Close the gaps! Recent highlights in searches for supersymmetry with the ATLAS detector

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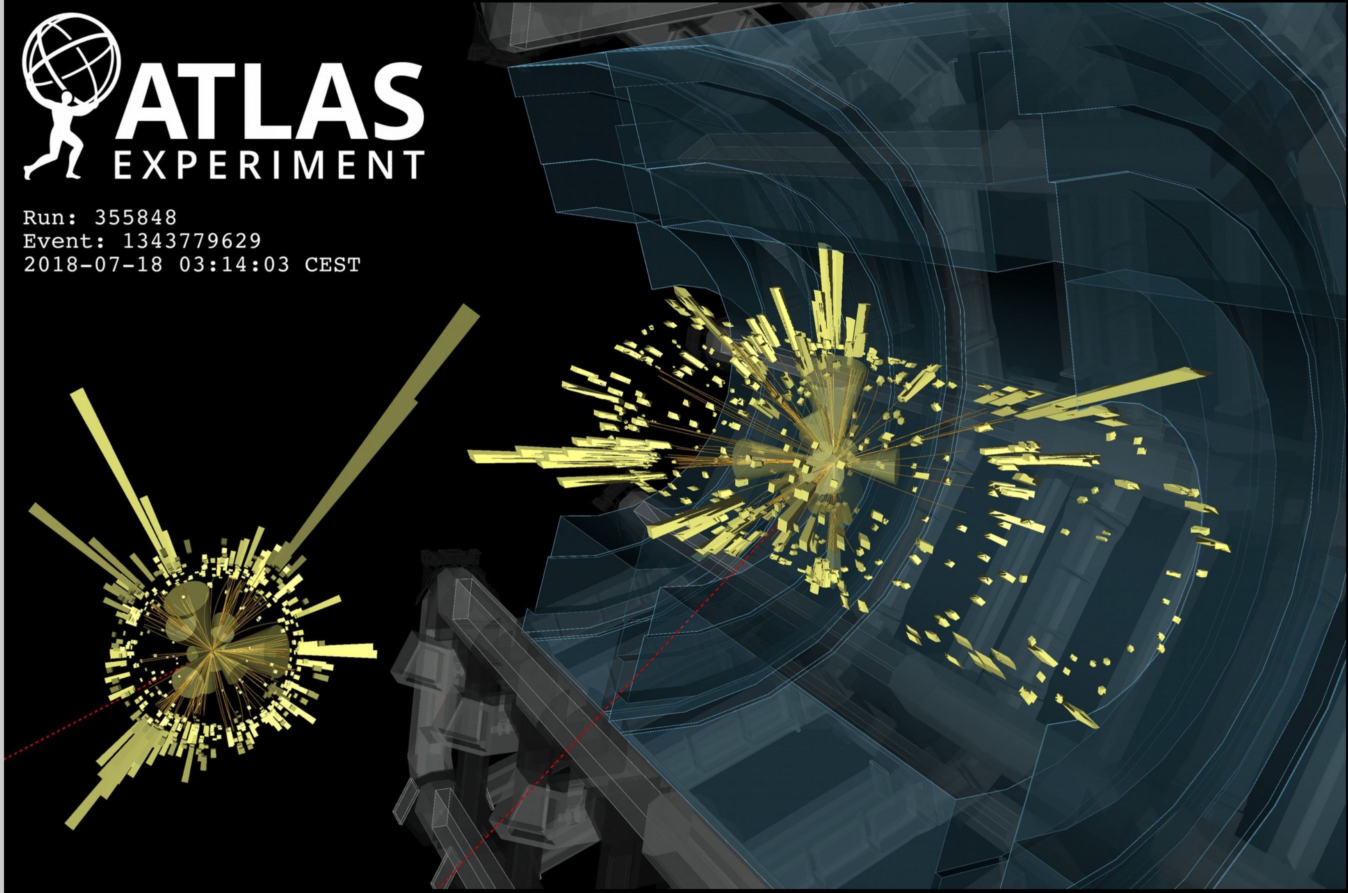


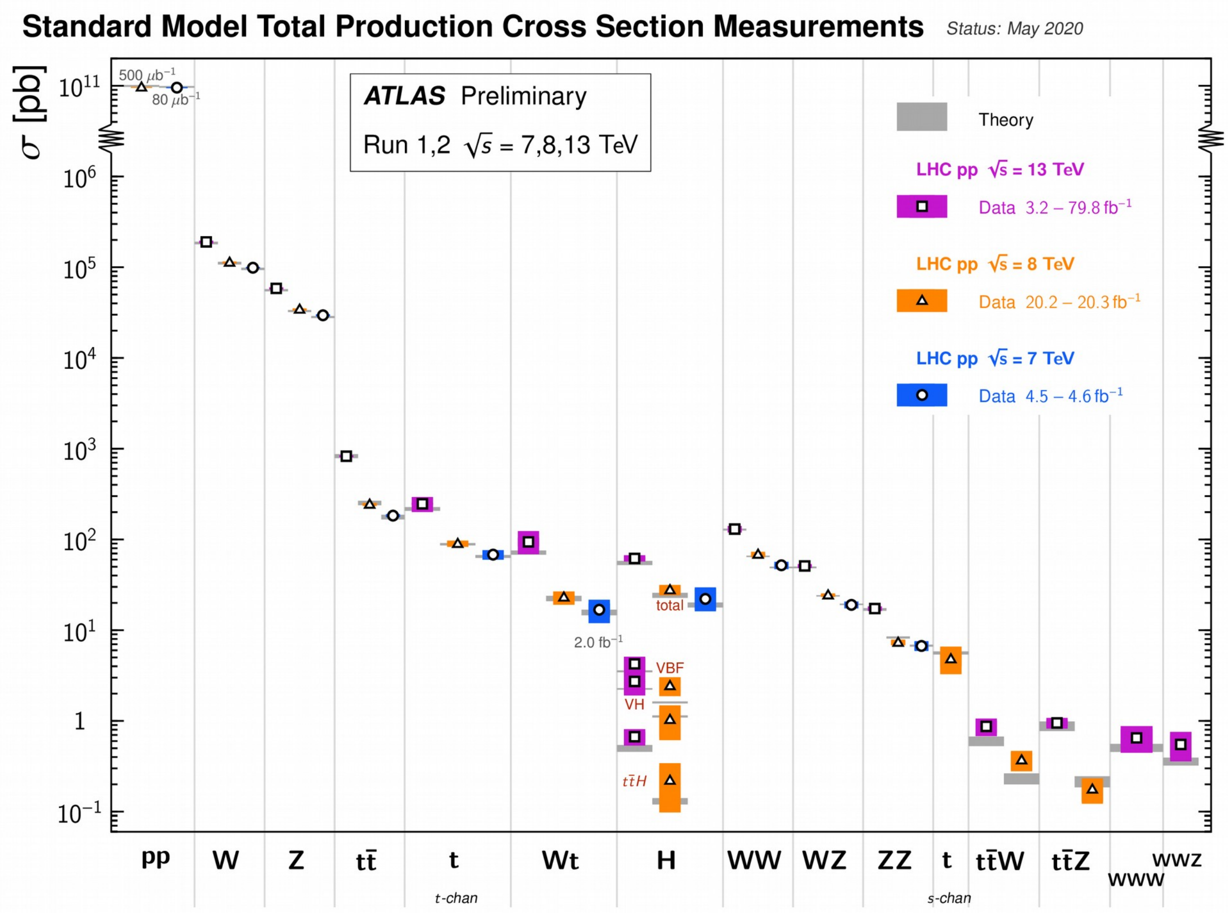
PSI, virtual, 04.03.2021

Precision measurements of the Standard Model (SM)

[ATL-PHYS-PUB-2020-010]

Impressive set of measurements. Good agreement of measurements with theoretical predictions.

Including Higgs sector.



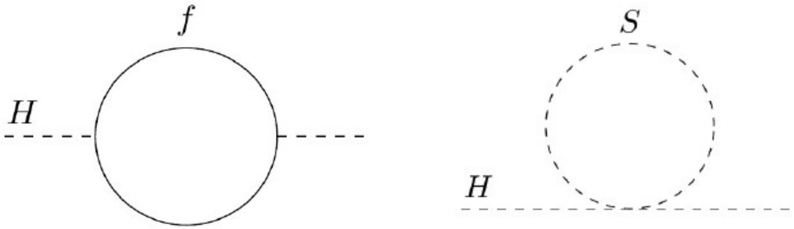
Why to search for physics beyond the SM?

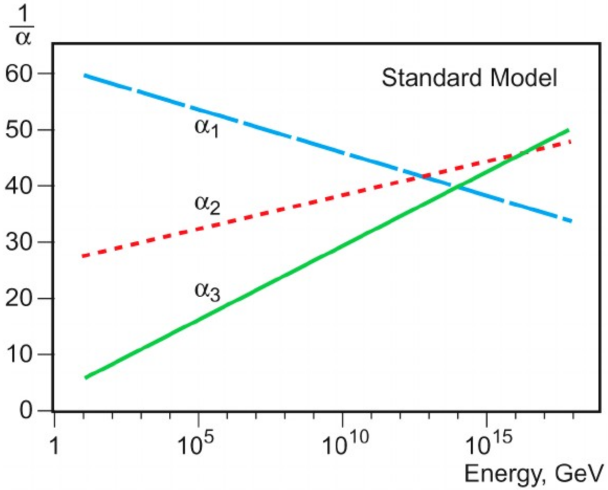
No cold dark matter candidate.

[https://chandra.harvard.edu/photo/2006/1e0657/more.html]

+ many more…

Higgs mass not stabilized → hierarchy problem.

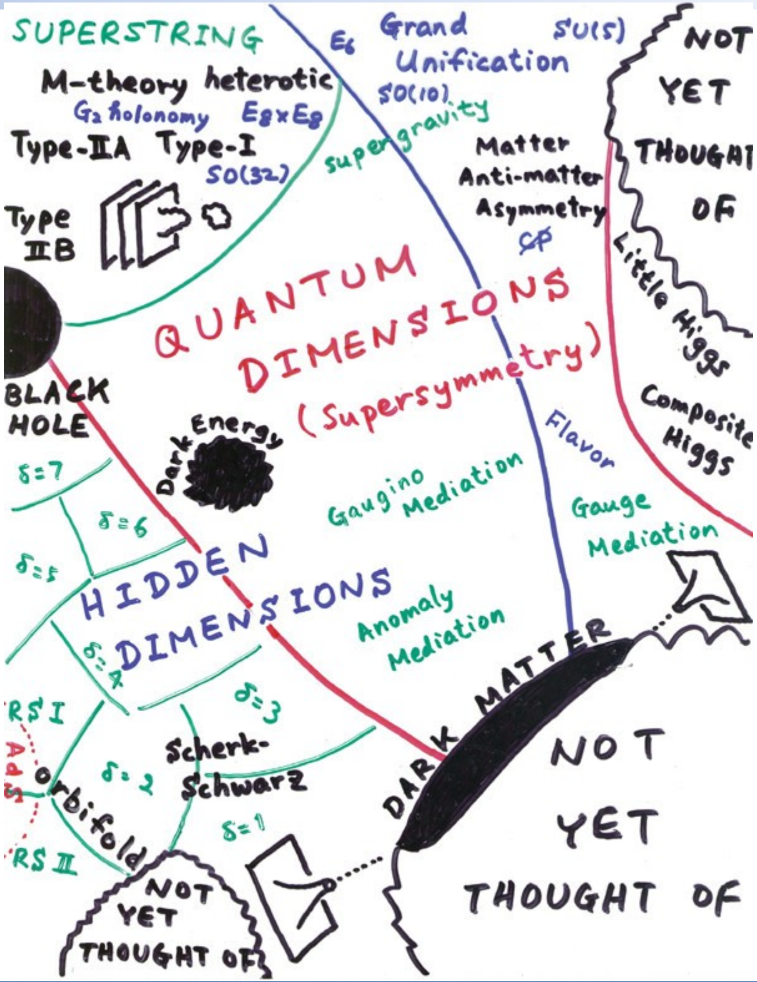




No unification of gauge couplings.

Possible solutions?

Vast amount of theories and ideas proposed to address these open questions.



[Illustration by Hitoshi Murayama]

One solution: Supersymmetry (SUSY)

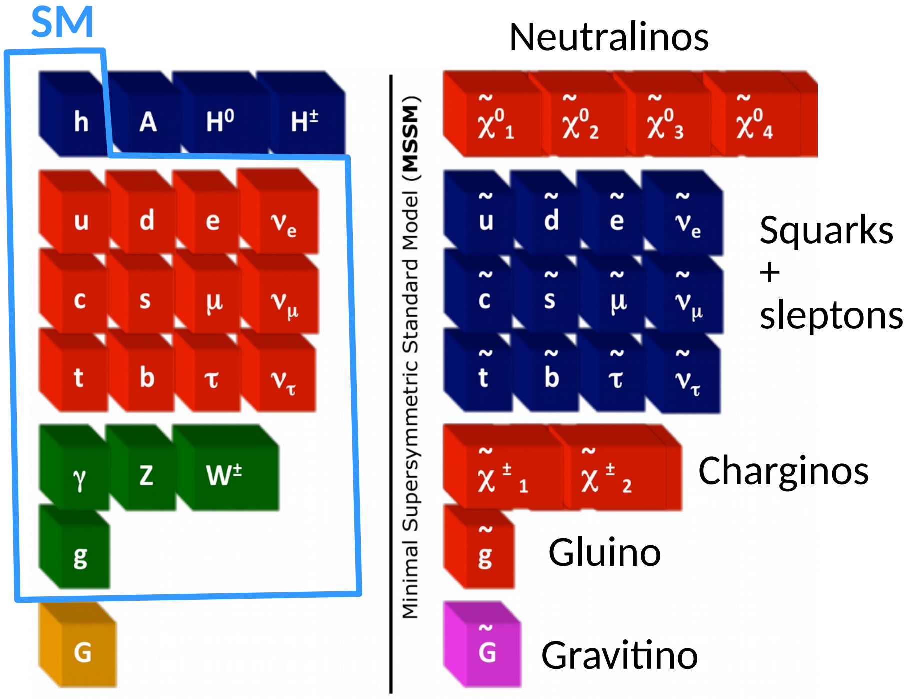
- Symmetry between fermions and bosons
- Supersymmetric partner particles to every Standard Model particle

→ *Roughly doubling the number of particles wrt Standard Model in the* ***M****inimal* ***S****upersymmetric* ***S****tandard* ***M****odel (MSSM).*

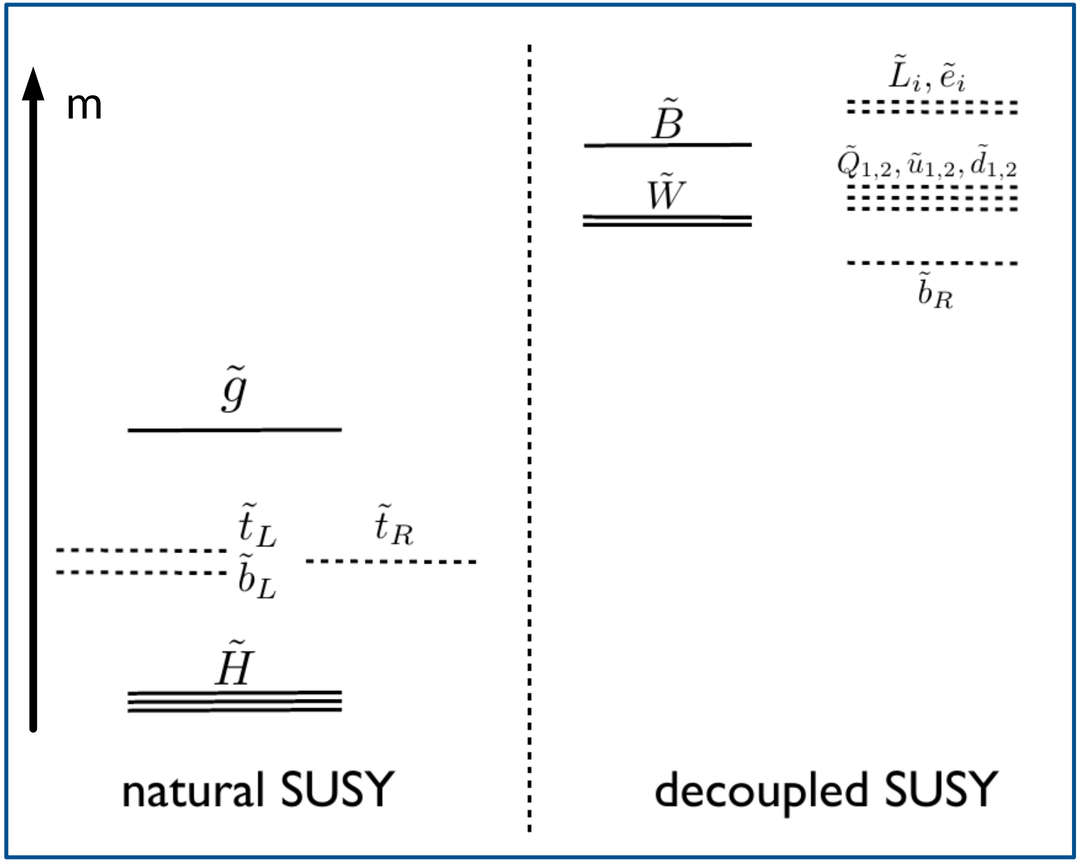
Extended Higgs sector necessary.

Lightest supersymmetric particle (LSP) stable in R-parity conserving SUSY theories.

Possible dark matter candidates, Higgs boson mass stabilized, possible unification of inverse gauge couplings,…



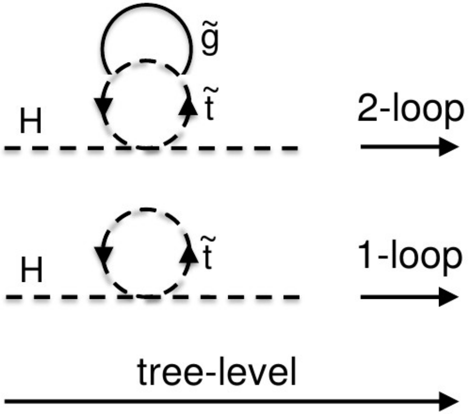
Natural SUSY



[JHEP 1209 (2012) 035]

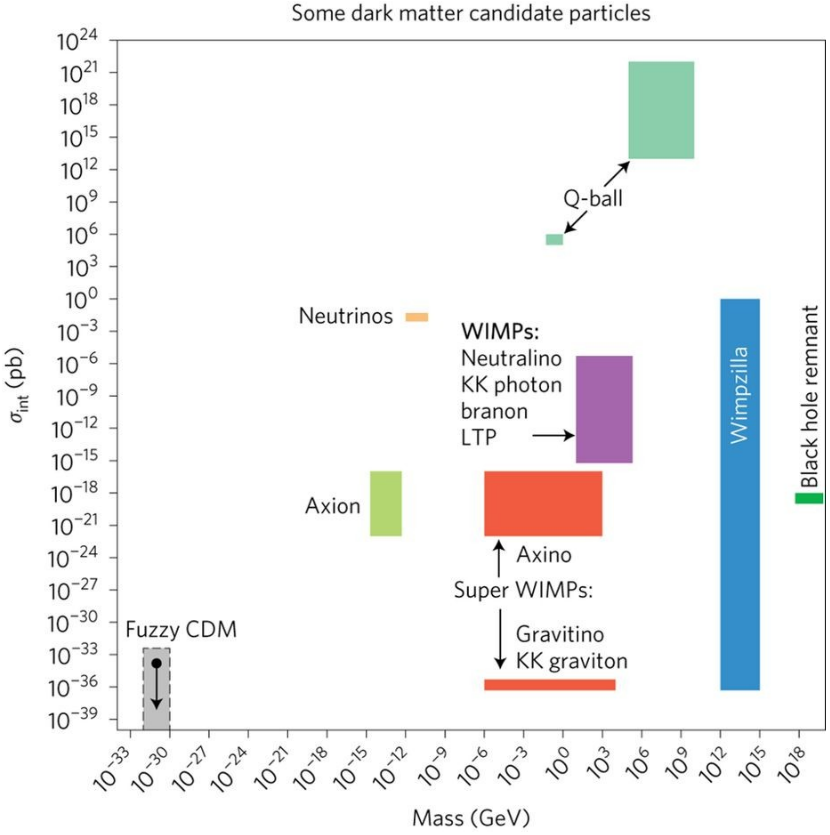
In MSSM **stop masses enter at one-loop** level into Higgs mass matrix, **gluino masses at two-loop level** and the **higgsino mass parameter μ at tree level**.

→ Searches focus on *natural* SUSY with relatively light stops, gluinos and higgsinos. (And left-handed sbottom due to weak iso-spin symmetry.) Other SUSY particles might be decoupled.



Dark matter candidates

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



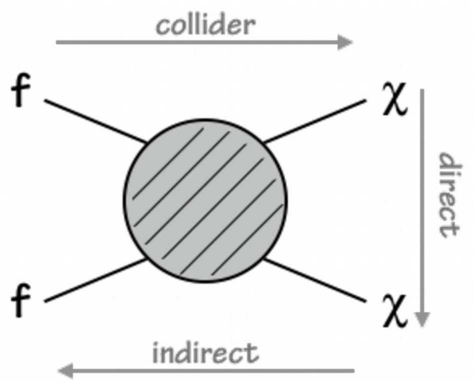
SUSY can provide a DM candidate, but also other possibilities.

→ Often, searches for SUSY can also help in constraining other DM theories.

→ SUSY searches are an essential ingredient in searches for DM in general.

LHC ...

[ATLAS-CONF-2018-051]

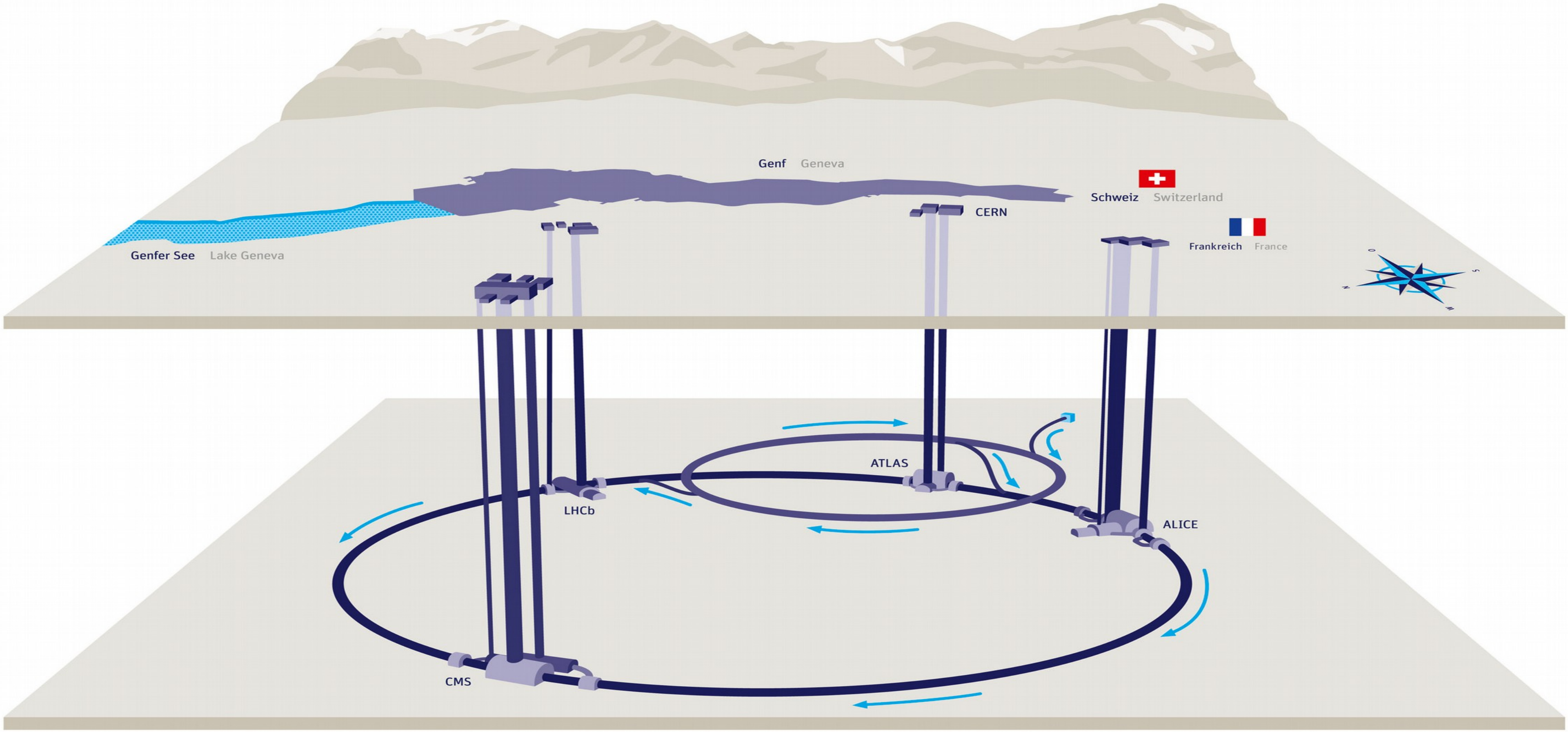


XENON1T, LUX, Panda-X, Picasso...

Fermi-LAT, MAGIC, Planck, H.E.S.S. ...

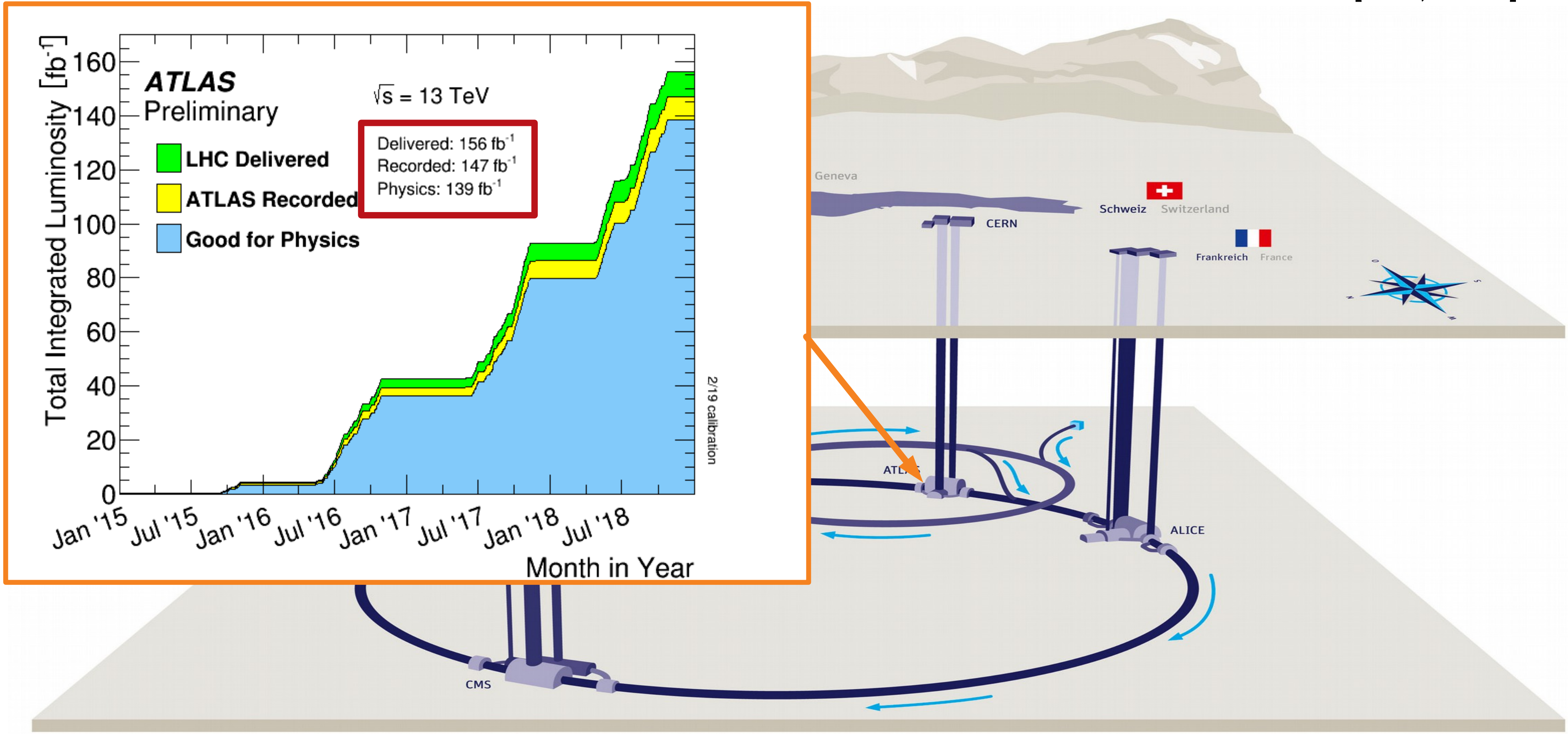
Large Hadron Collider (LHC)

[Link]

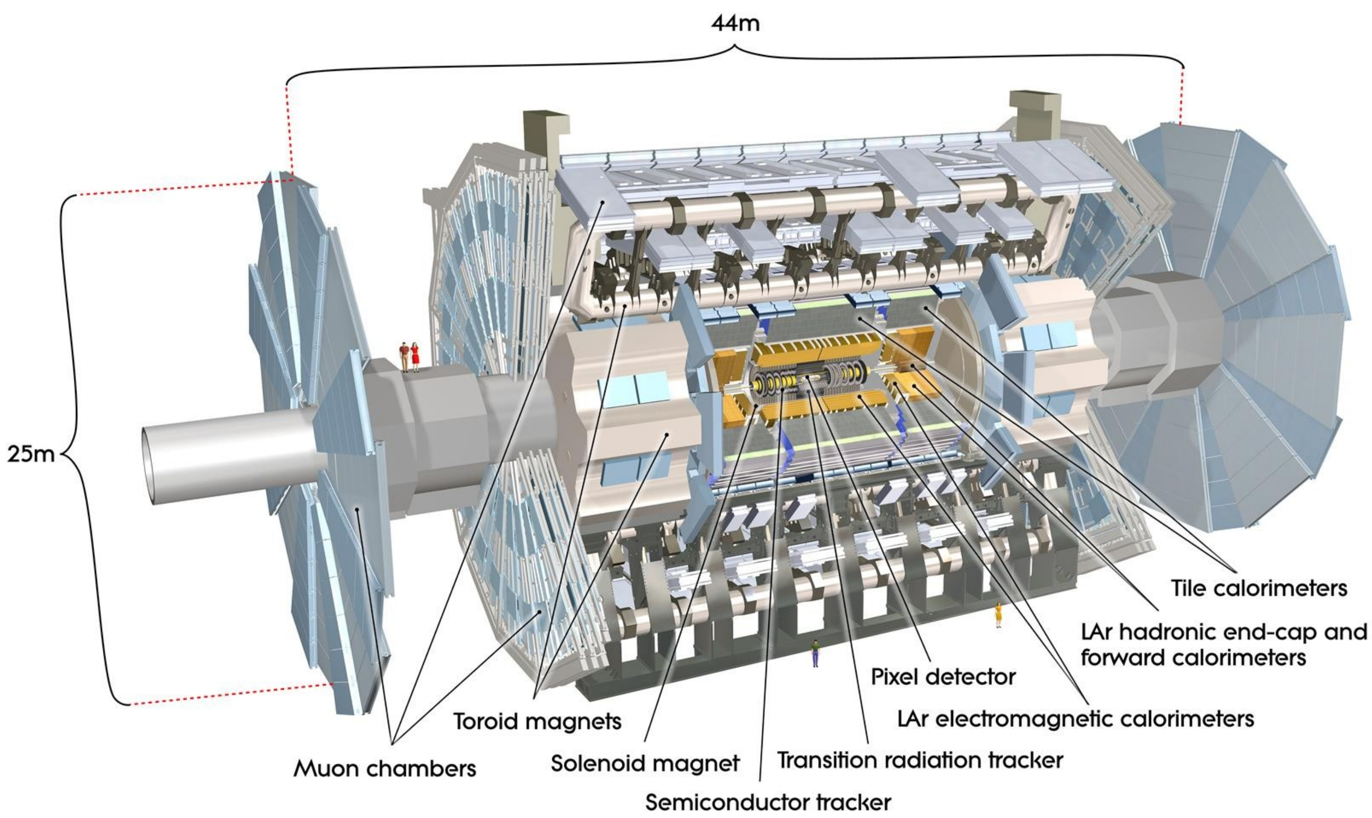


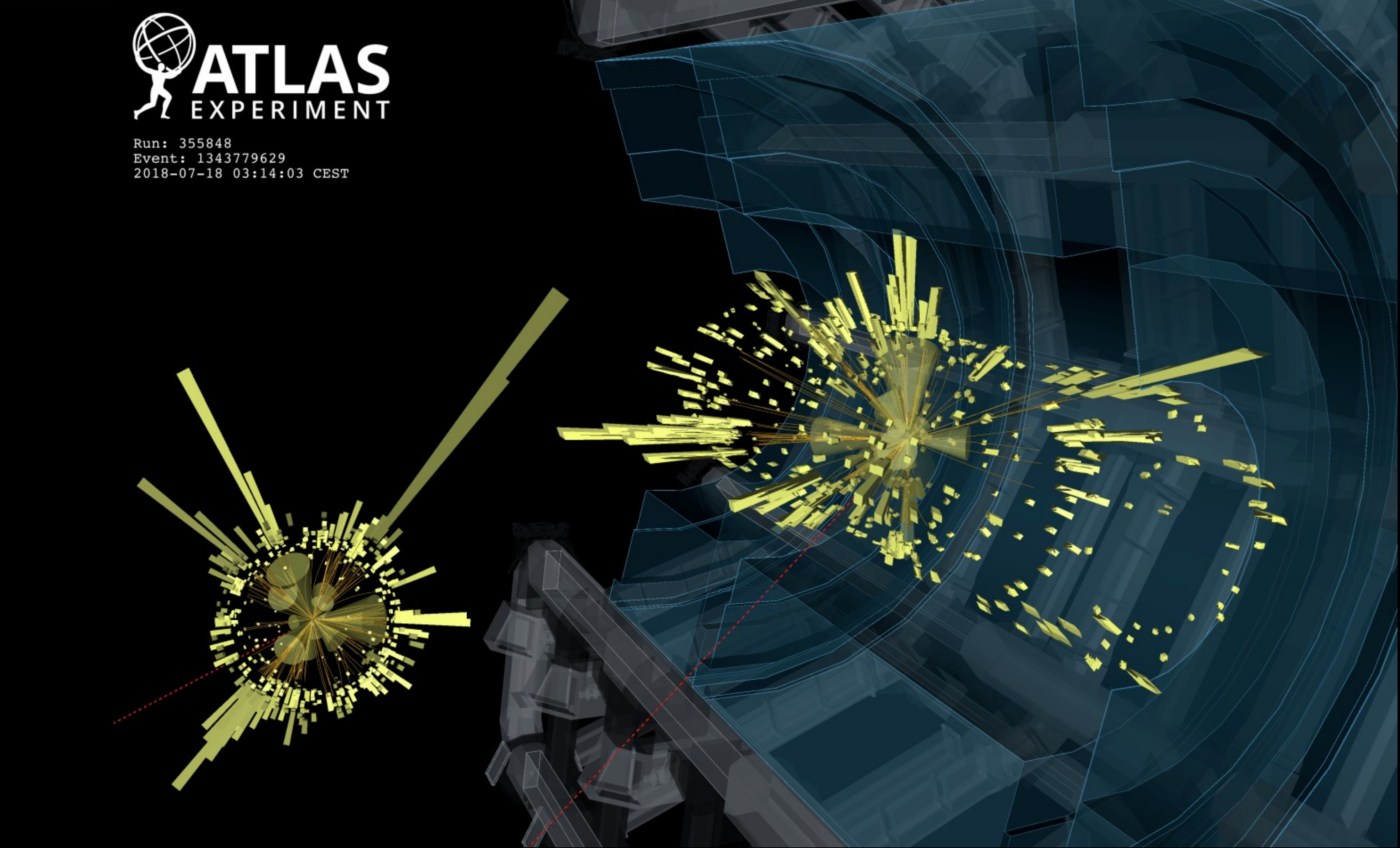
Data statistics

[Link, Link2]



ATLAS detector




ATLAS
EXPERIMENT
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST

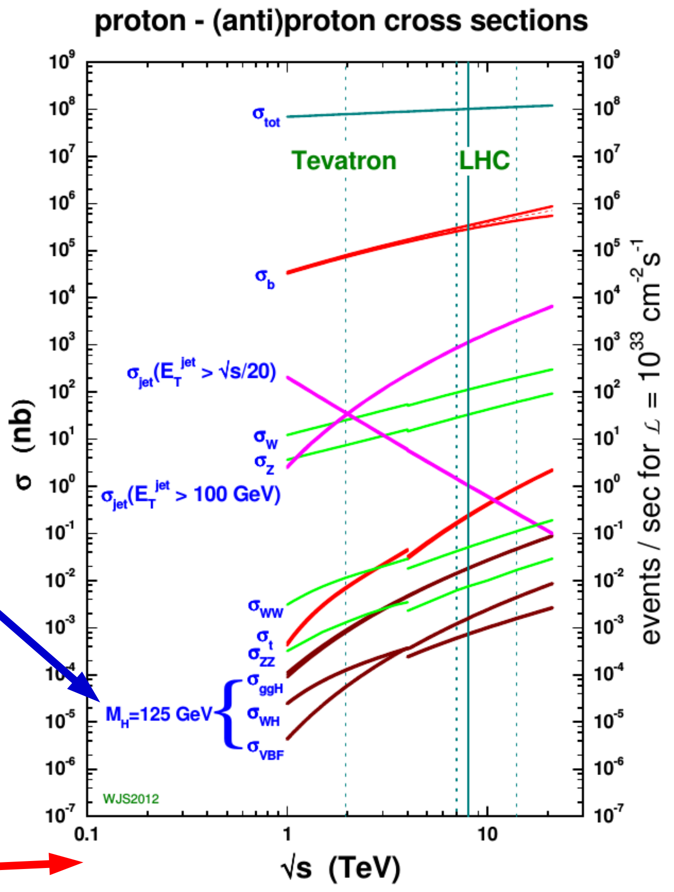
What can we measure at the LHC?

- 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*

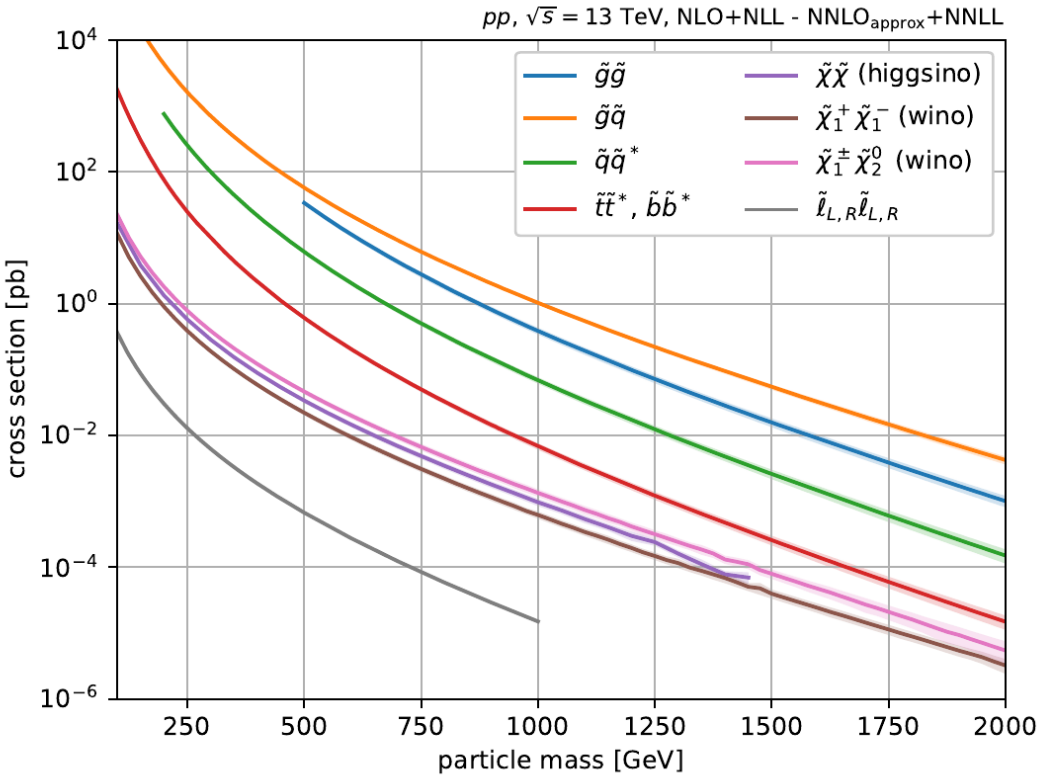
Maybe unknown physics down there? E.g. SUSY



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

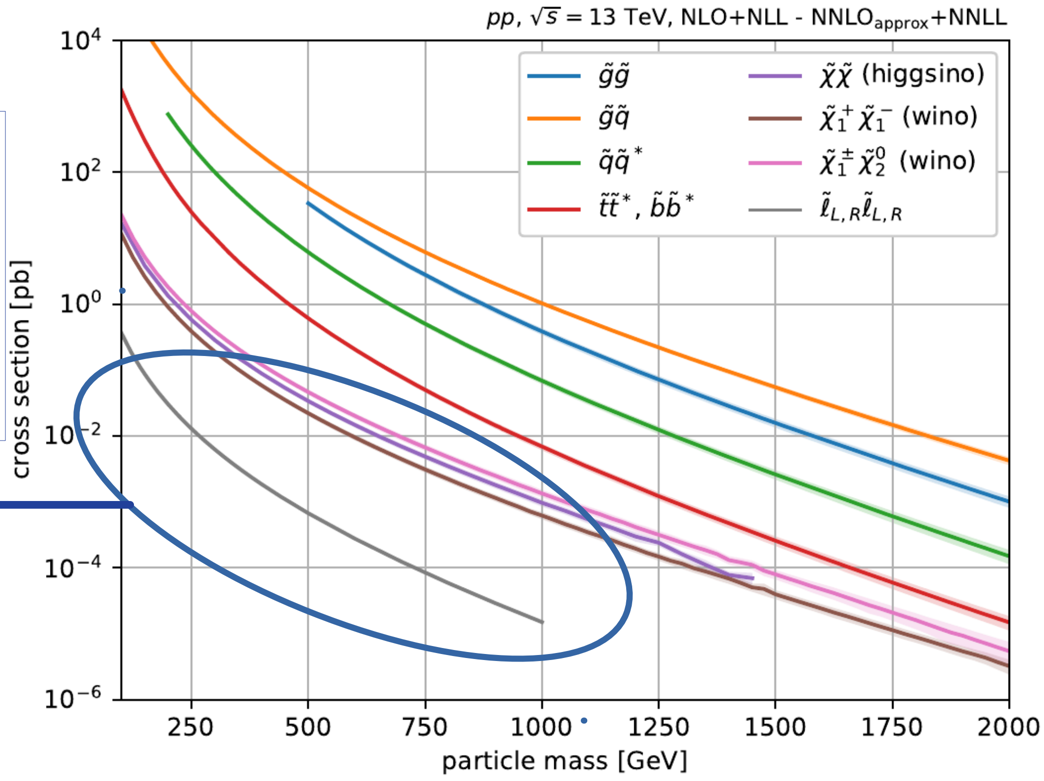
SUSY searches

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections]



SUSY searches

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections]



Electroweak SUSY searches

→ Small cross sections. Profit from full Run-2 statistics

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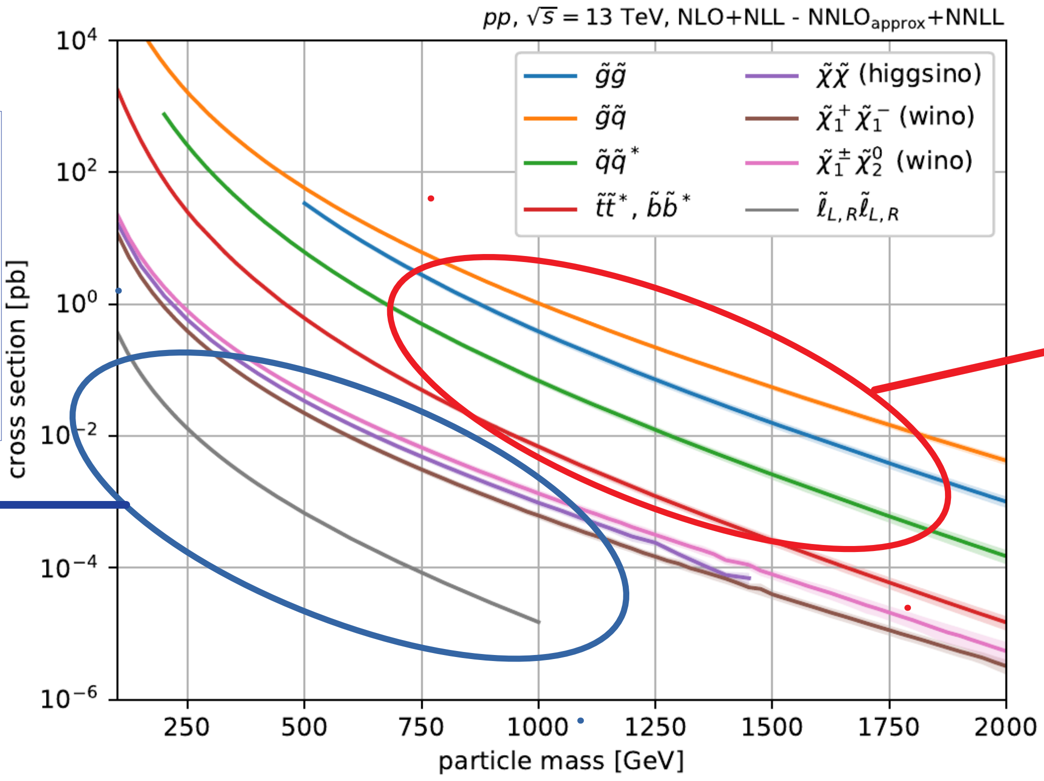
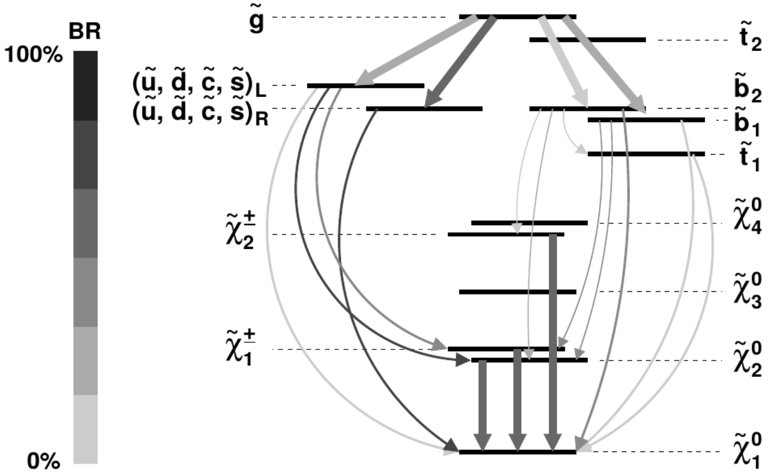


Searches for gluinos/squarks/ stops/sbottoms

→ Profit more from the CMS energy. Plenty of statistics allow for the use of very sophisticated analysis techniques.

Supersymmetric models

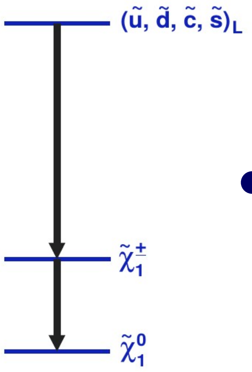


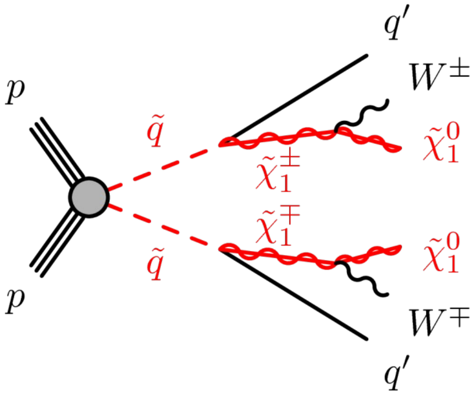
In case of MSSM 124 free parameters!

We cannot deal with that many free parameters!*

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

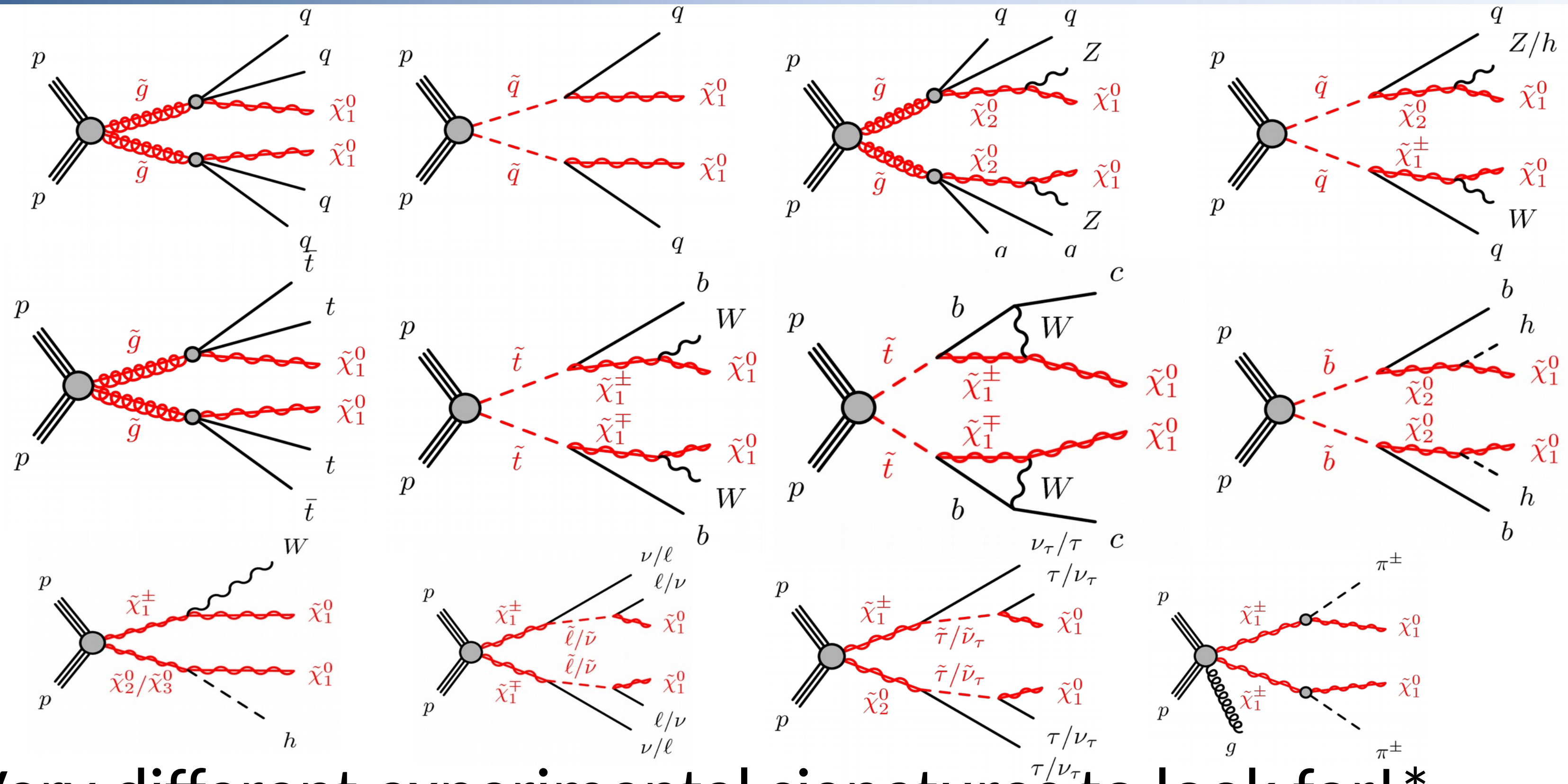
Usually only look at a specific decay chain





Simplified model

Many different simplified models



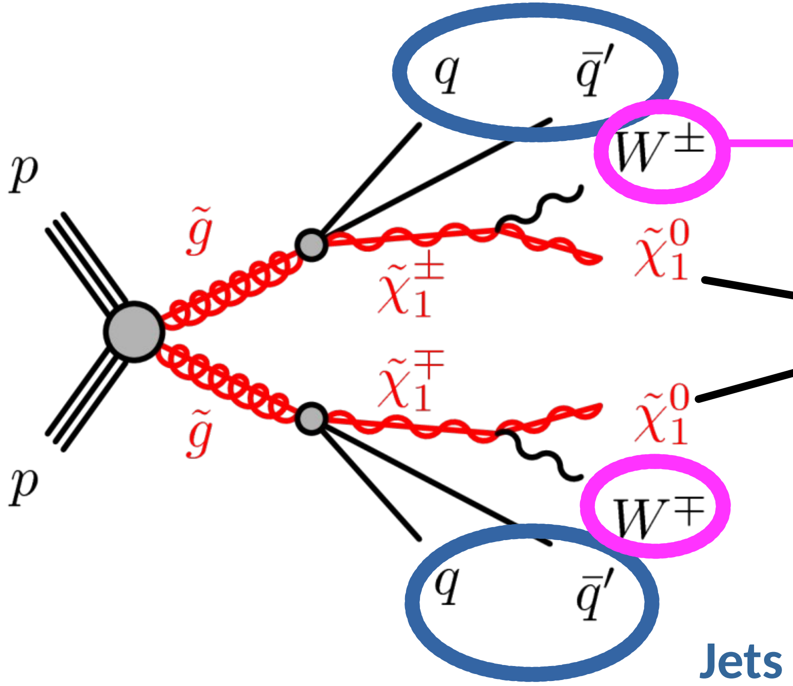
. . .

=> Very different experimental signatures to look for! *

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

Example signature

E. g. strong production of gluinos:



Possibly leptons

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

→ Jets + leptons + E_T^{miss}

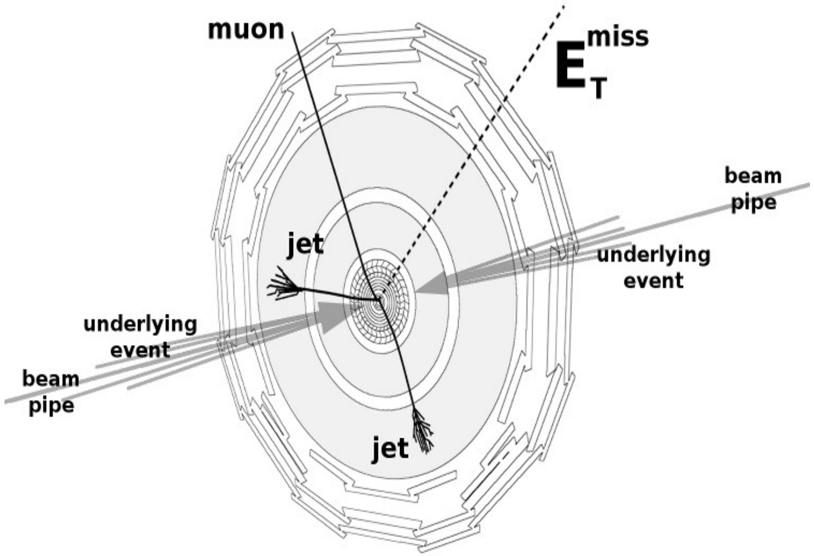
E_T^{miss} + E_T^{miss} significance

[ATLAS-CONF-2018-038]

Particles invisible to the detector (like neutrinos or dark matter particles) result in a momentum imbalance in the perpendicular plane to the beam direction.

→ **missing transverse momentum** (E_T^{miss})

[Jet Goodson]



Object-based E_T^{miss} significance

Provides measure of how inconsistent E_T^{miss} is with originating purely from fluctuations and mismeasurement

→ *High if from non-interacting particles*

$$S^2 = 2\ln\left(\frac{\max_{\vec{p}_T^{\,\rm inv}\neq 0} \mathcal{L}\left(\vec{E}_T^{\rm miss}|\vec{p}_T^{\,\rm inv}\right)}{\max_{\vec{p}_T^{\,\rm inv}=0} \mathcal{L}\left(\vec{E}_T^{\rm miss}|\vec{p}_T^{\,\rm inv}\right)}\right)$$

Computed using energy and momentum resolutions of all objects entering E_T^{miss} calculation.

Distinguish signal from background

Use kinematic variables to discriminate signal from background.

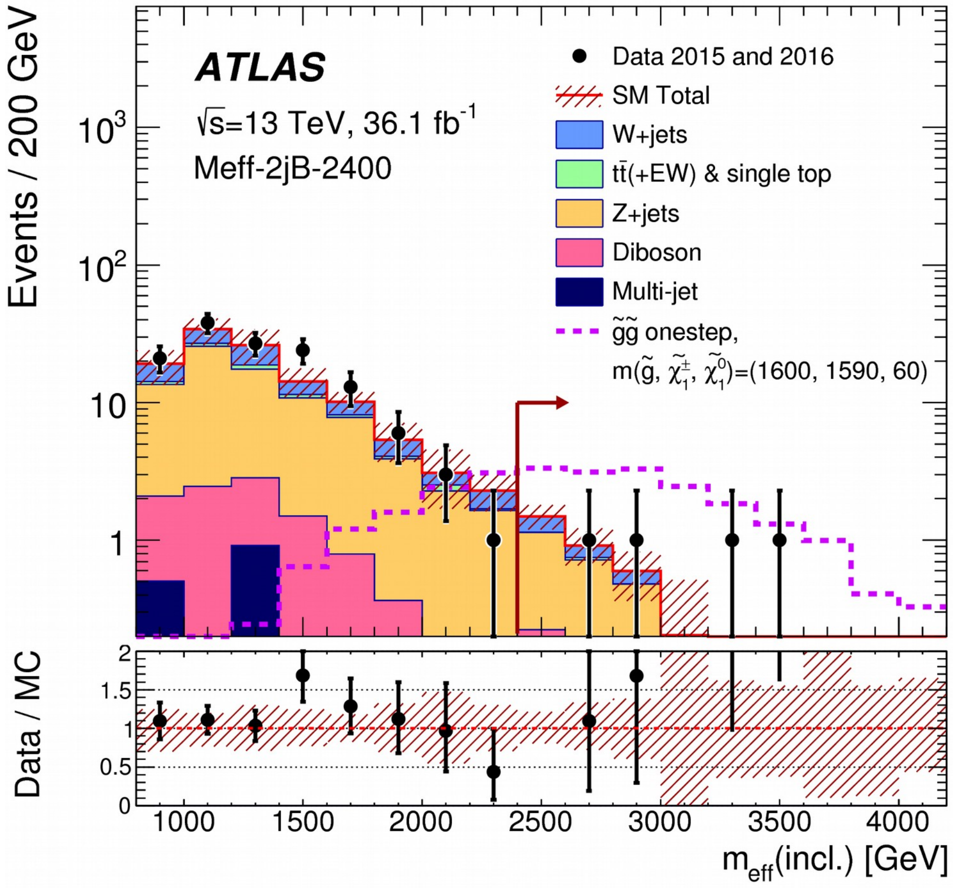
E.g. $m_{eff} = \sum p_T^{jets} + \sum p_T^{leptons} + E_T^{miss}$

→ *Correlated with mass of pair-produced SUSY particles and mass difference between heaviest and lightest SUSY particle in decay cascade.*

Analysis strategy:

→ *Some analyses use simple combination of cuts on kinematic variables → 'cut-and-count', but most analyses perform a shape analysis (multi-bin fit) or use sophisticated techniques, e.g. machine learning.*

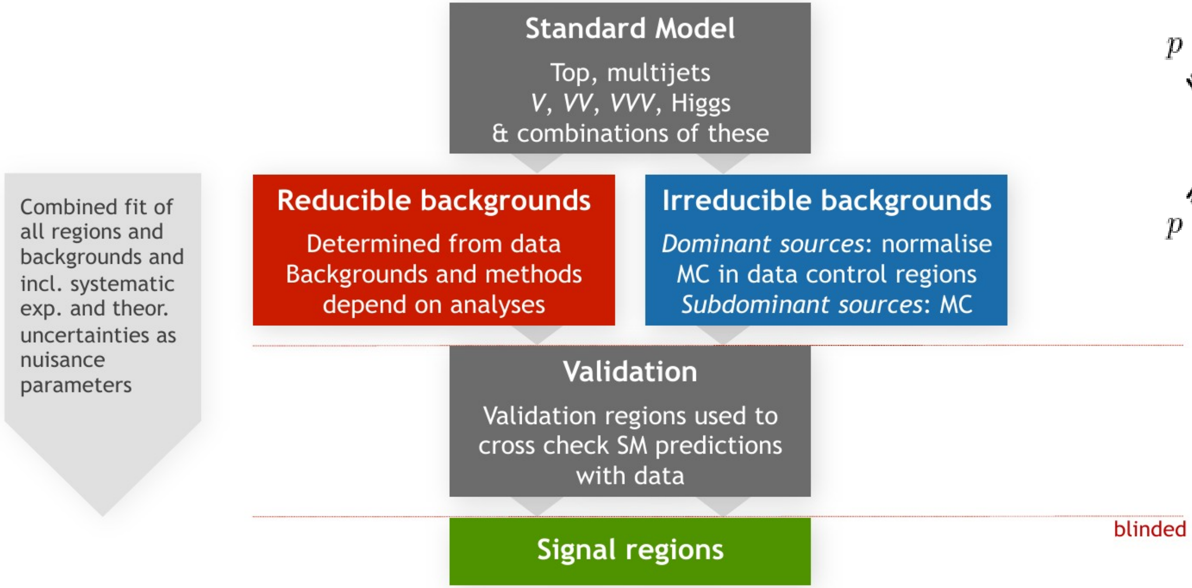
Comparison of methods very interesting!

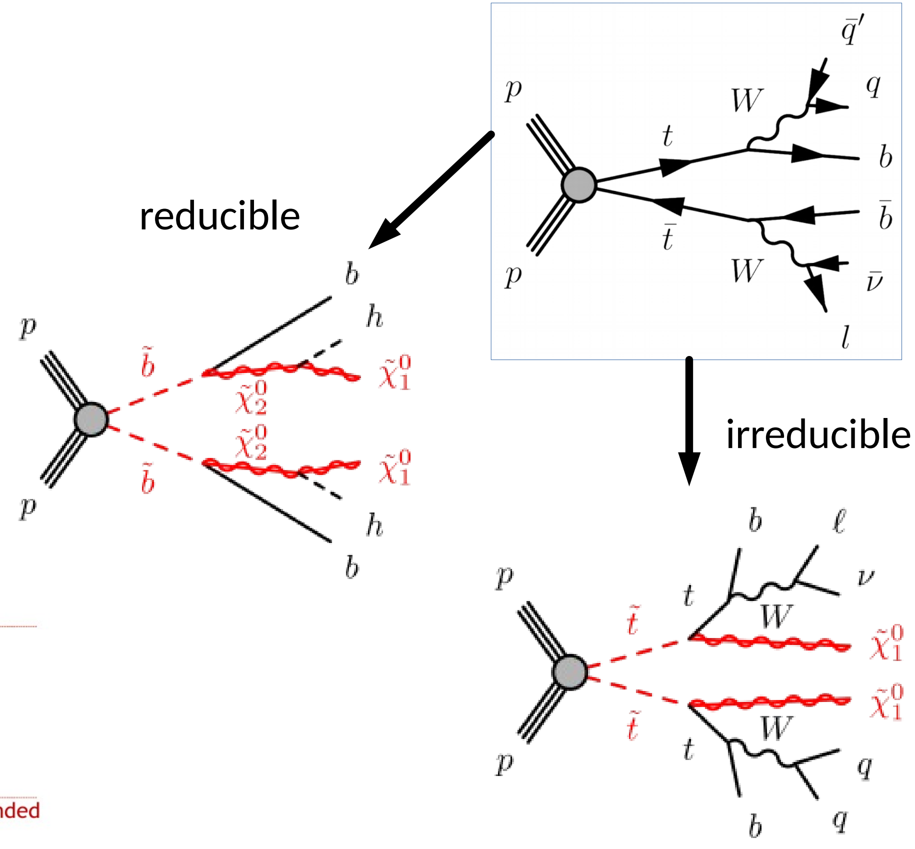


[Phys. Rev. D 97 (2018) 112001]

Analysis flow – background estimation

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



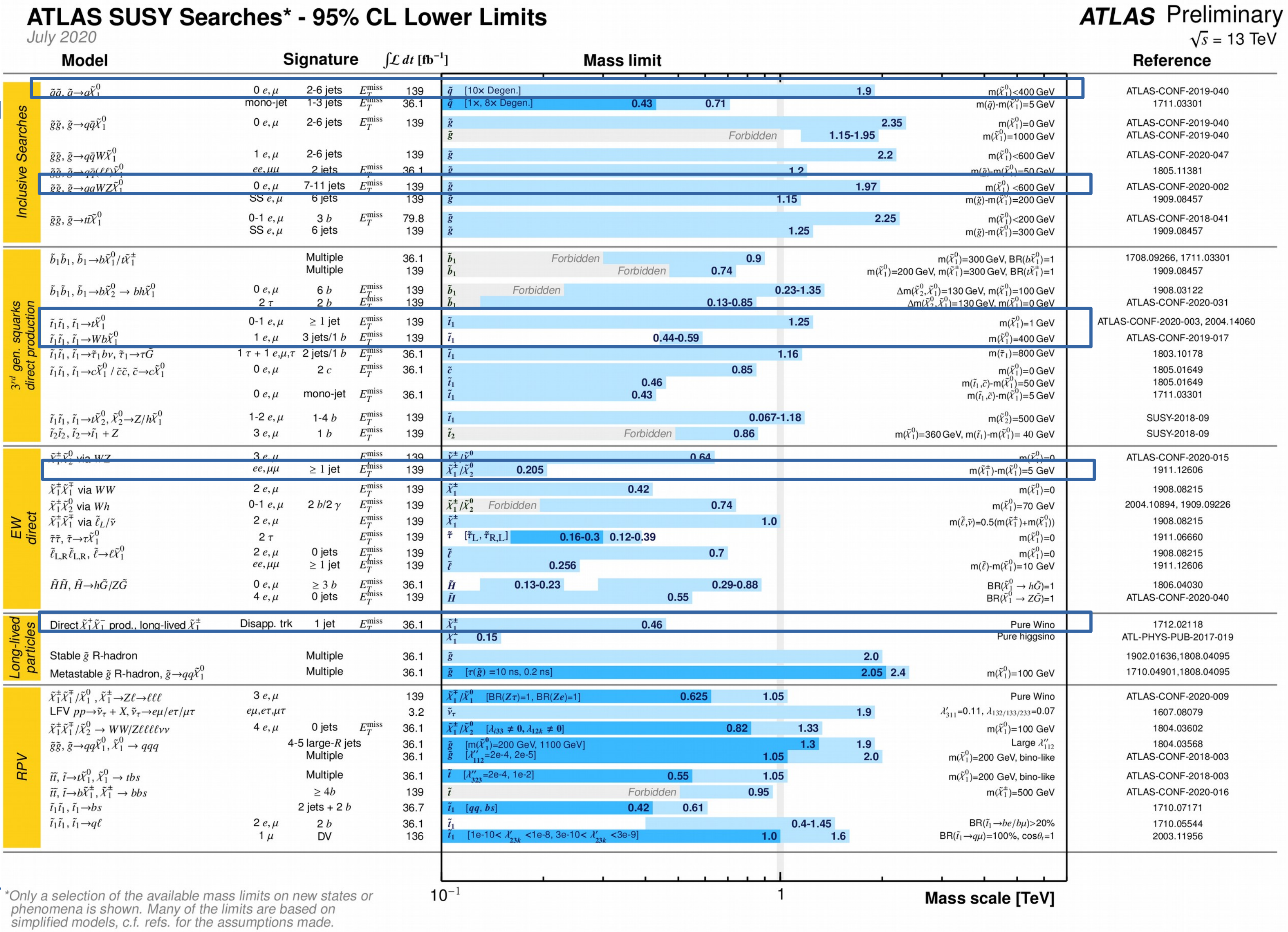


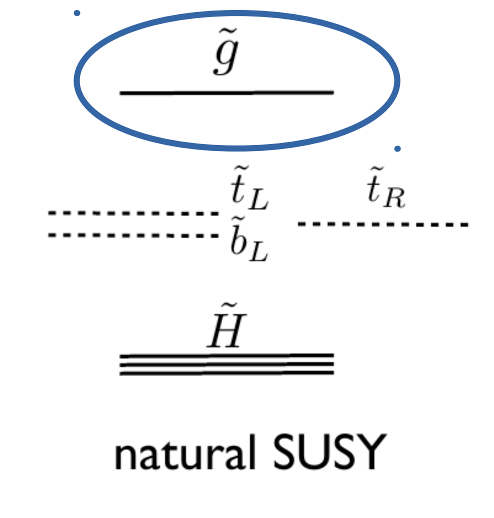
Comprehensive search program
→ *presenting only a few highlights*

Also demonstrating:

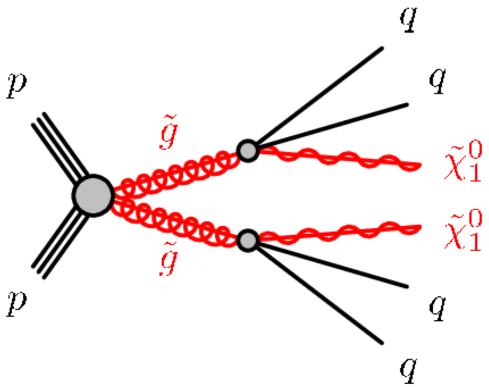
- Sophisticated analysis techniques,
- Applications of results to other BSM scenarios,
- How to use these results and where to go with this!

Results available at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults





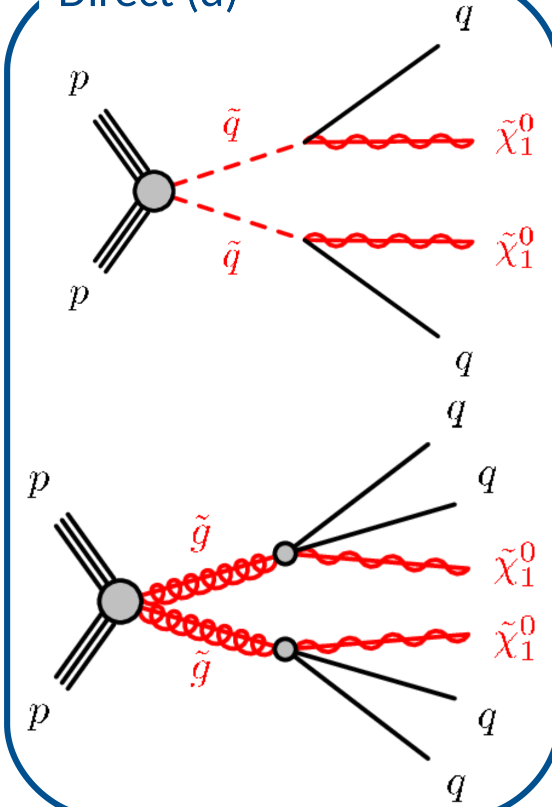
Searches for gluinos



Search for squarks and gluinos in final states with jets

JHEP 02 (2021) 143

Direct (d)



Target cascade decays of squarks or gluinos into jets + LSPs → E_T^{miss}

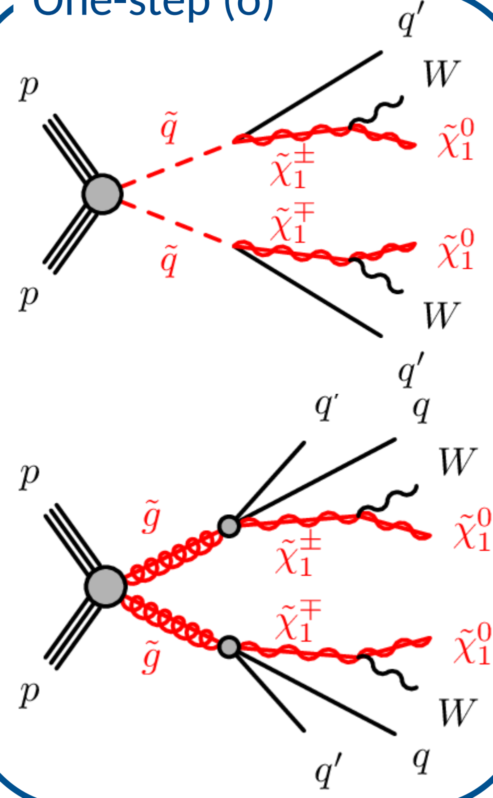
Squark pair-production, direct **→ ≥ 2 jets**

Gluino pair-production, direct **→ ≥ 4 jets**

Squark pair-production, via chargino **→ ≥ 2 - 6 jets**

Gluino pair-production, via chargino **→ ≥ 4 - 8 jets**

One-step (o)

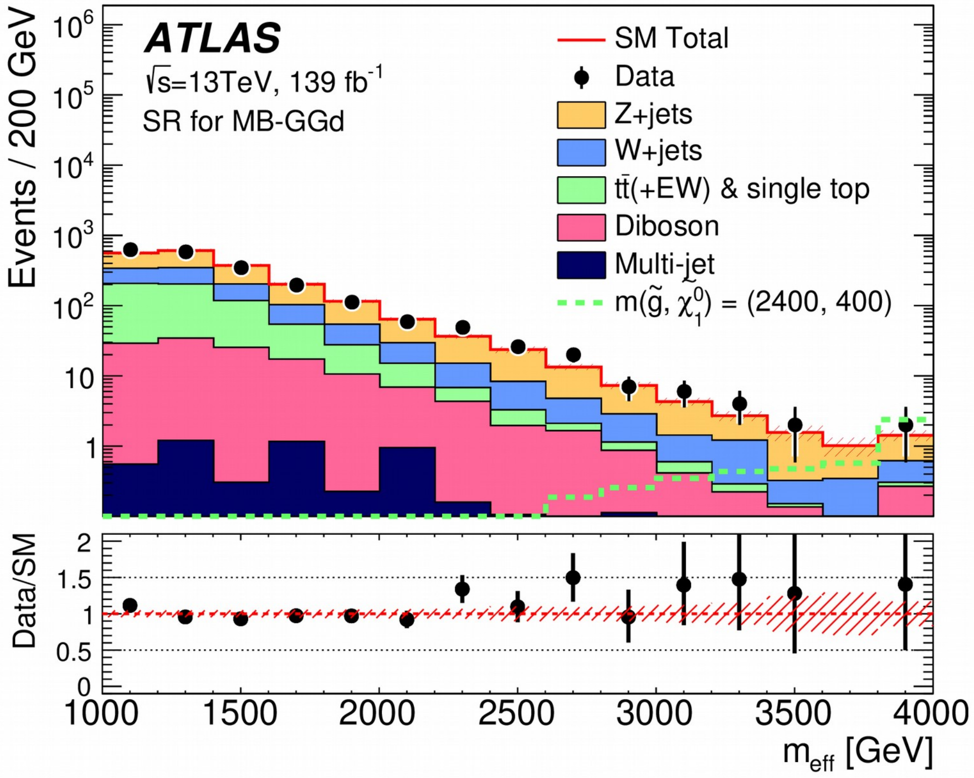


Signal regions

[JHEP 02 (2021) 143]

Three complementary set of signal regions

- **Multi-bin:**
  → *Three sets of SRs, requiring ≥ 2 jets to cover wide range of possible cascade decays.*
  → *Binned in jet multiplicity, m_{eff} and $E_T^{miss}/\sqrt{H_T}$*
  $\left(H_T = \sum p_T^{jets}\right)$
- **Boosted decision trees:**
  → *Better use of correlated variables for one-step gluino decays.*
  → *8 regions, trained individually.*
  → *Preselection on jet multiplicity, E_T^{miss}/m_{eff} and m_{eff} before training.*
- **Model-independent** → *one bin*

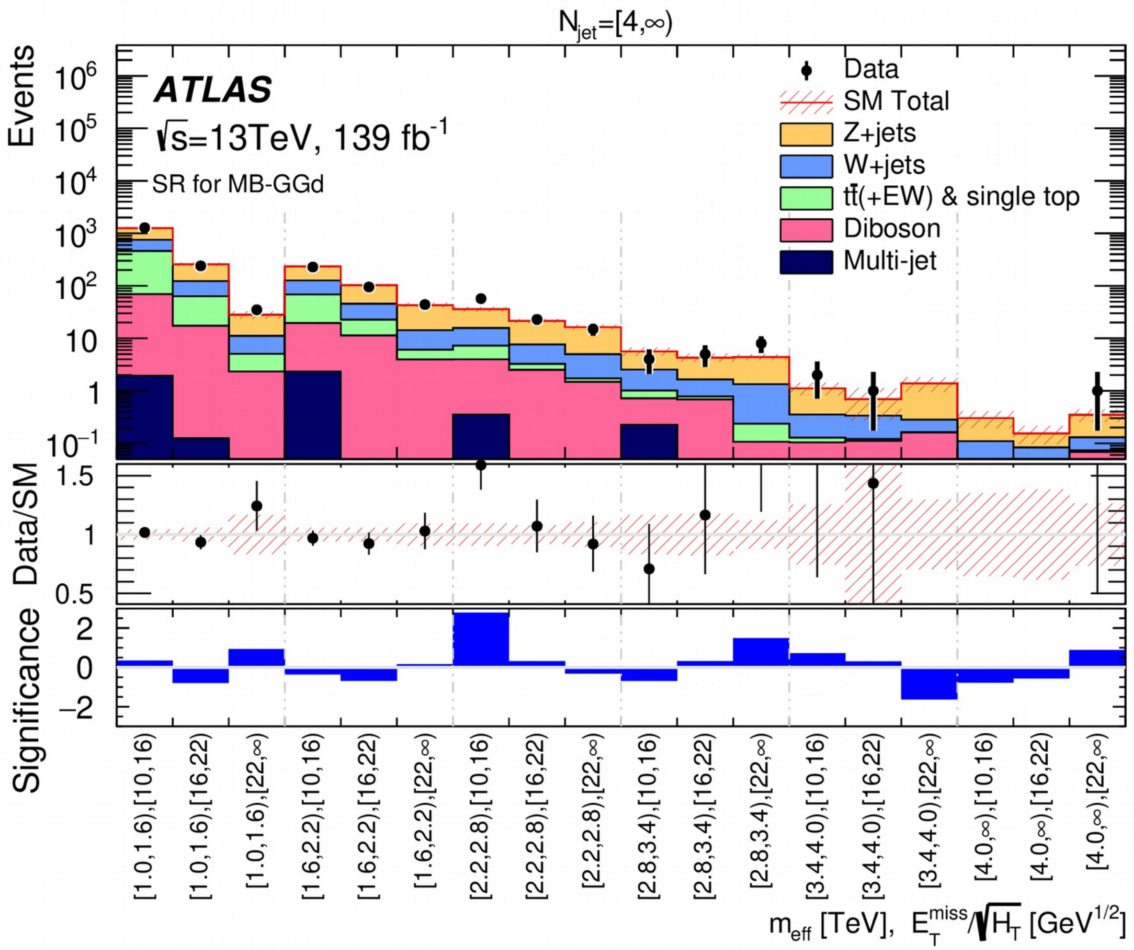


Results

[JHEP 02 (2021) 143]

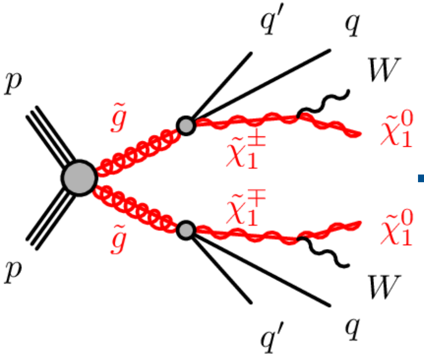
No significant deviation from SM prediction in any of the SR bins.

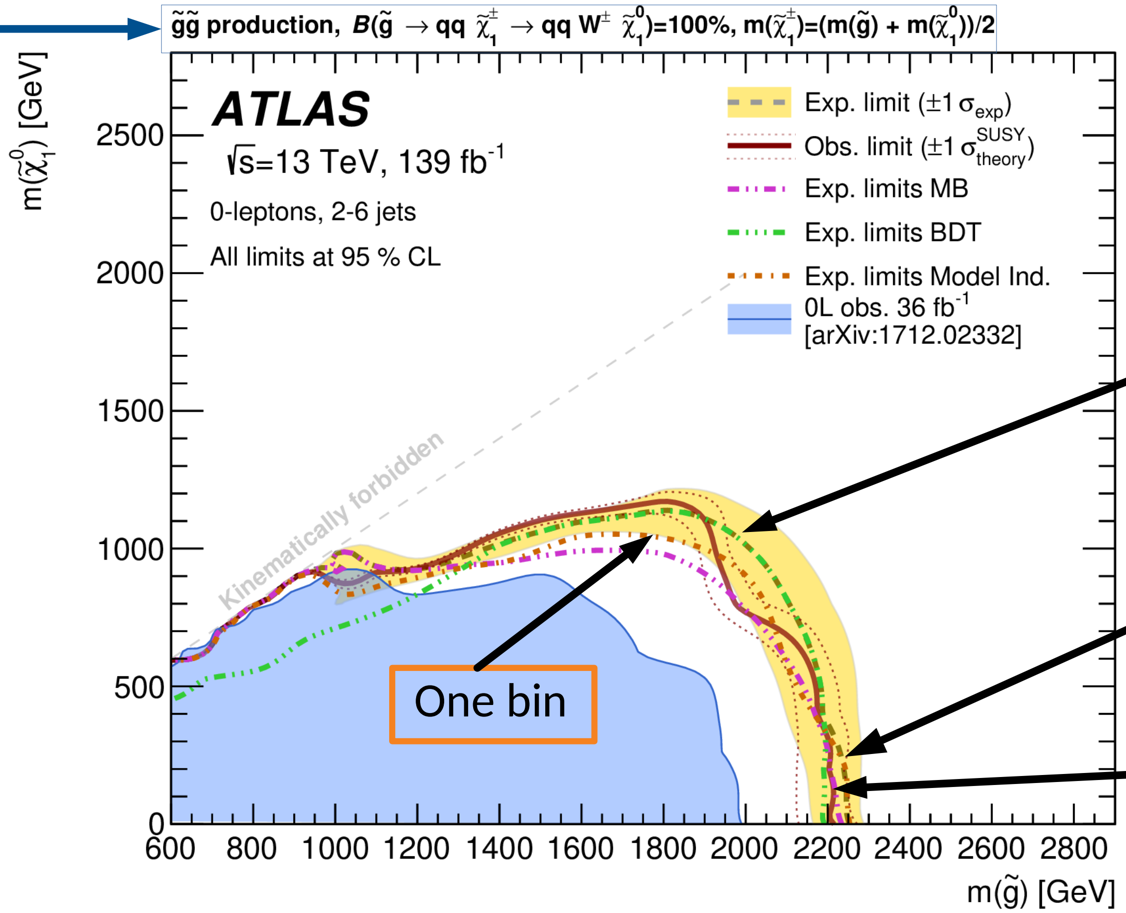
E.g. multi-bin SRs for gluino pair-production with direct decays



Exclusion limits

[JHEP 02 (2021) 143]





Limits only valid for specific simplified model!

Expected limit BDTs

Expected limit multi-bin

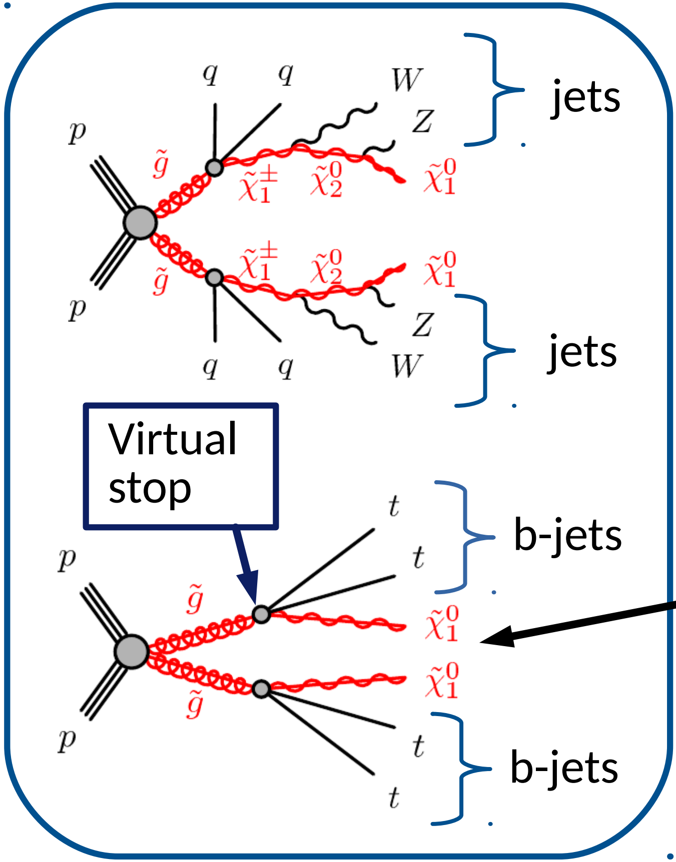
Observed limit (best-expected of the two strategies)

BDTs outperform multi-bin SRs for medium mass splittings gluino – LSP.

Limits up to 2.22 TeV for massless LSPs.

Search for gluinos in final states with large jet multiplicities (including b-jets)

JHEP 10 (2020) 062

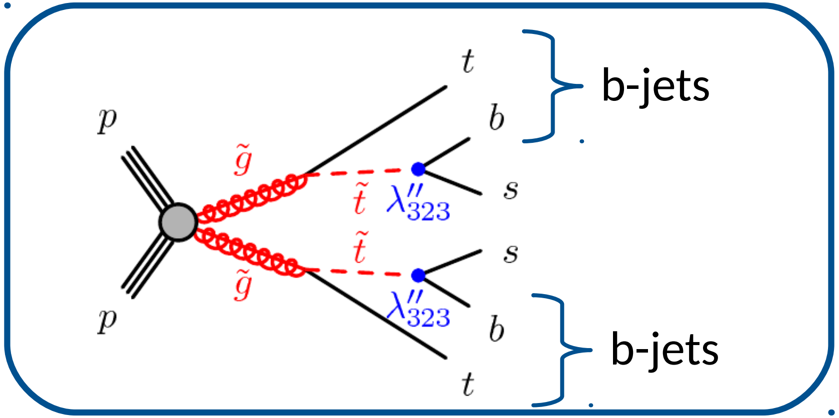


Search targets long cascade decays of heavy SUSY particles

→ *Large jet multiplicity,*
→ *Including b-jets if tops created in decay,*
→ *E_T^{miss} from stable LSPs (RPC decays) or neutrinos (RPV decays).*

Model highly motivated by naturalness!

RPC RPV



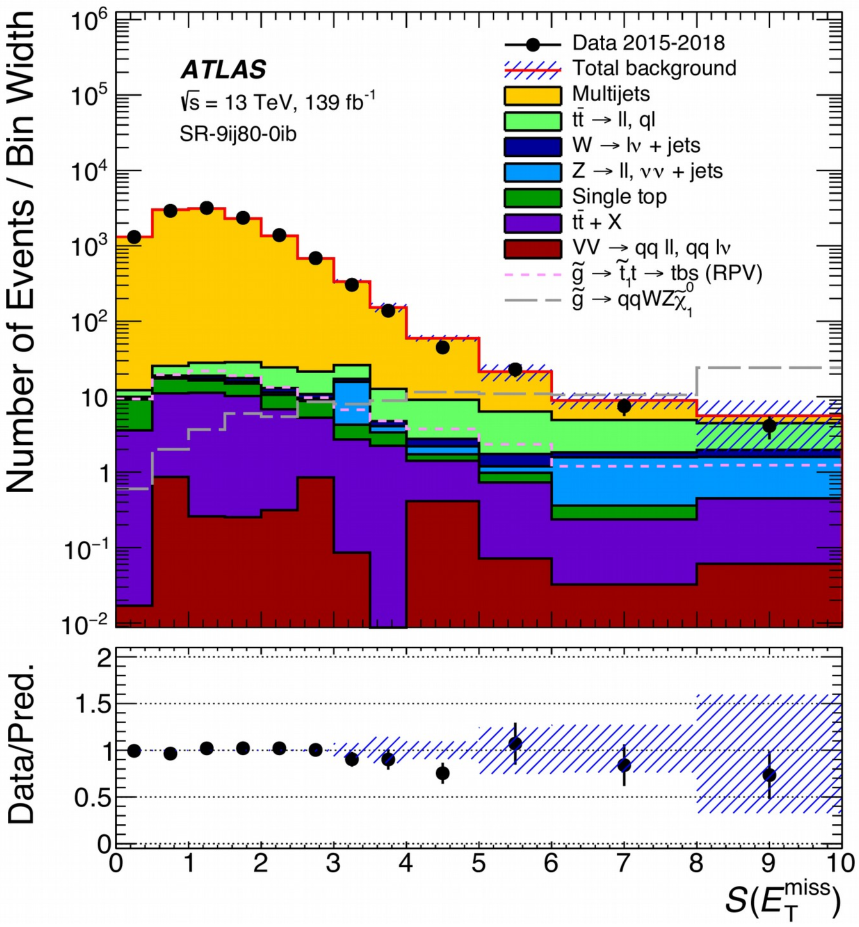
Signal regions

[JHEP 10 (2020) 062]

- Select events with ≥ 8,9,10,11,12 jets.
- Veto electrons or muons.
- Event categories in different b-tagging requirements (0,1 or 2 b-tagged jets) and in

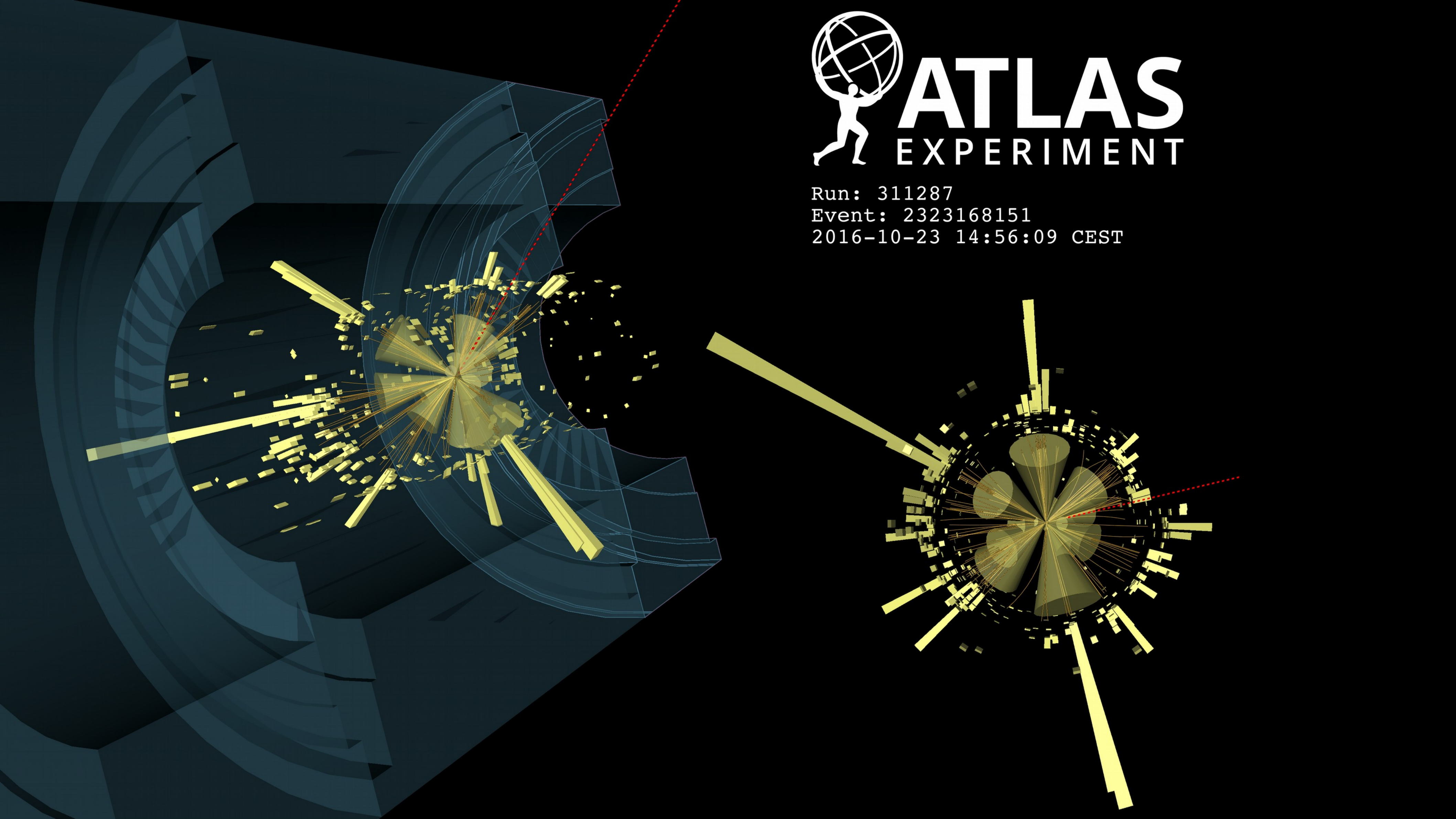
$$M_J^{\Sigma} = \sum_j m_j^{R=1.0}$$

(sum of mass of large-R=1.0 jets)



Powerful sensitivity:

- Use of object-based **E_T^{miss} significance**
- First SUSY analysis to use **PFlow jets –** jets using information from the calorimeters and the inner detector.
- Multi-bin fit.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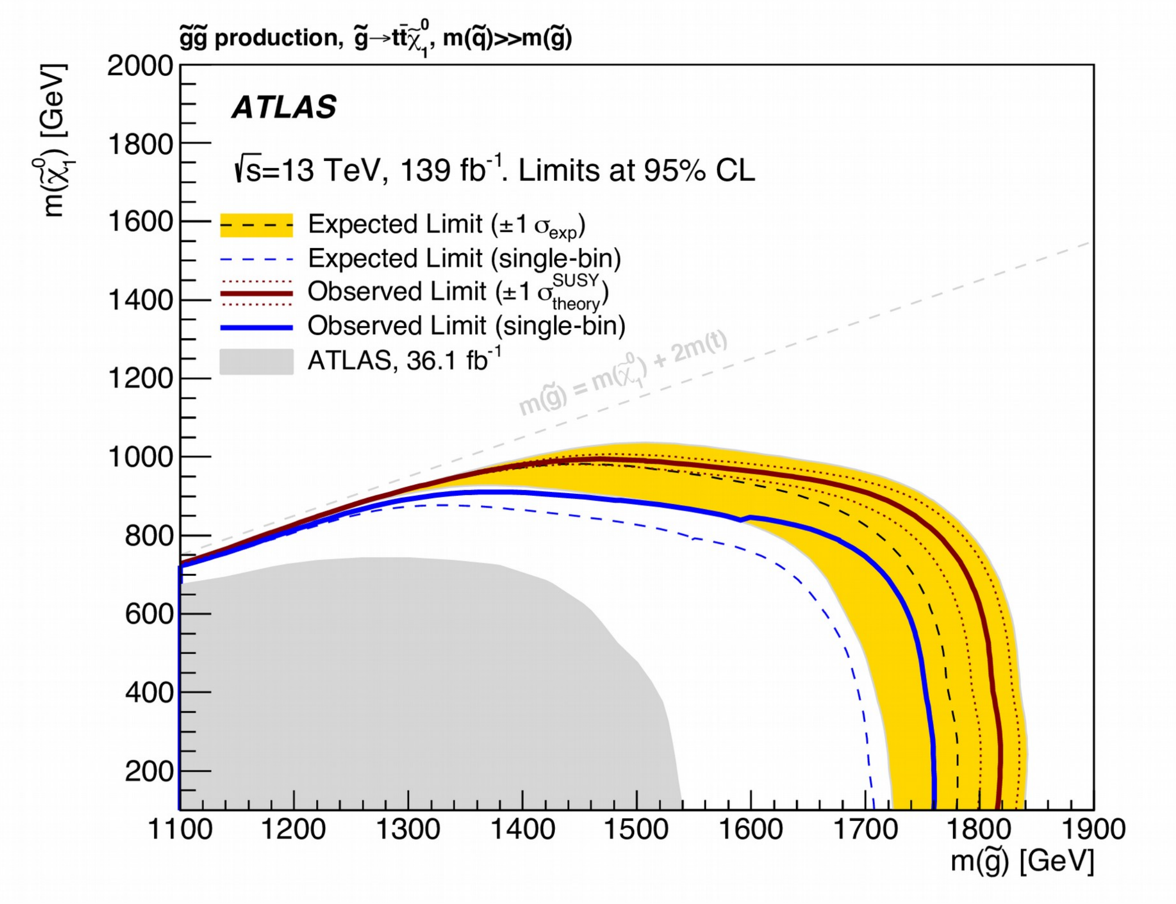
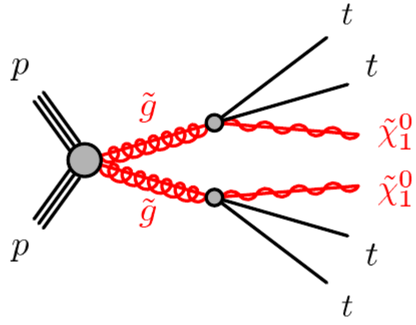
Limits on natural SUSY

[JHEP 10 (2020) 062]



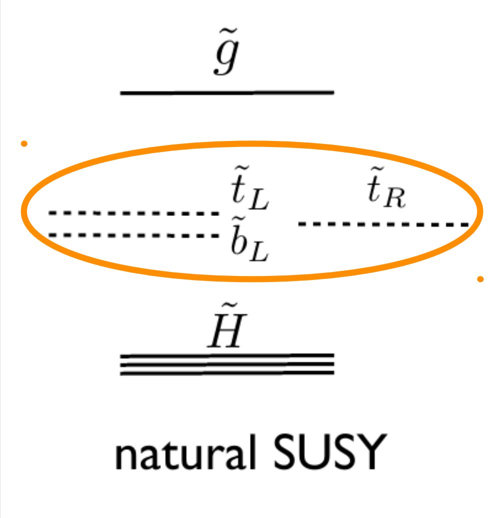
No significant excess over SM expectations seen.



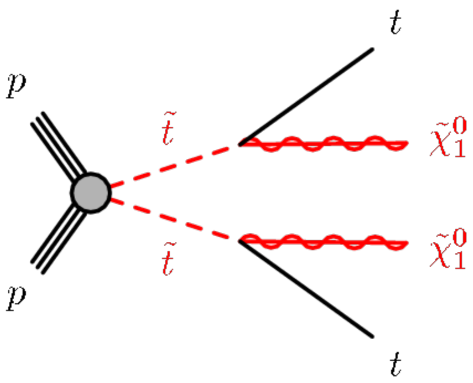
Model motivated by naturalness. Final state very rich in b-jets → use case for the b-jet rich signal regions.

Exclude gluino masses at most up to 1.8 TeV.

Clear improvement due to the multi-bin fit.



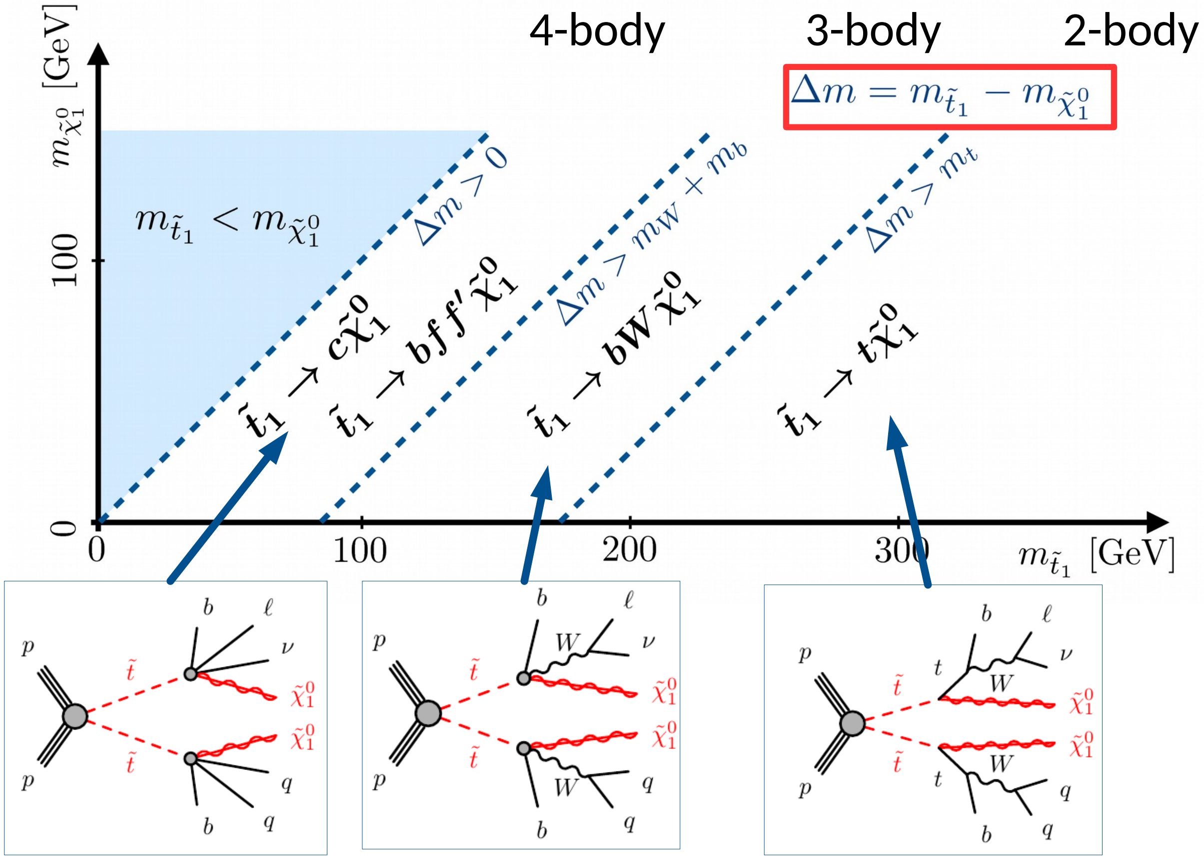
Searches for stops



Search for stops in final states with a lepton

arXiv:2012.03799

Search targets stop decays to final states with an isolated electron or a muon.



Highlights!

- 2-body with special signal regions for Δm = m(top), using specialized variables, e.g. hadronic top tagging.
- 3-body with a set of neural networks.
- 4-body with signal region requiring soft objects or signal region using soft b-tagging.

2-body

[arXiv:2012.03799]

Four signal regions:

- High Δm(stop,LSP) >> m(top):

  → *Two signal regions relying on multi-bin fit based on E_T^{miss} and*

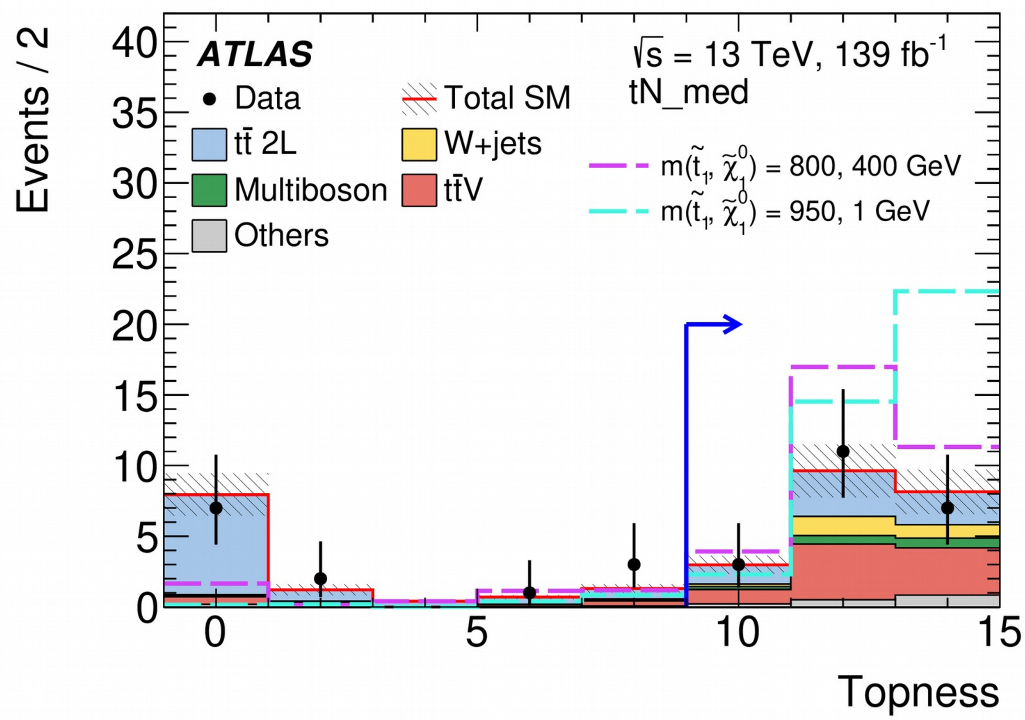
  $$m_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos([\Delta \varphi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})]))}$$

  → *Further criteria on e.g. topness – rejection of di-leptonic decaying $t\bar{t}$ via testing how well an event can be reconstructed under this assumption using a likelihood method.*

- Δm(stop,LSP) ~ m(top):

  → *Signal similar to $t\bar{t}$ production.*

  → *Two signal regions based on selection of an ISR jet, boosting the system.*



$$\mathcal{S}(p_{Wx}, p_{Wy}, p_{Wz}, p_{\nu z}) = \frac{(m_W^2 - p_W^2)^2}{a_W^4} + \frac{(m_t^2 - (p_{b1} + p_\ell + p_\nu)^2)^2}{a_t^4} + \frac{(m_t^2 - (p_{b2} + p_W)^2)^2}{a_t^4} + \frac{(4m_t^2 - (\Sigma_i p_i)^2)^2}{a_{CM}^4},$$

3-body

[arXiv:2012.03799]

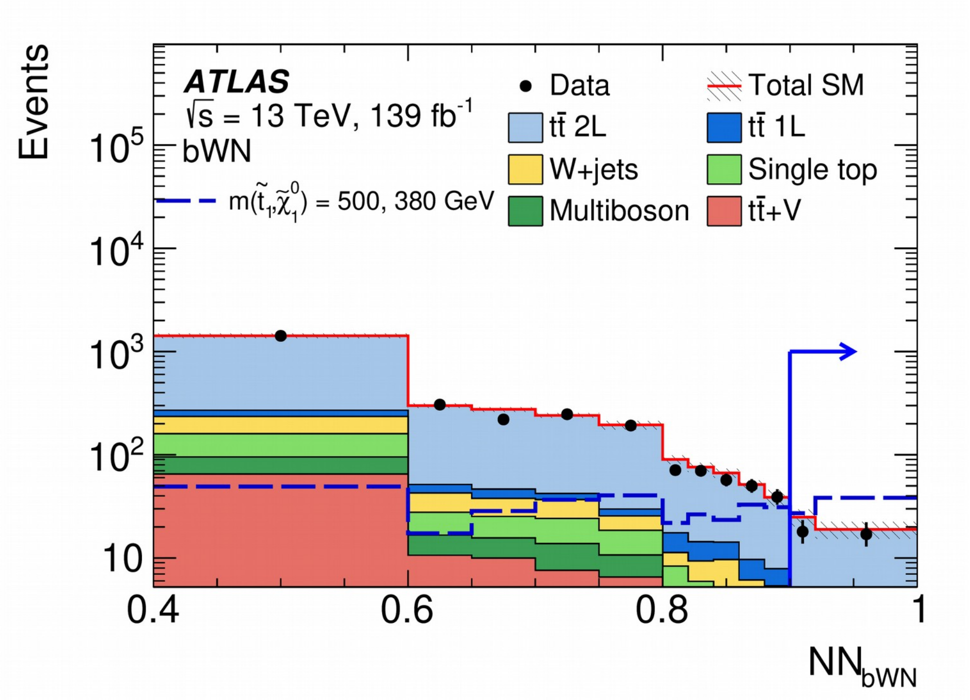
Event selection based on two neural networks:

- **Recurrent neural network** to handle variable-length jet inputs.
- Output of recurrent neural network + high- (E_T^{miss}, m_T) and low-level variables (e.g. momentum and angles of the lepton) fed into a **shallow neural network**.

Multi-bin fit in output of neural networks.

Background estimation via control regions at lower values of the neural network output scores.

Sensitivity not only to 3-body region, but also to neighboring area in 2-body and 4-body regions.



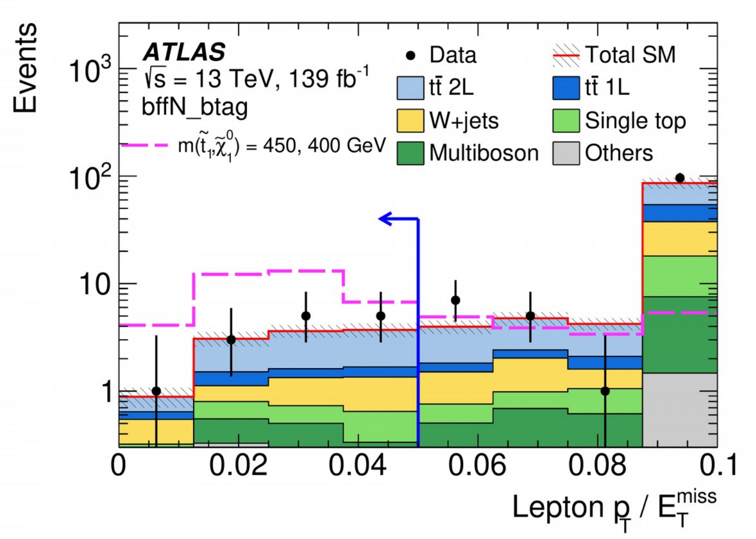
4-body

[arXiv:2012.03799]

Δm(stop,LSP)

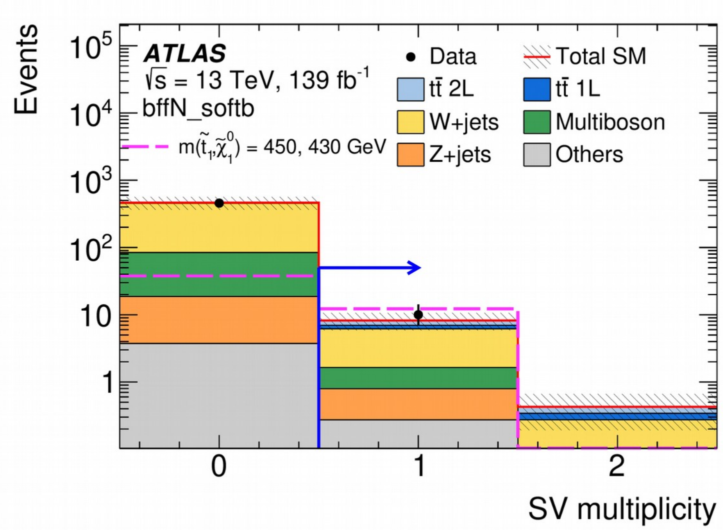
>40 GeV, <m(W)

- Standard b-tagging.
- Require low-energetic lepton + high-p_T ISR jet to boost final state particles.
- **Multi-bin fit** in p_T(lepton)/E_T^{miss} + $\Delta\phi(p_T^{b\text{-jet}}, \mathbf{p_T^{miss}})$.



≤ 40 GeV

- For very soft jets standard b-tagging does not work.
- **Soft b-tagging algorithm** using secondary vertices.
- **Multi-bin fit** in p_T(lepton)/E_T^{miss}



Advances for 4-body: soft b-tagging

[ATLAS-CONF-2019-027]

Standard algorithms for identification of jets from b-hadrons not efficient if jets too soft.

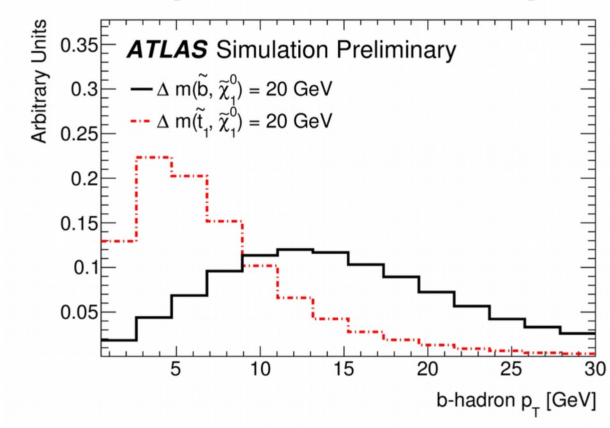
→ *Case for 4-body regions.*

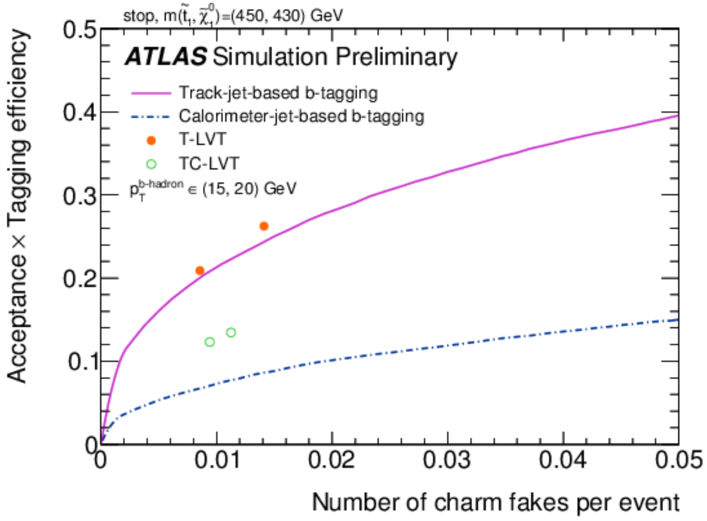
Different **soft b-tagging** algorithms developed:

- Using b-tagging on **track jets** with p_T > 5 GeV.
- **Identification of secondary vertices using tracks** (without dependence on track or calorimeter jets):

  → *Vertex construction algorithm based on an incompatibility graph technique + further criteria to reject vertices unlikely from b-hadron decays.*

  → *Vertex finding algorithm on cluster of tracks.*

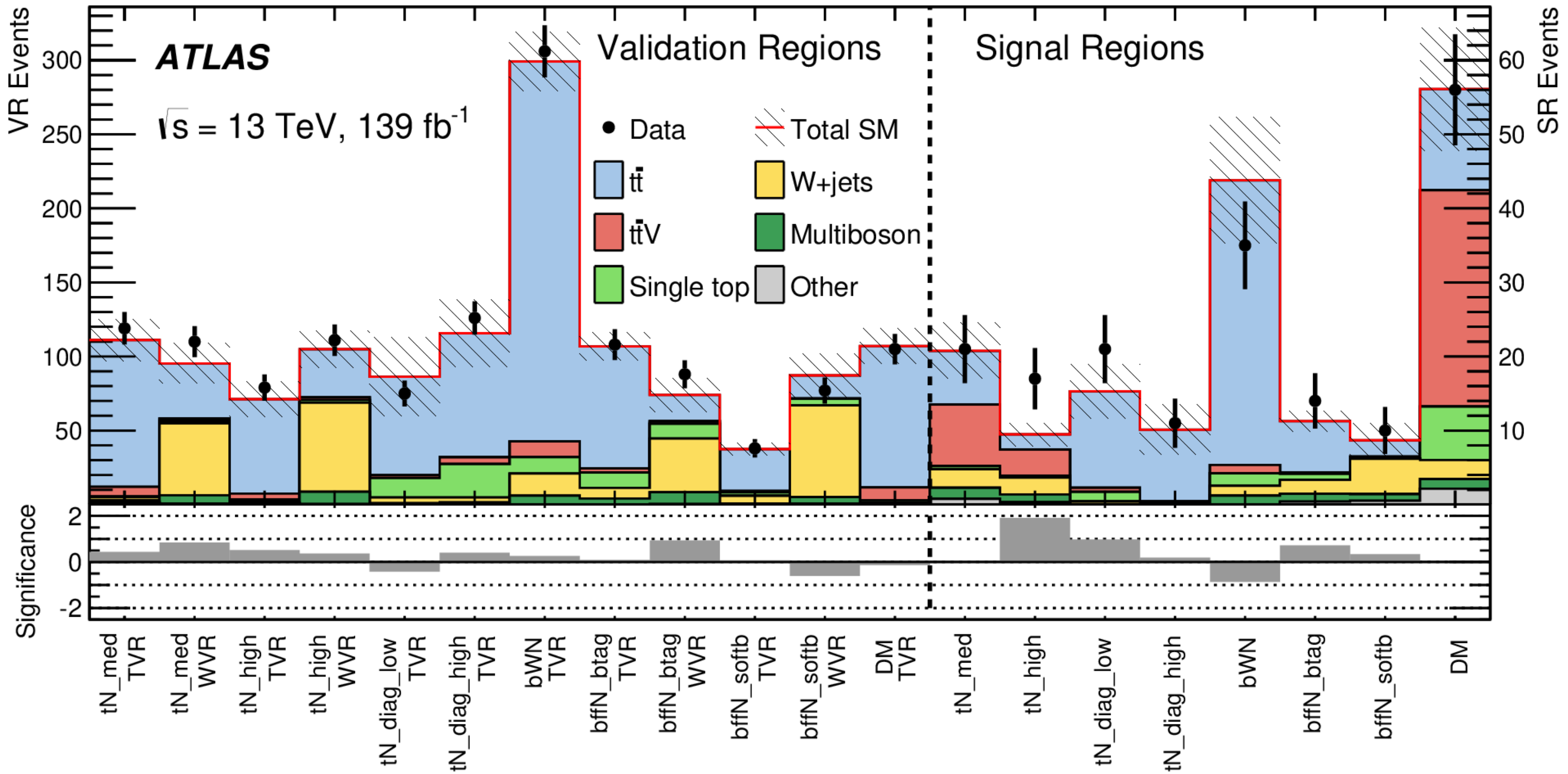




Results

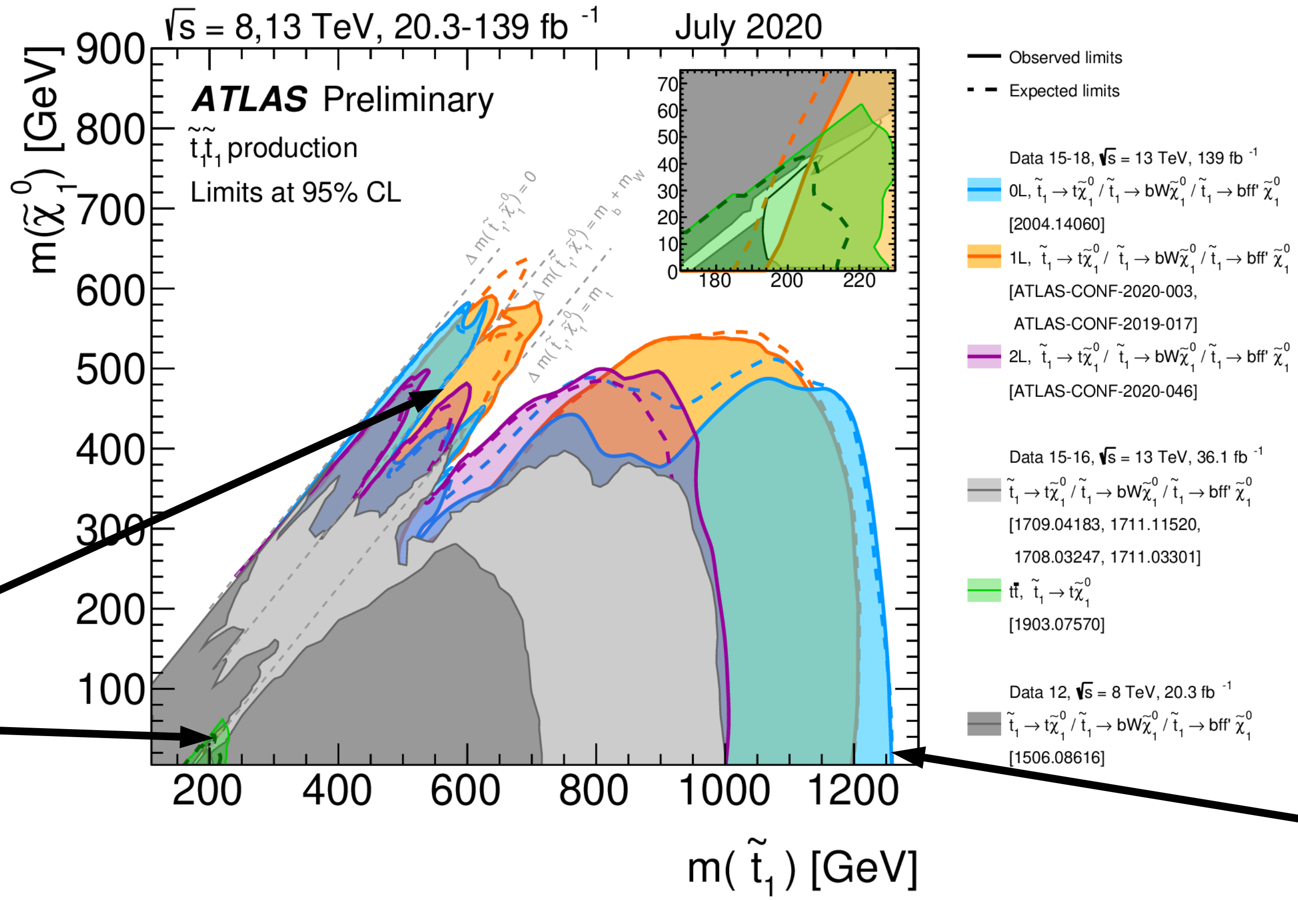
[arXiv:2012.03799]

No significant deviation from SM expectation.



Status stop searches

[Link]

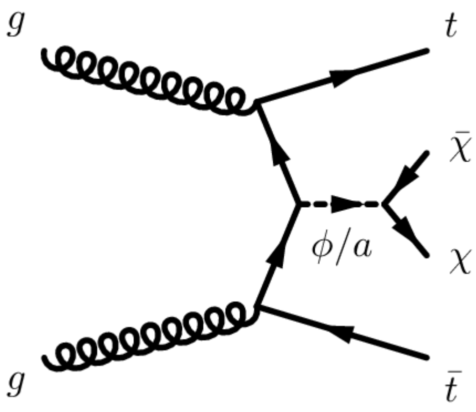


Successfully closed the gaps!

Up to 1.25 TeV

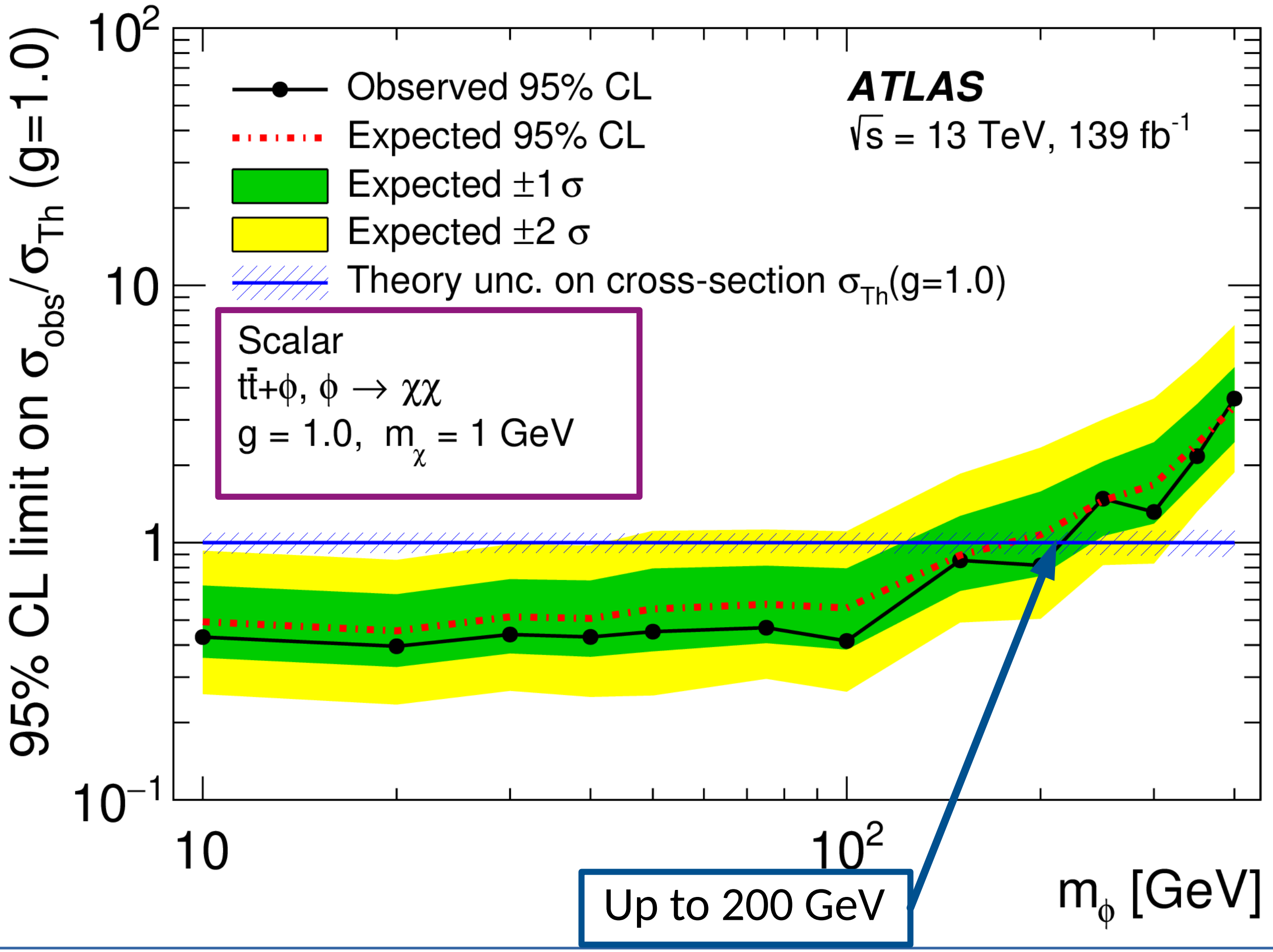
Sensitive to dark-matter mediator models

[arXiv:2012.03799]



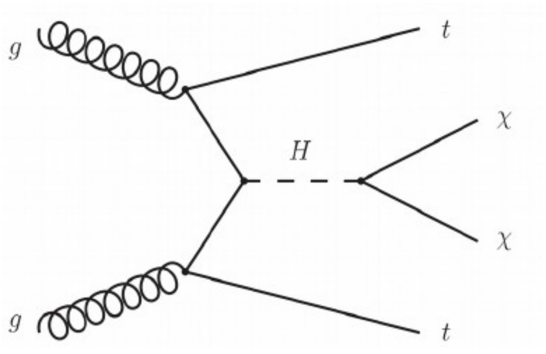
Searches for stops are sensitive to dark matter mediator models with scalar or pseudoscalar mediators and associated production of top quarks.

→ *E.g. the search for stops with decays to final states with a lepton has a dedicated signal region.*



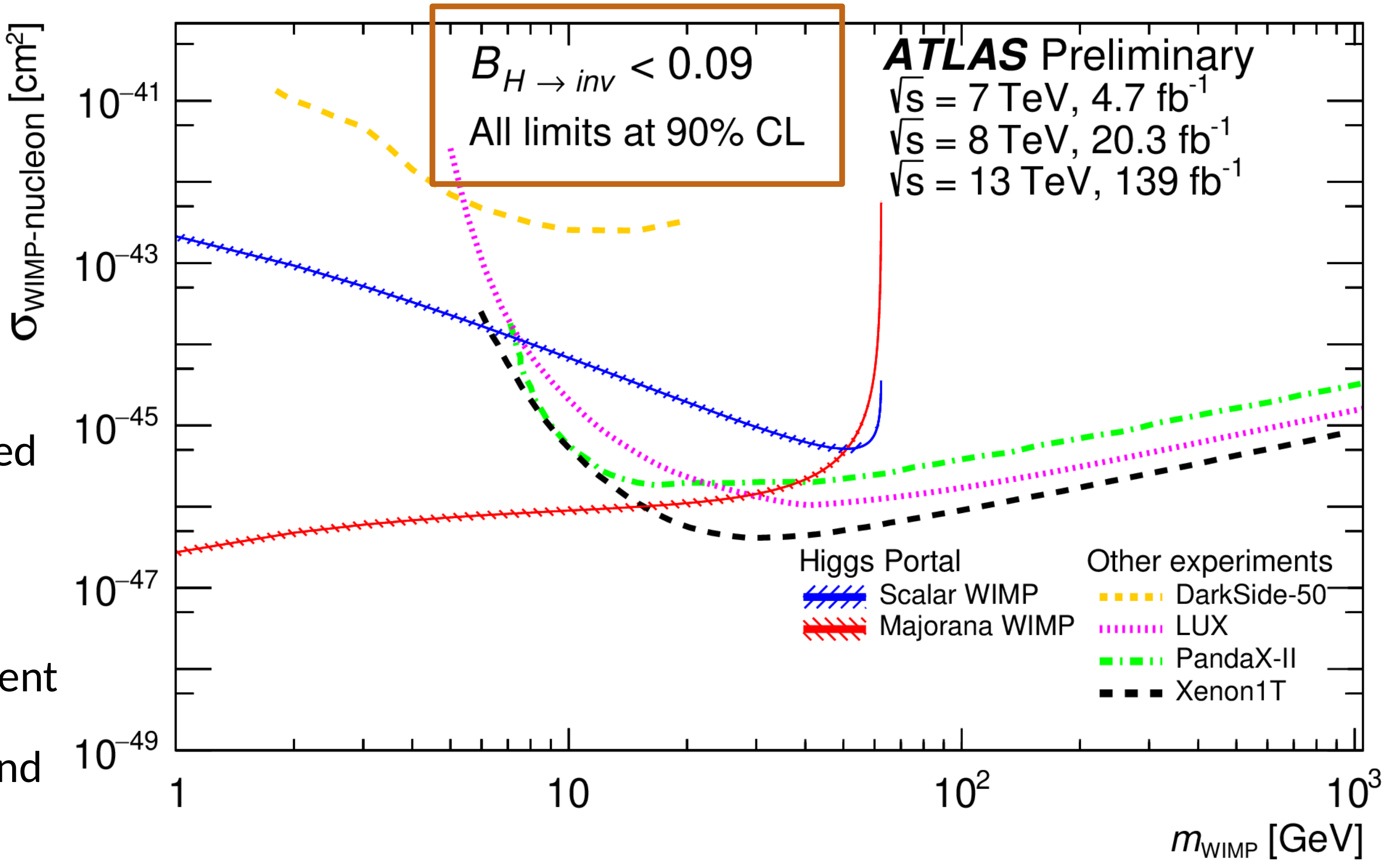
Sensitive to invisible Higgs boson decays

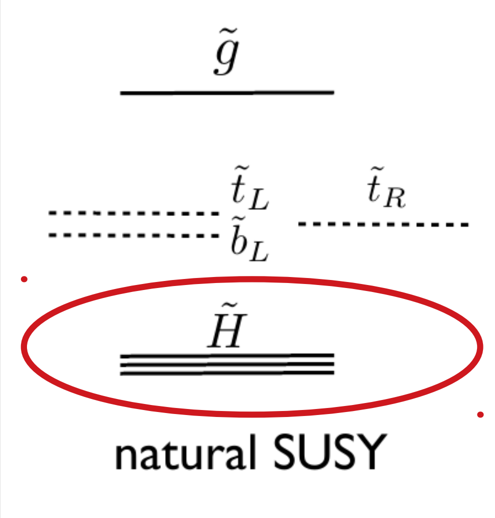
[ATLAS-CONF-2020-052]



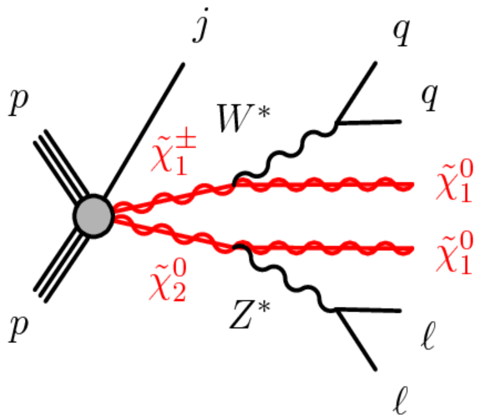
Searches for stops can be used to constrain invisible Higgs boson decays, produced in association with top quarks.

Recent combination of different stop searches + search for vector boson fusion + E_T^{miss} and Run-1 results



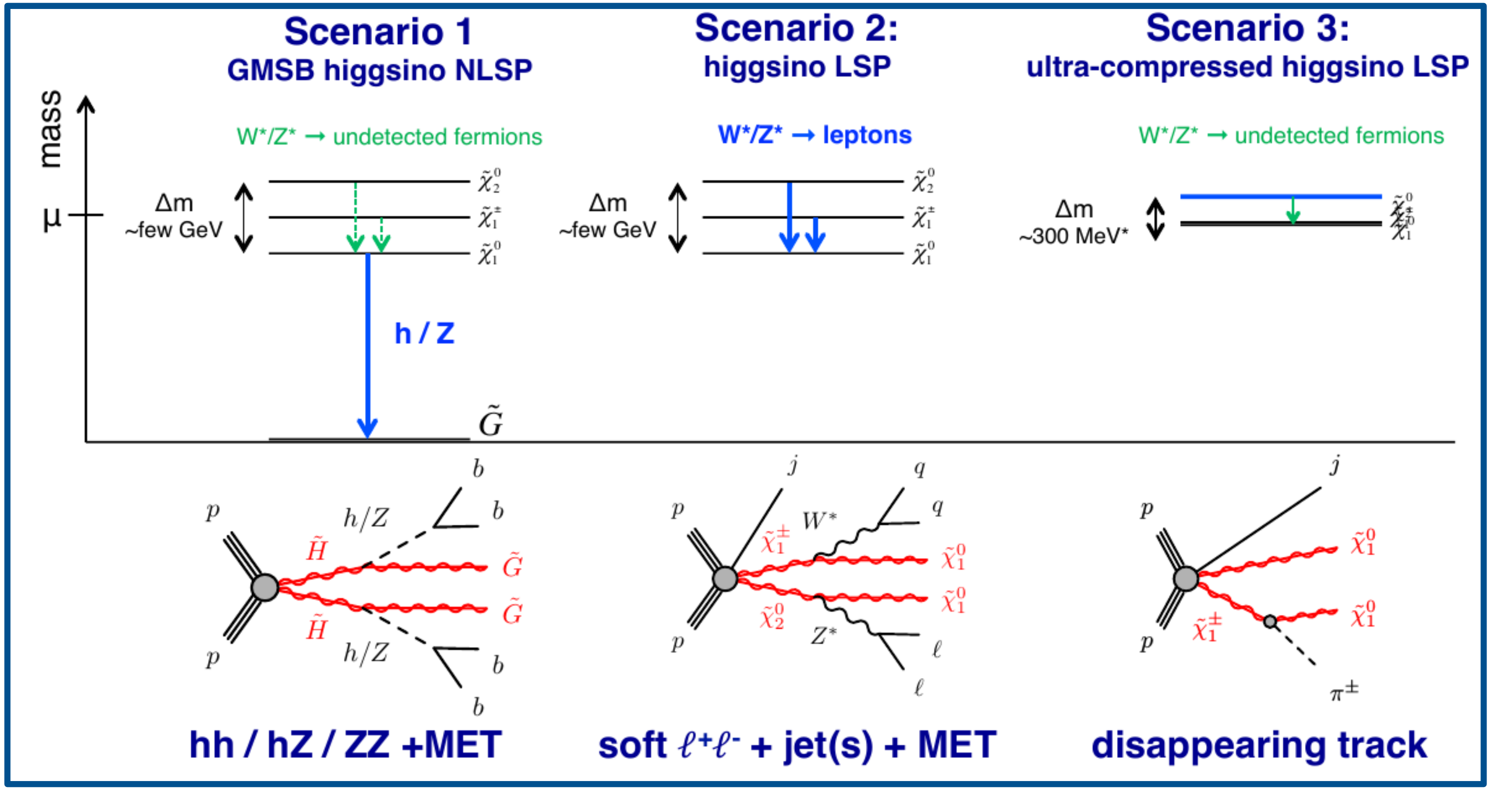


Searches for electroweakinos/ sleptons



Higgsinos searches

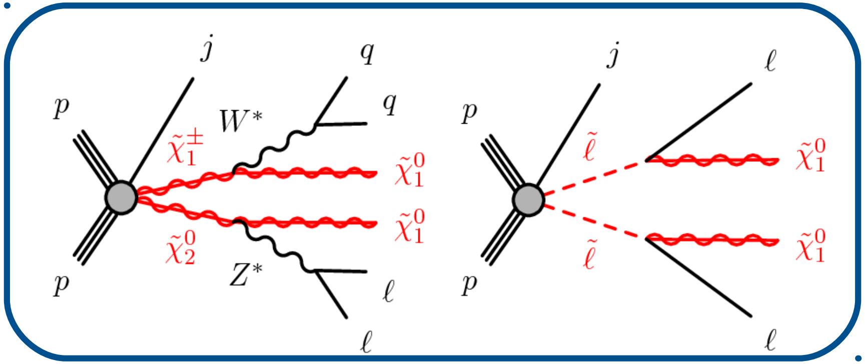
Naturalness arguments requires light higgsinos with similar masses.



[B. Hooberman, SUSY17]

Search for compressed electroweakinos and sleptons

Phys. Rev. D 101 (2020) 052005

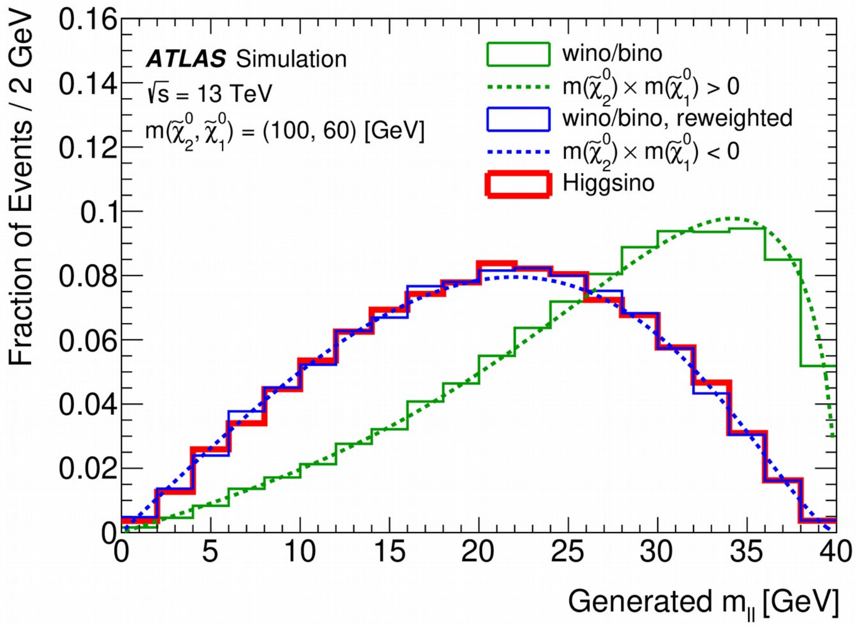


Search for higgsinos and wino/binos with very small mass splittings, or sleptons.

Reconstruction of very low-energetic leptons essential

→ *Electrons p_T > 4.5 GeV, muons p_T > 3 GeV, m_{ll} > 1 GeV*

→ *Possible due to significant progress in lepton reconstruction/identification*



Compressed higgsinos/sleptons

[Phys. Rev. D 101 (2020) 052005]

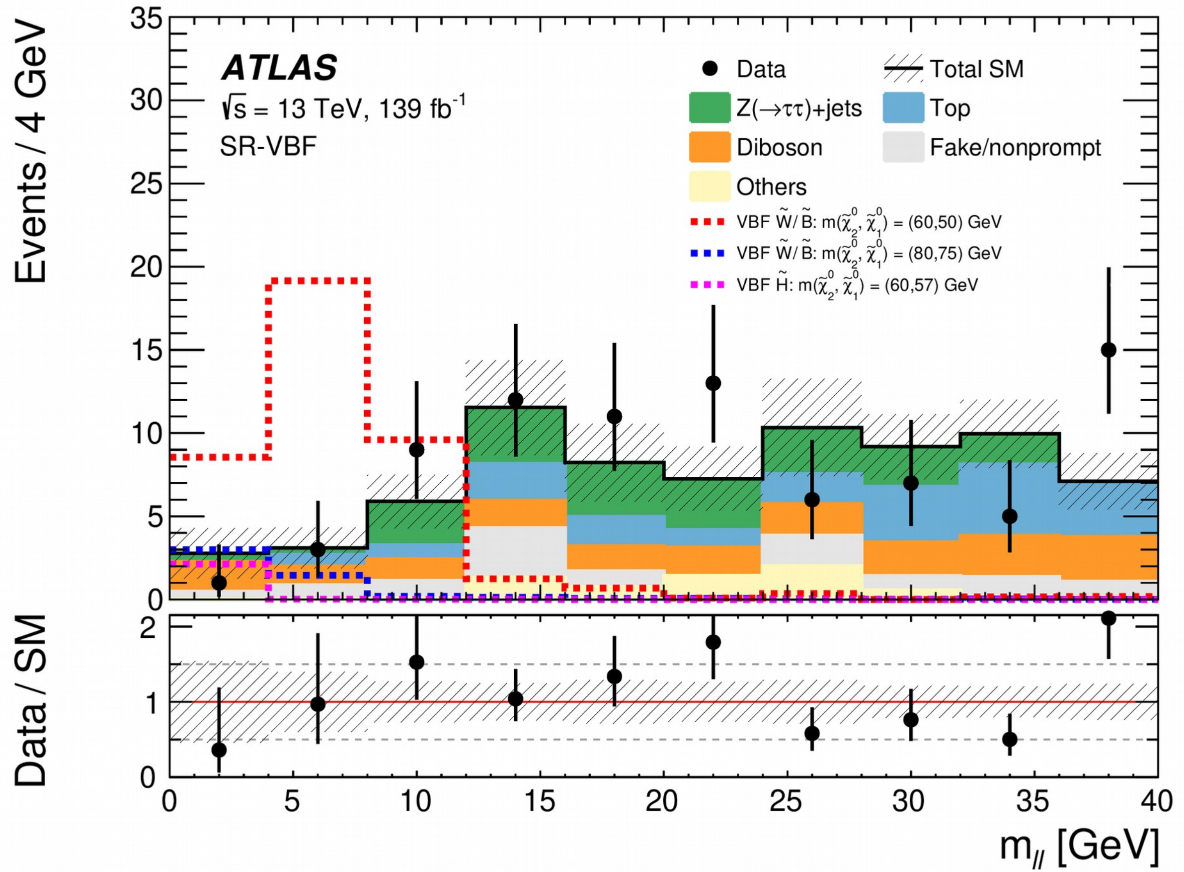
Four searches:

- **Direct production of electroweakinos exploiting the presence of an ISR jet**

  → *Requiring 2 leptons, or 1 lepton + an isolated track,*
- **Production of electroweakinos through vector-boson-fusion** with two additional jets.
- **Direct production of sleptons** using m_{T2} =

$$\min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T)\right)\right]$$

→ *Key is estimation of fake backgrounds!*



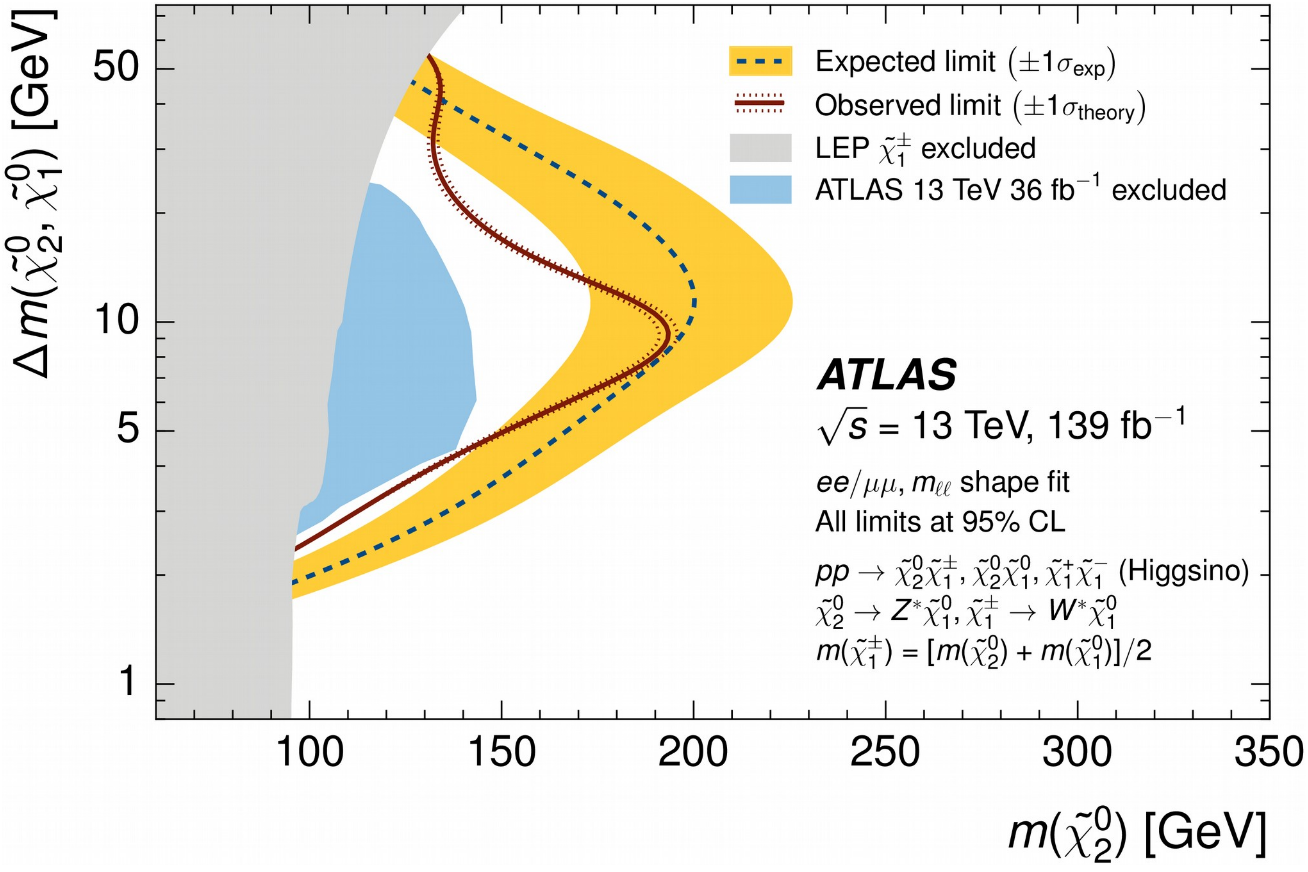
Compressed higgsinos/sleptons

[Phys. Rev. D 101 (2020) 052005]

No significant excess seen.

Exclusion limits e.g. for higgsinos up to 193 GeV for a mass splitting of 9.3 GeV.

Powerful exclusion limits through binning signal regions in m_{ll} and simultaneous fit of regions.

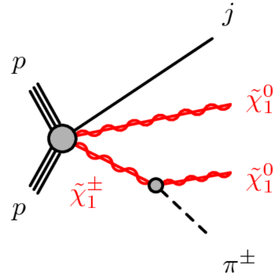


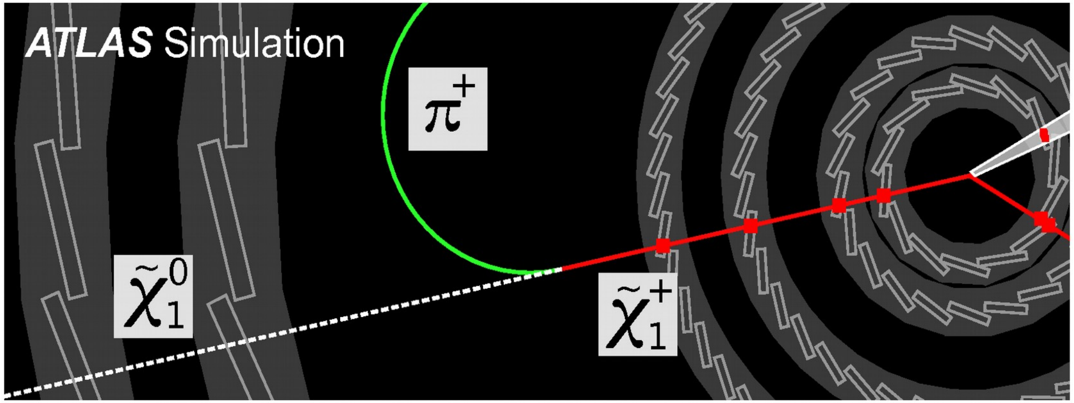
Disappearing tracks

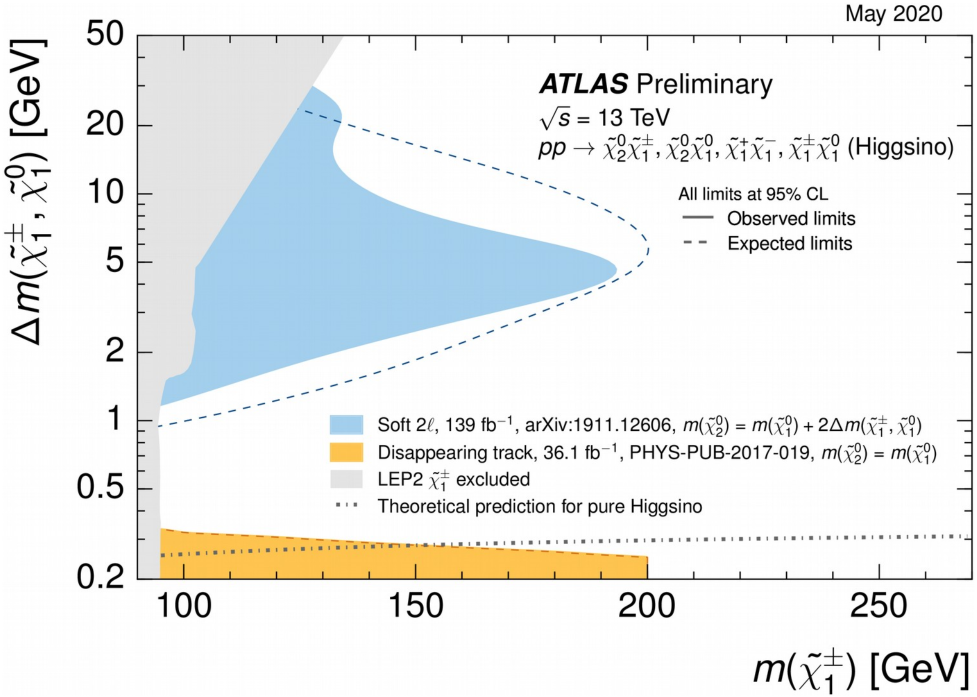
[JHEP 06 (2018) 022, ATL-PHYS-PUB-2017-019]

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*

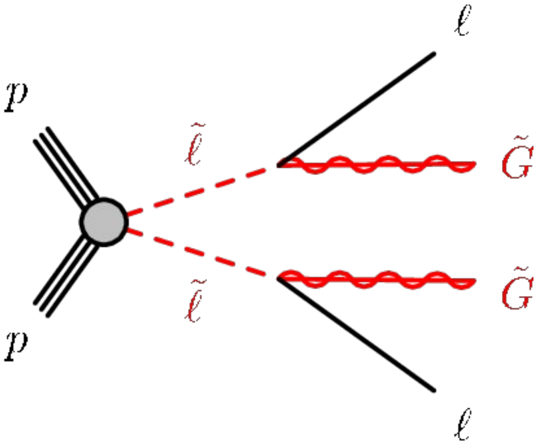






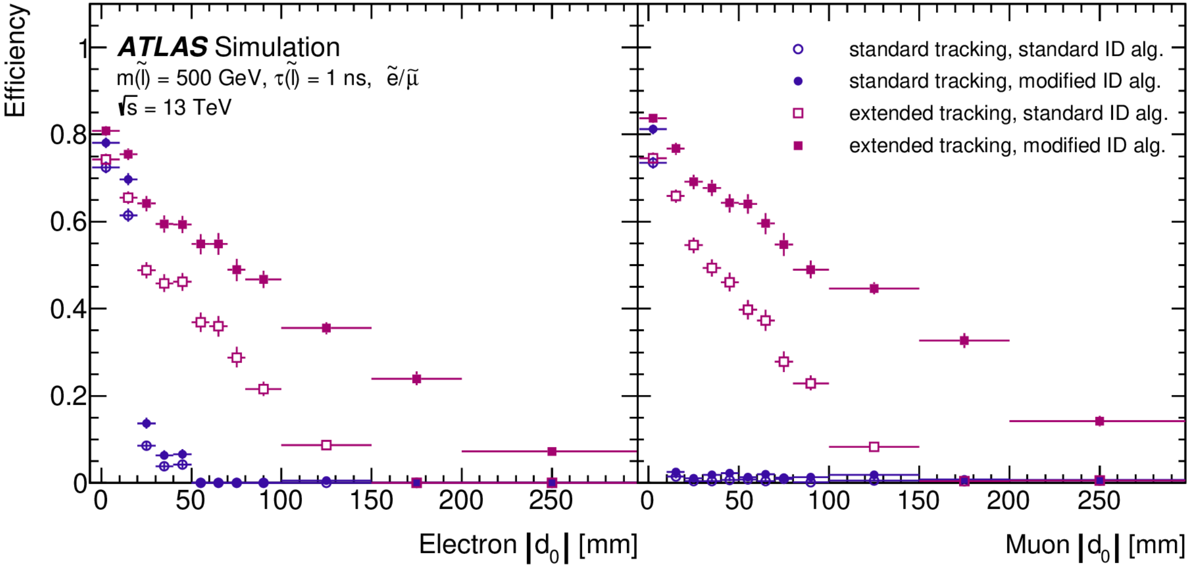
Displaced leptons

arXiv:2011.07812



Most searches target prompt particle decays
→ *Not sensitive to particles decaying delayed because of a long lifetime.*
→ *E.g. predicted in models with a next-to-LSP decaying to a LSP gravitino*
→ *Only couples gravititationally.*

Standard identification/reconstruction algorithms not efficient
→ *Use modified algorithms, in particular lifting requirements on the transverse impact parameter.*



Displaced leptons

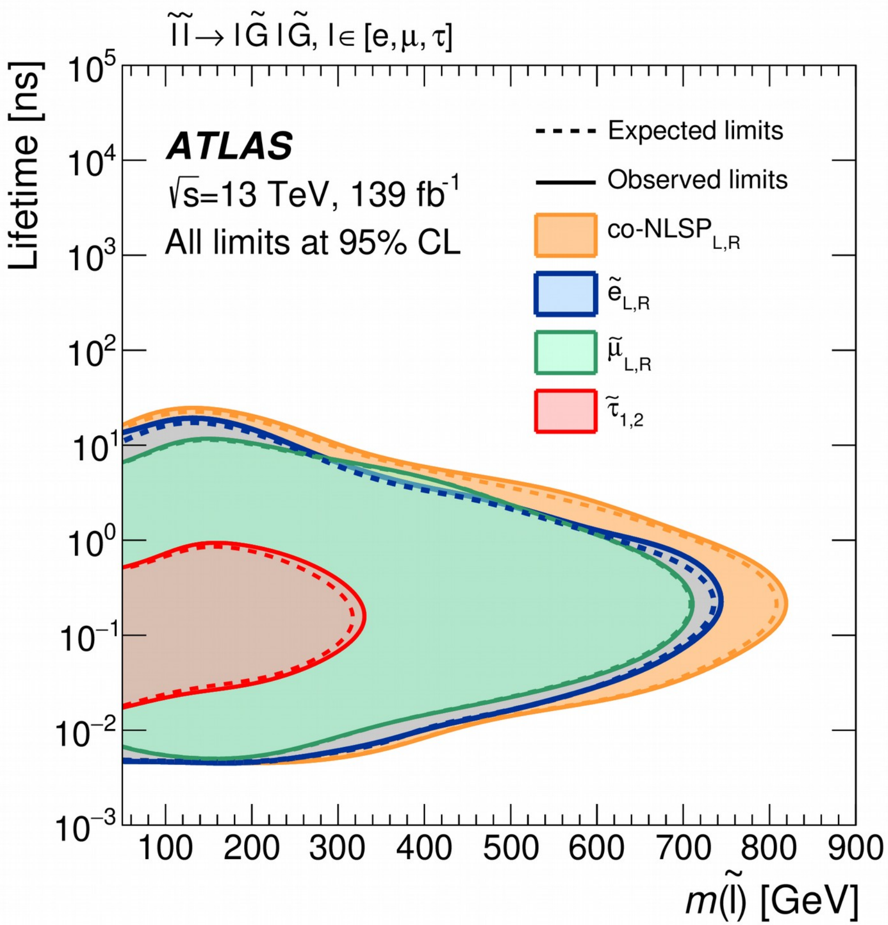
[arXiv:2011.07812]

- Signal regions with two leptons (either electron or muon).
- Rejection of cosmic muons, other backgrounds from misidentified electrons or muons.

No events observed in the signal regions

→ Exclusion limits placed on different next-to-LSP types or considering a mixture.

Surpassing previous LEP limits (~60 - 90 GeV) significantly.



Reinterpretation and summary of results

pyhf

∂ifferentiable ℒikelihoods

How to maximise usefulness of data and analysis?

Analyses typically focus on a small number of benchmark simplified models, but are typically more general (→ *other DM searches*, *leptoquarks*, *other than the target models*)

New tools/material for re-interpretation of the analyses available!

Preservation of the full analysis software: can rerun the analysis with a different signal assumption at a later point

↓

RECAST for ATLAS

Full likelihood

↓

pyhf
∂ifferentiable
ℒikelihoods

Full likelihood → Sometimes simplifications possible and required → Simplified likelihoods

Analysis flow → pseudo-code

↓

SimpleAnalysis

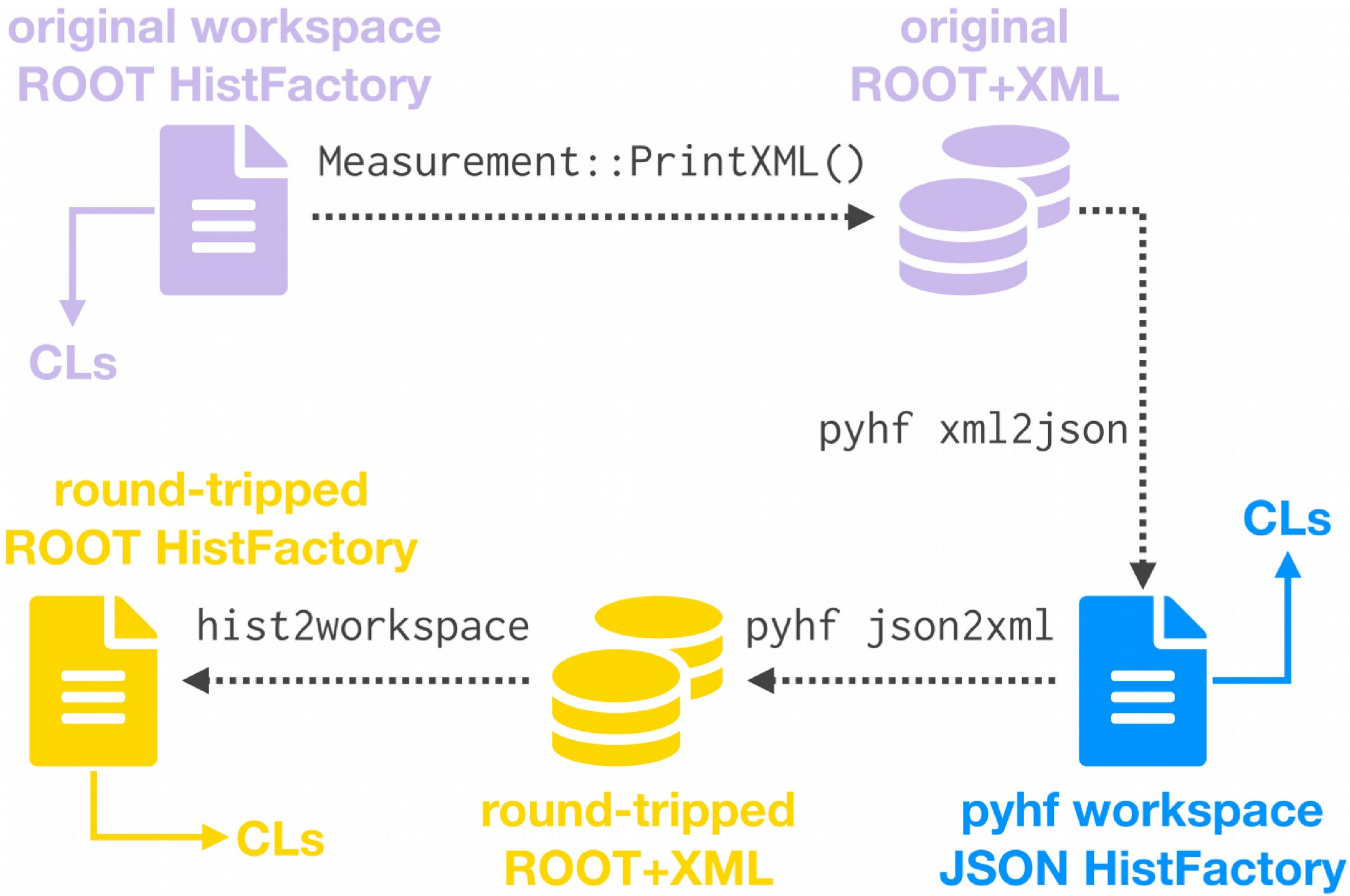
Full likelihood

[ATL-PHYS-PUB-2019-029]

Release of full analysis likelihoods possible via a workspace represented as json file.

Mathematical model of HistFactory re-implemented in pyhf using only standard python packages such as scipy and numpy.

Reproduction of the analysis possible using either pyhf or ROOT.



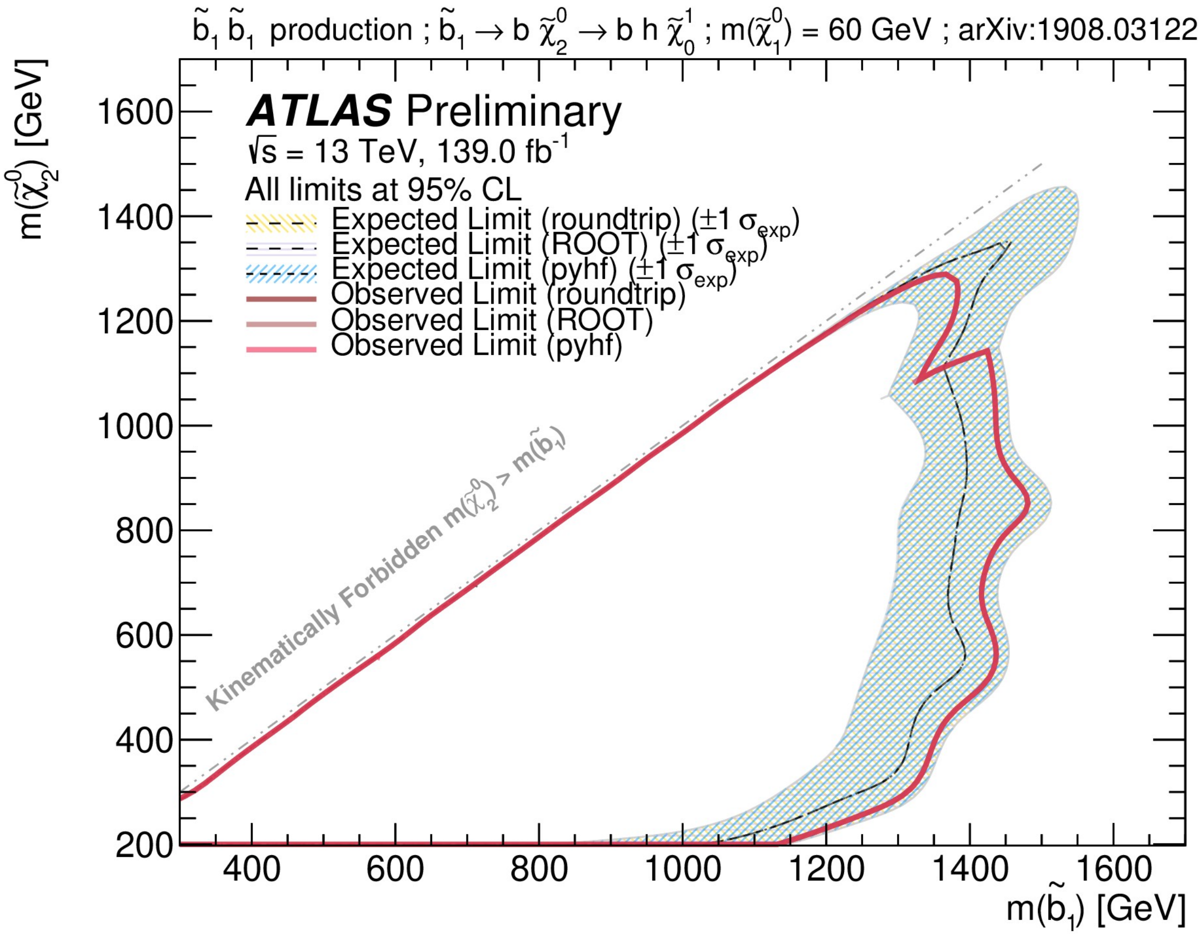
Full likelihood

[ATL-PHYS-PUB-2019-029]

Proof-of-principle: Reimplementation of the likelihood of the sbottom analysis + different tools to calculate limits.

Easily possible to replace original signal in the full likelihood for reinterpretation → *likelihood patch*.

Full likelihood of the sbottom analysis: link



Different likelihoods available

Analysis characteristics	
	Double parton scattering, BSM search, BSM reinterpretation, LFV, FCNC, Particle flow, MVA / machine learning, EFT interpretation, Differential measurement, Displaced vertex, Lepton-jets, Trigger-level analysis, High luminosity upgrade studies, Likelihood available
Min luminosity :	0 fb^{-1} Filter by minimum integrated luminosity
Date :	Min. YYYY-MM-DD Max. YYYY-MM-DD Filter by date: ArXiv relase Publication

Quick links: Papers Confnotes Pubnotes

Papers and publications (7 shown of 167 total)
(Full list of ATLAS papers, List/RSS from CDS)

Hide table

Short Title	Journal Reference	Date	√s (TeV)	L	Links
Search for chargino and neutralino pair RPV decays; 3L	Submitted to PRD	20-NOV-20	13	139 fb^{-1}	Documents | 2011.10543 | Inspire HepData | Briefing | Internal
Search for displaced leptons	Submitted to PRL	13-NOV-20	13	139 fb^{-1}	Documents | 2011.07812 | Inspire HepData | Briefing | Internal
Chargino-neutralino pair; 3 leptons, weak-scale mass splittings	Phys. Rev. D 101 (2020) 072001	18-DEC-19	13	139 fb^{-1}	Documents | 1912.08479 | Inspire HepData | Internal
Staus; taus	Phys. Rev. D 101 (2020) 032009	15-NOV-19	13	139 fb^{-1}	Documents | 1911.06660 | Inspire HepData | Briefing | Internal
Chargino-neutralino pair; Higgs boson in final state, 2 b-jets and 1 lepton	Eur. Phys. J. C 80 (2020) 691	19-SEP-19	13	139 fb^{-1}	Documents | 1909.09226 | Inspire HepData | Internal
Stop pair, sbottom pair, gluino pair; two same-sign leptons or three leptons	JHEP 06 (2020) 46	18-SEP-19	13	139 fb^{-1}	Documents | 1909.08457 | Inspire HepData | Internal
Sbottom; b-jets	JHEP 12 (2019) 060	08-AUG-19	13	139 fb^{-1}	Documents | 1908.03122 | Inspire HepData | Briefing | Internal

Simplified likelihoods

[talk at Reinterpretation workshop]

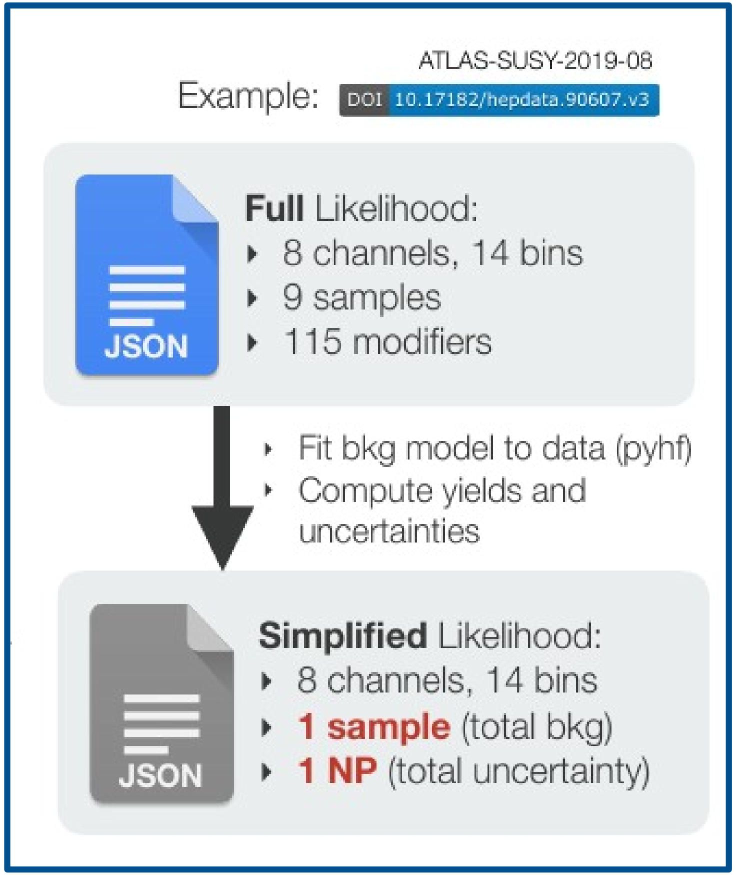
Full likelihoods are sometimes too complex:

→ *Too much CPU time needed, or precision of full likelihood not needed,*

→ *As frequent in reinterpretation efforts considering many new models.*

In certain cases, the full likelihood can be approximated by a simplified background model, with a significantly reduced number of nuisance parameters

→ *Significant reduction of CPU resources.*



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[talk at Reinterpretation workshop]

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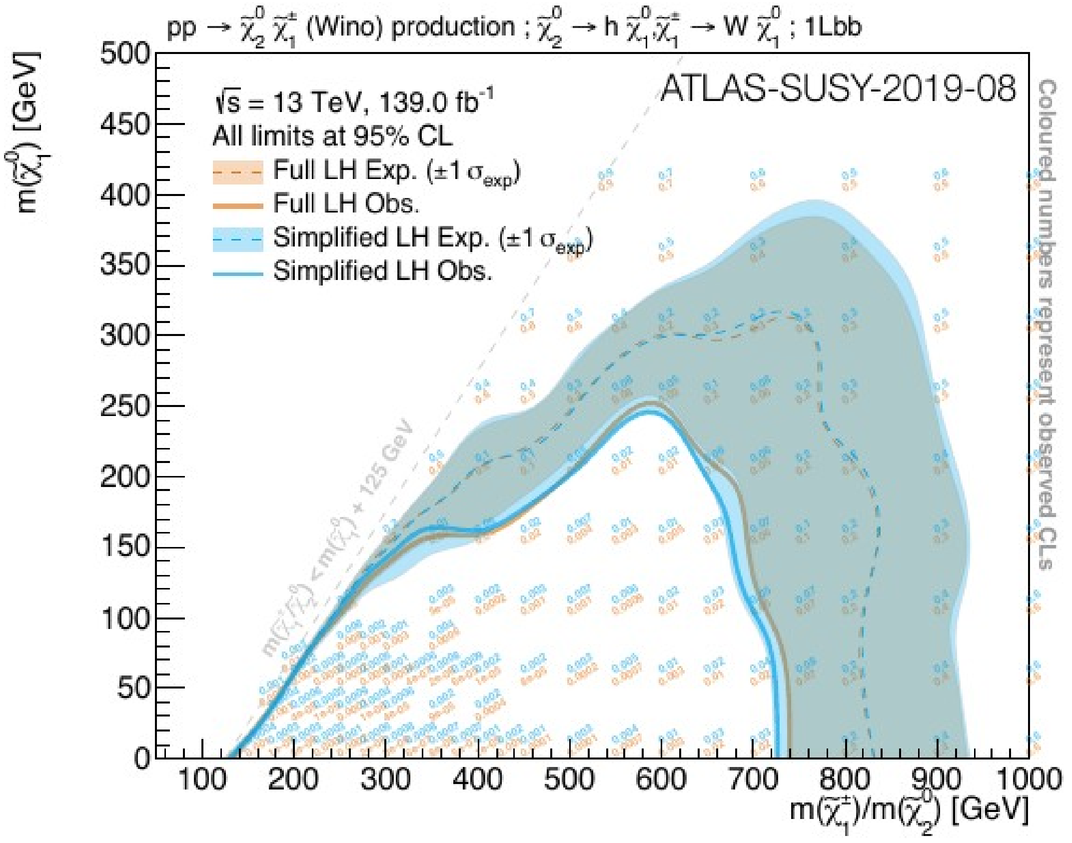
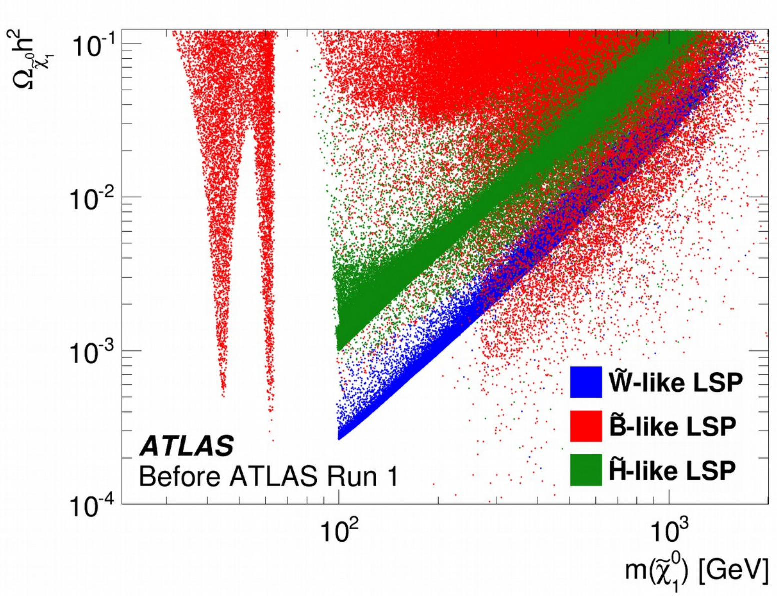
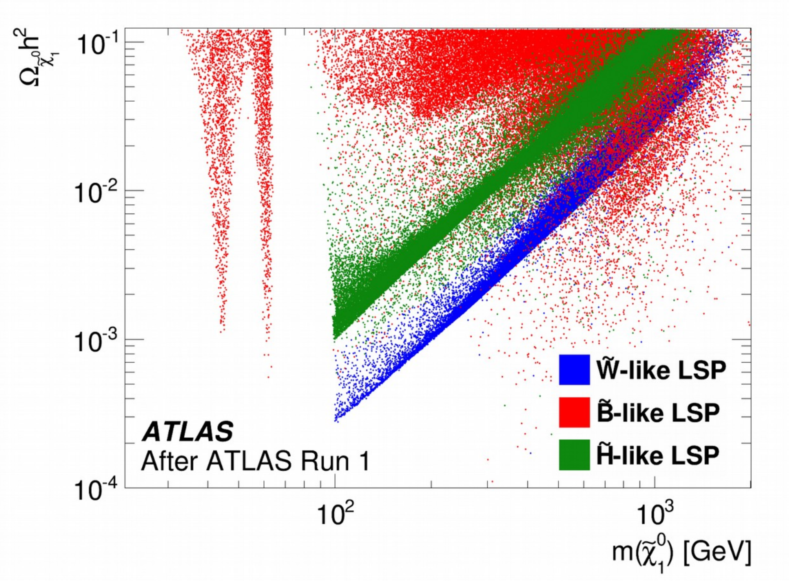


[JHEP 10 (2015) 134]

The **p**henomenological **MSSM** is a 19-dimensional reduction of the MSSM, based on theoretical assumption (e.g. the first two generation sparticles degenerate)
→ *more 'realistic' than simplified models, but still processable.*





Using the reinterpretation tools, we are checking the coverage of the pMSSM by our analyses – also confront with results by non-SUSY analyses and other experiments.

Where to go from here?

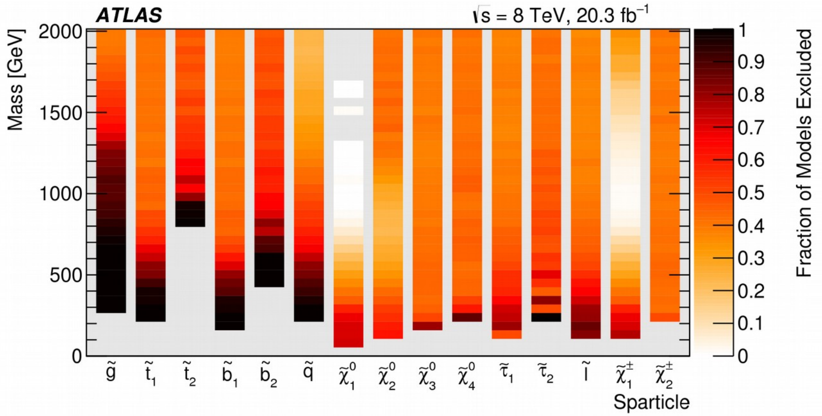
- Very comprehensive set of analyses available, using a **wealth of different methods**.
- Sensitive to the supersymmetric model originally designed for, but also beyond
  → Implications on other **Dark Matter searches, leptoquark** searches etc.

- We have invested in building up reinterpretation tools, offering now the **unique and first** time possibility to reinterpret our searches **correctly** - **big step forward for open science!**
- Internally we work on connecting our searches and identifying holes and gaps, by statistical combinations and large scale scans, using the reinterpretation tools.

Stay tuned for upcoming summary results

-

And we look forward to you using our results!



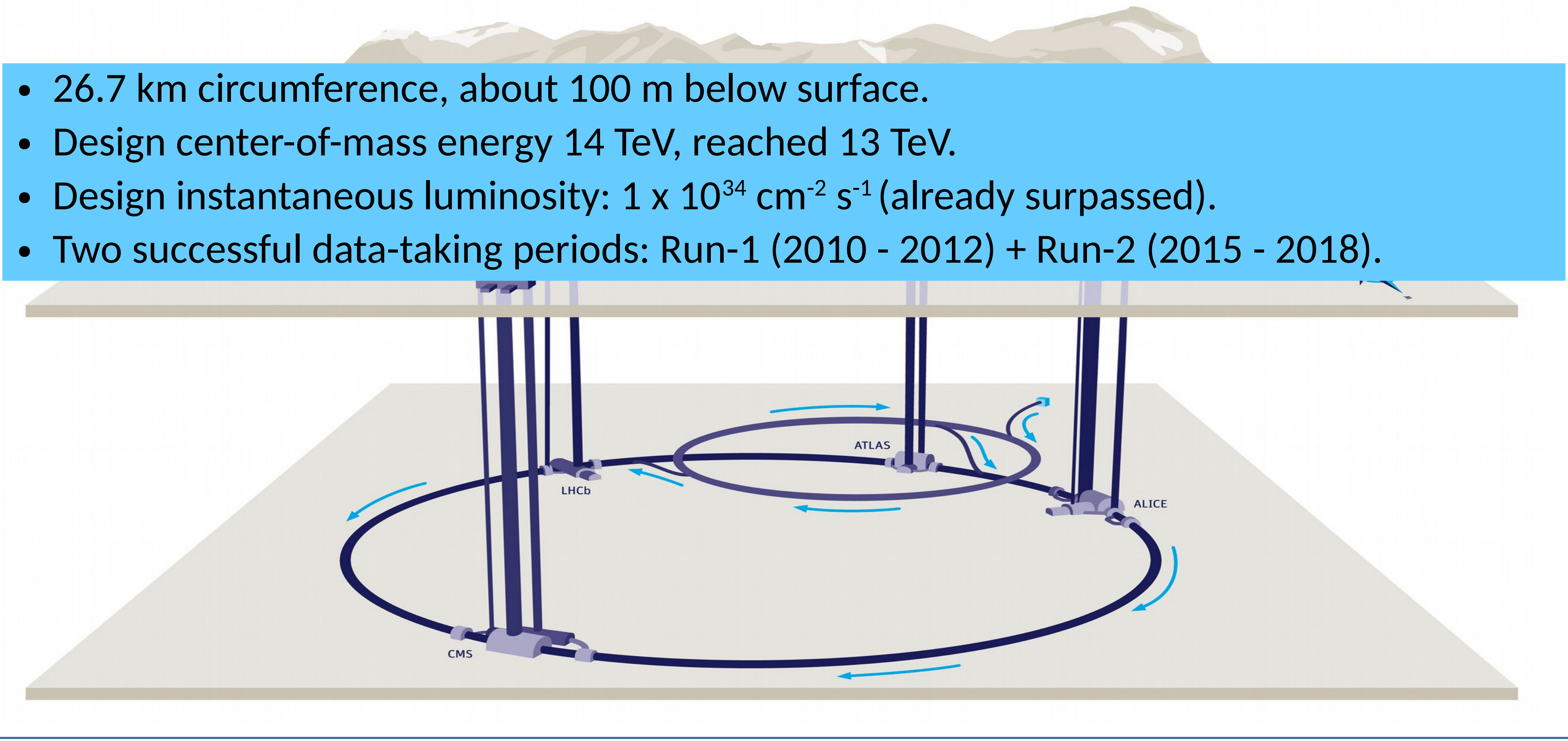
[JHEP 10 (2015) 134]

Backup

Large Hadron Collider (LHC)

[Link]

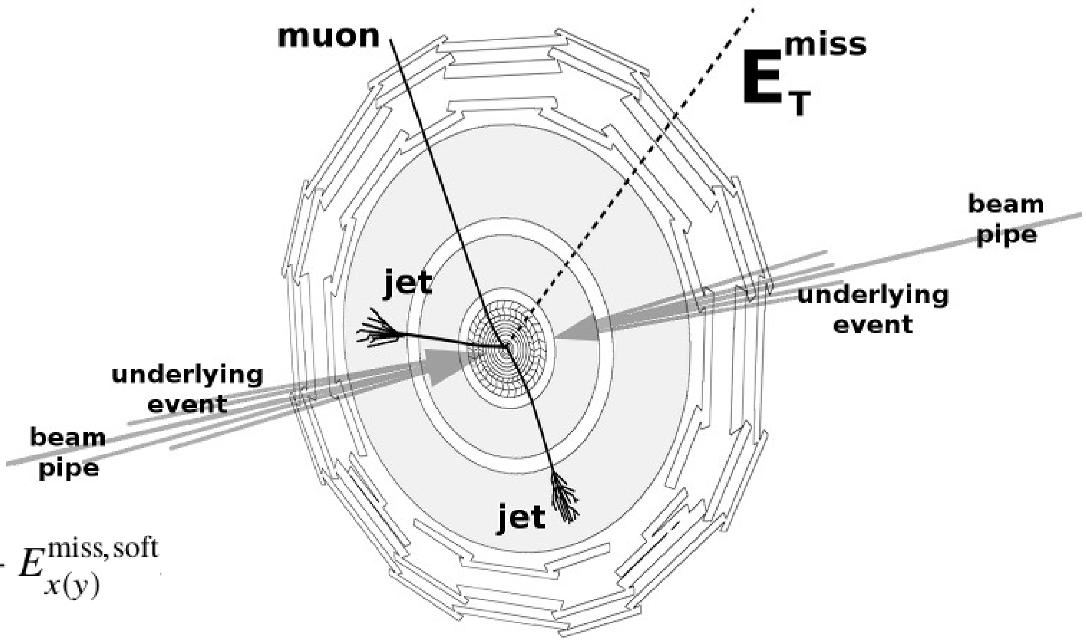
- 26.7 km circumference, about 100 m below surface.
- Design center-of-mass energy 14 TeV, reached 13 TeV.
- Design instantaneous luminosity: 1 x 10^{34} cm^{-2} s^{-1} (already surpassed).
- Two successful data-taking periods: Run-1 (2010 - 2012) + Run-2 (2015 - 2018).



Missing transverse momentum: E_T^{miss}

Invisible particles to the detector (like neutrinos or dark matter particles) result in a momentum imbalance in the perpendicular 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.

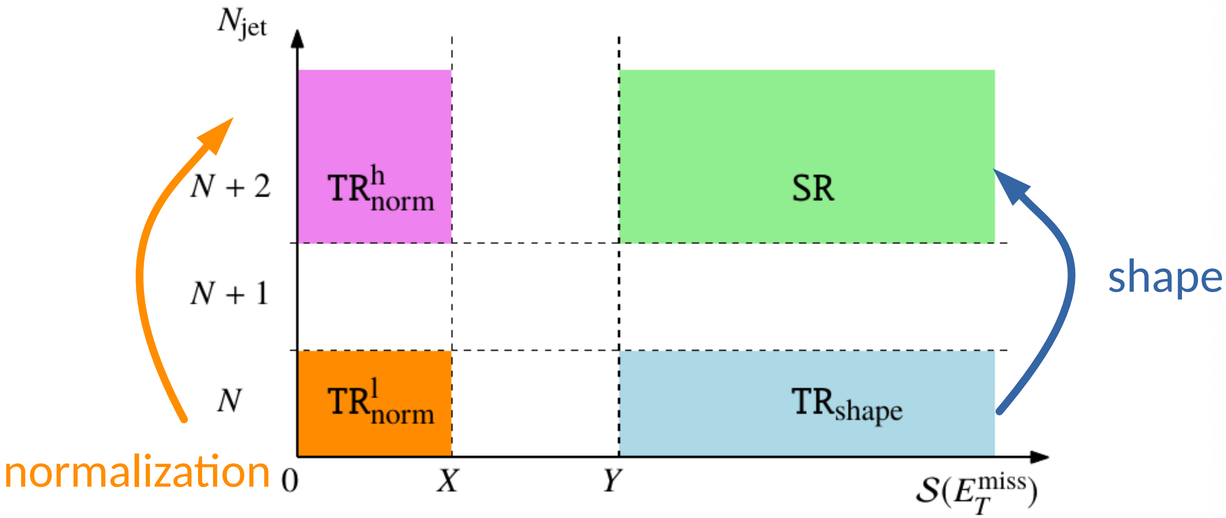
E_T^{miss} can also arise from mis-measurements → Important to minimize!

Background estimation in the multi-jet analysis

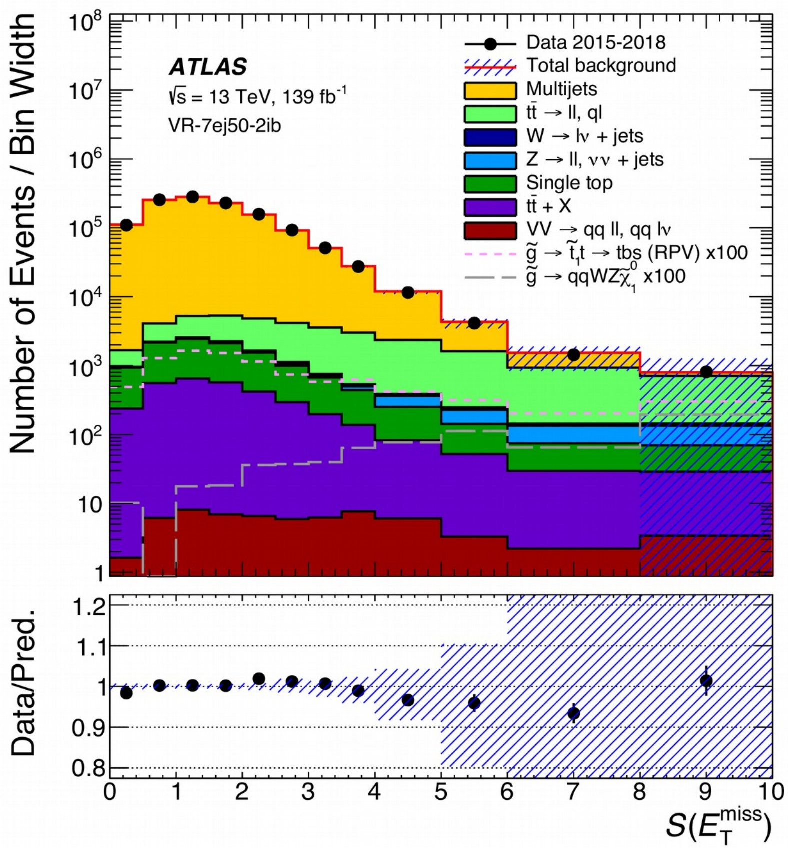
[JHEP 10 (2020) 062]

Backgrounds:

- Leptonic ($t\bar{t}$, W+jets) → *control regions.*
- QCD multijet → *ABCD-template method based on E_T^{miss} significance distributions, obtained from lower jet multiplicity regions.*



Validation region

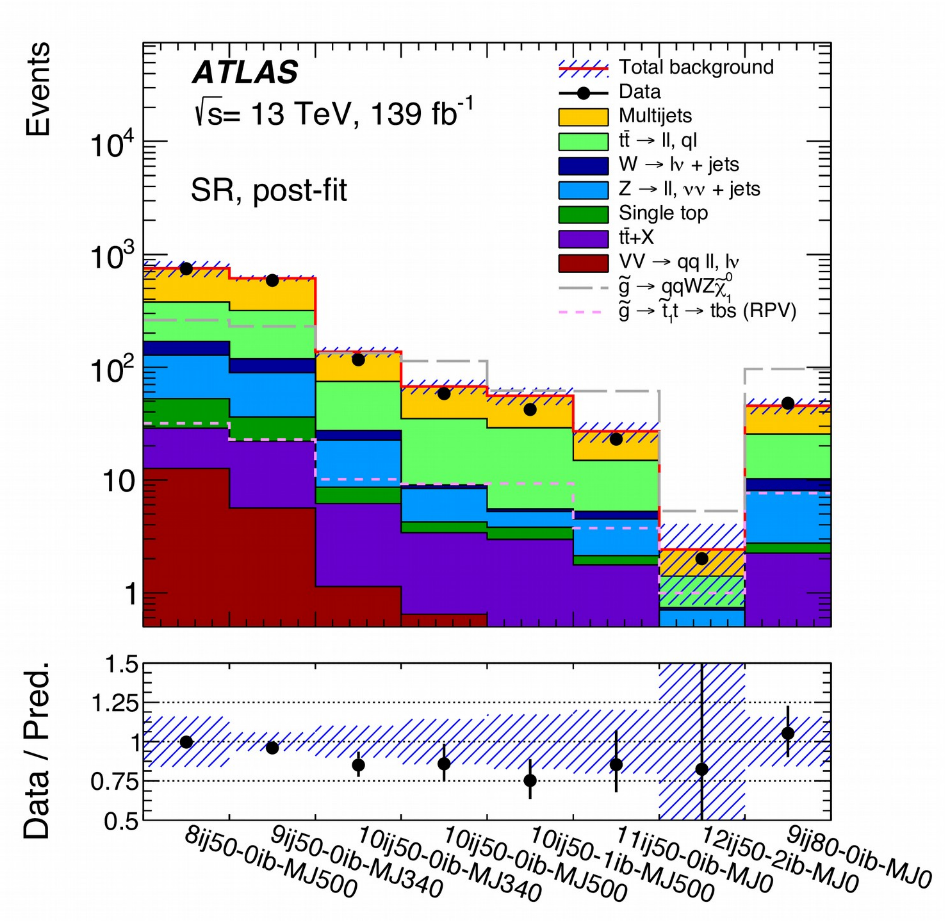


Results of the multi-jet analysis

[JHEP 10 (2020) 062]

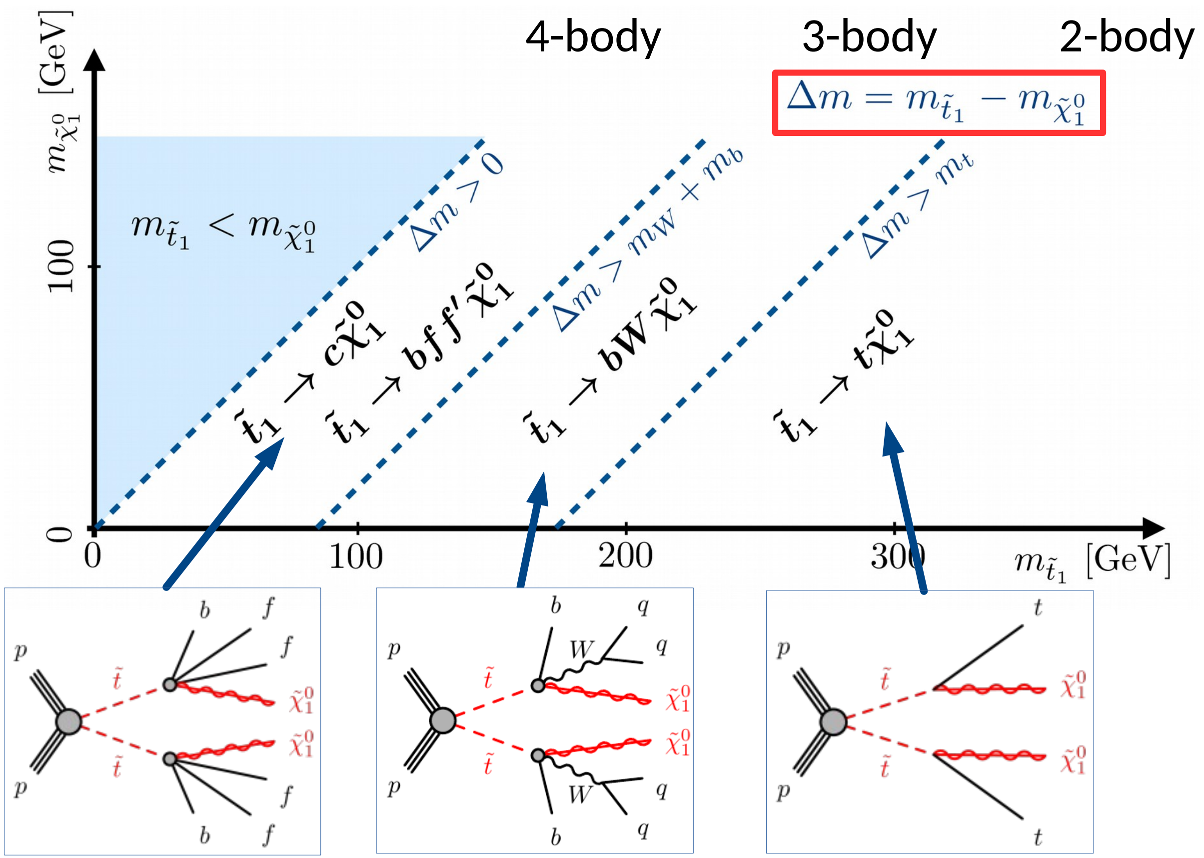
No significant excess over SM expectations seen in any bin.

E.g. one-bin SRs used to calculate model-independent upper limits.



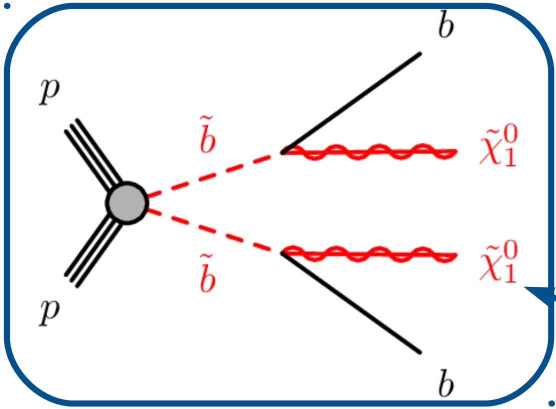
Characteristics of stop searches

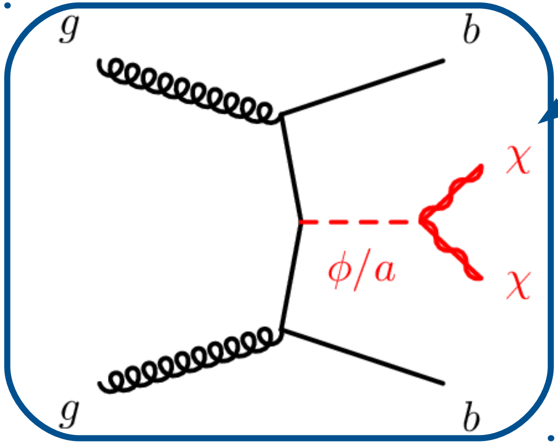
Different kinematic regions; particular difficult to obtain sensitivity to **Δm = m(top)** and **Δm < m(b) + m(W)**



Search for sbottoms/*or Dark Matter + b-jets*

arXiv:2101.12527

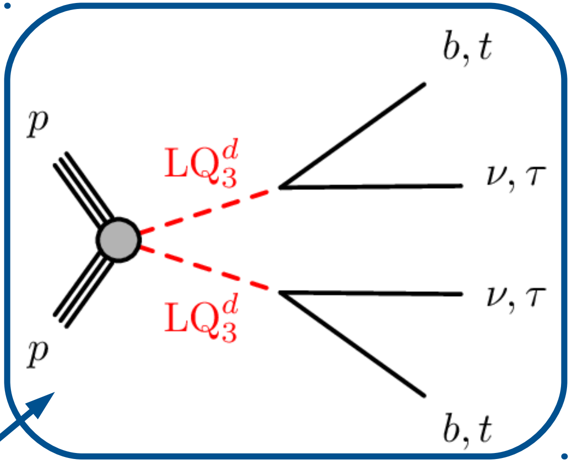




Search for E_T^{miss} in association with two b-tagged jets

→ Signature appears in many BSM scenarios:

- Pair-production of sbottom quarks, direct decays,
- Production of Dark Matter particles through decay of a (pseudo)scalar mediator particle + 2 b-tagged jets,
- Pair-production of leptoquarks.



Signal regions with specialized techniques

[arXiv:2101.12527]

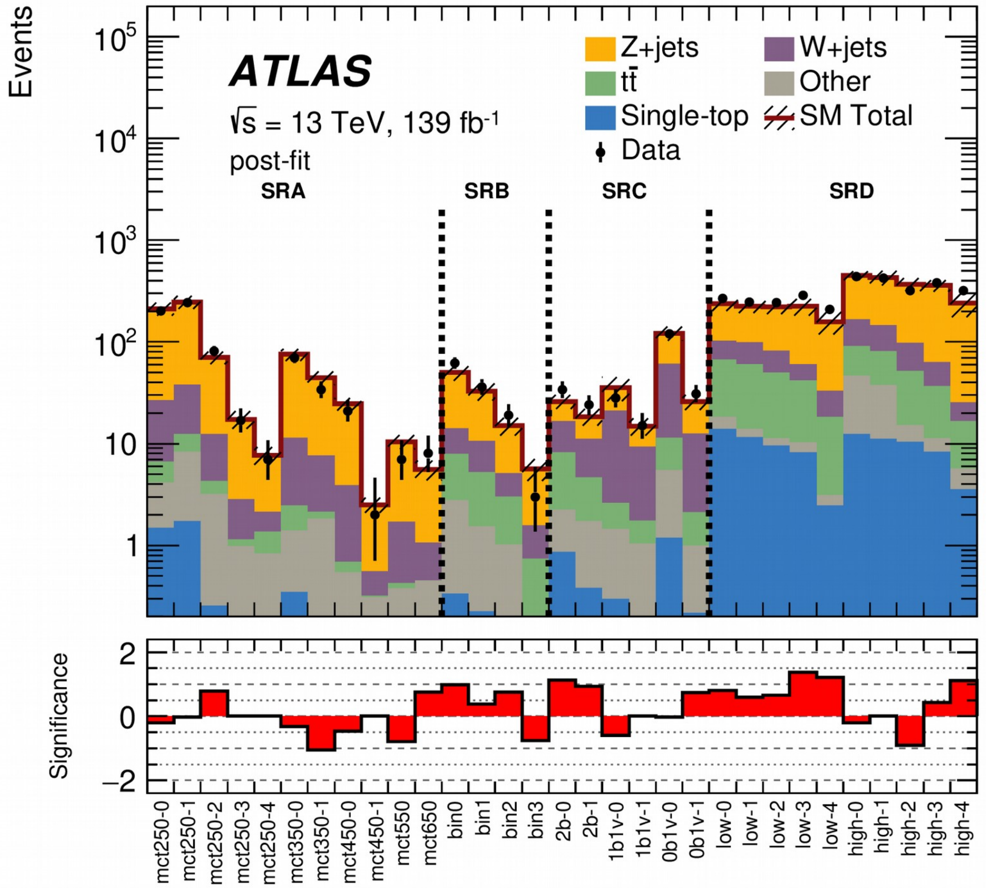
Set of three signal regions targeting sbottom quark pair production + one set dedicated to DM scenarios (BDT used).

Different methods depending on mass difference Δm between sbottom and LSP:

- Δm > 200 GeV
- *→ 2D-fit (in m_{CT} and m_{eff})*
- 50 < Δm < 200 GeV

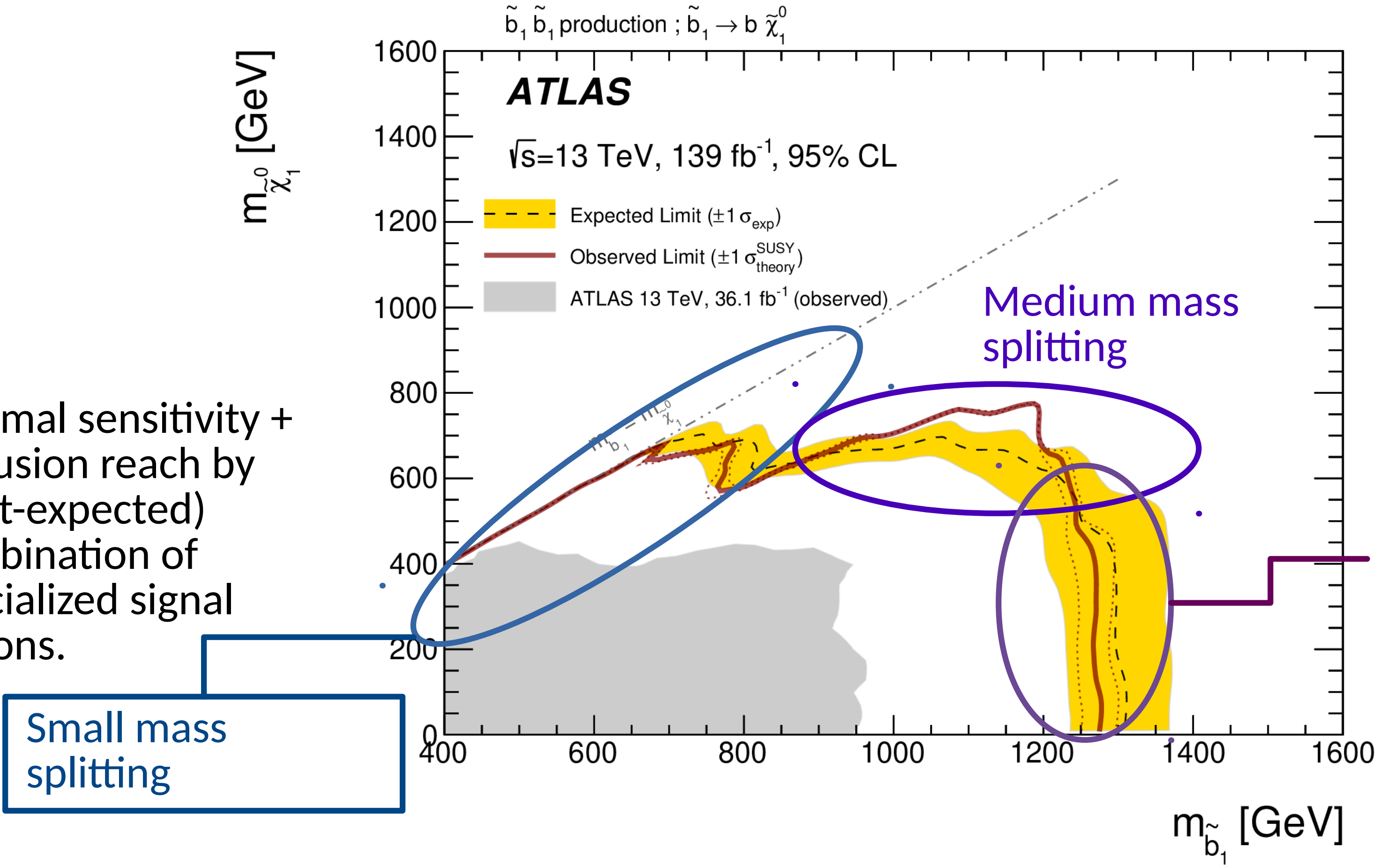
  → increased sensitivity by special-trained BDT.
- Δm < 50 GeV

  → low-energetic sbottom quarks recoiling against ISR-jet, use soft b-tagging based on vertex finding algorithm.



Exclusion limits

[arXiv:2101.12527]

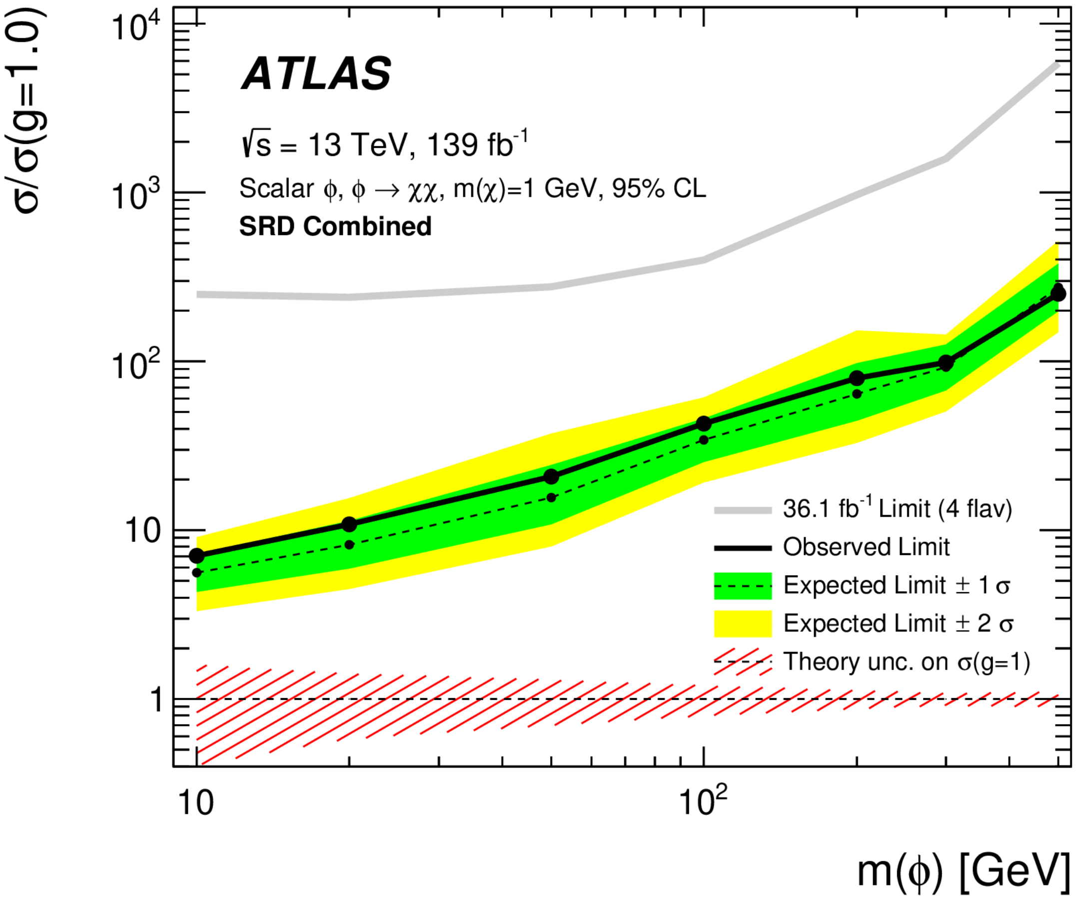


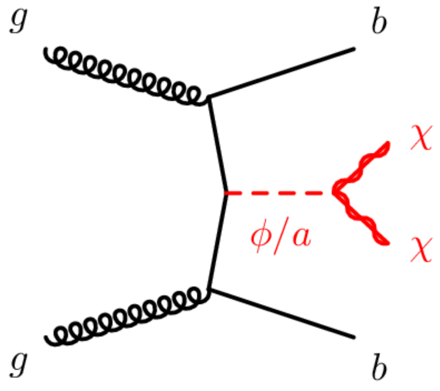
Optimal sensitivity + exclusion reach by (best-expected) combination of specialized signal regions.

Exclusion limits reach up to 1.27 TeV

Exclusion limits on a scalar mediator Dark Matter model

[arXiv:2101.12527]

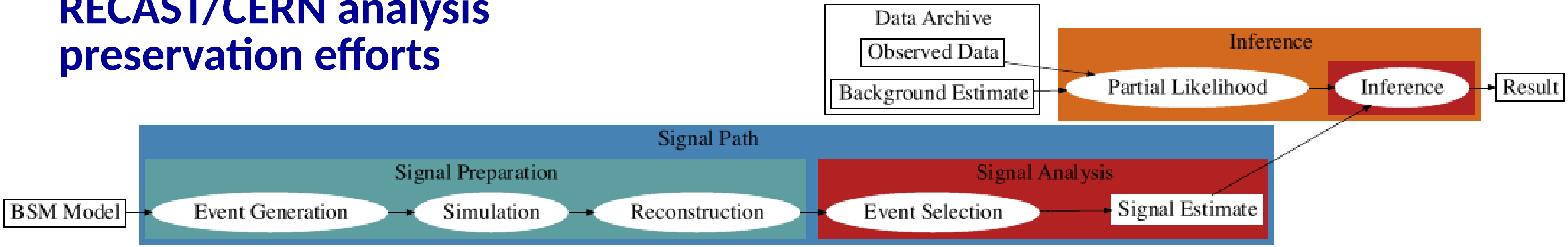




RECAST

[JHEP 1104:038,2011]

RECAST/CERN analysis preservation efforts



RECAST preserves the full analysis software + background model.

Easy to process any other signal model of interest for reinterpretation.

The presented analyses will be preserved.

Why we need truth-level analyses

Detector-level simulation is not always available or feasible to be used

→ A truth-level analysis allows to implement an analysis also without the knowledge of the detector.

Used both inside and outside of experimental collaborations:

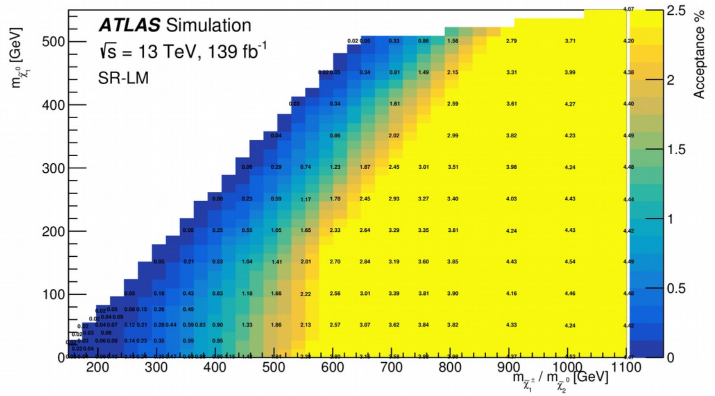
- *External*:

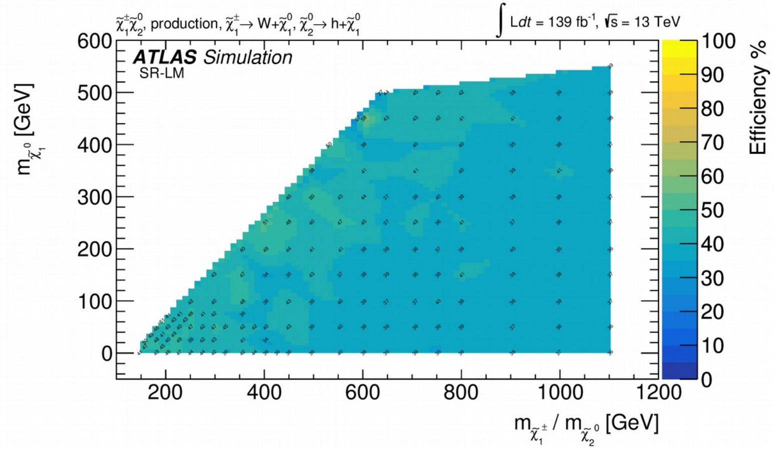
  → Reinterpretation of analyses & suggesting new analyses.
- *Internal*:

  → Calculation of acceptances and efficiencies.

  → Calculation of some theoretical uncertainties, if full simulation too expensive.

  → In reinterpretation efforts like scans of the phenomenological MSSM.



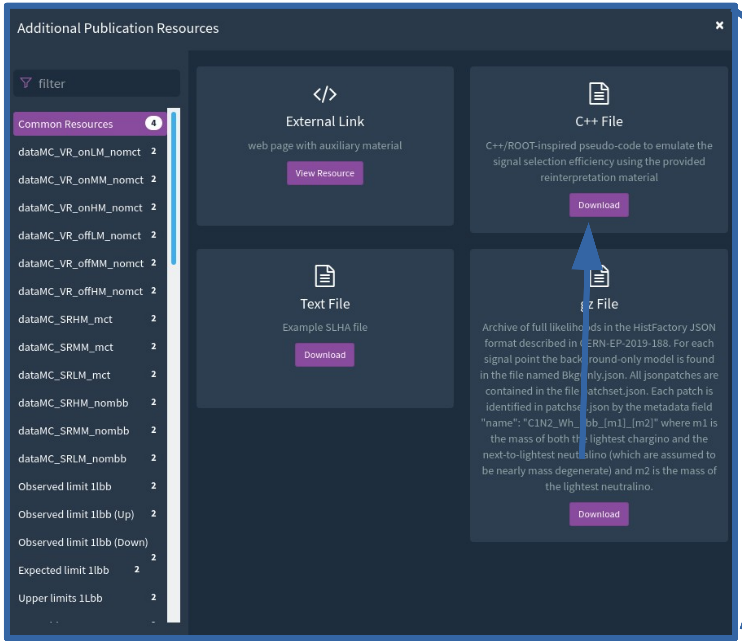


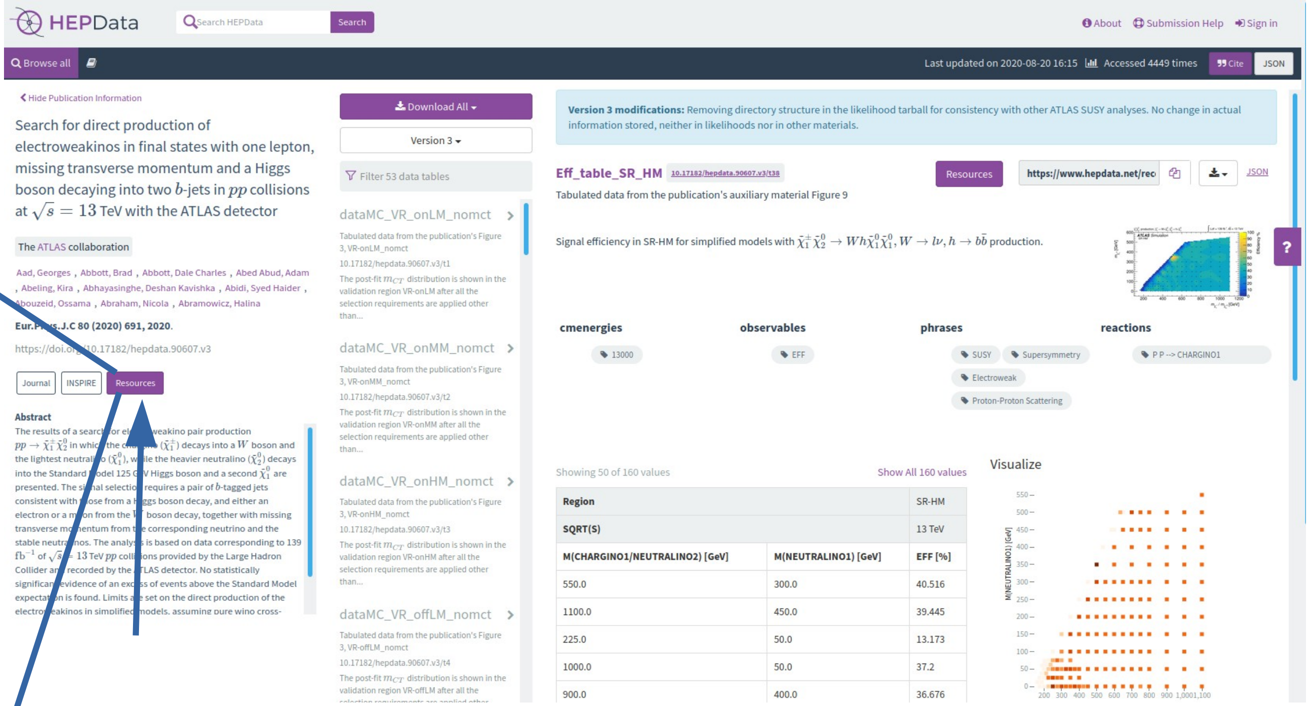
[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2019-08/]

Truth code snippets available in HEPData

[https://www.hepdata.net/record/ins1755298]

ATLAS SUSY searches release a C++ pseudocode for each analysis within HEPData since a while.





Pseudocode

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Documents

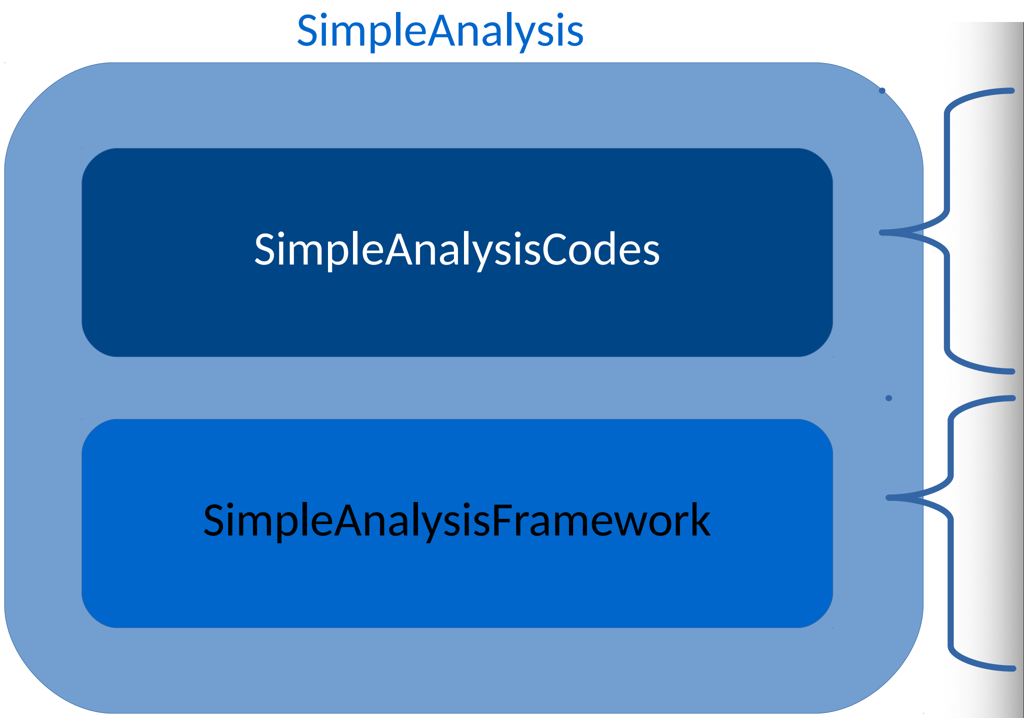
EwkOneLeptonTwoBjets2018.cxx

```
#include "SimpleAnalysis/AnalysisClass.h"
#include "SimpleAnalysis/NtupleMaker.h"
#include "SimpleAnalysis/PDFReweight.h"
#include <LHAPDF/LHAPDF.h>
#include "TMath.h"

DefineAnalysis(EwkOneLeptonTwoBjets2018)
// Wh->1l+bb+met analysis (Run2 data)

void EwkOneLeptonTwoBjets2018::Init()

{
  // Define signal/control regions
  addRegions({"SR_h_Low", "SR_h_Med", "SR_h_High"} );
  addRegions({"SR_h_Low_Incl", "SR_h_Med_Incl", "SR_h_High_Incl"} );
  addRegions({"SR_h_Low_bin1", "SR_h_Low_bin2", "SR_h_Low_bin3"});
  addRegions({"SR_h_Med_bin1", "SR_h_Med_bin2", "SR_h_Med_bin3"});
  addRegions({"SR_h_High_bin1", "SR_h_High_bin2", "SR_h_High_bin3"});
  addRegions({"CR_tt_Low", "CR_tt_Med", "CR_tt_High"});
  addRegions({"WCR", "STCR"});
  addRegions({"VR_off_Low", "VR_off_Med", "VR_off_High"});
  addRegions({"VR_on_Low", "VR_on_Med", "VR_on_High"});
}

void EwkOneLeptonTwoBjets2018::ProcessEvent(AnalysisEvent *event)
{
  //
  // Soft Objects
  //
  auto  Soft_Elec = event->getElectrons(7,2.47,ELooseBLLH | EZ05mm);
  auto  Soft_Muon = event->getMuons(6,2.70, MuMedium| MuNotCosmic | MuGood | MuZ05mm);
  auto  Soft_Jets = event->getJets(20.,4.5);
  auto  met_Vect  = event->getMET();
  float met       = met_Vect.Pt();
   //
  // Baseline objects
  //
  // Reject events with bad jets
  auto radiusCalcLep = [] (const AnalysisObject& lep,const AnalysisObject&) {return (0.04 + 10/lep.Pt()) > 0.4 ? 0.4 : 0.04 + 10/lep.Pt();};
  auto Base_Elec      = overlapRemoval(Soft_Elec,Soft_Elec,0.01);
  Base_Elec      = overlapRemoval(Soft_Elec,Soft_Muon,0.01);
//  auto Base_Jets      = overlapRemoval(Soft_Jets,Base_Elec,0.2, NOT(BTag77MV2c10));
//  Base_Elec           = overlapRemoval(Base_Elec,Base_Jets,radiusCalcLep);
  Base_Elec           = overlapRemoval(Base_Elec,Soft_Jets,radiusCalcLep);
  auto Base_Jets      = overlapRemoval(Soft_Jets, Soft_Muon, 0.2);
  auto Base_Muon      = overlapRemoval(Soft_Muon,Base_Jets,radiusCalcLep);

   auto Signal_Elec = filterObjects(Base_Elec,7.,2.47,ETightLH | ED0Sigma5  | EZ05mm  | EIsoGradientLoose);
  auto Signal_Muon = filterObjects(Base_Muon,6.,2.7,MuMedium | MuD0Sigma3 | MuZ05mm |MuIsoGradientLoose);
  auto Signal_Jets = filterObjects(Base_Jets,30.,2.80,JVT50Jet);
  auto Signal_BJet = filterObjects(Signal_Jets,30.,2.8,BTag77MV2c10);

  //
  auto Signal_Lep = Signal_Elec + Signal_Muon;
  //Count the number of signal objects
  unsigned int N_Signal_Elec = Signal_Elec.size();
  unsigned int N_Signal_Muon = Signal_Muon.size();
  unsigned int N_Signal_Lept = N_Signal_Elec + N_Signal_Muon;
  unsigned int N_Signal_Jets = Signal_Jets.size();
  unsigned int N_Signal_BJet = Signal_BJet.size();
  float mt=0, m_CT=0,  mbb=0, b2jetpt=0, mlb1=0;
  if (Signal_Lep.size()==1   && Signal_BJet.size()==2 ) {
    mt   = calcMT(Signal_Lep[0], met_Vect);
    m_CT = calcMCT(Signal_BJet[0],Signal_BJet[1]);
    mbb= (Signal_BJet[0]+Signal_BJet[1]).M();
    mlb1= (Signal_BJet[0]+Signal_Lep[0]).M();
        b2jetpt = Signal_BJet[1].Pt();
  }

  //Define ntupleVar variables for Hamish
  int SR_h_Low(0), SR_h_Med(0), SR_h_High(0);
  int SR_h_Low_Incl(0), SR_h_Med_Incl(0), SR_h_High_Incl(0);
```

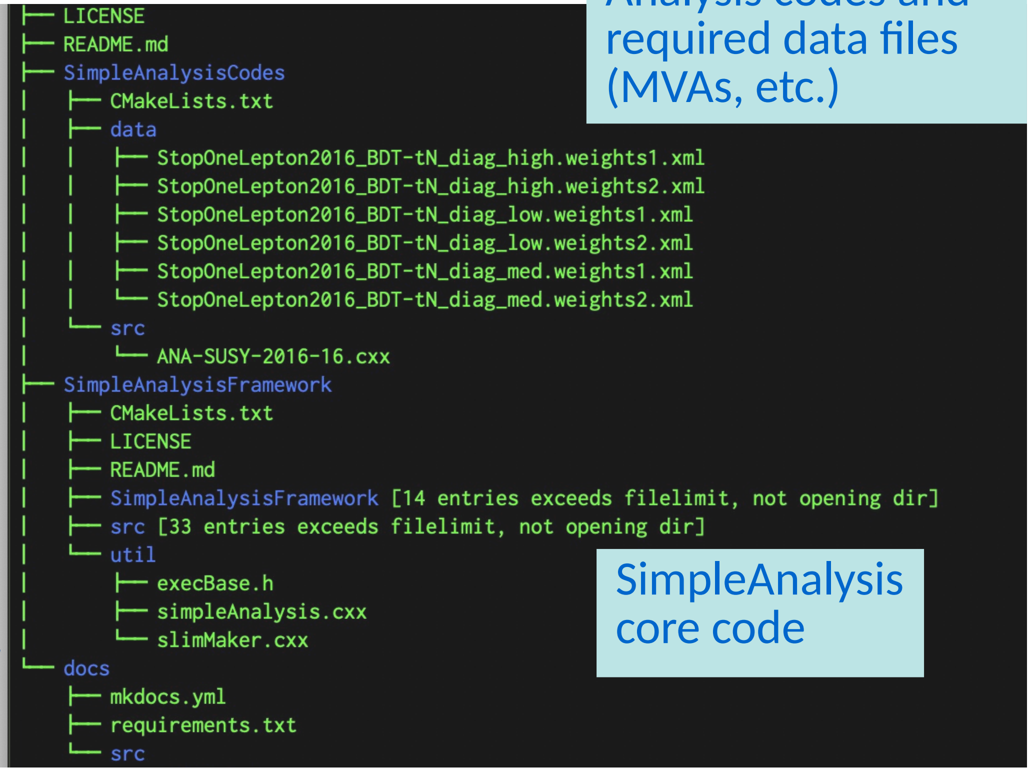
- Definition and selection of objects
- Precise cut sequence to define signal regions (and possibly other regions).

```
// Preselection
if(N_Signal_Lept != 1) return;
if(N_Signal_BJet != 2) return;
if(N_Signal_Jets>3 || N_Signal_Jets < 2) return;
if(mt< 50.) return;

 if(met< 220.) return;
// Signal regions
if(met>240 && mbb>100 && mbb<=140 && m_CT>180){
  if(mt>100 && mt<160){
            accept("SR_h_Low");
            SR_h_Low = 1;
            if(m_CT > 180 && m_CT <= 230){
                    accept("SR_h_Low_bin1");
                    SR_h_Low_bin1 = 1;
            }else if(m_CT > 230 && m_CT <= 280){
                    accept("SR_h_Low_bin2");
                    SR_h_Low_bin2 = 1;
            }else{
                    accept("SR_h_Low_bin3");
                    SR_h_Low_bin3 = 1;
            }
    }
  else if(mt>160 && mt<240){
            accept("SR_h_Med");
            SR_h_Med = 1;
            if(m_CT > 180 && m_CT <= 230){
                    accept("SR_h_Med_bin1");
                    SR_h_Med_bin1 = 1;
            }else if(m_CT > 230 && m_CT <= 280){
                    accept("SR_h_Med_bin2");
                    SR_h_Med_bin2 = 1;
            }else{
                    accept("SR_h_Med_bin3");
                    SR_h_Med_bin3 = 1;
            }
    }
  else if(mt>240 && mlb1 > 120){
            accept("SR_h_High");
            SR_h_High = 1;
            if(m_CT > 180 && m_CT <= 230){
                    accept("SR_h_High_bin1");
                    SR_h_High_bin1 = 1;
            }else if(m_CT > 230 && m_CT <= 280){
                    accept("SR_h_High_bin2");
                    SR_h_High_bin2 = 1;
            }else{
                    accept("SR_h_High_bin3");
                    SR_h_High_bin3 = 1;
```

SimpleAnalysis



Link!



```
├── LICENSE
├── README.md
├── SimpleAnalysisCodes
│   ├── CMakeLists.txt
│   ├── data
│   │   ├── StopOneLepton2016_BDT-tN_diag_high.weights1.xml
│   │   ├── StopOneLepton2016_BDT-tN_diag_high.weights2.xml
│   │   ├── StopOneLepton2016_BDT-tN_diag_low.weights1.xml
│   │   ├── StopOneLepton2016_BDT-tN_diag_low.weights2.xml
│   │   ├── StopOneLepton2016_BDT-tN_diag_med.weights1.xml
│   │   └── StopOneLepton2016_BDT-tN_diag_med.weights2.xml
│   └── src
│       └── ANA-SUSY-2016-16.cxx
├── SimpleAnalysisFramework
│   ├── CMakeLists.txt
│   ├── LICENSE
│   ├── README.md
│   ├── SimpleAnalysisFramework [14 entries exceeds filelimit, not opening dir]
│   ├── src [33 entries exceeds filelimit, not opening dir]
│   └── util
│       ├── execBase.h
│       ├── simpleAnalysis.cxx
│       └── slimMaker.cxx
└── docs
    ├── mkdocs.yml
    ├── requirements.txt
    └── src
```

Analysis codes and required data files (MVAs, etc.)

SimpleAnalysis core code