Experimental Results on Exotic Searches

LHCP 2021

The Ninth Annual Large Hadron Collider Physics Conference

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June 8, 2021

LHC on Beyond the SM Physics

- 10+ years and counting, the **LHC physics program** is as **active** as ever.
  - **SM works at the energy frontier**, quite well
  - **H(125)** is here, and looking good

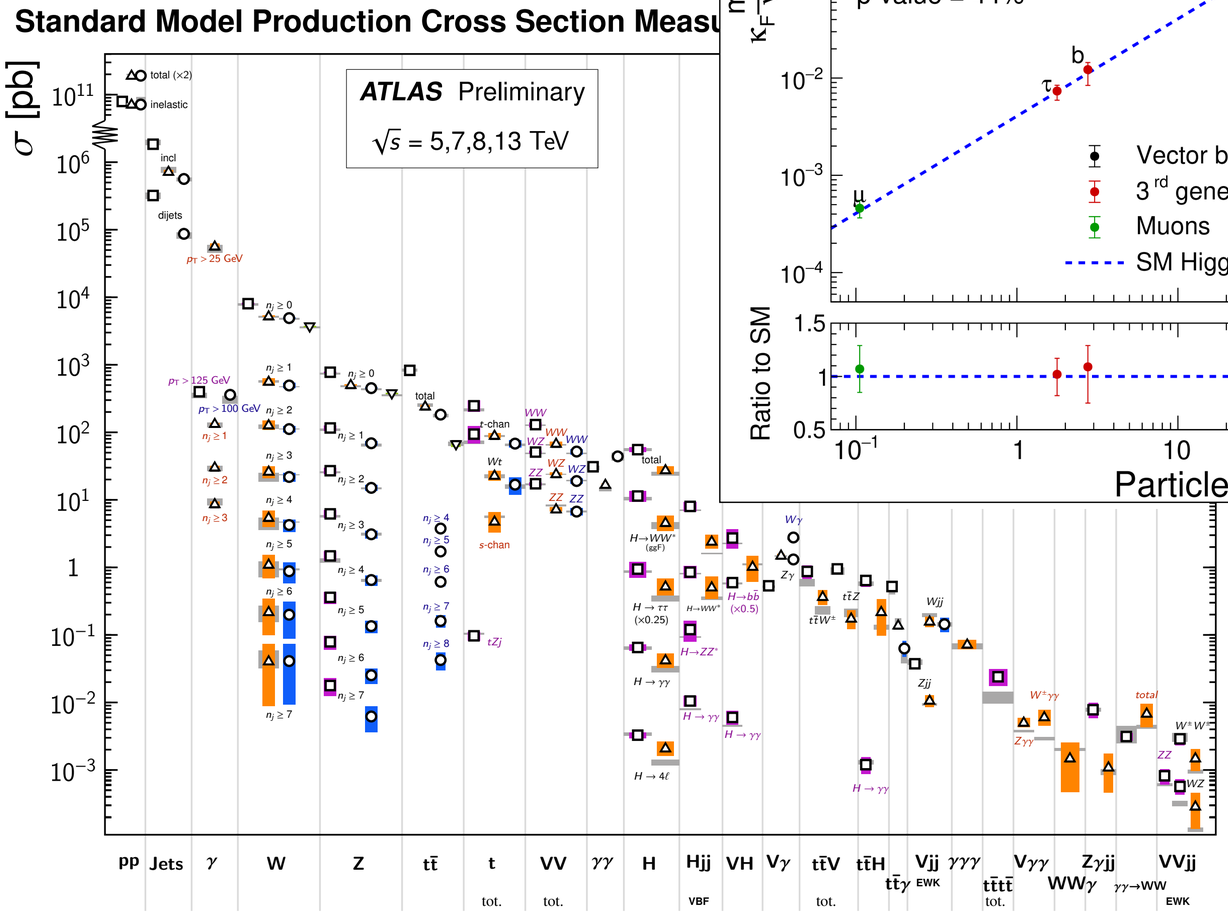
- But at some level, picture is not complete.
  - needs for **BSM** are also still here:

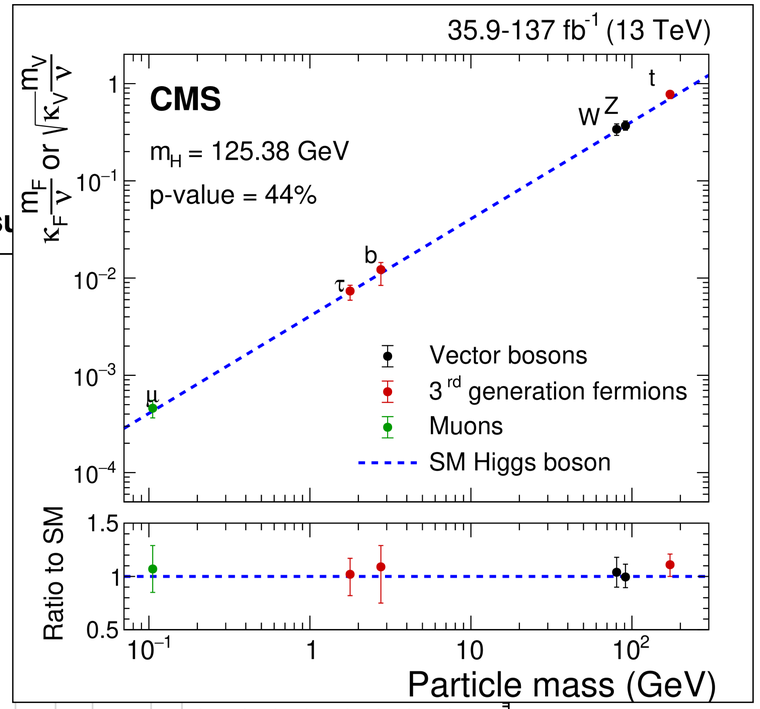
- Why BSM ? Motivations are varied

  Needs - **Elegance** - **Why not?**

  - *Matter-antimatter asymmetry*
  - *Dark matter*
  - *neutrino masses, oscillations*
  - *Hierarchy problem (Plank vs Weak scale)*
  - *Higgs stability*
  - *Unification of forces*
  - *Extended scalar sectors*
  - *Hidden portals*
  - *…*

- **LHC** experiments are **uniquely positioned** to address these competitively, and from complementary angles.



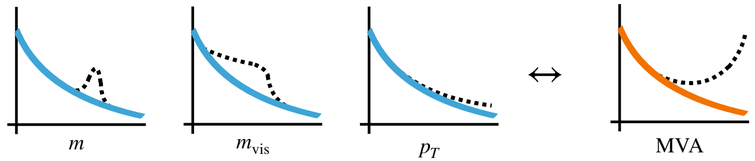


Playing the hand we are dealt

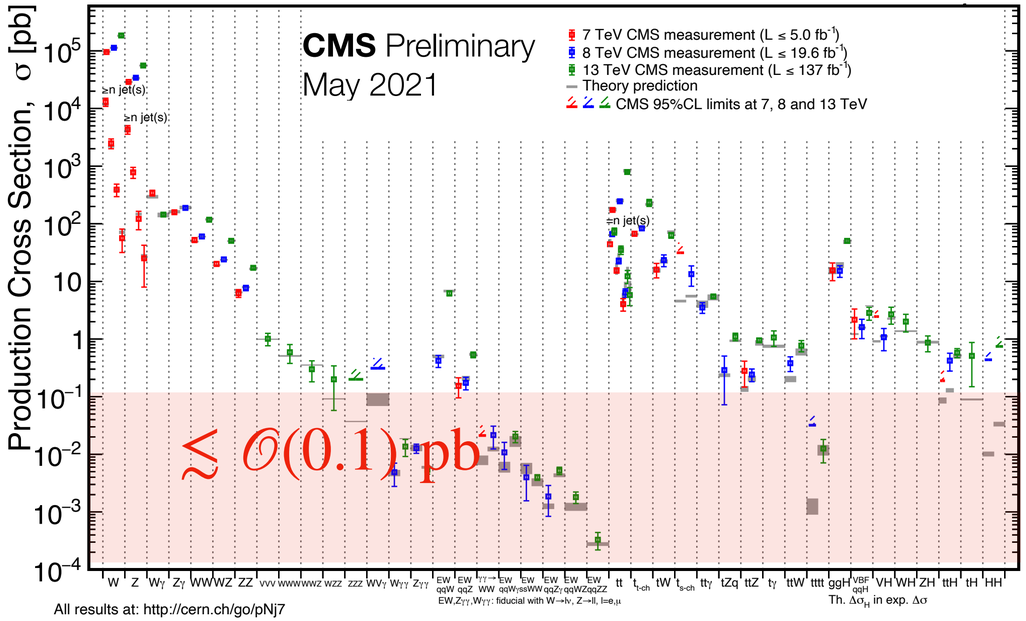
- LHC experiments provide a **well calibrated environment**, but we have a $\sigma(\mathrm{SM})$ to get past.

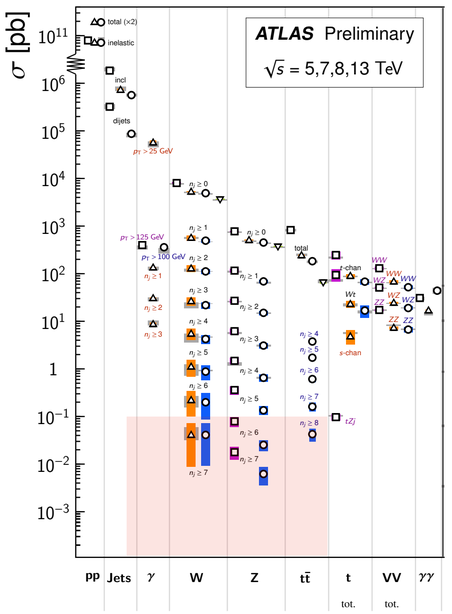
A typical BSM search **seeks**:
- *More leptons (useful at a hadron collider)*
- *More jets (or substructure, or flavor tagging, ..)*
- *More long-lived*

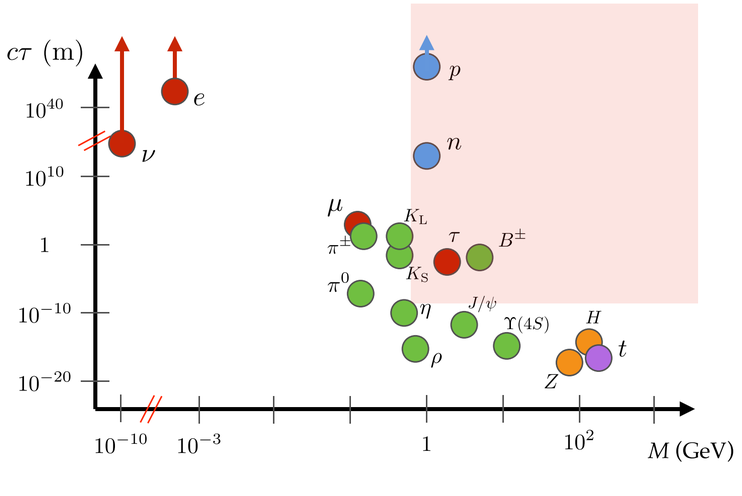
..and **probes for**:
- *Resonant*
- *Semi-resonant / end-point*
- *Non-resonant (tail enhancement)*



structures, oftentimes with multivariate techniques







Outline

- A limited survey of **LHC searches** for various extensions of the SM.

Extended Gauge Sector / New bosons

- Extra dimension models (V_{KK}, G_{KK}, …)
- Grand unification theories (leptoquarks, …)
- Technicolor, composite Higgs (W', Z',…)

New Heavy Fermions

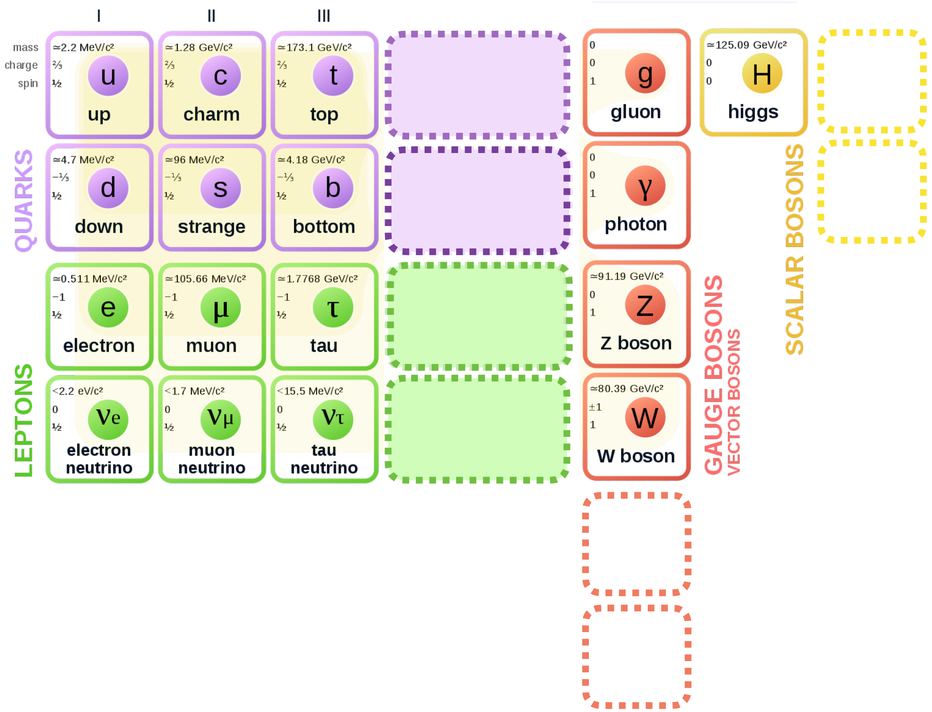
- Chiral structure important
- Mass independent of EWSB

Additional Scalar States

- A common feature in SUSY models
- Mixing with Higgs

Compositeness

- New forces/particles integrate out at low energies (SM)



A bias towards very **recent results** from **ATLAS, CMS, and LHCb**

Please see dedicated sessions on:
- Dark Matter, SUSY interpretations/searches
- precision SM, Higgs measurements and reinterpretations

Extended gauge sector

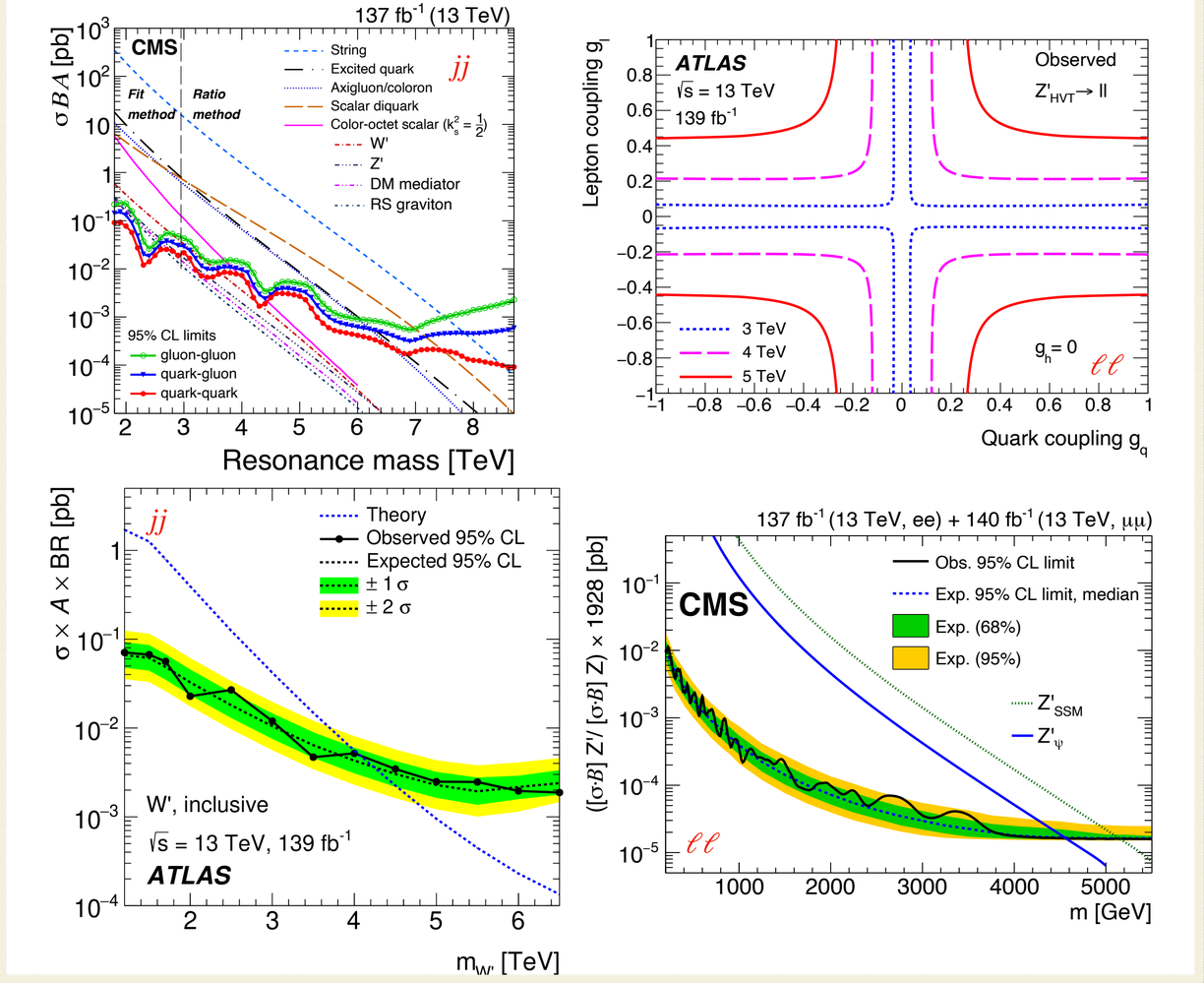
- Rich parameter space, and a vast program at the LHC
  - Various final states:

    $V' \to \ell\ell, qq, \ell\nu, VV, VH, \ldots$

- With Run-2 dataset, **multi-TeV masses** probed for the **benchmark** models:

  - **Classic *resonant* signatures** in leptonic/hadronic final states

  - On the other side of the spectrum are searches with **bosons / third generation / p_T^{miss} signatures**
    - — ***hadronic*** *techniques*
    - — *taus, b-tagging,* ***boson tagging***



arXiv:2103.02708
PLB 796 (2019) 68-87
JHEP 05 (2020) 033
JHEP 03 (2020) 145
PRD 100, 052013 (2019)
CMS EXO-19-017

Good to think in terms of **signatures** ↔ **Simplified models** help us to keep *track**

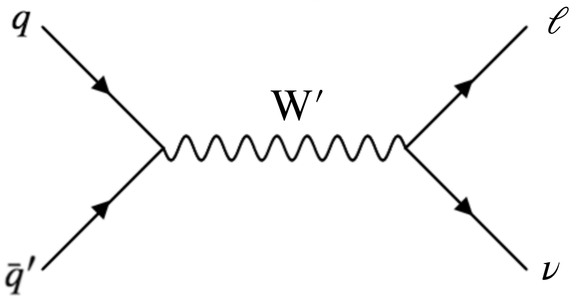
***Heavy Vector Triplet** model (HVT): couplings to quarks, leptons, Higgs are free parameters
- **Model A** [aka Sequential Standard Model (**SSM**)]: BR($V' \to ff$) important
- **Model B** : BR($V' \to VV/VH$) dominant - Model C : VBF production only,

Heavy charged bosons: $W' \to \ell\nu$

ATLAS CONF-2021-025

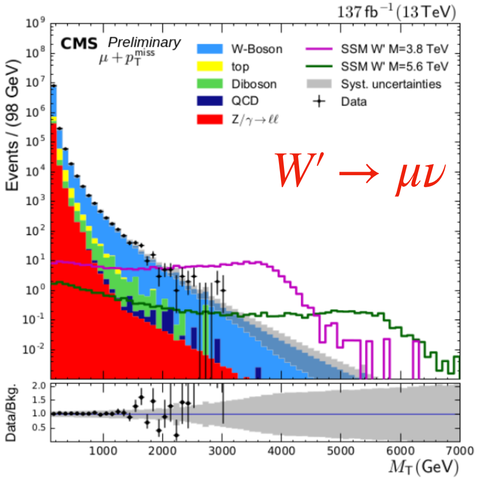
CMS PAS-EXO-19-017

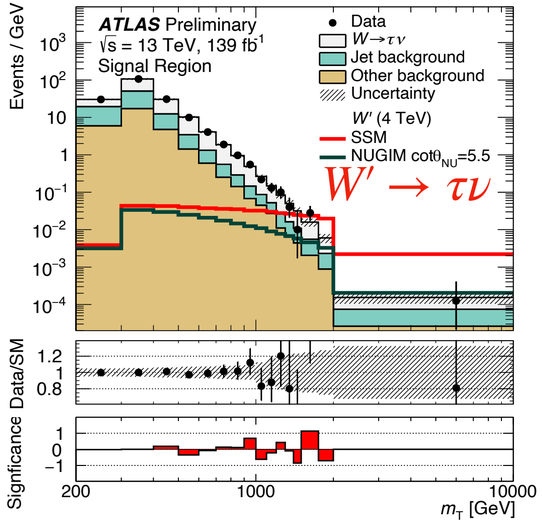
back-to-back ℓ-p_T^{miss}: $\Delta\phi \sim \pi$

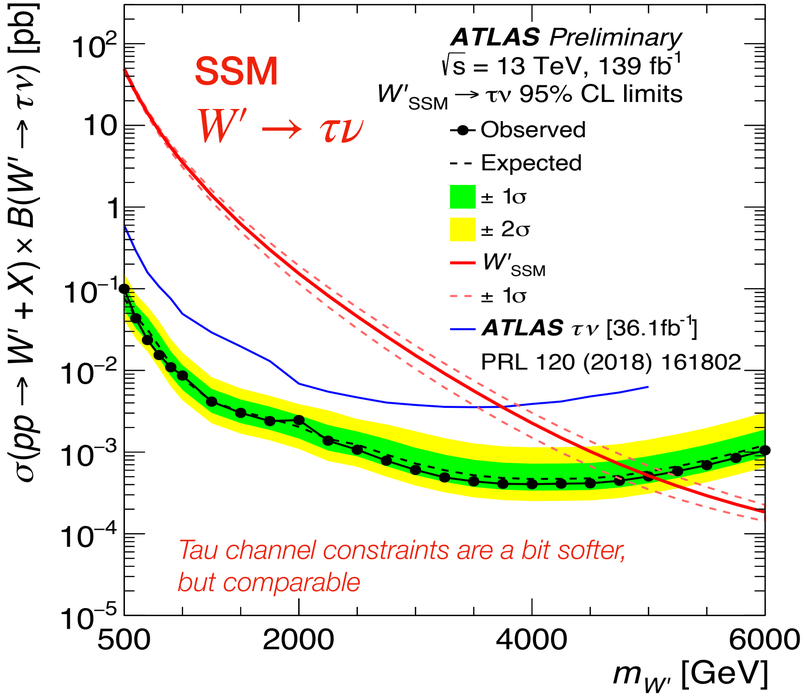


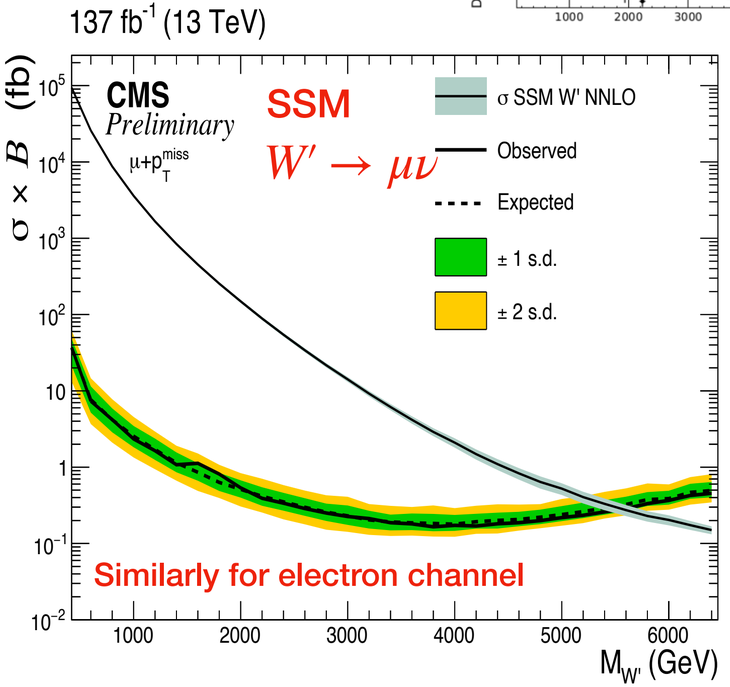
- Sole handle is the **lepton reconstruction** and identification
  - Events are collected by single lepton or p_T^{miss} triggers (e/μ vs τ)
- Probe the $m_T(\ell, p_T^{miss})$ spectrum for a very wide **kinematic endpoint**
  - *detector effects / calibration are particularly important*
- New results from ATLAS ($\tau\nu$) and CMS ($e\nu, \mu\nu$)
  - **Most stringent limits on W'** (assuming dominant decay mode to fermions)
  - W' decays into **any lepton flavor are excluded for** $m(W'_{SSM}) \leq 5$ TeV

  Model independent limits $\sim 10^{-2}$ fb at $m_T > 3$ TeV









~6 TeV exclusion from ATLAS Run2.
PRD 100, 052013

Heavy charged bosons: $W' \to WH$

ATLAS CONF-2021-026

CMS PAS-B2G-19-002

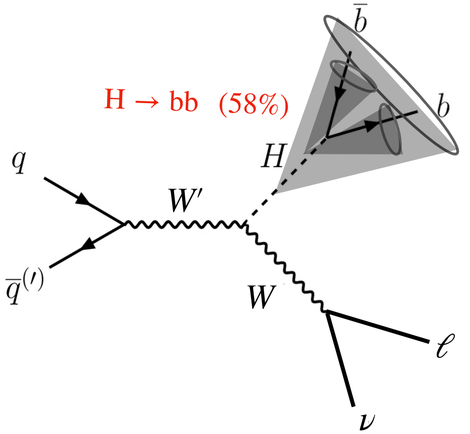
- Diboson searches a wide, inclusive "**heavy object**" program
  - Simple recipe: **bump hunt,** but …
  - **collimated** decay products, large-R jets → **substructure**

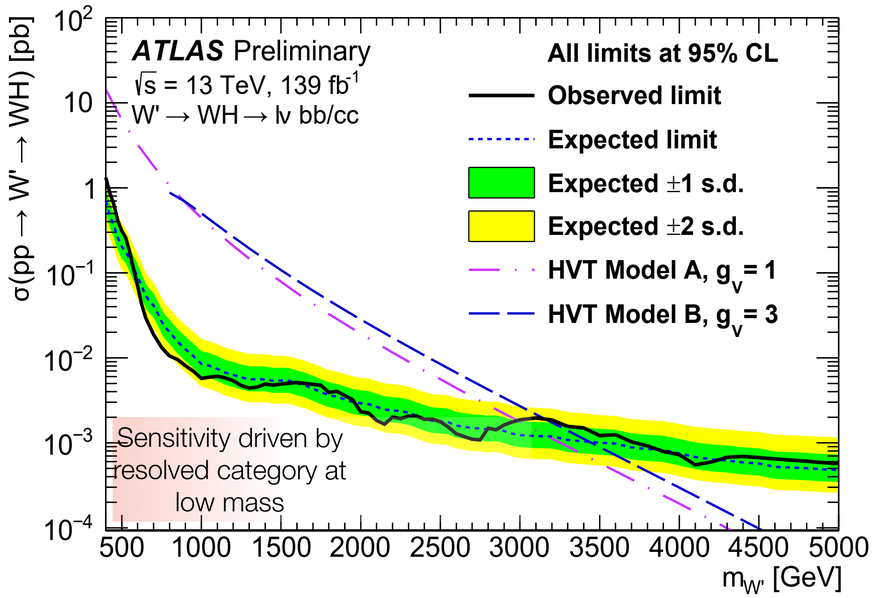
A thorough scan of HVT parameter space with Run-2 dataset is in the pipeline:
$\lesssim 1$ **fb level constraints** , for $m > 3$ TeV

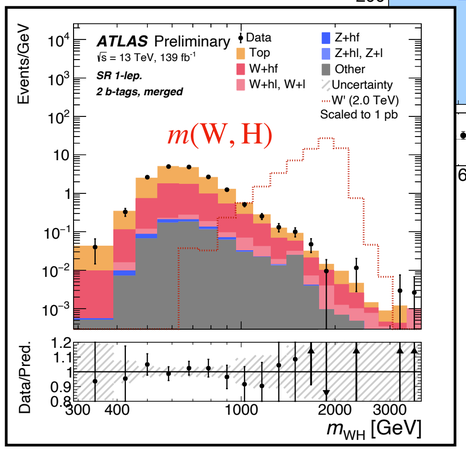
- Most sensitive probes of $W' \to WH$ are in **semileptonic** decays

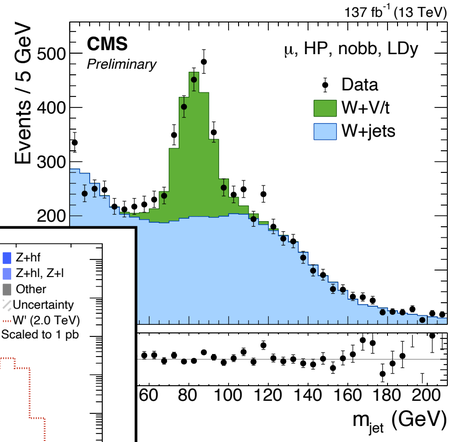
- ATLAS:
  - **Resolved** dijets or **merged** large-R jet: $m_{W'} = [0.4,5]$ TeV
  - **Higgs tagging** (single/double subjets b tagged)
  - HVT Model B: most stringent limits at at **lower masses (~5fb at 1 TeV)**

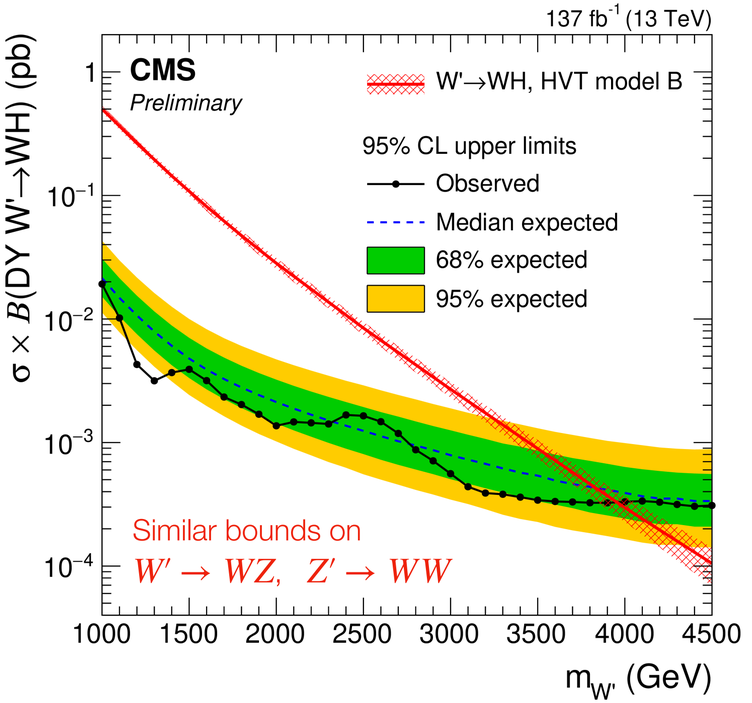
- CMS: (VV/VH inclusive analysis)
  - **merged** large-R jet, mass decorrelated tagger
  - **Higgs tagging** (dedicated double-b tagger)
  - 2-dimensional fit in the $m_{W'} - m_H$ plane
  - Mass exclusion at **4 TeV**











The ‘flavor issue’

- ***LFU tensions*** observed by LHCb* could hint at **BSM** physics
  - *possible explanations involve **new bosons** with preferential couplings to **third generation** SM fermions*

  * LHCb-PAPER-2021-004

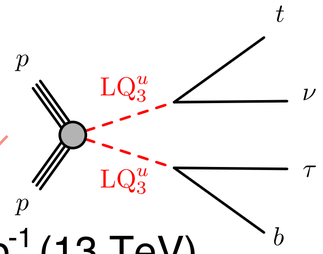
See talk on high mass mediators by Claudio Quaranta on Wednesday

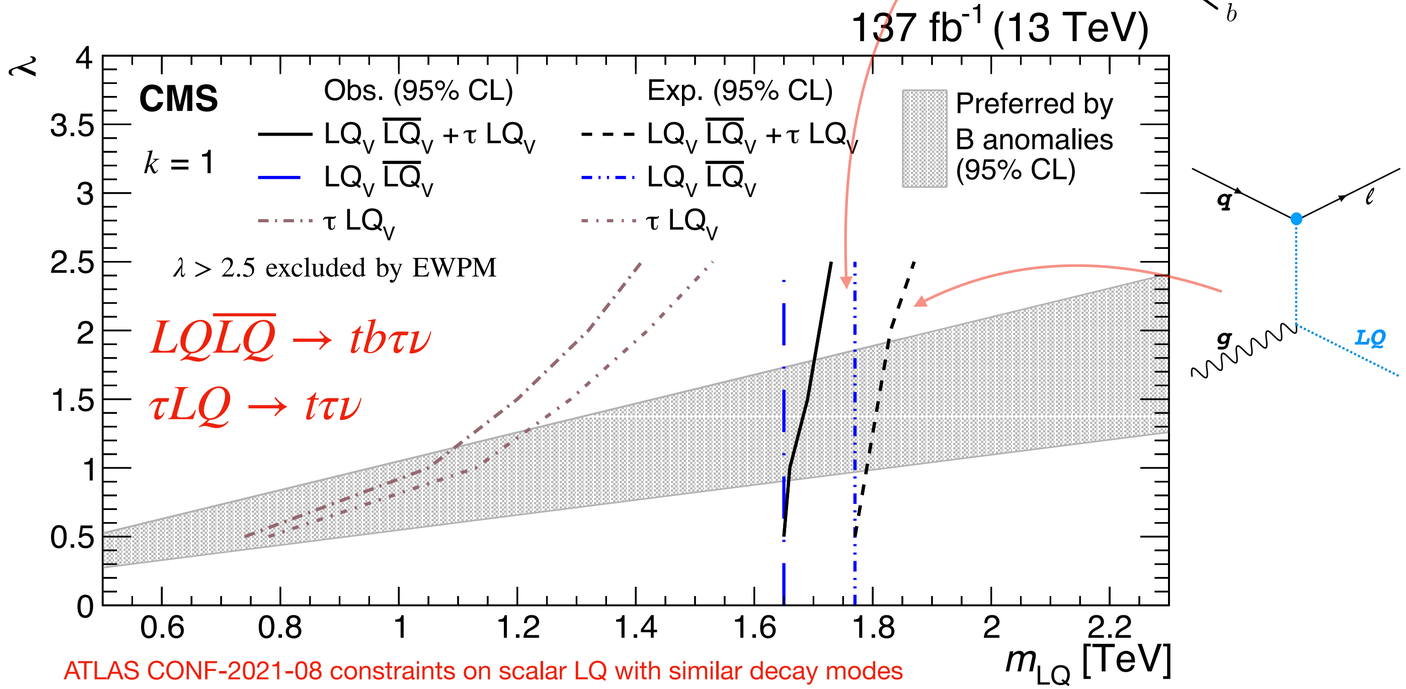
CMS EXO-19-015

ATLAS CONF-2021-08

ATLAS CONF-2021-19

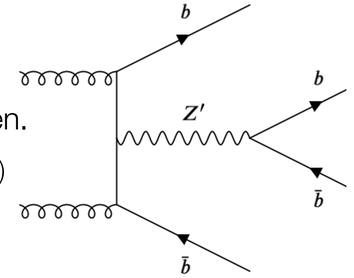
- “**Third** generation” **vector leptoquarks**
  - **pair + single** production mode
  - LQs with couplings to all third generation fermions
  - $t\tau\nu(b)$ final state (with **resolved/merged top)**
  - **Most stringent limits** for $\beta = 0.5$, ~1.7 TeV

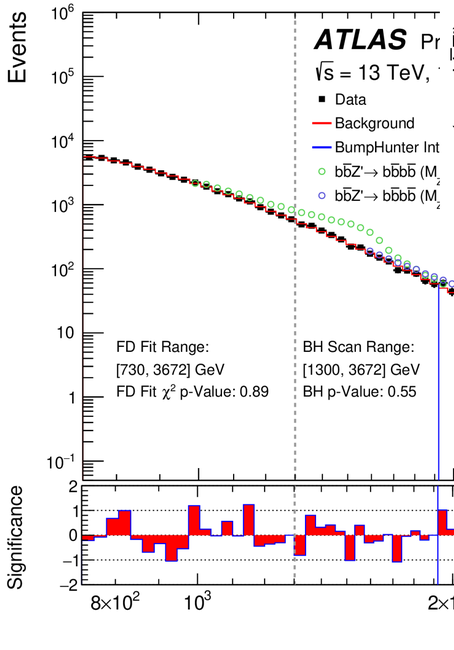


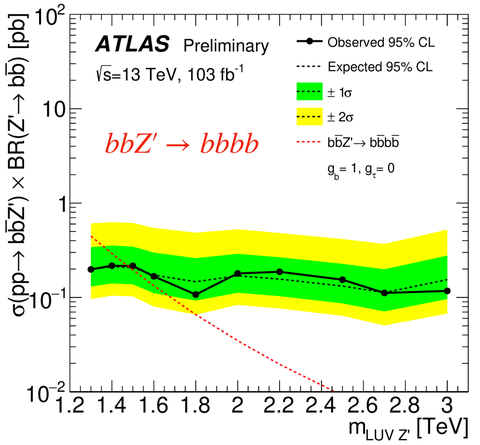


ATLAS CONF-2021-08 constraints on scalar LQ with similar decay modes

- **Lepton Universality Violating** Z'
  - enhanced couplings to **third generation** with non-negligible mixing between third and second gen.
  - **b-quark associated production** (proton PDF)
  - 4 jets, with at least 3 b-tags
  - **First search probing up to 3.6 TeV**

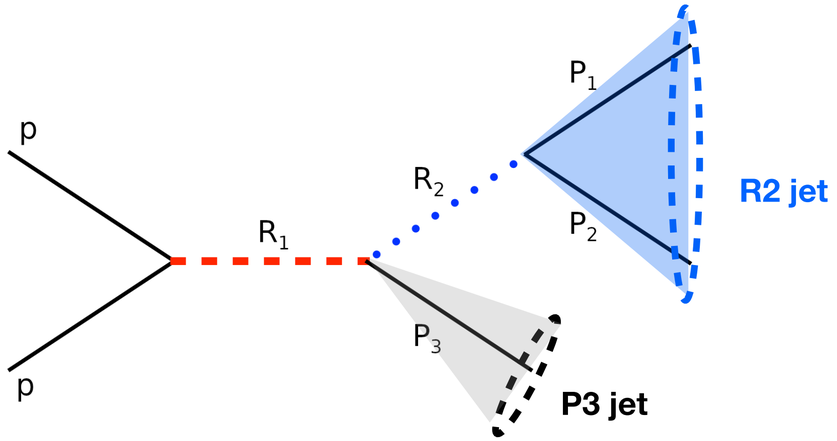






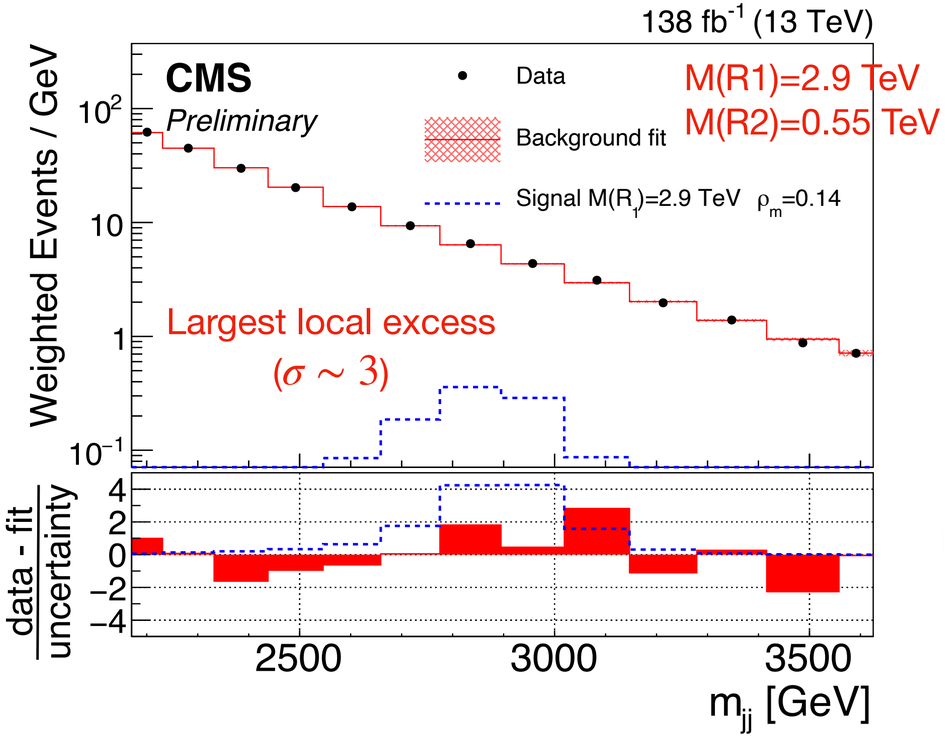
Tri-body resonances: $G_{KK} \rightarrow ggg$

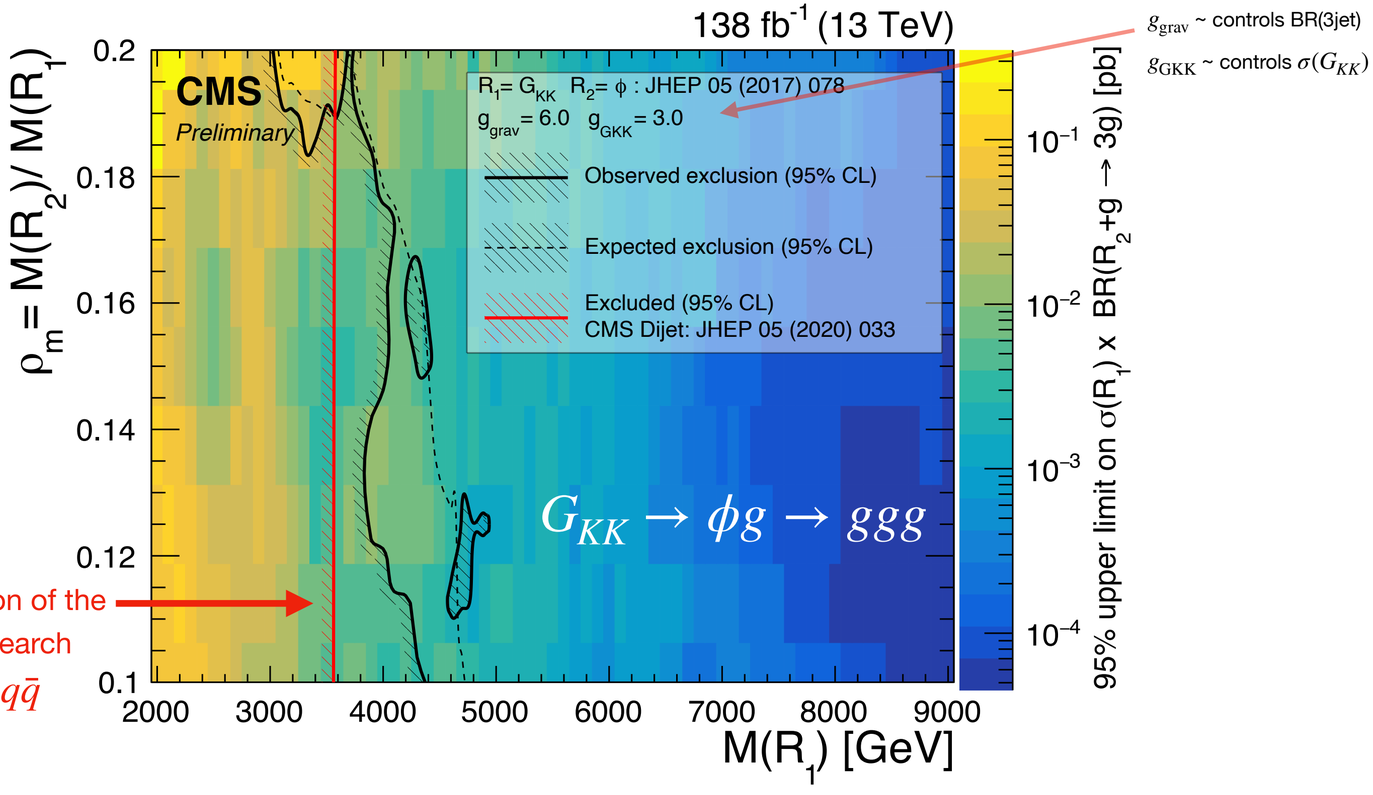
CMS PAS-EXO-20-007



- **First LHC search** for a **trijet resonance** with a boosted dijet
  - KK gluon decays into 3 SM gluons via a radion (spin-0)
- **Double resonance** in the M(**R1**)-M(**R2**) plane
  - Select on radion M(R2) mass, look for three-body resonance M(R1)
  - *Empirical 3-parameter fit to data, in up to 22 regions*
- Significant improvement (~500 GeV) on the bounds for the WED benchmark model
  -R2 **jet substructure** improves model sensitivity beyond the classic dijet searches

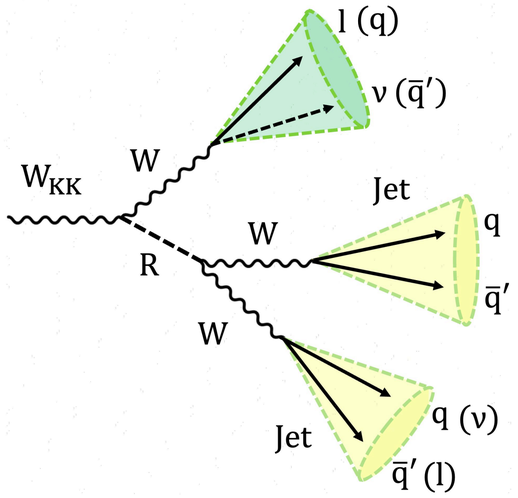
$M(R_1) \gtrsim 2$ TeV, $M(R_2)/M(R_1) \lesssim 0.2$

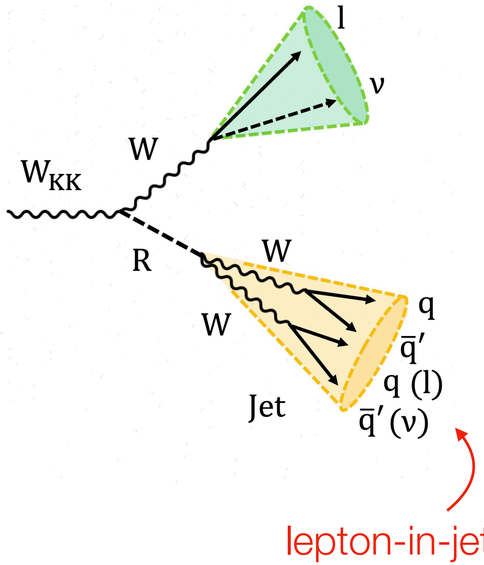




Tri-body resonances: $W_{KK} \rightarrow WWW$

CMS PAS-B2G-20-001

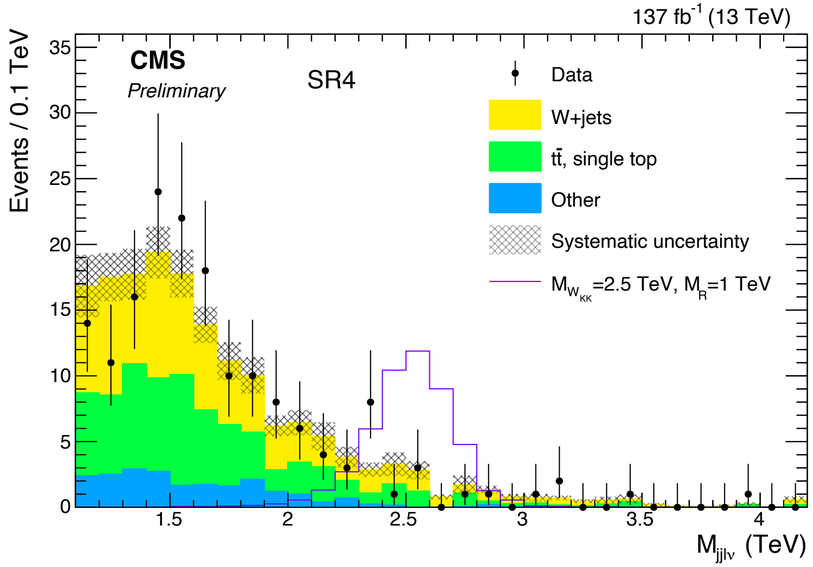


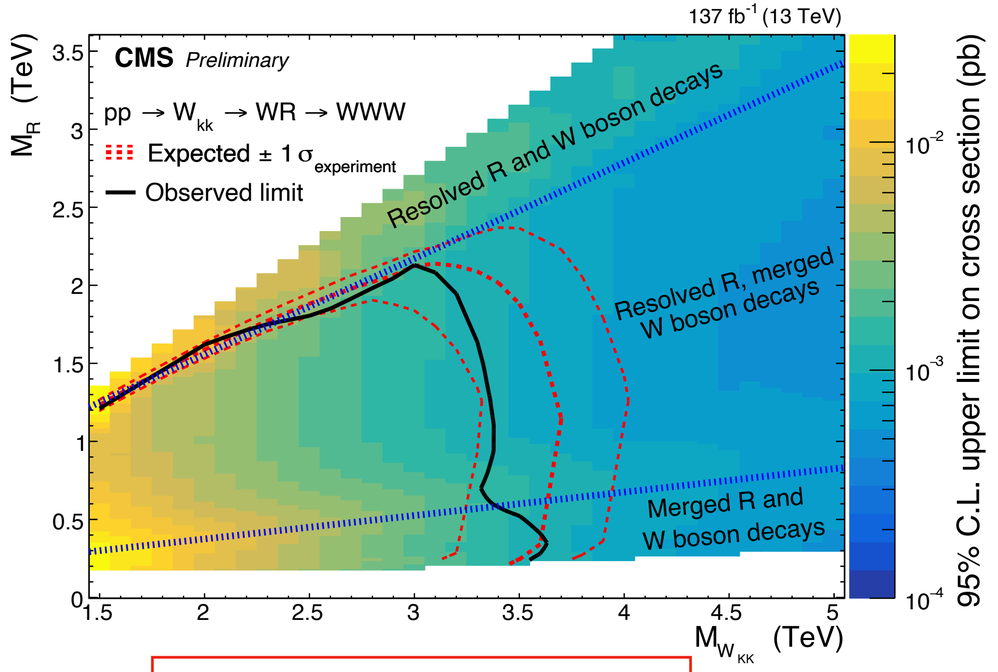


lepton-in-jets

- **First LHC search** on a **triboson resonance**
  - KK excited massive W boson (bulk RS WED model): $W_{KK} \rightarrow RW \rightarrow WWW$
- Targets events triggered by a lepton, with additional "large-R jets" (AK8)
  - **2 W-tagged jets**
  - **1 "WW"-tagged jets** including merged *hadronic+leptonic* WW decays (**lepton-in-jets**)
- Event categorization based on **jet masses and the NN tagger score** (substructure)
  - *need consistency with SM* $W \rightarrow jj$
- A **lepton+jets resonant peak** is sought after.

See talk by Antonis Agapitos on Di/Tri boson resonances on Monday

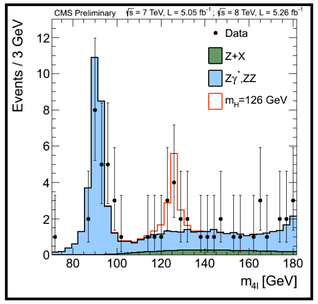




For $m_R = 1$ TeV, W_{KK} masses are excluded below 3.3 TeV

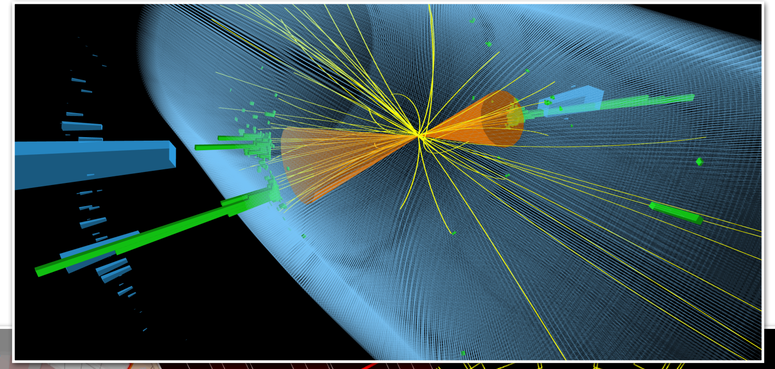
Higgs, as a gateway to BSM

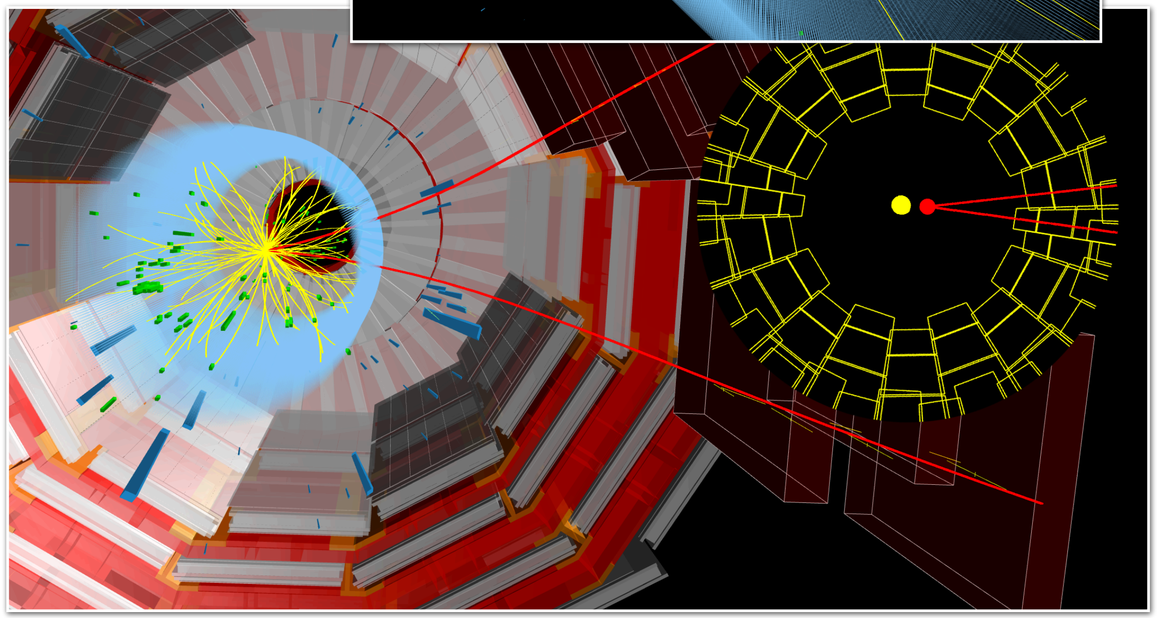
- In a decade, the journey of the SM Higgs boson:
  - signal
  - background (e.g Rare SM measurements, eg. VVV)
  - discovery tool



- H serves as a “standard candle” in BSM analyses
  - **known mass, known decays**

  H-tagging ($H \to bb$**)** -Re: Diboson searches!





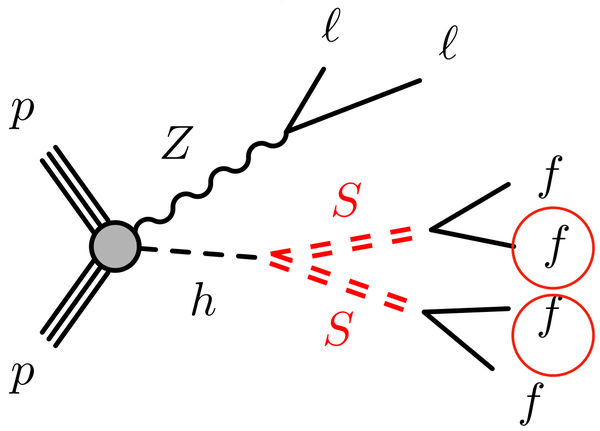
- H has quantum numbers of the “**vacuum**” (no coupling is forbidden)
  - Particles in an **extended scalar sector** (with hidden dynamics) would **mix** with the SM Higgs
  - **portal to hidden sectors**
  - Sufficient **freedom** for exotic couplings

  BR(H→Non-SM) could be up to $\mathcal{O}(10)\,\%$

Exotic Higgs decays: $ZH \to ZSS \to 2\ell 4b$

CMS PAS-EXO-20-003

ATLAS CONF-2021-005

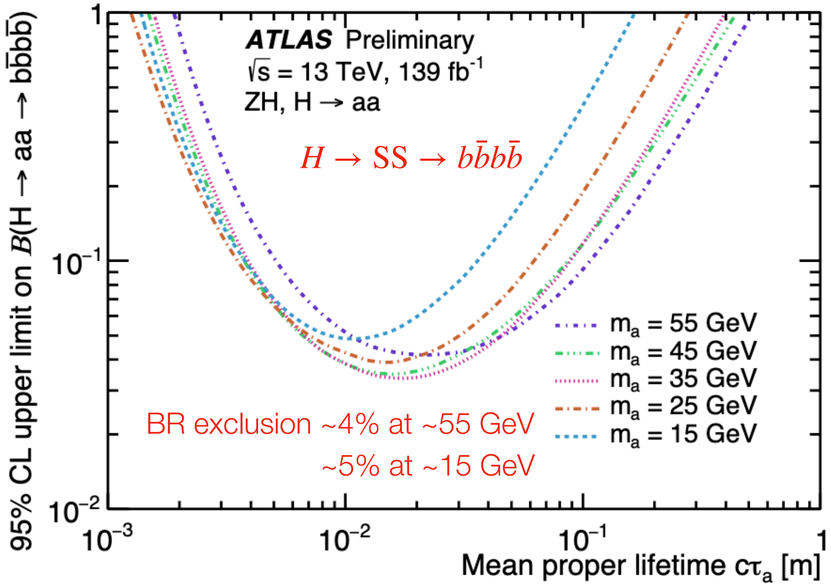


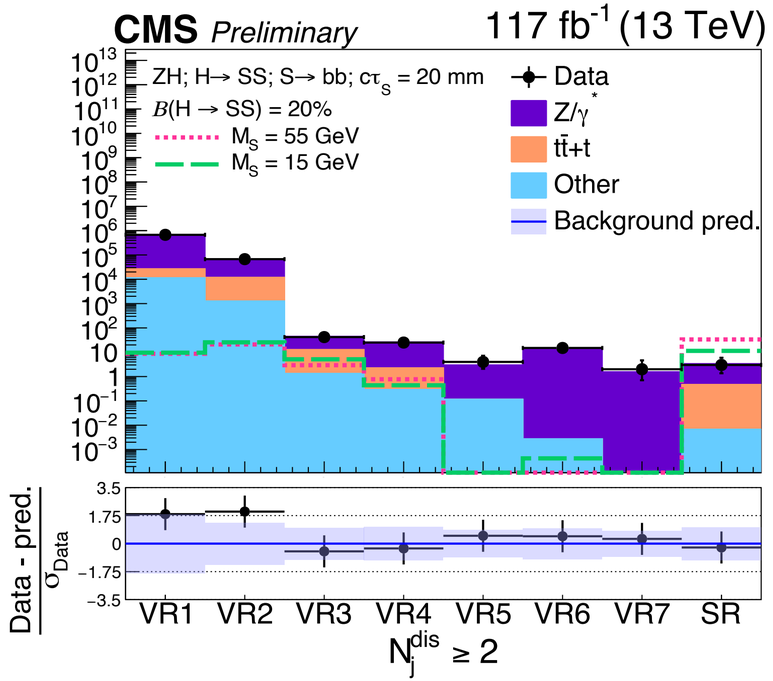
- Target **Exotic H boson decays** in associated production
  - S could be **light**, and/or with **small** couplings → **long lived**
- **Prompt** dilepton + **displaced** jets final state
- Displaced jet tagging (tracks' IP, transverse angle, PV-association)
  - ≥2 displaced jets (in tracker volume)
- Similar constraints from ATLAS and CMS on $BR(H \to SS \to 4b)$ for $c\tau$ = 1 mm - 1m

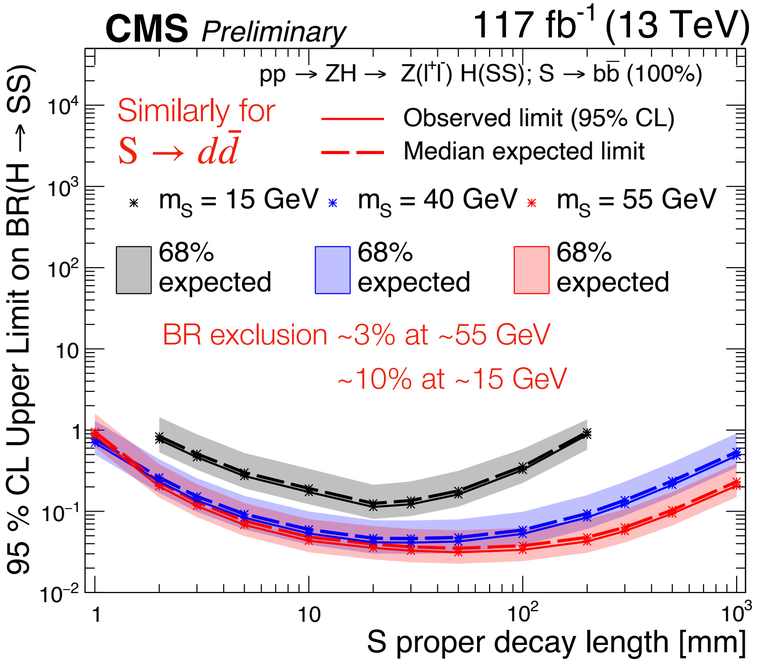
Most stringent constraints for $m_S \lesssim 15$ GeV w.r.t. inclusive searches at the LHC

arXiv:2012.01581
Eur. Phys. J. C 79 (2019) 481

See talks by Carlos V. Sierra and Rachel C. Rosten on LLPs on Monday





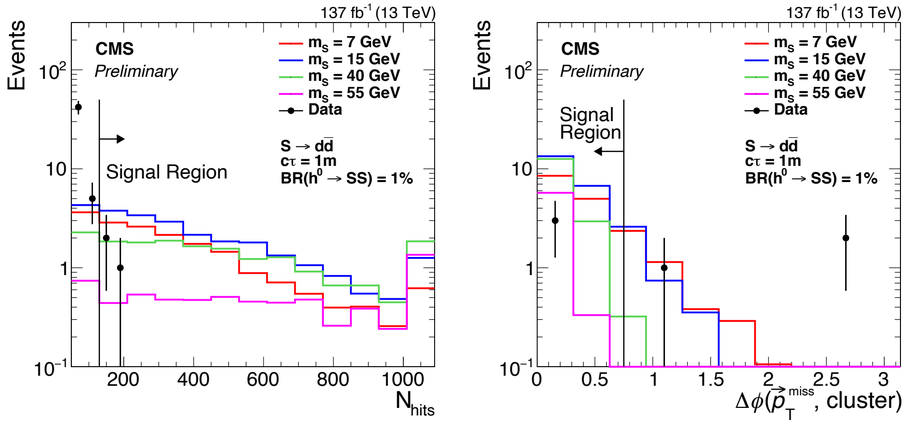


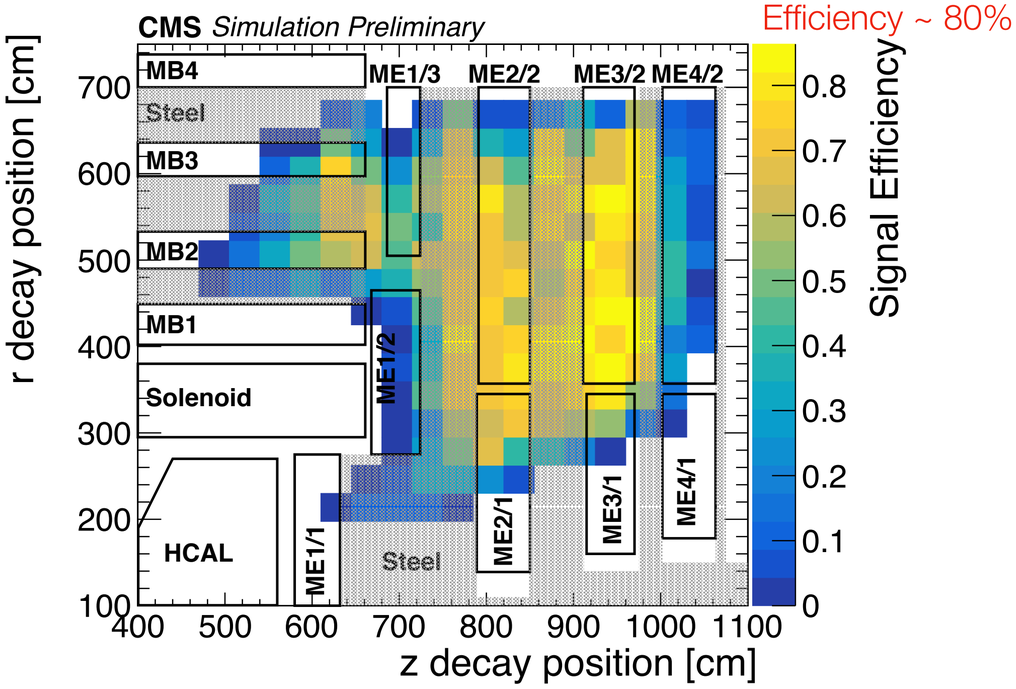
Exotic Higgs decays: $H \rightarrow SS \rightarrow 4j$

CMS PAS-EXO-20-015

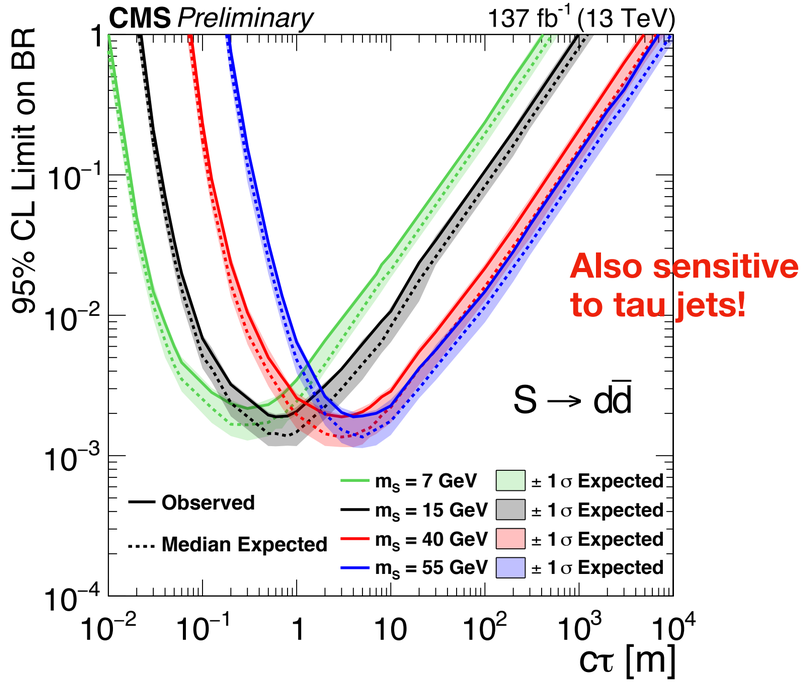
- **First CMS search** for long-lived "hadronic showers" in the Cathode Strip Chambers of the endcap muon system
- Magnetic flux-return yoke (steel) + CSC used as a sampling calorimeter (4 layers)
- Clusters are built in the CSCs with $[-5, 12.5]$ ns cluster timing
- No excess over SM: expected 2 ± 1 vs observed 3 events.

**Similar ATLAS search with partial Run2 data: PRD 99, 052005 (2019)*

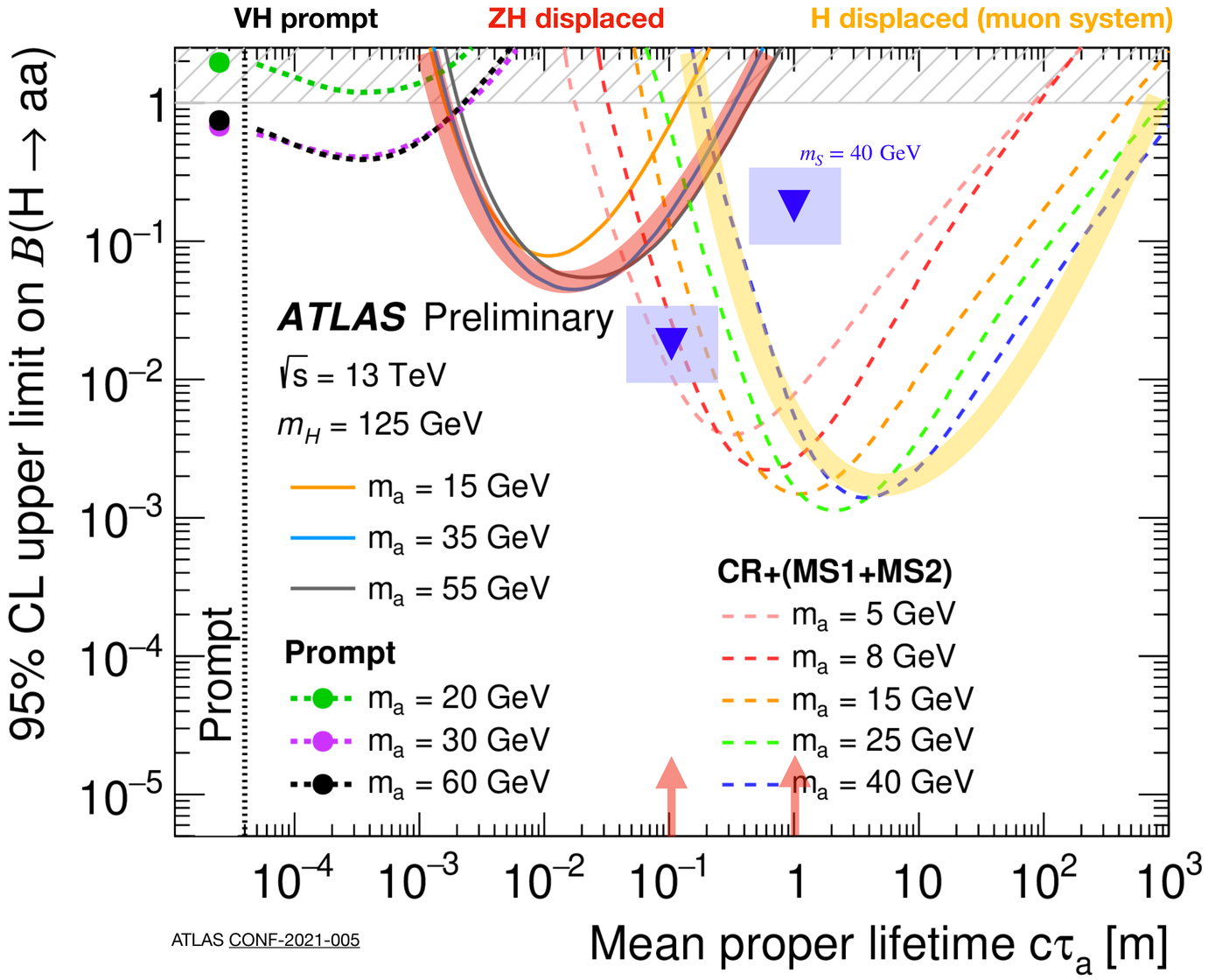




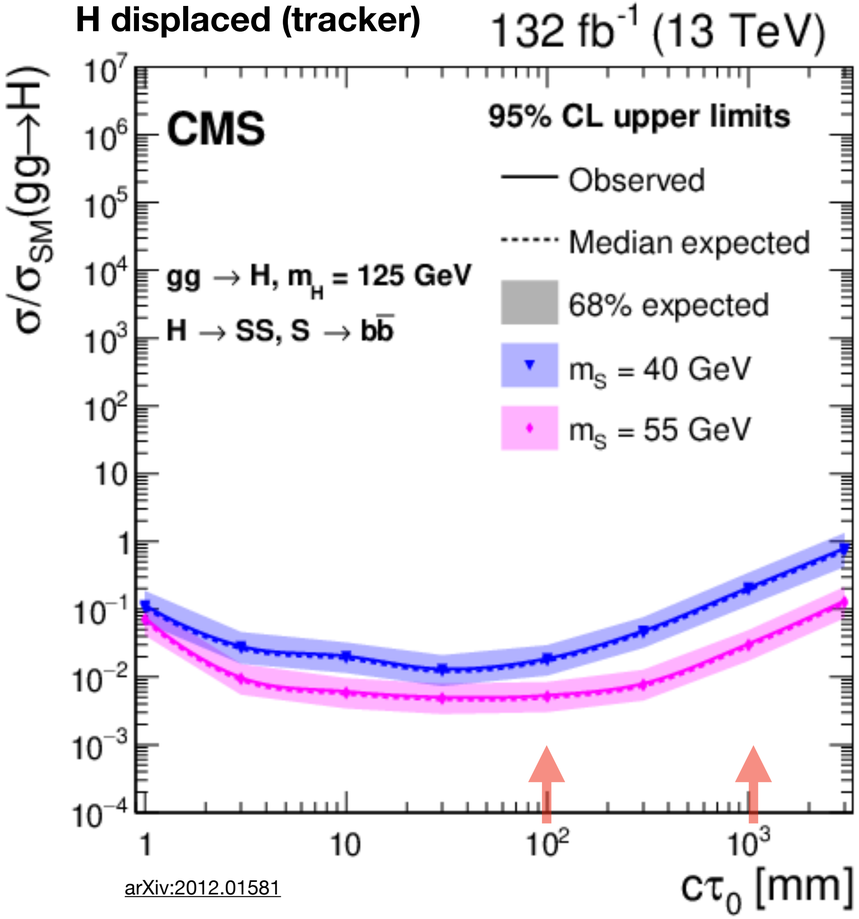
Most stringent limits on $BR(\mathrm{H} \rightarrow \mathrm{SS})$ for $c\tau \gtrsim \mathcal{O}(10)$ m



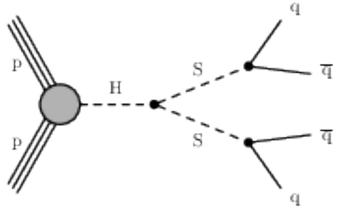
Exotic Higgs decays: complementarity



ATLAS CONF-2021-005



arXiv:2012.01581

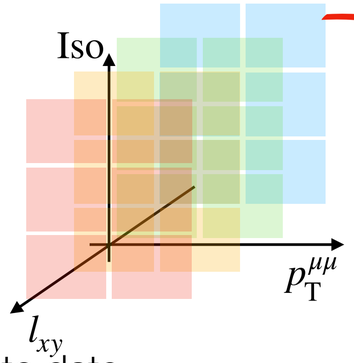


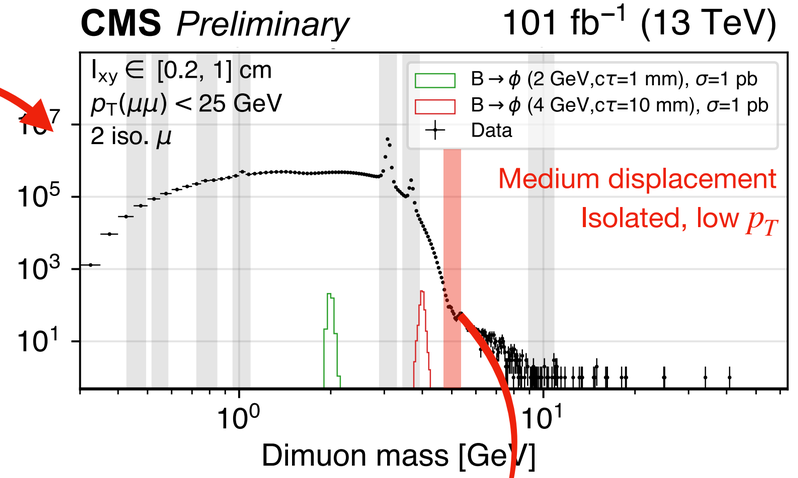
Very light bosons

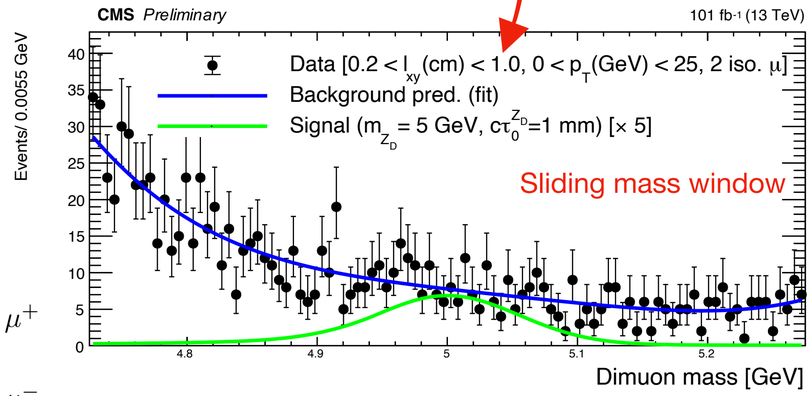
See Deborah Pinna's talk on DM interpretations, also talk by Federico Redi on Dark Photons today

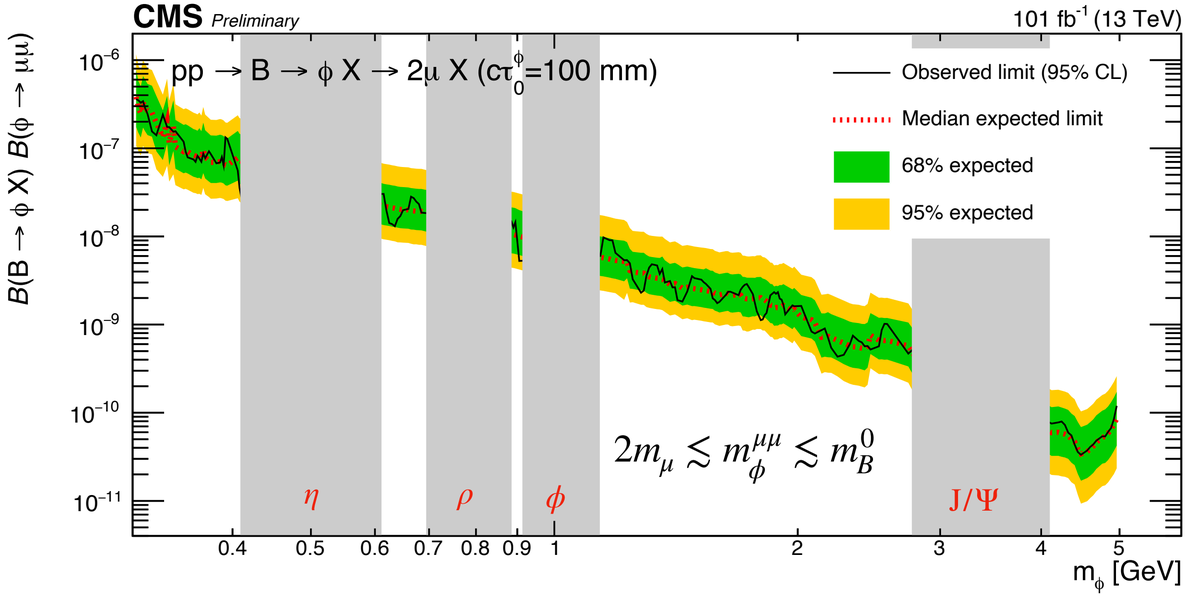
CMS PAS-EXO-20-014

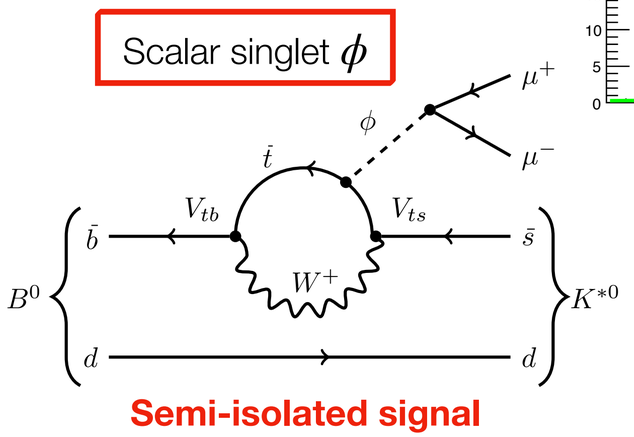
- CMS **scouting dataset** with a dedicated dimuon trigger stream
  - at a *high rate, with low thresholds, reduced event/muon information*
  - *nearly maximal acceptance to dimuon events in muon system*
- ≥ 1 dimuon pairs, with vertex (DV) trans. displacement $|l_{xy}| < 11$ cm
- A "**narrow signal**" bump hunt in **multi-dimensional space**
  - *Probed mass range: 0.3 - 50 GeV*
- Together with LHCb, the **most sensitive probe** of this phase space up to date
- Model specific limits for a light scalar singlet mixing with SM H











Semi-isolated signal

$m_\phi < m_B \sim 5$ GeV

Similar LHCb search: PRL 115 (2015) 161802
Comparable constraints, sensitivity.

The fermion sector

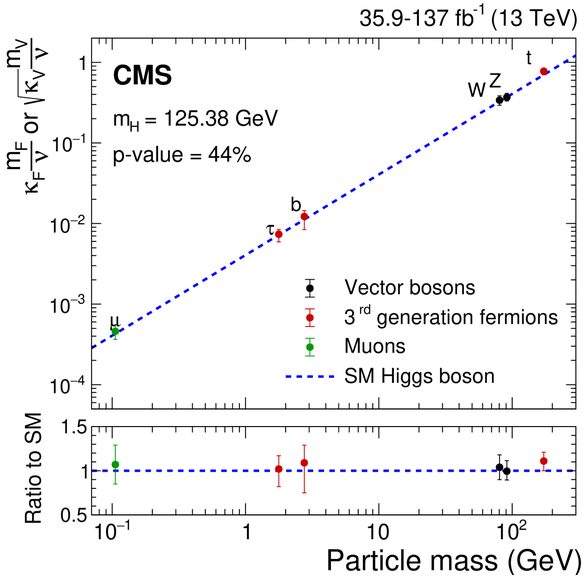
See talks by Matthias Kommon on HNLs on Monday, by Timothy R. Andeen on VLQs on Thursday

- Masses independent from the EWSB
  - Mixing with SM leptons, quarks, or neutrinos possible.

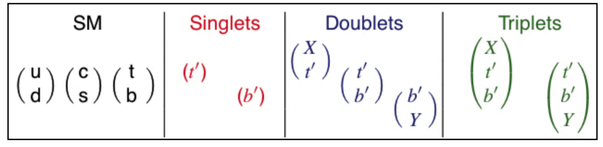
- **Heavy SU(2) fermions**
  - The SU(2) singlet : N
    (Heavy Neutral Leptons - HNL)
  - The SU(2) triplet : $N^0, L^{\pm}$

N mix with neutrinos → ~naturally light mass states (the **seesaw** mechanism)

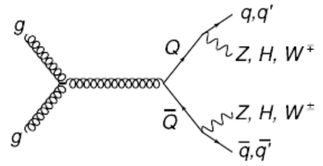
$$m_{\pm} = \frac{\sqrt{m_{\mathrm{M}}+4m_{\mathrm{D}}^2} \pm m_{\mathrm{M}}}{2} \rightarrow \begin{cases} m_+ \simeq m_{\mathrm{M}} \longleftarrow \textbf{New heavy state} \\ m_- \simeq m_{\mathrm{D}}^2/m_{\mathrm{M}} \end{cases}$$



- **Vectorlike fermions**
  - Help to stabilize Higgs mass (**third generation** favored)
  - Mix with SM fermions → could explain structure of fermion families
  - *Present in various scenarios: extra dimensions, SUSY, Little Higgs,..*

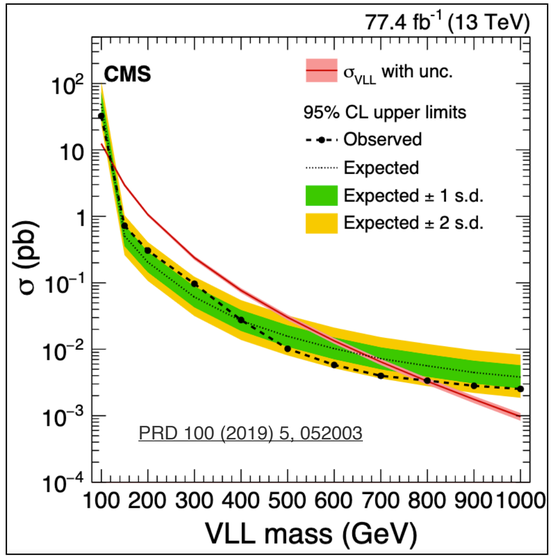


VLQs



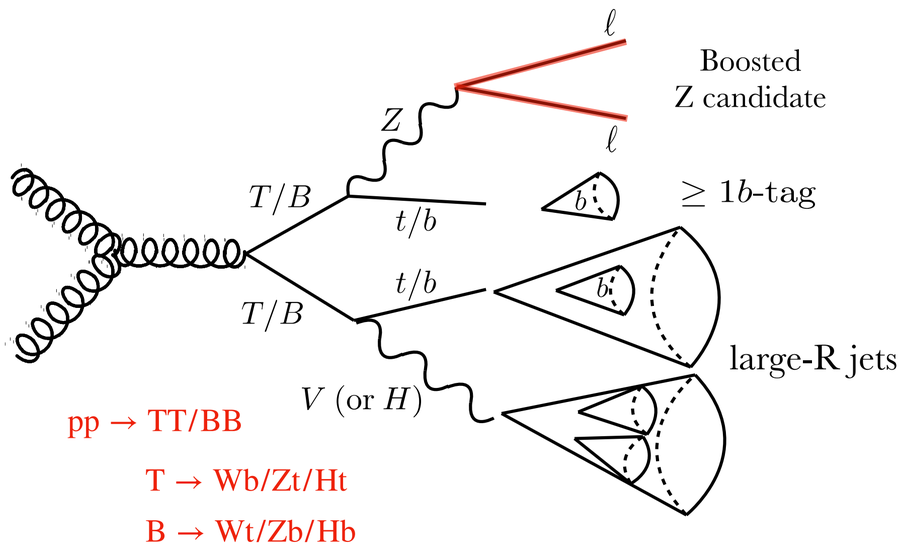
  - **Vectorlike top and bottom (T, B)** searches are a **major** program at CMS and ATLAS

  - "Leptons are not forgotten".
    First search on vectorlike taus (doublet) with partial Run-2 dataset



Vectorlike Quarks: pair production

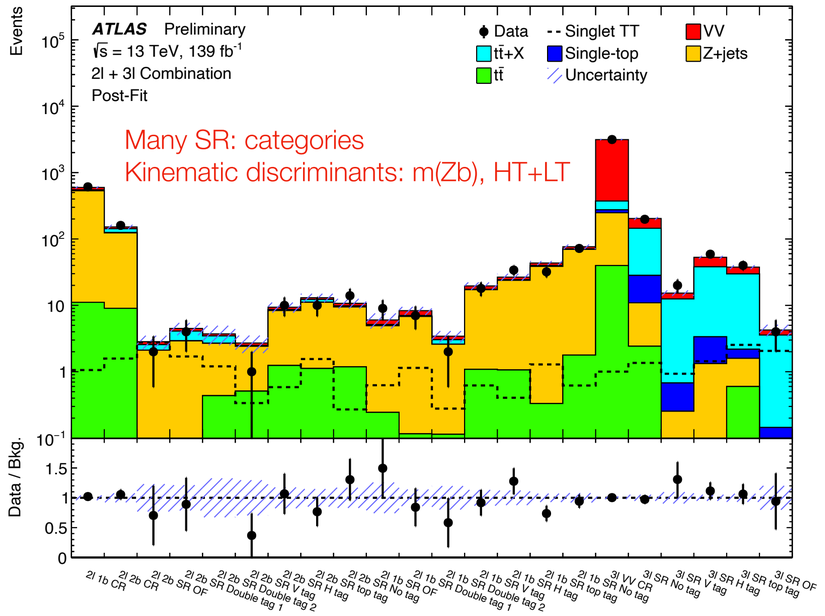
ATLAS CONF-2021-024

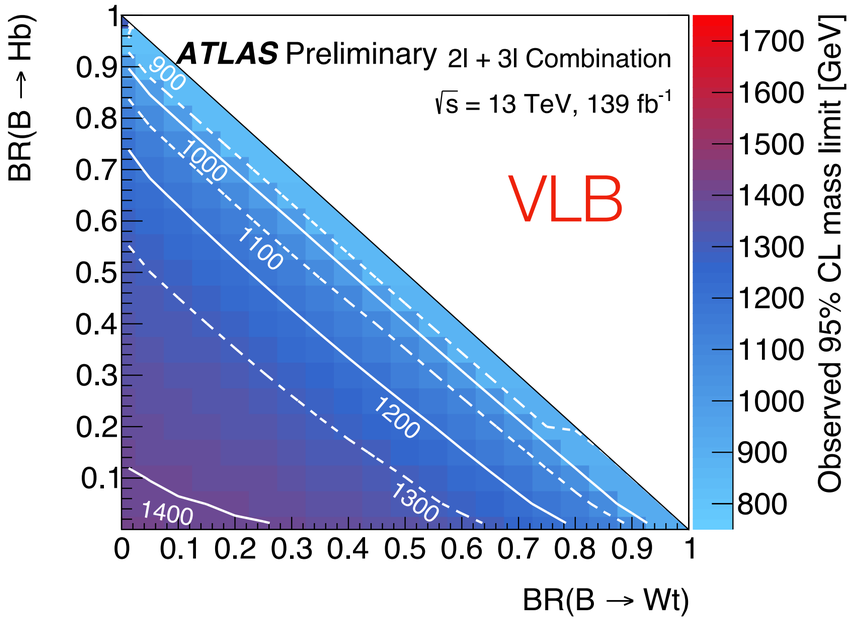


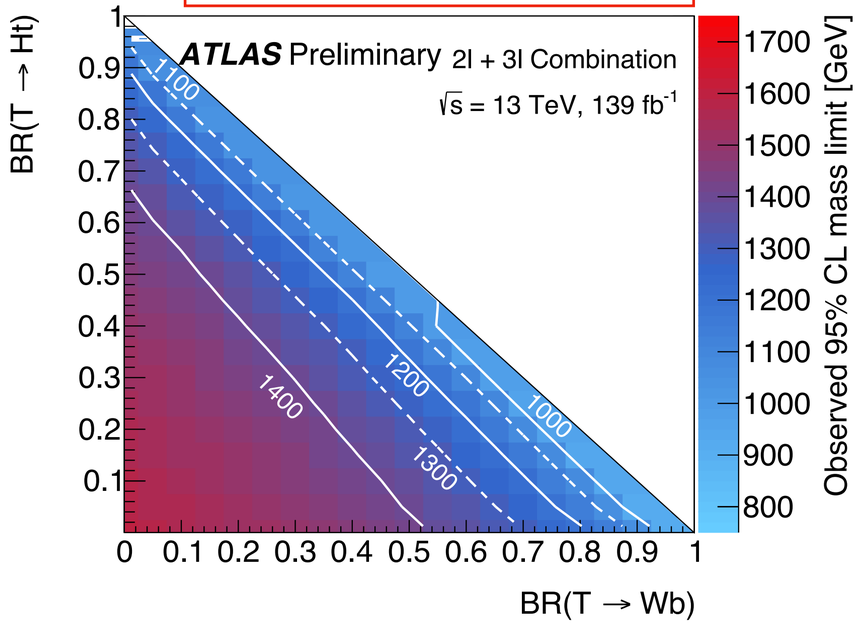
- Strong BB/TT production independent of mixing with SM fermions
- Final state with one **boosted leptonic Z** candidate:
  - 2L or 3L, with additional b-jets and large-R jets
  - Events are classified in "**boosted jet tag**" **type** and **multiplicity** (0,1,2+)
  Boosted jet tagger (V/H/t): NN multi-classifier, large-R (1.0) jets
- Among the best **constraints on Singlet/Doublet BB, TT: 1.2-1.4 TeV**
  - Upper limits on mass in the BR plane for model independent interpretations

Most stringent constraints on VLT doublet *(1.4TeV) improved by ~100 GeV**

**ATLAS combination: PRL 121, 211801 (2018),*
**CMS all hadronic: PRD 100, 072001 (2019)*



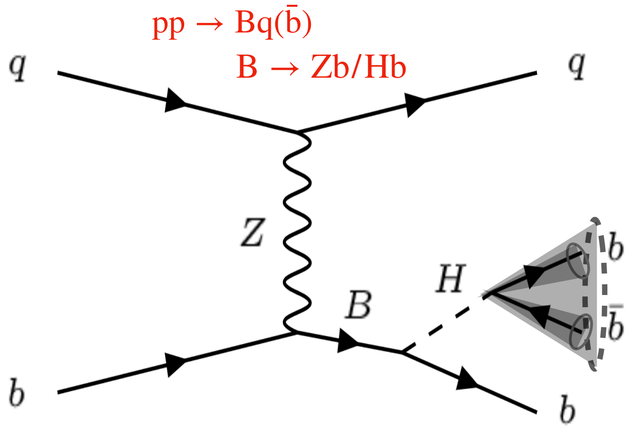




Vectorlike Quarks: single production

ATLAS CONF-2021-018

CMS PAS-B2G-19-004



Dominant single production mode if BR(B → Wt) ~ 0

- Production via **mixing** with SM quarks
  - **Single > pair production** for masses above ~**TeV**, depending on mixing strength
- Hadronic signatures with **forward jet**(s), and **b-tagged jets**

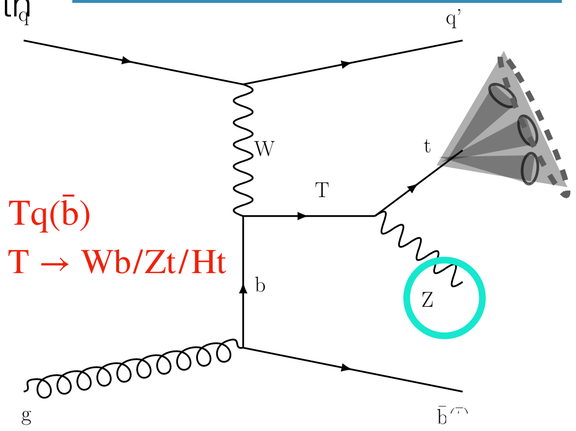
ATLAS: VLB → tri-b-jet resonance 'm_B'

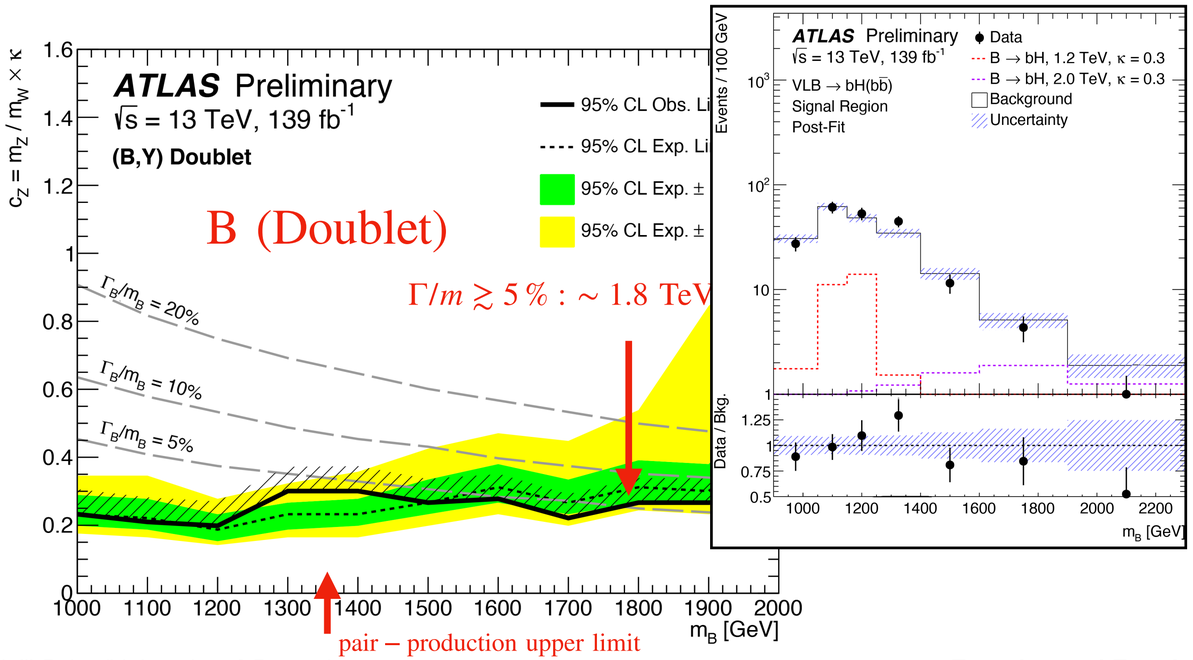
- A large-R jet with double b-tagged subjets consistent with Higgs mass

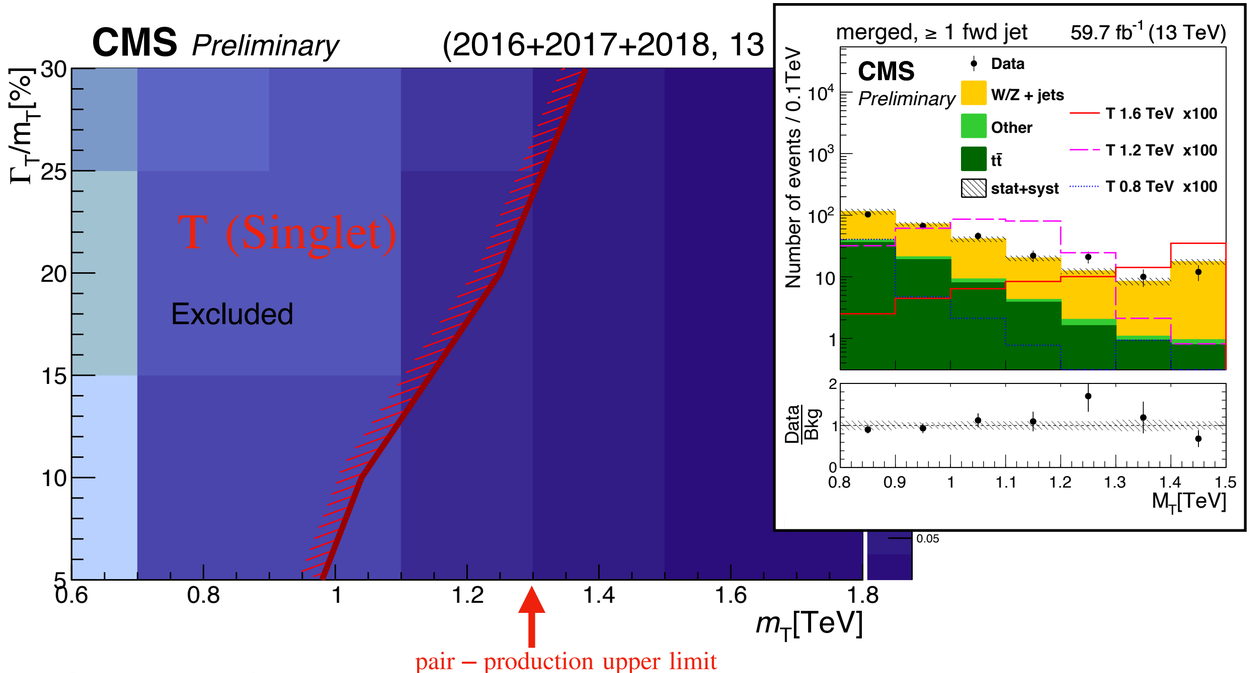
CMS: VLT → top-Z kinematic endpoint in $m_T(t, Z \to \nu\nu)$

- Resolved/partially boosted/boosted "top tagging"

- Best constraints on single production: ~1-2 TeV for a given width (5-30%)
  - **single production** constraints could be **comparable (or better) with respect to the pair production**.







Lepton flavor violation in Z

- Search for LFV in $Z \to e\tau$ $Z \to \mu\tau$ decays
  *Lepton flavor is **not a protected symmetry** in the SM*
  *Jets aside, LHC is also **Z producer**! (more than 8B Zs in Run2)*

- All **mixed flavor** final states are considered: $e\tau_h, \mu\tau_h, e\mu$

- **MVA methods needed** to sift out the signal from SM $Z \to \tau\tau$

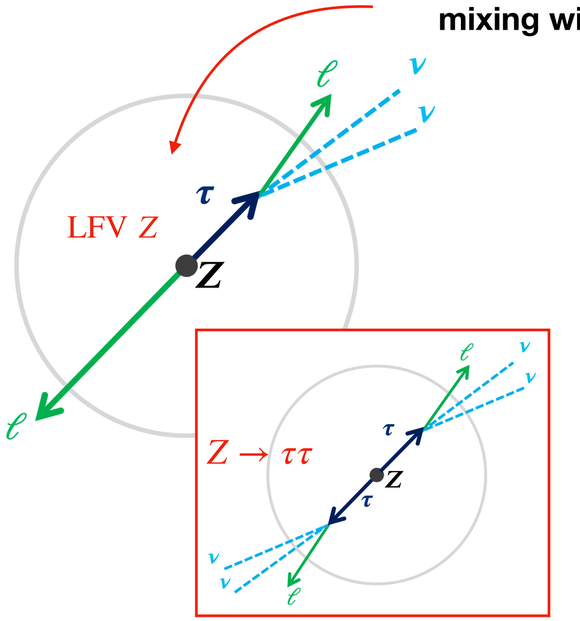
- Best bounds on LFV decays of Z with taus, surpassing LEP:
  $BR \lesssim 5 \times 10^{-6}$

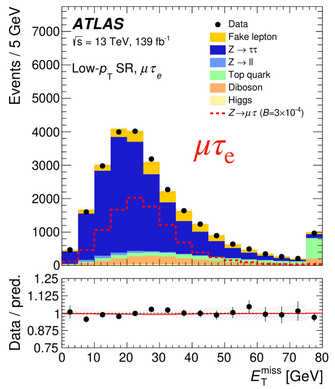
ATLAS EXPERIMENT CMS LHCb

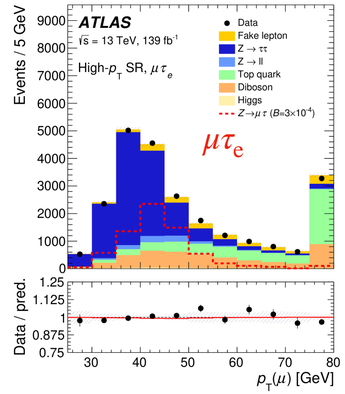
ATLAS EXOT-2020-28

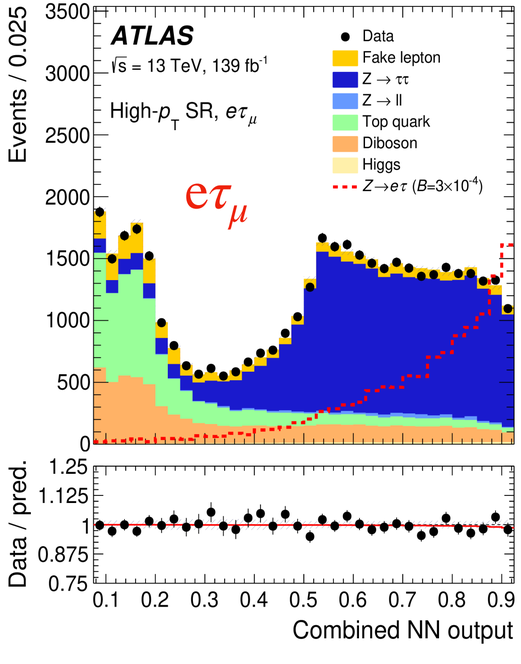
ATLAS EXOT-2018-36

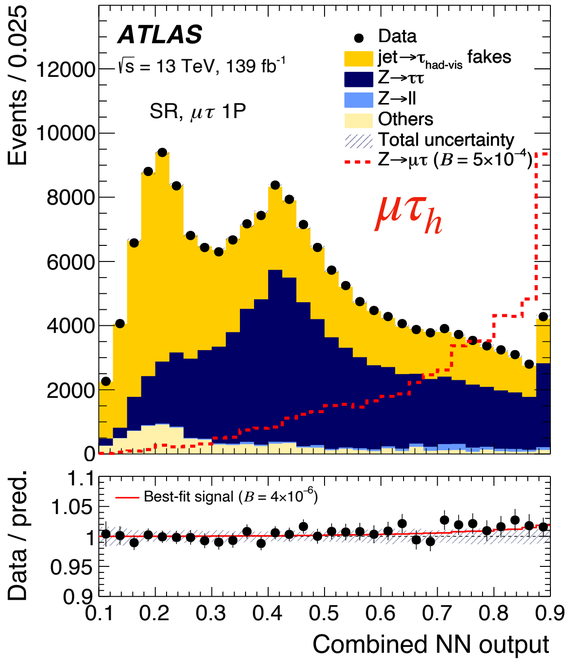
Heavy leptons mixing with SM ?







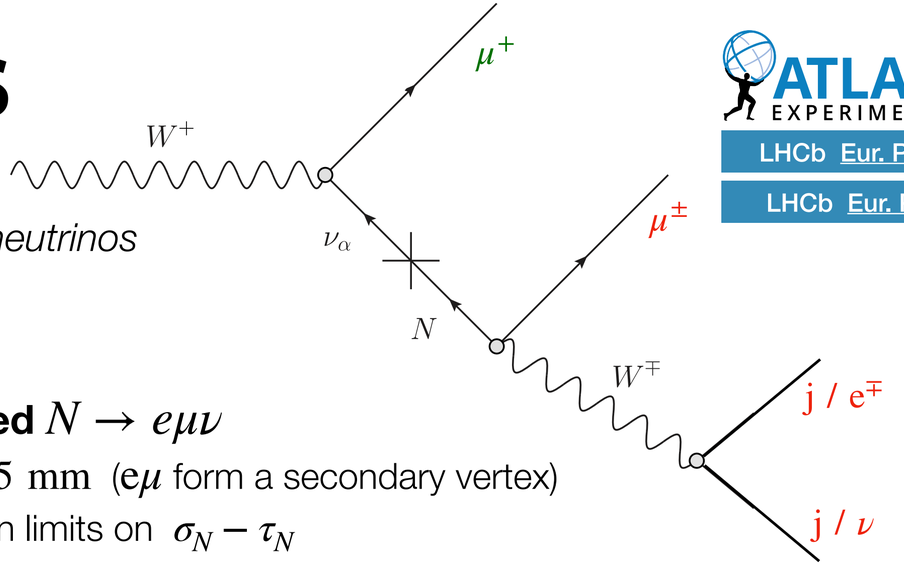




Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ [9]*	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

* to appear in Nature

Heavy leptons in W decays



LHCb Eur. Phys. J. C 81 (2021) 248

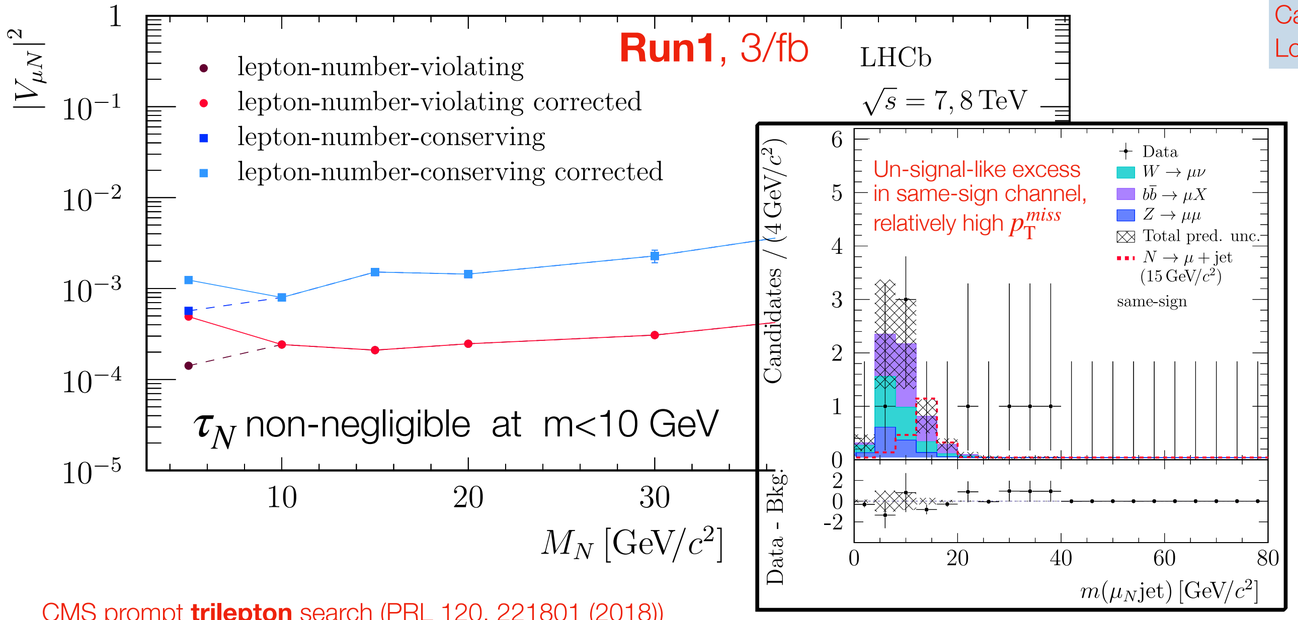
LHCb Eur. Phys. J. C 81 (2021) 81

- *Study of* ***W decays*** *to* ***probe low mass HNLs*** *through their* ***mixing*** *with neutrinos*
  - $5 \lesssim m_N < 50$ GeV

- **Prompt**, resonant $N \to \mu jj$ **signature**
  - Both **LNV** (SS) and **LNC** (OS) final states + jets
  - **First limit on LNC decays** of a prompt heavy neutrino $|V_{\mu N}|^2 \gtrsim 10^{-3}$ excluded for $m_N \sim 10$ GeV
  - Also first probe of $N \to \mu jj$ **decay** at low masses (<20 GeV)

- **Displaced** $N \to e\mu\nu$
  - $c\tau_N < 15$ mm ($e\mu$ form a secondary vertex)
  - Exclusion limits on $\sigma_N - \tau_N$
  - **First direct LLP→** $e\mu\nu$ **search at LHCb**

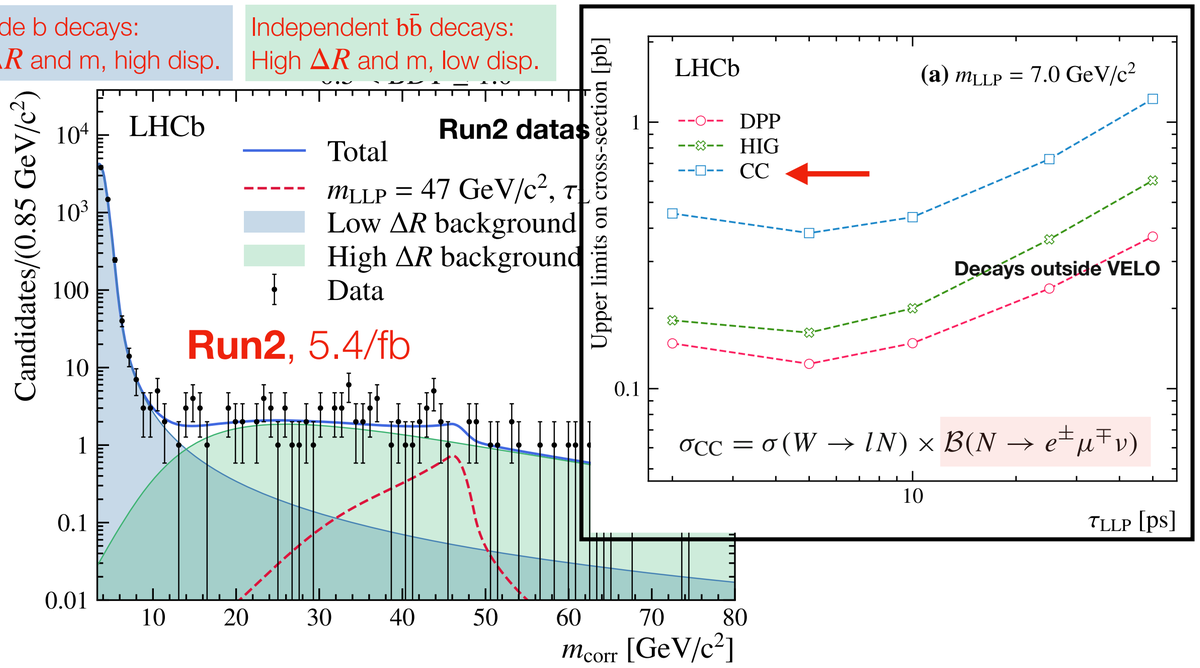
HNLs with light lepton flavor couplings: $W^+ \to e^+N/\mu^+N$



CMS prompt **trilepton** search (PRL 120, 221801 (2018)) excludes LFV N with $|V_{\mu N}|^2 \gtrsim 2 \times 10^{-5}$ at $m_N = 15$ GeV

Cascade b decays: Low ΔR and m, high disp.

Independent $b\bar{b}$ decays: High ΔR and m, low disp.

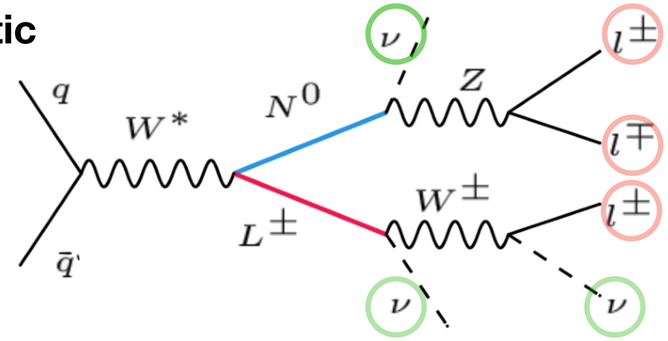


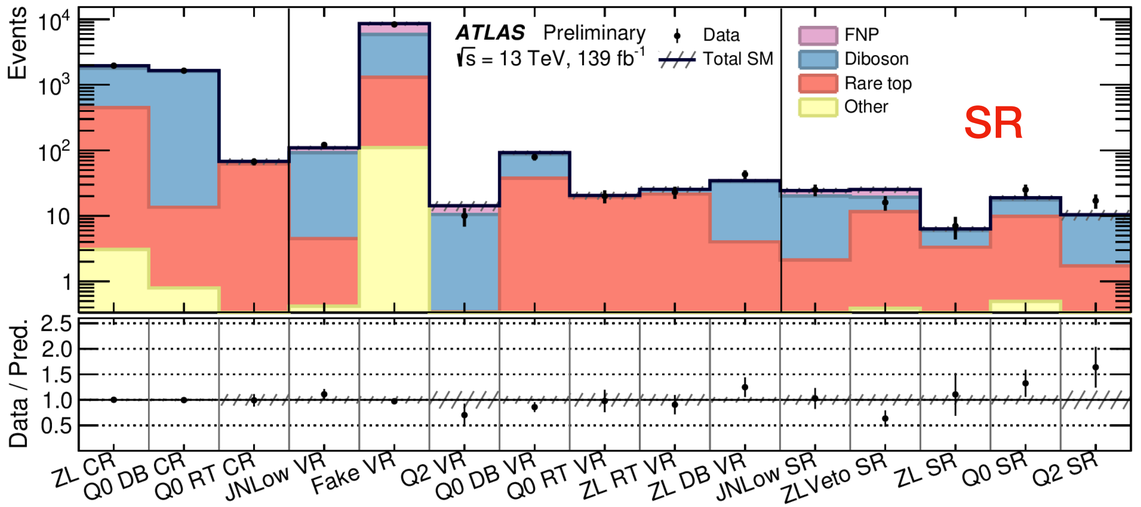
ATLAS **trilepton** displaced vertex search (JHEP 10 (2019) 265) excludes $|V_{\mu N}|^2 \gtrsim 2 \times 10^{-6}$ at $m_N = 7$ GeV

Heavy leptons: pair production

ATLAS CONF-2021-023

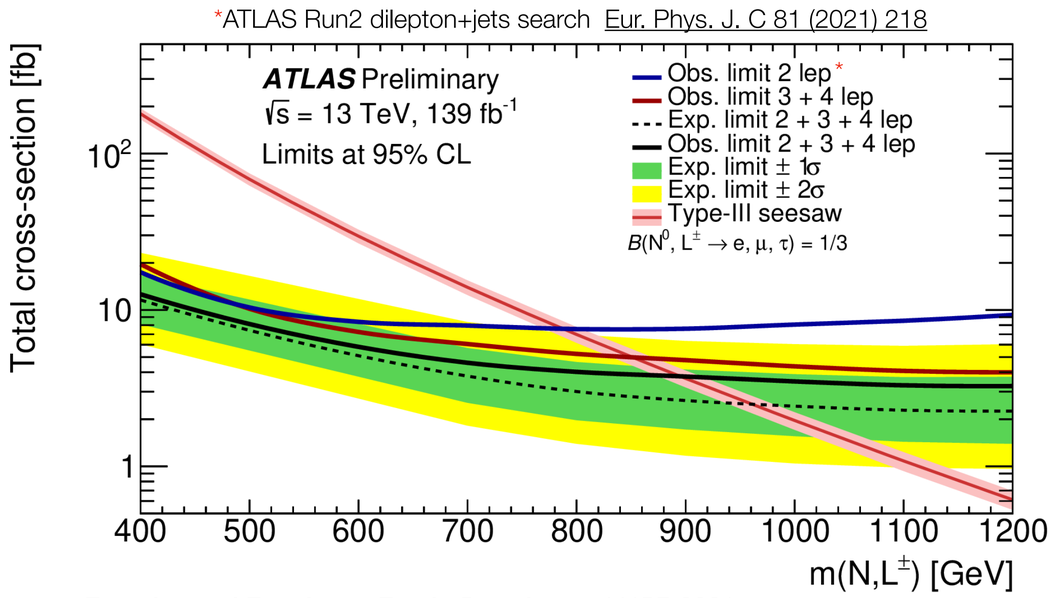
- **Pair production of heavy fermions, $N^0, L^\pm$ (Type III Seesaw)**
  - Production via **EWK interactions**
  - Mass degenerate SU(2) triplet
  - Decays via **flavor democratic mixings** with SM leptons

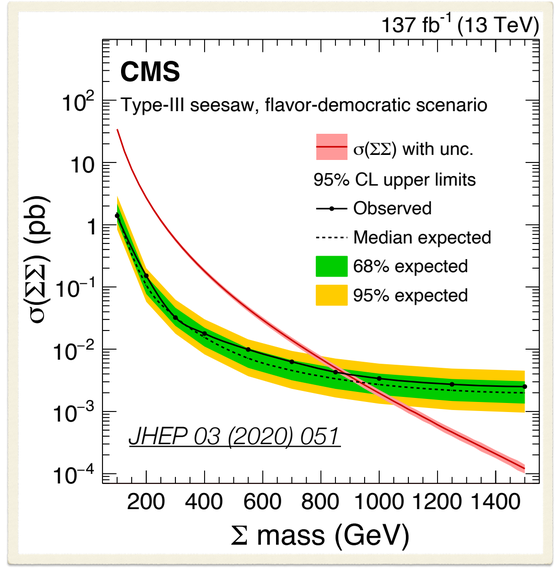




- Variety of final states with **electrons or muons**, jets, and p_{T}^{miss}
  - **3 leptons:** 0-1, 2 or more jets
  - **4 leptons**: $\Sigma Q_i = 0, \pm 2$

- **Most stringent limits** to date: ~ 910 GeV
  - *Very similar constraints from CMS as well*





To summarize

- **Diverse set of Exotic searches** probing a **multidimensional phase space** at the LHC
  - extended **boson** / **fermion** sectors (few GeV to few TeV)
  - **Higgs as a discovery tool** (light in the dark)
  - direct probes of new physics over **4 orders of magnitude in mass**

- Vibrant activity on the **mature Run-2 dataset** in the months to come,
  and rise of new innovative techniques and practices **in the wake of Run-3**
  - **Trigger level analysis** is a powerful tool *(less is more)*
  - **ML** is now an industry standard
    (jets are the new leptons, advanced analysis techniques)
  - *"**Non-standard**"* uses of our detectors
    (New triggers, detector upgrades to facilitate this further)

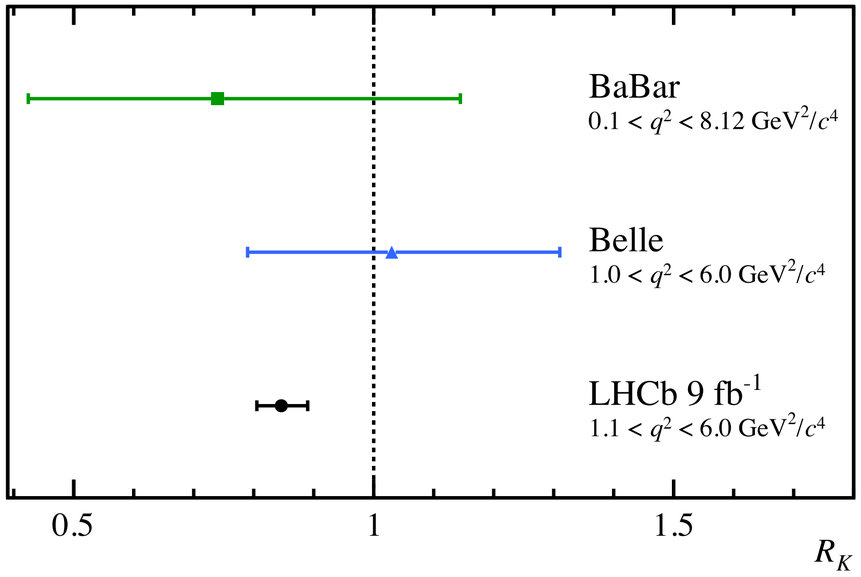
- Hadron colliders have been with us for only 50 years:
  - proven **discovery** machines!
  - we have all the reasons to look forward to the next ~20 years of the the LHC

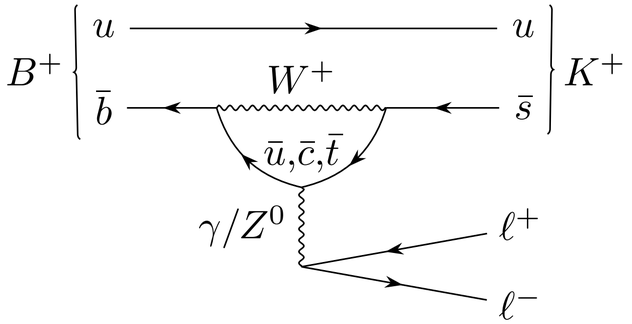
https://cerncourier.com/a/discovery-machines/


ATLAS
EXPERIMENT
CMS
LHCb

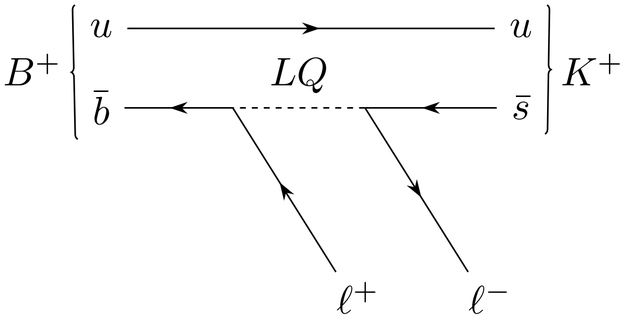
LHCb flavor anomalies: tests of LFU

LHCb-PAPER-2021-004





SM

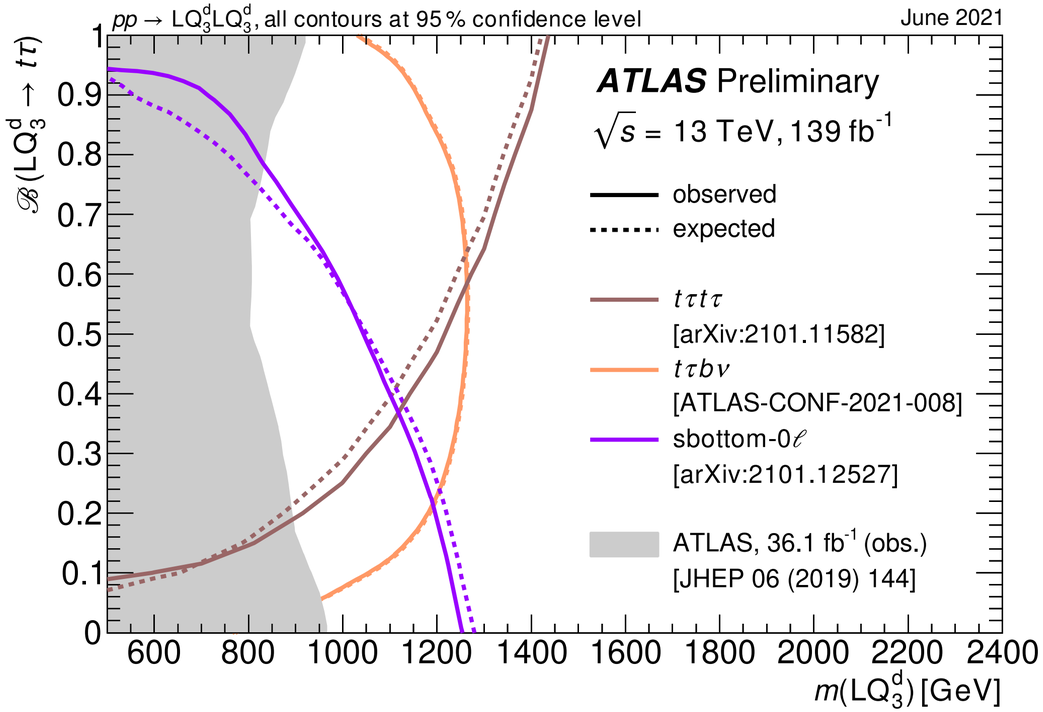


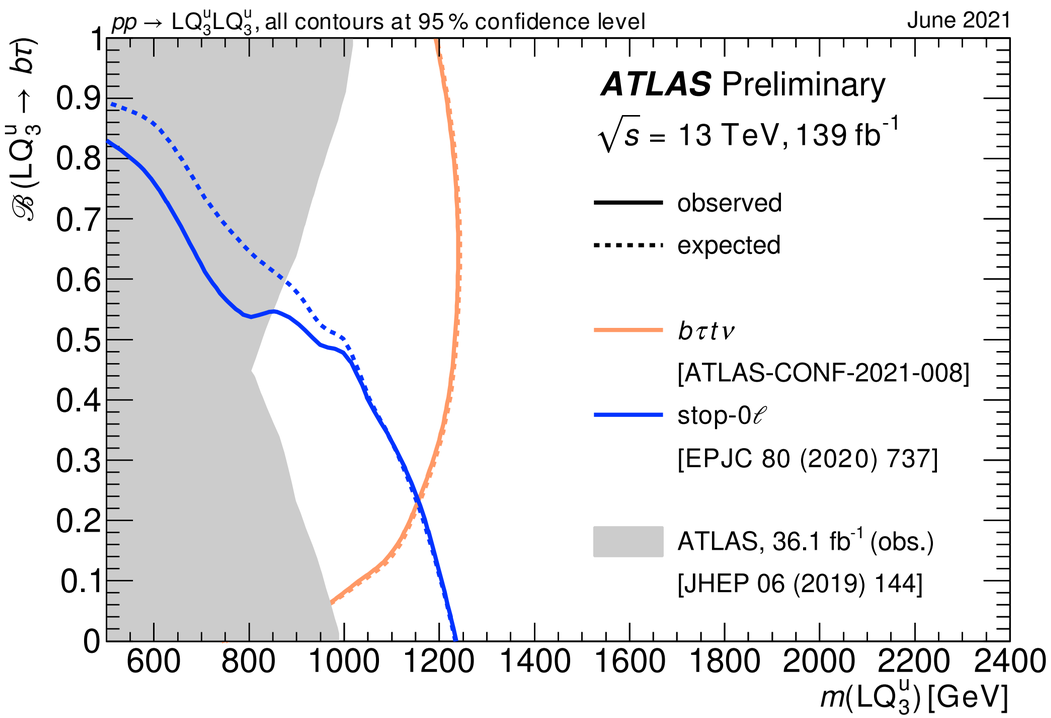
BSM
tree level contribution

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

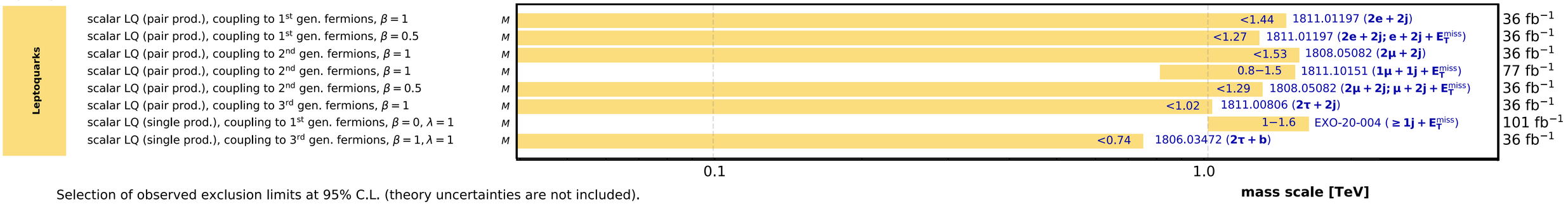
Leptoquark searches

ATL-PHYS-PUB-2021-017





CMS

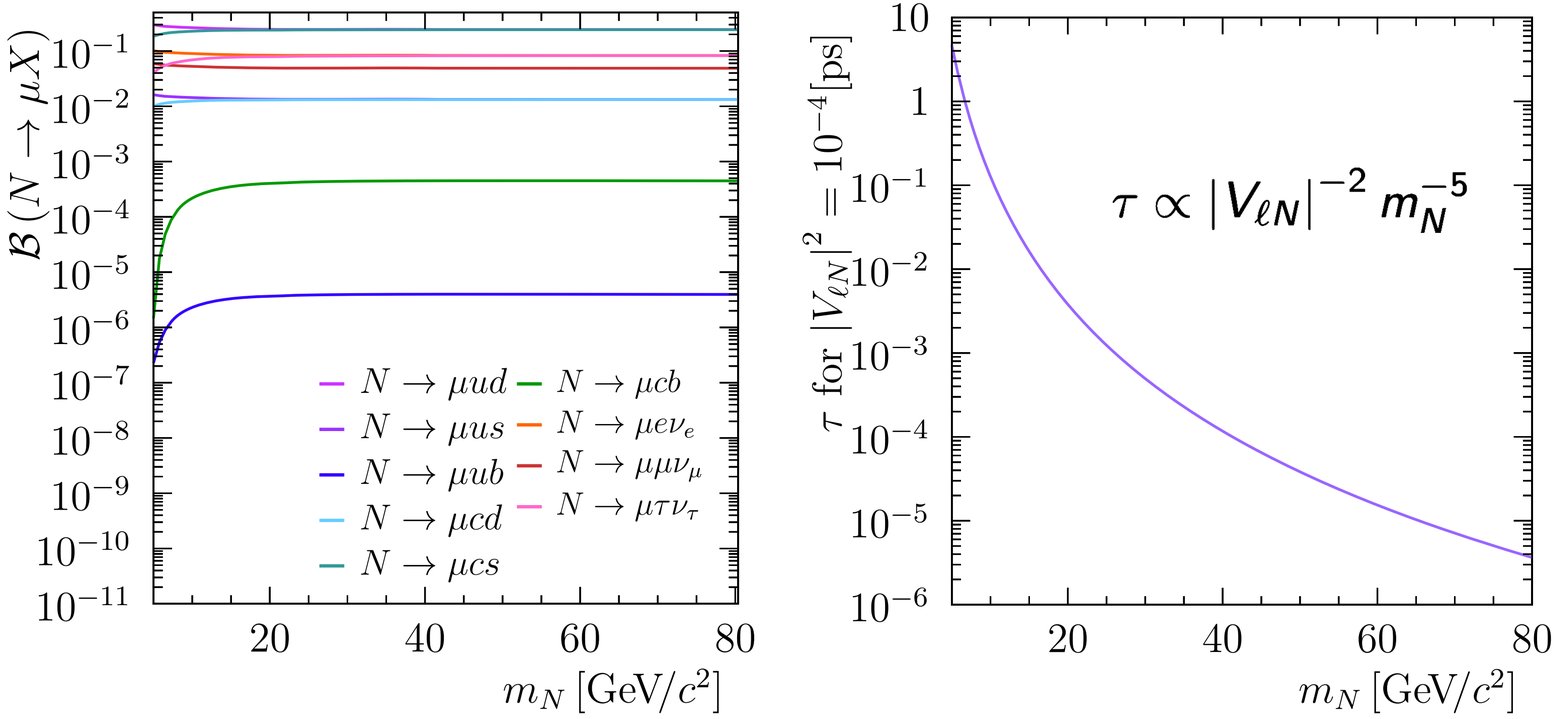


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Heavy neutral leptons

Eur. Phys. J. C (2021) 81:248

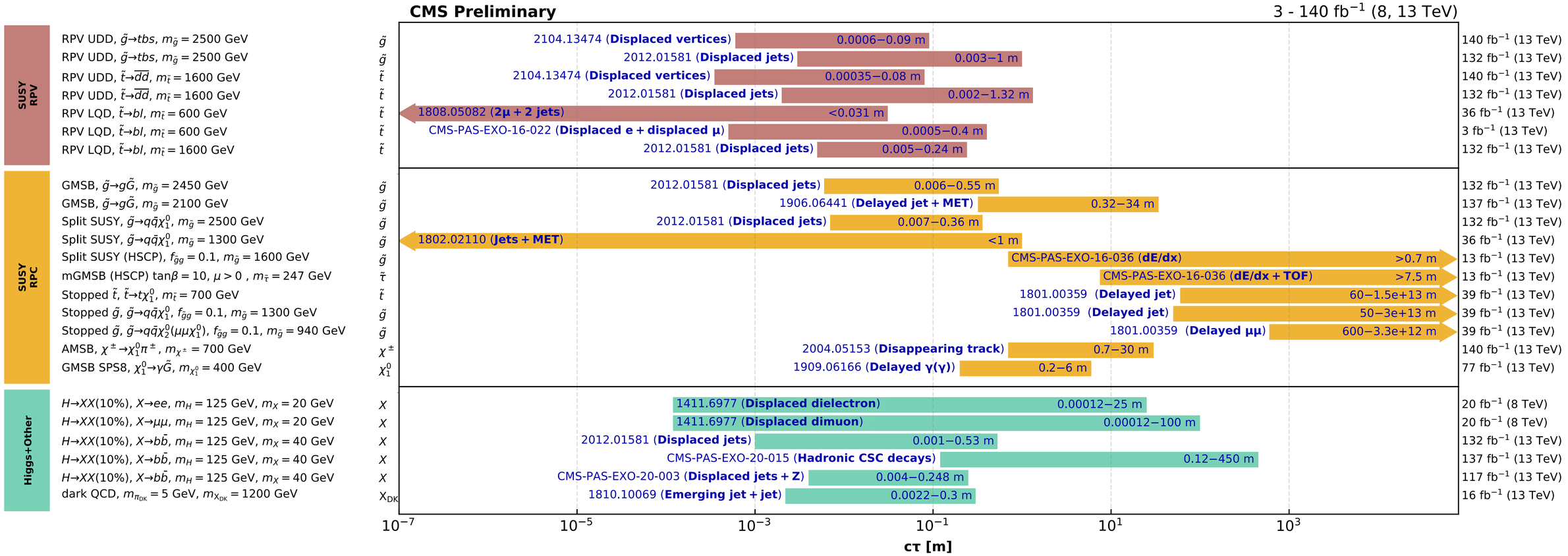
Fig. 1 Properties of a heavy neutrino as a function of its mass [21,22]: (left) the branching fractions to final states with a muon and (right) the lifetime, assuming a coupling of 10^{-4}



$$\sigma(pp \to W) \cdot \mathcal{B}(W \to \ell N) = \sigma(pp \to W) \cdot \mathcal{B}(W \to \ell \nu) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right)$$

CMS long-lived particle searches

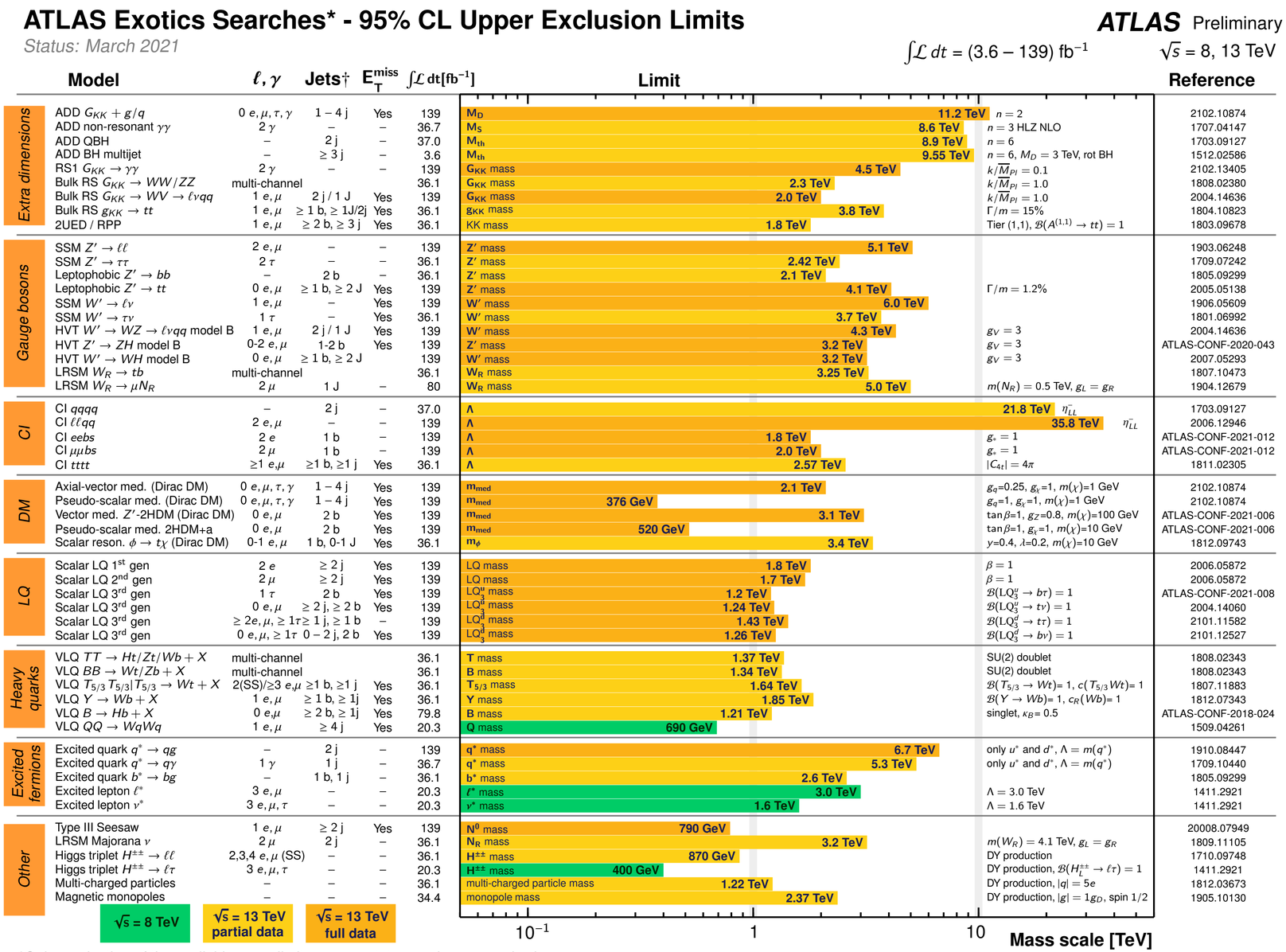
Overview of CMS long-lived particle searches



LHCP 2021

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

ATLAS Exotics searches



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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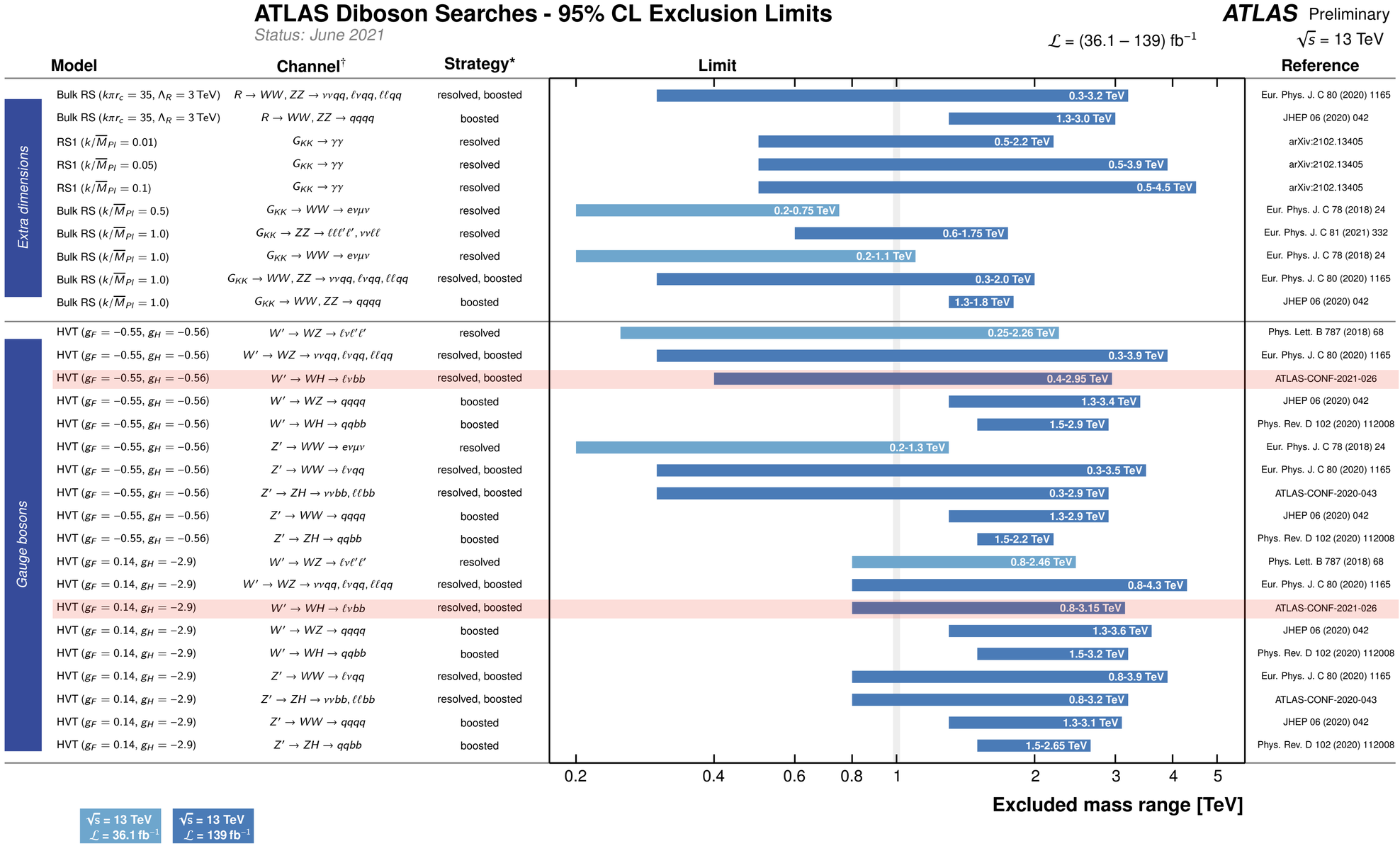
ATLAS Diboson searches



*small-radius (large-radius) jets are used in resolved (boosted) events

†with $\ell = \mu, e$