Exotic searches at the LHC

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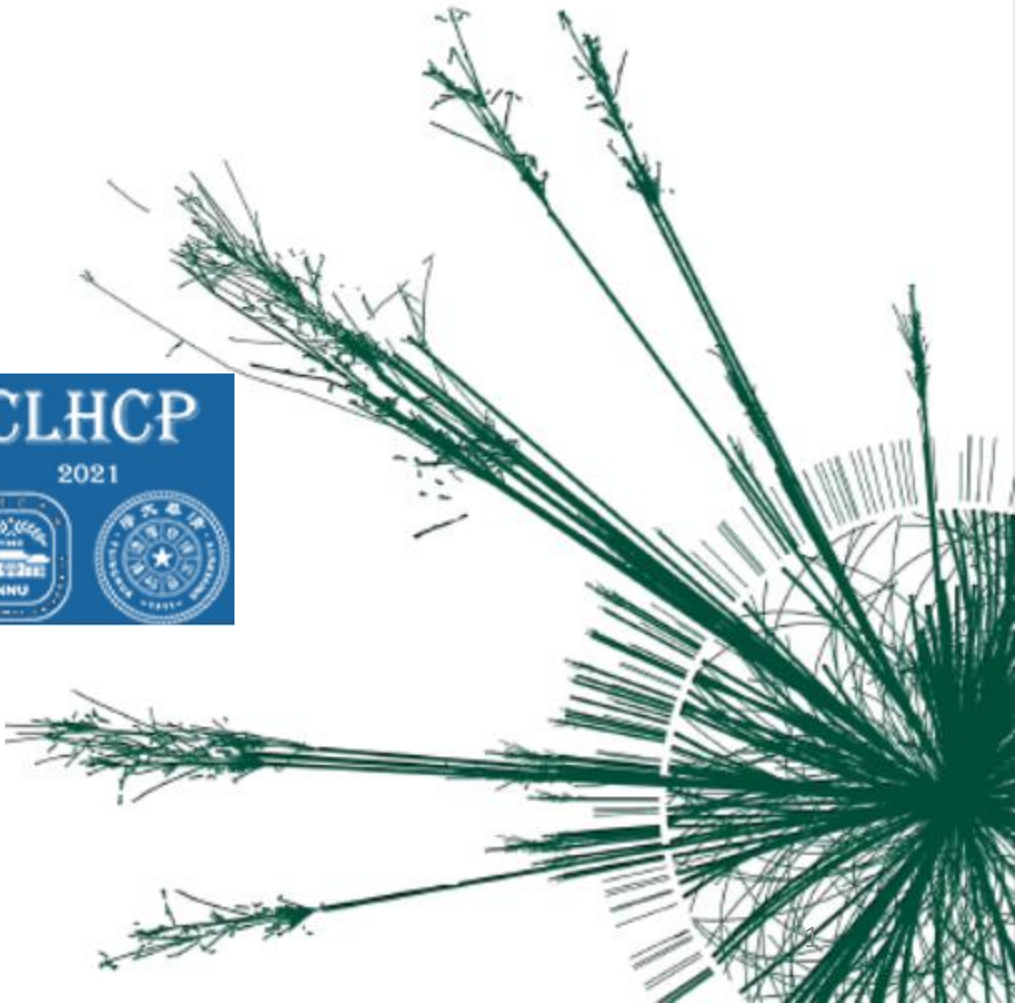
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

ATLAS EXPERIMENT

CMS Compact Muon Solenoid



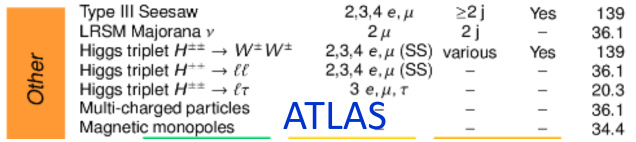
Introduction

- **Many BSM models exist to cover the limitations of the SM** : hierarchy problem, baryon asymmetry, neutrino masses, dark matter, …

- **LHC provides a great place to search for these models**

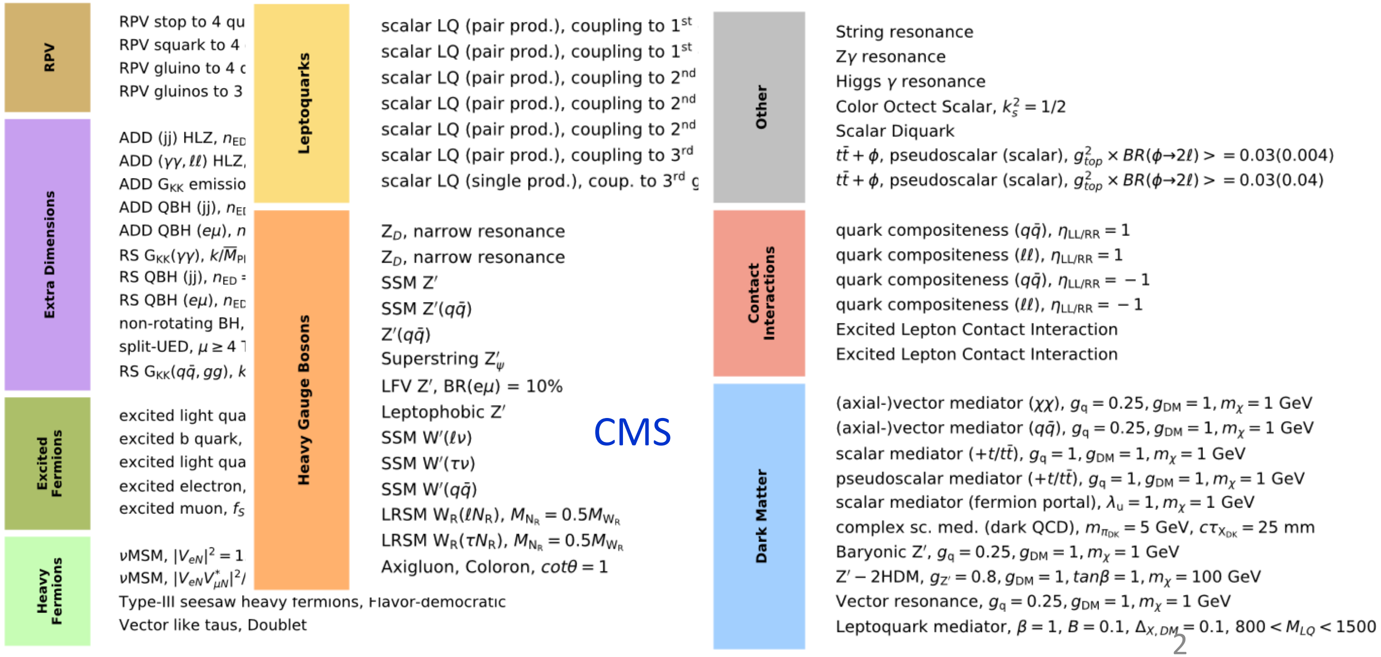
- **Lots of searches for such new physics have** being explored **in ATLAS and CMS**

- **Exotic searches (non-SUSY) cover a wide range of possibilities**
  - ✓ Additional Higgs boson and di-Higgs production
  - ✓ Leptoquarks
  - ✓ New fermions and gauge bosons
  - ✓ Dark matter
  - ✓ Long-lived particles
  - ✓ ……



Selected searches in this talk

- **new bosons**
- **new fermions**
- **dark matter***



* More in Lailin Xu's talk "Dark matter and unconventional searches at the LHC"

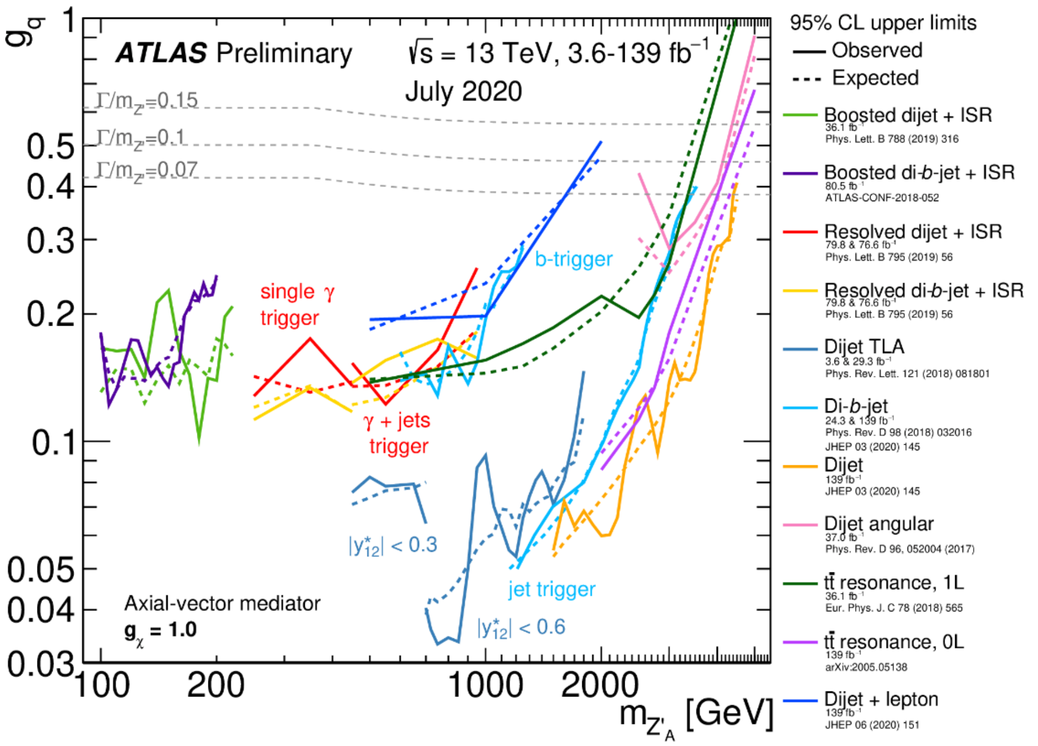
Many contributions from ATLAS-China and CMS-China groups on relevant topics, as summarized and presented on the first day

Searches for new bosons

- ➢ **Vast searches for new bosons have been performing at the LHC with many final states**
  - ✓ **Spin-0 h, H, A, $H^{\pm}$ in 2HDM**
    - Simplest BSM extension for SM Higgs sector

See Bing Li's talk "Search for BSM and rare Higgs at the LHC"

  - ✓ **Spin-1 W', Z'**
    - In many models, e.g. composite Higgs
    - Possible solution to hierarchy problem
  - ✓ **Spin-2 gravitons, spin-0 radions**
    - in extra dimension models
    - Possible solution to hierarchy problem
  - ✓ **Axion-like particles (spin-0 pseudoscalars)**
    - Specific case of axion is solution to Strong CP problem
    - DM candidate
  - ✓ **Leptoquarks (spin-0/1)**
    - possible explanation for LHCb flavour anomalies



- ➢ **Full Run-2 dataset: probe multi-TeV masses**

$Z' \rightarrow \ell\ell$

[JHEP07(2021)208](https://doi.org/10.1007/JHEP07(2021)208)

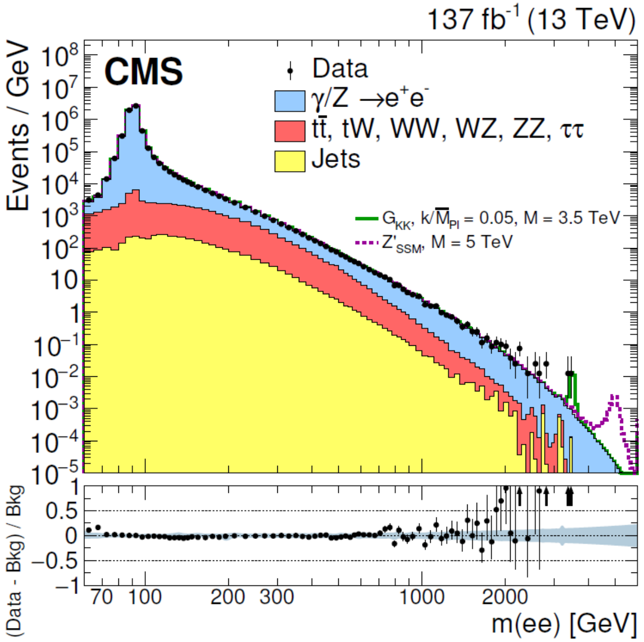
CMS search for high mass resonance in $\ell\ell$ final state

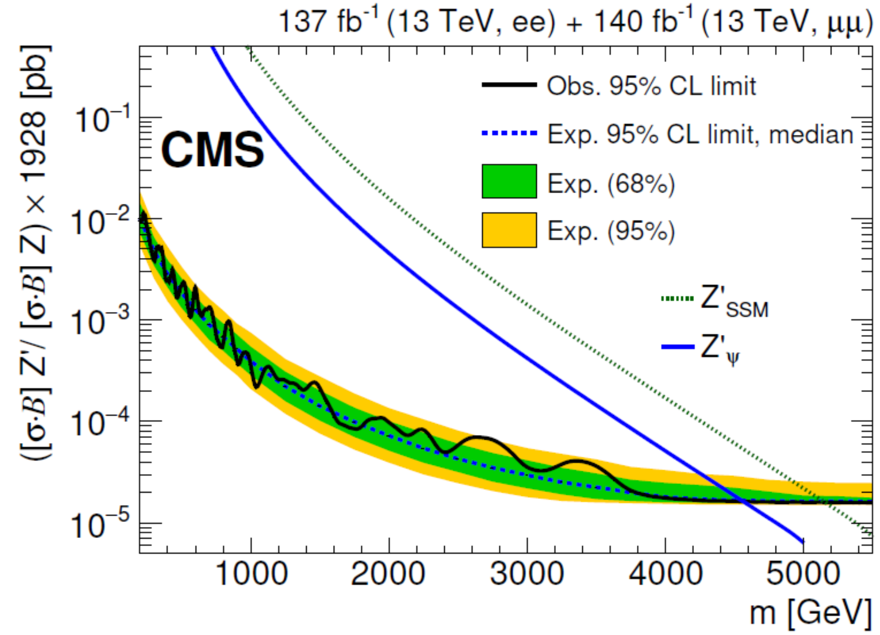
- Background shapes estimated from MC, normalisation from low m_{ll} (<120 GeV) region
- ee: **no requirement on the sign of electrons**, to avoid significant drop on the signal selection efficiency of high-energy electrons
- **Limits** are set on the **ratio of σ*B** for **$Z' \rightarrow \ell\ell$**

Exclude Sequential SM boson Z'_{SSM} mass up to 5.15 TeV
and Left-right-symmetric models Z'_{ψ} mass up to 4.56 TeV

Channel	Z'_{SSM} Obs. [TeV]	Z'_{SSM} Exp. [TeV]	Z'_{ψ} Obs. [TeV]	Z'_{ψ} Exp. [TeV]
ee	4.72	4.72	4.11	4.13
μμ	4.89	4.90	4.29	4.30
ee + μμ	5.15	5.14	4.56	4.55

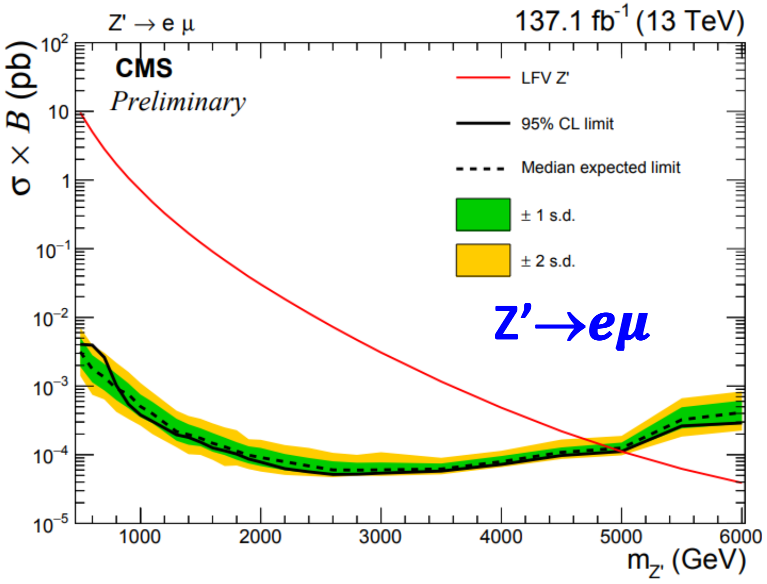
Comparable to ATLAS's results (*PLB 796 (2019) 68-87*) :
excluded below **5.1 (4.5) TeV for Z'_{SSM} (Z'_{ψ})**

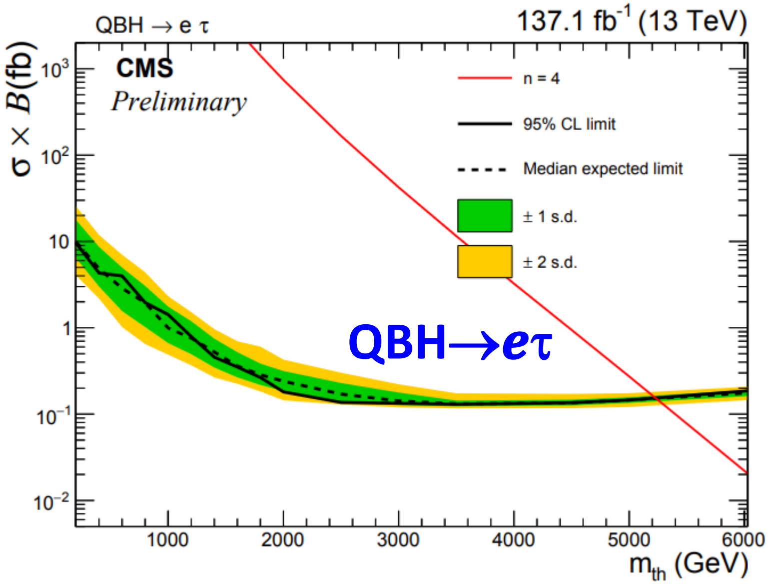




Heavy BSM $X \to e\mu, e\tau, \mu\tau$

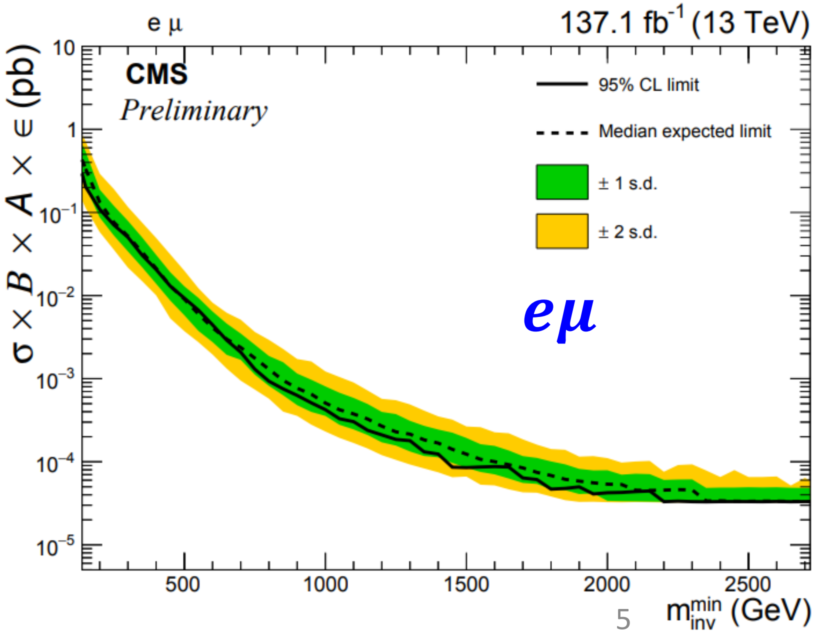
- CMS : search for **heavy resonance X** with **Lepton-flavor violating (LFV)** decays:
  - **U(1) Z' with LFV decays**: resonance (m_X)
  - **Quantum Black Holes (QBH):** threshold (m_{th})
- **Final states considered:** $e\mu$, $e\tau_h$, $\mu\tau_h$ (all isolated, prompt, no sign requirements)
- **Signal inference:**
  - **$e\mu$ channel:** dilepton mass
  - **$\ell\tau_h$ channels:** colinear mass ($m_{col} = m_{vis}/\mathrm{sqrt}(x_\tau^{vis})$ with *visible mass m_{vis}* and fraction of energy x_τ^{vis} of visible product); reported by CMS for the first time





CMS-PAS-EXO-19-014

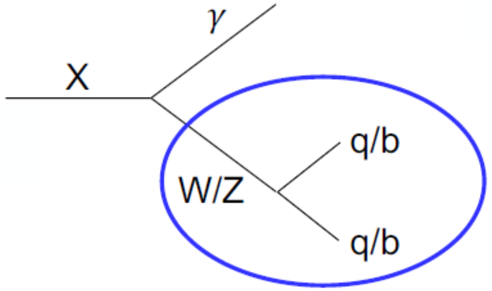
Best limits from the LHC in the considered models



- **No excess is observed:**
  - **Model-specific limits vs m**: **excluded Z' mass** up to **5.0/4.3/4.1 TeV**, **QBH threshold mass** up to **5.6/5.2/5.0 TeV**, for $e\mu/e\tau_h/\mu\tau_h$
  - **Model-independent limits on $\sigma^*\mathcal{B}^*A^*\epsilon$** for $m > m^{min}$: one can check if his/her favorite model with $X \to \ell\ell'$ (not tested in the paper) is excluded

Heavy resonance X → Vγ

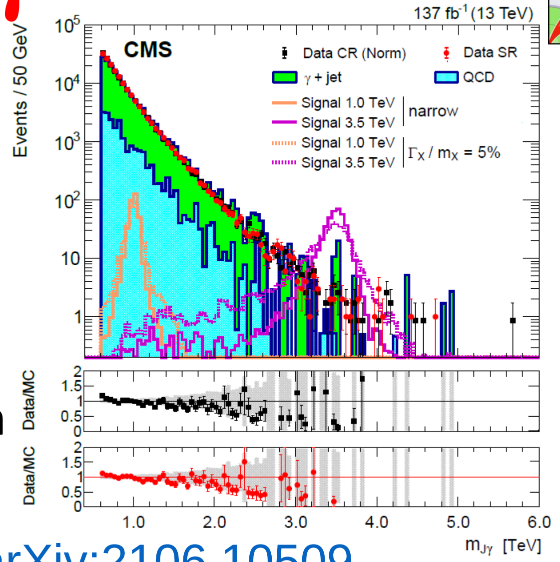
ATLAS: search for heavy charged and neutral bosons decaying to **Wγ and Zγ**



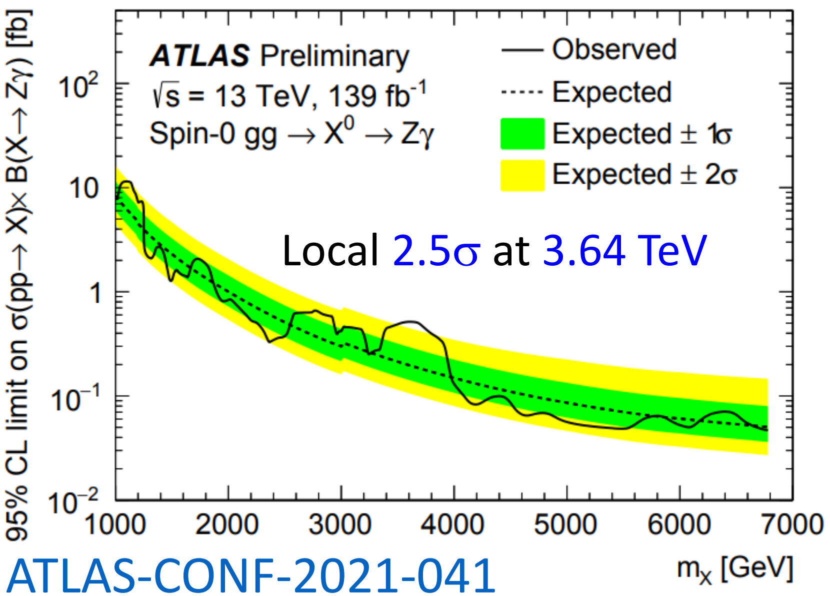
explored mass range: 1.0-6.8 TeV

- **Some commons for ATLAS and CMS:**
  - **Hadronic decays of V**
  - **Boosted V** reconstructed as a large-R jet
  - **$m_{j\gamma}$** spectrum to extract signals
- **Different strategy** of event categorization
- **Upper limits on σ*B**

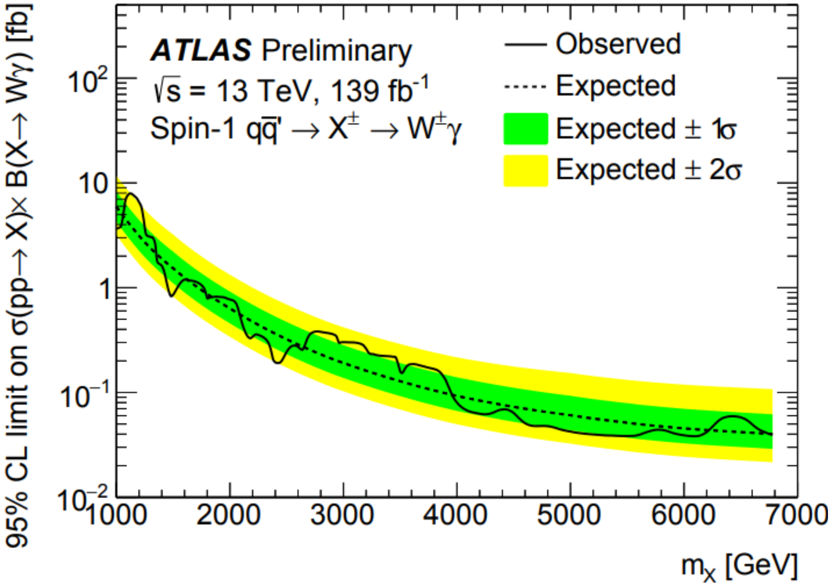
CMS W+ γ



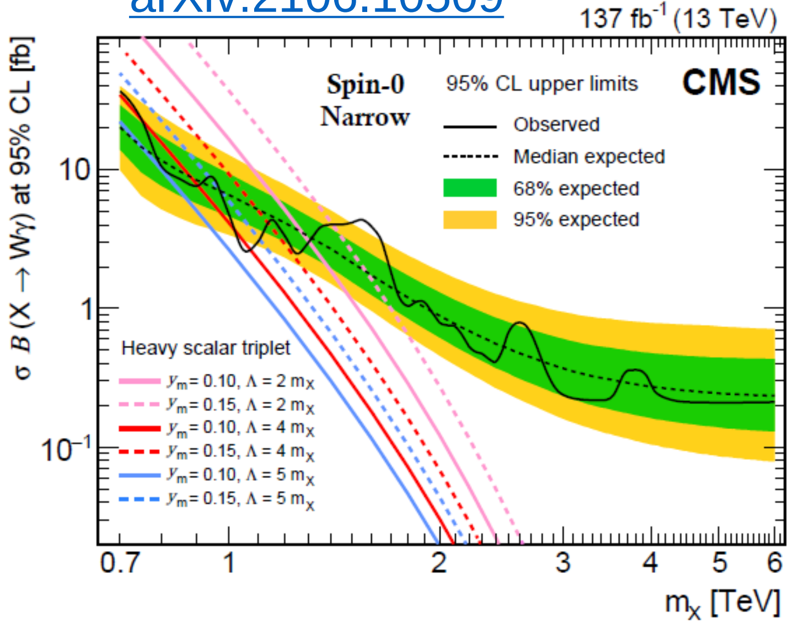
arXiv:2106.10509



Local 2.5σ at 3.64 TeV



ATLAS-CONF-2021-041

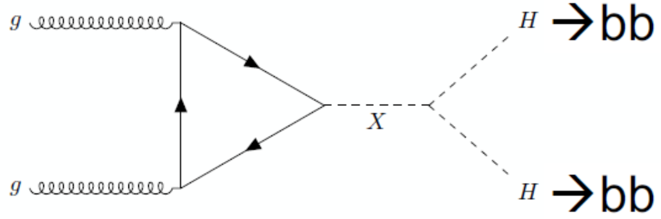


Current best exclusions of these processes

Local **2.8σ (3.1σ) at 1.58TeV** for narrow (broad) signals, for both spin-0 and spin-1

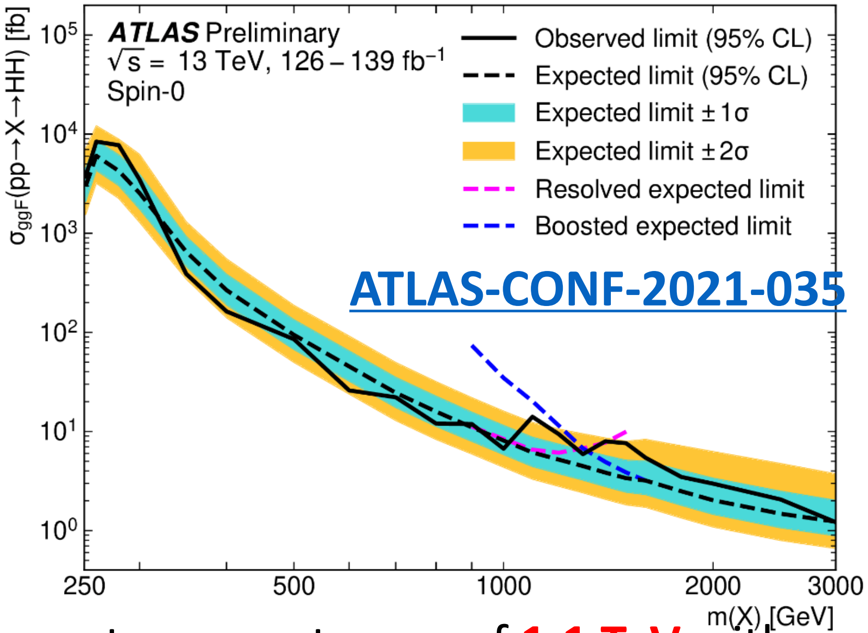
Heavy resonance : X → HH → 4b

Search for **spin-0 radion** and **spin-2 bulk graviton** for **pair production of Higgs boson** in the *4b final state*



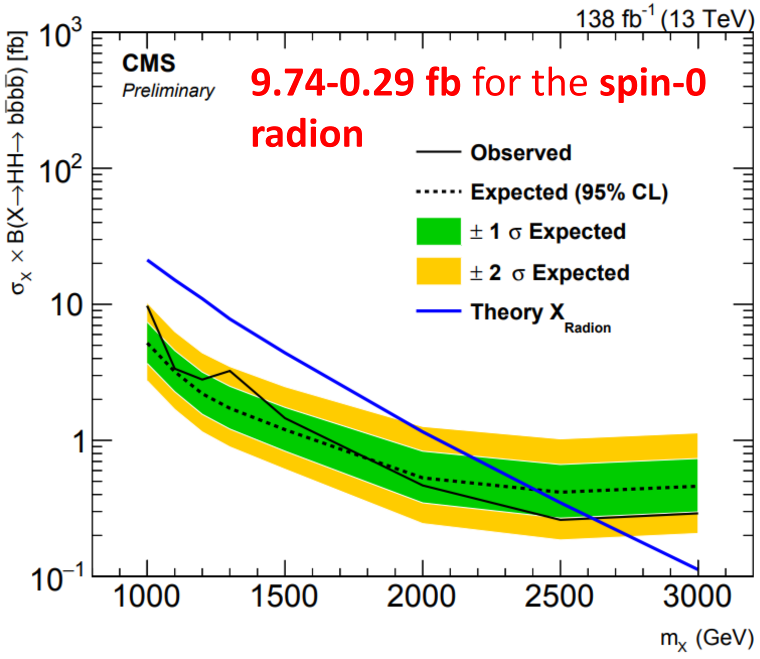
- **ATLAS** with two event topologies:
  - ✓ resolved with 4 b-tags (251-1500 GeV)
  - ✓ boosted with 2-, 3-, 4- b-tag categories (900-3000 GeV)

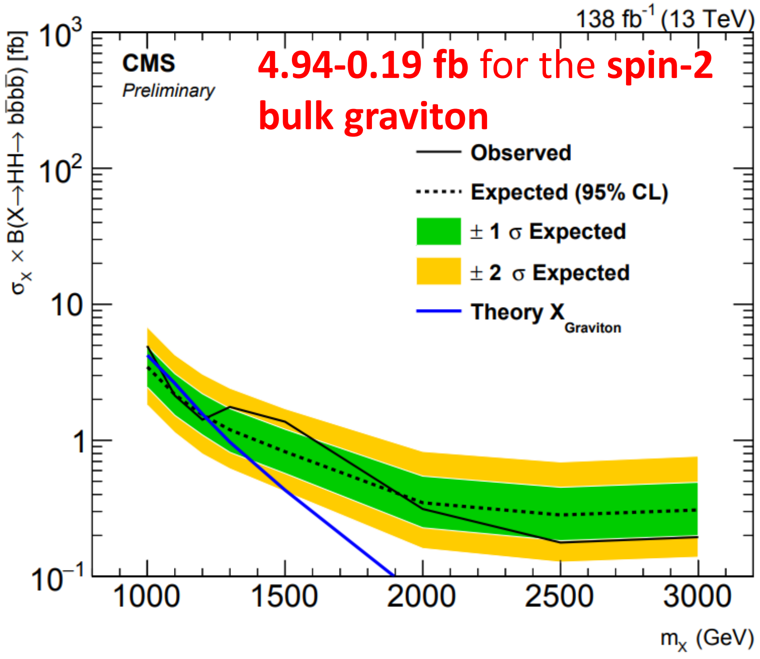
- **CMS**: two bb pairs with **at least one pair highly boosted** (reconstructed as a single large-area jet)
  - ✓ The other pair can be either boosted or resolved
  - ✓ X mass range **1–3 TeV**



[ATLAS-CONF-2021-035]

largest excess at mass of **1.1 TeV** with local (global) significance of **2.6σ (1σ)** for the **spin-0** model



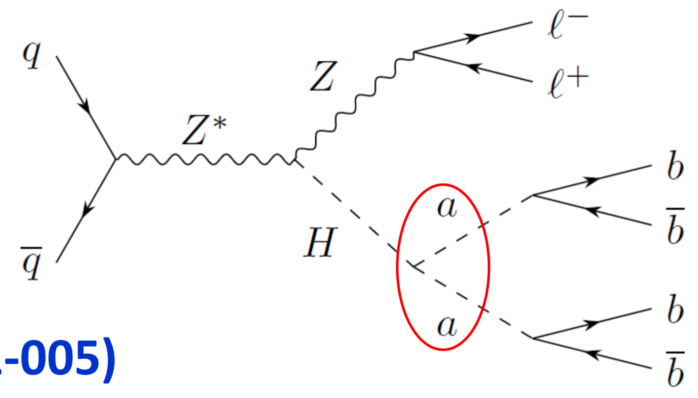


Most sensitive result above 1.5 TeV

[CMS-PAS-B2G-20-004]

Long-lived Scalars : ZH → ZSS → 2l + 4b

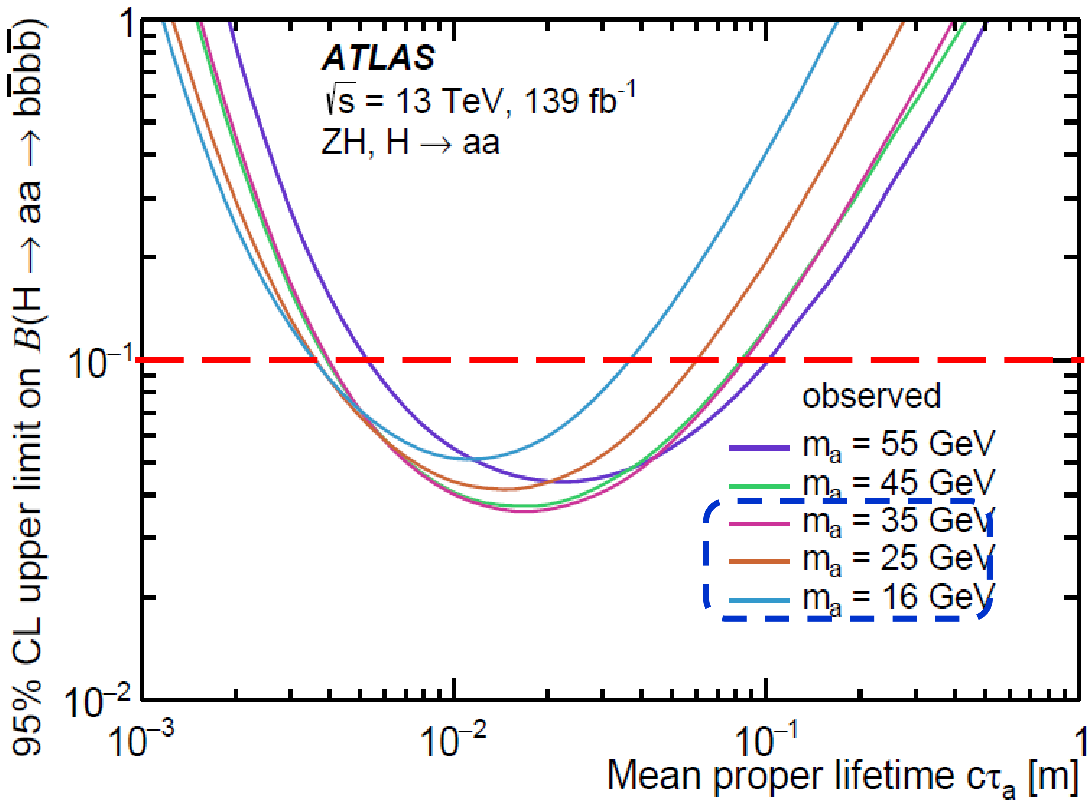
ATLAS : search for pairs of **long-lived scalars** using displaced vertices



- Benchmark: **Higgs boson production associated with Z**, H decaying to **long-lived scalars, Z→ ll**
- **Prompt dilepton + displaced jets** final state
- Reconstruct **large d0 tracks** (Large Radius Tracking, LRT) to **build displaced vertex (DV) :** match DV to displaced jet

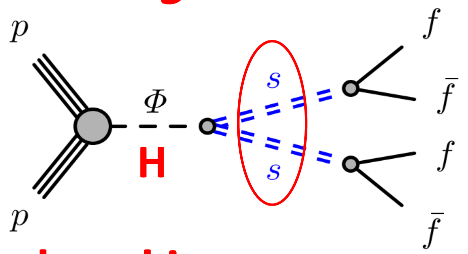
- **Branching ratios above 10%** are excluded at 95% CL for LLP $c\tau$ as small as **4 mm** and as large as **100 mm**
- For m_a<40 GeV, these results represent the **most stringent constraint** in this lifetime regime
- **First time** this lifetime range in tested in ATLAS

arXiv:2107.06092
(ATLAS-CONF-2021-005)



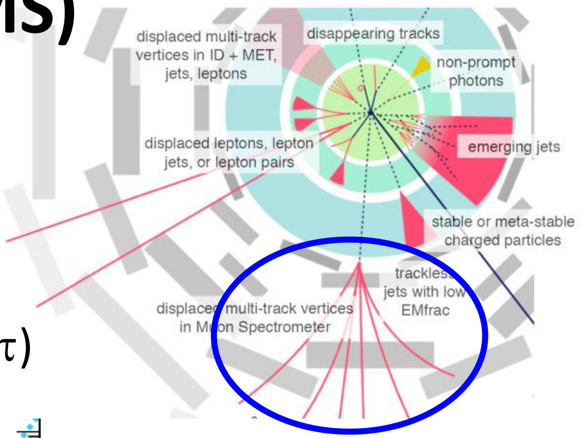
Long-lived Scalars : H → SS → 4j

Search for pairs of long-lived particles (LLP) decaying in the Muon Spectrometer (MS)

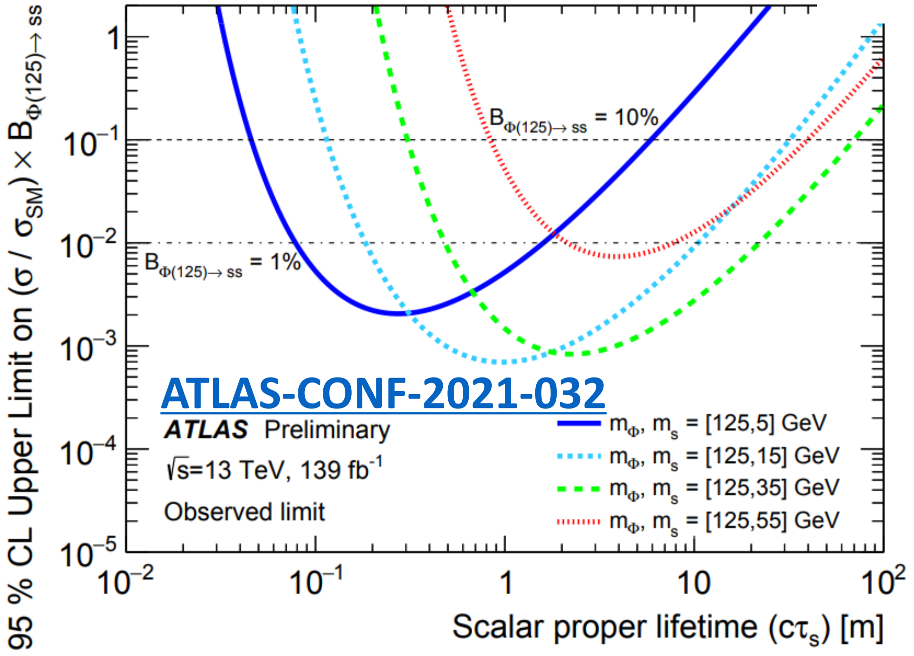


- **ATLAS using displaced vertices**
  - ✓ Reconstruct **two isolated vertices** in MS displaced by **3-14 m**

mainly to the heaviest fermion pair (bb/cc/ττ)

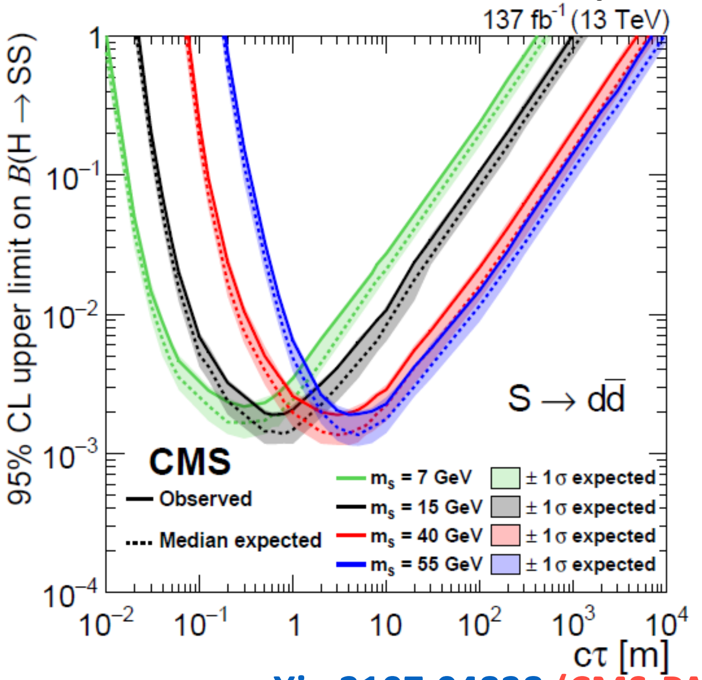


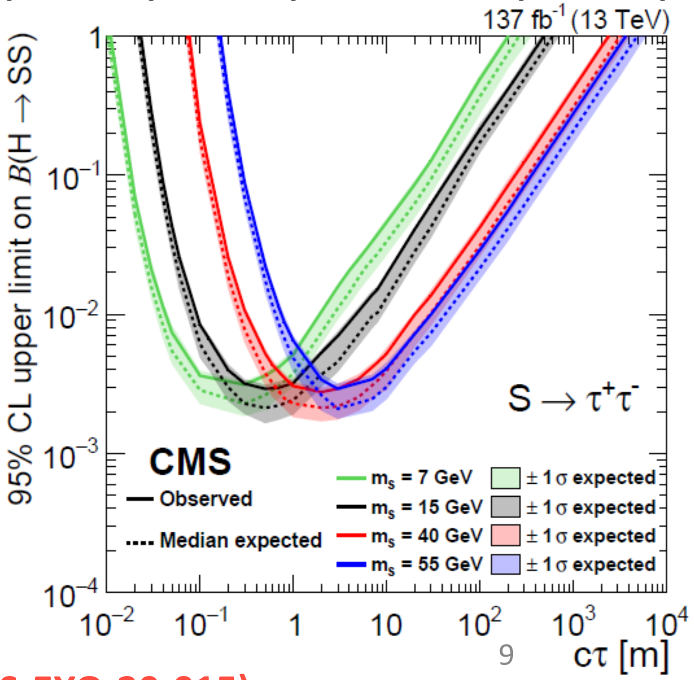
- **CMS using displaced jets :**
  - ✓ **First CMS search** for long-lived **hadronic showers** in the Cathode Strip Chambers
  - ✓ Subsequently **S decaying to quarks and $\tau^+\tau^-$**
  - ✓ **most stringent limits on B(H→SS) for $c\tau$ > 6m (7GeV), 20m (15GeV), and 40m (40GeV)**



ATLAS-CONF-2021-032

4cm to 71.3m excluded for B>10% and m_ϕ=125GeV





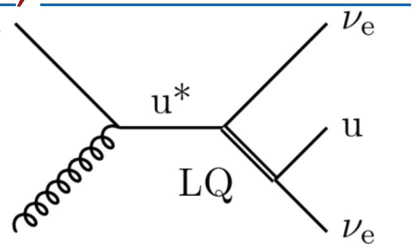
arXiv:2107.04838 (CMS-PAS-EXO-20-015)

Searches for Leptoquarks (LQ)

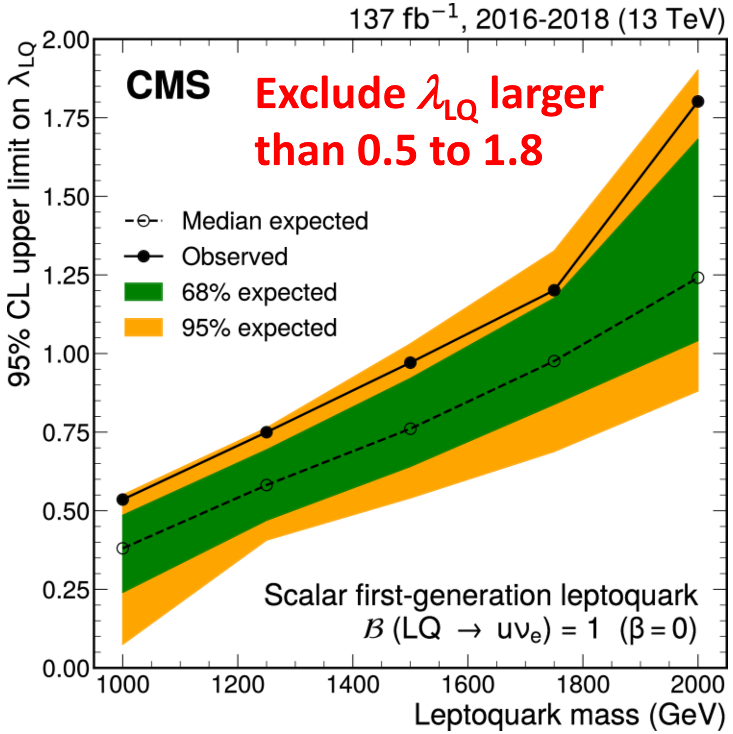
➢ **Multiple searches** published by ATLAS and CMS, e.g. ATL-PHYS-PUB-2021-017, CMS-EXO-19-015

CMS: LQ decay to **quark and neutrino**

arXiv:2107.13021 (CMS-EXO-20-004)



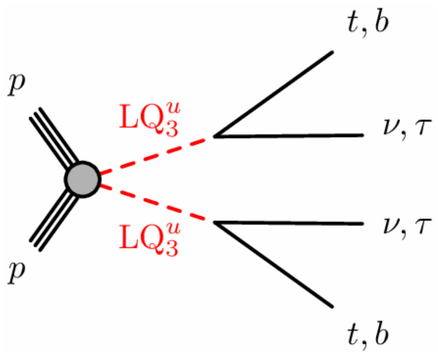
- **Machine learning techniques** is used to distinguish narrow ISR jets and fat jets from W/Z decay
- **Joint maximum likelihood fit in SR and CR** is used to constrain backgrounds



Upper limits at 95% CL on the LQ coupling λ_{LQ} as a function of the LQ mass

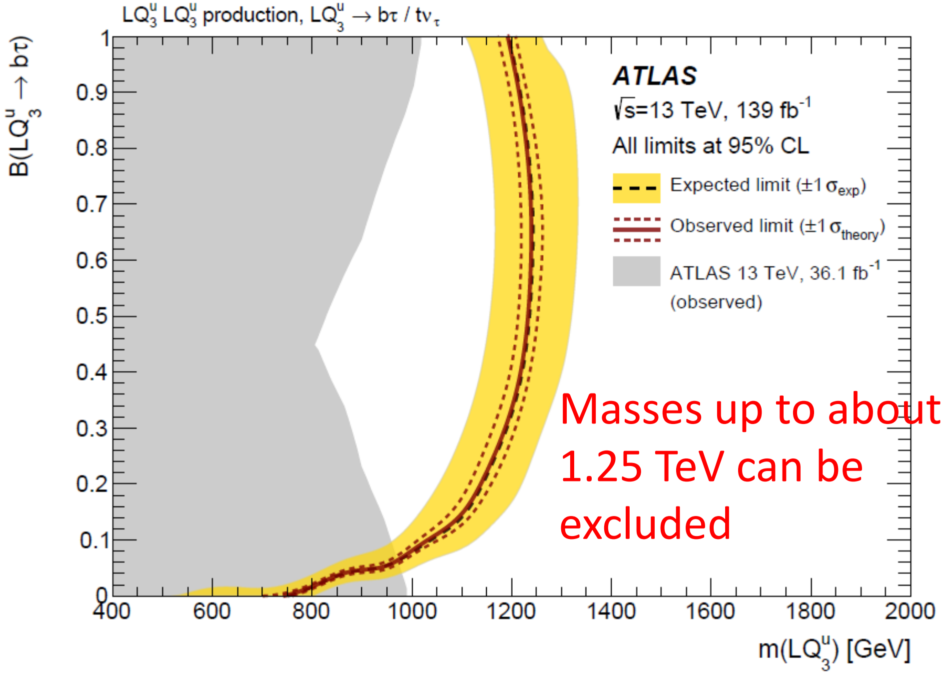
ATLAS : pair-produced scalar third-generation LQ with ***τ lepton* + b-jet + MET**

arXiv:2108.07665 (ATLAS-CONF-2019-18)



- LQ decay only to **3rd-generation SM particles**
- Search in **single-tau channel**

➔ **Data are found to be consistent with SM expectation**



Searches for new fermions

Many searches for new fermions at the LHC

- **Excited states of quarks/leptons (q*, l*)**
  - Composited Higgs can regulate Higgs boson mass
- **Vector-like quarks (VLQ)**
  - Present in various scenarios (extra dimensions, SUSY, Little Higgs,…) trying to solve the hierarchy problem
  - VLQs are colored **spin-1/2 fermions** but their L/R-handed components transform the same way under SU(2)
  - In simplified models VLQ mix with their SM partners to regulate the Higgs boson mass
- **Heavy neutral leptons/neutrinos (HNL)**
  - Can generate small neutrino mass via seesaw mechanism

Excited Fermions	excited light quark ($q\gamma$), $f_S = f = f' = 1, \Lambda = m_q^*$
	excited b quark, $f_S = f = f' = 1, \Lambda = m_q^*$
	excited light quark (qg), $\Lambda = m_q^*$
	excited electron, $f_S = f = f' = 1, \Lambda = m_e^*$
	excited muon, $f_S = f = f' = 1, \Lambda = m_\mu^*$
Heavy Fermions	νMSM, $\lvert V_{eN}\rvert^2 = 1.8$, $\lvert V_{\mu N}\rvert^2 = 1.8$
	νMSM, $\lvert V_{eN}V_{\mu N}^*\rvert^2/(\lvert V_{eN}\rvert^2 + \lvert V_{\mu N}\rvert^2) = 1.0$
	Type-III seesaw heavy fermions, Flavor-democratic
	Vector like taus, Doublet

CMS-EXO-Pub

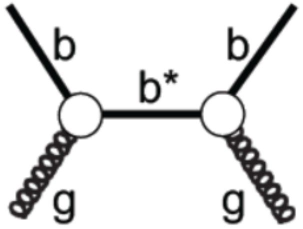
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139
Heavy quarks	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1
	Excited lepton ℓ^*	3 e, μ	–	–	20.3
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3

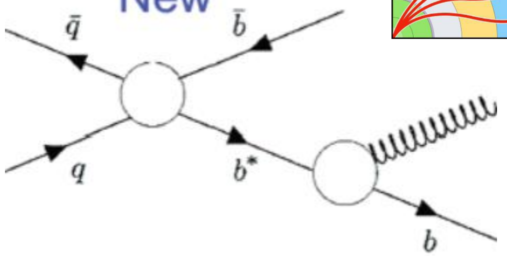
ATL-PHYS-PUB-2021-033

Excited bottom quark b* in dijets

- **CMS**: search for resonances (**b*** and **Z′**) decaying into **b quarks**
  - **bg→b*→bg** and **qq→bb*→bbg** (new)
  - **Z′ →bb** in Sequential Standard Model and Heavy Vector Triplet model (new)

New

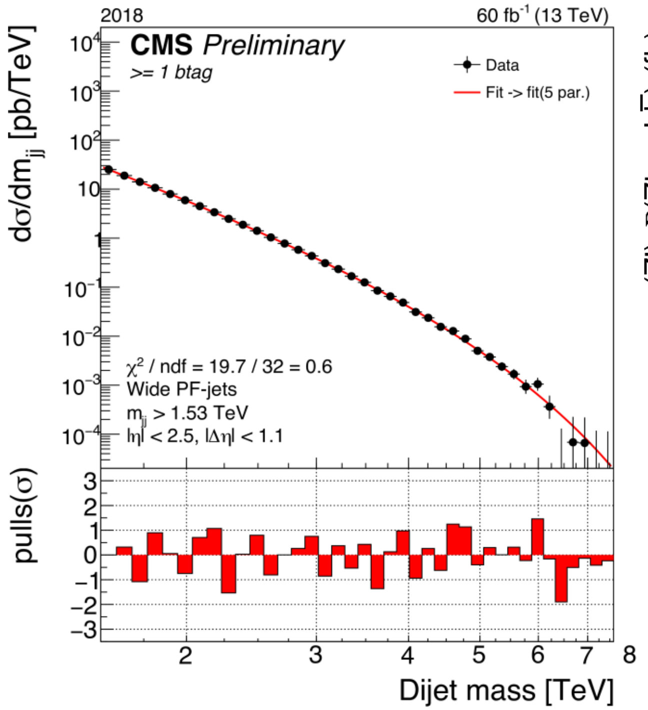


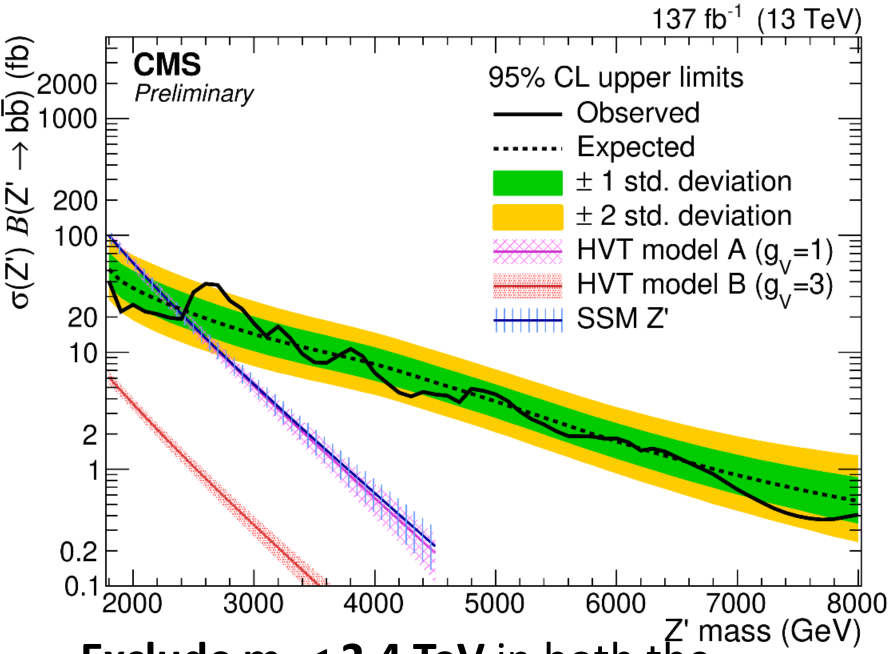


- Require **at least 2 jets with at least one b-tagged jet**
  - **DNN** to identify energetic b-tagged jets

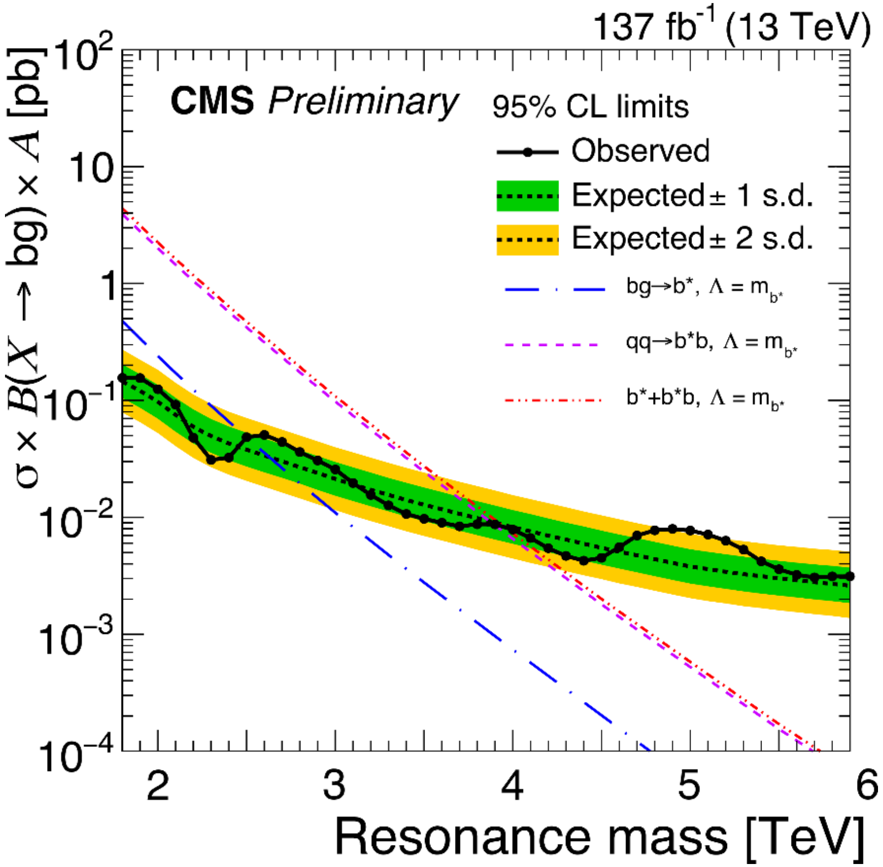
CMS-PAS-EXO-20-008

- Search for bumps in smoothly falling b-tagged **dijet mass** spectrum
  - mass spectrum well described by a smooth parametrization
    → background is estimated directly from data





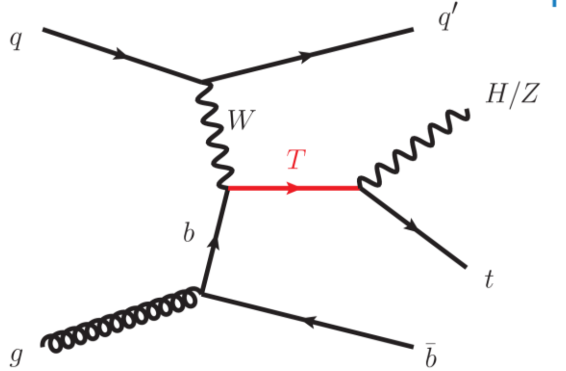
Exclude $m_{Z'}$< 2.4 TeV in both the SSM and the HVT model A



Most stringent limit of b* quark:
m_{b*} < 4.0 TeV is excluded

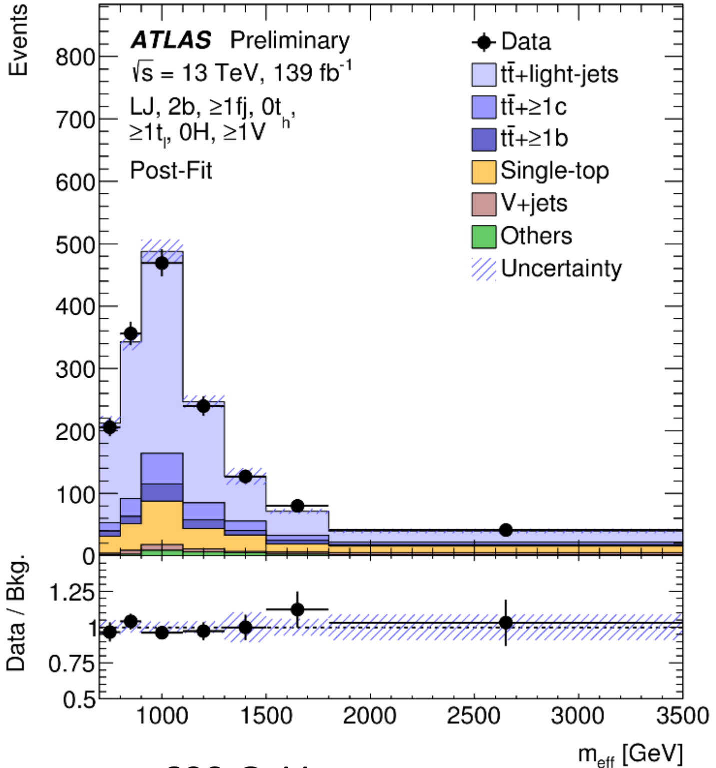
Single VLQ T→tH/tZ in lv+jets

- **ATLAS**: search for the **single production** of **an up-type vector-like quark (T)** decaying as **T→tH** or **T→tZ**, subsequently **H→bb** or **Z→qq**



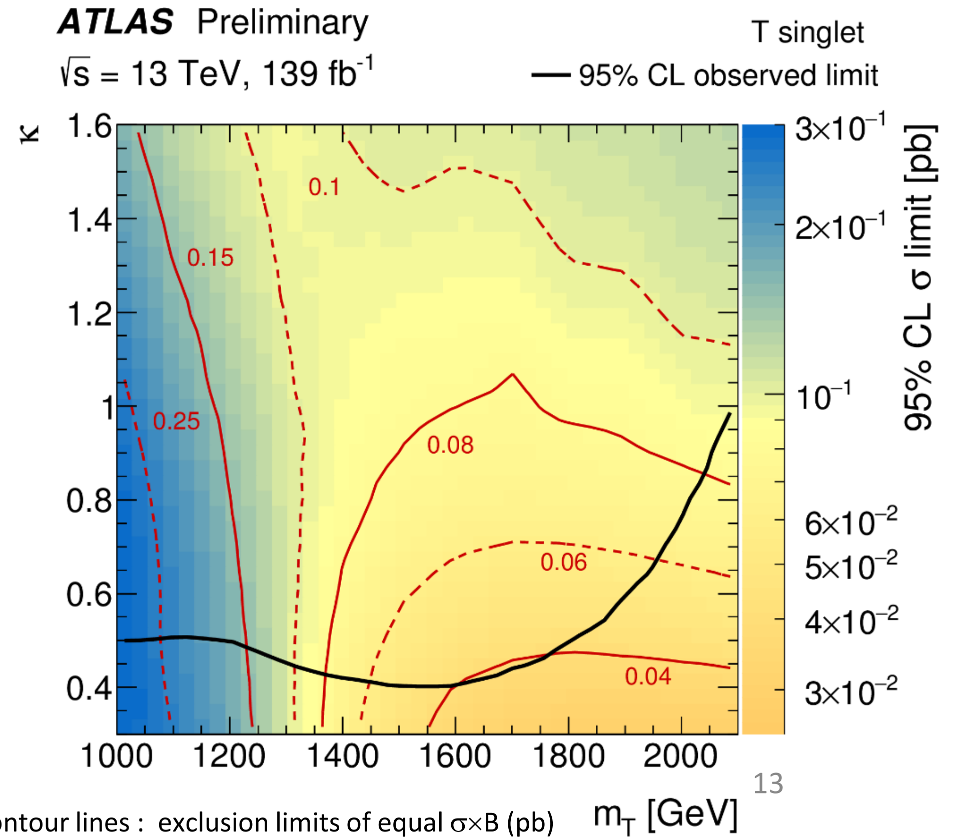
- Final states contain **a single lepton with multiple jets and b-jets**
- Search for excess in **effective mass** (scalar sum of objects' pT)

ATLAS-CONF-2021-040



m_{eff} > 600 GeV

- Limits on the **mass** and **universal coupling strength (κ)** of the vector like quark
  - ✓ κ values above 0.5 are excluded for all masses below 1.8 TeV
  - ✓ At a mass of **1.6 TeV**, κ values as low as **0.41** are excluded

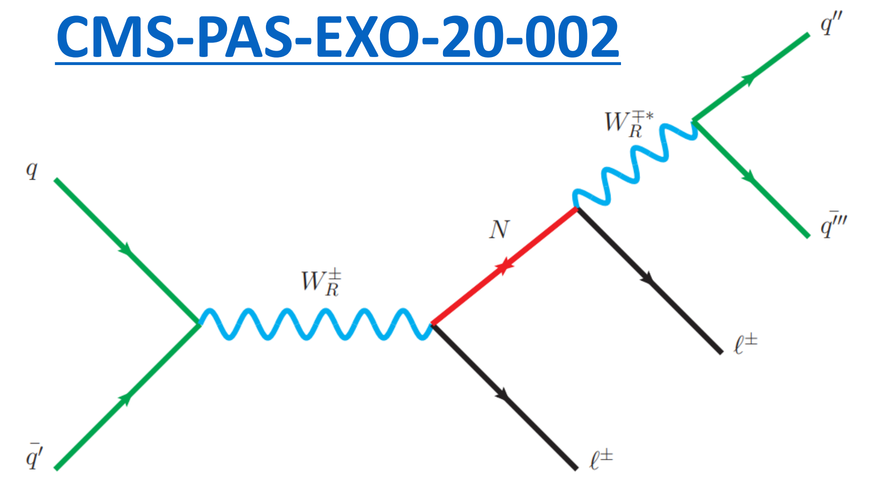


Red contour lines : exclusion limits of equal σ×B (pb)

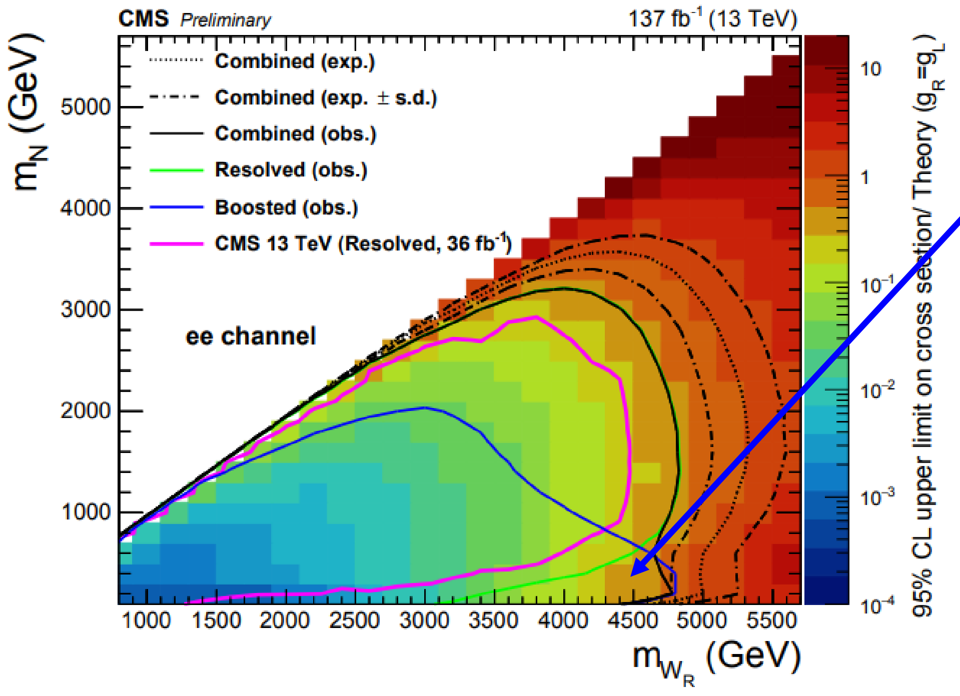
Heavy neutral lepton and heavy W_R

- **CMS**: search for a **right-handed W_R** and a **heavy neutrino**

CMS-PAS-EXO-20-002

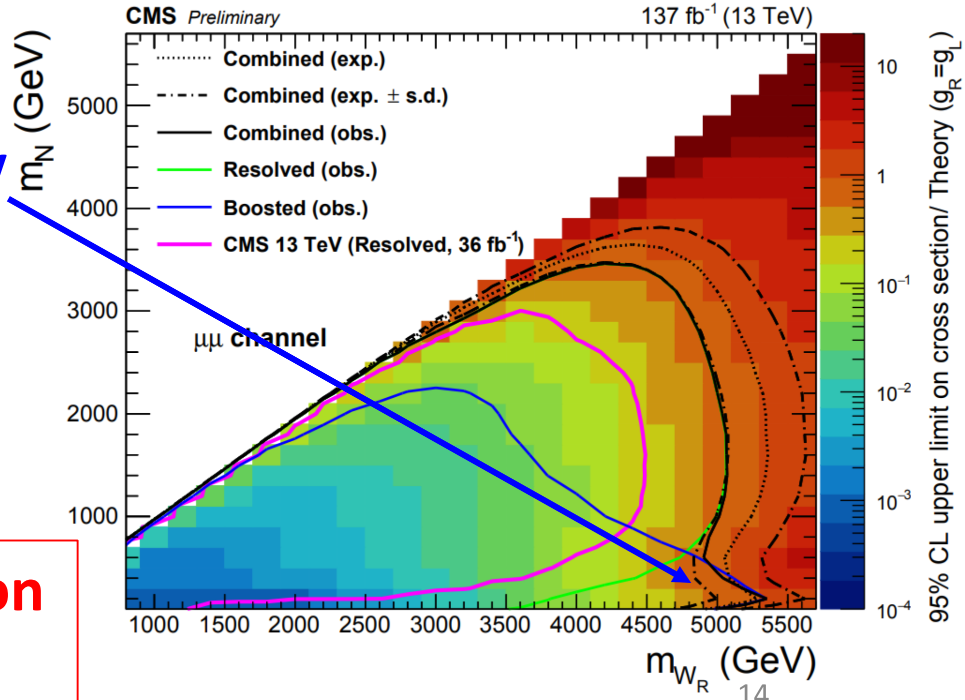


- Search covers **both regions** of phase space:
  - **resolved**: two same-flavor leptons (e or μ) and two quarks, **lljj**
  - **boosted** ($m(W_R) >> m_N$): decay products of the heavy neutrino are merged into a **single large-area jet** → one lepton (e or μ) and single jet, **lJ**
    - ✓ subleading lepton within **large-R jet** cone
    - ✓ **Jet substructure** used to identify boosted decay



- Boosted signature significantly improves sensitivity for **m_N<0.5 TeV**
- W_R is excluded at 95%CL up to 4.8 (4.7) / 5.4 (5.0) TeV obs(exp) for ee / μμ channel

Most stringent limits on the W_R mass to date

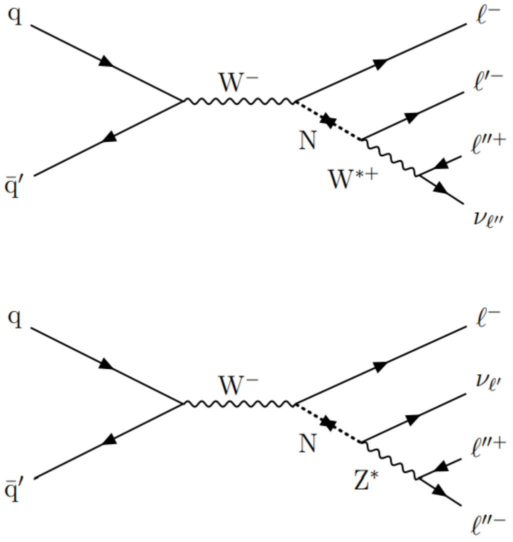


Heavy Neutral Lepton : displaced dilepton

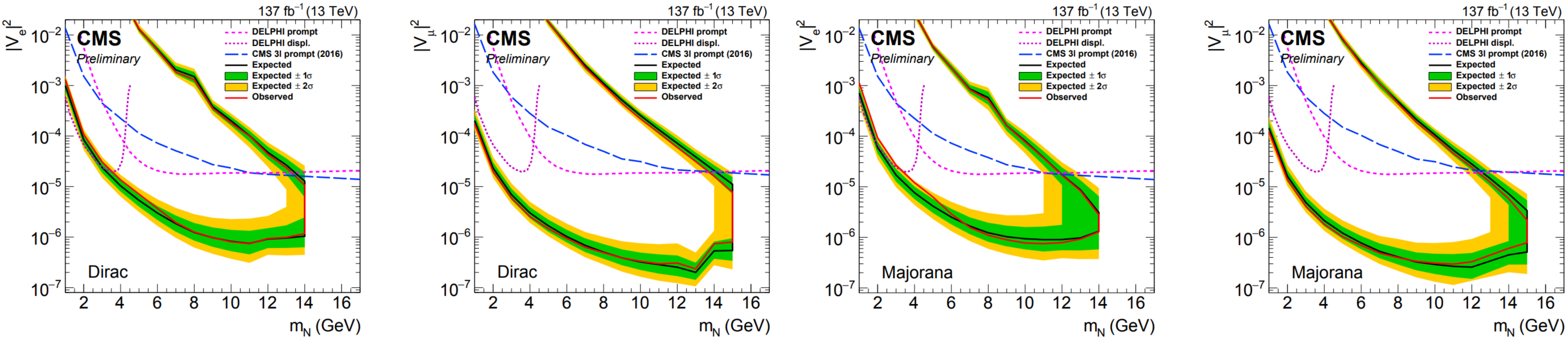
CMS-PAS-EXO-20-009

- CMS: search for heavy neutral leptons (**right-handed Dirac or Majorana neutrinos**) in final states with **three charged leptons** (e or μ)
- For **m_N < 20 GeV** and **small HNL-SM neutrino mixing parameter** ($|V_{\mu/e}|^2 < 10^{-2}$), **N can be long-lived**

$$\tau_N \propto m_N^{-5} V_{Nl}^{-2}$$



- **Exclusion limits on mixing parameter of *Dirac and Majorana* N with SM leptons improved by an order of magnitude wrt previous results : exclusions extend in the range of 10^{-7}–10^{-5}**

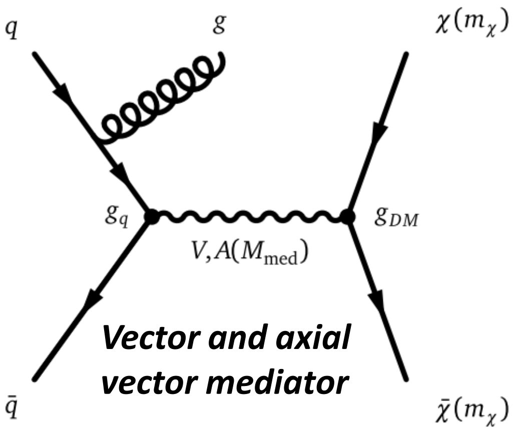


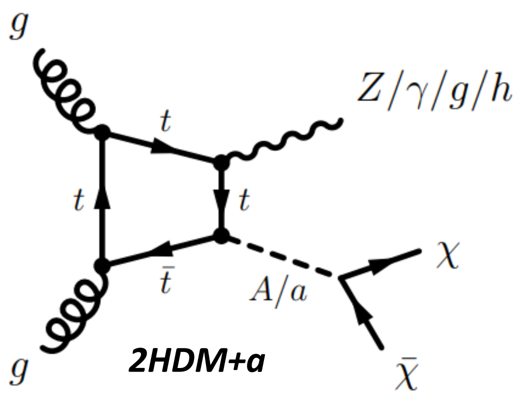
Exclusion limits on the coupling strength parameters of Dirac and Majorana neutrinos with e/μ

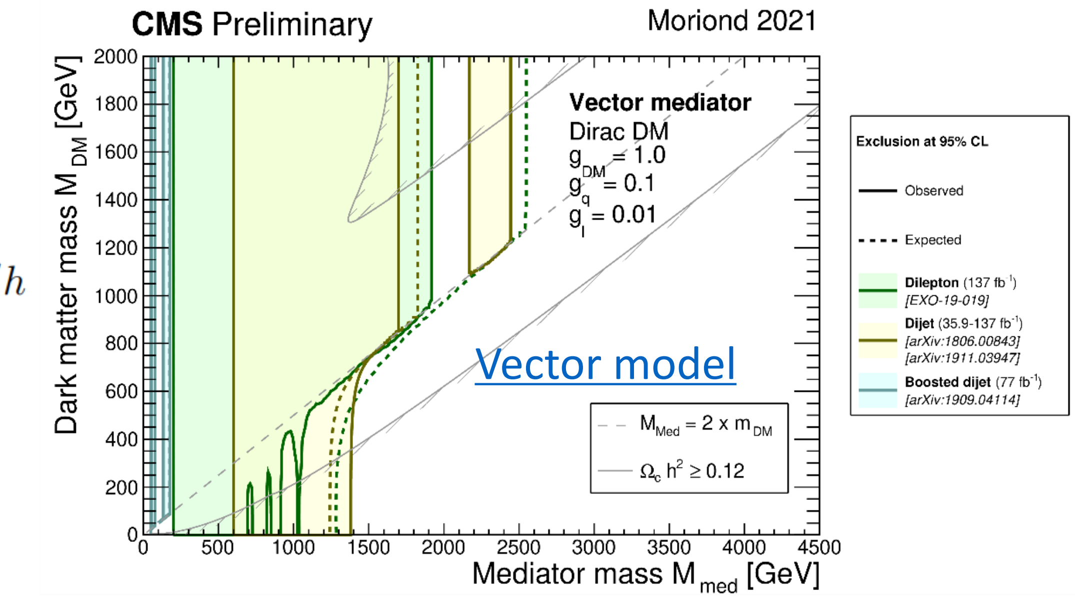
Dark Matter and dark sector

- Classical DM signature: **missing ET + X** with X = q/g (jets), γ, W, Z, H, t, tt → so called "**mono-X**" reactions

Produced in a **contact interaction** involving a quark–antiquark pair, or two gluons, and **two DM particles**

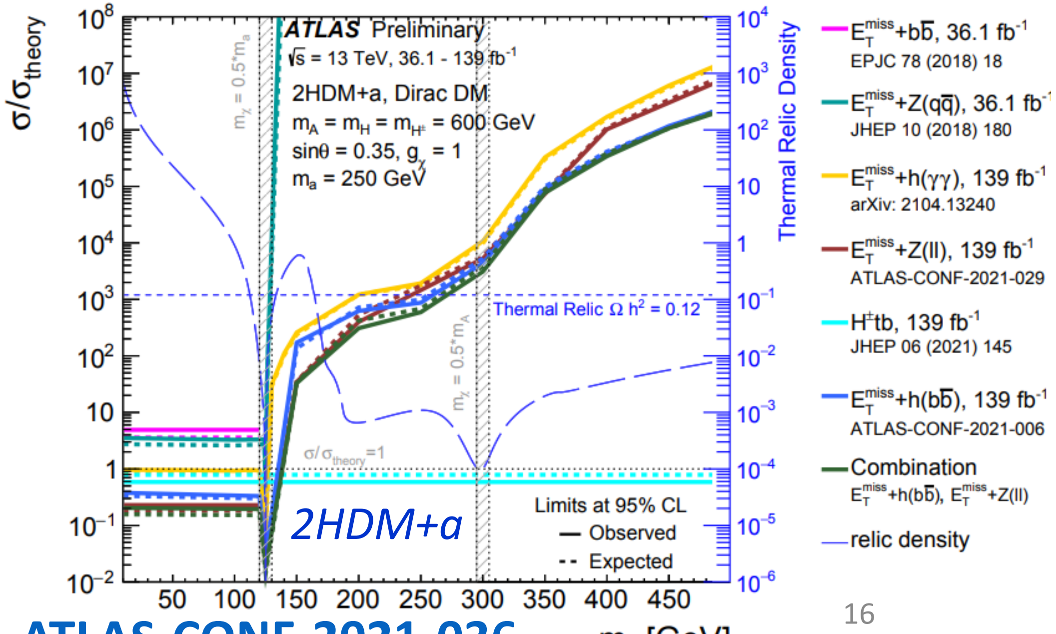






- **Allow comparisons with direct detections** (XENON1T, PandaX-II,…)

- Portal/**mediator** between SM and dark sector could be e.g. **dark photon, Higgs (exotic decays)**,…

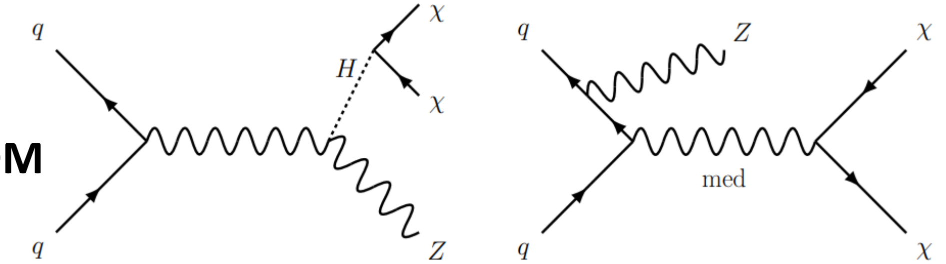


ATLAS-CONF-2021-036

More from Lailin Xu's talk "Dark matter and unconventional searches at the LHC"

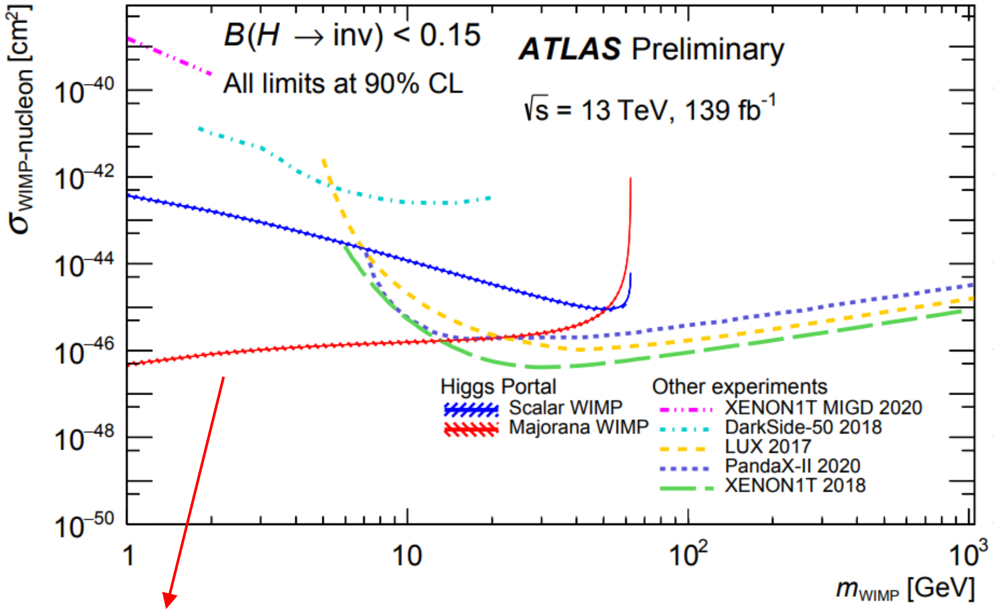
H/DM → inv : Z(ll) + MET

- ATLAS: search for **invisible decays of Higgs boson** or **dark matter candidates**, produced together with **a leptonically decaying Z boson**
  - ✓ Signal extracted from dedicated BDT for H->inv or from **m_T(ll+MET) for DM**
- **Upper limit: B(H→inv) < 18%** (observed at 95% CL)
  - ✓ re-interpreted and compared to limits from **direct DM experiments** at **90% CL**
- **Exclusion limits** are also set for **simplified DM models**



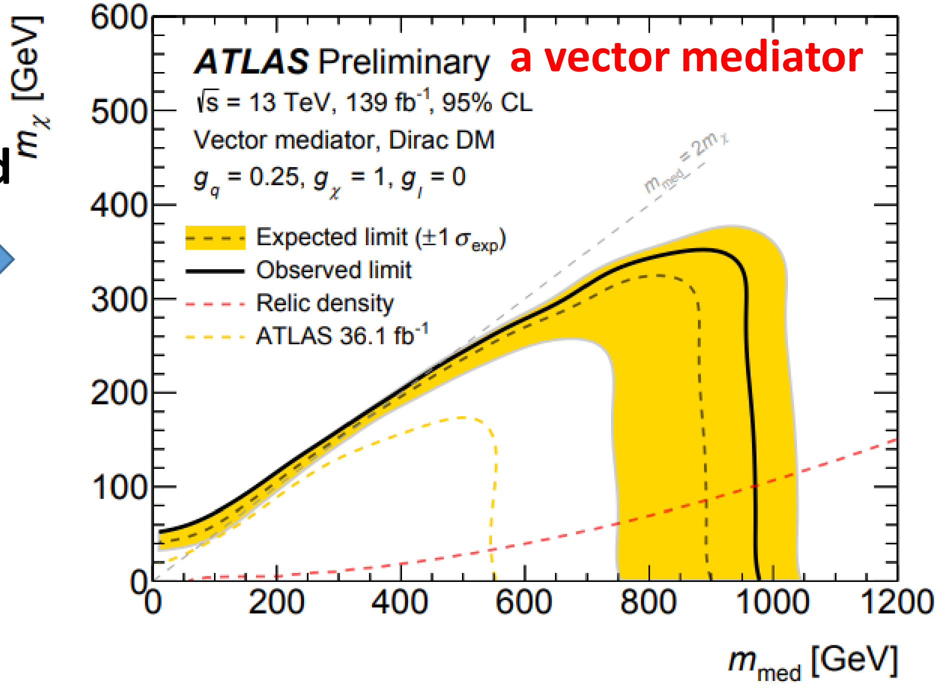
simplified DM models

ATLAS-CONF-2021-029



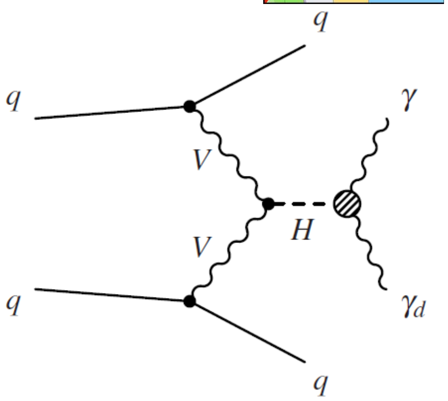
Limits from this search are particularly competitive for low DM masses

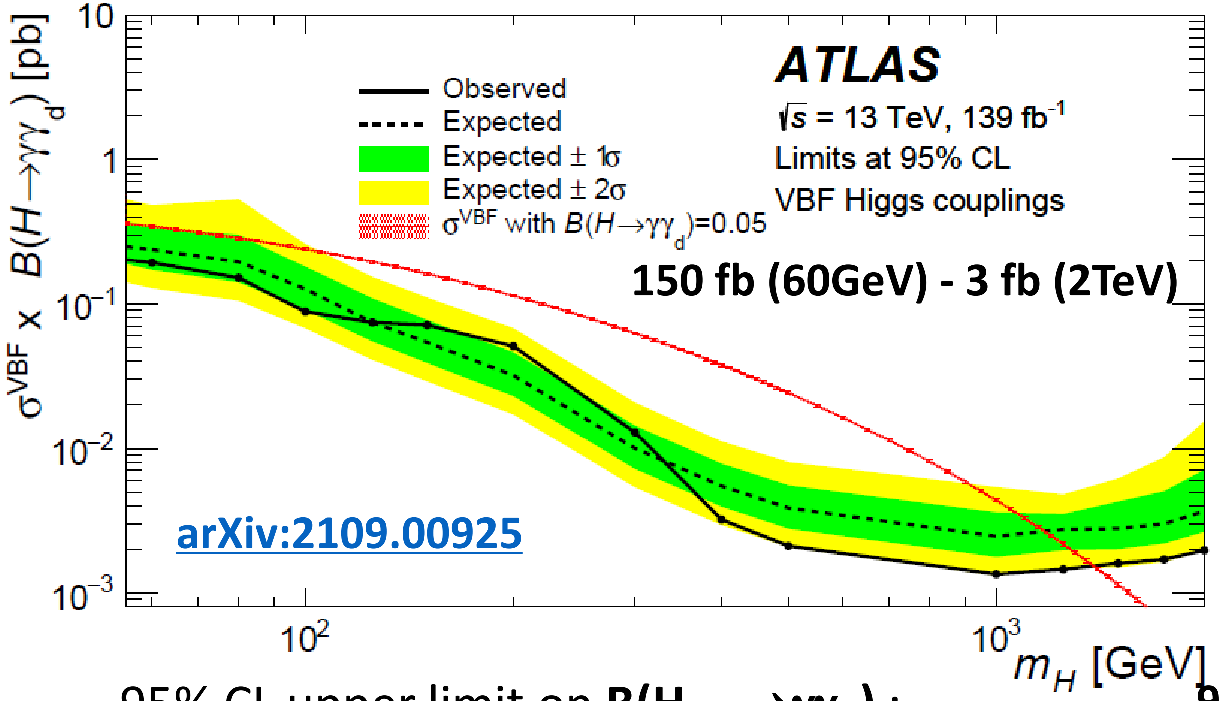
- **Compared to 2016 result, the excluded area enlarged significantly:** excluded mediator masses up to **975 GeV**, DM masses up to **350 GeV**



VBF H → Dark Photons

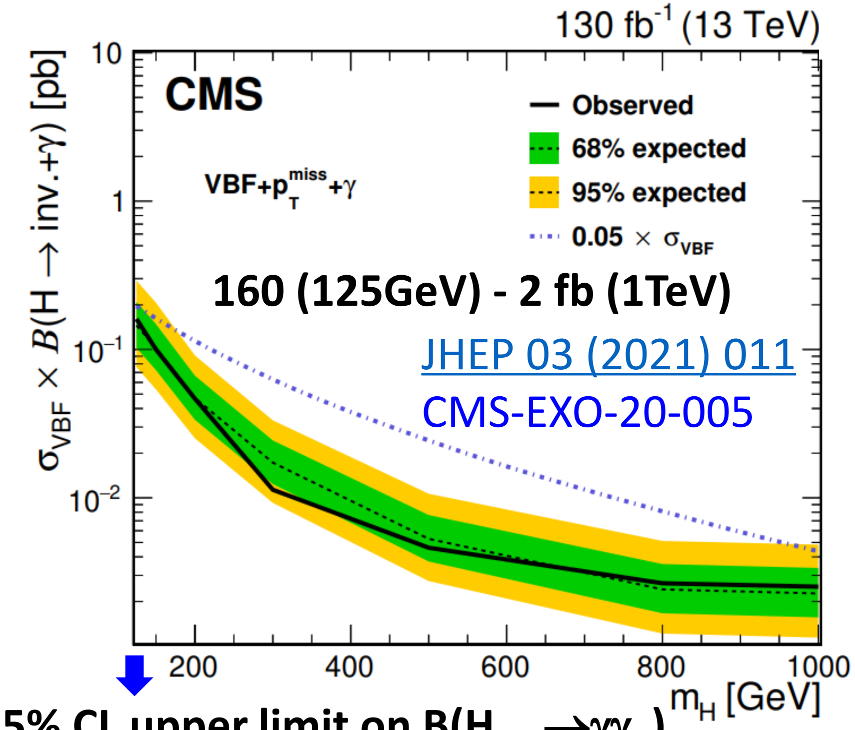
- Both ATLAS and CMS probed **coupling of a scalar Higgs boson to a dark photon** through **a dark sector** via **VBF Higgs boson production** (γ+dark-γ pair)
  - ✓ Takes advantage of 2 large |Δη| jets recoiling against MET + γ
  - ✓ Use **transverse mass** (γ+MET) as a discriminating variable to extract signal





150 fb (60GeV) - 3 fb (2TeV)

[arXiv:2109.00925]



160 (125GeV) - 2 fb (1TeV)

[JHEP 03 (2021) 011]

CMS-EXO-20-005

95% CL upper limit on $\mathbf{B(H_{125} \to \gamma\gamma_D)}$:
0.018 ($0.017^{+0.007}_{-0.005}$) obs (exp)
most stringent to date

95% CL upper limit on $B(H_{125} \to \gamma\gamma_D)$

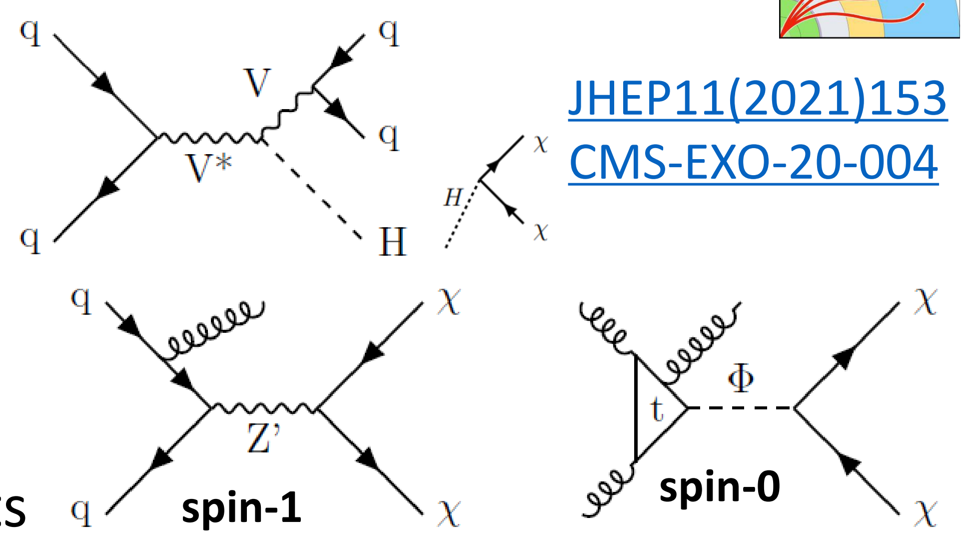
VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$

ZH: [JHEP10(2019)139]

Mono-jet and mono-V (had)

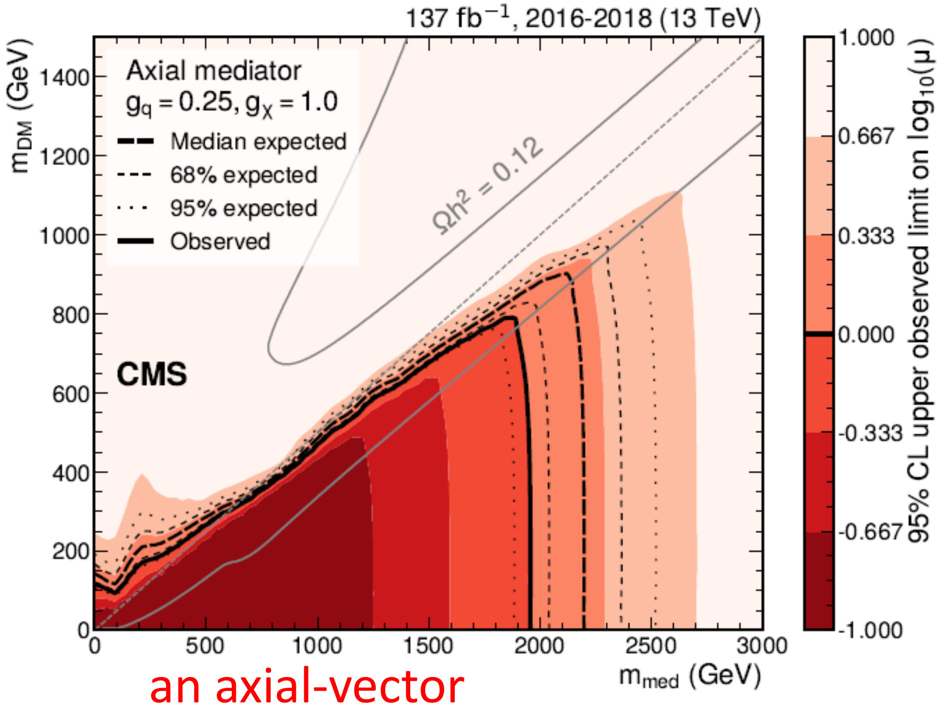
- CMS: search for new particles in events with **energetic jets** and **large MET**
- DM: decays of the **Higgs boson** or **colorless *spin-1*** and ***spin-0* mediators**
- **Mono-V: Machine learning** (Artificial Neural Networks) is used to identify **V-jets** and efficiently suppress the QCD jets

JHEP11(2021)153
CMS-EXO-20-004

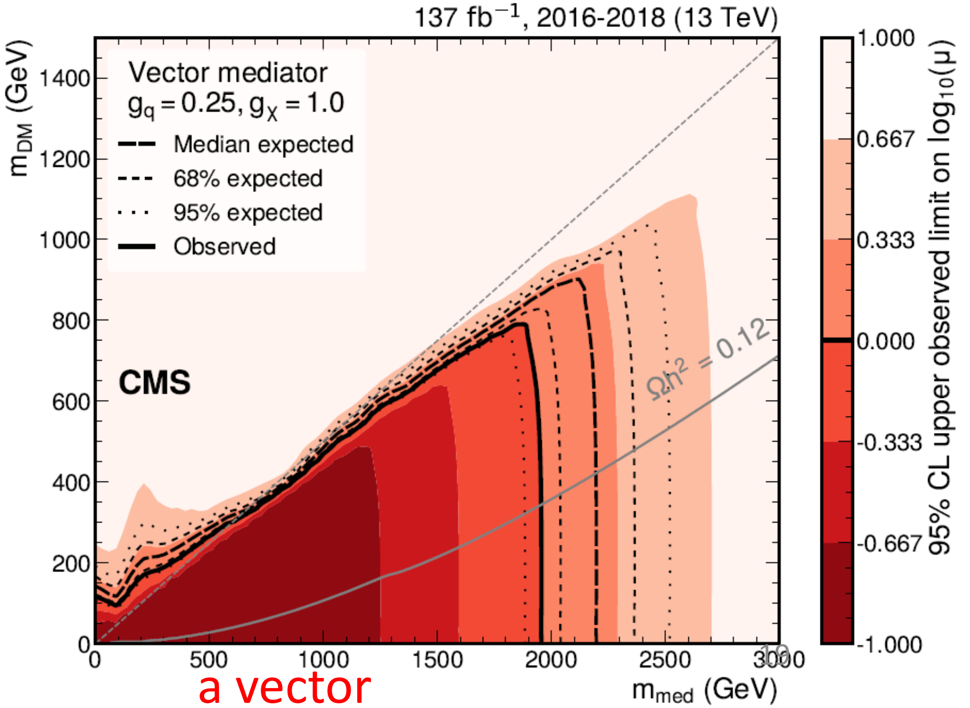


Observed exclusion reaches up to m_{med} = 1.95 TeV

Limits on **spin-1 dark matter mediators** are the most **restrictive** to date



an axial-vector

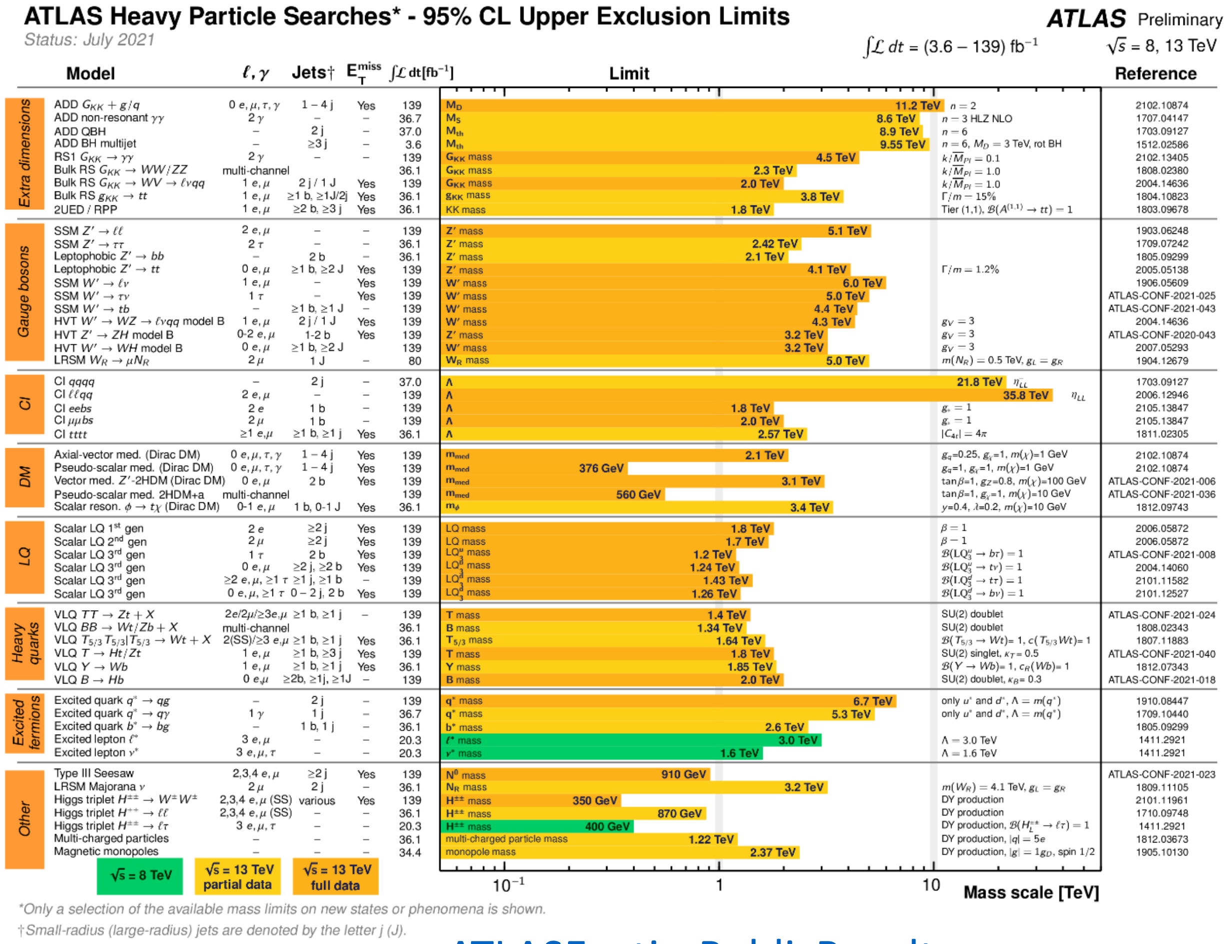


a vector

Summary

- **A large number of Beyond the Standard Model (SM) models** exist to cover the limitations of the SM : many of them being explored at the LHC

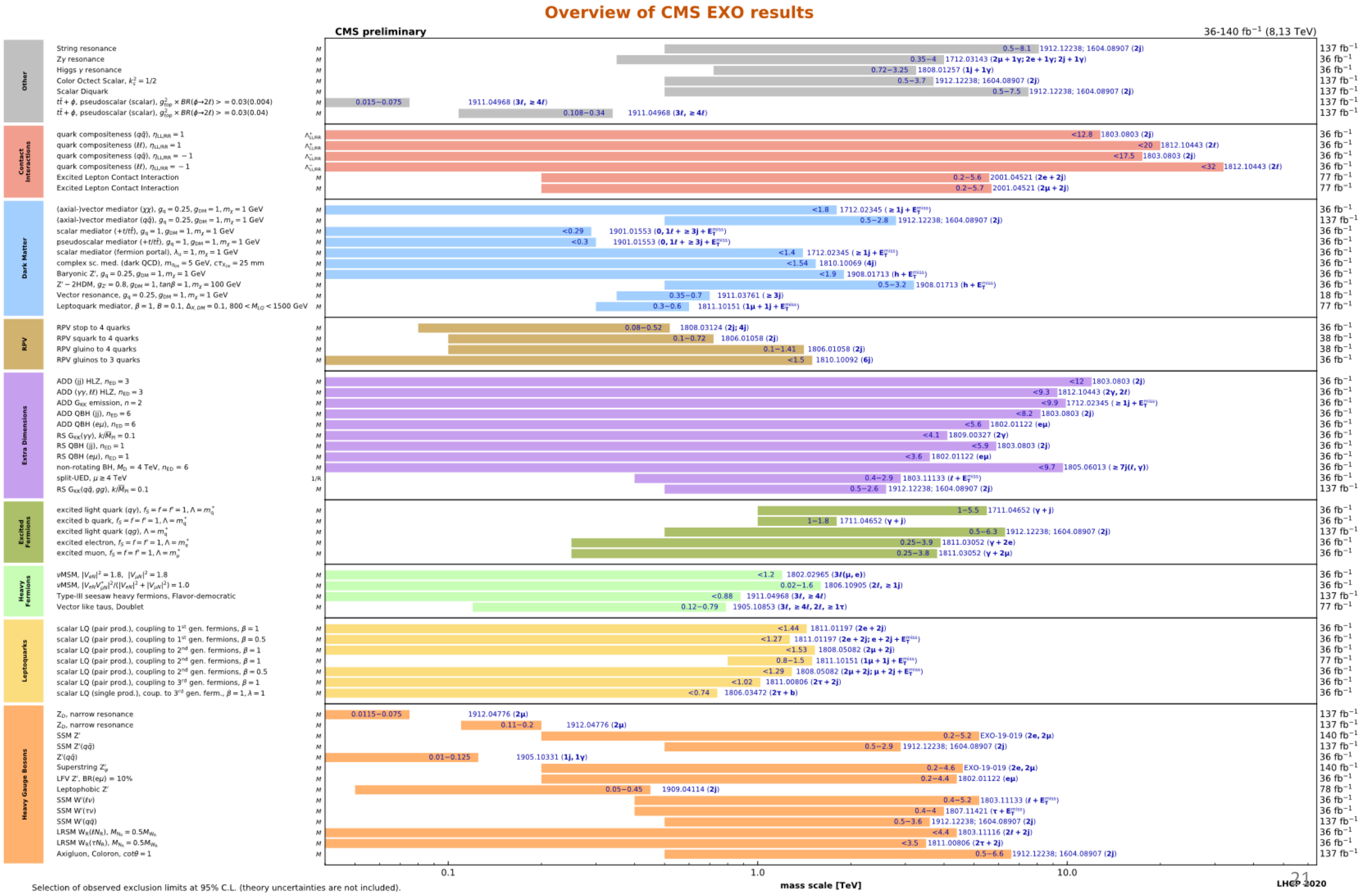
- **No significant sign of BSM observed so far**
  - ✓ Presented some models/signatures explored for **the first time**
  - ✓ Sensitivity with full Run 2 data significantly improving Run 1 result and early Run 2 data thanks to new analysis techniques
    → Extended phase-space excluded
  - ✓ Many more analyses ongoing!



ATLASExoticsPublicResults

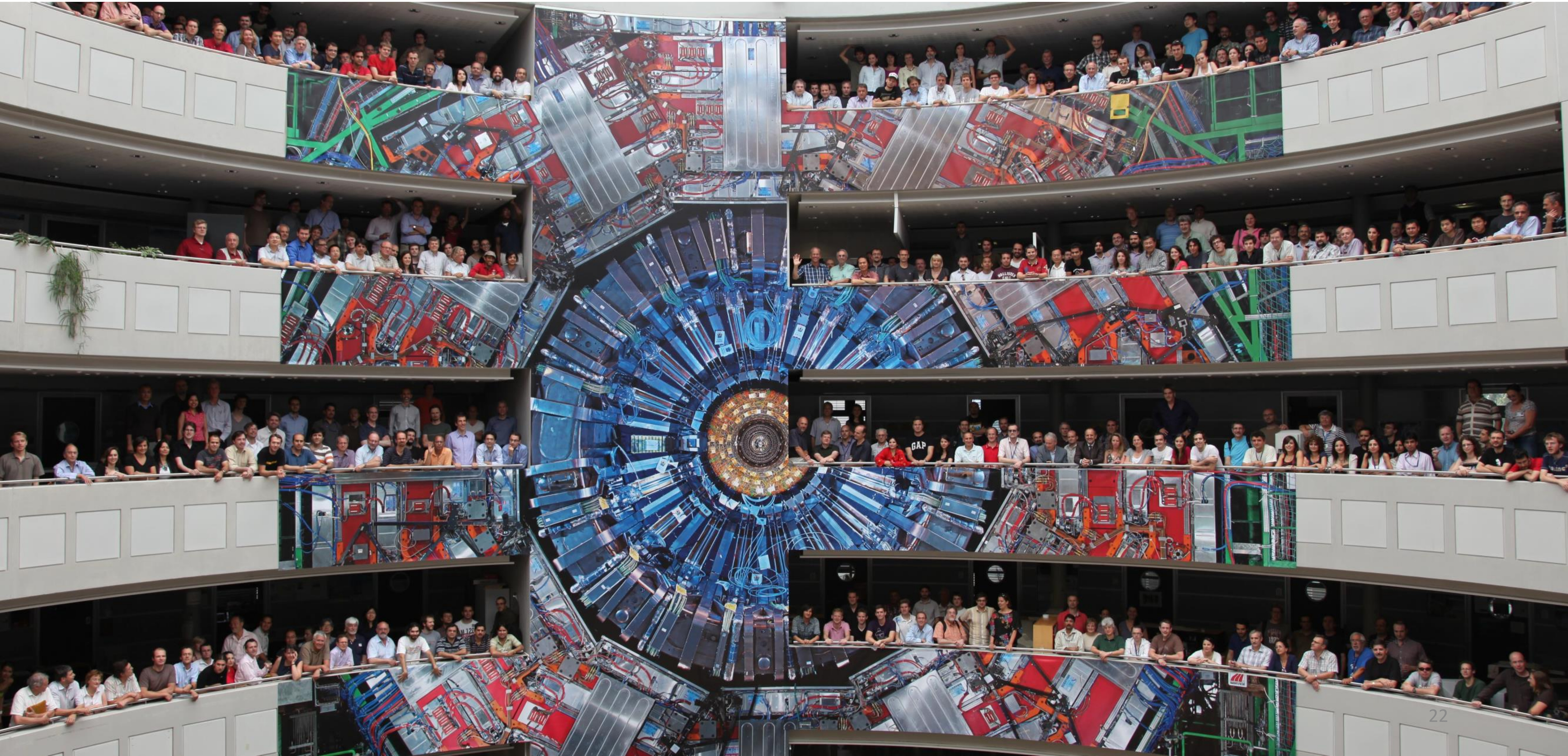
- **Run 3 is coming soon with:**
  - ✓ more data
  - ✓ new ideas (theory and experiment) to **probed uncovered phase-space**

CMS-EXO-Pub



Overview of CMS EXO results
CMS preliminary
36-140 fb^{-1} (8,13 TeV)
Other
Contact Interactions
Dark Matter
RPV
Extra Dimensions
Excited Fermions
Heavy Fermions
Leptoquarks
Heavy Gauge Bosons
0.1
1.0
10.0
mass scale [TeV]
LHCP 2020
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

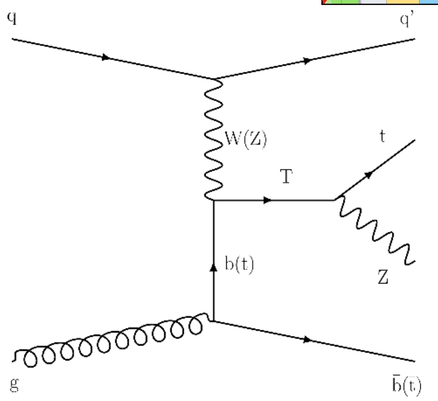
Thanks for your attention!



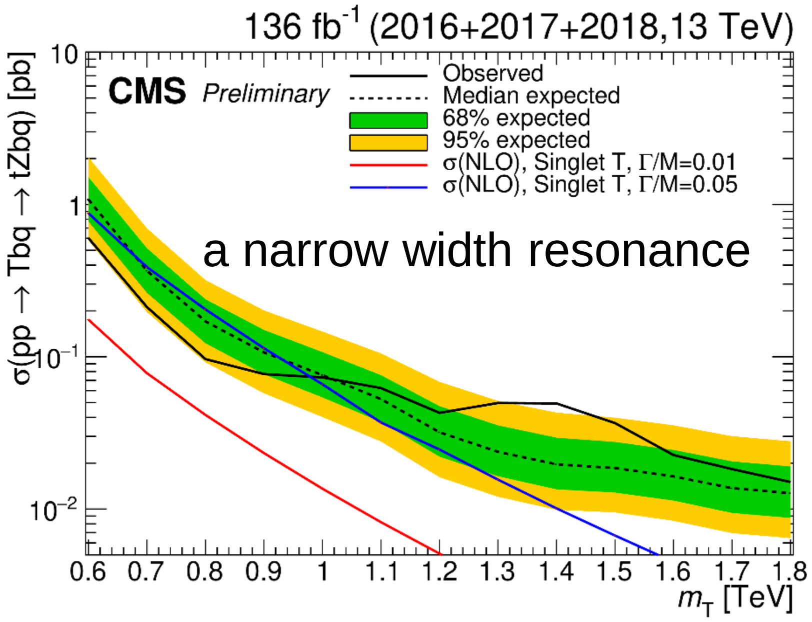
Backup slides

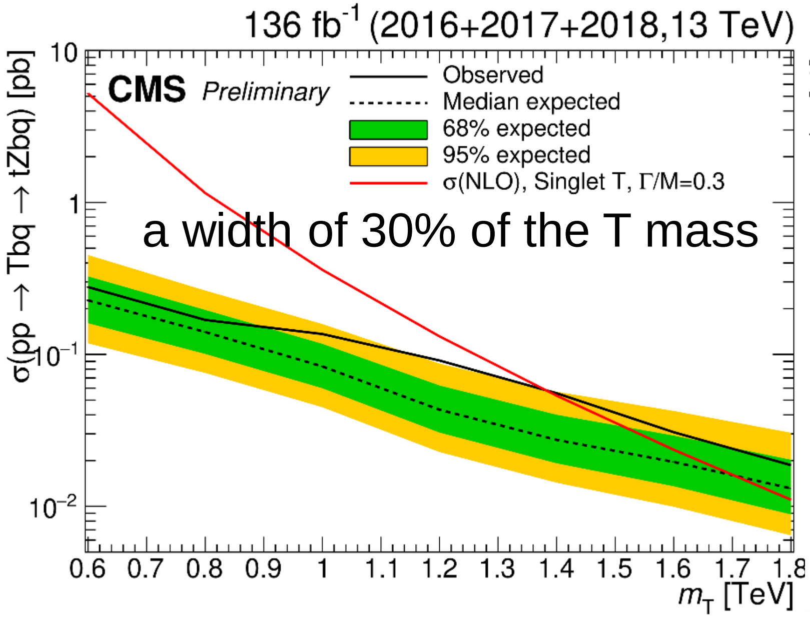
Single production of a VLQ T→tZ

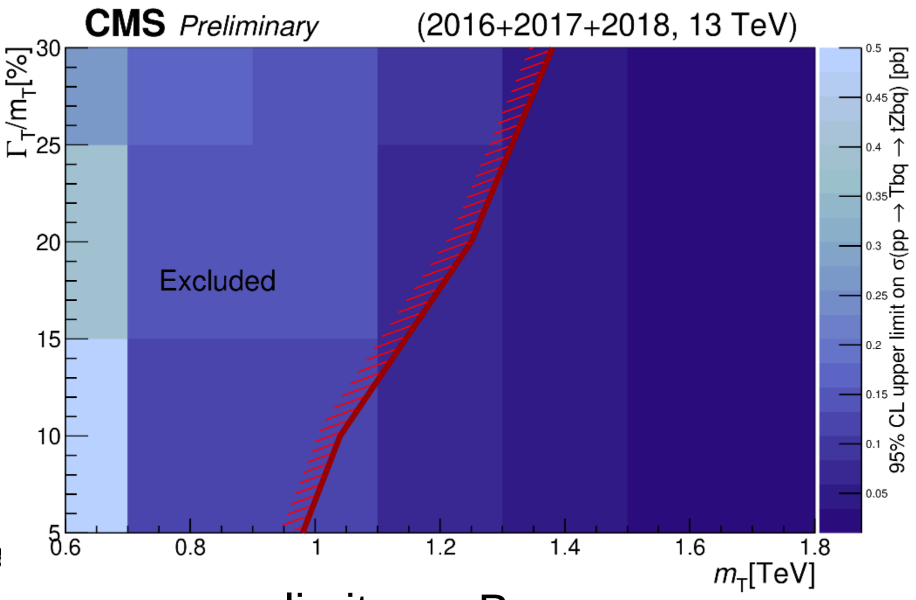
Top quark decaying hadronically and the Z boson decaying to neutrinos



- search is sensitive to a T quark mass between 0.6 and 1.8 TeV with decay widths ranging from narrow up to 30% of the T quark mass





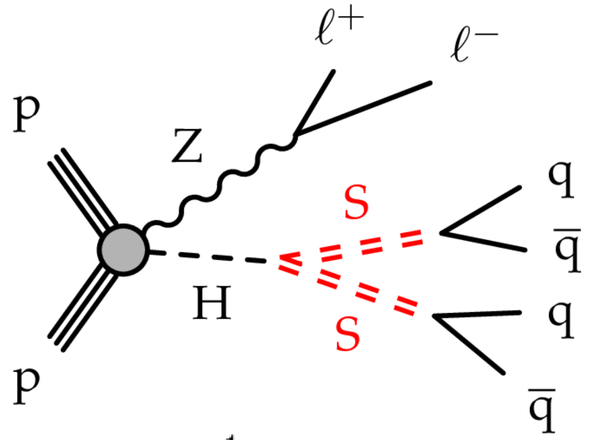


upper limit on σB

CMS-PAS-B2G-19-004

Long-lived Scalars : ZH → ZSS → 2l + 4q

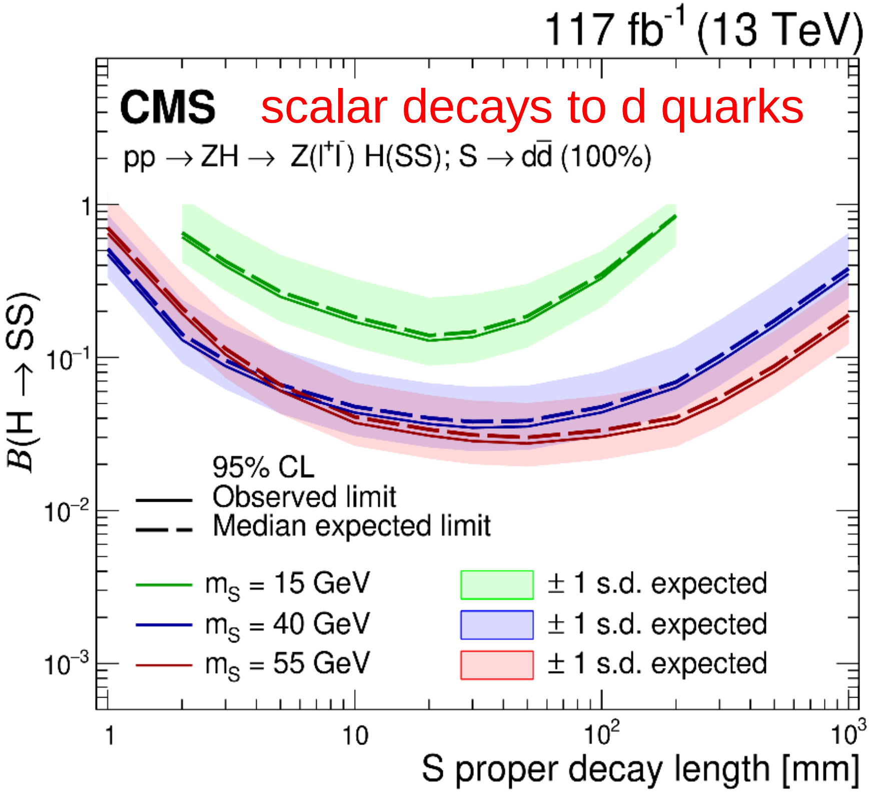
CMS: search for **long-lived particles (LLP) pairs decaying into jets, with associated Z production**

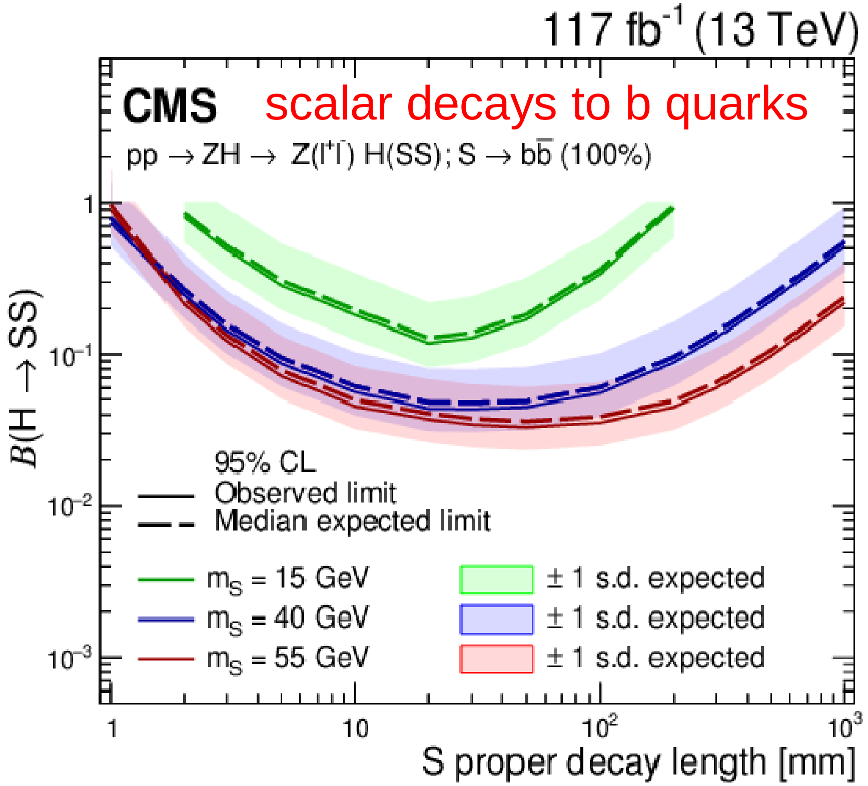


- Both **light (d)** and **heavy (b)** jets are considered
- Benchmark model: **Higgs decay to a pair of scalar LLPs**
  - ✓ Probing decay lengths from **1 mm to 1 m**
- **At least two displaced jets** (3 tracking-based displacement variables) + **2 leptons**

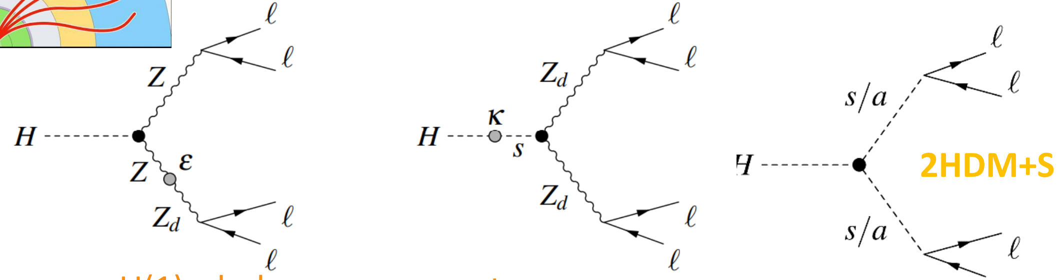
arXiv:2110.13218
[CMS-EXO-20-003]

Constrain **B<6%** for proper decay lengths of **10-100 mm** and for LLP masses **between 40 and 55 GeV**



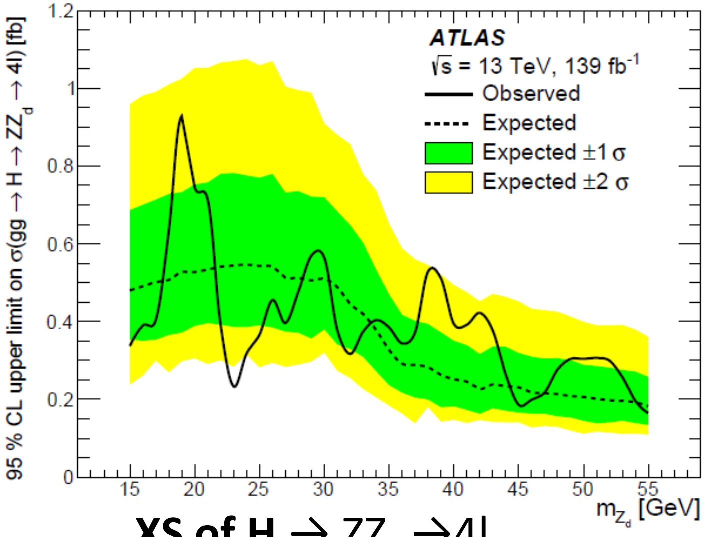


Exotic Higgs Decay H→XX/ZX→4l

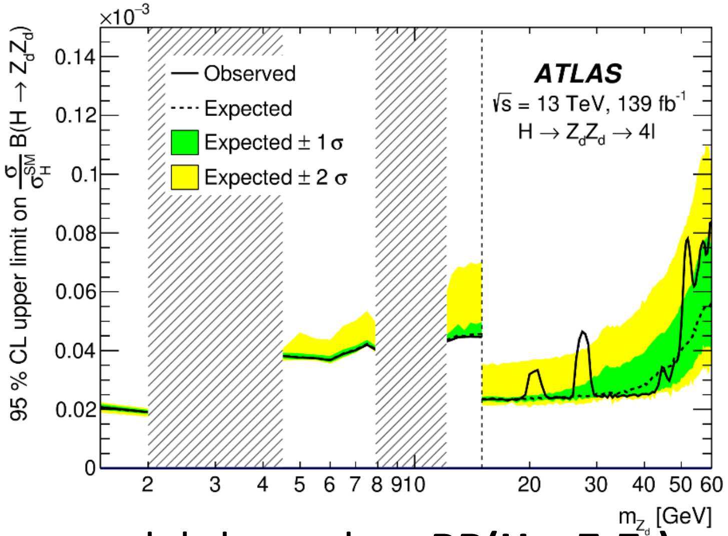


$U(1)_d$ dark gauge symmetry

- Consider X as **dark photon Z_d**, **dark Higgs *s*** or **pseudo-scalar *a***
- Different strategies for **ZX** and **XX** topologies
- Report **exclusions on cross section, branching fractions and dark photon model parameters**

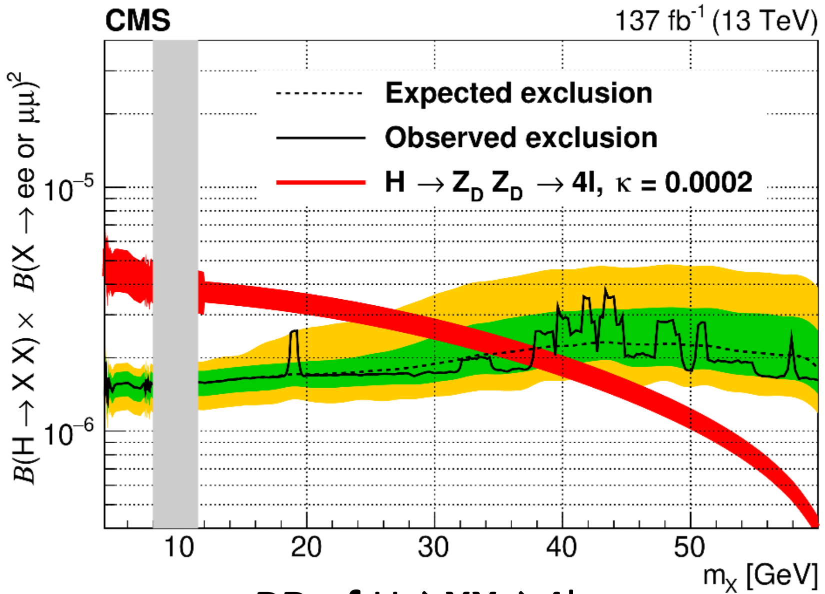


XS of H → ZZ$_d$ →4l

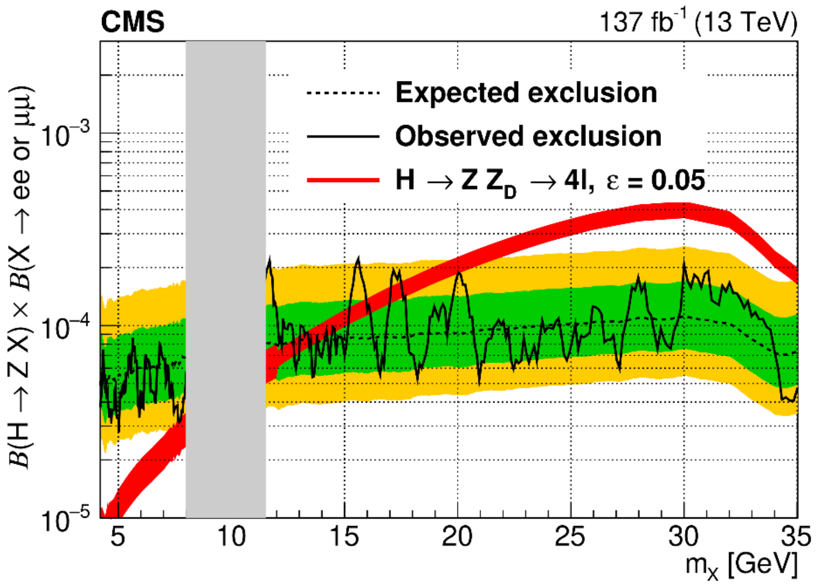


model-dependent **BR(H→Z_dZ_d)**

ATLAS: arXiv:2110.13673

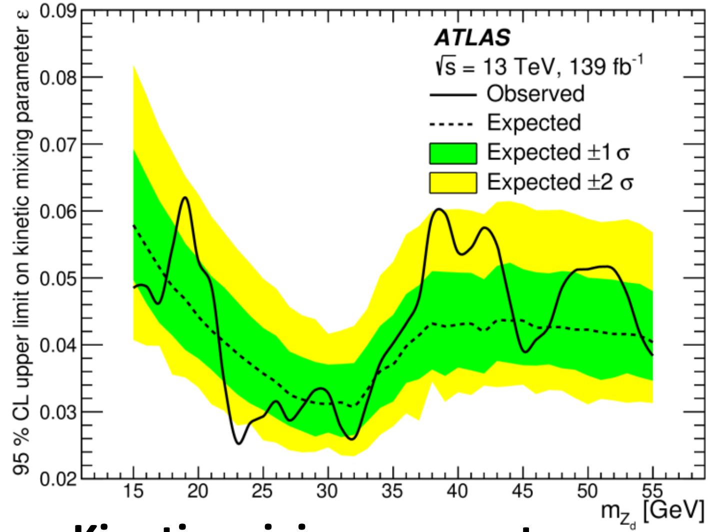


BR of H→XX→4l



BR of H→ZX→4l

CMS arXiv:2111.01299

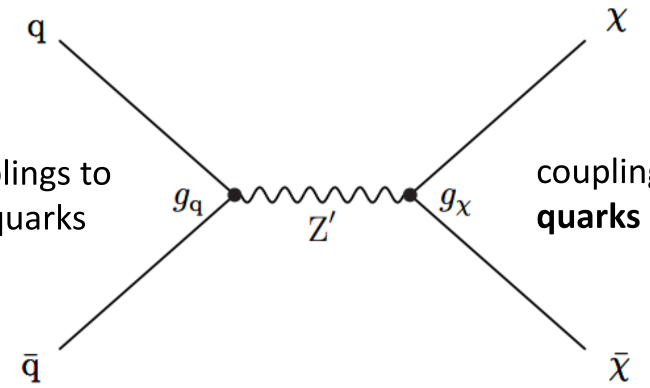


Kinetic-mixing parameter ε

Dark showers

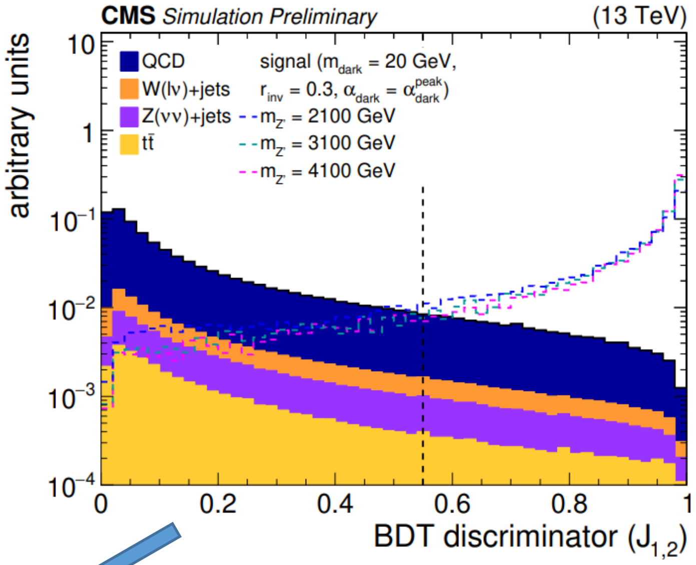
- CMS : search for **resonant production of strongly-coupled dark matter, for the first time at the LHC**
- **Benchmark**: hidden sector coupling to the SM via **a heavy leptophobic Z' mediator** arising from a broken U(1) symmetry
- Signature: **two "semi-visible" jets** (contain both visible matter and invisible dark matter), one of them aligned with MET
- **BDT** trained using **jet substructure** variables to distinguish between ***semi-visible jets*** from ***standard jets***

couplings to SM quarks

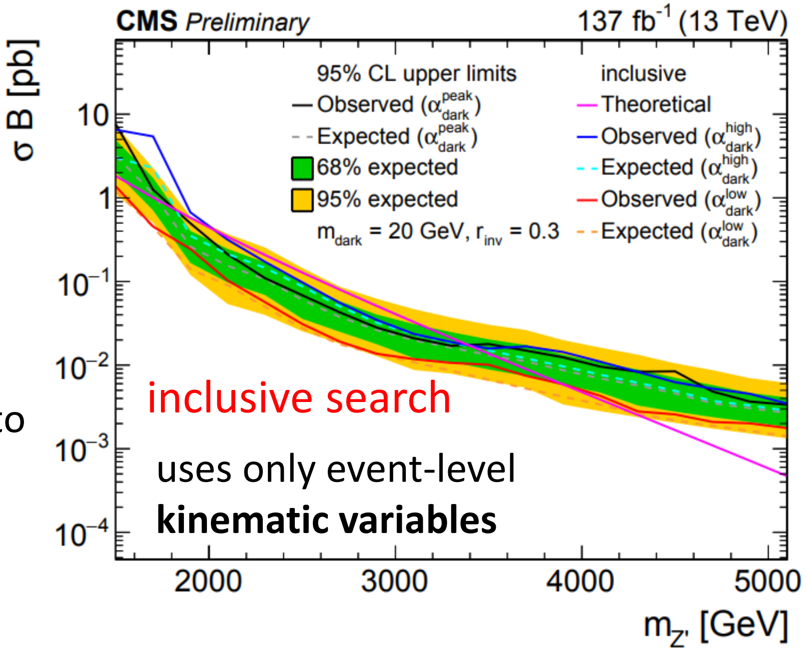


couplings to **dark quarks (dark hadrons)**

CMS-PAS-EXO-19-020

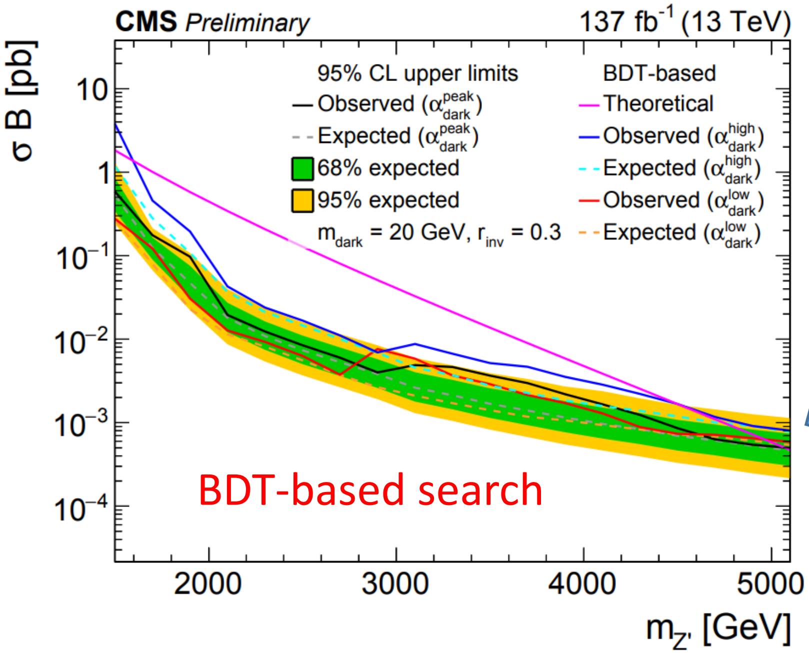


mediator masses up to **3.9 TeV** are excluded



inclusive search

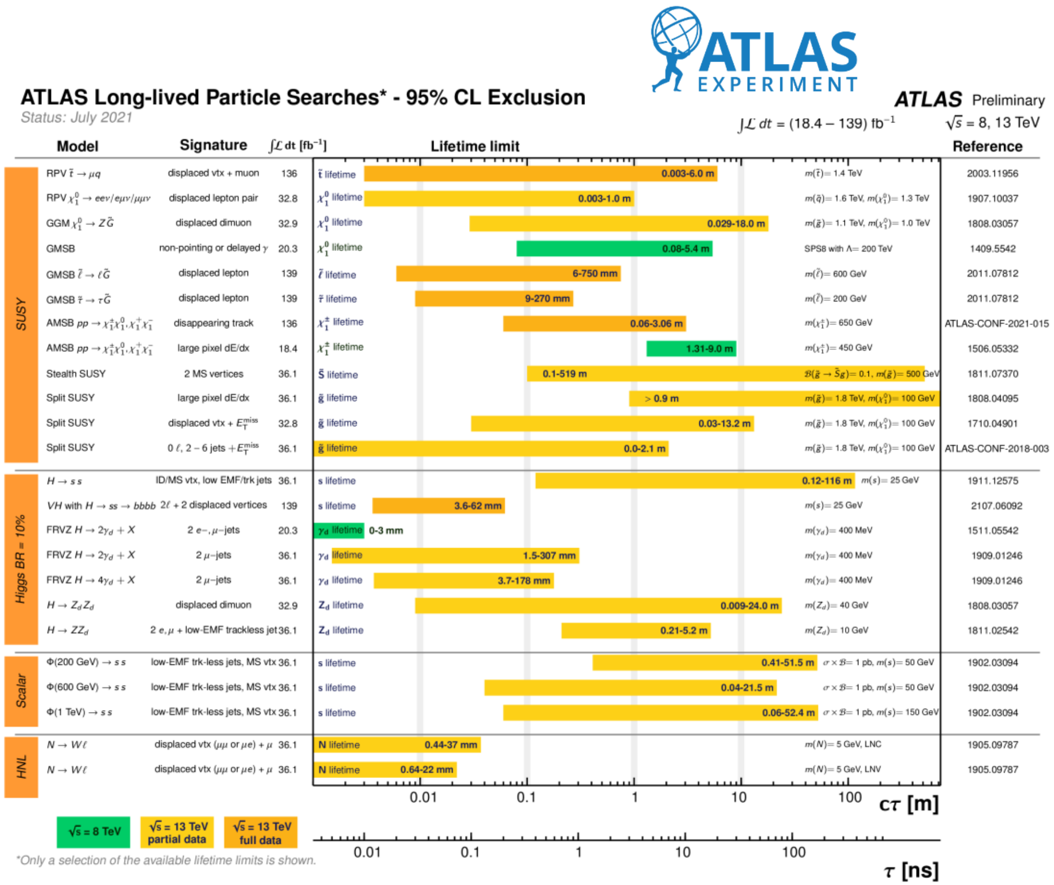
uses only event-level **kinematic variables**



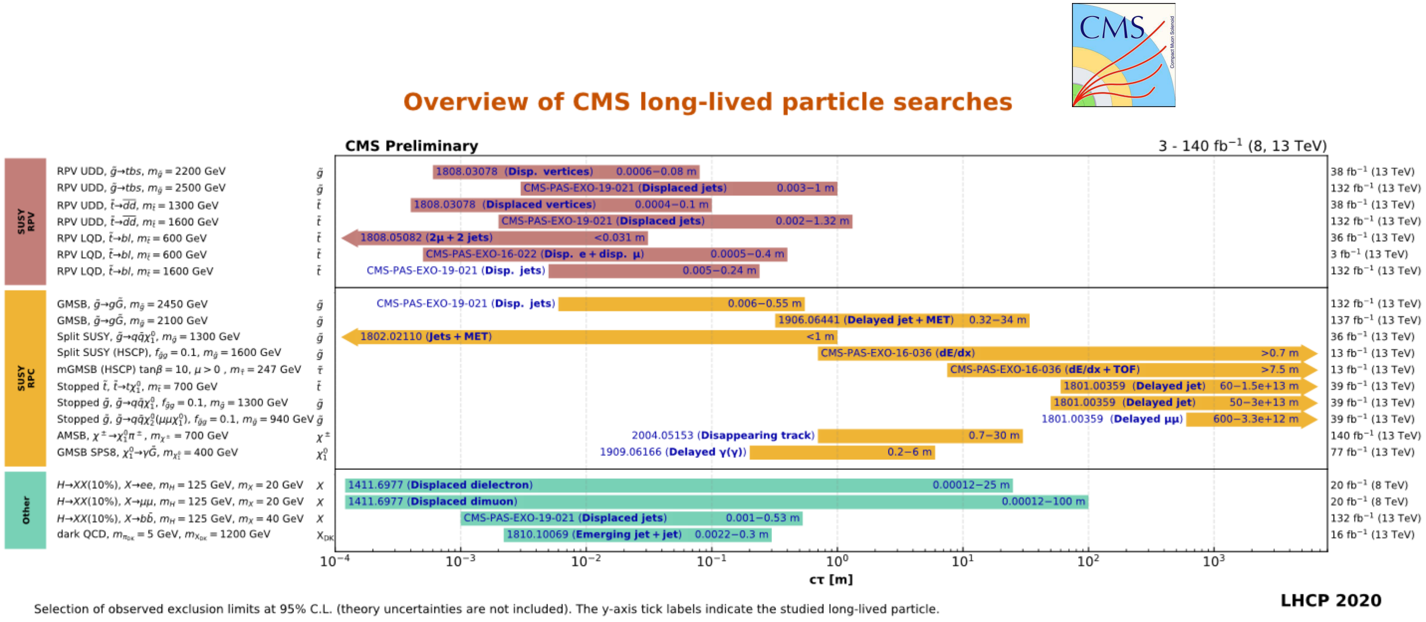
BDT-based search

mediator mass exclusion increases to **5.1 TeV**

Status of LLP searches at ATLAS and CMS



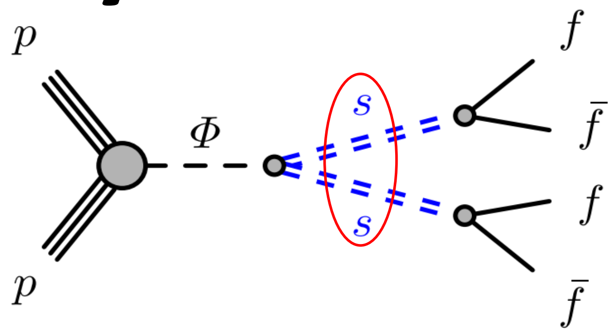
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-033/

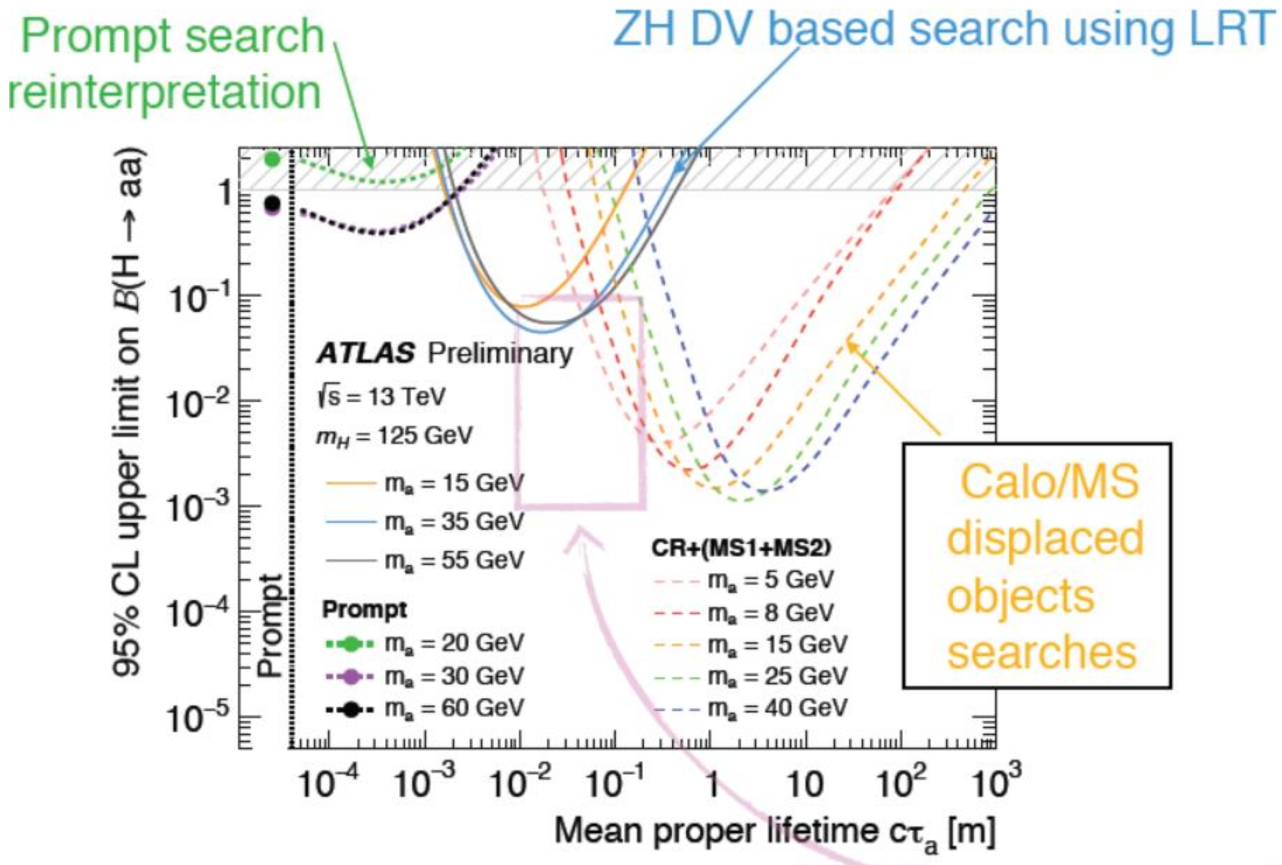


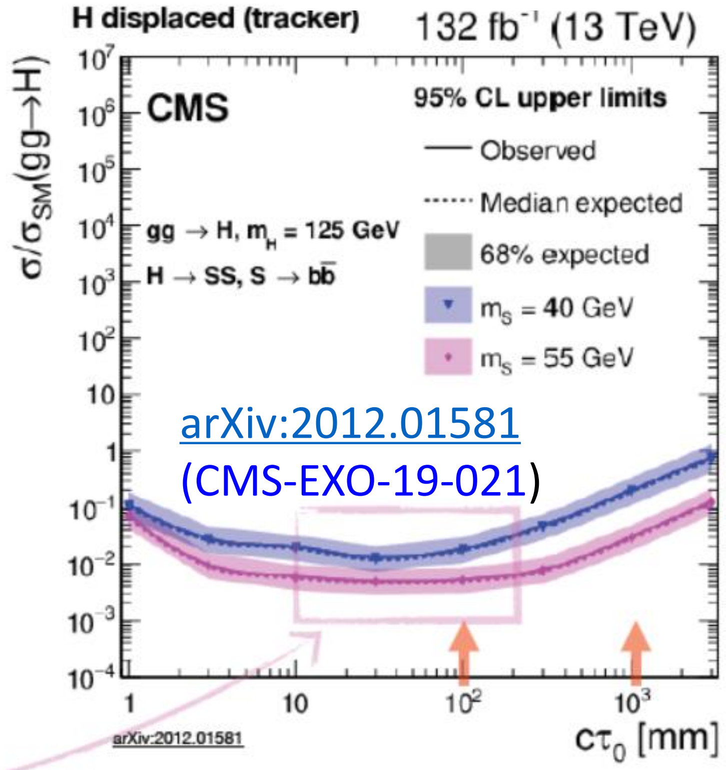
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

Long-lived Scalars : Complementary searches

➢ Searches for signatures in **different subdetectors** can be complementary







arXiv:2012.01581 (CMS-EXO-19-021)

CMS using displaced jets

Can expand the lifetime coverage by using multiple search strategies