Highlights from Beyond the Standard Model Searches at ATLAS and CMS

Sven Dildick
Rice University

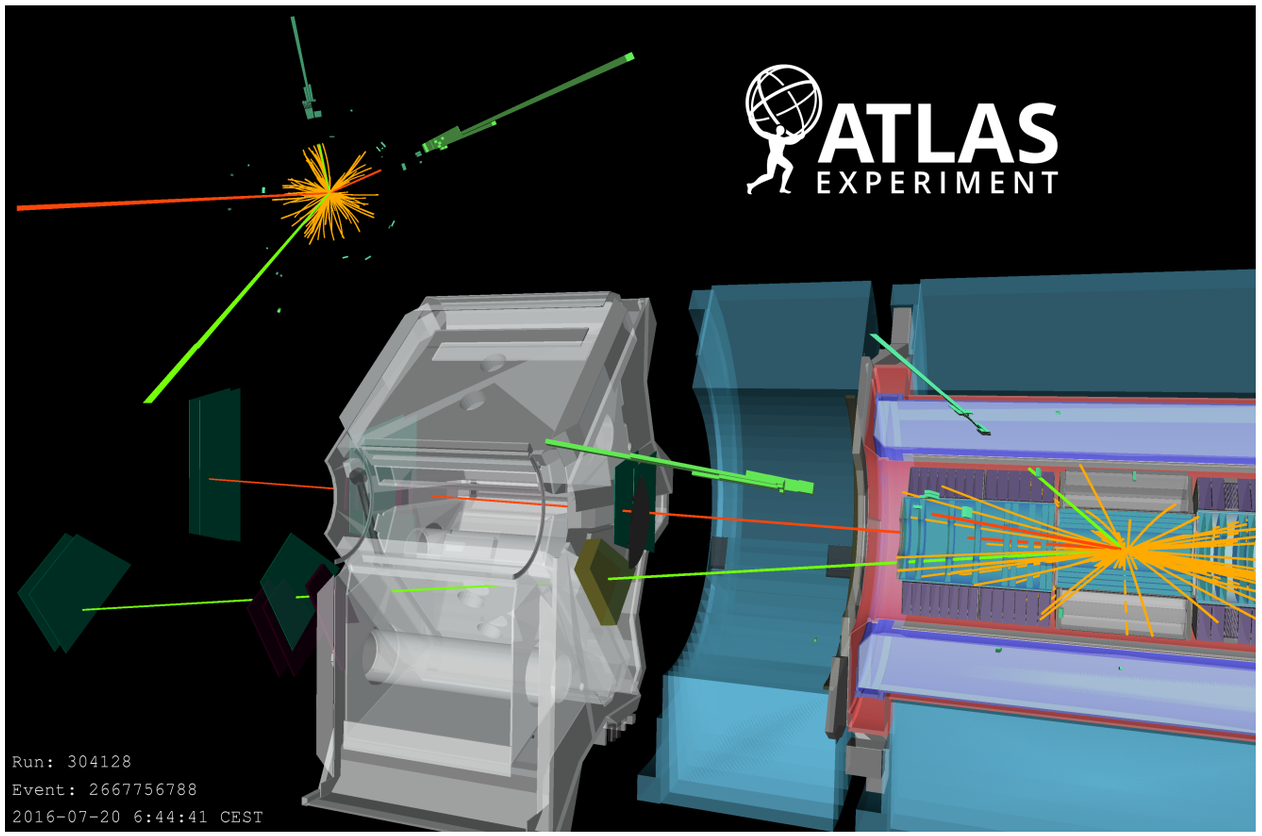
On behalf of the ATLAS and CMS Collaborations

Brookhaven Forum 2019
Particle Physics and Cosmology in the 2020's
Conference

September 25–27, 2019
Brookhaven National Laboratory
Upton, NY USA

Topics covered

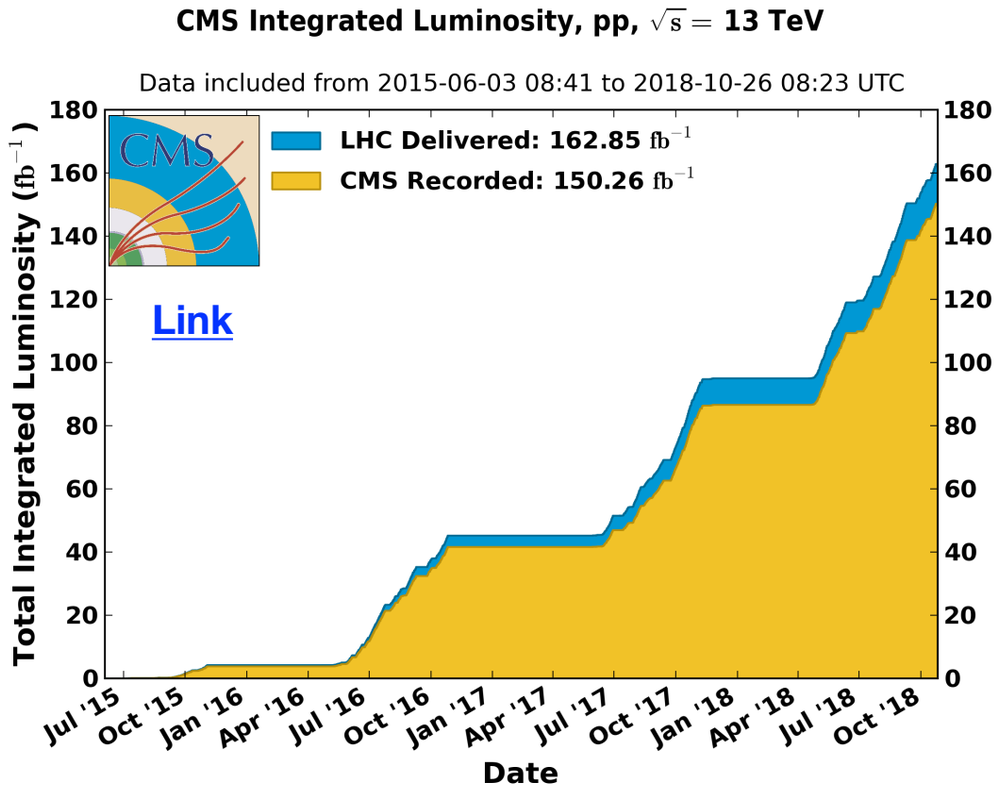
- This presentation covers a selection of new physics searches from ATLAS and CMS collaborations during Run-2
  - Too many new results to cover everything in half an hour
- Most searches here use at least 130 fb^{-1} of pp collision data
  - SUSY
  - Exotica
  - BSM Higgs
  - Long-lived particles
- More information on ATLAS and CMS public results webpages
  - ATLAS public results
  - CMS public results

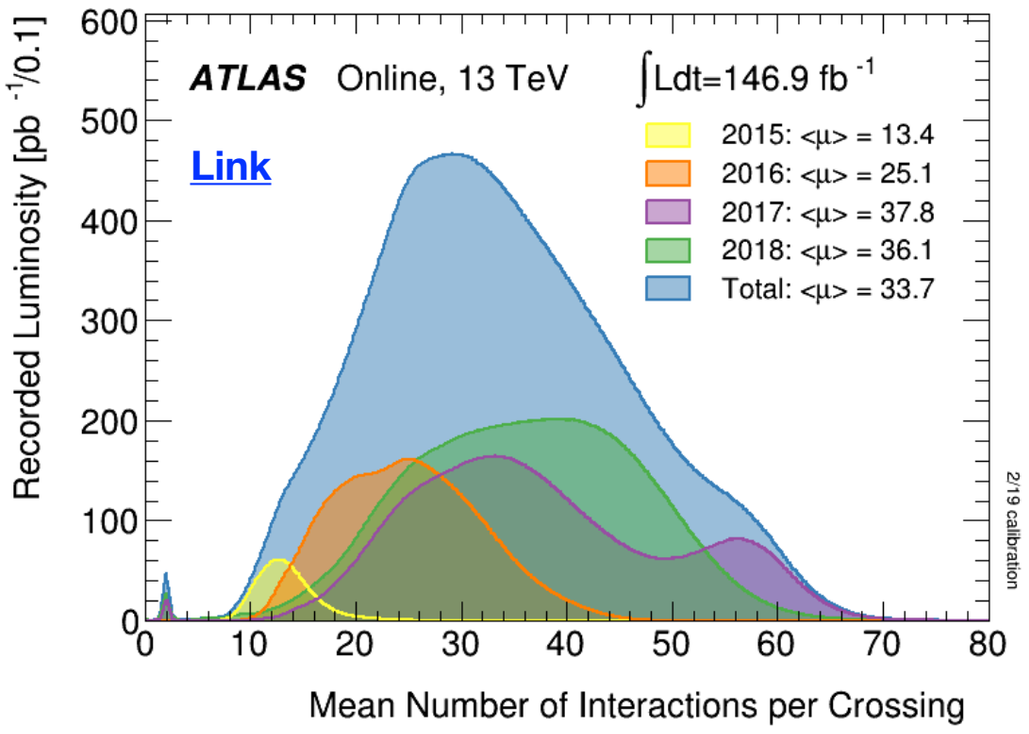


Event with four leptons in ATLAS in search for doubly charged Higgs boson (ATLAS-CONF-2017-053)

Run-2 Data

- Data taking period from 2015 to 2018 @ 13 TeV
- LHC delivered an impressive ~160 fb^{-1} of pp collision data
  - Of which about 140 fb^{-1} is good for physics
  - More than 8.5 million Higgs boson produced
- ATLAS and CMS data taking efficiency >92% during Run-2!



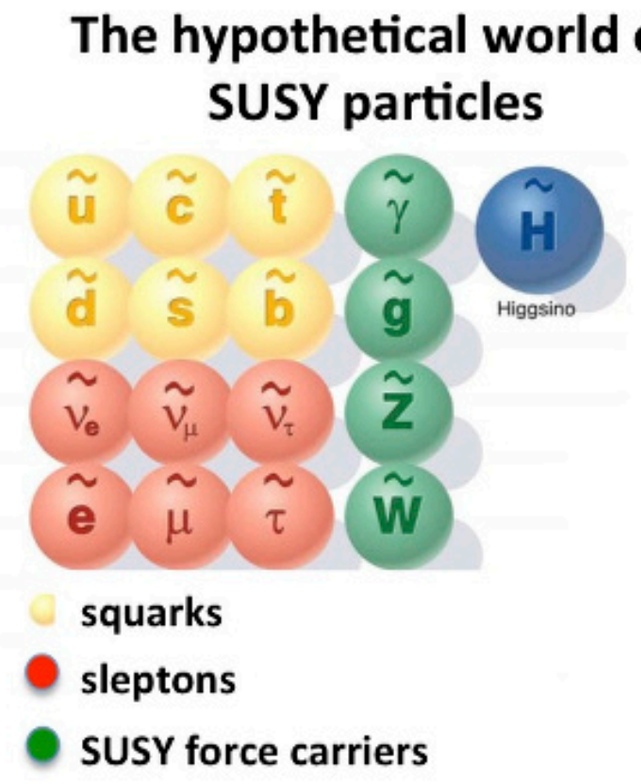


- Mean number of interactions per crossing rose from ~21 in Run-1 to ~34 in Run-2
  - Increasingly dense collision environment

Supersymmetry

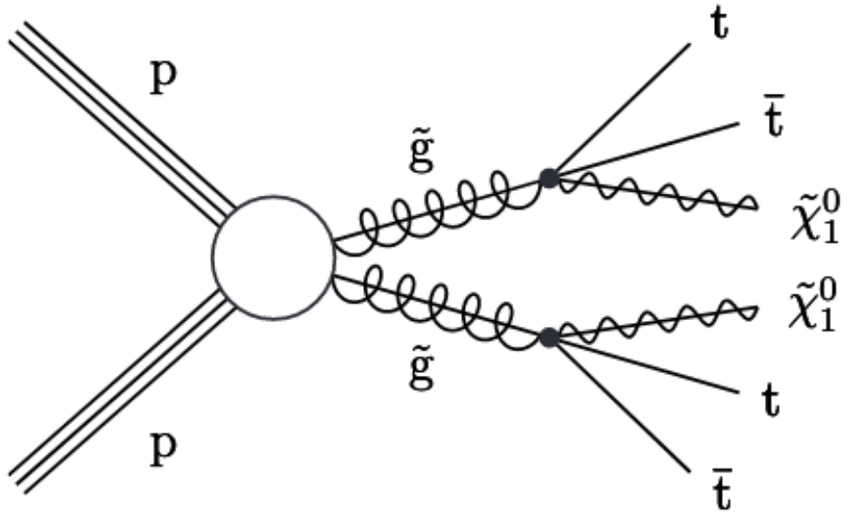
Supersymmetry

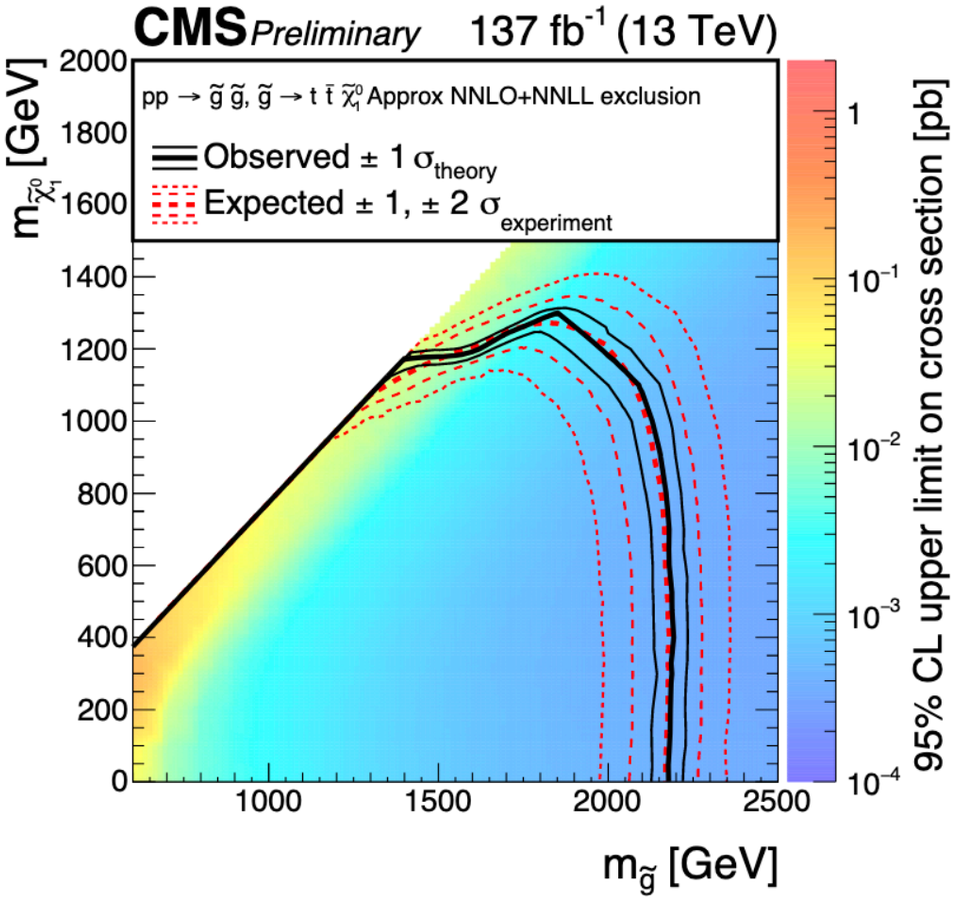
- Extension of the standard model that provides a *superpartner* for each SM particle
- One of the most promising models that can explain anomalies in particle physics and cosmology:
  - Hierarchy problem
  - Dark matter (LSP)
  - Baryon asymmetry
- Models can be *R*-parity conserving or violating
- SUSY particles should be in LHC energy range!
  - Few 100 GeV to few TeV



Search for SUSY with multiple jets and missing energy

- SUSY search for gluino and squark pair production
- Gluinos and squarks decay to SM particles and neutralinos
  - Hadronic jets originate from quarks
  - Neutralinos remain undetected as missing energy
- 95% CL lower limits are set on gluino and squark masses depending on the model
  - 2000 GeV to 2310 GeV for gluinos
  - 1190 to 1630 GeV for squarks

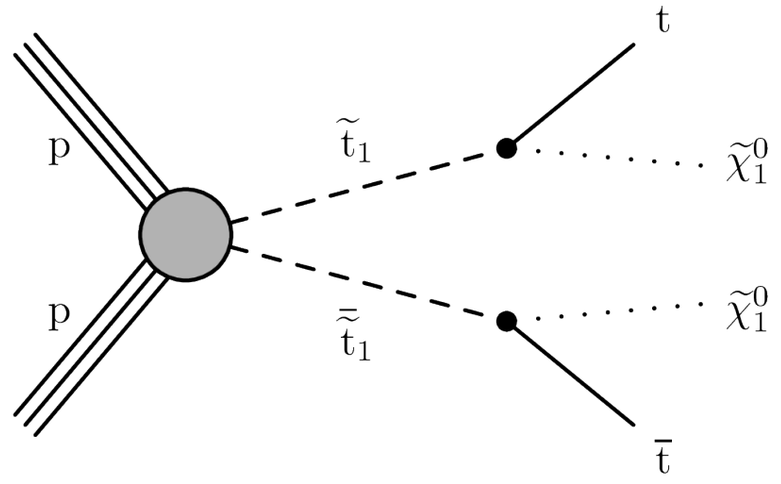


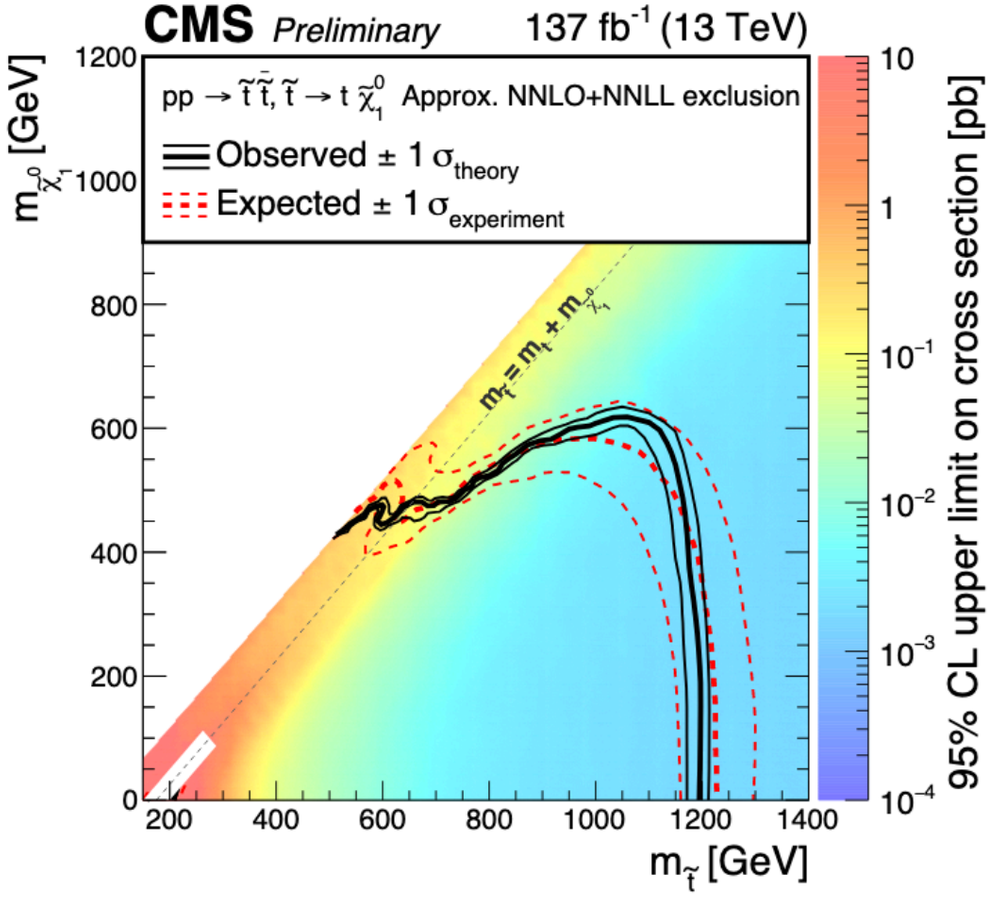


CMS-PAS-SUS-19-006

Search for SUSY with 1 lepton…

- In this search top squark are produced in pairs and decay to top quarks and neutralinos
- One of the top quarks decays to an electron or muon
  - With multiple jets and large missing energy in the signature
- Dominant background from WW where one lepton is lost
  - Lepton flies into the beam pipe or is misreconstructed
- Limits on top squark mass up to 1.2 TeV for massless LSP
- Models with 1 TeV top squarks exclude neutralino masses up to 600 GeV

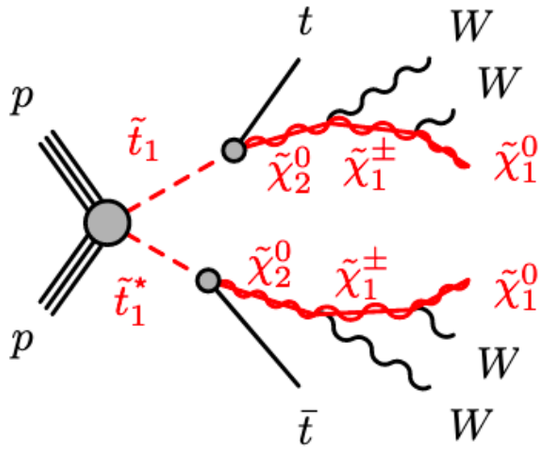


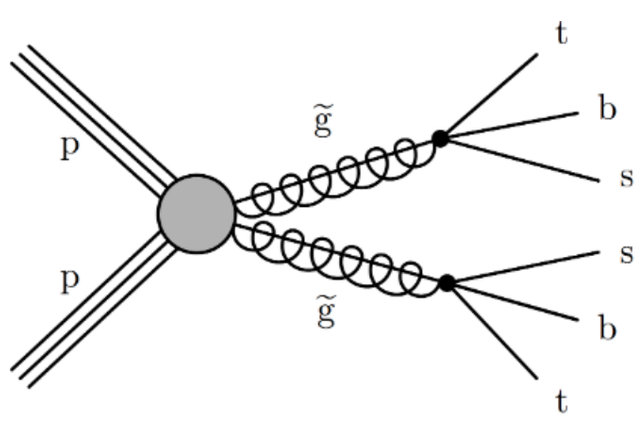


CMS-PAS-SUS-19-009

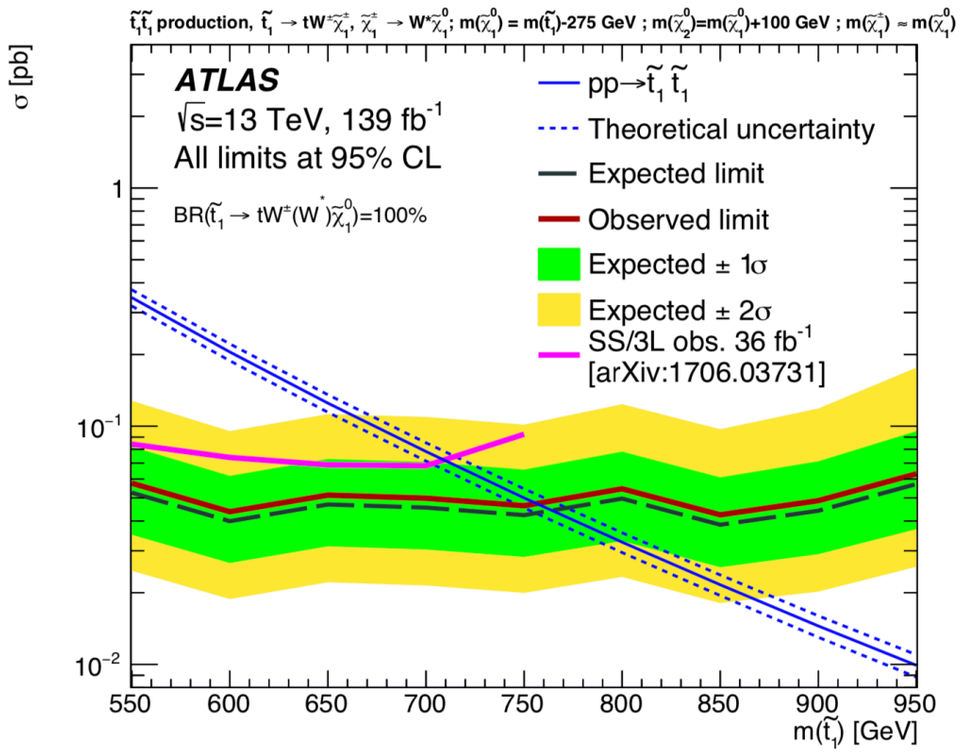
…or multiple leptons

- We are also searching for SUSY in signatures with multiple leptons
- Same sign lepton signature sensitive to new physics
  - Rare process in electroweak physics
  - Suppressed by x1000 compared to opposite sign leptons at LHC
- Interpretation for R-parity conserving or violating models





- Lower mass limits up to
  - 1.6 TeV for gluinos
  - 750 GeV for top and bottom squarks



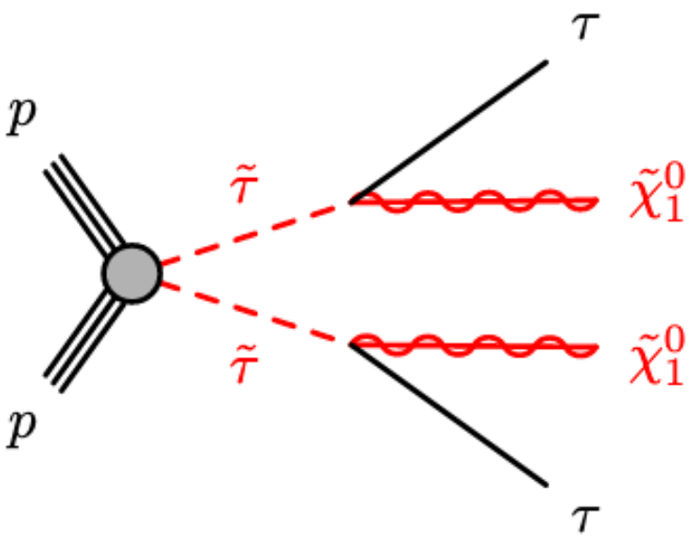
ATLAS-CONF-2019-015

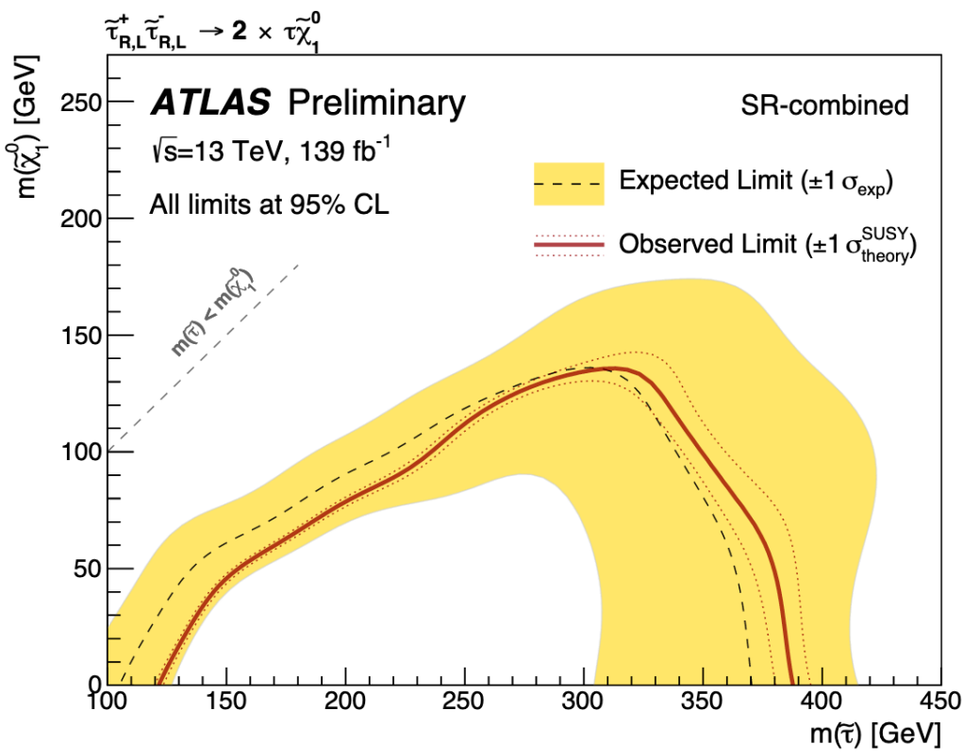
Stau searches in ATLAS

- Models with light staus are interesting at LHC
  - Well within LHC energy range
  - Could provide DM relic density consistent with cosmological observations
- With full Run-2 data, searches become sensitive to stau pair production
- This analysis looks for hadronically decaying tau leptons and missing energy from neutralinos

ATLAS-CONF-2019-040

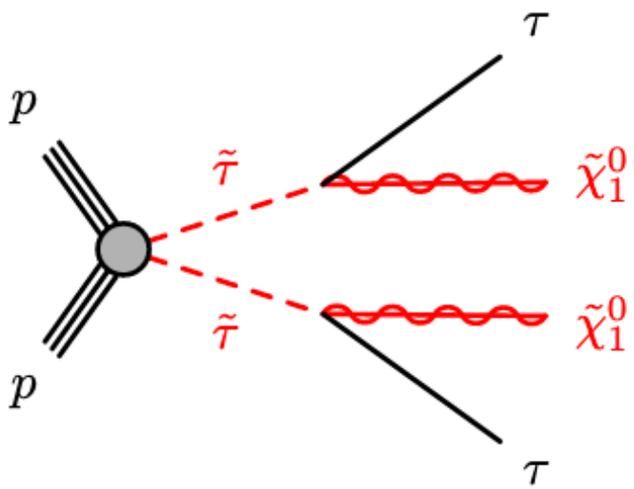
- Most sensitive limits on stau for massless neutralino, up to 120-390 GeV
  - Previous best limits obtained at LEP (~90 GeV)

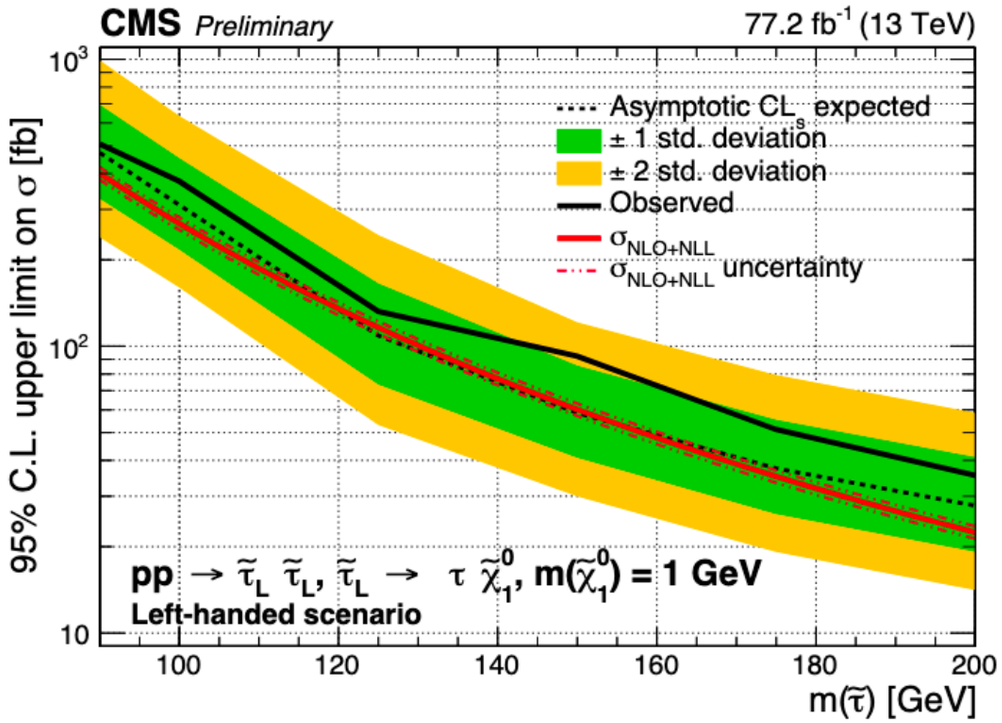




Stau searches in CMS

- New CMS search on partial Run-2 data also includes leptonic final states
  - $\tau_h\tau_h$, $e\tau_h$, and $\mu\tau_h$
- Usage of Machine Learning techniques in this analysis:
  - Deep neural network to identify τ_h
  - Boosted decision trees for $e\tau_h$, and $\mu\tau_h$ channel
- Limits set on the stau production cross section
  - Strongest limits for nearly massless neutralino

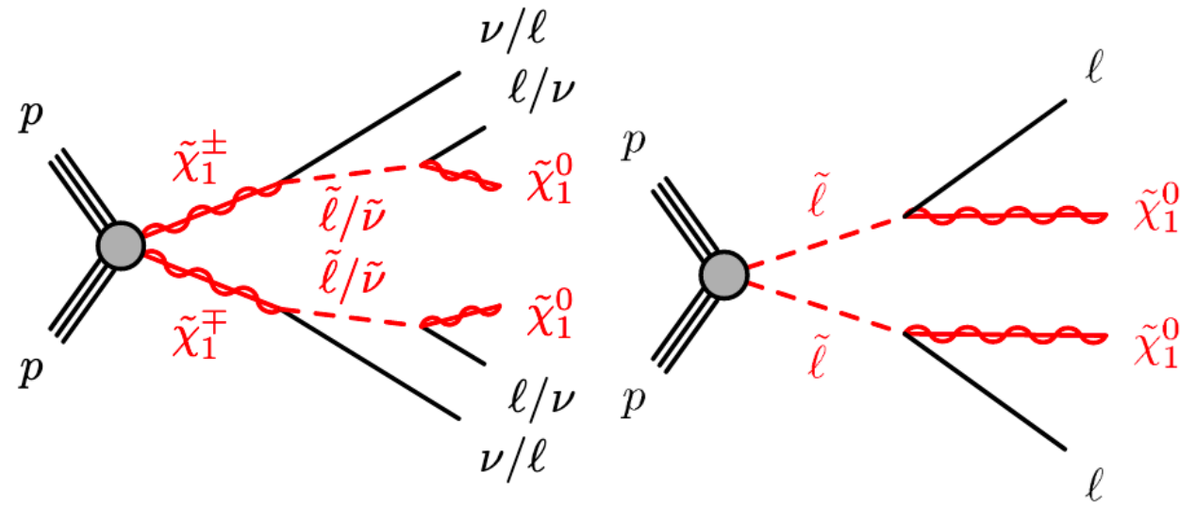


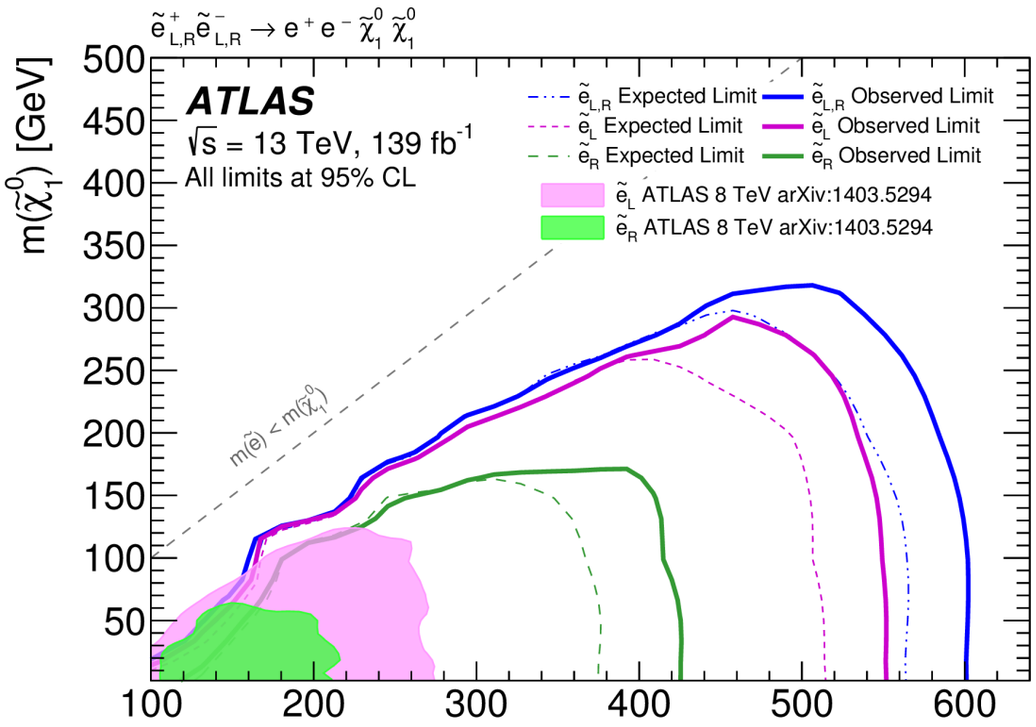


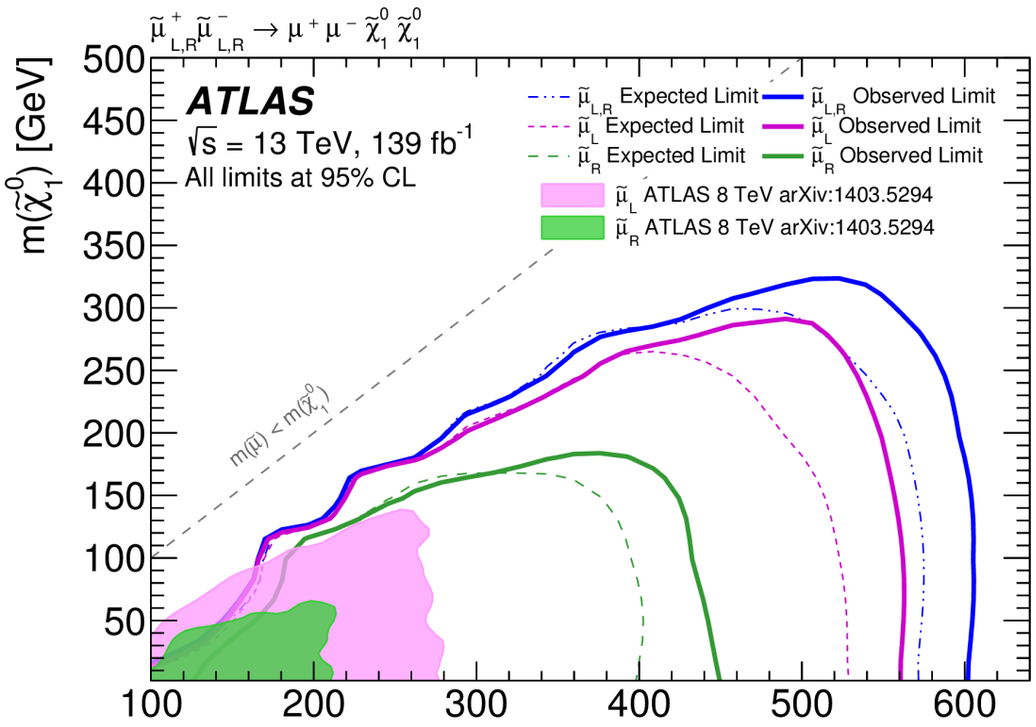
CMS-PAS-SUS-18-006

Searches for leptons

- In context of R-parity conserving models
- Lower limits on slepton mass extended in recent ATLAS analysis on full Run-2 data
  - Selectron: from ~200-250 to 420-600 GeV
  - Smuon: from ~200-275 to 450-600 GeV





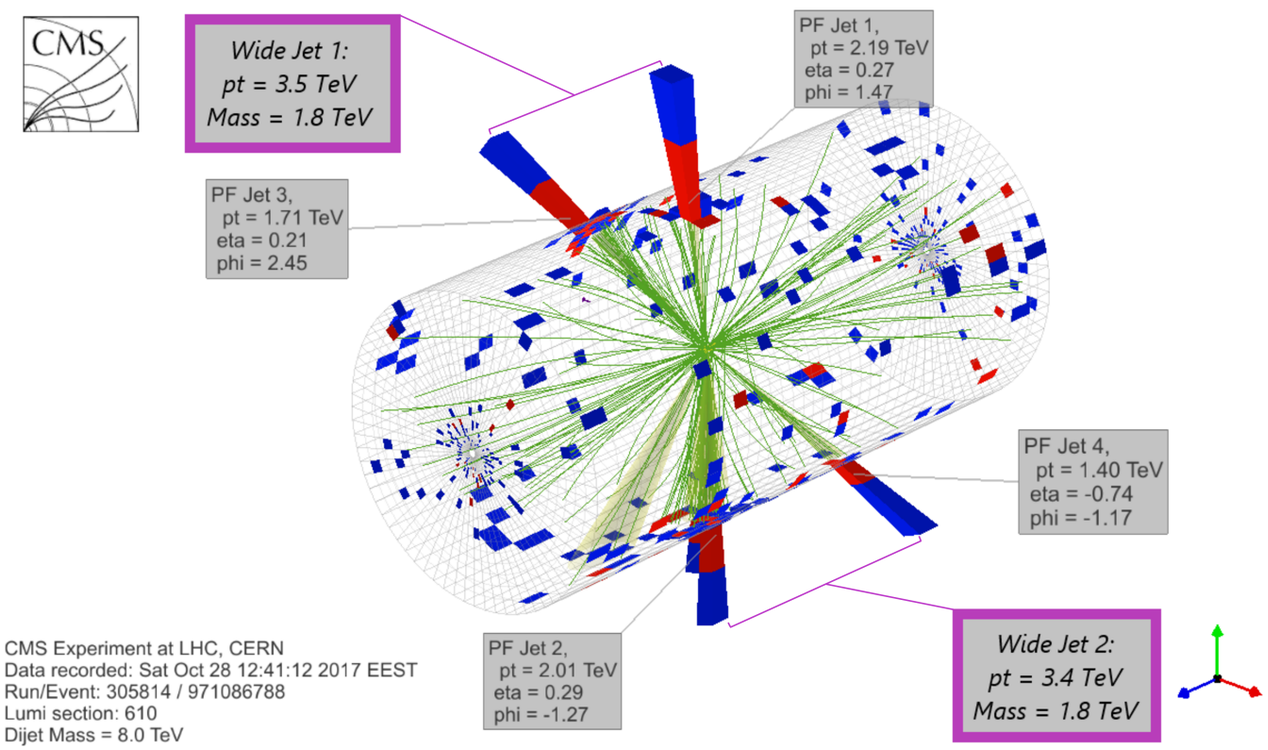


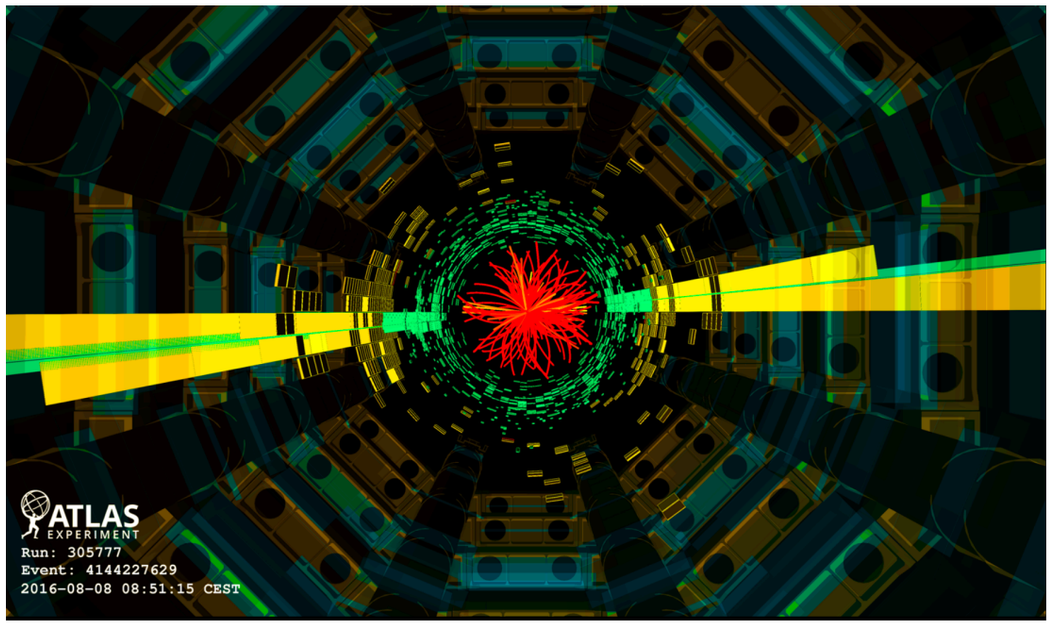
ATLAS-SUSY-2018-032

Exotica

Dijet resonances

- Typical searches for high-mass resonances decaying to gg/gq/qq
  - Two energetic jets in the final state
- Searches are done for heavy exotic objects
  - W', Z', gravitons, dark matter mediators, axigluons, colorons,…
- Searches are done for small cone jets (dR<0.4), but also boosted jets and large cone jets (dR<1)



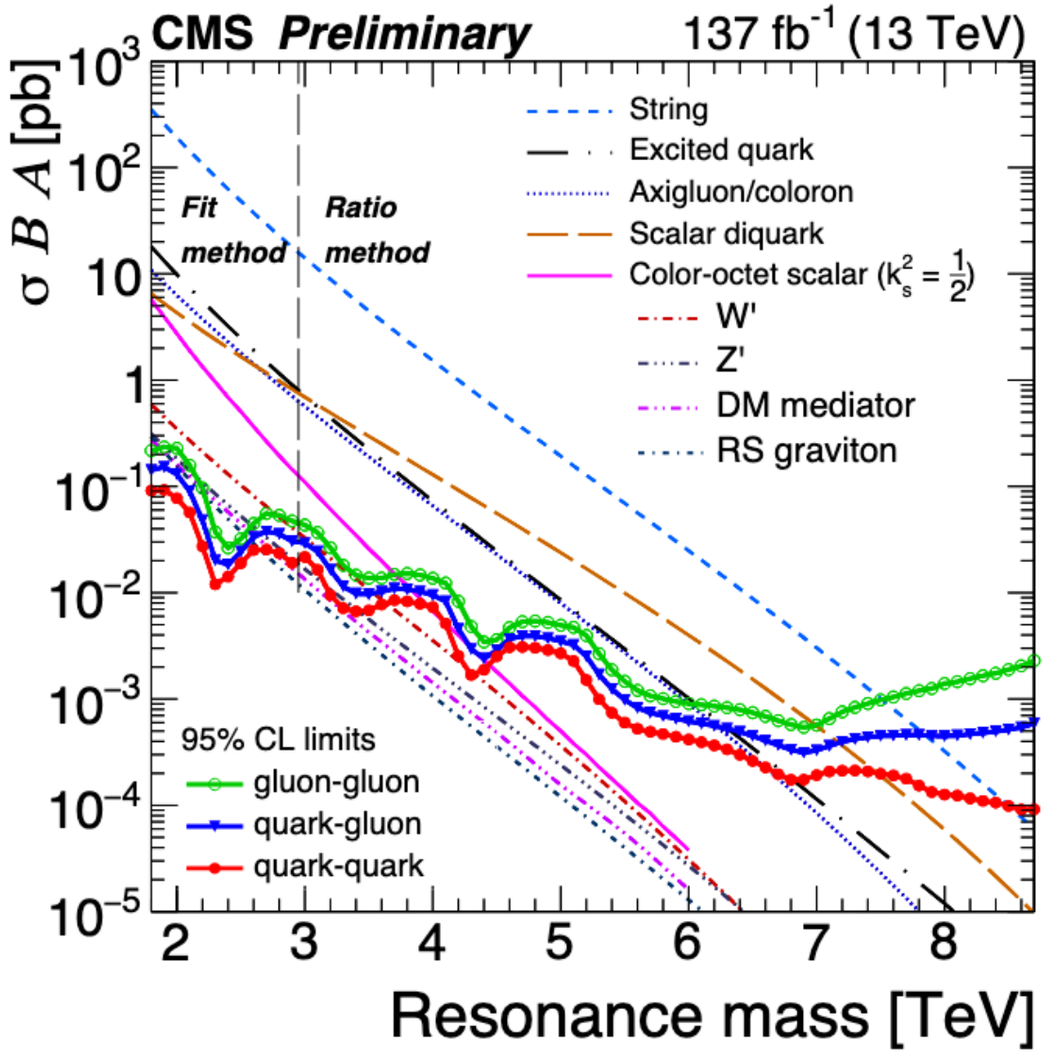


An event with 2 wide jets (|Δη| <1.1)

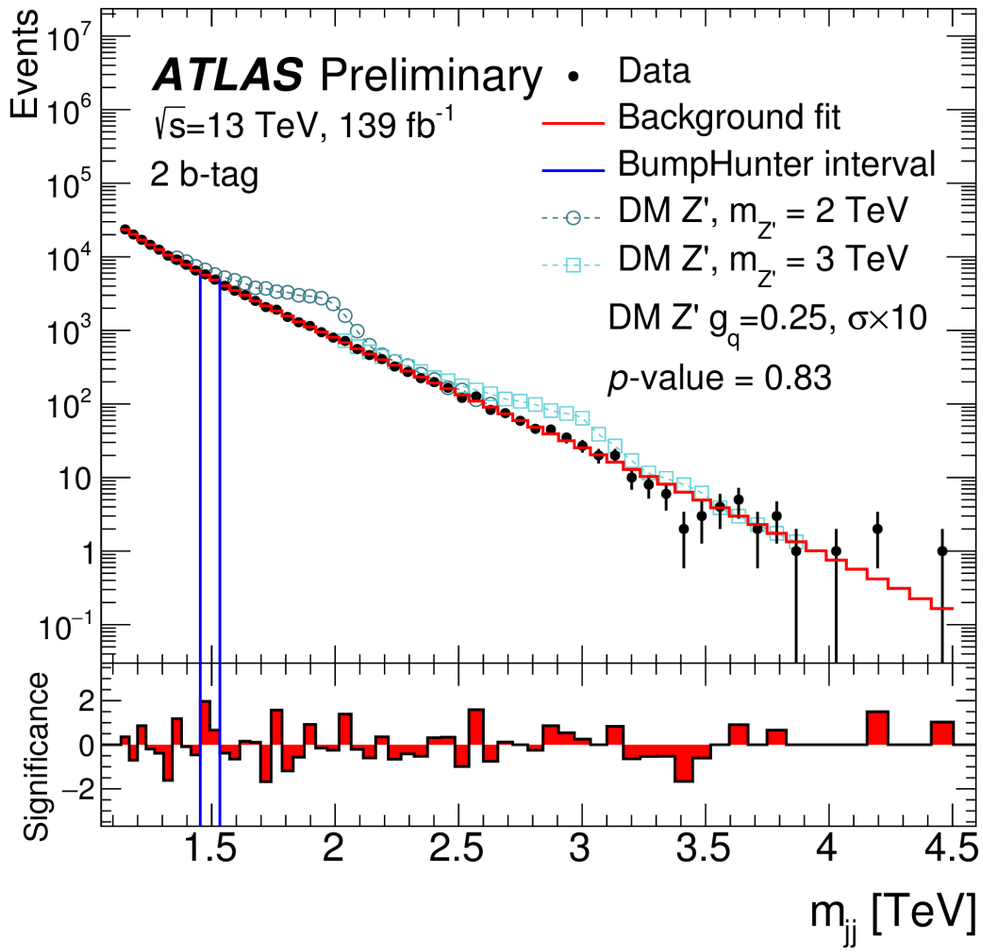
CMS-PAS-EXO-19-012

ATLAS-CONF-2019-007

Dijet resonances



- Exotic particles decaying to dijets excluded with masses up to 6-7 TeV



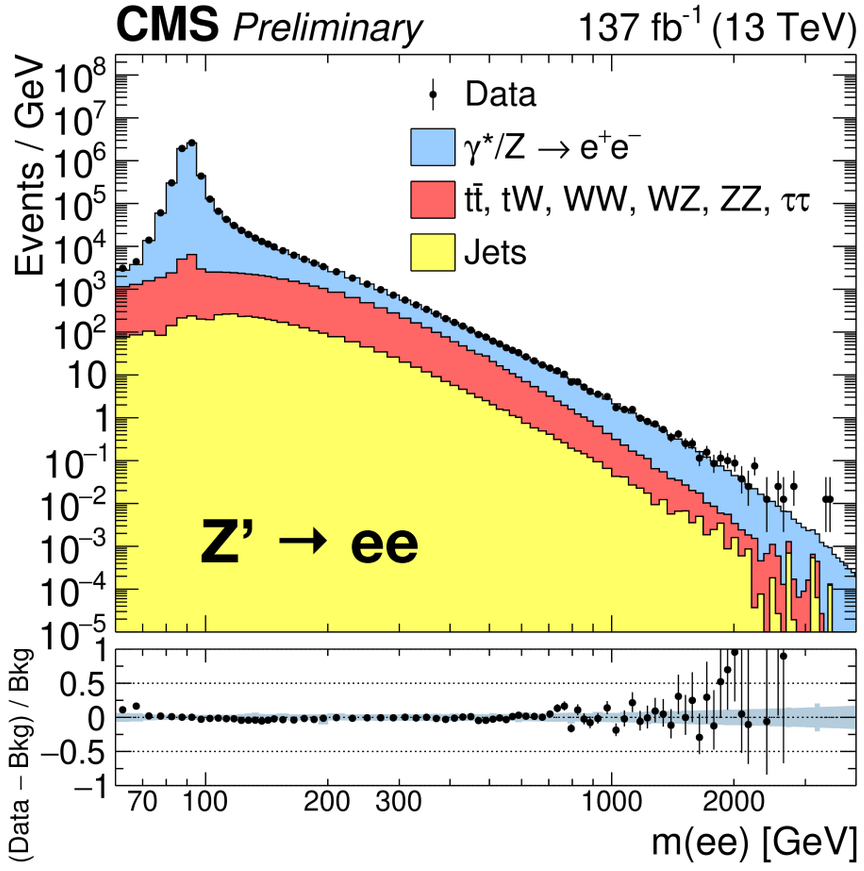
- Recent results from ATLAS with di-bjet resonances!

CMS-PAS-EXO-19-012

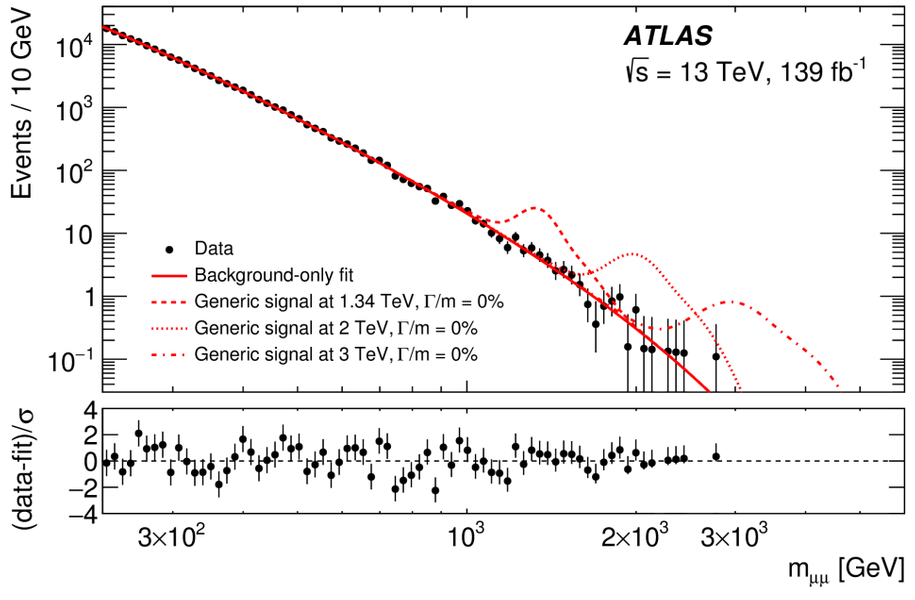
EXOT-2019-03

Dilepton resonances

- Search for bumps in mass spectrum
  - Similar as dijet resonance searches
- Bump in spectrum could be due to Z'
- Z's are motivated in extensions of the SM including
  - Sequential standard model
  - Heavy Vector Triplets
  - Grand Unified Theories
- In these searches, a heavy neutral Z' decays into a pair of leptons ee or μμ
- Resonances are excluded with masses up to 4-5 TeV
  - Interpret in context of spin-0, spin-1 or spin-2 models



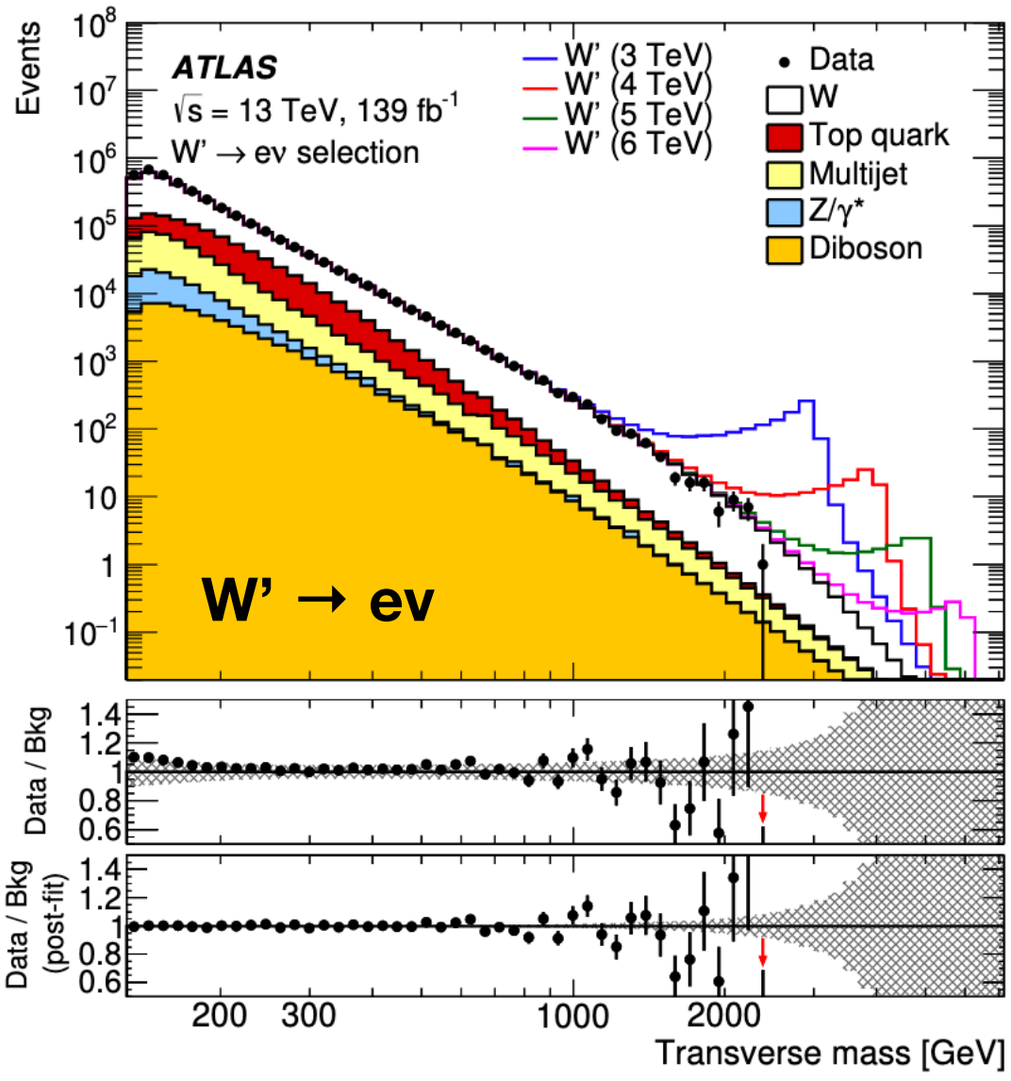
CMS-PAS-EXO-19-019

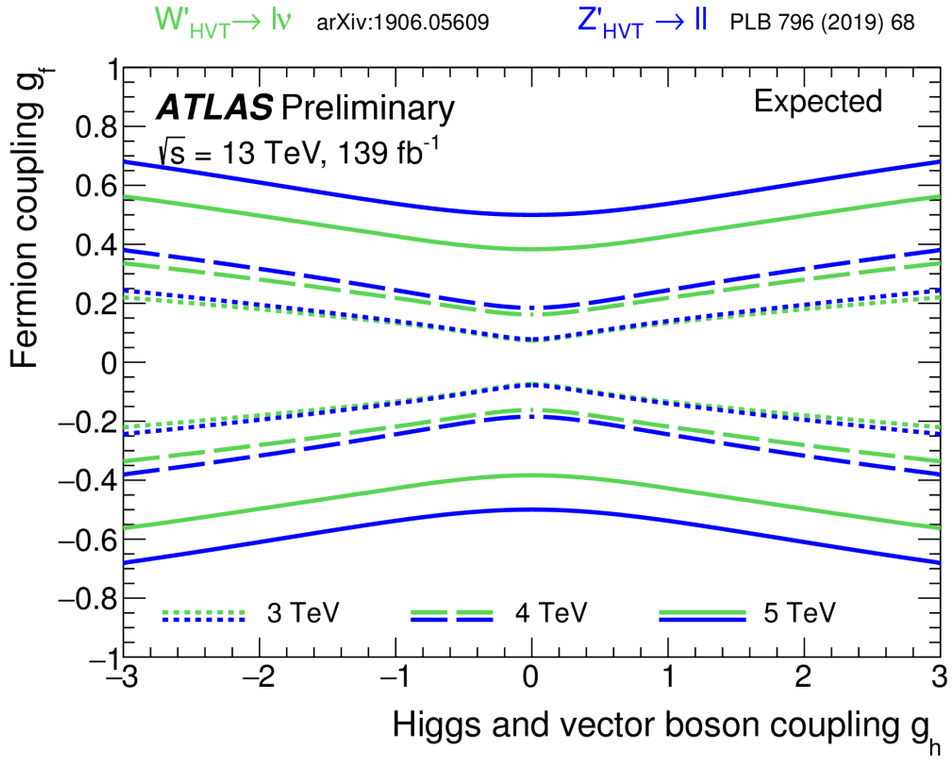


EXOT-2018-08

Heavy Charged W' boson

- In W’ searches we look for bumps in the transverse mass spectrum
  - W’ excluded with mass up to 5.1 and 6 TeV





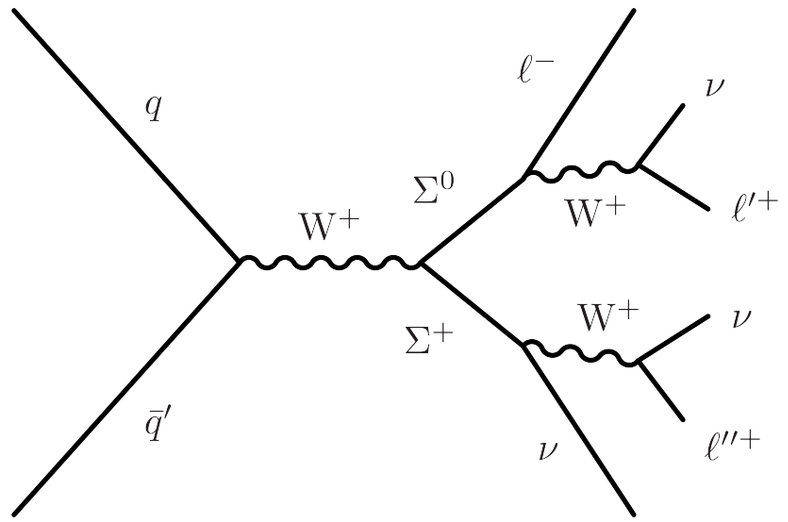
- W’ and Z’ results interpreted as limits on fermion and boson couplings for Heavy Vector Triplet model

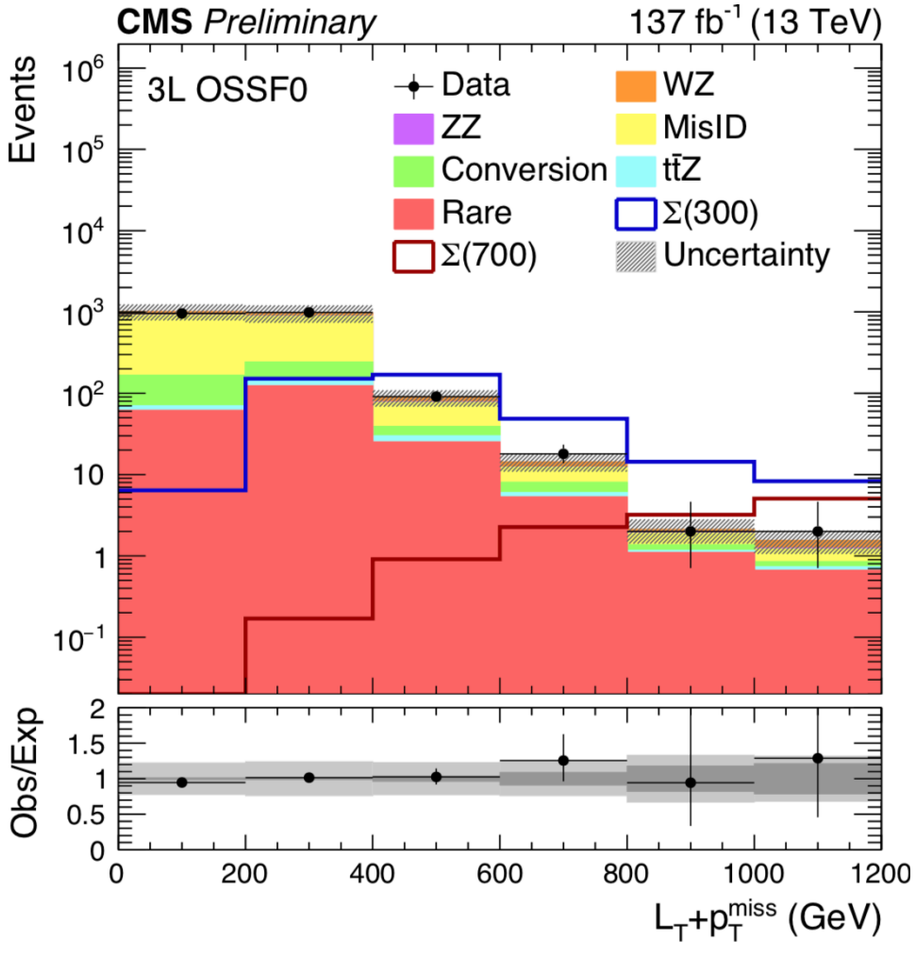
ATLAS-EXOT-2018-030

ATLAS-CONF-2019-001

Heavy exotic fermions

- Other searches probe the origin of neutrino mass
  - Neutrino oscillations
- Certain seesaw models predict neutrino is a Majorana particle
- With much heavier Σ (Σ±, Σ0) particles on the other side of the seesaw
  - Heavy Dirac charged leptons Σ±
  - Heavy Majorana neutral lepton Σ0
- This search looked for Σ±, Σ0 production in multi-lepton events with W bosons
  - Look for excesses in tails of $L_T+p_{T,miss}$ distribution

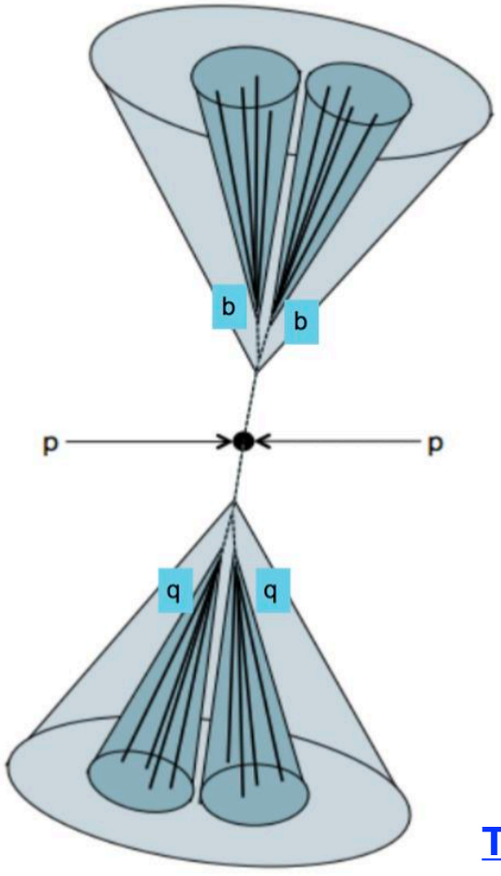




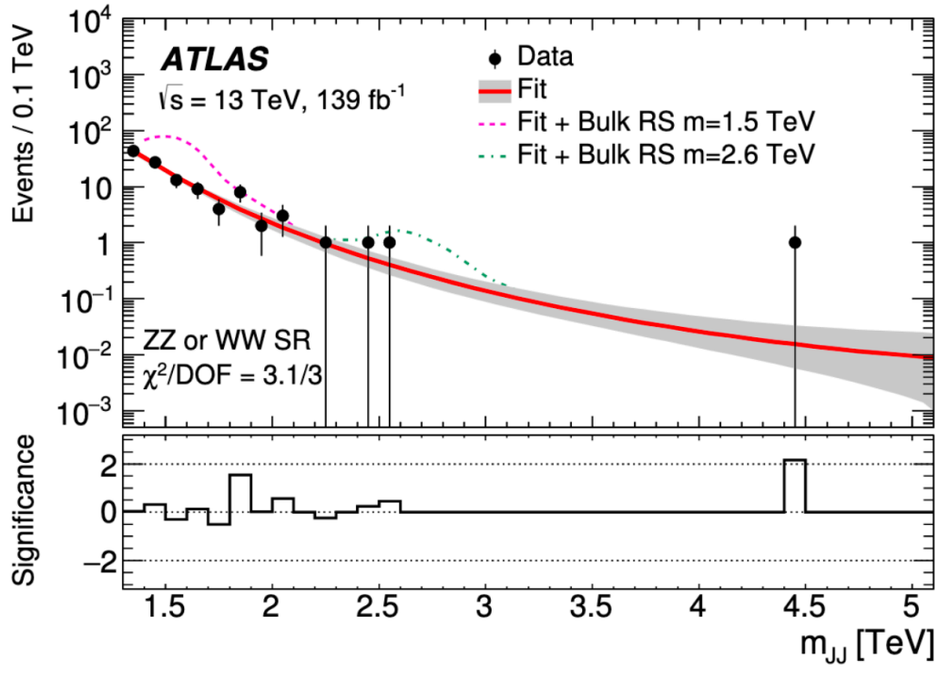
CMS-PAS-EXO-19-002

Resonances to dibosons

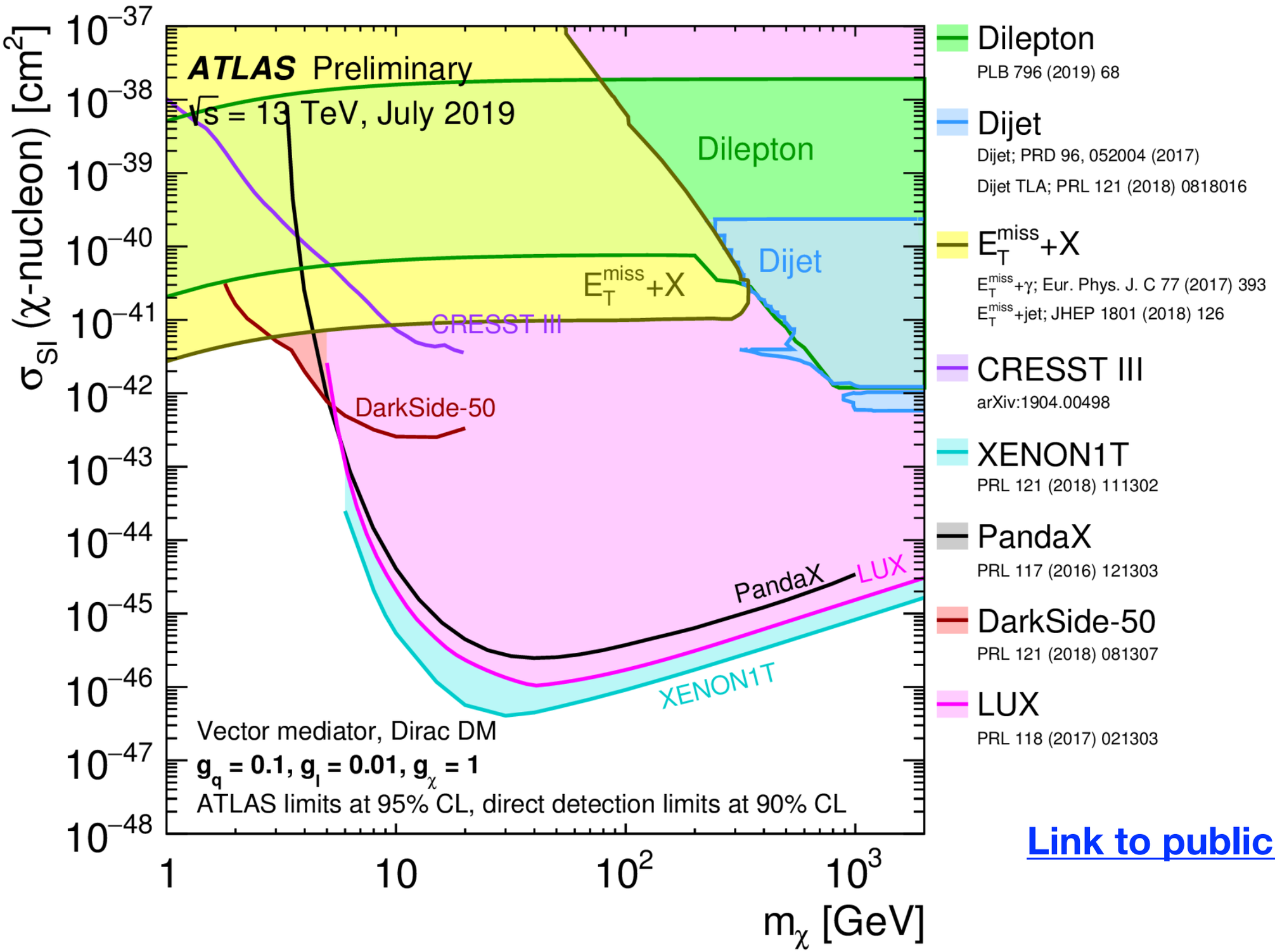
- Heavy exotic objects such as spin-0 radion, spin-1 heavy vector triplet can decay to pairs of V bosons
  - Look for signatures from WW, WZ, ZZ pairs
- This search focusses on boosted Ws or Zs to hadronic final states
  - Energetic, overlapping decay fragments
- Novel techniques in jet finding:
  - Jet substructure algorithms
  - Boosted W/Z boson Id algorithms
- These hadronic searches are most powerful at high mass, where background are reduced and sensitivity is driven by efficiency



Taken from this talk



Exotica and direct DM searches

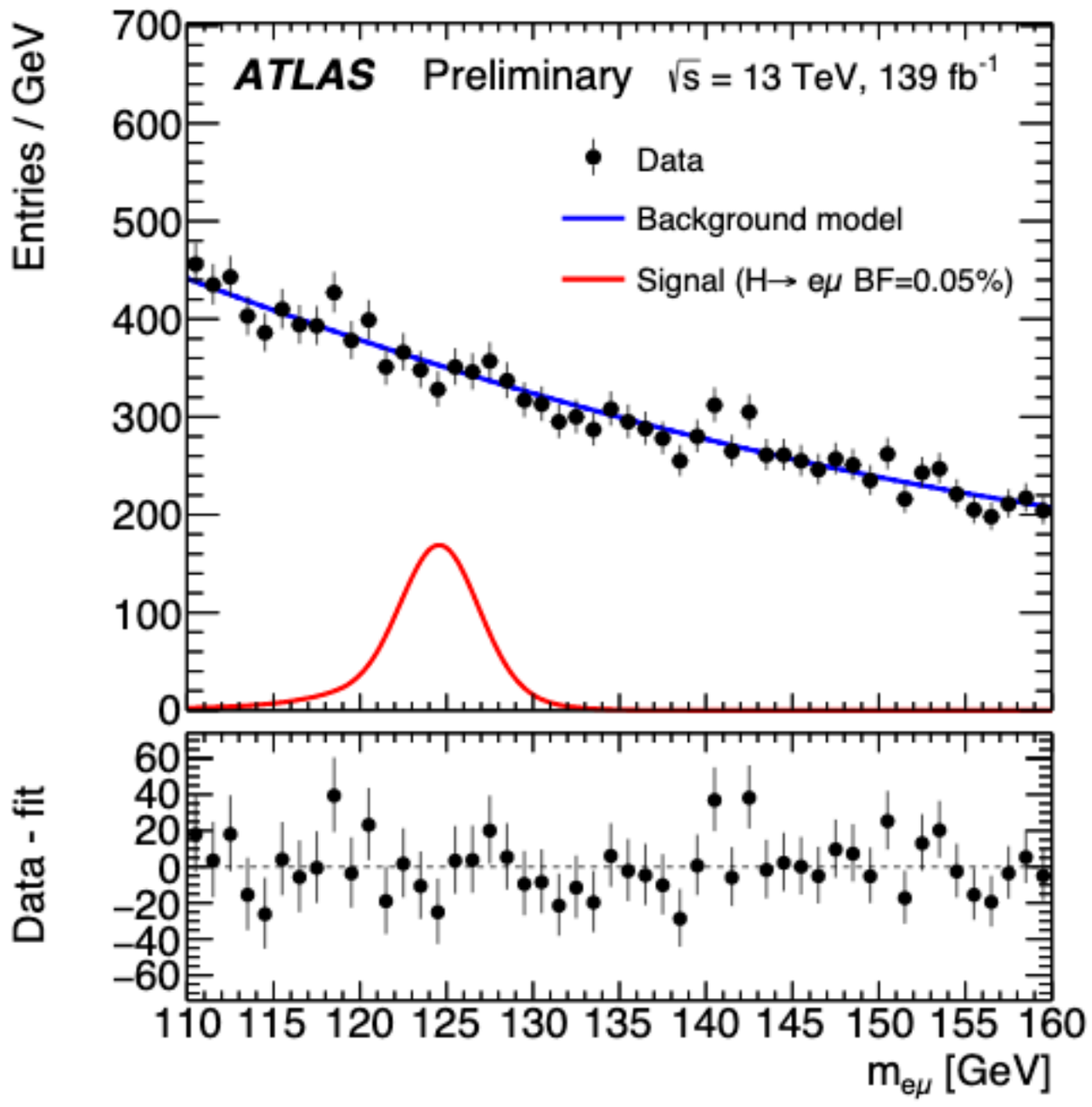


[Link to public page]

BSM Higgs

BSM $h \rightarrow e\mu$

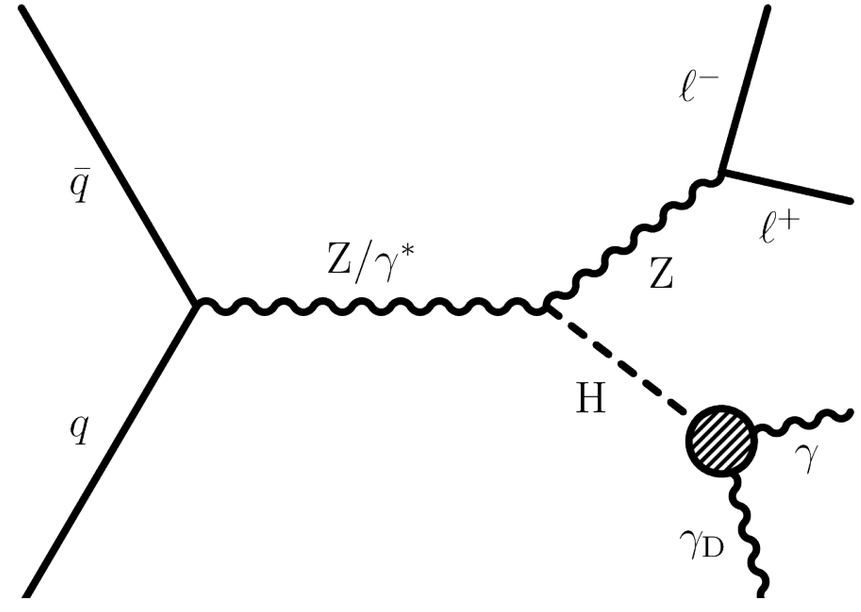
- Search for Lepton flavor violating Higgs decay to $e\mu$
  - Previous best result by CMS using full Run-1
- Higgs production in ggF, VBF, VH
  - Drell-Yan + jets as dominant background
- 95% CL upper limit on branching fraction B(h→eμ) of 6.1×10^{-5}
  - Improvement of factor 5-6 over previous measurements
  - No indication for LFV in Higgs decays

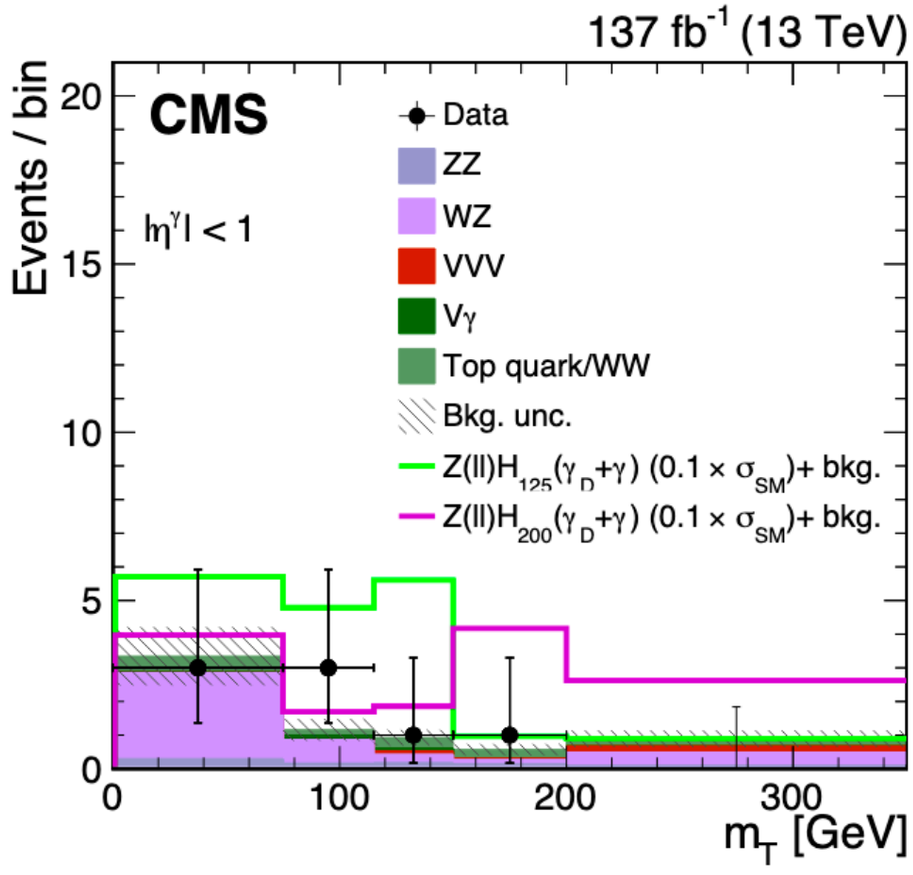


ATLAS-CONF-2019-037

Dark Photons in Higgs decays

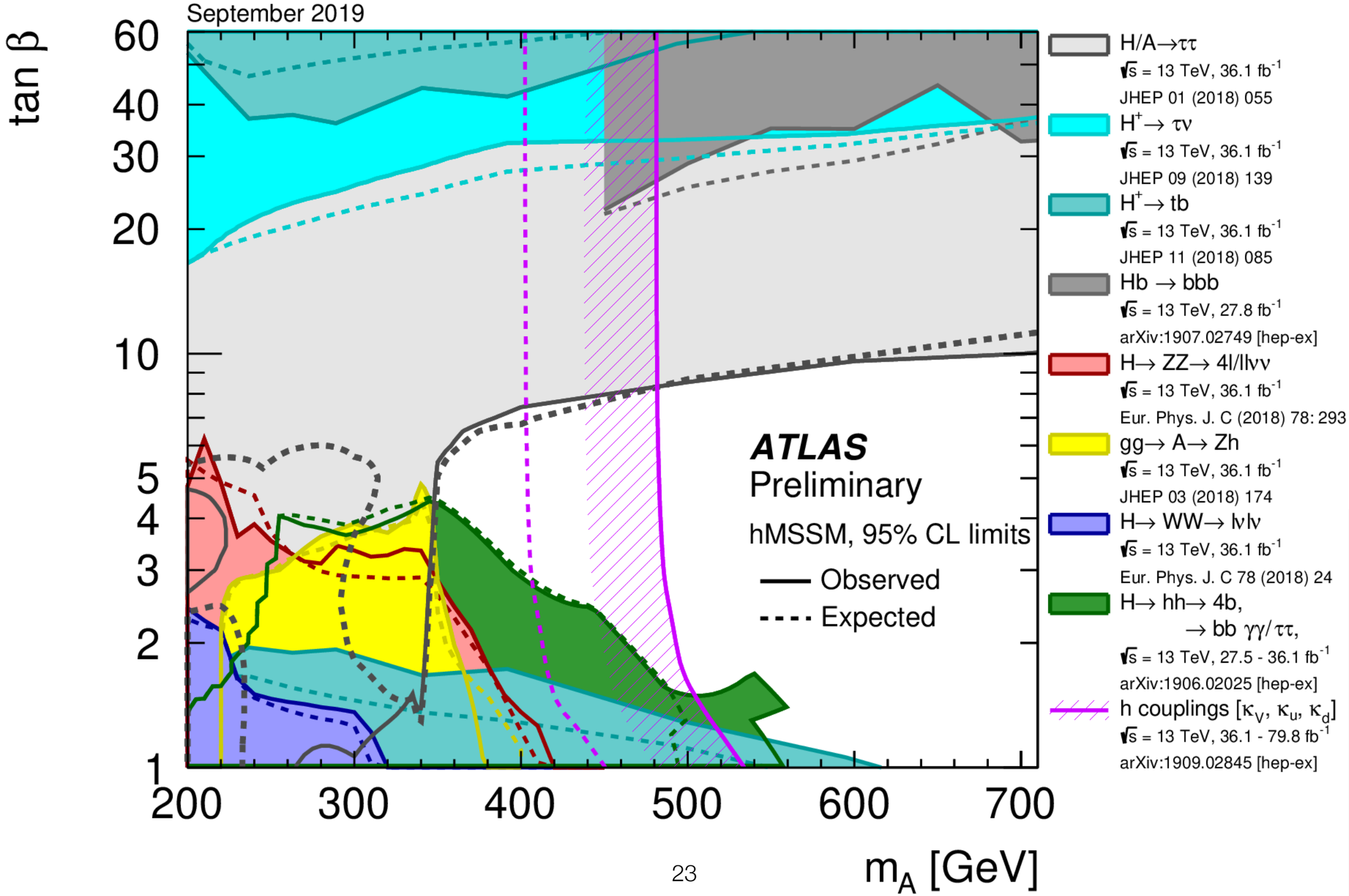
- Searching for exotic particles is another method to probe nature of Higgs
  - Current best limits: B(h →BSM) < 38% (95% CL)
- Dark photons are particularly interesting exotic objects
  - Many BSM extensions, can be long-lived, unusual signatures
- This analysis looks for ZH decays to a photon, dark photon and leptons
  - Dark photon is undetected
  - Very low background
- Upper limit on B(h → invisible + photon) of 4.6%





CMS-EXO-19-007

BSM Higgs interpreted in hMSSM



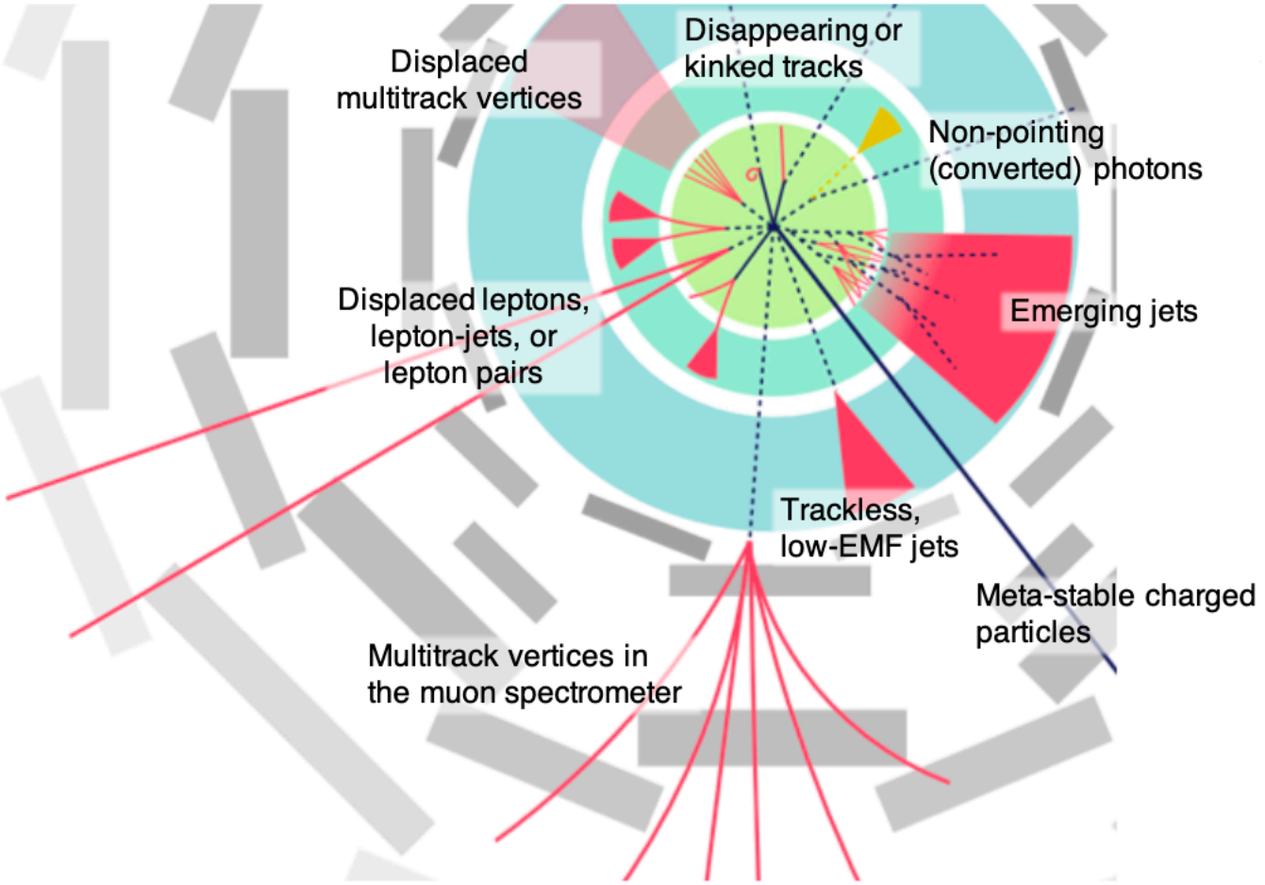
ATL-PHYS-PUB-2019-034

Long-lived Particles

Long-lived particles

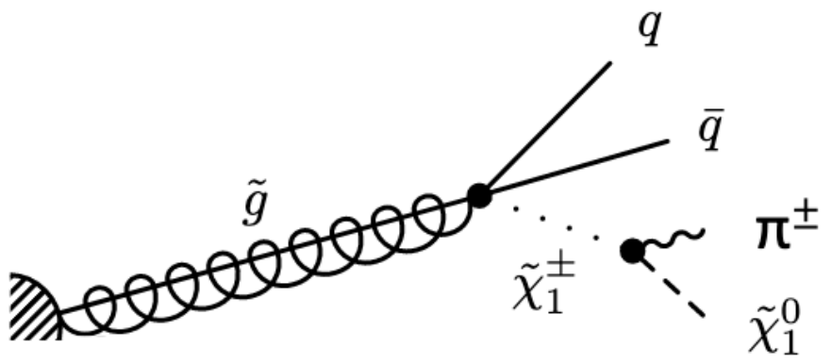
- So far no evidence of prompt BSM physics at the LHC
- Exotic particles could also be produced non-promptly
- Growing effort in ATLAS & CMS to search for long-lived particles

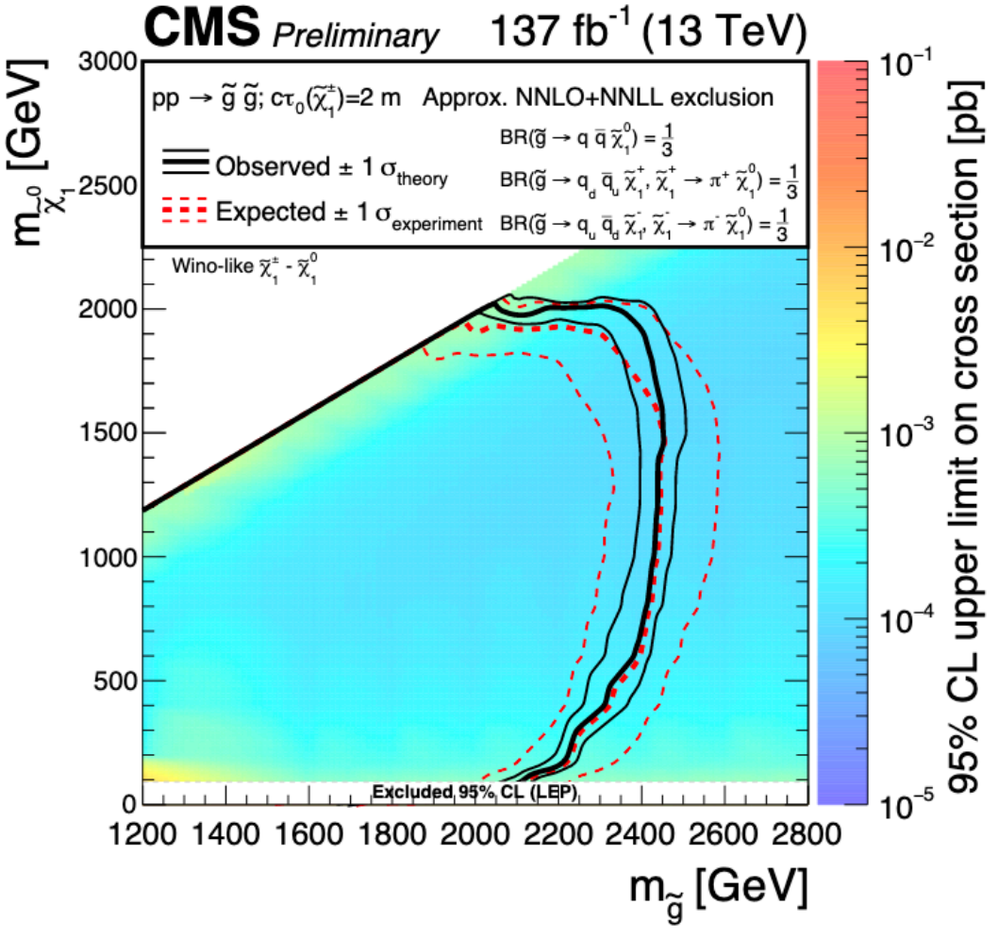
- Unconventional detector signature from LLP can be a handle to reduce background
- Searches typically use new algorithms in trigger and offline analysis



Disappearing tracks

- A recent result is a SUSY search for long-lived particles $\chi^{\pm 1}$
  - $\chi^{\pm 1}$ decays to pion (disappearing track) and a neutralino
- Presence of disappearing track is used to suppress the SM background
- Lower limits on gluino mass as high as 2460 GeV for $c\tau_0(\chi^{\pm 1})$=10 cm
  - Weaker mass limits for longer-lived charginos

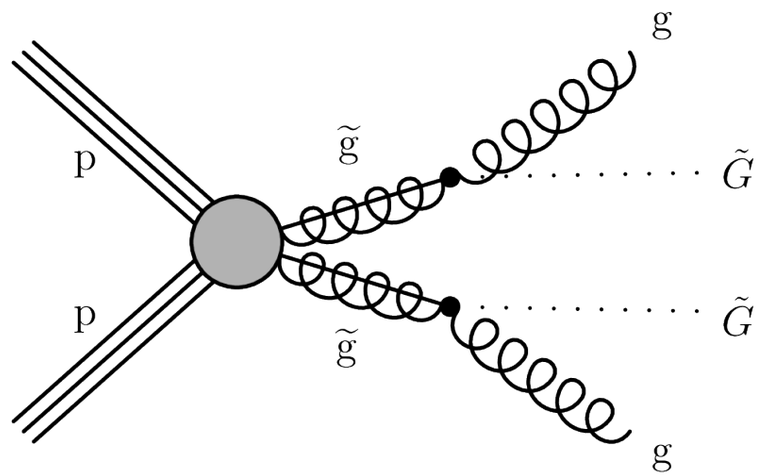


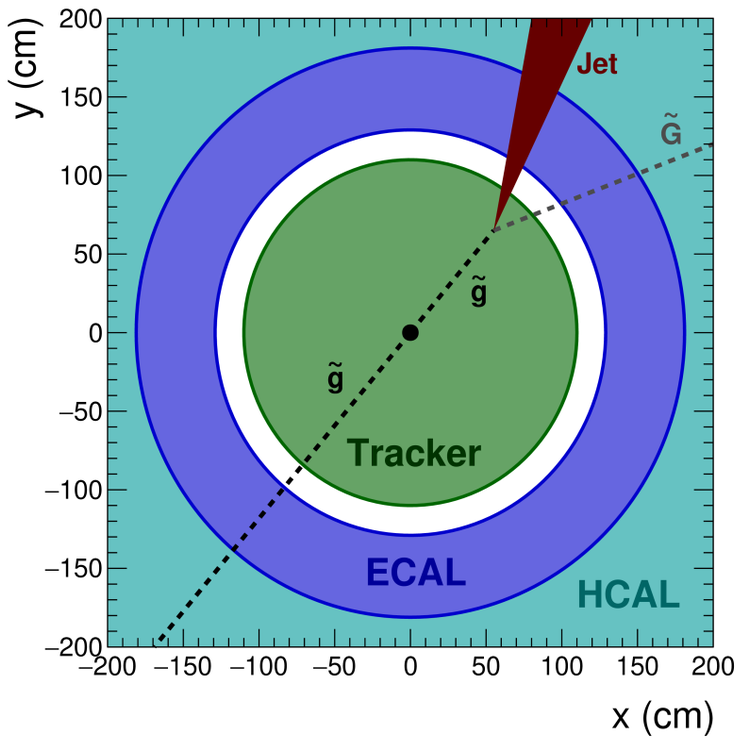


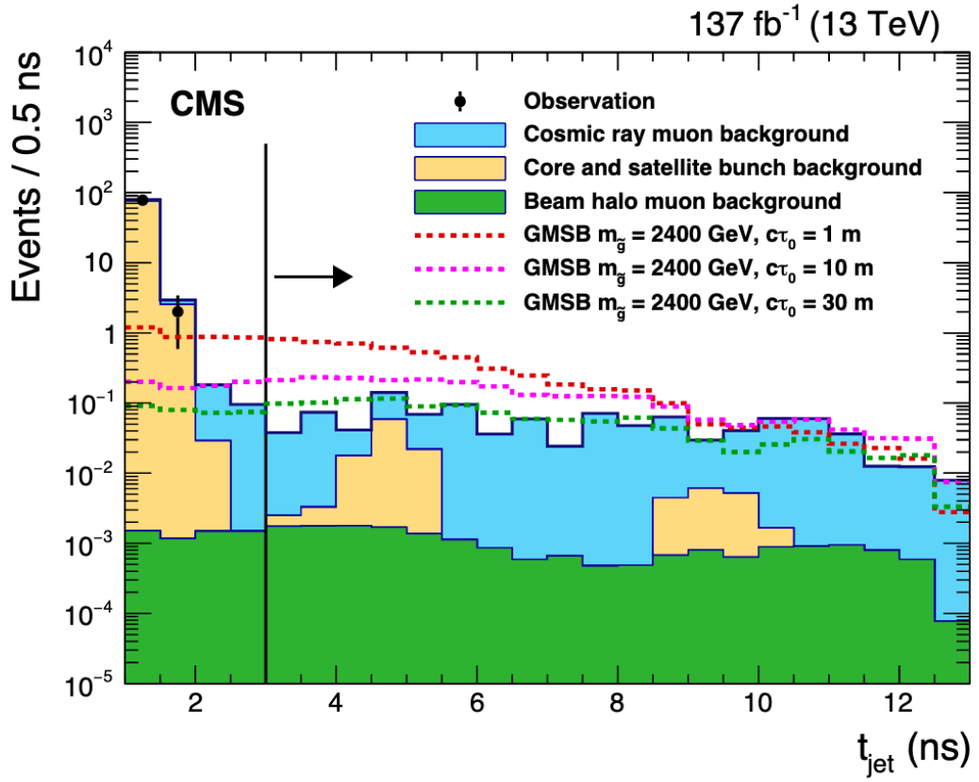
CMS-PAS-SUS-19-005

Delayed jets

- One can also search for jets outside outside the tracker volume
  - Delayed (displaced) jets
- This search: pair production of long-lived gluinos that each decay to a gluon and a gravitino
  - Gluon forms delayed jet
  - Gravitino escapes detection (missing energy)
- Use jet timing in calorimeter to suppress SM background



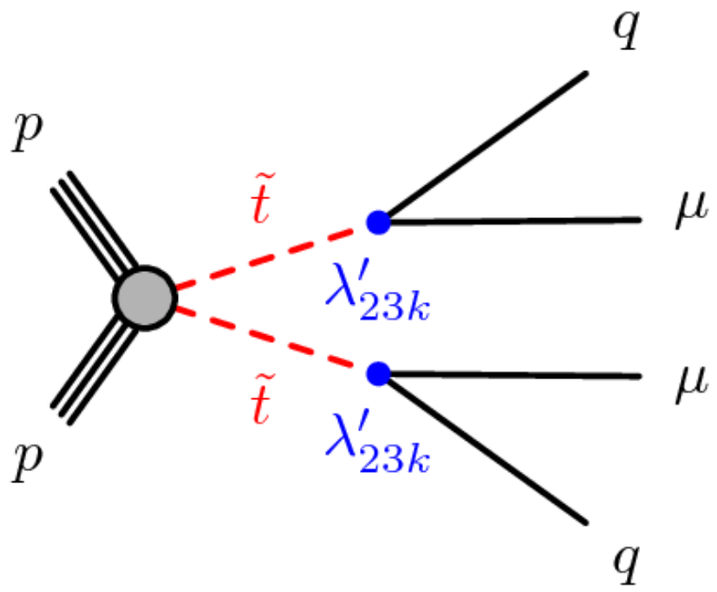




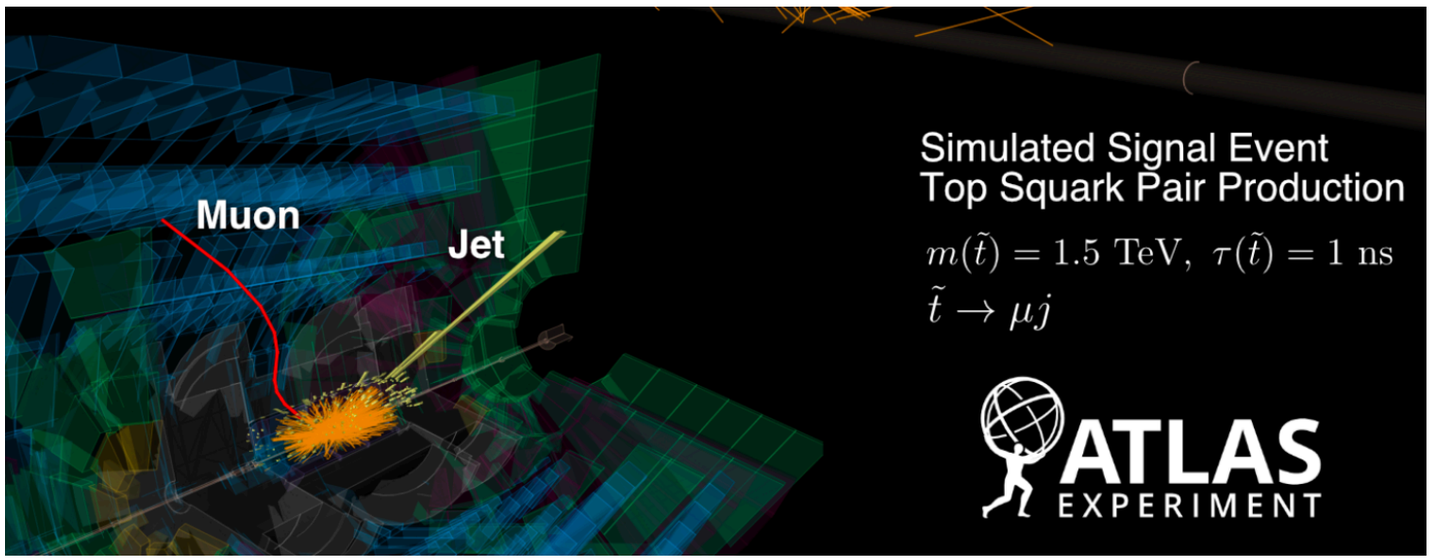
CMS-PAS-EXO-19-001

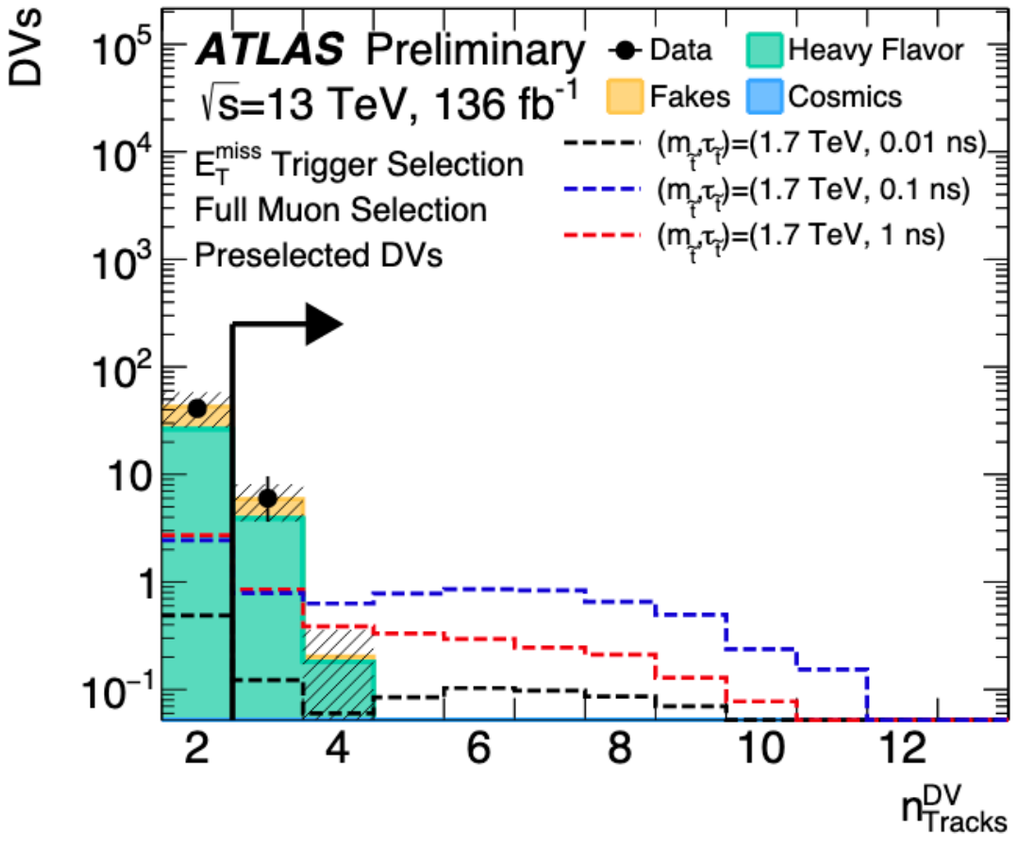
Long-lived stops

- ATLAS is also searching for LLP signatures,
- In this search a long-lived stop quarks decays in R-parity violating models
  - Two quarks form displaced jets
  - Two displaced muons
- Unusual signature with near-zero SM background
- Key variable in this analysis is number of tracks with displaced vertices

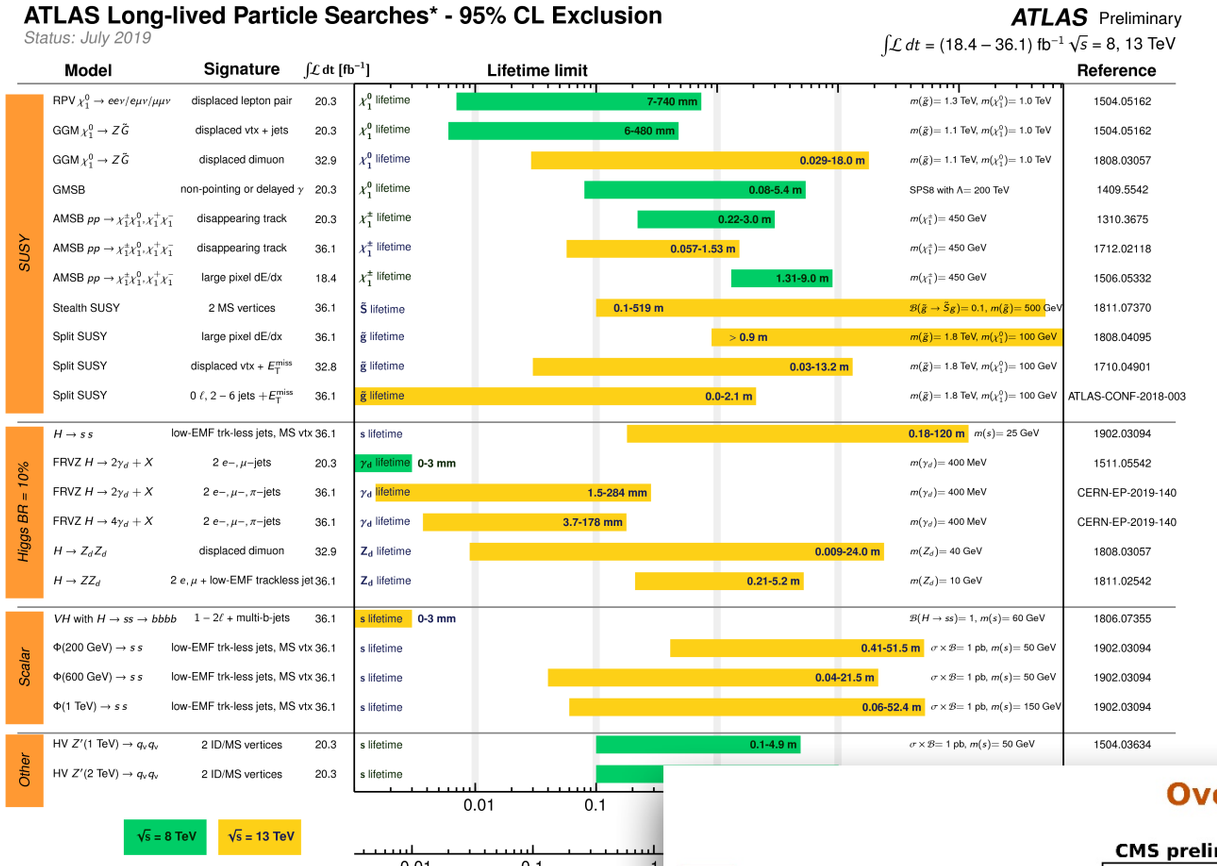


ATLAS-CONF-2019-006

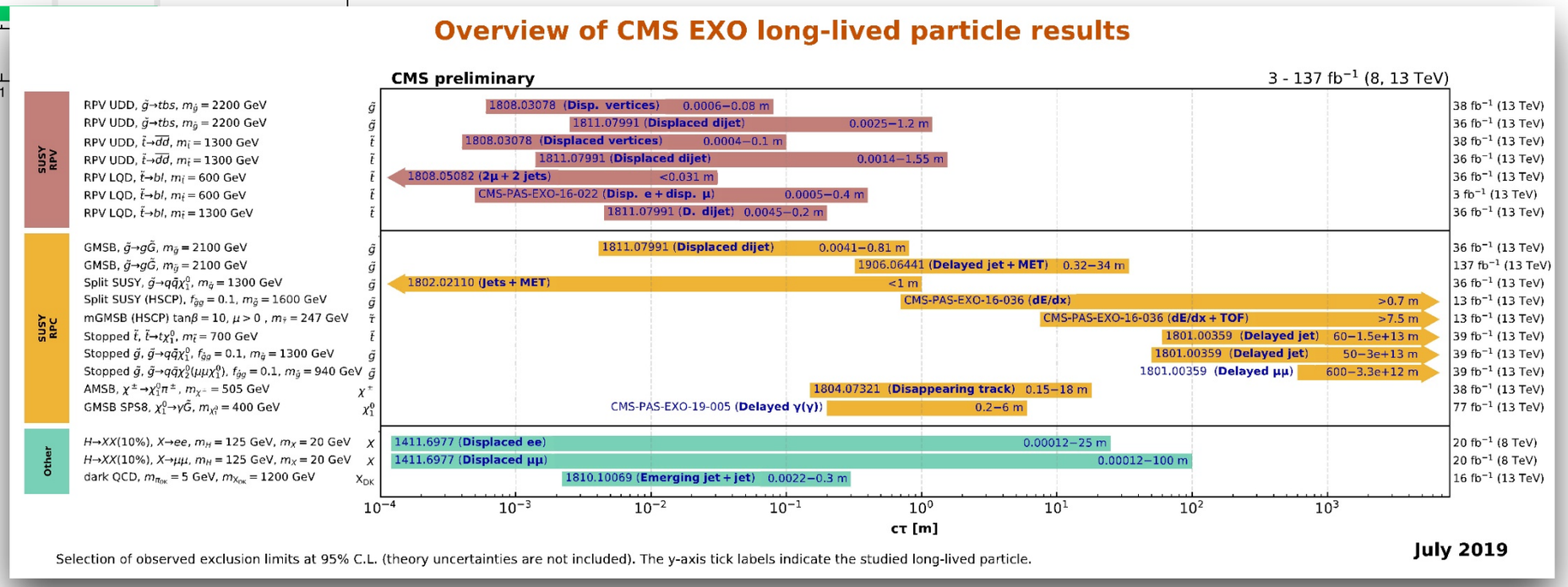




More long-lived results



*Only a selection of the available lifetime limits is shown.



Run-3

Towards Run-3

- Run-3 will provide an additional 150 fb^{-1} of data!
- Potential for discovery in the years to come
- In the mean time, detectors are being upgraded and prepared for commissioning
  - New Small Wheel for ATLAS; GE1/1 for CMS

New Small Wheel

New GE1/1 chambers

Summary

- Impressive set of results from ATLAS and CMS on full and partial Run-2 data sets in new physics searches
- No significant deviations from the standard model expectations
- Run-3 will bring new discovery potential by doubling the amount of data to 300 fb^{-1}

Thank you!

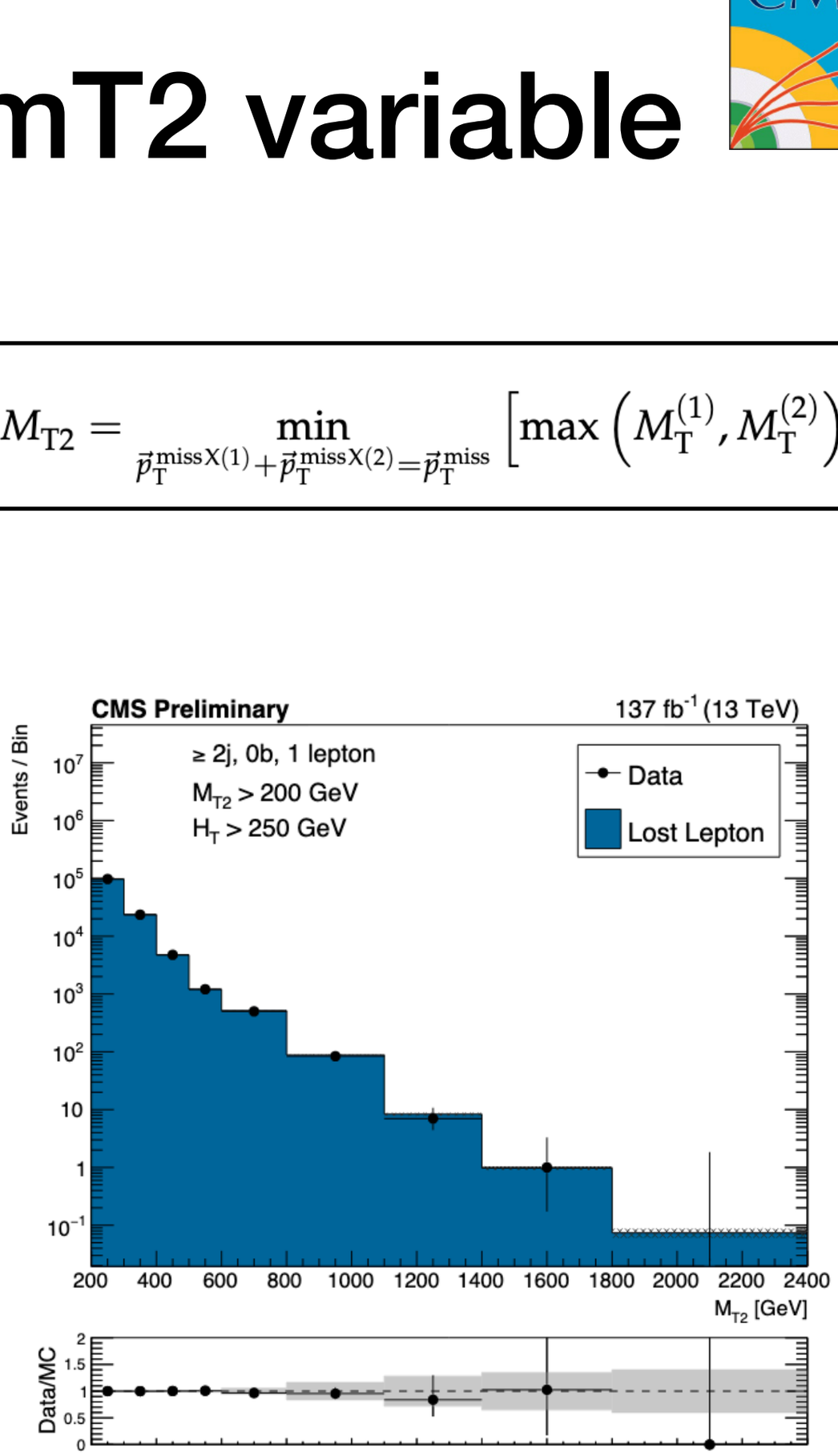
Backup

SUSY with the mT2 variable

- A new CMS analysis uses the mT2 variable in an inclusive search with multiple jets and MET

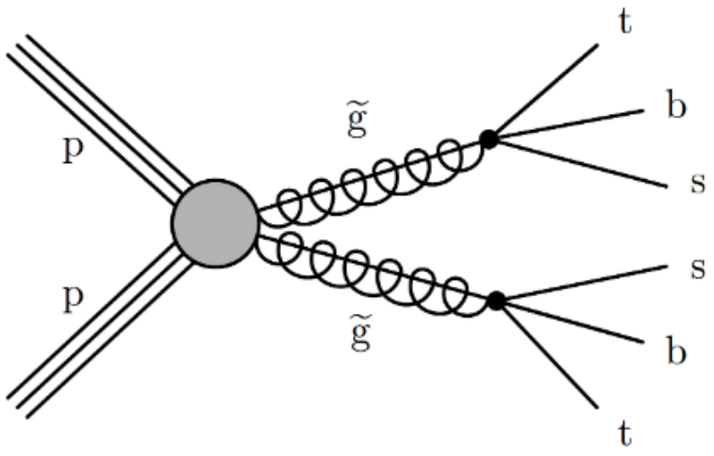
$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss,X(1)}} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss,X(2)}} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right]$$

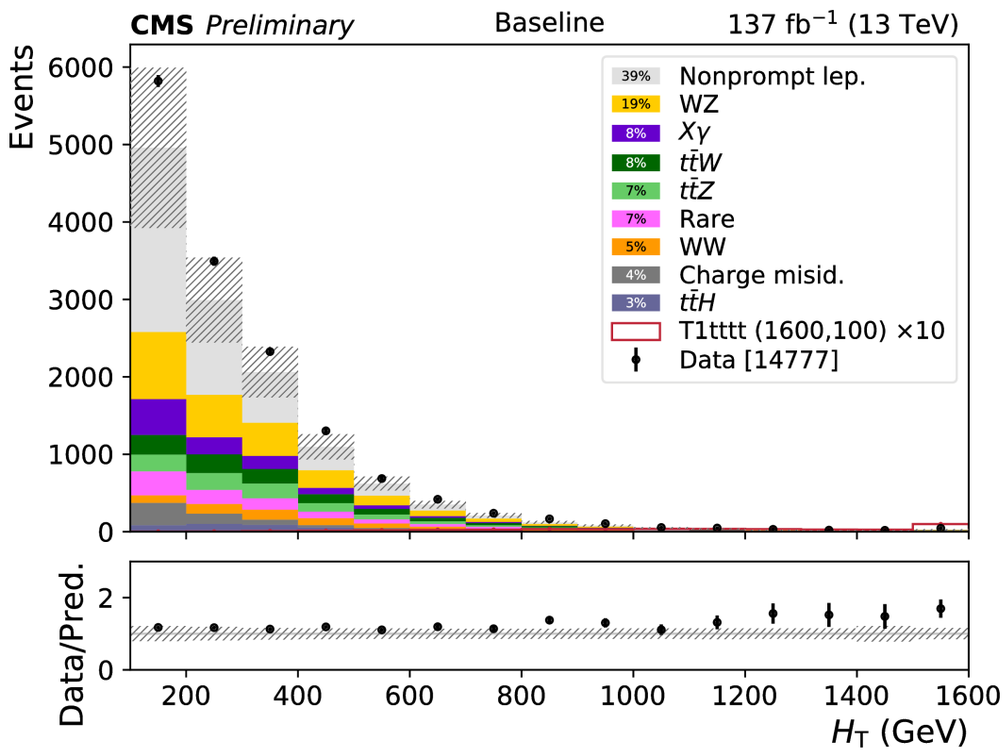
- mT2 variable to suppress SM background
  - Major background is Z to pair of neutrinos + jets
- Interpretation done in the context of R-parity conserving SUSY
  - Limits on gluino masses up to 2250 GeV, and neutralino masses up to 1525 GeV
    - ✓ Although, these are optimistic scenarios…
  - Limits on light flavor squarks, sbottoms and stops up to 1770, 1260, and 1225 GeV



CMS-PAS-SUS-19-005

…or 2 same sign leptons

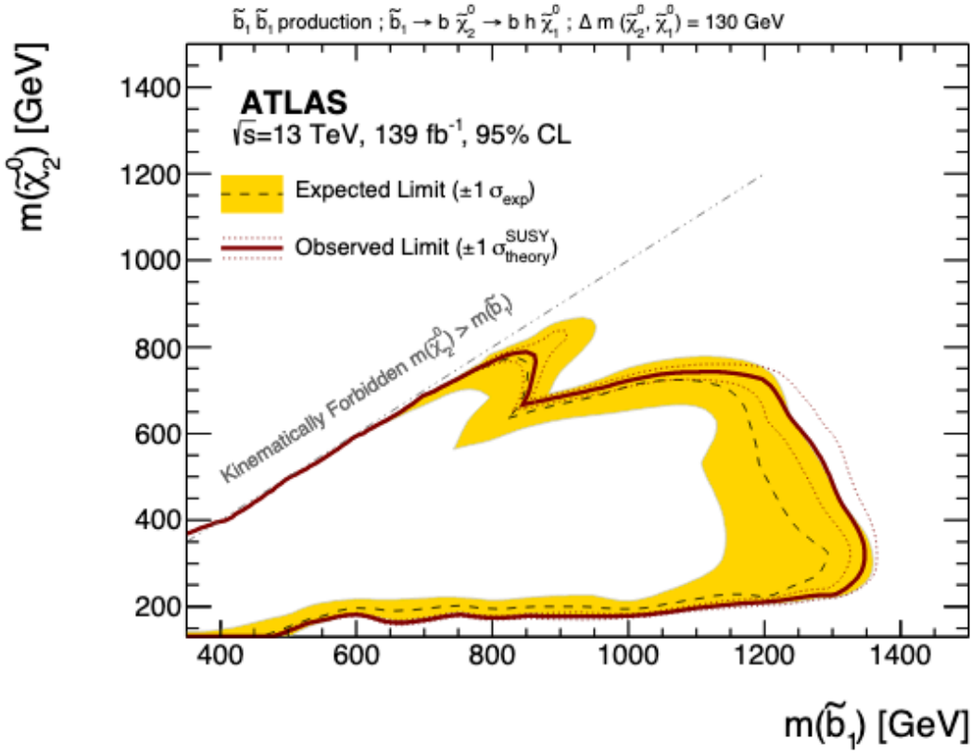




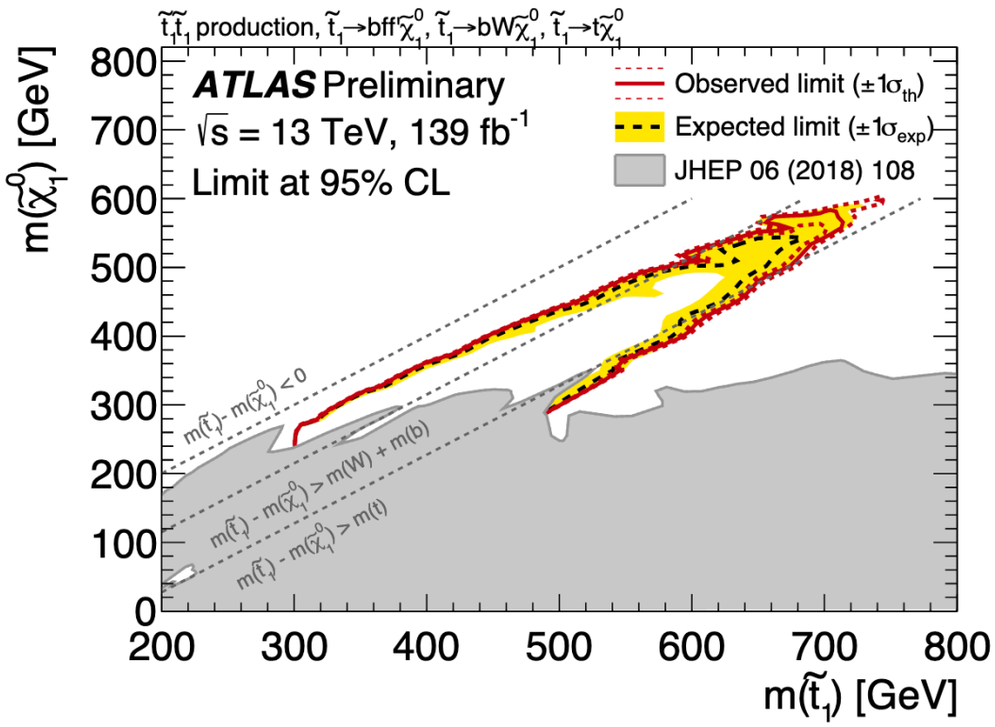
- We are also searching for SUSY with 2 same sign leptons
- Identification of b-jets using **DNNs**
- We find a good agreement between the data and the SM prediction
- Interpretation in SUSY conserving or violating R-parity models
- Lower mass limits up to
  - 2.1 TeV for gluinos
  - 0.9 TeV for top and bottom squarks

CMS-PAS-SUS-19-008

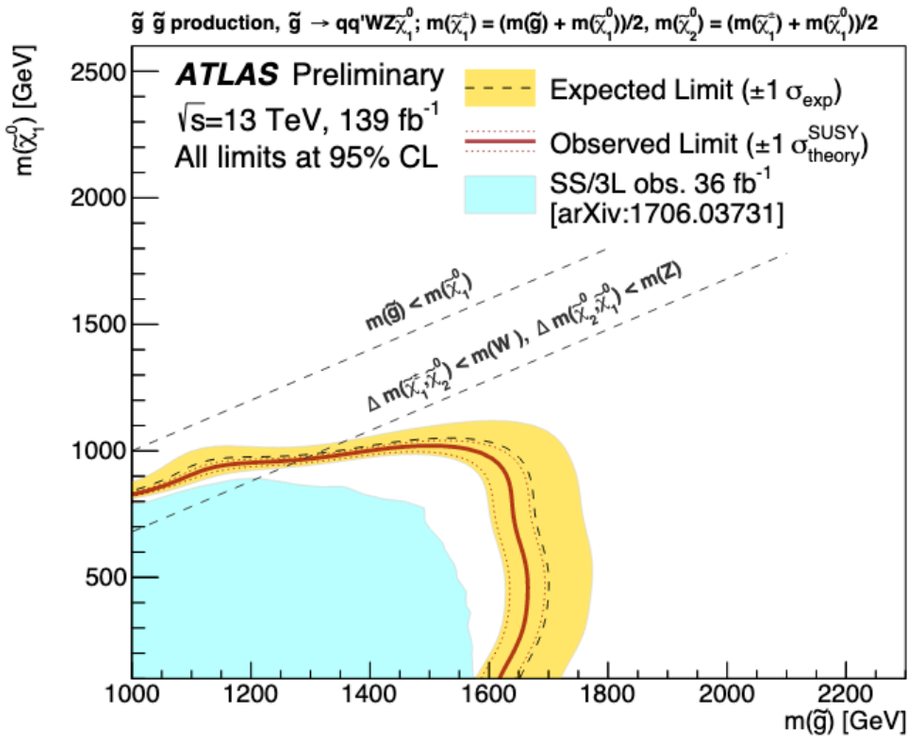
More SUSY results



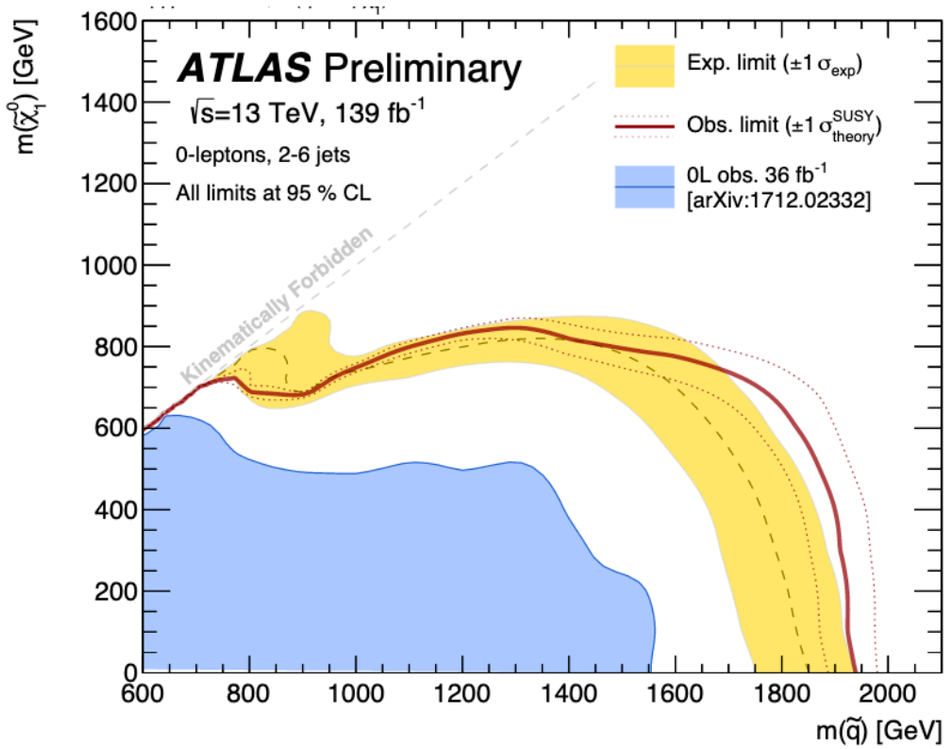
ATLAS-SUSY-2018-031



ATLAS-CONF-2019-017



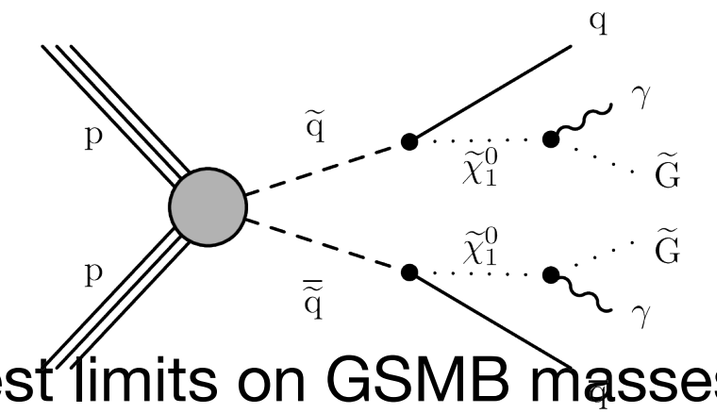
ATLAS-CONF-2019-015



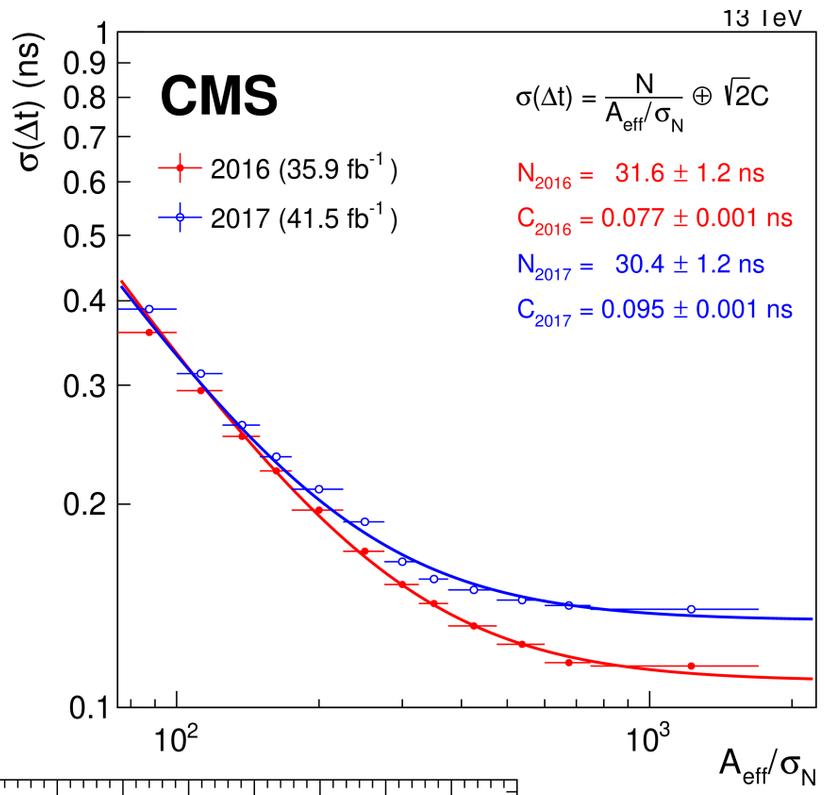
ATLAS-CONF-2019-040

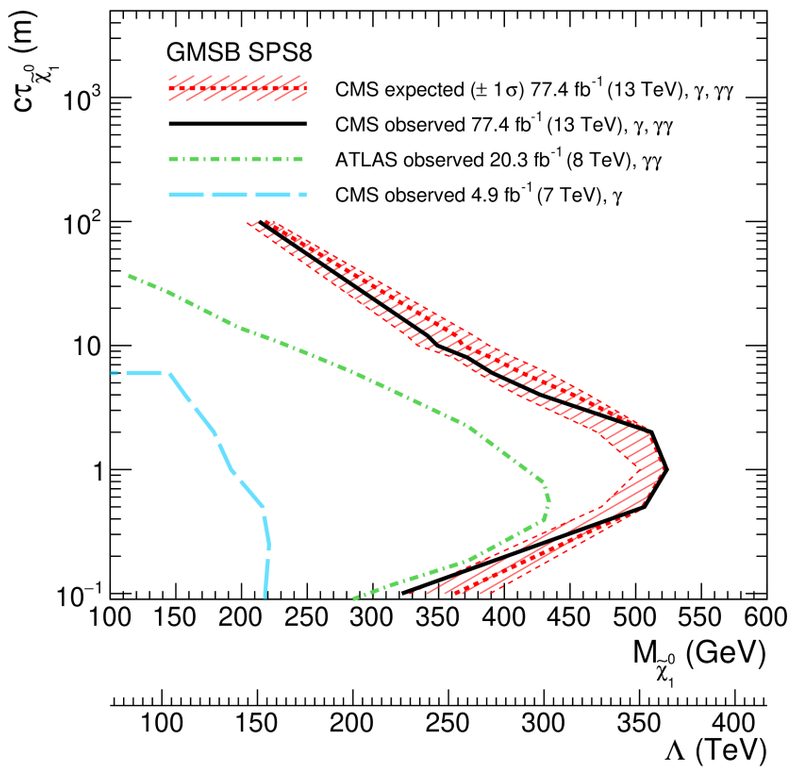
Delayed photons

- Searches have also been carried out for long-lived neutralinos that decay to photons
  - ECAL sees delayed photons
- Several models can produce long-lived neutralinos
  - GSMB
  - Neutralino decays to gravitino and photon



- Best limits on GSMB masses improved with 100 GeV





CMS-EXO-19-005