Dark Sector searches with jets

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on behalf of the ATLAS & CMS collaborations

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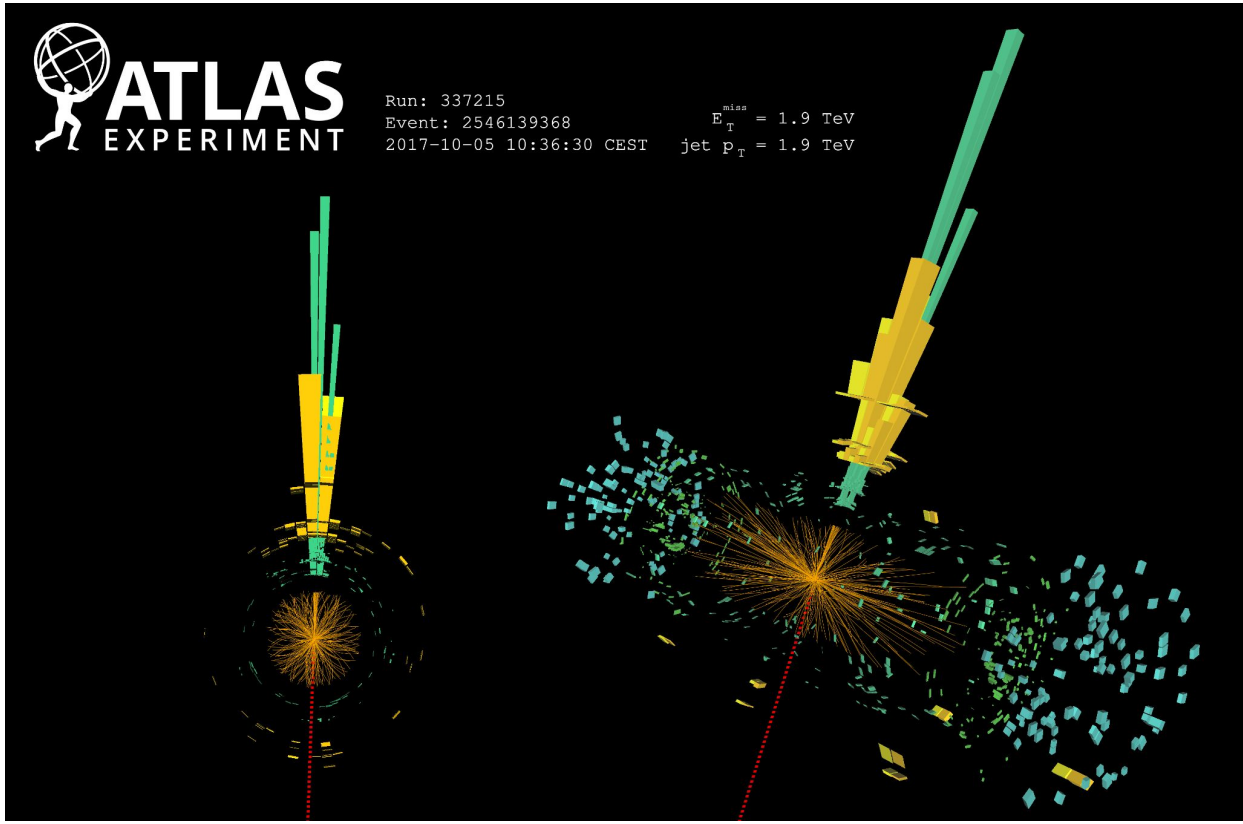


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

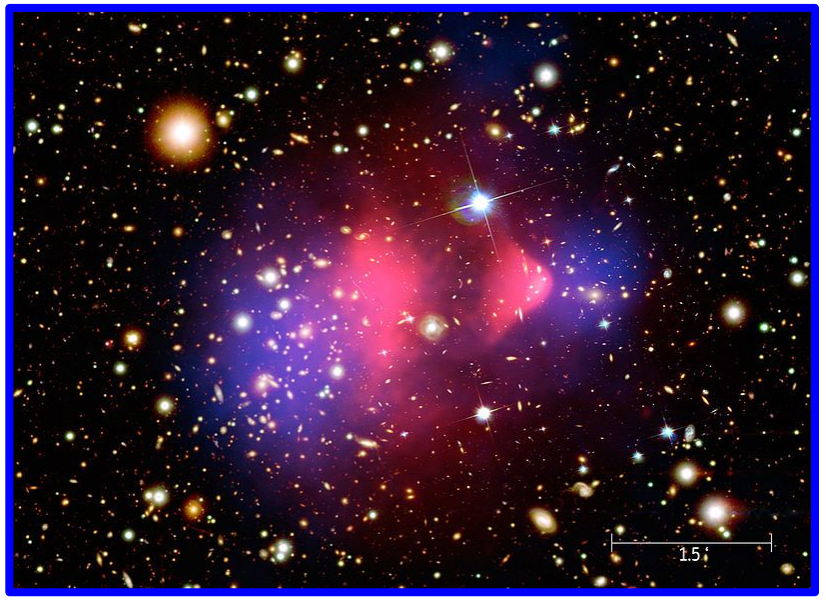
CMS

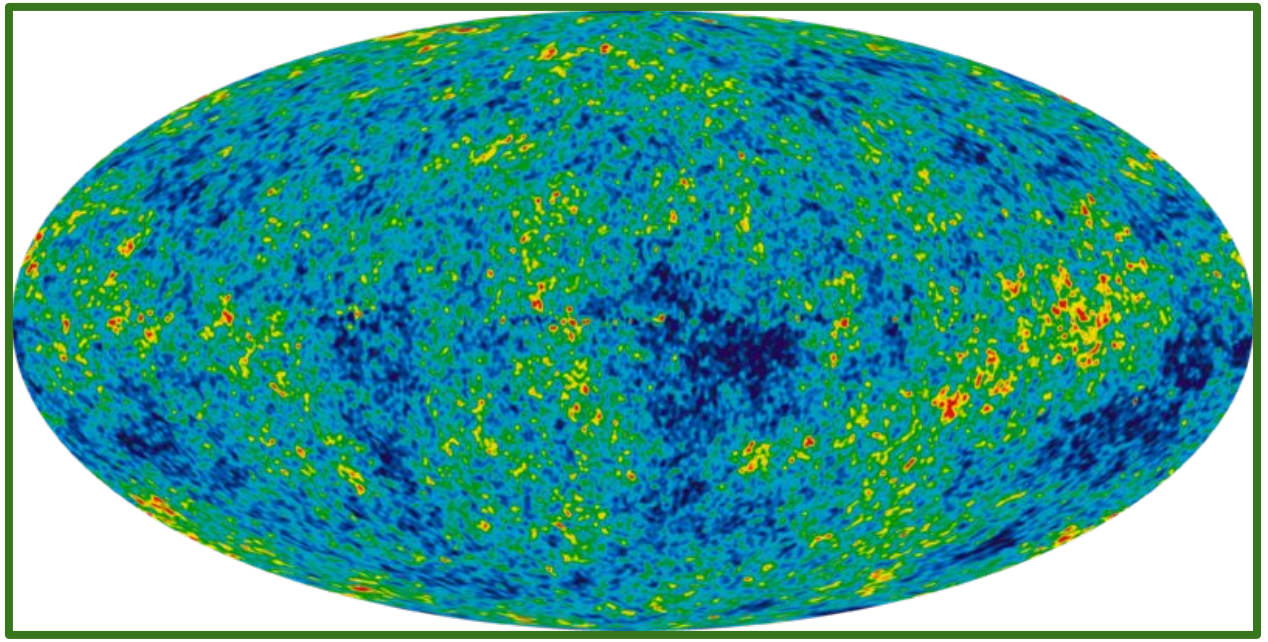
DESY.

Motivation

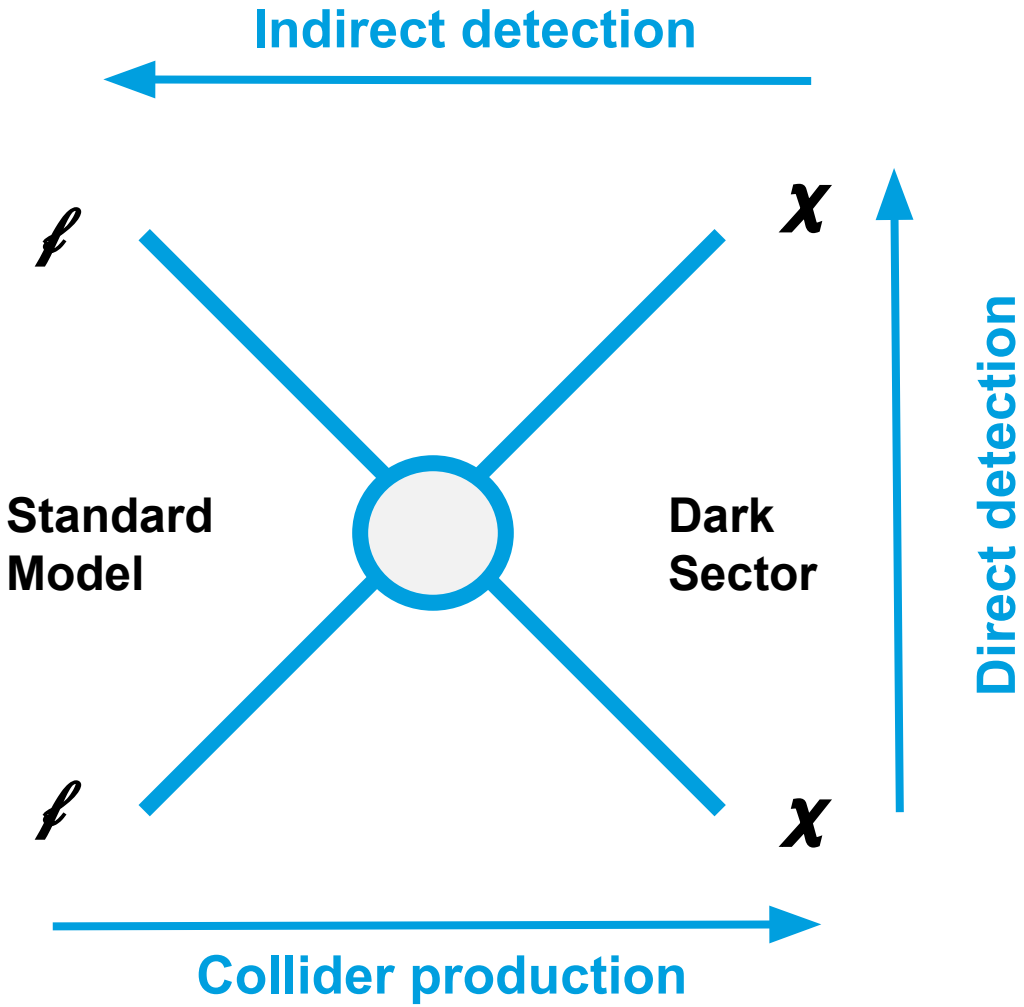
Observational evidence for Dark Matter (DM):

- Colliding galaxy clusters
- Rotation of spiral galaxies
- Angular power spectrum of the cosmic microwave background
- Mass-to-light ratio for galaxy clusters measured with gravitational lensing
- ...





Types of Dark Matter searches



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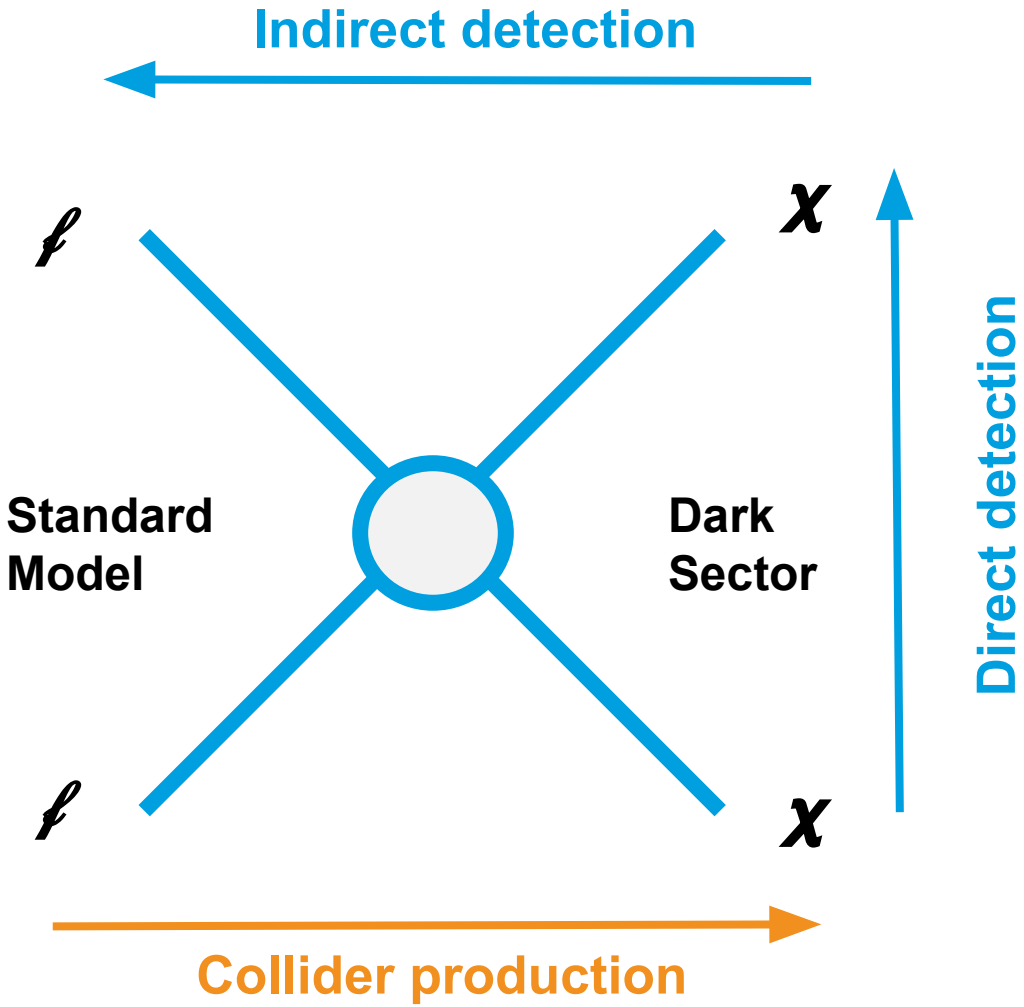
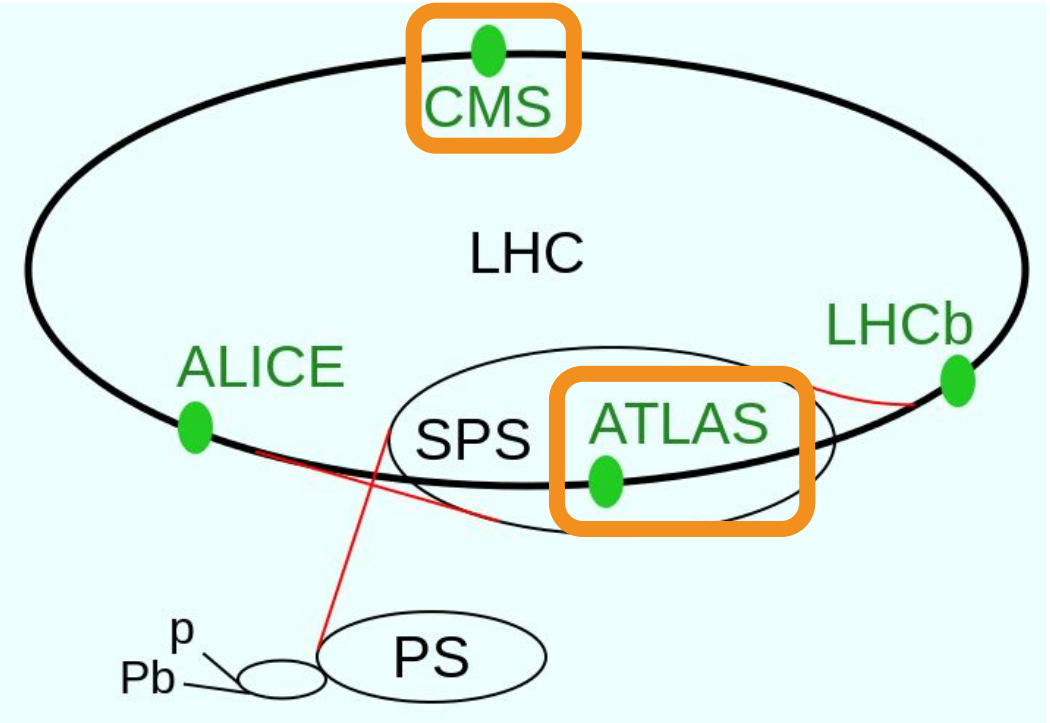
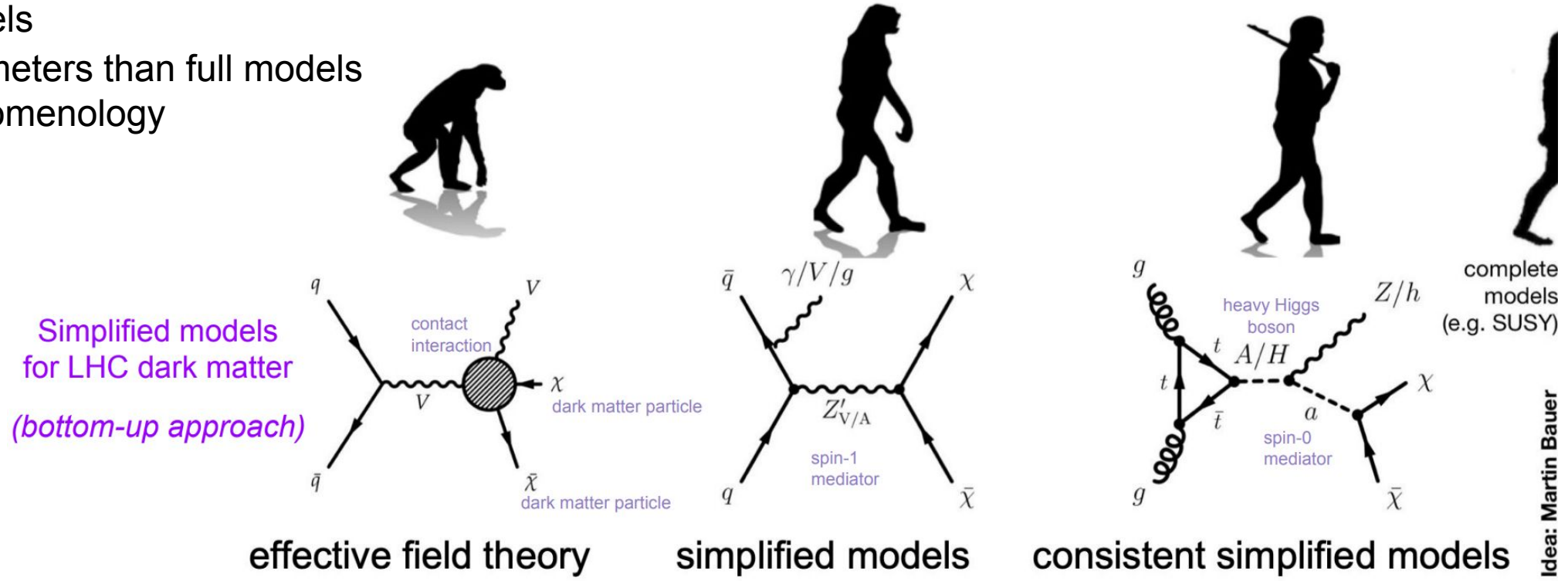


- This talk will focus on **DM searches with jets in the final state** performed by **ATLAS** and **CMS**
- LHC is colliding protons => many jets



Dark Matter models at the LHC

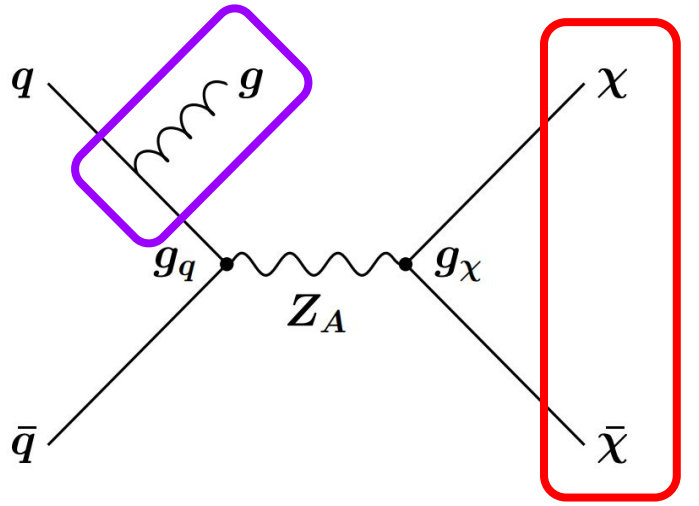
- To interpret and guide analyses, models that extend the SM can be a useful tool
- Effective field theory
  - Simplest approach
  - Not valid for interactions with large momentum transfer
- Simplified models
  - Less parameters than full models
  - Rich phenomenology

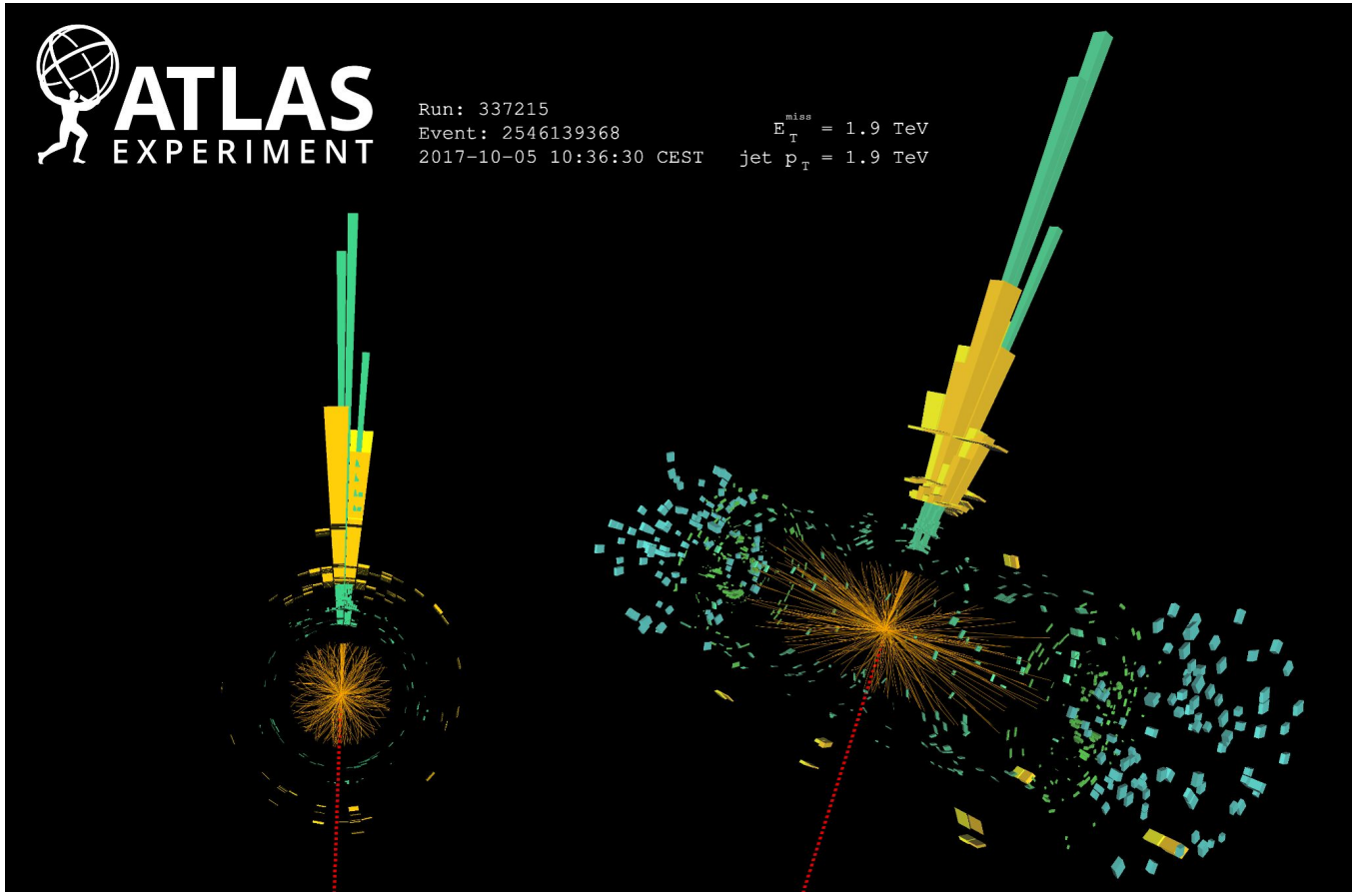


E_T^{miss}+jet search strategy

ATLAS / CMS publication

- DM cannot be directly detected by ATLAS/CMS
- => Need recoiling object (e.g. jet, Z, W, H)
- => Signatures with large transverse momentum imbalance (E_T^{miss})





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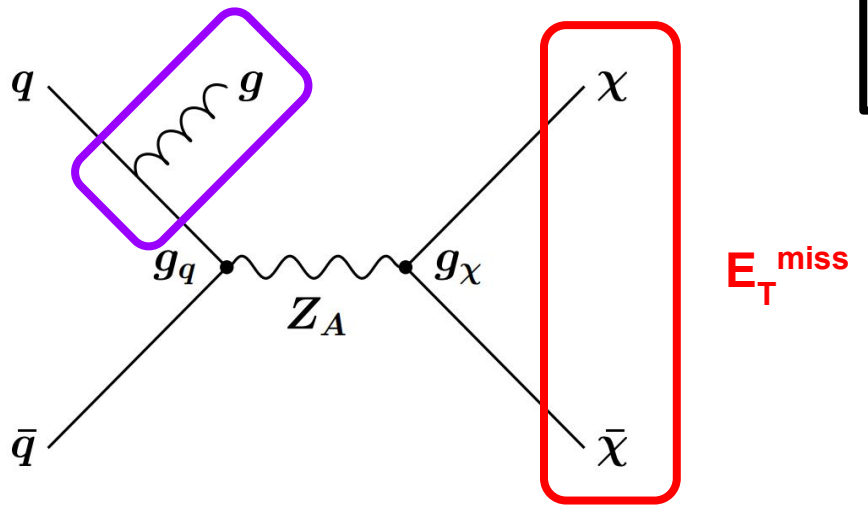
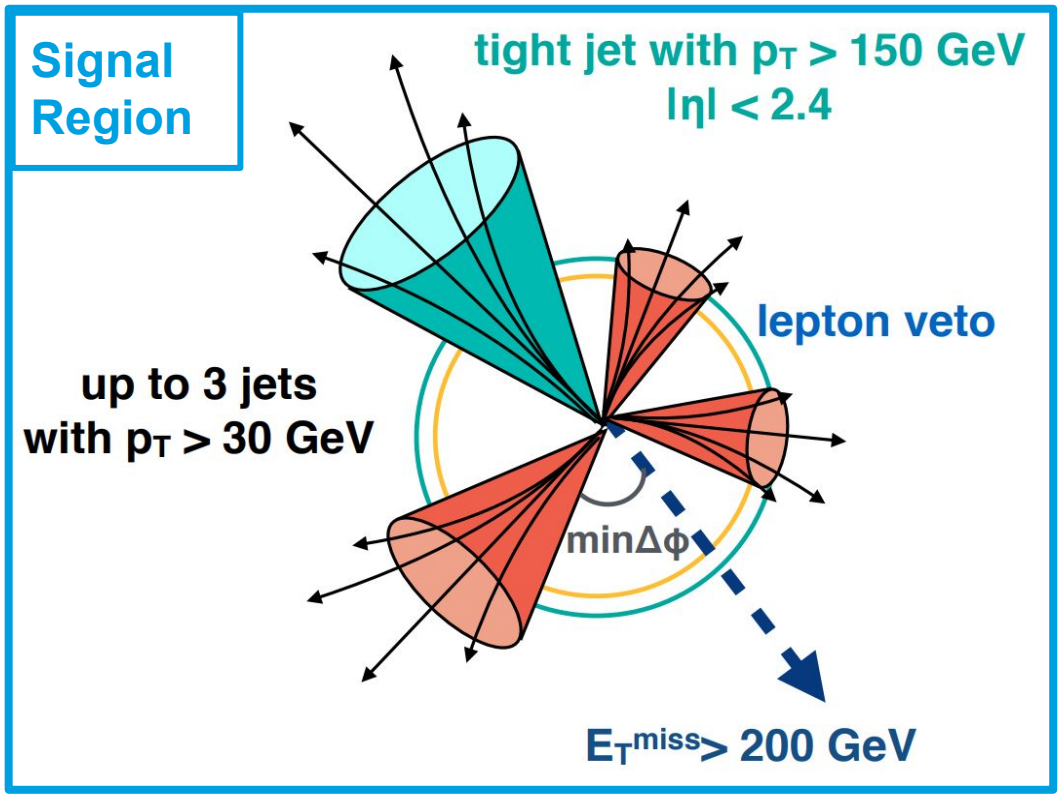


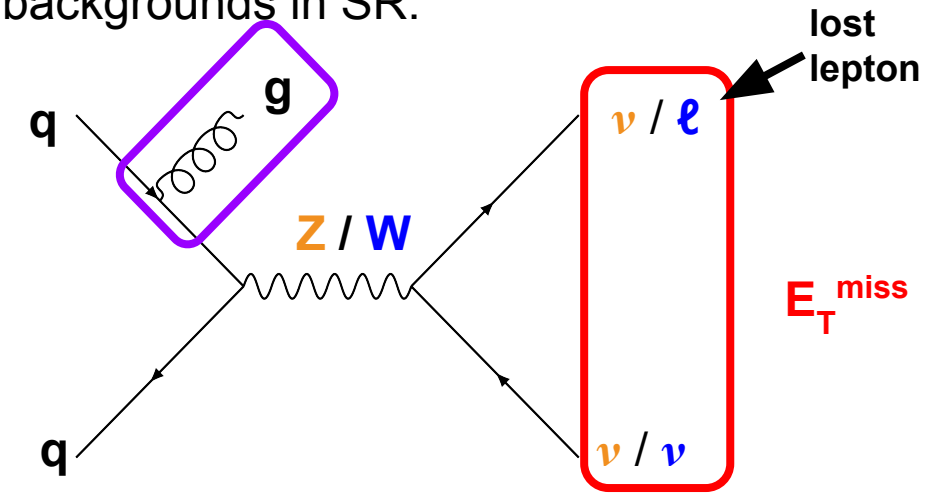
Signal Region



Control Regions:

- 4 (V+jets) + 1 (top) CRs
- Constructed by inverting lepton veto
- High level order corrections for V+jets are applied

V+jets backgrounds in SR:

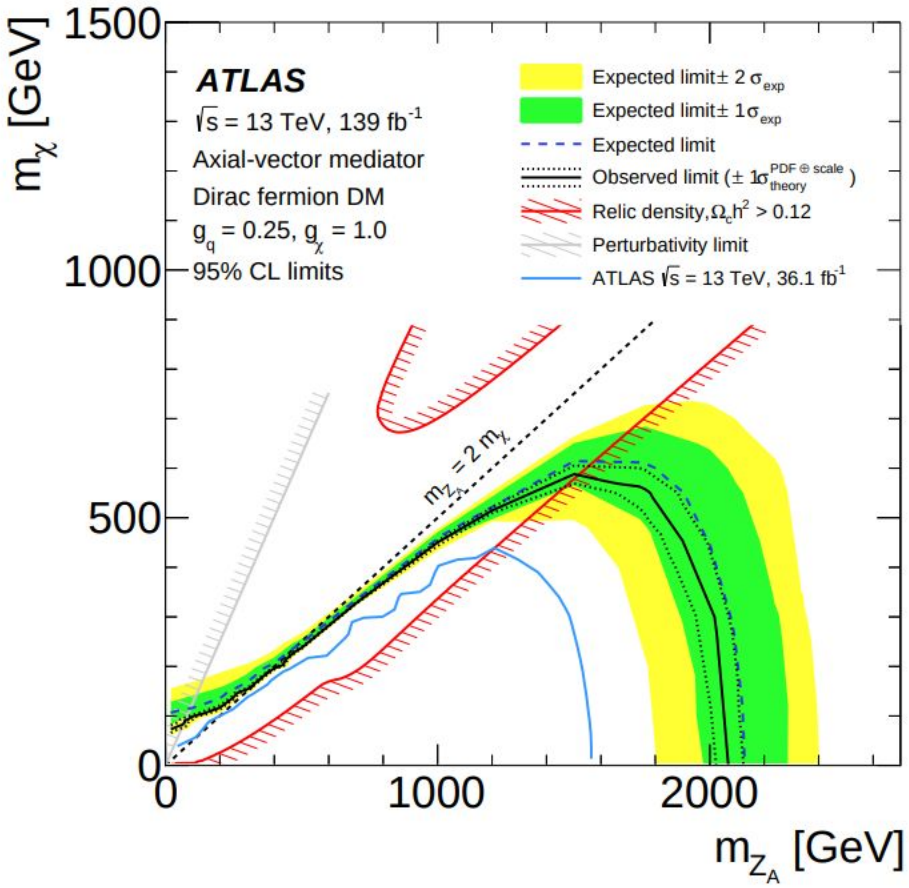


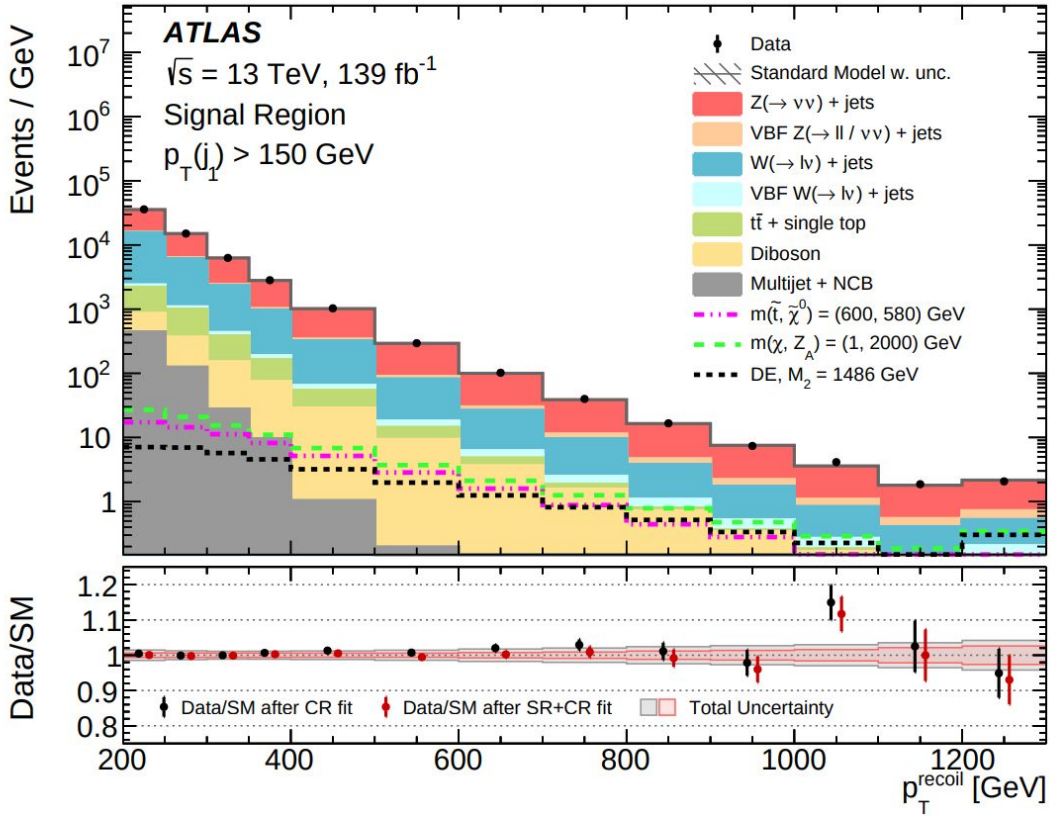
E_T^{miss}+jet results

ATLAS / CMS publication

Simultaneous fit of p_T^{recoil} in SR and CRs

- SR: $p_T^{recoil} = \sum p_T^{jet(s)}$
- CR: $p_T^{recoil} = \sum p_T^{jet(s)} + \sum p_T^{lepton(s)}$



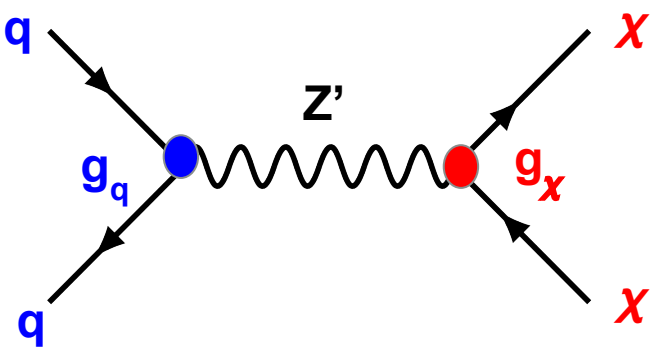


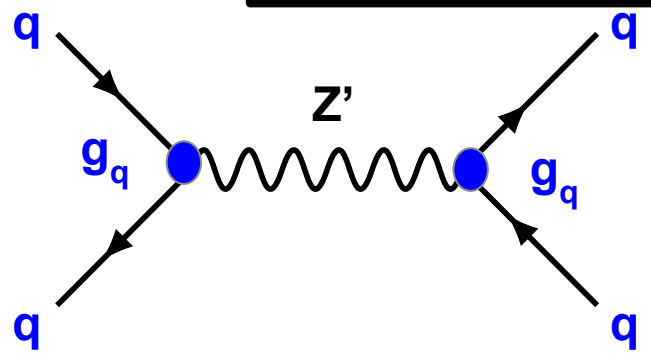
Besides constraining simplified models this analysis can also be interpreted in the context of:

- large extra spatial dimensions
- supersymmetric particles
- axion-like particles
- new scalar particles in dark-energy-inspired models
- invisible branching ratio of the Higgs boson

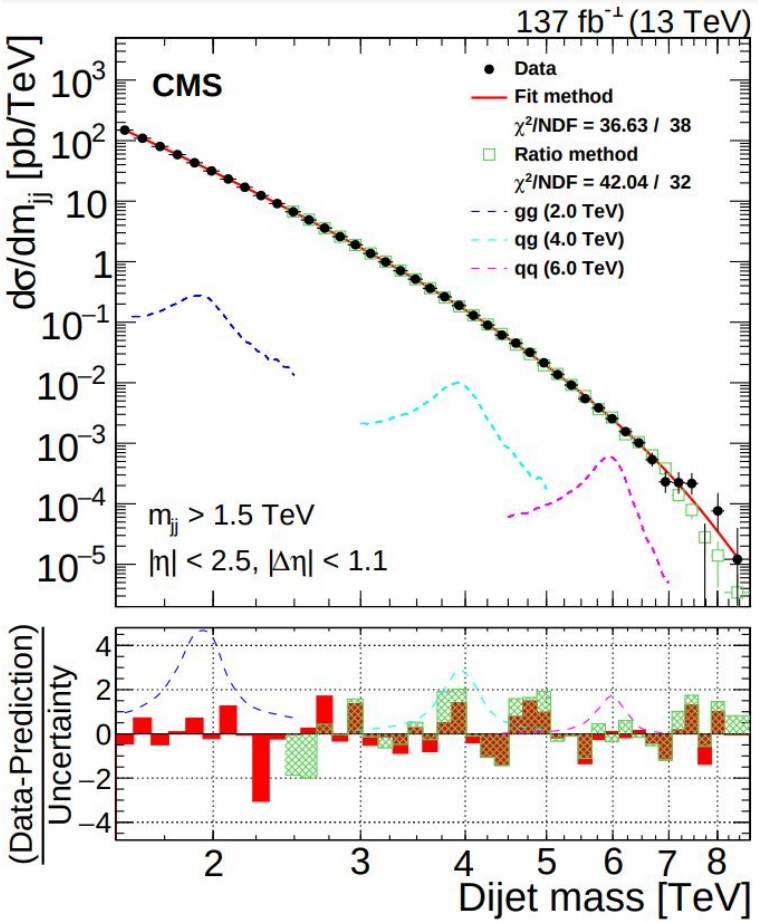
ATLAS / CMS publication

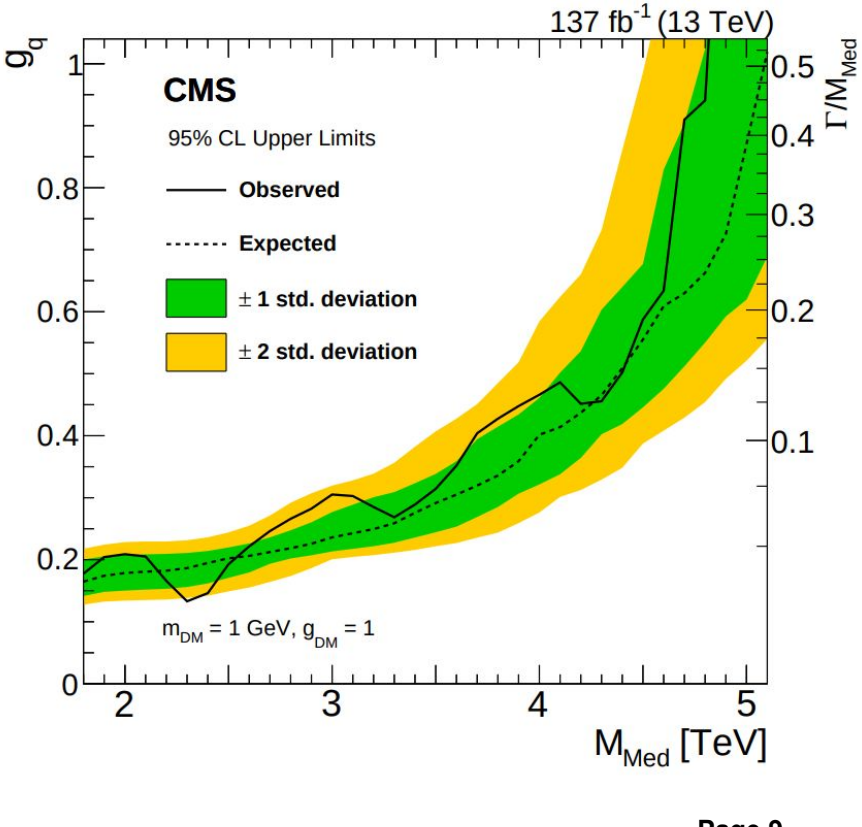
Dijet resonance search





- A new mediator that could couple to quarks would also have a resonance signature
- SM dijet mass spectrum is a smoothly falling spectrum
  - => Can be described by an analytical function
- **New resonance would create a bump in invariant mass distribution**





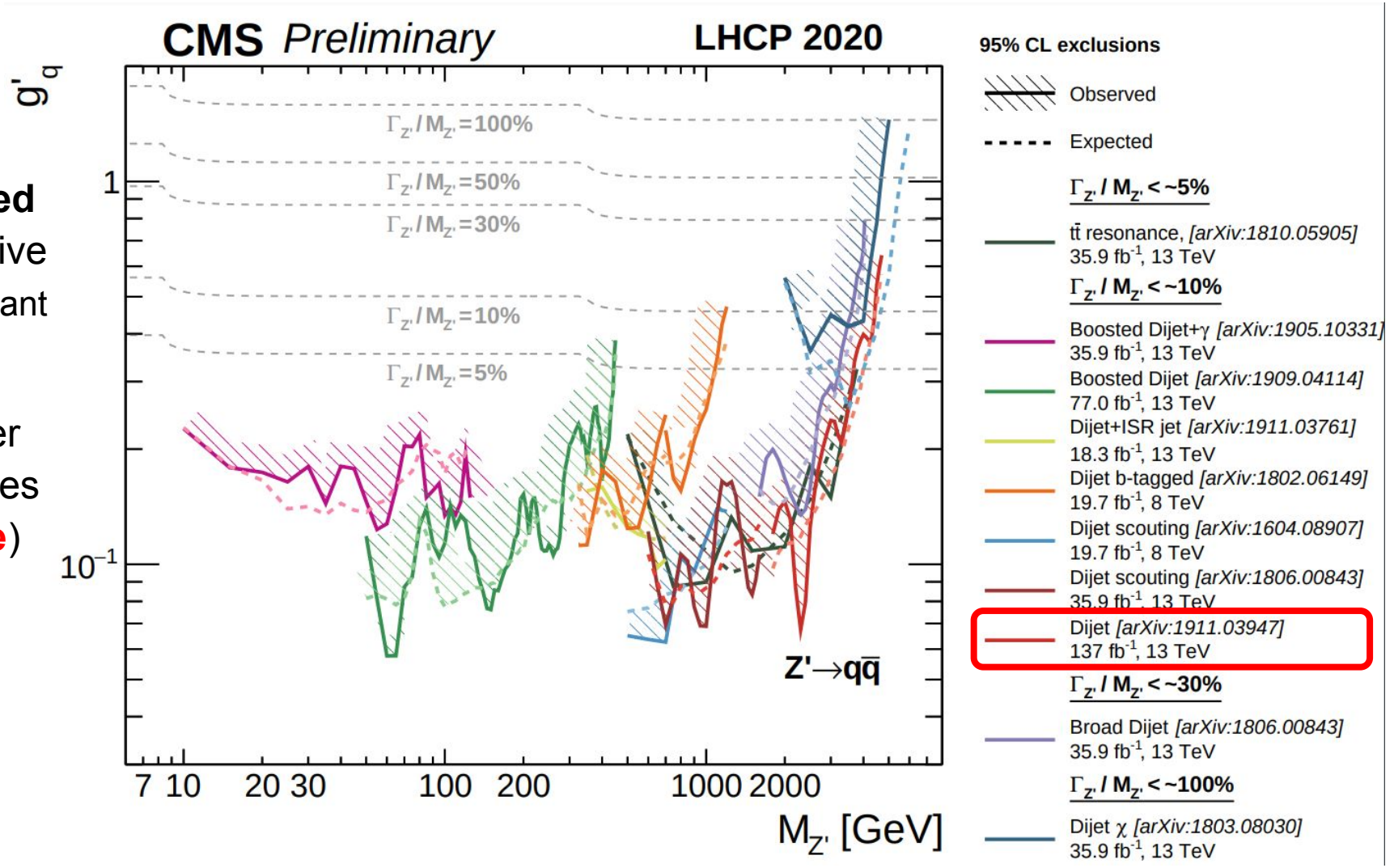
Limiting factor at low dijet masses:

- High event rate
- => Only prescaled trigger

Combination of dijet searches

ATLAS / CMS DM summary plots

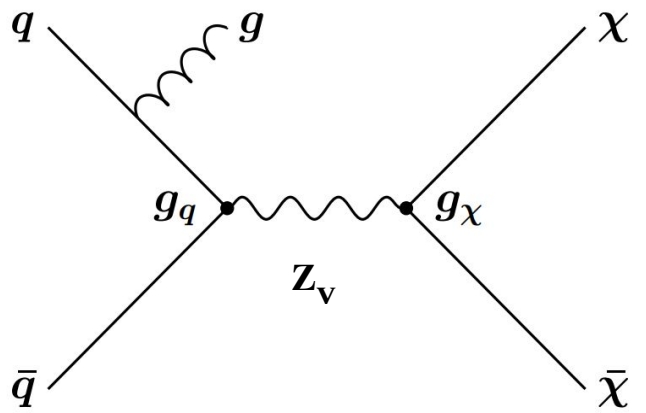
- At low mediator masses **boosted dijet + ISR** searches are sensitive
  - Jet substructure is very important here to distinguish signal from QCD background
- The various dijet searches cover a large range of mediator masses (almost **3 orders of magnitude**)

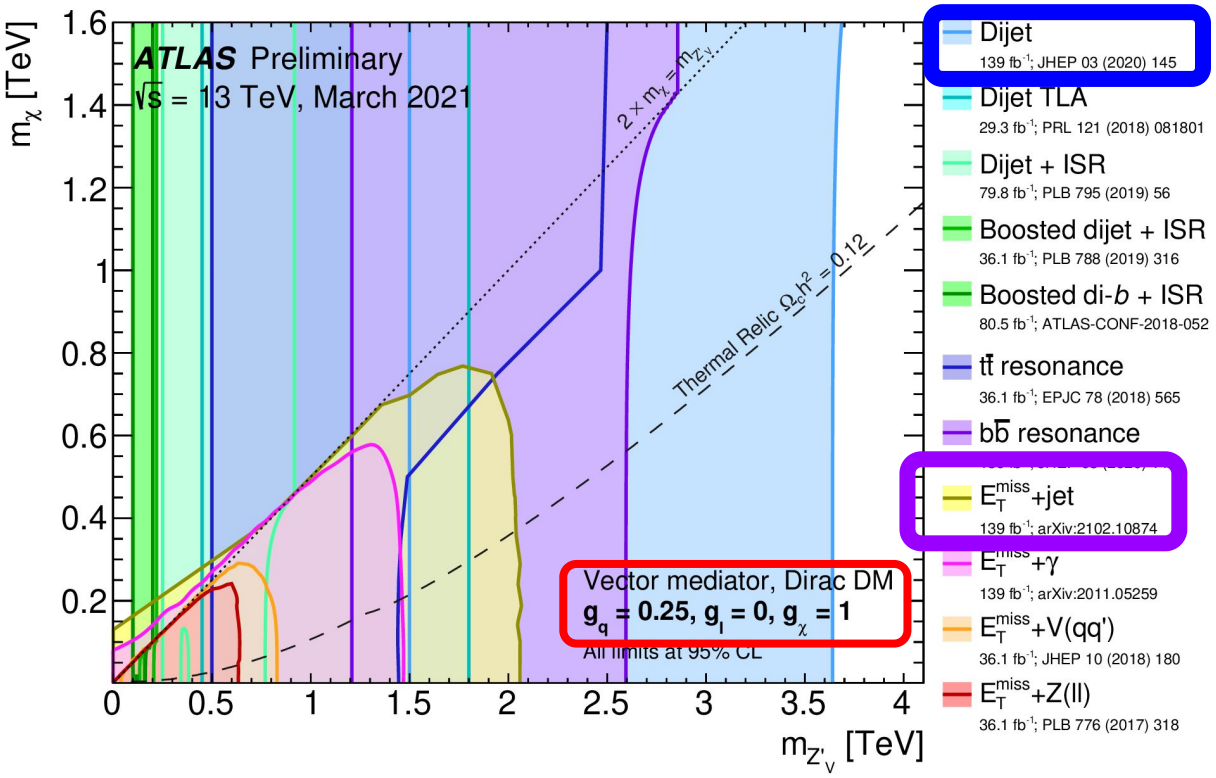


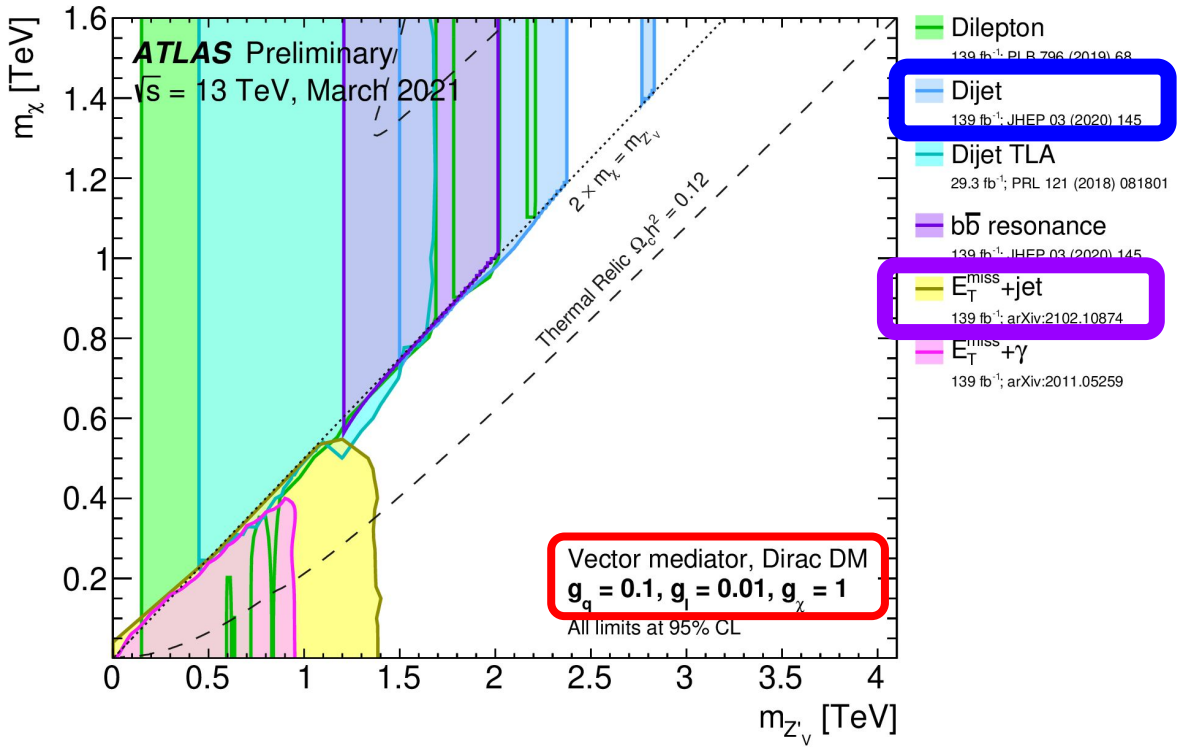
Resonance searches and E_T^{miss}+X searches

ATLAS / CMS DM summary plots

- **Exclusion contours (simplified spin-1 mediator) strongly depend on the choice of parameters**
- Complementary exploration of parameter space





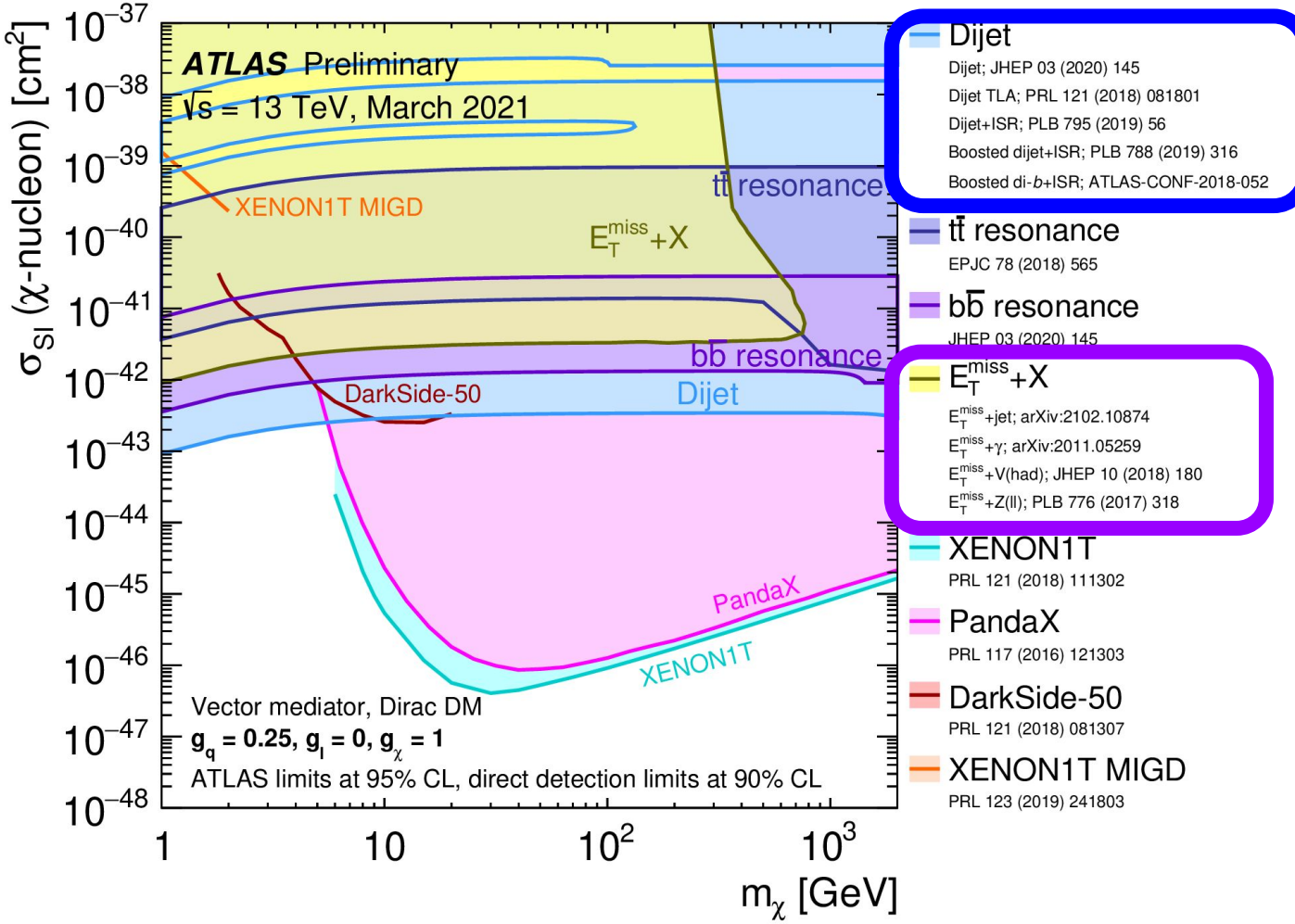


Collider and direct detection experiments

ATLAS / CMS DM summary plots

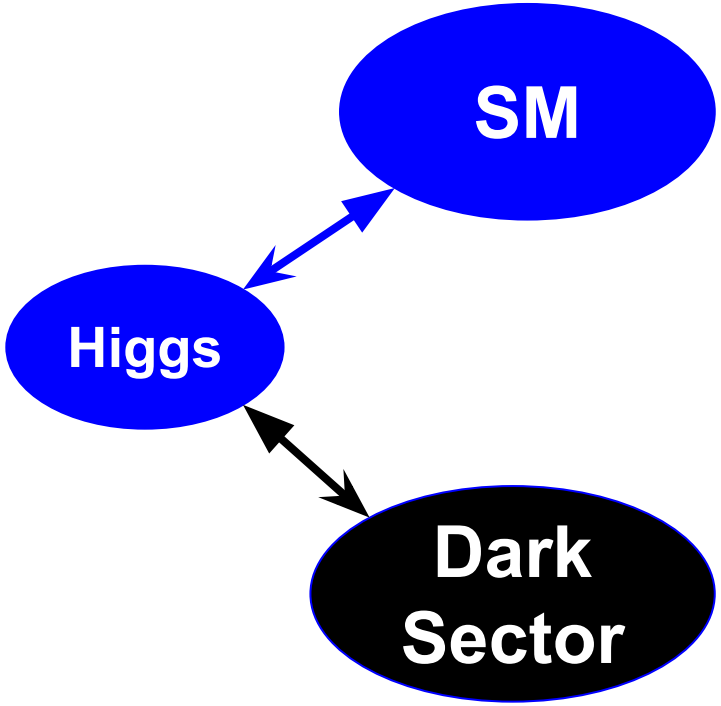
- Limits on the mediator mass can also be translated into **DM-nucleon scattering cross section limits**
  - **Depends strongly on assumptions and choice of parameters**
  - Low DM masses:
    - => Small momentum transfer (recoil)
    - => Low sensitivity for direct detection
  - High DM masses:
    - => Need large mediator masses
    - => Low production cross section @ LHC

- **Collider and direct detection experiments have complementary sensitivity**



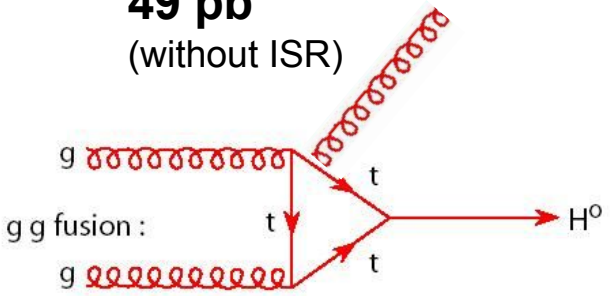
Invisible Higgs boson decays

- DM has mass and could therefore couple to the Higgs boson
- The Higgs boson could be the only bridge between SM particles and the dark sector (Higgs-portal)
- **=> Look for invisible Higgs decays**



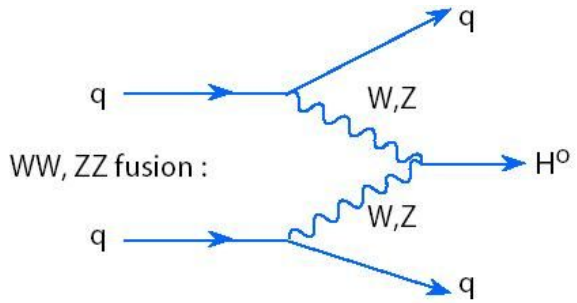
- The Higgs boson has 4 production modes at the LHC
  - gg-fusion + ISR has largest cross section but suffers from large QCD backgrounds
  - **Vector Boson Fusion (VBF) turns out to be the most sensitive**

49 pb
(without ISR)

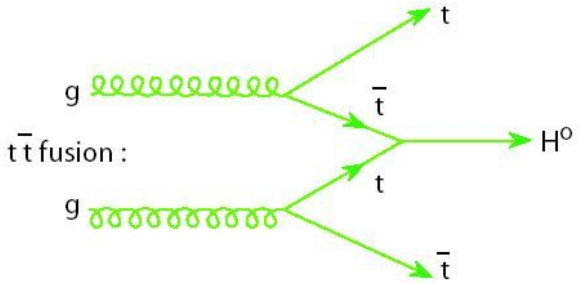


This is mono-jet signature from earlier!

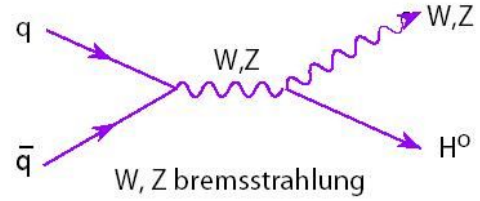
3.8 pb



0.09 pb



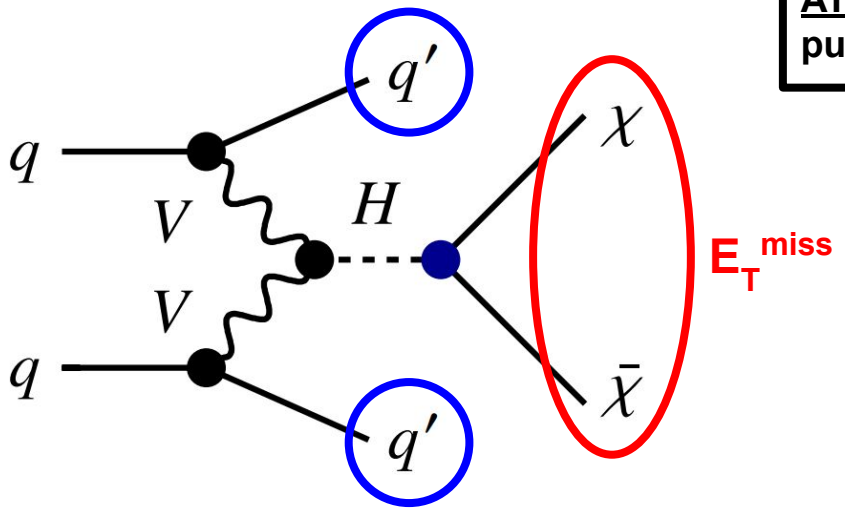
2.3 pb

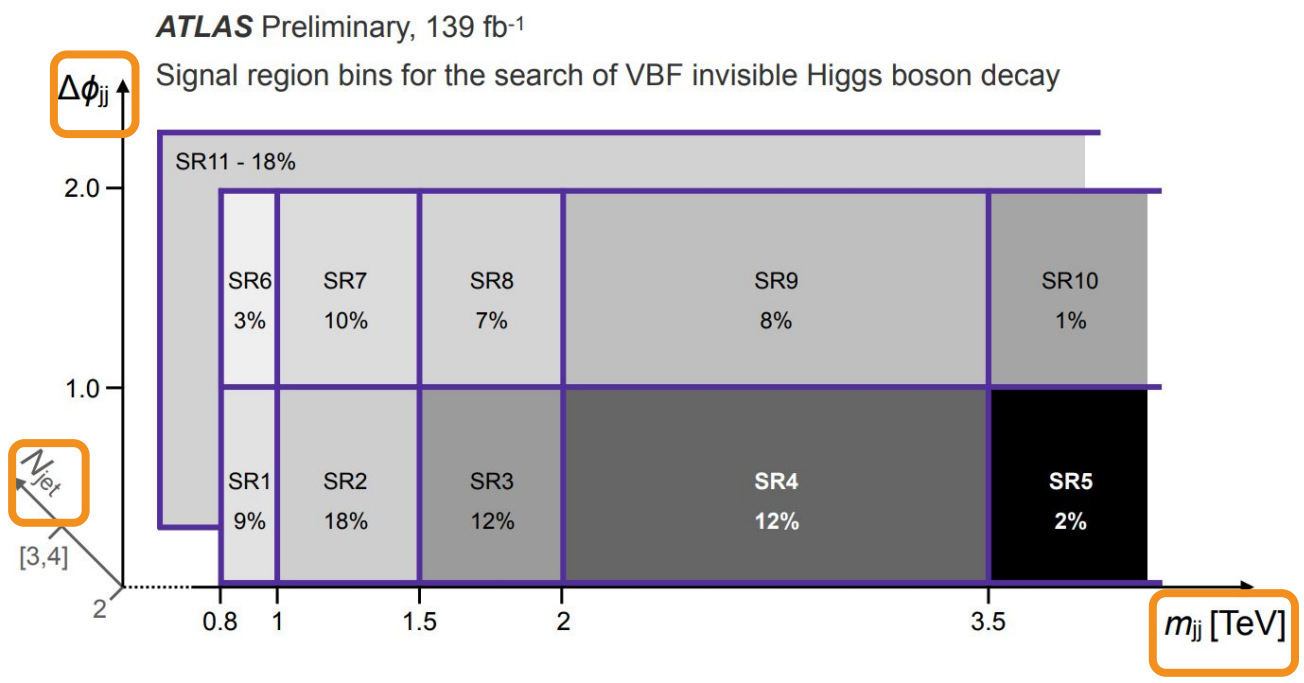


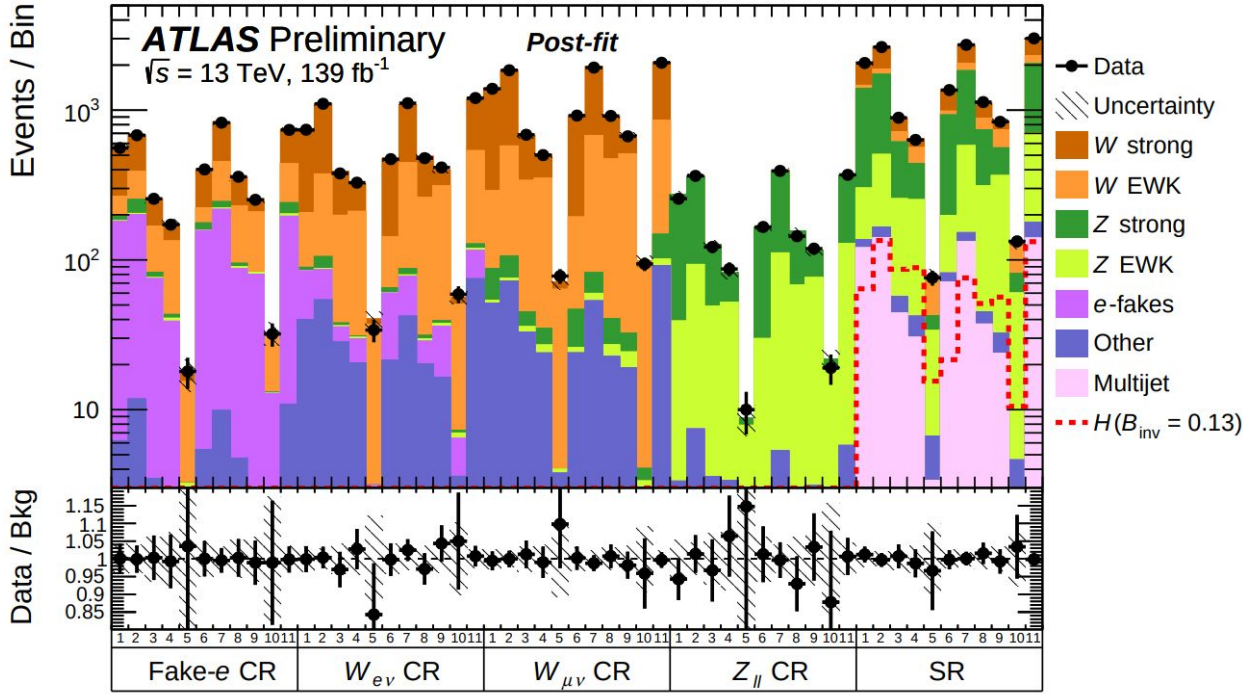
VBF-Higgs(->inv) strategy

ATLAS / CMS publication

- Signature:
  - $\Delta\eta_{jj} > 3.8$
  - Invariant dijet mass > 800 GeV
  - $E_T^{miss} > 200$ GeV
  - No leptons
- Split SR in 11 bins using **3 variables**
- W+jets and Z+jets CRs created by inverting lepton veto



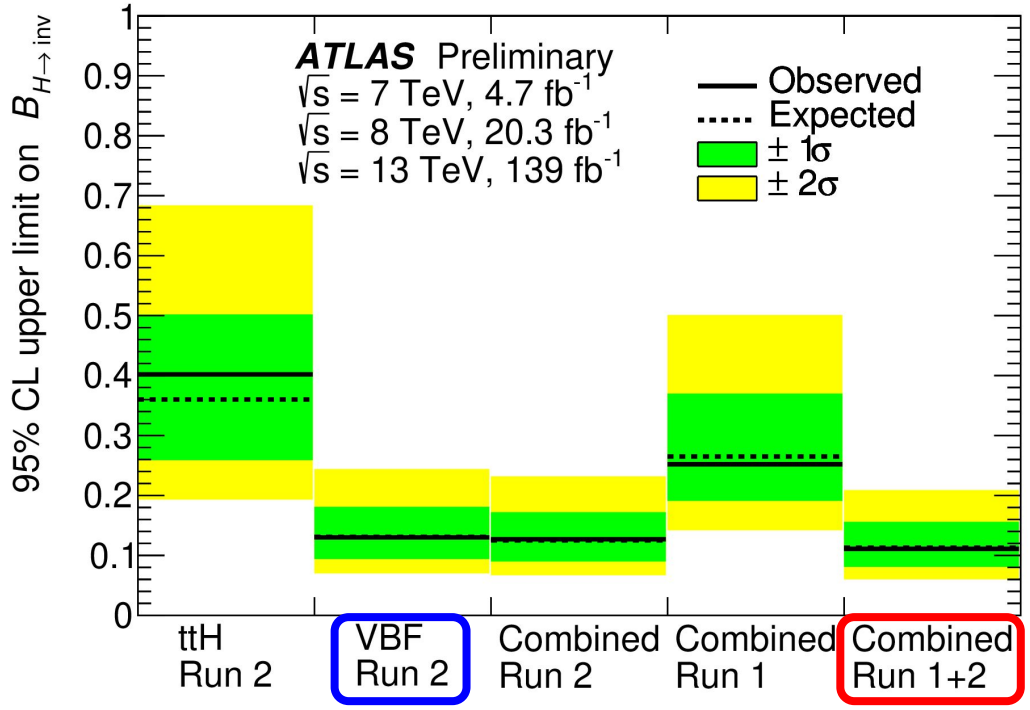




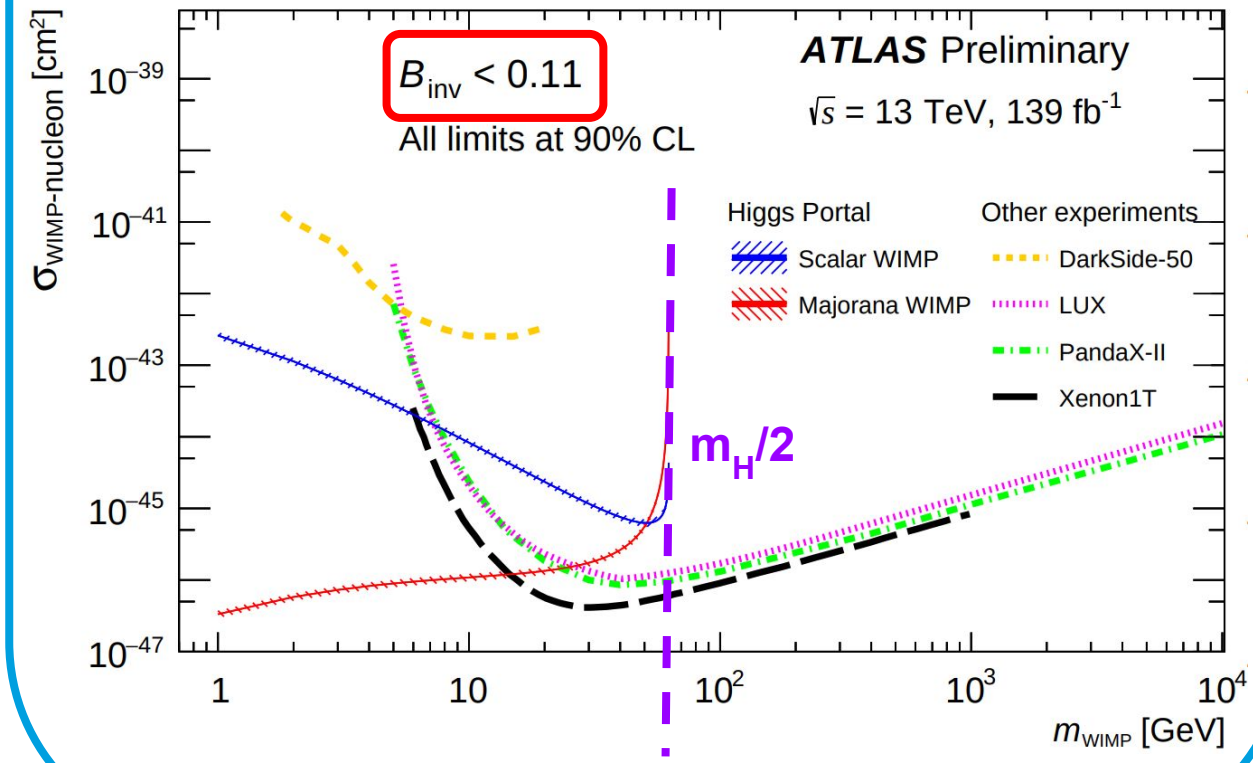
VBF-Higgs(->inv) results

ATLAS / CMS publication

- VBF-H has strongest individual constraint with **BR(H->inv)<13.2%**
- Preliminary combination (**ttH + VBF + Run 1**): **BR(H->inv)<11%**

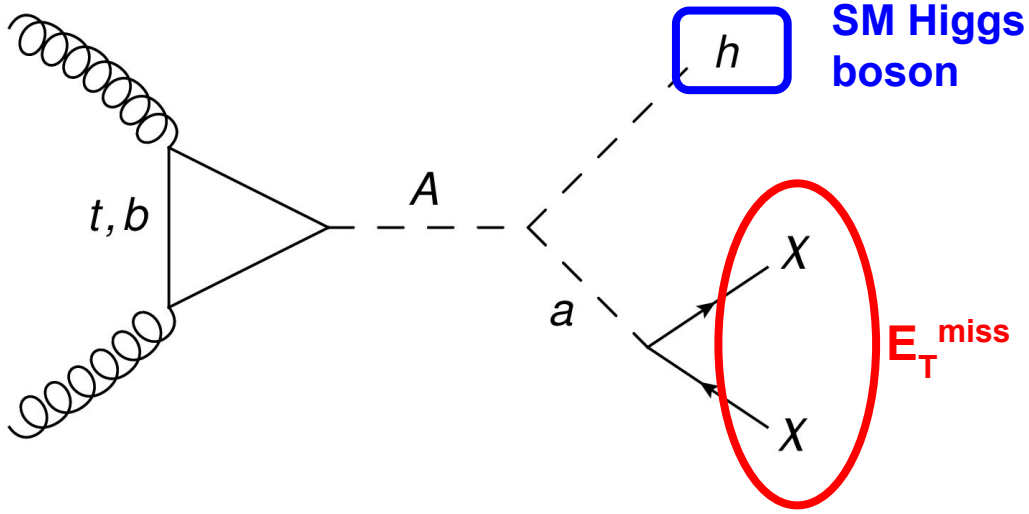


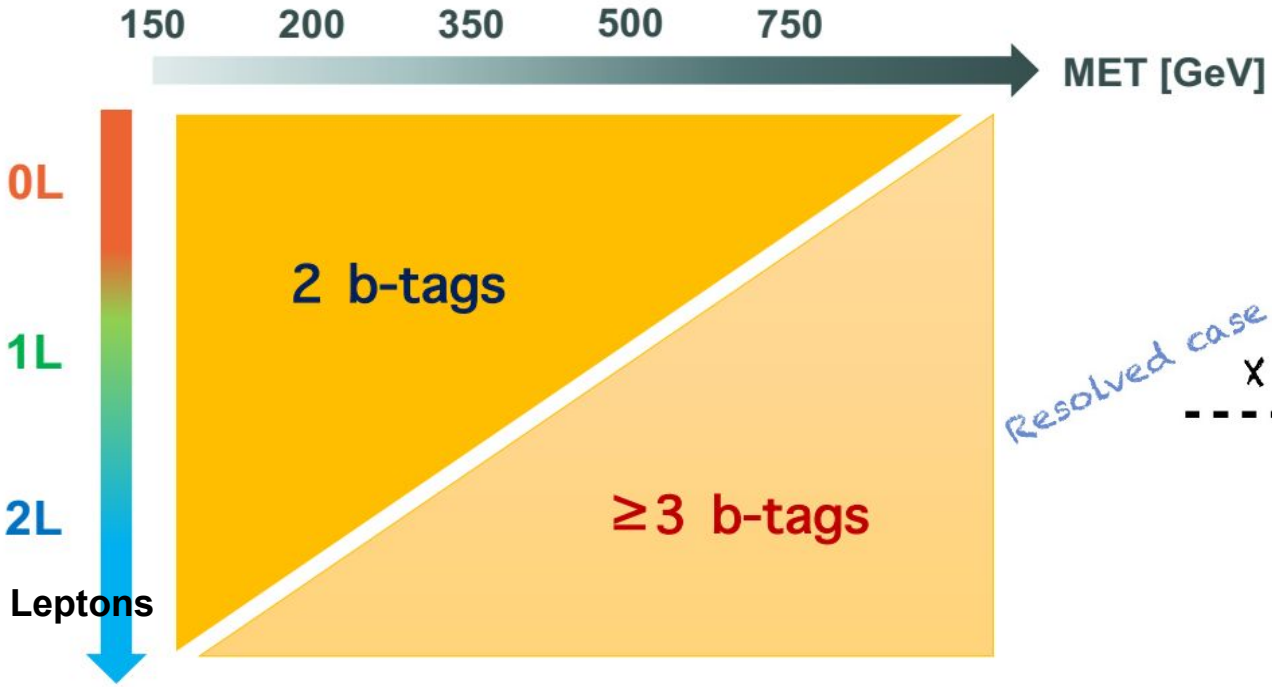
- Can also be interpreted as a limit on the WIMP-nucleon scattering cross section
- **Limits are complementary to those from direct detection experiments**

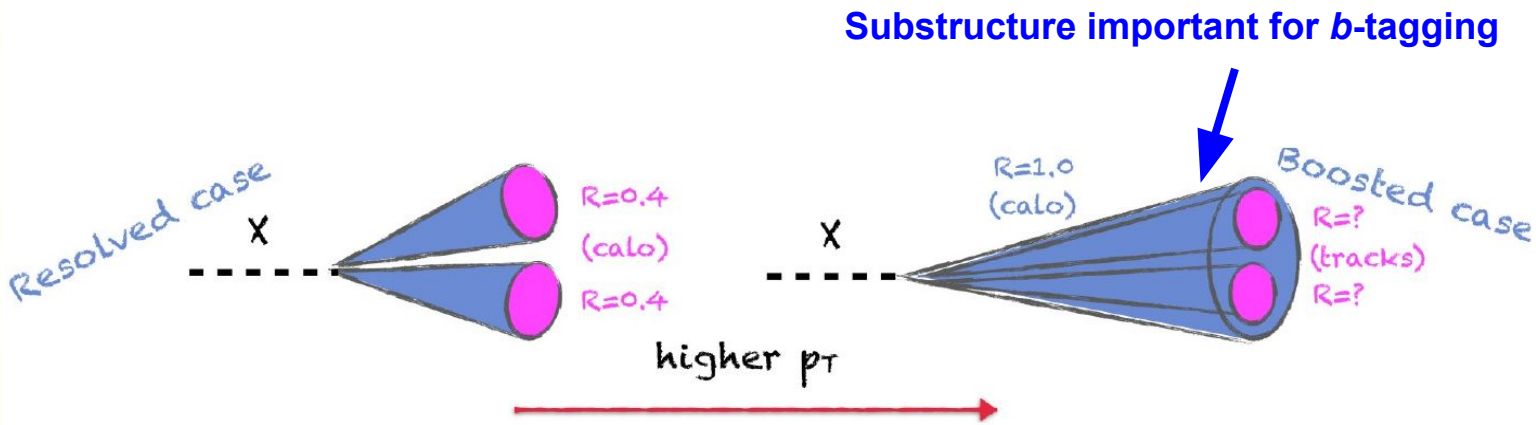


E_T^{miss} + H(->*bb*) strategy

- **Consistent simplified model:** 2HDM+a
  - extends SM with a second Higgs doublet
  - renormalisable and gauge-invariant
  - wide variety of experimental signatures
- Signal signature:
  - >=2 *b*-jets
  - E_T^{miss} > 150 GeV
  - no leptons



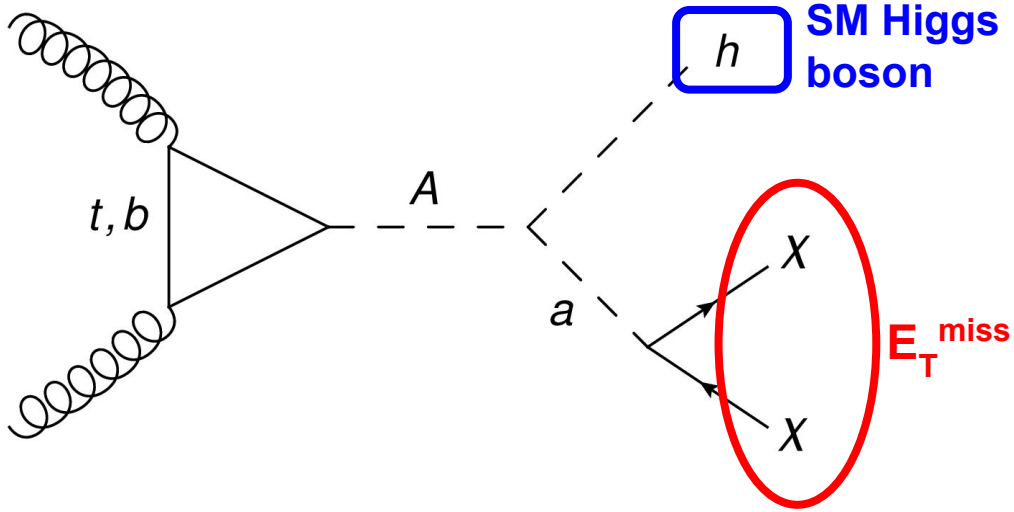


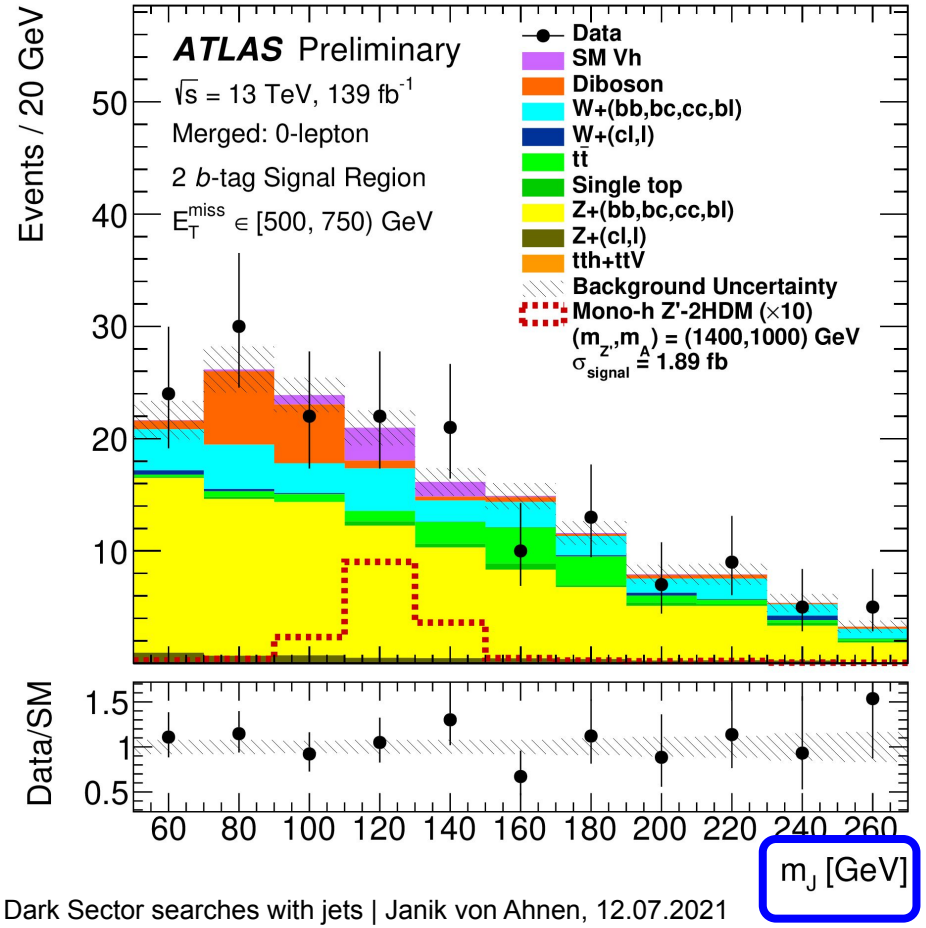


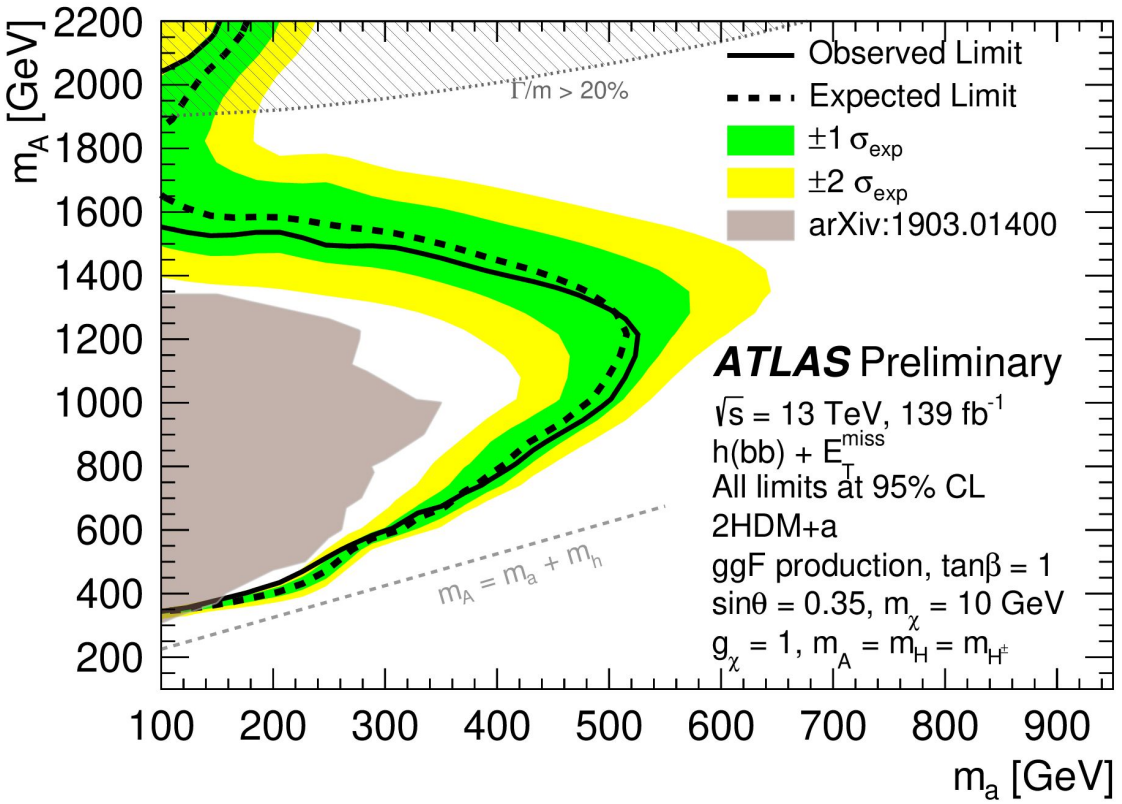
E_T^{miss} + H(->*bb*) results

ATLAS / CMS publication

- Final fit discriminant: m_{bb} / m_J

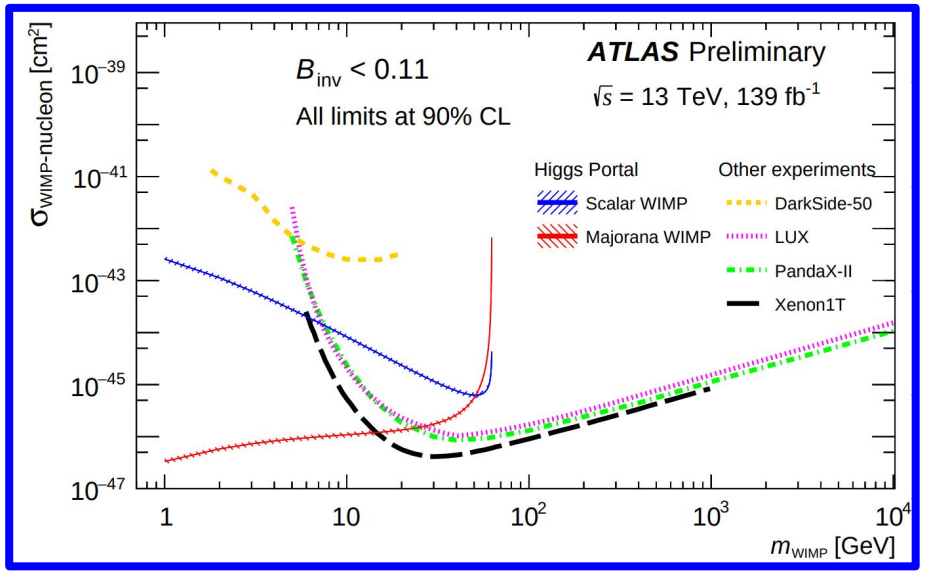


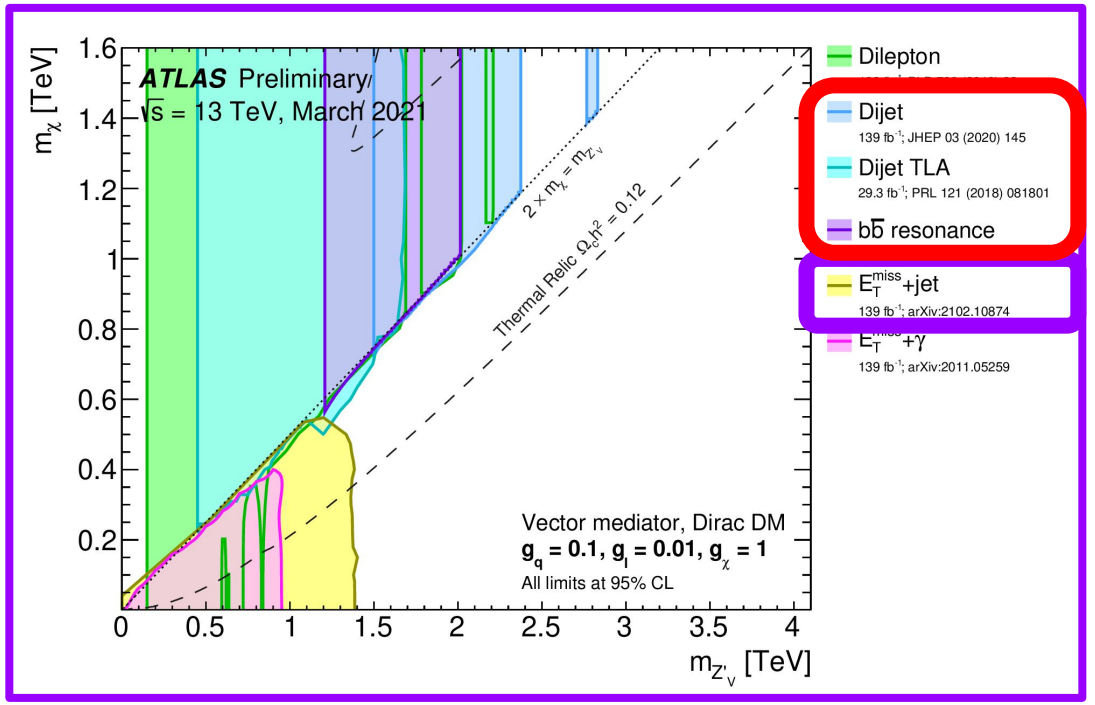


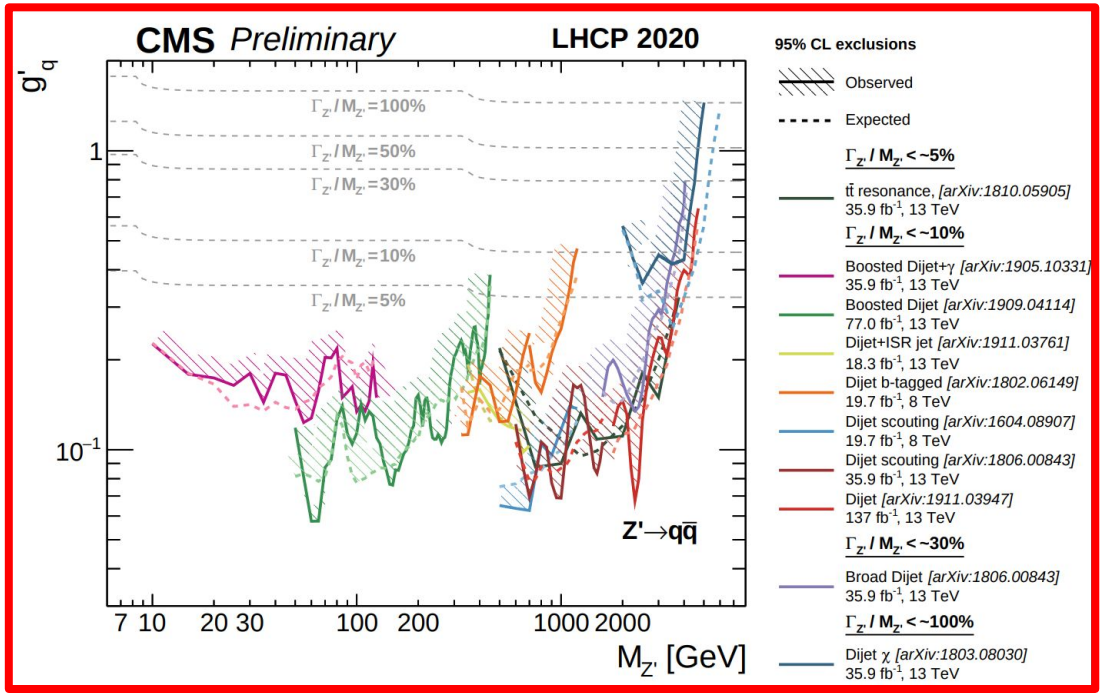


Summary

- E_T^{miss}+jet search
- Dijet resonance searches
- Higgs bosons and the Dark Sector







No evidence for DM yet => ATLAS & CMS need to look closer

- Collect more data (Run 3)
- Improve on experimental techniques (e.g. new triggers)
- Explore new final states

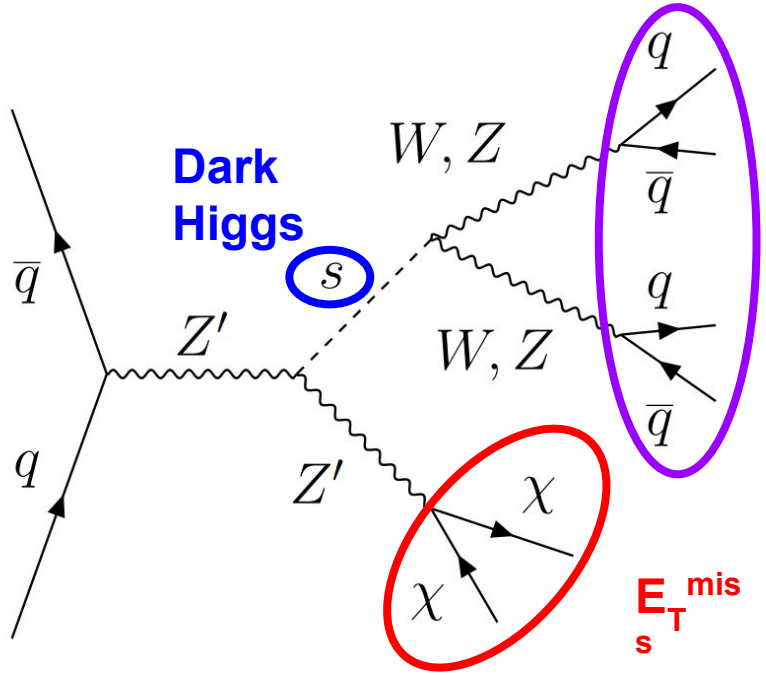
Backup

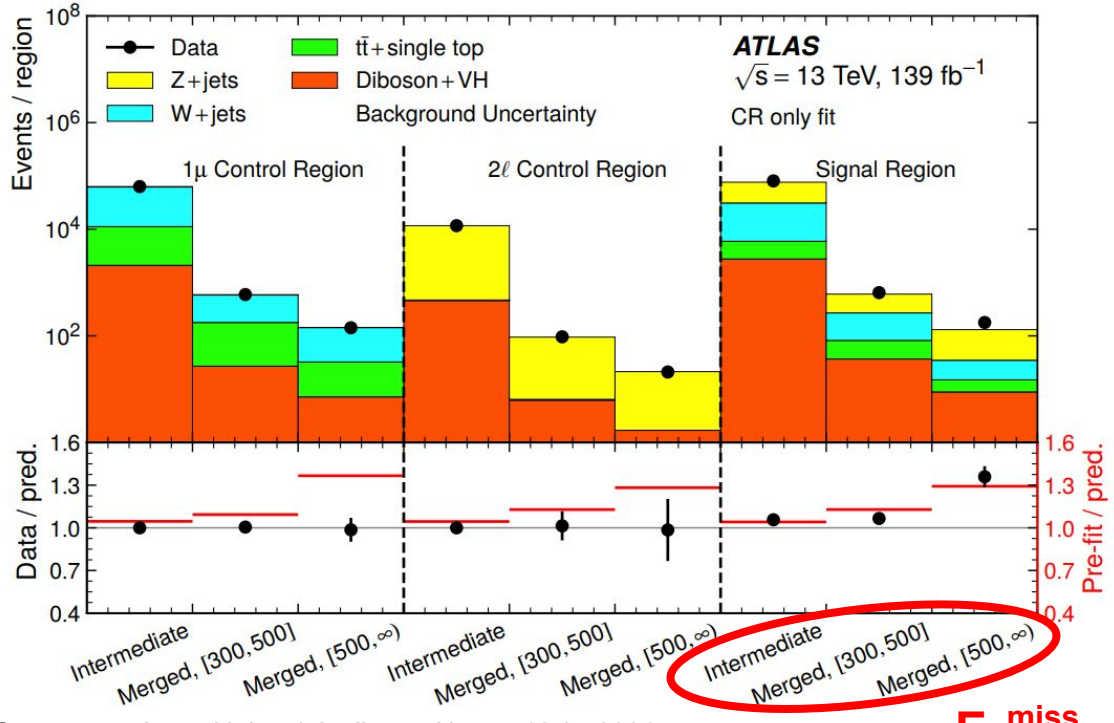
Dark Higgs bosons

Mono-s(->VV) strategy

Dark Higgs Model (JHEP04(2017)143):

- Analogous to the SM Higgs there could be a dark Higgs giving mass to DM particles
- Additional mediator (Z') introduced which couples to SM and the dark Higgs





E_T^{miss} regions

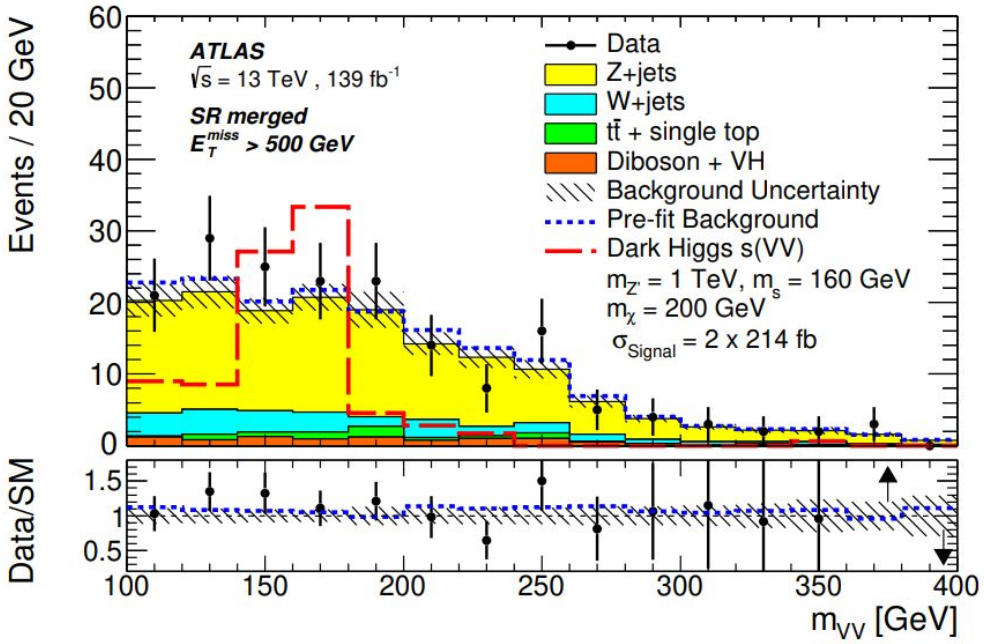
Strategy

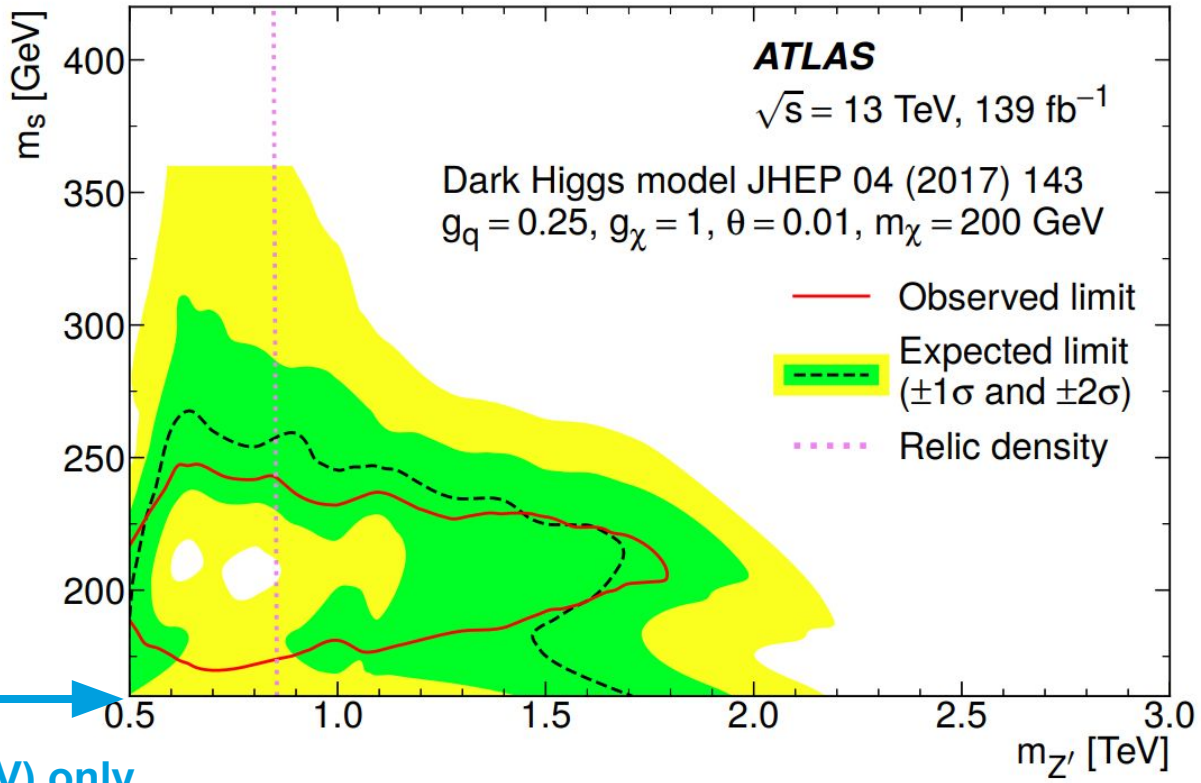
- Look for events with a large radius jet recoiling against large E_T^{miss}(>200 GeV)
- Use number of leptons in the event to classify SR as well as CRs for W+jets and Z+jets

Dark Higgs bosons

Mono-s(->VV) results

- Simultaneous fit on $\mathbf{m_{VV}}$ in the SR and CRs
- Dark higgs model has 5 parameters
- Exploring 2D $\mathbf{m_{Z'}}$-$\mathbf{m_s}$ slice of parameter space



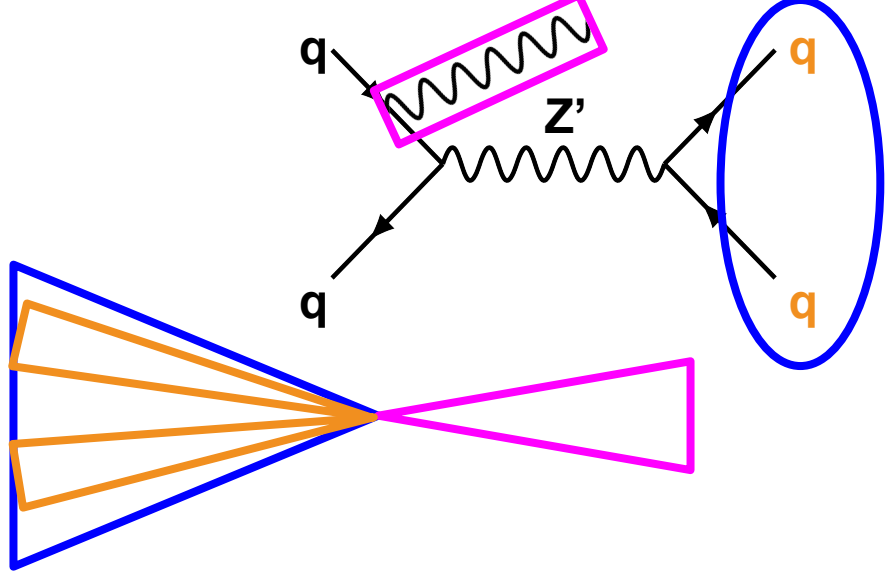


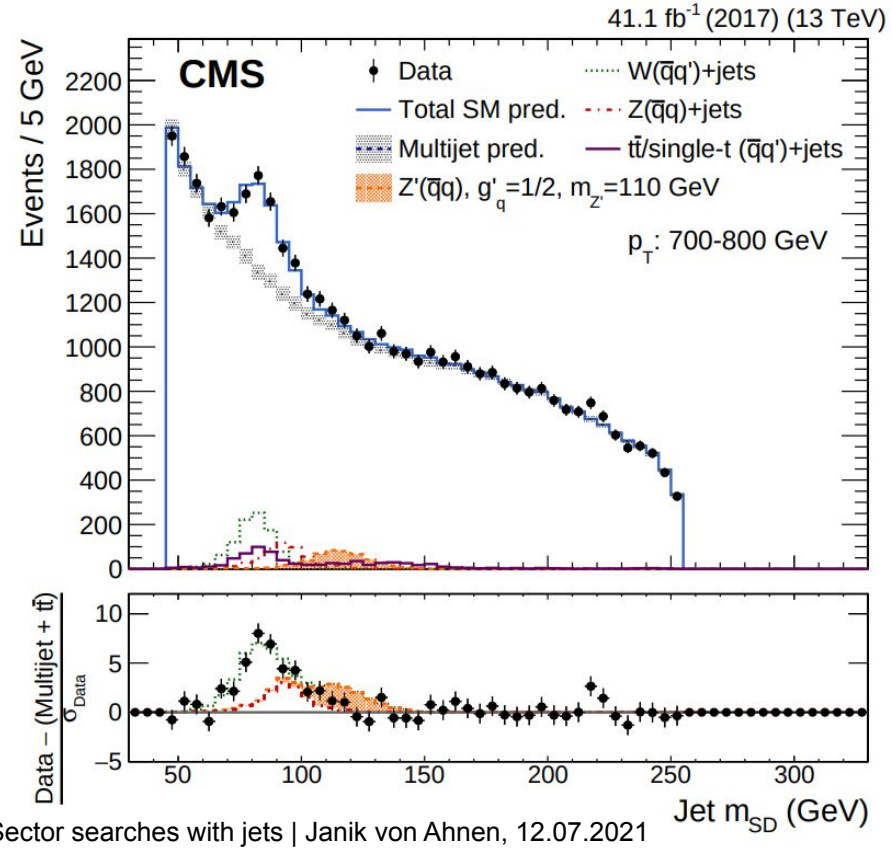
BR(s->VV) only significant for mS>160 GeV

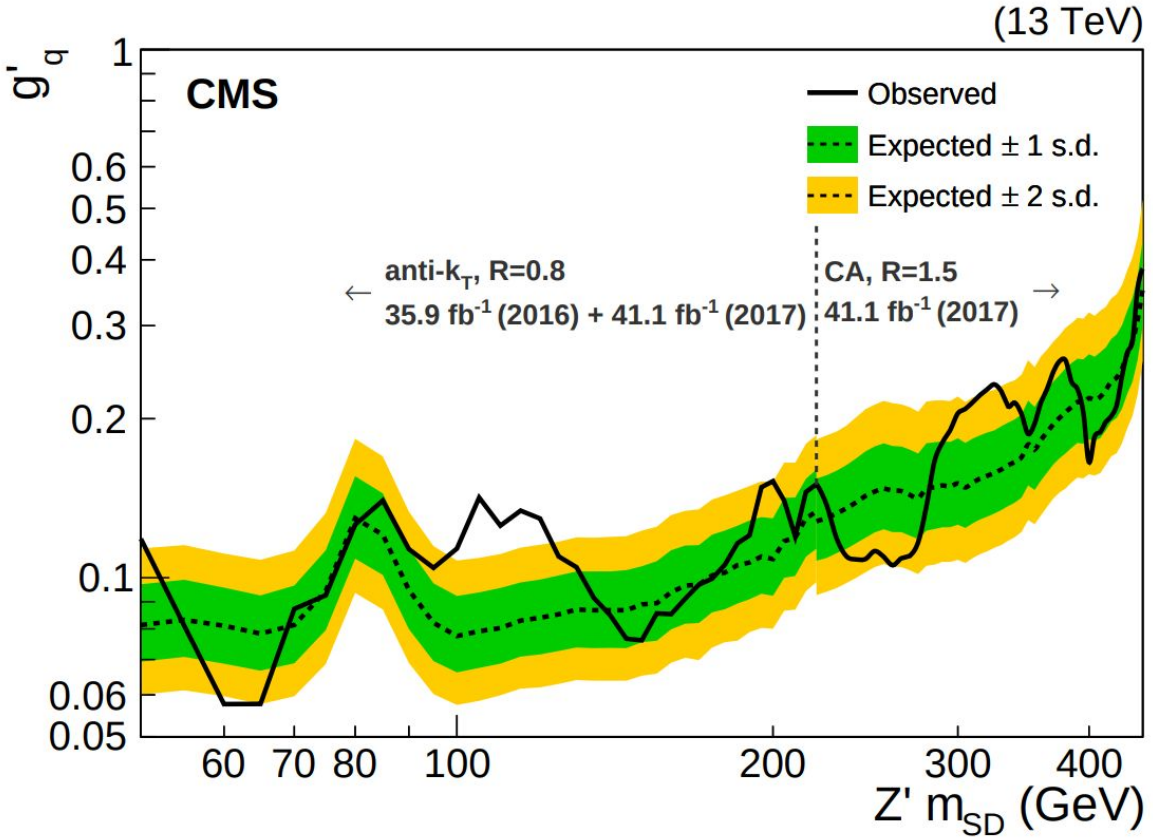
Low-mass resonance searches

Boosted dijet analysis

- Signature:
  - One large radius jet with a 2 prong substructure recoiling against a jet from initial state radiation
- 1-muon CR to control ttbar
- Fitting the large radius jet soft drop mass in different $\mathbf{p_T}$ bins

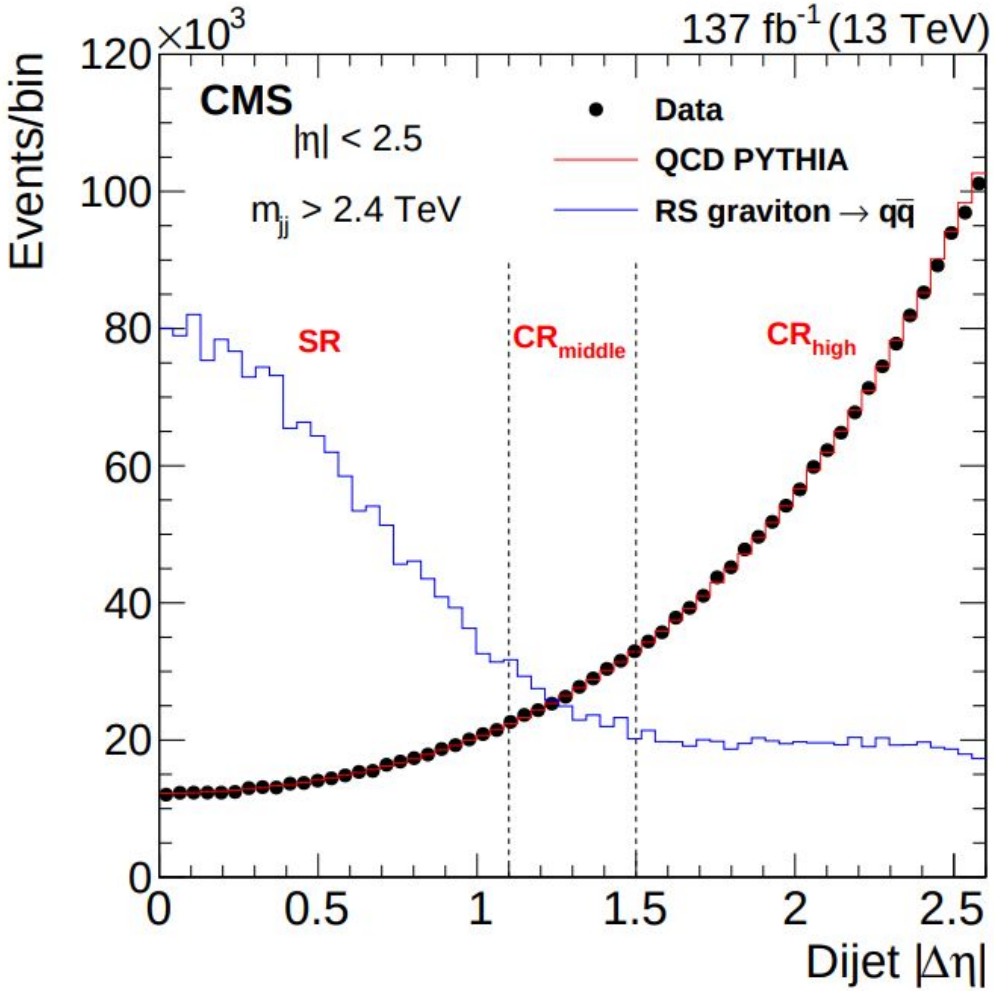


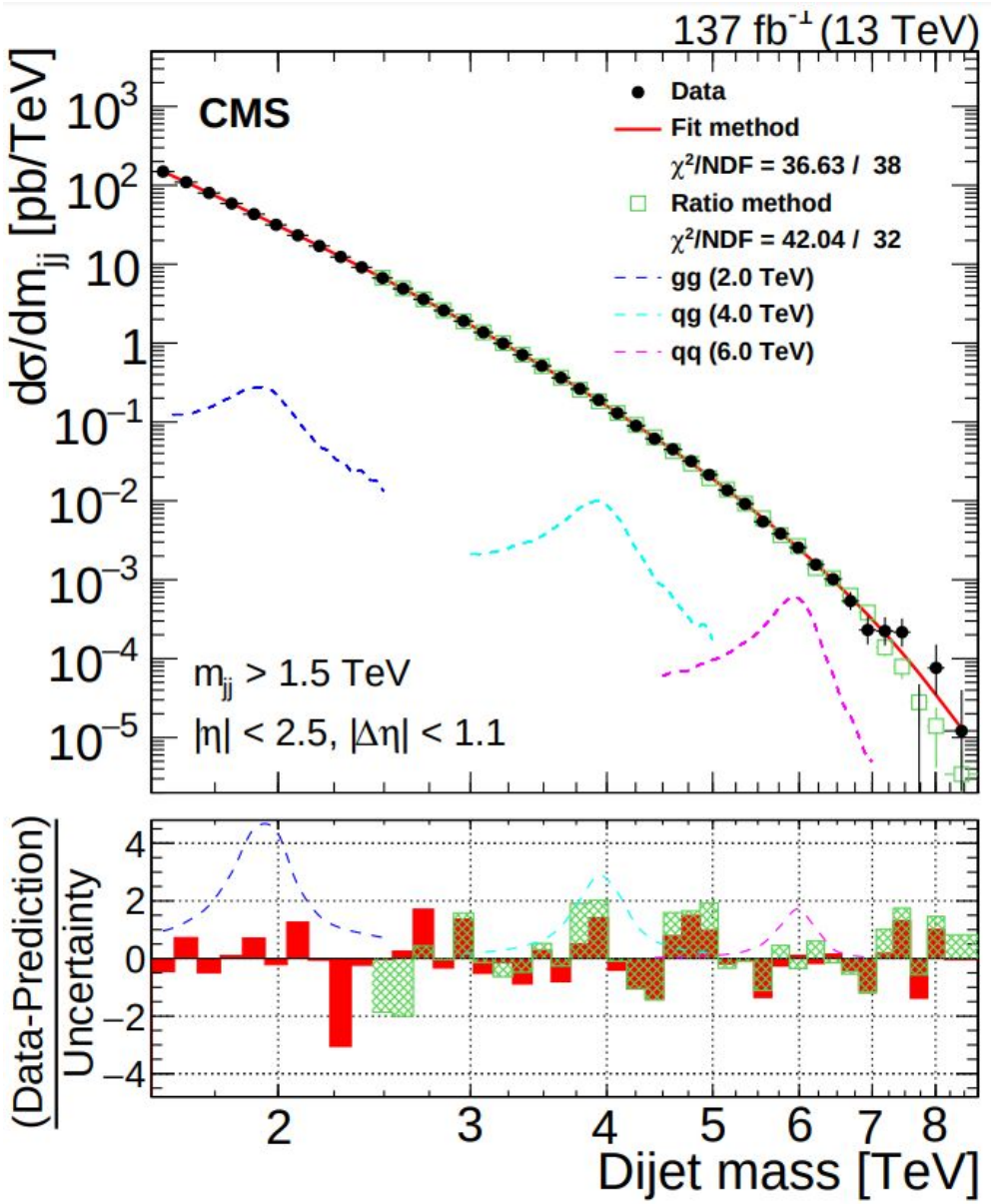




Resonance searches

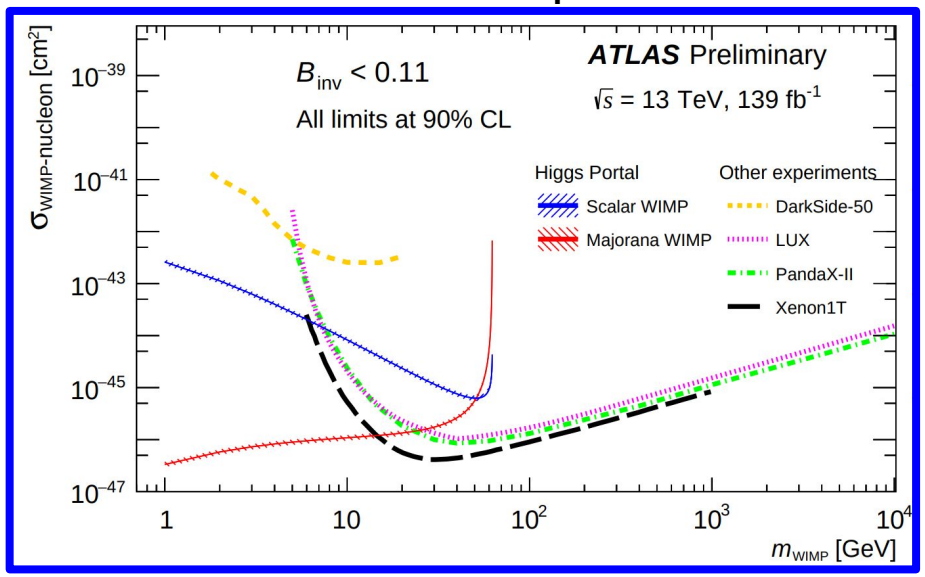
di-jet analysis

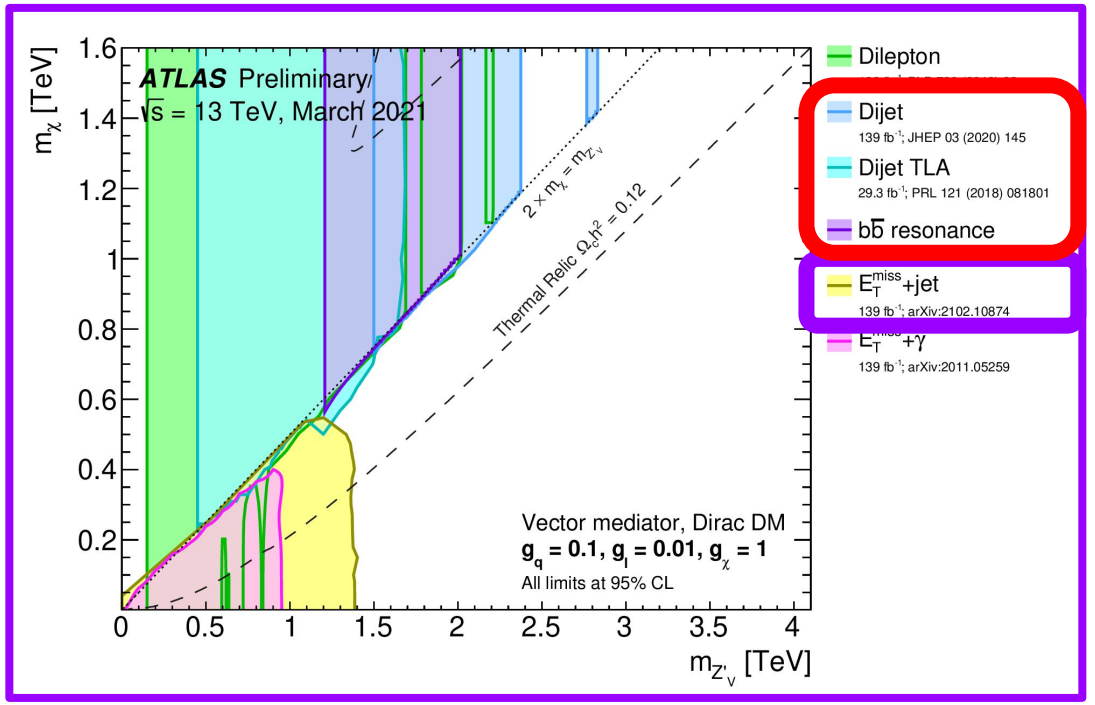


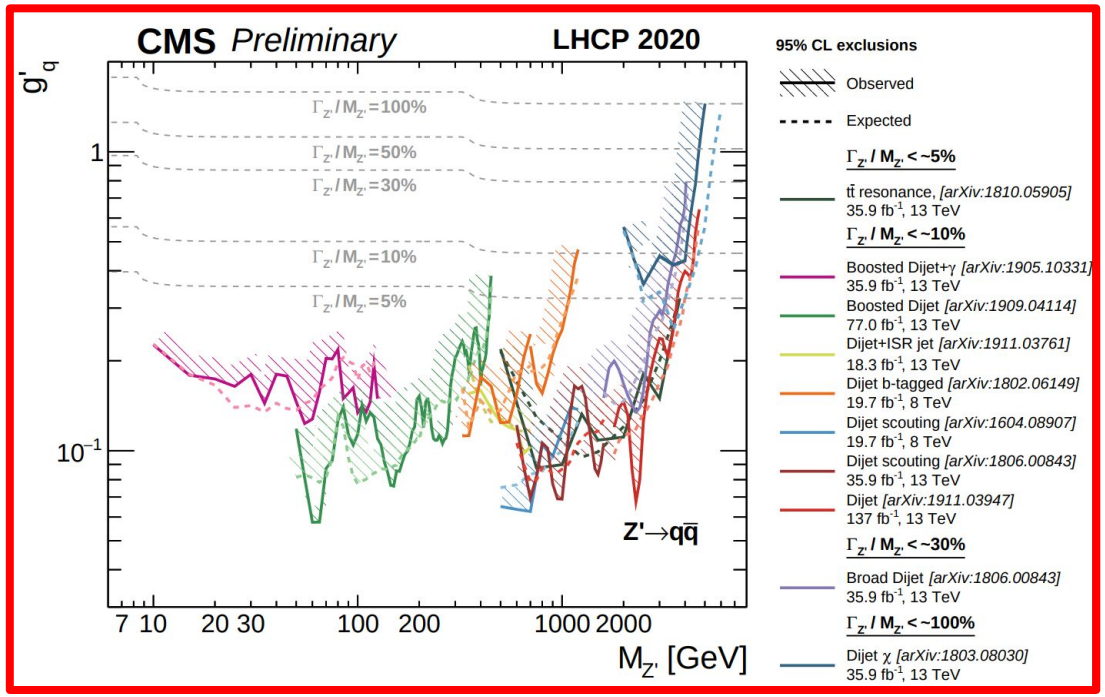


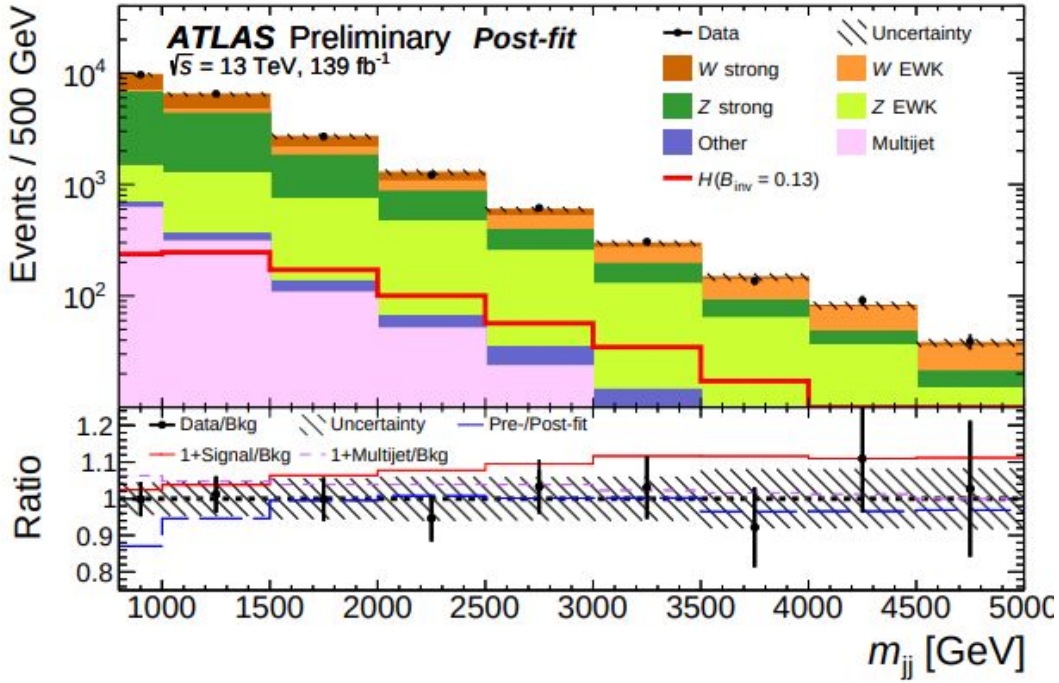
Summary

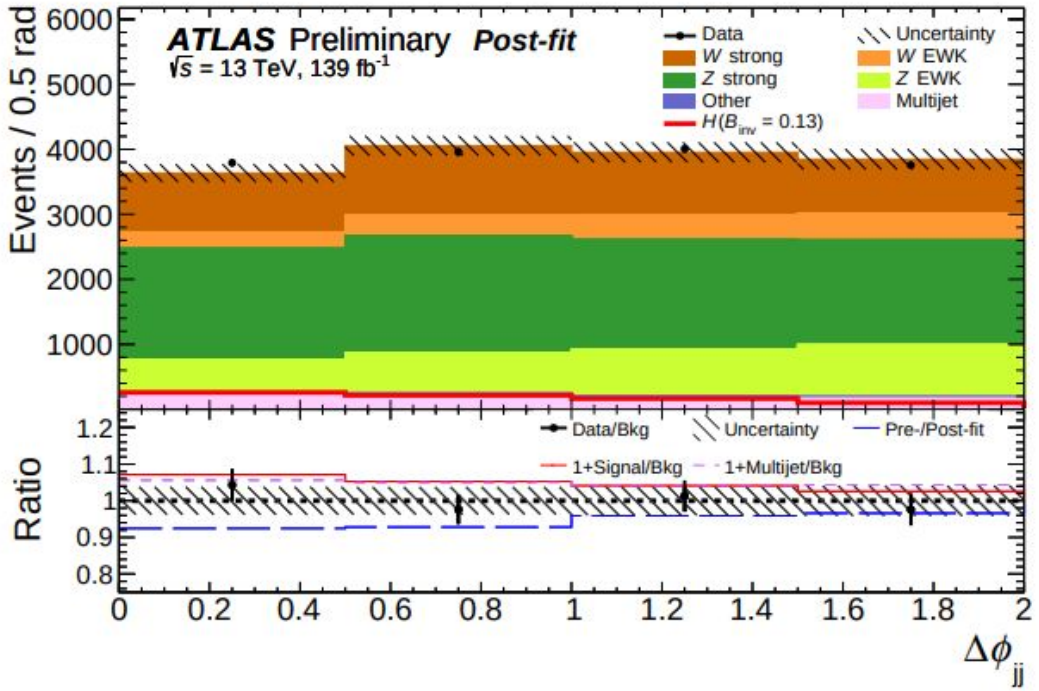
- **E_T^{miss}+jet search**
  - Variety of interpretations
- **Dijet resonance searches**
  - Cover a large range of mediator masses
  - Complementary approach to **E_T^{miss}+X**
- **Higgs bosons and the Dark Sector**
  - Invisible Higgs boson decays (VBF-H(->inv)) and direct detection have complementary sensitivity
  - Extended Higgs sector (**E_T^{miss}+H(->bb)**)

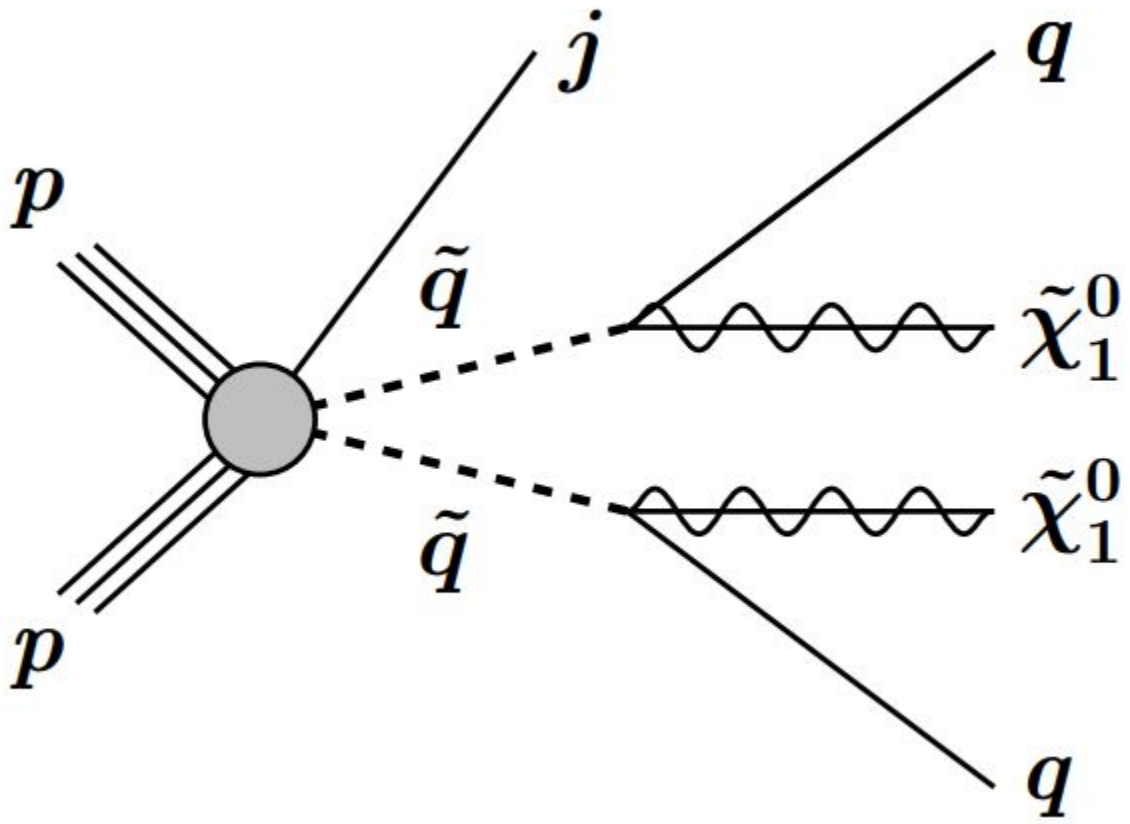







ATLAS Preliminary Post-fit
√s = 13 TeV, 139 fb-1
Data
W strong
Z strong
Other
H(Binv = 0.13)
Uncertainty
W EWK
Z EWK
Multijet
Events / 500 GeV
Data/Bkg
Uncertainty
Pre-/Post-fit
1+Signal/Bkg
1+Multijet/Bkg
Ratio
mjj [GeV]


ATLAS Preliminary Post-fit
√s = 13 TeV, 139 fb-1
Data
W strong
Z strong
Other
H(Binv = 0.13)
Uncertainty
W EWK
Z EWK
Multijet
Events / 0.5 rad
Data/Bkg
Uncertainty
Pre-/Post-fit
1+Signal/Bkg
1+Multijet/Bkg
Ratio
Δφjj


j
q
p
$\tilde{q}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
$\tilde{q}$
p
q

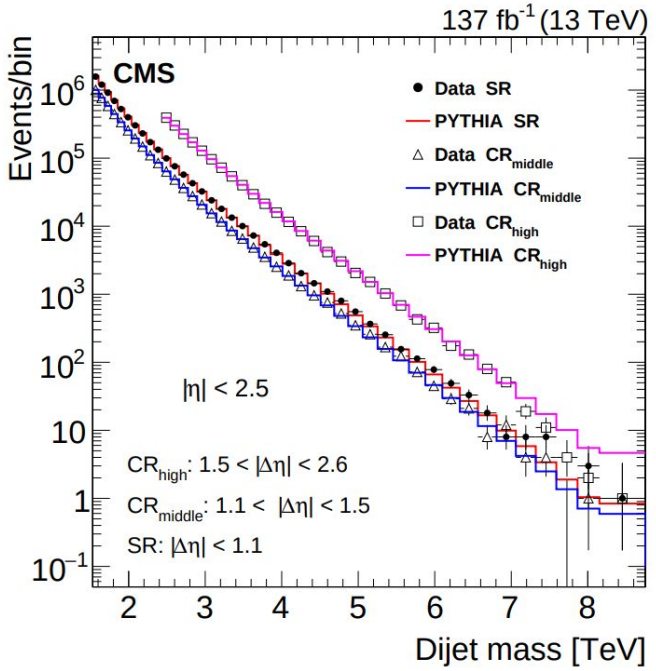
CMS dijet resonance

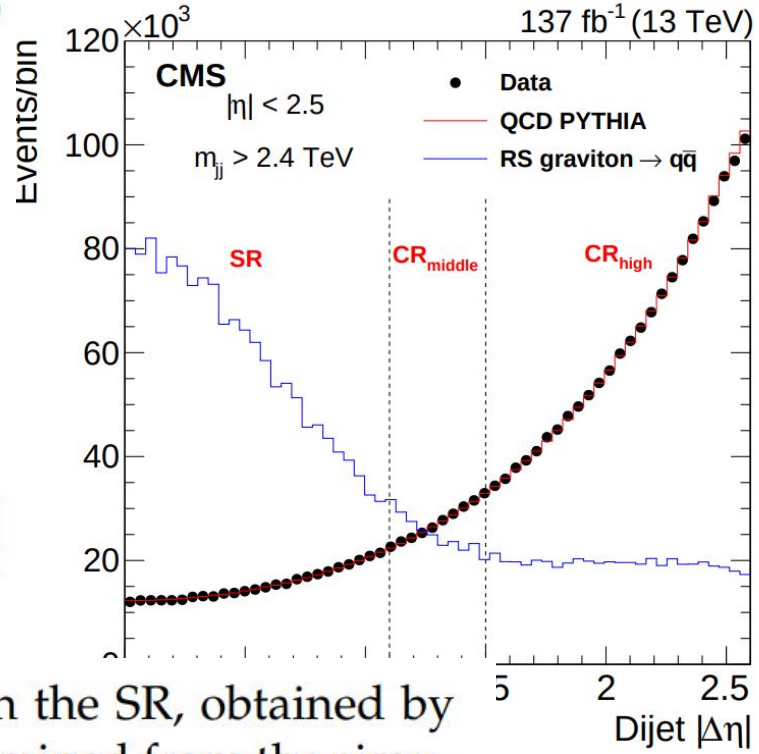
In the fit method, utilized here and in previous dijet resonance searches [17, 19–32, 50], the main background in the SR coming from QCD is parametrized with an empirical function of the form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{jj}}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}, \tag{1}$$

where $x = m_{\mathrm{jj}}/\sqrt{s}$, and P_0, P_1, P_2, and P_3 are four free parameters. The search for resonances

CMS dijet resonance ratio m





The ratio method is a data-driven prediction of the QCD background in the SR, obtained by multiplying the data in $\mathrm{CR_{high}}$ by a mass-dependent transfer factor determined from the simulated angular distribution of QCD dijet production. The transfer factor is the ratio, R, between the simulated dijet mass distribution of background events in the SR and $\mathrm{CR_{high}}$. The method makes use of the following definitions:

$$N(i)^{\mathrm{Prediction}}_{\mathrm{SR}} = R(m_{\mathrm{jj}}/\sqrt{s})\,N(i)^{\mathrm{Data}}_{\mathrm{CR_{high}}},$$
$$R(m_{\mathrm{jj}}/\sqrt{s}) = C(m_{\mathrm{jj}}/\sqrt{s})\,N(i)^{\mathrm{Sim.}}_{\mathrm{SR}}/N(i)^{\mathrm{Sim.}}_{\mathrm{CR_{high}}},$$

where $N(i)$ is the number of events in a given bin, i, of dijet mass and $C(m_{\mathrm{jj}}/\sqrt{s})$ is a correction to the simulated transfer factor. This correction is required because, as seen in the upper right panel of Fig. 4, differences are present between data and the simulation using PYTHIA. These