FERMILAB-SLIDES-21-041-PPD
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SUSY at the LHC

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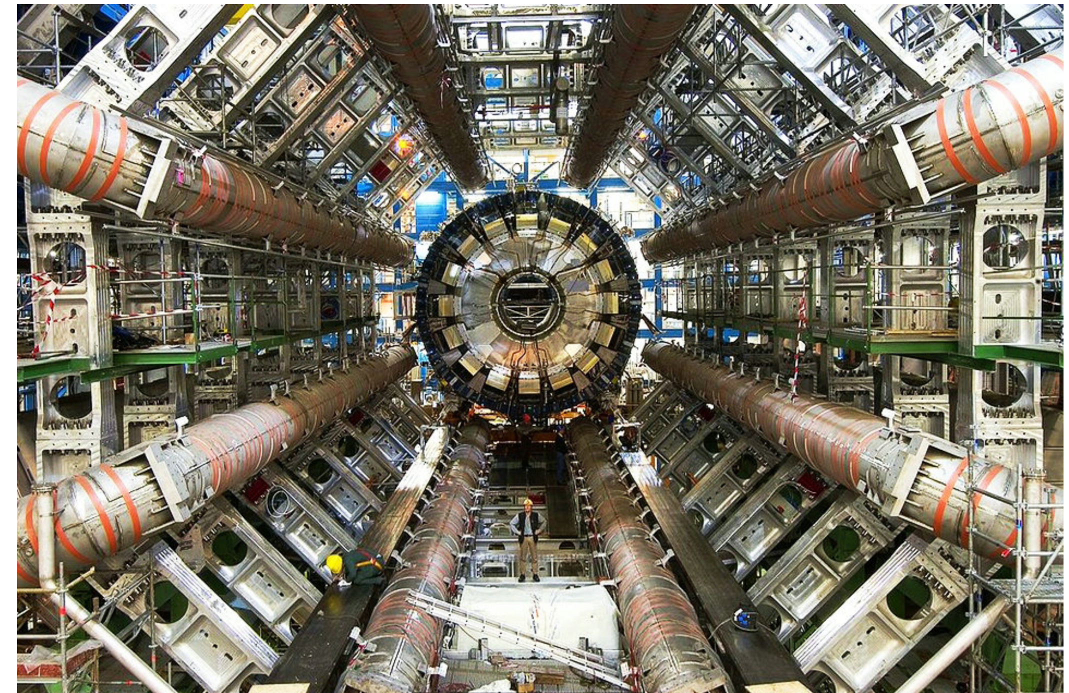
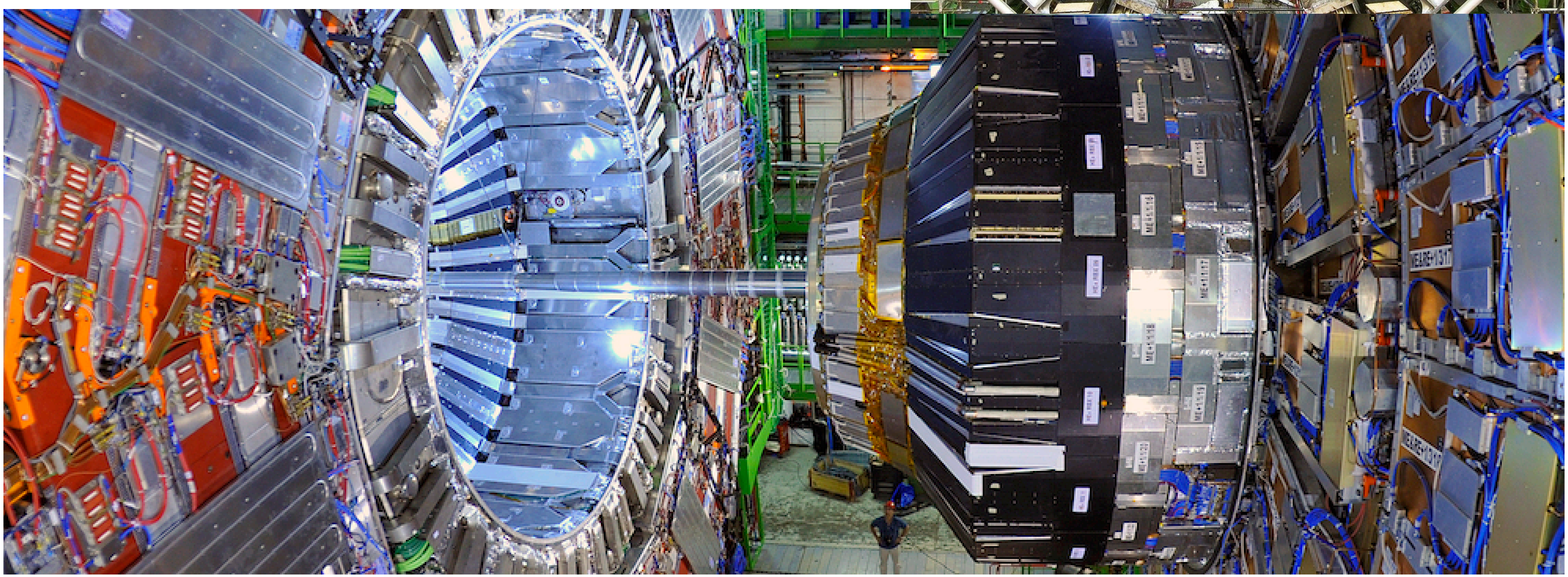
PPC2021: XIV International Workshop on Interconnections between Particle Physics and Cosmology

17-21 May 2021, Univ. of Oklahoma

Outline

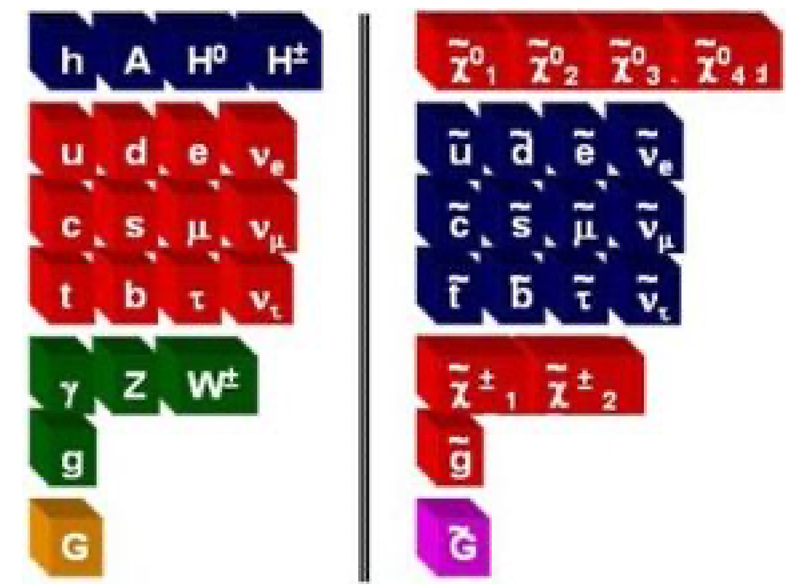
- Introduction to SUSY
- ATLAS and CMS at Run 2
- Latest results from SUSY searches
- Outlook

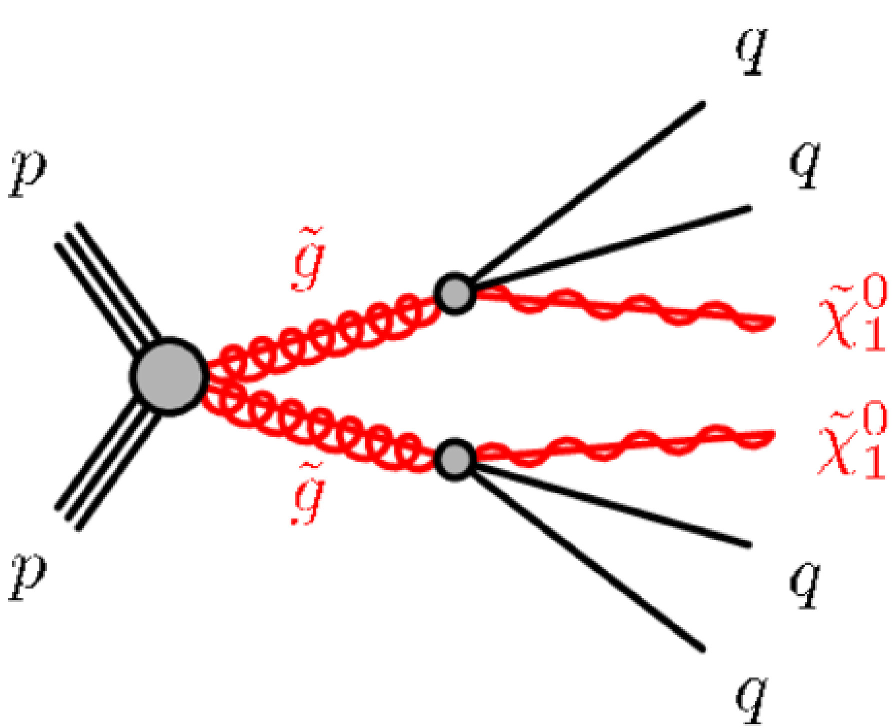


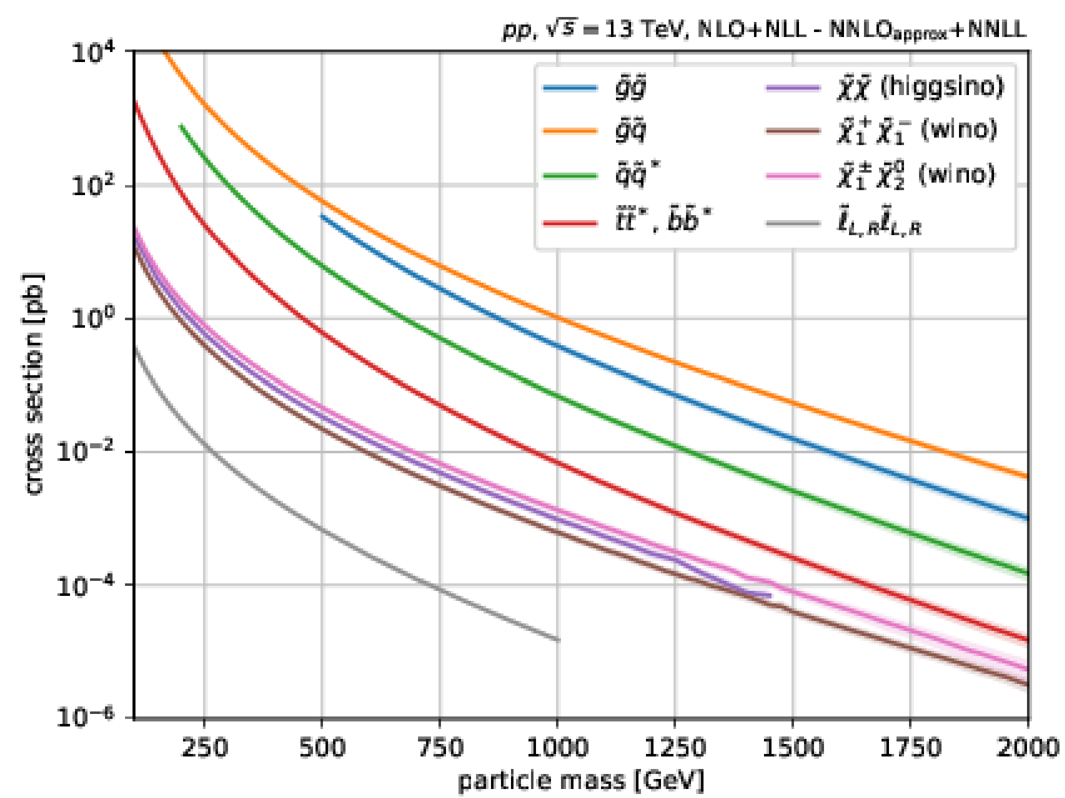


A brief reminder of SUSY

- The introduction of a new space-time symmetry requires the existence of SUSY partners of the SM particles with predictable couplings
- The experiments at LHC (LEP, Tevatron!) have adopted well motivated guiding principles to cast a **wide net to search for SUSY**
  - R-parity conservation (pair production, stable lightest SUSY particle)
  - Naturalness (gluinos, stops, electro-weakinos at TeV scale)

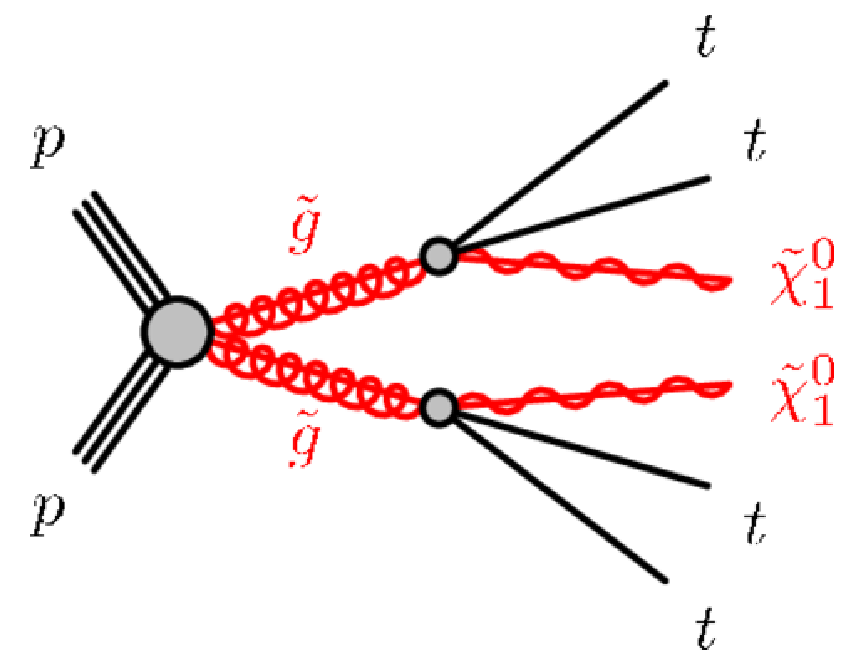


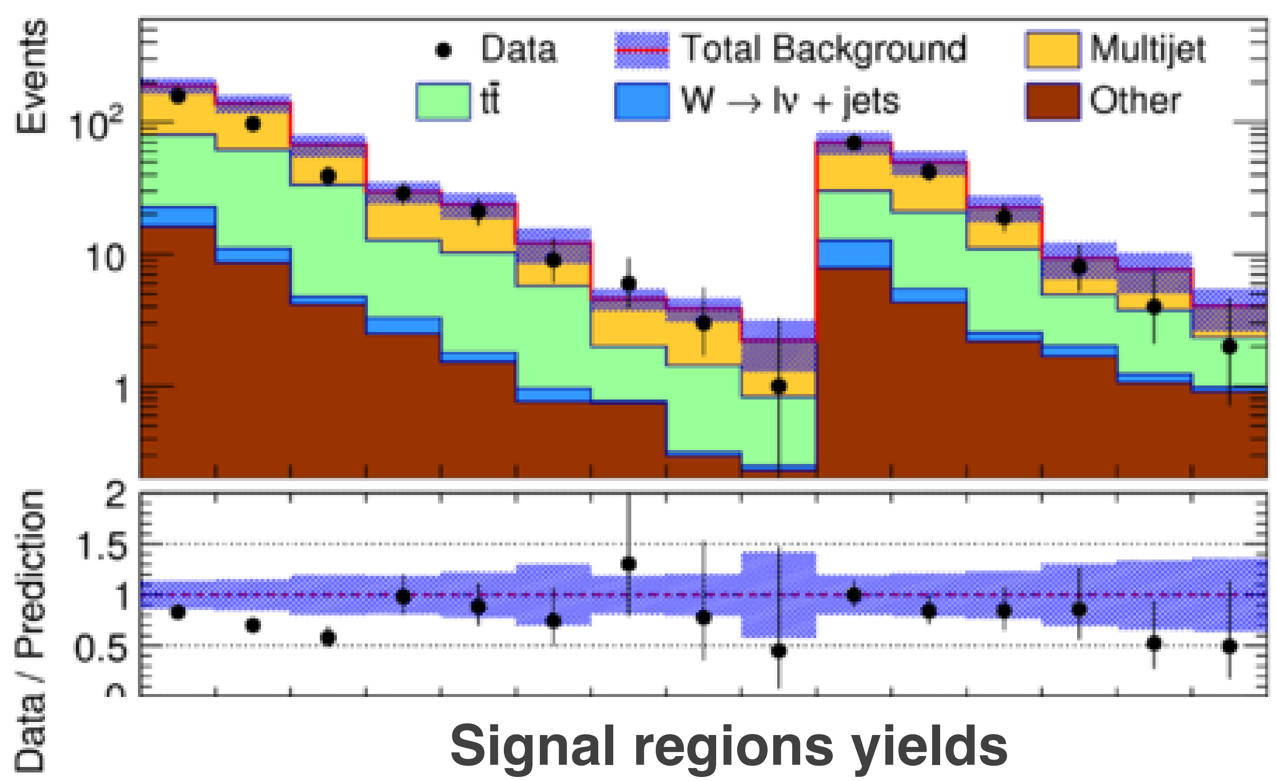




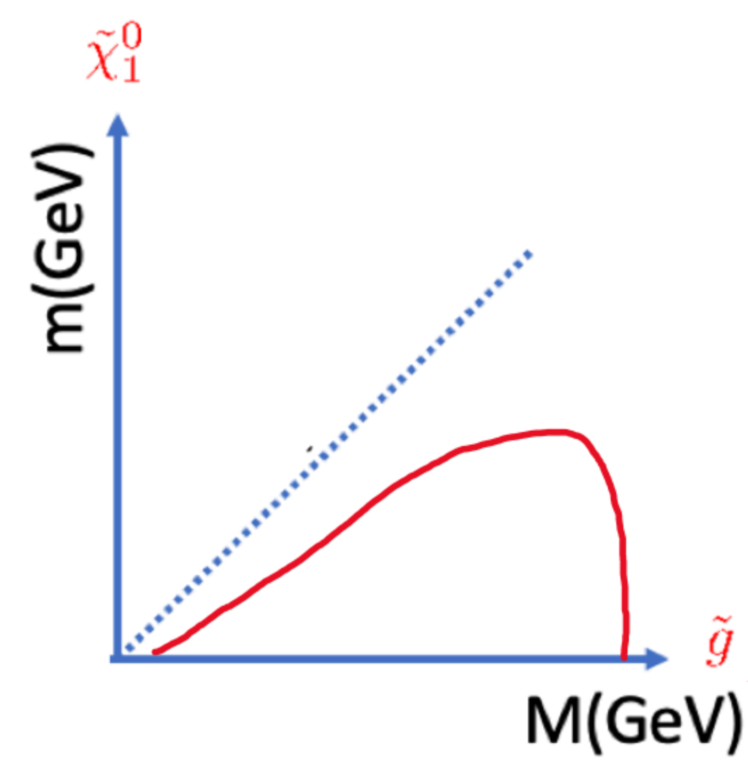
"Classic" SUSY search

- Events with large ETmiss and energetic jets
- SRs based on observables proxies of the SUSY mass scale and topological properties
- Control and validation regions for background estimate
- Simultaneous fit in both CRs and SRs (up to hundreds!) to look for excess
- Interpretation of results in simplified models



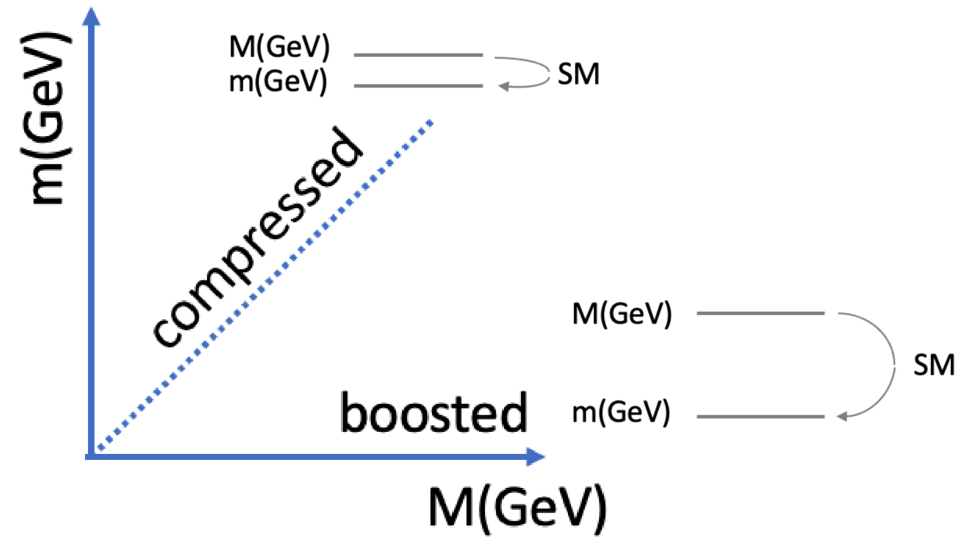


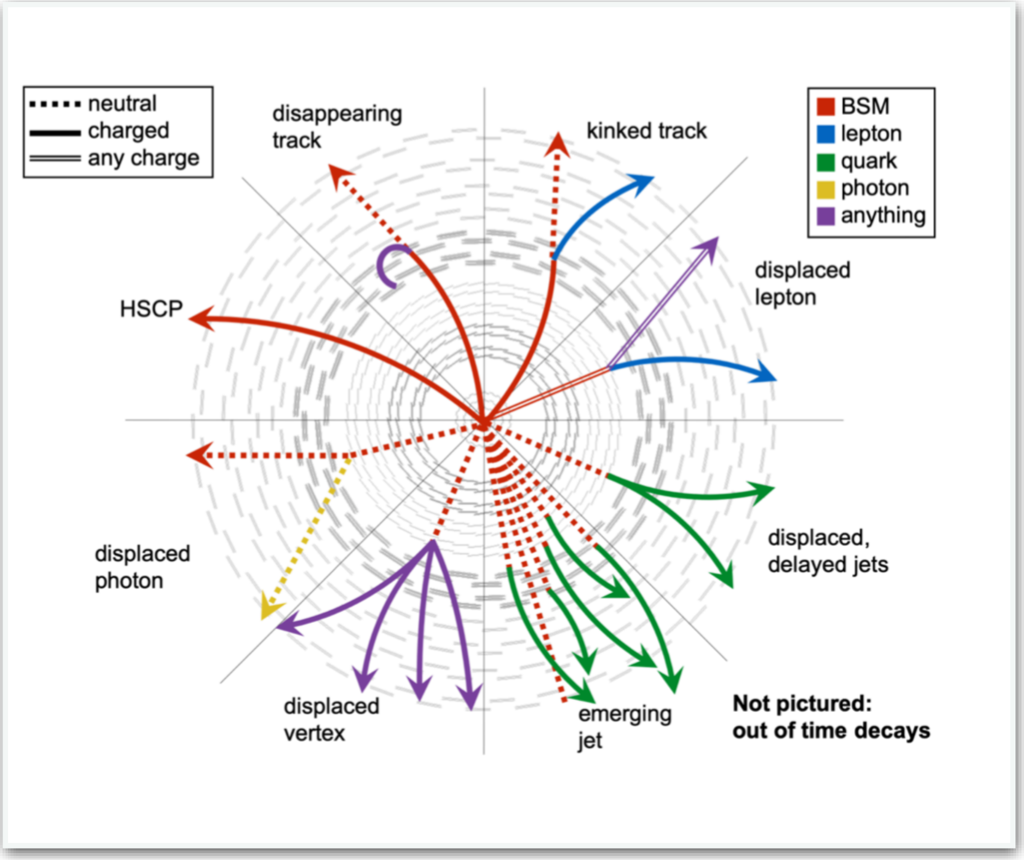
Signal regions yields



Where is SUSY?

- **No significant deviations from SM expectations**
- SUSY likely hidden in **challenging regions of parameter space**
  - Higher mass scale
    - Identify very high pT objects
  - Compressed spectra
    - Identify very low pT objects
  - Long-lived
    - Paradigm shift in object reconstruction
  - R-parity violation / Stealth
    - Explore events with low ETmiss
  - Unexpected

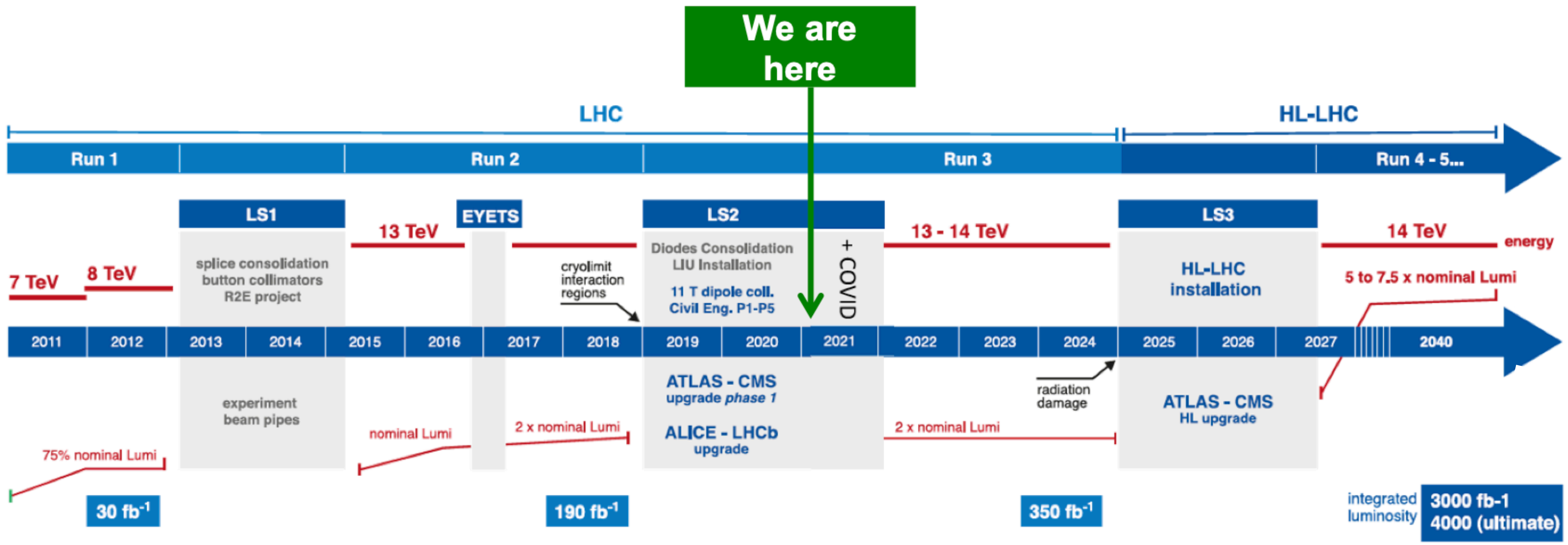


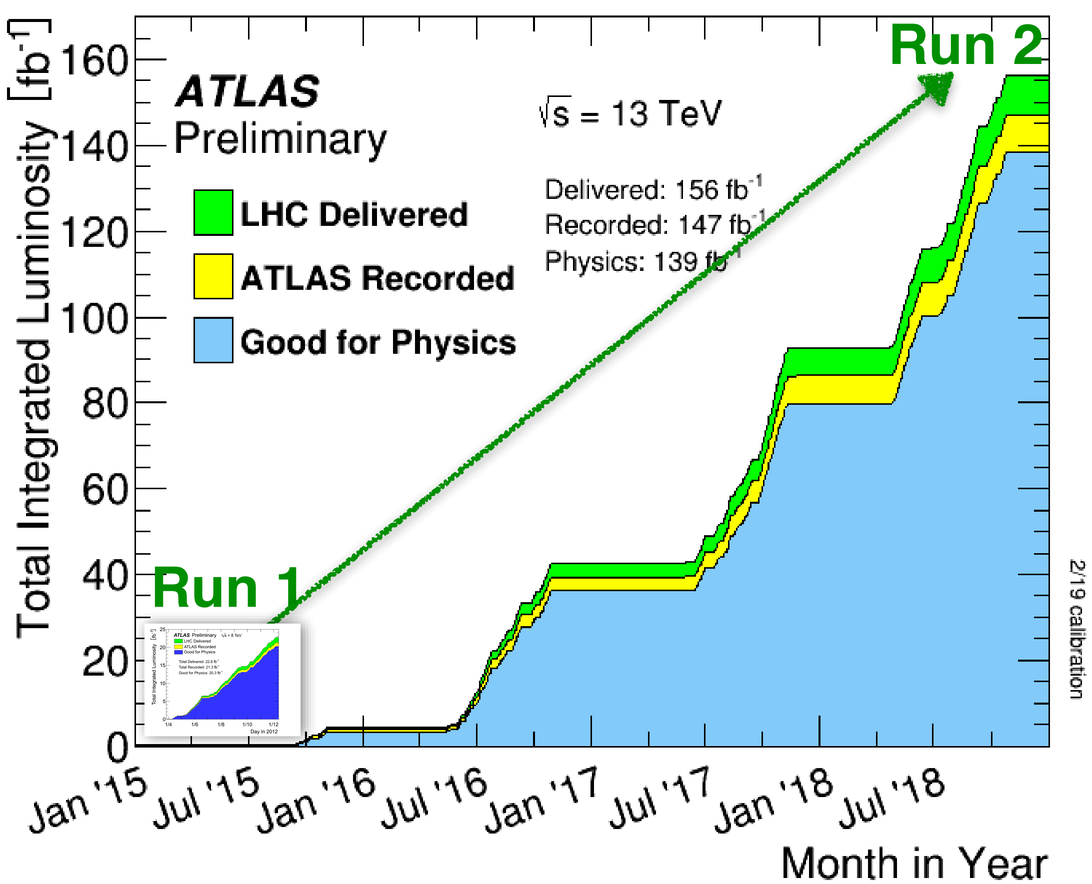


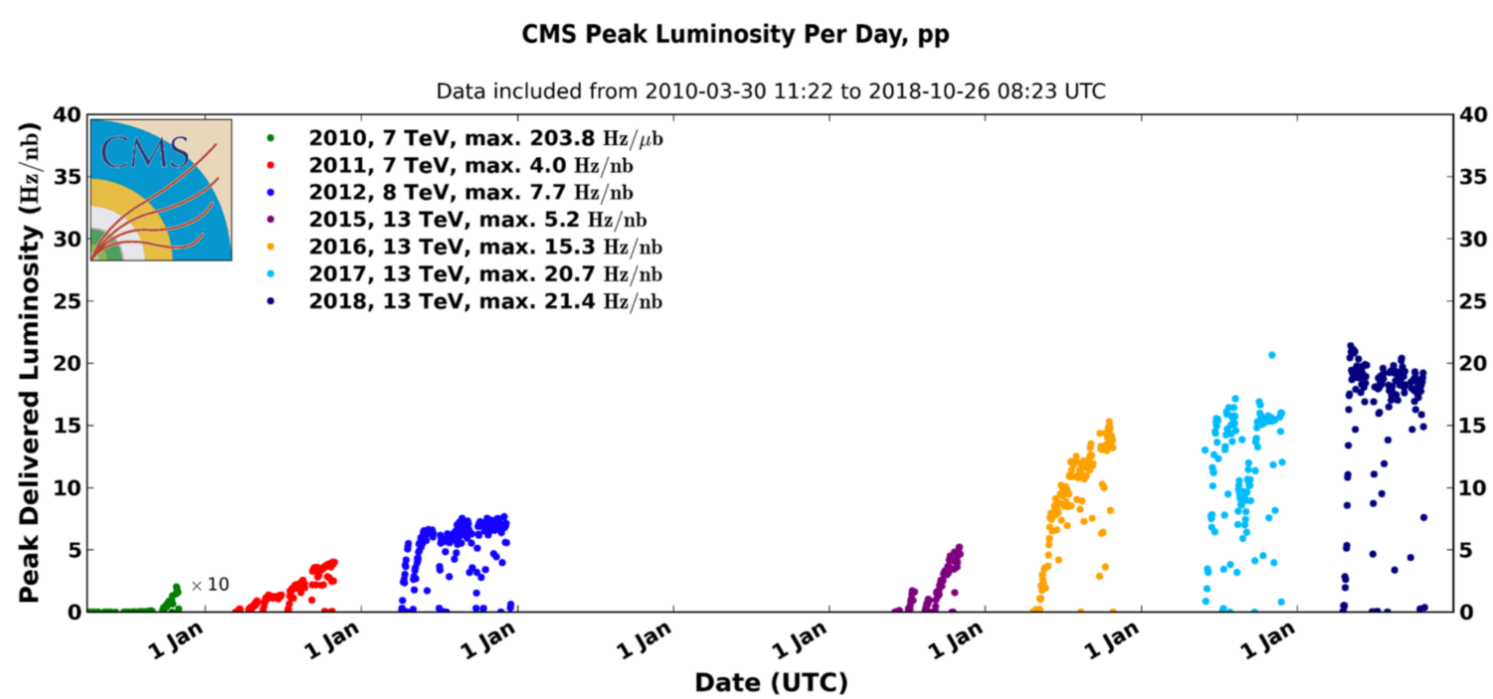
Focus on novel techniques targeting challenging signatures

All results from ATLAS and CMS searches at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

The LHC Run 2


We are here
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13 - 14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
11 T dipole coll.
Civil Eng. P1-P5
+ COVID
HL-LHC
installation
5 to 7.5 x nominal Lumi
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
350 fb-1
integrated
luminosity
3000 fb-1
4000 (ultimate)

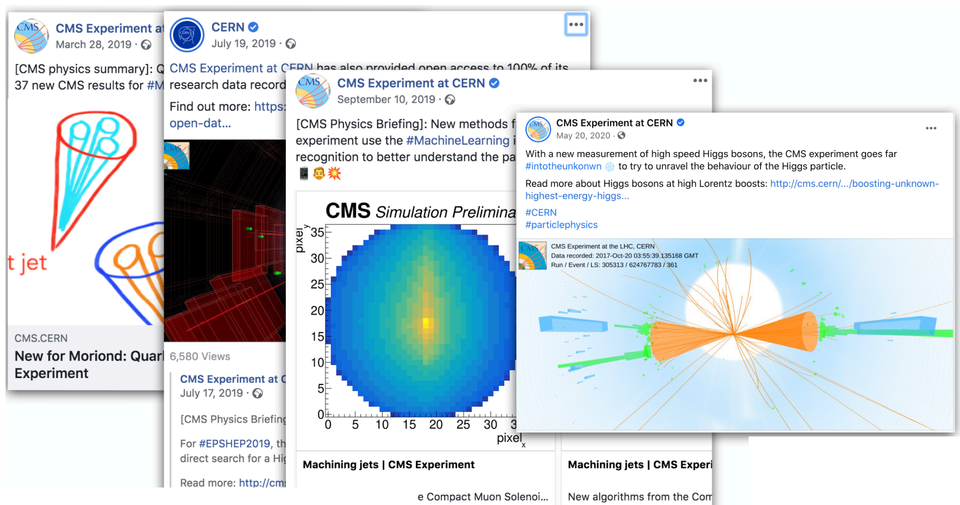

Run 2
Run 1
ATLAS
Preliminary
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Good for Physics
Delivered: 156 fb-1
Recorded: 147 fb-1
Physics: 139 fb-1
Total Integrated Luminosity [fb-1]
160
140
120
100
80
60
40
20
0
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Month in Year
2/19 calibration


CMS Peak Luminosity Per Day, pp
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC
2010, 7 TeV, max. 203.8 Hz/μb
2011, 7 TeV, max. 4.0 Hz/nb
2012, 8 TeV, max. 7.7 Hz/nb
2015, 13 TeV, max. 5.2 Hz/nb
2016, 13 TeV, max. 15.3 Hz/nb
2017, 13 TeV, max. 20.7 Hz/nb
2018, 13 TeV, max. 21.4 Hz/nb
× 10
Peak Delivered Luminosity (Hz/nb)
Date (UTC)
1 Jan

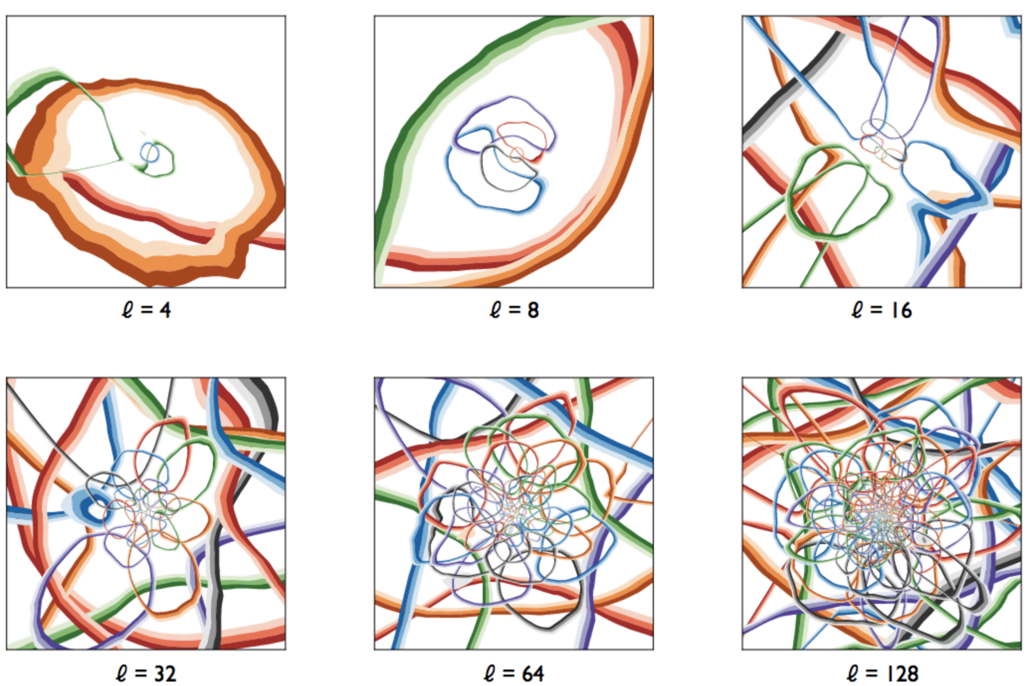
Run 2: Unprecedented dataset for HEP

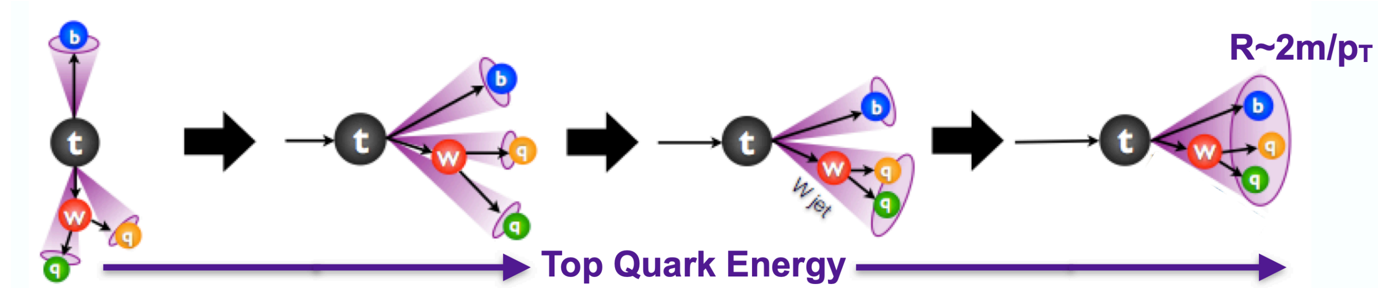
- Revolution in data reconstruction and analysis thanks to modern machine learning algorithms
  - Moving from MultiVariate to Deep Neural Networks
  - Ability to extract information from highly complex data sets
  - Leap forward in reconstructing very challenging signatures from boosted decays of top quarks and bosons using sub-structures, soft-drop mass, heavy flavor information, and more

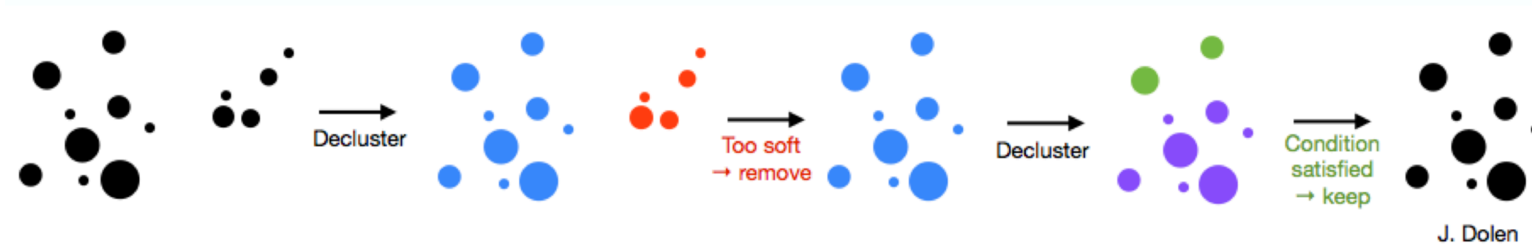
https://cms.cern/tags/physics-briefing



Courtesy of C. McLean



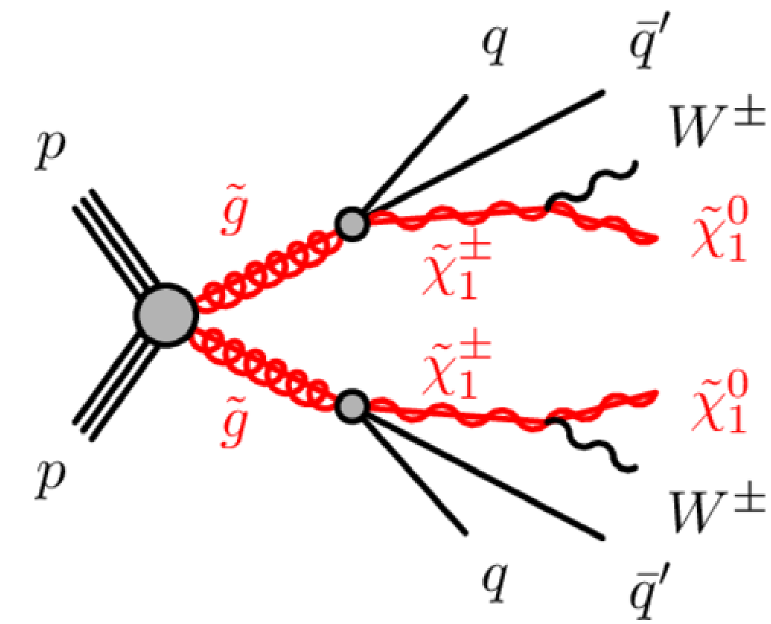


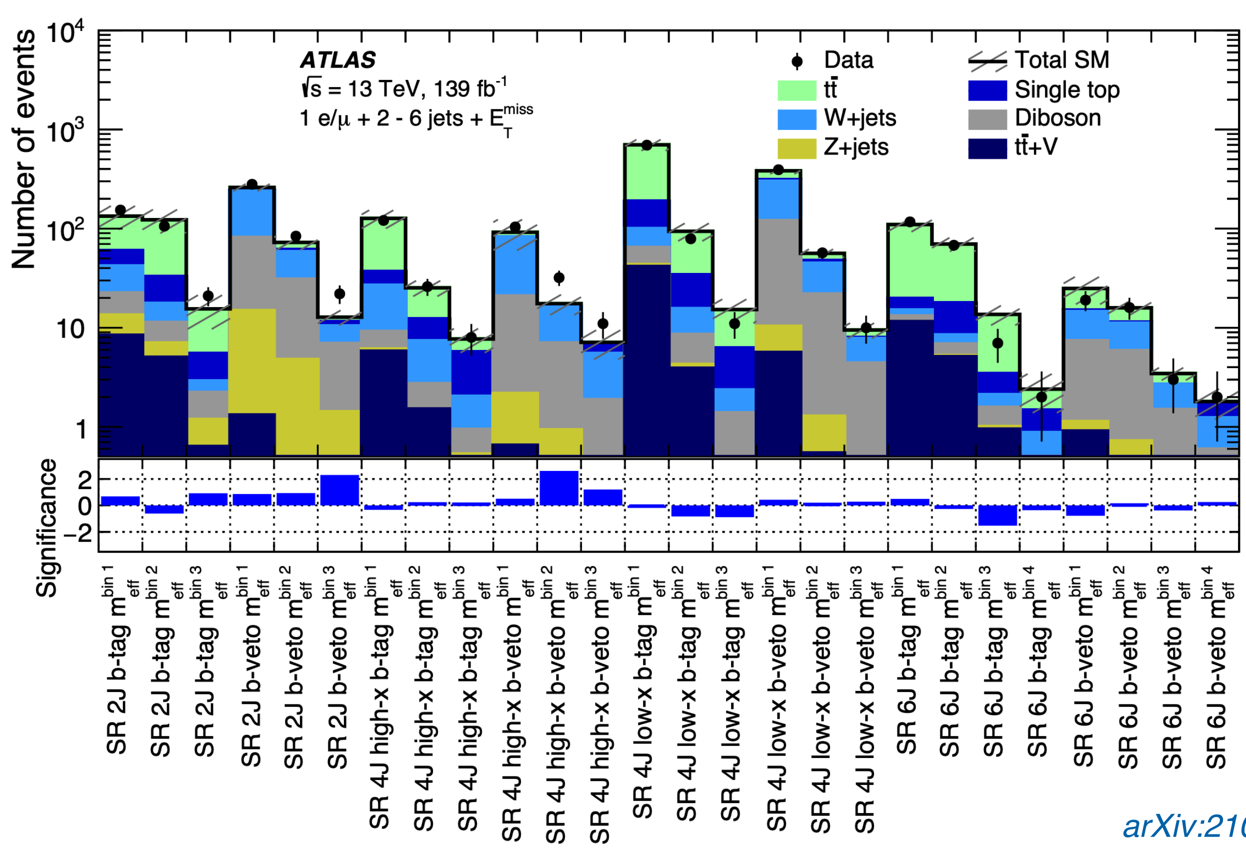


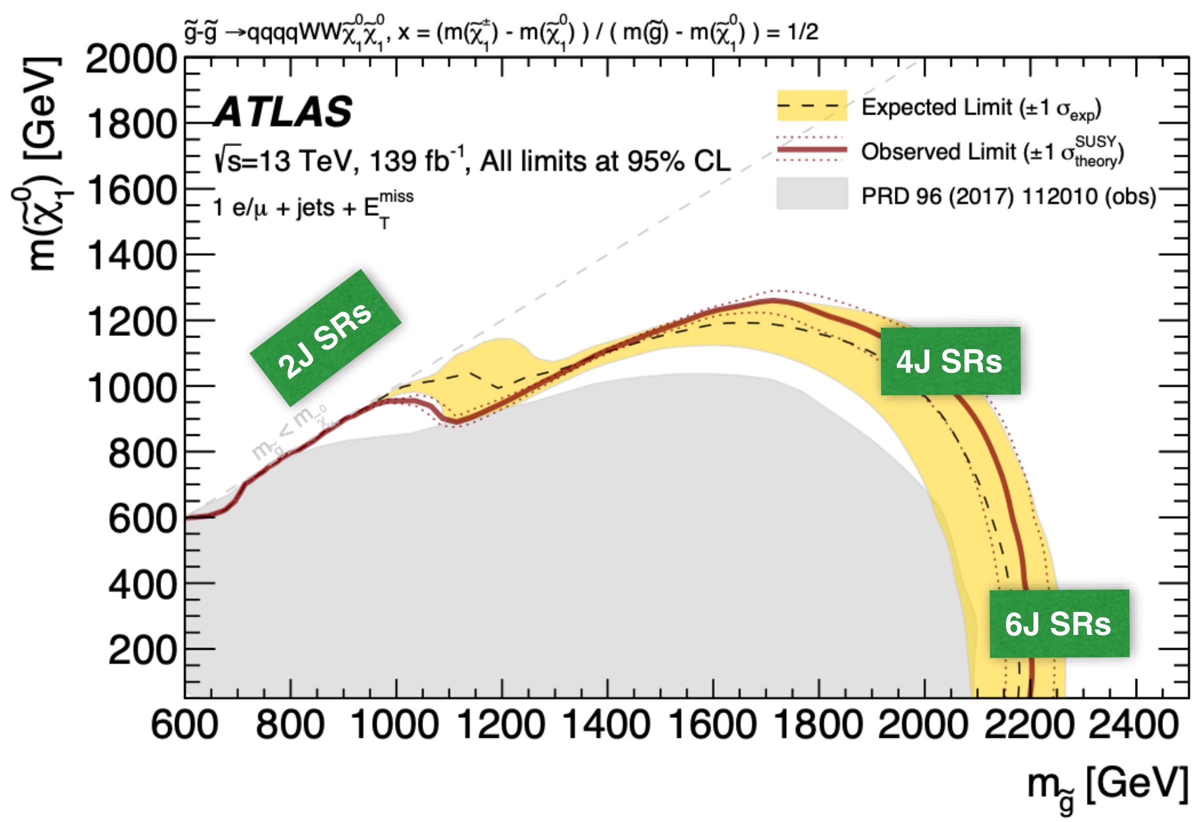
Searches for Gluinos and Squarks

“Classic” searches for gluinos and LF-squarks

- Legacy search for strongly produced light-flavor squarks and gluinos in the final state with one lepton, jets, and ETmiss
- Large Run 2 data enables classification of events in several SRs, CRs and **excellent control of systematic uncertainties** on tails of background
  - e.g. jet energy scale ~ few %





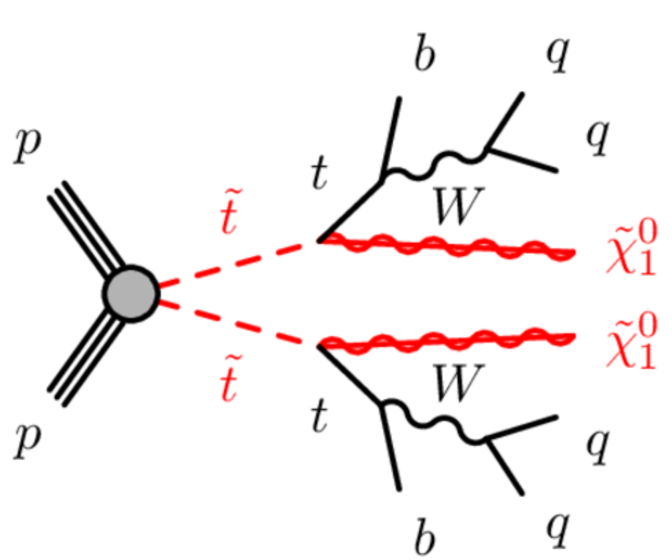


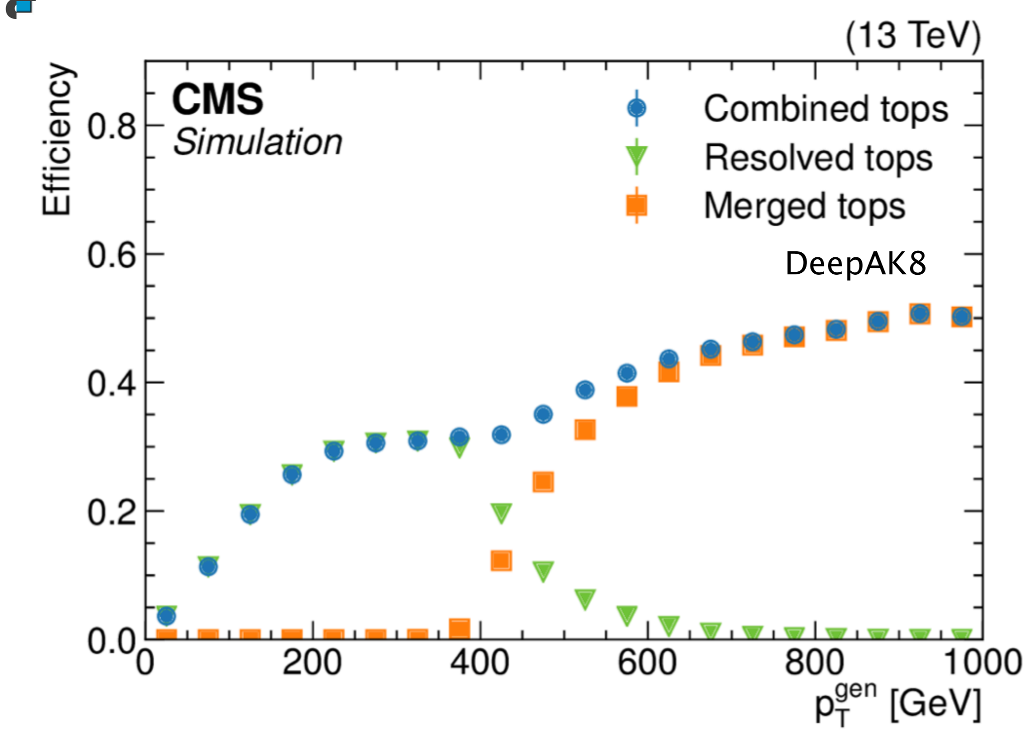
arXiv:2101.01629

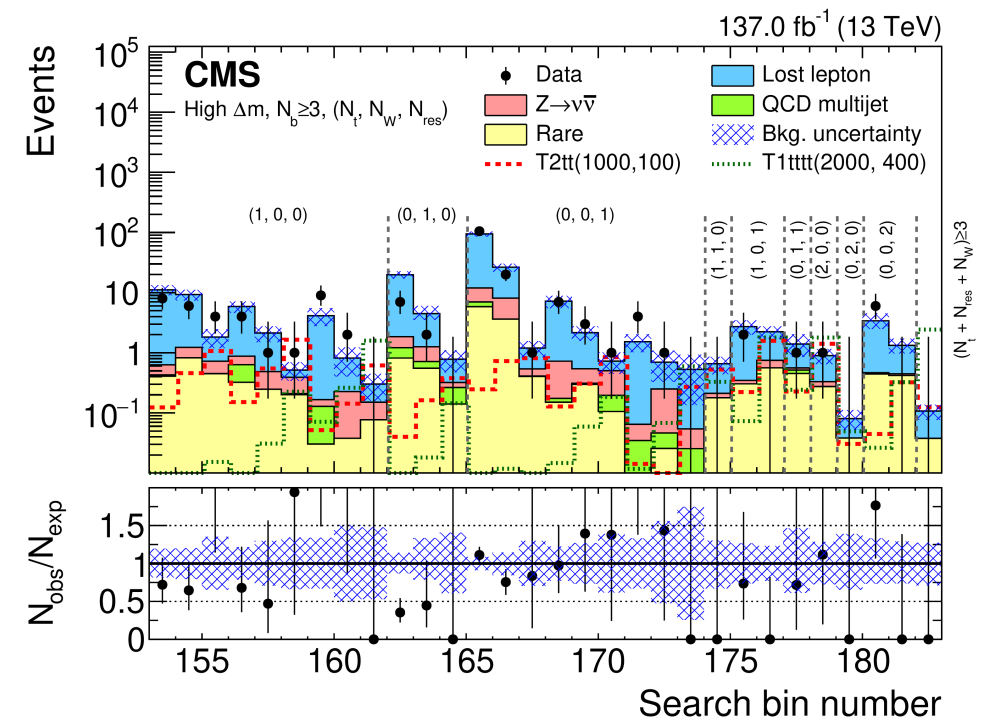
Searches for Stops and Sbottoms

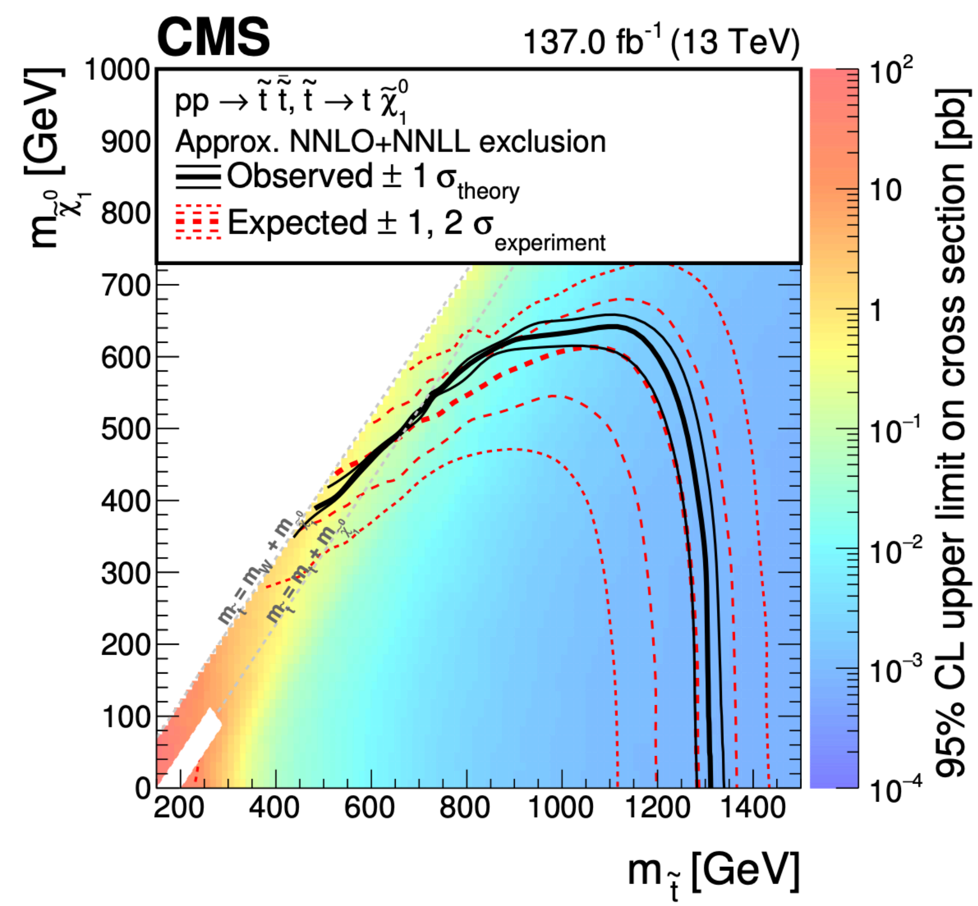
Searches for stops directly produced and in gluino decays

- Search in events with multiple (b-)jets, no leptons, and large ETmiss
- Advanced classification of events in 183 SRs
- Novel techniques based on **Deep Neural Networks to reconstruct highly boosted top quarks expected from high mass stop signals**
- **Soft b-tagging (pT < 20GeV) optimized for compressed spectra**





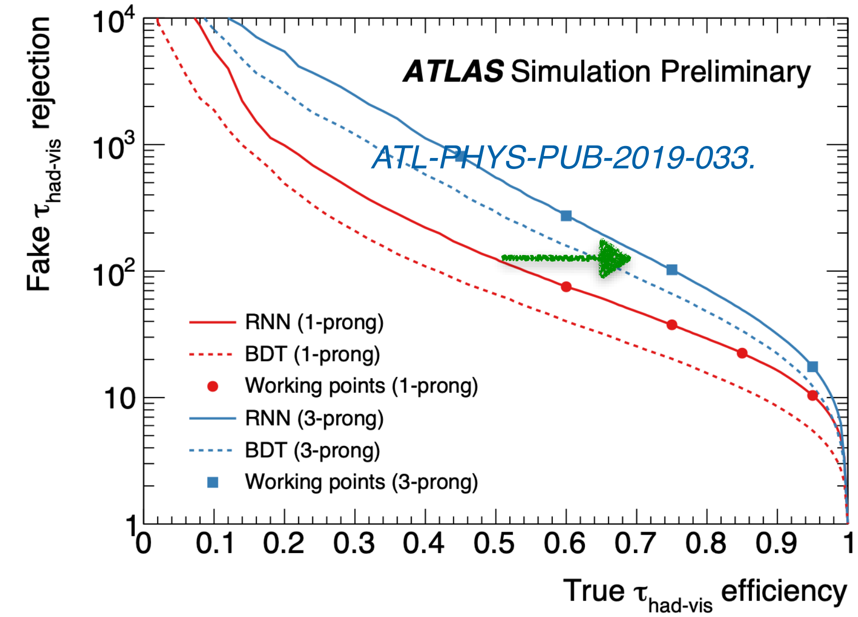


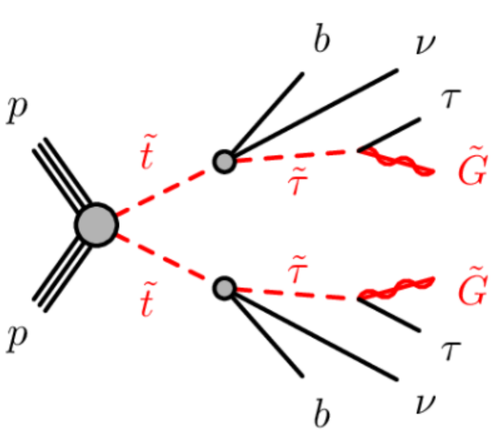


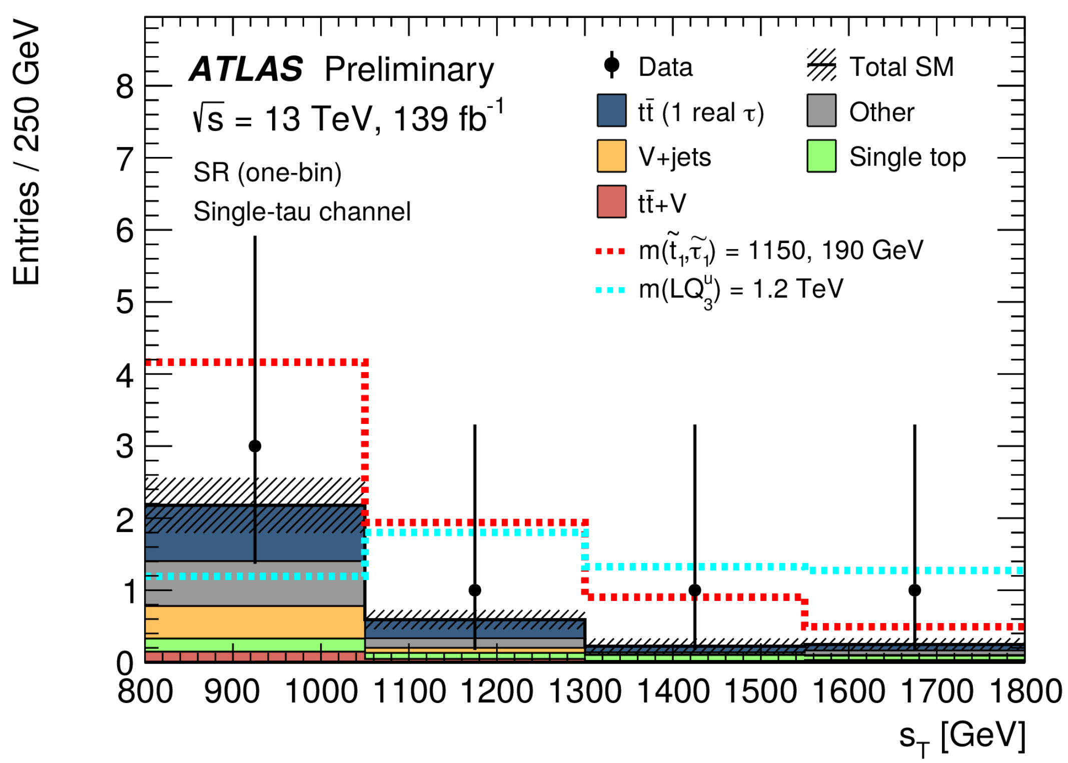
https://arxiv.org/pdf/2103.01290.pdf

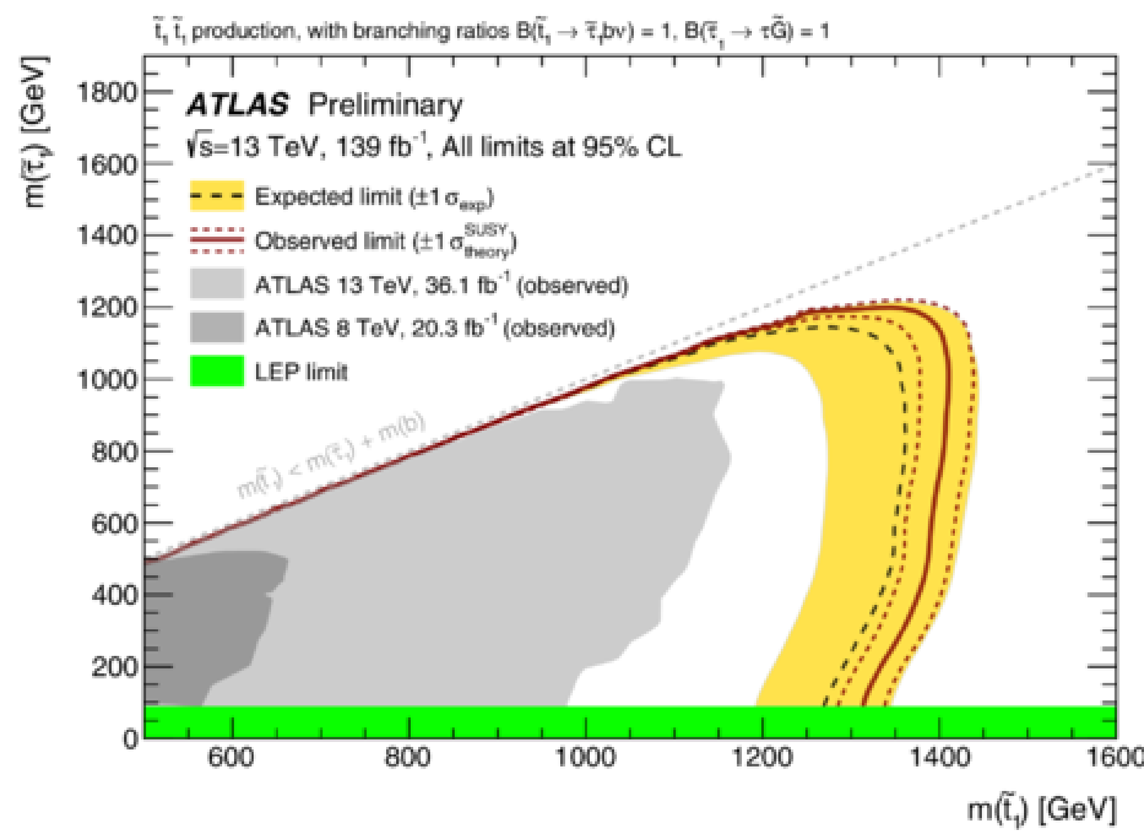
Searches for stops in the final states with taus

- Search exploiting the excellent performance of hadronic tau reconstruction
  - **Tracking information improving resolution at low pT by x2**
  - **Recurrent neural network algorithm to discriminate tau vs quarks and gluons, with efficiency of 75-60%**
- **Single-tau (new) and di-tau channels**
- “Stranverse mass”, ETmiss, scalar sum of tau and b-jets pT to extract signal





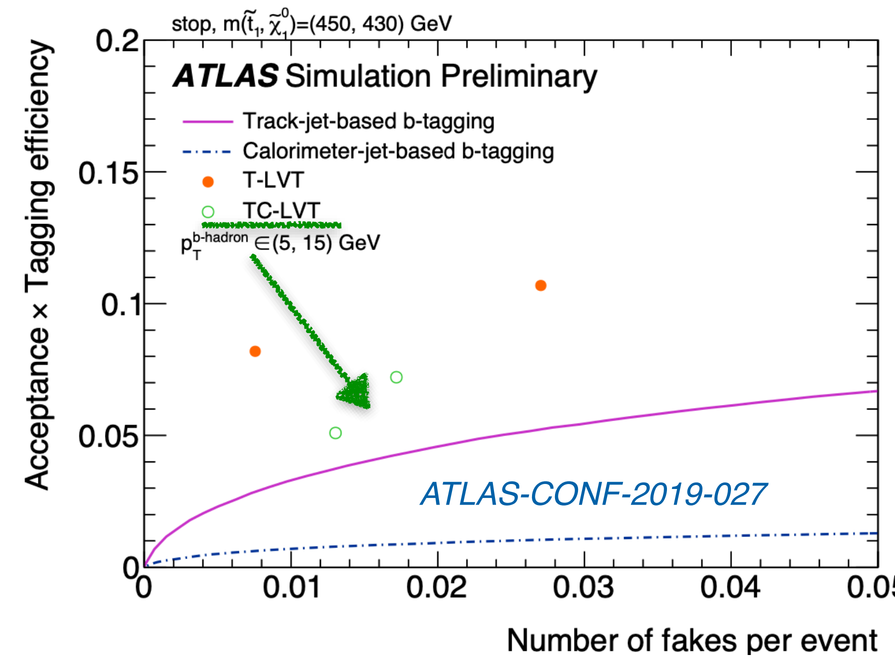


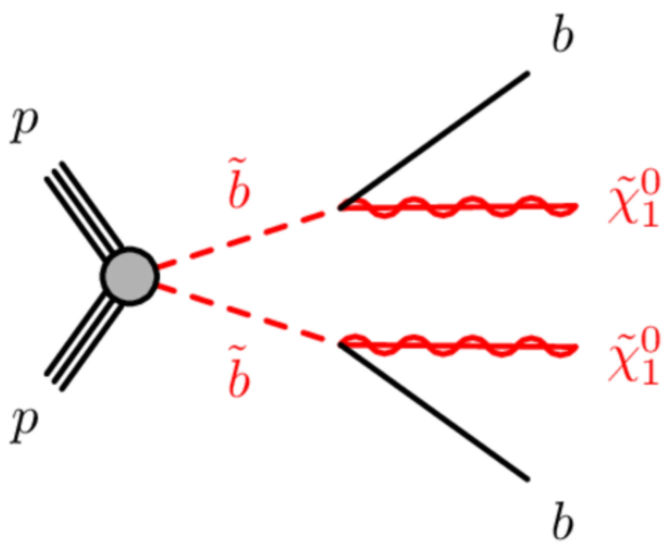


ATLAS-CONF-2021-008

Searches for sbottoms in the final states with b-jets

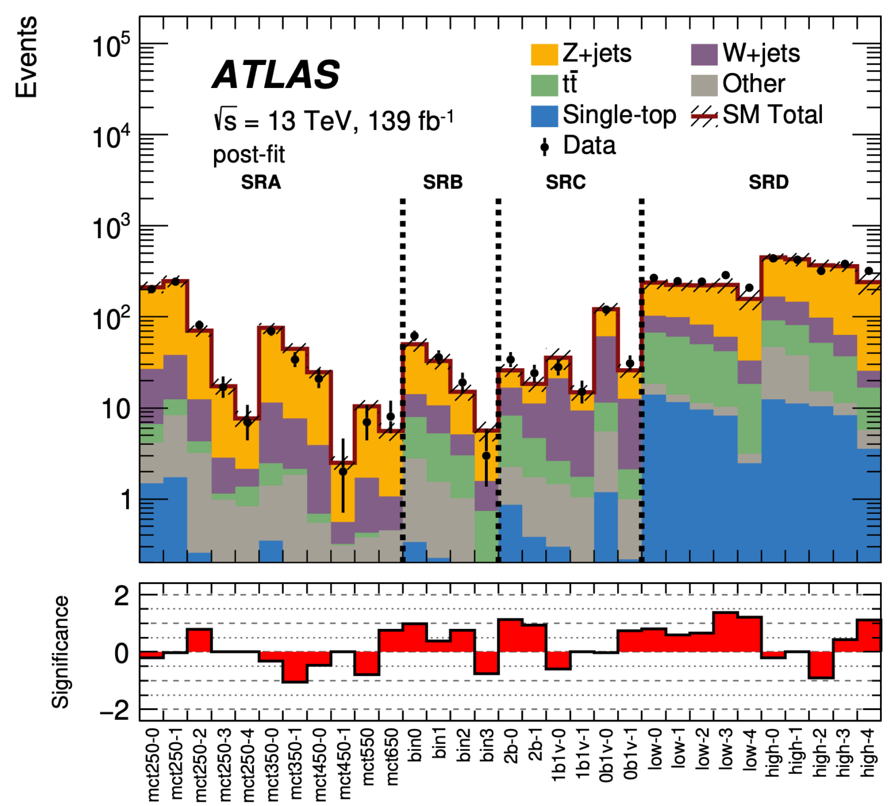
- Sensitivity of the “classic” search in the final state with two b-jets and ETmiss improved beyond luminosity scaling
  - SRA for large values of Δm, larger dataset is key
  - SRB targeting $\Delta m < 200$ GeV using BDT-based selection
  - SRC with one ISR-based selection for very compressed models (**Novel b-tagger for low pT jets, 5-15 GeV**)

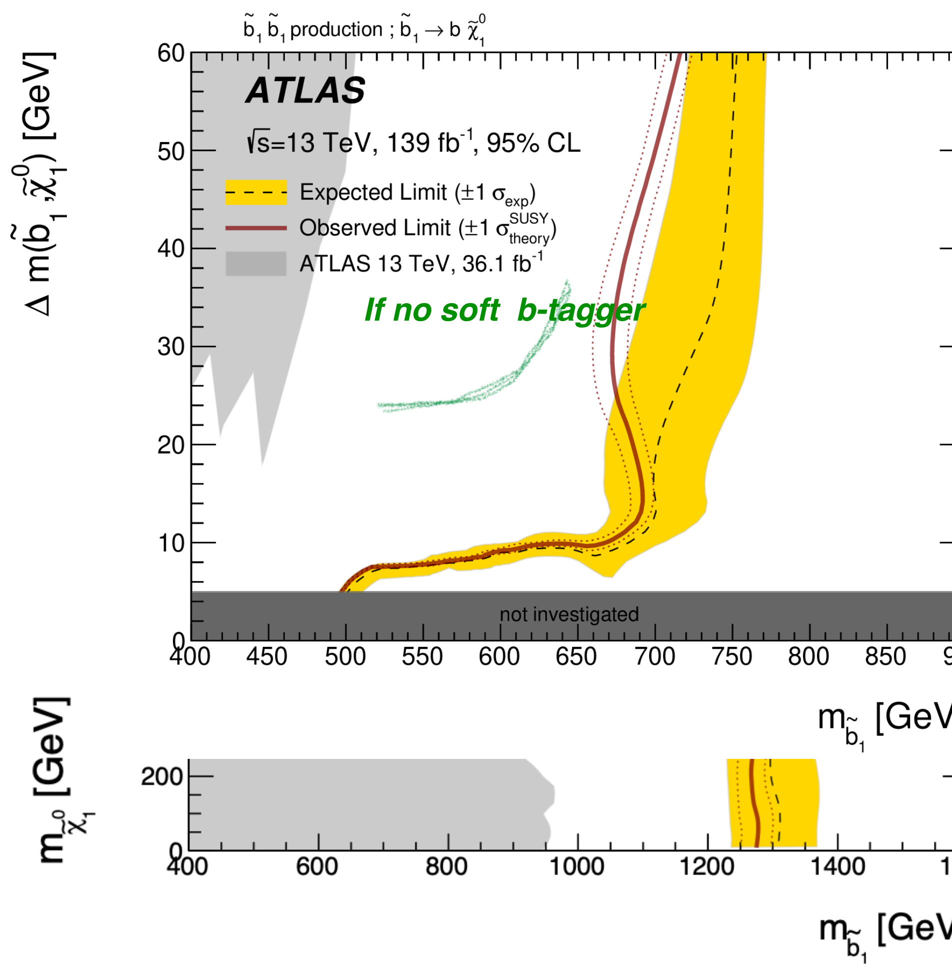




S vs B discrimination via:

- mbb, transverse and co-transverse masses, ETmiss significance, scalar sums of jet pT and ETmiss,
- Topological observables

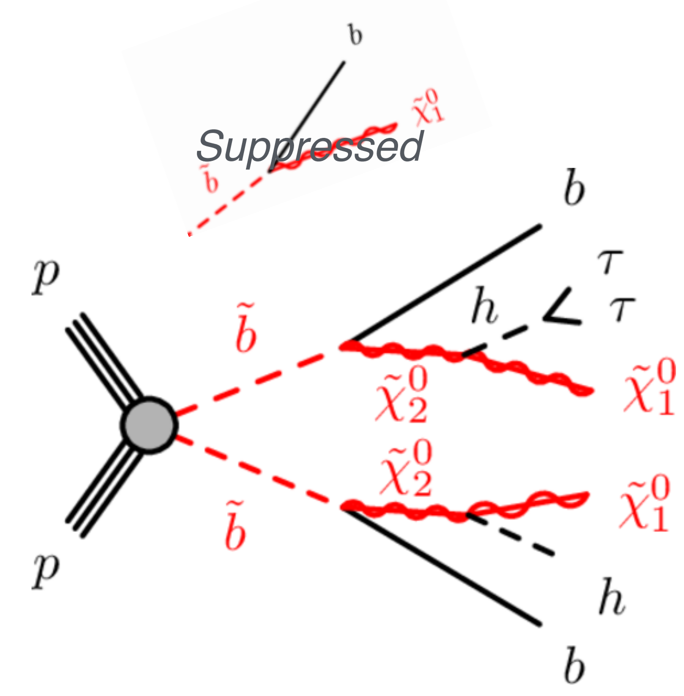


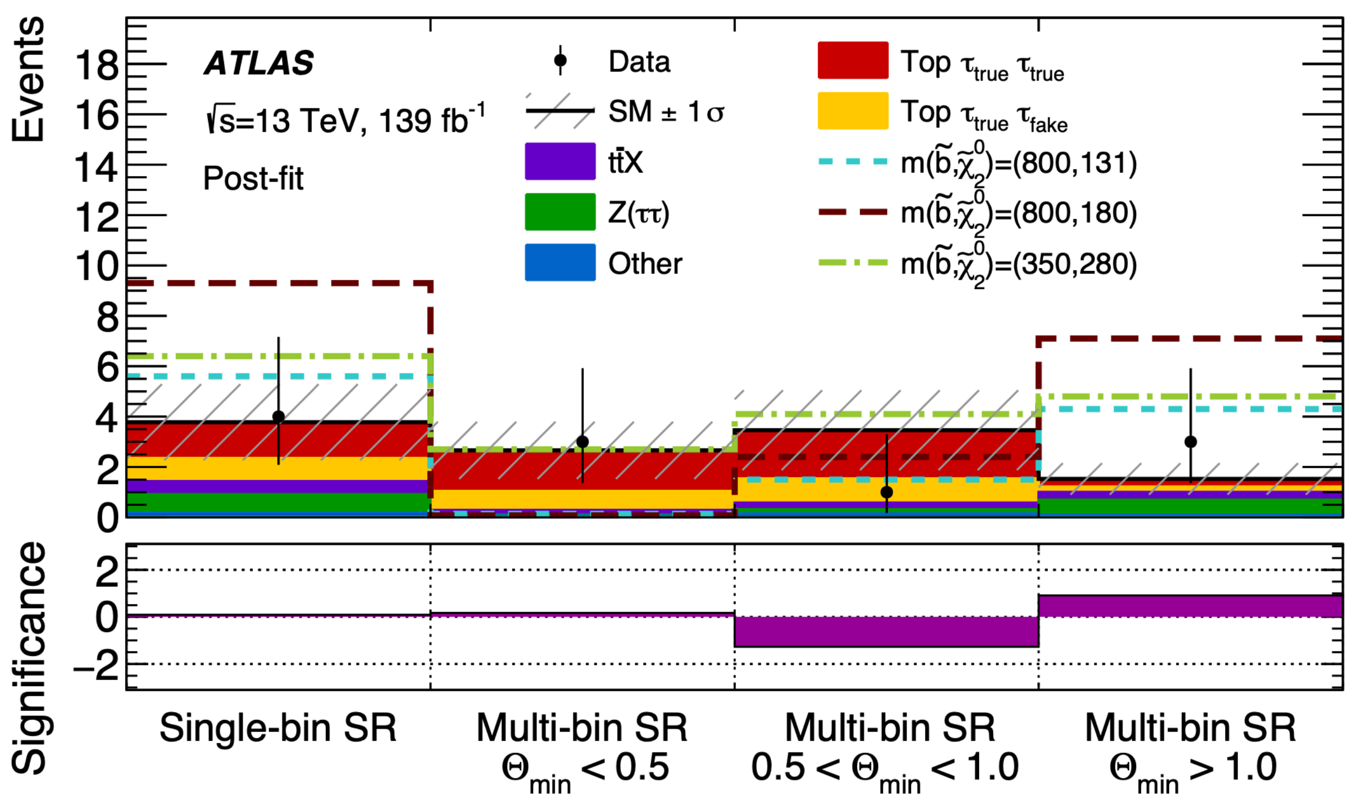


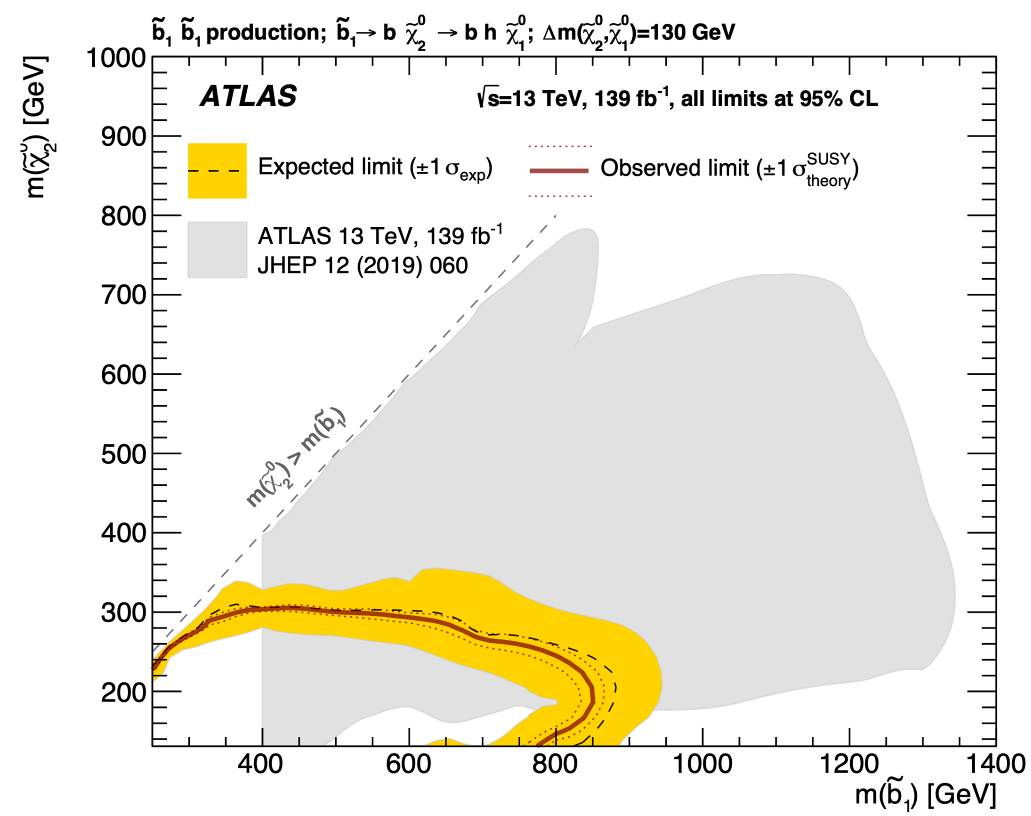
arXiv:2101.12527

Searches for sbottoms in the final states with taus

- Complementary search for sbottoms decaying via heavy wino-like neutralinos in final states with bs and tau lepton pairs in the Higgs mass range
  - Search optimized for low mass region
- Tau leptons identified with Recurrent Neural Network
- Signal extracted from background using kinematic observables and Θ_{min}, 3D angle between taus or b-jets pairs



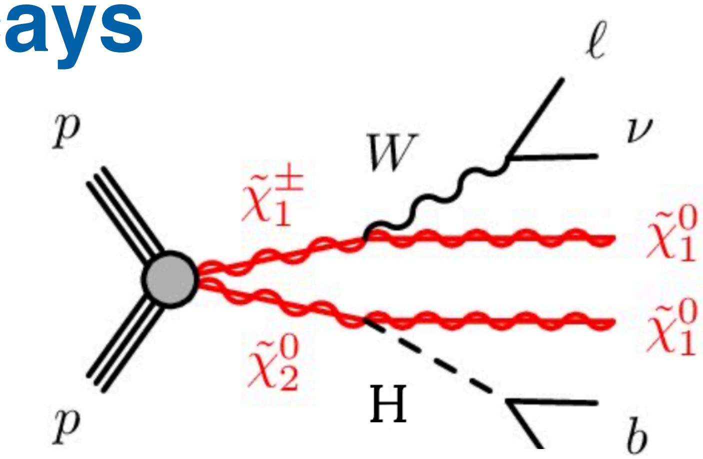




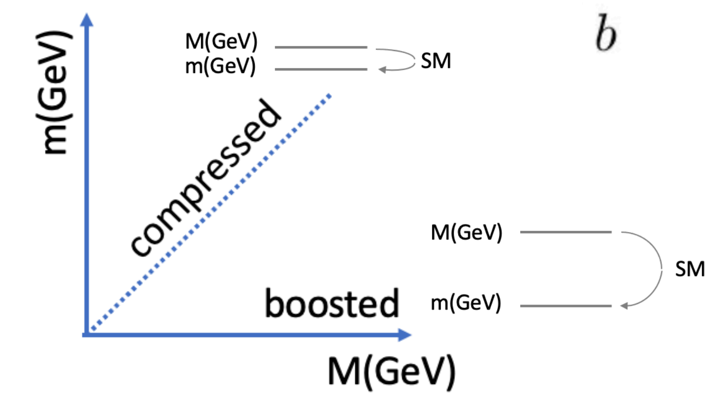
arXiv:2103.08189

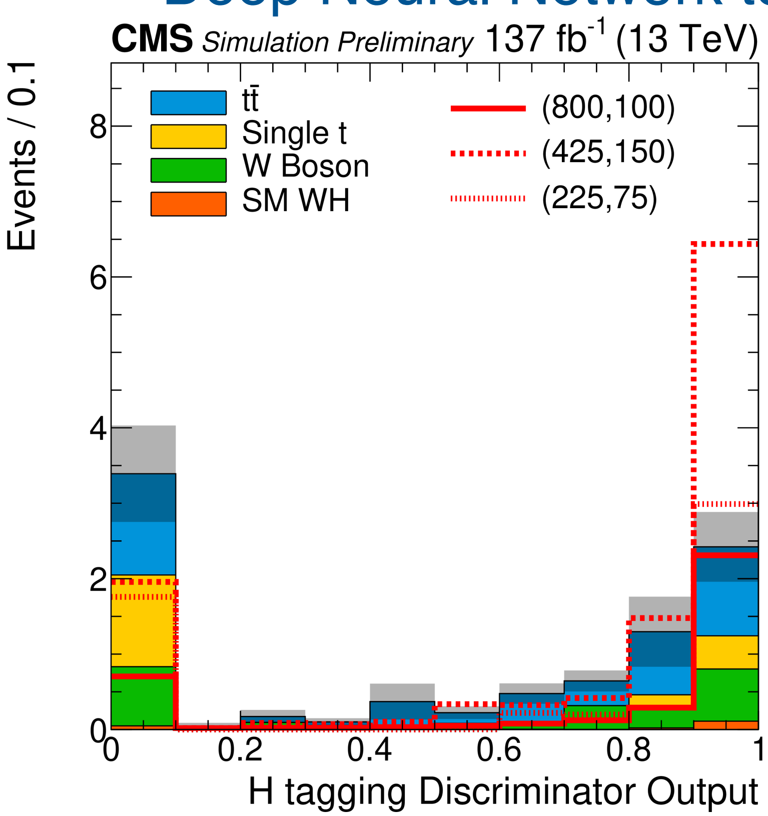
Searches for Charginos and Neutralinos

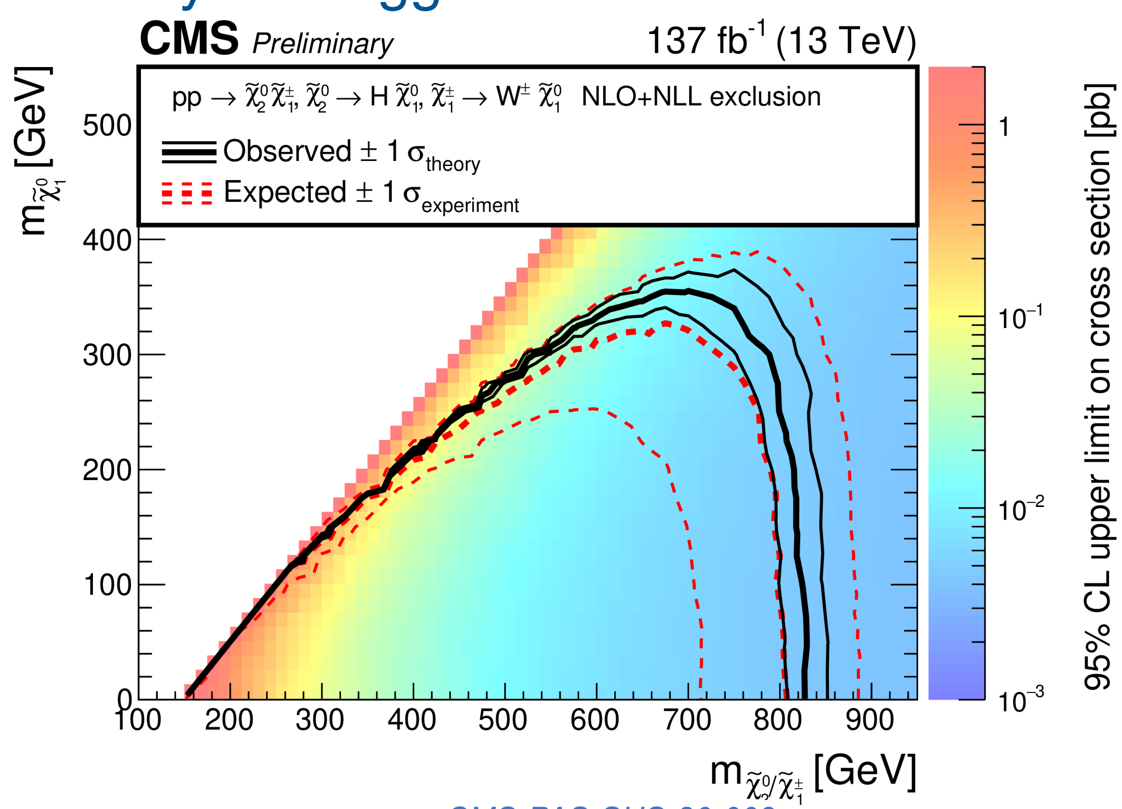
Search for Charginos and Neutralinos: WH decays



- Depending in the nature of the EWK-inos, the heavy neutrinos may decay into the LSP by emitting a Higgs bosons
- Signal in the tails of the Etmiss, co-transverse mass, and transverse mass
  - Fine binning allowed by large Run 2 dataset
- **New SR with highly boosted Higgs bosons** decaying into a large-cone jet containing the 2 b-quarks
  - Deep Neural Network to identify the Higgs candidates





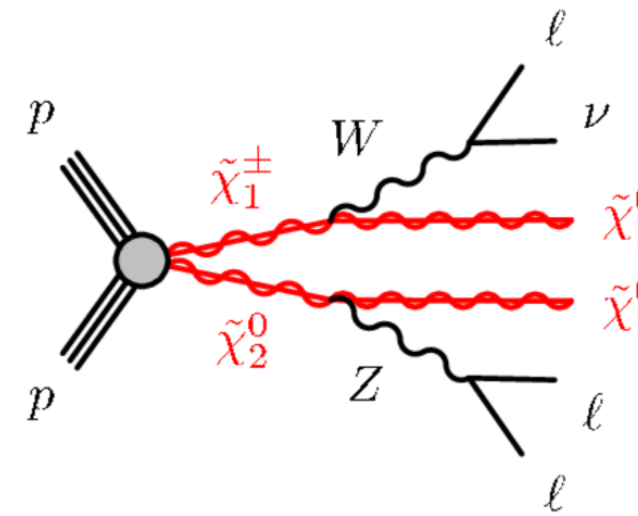


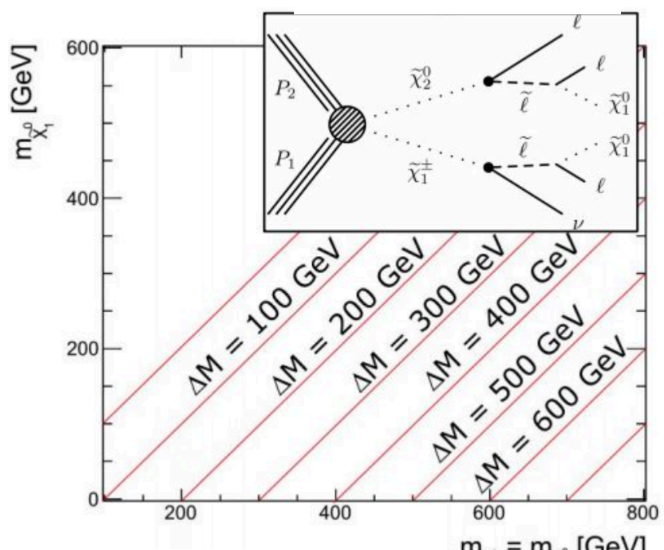
CMS-PAS-SUS-20-003

- **Sensitivity increased by ~350 GeV**
  - half gain from new search strategy
  - half gain from increased dataset

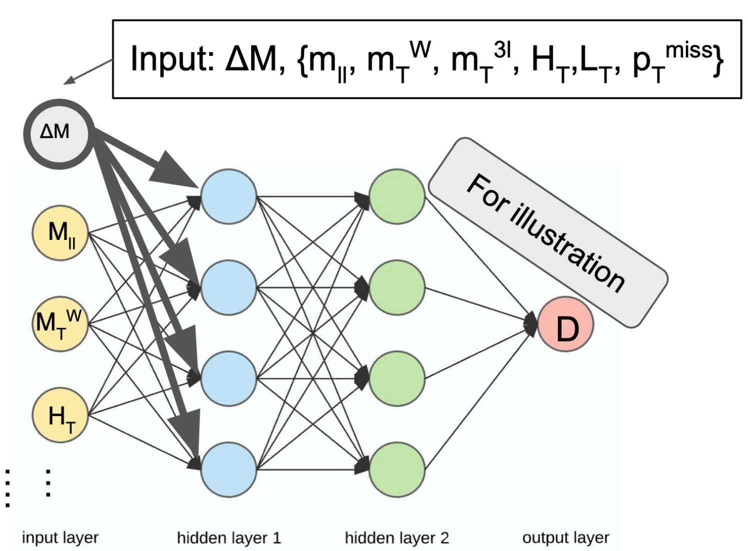
Search for Charginos and Neutralinos: Multilepton Analysis

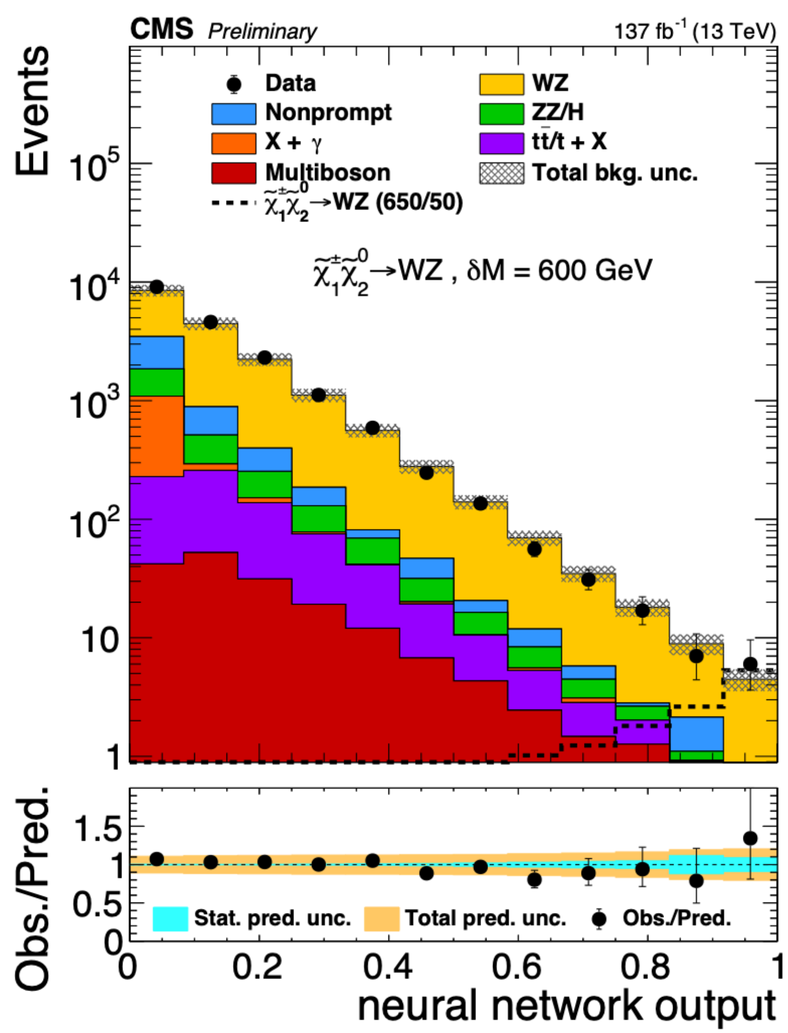
- Classic search in “clean” leptonic final states pushed to the extreme!
  - Events with 2, 3, ≥4 (including hadronic taus), targeting 13 decay modes
  - **BDT to discriminate real and fake leptons**
  - **Parametric Neural Network using DeltaM as input** for 3L channel





Courtesy of Carlos Erice Cid





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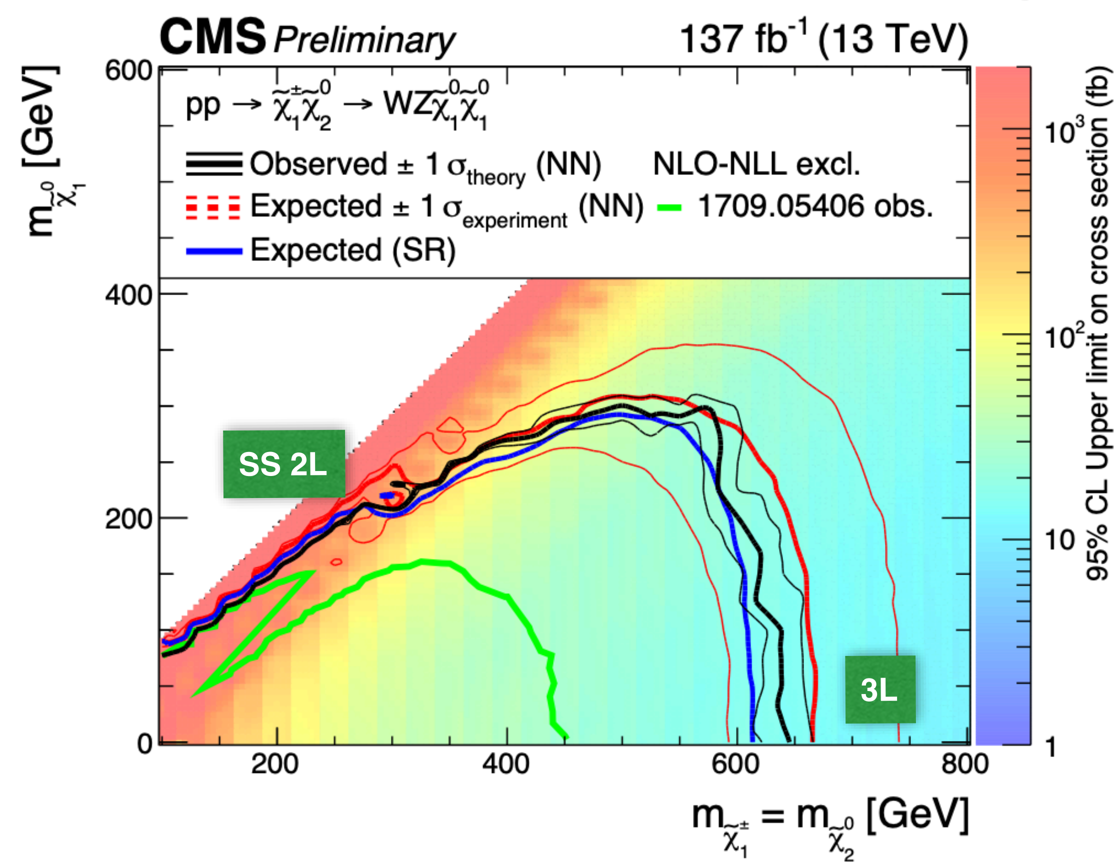
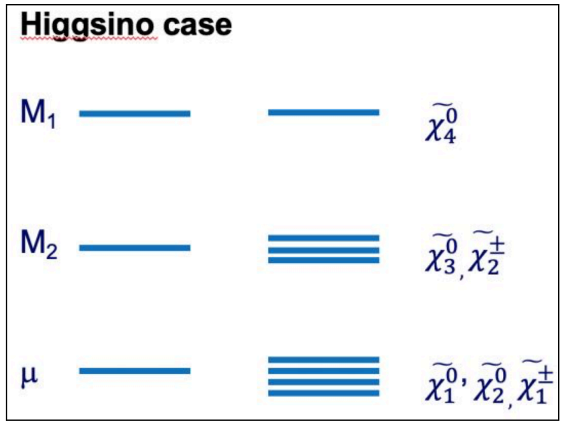
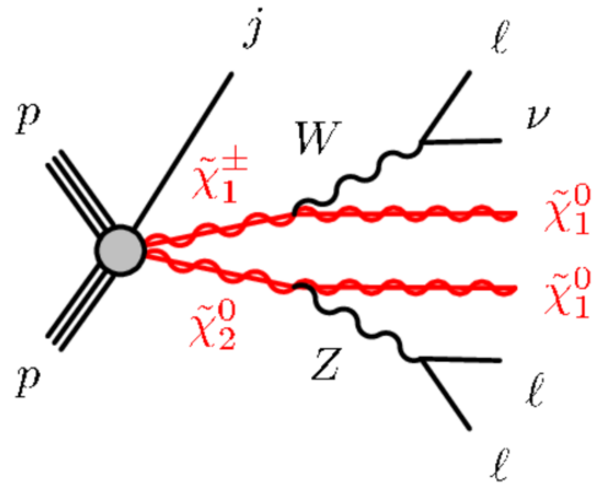


30-40% improvement in the excluded cross sections thanks to PNN, up to 200% at low DeltaM

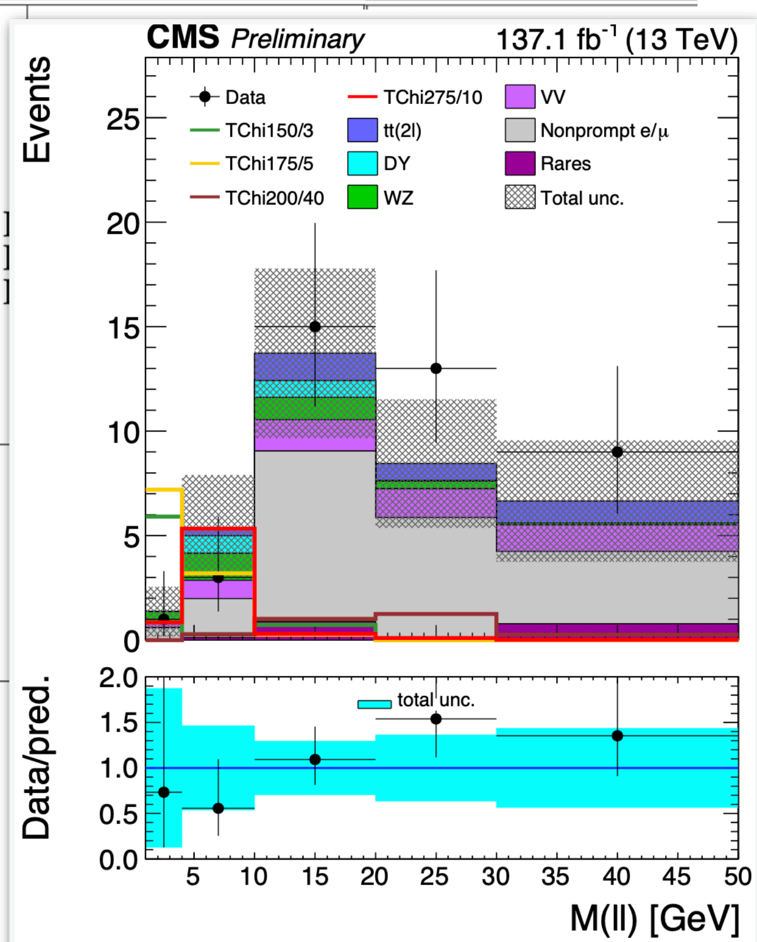
Search for Charginos and Neutralinos: Higgsinos

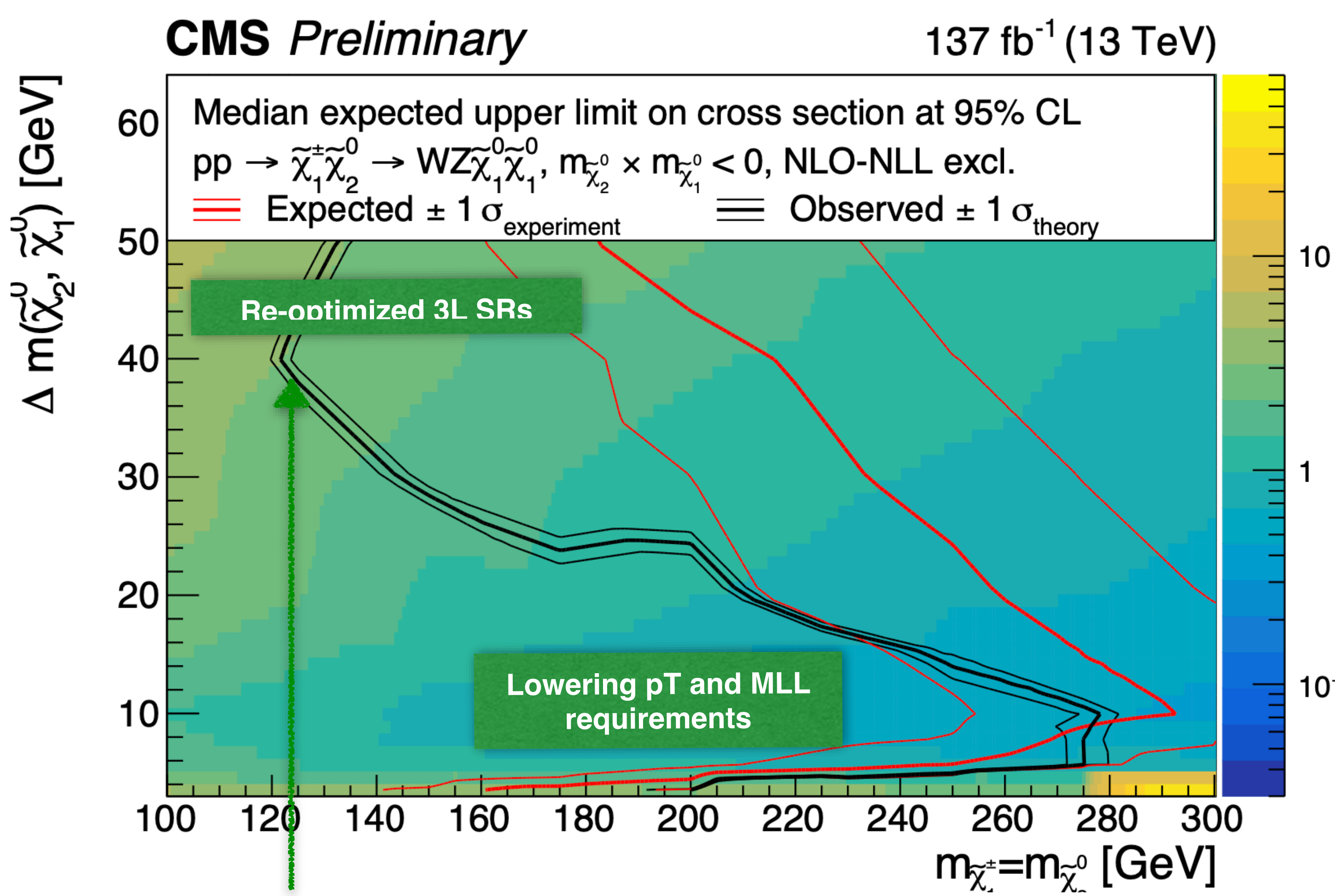




- Higgsino-like EWK-inos in the final state with one jet, **moderate ETmiss** and 2/3 **soft leptons**
  - **Muon (electron) pT > 3.5 (5) GeV**
  - **Dilepton invariant mass down to 1 GeV**
- Events classified based on ETmiss

Variable	2ℓ Ewk Low	2ℓ Ewk Med/High/Ultra	3ℓ Ewk Low	3ℓ Ewk Med/High/Ultra
N_{lep}				
$p_T(\ell_1)$ [GeV] for μ(e)				
$p_T(\ell_2)$ [GeV] for μ(e)				
$p_T(\ell_3)$ [GeV] for μ(e)				
1 OS pair				
1 OSSF pair				
$M(\ell\ell)_{SFOS}$ ($M(\ell\ell)^{min}_{SFOS}$ in 3ℓ) [GeV]				
$M(\ell\ell)_{SFOS}$ ($M(\ell\ell)^{min}_{SFOS}$ in 3ℓ) [GeV]				
$M(\ell\ell)_{SFOS}$ ($M(\ell\ell)^{min}_{SFOS}$ in 3ℓ) [GeV]				
$M(\ell\ell)^{max}_{SFAS}$(AS= any sign) [GeV]				
$p_T(\ell\ell)$ [GeV]				
$M_T(\ell_i, p_T^{miss})$ [GeV] ($i = 1,2$)				
$\Delta R(\ell\ell)_{ij}$ (i,j=1,2,3)				
p_T^{miss} [GeV]				
$p_T^{miss,corr}$ [GeV]				
H_T [GeV]				
p_T^{miss}/H_T				
Jet ID tight WP for leading jet				
$N_b(p_T > 25$ GeV)				
$M_{\tau\tau}$				





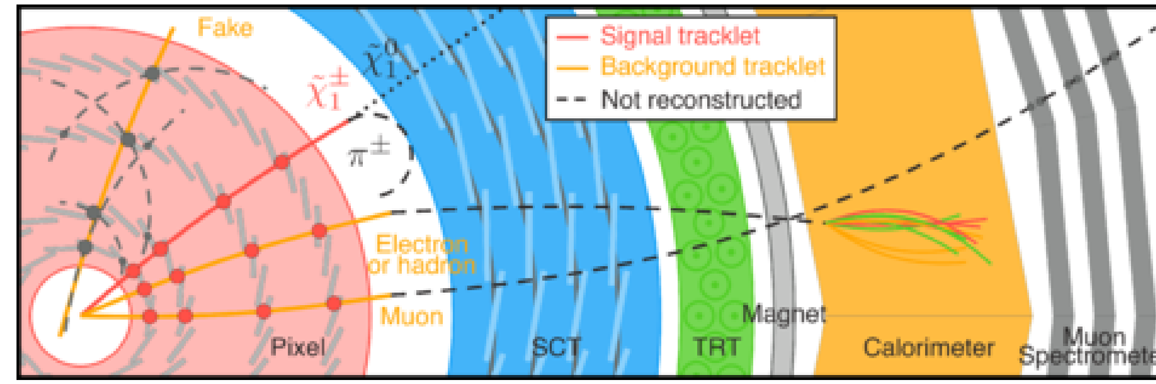
- Max local significance 2.4 sigma

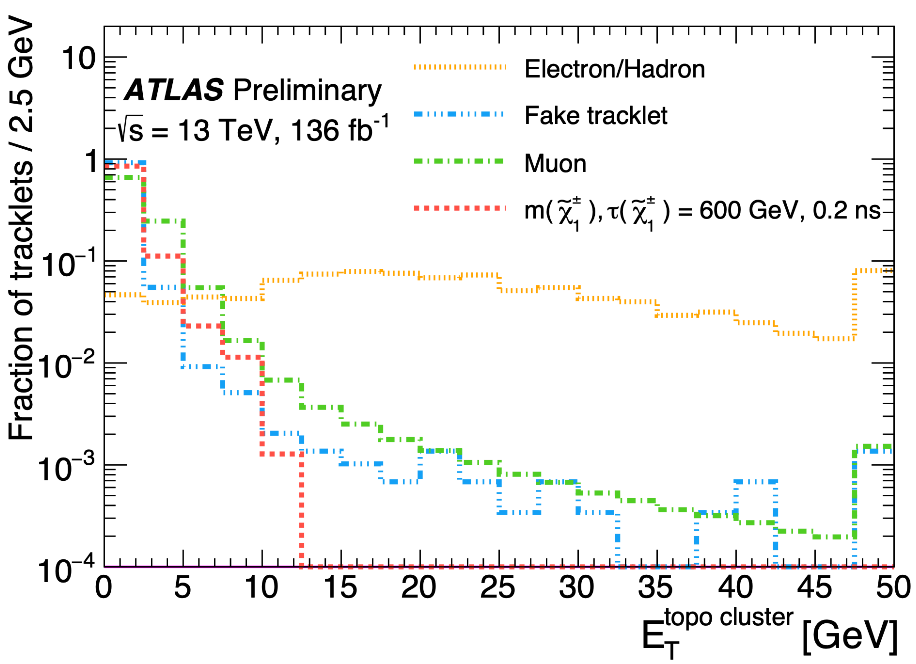
CMS-PAS-SUS-18-004

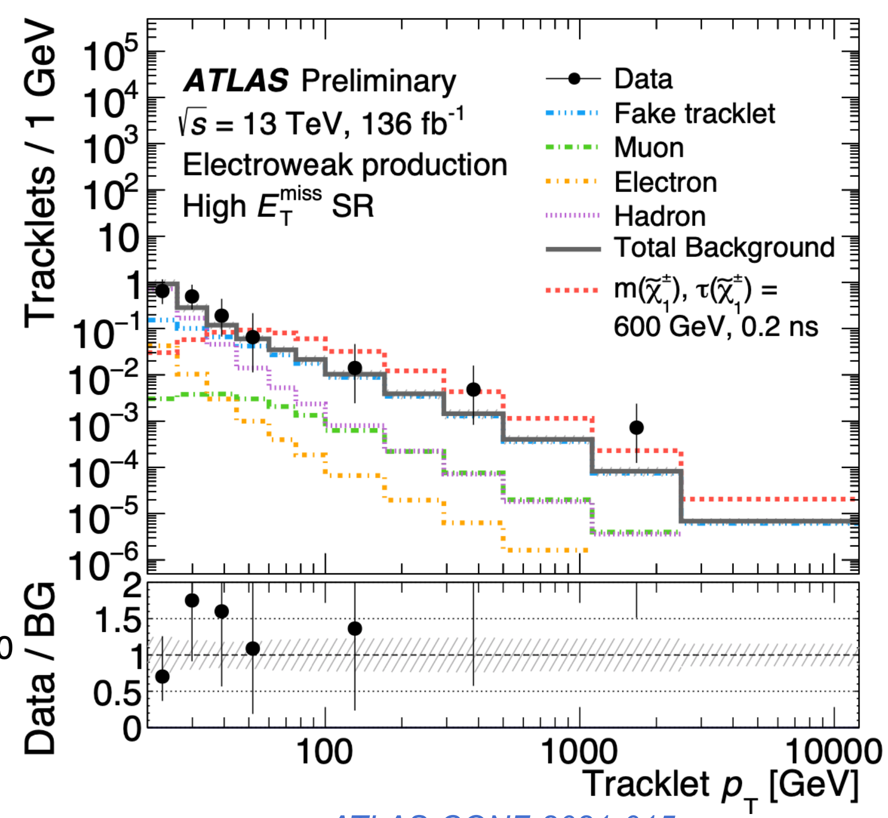
Fermilab

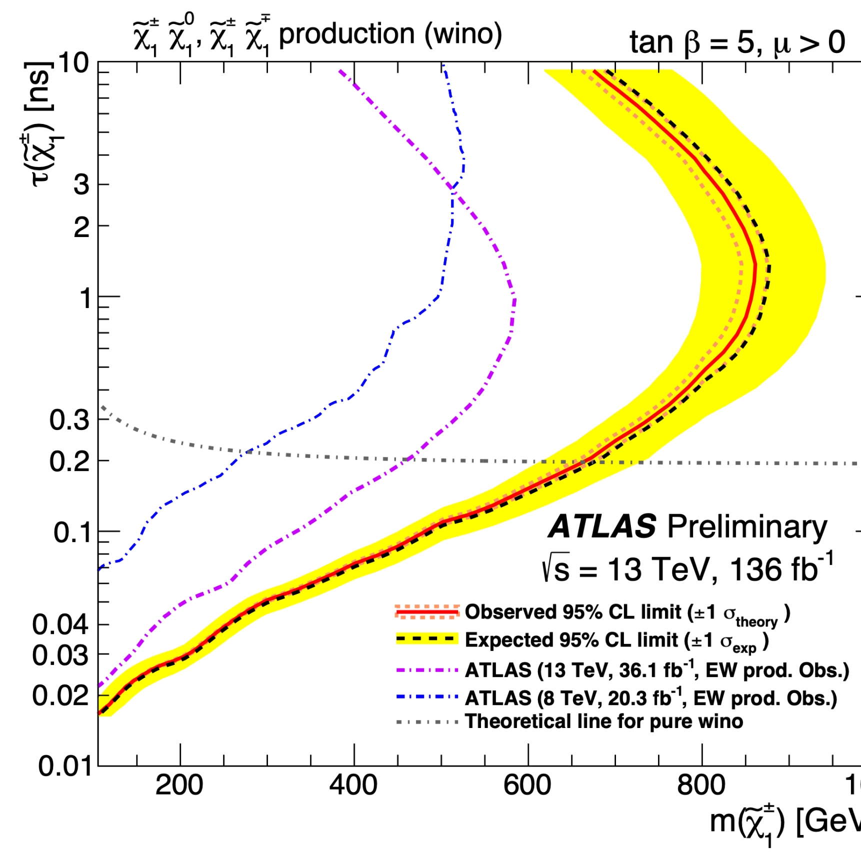
Search for long-lived charginos

- Charginos decaying as $\tilde{\chi}^{\pm} \to \pi^{\pm}\chi^{0}$ expected in models with very compressed spectra
- Striking signature with a ‘disappearing track’
  - Pixel tracklets with no hits in the outermost silicon trackers and no calorimeter activity (newly introduced requirement)
  - ETmiss and number of jets for S to B discrimination



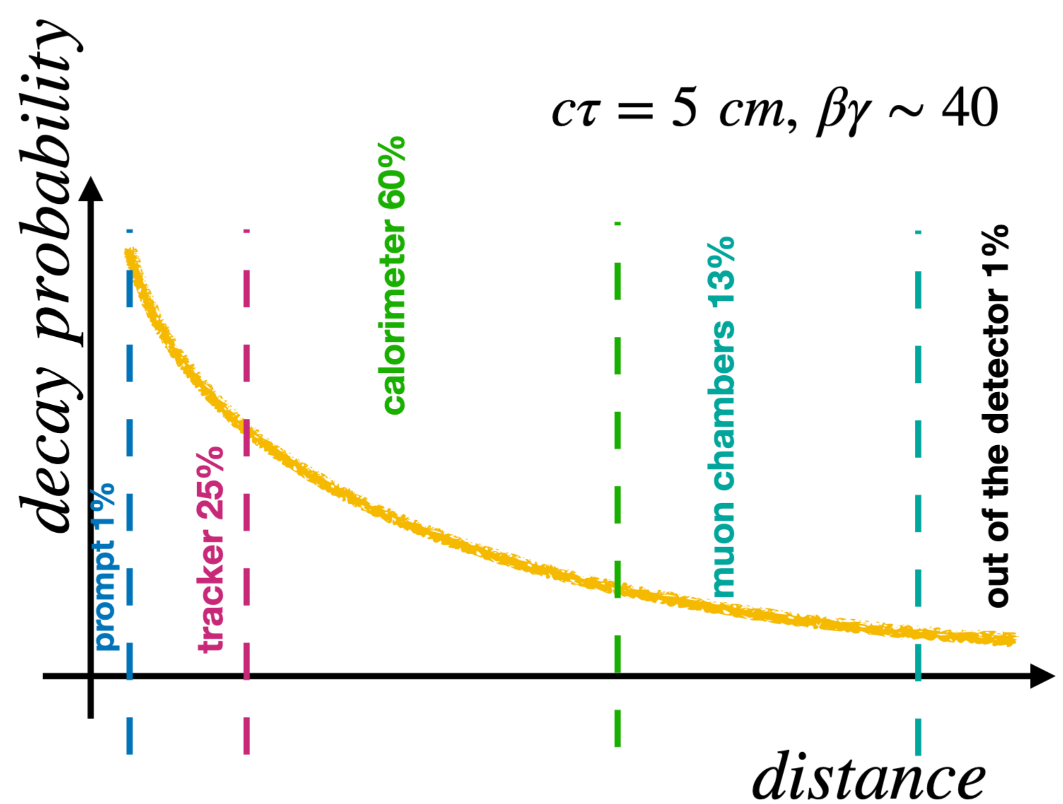






ATLAS-CONF-2021-015

Other Searches for Long Lived SUSY

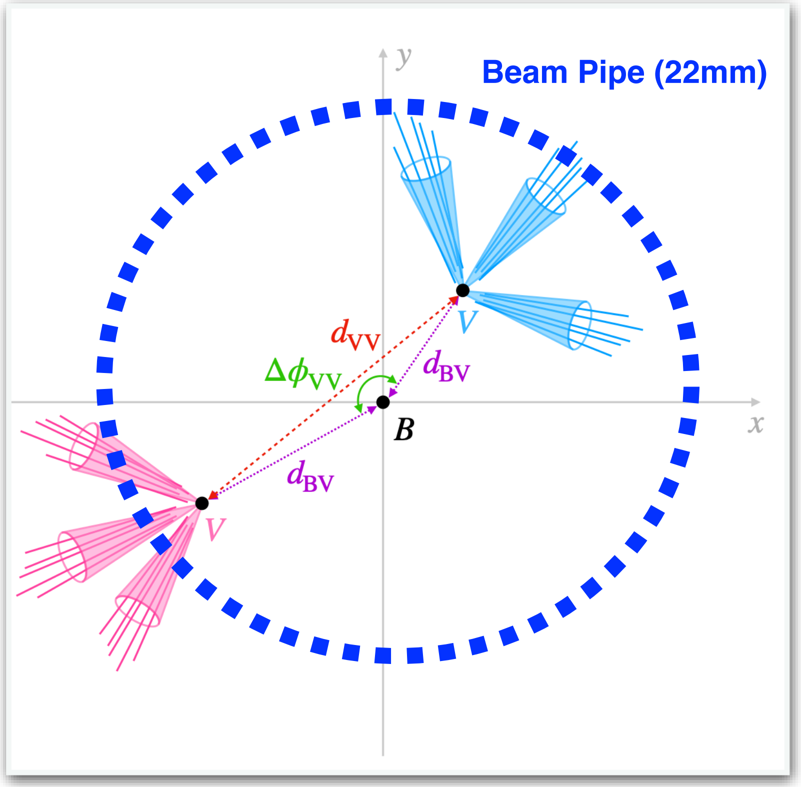


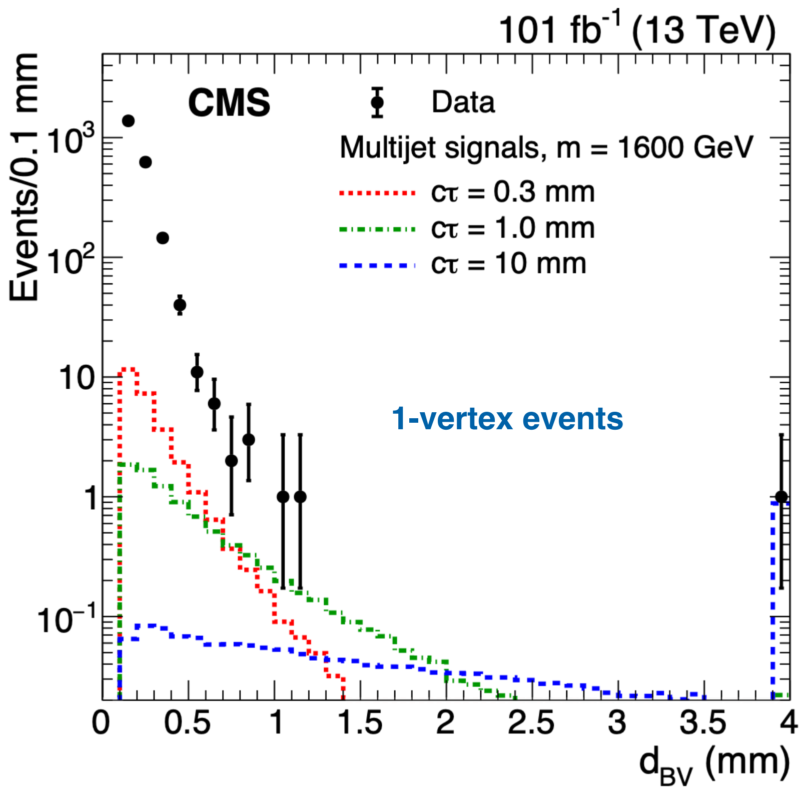
Courtesy of Cristiano Sebastiani

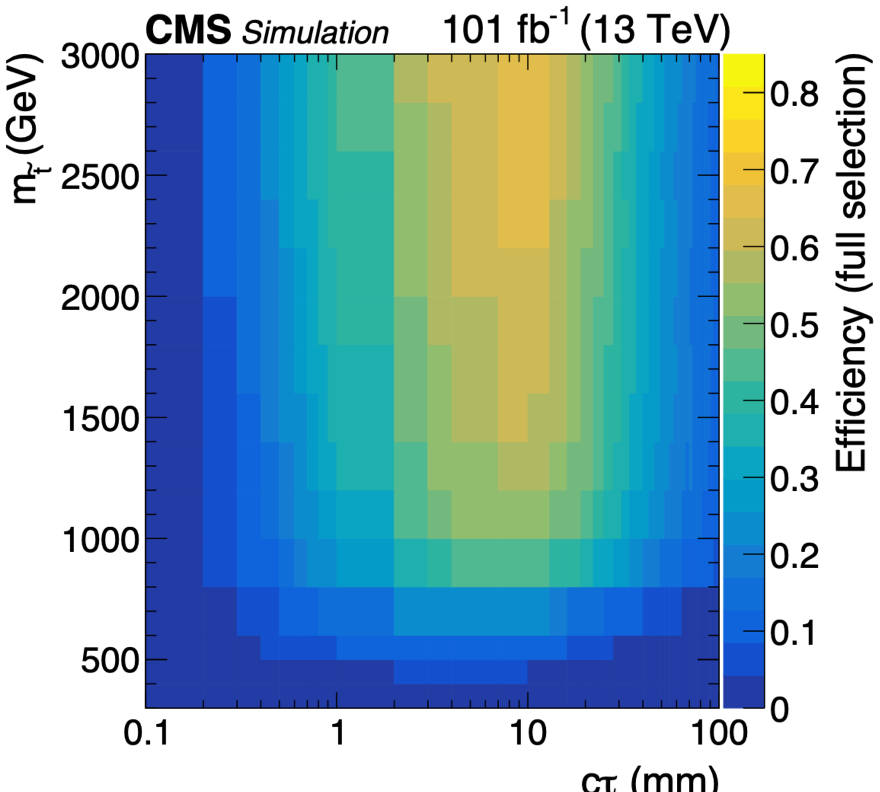
Fermilab

Long-lived particles decaying to jets with displaced vertices

- **(Model independent) search for long-lived particles** decaying into multiple jets
- Unique signature with 2 multi-track vertices displaced from the interaction point but within the beam pipe
  - **Custom vertex reconstruction**
- Fit to vertices separation in events with large hadronic scalar energy







arXiv:2104.13474

Fermilab

Long-lived particles decaying to jets with displaced vertices

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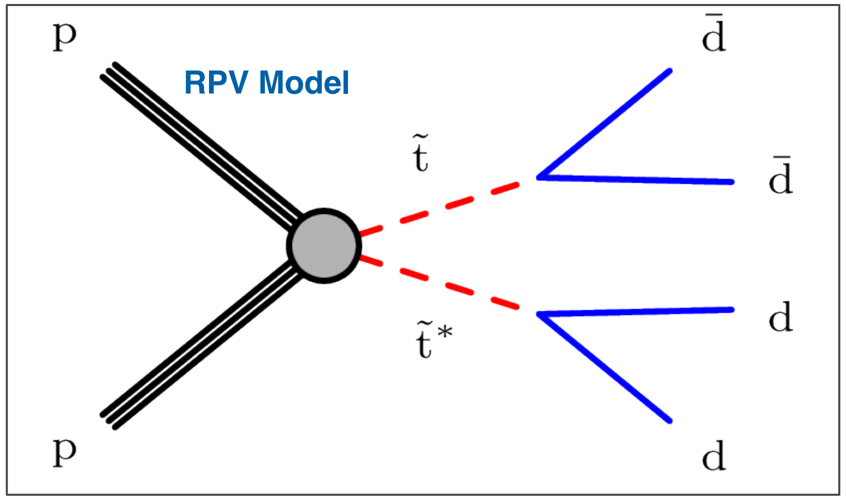
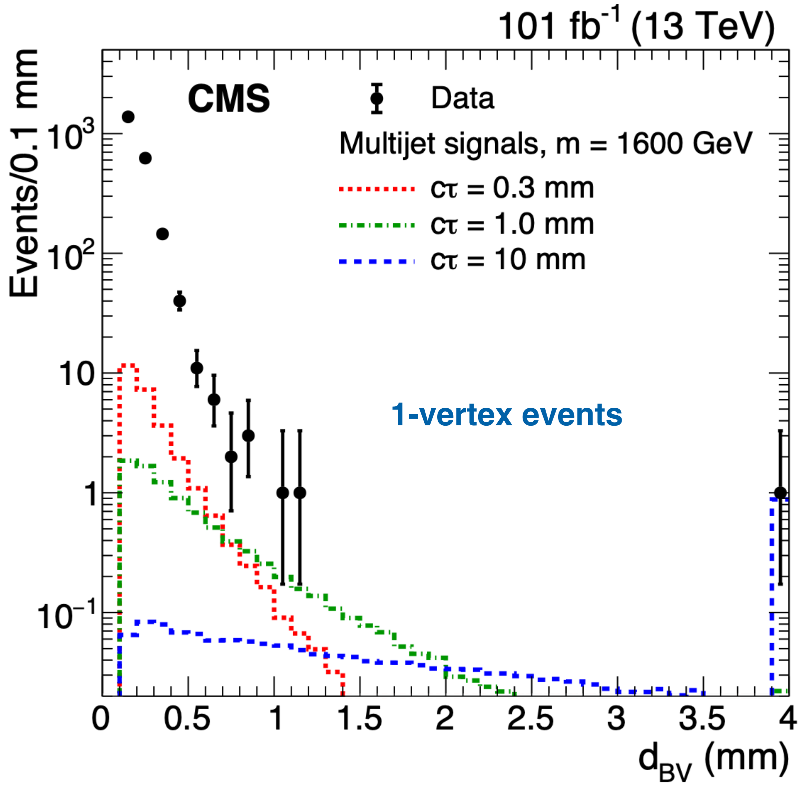
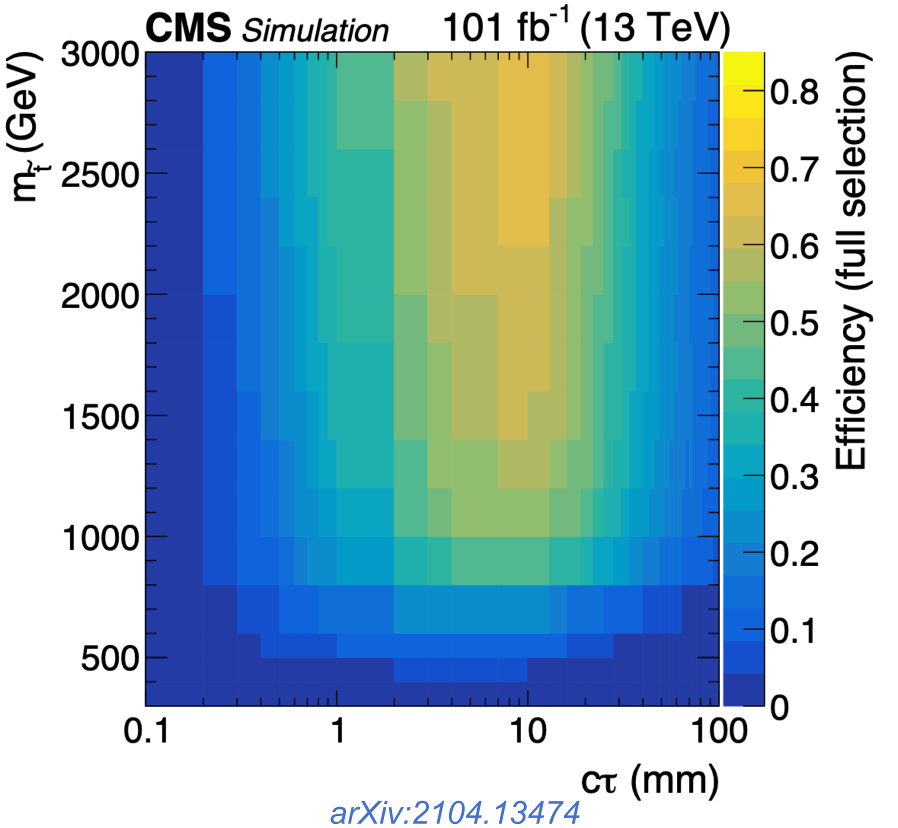
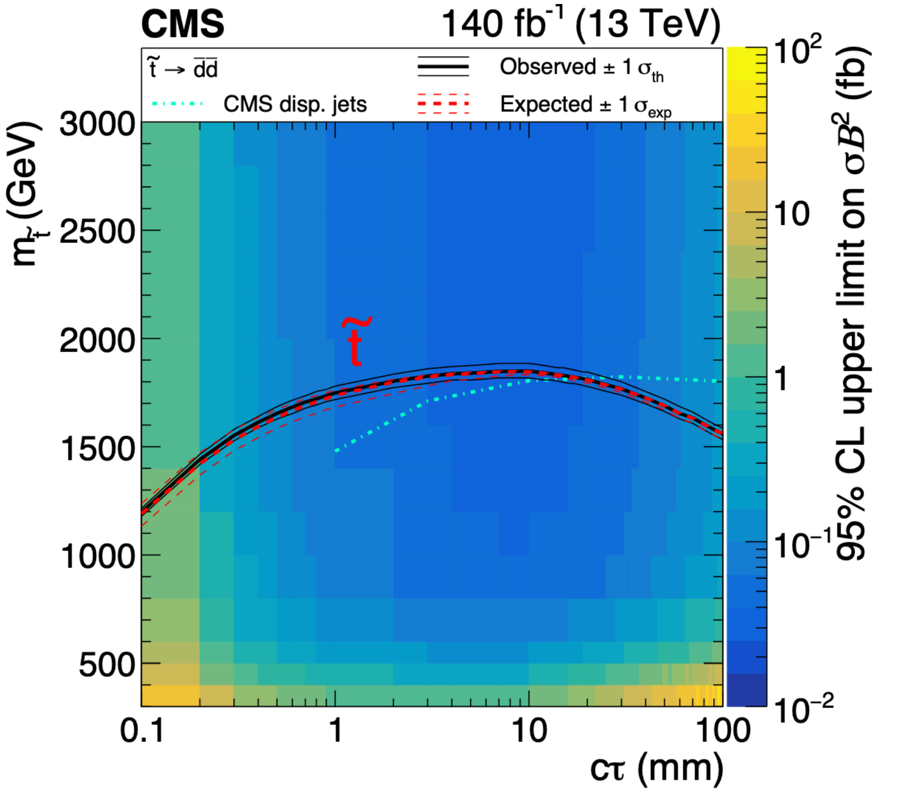




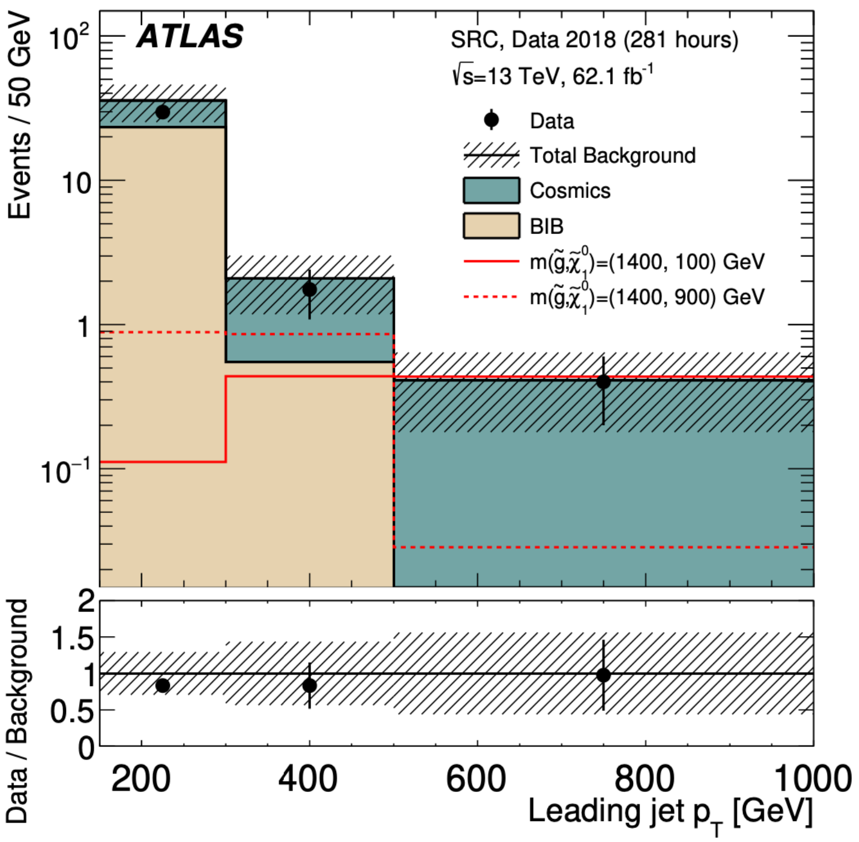


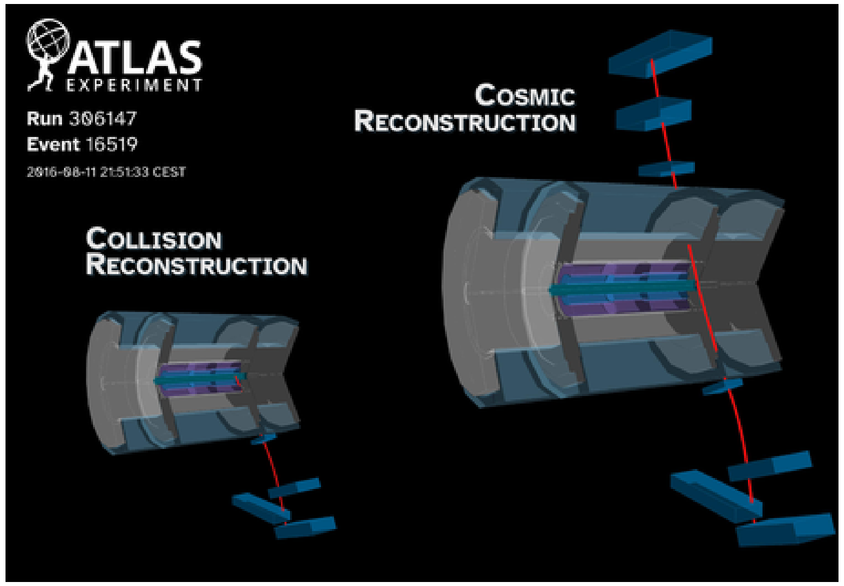


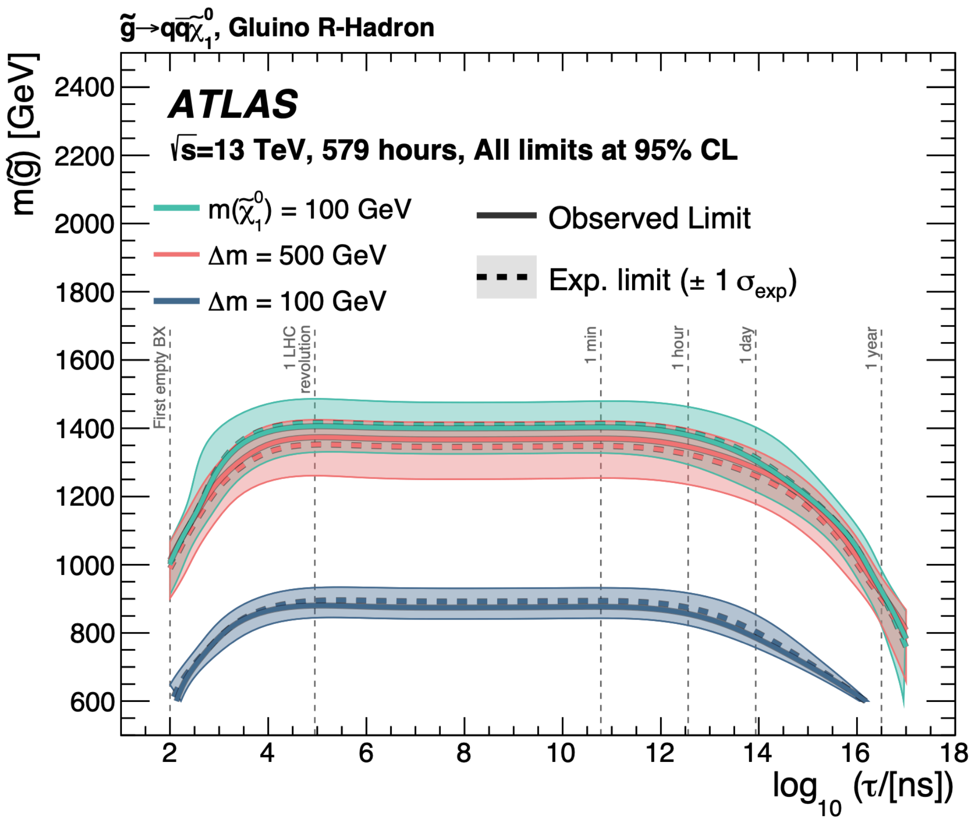
arXiv:2104.13474

Search for the decays of stopped long-lived particles

- **Long-lived particles can sit in the detector before decaying in jets** leading to a unique signatures with out of time energy deposits in calorimeter
  - Events with ETmiss and jets collected during the “empty” bunch crossings (total dataset of ~600 hours!)
  - **Challenging estimate of unusual backgrounds from cosmic rays, beam induced background, cavern background, calorimeter noise**







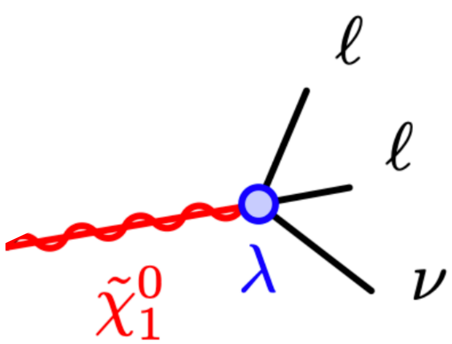
arXiv: 2104.03050

Searches for RPV and Stealth SUSY

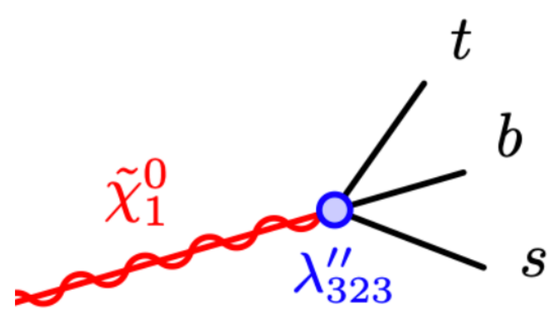
RPV SUSY in events with multiple leptons

$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$

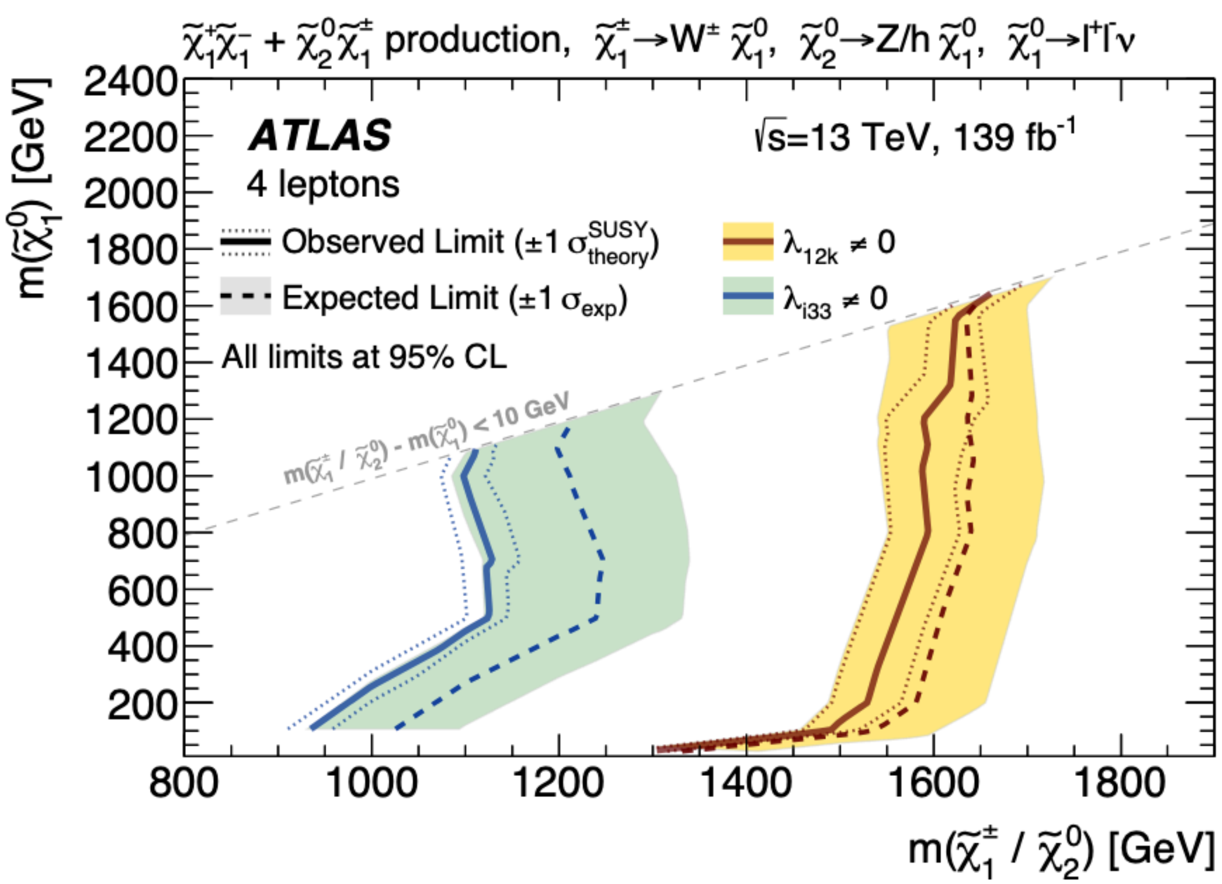
- Inclusive searches for gluinos, sleptons, charginos in **final states with small ETmiss**

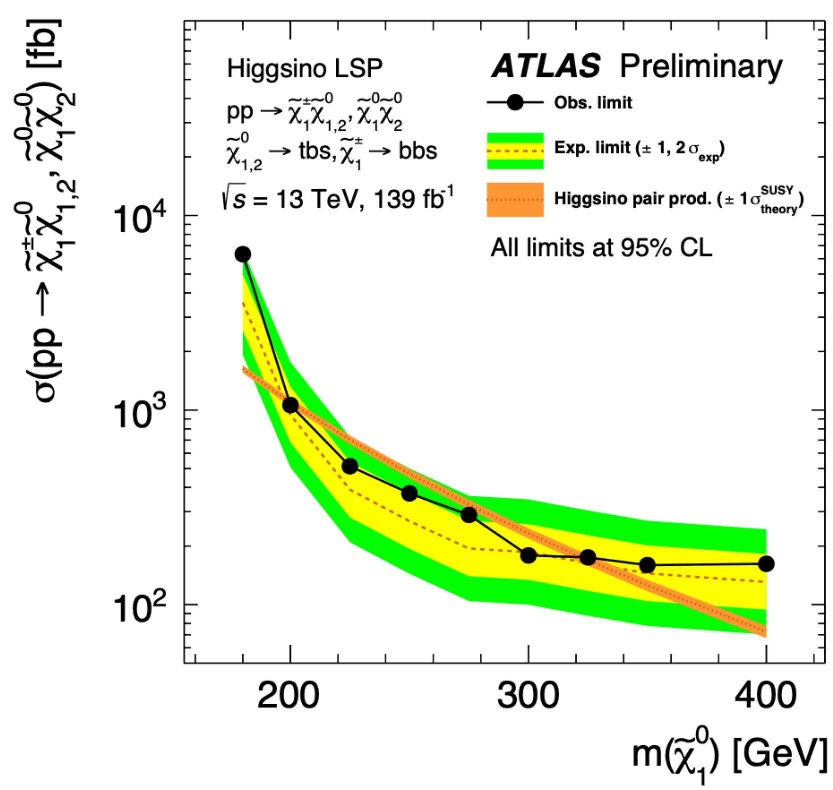


- 4 Leptons final states



- 1 lepton and (b-)jets
- Adversarial training of NN to select higgsinos





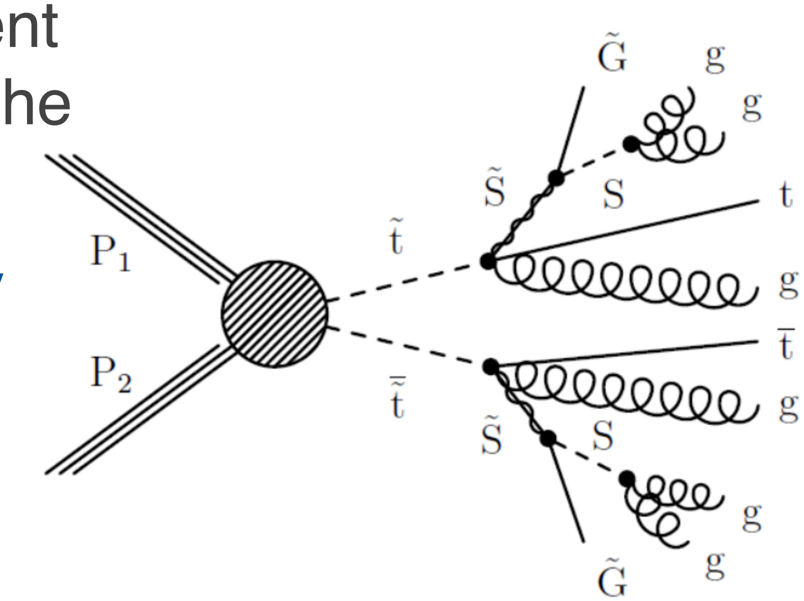
arXiv:2103.11684

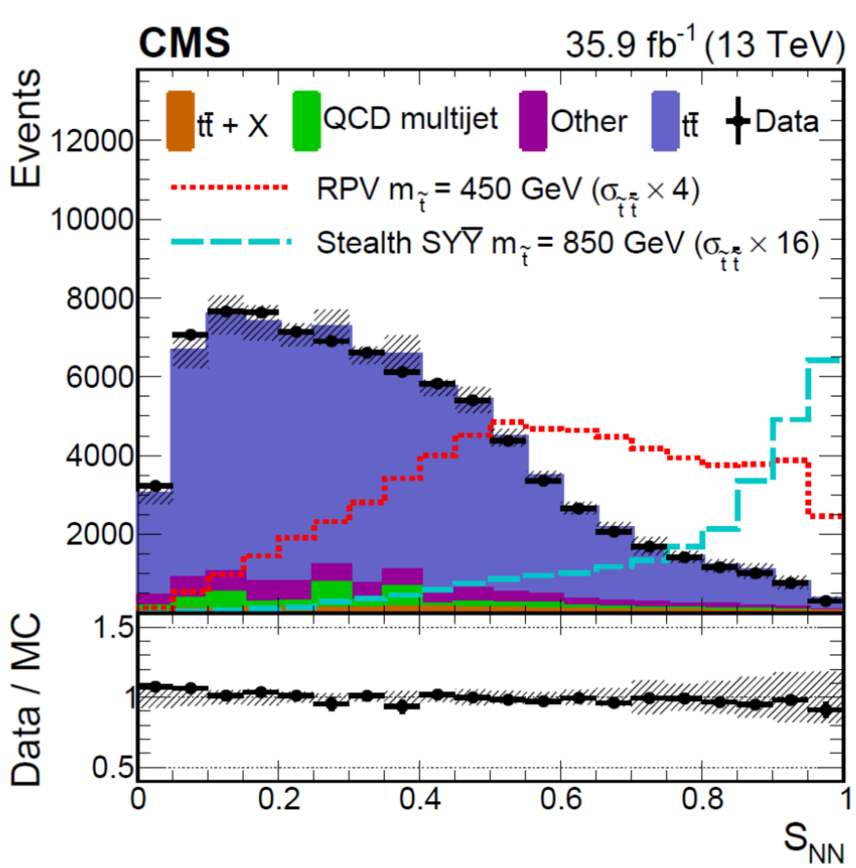
ATLAS-CONF-2021-007

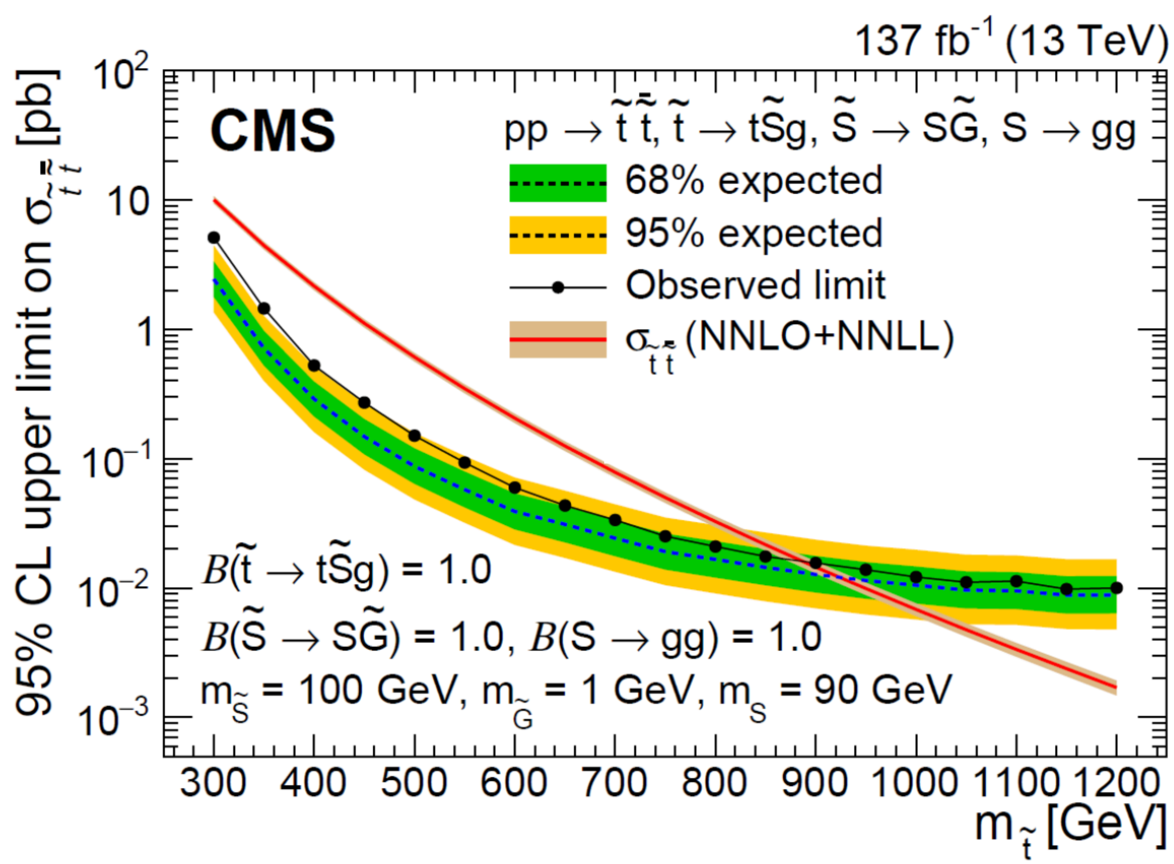
Searches for Stealth SUSY in the stop sector

First LHC search of this kind

- New hidden "stealth" sector of light particles with small or absent couplings to the SUSY breaking sector and finite couplings to the visible sector
  - SUSY approximately conserved, stealth particles remaining nearly mass-degenerate with their superpartners
- Challenging final states with one lepton, no ETmiss, ≥ 8jets
  - Neural Network with gradient reversal to discriminate S vs. B
  - 2D fit to NN score and Njet to extract signal







- 2.8σ local significance for 400GeV
- Sensitivity to RPV decays of stops up to ~700GeV

arxXiv:2102.06976

Fermilab

Outlook

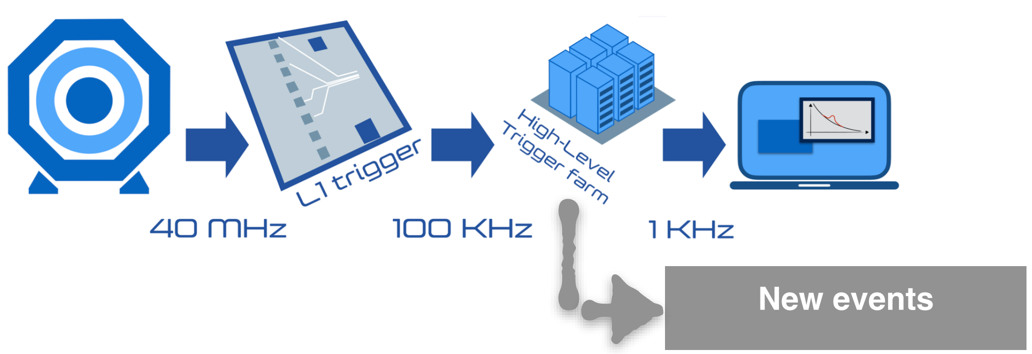
- **At the LHC, SUSY can manifest itself in a variety of (very challenging) signatures**
  - High and low ETmiss, high and low momentum objects, prompt and displaced objects, low and high object multiplicity, in time and out of time signals, ….
- **The ATLAS and CMS experiments have developed a broad and sophisticated search in Run 2 data adopting breakthrough experimental techniques**
  - Pushing the sensitivity for gluinos, stops, and EWK-inos as high as ~ 2, 1, 0.8 TeV scales for models with R-parity conservation
  - Shifting paradigm to probe for unconventional signatures expected in Long Lived, R-parity violation, Stealth, … SUSY
- **Special datasets collected with novel triggers remain to be explored**
- **Run 3 is around the corner, with great potential for discovery thanks to new capabilities of the upgraded ATLAS and CMS detectors**

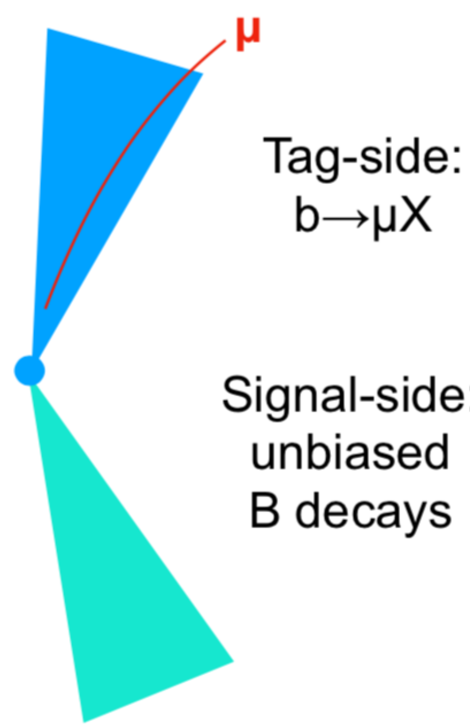
The search continues!

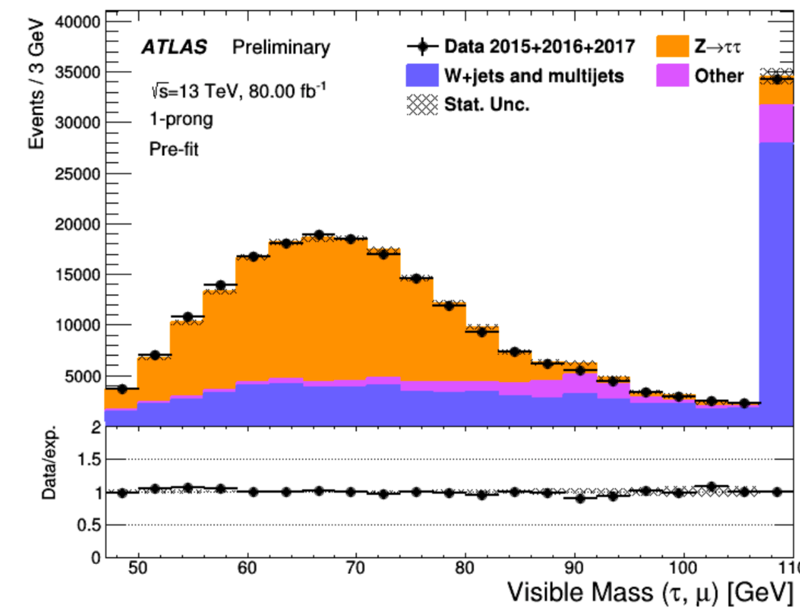
Additional material

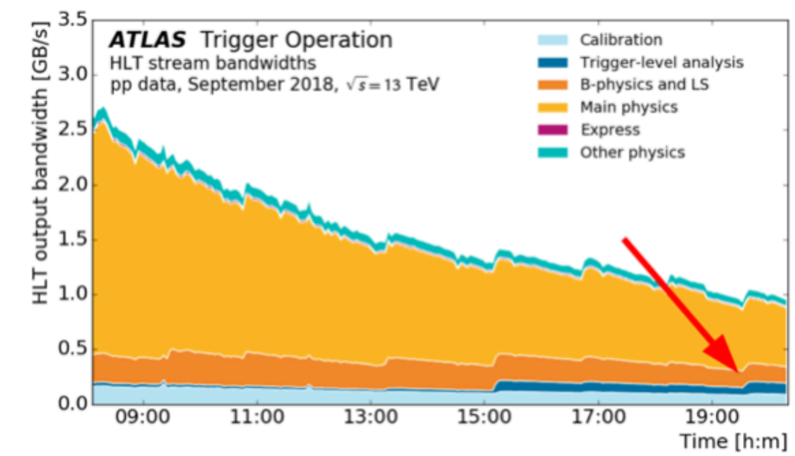
ATLAS and CMS at Run 2

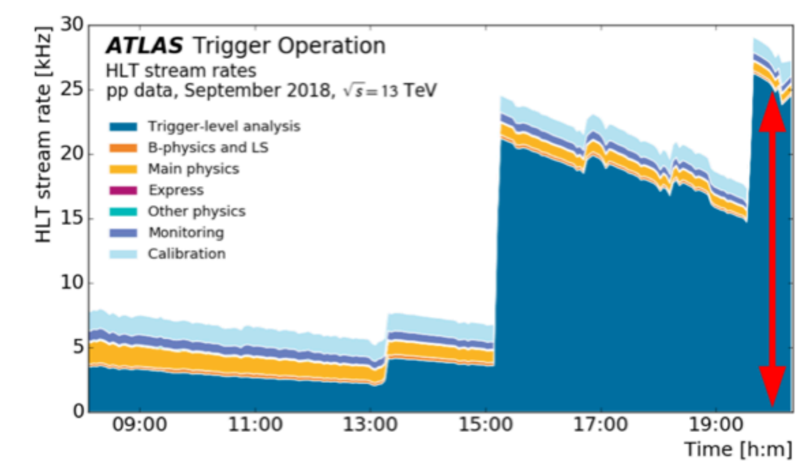
- **Run-2 represents an unprecedented dataset for HEP**
  - Outstanding understanding of detector performance and simulation at fundamental levels
  - Breakthrough triggers pushing the reach of the experiments
    - Reading out L1 triggered events, x10 more events (scouting, trigger level analysis)
    - “Parking” unbiased set of B-decays events (10B events in Run2)







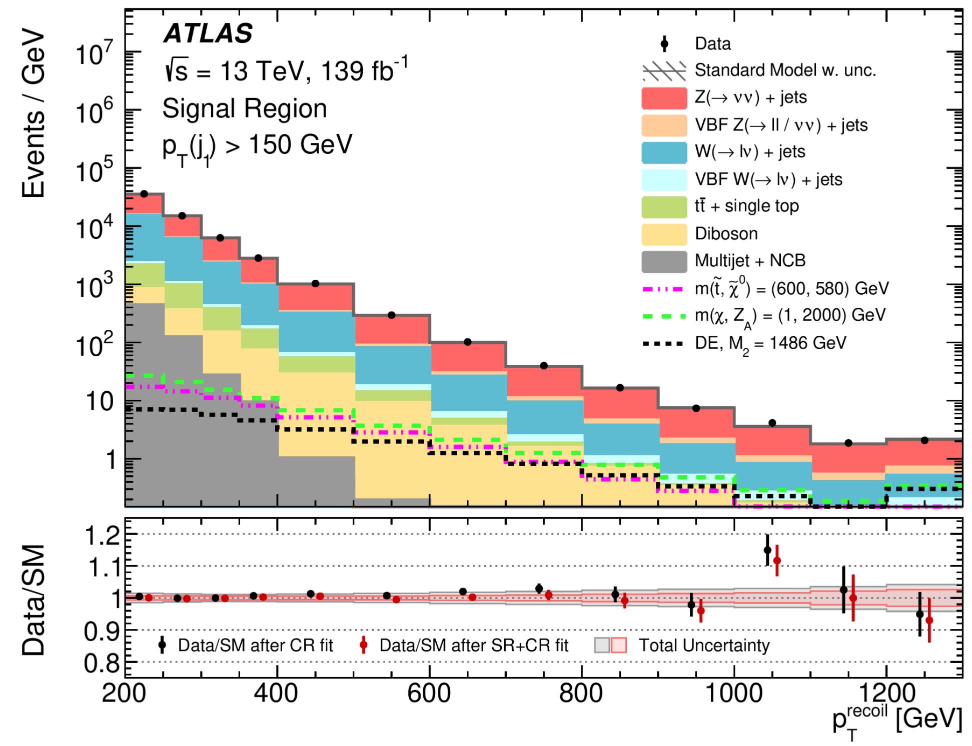


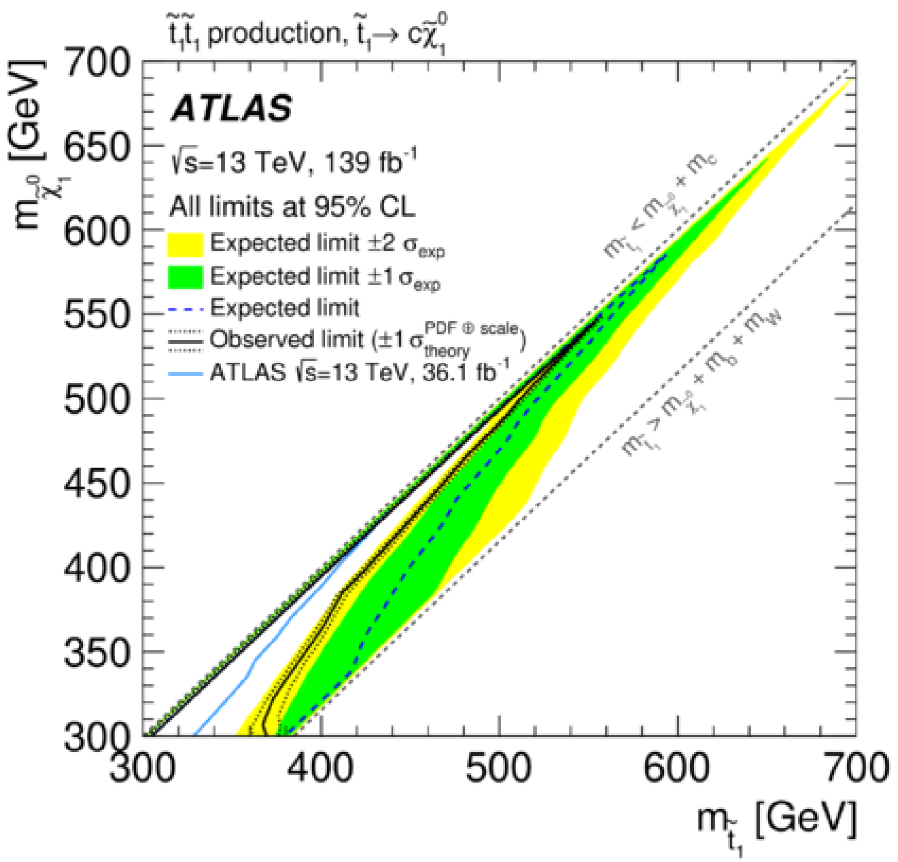


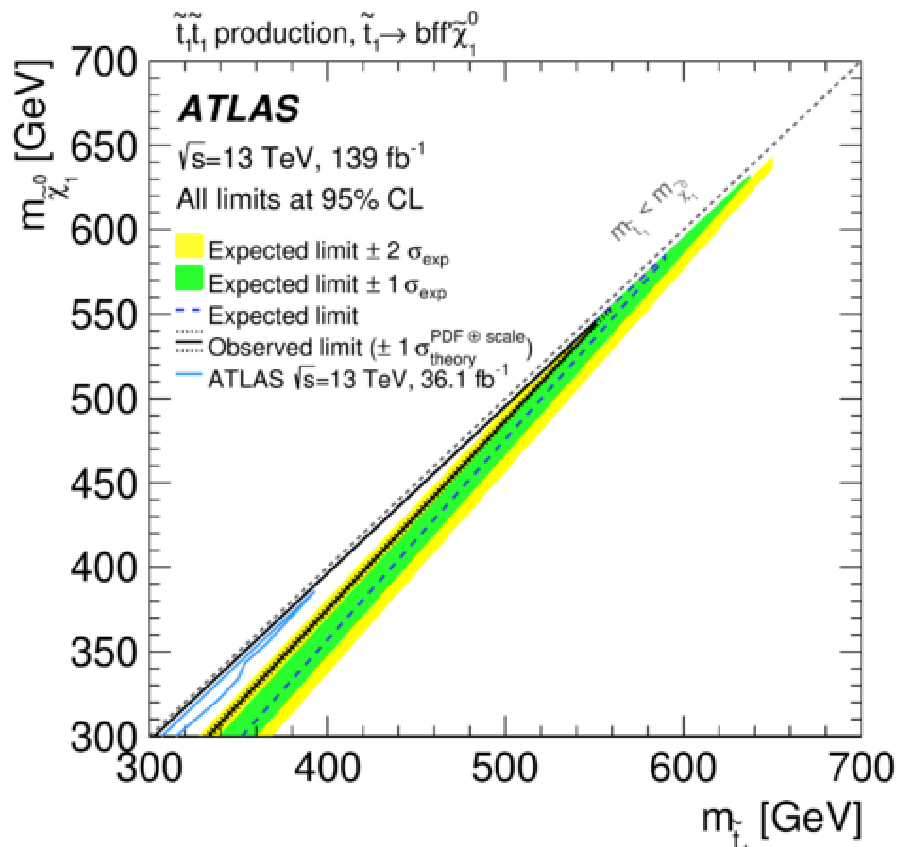
Fermilab

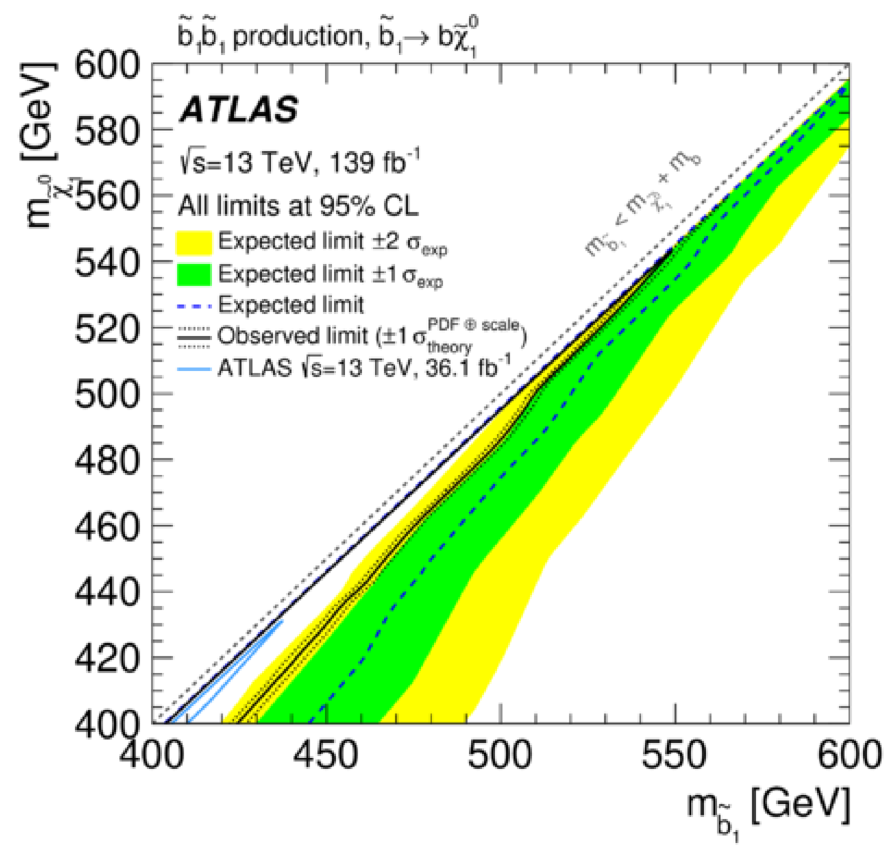
Looking in challenging corners of the MSSM parameter space

- Enhancing sensitivity to various decays of stops and sbottoms in very compressed scenarios
  - SM quarks too soft to be reconstructed
  - Request one initial state radiation jet to boost the system and look for deviations in jet pT tail
  - **Control of systematic uncertainties is key**
    - up to 4% on background in SR







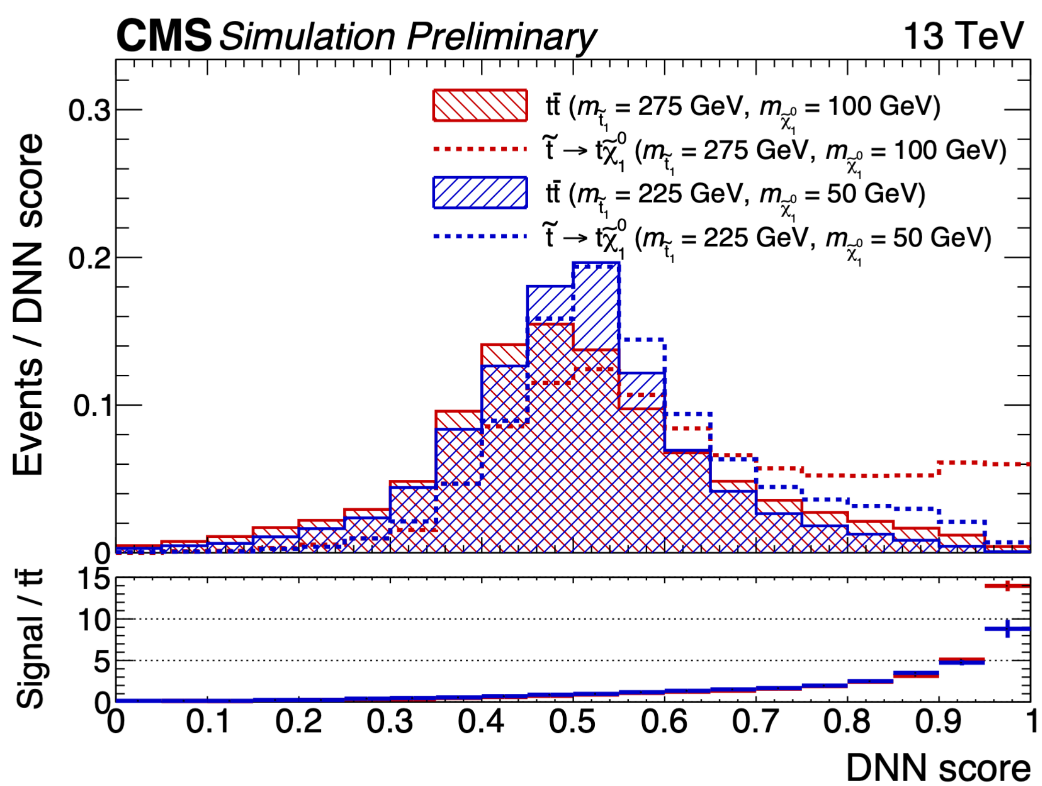


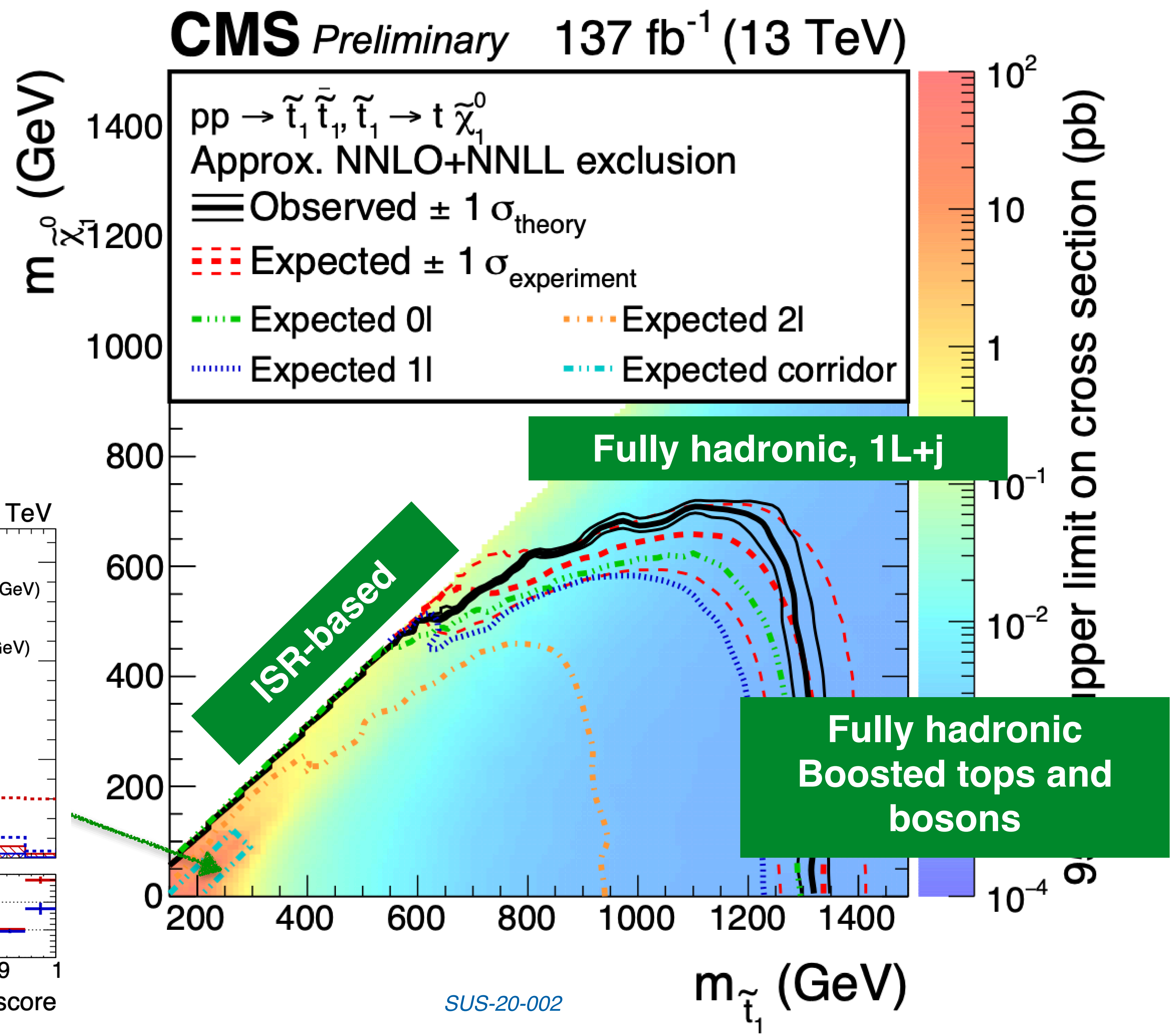
arXiv:2102.10874

Fermilab

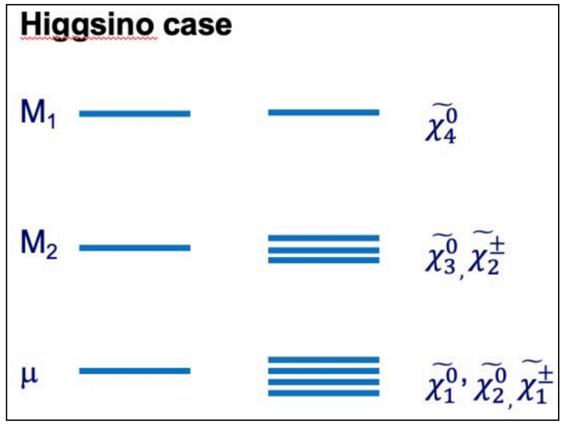
Searches for stops directly produced and in gluino decays

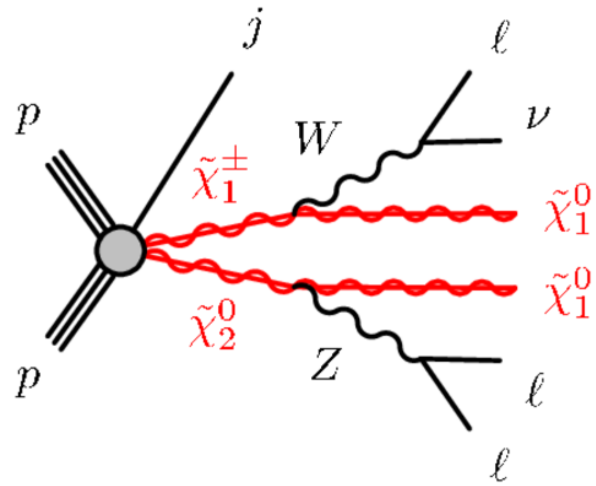
- **Parametric DNN** based selection of events with two leptons, b-jets and ETmiss to probe the “corridor”





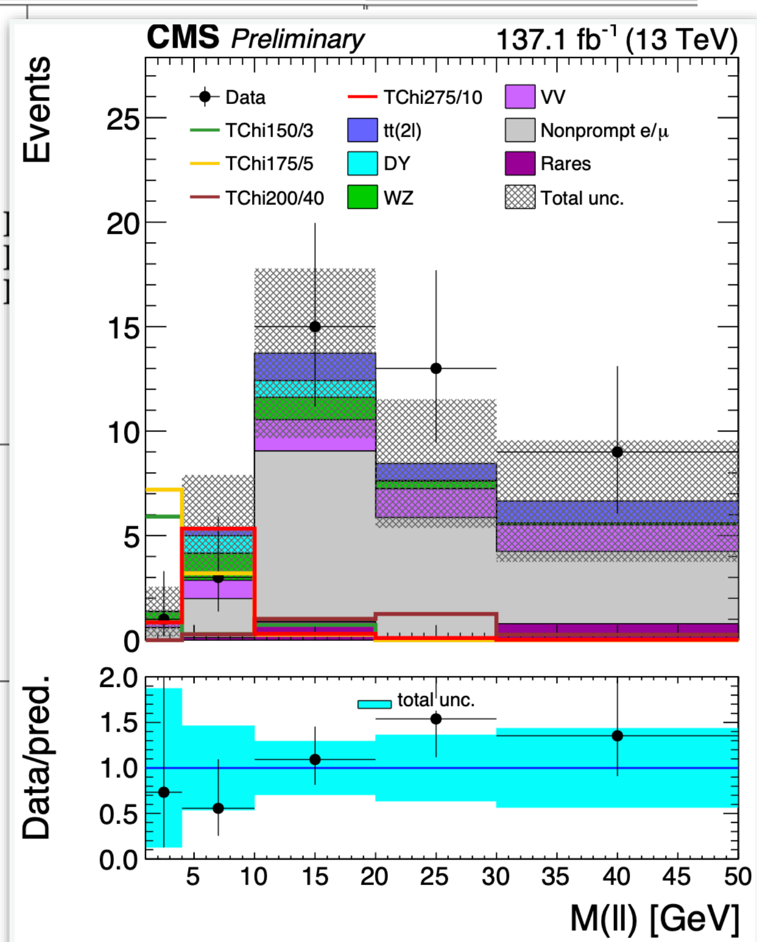
Search for Charginos and Neutralinos: pMSSM

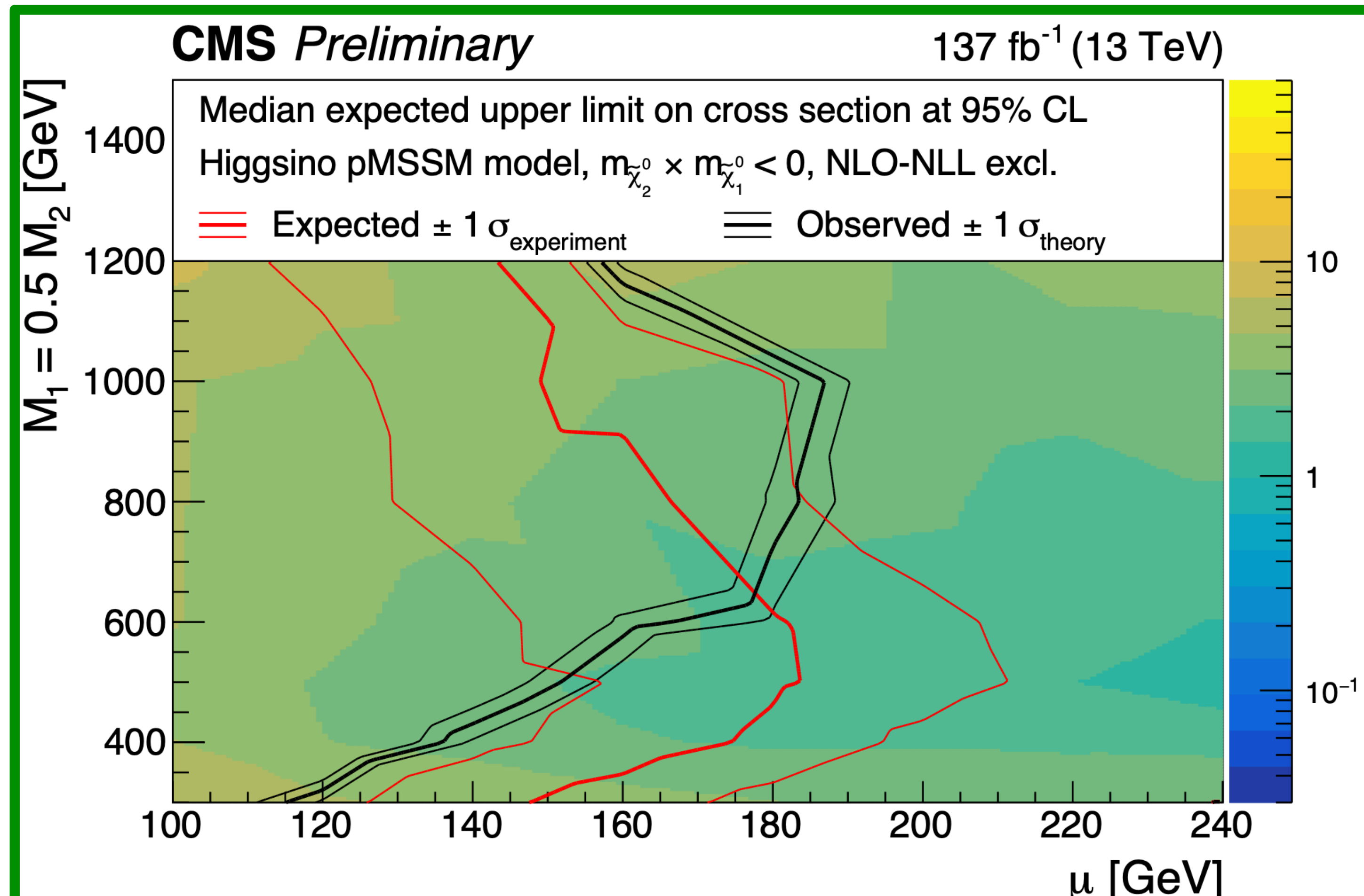




- Higgsino-like EWK-inos in the final state with one jet, **moderate ETmiss** and 2/3 **soft leptons**
  - **Muon (electron) pT > 3.5 (5) GeV**
  - **Dilepton invariant mass down to 1 GeV**
- Events classified based on ETmiss

Variable	2ℓ Ewk Low	2ℓ Ewk Med/High/Ultra	3ℓ Ewk Low	3ℓ Ewk Med/High/Ultra
N_{lep}				
$p_T(\ell_1)$ [GeV] for μ(e)				
$p_T(\ell_2)$ [GeV] for μ(e)				
$p_T(\ell_3)$ [GeV] for μ(e)				
1 OS pair				
1 OSSF pair				
$M(\ell\ell)_{SFOS}$ ($M(\ell\ell)^{min}_{SFOS}$ in 3ℓ) [GeV]				
$M(\ell\ell)_{SFOS}$ ($M(\ell\ell)^{min}_{SFOS}$ in 3ℓ) [GeV]				
$M(\ell\ell)_{SFOS}$ ($M(\ell\ell)^{min}_{SFOS}$ in 3ℓ) [GeV]				
$M(\ell\ell)^{max}_{SFAS}$(AS= any sign) [GeV]				
$p_T(\ell\ell)$ [GeV]				
$M_T(\ell_i, p_T^{miss})$ [GeV] ($i = 1,2$)				
$\Delta R(\ell\ell)_{ij}$ (i,j=1,2,3)				
p_T^{miss} [GeV]				
$p_T^{miss,corr}$ [GeV]				
H_T [GeV]				
p_T^{miss}/H_T				
Jet ID tight WP for leading jet				
$N_b(p_T > 25$ GeV)				
$M_{\tau\tau}$				

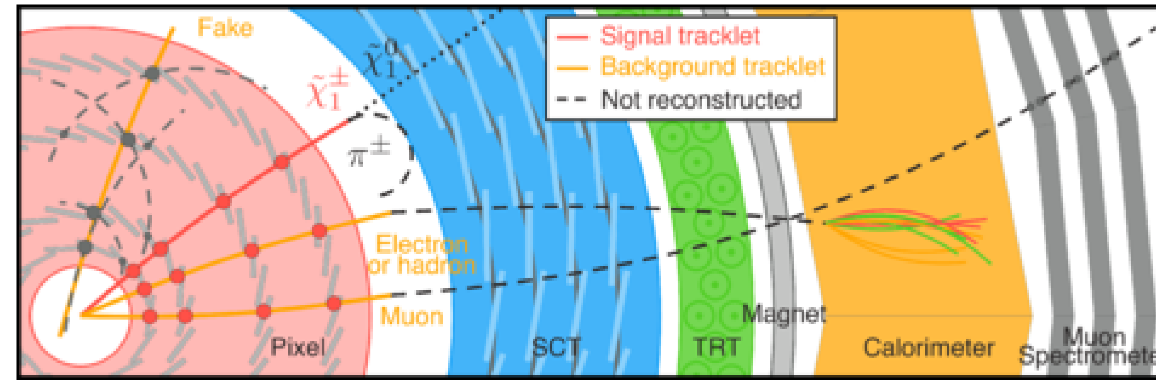


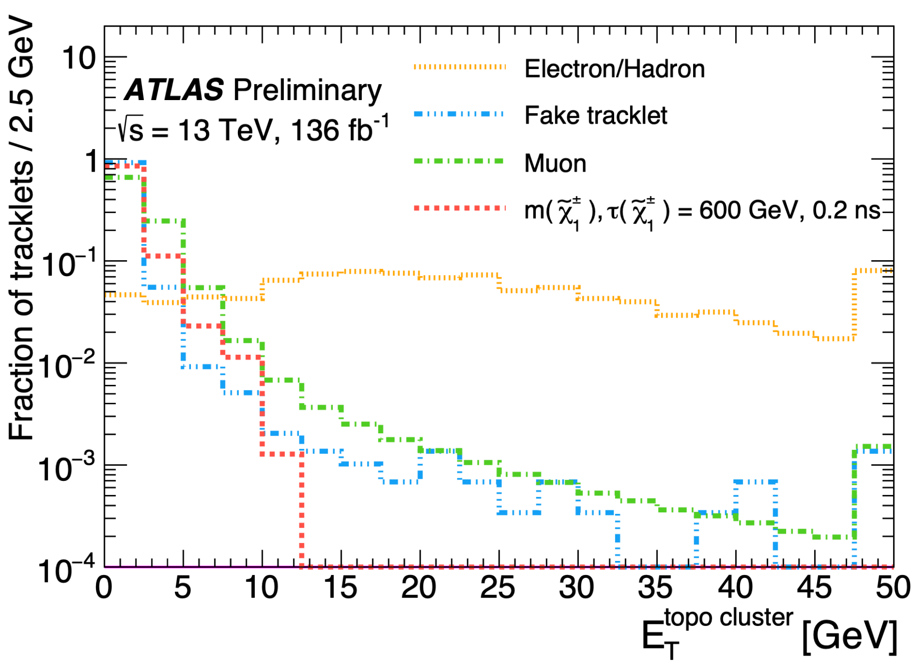


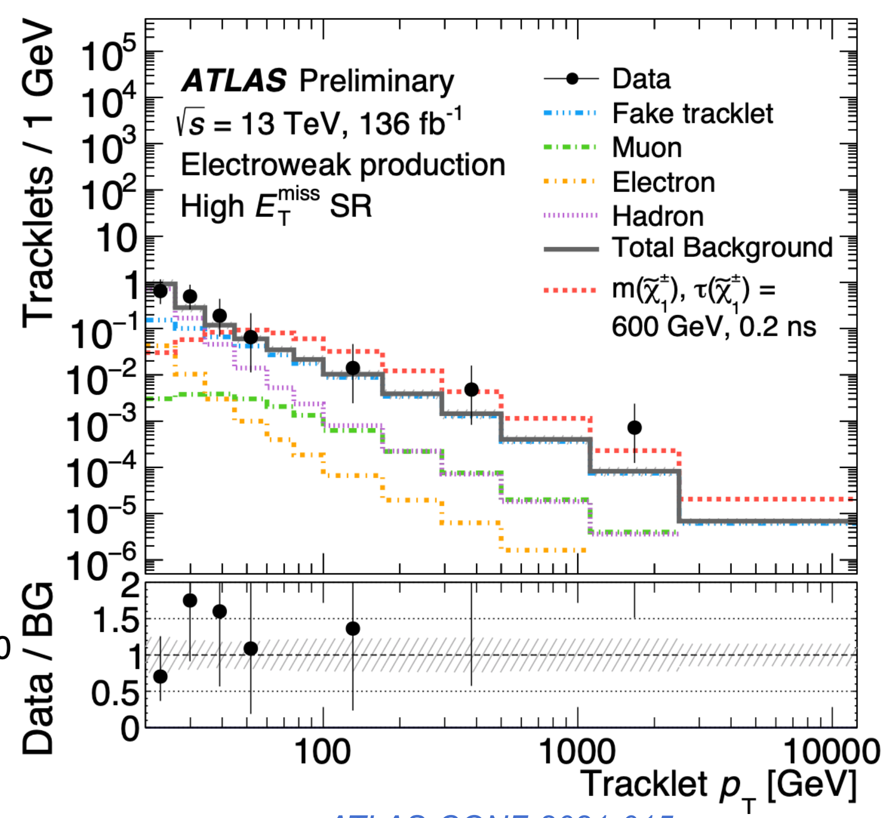
CMS-PAS-SUS-18-004

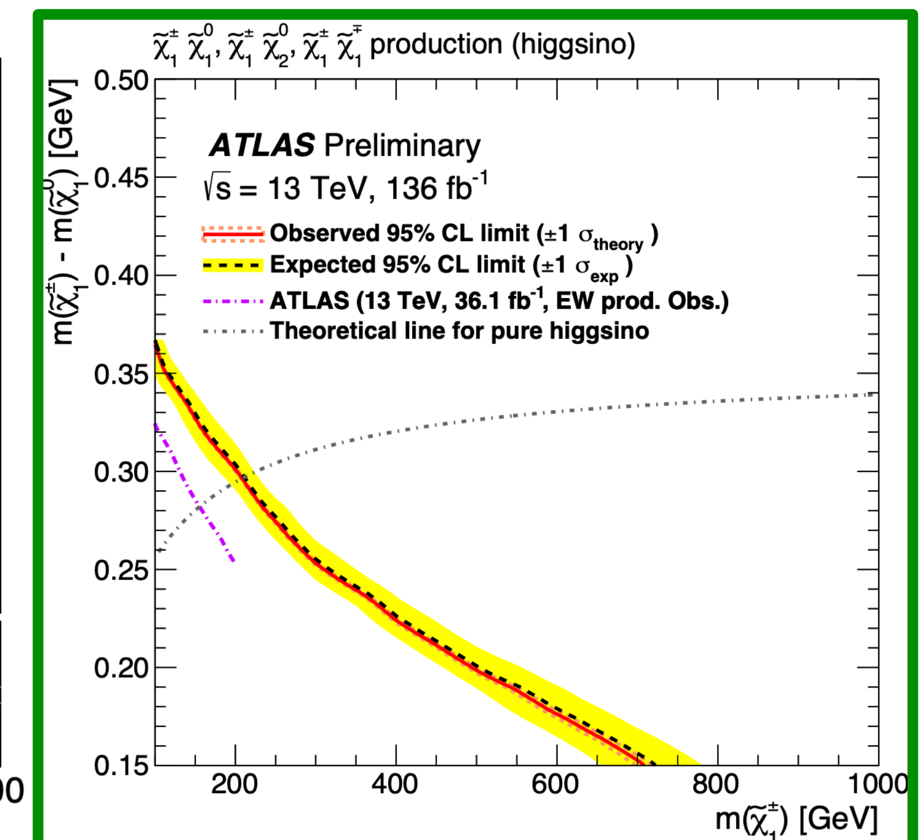
Search for long-lived charginos

- Charginos decaying as $\tilde{\chi}^{\pm} \rightarrow \pi^{\pm}\chi^{0}$ expected in models with very compressed spectra
- Striking signature with a ‘disappearing track’
  - Pixel tracklets with no hits in the outermost silicon trackers and no calorimeter activity (newly introduced requirement)
  - ETmiss and number of jets for S to B discrimination







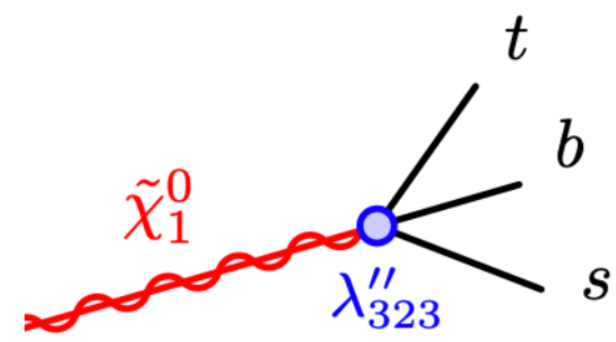


ATLAS-CONF-2021-015

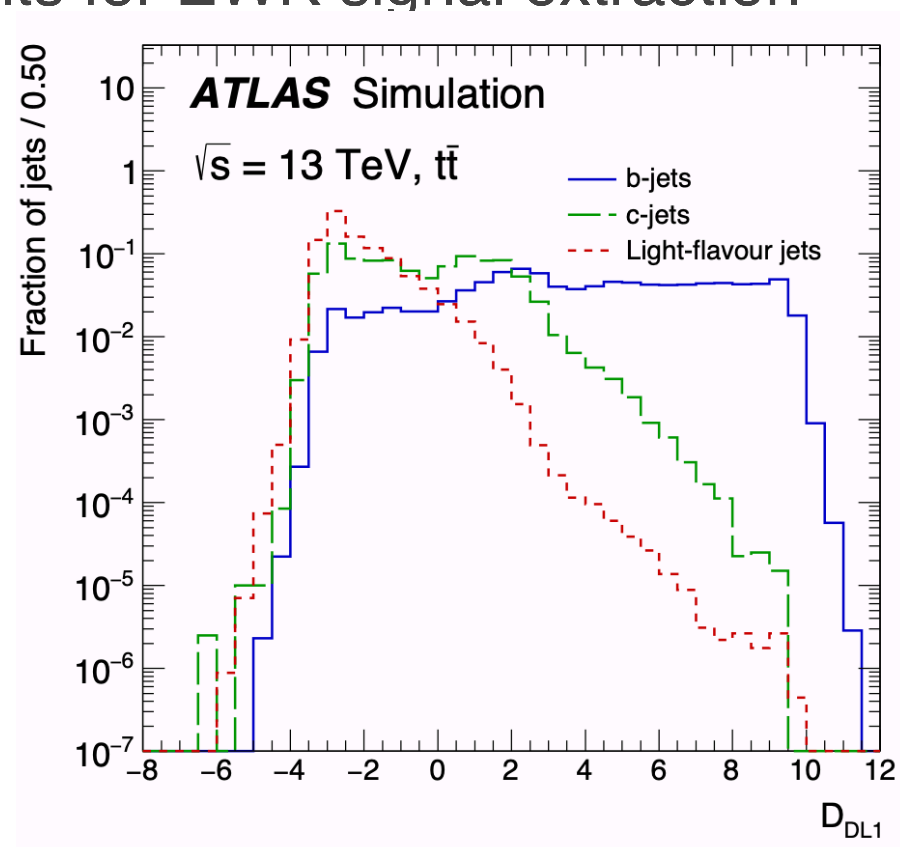
RPV SUSY in events with multiple (b-)jets

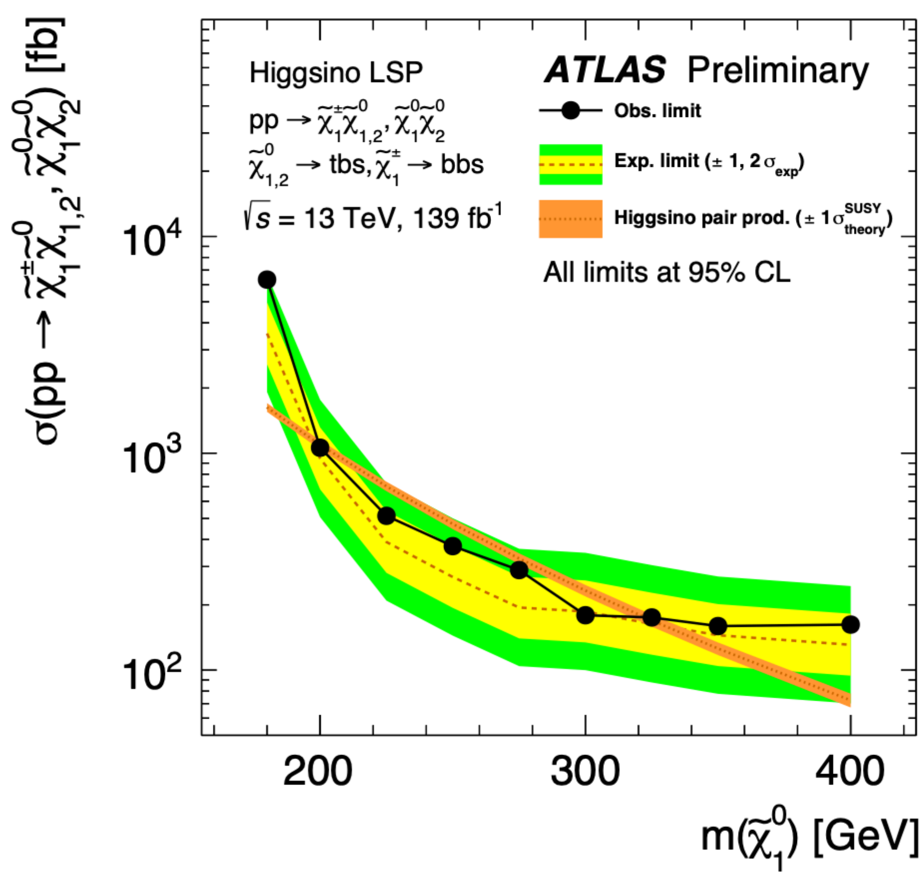
- If λ'' dominant (as predicted under the minimal flavour violation hypothesis), decays into multi (b-) jets states
- Search in events with one or two SS leptons, at least 8-15 (b-)jets sensitive to the production of gluinos, stops, electroweakinos
- **Novel *b*-tagging algorithm**, based on likelihood ratio of low-level tagger outputs, with adding RNNIP
- Multivariate discriminants for EWK signal extraction

First LHC search of this kind



$$D_{\mathrm{DL1}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\mathrm{light}}}\right)$$





ATLAS-CONF-2021-007

New trigger opportunities at Run 3

- At CMS
  - global Level-1 triggers, for e.g. VBF signals
  - low mass dimuon triggers using invariant mass
  - triggers on single LLP leg
  - increased data storage (data parking, data scouting)
  - overall improved performances thanks to adoption of GPUs for tracking at high level trigger (allows to run particle flow)
  - new triggers for long lived using upgraded calorimeter (better segmentation)
  - …

New trigger opportunities at Run 3

- At ATLAS
  - global Level-1 triggers, for e.g. VBF signals
  - Increased granularity of calorimeter information used in Level-1 triggers for electrons and photons
  - More sophisticated Level-1 triggers for Taus, ETmiss (e.g. capability to trigger on large cone jets) and event-level quantities
  - ML in tracking at High Level Trigger
  - Increased data storage (data scouting, data parking)
  - …