DSU 2018
25-29 June 2018 Annecy

Dark Matter searches in SUSY and other UV complete models at LHC searches

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Introduction

- "Two-ways" Models for dark matter to shape expectations and experimental search strategies at LHC: *(Kai Schmidt-Hoberg DM@LHC2018)*

This talk

UV

- Tackle fundamental problems such as e.g. hierarchy problem and look for implications
  - WIMPs
  - …
- **Well-motivated** dark matter candidates, but also **strong theoretical bias**

IR

- Naturalness arguments suggest new physics at the LHC
- Nothing yet → motivates broader thinking.
- **As model independent as possible**
- **EFTs** or **simplified models**

Searches at ATLAS and CMS are doing a great job of excluding huge amount of SUSY parameter space, but no signs of SUSY have been seen so far

Two possible hard-to-reach corners of parameter space where SUSY could have been hiding:

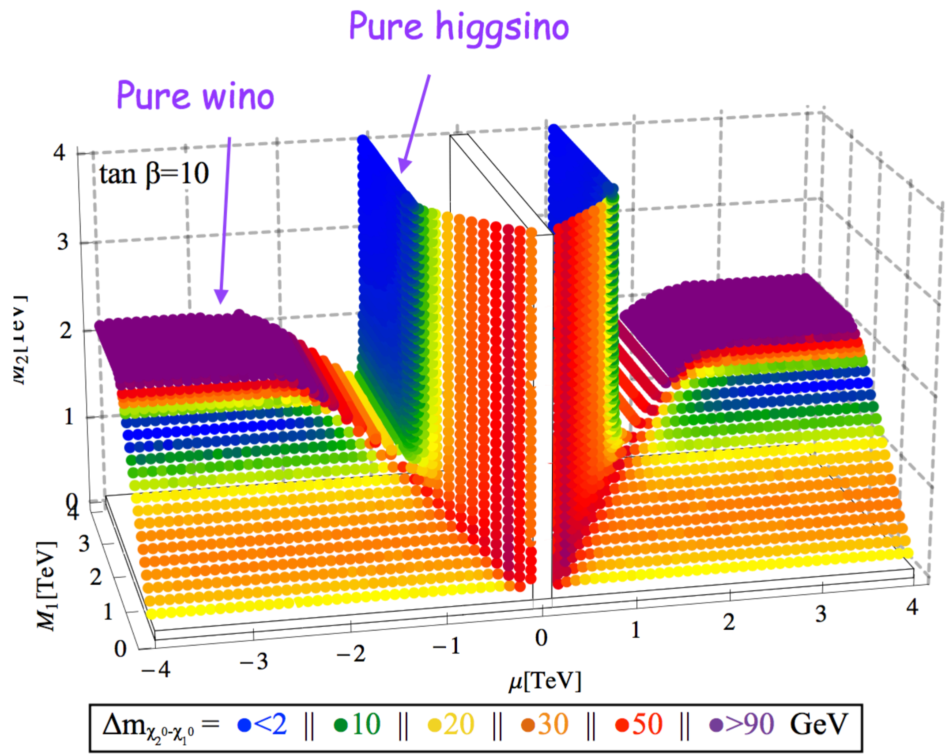
"Compressed spectra" - small mass differences in decay chain, soft leptons or jets might fail analysis cuts

"Long-lived particles - some analyses have quality cuts that reject jets or leptons with "non-prompt" tracks

Dark Matter searches in SUSY

- Neutralinos (mixture of Bino, Wino and Higgsino) and gravitino good dark matter candidates

- Neutralino scenarios:
  - Pure state
  - Well tempered
  - co-annihilation



Limits from the relic density:

Pure wino: m< ~3TeV
Pure higgsino: m< ~1 TeV

DM searches in SUSY : Theoretical Challenge

Theoretical interesting aspects:

- Relic density of compressed models expected to be consistent with cosmological observations **[C. Balázs et al, Phys. Rev. D 70 (2004)]**
- Pure bino DM plagued with overabundance ➔ Well-tempered ones strongly constrained by LUX/XENON1T data

$$\text{Higgsino LSP} \Rightarrow \Omega_{\tilde{\chi}_1^0} h^2 = 0.1\left(\frac{\mu}{1\,TeV}\right)^2$$

Pure Higgsino obtains right relic density for masses 1 TeV

$$\text{Wino LSP} \Rightarrow \Omega_{\tilde{W}} h^2 = 0.13\left(\frac{m_{\tilde{W}}}{2.5\,TeV}\right)^2 = 0.021 m_{\tilde{W}}^2$$

Pure Wino obtains right relic density for masses 2.5 TeV

- Coannihilation can make significant difference. It may increase or decrease the relic density
- In mSUGRA, bino-stau coannihilation widely studied ➔ reduction in relic density, but for a very small mass range because of the correlation of superpartner masses.
- pMSSM scenario: no correlation among sparticle masses ➔ can probe full potential of coannihilation.

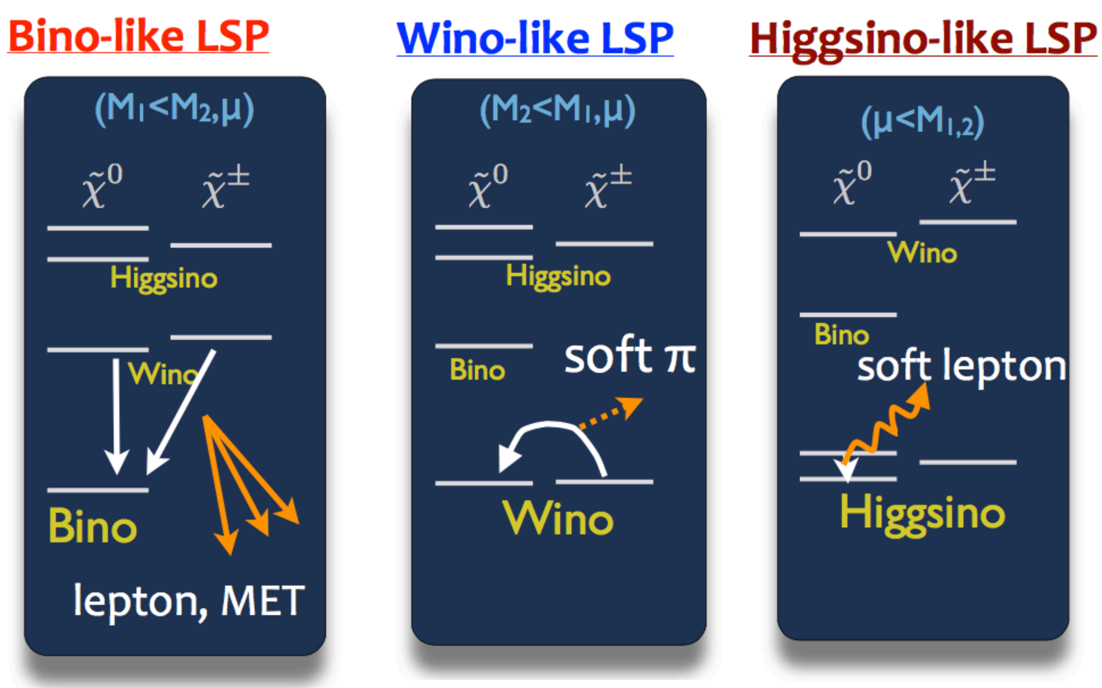
arxiv:1702.03954

SUSY:Searches for stable lightest neutralino

If R-parity conserved (RPC) lightest SUSY particle (LSP) is a dark matter candidate

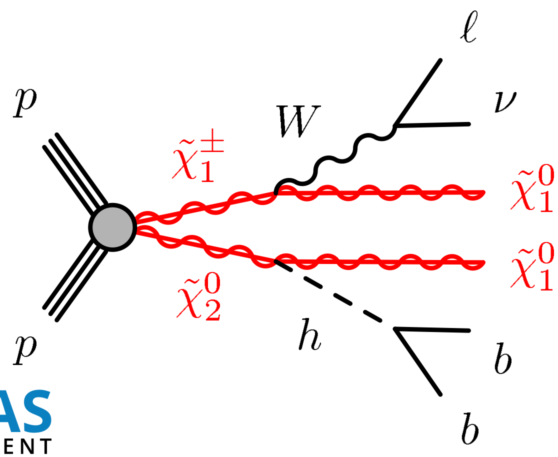
- In principle, any bino/wino/higgsino mass hierarchy is allowed
- Higgsino-like LSP motivated by naturalness (μ at weak scale) and by Higgs related measurements (mass, BRs etc.)

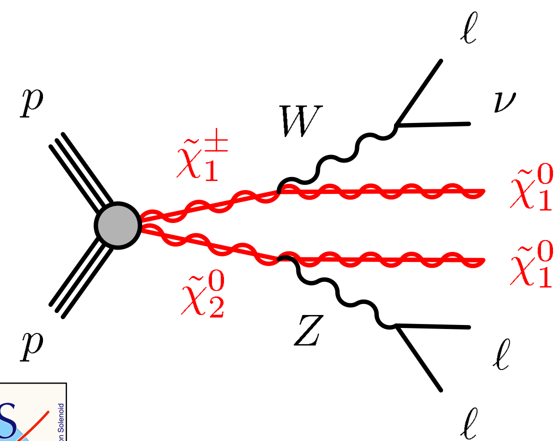
- **Bino-like LSP** with Wino-like NLSP motivated by DM relic constraint
- **Wino/Higgsino – like LSP** → compressed search + long lived search
- Anomaly-mediated SUSY breaking models predict pure Wino LS



Charginos and neutralinos→ SM bosons

- Models where the sleptons are too heavy. Charginos and neutralinos decay to SM bosons.
- Include Gauge Mediated Supersymmetry Breaking (GMSB) scenarios with near massless gravitinos.





ATLAS EXPERIMENT

SUSY channel	Signature	Ref
$\chi_1^\pm \chi_1^\pm \to WW$	2Leptons+ MET (Run1)	1403.5294
$\chi_1^\pm \chi_2^0 \to WZ$	2 soft leptons + MET 2L/3L + MET *2L/3L + MET RJR [New!]*	1712.08119 1803.02762 **SUSY-2017-03**
$\chi_1^\pm \chi_2^0 \to Wh$	Wh (Run1)	1501.0711

CMS

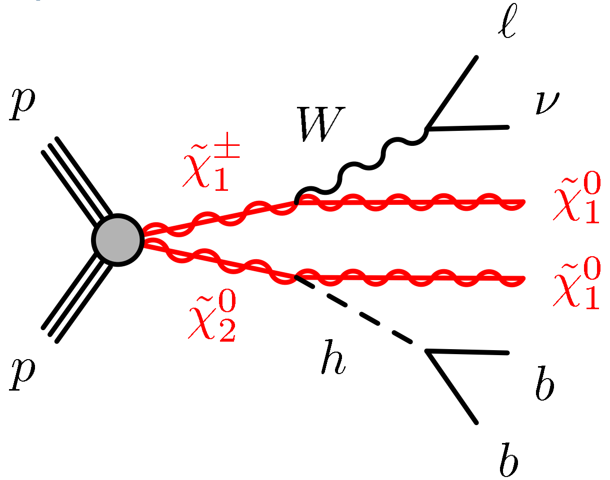
JHEP 03 (2018) 166 Multileptons + p_T miss
JHEP 03 (2018) 076 Two leptons on-Z + p_T miss
JHEP 11 (2017) 029 Lepton + two b-jets + p_T miss
Phys. Lett. B 779 (2018) 166 Two photons + p_T miss
Phys.Rev. D 97 (2018) 032007 4 b-tagged jets + p_T miss
Submitted to Phys. Lett. B Soft two leptons

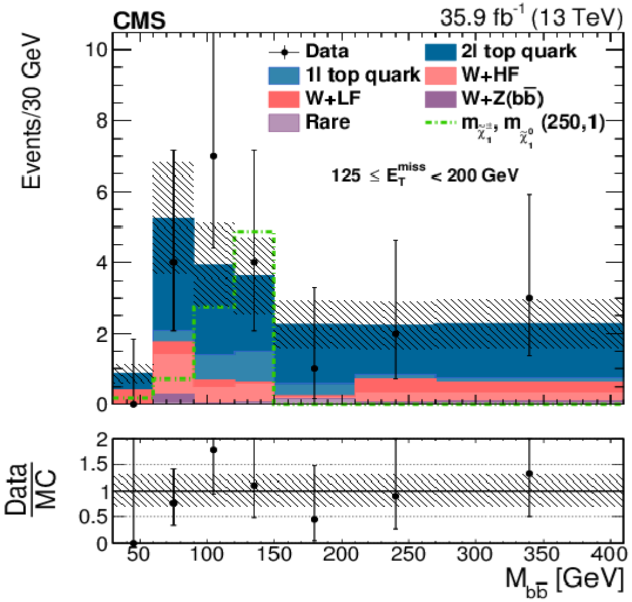
Combined result JHEP 03 (2018) 160

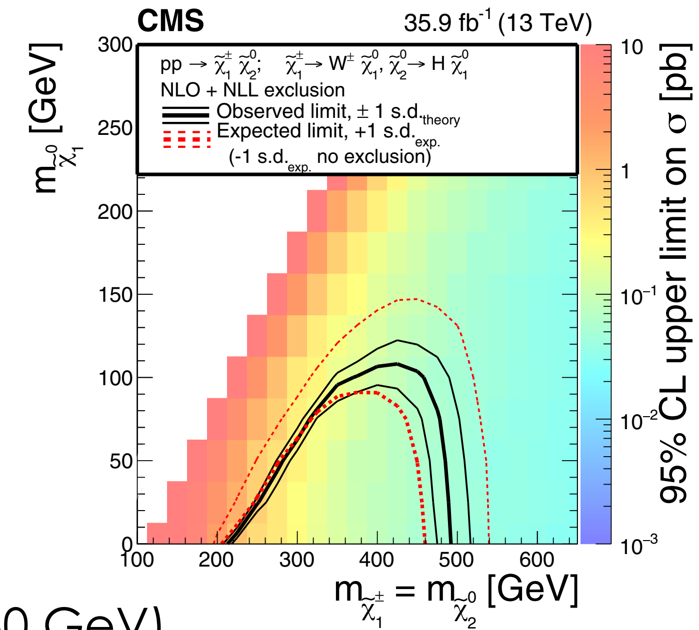
Wh(bb) + MET

JHEP 11 (2017) 029

- SUSY simplified model:
  - Wino-like NLSP mass spectrum $m_{\chi 1\pm} = m_{\chi 02}$
  - $BR(\chi_1^{\pm} \rightarrow W \chi_2^0) = BR(\chi_2^0 \rightarrow h \chi_2^0) = 100\%$
- Clean final state: 1lepton + bb +MET
- Main background from 2leptons ttbar directly controlled in sideband



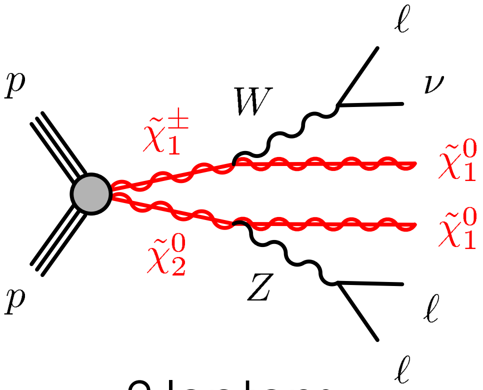




χ_2^0 excluded up to 110 GeV (for $m_{\chi 1}^{\pm}$ = 450 GeV)

WZ + MET

ATLAS EXPERIMENT Submitted to PRD 1806.02293



- **Recursive Jigsaw Reconstruction (RJR)**
  PRD 95, 035031 (2017) / 1705.10733

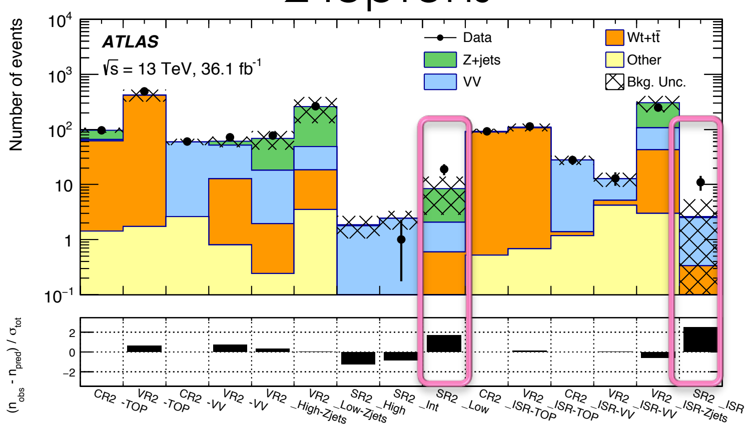
Algorithm recursively reconstructing the decay chain of pair produced heavy particles

Event selection with 8 SRs → different Δm(NLSP,LSP):
[2Leptons, 3Leptons] × [ISR, Low, Int, High]

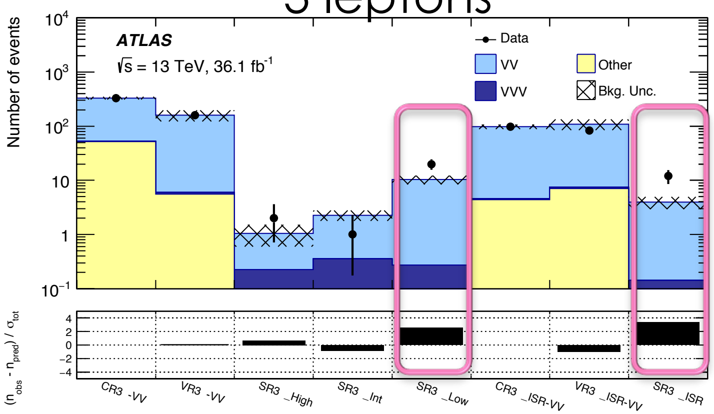
Result:

- **2.0σ/2.1σ/3.0σ excess in 2/3 leptons regions for** Δm = 100-200 GeV and didn't see in the conventional WZ+MET analysis (using the same dataset)

2 leptons

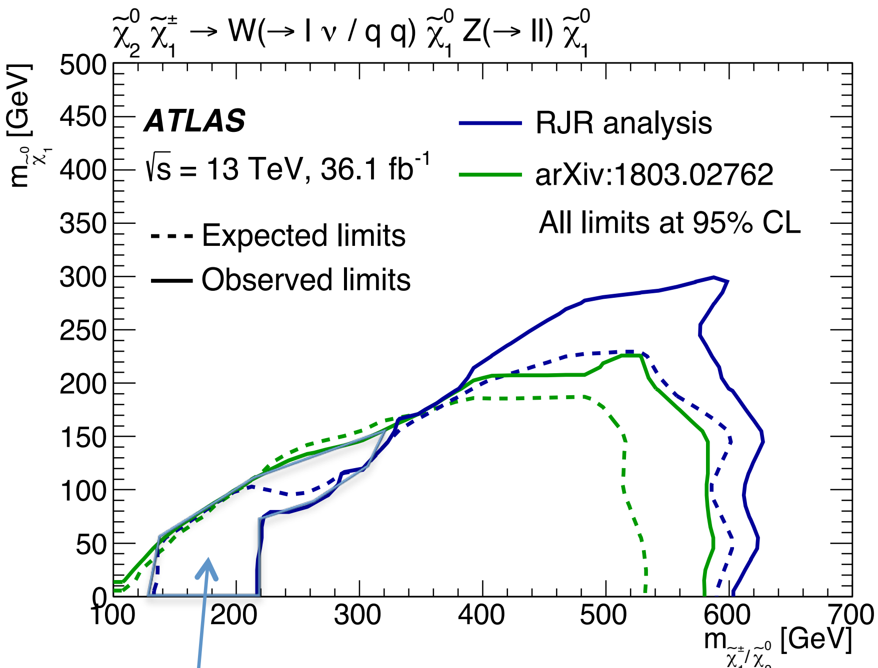


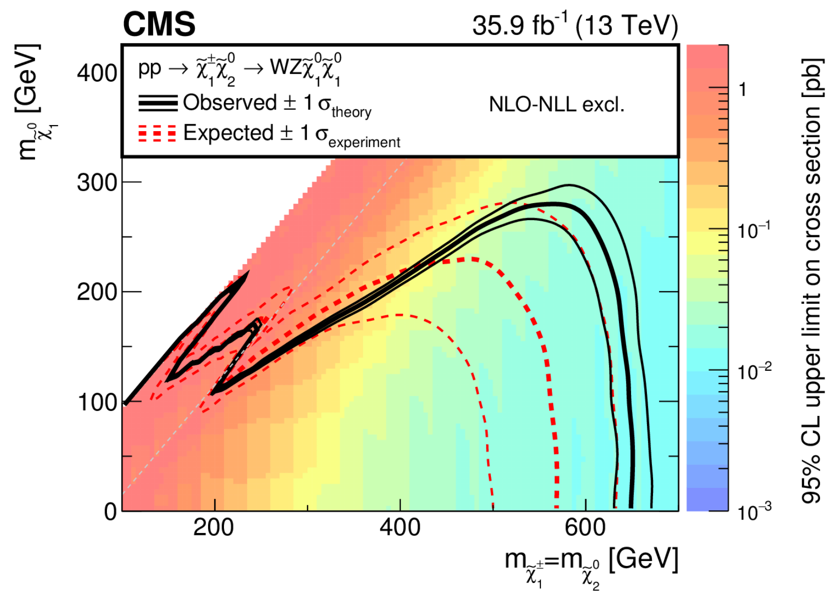
3 leptons



WZ + MET

Results used to set limit on wino NLSP → Bino LSP 1806.02293





Weak observed limit in low ΔM due to the excess

CMS Combination Paper
JHEP 03 (2018) 160

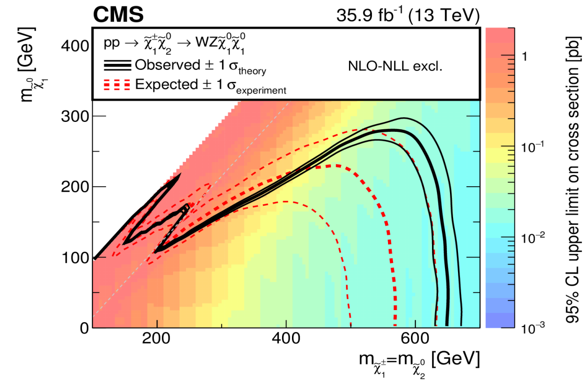
Chargino/neutralino pair production combination

Statistical combination of all CMS analysis targeting direct decays of neutralino/chargino pairs to SM bosons

	WZ	WH	ZZ	ZH	HH
1l2b		✓			
4b					✓
2l on-Z	✓		✓	✓	
2l soft	✓				
≥3l	✓	✓	✓	✓	✓
H(γγ)		✓		✓	✓

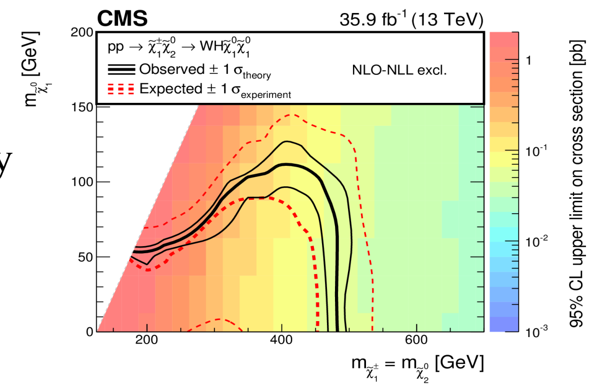
WZ topology

$\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$

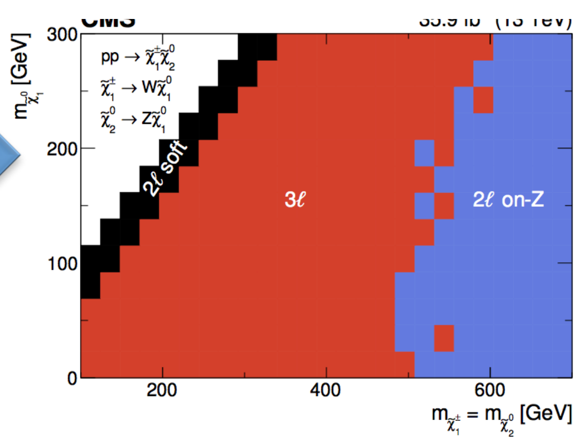


WH topology

$\tilde{\chi}_2^0 \rightarrow H\tilde{\chi}_1^0$

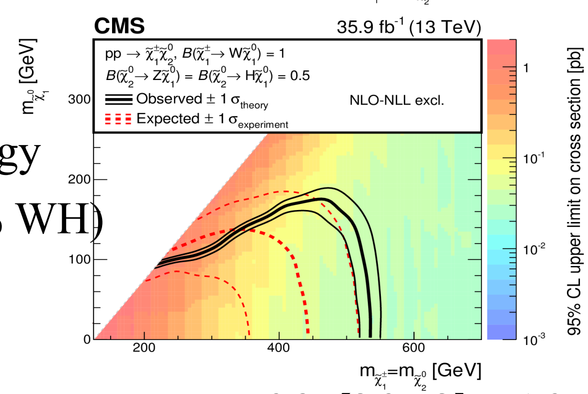


Combination to cover the full space



Mixed topology

(50% WZ and 50% WH)



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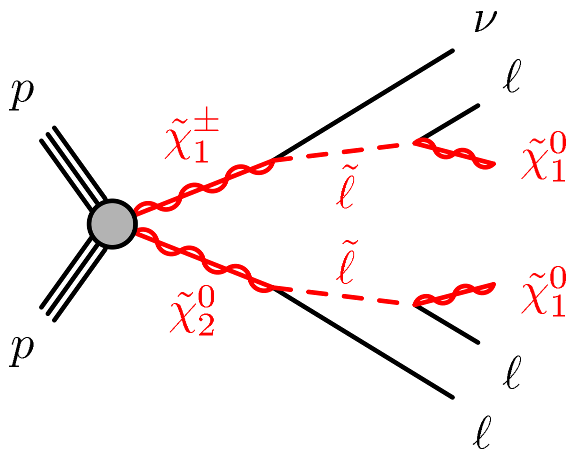
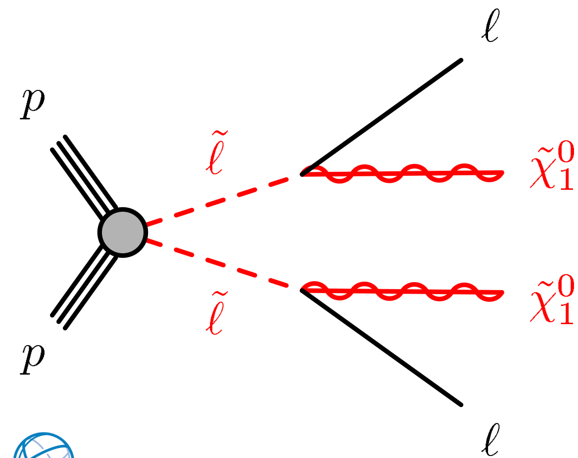
Slepton searches

Models where the sleptons are amongst the lightest SUSY partners·





- stau pair (leptonic) + p_T miss **SUS-17-002**
- stau pair (hadronic) + p_T miss **SUS-17-003**
- Direct light slepton **SUS-17-009**
- $\chi_1^{\pm}\chi_1^{\pm}$ and slight leptons **SUS-17-010**
- Multileptonic final states **JHEP 03 (2018) 166**

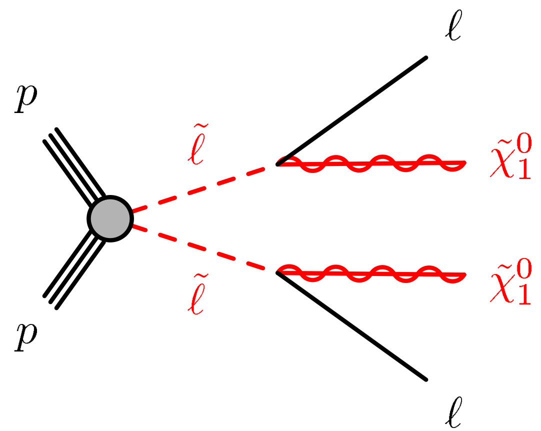
SUSY channel	Signature	Limit
Direct light slepton	2Leptons (soft) +MET	~500 GeV in slepton mass* ~200 GeV for ΔM~10 GeV
$\chi_1^{\pm}\chi_2^{0}/\chi_1^{\pm}\chi_1^{\pm}$ and slight leptons	2/3Leptons 0jets +MET	~1.1 TeV in $m(\chi^{1}_{\pm}\chi^{2}_{0})$
$\chi_1^{\pm}\chi_2^{0}/\chi_1^{\pm}\chi_1^{\pm}$ and stau	2 had tau + MET	~760 GeV in $m(\chi^{1}_{\pm}\chi^{2}_{0})$

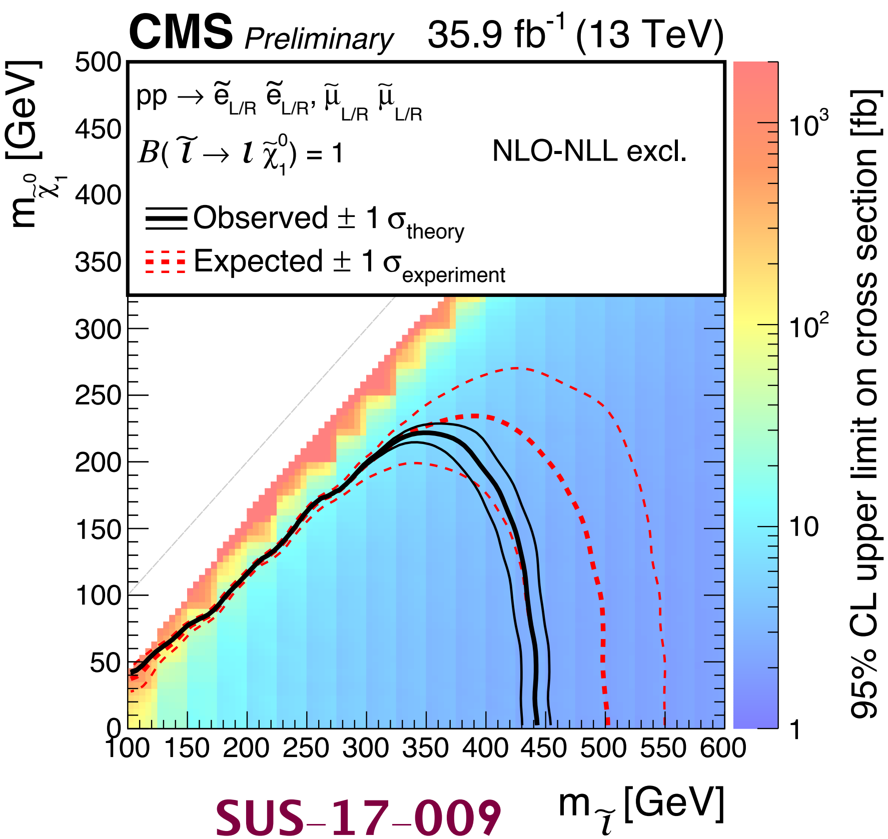
* Massless χ_1^{0}

Slepton searches

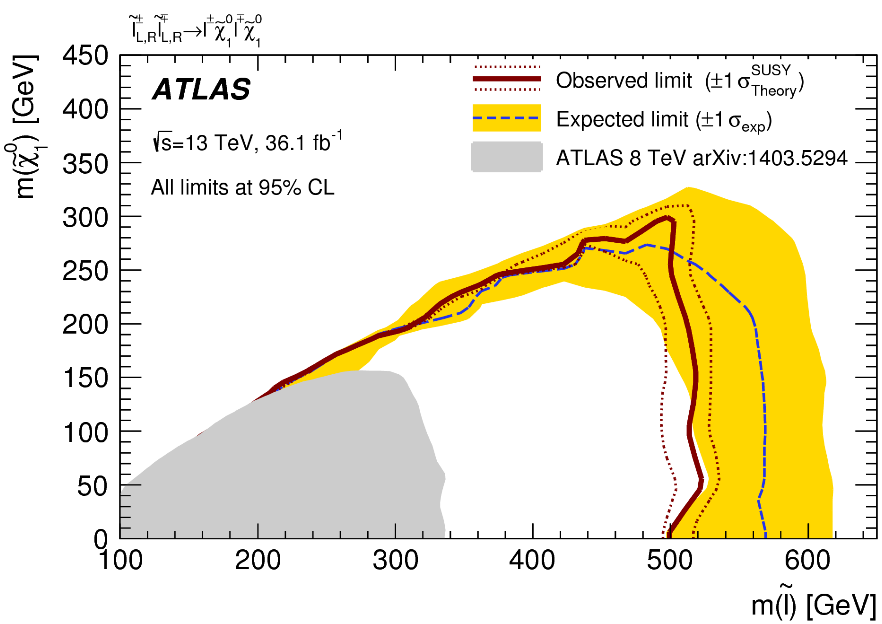
Models where the sleptons are amongst the lightest SUSY partners.

- 2 leptons final state (Jetless)
- Clean experimental signature
- Main background from WW and ttbar





SUS-17-009

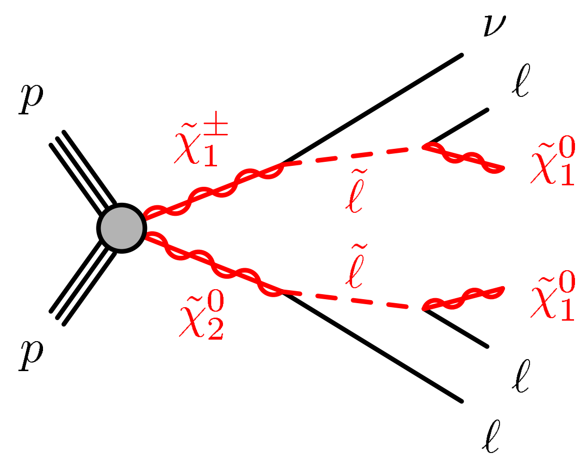


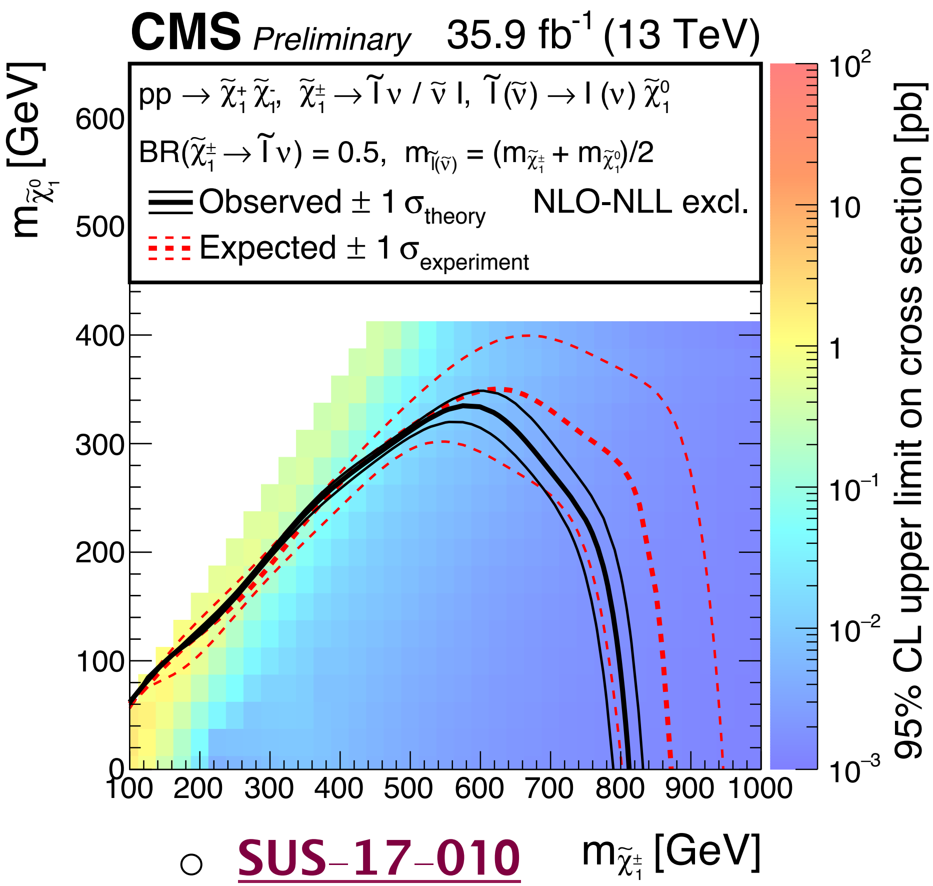
1803.02762

Slepton searches

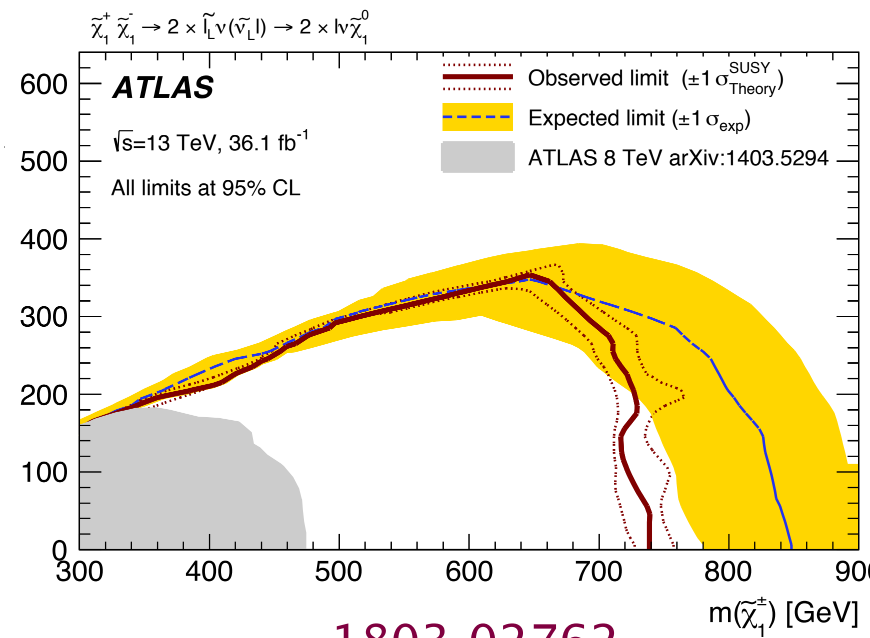
Models where the sleptons are amongst the lightest SUSY partners.

Chargino pair production with 2 leptons in final state



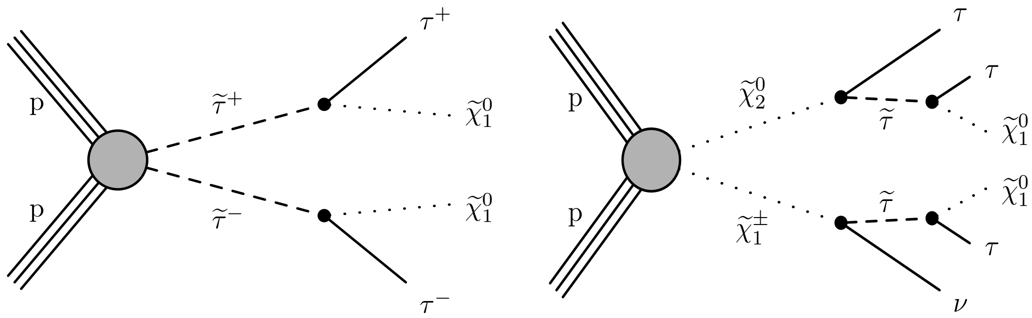


- [SUS-17-010](SUS-17-010)

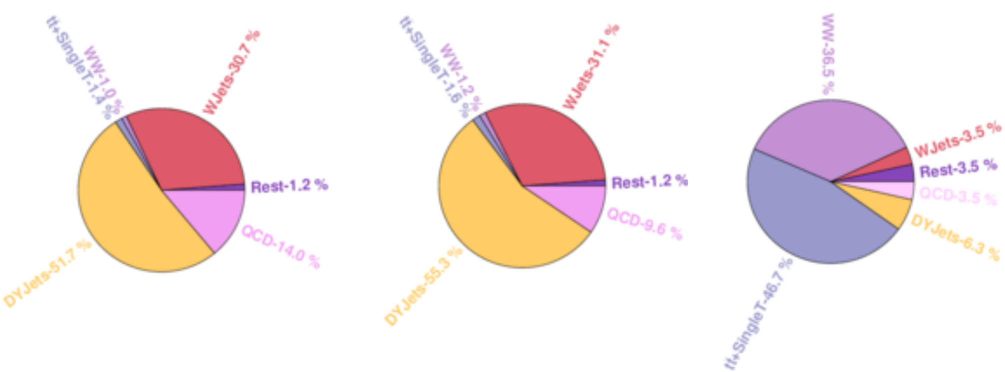


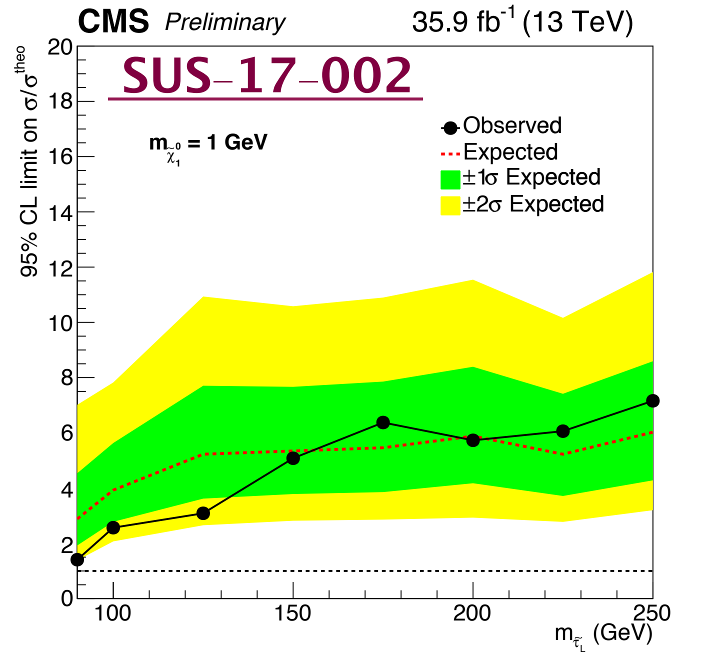
[1803.02762](1803.02762)

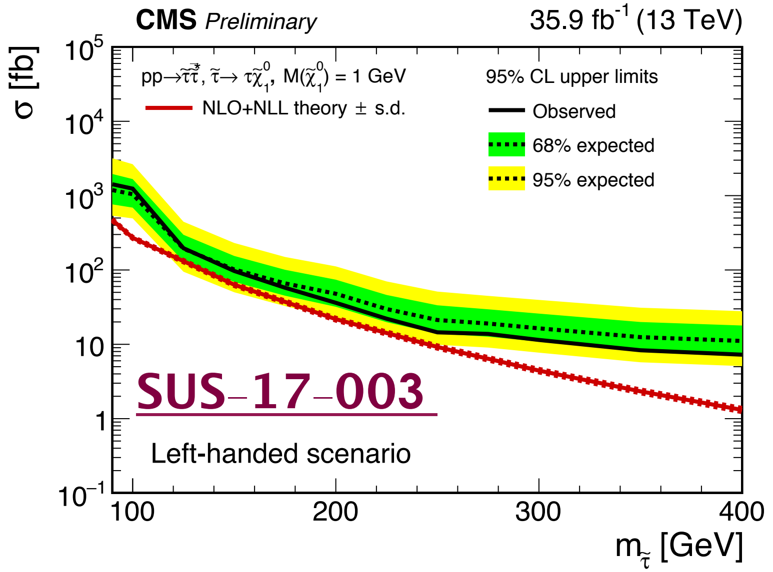
Stau production



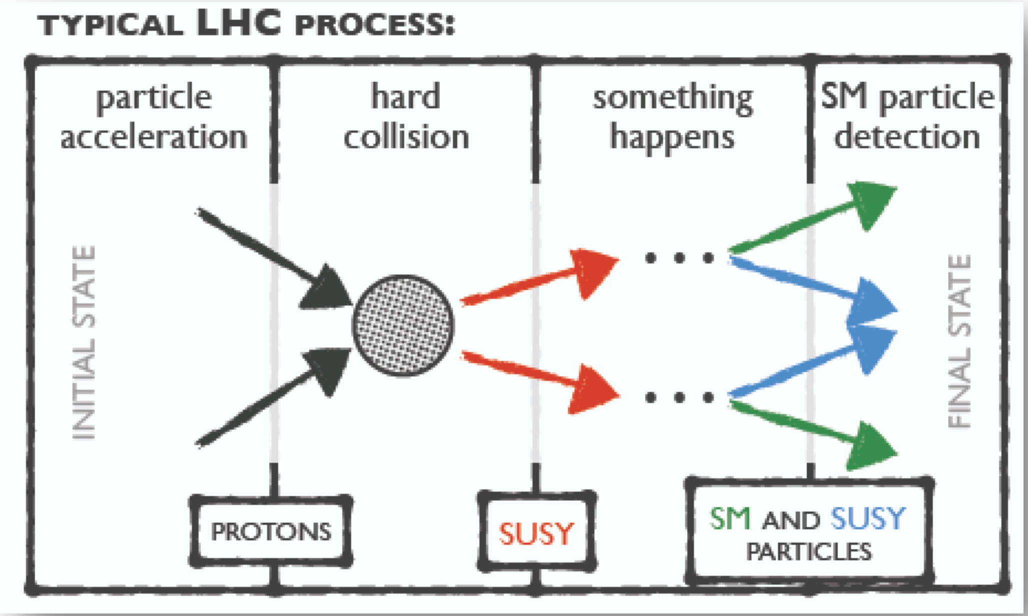
- Stau pair production model. Special interest in the compressed scenarios
- Stau-χ_1^0 mechanism could explain the current observed relic density of dark matter in the universe Phys. Rev. D 84(2011) 095015
- Hadronic and (semi) leptonic final state







What Does Compressed Spectra Mean?



EPS-HEP talk from Constantin Heidegger

Compressed Spectra = Small ΔM

$$\Delta M = m_Y - m_X$$

Y= Parent SUSY particle

X= Daughter SUSY particle

How compressed?

Pure Higgsino or pure Wino LSP: ΔM=O(100s MeV)

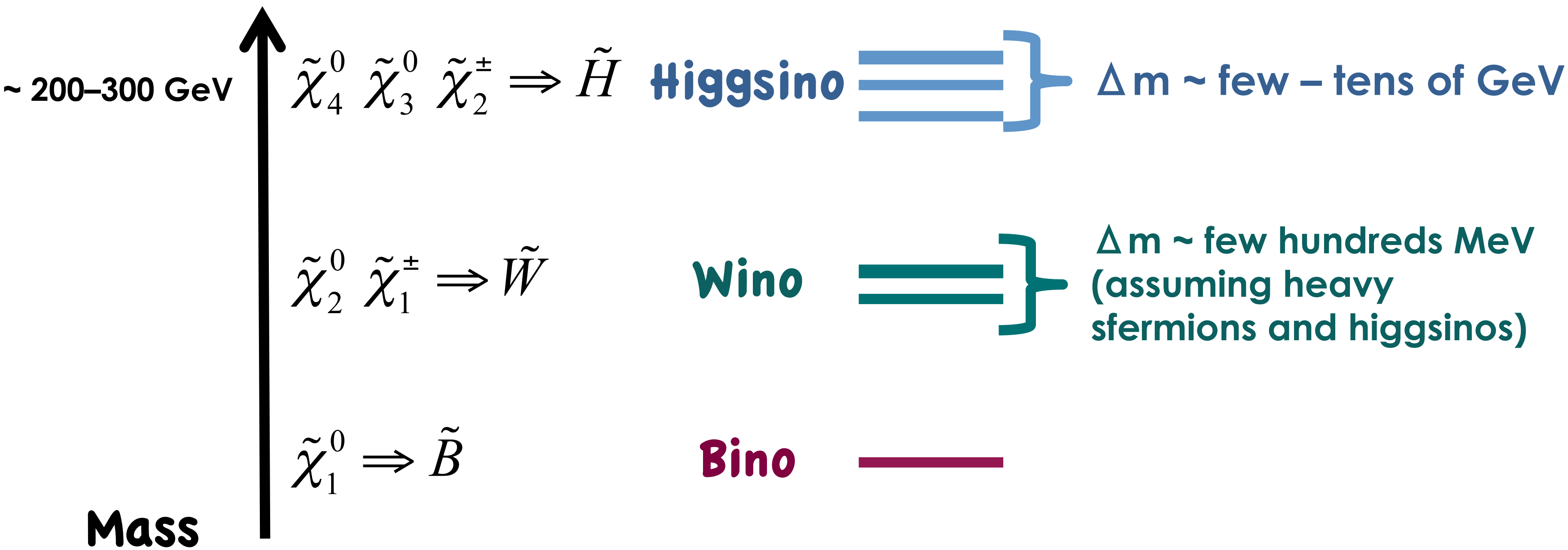
✦Long lifetimes ⟹ look for disappearing track

“Mostly” Higgsino LSP: ΔM=O(1-10s GeV)

✦Prompt decays ⟹ rely on soft leptons with p_T as low as 4 GeV

Compressed Electroweak SUSY

In principle, any bino/wino/higgsino mass hierarchy is allowed

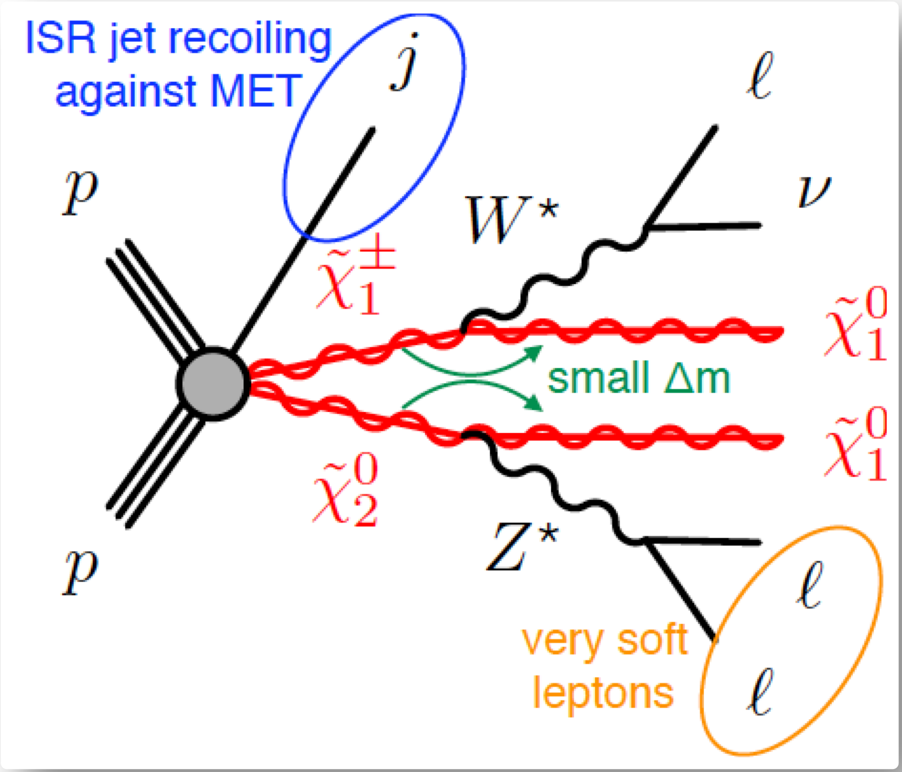


Natural SUSY, i.e. SUSY models that solve the hierarchy problem with little fine tuning, imposes mass constraints:

- m(Ĥ)< 200–300 GeV
- Compressed spectra: ingredient of Natural SUSY
- Existing limits: at LEP charginos excluded up to 100 GeV for all Δm

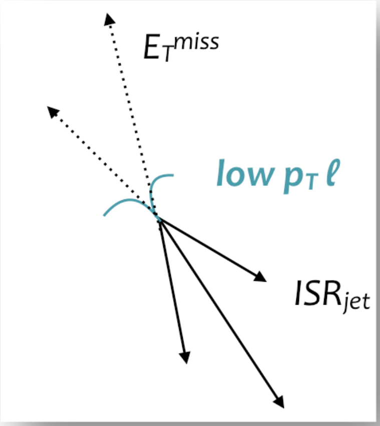
Phys. Rev. D 90, 115007 (2014)

Compressed Spectra: very challenging



Difficult phase-space:

- small Δm ➔ very soft leptons very small invariant masses
- moderate transverse missing energy (MET or E_T^{miss}) (enhanced with ISR object)



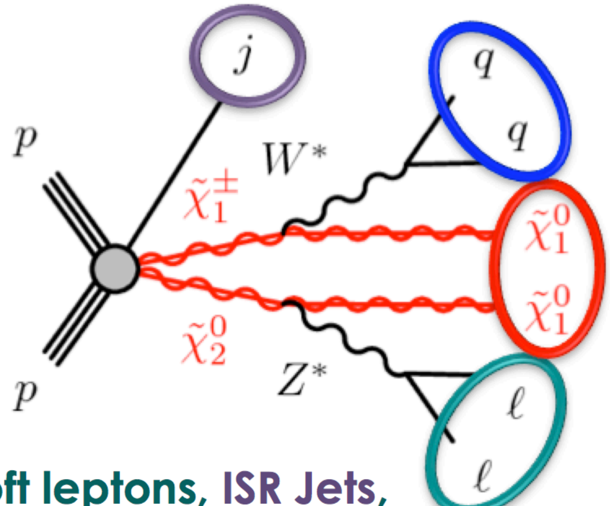
- Generally lower cross-sections: e.g. $\sigma_{Higgsino} = 0.23\ \sigma_{Wino}$
- Different challenges: trigger, lepton reconstruction and ID, isolation, background modeling, background rejection, fake lepton backgrounds…

Higgsino Signatures

Higgsino-like LSP

- Need ISR jet to boost the sparticle pair system and induce E_T^{miss} and other decay products remain soft
- if sleptons are too heavy decay happens through Z*/W* ➔ need Z*/W* leptonic decays to reconstruct decay product and reduce bkg

- Signature: soft $e^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}$(Opposite Sign Same Flavor) + E_T^{miss}
  - soft muons $p_T > 4$ GeV for ATLAS and $p_T > 3.5$ GeV for CMS
  - soft electrons $p_T > 4.5$ GeV for ATLAS and $p_T > 5$ GeV for CMS
  - $E_T^{miss} > 125$ GeV for CMS
  - $E_T^{miss} > 200$ GeV for ATLAS

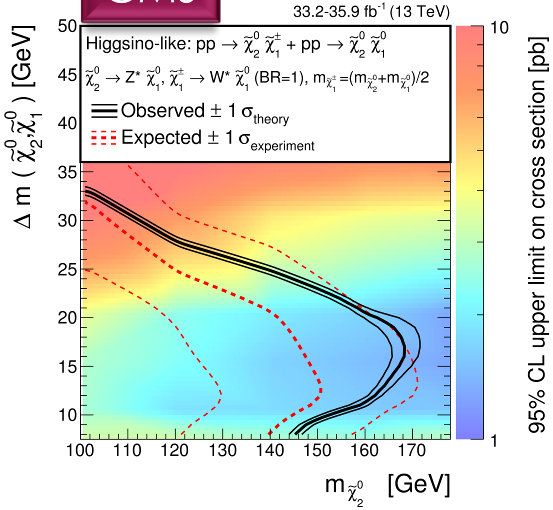


Soft leptons, ISR Jets, High-p_T Jets, Missing Energy E_T^{miss}

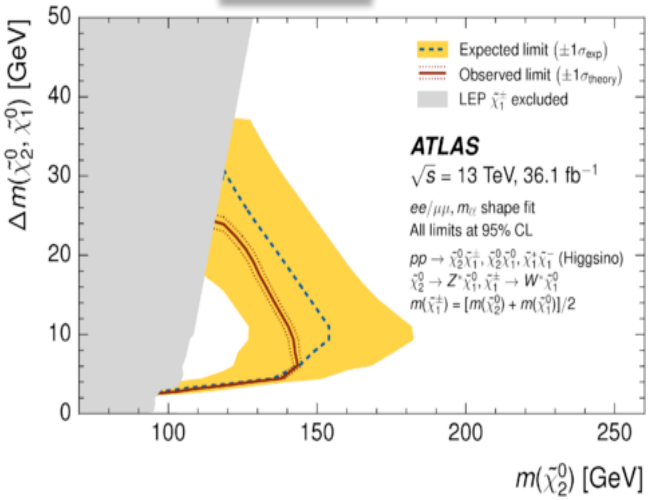
[**CMS:** 1801.01846 – **ATLAS** Phys. Rev. D 97, 052010 (2018), **arXiv:1803.02762**

ATLAS and CMS Interpretations: Higgsino

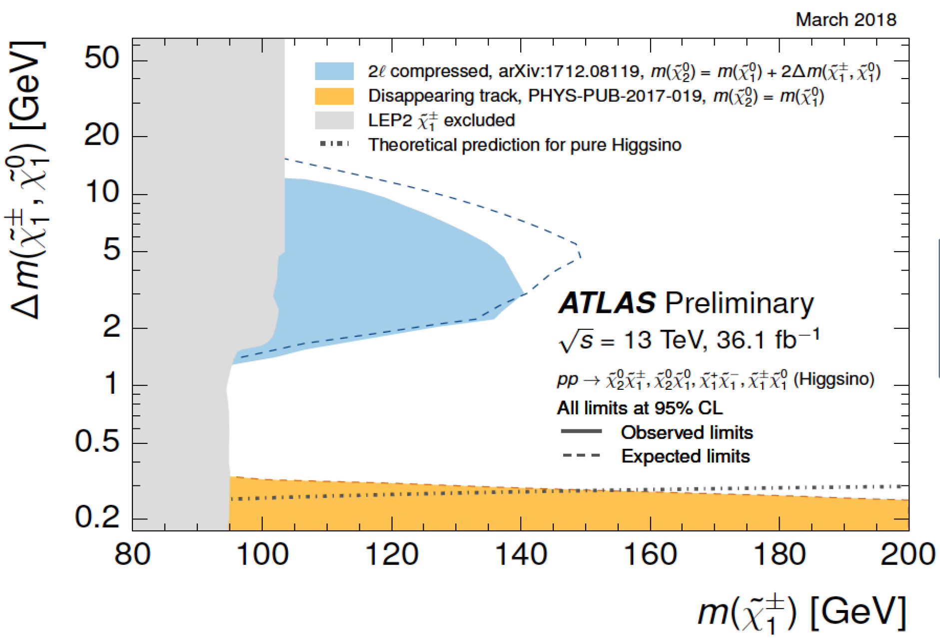
CMS



ATLAS



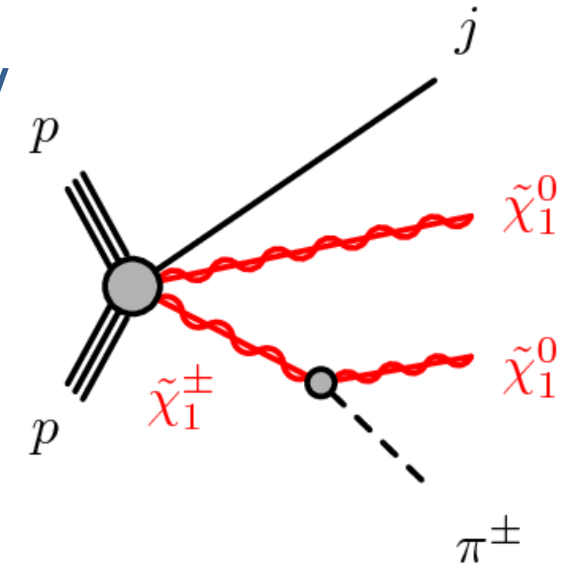
- Full 2016 dataset
- 100% BR into Z*/W*, other SUSY particles assumed to be heavy and decoupled
- Cross sections are computed at NLO+NLL



Extension of LEP limits in compressed scenarios!

Extremely compressed signatures

$\Delta m(\chi^2_0, \chi^1_\pm, \chi^1_0) \sim$ **300 MeV**

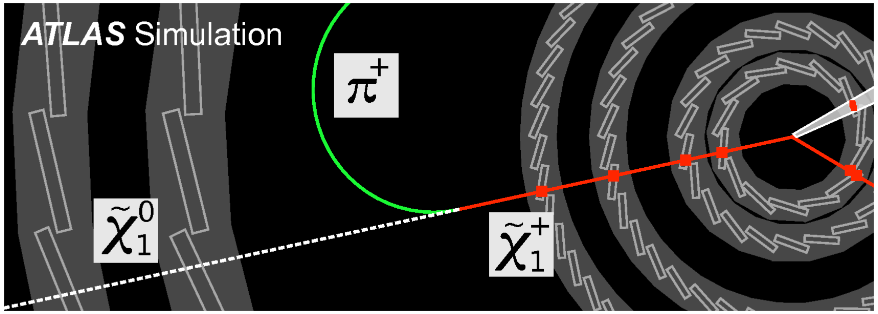


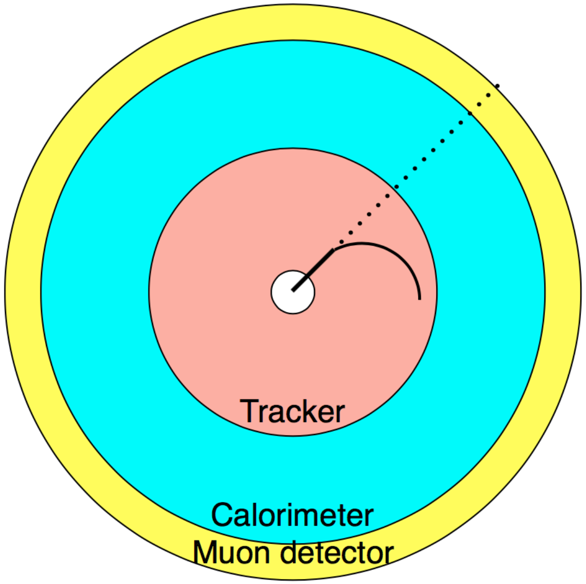
- Extremely compressed:

  Disappearing tracks signature

(Wino and Higgsino LSP searches)

- The chargino (LLP) could decay within the tracking volume
- No SM charged particles decay like this
- Instrumental background:
  - Scattered SM particles
  - Reconstructed tracks from hits by multiple particles

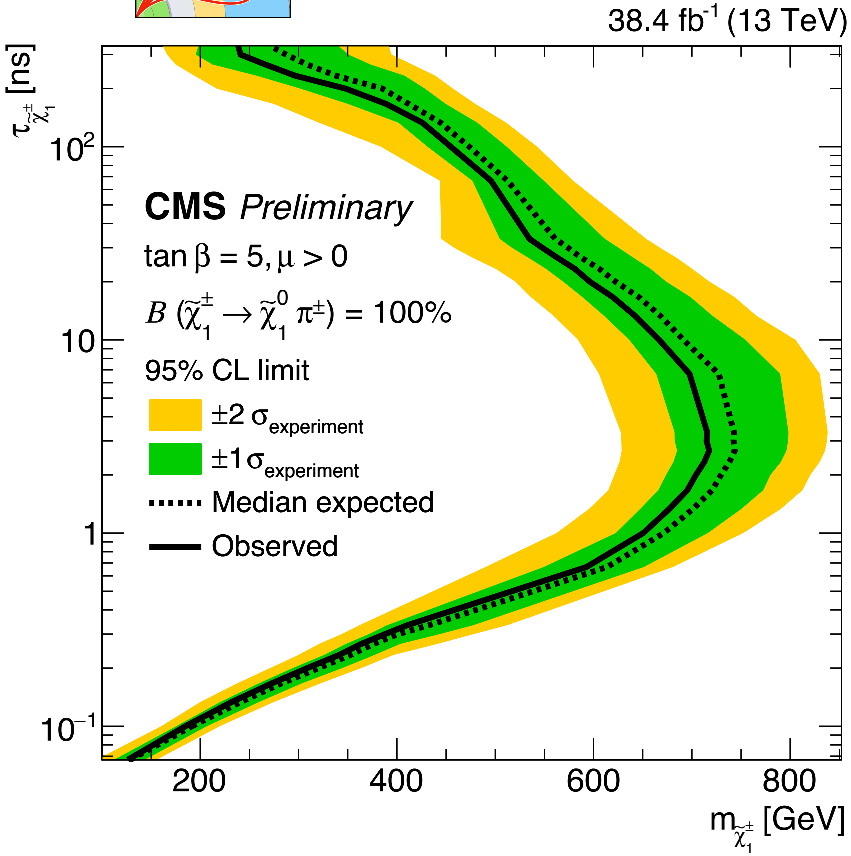




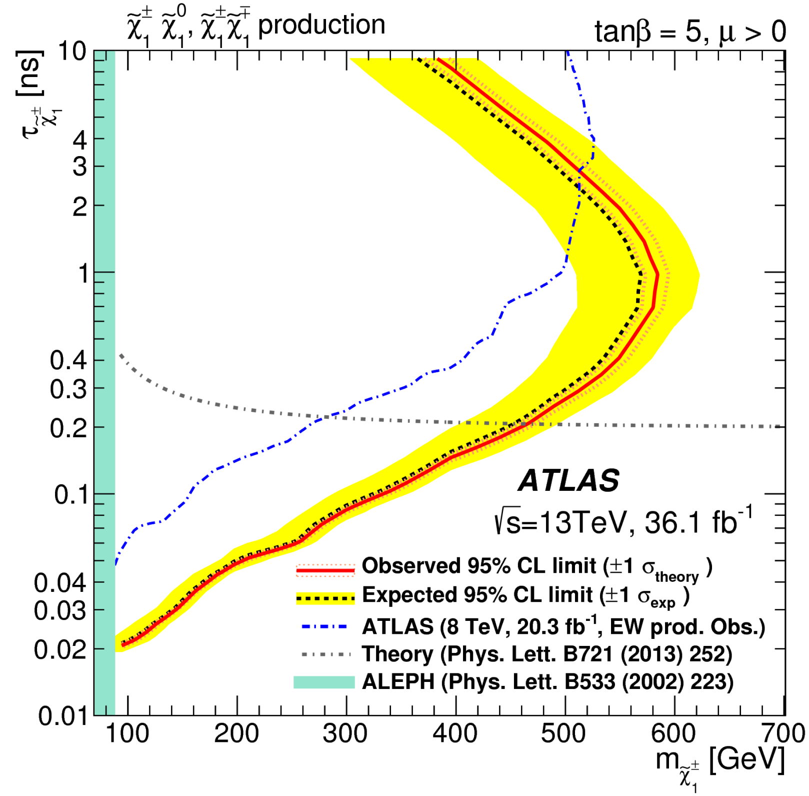
[CMS: 1804.07321 - ATLAS:1712.02118]

Extremely compressed signatures

AMSB Wino



CMS: 1804.07321

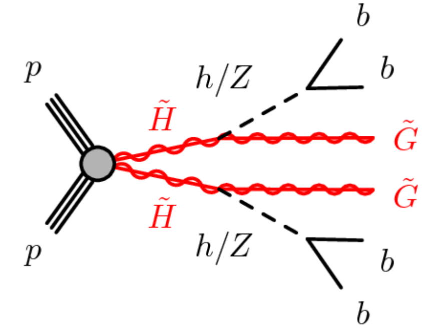


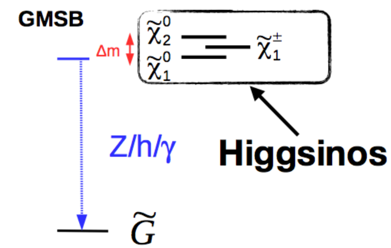
ATLAS:1712.02118

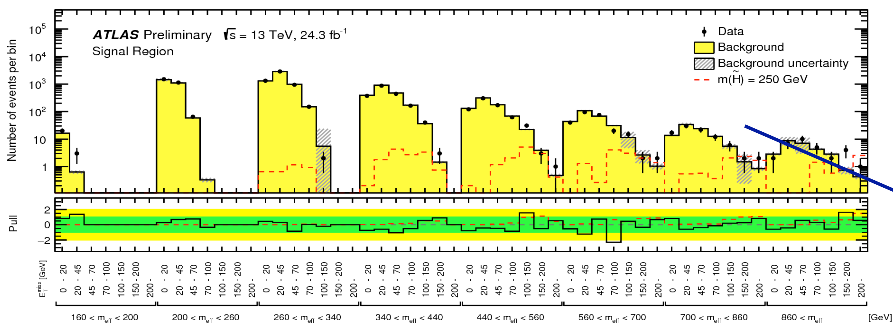
GMSB Higgsino

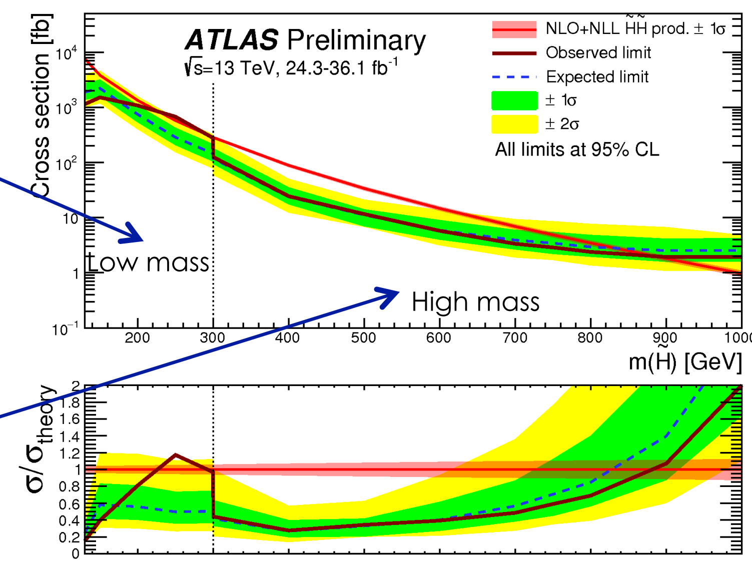
In SUSY models with low SUSY breaking scales (like GGM or GMSB) a gravitino is typically assumed to be the LSP and in natural models with light higgsinos, the χ^0_1 then becomes the NLSP particle ➔ $\chi^0_2 \to \chi^0_1 \to G$

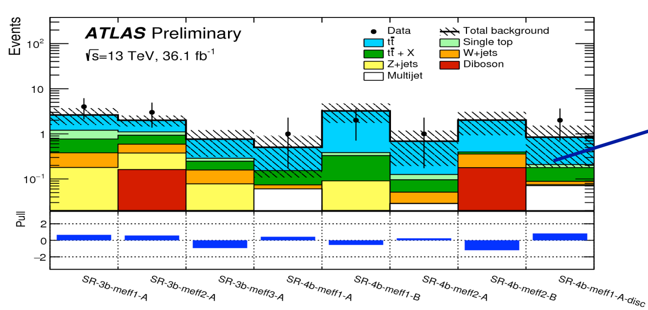
- Experimental signature:
  - Massless G allows on-shell h/Z decays
  - $h \to b\bar{b}$ gives powerful 4b final state w/ large branching ratios
  - Missing transverse momentum (MET) from G
  - Split in Low/High Higgsino mass search strategy











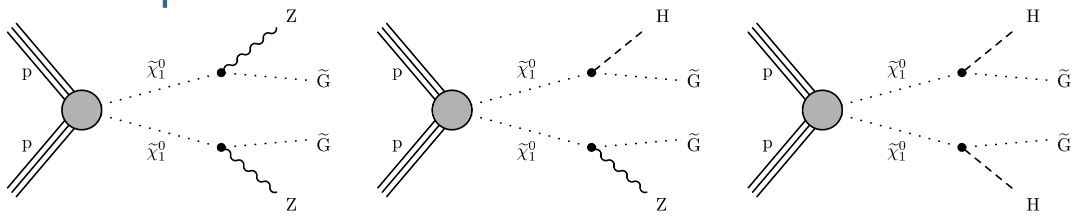
ATLAS EXPERIMENT

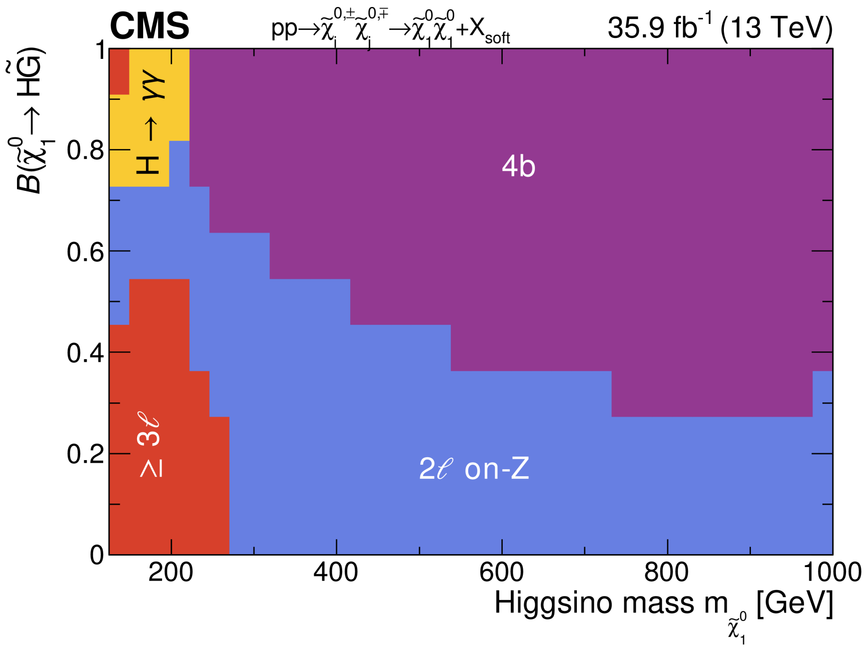
ATLAS_CONF_2017_081

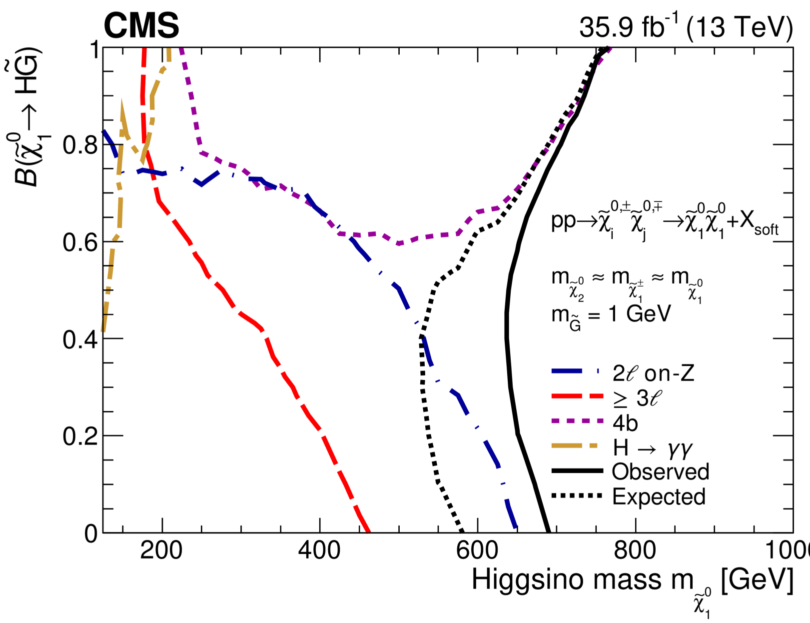
GMSB Higgsino

JHEP 03 (2018) 160

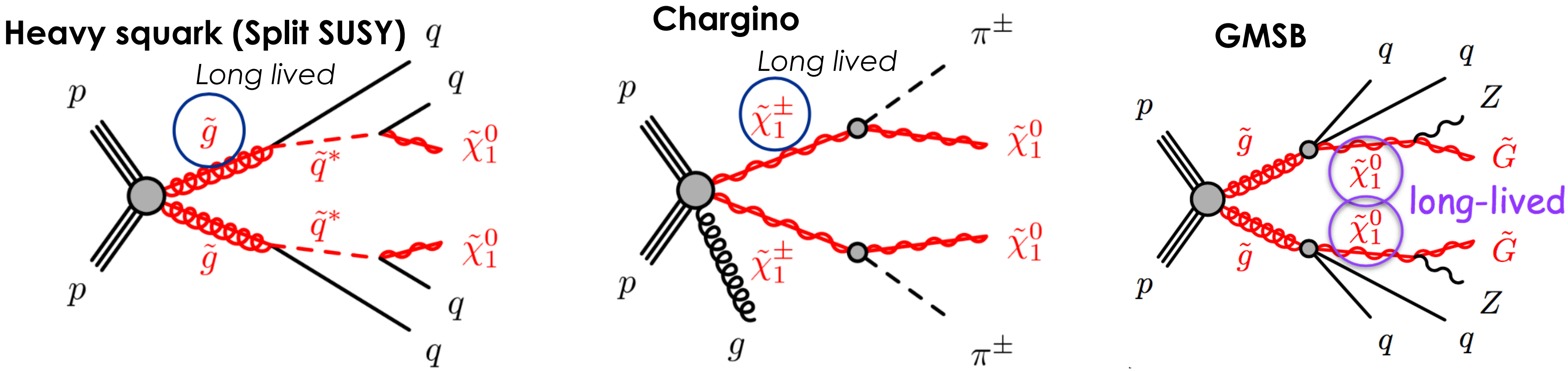
- Analyses combined to get inclusive coverage of SUSY parameter space





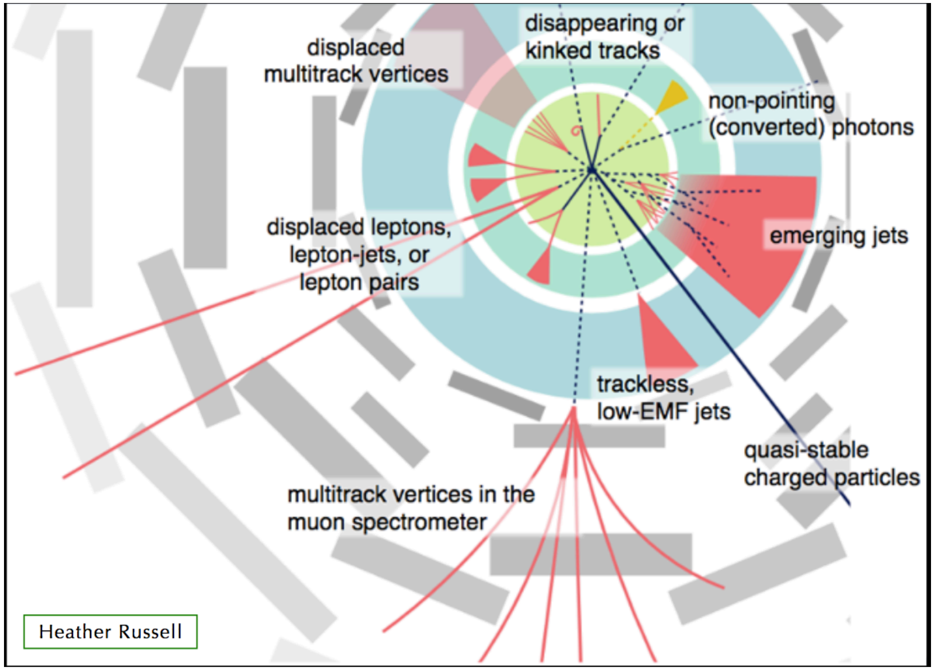


Long-lived particles (LLP) searches

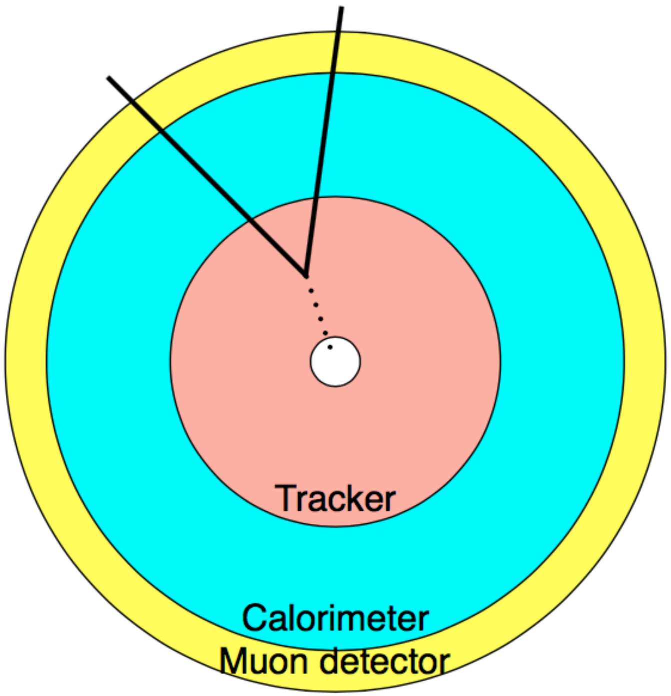


Long-lived particles naturally arise in a variety of other BSM theories:

- Dark photon
- Hidden valley
- Dark QCD
- Heavy neutral lepton



LLP: Displaced signatures



When a long-lived particle decay in flight, it makes displaced vertices:

- Split SUSY
- RPV SUSY
- Hidden-Valley (dark photon, scalar)
- Stealth SUSY
- Heavy neutral lepton

Many experimental signatures:

- Displaced lepton
- Displaced photon
- Displaced jets

some LLP results: CMS_PAS_EXO_17_018, 1801.00359, *Phys. Rev. D 94 (2016) 112004*

Displaced Vertices + MET

ATLAS EXPERIMENT

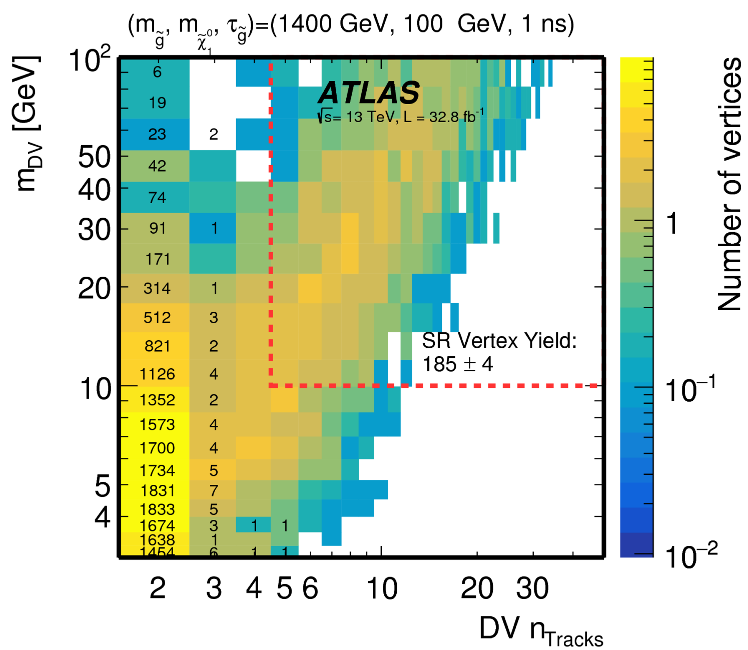
- Displaced vertices (DV) in events with large ET miss (> 200 GeV)
- Dedicated tracking algorithms studied in detail, very efficient:
  - Special secondary tracking for tracks far from the beam line.
  - Dedicated displaced vertex reconstruction.

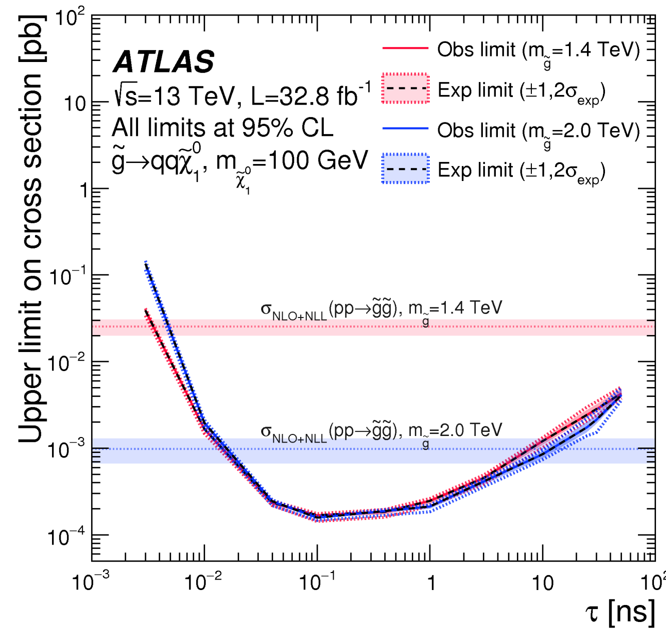
Phys. Rev. D 97 (2018) 052012

Expected BG: 0.02+0.02-0.01
Observed events : 0

Limits set on **long-lived gluino**

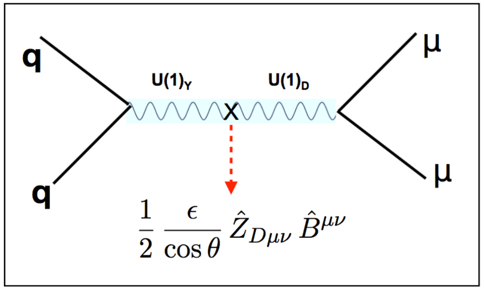
Up to 2.4 TeV gluino excluded for 100 GeV neutralino and moderate lifetime.

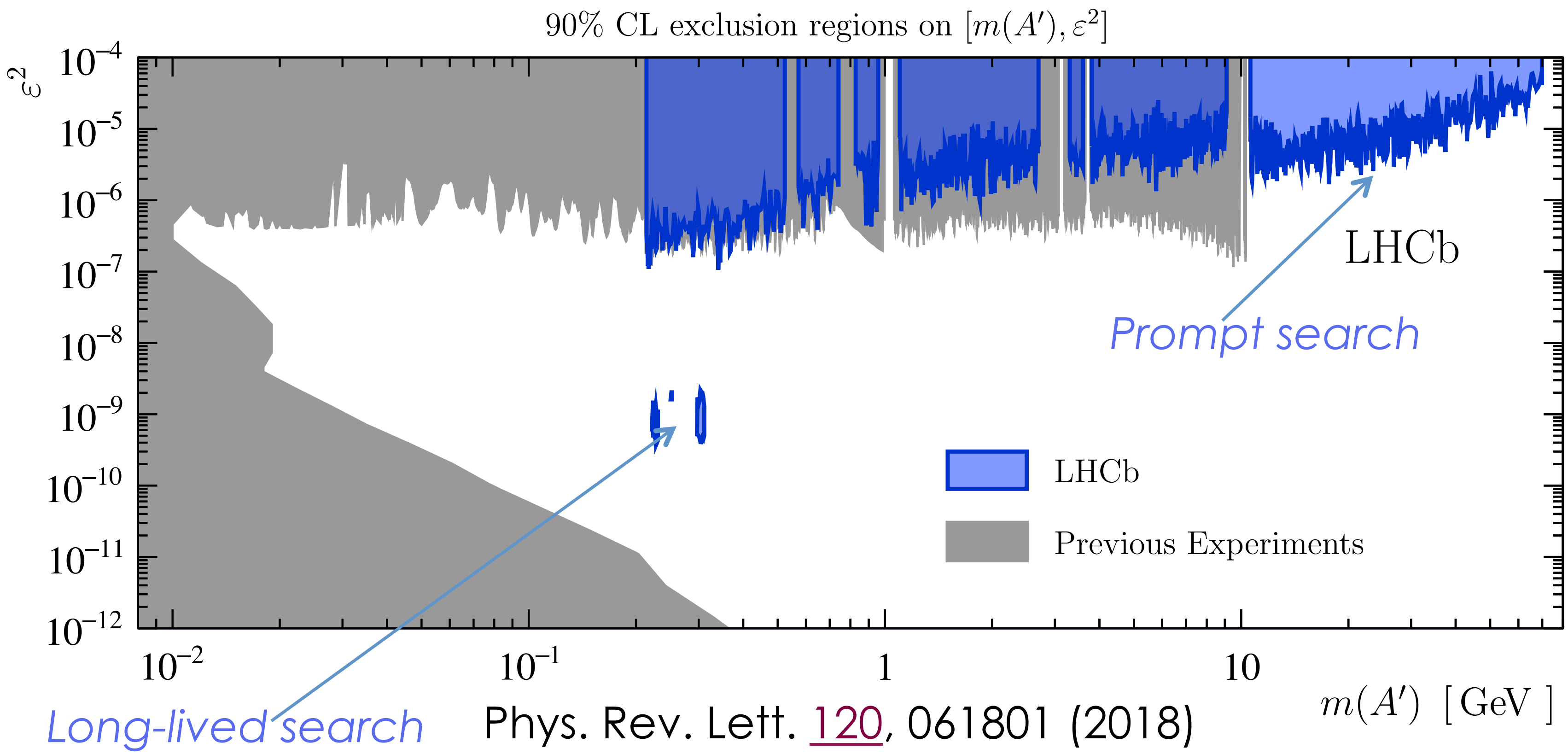




LHCb: Dark photon search

- Signal: **A'→** $\mu\ \mu$
- Prompt and displaced di-muons from dark photon decay
- Search region in dark photon mass : 2 × m_μ to 70 GeV
- Plan to cover all remaining low-mass parameter space with next data





Phys. Rev. Lett. 120, 061801 (2018)

Conclusions and Plans

- Excellent performance of LHC in 2016, data ready to be analyzed from 2017 and new data coming soon

- Extensive search program performed at ATLAS and CMS covering a huge variety of topologies
  - **Electroweak SUSY** search program performed by ATLAS and CMS
  - No hint for new physics observed, large regions of phase space probed.

- **Compressed SUSY searches:**
  - Compressed spectra require new approaches and ideas!!
  - Development and optimization of key analysis tools allows probing of compressed and very compressed regions

- **Long-lived particles** may still escape from our searches:
  - ATLAS / CMS detectors have excellent potential to discover them although the detectors and standard reconstruction algorithms are not designed for the purpose.
  - There are ideas of new signature.
  - Need a lot of effort to materialise such ideas and make results. There are several interesting “gaps” which should be covered in future.

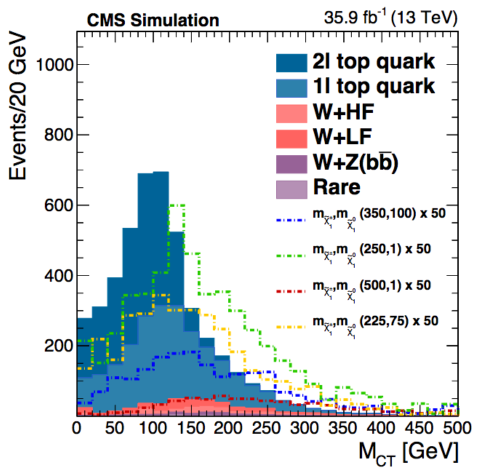
End Here

M_{CT} and M_{T2}

In order to further suppress both semileptonic and dileptonic $t\bar{t}$ backgrounds, we utilize the contransverse mass variable, M_{CT} [53, 54]:

$$M_{CT} = \sqrt{2 p_T^{b1} p_T^{b2} [1 + \cos(\Delta\phi_{bb})]}, \tag{2}$$

where p_T^{b1} and p_T^{b2} are the transverse momenta of the two jets, and $\Delta\phi_{bb}$ is the azimuthal angle between the pair. As shown in Refs. [53, 54], this variable has a kinematic endpoint at $(m^2(\delta) - m^2(\alpha))/m(\delta)$, where δ is the pair-produced heavy particle and α is the invisible particle produced in the decay of δ. In the case of $t\bar{t}$ events, when both jets from b quarks are correctly identified, the kinematic endpoint corresponds to the top quark mass, while signal events tend to have higher values of M_{CT}. This is shown in Fig. 2 (bottom right). We require $M_{CT} > 170$ GeV.



M_{CT} and M_{T2}

The kinematic variable M_{T2} [61, 62] is used to reduce backgrounds from $\mathrm{t\bar{t}}$ and WW processes. This variable was first introduced to measure the mass of pair-produced particles, each decaying to the same final state, consisting of a visible and an invisible particle. It is defined using $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ and two visible objects (leptons in this search) as:

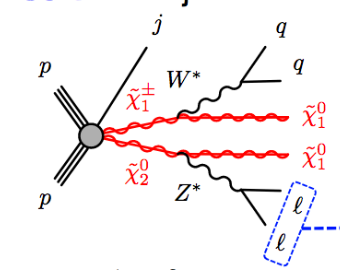
$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(1)} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(2)} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right], \tag{1}$$

where $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(i)}$ (i=1,2) are trial vectors obtained by decomposing $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. The transverse masses $M_{\mathrm{T}}^{(i)} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{vis}} p_{\mathrm{T}}^{\mathrm{miss}\,(i)} (1 - \cos(\Delta\phi))}$, where $\Delta\phi$ is the angle between the transverse momentum of the leptons and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(i)}$ and $p_{\mathrm{T}}^{\mathrm{vis}}$ is the p_{T} of the visible particle, are obtained by pairing either of these trial vectors with one of the two leptons. The minimization is performed over all trial momenta satisfying the $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ constraint. When building M_{T2} from the two selected leptons and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, denoted $M_{\mathrm{T2}}(\ell\ell)$, its distribution exhibits a sharp decline around the mass of the W boson for $\mathrm{t\bar{t}}$ and WW events and is therefore well suited to suppress these backgrounds. Hence, a requirement of $M_{\mathrm{T2}}(\ell\ell) > 90\,\mathrm{GeV}$ is imposed in this search.

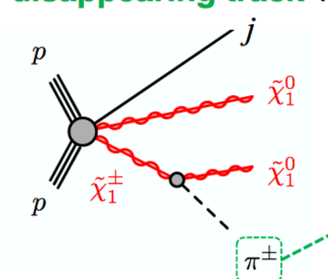
Physics Motivation: Higgsinos

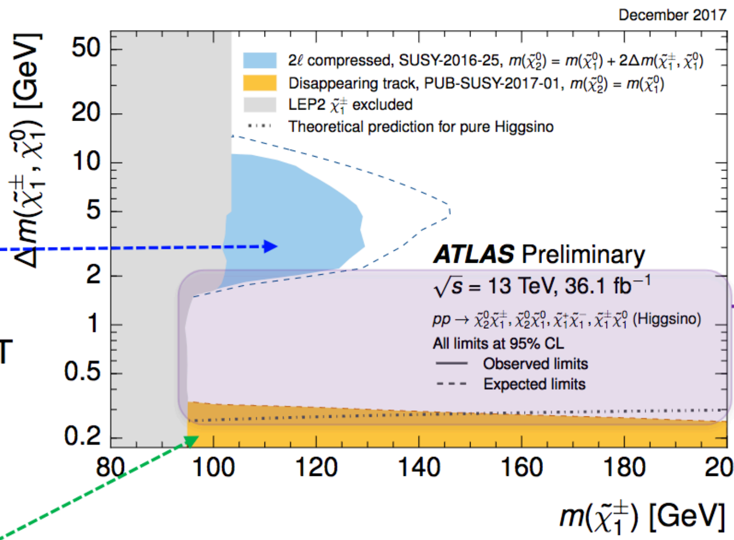
- **Higgsinos** are **key for naturalness** and **experimentally challenging** at LHC
- **Recently surpassed 16 year old LEP limit on higgsino LSPs with 2016 data!**
- Further progress requires **comprehensive program of searches** à la stops in Run-I
- In theoretically interesting region $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ ~ 1-2 GeV, **soft leptons drive the sensitivity** and conventional methods break down ➡ **good candidate for ML!**

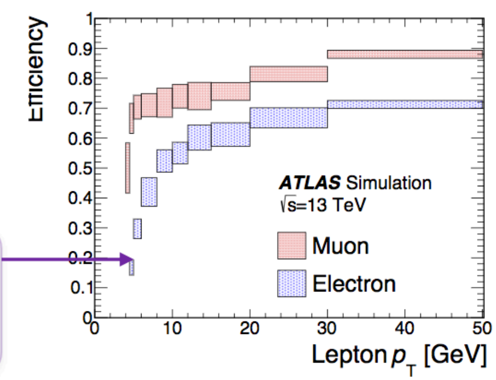
$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ ~ few GeV:
soft $\ell^+\ell^-$ + j + MET



$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim$ 300 MeV:
disappearing track + j + MET



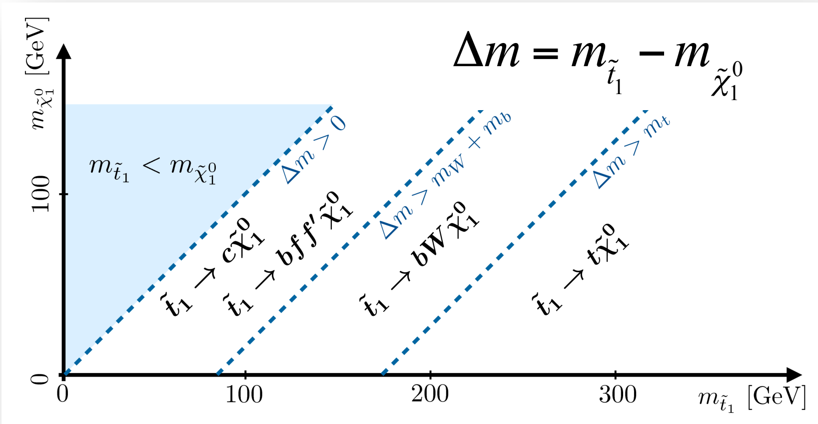




p_T = 4.5 GeV electrons:
15% efficiency & bkg is 80% fakes ➡ dominant σ_{syst}(bkg)

Searches with Stops in ATLAS and CMS

The stop decay depends on the SUSY mass spectrum



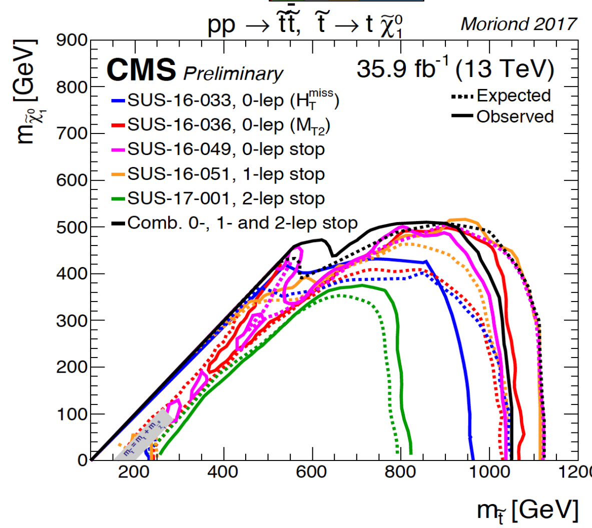
If only $\tilde{\chi}_1^0$ is lighter than $\tilde{t}_1$:

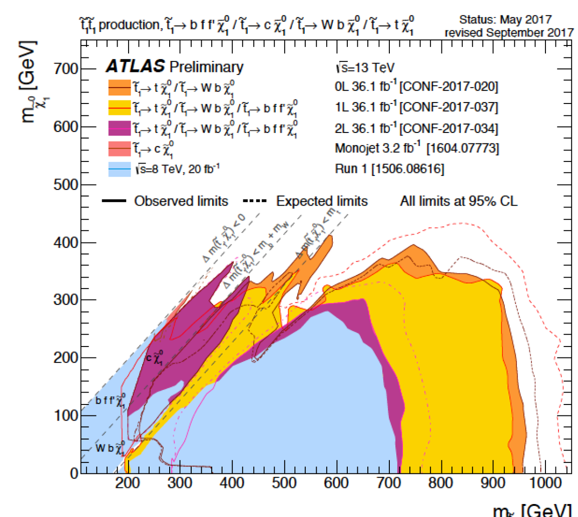
$$\tilde{t}_1 \to t\tilde{\chi}_1^0 \quad \tilde{t}_1 \to bW\tilde{\chi}_1^0 \quad \tilde{t}_1 \to bff'\tilde{\chi}_1^0 \quad \tilde{t}_1 \to c\tilde{\chi}_1^0$$

If also $\tilde{\chi}_1^{\pm}$ or $\tilde{\chi}_2^0$ is lighter than $\tilde{t}_1$:

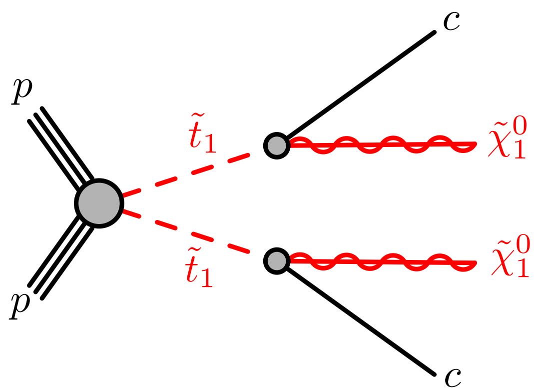
$$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm} \; and \; \tilde{t}_1 \to t\tilde{\chi}_2^0$$

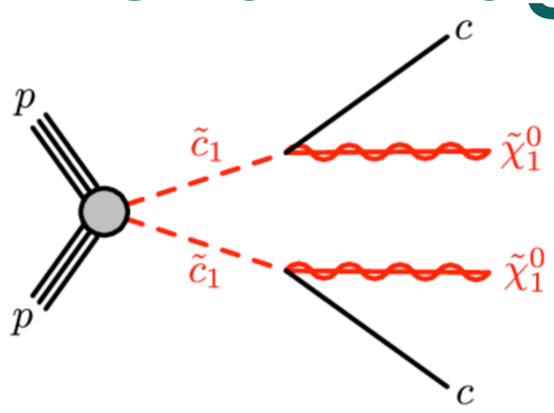
- Inclusive stop searches with multiple decay modes ➔ covering the broad range of parameter space (from compressed to uncompressed)
- Compressed Spectra dedicated analyses with $\Delta M < M_W$

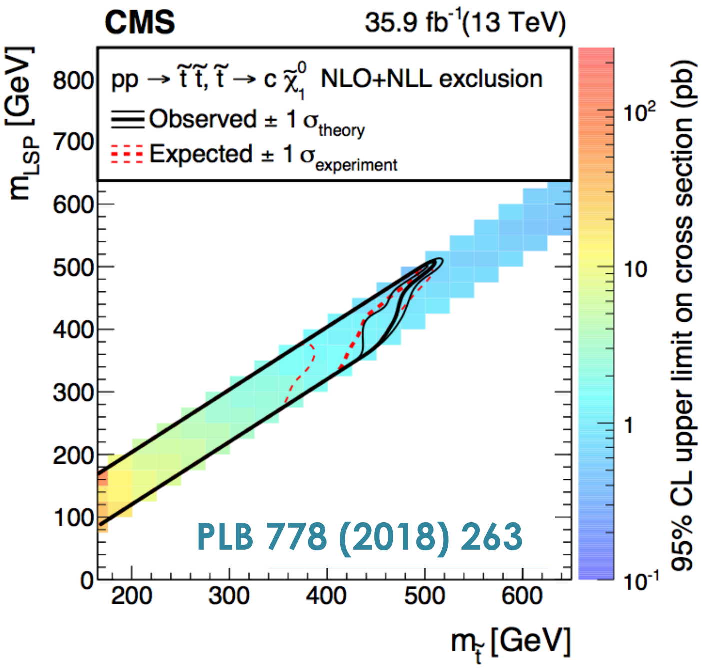


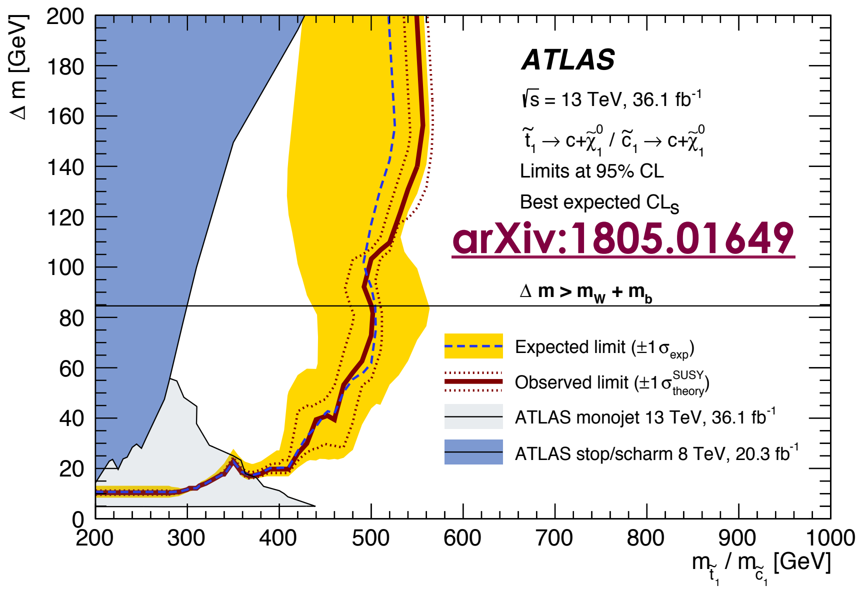


Search for SUSY with charm tagging





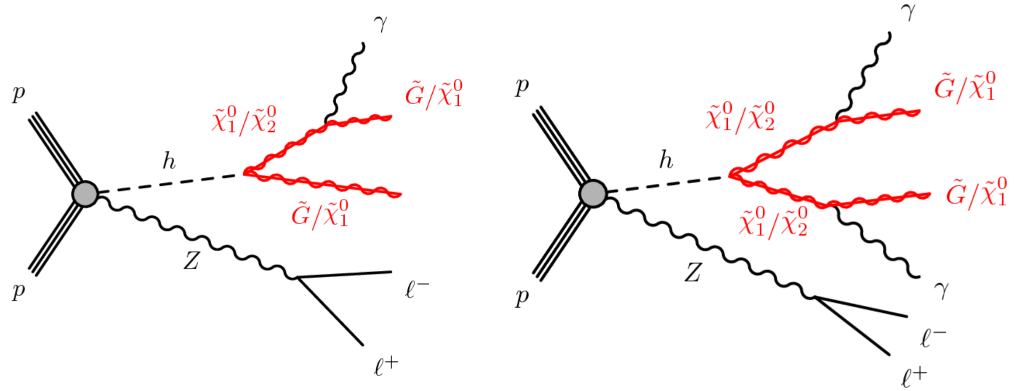


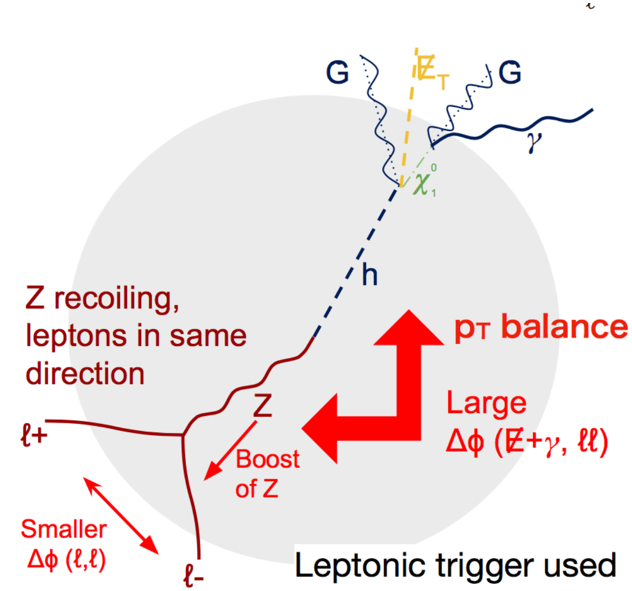


Exclude top/charm squarks up to ~500 GeV for small mass differences with the LSP

Zh, h→neutralino

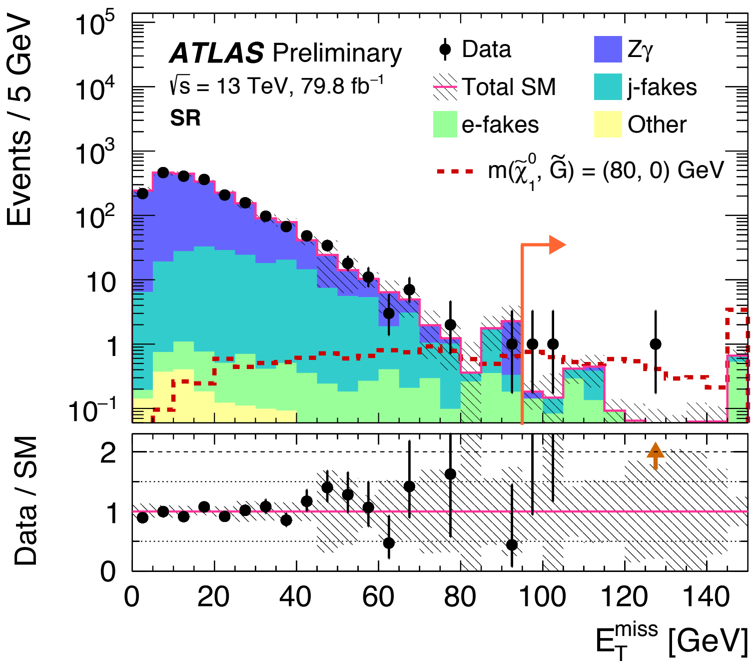
First 80 fb^{-1} SUSY result from ATLAS!!



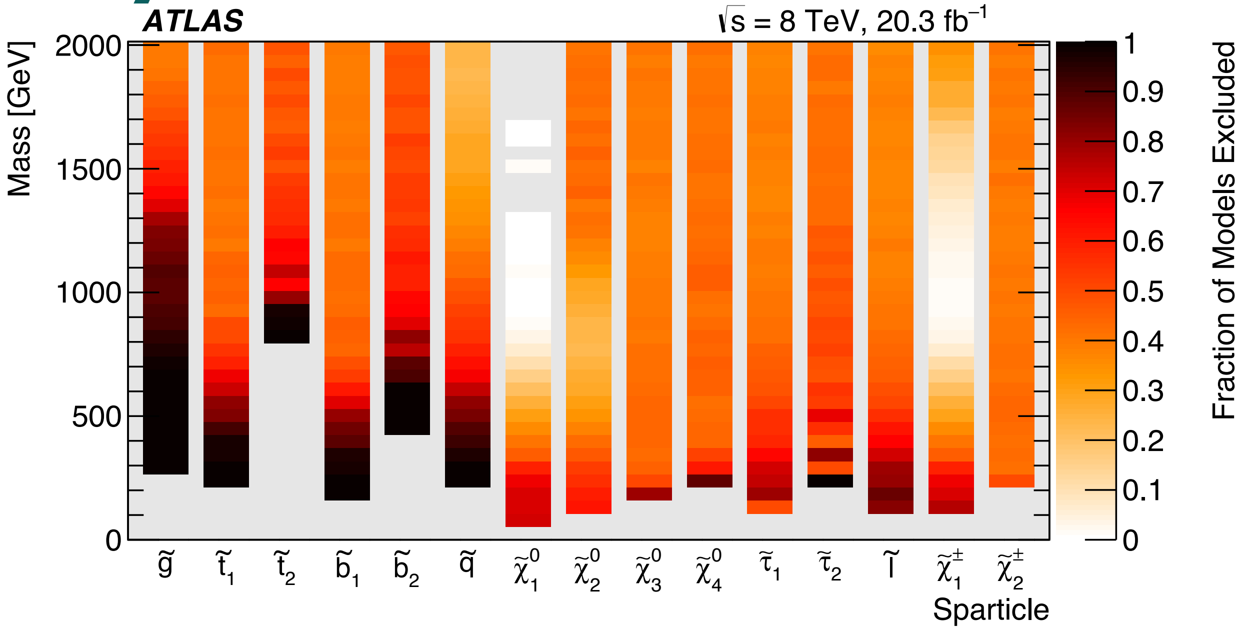


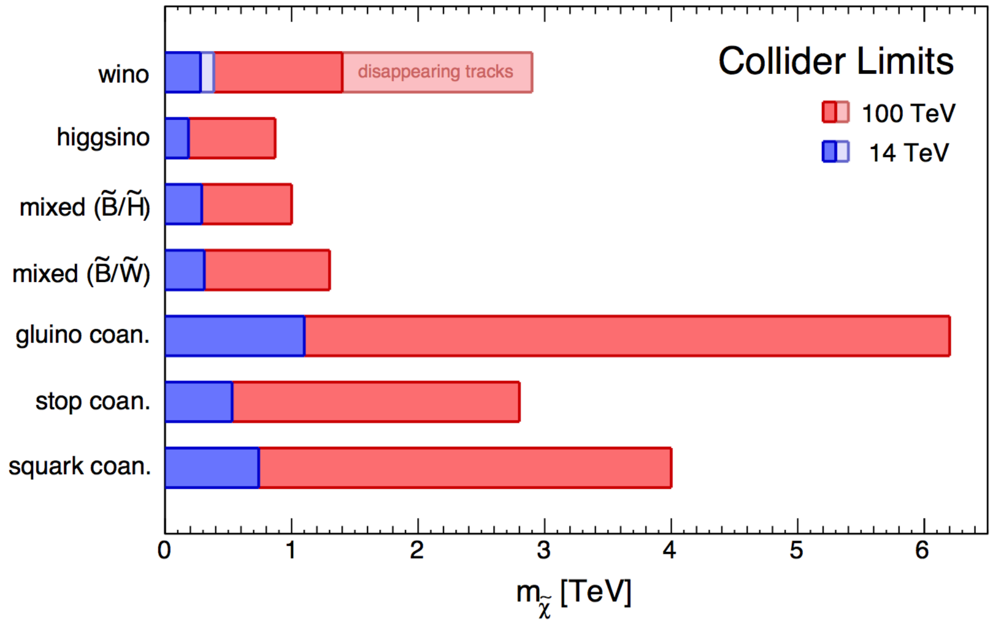
- Bino LSP has no generic collider limit when wino/higgsino are decoupled but it can be generated from higgs decay when it is lighter than 125 GeV
- GMSB signal assumed
- No significant excess observed → setting limit on higgs BR(H→ χ^0G) or BR(H→ $\chi^0 \chi^0$) to be less than 5-11% at 95% CL

ATLAS_CONF_2018_019



Summary for SUSY searches





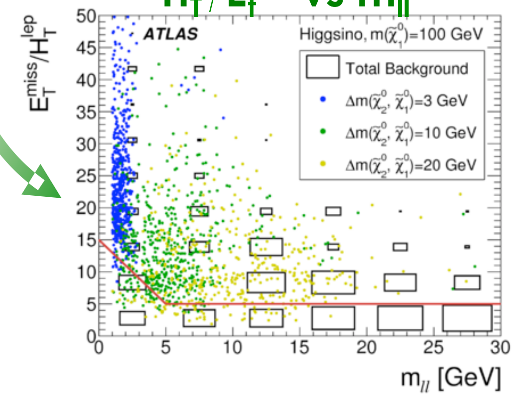
Higgsino Signatures in ATLAS and CMS (1)

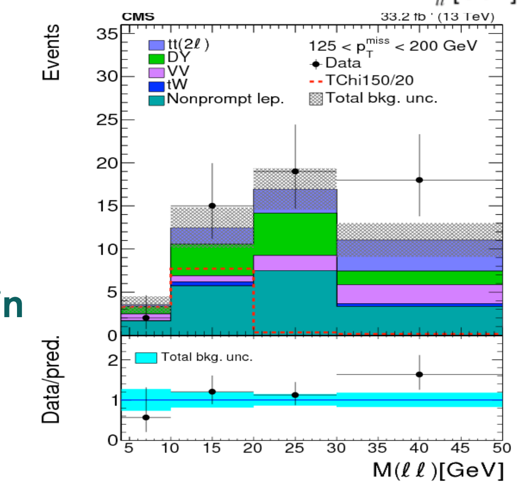
Key aspects of the search: Signature: soft $e^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}$ + E_T^{miss}

- Sensitivity driven by low-pT leptons (lower than any other ATLAS/CMS search!)
- High-pT jet(s) and MET (well separated)
- Cut on H_T/E_t^{mis} against QCD multijet events
- b-jet veto against ttbar
- $M_T(\ell_i, E_t^{mis})$<70GeV ➔ E_t^{mis} aligned with ℓ
- Trigger acceptance: dimuon invariant mass $m_{\mu\mu}$<60GeV to limit the trigger rate ➔ m_ℓ<50GeV and $p_{T\ell\ell}$>3GeV
- H_T>100 GeV: this requirement suppresses backgrounds with low hadronic activity in the event
- Signal Regions: ATLAS binned m_{ll} starting from 1GeV and CMS binned m_{ll} and E_t^{mis}

	ATLAS	CMS
muons p_T	> 4 GeV	> 3.5 GeV
electrons p_T	> 4.5 GeV	> 5 GeV
E_T^{mis}	>200 GeV	>125 GeV
Leading Jet p_T	>100 GeV	>25 GeV
H_T/E_T^{mis}	>max(5, 15-(2m_{ll}/1GeV))	0.6 -1.4

H_T/E_t^{mis} vs m_{ll}



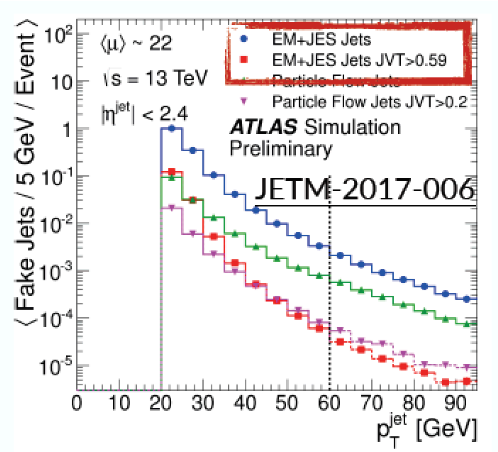


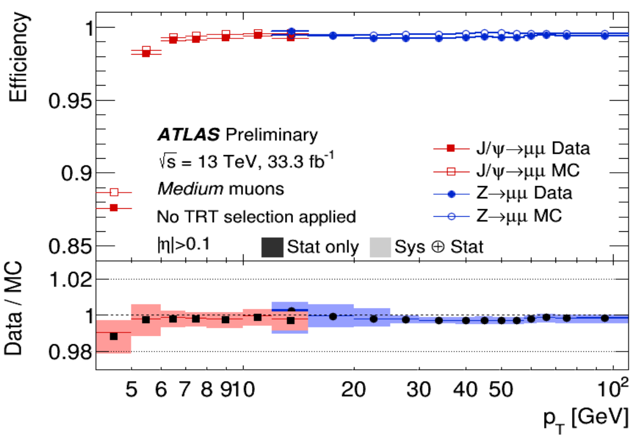
Backgrounds:

- tt (2l): normalized to data in control region and shapes from MC
- DY➔ $\tau\tau$: normalized to data in control region and shapes from MC
- VV(mainly WW/WZ): from MC validated in data control region
- Non-prompt prediction from tight-to-loose method, constraint in same-sign lepton control region

Compressed Spectra: Experimental Challenge

- **Increased acceptance by reconstructing low-p_T leptons:** particles with low transverse momentum („soft") produced in decay ➔ soft particles are hard to detect (at the LHC)
- **Use initial state radiation (ISR) jet:** it boosts the system and produces large missing transverse energy (MET) ➔ ISR jets + MET topologies to trigger and discriminate against backgrounds
- **New "compressed" triggers:** combined information from both soft leptons (p_T>5GeV) and MET (> 125 GeV)
- **New discriminating variables added** ➔ kinematic information about the lepton and the soft particles to distinguish "prompt" (signal) leptons from those that may have come from a jet and are thus "non prompt" (background)
- **Soft b-tagging:** soft b-tagging algorithm in addition to „default" b-tagged jets
- **Recursive Jigsaw Reconstruction and other peculiar discriminants**
- **Long lifetimes** ⟹ look for disappearing tracks is very challenging, LHC detectors not designed for this!





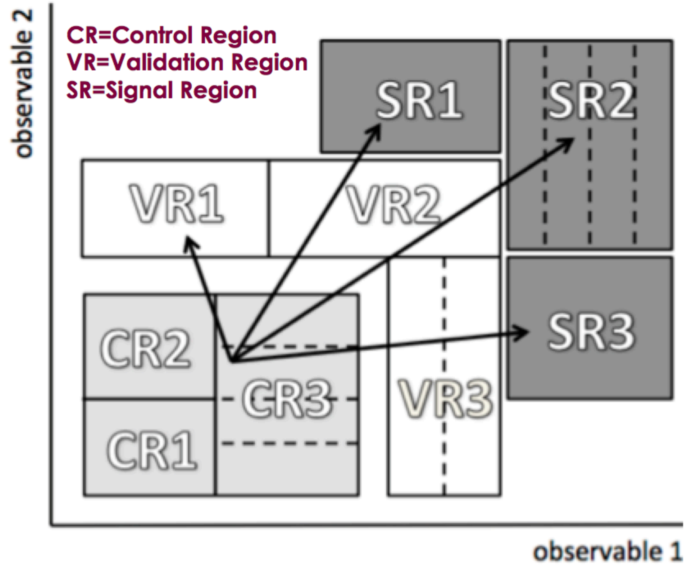
Reconstruction & Background Estimation

Background estimation methods

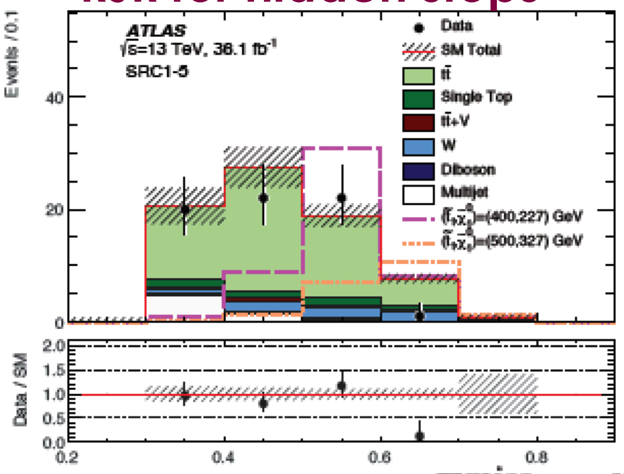
- **Irreducible Background (tt, DY,…):** normalized in data control regions and shapes from MC
- **Data-driven estimates:** for detector / instrumental effects, e.g. instrumental E_T^{miss}, fake / non-prompt leptons
- **VV(mainly WW/WZ):** from MC validated in data control region
- **Rare backgrounds (ttZ, VVV):** Raw MC
- **Non-prompt prediction:** constraint in same-sign lepton control region

Some recent updates & improvements

- ATLAS: Exploit IBL for long-lived particles
- CMS: soft b-tagging
- Recursive Jigsaw Reconstruction (RJR) **[PRD 95, 035031 (2017)]**
- Reduced lepton threshold
- Multi-bin shape fits



RJR for hidden stops*



*$m_{stop} = m_{top} + m_{LSP}$

$$R_{ISR} \equiv \frac{E_T^{miss}}{p_T^{ISR}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}$$

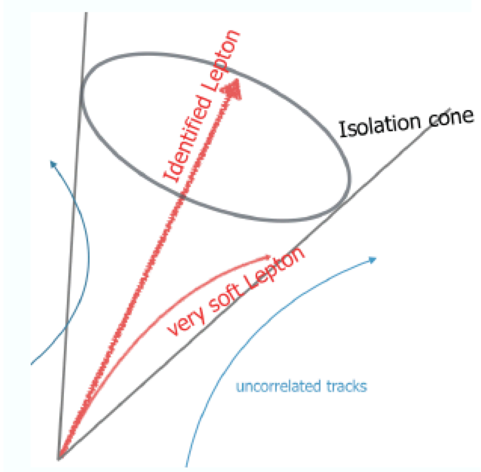
[1] Rogan, Jackson, Santoni, PRD 95, 035031 (2017)

Isolation for compressed signals

- Small ΔR expected for leptons from compressed signals
- Isolation can be corrected by nearby signal leptons entering isolation cone ➔ Dedicated tool developed (4L EWK)
- Important recovery of acceptance at low dilepton masses m_{ll}

Electron currently supported down to **4.5GeV (ATLAS) and 5GeV (CMS)**
Muon currently supported down to **4GeV (ATLAS) and 3.5GeV (CMS)**

Possible Upgrade: Replace lepton by isolated track supported down to ~1 GeV ➔ Potential 3 times signal increase (need to carefully check the background)



Study ongoing, still preliminary but promising

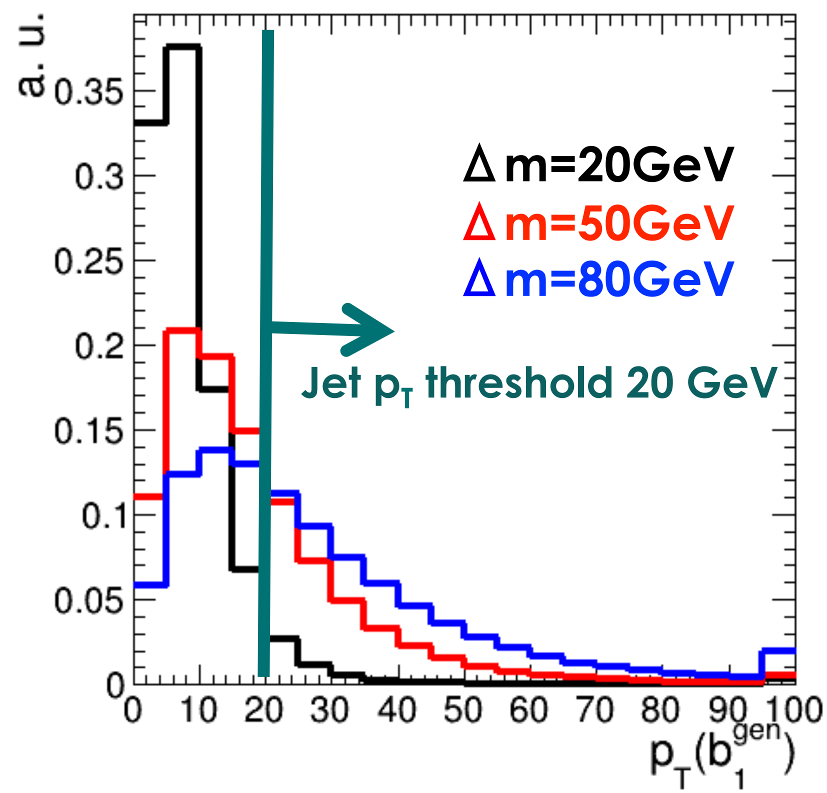
CMS Soft b-tagging

The lower ΔM, the less energy is available in the compressed case to produce a jet ➔ jet-pT threshold at 20 GeV will miss all the soft stuff

Small ΔM produce a large fraction of b quarks below the jet p_T threshold which escape identification through our primary jet collection.

In order to recover signal selection efficiency (and improve bkg rejection), deploy soft b-tagging algorithm in addition to „default" b-tagged jets

- collect all secondary vertices (SV) in the event
- Inclusive Vertex Finder (IVF) algorithm based on impact paramater variables
- Secondary Vertex: select low p_T tracks (<20 GeV) and no „default" jet associated to it
- The presence of a soft (p_T<20 GeV) non-isolated muon is used to estimate the fraction of soft b quarks in data.
- higher MET (in case of ISR boost) will more significantly displace b hadrons
- **20% selection efficiency at 3% mistag rate**



CMS-PAS-SUS-16-049