Heavy Resonance Searches

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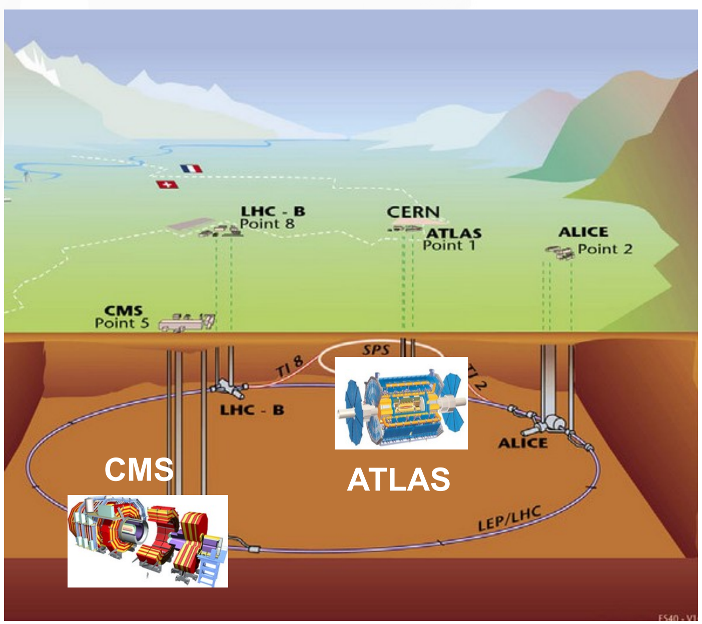
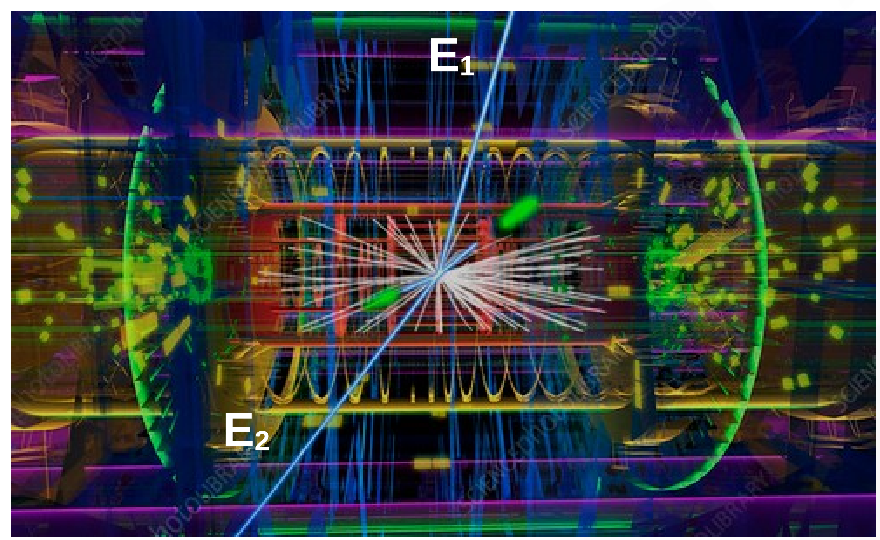
On behalf of the ATLAS and CMS collaborations

10th Edition of the Large Hadron Collider Physics Conference May 16-20, 2022 (Taipei, Taiwan)

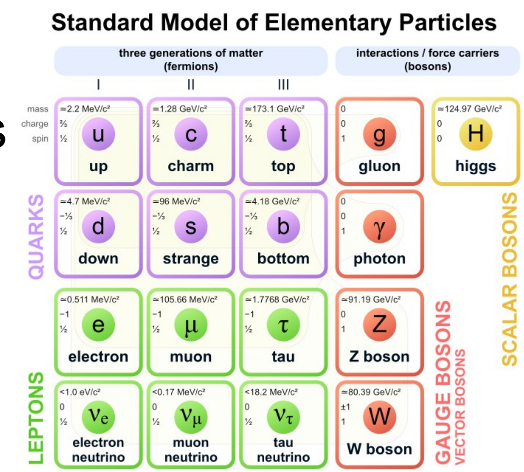
LHC experiments



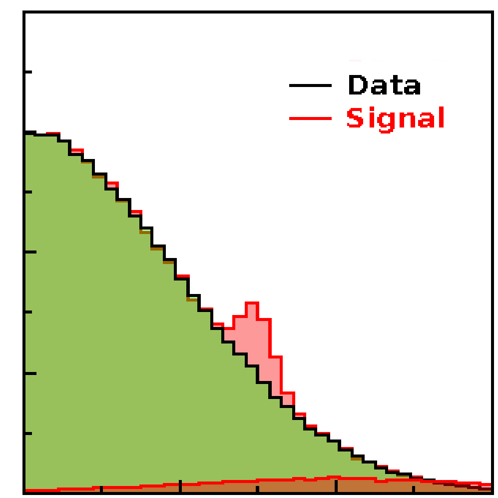


New particles at collider experiments

- Standard Model (SM) is successful for particle collisions
- Discrepancies may indicate new physics ≡ new particles/fields



- **<u>Direct observations</u> of new particles**
  - Combine known particles/jets to create "invariant masses" & search for "resonance" enhancements above background
  - or observe through unusual signatures in detector (anomalously high dE/dx tracks etc)



$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$

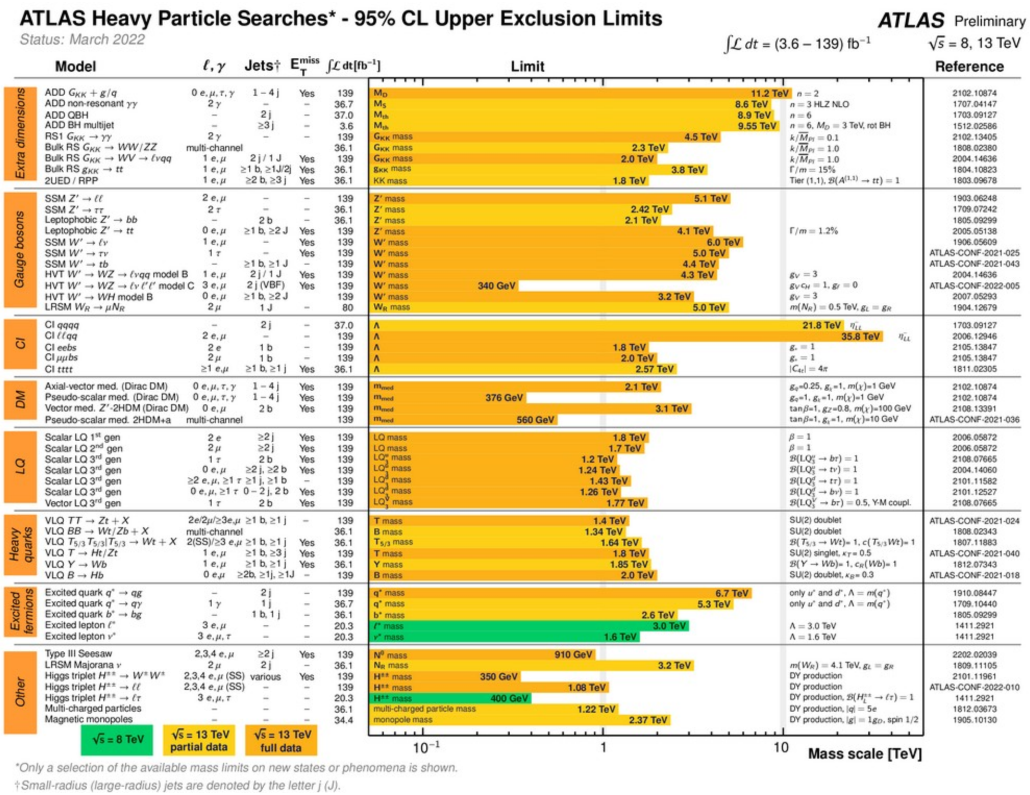
Invariant mass from known particle/jet with energy E and **p**

- **<u>Indirect observations</u> of new particles**
  - Compare SM predictions with data
  - Search for any discrepancy with SM background
  - Explain using theoretical frameworks beyond SM (BSM)

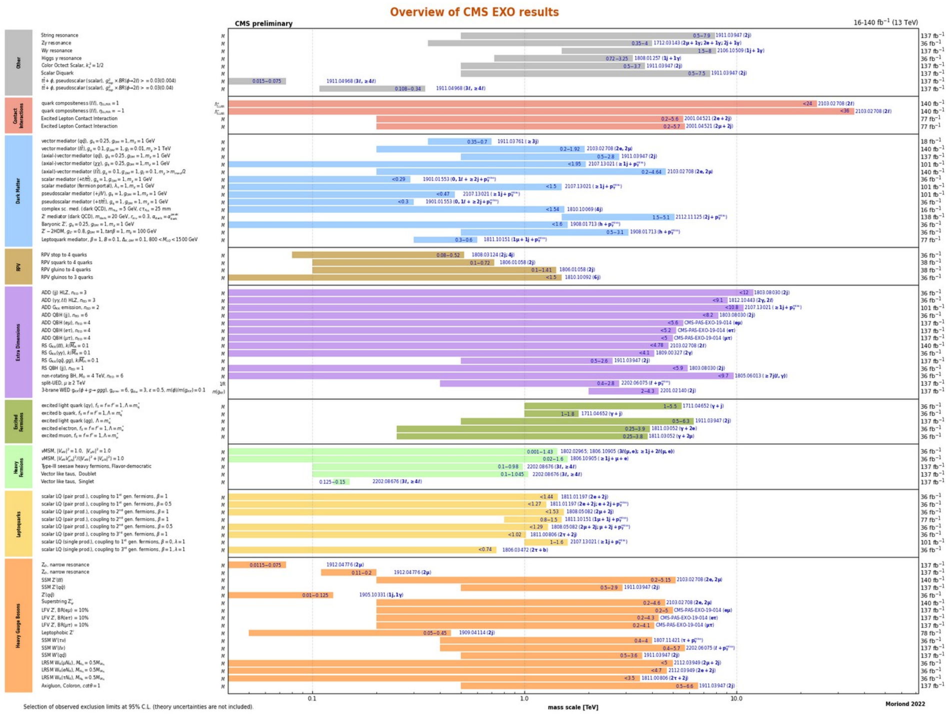
No evidence yet but no shortage of models predicting exotic heavy particles

LHC limits for direct and indirect BSM searches

ATLAS URL link to image

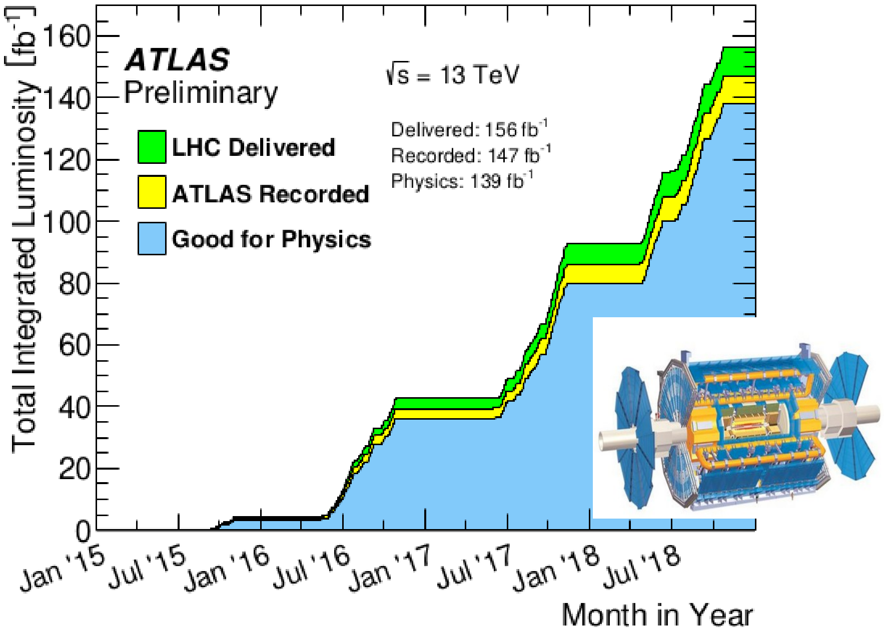


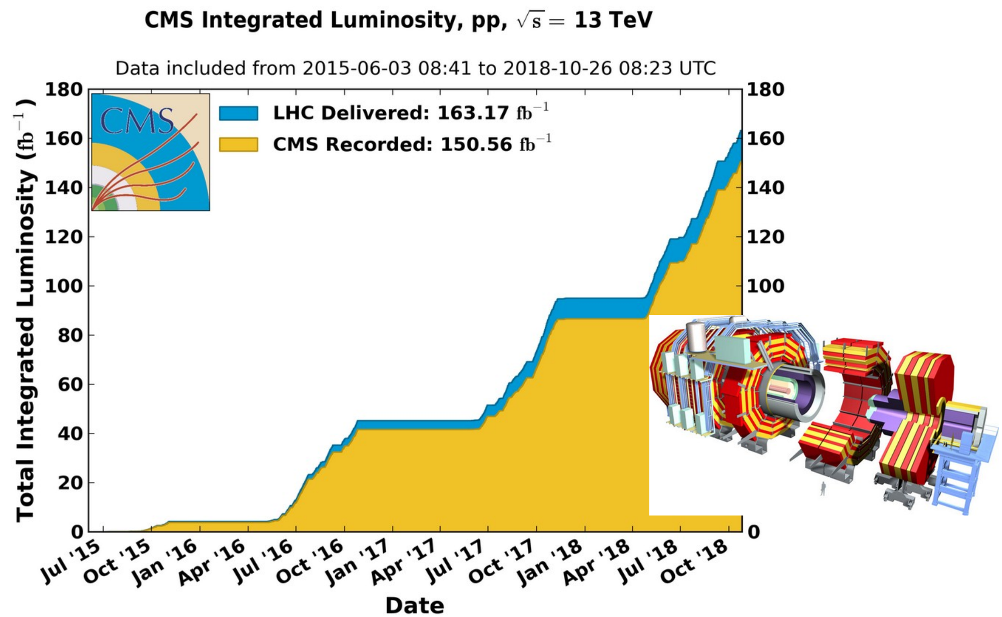
CMS URL link to image



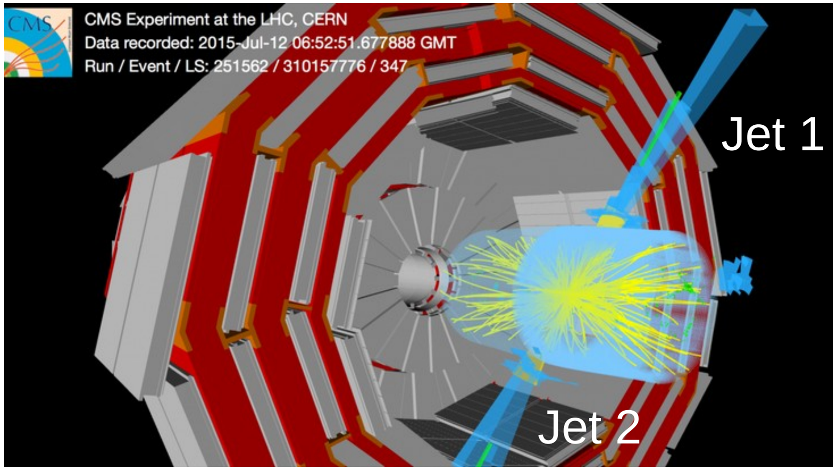
- ~100 decay channels studied for various models that predict certain production rate *(extra dimensions, gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, leptoquarks etc)*
- Commonly excluded masses ~ **0.4 – 12 TeV**
- But plenty of models that predict too small cross section for exclusion.

LHC operation





- Run2 pp collision data-set, √s= 13 TeV.
- ~140 fb^{-1} used for this talk

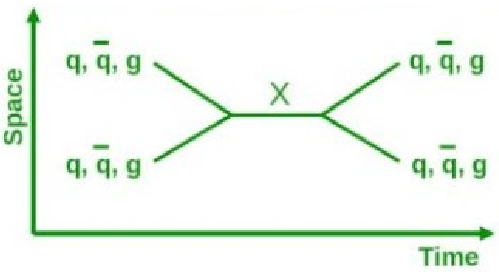


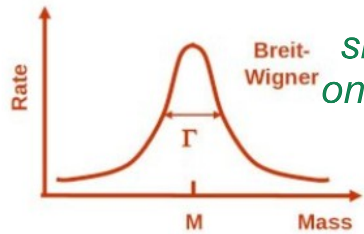
Typical search strategy:

- Select events with “X” (= jet, γ, Higgs, top, Z, W)
- Veto other activity (μ,e,..)
- Measure missing transverse momentum (MET)
- Combine reconstructed objects → compare with theory expectations

Search for high mass dijet resonances

ATLAS JHEP 03 (2020) 145
CMS JHEP 05 (2020) 033





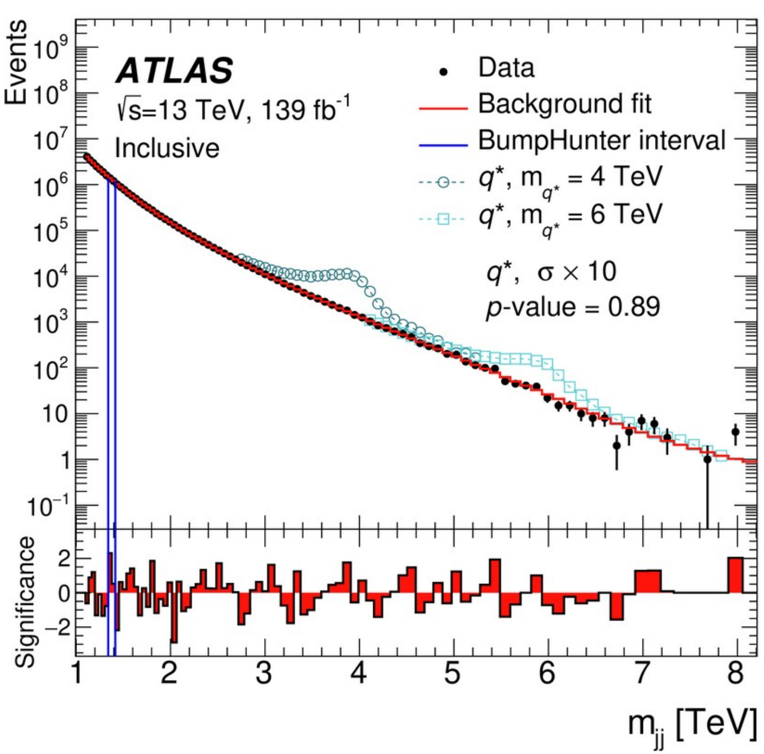
Resonance shapes depend on qq, qg and gg interactions

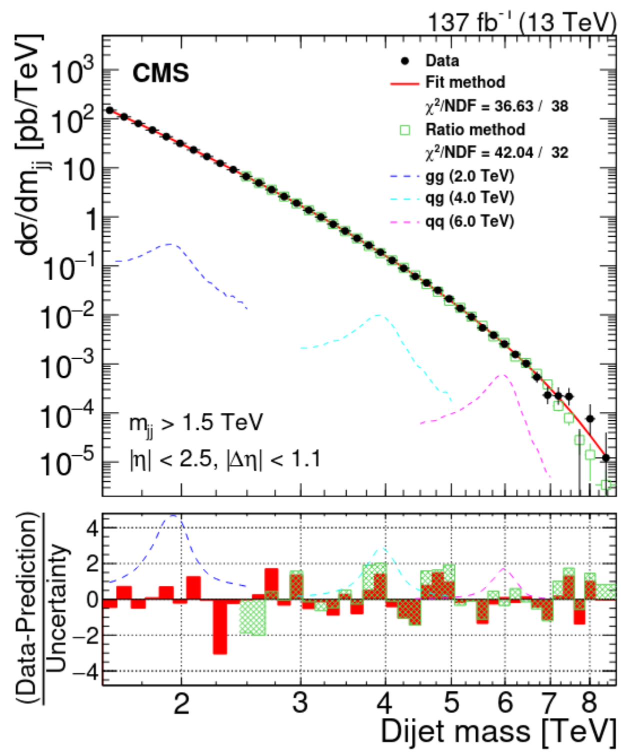
- Calculate invariant mass from 2 hadronic jets
- Fit with smooth analytic functions (red lines)
- Competitive limits up to ~8 TeV

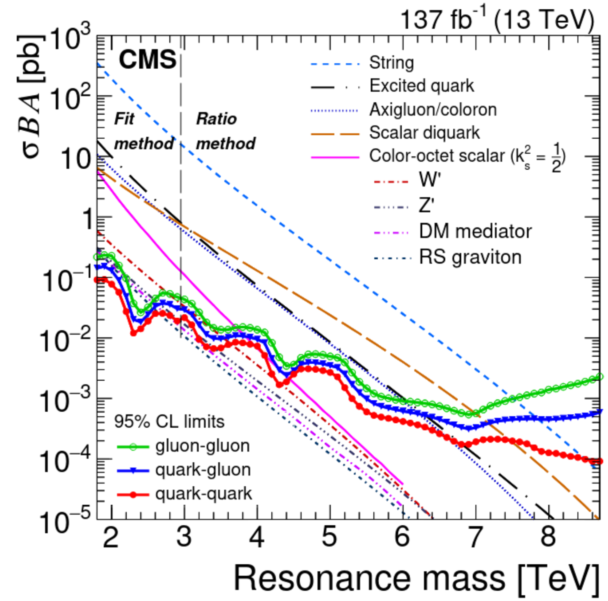
Physics of Z'/W' bosons:

(review by P.Langacker Rev.Mod.Phys.81:1199 (2009))

- *Similar to the SM W/Z bosons (but heavier)*
- *Extending SM to group SU(3) × SU(2) ×* ***U(1)***
- *Sequential Standard Model*
- *Grand unified theories, fine tuning problem*
- *Extra dimensions*
- *Dark matter mediator etc. etc.*





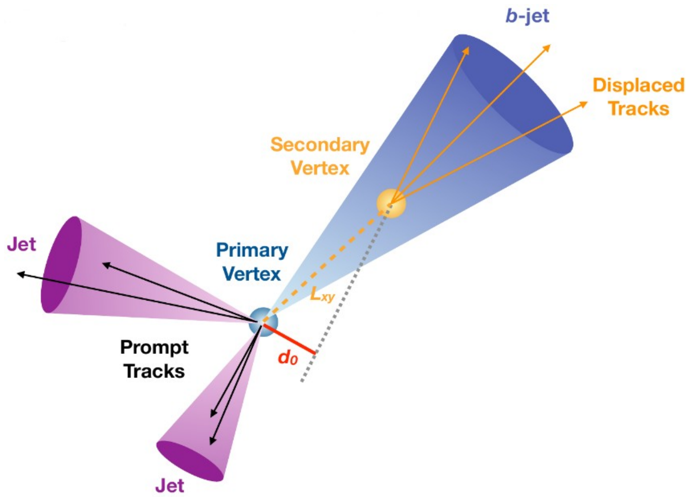


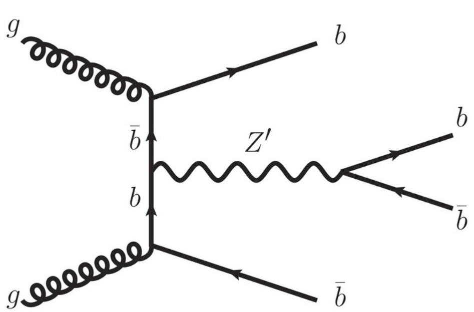
Observed and expected mass limits at 95% CL

Jets originating from b-quark

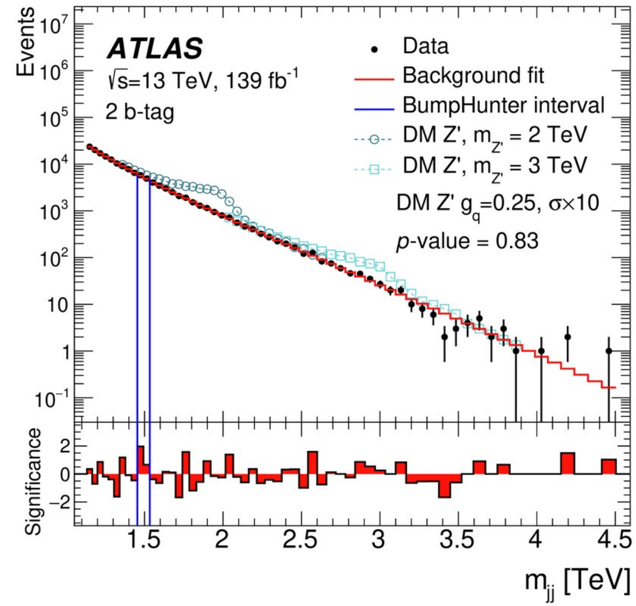
ATLAS JHEP 03 (2020) 145
ATLAS Phys. Rev. D 105 (2022) 012001

- Heavy Z' couples to SM particles (like $q\bar{q}$) similar to Z-bosons
- "Leptophobic" Z' (does not decay to leptons), can couple to third-generation quarks for some modes
- All-jet searches may fail. Instead, search for $Z' \rightarrow b\bar{b}$ by combining jets from b-quarks

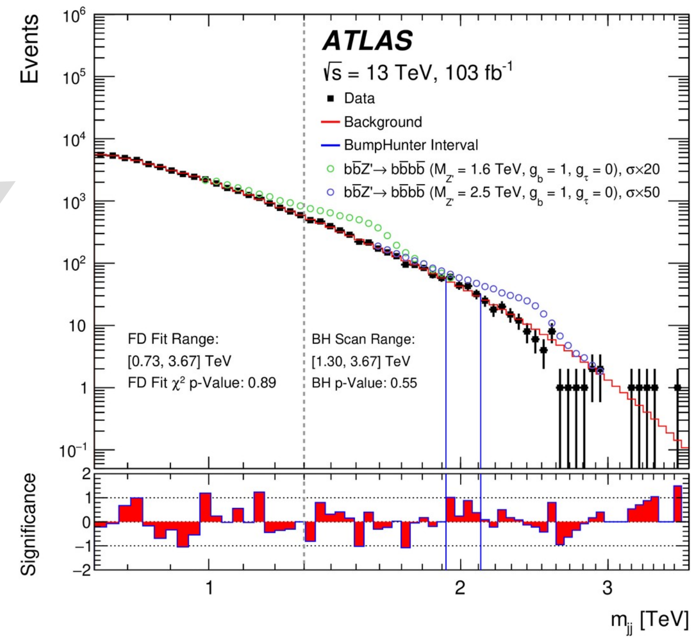




2-b jet mass in all events



2-b jet mass in events with multiple b-quarks



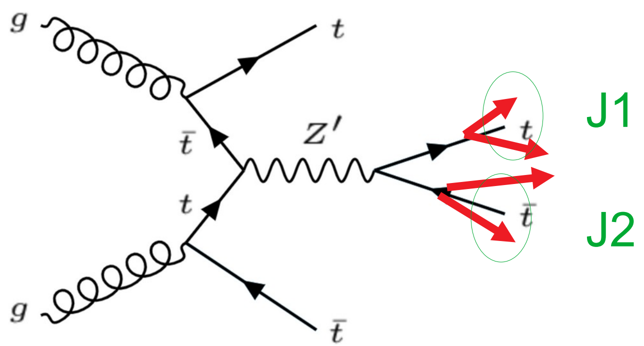
- No signals. Competitive limits for $Z' \rightarrow b\bar{b}$ processes

Top-associated production of Z’

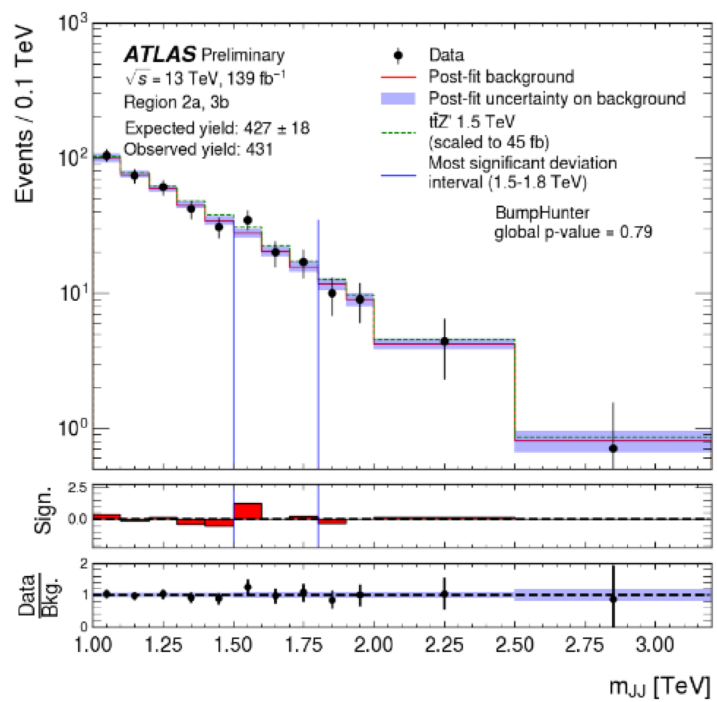
ATLAS: ATLAS-CONF-2021-048

- Some BSM models predict ‘top-philic’ vector resonances that couple mainly to top quark
- Best sensitivity → both top quarks decay hadronically & spectator top decays semi-leptonicaly
- Use two large radius jets as proxies of the hadronically decaying top quarks (anti-kT with R=1)

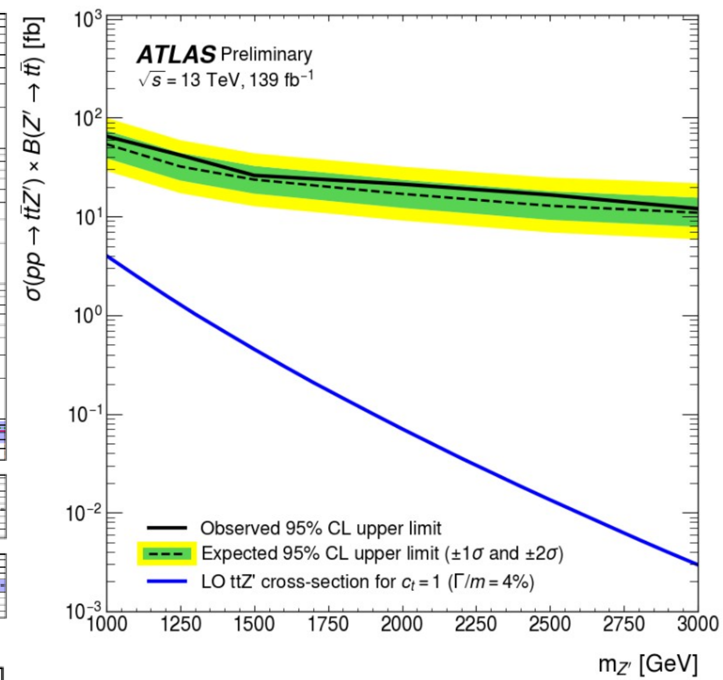
> 1 boosted jets
> 2 b-tagged jets
at least 1 lepton



Representative invariant mass of two large-radius jets



Experimental limits for tt̄Z’



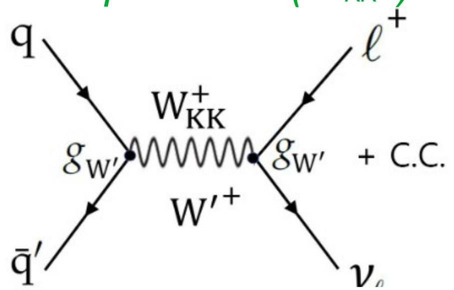
- No excess above the expected SM background
- Competitive Run II limits. Require more data to exclude tt̄Z’ production

Searches for W' heavy bosons - I

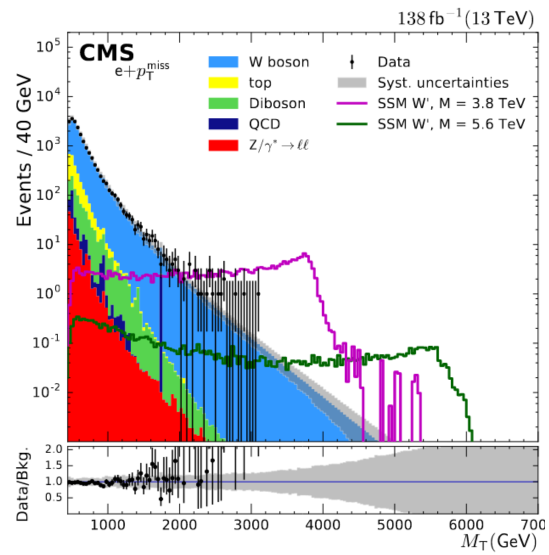
CMS arXiv:2202.06075
ATLAS ATLAS-CONF-2021-043

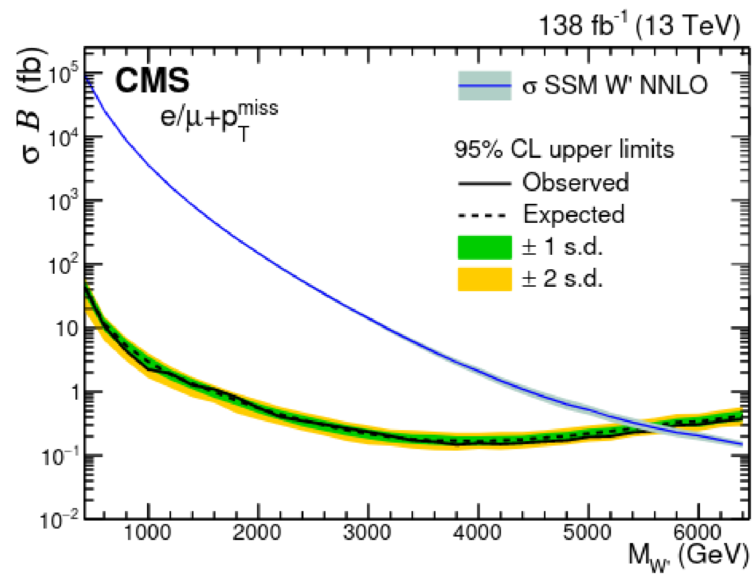
W' is analog of W bosons in several BSM scenarios

All leptonic W' (W_{KK}')



$$m_T = \sqrt{2E_T^{miss} p_T (1 - \cos\Delta\phi)}$$

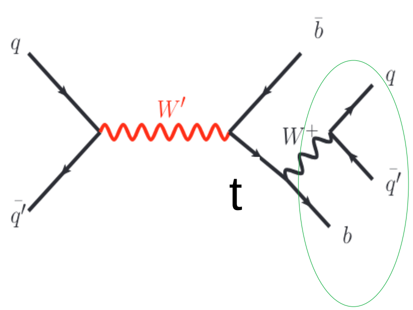




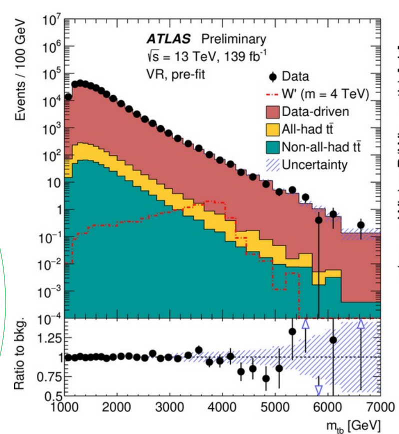
CMS: use transverse mass (m_T) calculated from charged lepton and the missing transverse momenta

ATLAS: Search for heavy W' decaying to boosted top and b-quark

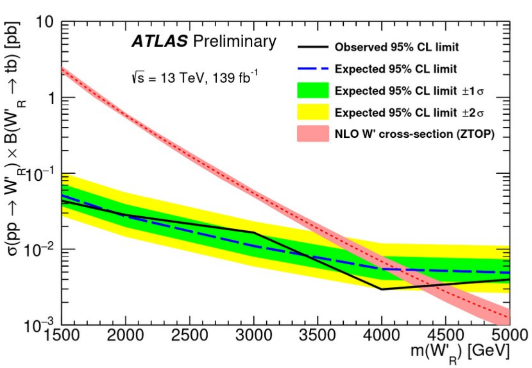
All-hadronic W'



anti-kT with R=1



top+b jet mass



LHC data exclude M(W'):

< 5.7 TeV (lepton + ν)

< 4.4 TeV (b-jet + boosted top)

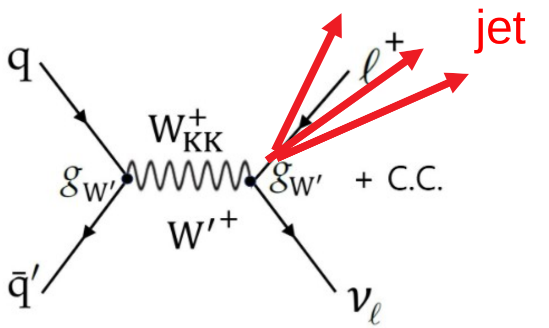
Exclude BSM models:

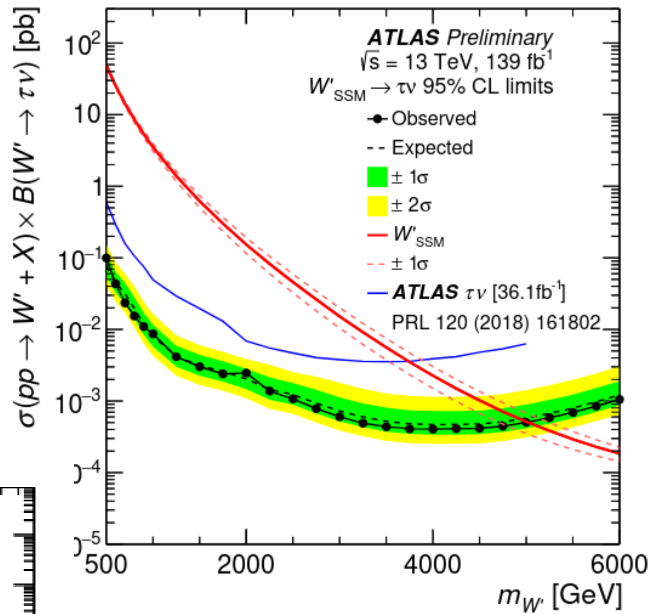
- Composite Higgs boson models
- Universal extra dimension
- Effective field theory (EFT)
- etc..

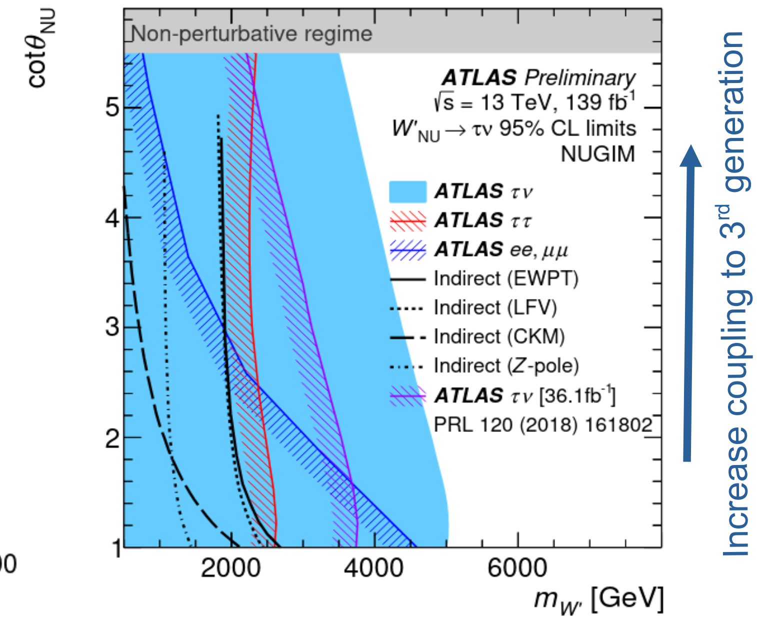
Searches for W' heavy bosons - II

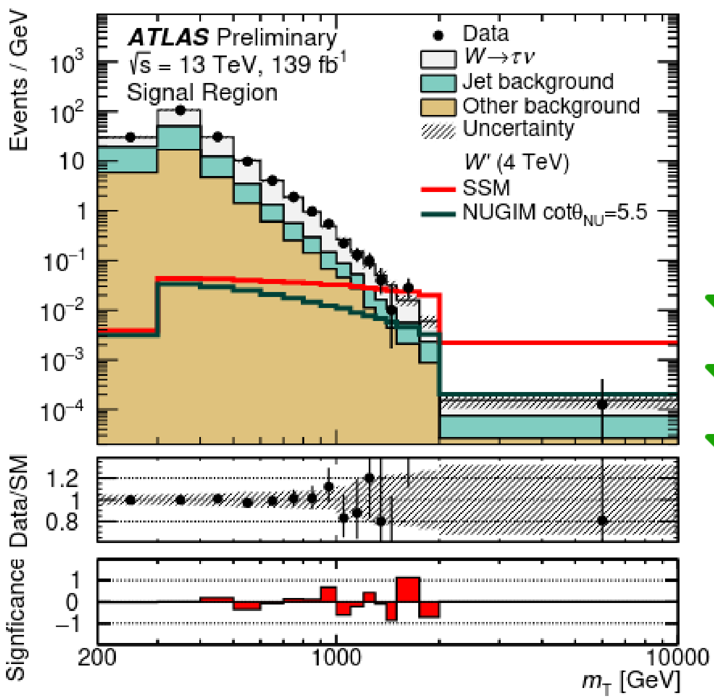
ATLAS ATLAS-CONF-2021-025

Hadronic decays of tau-leptons
Challenging background!
→ use machine learning (ML)







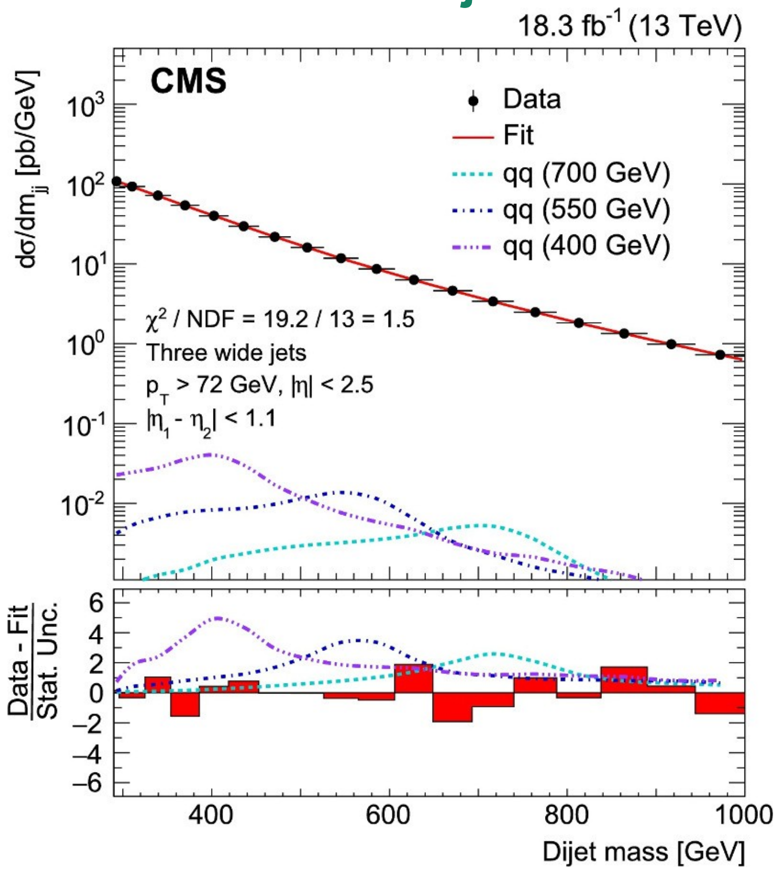


- Model independent limits
- <5 TeV 95% CL for Sequential Standard Model scenario
- Limits for Non-Universal Gauge Interaction Models (NUGIM) with additional parameter **cot θ_{NU}** used to scale the couplings to the first and second generations of fermions

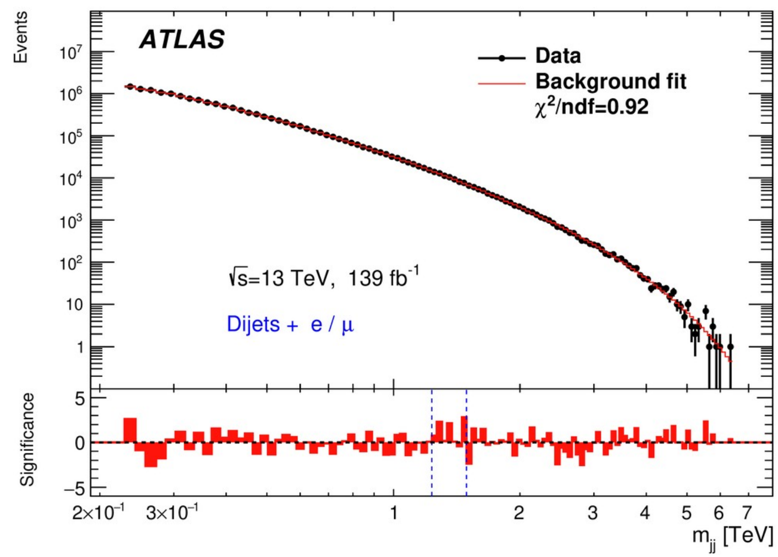
Searches using di-jets + X

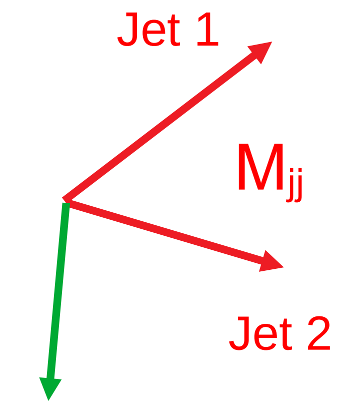
- Additional object X (lepton, jet, photon) helps triggering events with smaller masses (~ 300 GeV – 1 TeV)

X= 3rd jet

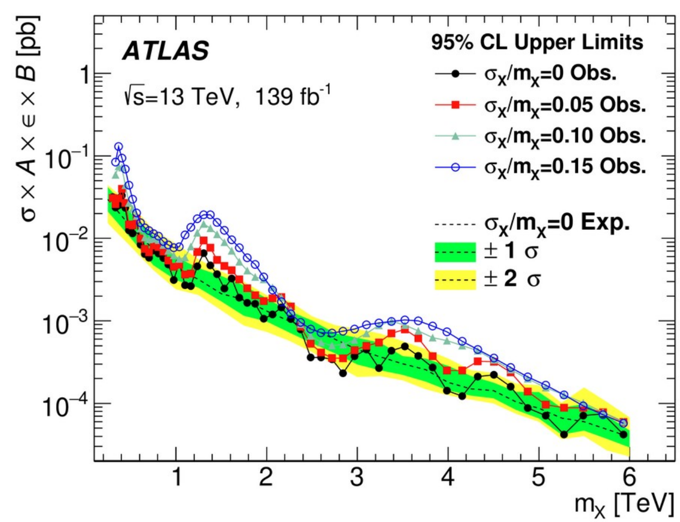


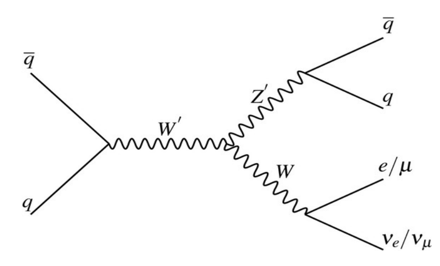
X= e,mu





X = event trigger





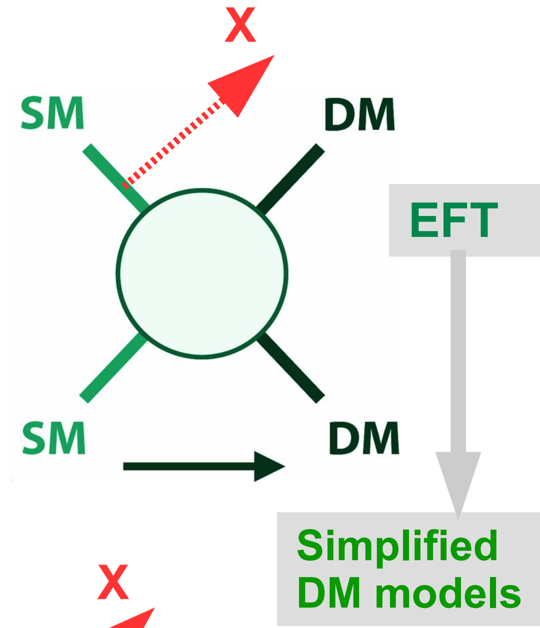
Limits on Sequential Standard model at 1.5 TeV

- Several specific models excluded, including technicolor, sequential SM, H+, DM with associated W

Searches for Dark Matter (DM) at the LHC

- Overwhelming evidence for DM
- If new particle → DM & SM particles in thermal equilibrium in the past
  - DM abundance determines annihilation cross section at freeze-out
  - DM is at electroweak scale? → within LHC energy reach

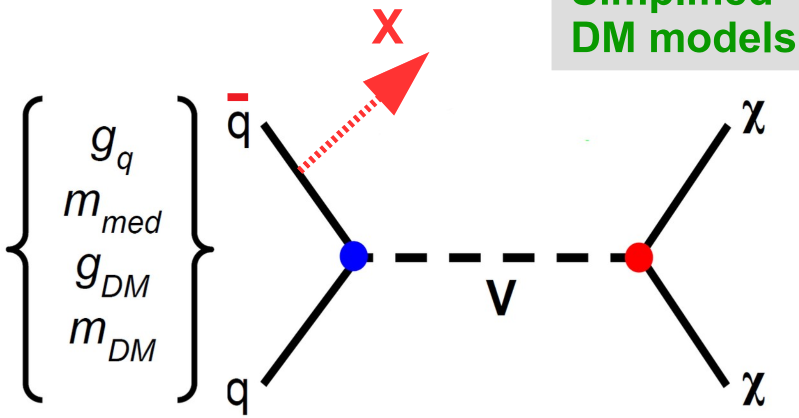
- LHC collides pp under well-controlled conditions
  - SM particles can radiate other SM particles "**X" (via ISR)**
  - Undetected DM → imbalance in transverse momentum



Adopt simplified DM model with a "mediator" **V**
- g_q (g_{DM}) – mediator coupling to quarks (DM)
- m_{med} (m_{DM}) – mass of mediator (DM)

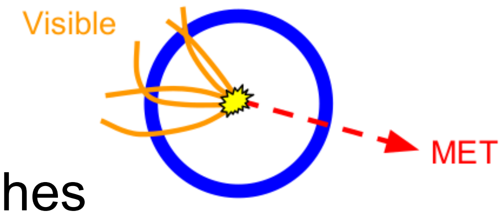
ATLAS & CMS: **g_q=0.25 (S=1), g_q=1 (S=0), g_{DM}=1**

Γ=minimum width formula

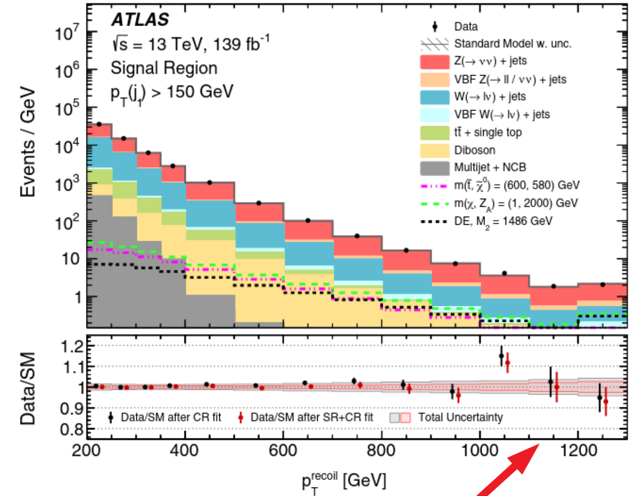


Mono jet searches

ATLAS Phys. Rev. D 103 (2021) 112006

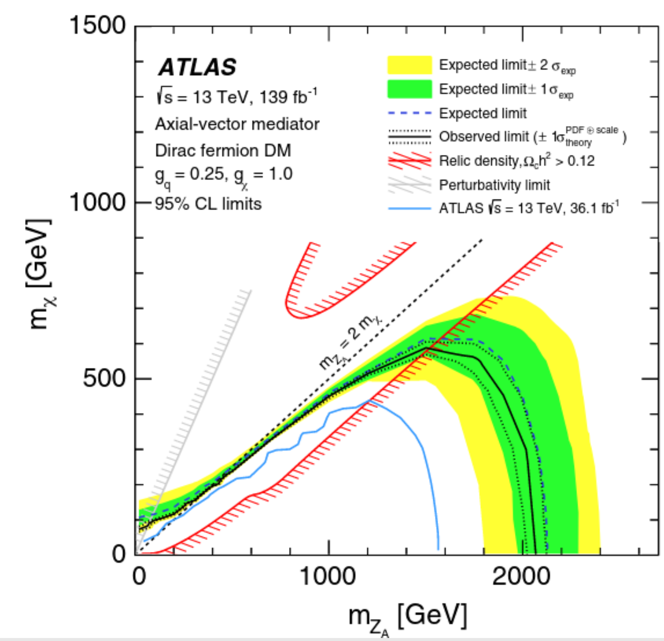


- Mono jet searches rely on MET
  - MET > 200 GeV for typical searches
- Challenging pileup and non-collision background
- SM background:
  - **Z(vv)+j – irreducible (real MET)** → MC with data on Z→ ll
  - **W(lv)+j, $t\bar{t}$ – reducible (loss of leptons from W)** → MC
  - **QCD multi-jet, non-collision BG** → data driven



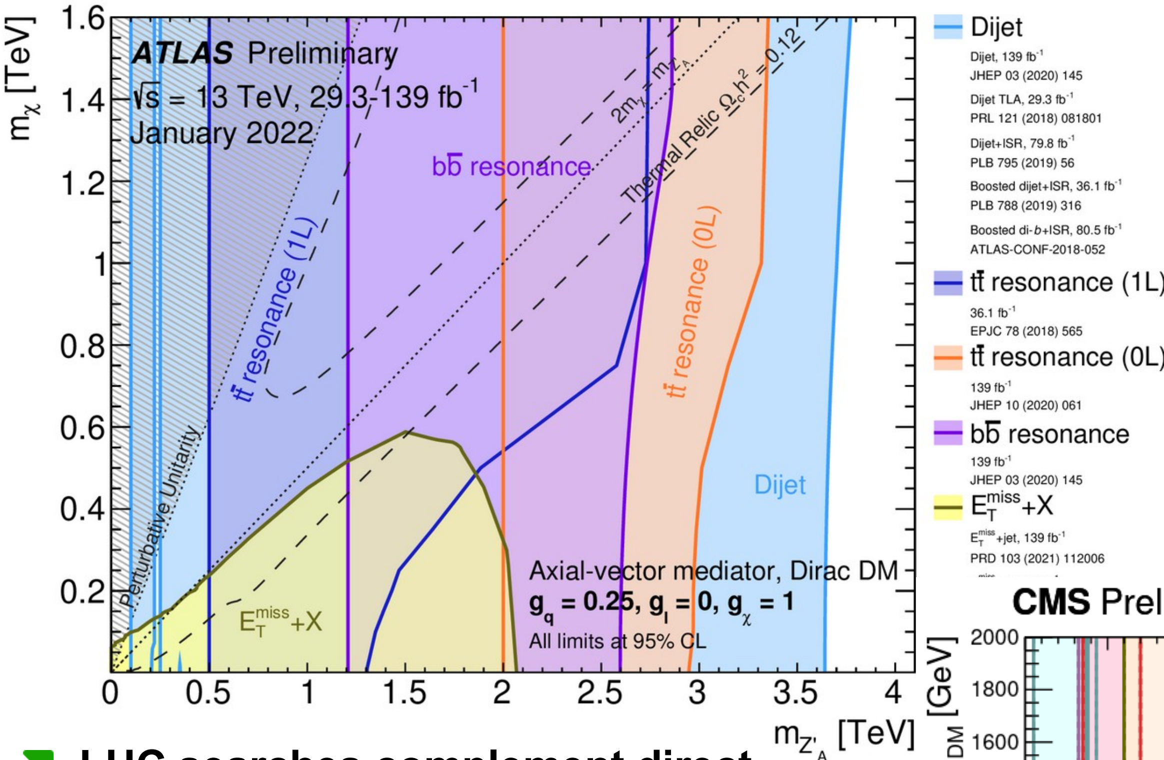
Typical precision for SM description

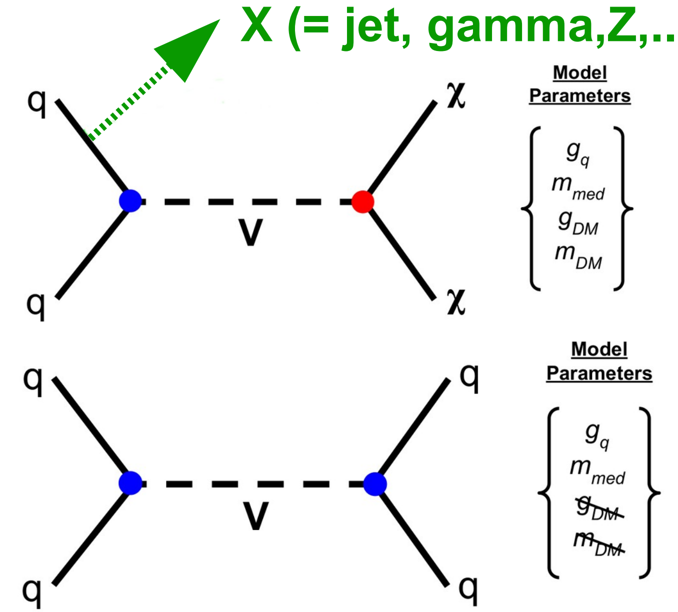
- Required high-precision SM measurements
  - Examples:
    - **jet+γ** – missing NNLO effects for Z(vv) (CMS)
    - **W+jet** control region also for Z(vv) (ATLAS)



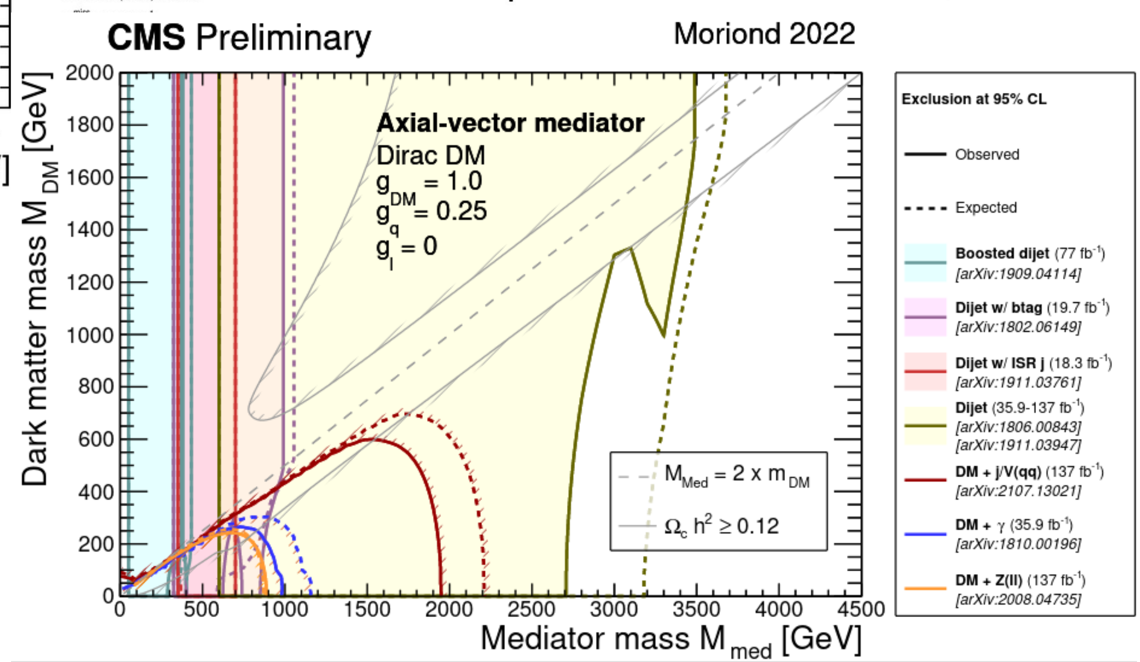
Dark Matter summary plots

ATLAS summary (2022)
CMS summary (2022)





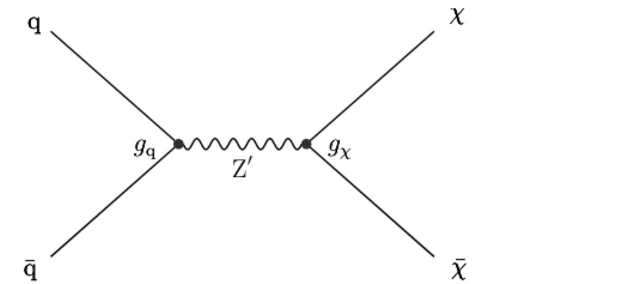
- **LHC searches complement direct detection experiments:**
  - Strong (model-dependent) limits for low mass m_{DM} (<10 GeV)
  - Strong limits for spin-dependent DM-nucleon cross section
  - Comprehensive searches for DM-SM mediators

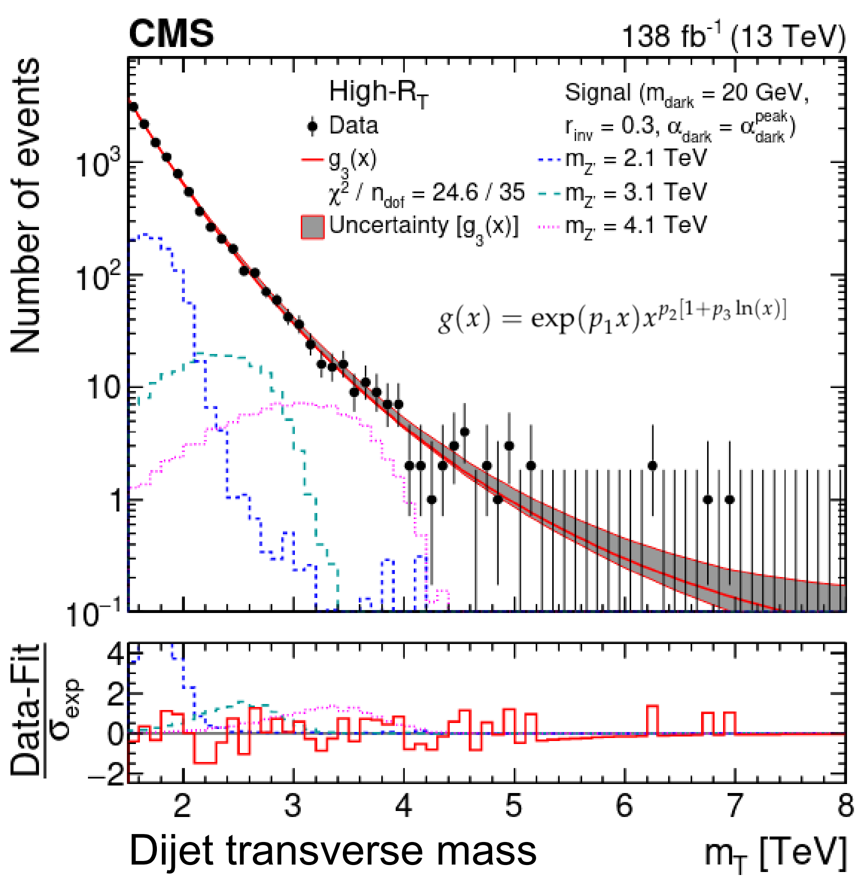


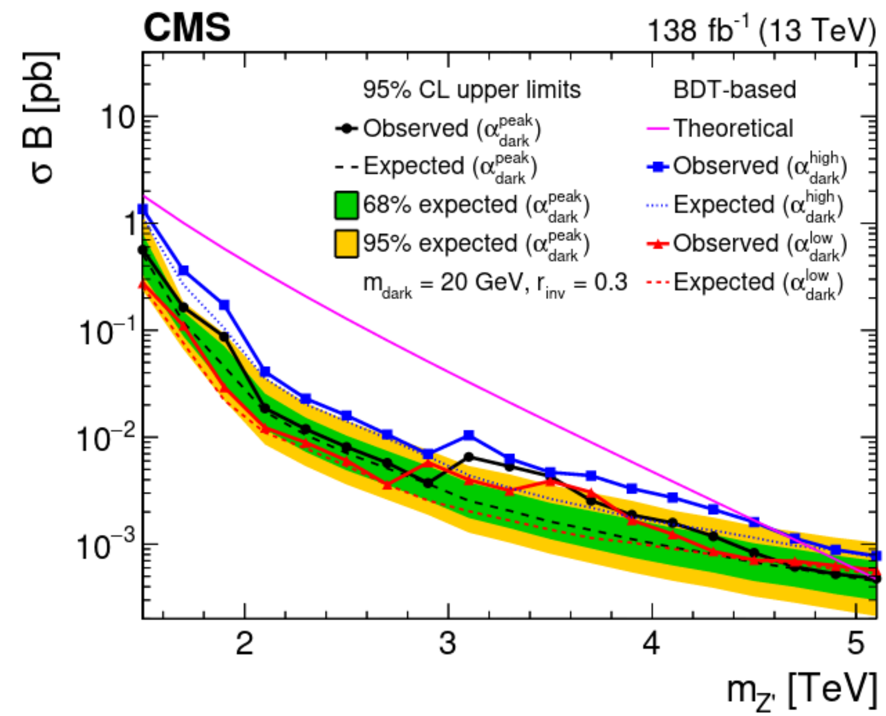
Resonant production of DM candidates

- Heavy *leptophobic* Z' mediator decays to two "semi-visible" jets, containing both visible matter and invisible dark matter ("dark hadrons" from "dark quarks")
- Unstable dark hadrons decay to SM quarks while the stable dark hadrons are DM candidates
- Train BDT to separate SM and wider "semi-visible" jets

$$r_{\mathrm{inv}} = N_{\mathrm{stable}}/(N_{\mathrm{stable}} + N_{\mathrm{unstable}})$$







Limits for Z' mass for m_{dark}=20 GeV and fraction of stable invisible dark hadrons

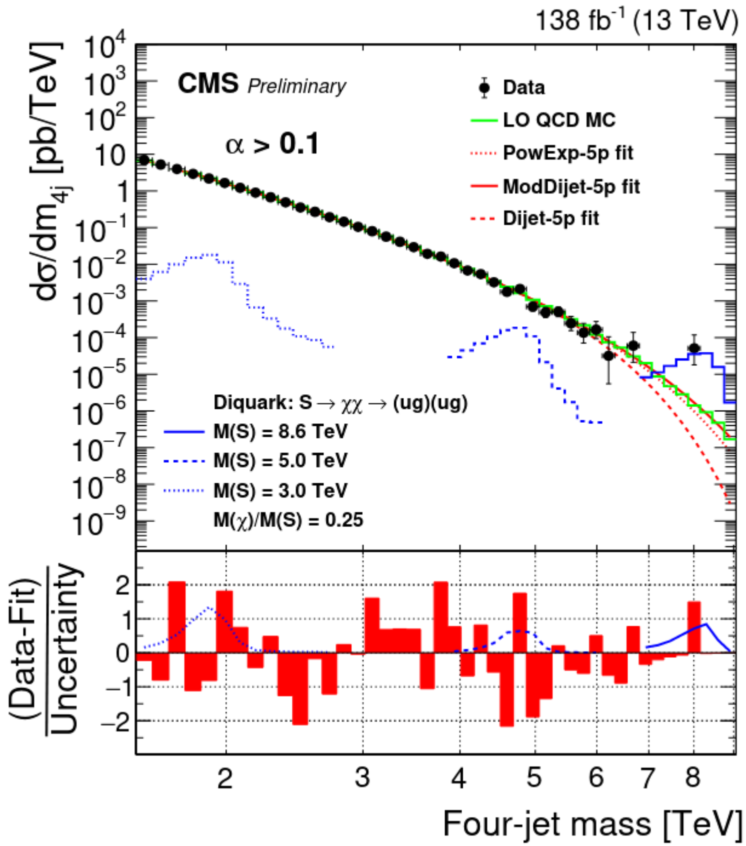
Complement DM searches using missing momentum and initial-state radiation

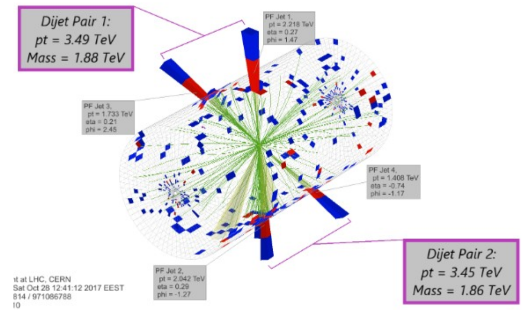
BSM particles decaying X → YY / YH

CMS CMS PAS EXO-21-010
CMS CERN-EP-2022-034

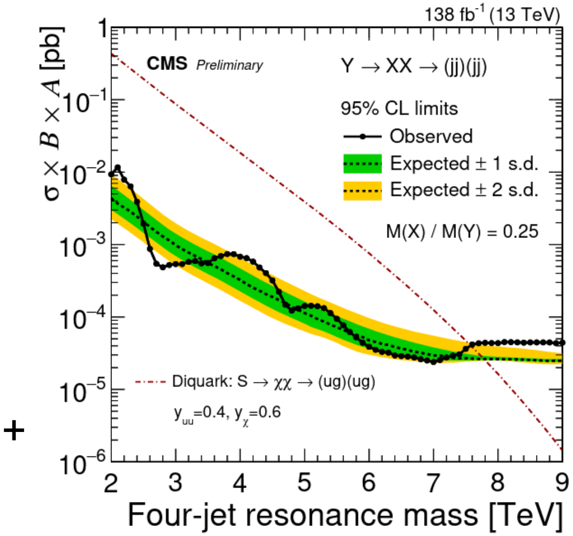
- Resonant pp → X → YY → (jj) (jj) & Non-resonant pp→ YY → (jj) (jj)
- Scan α (average mass of the two dijets divided by the four-jet mass)

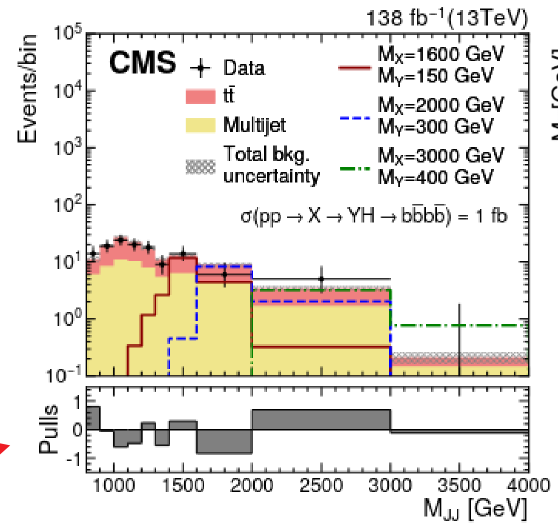
Example: Scalar diquark:
uu → S(uu) → χχ → (ug)(ug)

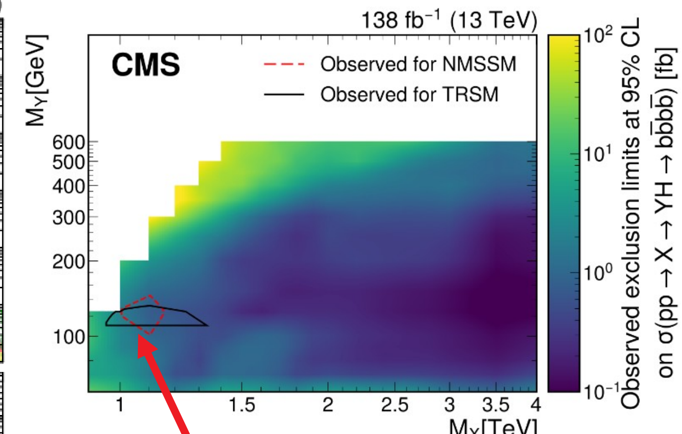




First model-independent upper limits at 95% confidence levels + R-parity violating SUSY







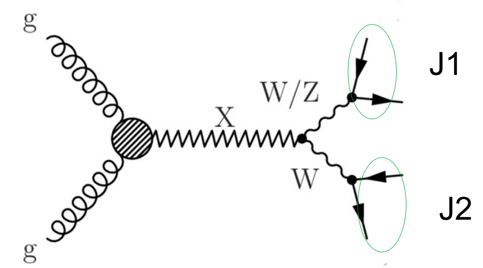
- pp→X (scalar)→ YH→ bb̄bb̄
- Boosted regime: 2 large R-jets (AK8 = anti-kT R=0.8)

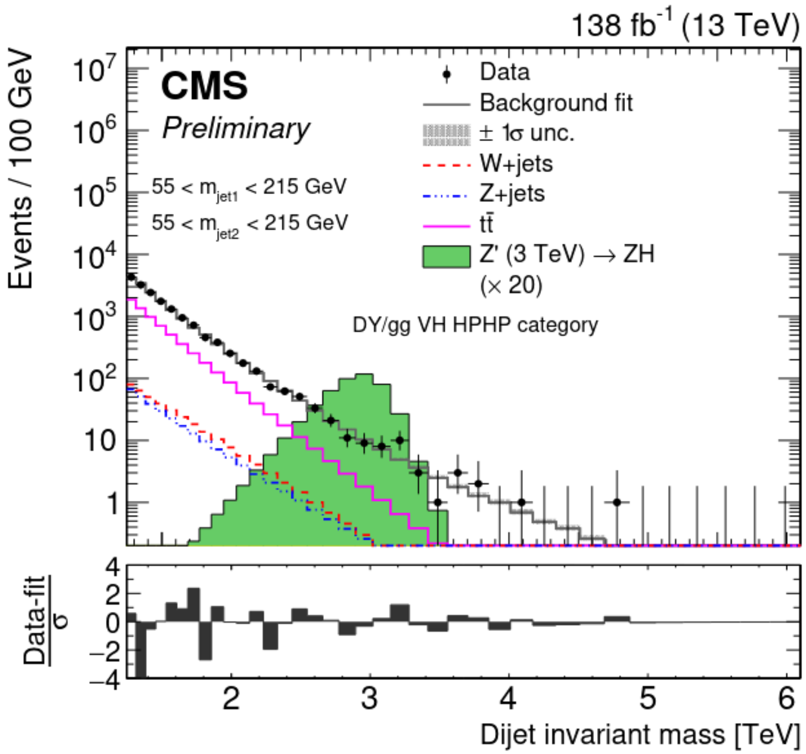
95% CL exclusions for M_X and M_Y

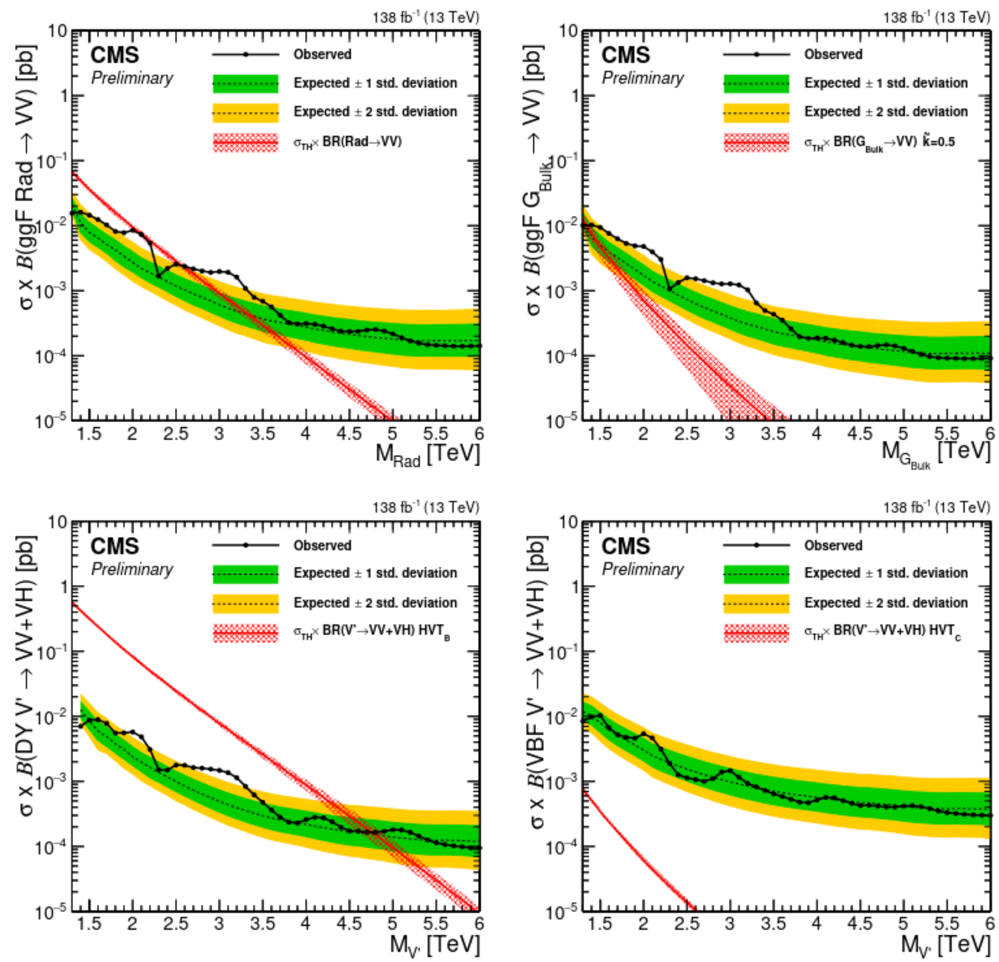
$X \rightarrow$ WW, WZ, ZZ, WH or ZH

CMS CMS-PAS-B2G-20-009

- W/Z/H decays to large R-jet (AK8) for heavy X
- Hadronic decays of W, Z, and H bosons identified using ML
- Measure masses of 2 jets (m_{J1}, m_{J2}) and dijet mass (m_{JJ})
- Simultaneous 3D likelihood fit





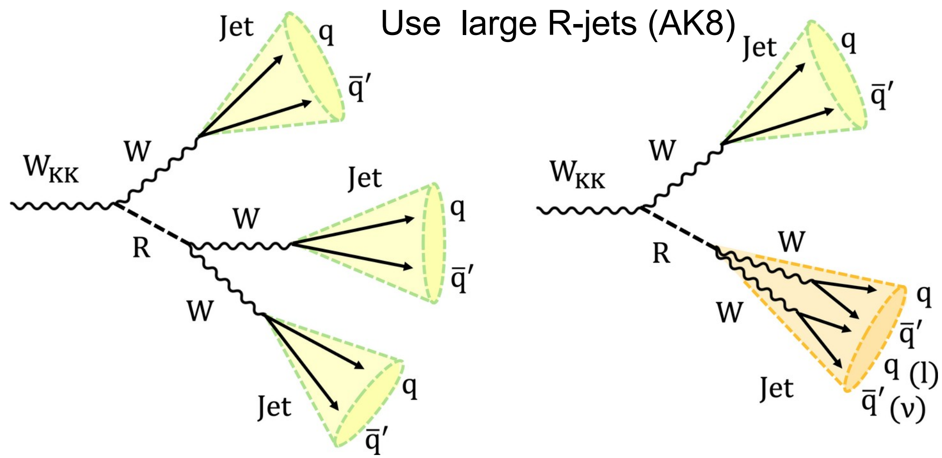


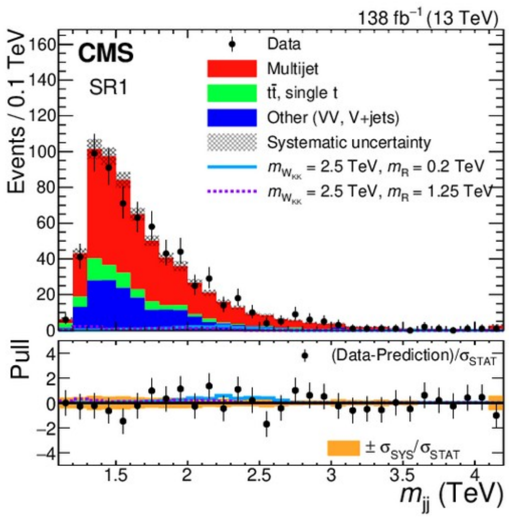
- No evidence for new resonances
- Largest excess at ~2-3 TeV has ~2.3 σ (global)
- Competitive limits for several BSM signals (including VBF mode)

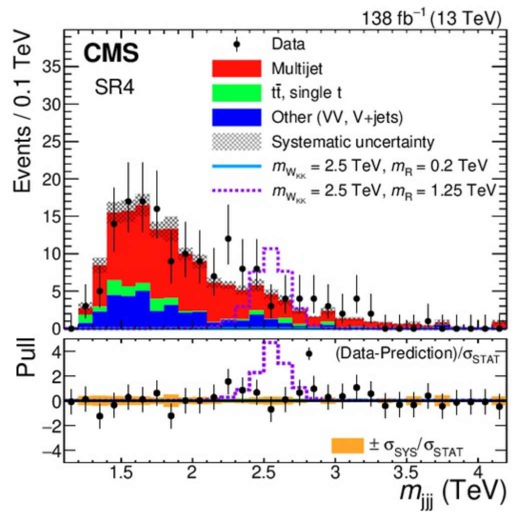
Resonances decaying to W bosons

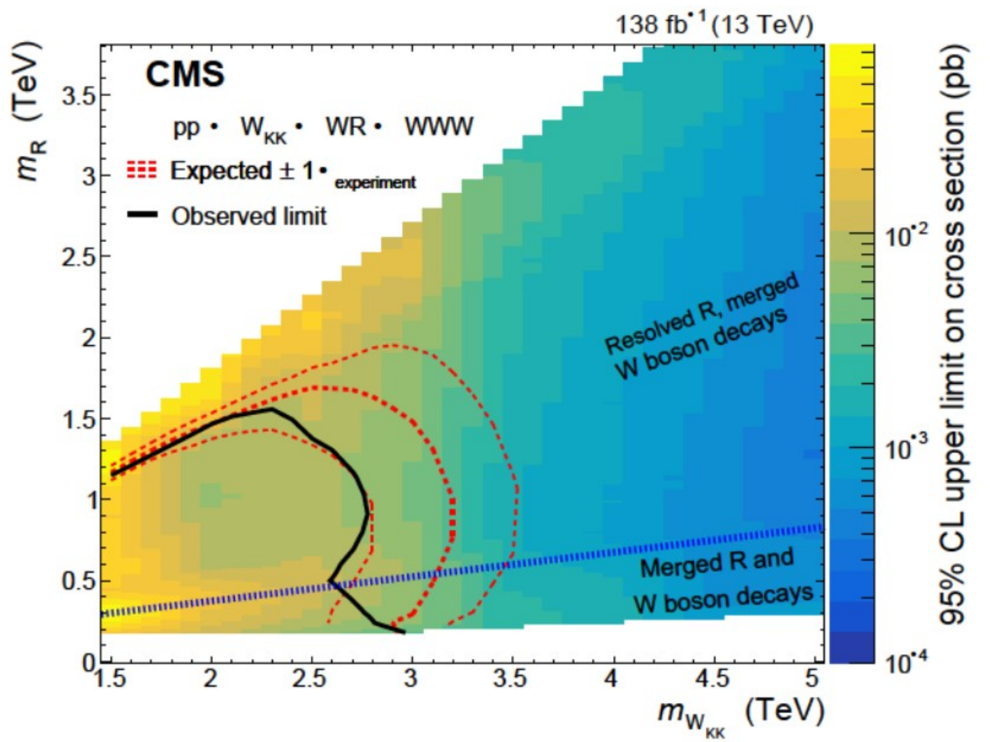
CMS CERN-EP-2021-253

- Search for Kaluza–Klein excited vector boson resonances, $W_{KK} \rightarrow R\ W \rightarrow WWW$ (R is a scalar radion)
- No signal-like excess over the background









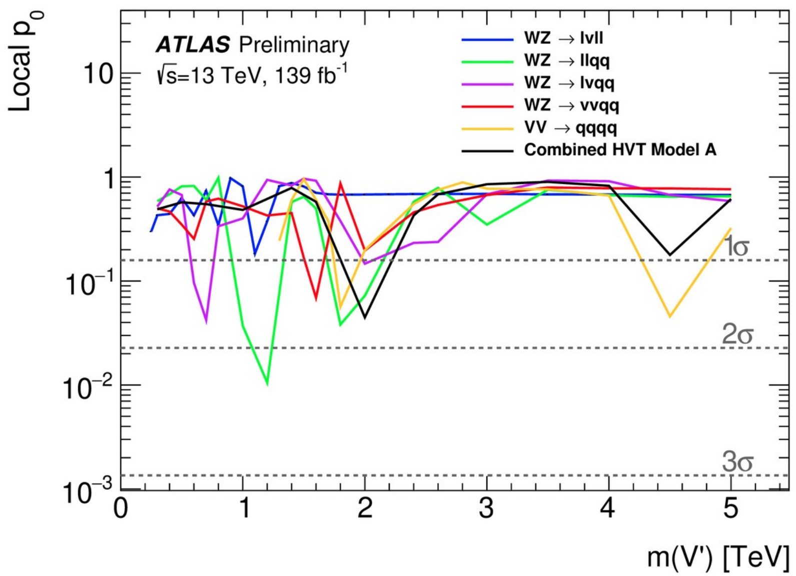
- First results using jet measurements
- Technical advances:
  - Novel jet substructure techniques
  - Dedicated "radion" taggers based on ML

Combination of searches for heavy resonances

ATLAS-CONF-2022-028

- Uses 16 (orthogonal) ATLAS publications during 2018 - 2022
- Combine bosonic decay modes $qqqq$, $\nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$, $\ell\nu\ell\ell$, $qqbb$, $\nu\nu bb$, $\ell\nu bb$
- Results are interpreted in terms in the context of Spin-1 Heavy Vector Triplet (HVT)
  - V' is collectively denotes $W'^{\pm}$ and Z'

Analysis	leptons	$E_{T_{miss}}$	jets	b-tags	Discr.
$WW/WZ/ZZ \to qqqq$	0	Veto	≥2J	-	m_{VV}
$WZ/ZZ \to \nu\nu qq$	0	Yes	≥1J	0	m_{VV}
$WW/WZ \to \ell\nu qq$	1e, 1μ	Yes	≥2j, ≥1J	0, 1, 2	m_{VV}
$WZ/ZZ \to \ell\ell qq$	2e, 2μ	-	≥2j, ≥1J	0	m_{VV}
$WZ \to \ell\nu\ell\ell$	3 ⊂ (e, μ)	Yes	-	0	m_{VV}
$WH/ZH \to qqbb$	0	Veto	≥2J	1, 2	m_{VH}
$ZH \to \nu\nu bb$	0	Yes	≥2j, ≥1J	1, 2	m_{VH}
$WH \to \ell\nu bb$	1e, 1μ	Yes	≥2j, ≥1J	1, 2	m_{VH}
$ZH \to \ell\ell bb$	2e, 2μ	Veto	≥2j, ≥1J	1, 2	m_{VH}
$\ell\nu$	1e, 1μ	Yes	-	-	m_T
$\tau\nu$	0	Yes	-	-	m_T
$\ell\ell$	≥2e, ≥2μ	-	-	-	$m_{\ell\ell}$



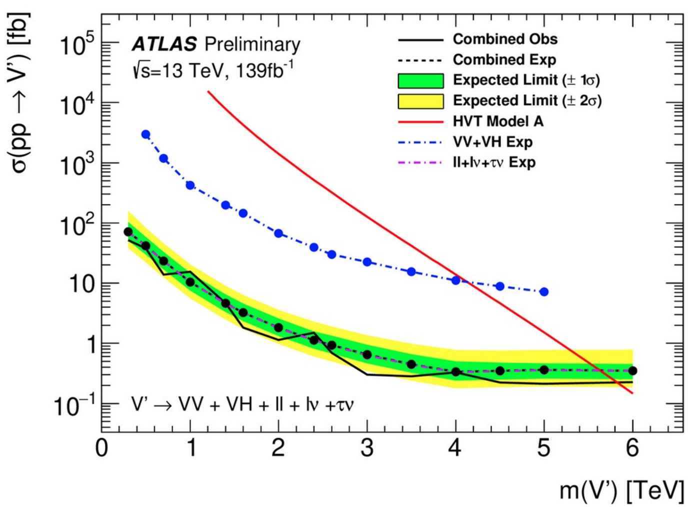
Typical example of p-value scan over the HVT pole masses up to 5 TeV

Scans for only-leptonic channel is extended up to 6 TeV (higher statistics!)

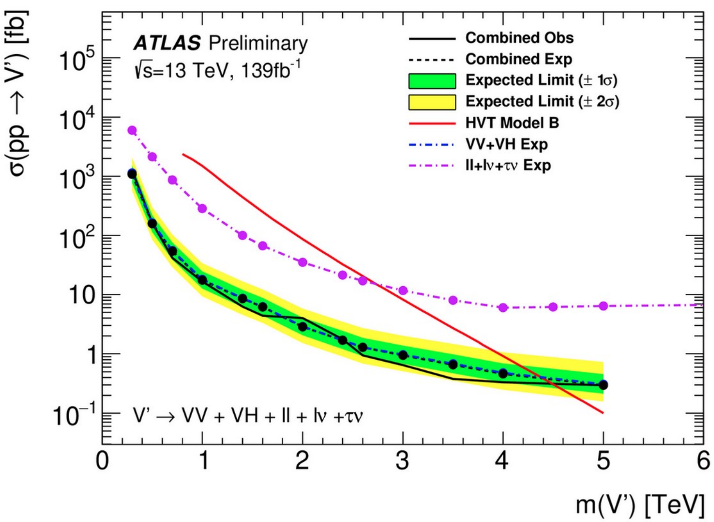
Combination of searches for heavy resonances

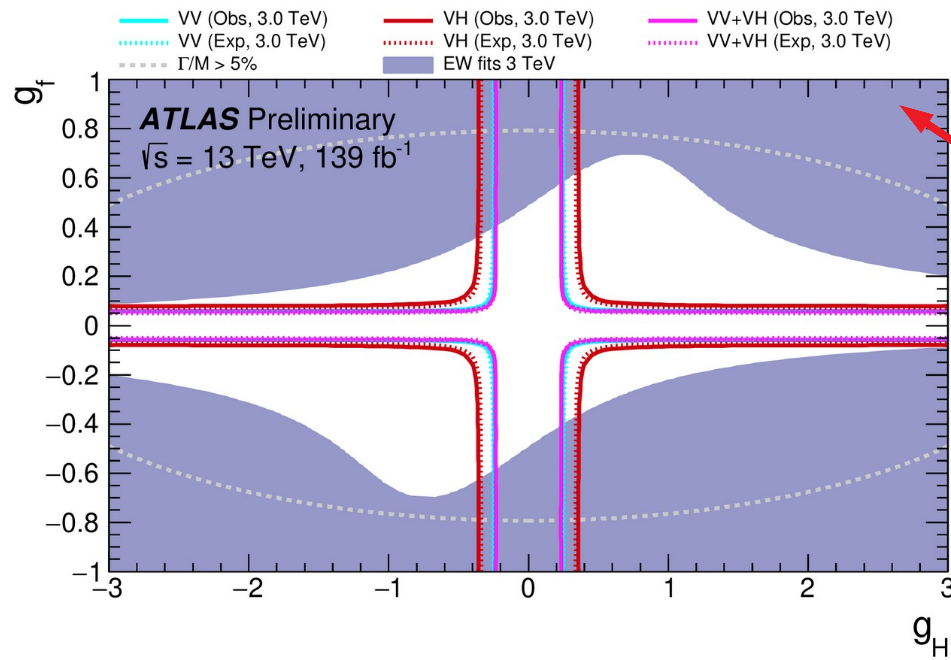
- Results interpreted in terms of exclusions limits on masses and coupling constants

Weakly coupled HVT-A coupling



Strongly coupled HVT-A coupling





Constraints from EWK measurements

See other channels & masses in the original CONF note

Typical exclusions for 3 TeV for { , } for $q\bar{q}$ production mode

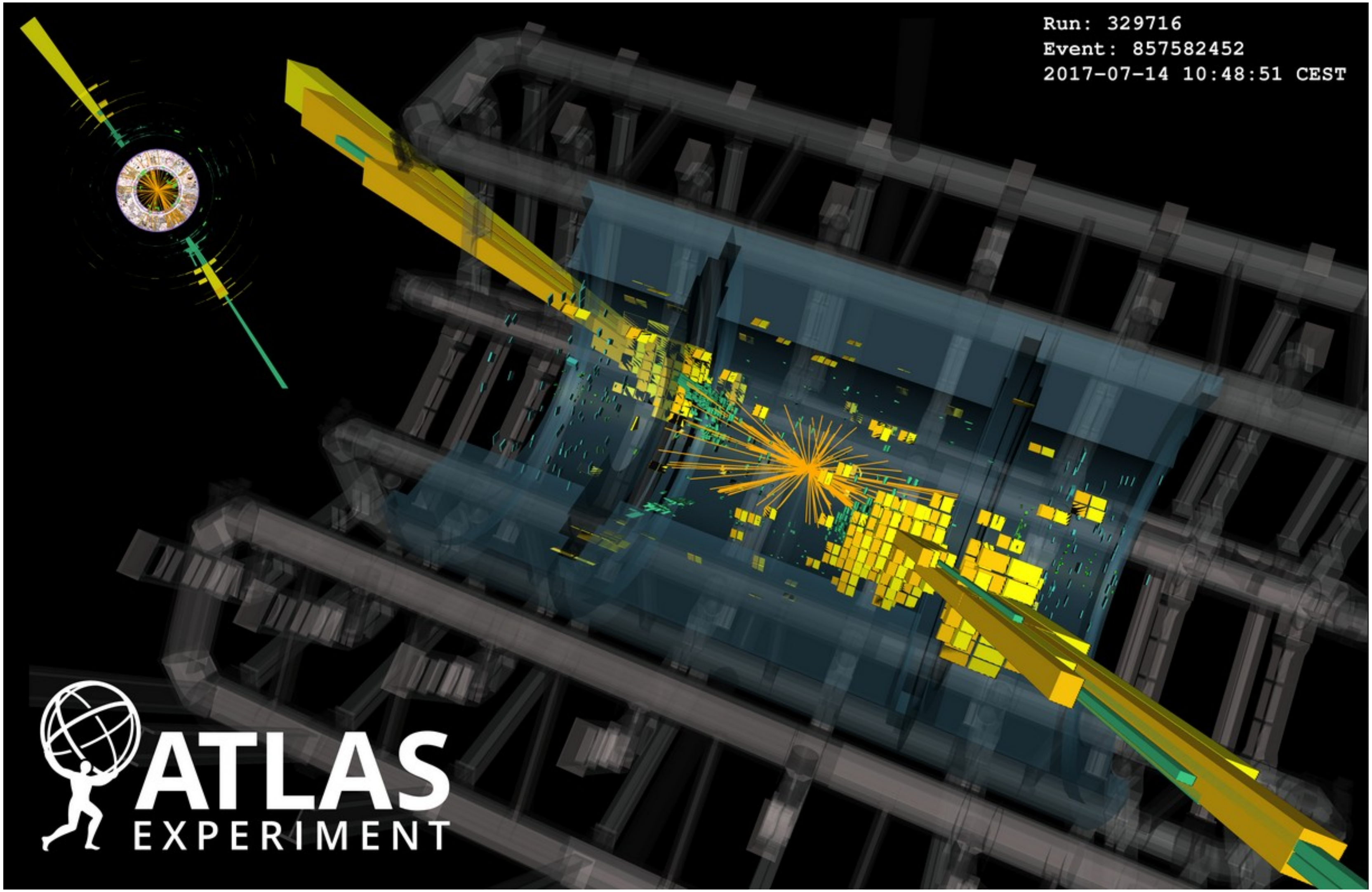
- Combined results strengthen the constraints on BSM physics and allow expressions of constraints in terms of couplings to quarks, leptons and fermions

Conclusions

- **Extensive program for searches for new heavy particles**
- **Refined studies with complex final state (jet, top, γ, $t\bar{t}$, W, Higgs, etc)**
- **Mass reach extends up to 8 TeV for many inclusive jet/lepton studies**
- **Constraints on simplified DM models that complement direct detection experiments:**
  - Strong (model-dependent) limits for low mass m_{DM} (<10 GeV)
  - Strong limits for spin-dependent DM-nucleon cross section
  - Comprehensive searches for DM-SM mediators
- **Combination of Run 2 searches for heavy resonances the context of HVT**
- **Stay tuned: Ongoing analysis using full Run 2 data**
- **Opportunities at Run 3:**
  - 13 TeV → 13.6 TeV CM energy
  - Increase in luminosity (x 2, statistics!)
  - Cutting edge analysis techniques

→ Can translate to ~1 TeV in mass reach for some channels

Backup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ATLAS
EXPERIMENT

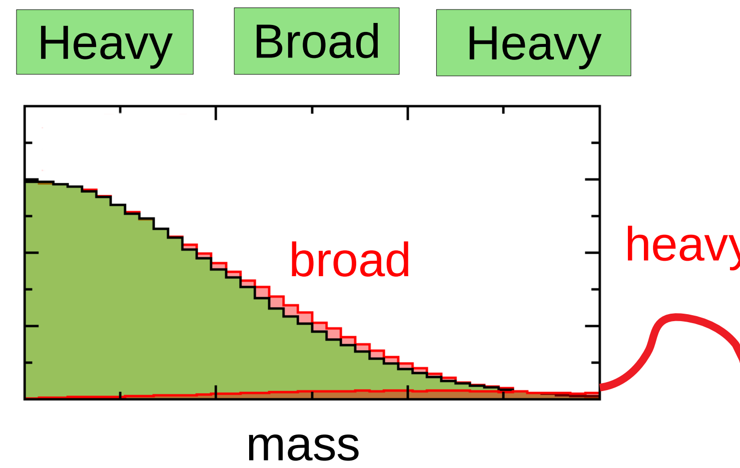
Non-resonant multilepton probes

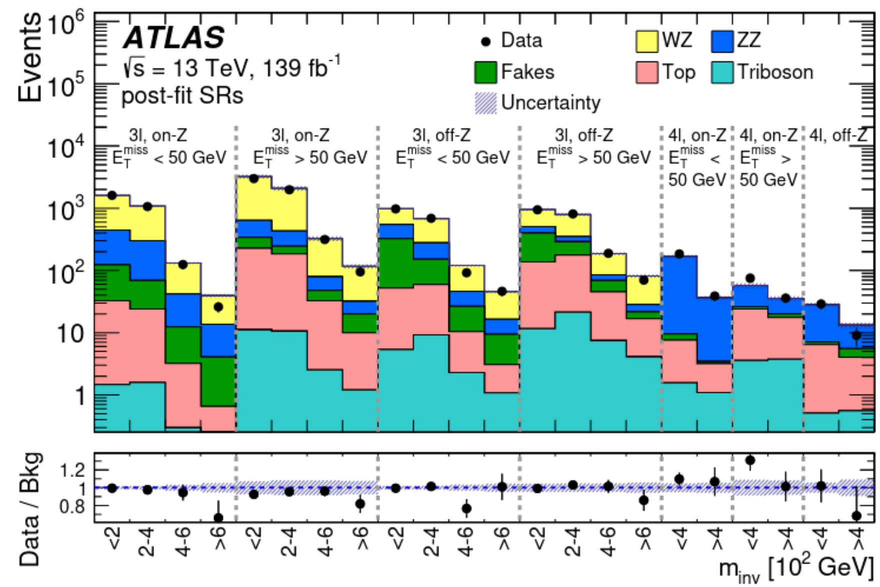
ATLAS CERN-EP-2021-063

- New physics may show up in deviations over expected rates (wide resonances, non-resonant production etc)
- More elusive for direct production, but:
  - can have larger cross section
  - affects the measured distributions
- Look at production rate of 3 or 4 leptons
  - 22 event categories according to the number of leptons in the event, the missing transverse momentum, the invariant mass of the leptons
- No deviations from the Standard Model

Non-resonant production

See M.Folgado & V.Sanz, Advances in High Energy Physics, Volume 2021, Article ID 2573471,

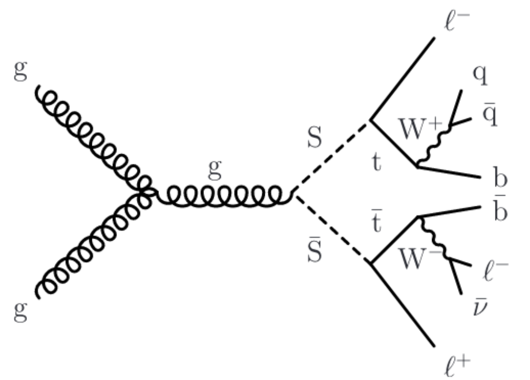


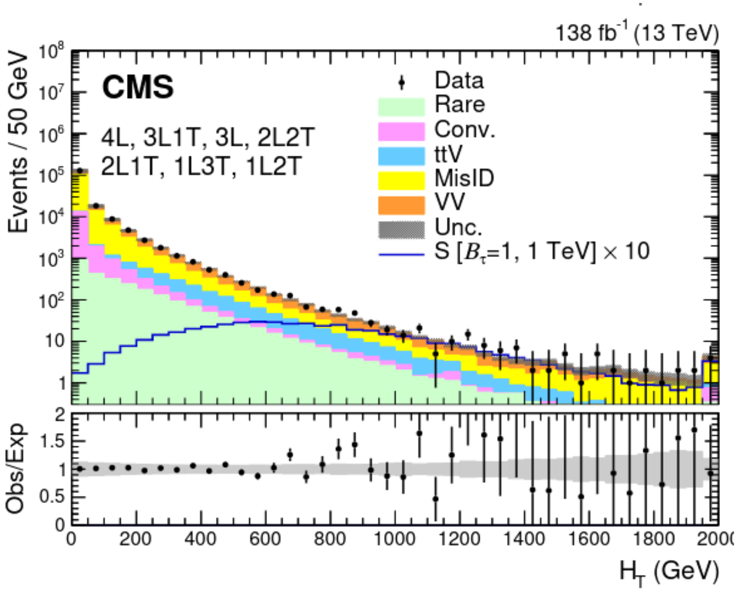


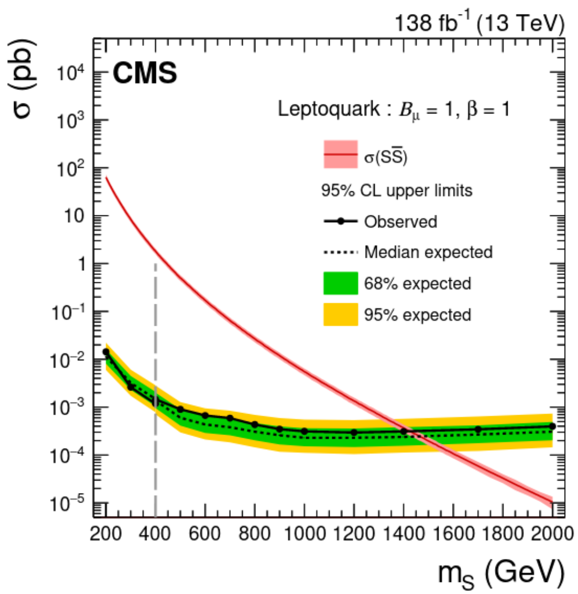
Non-resonant multilepton probes

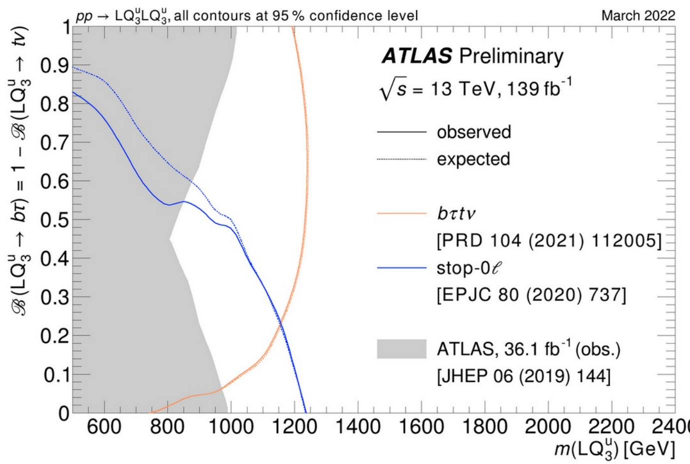
- Events with at least 3 leptons
- Boosted decision tree to define signal regions.
- Observations are consistent with the SM
- 95% CL limits for Leptoquarks (<1.4 TeV), Type-III seesaw heavy fermions (<1 TeV), Vector-like fermions (<1 TeV)

Example: Leptoquarks









H_T is the scalar pT sum of all jets

ATLAS updated summary for pair-produced scalar third-generation up-type leptoquarks