



Searches for Exotica

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on behalf of the ATLAS, CMS and LHCb collaborations

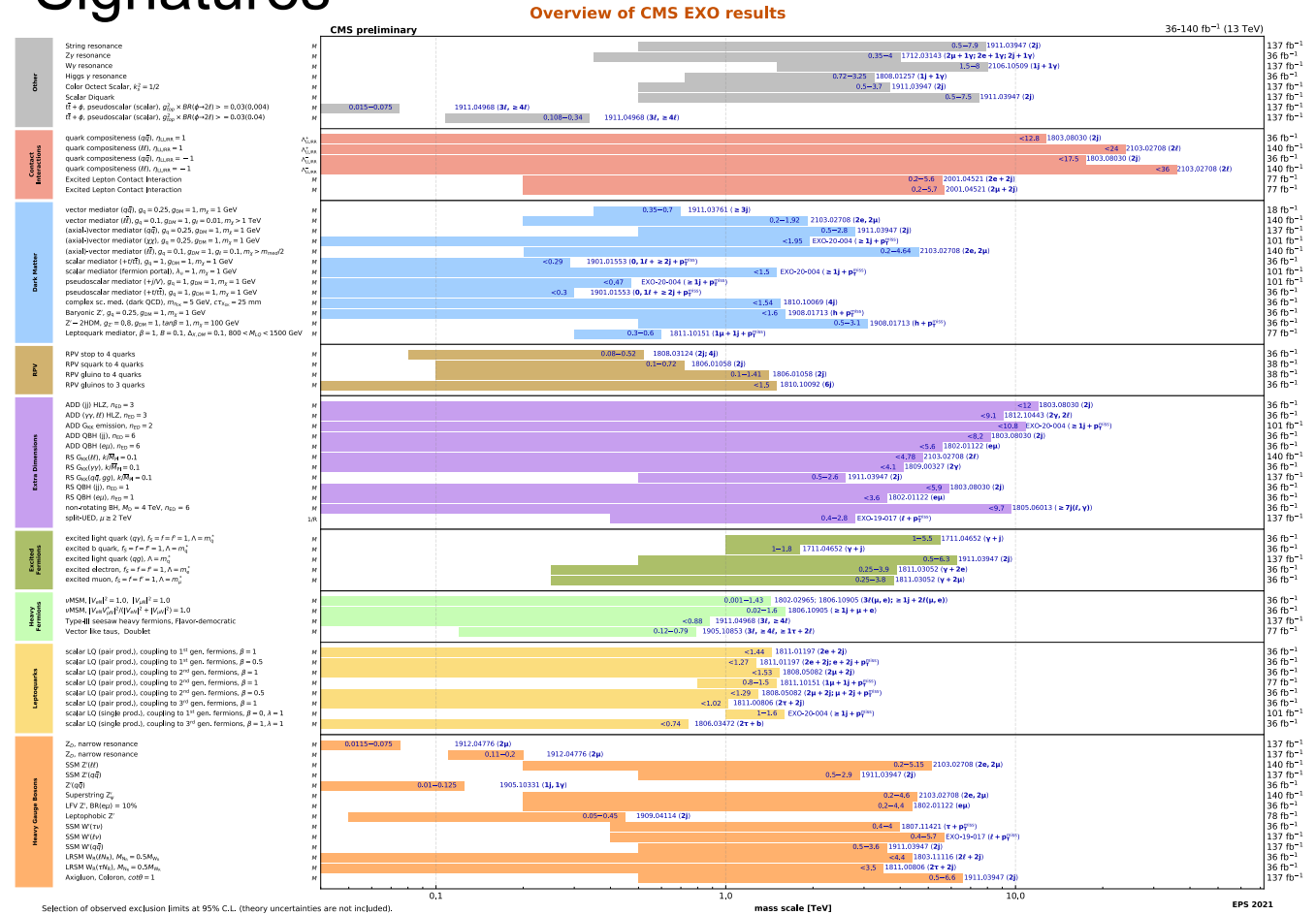


Introduction

- Searches for Exotica at LHC = leave no stone unturned
 - (Exotic) BSM scenarios
 - (Exotic) detector signatures
 - (Exotic) analysis techniques

Signatures

Models



BSM theories in plenary talk by Anson Hook

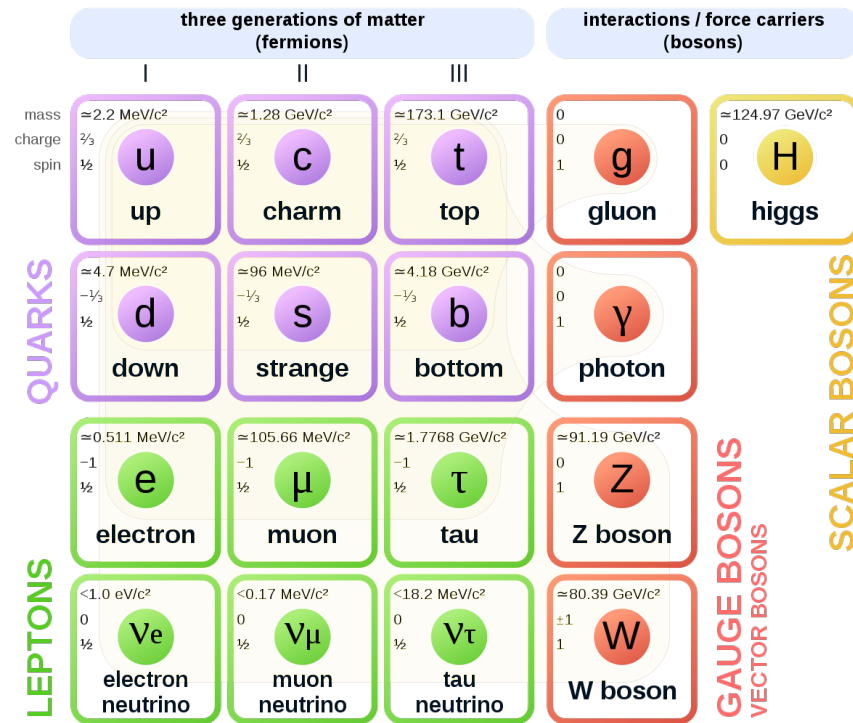
(+ CMS B2G + ATLAS Exotica + ATLAS HDBS + LHCb)

Introduction

- Searches for Exotica at LHC = leave no stone unturned
 - (Exotic) BSM scenarios
 - (Exotic) detector signatures
 - (Exotic) analysis techniques
- Where are we?
 - LHC Run2 data at 13 TeV collected 2015-2018
 - EPS2019: First results with full Run2 dataset (139/fb): simple resonances, SUSY
 - O(100) searches since then, O(100) to come
- 27 new search results for EPS2021
 - [ATLAS EXOT, HDBS, SUSY public results](#)
 - [CMS EXO, B2G, SUSY public results](#)
 - [LHCb QCD, Electroweak, Exotica public results](#)
- Focus of today:
 - Overview of BSM scenarios and signatures
 - New routes explored in exotic searches
 - New results

Outline

Standard Model of Elementary Particles



+

New fermions

New bosons

Dark matter, dark sector

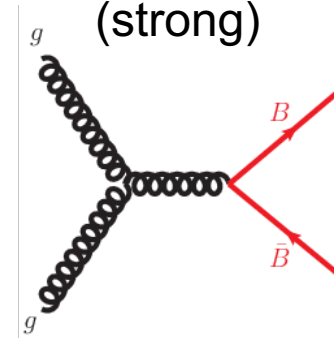
SUSY partners

Long-lived particles

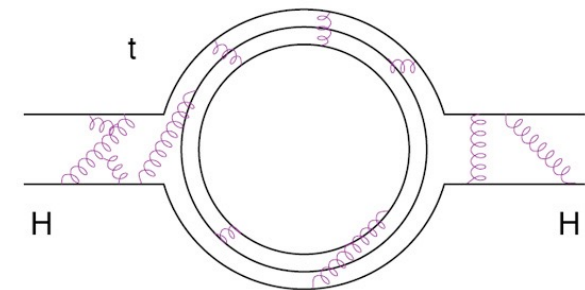
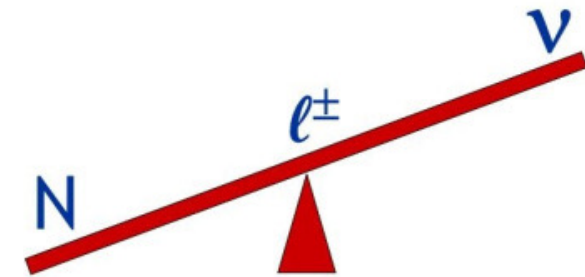
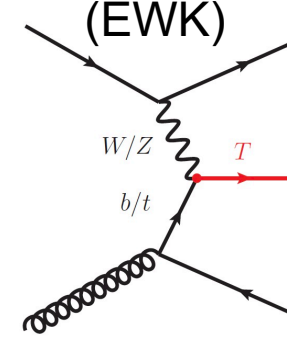
New fermions

- **Vector-like quarks (VLQ)**
 - L/R-handed transform same
 - Can mix with 3rd gen SM partners to regulate Higgs mass
- **Heavy neutral leptons/neutrinos (HNL)**
 - Can generate small neutrino mass via seesaw mechanism
- **Excited states of quarks/leptons (q^* , l^*)**
from compositeness
 - Composite Higgs can regulate Higgs mass

Pair production
(strong)



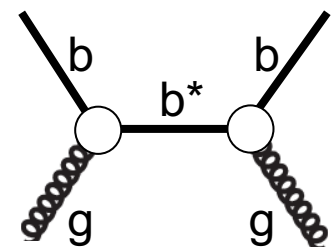
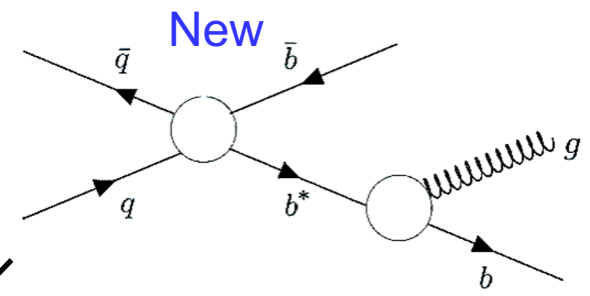
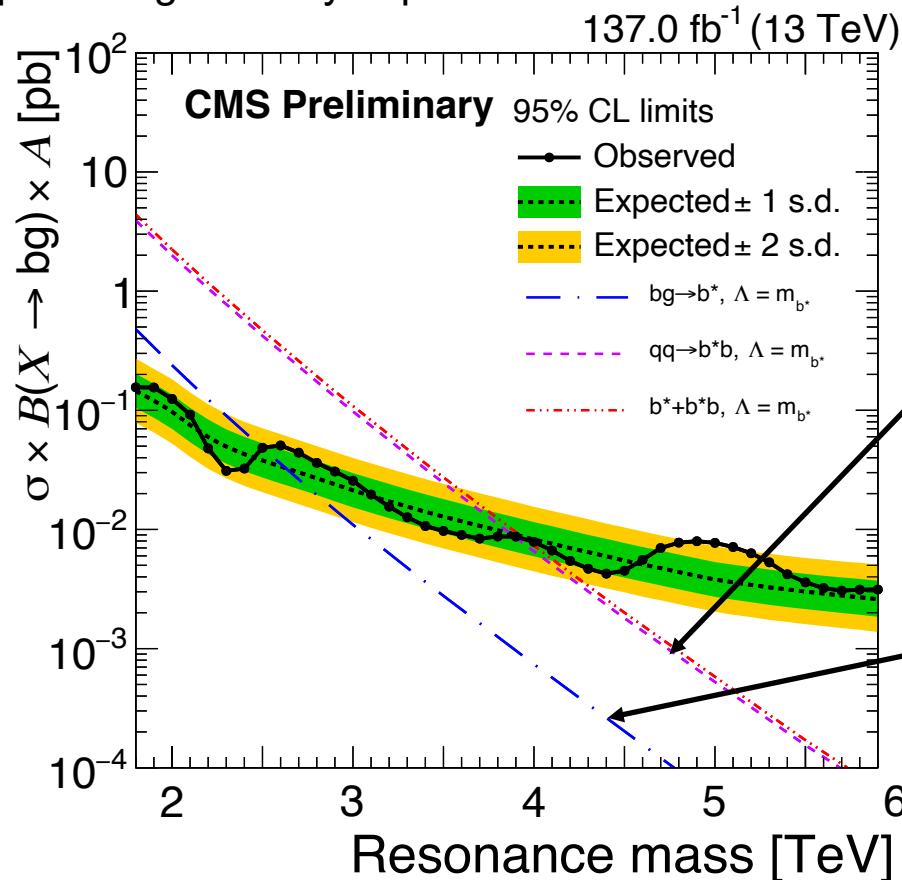
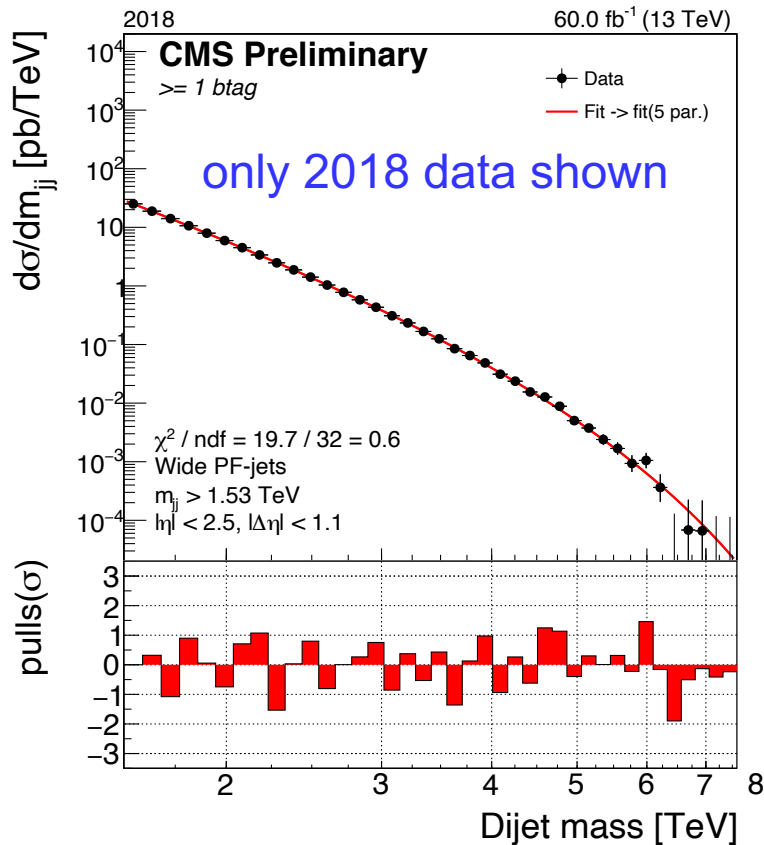
Single production
(EWK)



Excited bottom quark b^* in dijets



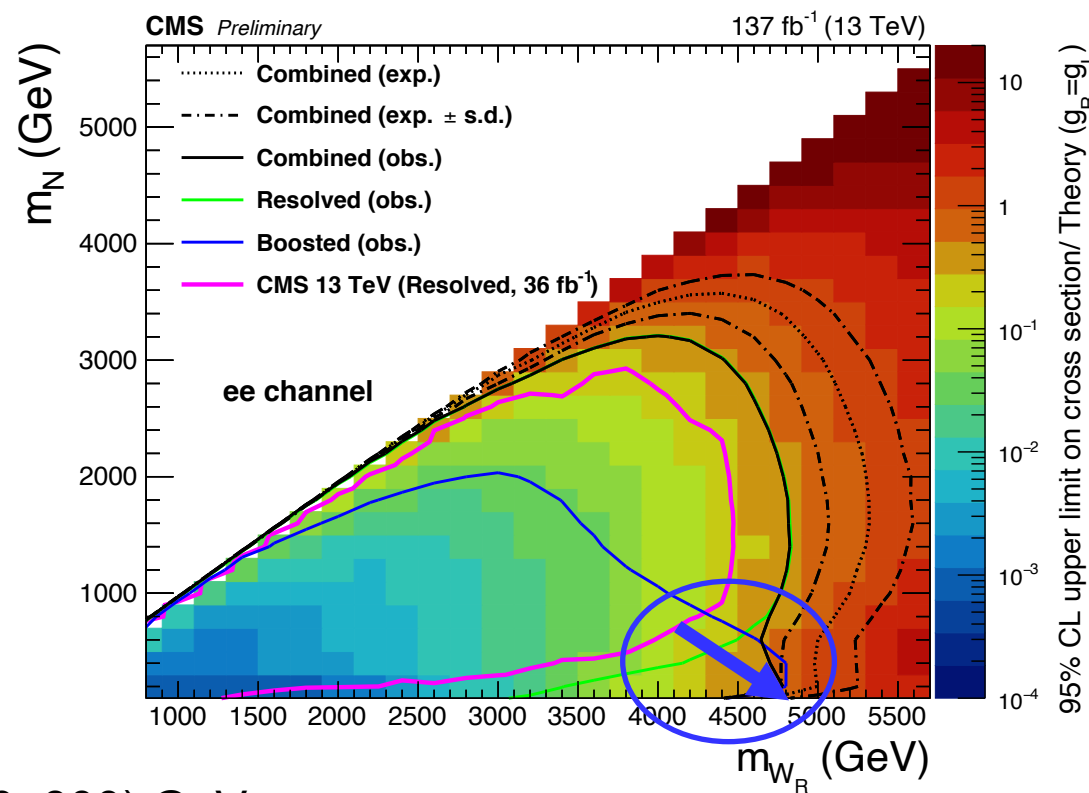
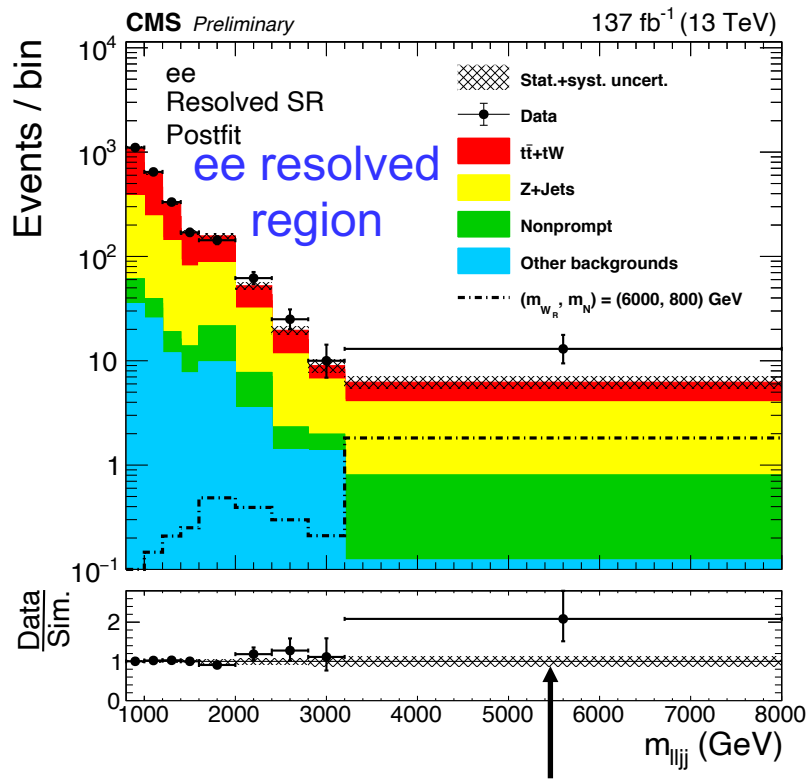
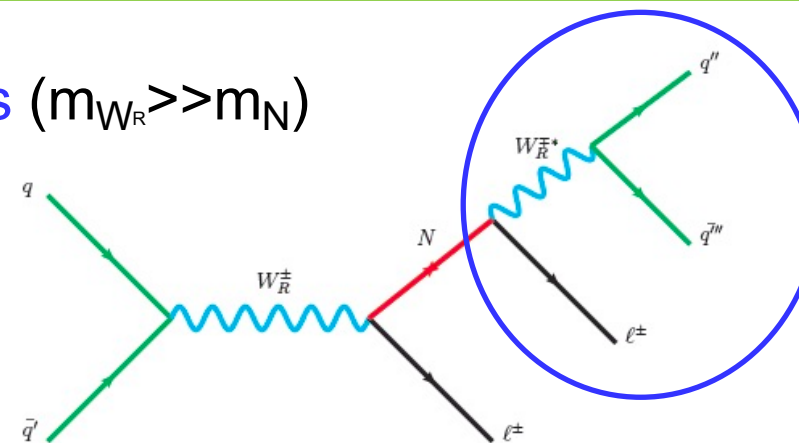
- Search for resonances on smoothly falling b-tagged dijet mass spectrum
 - DNN-based b-tag improves background rejection
 - Require at least one b-tag for $b^* \rightarrow bg$ signal
 - Background estimated from s+b fit with smooth functional form
- Most stringent b^* limit >4 TeV
 - Including b^* production process $qq \rightarrow bb^*$ significantly improves limits



Z' → bb search as well

Heavy neutral lepton and heavy W_R in $llqq$

- Target **resolved $lljj$ and boosted ll (new!) topologies** ($m_{W_R} \gg m_N$)
 - Identify boosted decay by lepton subjet fraction
 - 4 event categories $ee/\mu\mu$ resolved/boosted
 - tt yield and Z +jet shape constraint by control region
- **Significantly improved sensitivity for $m_N < 0.5$ TeV**



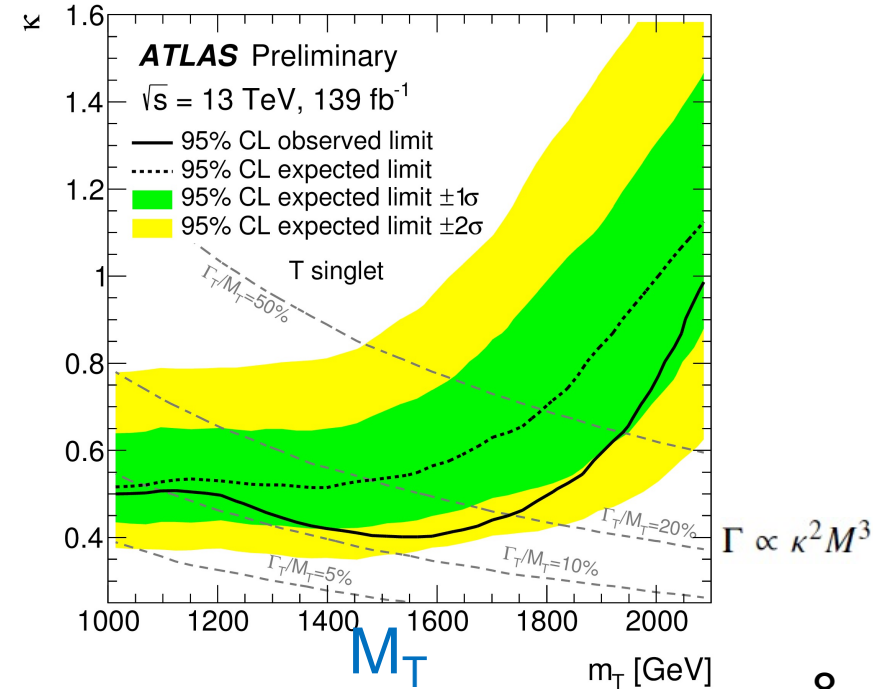
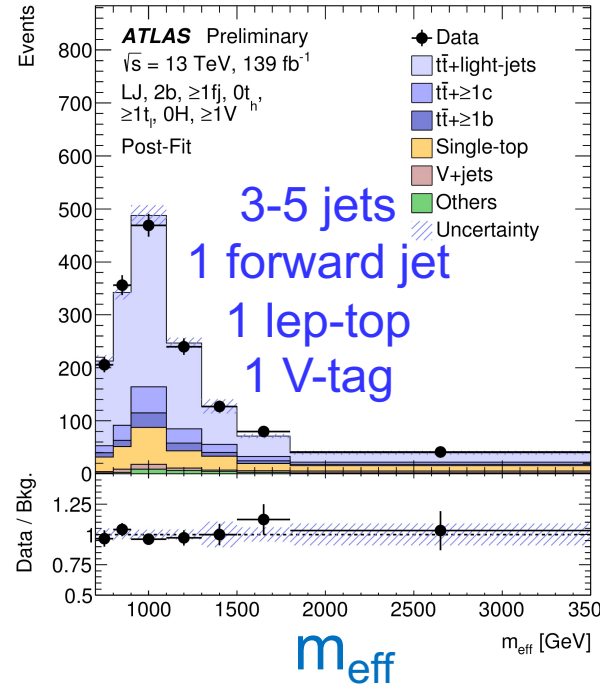
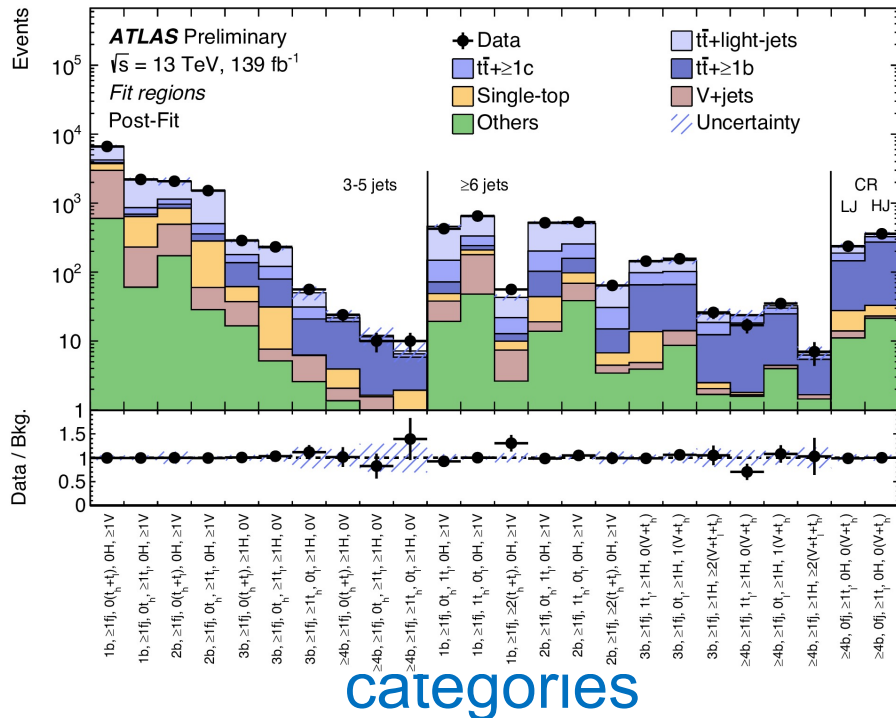
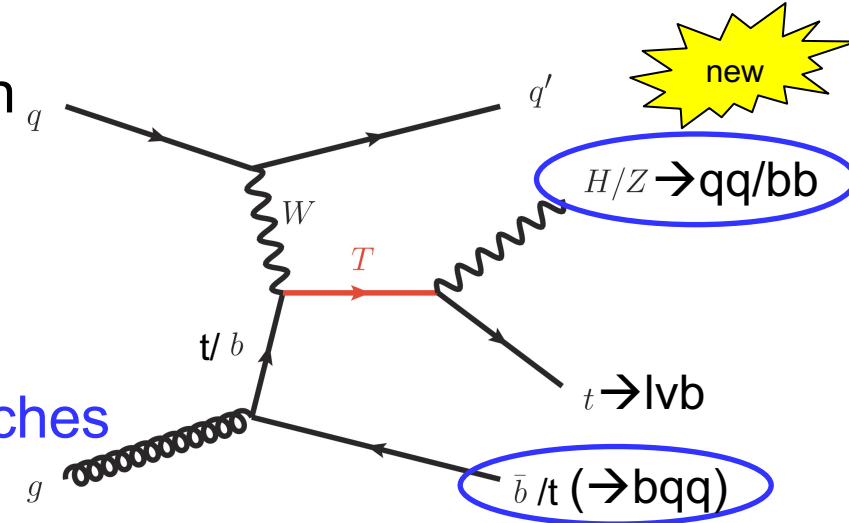
Local (global) 2.95σ (2.78σ) for $(m_{W_R}, m_N) = (6000, 800)$ GeV

Single vector-like T \rightarrow tH/tZ in lv+jets

- Target **resolved and boosted jet topologies** with one lepton

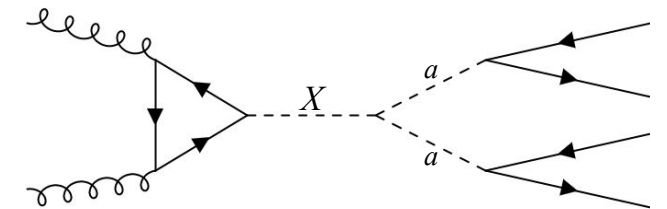
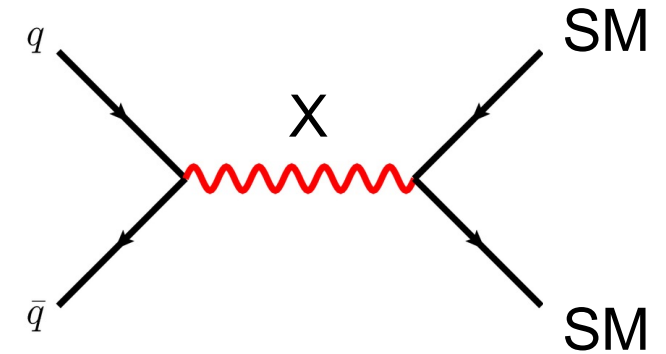
- Categorize events according to multiplicities:
 - jet, b-tag, forward-jet, lep-top, top-tag, H-tag, V-tag
- Search for excess in scalar sum of object p_T (m_{eff})
- Top and V+jet background reweighted data-driven vs. N_{jet} and m_{eff}
- Universal coupling strength $\kappa > 0.5$ excluded for $m_T < 1.8$ TeV

- Significantly improved limit w.r.t. previous single VLT searches**



New bosons

- Spin-0 h, H, A, H^{\pm} in 2HDM
 - Simplest BSM extension of SM Higgs sector
- Spin-1 W'/Z' : in many models, e.g. composite Higgs
 - Possible solution to hierarchy problem
 - Benchmark model: Heavy vector triplet ($m_{W'} \sim m_{Z'}$)
- Spin-2 gravitons, spin-0 radions in extra dimension models
 - Possibly solution to hierarchy problem
- Axion-like-particles (spin-0 pseudoscalar)
 - Specific case of axion is solution to Strong-CP-problem
 - Dark matter candidate
- Leptoquarks (spin-0/1)
 - Possible explanation for LHCb flavour anomalies



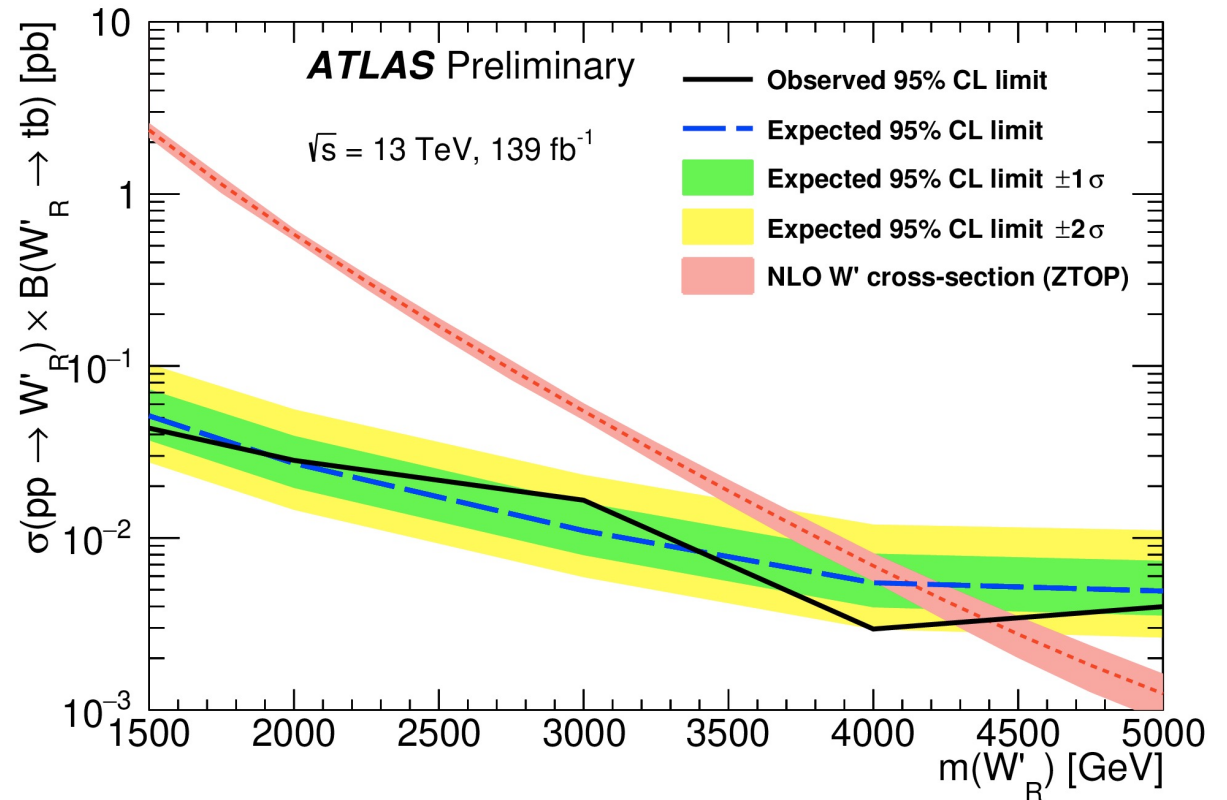
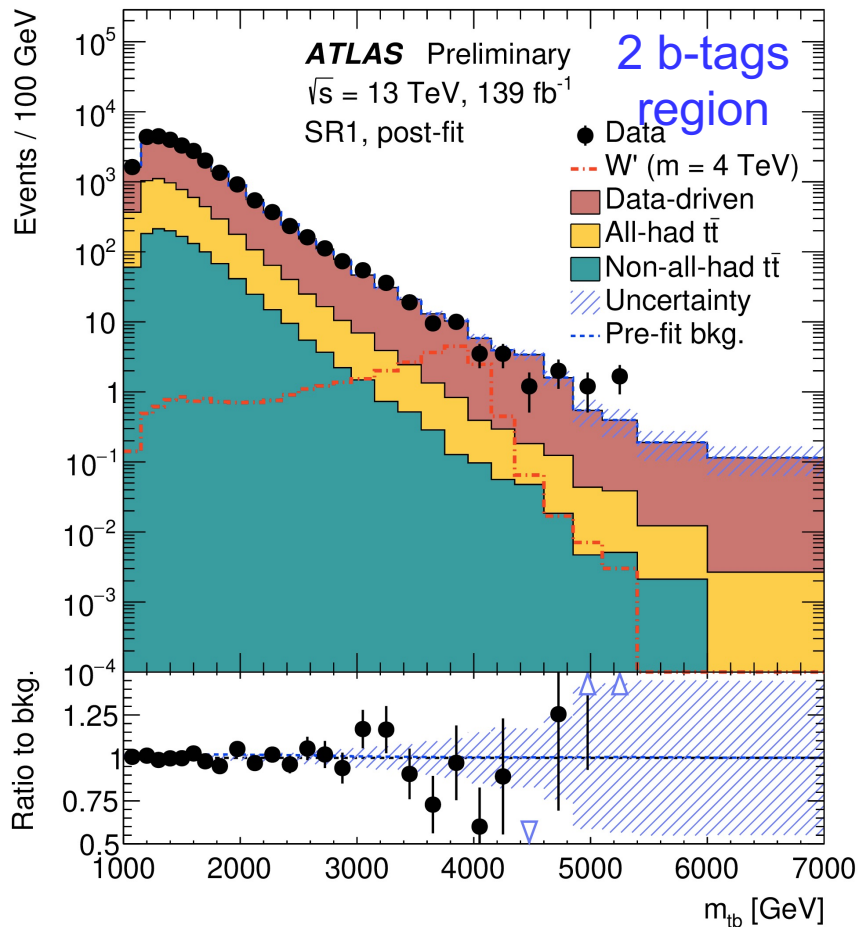
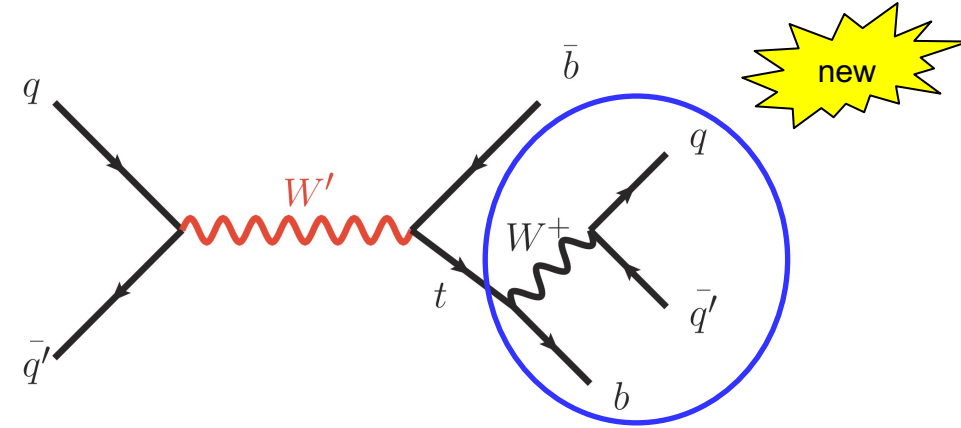
WWW resonance (CMS-PAS-B2G-21-002)
Charged Higgs in $t \rightarrow H^{\pm} b$ ([ATLAS-CONF-2021-037](#))
 $X \rightarrow aa \rightarrow 4\text{gamma}$ (CMS-PAS-HIG-21-003)



Plenary talk by Paula Alvarez Cartelle (Thu)

$W' \rightarrow tb$ resonance in all-jets final states

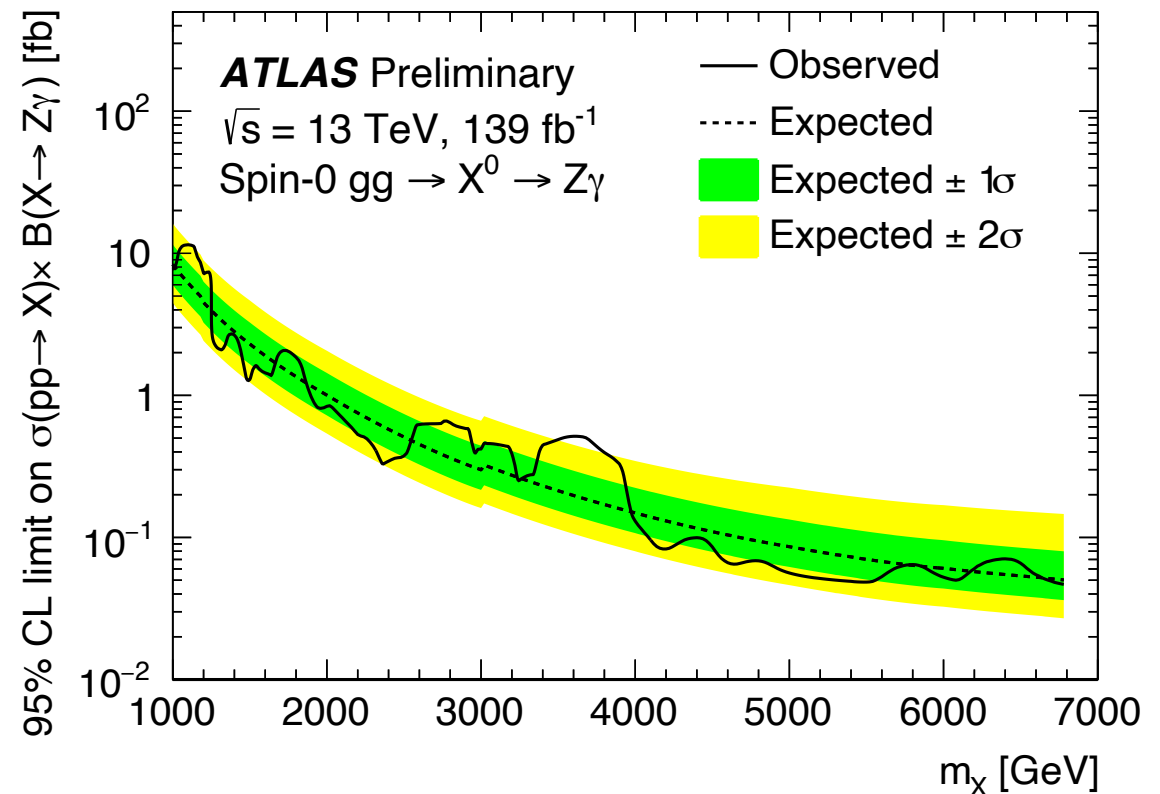
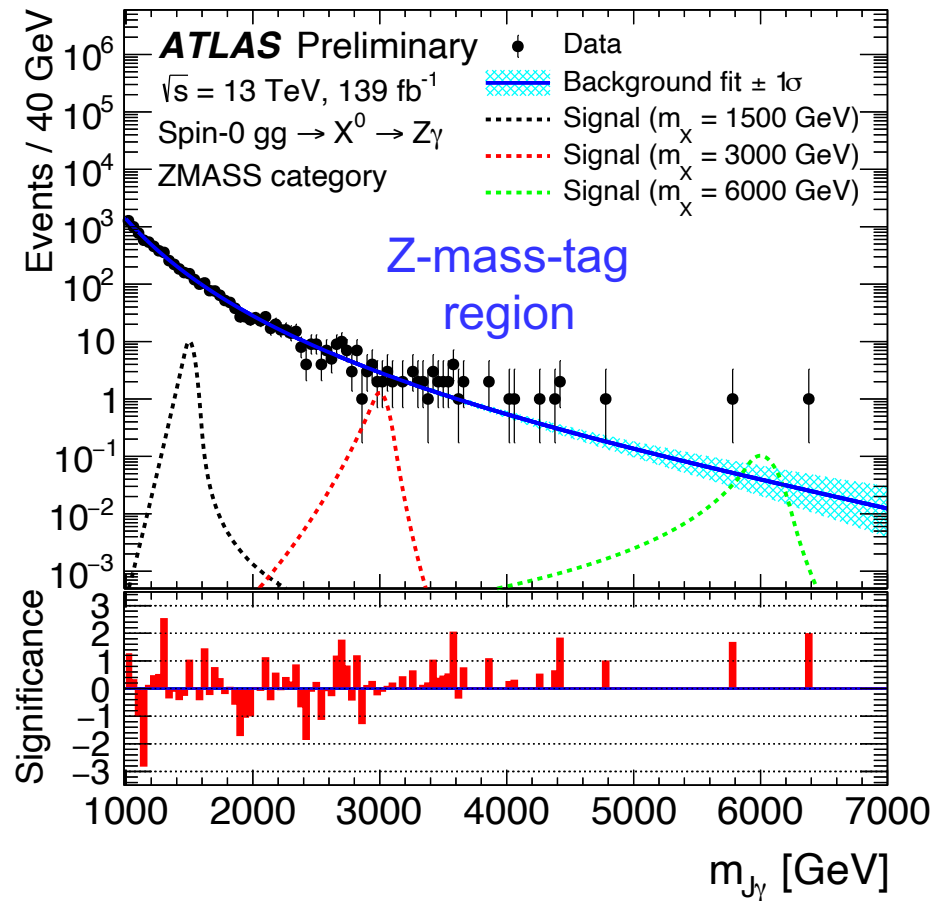
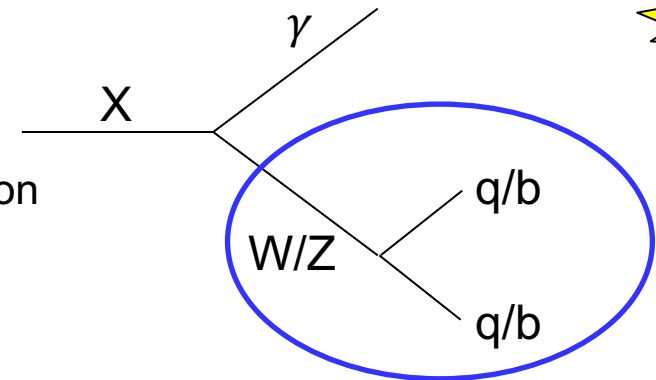
- Identify events with **DNN top tagger and b-tagger**
 - Signal event categories with 1 and 2 b-tags
 - Data driven background estimate from regions with looser b/top-tags
- 4.4 TeV most stringent limit to date**



Heavy resonance $X \rightarrow W\gamma/Z\gamma$ in γ +jet

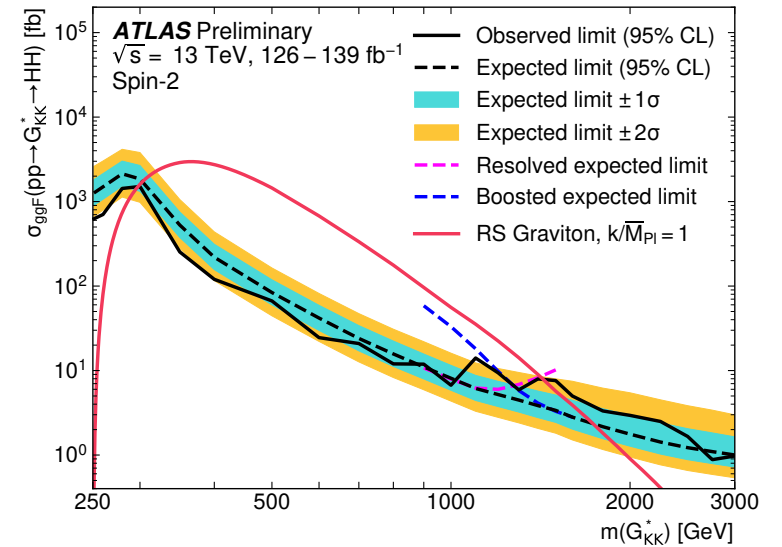
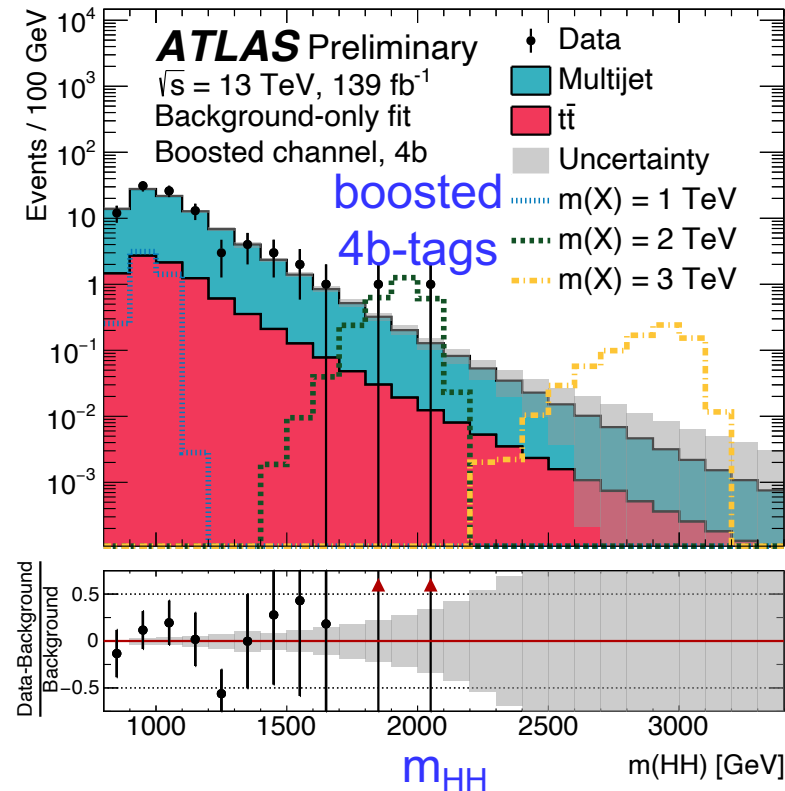
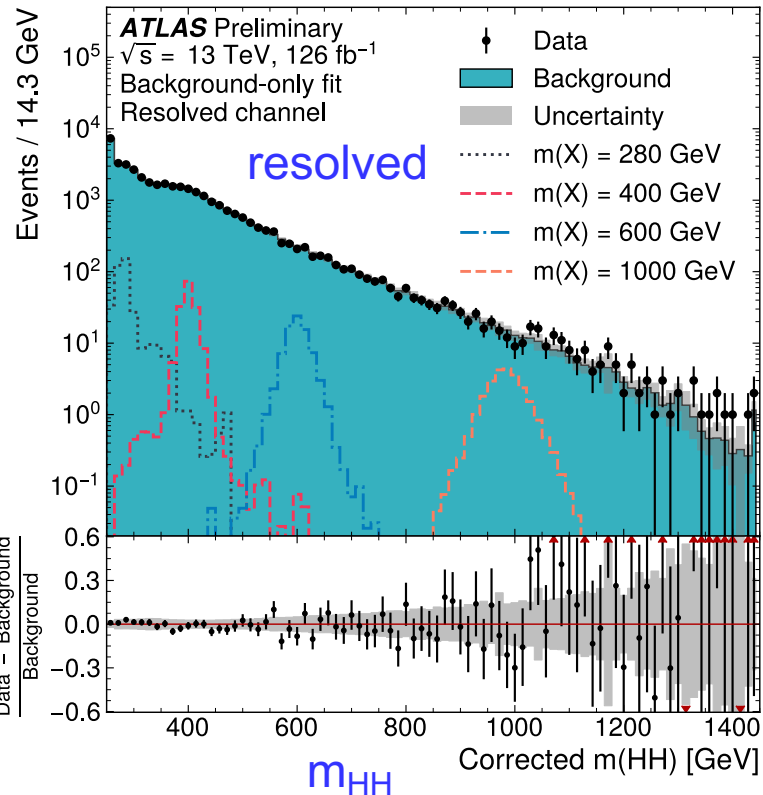
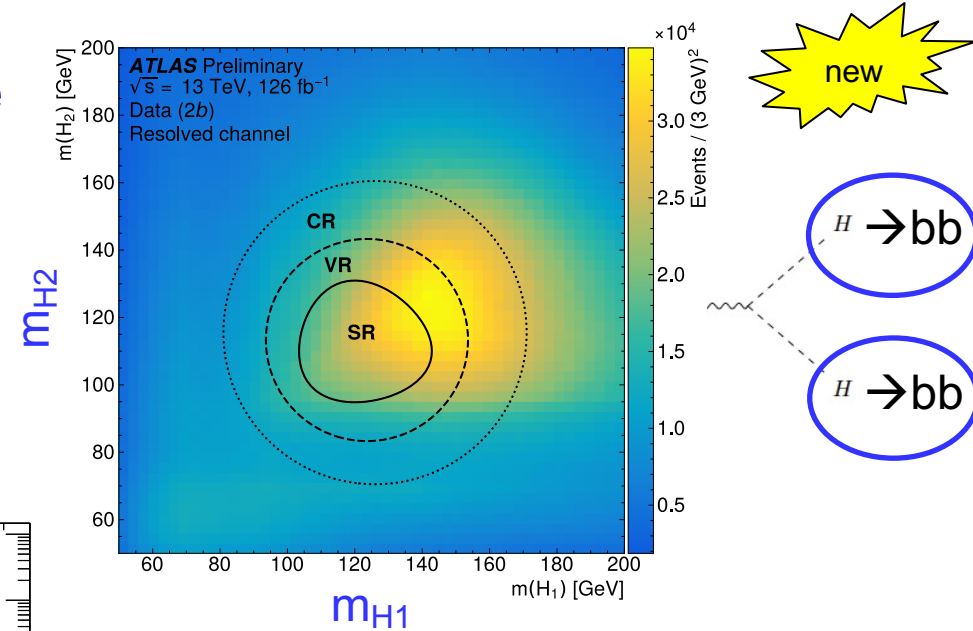


- Generic spin-0/1/2 narrow-width resonance X
 - Event categories based on jet substructure (D2) and mass, and b-tagging for $Z \rightarrow bb$
 - Background from s+b fit of smooth functional form, checked in control region
- Current best exclusions of these processes



Heavy resonance $X \rightarrow HH$ in 4b

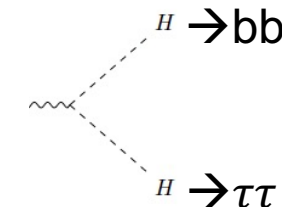
- Search for spin-0/2 resonance over wide mass range
 - Two event topologies:
 - Resolved with 4 b-tags (251-1500 GeV)
 - Boosted with 2-, 3-, 4-b-tag categories (900-3000 GeV)
 - Backgrounds dominated by multi-jet processes and re-weighted from lower-tag regions
- Most sensitive $X \rightarrow HH$ channel at high mass



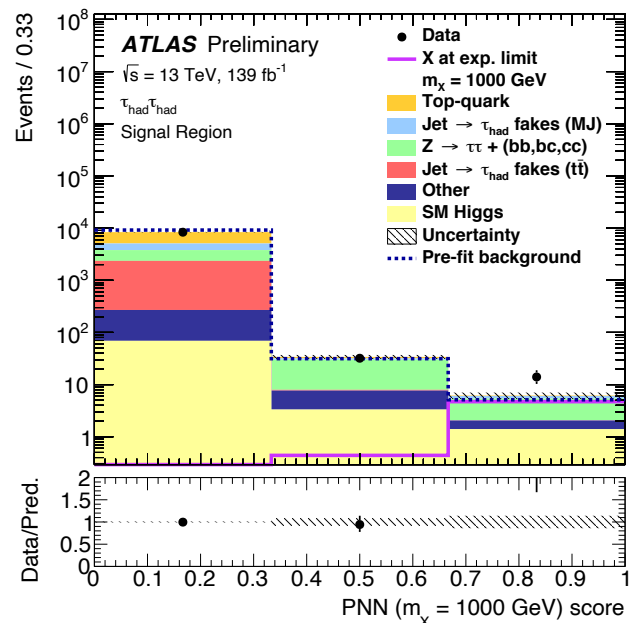
Heavy resonance $X \rightarrow HH$ in $2b\text{-jets} + \tau_h + \tau_{h/l}$



- Target resolved category and spin-0 resonances
 - Sensitivity gains wrt. 36/fb thanks to improved τ_h identification and b-taggers
 - Extract signal with parameterised NN in the HH mass
 - Data-driven techniques are used for jets faking hadronic taus
 - Three distinct signal regions based on trigger requirements
- Most sensitive $X \rightarrow HH$ search at intermediate masses

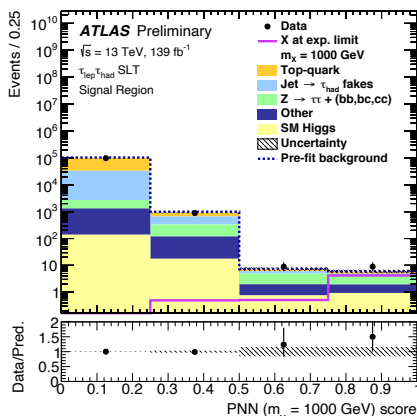


tau_h+(tau_h) triggers

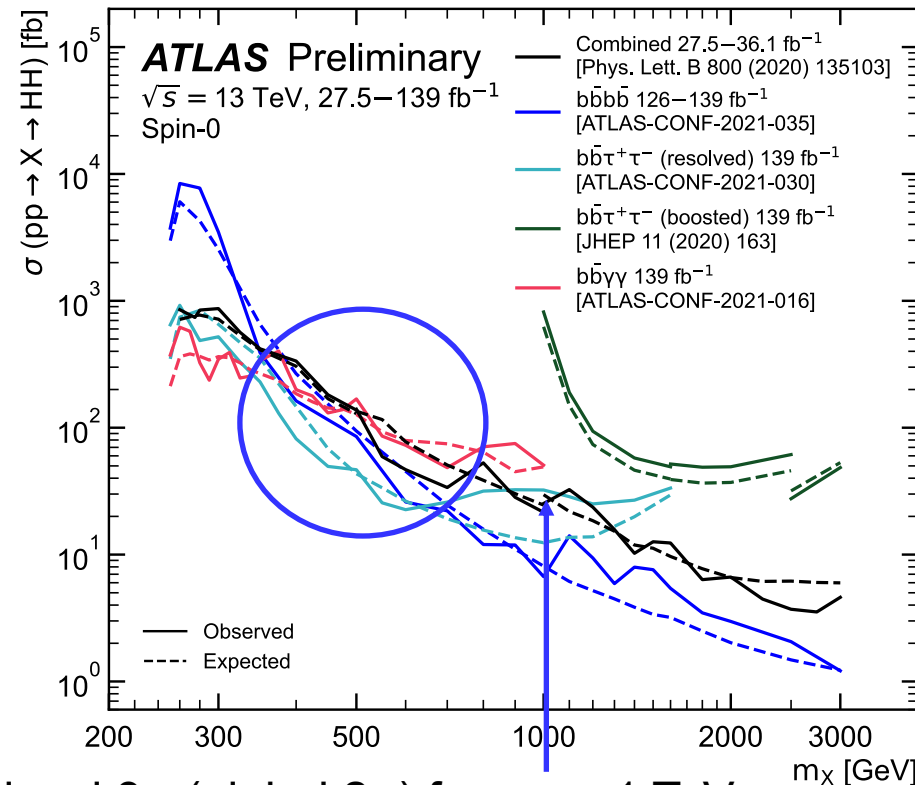
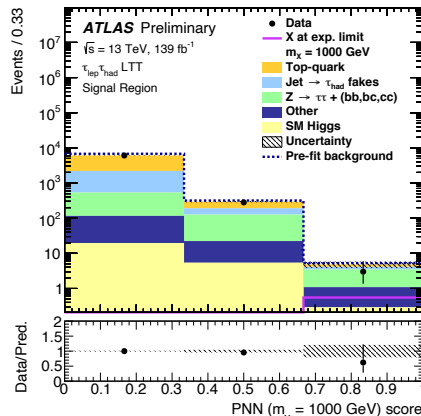


PNN score for m_{HH}=1 TeV

single-l triggers



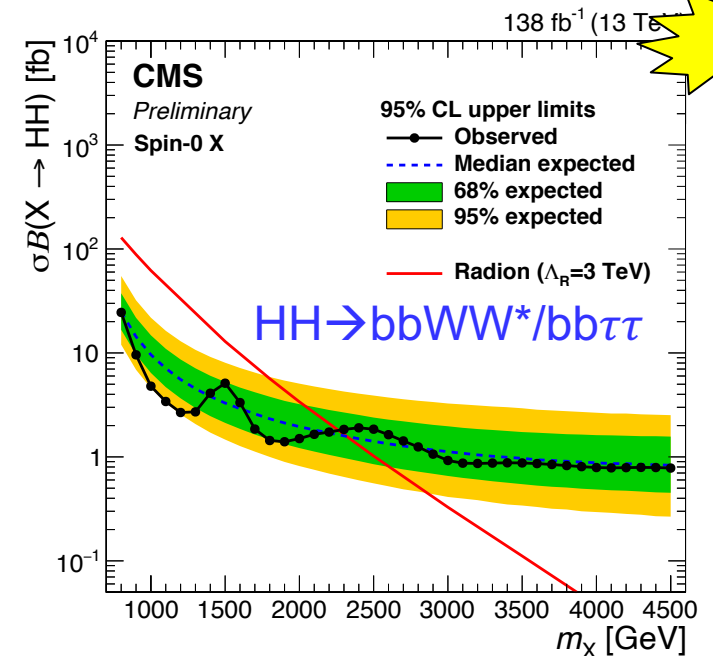
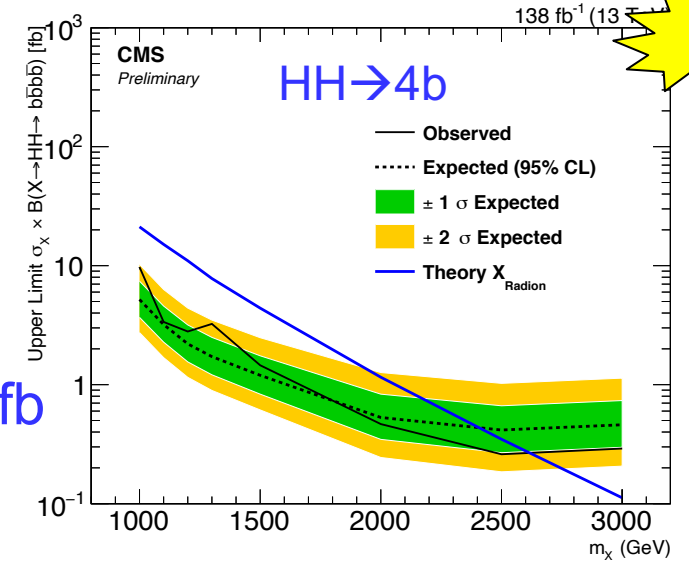
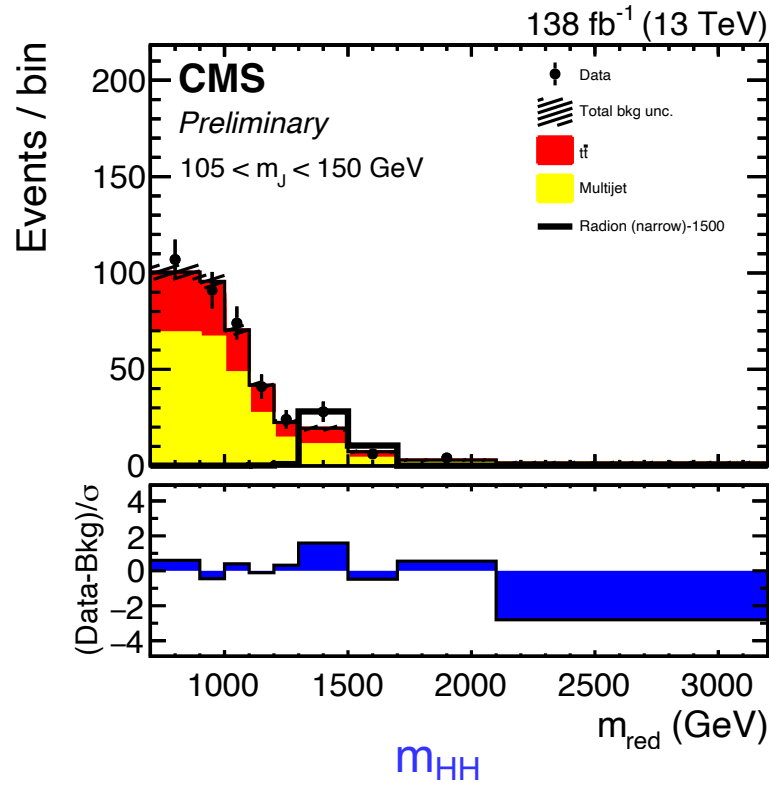
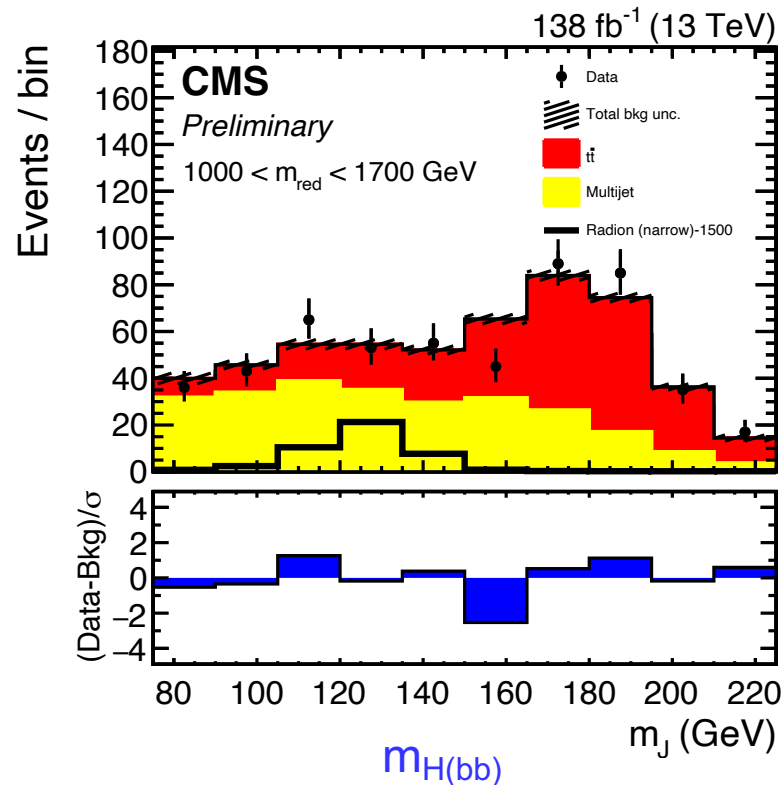
l+tau_h triggers



$2b\text{-jets} + \tau_h + \tau_{h/l}$ local 3σ (global 2σ) for $m_X = 1 \text{ TeV}$

Heavy resonance $X \rightarrow HH$ in 4b and $bbl(l)$

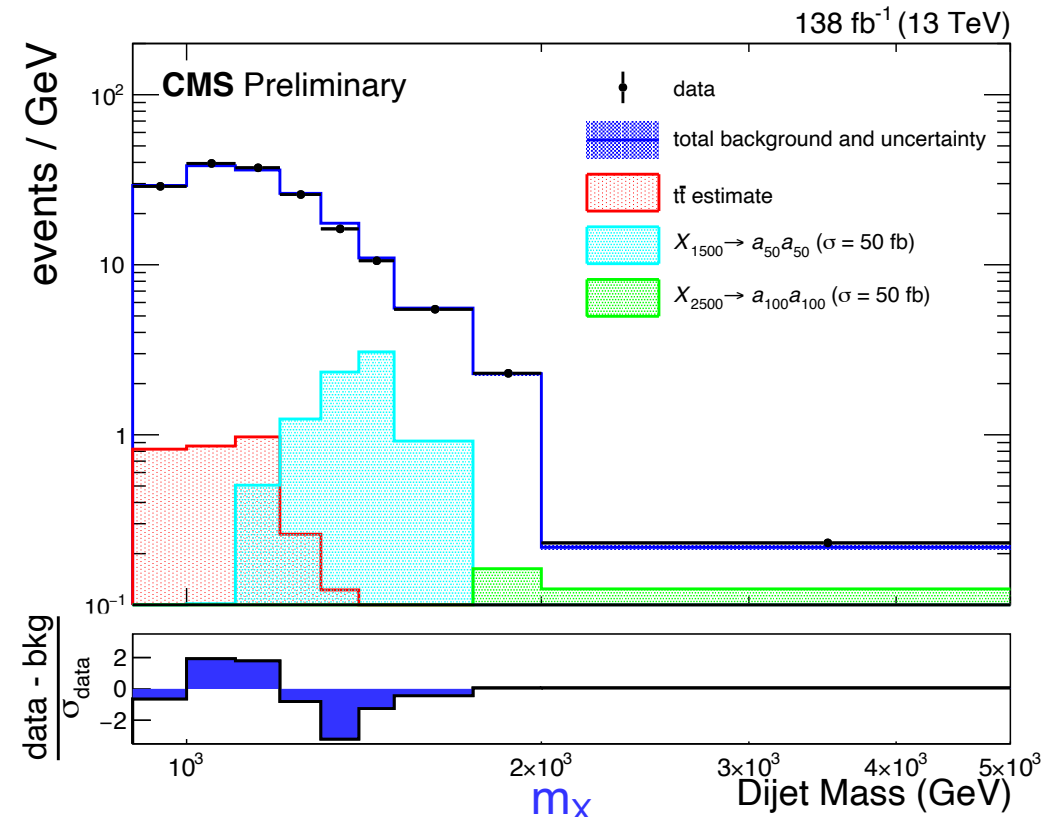
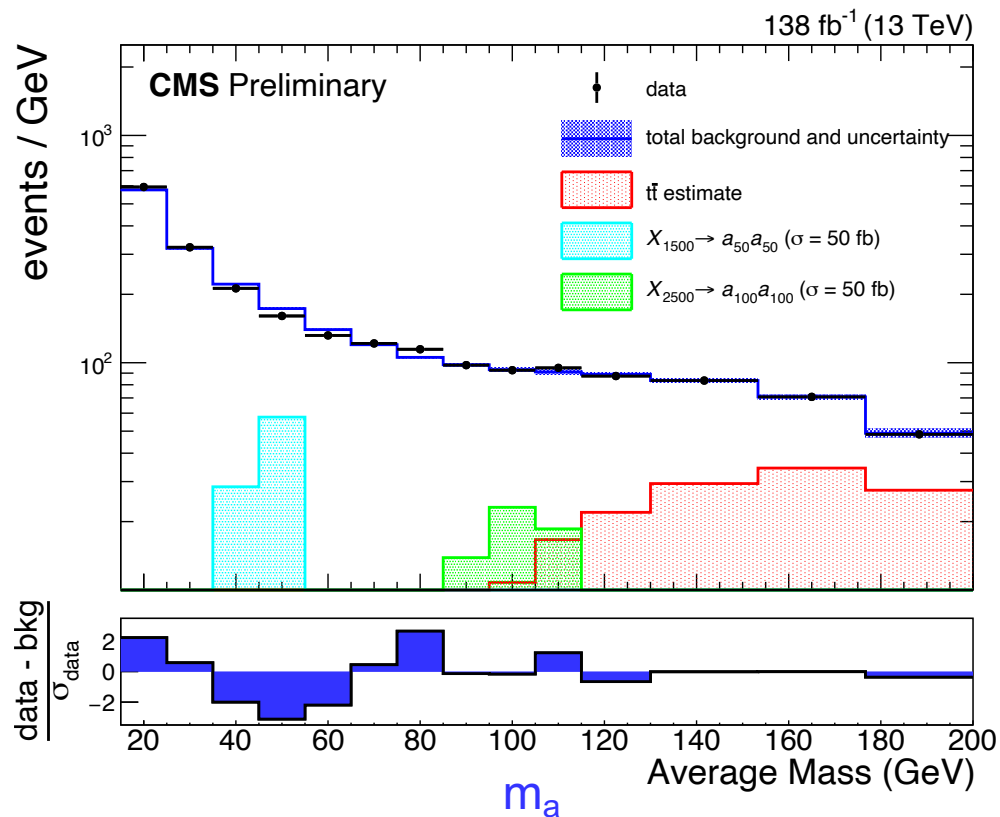
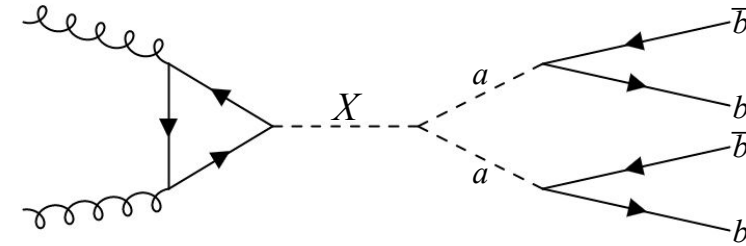
- Two new searches for $X \rightarrow HH$:
 - 4b boosted+semi-resolved, $bbWW^* \rightarrow bbl\nu q\bar{q}/bbl\nu l\nu$ and $bb\tau\tau \rightarrow bbl\nu l\nu$
 - Deep NN to tag $H(bb)$ -jets and categorize events
 - Data-driven background from $H(bb)$ -tag fail regions
 - Extract signal with 2D-fit of (m_J, m_{Red})
- Most sensitive of new $HH \rightarrow 4b$ results above 1.5 TeV
- Best sensitivity to $HH \rightarrow bbl(l)$, better by factor 6-14 wrt. 36/fb



$X \rightarrow aa$ resonances in 4b

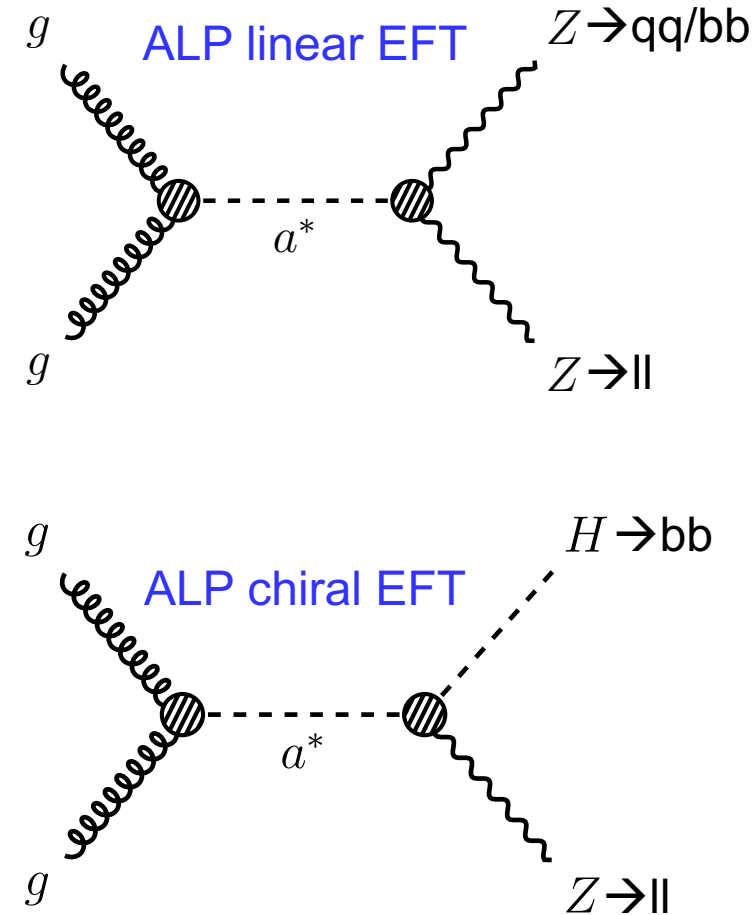
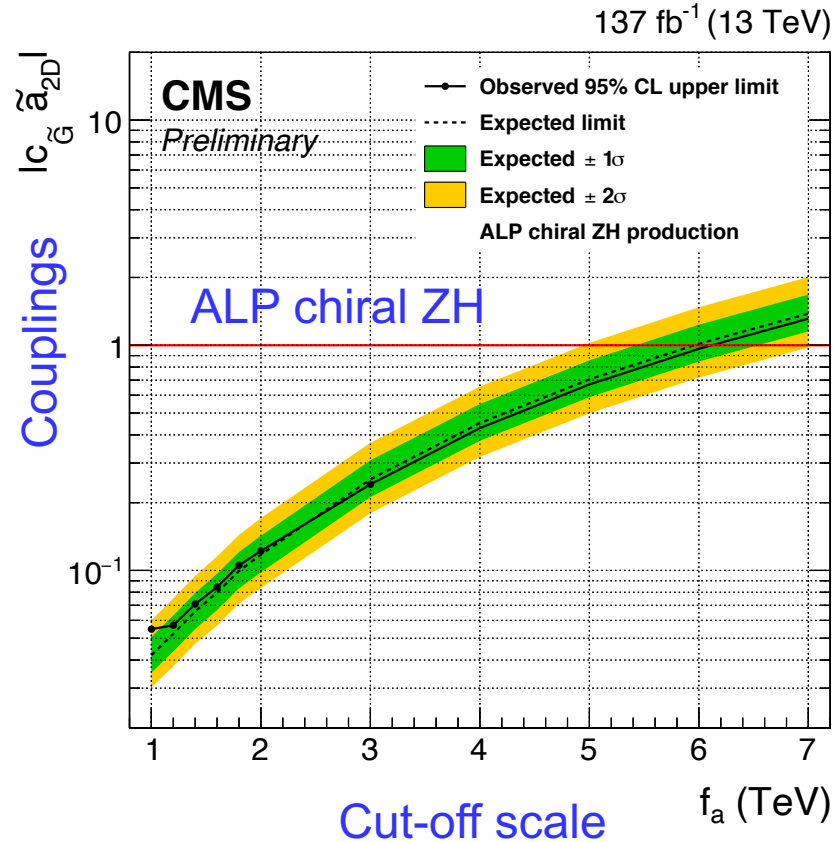
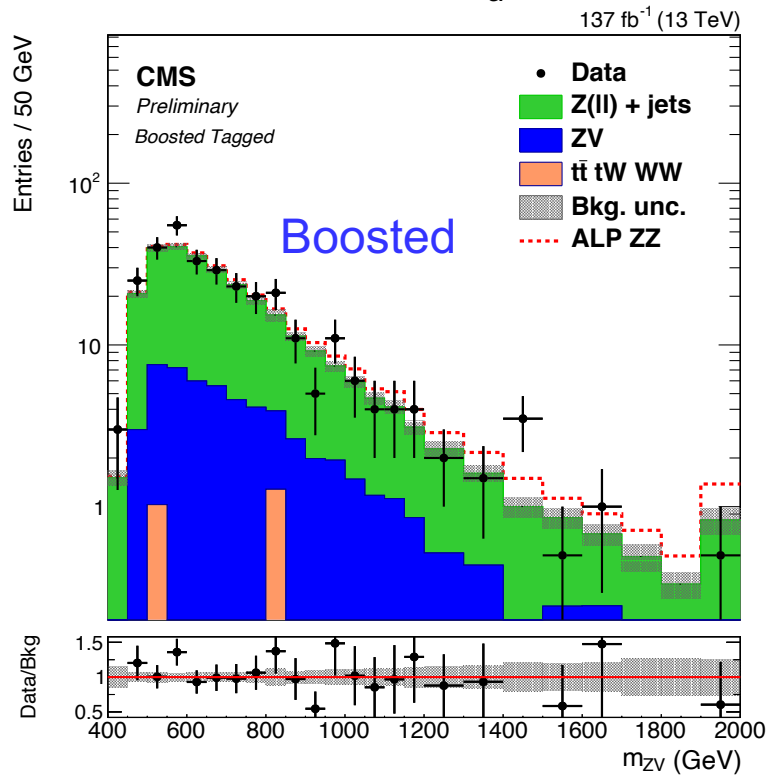


- First generic search for $X \rightarrow aa \rightarrow 4b$, $25 < m_a < 100$ GeV, $1 < X < 3$ TeV
 - Data driven background from $\Delta\eta$ and double-b-tag sideband
 - Extract signal with 2D-fit of average jet mass and dijet mass



- First limits on non-resonant ALP-mediated ZZ and ZH obtained by LHC experiments

- Target boosted and resolved final state with and without b-tag
- Constrain background shape from jet mass sidebands
- Spin-1/-2 resonances also probed
- Exclude events with $m_{ZH} > f_a$ when setting constraints (validity of the EFT)
- Limits valid in $m_a < 100$ GeV



- LFV $Z \rightarrow e\mu$

- BDT selection to suppress backgrounds

$$\mathcal{B}(Z \rightarrow e\mu) = \frac{N_{Z \rightarrow e\mu}}{(A \times \epsilon)_{Z \rightarrow e\mu} \times N_Z^{\text{avg}}}$$

N_Z^{avg} from $Z \rightarrow ee/\mu\mu$

- $\mathcal{B}(Z \rightarrow e\mu) < 3.04 \times 10^{-7}$

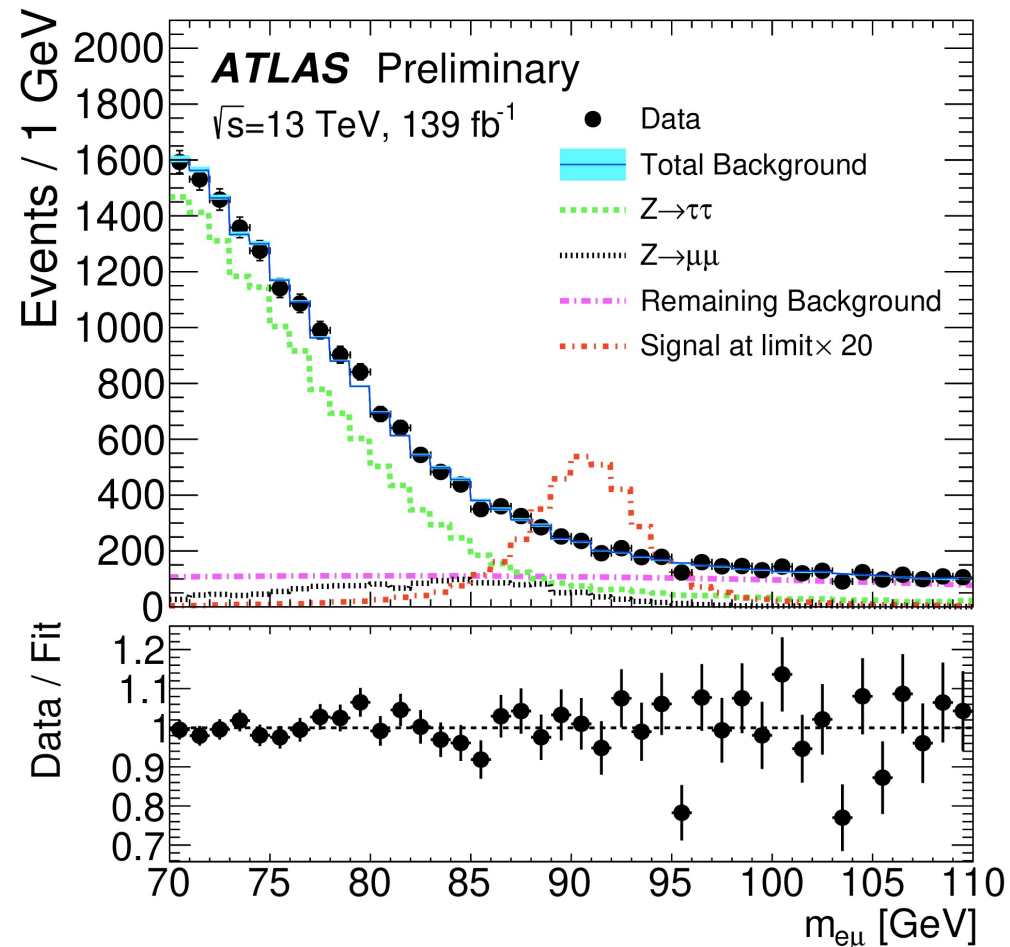
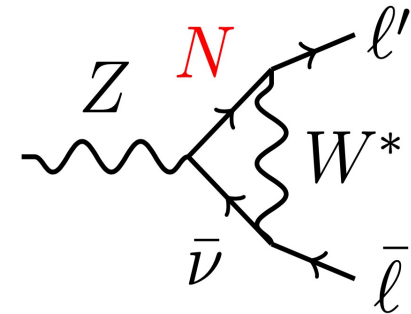
- Most stringent direct result

- 5x better than LEP

- Recent constraints from ATLAS

([arXiv:2105.12491](https://arxiv.org/abs/2105.12491))

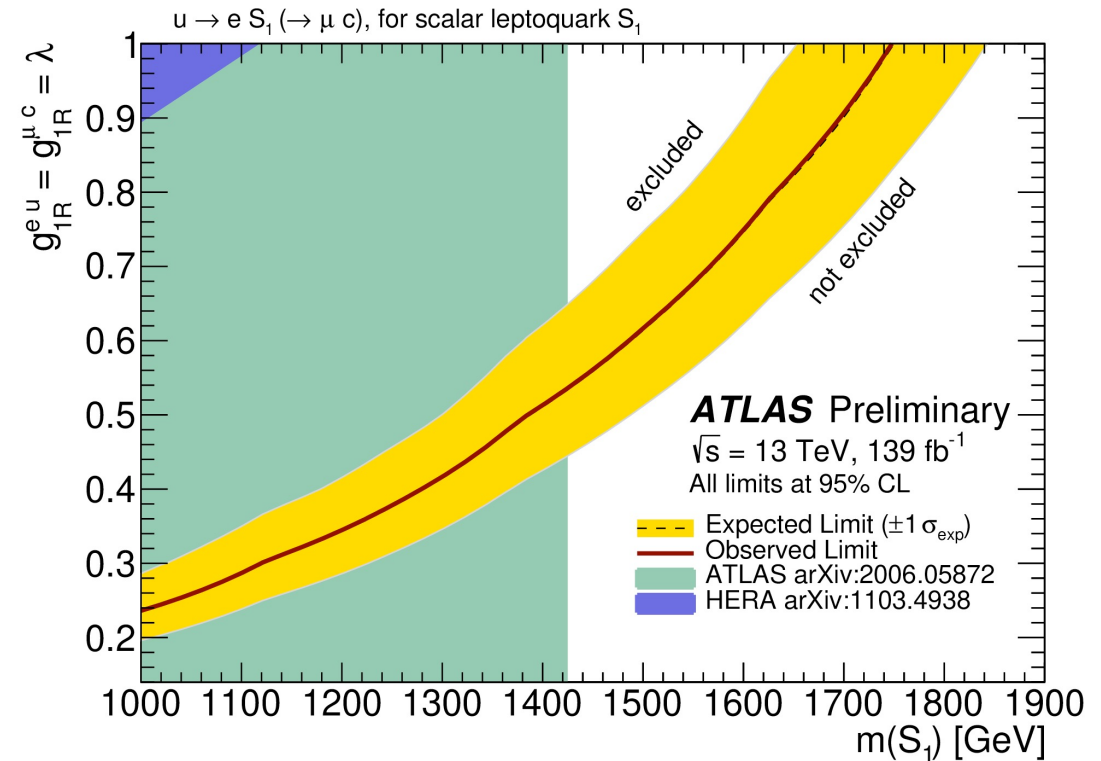
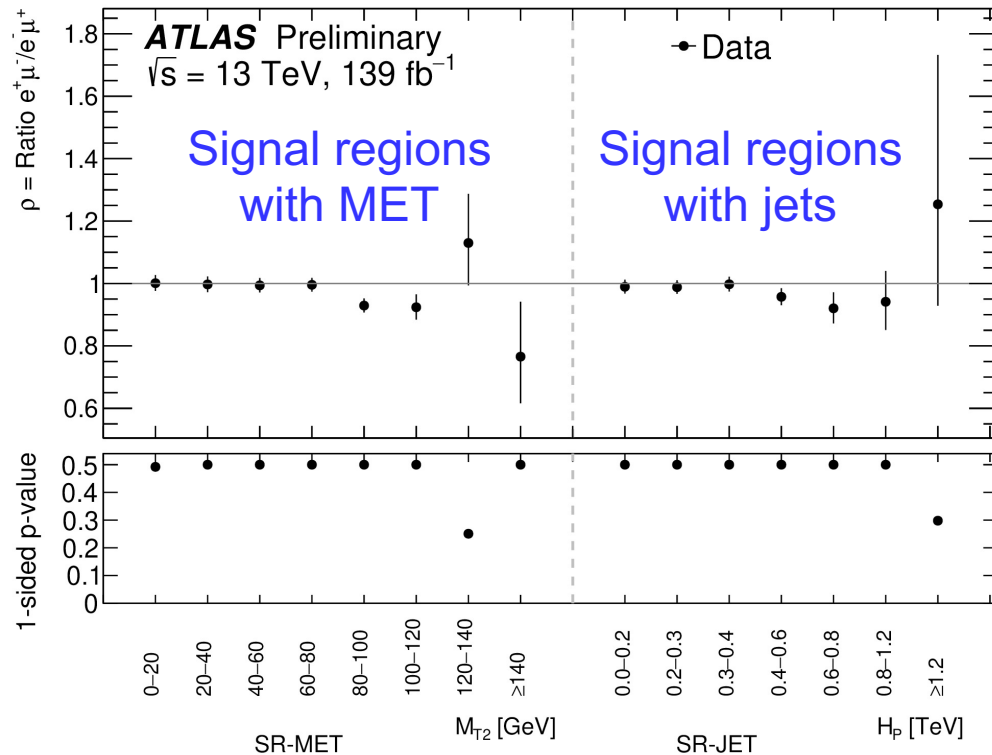
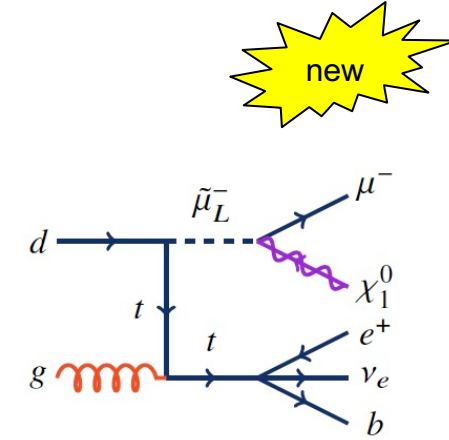
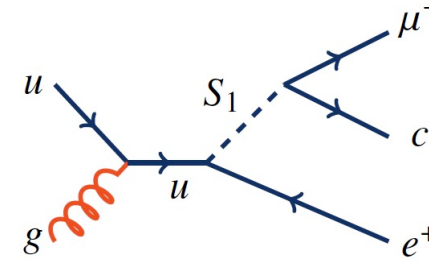
- $\mathcal{B}(Z \rightarrow e\tau) < 5.0 \times 10^{-6}$
- $\mathcal{B}(Z \rightarrow \mu\tau) < 6.5 \times 10^{-6}$



- First search at LHC for Charge-flavor asymmetry in $e\mu$

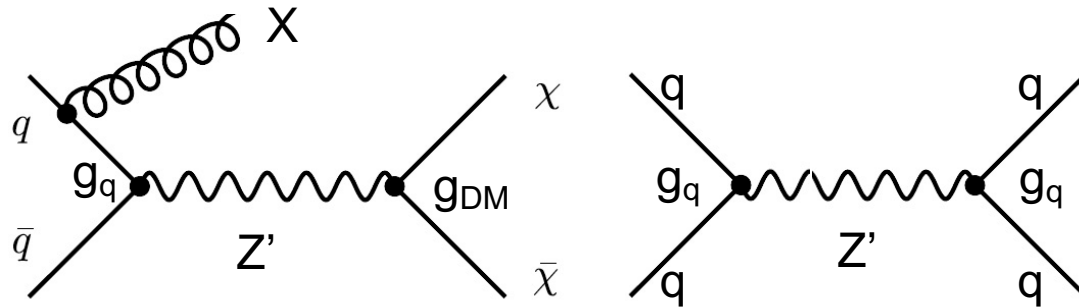
$$\rho \equiv \frac{\sigma(pp \rightarrow e^+ \mu^- + X)}{\sigma(pp \rightarrow e^- \mu^+ + X)}$$

- Approximately 1 in pp collisions
- General and dedicated event selections for RPV-SUSY smuon-neutralino and scalar LQ
- e fakes from W+jet events estimated data driven and subtracted



Dark matter and dark sector

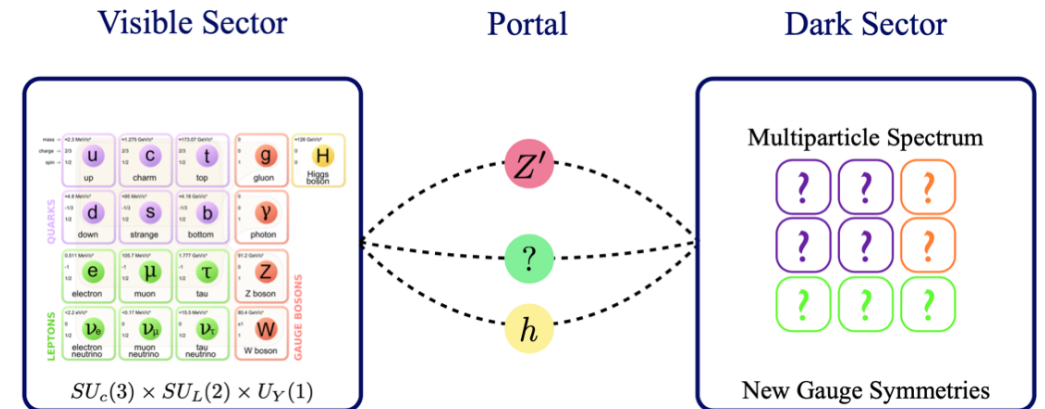
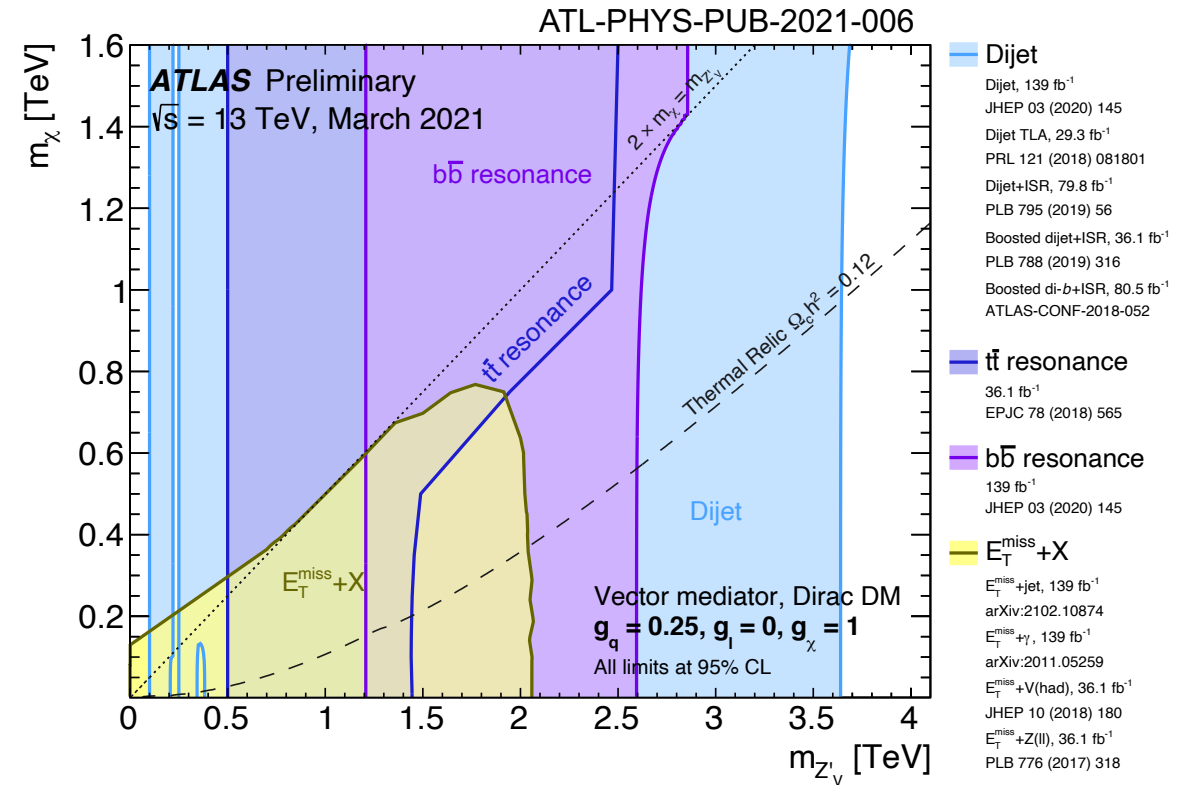
- Classical DM signature: $E_T^{\text{miss}} + X$
with $X = q, \gamma, W, Z, H, t, \text{tt}$
- Simplified models



- Allow comparison with direct detection

Plenary talk by Babette Döbrich (Thu)

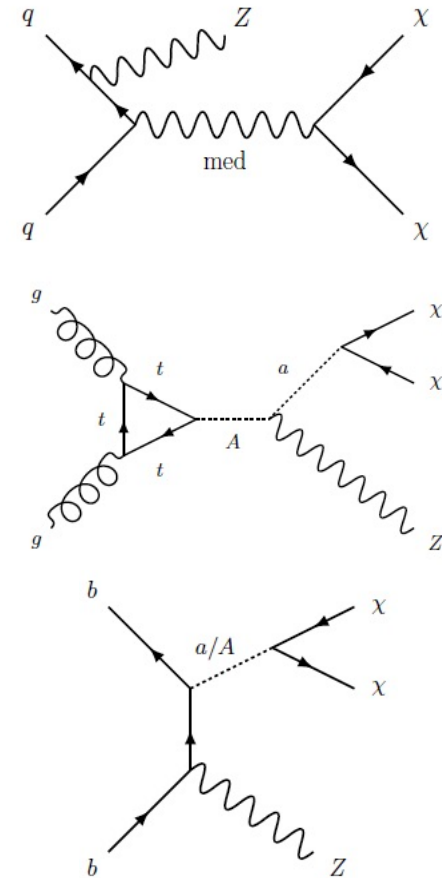
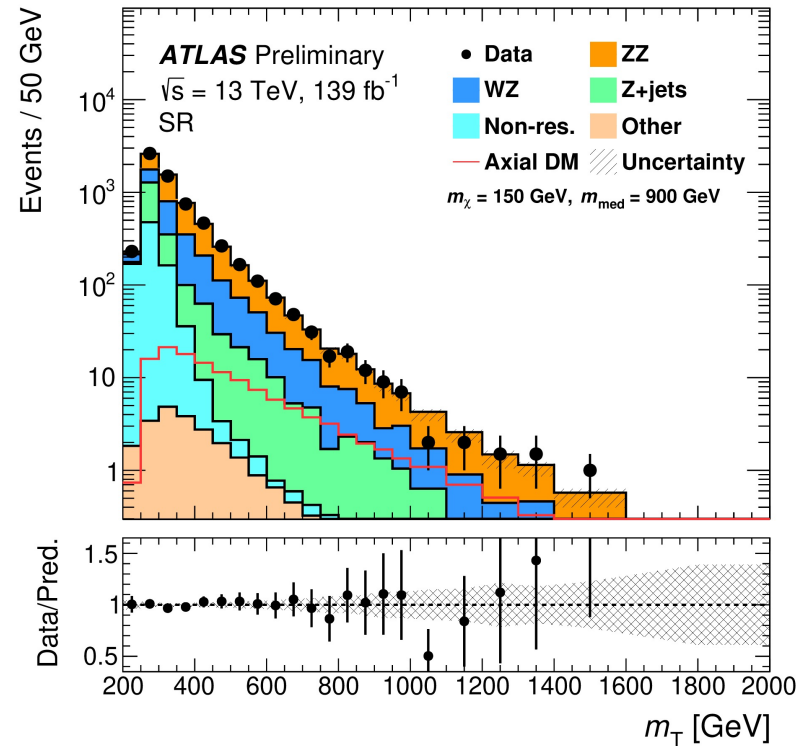
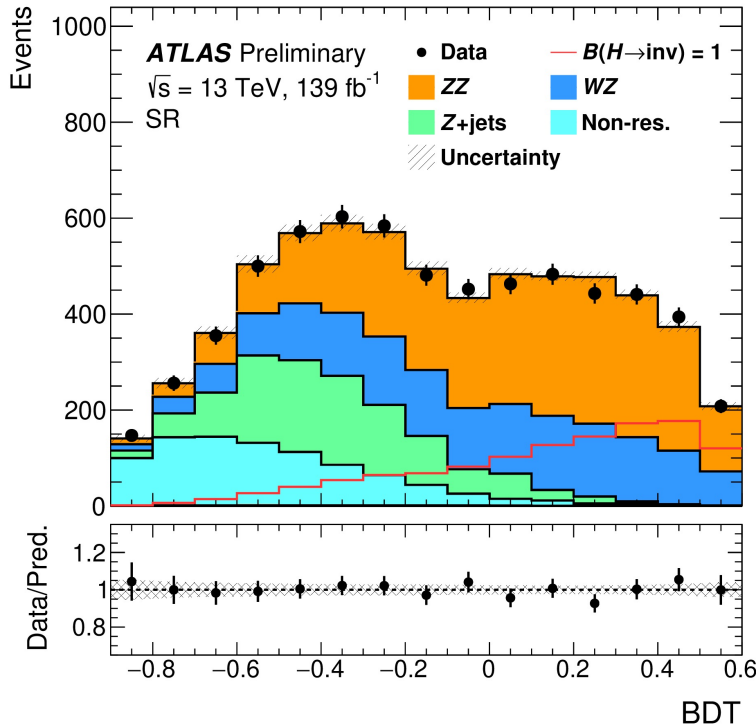
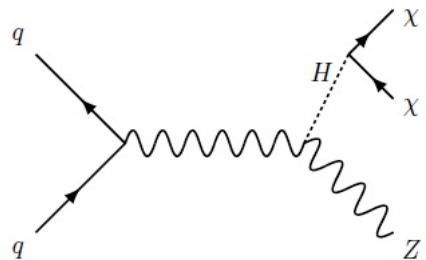
- Dark sector: multiple fermions/bosons making up dark matter
 - Portal/mediator between SM and dark sector could e.g. be dark photon, Higgs
 - Dark matter fermions could acquire mass from dark or SM Higgs
 - Relates DM to exotic decays of SM Higgs



Dark matter in Z(II) + MET

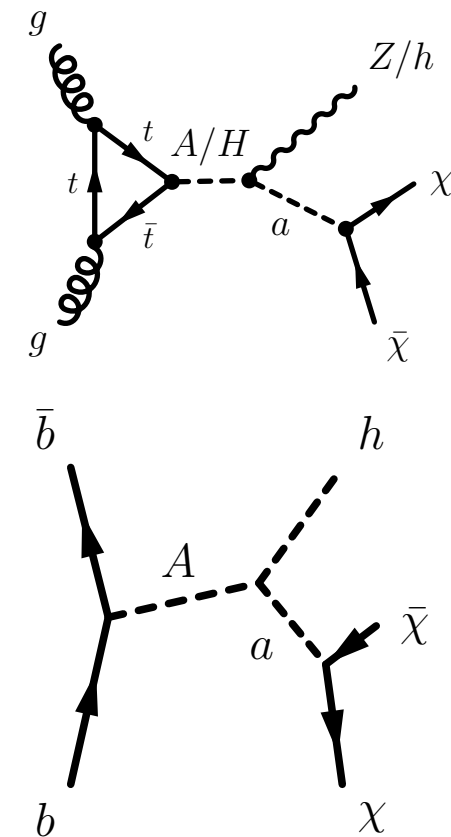
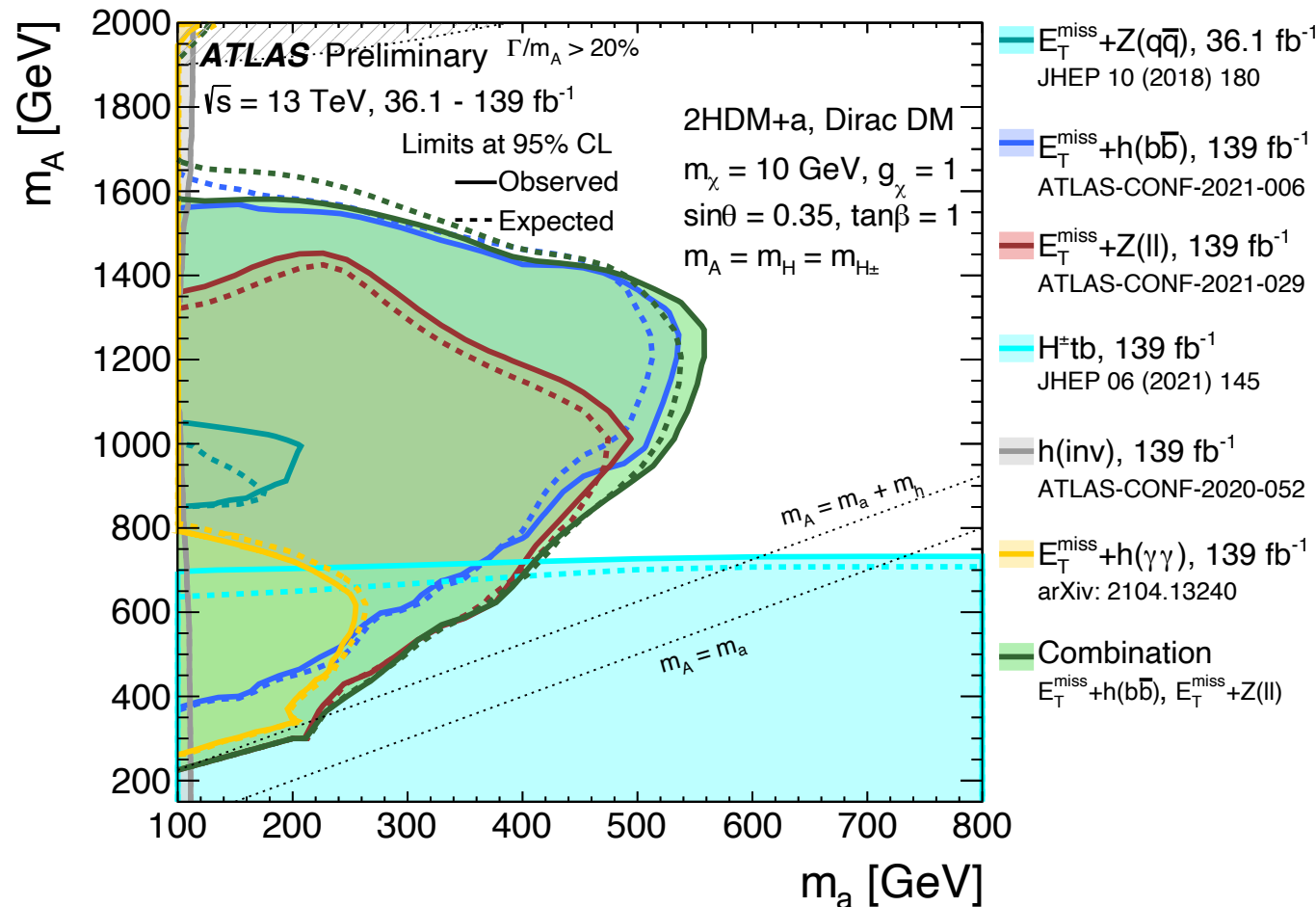


- Search for decay of Higgs \rightarrow DM and production of DM + Z(II)
 - Major backgrounds constraint in control regions
 - Extract signal dedicated BDT for $H \rightarrow \text{inv}$ or from $m_T(\text{II} + \text{MET})$
- $B(H \rightarrow \text{inv}) < 18\%$ @95% CL
 - compare to 11% combining Run2 VBF+ttH +Run1 (ATLAS-CONF-2020-052)





- 2HDM+a: simplest gauge-invariant and UV-complete extension of the simplified model with a pseudoscalar mediator
 - Pseudoscalar not strongly constrained by direct detection
- First combination of $E_T^{\text{miss}}+H(bb)$ and $E_T^{\text{miss}}+Z(ll)$ channels



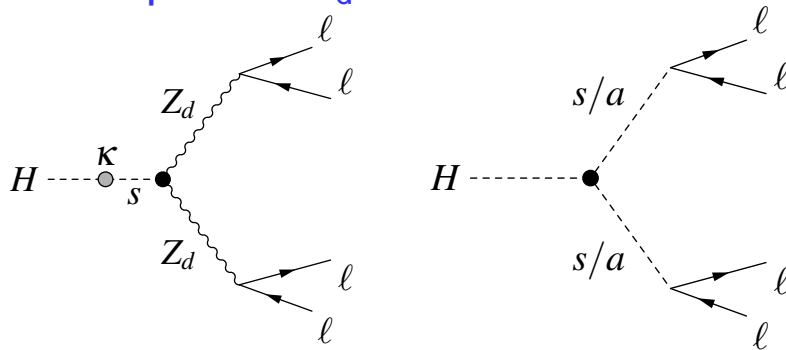
Higgs \rightarrow dark scalar/vector in 4l



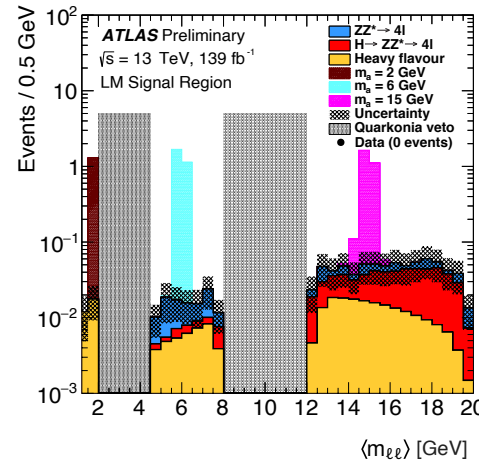
- Higgs decay via dark scalar or dark vector boson
 - XX and ZX topologies are probed
- Dedicated low mass 4 μ channel exploring resonances down to 1 GeV

Dark Higgs s
Dark photon Z_d

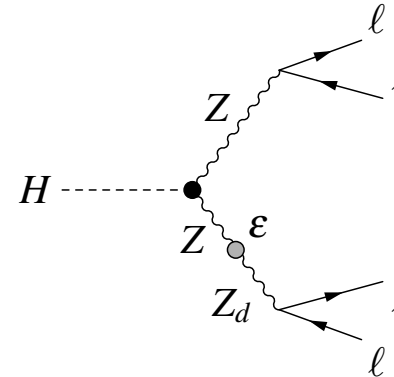
2HDM + S



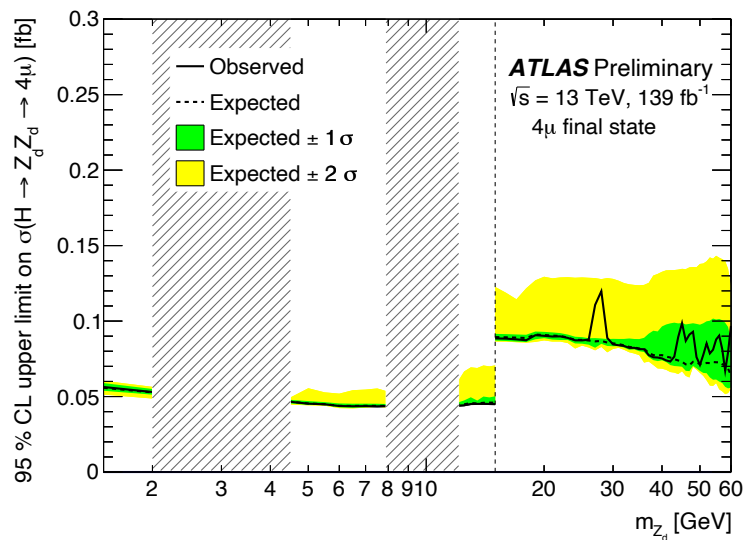
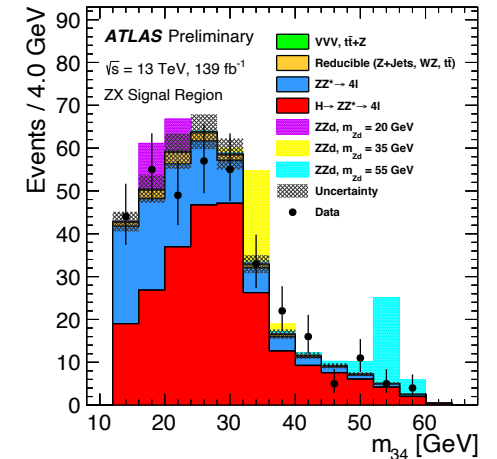
Low mass $H \rightarrow XX$



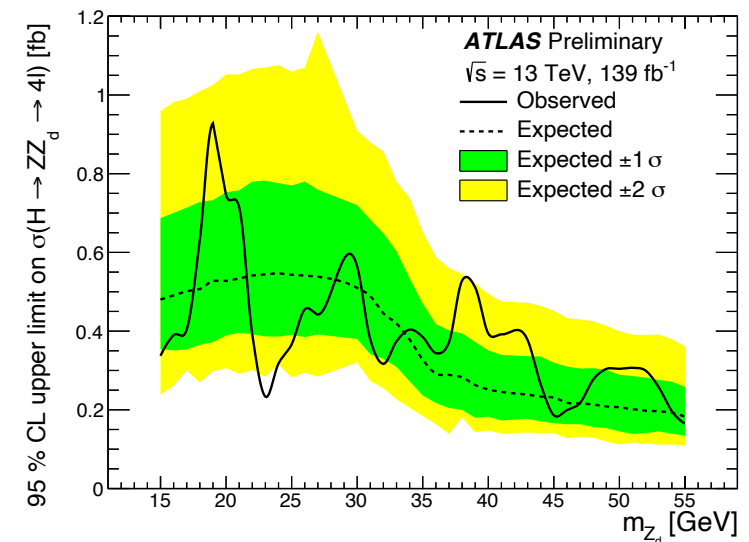
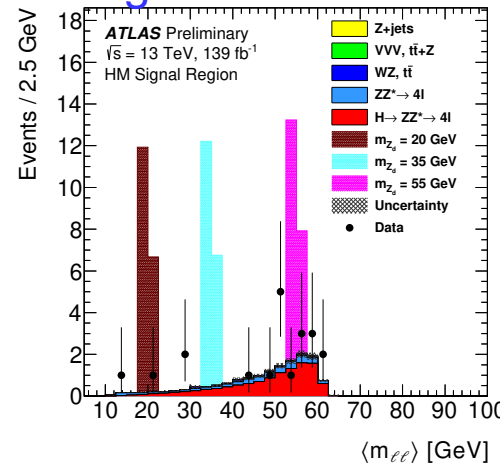
Dark photon Z_d



$H \rightarrow ZX$

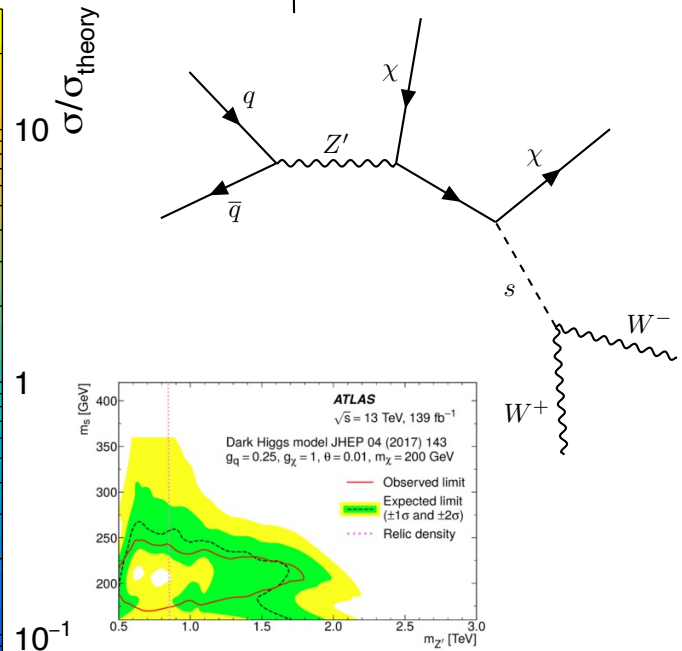
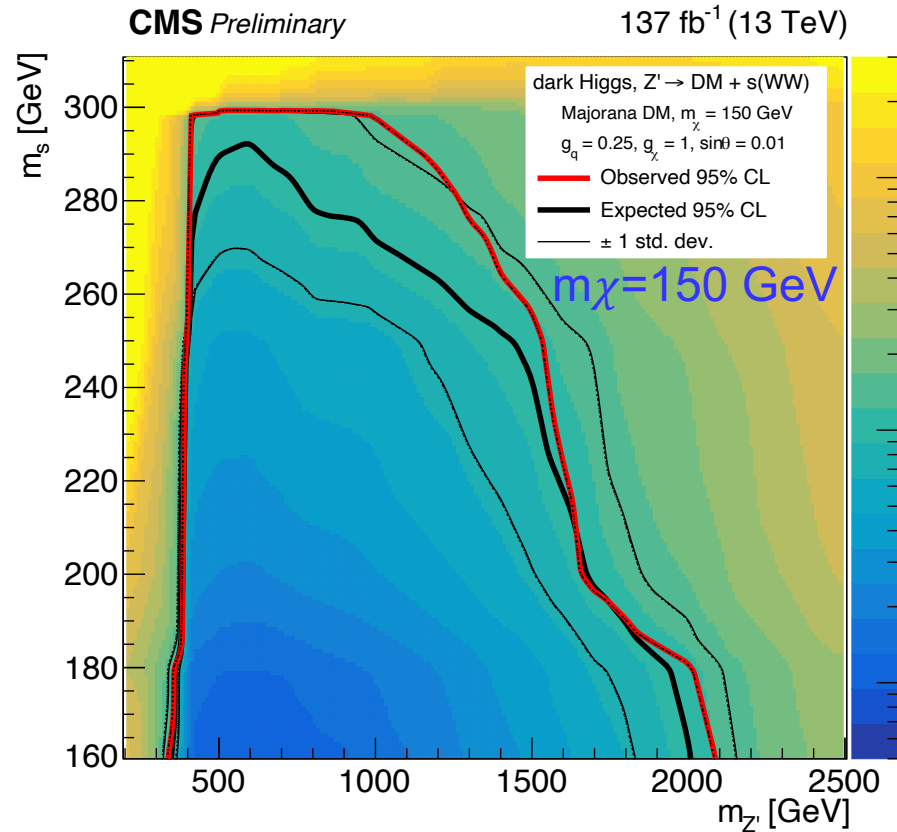
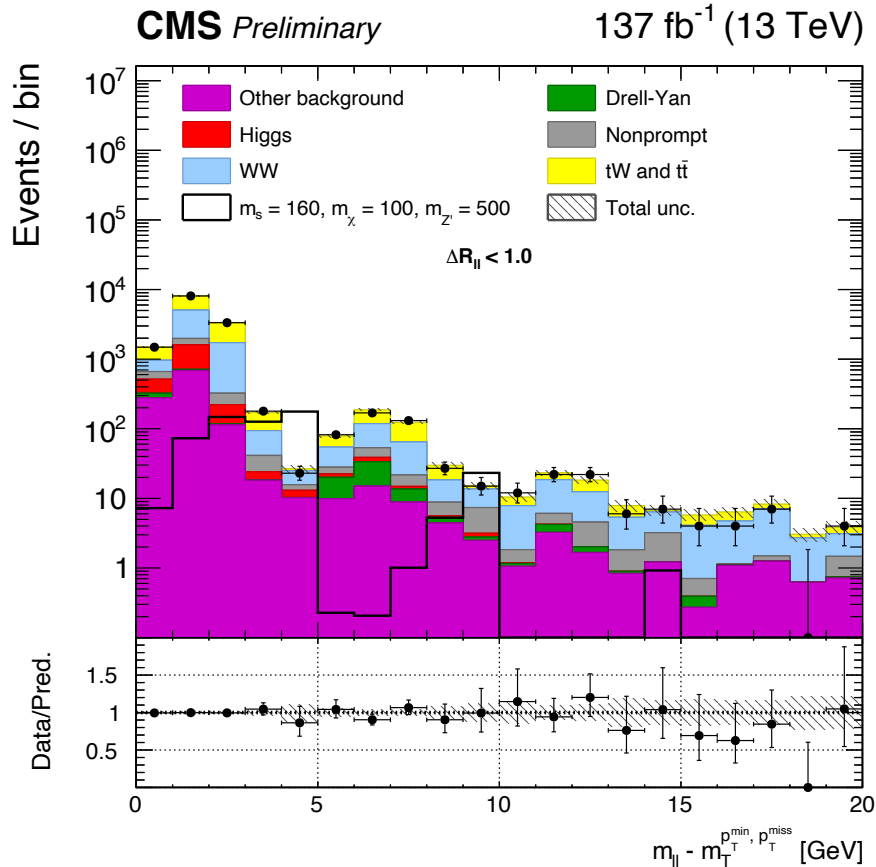
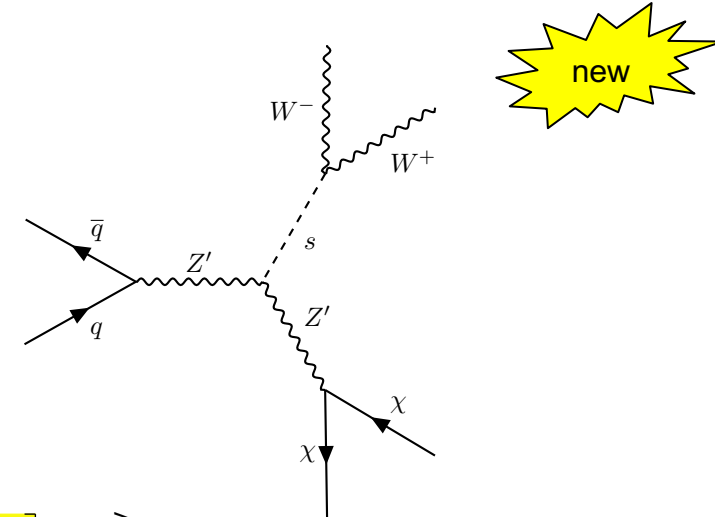


High mass $H \rightarrow XX$



Dark Higgs in MET+W(lv)W(lv)

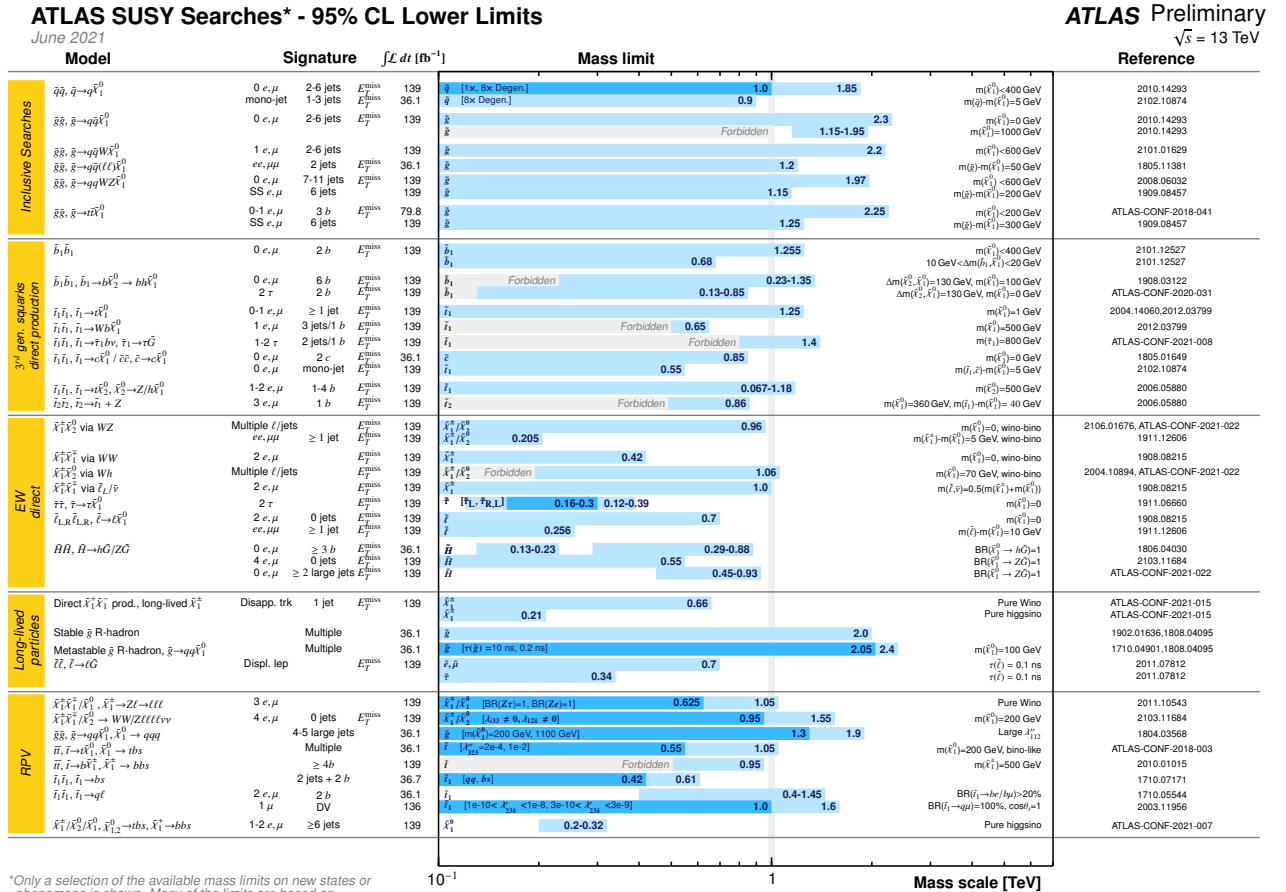
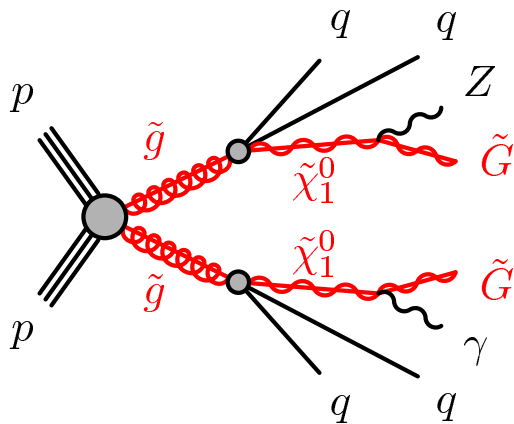
- Extends excluded region to m_s masses up to 300 GeV
 - ATLAS MET+W(qq)W(qq) [1] search reached up to ~ 250 GeV
 - 3 event categories in $\Delta R(\ell\ell)$ covering different boost
 - Dominant prompt background norms from control regions
 - 2D-fit of $m_{\ell\ell} - m_T^{\ell \min, p_T^{\text{miss}}}$



[1] Phys. Rev. Lett. 126 (2021) 121802

SUSY

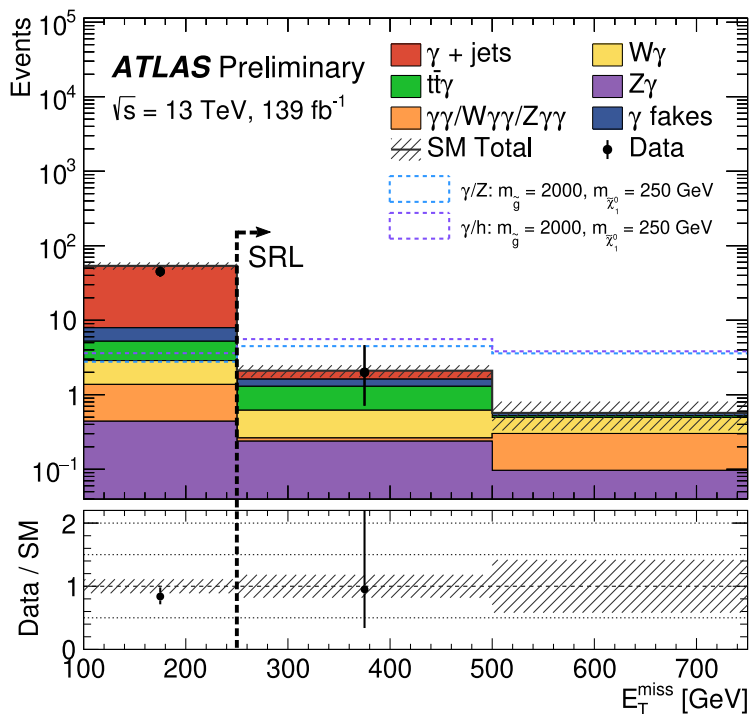
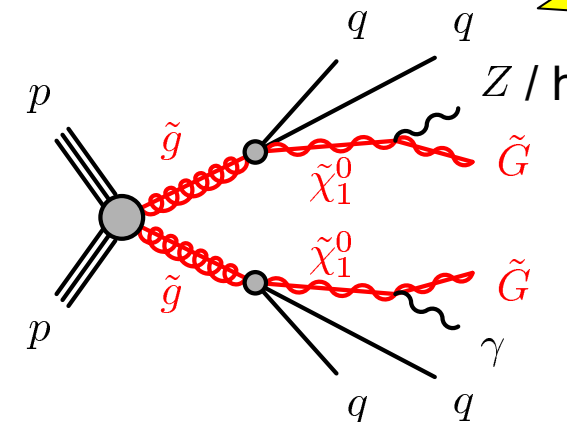
- A whole search program by itself
 - Can answer many of the unresolved questions
- Typical signature (RPC)
 - Pair production
 - (Long) decay chains to lightest SUSY partner (LSP)
- LSP potential dark matter candidate (if RPC) \rightarrow final states with MET



new
HH(4b)+MET (CMS-PAS-SUS-20-004)

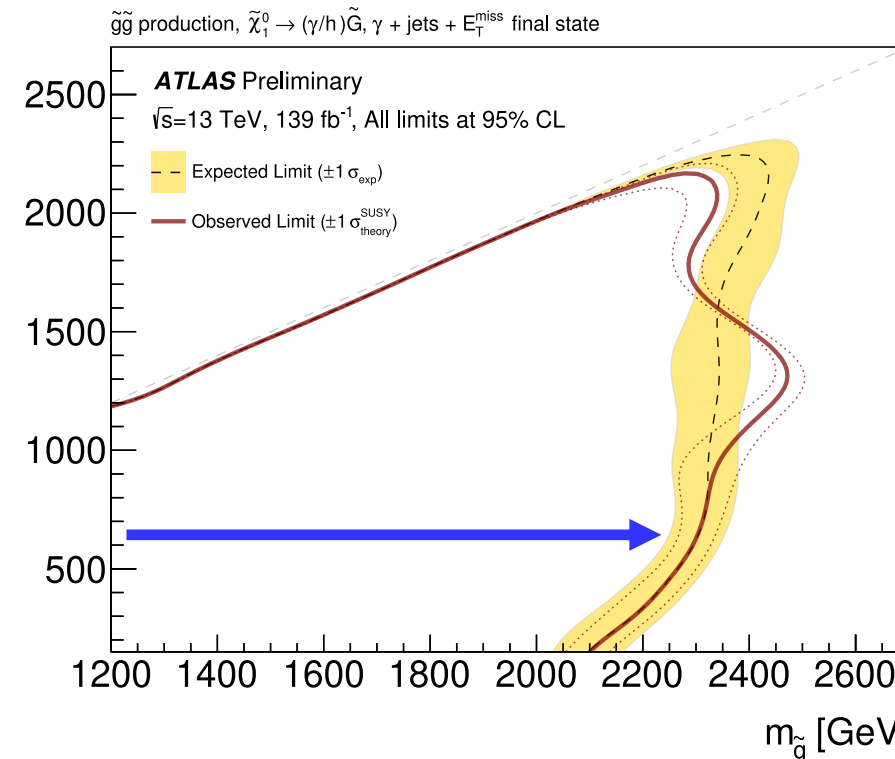
Neutralino/gravitino in $\gamma + \text{jets} + \text{MET}$

- Unique sensitivity to models with photons and jets in the final state, including SUSY General Gauge Mediation models
 - 3 signal regions based on photon p_T + event activity targeting different neutralino/gravitino mass ratios
 - $W\gamma$, $t\bar{t}\gamma$, γ +jets constraint in control regions, checked in validation regions
 - GGM scenario with a NLSP neutralino that is a mixture of higgsino and bino
- Sensitivity improved over Run1 result by up to 1000 (400) GeV for γ/H (γ/Z)

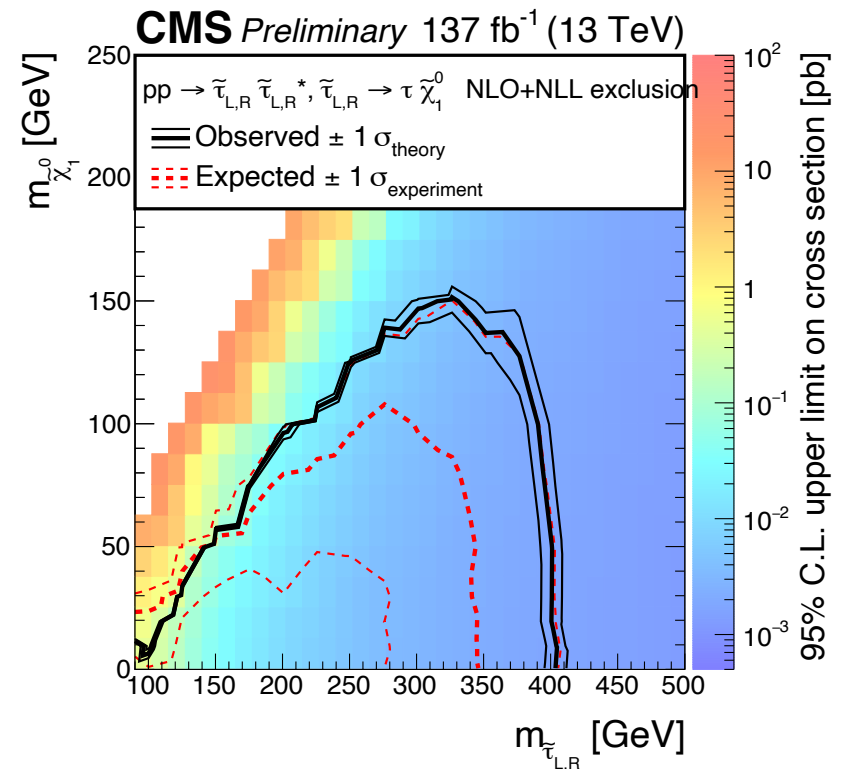
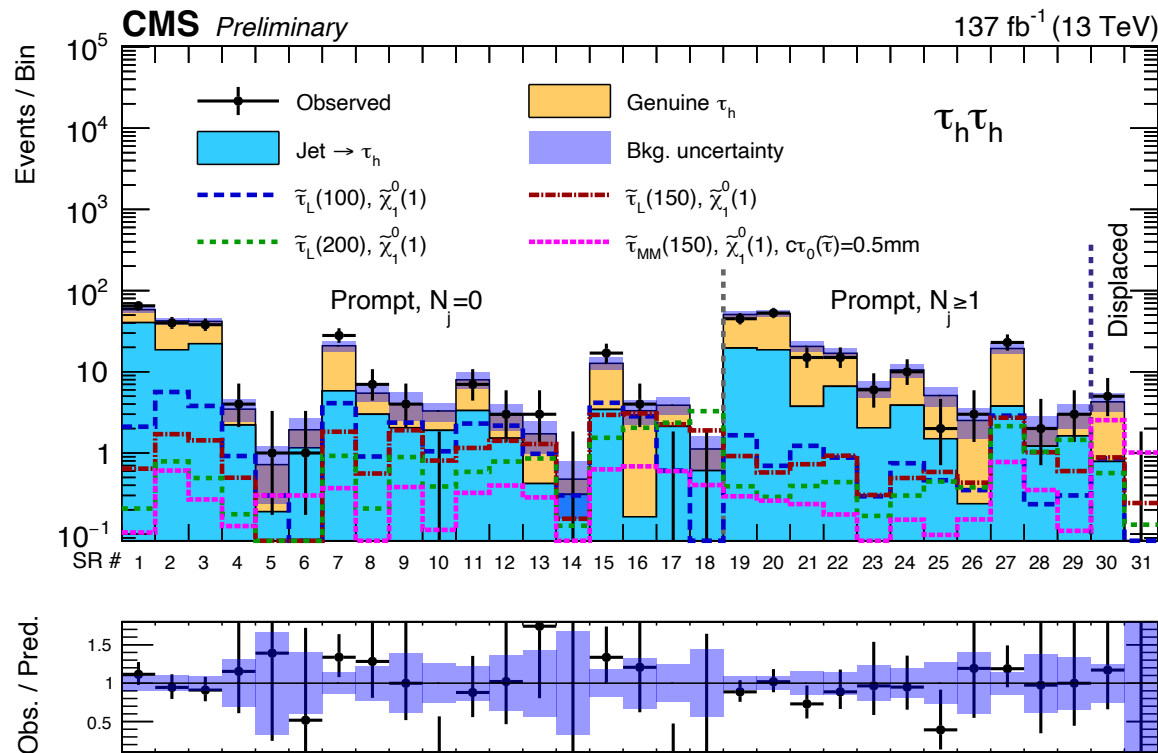
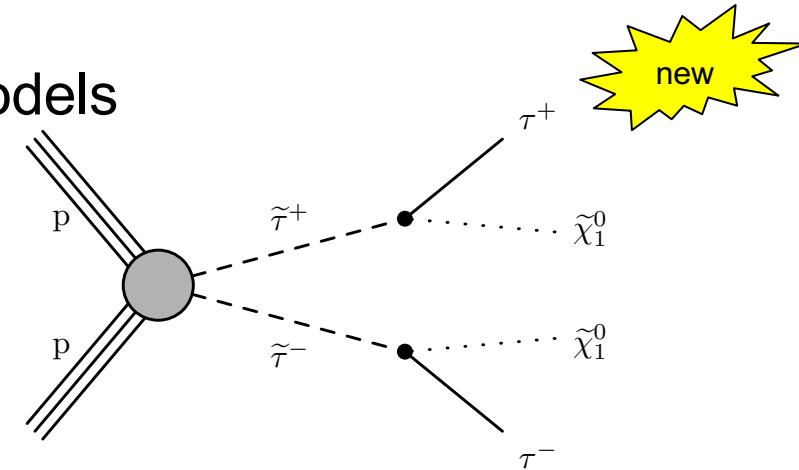


Signal Region	N_{obs}	N_{exp}
SRL	2	2.67 ± 0.75
SRM	0	2.55 ± 0.64
SRH	5	2.55 ± 0.44

$m_{\tilde{\chi}_1^0}$ [GeV]

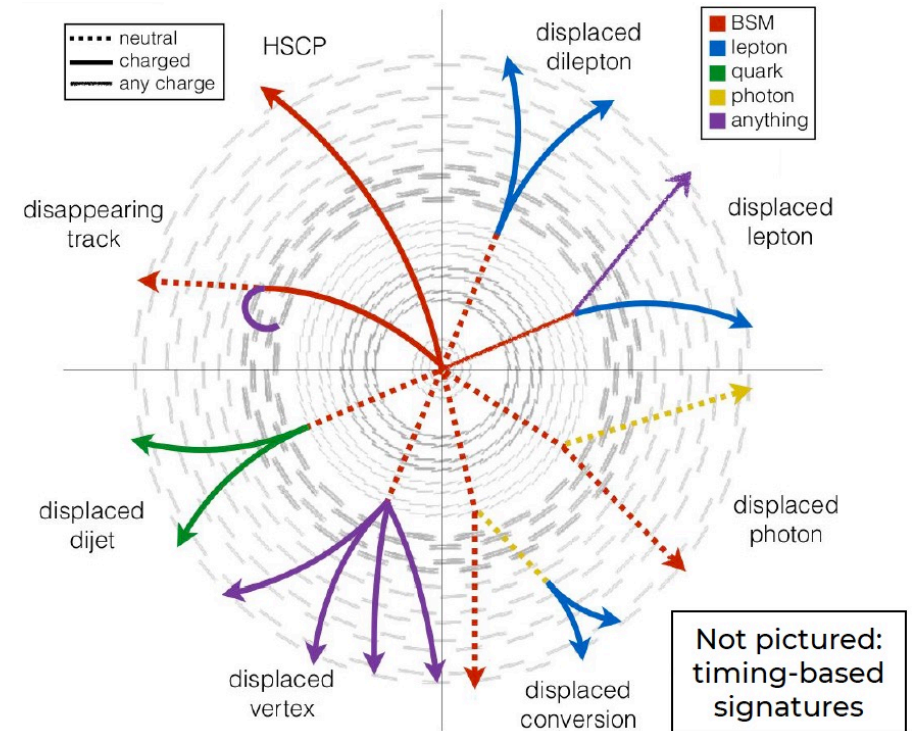
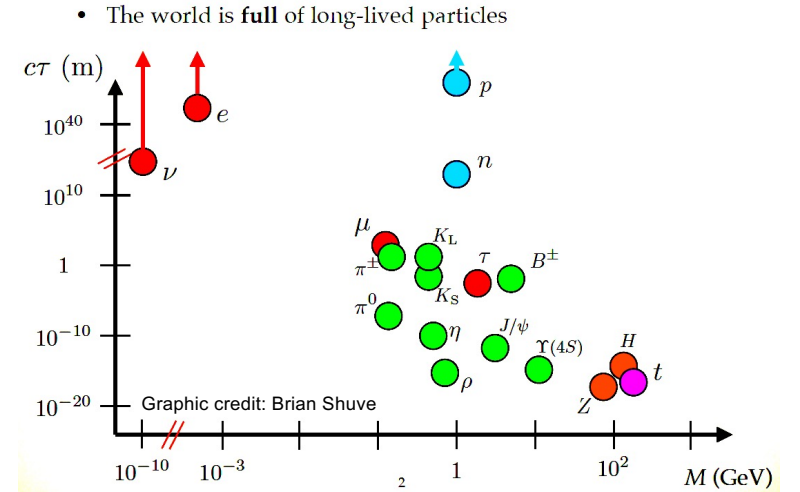


- Targets **prompt and long lived staus**, occurring in GMSB models
 - Events categorized according to $\Sigma m_T, m_{T2}, \tau p_T$
 - Dedicated search regions for displaced taus ($c\tau < 2.5\text{mm}$)
 - Background reduced with DNN τ identification
 - $\tau\tau$ background estimated with embedded sample
- Exclude degenerate stau production up to 400 GeV
 - For $c\tau = 0.1\text{mm}$, exclude mass range 150-220GeV



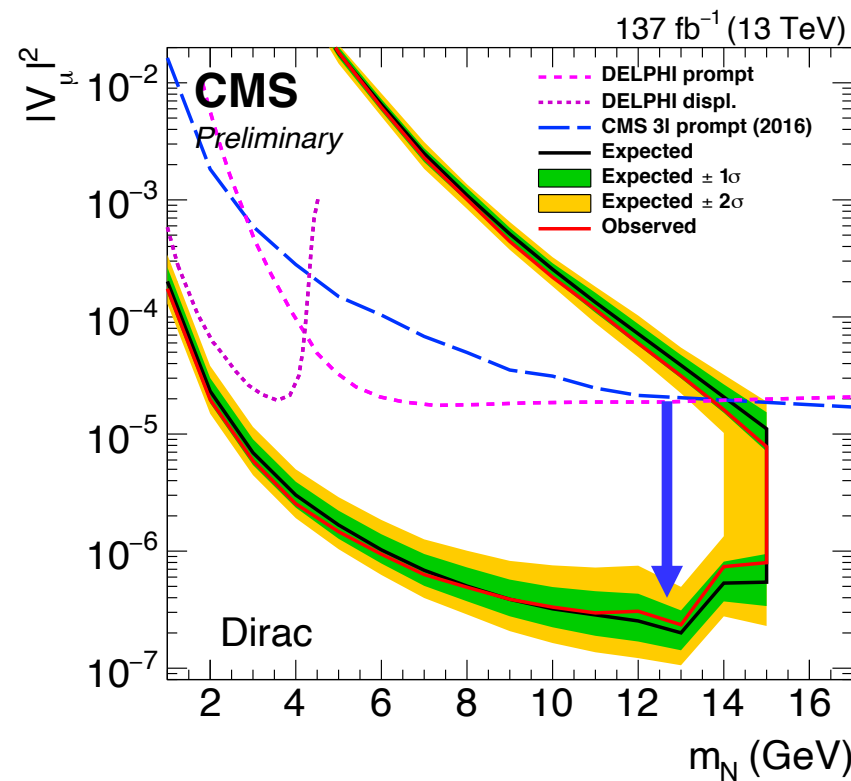
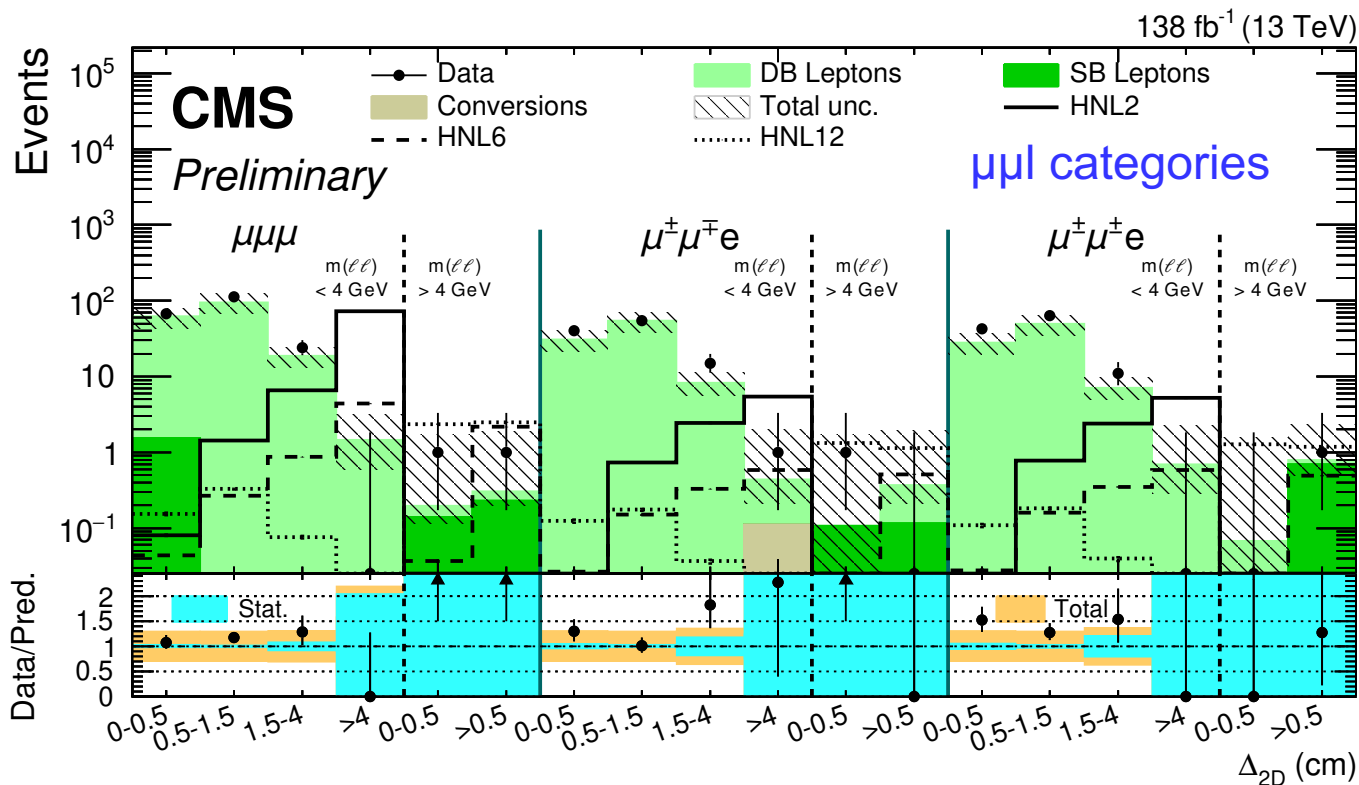
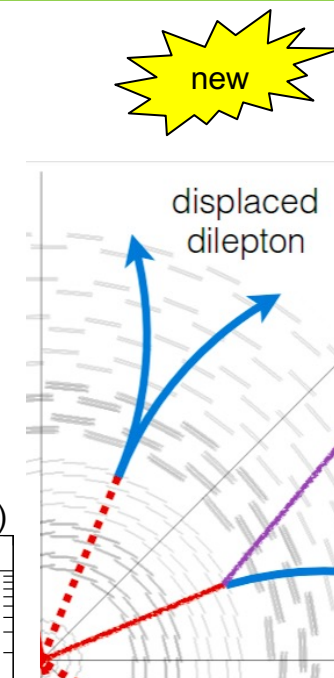
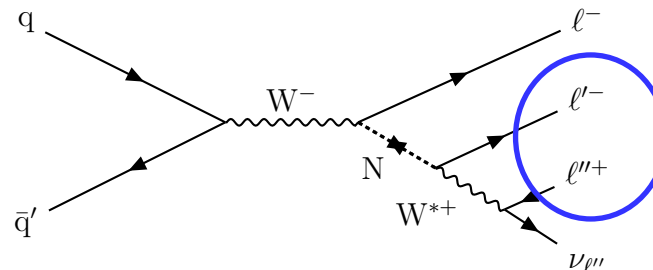
Long-lived particles

- Long-lived particles (LLP) appear in SM and BSM
 - Small couplings
 - Phase-space suppression
 - Heavy intermediate states
 - (almost) conserved symmetries
- Signatures
 - timing
 - ionization
 - displacement
- Dedicated reconstruction techniques
- Benchmark models with LLP
 - SUSY, HNL, dark sectors



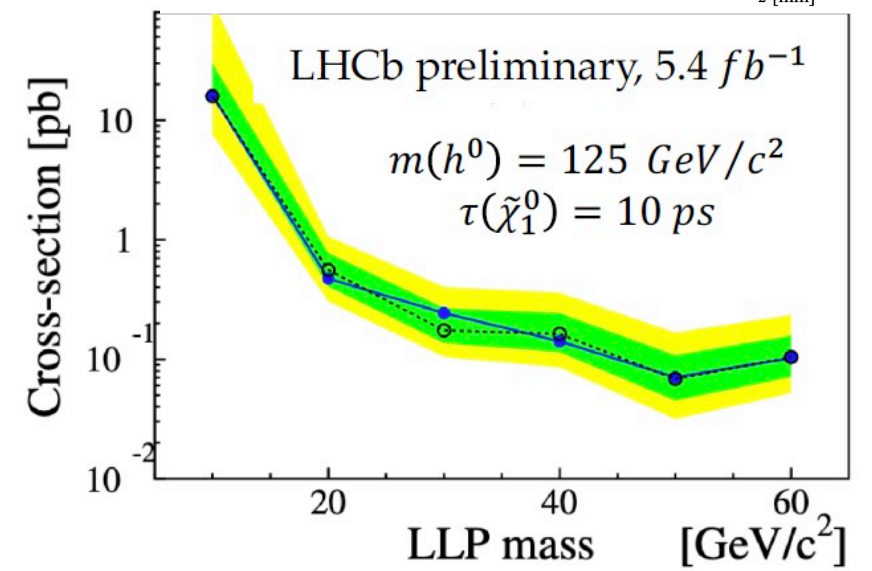
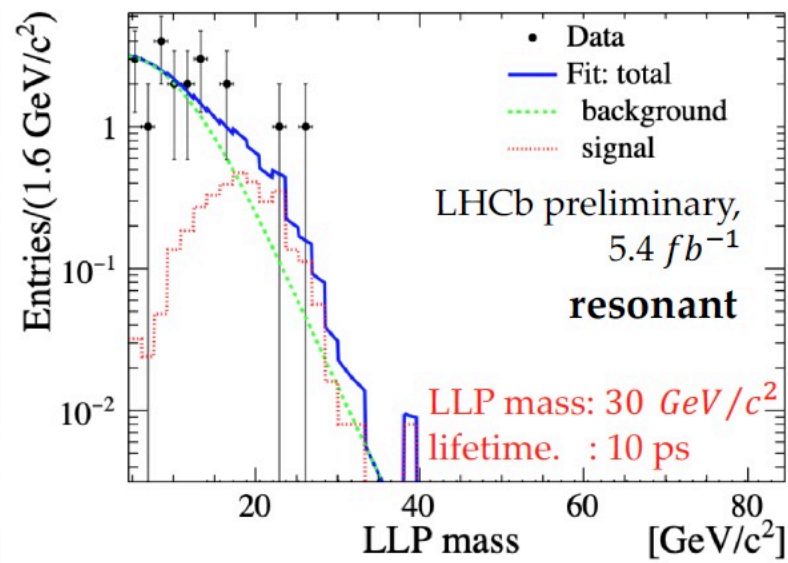
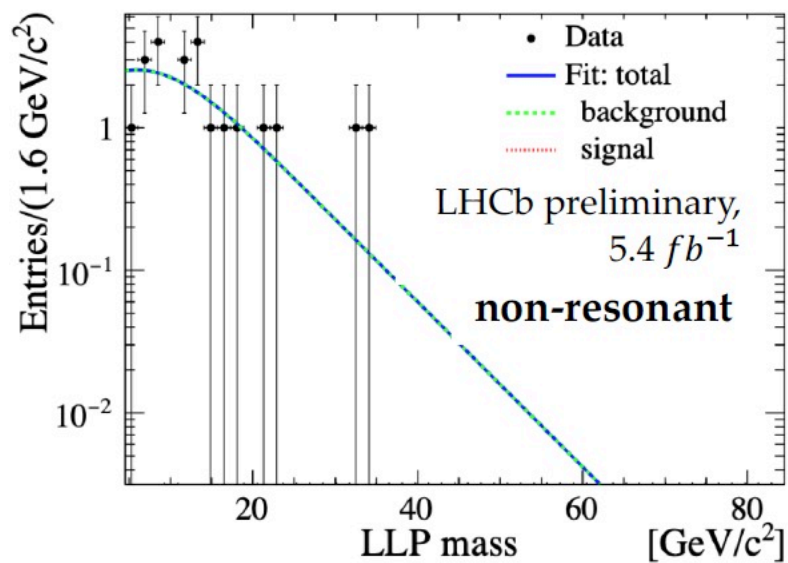
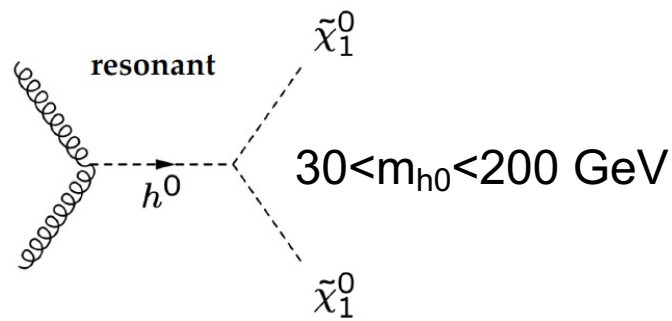
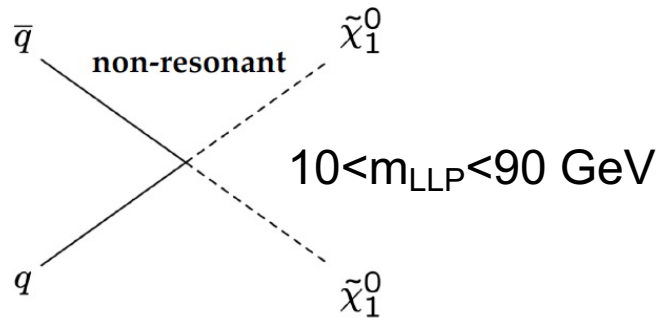
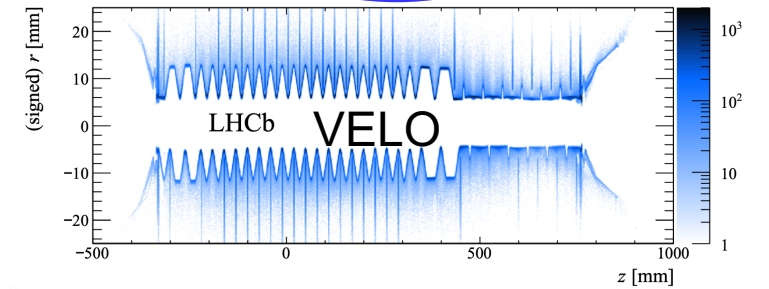
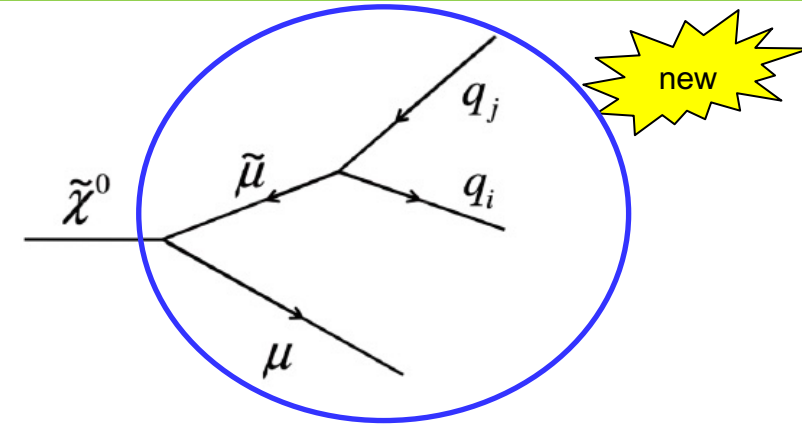
HNL \rightarrow displaced dilepton

- Reconstruct displaced lepton pair vertex in tracker
 - Event categories in distance between primary and secondary vertices Δ_{2D} , m_{ll} , flavor
 - Data driven background loose-to-tight method
- Limits on mixing of N with SM leptons improved by an order of magnitude, best limits



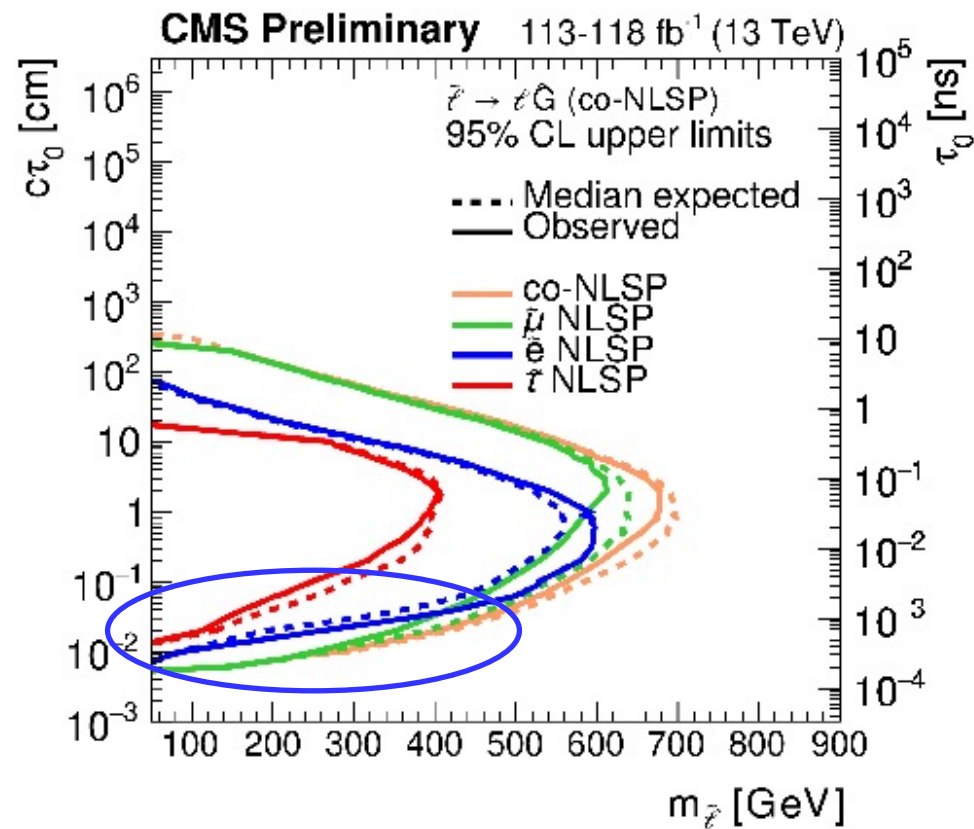
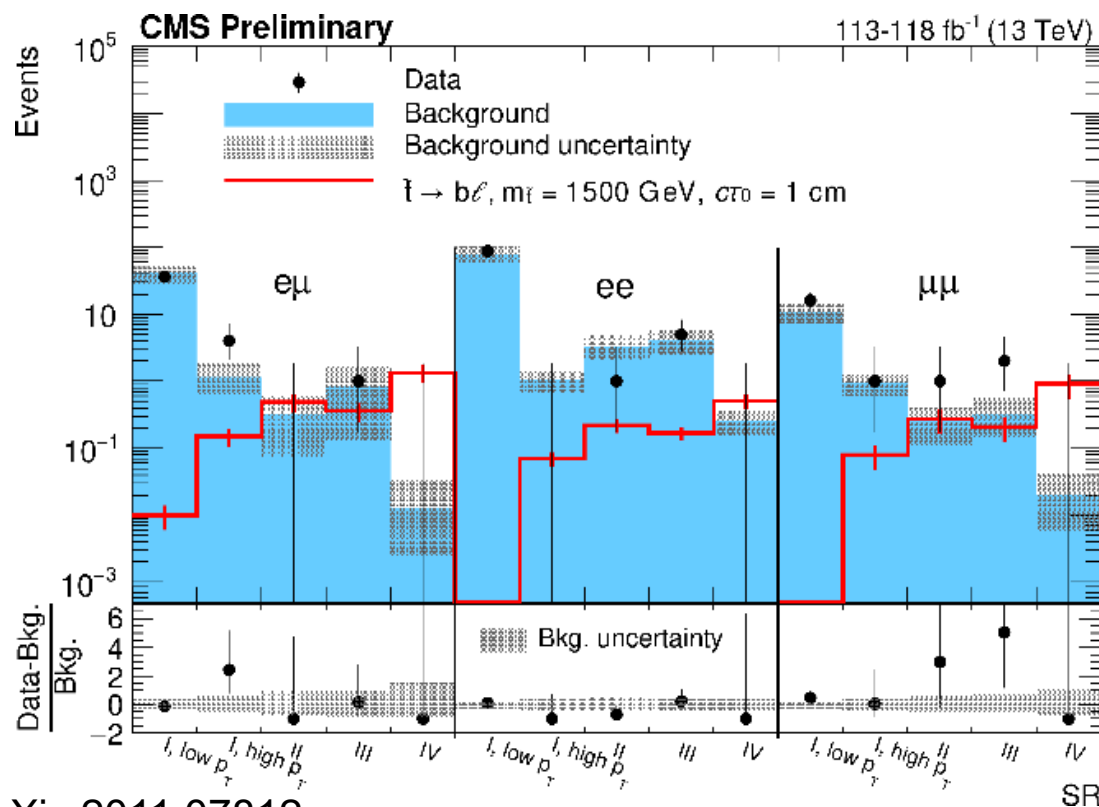
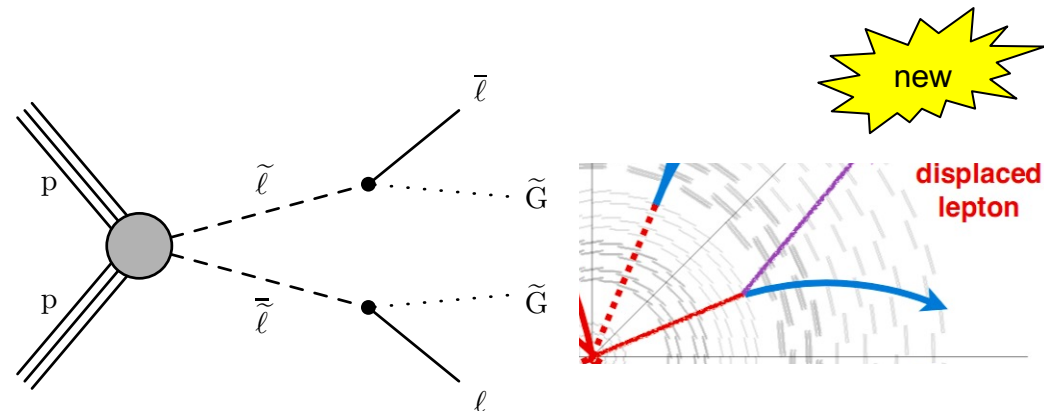
Massive long-lived particles in μ +jets

- Reconstruct displaced ($0.5 < R_{xy} < 20$ mm) high-multiplicity vertex with one associated isolated high- p_T muon
 - MVA kinematic selection
 - Resonant signal extracted from fit to reconstructed LLP mass

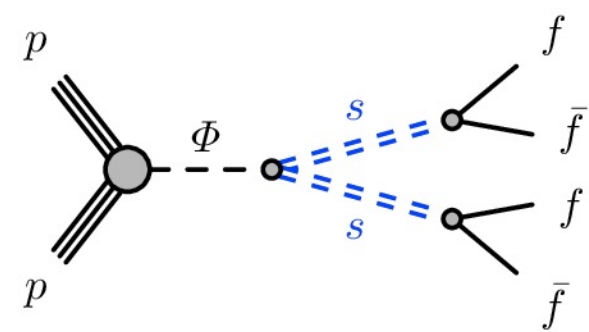
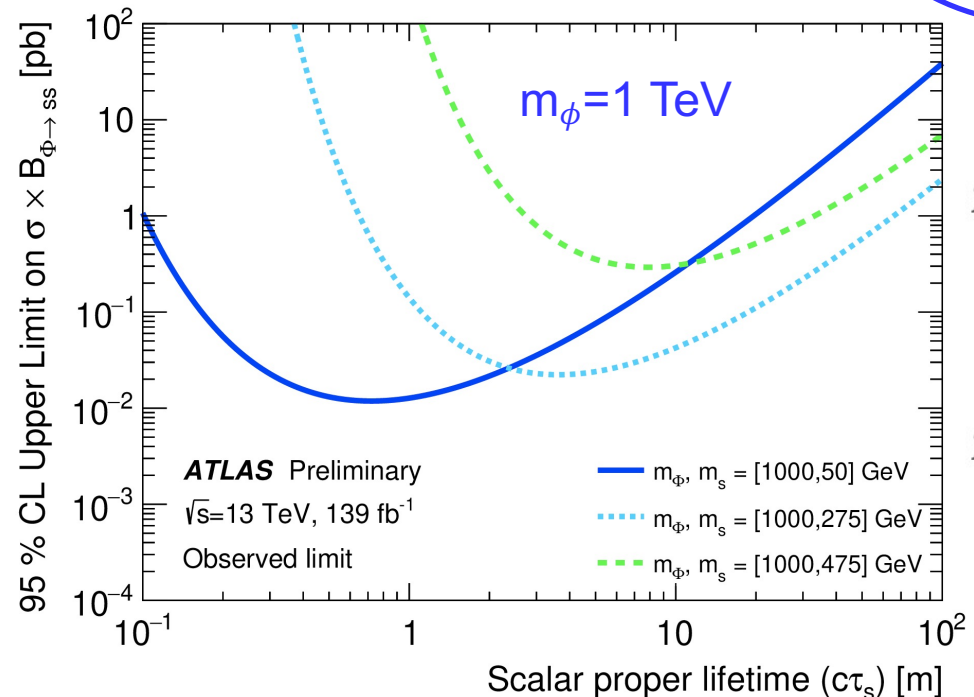
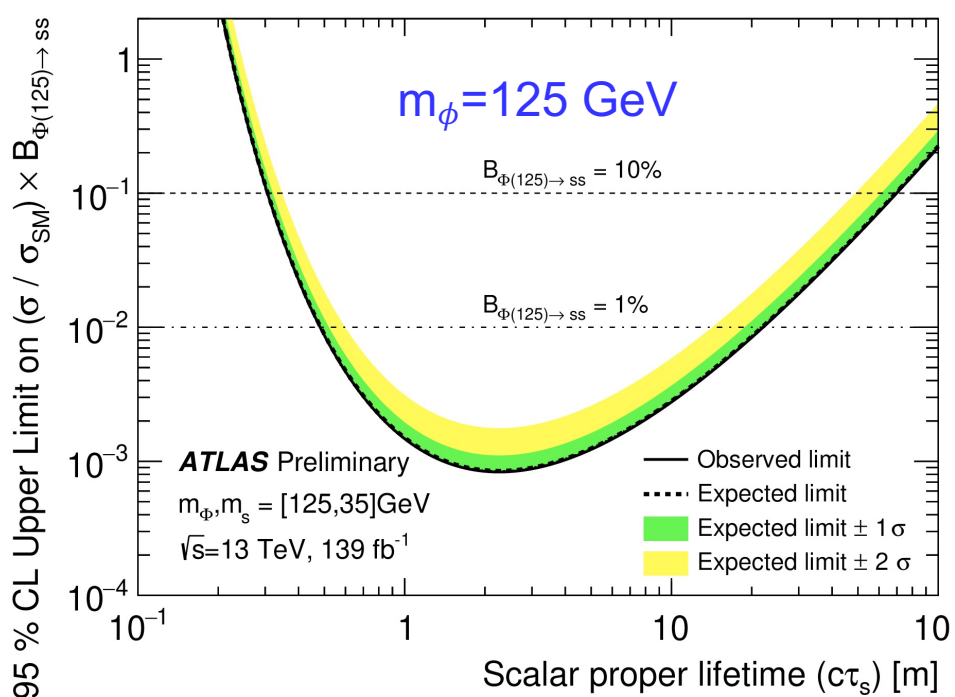
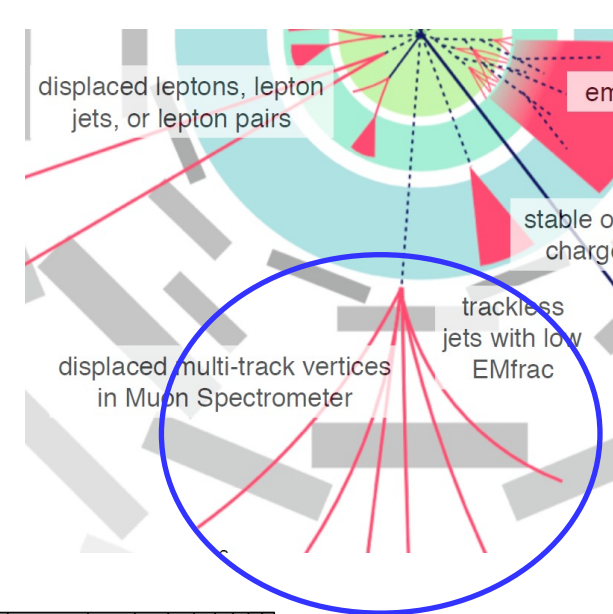


Search for displaced $ee/\mu\mu$

- Displaced $ee/\mu\mu$ search without req. same vertex
 - Detect displacement within pixel tracker
 - Transverse impact parameter $0.1 < |d_0| < 100\text{mm}$
 - Estimate background from prompt lepton region
- Exclusive sensitivity to $\lesssim 1\text{mm}$ compared to [1]



- Reconstruct two isolated vertices in muon spectrometer displaced by 3-14m
 - Data-driven background estimate to 0.32 ± 0.05 events
 - No event observed
- Most stringent constraints in probed lifetime regime



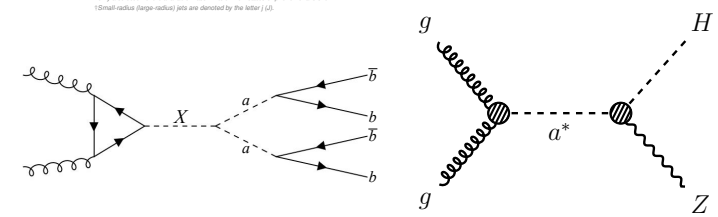
Conclusions

- Large number of models and signatures already explored with LHC Run2 data
- Besides amount of data, sensitivity significantly enhanced over previous early Run2 searches with **new reconstruction and analysis techniques**
- Several **new models/signatures explored for the first time**
- No new evidence for BSM to report today
- Significantly extended range of model phase-space excluded
- **Still many stones left unturned**
 - More exotic models
 - More exotic detector signatures
 - More exotic analysis techniques
 - LHC Run3 with new detector/trigger capabilities

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Model	ℓ, γ	Jets	E_{miss}^{min} [GeV]	Limit	Reference
ADD-GM $\rightarrow 4\ell$	e, μ, τ	0-1	Yes	21.2 TeV	ATLAS-CONF-2018-010
ADD-GM $\rightarrow 2\ell + 2\gamma$	e, μ, τ	0-1	Yes	21.2 TeV	ATLAS-CONF-2018-010
ADD-GM $\rightarrow 2\ell + \gamma + \gamma$	e, μ, τ	0-1	Yes	21.2 TeV	ATLAS-CONF-2018-010
ADD-GM $\rightarrow 2\ell + \gamma + \gamma$	e, μ, τ	0-1	Yes	21.2 TeV	ATLAS-CONF-2018-010
ADD-GM $\rightarrow 2\ell + \gamma + \gamma$	e, μ, τ	0-1	Yes	21.2 TeV	ATLAS-CONF-2018-010

*Only a selection of the available results from ATLAS or other experiments is shown. (Small-radius (large-radius) jets are denoted by the letter L(S)).



$$\rho \equiv \frac{\sigma(pp \rightarrow e^+ \mu^- + X)}{\sigma(pp \rightarrow e^- \mu^+ + X)}$$

