# Searching for Supersymmetry outside the box - Beyond cut-and-count in ATLAS analyses

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on behalf of the ATLAS Collaboration

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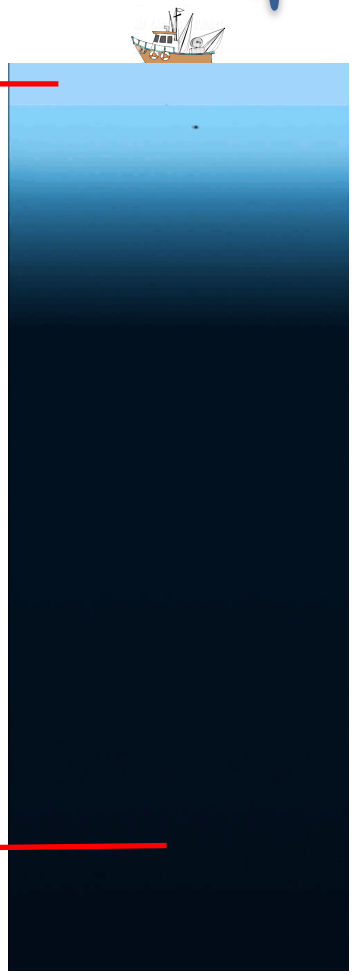
# Looking for Supersymmetry

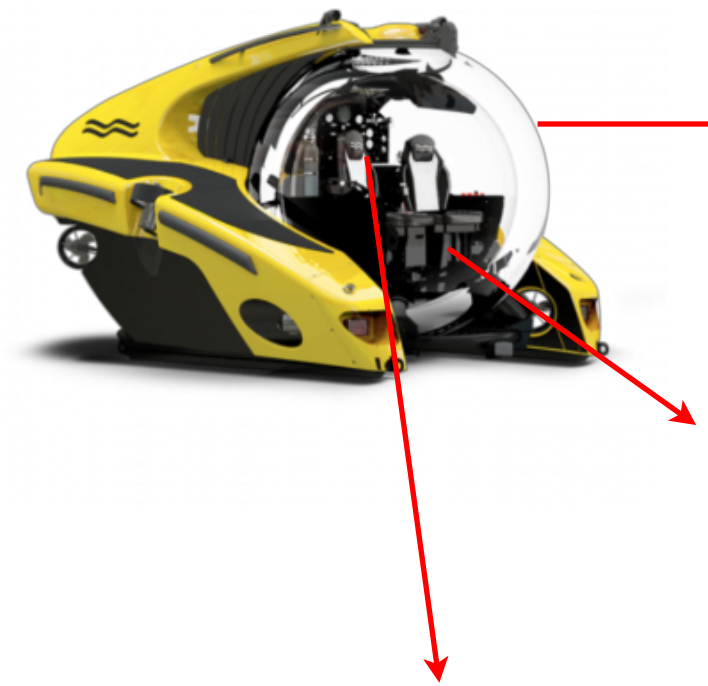
- Expectation before start of Large Hadron Collider (LHC):
  - Rich supersymmetry (SUSY) phenomenology "just below the surface"



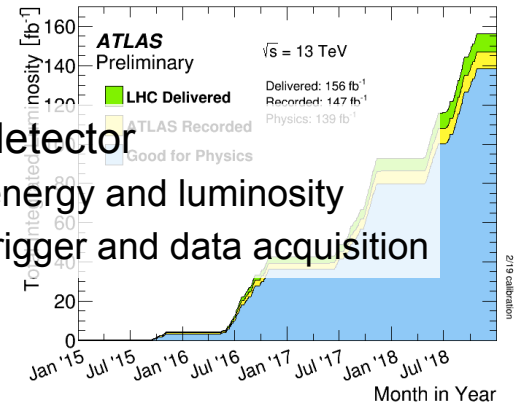
- Ten years after the start of data taking at the LHC, we need to accept it might actually be rather ….

- Difficult to find
- Largely unknown characteristics?
- Requires more and more sophisticated tools

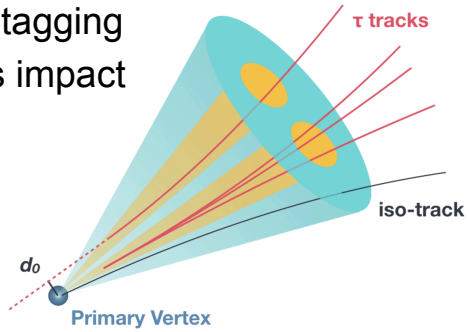
# What kind of tools?



- LHC and the ATLAS detector
  - Increase in beam energy and luminosity
  - Advancements in trigger and data acquisition
  - …




- Physics object reconstruction and performance
  - Reconstruction and calibration techniques
  - B-jet tagging and large-R jet tagging
  - Suppression of pileup and its impact
  - …



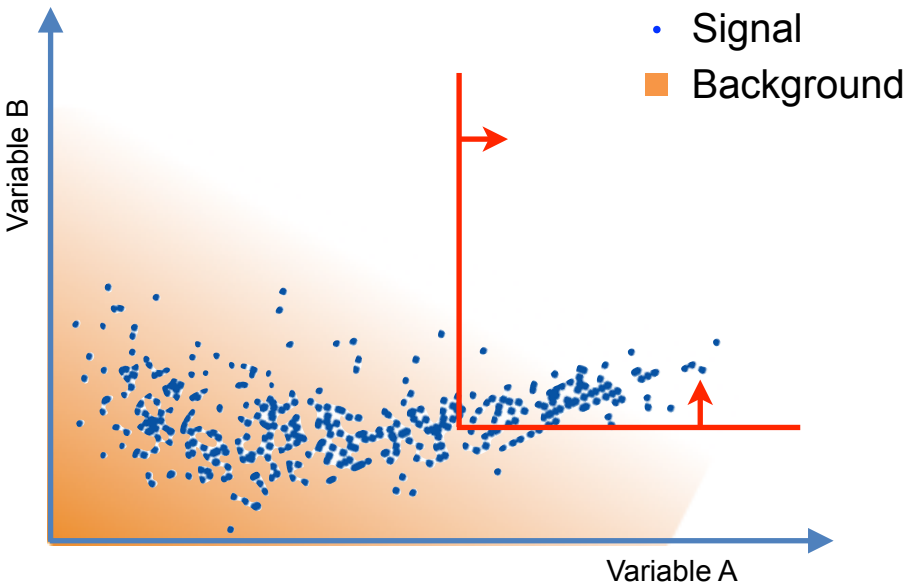

- Physics analysis
  - New and improved discriminating variables
  - **Search design and statistical tests**

this talk

# SUSY Search Design

- Pick or design discriminating variables in which signal and background distributions differ
- Define region of interest to compare background and signal predictions to data

- Simplest choice: determine set of selection criteria (cuts) and count events in the signal region
  - Straightforward determination of backgrounds and uncertainties
  - Good performance for signal hypotheses the selection was optimized for
  - Straightforward re-interpretation (within and outside experiment)



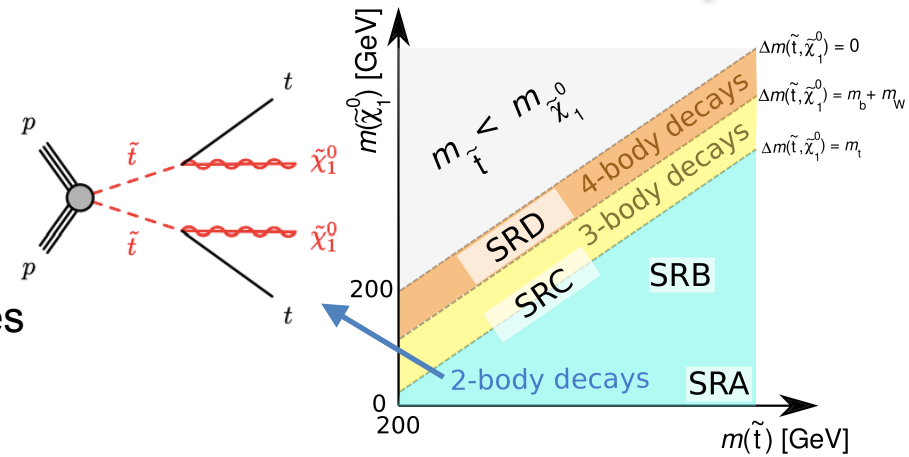

- Well suited to quantify potential disagreement with background only hypothesis
  - "Search phase" of data analysis before potentially moving on to exclusion of models

# Beyond cut-and-count

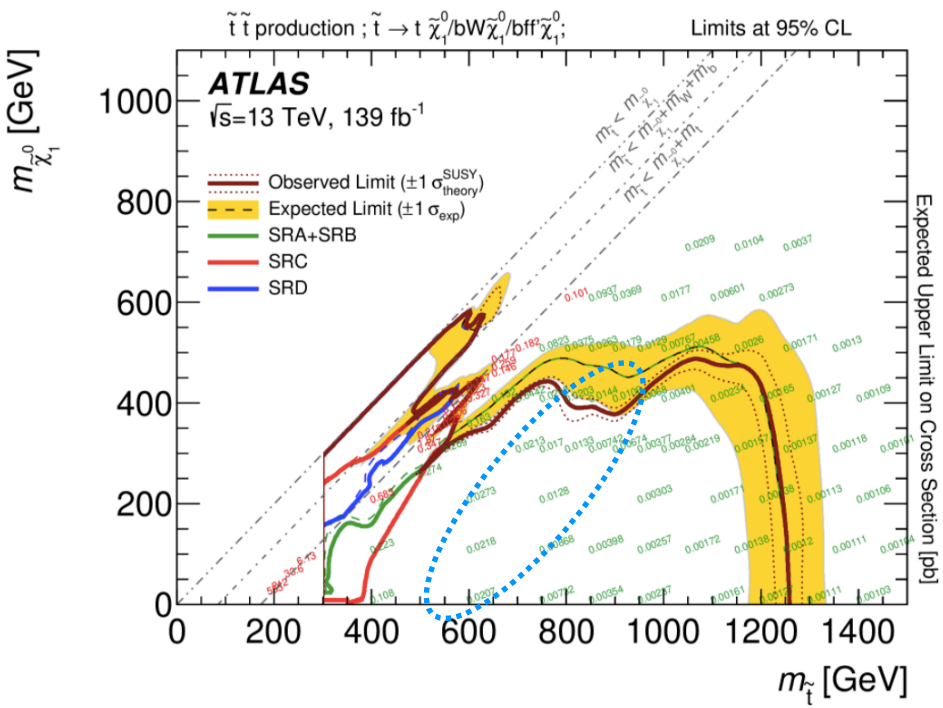
- Reasons to move beyond?

Example: **All-hadronic stop search**

- Distinct signal selections for regions in stop-neutralino mass plane of simplified models
- Sensitivity to targeted benchmark hypotheses dominated by single selection regions




arXiv:2004.14060

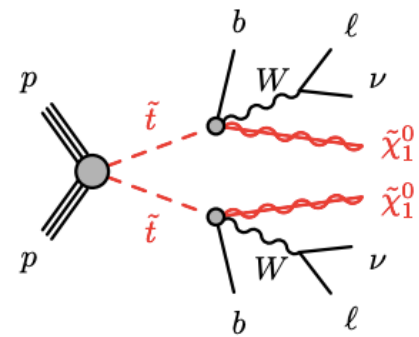



- Combination of SRA and SRB improves intermediate regime and **depth of exclusion**
- Both SRA and SRB split into three categories based on large-R jet masses
  - Increased flexibility and sensitivity to other signal hypotheses, e.g. leptoquark production

# Multi-channel Analysis

Example: Two-lepton stop search - 3-body region

- Split into no b-jet and b-jet, plus same and different flavour lepton categories
- Background compositions differ strongly
  - ➡ Multi-channel analysis

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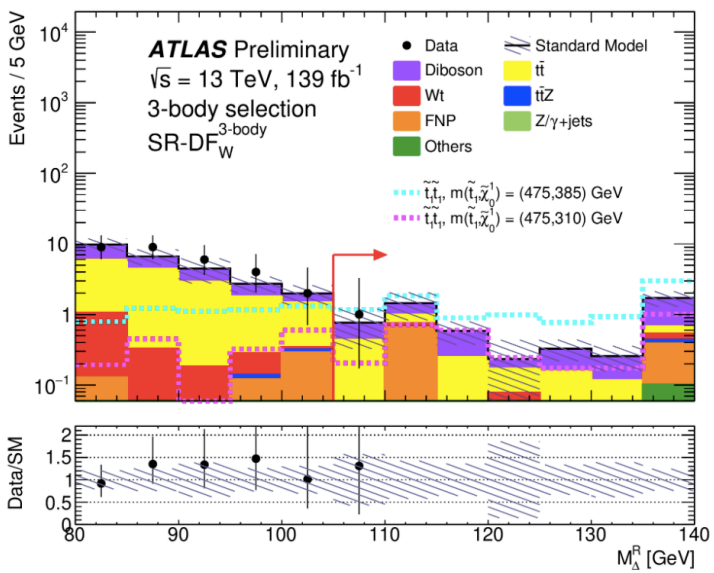
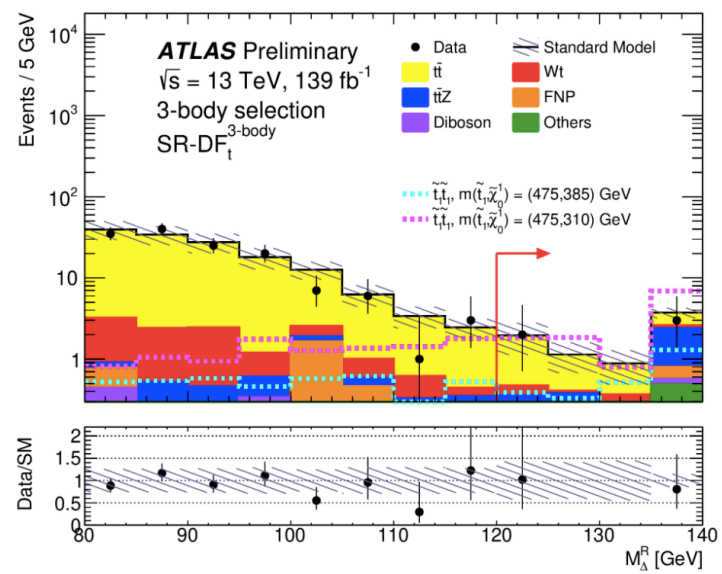
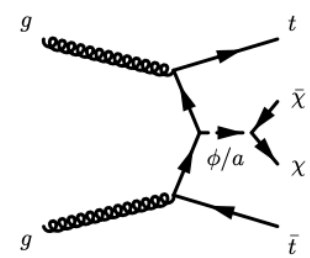
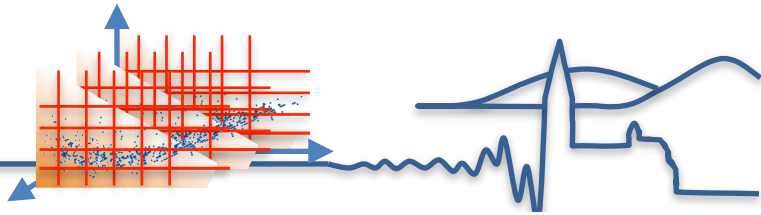


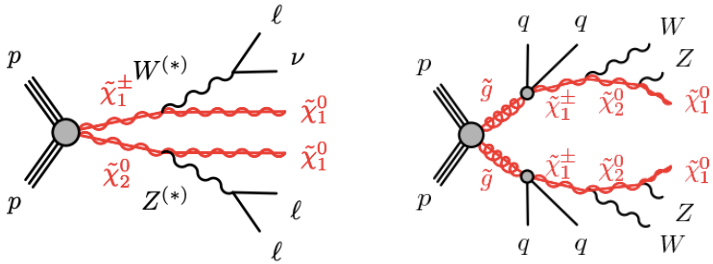

- 2-body region likewise split - additionally used to constrain models of dark matter production via scalar or pseudo-scalar mediator



# Multi-dimensional Fits



- Some cases warrant larger multi-dimensional grids of signal regions or bins
  - Examples:
    - Chargino-neutralino pair production
    - SUSY in high jet multiplicity events




- Different mass splittings can lead to significantly different event kinematics
  - Bin signal regions in e.g.
    - Missing transverse momentum
    - (b-)Jet multiplicities
    - Scalar sum of transverse jet momenta
    - …

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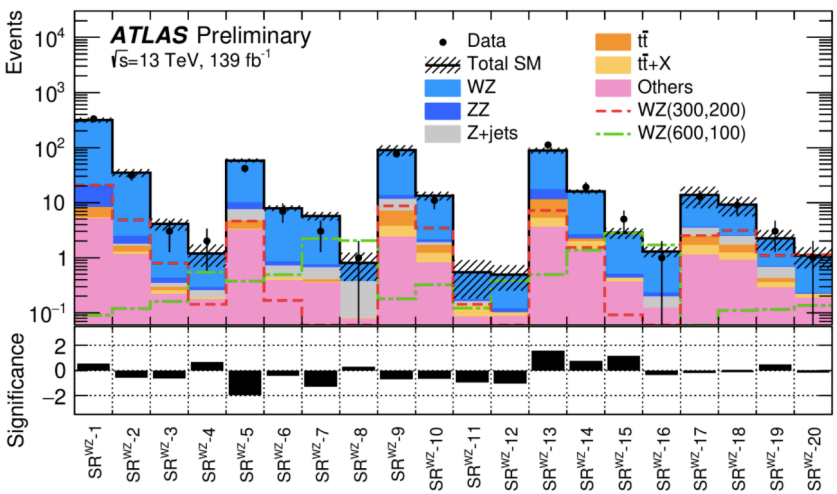
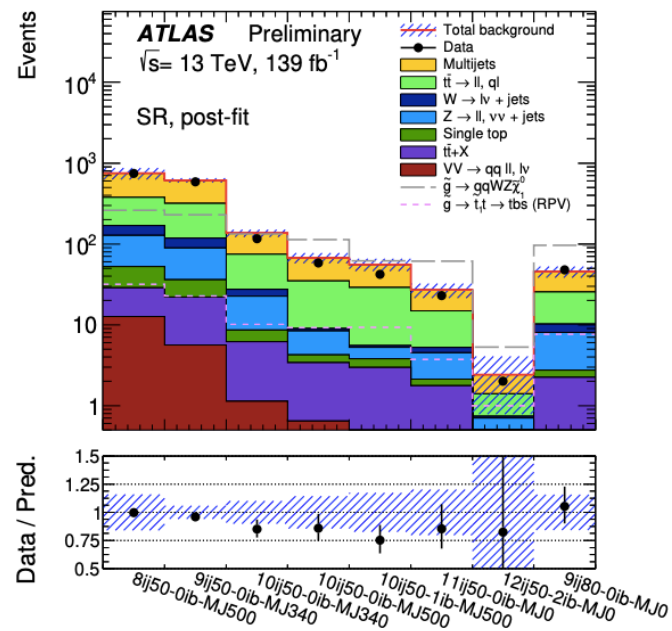



Typically: Also define
**single bin discovery signal regions**

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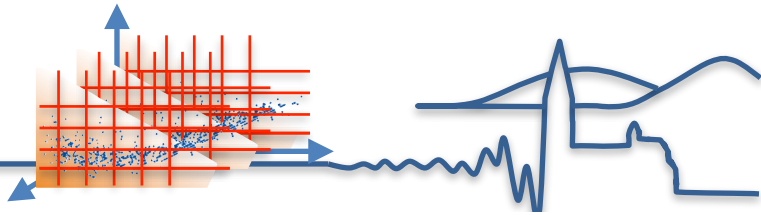
# Multi-dimensional Fits



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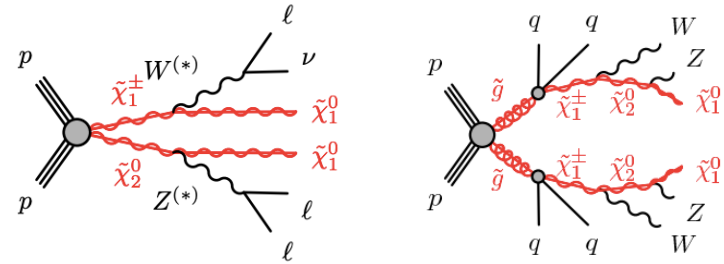


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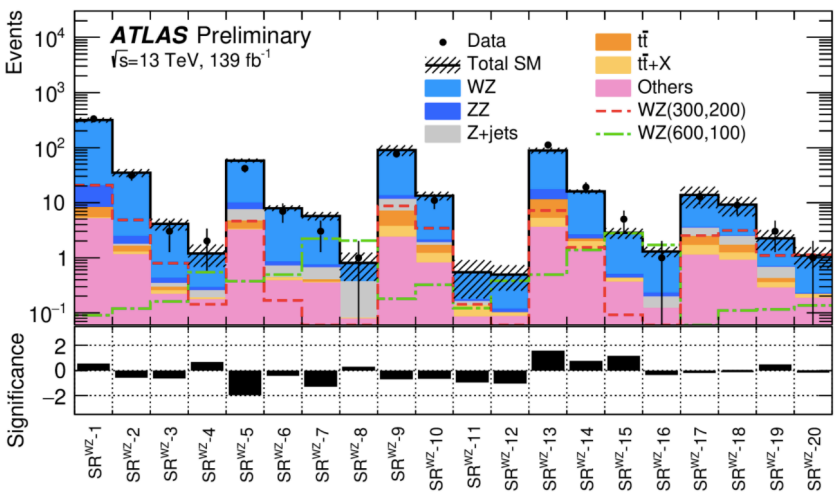


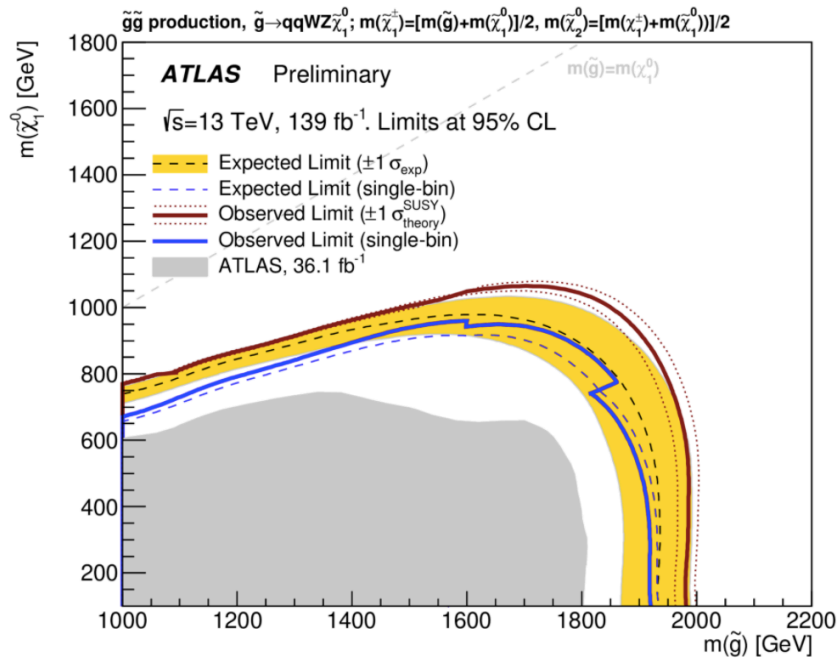


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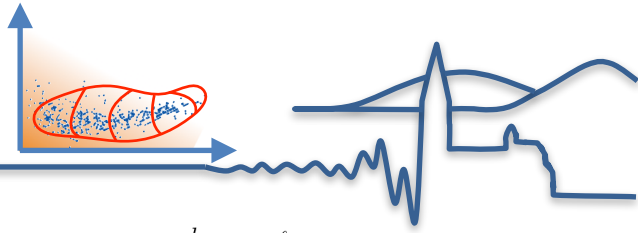
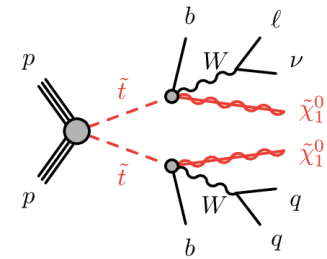
# Neural Networks and Multi-Bin Fits



- Multi-variate and machine learning techniques help to tackle challenging scenarios
  - Example: Stop production and 3-body decay




- Jet multiplicity varies strongly between events
  - Jet-based recurrent neural network (RNN) to best deal with variable length input
- Output of RNN fed to shallow neural network (NN) together with 12 other variables

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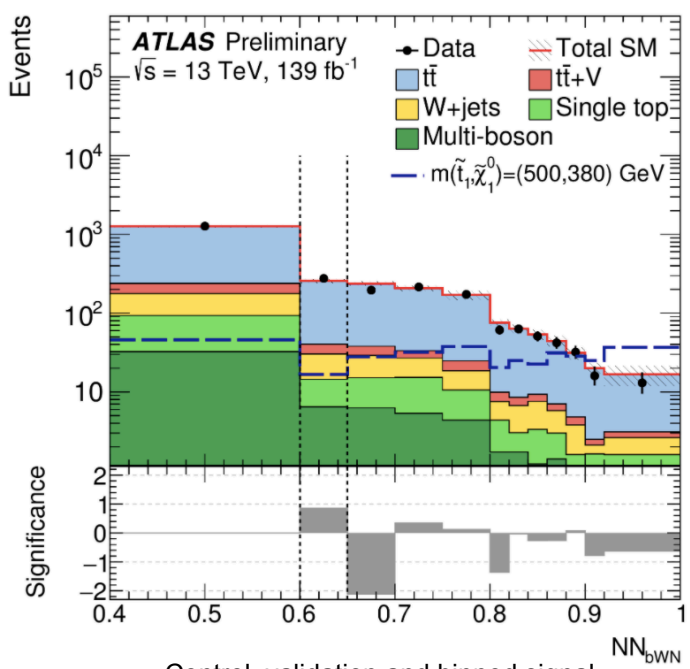
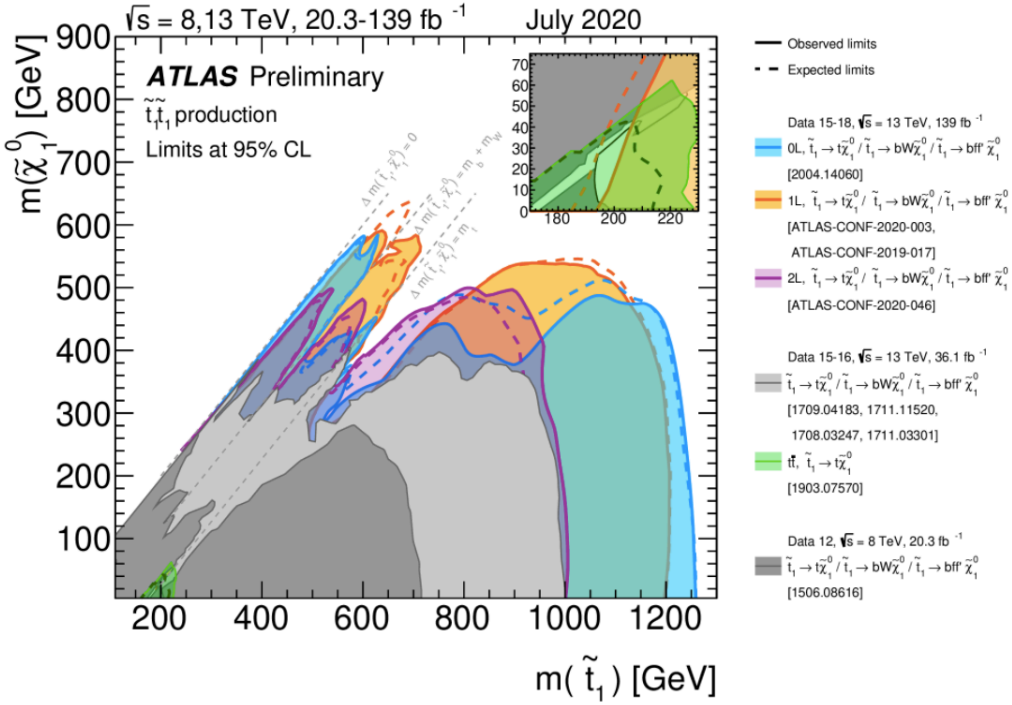


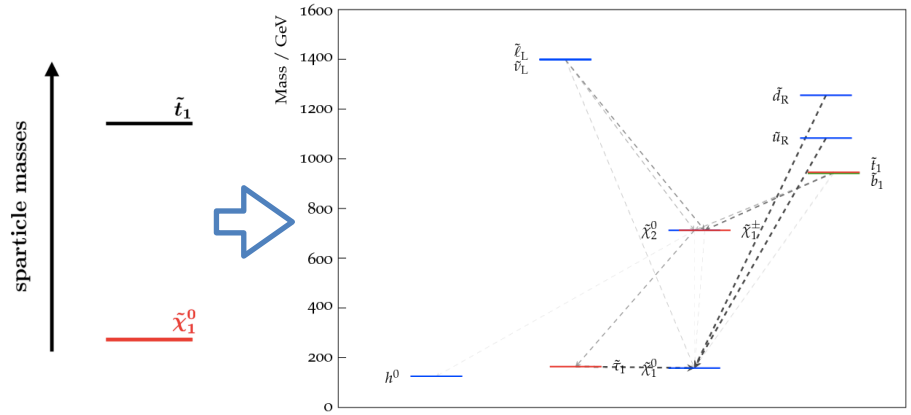

Control, validation and binned signal region definitions in NN classifier output




ATL-PHYS-PUB-2020-020

# Re-interpretation of results?

- Typical ATLAS SUSY publication:
  - Report results of discovery phase of search
  - Quantify sensitivity using grids of simplified models as benchmark




- Vital: Application of bounds on more complete and complex models
  - Straightforward for cut-and-count regions, what about more complex fits?

pyhf
∂ifferentiable
ℒikelihoods

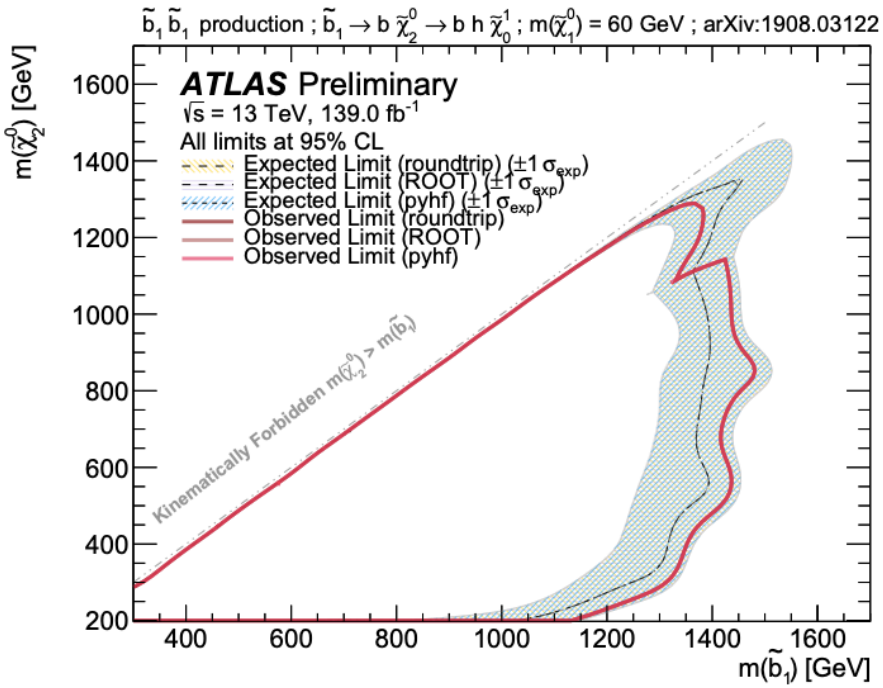
https://iris-hep.org/projects/pyhf.html

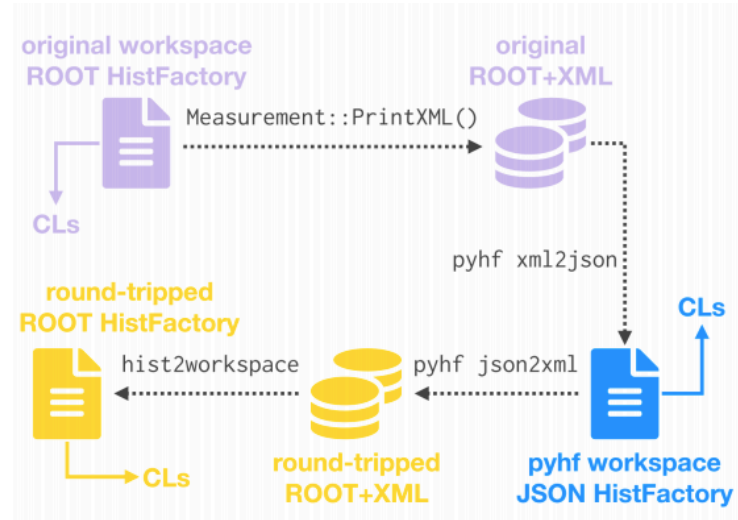
- Pure-python implementation of HistFactory p.d.f. template
- Publication of full likelihoods of ATLAS SUSY searches in JSON format
  - Allow rerunning of multi-bin/shape fits with identical inputs to published result
  - Include all uncertainties and correlations
  - Test new models utilising public “code snippets” of event selection

# pyHF - Proof of Concept

- Concept, JSON schema and proof of concept using search for sbottom pair production:
  - ATL-PHYS-PUB-2019-029

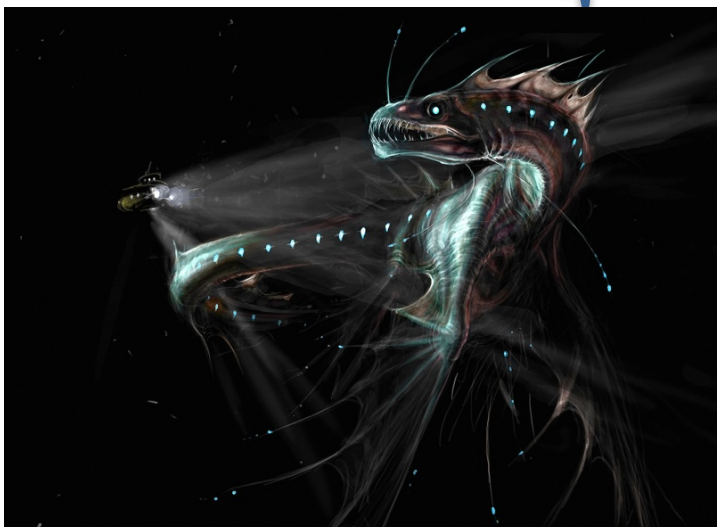
- Likelihoods for additional searches starting to appear on HEPData
  - Typically background only as well as patch files for benchmark signals




- pyHF includes conversion scripts to and from ROOT HistFactory workspace
  - E.g. allows “round-trip” for validation

# Summary and Conclusions



- Strong focus on search for supersymmetry in ATLAS, often using single bin search regions
  - No evidence for physics beyond the Standard Model yet
- Use of multi-channel analysis and shape fits in discriminator distributions to exclude specific signatures
  - Including non-SUSY signatures, e.g. dark matter production or leptoquarks
- Machine learning techniques are widespread in object tagging in ATLAS: b-jets, large-R jets, …
  - Direct use by searches becoming more common
- Challenge to efficiently communicate analysis setup, inputs and results for reuse and reinterpretation outside of ATLAS
  - Overcome by implementation and use of pyHF
  - Likelihoods start to become available, full list included here: https://iris-hep.org/projects/pyhf.html

# Backup

# Additional Info and ICHEP2020 Talks

- In addition to the cited sources (left and right edges of slides), a number of talks the following ICHEP2020 talks provide additional information about presented results:
  - When jets MET SUSY: ATLAS searches for squarks and gluinos
  - Searches for direct pair production of stops and sbottom with the ATLAS detector
  - Searches for the electroweak production of supersymmetric particles with the ATLAS detector

- All ATLAS public results on the search for supersymmetry can be found here:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults