LHC Exotica

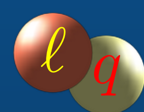
- Search for exotic physics signatures beyond motivations of SUSY and DM signatures
- Recent results and publications from ATLAS and CMS Experiments
  - Models
  - Search strategies
  - Sensitivities

Presented at the 3rd World Summit on Exploring the Dark Side of the Universe https://indico.cern.ch/event/801461/

LHC Exotica - topics

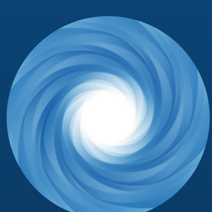
Fermions and φ's

- New heavies
- Light (pseudo)scalars
- Vector-like
- Leptoquarks



Heavy resonances

- ttbar and
- VV final states

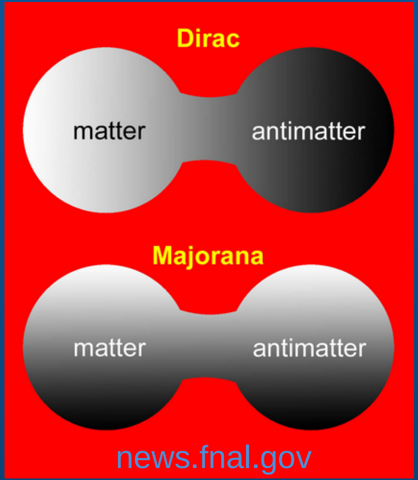


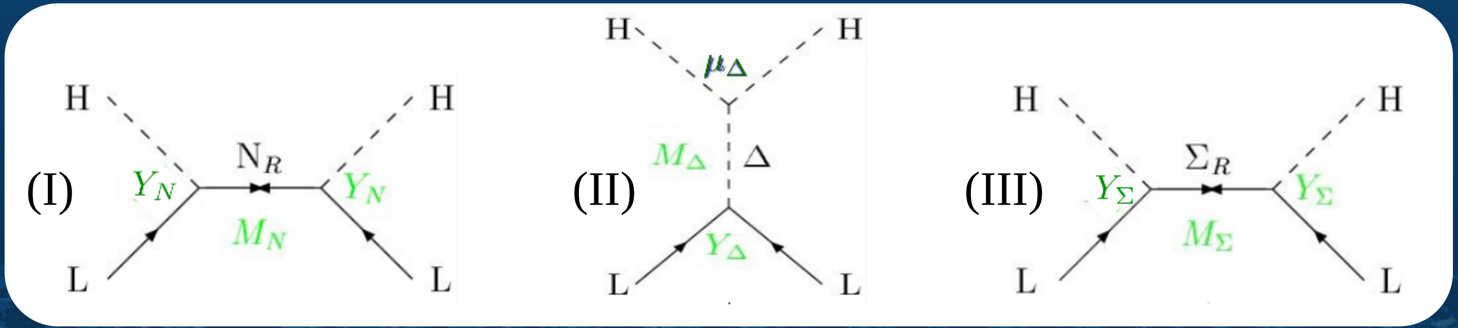
Deep dives

- Compositeness
- Monopoles and multi-charged particles

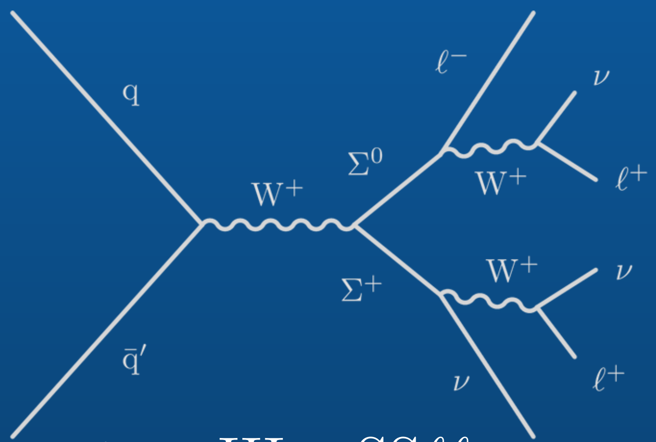
Seesaw models

- Widely adopted to explain small neutrino masses
- Include a range of scenarios and phenomena
  - Dirac/Majorana description of the neutrino
  - Heavy RH neutrinos
  - New scalar/fermion fields
- Suggest wide range of possible phenomena, including
  - Violation of B-L symmetry
  - Lepton number/flavor violating processes
- Type-I: heavy neutrino singlets
- Type-II: SU(2) scalar triplet
- Type-III: SU(2) fermion triplet

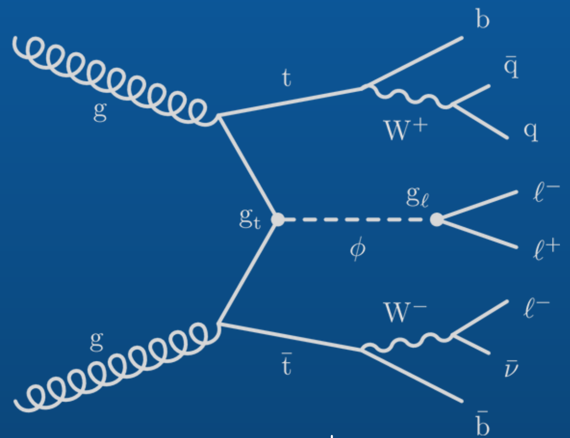




Like-sign lepton final states



$\text{type III} - \text{SS}\ell\ell$



$t\bar{t} + \{\phi \to \ell^+\ell^-\}$

Targeting signal processes:

1) pair production of type-III seesaw heavy fermions

2) light scalar or pseudoscalar boson in association with a pair of top quarks.

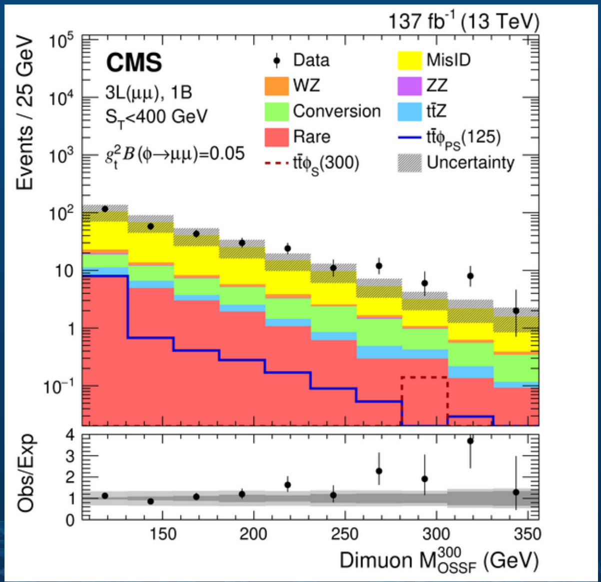
Suggested in extended Higgs & dark sectors, SUSY, ...

Categorize events based on:

leptons ; p_T^{miss} ;

$\Sigma p_T^{leptons} + p_T^{miss}$; M(OSSF leptons)

Largest observed deviation is 3.2σ for M_{ll}>206 GeV in μμ channel (no L.E.E.)

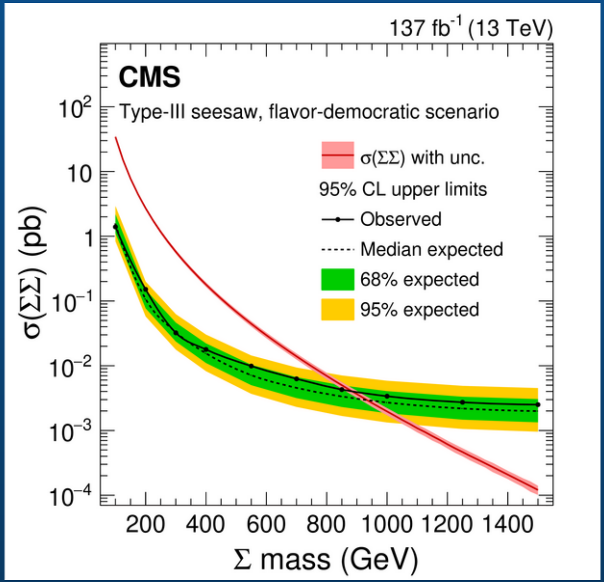


✵ Seesaw, type-III
✵ Light (pseudo)scalar

Like-sign lepton final states

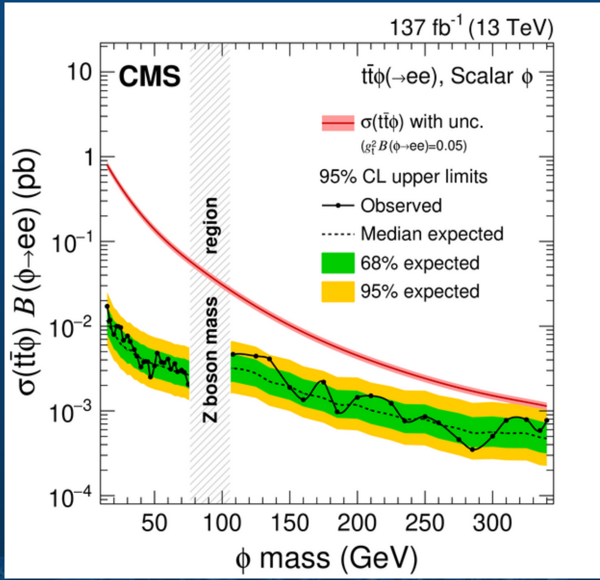
Data are found to be globally consistent with SM predictions within 2.7σ, no statistically significant excess compatible with signal models observed

Exclude heavy fermions of the type-III seesaw model for masses below 880 GeV at 95%



Most restrictive limits

For Yukawa coupling of 1 to top quark, exclusion limits set on BR of new scalars (pseudoscalars) to ee/μμ channels



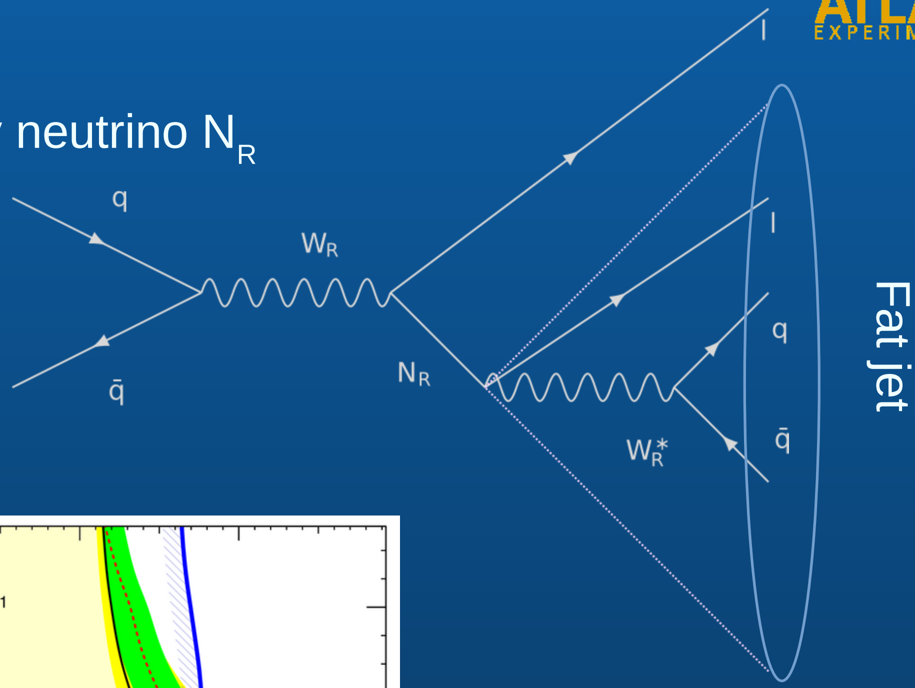
First limits in these channels

Type-I Seesaw

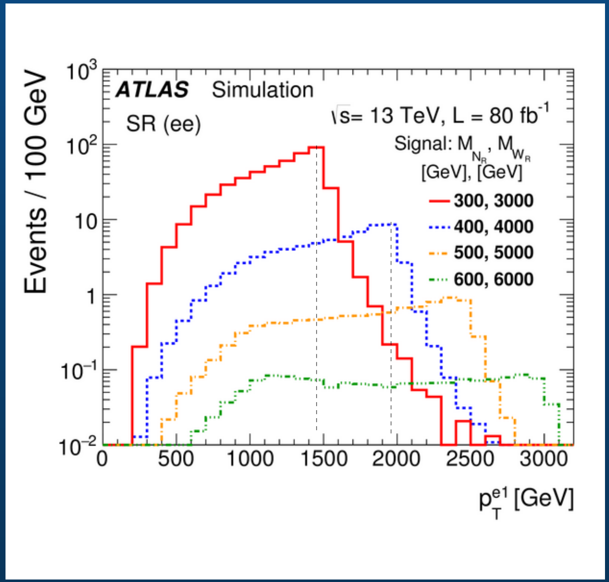
Decay of heavy right-handed gauge boson to heavy neutrino N_R

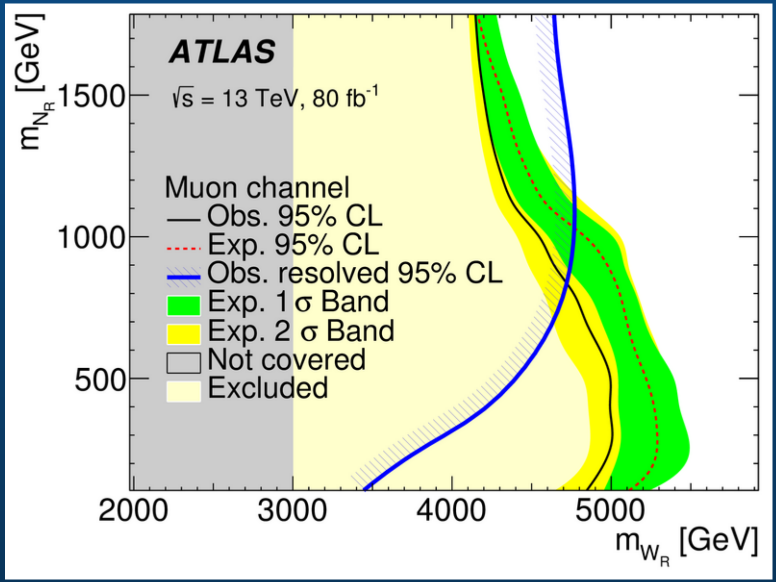
=> analyze final states consistent w/ boosted decay of $N_R \rightarrow l + (W_R^* \rightarrow jj)$

=> Significant reduction to SM bkg



Leading lepton p_T peaks ~$m_{WR/2}$





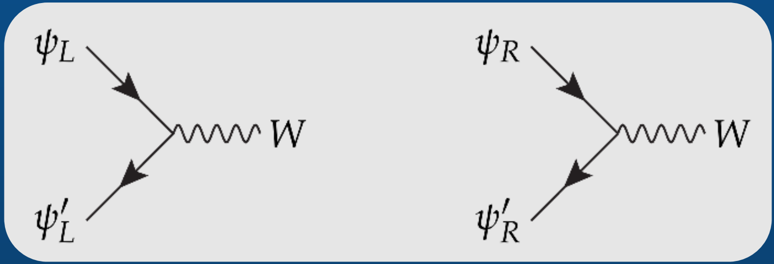
Exclude region m_{WR} up to 5 TeV and m_{NR} of 0.4–0.5 TeV

- R-L Symmetric model
- Heavy Neutrino

Vector-like fermions

4^{th} generation chiral fermions w/ similar properties to SM 3rd generation, but higher mass, are largely excluded by Higgs boson production cross section

- Gauge invariant mass term without the Higgs
- "vector-like" transformations under SU(2)xU(1) symmetry group of EW gauge bosons
- Interact via charged currents in both left and right sector
- Can mix with SM quarks
  => Strong bounds from FCNC



Present in a variety of models:

- Composite/Little Higgs, Extra dimensions, non-minimal SUSY, …
- Can also be applied to describe A^b_{FB} and A^{tt}_{FB} asymmetries

Rich phenomenology at LHC!

Vector-like quarks

$$T \to bW, \quad B \to tW,$$
$$T \to tZ, \quad B \to bZ,$$
$$T \to tH, \quad B \to bH.$$

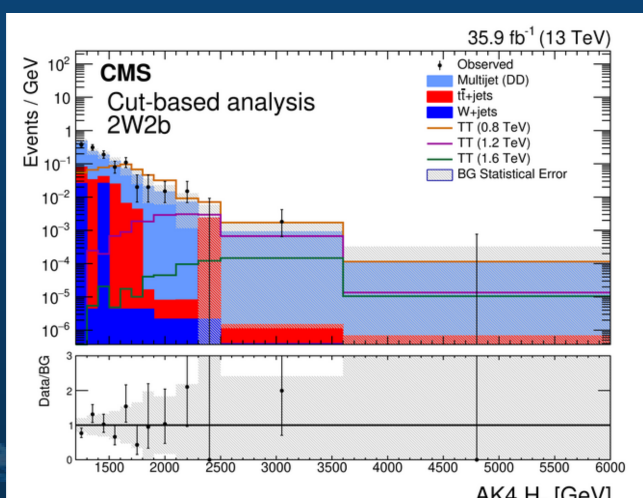
Target vector-like T or B quarks in fully hadronic final states, using:

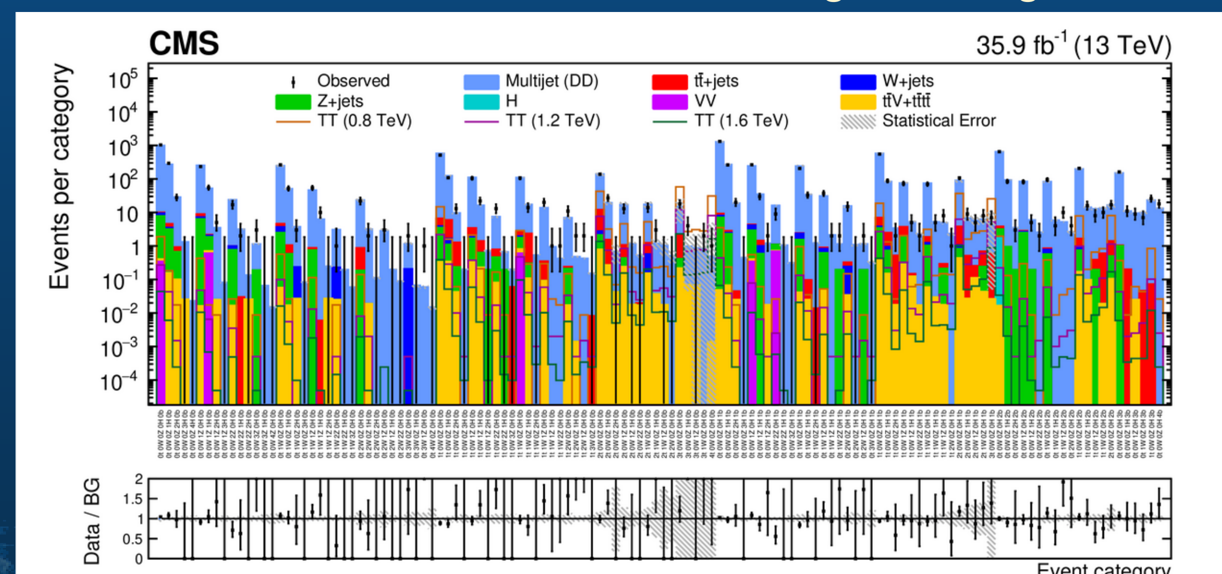
1) qW decay mode of T quark (pair) with fully reconstructed candidates

2) *boosted event shape tagger*, NN to label candidate jets as originating from top quarks, and W, Z, and H

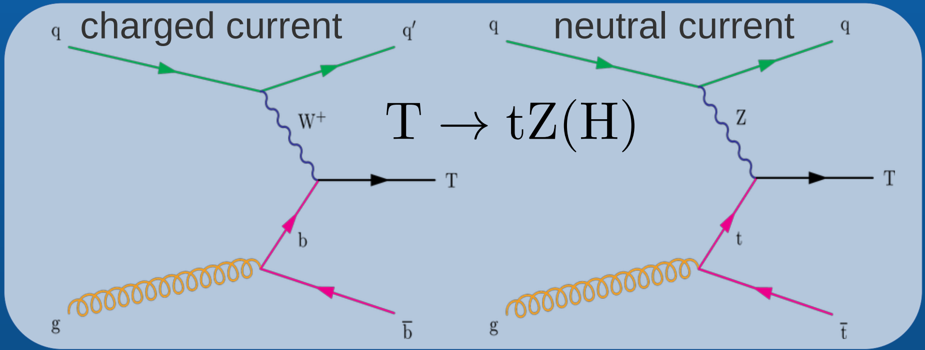
S/B discrimination in terms of H_T constructed from (fat) jets

Broad spectrum search in 126 signal region categories!





Vector-like quarks

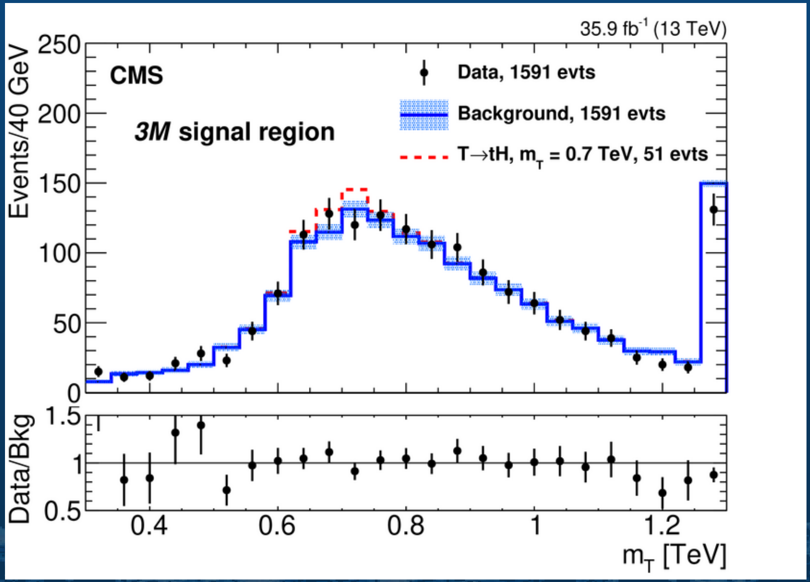


A related analysis looks for <u>electroweak production</u> of vector-like T in association w/ a top or b quark.

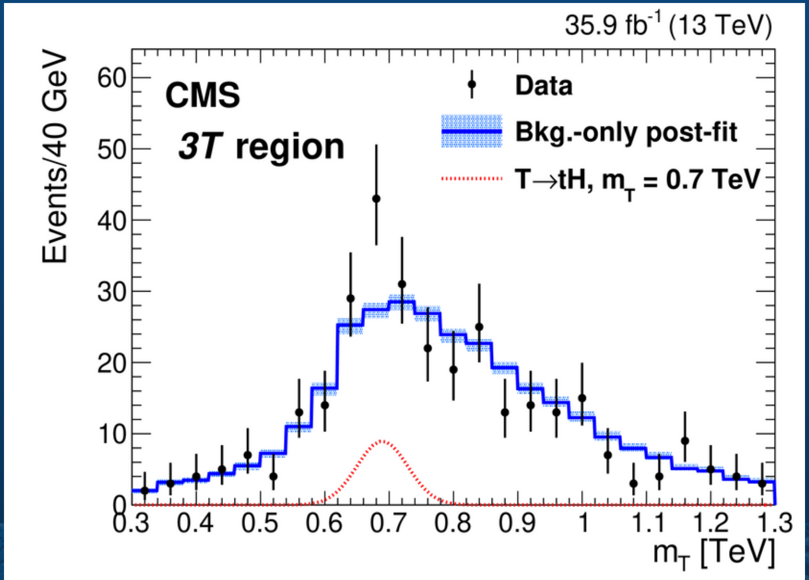
Consider wide range of Γ_T , narrow (<exp resolution) up to 30% of the T quark mass

Two strategies to reconstruct T in large jet multiplicity final states:

1) "low mass": resolved jet analysis
- combinatoric assignment to calc m_T

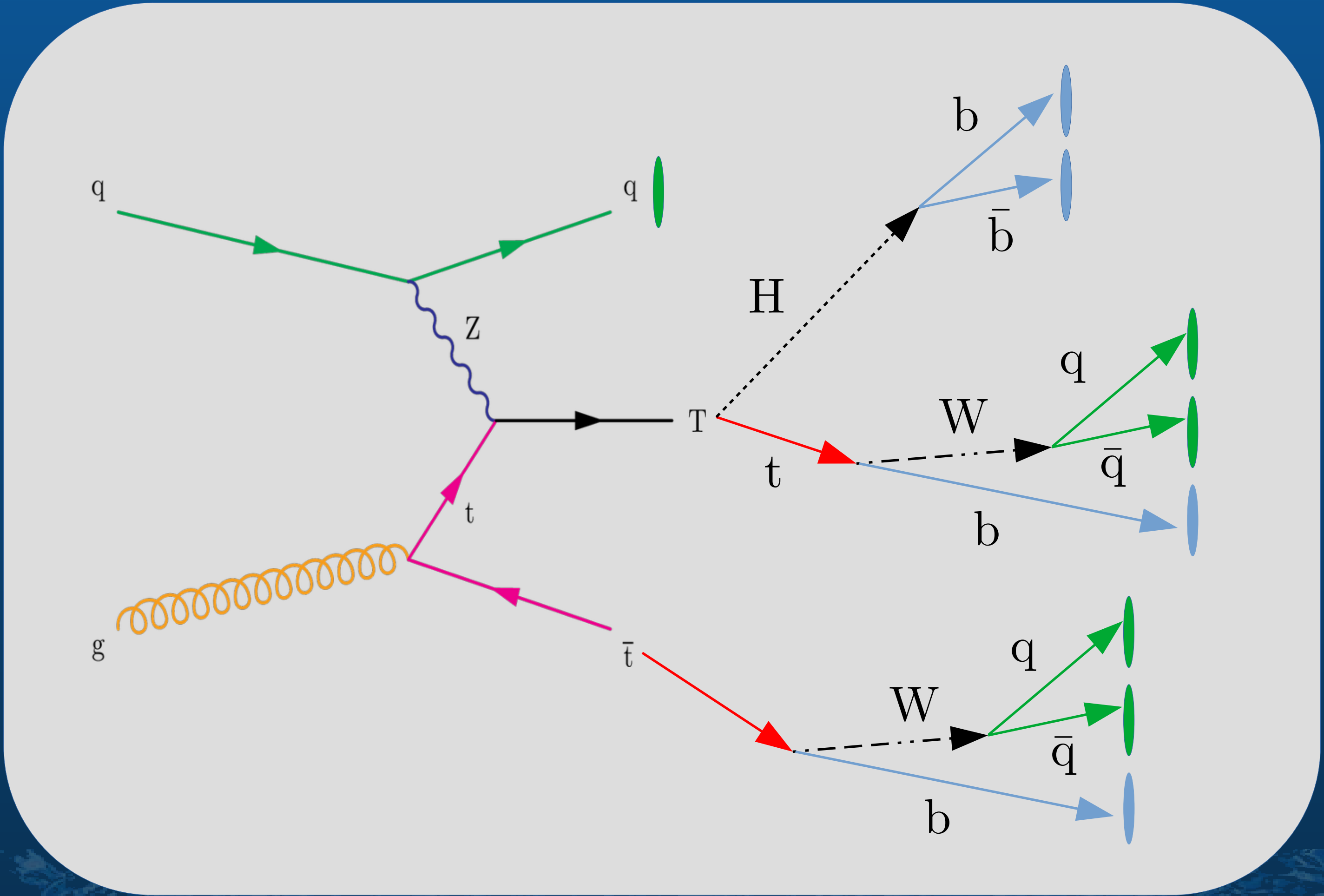


2) "high mass": boosted jet (substructure) analysis
- reconstruct T from two large-area jets



Ex: Resolved vs. boosted:

Example of fully resolved hadronic state



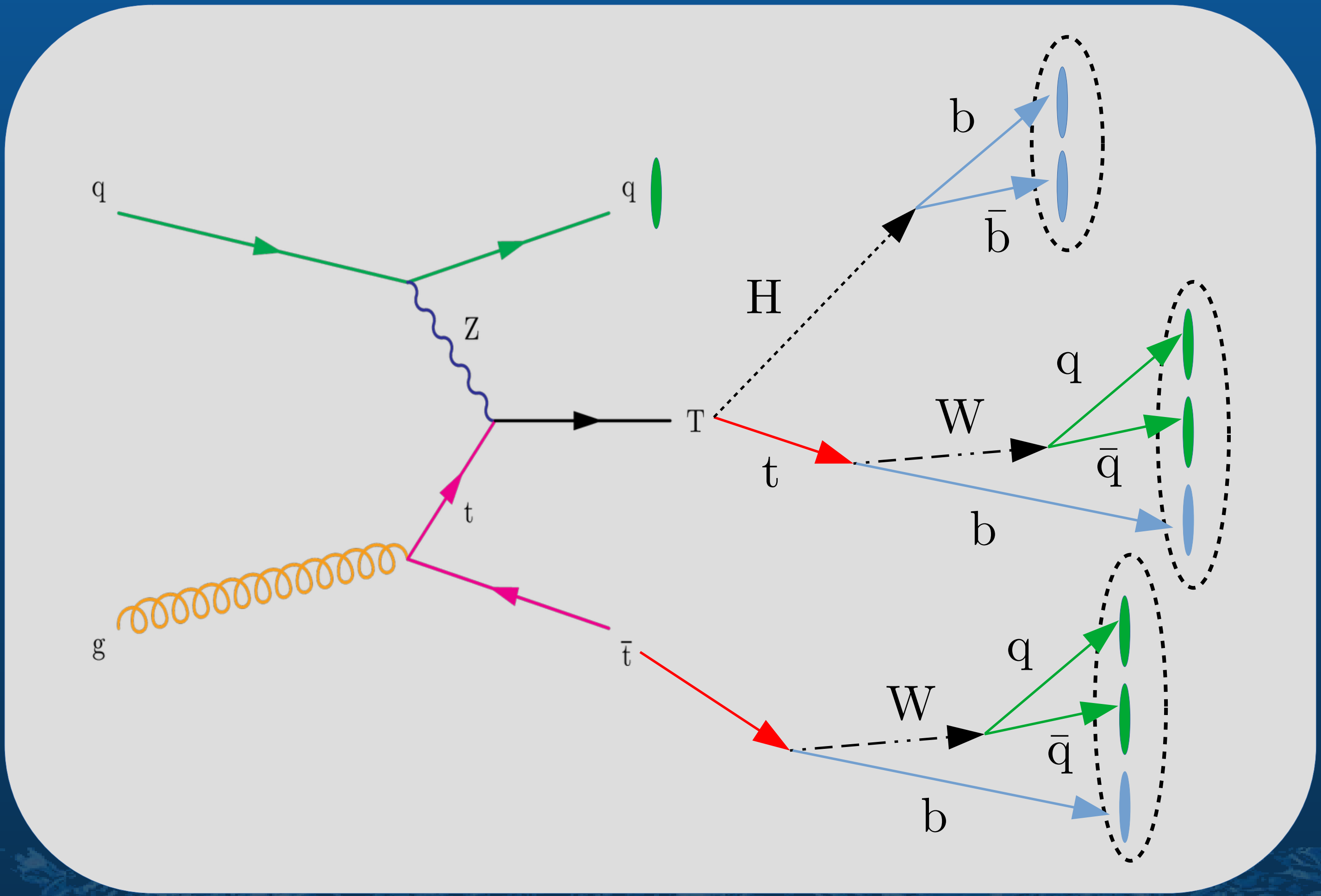
Large combinatoric problem to assign small-radius jets to final state particles

Help to resolve by requiring eg,

- masses of jet combinations to be close to H,W,Z,t,…
- Association of btagged jets w/ groups
- ...

Ex: Resolved vs. boosted:

Example of a highly boosted hadronic state

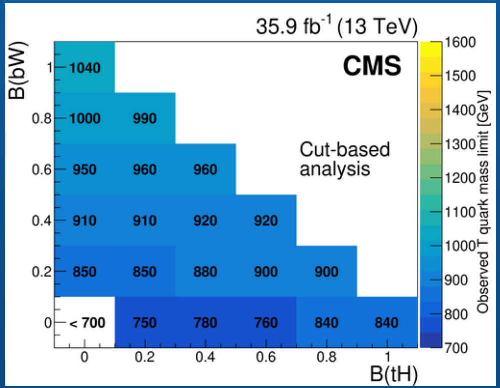


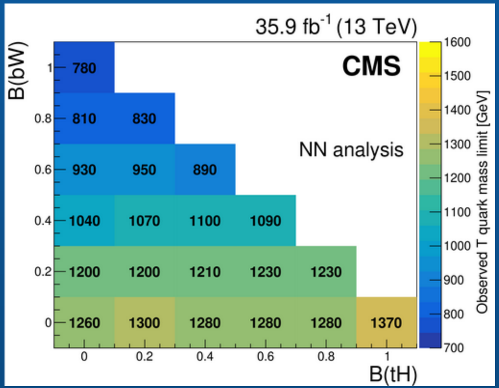
Can increase sensitivity through reduction of ambiguities in boosted final states

Results: VLQ results in hadronic final states

CMS B2G-18-003
CMS B2G-18-005

T/B Pair production





- New NN tagging techniques improve on previous searches
- Cross section limits for the pair production of T and B quarks vs mass and branching fractions considered.
- Excludes for T and B quarks from 740 to 1370 GeV, comparable in sensitivity to leptonic channel analysis.

Most stringent limits on pair produced vector-like quarks in the fully hadronic channel to date.

VL-Top EW production

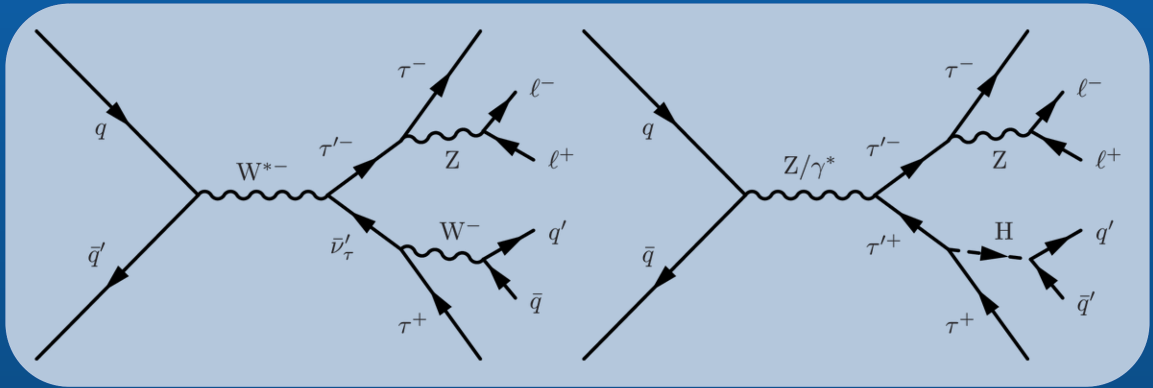
Some excess observed when fitting for the tH channel, local significance of 3.0 σ assuming a T quark mass of 0.68 TeV

- Search designed to be sensitive to fractional Γ_T of up to 30% over wide range of masses
- No significant excess considering LEE
- Limits set between 2 pb and 20 fb for $0.6 \leq m_T \leq 2.6$ TeV

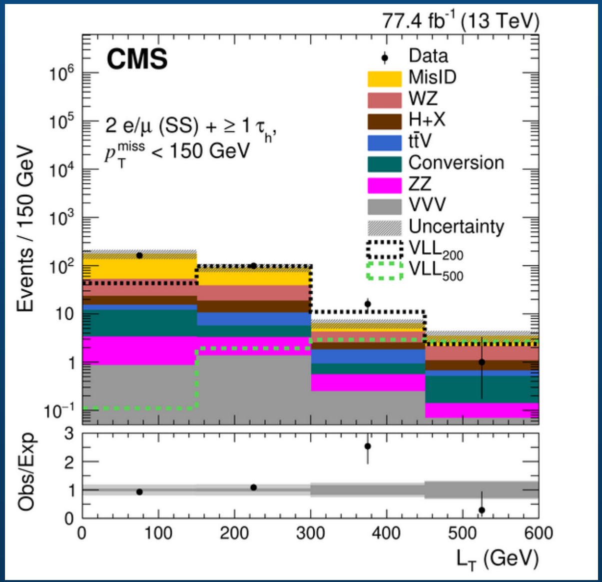
First constraints in this production mode on T → tZ for hadronic decays

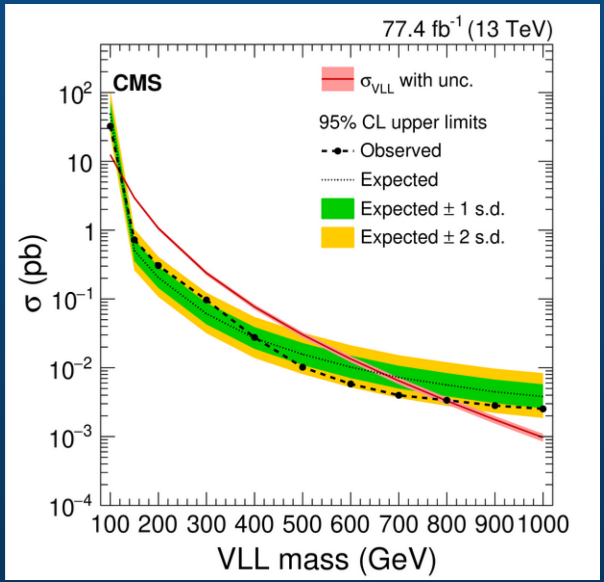
Vector-like leptons

Consider events with exactly 3 (4 or more) light-leptons [ℓ=e,μ] or 2ℓ + hadronic tau



Use scalar p_T of leptons as analysis variable

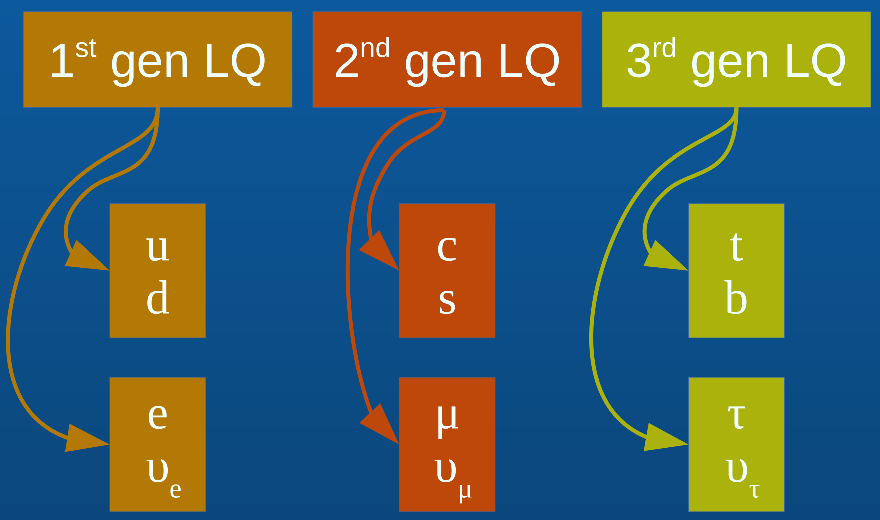




NSDfSMO

- Exclude VLL doublet, coupling 3rd gen. SM leptons in the mass range of 120-790 GeV.
- Most stringent limits on such a VLL model

Leptoquarks



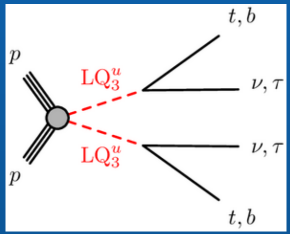
Properties

- Spin 0 or 1, have both lepton and baryon numbers
- Color triplet
- Fractional Electric Charge
- Constraints on FCNC, assume LQ's couple uniquely within a lepton/quark generation

Why study leptoquarks?

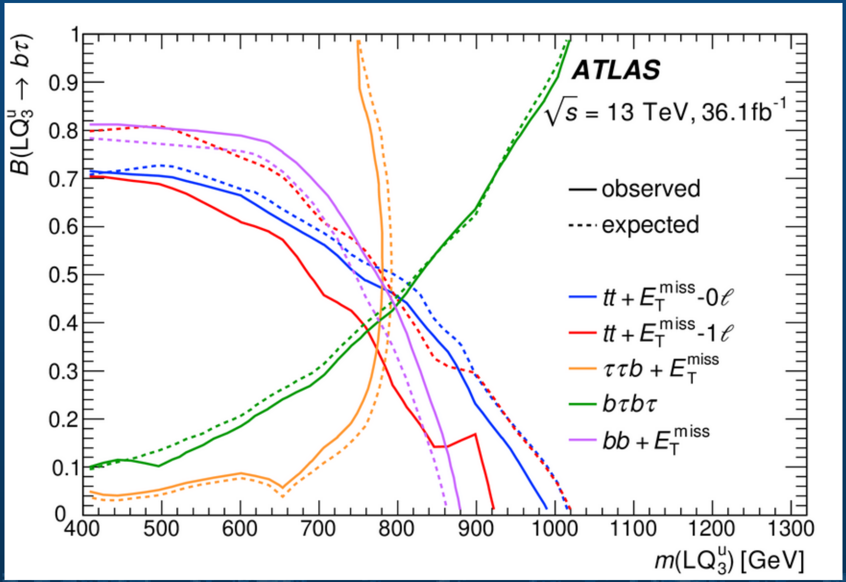
- Included in models beyond the SM (GUT's, Technicolor, composite models) assuming additional symmetry between leptons and quarks.
- Successfully addresses B anomalies b→clv, b→sll, hints of LFV, ...

3rd Generation LQs



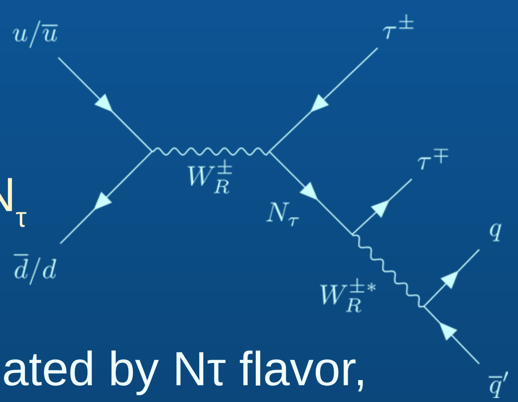
1) Consider all possible decays of the leptoquark into a quark (t, b) and a lepton (τ, ν) Employ BDT discriminators for sensitivity to LQ signal in each final state

Limits vs m_{LQ}, charged lepton BR for up/down-type LQs, m_{LQ}<~1TeV excluded

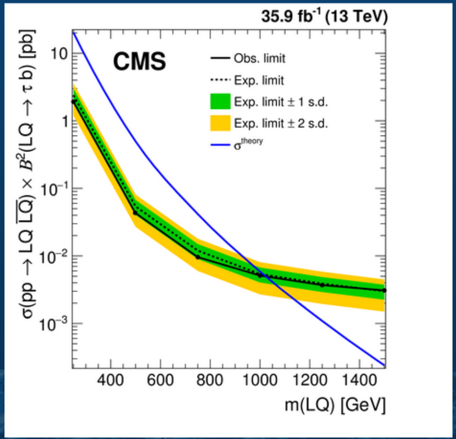


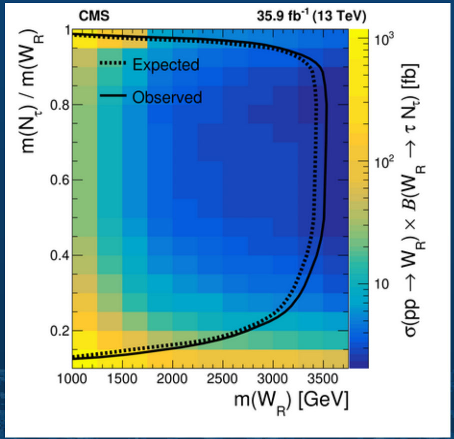
2) Search for heavy neutrinos and third-generation leptoquarks in hadronic states of two τ leptons

Right-handed charged bosons, W_R → heavy R-H Majorana neutrinos, N_τ



For W_R decay dominated by Nτ flavor, exclude W_R masses < 3.52 (2.75) TeV for Nτ mass is 0.8 (0.2) times m_{WR}



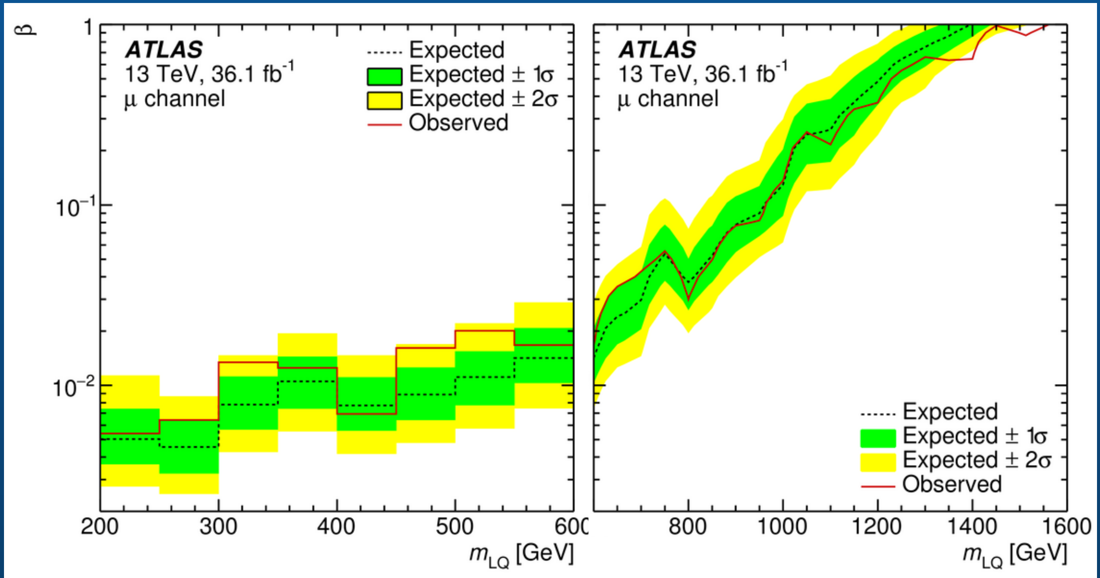


NSDfSMO

1st and 2nd Gen LQs

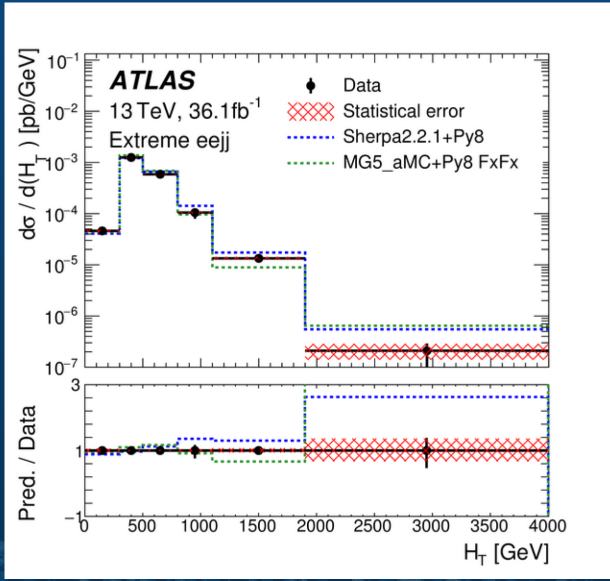
ee/μμ + ≥2j and e/μ + E_T^{miss} + ≥2j, final states

Employ BDTs based on m_{LQ} and lepton flavor



Also measure a variety of XS's in six ℓℓjj regions for major backgrounds.

"Extreme" regions used in searches are rarely measured. => useful for generator tuning.

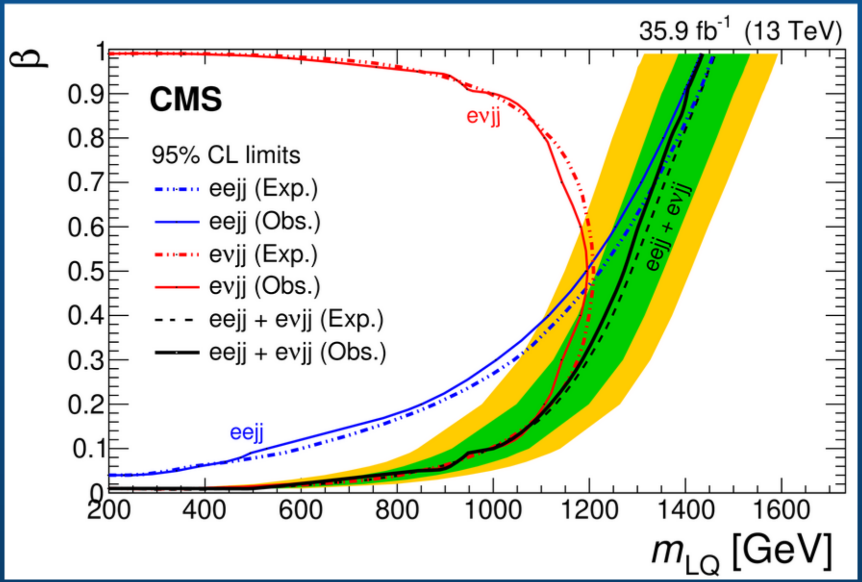


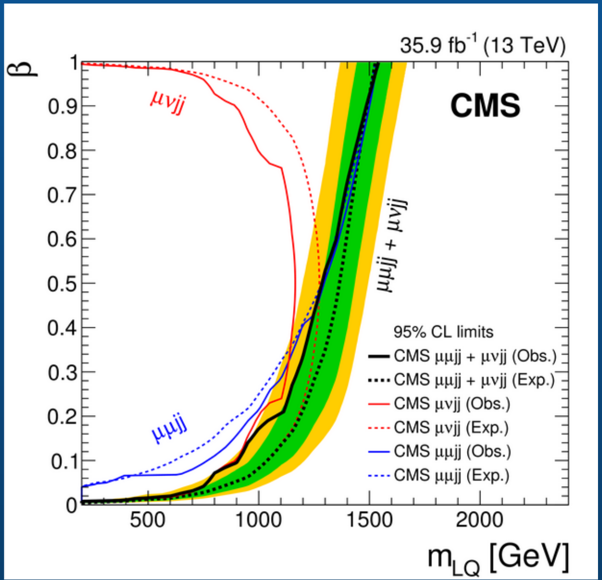
Significantly extend the sensitivity in mass compared to previous ATLAS results.

For BR into a charged lepton and a quark of 50%, exclude masses up to 1.29(1.23) TeV for first (second) generation LQs

1st and 2nd Gen LQs

CMS searches in ee(ν)+jj, μμ(ν)+jj channels, similarly in agreement ins SM expectations





Limits on mass of 1st gen scalar LQs set at 1435 (1270) GeV for β = 1.0 (0.5)

Limits on mass of 2nd gen scalar LQs set at 1530 (1285) GeV for β = 1.0 (0.5)

Heavy resonances / new bosons

Many extensions the SM predict the existence of heavy resonances, leading to new physics phenomena at the TeV scale.

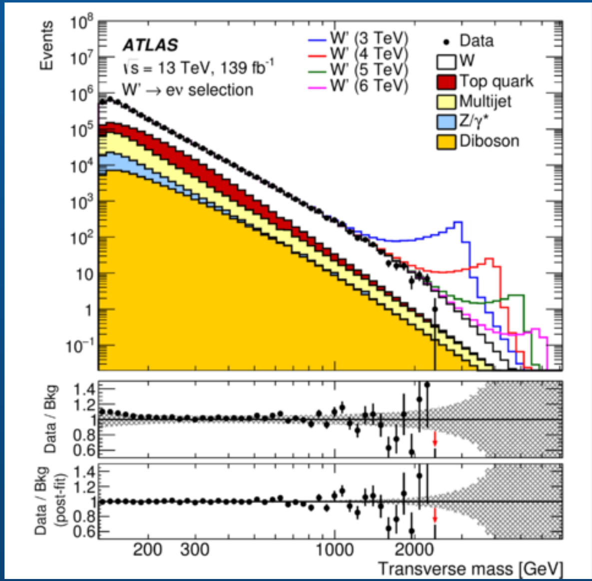
Such states appear in numerous frameworks, most of which aim to solve the hierarchy problem or other questions of fermion masses

- Grand Unified Theory models
- Left–Right symmetric models
- Little Higgs models
- models with extra dimensions
- two-Higgs-doublet model
- top color-assisted-technicolor
- ...

Phenomena include:

- Heavy spin-1 W or Z bosons with EW decays
- ttbar resonances
- spin-0 or spin-2 resonances decaying to EW boson or fermion pairs
- ...

W', Z', G

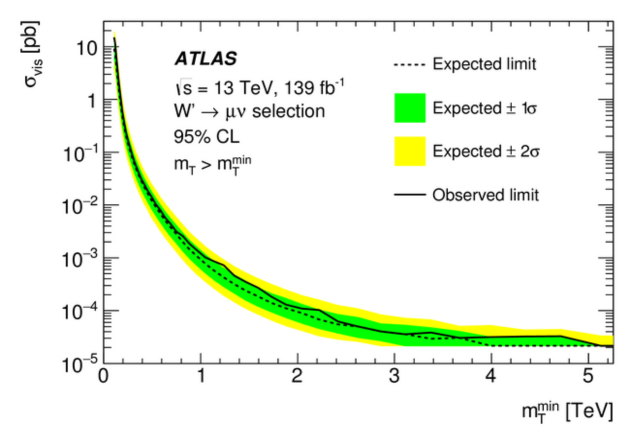


Search for heavy charged-boson resonance using transverse mass distributions in e, μ events

$$W' \to \ell\nu$$

NSDfSMO

- Limits combination of the e, μ channels from $0.15 \le m_{W}' \le 7.0$ TeV, w/ cross section limits from 1.3 pb to 0.05 fb
- Fiducial cross-section limits are set on production of resonances with different Γ/m values ranging from 1% to 15%

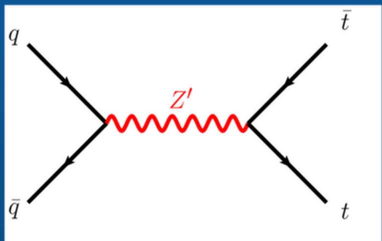


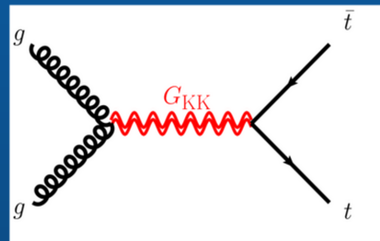
Model-independent upper limits are determined for the number of signal events and for the visible cross section above a given m_T threshold

Limits set from 4.6 (15) pb at $m_{T,min}$ = 130 (110) GeV to $\boxed{\text{22 (22) ab}}$ at $m_{T,min}$ = 5.1 TeV in the e (μ) channel

ATLAS EXOT-2016-24

W', Z', G





Scan of Benchmark Models:

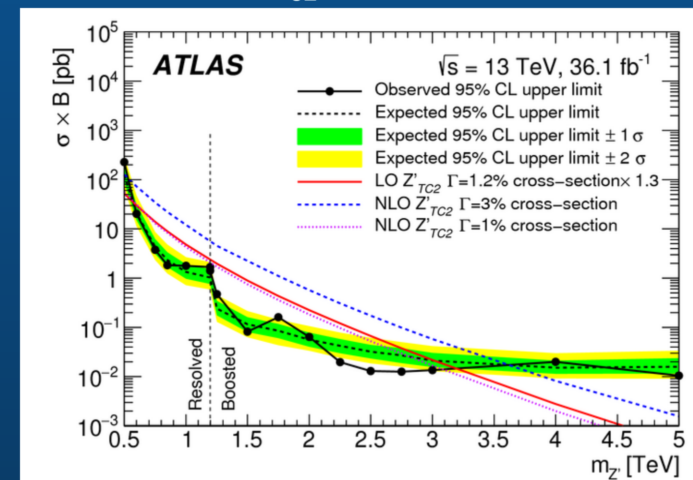
- Topcolor-assisted-technicolor leptophobic Z'_{TC}
- (axial)vector mediator $Z'_{(ax),med}$
- RS (bulk) model g_{KK} (G_{KK}) w/ spin-(2) color-octet boson
- Consider widths: "narrow" ≤ $\Gamma_{Z,G}$ ≤ $0.4M_{Z,G}$

Resolved and boosted analyses of $t\bar{t} \rightarrow$ all jets final states

NSDfSMO

A minumum local p-value of 2.1σ is observed in the boosted analysis for a narrow-width Z'_{TC} signal model at $m(Z'_{TC2}) = 1.75$ TeV

Resolved t | tau_{32} tagging



Exclusions:

Z'_{TC2} boson: m < 0.58 and 3.1 TeV (0.53 and 3.6 TeV) for Γ of 1% (3%)

(axial)vector Z'_{med}: 0.80 TeV < $m_{Z'}$ < 0.92 TeV and 2.0 TeV < $m_{Z'}$ < 2.2 TeV
(0.74 TeV < $m_{Z'}$ < 0.97 TeV and 2.0 TeV < $m_{Z'}$ < 2.2 TeV)

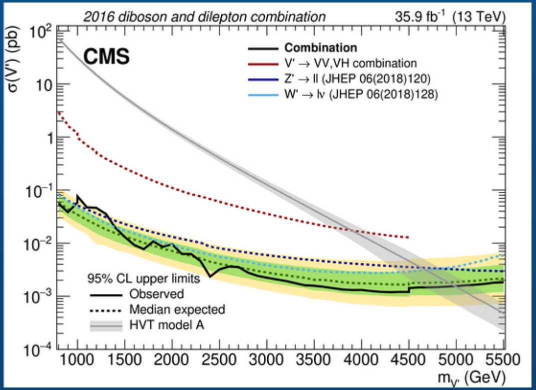
g_{KK}: m < 3.4 TeV for the decay width of 30%

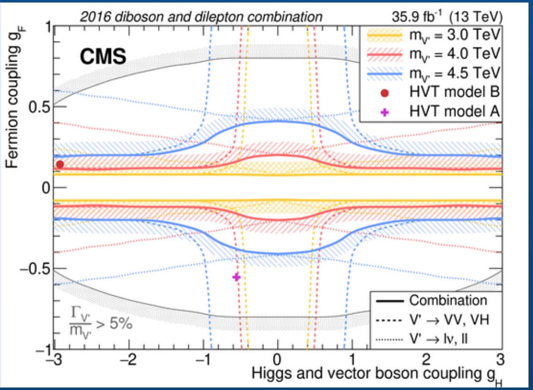
W', Z', G

Statistical combination of searches for heavy resonances decaying to pairs of bosons or leptons

Exclusion limits are set wrt models:

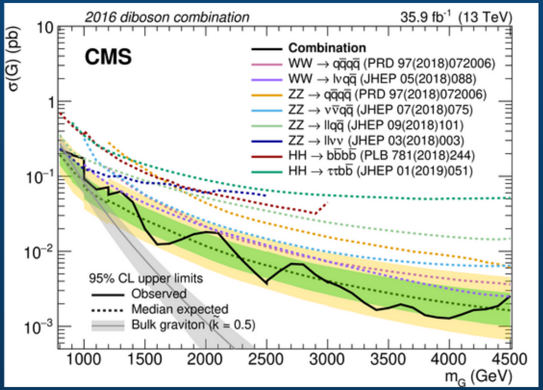
- spin-1 heavy vector triplets, for two SM boson/fermion coupling scenarios (arXiv:1402.4431)
- spin-2 bulk gravitons





The largest deviation from expected limit is observed in the V' model A at mass of 1.3 TeV, with local significance 2.7σ

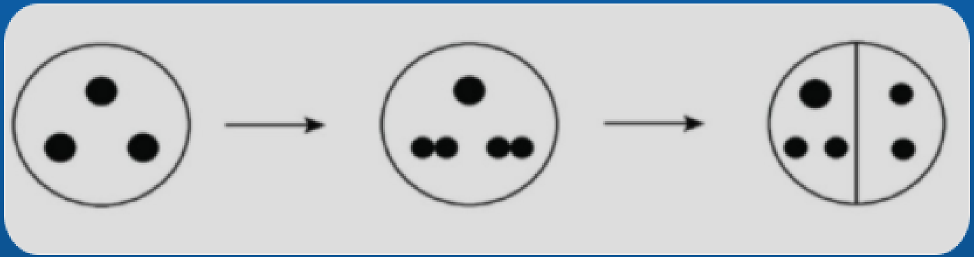
NSDfSMO



Exclusions:

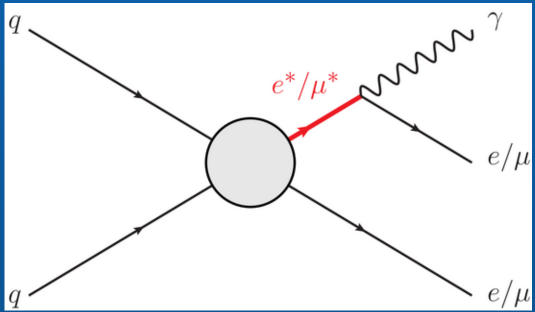
- Warped extra dimensions: σ < 1.1 fb for spin-2 bulk graviton
- Triplet of narrow spin-1 resonances: mW'(Z') < 5.0 and 4.5 TeV for with coupling predominantly to fermions (bosons)
- For Z', the statistical combination extends the exclusion limit by 700 GeV as compared to the best individual channel

Compositness



While the SM successfully describes a wide range of observations, it does not provide any explanation for many of its own features, for example the existence of three fermion generations of both leptons and quarks

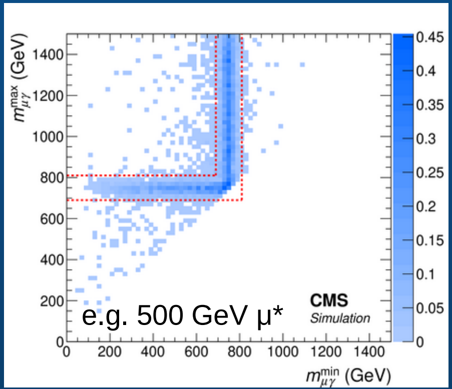
Composite model postulate that quarks and leptons are composite objects
- composed of more fundamental constituents
- bound by asymptotically free gauge interaction that becomes strong below a characteristic scale Λ
- predict the existence of excited states of quarks (q*) and leptons (ℓ*) at scale of the new binding interaction



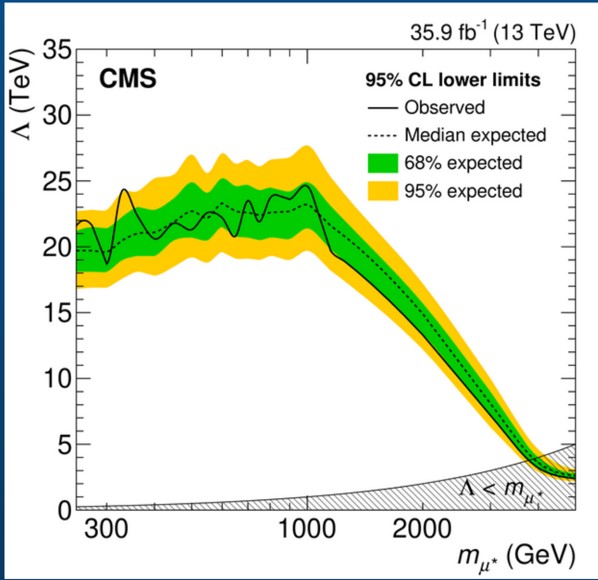
Excited leptons

Search for excited lepton (ℓ* = e*, μ*)
in same-flavor lepton pair + photon

- ℓ* is produced via a contact interaction of energy scale Λ
- Analysis uses $m_{\ell\gamma}$ distributions for both pairings



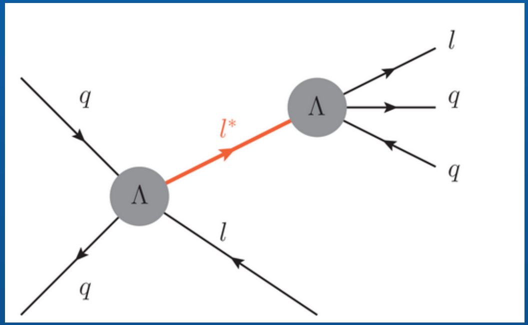
Set upper limits on the production cross sections of e*, μ* and corresponding lower limits on compositeness scale Λ vs m(ℓ*)



Assuming the ℓ* mass equals the compositeness scale,
e* (μ*) excluded for m(ℓ*) < 3.9 (3.8) TeV

Best observed limit on compositeness scale is obtained with m(ℓ*) around 1.0 TeV, excluding values below Λ=25 TeV for both excited electrons and muons.

Excited leptons

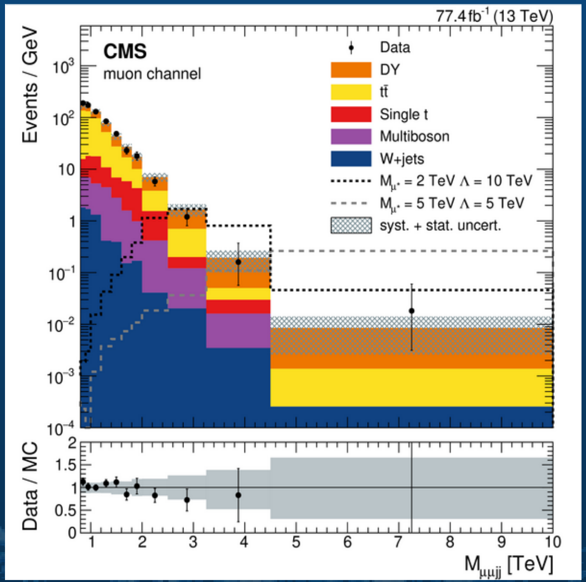


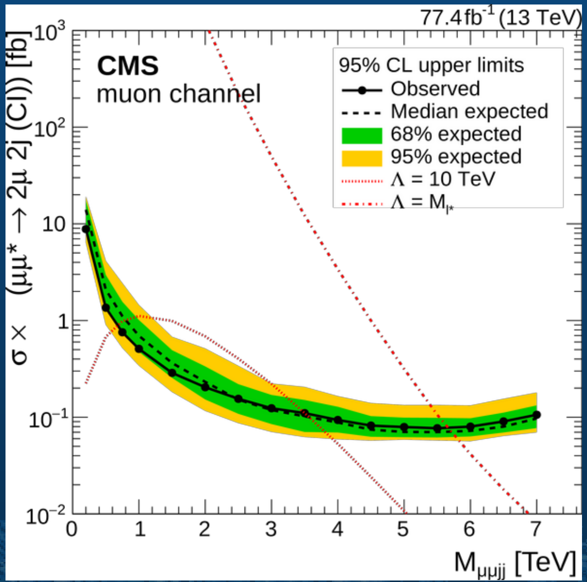
Search for excited lepton (ℓ^* = e*, μ*) in association with ordinary lepton of the same flavor.

- ℓ^* is produced via a contact interaction of energy scale Λ
- Decays to a lepton and two jets

Use 4-body invariant mass of the $2\ell2j$ system as analysis variable (NSDfSMO)

Taking Λ = m(ℓ^*) => exclude e* (μ*) with masses below 5.6 (5.7) TeV



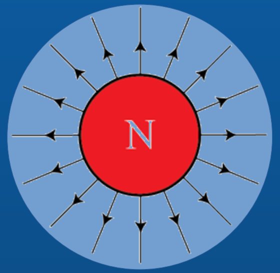


Best limits to date

See also:
ATLAS EXOT-2017-22

Many models suggest the existence of (heavy) stable charged particles

- Arguments for existence of magnetic monopoles
  - E&M symmetry in Maxwell's Equations
  - Dirac's explanation for electric q quantization
  - GUTs
  - EW monopoles at TeV mass scales in other extensions to SM



- Fundamental magnetic charge: multiple of g=ec/(2α)
  - Particle with one unit of |g| interacts line ion with elec. charge |z|=68.5
  - Ionization energy loss ~4700x than a proton.

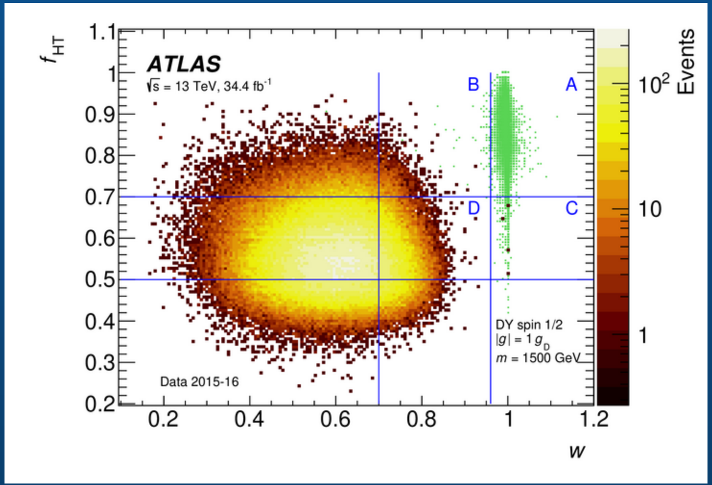
Other models with exotic stable high-electric-charge objects (HECOs)

- aggregates of ud/s-quark matter
- Q-balls
- micro black-hole remnants
- additional EW singlets (AC-models)
- Technibaryons
- L-R symmetric models of $H^{\pm\pm}$

Monopoles/HECOs

Non-standard signatures, require care for detection (beware the prescales!)

Trigger: L1 EM seed > 22(50) GeV
HLT used to select HIP candidates with HT hits on road in the TRT
Trigger variables, $N_{HT,trig}$ >30 and $f_{HT,trig}$>0.5
Select events w/ at least one high-ionization object

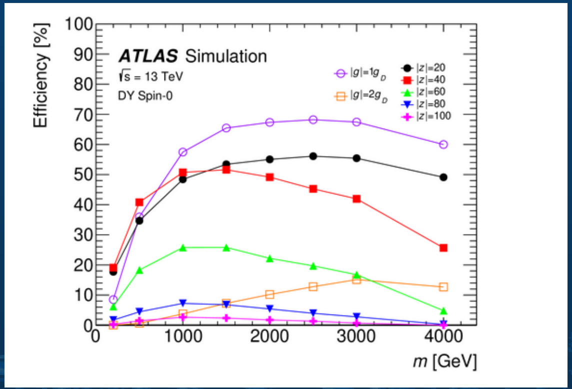


Offline:

Use signature based upon high ionization in the ATLAS TRT + associated, pencil-shape energy deposit in the ECAL

Discriminating variables:

- fraction of high threshold TRT hits (fHT)
- lateral energy dispersion of the EM cluster candidate (w)



Backgrounds from random combinations of rare processes, estimated directly from data. Ex, TRT hits from overlapping charged particles and noise in TRT straws

Monopoles/HECOs

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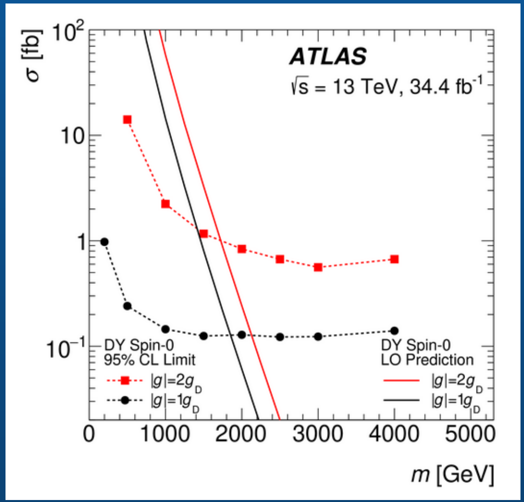
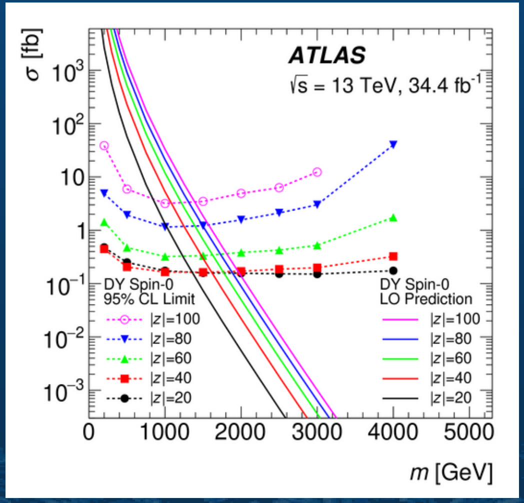


Interpret results in models of Drell–Yan pair production of stable particles with:

- spin hypotheses 0 and 1/2
- masses ranging from 200 GeV to 4000 GeV

Factor of ~5x improvement on constraints for

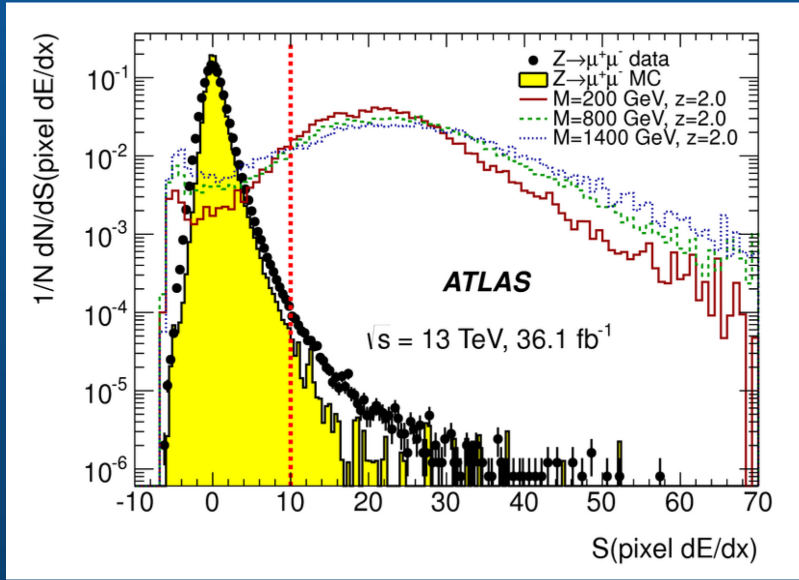
- direct production of magnetic monopoles carrying one or two Dirac magnetic charges
- stable objects with electric charge in the range 20 ≤ |z| ≤60 and extends previous search ranges to 60 < |z| ≤ 100



MCPs

Search for particles producing anomalously high ionization, consistent with long-lived massive particles of charge |q|=2e to |q|=7e

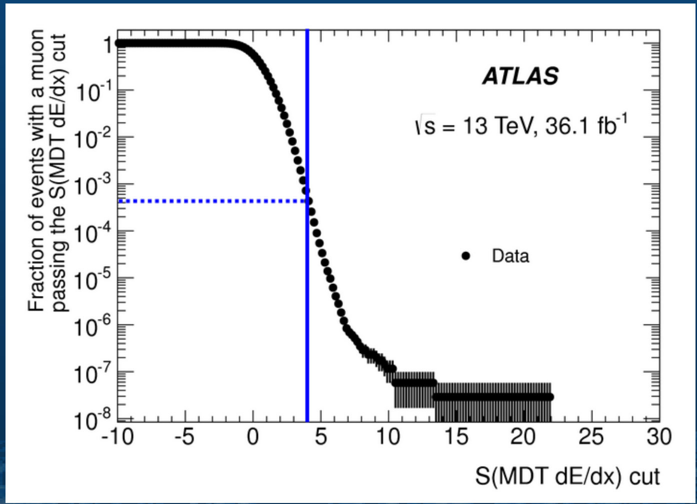
Trigger and event selection uses:
- muon system tracks
- missing ET (related to variations in calo energy, MDT times wrt mass and β)
- Large dE/dx in TRT and MDT



dE/dx distribution in Si pixels

Substantial slow down due to heavy ionization.

These signatures span a large space of interesting detection features, eg
- Range
- Timing
- dE/dX,
- cluster shape
- ...



Events passing MDT dE/dx cut

ATLAS EXOT-2017-13

MCPs

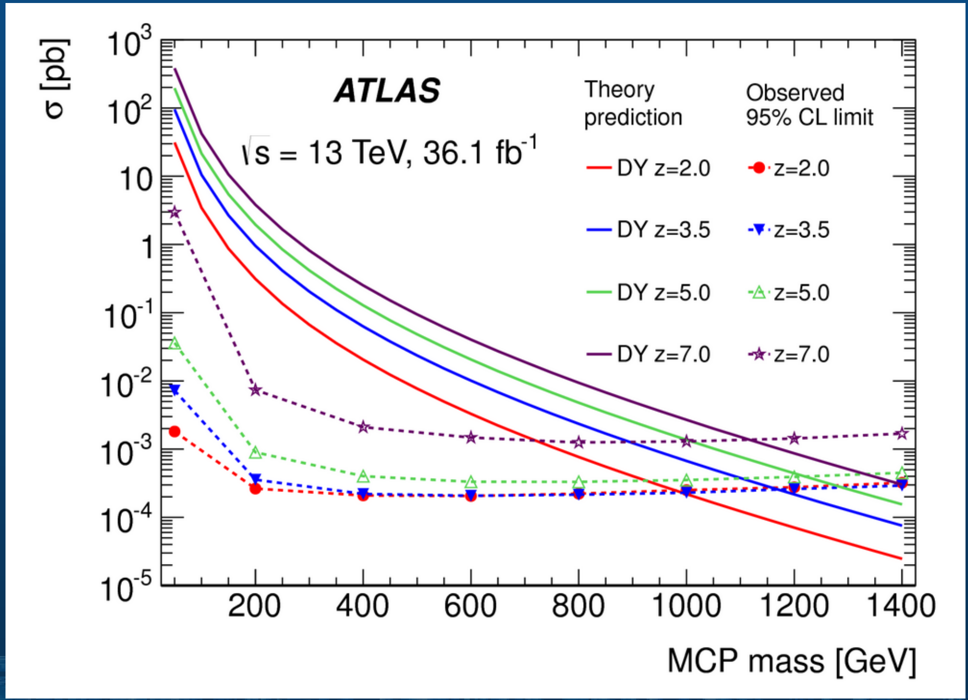
Search for particles producing anomalously high ionization, consistent with long-lived massive particles of charge |q|=2e to |q|=7e

Trigger and event selection uses:
- muon system tracks
- missing ET (related to variations in calo energy, MTD times wrt mass and β)
- Large dE/dx in TRT and MDT

Exclude heavy ionizing, lepton-like particles |q|=2e to |q|=7e traversing the full ATLAS detector

<1 one background event is expected and 0 events are observed

Upper limits on σ_{MCPs} using a Drell–Yan production model are derived for multi-charged particles of mass from 50GeV to 980–1220 GeV



In summary

- Some (local) fluctuations, but strong hints remain elusive
- Progress in exotics searches requires equal parts innovation and extending data sets
- Must keep looking for new regions of accessible phase space to explore, new tools to exploit:
  - Improvements to all tagging techniques
  - Scanning N-invisible-particles final state particles
  - New detection techniques and trigger capabilities, eg. timing, dE/dx, extended track ID,…
- Leave no stone unturned, our data may yet be richer than we know!

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Congratulations and thanks to organizers for a wonderful workshop on the dark side of things in sunny in Guadeloupe!