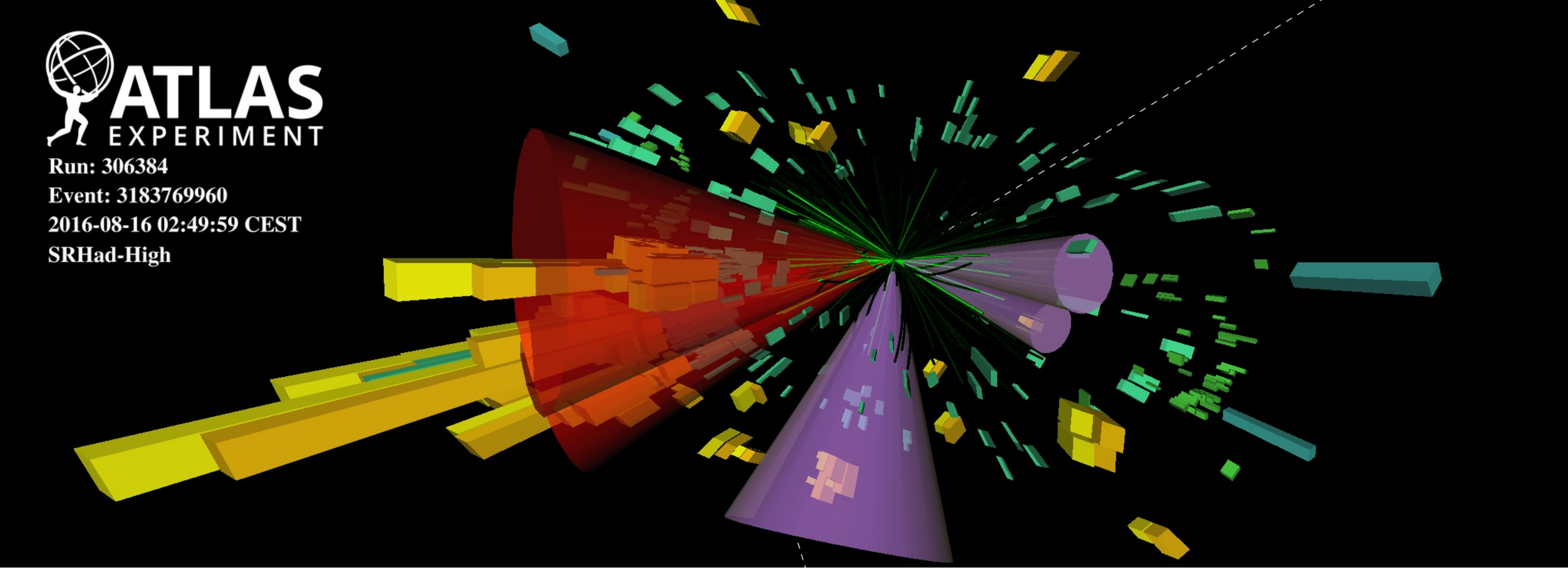

Searching for Dark Matter in association with Higgs bosons

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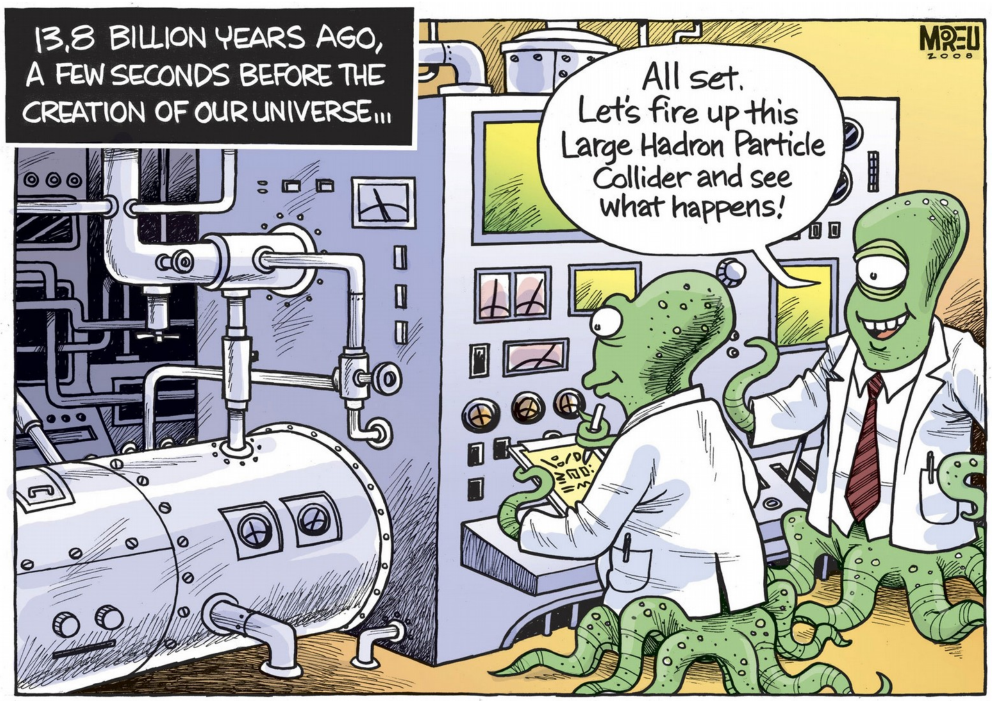
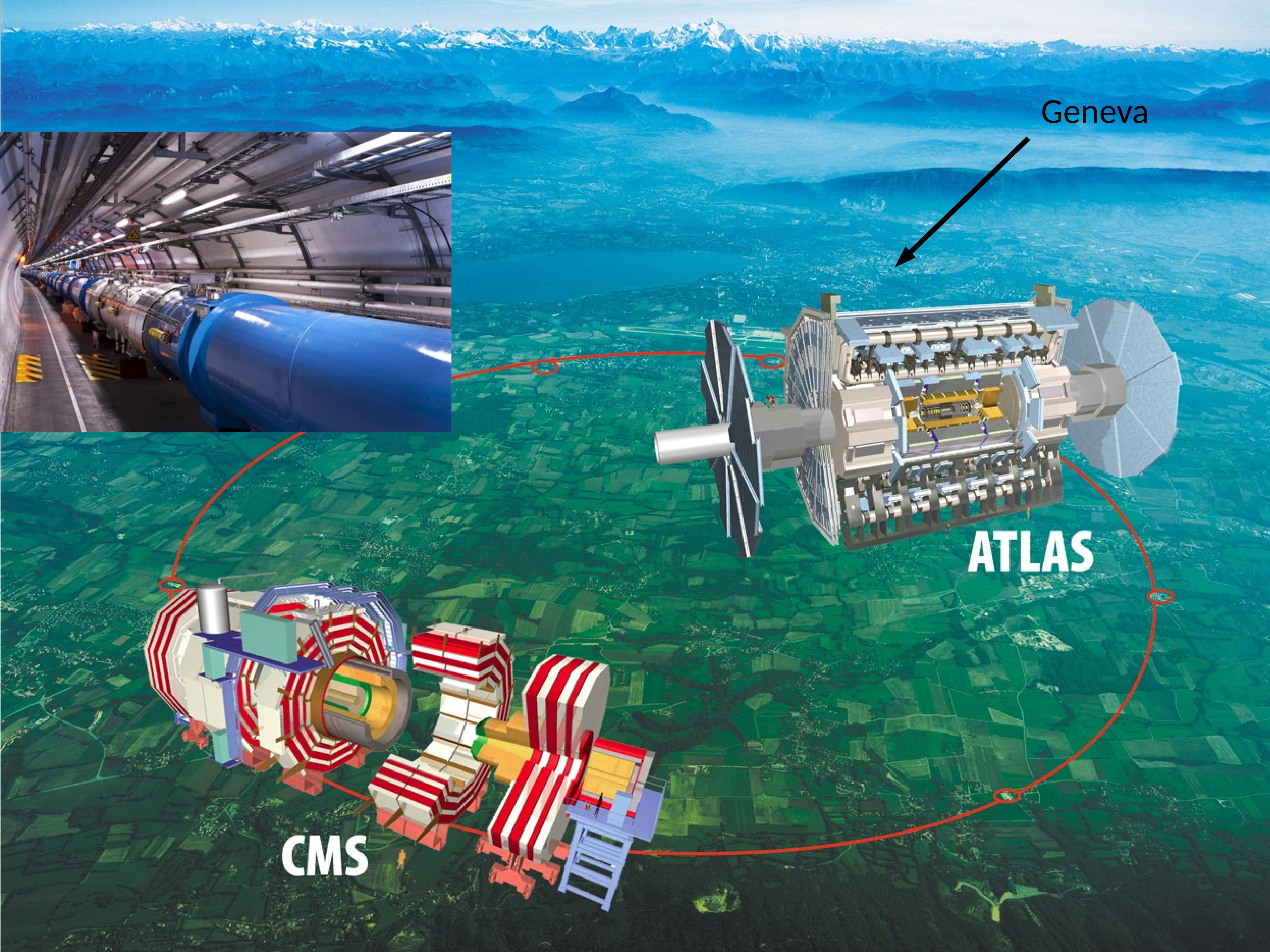
London, 05.12.2019

Outline

- LHC and ATLAS/CMS
- Standard Model and its shortcomings
- Searches for EWK SUSY with a Higgs boson
- Searches for Higgsinos
- Searches for Dark Matter in association with a Higgs boson
- Where to go next

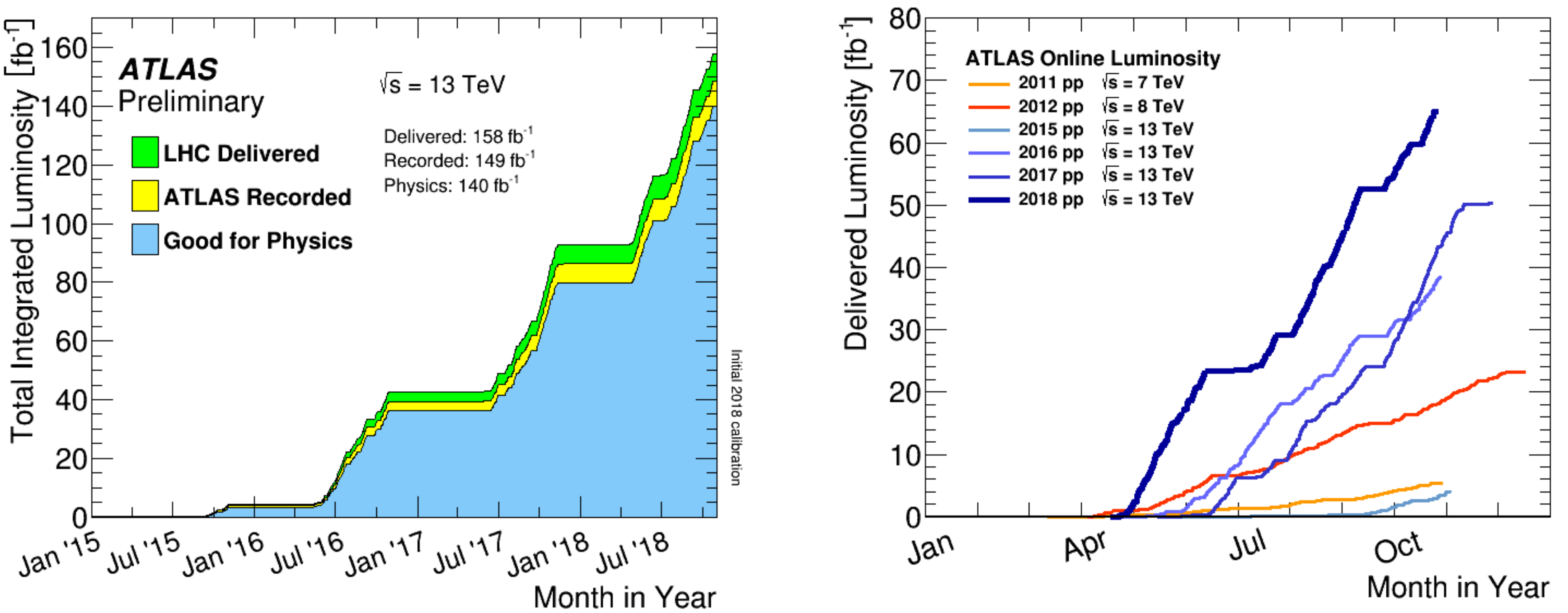


[CERN theory common room]


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
- Only very few analyses use the full dataset already, thus many more results to come.

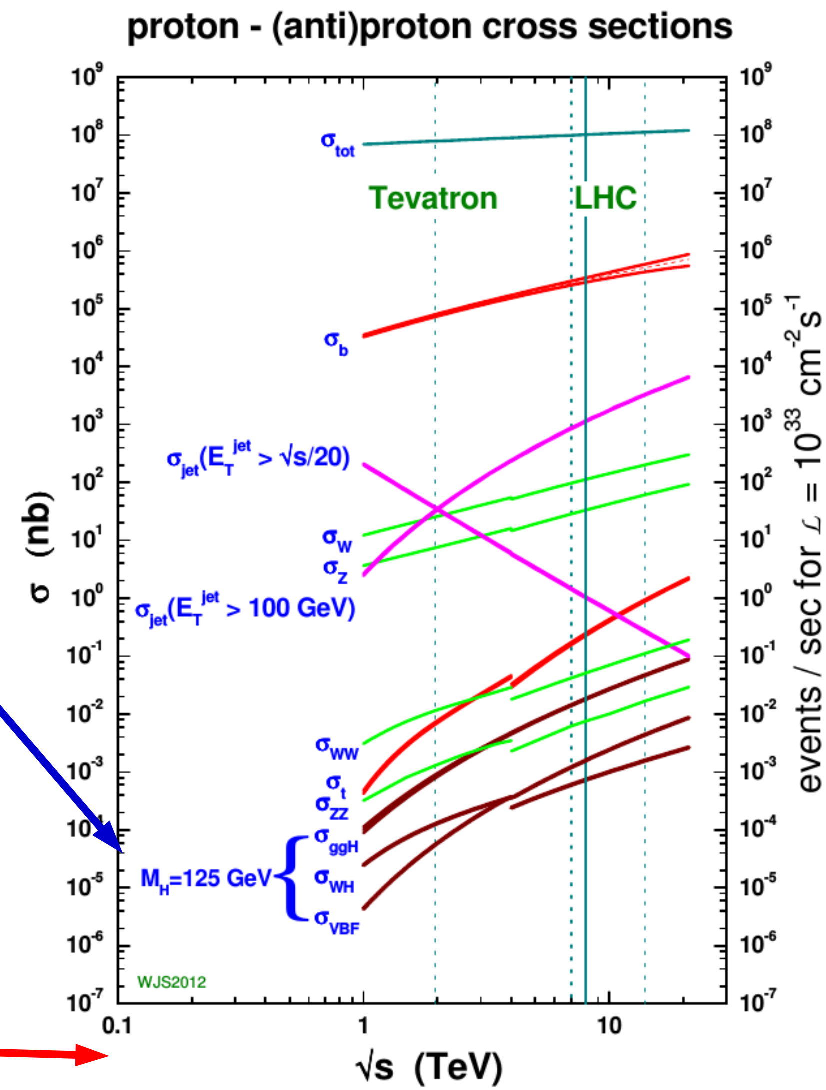
What can we measure?

- 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)

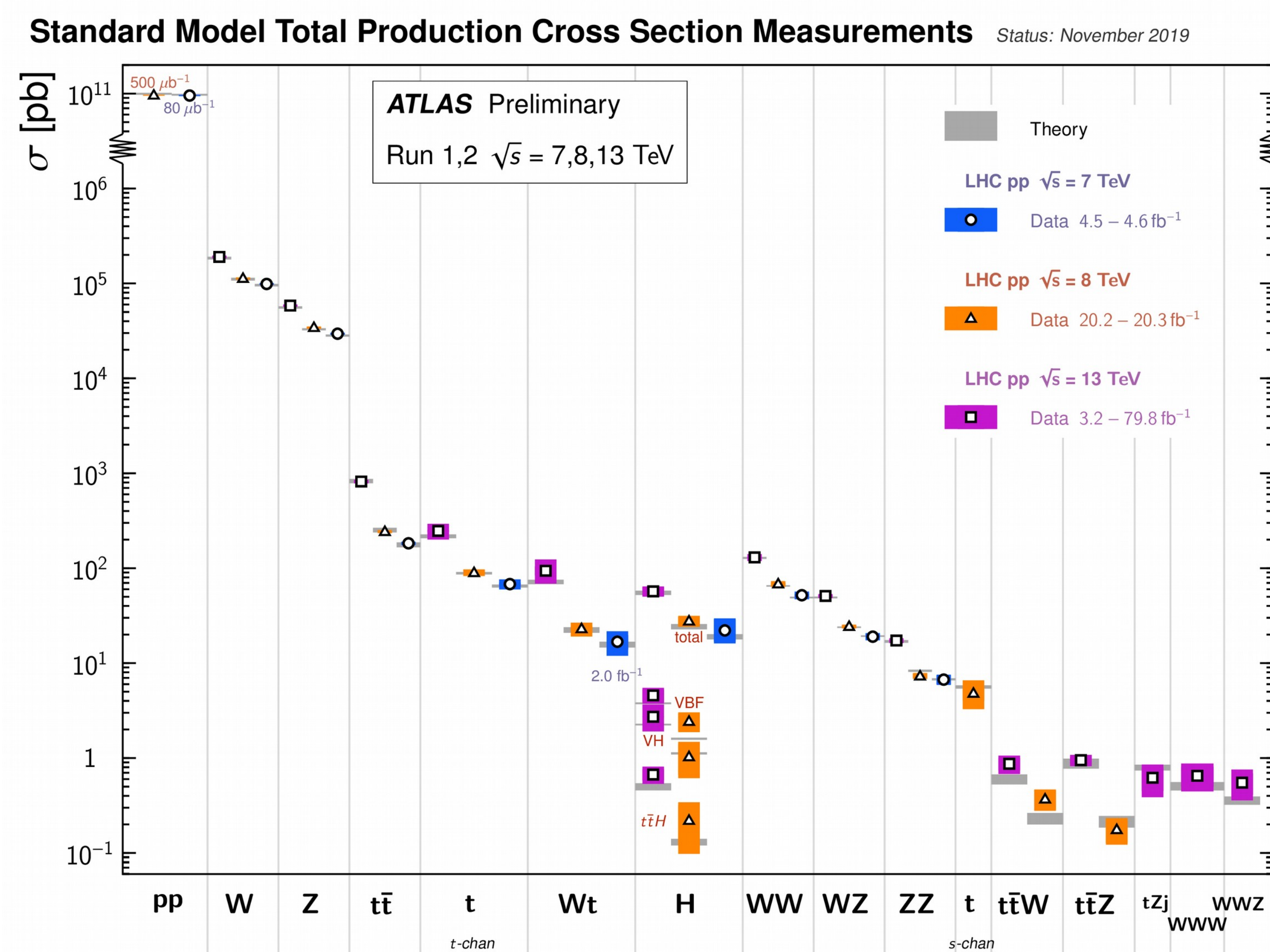
- Need to run complex algorithms during data-taking to filter processes we are really interested in….
  → *trigger*

Maybe unknown physics down there?



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

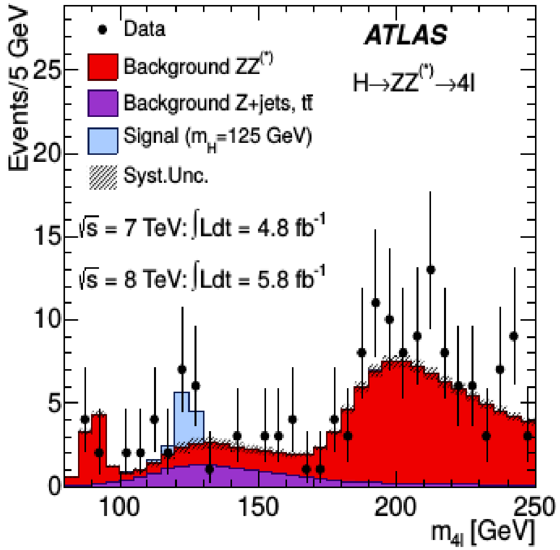
Precision measurements of the Standard Model



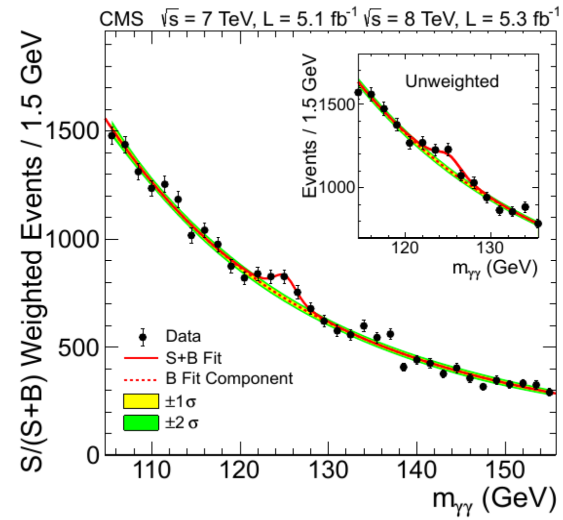
[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-024/fig_01.png]

Completing Standard Modell: Higgs boson

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

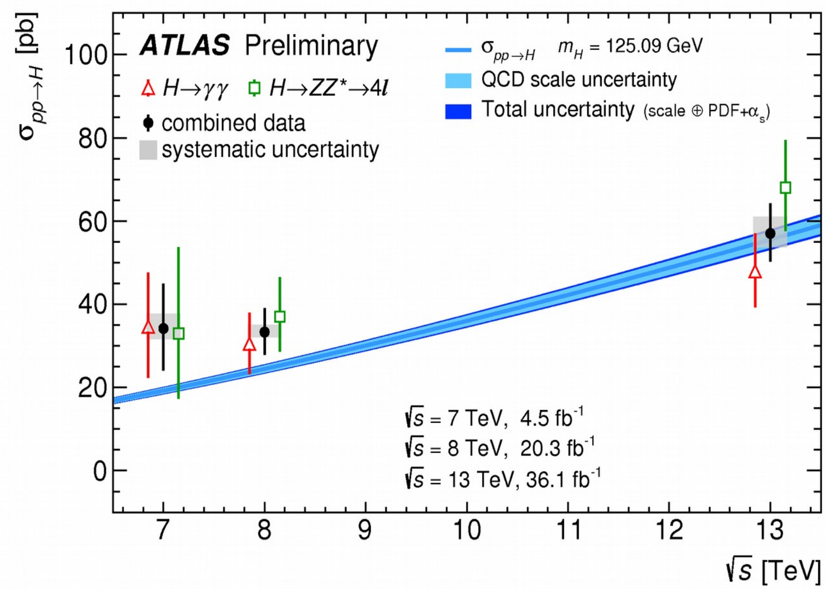


Discovery of Higgs boson in Run 1 data (4^{th} July 2012)



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

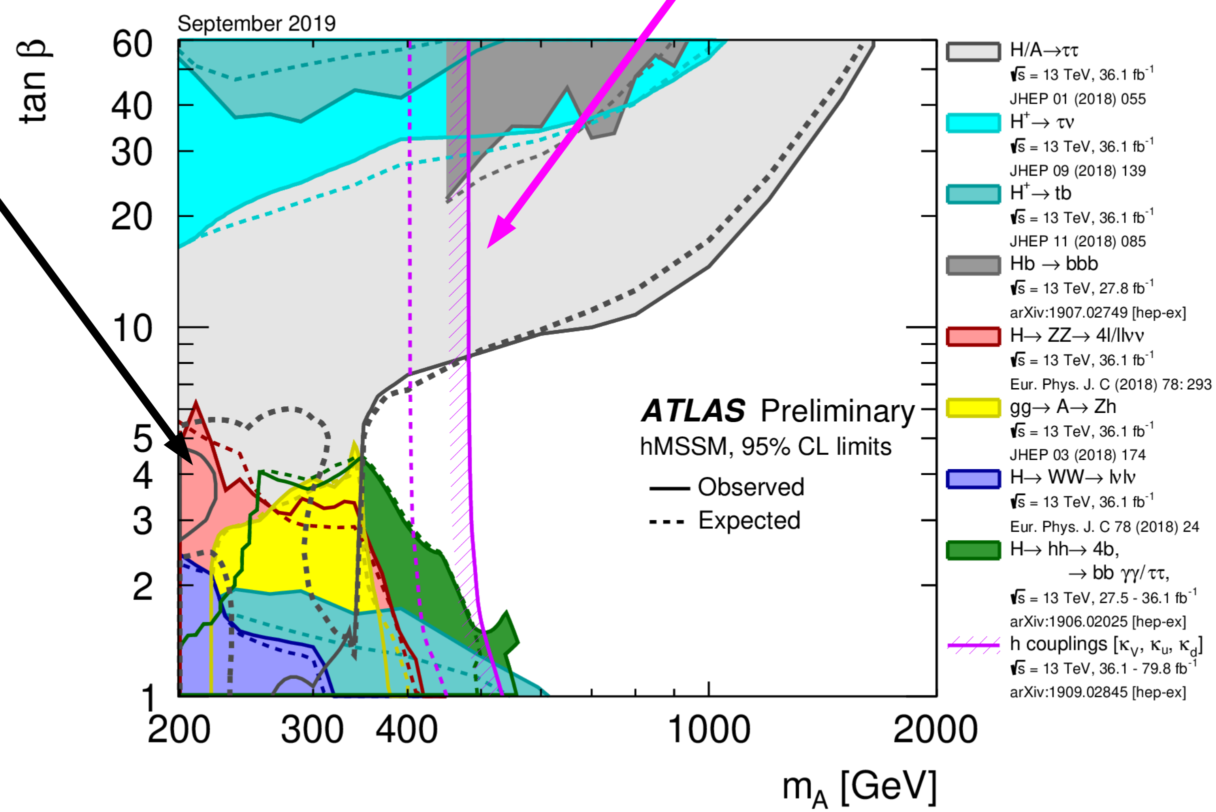
→ So far no deviations



More Higgs bosons?

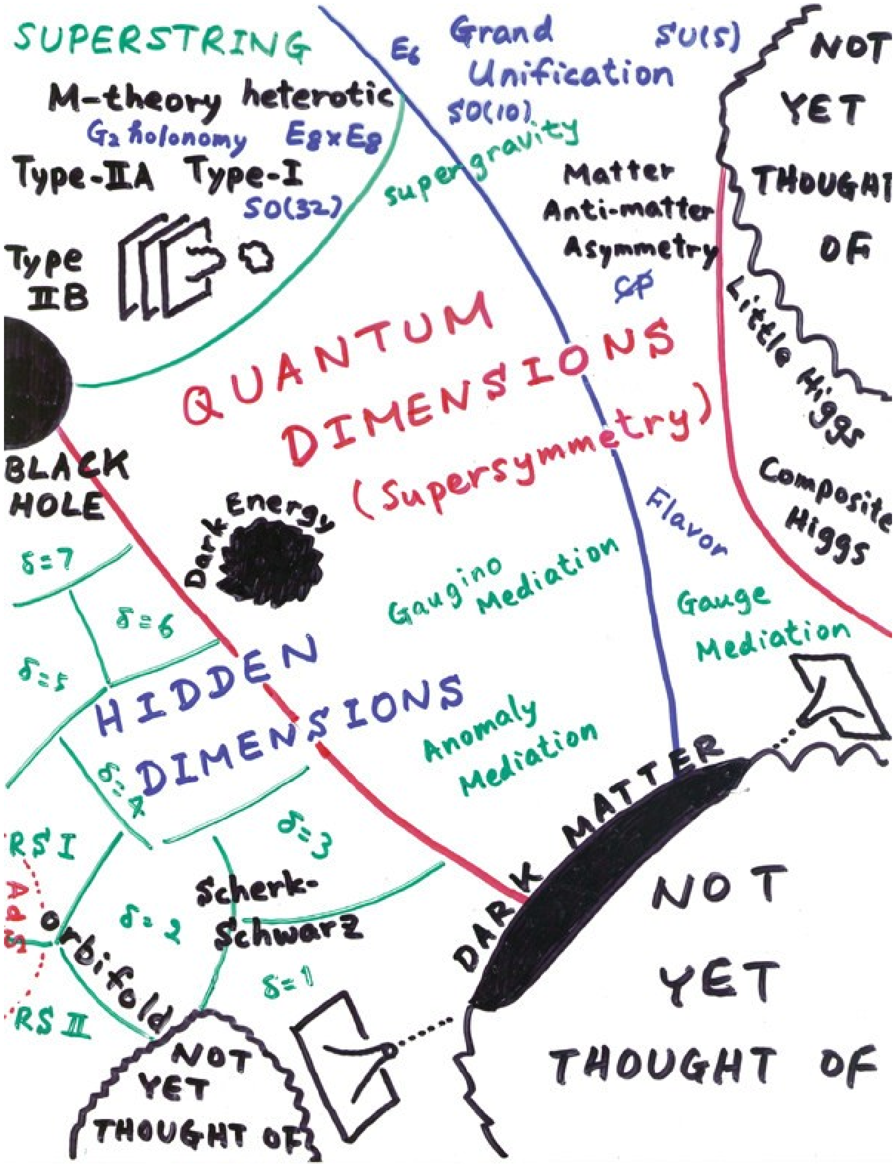
Many extensions of the Standard Model predict more than one Higgs boson:

- 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



[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-034/fig_01.png]

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]

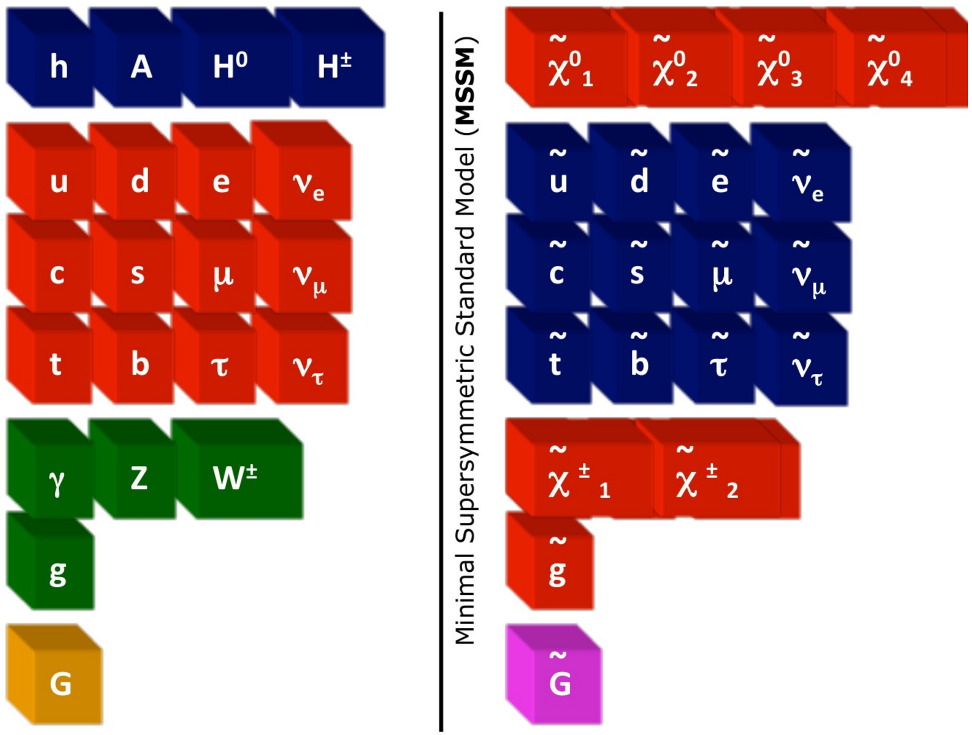
One solution: Supersymmetry (SUSY)

- 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

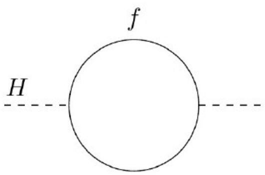
Supersymmetric partners of W, Z and Higgs bosons mix to charginos and neutralinos

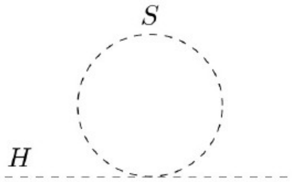


Motivations

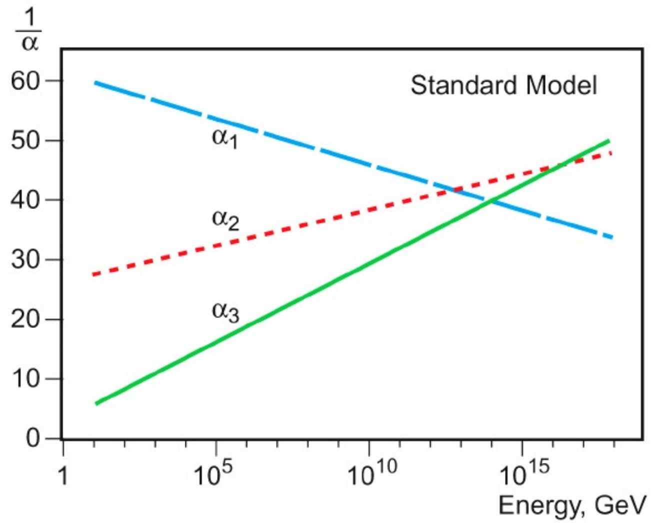
- Supersymmetry can offer a Dark Matter (DM) candidate
  …if R-Parity conserved

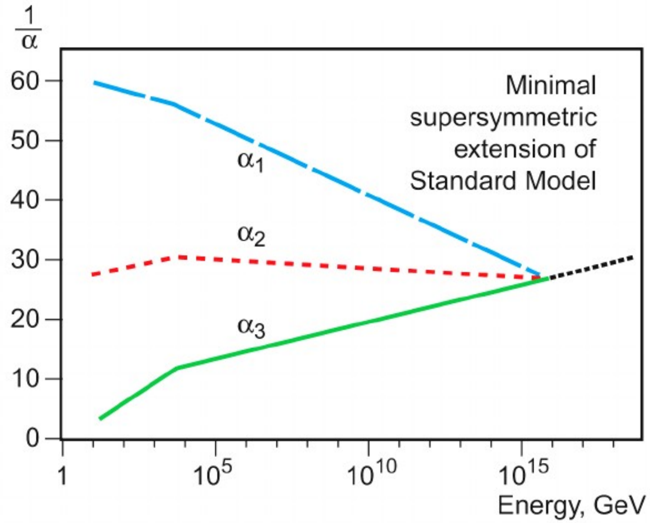
- Higgs mass might get stabilized





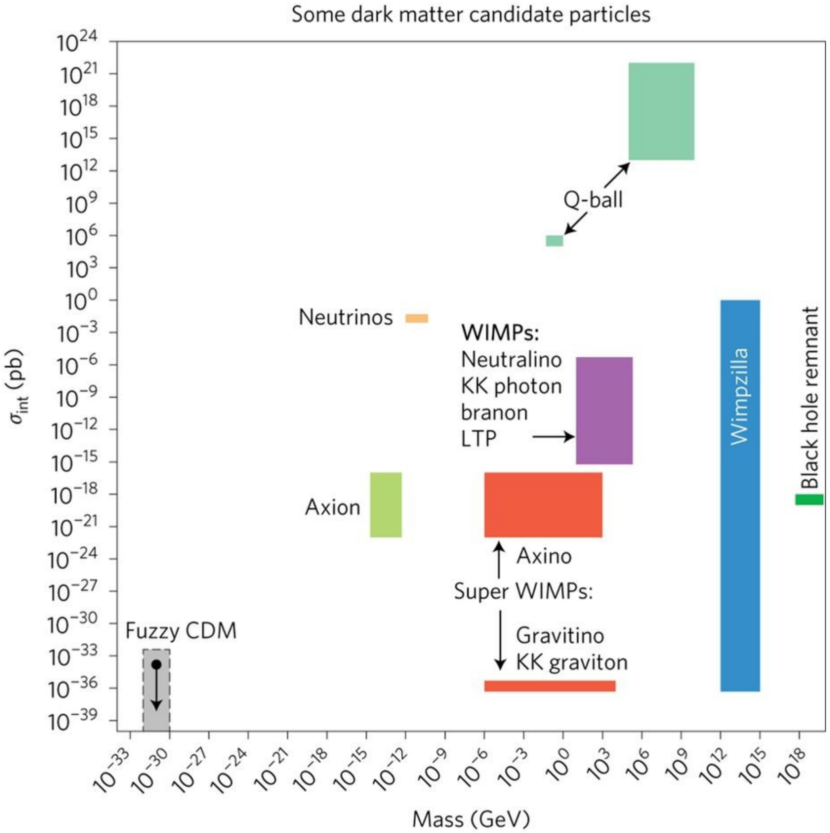
- Inverse of gauge couplings could be unified in the MSSM





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)]

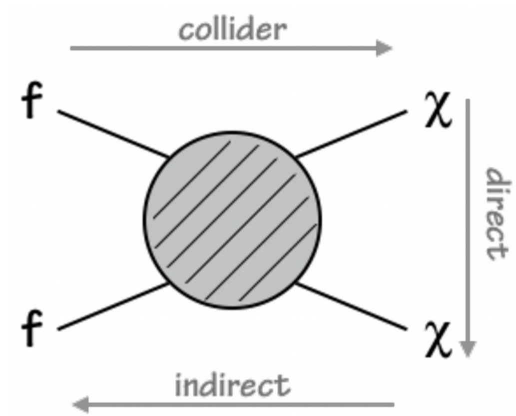


Many extensions beyond the SM provide DM candidates, not only SUSY.

→ Comprehensive search program by different experiments, and using different methods necessary.

LHC

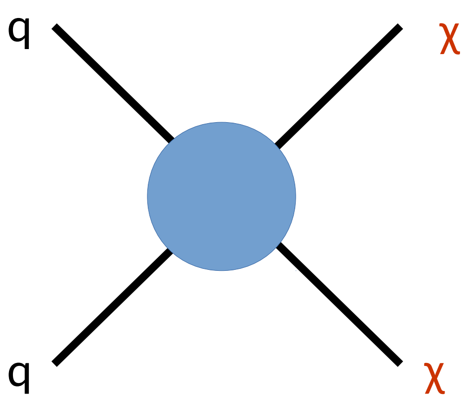
[ATLAS-CONF-2018-051]



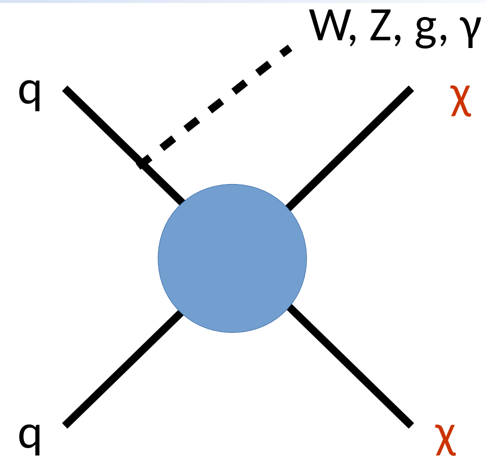
XENON1T, LUX, Panda-X, Picasso…

Fermi-LAT, MAGIC, Planck, H.E.S.S. …

Dark matter models at colliders



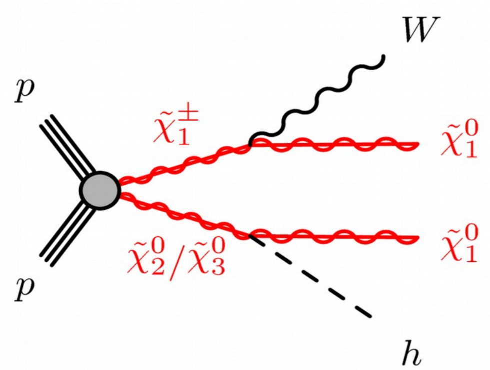
Dark matter particles invisible to LHC detectors → this signature cannot directly be detected



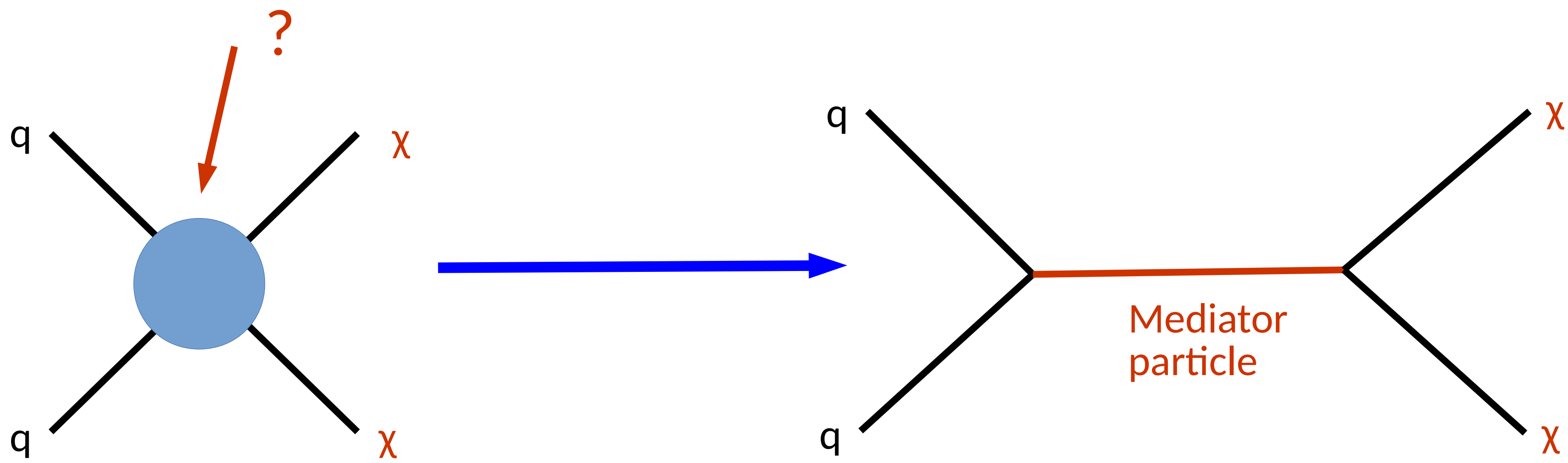
Initial state emission → recoils against dark matter particles

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)

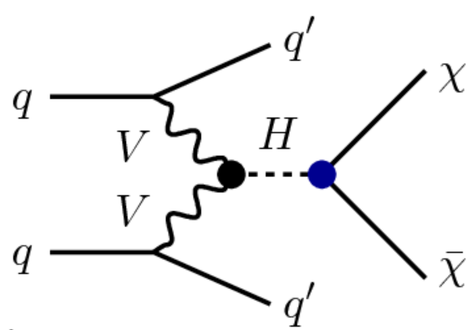


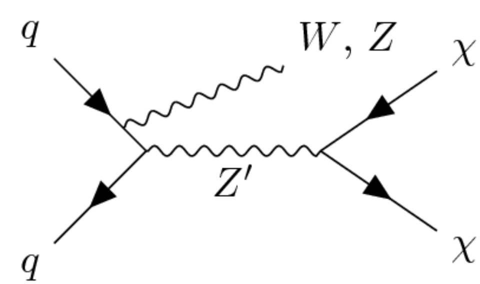
Dark matter models with mediators



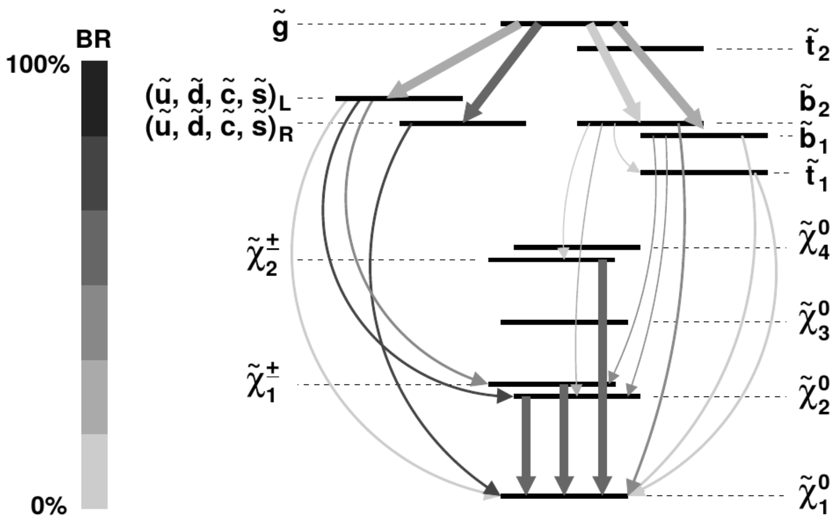
Mediator particle can be SM particle (Z or H)

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





Supersymmetric models



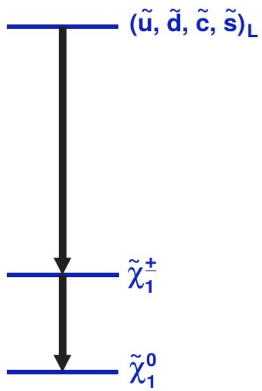
In case of MSSM 124 free parameters!

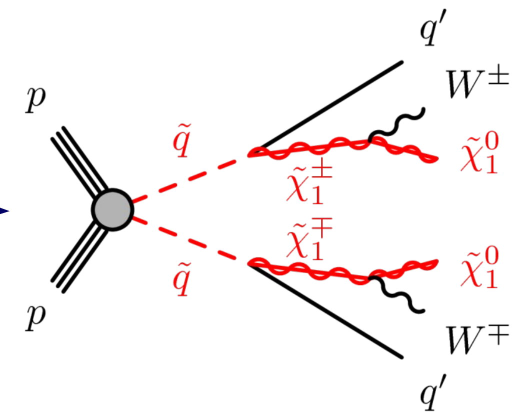
We cannot deal with that many free parameters!*

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

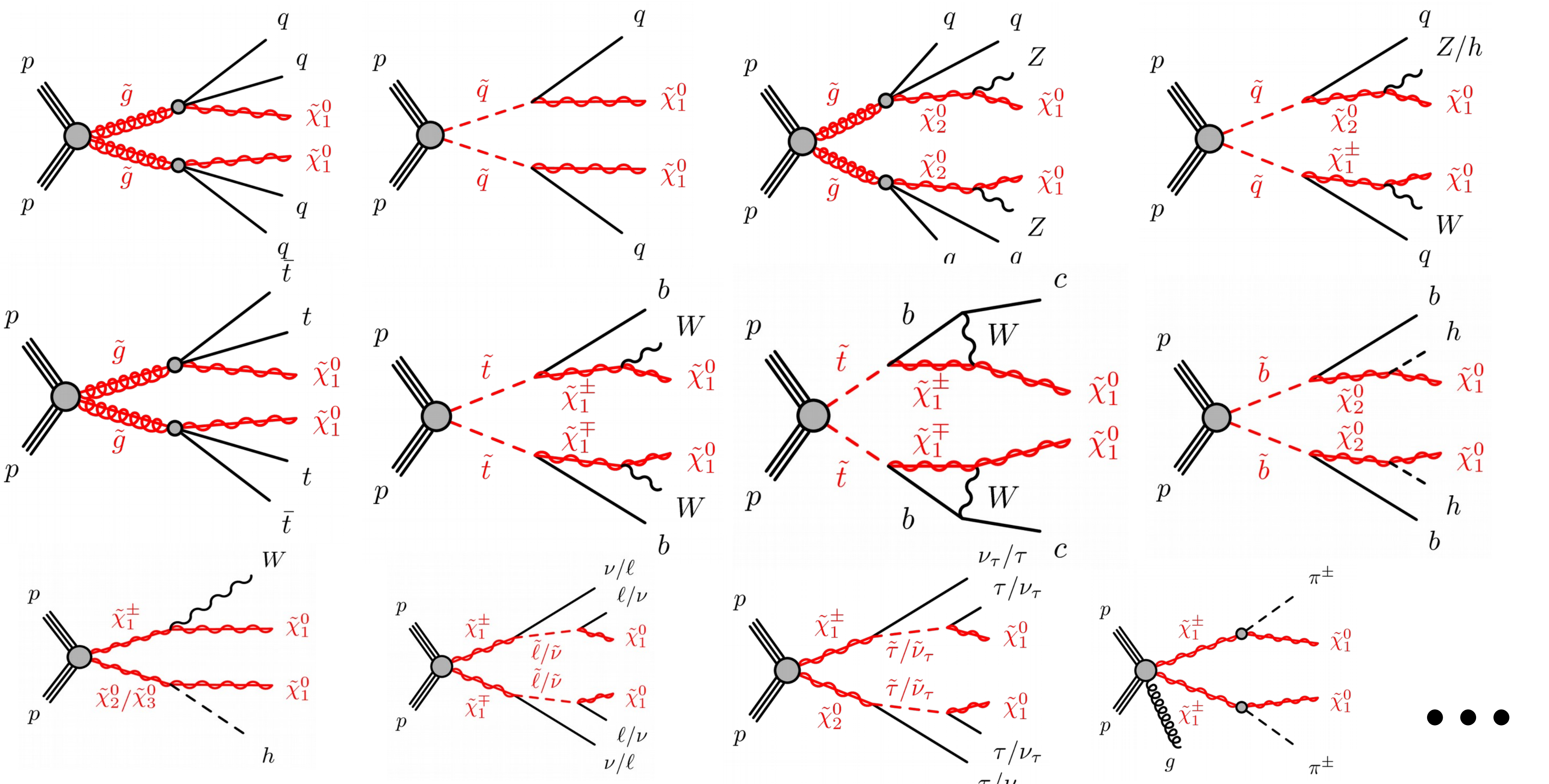
Simplified model

Usually only look at a specific decay chain





Many different simplified models

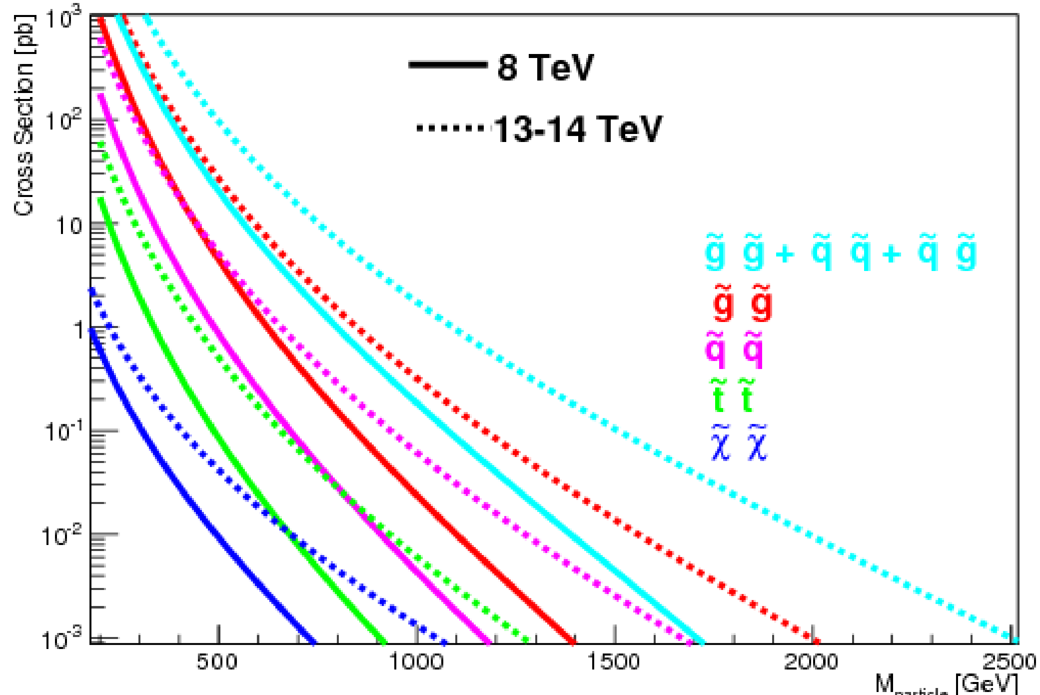


=> Very different experimental signatures to look for!*

* *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



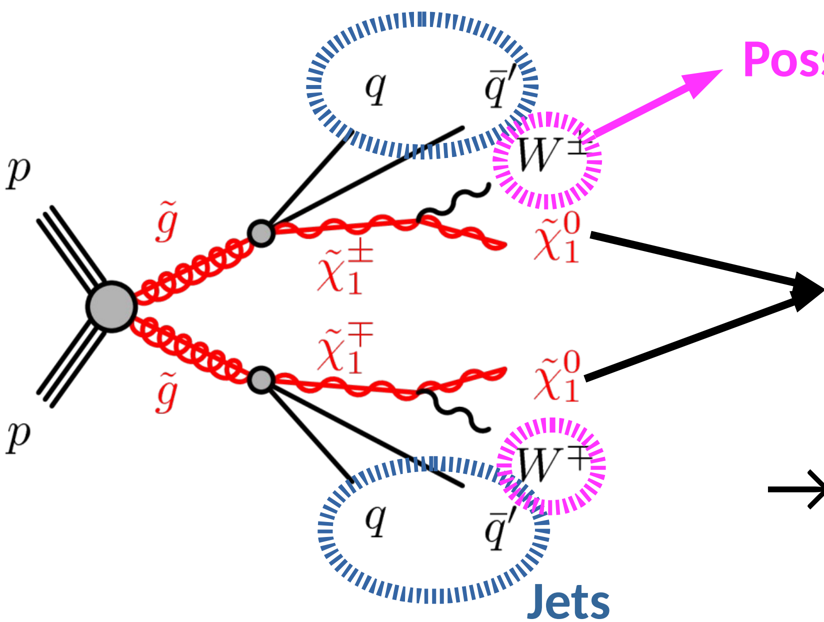
[http://inspirehep.net/record/1326406]

- 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*

- 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 signature

E. g. strong production:



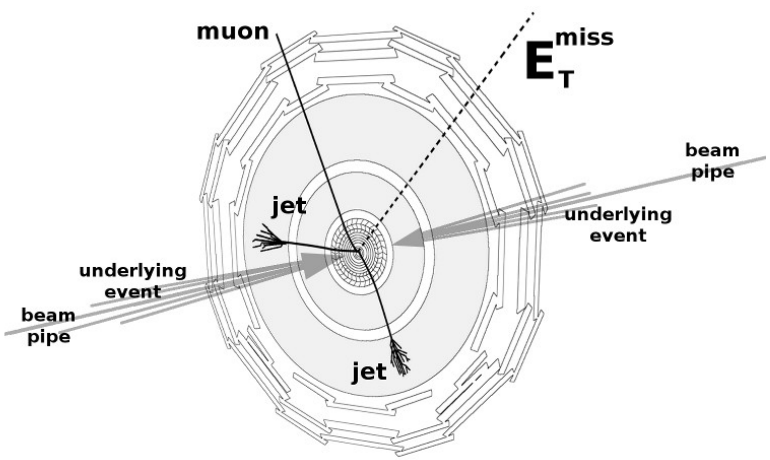
Lightest supersymmetric particle (LSP): stable in R-parity conserving theories → missing transverse momentum

→ Jets + leptons + E_T^{miss}

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]

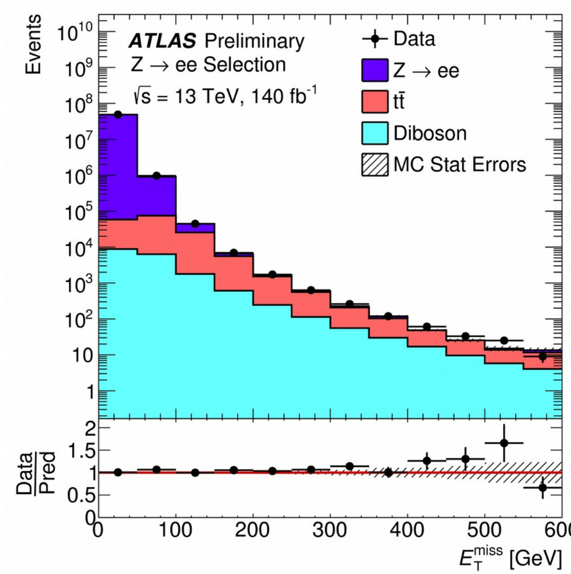


Calculated using the x- and y-components:

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

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

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

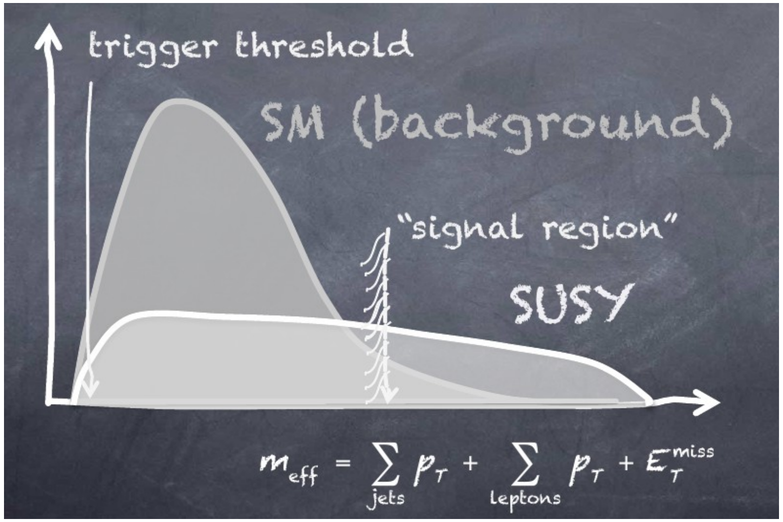


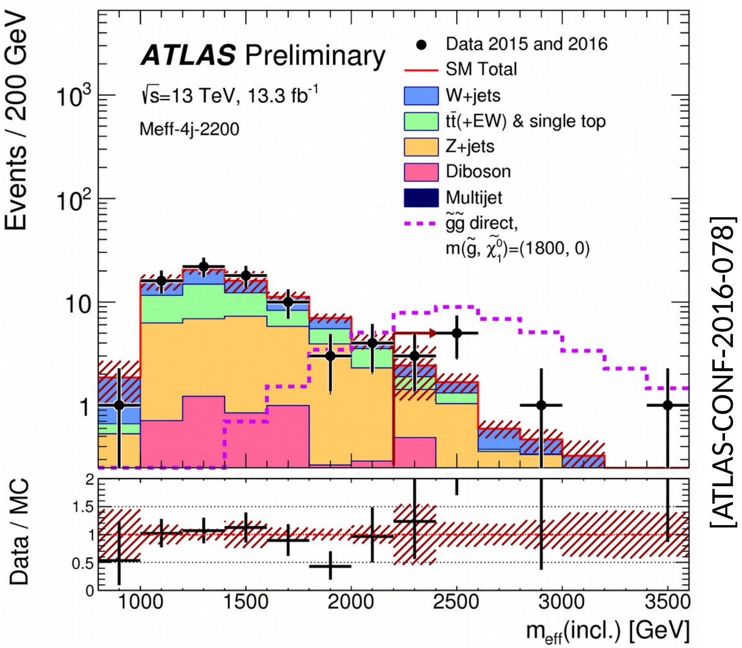
[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2019-03/]

Distinguish signal from background

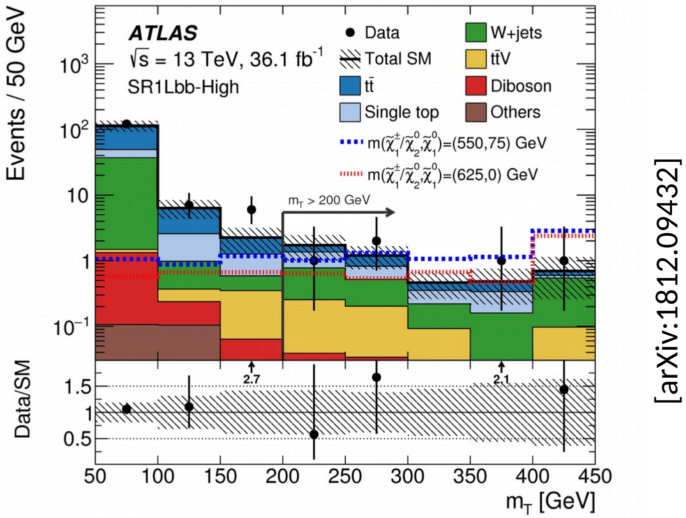
Use kinematic variables to discriminate signal from background.

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



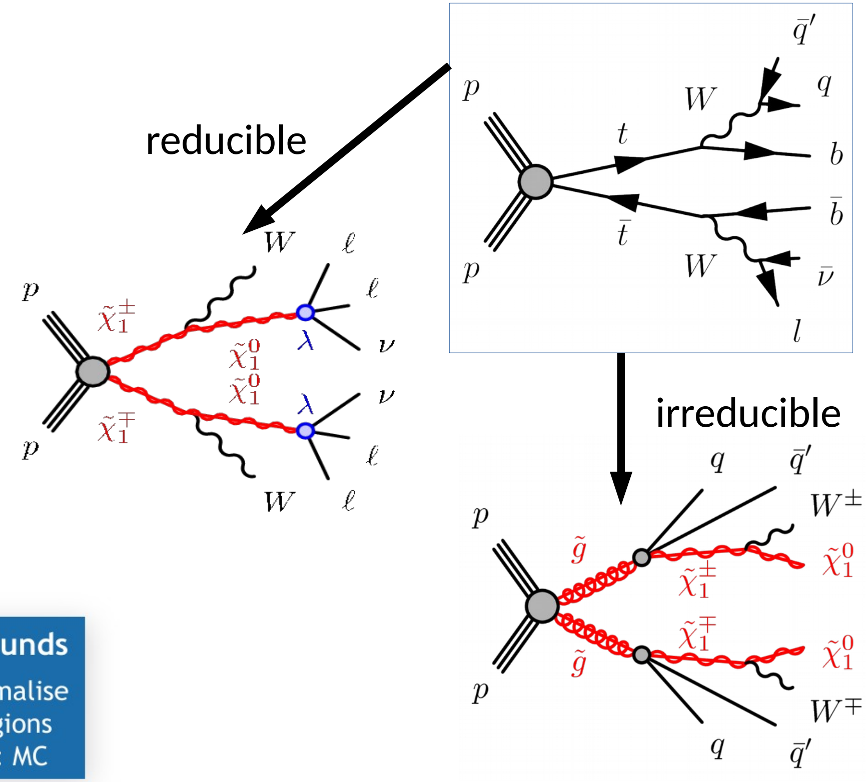


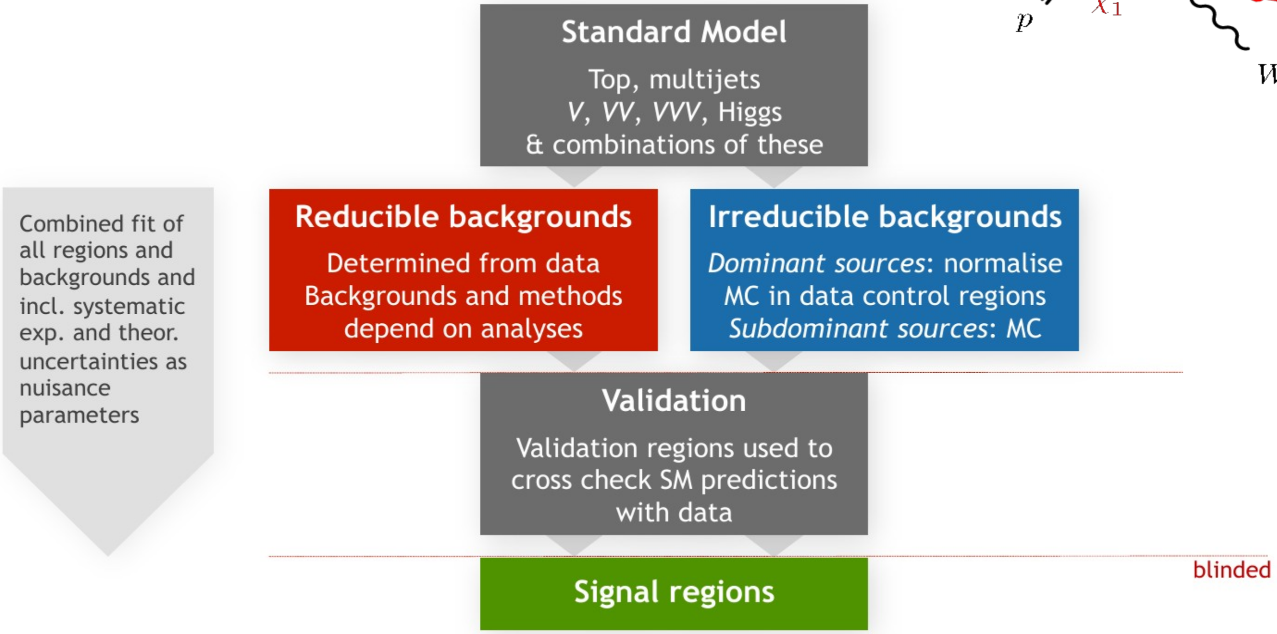
$$m_T = \sqrt{2\, p_T^l E_T^{miss} \left(1 - \cos\left(\left[\Delta\varphi\left(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss}\right)\right]\right)\right)}$$



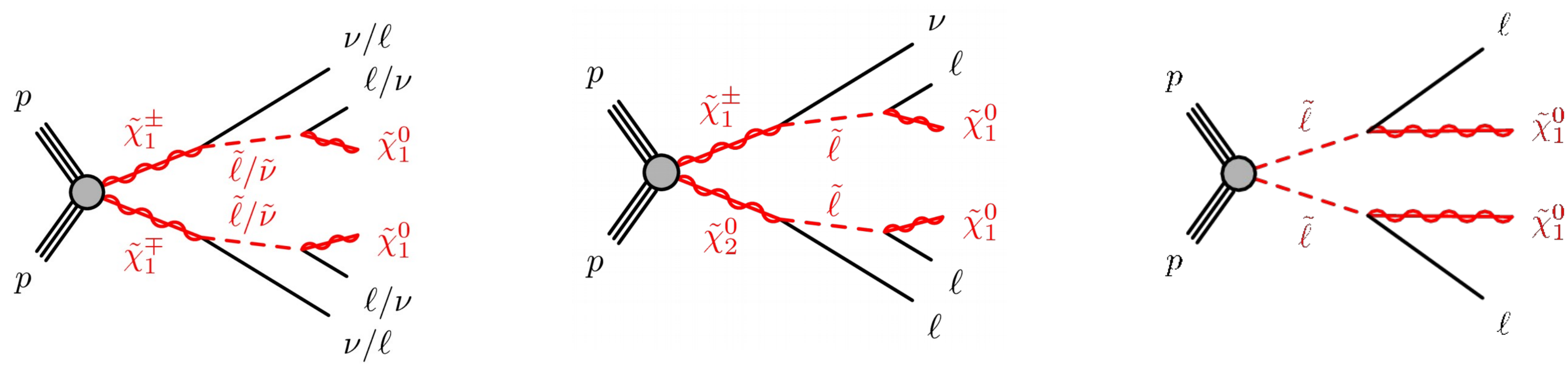
Essential to estimate the backgrounds

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





Focus on chargino/neutralino production - possible decay modes



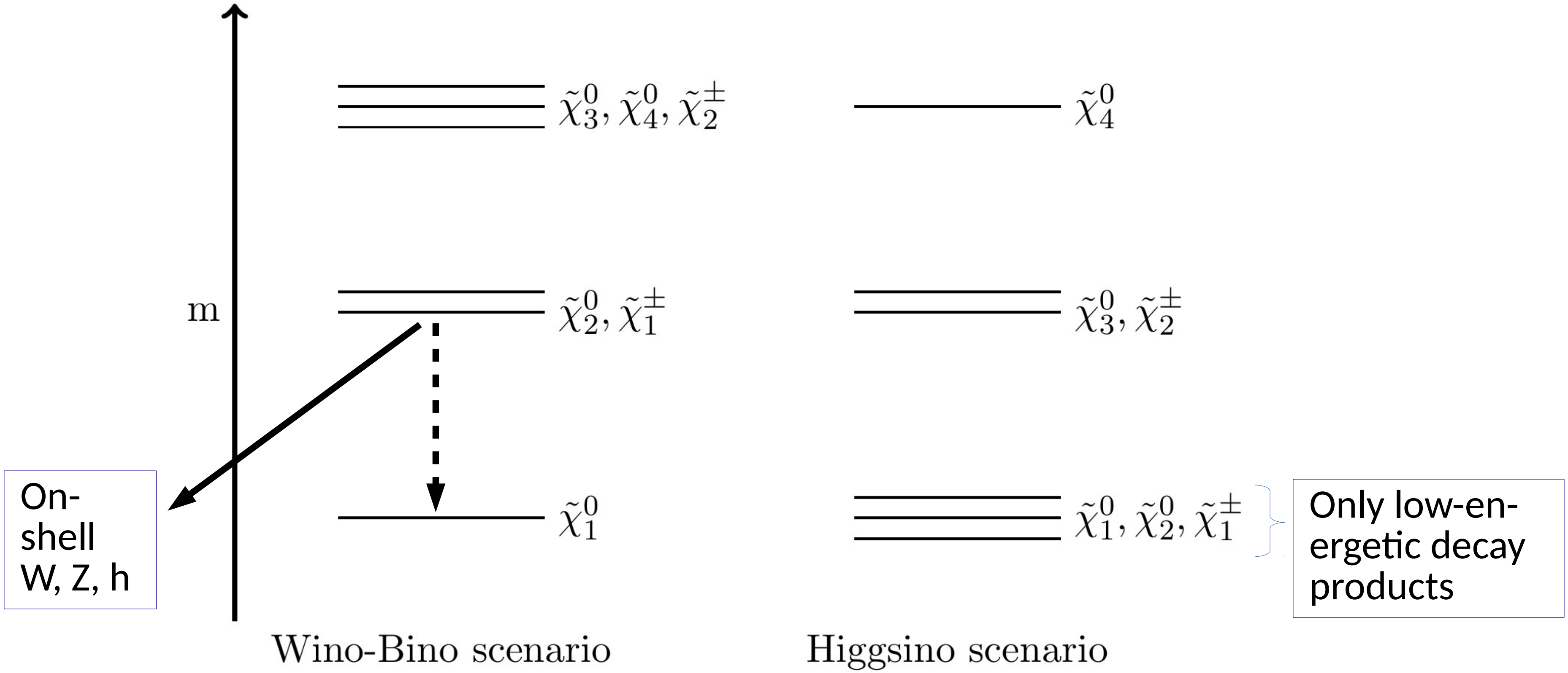
Decays of charginos/neutralinos/sleptons **often** studied in multi-lepton signatures + E_T^{miss}:

→ *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

Classification of searches for charginos and neutralinos

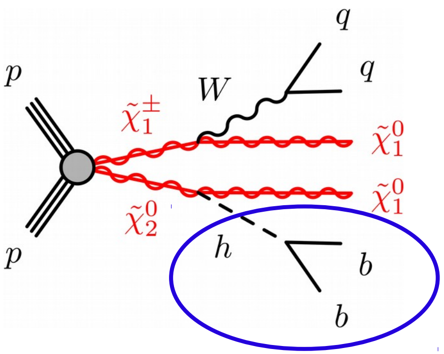


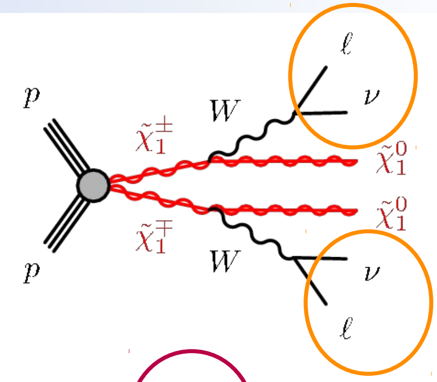
- Depending on parameters in the SUSY model, mass difference between LSP and lightest charginos/next-to-lightest neutralinos sizeable (so that on-shell emission of W, Z, h possible), or very compressed mass spectrum.
- Depends on the fraction of Wino, Bino, Higgsino component in LSP and lightest chargino/next-to-lightest neutralino.

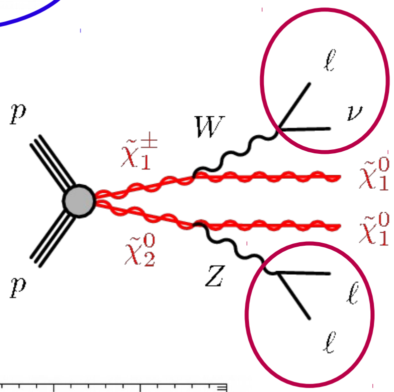
Searches for Wino/Bino scenarios

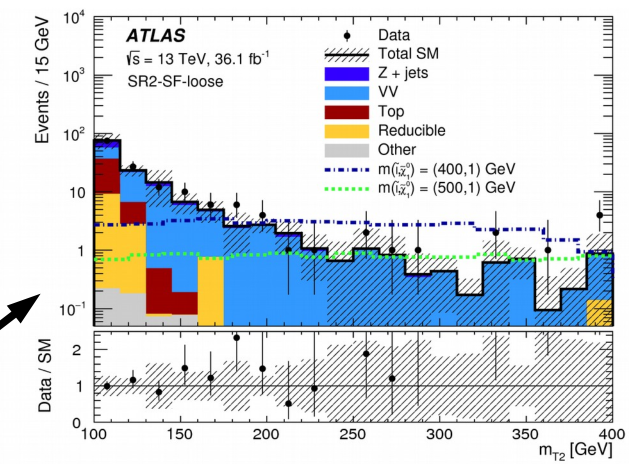
- Pair-production of charginos or next-to-lightest neutralino + chargino.
- Emission of on-shell (or not too much off-shell) W, Z and Higgs bosons.
- Can use decay products of these to search for these signatures.
- In case of emission of a Higgs boson, can exploit specific characteristics of Higgs boson decays, e.g. decays into $b\bar{b}$.
- In case of emission of WW or WZ, relatively clean signature of two or three leptons → dedicated searches for this in multi-lepton channels.

  e.g. search for 2 or 3 leptons + E_T^{miss}









[Eur. Phys. J. C 78 (2018) 995]

Searches for neutralinos/charginos with decays to a Higgs

[Phys. Rev. D 100 (2019) 012006]

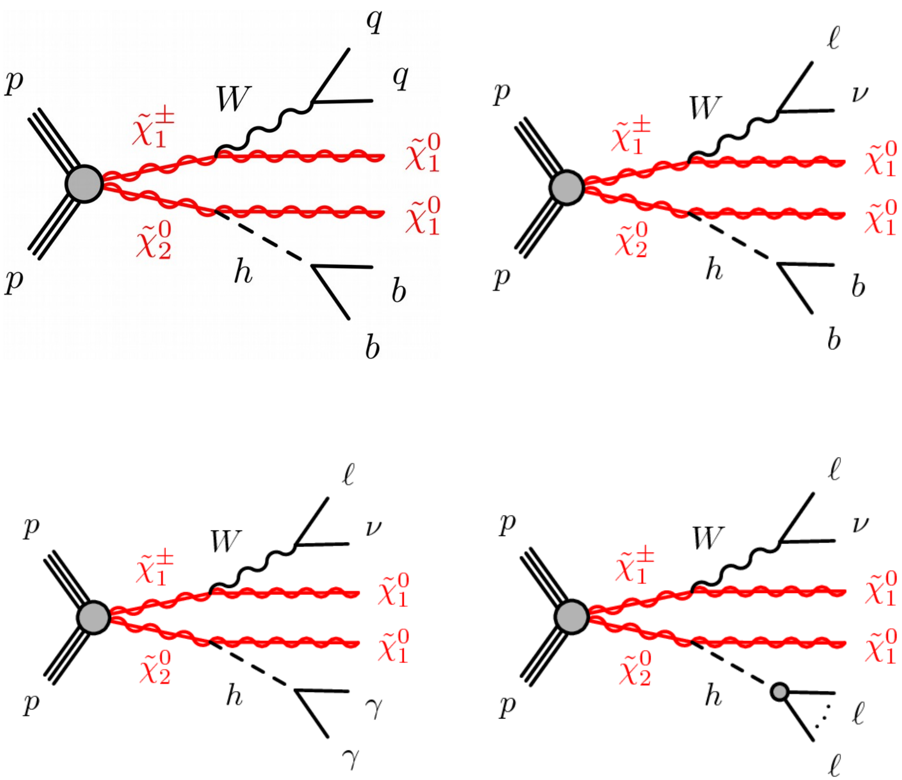
Often a Higgs boson is created in decays of neutralinos.

Discovering corresponding signatures would explicitly link Higgs bosons with supersymmetric particles.
Necessary for SUSY solving hierarchy problem!

Spezialized searches: Pair-production of charginos and neutralinos; chargino decays to W and LSP, neutralino to Higgs and LSP.

Different signatures depending on decay of Higgs:
- Hadronic (with $b\bar{b}$),
- 1 e/μ + $b\bar{b}$,
- two same-sign leptons,
- 3 leptons,
- 1 e/μ + γγ

→ *different searches*



Fully hadronic decays – 36.1 fb^{-1}

First time targeting this decay at LHC!

[Phys. Rev. D 100 (2019) 012006]

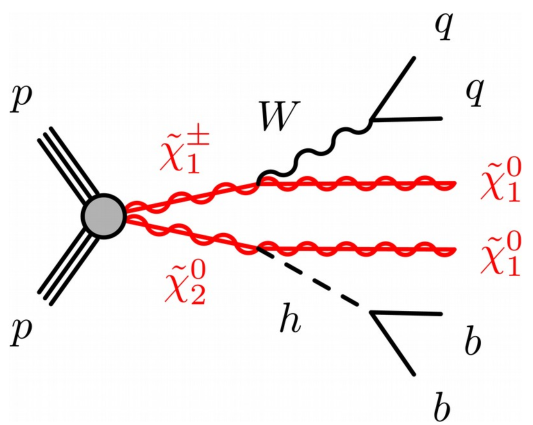
Fully hadronic signatures are very difficult to cover in searches for electroweak SUSY particles due to low object multiplicity.

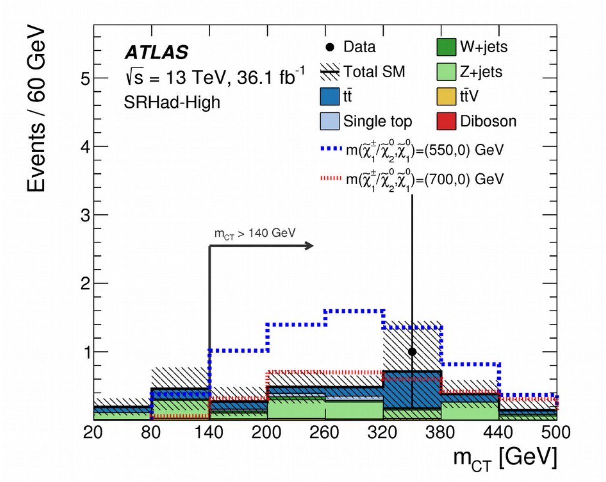
→ *Need additional handle for suppression of hadronic backgrounds.*

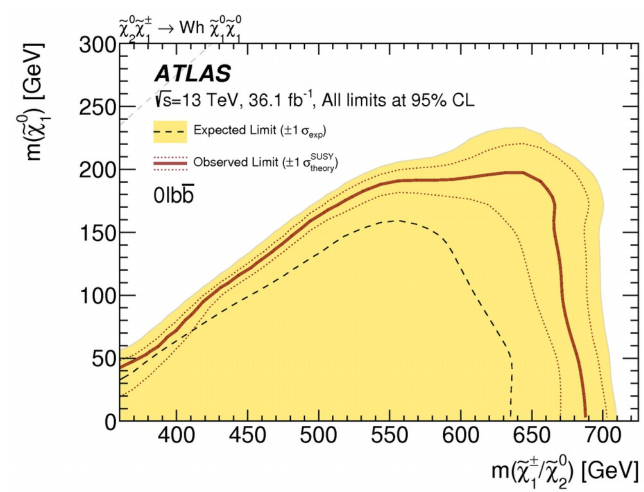
Achieved in this case by selecting events with two b-tagged jets + 2-3 other jets.

Mass of two b-tagged jet system needs to be consistent with Higgs mass; mass of 2 other jets consistent with W mass.
+ requirements on E_T^{miss}, and contransverse mass: $m_{CT} = \sqrt{2p_T^{b_1} p_T^{b_2} (1 + \cos \Delta\phi_{bb})}$,

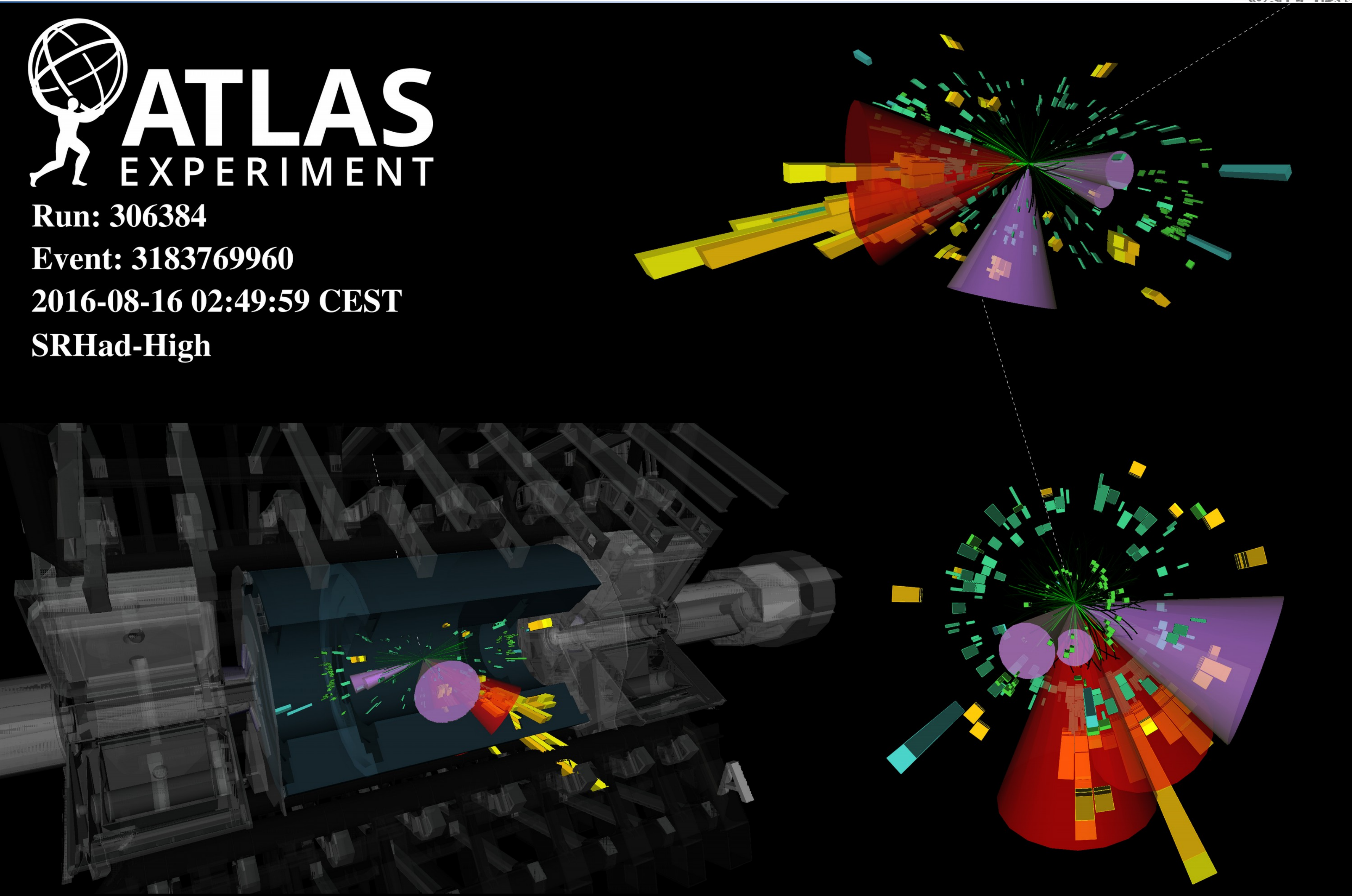
Useful for $t\bar{t}$ suppression.







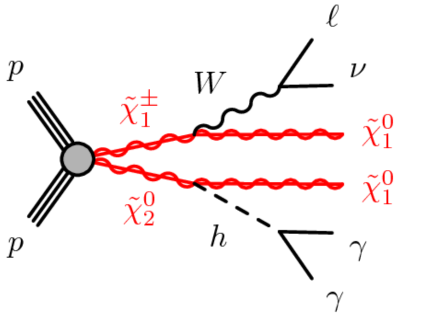
[Phys. Rev. D 100 (2019) 012006]



1 lepton + 2 photons – 36.1 fb^{-1}

[Phys. Rev. D 100 (2019) 012006]

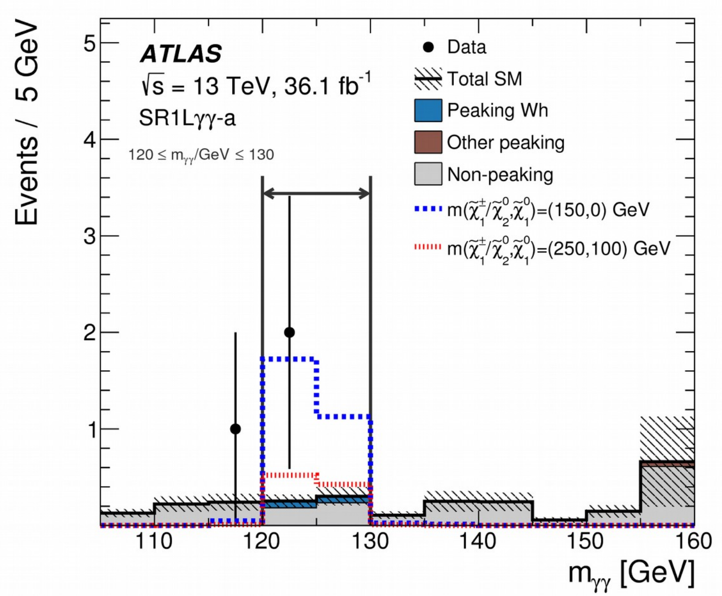
$H \rightarrow \gamma\gamma + W \rightarrow l\nu + E_T^{miss}$
very clean signature (although small branching ratio).

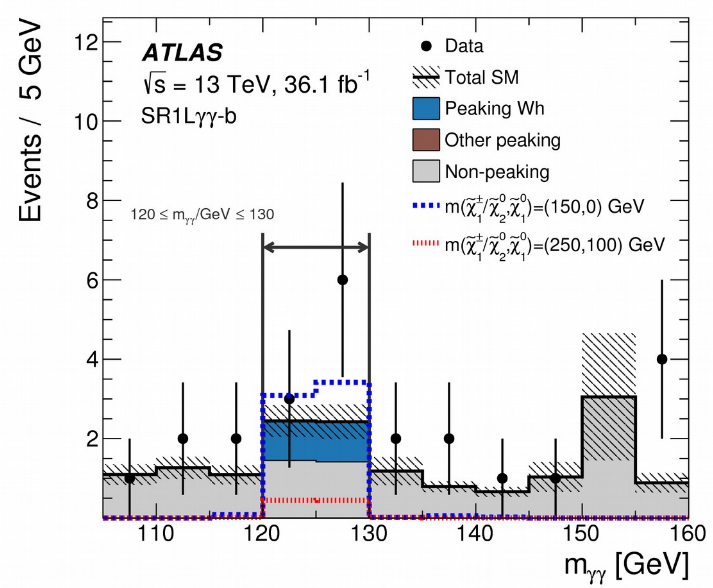


Select $m_{\gamma\gamma}$ consistent with Higgs mass + multiple criteria on transverse mass variables to reject backgrounds containing W bosons.

- Two background categories: non-peaking and peaking backgrounds.
- Peaking backgrounds (Wh) from MC.
- Non-peaking backgrounds from side-band fit.

Small excesses in both SRs of p_0 = 0.027 and 0.087





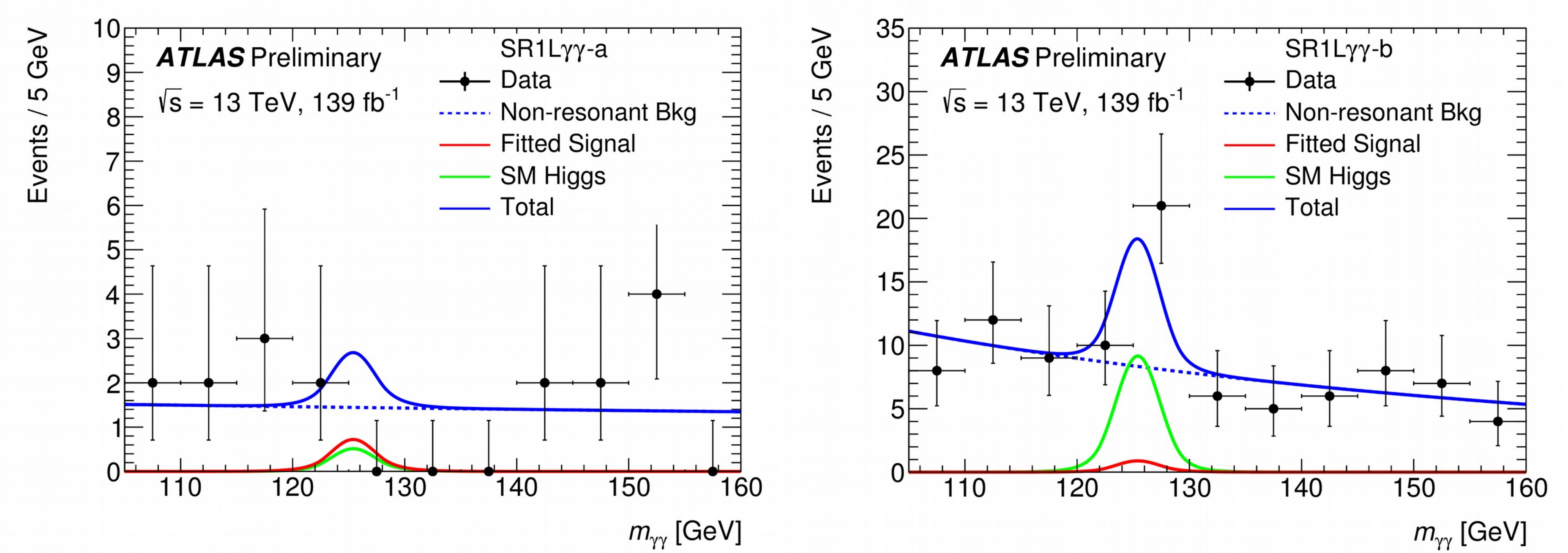
Improved 1 lepton + 2 photons analysis for 139 fb^{-1}

[ATLAS-CONF-2019-019]

- Re-look at signal regions with excesses in 139 fb^{-1}.

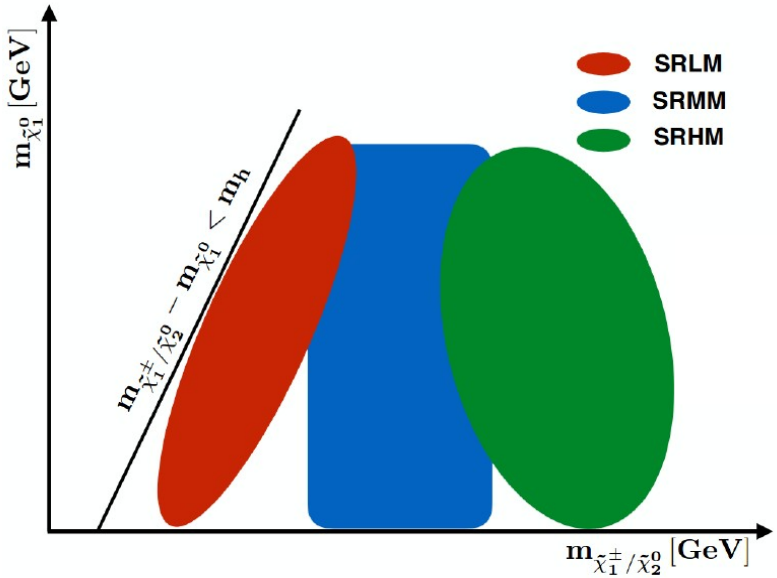
- Improved background and signal model:
  - Peaking background and signal described by double-sided Crystal Ball functions
  - Non-peaking backgrounds (side-band) by fitting $f_{k;d}(x; b, \{a_k\}) = (1 - x^d)^b x^{\sum_{j=0}^{k} a_j \log(x)^j}$

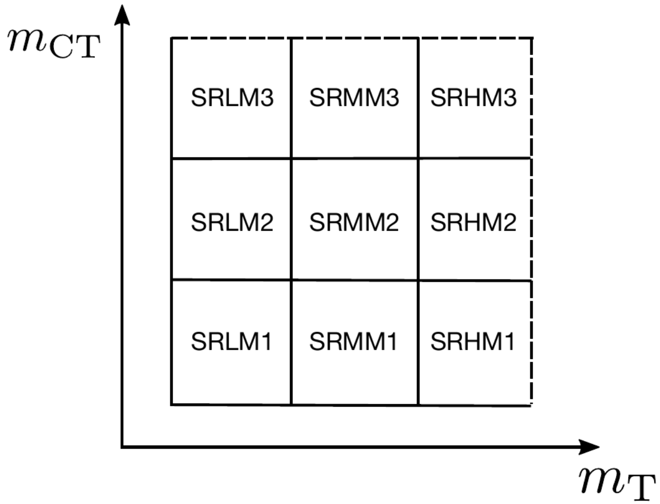
- Data consistent with background estimates.



1 lepton + 2 b-jets (139 fb^{-1})

[arXiv:1909.09226]



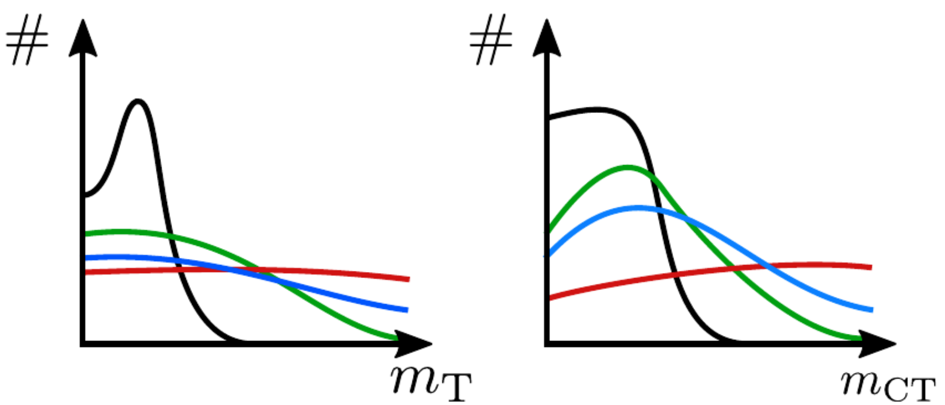


Define three regions in the phase space with different kinematics due to different mass differences between charginos/next-to-lightest neutralino and LSP

→ *low mass, medium mass, high mass*

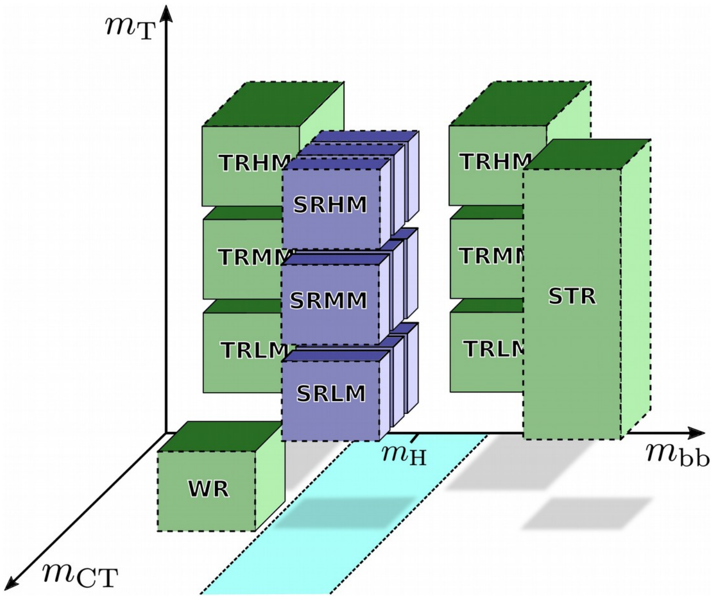
Particular powerful variables to select signal and suppress backgrounds:

- m_{bb}: selects peaking signal
- m_T: suppression of backgrounds with W bosons
- m_{CT}: Suppression of $t\bar{t}$ backgrounds
- E_T^{miss}: due to LSP escaping



1 lepton + 2 b-jets (139 fb^{-1})

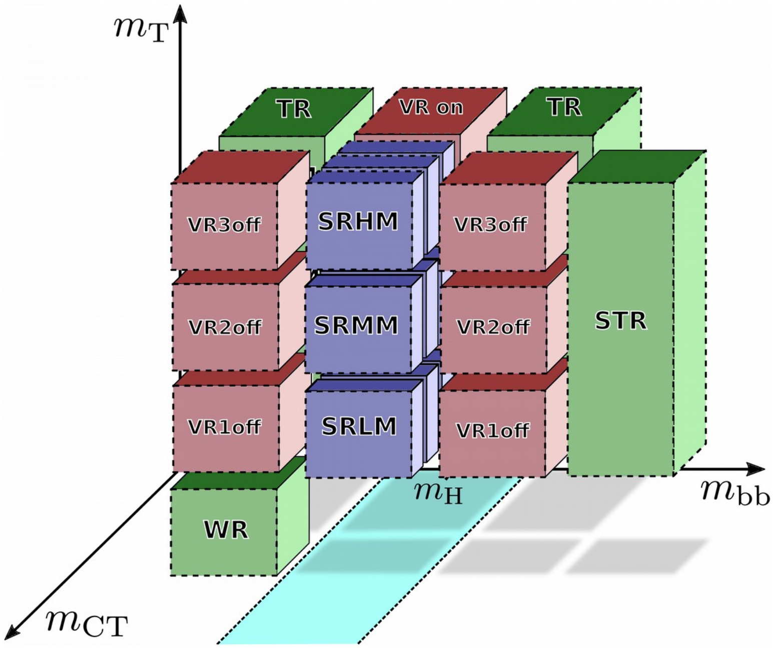
[arXiv:1909.09226]



Dominant backgrounds $t\bar{t}$, single top, W+jets

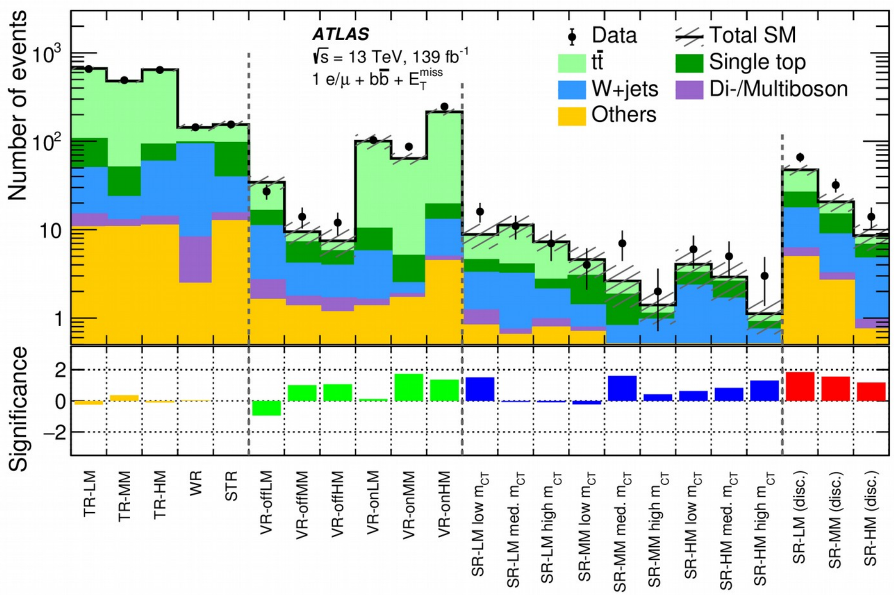
- → *irreducible, estimated via control regions*
- → *low m_T for W+jets*
- → *m_{bb} sidebands and low m_{CT} for $t\bar{t}$*
- → *high m_{CT} and m_{bb} sideband for single top*

Validation regions defined to check extrapolation directions.



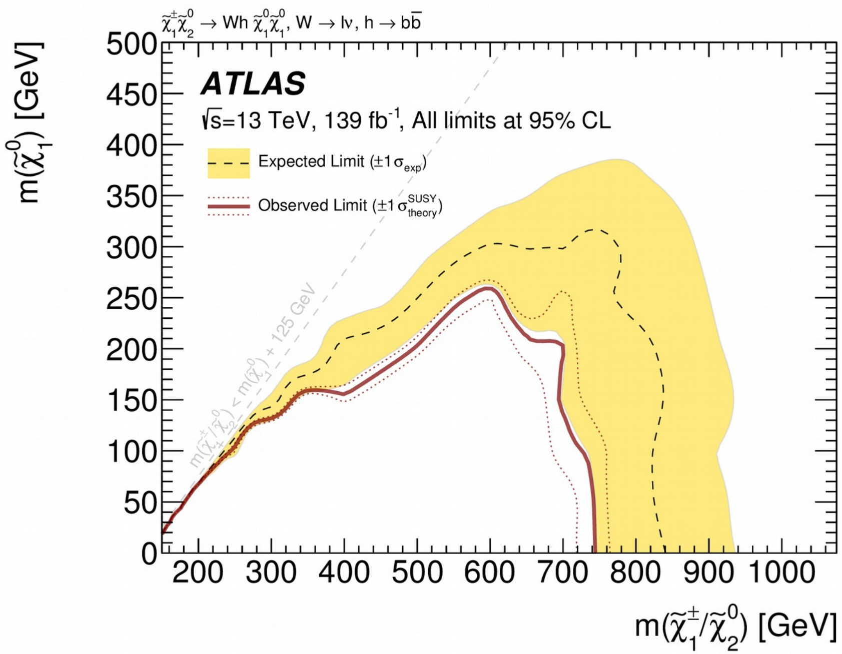
1 lepton + 2 b-jets (139 fb^{-1})

[arXiv:1909.09226]



Slight overshoot in data, but consistent with background expectations.

Powerful exclusion limits due to multi-bin fit.



Multi-lepton

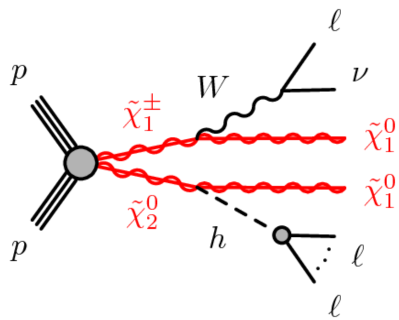
[Phys. Rev. D 100 (2019) 012006]

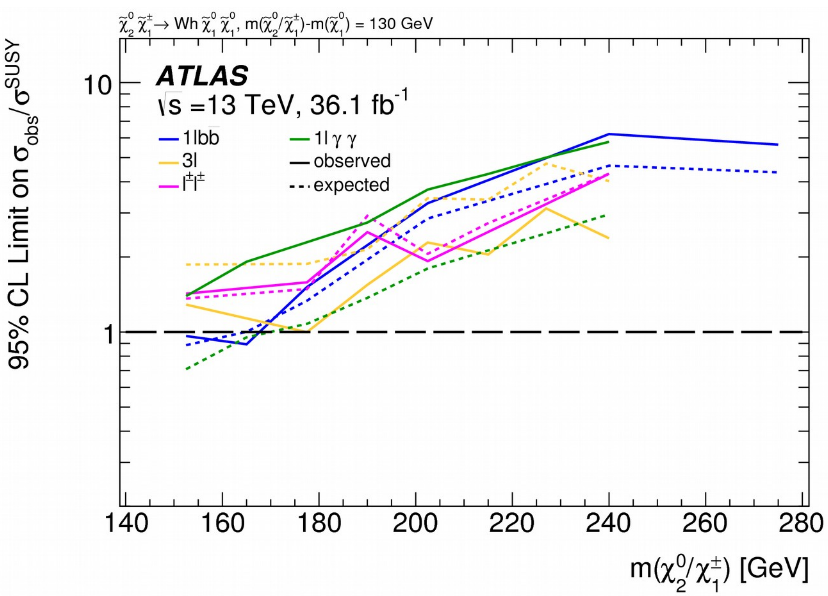
Can also select decay modes of h → WW or → ZZ
→ *leptonic signatures*

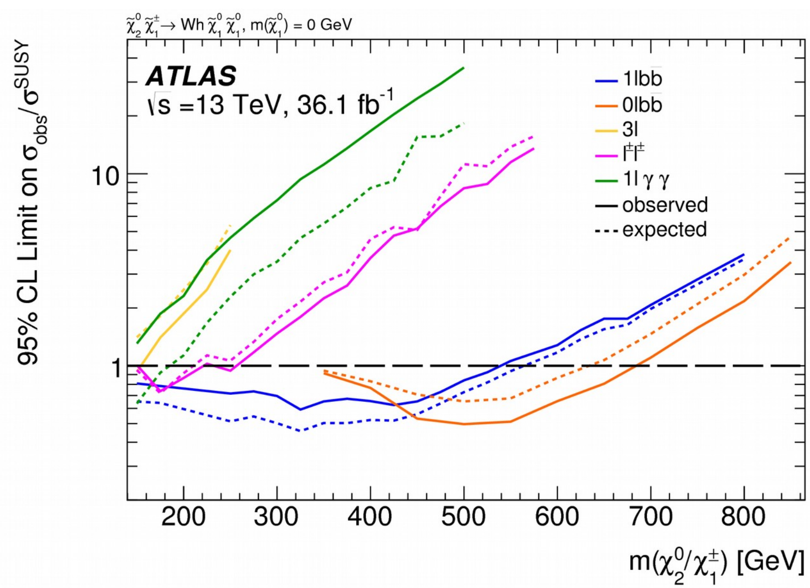
Selection of two leptons (e or μ) of the same charge
→ *Good background suppression (i.e. $t\bar{t}$), but precise estimate of fake background needed*

Or: Selection of events with three leptons

Channels more sensitive towards smaller mass differences.





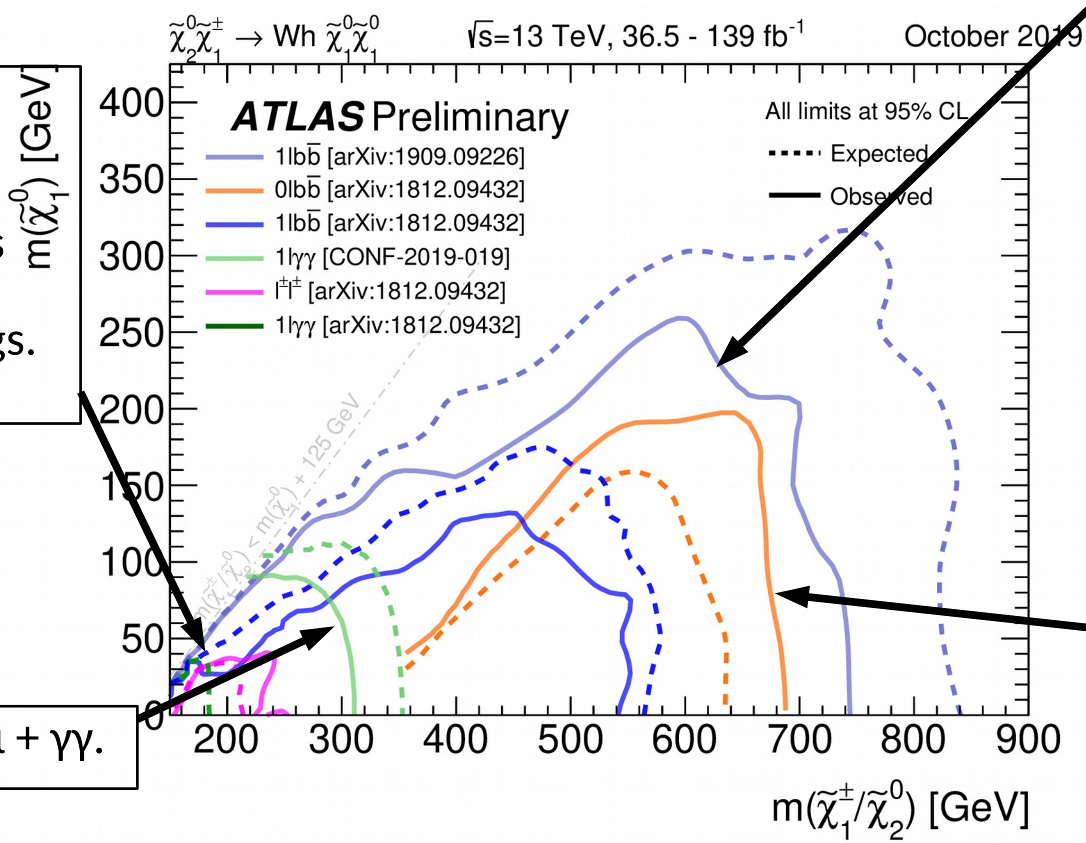


Searches for neutralinos with decays to a Higgs

[ATL-PHYS-PUB-2019-044]

Nice complementarity of the different searches:

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



1 e/μ + γγ.

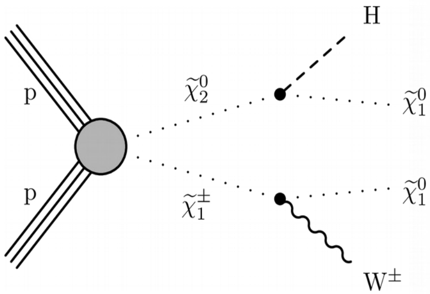
1 e/μ + $b\bar{b}$ covers bulk of the plane. Strong limit since small uncertainties.

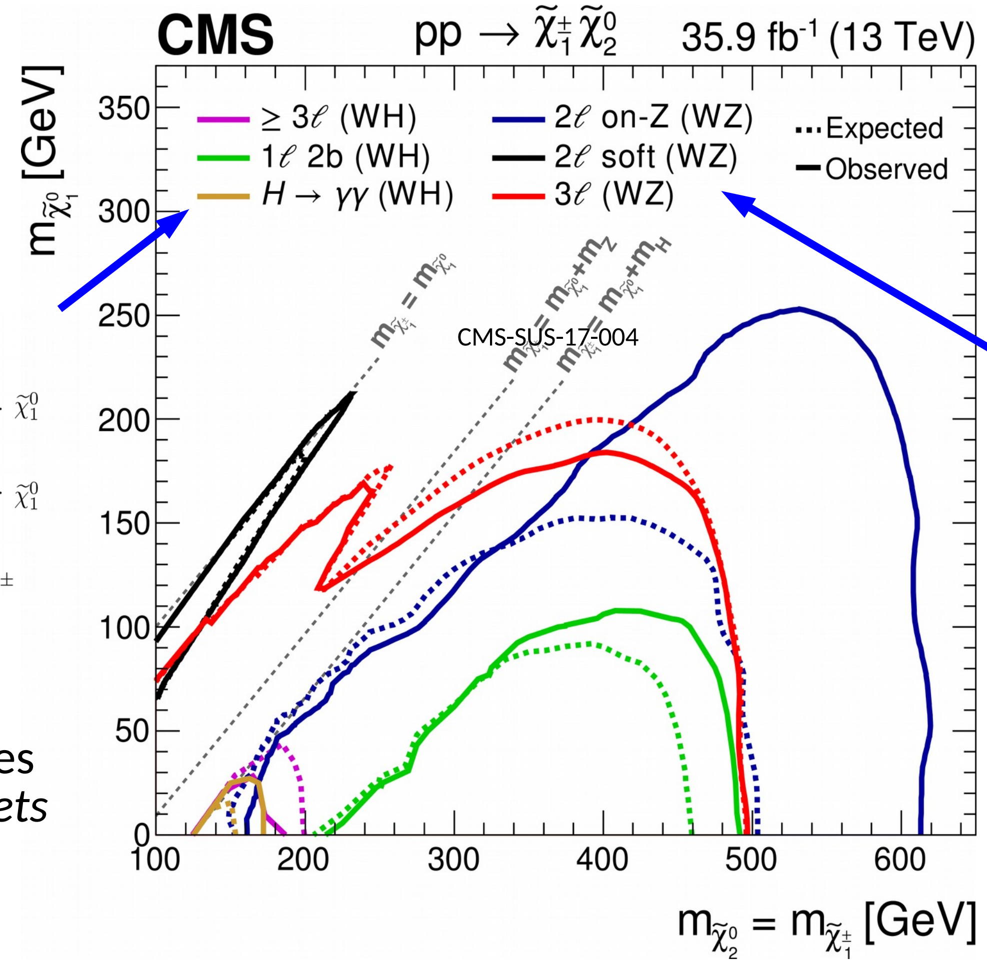
Hadronic analysis covers high neutralino/ chargino masses.

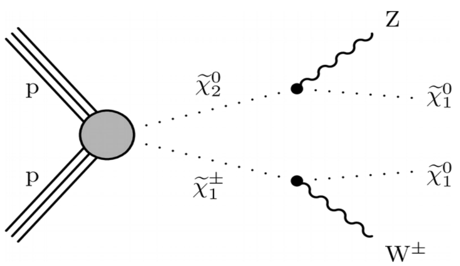
Chargino/neutralino production with different decays

[JHEP 03 (2018) 160]

CMS combined different EWK searches







Different decay modes of H - different final states

→ *1 lepton + 2 b-jets*

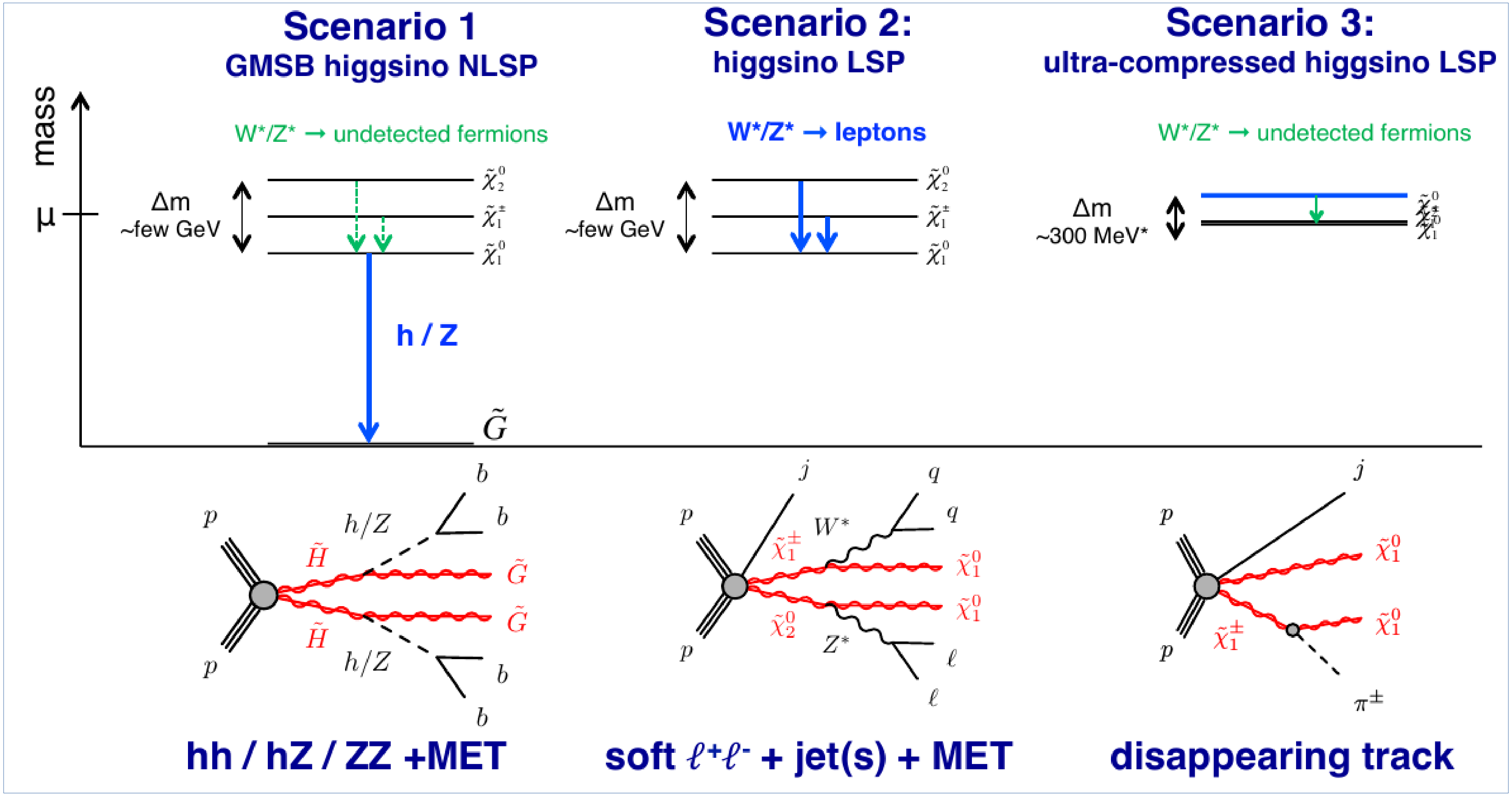
→ *2 photons*

→ *3 leptons*

Searches with 2 or 3 leptons

Higgsinos searches

Naturalness arguments requires light higgsinos with similar masses.



[B. Hooberman, SUSY17]

Compressed higgsinos/sleptons

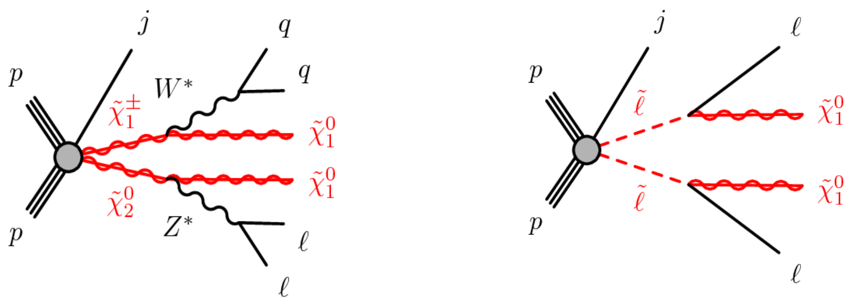
[ATLAS-CONF-2019-014]

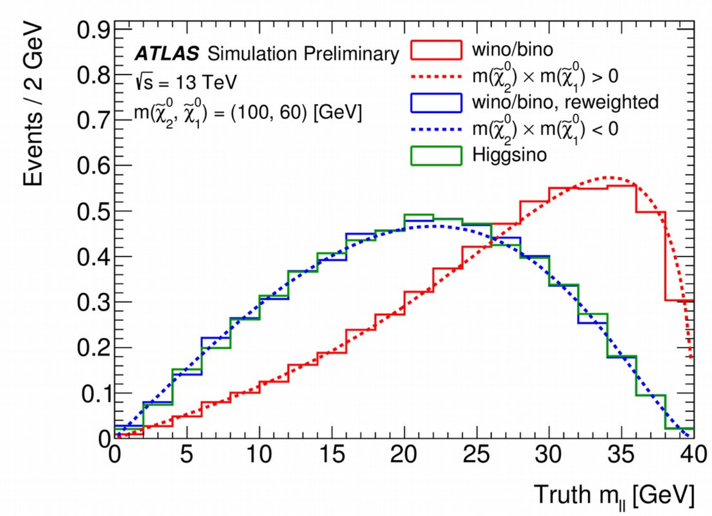
Significant lower invariant mass m_{ll} for models with Higgsinos

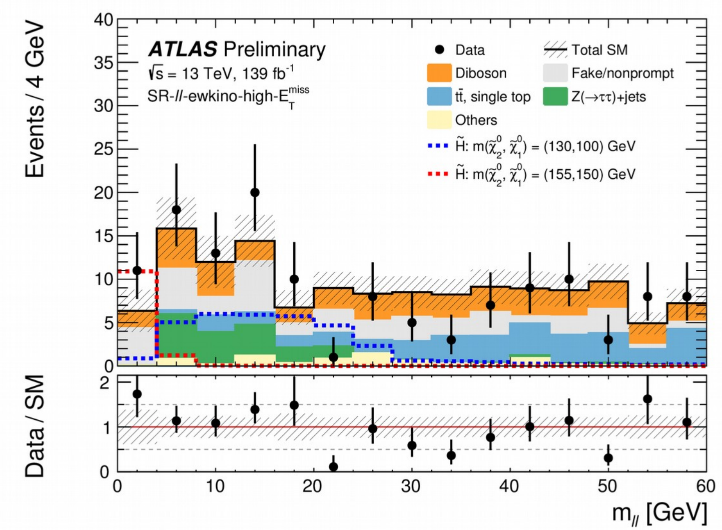
→ analysis requiring extremely low energetic leptons and low m_{ll}

→ using electrons down to p_T = 4.5 GeV and muons down to p_T = 3 GeV and m_{ll} = 1 GeV

→ huge progress in reconstruction of low energetic leptons







Two searches:

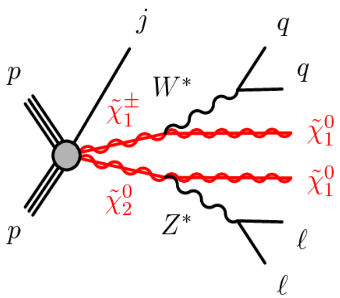
- Direct production of higginos using m_{ll}
- Direct production of sleptons using m_{T2}

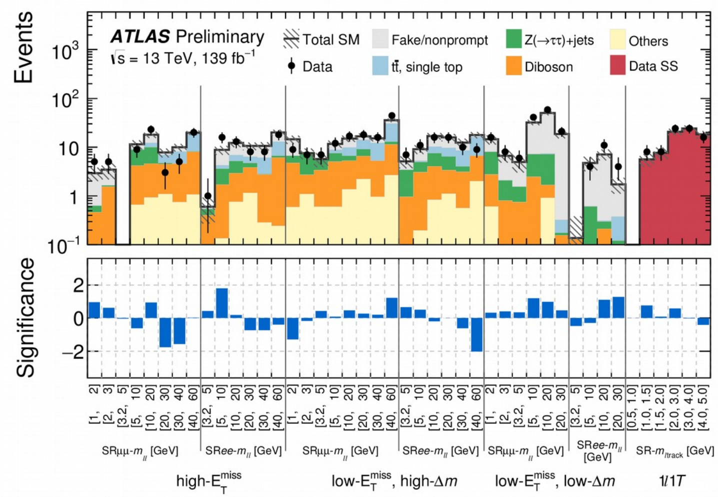
→ key is estimation of fake backgrounds!

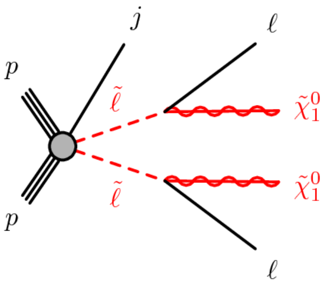
Compressed higgsinos/sleptons

[ATLAS-CONF-2019-014]

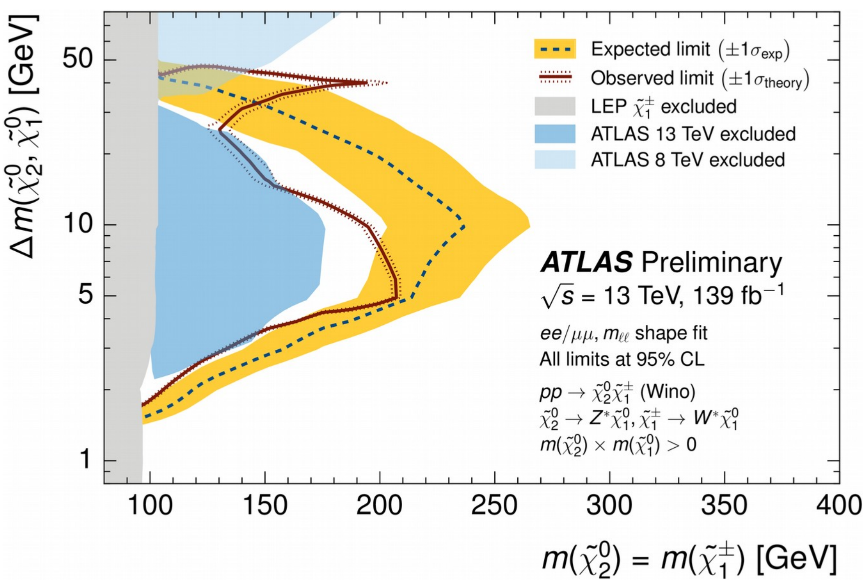
No significant excess seen.

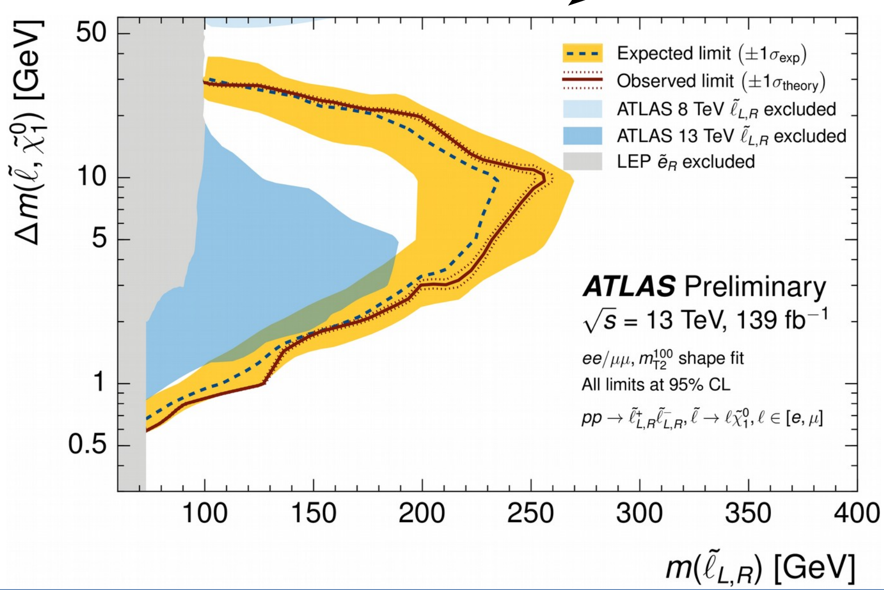






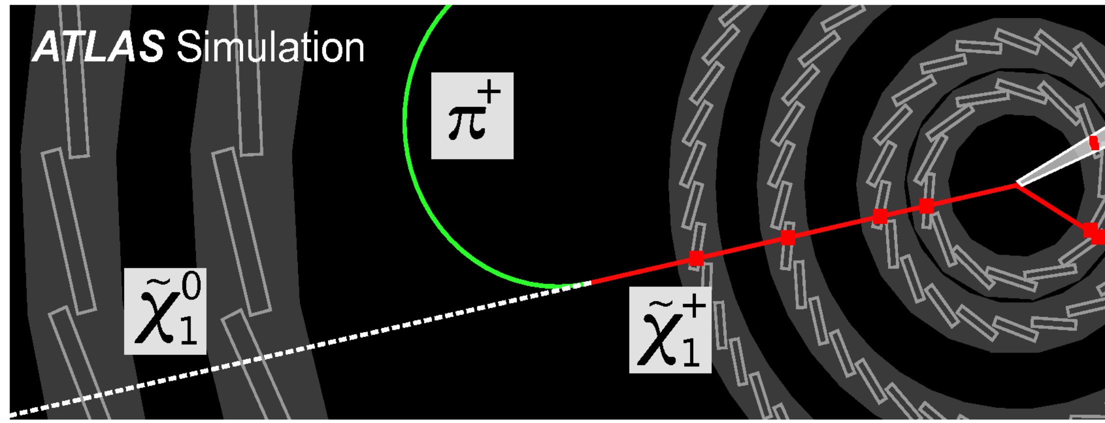
Slepton signal regions





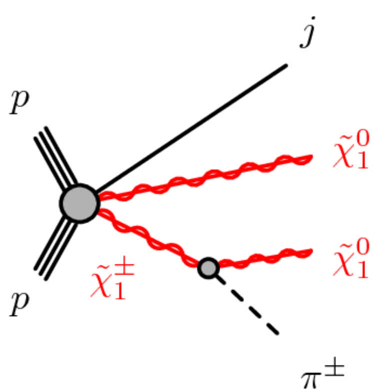
Disappearing tracks

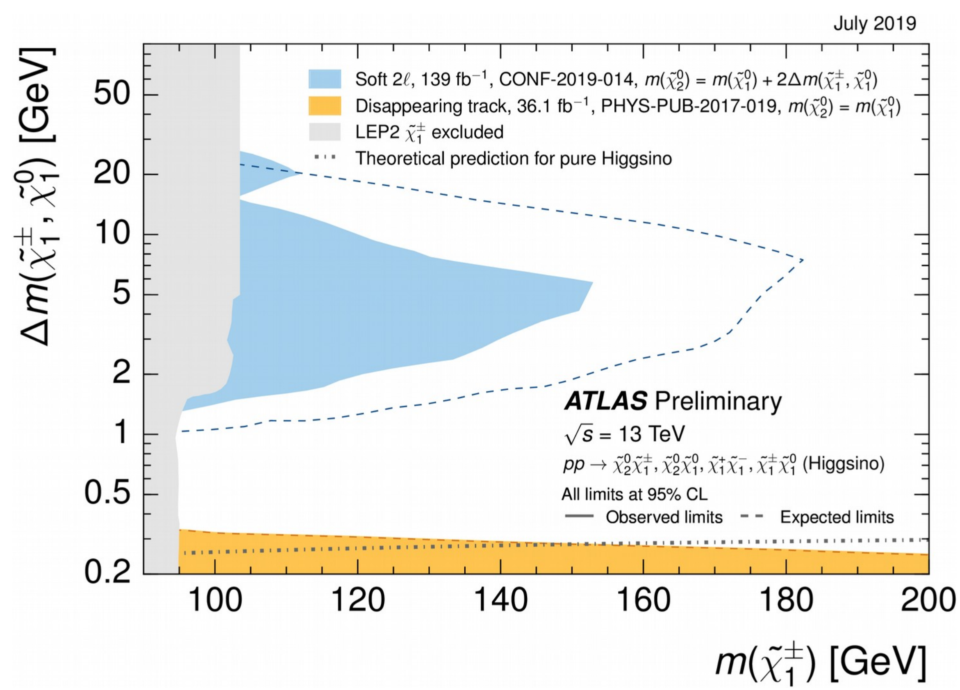
[JHEP 06 (2018) 022,ATL-PHYS-PUB-2019-044]



Long-lived chargino decaying to invisible + pion
→ *disappearing track*

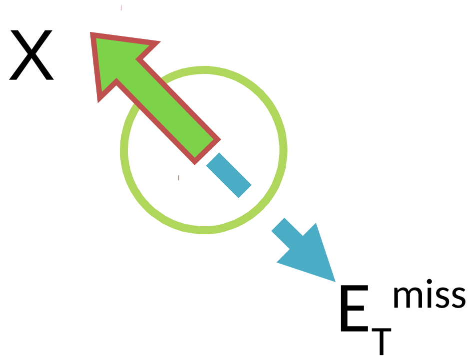
Addition of IBL in LS1 allowed reconstruction of smaller minimal track lengths down to 12 cm
→ *pixel-only tracklets*





Old LEP limits partially superseded now.

Searches for dark matter in BSM mediator searches

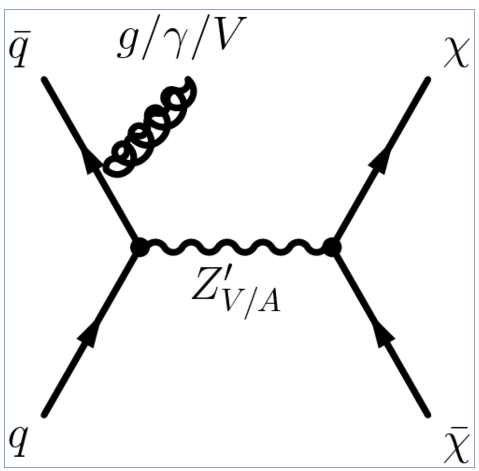


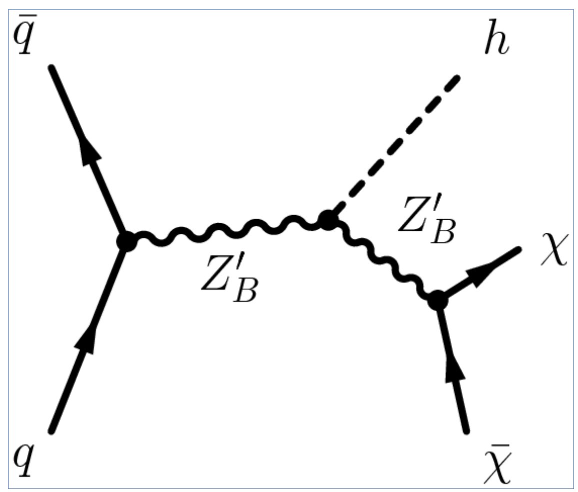
Pure production of dark matter particles invisible, need some other SM particle the dark matter particles are recoiling against.

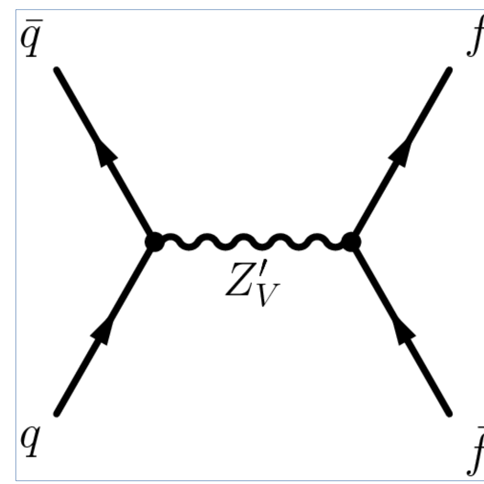
Two possibilities:

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

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







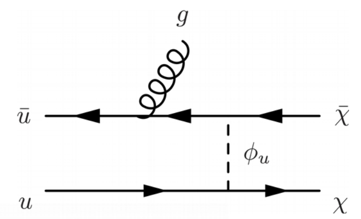
Examples

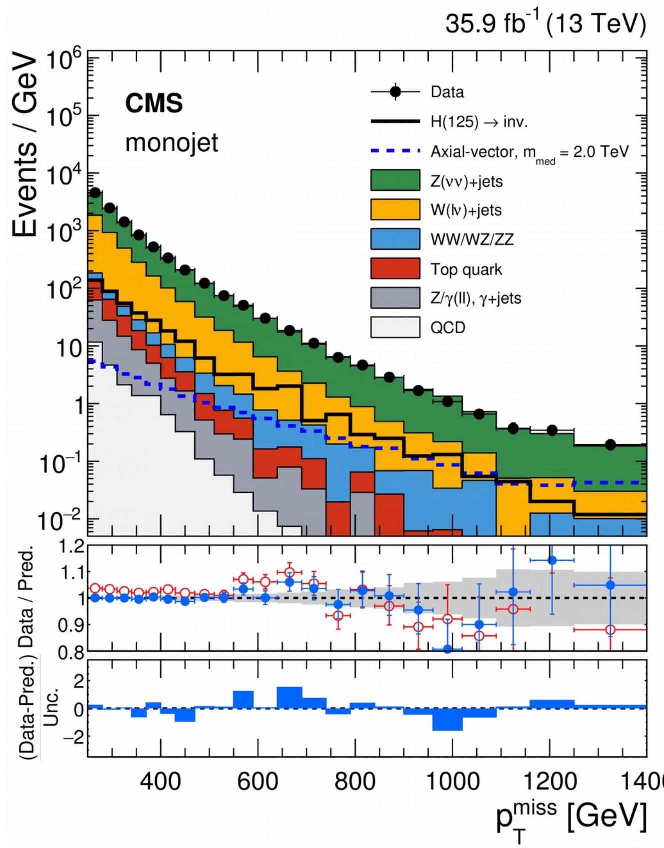
[Phys. Rev. D 97 (2018) 092005]

[arXiv:1911.03947]

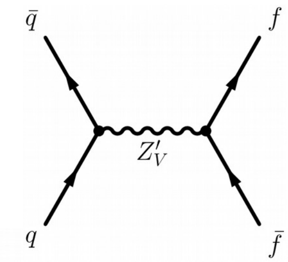
Emission of particle from initial state

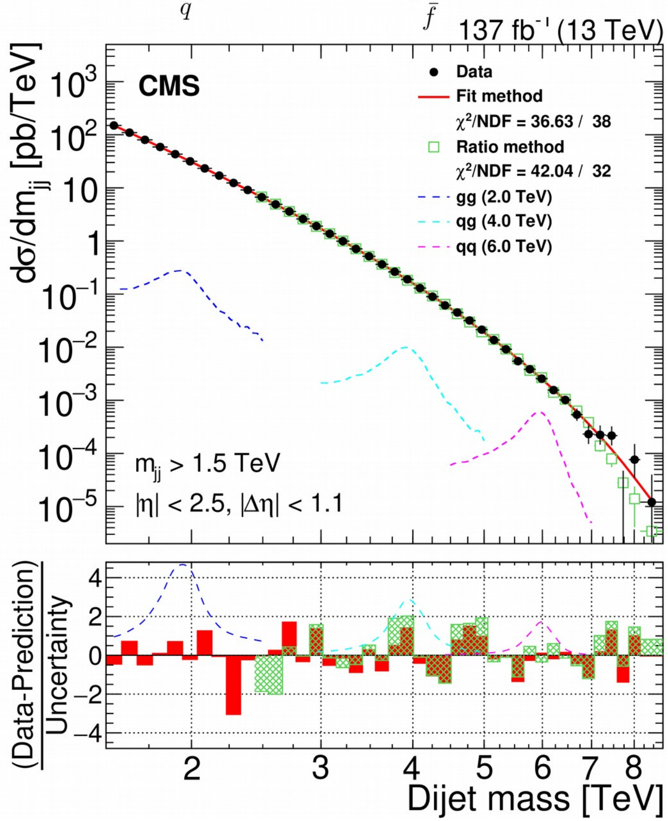
→ *e.g. mono-jet*



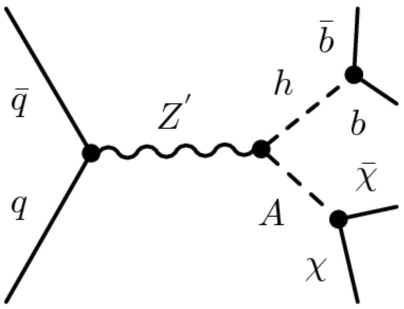


Search for a di-jet resonance





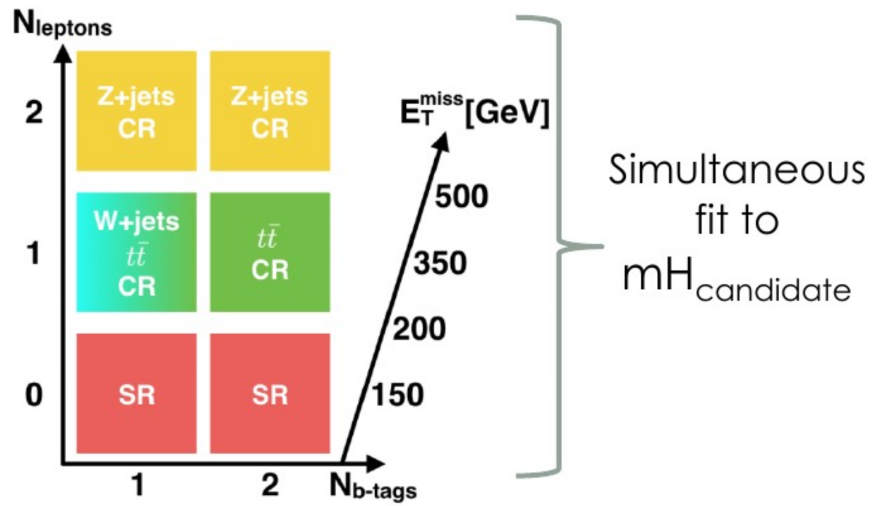
Mono-h



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)*

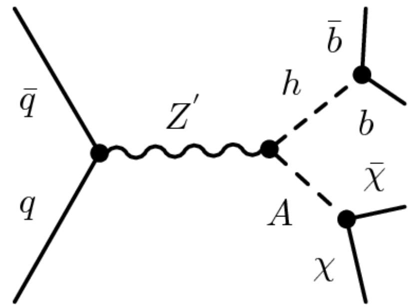
- *Signal region without leptons, control regions with 1 (W+jets, $t\bar{t}$) or 2 leptons (Z+jets).*



Mono-h

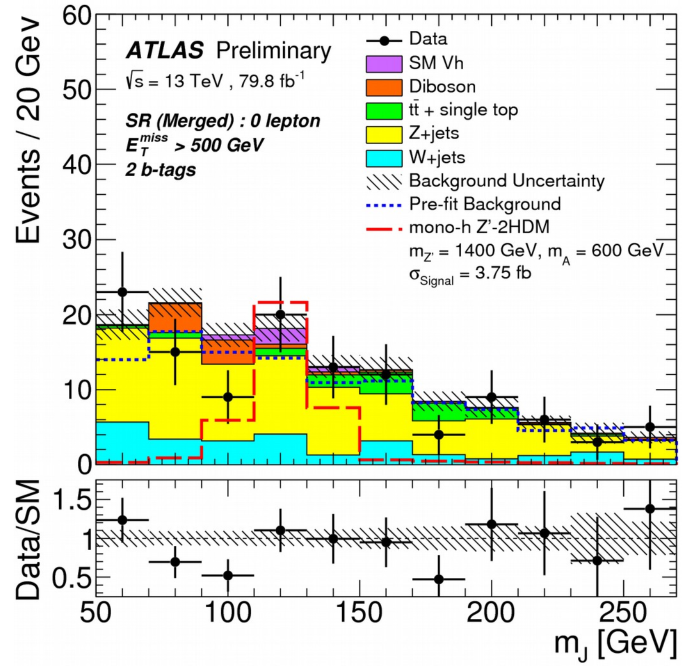
[ATLAS-CONF-2018-039]

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)*

- *Binned in b-jet multiplicity and E_T^{miss} to increase sensitivity, simultaneous fit in mass of Higgs 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.

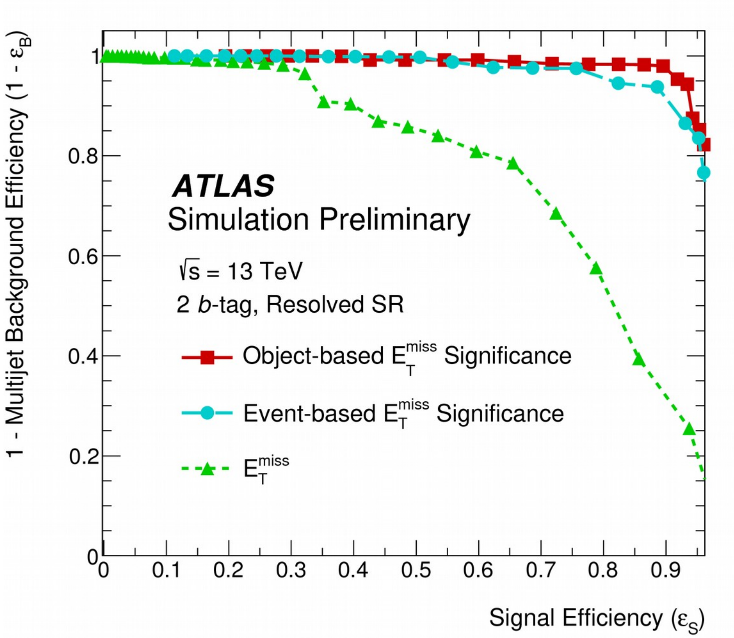
→ *formerly used for this* $S = \frac{E_T^{miss}}{\sqrt{H_T}}$

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

Covariance Matrix for each object

=> $S^2 = \frac{\left|\boldsymbol{E}_T^{miss}\right|^2}{\sigma_L^2\left(1-\rho_{LT}^2\right)}.$

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.

Improvements: VR track jets

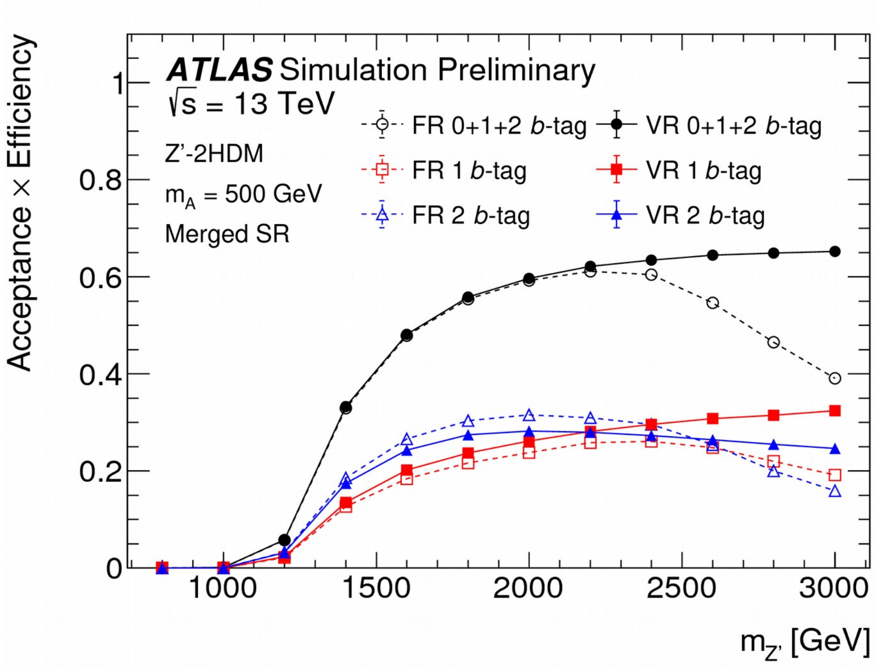
[ATLAS-CONF-2018-039]

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*

$$\mathrm{R} \rightarrow \mathrm{R}_{\mathrm{eff}}(p_{\mathrm{T}}) \approx \frac{\rho}{p_{\mathrm{T}}}$$

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

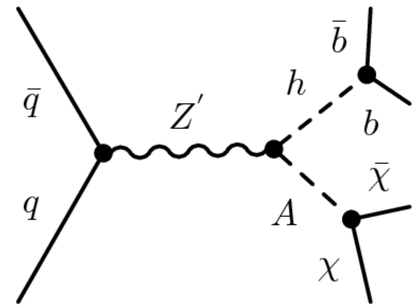
Instead of using two small R=0.2 track jets.

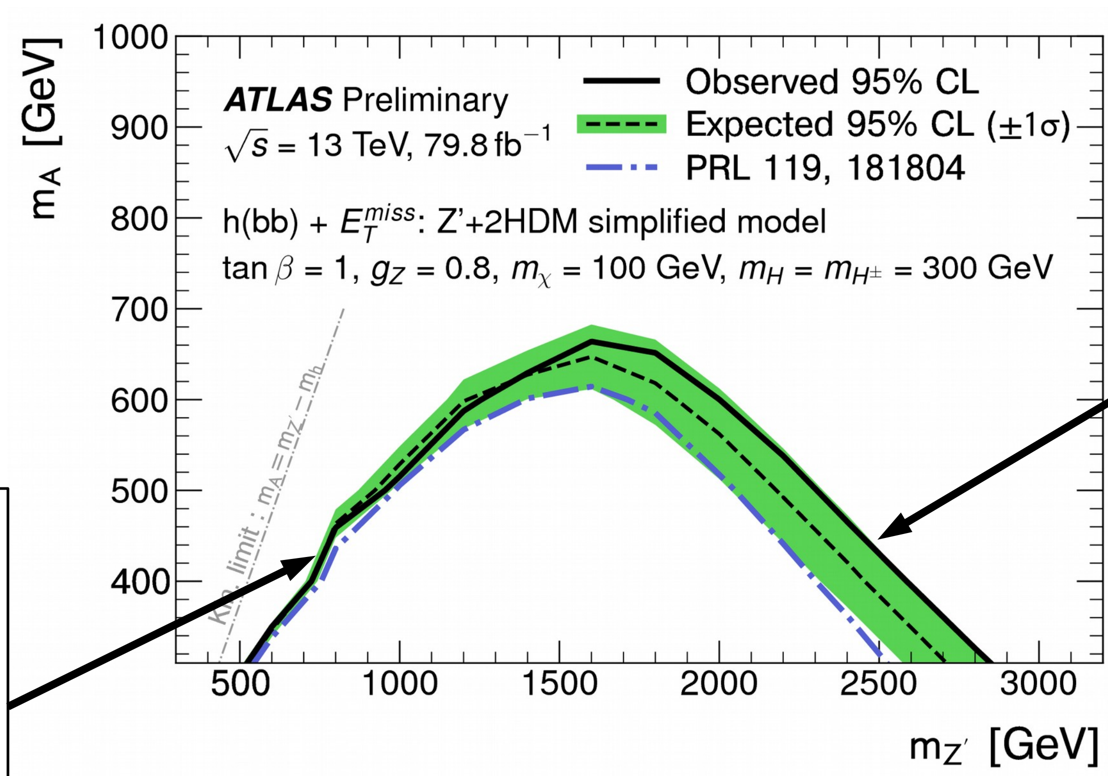


Mono-h

[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.





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

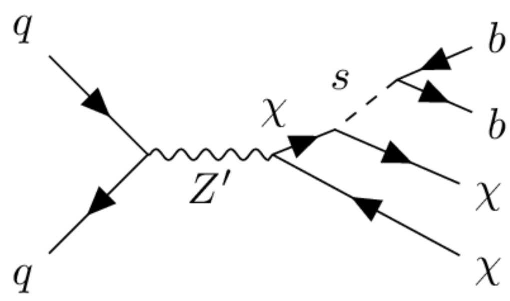
Improvements due to use of VR track jets.

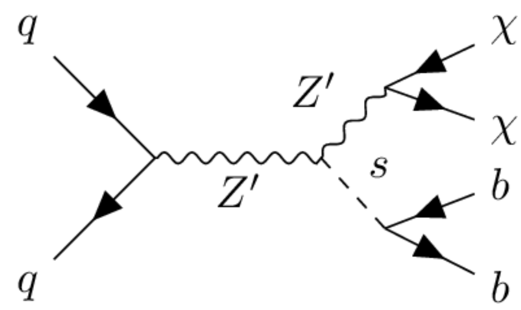
Reinterpreation of the mono-h search for dark Higgs models

[ATL-PHYS-PUB-2019-032]

Dark Higgs model:

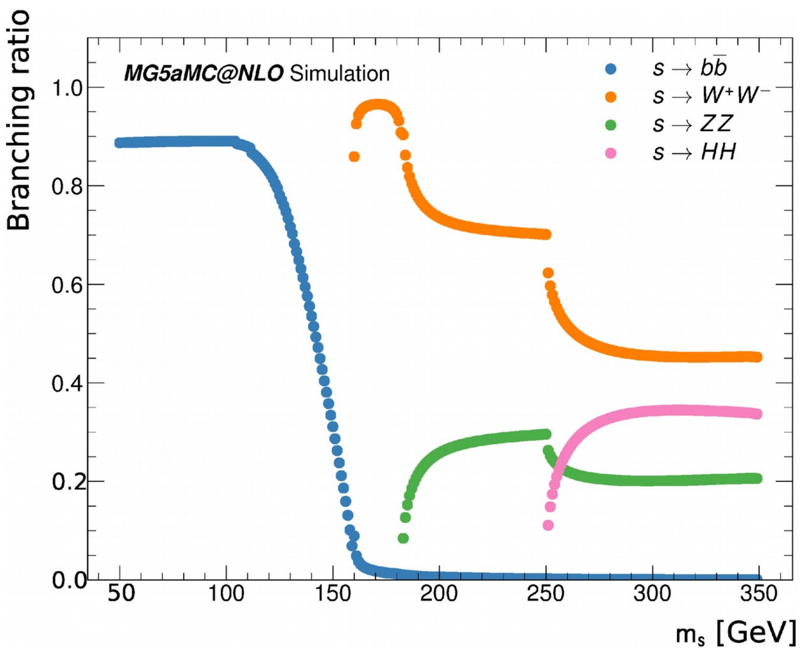
- Additional Higgs boson s.
- Motivated by need to generate masses in DM sector.
- Can relax DM relic abundance constraints by opening up additional annihilation channel.





Decays depend on mass of s – for small masses s → bb̄

Thus reinterpretation of mono-h search possible.

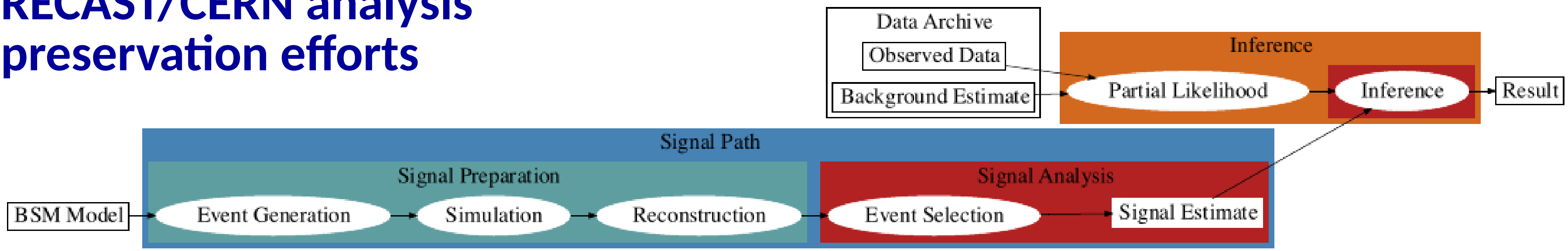


Decays s → WW, ZZ, HH topic of future analyses

Reinterpreation of the mono-h search for dark Higgs models

[ATL-PHYS-PUB-2019-032]

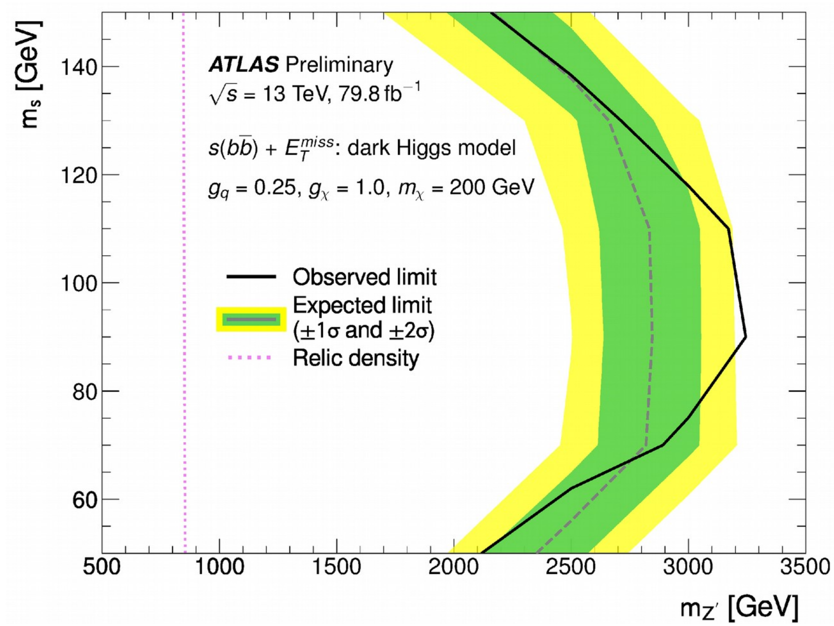
RECAST/CERN analysis preservation efforts



Mono-h search preserved in RECAST – one of the first analyses preserved at ATLAS!

Allows analysis of any other signal model/scenario in the future using the original (preserved) analysis software with minimal effort.

Exclusion limits up to a Z' mass of 3.2 TeV.

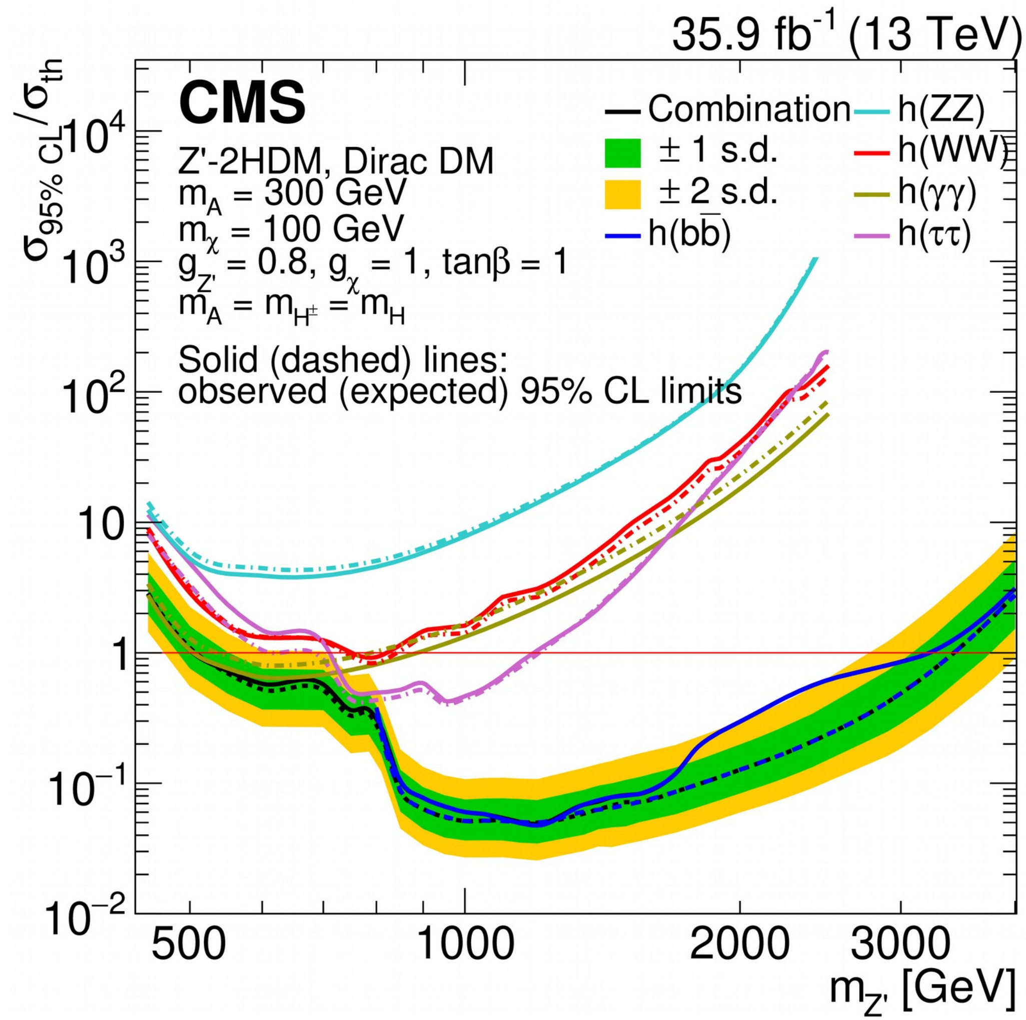


Mono-h searches at CMS

[arXiv:1908.01713 [hep-ex]]

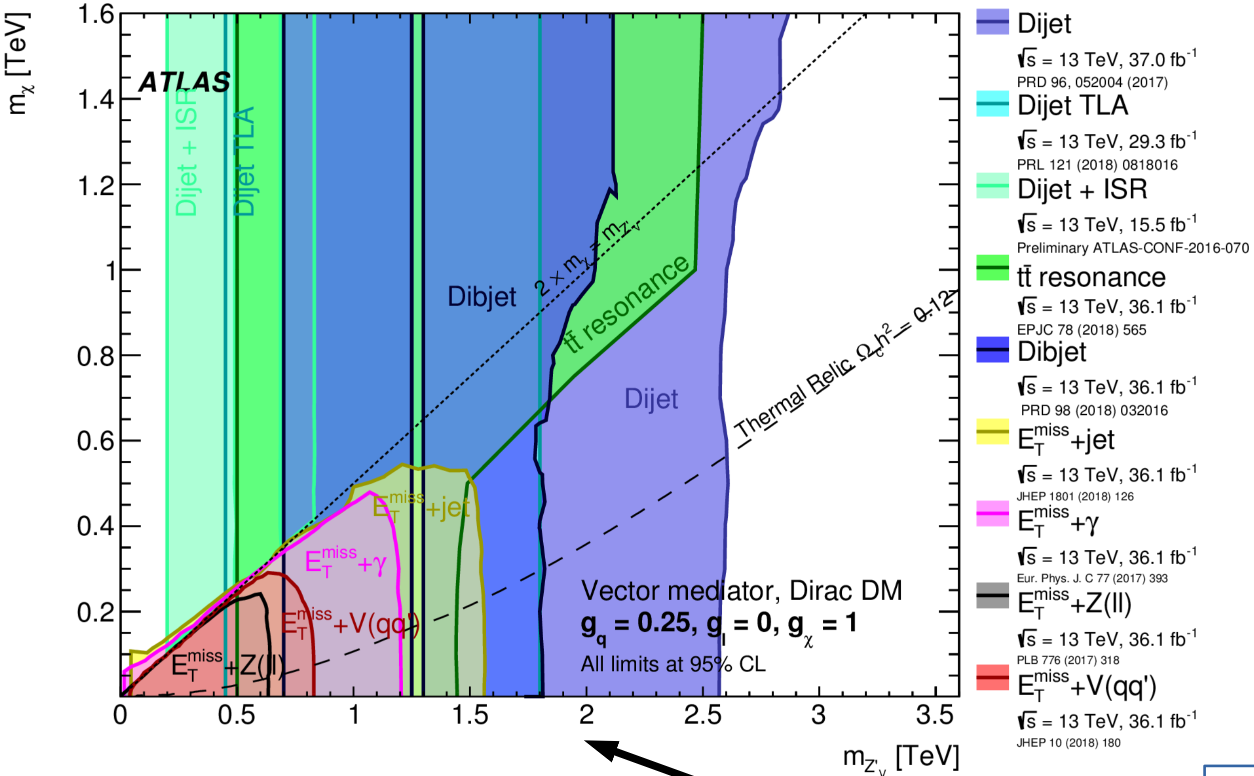
- Searches for $h \rightarrow b\bar{b} + E_T^{miss}$ in case of low Z' masses in certain models not sensitive (as then relatively low E_T^{miss} needed).
  → *Study other channels like $h \rightarrow \tau\tau$ and $h \rightarrow \gamma\gamma$, and also $h \rightarrow ZZ$ and $h \rightarrow WW + E_T^{miss}$*

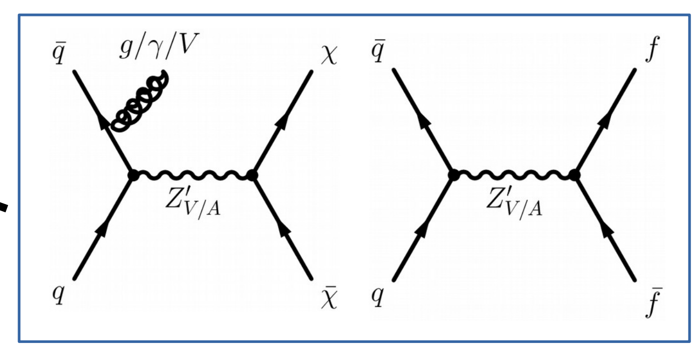
- Combination of all channels.



Summary of searches for dark matter in BSM mediator models

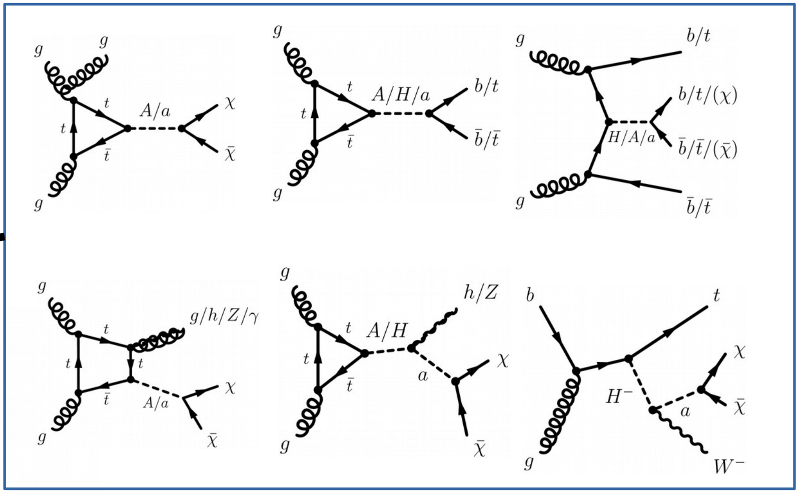
[JHEP 05 (2019) 142]

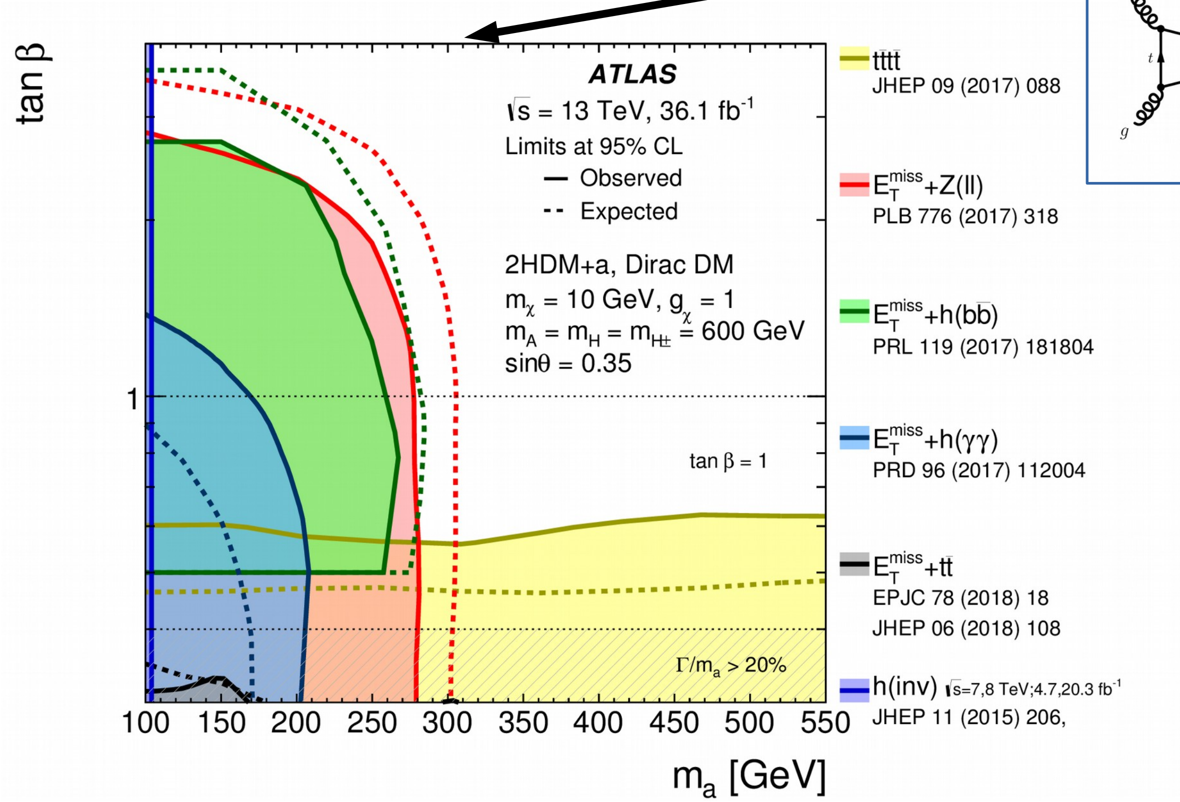




Summary of searches for dark matter in BSM mediator models

[JHEP 05 (2019) 142]



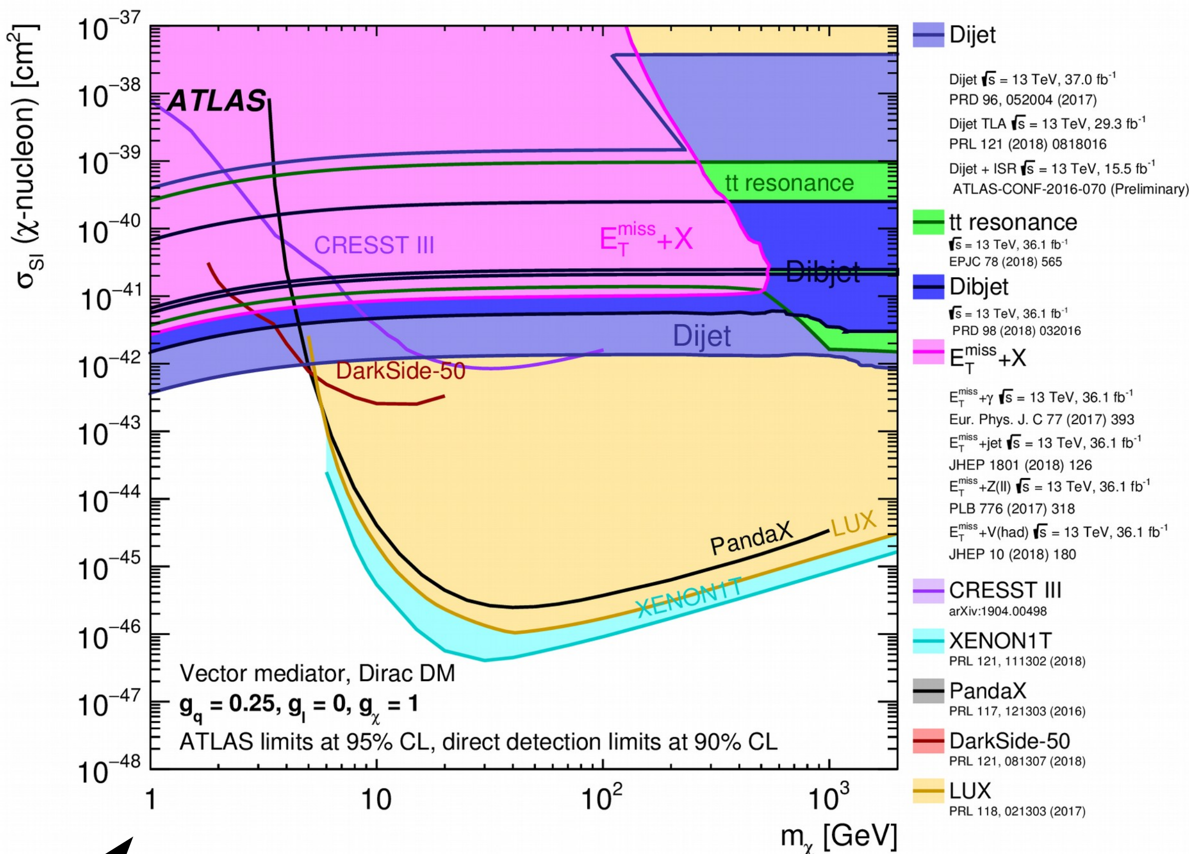


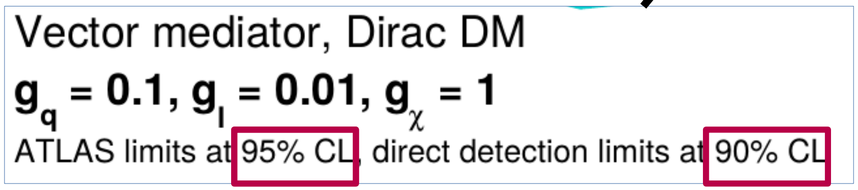
Comparison to non-collider dark matter searches

[JHEP 05 (2019) 142]

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

→ *collider experiments cover dark matter masses down to 1 GeV in these models*

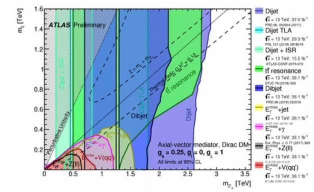




Comparison only valid for a very specific model with specific parameters!

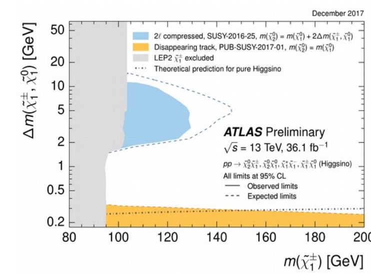
New directions

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



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

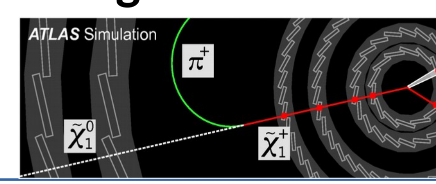
- **Particular interest in models with Higgs bosons, due to need to generate mass for the DM particles/link the Higgs bosons to the DM sector.**
  + for SUSY: Higgs needs to be linked to SUSY particles to solve hierarchy problem!



- **Only getting now sensitive to difficult SUSY EWK scenarios**
  → Small Higgsino masses motivated by naturalness arguments.

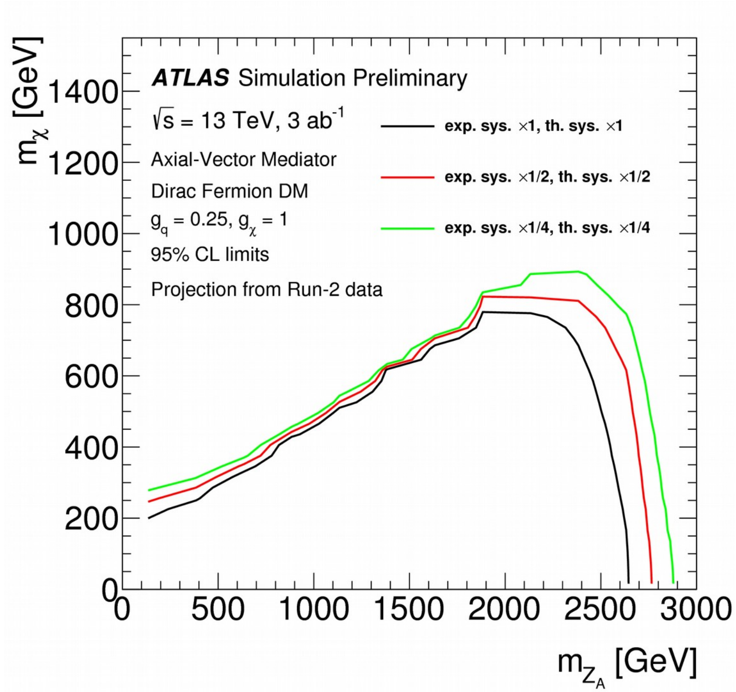
- **Using sophisticated modern techniques helps!**
  → Separate signal from background better by using shape differences
  → *Machine learning*, *boosted jets*, *multi-bin/shape fits*

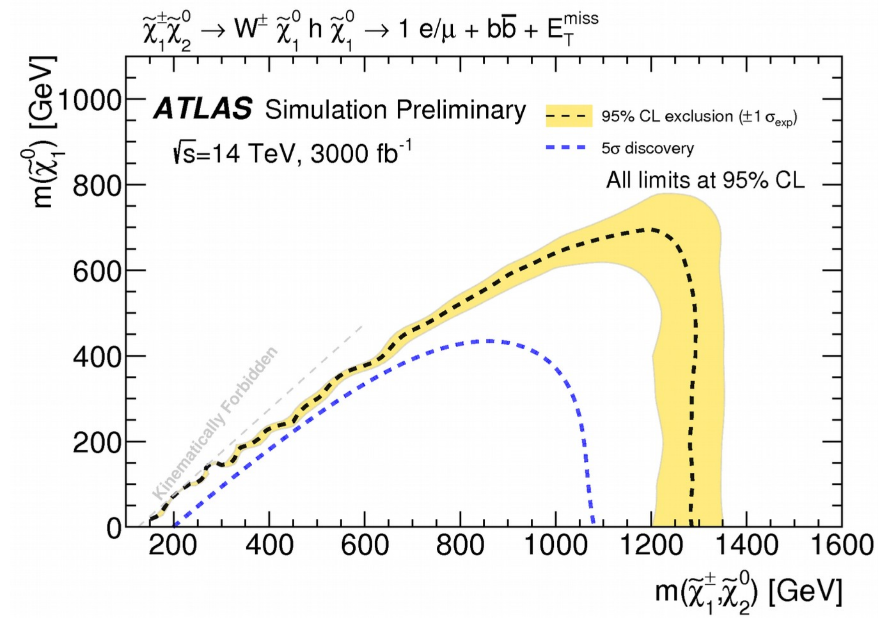
- **Not covered in this talk, but comprehensive search program: long-lived particles**
  → E.g. disappearing track searches
  → Also new particle experiments proposed, e.g. FASER, ShiP, …



Where we might 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

...and what we could do at future colliders

[CERN-ESU-004]

Constraints from relic density:

- Pure Wino: 3 TeV
- Pure Higgsino: 1.1 TeV

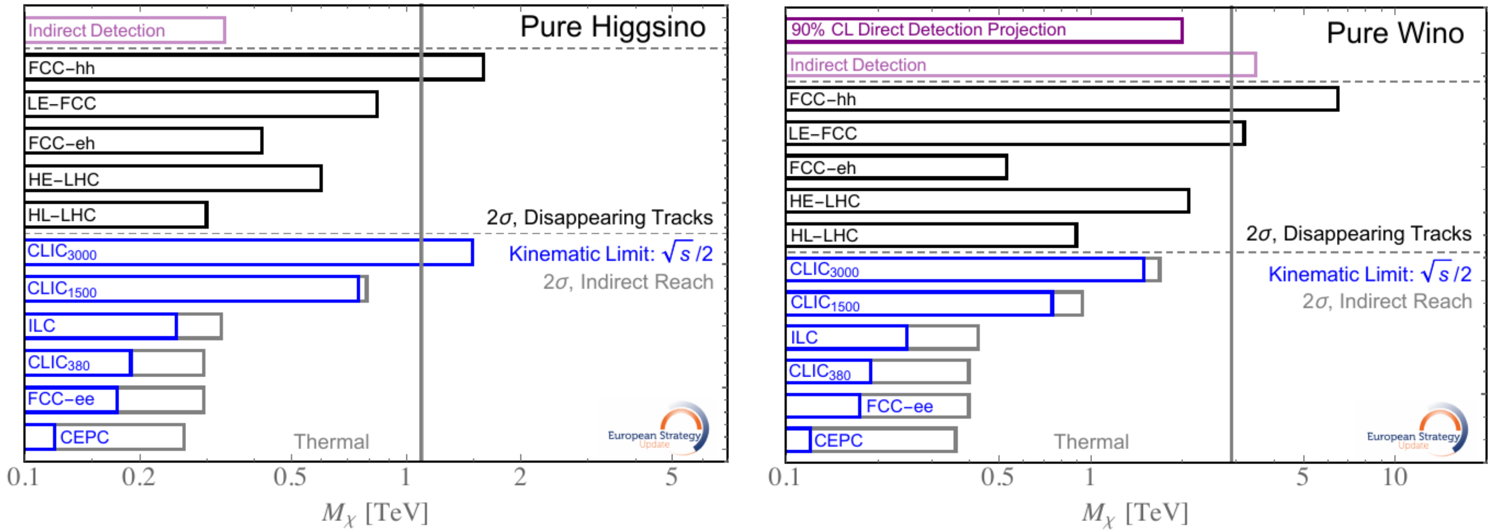
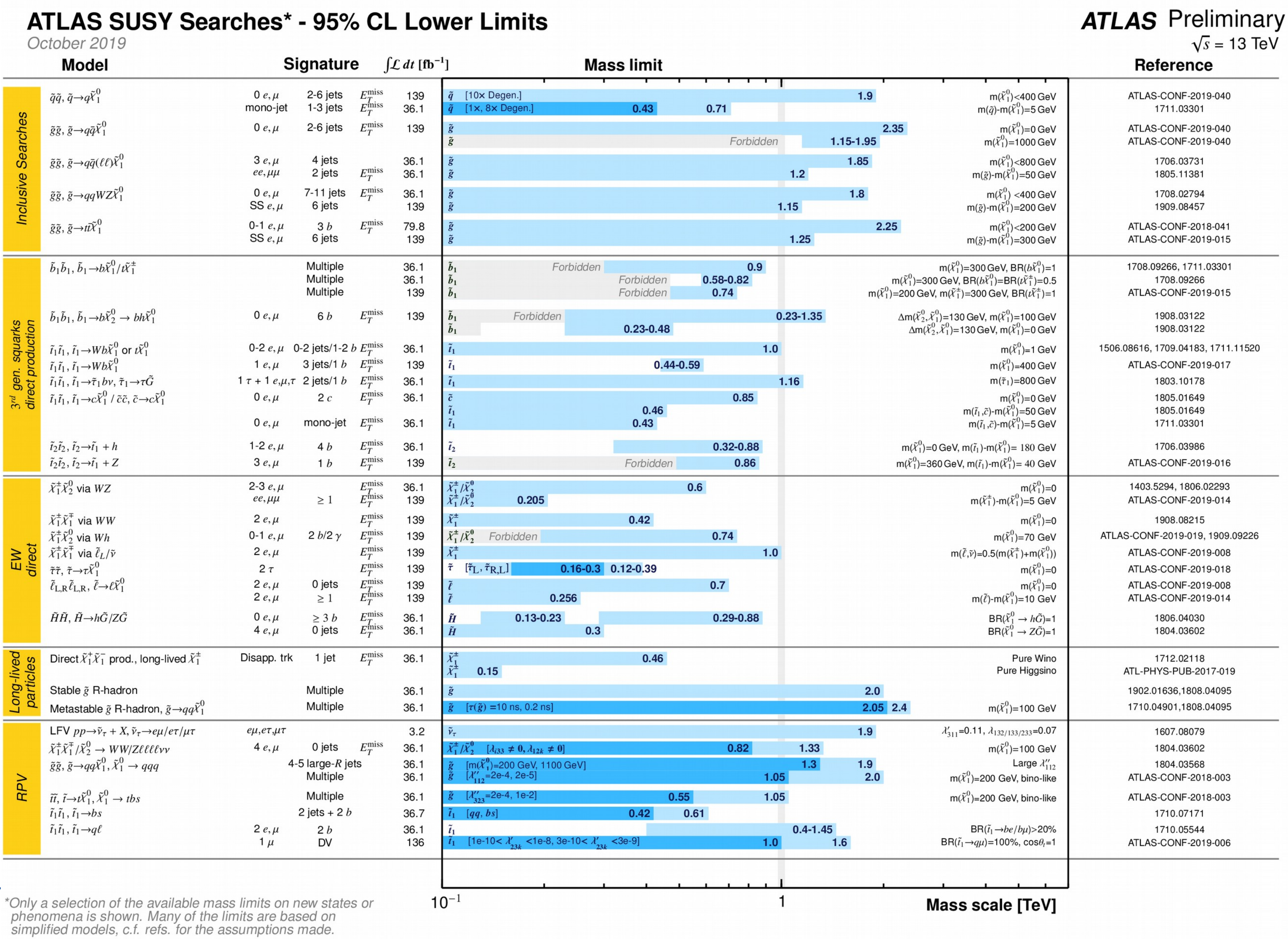


Fig. 8.14: Summary of 2σ sensitivity reach to pure Higgsinos and Winos at future colliders. Current indirect DM detection constraints (which suffer from unknown halo-modelling uncertainties) and projections for future direct DM detection (which suffer from uncertainties on the Wino-nucleon cross section) are also indicated. The vertical line shows the mass corresponding to DM thermal relic.

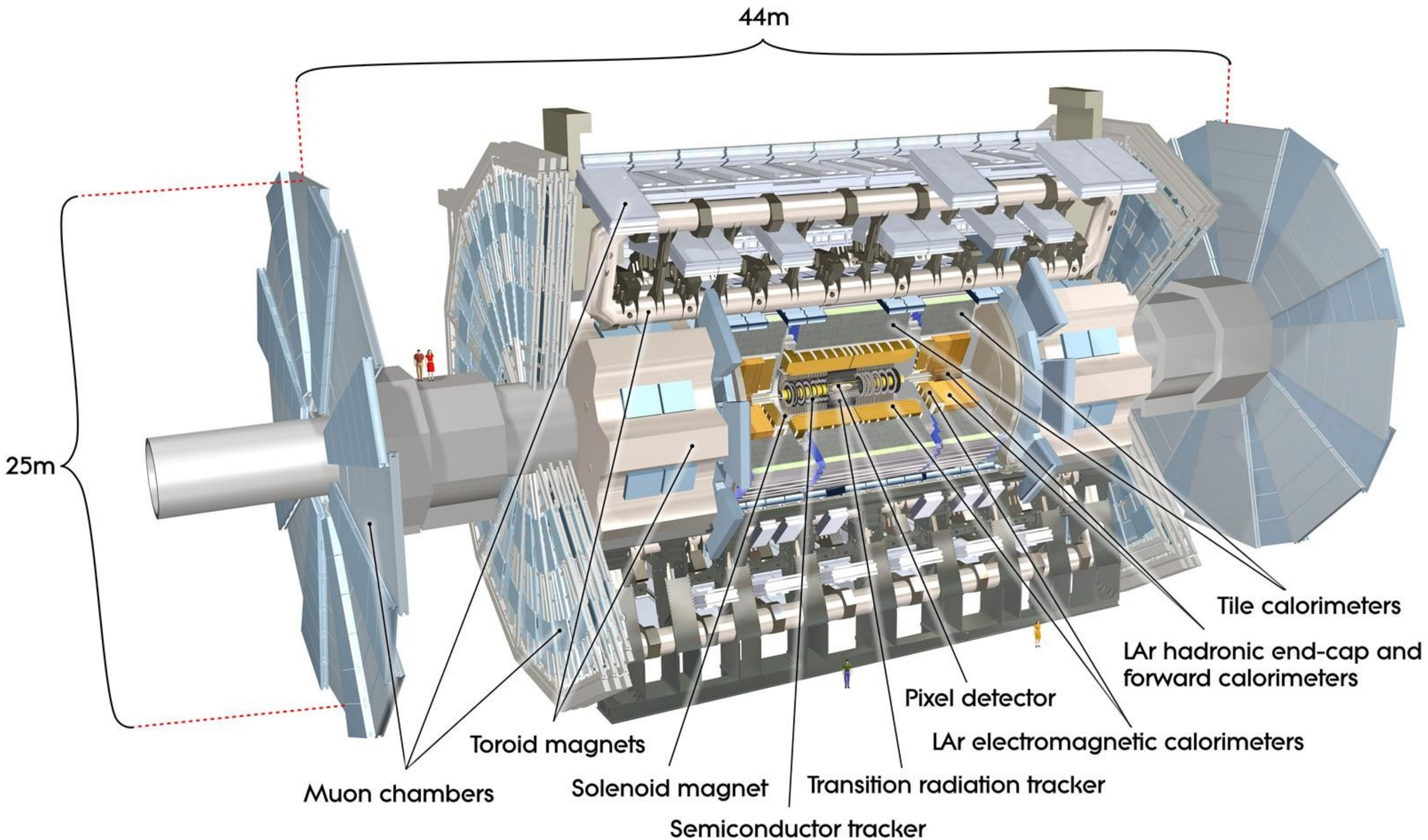
Summary



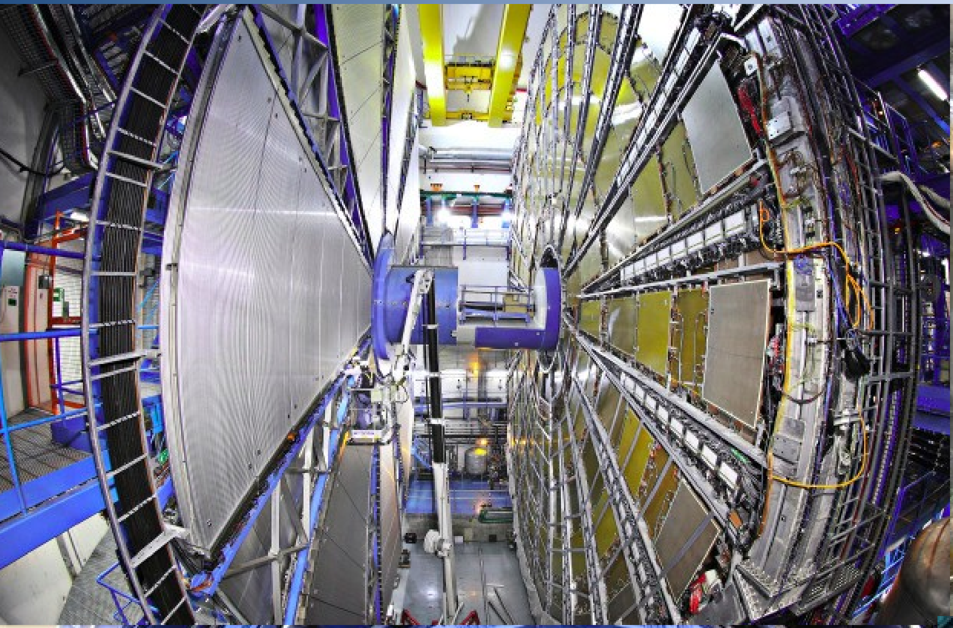
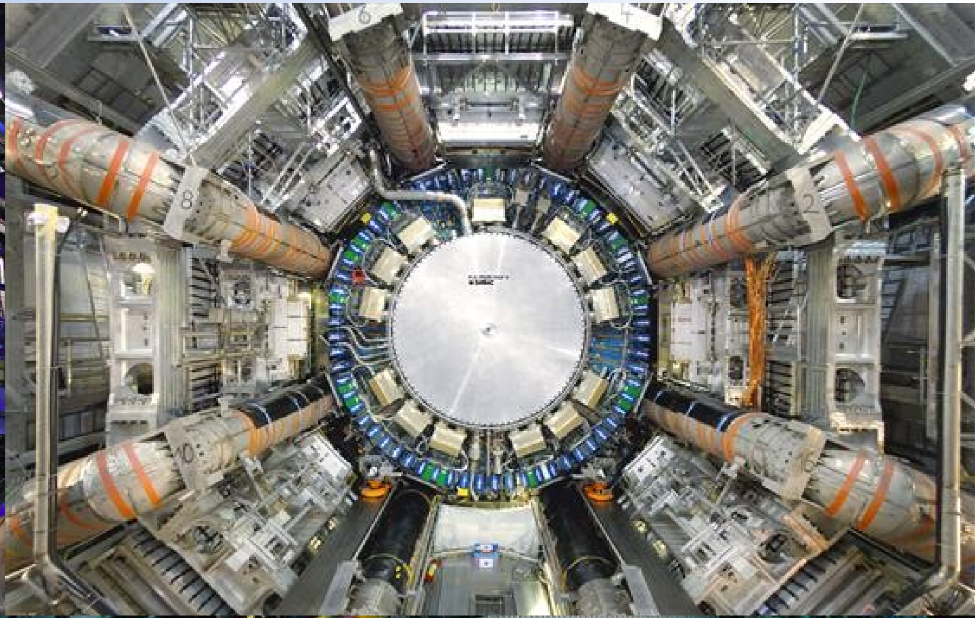
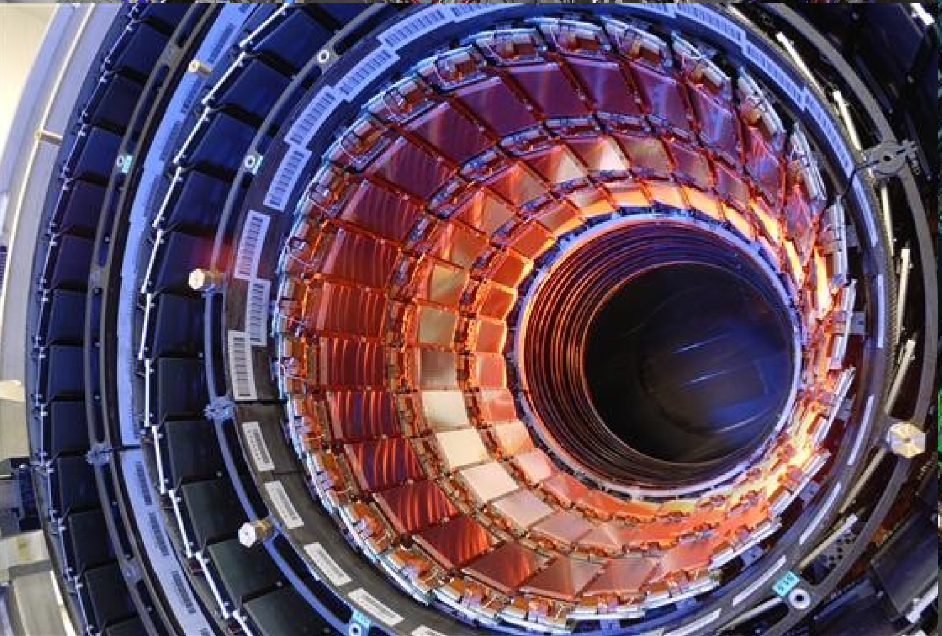
ATLAS SUSY Searches* - 95% CL Lower Limits
October 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model | Signature | $\int \mathcal{L}\, dt$ [fb^{-1}] | Mass limit | Reference
Inclusive Searches
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 e,μ 2-6 jets E_T^{miss} | 139 | $\tilde{q}$ [10× Degen.] 1.9 | m($\tilde{\chi}_1^0$)<400 GeV | ATLAS-CONF-2019-040
mono-jet 1-3 jets E_T^{miss} | 36.1 | $\tilde{q}$ [1×, 8× 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 e,μ 2-6 jets E_T^{miss} | 139 | $\tilde{g}$ 2.35 | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2019-040
$\tilde{g}$ Forbidden 1.15-1.95 | m($\tilde{\chi}_1^0$)=1000 GeV | ATLAS-CONF-2019-040
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ | 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 E_T^{miss} | 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 e,μ 7-11 jets E_T^{miss} | 36.1 | $\tilde{g}$ 1.8 | m($\tilde{\chi}_1^0$) <400 GeV | 1708.02794
SS e,μ 6 jets | 139 | $\tilde{g}$ 1.15 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV | 1909.08457
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 e,μ 3 b E_T^{miss} | 79.8 | $\tilde{g}$ 2.25 | m($\tilde{\chi}_1^0$)<200 GeV | ATLAS-CONF-2018-041
SS e,μ 6 jets | 139 | $\tilde{g}$ 1.25 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV | ATLAS-CONF-2019-015
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 | 139 | $\tilde{b}_1$ Forbidden 0.74 | m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1 | ATLAS-CONF-2019-015
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$ | 0 e,μ 6 b E_T^{miss} | 139 | $\tilde{b}_1$ Forbidden 0.23-1.35 | Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV | 1908.03122
$\tilde{b}_1$ 0.23-0.48 | Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV | 1908.03122
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 e,μ 0-2 jets/1-2 b E_T^{miss} | 36.1 | $\tilde{t}_1$ 1.0 | m($\tilde{\chi}_1^0$)=1 GeV | 1506.08616, 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 1 e,μ 3 jets/1 b E_T^{miss} | 139 | $\tilde{t}_1$ 0.44-0.59 | m($\tilde{\chi}_1^0$)=400 GeV | ATLAS-CONF-2019-017
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$ | 1 τ + 1 e,μ,τ 2 jets/1 b E_T^{miss} | 36.1 | $\tilde{t}_1$ 1.16 | m($\tilde{\tau}_1$)=800 GeV | 1803.10178
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$ | 0 e,μ 2 c E_T^{miss} | 36.1 | $\tilde{c}$ 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 e,μ mono-jet E_T^{miss} | 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 E_T^{miss} | 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
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$ | 3 e,μ 1 b E_T^{miss} | 139 | $\tilde{t}_2$ Forbidden 0.86 | m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV | ATLAS-CONF-2019-016
EW direct
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ | 2-3 e,μ E_T^{miss} | 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 E_T^{miss} | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205 | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV | ATLAS-CONF-2019-014
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW | 2 e,μ E_T^{miss} | 139 | $\tilde{\chi}_1^\pm$ 0.42 | m($\tilde{\chi}_1^0$)=0 | 1908.08215
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh | 0-1 e,μ 2 b/2 γ E_T^{miss} | 139 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 0.74 | m($\tilde{\chi}_1^0$)=70 GeV | ATLAS-CONF-2019-019, 1909.09226
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$ | 2 e,μ E_T^{miss} | 139 | $\tilde{\chi}_1^\pm$ 1.0 | m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2019-008
$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$ | 2 τ E_T^{miss} | 139 | $\tilde{\tau}$ [$\tilde{\tau}_L, \tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39 | m($\tilde{\chi}_1^0$)=0 | ATLAS-CONF-2019-018
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e,μ 0 jets E_T^{miss} | 139 | $\tilde{\ell}$ 0.7 | m($\tilde{\chi}_1^0$)=0 | ATLAS-CONF-2019-008
2 e,μ ≥ 1 E_T^{miss} | 139 | $\tilde{\ell}$ 0.256 | m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV | ATLAS-CONF-2019-014
$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 e,μ ≥ 3 b E_T^{miss} | 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 jets E_T^{miss} | 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 E_T^{miss} | 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 | Multiple | 36.1 | $\tilde{g}$ 2.0 | 1902.01636,1808.04095
Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$ | Multiple | 36.1 | $\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4 | m($\tilde{\chi}_1^0$)=100 GeV | 1710.04901,1808.04095
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 jets E_T^{miss} | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33 | m($\tilde{\chi}_1^0$)=100 GeV | 1804.03602
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | 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
$t\bar{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$ | 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
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 2 jets + 2 b | 36.7 | $\tilde{t}_1$ [qq, bs] 0.42 0.61 | 1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$ | 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
1 μ DV | 136 | $\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6 | BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1 | ATLAS-CONF-2019-006
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Backup

ATLAS detector

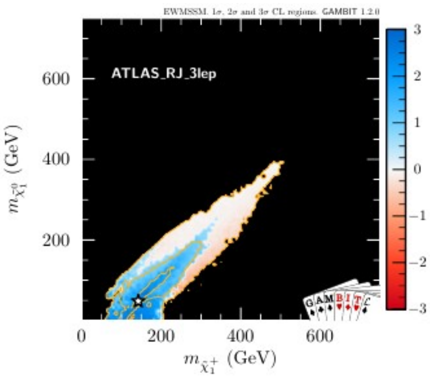


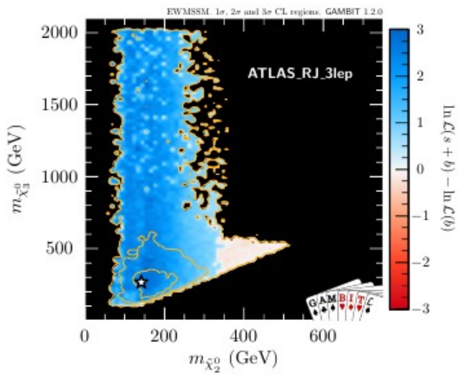
ATLAS and CMS detector


Loopholes? Analysis of electroweak searches by Gambit

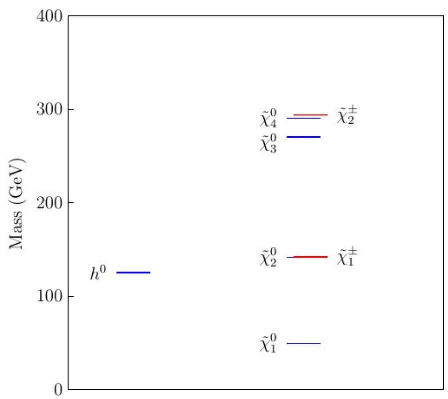
[arXiv:1809.02097]

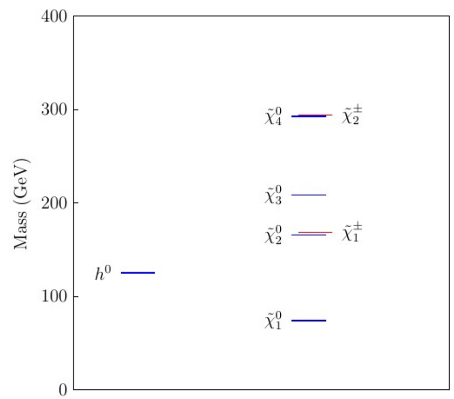




Likelihood combination of various LEP, ATLAS and CMS searches for electroweakinos:

→ *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.