Searches for BSM physics in low-mass, non-resonant, or long-lived signatures with the ATLAS detector

Tiesheng Dai

The University of Michigan

On behalf of the ATLAS Collaboration

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Introduction

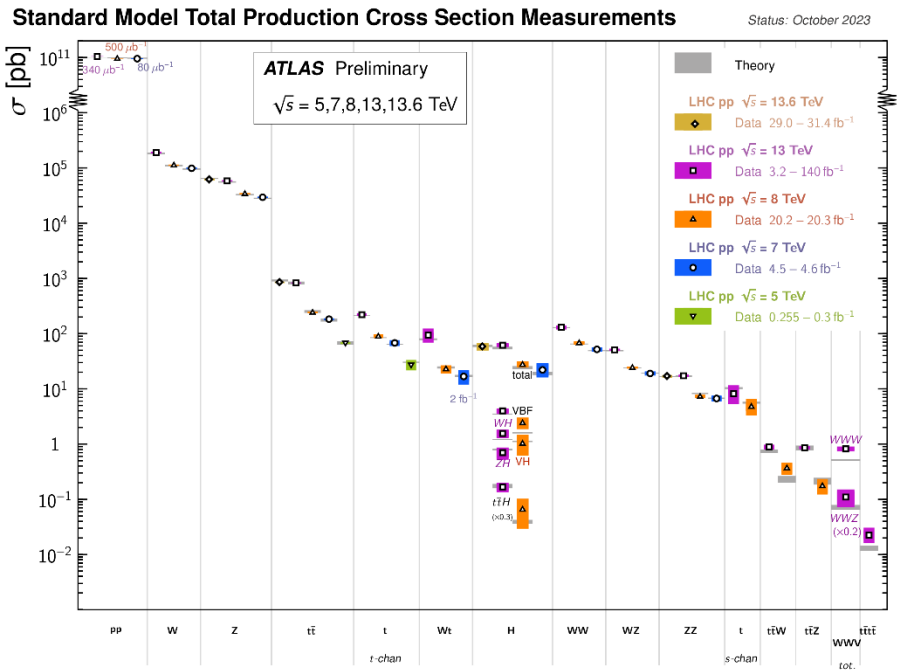
- **SM is very successful with Higgs discovery, data agree with the SM predictions**
- **But some big questions are not explained:**
  - ❑ What are the origins of 95% energy and mass in the universe (dark matter and energy)?
  - ❑ What is the source of matter-antimatter asymmetry in our universe?
  - ❑ Hierarchy problem, why SM m_H << m_{Planck} (Grand Unification Energy) ?
  - ❑ Reasons for observed quark & lepton masses and mixing angles;

ATL-PHYS-PUB-2023-039

- **Many theoretical models beyond the Standard Model (BSM) predict new particles or interactions: SUSY, extra Higgs doublets, 2HDM, Quark-singlet, Composite Higgs, $L_\mu - L_\tau$ models …**

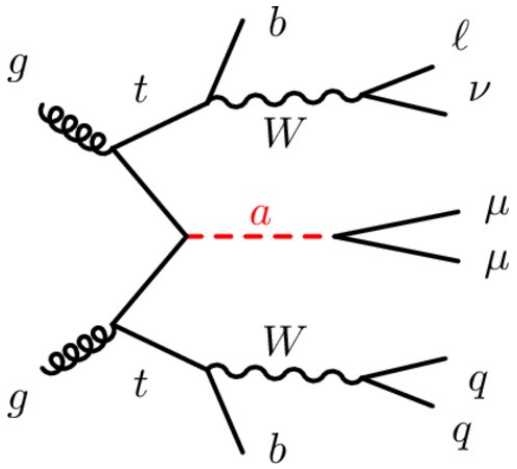
- **Rich phenomenology and final states to explore at the ATLAS**

- **Will report selected recent ATLAS Run-2 results**



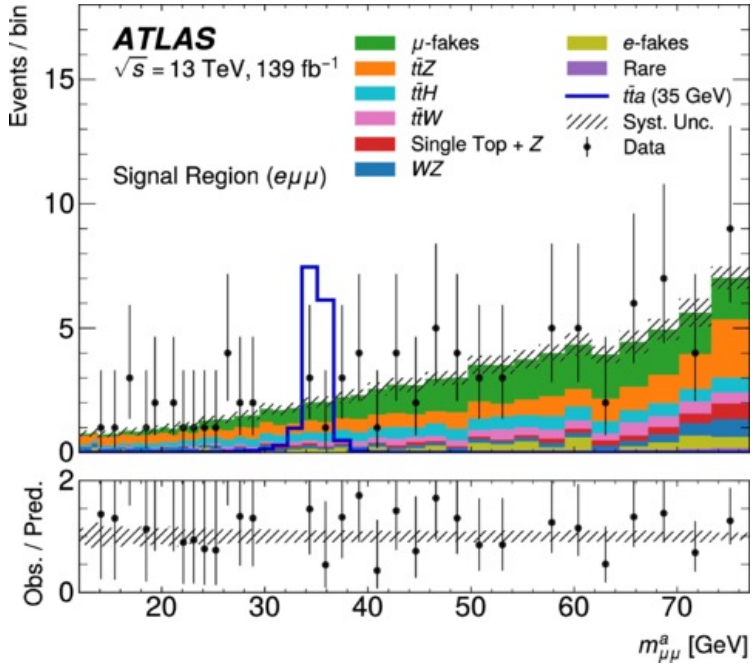
Pseudoscalar a → μμ

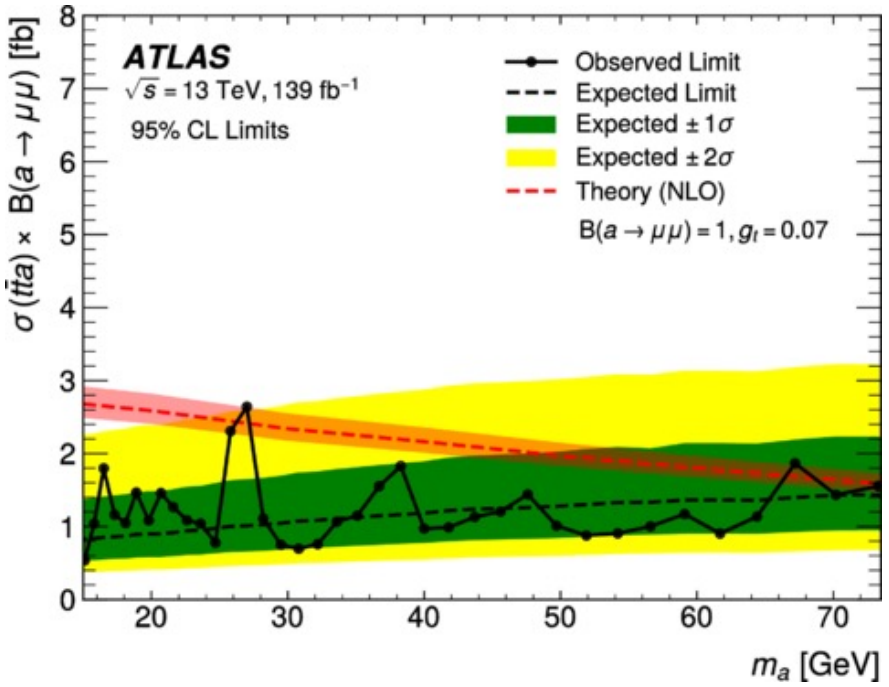
[Phys. Rev. D 108 (2023) 092007]



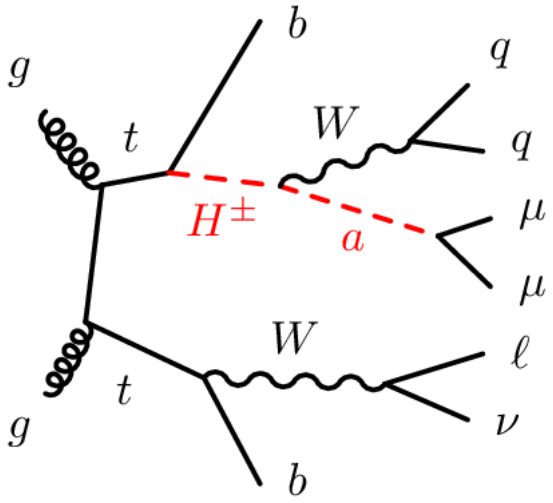
- **Pseudo-scaler "a" produced in association with a pair of pp → tta, a→μμ;**
- Events: $\mu^+\mu^-$, 1 e/μ, ≥ 3 jets & ≥ 1 b-jet;
- Prompt BKGs: leading ttZ, sub-leading ttH, $ttW^{\pm}$, single t, WZ from simulation normalized to data from CRs around Z pole. Data driven method is used to determined the non-prompt μ-fakes and e-fakes BKGs;

- No signal observation on signal strength μ_{sig} of each pseudoscalar "a" mass point by the profile likelihood ratio from signal + BKG fit on different $m_{\mu\mu}$ ➔ exclude signals with **$\sigma(tta^-)B(a \to \mu\mu)$ above 0.5–3 fb** at 95% confidence level.
- A non-significant "bump" at m_a = 27 GeV, corresponding to a local significance of about 2.4 σ.

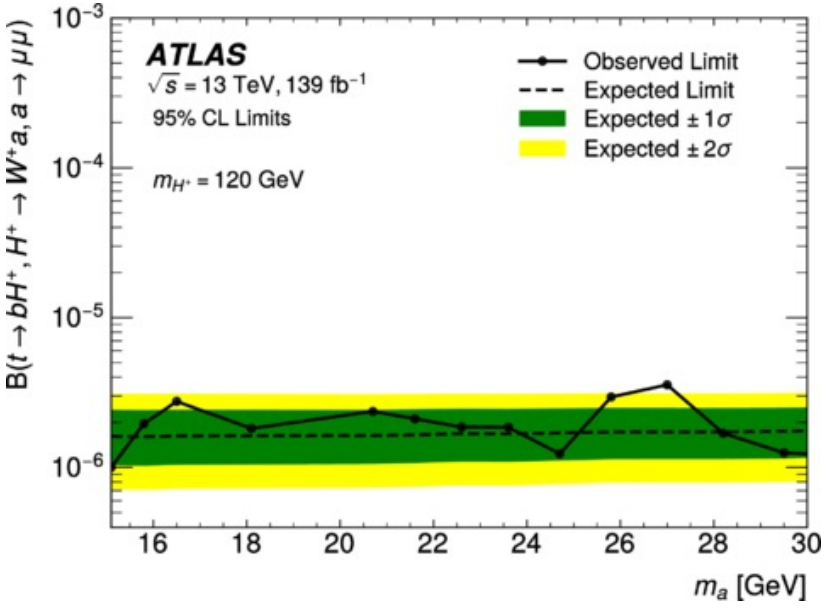


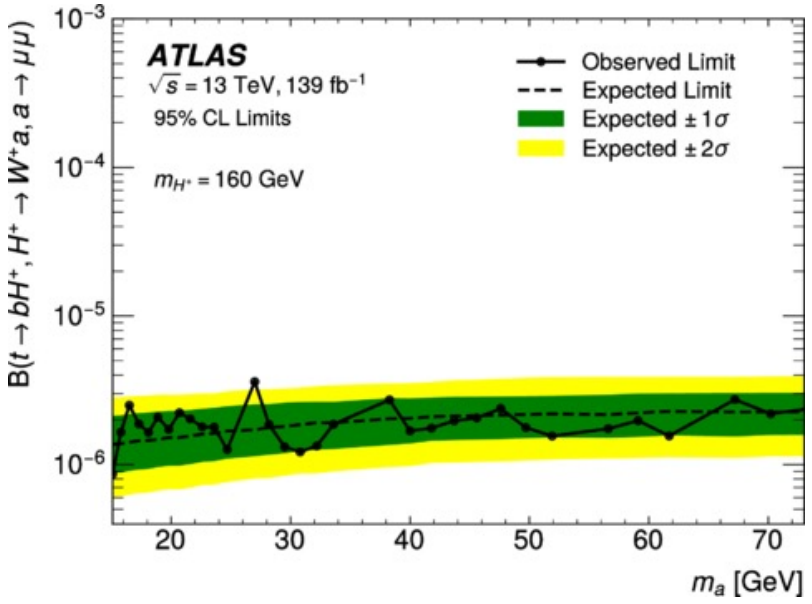


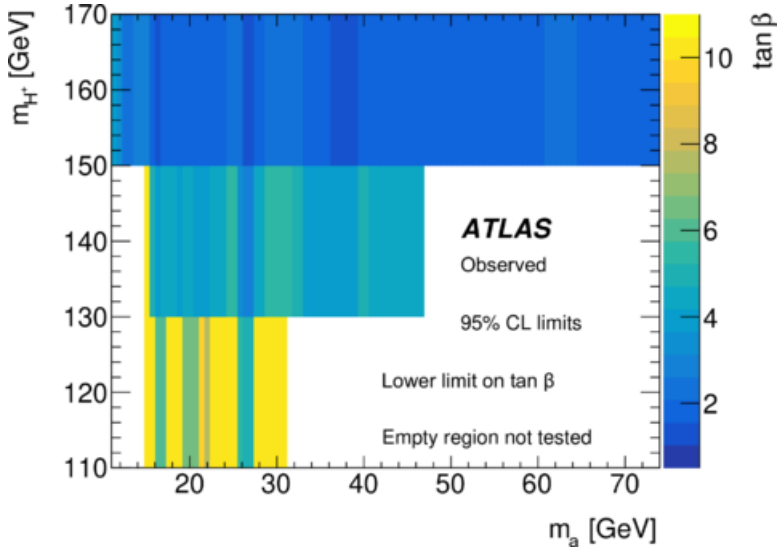
Light Charged/Pseudoscalar $H^{\pm} \rightarrow aW^{\pm} \rightarrow \mu\mu W^{\pm}$ [Phys. Rev. D 108 (2023) 092007]



- **2HDM charged Higgs from top decaying to a pseudoscalar and a W with a→μμ;**
- Events: $\mu^+\mu^-$, 1 e/μ, ≥ 3 jets & ≥ 1 b-jet;
- Prompt leading BKGs ttZ, sub-leading BKS, ttH, $ttW^{\pm}$, single t, WZ from simulation normalized to data from CRs around Z pole. Data driven method is used to determined the non-prompt μ-fakes and e-fakes.
- No signal observation for pseudoscalar "a" mass region of 15 to 72 GeV with charge higgs $H^{\pm}$ mass region of 110 to 160 GeV. by the profile likelihood ratio from signal + BKG fit on $m_{\mu\mu}$ ➔ Set upper limits on the branching ratio $B(t \rightarrow bH+, H+ \rightarrow W+a, a \rightarrow \mu\mu)$ in the range (0.9–3.9) × 10^{-6} at 95% CL.

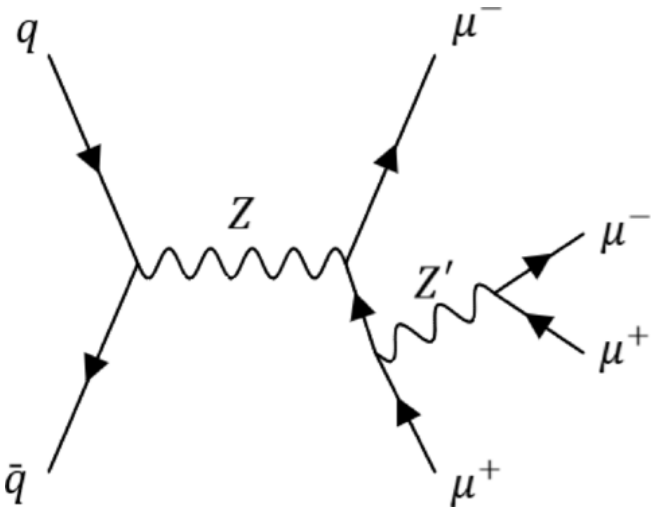




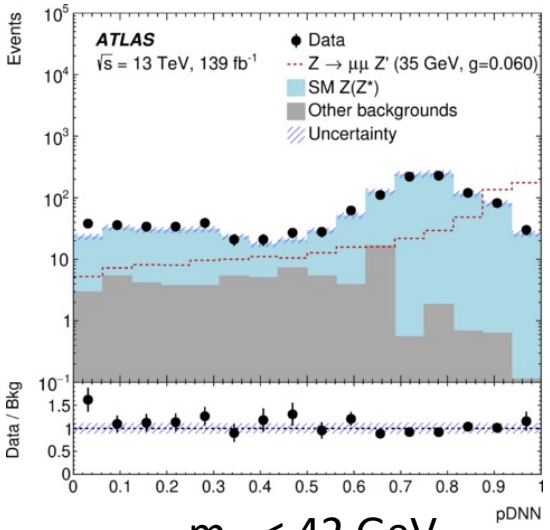


New Z' Vector Boson in 4μ Events

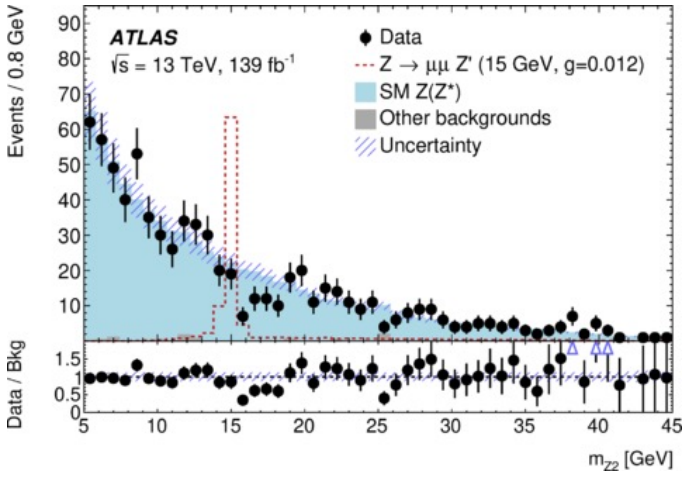
JHEP 07 (2023) 90



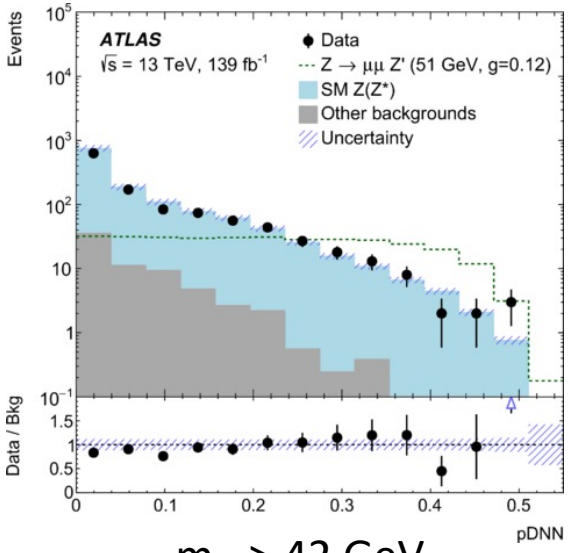
- **Gauged $L_\mu - L_\tau$ models predicts a new Z' only couples to left-handed μ, τ and their ν doublets and right-handed μ and τ singlets;**
- **At the LHC, the Z' from the final-state radiation of or μ, τ and their neutrinos;**
- **Signature: 4μ opposite-charge pair events around Z pole;**
- Major BKG Z or ZZ* → 4μ with small contribution from gg → ZZ*, ttV, VVV & H determined by MC. Z+jets and tt^- fake/non-prompt BKGs are estimated by data driven fake-factor method from CRs.
- Parameterized deep neural network (pDNN) score to categorize 4μ events as signal or background at different Z' hypothesis masses. The model is optimized by Bayesian method for hyper-parameters in order to automatically to the optimal performance



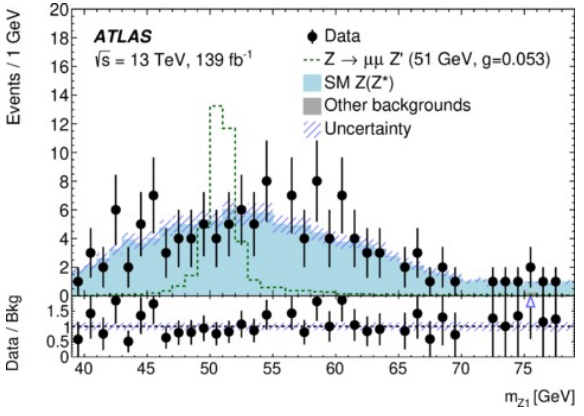
$m_{Z'} < 42$ GeV



Z_2 for Z'



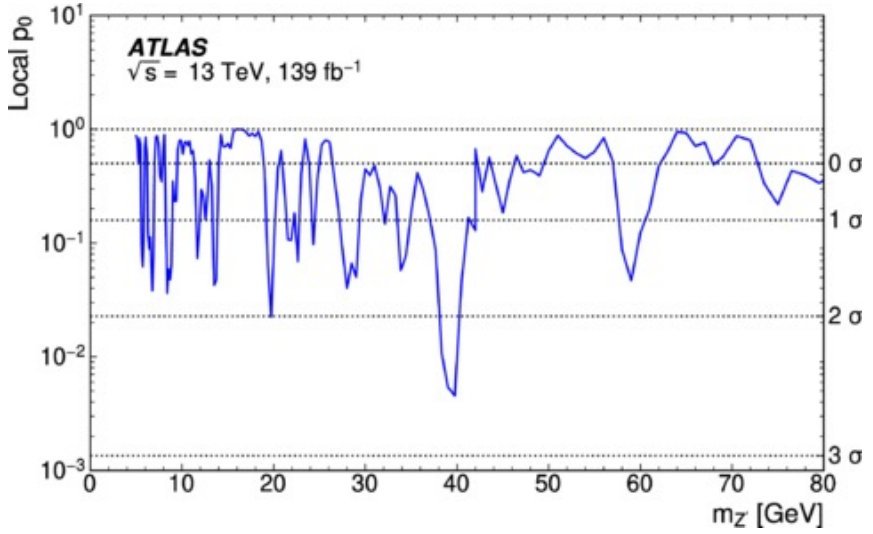
$m_{Z'} > 42$ GeV



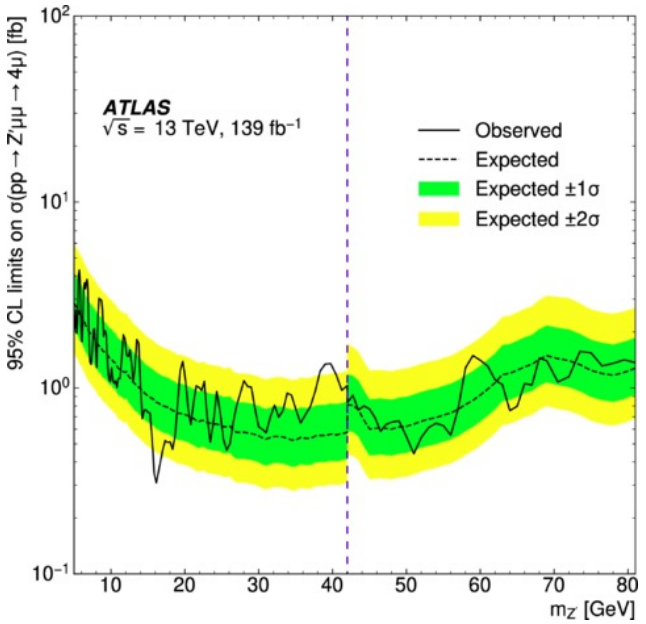
Z_1 for Z'

Results of New Z' Vector Boson in 4μ Events

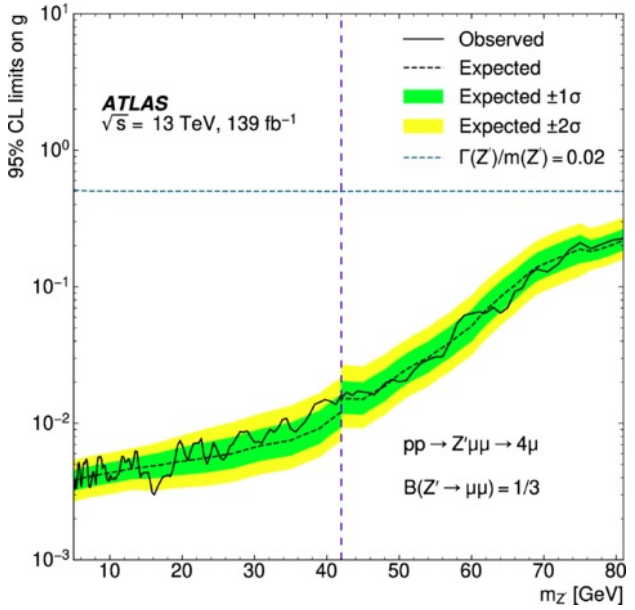
JHEP 07 (2023) 90



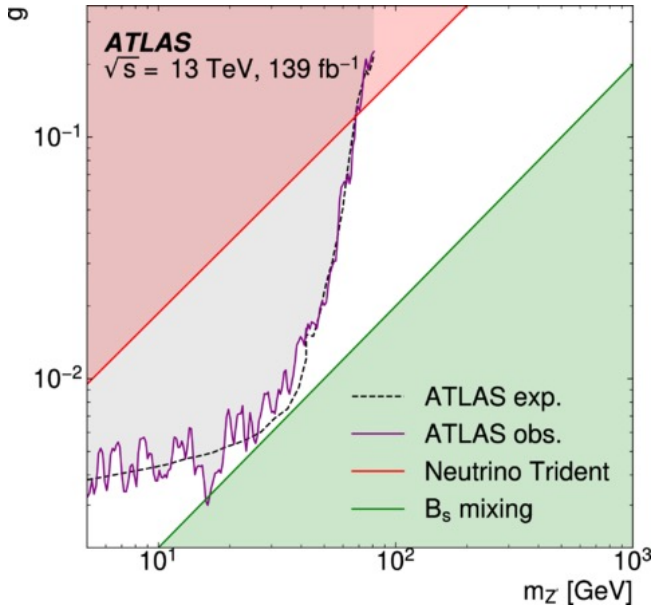
The p_0 scan across the Z' mass signal regions.



σ limits



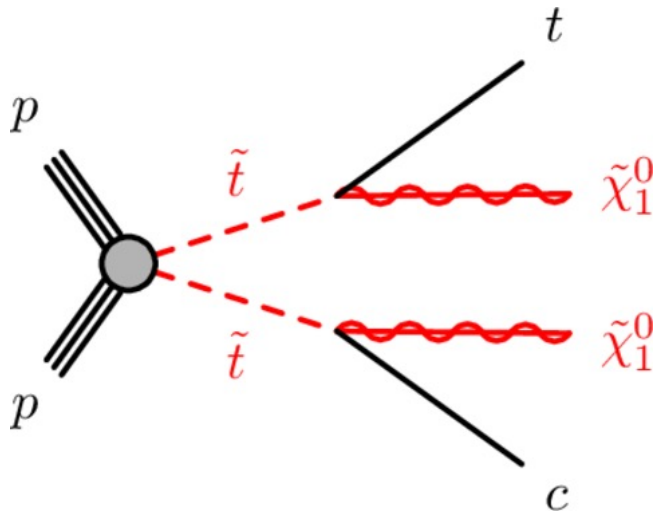
Coupling constant g limits



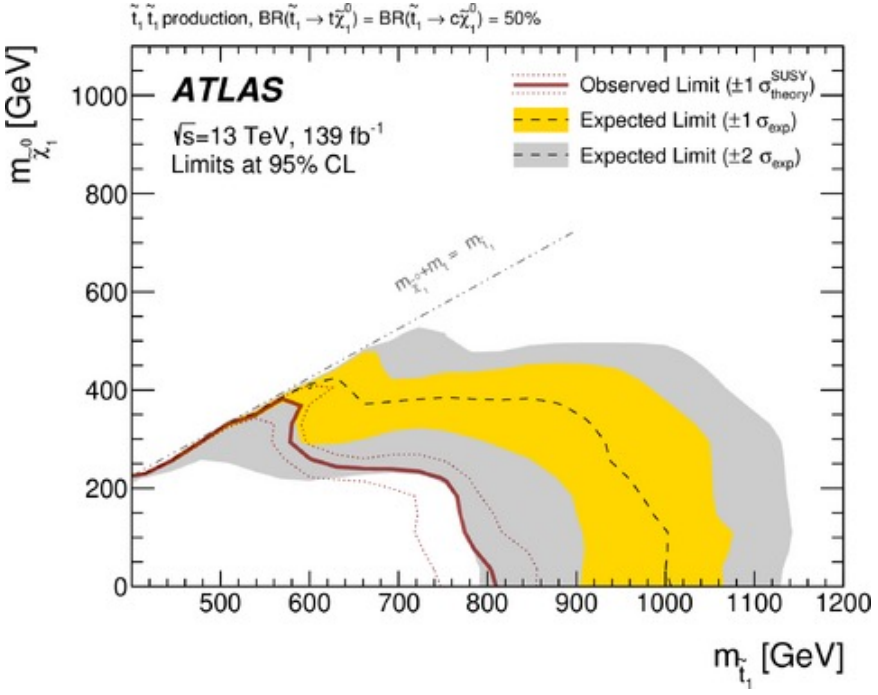
- Obtained cross-section limits by fitting data to the Z_1 and Z_2 mass spectra;
- Excluded coupling strength g of the Z' to u & τ from 0.003 to 0.2;
- Explored Z' coupling g parameter space compared with other experiment results → An interesting parameter space was not excluded by previous experiments is now largely excluded by this search.

New Physics with tc+E_T^{miss}

arXiv:2402.12137

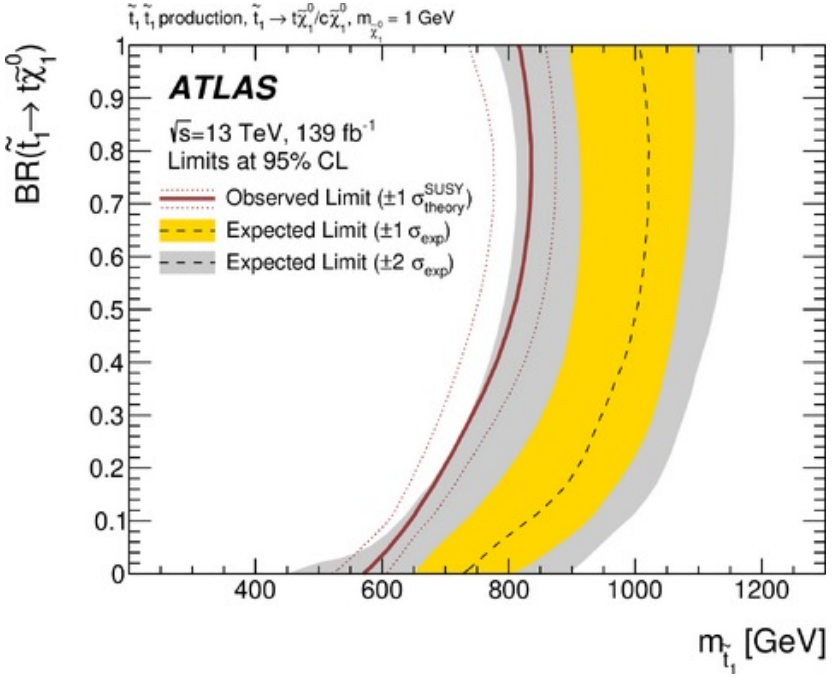


- **Model: a non-minimal flavour violation (MFV) extension of the MSSM with the 2nd and 3rd generation squark mixing, allow $\tilde{t}$ → c$\tilde{\chi}_1$;**
- The DNN top tagger to identify large-R t-jet, special DL1r b-tagger & DL1r$_c$ c-tagger to select b- and c-jets, developed a multi-class NN to isolate signal from BKGs in SRD;
- Signal events: 0 e/μ, >= 3 jets, >= 1 b-jet, >= 1 c-jet and high E_T^{miss}
- 4 SR[A-D], 6 CRs and 2 VRs, where common CRs for predicting the main SM backgrounds and common VRs to validate the background modelling.



Three likelihood fits:

- "BKG-only" fit on CRs for SM BKG modelling;
- "model-dependent" fit on SRs and CRs for establish CLs for a specific BSM hypothesis;
- "model-independent" fit on SRs and CRs to compute the p-value of the SM-only hypothesis

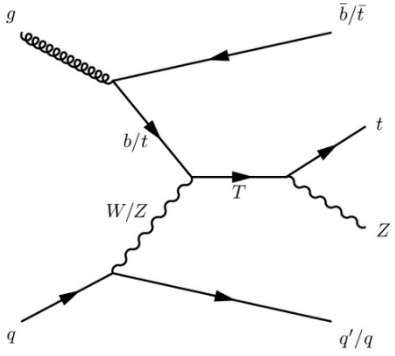


No significant deviations: an exclusion on the m($\tilde{t}$) up to 800 GeV in optimal scenario; up to 600 GeV in compressed region

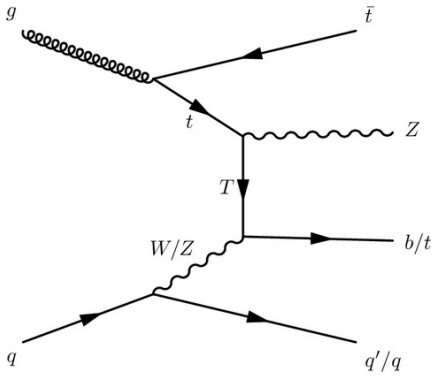
Single VLQ Top Partner in Multi-lep Final State

arXiv:2307.07584
Accepted by PRD

s-channel



t-channel



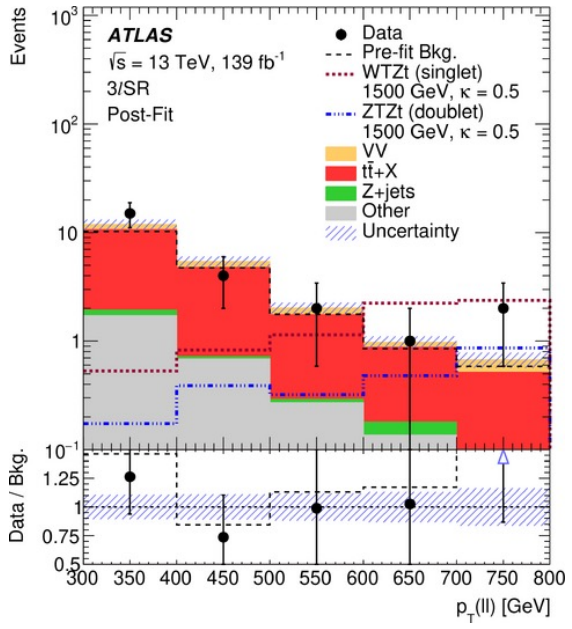
2ℓ Signal/Control/Validation Regions

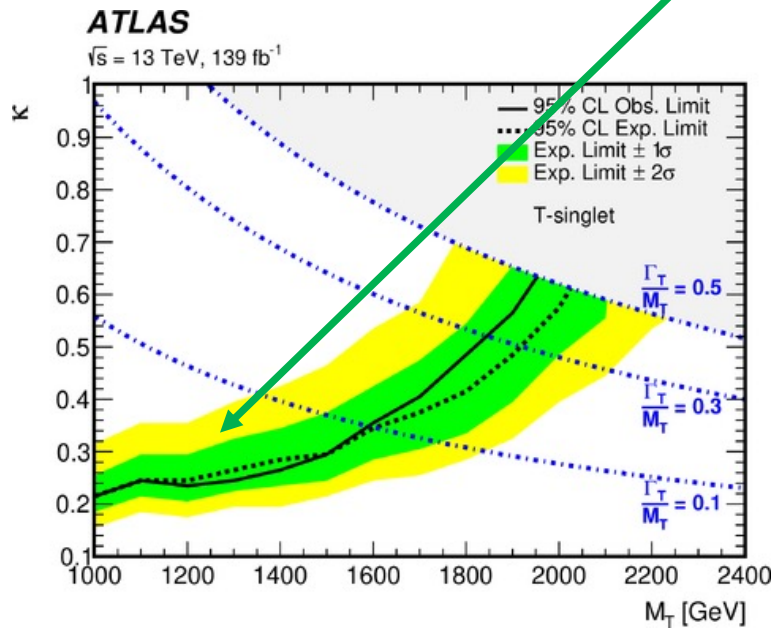
	2ℓCR1	2ℓCR2	2ℓCR3	2ℓVR1	2ℓVR2	2ℓSR
Preselection	= 2 OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV $p_T(\ell\ell) > 200$ GeV, $H_T > 300$ GeV ≥ 1 vRC jet $H_T + E_T^{miss} < m_{\ell\ell J}$					
forward jets	≥ 1	0	0	≥ 1	0	≥ 1
b-tagged jets	0	≥ 1	0	0	≥ 1	≥ 1
top-tagged jets	–	–	≥ 1	≥ 1	≥ 1	≥ 1
top-vetoed jets	≥ 1	≥ 1	–	–	–	–

3ℓ Signal/Control/Validation Regions

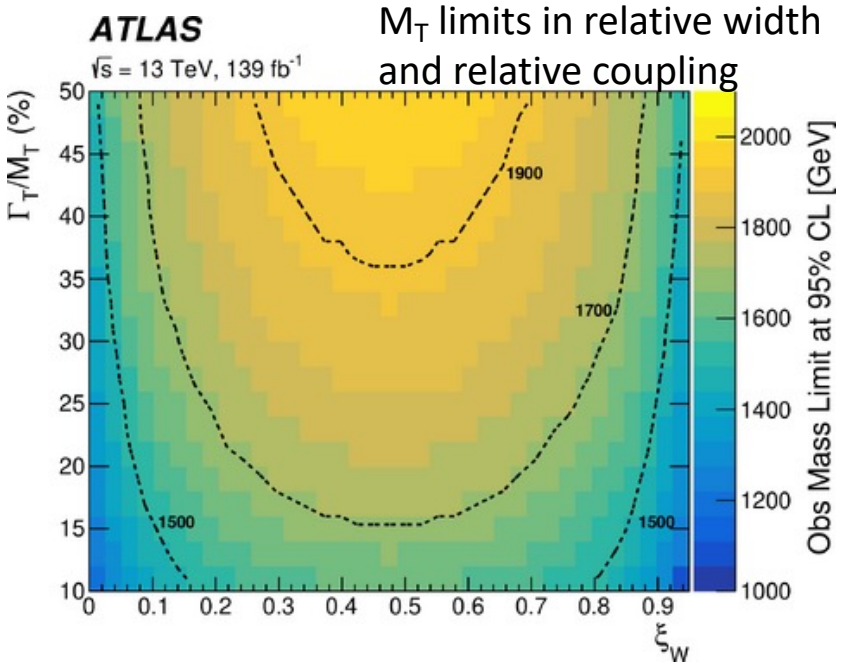
	3ℓVV	3ℓMixed	3ℓttX	3ℓVR	3ℓSR
Preselection	≥ 3 leptons ≥ 1 pair of OS-SF leptons with $\lvert m(\ell\ell) - m_Z \rvert < 10$ GeV ≥ 2 central jets				
b-tagged jets	0	1	≥ 2	≥ 1	≥ 1
forward jets	–	0	0	≥ 1	≥ 1
$\Delta\phi$ selections	–	$\Delta\phi(Z,\ell_3) < 2.6$	$\Delta\phi(Z,\ell_3) < 2.6$	$\Delta\phi(Z,\ell_3) < \frac{\pi}{2}$ **OR** $\Delta\phi(Z,b_{lead}) < \frac{\pi}{2}$	$\Delta\phi(Z,\ell_3) > \frac{\pi}{2}$ **AND** $\Delta\phi(Z,b_{lead}) > \frac{\pi}{2}$
other selections	–	–	–	–	$\max(p_T(\ell)) > 200$ GeV $p_T(\ell\ell) > 300$ GeV $H_T \cdot n(\text{jets}) < 6$ TeV

- **Dominant BKGs (2ℓ sample) from Z+jets, and smaller contribution from VV and $t\bar{t}$, (3ℓ sample) from VV, ttV, ttH;**
- **Signal and SM expectation: extracted from simultaneous binned profile likelihood fit in the discriminating variable $p_T(\ell\ell)$ on CRs and SRs;**
- **No significant deviation from SM ➔ For M_T from 1000 to 1975 GeV, up limits of coupling κ from 0.22 and 0.64.**





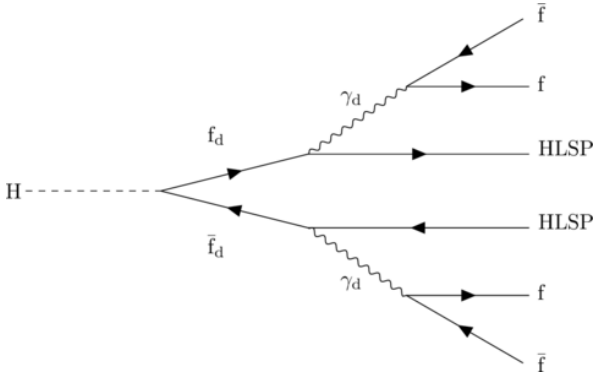
M_T limits in relative width and relative coupling



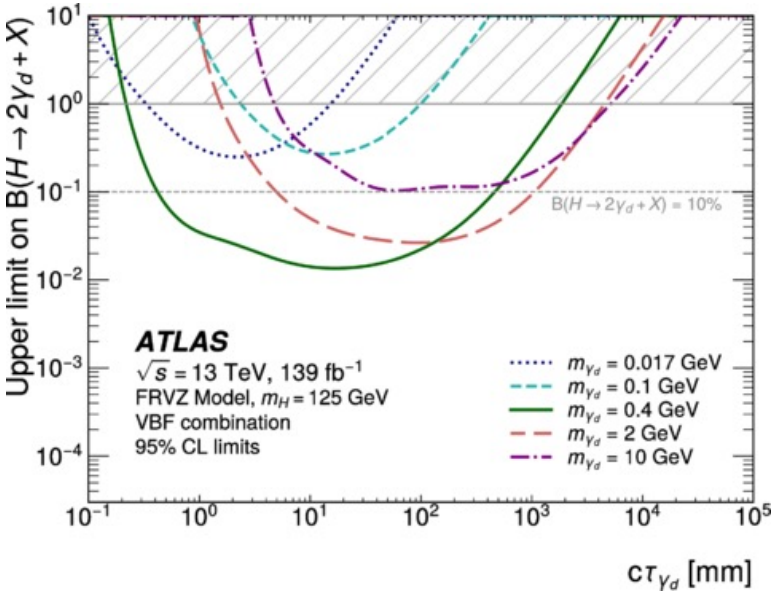
Long-Live Dark Photon

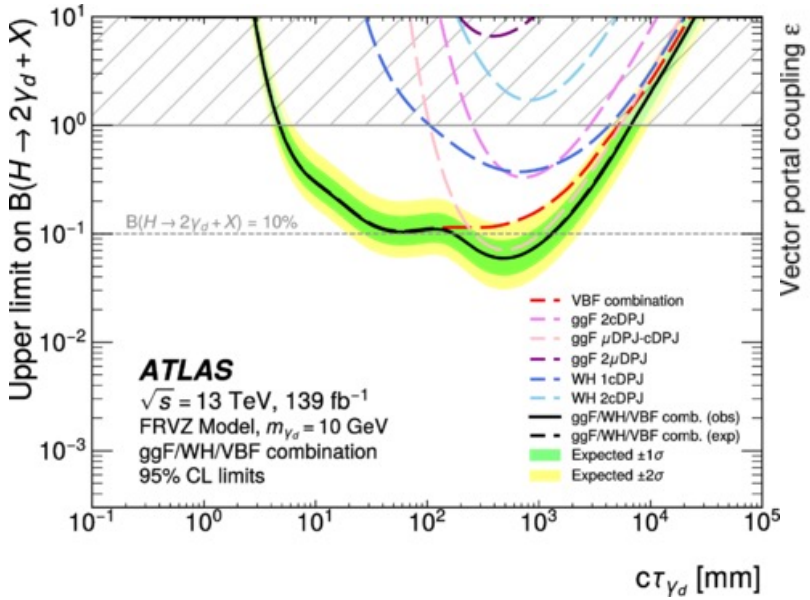
arXiv:2311.18298

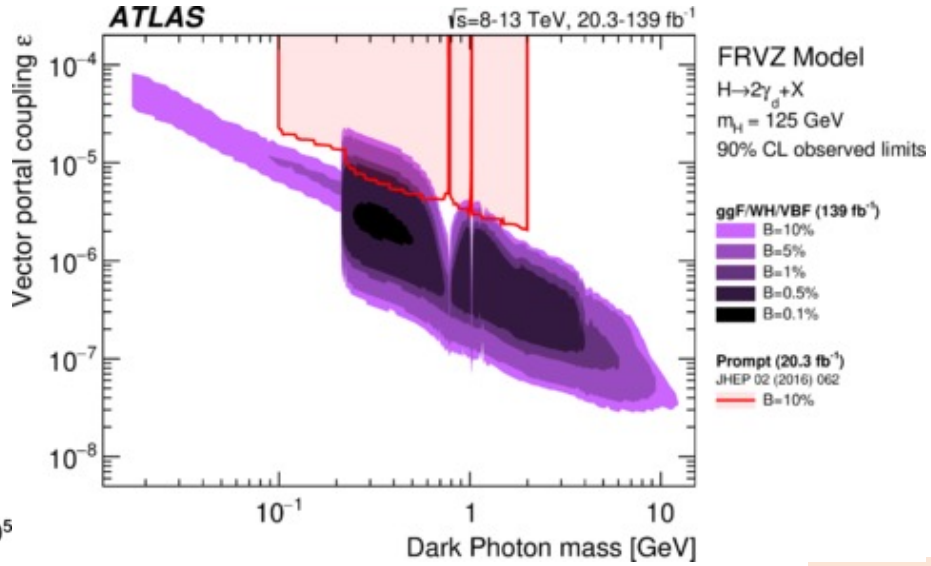
- Search for light long-lived dark photon from Higgs boson decays via VBF;
- QCD tagger based on NN to assign score to each caloDPJ (calorimeter dark-photo-jet);
- BIB tagger with similar strategy as QCD tagger to reduce beam-induced BKGs (BIB);
- Cosmic-ray tagger based on DNN to minimize BGK events from cosmic rays.



- **BKGs are estimated by data driven techniques;**
- **Signal yield obtained from simultaneous maximum-likelihood fit to four (i.e., ABCD) regions;**
- **Data is consistent with expected BKGs**

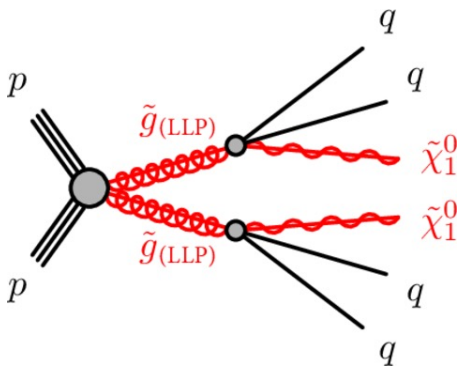






Massive, long-lived Charged Particles

ATLAS-CONF-2023-044



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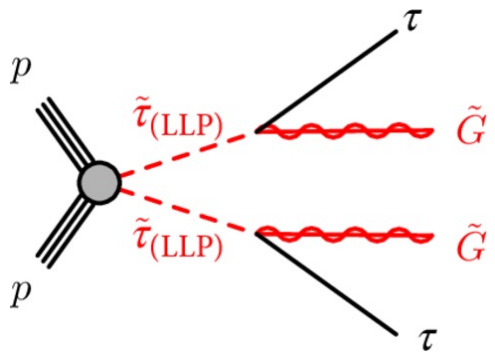
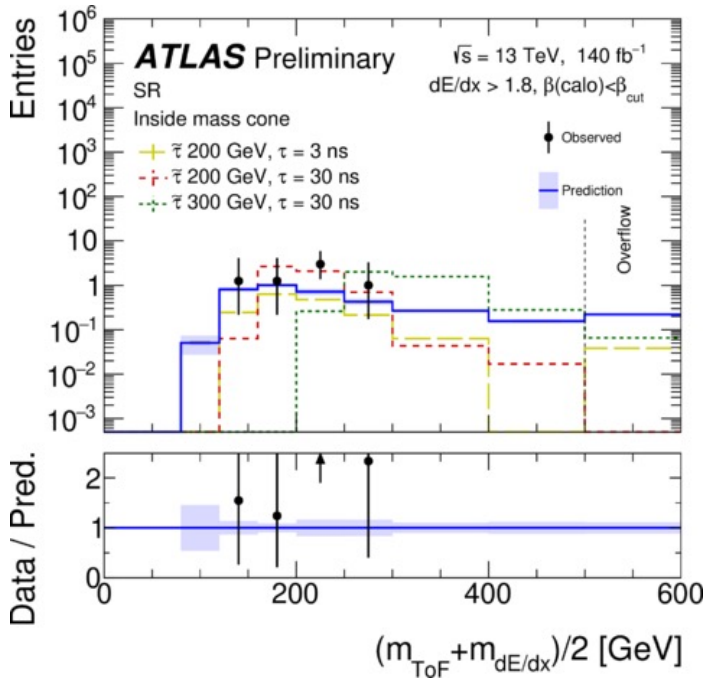
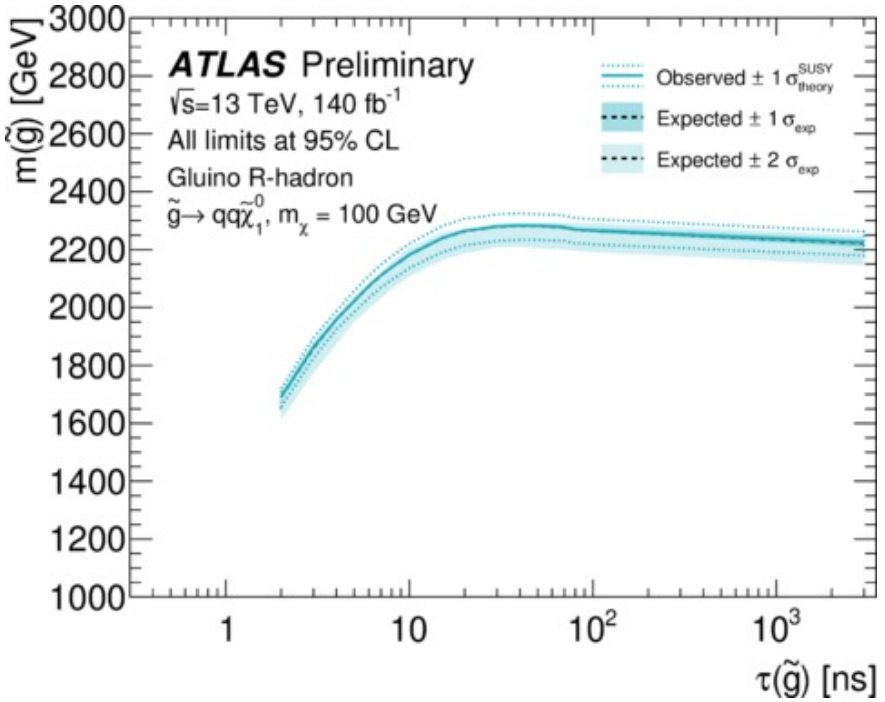


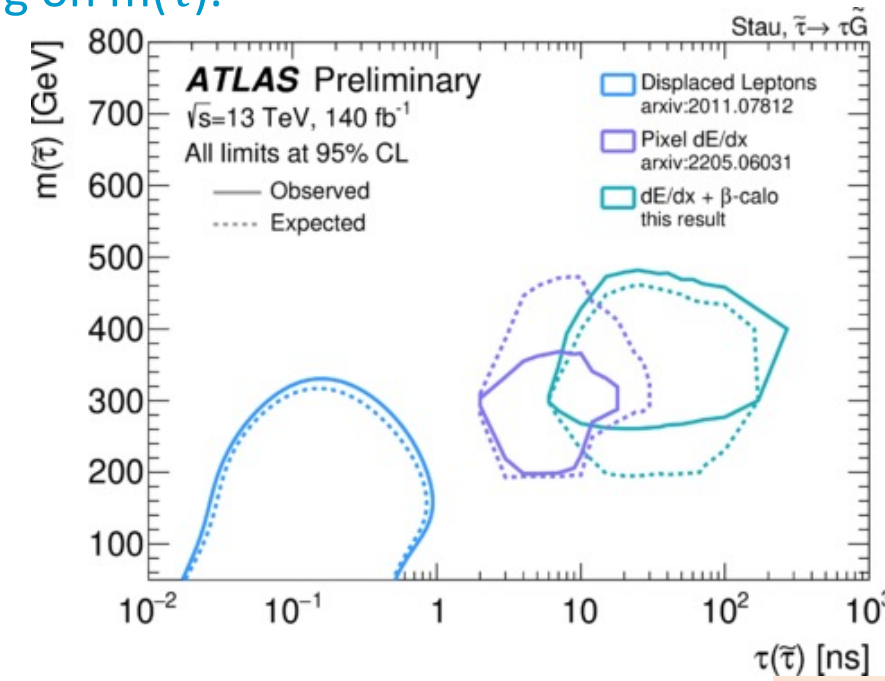
pair-produced staus

- **Search for hypothetical massive, charged, long-lived particles**
- Events with high-momentum isolated tracks with large $\mathrm{d}E/\mathrm{d}x$ and low β_{ToF} ➔ two independent mass measurements per candidate track $m_{\mathrm{d}E/\mathrm{d}x}$ and m_{ToF} using $\beta\gamma$ measured from $\mathrm{d}E/\mathrm{d}x$ and ToF;
- BKGs modeled by using a data-driven technique from CRs and predicted BKGs compared in VRs to validate BKG modelling.

- **No significant deviation from SM predictions** ➔ 95% CL limits in $\tau(\tilde{g})/\tau(\tilde{\tau})$ vs $m(\tilde{g})/m(\tilde{\tau})$ spaces, up to 2.3 TeV for $m(\tilde{g})$ & $\tau(\tilde{g})$ over 200 ns, while extended $\tau(\tilde{\tau})$ to 10 to 100 s depending on $m(\tilde{\tau})$.

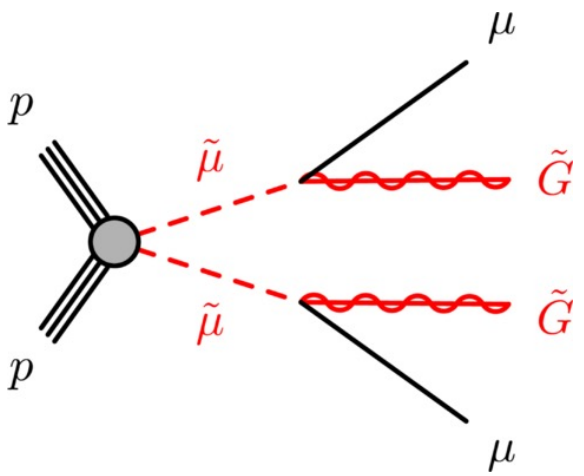


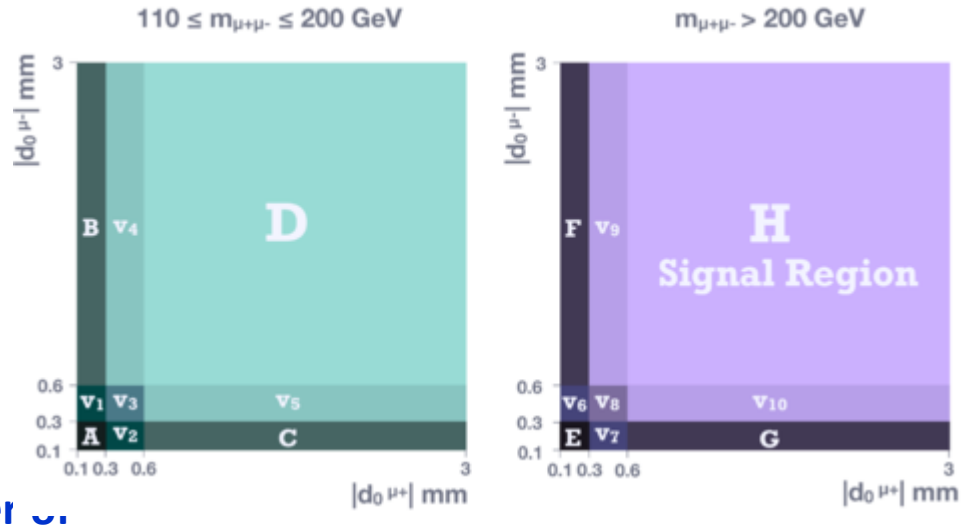




$\mu^+\mu^-$ with Small Displacement

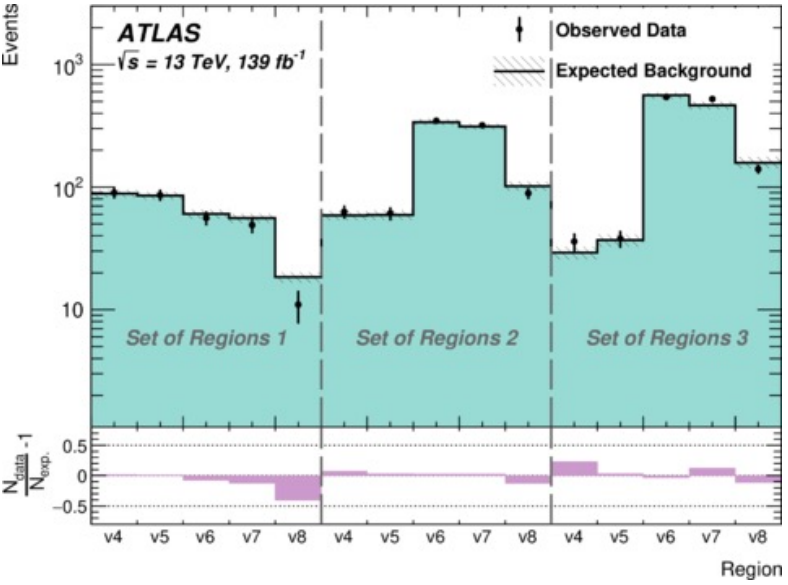
Phys. Lett. B 846 (2023) 138172

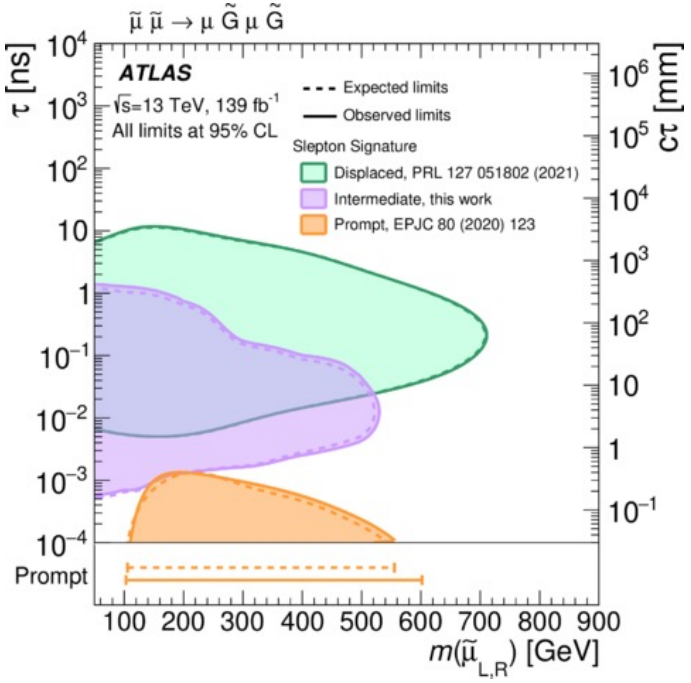




- Search for $\mu^+\mu^-$ (p_T > 20 GeV) from muon supersymmetric partner decays ($\tilde{\mu}\rightarrow\mu\tilde{G}$) motivated by GMSB SUSY models;
- Events categorized based on muon vertex and $m_{\mu+\mu-}$

Expected and observed number of events in the validation regions v4-v8 for each set of regions





- Extended ABCD method with gaps from data to estimate BKGs;
- No surprise ➔ Set 95% CL limits in $\tilde{\mu}$ lifetime vs m($\tilde{\mu}$) spaces, this work (pink area) fills some gap of previous searches with lifetime down to 1ps with m($\tilde{\mu}$)=100 GeV and m($\tilde{\mu}$) up to 520 GeV with $\tilde{\mu}$ lifetime 10 ps

Conclusion

- **ATLAS searched for signatures of BMS including low mass resonances, new physics without resonances and long-live particles;**
- **Multivariable analysis widely used and enhances new physics searching sensitivities;**
- **No deviation is observed from the SM background predictions**
- **Still explore new experiment techniques together with Run 3 data of 13.6 TeV collisions ➔ expecting many new exciting results with potential new physics discovery.**

Thank you!!!

Backups

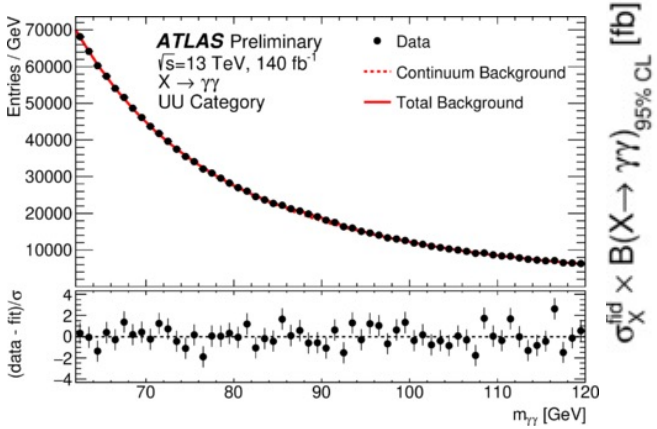
Next two slides of "Diphoton Resonances " and "Light Charged Higgs ($m_{H^{\pm}}$<m_t): $H^{\pm}$→cb ", covered by Matteo Bauce, talk "Searching for additional Higgs bosons at ATLAS (12+3)" under https://indico.cern.ch/event/1382379/

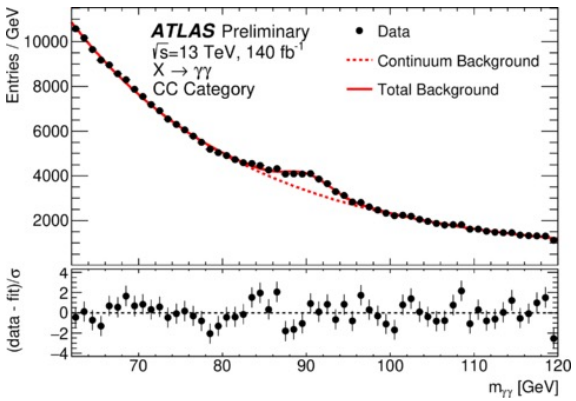
$$E_T^{miss}$$

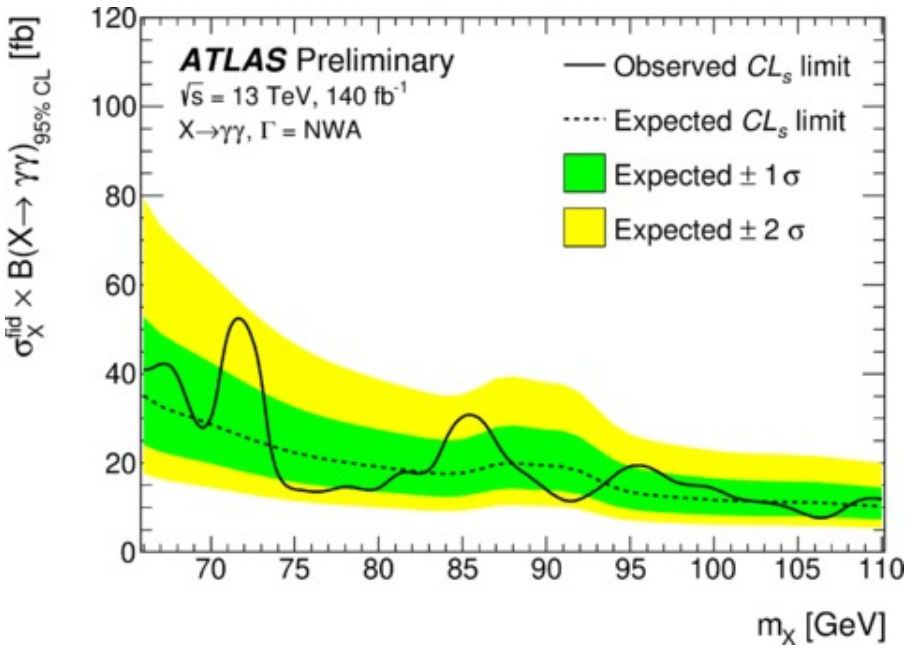
Diphoton Resonances

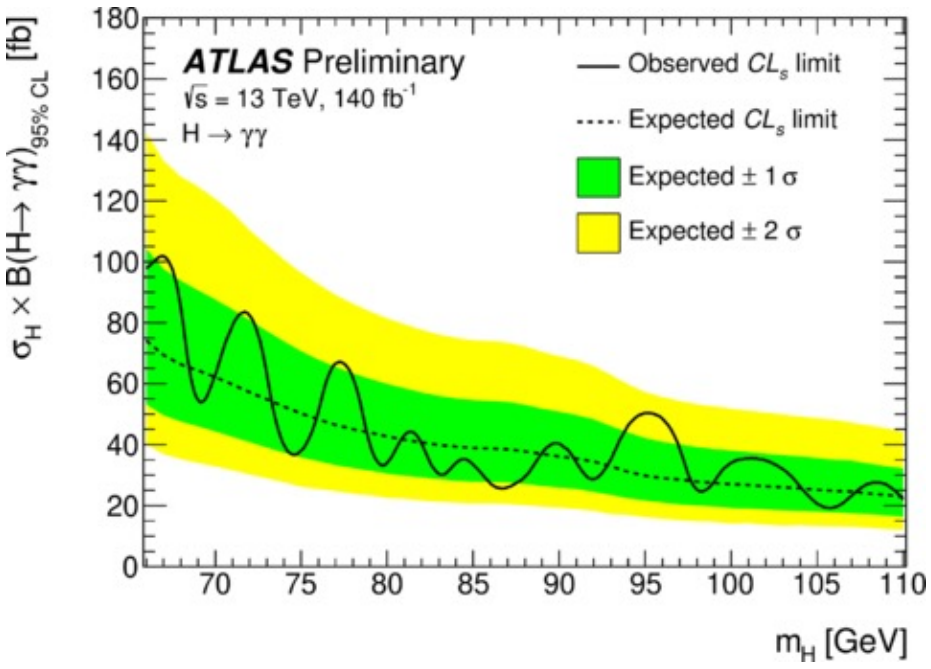
ATLAS-CONF-2023-035

- **BDT for photon–electron discrimination and diphoton BDT to categorize to 3 classes;**
- **2 photons either converted (C) or unconverted (U) to electron pairs ➔ 9 categories (UU1/2/3, UC1/2/3 & CC1/2/3);**
- Signals (66 to 110 GeV): narrow width approximation (NWA) modeled by a double-sided Crystal Ball function (DSCB), composed of a Gaussian core with power-law tails;
- BKG template by using $\gamma\gamma$ MC events and by fitting to γ+jet and jet+jet events from data of control region;
- **No significant deviation from SM predictions ➔ Upper limit of fiducial σ 8 to 53 fb (model independent) and total σ 19 to 102 fb (model dependent).**









Two analysis differences are expected due to the model assumptions and additional categories used in the model-dependent analysis

Light Charged Higgs ($m_{H^\pm} < m_t$): $H^\pm \rightarrow cb$

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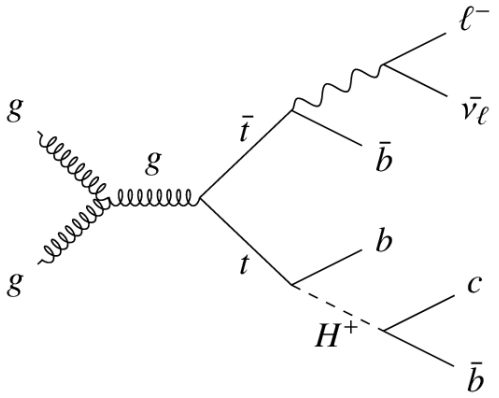
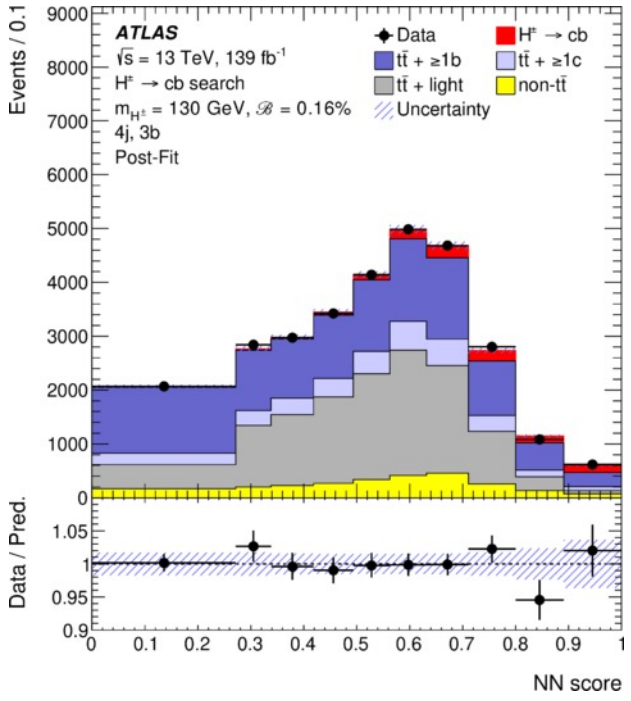
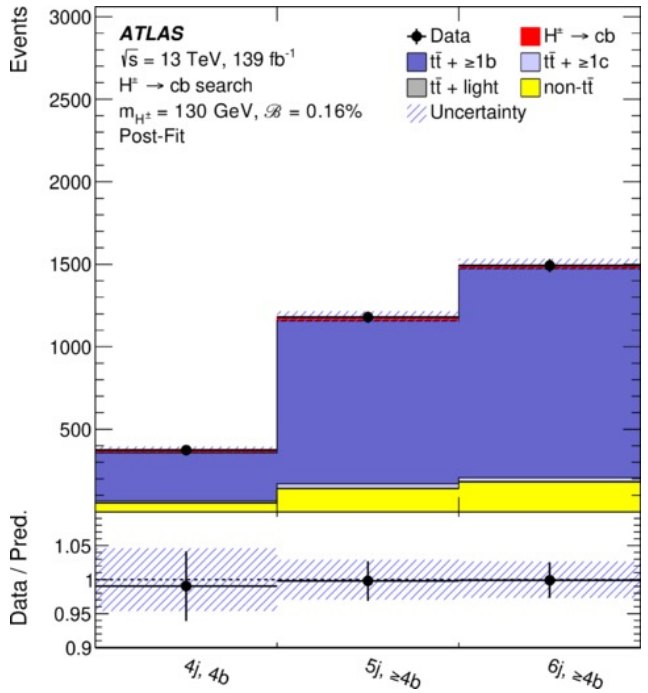
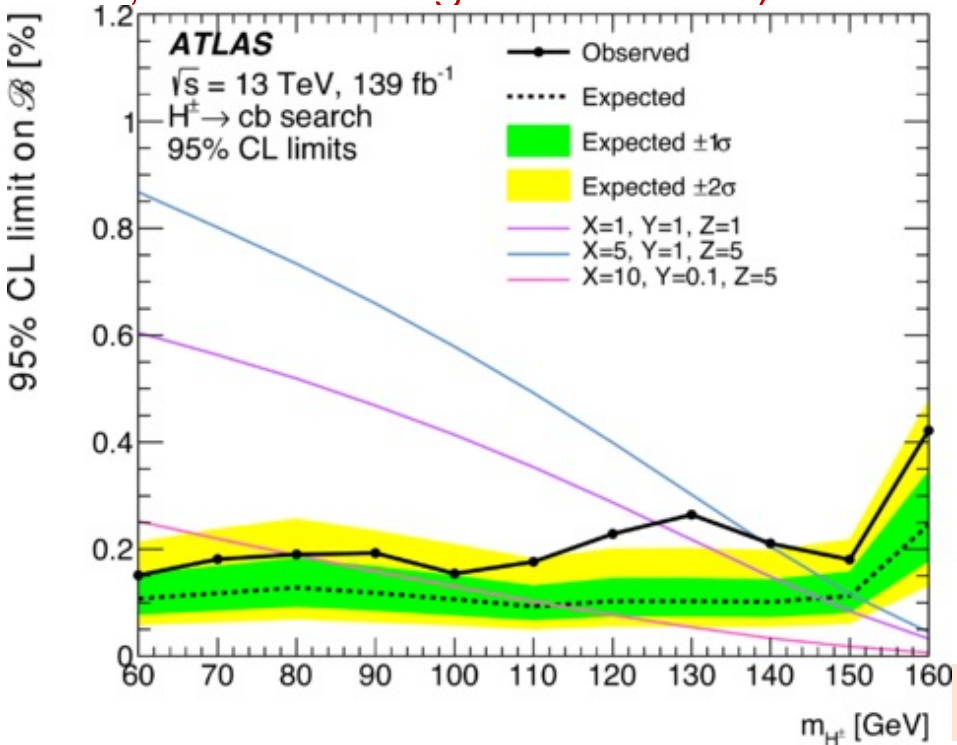


- **3HDM : top pair production with one t → H^+b, $H^+ \rightarrow cb$, another t → W^-b;**
- **Signature: 1 lep (e, μ) + missing energy, at least 4-jets with 3 b-jets;**
- 9 analysis regions based on jet and b-jet multiplicities to allows data-driven corrections to background tt (mis)modelling
- The signal extraction from a binned maximum likelihood fit to the final Neural Network (NN) discriminant on 3 SRs and 6 CRs

No significant excess beyond SM predictions ➔ an upper limit in the range 0.15–0.42% on Br(t → H^+b) for a charged m(H^+) between 60 and 160 GeV (mild excess at m_{H^+} = 130 GeV, with local significance 3σ)







Scalar Resonance in FCNC $t \to qX$ ($q=u/c$), $X \to bb$

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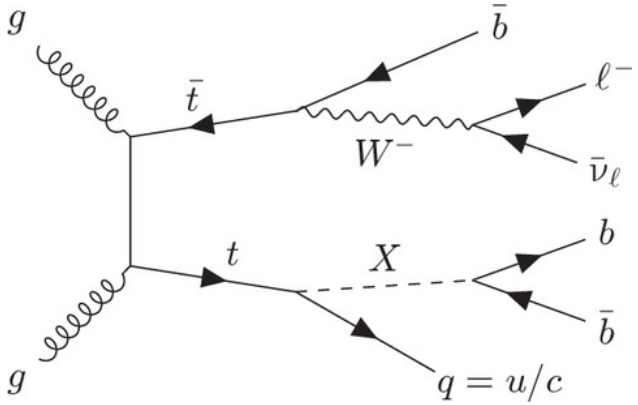
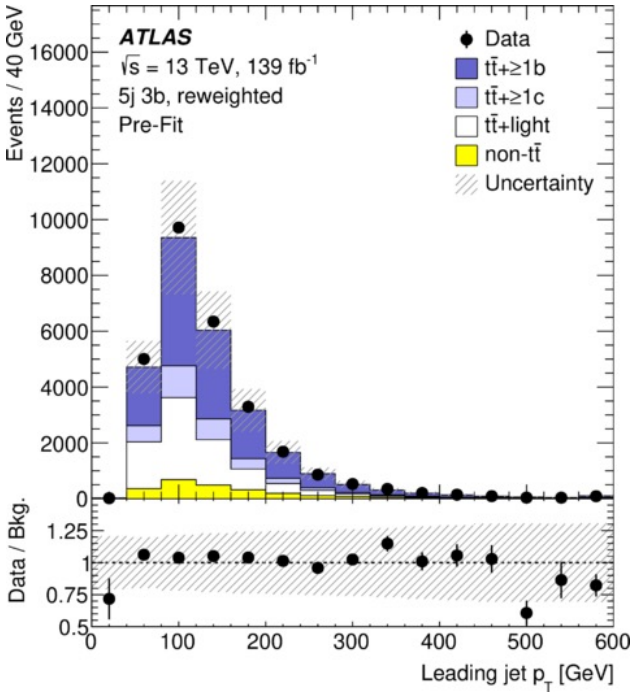
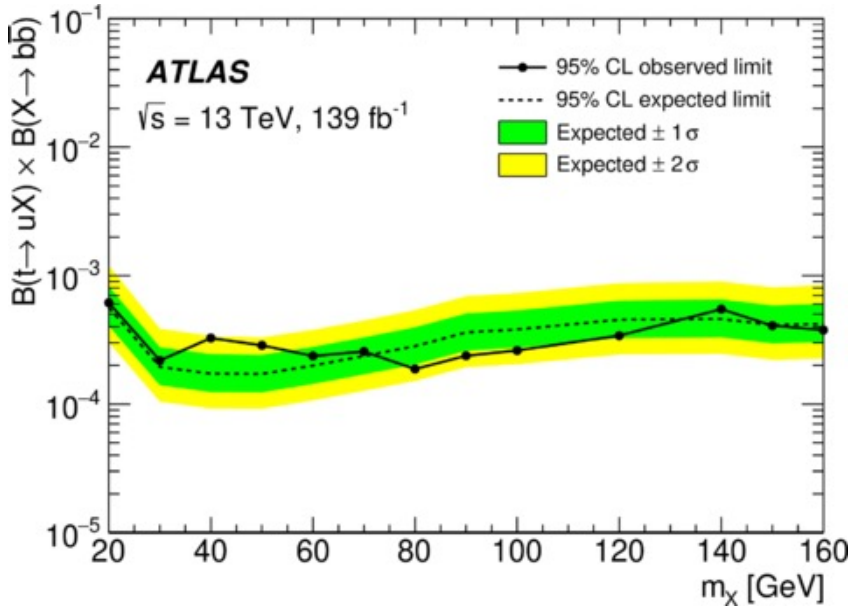
Removed, published on Jan. 10, 2023

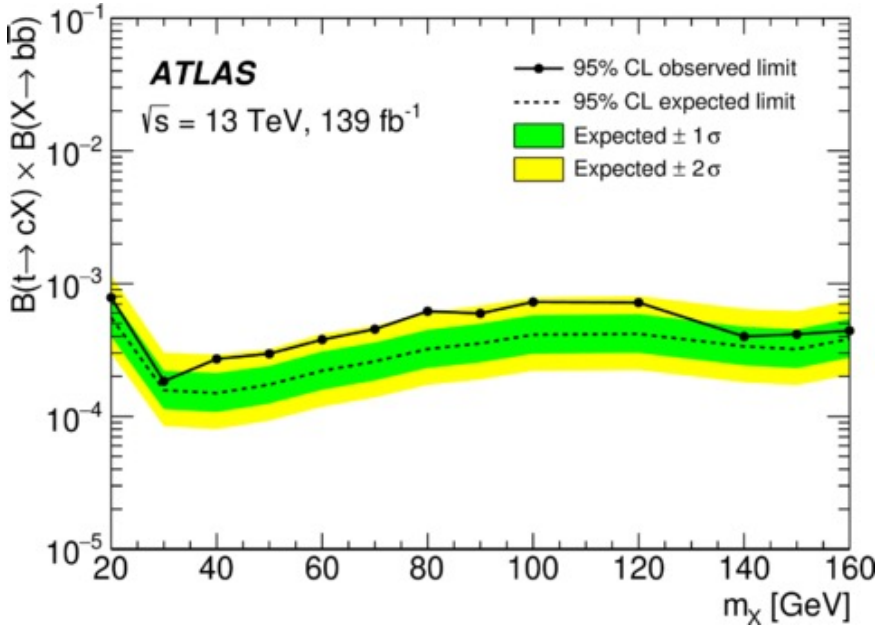
- **Search new physics with SM strongly suppressed flavor change neutral current;**
- **Signature: 1 lep (e, μ) + missing energy, at least 4-jets with 3 b-jets;**
- 9 analysis regions based on jet and b-jet multiplicities to allows data-driven corrections to background tt (mis)modelling
- The signal extraction from a binned maximum likelihood fit to the final Neural Network (NN) discriminant on 3 SRs and 6 CRs



No significant resonance in FCNC observed → an upper limit in the range 0.019–0.062% on Br(t → uX) and 0.018% to 0.078% on Br(t → cX) for a scalar m_X between 20 and 160 GeV.



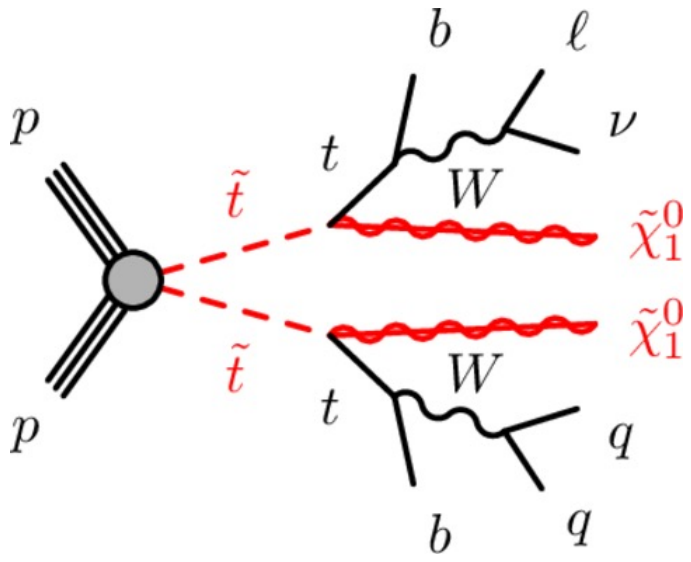




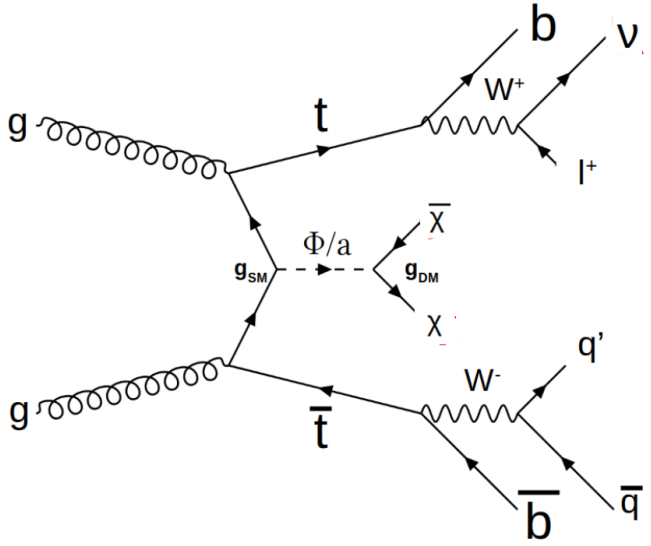
Next two slides of "Dark Photon in Rare Z Decays", covered by Matteo Bauce, talk "Searches for Dark Matter with the ATLAS Experiment at the LHC (12+3)" under https://indico.cern.ch/event/1370675/ based on paper https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2023-22/

New Physics with tt+E_T^{miss}, Analysis Strategy

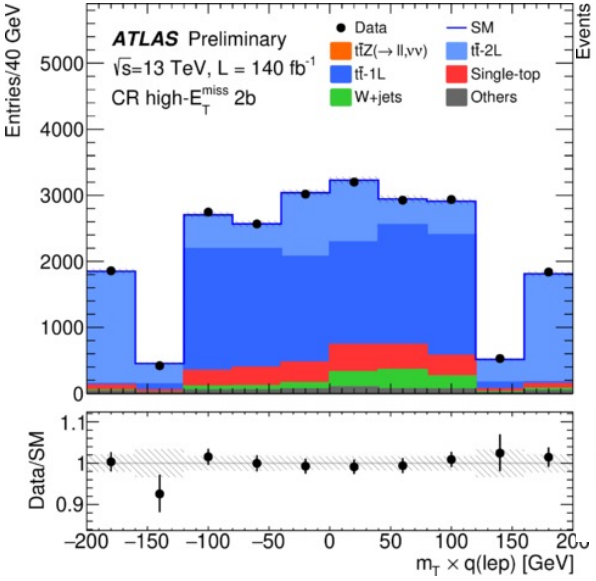
ATLAS-CONF-2023-043

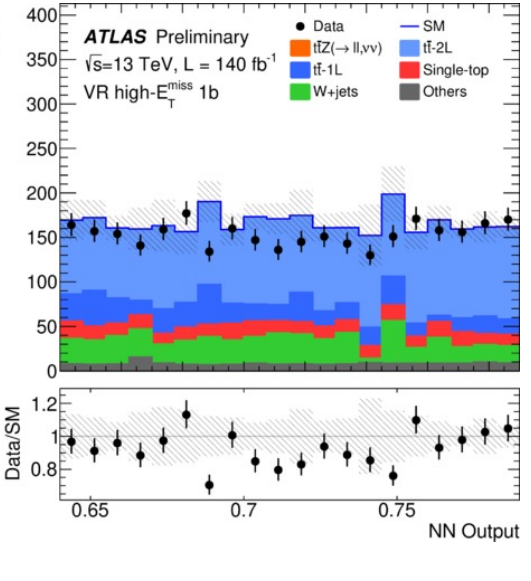


- (Left) SUSY, Stop pair production;
- (Right) Simplified benchmark model for the tt+DM production via a (pseudo)scalar mediator ϕ (a)
- One W→l(e/μ)ν and another W→qq, signature 1 lep +multi-jets + 1/2 bjets + large missing transverse energy.



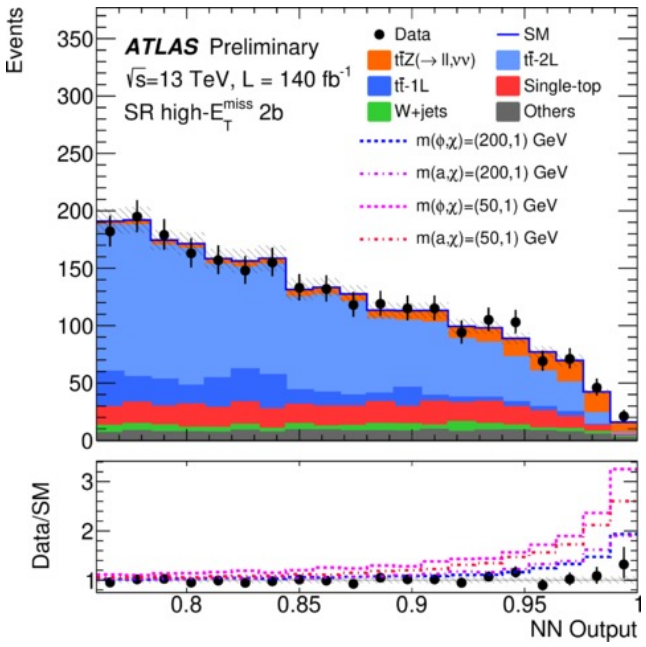
- Events to 8 category: High-E_T^{miss}1b,High-E_T^{miss}2b,2b+1t,1b-had-1t,1b-lep-1t,2b-0t,1b-had-0t,1b-lep-0t;
- Use Neural Network (NN) to reconstruct the hadronic top quark in the event in order to catch signals;
- Use NN score for defining regions and performing multi-fits on CRs+VRs (BKG validation, SRs+CRs (data compatibility, then results);
- The fit to data in different observables using independent normalization factors (NFs) to determine the main backgrounds in situ



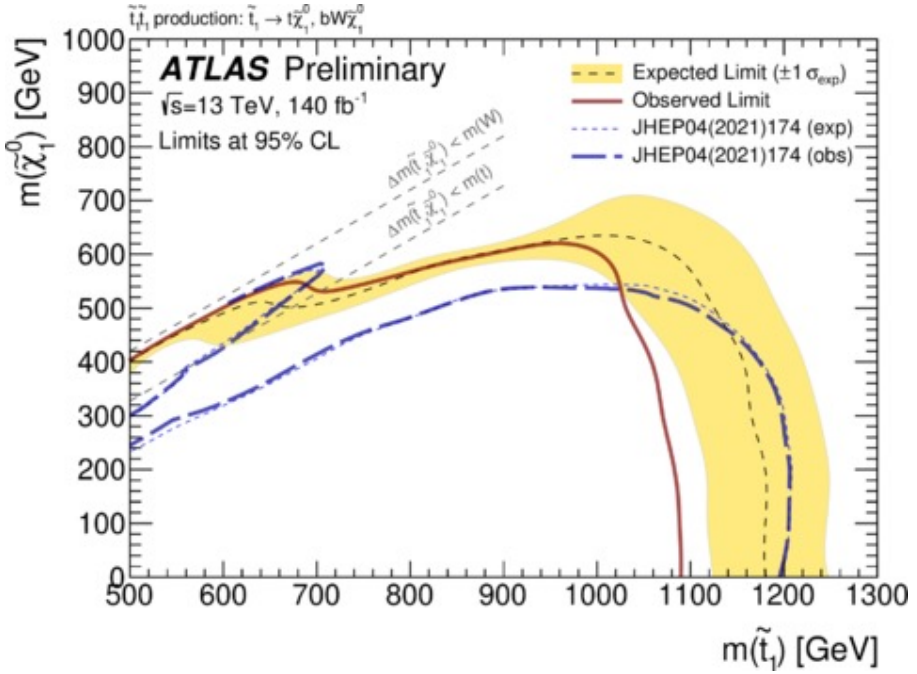


New Physics with tt+E_T^{miss}, Results

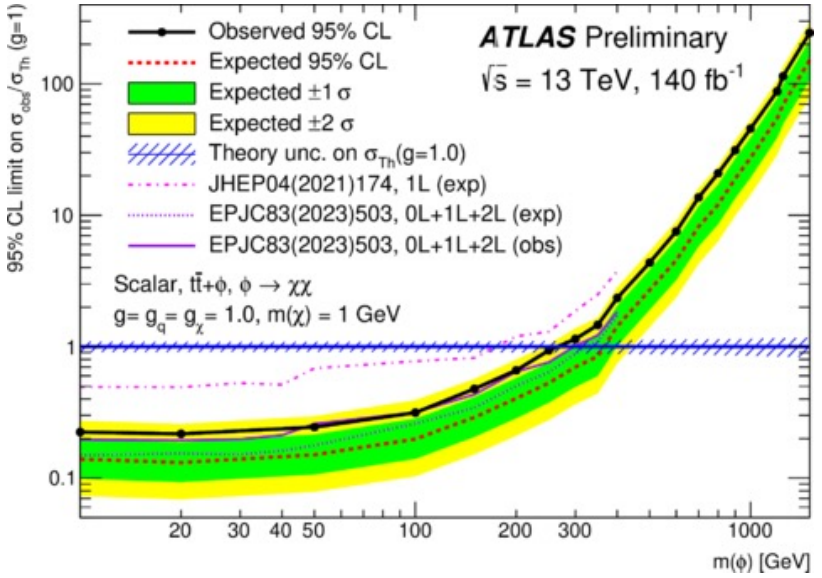
ATLAS-CONF-2023-043

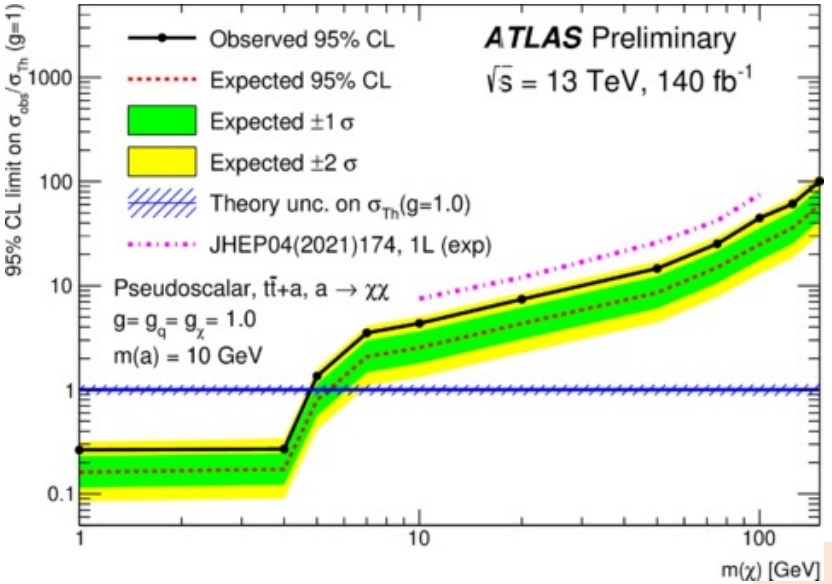


- No significant excess above the Standard Model backgrounds
- Excluded stops for masses up to 1090 GeV, while exclude neutralinos for masses up to 600 GeV;
- Significantly improved the sensitivity for high neutralino masses covering the parameter region at $\Delta m(\tilde{t}, \tilde{\chi}) \sim m_t$.



- For tt+DM searches, both limits on scalar and pseudoscaler are significantly improved in all parameter space;
- Excluded scalar (pseudoscalar) dark matter mediator masses as large as 250 (300) GeV;
- Set fraction predication limits at lower mediator masses.

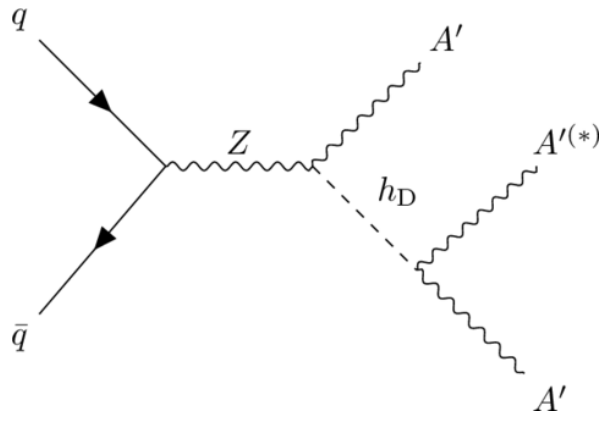




Next slide of "Dark Photon in Rare Z Decays", covered by Matteo Bauce, talk "Searches for Dark Matter with the ATLAS Experiment at the LHC (12+3)" under https://indico.cern.ch/event/1370675/ based on paper https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2019-32/

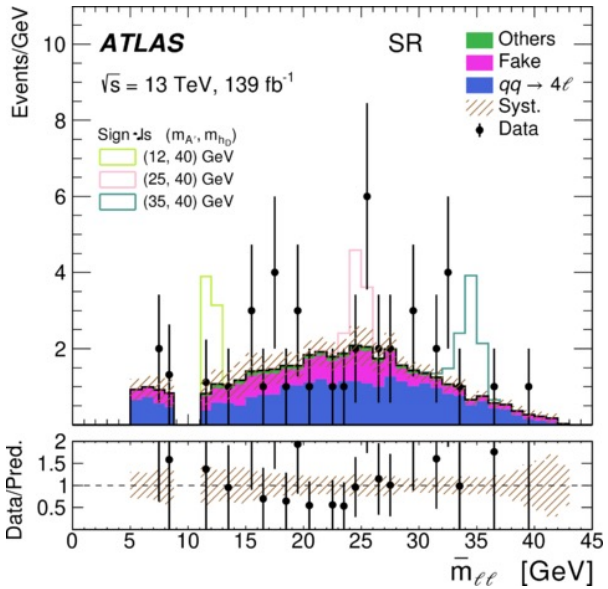
Dark Photon in Rare Z Decays

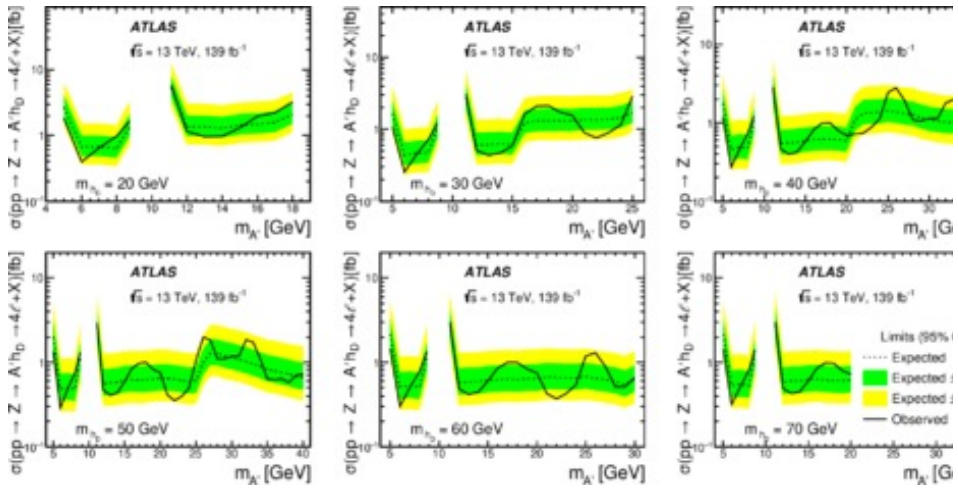
Phys. Rev. Lett. 131 (2023) 251801

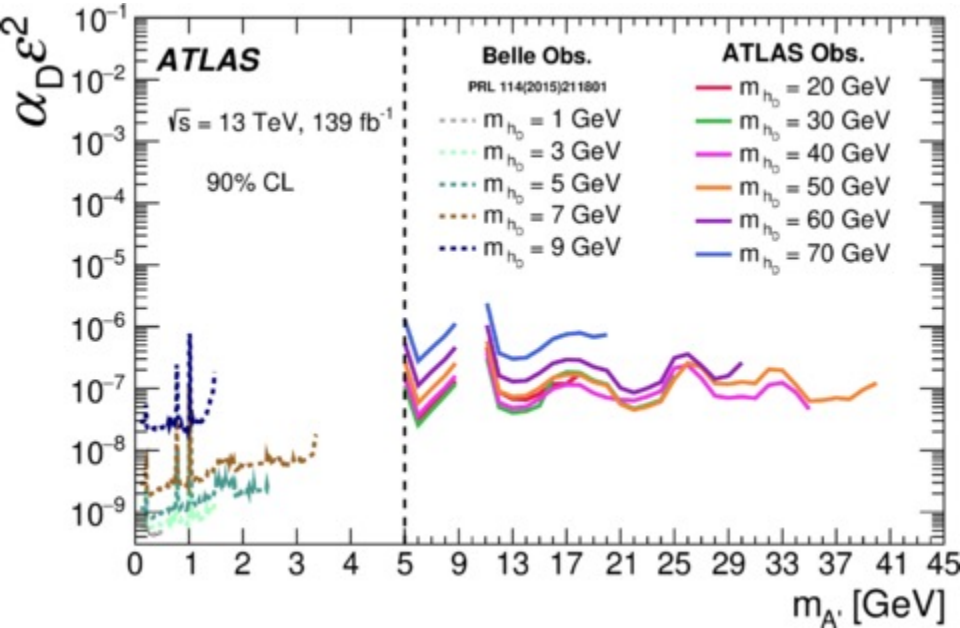


- The minimal secluded U(1) model predicts rare Z decaying to dark photon (A') and dark Higgs (h_D) with $h_D \rightarrow A'A'$, two of A's decay to e or μ pairs.
- The first search for a dark photon and dark Higgs boson produced via the dark Higgs-strahlung process in rare Z boson decays at the LHC;
- **Signature: at least two same-flavor opposite-charge lepton pairs (≥ 4 e/μ) with consistent m_{ll} of two lepton pairs by excluding Y(1s) and Y(3s) mass regions;**
- Major BKG qq → 4l from simulation and fake-factor method from data driven to determine fake/non-prompt background of CR and VR.

No surprise ➔ set on the production cross-section times branching fraction, $\sigma(p\,p \rightarrow Z \rightarrow A'h\mathrm{D} \rightarrow 4\ell + X)$, explore the dark photon to dark higgs coupling $\alpha_D\varepsilon^2$ space not previously excluded by other experiments.







Next slide of "Pair-production of VLQ Searches", covered by Marija Marjanovic, talk "Searches for Exotic Heavy Resonances with the ATLAS detector (12+3)" under https://indico.cern.ch/event/1370675/
based on paper https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2019-04/

Single VLQ B Production, B → bH→ bbb

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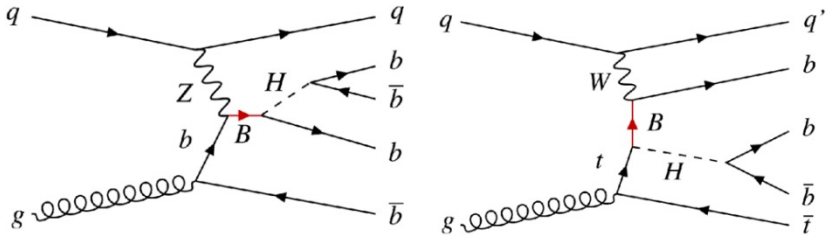
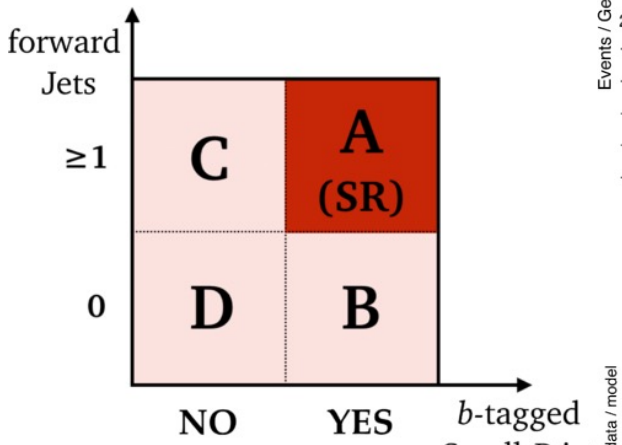
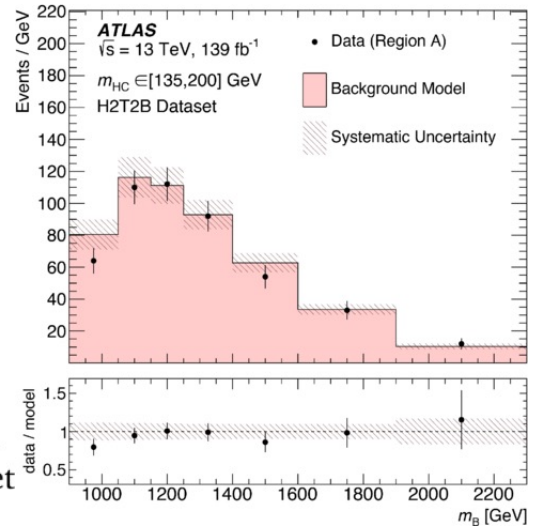
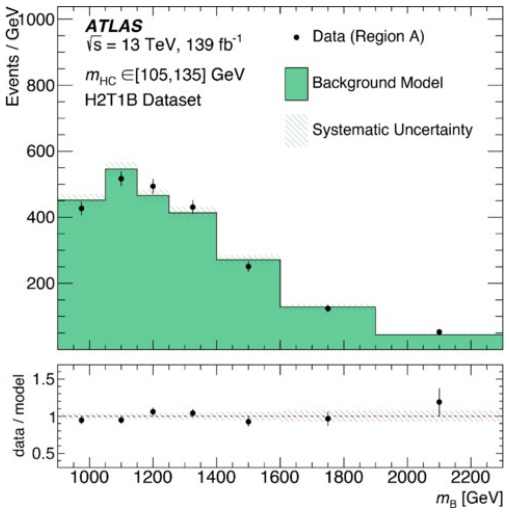
- **s-channel & t-channel B production mediated by a Z/W boson**
- **Events: at least 3 b-jets, 1 forward jet, a Higgs candidate (HC, 2 trk-jets, reconstructed as a large-R jet)**

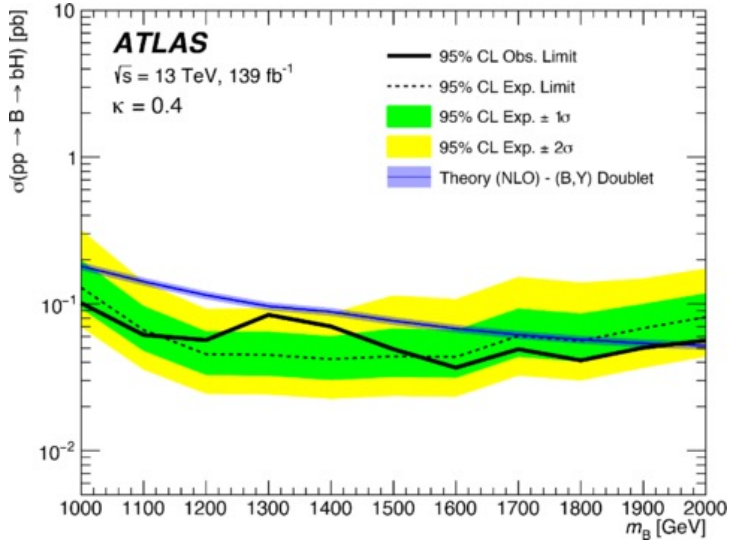


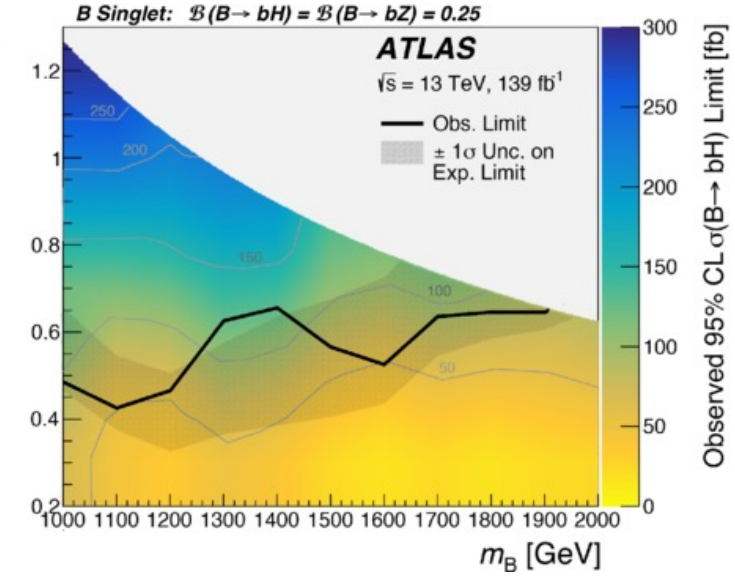


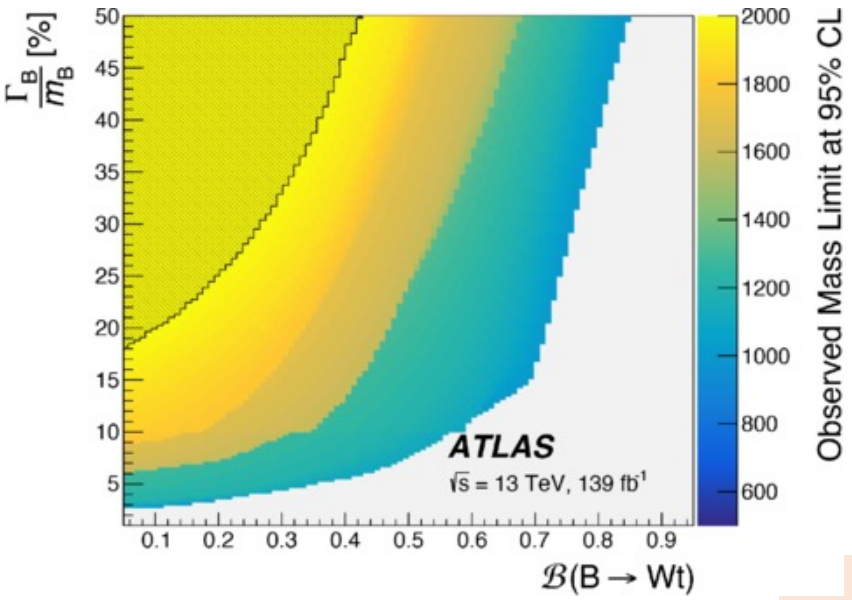




- **Data driven ABCD method is used for BKG modelling and is validated by control samples;**
- **Signals extracted by binned maximum-likelihood fit to m_B of reconstructed VLQ candidates;**
- **No deviation from SM, excluded 1 to 2 TeV B-quark depending on coupling constant.**







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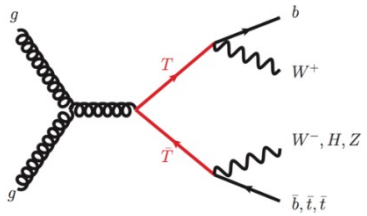
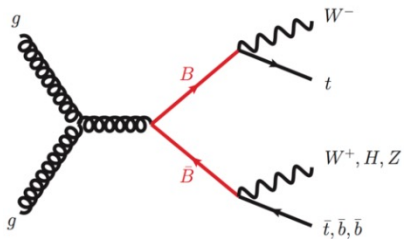
based on paper https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2019-06/

Pair-production of VLQ Searches

ATLAS-CONF-2023-070

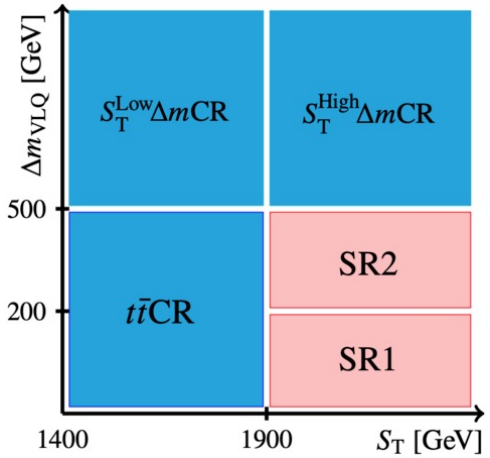


TT Production

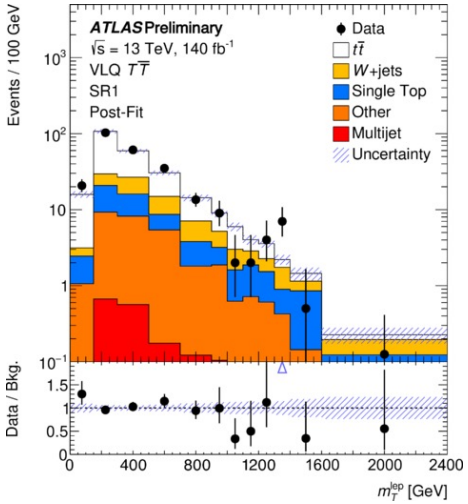


BB Production

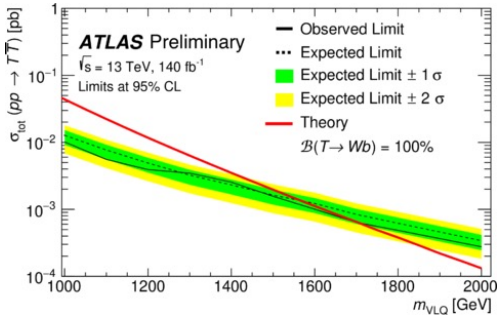
Optimized searches for T → Wb decays, One W→ lν, & other W → $\bar{q}q'$

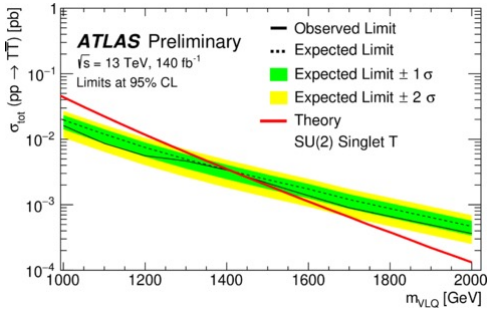


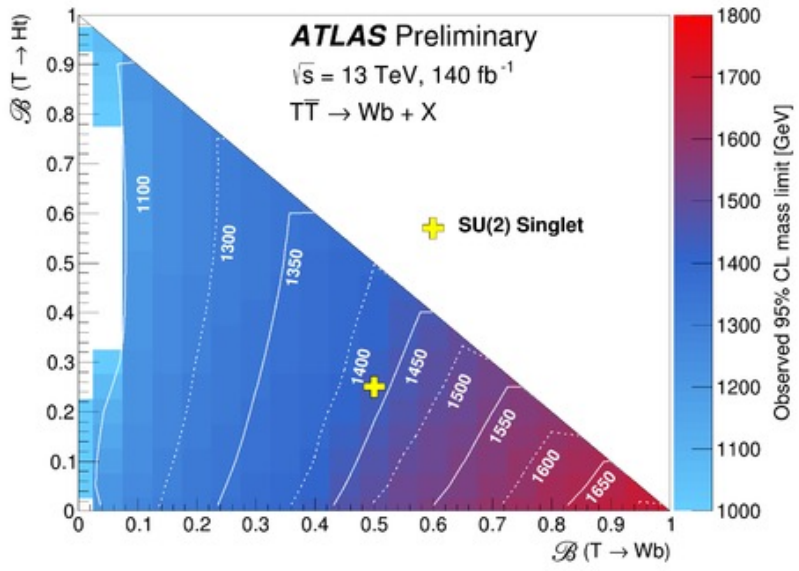
- Event: 1 μ/e with p_T > 27/60 GeV, E_T^{miss} > 60 GeV, at least 3 small-R jets, where >=1 b-tag jets;
- BKGs from **tt, W+jets** and t, Z+jets, VV with prompt lepton: MC with data driven corrections;
- BKG from multi-jet estimated using data driven approach.

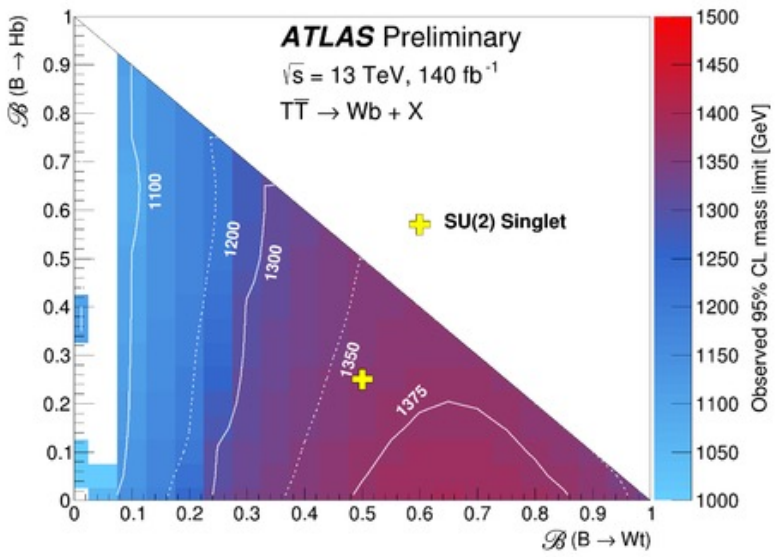


- **Signals extracted by simultaneous binned profile likelihood fit using the reconstructed m_T^{lep} distributions of the T candidate with W → lν on SRs and CRs;**
- **No deviation from SM ➔ observed (expected) limits at 95% CL 1700 (1500) GeV for TT & 1420 (1410) GeV for singlet-T.**





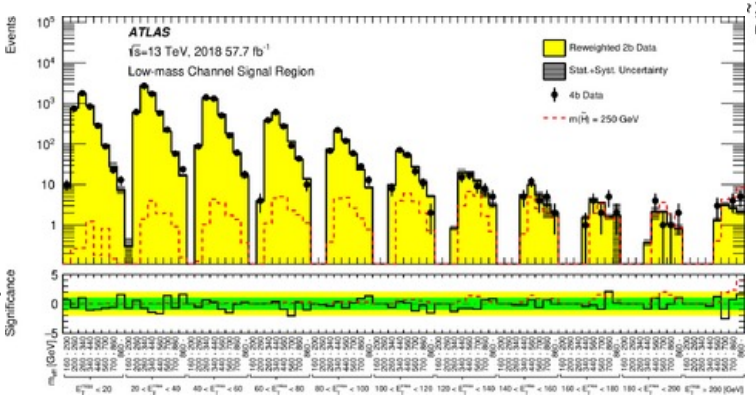


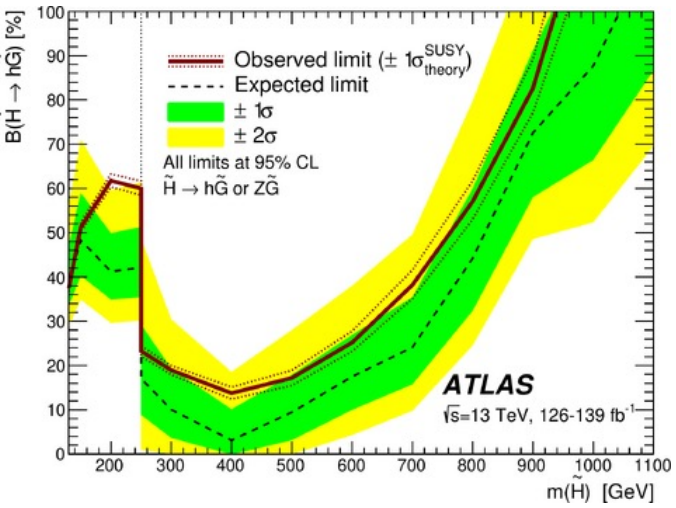


$\widetilde{H} \rightarrow h\widetilde{G} \rightarrow 2b\widetilde{G}$

arXiv:2401.14922

- **Signal: higgsino pair production with $\widetilde{H}$ into a Higgs boson (→bb) and a nearly massless gravitino;**
- Using ≥3 b-jets + E_T^{miss} events & BDT to discriminate between background and signal events
- Low mass (m_H<250GeV), BKGs from QCD multi-jet and tt using "ABDC" data driven method;
- Used multi-complementary bins;





- **Excluded B($\widetilde{H} \rightarrow h\widetilde{G}$) ~50% for low higgs mass, while the lowest limit on higgsino branching ratio 14% with $m_{\widetilde{H}}$ 400 GeV.**

LLP Searches @ATLAS

ATL-PHYS-PUB-2023-008

- Rich physics and a lot of searches