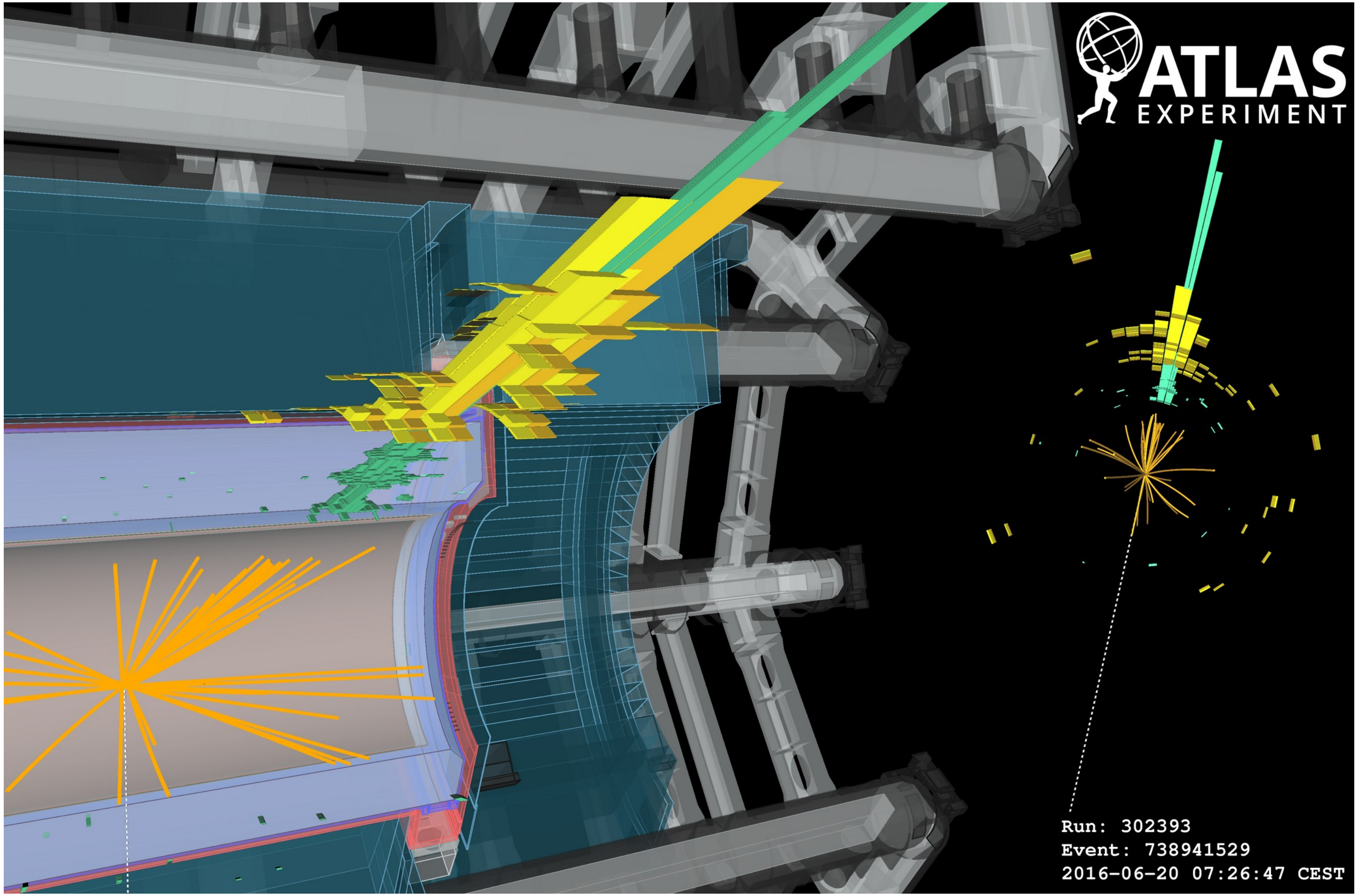
Searches for BSM physics at the LHC: Where do we stand, where will we go?



Klaus Mönig
on behalf of the ATLAS and CMS Collaborations

Introduction

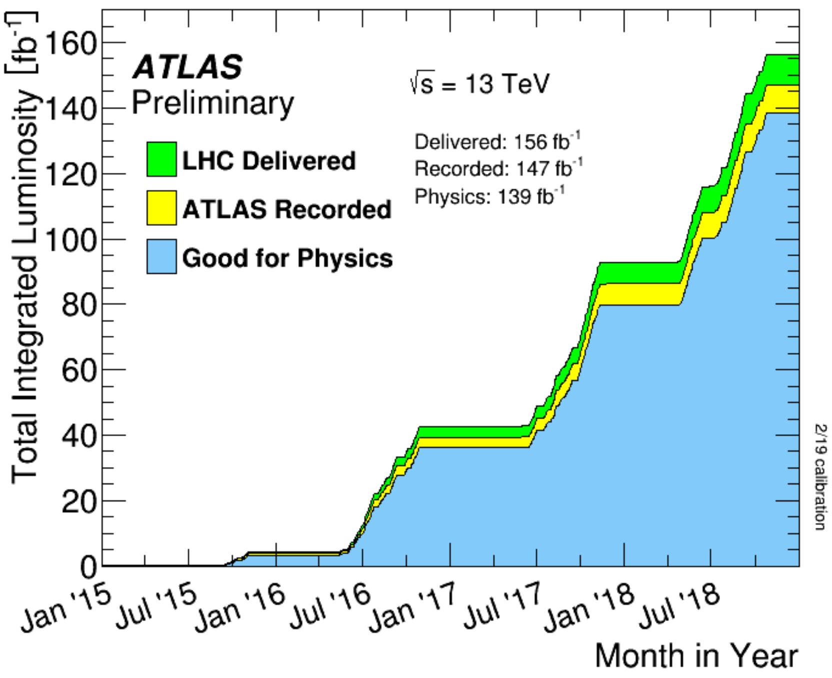
- The Standard Model describes (almost) all particle physics measurements with high precision
- However there are several reasons to believe that there must be more:
  - astrophysics gives overwhelming evidence for dark matter
  - we don't understand why there is only matter in the universe
  - we don't understand why the Higgs is so much lighter than the scale of gravity (Hierarchy problem)
  - the Standard Model is complex with many free parameters
  - why are neutrino masses so low but not 0?
- Many possible answers to these questions require new physics at the TeV scale
- In addition some anomalies have shown up in the recent years
  - lepton flavour non-universality in b decays
  - g-2 of the muon (although beware of hadronic vacuum polarisation!)
  - m_W (be careful: CdF measurement is inconsistent with LHC & D0)
- These anomalies can be explained by new physics required to solve the open questions
- They can also be tested by searches at the LHC

Searches at the LHC

- In the recent years LHC has preformed many searches with typical limits:
  - 4-5 TeV for s-channel resonances
  - 1-2 TeV for pairs of strongly interacting particles
  - few 100 GeV for pairs of weakly interacting particles
- These limits strongly constrain the parameter space of the models
- Especially if the models were meant as a solution to the hierarchy problem they start to be under tension
- In this talk I will concentrate on recent results in a few key areas:
  - Supersymmetry: Most complete theory to solve the open problems
  - Dark matter/dark sector
    - dark matter: very active field with many possibilities
    - dark sector: small couplings and unconventional experimental signatures
  - Leptoquarks: most popular explanation of the B anomalies
  - Heavy neutral leptons: explanation of neutrino masses and properties

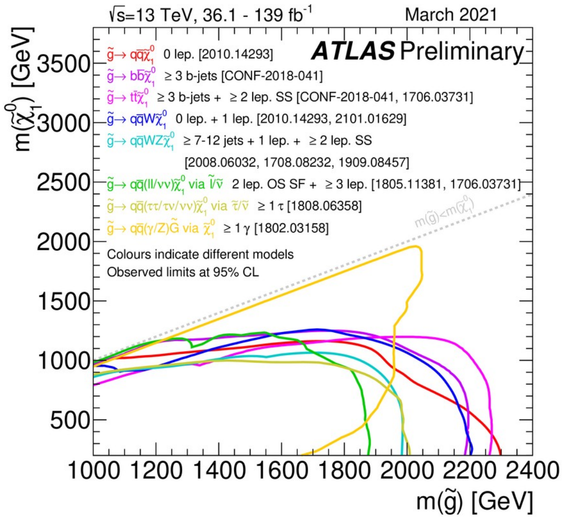
LHC datasets

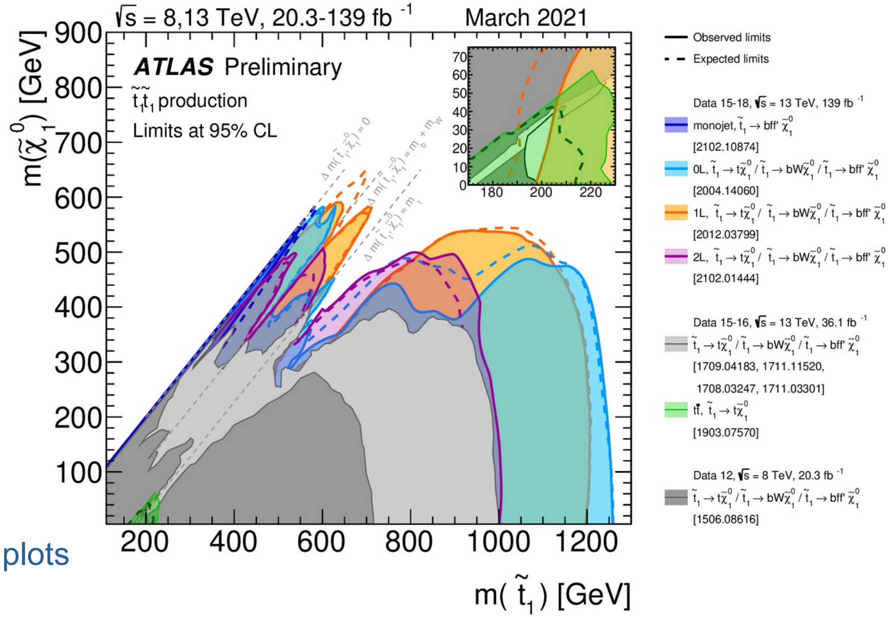
- In run 1 the experiments have recorded 5 fb^{-1} at $\sqrt{s}$=7 TeV and 20 fb^{-1} at $\sqrt{s}$=8 TeV each, the results are almost completely superseded by run 2
- The run 2 dataset is ≈140 fb^{-1} each at $\sqrt{s}$=13 TeV, which is still being analysed
- Future datasets:
  - Run 3 is starting, expect ~200 fb^{-1}/experiment at $\sqrt{s}$=13.6 TeV in 2022 to 2025
  - Long-term future:
    - ~3 ab^{-1}/experiment in 2029-2040, hopefully at $\sqrt{s}$=14 TeV
    - exact end and correspondingly the luminosity depends on the CERN future program



Supersymmetry searches

- Supersymmetry is the only complete theory beyond the SM that has the potential to solve most of the open problems
  - SUSY solves the hierarchy problem if SUSY masses (especially the top-partners) are not too heavy
  - SUSY has a natural dark matter candidate, the lightest supersymmetric particle (LSP)
  - Loops with SUSY particles can explain the anomalies, especially g-2 (and m_W)
- Gluinos can be excluded up to 2 TeV depending on the model, further progress will be slow because of the strongly falling PDFs
- The stop, that plays the main role in the hierarchy problem, is excluded up to 1.2 TeV for a not too heavy LSP

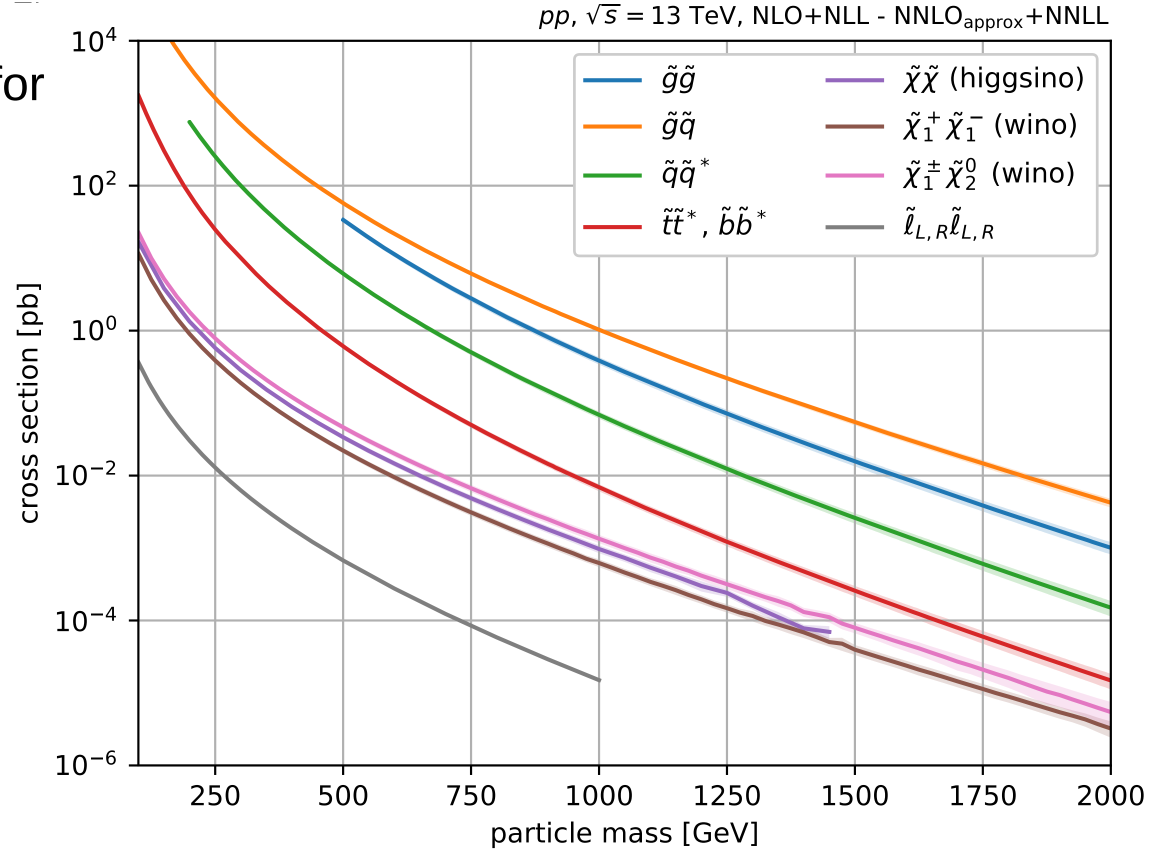




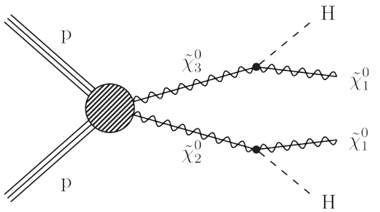
ATLAS SUSY summary plots

Searches for weakly interacting SUSY particles

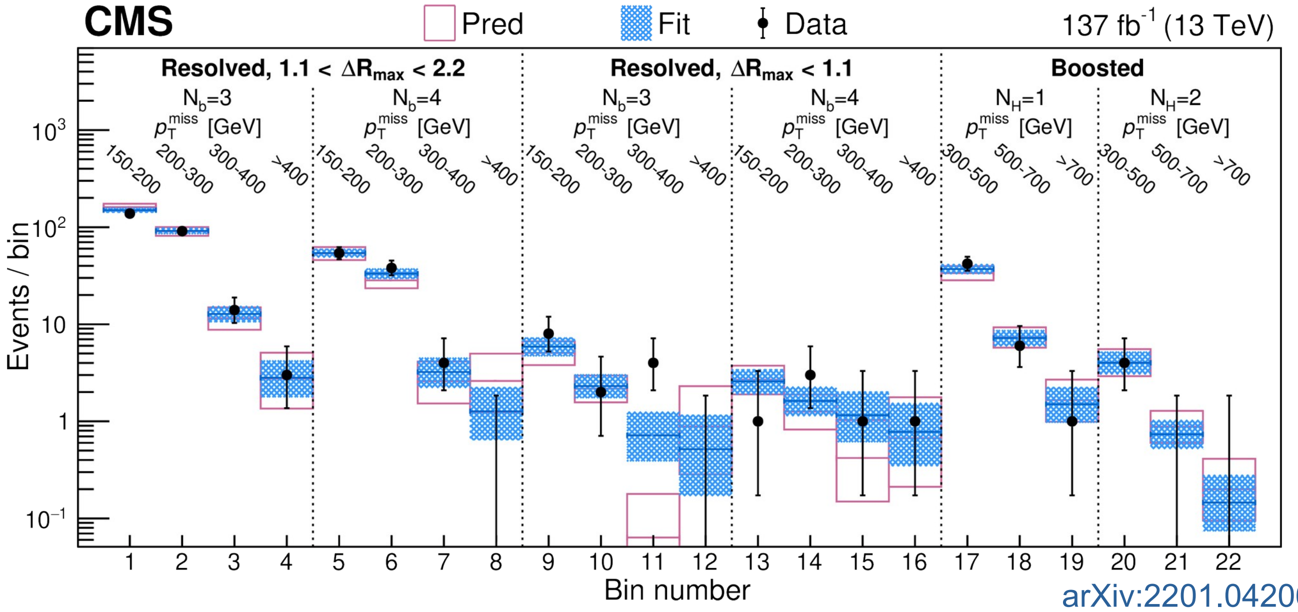
- The cross sections for weakly interacting SUSY particles are much smaller ⇒ can profit more from an increased luminosity
- For the explanation of the anomalies the weakly interacting particles with lower mass are more relevant
- Recent searches have been performed for sleptons decaying into leptons or for neutralinos decaying into Higgses



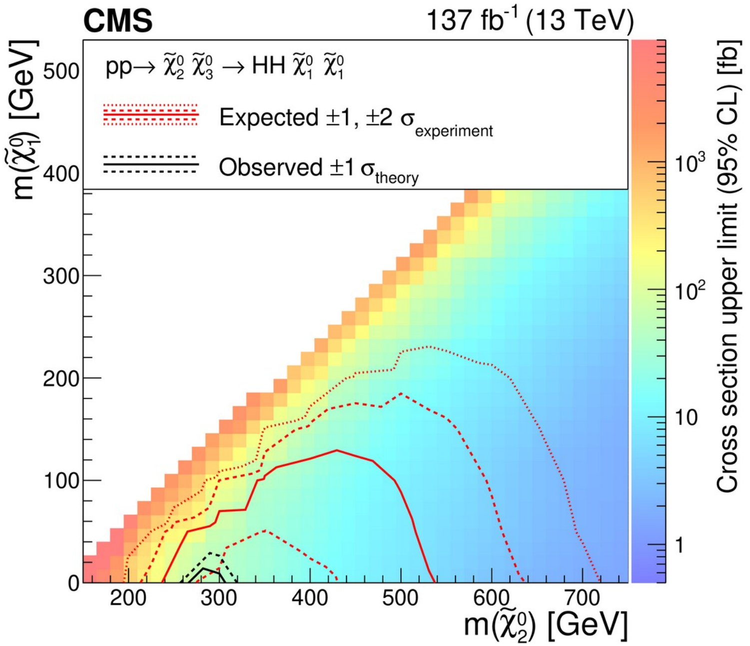
Search for higgsinos decaying to two Higgs bosons and missing transverse momentum



- Among other signatures $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production has been searched for with $\tilde{\chi}_{2,3}^0 \to H\tilde{\chi}_1^0$ and $H \to b\bar{b}$
- The Higgs has been searched for in the resolved and in the boosted topology
- A small upward fluctuation in one bin of the resolved channel is seen (2.1σ global)
- Correspondingly the observed limit is weak although the analysis is very sensitive

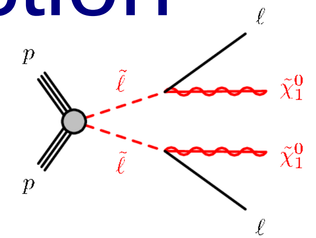


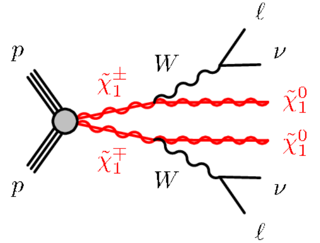
arXiv:2201.04206

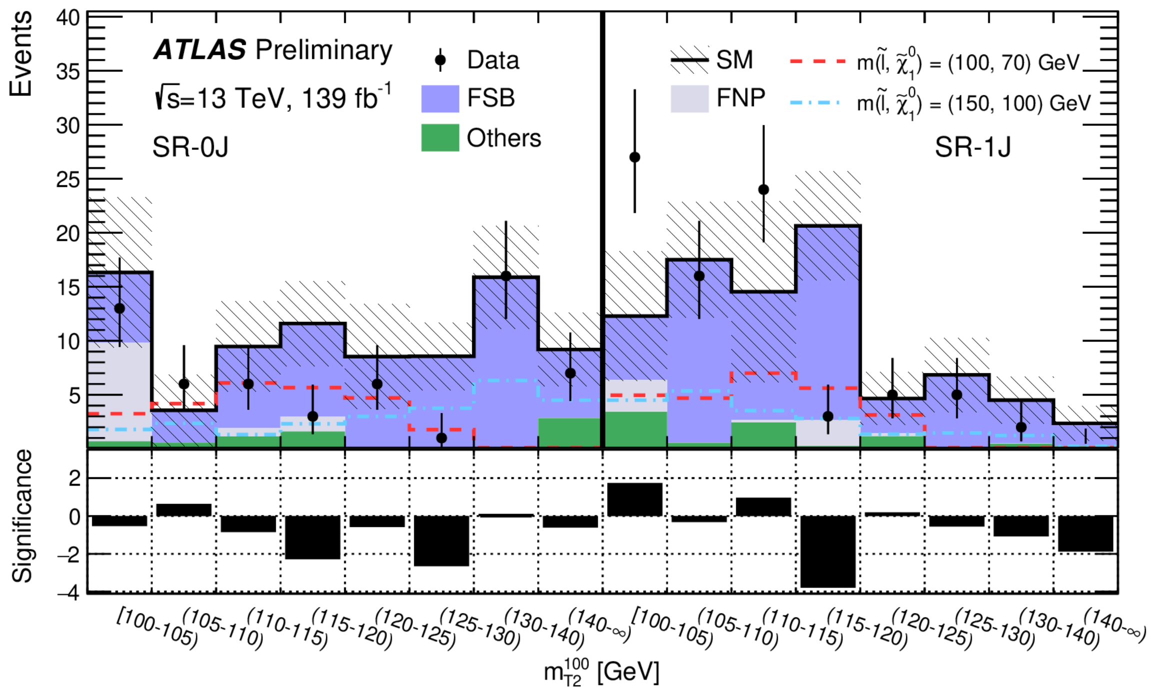


Search for slepton and chargino production

- ATLAS has searched for the production of sleptons and charginos that decay into leptons
- The analysis is optimised for mass differences around m_W
- In general the observed event yields agree well with the prediction







ATLAS-CONF-2022-006

Search for slepton and chargino production

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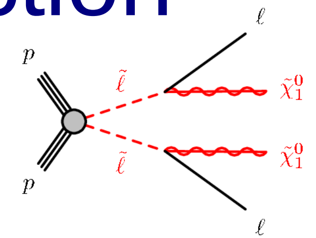
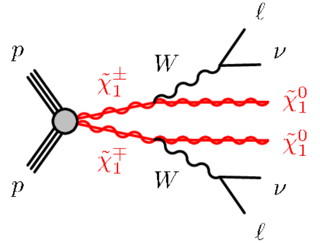
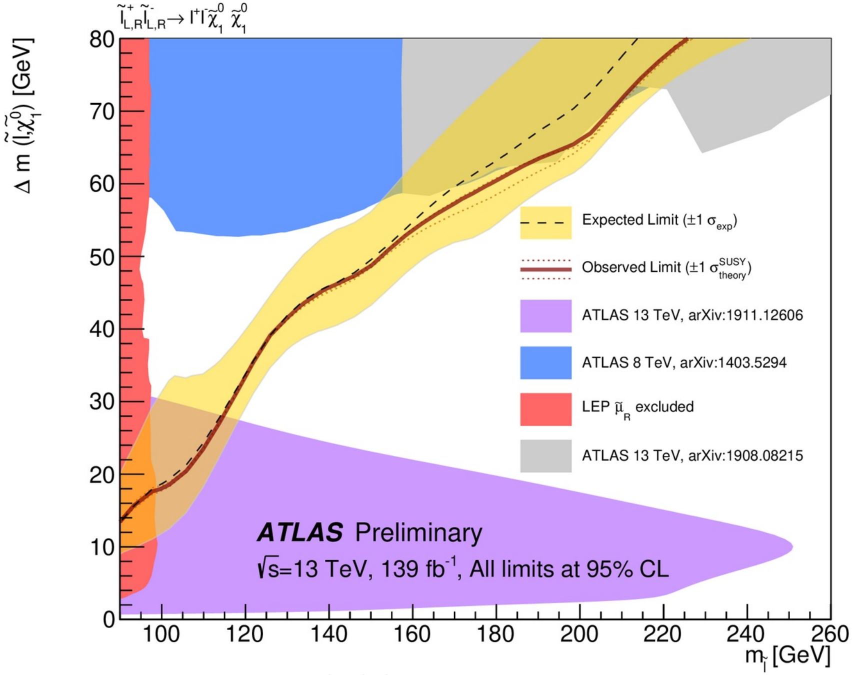
- This allows to fill wholes from the previous analyses







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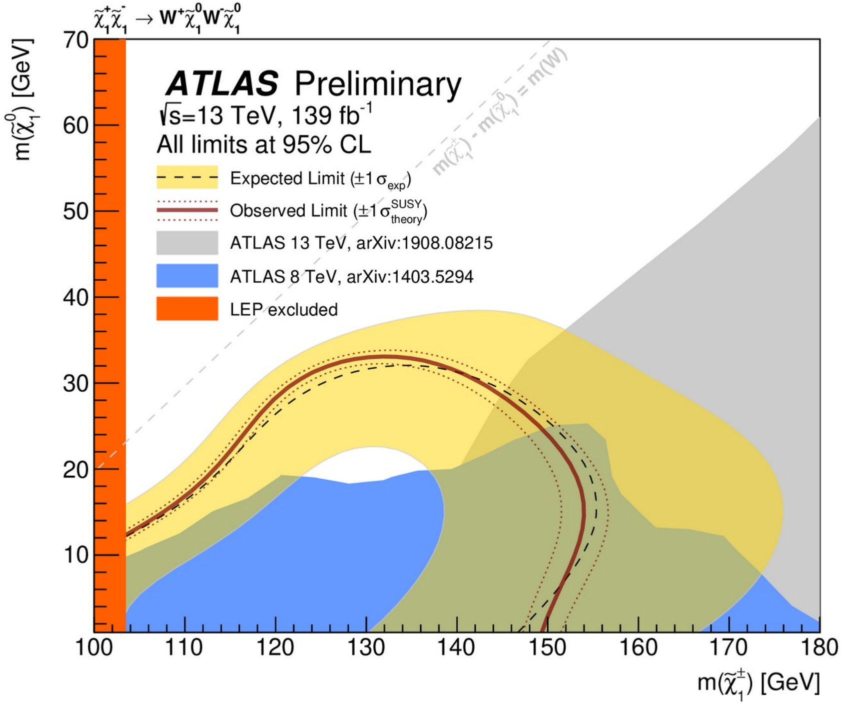
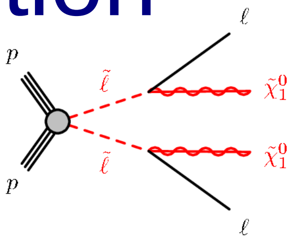


Search for slepton and chargino production



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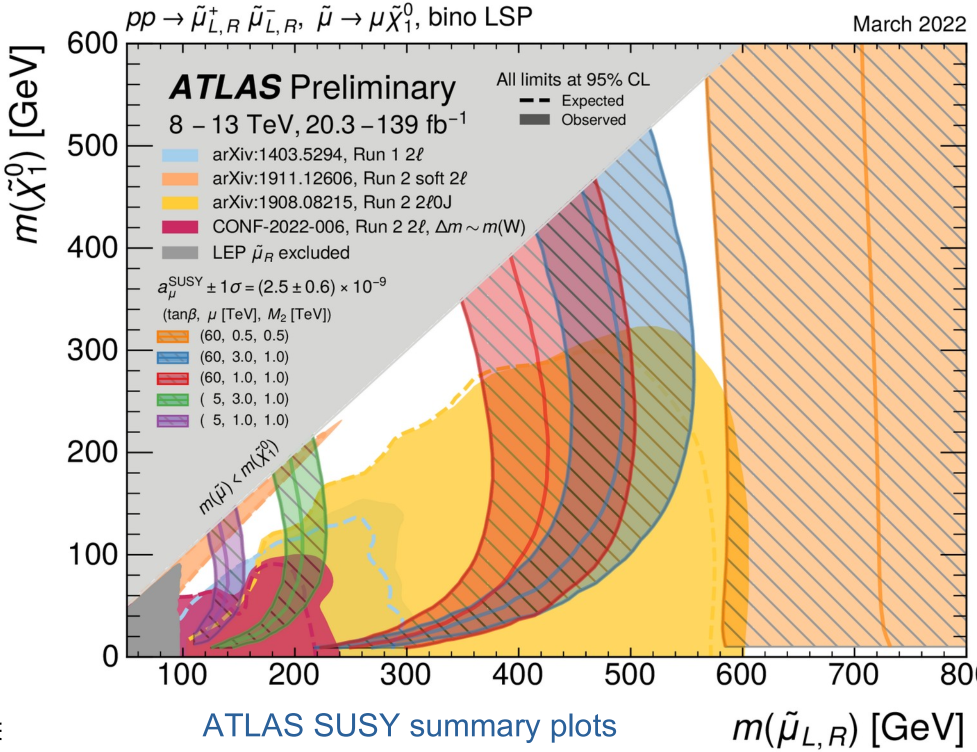
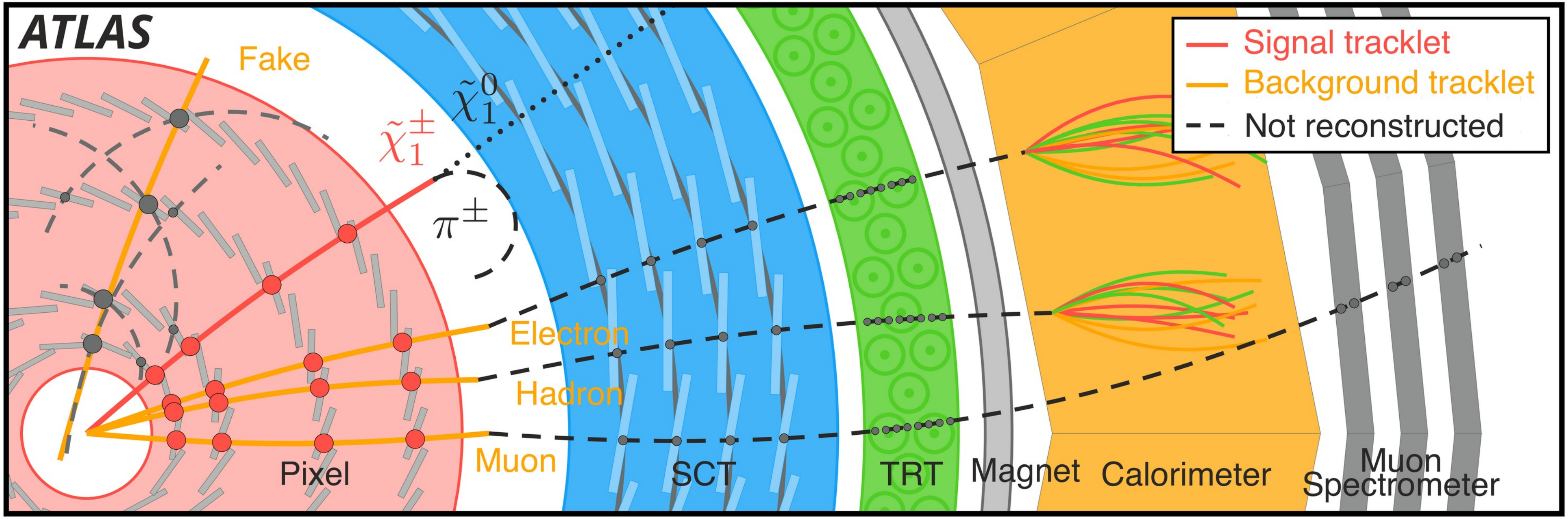
- The analysis is optimised for mass differences around m_W
- In general the observed event yields agree well with the prediction
- This allows to fill wholes from the previous analyses
- Together with the previous analyses this puts strong constraints on the regions that could explain the g-2 anomaly



SUSY with long lived particles

- In SUSY particles can be long lived mainly for two reasons:
  - in GMSB the NLSP can decay into a gravitino with very weak couplings
  - if the NLSP-LSP mass difference is very small the NLSP can be long lived
- If the NLSP is charged this can result in tracks that "disappear"



arXiv:2201.02472

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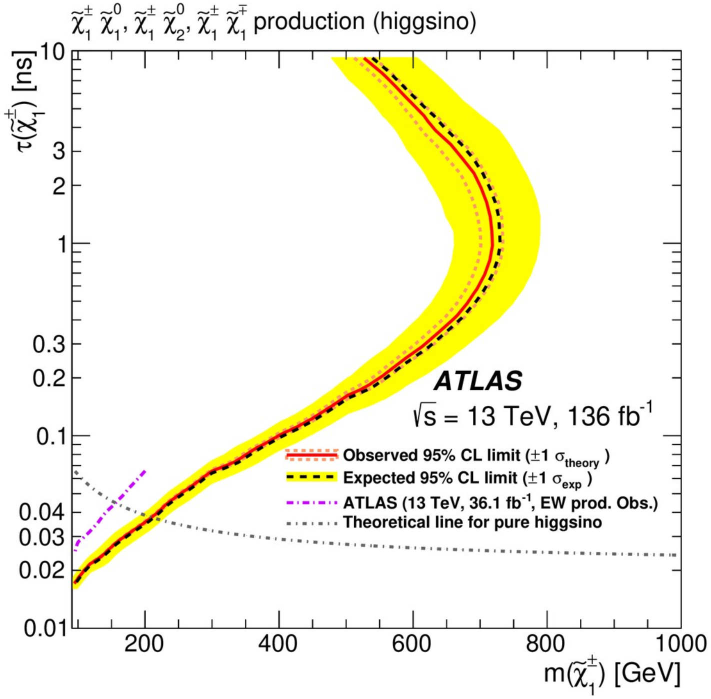
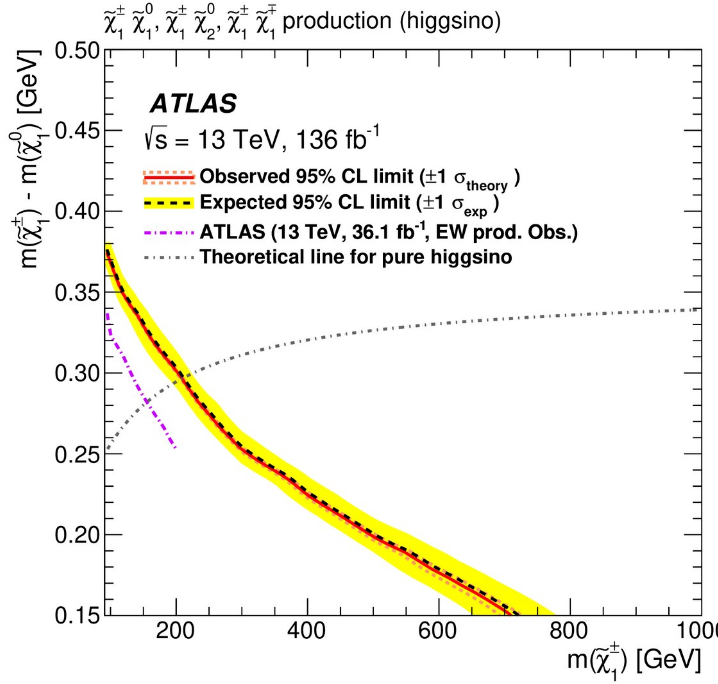
- If the NLSP is charged this can result in tracks that “disappear”
- With this signature lifetimes in the ns range can be probed corresponding to mass differences of a few 100 MeV





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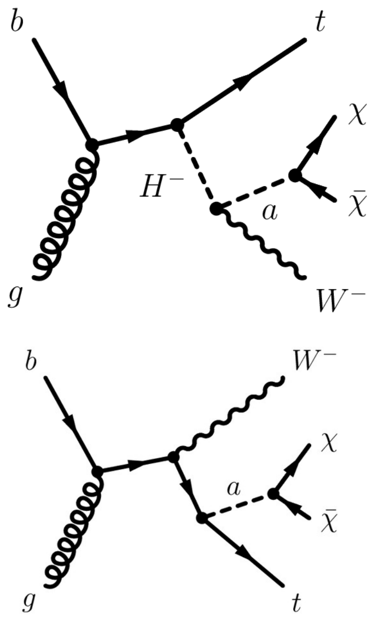
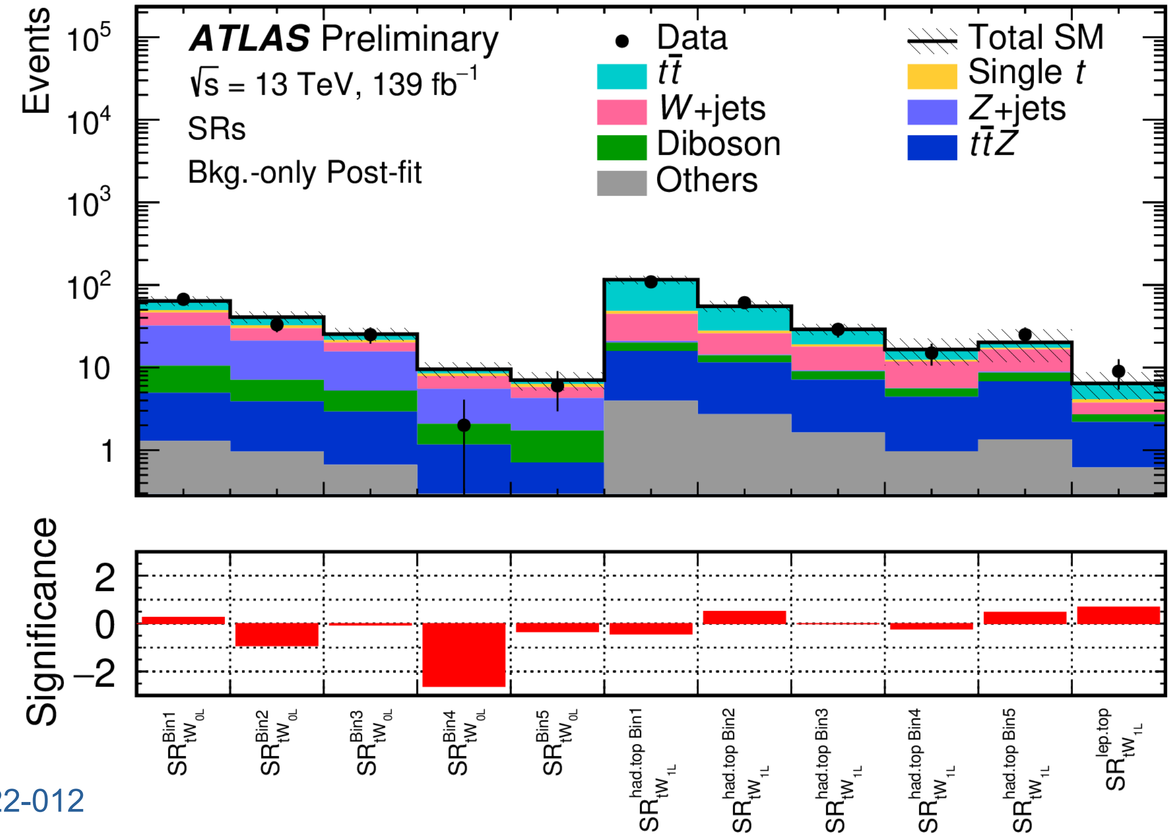
Dark matter/dark sector

- It is widely accepted that the matter in our universe is dominated by dark matter
- There are many possibilities what the dark matter could be composed of
- At the LHC the focus of dark matter searches currently goes in two directions
  - Weakly interacting massive particles (WIMPs)
    - A new particle with interactions of the size of the weak interaction
    - R-parity conserving SUSY typically provides a WIMP candidate
    - WIMPs can also come from other models, produced via different types of mediators
  - Dark sector
    - There exists a new sector which couples to the known particles only very weakly
    - The lightest particles in this sector are often dark matter candidates
    - Some of the new sector particles are long lived and decay into visible particles at some distance from the interaction point

Higgs portal models

- A frequently studied case is WIMPs produced via an extended Higgs sector
- The model is a 2HDM with an additional pseudoscalar, a, that acts as mediator to the DM
- In a recent analysis ATLAS searched for this model in final states with a W-boson and a top-quark





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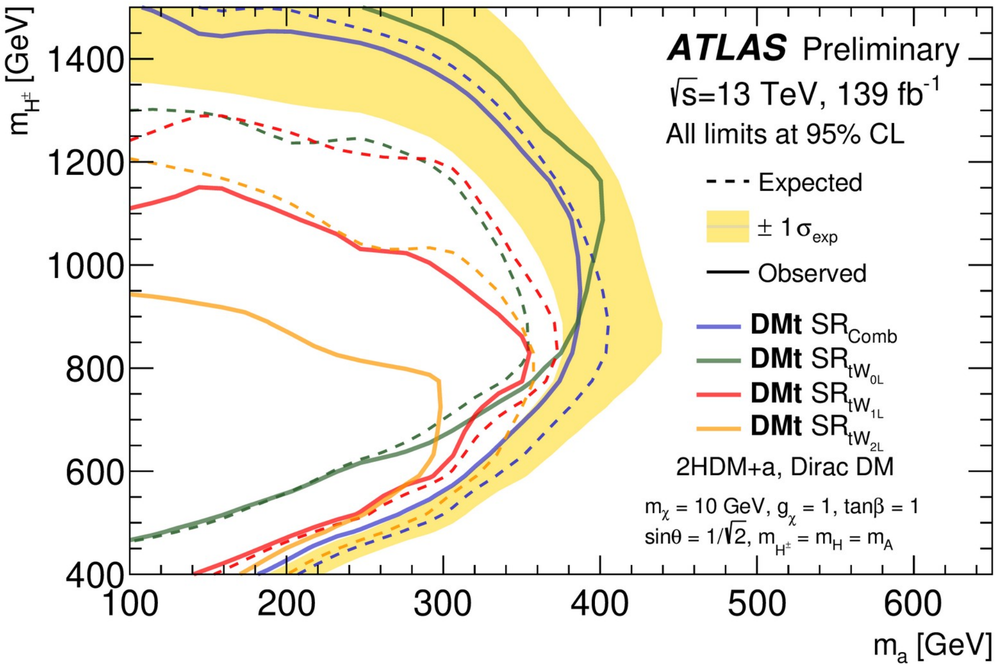
Higgs portal models

- With this search a masses up to around 400 GeV can be excluded
- Combining different analyses, including pure 2HDM searches, stronger limits are possible
- Details of the exclusion limits always depend on the parameter assumptions



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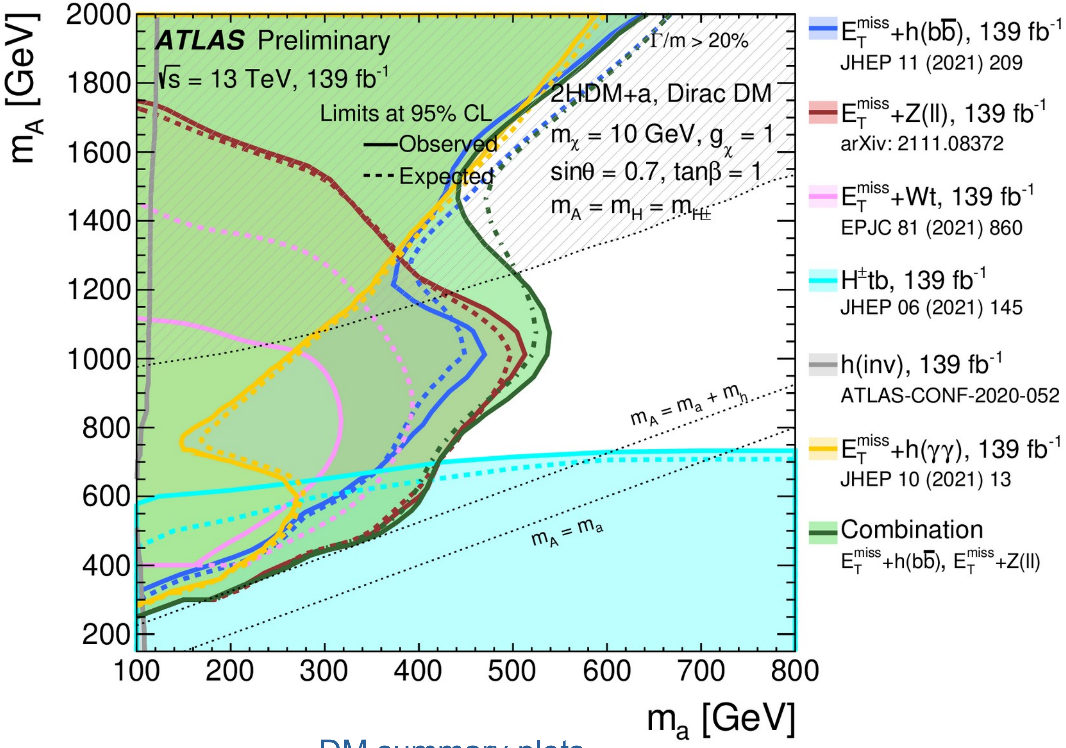
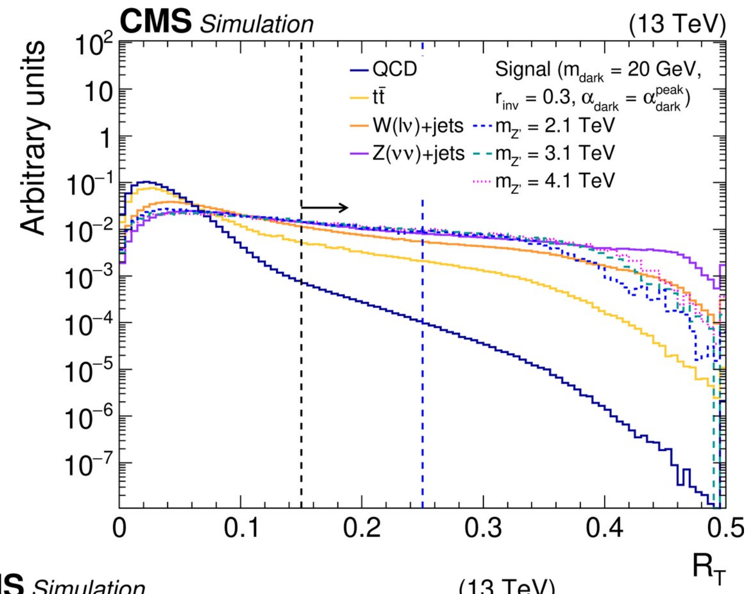


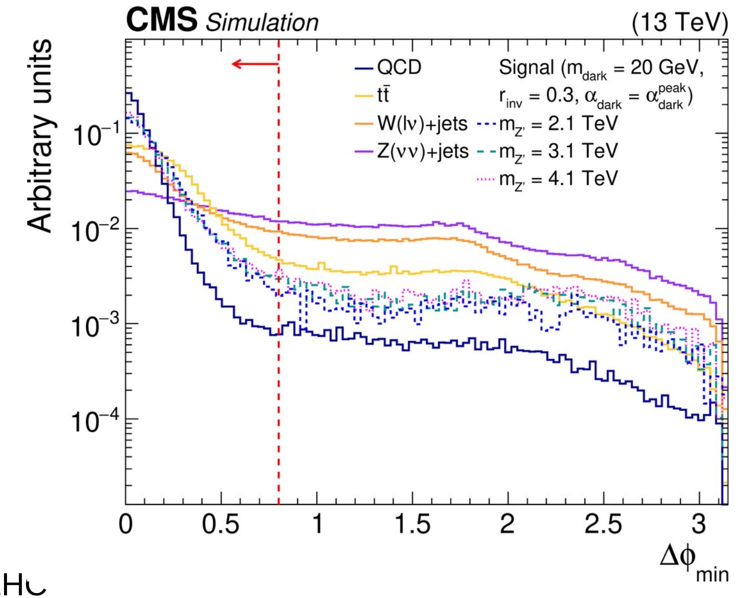
DM summary plots

Dark sector

- Dark sector searches usually take longer than other searches because they use special features of the detectors
- Recently first searches became available with a strong interaction in the dark sector
- In the model presented here the dark quarks are produced resonantly from a Z'
- The dark hadrons either decay promptly or are stable
- The average fraction of invisible energy (r_{inv}) is a free parameter in the theory
- The missing transverse momentum can be small because of cancellation and points in the direction of the jets

arXiv:2112.11125

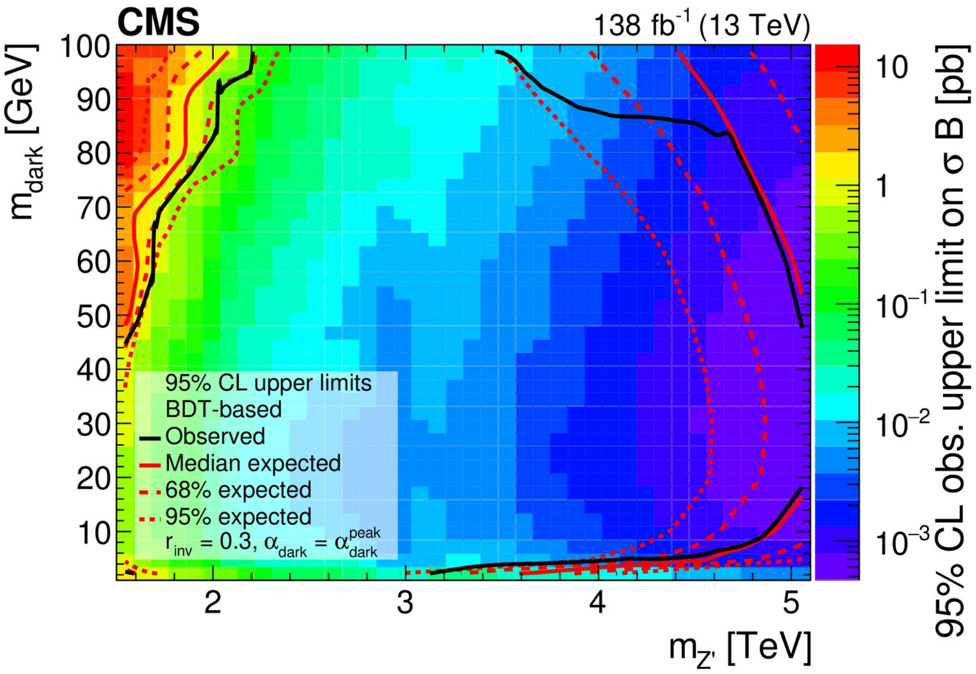


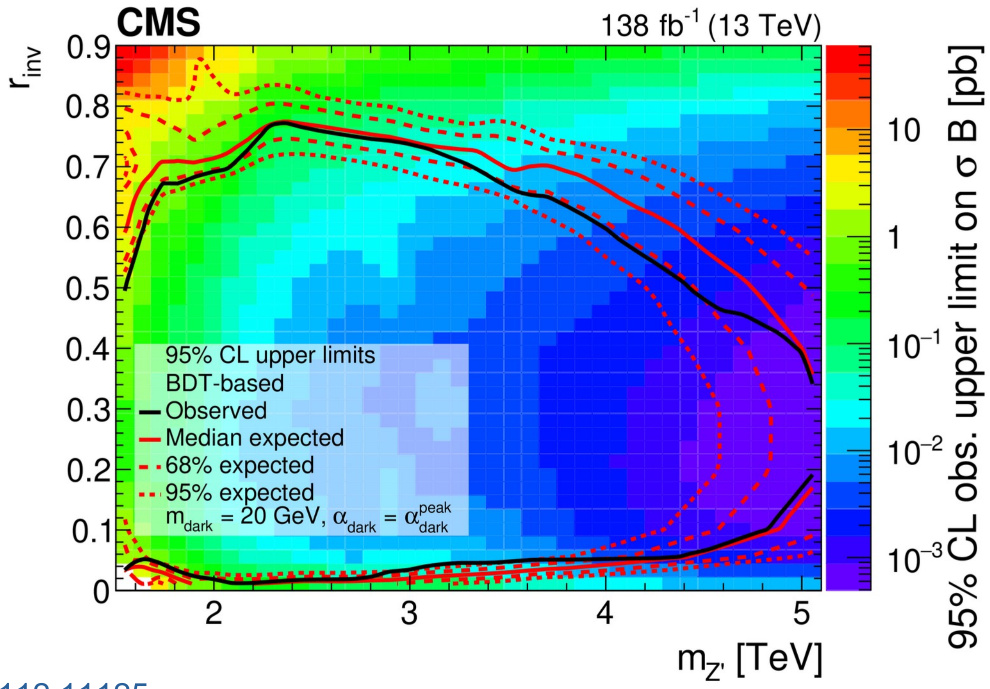


$$R_T = \frac{E_T^{miss}}{M_T}$$

Dark sector

- Signal and background are further separated with a BDT
- Limits on the Z' mass up to 5 TeV and the dark quark mass up to 100 GeV can be set for a large range of r_{inv}

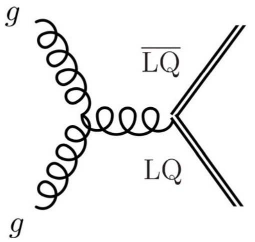


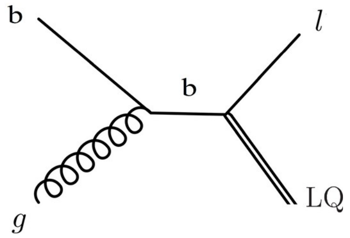


arXiv:2112.11125

Leptoquarks

- Leptoquarks are bosons that carry lepton- and baryon-number
- They appear naturally in grand unified theories where quarks and leptons are in the same multiplet
- They are the favourite explanation for the B-physics anomalies concerning LFV
- If they explain the anomalies they must be flavour non-diagonal, however the present searches mostly assume that they are flavour diagonal
- LQs can exist as scalars and vectors where the production cross section for vector LQs is significantly larger
- They can be produced singly or in pairs



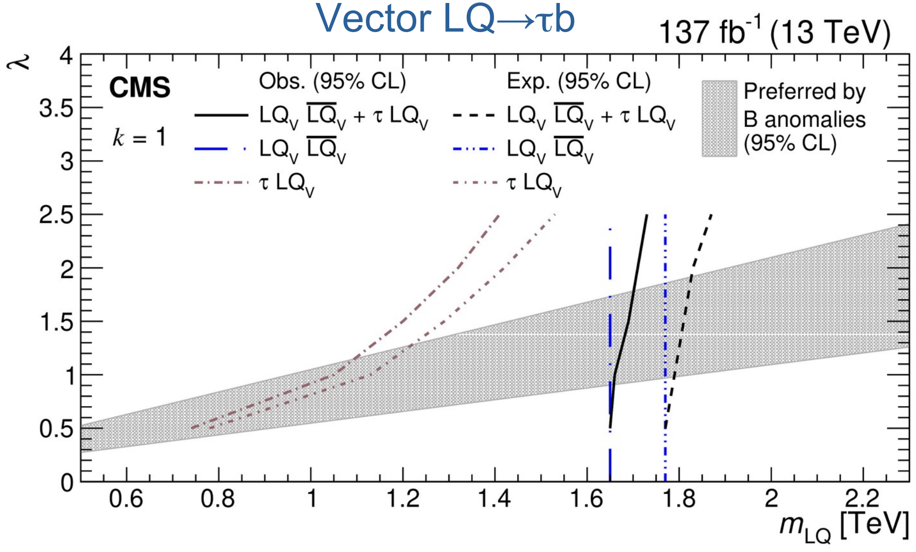


- Pair production:
  - Strong production, (almost) model independent
- Single production:
  - cross section depends on LQ coupling,
  - however potentially higher mass reach

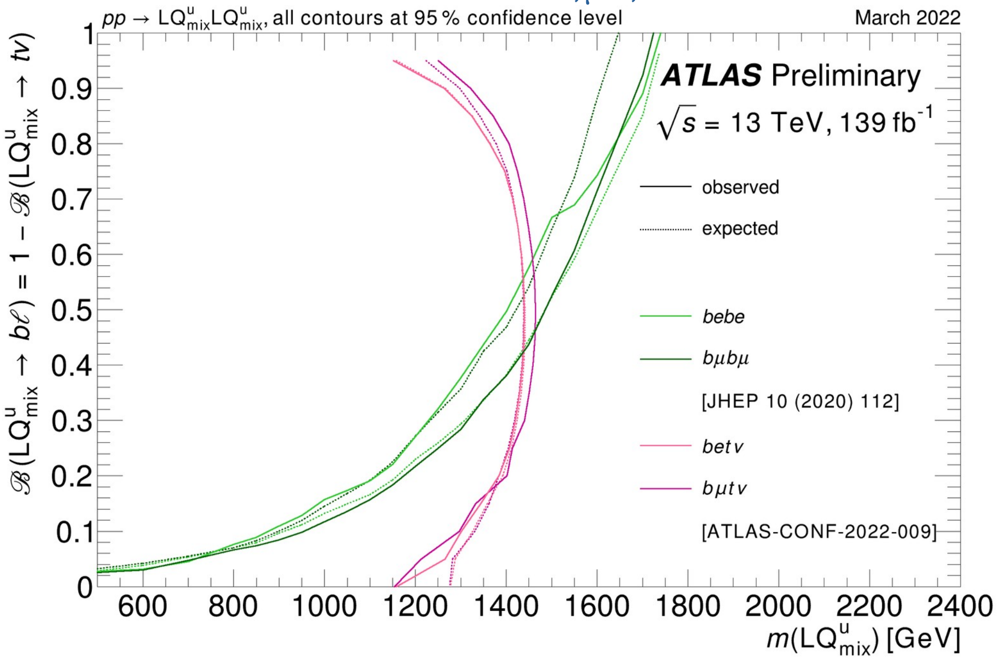
Leptoquark searches

- CMS has searched for 3rd generation scalar and vector leptoquarks (R(D(*)) in single and pair production covering part of the region that explains the anomalies
- ATLAS has searched for scalar cross-generation LQs (R(K(*)) combining the l± and ν decay modes
- LHC probes the interesting region but probably will not be able to cover it all

Vector LQ→τb



Scalar LQ→eb,μb,νt

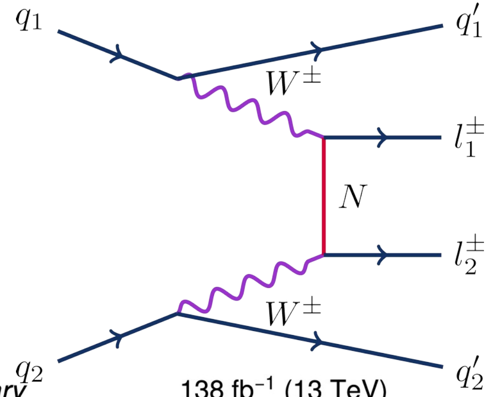


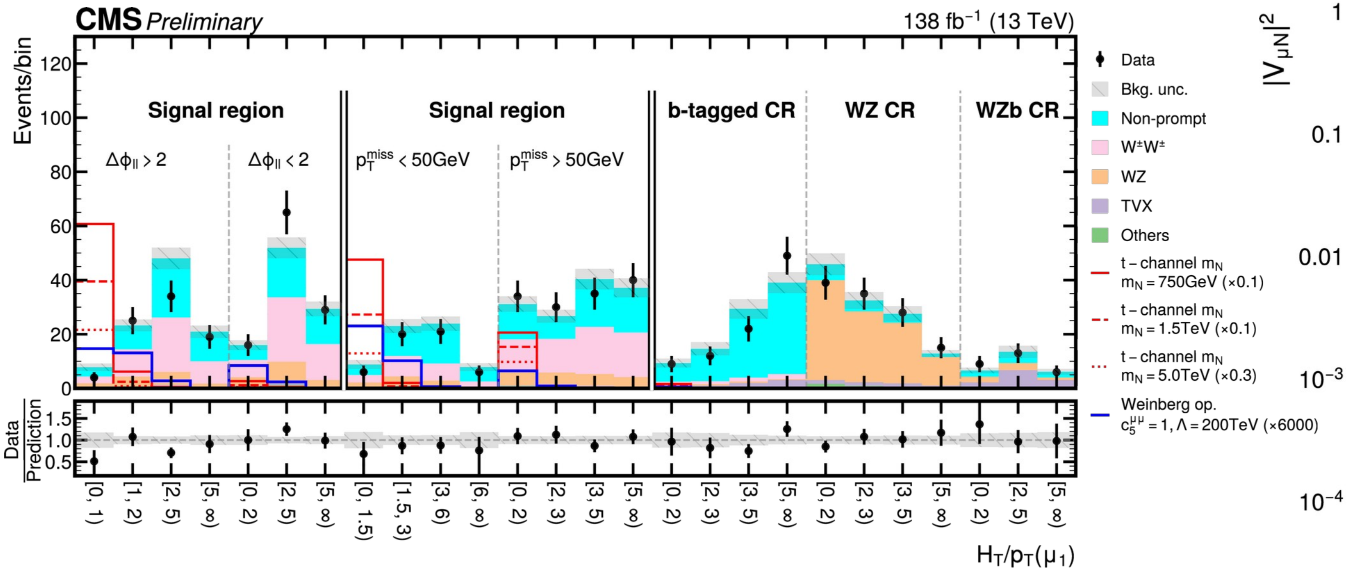
Heavy neutrinos

- The lightness of the SM neutrinos is still a mystery
- One of the favourite explanations is that the masses are generated by a sea-saw mechanism which requires the existence of heavy right-handed neutrinos
- Because of the see-saw mechanism the heavy neutrino must contain a small left-handed component
- The heavy neutrino can be a Majorana or a Dirac particle
- Such models can also explain the matter-anti-matter asymmetry in the universe
- Two ways to search for such neutrinos at the LHC
  - the heavy neutrinos are produced in the decay of a right-handed W_R
    - cross section large with small model dependence
    - however only possible if the W_R mass is in the LHC range
  - the heavy neutrinos are produced via their mixing with the left-handed states
    - cross section much smaller and depending on mixing angle
    - however independent on the existence of additional particles

Search for heavy Majorana neutrinos in VBF

- If the heavy neutrinos are of Majorana nature they can produce same-sign lepton final states without E^T_{miss} in the vector boson fusion topology
- This final state has very little SM background
- This allows to set limits up to high masses, however only for fairly large mixing angles





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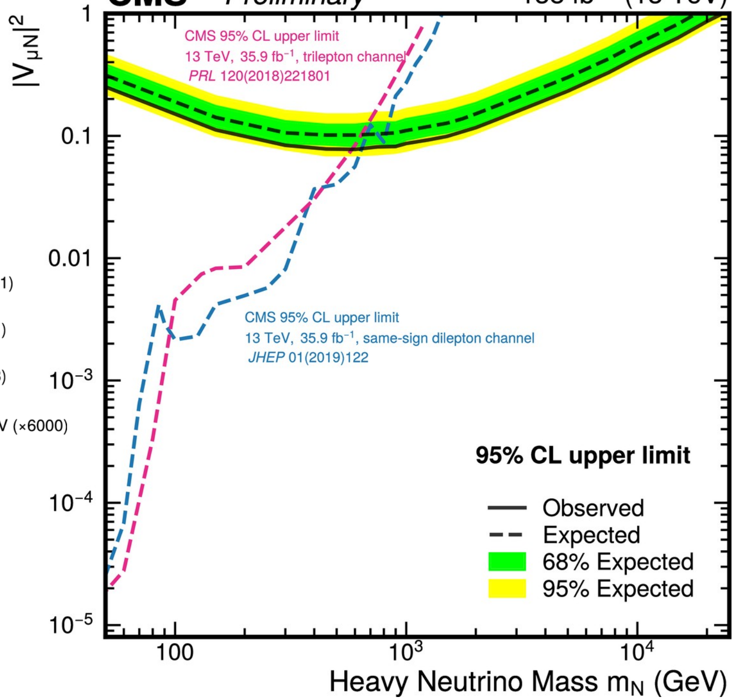
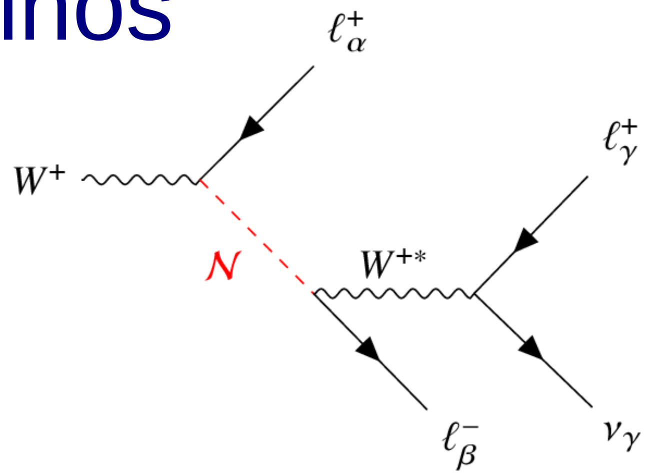
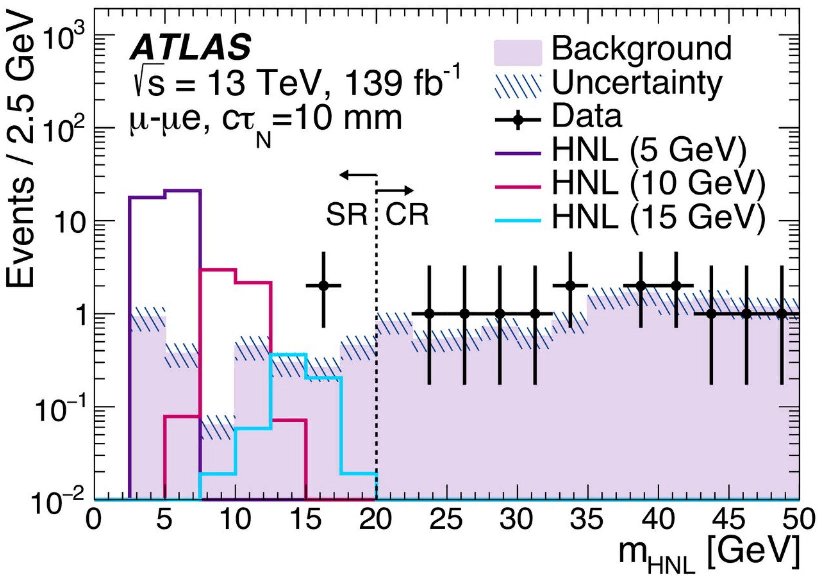


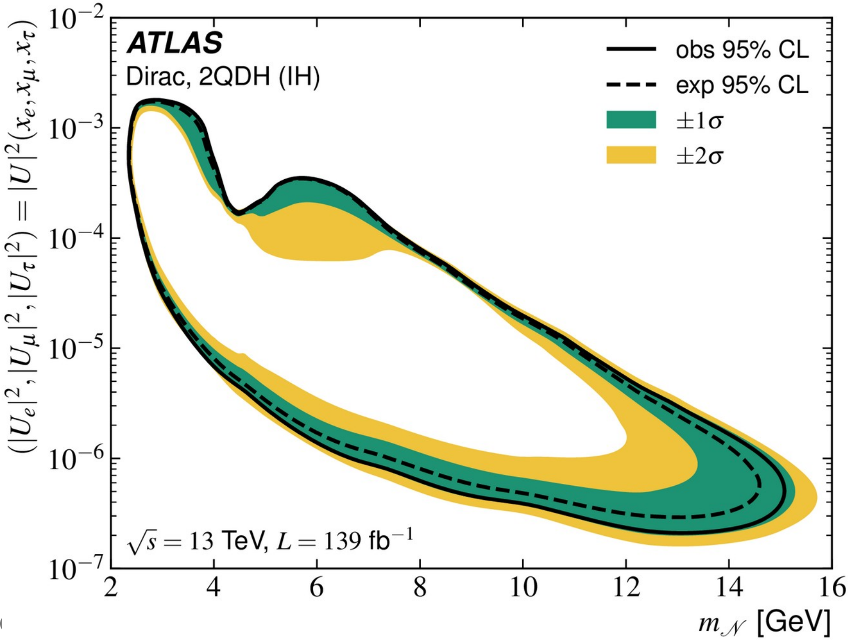
Long-lived heavy neutrinos

- If the mixing angle is small the heavy neutrino can be long-lived
- A 2-lepton decay vertex can be reconstructed in the detector
- As the neutrino flight direction is known from the vertex position, the neutrino mass can be reconstructed
- Similar limits for Dirac and Majorana neutrinos can be achieved
- Due to the small cross section the analysis is only sensitive to small masses, however for very low mixing angles





arXiv:2204.11988

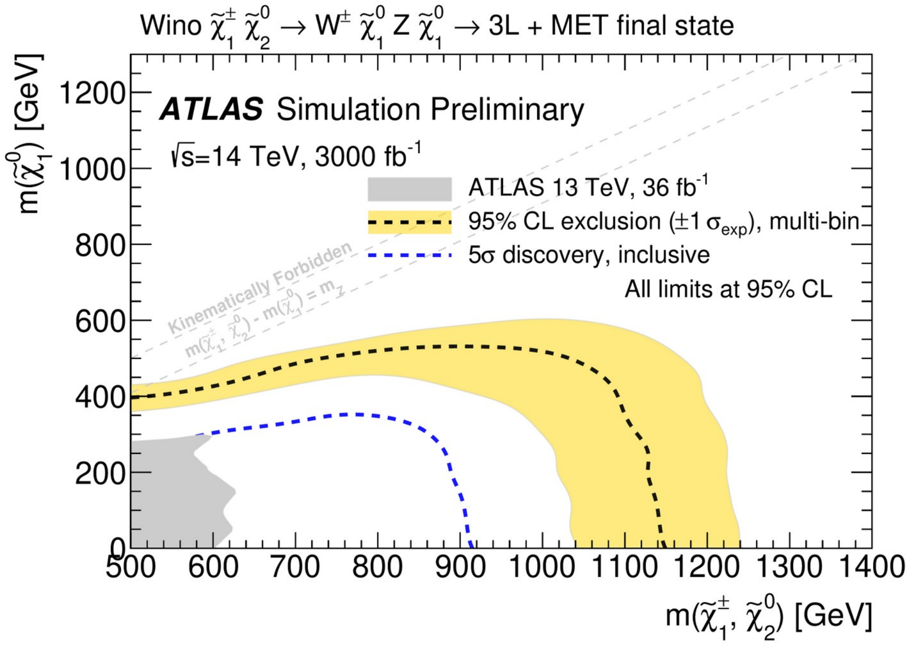


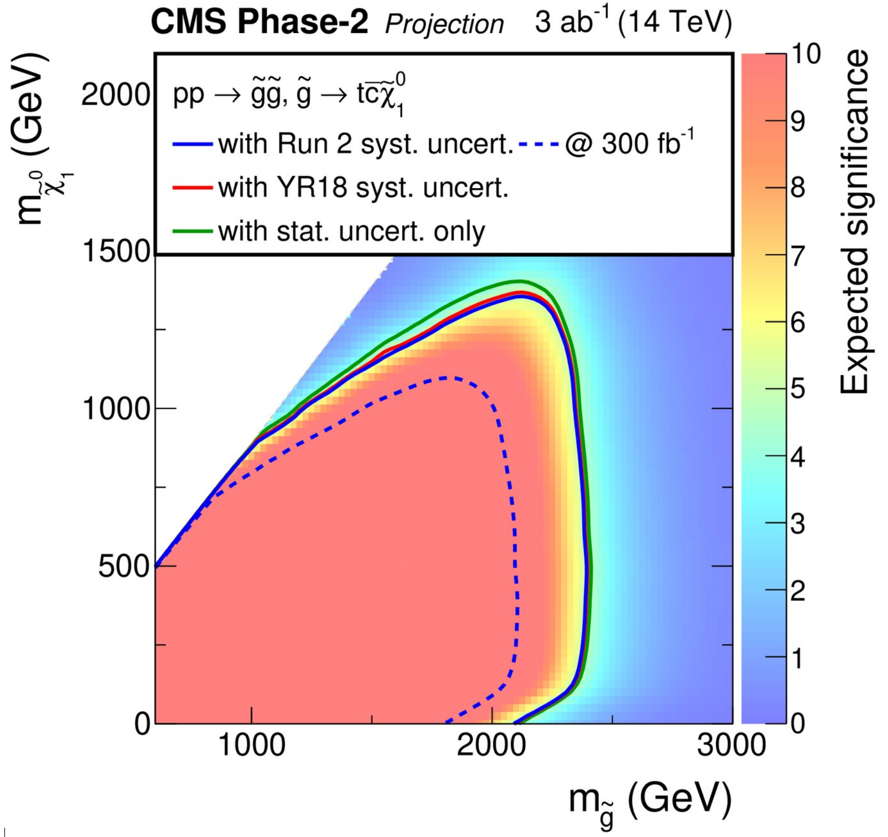
Future searches at the LHC

- The LHC will ~double the luminosity in run 3 and then get a factor >20 at the HL-LHC
- Cross sections limits improve by a factor $1/\sqrt{L}$ for searches with large background and $1/L$ for background free searches
- Especially for high masses the gain in mass reach will be limited due to strongly falling PDFs
- The increase in energy will be <10%
- However there is more than energy and luminosity:
  - If new ideas require new triggers only new data can be used
  - New trigger hardware and software allows more sophisticated triggers on unconventional signatures
  - Detector upgrades for the HL-LHCs give more sensitivity:
    - ATLAS will extend silicon tracking to a larger radius
    - ATLAS will introduce a fast timing detector in the endcap and CMS in 4π
    - CMS will add a track trigger in their inner tracker
- We can hope for many new results in in the Dark Sector and other long-lived particles, however no detailed studies exist at the moment
- All results in the following slides are from the ATLAS/CMS snowmass report

Future of SUSY searches

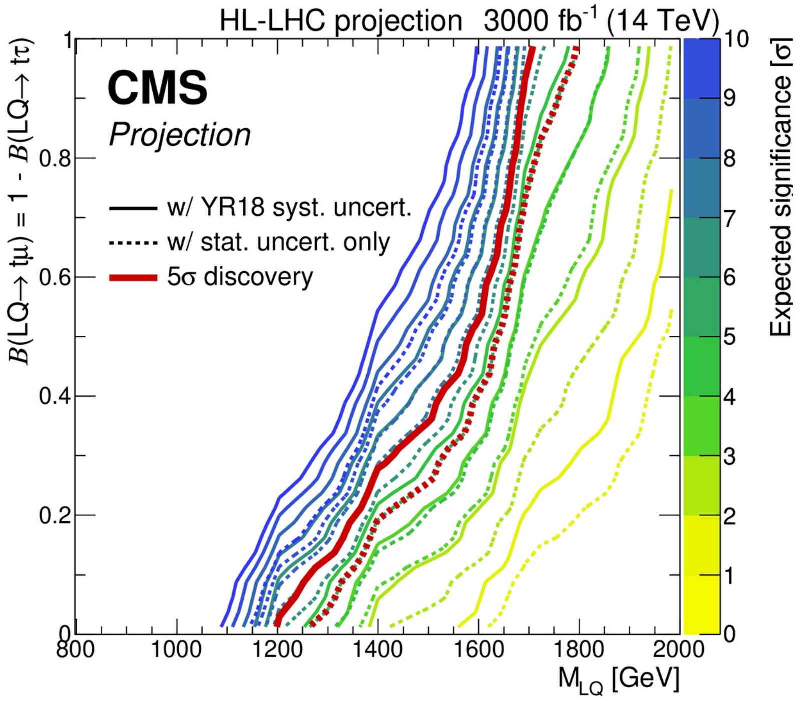
- For low cross section searches still an improvement in the mass reach up to a factor 2 is possible
- For high cross section searches the improvement is more in the 20% region, especially if the process is dominantly gluon induced
- However in both cases there remains a discovery reach for not already excluded regions

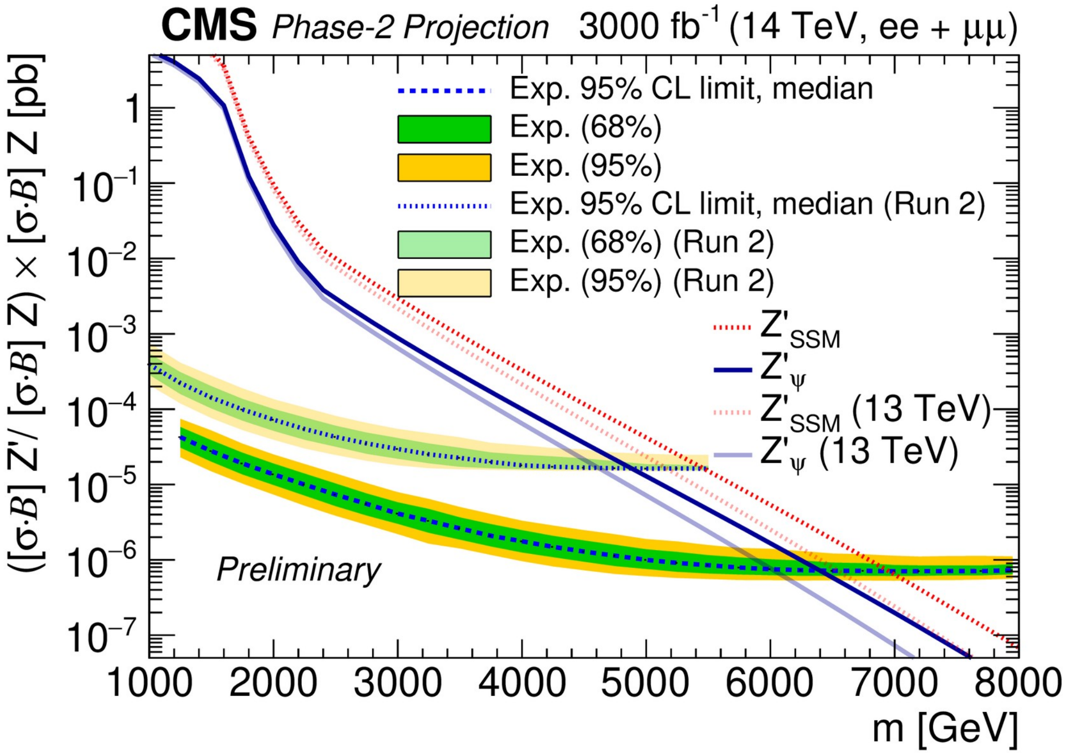




Other searches

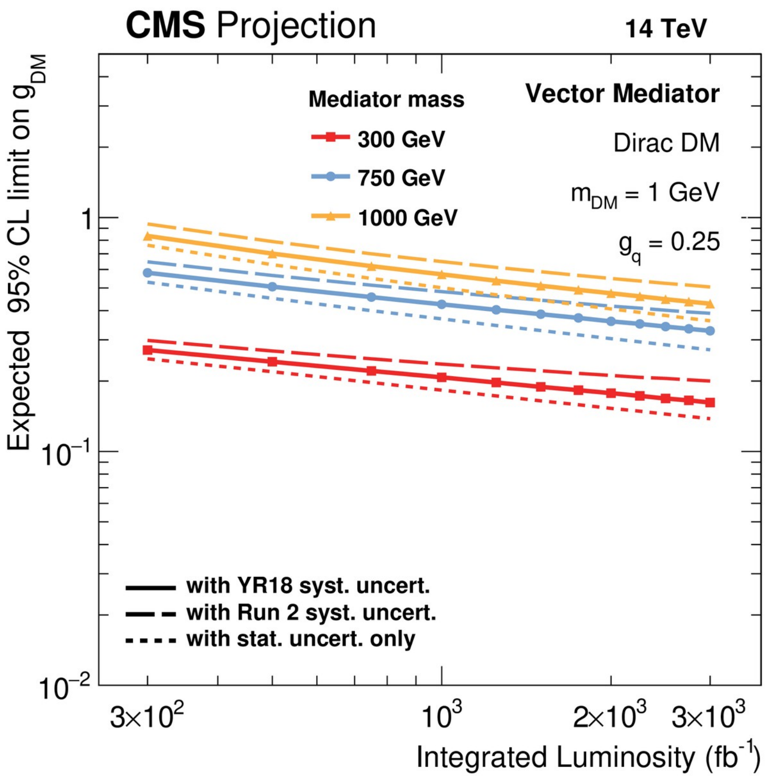
- For strongly interacting particles like leptoquarks the gain at the HL-LHC is modest
- Also at high mass large gains are possible, e.g. for Z’ where valence quarks are involved
- However we can be sure that there will be new ideas profiting also from the detector upgrades and the more selective triggers, especially in the area of long lived particles and other unconventional signatures

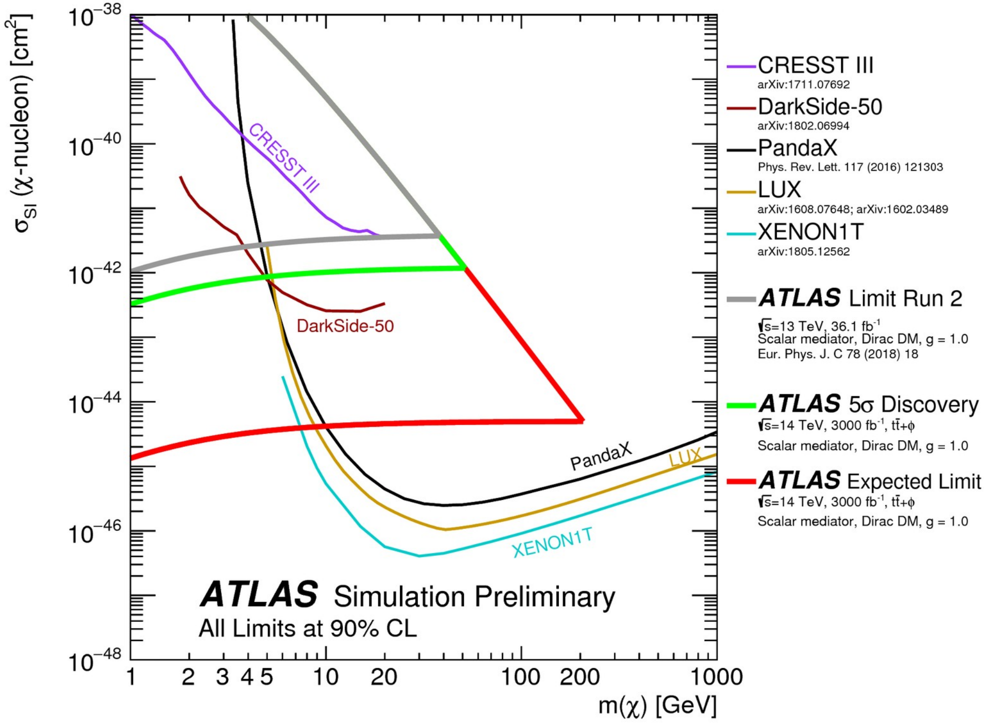




Dark matter searches

- For the background limited mono-jet type searches only improvements of a factor ~2 are possible
- However huge improvements are in reach for some channels where the dark matter couples to heavy quarks



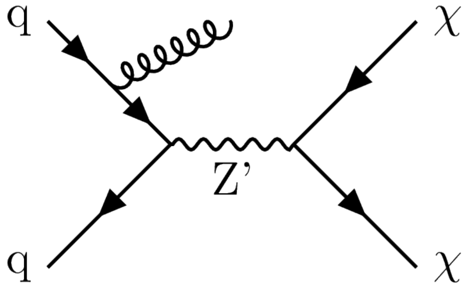


Conclusions

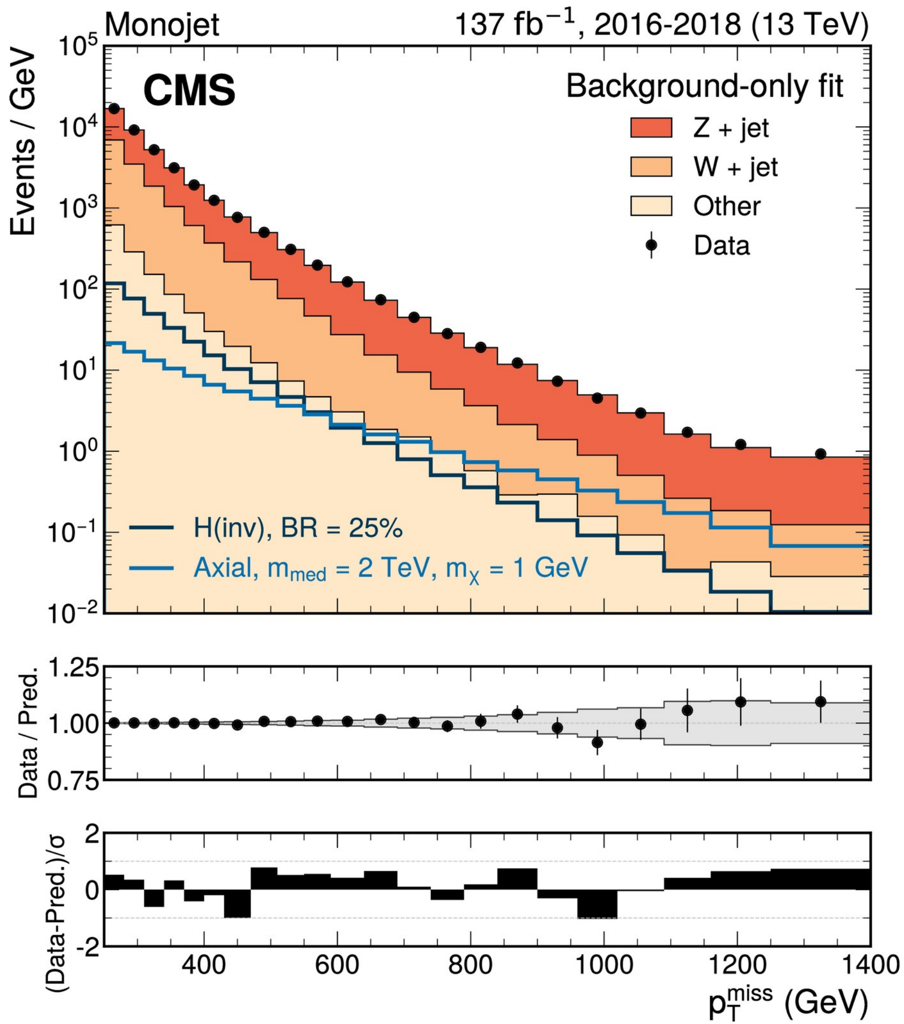
- Unfortunately no physics beyond the Standard Model was found yet
- However many BSM models could be constrained significantly
- For SUSY a large part of the parameter space that can explain the hierarchy problem or the muon g-2 anomaly could be excluded
- For other open problems like the LFV anomalies, neutrino masses, dark matter the possible parameter space is still large
- Especially for small cross sections the high luminosity LHC enables large improvements
- With the improved detectors and trigger we can also expect important results in up to now uncovered areas
- There is no reason, to give up. The LHC can still open the door to a new world!

Backup

Mono-jets



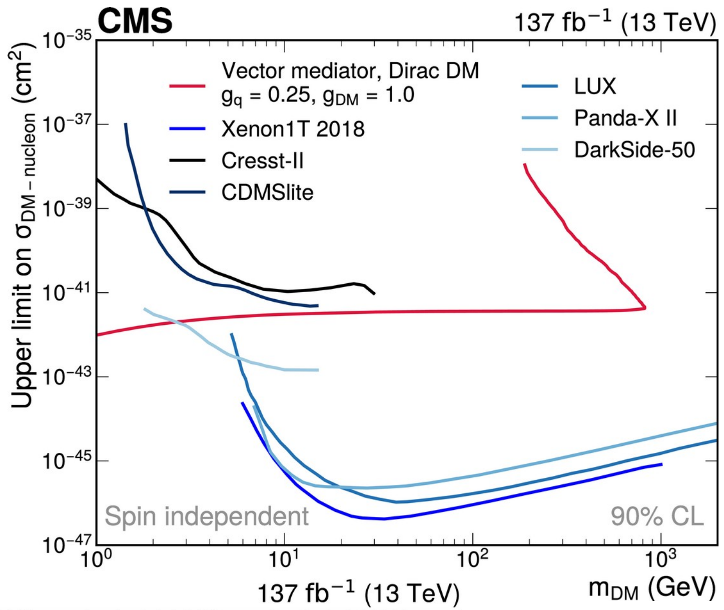
- The search for ≥1 jet + missing transverse momentum is sensitive to many kinds of dark matter
- For some models like dark matter predicted by a mediator Z' it is the most sensitive search
- However the search has a significant irreducible background from V+jets due to neutrinos
- In a common theory+experiment effort a procedure has been derived to measure this background from Z(→ll)+jets, W+jets and γ+jets control regions

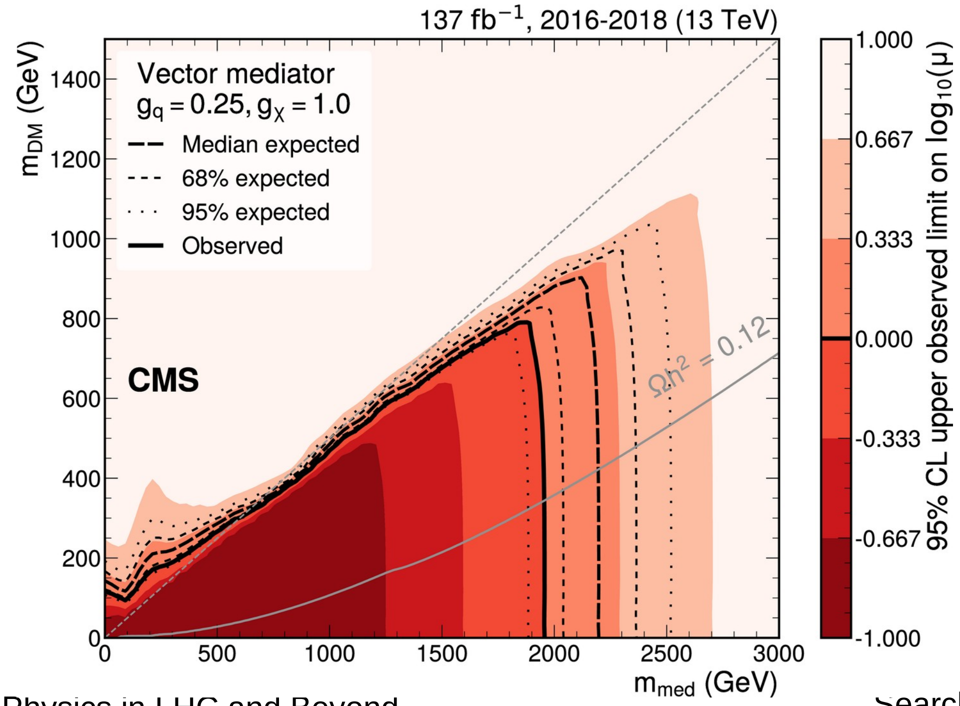


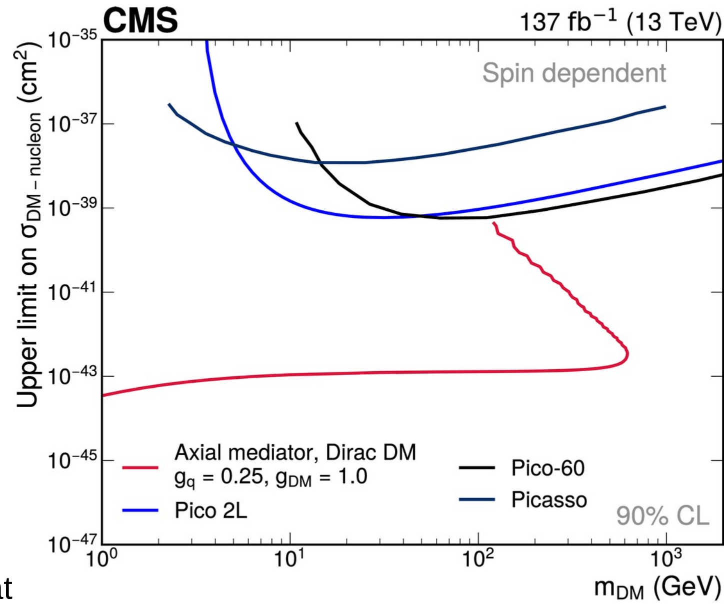
arXiv:2107.13021

Mono-jets

- This search constraints a mediator Z’ up to around 2 TeV
- It nicely complements the direct searches at low masses, especially in the dependent case







arXiv:2107.13021