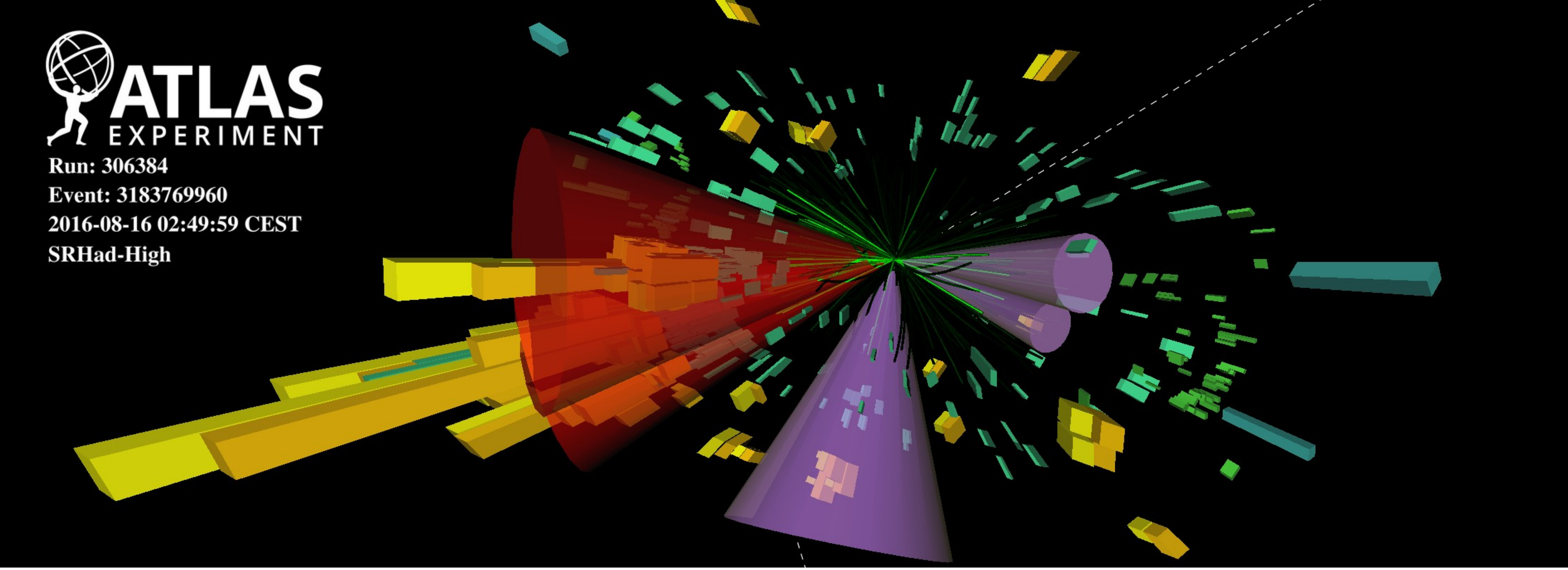


SUSY and the collider DM picture

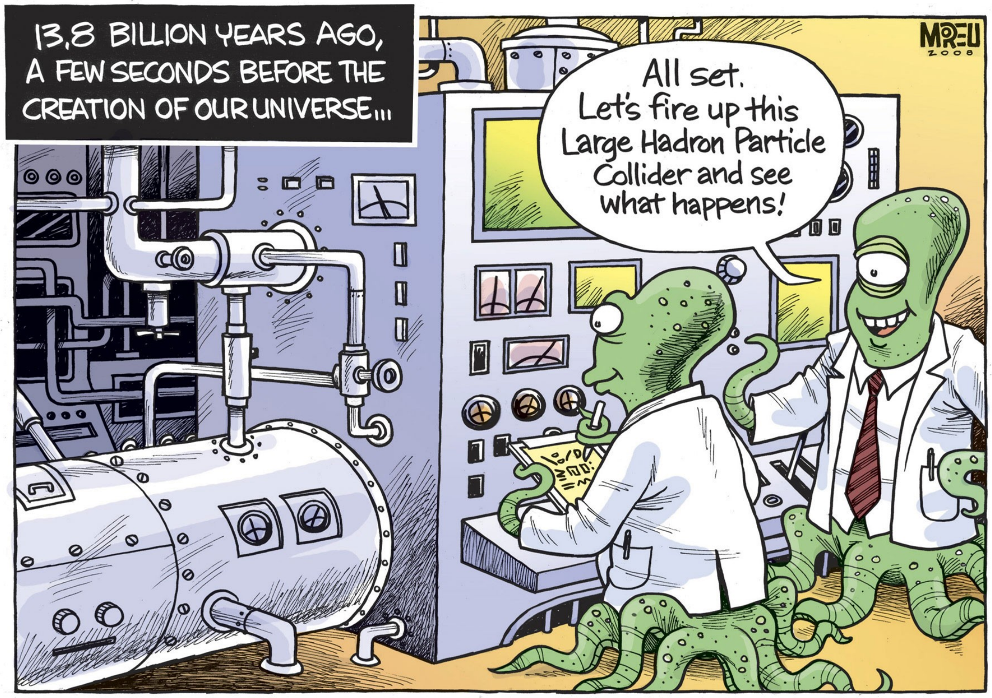
Jeanette Lorenz (LMU München)

LMU
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Oxford, 26.02.2019

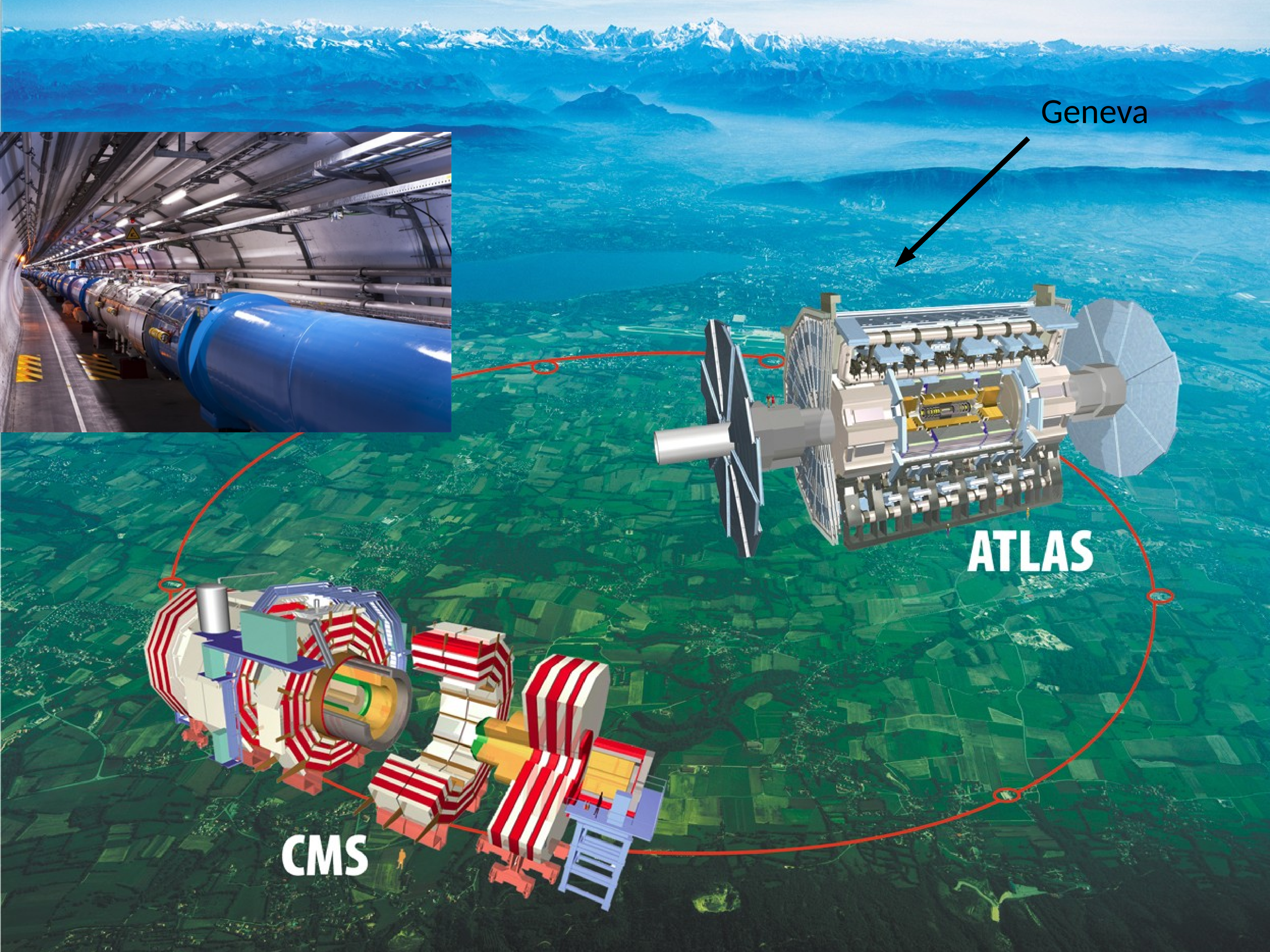
Outline

- LHC and ATLAS/CMS
- Standard Model and its shortcomings
- Searches for EWK SUSY
- Searches for Dark Matter
- Where to go next



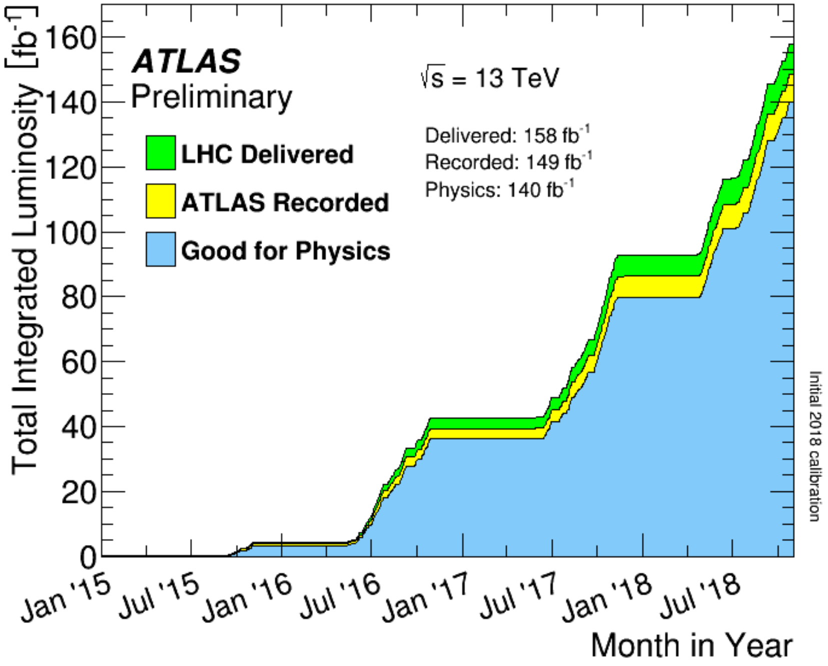
[CERN theory common room]

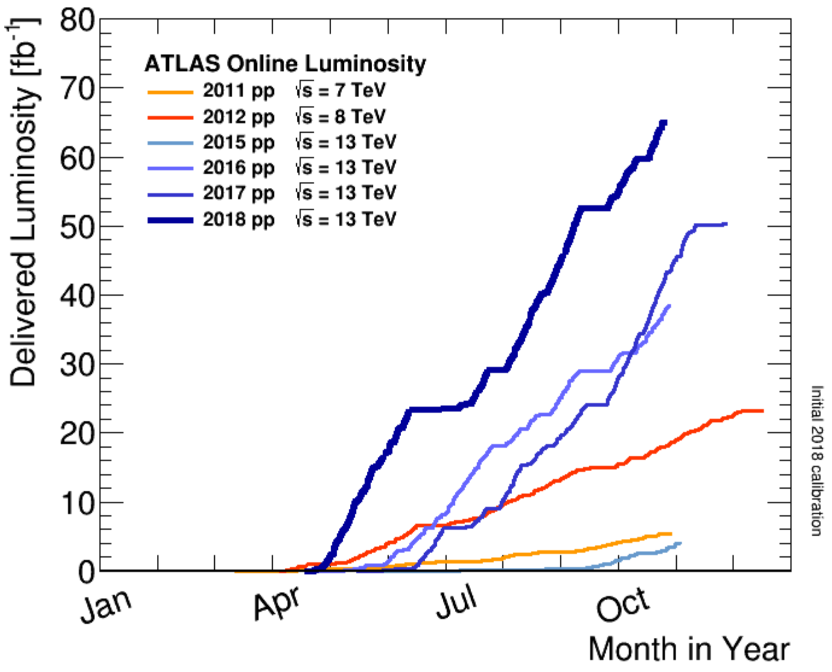
Disclaimer: I'll not talk about long-lived particles and results by LHCb, although both are important in this context too.


Geneva
ATLAS
CMS

Excellent performance of LHC and detectors

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2]





- Proton-proton data taking in Run 2 finished.
- 158 fb^{-1} proton-proton data delivered by the LHC 2015 -2018.
- About 140 fb^{-1} available for analyses.
- Significantly more data than in Run 1
- Most searches only use 2015 + 2016 data so far, few also 2017 data → much more data to analyze!

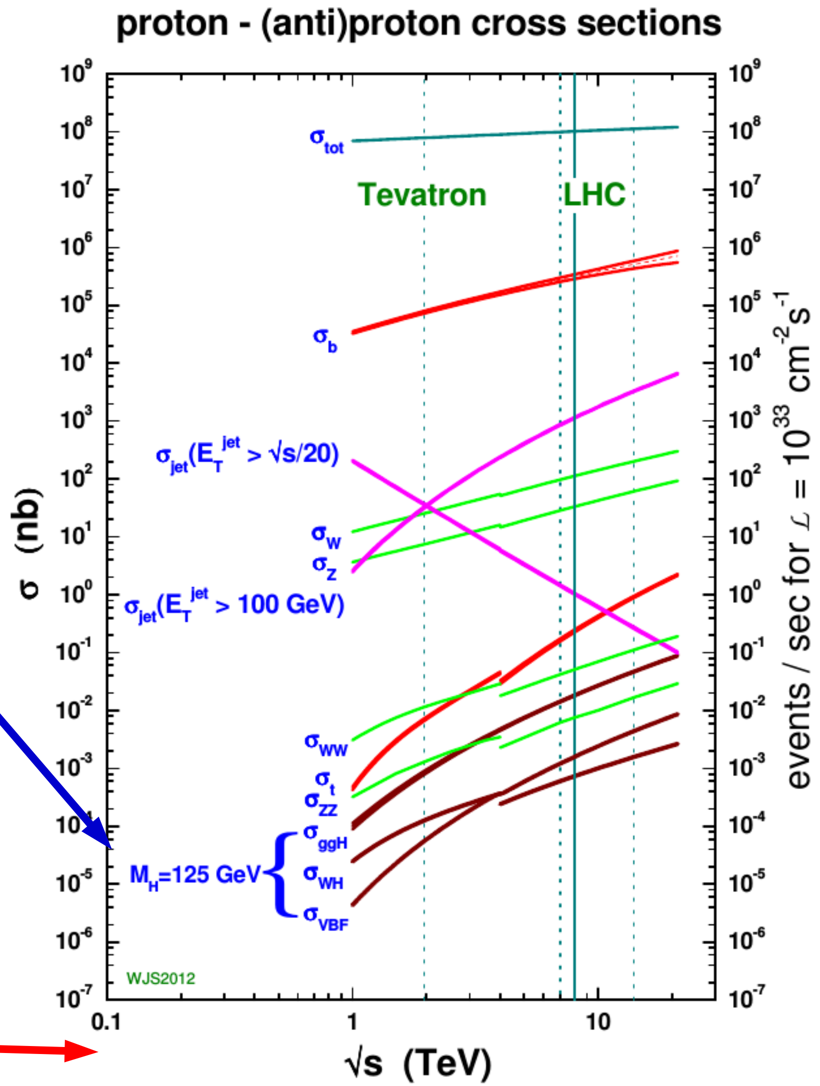
What can we measure?

- Predictions for processes of the Standard Model
  (cross section is measure on how frequent a process occurs)

- Higgs boson productions:
  1 Higgs bosons in about 10^{10} collisions
  (e.g. in 2017: about 3 million collisions per second)

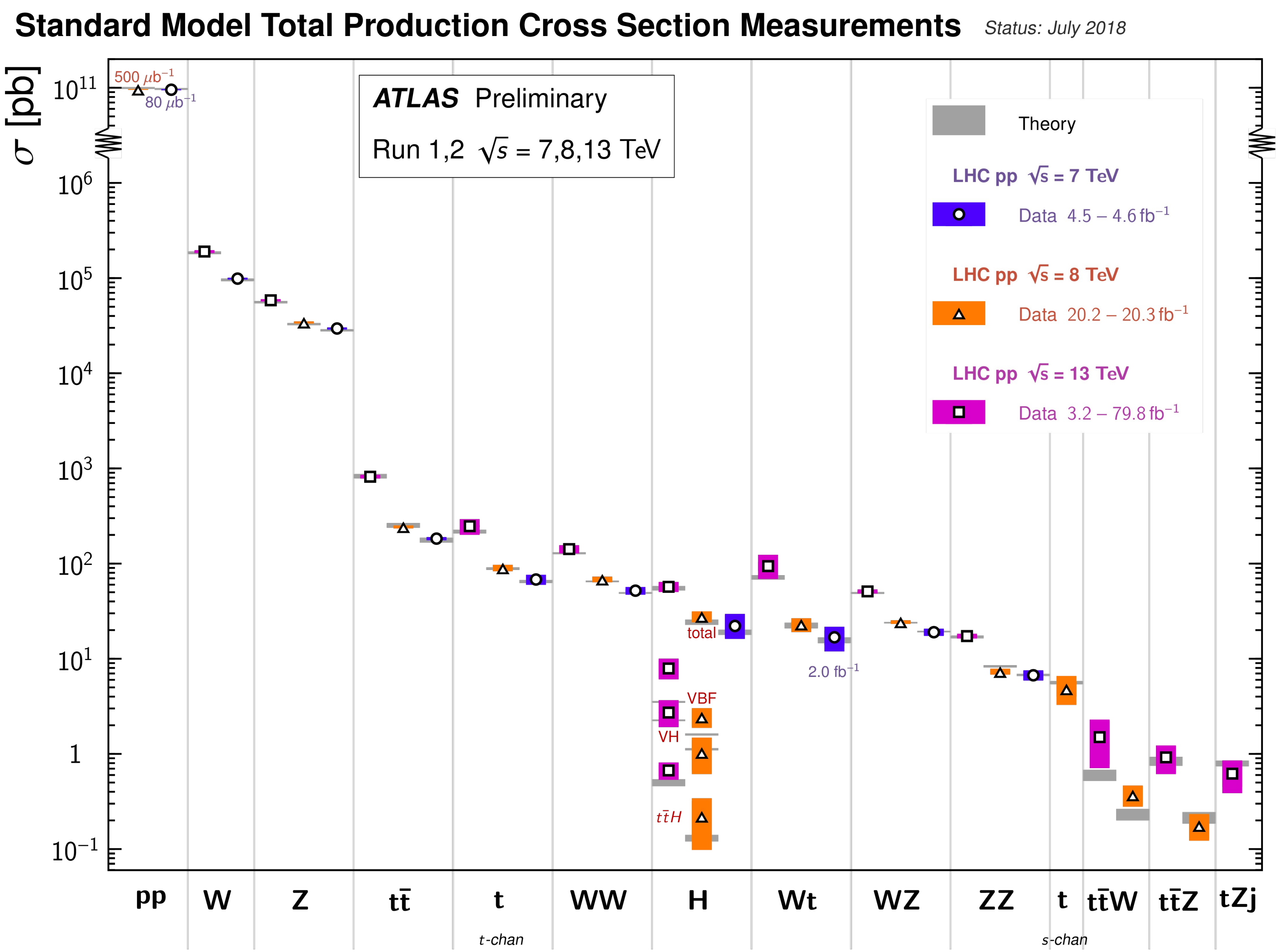
- Need to run complex algorithms during data-taking to filter processes we are really interested in….
  → *trigger*

Maybe unknown physics down there?



[http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html]

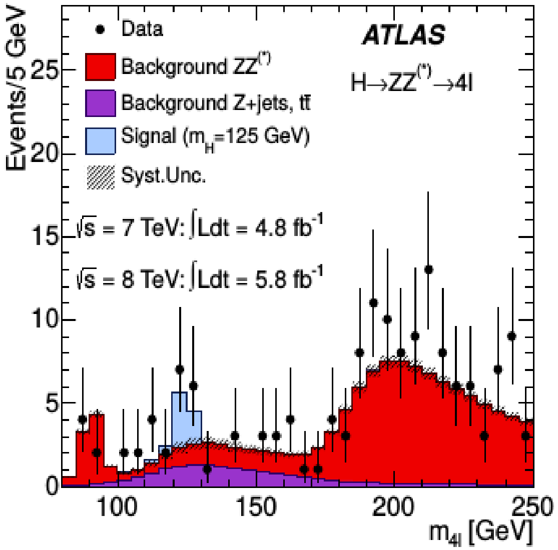
Precision measurements of the Standard Model



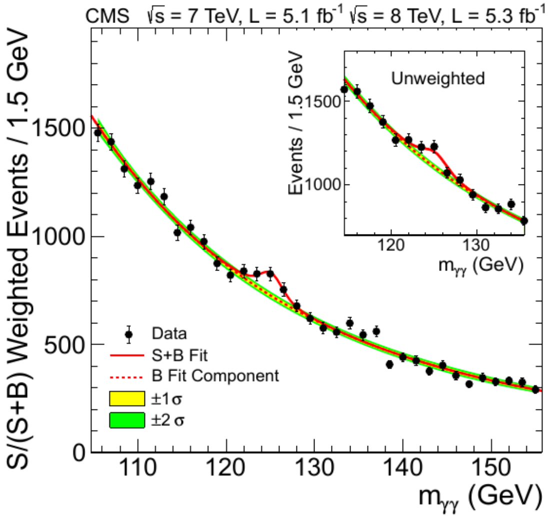
[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_a_SMSummary_TotalXsect/ATLAS_a_SMSummary_TotalXsect.png]

Completing Standard Modell: Higgs boson

[Phys. Lett. B 716 (2012) 1-29,ATLAS-CONF-2017-047]

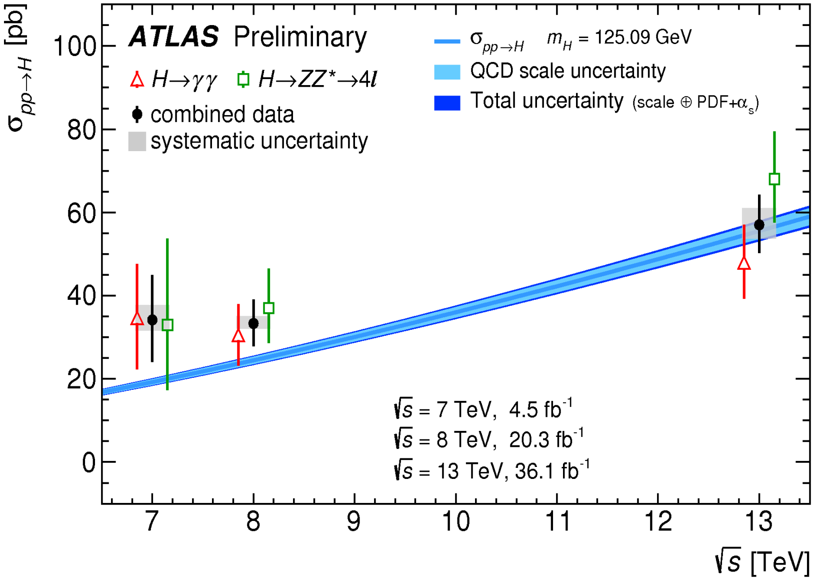


Discovery of Higgs boson in Run 1 data (4th July 2012)



Since then searches for Higgs bosons turned into measurements – compatible with predictions of Standard Model?

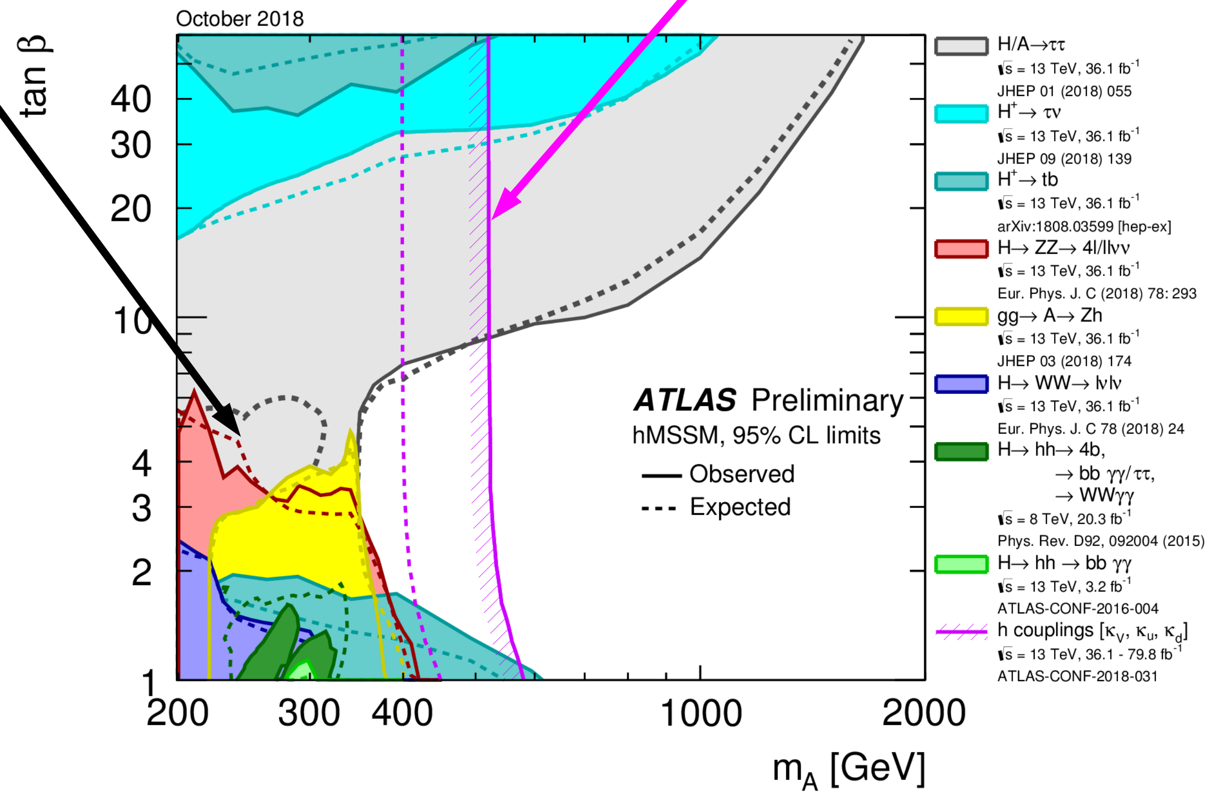
→ So far no deviations



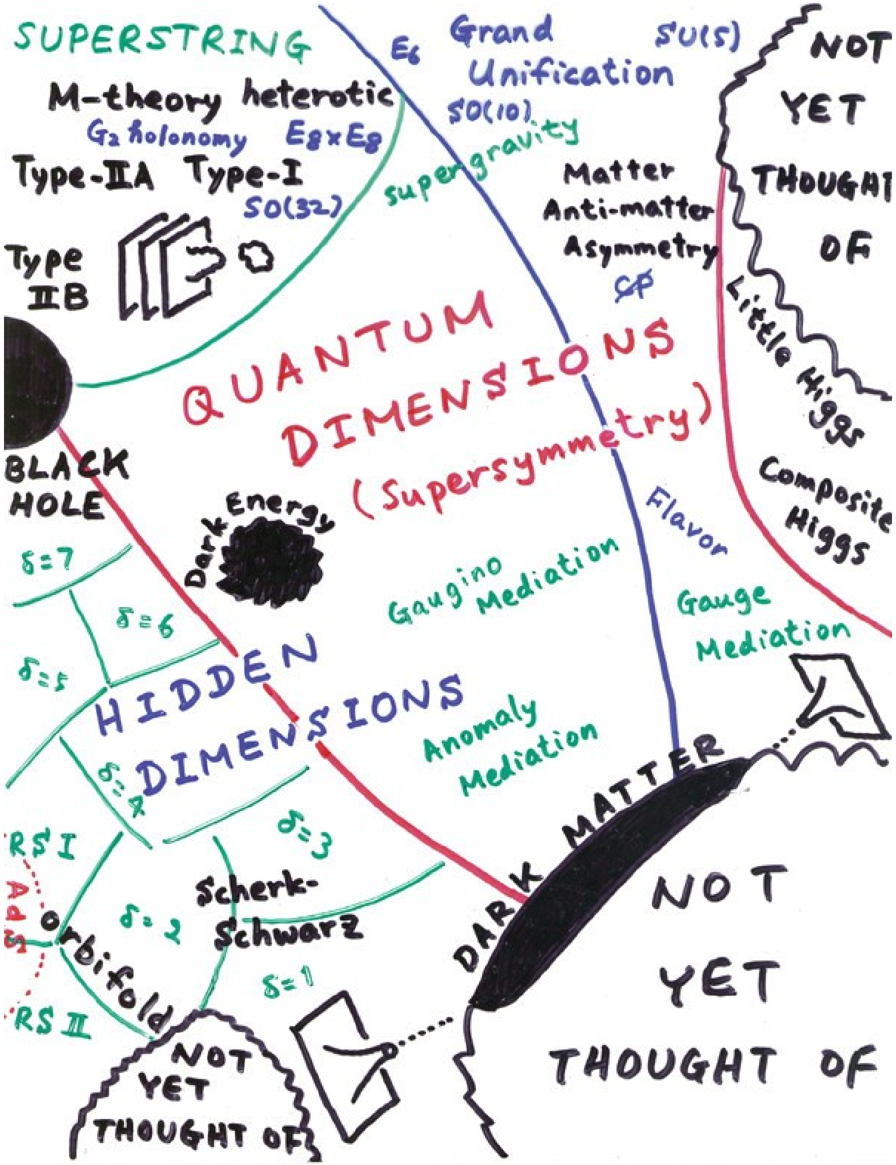
More Higgs bosons?

Many extensions of the Standard Model predict more than one Higgs boson:

- E.g. 2HDM models predict 5 Higgs bosons: two neutral CP even (h, H), one CP odd (A) and two charged Higgs bosons (H^{+-})
- Can reinterpret measurements of the Higgs boson found in these models
- Can search for additional Higgs bosons



Is there anything else?



SM not perfect:

- *No explanation for Dark Matter (DM)*
- *No explanation for matter-antimatter asymmetry*
- …

Plenty of ideas to solve *at least some of them*

Lots of possibilities to look for

[Illustration by Hitoshi Murayama]

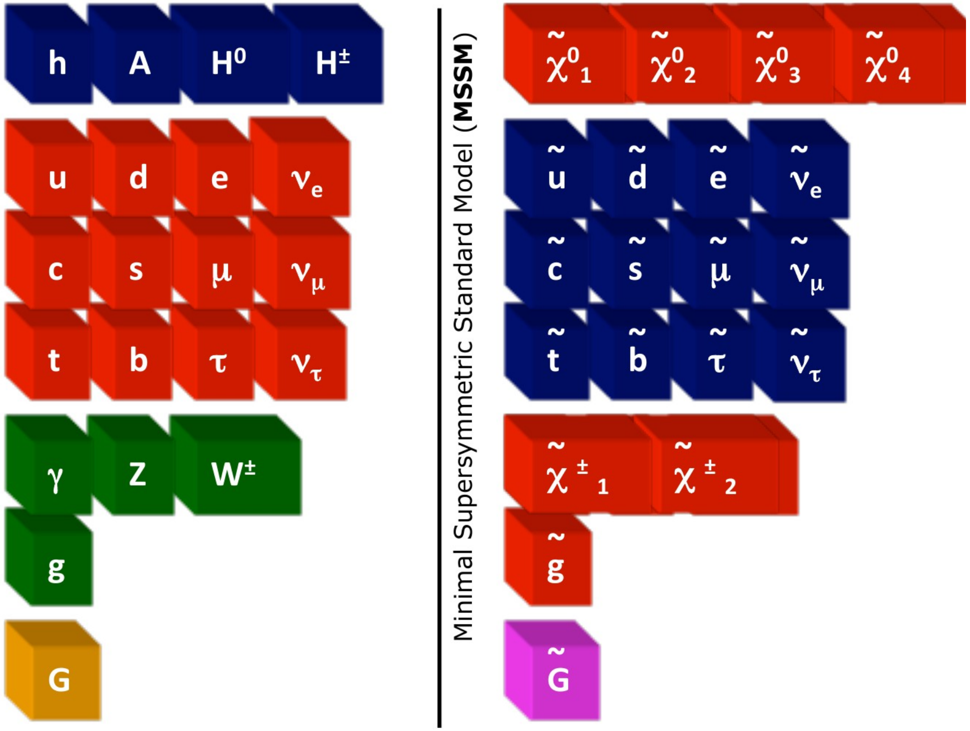
One solution: Supersymmetry (SUSY)

- Symmetry between fermions and bosons
- Supersymmetric partner particles to every Standard Model particle

→ roughly doubling of number of particles wrt Standard Model in the Minimal Supersymmetric Standard Model

Extended Higgs sector necessary

Supersymmetric partners of W, Z and Higgs bosons mix to charginos and neutralinos

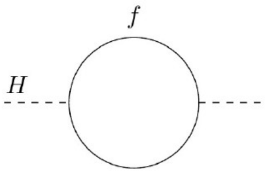


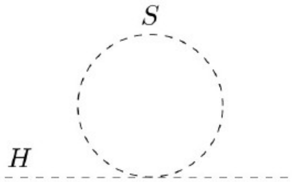
Motivations

- Supersymmetry can offer a Dark Matter (DM) candidate

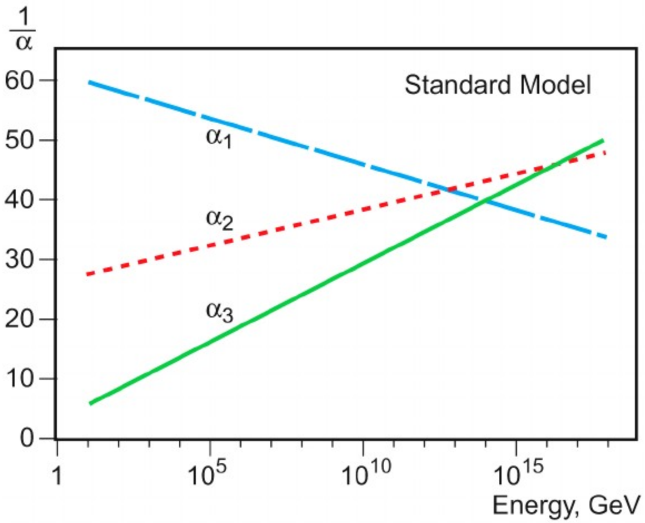
  ...if R-Parity conserved

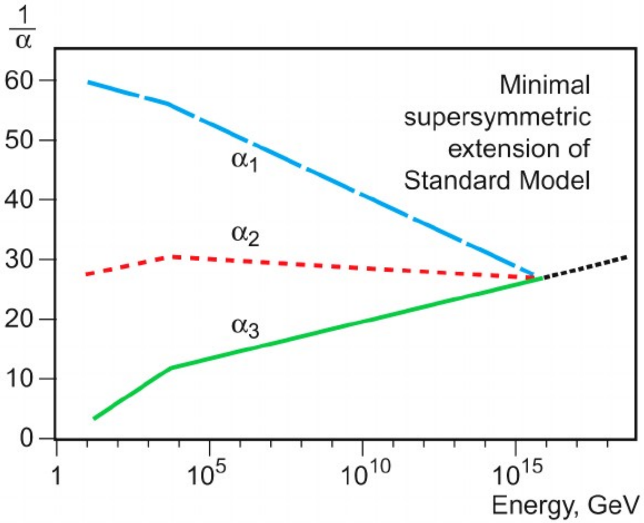
- Higgs mass might get stabilized





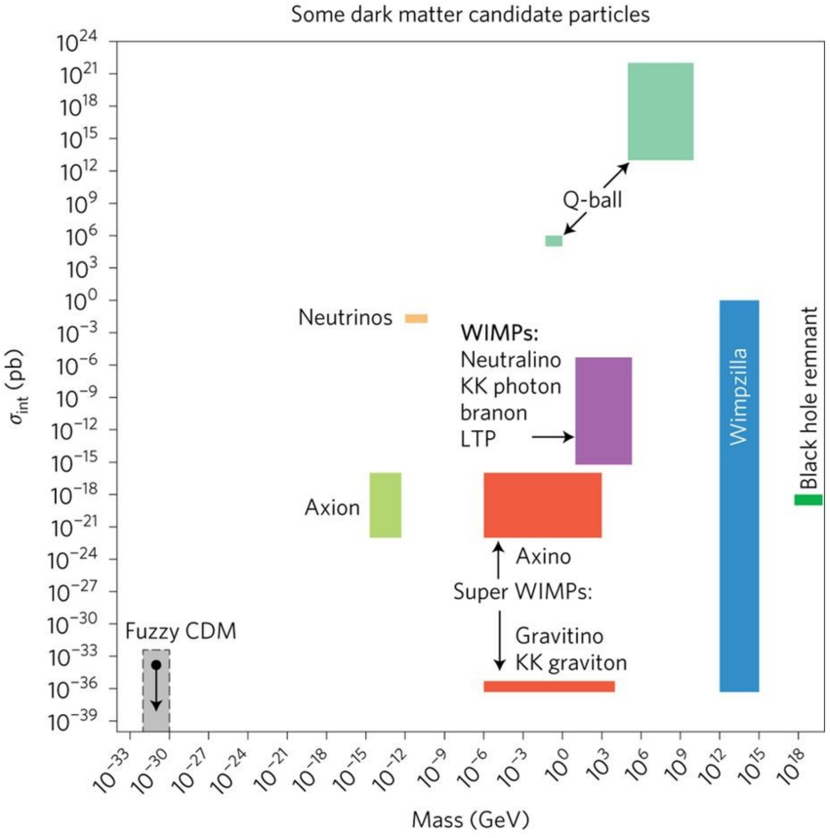
- Inverse of gauge couplings could be unified in the MSSM





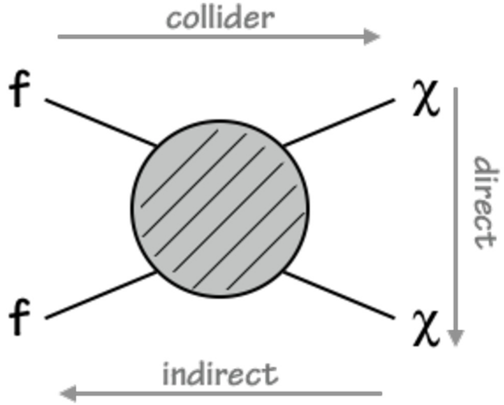
But not the only candidate for Dark Matter!

[https://www.nature.com/articles/nphys4049/figures/1 from Nature Physics volume 13, pages 224–231 (2017)]



Many extensions beyond the SM provide DM candidates, not only SUSY.

→ Comprehensive search program by different experiments, and using different methods necessary (besides the searches for SUSY).



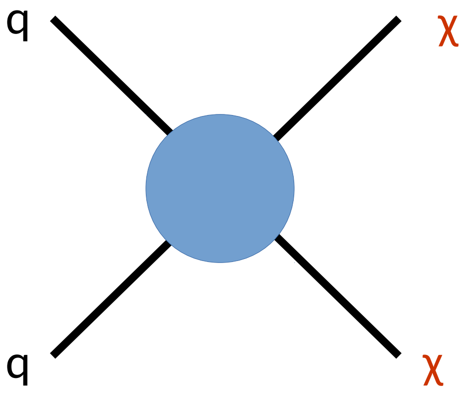
LHC

XENON1T, LUX, Panda-X, Picasso…

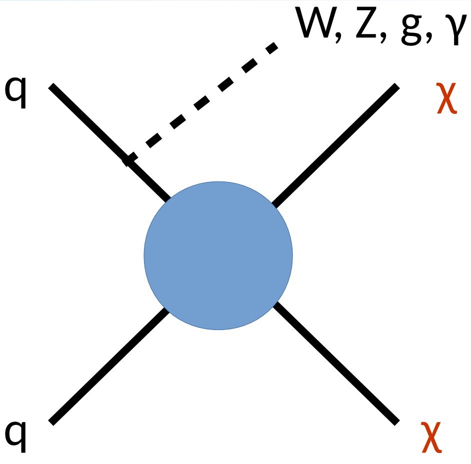
Fermi-LAT, MAGIC, Planck, H.E.S.S. …

[ATLAS-CONF-2018-051]

Dark matter models at colliders

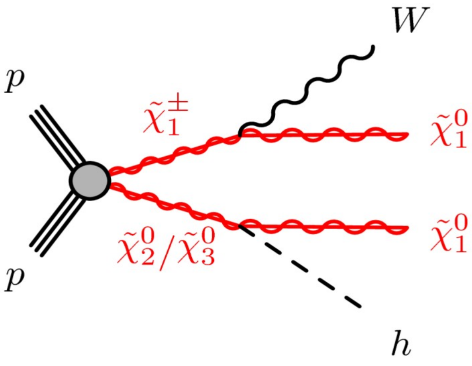


Dark matter particles invisible to LHC detectors → this signature cannot directly be detected



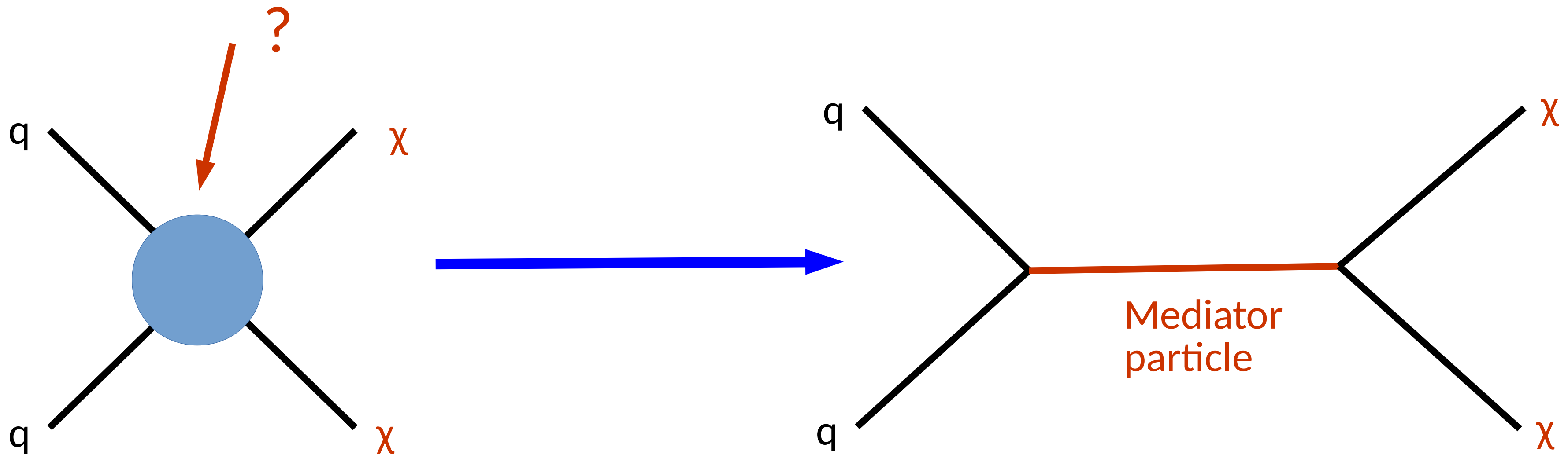
Initial state emission → recoils against dark matter particles

Generic model good for sizable cross-sections, a priori no assumptions on specific model

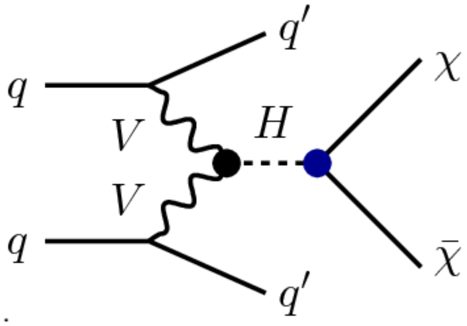


Or detect dark matter particles in decay of other new particles
→ specific models/extensions of SM (like SUSY)

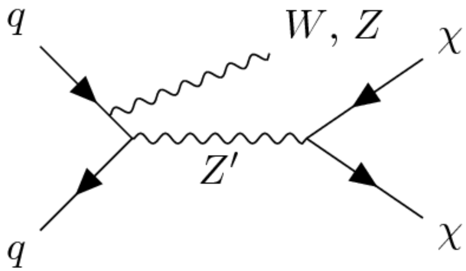
Dark matter models with mediators



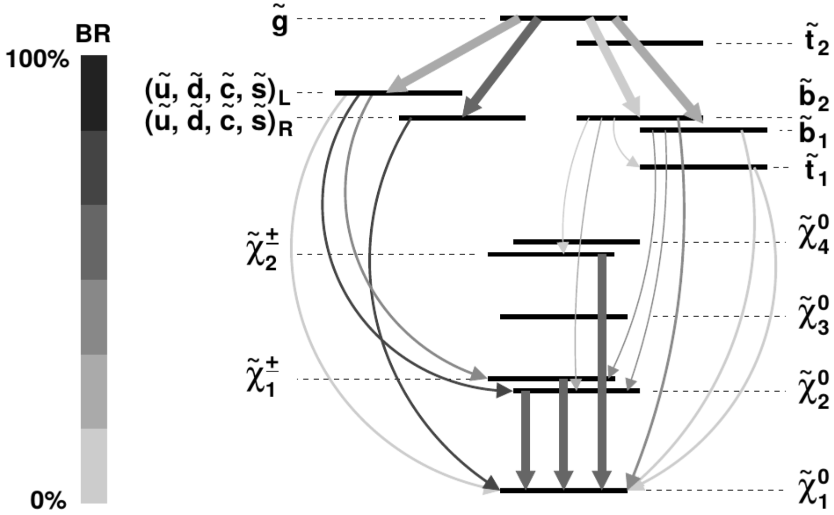
Mediator particle can be SM particle (Z or H)



or a new particle – either spin 1 or 0 – vector-like particle or scalar-like, or Two-Higgs-Doublet Model



Supersymmetric models



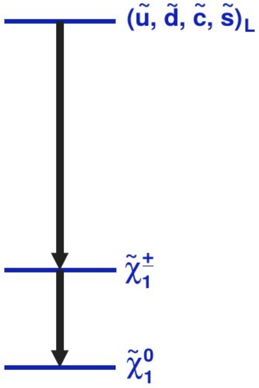
In case of MSSM 124 free parameters!

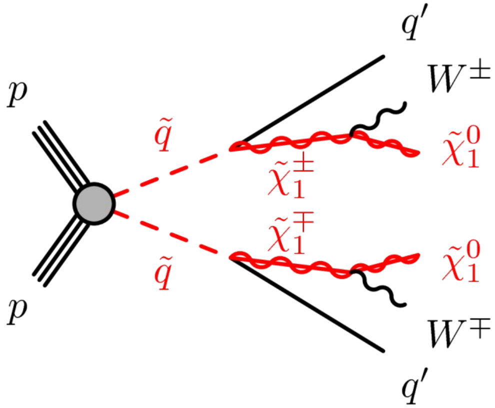
We cannot deal with that many free parameters!*

**but sometimes we at least look at certain reductions, like the pMSSM with 19 parameters*

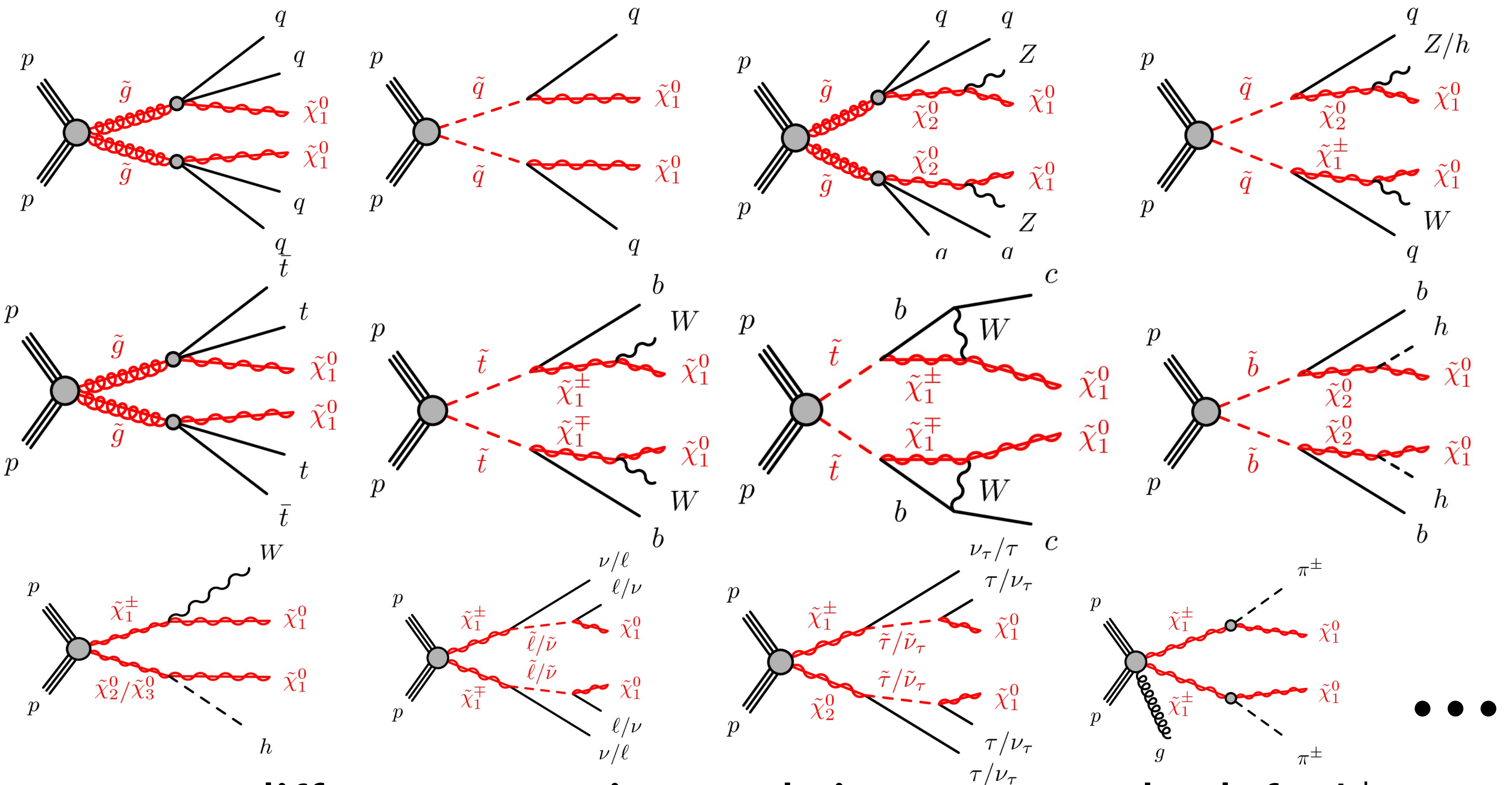
Simplified model

Usually only look at a specific decay chain





Many different simplified models



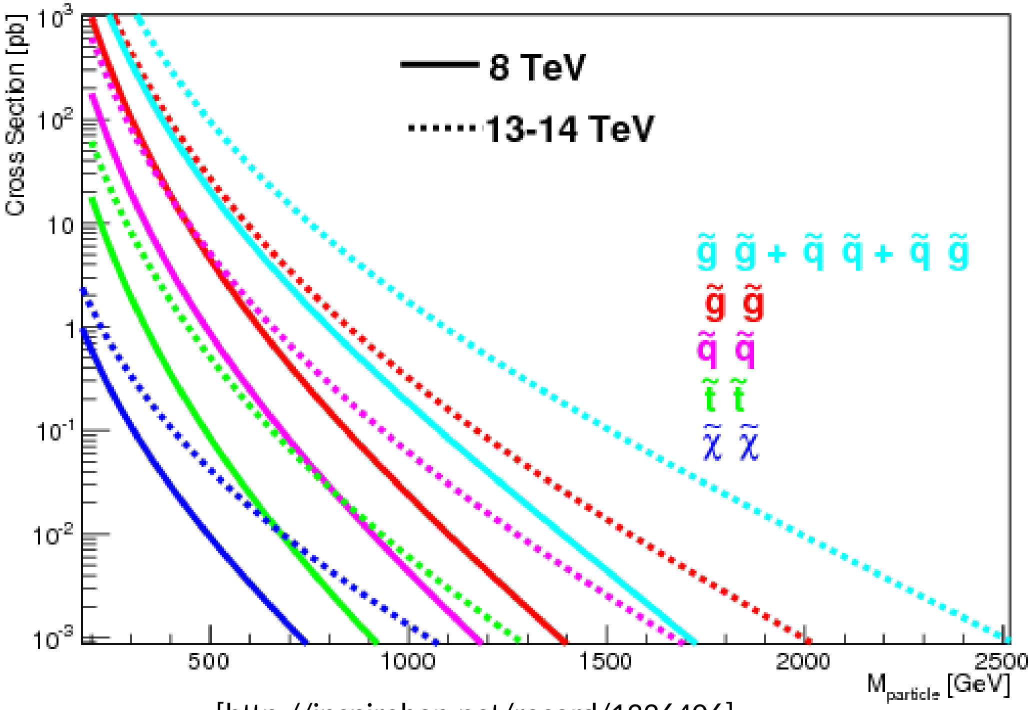
=> Very different experimental signatures to look for!*

* *We can get back to complete SUSY model by combining different simplified models/signatures.*

Searches for supersymmetric particles

Typically organize searches from 'easy' to 'more challenging'
→ cross section

- High cross section for production of gluinos and squarks if not too heavy
  → *early searches in Run 2, many results available, not the focus of this talk*

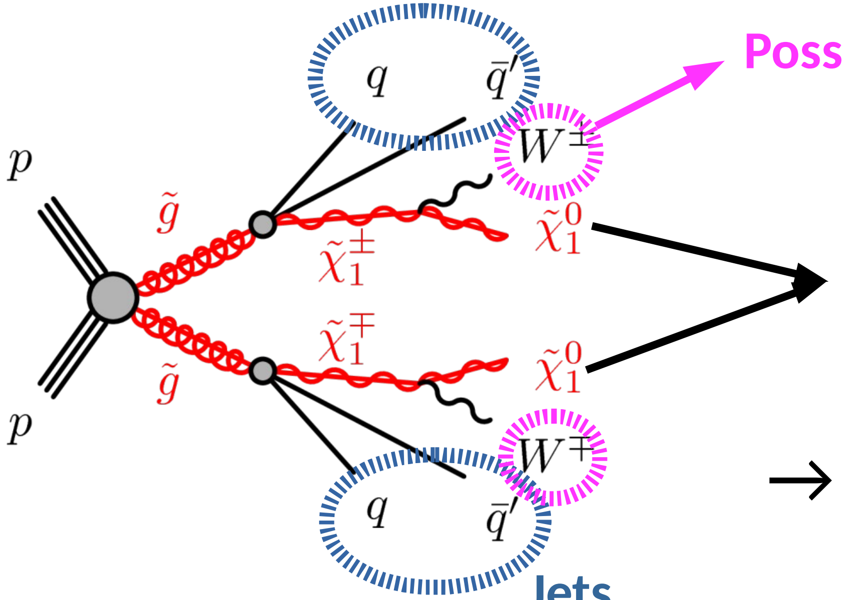


[http://inspirehep.net/record/1326406]

- Smaller cross section for chargino and neutralino production
  → *but obtain sensitivity by using much more data statistics*
  → *profit significantly from the full Run 2 statistics*

Example signatures

E. g. strong production:

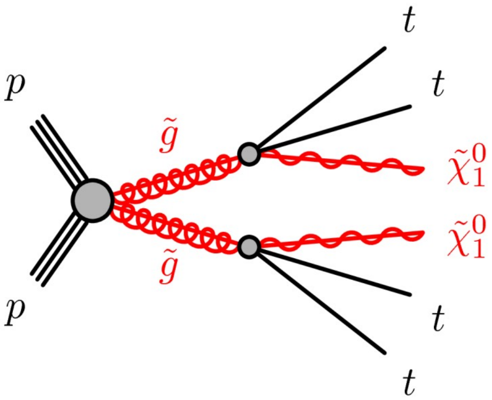


Possibly leptons

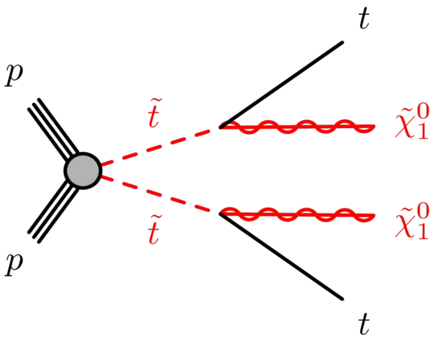
Lightest supersymmetric particle (LSP): stable in R-parity conserving theories → missing transverse momentum

Jets

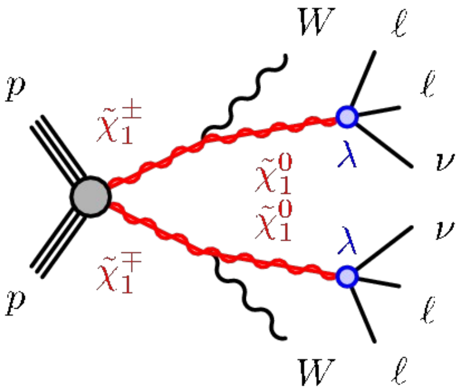
→ Jets + leptons + E_T^{miss}



Gluino-mediated stop quark production



Direct stop quark production

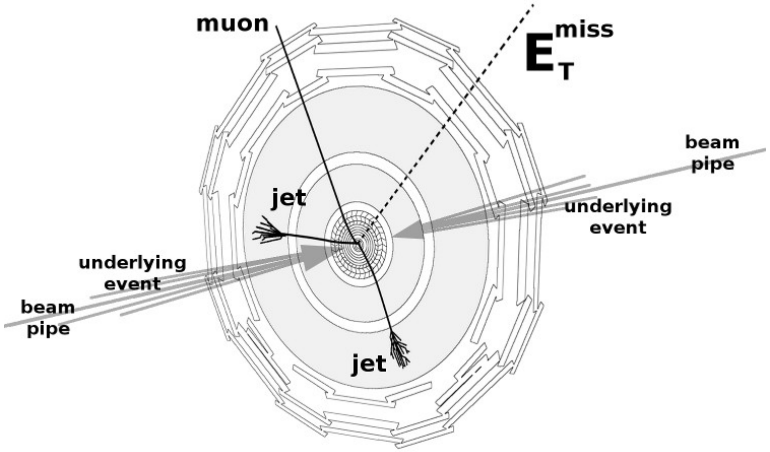


Chargino production + RPV decay

Common to all searches in this talk: E_T^{miss}

Invisible particles to the detector (like neutrinos or dark matter particles) result in a momentum imbalance in the transverse plane to the proton-proton collision
=> **missing transverse momentum** (E_T^{miss})

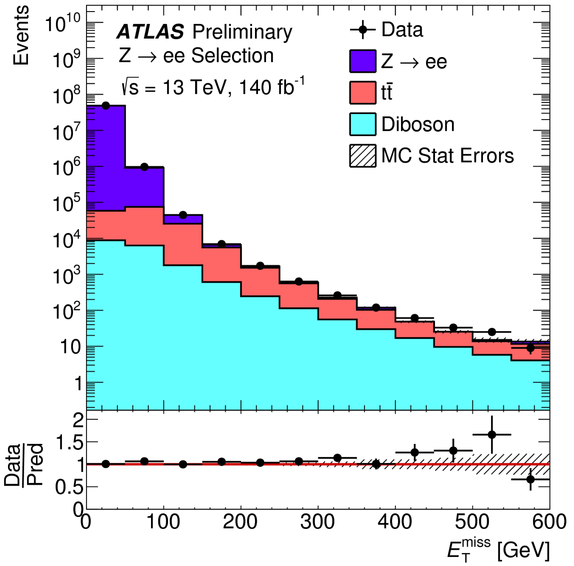
[Jet Goodson]



Calculated using the x- and y-components:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},\mu} + E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,soft}}$$

The **soft term** is composed of all tracks or energy deposits not associated to a reconstructed particle.



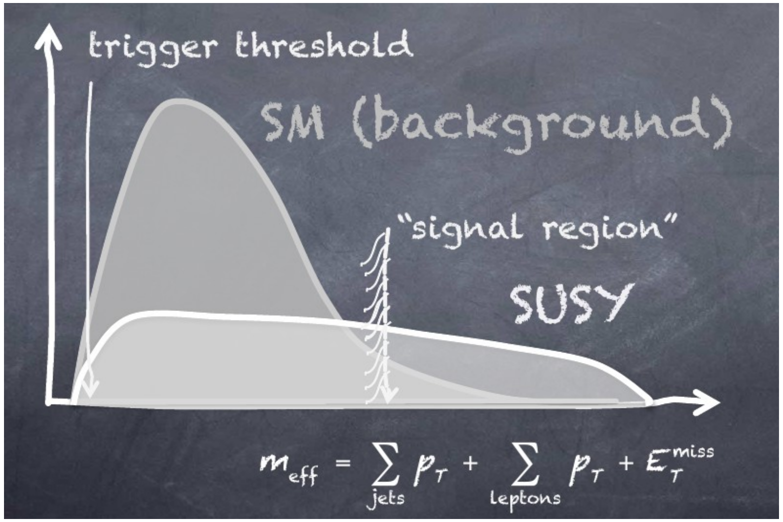
[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2019-03/]

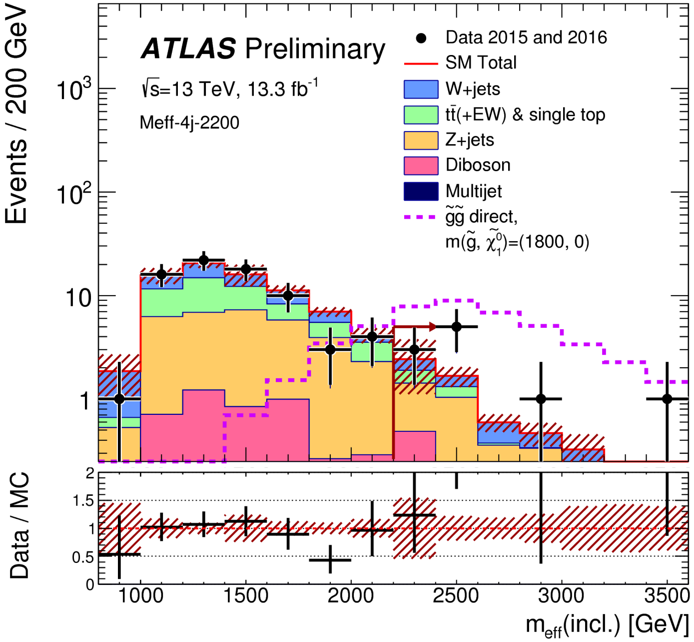
E_T^{miss} can also arise from mis-measurements or pile-up → important to minimize this!

Distinguish signal from background

Use kinematic variables to discriminate signal from background.

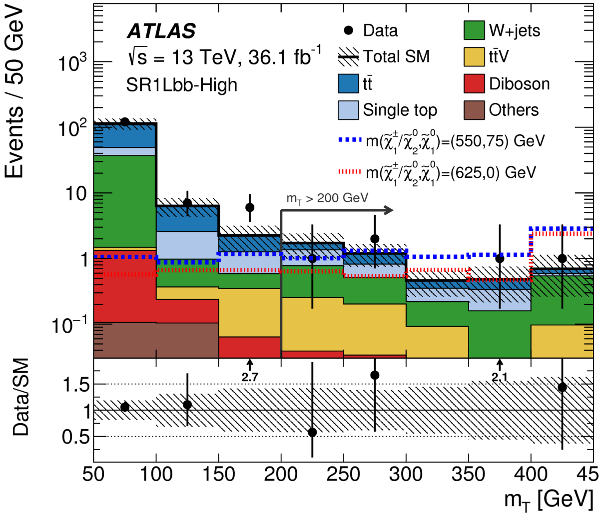
Some analyses just use simple combination of cuts on kinematic variables → ' cut-and-count', but also more and more shape analyses or analyses using more sophisticated techniques, e.g. machine learning





[ATLAS-CONF-2016-078]

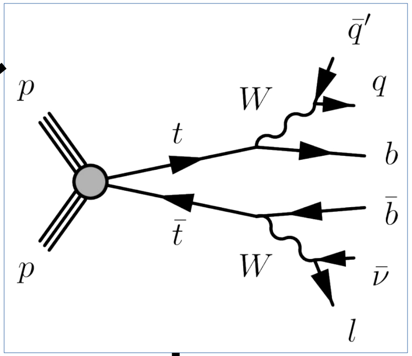
$$m_T = \sqrt{2 p_T^l E_T^{miss} \left(1 - \cos\left(\left[\Delta \phi\left(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss}\right)\right]\right)\right)}$$



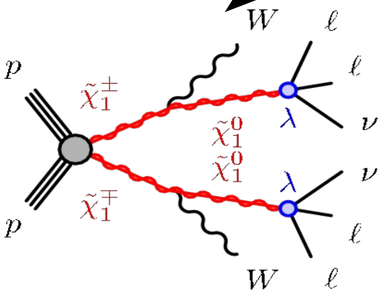
[arXiv:1812.09432]

Essential to estimate the backgrounds

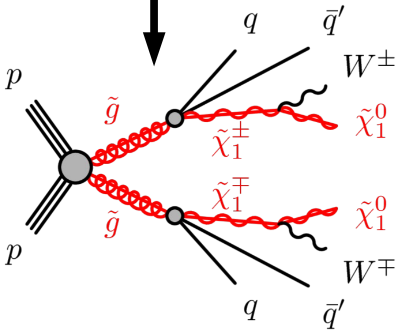
- **Reducible backgrounds:** backgrounds with another final state in comparison to the signal
- **Irreducible backgrounds:** backgrounds show the same final state as the signal

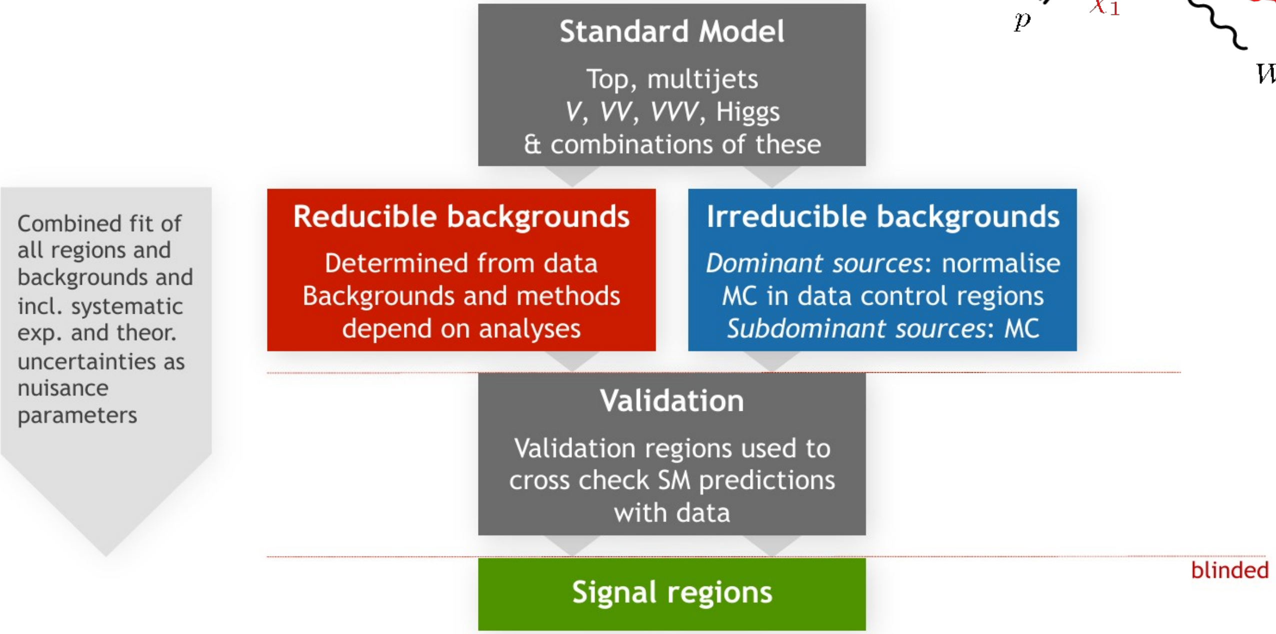


reducible



irreducible





Standard Model

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

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Irreducible backgrounds

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

Validation

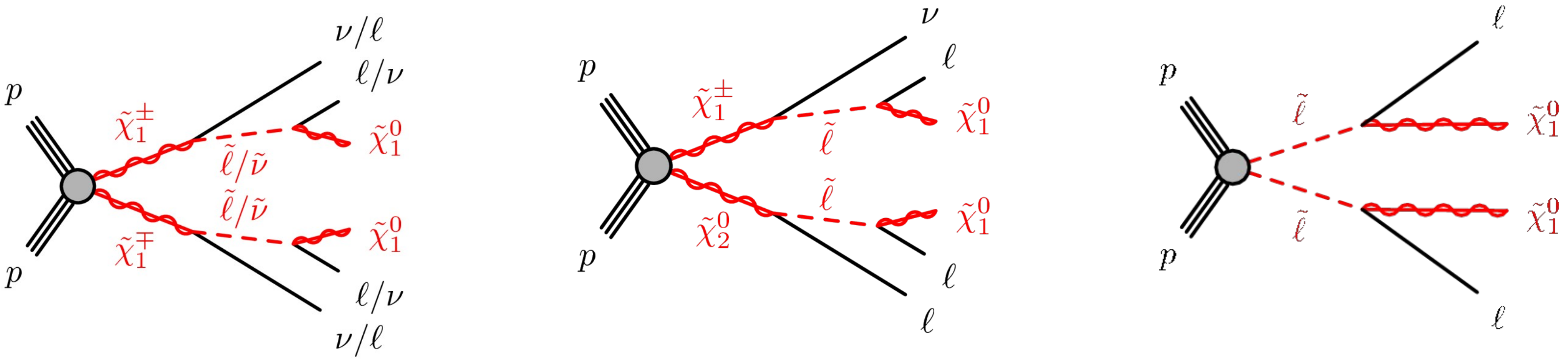
Validation regions used to cross check SM predictions with data

blinded

Signal regions

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

Focus on chargino/neutralino production - possible decay modes



Decays of charginos/neutralinos/sleptons **often** studied in multi-lepton signatures + E_T^{miss}:

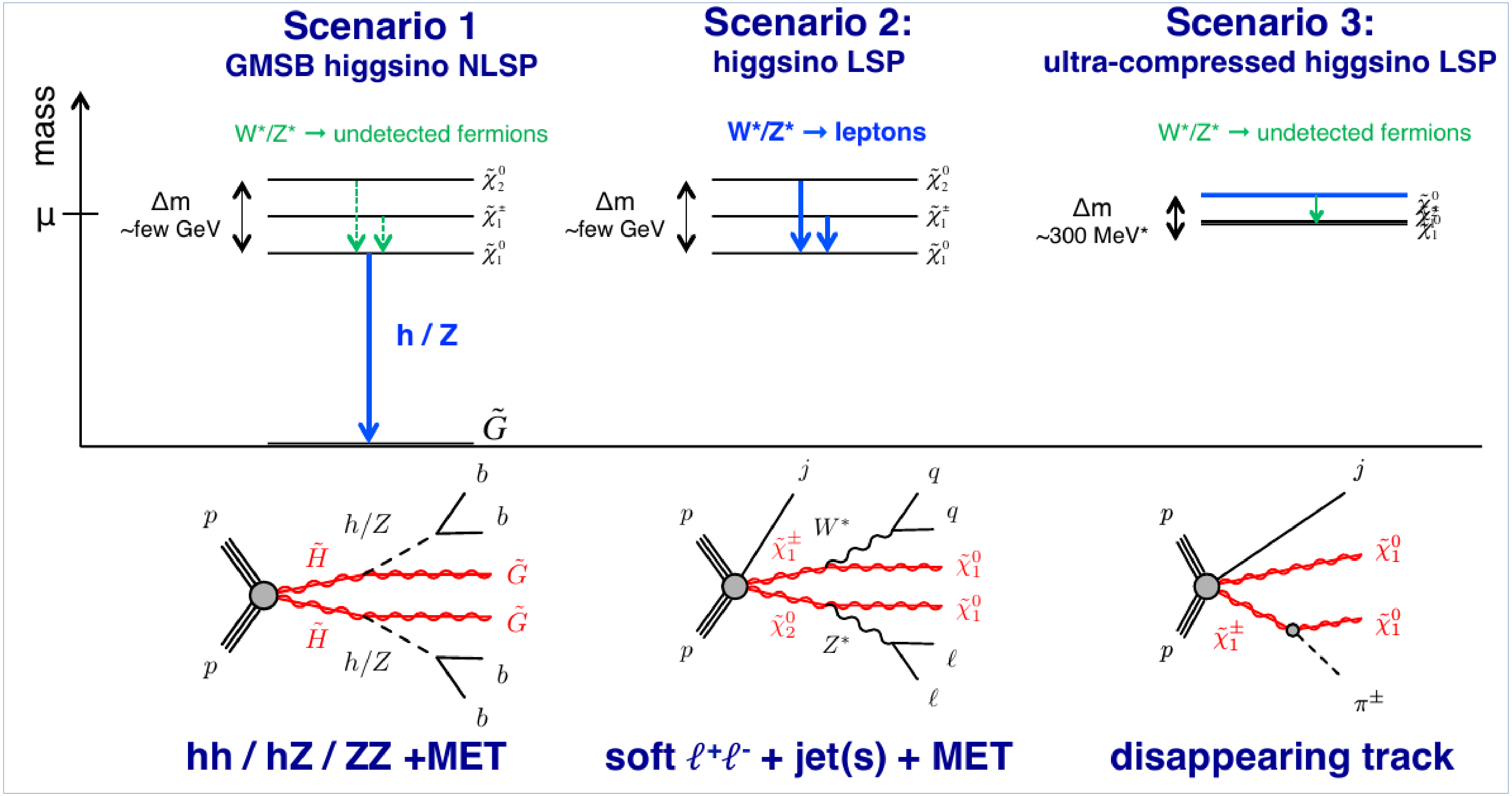
→ *2,3 or 4 leptons*
→ *rather clean signatures*

But not only!

- **Main backgrounds:**
  - Irreducible: mainly diboson production, sometimes $t\bar{t}$ (+ X)
    → *estimation using control and validation regions*
  - Reducible: fakes → data-driven background estimation
- Often suppression of top backgrounds by (b-tagged) jet veto

Higgsinos searches

Naturalness arguments requires light higgsinos with similar masses.



Scenario 1
GMSB higgsino NLSP

W*/Z* → undetected fermions

Δm
~few GeV

h / Z

Scenario 2:
higgsino LSP

W*/Z* → leptons

Δm
~few GeV

Scenario 3:
ultra-compressed higgsino LSP

W*/Z* → undetected fermions

Δm
~300 MeV*

hh / hZ / ZZ +MET

soft $\ell^+\ell^-$ + jet(s) + MET

disappearing track

[B. Hooberman, SUSY17]

Compressed higgsinos/sleptons

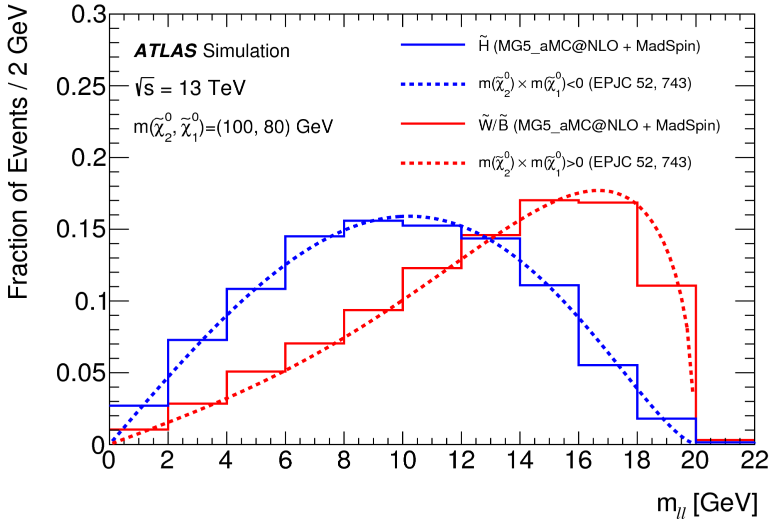
[Phys. Rev. D 97 (2018) 052010]

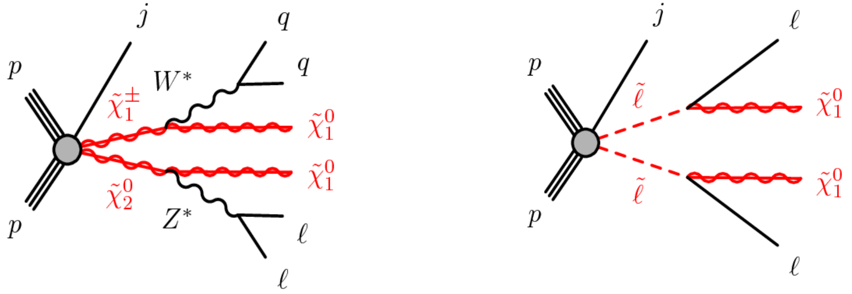
Significant lower invariant mass m_{ll} for models with Higgsinos

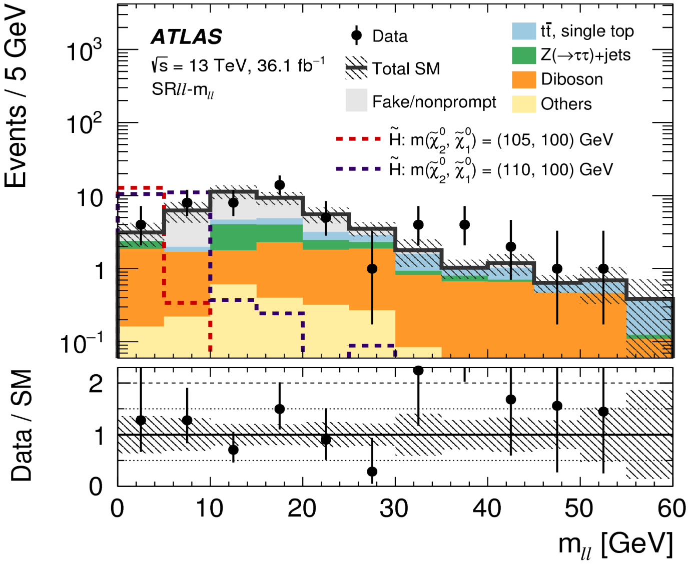
→ *analysis requiring extremely low energetic leptons and low m_{ll}*

→ *using electrons down to p_T = 4.5 GeV and muons down to p_T = 4 GeV and m_{ll} = 1 GeV*

→ *huge progress in reconstruction of low energetic leptons*







Two searches:

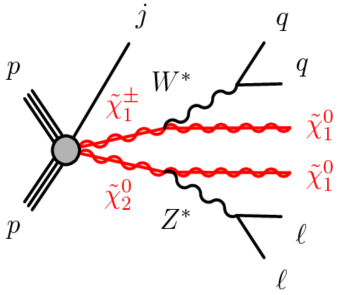
- Direct production of higginos using m_{ll}
- Direct production of sleptons using m_{T2}

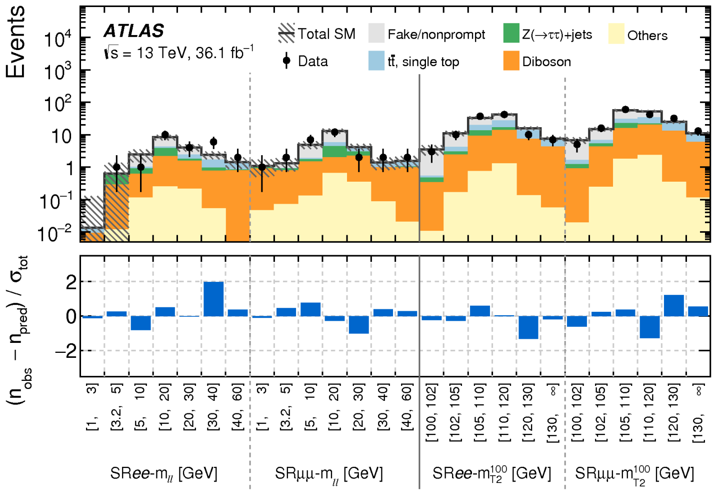
→ *key is estimation of fake backgrounds!*

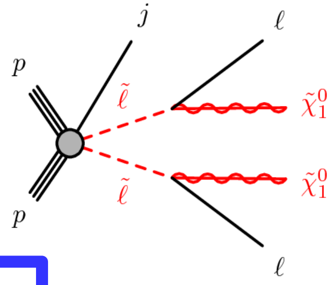
Compressed higgsinos/sleptons

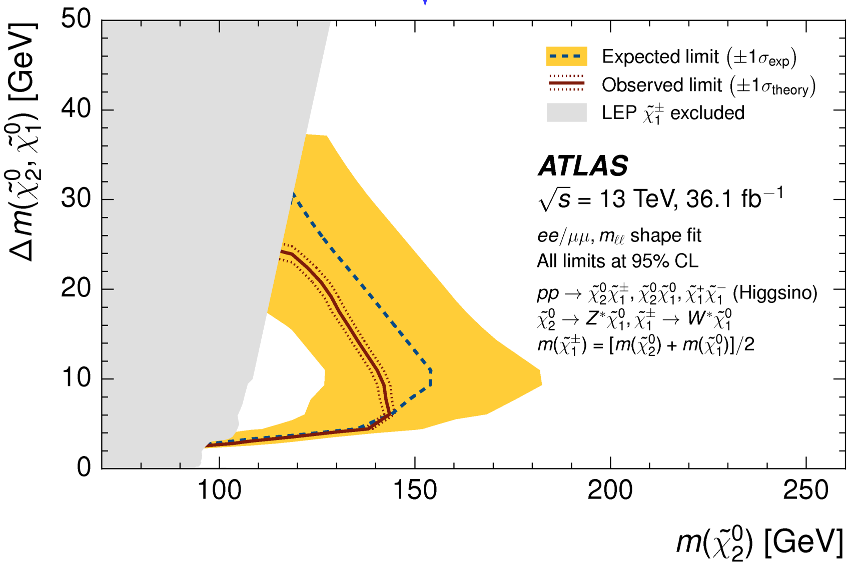
[Phys. Rev. D 97 (2018) 052010]

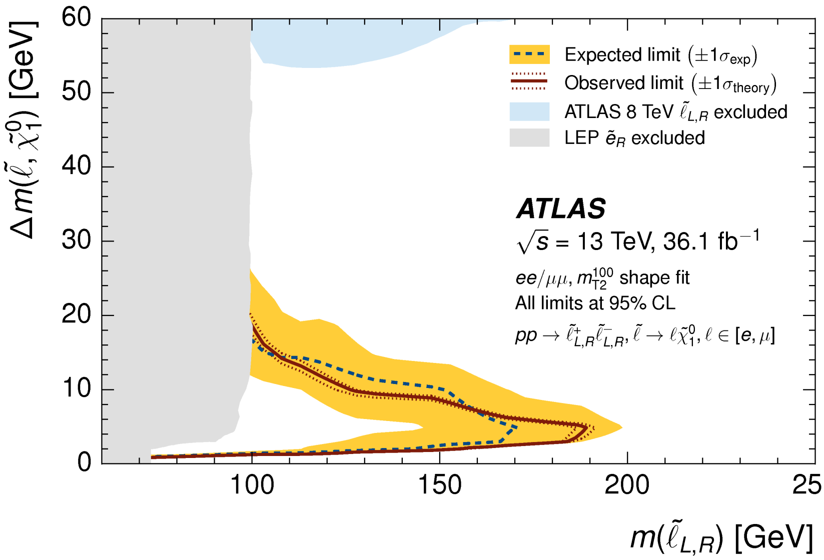
No significant excess seen.





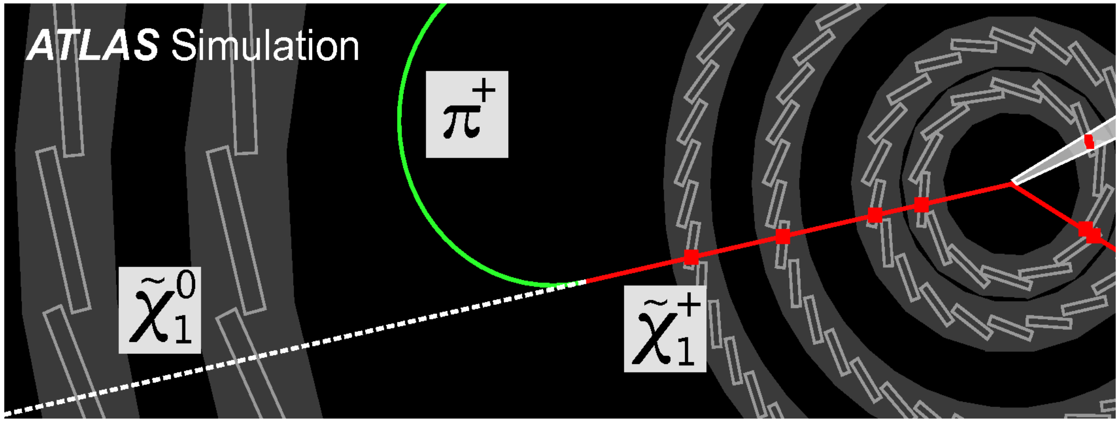






Disappearing tracks

[JHEP 06 (2018) 022]

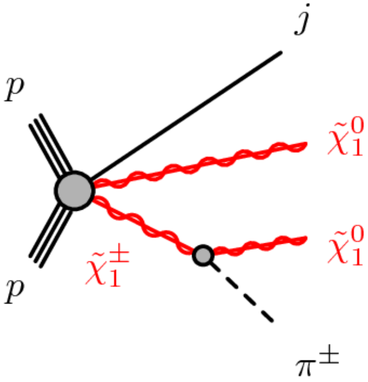


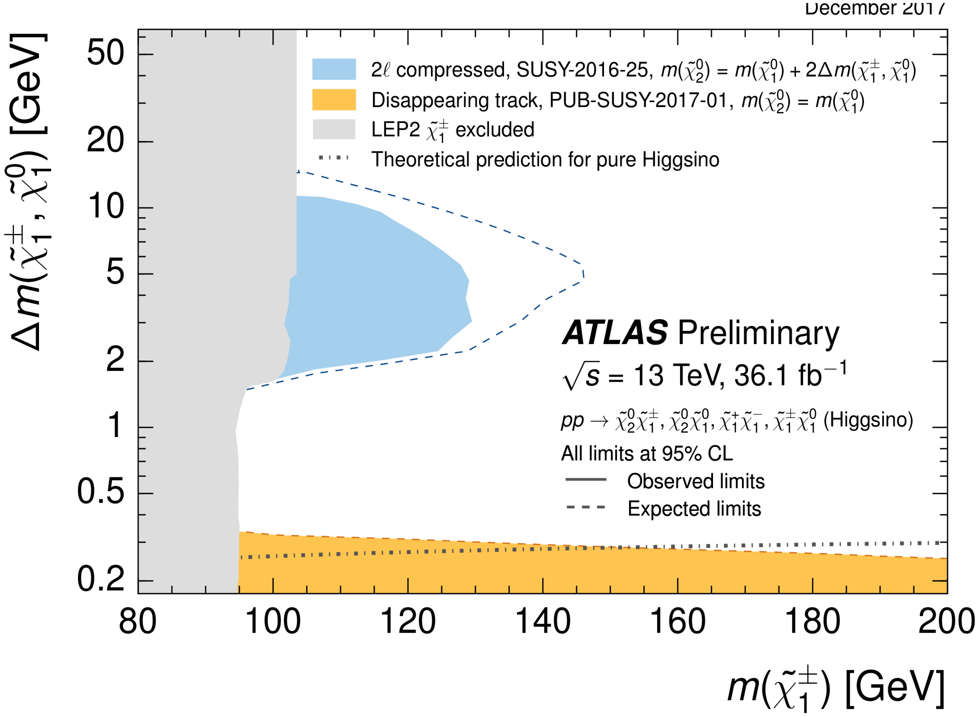
Long-lived chargino decaying to invisible + pion

→ *disappearing track*

Addition of IBL in LS1 allowed reconstruction of smaller minimal track lengths down to 12 cm

→ *pixel-only tracklets*





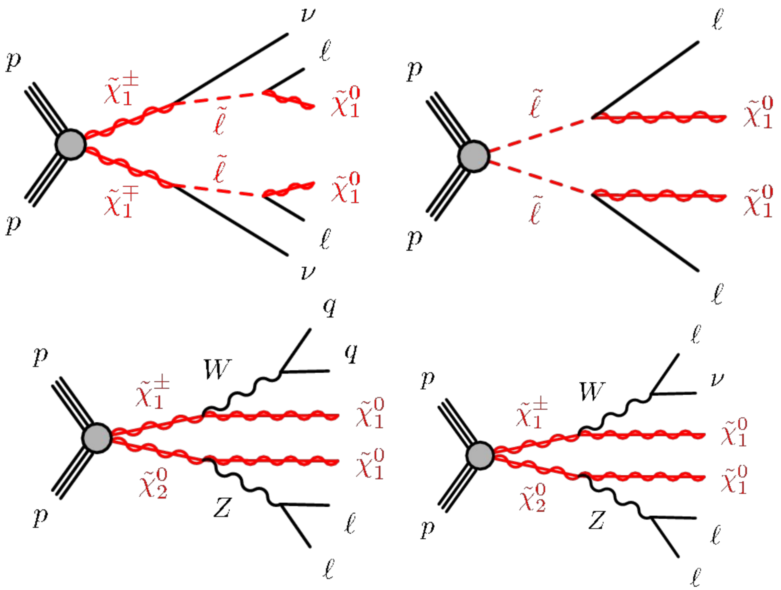
Old LEP limits partially superseded first time at LHC.

Searches for Winos + Binos: 2 or 3 leptons

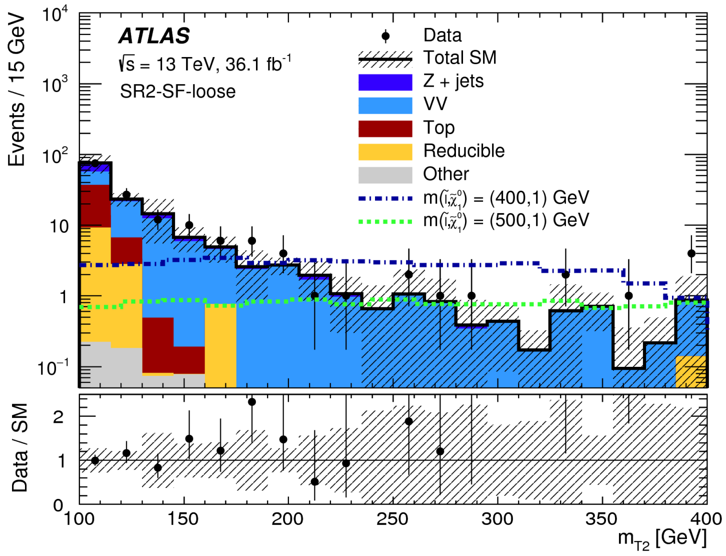
[arXiv:1803.02762]

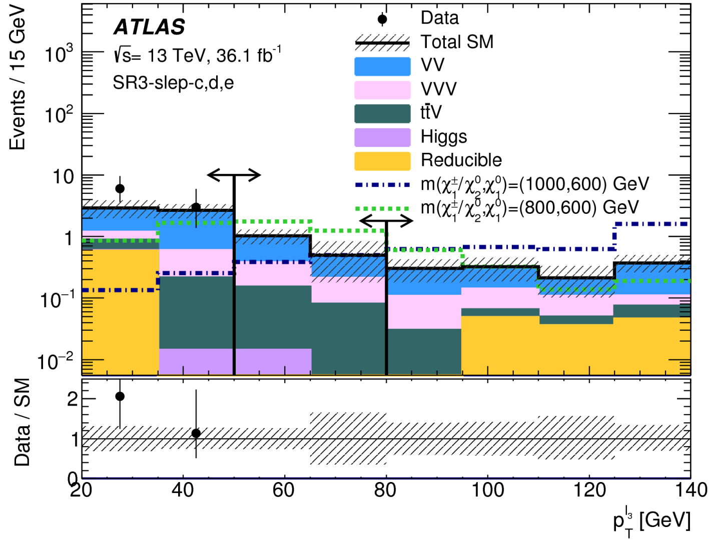
Three categories:

- 2 leptons + 0 jets
  → *direct or indirect production of sleptons*
- 2 leptons + >= 2 jets
  → *chargino/neutralino decays mediated by gauge bosons*
- 3 leptons
  → *chargino/neutralino pair production*



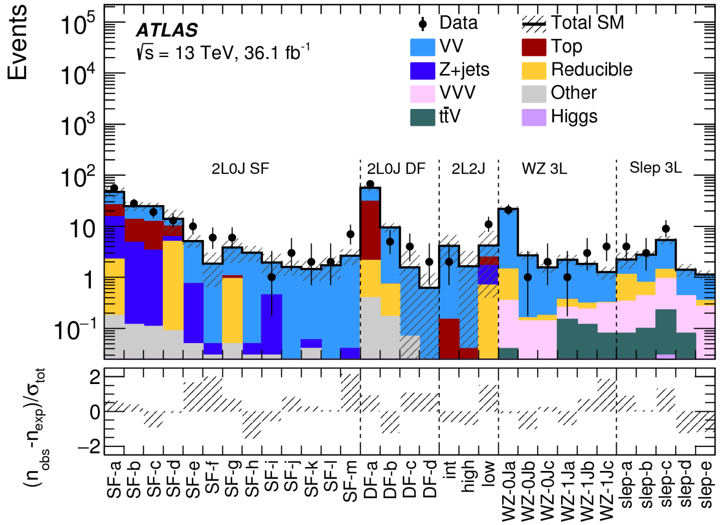
Separation (depending on channel) via $m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{\mathrm{miss}} - \mathbf{q}_T)\right)\right]$, m_{ll}, E_T^{miss}, p_T (third lepton)





2 or 3 leptons

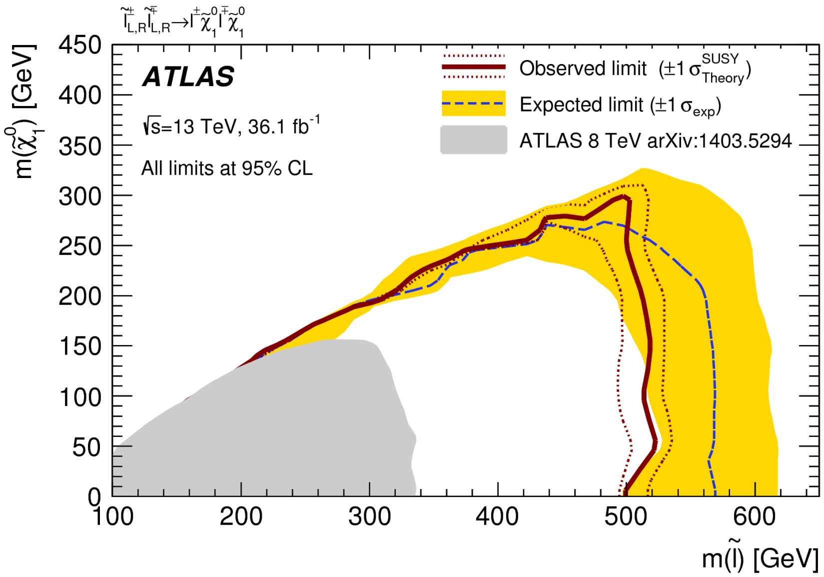
[arXiv:1803.02762]

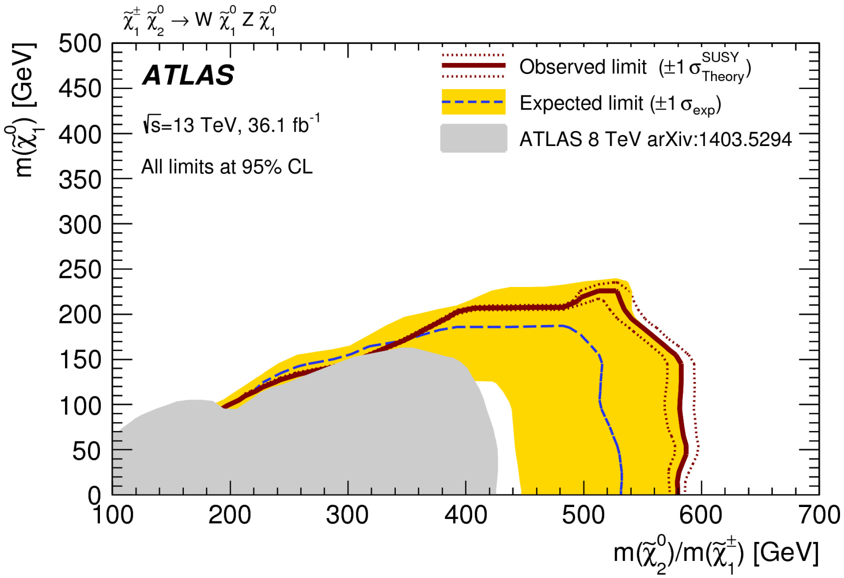


No significant excess seen.

Signal regions fitted simultaneously to derive limits.

- *Limits on sleptons reaching up to 500 GeV.*
- *Limits on charginos/neutralinos with gauge-mediated decays reaching up to 580 GeV.*

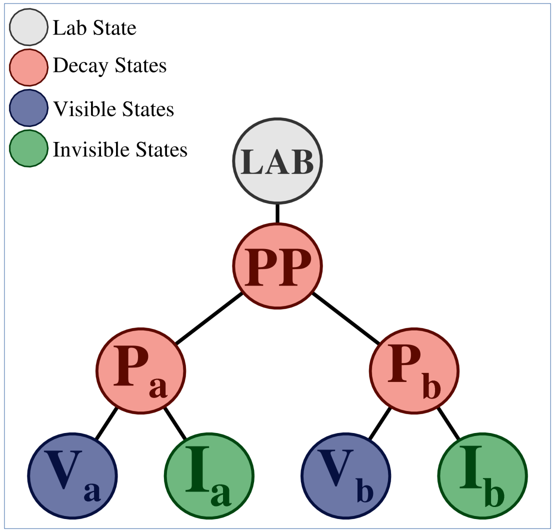


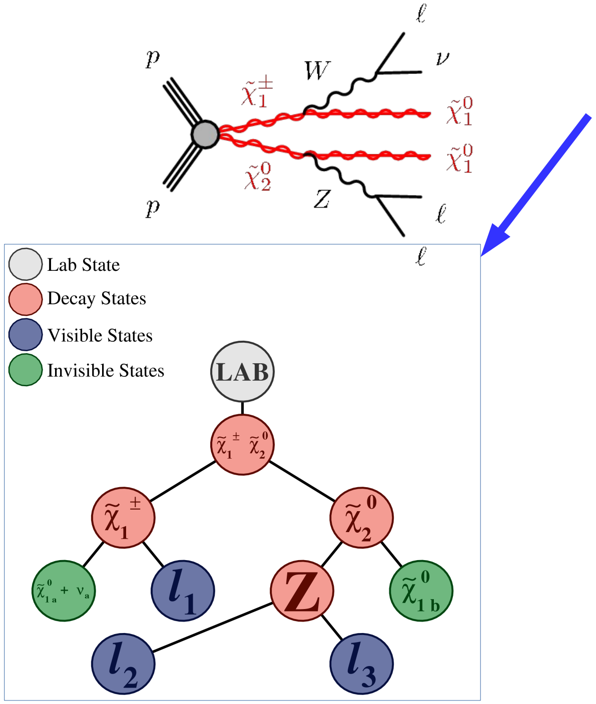


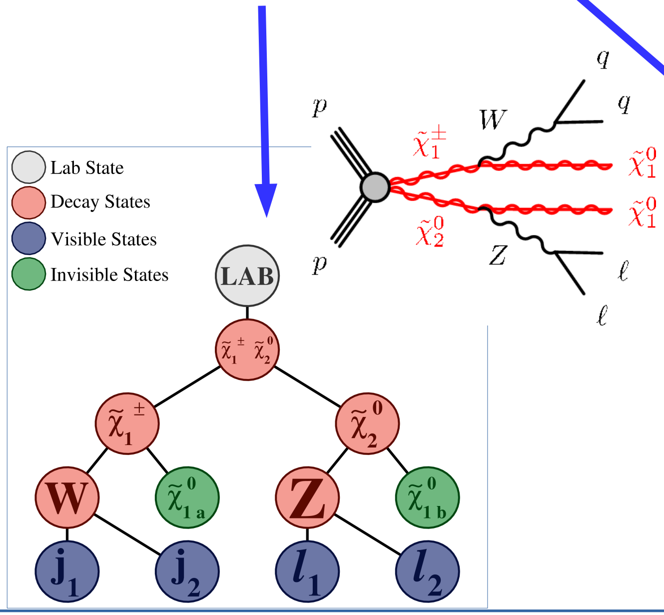
Alternative to conventional search: Using RJigsaw variables

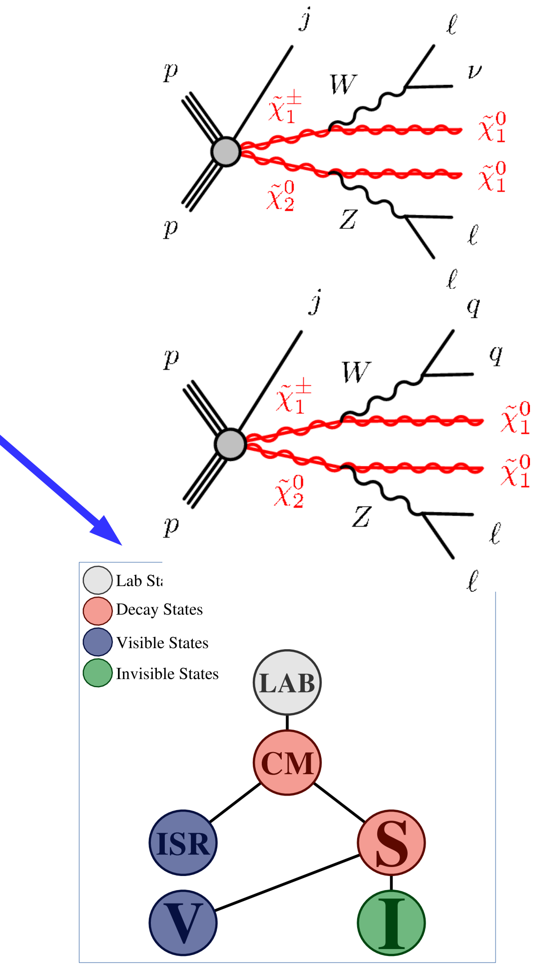
[arxiv:1806.02293]

- Assume pair-production of particles with specific decay trees
- Sort all visible and invisible particles in the event into these assumptions
- (For invisible particles some minimization algorithm at works)









Construction of variables

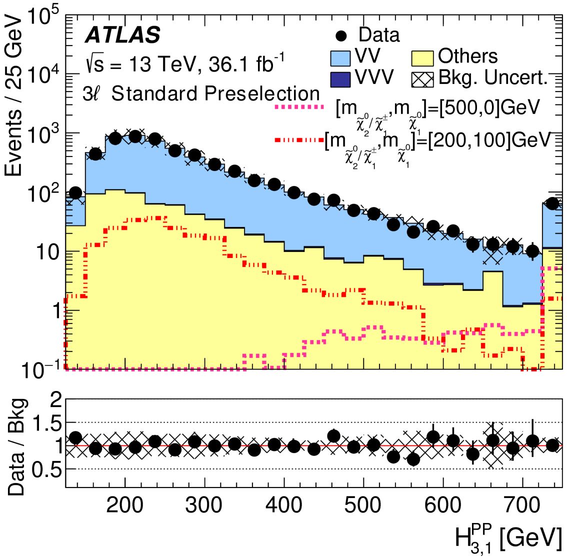
[arxiv:1806.02293]

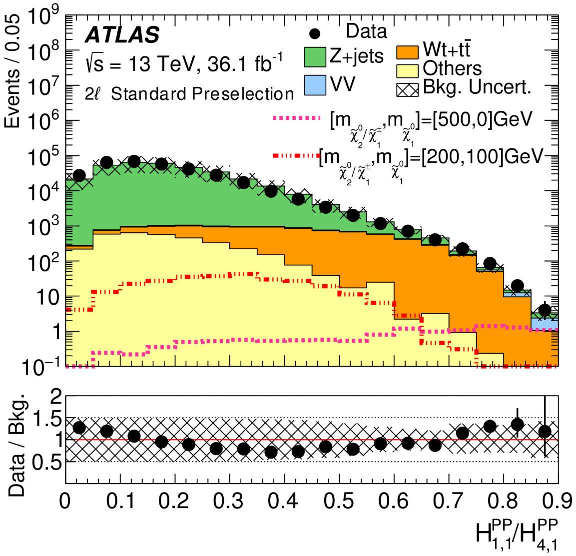
- Using the decay trees, construct kinematic variables within the defined rest frames.

→ $$H^{F}_{n,m} = \sum_{i=1}^{n} |\vec{p}^{\,F}_{\text{vis},\,i}| + \sum_{j=1}^{m} |\vec{p}^{\,F}_{\text{inv},\,j}|$$

→ *Scale variable!*

- Examples:
  - $H_{n,1}^{PP}$: scale variable in the rest frame of both initial particles → behaves similar to m_{eff}
  - $H_{1,1}^{PP} / H_{4,1}^{PP}$: provides additional information in testing the balance of the two scale variables – like E_T^{miss}/m_{eff}, provides discrimination against unbalanced events – used as Z+jets rejection in some of the 2-lepton regions





Analysis design

[arxiv:1806.02293]

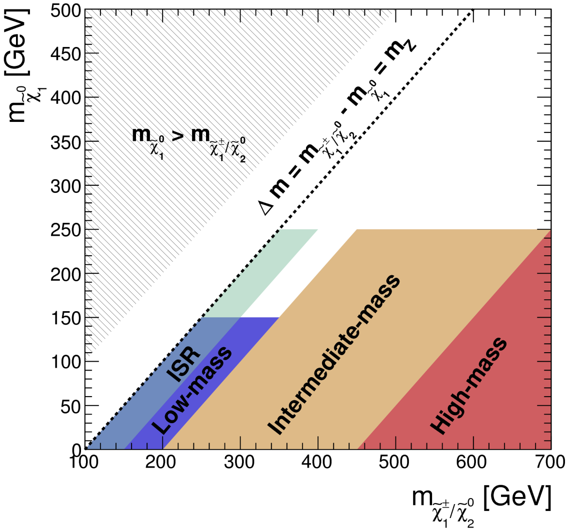
Different signal regions depending on mass difference between LSP and chargino/neutralino2 + requirements of 2 or 3 leptons

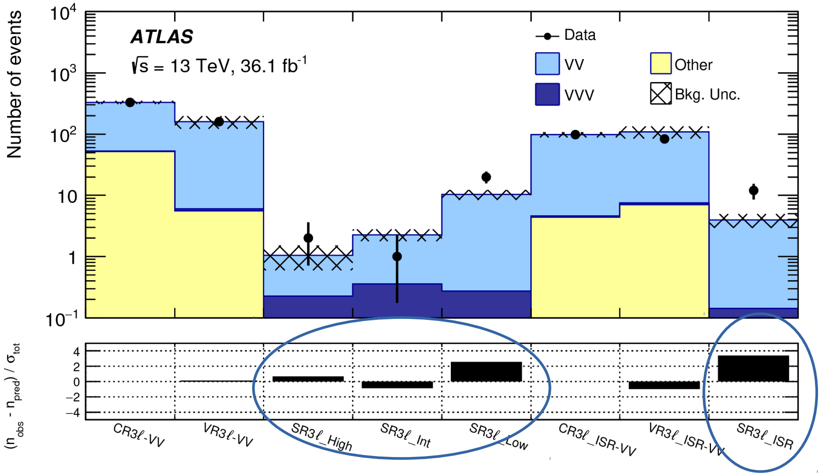
→ 8 signal regions

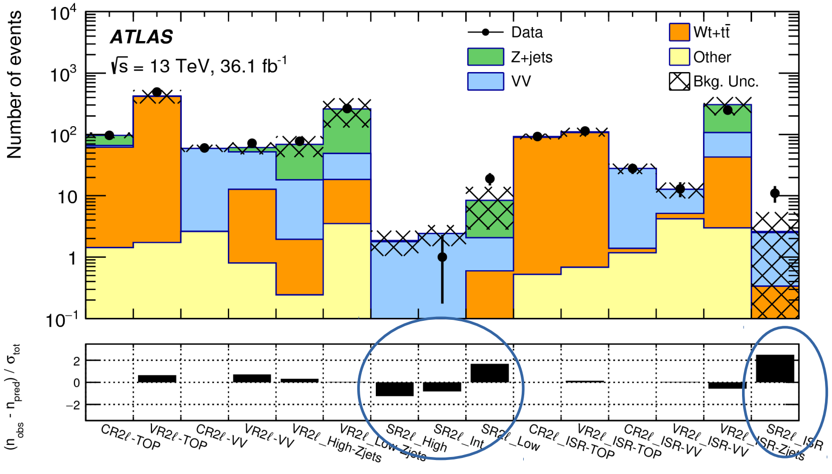
Preselection on conventional variables like jet multiplicity, lepton and jet momenta, m_T and m_{jj}, then series of RJigsaw variables

Main backgrounds Z+jets and diboson

Excess in 4 low mass/ISR signal regions, highest one 3 sigma







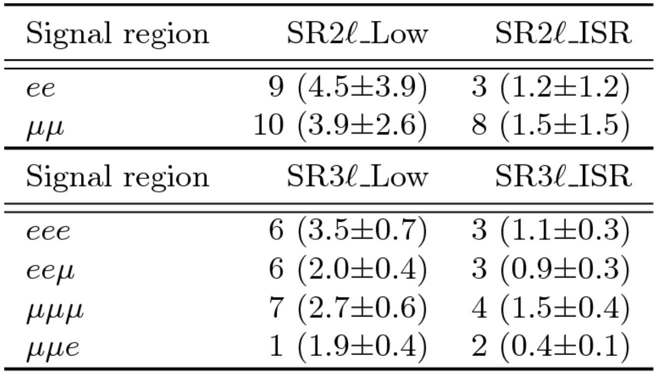
Results & cross checks

[arxiv:1806.02293]

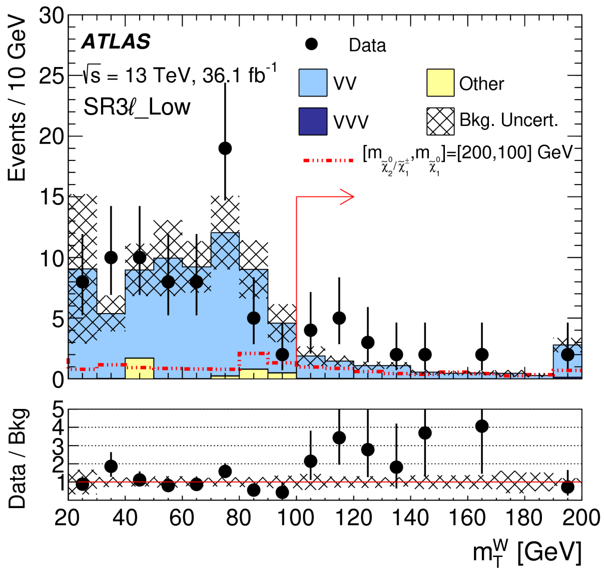
- Given the excesses multiple cross-checks performed – in particular background estimations and modeling – validation regions show good agreement.

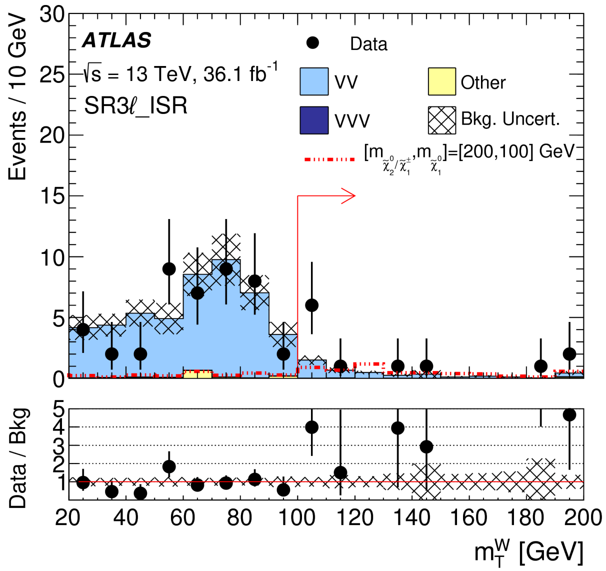
- Split in lepton flavor studied.

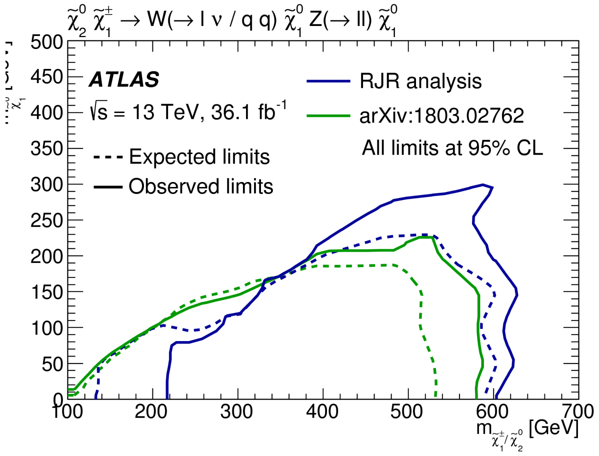
- Limits thus weaker than expected, however in a region that is excluded by conventional 2/3-lepton analysis. **The analyses share however no events.**



Signal region	SR2ℓ_Low	SR2ℓ_ISR
ee	9 (4.5±3.9)	3 (1.2±1.2)
$\mu\mu$	10 (3.9±2.6)	8 (1.5±1.5)
Signal region	**SR3ℓ_Low**	**SR3ℓ_ISR**
eee	6 (3.5±0.7)	3 (1.1±0.3)
$ee\mu$	6 (2.0±0.4)	3 (0.9±0.3)
$\mu\mu\mu$	7 (2.7±0.6)	4 (1.5±0.4)
$\mu\mu e$	1 (1.9±0.4)	2 (0.4±0.1)







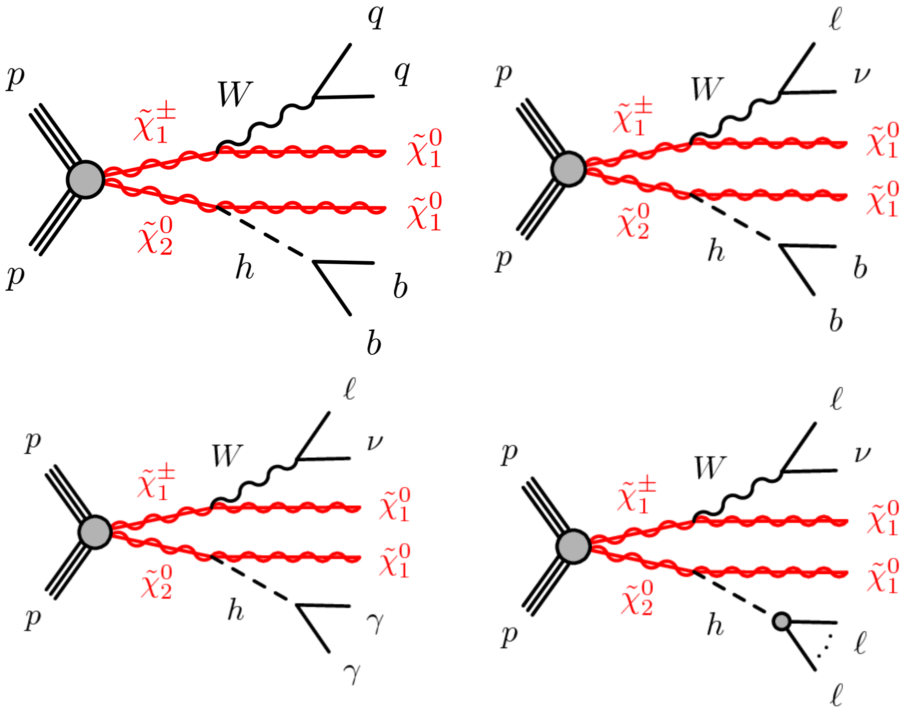
Searches for neutralinos with decays to a Higgs

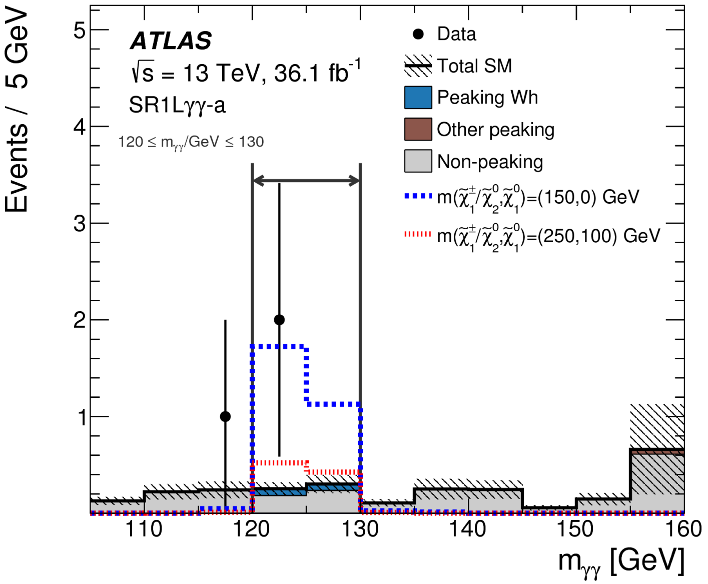
[arXiv:1812.09432]

Search for pair-production of chargino and neutralino

Chargino decays to W and LSP, neutralino to Higgs and LSP.

Different signatures depending on decay of Higgs: hadronic, 1 e/µ + b$\bar{b}$, two same-sign leptons, 3 leptons, 1 e/µ + γγ
→ *different searches*





E.g. search for 1 e/µ + γγ:

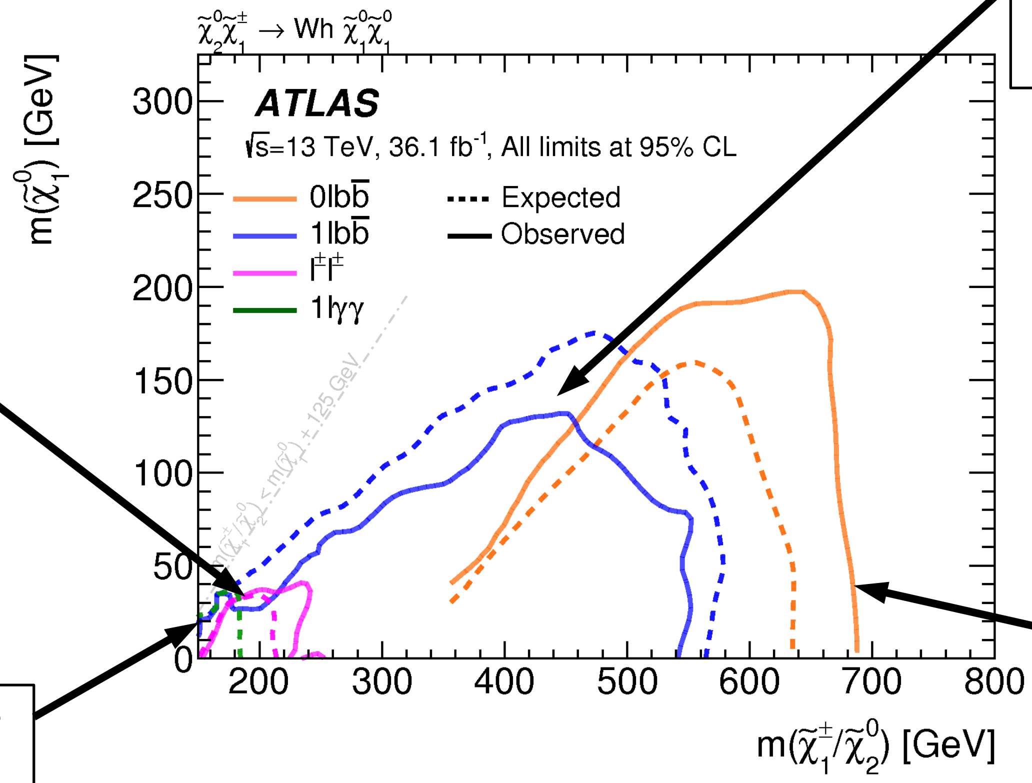
- Profit from clean signature.
- Estimate non-Higgs-backgrounds from side-band.
- Higgs backgrounds from MC

Small excess seen.

Searches for neutralinos with decays to a Higgs

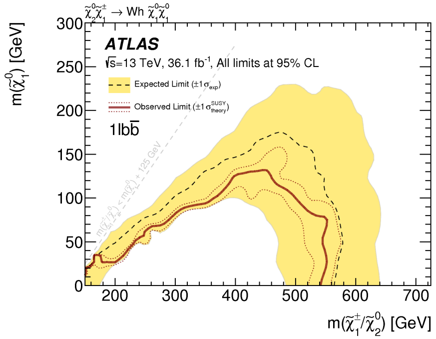
[arXiv:1812.09432]

Nice complementarity of the different searches:



1 e/μ + b$\bar{b}$ covers bulk of the plane. Strong limit since small uncertainties.

Same-sign analysis sensitive to lower masses and smaller mass splittings.

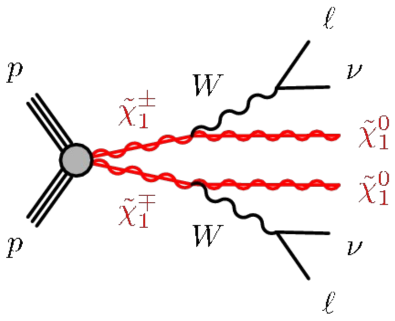


No exclusion due to small excess for 1 e/μ + γγ.

Hadronic analysis covers high neutralino/ chargino masses.

Search for charginos decaying to WW

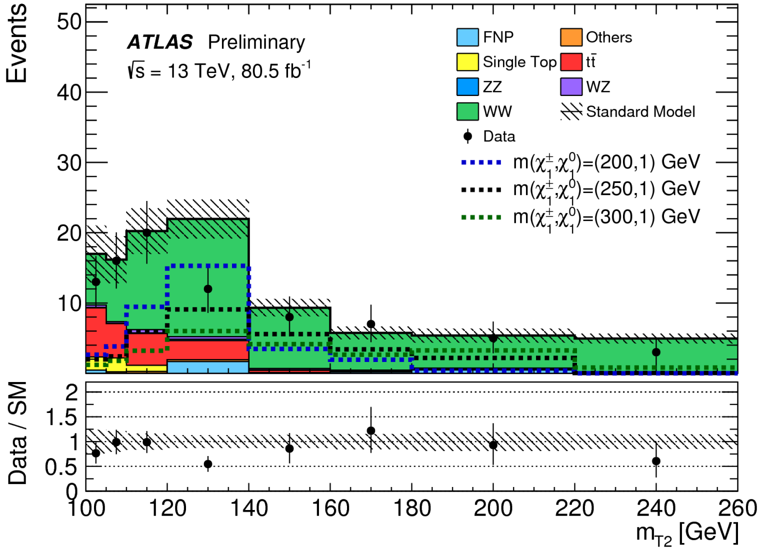
[ATLAS-CONF-2018-042]

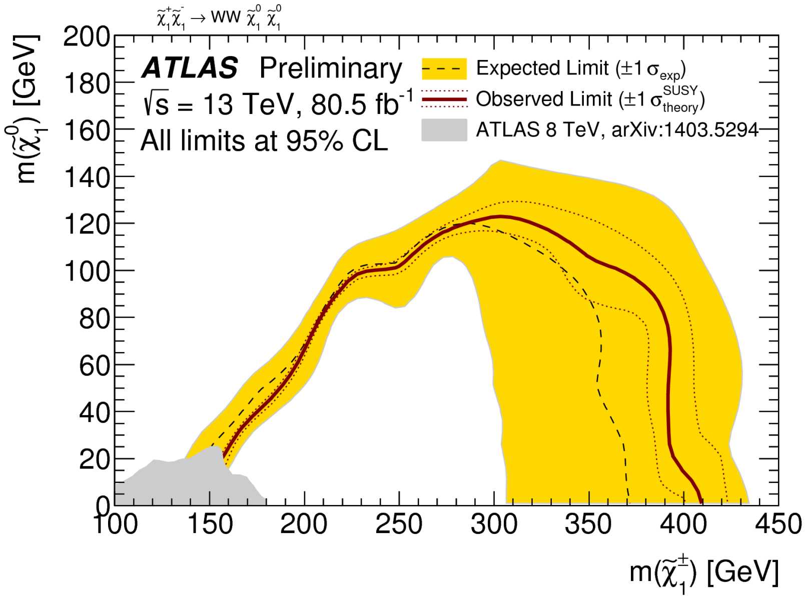


Extremely challenging signature due to very low cross-sections (58.6 +- 4.7 fb for a chargino mass of 400 GeV) and high SM backgrounds (diboson)

→ *Selection of two oppositely charged leptons, which may be of different flavor*
→ *Use of all of 2015 – 2017 data*
→ *rejection of top background by veto on b-tagged jets*
→ *four signal regions binned in* m_{T2}*: same + different flavor, 0 or 1 non-b-tagged jet*
→ *shape fit in* m_{T2}

No excess seen.

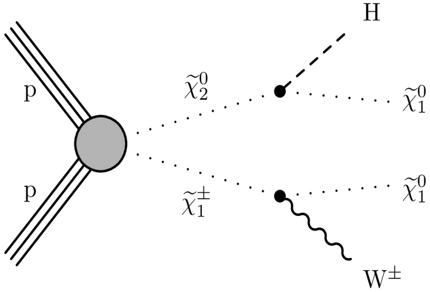


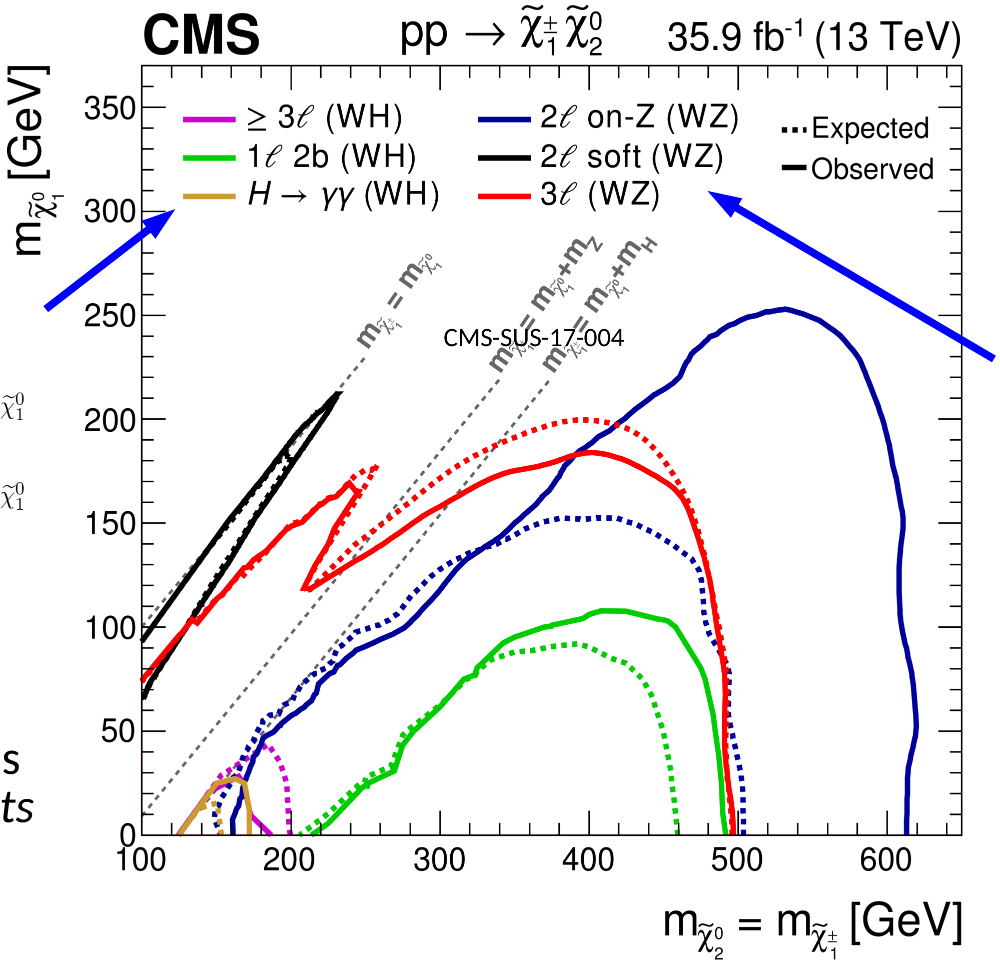


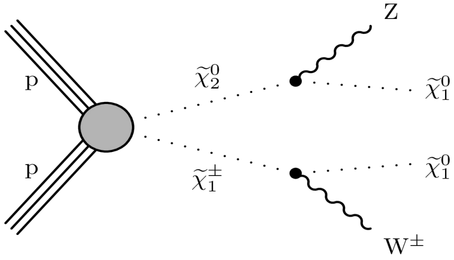
Chargino/neutralino production with different decays

[JHEP 03 (2018) 160]

CMS combined different EWK searches





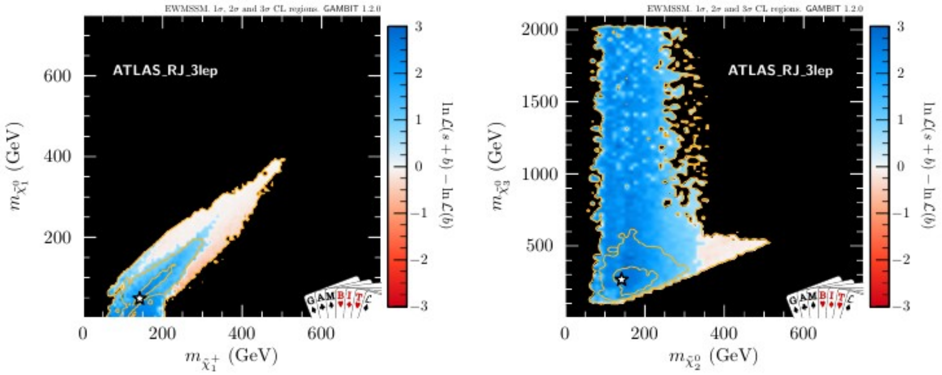


Different decay modes of H - different final states
→ *1 lepton + 2 b-jets*
→ *2 photons*
→ *3 leptons*

Searches with 2 or 3 leptons

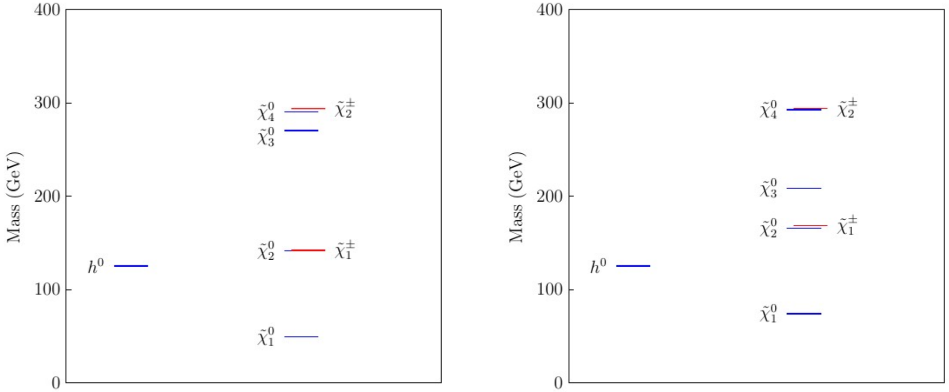
Loopholes? Analysis of electroweak searches by Gambit

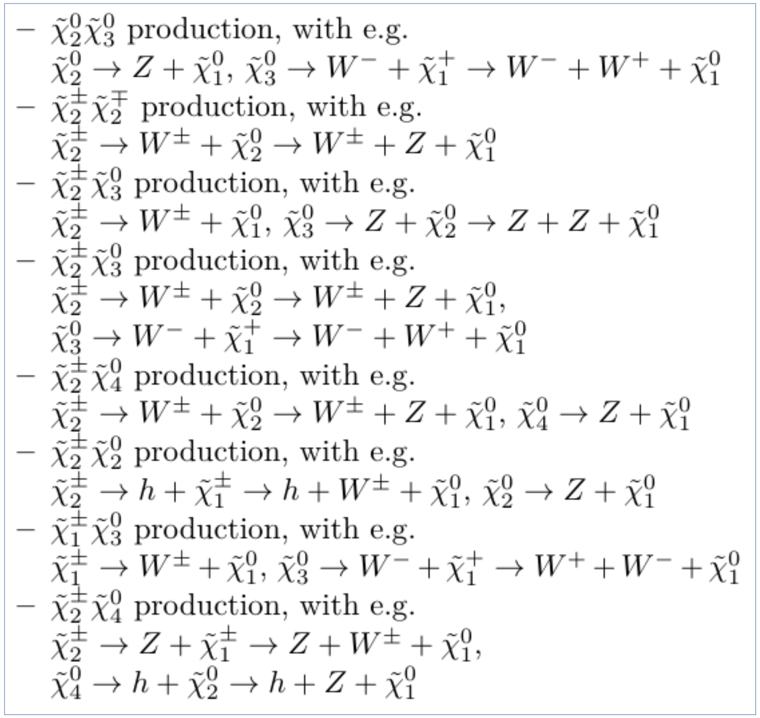
[arXiv:1809.02097]



Likelihood combination of various LEP, ATLAS and CMS searches for electroweakinos:

→ *using best possible signal region in case of the multi-bin signal regions in cases where no information on correlations provided, else approximation of full likelihood of search.*





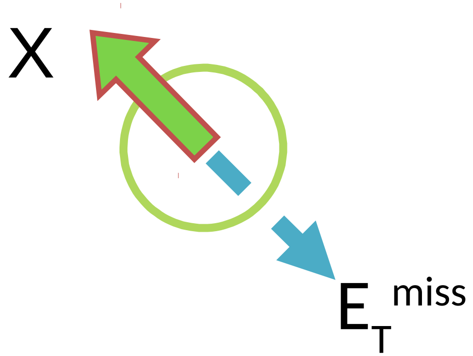
- $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^\mp$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to Z + \tilde{\chi}_2^0 \to Z + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$, $\tilde{\chi}_4^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$ production, with e.g. $\tilde{\chi}_2^\pm \to h + \tilde{\chi}_1^\pm \to h + W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_1^\pm \to W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^+ + W^- + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g. $\tilde{\chi}_2^\pm \to Z + \tilde{\chi}_1^\pm \to Z + W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_4^0 \to h + \tilde{\chi}_2^0 \to h + Z + \tilde{\chi}_1^0$

Due to little excesses at different places two interpretations:

- *Potential model that could result in the excesses,*
- *Shortcomings of current searches.*

Conclusion is that current searches are not sensitive to longer decay chains.

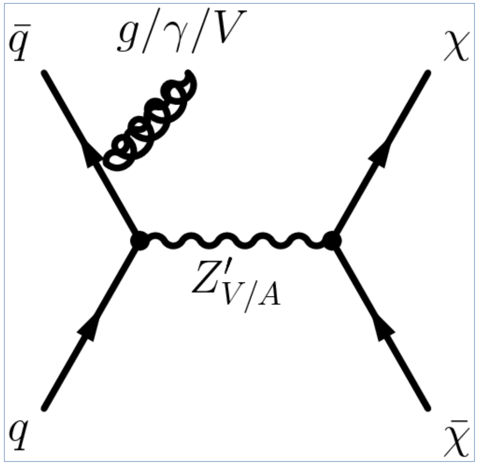
Searches for dark matter with mono-X searches

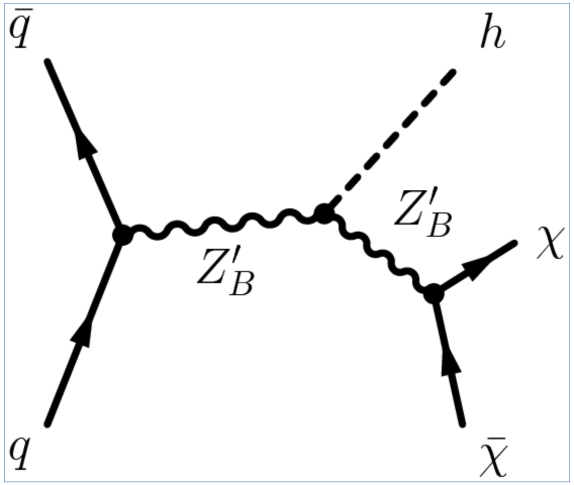


Pure production of dark matter particles invisible, need some other SM particle the dark matter particles are recoiling against.

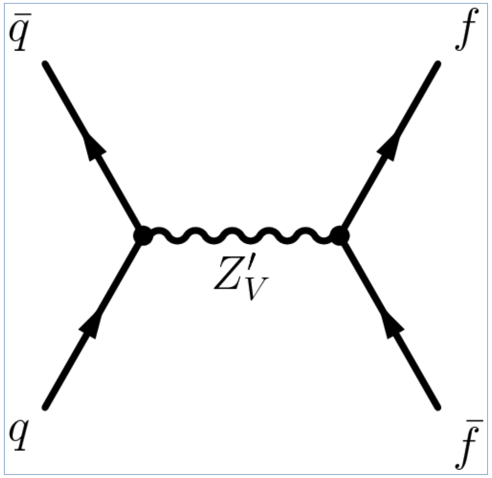
Two possibilities:

- Radiation in the initial state.
- Emission of SM particle from mediator.



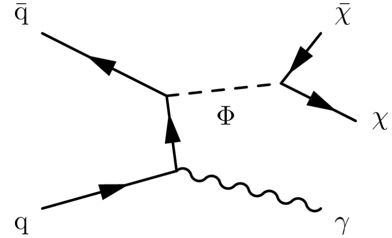


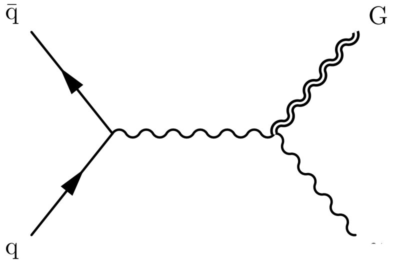
Can also search for decays of mediator particle to SM particles.



Search for mono-photon

[arXiv:1810.00196]

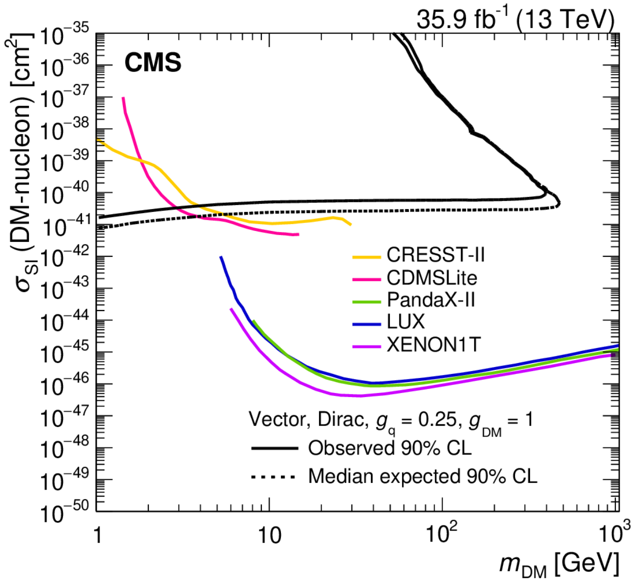


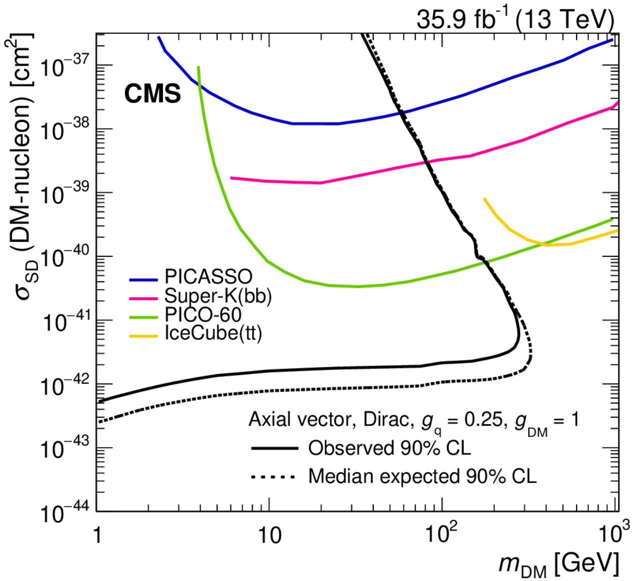


→Searching for production of DM via a mediator particle ϕ, for EWK-DM effective interaction or for extra dimensions (ADD model).

1 isolated photon with p_T > 175 GeV, E_T^{miss}> 170 GeV + various other criteria to reject lepton backgrounds (Z/W+γ), and background from beam halo or mismeasurements.

Results complementary to direct detection experiements.

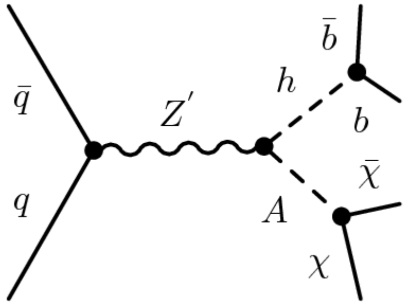




Mono-H

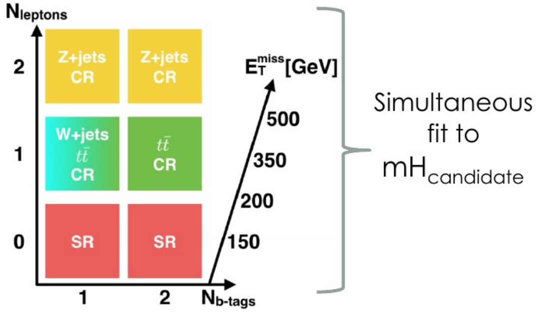
[ATLAS-CONF-2018-039]

Search for dark matter produced in association with a SM Higgs boson decaying to $b\bar{b}$



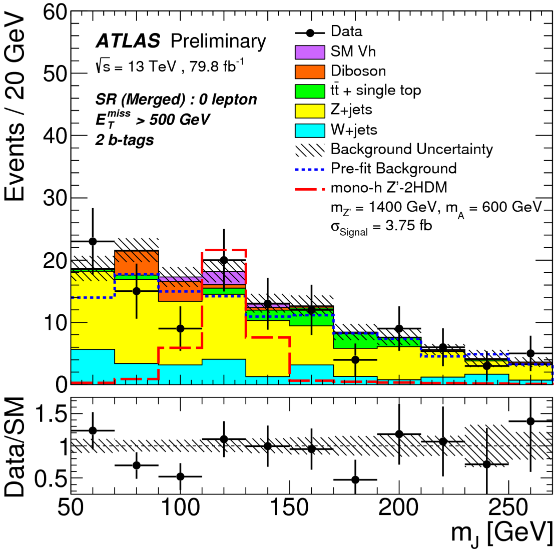
- *Signal regions for the resolved (two small-R jets) and merged regime (one large-R jet)*

- *Signal region without leptons, control regions with 1 (W+jets, $t\bar{t}$) or 2 leptons (Z+jets).*
- *Binned in b-jet multiplicity and E_T^{miss} to increase sensitivity, simultaneous fit in mass of Higgs candidate.*



$N_{leptons}$	1	2
2	Z+jets CR	Z+jets CR
1	W+jets $t\bar{t}$ CR	$t\bar{t}$ CR
0	SR	SR

Simultaneous fit to $mH_{candidate}$



No excess seen.

Improvements: E_T^{miss} Significance

[ATLAS-CONF-2018-039]

E_T^{miss} Significance S provides information on how likely the measured E_T^{miss} is due to a resolution fluctuation.

→ *formerly used for this* $S = \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sqrt{H_{\mathrm{T}}}}$

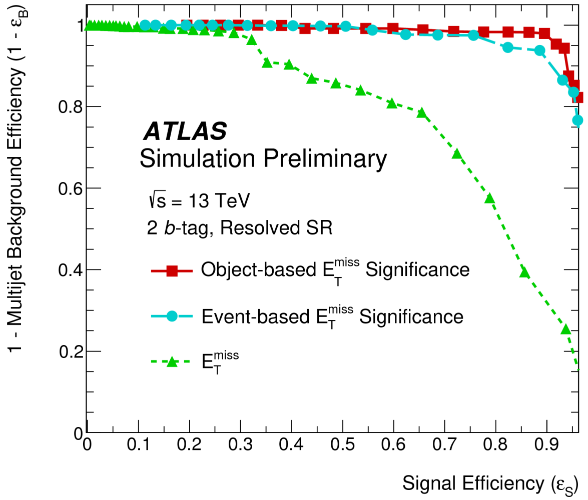
New development: **Object-based Significance**: $S^2 = \left(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^{\mathrm{T}} \left(\sum_i \mathbf{V}_i\right)^{-1} \left(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right)$

Covariance Matrix for each object

=> $$S^2 = \frac{\left|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}{\sigma_{\mathrm{L}}^2\left(1-\rho_{\mathrm{LT}}^2\right)}.$$

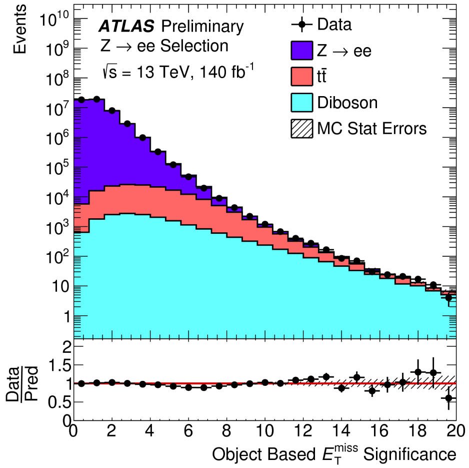
Depends on longitudinal variance and the correlation between longitudinal and transverse measurements.

→ depends on input objects to E_T^{miss} and their uncertainties; good discrimination between real and fake E_T^{miss}



Object-based Etmiss significance shows superior performance.

First results show also good modeling for full Run 2 data.



[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2019-03/]

Improvements: VR track jets

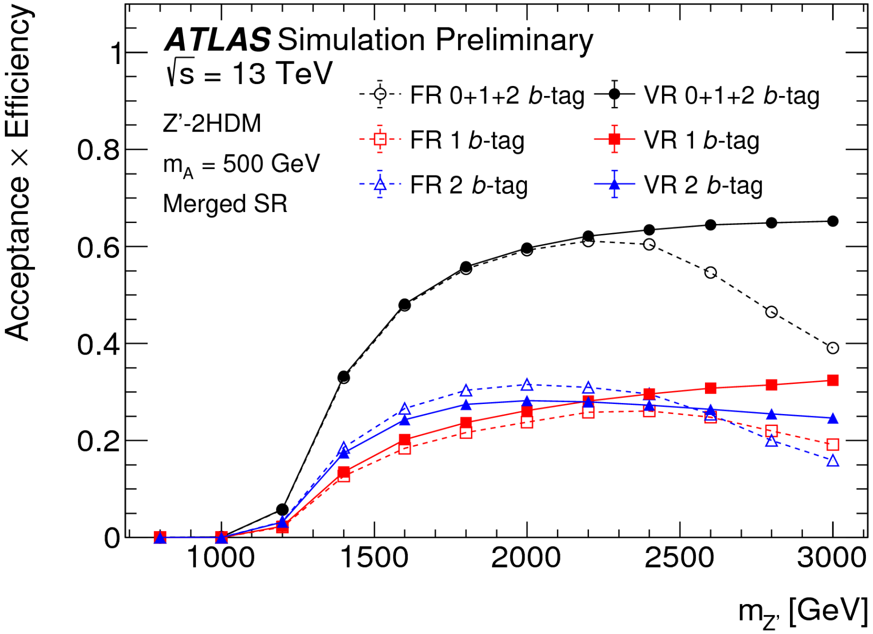
[ATLAS-CONF-2018-039]

For the merged signal region improvements for high Z’ masses in the identification of the two-b-tagged jets by using *variable radius track jets*

$$R \rightarrow R_{\mathrm{eff}}(p_T) \approx \frac{\rho}{p_T}$$

with $\rho = 30\ \mathrm{GeV},\ R_{\min} = 0.02 \text{ and } R_{\max} = 0.4$

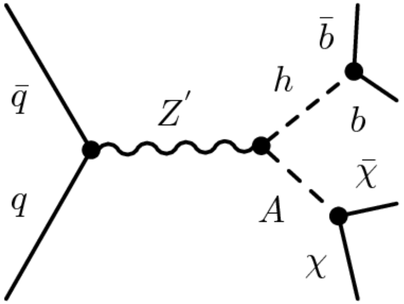
Instead of using two small R=0.2 track jets.

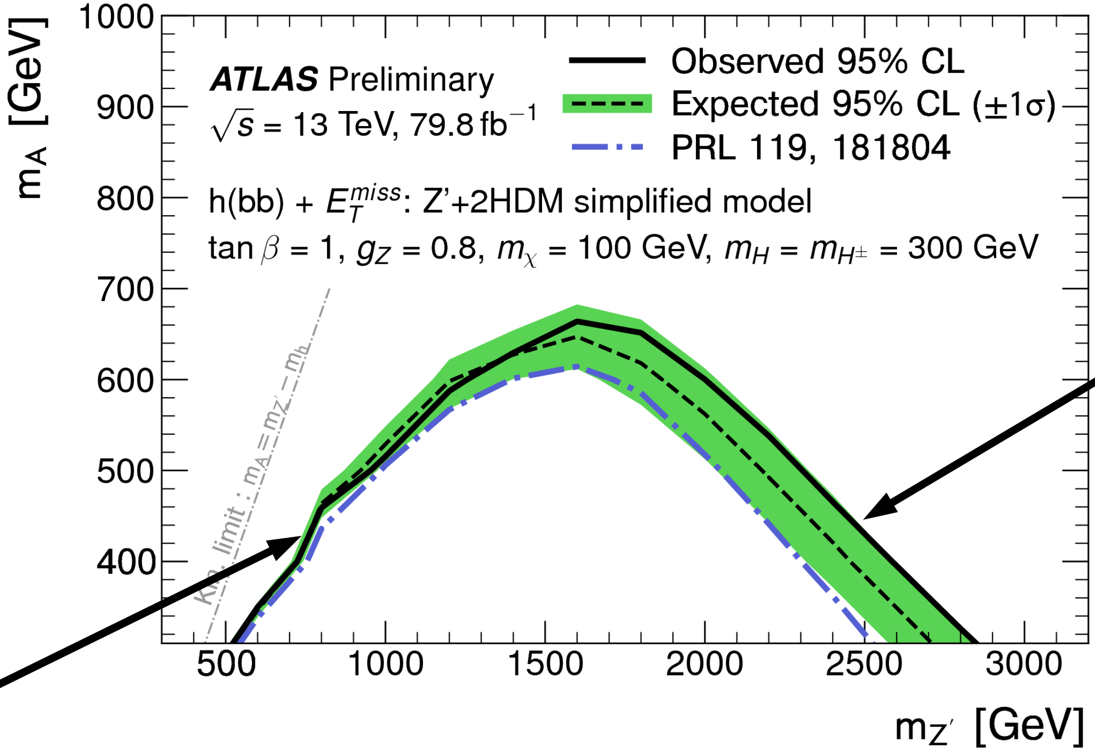


Mono-H

[ATLAS-CONF-2018-039]

Limits set on mass of mediator (Z’) and boson A. Dark matter mass fixed, as well as coupling strength and mass of other Higgs bosons.



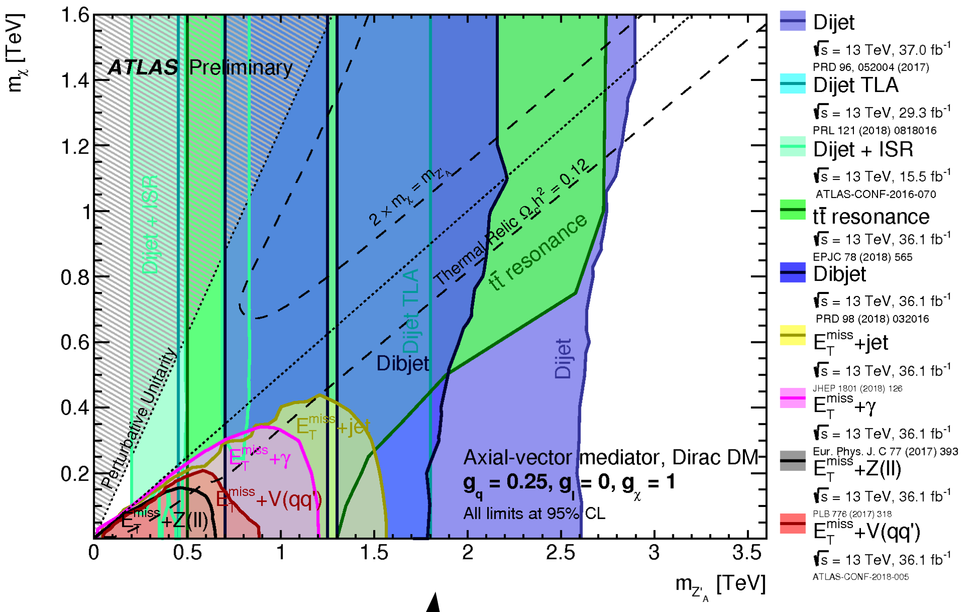


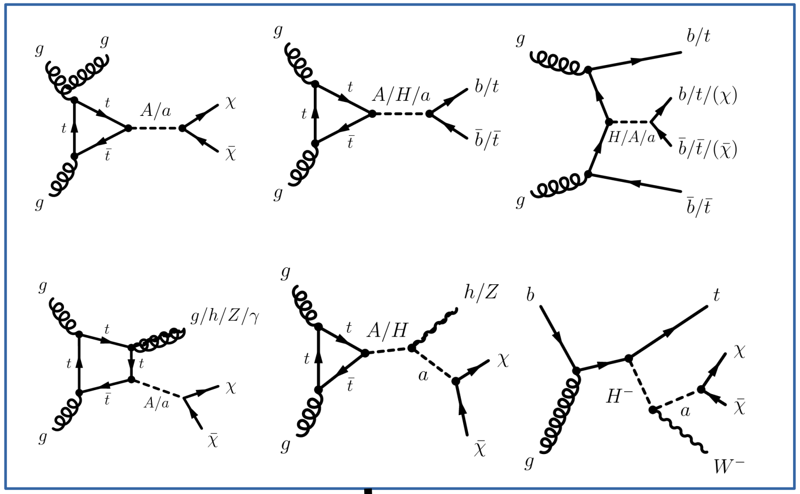
Improvements due to use of VR track jets.

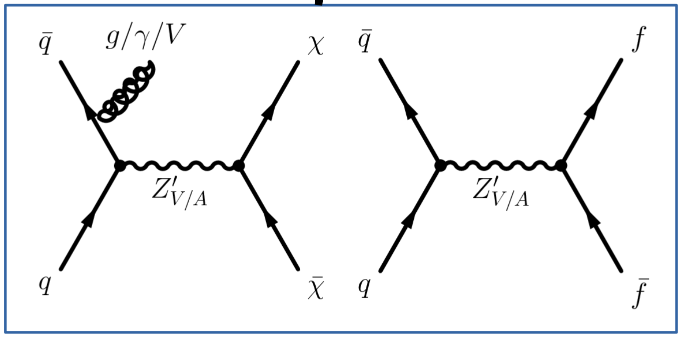
Region where object-based E_T^{miss} significance gets relevant.

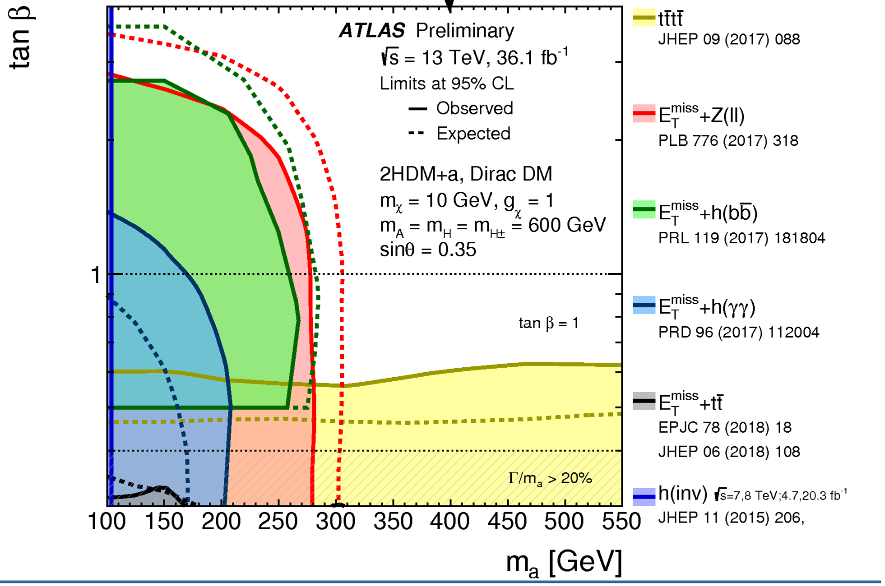
Summary of searches for non-SUSY dark matter

[ATLAS-CONF-2018-051]







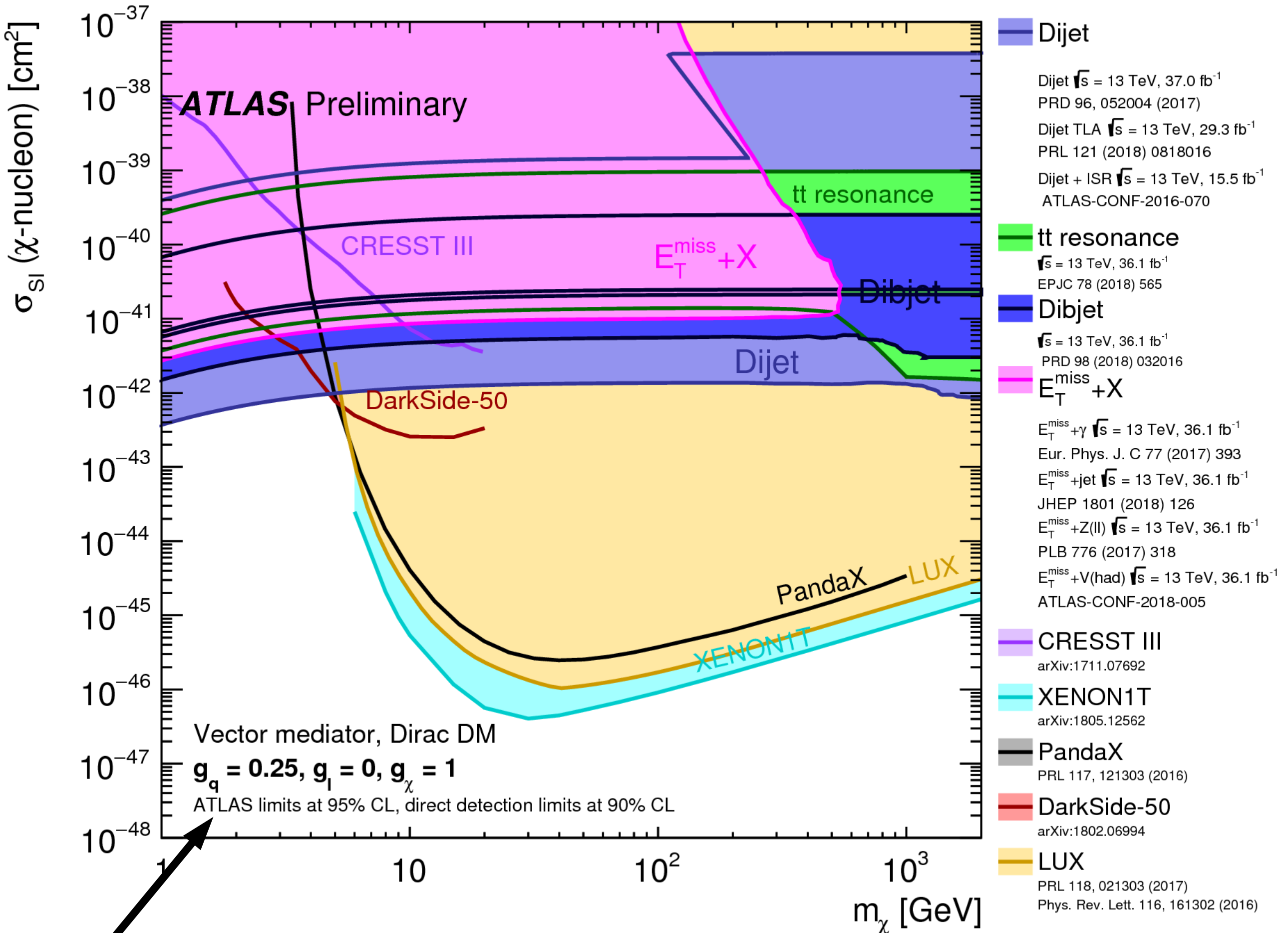


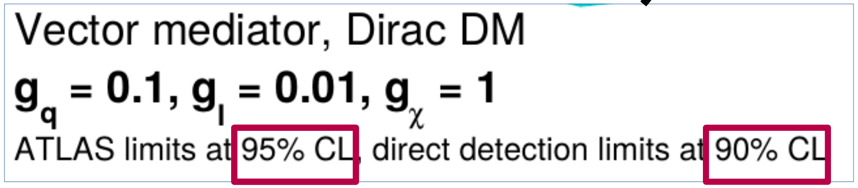
Comparison to non-collider dark matter searches

[ATLAS-CONF-2018-051]

For specific models and parameter assumptions comparison between collider and direct detection experiments possible

→ *collider experiments cover lower dark matter masses*





Vector mediator, Dirac DM

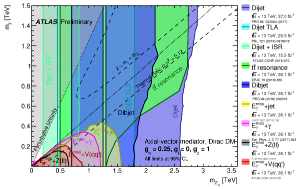
$g_q = 0.1, g_l = 0.01, g_\chi = 1$

ATLAS limits at 95% CL, direct detection limits at 90% CL

Comparison only valid for a very specific model with specific parameters!

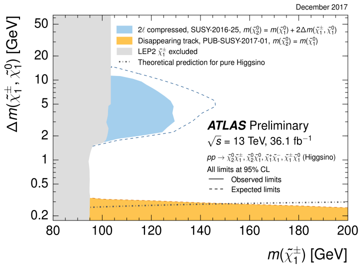
New directions

So far no dark matter particles discovered (although fluctuations present in SUSY searches), but may hide in more difficult scenarios!



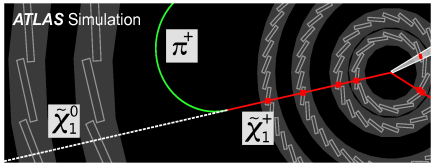
- **Comprehensive search program for DM – be aware of the model dependency!**

- **Only getting now sensitive to difficult SUSY EWK scenarios**
  → Most of Run 2 data not yet analyzed
  → Ultra compressed scenarios for Higgsino searches
  → Not many results on stau production yet
  → Not sensitive to longer decay chains at the moment



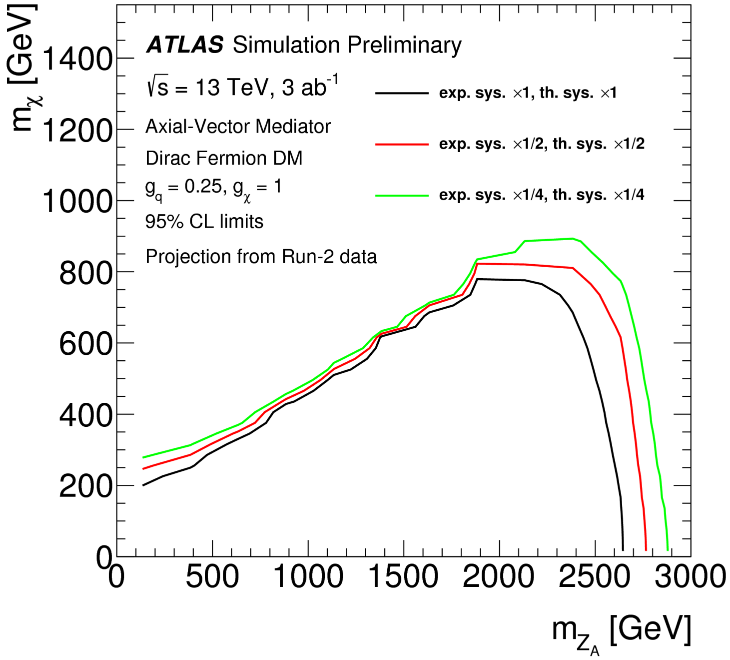
- **Using sophisticated modern techniques helps!**
  → Separate signal from background better by using shape differences
  → *Machine learning*, *boosted jets*, *multi-bin/shape fits*

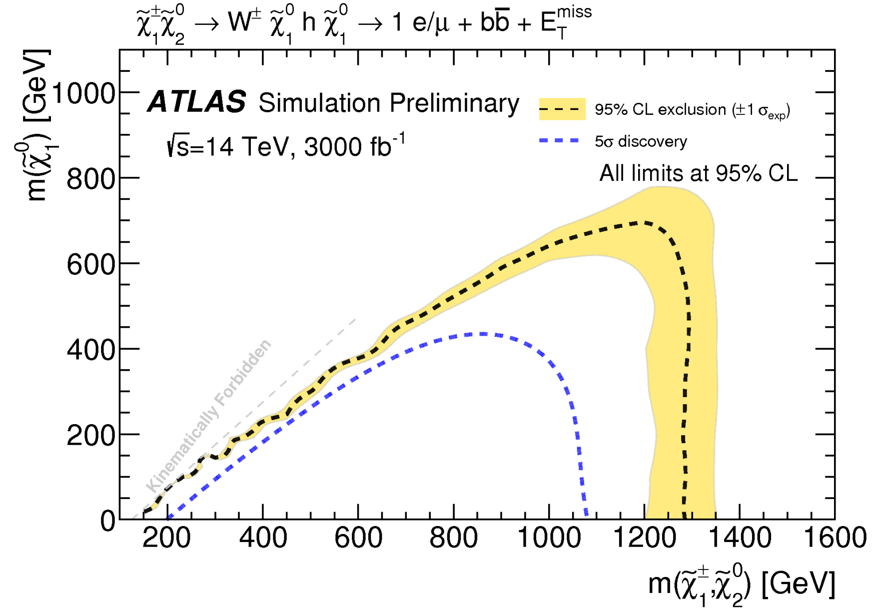
- **Not covered in this talk, but comprehensive search program: long-lived particles**
  → E.g. disappearing track searches
  → Also new particle experiments proposed



Where we may go to with HL-LHC

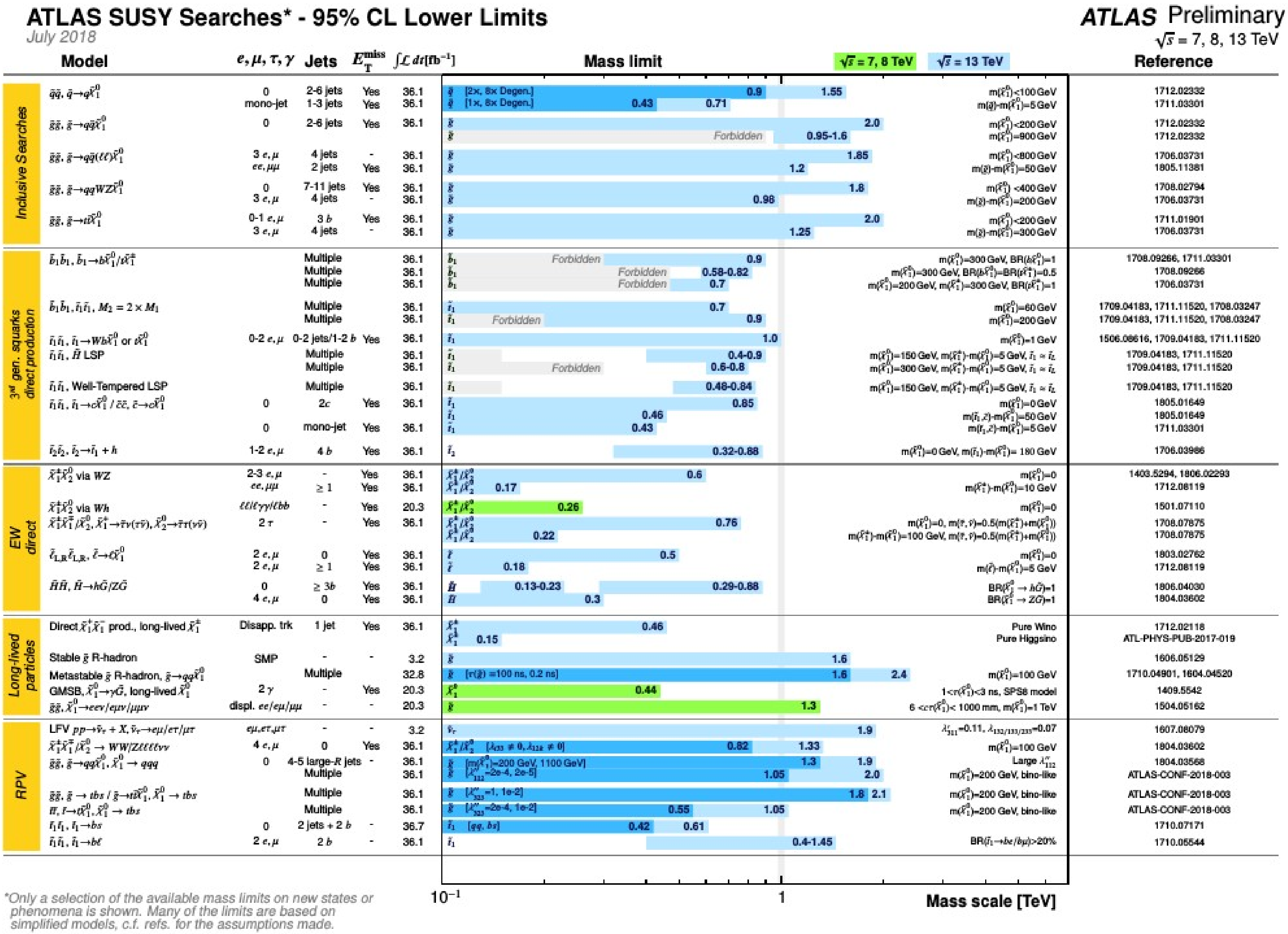
[ATL-PHYS-PUB-2018-043, ATL-PHYS-PUB-2018-048]





- Expected to reach limits up to ~1200 GeV for specific chargino/neutralino decays for HL-LHC
- Dark matter searches also reaching limits in 2.5 – 3 TeV ballpark (on the mediator)
- Searches not only profit from higher statistics, but also from improvements in techniques, like machine learning

Summary



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

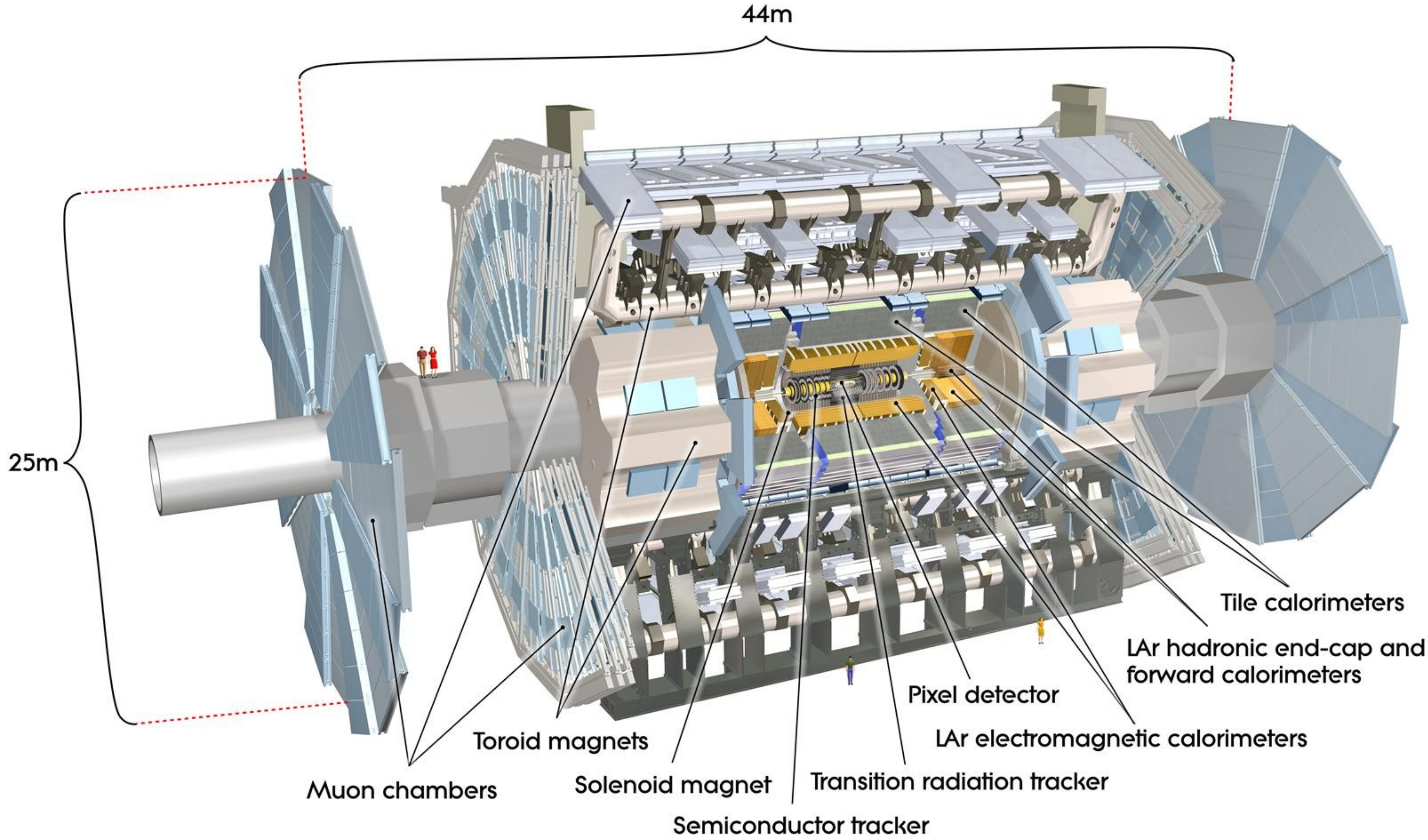
$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2x, 8x Degen.] 0.9 1.55	$m(\tilde{\chi}_1^0)$<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1x, 8x Degen.] 0.43 0.71	$m(\tilde{q})-m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)$=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.85	$m(\tilde{\chi}_1^0)$<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 0.98	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1711.01901
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.25	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=300 GeV	1706.03731
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^{\pm}$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^{\pm}$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	$m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^{\pm})$=300 GeV, BR($t\tilde{\chi}_1^{\pm}$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1$, $\tilde{t}_1\tilde{t}_1$, $M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	$m(\tilde{\chi}_1^0)$=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	$m(\tilde{\chi}_1^0)$=300 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0)$=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.6	$m(\tilde{\chi}_1^0)$=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.17	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=10 GeV	1712.08119
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.26	$m(\tilde{\chi}_1^0)$=0	1501.07110
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^{+}\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.76	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0)$)	1708.07875
						$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.22	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=100 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0)$)	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	$m(\tilde{\chi}_1^0)$=0	1803.02762
		2 e, μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	$m(\tilde{\ell})-m(\tilde{\chi}_1^0)$=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	≥ 3b	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e, μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^{\pm}$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde{\chi}_1^0)$=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, $m(\tilde{\chi}_1^0)$=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\lambda_{133}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	$m(\tilde{\chi}_1^0)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g}\to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		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	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

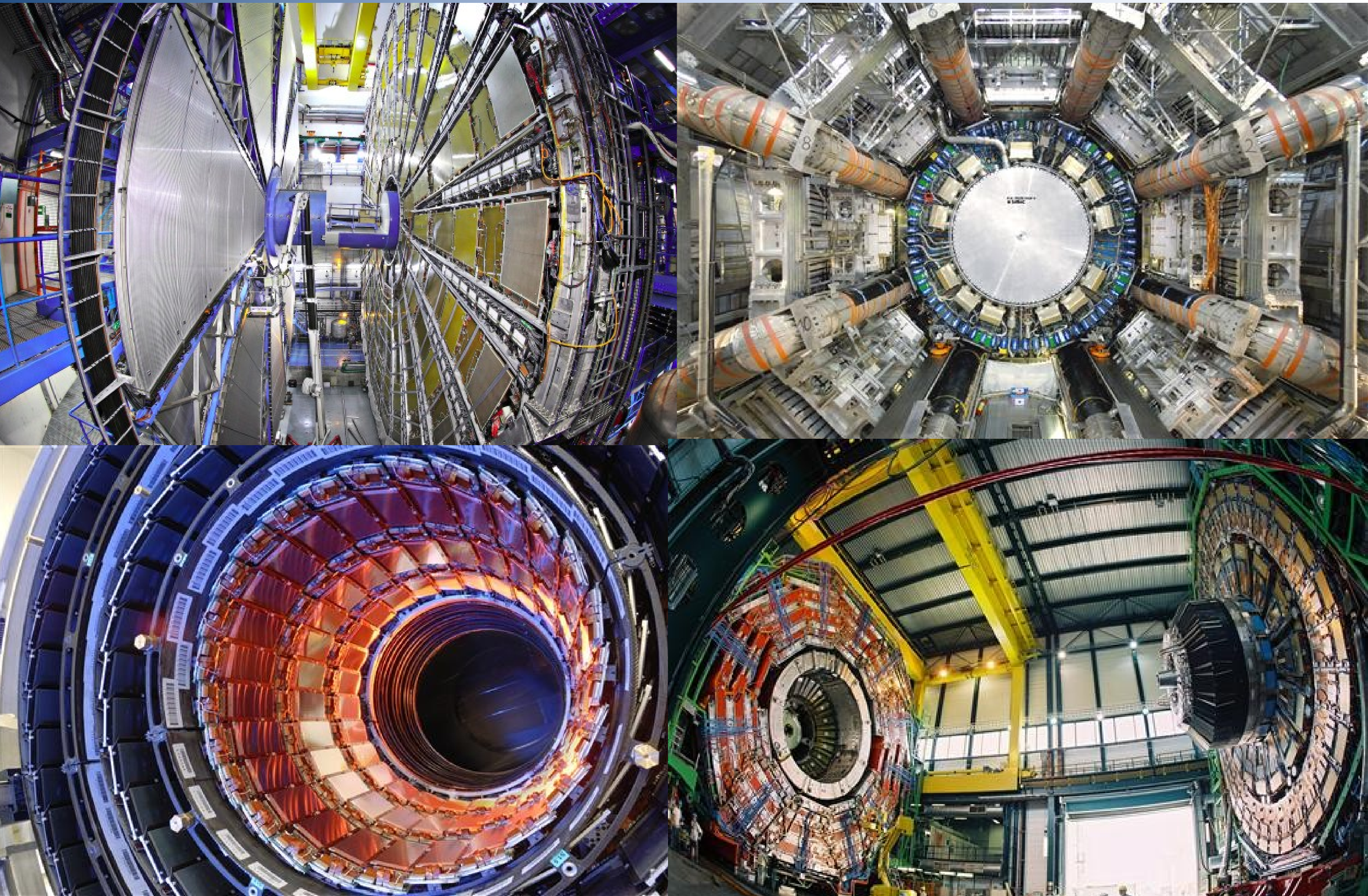
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Backup

ATLAS detector

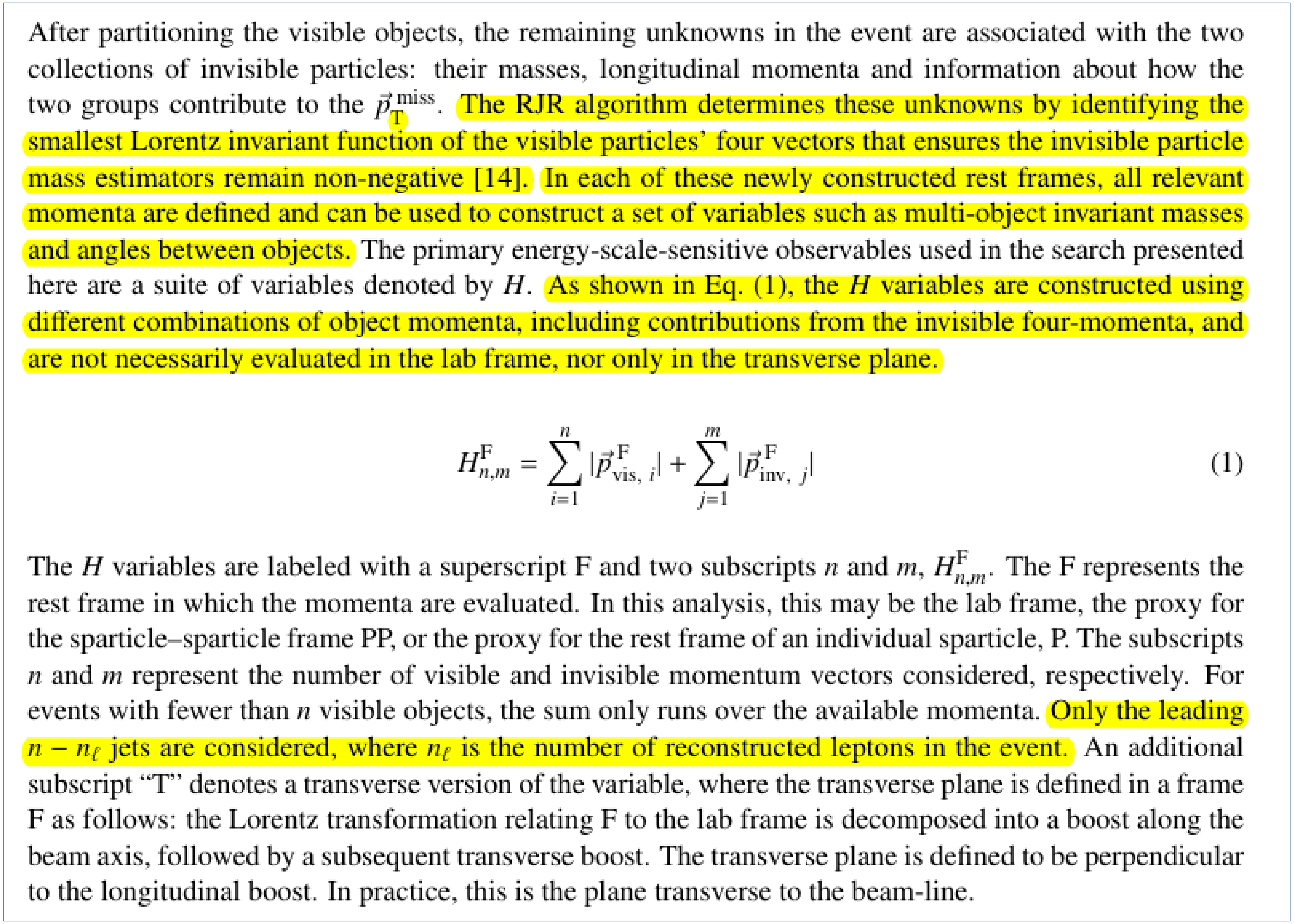


ATLAS and CMS detector



More RJigsaw variables

[arxiv:1806.02293]



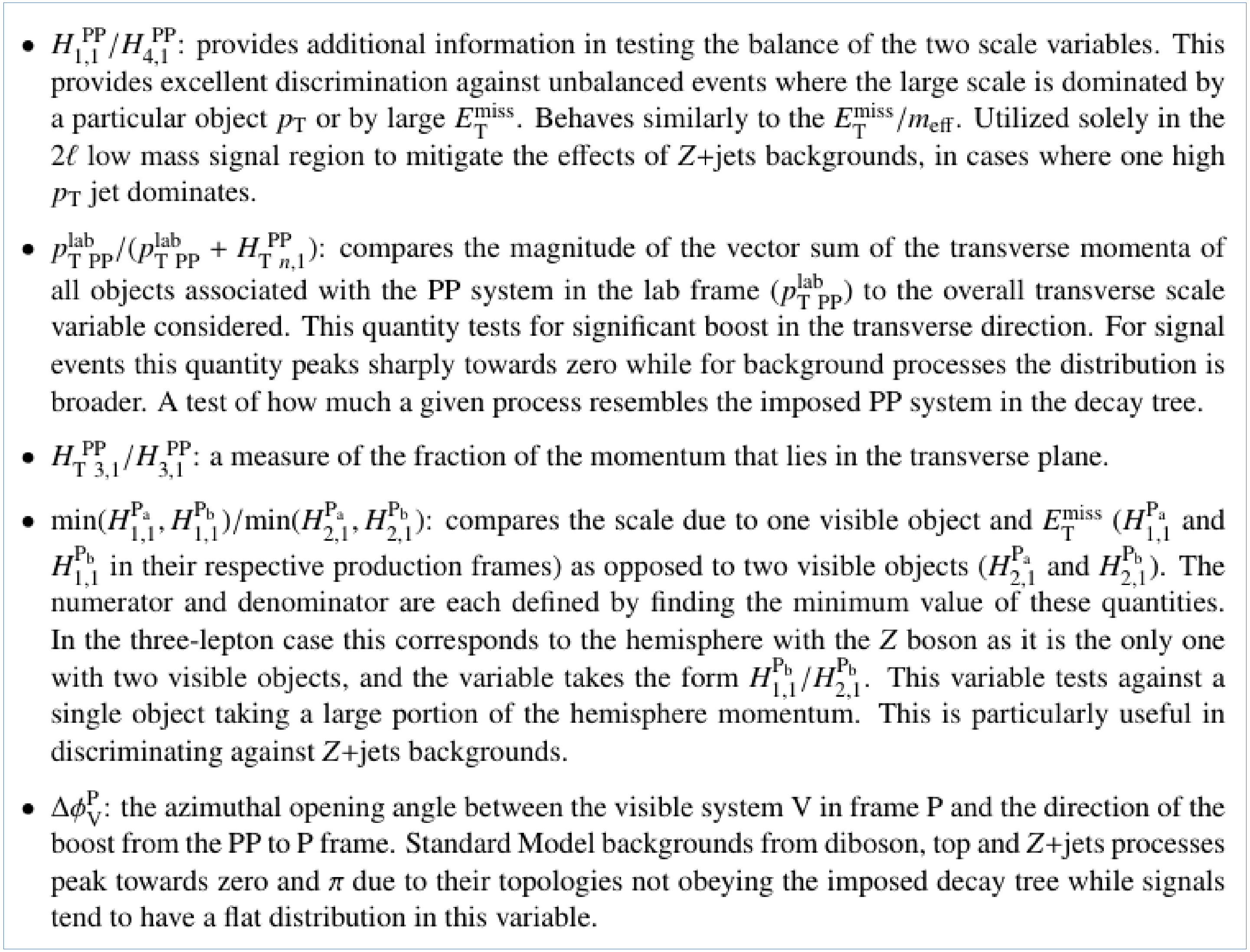
After partitioning the visible objects, the remaining unknowns in the event are associated with the two collections of invisible particles: their masses, longitudinal momenta and information about how the two groups contribute to the $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. The RJR algorithm determines these unknowns by identifying the smallest Lorentz invariant function of the visible particles' four vectors that ensures the invisible particle mass estimators remain non-negative [14]. In each of these newly constructed rest frames, all relevant momenta are defined and can be used to construct a set of variables such as multi-object invariant masses and angles between objects. The primary energy-scale-sensitive observables used in the search presented here are a suite of variables denoted by H. As shown in Eq. (1), the H variables are constructed using different combinations of object momenta, including contributions from the invisible four-momenta, and are not necessarily evaluated in the lab frame, nor only in the transverse plane.

$$H^{\mathrm{F}}_{n,m} = \sum_{i=1}^{n} |\vec{p}^{\,\mathrm{F}}_{\mathrm{vis},\ i}| + \sum_{j=1}^{m} |\vec{p}^{\,\mathrm{F}}_{\mathrm{inv},\ j}| \qquad (1)$$

The H variables are labeled with a superscript F and two subscripts n and m, $H^{\mathrm{F}}_{n,m}$. The F represents the rest frame in which the momenta are evaluated. In this analysis, this may be the lab frame, the proxy for the sparticle–sparticle frame PP, or the proxy for the rest frame of an individual sparticle, P. The subscripts n and m represent the number of visible and invisible momentum vectors considered, respectively. For events with fewer than n visible objects, the sum only runs over the available momenta. Only the leading $n - n_{\ell}$ jets are considered, where n_{ℓ} is the number of reconstructed leptons in the event. An additional subscript "T" denotes a transverse version of the variable, where the transverse plane is defined in a frame F as follows: the Lorentz transformation relating F to the lab frame is decomposed into a boost along the beam axis, followed by a subsequent transverse boost. The transverse plane is defined to be perpendicular to the longitudinal boost. In practice, this is the plane transverse to the beam-line.

More RJigsaw variables

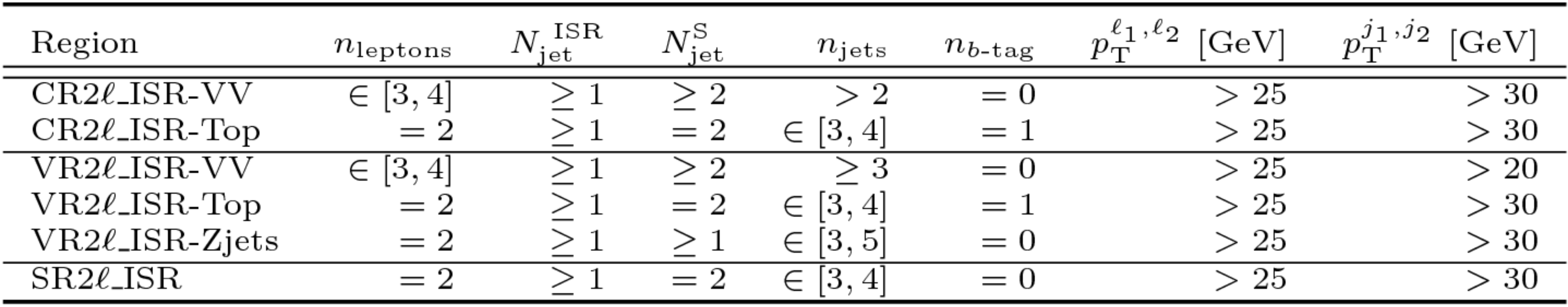
[arxiv:1806.02293]



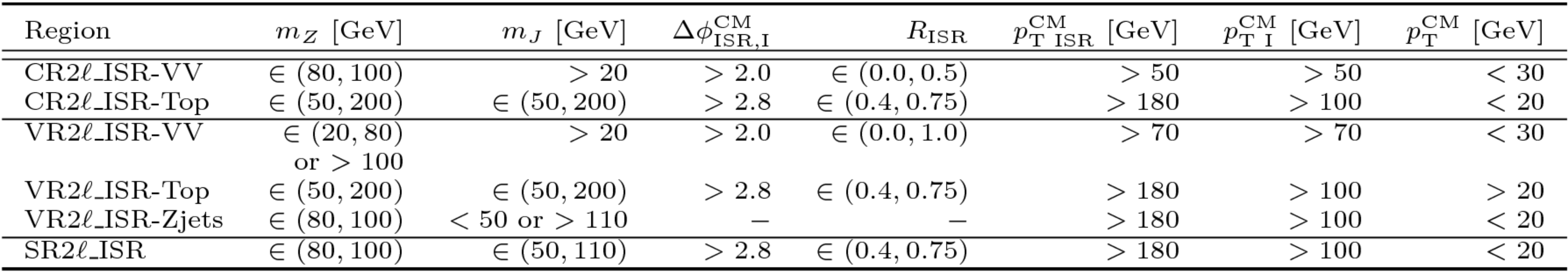
- $H^{\mathrm{PP}}_{1,1}/H^{\mathrm{PP}}_{4,1}$: provides additional information in testing the balance of the two scale variables. This provides excellent discrimination against unbalanced events where the large scale is dominated by a particular object p_{T} or by large $E_{\mathrm{T}}^{\mathrm{miss}}$. Behaves similarly to the $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$. Utilized solely in the 2ℓ low mass signal region to mitigate the effects of Z+jets backgrounds, in cases where one high p_{T} jet dominates.
- $p^{\mathrm{lab}}_{\mathrm{T\,PP}}/(p^{\mathrm{lab}}_{\mathrm{T\,PP}} + H^{\mathrm{PP}}_{\mathrm{T}\,n,1})$: compares the magnitude of the vector sum of the transverse momenta of all objects associated with the PP system in the lab frame ($p^{\mathrm{lab}}_{\mathrm{T\,PP}}$) to the overall transverse scale variable considered. This quantity tests for significant boost in the transverse direction. For signal events this quantity peaks sharply towards zero while for background processes the distribution is broader. A test of how much a given process resembles the imposed PP system in the decay tree.
- $H^{\mathrm{PP}}_{\mathrm{T}\,3,1}/H^{\mathrm{PP}}_{3,1}$: a measure of the fraction of the momentum that lies in the transverse plane.
- $\min(H^{\mathrm{P_a}}_{1,1}, H^{\mathrm{P_b}}_{1,1})/\min(H^{\mathrm{P_a}}_{2,1}, H^{\mathrm{P_b}}_{2,1})$: compares the scale due to one visible object and $E_{\mathrm{T}}^{\mathrm{miss}}$ ($H^{\mathrm{P_a}}_{1,1}$ and $H^{\mathrm{P_b}}_{1,1}$ in their respective production frames) as opposed to two visible objects ($H^{\mathrm{P_a}}_{2,1}$ and $H^{\mathrm{P_b}}_{2,1}$). The numerator and denominator are each defined by finding the minimum value of these quantities. In the three-lepton case this corresponds to the hemisphere with the Z boson as it is the only one with two visible objects, and the variable takes the form $H^{\mathrm{P_b}}_{1,1}/H^{\mathrm{P_b}}_{2,1}$. This variable tests against a single object taking a large portion of the hemisphere momentum. This is particularly useful in discriminating against Z+jets backgrounds.
- $\Delta\phi^{\mathrm{P}}_{\mathrm{V}}$: the azimuthal opening angle between the visible system V in frame P and the direction of the boost from the PP to P frame. Standard Model backgrounds from diboson, top and Z+jets processes peak towards zero and π due to their topologies not obeying the imposed decay tree while signals tend to have a flat distribution in this variable.

Signal region definition in 2/3-lepton RJigsaw

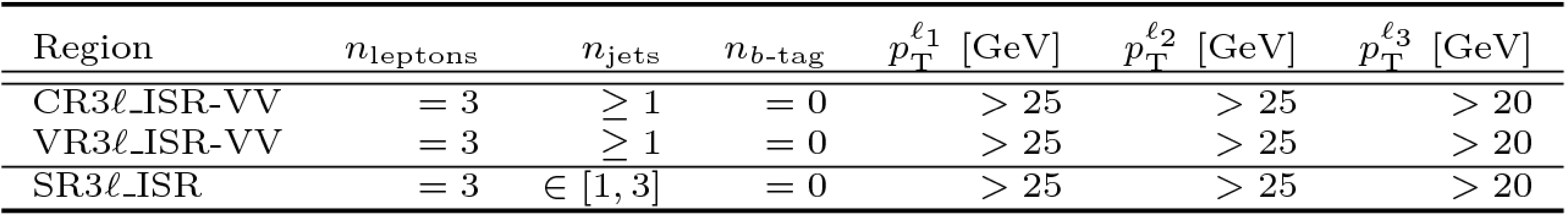
[arxiv:1806.02293]



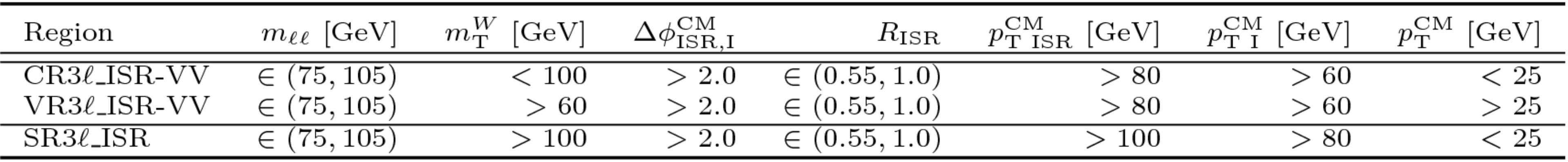
Region	n_{leptons}	$N_{\mathrm{jet}}^{\mathrm{ISR}}$	$N_{\mathrm{jet}}^{\mathrm{S}}$	n_{jets}	$n_{b\text{-tag}}$	$p_{\mathrm{T}}^{\ell_1,\ell_2}$ [GeV]	$p_{\mathrm{T}}^{j_1,j_2}$ [GeV]
CR2ℓ_ISR-VV	$\in [3,4]$	≥ 1	≥ 2	> 2	$= 0$	> 25	> 30
CR2ℓ_ISR-Top	$= 2$	≥ 1	$= 2$	$\in [3,4]$	$= 1$	> 25	> 30
VR2ℓ_ISR-VV	$\in [3,4]$	≥ 1	≥ 2	≥ 3	$= 0$	> 25	> 20
VR2ℓ_ISR-Top	$= 2$	≥ 1	$= 2$	$\in [3,4]$	$= 1$	> 25	> 30
VR2ℓ_ISR-Zjets	$= 2$	≥ 1	≥ 1	$\in [3,5]$	$= 0$	> 25	> 30
SR2ℓ_ISR	$= 2$	≥ 1	$= 2$	$\in [3,4]$	$= 0$	> 25	> 30



Region	m_Z [GeV]	m_J [GeV]	$\Delta\phi_{\mathrm{ISR,I}}^{\mathrm{CM}}$	R_{ISR}	$p_{\mathrm{T\,ISR}}^{\mathrm{CM}}$ [GeV]	$p_{\mathrm{T\,I}}^{\mathrm{CM}}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{CM}}$ [GeV]
CR2ℓ_ISR-VV	$\in (80,100)$	> 20	> 2.0	$\in (0.0,0.5)$	> 50	> 50	< 30
CR2ℓ_ISR-Top	$\in (50,200)$	$\in (50,200)$	> 2.8	$\in (0.4,0.75)$	> 180	> 100	< 20
VR2ℓ_ISR-VV	$\in (20,80)$ or > 100	> 20	> 2.0	$\in (0.0,1.0)$	> 70	> 70	< 30
VR2ℓ_ISR-Top	$\in (50,200)$	$\in (50,200)$	> 2.8	$\in (0.4,0.75)$	> 180	> 100	> 20
VR2ℓ_ISR-Zjets	$\in (80,100)$	< 50 or > 110	–	–	> 180	> 100	< 20
SR2ℓ_ISR	$\in (80,100)$	$\in (50,110)$	> 2.8	$\in (0.4,0.75)$	> 180	> 100	< 20



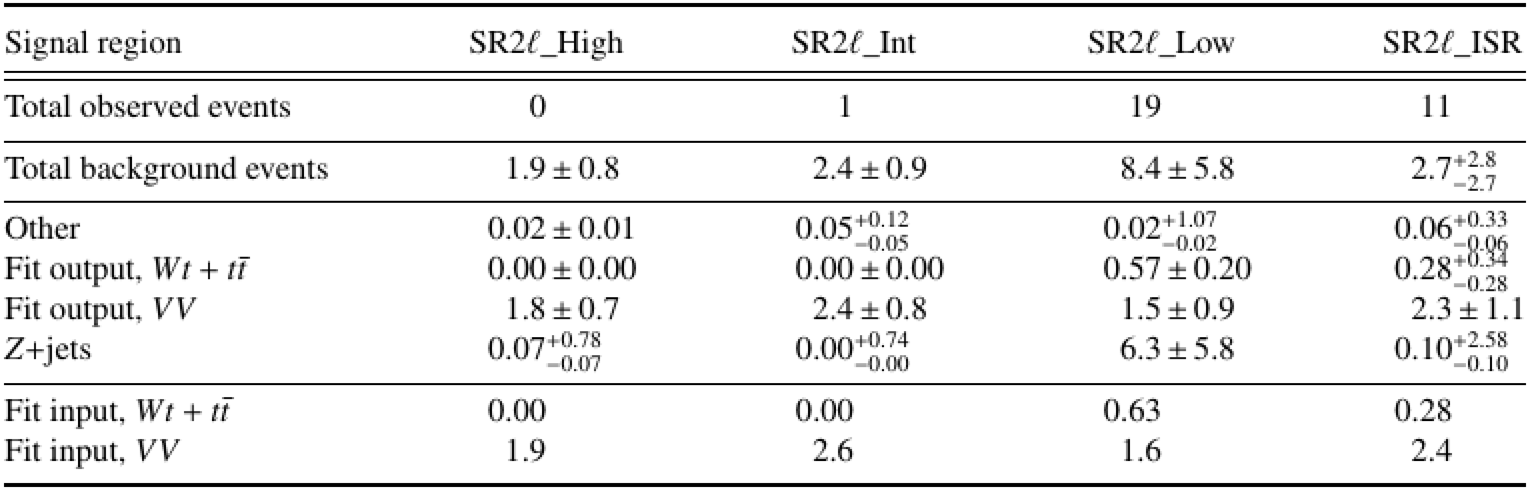
Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_{\mathrm{T}}^{\ell_1}$ [GeV]	$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$p_{\mathrm{T}}^{\ell_3}$ [GeV]
CR3ℓ_ISR-VV	$= 3$	≥ 1	$= 0$	> 25	> 25	> 20
VR3ℓ_ISR-VV	$= 3$	≥ 1	$= 0$	> 25	> 25	> 20
SR3ℓ_ISR	$= 3$	$\in [1,3]$	$= 0$	> 25	> 25	> 20



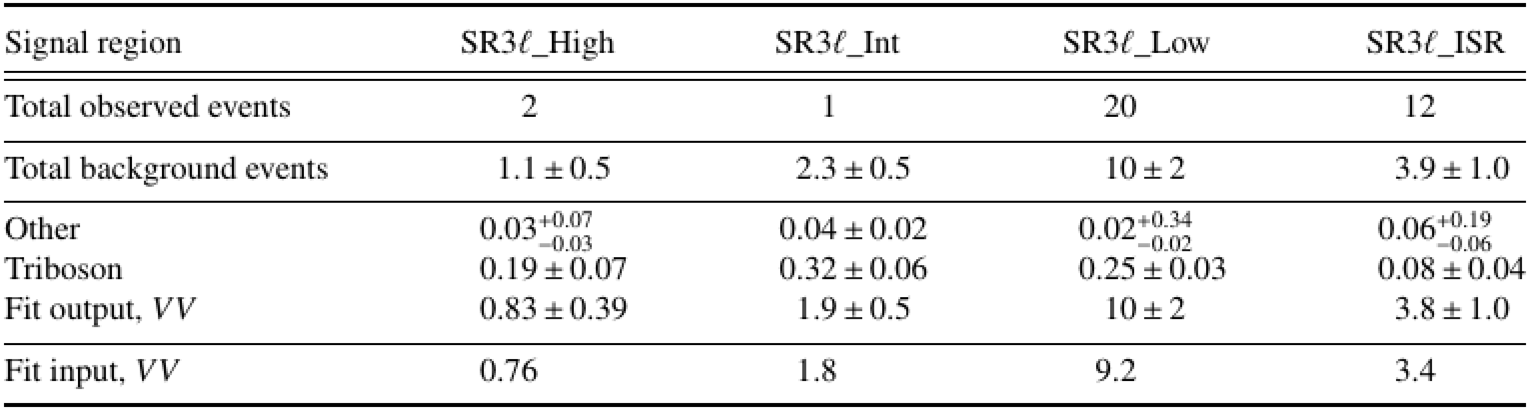
Region	$m_{\ell\ell}$ [GeV]	m_{T}^{W} [GeV]	$\Delta\phi_{\mathrm{ISR,I}}^{\mathrm{CM}}$	R_{ISR}	$p_{\mathrm{T\,ISR}}^{\mathrm{CM}}$ [GeV]	$p_{\mathrm{T\,I}}^{\mathrm{CM}}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{CM}}$ [GeV]
CR3ℓ_ISR-VV	$\in (75,105)$	< 100	> 2.0	$\in (0.55,1.0)$	> 80	> 60	< 25
VR3ℓ_ISR-VV	$\in (75,105)$	> 60	> 2.0	$\in (0.55,1.0)$	> 80	> 60	> 25
SR3ℓ_ISR	$\in (75,105)$	> 100	> 2.0	$\in (0.55,1.0)$	> 100	> 80	< 25

Signal region yields in 2/3-lepton RJigsaw

[arxiv:1806.02293]



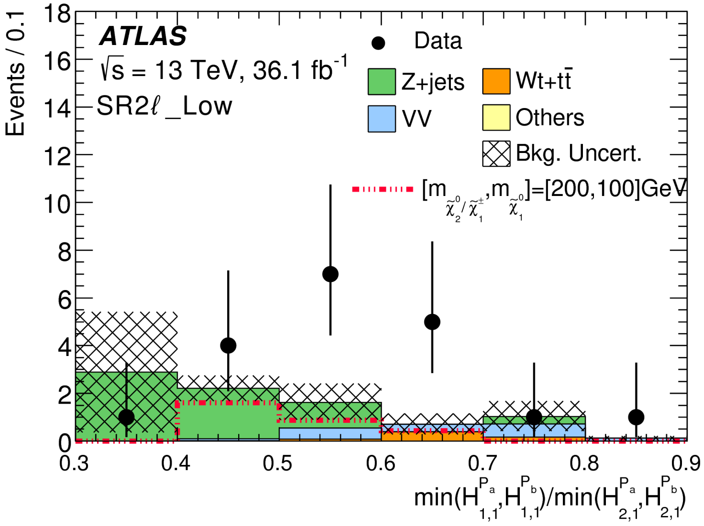
Signal region	SR2ℓ_High	SR2ℓ_Int	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	0	1	19	11
Total background events	1.9 ± 0.8	2.4 ± 0.9	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$
Other	0.02 ± 0.01	$0.05^{+0.12}_{-0.05}$	$0.02^{+1.07}_{-0.02}$	$0.06^{+0.33}_{-0.06}$
Fit output, $Wt + t\bar{t}$	0.00 ± 0.00	0.00 ± 0.00	0.57 ± 0.20	$0.28^{+0.34}_{-0.28}$
Fit output, VV	1.8 ± 0.7	2.4 ± 0.8	1.5 ± 0.9	2.3 ± 1.1
Z+jets	$0.07^{+0.78}_{-0.07}$	$0.00^{+0.74}_{-0.00}$	6.3 ± 5.8	$0.10^{+2.58}_{-0.10}$
Fit input, $Wt + t\bar{t}$	0.00	0.00	0.63	0.28
Fit input, VV	1.9	2.6	1.6	2.4

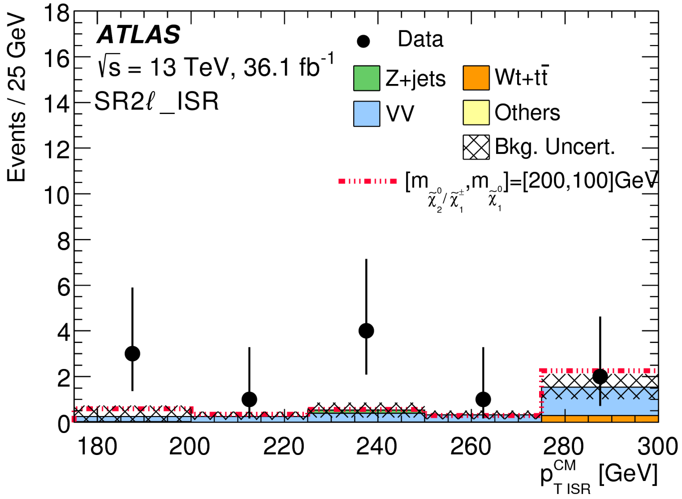


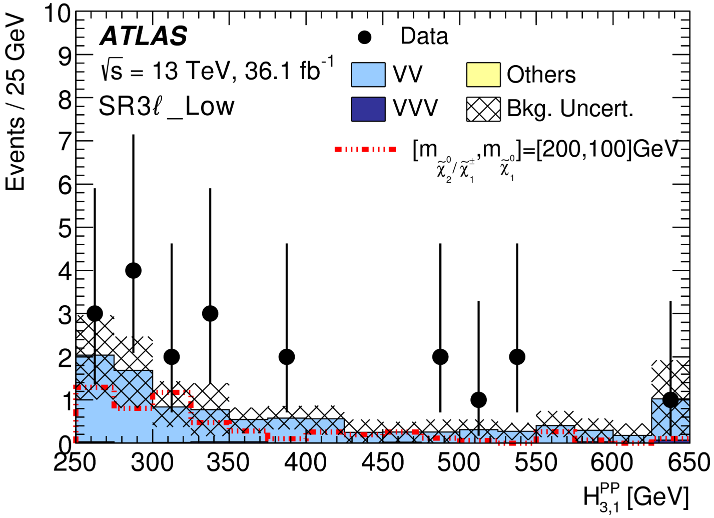
Signal region	SR3ℓ_High	SR3ℓ_Int	SR3ℓ_Low	SR3ℓ_ISR
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0
Other	$0.03^{+0.07}_{-0.03}$	0.04 ± 0.02	$0.02^{+0.34}_{-0.02}$	$0.06^{+0.19}_{-0.06}$
Triboson	0.19 ± 0.07	0.32 ± 0.06	0.25 ± 0.03	0.08 ± 0.04
Fit output, VV	0.83 ± 0.39	1.9 ± 0.5	10 ± 2	3.8 ± 1.0
Fit input, VV	0.76	1.8	9.2	3.4

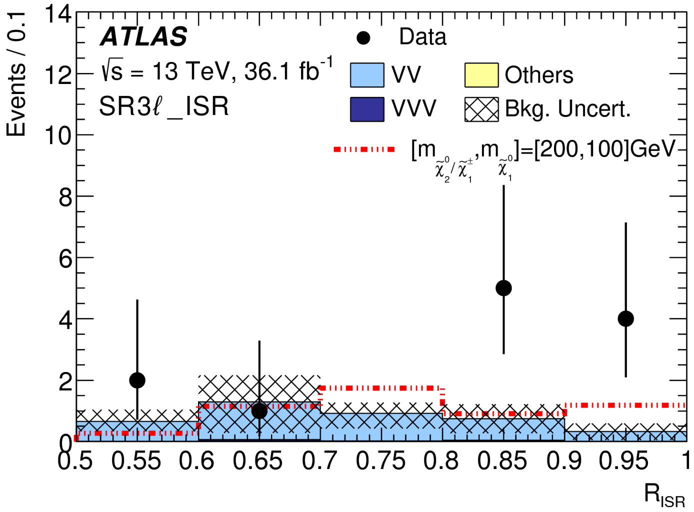
2/3-lepton Rjigsaw: more kinematic plots

[arxiv:1806.02293]



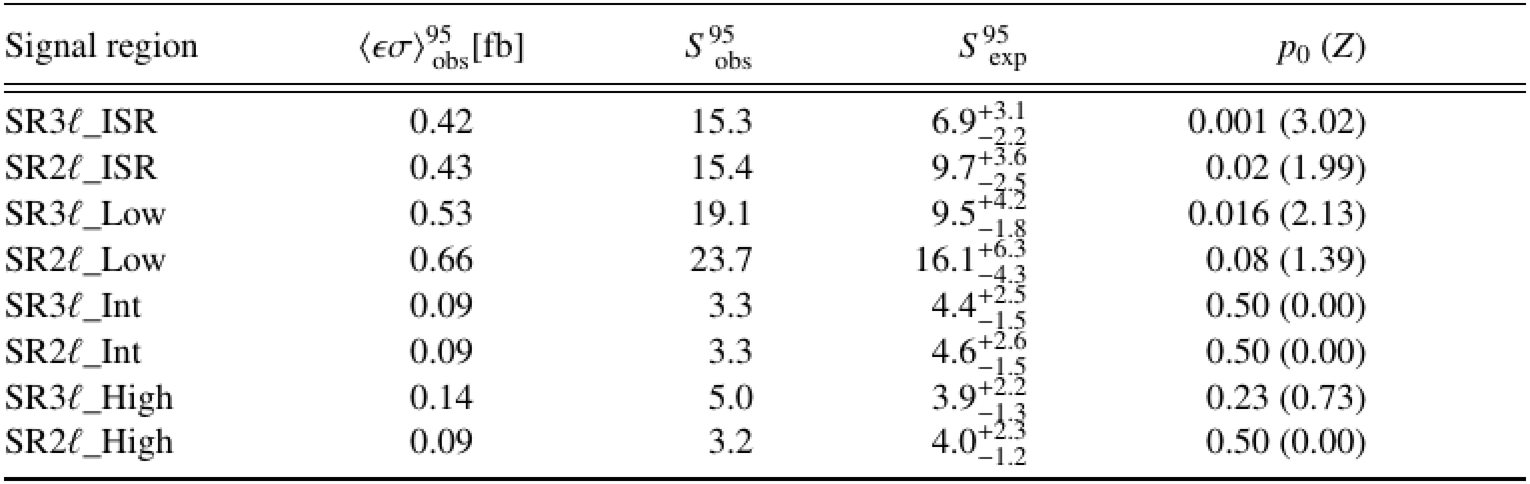






2/3-lepton Rjigsaw: significance

[arxiv:1806.02293]



Signal region	$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$[fb]	S^{95}_{obs}	S^{95}_{exp}	p_0 (Z)
SR3ℓ_ISR	0.42	15.3	$6.9^{+3.1}_{-2.2}$	0.001 (3.02)
SR2ℓ_ISR	0.43	15.4	$9.7^{+3.6}_{-2.5}$	0.02 (1.99)
SR3ℓ_Low	0.53	19.1	$9.5^{+4.2}_{-1.8}$	0.016 (2.13)
SR2ℓ_Low	0.66	23.7	$16.1^{+6.3}_{-4.3}$	0.08 (1.39)
SR3ℓ_Int	0.09	3.3	$4.4^{+2.5}_{-1.5}$	0.50 (0.00)
SR2ℓ_Int	0.09	3.3	$4.6^{+2.6}_{-1.5}$	0.50 (0.00)
SR3ℓ_High	0.14	5.0	$3.9^{+2.2}_{-1.3}$	0.23 (0.73)
SR2ℓ_High	0.09	3.2	$4.0^{+2.3}_{-1.2}$	0.50 (0.00)

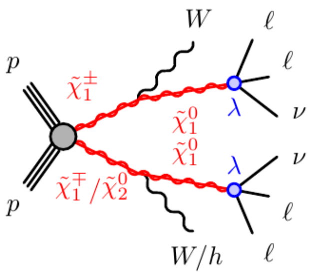
Starting with one very clean decay mode: 4 leptons

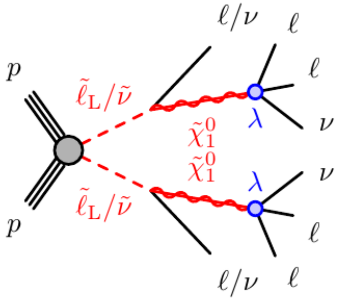
[Phys. Rev. D 98 (2018) 032009]

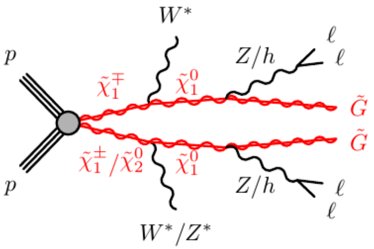
Lightest neutralino decaying to SM particles in RPV scenarios → potentially high lepton multiplicity in final state

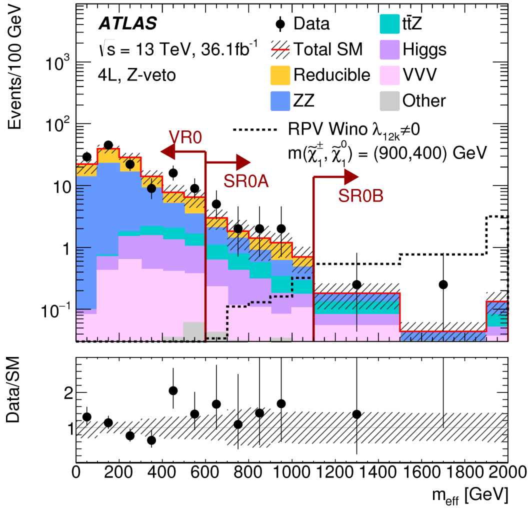
- >=4 leptons, 0 - 2 hadronically decaying taus
- 6 different SRs to gain optimal sensitivity to different models
- Cutting on m_{eff} or E_T^{miss} and veto or requirement on Z bosons
- Main backgrounds: ZZ, $t\bar{t}Z$ and fakes

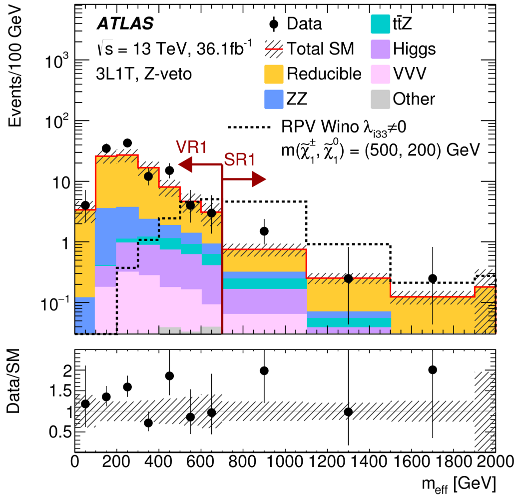
- No significant excess seen

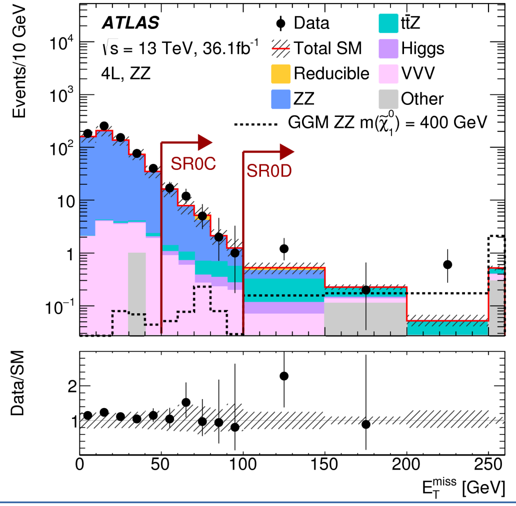










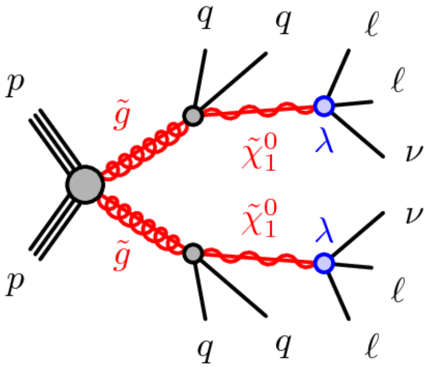


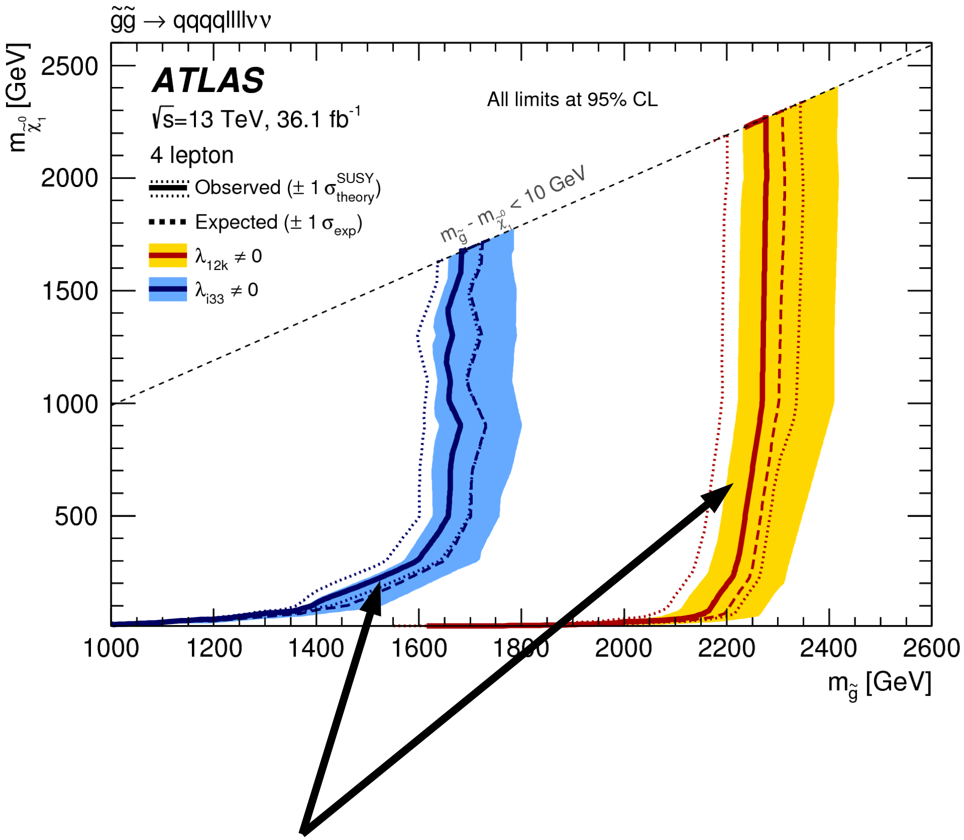
Intermezzo: sensitivity to strong production

[Phys. Rev. D 98 (2018) 032009]

Signatures with 4 leptons in the final state also possible for strong production modes

→ *this analysis is sensitive to a variety of different SUSY production modes by means of a relatively simple analysis (just requiring 4 leptons +* m_{eff}*)*



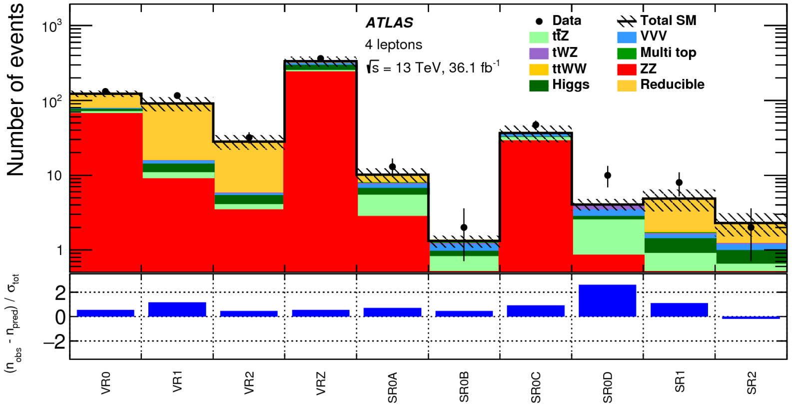


Limits depending on the RPV coupling

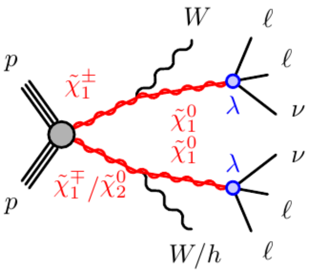
4 leptons

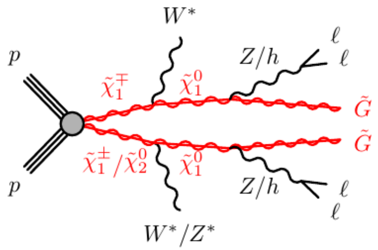
[Phys. Rev. D 98 (2018) 032009]

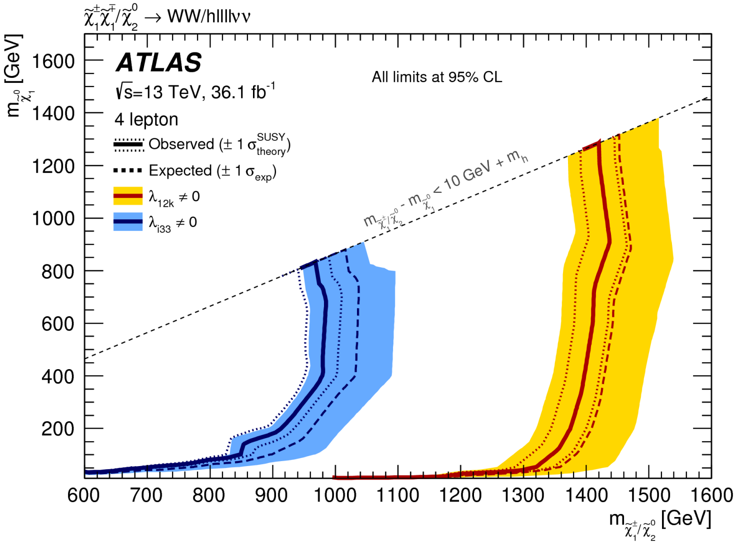
Example limits:



Gaugino production with RPV decay

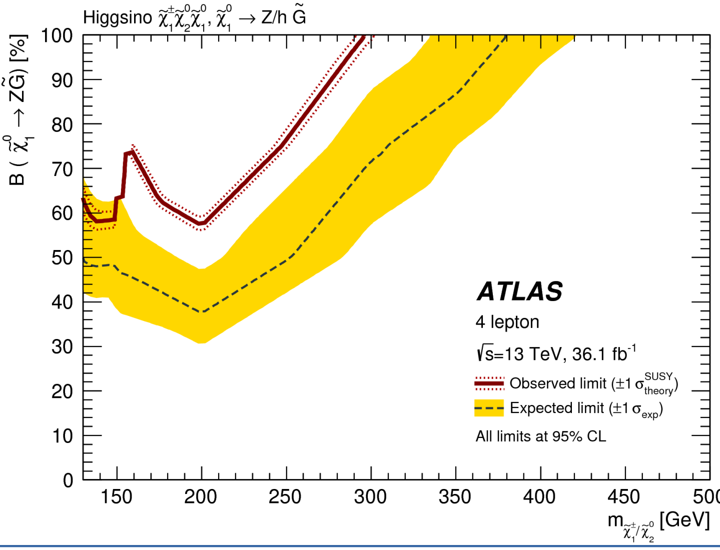






General gauge mediated:

- Compressed Higgsino states
- 4 leptons from $\tilde{\chi}^0_1$ to gravitino



Higgsino searches with 4b

[arXiv:1806.04030]

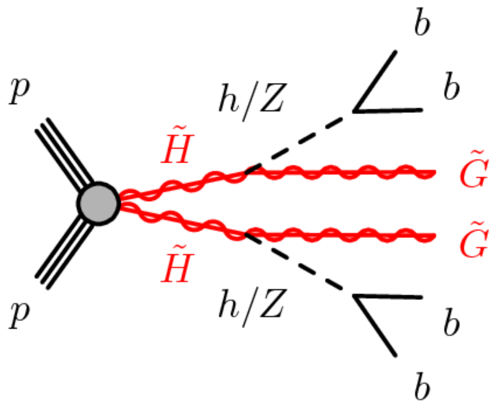
Final state with 4 b-jets

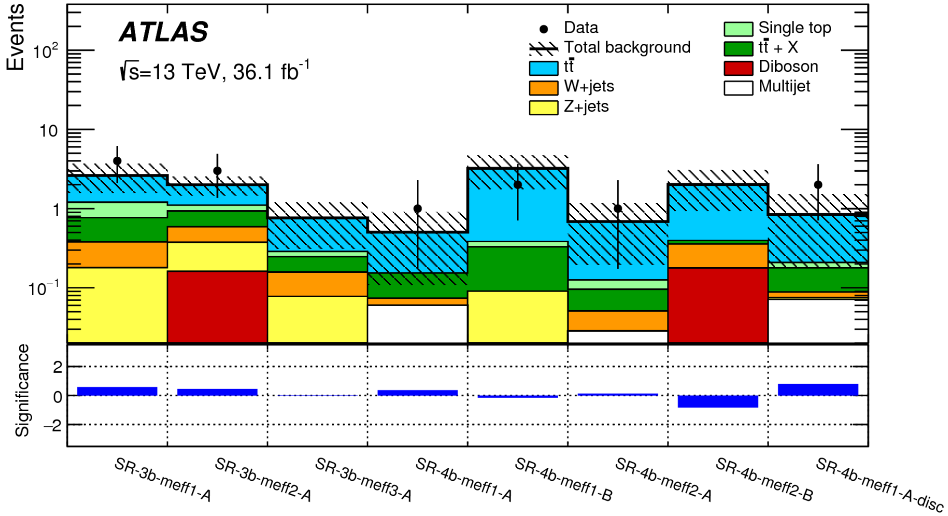
→ *key to separate from high hadronic background*

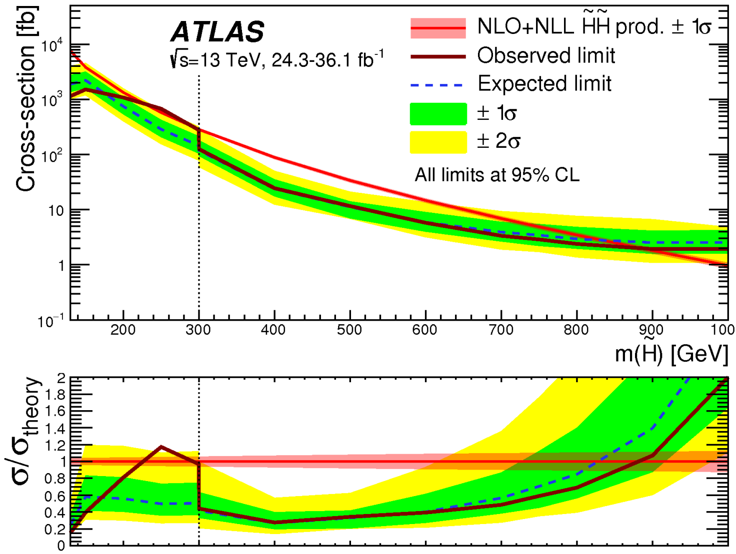
2 different sets of SRs: >= 4 jets of which >= 3 b-jets + E_T^{miss}

→ *low mass, targeting low μ with low E_T^{miss}*

→ *high mass, targeting high μ with high E_T^{miss}*



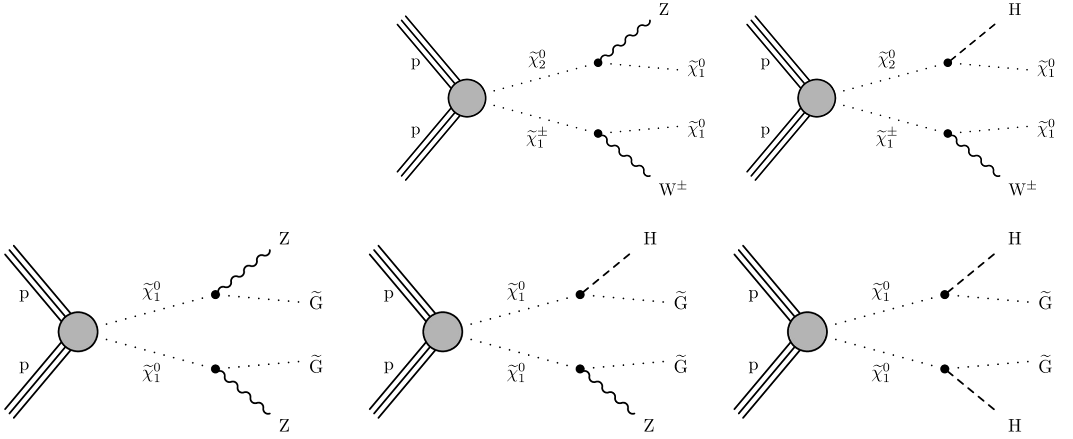




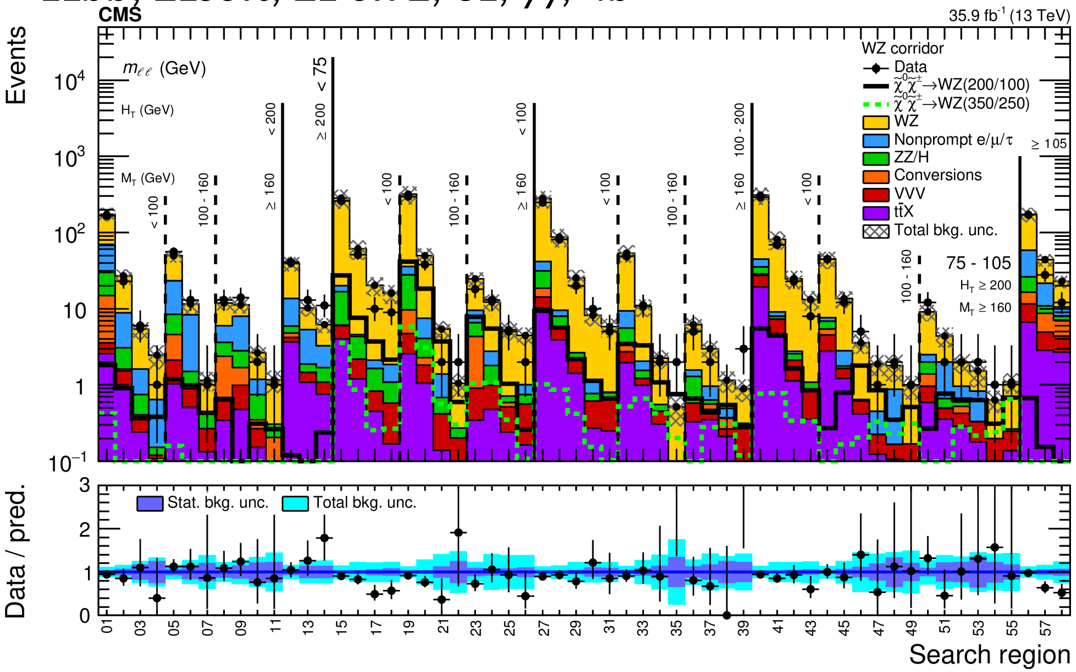
But not only W and Z bosons! Decays via Higgs bosons

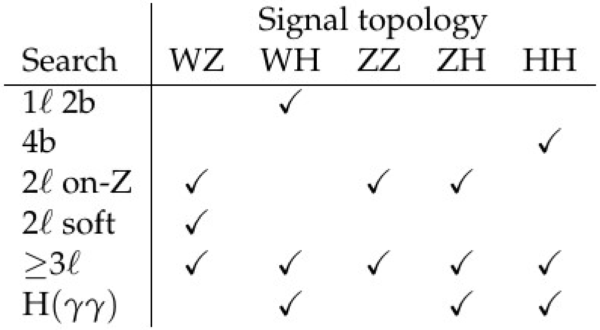
[JHEP 03 (2018) 160]

Full statistical combination of various searches by CMS – extend searches by decays of neutralinos to LSPs by emission of Higgs + also covers challenging scenarios where mass difference between second lightest neutralino and LSP at Z mass



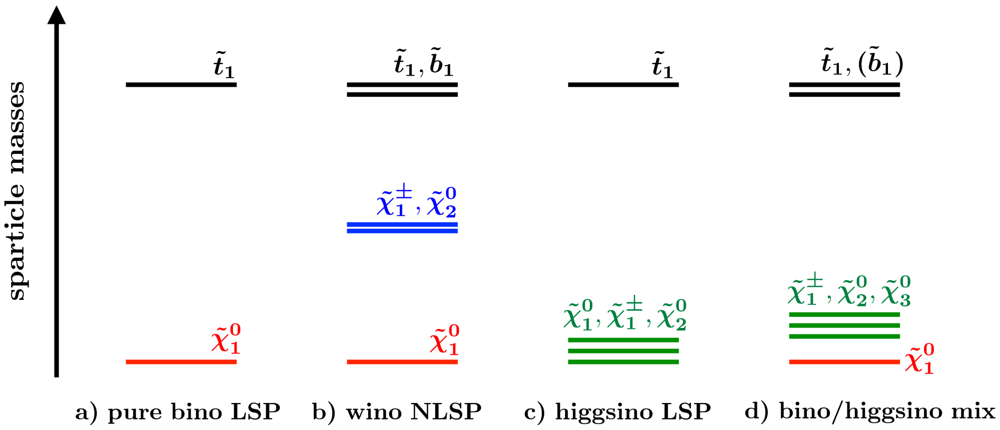
→covering very different final states: 1Lbb, 2Lsoft, 2L on Z, 3L, γγ, 4b





Search	Signal topology				
	WZ	WH	ZZ	ZH	HH
1ℓ 2b		✓			
4b					✓
2ℓ on-Z	✓		✓	✓	
2ℓ soft	✓				
$\geq 3\ell$	✓	✓	✓	✓	✓
H(γγ)		✓		✓	✓

Categorization of stop searches



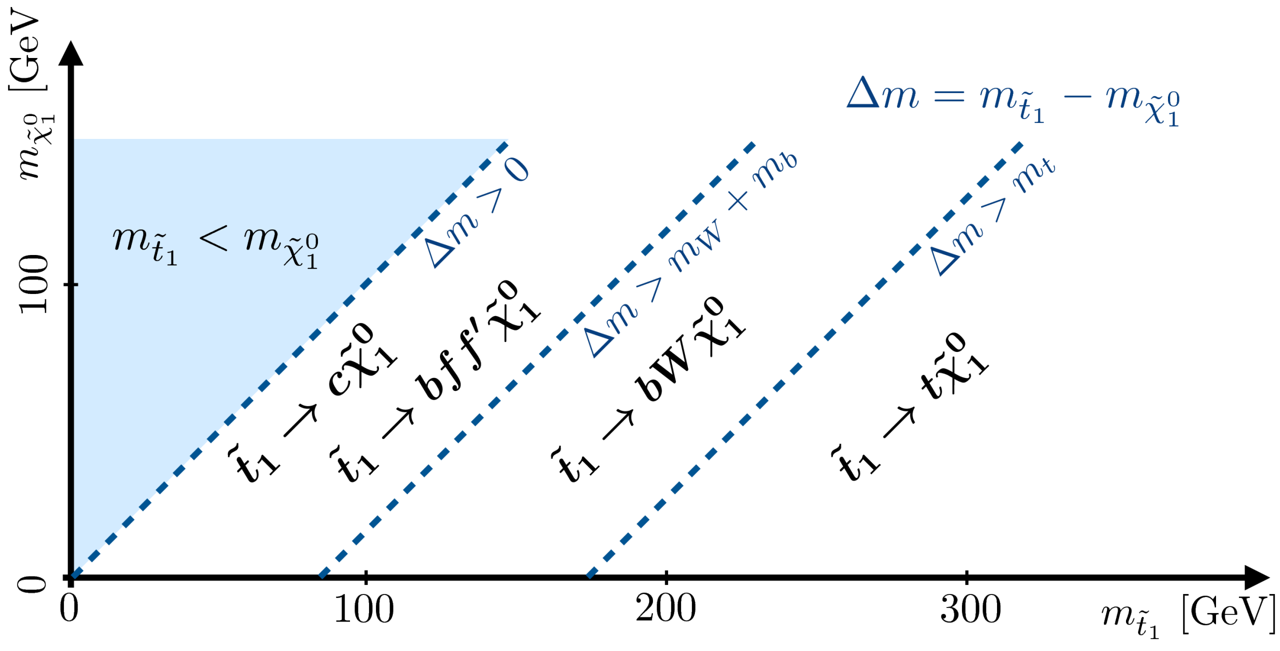
Decay pattern depend on the type of the LSP

→ *for higgsino LSP masses of charginos and neutralinos close*

→ *low energetic leptons*

Allowed decays of the stops depends on the available phase space:

- *4-body – large mass difference between stop and LSP*
- *3-body – medium mass difference*
- *2-body – small mass difference*

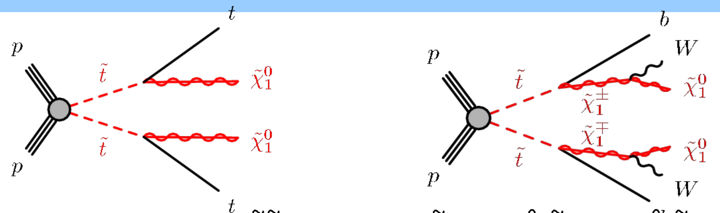


Stop 1-lepton

[arXiv:1712.02118]

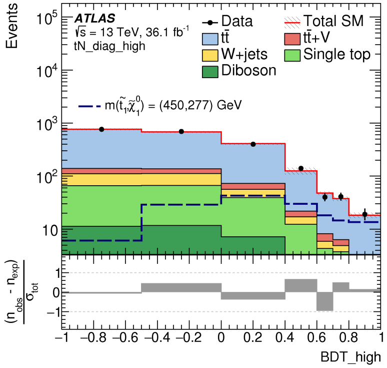
Different search channels for different mass differences between stop and LSP and for different LSP types

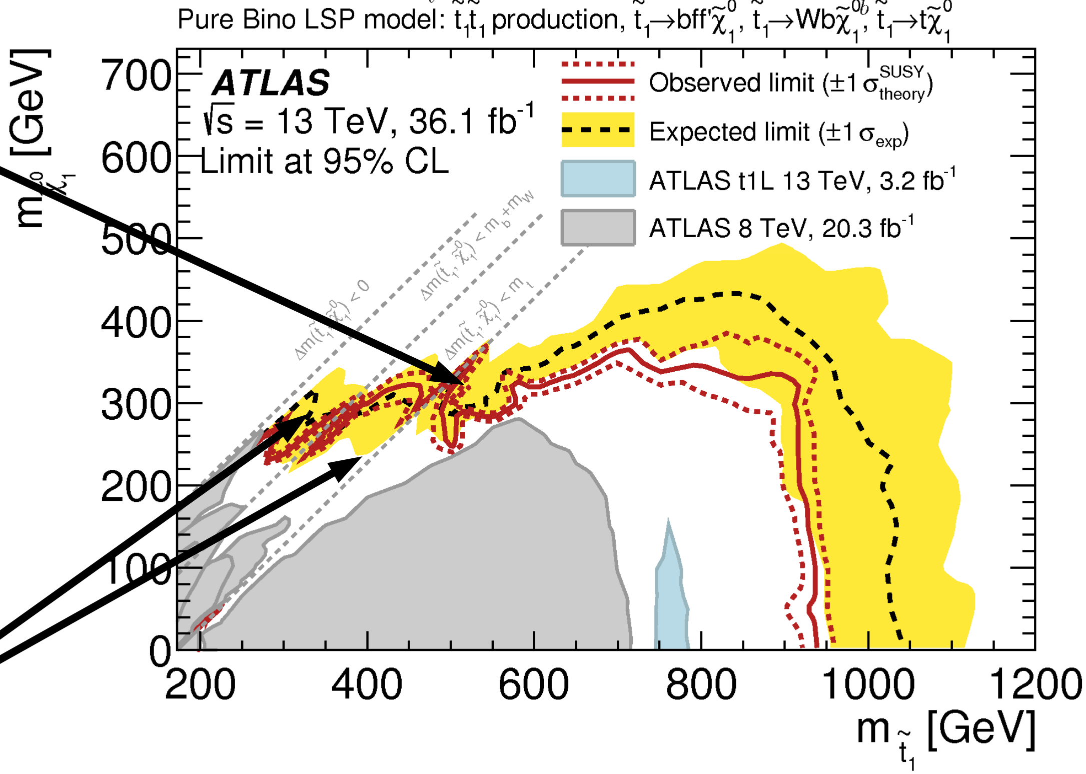
→ *use different techniques depending on search channel*



Two-body:

- *Select events with 1 lepton + >= 4 jets and high m_T*
- *For m(~t) close to m(LSP) + m(top) machine learning methods (BDT) used*





Three-body/four-body:

- *Using shape differences in key variables to fit distributions*

Summary of stop searches