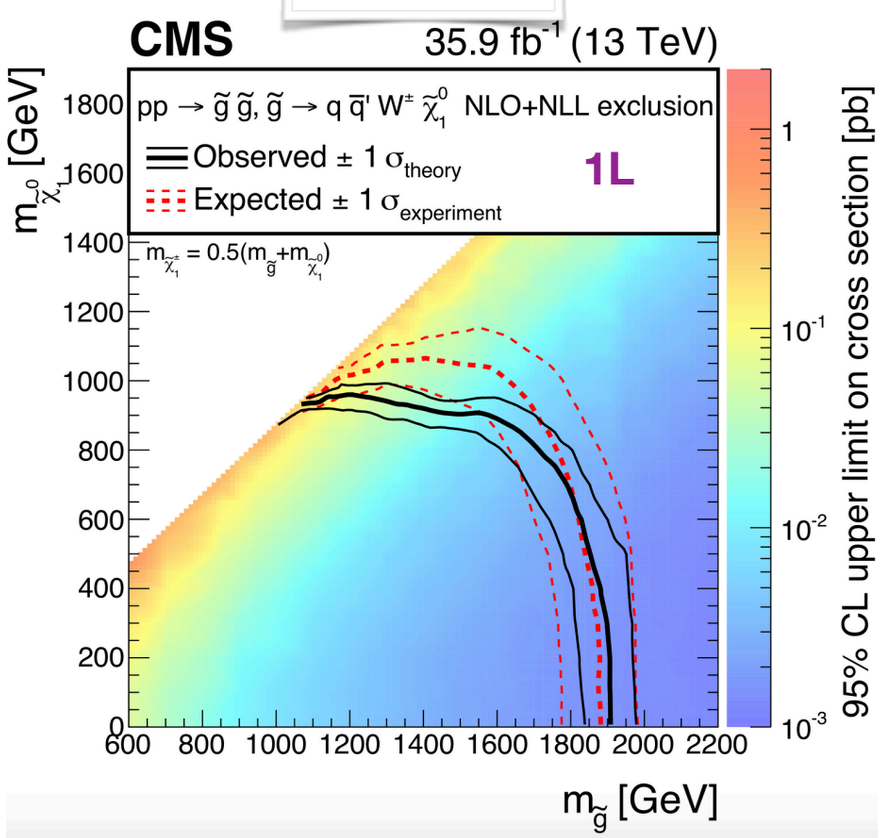
Gluino/squark 1-step decay



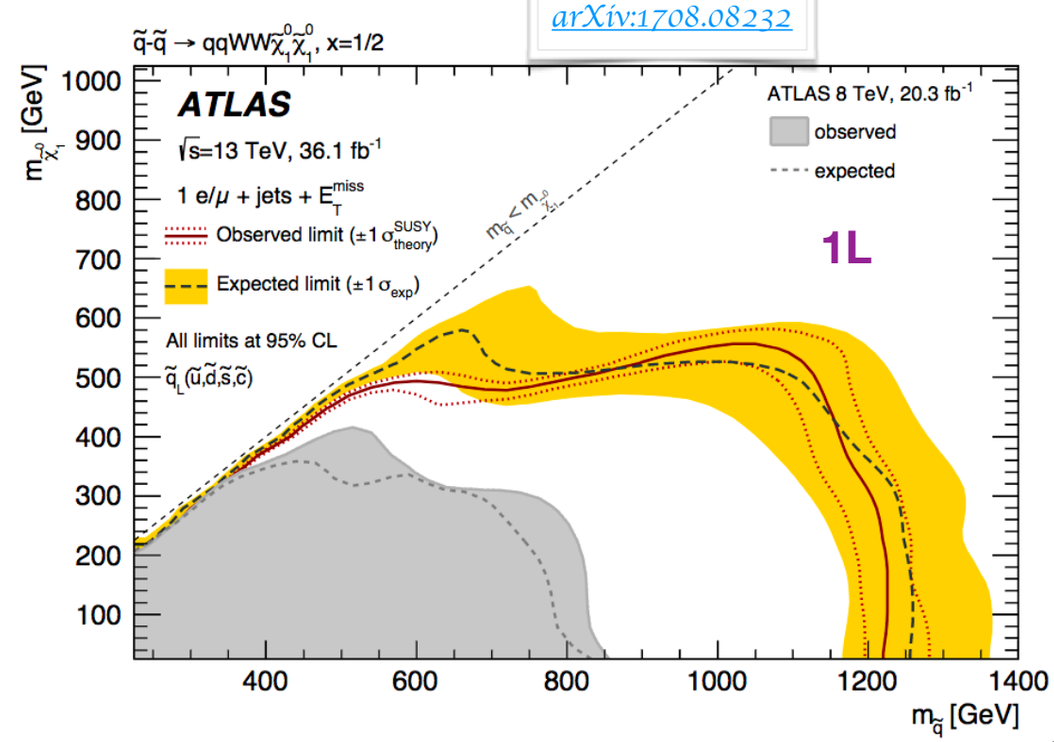
- Longer decay chains can be targeted in the final state with additional lepton.
- **1L** channel provides better suppression on the multi-jet background : signal regions are binned in Njet, Nbjet, Meff, to maximize the phrase spaces.



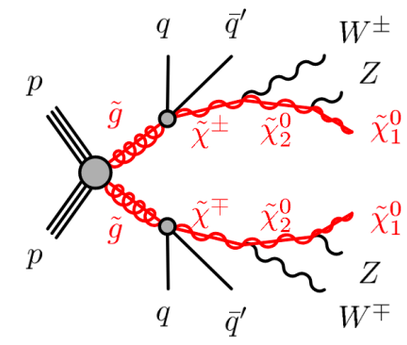
arXiv:1709.09814



arXiv:1708.08232

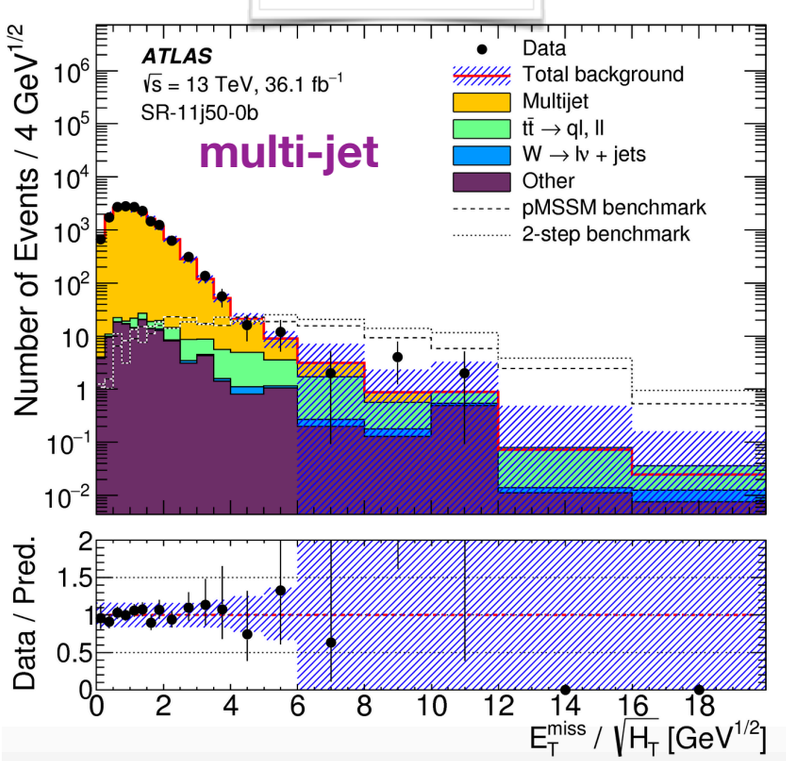


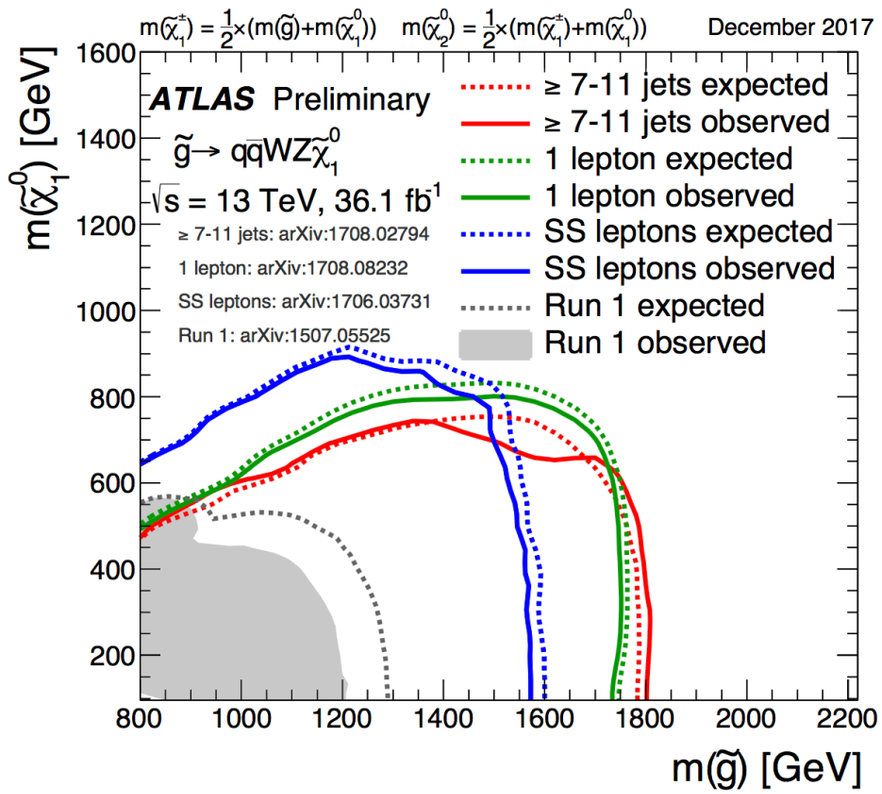
Gluino/squark 2-step decay



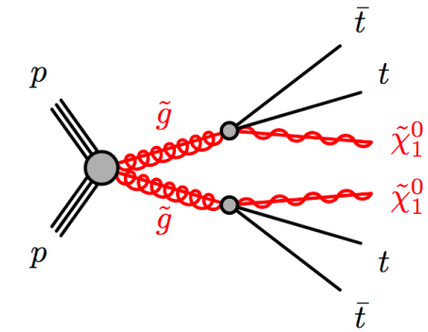
- Long SUSY decay chains produce multi-object final state.
- **Multi-jet (0L with 7-11 jets)** targets full hadronic final states: powerful in the high mass region. MET significance approximately invariant in jet multiplicity.
- Due to independent gluino decays, **same-sign leptons(SS2L/3L)** is powerful to constrain strong production. Low SM background allows loose MET requirement and gain in sensitivity to **compressed SUSY**.

arXiv:1708.02794

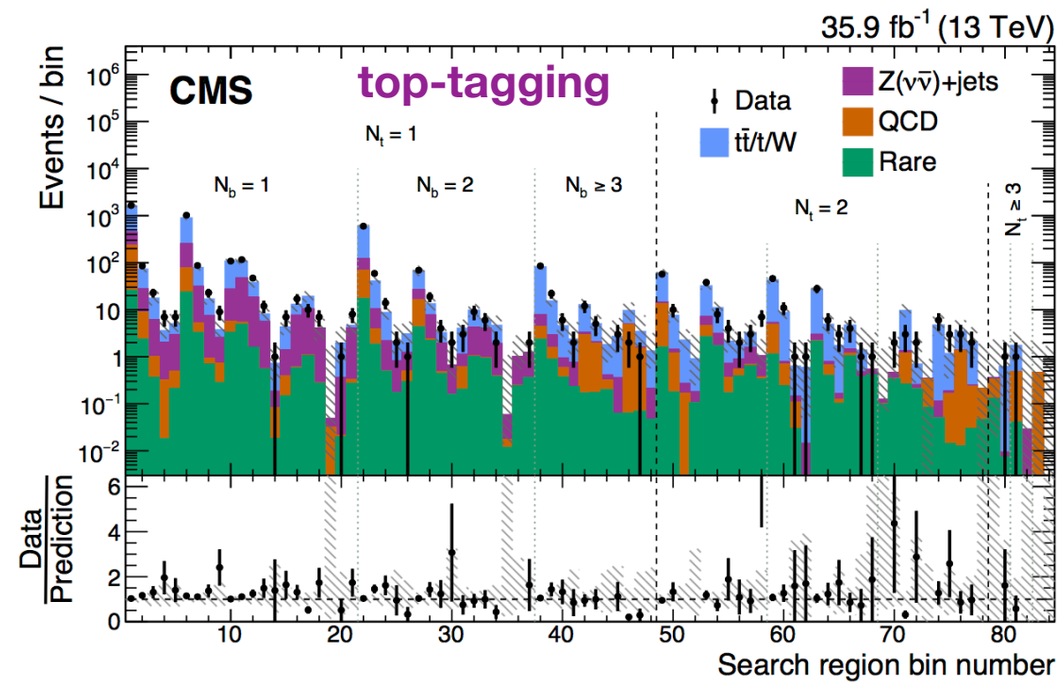


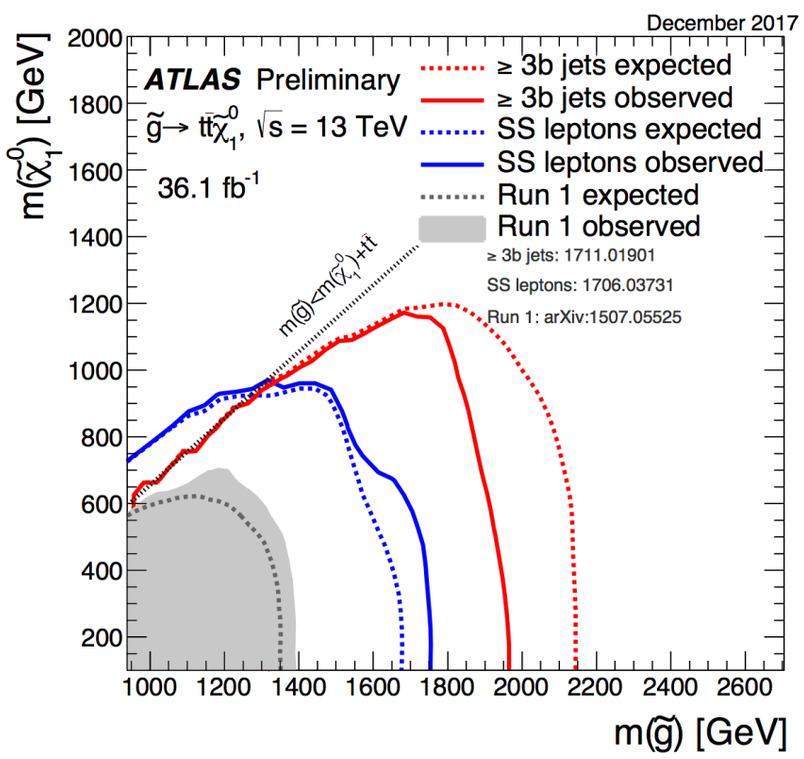


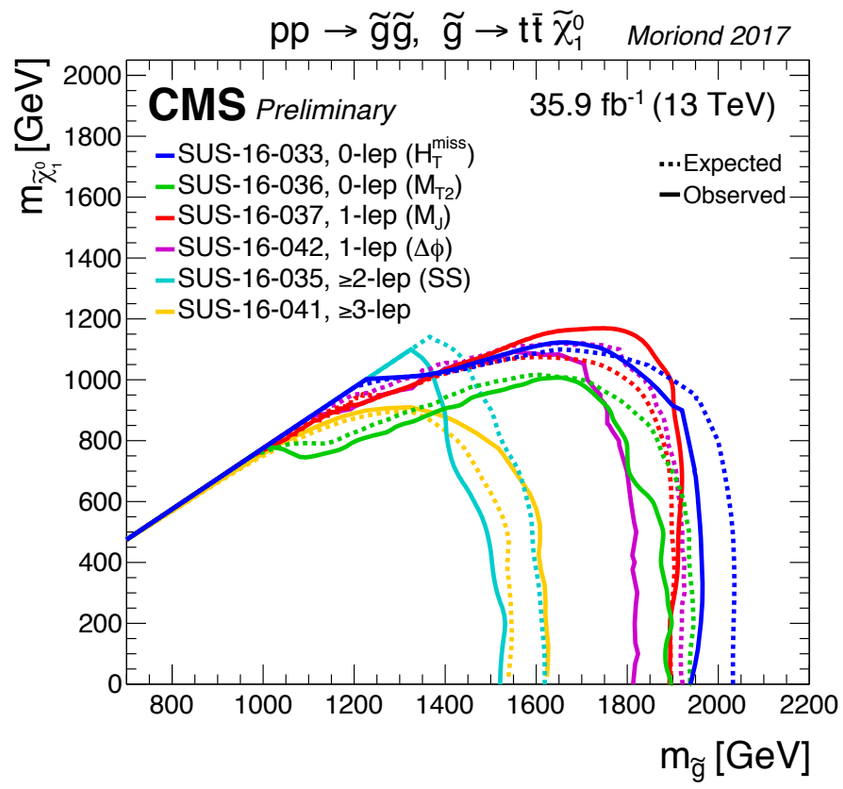
Gluino-mediated stop

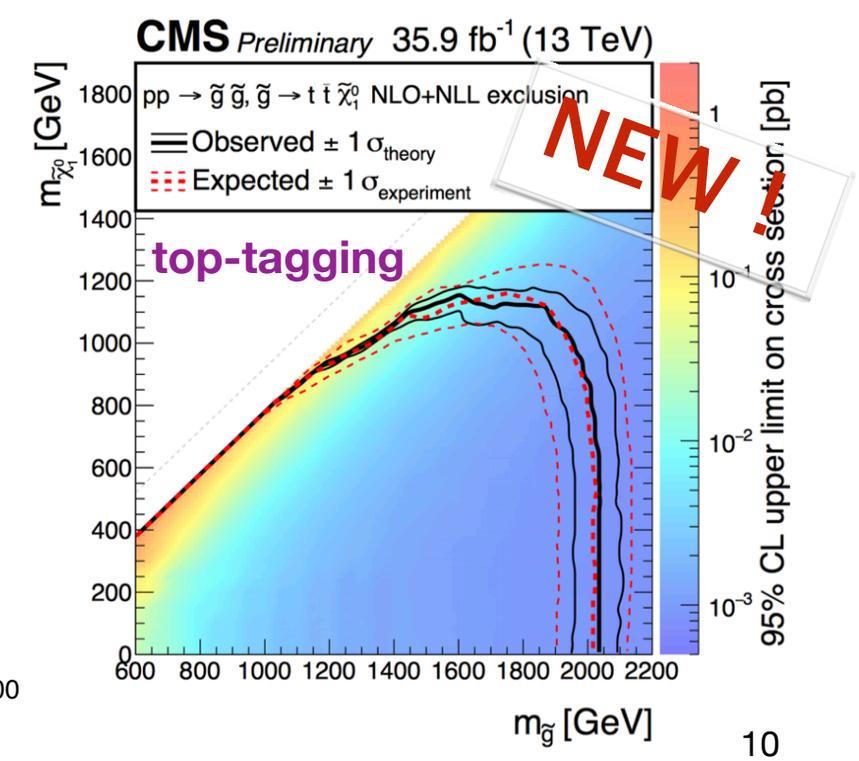


- Gluino pair production decay via stop also excluded up to ~2TeV.
- Multiple channels are designed to target signal-like phrase space: **multi-b, SS2L, 0L, 1L, 3L** etc.
- The latest **hadronic top-tagging** analysis employs three top tagging algorithm to identify different decay topologies of top quark.

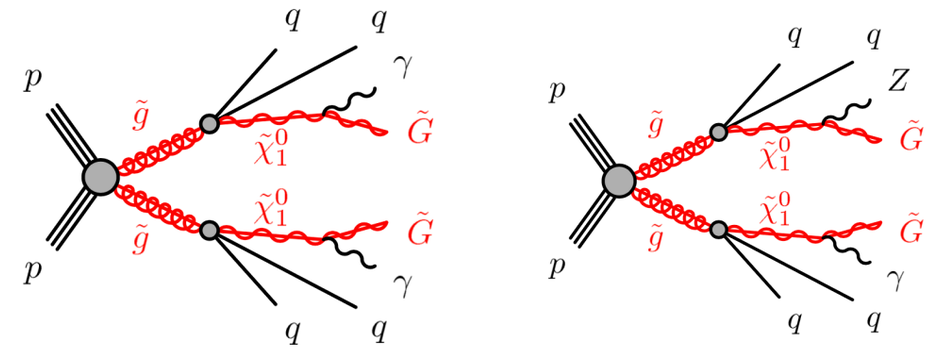






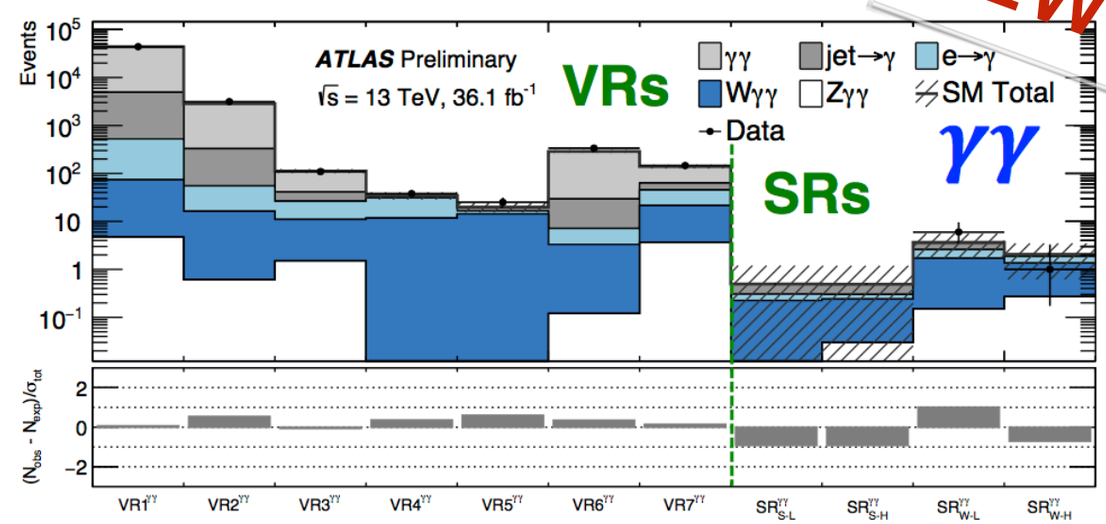


GMSB



- Search for GMSB with photon in the final state. **Gravitino LSP**.
- **di-photon** analysis for **bino-like NLSP**
- **photon+jets** analysis for **Higgsino-bino mixture NLSP**

NEW !



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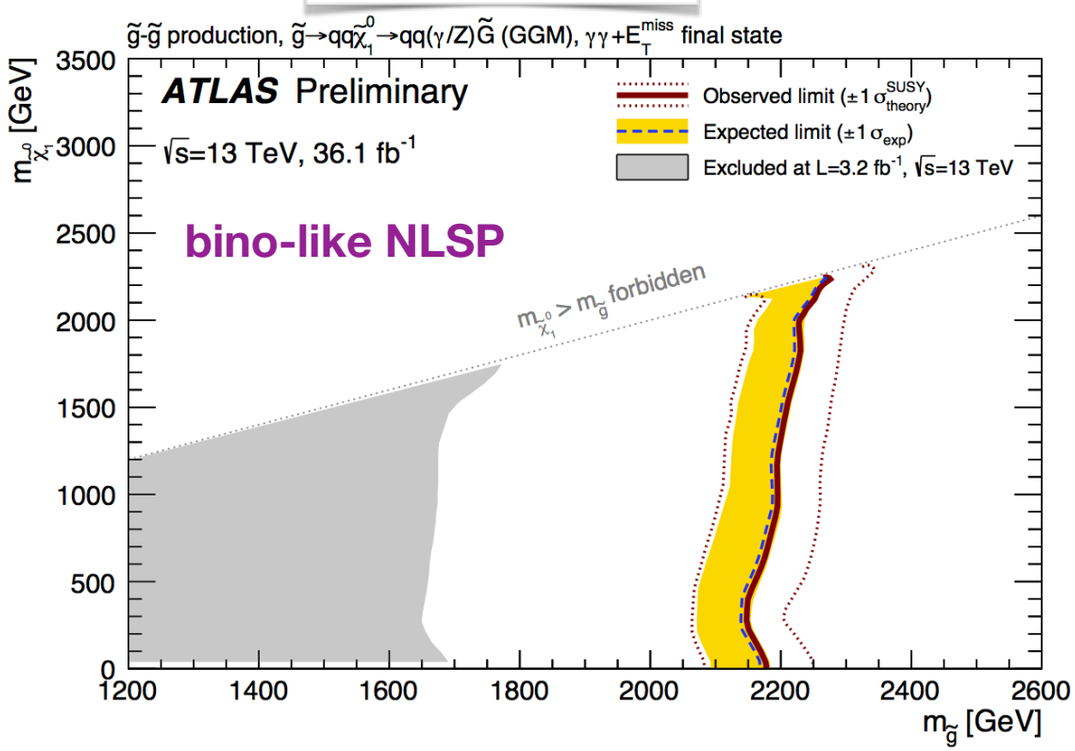
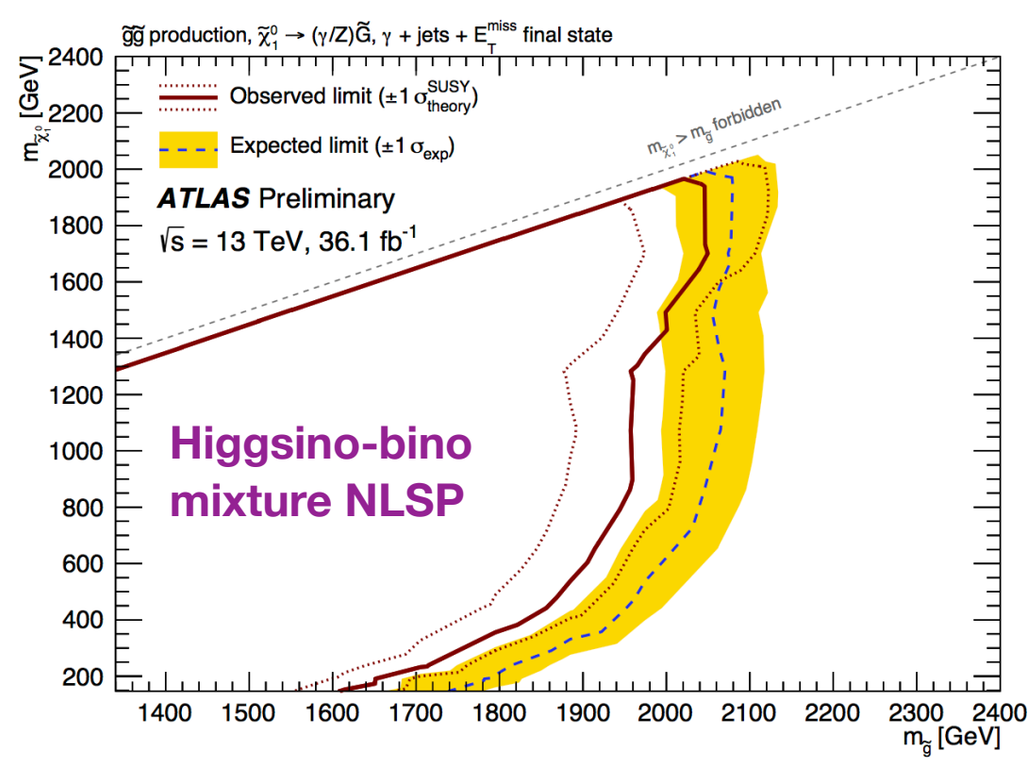
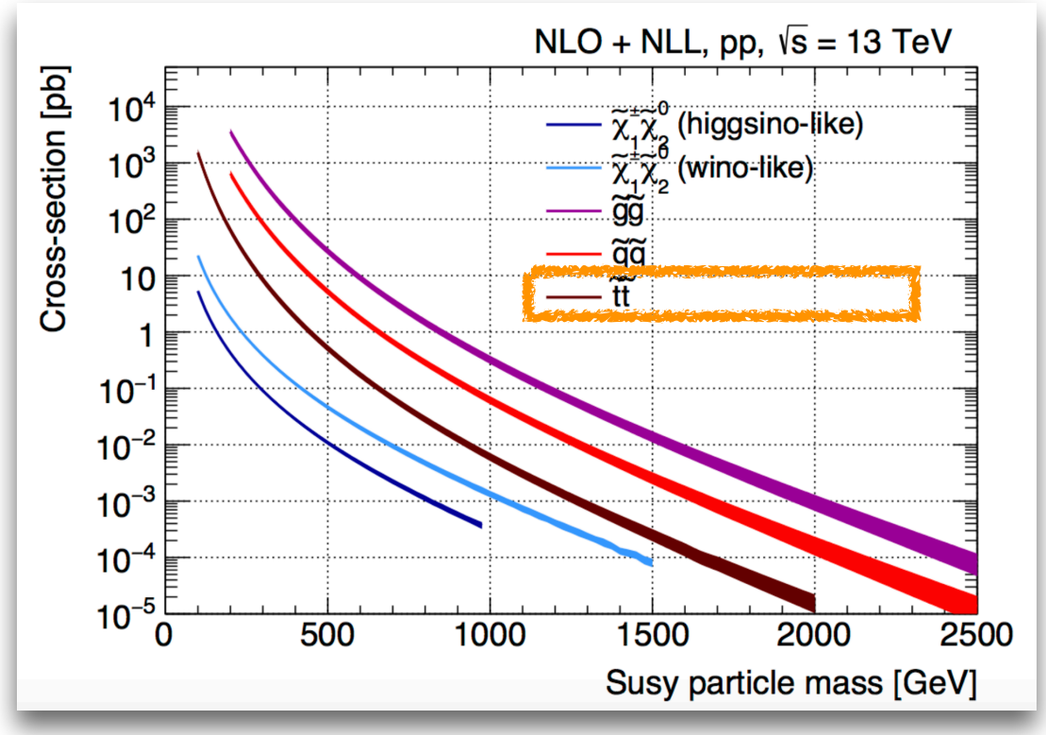


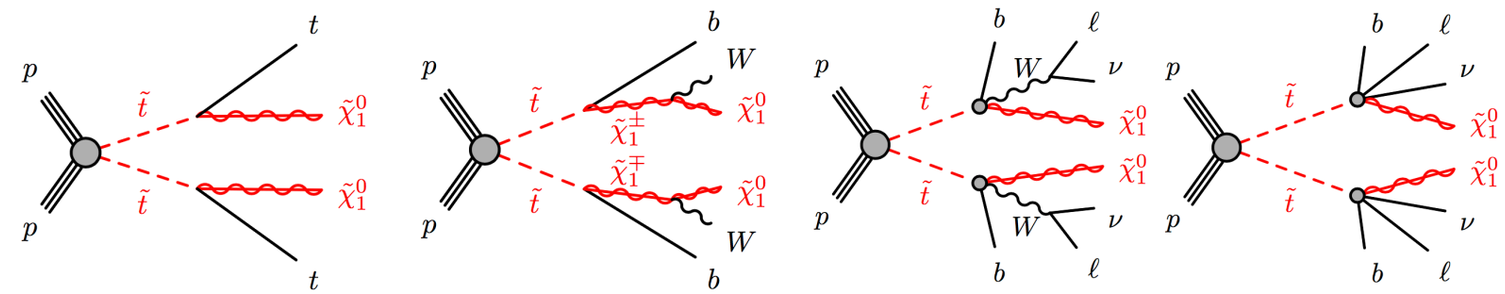




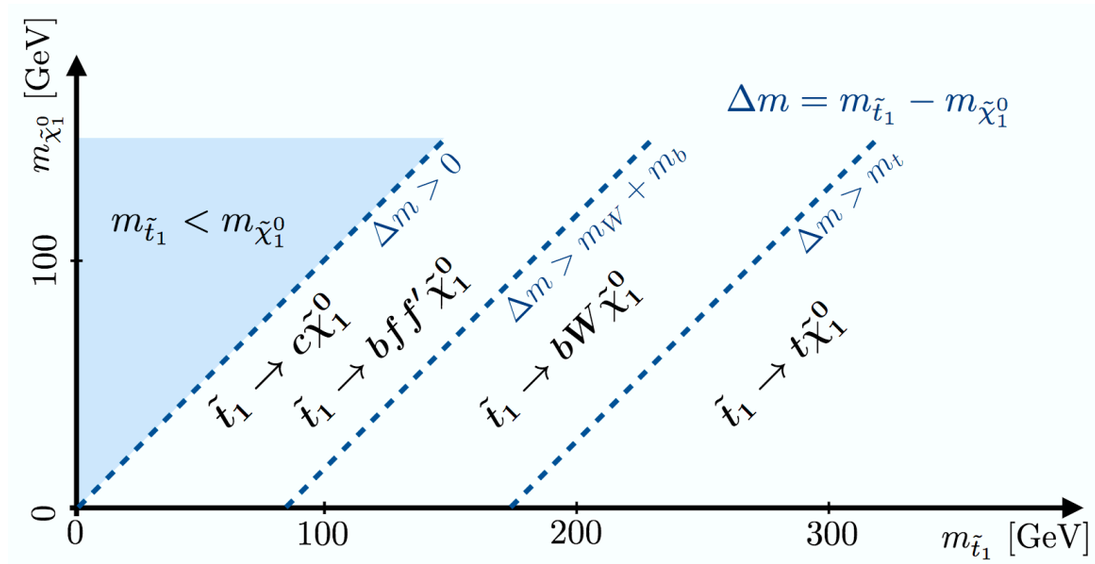
3rd generation

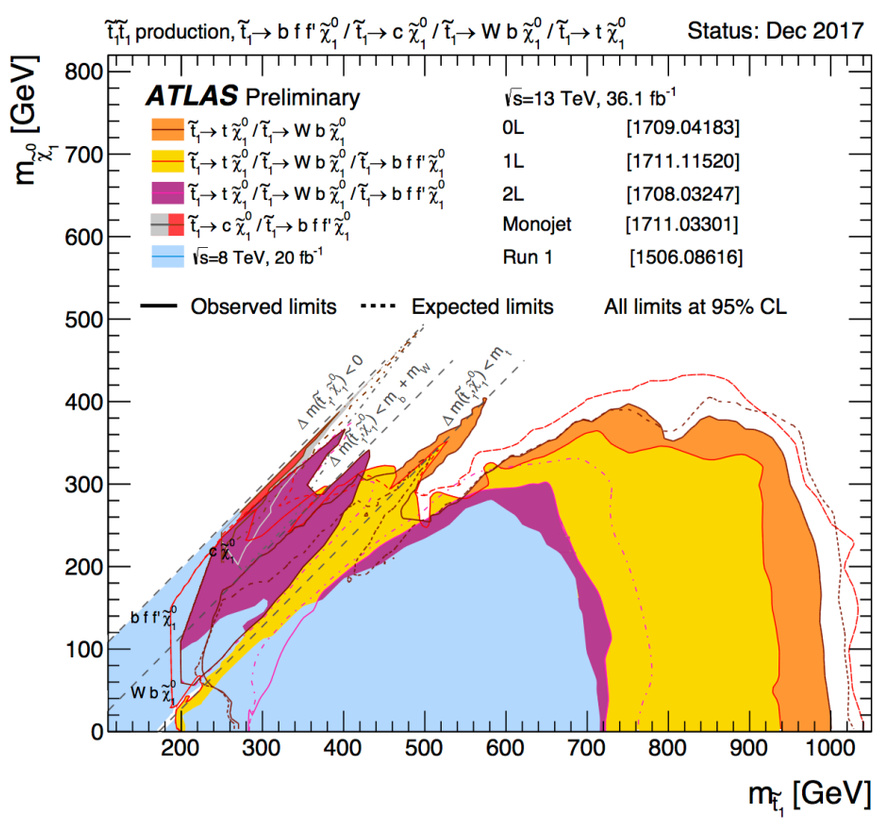
- Production of stops and sbottoms
- Moderate cross-section: ~ two orders of magnitude lower than gluino / squark (*for squark production: degenerated squarks are assumed*)
- Generic feature:
    - heavy flavor jets
    - large Etmiss

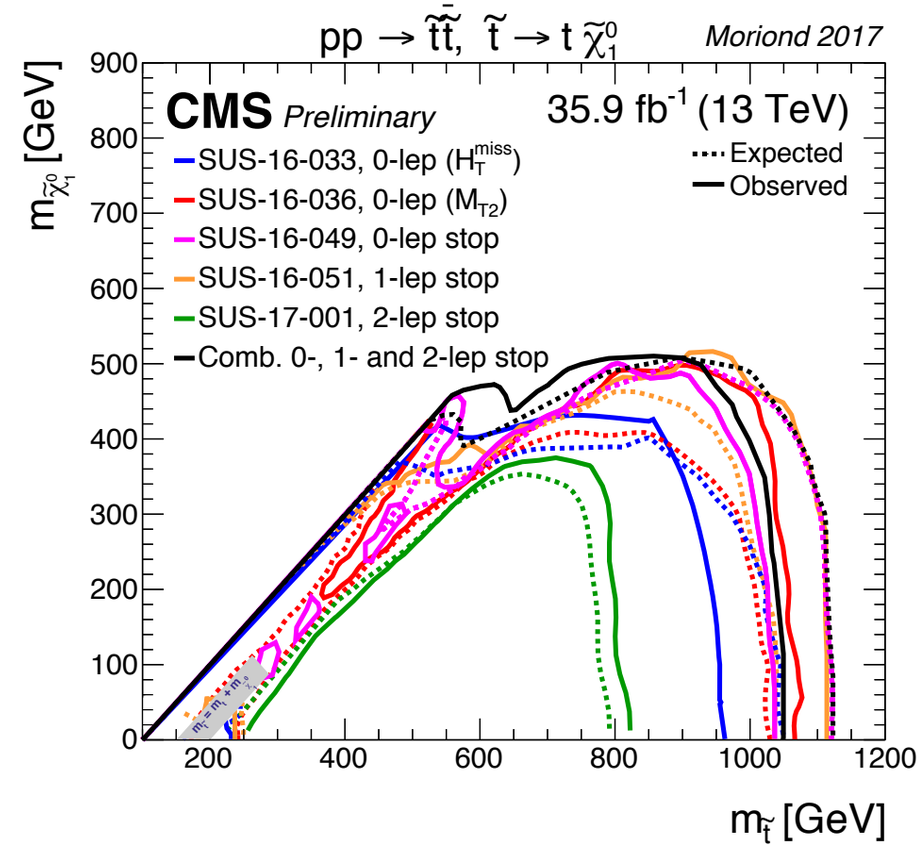
Direct stop decay



- Stop pair production decay excluded up to ~1TeV.
- Complex stop decay topologies due to large top mass.
- Various searches performed to largely exploit the phrase space: **0L, 1L, 2L**.
- Compressed regions are also nicely exploited with various/novel techniques: ISR, BDT, Recursive Jigsaw…



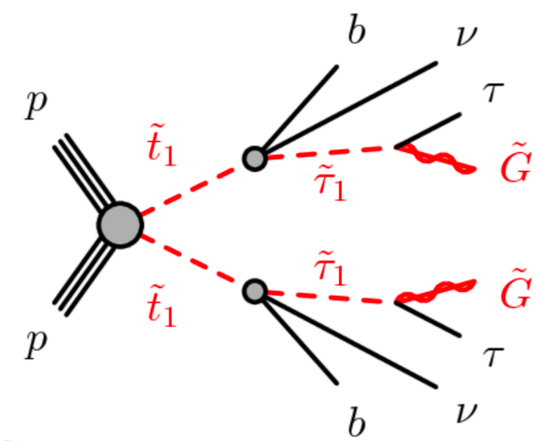




NEW !

Direct stop decay to stau

- Scenarios motivated by **GMSB**.
- Light stop, light stau, massless gravitino.
- Final states with **two tau leptons, b-jets and Etmiss.**
- Two channels: had-had; lep-had; probe up to 1.16 TeV stops.



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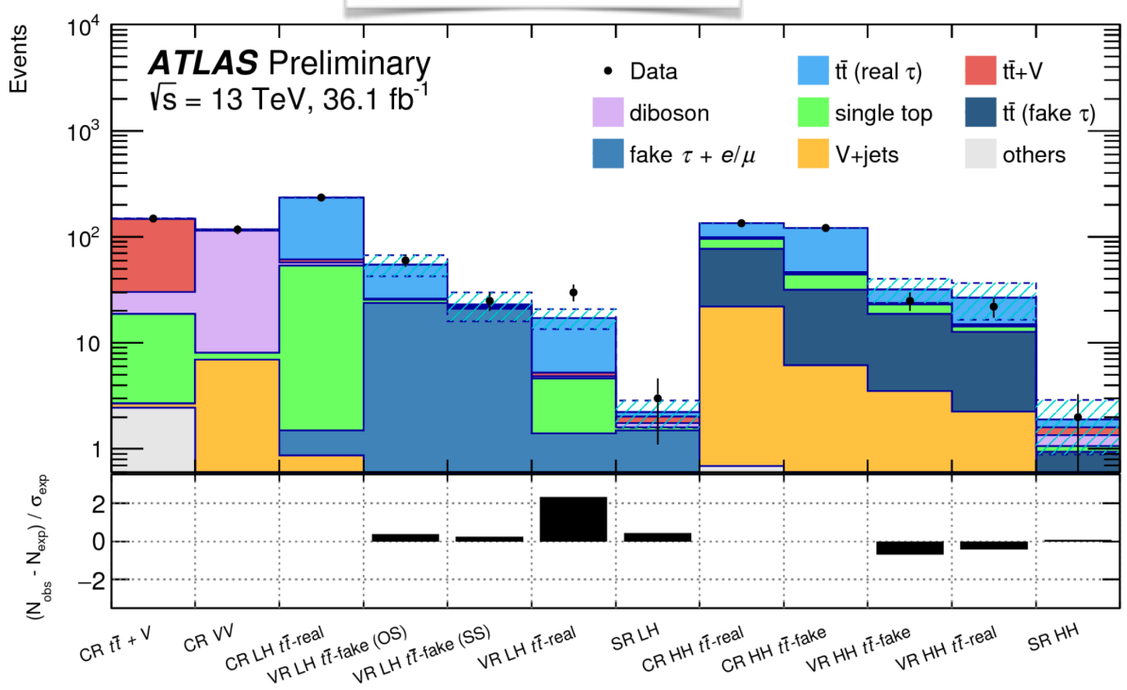
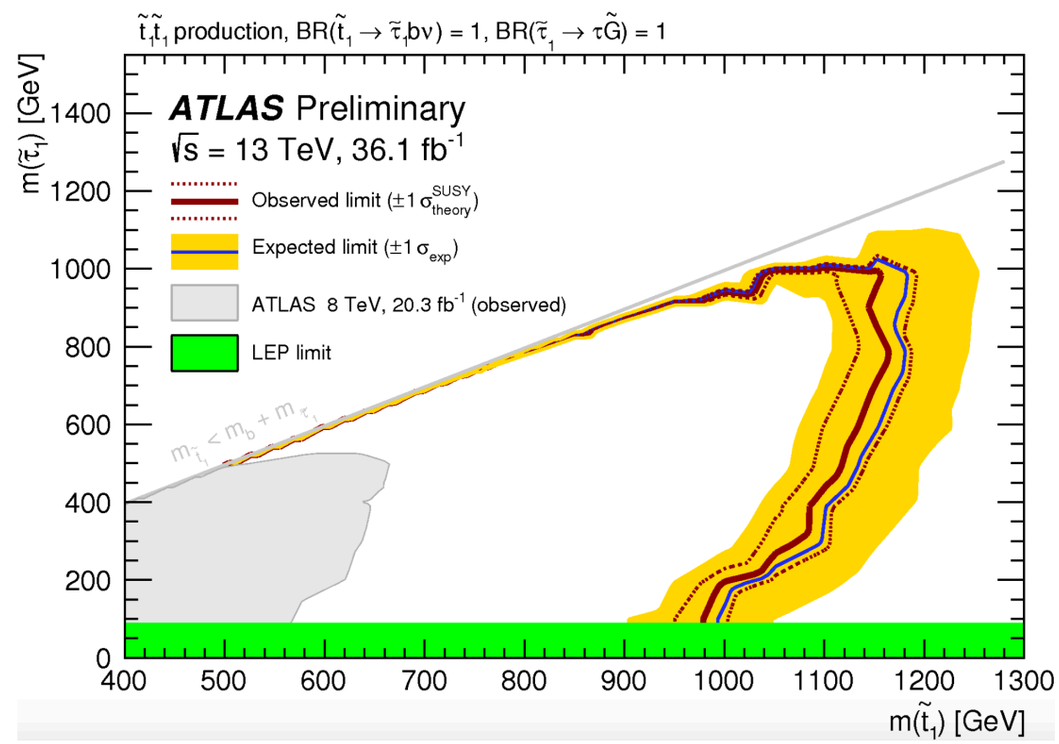
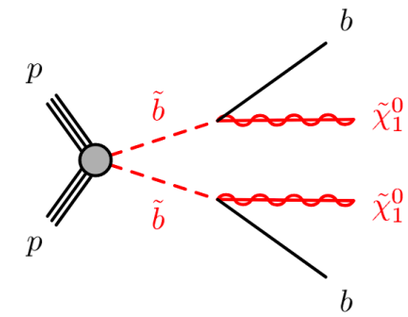
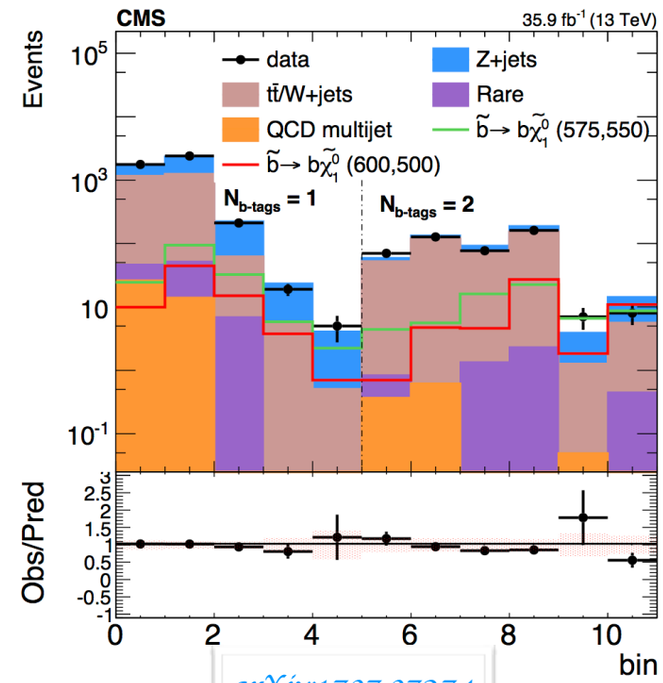




Direct sbottom decay

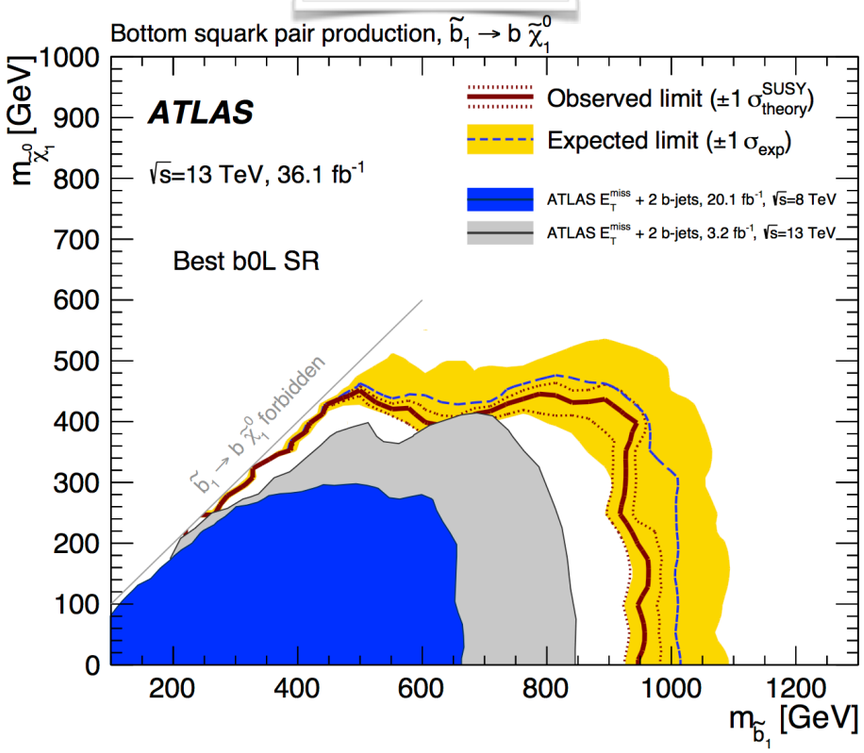


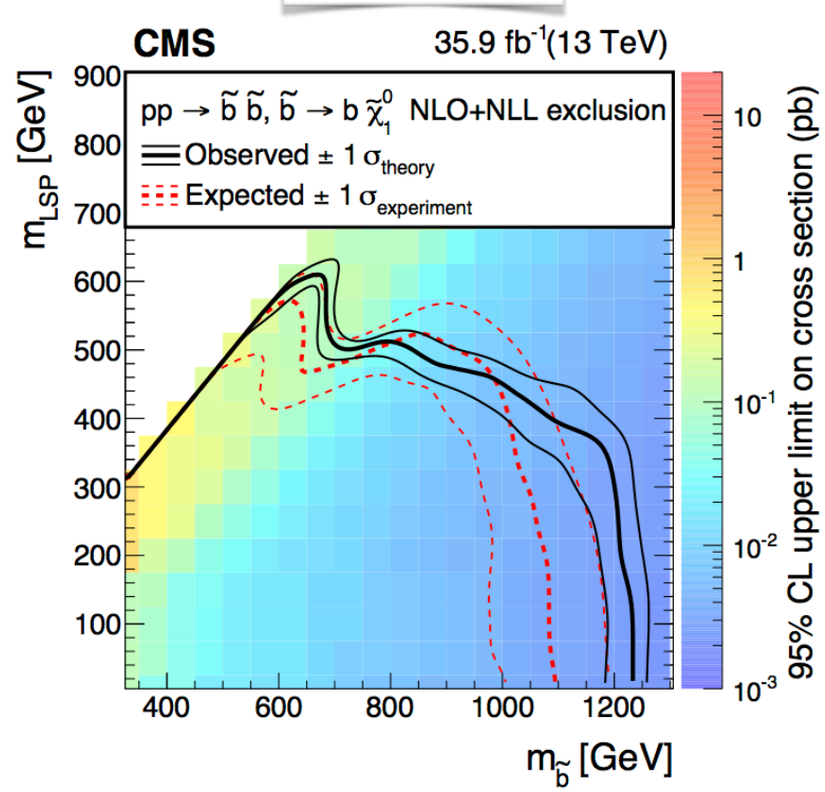
- Specific channels are designed to target sbottom production.
- Signal regions are binned in Nbjet.
- Compressed region is designed by requiring ISR jet (light flavor), less jet activity.



arXiv:1708.09266

arXiv:1707.07274

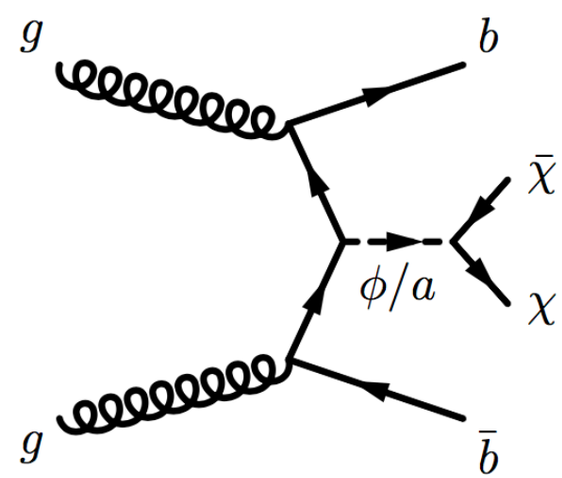


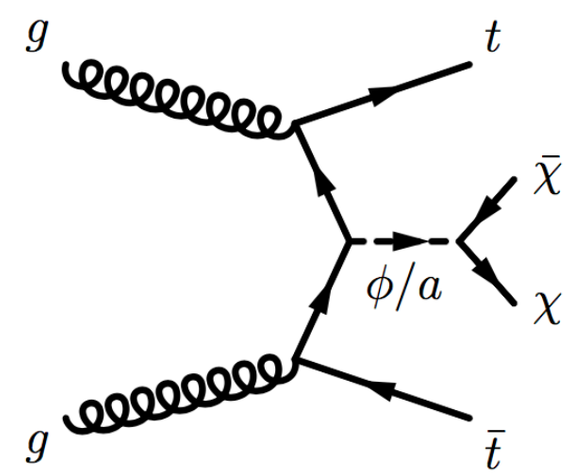


WIMP DM in association with b/t-quarks

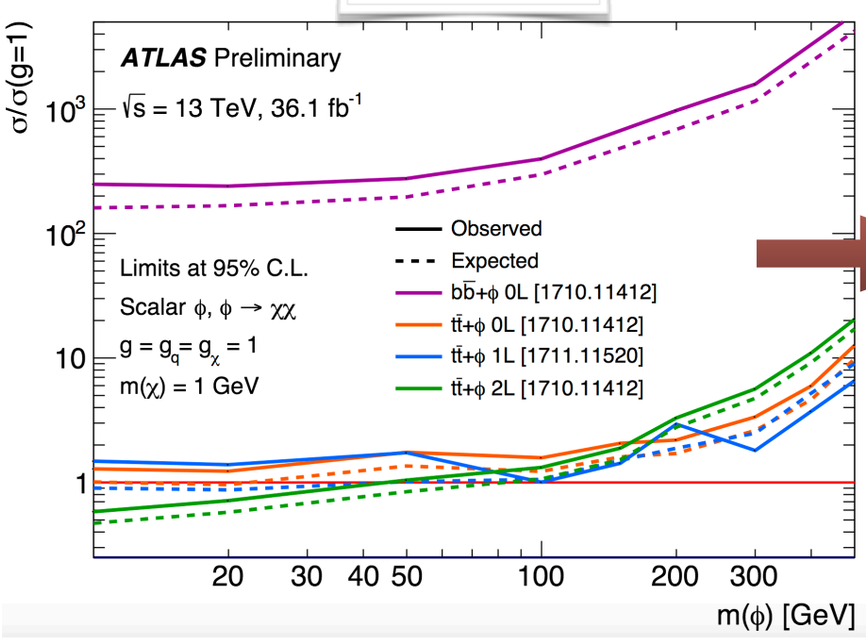
NEW !

- Final states: 3rd gen. quarks and Etmiss.
- 2-lepton channel performs the best.
- Reinterpretation of color-neutral scalar limit in terms of DM-nucleon scattering cross section.

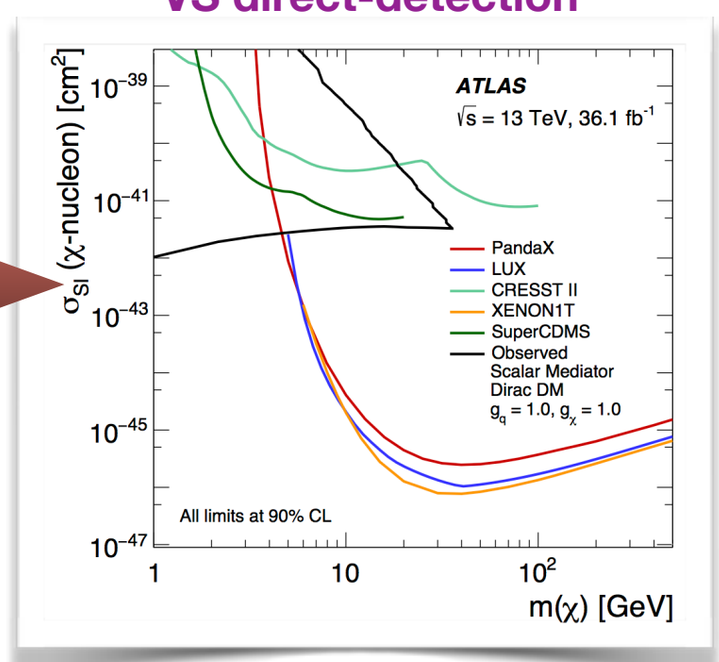




arXiv:1710.11412

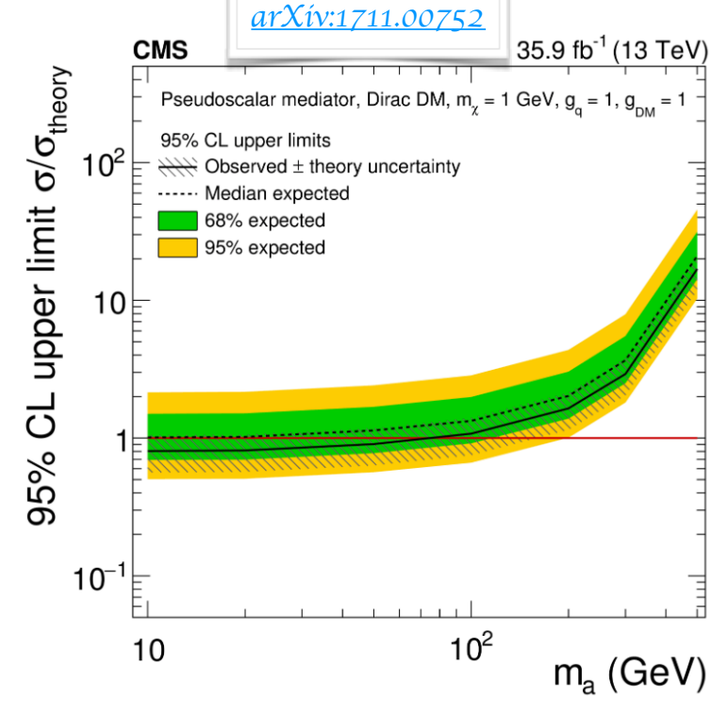


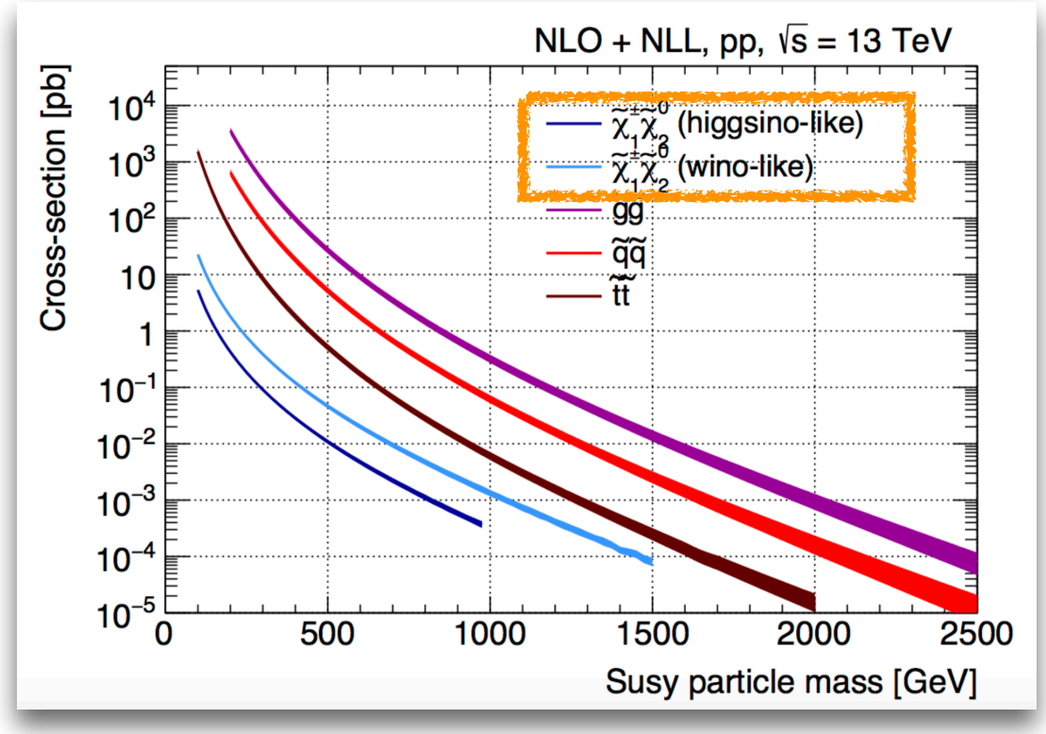
VS direct-detection



arXiv:1603.04156

arXiv:1711.00752



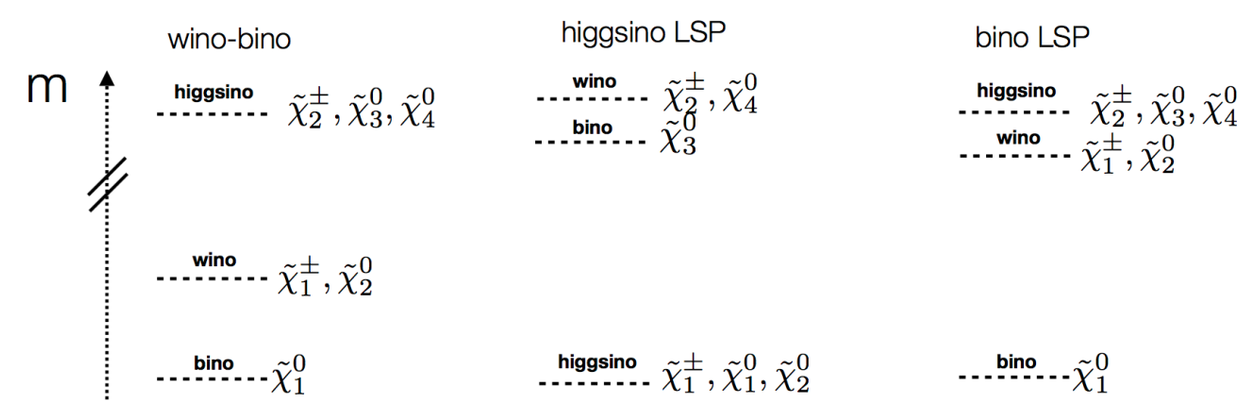


Electroweak production

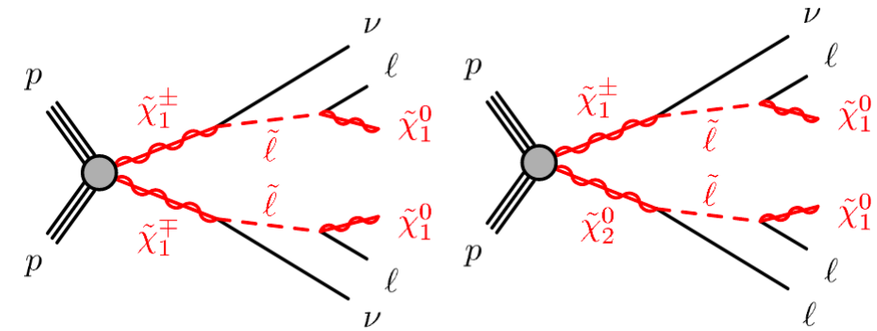
- Production of **C**harginos/**N**eutralinos/sleptons
- Small cross-section
- Generic feature:
  - less jet activity
  - large Etmiss

$\tilde{B}$ b-ino, 1 neutral state
$\tilde{W}$ w-ino, 1 neutral, 1 charged states
$\tilde{h}$ higgs-ino, 2 neutral, 1 charged states

$\Rightarrow$ $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$, $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$



C1N2/C1C1 via slepton

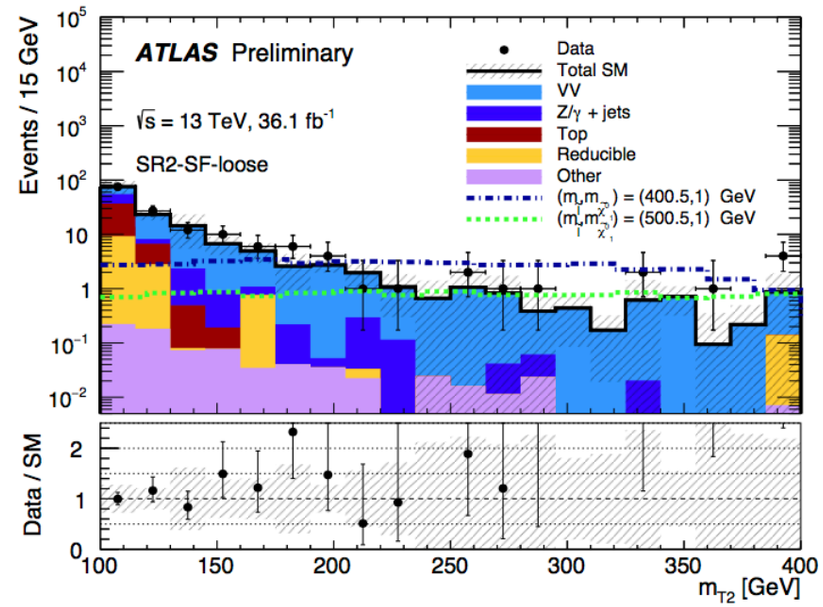


Wino-like C1/N2; bino-like N1

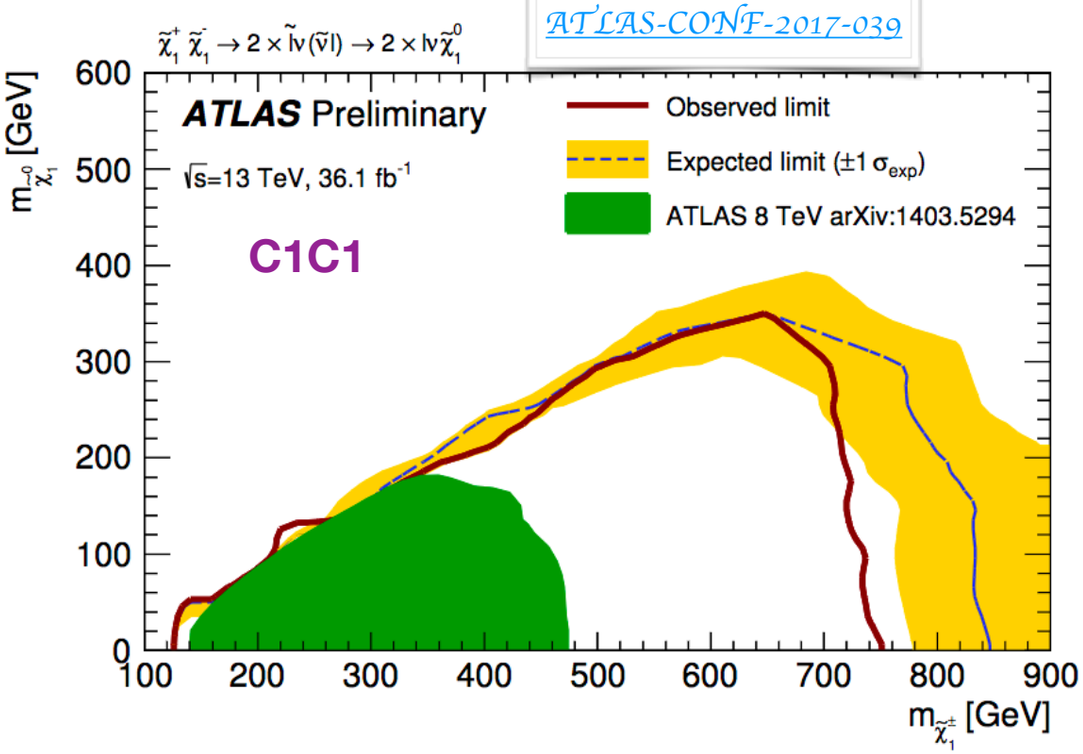
- Search for final states with light leptons without jets.
- **OS2L** channel targets C1C1 production; **3L/SS2L** channel targets C1N2 production. Key variable: mT2.

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

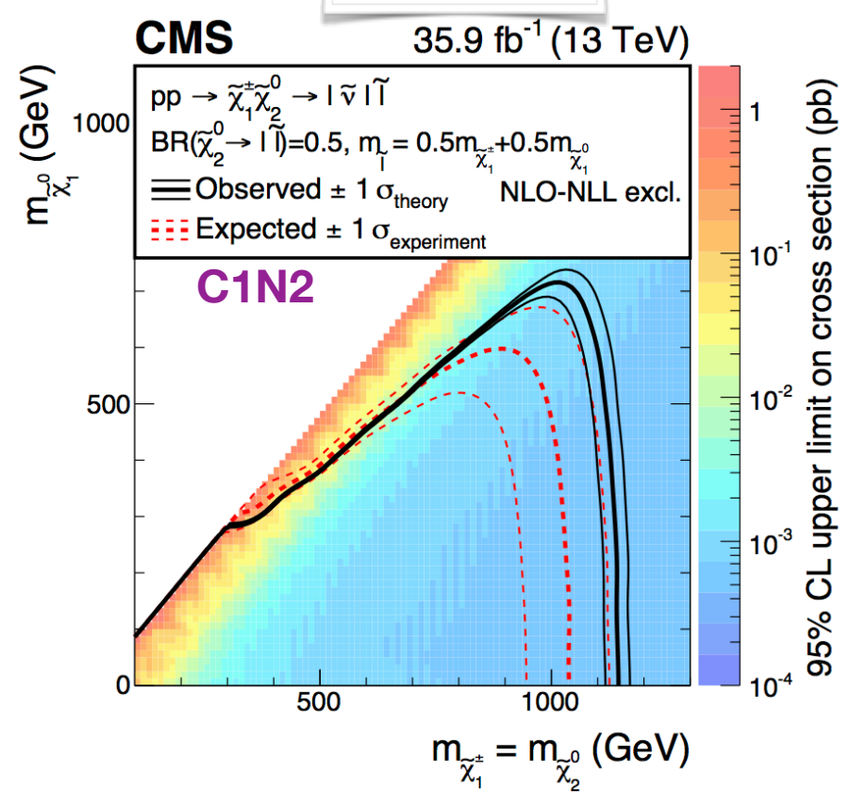
- The chargino-neutralino (C1N2) exclusion sensitivity already reaches above 1TeV.



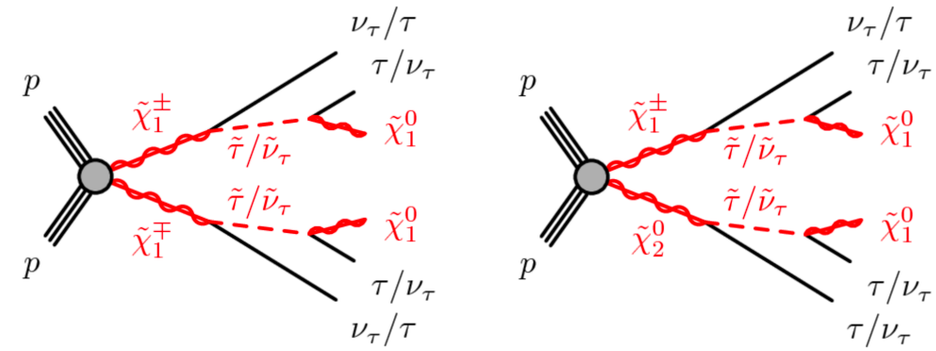
ATLAS-CONF-2017-039



arXiv:1709.05406

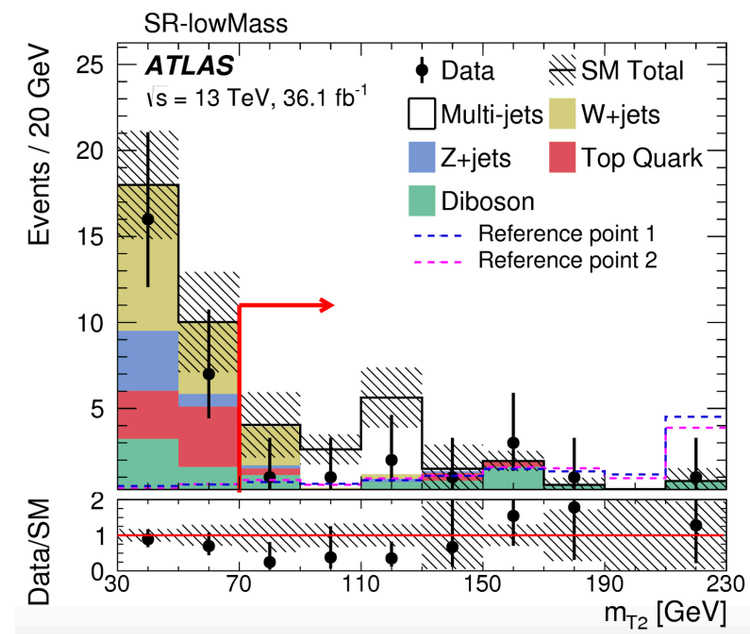


C1N2/C1C1 via stau



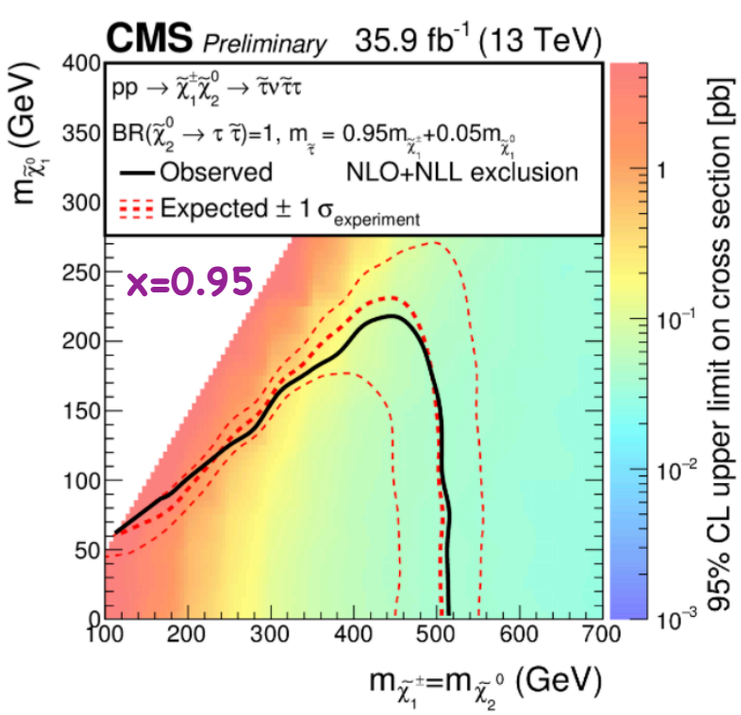
What if light stau?

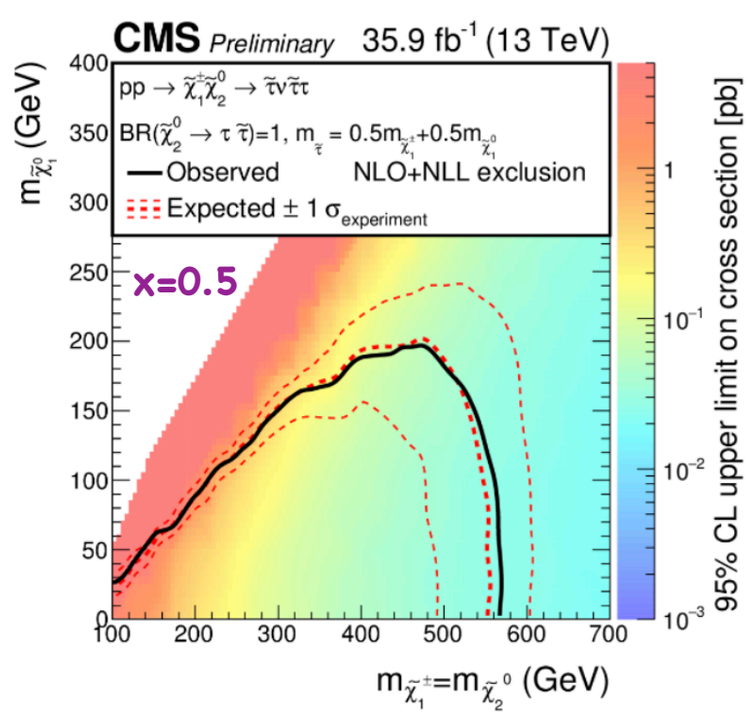
- **Hadronic tau** final states <— challenge channel.
- Major background from fake-tau; estimated by data-driven method.
- The limits have been provided for different mass splitting: $m_{\tilde{\tau}} = m_{\tilde{\chi}_1^0} + x(m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0})$

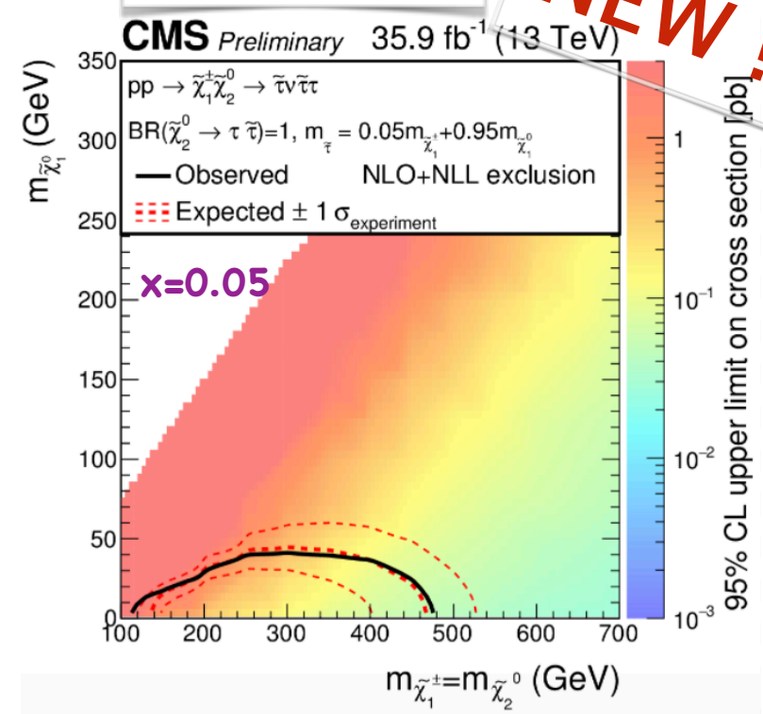


CMS-PAS-SUS-17-002

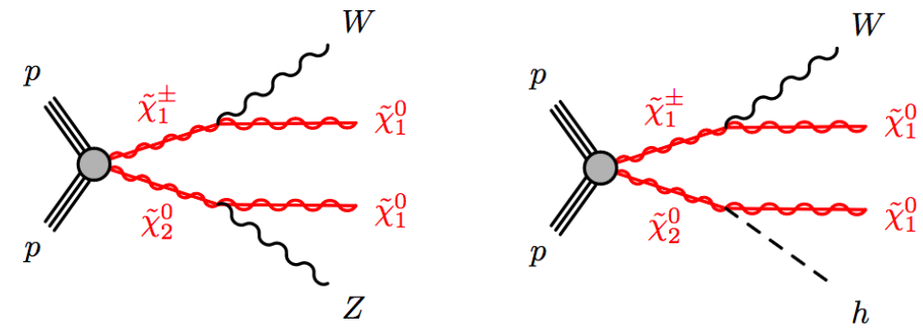
NEW !



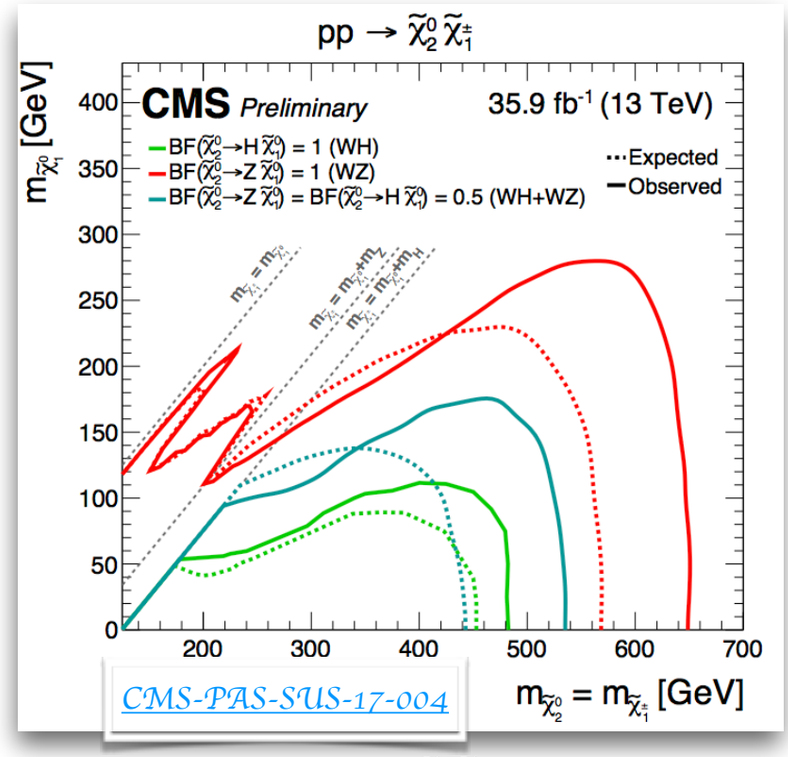


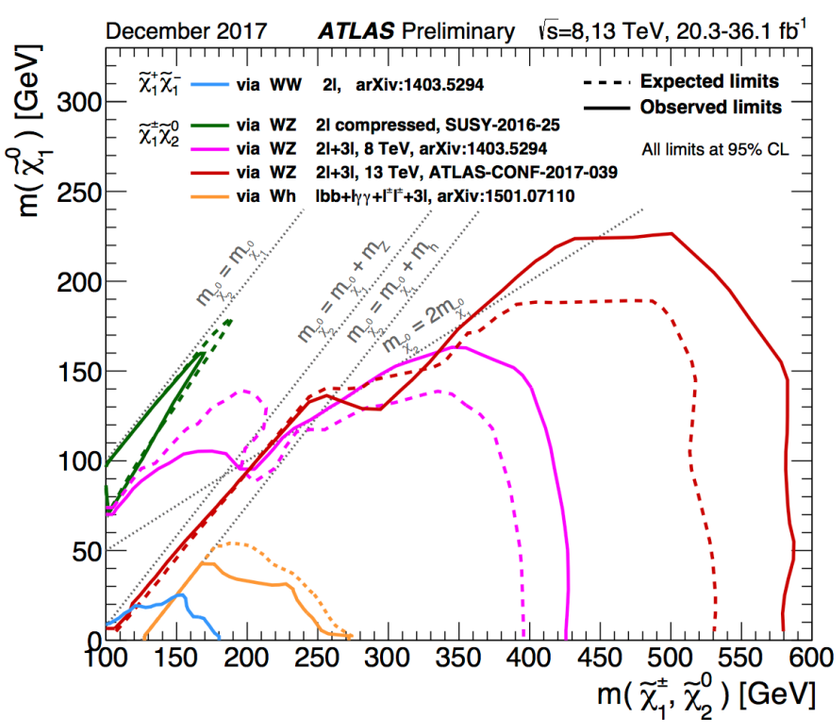


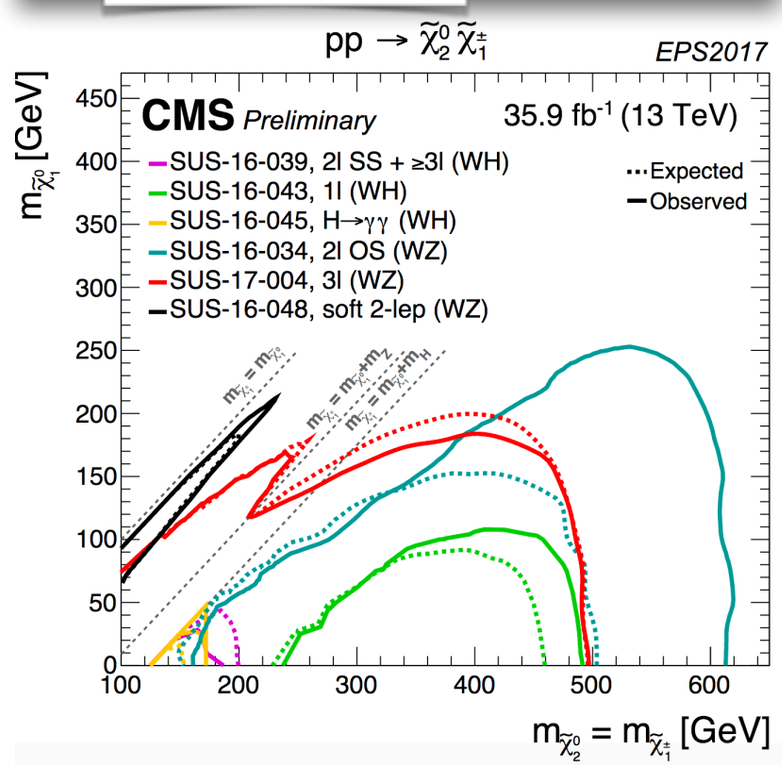
C1N2 via boson



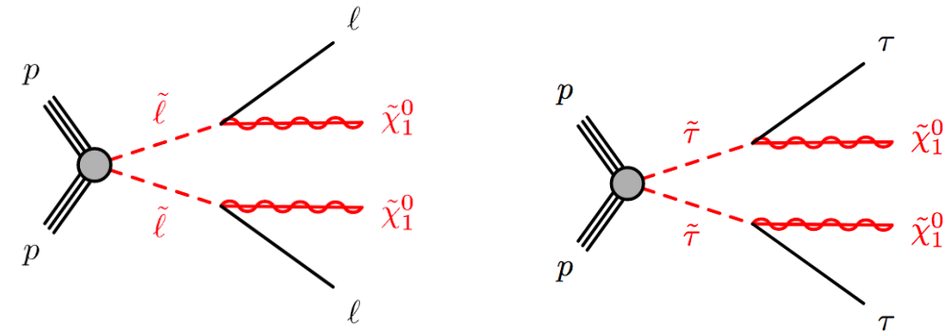
- Sleptons assumed to be heavy; C1N2 decay via boson.
- Multiple channels are designed depending on the assumption of BR:
- 100% via WZ: **OS2L/3L/soft2L(compressed region)**
- 100% via WH: **SS2L/3L/1Lgamgam/1Lbb(powerful)**
- Weaker limits with increasing BR into WH.







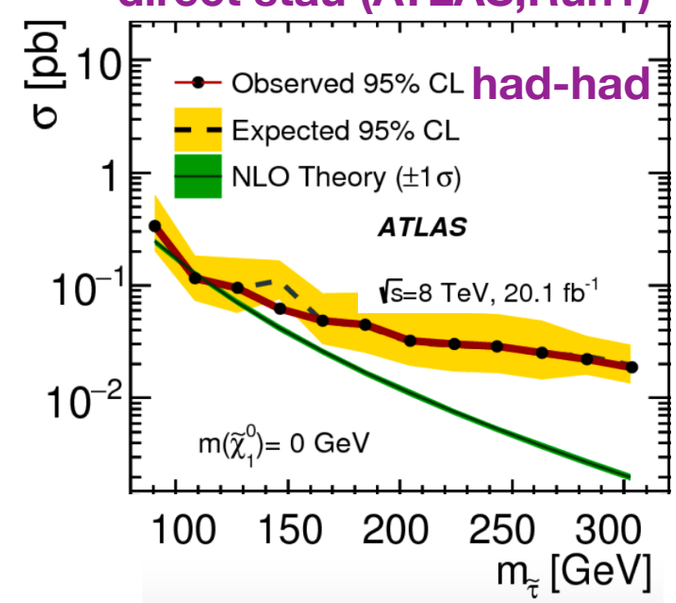
Direct slepton/stau



- Very low cross section.
- **2L** channel probes the direct slepton limit up to ~450-500GeV.
- Stau pair has been checked with **had-had** and **lep-had** channel: only 1 point excluded in Run 1.

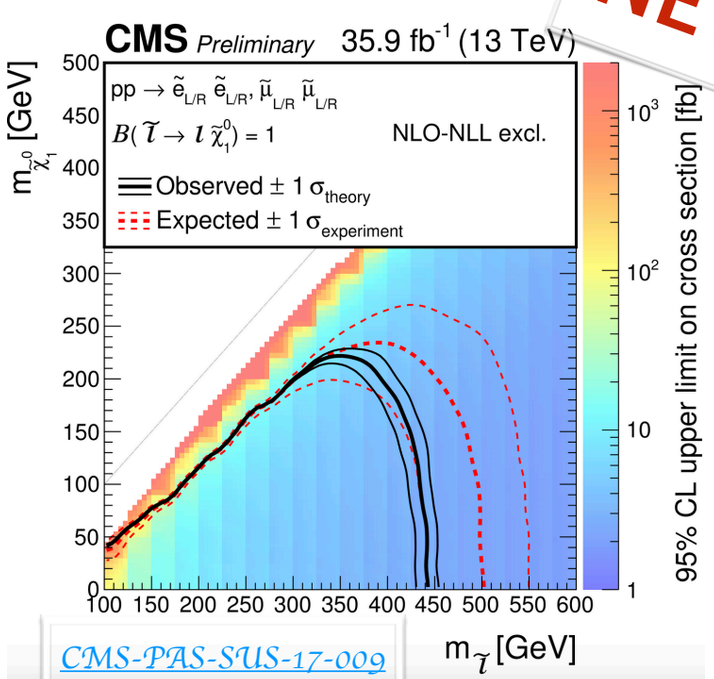
direct stau (ATLAS,Run1)

arXiv:1509.07152



direct slepton

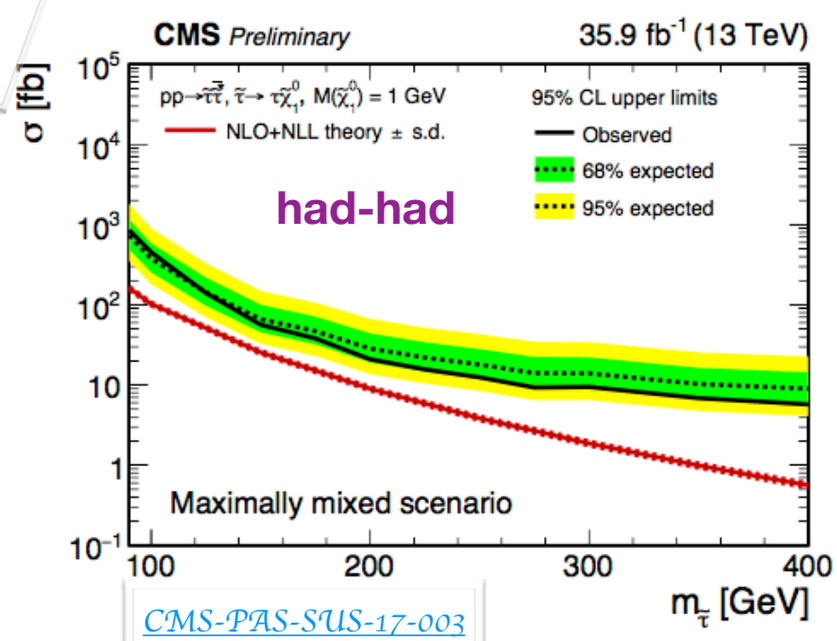
NEW !



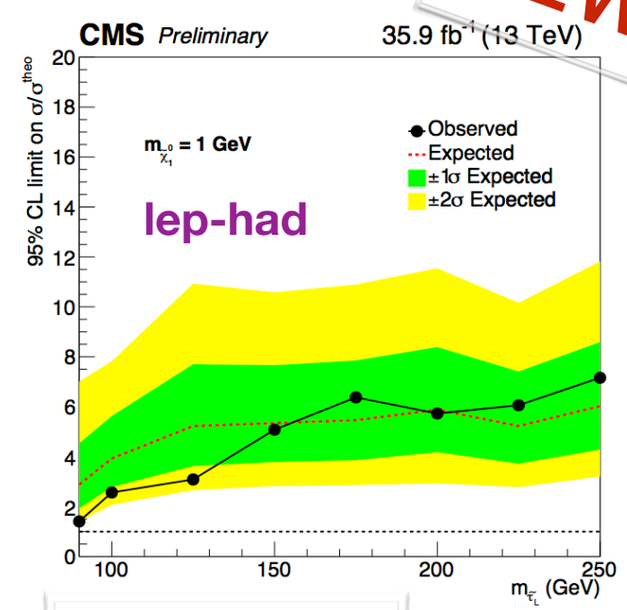
CMS-PAS-SUS-17-009

direct stau (CMS,Run2)

NEW !

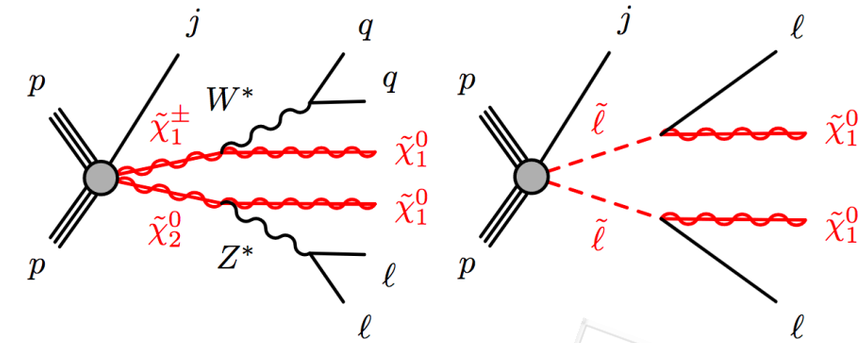


CMS-PAS-SUS-17-003



CMS-PAS-SUS-17-002

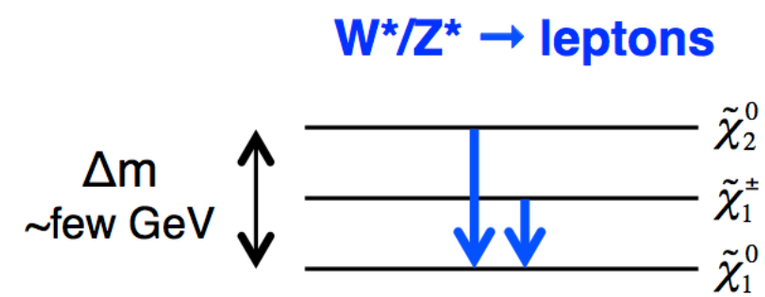
Compressed higgsino/slepton

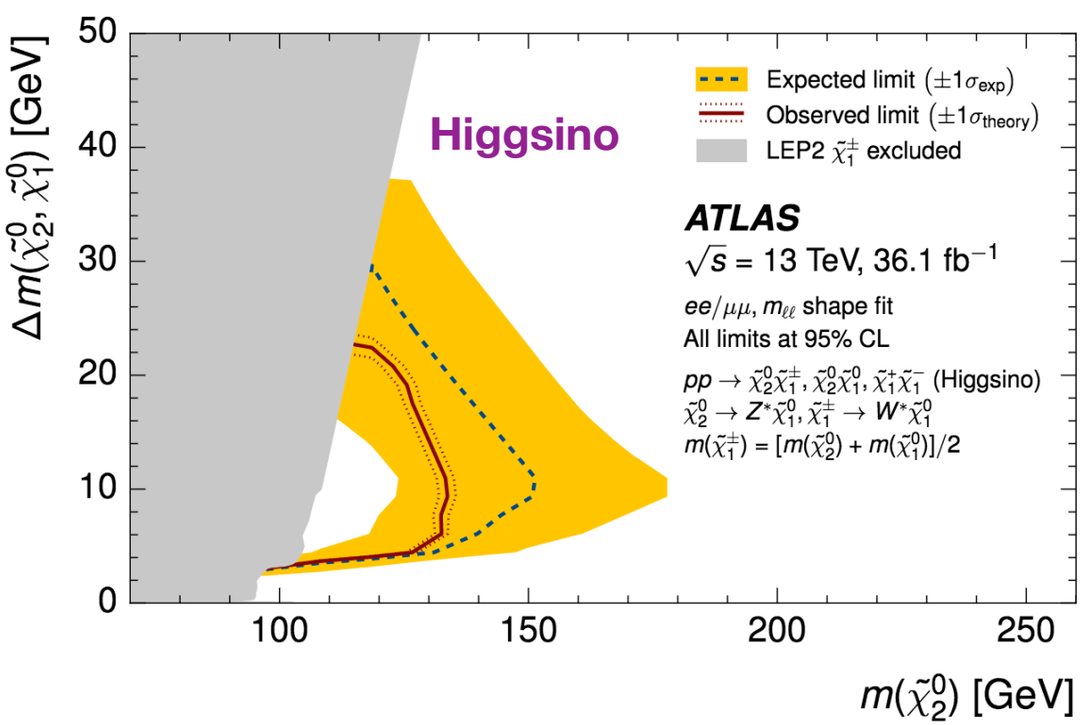


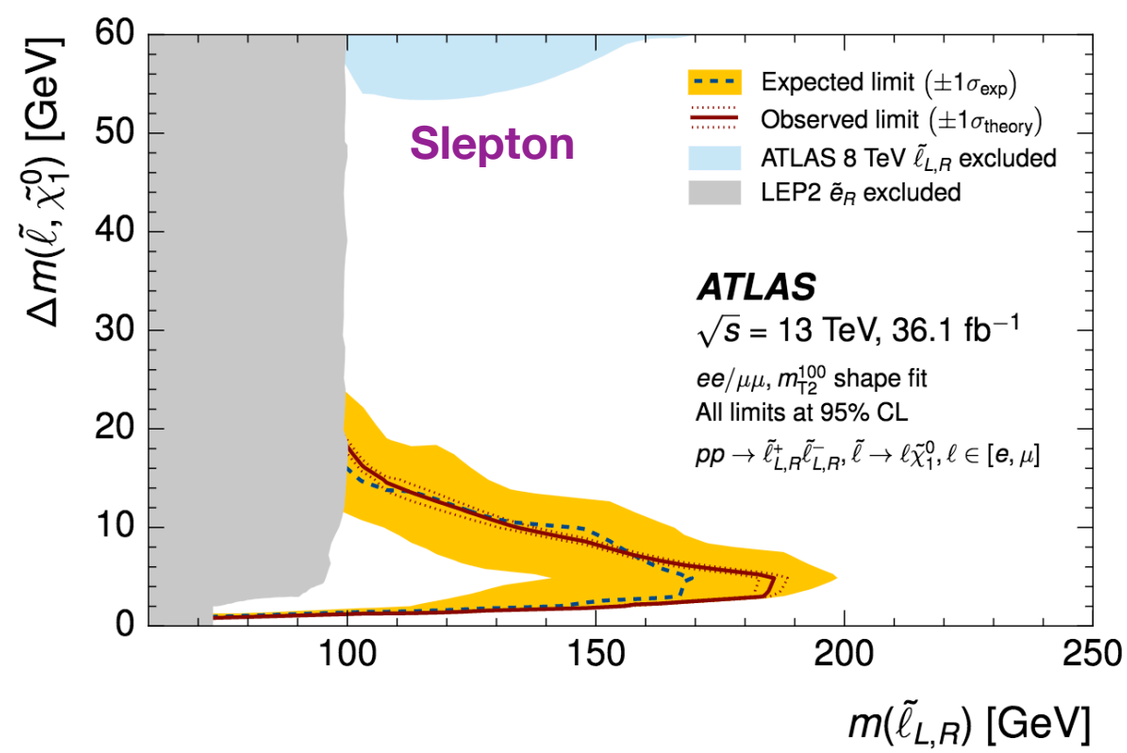
NEW !

SUSY-2016-25

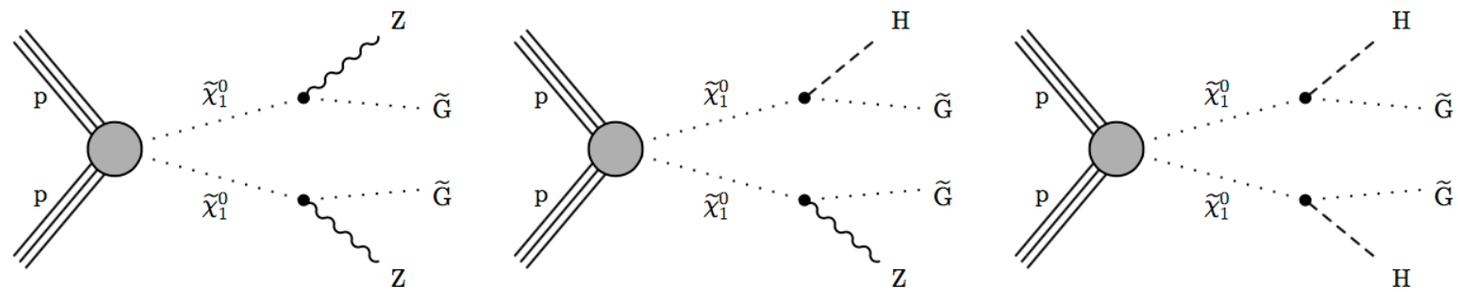
- **Higgsino LSP** or **slepton NLSP**.
- Compressed scenarios: **soft leptons + ISRjets + Etmiss**.
- Key: accessing leptons lower to pT(e/mu)>4.5/4 GeV.



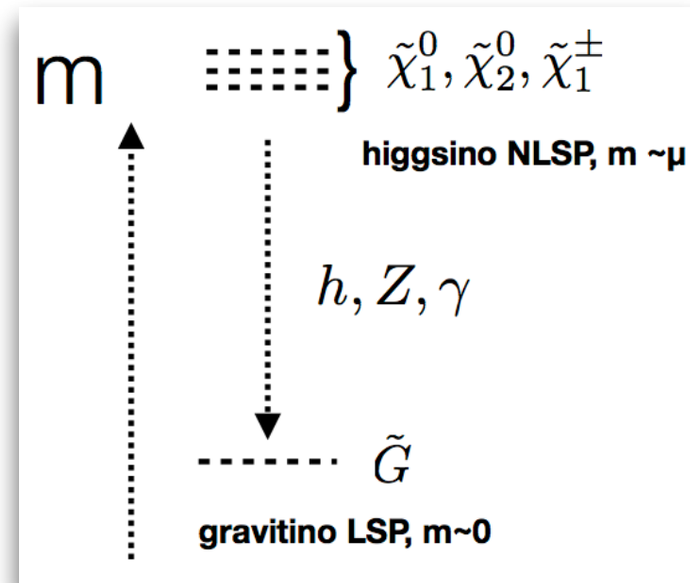




GMSB

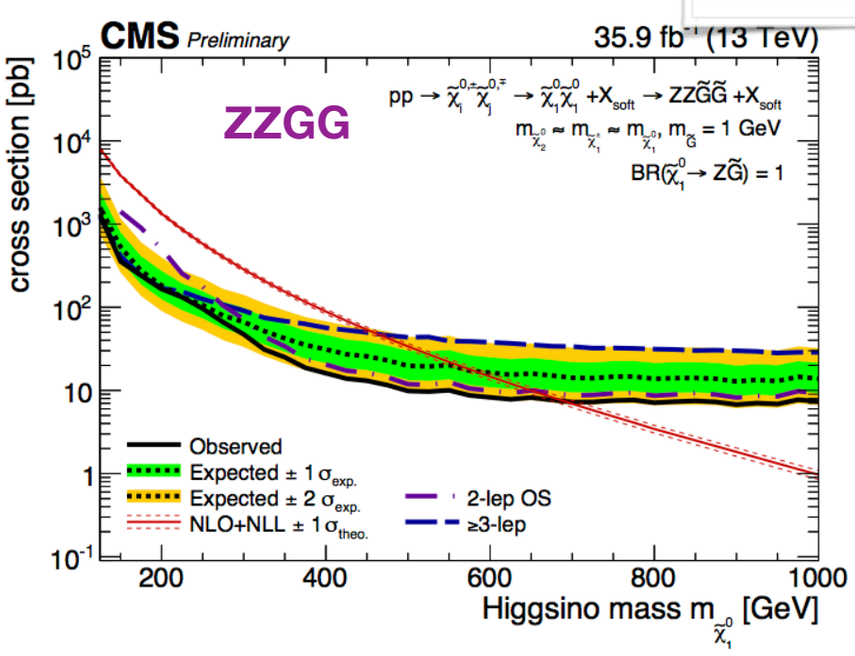


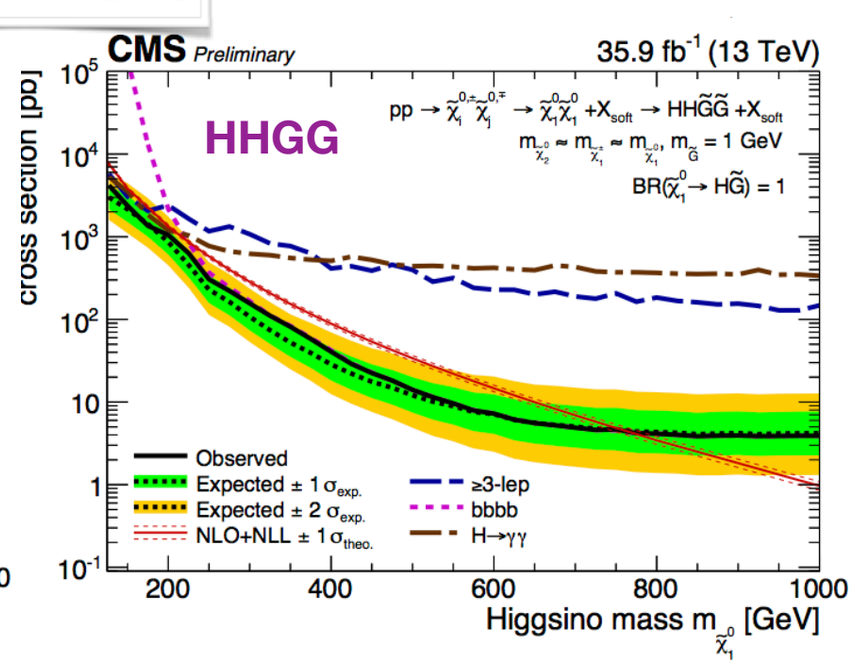
- **Higgsino NLSP; Gravitino LSP.**
- Dedicated channels: **2L, 3L, 4b, 2photon**.
- The exclusion limits on Higgsino mass extend up to 650-880 GeV depending on the BR assumption.



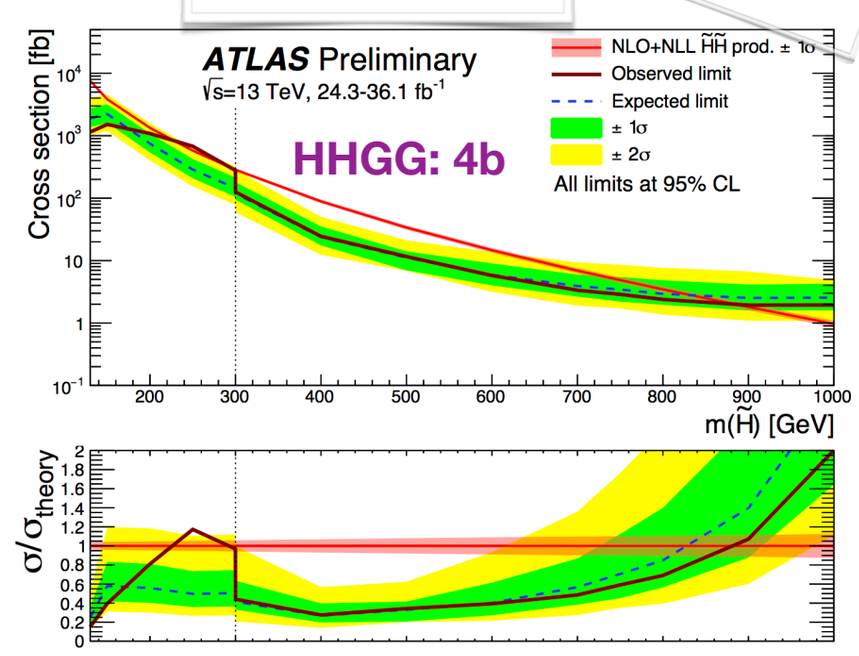
NEW !

CMS-PAS-SUS-17-004





ATLAS-CONF-2017-081



R-parity violating (RPV) and long-lived signatures

RPV

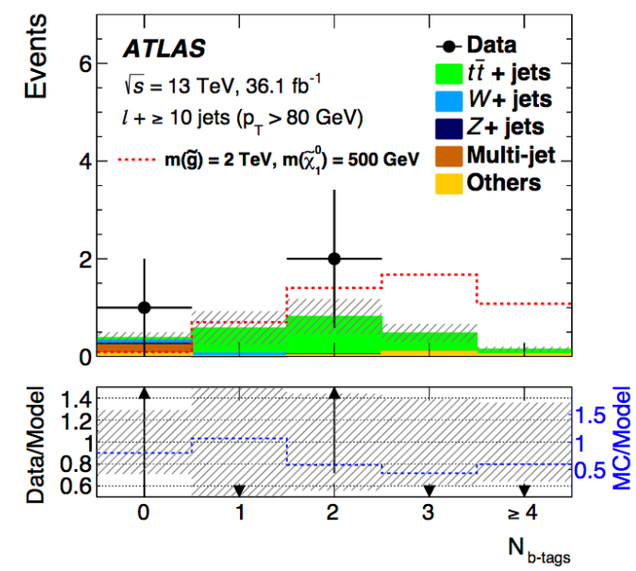
- LSP can decay
- Don't feature large Etmiss

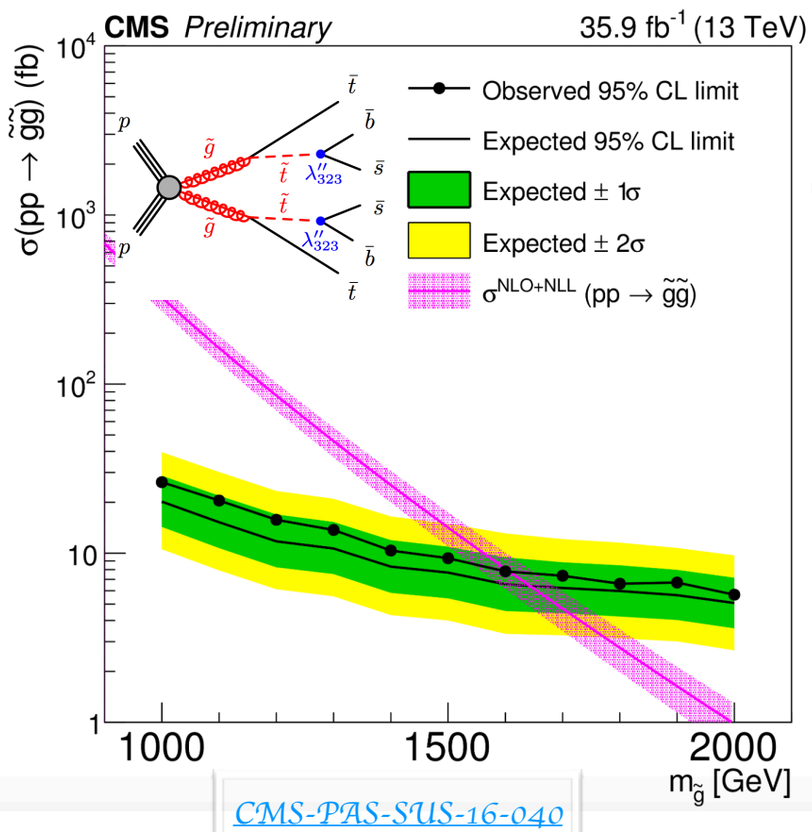
Long-lived signatures

- Weak RPV couplings
- Highly virtual intermediate state
- Mass degeneration

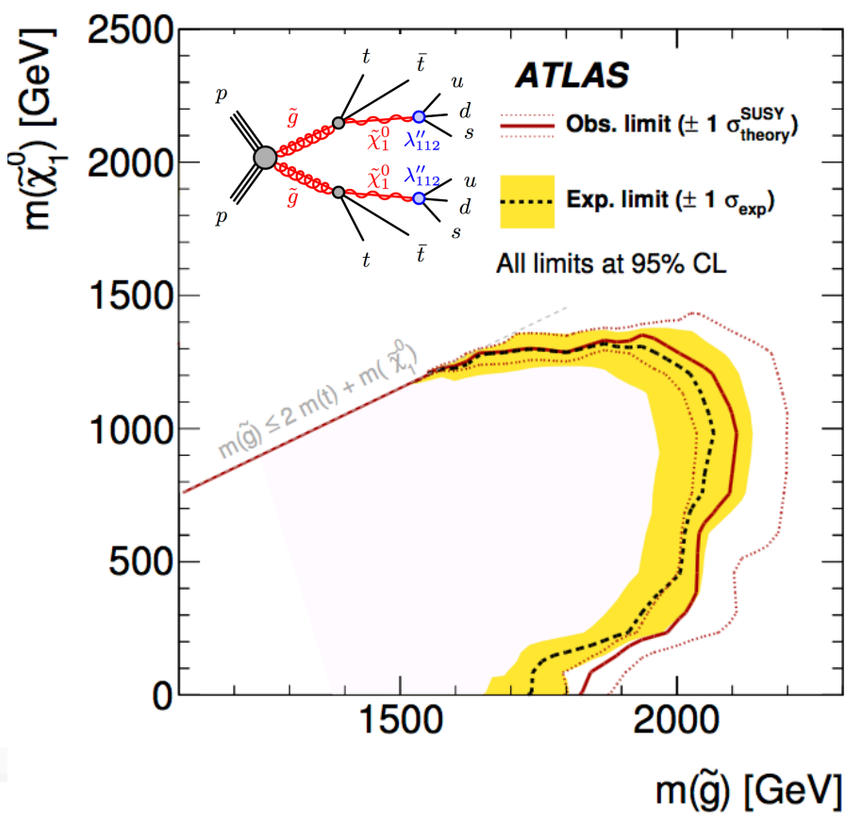
Gluino/stop—>multijet

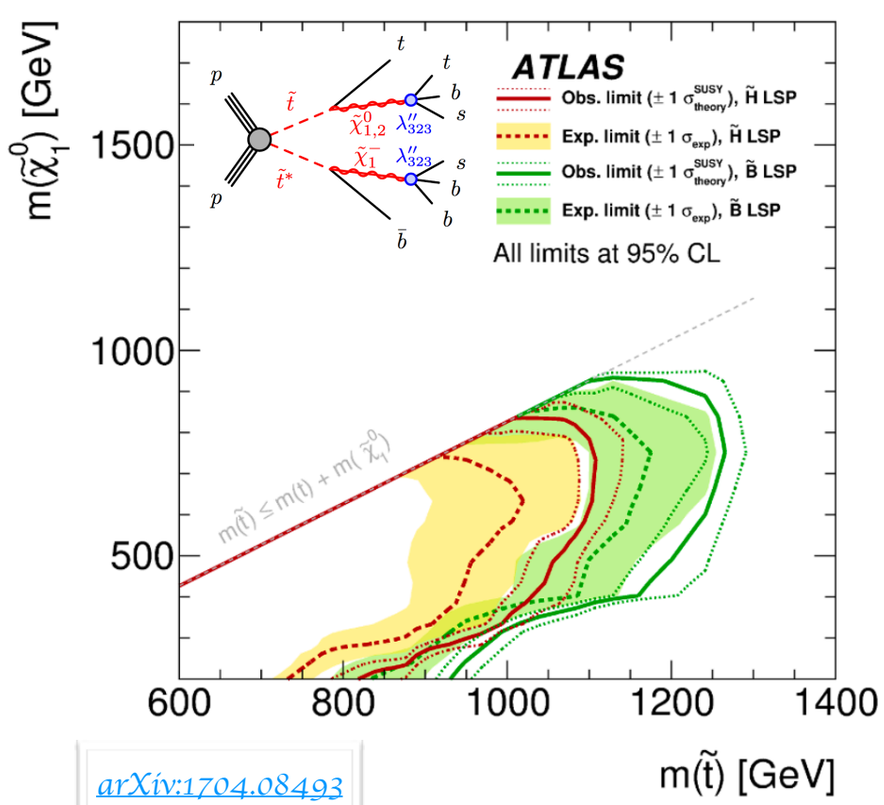
- **Neutralino1/stop as LSP**: decay promptly into quarks.
- Search for **1-lepton, high jet multiplicity** (8-12), NO Etmiss requirement.
- Multi-bin fit in Njet and Nbjet.
- Limits are also competitive: ~2.1 TeV for gluino mass and ~1.2 TeV for stop mass.





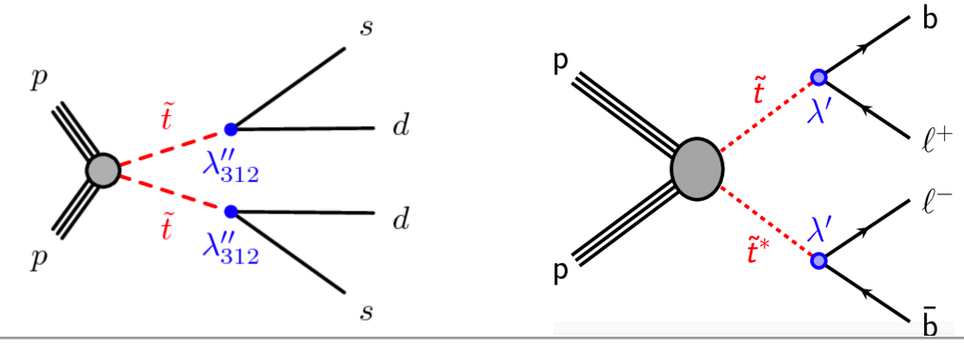
CMS-PAS-SUS-16-040



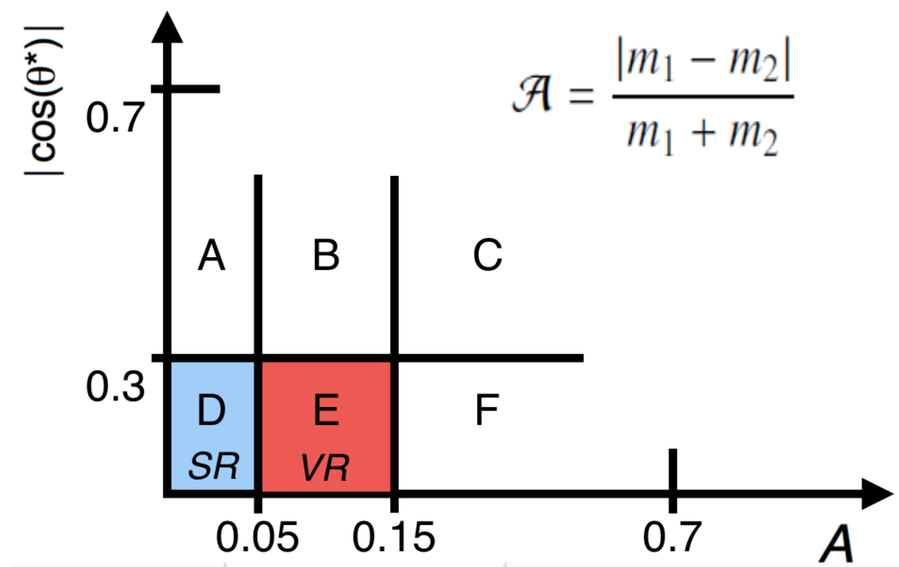


arXiv:1704.08493

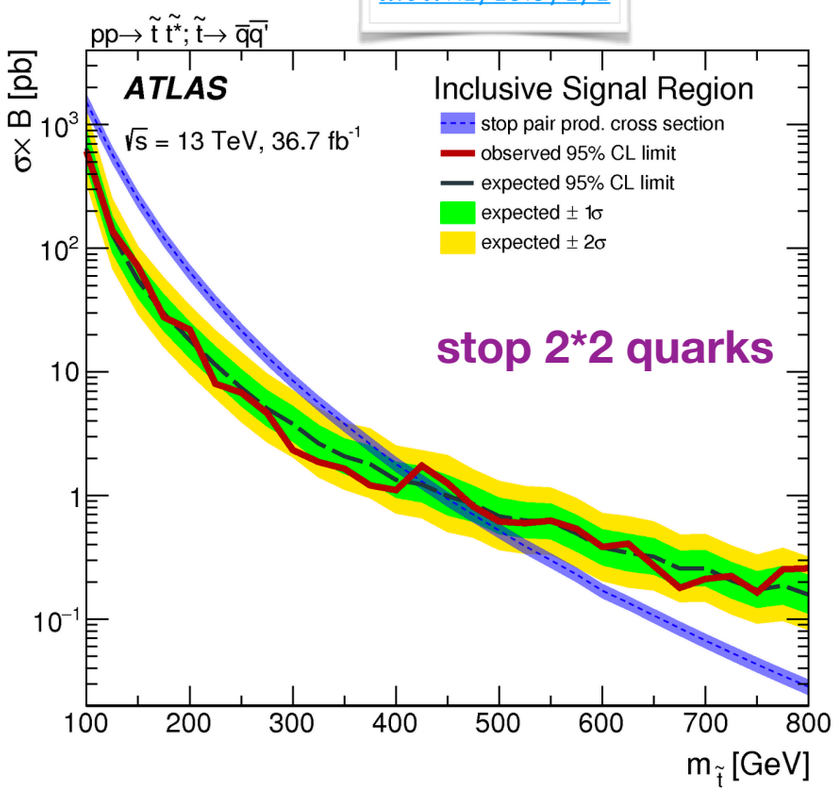
Direct stop production



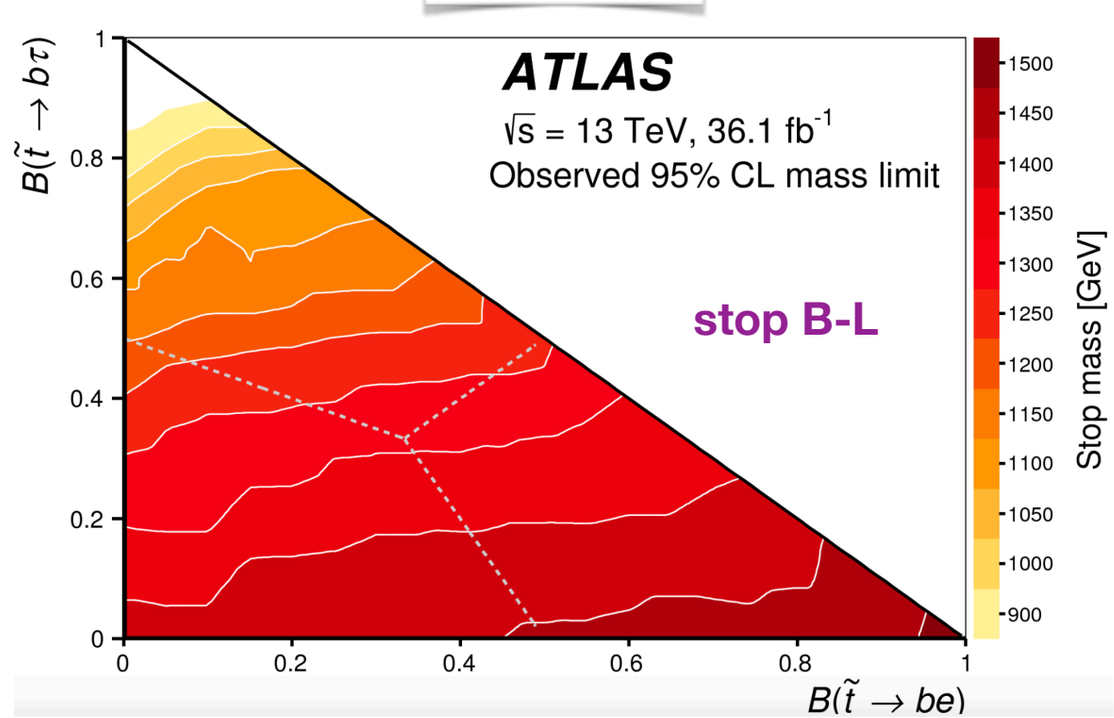
- **Stop as LSP**: decay promptly into
  - **two quarks** via baryon-number-violating RPV couplings
  - **lepton+bjet** via lepton-number-violating RPV couplings
- For both analyses: candidate resonances are constructed by pairing the 4j/2l2j using angular/mass information: mass asymmetry.

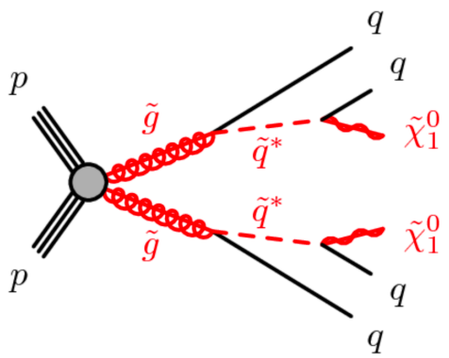


arXiv:1710.05544

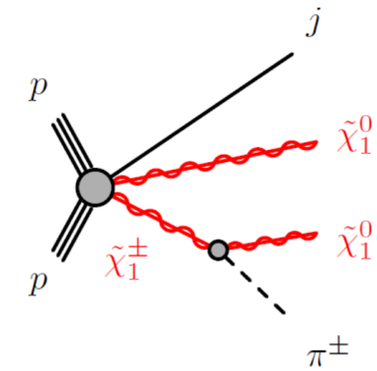


arXiv:1710.07171

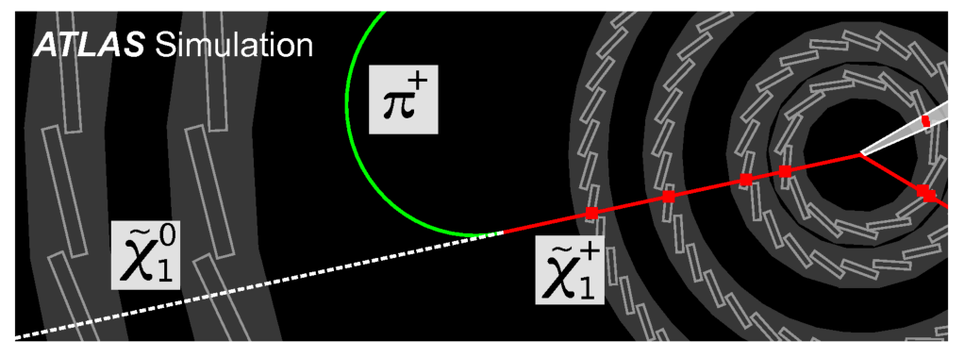




Long-lived particles

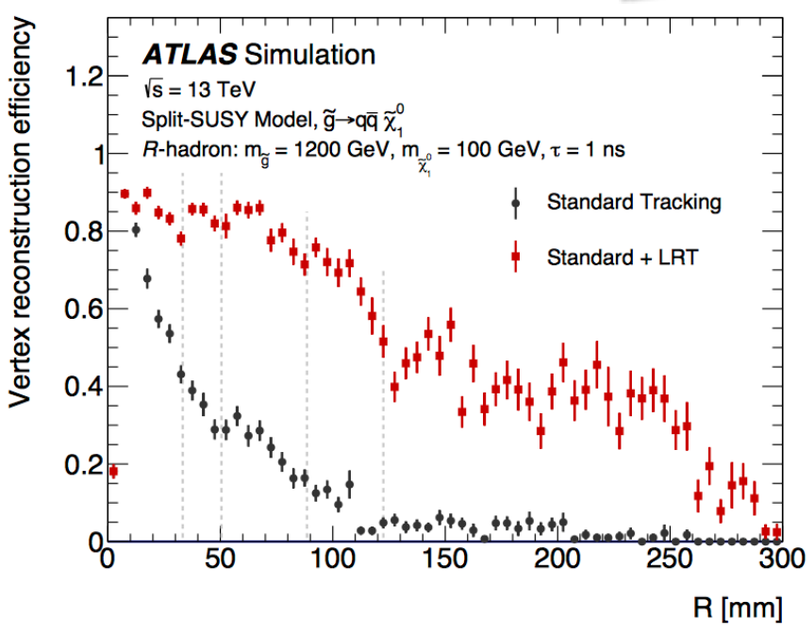


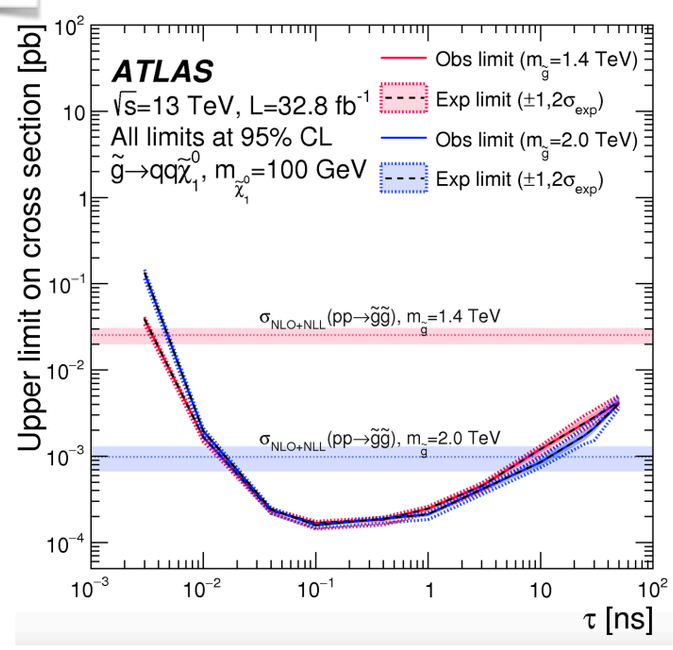
- Squark-mediated gluino decay: **long-lived gluino** if squark mass is large —> **displaced vertices**
- Large radius tracking algorithm improves the vertex reconstruction efficiency.
- Wino-LSP: chargino nearly degenerated with a stable neutralino —> **long-lived chargino** —> **disappearing tracks**



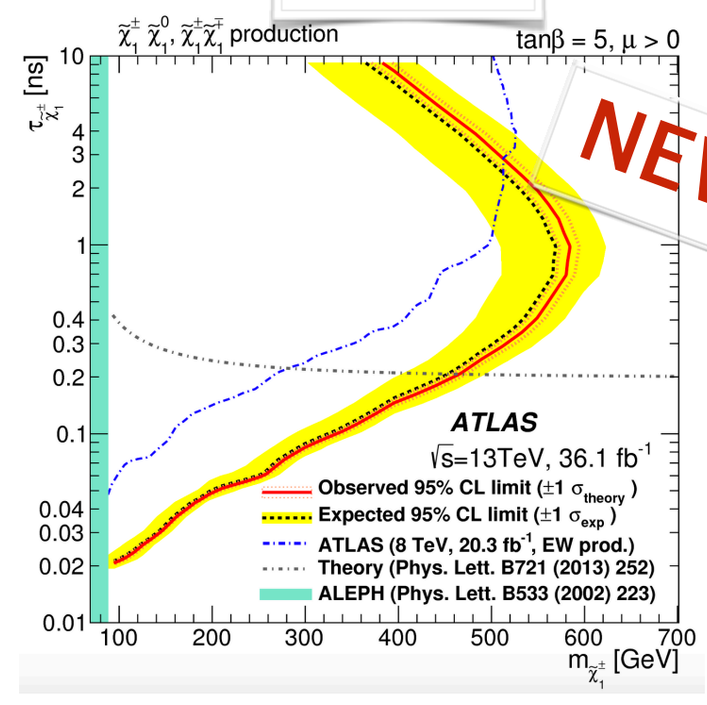
- Exclude pure winos up to 460 GeV.

arXiv:1710.04901





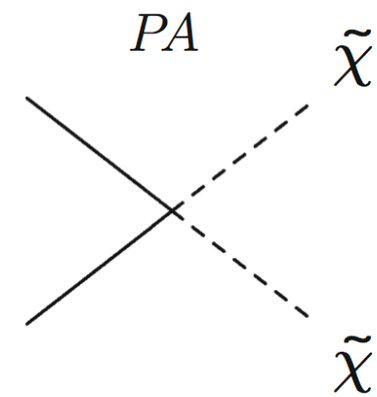
arXiv:1712.02118

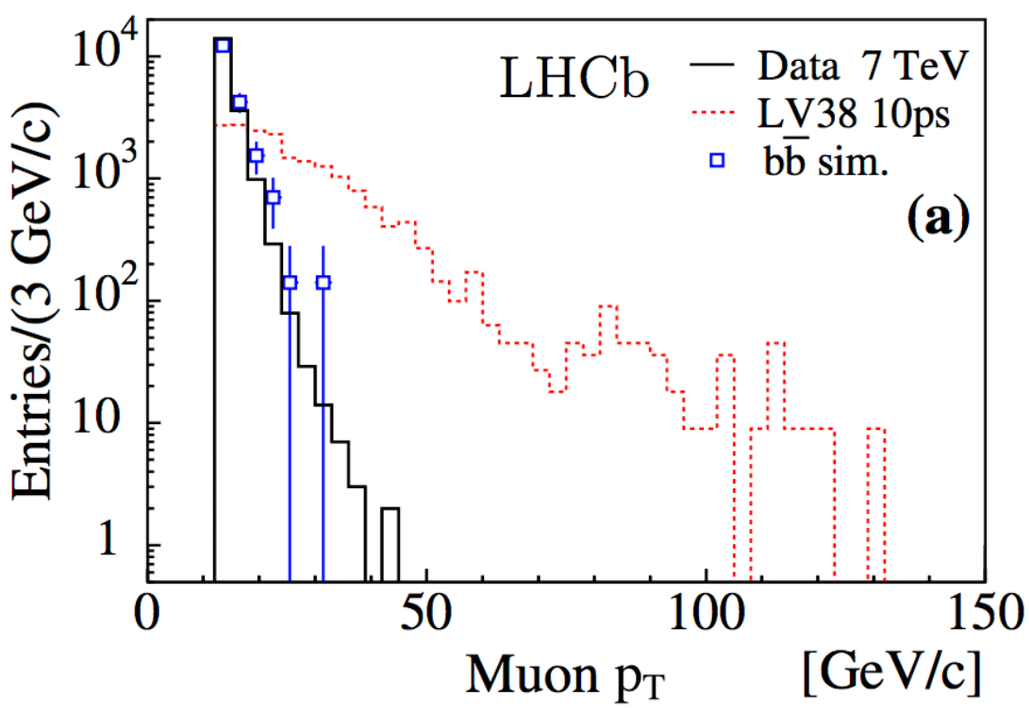


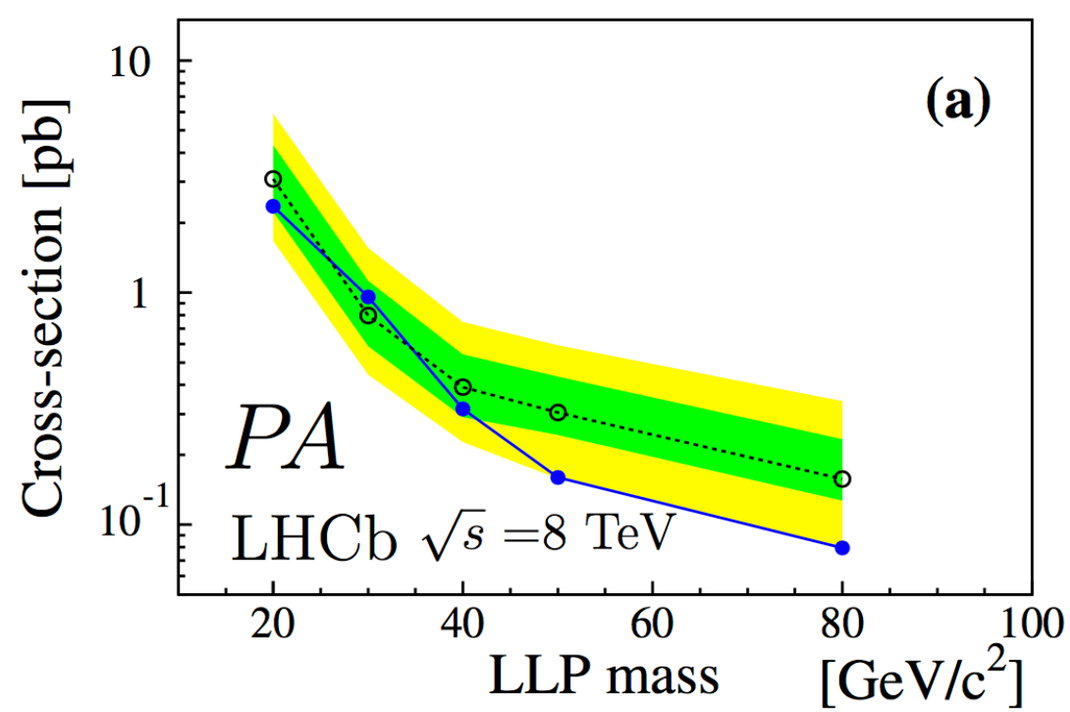
Long-lived particles

- **LHCb** results on long-lived particles decaying semi-leptonically.
- **Neutralino** decays into a muon and two jets.
- A displaced vertex associated with a high pT muon.
- Using 1(2) fb-1 of 7(8) TeV data.

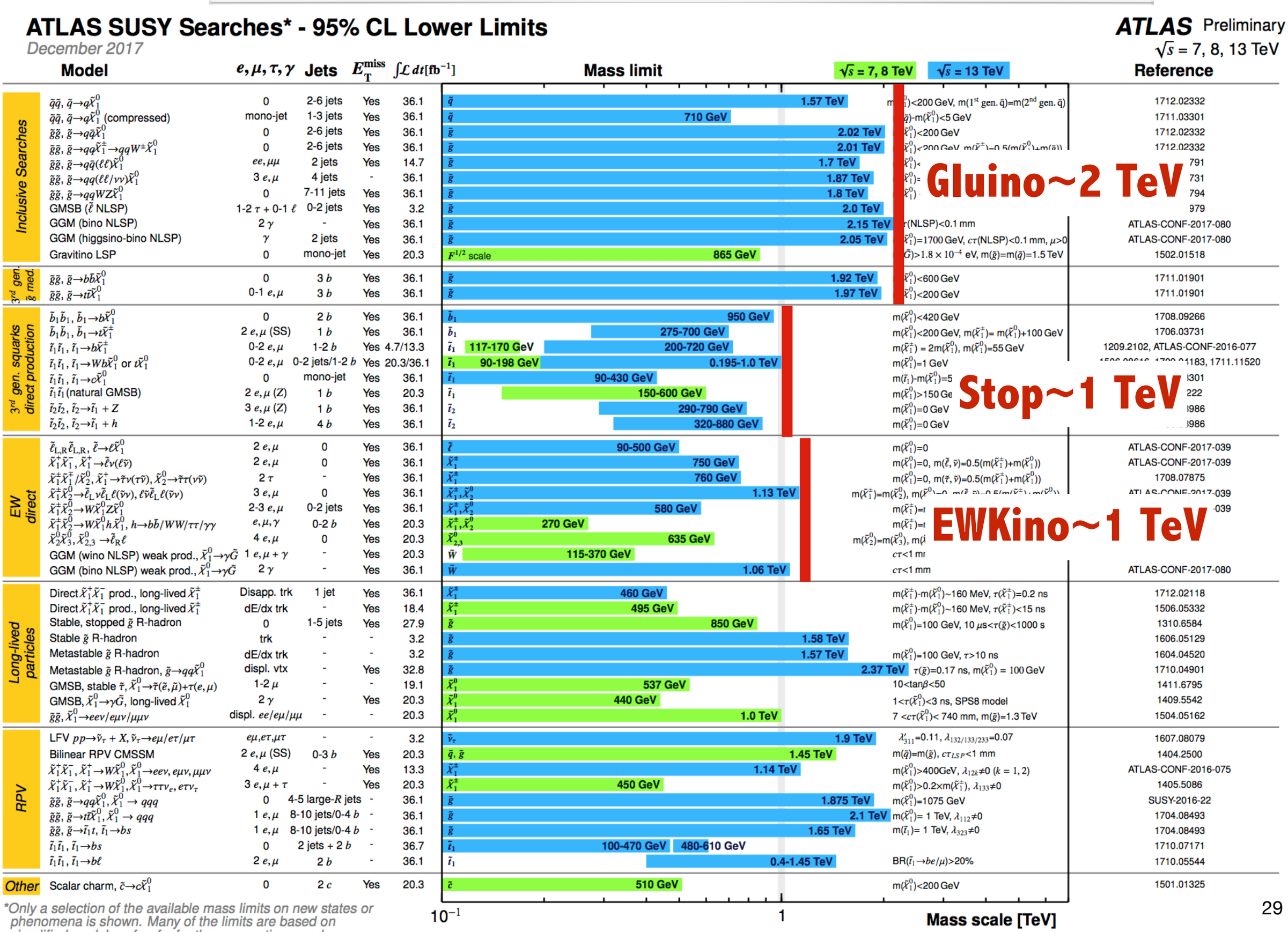
arXiv:1612.00945







A Big Picture

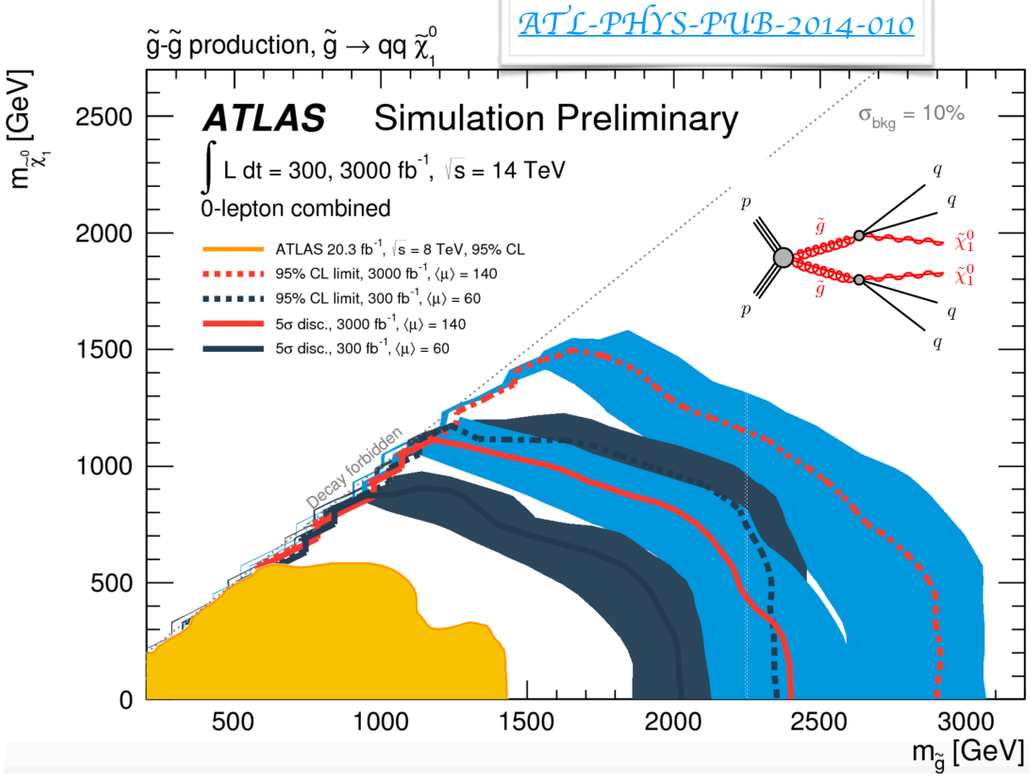


Prospect

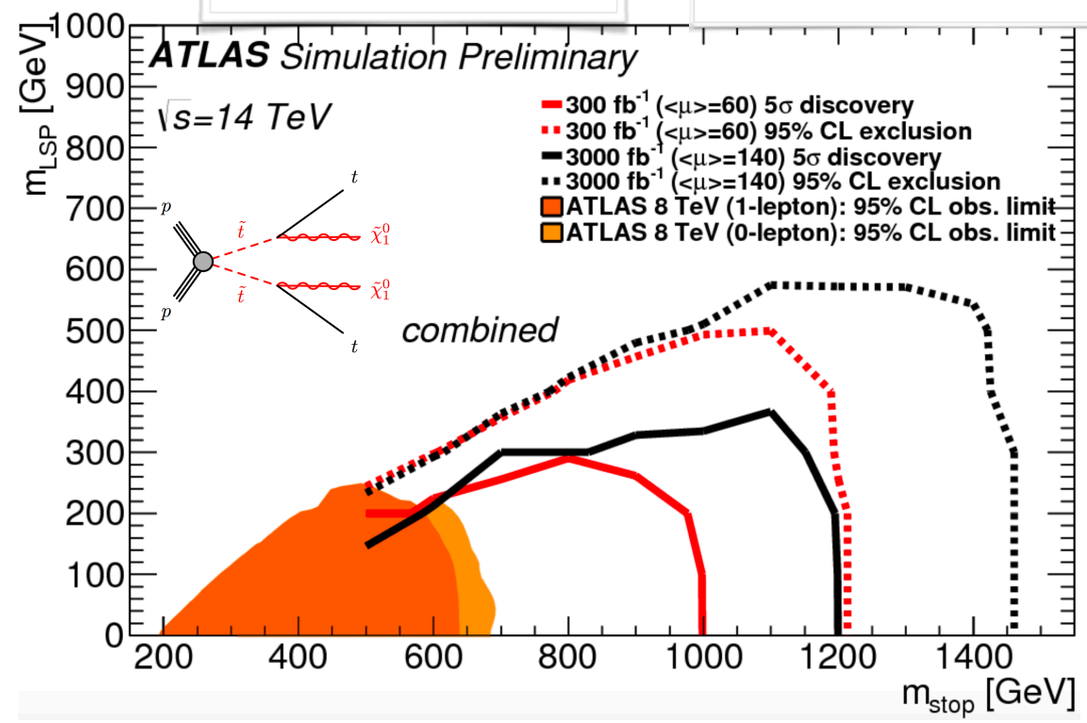
Discovery power @ HL-LHC ~3000 fb-1

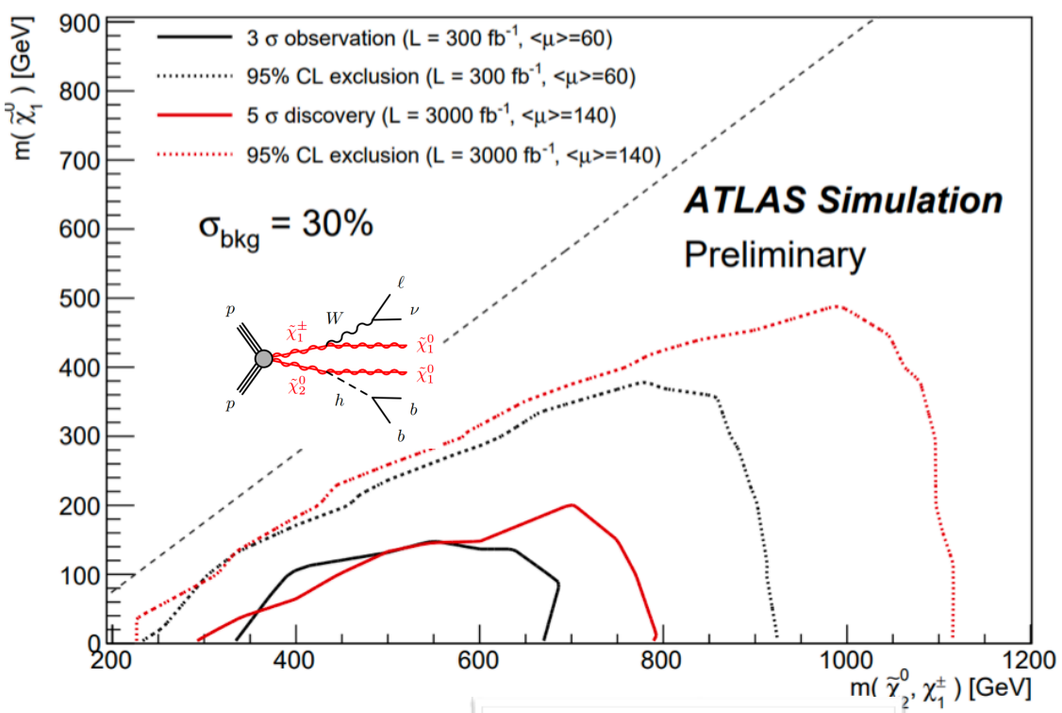
Gluino~2.5 TeV
Stop~1.2 TeV
Chargino~0.8 TeV
Stau~0.5 TeV

ATL-PHYS-PUB-2014-010



ATL-PHYS-PUB-2013-011





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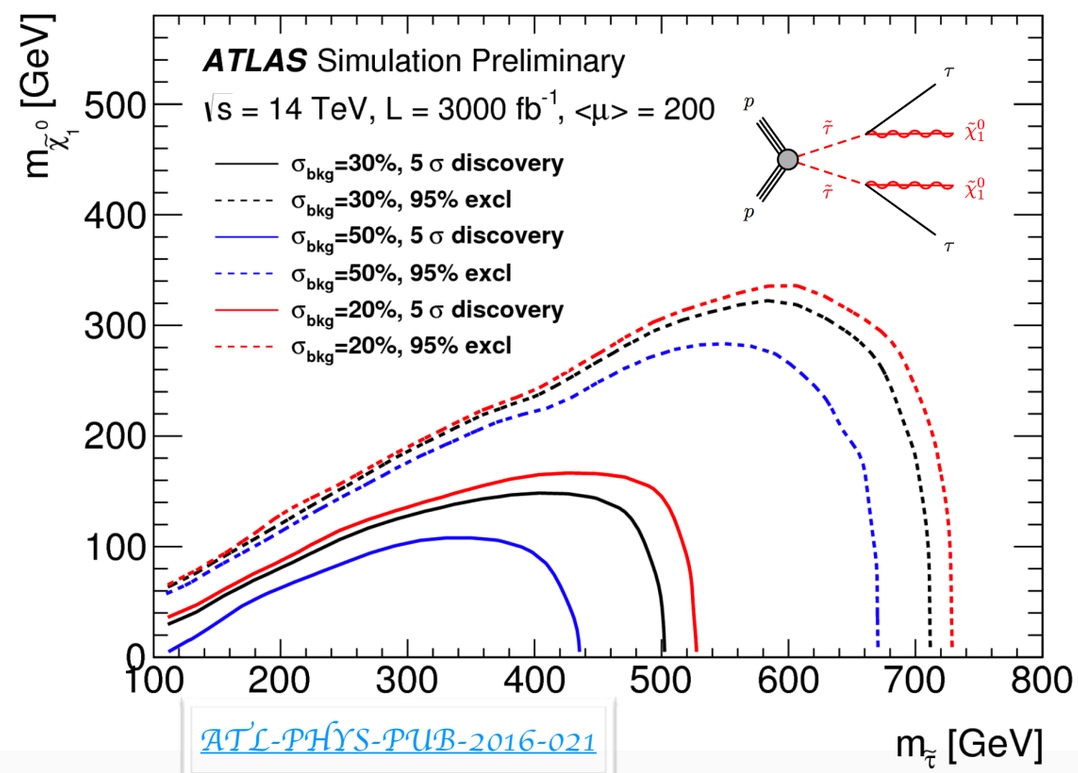


ATL-PHYS-PUB-2016-021

Summary

A board spectrum of searches have been performed at ATLAS, CMS and LHCb.

No sign of SUSY YET with the current data (13 TeV, 36 fb-1).

Now, moving towards

- new/challenge scenarios
- w/ more sophisticated techniques
- + increased luminosity/energy

ATLAS pub page

CMS pub page

LHCb pub page

STAY TUNED FOR SUSY :-)

Thanks!

Parallel: SUSY - Lecture Hall, 1st floor, Knowledge & Action Building

（知行楼一楼报告厅） （16:10-17:50）

- Conveners: Dr. ZHUANG, Xuai

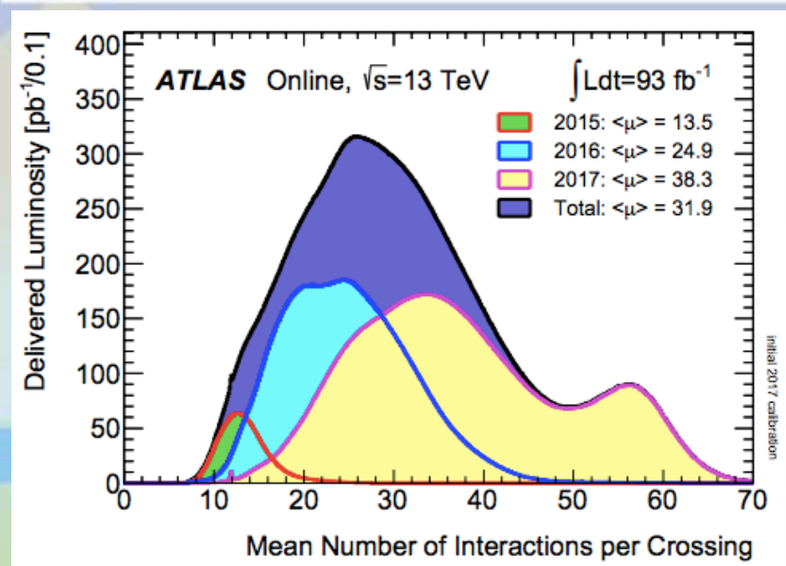
time	title	presenter
16:10	Sneutrino DM in the NMSSM with inverse seesaw mechanism	Prof. CAO, Junjie
16:30	Stop in Natural SUSY at the LHC	Dr. WU（武）, Lei（雷）
16:50	Inclusive SUSY search with one isolated lepton	CHENG, Huajie
17:10	Electroweak SUSY search with ditau	ZHU CHENZHENG
17:30	SUSY search with SS/3L	LIU YANG

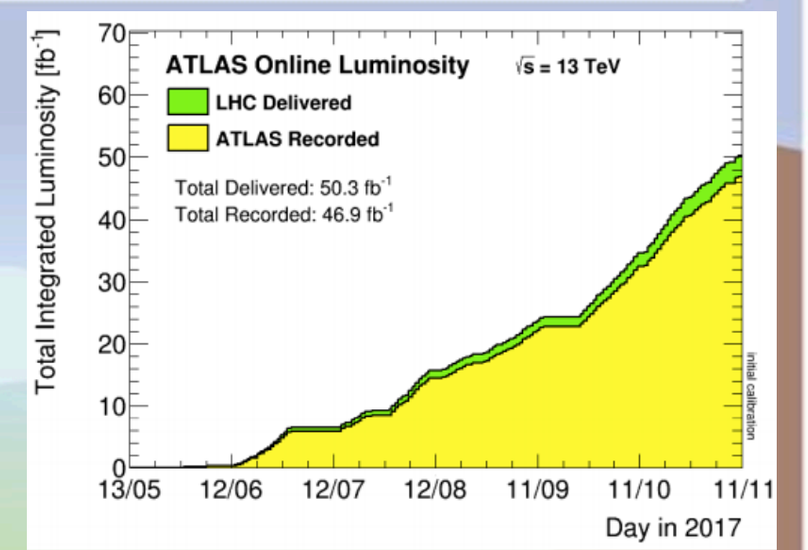
BACKUP

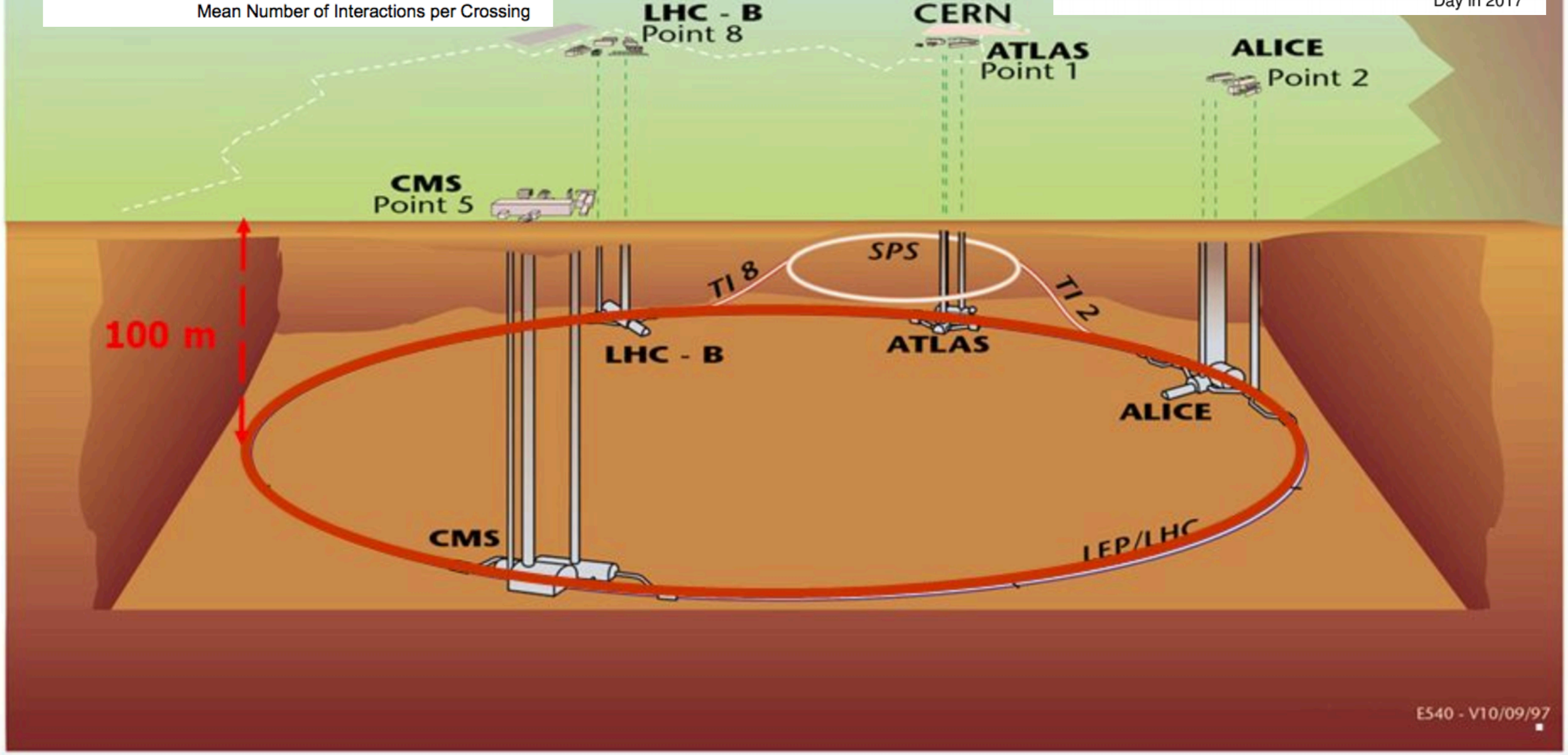
Gluino pair, squark pair, gluino-squark; 0 lepton	Submitted to PRD	Documents | 1712.02332 | Inspire Internal
Gaugino pair, gluino pair; disappearing track	Submitted to JHEP	Documents | 1712.02118 | Inspire HepData | Internal
Stop pair, WIMP DM pair; 1 lepton	Submitted to JHEP	Documents | 1711.11520 | Inspire Internal
Gluino pair; 0-1 leptons, many b-jets	Submitted to JHEP	Documents | 1711.01901 | Inspire Internal
WIMP DM pair + HF quarks; 0, 2 leptons	Submitted to EPJC	Documents | 1710.11412 | Inspire HepData | Internal
Stop pair; dijet pairs, RPV	Submitted to EPJC	Documents | 1710.07171 | Inspire HepData | Internal
Stop pair; 2 leptons, b-jets, RPV	Submitted to PRD	Documents | 1710.05544 | Inspire HepData | Internal
Gluino pair, squark pair; displaced vertices	Submitted to PRD	Documents | 1710.04901 | Inspire HepData | Internal
Stop pair; 0 lepton	Submitted to JHEP	Documents | 1709.04183 | Inspire HepData | Internal
Sbottom pair, stop pair; 0-1 leptons, b-jets	JHEP 11 (2017) 195	Documents | 1708.09266 | Inspire HepData | Internal
Gluino pair, squark pair; 1 lepton	Submitted to PRD	Documents | 1708.08232 | Inspire HepData | Internal
Chargino-neutralino pair; taus	Submitted to EPJC	Documents | 1708.07875 | Inspire HepData | Internal
Stop pair; 2 leptons	Submitted to EPJC	Documents | 1708.03247 | Inspire HepData | Internal
Gluino pair, squark pair; 0 lepton, high jet multiplicity	JHEP12 (2017) 034	Documents | 1708.02794 | Inspire HepData | Internal
Stop pair; Z/h boson	JHEP 08 (2017) 006	Documents | 1706.03986 | Inspire HepData | Internal
Two same-sign leptons or three leptons	JHEP 09 (2017) 084	Documents | 1706.03731 | Inspire HepData | Internal
Gluino pair, stop pair; 1 lepton, RPV	JHEP 09 (2017) 88	Documents | 1704.08493 | Inspire HepData | Internal
Stop pair; taus	ATLAS-CONF-2017-079	Documents Internal
Chargino-neutralino pair; 2-3 leptons	ATLAS-CONF-2017-039	Documents Briefing Internal
Gluino pair, squark pair, gluino-squark; 0 lepton	ATLAS-CONF-2017-022	Documents Briefing Internal

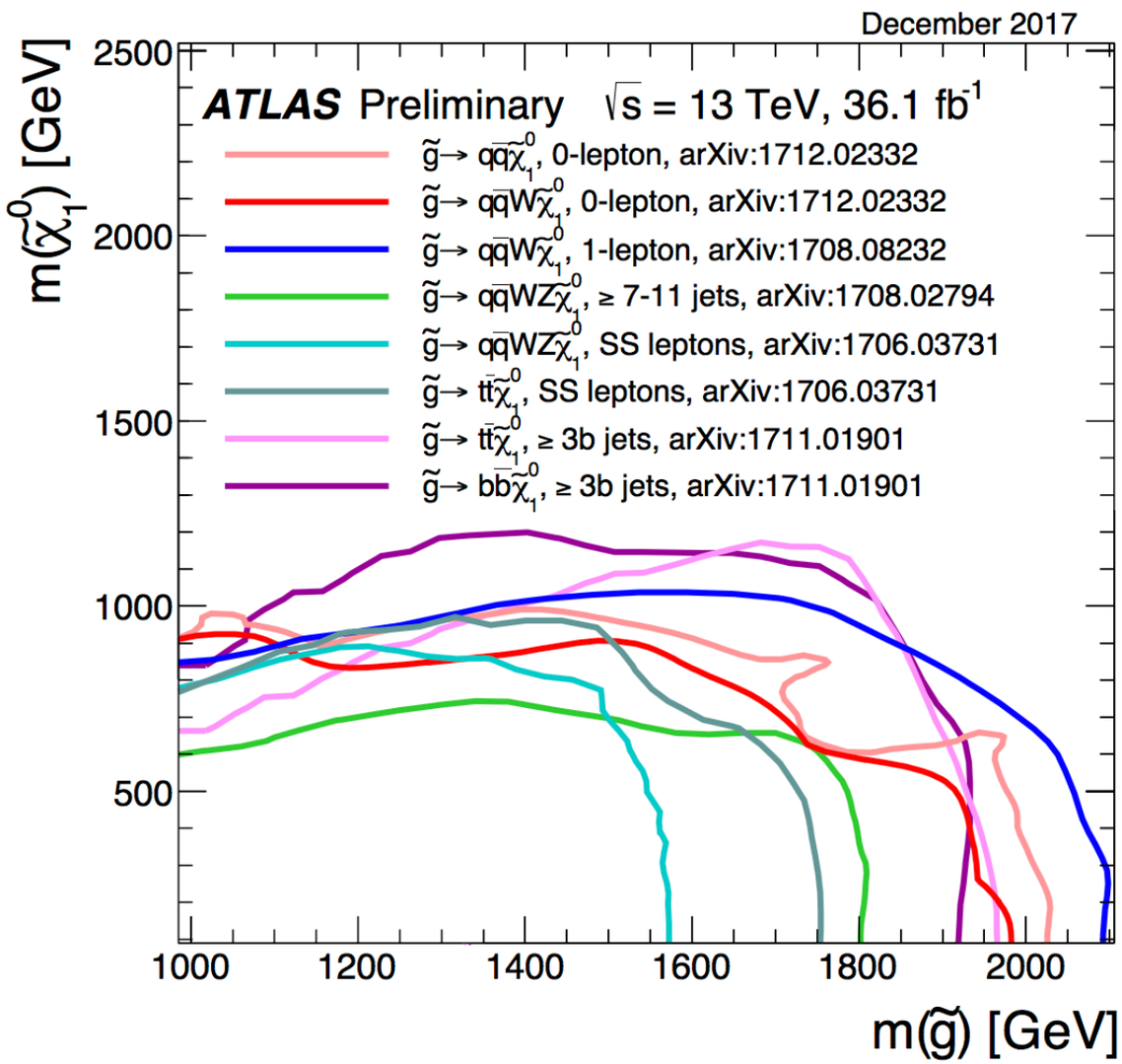
CMS-PAS-SUS-17-002	Search for supersymmetry in events with tau leptons and missing transverse momentum in proton-proton collisions at s	
CMS-PAS-SUS-17-009	Search for selectrons and smuons at s	
CMS-PAS-SUS-17-006	Search for physics beyond the standard model in events with Higgs bosons and missing transverse momentum in proton-proton collisions at s	
CMS-PAS-SUS-16-040	Search for R	
CMS-PAS-SUS-17-004	Combined search for electroweak production of charginos and neutralinos in pp collisions at s	
CMS-PAS-SUS-17-003	Search for pair production of tau sleptons in s	
CMS-PAS-SUS-16-052	Search for supersymmetry in events with at least one soft lepton, low jet multiplicity, and missing transverse momentum in proton-proton collisions at s	
CMS-PAS-SUS-16-050	Search for supersymmetry using hadronic top quark tagging in 13 TeV pp collisions	Submitted to PRD
CMS-SUS-16-033	Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV	PRD 96 (2017) 032003
CMS-PAS-SUS-16-043	Search for electroweak production of charginos and neutralinos in the WH final state in proton-proton collisions at s	JHEP 11 (2017) 029
CMS-PAS-SUS-16-051	Search for top squark pair production in the single lepton final state in pp collisions at s	JHEP 10 (2017) 019
CMS-PAS-SUS-16-042	Search for supersymmetry in events with one lepton and multiple jets in proton-proton collisions at s	Submitted to PLB
CMS-PAS-SUS-16-034	Search for new physics in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum in pp collisions at s	Submitted to JHEP
CMS-PAS-SUS-16-036	Search for new physics in the all-hadronic final state with the M	Eur. Phys. J C 77 (2017) 710
CMS-PAS-SUS-16-047	Search for supersymmetry in events with at least one photon, missing transverse momentum, and large transverse event activity in proton-proton collisions at 13 TeV	Accepted by JHEP
CMS-PAS-SUS-16-035	Search for beyond the standard model physics in events with two leptons of the same sign, missing transverse momentum, and jets in proton-proton collisions at s	EPJC 77 (2017) 578
CMS-PAS-SUS-16-046	Search for GMSB supersymmetry in events with at least one photon and missing transverse momentum in pp collisions at s	Submitted to PLB
CMS-PAS-SUS-17-001	Search for direct stop pair production in the dilepton final state at s	Submitted to PRD
CMS-PAS-SUS-16-037	Search for supersymmetry in pp collisions at s	PRL 119 (2017) 151802
CMS-PAS-SUS-16-044	Search for the pair production of Higgsinos in pp collisions at s	Submitted to PRD
CMS-PAS-SUS-16-048	Search for new physics in events with two low momentum opposite-sign leptons and missing transverse energy at s	
CMS-PAS-SUS-16-049	Search for direct top squark pair production in the all-hadronic final state in proton-proton collisions at s	JHEP 10 (2017) 005
CMS-PAS-SUS-16-032	Search for direct production of bottom and top squark pairs in proton-proton collisions at s	Submitted to PLB
CMS-PAS-SUS-16-045	Search for supersymmetry with Higgs to diphoton decays using the razor variables at s	Submitted to PLB
CMS-PAS-SUS-16-041	Search for new physics in events with multileptons and jets in 35.9 fb	Submitted to JHEP
CMS-PAS-SUS-16-039	Search for electroweak production of charginos and neutralinos in multilepton final states in pp collision data at s	Submitted to JHEP

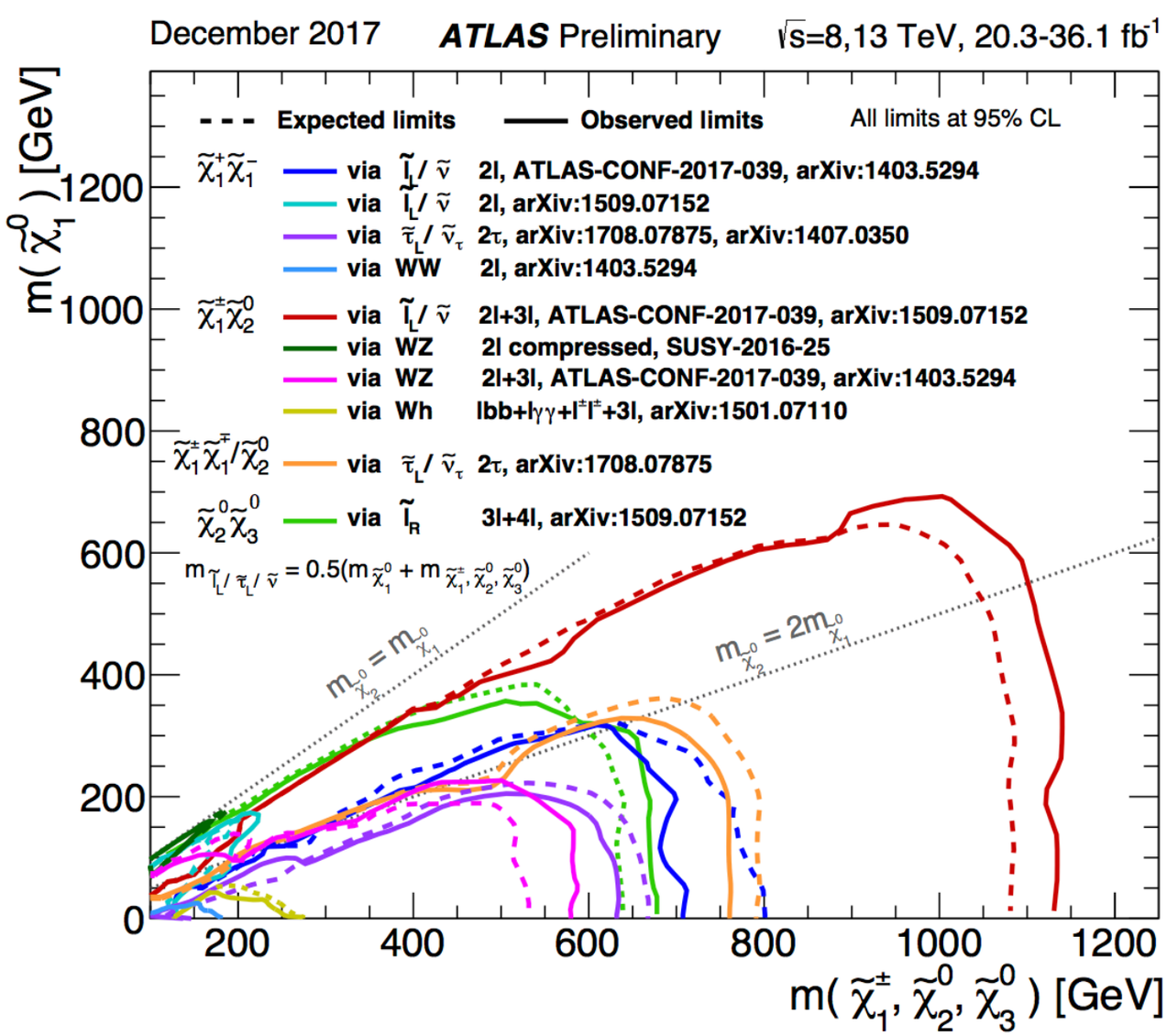
Overall view of the LHC experiments.

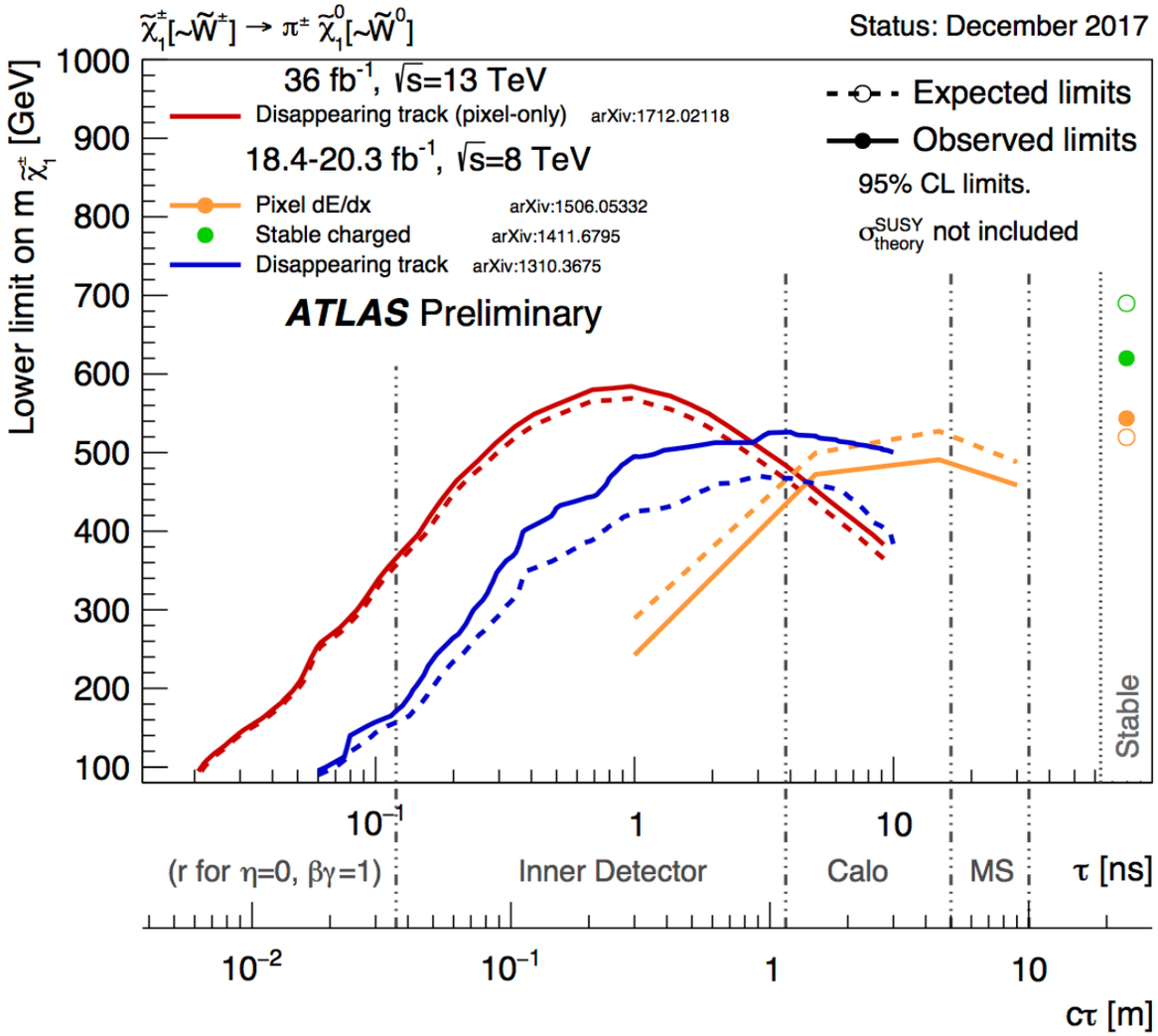


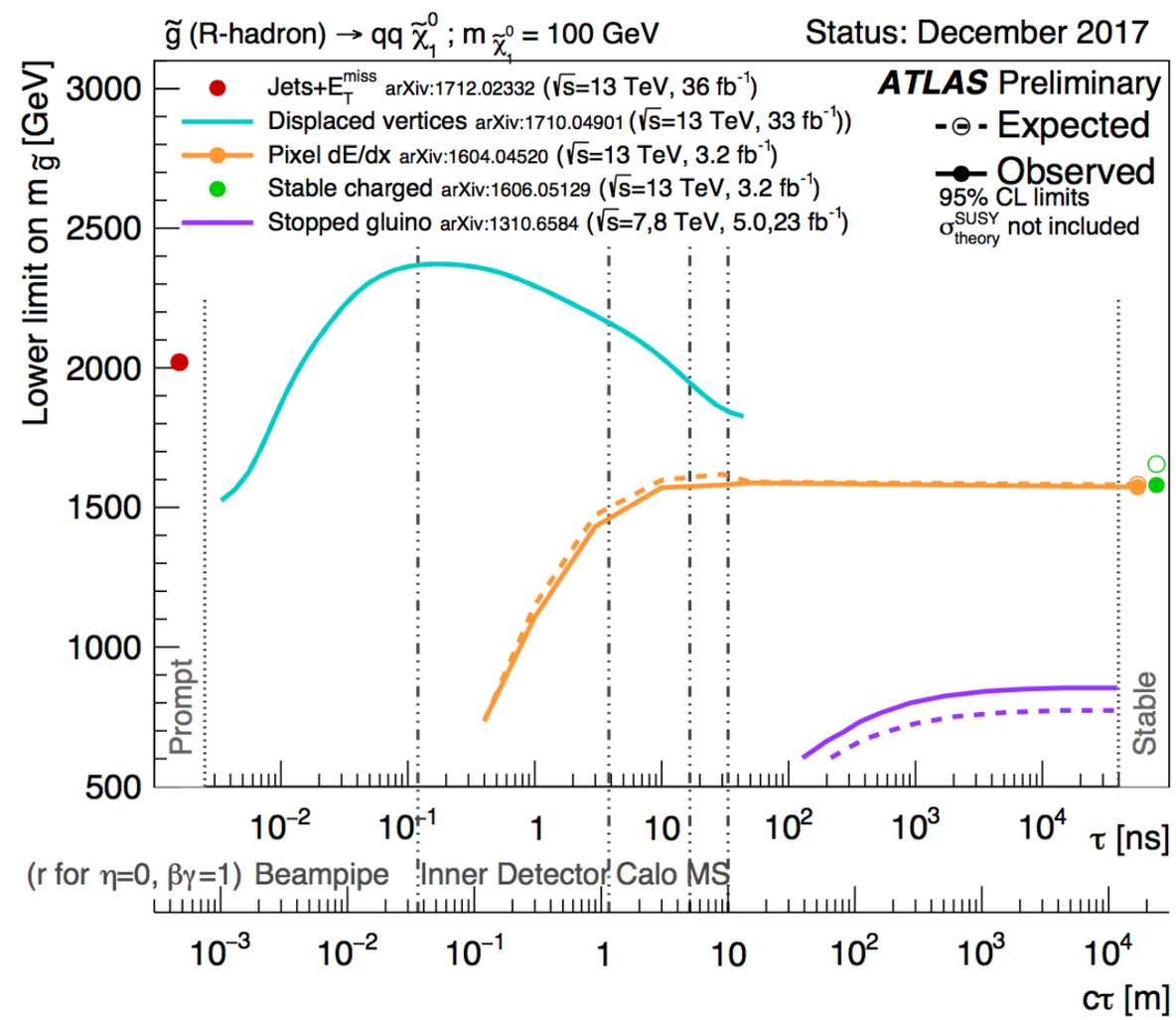




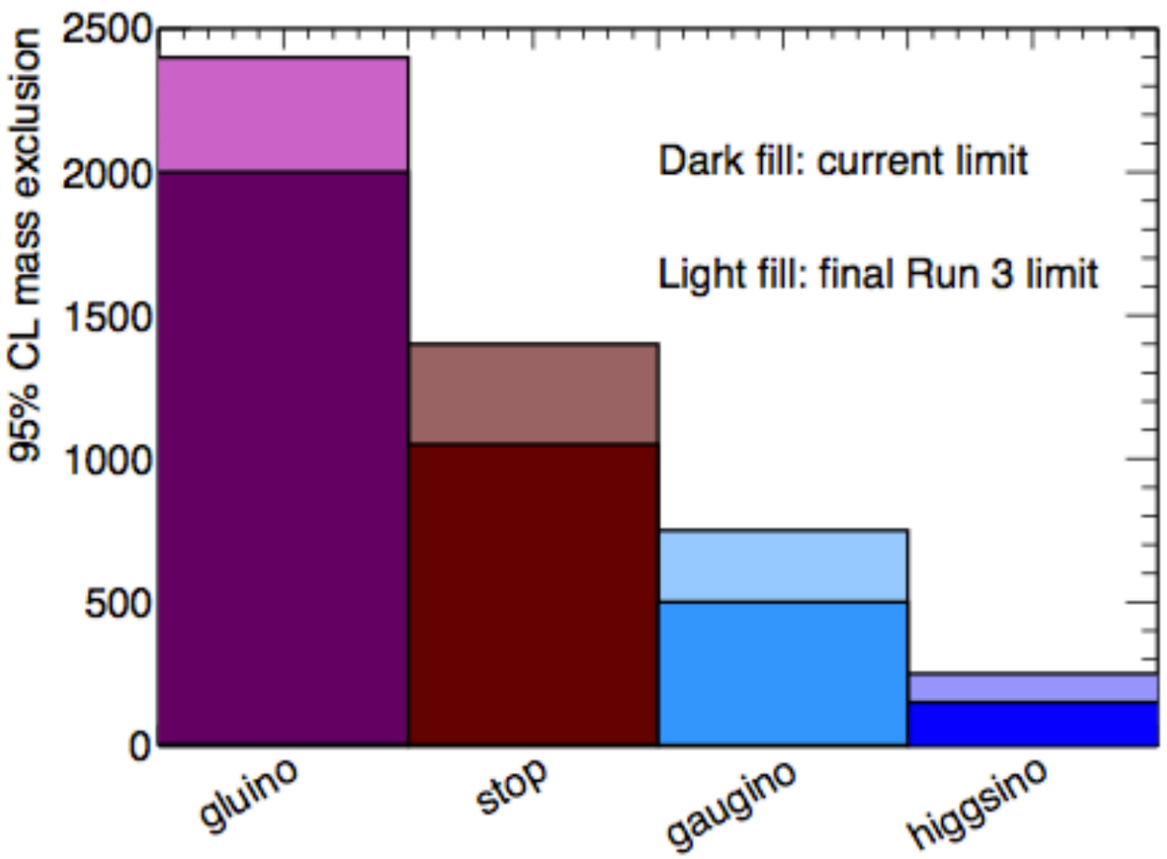

December 2017
ATLAS Preliminary √s = 13 TeV, 36.1 fb-1
g̃→ qq̄χ̃01, 0-lepton, arXiv:1712.02332
g̃→ qq̄Wχ̃01, 0-lepton, arXiv:1712.02332
g̃→ qq̄Wχ̃01, 1-lepton, arXiv:1708.08232
g̃→ qq̄WZχ̃01, ≥ 7-11 jets, arXiv:1708.02794
g̃→ qq̄WZχ̃01, SS leptons, arXiv:1706.03731
g̃→ tt̄χ̃01, SS leptons, arXiv:1706.03731
g̃→ tt̄χ̃01, ≥ 3b jets, arXiv:1711.01901
g̃→ bb̄χ̃01, ≥ 3b jets, arXiv:1711.01901
m(χ̃01) [GeV]
m(g̃) [GeV]


December 2017
ATLAS Preliminary
√s=8,13 TeV, 20.3-36.1 fb-1
Expected limits
Observed limits
All limits at 95% CL
χ̃1±χ̃1∓
via l̃L/ ν̃ 2l, ATLAS-CONF-2017-039, arXiv:1403.5294
via l̃L/ ν̃ 2l, arXiv:1509.07152
via τ̃L/ ν̃τ 2τ, arXiv:1708.07875, arXiv:1407.0350
via WW 2l, arXiv:1403.5294
χ̃1±χ̃02
via l̃L/ ν̃ 2l+3l, ATLAS-CONF-2017-039, arXiv:1509.07152
via WZ 2l compressed, SUSY-2016-25
via WZ 2l+3l, ATLAS-CONF-2017-039, arXiv:1403.5294
via Wh lbb+lγγ+l±l±+3l, arXiv:1501.07110
χ̃1±χ̃1∓/χ̃02
via τ̃L/ ν̃τ 2τ, arXiv:1708.07875
χ̃02χ̃03
via l̃R 3l+4l, arXiv:1509.07152
m l̃L/ τ̃L/ ν̃ = 0.5(m χ̃01 + m χ̃±1, χ̃02, χ̃03)
m χ̃02 = m χ̃01
m χ̃02 = 2m χ̃01
m(χ̃01) [GeV]
m(χ̃±1, χ̃02, χ̃03) [GeV]

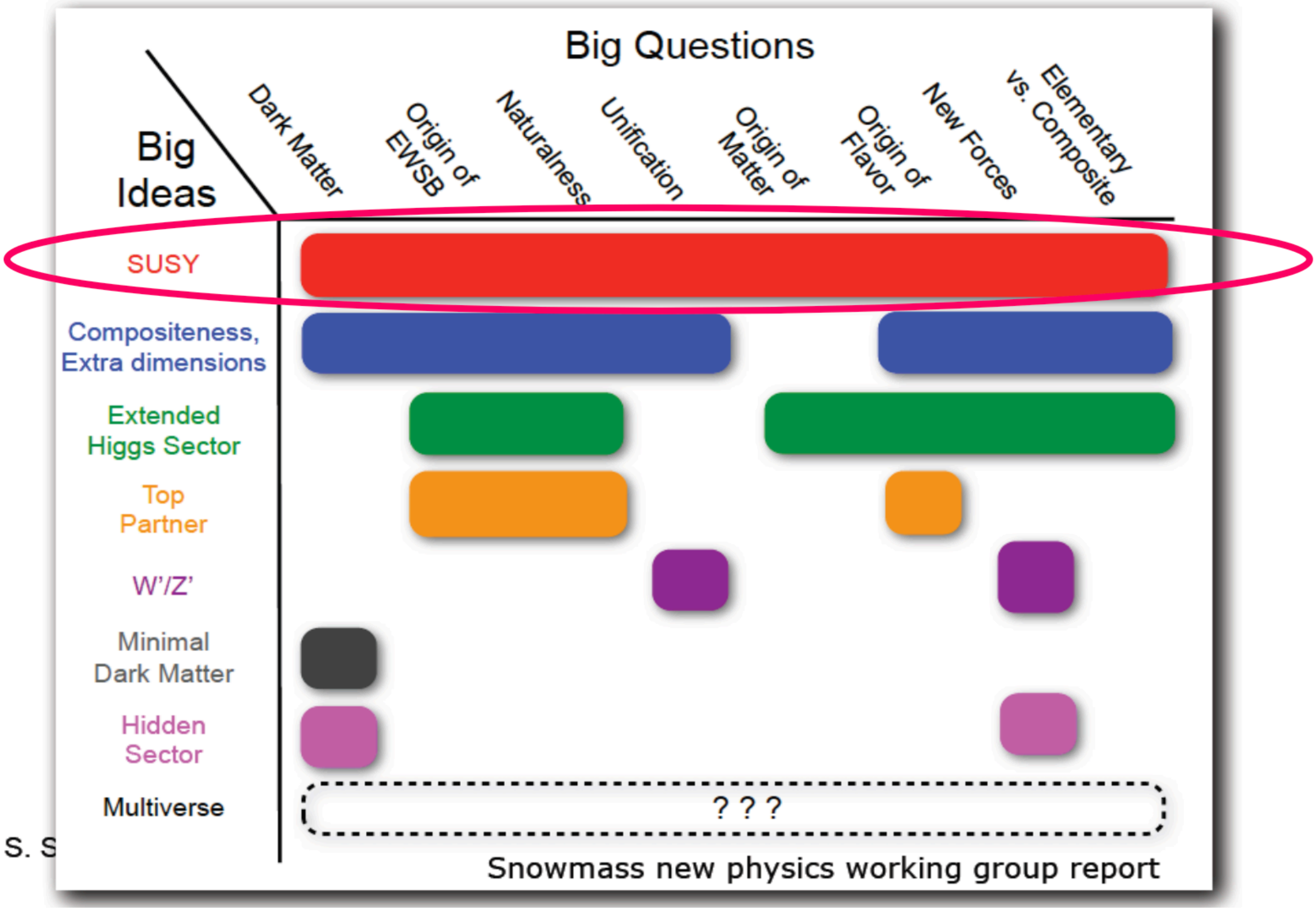

$\tilde{\chi}_1^{\pm}[\sim\tilde{W}^{\pm}] \rightarrow \pi^{\pm}\,\tilde{\chi}_1^0[\sim\tilde{W}^0]$
Status: December 2017
36 fb^{-1}, $\sqrt{s}$=13 TeV
Disappearing track (pixel-only) arXiv:1712.02118
18.4-20.3 fb^{-1}, $\sqrt{s}$=8 TeV
Pixel dE/dx arXiv:1506.05332
Stable charged arXiv:1411.6795
Disappearing track arXiv:1310.3675
ATLAS Preliminary
Expected limits
Observed limits
95% CL limits.
σ^{SUSY}_{theory} not included
Lower limit on m $\tilde{\chi}_1^{\pm}$ [GeV]
Stable
(r for η=0, βγ=1)
Inner Detector
Calo
MS
τ [ns]
cτ [m]


$\tilde{g}$ (R-hadron) → qq $\tilde{\chi}_1^0$; m $\tilde{\chi}_1^0$ = 100 GeV
Status: December 2017
Jets+E_T^{miss} arXiv:1712.02332 ($\sqrt{s}$=13 TeV, 36 fb^{-1})
Displaced vertices arXiv:1710.04901 ($\sqrt{s}$=13 TeV, 33 fb^{-1}))
Pixel dE/dx arXiv:1604.04520 ($\sqrt{s}$=13 TeV, 3.2 fb^{-1})
Stable charged arXiv:1606.05129 ($\sqrt{s}$=13 TeV, 3.2 fb^{-1})
Stopped gluino arXiv:1310.6584 ($\sqrt{s}$=7,8 TeV, 5.0,23 fb^{-1})
ATLAS Preliminary
Expected
Observed
95% CL limits
σ^{SUSY}_{theory} not included
Lower limit on m $\tilde{g}$ [GeV]
Prompt
Stable
τ [ns]
(r for η=0, βγ=1)
Beampipe
Inner Detector
Calo
MS
cτ [m]

Expected excl. space to explore till Run 3



- ~85% for gluino
- ~75% for stop
- ~60% for gaugino
- ~>50% for higgsino


Big Questions
Big Ideas
Dark Matter
Origin of EWSB
Naturalness
Unification
Origin of Matter
Origin of Flavor
New Forces
Elementary vs. Composite
SUSY
Compositeness, Extra dimensions
Extended Higgs Sector
Top Partner
W'/Z'
Minimal Dark Matter
Hidden Sector
Multiverse
? ? ?
Snowmass new physics working group report

S. S